STANDARD MODEL PHYSICS AT THE LHC (pp COLLISIONS)

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This is the summary of the work done in the ECFA/LHC Working Groups studying the possibilities for Standard Model physics in pp collisions at the LHC. It is organized as follows:

1. Standard processes:
   - $\sigma_{\text{tot}}$ and $\sigma_{\text{el}}$: minimum-bias event
   - jets and direct photons
   - $W$, $Z$ production; $WZ$, $WY$ pair production

2. B physics:
   - possibilities of observing CP violation
   - collider versus fixed-target mode

3. Top physics:
   - top-quark searches, signal versus background
   - mass determination, branching ratios

4. The Standard Model Higgs:
   - searches for $m_H > 2m_Z$
   - searches for $m_H < 2m_Z$

5. Possibilities for neutrino physics at the LHC:
   - direct observation of the $\nu_\tau$
   - possibilities for $\nu_e$, $\nu_\mu$ studies

6. Conclusion

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INTRODUCTION

Within the framework of the ECFA Workshop on physics at the LHC, the study of the Standard Model phenomena in pp interactions at the LHC has been subdivided into four distinct subjects, with corresponding working groups: standard processes, B physics, top-quark physics, and the search for the Higgs boson. The working group on standard processes was in practice subdivided into three subgroups, dealing respectively with i) the determination of the elastic and total cross-sections; ii) the investigation of the possibilities for doing neutrino physics at the LHC; and iii) the study of the hard-collision phenomena: jets, direct photons, W and Z production, intermediate vector boson pair production (WZ, Wγ, ZZ), and heavy-flavour (b b̅ and t t̅) production cross-sections – the latter being used in part as an input for the groups studying specifically bottom- and top-quark physics. In the following, we will summarize the work of the various working groups in about the same order, starting with σtot and σel and finishing with neutrino physics. There was, in addition, a special working group devoted to event generators. Its activity consisted in comparing the various Monte Carlo generators among themselves and in understanding their limitations, fixing some problems, or inserting new mechanisms as the need arose. Although not often quoted in the following, they provided us with a critical understanding and optimization of the models used in the physics simulations. The list of conveners and active participants in each of the working groups is given in Ref. [1]. This summary is complemented by a similar one on physics beyond the Standard Model, by F. Pauss, and by an overview of all the pp/LHC workshop activities given by G. Altarelli, with more emphasis on theoretical issues.

Before summarizing the investigations of the various LHC/pp physics working groups, and to settle the order of magnitude of the various phenomena investigated, Fig. 1 shows the energy dependence of some characteristic cross-sections, and the event rates we expect at the LHC. At a luminosity of $10^{34}$ cm$^{-2}$ s$^{-1}$, the expected total cross-section of $\sim 100$ mb should be responsible for $\sim 10$ interactions per bunch crossing (every 15 ns). The expected rise of $\sigma_b \ b$ over the energy range considered shows that, already at a luminosity of $10^{32}$ cm$^{-2}$ s$^{-1}$, of the order of $10^{11}$ $b \ b\bar{b}$ pairs are produced in one year of running (i.e. for $10^7$ s), thus indicating the potential of such machines for B physics. The cross-section for jets of $E_T > 250$ GeV results in there being $> 10^3$ such jets produced per second at a luminosity of $10^{34}$ cm$^{-2}$ s$^{-1}$, indicating the need for selective triggers. The production cross-sections for W (or Z) $\rightarrow \ell \ell$ are expected to be a factor of $\sim 20$ times greater than at present colliders. Large-p$_T$ W, Z production will doubtless provide an interesting test of QCD, but it is also a major source of background for the potential signals looked for at the LHC, such as the top-quark and the Higgs, and has to be well understood. For $m_t = 200$ GeV, the top-quark is produced at a rate of $\approx 10^6$ $t \ t\bar{t}$ pairs per year already at a luminosity of $10^{32}$ cm$^{-2}$ s$^{-1}$, where detection is not expected to present particular problems. This makes machines such as the LHC or the SSC into real 'top factories'. It allows a detailed study of t-quark production and decay
properties — and a fortiori its discovery, if not yet made. Finally, Fig. 1 also shows that at a luminosity of $10^{34}$ cm$^{-2}$ s$^{-1}$ the much-desired Higgs boson is produced at the rate of $\sim 10^5$ events per year for $m_H = 500$ GeV. However, as the Higgs decay mode that provides the best experimental signature, $H \rightarrow ZZ \rightarrow 4\ell^\pm$, has a small branching ratio of $3 \times 10^{-4}$, the Higgs search in this most favourable channel should still be largely limited by statistics.

![Energy dependence of some characteristic cross-sections, from present colliders to the LHC/SSC.](image)

**Fig. 1** Energy dependence of some characteristic cross-sections, from present colliders to the LHC/SSC.
1. STANDARD PROCESSES

Total and elastic cross-sections

Figure 2a shows a compilation of present measurements of $\sigma_{\text{tot}}$ [2], including the latest Fermilab collider result from experiment E710: 72.1 ± 3.3 mb [3]. If the present rise is extrapolated to LHC energies according to $\sigma_{\text{tot}} \sim \log^2 s$ (Fig. 2a), we expect $\sigma_{\text{tot}} \approx 130$ mb at the LHC; if, however, as $s \to \infty$, $\sigma_{\text{tot}}$ tends instead to a constant, then the expectation is $\sigma_{\text{tot}} \approx 90$ mb (A. Martin). In conclusion, the expectation for the LHC is $\sigma_{\text{tot}} \approx 110 \pm 20$ mb (see also Ref. [4]).

Figure 2b shows the ratio of $\sigma_{\text{el}}/\sigma_{\text{tot}}$, which rises from $\approx 0.17$ at the ISR to $\approx 0.21$ at the Sp $\bar{p}S$ and to $\approx 0.23$ at Fermilab (0.23 ± 0.02) [2, 3]. The extrapolation of this behaviour leads us to expect $\sigma_{\text{el}}/\sigma_{\text{tot}} \approx 0.26$ at the LHC [4]. This ratio is related to the 'grayness of the proton', and its rise is limited by unitarity to the 'black disk limit' of 0.5 – $\varepsilon_{\text{diff}}$ (Pumplin's bound), where $\varepsilon_{\text{diff}}$ is the fraction of the diffractive cross-section due to single- and double-diffractive dissociation.

Figure 2c is a compilation of present measurements of the forward elastic slope $B$ [d$\sigma$/d$\tau$ ~ exp (-Bt)] [1]. Extrapolating present parametrizations, the expectation for the LHC is $B = 21$ GeV$^{-2}$ [2]. There is, however, much more to the elastic scattering than just the forward slope; the larger-t region $t \sim 1$ GeV$^2$ is very interesting too. Figure 3a shows the expectations for the large-t elastic scattering behaviour at LHC/SSC energies according to the impact-parameter model of Bourrely, Soffer and Wu [4]. In this model, the 'edge of the proton' becomes sharper with increasing $\sqrt{s}$, thus resulting in a more pronounced diffractive pattern. The fall-off between the forward maximum and the first secondary maximum is about three orders of magnitude; here the experimental difficulty is not in the event rate or the optics, but rather in the backgrounds present at larger $t$. In this model, no difference is expected between $pp$ and $p \bar{p}$ scattering at LHC energies. This is not the case, however, in the 'odderon model' (Gauron, Leader, Nicolescu, [5]) shown in Fig. 3b, and for which there are substantial differences between $pp$ and $p \bar{p}$, in particular in the region of the first minimum at $-t = 0.3$ GeV$^{-2}$. This model also predicts that $\sigma_{pp} > \sigma_{p \bar{p}}$. If the UA4 result $\rho = 0.24 \pm 0.04$ [6] (Fig. 4) is confirmed by the renewed experiment UA4/2, this would provide strong support for this 'odderon model', as it is the only one to expect such large values of $\rho$ at the Sp $p \bar{p}$ energies, whilst standard expectations are $\rho \approx 0.10$ to 0.15 [2, 4]. In this case, it would be interesting to check its other predictions concerning differences between $pp$ and $p \bar{p}$, i.e. it would then be important to keep open the possibility of doing also $p \bar{p}$ at the LHC. A luminosity of $\sim 10^{28}$ cm$^{-2}$ s$^{-1}$ would be possible with the present high-$\beta$ insertion discussed below (Scandale); this is sufficient for studying the difference between $pp$ and $p \bar{p}$ in the dip region, it would provide $\sim 10^4$ events per GeV$^2$ in 10 days of running (see Matthiae in Vol. II of these Proceedings). This $p \bar{p}$ option would not be possible at the SSC, where no $\bar{p}$ source is foreseen.

The present (provisional) high-$\beta$ insertion of W. Scandale is shown in Fig. 5. This
Fig. 2  a) Total cross-sections, b) ratio of elastic to total cross-sections, and c) forward elastic slope, with extrapolations to the LHC.

\[ \frac{d \sigma}{dt} \sim e^{-B|t|} \]

\[ t = 0.02 \text{ (GeV/c)}^2 \]
insertion, providing a luminosity of up to \( \sim 1.1 \times 10^{31} \text{ cm}^{-2} \text{ s}^{-1} \), has at the beam crossing point \( \beta^* = 750 \text{ m}, \Delta x^* = 300 \text{ \textmu m} \) for the beam size, and \( \Delta \theta_x^* = 0.5 \text{ \textmu rad} \) for the beam angular divergence. At the detectors – which are about 200 m from the crossing point – at \( \Delta \psi = \pi/2 \) (\( \Delta \psi \) is the betatron phase advance), \( \beta_{\text{det}} \sim 5 \text{ m} \) with \( \Delta x \sim 30 \text{ \textmu m} \), i.e. \( \theta_{\text{min}} \sim 9 \text{ \textmu rad} \) and \( t_{\text{min}} \sim 5 \times 10^{-3} \text{ GeV}^2 \) with a 0.5 mm minimal distance of approach of the detectors (probably fibre detectors in 'Roman pots', see Mondardini and Bernard in Vol. II) to the beams. It would be more favourable to have larger \( \beta \) at the detectors, and this could be remedied (Jeanneret). This \( t_{\text{min}} \) is adequate for the \( \sigma_{\text{tot}} \) measurement (10% extrapolation to the optical point). The total cross-section is then given by the luminosity-independent measurement

\[
\sigma_{\text{tot}} = \frac{16\pi}{(1 + \rho^2)} \frac{(dN_{\text{el}}/dt)_{t = 0}}{(N_{\text{el}} + N_{\text{inel}})},
\]

where \( N_{\text{el}} \) and \( N_{\text{inel}} \) are the total elastic and inelastic event rates, respectively (the effect of \( \rho^2 \) on \( \sigma_{\text{tot}} \) is almost negligible). The size of the beam pipe (4 cm) and the free space around the crossing point makes it possible to cover in a satisfactory way the forward rapidity range for the measurement of the total inelastic rate, with \( \eta \) coverage up to \( \sim 8.9 \), i.e. \( \theta_{\text{min}} = 0.27 \text{ mrad} \) (\( \gamma_{\text{beam}} \) is at 9.7). The exact position and shape of the forward counters measuring the total inelastic rate is not yet determined. However, the \( \eta \)-coverage must be such that the extrapolation uncertainty on \( N_{\text{inel}} \) is not larger than a few per cent (\( \sim 3\% \)), and is considered feasible (for more details, see Matthiae in Vol. II).

If \( \rho = 0.24 \) were confirmed by UA4/2, thus indicating that \( \rho \) continues to grow over the Sp pS range, it would be very important to measure it also at the LHC, as it is expected to peak at \( \rho \approx 0.12 \) to 0.15 and then decrease in any 'reasonable model' (A. Martin): if \( \sigma_{\text{tot}} \rightarrow \log^2 s \), then \( \rho \rightarrow \pi/\log s \); if \( \sigma_{\text{tot}} \rightarrow \log s \), then \( \rho \rightarrow \pi/2\log s \); if \( \sigma_{\text{tot}} \rightarrow \text{const} \), then \( \rho \rightarrow 0 \) faster, possibly as fast as 1/\( \sqrt{s} \). The measurement of \( \rho \) would, however, require measurements in the Coulomb scattering region, in a t-range substantially below the \( t_{\text{min}} \approx 5 \times 10^{-3} \text{ GeV}^2 \) that is accessible with the present (provisional) high-\( \beta \) insertion of Fig. 5. It might be possible either to increase \( \beta^* \) to \( \sim 2 \text{ km} \) or (and) to increase \( \beta_{\text{det}} \) (Scandale, Jeanneret), but here the SSC with its longer straight sections has an advantage.

The minimum-bias event

The properties of the 'minimum-bias event' are not calculable in QCD, thus we have to resort to various models. The understanding of the minimum-bias event, and of the related 'underlying event' in a hard-scattering process, is important, as they can limit or spoil the lepton (or \( \gamma \)) isolation, which is a crucial selection criterion in t-quark or Higgs searches. The underlying event is part of the hard collision event itself and is thus unavoidable, whilst the minimum-bias events enter through event superpositions during same bunch crossing when
Fig. 3  Elastic differential cross-sections in the large-t range.

Fig. 4  Compilation of data on $\rho$; the dashed line is the 'odderon model' prediction, solid line is the standard prediction.
Fig. 5  A provisional high-β insertion for the LHC.

Fig. 6  \( \langle n^\pm \rangle \) and \( \langle p_T \rangle \) in minimum bias events versus \( \sqrt{s} \).
running at high luminosity.

Figure 6a shows the expected $\sqrt{s}$ evolution of the mean charged-particle multiplicity $d\pi^+/d\eta$ (in $|\eta| < 2.5$) as predicted by various Monte Carlo generators (ISAJET, PYTHIA, GENCL). The data of UA1 and CDF are also shown. The models, even when tuned to reproduce the current data, present a spread of predictions. The extrapolation to the LHC gives $d\pi^+/d\eta \approx 5$ to $6$, i.e. $n^\pi_{\text{tot}} \approx 80$ charged particles per event on the average. Figure 6b shows the $\sqrt{s}$ variation of $<p_T>$ (for $|\eta| < 2.5$): at the LHC we expect $<p_T> \approx 530$ MeV/c (Di Ciaccio, Ciapetti, Sjöstrand).

**Hard collisions**

**Jet production**

Figure 7a shows the single-jet inclusive $E_T^{\text{jet}}$ production cross-section at $\sqrt{s} = 16$ TeV, as obtained from a lowest-order Monte Carlo (PYTHIA) calculation (Cox). Event rates are also given for a luminosity of $10^{33}$ cm$^{-2}$ s$^{-1}$ in bins of $\Delta E_T^{\text{jet}} = 100$ GeV and $\Delta y = 1$ at $y = 0$. In these conditions we would have a 1 kHz rate for $E_T^{\text{jet}} = 150$ GeV, and still about one event per hour at $E_T^{\text{jet}} \sim 1.5$ TeV. Thus jets in the TeV range are accessible, and in a year ($10^7$ s) of running, the expected QCD jet differential cross-section fall-off could be followed over 10 to 11 orders of magnitude. Next-to-leading order QCD calculations now exist (Guillet, and Ref. [7]); these, however, require a theoretical jet algorithm/jet-separation-cone definition in terms of, for example, $\Delta R = \sqrt{(\Delta y^2 + \Delta \phi^2)}$, and before comparison with data we must be sure of the experimental and theoretical compatibility of such criteria.

An important goal of jet physics is to look for possible deviations at high-$E_T^{\text{jet}}$ from the expected QCD point-like behaviour, which could reveal a possible composite structure of the quarks, as shown in Fig. 7b. Taking into account the uncertainties in the exact shape of the QCD fall-off due to the various possible choices of structure functions, in a year of running at $10^{33}$ cm$^{-2}$ s$^{-1}$ we would be sensitive, in terms of the usual compositeness scale parameter, to $\Lambda_c \approx 13$ TeV (Nessi). This can be compared with the present CDF result of $\Lambda_c = 0.95$ TeV [8].

**Direct photon production**

Figure 8a shows the expected inclusive isolated direct-photon production spectrum (Aurenche et al.), with event rates at $L = 10^{33}$ cm$^{-2}$ s$^{-1}$ in $\Delta E_{\gamma} = 100$ GeV and $\Delta y = 1$ at $y = 0$. Again, the rates are large, with about one $E_T^{\gamma} = 1$ TeV photon per day, and there is the possibility to follow the expected QCD differential cross-section fall-off over 8 to 9 orders of magnitude in a year of running. This would again provide an important test of QCD, in particular as next-to-leading order calculations now exist [9]. These require a theoretical definition of an isolated $\gamma$, and care must be taken that this definition is consistent with the experimental one, needed to extract the direct photon signal. The sensitivity to the quark compositeness scale for a year of running at $10^{34}$ cm$^{-2}$ s$^{-1}$ would be at $\Lambda_c \sim 7$ TeV (for details,
see Werlen in Vol. II).

At the low-$E_T\gamma$ end of the spectrum, as $gq \rightarrow q\gamma$ is the dominant production mechanism, direct-photon production allows investigation of the poorly known low-x behaviour of the gluon structure function. The direct photons are statistically separable from jets for $E_T\gamma > 50$ GeV (Werlen), which would allow $g(x)$ to be directly probed at $x > 10^{-3}$. The working group has also investigated additional contributions to two-photon production from $q\bar{q} \rightarrow \gamma\gamma$ and $gg \rightarrow$ quark loop $\rightarrow \gamma\gamma$ (Aurenche et al.; Bonesini, Camilleri, Werlen). As this production mechanism is the main irreducible background to the $H \rightarrow \gamma\gamma$ search, we postpone this discussion to the Higgs section.

Figure 8b compares the inclusive jet, direct photon, single particle ($\pi^0$), and 'isolated $\pi^0$' $p_T$ spectra at $\sqrt{s} = 16$ TeV (Aurenche et al., Guillet et al.). Isolated $\pi^0$ here means an inclusive $\pi^0$ with a fragmentation fractional momentum $z > 0.85$. The $\gamma$jet ratio is $\sim 2 \times 10^{-4}$ to $10^{-3}$, increasing with $p_T$, whilst the 'isolated $\pi^0$/jet ratio is $\sim 10^{-4}$ to $10^{-5}$ at $p_T > 150$ GeV/c, rapidly increasing at low $p_T$. This ratio is an important input, especially at low $p_T$, when estimating the contamination of direct photon or diphoton samples by jets.

**W, Z production**

The energy dependence of $\sigma_{W}^{\text{tot}}$ from present collider to the LHC/SSC energies is shown in Fig. 9 for a number of recent sets of structure functions (Plithow-Besch, and Refs. [10]). The $(p \bar{p})$ data of UA1, UA2, and CDF are also shown [11]. At LHC/SSC energies, pp and $p \bar{p}$ production cross-sections are the same within a few per cent, and about a factor of 20 larger than at present colliders. The Z total production cross-section is about a third of the W one. At the LHC, the expectations for $\sigma_{W}^{\text{tot}}$ vary between 90 nb and 270 nb, and for $\sigma_{Z}^{\text{tot}}$ between 30 nb and 80 nb, according to the various sets of structure functions. This $\sim \pm 50\%$ uncertainty on $\sigma_{W}$ and $\sigma_{Z}$ expectations makes the Z production rate unsuitable for a luminosity measurement. At a luminosity of 10$^{33}$ cm$^{-2}$ s$^{-1}$, these cross-sections correspond to a production rate of $\sim 10$ W $\rightarrow$ ev events per second and to $\sim 1$ Z $\rightarrow$ ee event per second, exceeding the LEP rates! This large W, Z production gives rise to a high rate of hard and isolated single leptons and dileptons, and is a source of a substantial background to t-quark and Higgs searches, especially at large $p_T^{WZ}$. Complete order $\alpha_s^2$ computations of large-$p_T$ W and Z production now exist [10]. The result is a 1 Hz production rate of $W \rightarrow$ ev events at $p_T^{W} \geq 150$ GeV/c and 1 Hz of $Z \rightarrow$ ee events at $p_T^{Z} \geq 60$ GeV/c, at a luminosity of 10$^{34}$ cm$^{-2}$ s$^{-1}$ (Wood).

**WZ and Wγ pair production and tests of anomalous couplings**

Pair production of intermediate vector bosons provides an essential test of the three-vector-boson couplings characteristic of the electroweak Standard Model. In the case of the WZ final state, for example, the interesting amplitude is the q q$\bar{q}$ annihilation diagram: q q$\bar{q}$ $\rightarrow W^{*} \rightarrow WZ$. Figure 10 shows the energy dependence of the $\sigma_{WZ}^{BR}(W \rightarrow ev) \cdot BR(Z \rightarrow ee)$
Fig. 7a  Inclusive jet production at the LHC;

Fig. 7b  Inclusive jet production at the LHC and expected effects of quark compositeness.

Fig. 8a  Inclusive direct-photon production at the LHC;

Fig. 8b  Inclusive jet, photon, single $\pi^0$, and isolated $\pi^0$ spectra at the LHC.
cross-section in pp interactions (Plouthow-Besch). At LHC/SSC energies, this cross-section is \( \sim 0.1 \) pb, which means the production of \( \sim 10^3 \) WZ \( \rightarrow (e\nu) \) (e\nu) events per year for \( L = 10^{33} \) cm\(^{-2}\) s\(^{-1}\). Figure 10 also shows the expected \( p \overline{p} \rightarrow WZ + X \) cross-section in the Fermilab Collider range: for an integrated luminosity of \( \sim 200 \) pb\(^{-1}\), this would imply only a few such events produced. This may be enough for a first observation of gauge boson pair-production, but is insufficient for studying the expected gauge cancellations.

From the experimental point of view, it is the WZ channel with W and Z decaying to leptons which is the most convenient one. The WW channel (Mele) is submerged by \( t \overline{t} \rightarrow W W b \overline{b} \) production, and WZ production with either the W or the Z decaying to q \overline{q} \rightarrow jet-jet is buried under QCD W(Z) + jets production, as can be seen in Fig. 22 discussed later in connection with t-quark physics (Denegri, Rodrigo, Sajot). In contrast, the WZ \( \rightarrow \ell\nu \ell\ell \) channel is essentially background-free, as can be deduced from Fig. 11, showing the inclusive \( p_T \)-integrated three-muon spectrum at \( \sqrt{s} = 16 \) TeV (Nisati). Before any cuts, the main background to WZ production is due to c, b and t-quark production. However, c and b production can be suppressed by a factor of \( \sim 10^3 \) to \( 10^4 \) by an \( M_{\ell\ell} = m_Z \pm 5 m_Z \) mass cut and by a lepton isolation criterion. The lepton isolation rejection factor is \( > 10 \) for leptons of \( p_T \ell > 30 \) GeV/c, and increases with increasing \( p_T \ell \) (for details, see Rodrigo in Vol. II). Similarly, the t-quark background can be reduced by a factor of \( \sim 10^2 \), with again the \( M_{\ell\ell} \) mass cut and an isolation requirement on the third lepton, which in \( t \overline{t} \rightarrow Wb \) production usually comes from the b decay (from \( t \rightarrow Wb \)).

For a comparison with LEP 200 possibilities, note that the rate of WW production at LEP is comparable to the WZ \( \rightarrow \ell\nu \ell\ell \) rate at the LHC at \( 10^{33} \) cm\(^{-2}\) s\(^{-1}\). But \( M_{WW} \) is limited to \( \leq 200 \) GeV at LEP, whilst \( M_{WZ} \sim 1 \) TeV is accessible at the LHC, and the gauge cancellations are largest at large boson-pair invariant masses [12]. This makes the LHC/SSC much more sensitive than LEP 200 to anomalous couplings. Figure 12 shows the expected WZ transverse mass \( M_T^{WZ} \) distribution (the directly measurable quantity, since the longitudinal neutrino momentum component is not measurable) according to the Standard Model couplings, and for an anomalous coupling characterized by two values of the parameter, \( \lambda = 0.1 \) and \( \lambda = 0.04 \) (Plouthow-Besch). In the SM, \( \lambda = 0 \), and the rate at large \( M_T^{WZ} \) is smallest. The lepton selection cuts are \( p_T^e > 25 \) GeV/c and \( \ln | e | < 2.5 \). With an experimental sensitivity of \( 10^5 \) pb\(^{-1}\) (i.e. \( 10^7 \) s at \( 10^{34} \) cm\(^{-2}\) s\(^{-1}\)), the expected signal and background rates would be: 11240 events for the signal from \( W^+Z + W^-Z \), 550 events from the background of \( Z + b \rightarrow \ell\ell + \Delta c \), and < 2000 events from the \( t \overline{t} \) background, assuming a lepton isolation rejection factor of \( R_{ISO} = 5 \), which is very conservative for leptons of \( p_T^\ell > 25 \) GeV/c, and a Z mass cut rejection factor of 10 against \( t \overline{t} \). The event rates are large enough, so that more stringent rejection cuts could be employed at the expense of some loss in efficiency; thus no problems are expected with backgrounds in this channel, as previously argued (Fig. 11). As a measure of the experimental sensitivity limit, for an integrated luminosity of \( 10^5 \) pb\(^{-1}\) we expect 10
Fig. 9 W production cross-section versus √s.

Fig. 10 WZ production cross section in pp collisions versus √s.

Fig. 11 Inclusive three-muon spectrum versus p_T threshold.
Fig. 12  WZ transverse mass at $\sqrt{s} = 16$ TeV.

Fig. 13  Photon transverse momentum from $W\gamma$ events at $\sqrt{s} = 16$ TeV.
events at $M_{T,WZ} > 1.0$ TeV for the SM, 10 events at $M_{T,WZ} > 1.12$ TeV if $\lambda = 0.04$, and 10 events at $M_{T,WZ} > 1.64$ TeV if $\lambda = 0.1$ (for details, see Plothow Besch, Vol. II). The expectation is thus that gauge couplings could be checked at the few per cent level, which is almost an order of magnitude better than at LEP 200.

Another promising channel for studying gauge cancellations and possible anomalous couplings is $W\gamma$ production [13]. Anomalies in the $WW\gamma$ coupling would again reveal themselves best at large $W\gamma$ masses or, equivalently, at large $p_T\gamma$, which is the directly measured quantity. Figure 13 shows the expected $p_T\gamma$ behaviour at $\sqrt{s} = 16$ TeV if the anomalous coupling $\lambda$, entering the $W$ magnetic dipole and electric quadrupole coupling [13], takes a value $\lambda = 0.1$, and for the Standard Model value $\lambda = 0$. For $\lambda = 0.1$ and the following data selection cuts: $p_T\gamma > 100$ GeV/c, $|\eta|<2.5$, $p_T^{e,\nu} > 25$ GeV/c, $|\eta_e|<2.5$, and $|M_{e,\nu}-m_W|<20$ GeV, the total number of events expected would be $\approx 6900$ $W^{+}\gamma$ and $\approx 5200$ $W^{-}\gamma$ events, for a luminosity of $10^5$ pb$^{-1}$ (Pepe, Pastore). These numbers of events take into account the electron identification and isolation cuts and efficiency. As can be seen in Fig. 13, the cross-section for $\lambda = 0.1$ is about a factor of 2 larger than in the SM, and we would be sensitive up to $p_T\gamma = 800$ GeV (i.e. 10 events expected at $p_T\gamma > 800$ GeV for $\lambda = 0.1$). Assuming conservatively a jet-to-$\gamma$ misidentification probability of $10^{-4}$ for $p_T\gamma > 100$ GeV/c, the background of $W + \text{jets} \rightarrow e\nu + \text{jet}$ events is not negligible, and amounts to $\sim 20\%$ of the signal. However, the background is more concentrated at low $p_T\gamma$ than the signal, and increased rejection is possible at the expense of efficiency, which can be afforded as the rates are high enough. At $p_T\gamma > 200$ GeV/c, for example, and relaxing the $M_{e,\nu}^{e,\nu}$ cut, the signal is reduced to $\approx 2170$ events and the background to $\sim 40$ events. In conclusion, we should be sensitive to values of $\lambda$ down to $\sim 0.05$, and no major difficulties are foreseen for this channel, in particular not in the interesting large-$p_T\gamma$ range (Pepe, Pastore).

The ZZ pair production has also been studied (Mele). However, as distinct from WW, WZ and W$\gamma$, the ZZ (and Z$\gamma$) final state brings no information about the triple-gauge-boson couplings; it does, however, represent an important background in Higgs searches and we postpone its discussion to the Higgs section.

2. B PHYSICS AT THE LHC

Hadron machines are a powerful tool for observing particles containing heavy quarks, when such particles have a measurable decay length. The success obtained with silicon microvertex detectors in the search for charmed particles is evidence that decay-length measurements can indeed be used. The main issue in B physics at the LHC is the observation of CP violation in the B system, and the ultimate goal is to measure the three interior angles of the Cabbibo-Kobayashi-Maskawa (CKM) matrix unitarity triangle [14].

In the small generation-mixing-angle approximation, the CKM matrix can be written as (the Wolfenstein parametrization):
\[ V_{\text{CKM}} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1 & -\lambda^2/2 & \lambda A\lambda^3(\rho - i\eta) \\ -\lambda & 1 & -\lambda^2/2 A\lambda^2 \\ A\lambda^3(1 - \rho - i\eta) & -A\lambda^2 & 1 \end{pmatrix}, \]

where \( \lambda = \sin\theta_C \approx 0.22 \), and where the parameter \( A \) is determined by the B lifetime, \(|A| = 1.0\). In this parametrization, only the elements \( V_{ub} \) and \( V_{td} \) have a phase, provided \( \eta \neq 0 \), which implies CP violation in the framework of the SM and vice versa [14,15]. The unitarity of the CKM matrix implies a relation between the elements

\[ V_{td} + V_{ub}^* = \lambda V_{cb}, \]

which can be represented by the 'unitarity triangle' sketched in Fig. 14a, with the three interior angles \( \phi_i \) indicated. The values of the parameters \( \rho \) and \( \eta \), or equivalently of the angles \( \phi_i \), are at present poorly determined from the CP measurements in the \( K \bar{K} \) system. The allowed domain of variation of \( \rho,\eta - \) if we take into account constraints provided by measurements of \( \varepsilon, |V_{ub}/V_{cb}|, \) and \( x_d \) for two values of \( m_t - \) is shown in Fig. 14b (shaded area), taken from Ref. [14]. The use of the \( B \bar{B} \) system for CP-violation measurements would be much more constraining for the Standard Model, hence the interest in checking in detail the SM scenario for CP violation. The point is that the three angles \( \phi_i \) are, in principle, all accessible to direct experimental measurements.

We consider \( B^0 \) decays to final-state \( f: B^0 \rightarrow f \) and \( \bar{B}^0 \rightarrow \bar{f} \). In the case where these are CP eigenstates, i.e. \( \bar{f} = \pm f \), the experimentally measurable decay-rate asymmetry \( A \), defined as

\[ A = \frac{N(B^0 \rightarrow f) - N(\bar{B}^0 \rightarrow \bar{f})}{N(B^0 \rightarrow f) + N(\bar{B}^0 \rightarrow \bar{f})}, \]

depends only on the angles \( \phi_i \) of the unitarity triangle with no hadronic physics complications in appropriately chosen channels (Lusignoli, Pich, and Refs. [14,15]). For example:

\[ A \sim \sin 2\phi_1 \quad \text{for decays such as } B^0_d \rightarrow \psi K^0_S, \ldots, \]
\[ A \sim \sin 2\phi_2 \quad \text{for decays such as } B^0_d \rightarrow \pi^+\pi^-, \ldots, \]
\[ A \sim \sin 2\phi_3 \quad \text{for decays such as } B^0_s \rightarrow \rho K^0_S, \ldots. \]

Thus \( B^0_{d,s} \) decay channels exist, giving direct access to these angles (Fig. 14). Large CP-violating asymmetries \( A \), in the \( \sim 5\% \) to \( \sim 50\% \) range, are necessarily found in the small branching ratio modes, with typically \( BR = 10^{-4} \) to \( 10^{-6} \). The asymmetry must be substantial
in at least one of these three classes of decays [14]. The $B^0_d \to \psi K^0_S$ is one of the most favourable decays, since from Fig. 14b the angle $\phi_1$ cannot take values of $\approx 0^\circ$ or $\approx 90^\circ$ where the asymmetry would vanish: thus a finite asymmetry is guaranteed. For this Workshop, the lower limit of $|\sin 2\phi_1| > 0.08$ from Ref. [14] has been updated to $> 0.20$ (Lusignoli, Prades, Pich), making the situation even more favourable. The branching ratio in this mode is known, $\text{BR}(B^0_d \to \psi K^0_S) \cdot \text{BR}(\psi \to \ell \ell) \cdot \text{BR}(K^0_S \to \pi^+\pi^-) = 3 \times 10^{-5}$, whilst for $B^0_d \to \pi^+\pi^-$ and $B^0_s \to \rho K^0_S$ the expected branching ratio is $\text{BR} \sim 2 \times 10^{-5}$. There is, in fact, a variety of ways in which CP can be violated in the B system [15], but the theoretical predictions are reliable and constraining only in the case of decays to CP eigenstates.

The main issues addressed by the working group were:

i) the best channels for observing the asymmetry – with Lusignoli, Prades and Pich updating the work of Ref. [14] in the light of more recent QCD sum rules and lattice calculations applicable to $B^0_d$ mixing, the range for $f_B$ now being 160 to 250 MeV (see working group report in Vol. II);

ii) the experimental possibilities of triggering, reconstructing and tagging such decays in a collider mode, with a very detailed simulation of an appropriate apparatus and its response (Erhan, Schlein), and the sensitivity it would provide to a measurement of $\sin 2\phi_1$;

iii) a discussion of the relative advantages of the various machines for CP-violation measurements (Fridman), and in particular of the possibilities of high-energy pp machines in the collider versus fixed-target mode of operation (Grancagnolo, Lemoigne, Denegri, Zolnierowski), or in a beam-dump type of experiment (Fidecaro); and finally,

iv) the study of the effect of 'fake asymmetries' present in pp machines (and $p \bar{p}$ in each arm independently) owing to the presence of valence quarks (Lusignoli, Pugliese, Steger; Fridman).

The beauty-charmed mesons, a subject not related to CP violation, was also discussed (Lusignoli and Masetti).

**B production at hadron colliders**

i) Collider mode

The expected production cross-section $\sigma_b \bar{b}$ over the LHC/SSC energy range is shown in Fig. 15a [15,16]. There are large uncertainties in the estimate of $\sigma_b \bar{b}$. On the one hand, they are related to the poor knowledge of the gluon structure function at low $x$ ($x \sim 10^{-3}$ to $10^{-4}$ is probed here), used as an input in the calculation. On the other hand, they are due to the questionable applicability of perturbative QCD calculations (at order $\alpha_s^3$) in this regime, where $2m_b/\sqrt{s} \ll 1$. The perturbative QCD estimate of Nason for $\sqrt{s} = 16$ TeV is $\sigma_b \bar{b}$ in the 0.1 to 0.7 mb range. An independent estimate, based on a quark–gluon string model by Kaidalov [17], is again $\sigma_b \bar{b} \sim 0.1$ to 0.7 mb, whilst the scaling-law approach of De Rujula and Rückl gives $\sigma_b \bar{b} \sim 0.5$ mb within a factor of $\sim 2$ [18]. The overall uncertainty is thus about an order of magnitude at $\sqrt{s} = 16$ TeV. In the following, we use $\sigma_b \bar{b} = 0.3$ mb. The fraction of $b \bar{b}$ events is $\sigma_b \bar{b}/\sigma_{tot} \approx 1/500$ at the LHC and $\approx 1/300$ at the SSC. At a
luminosity of $10^{32}$ cm$^{-2}$ s$^{-1}$ (to avoid multiple interactions per bunch crossing), these cross-sections imply the production of $\sim 3 \times 10^{11}$ $b\bar{b}$ events per year ($10^7$ s).

ii) Fixed-target mode

If the 8 TeV proton beam of the LHC is used in a fixed-target mode, either as an extracted beam on an external target, or as a circulating beam on a gas-jet or wire target, the pp centre-of-mass energy $\sqrt{s}$ is 123 GeV for the LHC (and 193 GeV for the SSC). Figure 15b shows the expected $b\bar{b}$ production cross-section in this fixed-target regime of the LHC/SSC, from a QCD computation by K. Ellis. The UA1 point (in $p\bar{p}$ interactions, $19.3^{+11}_{-8.5}$ µb) is also shown for comparison [19]. The QCD expectations are now somewhat more reliable and lead us to expect $\sigma_{b\bar{b}}(LHC) \approx 0.3$ to 1.5 µb at $\sqrt{s} = 120$ GeV, with $\sigma_{b\bar{b}}(SSC)/\sigma_{b\bar{b}}(LHC) \approx 5$. As $\sqrt{s}$ is much smaller than in the collider mode, there are two significant consequences: $\sigma_{b\bar{b}}(collider\ mode)/\sigma_{b\bar{b}}(fixed\-target\ mode) = 250$, i.e. the production cross-section is substantially smaller, and also $\sigma_{b\bar{b}}/\sigma_{tot}$ is now $\sim 10^{-4}$, as compared with $\sim 1/500$ in the collider mode. Nonetheless, for $10^8$ protons per second on a few per cent $\lambda_{int}$ W-target, the above cross-sections would lead to $\sim 5 \times 10^9$ $b\bar{b}$ produced per $10^7$ s of running at the LHC.

*Fixed-target versus collider modes*

Hadron colliders have very large $b\bar{b}$ production rates, in particular in the collider mode (Table 1). Provided the B's can be isolated – which is not yet proven – these machines give the possibility to study in detail the CP violation sector of the Standard Model [20, 21]. The rates in the fixed-target mode are significantly smaller, which probably would not allow such a comprehensive study, but it should be sufficient to observe CP violation in the most favourable modes, whilst being experimentally simpler and less expensive (Grancagnolo, and Ref. [21]). For comparison, the highest luminosity $e^+e^-$ colliders now considered would produce $\sim 10^8$ $b\bar{b}$ pairs per year at a luminosity of $10^{34}$ cm$^{-2}$ s$^{-1}$ (the CESR project), and in spite of the much more favourable signal-to-background ratio, this event rate seems marginal for detailed CP violation studies, except in the more favourable scenarios [14].

The two disadvantages of the fixed target mode – smaller $\sigma_{b\bar{b}}$ and poorer signal-to-background ratio – are, however, compensated by a number of advantages. At $\sqrt{s} = 123$ GeV the average event charged multiplicity is $\sim 18$, as compared with $\sim 80$ in the collider mode at $\sqrt{s} = 16$ TeV. The decay kinematics is also more favourable in the fixed-target mode. The large Lorentz boost gives average B flight-paths of a few centimetres, as compared with a few millimetres in the collider mode. This is illustrated by Fig. 16 (Lemoign, Zolnierowski). The larger lab. momenta of the B decay products should also substantially ease the problems of triggering and tagging.

Before the goal of making a detailed study of CP violation can be achieved in pp colliders, there are many experimental problems to be solved [20, 21, 22].
Fig. 14  a) the unitarity triangle, and b) the allowed domains of $\rho$ and $\eta$ from Ref. [14].

Fig. 15  $b \bar{b}$ production cross-sections versus $\sqrt{s}$.

Fig. 16  B decay length in collider and fixed-target modes for various acceptances on the B.
1) How to trigger on the interesting decay modes. The possibilities are to use $\mu$ or $\mu\mu$, or more generally leptons, at large p (E) in fixed-target mode, or large $p_T$ (> 1.5 GeV/c) in collider mode. For $B^0_d \rightarrow \psi K^0_S$, a trigger on the $\psi \rightarrow \mu \mu$ decay is possible (see Schlein, Grancagnolo and Fidecaro contributions in Vol. II, and Refs. [20, 21, 22]). For $B^0_{d,s} \rightarrow \pi^+\pi^-, K^+K^-, \rho^-\rho$, a possibility could be a secondary-vertex trigger and the presence of harder-$p_T$ tracks than in usual minimum-bias events (two-body decays with a large Q-value).

With respect to triggering, a fixed-target experiment may have a substantial advantage, as the B-decay tracks are much harder, with $<p> = 100$ to 300 GeV/c for $B^0_d \rightarrow \psi K^0_S$ or $\pi^+\pi^-$ in a fixed-target mode, as compared with $<p> = 20$ to 50 GeV/c in the collider mode, depending on acceptance (Table 1). The geometry of fixed-target experiments should make the trigger easier [20, 21]. With a thin target, it is possible to have a point-like source of B's, and with straight tracks and as little material as possible around the target, events could be selected with tracks not originating from the point source (secondary-vertex trigger à la WA82).

2) The necessity of tagging the decaying $B^0_{d,s}$ through the B produced in association. Although some CP violation measurements are possible without tagging, the tagging is an absolute necessity for the decays to CP eigenstates [15]. The possibilities for tagging are the use of: i) the lepton charge from the associated $B(\bar{B}) \rightarrow \ell^+\ell^- + X$; ii) the kaons from the $b \rightarrow c \rightarrow s$ sequence [22]; iii) the use of the charge of the associated $B^\pm$, through a complete $B^\pm$ reconstruction at a secondary vertex.

Here again the fixed-target mode may have an advantage, as long (centimetre) decay lengths may ease secondary-vertex reconstruction, and all decay products are hard (Lorentz boosted), whilst in the collider mode a few-hundred MeV/c pion can more easily be lost at the decay vertex.

3) There is a need for particle identification. This is essential for a comprehensive study of CP violation in $B^0_{d,s} \rightarrow \pi^+\pi^-, K^+K^-, \rho^-\rho, K\pi$, etc., final states. The interesting modes necessarily have small branching ratios and must be cleanly separated from the dominant decay modes. It is clear that particle identification with B-decay products in the hundreds of GeV/c momentum range will place very great demands on RICH spatial resolution, and in this respect the collider mode may have an advantage.

4) The need for good $B^0$ mass resolution: $\delta m_B \ll 200$ MeV (in all-charged decay modes), to distinguish between $B^0_d$ and $B^0_s$ decays to $\pi^+\pi^-$ or $K^+K^-$, and to distinguish between $B^0_d \rightarrow \psi K^0_S$ and $B^0_d \rightarrow \psi K^0_S \pi^0$, where the CP asymmetry may be of opposite sign [14].

These measurements, in both collider and fixed-target mode, are rendered more difficult by various (unavoidable) dilution factors (Steger, Lusignoli, Pugliese, Fridman, and Ref. [20]).

1) Dilution due to oscillations of the decaying $B^0$. This cannot be avoided, since it is precisely
because mixing is present that there is CP violation in the most interesting CP eigenstates, i.e. without mixing there would be nothing to observe.

2) Dilution due to oscillations of the tagging $B^0$. In this respect the $B^\pm$ is the best tagger, if it is clearly recognizable. Here again there may be a potential advantage for a fixed-target mode, if a $B^\pm$ can be fully and reliably reconstructed as a secondary-vertex $B^\pm$ decay. As for the $B^0_s$, it is expected to oscillate so rapidly ($x_s = \Delta m/\Gamma_{10}$ is expected) that it is useless as a tagger. A consequence of the large expected value of $x_s$ is that time-integrated measurements of the asymmetry for $B^0_s \rightarrow \rho K^0_s, \pi^+\pi^-, K^+K^- \ldots - \sin2\phi_3$ are useless ($A = 0$). The measurement of the angle $\phi_3$ is particularly difficult, as in practice it is accessible only through $B^0_s$ decays, which requires good proper-time (i.e. space and momentum) resolution, in order to study the proper-time evolution of the system.

3) Attention must also be paid to the unavoidable, but small, fake asymmetry resulting from the unequal $B$ and $\bar{B}$ production in hadron collisions, and which is due to valence quarks. It is estimated at the few per cent level (Lusignoli, Pugliese and Steger; Fridman), whilst, for comparison, the expected CP-violating asymmetries in the interesting modes may be at the 5% to 50% level. These fake asymmetries can be measured, either from the difference between production rates of $B^+$ and $B^-$ decaying to $CP$-non-violating modes, or by measuring the apparent asymmetry $A$ in a $B^0$ decay mode where no $CP$ violation is expected, as in $B^0 \rightarrow \psi\phi$ [14, 20].

In Table 1 (Lemoigne, Fridman, Denegri, Zolnierowski) we attempt to summarize the relative merits of the two pp machine possibilities – collider mode versus fixed-target mode – using as reference experiments, BCD [20] and P238 [22] for the collider mode, the SFT [21] for the fixed-target mode, and the experience gained with NA14. The fixed-target option seems more advantageous, but is ultimately limited by the total production rate. Detailed estimates of achievable sensitivities to $\sin2\phi_3$ in the fixed-target mode have yet to be made. A study of a crystal channelling extraction scheme by Jeanneret and Scandale shows that, provided outstanding progress can be made in the precise alignment of the atomic planes in the crystal and its surface, about 1 to $2 \times 10^8$ protons per second could be extracted from the LHC, which is comparable to the flux extracted in the SSC. The possibilities for B physics with an internal target have not yet been looked into; those for a beam-dump type of experiment, according to the suggestion of Kekelidze [24], have been discussed by Fidecaro (see Vol. II for more details). Much more work is clearly needed, but we may expect that a number of questions just raised will be answered in the (near) future: the feasibility of a 'secondary vertex' trigger at colliders by experiment P238 (Schlein and collaborators, Ref. [22]), and in fixed-target mode by the on-going SPS and Fermilab B-physics experiments; for the performance of both $\psi$ triggers and microvertex detectors at higher rates, by experiments E771, CDF, etc.
Table 1 Comparison of some experimental conditions in collider and fixed-target mode (kinematics from ISAJET and/or PYTHIA); stars = quality of merit in each mode;

<table>
<thead>
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<th>Fixed target mode</th>
<th>Collider mode</th>
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<tr>
<td></td>
<td>LHC F-T</td>
<td>SSC F-T</td>
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<tr>
<td>√s GeV</td>
<td>123</td>
<td>193</td>
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<tr>
<td>σ(B → B̄) (μb)</td>
<td>1</td>
<td>3</td>
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<tr>
<td>σ(B → B̄)/σtot</td>
<td>1 / 10000</td>
<td>1 / 5000</td>
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<tr>
<td>&lt; n charg.</td>
<td>18</td>
<td>20</td>
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**KINEMATICS**

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<th>Collider mode</th>
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<tr>
<td>&lt; p B &gt; GeV/c</td>
<td>560</td>
<td>967</td>
</tr>
<tr>
<td>&lt; p^μ(B→μπ) &gt; GeV/c</td>
<td>275</td>
<td>475</td>
</tr>
<tr>
<td>&lt; p^μ(B→μψK) &gt; GeV/c</td>
<td>192</td>
<td>315</td>
</tr>
<tr>
<td>&lt; p^π(B→πψK) &gt; GeV/c</td>
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<td>155</td>
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**Ref. EXPERIMENT**

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<td>θ min</td>
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<td>2</td>
</tr>
<tr>
<td>ΔΩ</td>
<td>75 mrad</td>
<td>600x2π mrad</td>
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**KINEMATICS for Ref. Experiment**

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<tr>
<td>p B &gt; θ &gt; θmin GeV/c</td>
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<td>480</td>
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<tr>
<td>Median B-decay length (mm)</td>
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<td>45</td>
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<tr>
<td>&lt; θ B &gt; θ &gt; θ min</td>
<td>0.6°</td>
<td>0.5°</td>
</tr>
<tr>
<td>&lt; p B-decays &gt; θ &gt; θ min</td>
<td>42</td>
<td>48</td>
</tr>
<tr>
<td>&lt; θ B-decays &gt; θ &gt; θ min</td>
<td>1.5°</td>
<td>1.1°</td>
</tr>
<tr>
<td>&lt; p^μ(B→μπ) &gt; θ &gt; θ min (GeV/c)</td>
<td>201</td>
<td>235</td>
</tr>
<tr>
<td>&lt; p^μ(B→μψK) &gt; θ &gt; θ min (GeV/c)</td>
<td>131</td>
<td>155</td>
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**PARTICLE IDENTIFICATION**

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<tr>
<td>Momentum range</td>
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<td>5 - 70 GeV/c</td>
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<tr>
<td>Interactions/sec</td>
<td>10^7</td>
<td>10^7</td>
</tr>
<tr>
<td>N(B B̄)/10^7 sec</td>
<td>≤10^10</td>
<td>10^10</td>
</tr>
</tbody>
</table>

**TRIGGER**

- Lepton
  p (eμ) > 100 GeV/c *
- 2nd vertex
  possible if thin target **
- Lepton/ψ
  hard lepton(s) : easier ? *
- Charge (B+/−)
  possible ? *

**TAGGING**

- Lepton/ψ
  soft lepton(s) : difficult !
- Charge (B+/−)
  not easy !
Detailed simulation of $B^0_d \rightarrow \psi K^0_S$ in the LHC collider mode and sensitivity to $\sin 2\phi_1$

In the framework of the P238 proposal for B physics at the Sp $p\bar{p}$ (Schlein et al., and Ref. [22]), a detailed study has been made of the possibility to study CP violation at the LHC in the collider mode. Since most of the B production cross-section is at low $p_T$ and forward angles, a large-aperture forward spectrometer is needed. The 'forward beauty detector' envisaged, and Monte Carlo-simulated in detail, is shown in Fig. 17 (Erhan, Schlein). It consists of three spectrometers covering the angular ranges from 2 to 10 mrad, from 10 to 100 mrad, and from 100 to 600 mrad with respect to the beam line. The correlation between the average B-decay product lab. momentum and lab. angle at $\sqrt{s} = 16 \text{ TeV}$ is shown in Fig. 18; the coverage of the spectrometer is indicated also.

The basic problem of collider-mode B-physics experiments is to devise an efficient B trigger. Here a Si microvertex detector is envisaged, with 16 Si planes 4 cm apart, perpendicular to the beam in a fixed-target type of geometry, surrounding the interaction region [22]. A scaled-down (6 planes) version of this vertex detector is now undergoing tests at the $p\bar{p}$ Collider. For the B trigger, events that are inconsistent with a single vertex would be selected on-line, using just the Si detector information. The trigger algorithm is implemented in a data-driven processor. A detailed software simulation indicates a rejection factor of $\sim 500$ against minimum-bias events, with a $\sim 10\%$ efficiency for B $\bar{B}$ (B to $\psi K$) events.

Assuming a cross-section of $\sigma_B = 300 \mu b$ and $2 \times 10^7$ s of running time at a (modest) luminosity of $10^{31} \text{ cm}^{-2} \text{ s}^{-1}$, and after taking into account the geometrical acceptance, the trigger efficiency, the reconstruction efficiency, and a $15\%$ tagging efficiency using charged kaons, it is found that $\sim 1350$ B $B^0_d$ and $\sim 1350$ $B^0_d \rightarrow \psi K^0_S$, $\psi \rightarrow \ell \ell$, $K^0_S \rightarrow \pi^+\pi^-$ decays are fully reconstructed and tagged. The tagging dilution factor (good – bad)/(good + bad) is 0.54. The observable asymmetry, in a time-dependent measurement, is then

$$A = \frac{N(B^0 \rightarrow f, t) - N(\bar{B}^0 \rightarrow \bar{f}, t)}{N(B^0 \rightarrow f, t) + N(\bar{B}^0 \rightarrow \bar{f}, t)} = A_{\text{obs}} \sin(\chi_d \cdot t)$$

with

$$A_{\text{obs}} = k_1 \cdot k_2 \cdot \sin 2\phi_1,$$

where $k_1 = \Sigma f_i / (1 + x_i^2) = 0.73$ is the dilution factor due to oscillations of the tagging B, with $f_i$ the fractions of $B_u$, $B_d$, and $B_s$, respectively, and $k_2$ is the dilution factor due to mistaggings (0.54). The statistical significance of the measurement of $\sin 2\phi_1$ is

$$S = \frac{\sin 2\phi_1}{\delta \sin 2\phi_1} = \frac{0.9 \cdot k_1 \cdot k_2 \cdot \sqrt{2N} \cdot \sin 2\phi_1}{\sqrt{[1 - (\sin 2\phi_1)^2]}}$$
P 238 SPECTROMETER

Fig. 17 P-238 spectrometer layout.

Fig. 18 Lab. momentum vs. lab. angle correlation for B decay products at $\sqrt{s} = 0.6$ and 16 TeV.

Fig. 19 Sensitivity to measurements of $\sin 2\phi_1$ from $B^0_d \to \psi K^{0_s}$ decays for various experiments.
(the factor 0.9 is due to the time-resolution function). The sensitivity of a measurement of sin2$\phi_1$, expressed in terms of the significance $S$ versus sin2$\phi_1$, is shown if Fig. 19. It is compared with similar expectations for the BCD proposal [20] or for an e$^+e^-$ B-factory in the ISR tunnel [23]. If sin2$\phi_1 = 0.3$, for example, it would be measured at a 5$\sigma$ significance level, and a > 3$\sigma$ significance measurement would be possible for sin2$\phi_1 > 0.15$. Ways of optimizing the trigger for the interesting low-multiplicity B-decay modes have to be studied further, as well as possibilities for lepton or $\psi$ triggers and lepton tags. The ways of measuring simultaneously also $\phi_2$ and $\phi_3$ and the achievable sensitivities have not yet been studied.

3. TOP PHYSICS

Direct searches in collider experiments have so far failed to yield evidence for the top-quark [25]. At present, the most stringent lower limit on $m_t$ is from CDF: $m_t > 89$ GeV [26]. These collider limits depend, however, on the assumed (but very plausible) $t \rightarrow \bar{W}b$ semileptonic branching ratio of 1/9. Model-independent lower limits on $m_t$ from LEP or from $\Gamma_W$ are in the 45 to 50 GeV range [27, 28]. As is well known, electroweak radiative corrections to $m_Z$ (and $m_W$) provide upper limits on $m_t$. The recent LEP precision measurements of $m_Z$, when combined with the measurement of $\sin^2\theta_W = 1 - m_W^2/m_Z^2$ by UA2 and CDF, imply an upper limit of $m_t \leq 200$ GeV [29]. A comprehensive analysis of all the relevant experimental data, including low-energy processes, yields as a best fit: $m_t = 135 \pm 35$ GeV [29]. If $m_t \leq 150$ GeV, it is likely that the top-quark will be found at Fermilab, before the advent of the LHC. With an experimental sensitivity of $\sim 200$ pb$^{-1}$, the region $150 \leq m_t \leq 200$ GeV may, however, be more difficult to explore owing to the lack of statistics and to increasing backgrounds. In any case, the observation of the top-quark in this mass range would be limited to few tens of events at best.

The working group devoted to top-quark physics has thus addressed three main questions: i) how to find the t-quark, if it has not yet been found, and how to separate the signal from the backgrounds in order to make detailed studies; ii) how, and with what precision, could $m_t$ be best determined; iii) how to measure the t-quark semileptonic branching ratios, in particular for a check of e/\mu/\tau universality. This is expected to hold if $t \rightarrow Wb$ is the only decay mode. It might, however, fail if an $H^\pm$ exists with a kinematically allowed and competitive $t \rightarrow H^\pm b$ decay mode and a large $H^\pm \rightarrow \tau\nu$ branching ratio, as is expected in some region of the SUSY parameter ($\tan\beta = \nu_2/\nu_1$) space. These questions have been studied mostly in the $t\bar{t}$ production channel, but a study has also been made of the single-top-quark production channel $Wg \rightarrow t\bar{b}$.

**Top-quark production cross-sections**

Figure 20 shows the t-quark production cross-section at hadron colliders (Meng et al.). The QCD $t\bar{t}$ production cross-sections are now known to order $\alpha_s^3$ [30], and have been
computed for the LHC/SSC regime by Nason and by Meng et al. There are uncertainties of the order of $\sim \pm 30\%$ due to various choices of structure functions and to the $Q^2$ scale. Electroweak radiative corrections to $t\bar{t}$ have also been computed and are found to be small (Hollik et al.; for details, see Reya and Zerwas in Vol. II). For $m_t = 200$ GeV, the production cross-section at the LHC (Fig. 20) is larger by a factor of $\sim 300$ than at the Fermilab $p\bar{p}$ Collider. The expected production rate at a luminosity of $10^{33}$ cm$^{-2}$ s$^{-1}$ is large, with $\sim 10^6$ to $10^7$ $t\bar{t}$ produced per year. The LHC and SSC are in fact 't-quark factories', with a large potential for discovering the t-quark, and for studying it in detail. In the expected Standard Model $m_t$ range, $100 \leq m_t \leq 200$ GeV, it is the $t\bar{t}$ production mechanism that dominates t-quark production. If, however, the t-quark succeeds in evading the radiative correction upper limit of $\sim 200$ GeV, the mass reach of the LHC for a t-quark, or for a top-like fourth-generation fermion, is in the $\sim 1$ TeV range. In fact, as can be seen in Fig. 21 showing the four different production mechanisms responsible for t-quark production at $\sqrt{s} = 16$ TeV (Phillips, Zerwas, Zunft), for $m_t \geq 300$ GeV the dominant contribution is single-t-quark production through the process $Wg \rightarrow t\bar{b}$.

For a t-quark in the 100 to 200 GeV mass range, the top decays to $t \rightarrow Wb$ and $t\bar{t}$ production gives $WWb\bar{b}$ final states. Two main search strategies are then possible, with either one or both of the W's decaying to $W \rightarrow \ell\nu$ (the purely hadronic modes are overwhelmed by QCD multijet backgrounds, Kleiss and Refs. [31]). The $t\bar{t} \rightarrow WWb\bar{b} \rightarrow \ell\nu q\bar{q}b\bar{b}$ single-lepton channel has a larger cross-section and may allow the first observation at machine start-up at low luminosity. It can also be used for $m_t$ determination, since the t-quark decay products $t \rightarrow q\bar{q}b\bar{b}$ are all observable. The $t\bar{t} \rightarrow WWb\bar{b} \rightarrow \ell\nu \ell\nu b\bar{b}$ two-lepton mode requires more luminosity. It is, however, less contaminated by backgrounds, as will be discussed in the following.

**Top-quark search in the single-isolated-lepton mode**

In the $t\bar{t} \rightarrow WW b\bar{b} \rightarrow \ell\nu q\bar{q}b\bar{b} \rightarrow \ell\nu + \text{jets}$ single-lepton channel, the main backgrounds to consider are $W^+\text{jets}$, electroweak WW, and $b\bar{b}(g)$ production. The $b\bar{b}(g)$ $\rightarrow \ell\nu + \text{jets}$ background can be reduced below the unavoidable $W^+\text{jets}$ background by a number of possible cuts on the lepton $p_T$ threshold, on lepton isolation, on the $W$ mass $M_{jj} = m_W \pm 5 m_W$, on the missing transverse energy, and with a lepton-jet non-back-to-back azimuthal correlation cut (Cavanna, Rodrigo, Unal). For example, with the following cuts on the lepton alone: $p_T^{\ell} > 50$ GeV/c, $\Delta R_{\ell,\ell} < 1.5$, and an isolation rejection factor of $\sim 50$ (as appropriate for $p_T^{\ell} > 50$ GeV/c, see Vol. II for details), the signal-to-background ratio is already $\approx 10$. Clearly, less stringent cuts on $p_T^{\ell}$ or isolation can be required if, in addition, a $W$-mass cut is applied.

Figure 22 shows the energy dependence of the $t\bar{t}$ signal, of the electroweak WW background, and of the more dangerous $W^+\text{jets}$ QCD-induced background (Cavanna, Denegri, Rodrigo, Sajot). At $\sqrt{s} = 16$ TeV the electroweak WW pair production is a factor of
10 to 100 – depending on $m_t$ – below $t \bar{t} \rightarrow WW b \bar{b}$, and can be neglected. However, the $W + 2$ or 3 jets background is significant, and before any specific background-reduction cuts, it exceeds the signal by a factor of $\sim 2$ to 10, depending on $m_t$. The $W + 2, 3$ jets background is obtained from the EKS (Leiden -Wisconsin -Durham group) Monte Carlo. The lowest-order $W + 4$ jets contributions were also computed for this Workshop (Berends, Giele).

The reduction of the $W + 4$ jets background is possible through various kinematics cuts on the transverse energy and on the rapidity of jets and leptons, since $t \bar{t}$ production with two massive $t$-quarks is more central than $W + 4$ jets, and exhibits Jacobian-peak-type $E_T$ spectra. Fig. 23 shows the observable $t \bar{t}$ signal as a function of $m_t$ and the remaining $W + 4$ jets background, asking for at least three jets of $E_T^{\text{jet}} > 40 \text{ GeV}$ with $|\eta|^{\text{jet}} < 1.5$, and for a hard and central lepton $p_T^{\ell > 30 \text{ GeV}}$ with $|\eta|^{\ell} < 1.5$, cuts optimized for a 150 GeV $t$-quark (Cavanna; for details see Vol. II). The signal-to-background ratio is now $\sim 2$. A further rejection factor of $\sim 3$ is obtained, asking for a jet-jet invariant mass cut $M^{jj} = m_W \pm 20 \text{ GeV}$ (Fig. 22). At a luminosity of $10^{32} \text{ cm}^{-2} \text{ s}^{-1}$, the number of observed $t \bar{t}$ events would thus be $\sim 6 \times 10^4$ per year for $m_t = 150 \text{ GeV}$. This rate is large enough, so that, if needed, a significant further improvement in the signal-to-background ratio could be obtained, at the expense of efficiency, requiring $b$-tagging. The average $p_T^{b}$ depends on $m_t$, but is of the order of $\sim 40 \text{ GeV}$. The possibilities are either to ask for an additional non-isolated muon from the $b$ decays, which is particularly useful at higher luminosity, or to look for displaced vertices with a microvertex detector (limited to lower luminosity). The present experience of CDF with muons in jets is encouraging, and their future experience with a microvertex detector will tell us how useful and realistic the second possibility is.

Owing to its larger cross-section, this single-lepton mode is most profitable at lower luminosity. It requires a well-segmented calorimeter in order to apply a stringent lepton isolation requirement, or a calorimetric coverage that is sufficient to implement an $E_T^{\text{miss}}$ cut, so as to suppress the $b \bar{b}$ ($g$) $\rightarrow \ell \nu +$ jets background below the $W +$ jets background. At higher luminosity, and/or for detailed studies (e.g. mass and branching ratio determinations) requiring little background, the $b \bar{b}$ ($g$) background can be suppressed merely by raising the $p_T^{\ell}$ threshold cut, whilst $b$-tagging with a muon-in-jet is a necessity for suppressing the $W +$ jets background.

**Top-quark search in the $t \bar{t} \rightarrow WW b \bar{b} \rightarrow \ell \nu \ell \nu b \bar{b}$ two-isolated-leptons mode**

In the two-lepton channel, the main background to worry about is $b \bar{b}$ ($g$) $\rightarrow \ell \nu \ell \nu +$ jets. Figure 24 shows the energy dependence of the $t \bar{t}$ signal and of the $b \bar{b}$ and WW backgrounds up to the LHC energy range (Cavanna, Denegri, Rodrigo, Sajot). The various theoretical expectations for $b \bar{b}$ production discussed in the previous section are shown [16, 17]. The Monte Carlo estimates employed in the simulations are also shown. The initial $b \bar{b}$ background level is 6 to 7 orders of magnitude larger than the $t \bar{t}$ signal. However, as
Fig. 20  $t\bar{t}$ production cross-sections versus $m_t$ and $\sqrt{s}$.

Fig. 21  Various mechanisms contributing to t-quark production at the LHC.
Fig. 22 Energy dependence of $t\bar{t}$, $W + n$ jets, $WW$ and $WZ$ cross-sections.

Fig. 23 Observable $t\bar{t}$ cross-section versus $m_t$ in the single-isolated-lepton channel.
\( <p_T^b> \sim m_b \sim 5 \text{ GeV}, \) whilst \( <p_T^t> \sim m_t \sim 100 \text{ GeV}, \) the obvious cut is to select hard (and central) dileptons from the semileptonic heavy-quark decays. The effect of cuts on the two leptons at \( p_T^\ell > 50 \text{ GeV/c} \) and \( \eta_\ell < 1.5 \) for both \( t \bar{t} \) and \( b \bar{b} \) is shown also in Fig. 24. With just the \( p_T^\ell \) cuts, the signal-to-background ratio has already improved to \( \sim 1/5 \) for a 200 GeV t-quark.

Figure 25 shows the (integrated) inclusive dilepton spectrum versus the \( p_T \)-threshold (Nisati, Ten Have) for the \( t \bar{t} \) signal and for all the backgrounds investigated: charm and beauty production, \( Z \) and Drell–Yan (DY) pair production. A cut on both leptons at \( p_T^\ell > 100 \text{ GeV/c} \) alone would be enough, since the \( Z \) can be eliminated by an explicit mass cut, whilst the DY pairs are concentrated at low masses. Both the \( Z \) and the DY background can also be eliminated by looking at \( e\mu \) final states only. But such a high-\( p_T^\ell \) cut would be too costly in terms of event rates. It is more profitable to use a lower \( p_T^\ell \) lepton cut and achieve further background reduction through: i) lepton isolation cuts, and ii) lepton azimuthal correlation cuts.

Figure 26 compares the expected lepton isolation distribution in \( t \bar{t} \) and \( b \bar{b} \) production (any lepton in the \( t \bar{t} \) final state satisfying the \( p_T^\ell \) cut is considered). The lepton isolation is measured in terms of the transverse energy flow \( \Sigma E_T \) into a \( \Delta R = \sqrt{(\Delta y^2 + \Delta \phi^2)} = 0.4 \) cone centred on the lepton. Requiring \( \Sigma E_T < 10 \text{ GeV} \), for example, has an efficiency of \( \approx 80\% \) per \( t \bar{t} \) lepton and of \( \approx 5\% \) per \( b \bar{b} \) lepton. That is, this is equivalent to a rejection factor \( R_{\text{iso}} = 20 \) per lepton of \( p_T^\ell > 30 \text{ GeV/c} \) (Rodrigo). An additional way of reducing \( b \bar{b} \) is to use the angular correlation between the two leptons in the transverse plane (azimuthal correlation). This is illustrated by Fig. 27 (Rodrigo). The \( \Delta \phi \) distribution is much flatter for \( t \bar{t} \) than for \( b \bar{b} \), owing to the large Q-value at t-quark decay. About 60\% of \( t \bar{t} \) dileptons are in a \( \Delta \phi \) interval 30° to 150°, whilst for \( b \bar{b} \) production this fraction is 12\%.

The two peaks in \( b \bar{b} \) at \( \Delta \phi = 180° \) and 0° correspond to the two large \( p_T^b \) production mechanisms, \( gg(q \bar{q}) \to b \bar{b} \) production and the gluon splitting mechanism \( gg \to g \to g b \bar{b} \), respectively. Thus a cut on the relative azimuthal angle provides an additional rejection factor of \( \sim 5 \). Figure 28 shows the expected \( t \bar{t} \to \ell \ell \) signal and \( b \bar{b} \) background cross-sections after such selection cuts, as a function of \( m_t \) mass (Cavanna, Rodrigo). At \( \sqrt{s} = 16 \text{ TeV} \), the observable \( t \bar{t} \) signal in the two-hard-and-isolated leptons channel is at the level of \( \sim 10^4 \) events for an experimental sensitivity of \( 10^4 \text{ pb}^{-1} \), and the signal-to-heavy-flavour background ratio is \( \sim 100 \). Clearly, in this channel less stringent isolation requirements can be applied. At this level, and for \( m_t = 200 \text{ GeV} \), the main residual background becomes the electroweak WW production (Fig. 22). The signal-to-background ratio is \( > 20 \) for a \( p_T^\ell > 50 \text{ GeV/c} \) cut, and since \( < E_T^b > = 80 \text{ GeV} \) for \( m_t = 200 \text{ GeV} \), this background can be further suppressed by asking for two hard and central (b)-jets.

A substantial advantage of this two-lepton channel is that it depends only on locally measurable quantities, such as \( p_T^\ell \) and lepton isolation, and does not require selection cuts on
Fig. 24 Energy dependence of the $t\bar{t}$ signal and $b\bar{b}$ (and WW) background cross-sections, with the effects of the various cuts.

Fig. 25 Inclusive dilepton spectrum versus $p_T$ threshold at $\sqrt{s} = 16$ TeV.
Fig. 26  Lepton isolation distribution in $t \bar{t}$ and $b \bar{b}$ production.

Fig. 27  Azimuthal correlation between the two leptons in $t \bar{t}$ and $b \bar{b}$ production.

Fig. 28  Expected $t \bar{t}$ signal versus $b \bar{b}$ background level, in the two-isolated-leptons channel.
a global variable such as the missing transverse energy. In fact, this channel can be exploited for t-quark physics up to the highest luminosity envisaged, as the loss of rejection by lepton isolation due to event superposition can be compensated by a higher $p_T^\ell$ cut, and at $10^{34}$ cm$^{-2}$ s$^{-1}$, event rates are large enough to afford it. Thus no major difficulties that may hamper the observation of the t-quark at the LHC are foreseen at present.

**Determination of the top-quark mass**

The measurement of $\sigma_t t$ alone gives $m_t$ with, at best, $\delta m_t \sim \pm 15$ GeV. It is therefore important to study the various ways in which $m_t$ could be determined directly. In the $t \rightarrow WW b \overline{b} \rightarrow \Delta \ell j b \overline{b}$ channel, two methods can be used: either the reconstruction of the complete $t \rightarrow Wb \rightarrow jjb$ decay, or the t-quark decaying to $t \rightarrow \Delta \nu b$. In the latter case, the $\ell$-v-jet effective mass is computed using, for the non-measurable neutrino longitudinal momentum component, the value reconstructed from the W mass constraint. At high luminosity, if b-tagging with a muon-in-jet is applied, still another method can be used. The distribution in the effective mass of the isolated-lepton and the muon (selected in the same hemisphere to favour the same top-quark parentage) is sensitive to $m_t$ and can be used for its determination (Fayard, Unal, Reithler; for details see Vol. II).

Figure 29 illustrates the first mass determination method, which is also the simplest (PYTHIA simulations). The jets are reconstructed in a cone of size $\Delta R = 0.4$, in agreement with GEANT simulations (Unal). The resolutions assumed are: $\Delta E/E = 50\% / \sqrt{E} + 2\%$ for jets, $\Delta E/E = 15\% / \sqrt{E} + 1\%$ for electrons, and $\Delta p/p = 15\%$ for muons. The selection cuts are the following: $p_T^\ell > 40$ GeV/c, $E_T^{\text{jett1}} > 50$ GeV, $E_T^{\text{jett2,3}} > 40$ GeV, with jets 1, 2, and 3 chosen in the hemisphere opposite to the isolated lepton. Figure 29a shows the jet-jet effective mass, for jets opposite to the lepton, all combinations included. The W peak is clearly visible. If we now choose events within the W band: $M_{ jj} = m_W \pm 20$ GeV, Fig. 29b shows the resulting three-jet effective mass, where the reconstructed t-quark signal at 130 GeV is clearly visible over the event combinatorial background ($m_t = 130$ GeV was generated). B-tagging (with a muon) further increases the significance of the t-quark mass peak. Note that in Fig. 29 the background from $W +$ jets is not included (and signal-to-background $\sim 3$), but again, if b-tagging is included in the simulation, the $W +$ jets background is much smaller than the signal. After the evaluation of the various sources of errors and uncertainties (b-fragmentation, underlying event, electron-to-hadron calorimeter response ratio, etc.), it is estimated that a precision of $\delta m_t = \pm 8$ GeV can be achieved in this channel, already with a luminosity of $\sim 10^{32}$ cm$^{-2}$ s$^{-1}$.

In the two-isolated-leptons channel, again several methods can be used to determine $m_t$. The lepton-jet effective mass is one possibility. However, the most precise and least background-prone determination is obtained by asking for an additional semileptonic b decay, i.e. in a three-lepton final state. The variable to look at is the effective mass of the hard-and-isolated lepton (from the W decay) and the non-isolated muon from the b decay from
the same parent t-quark (t → Wb → Lν b → Lν Lν c). As before, this two-lepton effective mass distribution is sensitive to the parent t-quark mass, although it is not giving m_t directly owing to the missing neutrinos. Taking into account the various uncertainties (b-fragmentation predominantly), the expected statistical errors, and the possible backgrounds in this three-lepton channel, it is estimated that a precision of \( \delta m_t = \pm 5 \text{ GeV} \) can be achieved (Unal, Fayard). This method, however, requires \( L > 10^{33} \text{ cm}^2 \text{ s}^{-1} \), as it is penalized by three semileptonic decays (for details, see Fayard in Vol. II).

Top-quark branching ratios and the search for \( H^\pm \)

In the Minimal Standard Model (MSM), \( t \rightarrow Wb \) is the only decay mode. In models with two Higgs doublets we can have \( t \rightarrow H^+ b \), and if \( m_{H^+} < m_t \), then the production is in fact the dominant \( H^\pm \) production mechanism (Phillips, Zerwas, Zunf, and Refs. [32]). The \( H^\pm \) can be revealed either by a measurement of the branching ratio \( \text{BR}(t \rightarrow Wb) \neq 1 \), that is \( \text{BR}(t \rightarrow \mu) \neq 1/9 \), or by a direct search for \( H^\pm \) decaying to \( H^\pm \rightarrow c\nu \) or \( \tau\nu \), after selecting events through the decay \( t \rightarrow Wb \rightarrow \text{isolated lepton} \) (Felcini).

The \( t \rightarrow \text{lepton} \) branching ratio can be measured by comparing the number of events in the single-isolated-lepton channel with those in the two-isolated-leptons channel, as this ratio is obviously determined by \( \text{BR}(t \rightarrow Wb) \), since isolated leptons (e's and \( \mu \)'s) can come only from \( W \) and not from \( H^\pm \) decays. After the uncertainties due to backgrounds (\( W + \text{jets} \), b \( \bar{b} \)) in the single-isolated-lepton mode have been reduced by requiring a non-isolated \( \mu \) tagging the accompanying b, the study shows that (for \( m_t = 200 \text{ GeV} \)) the attainable precision on \( \text{BR}(t \rightarrow \mu) \) is \( \approx 7\% \) for an integrated luminosity of \( 10^4 \text{ pb}^{-1} \) and the dominant error is statistical. For \( 10^5 \text{ pb}^{-1} \) the precision is \( \approx 5\% \), limited now by systematics (Unal). The expected branching ratios \( \text{BR}(t \rightarrow Wb) \) and \( \text{BR}(t \rightarrow Hb) \) versus \( \tan \beta \) for \( m_t = 200 \text{ GeV} \) and \( m_{H^\pm} = 100 \text{ GeV} \) are shown in Fig. 30a (Zerwas, Zunf, and Refs. [32]). In the minimal SUSY model the preferred range of \( \tan \beta \) is \( 1 \leq \tan \beta \leq 4 \), and LEP measurements indicate \( \tan \beta > 1.6 \) [33].

Figure 30b shows the branching ratios \( \text{BR}(H^\pm \rightarrow c\nu) \) and \( \text{BR}(H^\pm \rightarrow \tau\nu) \) versus \( \tan \beta \). Note that in the favoured range \( \tan \beta > 1 \), \( H^\pm \rightarrow \tau\nu \) is dominant. In a direct search of \( H^\pm \), the simplest \( H^\pm \) signature to exploit is the expected excess of \( H^\pm \rightarrow \tau\nu \) decays relative to SM expectations. This amounts to looking for the breakdown of lepton universality in the t-quark decay \( t \rightarrow L\nu b \). The starting point of such an analysis is the selection of a sample of single-isolated-lepton (e or \( \mu \)) t-quark events, with a second non-isolated muon tagging the b to reduce backgrounds. This provides a sample of tagged t-quarks. In a second step, a search is then performed for an excess of isolated \( \tau \)'s, as compared with isolated \( \mu \)'s, in the decays of the second t-quark. The key element of the analysis is a good selection of \( \tau \rightarrow \text{low-multiplicity (<4 charged hadrons)} \) decays in a collimated (\( \Delta R = 0.2 \)) jet of \( E_T > 30 \text{ GeV} \), with a good rejection of jets from \( W \rightarrow q \bar{q} \) faking \( \tau \)'s (Felcini; for details, see Vol. II). Figure 30c shows the expectation for the ratio of \( t \rightarrow \tau\nu b \rightarrow t \rightarrow \mu\nu b \) branching ratios as a
Fig. 29 Determination of $m_t$ from the $t \bar{t} \rightarrow \ell \nu + \text{jets}$ final state.

Fig. 30 a) $t \rightarrow W^\pm b$ and $t \rightarrow H^\pm b$ branching ratio versus $\tan \beta$; b) $H^\pm \rightarrow c\bar{s}$ and $H^\pm \rightarrow \tau \nu$ branching ratio versus $\tan \beta$; c) ratio of $t \rightarrow \tau \nu b$ to $t \rightarrow \mu b$ branching ratios versus $\tan \beta$, and the expected sensitivity limit.
function of $\tan \beta$, and the range of $\tan \beta$ that can be explored by this method with a $10^4$ pb$^{-1}$ sensitivity. (In Fig. 30c it is also assumed that the $h^0$ mass is large enough not to allow a $H^\pm \to W h^0$ decay; for details, see Vol. II). The dotted line shows the expected 90% CL limit on the departure from unity in this ratio. The main limitation in this study is statistical, with a 15% stat. error and 6% syst. error for $10^4$ pb$^{-1}$, i.e. $\delta \text{BR}(t \to \tau) \approx 20\%$, since $\tau$ identification, as done in this analysis, is not considered possible at a luminosity higher than $10^{33}$ cm$^{-2}$ s$^{-1}$. None the less, a relatively large region of the $m_t, m_H, \tan \beta$ parameter space can be explored, the LHC being sensitive to $m_{H^+} \leq 150$ GeV for $m_t \leq 200$ GeV (Phillips, Felcini, Zerwas, Zunfit).

4. HIGGS SEARCH AT THE LHC

Higgs production

The search strategies and methods to be employed are rather well defined for the Standard Model Higgs – for if you know its mass, you know nearly everything concerning both its production and decays, up to relatively minor uncertainties related to the mass of the $t$-quark or to the gluon structure functions (see Kunszt and Stirling in Vol. II, and Refs. [31, 34]). At hadron colliders the basic Higgs production mechanisms, sketched in Fig. 31 are gluon–gluon fusion, $WW(ZZ)$ fusion, $t \bar{t}$ fusion, and $W(Z)$ bremsstrahlung production. The Higgs production cross-section at $\sqrt{s} = 16$ TeV according to these various mechanisms is shown in Fig. 32 (Kunszt and Stirling). Figure 32 also gives the expected number of events for an experimental sensitivity of $10^5$ pb$^{-1}$. At the LHC (and SSC) the gluon–gluon fusion mechanism provides the dominant contribution over most of the accessible mass range. At the highest masses $m_H \geq 0.7$ TeV, the $WW(ZZ)$ fusion, labelled $qq \to Hqq$ in Fig. 32, becomes comparable or takes over, depending on the $t$-quark mass. Even if not dominant, this $qq \to Hqq$ mechanism provides an additional event signature, thanks to the two energetic and forward ‘tagging’ jets [35, 31]. At the lower end of the Higgs mass range, the $WH$ (and $ZH$) associated-production bremsstrahlung mechanism may again provide an additional experimental signature owing to the accompanying $W$ (or $Z$).

The ratio of Higgs production cross-sections at the LHC and SSC varies from values $\sigma_H^{SSC}/\sigma_H^{LHC} = 3$ at $m_H = 0.1$ TeV to $\approx 10$ at $m_H = 1$ TeV. The expected Higgs production rates are large at the LHC, from $\sim 10^6$ to $10^4$ events per year at $10^{34}$ cm$^{-2}$ s$^{-1}$ for $m_H$ varying from 0.1 to 1 TeV. Unfortunately, the decay channel providing the best experimental signature has a small branching ratio, $\text{BR}(H \to ZZ \to 4 \ell^+\ell^-) = 1.2 \times 10^{-3}$; statistics is thus the limiting factor, and the highest luminosity is desirable.

Higgs decays and experimental signatures

Figure 33 shows the variation of the Higgs total width $\Gamma_H$ with $m_H$ (Kunszt, Stirling); $\Gamma_H$ is a rapidly increasing function of $m_H$. For $m_H < 0.2$ TeV, $\Gamma_H < 2$ GeV, and in this mass range, the experimental mass resolution plays an important role; $\Gamma_H = 60$ GeV for $m_H$
Fig. 31 Higgs production mechanisms at hadron colliders.

Fig. 32 Higgs production cross-sections at $\sqrt{s} = 16$ TeV.

Fig. 33 Variation of the Higgs total width versus $m_H$. 
Fig. 34a  Higgs decay branching ratios for $m_H > 2m_Z$ and $m_t = 90$ and 200 GeV;

Fig. 34b  Higgs decay branching ratios for $m_H < 2m_Z$ and $m_t = 90$ GeV.
= 0.5 TeV and $\Gamma_H \approx 0.5$ TeV for $m_H = 1$ TeV. For large masses ($m_H >> m_W$) the width varies as $\Gamma_H \approx 0.5$ TeV ($m_H / 1$ TeV)$^3$, and the Higgs broadens and dissolves into the background shape [31, 34].

The Higgs decay branching ratios are shown in Fig. 34a for the 'heavy Higgs' mass range $m_H > 2m_Z$, and in Fig. 34b for the 'intermediate Higgs' mass range $m_Z < m_H < 2m_Z$. For the $m_H > 2m_Z$ regime, the $H \to WW$ and $ZZ$ partial widths dominate entirely, with $\Gamma(H \to WW) \approx 2\Gamma(H \to ZZ)$. The effect of the $t$-quark over its entire allowed mass range is only minor (Kunszt, Stirling, Pancheri). For the $m_H < 2m_Z$ mass range, (Fig. 34b), the dominant decay mode is $H \to b \bar{b}$, but this mode is of little use. No practical way has yet been found to exploit it, in face of the overwhelming QCD $b \bar{b}$ pair-production background [36, 37] (see Fig. 1, for example). The decay modes providing the best experimental signature in this mass range are $H \to ZZ^* \to 4\ell^\pm$ (Higgs decaying into an on-shell plus an off-shell $Z$), with a rapidly varying branching ratio as a function of $m_H$, and the $H \to \gamma\gamma$ mode with a BR $\sim 10^{-3}$ for $m_H \lesssim 150$ GeV [38] (for details, see Kunszt and Stirling in Vol. II). Under some conditions the $H \to \tau^- \tau^+$ mode may also be put to use in SUSY Higgs searches (see Kunszt and Zwirner in Vol. II).

The $H \to ZZ \to 4\ell^\pm$ channel

This channel is the most convenient Higgs detection mode over the entire mass range $\sim 130$ GeV $< m_H \leq 0.8$ TeV. The $\sigma$BR ($H \to 4\ell^\pm$) production cross-section and the expected event rate for a sensitivity of $10^5$ pb$^{-1}$ is shown in Fig. 35. At both the lower and upper end of the mass range the experimental search is largely, but not exclusively, limited by statistics. At $m_H \approx 120$ to $130$ GeV, about 100 $H \to 4\ell^\pm$ events are produced, but acceptance is low; about 1500 $H \to 4\ell^\pm$ events are expected for $m_H = 200$ GeV, $\sim 200$ $H \to 4\ell^\pm$ events for $m_H = 0.5$ TeV, and $\sim 10$ events for $m_H = 1$ TeV, where the problem is not only statistics, but also that the signal dissolves owing to the $\approx 0.5$ TeV total width. The Higgs working group has made a detailed study of the observability of this Higgs signal in the presence of all the possible backgrounds, taking into account reasonable detector performances. As the detection problems and backgrounds are rather different over this entire mass range, we discuss them separately for $m_H$ larger or smaller than $2m_Z$.

i) The 'heavy Higgs' $H \to ZZ \to 4\ell^\pm$ regime.

Figure 36a shows the Higgs signal in the specific $H \to ZZ \to 4\mu^\pm$ channel for a sensitivity of $10^5$ pb$^{-1}$. All the known potential $4\mu^\pm$ backgrounds are also shown, $\tau^+ \tau^-$ production, $Z\mu \bar{\mu}$ production, ZZ continuum production, and two-$Z$-event pile-up at $L = 10^{34}$ cm$^{-2}$ s$^{-1}$ with $\Delta t = 15$ ns time separation – that is, assuming event superposition only from the same bunch crossing (all estimated with ISAJET; Nisati, Della Negra). This is before any background reduction cuts and for a perfect detector. Under these conditions the $\tau^+ \tau^-$ background is the dominant one, and at the resonance peak the signal-to-background ratio is $\sim$ 1. The ways of reducing backgrounds in $4\ell^\pm$ final states are: i) to require the presence of
two Z – that is, a mass cut \( M_{\ell\ell} = m_Z \pm \delta m_Z \), and ii) lepton isolation. Figure 36b shows the effect of the Z mass cuts alone, in a detector of a modest muon momentum resolution of \( \Delta p/p = 12\% \), as is expected for an iron toroid in this momentum range (Nisati). The mass cut is \( M_{\ell\ell} = m_Z \pm 16 \text{ GeV} \) for both \( \mu^+\mu^- \) pairs, and no lepton isolation has yet been required. Now the signal stands out clearly above the background, with the \( t \bar{t} \) and Zb backgrounds reduced below the irreducible ZZ continuum background. The \( t \bar{t} \) background is not yet entirely negligible at \( m_H \sim 200 \text{ GeV} \), and it can be further suppressed by means of lepton isolation cuts. Notice also that at \( m_H \sim 200 \text{ GeV} \), the limited momentum resolution assumed in the simulation does not make the signal stand out so clearly over the ZZ continuum. However, by applying a Z-mass constraint on the two muon pairs, the resolution on the Higgs mass can be rescued and the signal made to stand out more prominently. It is possible, by rescaling the measured muon momenta and forcing \( M_{\mu\mu}^{\text{measured}} = m_Z \), whilst keeping the relative space angle between the two muons fixed, to improve the mass resolution to \( \delta m_H \approx 2\% \) (Nisati; for details see Vol. II). This means that even in this Higgs mass range, a modest \( M_{\mu\mu} \) mass resolution can do the job.

At the upper end of this mass range the Higgs is broad and the resolution plays no significant role. The ratio of signal to irreducible ZZ background can still be improved by applying cuts on \( p_T^Z \) to favour the Jacobian peak from the isotropic \( H \rightarrow ZZ \) decay over the continuum ZZ production from \( q \bar{q} \rightarrow ZZ \) and \( gg \rightarrow \text{quark loop} \rightarrow ZZ \) production [31]. Figure 37 shows how, after such an optimization, a high-mass Higgs would stand out above the background in an experiment detecting both electrons and muons with reasonable acceptances and efficiencies, and for an experimental sensitivity of \( 10^5 \text{ pb}^{-1} \) (Froidevaux). Clearly, the Higgs mass reach is \( \sim 800 \text{ GeV} \), limited by statistics and by the difficulty to recognize an intrinsically broad signal.

ii) The \( m_H < 2m_Z \) regime in the \( H \rightarrow ZZ^* \rightarrow 4\ell^\pm \) final state.

Figure 35 shows the \( \sigma\text{-BR} \) cross-section in the \( H \rightarrow ZZ^* \rightarrow Z\ell^+\ell^- \rightarrow 4\ell^\pm \) final state, and the expected number of events. At both the lower end (\( \sim 130 \text{ GeV} \)) and around the dip (\( \sim 160 \) to \( 170 \text{ GeV} \)) the statistics is a limiting factor. In this mass range, the acceptance plays also a crucial role. This is visible from Fig. 38 where the effects of the lepton \( p_T^\ell \) threshold cut and of the geometrical acceptance are shown; the cuts are applied to all four leptons (Della Negra, Froidevaux). For \( m_H < 2m_Z \), a lepton detection threshold at \( p_T^\ell = 10 \text{ GeV}/c \) is essential. Note that the two leptons from the on-shell Z are systematically harder, with \( <p_T^\ell> = 35 \text{ GeV} \). Figure 38 also shows that a large geometrical acceptance, \( \ln \beta \lesssim 3 \), is essential in this mass range, and is still very useful at \( m_H \sim 0.3 \text{ TeV} \).

What are the backgrounds in this mass range? There are irreducible backgrounds such as \( q \bar{q}, gg \rightarrow ZZ^*, Z\gamma^* \rightarrow 4\ell^\pm \) with isolated leptons, and potentially large but reducible ones due to the \( t \bar{t} \) and Zb backgrounds. These backgrounds can be reduced by asking for one on-shell Z to suppress the \( t \bar{t} \) background, and for lepton isolation to suppress both \( t \bar{t} \) and the Zb backgrounds. Figure 39a shows the signal at three mass values
Fig. 35 $\sigma \cdot \text{BR}(H \to 4\ell^\pm)$ versus $m_H$ at $\sqrt{s} = 16$ TeV.

Fig. 36 a) Higgs signal in the $H \to ZZ \to 4\mu^\pm$ channel, and $4\mu^\pm$ backgrounds; perfect resolution; b) same as a), but assuming $\Delta p/p = 12\%$ and a $Z$-mass cut on both $\mu\mu$ pairs.
Fig. 37 Expected Higgs signal and ZZ continuum background at $\sqrt{s} = 16$ TeV.

Fig. 38 Number of detected Higgs events versus lepton $p_T^{\ell}$ threshold and geometrical acceptance cuts.

Fig. 39 a) Higgs signal in the $H \rightarrow ZZ^* \rightarrow 4 e^\pm$ channel and the $4 \ell^\pm$ backgrounds, with a Z-mass cut; b) same as in a), but with, in addition, a lepton isolation cut.
superimposed on the sum of all backgrounds investigated: $t\bar{t}$ (ISAJET), $Zb\bar{b}$ (Kleiss, QCD computation plus PYTHIA), $ZZ^*$, $Z\gamma^*$ (PYTHIA) (Della Negra, Froidevaux, Kinnunen, Nisati; for details, see Della Negra in Vol. II). (The ISAJET prediction for $Zb\bar{b}$ is also shown, but is not included in the sum of backgrounds). In Fig. 39a the following conditions and cuts have been assumed: $p_T^{\ell} \geq 10$ GeV/c, $|\eta_{\ell}| \leq 3$, efficiency per lepton $\epsilon = 0.9$, a Z-mass cut $M_{\ell\ell} = m_Z \pm 10$ GeV (assuming $\Delta E/E = 15%/\sqrt{E + 2\%}$), and $M_{\ell\ell} > 12$ GeV to suppress continuum $ZZ^*$ and $Z\gamma^*$, and lepton pairs from the same b-decay. No lepton isolation is required in Fig. 39a. Figure 39b shows the signal versus the full background, now asking also for lepton isolation, assuming a rejection factor $R_{iso} \approx 7$ and an efficiency $e_{iso} \approx 0.85$ per lepton (these are leptons of $p_T^{\ell} \approx 15$ to 20 GeV/c). The signal now stands out clearly over the mass range $m_H \approx 130$ to 2$m_Z$. Note, however, that before the isolation cuts (Fig. 39a) the $t\bar{t}$ is the largest background contribution. It can already be reduced at this stage in direct proportion to the $M_{\ell\ell} = m_Z \pm \delta m_Z$ mass-bite applied, this one being directly determined by the lepton-pair mass resolution and limited, of course, by the Z width. So there is here some latitude in the possible experimental apparatus choices, as a trade-off is possible between reliance on mass (momentum) resolution versus lepton isolation (calorimeter granularity). Since in this mass range the event rate is small, it is desirable to function at maximal luminosity, and this consideration could influence the instrumental choices.

The $H \rightarrow ZZ \rightarrow 4\ell^\pm$ channel thus makes it possible to cover the mass range $\sim 130 < m_H < 800$ GeV. We can now try to extend this mass range at both ends, either using decay modes with larger branching ratios or by providing a different experimental signature. This is particularly important at the lower end in order to close the gap between $m_H \approx 130$ GeV and the domain that can be explored by LEP 200, which is $m_H \approx 80$ to 90 GeV. It is also desirable to have some redundancy in the methods of investigation, especially in the lower LHC mass range, where the experiments will clearly be difficult ones.

The $H \rightarrow ZZ \rightarrow \ell^+\ell^- \nu\nu$ channel

If we detect both electrons and muons, this decay mode has a branching ratio of 0.8%, i.e. six times larger than for $H \rightarrow 4\ell^\pm$. This might allow the $m_H \approx 1$ TeV region to be probed. The event signature is a Jacobian peak in the $p_T^{Z}(Z \rightarrow \ell^+\ell^-)$ distribution from the two-body $H \rightarrow ZZ$ decay. Figure 40 shows the expected signal for $m_H = 0.8$ and 1 TeV, superimposed on the irreducible $q\bar{q}$, $gg \rightarrow ZZ$ electroweak continuum background (Della Negra). The Jacobian peak is very broad, owing firstly to the intrinsic Higgs width, and secondly to the Higgs transverse momentum, which is of the order of $p_T^H \sim \alpha_s m_H \sim 100$ GeV for $gg \rightarrow H$ [39] and $p_T^H \sim m_W \sim 100$ GeV also for $qq \rightarrow qqH$ [40], the two mechanisms contributing at high Higgs masses. At $m_H \approx 1$ TeV, the Higgs signal is not very distinctive, but it could be detected by a change of slope in the continuum $p_T^{Z}$ distribution. This requires a good knowledge of the background shape and is sensitive to the experimental
resolution in $p_T^Z$. The prerequisite is, however, that the other significant backgrounds can be suppressed.

Figure 40 also shows the (reducible) QCD background of $Z$ + jet production. It exceeds the signal by about three orders of magnitude before any cuts. It can be reduced below the ZZ continuum by a missing transverse energy cut. The shape of the $E_T^{miss}$ distribution from the $Z \rightarrow \nu\bar{\nu}$ decay is the same as that of the $p_T^Z$ distribution for the visible $Z \rightarrow \ell^+\ell^-$ decay. The decisive element is here the calorimetric coverage, which allows the transverse energy balance to be measured in the event [41]. The (integrated) $E_T^{miss}$ distribution is shown in Fig. 41 for calorimetric jet detection up to $|\eta|_{\text{max}} = 2$, 3, and 4 units in rapidity (Froidevaux). For the Higgs signal to emerge above the $Z$ + jets background, a calorimetric coverage up to at least $|\eta| = 4$ is required at the LHC. About 0.5 unit more is needed at the SSC. This is probably the minimal coverage needed, since this simulation is only at parton level and does not include fragmentation, hadron showers, and the $E_T^{miss}$ resolution degradation due to cracks, large-angle leakage, or non-containment, etc.

Thus, provided a large-geometrical-coverage calorimeter can be built to limit the background to the ZZ continuum one, the Higgs signal for $m_H = 0.8$ TeV would appear as in Fig. 42 (signal of $\sim 190$ events) at $10^5$ pb$^{-1}$ (Froidevaux). A $p_T^Z$ cut has been applied to enhance the signal-to-background ratio, but clearly a very good knowledge of the continuum shape and absolute magnitude is mandatory in order to observe the signal.

The $H \rightarrow WW$ (ZZ) $\rightarrow \ell\ell$ jet jet channel

This mode might be interesting for extending the mass reach, because of the much more favourable $W$ (Z) $\rightarrow q\bar{q}$ jet jet branching ratios of $\sim 70\%$, as compared with the leptonic modes. Figure 43 shows the various backgrounds generating $WW$ or quasi-$W'^W'$ final states that have to be faced. For $H \rightarrow WW$, the dominant backgrounds are $t\bar{t} \rightarrow WWbb [42]$ and $W +$ jets (i.e. $W^W'$) production [43]; for $H \rightarrow ZZ$ it is the $Z +$ jets production. Note that all backgrounds have continuum $WW$ or $ZZ$ mass distributions, as compared with a (very broad) resonant peak for the signal.

It is here that the Higgs production mechanism may help. For $m_H = 1$ TeV, the $WW(ZZ)$ fusion mechanism $qq \rightarrow Hqq$ of Fig. 31 becomes comparable to $gg \rightarrow H$, or even takes over (Fig. 32). Advantage can then be taken of the additional signature, provided by the two forward 'tagging' jets, to suppress the W, Z + jets and $t\bar{t}$ backgrounds [35, 31]. The rapidity distribution of the tagging jets is shown in Fig. 44 (Seymour). These are TeV jets with $<p_T^q> \sim 1$ TeV at the LHC (and $\sim 2.5$ TeV at the SSC) and $<p_T^q> \sim m_W \sim 100$ GeV. These tagging jets are emitted at $\sim 1^\circ$ to $5^\circ$ from the beams. The detection of these jets thus requires a calorimetric coverage over the $\sim 2.5$ to $4.5$ rapidity range at the LHC ($\sim 2.5$ to 5 at the SSC). It is a real experimental challenge to build such a calorimeter, able to sustain $L > 10^{33}$ cm$^{-2}$ s$^{-1}$.

An important question is also how these forward tagging jets survive the hadronization.
Higgs → ZZ → ℓℓ ν ν ; \( \sqrt{s} = 16 \text{ TeV} \)

**Fig. 40** Expected Higgs signals in the \( H \rightarrow ZZ \rightarrow ℓℓ ν ν \) channel, and the backgrounds.

**Fig. 41** Integrated \( E_T^{\text{miss}} \) distribution in \( Z + \text{jets} \) for various calorimetric coverages.

**Fig. 42** Expected Higgs \( H \rightarrow ℓℓ ν ν \) signal for \( m_H = 800 \text{ GeV} \).
Fig. 43 Energy dependence of $H \to WW$, and WW or quasi-WW final states.

Fig. 44 Rapidity distribution of tagging jets at $\sqrt{s} = 16$ TeV.

Fig. 45 Energy flow within tagging jets, 16 m downstream the interaction point.
phase (previous studies were at the partonic level only), and whether they can be recognized close to the beams in the presence of the underlying event and the superposition of minimum-bias events in high-luminosity running. Progress has been made in the understanding of these problems. The spatial distribution of tagging jet fragments (the jet 'width' in terms of the energy flow), 16 metres downstream from the interaction region, as obtained from the parton-shower Monte Carlo HERWIG, is shown in Fig. 45 (Seymour). Jets are well collimated, and at such a distance more than 95% of the jet energy flow is contained within 20 cm from the jet axis. The evaluation of the experimental feasibility of this detection is not yet finished, but, provided jet tagging is possible, the statistical significance for a 1 TeV Higgs signal at the LHC, for an experimental sensitivity of $10^5$ pb$^{-1}$, is estimated to be: signal/$\sqrt{\text{background(continuum)}} = 6.0$, whilst $S/\sqrt{B} = 2.5$ at $10^4$ pb$^{-1}$ (for details, see Seymour in Vol. II).

These tagging feasibility studies will be pursued, as tagging is the only way to reach the $m_H \approx 1$ TeV domain, and more generally to study both resonant and non-resonant electroweak WW, WZ, and ZZ interactions at high $M_{VV} \gg 1$ TeV, which is an important issue in itself (Baur, and Refs. [44, 45]).

The $H \to \gamma\gamma$ mode

As previously mentioned, this mode has a slowly varying branching ratio at the $10^{-3}$ level for $m_H \lesssim 150$ GeV. It may be useful for extending the Higgs detection below the $2m_Z$ mass range. The signature is the presence of two isolated photons with $E_T \gamma \sim 50$ GeV. Figure 46 shows the $\sigma \cdot \text{BR}(H \to \gamma\gamma)$ in the interesting mass range. The number of events expected for $10^5$ pb$^{-1}$ is also shown, and amounts to $\sim 3 \times 10^3$ events produced. The $H \to \gamma\gamma$ signal must, however, be searched for in the presence of two formidable backgrounds. First, the irreducible continuum QCD diphoton production via $q \bar{q}$, $gg \to \gamma\gamma$ (Bonesini, Camilleri, Werlen, and Refs. [37, 38]). Figure 47 shows a sketch (not a simulation) of a possible signal superimposed on this background. As in this mass range $\Gamma_H/m_H \sim 10^{-4}$, the calorimeter $M_{\gamma\gamma}$ resolution is very important: the better the resolution, the smaller the mass-bite required, and the more significant will be the signal. A detailed study shows that a mass resolution of better than 1% is required (Seez, Virdee, and Ref. [37]). This, combined with the necessity of working at $10^{-34}$ cm$^2$ s$^{-1}$, is very demanding on calorimetry.

The second – dangerous, but reducible – background comes from QCD jet-jet events faking $\gamma\gamma$ events. Figure 48 shows the inclusive jet, $\pi^0$, single-photon, and the irreducible $\gamma\gamma$ background in the relevant $E_T$ range. The ratio of jet-jet to $\gamma\gamma$ events is $\sim 10^7$. This is thus the minimal rejection factor needed against jet-jet events. The solutions here are detector (calorimeter) granularity and a good resolution position detector to separate isolated photons and suppress $\pi^0 \to \gamma\gamma$ decays. The study shows that, by requiring that there be no particle with $p > 2$ GeV within $\Delta\eta\Delta\phi = 0.2 \times 0.2$ around the $\gamma$ candidate, and with the ability to detect the presence of two photons with an angular separation of $\Delta \theta > 5$ mrad, the probability for a
Fig. 46 $\sigma \cdot \text{BR}(H \rightarrow \gamma \gamma)$ versus $m_H$ at $\sqrt{s} = 16 \text{ TeV}$.

$\sqrt{s} = 16 \text{ TeV}$

$m_t = 100, 150, 200 \text{ GeV}$

Fig. 47 Continuum QCD $\gamma\gamma$ production, with a sketch of the $H \rightarrow \gamma\gamma$ signal.

Fig. 48 Inclusive jet, $\pi^0$, direct $\gamma$, $\gamma\gamma$, and 'fake $\gamma$ (jet $\rightarrow \gamma$) $E_T$ spectrum.
$E_T \sim 50$ GeV jet to fake a \( \gamma \) is \(< 10^{-4} \), as is visible from the curve labelled '\( \gamma \) in Fig. 48. Thus the needed rejection can be attained, and we have to worry only about the irreducible \( \gamma \gamma \) background. The isolation region is chosen to be small, in order not to reject too many genuine events at high luminosity owing to event pile-up. At a luminosity of \( 10^{34} \text{ cm}^{-2} \text{ s}^{-1} \), 93% of the signal would still be kept (Seez, Virdee).

The statistical significance of the \( H \rightarrow \gamma \gamma \) signal that would be observed with an integrated luminosity of \( 10^5 \text{ pb}^{-1} \), in an excellent calorimeter with resolution \( \Delta E/E = 2\%/\sqrt{E} + 0.5\% \), and assuming a longitudinal vertex position known to \( \sigma_{vtx} = 1 \text{ cm} \), would be the following: signal/\( \sqrt{\text{background}} = 4.5 \) at \( m_H = 80 \text{ GeV} \), \( S/\sqrt{B} = 8.4 \) for \( m_H = 100 \text{ GeV} \), and \( S/\sqrt{B} = 10.7 \) for \( m_H = 150 \text{ GeV} \). If, because of event pile-up, the event-vertex information were lost – that is, taking \( \sigma_{vtx} = 5 \text{ cm} \) – the significance of the signal for \( m_H \) in the 100 to 150 GeV range would fall to \( S/\sqrt{B} = 5.0 \) (for details, see Seez in Vol. II). In conclusion, this would be a very demanding experiment and may require a dedicated detector.

**The \( WH \rightarrow \ell \nu \gamma \gamma \) channel**

The associated \( WH \) (or \( ZH \)) production is the way to bridge the possible gap between the domains that could be explored at LEP 200 and at the LHC. The \( \sigma \cdot \text{BR}(W \rightarrow \ell \nu) \cdot \text{BR}(H \rightarrow \gamma \gamma) \) channel cross-section is shown in Fig. 49 (Kleiss, Kunszt, Stirling). For an integrated luminosity of \( 10^5 \text{ pb}^{-1} \), the yield is thus \( \sim 30 \) \( WH \) and \( \sim 4 \) \( ZH \) events – before any acceptance cuts. Clearly, statistics is an important limitation. At the SSC the production cross-sections are larger by a factor of \( \sim 3 \).

There are two types of backgrounds to contend with. An irreducible background of \( W\gamma \gamma \) events, with a continuum \( M_{\gamma \gamma} \) mass distribution shown in Fig. 50 together with the expected \( WH \) signal, assuming the detector has a \( \gamma \gamma \) mass resolution of \( \leq 5 \text{ GeV} \). The acceptance cuts are also indicated. The signal-to-background ratio is of order 1, with \( \sim 20 \) events per signal bin and per \( 10^5 \text{ pb}^{-1} \) of integrated luminosity. The other backgrounds investigated are the various QCD-induced backgrounds from \( W \) +jets, \( b \bar{b} \), \( b \bar{b} \gamma \), etc. These can be either eliminated or reduced below the \( W\gamma \gamma \) level, provided: i) the probability for a jet to fake a \( \gamma \) can be kept lower than \( 10^{-4} \), and ii) a lepton isolation criterion can be implemented with a rejection factor \( R_{\text{iso}} > 5 \) (Di Lella et al.; for details, see Vol. II). Under these conditions the only important background would be the irreducible one (Fig. 50), and the main limitation is the statistics, with \( \sim 20 \) observable signal events per year at \( 10^{34} \text{ cm}^{-2} \text{ s}^{-1} \), and with, in addition, a few \( ZH \rightarrow \ell \ell \gamma \gamma \) events (Pancheri). None the less, this \( WH \) channel is very important since it is complementary to the \( H \rightarrow \gamma \gamma \). It works best at lower Higgs masses and makes it possible to probe the \( m_H \leq 100 \text{ GeV} \) region best, thus providing a junction with the LEP 200 domain.

**Review of Higgs detection possibilities and limitations**

As the Higgs search is central to the LHC physics programme, it is worth reviewing
briefly the possibilities and limitations of the various modes investigated (Fig. 51):

i) $H \rightarrow ZZ \rightarrow 4 \ell^\pm$, with $\ell = e, \mu$; $m_H > 2m_Z$:
   - mass reach: up to $\sim 0.8$ TeV with $10^5$ pb$^{-1}$;
   - backgrounds: ZZ continuum dominant, $t \bar{t}$ reducible with lepton isolation;
   - resolution: not crucial; $\Delta p/p \sim 10\%$ plus a Z mass constraint would do it.

ii) $H \rightarrow ZZ^* \rightarrow 4 \ell^\pm$, $\ell = e, \mu$; for $m_H < 2m_Z$:
   - mass reach: $\sim 130 < m_H < 2m_Z$ with $10^5$ pb$^{-1}$;
   - acceptance: needs $p_T \ell \geq 10$ GeV/c with $|\eta_{\ell}| \leq 3$;
   - backgrounds: $qq \rightarrow ZZ^*$ small; Zb $\overline{b}$ is larger, reducible with lepton isolation;
   - $t \bar{t}$ is largest, reducible with $M_{\ell \ell} = m_Z$ mass cut and/or lepton isolation, a resolution-isolation trade-off possible.

iii) $H \rightarrow ZZ \rightarrow \ell \ell \nu \nu$:
   - mass reach: possibly up to $\sim 0.9$ TeV for $10^5$ pb$^{-1}$;
   - backgrounds: ZZ continuum, Z + jets very dangerous, reducible with $E_T^{miss}$
     cuts or veto on jets back-to-back to Z, to be studied further;
   - acceptance: calorimetric coverage must extend up to at least $|\eta| = 4$.

iv) $H \rightarrow WW, ZZ \rightarrow \ell \ell$ jet jet from WW(ZZ) fusion:
   - mass reach: $\sim 1$ TeV;
   - acceptance: tagging of forward jets in $|\eta| = 2$ to 4.5 is mandatory;
   - backgrounds: W, Z + jets and $t \bar{t}$ reducible by jet tagging; the non-resonant
     WW, ZZ electroweak interactions are irreducible, but small.

v) $H \rightarrow \gamma \gamma$, for $m_H < 2m_Z$:
   - mass reach: $100 \leq m_H \leq 150$ GeV for $10^5$ pb$^{-1}$;
   - acceptance: $E_T^{\gamma} \geq 25$ GeV in $|\eta_{\gamma}| \leq 2$;
   - backgrounds: irreducible $q \overline{q}, gg \rightarrow \gamma \gamma$; reducible jet-jet and jet-$\gamma$, eliminated
     provided Prob (jet $\rightarrow \gamma$) $< 10^{-4}$;
   - resolution: $M_{\gamma \gamma}$ resolution is crucial: $\delta M_{\gamma \gamma} / M_{\gamma \gamma} \leq 1\%$ needed, with vertex
     known to $\leq 1$ cm; two-$\gamma$ separability at $\geq 5$ mrad needed;
     requires a dedicated detector.

vi) $H \rightarrow \gamma \gamma$ from WH (ZH) $\rightarrow \ell \nu \gamma \gamma$, $\ell = e, \mu$; for $m_H < 2m_Z$:
   - mass reach: $80 \leq m_H \leq 130$ GeV for $10^5$ pb$^{-1}$;
   - acceptance: $p_T \ell \gamma \geq 20$ GeV/c in $|\eta_{\ell \gamma}| \leq 2.5$;
   - backgrounds: irreducible W$\gamma \gamma$ requires resolution $\delta M_{\gamma \gamma} \leq 5$ GeV; W + jets, b $\overline{b}$, b $\overline{b}$, etc., are reducible, eliminated provided
     Prob (jet $\rightarrow \gamma$) $< 10^{-4}$ and with lepton isolation;
     a $H \rightarrow \gamma \gamma$ dedicated detector plus a muon/electron capability
     would do it.
Fig. 49  Cross-sections for associated WH and ZH production at $\sqrt{s} = 16$ and 40 TeV.

Fig. 50  $M_{\gamma\gamma}$ from the $W\gamma\gamma$ background and the WH ($H \rightarrow \gamma\gamma$) signal at $\sqrt{s} = 16$ TeV.

Fig. 51  Higgs mass range covered by the various channels, and the luminosities required.
Conclusions on the SM Higgs search

The present limit from LEP searches is at $m_H > 44$ GeV [46], and the expectations are that LEP 100 and LEP 200 will explore up to $m_H \sim 80$ to 90 GeV. The LHC and the SSC will explore the $\sim 80 < m_H \leq 1$ TeV domain.

The range $-2m_Z < m_H < 0.7$ to 0.8 TeV is relatively 'easy', with $H \rightarrow ZZ \rightarrow 4 \ell^\pm$. The range $m_H > 0.8$ TeV, with $H \rightarrow ZZ \rightarrow 4 \ell^\pm$, $\ell^+ \ell^- v v$, is harder, as the Higgs peak broadens and dissolves into the background shape. The LHC, at a $10^{34}$ cm$^{-2}$ s$^{-1}$ luminosity, is energy-limited to $m_H \approx 1$ TeV, and this mass range can be accessed using the $qqH \rightarrow qq \ell^+ \ell^- q \bar{q}$ or $qqZZ \rightarrow qq \ell^+ \ell^- q \bar{q}$ final states, provided jet tagging works. The SSC at $10^{33}$ cm$^{-2}$ s$^{-1}$ has a comparable mass reach.

The range $-130 < m_H < 2m_Z$, with $H \rightarrow ZZ^* \rightarrow 4 \ell^\pm$, is hard but feasible; the range $-80 < m_H < 140$ GeV, with $H \rightarrow \gamma \gamma$, is harder still, and requires an excellent calorimeter, but the WH process complements it at $m_H \approx 100$ GeV; the WH $\rightarrow \Delta \gamma \gamma$ (and $ZH \rightarrow \ell^\pm \gamma \gamma$) final state is largely limited by statistics. For $H \rightarrow \gamma \gamma$, the $S/\sqrt{B}$ is better at the LHC for $10^{34}$ cm$^{-2}$ s$^{-1}$ than at the SSC with $10^{33}$ cm$^{-2}$ s$^{-1}$, but it places more demands on the detectors.

It is clear that for $m_H < 2m_Z$, an $e^+e^-$ collider with $\sqrt{s} = 350$ to 400 GeV and $L > 10^{32}$ cm$^{-2}$ s$^{-1}$ would have a much easier time, as the signal-to-background ratio is much more favourable than at a hadron collider [31].

5. NEUTRINO PHYSICS AT THE LHC

Of the 12 fundamental fermions implied by the neutrino count of three generations, the only as yet unobserved members are the $t$-quark and the $\tau$-neutrino $\nu_\tau$. The evidence for the $\nu_\tau$ comes from several sources: the $Z$ total width, giving for the number of neutrino species $N_\nu = 2.89 \pm 0.10$ [47]; the measurement of the axial coupling of the $\tau$, indicating that its weak isospin is indeed 1/2 ($I_3 = -1/2$) requiring an $I_3 = +1/2$ partner [48]; the ratios of $W \rightarrow \nu/\ell \nu/\mu \nu$ final states measured by UA1 [11], etc. The evidence is certainly convincing, yet indirect. It would be satisfactory to have direct evidence for the $\nu_\tau$ as a distinct particle species, from its specific interactions with matter. What is needed is the observation of the $\nu_\tau \rightarrow \tau$ transition in a reaction $\nu_\tau N \rightarrow \tau + X$. This has not yet been achieved, owing to the smallness of $\nu_\tau$ fluxes produced at present machines and to the space resolution required for the detector to reveal the short-lifetime signature of the produced $\tau$ [48].

Neutrino-$\tau$ production at the LHC

Neutrino beams at the LHC (and the SSC) are produced via $pp \rightarrow c \bar{c}$, $b \bar{b}$ heavy flavour production followed by the prompt (semi)leptonic decays $c, b \rightarrow \mu\nu_\mu/\ell\nu_\ell/\tau \nu_\tau + X$. The main source of $\nu_\tau$ is the leptonic mode $D_s \rightarrow \tau \nu_\tau$ (expected BR $\sim 3\%$) with $\tau \rightarrow \nu_\tau + X$, and the semileptonic $b \rightarrow c \nu_\tau \tau$ decay (BR $\sim 6\%$). The $c \bar{c}, b \bar{b}$ production cross-sections are large at a multi-TeV $\sqrt{s}$ collider, and the LHC/SSC can provide the fluxes
of \( \nu_\tau \) that are needed for its observation, as well as larger and comparable fluxes of prompt \( \nu_e, \nu_\mu \).

Three distinct ways of producing prompt \( \nu_\tau \) (and \( \nu_e, \nu_\mu \)) can be envisaged. The beam-dump mode requires an extracted proton beam on a dump, shielding, and a \( \nu_\tau \) target-detector. In this fixed-target mode the \( \nu \)'s result from decays of D's and B's produced in p-nucleus interactions at \( \sqrt{s} = 120 \) GeV for an 8 TeV incident beam. This is also the case for the beam internal-gas-jet target mode of operation, with the advantage that no external beam is needed. However, as discussed later on, the equivalent luminosity that can be achieved is substantially lower. The third possibility, first suggested by De Rújula and Rückl [18], is to exploit the collider mode of the machine, taking advantage of the substantially larger c̅c, b̅b̅ production rates and the forward collimation of produced D's and B's. The prompt-decay neutrinos (\( \nu_e, \nu_\mu, \nu_\tau \)) are emitted preferentially at 0°, i.e. tangentially to the beams. At \( \sqrt{s} = 16 \) TeV, the c̅c̅ production cross-section is of the order of a few millibarns, which is a factor of \( \sim 20 \) higher than in a fixed-target mode, whilst b̅b̅ production is a factor of \( \sim 200 \) higher (section 2). To be competitive, however, this scheme requires a high luminosity (\( \sim 10^{33} \) to \( 10^{34} \) cm\(^{-2}\) s\(^{-1}\)) interaction region. The main advantage is that the neutrino fluxes are for free, the experiments running in parallel with a high-luminosity, hard-collision search. The sharp forward collimation of the \( \nu_\tau \) beam also means that the detector located at 0° to the beam line, if it can be brought close to the interaction point, can be of smaller transverse dimensions.

In order to estimate the \( \nu_\tau \) flux produced, realistic estimates of the c̅c̅, b̅b̅ production cross-sections are needed, in both absolute magnitude and shape, i.e. in the \( x_F = 2p_T/\sqrt{s} \) longitudinal momentum distribution of produced D's and B's. Perturbative QCD calculations are less reliable when applied to c̅c̅ than to b̅b̅ production, and uncertainties are necessarily large [16]. The multiparticle production quark - gluon string model of Kaidalov et al. [17] has been used to compute D and B cross-sections. At lower energies this model describes successfully the production of light and heavy flavours in hadron - hadron collisions. The model's predictions have been compared with PYTHIA-QCD predictions for c̅c̅ and with perturbative QCD predictions for b̅b̅ production as illustrated by Figs. 15a and 24. The model predicts \( \sigma_D \; \bar{D} \sim 1 \) mb per D\(^+\), D\(_D\), and D\(_S\), with \( \sigma_{D^+} = \sigma_{D_D} = \sigma_{D_S} \), and \( \sigma_B \; \bar{B} \sim 75 \) \( \mu b \). The scaling-law approach of De Rújula - Rückl gives \( \sigma_{c \bar{c}} \sim 5 \) mb, and \( \sigma_{b \bar{b}} \sim 1/10 \sigma_{c \bar{c}} \) at \( \sqrt{s} = 16 \) TeV [18].

Figure 52a shows the expected energy-weighted \( \nu_\tau \) flux \( E_\nu dN/dE_\nu \), and Fig. 52b the \( \nu_\tau \) laboratory production angular distribution, from \( D_s \rightarrow \tau_\nu_\tau \) decays, the main source of \( \nu_\tau \) (De Rújula, Fernandez, Gomez). The secondary \( \nu_\tau \) from the \( \tau \) decay has a much harder spectrum, \( <E_\nu> \sim 300 \) GeV, than the primary one with \( <E_\nu> \sim 60 \) GeV, thanks to the large Lorentz boost of the parent \( \tau \). The beam is forward-collimated within few milliradians. The contribution to the \( \nu_\tau \) flux from b̅ \( \rightarrow \tau_\nu_\tau + X \) is intermediate in hardness to the two components from D\(_S\) in Fig. 52a, and at an \( \sim 10\% \) level in magnitude at \( E_\nu = 750 \)
GeV. The stability of these predictions has been studied, varying the magnitude of the $D_s$ cross-section and the $x_F$ shape within reasonable limits. Both $<E_V>$ and $<\theta_V>$ are sensitive to the assumed $(1-x_F)^n$ power-law exponent n parametrizing the model predictions (De Rujula - Rückl and Kaidalov et al.), and the present estimates are probably conservative. The fluxes of prompt $\nu_e$, $\nu_\mu$ are discussed by Camilleri and Winter in Vol. II.

What would the event rates be? Of the three methods that can be used to produce ($\tau$) neutrinos at the LHC, the beam on a gas-jet target is the most limited one in terms of rate. With a gas density of $\sim 4\times 10^{14}$ nucl. per $cm^3$ and a circulating beam of $5\times 10^{14}$ protons, the equivalent luminosity is $\sim 2\times 10^{33}$ $cm^{-2}$ $s^{-1}$ (Camilleri). The beam-dump mode with a slow ejection of $10^{10}$ protons per second, is equivalent to $L = 2\times 10^{35}$ $cm^{-2}$ $s^{-1}$, whilst in the collider mode $L = 1$ to $4 \times 10^{34}$ $cm^{-2}$ $s^{-1}$. For a year of running ($10^7$ s) in a detector at $0^\circ$ subtending $\pm 2.5$ mrad with a mass of $2$ kg/$cm^2$ (i.e. $2$ g/$cm^3$ density, 10 m long) and $\approx 5$ t of total mass if located 100 m downstream from the interaction point, the number of expected $\nu_\tau$ interaction is the following: $\sim 25 \nu_\tau$ events for the gas-jet target mode, $\sim 2500 \nu_\tau$ events for the beam-dump mode, and $\sim 3800$ events for the beam-beam mode at $L = 10^{34}$ $cm^{-2}$ $s^{-1}$.

$\nu_\tau$ detection

How to detect the $\tau$ signing the $\nu_\tau$ interaction? The best signature to exploit is the short $\tau$ lifetime (and flight path) followed by a $\tau \rightarrow \nu_\tau \mu \nu_\mu$ muonic decay ($BR = 18\%$), Fig. 53 [48]. The $\tau$ transverse impact parameter (or transverse decay length) $i_T \sim ct \sim 100 \mu m$ is almost Lorentz-invariant and provides a measurement that is independent of the wide $\nu_\tau$ (or $\tau$) energy spectrum. The idea is to look for tracks with kinks or significant impact parameters. Whilst in a longitudinal view of the interaction the $\tau \rightarrow \mu$ kink angle is small, in the transverse view the $\tau \rightarrow \mu$ decay angle is isotropic, i.e. large, and $E_\nu$-independent. Detection of this $\tau \rightarrow \mu$ decay requires a detector with a space resolution of the order of $\sim 20 \mu m$. A time resolution of $\sim 1 \mu s$ is also needed, as the expected muon flux is $10^5$ to $10^6 \mu/s$. The high granularity and the large number of output channels limits the vertex detector size, which must therefore be located as close as possible to the interaction point.

A possible detector discussed in more detail is a scintillating-fibre detector (CHARM II/Zeuthen group, and Ref. [48]) with fibres of a few tens of microns in diameter, and fibre bundles along the $\nu$ beam direction, as sketched in Fig. 54a. It would have the desired spatial and time resolutions. The $\nu_\tau \rightarrow \tau \rightarrow \mu$ event in the transverse plane would appear as sketched in Fig. 54b. The possible detector locations could be at $\sim 85$ m and/or $\sim 130$ m from the interaction point, as indicated in Fig. 55 (Camilleri, De Rujula). In the beam-beam mode, the vertex detector would be located between (and surrounding) the two beam pipes (18 cm apart), and in the beam-gas mode, tangentially to the outgoing proton beam in the region of the LHC beam-crossing dipoles. The transverse size would be $\sim 20 \times 20$ $cm^2$ (for details, see Winter in Vol. II).
Fig. 52  

a) Energy-weighted $\nu_\tau$ flux, and b) $\nu_\tau$ lab. angular distribution, for $D_s \rightarrow \nu_\tau \tau \rightarrow \nu_\tau \nu_\tau \nu_\mu \mu$ at $\sqrt{s} = 16$ TeV.

Fig. 53  

Method for the detection of the $\nu_\tau$.  

Transverse impact parameter
Fig. 54 a) Scintillating-fibre $\nu_\tau$ vertex detector, and b) simulation of a $\tau \to \mu$ decay in such a detector.

Fig. 55 Possible locations for $\nu_\tau$ detectors at the LHC.
Other detection possibilities are also investigated: with silicon strips, with fibres transverse to the beam (CHARM II/Zeuthen group, and Ref. [48]), or with a liquid-argon drift chamber (Dumarchez, Nedelec, Vannucci). In the latter case, the space resolution achieved up to now is $\approx 60 \mu m$ in the drift direction [49]; the problem is the poor resolution on the other coordinate and the two-track resolution. An advantage of this technique is, however, the possibility of having a large detection volume. More work is needed before a choice can be made.

The backgrounds to this $\tau \rightarrow \mu$ topological signature have been studied. They come from charm $\rightarrow \mu$ decays in $\nu_e, \nu_\mu$ interactions, and are reducible to $\leq 5\%$ of the expected signal (Winter). The background from $\pi, K \rightarrow \mu$ decays or from elastic hadron scattering near the production vertex can be reduced, by a transverse momentum $p_T > 0.2$ GeV/c cut, to such a level that the sum of all investigated backgrounds does not exceed $\sim 10\%$ of the signal in the $\tau \rightarrow \mu\nu\nu$ mode. (For more details about background, halo backgrounds, shielding problems, etc., see Camilleri and Winter in Vol. II).

In conclusion, the $\nu_\tau$ flux seems to be sufficient for $\nu_\tau$ detection in both the beam-dump and beam – beam modes, but rather marginal in the beam – gas-jet mode. For a beam-dump type of experiment, however, a slow ejection with $10^{10}$ protons per second would be necessary, whilst in the beam-beam (and beam-gas) mode the neutrino beam is free. Schemes for detecting the $\nu_\tau \rightarrow \tau \rightarrow \mu$ chain exist, but more work is needed before a practical detector can be developed. The $\nu_\tau N \rightarrow \tau + X$ reaction should be detectable, with no excessive backgrounds expected, provided the $\sim 20 \mu m$ resolution can be achieved.

$\nu_e, \nu_\mu$ interactions

The observation of the $\nu_\tau$ may be among the first motivations for neutrino experiments at the LHC, especially if the $\nu_\tau$ has not been observed by then, for example at UNK [48]. The high spatial resolution needed will of necessity require a costly specialized detector of limited size, located close to the interaction region. However, as already mentioned, the large $c \bar{c}$ and $b \bar{b}$ production cross-sections provide also larger and comparable fluxes of $\nu_e, \nu_\mu$. A coarser and much larger ($\sim 2$ m radius) conventional detector for energetic $\nu_e, \nu_\mu$ interactions, which require a large calorimeter, could be located $\sim 500$ m downstream from interaction point 1, in a hall for which an access shaft already exists. At this location the interaction-point $0^\circ$-degree line is $\approx 8.5$ m from the beam (Camilleri, De Rújula). Clearly the classical programme of neutrino physics could be pursued with energetic neutrinos, 15% of $\nu_{e,\mu}$ having $E_\nu > 500$ GeV. In a 15 m long Fe detector subtending $\pm 2.5$ mrad, there would be $\approx 15000 \nu_e$ interactions, and as many $\nu_\mu$ ones, at $E_\nu > 500$ GeV, for a collider luminosity of $10^{34}$ cm$^{-2}$ s$^{-1}$. The potential of such a high energy neutrino programme, never pursued before with electron-neutrinos, has not yet been analysed in full detail. It would be more appealing with dedicated full-intensity external beams. These are, however, unlikely, since the LHC lattice is not optimized for slow extractions (Scandale).
6. CONCLUSIONS

$\sigma_{\text{tot}}$ and $\sigma_{\text{cl}}$: Important to measure; no particular difficulty foreseen; the present high $\beta^*$ insertion gives $L \sim 10^{31}$ cm$^{-2}$ s$^{-1}$ and allows a $t_{\text{min}}$ of $\sim 5 \times 10^{-3}$. The differential cross-section can be measured up to $|t| = \text{a few GeV}$. If the value of $\rho = 0.24$ is confirmed by UA4/2, then it would be important to have both the pp and p $\bar{p}$ options (a luminosity of $\sim 10^{28}$ cm$^{-2}$ s$^{-1}$ would be possible with the present high-$\beta^*$ insertion, and is adequate); the p $\bar{p}$ option will not exist at the SSC. If a measurement of $\rho$ is considered important, then access to the Coulomb region is needed, and a $\beta^*$ in the few km range is required; a $\beta^*$ of $\sim 2$ km may be possible but difficult; here, the SSC has an advantage with its longer straight sections.

Hard Collisions: Jets and direct photons in the TeV transverse energy range are accessible; QCD can be tested over 10 to 11 orders of magnitude with jets, and 8 to 9 orders of magnitude with direct photons. Sensitivity to compositeness scale in a year of running at $10^{33}$ cm$^{-2}$ s$^{-1}$ is $\Lambda_C = 13$ TeV with jets and $= 8$ TeV with photons.

W, Z production: the pride and glory of yester-year will be a big nuisance at the LHC, generating backgrounds to t-quark and Higgs searches; large $p_T$ W, Z production will none the less provide an interesting test of QCD.

WZ and Wγ pair production is an important issue at hadron colliders (LHC or SSC) and is much more sensitive, at the few per cent level, to anomalous gauge couplings, i.e. possible deviations from Standard Model couplings, than at LEP 200 (at the $\sim 10\%$ level), because of access to vector-boson-pair masses in the TeV range.

B Physics: pp colliders (LHC and SSC) are perhaps the desired 'b-factories', in the collider and/or the fixed-target modes. If experimentally feasible (b-triggering and tagging in particular) – which is not yet proven but may at least be partly illuminated by on-going collider and fixed-target experiments – such experiments would provide a unique potential for testing the Standard Model scenario of CP violation. For a fixed target option, an extracted beam of $>10^8$ protons per second is needed, which may be easier at the SSC. In the collider mode the two machines are rather comparable.

Top Physics: The LHC/SSC are 'top factories', with $\sim 10^7$ t $\bar{t}$ events produced per year at $10^{33}$ cm$^{-2}$ s$^{-1}$, and a few times $10^4$ observable t $\bar{t}$ events per year in channels with large signal-to-background ratios, the two-hard-and-isolated-leptons mode, and the single-lepton mode with b-tagging. The single-lepton mode may also allow first observation at low luminosity, i.e. at machine start-up, if not observed by then. The mass reach of the LHC for a heavy quark is in general $\sim 1$ TeV. The precision obtainable on the Standard Model t-quark mass is $\delta m_t = 5$ GeV; t-quark decays are a potential source of Higgs, detectable through a breakdown of e-μ-τ universality.
Higgs Physics: The Higgs, 'l'objet de tous nos désirs', if $2m_Z < m_H \leq 0.8$ TeV, is relatively 'easy' to detect in the $H \rightarrow ZZ \rightarrow 4\ell^\pm$ modes (with $\sim 10^{34}$ cm$^{-2}$ s$^{-1}$). It is perhaps detectable up to $m_H = 1$ TeV with jet tagging in the $qqH \rightarrow qqWW(ZZ) \rightarrow qq\ell\ell$ jet jet final states.

For $m_H^{\text{LEP200}} = m_Z < m_H \leq 2m_Z$, it is harder. The mode $H \rightarrow ZZ^* \rightarrow 4\ell^\pm$ is appropriate for $\sim 130$ GeV $< m_H \leq 2m_Z$; it requires good acceptance for $p_T \ell^\pm \geq 10$ GeV leptons and $\sim 10^{34}$ cm$^{-2}$ s$^{-1}$ luminosity.

For $\sim 100$ GeV $< m_H \leq 150$ GeV, the $H \rightarrow \gamma\gamma$ mode requires an excellent calorimeter and high luminosity ($\sim 10^{34}$ cm$^{-2}$ s$^{-1}$) – a difficult experiment, but one that seems feasible.

For $\sim 80$ GeV $\leq m_H \leq 130$ GeV, the $WH \rightarrow W\gamma\gamma$ production channel would make it possible to bridge the gap with LEP 200; again, it requires an excellent calorimeter and the maximum luminosity available; it is mainly limited by statistics. The LHC at $10^{34}$ cm$^{-2}$ s$^{-1}$ and the SSC at $10^{33}$ cm$^{-2}$ s$^{-1}$ are comparable in terms of the Higgs mass reach.

Neutrino Physics: The $\nu_\tau$ flux seems to be sufficient for $\nu_\tau$ detection in both the beam-dump and beam – beam modes, but rather marginal in the beam – gas-jet mode. The $\nu_\tau N \rightarrow \tau + X$ reaction should be detectable, with no excessive backgrounds expected, provided the $\sim 20$ μm resolution can be achieved. For a beam-dump type of experiment, a slow ejection with $10^{10}$ protons per second would be necessary, whilst in the beam-beam (and beam-gas) mode the neutrino beam is for free, experiments running in parallel with a high-luminosity hard-collision search. Conventional high-energy $\nu_e$ and $\nu_\mu$ physics is also a possibility.

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