LHC: Overview and Outlook

LHC Status
Results on QCD at the LHC
HL LHC, Partons, Precision
Future Higgs
LHeC Development
Remarks

Max Klein, University of Liverpool

Introduction of/to QCD@LHC, DESY, 2.9.2013

Elbe Fireworks in May 2009
1720 Power converters
> 9000 magnetic elements
7568 Quench detection systems
1088 Beam position monitors
~4000 Beam loss monitors

150 tonnes Helium, ~90 tonnes at 1.9 K
140 MJ stored beam energy in 2012
450 MJ magnetic energy per sector at 4 TeV
### Development of LHC 2010-2012

<table>
<thead>
<tr>
<th></th>
<th>2010</th>
<th>2011</th>
<th>2012</th>
<th>Nominal</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Bunch spacing [ns]</strong></td>
<td></td>
<td></td>
<td></td>
<td>25</td>
</tr>
<tr>
<td></td>
<td>150</td>
<td>50</td>
<td>50</td>
<td></td>
</tr>
<tr>
<td><strong>No. of bunches</strong></td>
<td></td>
<td></td>
<td></td>
<td>2808</td>
</tr>
<tr>
<td></td>
<td>368</td>
<td>1380</td>
<td>1380</td>
<td></td>
</tr>
<tr>
<td><em><em>beta</em> [m]</em>*</td>
<td></td>
<td></td>
<td></td>
<td>0.55</td>
</tr>
<tr>
<td>ATLAS and CMS</td>
<td>3.5</td>
<td>1.0</td>
<td>0.6</td>
<td></td>
</tr>
<tr>
<td><strong>Max bunch intensity</strong> [protons/bunch]</td>
<td>1.2 x 10^{11}</td>
<td>1.45 x 10^{11}</td>
<td>1.7 x 10^{11}</td>
<td>1.15 x 10^{11}</td>
</tr>
<tr>
<td><strong>Normalized emittance</strong> [mm.mrad]</td>
<td>~2.0</td>
<td>~2.4</td>
<td>~2.5</td>
<td>3.75</td>
</tr>
<tr>
<td><strong>Peak luminosity</strong> [cm^{-2}s^{-1}]</td>
<td>2.1 x 10^{32}</td>
<td>3.7 x 10^{33}</td>
<td>7.7 x 10^{33}</td>
<td>1.0 x 10^{34}</td>
</tr>
</tbody>
</table>

Major success of CERN and the basis for the existence of modern particle physics
Outstanding efficiency for luminosity recording by the experiments.
Measured with beam scans and forward detectors to 2-4% precision!
4 TeV beam energy: 3988 +/- 5 +/- 26 GeV → J.Wenninger CERN-ATS-2013-040
Vacuum, RF fingers 7R7, August 2012.
not Au coated..

Beam induced heating

UFOs
- 20 dumps in 2012
- Timescale 50-200 µs
- Conditioning observed
- Worry about 6.5 TeV

Blow up of emittance in LHC wrt injectors, Impedance and beam stability
UFOs
Time for scrubbing – e cloud – 25ns?
Electronics away from radiation..

....owing to superb accelerator team

Spark discharges at injection kicker and arcs
Increase with E and reduced bunch spacing
New calibration of beam loss signals..
The main 2013-14 LHC consolidations

1. 1695 Openings and final reclosures of the interconnections
2. Complete reconstruction of 1500 of these splices
3. Consolidation of the 10170 13kA splices, installing 27000 shunts
4. Installation of 5000 consolidated electrical insulation systems
5. 300 000 electrical resistance measurements
6. 10170 orbital welding of stainless steel lines
7. 18 000 electrical Quality Assurance tests
8. 10170 leak tightness tests
9. 4 quadrupole magnets to be replaced
10. 15 dipole magnets to be replaced
11. Installation of 612 pressure relief devices to bring the total to 1344
12. Consolidation of the 13 kA circuits in the 16 main electrical feedboxes
LHC back for physics in April 2015 with most probably 13 TeV, i.e. 1.6 times enlarged energy
## Conditions for Restart in 2015

<table>
<thead>
<tr>
<th></th>
<th>Numbe r of bunche s</th>
<th>Bunch intensity LHC [1e11]</th>
<th>β<em>X/β</em>sep/ Xangle</th>
<th>Emit LHC [µm]</th>
<th>Peak Lumi [cm⁻²s⁻¹]</th>
<th>~Pile-up</th>
<th>Int. Lumi per year [fb⁻¹]</th>
</tr>
</thead>
<tbody>
<tr>
<td>25 ns</td>
<td>2760</td>
<td>1.15</td>
<td>55/43/189</td>
<td>3.75</td>
<td>0.93 x 10³⁴</td>
<td>25</td>
<td>~24</td>
</tr>
<tr>
<td>25 ns low emit</td>
<td>2520</td>
<td>1.15</td>
<td>45/43/149</td>
<td>1.9</td>
<td>1.7 x 10³⁴</td>
<td>52</td>
<td>~45</td>
</tr>
<tr>
<td>50 ns</td>
<td>1380</td>
<td>1.6</td>
<td>42/43/136</td>
<td>2.5</td>
<td>1.6 x 10³⁴ level to 0.8 x 10³⁴</td>
<td>87</td>
<td>~40</td>
</tr>
<tr>
<td>50 ns low emit</td>
<td>1260</td>
<td>1.6</td>
<td>38/43/115</td>
<td>1.6</td>
<td>2.3 x 10³⁴ level to 0.8 x 10³⁴</td>
<td>138</td>
<td>~40</td>
</tr>
</tbody>
</table>

O.Brüning at ATLAS US 7/13

→ Increase in $L_{peak}$ by 2-3 and energy by 1.6
This fall machine workshop to discuss near and further schedule and plans
Huge success of the HEP Community

4.7.2012 greeting Melbourne from CERN

“The Higgs: So simple and yet so unnatural” G.Altarelli, arXiv:1308.0545
| Model                  | e, μ, τ | Jets | E_{T} | \|d\sigma/dt[fb^{-1}]\| | Mass limit |
|------------------------|--------|------|-------|----------------------------|
| MSUGRA/CMSSM           | 0      | 2-6  | Yes   | 20.3                       | 1.7 TeV    |
| MSUGRA/CMSSM           | 1 e, μ | 3-6  | Yes   | 20.3                       | 1.7 TeV    |
| MSUGRA/CMSSM           | 0      | 7-10 | Yes   | 20.3                       | 1.1 TeV    |
|\(\tilde{g}, \tilde{g} \rightarrow q\bar{q}VV\)  | 0      | 2-6  | Yes   | 20.3                       | 1.3 TeV    |
|\(\tilde{g}, \tilde{g} \rightarrow q\bar{q}V\)  | 1 e, μ | 3-6  | Yes   | 20.3                       | 1.18 TeV   |
| GMSB (f NLSP)           | 2 e, μ | 2-4  | Yes   | 20.3                       | 1.1 TeV    |
| GMSB (f NLSP)           | 1-2 τ | 0-2  | Yes   | 20.7                       | 1.24 TeV   |
| GGM (higgsino NLSP)     | 2 τ    | Yes   | 4.8   | 1.4 TeV                    |
| GGM (higgsino NLSP)     | 0 e, μ | 0-3  | 1 b   | 4.8                         |
| Gravitino LSP           | 0      | mono-jet | Yes  | 10.5                      |

**Inclusive Searches**

| e, μ, τ | Jets | E_{T} | \|d\sigma/dt[fb^{-1}]\| | Mass limit |
|--------|------|-------|----------------------------|
| 0      | 3 b  | Yes   | 20.1                       | 1.2 TeV    |
| 0      | 7-10 | Yes   | 1.1 TeV                    |
| 0      | 3 b  | Yes   | 1.3 TeV                    |

**Direct production**

| e, μ, τ | Jets | E_{T} | \|d\sigma/dt[fb^{-1}]\| | Mass limit |
|--------|------|-------|----------------------------|
| 0      | 4 b  | Yes   | 20.1                       | 1.1 TeV    |

**EW direct**

| e, μ, τ | Jets | E_{T} | \|d\sigma/dt[fb^{-1}]\| | Mass limit |
|--------|------|-------|----------------------------|
| 0      | 3 b  | Yes   | 20.3                       | 85-315 GeV |
| \tilde{g}, \tilde{g} \rightarrow WVV | 2 e, μ | 0 | 20.3 | 120-430 GeV |
| \tilde{g}, \tilde{g} \rightarrow WWX | 2 e, μ | 0 | 20.3 | 120-430 GeV |
| \tilde{g}, \tilde{g} \rightarrow psi | 2 e, μ | 0 | 20.3 | 120-430 GeV |

**Long-lived particles**

| e, μ, τ | Jets | E_{T} | \|d\sigma/dt[fb^{-1}]\| | Mass limit |
|--------|------|-------|----------------------------|
| 0      | 1 μ  | Yes   | 20.3                       | 1.0 TeV    |

**RPV**

| e, μ, τ | Jets | E_{T} | \|d\sigma/dt[fb^{-1}]\| | Mass limit |
|--------|------|-------|----------------------------|
| 0      | 4 jets | Yes | 4.6 | 1.061 TeV |

**Other**

| e, μ, τ | Jets | E_{T} | \|d\sigma/dt[fb^{-1}]\| | Mass limit |
|--------|------|-------|----------------------------|
| 2 e, μ | 0 mono-jet | Yes | 10.5 | 100-267 GeV |

**Reference**

- ATLAS CONF-2013-047
- ATLAS CONF-2013-062
- ATLAS CONF-2013-047
- ATLAS CONF-2013-062
- ATLAS CONF-2013-062
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- ATLAS CONF-2013-062

*Only a selection of the available mass limits on new states or phenomena is shown. All limits quoted are observed minus 1σ theoretical signal cross section uncertainty.*
Results on QCD at the LHC
“We like to see particle physics as driven by experiment ...”

Burt Richter
2009

QCD yet a prime example of the joint efforts of experiment AND theoretical physics

Rapporteur talk by M. Froissart, Rochester Conference 1966
The rise of $F_2$ to Low $x$

Not rigorously predicted though in accord with QCD:

“Possible non-Regge behaviour of Electroproduction Structure Functions”

First measurements of low $x$ scaling violations with $\sim 20\text{nb}^{-1}$ (!), by H1 and ZEUS at HERA

“Not for the New York Times but for the textbooks of physics..”
Bjoern Wiik

Practically free of background, apart from a bit of $\gamma p$ at high $y$..
Redundant e-h kinematics $\rightarrow$ precision
Inclusive jet cross sections and their energy dependent ratios well described by NLO QCD

\[ \alpha_s = 0.111 \pm 0.006 +0.016-0.003 \] (thy)
QCD at the LHC

Jets, Photons, Vector Bosons, Vector Bosons+Jets, Soft QCD [lowx, MPI, diffraction]

Di-jet cross sections to about 10% in agreement with QCD + different PDFs
QCD at the LHC

Jets, Photons, Vector Bosons, Vector Bosons+Jets, Soft QCD [lowx, MPI, diffraction]

Diffraction (SD+DD) up to $\Delta\eta = 8$

CMS-PAS-FSQ-12-028

MPI’s in $W+\ell\ell$ data

Consistent with ATLAS EPJC72(2012)1926
Comparisons with PYTHIA and PHOJET

CMS-PAS-FSQ-12-005
Jets, Photons, Vector Bosons, Vector Bosons+Jets, Soft QCD [lowx, MPI, diffraction] and since summer 13: Higgs as a QCD object

First differential cross sections of $pp \rightarrow X+H \rightarrow \gamma \gamma$. Large background but clear signal observed.
Small width (4 MeV) results in \( p_T(H) \) dependent reduction of \( M_{\gamma\gamma} \). Very high precision required to verify this and thus access Higgs width at the LHC.

cf C. Grojean at EPS Stockholm

ATLAS-CONF-2013-072

Dixon, Li ’13

The first \( p_T \) measurement of H:
### Experimenters NLO wishlist les Houches 05-09

#### Theory

“The NLO Industrial Revolution”

- Subtracting loops as master integrals
- Feynmanian reduction
- Unitarian approach
- Semiautomated programs (BlackHat..)
- Automated subtraction
- Standalone codes...

cf S. Hoeche ly SLAC 7/13

Now various processes, as $gg \rightarrow H$, are being calculated at NNLO

<table>
<thead>
<tr>
<th>Process ($V \in {Z, W, \gamma}$)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. $pp \rightarrow VV$ jet</td>
<td>(WW) jet completed by Dittmaier/Kallweit/Uwer; Campbell/Ellis/Zanderighi; ZZ jet completed by Binoth/Gleisberg/Karg/Kauer/Sanguinetti; WZ jet, (W\gamma) jet completed by Campanario et al. NLO QCD to the (gg) channel completed by Campbell/Ellis/Zanderighi; NLO QCD+EW to the VBF channel completed by Ciccolini/Denner/Dittmaier; Interference QCD-EW in VBF channel.</td>
</tr>
<tr>
<td>2. $pp \rightarrow \text{Higgs+2 jets}$</td>
<td>(ZZZ) completed by Lazopoulos/Melnikov/Petriello and (WWZ) by Hankele/Zeppenfeld; see also Binoth/Ossola/Papadopoulos/Pittau VBFNLO meanwhile also contains (WWW, ZZW, ZZZ, WW\gamma, ZZ\gamma, WZ, W\gamma\gamma, Z\gamma\gamma, W\gamma\gamma\j</td>
</tr>
<tr>
<td>3. $pp \rightarrow VVV$</td>
<td>relevant for (t\bar{t}H), computed by Bredenstein/Denner/Dittmaier/Pozzorini and Bevilacqua/Czakon/Papadopoulos/Pittau/Worek.</td>
</tr>
<tr>
<td>4. $pp \rightarrow t\bar{t}b\bar{b}$</td>
<td>relevant for (t\bar{t}H), computed by Bevilacqua/Czakon/Papadopoulos/Worek.</td>
</tr>
</tbody>
</table>
| 5. $pp \rightarrow V+3\text{ jets}$ | \(W+3\text{ jets calculated by the Blackhat/Sherpa and Rocket collaborations.}
| 6. $pp \rightarrow t\bar{t}+2\text{ jets}$ | \(Z+3\text{ jets by Blackhat/Sherpa relevant for }t\bar{t}H\), computed by Bevilacqua/Czakon/Papadopoulos/Worek. |
| 7. $pp \rightarrow VV b\bar{b}$, | Pozzorini et al. Bevilacqua et al. |
| 8. $pp \rightarrow VV+2\text{ jets}$ | \(W^+W^+\text{+2 jets, }W^+W^-\text{+2 jets relevant for VBF }H \rightarrow VV\text{ VBF contributions by (Bozzi/)}Jäger/Oleari/Zeppenfeld Binoth et al. |
| 9. $pp \rightarrow b\bar{b}b\bar{b}$ | top pair production, various new physics signatures Blackhat/Sherpa: \(W+4\text{jets, }Z+4\text{jets see also HEJ for }W+n\text{jets.}
| 10. $pp \rightarrow V+4\text{ jets}$ | top, new physics signatures, Reina/Schutzmeier various new physics signatures, Bevilacqua/Worek |
| 11. $pp \rightarrow Wb\bar{b}j$  | Campanario/Englert/Rauch/Zeppenfeld Blackhat/Sherpa |
| 12. $pp \rightarrow t\bar{t}t\bar{t}$ | |
Lattice QCD
HL LHC, Partons and the need for precision

HL-LHC is the program to achieve 3ab⁻¹ in pp at 14 TeV by 2030+
Geometric reduction factor $\Rightarrow \beta^* \geq 10 \text{ cm} \& \text{ Crab Cavities}$

Triplet aperture $\Rightarrow$ New large aperture triplet magnets

Bunch intensity $\Rightarrow N_b = 2.2 \times 10^{11}$ (limited in LHC by e-cloud) $\Rightarrow$ injector complex upgrade prerequisite for HL-LHC!!!

Event pile-up in detectors $\Rightarrow$ luminosity leveling

Beam Losses and Radiation $\Rightarrow$ shielding, Cryo upgrade & relocation of electronics and PC

Collective effects and impedance $\Rightarrow$ Collimator Upgrade

Electron cloud effect $\Rightarrow$ beam scrubbing & feedback
LHeC - electron beam upgrade

CDR: default design. 60 GeV. $L=10^{33-34} \text{cm}^{-2}\text{s}^{-1}$, ERL, synchronous ep/pp
Figure 1: Regions of absolute stability, meta-stability and instability of the SM vacuum in terms of the top and Higgs masses. The frame on the right zooms into the preferred experimental region (the grey ellipses denote the allowed region at 1, 2, and 3σ). The three boundary lines correspond to \( \alpha_s(M_Z) = 0.1184 \pm 0.0007 \), and the grading of the colours indicates the size of the theoretical error. The dotted contour lines show the instability scale in GeV, assuming the central value of \( \alpha_s(M_Z) \). (For details see refs. [10,11].)
The strong coupling “constant”

<table>
<thead>
<tr>
<th>Method</th>
<th>Current relative precision</th>
<th>Future relative precision</th>
</tr>
</thead>
<tbody>
<tr>
<td>$e^+e^-$ evt shapes</td>
<td>expt $\sim$ 1% (LEP)\hspace{1cm} thry $\sim$ 3% (NNLO+NLL, n.p. signif.)</td>
<td>&lt; 1% possible (ILC/TLEP)\hspace{1cm} $\sim$ 1.5% (control n.p. via $Q^2$-dep.)</td>
</tr>
<tr>
<td>$e^+e^-$ jet rates</td>
<td>expt $\sim$ 2% (LEP)\hspace{1cm} thry $\sim$ 1% (NNLO, n.p. moderate)</td>
<td>&lt; 1% possible (ILC/TLEP)\hspace{1cm} $\sim$ 0.5% (NLL missing)</td>
</tr>
<tr>
<td>precision EW</td>
<td>expt $\sim$ 3% ($R_Z$, LEP)\hspace{1cm} thry $\sim$ 0.5% (N$^3$LO, n.p. small)</td>
<td>0.1% (TLEP [8]), 0.5% (ILC [9])\hspace{1cm} $\sim$ 0.3% (N$^4$LO feasible, $\sim$ 10 yrs)</td>
</tr>
<tr>
<td>$\tau$ decays</td>
<td>expt $\sim$ 0.5% (LEP, B-factories)\hspace{1cm} thry $\sim$ 2% (N$^3$LO, n.p. small)</td>
<td>&lt; 0.2% possible (ILC/TLEP)\hspace{1cm} $\sim$ 1% (N$^4$LO feasible, $\sim$ 10 yrs)</td>
</tr>
<tr>
<td>$ep$ colliders</td>
<td>$\sim$ 1–2% (pdf fit dependent)\hspace{1cm} (mostly theory, NNLO)\hspace{1cm} [27, 28, 29, 30]</td>
<td>0.1% (LHeC + HERA [21])\hspace{1cm} $\sim$ 0.5% (at least N$^3$LO required)</td>
</tr>
<tr>
<td>hadron colliders</td>
<td>$\sim$ 4% (Tev. jets), $\sim$ 3% (LHC $t\bar{t}$)\hspace{1cm} (NLO jets, NNLO $t\bar{t}$, gluon uncert.)\hspace{1cm} [15, 19, 31]</td>
<td>&lt; 1% challenging\hspace{1cm} (NNLO jets imminent [20])</td>
</tr>
<tr>
<td>lattice</td>
<td>$\sim$ 0.5% (Wilson loops, correlators, ...)\hspace{1cm} (limited by accuracy of pert. th.)\hspace{1cm} [32, 33, 34]</td>
<td>$\sim$ 0.3% \hspace{1cm} ($\sim$ 5 yrs [35])</td>
</tr>
</tbody>
</table>

Table 1-1. Summary of current uncertainties in extractions of $\alpha_s(M_Z^2)$ and targets for future (5–25 years) determinations. For the cases where theory uncertainties are considered separately, the theory uncertainties for future targets reflect a reduction by a factor of about two.

Snowmass QCD WG report 9/2013

Prospects to measure $\alpha_s(M_Z^2)$ to per mille precision with future ep and ee colliders Important for gauge unification, precision Higgs at LHC, and to overcome the past..
Need to know the PDFs much better than so far, for nucleon structure, q-g dynamics, Higgs, Searches, future colliders, and the development of QCD
(Un)certainty on PDFs

Light Quarks:
valence $x < 0.01$, $u_v x > 0.8$, $d_v x > 0.6$
light sea (related to strange) -8% ATLAS/F2,
light sea quark asymmetry, $d/u=?$
Isospin relations (en!) ??

Strange: unknown, =$\bar{d}d$? strange valence?

Charm: need high precision to % for $\alpha_s$
(recent HERA 5%)

Beauty: HERA 10-20%, $bb \rightarrow A$?

Top: tPDF at high $Q^2 > M_t^2$ - unknown

Gluon: low $x$, saturation?, high $x$ - unknown
medium $x$: preciser for Higgs!

Recent review: cf E.Perez, E.Rizvi 1208.1178, in RPP

..unintegrated, diffractive, generalised, polarised, photonic, nuclear PDFs ???
Constraining PDFs at high $Q^2 \sim M_{W,Z}^2$ - in large rapidity range (very fwd LHCb).

Measurements reach 1% precision level in differential distributions + $\delta$(Lumi).

QCD analysis to NNLO + electroweak corrections to per mille level $\rightarrow s/d=1$
Strange Quark Distribution

Leads to first \((x, Q^2)\) measurement of the (anti-)strange density, HQ valence? 
\(x = 10^{-4} \ldots 0.05\)
\(Q^2 = 100 - 10^5 \text{ GeV}^2\)

ATLAS+HERA: Recent surprise: \(s/d = 1\)

Important PDF constraints from LHC though no direct determinations \((Q^2, x)\)
PDF4LHC \(\rightarrow\) PDFs from LHC

cf also HERMES: \(N_{\kappa}\) PLB666(2008)446
W+c measurements from ATLAS+CMS
Understanding of heavy flavour dynamics in the proton is crucial for QCD [VFNS?, light-heavy?, intrinsic c?..], VHE ν, interpretation of LHC data.
Top at the LHC

Pair production, Decay, Single Top, Top Loop → H, Mass and the SM Universe.

M_{top} to 0.5% precision from Tevatron and now also the LHC experiments

Top lead the way to Higgs and it may to further new physics.

Is there a “light” stop partner of the top?
LHC physics @ 3ab⁻¹

Higgs precision and rarer channels

New particles: pairs to ~4 TeV
singly to ~8 TeV
leptoquarks to ~2 TeV

Rare processes as FCNC top decays...

Increase of L especially important for the investigation of new signals ..
With high energy and luminosity, the search range will be extended to high masses, up to 4-5 TeV in pair production, and PDF uncertainties come in $\sim 1/(1-x)$, CI effects?
High precision PDFs are needed for the HL-LHC Searches in order to probe into the range opened by the luminosity increase and to interpret possibly intriguing effects based on external information.

LHeC BSM poster at EPS13 M.D’Onofrio et al. see also arXiv:1211:5102 Relation LHeC-LHC Simulated PDFs from LHeC are on LHAPDF (Partons from LHeC, MK, V.Radescu LHeC-Note-2013-002 PHY)
Future Higgs
Lepton collider options beyond LHC

- **ILC** (phase 1 to full, up to 1 TeV c.m.)
- **CLIC** (similar footprint for up to 3 TeV c.m.)
- **LEP/LHC** (injector to TLEP?)
- **LHeC** (e-p, ERL)
- **TLEP** (up to 0.35 TeV c.m.)
- **VHE-LHC** (100 km version)

New compact accelerators:
- **μ⁺μ⁻ collider**
- **Plasma Linear Collider**

R&D on feasibility ongoing

R. Abmann, EPS13
Higgs with HL-LHC

LHC 300 fb\(^{-1}\) at 14 TeV:
- Mass: <100 MeV (statistical)
- Coupling \(\kappa\) rel. precision*
  - \(Z, W, b, \tau\) 10-15%
  - \(t, \mu\) 3-2 \(\sigma\) observation
  - \(\gamma\gamma\) and \(gg\) 5-11%

HL-LHC 3000 fb\(^{-1}\) at 14 TeV:
- Mass: \(<< 50\) MeV (statistical)
- Couplings \(\kappa\) rel. precision*
  - \(Z, W, b, \tau, t, \mu\) 2-10%
  - \(\gamma\gamma\) and \(gg\) 2-5%

*Assuming sizeable \((1/2)\) reduction of theory errors
- “QCD scale” go to Higher order QCD computation ?
- \(gg\) “PDF” from LHC data ?

Mass Measurement:
Several exp./theory challenges to reach 50 MeV (e/\(\gamma/\mu\) calibration E-scale, Interference, FSR, ..)

F.Cerutti, “Properties of the New Boson” EPS13 Stockholm

Higgs physics at the LHC is a long term challenge [di-H, CP, M, VV damping..]
Will need ultraprecise PDFs to match thy and make the LHC a precision Higgs factory
LHeC:

Exp uncertainty of predicted H cross section is 0.25% (sys+sta), using LHeC only.

Leads to H mass sensitivity.

Strong coupling underlying parameter (0.005 – 10%).

LHeC: 0.0002

Needs N^3LO

HQ treatment important ...
Higgs with the LHeC

<table>
<thead>
<tr>
<th>LHeC Higgs</th>
<th>CC ($e^-p$)</th>
<th>NC ($e^-p$)</th>
<th>CC ($e^+p$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polarisation</td>
<td>-0.8</td>
<td>-0.8</td>
<td>0</td>
</tr>
<tr>
<td>Luminosity [ab$^{-1}$]</td>
<td>1</td>
<td>1</td>
<td>0.1</td>
</tr>
<tr>
<td>Cross Section [fb]</td>
<td>196</td>
<td>25</td>
<td>58</td>
</tr>
</tbody>
</table>

Decay | BrFraction | $N_{CC}^H e^-p$ | $N_{NC}^H e^-p$ | $N_{CC}^H e^+p$ |
<table>
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</tr>
</thead>
<tbody>
<tr>
<td>$H \to b\bar{b}$</td>
<td>0.577</td>
<td>113 100</td>
<td>13 900</td>
<td>3 350</td>
</tr>
<tr>
<td>$H \to c\bar{c}$</td>
<td>0.029</td>
<td>5 700</td>
<td>700</td>
<td>170</td>
</tr>
<tr>
<td>$H \to \tau^+\tau^-$</td>
<td>0.063</td>
<td>12 350</td>
<td>1 600</td>
<td>370</td>
</tr>
<tr>
<td>$H \to \mu\mu$</td>
<td>0.00022</td>
<td>50</td>
<td>5</td>
<td>-</td>
</tr>
<tr>
<td>$H \to ll$</td>
<td>0.00013</td>
<td>30</td>
<td>3</td>
<td>-</td>
</tr>
<tr>
<td>$H \to 2l2\nu$</td>
<td>0.0106</td>
<td>2 080</td>
<td>250</td>
<td>60</td>
</tr>
<tr>
<td>$H \to gg$</td>
<td>0.086</td>
<td>16 850</td>
<td>2 050</td>
<td>500</td>
</tr>
<tr>
<td>$H \to WW$</td>
<td>0.215</td>
<td>42 100</td>
<td>5 150</td>
<td>1 250</td>
</tr>
<tr>
<td>$H \to ZZ$</td>
<td>0.0264</td>
<td>5 200</td>
<td>600</td>
<td>150</td>
</tr>
<tr>
<td>$H \to \gamma\gamma$</td>
<td>0.00228</td>
<td>450</td>
<td>60</td>
<td>15</td>
</tr>
<tr>
<td>$H \to Z\gamma$</td>
<td>0.00154</td>
<td>300</td>
<td>40</td>
<td>10</td>
</tr>
</tbody>
</table>

H-bbar coupling to 0.7% precision with 1ab$^{-1}$, at an S/B of 1 – studies of $\tau$, $c$, .. to come

The LHeC WW $\rightarrow$ H cross section is as large as the ILC Z*$\rightarrow$ZH cross section (300fb)...

→ 50pb@LHC, hiLumi + ep [H + PDFs] +QCD@h.o. : LHC - a high precision H factory
LHeC Development

The theory of DIS has developed much further: J.Blümlein Prog.Part.Nucl.Phys. 69(2013)28
DIS is an important part of particle physics: G.Altarelli, 1303.2842, S.Forte, G.Watt 1301:6754
Physics' and 'Range

- Large x
- Gluon
- Higgs Boson

-

- Bjorken
- High Precision QCD & El.weak Physics
- RPV SUSY, LQ Substructure
- Nuclear Structure
- High Density Matter
- QGPlasma

- Fixed Target Experiments:
  - NMC
  - BCDMS
  - E665
  - SLAC

- HERA Experiments:
  - H1 and ZEUS

- LHeC Experiment:
  - L1
3-4 orders of magnitude extension of IA kinematic range

⇒ LHeC has huge discovery potential for new HI physics (bb limit, saturation.. will put nPDFs on completely new ground)

Max Klein, Mainz, 6/2013
LHeC at $10^{34}\text{cm}^{-2}\text{s}^{-1}$ Luminosity

$$L = \frac{N_e N_p f \gamma_p}{4\pi \epsilon_p \beta^*}$$

$\sigma(H)=200\text{fb}$

Access of rare channels and differential measurements:

How to reach $10^{34}$?

$N/\epsilon = \text{brightness} \times 2.5$

$\beta^* = 5\text{ cm}$

$I_e = 12\text{ mA}$

HERA: $1-4\times10^{31}\text{cm}^{-2}\text{s}^{-1}$

<table>
<thead>
<tr>
<th>parameter [unit]</th>
<th>LHeC</th>
</tr>
</thead>
<tbody>
<tr>
<td>species</td>
<td>$e^-\quad p,^{208}\text{Pb}^{82+}$</td>
</tr>
<tr>
<td>beam energy (/nucleon) [GeV]</td>
<td>60, 7000, 2760</td>
</tr>
<tr>
<td>bunch spacing [ns]</td>
<td>25, 100, 25, 100</td>
</tr>
<tr>
<td>bunch intensity (nucleon) [$10^{19}$]</td>
<td>0.1 (0.2), 0.4 17 (22), 2.5</td>
</tr>
<tr>
<td>beam current [mA]</td>
<td>6.4 (12.8), 860 (1110), 6</td>
</tr>
<tr>
<td>rms bunch length [mm]</td>
<td>0.6, 75.5</td>
</tr>
<tr>
<td>polarization [%]</td>
<td>90, none, none</td>
</tr>
<tr>
<td>normalized rms emittance [$\mu$m]</td>
<td>50, 3.75 (2.0), 1.5</td>
</tr>
<tr>
<td>geometric rms emittance [nm]</td>
<td>0.43, 0.50 (0.31)</td>
</tr>
<tr>
<td>IP beta function $\beta^*_{x,y}$ [m]</td>
<td>0.12 (0.032), 0.1 (0.05)</td>
</tr>
<tr>
<td>IP spot size [$\mu$m]</td>
<td>7.2 (3.7), 7.2 (3.7)</td>
</tr>
<tr>
<td>synchrotron tune $Q_s$</td>
<td>$-\quad 1.9 \times 10^{-3}$</td>
</tr>
<tr>
<td>hadron beam-beam parameter</td>
<td>0.0001 (0.0002)</td>
</tr>
<tr>
<td>lepton disruption parameter $D$</td>
<td>6 (30)</td>
</tr>
<tr>
<td>crossing angle</td>
<td>0 (detector-integrated dipole)</td>
</tr>
<tr>
<td>hourglass reduction factor $H_{hg}$</td>
<td>0.91 (0.67)</td>
</tr>
<tr>
<td>pinch enhancement factor $H_D$</td>
<td>1.35</td>
</tr>
<tr>
<td>CM energy [TeV]</td>
<td>1300, 810</td>
</tr>
<tr>
<td>luminosity / nucleon [$10^{33}\text{cm}^{-2}\text{s}^{-1}$]</td>
<td>1 (10), 0.2</td>
</tr>
</tbody>
</table>

Table 1: LHeC $e^p$ and $eA$ collider parameters. The numbers give the default CDR values, with optimum values for maximum $e^p$ luminosity in parentheses and values for the $e^p\text{Pb}$ configuration separated by a comma.

Test of ERL, Operation experience, Sources, Magnet Tests, Injector for the LHeC Physics: $ep$ with $10^{40}\text{cm}^{-2}\text{s}^{-1}$ : $\sin^2\Theta$ [high E MESA], proton radius; Testbeam facility

Under design at CERN in international collaboration. $f=801.58$ MHz SC RF

A.Valloni, LHeCmeeting, 16.7.2013, see also LHeC-Note 2012-001 ACC, and Contribution to IPAC2013
Energy frontier deep inelastic scattering - following HERA with the LHC

LHeC: A new laboratory for particle physics, a 5th large LHC experiment
QCD is the richest part of the Standard Model Gauge Field Theory and will (have to) be developed much further, on its own and as background
Future Rings at CERN*)

LEGEND
- Black: LHC and SPS
- Pink: LHeC project area
- Yellow: TLEP and VHE-LHC project area
- Red: Main tunnel
- Red: Service tunnel
- Orange: Access shaft
- Yellow: Inclined tunnel access

100km with 20T provides 50 TeV per beam.

80km may not be clever due to Saleve, if placed below Lac Leman → 100km.

New tunnel may host a Triple LEP Higgs facility.

LHeC to run with LHC and later with VHE-LHC

*) “Civil Engineering Feasibility Studies for Future Ring Colliders at CERN”, Contributed by O.Brüning, M.Klein, S.Myers, J.Osborne, L.Rossi, C.Waaijer, F.Zimmerman to IPAC13 Shanghai
A 100km machine is very challenging, it will not be cheap and demands firm, excellent science reason to become real.
30 years from the first p-LEP = LHC paper to LS1
The challenge, again, is to find the way forward, through the dark matter of the universe and towards a genuine unification of the known and hidden forces:

Theory needs help and much hope is directed to the near and far future of the LHC. Particle physics is one coherent subject and it better is pursued as an entity further.

Sincere thanks to many colleagues on H1, ATLAS, LHeC, LHC, Theory, ..

Elbe Fireworks in May 2009
Gluon measurement down to $x=10^{-5}$, **Saturation or no saturation** ($F_2$ and precise $F_L$)  
Non-linear evolution equations? Relations to string theory, and **SUSY at ~10 TeV**?

Perhaps surprising, recent results indicate that the flow in pPb resembles PbPb. Possibly the determination of nPDFs in AA and pA is reduced to $W,Z$ production [collective effects in final state – rescattering of produced partons – hydrodynamics].

\[ \frac{dN}{d\Phi_z} \propto \sum_n [1 + v_n \cos(n(\Phi_z - \Phi_{EP}))] \]

- $\Phi_z$: boson azimuthal emission angle
- $\Phi_{EP}$: event plane azimuth

$v_2$ for Z is zero, it decays before the plasma is formed..