Tau leptons as a probe for New Physics at LHC

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(On behalf of the ATLAS collaboration)

1. Motivation
2. ATLAS experiment
3. Early physics: $Z \rightarrow \tau \tau$, $W \rightarrow \tau \nu$
4. Taus in searches for:
   - SM and MSSM Higgs
   - SUSY
   - XD
5. Conclusions
Why tau leptons are an important signature at LHC experiments

**Taus**

- massive particles, EW interaction only
- Yukawa coupling to SUSY particles, free from QCD effects
- production and decay well separated in time, potential for measurement of the polarisation, spin correlations, parity
- excellent knowledge about decay modes from low-energy experiments

Ideal signature to probe “New Physics”

however ..... 
- several decay modes possible
- jet-like signature
- difficult because of huge QCD bkg

Make it quite difficult for observing in the pp collision experimental environment

**At the LHC**

- Large statistics already in the first data: $W \rightarrow \tau \nu, Z \rightarrow \tau \tau$
  - detector calibration, bkg normalisation, algorithms tuning, control channels

- Signature for Higgs boson(s) discovery
- Signature for SUSY discovery
- Polarisation sensitive to SUSY parameters
- Signature for “extra dimensions”
**ATLAS (A Toroidal LHC ApparatuS)**

**Muon Detectors:** fast response for trigger, good $p$ resolution

**Energy-scale:**
- $e/\gamma \sim 0.1\%$
- Muons $\sim 0.1\%$
- Jets $\sim 1\%$

**Electromagnetic Calorimeters:**
- excellent $e/\gamma$ identification,
- E and angular resolution,
- response uniformity

**Inner Detector:**
- high efficiency tracking,
- good impact parameter resolution

**Hadron Calorimeters:**
- Good jet and $E_T$ miss performance

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Hadron Calorimeters:
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-40MHz beam crossing
- Readout: 160M channels (3000 km cables)
- Raw data = 320Mbyte/sec (1TB/hour)
Machine start up scenario

~ March 2007 - last LHC magnet installed
~ August 2007 - machine and experiments closed
~ November 2007 - first collisions ($\sqrt{s}$ = 900 GeV, $L$~$10^{29}$ cm$^{-2}$s$^{-1}$)
Commissioning run at injection energy until end 2007, then shutdown (3 months ?)
~ June 2008 - first collisions at $\sqrt{s}$=14 TeV (followed by first physics run), $L$~$10^{32}$ cm$^{-2}$s$^{-1}$

Goal: deliver integrated luminosity of few fb$^{-1}$ by end 2008 (with 50% efficiency of data taking)
Prospects for taus with 10-100 pb\(^{-1}\) at L \(\sim 10^{31-32}\) over the first weeks of running: extract signal from most abundant sources of \(\tau\) leptons as early as possible \(\Rightarrow\) requires a performant \(\tau\) and \(E_T^{\text{miss}}\) trigger from the very start.

<table>
<thead>
<tr>
<th>Expected rates for 100 pb(^{-1})</th>
<th>(W \rightarrow \tau \nu), (\tau \rightarrow \text{hadron})</th>
<th>(W \rightarrow e\nu)</th>
<th>(Z \rightarrow \tau\tau), (1\tau \rightarrow \text{hadron})</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\sigma.B) (pb)</td>
<td>11200</td>
<td>17300</td>
<td>1500</td>
</tr>
<tr>
<td>(\tau 30i + xE35)</td>
<td>(\sim 15,000)</td>
<td>(\sim 250,000)</td>
<td>(\sim 1300)</td>
</tr>
<tr>
<td>(\tau 20i + xE25)</td>
<td>(\sim 60,000)</td>
<td>(\sim 560,000)</td>
<td>(\sim 3500)</td>
</tr>
</tbody>
</table>

Assuming \(\text{eff} \sim 80\%\) for \(\tau\) trigger, \(\sim 50\%\) for \(\tau\) reco/id.

It will be “counting” experiment: evidence in the \(N_{\text{Track}}\) spectrum. Signal \(\times 10\) and bgd \(\times 100\) with respect to 2 TeV collisions. Profit from low-luminosity operation to trigger at lowest possible thresholds (\(E_T^{\tau 15i}\)), raise \(E_T^{\text{miss}}\) cut as luminosity goes up. Require QCD jet rejection of \(10^3 - 10^4\) at 50\% efficiency and \(p_T \sim 20\) GeV.

Events exp in 100pb\(^{-1}\) vs N Tau tracks

Final off-line (\(E_T^{\text{miss}} > 40\) GeV):
- \(W \rightarrow \tau \nu\) events
- \(Z \rightarrow \tau \tau\) events
- QCD events

Preliminary
First data: \( Z \rightarrow \tau \tau \) events

Observation of \( Z \rightarrow \tau \tau \) events will be “easier”, but 10x less events produced

\( \rightarrow \) trigger on lepton (electron, muon)

\( \rightarrow \) use same-sign (lep,tau) events to control bgd for the signal events, which are opposite-sign

\( \rightarrow \) evidence in Ntrack spectrum and Mvis (lep-had) system

\( \rightarrow \) reconstruct invariant mass of the \( \tau \tau \) system (collinear approximation)

\( Z \rightarrow \tau \tau \) (lh)

Signal \( Z \rightarrow \tau \tau \)

- Inclusive \( W \rightarrow e \nu \)
- Inclusive \( W \rightarrow \mu \nu \)

\( \sigma \approx 16 \)

Expect in 100pb\(^{-1}\) about 300 evt observed (e,\( \mu \)) with 20% bgd possibility to loosen cuts? bb bkg still to be included/checked

With \( 10^{31} \) luminosity, lower threshold on lepton and tau to 15 GeV. Tighten selection to improve resolution of invariant mass.

Sensitivity of the measured \( Z \)-mass to the absolute energy scale on reconstructed missing energy: \( \pm 10\% \) variation on \( E_{T}^{\text{miss}} \) results in shift of about 3% of the measured mass.
Prospects for discovery of Standard Model Higgs boson

Standard Model Higgs boson
(first few years of operation)

\[ \int L \, dt = 30 \, \text{fb}^{-1} \]
(no K-factors)

ATLAS

<table>
<thead>
<tr>
<th>Signal significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>10^2</td>
</tr>
<tr>
<td>10</td>
</tr>
<tr>
<td>1</td>
</tr>
</tbody>
</table>

\[ M_H \, (\text{GeV}) \]

- VBF \( \sim 20\% \) of tot \( \sigma \) for \( m_H < 2m_Z \) but event characteristics can be exploited to suppress large bkg
- about 5 \( \sigma \) sensitivity for Higgs mass 110-140 GeV for 30 fb\(^{-1}\)
- combined results for l-l and l-h modes
- better performance for l-h (mass resolution, efficiencies)
- gives access also to the measurement of the Higgs couplings: \( H \tau\tau/HHW \)

\[ \sigma : 300-64 \, \text{fb} \text{ for } M_H = 120-150 \, \text{GeV} \]

\( \text{BR}(H \rightarrow \tau\tau) \sim \text{few \%} \)
Vector Boson Fusion: $H \rightarrow \tau\tau$

Central Jet Veto:
- Sensible to PileUp

Forward Tagging Jets:
- Difficult Forward Region
- Jet Calibration

$E_T$ Miss:
- Central to Tau Reconstruction
- Reconstructed Higgs Mass
- Dominant Experimental Issue

Electron ID
Muon ID

Hadronic Tau ID

ET Miss

Dominant backgrounds:
$Zjj$, $WWjj$ EW & QCD
$tt$ production

$H \rightarrow \tau\tau(e\mu)$ 30fb$^{-1}$

$\sigma_M \sim 11-12$ GeV

$E_T$ Miss

$E_T$ Miss

Central Jet Veto:
- Sensible to PileUp

Forward Tagging Jets:
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Dominant backgrounds:
$Zjj$, $WWjj$ EW & QCD
$tt$ production

$\sigma_M \sim 11-12$ GeV
Prospects for discovery of MSSM Higgs boson

Neutral H and A
- prod: $gg \rightarrow H/A$ and $gg \rightarrow bbH/A$
  (for high tan\(\beta\))
- $BR(H/A \rightarrow \tau\tau) \sim 10\%$
- $BR(H/A \rightarrow bb) \sim 90\%$

Charged Higgs
- prod:
  $m_H < m_t$: $tt \rightarrow Wb b H^+$
  $mt > m_t$: $gb \rightarrow t H^+$, $gg(qq) \rightarrow tb H^+$,
  $qq \rightarrow H^+$
- decay modes: $H^+ \rightarrow \tau\nu$, $H^+ \rightarrow tb$ for
  $m_H > m_t$
- $BR(H^{\pm} \rightarrow \tau\nu) \sim 100\%$ below $tb$
  kinematical threshold

$\rightarrow$ discovery modes for large and moderate tan\(\beta\)
$\rightarrow$ measurement of tan\(\beta\)
The tau decays provide the cleanest signature for the heavy Higgs discovery at high mass (and relatively high tan\(\beta\)).

Investigated all the final states (ll, lh, hh). All of them contribute (at different \(M_A\)).

The associated production (bbA/H) provides additional rejection against the main backgrounds: Z+jet, W+jet, QCD (h-h only)

**Backgrounds:**
- l-h: W+jets, Z+jets, tt, bb
- h-h: W+jets, Z+jets, tt and QCD

\[ \text{ATLAS} \]
\[ \int L \, dt = 30 \text{ fb}^{-1} \]
Closer look at charged $H^\pm \rightarrow \tau \nu$

**Mass reconstruction**

- $gb \rightarrow tH^+$
- $t \rightarrow jjb$, $H^+ \rightarrow \tau \nu$

**Tanβ measurement**

- Determination of tanβ by measuring of the rate in this channel
  \[ \sigma (gb \rightarrow tH^+) \times BR(H^+ \rightarrow \tau \nu) \sim \tan^2 \beta \]
- Precision improves as the rate of $H^+ \rightarrow \tau \nu$ improves with tanβ

→ final state: hadronic tau, 3 jets, $E_T^{\text{miss}}$

→ only transverse mass can be reconstructed (as ν in final state) but $m_H$ can be obtained with likelihood method

→ almost bgd free channel (tt, Wt)

→100% tau polarisation enhances signal observability above bgd from W events
If large “extra dimensions” exist ....?

- In 2-Higgs Doublet Model of type II, 2HDM-II (MSSM)
  \[ H^- \rightarrow \tau^- R \bar{\nu}, \quad H^- \text{ to } \tau^- L \text{ suppressed} \]

- In Large Extra Dimensions \( H^- \rightarrow \tau^+ L \psi \) can be enhanced by large number of Kaluza-Klein states. Thus:
  \[ H^- \rightarrow \tau^- R \bar{\nu} + \tau^- L \psi \]

- Measurement of the polarisation asymmetry can be used (\( A \sim \text{func (model parameters)} \))
  \[ A = \frac{\Gamma(H^- \rightarrow \tau^- L \psi) - \Gamma(H^- \rightarrow \tau^- R \bar{\nu})}{\Gamma(H^- \rightarrow \tau^- L \psi) + \Gamma(H^- \rightarrow \tau^- R \bar{\nu})} \]

- Observation of signal in \( m_T \) distribution is not sufficient to distinguish between 2HDM and L.E.D.
- The reconstruction of \( p_\pi / E_{\text{jet}} \) should determine the scenario: 2HDM or L.E.D.
- Further measurement of the asymmetry may provide a distinctive signature for L.E.D.
Interesting prospects in SUSY events

- Tau signatures important in much of the mSUGRA (minimal SuperGravity) parameter space, particularly at high \( \tan \beta > 10 \)

- In mSUGRA R-parity conserved, all events contain 2 neutralinos escaping the detector \( \rightarrow \) one can measure kinematic endpoints in invariant mass distributions rather than mass peaks

- At some points in the parameter space (e.g. funnel) can only observe kinematic endpoints in \( \tau \) invariant mass distributions,

\[
\tilde{\chi}_2^0 \to \tilde{\tau}_1^\pm \tilde{\tau}^\mp \to \tilde{\chi}_1^0 \tau^\pm \tau^\mp
\]

\( M_{\text{max}} = f n \) (masses involved SUSY particles)

- Only consider hadronic tau decays. No sharp edge because of \( \nu \), but end-point can still be measured.

- Can use tau polarization measurement to further constrain the underlying SUSY model.

\[ m_{\text{vis}} (\tau^\pm \tau^\mp) - m_{\text{vis}} (\tau^\pm \tau^\pm) \]
Conclusions

- Events with tau's will be observed with the first data of LHC, excellent possibility to understand detector performance.
- Identification of tau leptons will be the key for New Physics discovery:
  - SM Higgs in VBF production, $H \rightarrow \tau \tau$
  - MSSM Higgs, $bbH/A$, $H/A \rightarrow \tau \tau$
  - MSSM $H^+$ in $tt \rightarrow H^+b\bar{W}b$, $gb \rightarrow bH^+$, $H \rightarrow \tau \nu$
  - SUSY signatures with tau's in final states
  - extra dimensions(?)... new theories(?)...
- Polarisation measurements should be possible
- Given large dynamic range of required observability in hadronic channel mandatory development of several dedicated algorithms for reconstruction and identification (see Fabien Tarrade talk).
Backup Slides
A number of systematic effects need to be considered.
- Uncertainties arise in the simulation of the level of the backgrounds. QCD Zjj events produced with M.E. calculations yield a higher contribution, by at least a factor of two relative to PYTHIA, to the final number of background events.
- Uncertainties in detector performance, such as tau-jet and lepton reconstruction efficiencies and rejection factors.
- Other systematic errors relating to calibration, pileup effects, luminosity measurement,

With M.E. QCD Z+jet bkg estimation
30 fb⁻¹
• **Detector resolution:** A worse resolution in the reconstruction of ETmiss results in a broader distribution of the reconstructed mass. In order to estimate this effect, the mass window has been increased by 20%. The signal acceptance has been kept at the value of the standard analysis.

• **Identification of the \(\tau\) and b-jets:** An efficiency of the tau-ID of 55% has been used. This value has been decreased to 40%, while the jet rejection values remain unchanged. The b-tagging efficiency has been lowered from \(\text{eff} = 0.7\) to \(0.6\), while keeping the same rejection factors.

• **Jet energy scale:** The absolute jet energy scale at the ATLAS are estimated to be known with 3% accuracy. Therefore, all jet energies in the study have been raised by 3% to estimate the effect of this uncertainty, which alters the acceptance due to the cuts of the transverse energy of jets used in the event selection.

<table>
<thead>
<tr>
<th></th>
<th>(m_{A/H})</th>
<th>(\tan\beta)</th>
<th>Signal</th>
<th>Background</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standard analysis</td>
<td>600</td>
<td>30</td>
<td>20.4</td>
<td>7.4</td>
<td>5.8 (\sigma)</td>
</tr>
<tr>
<td></td>
<td>800</td>
<td>45</td>
<td>19.6</td>
<td>6.8</td>
<td>5.8 (\sigma)</td>
</tr>
<tr>
<td>Detector resolution</td>
<td>600</td>
<td>30</td>
<td>20.4</td>
<td>9.4</td>
<td>5.2 (\sigma)</td>
</tr>
<tr>
<td></td>
<td>800</td>
<td>45</td>
<td>19.6</td>
<td>8.3</td>
<td>5.3 (\sigma)</td>
</tr>
<tr>
<td>(\tau) identification and b-tagging</td>
<td>600</td>
<td>30</td>
<td>14.9</td>
<td>7.5</td>
<td>4.3 (\sigma)</td>
</tr>
<tr>
<td></td>
<td>800</td>
<td>45</td>
<td>13.8</td>
<td>5.7</td>
<td>4.4 (\sigma)</td>
</tr>
<tr>
<td>Jet energy scale</td>
<td>600</td>
<td>30</td>
<td>18.6</td>
<td>8.6</td>
<td>5.0 (\sigma)</td>
</tr>
<tr>
<td></td>
<td>800</td>
<td>45</td>
<td>16.7</td>
<td>7.3</td>
<td>4.8 (\sigma)</td>
</tr>
</tbody>
</table>

Table 10: Study of the influence of systematic uncertainties of the significance of the channel \( (b\bar{b}) A/H \rightarrow (b\bar{b}) \tau \ (had) \tau \ (had)\).
Closer look at charged $H^\pm \rightarrow \tau \nu$

Table 1: The statistical precision on the mass determination in the $H^\pm \rightarrow \tau \nu$ channel. The reference masses are listed in the first column. The reconstructed masses $<m>$ (GeV) and the corresponding precision $\delta m$ (GeV) are calculated for 100 and 300 fb$^{-1}$. We take $\tan \beta = 45$. The statistical precision deteriorates as the Higgs mass increases because of the reduction in rate.

<table>
<thead>
<tr>
<th>$m_H^\pm$ (GeV)</th>
<th>$\mathcal{L} = 100$ fb$^{-1}$</th>
<th>$\mathcal{L} = 300$ fb$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m_0$</td>
<td>$&lt;m&gt;$</td>
<td>$\delta m$</td>
</tr>
<tr>
<td>225.9</td>
<td>226.4</td>
<td>3.0</td>
</tr>
<tr>
<td>271.1</td>
<td>271.0</td>
<td>3.4</td>
</tr>
<tr>
<td>317.8</td>
<td>318.3</td>
<td>5.2</td>
</tr>
<tr>
<td>365.4</td>
<td>365.5</td>
<td>7.8</td>
</tr>
<tr>
<td>413.5</td>
<td>413.6</td>
<td>7.7</td>
</tr>
<tr>
<td>462.1</td>
<td>462.3</td>
<td>10.2</td>
</tr>
<tr>
<td>510.9</td>
<td>511.5</td>
<td>13.0</td>
</tr>
</tbody>
</table>

Table 2: The systematic effects on the mass determination in the $H^\pm \rightarrow \tau \nu$ channel are small. Columns 2 and 3 show the statistical uncertainties for an integrated luminosity of 300 fb$^{-1}$. Columns 4 and 5 include the systematic uncertainties. The total uncertainties are dominated by the statistical errors.

<table>
<thead>
<tr>
<th>$m_H^\pm$ (GeV)</th>
<th>No systematics</th>
<th>With systematics</th>
</tr>
</thead>
<tbody>
<tr>
<td>$&lt;m&gt;$</td>
<td>$\delta m$</td>
<td>$&lt;m&gt;$</td>
</tr>
<tr>
<td>225.9</td>
<td>226.4</td>
<td>1.7</td>
</tr>
<tr>
<td>271.1</td>
<td>271.1</td>
<td>2.0</td>
</tr>
<tr>
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<td>318.3</td>
<td>3.0</td>
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<td>462.6</td>
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<tr>
<td>510.9</td>
<td>511.9</td>
<td>7.4</td>
</tr>
</tbody>
</table>

Systematic uncertainties:
- the shape of the background
- the background rate (known to 5%)
- the energy scale -1% for jets and 0.1% for photons, electrons and muons.
**Closer look at charged $H^\pm \rightarrow \tau \nu$**

Table 4: The overall precisions on the rate determination in the $H^\pm \rightarrow \tau \nu$ channel for $\mathcal{L} = 30, 100$ and $300$ fb$^{-1}$. The total number of background events is $B = 6.7$ for $30$ fb$^{-1}$ [10]. The number of signal events listed in the second column correspond to an integrated luminosity of $30$ fb$^{-1}$ [10].

<table>
<thead>
<tr>
<th>$(m_{H^\pm}$ [GeV], $\tan \beta)$</th>
<th>$S \equiv$ Signal events $\Delta(\sigma \times BR)/(\sigma \times BR)$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>30 fb$^{-1}$</td>
</tr>
<tr>
<td>200, 30</td>
<td>46.3</td>
</tr>
<tr>
<td>250, 40</td>
<td>60.3</td>
</tr>
<tr>
<td>300, 45</td>
<td>70.5</td>
</tr>
<tr>
<td>350, 25</td>
<td>18.8</td>
</tr>
<tr>
<td>400, 35</td>
<td>30.6</td>
</tr>
<tr>
<td>450, 60</td>
<td>66.9</td>
</tr>
<tr>
<td>500, 50</td>
<td>36.2</td>
</tr>
</tbody>
</table>

The main systematic error would come from the knowledge of the luminosity (+-10%).
Mass can be reconstructed in collinear approximation

Observe missing transverse momentum and visible Tau-decay products

Assume Tau decay products collinear with original Tau

Solve 2 linear equations for the neutrinos

Taus can be reconstructed

Higgs can be reconstructed

\[ x_{\tau h} = \frac{h_x l_y - h_y l_x}{h_x l_y + p_x l_y - h_y l_x - p_y l_x} \]

\[ x_{\tau l} = \frac{h_x l_y - h_y l_x}{h_x l_y - p_x h_y - h_y l_x + p_y h_x} \]

\( x_{\tau} \) = momentum fraction carried by tau decay products
Reconstruction of the transverse mass

\[ m_T = \sqrt{2p_T^{\tau}p_T^{\bar{\tau}} [1 - \cos(\Delta \phi)]} \]

⇒ Observation of signal in \( m_T \) distribution is not sufficient to distinguish between 2HDM (MSSM) and L.E.D.

FIG. 6: Polarization of the decay \( \tau \) from \( H^\pm \) in MSSM and in models with a singlet neutrino in large extra dimensions. In the latter case, both left and right handed \( \tau \)'s can be produced with some polarization asymmetry. In the backgrounds, the \( \tau \) comes from the decay of the \( W^\pm \). The signal to be studied is in the box — the polarization of the decay \( \tau \) in this signal is the same as in the background. Thus, \( \tau \) polarization effects would not help in suppressing the backgrounds but they may help distinguish between the 2HDM and other models.
The tau lepton lifetime:

\[ 289.4 \pm 0.91 \text{(stat)} \pm 0.90 \text{ (syst)} \text{ fs} \]
(preliminary) BABAR, SLAC-PUB-11317

\[ 290.9 \pm 1.4 \text{ (stat)} \pm 1.0 \text{ (syst)} \text{ fs} \]

With ATLAS, use \( Z \to \tau \tau \) or \( W \to \tau \nu \) events, three-prong decays,

- \( Z \to \tau \tau \) events: \( \rightarrow \) statistical error of 1.8 fs, not competitive with other measurements

- \( W \to \tau \nu \) events: \( \rightarrow \) statistical error of 0.25-0.35 fs, competitive with measurements at \( e^+e^- \) colliders

\( \rightarrow \) expect 780 000 hadronic tau-decay events for 30 fb\(^{-1}\)
\( \rightarrow \) not proven yet that systematic error can be kept under control

D. Cavalli & B. Osculati, ATL-PHYS-2000-014
NLSP in large part of MSSM parameter space

Decay chains often end with:

\[ \tilde{\tau}_1^\pm \rightarrow \tau^\pm \tilde{Z}_1 \]

- Hadronic decays: sensitive to tau polarization
- 1-prong decays: good tau identification

\[ \rightarrow \pi^\pm \nu(12.5\%), \ p^\pm \nu(26\%), \ a_1^\pm \nu(7.5\%) \]

Tau polarization depends on composition of LSP

LSP composition dependence of tau polarization:

\[
P_\tau = \frac{(a_{11}^R)^2 - (a_{11}^L)^2}{(a_{11}^R)^2 + (a_{11}^L)^2}.
\]

With

\[
a_{11}^R = -\frac{2g}{\sqrt{2}}N_{11} \tan \theta_W \sin \theta_T - \frac{g_{m_T}}{\sqrt{2}m_W \cos \beta} N_{13} \cos \theta_T,
\]

\[
a_{11}^L = \frac{g}{\sqrt{2}}[N_{12} + N_{11} \tan \theta_W] \cos \theta_T - \frac{g_{m_T}}{\sqrt{2}m_W \cos \beta} N_{13} \sin \theta_T.
\]

LSP composition

\[ \tilde{Z}_1 = N_{11} \tilde{B} + N_{12} \tilde{W} + N_{13} \tilde{H}_1 + N_{14} \tilde{H}_2, \]

\[ \tilde{\tau}_1^\pm \] composition

\[ \tilde{\tau}_1 = \tilde{\tau}_R \sin \theta_T + \tilde{\tau}_L \cos \theta_T. \]

- Universal SUGRA models:

\[ P_\tau \simeq +1 \]

- For most non-universal SUGRA models:

\[ P_\tau \simeq \cos^2 \theta_T - \sin^2 \theta_T \]

- AMSB models:

\[ P_\tau \simeq -1 \]

- For many GMSB models (\[ \tilde{\tau}_1 \rightarrow \tau \tilde{G} \] decay):

\[ P_\tau = \sin^2 \theta_T - \cos^2 \theta_T \]
Sugra models

Reminder:

- Minimal Sugra (mSUGRA) has 4 parameters + a sign:
  - $m_0$: common scalar mass at GUT scale
  - $m_{1/2}$: common gaugino mass at GUT scale
  - $A$: common trilinear Higgs sfermion-sfermion coupling at GUT scale
  - $\tan \beta$: ratio of the Higgs vacuum expectation values
  - $\text{sgn}(\mu)$: $\mu$ being the SUSY conserving Higgsino mass
mSUGRA: selected points

- **DC1 bulk region point** (new underlying event in generation)
  - $m_0 = 100$ GeV, $m_{1/2} = 300$ GeV, $A_0 = -300$ GeV, $\tan \beta = 6$, $\text{sgn(}\mu\text{)} = +$
  - LSP is mostly bino, light $t_R$ enhance annihilation. 'Bread and butter' region for the LHC experiments
  - llq distributions, tau-tau measurements, third generation squarks (both tau identification and B tagging improved)

- **Coannihilation point**
  - $m_0 = 70$ GeV, $m_{1/2} = 350$ GeV, $A_0 = 0$ GeV, $\tan \beta = 10$, $\text{sgn(}\mu\text{)} = +$
  - LSP is pure bino. LSP/sparticle coannihilation. Small slepton-LSP mass difference gives soft leptons in the final state

- **Focus point**
  - $m_0 = 3350$ GeV, $m_{1/2} = 300$ GeV, $A_0 = 0$ GeV, $\tan \beta = 10$, $\text{sgn(}\mu\text{)} = +$
  - LSP is Higgsino, near $\mu^2 = 0$ bound. Heavy sfermions; all squarks and sleptons have mass $> 2$ TeV, negligible FCNC, CP, $g_\mu - 2$, etc. Complex events with lots of heavy flavor

- **Funnel region point**
  - $m_0 = 320$ GeV, $m_{1/2} = 375$ GeV, $A_0 = 0$ GeV, $\tan \beta = 50$, $\text{sgn(}\mu\text{)} = +$
  - wide H, A for $\tan \beta >> 1$ enhance annihilation. Heavy Higgs resonance (funnel); main annihilation chain into bb pairs
  - dominant tau decays

- **Low mass point** at limit of Tevatron RunII reach
  - $m_0 = 200$ GeV, $m_{1/2} = 160$ GeV, $A_0 = -400$ GeV, $\tan \beta = 10$, $\text{sgn(}\mu\text{)} = +$
  - big cross section, but events rather similar to top
  - measure SM processes in presence of SUSY background to show detector is understood
Inclusive analysis

Select events with at least 4 jets and Missing $E_T$

A simple variable

$M_{\text{eff}} = P_{t,1} + P_{t,2} + P_{t,3} + P_{t,4} + E_T$

At high $M_{\text{eff}}$ non-SM signal rises above background note scale

Peak in $M_{\text{eff}}$ distribution correlates well with SUSY mass scale

$M_{\text{SUSY}} = \min(M_{\tilde{u}}, M_{\tilde{g}})$

Will determine gluino/squark masses to $\sim 15\%$
Tau decay modes

\[ \tau \sim 87 \mu \text{m}, \ m_\tau = 1.78 \ \text{GeV}/c^2 \]

Leptonical decays

\[ \tau \rightarrow e(\mu) \nu \nu : \sim 35.2 \% \]

Identification done through the final lepton

Hadronical decays

1 prong

\[ \tau \rightarrow \nu_\tau + \pi^{\pm/-} + n(\pi^0) : 49.5 \% \]

3 prongs

\[ \tau \rightarrow \nu_\tau + 3\pi^{\pm/-} + n(\pi^0) : 15.2 \% \]

“\(\tau\)–jet” is produced

Quite often taus are produced in pairs: 42% of final states contains two “tau-jet”

<table>
<thead>
<tr>
<th>(\tau\tau) decay mode</th>
<th>BR</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\ell\ell\nu)</td>
<td>12 %</td>
</tr>
<tr>
<td>(\ell)jet (\nu)</td>
<td>46 %</td>
</tr>
<tr>
<td>jet jet (\nu)</td>
<td>42 %</td>
</tr>
</tbody>
</table>

• tau jets at LHC:
  • very collimated
    • 90% of the energy is contained in a ‘cone’ of radius \(R=0.2\) around the jet direction for \(ET>50\ \text{GeV}\)
  • Low multiplicity
    • One, three prongs
    • Hadronic, EM energy deposition
    • Charged pions
    • Photons from \(\pi^0\)
The ATLAS detector at LHC

**Thin Superconducting Solenoid**
(B=2T)

**LAr EM Calorimeter**:  
\[ L \times R = 13.3 \times 2.25 \text{m} \]  
\[ |\eta| \leq 3.2 \ (4.9) \]  
\[ \sigma_E / E = 10\% / \sqrt{E} \oplus 0.7\% \]  
PB-LAr

**Hadronic Calorimeter**:
Endcaps LArg  
Barrel Scintillator-tile  
\[ L \times R = 12.2 \times 4.25 \text{m} \]  
\[ \sigma_E / E = 50\% / \sqrt{E} \oplus 3\% \ (|\eta| \leq 3) \]

**Large Superconducting Air-Core Toroids**

**Muon Spectrometer**
\[ L \times R = 25 \ (46) \text{m} \times 11 \text{m} \]

\[ \sigma(E_{\text{miss}}) = 0.46 \times \sqrt{\text{SumET}} \]
SM Higgs with mass below 200 GeV

A difficult case: a light Higgs ($m_H \sim 115$ GeV)...

If clean had-had channel observable, sensitivity to Higgs parity might be established but which production process use to allow to trigger such events?

**BR**(H→ττ) ~ few %

<table>
<thead>
<tr>
<th>ATLAS</th>
<th>H → γγ</th>
<th>ttH → ttbb</th>
<th>qqH → qqlτ (l*l-had)</th>
</tr>
</thead>
<tbody>
<tr>
<td>S</td>
<td>130</td>
<td>15</td>
<td>~ 10</td>
</tr>
<tr>
<td>B</td>
<td>4300</td>
<td>45</td>
<td>~ 10</td>
</tr>
<tr>
<td>S/ √B</td>
<td>2.0</td>
<td>2.2</td>
<td>~ 2.7</td>
</tr>
</tbody>
</table>

Full GEANT simulation, simple cut-based analyses

If clean had-had channel observable, sensitivity to Higgs parity might be established but which production process use to allow to trigger such events?
SM Higgs production at LHC

**gg fusion**

- $H \rightarrow \gamma \gamma$
- $t\bar{t}H \rightarrow \ell \nu \bb + X$
- $H \rightarrow ZZ^* \rightarrow 4\ell$
- $H \rightarrow WW^* \rightarrow \ell \nu \ell \nu$
- $WH \rightarrow WWW^* \rightarrow \ell \nu \ell \nu$, $\ell \pm \ell \pm \nu \nu$

**WW/ZZ fusion**

- $m_H < 2 m_Z$
  - $H \rightarrow \gamma \gamma$
  - $t\bar{t}H \rightarrow \ell \nu \bb + X$
  - $H \rightarrow ZZ^* \rightarrow 4\ell$
  - $WH \rightarrow WWW^* \rightarrow \ell \nu \ell \nu$, $\ell \pm \ell \pm \nu \nu$

- $m_H > 2 m_Z$
  - Main channel is $H \rightarrow ZZ \rightarrow 4\ell$ (gold-plated)
  - $H \rightarrow ZZ \rightarrow \ell \ell \nu \nu$
  - $H \rightarrow ZZ \rightarrow \ell \ell \ jj$
  - $H \rightarrow WW \rightarrow \ell \nu \ jj$

- fully hadronic final states dominate but cannot be extracted from large QCD backgrounds
MSSM Higgs searches

Two Higgs Doublets with 5 physical states

- 2 CP-even neutral Higgs bosons $h^0, H^0$
- 1 CP-odd neutral Higgs boson $A^0$
- 2 charged Higgs bosons $H^\pm$
- free parameters $\tan \beta = \frac{\nu_1}{\nu_2}$, $m_A$

Tree level:
- $m_h \leq m_Z$
- $m_A \leq m_H$
- $m_W \leq m_{H^\pm}$

Rad. corrected: $m_h < 130$ GeV

Many possible search channels @ LHC
- $h \to \gamma \gamma$, $tt \to tt bb$, $H \to ZZ (*) \to 4\ell$ like SM
- $A/H \to \mu \mu, \tau \tau, tt$, $H^\pm \to \tau \nu, cs, tb$
- $H \to hh$, $A \to Z h$

Typical for MSSM

$A/H \to \chi^0_2 \chi^0_2$
$\chi^0_2 \to h \chi^0_1$

If SUSY particles accessible
What data samples in 2007?

ATLAS preliminary $\sqrt{s} = 900$ GeV, $L = 10^{29} \text{ cm}^{-2} \text{ s}^{-1}$

- 30% data taking efficiency included (machine plus detector)
- Trigger and analysis efficiencies included

- $\text{Jets } p_T > 15 \text{ GeV}$
  (b-jets: $\sim 1.5\%$)
- $\text{Jets } p_T > 50 \text{ GeV}$
- $\text{Jets } p_T > 70 \text{ GeV}$
- $Y \rightarrow \mu\mu, J/\psi \rightarrow \mu\mu$
- $W \rightarrow e\nu, \mu\nu$
- $Z \rightarrow e\mu, \mu\mu$
- + 1 million minimum-bias/day

- Start to commission triggers and detectors with collision data (minimum bias, jets, ..) in real LHC environment
- Maybe first physics measurements (minimum-bias, underlying event, QCD jets, ..)?
- Observe a few $W \rightarrow l\nu, Y \rightarrow \mu\mu, J/\psi \rightarrow \mu\mu$?

Anna Kaczynska

F. Gianotti, ICHEP06, Moscow, 02/08/2006
With the first physics run in 2008 ($\sqrt{s} = 14$ TeV)...

1 fb$^{-1}$ (100 pb$^{-1}$) $\equiv$ 6 months (few days) at $L = 10^{32}$ cm$^{-2}$s$^{-1}$ with 50% data-taking efficiency → may collect a few fb$^{-1}$ per experiment by end 2008

<table>
<thead>
<tr>
<th>Channels (examples ...)</th>
<th>Events to tape for 100 pb$^{-1}$ (per expt: ATLAS, CMS)</th>
<th>Total statistics from some of previous Colliders</th>
</tr>
</thead>
<tbody>
<tr>
<td>$W \rightarrow \mu \nu$</td>
<td>$\sim 10^6$</td>
<td>$\sim 10^4$ LEP, $\sim 10^6$ Tevatron</td>
</tr>
<tr>
<td>$Z \rightarrow \mu \mu$</td>
<td>$\sim 10^5$</td>
<td>$\sim 10^6$ LEP, $\sim 10^6$ Tevatron</td>
</tr>
<tr>
<td>$t\bar{t} \rightarrow WbWb \rightarrow \mu \nu +X$</td>
<td>$\sim 10^4$</td>
<td>$\sim 10^4$ Tevatron</td>
</tr>
<tr>
<td>QCD jets $p_T &gt; 1$ TeV</td>
<td>$&gt; 10^3$</td>
<td>---</td>
</tr>
<tr>
<td>$gg \rightarrow m = 1$ TeV</td>
<td>$\sim 50$</td>
<td>---</td>
</tr>
</tbody>
</table>

With these data:

- Understand and calibrate detectors in situ using well-known physics samples
  e.g. - $Z \rightarrow ee, \mu\mu$ tracker, ECAL, Muon chambers calibration and alignment, etc.
  - $t\bar{t} \rightarrow blv bjj$ jet scale from $W \rightarrow jj$, b-tag performance, etc.

- Measure SM physics at $\sqrt{s} = 14$ TeV: $W, Z, t\bar{t}$, QCD jets ...
  (also because omnipresent backgrounds to New Physics)

→ prepare the road to discovery ...... it will take time ...
Experimental conditions

- Proton-Proton collisions @ 14 TeV
- Luminosity:
  - First run in 2007 at 900 GeV
  - First run @ 14 TeV in 2008, luminosity increasing to reach 
    $\sim 10^{33}\text{cm}^{-2}\text{s}^{-1}$ “low luminosity” phase
    
    $\Rightarrow \sim 30 \text{ fb}^{-1}$ between 2008 and 2010/2011

  - $\sim 10^{34}\text{cm}^{-2}\text{s}^{-1}$ “high luminosity” phase
    
    $\Rightarrow \sim 300 \text{ fb}^{-1}$ by 2014/2015

- Pile-up: $\sim 2$ (low luminosity) to 20 (high luminosity) pp interactions
  (“minimum bias”) per bunch crossing (every 25 ns)

- Trigger to go from 40 MHz interaction rate to $\sim 200\text{Hz}$ to disk for offline analysis