Spare slides
\( H \rightarrow \gamma\gamma \) \hspace{1cm} \( m_H \leq 150 \text{ GeV} \)

- \( \sigma \times \text{BR} \approx 50 \text{ fb} \) \hspace{1cm} (BR \approx 10^{-3})

- Backgrounds:

-- \( \gamma\gamma \) (irreducible): e.g. \( q \rightarrow \gamma \gamma \) \( q \rightarrow \gamma \gamma \)

\[
\sigma_{\gamma\gamma} \approx 2 \text{ pb / GeV} \quad \Gamma_H \approx \text{MeV}
\]

\[ \rightarrow \text{need } \sigma(m)/m \approx 1\% \]

-- \( \gamma j^+ jj \) (reducible):

\[
\sigma_{\gamma j^+ jj} \sim 10^6 \sigma_{\gamma\gamma} \quad \text{with large uncertainties}
\]

\[ \rightarrow \text{need } R_j > 10^3 \quad \text{including } R(\pi^0) > 3, \text{ for } \varepsilon_\gamma \approx 80\% \text{ to get } \sigma_{\gamma j^+ jj} \ll \sigma_{\gamma\gamma} \]

\[ \rightarrow \text{most demanding channel for EM calorimeter performance: energy and angle resolution, response uniformity, } \gamma/\text{jet and } \gamma/\pi^0 \text{ separation} \]

ATLAS and CMS: different technology and design, complementary performance
$\text{ttH} \rightarrow \text{ttbb}$ \hspace{1cm} $m_H \leq 130$ GeV

- $\sigma \times \text{BR} \approx 300$ fb
- Complex final state: $H \rightarrow bb, t \rightarrow bjj, t \rightarrow blv$

- Main backgrounds:
  - combinatorial from signal (4b in final state)
  - $Wjjjjjjj, WWbbjj$, etc.
  - $ttjj$ (dominant, non-resonant)

$\rightarrow$ crucial performance aspect: b-tagging

$\Gamma = e, \mu$ for trigger and background rejection

reduced by b-tagging the four b-jets and reconstructing both top quarks

$C_{MS}$

$\text{ttH, } H \rightarrow bb$

$m_H: 115$ GeV$/c^2$

$k = 1.5$

$\text{CMS, } \text{ttH} \rightarrow \text{ttbb}$

30 fb$^{-1}$

$\sigma_m \sim 15$ GeV

F. Gianotti, Bruno Touschek school, Frascati, 15/5/2006
Vector Boson Fusion $qqH \rightarrow \tau\tau$

$m_H \leq 200$ GeV

$\sigma = 4$ pb (20% of total cross section for $m_H = 130$ GeV)

Very distinct signature:
- two forward jets
- little jet activity in central region

Experimental issues:
- forward jet reconstruction (hermetic calorimetry over $|\eta|<5$)
- jet veto in the central region

$Zjj$ ($Z \rightarrow \tau\tau$) background from $Zjj$ ($Z \rightarrow ee$)

ATLAS, $qqH \rightarrow \tau\tau$

30 fb$^{-1}$

$m_H = 120$ GeV

$Zjj$

$t\bar{t}$, $WW$ EW

F. Gianotti, Bruno Touschek school, Frascati, 15/5/2006
What is wrong with the SM?

- **Origin of particle masses** → where is the Higgs boson?

- "**Naturalness**" problem:
  
  radiative corrections

  \[ \delta m_H^2 \sim \Lambda^2 \]

  \( \rightarrow \Lambda \equiv \text{scale up to which SM is valid} \)

- "**Hierarchy**" problem: why \( M_{EW}/M_{Planck} \sim 10^{-17} \)? Is there anything in between?

- Flavour/family problem, CP-violation, coupling unification, gravity incorporation, \( \nu \) masses/oscillations, dark matter and dark energy, etc.

All this calls for

**A more fundamental theory of which SM is low-E approximation**

\[ \rightarrow \text{New Physics} \]

Difficult task: solve SM problems without contradicting (the very constraining) EW data
Examples of detector performance requirements

**Very selective trigger:** 40 MHz (interaction rate) $\rightarrow$ 200 Hz (affordable rate-to-storage)  
1 H $\rightarrow$ 4e event every $10^{13}$ interactions

**Lepton measurement:** $p_T \approx$ GeV $\rightarrow$ 5 TeV (b $\rightarrow$ l+X, W'/Z', ...)

**Mass resolutions:**
- $\approx 1\%$ decays into leptons or photons (Higgs, new resonances)
- $\approx 10\%$ W $\rightarrow$ jj, H $\rightarrow$ bb (top physics, Higgs, ...)

**Hadron calorimeter linearity** understood to $< 1.5\%$ at $E_{jet} \sim 4$ TeV (q compositeness)

**Calorimeter coverage:** $|\eta|<5$ (SUSY/$E_T^{miss}$, Higgs/forward jet tag, ...)

Jet energy scale
• mainly from $Z \rightarrow \ell \ell$ events
• $\sim 1 \%$ uncertainty achieved by CDF, D0 (dominated by statistics of control samples)
• goal: $0.2 \%$, to measure $m_W$ to $\sim 15$ MeV
• systematics dominated by detector: knowledge of tracker material to 1%, overall alignment to $<1\mu$m, B-field to better than 0.1%, etc.

Particle identification:
• $\varepsilon (b) \approx 50\%$ $R(jet) \approx 100$ ($H \rightarrow bb$, SUSY, 3rd generation !!)
• $\varepsilon (\tau) \approx 50\%$ $R(jet) \approx 100$ ($A/H \rightarrow \tau\tau$, SUSY, 3rd generation !!)
• $\varepsilon (\gamma) \approx 80\%$ $R(jet) > 10^3$ ($H \rightarrow \gamma\gamma$)
• $\varepsilon (e) > 70\%$ $R(jet) > 10^5$ (inclusive electron sample)

Absolute luminosity to $<5\%$ ($W/Z/tt$ cross-section measurements, new physics through $\sigma \times BR$ measurements, ....)
Trigger: one of the big challenges

Must reduce rate from 40 MHz (interaction rate) to ~ 200 Hz (affordable rate to storage)
Must be very selective: e.g. 1 H → 4e event every $10^{13}$ interactions

⇒ 3-level system

**LEVEL 1 TRIGGER**
- Hardware-Based (FPGAs ASICs)
- Coarse granularity from calorimeter & muon systems
- 2 µs latency (2.5 µs pipelines)

**LEVEL 2 TRIGGER**
- Regions-of-Interest “seeds”
- Full granularity for all subdetector systems
- Fast Rejection “steering”
- O(10 ms) processing time

**EVENT FILTER**
- “Seeded” by Level 2 result
- Potential full event access
- Offline-like Algorithms
- O(1 s) processing time

**RATES**
- 40 MHz
- 75 kHz
- 2 kHz
- 200 Hz

**Trigger/DAQ System**
- CALO
- MUON
- TRACKING
- PIPELINE MEMORIES
- DERANDOMIZERS
- READ-OUT DRIVERS (RODs)
- READ-OUT BUFFERS (ROBs)
- EVENT BUILDER
- FULL-EVENT BUFFERS & PROCESSOR SUBFARMS
- MASS STORAGE FOR OFFLINE ANALYSIS
Examples of possible LVL1 and HLT menus

<table>
<thead>
<tr>
<th>Channel</th>
<th>Threshold [GeV]</th>
<th>Rate [kHz]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inclusive isolated EM</td>
<td>25</td>
<td>12</td>
</tr>
<tr>
<td>Two EM clusters</td>
<td>15</td>
<td>4</td>
</tr>
<tr>
<td>Inclusive isolated muon</td>
<td>20</td>
<td>0.8</td>
</tr>
<tr>
<td>Di-muons</td>
<td>6</td>
<td>0.2</td>
</tr>
<tr>
<td>Tau+ + E_T^miss</td>
<td>25/30</td>
<td>2</td>
</tr>
<tr>
<td>1 jet or 3 jets or 4 jets</td>
<td>200, 90, 65</td>
<td>0.6</td>
</tr>
<tr>
<td>Jet + E_T^miss</td>
<td>50/60</td>
<td>0.4</td>
</tr>
<tr>
<td>Other (calib., pre-scale)</td>
<td></td>
<td>5</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td><strong>~25 kHz</strong></td>
</tr>
</tbody>
</table>

- LVL1 rate limited by staging of HLT processors
- HLT rate by cost of offline computing (1 PB/yr)
- Guiding principles of LHC trigger:
  - inclusive approach to the “unknown”, safe overlap with Tevatron reach, avoid biases from exclusive selections, margin for offline optimization and QCD uncertainties, enough bandwidth for calibration/control triggers (esp. at beginning !)
Mass resolution \((m_H \sim 100 \text{ GeV, high } L)\):

**ATLAS**: 1.3 GeV (sampling calorimeter)

**CMS**: 0.7 GeV (homogeneous calorimeter)

\[
\frac{\sigma(E)}{E} \approx \frac{10\%}{\sqrt{E}}
\]

\[
\frac{\sigma(E)}{E} \approx 2-5\% \sqrt{E}
\]

---

**ATLAS Pb-LAr**

- Full resolution
- Noise contribution
- Subtracted resolution \(dE/E = a \times E + b\)
  - \(a = 9.18 \pm 0.13\%\)
  - \(b = 0.27 \pm 0.04\%\)

**CMS (crystals)**

- \(\frac{\sigma(E)}{E} = 3.3\% / \sqrt{E} \oplus 0.27\%\)

---

June 1999
Tower 14 (2080)
Noise = 190 MeV
Runs 29569-30442

F. Gianotti, Bruno Touschek school, Frascati, 15/5/2006
Total acceptance: ≈ 25% larger in ATLAS

CMS:
- \( B = 4T \): 30% of \( \gamma \rightarrow e^+e^- \) lost, some others in the tails of mass spectrum
- no ECAL longitudinal segmentation → vertex measured using secondary tracks of underlying event → often pick up wrong vertex → more tails in the pass spectrum than ATLAS

\[
\frac{S}{\sqrt{B}} \sim \epsilon_\gamma \times \epsilon_{\text{mass bin}}
\]

ATLAS, full simulation
Vertex resolution using EM calo longitudinal segmentation

\( \sigma_z \sim 5.3 \text{ cm at LHC} \)

\[
\frac{S}{\sqrt{B}} \text{ (CMS)} \approx \frac{S}{\sqrt{B}} \text{ (ATLAS)} \approx 6 \quad 100 \text{ fb}^{-1}
\]
LHC: $R(\pi^0) \geq 3$ for $\epsilon(\gamma) \sim 90\%$ needed to reject $\gamma j + jj$ background to $H \rightarrow \gamma\gamma$

Using 4mm $\eta$-strips in 1st ECAL compartment

\begin{align*}
\text{Data:} \quad \langle R(\pi^0) \rangle &= 3.54 \pm 0.12 \\
\text{MC:} \quad \langle R(\pi^0) \rangle &= 3.66 \pm 0.10
\end{align*}
Rejection of $\gamma j + jj$ background

ATLAS EM calorimeter:
- 4 mm $\eta$-strips in first compartment for $\gamma/\pi^0$ separation
- Longitudinal segmentation into 3 compartments

$R_j > 10^3$ achieved

$\gamma/\pi^0$ separation studied also with test-beam data

What about CMS (crystal size ~ 2.5 cm x 2.5 cm, no longitudinal segmentation; preshower only in end-cap)?
How many “candle” events in ATLAS at the beginning?

- $>10^6-10^7$ minimum bias and QCD jets $p_T > 150$ GeV (if 1% of trigger bandwidth)

Similar statistics to CDF, D0 today

$10 \text{ pb}^{-1} \equiv 1 \text{ month at } 10^{30}$ + < 2 weeks at $10^{31}$, $\varepsilon=50%$

$100 \text{ pb}^{-1} \equiv \text{ few days at } 10^{32}$, $\varepsilon=50%$

$1 \text{ fb}^{-1} \equiv 6 \text{ months at } 10^{32}$, $\varepsilon=50%$

$5 \text{ fb}^{-1} \equiv 3 \text{ months at } 10^{32}$ + 3 months at $10^{33}$, $\varepsilon=50%$

$\rightarrow \text{ end 2007?}$

$\rightarrow \text{ end 2008?}$
Commissioning ATLAS detector and physics with top events

Can we observe an early top signal with limited detector performance? Can we use such a signal to understand detector and physics?

\[ \sigma_{tt} (LHC) \approx 250 \text{ pb} \] for gold-plated semi-leptonic channel

\( \begin{align*}
\text{use simple and robust selection cuts:} \\
p_T(l) &> 20 \text{ GeV} \\
E_T^{\text{miss}} &> 20 \text{ GeV} \\
\text{only 4 jets with } p_T &> 40 \text{ GeV} \\
\end{align*} \}
\varepsilon \sim 5\%$

\( \begin{align*}
\text{no b-tagging required (early days ...)} \\
\text{m (top} \rightarrow \text{jjj) from invariant mass of 3 jets} \\
\text{giving highest top } p_T \\
\text{m (W} \rightarrow \text{jj) from 2 jets with highest momentum in jjj CM frame} \\
\end{align*} \)

Total efficiency, including \( m_{jjj} \) inside \( m_{\text{top}} \) mass bin : \( \sim 1.5\% \) (preliminary and conservative ...)
Expect ~ 100 events inside mass peak for 30 pb$^{-1}$

$\rightarrow$ top signal observable in early days with no b-tagging and simple analysis

Cross-section to 20%, $m_{\text{top}}$ to 7 GeV (LHC goal ~1 GeV) with 100 pb$^{-1}$?

$tt$ is excellent sample to:

- commission b-tagging, set jet E-scale using $W \rightarrow jj$ peak
- understand detector performance and reconstruction of several physics objects ($e$, $\mu$, jets, b-jets, missing $E_T$, ..)
- understand / tune MC generators using e.g. $p_T$ spectra
- measure background to many searches
Higgs production at LHC

Production mechanisms and cross sections

F. Gianotti, Bruno Touschek school, Frascati, 15/5/2006
Pixels : $\sim 10^8$ channels  
First layer at $R \sim 5$ cm  
$\sigma (R\phi) \sim 10 \mu m$  
$\sigma (z) \sim 60 \mu m$

**ATLAS, full simulation**

2D b-tag (used here):  
$\varepsilon_b = 50\% \hspace{1em} R_j (uds) = 100$ at high L

3D b-tag: $R_j$ is $\sim 2$ larger for same $\varepsilon_b$

Note:  
-- complementary channel to $H \rightarrow \gamma\gamma$  
-- large coverage in MSSM  
-- allows measurement of top Yukawa coupling
Rapidity distribution of most fwd jets
VBF Higgs events vs tt background

Forward tag jet reconstruction

- ATLFAST no pile-up
- Full simulation no pile-up $E_T > 15$ GeV
- Full simulation with pile-up constant fake tag rate 10%
\[ \sigma_m \sim 1.5 \text{ GeV} \]

**CMS, \( t\bar{t}H \rightarrow t\bar{t}bb \)\]

\[ m_{t\bar{t}}: 115 \text{ GeV/c}^2 \]

\[ k = 1.5 \]

\[ \sigma_m \sim 15 \text{ GeV} \]

**ATLAS, \( H \rightarrow \gamma\gamma \)\]

100 fb\(^{-1}\)

\[ \gamma\gamma \text{ background from side bands} \]

\[ \sigma_m \sim 1.4 \text{ GeV} \]

**ATLAS, \( qqH \rightarrow \tau\tau \)\]

30 fb\(^{-1}\)

\[ m_H = 120 \text{ GeV} \]

\[ \sigma_m \sim 11 \text{ GeV} \]

**Zjj (\( Z \rightarrow \tau\tau \))\]

background from \( Zjj (Z \rightarrow ee) \)

Background dominated by irreducible component in all cases

**Expected signals in low-mass region**

\[ \sigma_m \sim 15 \text{ GeV} \]

**ttbb background from \( ttjj \) with j anti b-tagged**

2006
If \( m_H > 180 \text{ GeV} \): early discovery may be easier with \( H \to ZZ \to 4l \) channel

\[ H \to 4l \text{ (l=e,\( \mu \))} \]

Events \( /0.5 \text{ GeV} \)

CMS, 10 fb\(^{-1}\)

Signal
Backgr

May be observed with 3-4 fb\(^{-1}\)
(end 2008 ?)
A difficult case: a light Higgs ($m_H \sim 115$ GeV) ...

- Needed $\mathcal{L} dt$ per experiment

- $1 \text{ fb}^{-1}$: 95% C.L. exclusion
- $5 \text{ fb}^{-1}$: 5$\sigma$ discovery
- Over full allowed mass range
- End 2008?

**m_H \sim 115$ GeV $10 \text{ fb}^{-1}$**

**total $S/\sqrt{B} \approx 4^{+2.2}_{-1.3}$**

<table>
<thead>
<tr>
<th>ATLAS</th>
<th>$H \to \gamma\gamma$</th>
<th>$ttH \to ttbb$</th>
<th>$qqH \to qq\tau\tau$ (ll + l-had)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$S$</td>
<td>130</td>
<td>15</td>
<td>$\sim 10$</td>
</tr>
<tr>
<td>$B$</td>
<td>4300</td>
<td>45</td>
<td>$\sim 10$</td>
</tr>
<tr>
<td>$S/\sqrt{B}$</td>
<td>2.0</td>
<td>2.2</td>
<td>$\sim 2.7$</td>
</tr>
</tbody>
</table>

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K-factors = $\sigma$(NLO)/$\sigma$(LO) $\approx 2$ not included
Remarks:

Each channel contributes $\sim 2\sigma$ to total significance $\rightarrow$ observation of all channels important to extract convincing signal in first year(s)

The 3 channels are complementary $\rightarrow$ robustness:

- different production and decay modes
- different backgrounds
- different detector/performance requirements:
  -- ECAL crucial for $H \rightarrow \gamma\gamma$ (in particular response uniformity): $\sigma/m \sim 1\%$ needed
  -- b-tagging crucial for ttH: 4 b-tagged jets needed to reduce combinatorics
  -- efficient jet reconstruction over $|\eta| < 5$ crucial for qqH $\rightarrow$ qq$\tau\tau$
    : forward jet tag and central jet veto needed against background

Note: -- all require "low" trigger thresholds
  E.g. ttH analysis cuts: $p_T(l) > 20$ GeV, $p_T$(jets) > 15-30 GeV
  -- all require very good understanding (1-10%) of backgrounds
### Best low-mass channel at the Tevatron

**WH → lν bb**  
(m\(_H\) = 120 GeV)

<table>
<thead>
<tr>
<th>S (14 TeV/ 2 TeV)</th>
<th>B (14 TeV/ 2 TeV)</th>
<th>S/B (14 TeV/ 2 TeV)</th>
<th>S/√B (14 TeV/ 2 TeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>≈ 5</td>
<td>≈ 25</td>
<td>≈ 0.2</td>
<td>≈ 1</td>
</tr>
</tbody>
</table>

**H → WW(*)**  
(m\(_H\) = 160 GeV)

<table>
<thead>
<tr>
<th>S (14 TeV/ 2 TeV)</th>
<th>B (14 TeV/ 2 TeV)</th>
<th>S/B (14 TeV/ 2 TeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>≈ 17</td>
<td>≈ 6</td>
<td>≈ 3</td>
</tr>
</tbody>
</table>

Assuming same integrated luminosity and same detector performance at Tevatron and LHC

Tevatron projections are a bit optimistic:
- no systematics
- optimistic detector performance (e.g. H → bb mass resolution)
- sensitivity from combination of channels with individual significances ≪ 2\(\sigma\)

Still ....

competition between Tevatron and LHC in 2008–2009 if m\(_H\) < 130 GeV?
Measurements of the SM Higgs parameters

Dominant systematic uncertainty is $\gamma/l$ absolute energy scale:
- assumed here: 1‰
- goal: 0.2‰ (for $m_W$ measurement)

E-scale from $Z \rightarrow ll$ events
(close to light Higgs)
Measurement of the SM Higgs couplings

Couplings can be obtained from measured rate in a given production channel:

\[ R_{ff} = \int L \, dt \, \sigma \left( t^{\pm}, pp \rightarrow H + X \right) \, \text{BR} \left( H \rightarrow \text{ff} \right) \]

\[ \text{BR} \left( H \rightarrow \text{ff} \right) = \frac{\Gamma_f}{\Gamma_{tot}} \rightarrow \text{deduce} \quad \Gamma_f \sim g_{Hff}^2 \]

\[ \Gamma_{tot} \] and \[ \sigma \left( pp \rightarrow H + X \right) \] from theory \( \rightarrow \) without theory inputs measure ratios of rates in various channels \( \left( \Gamma_{tot} \text{ and } \sigma \text{ cancel} \right) \rightarrow \Gamma_f / \Gamma_{f'} \rightarrow \) several theory constraints

- LHC luminosity upgrade (SLHC, \( L = 10^{35} \)) could improve LHC precision by up to \( \sim 2 \) before first LC becomes operational
- Not competitive with LC precision of \( \sim \% \), but useful insight into EWSB mechanism
Higgs self-coupling $\lambda$
- not accessible at LHC
- may be constrained to $\approx 20\%$
  at SLHC ($L=10^{35}$ cm$^{-2}$ s$^{-1}$)

$H_2^2 = 2 \lambda v^2$

Higgs spin and CP
Promising for $m_H > 180$ GeV ($H \to ZZ \to 4l$),
difficult at lower masses

Significance for exclusion of other $J^{CP}$ states than $0^+$

<table>
<thead>
<tr>
<th>$m_H$ (GeV)</th>
<th>$J^{CP}=1^+$</th>
<th>$J^{CP}=1^-$</th>
<th>$J^{CP}=0^-$</th>
</tr>
</thead>
<tbody>
<tr>
<td>200</td>
<td>6.5 $\sigma$</td>
<td>4.8 $\sigma$</td>
<td>40 $\sigma$</td>
</tr>
<tr>
<td>250</td>
<td>20 $\sigma$</td>
<td>19 $\sigma$</td>
<td>80 $\sigma$</td>
</tr>
<tr>
<td>300</td>
<td>23 $\sigma$</td>
<td>22 $\sigma$</td>
<td>70 $\sigma$</td>
</tr>
</tbody>
</table>

Buszello et al. SN-ATLAS-2003-025

F. Gianotti, Bruno Touschek school, Frascati, 15/5/2006
Motivations:

- stabilizes $m_H$
- predicts light Higgs (in agreement with EW data)
- enable gauge-coupling unification
- provides a dark matter candidate, etc.
<table>
<thead>
<tr>
<th><strong>e^+e^- colliders</strong></th>
<th><strong>versus</strong></th>
<th><strong>hadron colliders</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Sparticles produced</strong> ~ democratically</td>
<td><strong>(\tilde{q}\tilde{g}, \tilde{g}\tilde{g}) dominates</strong></td>
<td></td>
</tr>
</tbody>
</table>
| | **\(\tilde{q}\tilde{g}\) \(\approx 100\) pb** | \(q\rightarrow g\rightarrow \tilde{q}\rightarrow\tilde{\chi}^0\)  \(m=150\) GeV Tevatron  
| | **\(\tilde{e}\tilde{e}\) \(\approx 5\) fb** |  
| e^+ \(\gamma, Z^*\) \(\tilde{\tau}^+, \tilde{\tau}^-, \tilde{\chi}^+, \tilde{\chi}^-\) \(\tilde{\chi}_i^0\) |  
| e^- \(\tilde{\tau}^-, \tilde{\chi}^-, \tilde{\chi}_i^0\) |  
| **Direct decays to LSP dominate:** | **~ all decay modes** |  
| e.g. \(\tilde{q}\rightarrow q\tilde{\chi}_1^0\) \(\tilde{\tau}\rightarrow l\tilde{\chi}_1^0\) \(\chi^* \rightarrow W^*\chi_1^0\) |  
| \(\rightarrow\) main topology is 2 acoplanar objects + missing E | **\(\tilde{q}, \tilde{g} \) heavy \(\rightarrow\) cascade decays important**  
| e.g. \(\tilde{g}\rightarrow \tilde{q}q\rightarrow qq\tilde{\chi}_2^0\rightarrow qqZ\tilde{\chi}_1^0\) |  
| **Moderate backgrounds** \((\gamma\gamma \rightarrow ff, WW, ZZ)\) | **Huge backgrounds** \((QCD, W/Z+\text{jets})\) |  
| **Sensitive to:** | **Sensitive to:** |  
| ~ all kinematically accessible \(\tilde{p}\) | ~\(\tilde{q}, \tilde{g}\) (high \(\sigma\), heavy, clear signature)  
| ~ all decay modes | and \(\chi_1^+ \chi_2^0 \rightarrow 3l\) (clean signature)  
| \(\Delta m = m(\tilde{p}) - m(\tilde{\chi}_1^0)\approx \text{GeV} \) (small visible E) | ~\(\Delta m \gg 10\) GeV (large visible E needed) |  
| **Mass reach** \(m \leq \sqrt{s}/2\) for ~ any sparticle  
| over most accessible parameter space | **High mass reach for \(\tilde{q}, \tilde{g}\) but holes** in parameter space \(\rightarrow\) ~ no absolute limit |  
| **LEP2 :** \(m > 100\) GeV for \(\chi^\pm\), squarks, sleptons | **Tevatron today:** \(\tilde{q}, \tilde{g}\) excluded up to  
| \(m \sim 330\) GeV (Run 2 reach: ~ 400 GeV) |  

F. Gianotti, Bruno Touschek school, Frascati, 15/5/2006
Discovery reach vs time with jets + $E_T^{\text{miss}}$ signature (most model-independent)

ATLAS
5σ discovery curves

- Band indicates factor ± 2 variation in background estimate

- ~1 day @ $10^{33}$: up to 1.5 TeV
- ~100 days: up to 2.3 TeV
- ~"10 days": up to 2 TeV
- Ultimate (300 fb$^{-1}$): ~2.5-3 TeV

But: it will take a lot of time to understand the detectors and the backgrounds …
Main backgrounds to SUSY searches in jets + $E_{T}^{\text{miss}}$ topology (one of the most “dirty” signatures …):

• $W/Z + \text{jets}$ with $Z \rightarrow \nu\nu$, $W \rightarrow \tau\nu$; $t\bar{t}$; etc.
• QCD multijet events with fake $E_{T}^{\text{miss}}$ from jet mis-measurements (calorimeter resolution and non-compensation, cracks, …)
• cosmics, beam-halo, detector problems overlapped with high-$p_{T}$ triggers, …

1) “Clean-up” procedure:
• at least 2-3 jets with $p_{T}>80-100$ GeV, $E_{T}^{\text{miss}} > 80-100$ GeV (for masses at overlap with Tevatron reach, higher otherwise)
• good event vertex
• no jets in detector cracks
• $p_{T}^{\text{miss}}$ vector not pointing along or opposite to a jet in transverse plane
2) Estimate backgrounds using *as much as possible data (control samples)* and *MC*

<table>
<thead>
<tr>
<th>Background process (examples ....)</th>
<th>Control samples (examples ....)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Z \rightarrow \nu \nu + \text{jets})</td>
<td>(Z \rightarrow ee, \mu \mu + \text{jets})</td>
</tr>
<tr>
<td>(W \rightarrow \tau \nu + \text{jets})</td>
<td>(W \rightarrow e\bar{\nu}, \mu \bar{\nu} + \text{jets})</td>
</tr>
<tr>
<td>(t\bar{t} \rightarrow b\bar{\nu} b\bar{\nu} )</td>
<td>(t\bar{t} \rightarrow b\nu b\nu )</td>
</tr>
<tr>
<td>QCD multijets</td>
<td>lower (E_T) sample</td>
</tr>
</tbody>
</table>

Additional handles from changing (loosening ..) cuts, varying the number of leptons, etc., which will change the background composition.

Normalization point

Normalise MC to data at low \(E_T^{\text{miss}}\) and use it to predict background at high \(E_T^{\text{miss}}\) in “signal” region.

Understanding \(E_T^{\text{miss}}\) spectrum (and tails from instrumental effects) is one of most crucial and difficult experimental issues for SUSY searches at hadron colliders.

![Graph](image)
Hermetic calorimetry coverage: \(|\eta| < 5\), minimal cracks and dead material
→ minimise fake \(E_T^{\text{miss}}\) from lost or badly measured jets

ATLAS: full simulation of \(Z + \text{jet(s)}\) events, with \(Z \rightarrow \mu\mu\) and \(p_T(Z) > 200\) GeV

- - - - - reconstructed \(E_T^{\text{miss}}\) spectrum
- - - - - \(E_T^{\text{miss}}\) spectrum if leading jet is undetected

Events with \(E_T^{\text{miss}} > 50\) GeV

“crack” barrel/extended barrel Tilecal

Particles parallel to Tilecal scintillating tiles

2 events with \(E_T^{\text{miss}} > 200\) GeV contain a high-\(p_T\) neutrino
If SUSY is there, to progress further and constrain the underlying theory we will need to perform precision measurements (e.g. of sparticle masses)

Mass peaks cannot be directly reconstructed ($\chi^0_1$ undetectable)
→ measure invariant mass spectra (end-points, edges,..) of visible particles
→ deduce constraints on combinations of sparticle masses

Ex. : LHC “Point 5” : m$_0$ = 100 GeV, m$_{1/2}$ = 300 GeV, A$_0$ = 300 GeV, tan$\beta$ = 2, \(\mu > 0\)

m(\(\tilde{g}\)) \sim 700 GeV
m(\(\tilde{q}\)) \sim 800 GeV
m(\(\chi^0_1\)) \sim 120 GeV
Example of a typical chain:

\[ \tilde{q}_L \rightarrow q \chi^0_2 \rightarrow \tilde{\tau}_R \chi^0_1 \]

- \( m(\tilde{q}_L) \): spectrum end-point: 109 GeV, exp. precision ~0.3%
- \( m(\tilde{q}_L \chi^0_2 \tilde{\tau}_R \chi^0_1) = 690, 232, 157, 121 \text{ GeV} \)
- \( m(\tilde{l}^\pm j) \): spectrum end-point: 479 GeV, exp. precision ~1%
- \( m(\tilde{l}^\pm j) \): spectrum end-point: 552 GeV, exp. precision ~1%

---

ATLAS
100 fb\(^{-1}\)
LHC Point 5
Putting all constraints together:

\[
\begin{align*}
\widetilde{q}_L \rightarrow q \chi_0^0, \\
\widetilde{q}_L \rightarrow h \chi_0^0, \\
\widetilde{q}_L \rightarrow t_R \chi_0^0, \\
\widetilde{q}_L \rightarrow b b \chi_0^0
\end{align*}
\]

<table>
<thead>
<tr>
<th>Sparticle mass</th>
<th>Expected precision 100 fb⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>squark left</td>
<td>± 3%</td>
</tr>
<tr>
<td>\chi_0^0</td>
<td>± 6%</td>
</tr>
<tr>
<td>slepton mass</td>
<td>± 9%</td>
</tr>
<tr>
<td>\chi_0^1</td>
<td>± 12%</td>
</tr>
</tbody>
</table>

“Model-independent”, pure kinematics

Sparticles directly observable at Point 5:

\[\widetilde{q}_L, \widetilde{q}_R, \widetilde{g}, \widetilde{t}_1, \widetilde{T}_R, \widetilde{T}_L, h, \chi_2^0\]

Note: can measure much more than masses: cross-sections, maybe some couplings and branching ratios, etc.
Then, assuming a model and from fit of model to all experimental measurements derive:

- sparticle masses with higher accuracy
- fundamental parameters of theory to 1-30%
- dark matter ($\chi^0_1$) relic density and $\sigma (\chi^0_1 - \text{nucleon})$

---

Demonstrated so far in mSUGRA (5 param.) and in more general MSSM (14 param.)

As with SM at SLD, LEP, Tevatron

---

ATLAS, 300 fb$^{-1}$

$mSUGRA$, Point "SPS1A"

$\delta (\Omega_{\chi} h^2) \approx 3\%$

Direct Dark Matter searches

Zepelin, CDMS, Edelweiss

— present limit

--- projected

---
General strategy toward understanding the underlying theory
(SUSY as an example …)

Discovery phase: inclusive searches ... as model-independent as possible

First characterization of model: from general features: Large \( E_T \text{miss} \)? Many leptons? Exotic signatures (heavy stable charged particles, many \( \gamma \)'s, etc.)? Excess of b-jets or \( \tau \)'s? ...

Interpretation phase:
• reconstruct/look for semi-inclusive topologies, eg:
  -- \( h \to bb \) peaks (can be abundantly produced in sparticle decays)
  -- di-lepton edges
  -- Higgs sector: e.g. \( A/H \to \mu\mu, \tau\tau \) ⇒ indication about \( \tan\beta \), measure masses
  -- \( tt \) pairs and their spectra ⇒ stop or sbottom production, gluino ⇒ stop-top
• determine (combinations of) masses from kinematic measurements (e.g. edges ...)
• measure observables sensitive to parameters of theory (e.g. mass hierarchy)

At each step narrow landscape of possible models and get guidance to go on:
• lot of information from LHC data (masses, cross-sections, topologies, etc.)
• consistency with other data (astrophysics, rare decays, etc.)
• joint effort theorists/experimentalists will be crucial
Combining collider data with other “constraints”…..

Disfavoured by BR \( b \rightarrow s\gamma \)
from CLEO, BELLE
BR \( b \rightarrow s\gamma = (3.2 \pm 0.5) \times 10^{-4} \)
used here

Favoured by \( g_\mu - 2 \) (E821)
assuming that
\( \delta \alpha_\mu = (43 \pm 16) \times 10^{-10} \) (OLD !!)
is from SUSY (\( \pm 2 \sigma \) band)

Favoured by cosmology
assuming 0.1 \( \leq \Omega \chi h^2 \leq 0.3 \)
Complementarity between LHC and future $e^+e^-$ Colliders

In general:

- LHC most powerful for $\tilde{q}$ and $\tilde{g}$ (strongly interacting) but can miss some EW sparticles (gauginos, sleptons) and heavy Higgs bosons.

- Depending on $\sqrt{s}$, LC should cover part/all EW spectrum (usually lighter than squarks/gluinos) → should fill holes in LHC spectrum. Squarks could also be accessible if $\sqrt{s}$ large enough.

LC can perform precise measurements of masses (to ~ 0.1%), couplings, field content of sparticles with mass up to ~ $\sqrt{s}/2$, disentangle squark flavour, etc.
What the LHC can do and cannot do ....

In general the LHC can (examples ...):
  • discover SUSY up to $m(\tilde{q}, \tilde{g}) \sim 2.5$ TeV
  • measure lightest Higgs h mass to $\sim 0.1$
  • derive sparticle masses (typically $\tilde{q}, \tilde{g}, \chi^0_2$) from kinematic measurements
  • constrain underlying theory by fitting a model to the data

More difficult or impossible (examples ...):
  • disentangle squarks of first two generations
  • observe / measure sleptons if $m > 350$ GeV
  • measure full gaugino spectrum
  • measure sparticle spin-parity and all couplings
  • constrain underlying theory in model-indep. way

$\rightarrow$ complementarity with LC

Ultimate goal: from precise measurements of e.g. gaugino masses at the TeV scale reconstruct high-E theory
Extra-dimensions
Additional dimensions
→ $M_{\text{gravity}} \sim M_{\text{EW}}$
New states at TeV scale

Little Higgs
SM embedded in larger gauge group
New particles at TeV scale, stable $m_H$

Technicolour
New strong interactions break EW symmetry
→ Higgs (elementary scalar) removed
New particles at TeV scale

Split SUSY
Accept fine-tuning of $m_H$
(and of cosm. constant)
by anthropic arguments
Part of SUSY spectrum at TeV scale
(for couplings unification and dark matter)

Strong motivations for a machine
able to explore the TeV-scale

LHC
Search for Extra-dimensions

Basic idea: solve hierarchy problem $\frac{M_{EW}}{M_{Planck}} \sim 10^{-17}$ by lowering gravity scale from $M_{Planck} \sim 10^{19}$ GeV to $M_D \sim 1$ TeV Possible if gravity propagates in $4 + \delta$ dimensions.
If gravity propagates in $4 + \delta$ dimensions, a gravity scale $M_D \approx 1$ TeV is possible.

If $M_D \approx 1$ TeV:

$\delta = 1 \quad R \approx 10^{13}$ m $\rightarrow$ excluded by macroscopic gravity

$\delta = 2 \quad R \approx 0.7$ mm $\rightarrow$ limit of small-scale gravity experiments

$\delta = 7 \quad R \approx 1$ Fm

Extra-dimensions are compactified over $R < \text{mm}$.
• **Gravitons in Extra-dimensions** get quantized mass:

\[ m_k \sim \frac{k}{R} \quad k = 1, \ldots, \infty \]

\[ \Delta m \sim \frac{1}{R} \quad \text{e.g. } \Delta m \approx 400 \text{ eV} \quad \delta = 3 \]

\[ \begin{array}{c}
\text{continuous tower of massive gravitons} \\
(\text{Kaluza-Klein excitations})
\end{array} \]

\[ \mathcal{O} \left( \frac{f}{M_{Pl}} \right)^2 N_{kk} \approx \frac{1}{M_{Pl}^2} \left( \frac{\sqrt{s}}{\Delta m} \right)^\delta \approx \frac{1}{M_{Pl}^2} \sqrt{s} \delta R^\delta \approx \frac{\sqrt{s}^\delta}{M_D^{\delta+2}} \]

Due to the large number of \( G_{kk} \), the coupling SM particles - Gravitons becomes of EW strength

• Only one scale in particle physics: EW scale
• Can test geometry of universe and quantum gravity in the lab
Look for a continuum of Graviton KK states:

\[ q \rightarrow \text{topology is jet(s) + missing } E_T \]

Cross-section:\[ \sigma \approx \frac{1}{M_D^{\delta+2}} \]

- \( M_D \) = gravity scale
- \( \delta \) = number of extra-dimensions

To characterize the model need to measure \( M_D \) and \( \delta \)

Measurement of cross-section gives ambiguous results: e.g. \( \delta=2, M_D=5 \text{ TeV} \)
very similar to \( \delta=4, M_D=4 \text{ TeV} \)

Solution may be to run at different \( \sqrt{s} \)s:

Discriminating between models:
- SUSY: multijets plus \( E_T^{\text{miss}} \) (+ leptons, ...)
- ADD: monojet plus \( E_T^{\text{miss}} \)

Good discrimination between various solutions possible with expected <5% accuracy on \( \sigma(10)/\sigma(14) \) for 50 fb\(^{-1}\)
$G \rightarrow e^+e^-$ resonance with $m \sim 1$ TeV

The easiest object to discover at the LHC ...

BR ($G \rightarrow ee \approx 2\%$), $c = 0.01$ (small/conservative coupling to SM particles)

<table>
<thead>
<tr>
<th>Mass (TeV)</th>
<th>Events for 10 fb$^{-1}$ (after all cuts)</th>
<th>$\int L , dt$ for discovery ($\geq 10$ observed events)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.9</td>
<td>~ 80</td>
<td>~ 1.2 fb$^{-1}$</td>
</tr>
<tr>
<td>1.1</td>
<td>~ 25</td>
<td>~ 4 fb$^{-1}$</td>
</tr>
<tr>
<td>1.25</td>
<td>~ 13</td>
<td>~ 8 fb$^{-1}$</td>
</tr>
</tbody>
</table>

• large enough signal for discovery with $\sim 1$ fb$^{-1}$ for $m \rightarrow 1$ TeV
• dominant Drell-Yan background small
• signal is mass peak above background

C. Collard

Randall Sundrum Graviton

$G \rightarrow ee$

CMS: Full Simulation and reconstruction

$c=0.01$ and $\int L = 10$ fb$^{-1}$

One experiment

Graviton ($s=2$) or $Z'$ ($s=1$)?

→ look at $e^\pm$ angular distributions

ATLAS, 100 fb$^{-1}$, $m_G=1.5$ TeV

"data"
Mini black holes production at LHC?

- Schwarzschild radius (i.e. within which nothing escapes gravitational force):

\[
\begin{align*}
\text{4-dim., } M_{\text{gravity}} &= M_{\text{Planck}} : \\
R_S &\sim \frac{2}{M_{\text{Pl}}^2} \frac{M_{\text{BH}}}{c^2} \\
\text{4+δ-dim., } M_{\text{gravity}} &= M_D \sim \text{TeV} : \\
R_S &\sim \frac{1}{M_D} \left( \frac{M_{\text{BH}}}{M_D} \right)^{\frac{1}{δ+1}}
\end{align*}
\]

Since \( M_D \) is low, tiny black holes of \( M_{\text{BH}} \sim \text{TeV} \) can be produced if partons \( ij \) with \( \sqrt{s_{ij}} = M_{\text{BH}} \) pass at a distance smaller than \( R_S \).

- Large partonic cross-section: \( \sigma(ij \rightarrow \text{BH}) \sim \pi R_S^2 \)
  
  e.g. For \( M_D \sim 3 \text{ TeV} \) and \( δ = 4 \), \( \sigma(pp \rightarrow \text{BH}) \sim 100 \text{ fb} \) → 1000 events in 1 year at low \( L \).

- Black holes decay immediately (\( τ \sim 10^{-26} \text{ s} \)) by Hawking radiation (democratic evaporation):
  - large multiplicity
  - small missing \( E \)
  - jets/leptons \( \sim 5 \)
  
  \[ \text{expected signature (quite spectacular ...)} \]
A black hole event with $M_{BH} \sim 8$ TeV in ATLAS

From preliminary studies: reach is $M_{D} \sim 6$ TeV for any $\delta$ in one year at low luminosity.

By testing Hawking formula $\rightarrow$ proof that it is BH $+$ measurement of $M_{D}, \delta$

$$\log T_{H} = - \frac{1}{\delta + 1} \log M_{BH} + f(M_{D}, \delta)$$

precise measurements of $M_{BH}$ and $T_{H}$ needed ($T_{H}$ from lepton and photon spectra)
Construction quality

Thickness of Pb plates must be uniform to 0.5% (~10 μm)

End-cap: 1536 plates

< > ~ 2.2 mm
σ ≈ 9 μm

Test-beam measurements

Scan of a barrel module (Δφ×Δη=0.4×1.4) with high-E electrons

After correction:
n.m.s. ≈ 0.57%
over ~ 500 spots
3 **Cosmics runs:**

Measured cosmic $\mu$ rate in ATLAS pit: few Hz
$\rightarrow$ $\sim 10^6$ events in $\sim$ 3 months of cosmics runs beginning 2007
$\rightarrow$ enough for initial detector shake-down
$\rightarrow$ ECAL: check calibration vs $\eta$ to 0.5%

4 **First collisions:** calibration with $Z \rightarrow ee$ events (rate $\approx$ 1 Hz at $10^{33}$)

Use $Z$-mass constraint to correct long-range non-uniformities (module-to-module variations, effect of upstream material, etc.)
$\sim 10^5 Z \rightarrow ee$ events (few days data taking at $10^{33}$) enough to achieve constant term $c \leq 0.7$

Nevertheless, let's consider the worst (unrealistic ?) scenario: no corrections applied

ECAL non-uniformity at construction level, i.e.:
-- no test-beam corrections
-- no calibration with $Z \rightarrow ee$

$H \rightarrow \gamma\gamma$ significance $m_H \sim 115$ GeV degraded by $\sim 25$
$\rightarrow$ need 50% more $L$ for discovery
2 The first year(s) of data taking

First collisions (Summer 2007): $L \sim 5 \times 10^{28}$
Plans to reach $L \sim 10^{33}$ in/before 2009
Hope to collect few fb$^{-1}$ per experiment by end 2008

<table>
<thead>
<tr>
<th>Channels (examples …)</th>
<th>Events to tape for 1 fb$^{-1}$ (per expt: ATLAS, CMS)</th>
<th>Total statistics from previous Colliders</th>
</tr>
</thead>
<tbody>
<tr>
<td>$W \rightarrow \mu \nu$</td>
<td>$7 \times 10^6$</td>
<td>$\sim 10^4$ LEP, $\sim 10^6$ Tevatron</td>
</tr>
<tr>
<td>$Z \rightarrow \mu \mu$</td>
<td>$\sim 10^6$</td>
<td>$\sim 10^6$ LEP, $\sim 10^5$ Tevatron</td>
</tr>
<tr>
<td>$tt \rightarrow W b W b \rightarrow \mu \nu +X$</td>
<td>$\sim 10^5$</td>
<td>$\sim 10^4$ Tevatron</td>
</tr>
<tr>
<td>$\tilde{g}\tilde{g}$ m = 1 TeV</td>
<td>$10^2 - 10^3$</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.
  - $tt \rightarrow b\nu bjj$ jet scale from $W \rightarrow jj$, b-tag performance, etc.

- Measure SM physics at $\sqrt{s} = 14$ TeV: $W, Z, tt, QCD$ jets … (omnipresent backgrounds to New Physics)

→ prepare the road to discovery …… it will take a lot of time …
SUSY Higgs sector: \( h, H, A, H^\pm \)

\[ m_h < 135 \text{ GeV}, \quad m_A = m_H = m_{H^\pm} \]

Assuming decays to SM particles only

Here only \( h \) (SM-like) observable at LHC, unless \( A, H, H^\pm \rightarrow \text{SUSY} \)

\( \rightarrow \text{LHC may miss part of the MSSM Higgs spectrum} \)

Observation of full spectrum may require high-E (\( \sqrt{s} \approx 2 \text{ TeV} \)) Lepton Collider
Most of MSSM Higgs plane already covered after 1 year at $L = 10^{33}$ ...

Large variety of channels and signatures accessible
Extended gauge groups: \( Z' \rightarrow l^+l^- \)

- Reach in 1 year at \( 10^{34} \): 4-5 TeV
- Discriminating between models possible up to \( m \sim 2.5 \) TeV by measuring:
  -- \( \sigma \times \Gamma \) of resonance
  -- lepton F-B asymmetry
  -- \( Z' \) rapidity
Little Higgs models

Alternative approach to the hierarchy problem predicting heavy top $T$ (EW singlet), new gauge bosons $W_H, Z_H, A_H$ and Higgs triplet $\Phi^0, \Phi^+, \Phi^{++}$.

Observation of $T \rightarrow Zt, Wb$ discriminates from 4th family quarks.
Observation of $V_H \rightarrow Vh$ discriminates from $W', Z'$.
Other scenarios ..... 

Leptoquarks: \( lq lq \rightarrow lj lj \)

Large number of scenarios studied:
⇒ demonstrated detector sensitivity to many signatures
⇒ robustness, ability to cope with unexpected scenarios
⇒ LHC direct discovery reach up to \( m \approx 5-6 \text{ TeV} \)
LHC and high-energy cosmic rays

$\sqrt{s} = 14$ TeV corresponds to $E \sim 100$ PeV fixed target proton beam

LHC studies most relevant to HECR:
- most energetic particles from the collisions
- pp (and pA, AA) cross-sections
both require detection in the forward region

Charged particle multiplicity and energy in pp inelastic events at $\sqrt{s} = 14$ TeV

F. Gianotti, Bruno Touschek school, Frascati, 15/5/2006
**Measurement of $\sigma_{\text{tot}}(pp)$**

Curves are $\sim (\log s)^\gamma$

Goal of TOTEM:
$\sim 1\%$ precision

**TOTEM**: 3 stations of detectors ("Roman Pots" RP1, RP2, RP3) at both sides of IP5 (integrated with beam pipe) to measure scattered proton in elastic interactions down to $\theta_{\text{scat}} \approx 20\, \mu\text{rad}$
With the first collision data ($1 \rightarrow 100 \text{ pb}^{-1}$?)

- understand detector performance in situ ↔ physics (the two are correlated!)
- measure particle multiplicity in minimum bias (a few hours of data taking ...)
- measure QCD jets ($>10^3$ events with $E_T(j) > 1$ TeV with 100 pb$^{-1}$) and their underlying event
- measure W,Z cross-sections: to 15% with <10 pb$^{-1}$ and 10% with 100 pb$^{-1}$?
- observe a top signal with ~ 30 pb$^{-1}$
- measure $t\bar{t}$ cross-section to 20% and $m(\text{top})$ to 7-10 GeV with 100 pb$^{-1}$?
- improve knowledge of PDF (low-$x$ gluons!) with W/Z: with O(100) pb$^{-1}$?
- first tuning of MC (minimum bias, underlying event, $t\bar{t}$, W/Z+jets, QCD jets,...)

And, more ambitiously:
- discover SUSY up to squark and gluino masses of ~ 1.3 TeV?
- discover a Z' up to masses of ~ 1.3 TeV?
- surprises?