Missing Transverse Energy
Missing ET

Calculated from all Calo Cells within $|\eta_{\text{cell}}| < 5$

- $E_{x(y)\text{Miss}} = \sum E_{x(y)\text{cells}}$

$$E_{T\text{Miss}} = \sqrt{E_{y\text{Miss}}^2 + E_{y\text{Miss}}^2}$$

— Calorimeter coverage important for resolution
Tracking
Tracking at LHC

- p-p collision @ $\sqrt{s} = 14$ TeV
- bunch spacing of 25 ns
- Luminosity
  - low-luminosity: $2 \times 10^{33}$ cm$^{-2}$s$^{-1}$ (first years)
  - high-luminosity: $10^{34}$ cm$^{-2}$s$^{-1}$
    - ~20 minimum bias events per bunch crossing
    - ~1000 charged tracks per event

Radius: 2cm 10cm 25cm 60cm

$N_{\text{Tracks}}/(\text{cm}^2 \times 25\text{ns})$: 10.0 1.0 0.10 0.01
Tracker Requirements

- **Efficient & robust Pattern Recognition algorithm**
  - Fine granularity to resolve nearby tracks
  - Fast response time to resolve bunch crossings
- **Ability to reconstruct narrow heavy object**
  - $1\sim2\%$ $p_t$ resolution at $\sim100$ GeV
- **Ability to operate in a crowded environment**
  - $N_{ch}/(cm^2*25ns) = 1.0$ at 10 cm from PV
- **Ability to tag b/τ through secondary vertex**
  - Good impact parameter resolution
- **Reconstruction efficiency**
  - 95% for hadronic isolated high $p_t$ tracks
  - 90% for high $p_t$ tracks inside jets
ATLAS Inner Detector

ID inside 2T solenoid field
Tracking based on many points

Precision Tracking:
- Pixel detector (2-3 points)
- Semiconductor Tracker – SCT (4 points)

Continuous Tracking:
(for pattern recognition & e id)
- Transition Radiation Tracker – TRT (36 points)
ID performance
Muons
Traversing Atlas a $\mu$ is detected in
- 2 high precision tracking systems: Inner Detector and $\mu$ System
- Calorimeters

$\mu$ Syst Best at higher $p_T$
E loss $>3$GeV
ID Best at lower $p_T$

Muon measurement

- Solenoidal Field
- Inhomogeneous Toroidal Field

RPC TGC
Muon Performance

- Muon Spectrometer resolution dominates for $P_T > 100$ GeV/c
- Resolution fairly constant over whole eta range
- Coverage $|\eta| < 2.7$

Fake rate increases at high luminosity to $\sim 5\%$
Tau Lepton
Decays

- **τ decay modes**
  - **Leptonical decay modes**
    - \( \tau \to \nu_\tau + \nu_e + e \) (17.4%)
    - \( \tau \to \nu_\tau + \nu_\mu + \mu \) (17.8%)
  - **Hadronical decay modes**
    - **1 prong**
      - \( \tau \to \nu_\tau + \pi^\pm \) (11.0%)
      - \( \tau \to \nu_\tau + \pi^\pm + \pi^0 \) (25.4%)
      - \( \tau \to \nu_\tau + \pi^\pm + \pi^0 + \pi^0 \) (10.8%)
      - \( \tau \to \nu_\tau + K^\pm + \nu\pi^0 \) (1.4%)
      - \( \tau \to \nu_\tau + \pi^\pm + \nu\pi^0 \) (1.6%)
    - **3 prong**
      - \( \tau \to \nu_\tau + 3\pi^\pm + \nu\pi^0 \) (15.2%)

How to identify them?

- 1 track, impact parameter
- Shower shape, energy sharing
- 3 tracks, impact parameter, secondary vertex, shower shape, energy sharing
**τ identification**

Shower shape, $N_{\text{strip}}$, Charge, $N_{\text{track}}$, Impact parameter, $E_T/p_T(1^{\text{st}}\text{track})$

Signal $A \rightarrow \tau \tau$, background QCD

- $\tau s$, $0 < p_T < 11$
- $\tau s$, $134 < p_T < 334$
- QCD jets, $0 < p_T < 44$
- QCD jets, $134 < p_T < 334$

- $N_{\text{track}}$
- $E_T/p_T(1^{\text{st}}\text{track})$

- $R_{\text{EM}}$
- $F_{\text{ISO}}$

- N_{\text{strips}}
$\tau$ id: efficiency vs Background rejection

for hadronic decays

$\epsilon_{\tau}\sim50\%$  $R\sim200$

$\epsilon_{\tau}\sim60\%$  $R\sim60$
b-quark jet tagging
b jet tagging

Secondary Vertex

Primary vertex

Jet axis

$\sigma(a_0) \approx 11 \, \mu m$

$\sigma(z_0) \approx 120 \, \mu m$
Reconstructed primary vertex
low luminosity pile-up

**signal:**
WH(120,400)→ bb,uu
ttH→ bb

**background:**
ttjj → b l ν b jjjj

b-tagging performance is limited by physics:

- gluon splitting and occasional coincidence between light jet and b-quark directions.
Summary of particle identification

• Good identification capability of detectors
  – $\varepsilon_e \sim 70\%$, $R_j \sim 10^6$  $\varepsilon_e \sim 80\%$, $R_j \sim 10^5$  ****
  – $\varepsilon_{\gamma} \sim 80\%$, $R_j \sim \text{few } 10^4$  ****
  – $\varepsilon_{\tau} \sim 50\%$, $R_j \sim 200$  $\varepsilon_{\tau} \sim 60\%$, $R_j \sim 60$  **
  – $\varepsilon_{b} \sim 50\%$, $R_u \sim 320$  $\varepsilon_{b} \sim 60\%$, $R_u \sim 160$  **
  – $\varepsilon_{\mu} \sim 90\%$, fakes $<<\%$  ****

• Always some trade-off between efficiency and rejection (except muons)

• Every analysis has its optimum “working point” depending on the background
Is that all you need?

• Do not forget, you have to trigger on the interesting events!!!

• Otherwise, you will only keep QCD background
Physics and Trigger

• High $p_T$ Physics

Production of heavy objects may be detected via one or more of the following signatures:

- One or more isolated, high-$p_T$ charged leptons
- Large missing $E_T$ (from neutrinos, dark matter candidates)
- High multiplicity of large $p_T$ jets
- Isolated high-$p_T$ photons
- Copious $b$ production relative to QCD
## Inclusive Selection Signatures

- To select an extremely broad spectrum of “expected” and “unexpected” Physics signals (hopefully!).
- The selection of Physics signals requires the identification of objects that can be distinguished from the high particle density environment.

<table>
<thead>
<tr>
<th>Object</th>
<th>Examples of physics coverage</th>
<th>Nomenclature</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electrons</td>
<td>Higgs (SM, MSSM), new gauge bosons, extra dimensions, SUSY, W/Z, top</td>
<td>( e_{25i}, 2e_{15i} )</td>
</tr>
<tr>
<td>Photons</td>
<td>Higgs (SM, MSSM), extra dimensions, SUSY</td>
<td>( \gamma_{60i}, 2\gamma_{20i} )</td>
</tr>
<tr>
<td>Muons</td>
<td>Higgs (SM, MSSM), new gauge bosons, extra dimensions, SUSY, W/Z, top</td>
<td>( \mu_{20i}, 2\mu_{10} )</td>
</tr>
<tr>
<td>Jets</td>
<td>SUSY, compositeness, resonances</td>
<td>( j_{360}, 3j_{150}, 4j_{100} )</td>
</tr>
<tr>
<td>Jet+missing ( E_T )</td>
<td>SUSY, leptoquarks, &quot;large&quot; extra dimensions</td>
<td>( j_{60} + xE_{60} )</td>
</tr>
<tr>
<td>Tau+missing ( E_T )</td>
<td>Extended Higgs models (e.g. MSSM), SUSY</td>
<td>( \tau_{30} + xE_{40} )</td>
</tr>
<tr>
<td></td>
<td>also inclusive missingET, SumET, SumET_jet</td>
<td>&amp; many prescaled and mixed triggers</td>
</tr>
</tbody>
</table>

The list must be non-biasing, flexible, include some redundancy, extendable, to account for the “unexpected”.
Region of Interest (RoI) Mechanism

**Hardware**

40 Mhz

- **LVL1 triggers on high $p_T$ objects**
  - calorimeter cells and muon chambers
to find $e/\gamma, \tau, jet, \mu$ candidates above thresholds
- identifies Regions of Interest
- fixed latency 2.5 $\mu$s

**Software**

75 khz

- **LVL2 uses Regions of Interest**
  - local data access, reconstruction & analysis
  - sub-detector matching of RoI data
  - produces LVL2 result
  - average latency $\sim 10$ ms

**Software**

2 kHz

- **Event Filter**
  - can be “seeded” by LVL2 result
  - potential full event access,
  - offline-like Algorithms $O(1 \text{ s})$ latency

200 hz

H $\rightarrow$ 2e + 2$\mu$
## LVL1 Trigger Rates

<table>
<thead>
<tr>
<th>Selection</th>
<th>$2 \times 10^{33} \text{ cm}^{-2}\text{s}^{-1}$</th>
<th>$10^{34} \text{ cm}^{-2}\text{s}^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>MU20</td>
<td>0.8</td>
<td>4.0</td>
</tr>
<tr>
<td>2MU6</td>
<td>0.2</td>
<td>1.0</td>
</tr>
<tr>
<td>EM25I</td>
<td>(30)</td>
<td>12.0</td>
</tr>
<tr>
<td>2EM15I</td>
<td>(20)</td>
<td>4.0</td>
</tr>
<tr>
<td>J200</td>
<td>(290)</td>
<td>0.2</td>
</tr>
<tr>
<td>3J90</td>
<td>(130)</td>
<td>0.2</td>
</tr>
<tr>
<td>4J65</td>
<td>(90)</td>
<td>0.2</td>
</tr>
<tr>
<td>J60 + xE60</td>
<td>(100+100)</td>
<td>0.4</td>
</tr>
<tr>
<td>TAU25 + xE30</td>
<td>(60+60)</td>
<td>2.0</td>
</tr>
<tr>
<td>MU10 + EM15I</td>
<td>0.1</td>
<td>0.4</td>
</tr>
<tr>
<td>Others (pre-scales, calibration, ...)</td>
<td>5.0</td>
<td>5.0</td>
</tr>
<tr>
<td>Total</td>
<td>~ 25</td>
<td>~ 40</td>
</tr>
</tbody>
</table>

- Rates given in kHz
- No safety factor included!

→ $E_T$ values imply 95% efficiency w.r.t. to asymptotic value

**LVL1 rate is dominated by candidate electromagnetic clusters: 78% of physics triggers**
# Inclusive High Level Trigger Event Selection

Current global understanding of trigger rates

<table>
<thead>
<tr>
<th>Selection</th>
<th>$2 \times 10^{33} \text{ cm}^{-2}\text{s}^{-1}$</th>
<th>Rates (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electron</td>
<td>$e^{25i}, 2e^{15i}$</td>
<td>~40</td>
</tr>
<tr>
<td>Photon</td>
<td>$\gamma^{60i}, 2\gamma^{20i}$</td>
<td>~40</td>
</tr>
<tr>
<td>Muon</td>
<td>$\mu^{20i}, 2\mu^{10}$</td>
<td>~40</td>
</tr>
<tr>
<td>Jets</td>
<td>$j^{400}, 3j^{165}, 4j^{110}$</td>
<td>~25</td>
</tr>
<tr>
<td>Jet &amp; $E_T^{miss}$</td>
<td>$j^{70} + xE^{70}$</td>
<td>~20</td>
</tr>
<tr>
<td>$\tau$ &amp; $E_T^{miss}$</td>
<td>$\tau^{35} + xE^{45}$</td>
<td>~5</td>
</tr>
<tr>
<td>B-physics</td>
<td>$2\mu 6$ with $m_B/m_{\psi}$</td>
<td>~10</td>
</tr>
<tr>
<td>Others</td>
<td>pre-scales, calibration, ...</td>
<td>~20</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>~200</td>
</tr>
</tbody>
</table>

No safety factors - large uncertainties!
Summary

• Detectors have been built following the requirements of LHC physics
• A lot of effort went into R&D, test beam, simulation
• Still, it will not be easy to get the detector to work at their nominal performance levels
• In the next lectures we will see examples of physics channels that rely on the properties that were shown: resolution, efficiency, rejection ....
• It will not be enough to try to get the detector to work as well as possible, one needs also to quantify resolution, reconstruction efficiency and trigger efficiencies
  → to calculate cross-sections, to subtract backgrounds, etc...
• It will take a while until the detector is at its best and fully understood
Back-up slides
## Back-up slides

### Cross sections @ LHC and Tevatron

<table>
<thead>
<tr>
<th>Process</th>
<th>Tevatron</th>
<th>LHC</th>
<th>Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>&gt;20 GeV Jet</td>
<td>~ few mb</td>
<td>~20 µb</td>
<td>1/2000</td>
</tr>
<tr>
<td>&gt;100 GeV Jet</td>
<td>~ 200 nb</td>
<td>&gt; 250 GeV Jet</td>
<td>1/10</td>
</tr>
<tr>
<td>W → ℓ ν</td>
<td>~ 10 nb</td>
<td>W → ℓ ν</td>
<td>1/10</td>
</tr>
<tr>
<td>Z → ℓ ℓ</td>
<td>~ 1.5 nb</td>
<td>Z → ℓ ℓ</td>
<td>1/10</td>
</tr>
<tr>
<td>ttbar</td>
<td>~ 1 nb</td>
<td>ttbar</td>
<td>1/500</td>
</tr>
<tr>
<td>Higgs(100 GeV)</td>
<td>~ 20 pb</td>
<td>Higgs(100 GeV)</td>
<td>1/200</td>
</tr>
<tr>
<td>Gluino(500 GeV)</td>
<td>~ 20 pb</td>
<td>Gluino(500 GeV)</td>
<td>-</td>
</tr>
</tbody>
</table>

- 0.001 Hz for L = 10^{31} cm^{-2}s^{-1}
- 1 Hz for L = 10^{33} cm^{-2}s^{-1}
LHC phenomenology – problem I

Simple numerology

<table>
<thead>
<tr>
<th>TEVATRON</th>
<th>LHC</th>
</tr>
</thead>
<tbody>
<tr>
<td>$L = 10^{31} \text{cm}^{-2}\text{s}^{-1}$</td>
<td>$L = 10^{33} \text{cm}^{-2}\text{s}^{-1}$</td>
</tr>
<tr>
<td>$10^{32} \text{cm}^{-2}\text{s}^{-1}$</td>
<td>$10^{34} \text{cm}^{-2}\text{s}^{-1}$</td>
</tr>
</tbody>
</table>

One year (30%) = $10^7 \text{s}$

Calculate integrated luminosity in one year

Event rates for cross-section $\sigma = 1 \text{nb}$
LHC phenomenology – problem I

Simple numerology

**TEVATRON**

$L = 10^{31} \text{cm}^{-2}\text{s}^{-1}$  
$10^{32} \text{cm}^{-2}\text{s}^{-1}$

**LHC**

$L = 10^{33} \text{cm}^{-2}\text{s}^{-1}$  
$10^{34} \text{cm}^{-2}\text{s}^{-1}$

One year (30%) = $10^7$ s

1 barn = $10^{-24} \text{cm}^2$  
1 pb = $10^{-12}$ barn  
1 fb = $10^{-15}$ barn

1 pb$^{-1}$ = $10^{36} \text{cm}^{-2}$  
1 fb$^{-1}$ = $10^{39} \text{cm}^{-2}$

Integrated luminosity in one year:

100 pb$^{-1}$  
1 fb$^{-1}$  
10 fb$^{-1}$  
100 fb$^{-1}$

Event rates: $\sigma = 1 \text{nb}$

0.01 Hz  
0.1 Hz  
1 Hz  
10 Hz

Event collected in one year:

$10^5$ events  
$10^6$ events  
$10^7$ events  
$10^8$ events
LHC phenomenology – problem II

QCD as a background for SM Higgs searches:

- Higgs production cross-section dominated by gluon-gluon fusion: $gg \rightarrow H \quad \sigma H(100\text{GeV}) \sim 20\text{pb}$
- Light SM Higgs $\text{Br}(H \rightarrow bb) \sim 40\%$
- QCD cross-section for jets with $p_T > 20\text{GeV}$ is $10^8 \times$ Higgs production cross-section
- $p_T$ jets from $H$ decays $>\sim 20$ GeV
- Jet rejection in b-tagging $\varepsilon_b \sim 50\% \quad R_j \sim 320$

Se puede observar $H \rightarrow bb$?
LHC phenomenology – problem II

QCD as a background for searches:
- Higgs production cross-section dominated by gluon-gluon fusion: $gg \rightarrow H$: $\sigma_H(100\text{GeV}) \sim 20\text{pb}$
- Light SM Higgs $\text{Br}(H \rightarrow bb) \sim 40\%$
- QCD cross-section for jets with $p_T > 20\text{GeV}$ is $10^8 \times$ Higgs production cross-section
- $p_T$ jets from $H$ decays $>\sim 20$ GeV
- Jet rejection in b-tagging $\varepsilon_b \sim 50\%$ $R_j \sim 320$

Se puede observar $H \rightarrow bb$?
- identify 2 b-jets: rejection factor $(1/R_j)^2 \sim 10^{-5}$
- branching fraction for $H \rightarrow bb$ is $\sim 40\% \sim 0.4$
- efficiency for identifying 2 b-jets $(\sim 50\%)^2 \sim 0.25$

⇒ $S/B \sim \text{BR} \times \text{Eff(b-tagging)}^2 / (q/g \text{ jet rejection})^2$

⇒ $S/B \sim (0.4 \times 0.25) / (10^8 \times 10^{-5}) \sim 10^{-4}$
LHC phenomenology – problem II

QCD as a background for searches:
- Higgs production cross-section dominated by gluon-gluon fusion: \( gg \rightarrow H : \sigma_H(150\text{GeV}) \sim 10\text{pb} \)
- one year at \( L = 10^{33}\text{cm}^{-2}\text{s}^{-1} \rightarrow 10^5 \) Higgs produced
- \( 10^4 \)bb decays tagged – \( 10^8 \) background jets

Significance \( \sim 1 \)
to reach 5, needs factor 25 in statistics!

And what do you trigger on ??????