Particle detection and reconstruction at the LHC (III)

CERN-Fermilab Hadron Collider Physics Summer School, CERN, 2007
11th to 14th of August 2007 (D. Froidevaux, CERN)
Particle detection and reconstruction at the LHC (and Tevatron)

**Lecture 1**
- Historical introduction: from UA1/UA2 to ATLAS/CMS

**Lecture 2**
- Experimental environment, main design choices and intrinsic performance

**Lecture 3**
- Global performance overview, electrons and photons (and particle-ID in ALICE/LHCb)

**Lecture 4**
- Muons and hadronic jets

**Not covered here**
- Trigger, data acquisition and offline (see lectures by A. Yagil)
- Calibration, alignment and commissioning (see lectures by D.
Performance of CMS tracker is undoubtedly superior to that of ATLAS in terms of momentum resolution. Vertexing and b-tagging performances are similar. However, impact of material and B-field already visible on efficiencies.
ATLAS/CMS: from design to reality
R&D and construction for 15 years → excellent EM calo intrinsic performance

- Stand-alone performance measured in beams with electrons from 10 to 250 GeV

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ATLAS/CMS: from design to reality

Amount of material in ATLAS and CMS inner trackers

- Active sensors and mechanics account each only for ~ 10% of material budget
- Need to bring 70 kW power into tracker and to remove similar amount of heat
- Very distributed set of heat sources and power-hungry electronics inside volume: this has led to complex layout of services, most of which were not at all understood at the time of the TDRs
**ATLAS/CMS: from design to reality**

<table>
<thead>
<tr>
<th>Date</th>
<th>ATLAS $\eta \approx 0$</th>
<th>ATLAS $\eta \approx 1.7$</th>
<th>CMS $\eta \approx 0$</th>
<th>CMS $\eta \approx 1.7$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1994 (Technical Proposals)</td>
<td>0.20</td>
<td>0.70</td>
<td>0.15</td>
<td>0.60</td>
</tr>
<tr>
<td>1997 (Technical Design Reports)</td>
<td>0.25</td>
<td>1.50</td>
<td>0.25</td>
<td>0.85</td>
</tr>
<tr>
<td>2006 (End of construction)</td>
<td>0.35</td>
<td>1.35</td>
<td>0.35</td>
<td>1.50</td>
</tr>
</tbody>
</table>

The numbers are given in fractions of radiation lengths ($X/X_0$). Note that for ATLAS, the reduction in material from 1997 to 2006 at $\eta \approx 1.7$ is due to the rerouting of pixel services from an integrated barrel tracker layout with pixel services along the barrel LAr cryostat, to an independent pixel layout with pixel services routed at much lower radius and entering a patch panel outside the acceptance of the tracker (this material appears now at $\eta \approx 3$). Note also that the numbers for CMS represent almost all the material seen by particles before entering the active part of the crystal calorimeter, whereas they do not for ATLAS, in which particles see in addition the barrel LAr cryostat and the solenoid coil (amounting to approximately $2X_0$ at $\eta = 0$), or the end-cap LAr cryostat at the larger rapidities.

- Electrons lose between 25% and 70% of their energy before reaching EM calo
- Between 20% and 65% of photons convert into $e^+e^-$ pair before EM calo
- Need to know material to ~ 1% $X_0$ for precision measurement of $m_W (< 10$ MeV)!
ATLAS/CMS: from design to reality
Actual performance expected in real detector quite different!!

Photons at 100 GeV
ATLAS: 1-1.5% energy resol. (all $\gamma$)
CMS: 0.8% energy resol. ($\epsilon_\gamma \sim 70\%$)

Electrons at 50 GeV
ATLAS: 1.3-2.3% energy resol.
(use EM calo only)
CMS: ~ 2.0% energy resol.
(combine EM calo and tracker)

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TABLE 10  Main performance parameters of the different hadronic calorimeter components of the ATLAS and CMS detectors, as measured in test beams using charged pions in both stand-alone and combined mode with the ECAL

<table>
<thead>
<tr>
<th>ATLAS</th>
<th></th>
<th>CMS</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Barrel LAr/Tile</strong></td>
<td></td>
<td><strong>End-cap LAr</strong></td>
</tr>
<tr>
<td><strong>Electron/hadron ratio</strong></td>
<td>1.36</td>
<td></td>
</tr>
<tr>
<td><strong>Stochastic term</strong></td>
<td>45%/$\sqrt{E}$</td>
<td></td>
</tr>
<tr>
<td><strong>Constant term</strong></td>
<td>1.3%</td>
<td></td>
</tr>
<tr>
<td><strong>Noise</strong></td>
<td>Small</td>
<td></td>
</tr>
</tbody>
</table>

The measured electron/hadron ratios are given separately for the hadronic stand-alone and combined calorimeters when available, and for the contributions (added quadratically except for the stand-alone ATLAS tile calorimeter) to the pion energy resolution from the stochastic term, the local constant term, and the noise are also shown, when available from published data.

**Huge effort in test-beams to measure performance of overall calorimetry with single particles and tune MC tools: not completed!**
One word about neutrinos in hadron colliders:

✓ since most of the energy of the colliding protons escapes down the beam pipe, one can only use the energy-momentum balance in the transverse plane

→ concepts such as $E_T^{\text{miss}}$, missing transverse momentum and mass

are often used (only missing component is $E_z^{\text{miss}}$)

→ reconstruct “fully” certain topologies with neutrinos, e.g. $W \rightarrow l\nu$ and even better $H \rightarrow \tau\tau \rightarrow l\nu_\tau l\nu_\tau$

✓ the detector must therefore be quite hermetic

→ transverse energy flow fully measured with reasonable accuracy

→ no neutrino escapes undetected

→ no human enters without major effort

(fast access to some parts of ATLAS/CMS quite difficult)
ATLAS/CMS: from design to reality

Interaction lengths

11\lambda

CMS

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ATLAS/CMS: from design to reality

Hadronic Collider Physics Summer School, CERN, 11/08/2007 to 14/08/2007

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ATLAS/CMS: from design to reality

For an integrated luminosity of $\sim 100 \text{ pb}^{-1}$, expect a few events like this? This is apparent $E_T^{\text{miss}}$ occurring in fiducial region of detector!
ATLAS/CMS: from design to reality

Biggest difference in performance perhaps for hadronic scale

Jets at 1000 GeV

ATLAS ~ 2% energy resolution
CMS ~ 5% energy resolution, but expect sizable improvement using tracks (especially at lower E)

$E_T^{\text{miss}}$ at $\Sigma E_T = 2000$ GeV
ATLAS: $\sigma \sim 20$ GeV
CMS: $\sigma \sim 40$ GeV

This may be important for high mass H/A to $\tau\tau$

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ATLAS/CMS: from design to reality

Biggest difference in performance perhaps for hadronic calor: how much can be recovered using energy-flow algorithms?

Jets in 20-100 GeV range are particularly important for searches (e.g. H → bb)

For $E_T \sim 50$ GeV in barrel:

- ATLAS: ~ 10% energy resolution
- CMS: ~ 19% energy resolution (with calo only), ~ 14% energy resolution (with calo + tracks)

Some words of caution though:

- danger from hadronic interactions in tracker material → non-Gaussian tails in response
- gains smaller at large $\eta$ (material) and at high energy
- linearity of response at low
CMS muon spectrometer

- Superior combined momentum resolution in central region
- Limited stand-alone resolution and trigger (at very high luminosities) due to multiple scattering in iron
- Degraded overall resolution in the forward regions ($|\eta| > 2.0$) where solenoid bending power becomes insufficient
ATLAS muon spectrometer

- Excellent stand-alone capabilities and coverage in open geometry
- Complicated geometry and field configuration (large fluctuations in acceptance and performance over full potential $\eta \times \phi$ coverage ($|\eta| < 2.7$)
ATLAS/CMS: from design to reality

**TABLE 12** Main parameters of the ATLAS and CMS muon measurement systems as well as a summary of the expected combined and stand alone performance at two typical pseudorapidity values (averaged over azimuth)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>ATLAS</th>
<th>CMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pseudorapidity coverage</td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Muon measurement</td>
<td>$</td>
<td>\eta</td>
</tr>
<tr>
<td>- Triggering</td>
<td>$</td>
<td>\eta</td>
</tr>
<tr>
<td>Dimensions (m)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Innermost (outermost) radius</td>
<td>5.0 (10.0)</td>
<td>3.9 (7.0)</td>
</tr>
<tr>
<td>- Innermost (outermost) disk (z-point)</td>
<td>7.0 (21–23)</td>
<td>6.0–7.0 (9–10)</td>
</tr>
<tr>
<td>Segments/superpoints per track for barrel (end caps)</td>
<td>3 (4)</td>
<td>4 (3–4)</td>
</tr>
<tr>
<td>Magnetic field B (T)</td>
<td>0.5</td>
<td>2</td>
</tr>
<tr>
<td>- Bending power (BL, in T·m) at $</td>
<td>\eta</td>
<td>\approx 0$</td>
</tr>
<tr>
<td>- Bending power (BL, in T·m) at $</td>
<td>\eta</td>
<td>\approx 2.5$</td>
</tr>
<tr>
<td>Combined (stand-alone) momentum resolution at $p = 10$ GeV and $\eta \approx 0$</td>
<td>1.4% (3.9%)</td>
<td>0.8% (8%)</td>
</tr>
<tr>
<td>$p = 10$ GeV and $\eta \approx 2$</td>
<td>2.4% (6.4%)</td>
<td>2.0% (11%)</td>
</tr>
<tr>
<td>$p = 100$ GeV and $\eta \approx 0$</td>
<td>2.6% (3.1%)</td>
<td>1.2% (9%)</td>
</tr>
<tr>
<td>$p = 100$ GeV and $\eta \approx 2$</td>
<td>2.1% (3.1%)</td>
<td>1.7% (18%)</td>
</tr>
<tr>
<td>$p = 1000$ GeV and $\eta \approx 0$</td>
<td>10.4% (10.5%)</td>
<td>4.5% (13%)</td>
</tr>
<tr>
<td>$p = 1000$ GeV and $\eta \approx 2$</td>
<td>4.4% (4.6%)</td>
<td>7.0% (35%)</td>
</tr>
</tbody>
</table>

**CMS muon performance driven by tracker: better than ATLAS at $\eta \sim 0$**  
**ATLAS muon stand-alone performance excellent over whole $\eta$ range**
Remember that tracking at the LHC is a risky business!

**CMS silicon strips**
- 200 m² Si, 9.6 million channels
- 99.8% fully operational
- Signal/noise ~ 25/1
- 20% cosmic test under way

**ATLAS pixels, September 2006**

- All modules and services integrated and tested
- 80 million channels!
- 10%-scale system test with cosmic test done at CERN

**CMS Tracker Inner Barrel, November 2006**

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Remember that tracking at the LHC is a risky business!

**ATLAS pixel beam tests:**
- Intrinsic resolution in bending plane before and after irradiation to a fluence of $10^{15}$ neutrons$_{equ}$ per cm$^2$

**CMS pixel beam tests in 3T field:**
- Extrapolate by simulation to expected behaviour versus incidence angle, voltage bias and total neutron fluence collected in 4T field

**Pixel size**
- ATLAS: 50 μm x 400 μm in R$\phi$ x z
- CMS: 150 μm x 150 μm in R$\phi$ x z

But ATLAS/CMS tracking specs do not marry well with detailed particle ID.
What are the limitations of ATLAS/CMS tracking detectors in terms of particle-ID? Look at

**ALICE TPC (Time Projection Chamber)**
- Measure many samples of dE/dx per track (need >> 25 ns!!)
- At low momenta, non-relativistic particles can be separated from each other through precise dE/dx measurements:

\[
\text{Bethe-Bloch: } -\langle dE/dx \rangle = k \frac{1}{\beta^2} \left( 0.5 \log(2m_e c^2 \beta^2 \gamma^2 T_{\text{max}} / l^2) - \beta^2 - \delta/2 \right)
\]
What are the limitations of ATLAS/CMS tracking detectors in terms of particle-ID? Look at Overall particle-ID in ALICE for heavy-ion physics

- **stable hadrons (π, K, p):** 100 MeV < p < 5 GeV
  - dE/dx in silicon (ITS) and gas (TPC) + Time-of-Flight (TOF) + Čerenkov (RICH)
  - dE/dx relativistic rise under study => extend PID to several 10 GeV ??

- **decay topology (K⁰, K⁺, K⁻, Λ)***
  - still under study, but expect K and Λ decays up to at least 10 GeV

- **leptons (e, μ), photons, π⁰**
  - electrons in TRD: p > 1 GeV
  - muons: p > 5 GeV
  - π⁰ in PHOS: 1 < p < 80 GeV

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*Alice uses ~ all known techniques!*
What are the limitations of ATLAS/CMS tracking detectors in terms of particle-ID? Look at LHC-b RICH detectors

<table>
<thead>
<tr>
<th>Detector Type</th>
<th>C_{4}F_{10}</th>
<th>3 GeV</th>
<th>30 GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>β (pion)</td>
<td>0.9989</td>
<td>0.999989</td>
<td></td>
</tr>
<tr>
<td>θ (Cerenkov)</td>
<td>0.160 rad</td>
<td>0.0526 rad</td>
<td></td>
</tr>
<tr>
<td>β (kaon)</td>
<td>0.9864</td>
<td>0.99986</td>
<td></td>
</tr>
<tr>
<td>θ (Cerenkov)</td>
<td>0.020 rad</td>
<td>0.0502 rad</td>
<td></td>
</tr>
</tbody>
</table>

**RICH1:**
larger solid angle, lower part of momentum spectrum

- Aerogel (hygroscopic...)
  - n=1.03 → θ (β=1)=242 mrad
  - thickness=5 cm
  - nb detected photons=~7/ring (β=1)

- C_{4}F_{10} p=1013 mb at –1.9C
  - n=1.0014 /260 nm θ (β=1)=53 mrad
  - thickness=85cm
  - nb photons=~30/ring

**RICH2:**

- CF_{4} n=1.0005 /260 nm θ (β=1)=32 mrad
  - thickness=180cm
  - nb photons=~30/ring
What are the limitations of ATLAS/CMS tracking detectors in terms of particle-ID? Look at ALICE/LHCb.

LHC-b RICH detectors
Electrons and photons in ATLAS/CMS

Electron identification

- **Isolated electrons: e/jet separation**
  - $R_{\text{jet}} \sim 10^5$ needed in the range $p_T > 20$ GeV
  - $R_{\text{jet}} \sim 10^6$ for a pure electron inclusive sample ($\varepsilon_e \sim 60\%$)

- **Soft electron identification – e/\pi separation**
  - B physics studies (J/ψ)
  - soft electron b-tagging (WH, ttH with H $\rightarrow$ to bb)

Photon identification

- **\gamma/jet and \gamma/\pi^0 separation**
  - main reducible background to $H \rightarrow \gamma \gamma$
    - comes from jet-jet and is 2x10^6 larger than signal
  - $R_{\text{jet}} \sim 5000$ in the range $E_T > 25$ GeV
  - $R$ (isolated high-$p_T$ $\pi^0$) $\sim 3$

General detector requirements for e/\gamma id at the LHC:

- Trigger efficiency
- Understanding of detector (alignment, material)
- Momentum measurement in the Inner Detector
- ECAL calibration
Can lessons be learned from Tevatron?

ID: Tracking

- Tracking important part of electron/photon ID
- Requiring or vetoing a high $p_T$ track reduces background by x10
- Tracking more difficult in forward regions
- Very sensitive to the amount of material
  - Radiation reduces track $p_T$
  - Converted photons are lost
  - Uncertainty in acceptance dominated early W/Z cross section measurements
    - 5.5% $X_0$ uncertainty in material gave a 4.7% uncertainty in the acceptance for $Z \rightarrow ee$
Can lessons be learned from Tevatron?

Material from E/P

- Use radiative tail of E/P to measure material
- Gives average material
- Can be combined with energy-loss measurements of muons ($J/\psi$) to give roughly type of material
  
  → CDF discovered it was missing Copper cables this way
Can lessons be learned from Tevatron?

Material: X-raying the detector

- Conversions can indicate location of material in detector
  - Normalized to inner cylinder of tracking chamber
  - Overall normalization difficult
    - Acceptance and efficiency depend on r
- Useful to find missing (or misplaced!) pieces
Electrons and photons in ATLAS/CMS

Radiography $|\eta| < 2.5$ ATLAS tracker

ATLAS Inner Detector
--- Pixel services
--- SCT services
--- TRT services
Electrons and photons in ATLAS/CMS

ATLAS and CMS will know the amount of material in their Inner Detector sub-systems very well (15 years of simulation work and preparation). But there is a lot more material than in Tevatron/LEP detectors (0.4 to 1.5 $X_0$ compared to 0.1–0.2 $X_0$)!!

Example: weight of an ATLAS pixel stave (2005)

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>13 Modules</td>
<td>25.48 g</td>
<td>25.74 g</td>
</tr>
<tr>
<td>TMT+omega+Tube (no liquid)</td>
<td>32.35 g</td>
<td>37.95 g +glue</td>
</tr>
<tr>
<td>Cooling liquid</td>
<td>~ 4.2 g</td>
<td>10.9 g (estimate)</td>
</tr>
<tr>
<td>Pigtails+connectors+cables</td>
<td>6.39 g</td>
<td>7.8+13.2=21.0 g</td>
</tr>
</tbody>
</table>
Can lessons be learned from Tevatron?

Energy calibrations II

- Generally calibrated to $Z \rightarrow ee$ resonance
- E/P can give another handle

→ Track momentum scale is measured with muons from $J/\psi$, $\Upsilon$, and $Z \rightarrow \mu\mu$

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Can lessons be learned from Tevatron?

Background Estimation: e

- **Sources:**
  - $b$ decays semi-leptonically
  - $\pi^0$ & $\pi^\pm$ give EM and track
  - Photon conversions
  - Composition depends on cuts

- Fake rates are common way to measure backgrounds
  - Measure rate of jets and electrons in jet triggered events
  - Apply to sample with signal topology with jet instead of electron

- Generally, jet background is small, but has large uncertainty (~25-50%)
  - **Absolute rates** $\sim 10^{-3}$-$10^{-4}$
Can lessons be learned from Tevatron?

From CDF RUN II
WW dileptons channel
Fakes are QCD dijets

Could be a problem for
Lepton (s) channels
@ LHC

These results may seem quite surprising but remember that cuts are often loosened to improve sensitivity in searches for rare processes!
Electrons and photons in ATLAS/CMS

CMS PbWO$_4$ crystal calorimeter

- Barrel: 62k crystals 2.2 x 2.2 x 23 cm
- End-caps: 15k crystals 3 x 3 x 22 cm

Barrel ECAL (EB)

Preshower (SE)

1.290 m

\( \phi = 85 \text{ mm} \)
Electrons and photons in ATLAS/CMS

ATLAS LAr EM Calorimeter description

EM Calo (Presampler + 3 layers):
- Presampler 0.025x0.1 ($\eta \times \phi$) => Energy lost in upstream material
- Strips 0.003x0.1 ($\eta \times \phi$) => optimal separation of showers in non-bending plane, pointing
- Middle 0.025x0.025 ($\eta \times \phi$) => Cluster seeds
- Back 0.05x0.025 ($\eta \times \phi$) => Longitudinal leakage

• LAr-Pb sampling calorimeter (barrel)
• Accordion shaped electrodes
• Fine longitudinal and transverse segmentation
• EM showers (for $e^{\pm}$ and photons) are reconstructed using calorimeter cell-clustering
Electrons and photons in ATLAS/CMS

ATLAS EM Calorimeter energy reconstruction

Two main clusterization methods:
- **Fixed size sliding window:**
  - $3 \times 3$, $3 \times 7$... cells, 2nd sampling $\eta \times \phi$;
  - Some energy left out, especially for small sizes.
- **Topological clusters:**
  - Variable size cluster, minimize noise impact;
  - Additional splitting algorithm is also provided.

Corrections due to cluster position:
- $\Delta \eta$ (S-shape modulation) $\pm 0.005$
- $\Delta \phi$ (offset in accordion) $\pm 0.001$

Corrections for energy losses:
- 1. Before PS
- 2. Between PS & Calo
- 3. Outside cluster: depends on clustering method
- 4. After calorimeter:
  - ~ Energy in BACK

2-7% overall energy correction
>7% at low energy, high $\eta$
ATLAS: e/jet separation in simulated data

- Results for inclusive electrons with $p_T > 20$ GeV
  - for $\varepsilon_e = 70\%$ (flat in $\eta$), a jet rejection factor of $>10^6$
  - importance of TRT which improves final purity
  - rejection can be improved using multivariate analysis

<table>
<thead>
<tr>
<th></th>
<th>$\varepsilon$ (%)</th>
<th>$R_{\text{jet}}$ ($E_T &gt; 17$ GeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calo</td>
<td>91.5±0.4</td>
<td>3000</td>
</tr>
<tr>
<td>$\exists$ track</td>
<td>87.4±0.5</td>
<td>36000</td>
</tr>
<tr>
<td>Matching</td>
<td>82.2±0.6</td>
<td>103000</td>
</tr>
<tr>
<td>TRT/conv.</td>
<td>70.0±1.0</td>
<td>$&gt;10^6$</td>
</tr>
</tbody>
</table>

Results at low luminosity: TRT important!

- Cross checks
  - electrons from W/Z: $\varepsilon_e = 69\pm5\%$ with purity $>0.9$
  - electrons from heavy flavour decays: $\varepsilon_e = 2.5\pm1\%$ (non isolated electrons !)
ATLAS: low $p_T$ electron identification in simulated data

Start with a track as a seed. Extrapolate it to calorimeters and build cluster around.

Discriminating variables are similar: use of TRT + shower shapes in calorimeter.

Performance on single tracks:

- $\varepsilon_{e-id} (J/\psi) = 80\%$
- $R_\pi (bb \rightarrow \mu X) = 1050 \pm 50$

This allows a S/B $\sim 2$ in the $J/\psi$ mass window after vertex refitting.

- $\varepsilon_{e-id} (WH_{120}) = 80\%$
- $R_\pi (WH) = 245 \pm 17$

Once the electron is identified inside a jet, it can be used for b-tagging.

- $\varepsilon_{b-id} = 60\%$
- $R_\pi (WH_{120}) = 151 \pm 2$

Complementary to standard vertexing method $R_\psi (WH_{120}) = 115$ but $\varepsilon = \varepsilon_{b-id} (60\%) \times BR \sim 8\%$
SM $H \rightarrow \gamma \gamma$

**Signal reconstruction**

One wants to reconstruct:

$$M_{\gamma \gamma}^2 = 2 E_{\gamma_1} E_{\gamma_2} (1 - \cos \theta_{12})$$

What contributes to resolution on $m_{\gamma \gamma}$?

1) **Measurement of $E_\gamma$**:
   - Intrinsic resolution of calo
   - Calibration/uniformity of calo
   - Pile-up effects

2) **Measurement of $\theta_{12}$**
   - Measurement of position and direction of em showers
SM $H \rightarrow \gamma\gamma$

Energy resolution

CMS EM calorimeter (crystals):

\[
\frac{\sigma(E)}{E} \approx 3 - 5\% \frac{\sigma}{\sqrt{E}}
\]

ATLAS EM calorimeter (liquid-argon/lead sampling calorimeter):

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

Module zero test beam data

\[\eta = 0.94\]

Sampling term = 10.7%
Constant term = 0.3%

Mass resolution ($m_H=100$ GeV, low L):

\[
\frac{S}{\sqrt{B}} \sim \frac{1}{\sqrt{\sigma_m}}
\]

ATLAS : 1.1 GeV
CMS : 0.6 GeV

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SM $H \rightarrow \gamma\gamma$

Angular resolution and acceptance

- ATLAS calorimeter has longitudinal segmentation
  → can measure $\gamma$ direction

ATLAS, full simulation
Vertex resolution using EM calo longitudinal segmentation

Photons from $H \rightarrow \gamma\gamma$

CMS has no longitudinal segmentation (and no preshower in barrel)
→ vertex measured using secondary tracks from underlying event
→ often pick up the wrong vertex
→ smaller acceptance in the Higgs mass window

\[ \sigma(\theta) \approx \frac{50 \text{ mrad}}{\sqrt{E}} \]

vertex spread
\(\sim 5.6 \text{ cm} \)
SM $H \rightarrow \gamma \gamma$

**Backgrounds**

1) Irreducible background from $qq \rightarrow \gamma \gamma$ and $gg \rightarrow \gamma \gamma$ (box)

2) Reducible background from $\pi^0, \eta$ ($\rightarrow \gamma \gamma$) in jet fragmentation:
   - final states with many photons $\rightarrow$ look for single photons
   - non-isolated photons inside jets $\rightarrow$ look for isolated photons
   - Very difficult problem: at $p_T \approx 50$ GeV, jet-jet / $\gamma \gamma \approx 10^7$
     $\rightarrow$ need to reject each jet by a factor 10,000 to bring the reducible background well below the irreducible one
   - However, at $p_T \approx 50$ GeV, $\pi^0$/jet $\approx 10^{-3}$
     $\rightarrow$ separate isolated photons from $\pi^0$ decays at 50 GeV
     $\rightarrow$ photons from $\pi^0$ decays will be distant by $\approx 1$ cm
     $\rightarrow$ need granular position detector after $\sim 4\text{-}5 X_0$ in...
$\text{SM H} \rightarrow \gamma \gamma$

**Graph 1:**
- **Axes:** $p_T$ on the X-axis, $d\sigma/dp_T$ on the Y-axis.
- **Graphs:**
  - Jets
  - Inclusive $\pi^0$
  - Isolated $\pi^0$
  - Isolated "photons"

**Graph 2:**
- **Axes:** $m_{\gamma\gamma}$ on the X-axis, $d\sigma/dm$ on the Y-axis.
- **Graphs:**
  - Inclusive $\pi^0$
  - Isolated $\pi^0$
  - Irreducible $\gamma\gamma$ background
  - Isolated "photons" from $\pi^0$
Can lessons be learned from Tevatron?

Background Estimation: $\gamma$

- Major Source
  $\rightarrow \pi^0 \rightarrow \gamma \gamma$
- Fake rate measured in similar way to electrons
  $\rightarrow$ Prompt photons need to be removed
  $\rightarrow$ Rates from different jet samples are compared for systematic
  $\rightarrow$ If jets are $E_T$-ordered, find rate is different for 1st, 2nd, and lower $E_T$ jets
- Rates $\sim 5 \times 10^{-4}$ for high $E_T$
Jet background composition (true photons removed-quark brem,...) after “general” calorimeter cuts:

- « Isolated » $\pi^0$: 72%
- $\eta \rightarrow \gamma \gamma$, $\omega \rightarrow \gamma \pi^0$, KS $\rightarrow 2\pi^0$: 13%
- « multi » $\pi^0$: 4%
- electron: 4%
- single charged hadron: 4%
- single neutral hadron: 1%
- Others: 2%

- Further rejection of $\pi^0$ can be obtained exploiting the fine granularity of the first sampling ($\delta\eta = 0.003$ or 5mm). The two photons of a 60 GeV $E_T$ symmetric $\pi^0$ decay are separated by >7mm at the calorimeter face!
Photon ID in ATLAS (2)

Overall jet rejection obtained in MC:
-1050 for quark jets
-6000 for gluon jets  →Ultimate performance process dependent!
(probability of a high x isolated $\pi^0$ is higher in a quark jet than in a gluon jet)
SM H→γγ

Rejection of QCD jet background

ATLAS EM calo: full simulation

ε_γ = 80%

Most rejection from longitudinal calo segmentation and 4 mm η-strips in first compartment (γ / π^0 separation)
Towards the complete experiment: ATLAS combined test beam 2004

Full « vertical slice » of ATLAS tested on CERN H8 beam line May-November 2004

- 90 million events collected
- 4.6 Tbytes of data
- Beams:
  - $e, \pi \rightarrow 250 \text{ GeV}$
  - $\mu, \pi, p \rightarrow 350 \text{ GeV}$
  - $\gamma \sim 20-100 \text{ GeV}$
- B from 0 $\rightarrow 1.4 \text{ T}$

For the first time, all Atlas sub-detectors integrated and run together with:
- « final » electronics
- common DAQ
- common Atlas software to analyse the data

First experience with:
- Inner Detector alignment
- ID/Calo alignment
- ID/Calo track matching
- ID/Calo combined reconstruction
- ID/muon combined reconstruction
**e/π separation using the barrel TRT and LAr EM calorimeter with mixed e/π low-energy beams**

Electron identification makes use of the large energy depositions due to the transition radiation (X-rays) when they traverse the radiators.

**Results from TB 2002 @20 GeV**

- 20-GeV electrons
  - beam-test data
  - Monte-Carlo simulation

- 20-GeV pions
  - beam-test data
  - Monte-Carlo simulation

Typical TR photon energy depositions in the TRT are 8-10 keV. Pions deposit about 2 keV.

**Results from CTB2004 @9 GeV**

- 90% electron efficiency
- 2×10⁻² pion efficiency

Preliminary
Topological clusterisation for photon runs

Parameters for the EM portion only:
- Seed Threshold > 6σ
- Neighbour Threshold > 3σ
- Cell Threshold > 3σ

In addition:
1) Use only samplings 2 & 3 for splitting clusters, sampling 1 having a very coarse φ granularity;
2) Introduce energy sharing between common cluster cells in sampling 1.
Matching tracks to clusters

Photon Run 2102857 event # 88

Primary Electron

Converted photon
Electrons and photons in ATLAS/CMS: conclusions

Electron/photon ID in ATLAS and CMS will be a challenging and exciting task (harsher environment than at Tevatron, larger QCD backgrounds, more material in trackers)

But LHC detectors are better in many respects! Software is on its way to meet the challenge!

Huge effort in terms of understanding performance of detectors as installed ahead of us (calibration of calorimeters and alignment of trackers, material effects)