Particle reconstruction and identification at the LHC: ATLAS and CMS
Historical introduction

Higgs boson has been with us for several decades as:

1. a theoretical concept,

1. a scalar field linked to the vacuum,

1. the dark corner of the Standard Model,

1. an incarnation of the Communist Party, since it controls the masses (L. Alvarez-Gaumé in lectures for CERN summer school in Alushta),

1. a painful part of the first chapter of our Ph. D. thesis

P.W. Higgs, Phys. Lett. 12 (1964) 132

Only unambiguous example of observed Higgs (apologies to ALEPH collab.)
**Historical introduction**

**1964:** First formulation of Higgs mechanism (P.W. Higgs)

**1967:** Electroweak unification, with W, Z and H (Glashow, Weinberg, Salam)

**1973:** Discovery of neutral currents in $\nu_\mu e$ scattering (Gargamelle, CERN)

**1974:** Complete formulation of the standard model with $SU(2)_W \times U(1)_Y$ (Iliopoulos)

**1981:** The CERN SpS becomes a proton-antiproton collider

LEP and SLC are approved before W/Z boson discovery

**1983:** LEP and SLC construction starts

W and Z discovery (UA1, UA2)

One of the first Z-bosons detected in the world

- $q\bar{q} \rightarrow Z^0 \rightarrow e^+ e^- \gamma$

D. Froidevaux
UA2 at the SppS collider

• UA2 proposed and approved in 1978

• UA2 constructed in 1979-1980

• First proton-antiproton run in 1981

• Discovery of W and Z in 1983

• Upgrade of UA2 to UA2’ from 1984 to 1987

• Data taking with UA2’ from 1987 to 1990 (at which point CDF at the Tevatron took over for ppbar physics)
Equivalent of µsoftProject for UA2 construction

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**D.**
UA2 ready to roll into the interaction region
September 1981: first (small) run for UA2
First observation of jets in hadronic collisions

A spectacular 'jet' event seen by the UA2 experiment, in which the
fragments of a violent 540 GeV proton-antiproton collision contained
127 GeV of energy flying off at right angles to the initial collision axis.
The line lengths are proportional to particle energies.

Enlèvement spectaculaire "en jet" observé au cours de l'expérience UA2 et
daussi dans les fragments d'une violente collision proton-antiproton de
540 GeV contenant une énergie de 127 GeV venant à angle droit par
rapport à l'axe initial de la collision. La longueur des lignes est propor-
tionnelle à l'énergie des particules.

Jets et particules
Parmi les nouveaux résultats de physique annoncés lors
de la Conférence internationale de physique des particules
qui s'est tenue récemment à Paris, le plus remar-
From the beginning, with the observation of two-jet dominance and of $4 \ W \rightarrow e \nu$ and $8 \ Z \rightarrow e^+e^-$ decays.
To the end, with first accurate measurements of the W/Z masses and the search for the top quark and for supersymmetry
Software design in 1984

UA2 was perceived as large at the time:

♥ 10-12 institutes
♥ from 50 to 100 authors
♥ cost ~ 10 MCHF
♥ duration 1980 to 1990

Physics analysis was organised in two groups:

12. Electrons → electroweak
13. Jets → QCD
For each value of $M_w$, generate $d\eta/dp^e_T d\phi$, using parametrisation of $P_L^w$ from Glück et al. 

- $P^w_T$ from Halzen et al.

$V-A$ production and decay

$\Gamma(w) = 3 \text{ GeV}$

Maximum likelihood for events with $p_T > 25$:

$$M_w = 82.5 \pm 1.5 \pm 1.3 \text{ GeV}/c^2$$

Same result from fit to $M_T$ - dist for events with $p_T^w < 5 \text{ GeV}/c$:

$$M_T = \sqrt{2p^e_T p^\nu_T (1 - \cos \Delta \Phi)}$$

generated with $M_w = 82.5 \text{ GeV}$

Software documentation in 1984

Analysis results in 1984

D. Froidevaux
1984-1985 were exciting (and confusing) times!

“Over-abundance” of $Z \rightarrow e\gamma$ events

Monojets

Dijets with missing $E_T$

High-$p_T$ electrons with jets and missing $E_T$

Top quark “discovery”

Bumps in distributions

(jet-jet mass in UA2, $W$ decay electron spectrum in UA1)

Many lessons learned by young physicists in UA1/UA2 collaborations from our more experienced colleagues

• take care with statistics!
• bizarre events are usey unforeseen manifestations of SM physics
• constrain background estimates as much as feasible using data
UA2 authors could make it into a deck of playing cards!

Pictures courtesy of Pierre Darriulat
From Ph.D. student (egg) to C4 professor (rooster?): a great career!
1984: Glimmerings of LHC and SSC

1987: First comparative studies of physics potential of hadron colliders (LHC/SSC) and $e^+e^-$ linear colliders (CLIC)

1989: First collisions in LEP and SLC

Precision tests of the SM and search for the Higgs boson begin in earnest

R&D for LHC detectors begins

1993: Demise of the SSC

1994: LHC machine is approved (start in 2005)

1995: Discovery of the top quark at Fermilab by CDF (and D0)

Precision tests of the SM and search for the Higgs boson continue at LEP2

Approval of ATLAS and CMS

2000: End of LEP running

2001: LHC schedule delayed by two more years

During the last 13 years, three parallel activities have been ongoing, all with impressive results:

7) Physics at LEP with a wonderful machine

8) Construction of the LHC machine

9) Construction of the LHC detectors after an initial very long R&D period
Historical introduction
What has been the evolution of our HEP culture over these past 30 years?

3. In the 70-80’s, the dogma was that e^+e^- physics was the only way to do clean and precise measurements and even discoveries (hadron physics were dirty).

1. With the advent of high-energy colliders, the 80-90’s have demonstrated that:
   ✔ Most discoveries have occurred in hadronic machines
   ✔ Unprecedented precision has been reached in electroweak measurements at LEP with state-of-the-art detectors
      ✔ remember the first time ALEPH announced that luminosity could be measured to 0.1%!
   ✔ Hadronic colliders can rival with the e^+e^- machines in certain areas of precision measurements
      ✔ remember the almost simultaneous publication of the Z-mass measurements from CDF and SLC with comparable precision (200 MeV!)
      ✔ even with Run I (100 pb^-1), CDF has been able to compete with LEP in the field of B-physics
Historical introduction

Parton luminosities  $F_{ij}(E_{cm})$

where $E_{cm}$ is the centre-of-mass energy of two “partons” i and j,

are useful to compare intrinsic potential of different machines

Important to note that:

2. as centre-of-mass energy grows, processes without beam-energy constraint such as vector-boson fusion become also important at $e^+e^-$ machines;

3. Proton-proton collisions are equivalent to $e^+e^-$ collisions for $\sqrt{s_{pp}} \approx 5 \sqrt{s_{e^+e^-}}$
All particles in plot were discovered first at hadron machines with one notable exception:

- the τ-lepton was (and could have been) observed only in vector-boson decays at the CERN proton-antiproton collider.
Historical introduction

What has been the evolution of our HEP culture over these past 30 years?

3. Today’s culture is the result of the experience gathered over the past years, which has displayed the nice feature, at least to experimentalists, of being largely unpredictable in terms of future measurements:

❖ There is no doubt that Tevatron and LHC will do precision physics

❖ There is also no doubt that the ultimate precision physics on e.g. the lightest supersymmetric Higgs boson (h) cannot be done at the LHC but could be done at a future e+e− linear collider

❖ The ultimate precision which one needs can however be debated:

✓ What would one really learn by measuring e.g. the $H \rightarrow cc$ branching ratio to 1% or $m_{top}$ to 0.3 GeV in a machine like the ILC?

✓ Measuring self-coupling of Higgs boson is a far more important task, which is unlikely to be fulfilled with good accuracy at the LHC nor the ILC (as currently planned).
Historical introduction

What has been the evolution of our HEP culture over these past 30 years?

Other facts have intruded into our awareness and shaped perhaps even subconsciously today's culture (especially perhaps for the younger generation)

The mainstream path (higher and higher energies together with larger and larger detectors and longer and longer timescales) is becoming dinosaur-like

The equivalent of the Iridium-meteorite causing extinction could be nature refusing to give us any major insight into beyond the Standard Model, thereby causing the refusal worldwide of governments to pursue this path further...

It is wellnigh impossible to predict construction schedules for machines at these scales (at least in the R&D and design phase)

Astroparticle physics has developed exponentially over the last decades and the observation of neutrino oscillations has opened different paths towards a better understanding of the fundamental aspects of high-energy physics

LEP I: 1989 to 1993

LEP II: 1994 to 1997

LHC starts 1998!

D. Froidevaux
SM Higgs: direct searches at LEP2

Golden 4-jet event (ALEPH, 14/06/00, 206.7 GeV)

- Mass 114 ± 3 GeV
- Good HZ fit
- Poor WW and ZZ fits
- $P(\text{Background}) \approx 2\%$
- $s/b(115) = 4.6$

b-tagging
(0 = light quarks, 1 = b quarks)
- Higgs jets: 0.99 and 0.99;
- Z jets: 0.14 and 0.01.

D. Froidevaux
Higgs at LEP/SLD: conclusions

- SM Higgs-boson mass now quite constrained:
  \[ 114.4 < m_H < \sim 200 \text{ GeV at 95\% C.L.} \]

  from beautiful precision measurements and direct searches

- But some 2-3\(\sigma\) effects mar the beauty of the landscape:
  - discrepancy between \(A_{fb}\) and \(A_{LR}\)
  - a few intriguing events at \(m_H \approx 114\) GeV:
    the hint of a discovery or a statistical fluctuation?

Baby HIGGS left by CERN in LEP
- Size: 1.7\(\sigma\)
- Weight: 115 GeV

Dream of a few??
or
Underlying reality??

Courtesy of P. Janot

Need to wait for a while to really corner the SM
Higgs at LEP: conclusions

“This does not necessarily mean that this is the Higgs mass!"

The number 115 GeV will remain stuck in our heads for quite some time

Tevatron ??

LHC ?

2010 (±1 year)?
How huge are ATLAS and CMS?

- **Size of detectors**
  - Volume: 20 000 m$^3$ for ATLAS
  - Weight: 12 500 tons for CMS
  - 66 to 80 million pixel readout channels near vertex
  - 200 m$^2$ of active Silicon for CMS tracker
  - 175 000 readout channels for ATLAS LAr EM calorimeter
  - 1 million channels and 10 000 m$^2$ area of muon chambers
- **Very selective trigger/DAQ system**
- **Large-scale offline software and worldwide computing (GRID)**

- **Time-scale** will have been about **25 years** from first conceptual studies (Lausanne 1984) to solid physics results confirming that LHC will have taken over the high-energy frontier from Tevatron (early 2009?)

- **Size of collaboration**
- **Number of meetings and Powerpoint slides to browse through**
ATLAS physics workshop in Rome (June 2005)

Speakers age distribution

About 100 talks, ~22% women

~450 participants
Generic features required of ATLAS and CMS

- **Detectors must survive for 10 years or so of operation**
  - Radiation damage to materials and electronics components
  - Problem pervades whole experimental area (neutrons): NEW!

- **Detectors must provide precise timing and be as fast as feasible**
  - 25 ns is the time interval to consider: NEW!

- **Detectors must have excellent spatial granularity**
  - Need to minimise pile-up effects: NEW!

- **Detectors must identify extremely rare events, mostly in real time**
  - Lepton identification above huge QCD backgrounds (e.g. e/jet ratio at the LHC is \( \sim 10^{-5} \), i.e. \( \sim 100 \) worse than at Tevatron)
  - Signal X-sections as low as \( 10^{-14} \) of total X-section: NEW!
  - Online rejection to be achieved is \( \sim 10^7 \): NEW!
  - Store huge data volumes to disk/tape (\( \sim 10^9 \) events of 1 Mbyte size per year): NEW!
Generic features required of ATLAS and CMS

- **Detectors must measure and identify according to certain specs**
  - Tracking and vertexing: $ttH$ with $H \rightarrow bb$
  - Electromagnetic calorimetry: $H \rightarrow \gamma \gamma$ and $H \rightarrow ZZ \rightarrow eeee$
  - Muon spectrometer: $H \rightarrow ZZ \rightarrow \mu\mu\mu\mu$
  - Missing transverse energy: supersymmetry, $H \rightarrow \tau\tau$

- **Detectors must please**
  - Collaboration: physics optimisation, technology choices
  - Funding agencies: affordable cost (originally set to 475 MCHF per experiment by CERN Council and management)
  - Young physicists who will provide the main thrust to the scientific output of the collaborations: how to minimise formal aspects? How to recognise individual contributions?

Review article on ATLAS and CMS as built (DF and P. Sphicas) at http://arjournals.annualreviews.org/eprint/HMcWjWGjGZHCFNgVvabl/full/10.1146/annurev.nucl...
Physics at the LHC: the environment

Experimental environment ≡ Machine performance x Physics

Event rates in detectors:
- number of charged tracks expected in inner tracking detectors
- energy expected to be deposited in calorimeters
- radiation doses expected (ionising and neutrons)
- event pile-up issues (pile-up in time and in space)

Need to know the cross-section for uninteresting pp inelastic events:
- simple trigger on these ≡ “minimum bias” trigger
Charged particle multiplicity and energy in pp inelastic events at $\sqrt{s} = 14$ TeV

$\langle p_T \rangle \sim 500$ MeV

Present models extrapolated from Tevatron give sizeable differences at the LHC
Physics at the LHC: the environment

$(1 \text{ MeV } n_{eq}/\text{cm}^2/\text{yr})$

ATLAS neutron fluences
1. **Damage caused by ionising radiation**

- caused by the energy deposited by particles in the detector material: \( \approx 2 \text{ MeV g}^{-1} \text{ cm}^{-2} \) for a min. ion. particle
- also caused by photons created in electromagnetic showers
- the damage is proportional to the deposited energy or dose measured in Gy (Gray):
  - 1 Gy = 1 Joule / kg = 100 rads
  - 1 Gy = \( 3 \times 10^9 \) particles per cm\(^2\) of material with unit density

At LHC design luminosity, the ionising dose is:

\[
\approx 2 \times 10^6 \text{ Gy} / r_T^2 / \text{year},
\]

where \( r_T \) (cm) is the transverse distance to the beam
1. **Damage caused by neutrons**
   - The neutrons are created in hadronic showers in the calorimeters and even more so in the forward shielding of the detectors and in the beam collimators themselves.
   - These neutrons (with energies in the 0.1 to 20 MeV range) bounce back and forth (like gas molecules) on the various nuclei and fill up the whole detector.

   - Expected neutron fluence is about $3 \times 10^{13}$ per cm$^2$ per year in the innermost part of the detectors (inner tracking systems).
   - These fluences are moderated by the presence of Hydrogen:
     - $\sigma(n,H) \sim 2$ barns with elastic collisions.
     - Mean free path of neutrons is $\sim 5$ cm in this energy range.
     - At each collision, neutron loses 50% of its energy (this number would be e.g. only 2% for iron).
Physics at the LHC: the environment

- the neutrons wreak havoc in semiconductors, independently of the deposited energy, because they modify directly the crystalline structure
  → need radiation-hard electronics (military applications only in the early R&D days)
    - off-the-shelf electronics usually dies out for doses above 100 Gy and fluences above $10^{13}$ neutrons/cm$^2$
    - rad-hard electronics (especially deep-submicron) can survive up to $10^5$-$10^6$ Gy and $10^{15}$ neutrons/cm$^2$

- most organic materials survive easily to $10^5$-$10^6$ Gy (beware!)

Material validation and quality control during production are needed at the same level as for spatial applications!!
Physics at the LHC: the environment

Pile-up effects at high luminosity

Pile-up is the name given to the impact of the 23 uninteresting (usually) interactions occurring in the same bunch crossing as the hard-scattering process which generally triggers the apparatus.

Minimising the impact of pile-up on the detector performance has been one of the driving requirements on the initial detector design:

• a precise (and if possible fast) detector response minimises pile-up in time
  → very challenging for the electronics in particular
  → typical response times achieved are 20-50 ns (!)

• a highly granular detector minimises pile-up in space
  → large number of channels (100 million pixels, 200,000 cells in electromagnetic calorimeter)
Physics at the LHC: the environment

Pile-up effects at high luminosity

Photon converts at $R = 40$ cm and electron pair is visible in ATLAS TRT and EM calo
Physics at the LHC: the environment

Pile-up effects at high luminosity

ATLAS barrel

$H \rightarrow ZZ^* \rightarrow e^+e^-\mu^+\mu^- \ (m_H = 130 \text{ GeV})$
First consequence of pile-up $\rightarrow$ reconstruction of vertex position along beam for a given bunch crossing of interest

At the LHC, $\sigma_{\text{bunch}} = 8 \text{ cm}$ $\rightarrow$ spread of interaction vertex is 5.6 cm

- Need to find about 25 vertices along beam for each trigger

- Hard-scattering process usually has higher-momentum tracks and multiplicity, but no clean separation vertex-by-vertex

- Simulation results for $H \rightarrow \gamma\gamma$ at high luminosity:
  - Find on average 5 out of 25 vertices produced
  - Find $H \rightarrow \gamma\gamma$ vertex in 72% of the cases with r.m.s. = 106 $\mu$m
Second consequence of pile-up $\Rightarrow$ at very high luminosity, risk of producing a given final state from the superposition of two independent events

How likely is this to happen for the final state of a process with cross-section $\sigma_{12}$, which could be produced by the overlap of two processes 1 and 2 with cross-sections $\sigma_1$ and $\sigma_2$?

The relationship between $\sigma_{12}$ and $\sigma_{12}^{\text{pile-up}} = \sigma_{12}^p$ depends on the luminosity $L$ and on the spacing $\Delta t$ between bunches ($\langle n \rangle = L \Delta t$)

Pile-up probability: $P_e = n \sigma_{12}^p / \sigma_{\text{inel}}$ and $P_e = n(n-1)P_1P_2/2$, where $P_1 = \sigma_i / \sigma_{\text{inel}} \ll 1$,
and therefore $\sigma_{12}^p = \sigma_1 \sigma_2 L \Delta t / 2$
Higgs at the LHC: the environment

Pile-up effects at high luminosity

In practice, if \( L = 1 \cdot 10^{34} \text{ cm}^{-2} \text{ s}^{-1} \) and \( \Delta t = m \cdot 25 \text{ ns} \), one obtains

\[ \sigma_{12}^p < \sigma_{12} \text{ if } \sigma_1 \sigma_2 / \sigma_{12} < 0.8 \cdot 10^{10} / \text{ l.m pb} \]

First example: search for ZZ final states at the LHC

\[ \sigma_{12} = 10 \text{ pb for ZZ continuum} \]

or \( \sigma_{12} = 1 \text{ pb for } \text{H} \rightarrow \text{ZZ}, m_{\text{H}} = 800 \text{ GeV} \) and

\[ \sigma_1 = \sigma_2 = \sigma_Z = 40 \text{ nb} = 40,000 \text{ pb} \]

One then obtains \( \sigma_1 \sigma_2 / \sigma_{12} = 1.6 \cdot 10^8 \), from which one deduces that

\[ \sigma_{ZZ}^e = \sigma_{ZZ} \text{ for } L \approx 5 \cdot 10^{35} \text{ cm}^{-2} \text{ s}^{-1} \]
Higgs at the LHC: the environment

Pile-up effects at high luminosity

**Second example:** search for events with two muons, $p_T^\mu > 10$ GeV

\[
\sigma_{12} = \sigma_{\mu\mu}(p_T^\mu > 10 \text{ GeV}) \approx 10 \text{ nb (} Z \rightarrow \mu\mu \text{ or } pp \rightarrow bb \rightarrow \mu\mu + X) \\
\sigma_1 = \sigma_2 = \sigma_{\mu}(p_T^\mu > 10 \text{ GeV}) \approx 1000 \text{ nb (semileptonic decays of } b' \text{'s)}
\]

One obtains $\sigma_1 \sigma_2 / \sigma_{12} \approx 10^8$, with same result.

**Conclusions:** in general, pile-up of rare events to mimic even rarer events is negligible.
Physics at the LHC: the environment

- In 25 ns particles travel 7.5 m
- In 25 ns signals travel 5 m

Cable length ~100 meters ...
Physics at the LHC: the challenge

Unprecedented scope and timescales for simulations

Many examples from ATLAS/CMS (and also ALICE/LHCb):

• $\approx 30$ million volumes simulated in GEANT

• Tbytes (hundreds of millions) of simulated events over 10 years

• Full reconstruction of all benchmark Higgs-boson decays

• Unprecedented amount of material in Inner Detectors leads to significant losses of e.g. charged-pion tracks (up to 20% at 1 GeV) and to significant degradation of EM calo intrinsic performance (mostly for electrons but for photons too)

• b-tagging at low luminosity, for e.g. $H \rightarrow bb$ searches, yields performance similar to that which has been achieved at LEP
Main specific design choices of ATLAS/CMS

- Size of ATLAS/CMS directly related to energies of particles produced: need to absorb energy of 1 TeV electrons (30 $X_0$ or 18 cm of Pb), of 1 TeV pions (11 $\lambda$ or 2 m Fe) and to measure momenta of 1 TeV muons outside calorimeters ($BL^2$ is key factor to optimise)

- Choice of magnet system has shaped the experiments in a major way
  - Magnet required to measure momenta and directions of charged particles near vertex (solenoid provides bend in plane transverse to beams)
  - Magnet also required to measure muon momenta (muons are the only charged particles not absorbed in calorimeter absorbers)
  - ATLAS choice: separate magnet systems (“small” 2 T solenoid for tracker and huge toroids with large $BL^2$ for muon spectrometer)
  - Pros: large acceptance in polar angle for muons and excellent muon momentum resolution without using inner tracker
  - Cons: very expensive and large-scale toroid magnet system
  - CMS choice: one large 4 T solenoid with instrumented return yoke
  - Pros: excellent momentum resolution using inner tracker and more compact experiment
  - Cons: limited performance for stand-alone muon measurements (and trigger) and limited space for calorimeter inside coil
Main specific design choices of ATLAS/CMS

• At the LHC, which is essentially a gluon-gluon collider, the unambiguous identification and precise measurement of leptons is the key to many areas of physics:

  • electrons are relatively easy to measure precisely in EM calorimeters but very hard to identify (imagine jet → leading π with π → leading π⁰ very early in shower)
  • muons in contrast are relatively easy to identify behind calorimeters but very hard to measure accurately at high energies

→ This has also shaped to a large extent the global design and technology choices of the two experiments

• EM calorimetry of ATLAS and CMS is based on very different technologies
  • ATLAS uses LAr sampling calorimeter with good energy resolution and excellent lateral and longitudinal segmentation (e/γ identification)
  • CMS use PbWO₄ scintillating crystals with excellent energy resolution and lateral segmentation but no longitudinal segmentation
  • Broadly speaking, signals from H → γγ or H → ZZ* → 4e should appear as narrow peaks (intrinsically much narrower in CMS) above essentially pure background from same final state (intrinsically background from fakes smaller in ATLAS)
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.
Stand-alone performance measured in beams with electrons from 10 to 250 GeV
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 5  Evolution of the amount of material expected in the ATLAS and CMS trackers from 1994 to 2006

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<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.

- Material increased by ~ factor 2 from 1994 (approval) to now (end constr.)
- 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. ($\varepsilon_\gamma \sim 70\%$)

Electrons at 50 GeV
ATLAS: 1.5-2.5% energy resol. (use EM calo only)
CMS: $\sim 2.0\%$ energy resol. (combine EM calo and tracker)
ATLAS/CMS: from design to reality

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></th>
<th>ATLAS</th>
<th>CMS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Barrel LAr/Tile</td>
<td>End-cap LAr</td>
</tr>
<tr>
<td></td>
<td>Tile</td>
<td>Combined</td>
</tr>
<tr>
<td>Electron/hadron ratio</td>
<td>1.36</td>
<td>1.37</td>
</tr>
<tr>
<td>Stochastic term</td>
<td>45%/√E</td>
<td>55%/√E</td>
</tr>
<tr>
<td>Constant term</td>
<td>1.3%</td>
<td>2.3%</td>
</tr>
<tr>
<td>Noise</td>
<td>Small</td>
<td>3.2 GeV</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 $H \rightarrow \tau\tau \rightarrow l\nu\nu_{\tau} \nu_{\tau}$

✓ 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

CMS

$11\lambda$

$\eta$

D. Froidevaux

Freiburg seminar, 12/11/2008
ATLAS/CMS: from design to reality

Absorption Length

$11\lambda$

Material in front of Muon System

End of active hadronic

Tile barrel

Extended barrel

Hadronic endcap

Forward calorimeter

EM barrel

EM endcap

cryostat walls

Pseudorapidity
For an integrated luminosity of ~ 100 pb\(^{-1}\), expect a few events like this? This is apparent \(E_T^{\text{miss}}\) occurring in fiducial region of detector!
Biggest difference in performance perhaps for hadronic calorimetry

Jets at 1000 GeV

- ATLAS: $\sigma \sim 25$ GeV
- CMS: $\sigma \sim 40$ GeV

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

$E_T^{\text{miss}}$ at $\Sigma E_T = 2000$ GeV

- ATLAS: $\sigma \sim 25$ GeV
- CMS: $\sigma \sim 40$ GeV

Energy resolution:

- ATLAS: $\sim 3\%$
- CMS: $\sim 5\%$

(but expect sizable improvement using tracks at lower energies)
ATLAS/CMS: from design to reality

Biggest difference in performance perhaps for hadronic calo: 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 energy!
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/CMS: from design to reality

- Excellent stand-alone capabilities and coverage in open geometry
- Complicated geometry and field configuration (large fluctuations in acceptance and performance over full potential $|\eta| < 2.7$)
# 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</td>
<td></td>
<td></td>
</tr>
<tr>
<td>- $p = 10$ 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!

**ATLAS pixels, September 2006**
- 80 million channels!
- Inst. in ATLAS: June 2007
- Operational in ATLAS: September 2008

**CMS silicon strips**
- 200 m² Si, 9.6 million channels
- 99.8% fully operational
- Signal/noise ~ 25/1
- Inst. in CMS: August 2007
- First measurements with cosmics and B-field in situ now!
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$^2$

Pixel size is 50 µm x 400 µm in R$\phi$ x z

**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 is 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/LHCb

ALICE TPC (Time Projection Chamber)

- Measure many samples of dE/dx per track (need $\gg 25$ ns!!)
- At low momenta, non-relativistic particles can be separated from each other through precise dE/dx measurements:

Bethe-Bloch: $-\langle dE/dx \rangle = k \frac{1}{\beta^2} (0.5 \log(2m_e c^2 \beta^2 \gamma T_{\text{max}}/I^2) - \beta^2 - \delta/2)$
What are the limitations of ATLAS/CMS tracking detectors in terms of particle-ID? Look at ALICE/LHCb

**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) + Cerenkov (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**
  - TPC + ITS (dE/dx): π/K, K/p, e/π
  - electrons in TRD: p > 1 GeV
  - muons: p > 5 GeV
  - π⁰ in PHOS: 1 < p < 80 GeV

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

### LHC-b RICH detectors

<table>
<thead>
<tr>
<th>C₄F₁₀</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>
</tr>
<tr>
<td>θ (Cerenkov)</td>
<td>0.160 rad</td>
<td>0.0526 rad</td>
</tr>
<tr>
<td>β (kaon)</td>
<td>0.9864</td>
<td>0.99986</td>
</tr>
<tr>
<td>θ (Cerenkov)</td>
<td>0.020 rad</td>
<td>0.0502 rad</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)
  - C₄F₁₀  p=1013 mb at −1.9°C
    - n=1.0014 /260 nm θ (β=1)=53 mrad
    - thickness=85 cm
    - nb photons=~30/ring

#### RICH2:
- CF₄  
  - n=1.0005 /260 nm θ (β=1)=32 mrad
  - thickness=180 cm
  - nb photons=~30/ring
What are the limitations of ATLAS/CMS tracking detectors in terms of particle-ID? Look at ALICE/LHCb

LHCb 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 (\( \varepsilon_e \sim 55\% \))

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

**Photon identification**

✈ **\( \gamma/\text{jet and } \gamma/\pi^0 \)** separation
- main reducible background to \( H \rightarrow \gamma\gamma \)
  comes from jet-jet and is \( 2 \times 10^6 \) larger than signal
- \( R_{\text{jet}} \sim 5000 \) in the range \( E_T > 25 \) GeV (factor 10 between q and g)
- \( R \) (isolated high-\( p_T \) \( \pi^0 \)) \( \sim 3 \) (better \( R \) for converted photons using \( p/E \))

✈ **Conversion identification**
- High trigger efficiency and excellent particle identification
- Understanding of detector (alignment, material)
- Momentum measurement in the Inner Detector
- ECAL calibration

General detector requirements for e/\( \gamma \) id at the LHC:
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 ∼ $10^{-3}$-$10^{-4}$
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!
• Largest signal cross-section is for $\gamma$-jet events:
  - for $E_T^\gamma > 20$ GeV, expect $\sim 5$M events with S/B $\sim 1:1$
  - measure fakes from data, extrapolate $\varepsilon$ from electrons

• Largest electron signal cross-section is from $b,c$ to $e$:
  - measure fakes using e.g. TRT, need MC for $\varepsilon$

• Largest electron pair cross-section is from direct $J/\psi$ to $ee$:
  - clean signal but only small fraction of total cross-section
  - use pre-scaled single $e5$ trigger to extract efficiencies

Electron candidates with $E_T > 10$ GeV:
$\sim 5$M $b,c \rightarrow e$ with S/B $> 5:1$ for 10 pb$^{-1}$

Electron pairs with $E_T > 5$ GeV:
$\sim 20k$ $J/\psi$, 5k $\Upsilon$ and 3k $Z$ for 10 pb$^{-1}$
The fact that di-jets background is roughly equal to γ-jets background indicates (to me?) that their background is dominated by conversions (expect ratio = dijet/γ-jets ~ 1) and not by fake hadrons (expect ratio ~ 10)

However, not completely clear discussing with CMS experts

---

2 Background to W→e

Electrons in ATLAS/CMS
Electrons in ATLAS/CMS

CSC Standard Model
ATL-COM-PHYS-2008-064

Perhaps the explanation arises from a higher efficiency for putting converted photons into the photon container in ATLAS?
## Electrons in ATLAS: use of TR

### ATL-COM-PHYS-2008-110

**Release 13**

### Conversions and Dalitz

<table>
<thead>
<tr>
<th>Cuts</th>
<th>$E_T &gt; 17$ GeV</th>
<th></th>
<th>$E_T &gt; 8$ GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Efficiency (%)</td>
<td>Jet rejection</td>
<td>Efficiency (%)</td>
</tr>
<tr>
<td></td>
<td>$Z \rightarrow ee$</td>
<td>$b,c \rightarrow e$</td>
<td>Single electrons ($E_T=10$ GeV)</td>
</tr>
<tr>
<td>Loose</td>
<td>87.96 ± 0.07</td>
<td>50.8 ± 0.5</td>
<td>567 ± 1</td>
</tr>
<tr>
<td>Medium</td>
<td>77.29 ± 0.06</td>
<td>30.7 ± 0.5</td>
<td>2184 ± 13</td>
</tr>
<tr>
<td>Tight (TRT)</td>
<td>61.66 ± 0.07</td>
<td>22.5 ± 0.4</td>
<td>(8.9 ± 0.3)10^4</td>
</tr>
<tr>
<td>Tight (isol.)</td>
<td>64.22 ± 0.07</td>
<td>17.3 ± 0.4</td>
<td>(9.8 ± 0.4)10^4</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Fraction of surviving candidates (%)</th>
<th>Isolated</th>
<th>Non-isolated</th>
<th>Jets</th>
<th>Non-isolated</th>
<th>Jets</th>
</tr>
</thead>
<tbody>
<tr>
<td>Medium</td>
<td>1.1</td>
<td>7.4</td>
<td>91.5 (5.5 + 86.0)</td>
<td>9.0</td>
<td>91.0 (5.0 + 86.0)</td>
</tr>
<tr>
<td>Tight (TRT)</td>
<td>10.5</td>
<td>63.3</td>
<td>26.2 (8.3 + 17.9)</td>
<td>77.8</td>
<td>22.2 (7.1 + 15.1)</td>
</tr>
<tr>
<td>Tight (isol)</td>
<td>13.0</td>
<td>58.3</td>
<td>28.6 (8.7 + 19.9)</td>
<td>75.1</td>
<td>24.9 (6.4 + 18.5)</td>
</tr>
</tbody>
</table>

**Charged hadrons (largely dominant)**
Electrons with early data in ATLAS

5802 - di-jets
- electrons
- hadrons

egamma objects after tight cut
TR ratio cut $\sim 0.08 \varepsilon_{el} \sim 90\%$
$\sim 0.15 \varepsilon_{el} \sim 75\%$

5802 - di-jets

Electrons with early data in ATLAS
Electrons with early data in ATLAS

5805 - di-jets

These plots most relevant to the first physics data (e10 trigger)

To control background electrons relax B-layer and E/p cuts
Electrons with early data in ATLAS

- Reminder: even in MC, fake rates from jets not yet understood as a function of physics processes
- Top plot - jet spectrum for the different data samples
- Bottom plot egamma object spectrum for the different data samples
Electrons with early data in ATLAS

- Illustration of kinematic ranges of truth jets and egamma objects in different physics sample
Electrons with early data in ATLAS

- Clearly see threshold effects - compare di-jet data sample with $P_T^{\text{hard}} > 35$ (green triangle) and di-jet with $P_T^{\text{hard}} > 17$ (black circle)
- Jet spectrum due to QCD correction is harder for $Z \rightarrow \text{ee}$ data sample
Electrons with early data in ATLAS
Matching truth jets to original parton quite complex (and frequently impossible)

<table>
<thead>
<tr>
<th></th>
<th>$Z\rightarrow\text{ee}$</th>
<th>Min. bias</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$E_T^{\text{truthjet}}&gt; 8$ GeV</td>
<td>$E_T^{\text{truthjet}}&gt; 30$ GeV</td>
</tr>
<tr>
<td>Jet per event</td>
<td>2.82</td>
<td>0.62</td>
</tr>
<tr>
<td>light quark, %</td>
<td>32.3</td>
<td>25.4</td>
</tr>
<tr>
<td>b,c quark, %</td>
<td>8.8</td>
<td>6.7</td>
</tr>
<tr>
<td>gluon, %</td>
<td>54.4</td>
<td>62.7</td>
</tr>
<tr>
<td>not matched, %</td>
<td>4.5</td>
<td>5.2</td>
</tr>
</tbody>
</table>
Electrons with early data in ATLAS

- Only gluon jets
  - 5001: $R = 1929 \pm 105$
  - 5144: $R = 195 \pm 6$

- Light quark jets
  - 5001: $R = 705 \pm 36$
  - 5144: $R = 106 \pm 3$

- $b,c$ quark jets
  - 5001: $R = 526 \pm 44$
  - 5144: $R = 100 \pm 5$

- Need to understand why min bias $R_g/R_q \sim 3$ and $Z-\text{ee}$ $R_g/R_q \sim 2$ and
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 $\times 10$
- 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
• Tracker material has severe impact on e/γ performance, especially material at low radius (pixels)
  - each pixel layer is ~ 3.5% $X_0$

• Use min. bias events to map material:
  - with 350k min. bias events, see structures corresponding to ~ 1% $X_0$
  - see also contributions from Dalitz decays and beam-pipe

• Control backgrounds and maintain below ~ 10% with TRT
  - but need reference surfaces to measure reconstruction efficiency
  - full material map with small systematics requires very large statistics

Extra material added in simulation (1% X0)
Electrons in ATLAS: low mass pairs using 2e5 trigger

Tight Selection Bkg Breakdown

<table>
<thead>
<tr>
<th></th>
<th>Eta</th>
<th>Iso</th>
<th>b,c→e</th>
<th>Conv</th>
<th>Hadrons</th>
<th>Total (ev)</th>
<th>Drell-Yan (ev)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tight</td>
<td>All</td>
<td>0.3%</td>
<td>65.2%</td>
<td>8.0%</td>
<td>26.4%</td>
<td>1025</td>
<td>22669 (24.0%)</td>
</tr>
<tr>
<td>Tight</td>
<td>&lt;2</td>
<td>0.5%</td>
<td>72.0%</td>
<td>8.8%</td>
<td>20.2%</td>
<td>883</td>
<td>21484 (22.7%)</td>
</tr>
<tr>
<td>TightNIso</td>
<td>All</td>
<td>0.5%</td>
<td>70.0%</td>
<td>8.7%</td>
<td>20.3%</td>
<td>840</td>
<td>19671 (20.8%)</td>
</tr>
<tr>
<td>TightNIso</td>
<td>&lt;2</td>
<td>0.6%</td>
<td>79.7%</td>
<td>8.0%</td>
<td>11.7%</td>
<td>698</td>
<td>18486 (19.6%)</td>
</tr>
</tbody>
</table>

Note: no TRT cuts are applied for |η| > 2 for egamma electrons. For TRT rejection use |η| < 2 throughout (better S/B).
Electrons in ATLAS: low mass pairs using $2e5$ trigger

### Tightening TRT selection

<table>
<thead>
<tr>
<th></th>
<th>Drell-Yan</th>
<th>Total Bkg</th>
<th>Iso Ele</th>
<th>$b,c\rightarrow e$</th>
<th>conversions</th>
<th>hadrons</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tight</td>
<td>19671 (100%)</td>
<td>840 (100%)</td>
<td>4</td>
<td>605 (100%)</td>
<td>61 (100%)</td>
<td>170</td>
</tr>
<tr>
<td>TightNoIso</td>
<td>18486 (93.5%)</td>
<td>698 (83.1%)</td>
<td>4</td>
<td>556 (91.9%)</td>
<td>56 (91.8%)</td>
<td>82</td>
</tr>
<tr>
<td>TR&gt;0.15</td>
<td>15532 (78.9%)</td>
<td>529 (63.0%)</td>
<td>3</td>
<td>461 (76.2%)</td>
<td>48 (78.7%)</td>
<td>17</td>
</tr>
<tr>
<td>TR&gt;0.20</td>
<td>9963 (50.6%)</td>
<td>355 (42.3%)</td>
<td>2</td>
<td>320 (52.9%)</td>
<td>30 (49.2%)</td>
<td>3</td>
</tr>
<tr>
<td>TR&gt;0.25</td>
<td>5946 (30.2%)</td>
<td>210 (25%)</td>
<td>2</td>
<td>195 (32.2%)</td>
<td>13 (21.3%)</td>
<td>0</td>
</tr>
</tbody>
</table>

**TRT provides good rejection of hadrons**

**Not dominant background: Need to study other variables**
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
Electrons and photons in ATLAS/CMS

ATLAS LAr EM Calorimeter description

- **Presampler** $0.025 \times 0.1$ ($\eta \times \phi$)
  - Energy lost in upstream material
- **Strips** $0.003 \times 0.1$ ($\eta \times \phi$)
  - Optimal separation of showers in non-bending plane, pointing
- **Middle** $0.025 \times 0.025$ ($\eta \times \phi$)
  - Cluster seeds
- **Back** $0.05 \times 0.025$ ($\eta \times \phi$)
  - 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:
  • 3×3, 3×7… cells, 2\textsuperscript{nd} 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) ±0.005
• \(\Delta\phi\) (offset in accordion) ±0.001

Corrections for energy losses:
• Before PS
• Between PS & Calo
• Outside cluster: depends on clustering method
• 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>$R_{\text{jet}} (E_T &gt; 17 \text{ GeV})$</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

- **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**

Electron id efficiency

Pion rejection

$\varepsilon_{e-id}(J/\psi) = 80\%$

$R_\pi(bb\rightarrow\mu X) = 1050 \pm 50$

Allows a S/B ~2 in the J/ψ mass window after vertex refitting.

$\varepsilon_{e-id}(WH_{120}) = 80\%$

$R_\pi(WH) = 245 \pm 17$

Once 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 $R_u(WH_{120}) = 115$ BUT

$\varepsilon = \varepsilon_{b-id}(60\%) \times \text{BR} \sim 8\%$
\[ M_{\gamma\gamma}^2 = 2E_{\gamma_1}E_{\gamma_2}(1-\cos\theta_{12}) \]

What contributes to resolution on \( m_{\gamma\gamma} \)?

8) Measurement of \( E_\gamma \):
   - Intrinsic resolution of calo
   - Calibration/uniformity of calo
   - Pile-up effects

9) Measurement of \( \theta_{12} \):
   - Measurement of position and direction of em showers
   - Measurement of interaction vertex \( z \)
Energy resolution

CMS EM calorimeter (crystals):

\[
\frac{\sigma(E)}{E} \approx 3-5\% \frac{1}{\sqrt{E}}
\]

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

\[
\frac{\sigma(E)}{E} \approx 10\% \frac{1}{\sqrt{E}}
\]

Module zero test beam data

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

Photons from \( H \to \gamma\gamma \)

CMS, full simulation high L

\( \eta = 0.94 \)

Sampling term = 10.7%
Constant term = 0.3%
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

$$\sigma(\theta) \approx \frac{50 \text{ mrad}}{\sqrt{E}}$$
SM H → γγ

Backgrounds

3) Irreducible background from qq → γγ and gg → γγ (box)

5) Reducible background from π^0, η (→ γγ) in jet fragmentation:
   • final states with many photons → look for single photons
   • non-isolated photons inside jets → look for isolated photons
   • Very difficult problem: at p_T ≈ 50 GeV, jet-jet / γγ ≈ 10^7
     → need to reject each jet by a factor 10,000 to bring the reducible background well below the irreducible one
   • However, at p_T ≈ 50 GeV, π^0/jet ≈ 10^{-3}
     → separate isolated photons from π^0 decays at 50 GeV
     → photons from π^0 decays will be distant by ≈ 1 cm
     → need granular position detector after ~ 4-5 X_0 in calo
     → need to convert both photons but to measure while showers still narrow (in addition worry about conversions)
$\text{SM H} \rightarrow \gamma \gamma$
Can lessons be learned from Tevatron?

Background Estimation: $\gamma$

- **Major Source**
  - $\pi^0 \rightarrow \gamma\gamma$

- **Fake rate measured in similar way to electrons**
  - Prompt photons need to be removed
  - Rates from different jet samples are compared for systematic
  - If jets are $E_T$-ordered, find rate is different for 1$^{\text{st}}$, 2$^{\text{nd}}$, 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:

<table>
<thead>
<tr>
<th>Component</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>« Isolated » $\pi^0$</td>
<td>72%</td>
</tr>
<tr>
<td>$\eta \rightarrow \gamma \gamma$, $\omega \rightarrow \gamma \pi^0$, $K_S \rightarrow 2\pi^0$</td>
<td>13%</td>
</tr>
<tr>
<td>« multi » $\pi^0$</td>
<td>4%</td>
</tr>
<tr>
<td>electron</td>
<td>4%</td>
</tr>
<tr>
<td>single charged hadron</td>
<td>4%</td>
</tr>
<tr>
<td>single neutral hadron</td>
<td>1%</td>
</tr>
<tr>
<td>Others</td>
<td>2%</td>
</tr>
</tbody>
</table>

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!
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)
Rejection of QCD jet background

Most rejection from longitudinal calo segmentation and 4 mm $\eta$-strips in first compartment ($\gamma / \pi^0$ separation)

$\varepsilon_\gamma = 80\%$

$\text{SM } H \rightarrow \gamma \gamma$

ATLAS EM calo: full simulation
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:
  - $e^{\pm}, \pi^{\pm}$ → 250 GeV
  - $\mu^{\pm}, \pi^{\pm}, p$ → 350 GeV
  - $\gamma$ ~20-100 GeV
- B from 0 → 1.4 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

S. Menke

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)
What next?

Why this fear that experimental particle physics is an endangered species?

The front-wave part of this field is becoming too big for easy continuity between the generations. I have been working on LHC for 25 years already. Most of the analysis will be done by young students and postdocs who will have no idea what the 7000 tonnes of ATLAS is made of. More importantly, fewer and fewer people remember for example that initially most of the community did not believe tracking detectors would work at all at the LHC.

The stakes are very high: one cannot afford unsuccessful experiments (shots in the dark) of large size, one cannot anymore approve the next machine before the current one has yielded some results and hopefully a path to follow

Theory has not been challenged nor nourished by new experimental evidence for too long

This is why the challenge of the LHC and its experiments is so exhilarating! A major fraction of the future of our discipline hangs on the physics which will be harvested at this new energy frontier.

How ordinary or extraordinary will this harvest be? Only nature knows.

Fortunately, there is much more to experimental particle physics than its dinosaurs!