From ATLAS Calorimeter building to LHC first physics

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1. pp colliders
2. ATLAS and object reconstruction in calorimeter
3. Possible approach for First Physics
4. Conclusions

! Warning ! This is not a review talk on ATLAS readiness/physics potential. This is my own (biased) view

Introduction

❑ Particle physics experiment on accelerator at the energy frontier

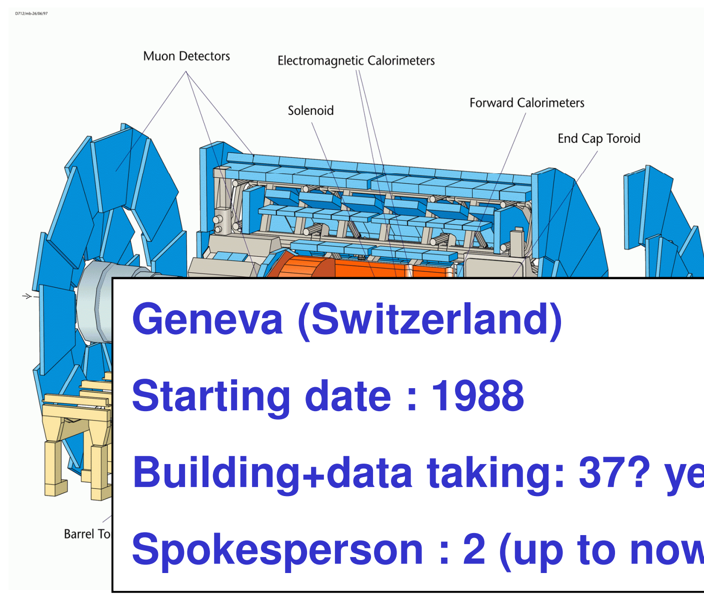
- World wide collaborations on few tens of years
- Like for Middle age catedrals use quintessence of knowledge and lot of manpower !

Reims (France)

Starting date : 1211

Building : 64 years

Architectes : 4



Geneva (Switzerland)

Starting date : 1988

Building+data taking: 37? years

Spokesperson : 2 (up to now)

→ We are at the beginning of a new area. First mass in 2 months !

→ You are lucky if you start PhD now !

Short story of pp colliders

- **Luminosity L (α Beam intensity) and center of mass energy ($\sqrt{s}$) for pp colliders :**

Machine	1rst run			Total		
	Year	L (pb^{-1})	$\sqrt{s}$ (TeV)	Years	L (fb^{-1})	$\sqrt{s}$ (TeV)
ISR @CERN	1971	0.1	0.05	13	1	0.06
SppS @CERN	1982	0.02	0.55	8	0.01	0.63
Tevatron @ FNAL	1987	0.07	1.8	23	8	1.96
LHC @ CERN	**2010**	**100**	**7**	**15?**	**300?**	**14?**

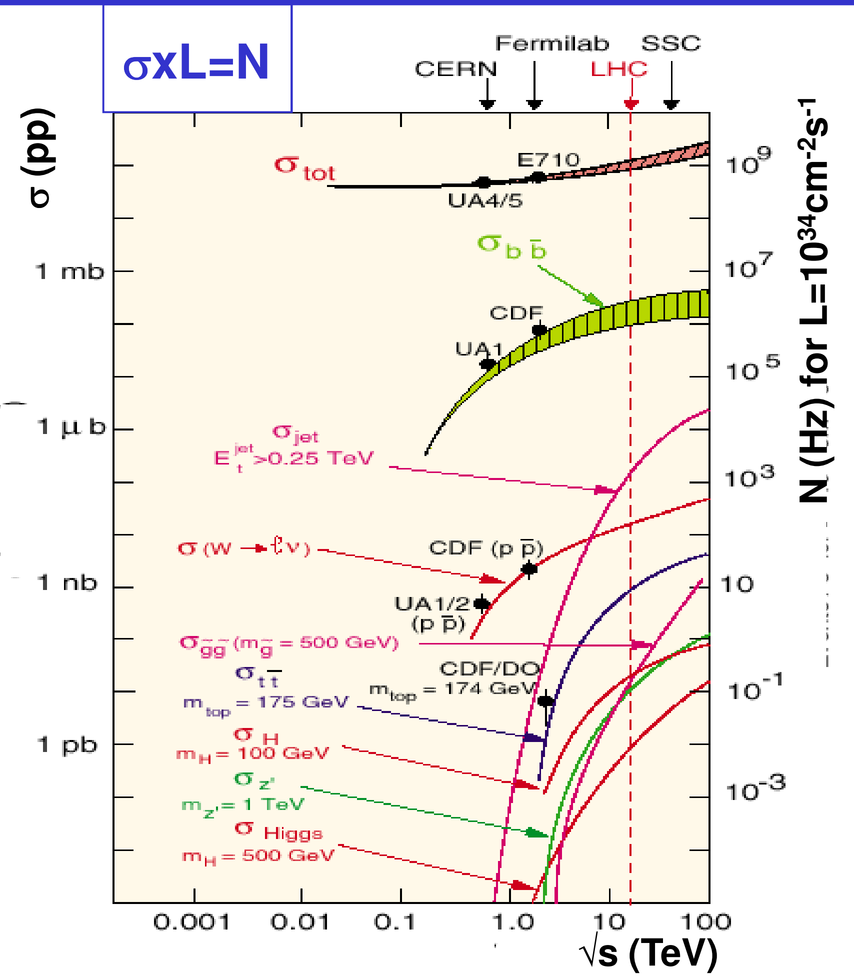
No so easy to gain a factor 3 in $\sqrt{s}$: 23 years !

➔ If no new technology developped probably the last step

➔ But since it is almost there ➔ High potential from LHC since the start (x3 $\sqrt{s}$ and X10000 L compare to Tevatron start)

Some pp collider awards

- **1983/1984: SpS (CERN)**
  - **W** and **Z** boson discovery
- **1995: Tevatron (FNAL)**
  - **Top** quark discovery
- **2007: Tevatron (FNAL)**
  - ΔM_W = 48 MeV (CDF) better than e+e- experiment (ALEPH) 51 MeV !

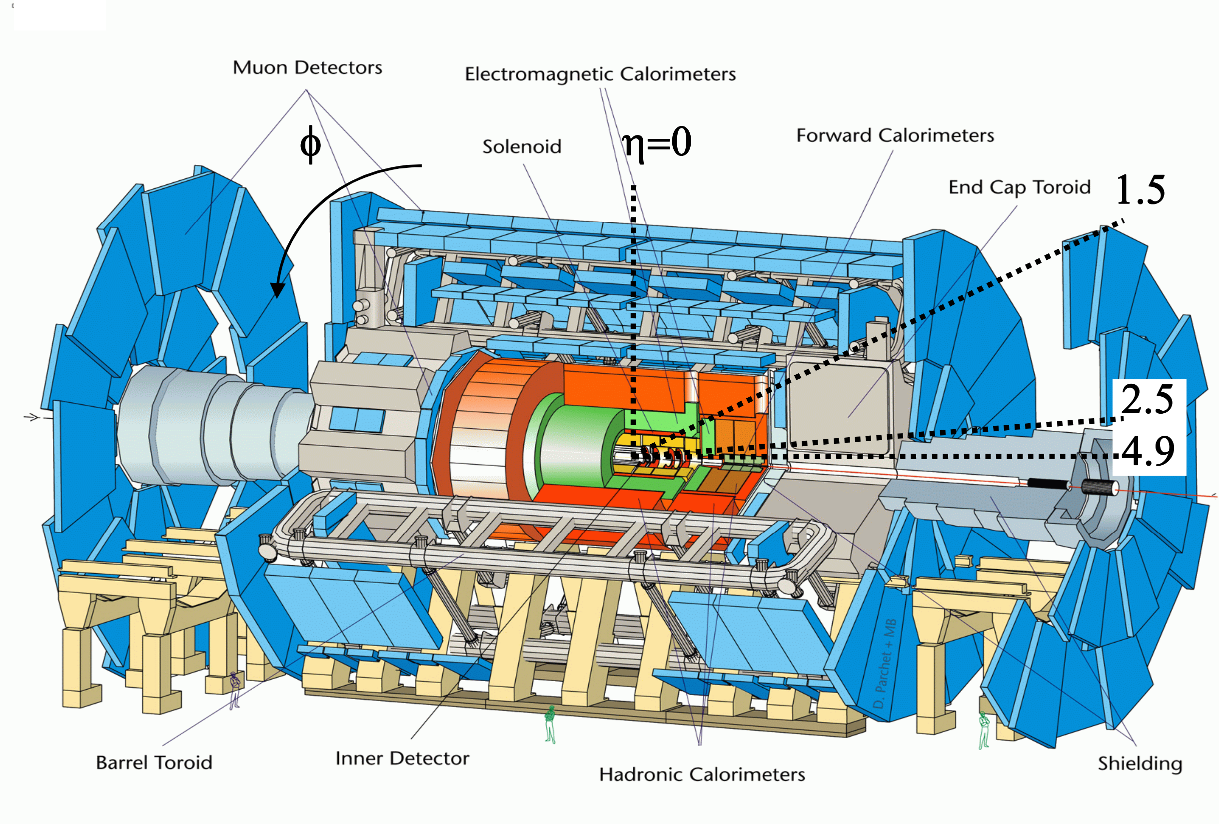


➔ **pp collider good for discovery and precision measurement !**

ATLAS : a pp collider experiment

❑ pp collider: Hard times for the detector

- Quick electronic (40 MHz) …
- … radiation tolerant
- Very granular detector
- Selective trigger ($\sigma_{signal} \sim 10^{-13}\ \sigma_{tot}$)

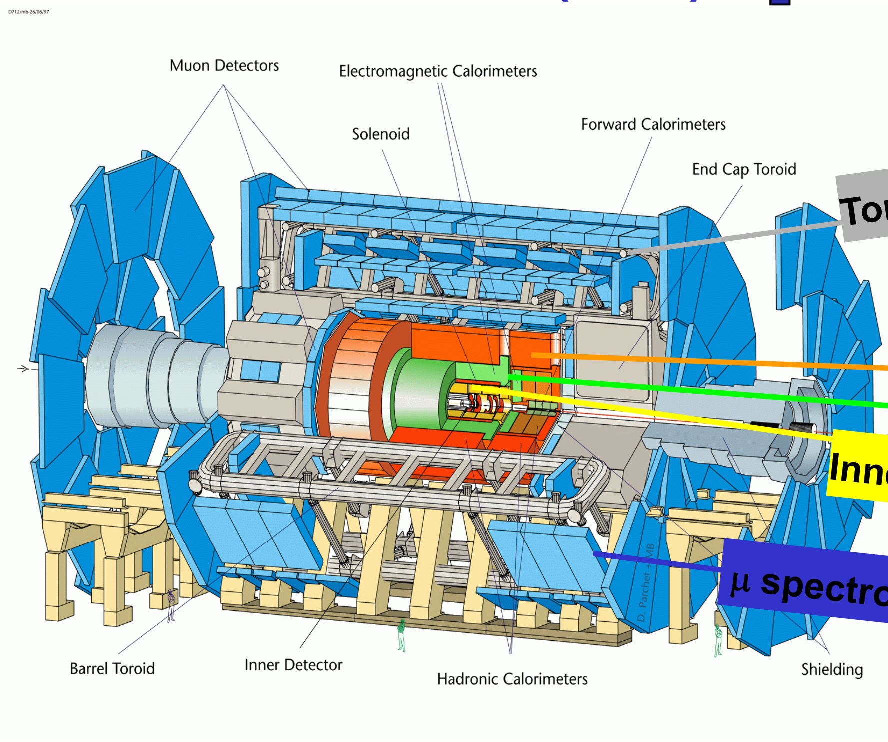


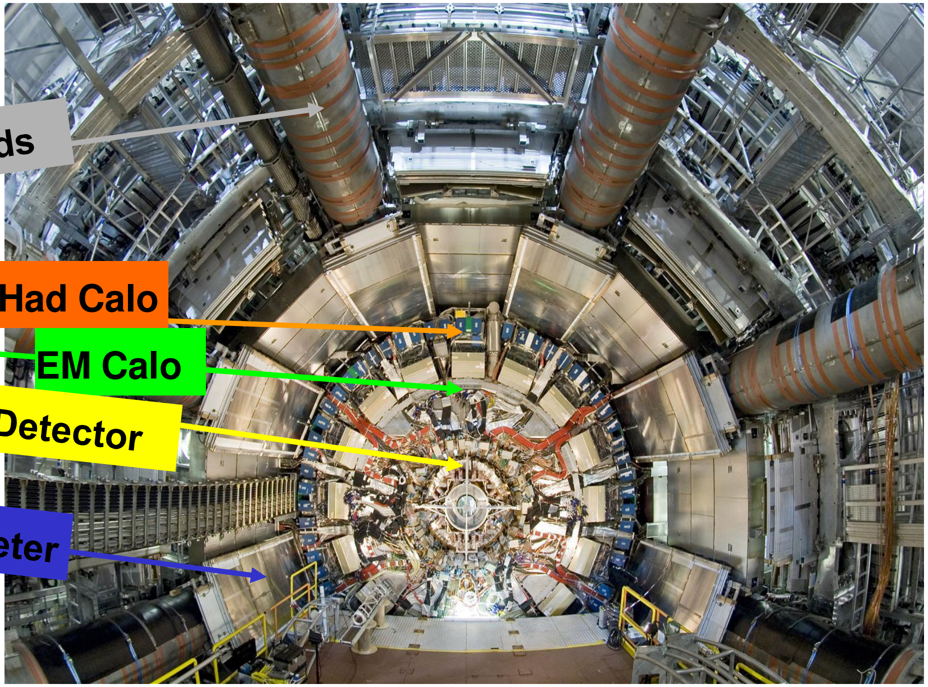
L ~ 44 m, ∅ ~ 22 m
7000 tons
2500 people

ATLAS in 2009

15 years of constant effort

From dream (1994) … to reality (2009)



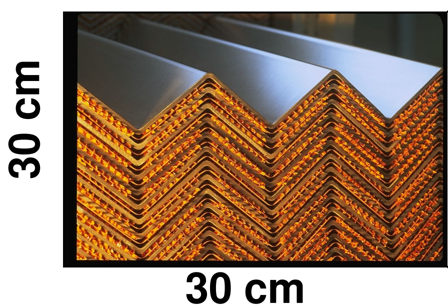


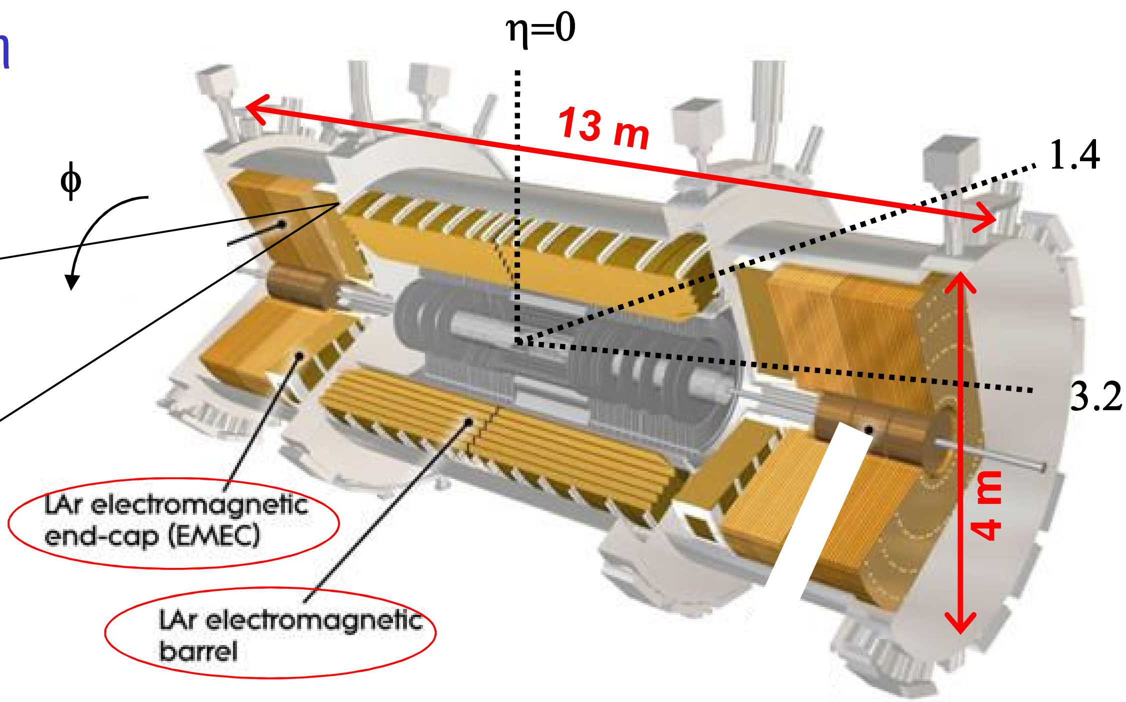
➔ **Let's concentrate on (EM) calorimeter now : my bias !**

EM Calorimeter : generalities

- **ATLAS choose a sampling electromagnetic (EM) calorimeter**
  - Absorber : lead with accordion shape (thickness = 2 cm)
  - Active material : liquid argon (90 K) → 3 cryostats
  - Electrode : large (2 m^2) with accordion shape

  → hermetic in ϕ, no crack in η

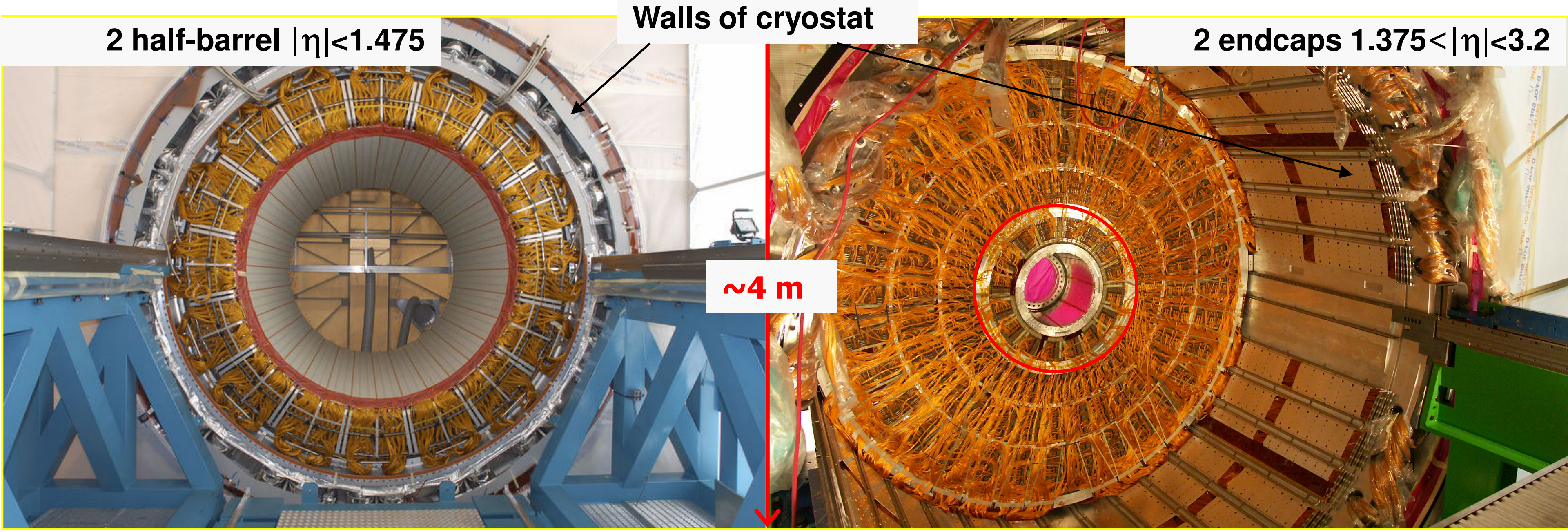




EM Calorimeter : building (1)

❑ 1994-2009 : a long road (Part I)

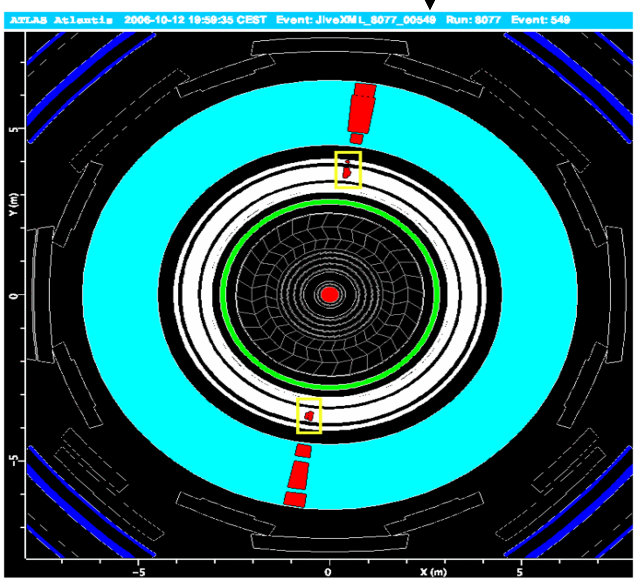
- 1988-1995: Intense R&D for detector and electronics
- 1996-2004: Module construction and integration in 3 cryostats

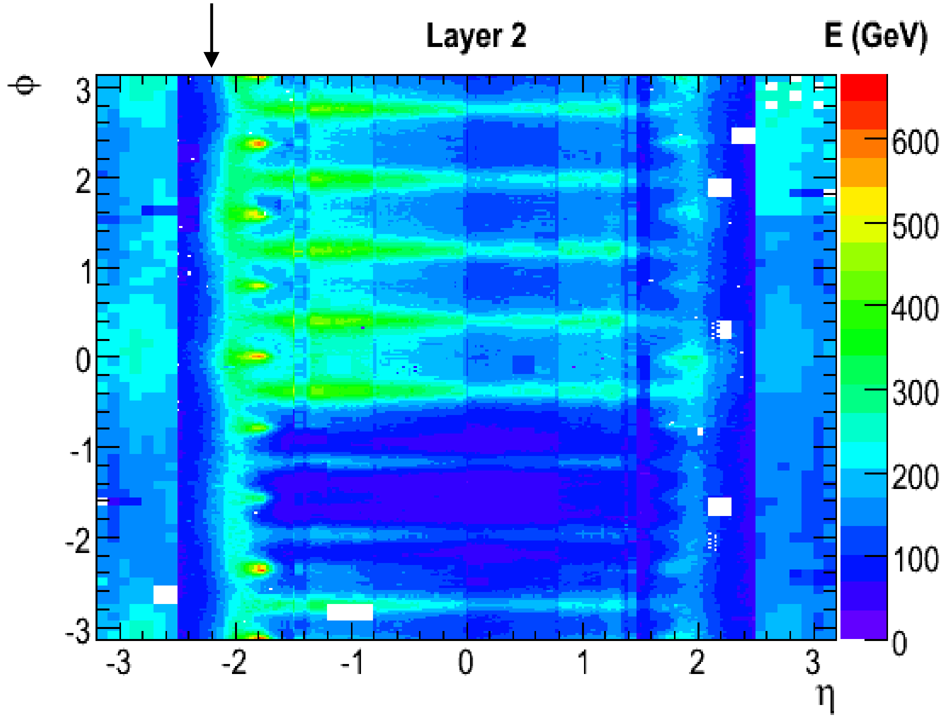


EM Calorimeter : building (2)

❑ 1994-2009 : a long road (Part II)

- 2004-2005: Cryostat testing in surface
- 2006-2008: Installation of cryostat and electronics in the ATLAS cavern
- 2008-2009: Cosmic muon and first LHC beam analyses



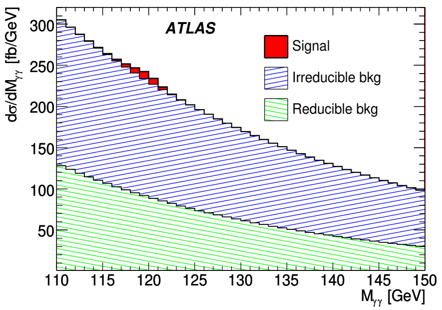


EM Calorimeter : goals

❑ **Measure Energy (E) and directions (η, φ) of e/γ in :**

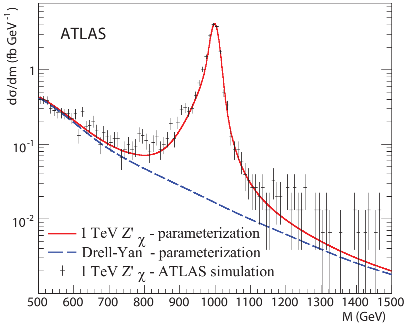
$\langle E_{\gamma,e}\rangle \sim 100$ GeV

- $H \to \gamma\gamma$
- $H \to 4e$



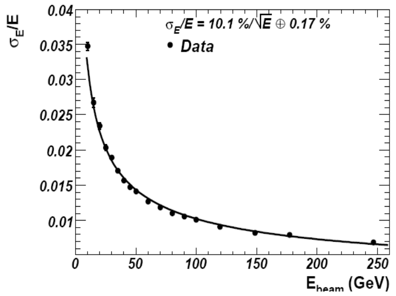
$E_e > 500$ GeV

- $W' \to e\nu$
- $Z' \to ee$



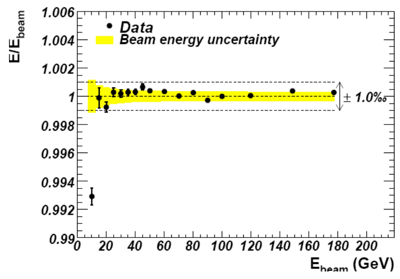
❑ **… with high precision on E** $\sigma_E/E = a/\sqrt{E} \oplus c \oplus n/E$

- Sampling term $a \sim 10\%\sqrt{\text{GeV}}$
- Constant term $c < 1\%$



❑ **… correct energy scale ∀ E** Linearity <0.5%

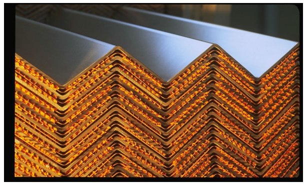
➔ Mass resolution $H \to \gamma\gamma$, 4e



❑ **… and high precision on η, φ** $a_\theta \sim 50$ mrad$/\sqrt{E}$

➔ Low contribution to $H \to \gamma\gamma$ mass resolution

EM Calorimeter : principles (1)



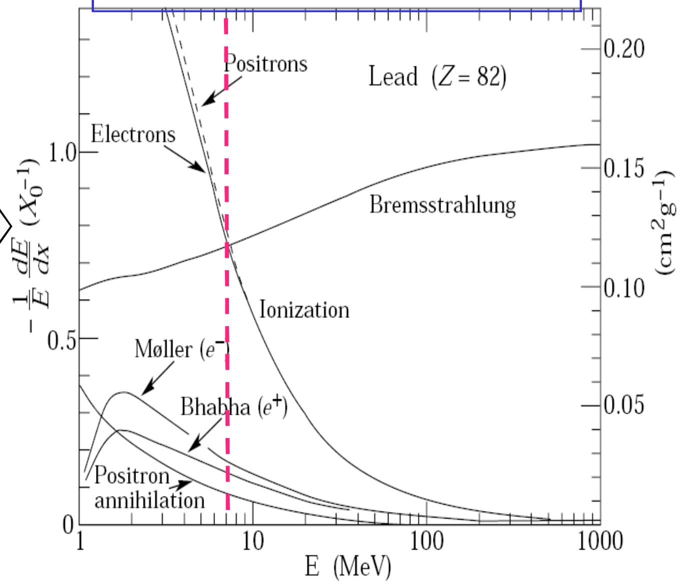
- ❑ **Electron loose all its energy in the calorimeter …**
  - Electron interacts in absorber ➔ EM shower ➔ Secondary electrons
  - Secondary electrons ionize liquid argon ➔ Ionisation electron

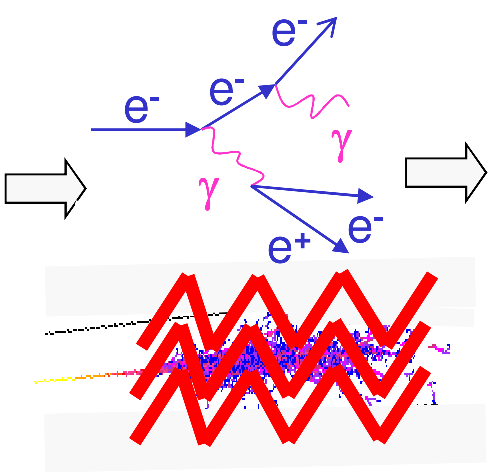
Interact with lead …

Create a shower …

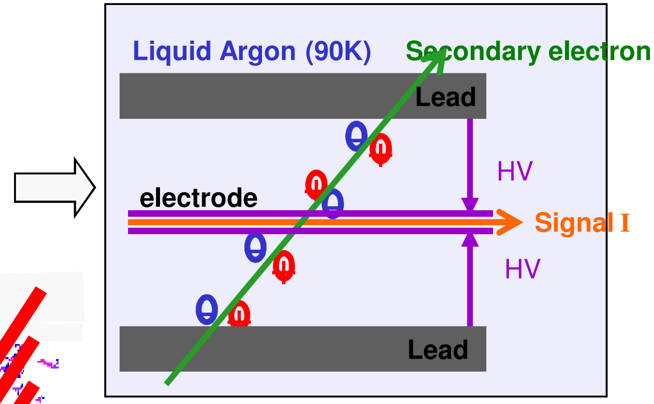
Ionize liquid argon …

e/γ





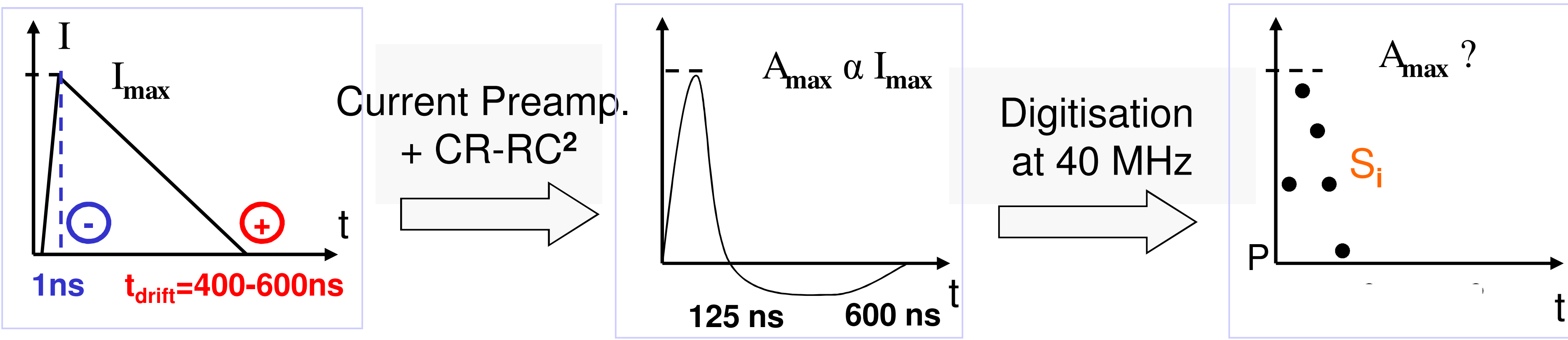
a~10% √GeV



EM Calorimeter : principles (2)

… and the output signal is read with fast read-out electronics

- Under Electric field (1kV/mm), ionization electrons derive …
- … creating a triangular signal on the electrode
- … treated by front-end electronics (on the cryostat)



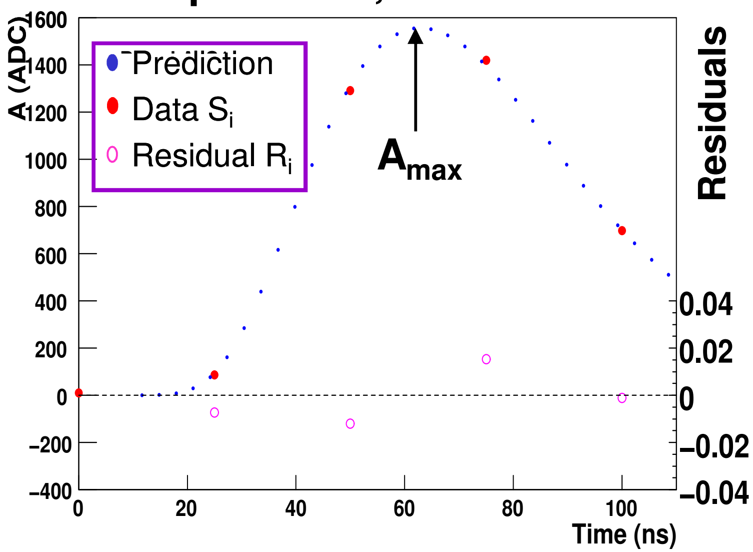
- In Back-end electronics : $A_{max} = \sum_{i=1}^{5} a_i (S_i - P)$ ⟹ $E = F \times g \times A_{max}$

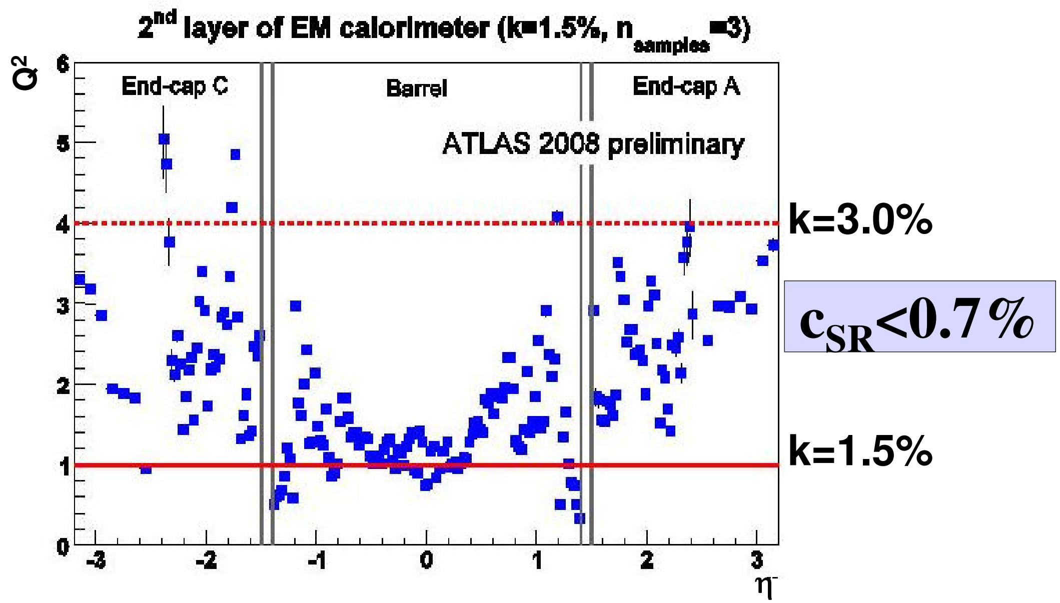
EM Calorimeter : signal reconstruction

- **Quality of signal reconstruction (SR)**
  - A_{max} accuracy (**k**) depends on the precision of electrical cell modelling
  - Check quality on high energetic cells (E>5 GeV) : σ_{noise} negligible

$$Q^2 = \frac{1}{NDoF}\sum_{i=1}^{n_{samples}} \frac{(S_i - \mathrm{A}_{\max} \times \mathrm{Pred.})^2}{(\mathrm{kA}_{\max})^2} = \frac{1}{NDoF}\sum_{i=1}^{n_{samples}} \left(\frac{\mathrm{R}_i}{\mathrm{k}}\right)^2$$

Exemple: Q^2=1, k=1.5%





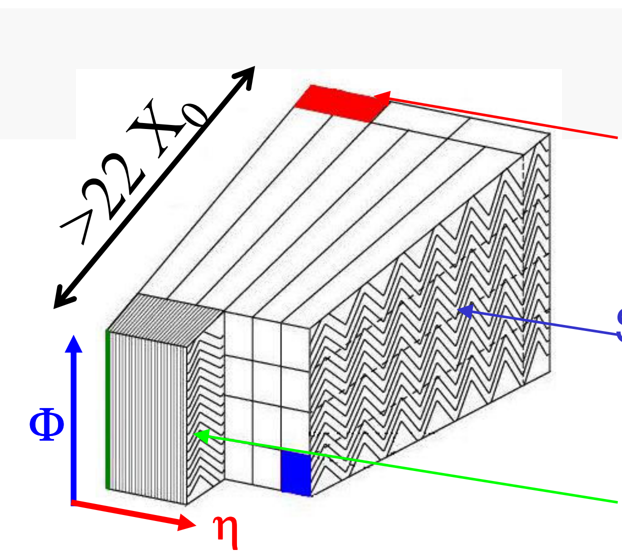
➔ **Signal reconstruction under control on the whole calorimeter coverage**

EM Calorimeter : electron (1)

❑ Electron and photon energy reconstruction

- An e/γ will deposit energy in several cells of the EM calorimeter
- Regroup cells per layer to compute the e/γ energy : E=E(S1)+E(S2)+E(S3)

  → sum cell energies in cluster of ~60 cells

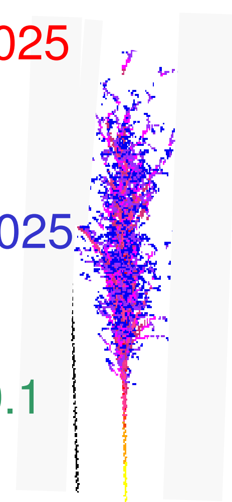


S3 : ΔηxΔϕ = 0.05x0.025
Shower ends

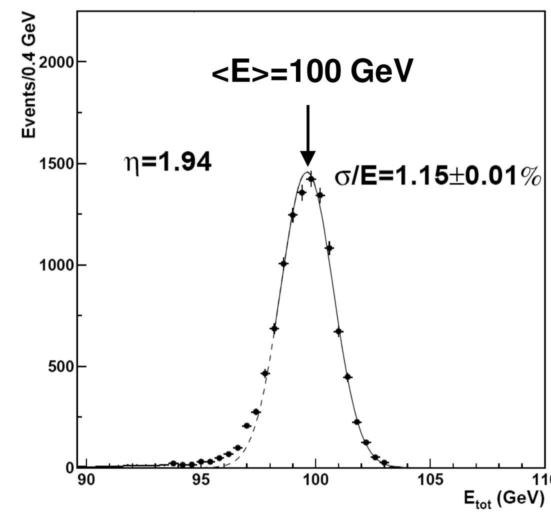
S2 : ΔηxΔϕ = 0.025x0.025
Shower develops

S1 : ΔηxΔϕ ~ 0.003x0.1
Shower starts

1 electron



10000 electrons of 100 GeV

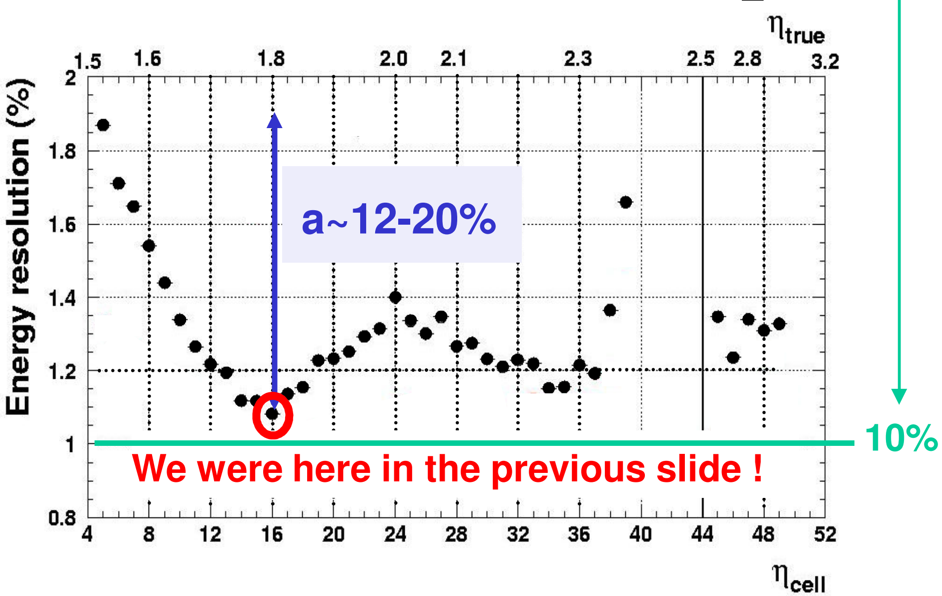


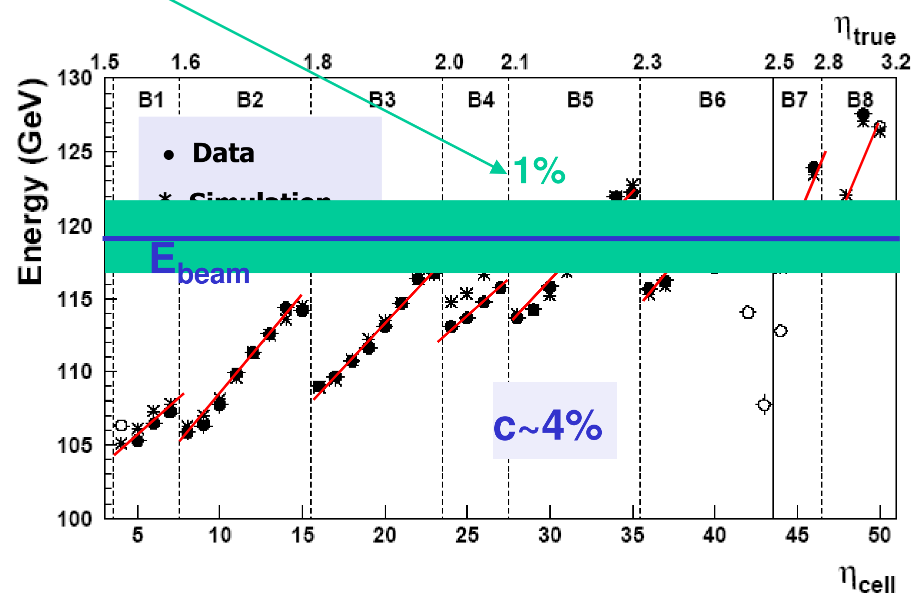
➔ **Close to requirements**

EM Calorimeter : electron (2)

❑ Check with electron beam (one module the EM endcap)

$$\sigma_E/E = a/\sqrt{E} \oplus c \oplus n/E$$



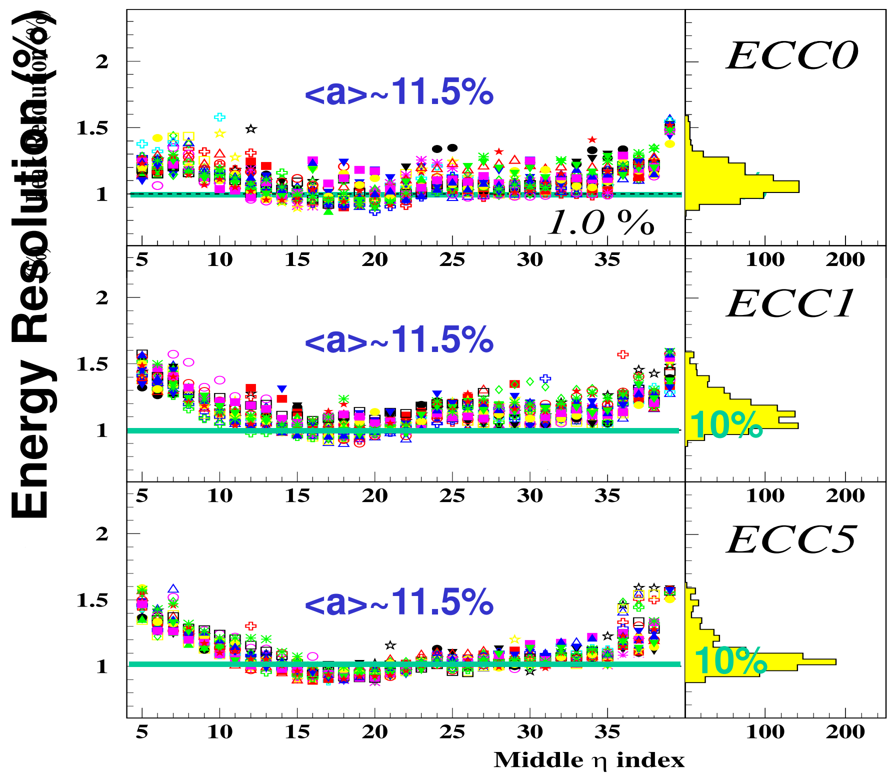


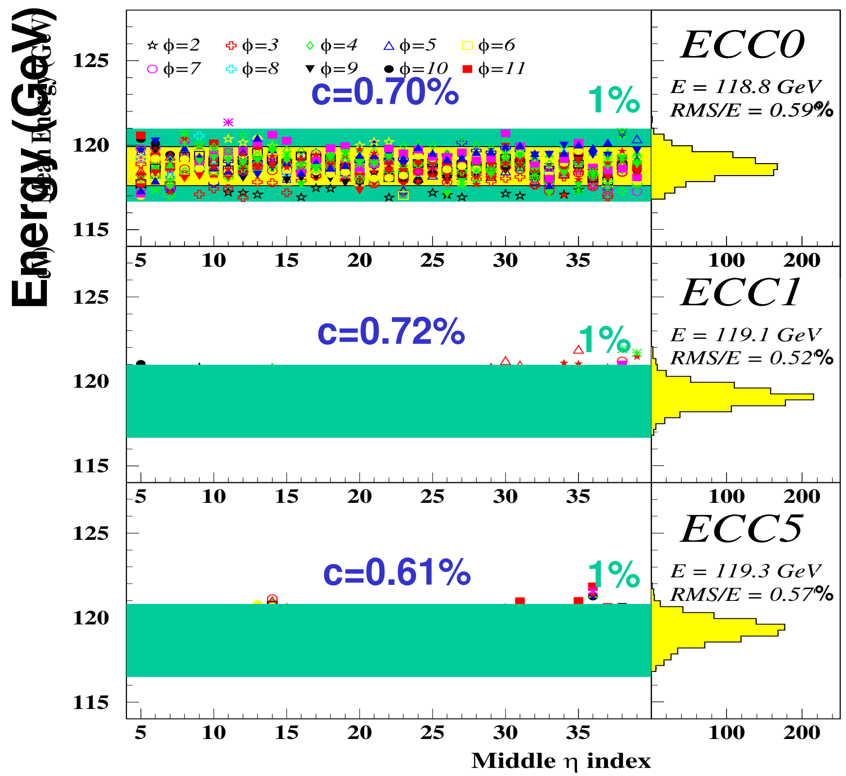
➔ Good agreement with simulation (i.e. you have what you expect) …

➔ … but far from expectations

EM Calorimeter : electron (3)

- **Possible to correct for non uniformity**
  - Requires lot of work (~3 years) … but it works !

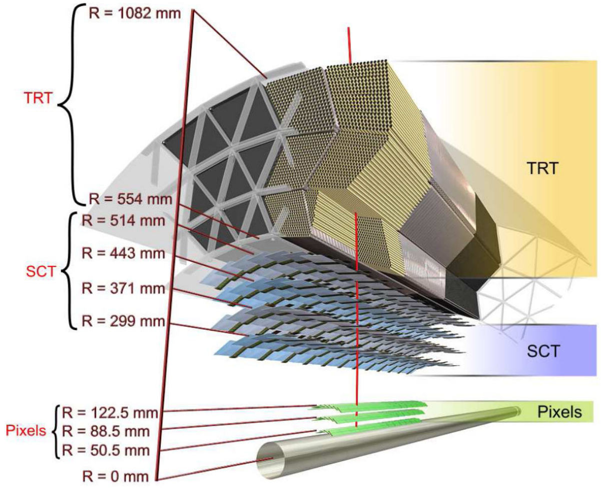


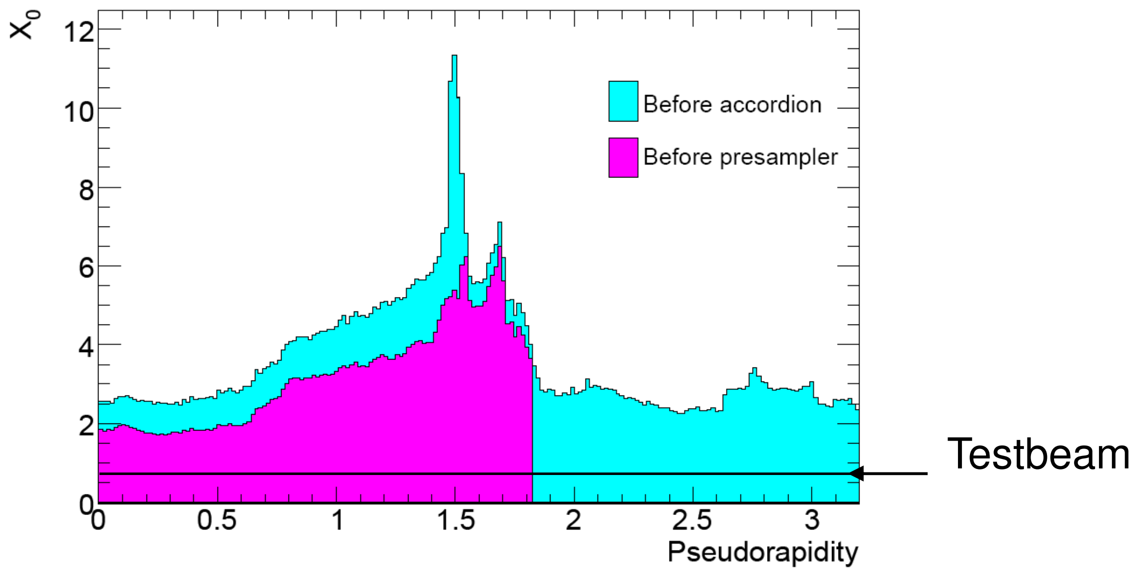


→ **Validation of building, signal reconstruction + corrections!**

EM Calorimeter : electron (4)

- **Energy reconstruction in ATLAS environnement will be harder**
  - e/γ must go through Inner Detector before reaching EM calo
  - Much more material than in test beam
    - ➔ Electron start to interact before the calorimeter

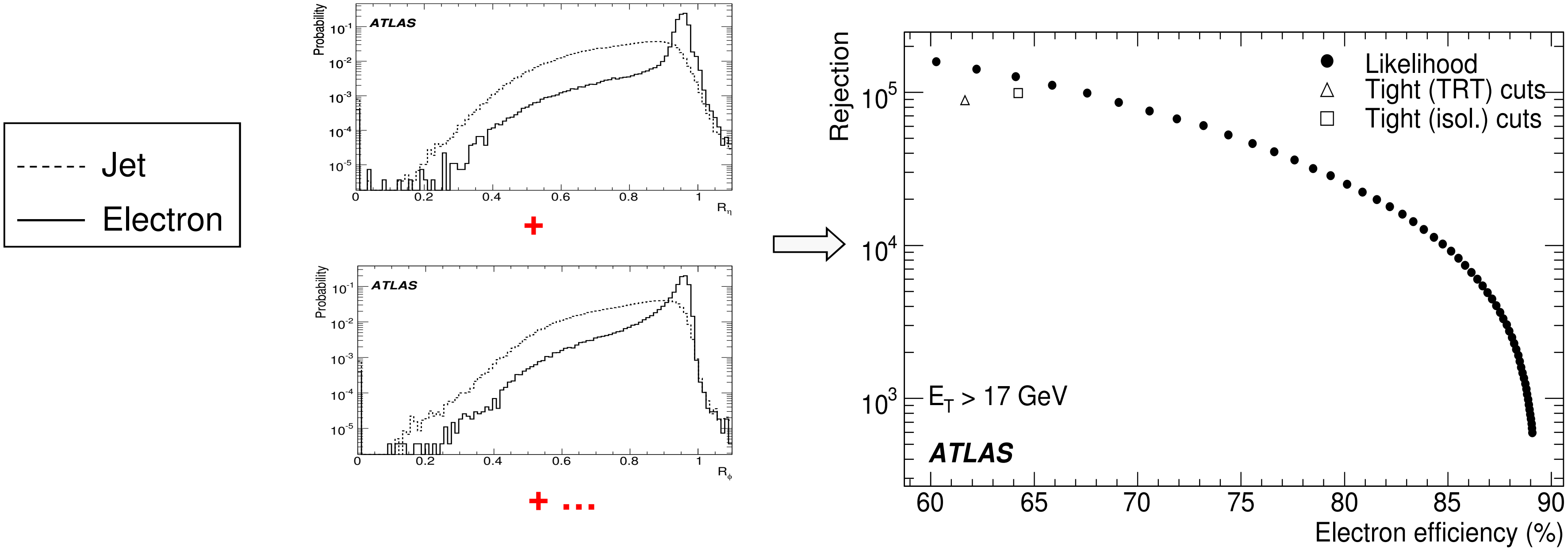




➔ **Few years of work in front of us !**

EM Calorimeter : electron (5)

- **Unlike in test beam, electron must be identified**
  - Jet may look like an electron (track + energy deposit in the EM calo)
  - Use shower shape and associated track



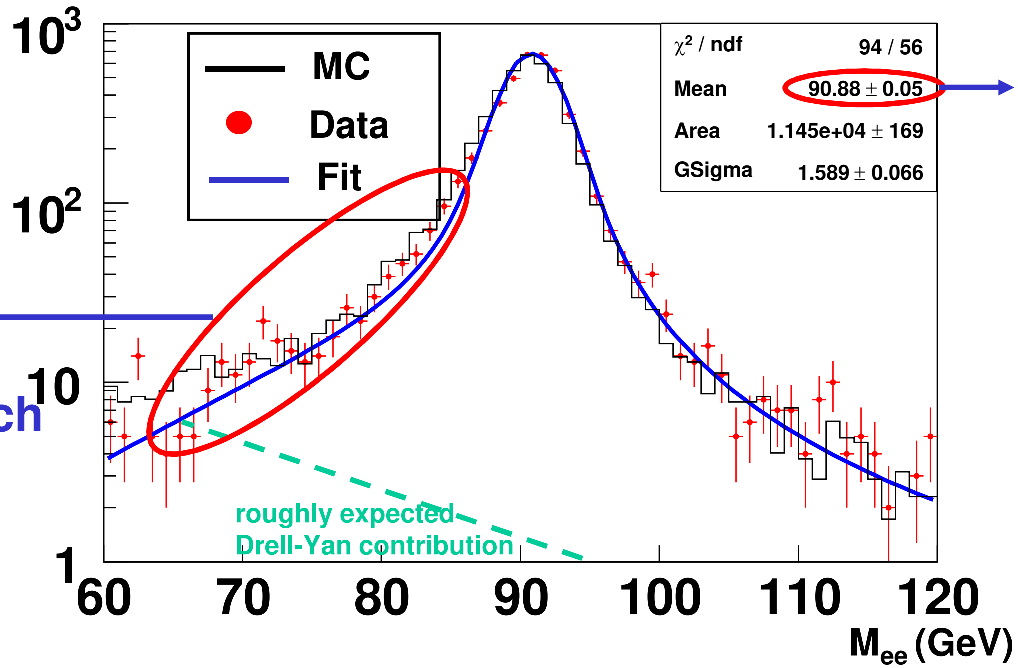
➔ **Few years of work to have optimal efficiency vs rejection**

EM Calorimeter : electron (6)

- **Ultimate electron performance obtained with electrons from Z**
  - Z very well known from LEP e+e- collider (m_Z, Γ_Z) : very good reference
  - ~20 000 pure Z→ee sample in 2010

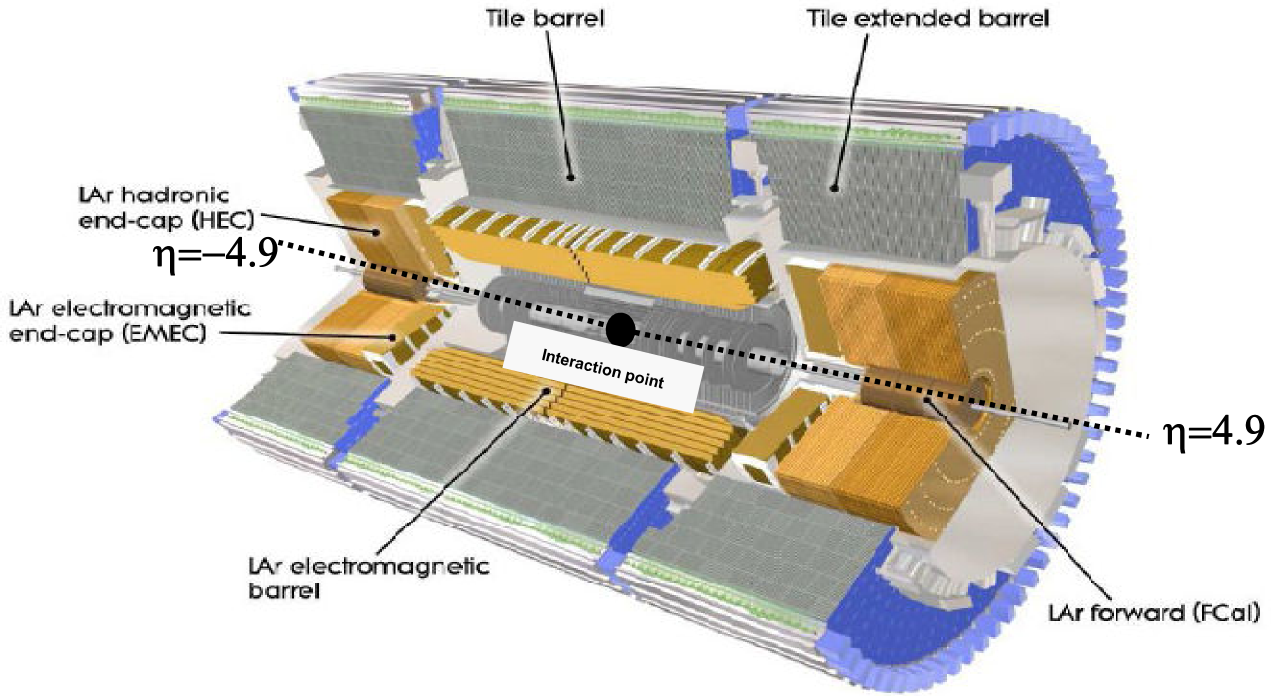
  ➔ Impact of material before EM calo, Correctness of energy scale

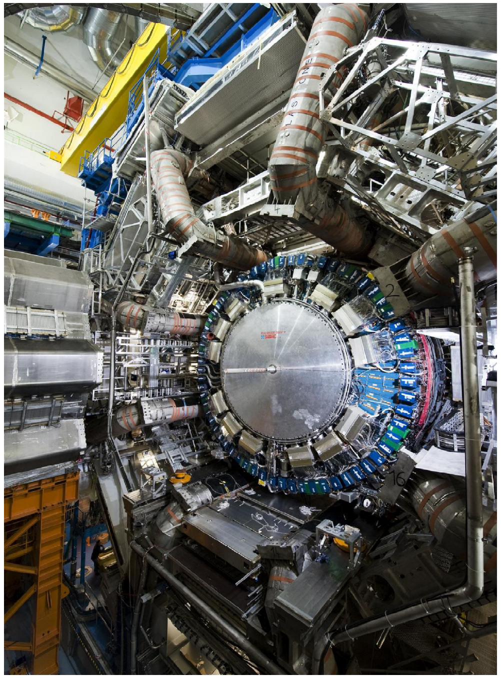
Adjust material description in simulation to match data



If energy scale correct should be 91.2 GeV

Calorimeter : Overview





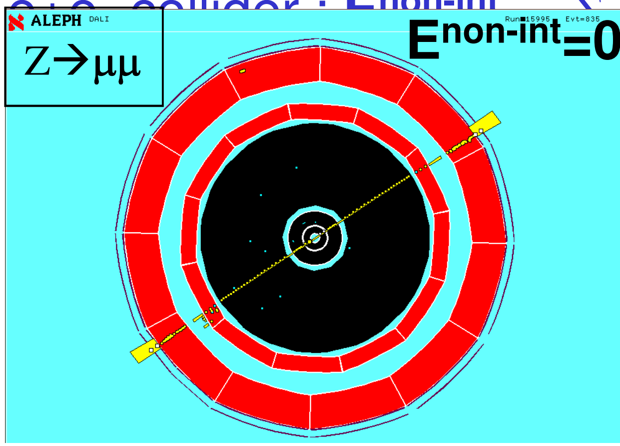
- **Non compensating calorimeter :** e/h~1.3
- **Very granular :** EM (173 500), HAD (14000 = 5 000 Tile + 5500 HEC + 3500 FCal)
- **Hermetic :** EM (22-35 X_0), HAD (11-15 λ) in $|\eta|<4.9$ ($0.7^o<\theta<179.3^o$)

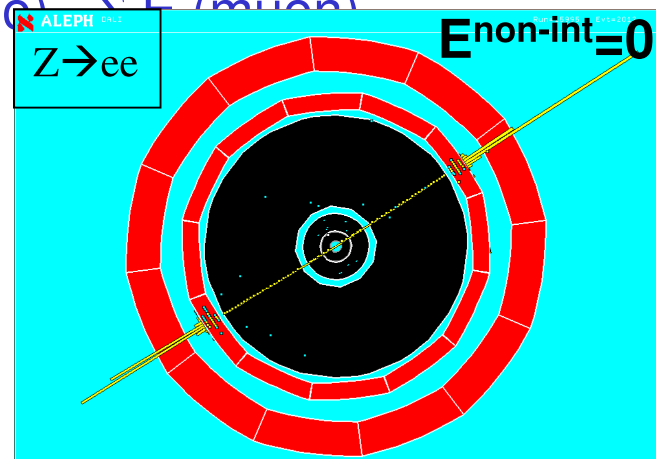
➔ **Very good and hermetic coverage around the interation point**

Calorimeter : E_T^{miss} (1)

❑ **Application : Measure the energy of non interacting particle ($E^{non-int}$)**

- In e^+e^- collider : $\vec{E}^{non-int} = \sum \vec{E}\,(calo) - \sum \vec{E}\,(muon)$ ← If needed



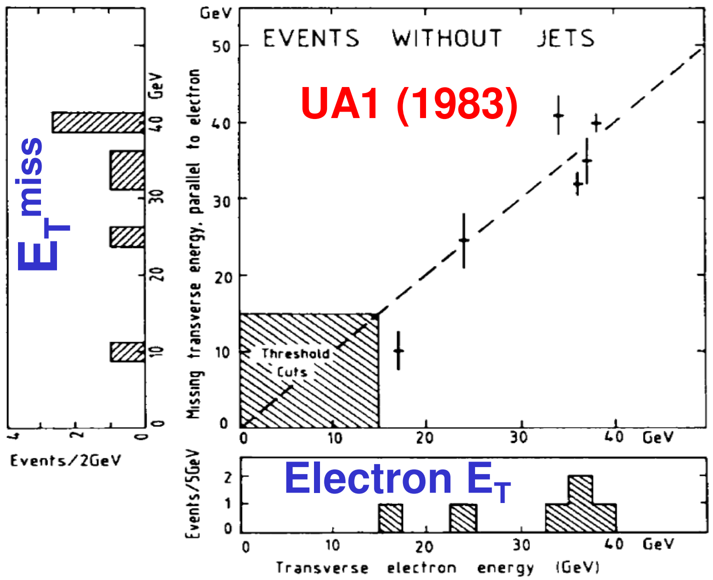


- Energy is also conserved in pp collision (!) but
  - ✓The colliding parton energies are NOT known
  - ✓In many cases, a sizeable part is not detected in ATLAS ($|\eta|>4.9$)

➔ **Can not measure $E^{non-int}$ in pp collisions !**

Calorimeter : E_T^{miss} (2)

- **Still parton momenta are 0 in the transverse plane**
  - Energy conservation: $\vec{E}_T^{miss} = \vec{E}_T^{non\text{-}int} = -\Sigma\, \vec{E}_T\,(\text{calo}) - \Sigma\, \vec{E}_T\,(\text{muon})$ If needed
  - Poor resolution but proven to be very usefull



⇨ W→e ν without jet : the electron energy should be very closely balanced by E_T^{miss}

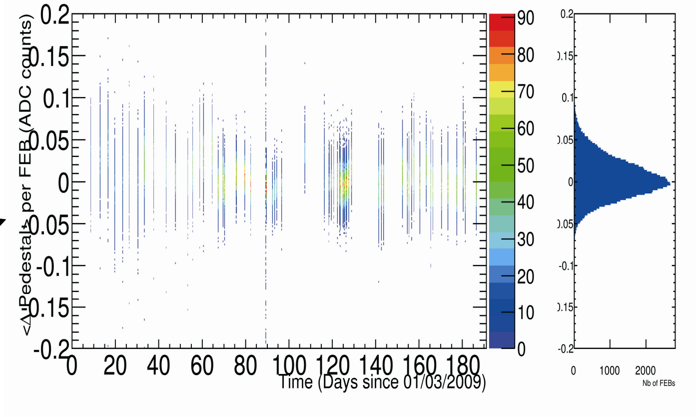
➔W discovery !

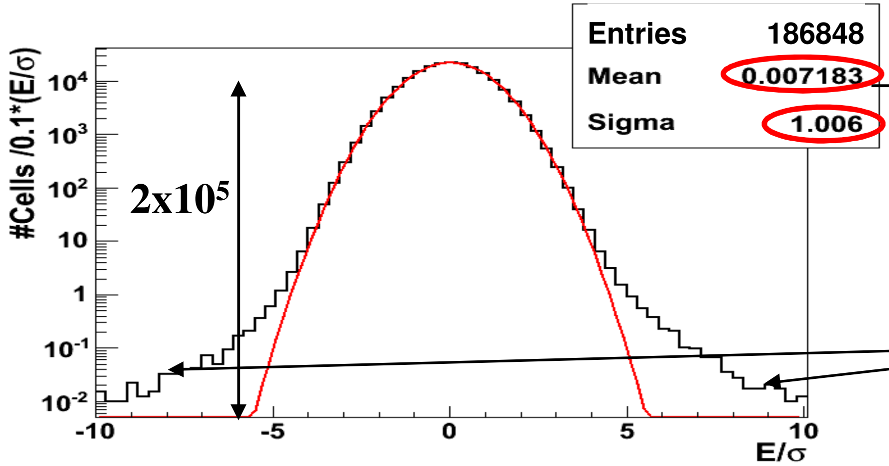
➔ **Very usefull to measure $E_T^{non\text{-}int}$ in pp collisions !**

Calorimeter : E_T^{miss} (3)

❑ **Current calorimeter cell status in ATLAS (Sep. 2009)**

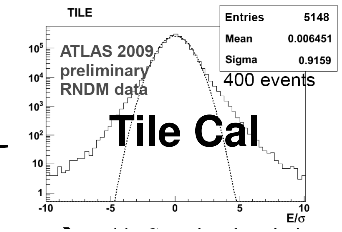
- **Consider 187500 calorimeter cells**
  - ✓Remove problematic cells
    - ❖ Non functionning (1.1%)
    - ❖ Erratic behaviour (0.03 %)
  - ✓Check electronic noise and pedestal stability





0 as expected if no pedestal shift

1 as expected if noise under control



➔ **Calorimeter cells under control**

Calorimeter : E_T^{miss} (4)

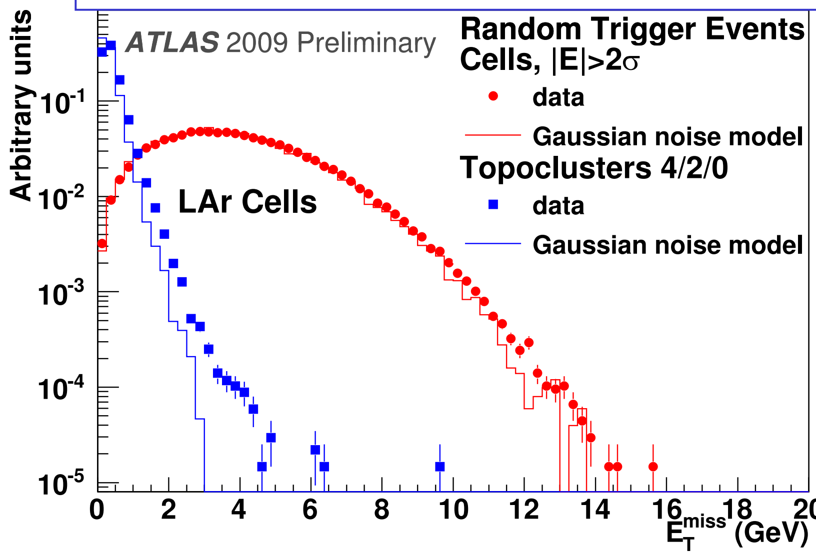
- **Current understanding of E_T^{miss} in ATLAS (Sep. 2009)**

To improve resolution, compute E_T^{miss} after noise reduction (/20 # cells)

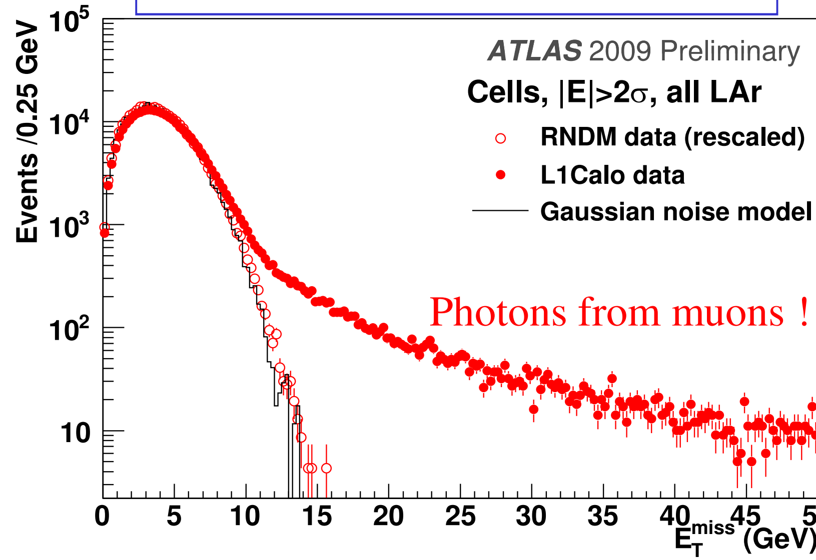
— 1.$|E|>2\ \sigma_{noise}$

— 2.Selecting localized energy deposit (topocluster)

Apply to randomly triggered event



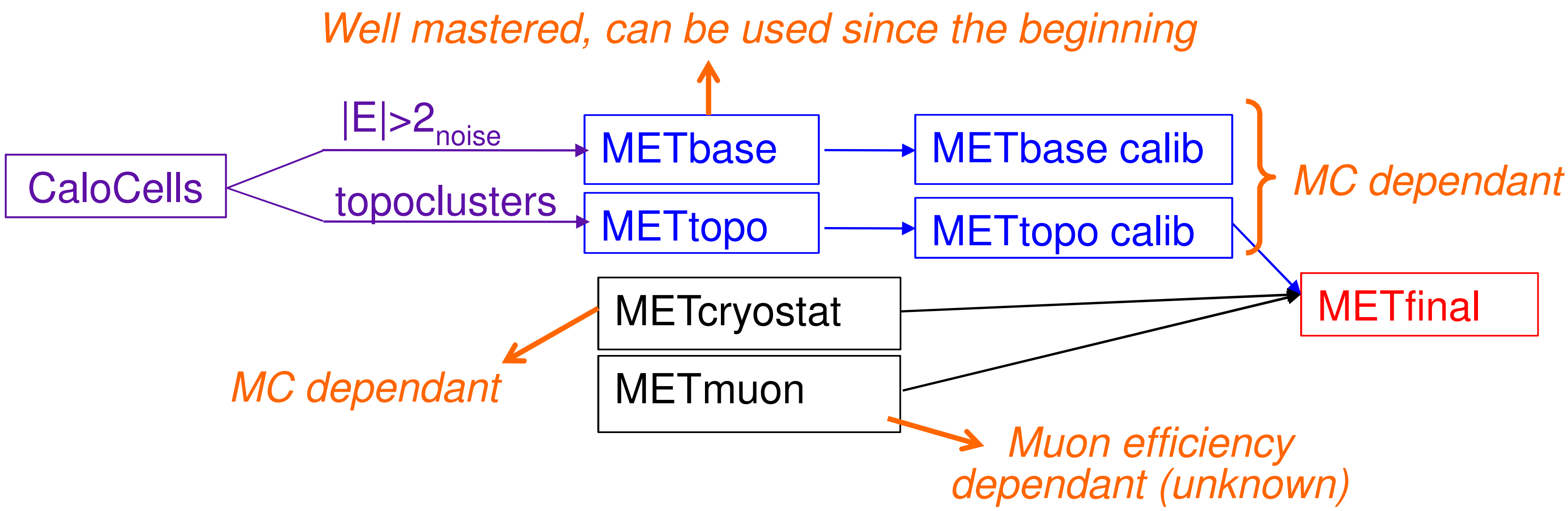
Apply to cosmic muon event



➔ **Very nice agreement with expectations. No tails. Encouraging !**

Calorimeter : E_T^{miss} (5)

- **E_T^{miss} reconstruction will be harder with collision data**
  - Non compensating calorimeter : calibration with cell energy density
  - Include muons to avoid tails
  - Should evaluate dead material (cryostat) contribution per event



➔ **Few years of work in front of us !**

Calorimeter : Jet

❑ **Application : Measure the energy of non interacting particle ($E^{non-int}$)**

longitudinal energy leakage

detector signal inefficiencies (dead channels, HV…)

pile-up noise from (off-time) bunch crossings

calo signal definition (clustering, noise suppression ,…)

electronic noise

dead material losses (front, cracks, transitions…)

detector response characteristics (e/h ≠ 1)

jet reconstruction algorithm efficiency

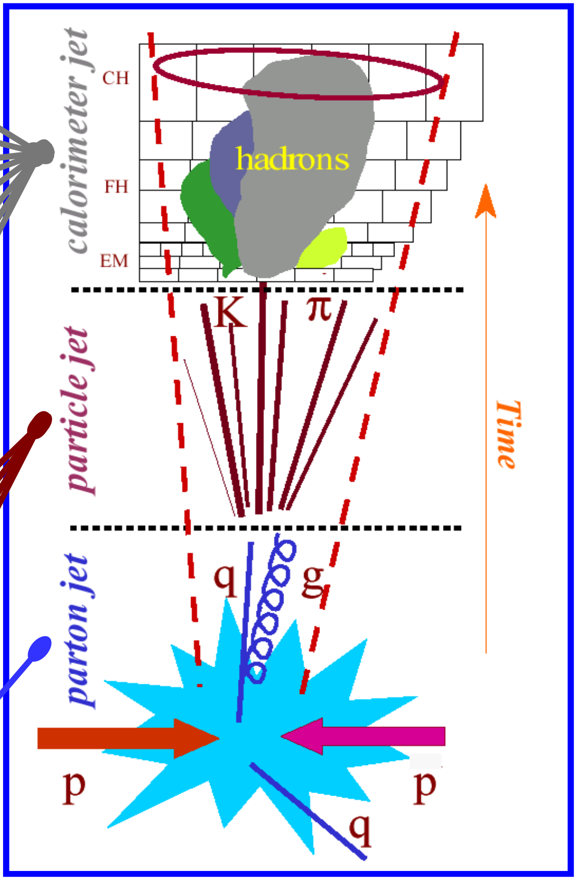
jet reconstruction algorithm efficiency

added tracks from in-time (same trigger) pile-up event

added tracks from underlying event

lost soft tracks due to magnetic field

physics reaction of interest (parton level)



➔ **Not so easy to reconstruct jet … Need lots of LHC data to check**

2009-2010 Physics

❑ Long preparation before LHC collisions

- Very frustating but some good sides :
  - ✓ Data acquisition and software intensively tested ➔ Ready !
  - ✓ Many object (e, γ, E_T^{miss}, jet, …) can be used (with some precautions) since the start
  - ✓ Monte Carlo tuning started (test beams, cosmic muons)

❑ In this game, ATLAS calorimetry very well prepared :

- e/γ standalone possible (but need tracker for ultimate performance)
- Jet/ E_T^{miss} standalone possible (but need muon for ultimate performance)

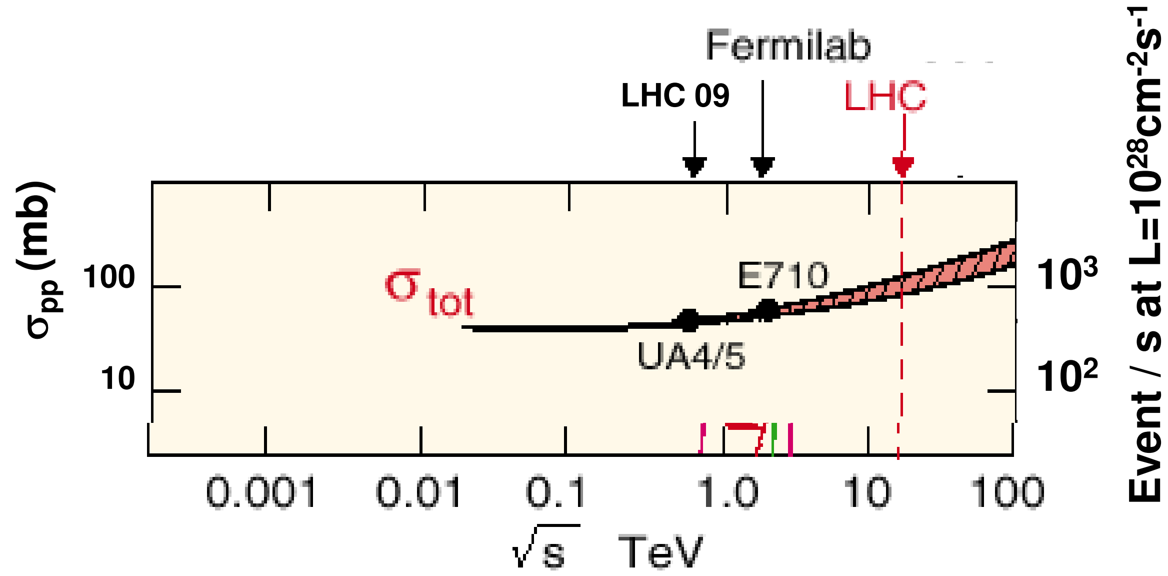
➔ **Let's see what physics we can do with first data**

√s=900 GeV, L=1nb^{-1}*

*3 days at 10^{28} $cm^{-2}s^{-1}$ with 30% efficiency

❑ First to come !

- First week of December 2009
- Object statistics very poor: ~20k jets, very few electrons
  ➔Can not do physics
- Concentrate on minimum bias events

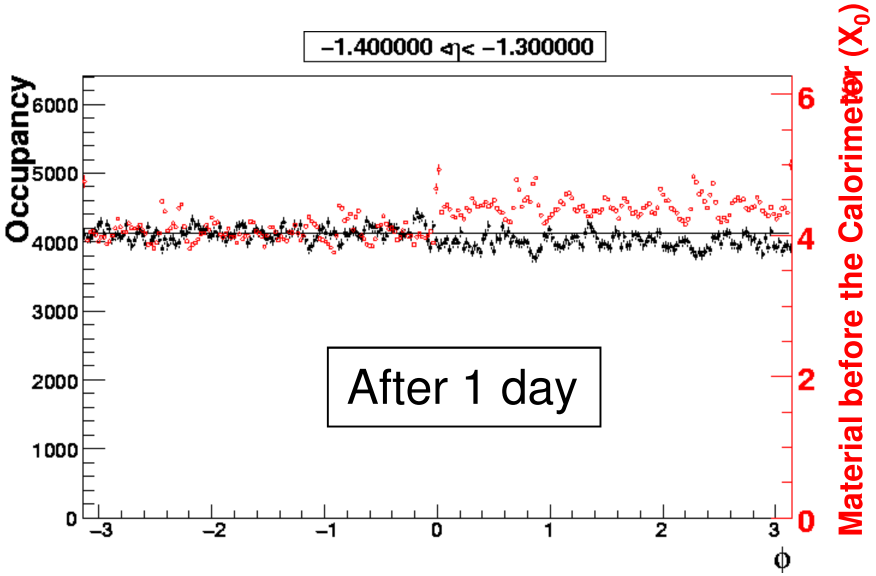


➔ **Trigger limited (100 Hz) ! Will collect ~1 Million of events per day !**

$\sqrt{s}$=900 GeV: Minbias in calorimeter

❑ Electron : First material mapping

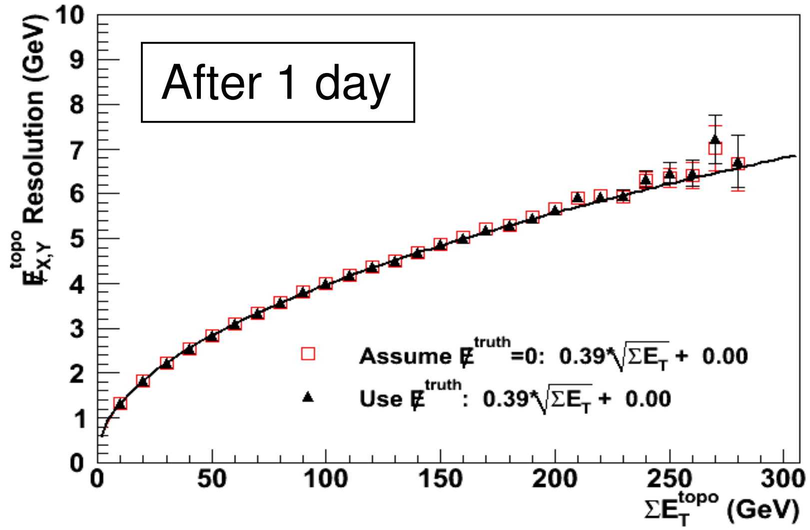
- Photon Energy flow in the EM calo (low pT pions deviated by B field)
- Cell Occupancy vs phi should be flat



- Complementary with γ conversion mapping

❑ E_T^{miss} : First performance / tails

- Total transverse energy = 0-300 GeV (but real E_T^{miss}=0)
- Can compute E_T^{miss} resolution



- Understand tails (fake E_T^{miss})

➔ **Can already learn many things with the calorimeter !**

$\sqrt{s} \geq 7$ TeV , $L \geq 100$ pb^{-1}* : Overview

*100 days at 10^{31} $cm^{-2}s^{-1}$

- **LHC discovery potential for 2010 is affected compare to expectations**
  - Mainly because of $\sqrt{s}$ reduction from 14 → 7-10 TeV
  - Higgs hunting not possible (apart may be from small region around 160 GeV)
- **But channel beyond Tevatron reach still exists**:
  - W'→lν (M ≥1 TeV)
  - Z'→ll (M ~1 TeV)
  - SUSY (especially l+jet+E_T^{miss} channel)
- **In any case, first need to rediscover the Standard Model**
  - W→lν (σ~10000 pb @ 7 TeV)
  - Z→ll (σ~ 1000 pb @ 7 TeV)
  - tt →WbWb→lνbjjb (σ~50 pb @ 7 TeV)

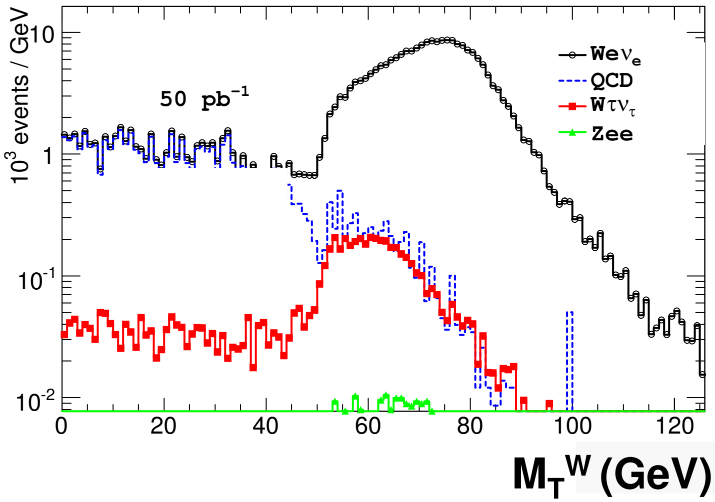
➔ **In the following concentrate on electron channels**

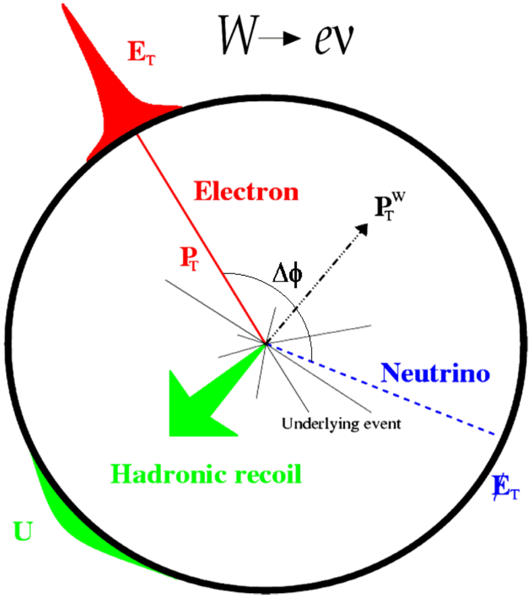
√s≥7 TeV: W→eν

❑ First channel to look at !

- Expect ~3000 W→eν evts / day
- Selection based on calorimeter : ε~25%
- Compute W transverse mass (because of ν)

$$M_T^W = \sqrt{2 p_T^e E_T^{miss} (1 - \cos \Delta\phi_{e\nu})}$$





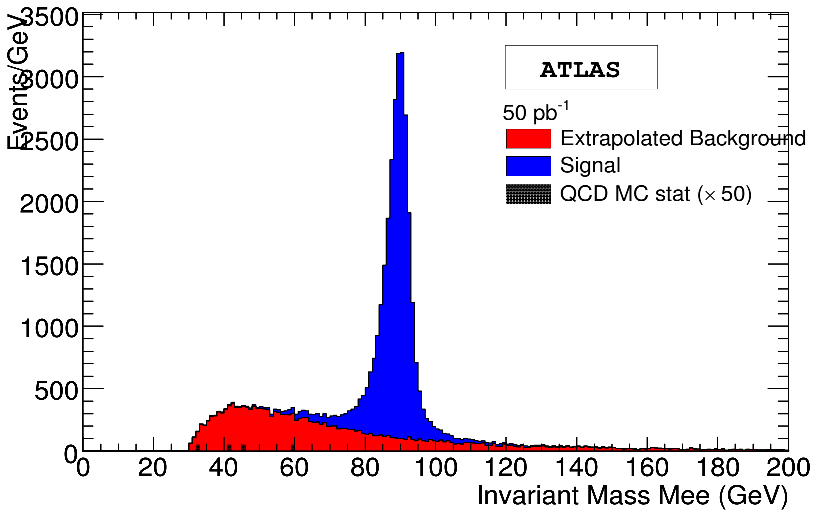
➔ **See W mass peak day 1 and then extract first σ_W**

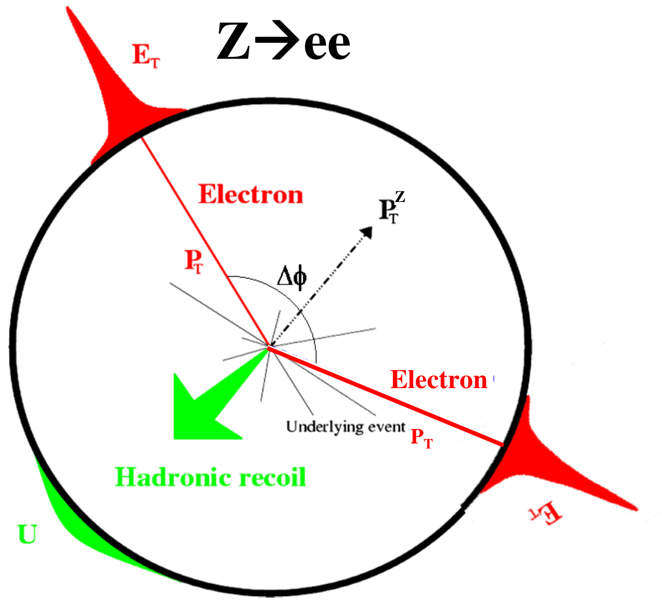
√s≥7 TeV: Z→ee

❑ If day1 is W then day 2 is Z !

- Expect ~300 evts / day
- Selection based on EM calo: ε~25%
- Compute Z mass :

$$M_Z = \sqrt{2(E_{e_1}E_{e_2} - \vec{p}_{e_1} \cdot \vec{p}_{e_2})}$$

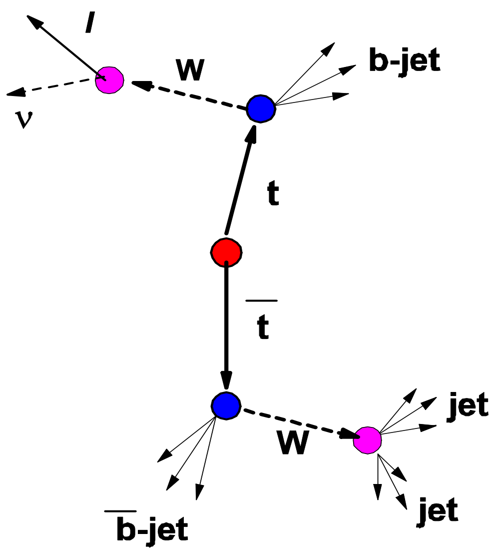


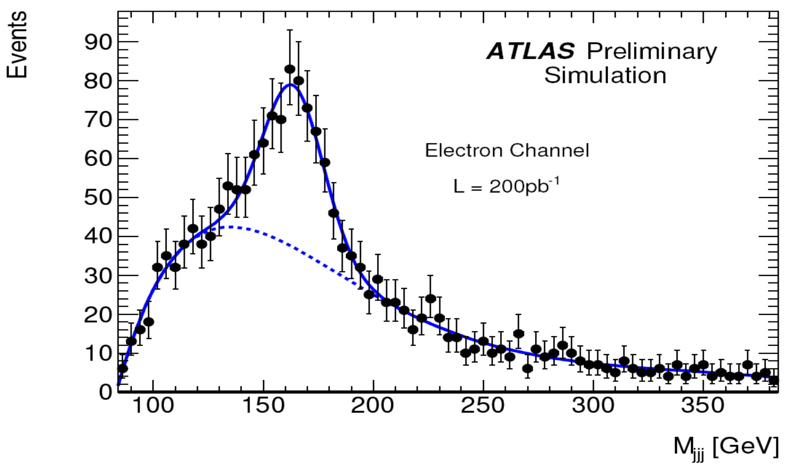


➔ **See Z mass peak after few days and then extract first σ_Z**

$\sqrt{s} \geq 7$ TeV: tt→evbjjb

- **And may be at the end of 2010**
  - Expect ~10 evts / day
  - Signature more complicated (ε~25%)
    - Trigger on electron
    - Etmiss + 4 Jets !
  - Compute invariant mass of 3 jets





→ Check jet energy scale with m_t

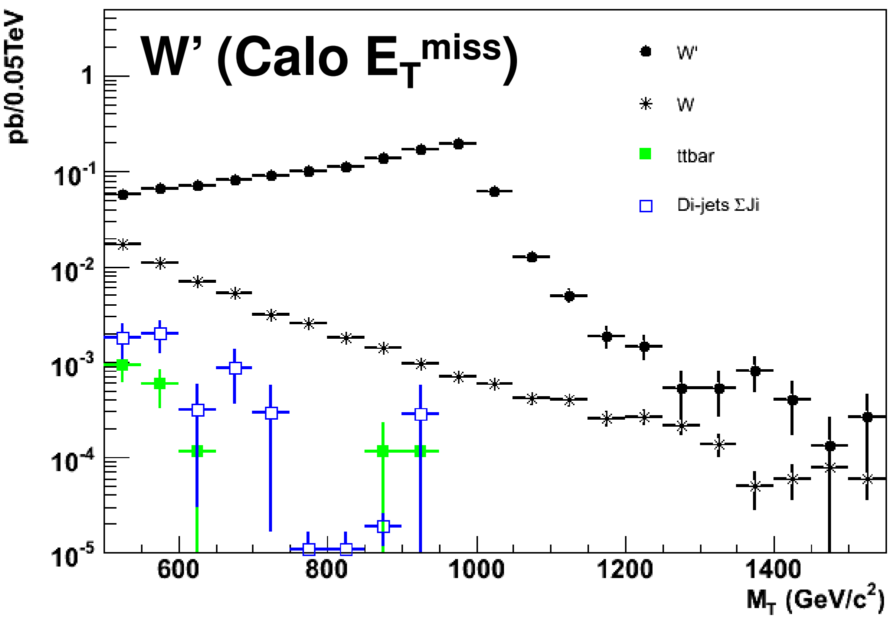
→ Can extract first measurement of σ(tt)

→ **Main background to SUSY search**

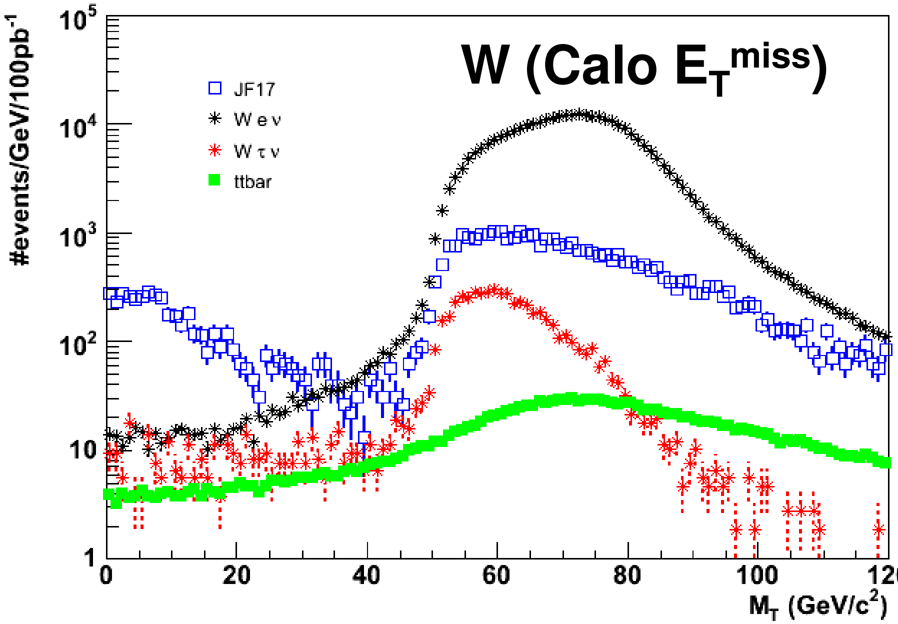
√s≥7 TeV: New Physics ? (1)

❑ W'→eν

- Main difficulty : control of Etmiss tails ➔ Choose a pure calorimetric Etmiss
- After selection expect 60 candidates for M=1 TeV, S/B~60



Signal and S/B not affected



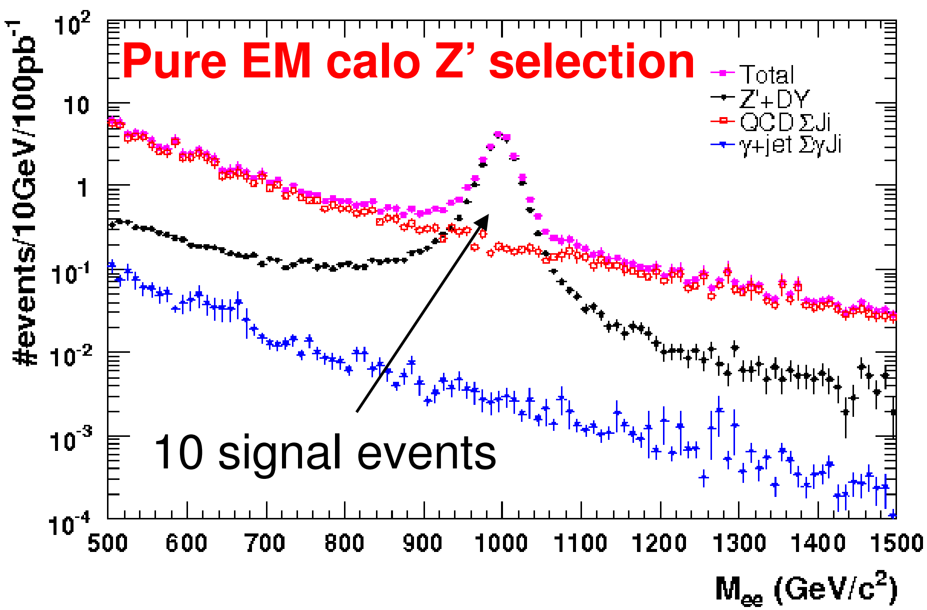
W→eν still visible (nice control sample)

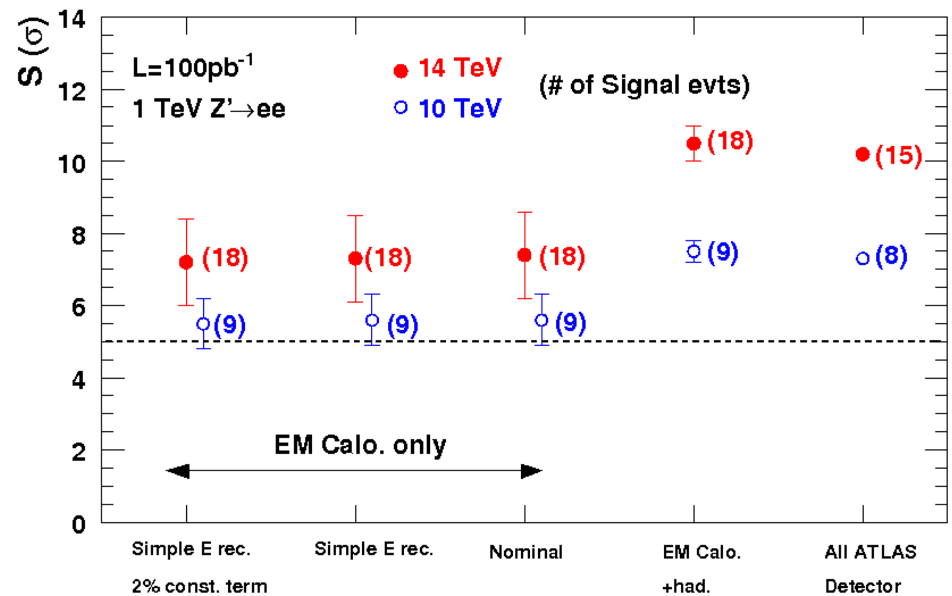
➔ **Can make a discovery in the range $M_{W'}$ =1-2 TeV with 100 pb^{-1}**

$\sqrt{s} \geq 7$ TeV: New Physics ? (2)

❑ Z'→ee

- Main difficulty: Signal limited search ➔ try a pure EM calo approach
- After selection expect 7 candidates for M=1 TeV, S/B~9





➔ Can possibly make a discovery in the range $M_{Z'}$ ~1 TeV with 100 pb^{-1}

Conclusions

- **ATLAS start to take LHC collision data beginning of December 2009**
  - Detector is ready (and not only calorimeter !!)
  - Several object already well advanced (electron, photon, E_T^{miss})
  - … but (of course) all this need confirmation/improvment with data !

- **Physics program for 2010 ($\sqrt{s} \geq 7$ TeV, $L \geq 100$ pb^{-1})**
  - Suffers from $\sqrt{s}$ reduction (very poor higgs hunting) and slightly compensated by detector readiness
  - Still some channels beyond Tevatron reach are open :
    - ✓ W' with a mass in the 1-2 TeV range
    - ✓ SUSY in 1 lepton + jet + E_T^{miss}

Usefull links

- **Some bibliography can be found here :**

http://pralavop.web.cern.ch/pralavop/phd.html

- **Web page of Marseille Master :**

http://www.cpt.univ-mrs.fr/master/

SPARE

$\sqrt{s} \geq 7$ TeV: $\sigma(W \rightarrow e\nu)$

$\sigma = (N_{signal} - N_{background}) / (A \cdot \varepsilon_{tot} \cdot \text{Lumi})$

	$\delta N/N$	$\delta B/N$	$\delta\varepsilon/\varepsilon$	$\delta A/A$
Systematics with 50 pb^{-1}	0.2%	4%	2%	2.3%

→ Acceptance uncertainty :

- only theoretical (ISR, PDFs, …)
- impact of missing E_T scale and resolution uncertainties has to be quantified

→ Overall uncertainty for 50 pb^{-1}: **± 0.2% (stat) ± 5% (syst) ± $\delta L/L$**

- Systematic errors dominate largely with 50 pb^{-1}
  - main from background uncertainty (except luminosity) → estimated directly on data
  - Luminosity uncertainty vanishes in σ ratios, e.g. σ_W/σ_Z → stringent test of QCD
- Comparable precision to muon channel (for which background less important, $Z \rightarrow \mu\mu$ dominates)
- Extrapolation to 1 fb^{-1} → limited to ~2.5% by acceptance uncertainties (PDF, ISR, …)

$\sqrt{s} \geq 7$ TeV: $\sigma(Z \rightarrow ee)$

$\sigma = (N_{signal} - N_{background}) / (A \cdot \varepsilon_{tot} \cdot Lumi)$

Systematics with 50 pb-1	δN/N	δB/N	δε/ε	δA/A
	0.8%	1.8%	3%	1.1%

Acceptance uncertainty (mainly limited knowledge of underlying physics: ISR, PDFs, …)
→ determined with MC

→ Overall uncertainty for 50 pb^{-1}: **± 0.8% (stat) ± 3.5% (syst) ± δL/L**

- Systematic errors dominate, even with 50 pb^{-1}
- Main systematics from electron selection efficiency (except luminosity)

  → estimated directly on data
- Comparable to muon channel
- Extrapolation to 1 fb^{-1} → limited to ~1.5% by acceptance uncertainties (PDF, ISR, …)
  - use differential cross sections (vs η and p_T)

$\sqrt{s}\geq 7$ TeV: Some number for Z',W'

Expected cross section at LHC (pb)

$\sqrt{s}$ (TeV)	7	10	14
W'→eν (1TeV)	0.7	1.6	3.2
W'→eν (2 TeV)	0.01	0.05	0.15
Z'→ee (1 TeV)	0.1	0.2	0.4

Selection efficiency, S/B

- Trigger + kinematics + mass cut
  Dominated by mass cut
- ε (W'→eν) = 0.58, S/B=60
- ε (Z'→ee) = 0.48 , S/B=9

Cut	Z'→ee	W'→eν
Trigger+kinematics	0.84	0.96
+electron eff.	0.77	0.89
+mass cut	0.48	0.58
Trigger+kinematics +mass cut	0.51	0.61

Running with 7-10 TeV, L=100 pb^{-1}

- N [W'→ee (1 TeV)] ~ 100 ➔ Rec. ~ 60 ➔ Sig ~ 60
- N [W'→ee (2 TeV)] ~ 3 ➔ Rec. ~ 2 ➔ Sig ~ 3.6
- N [Z'→ee (1 TeV)] ~ 15 ➔ Rec. ~ 7 ➔ Sig ~ 4.6