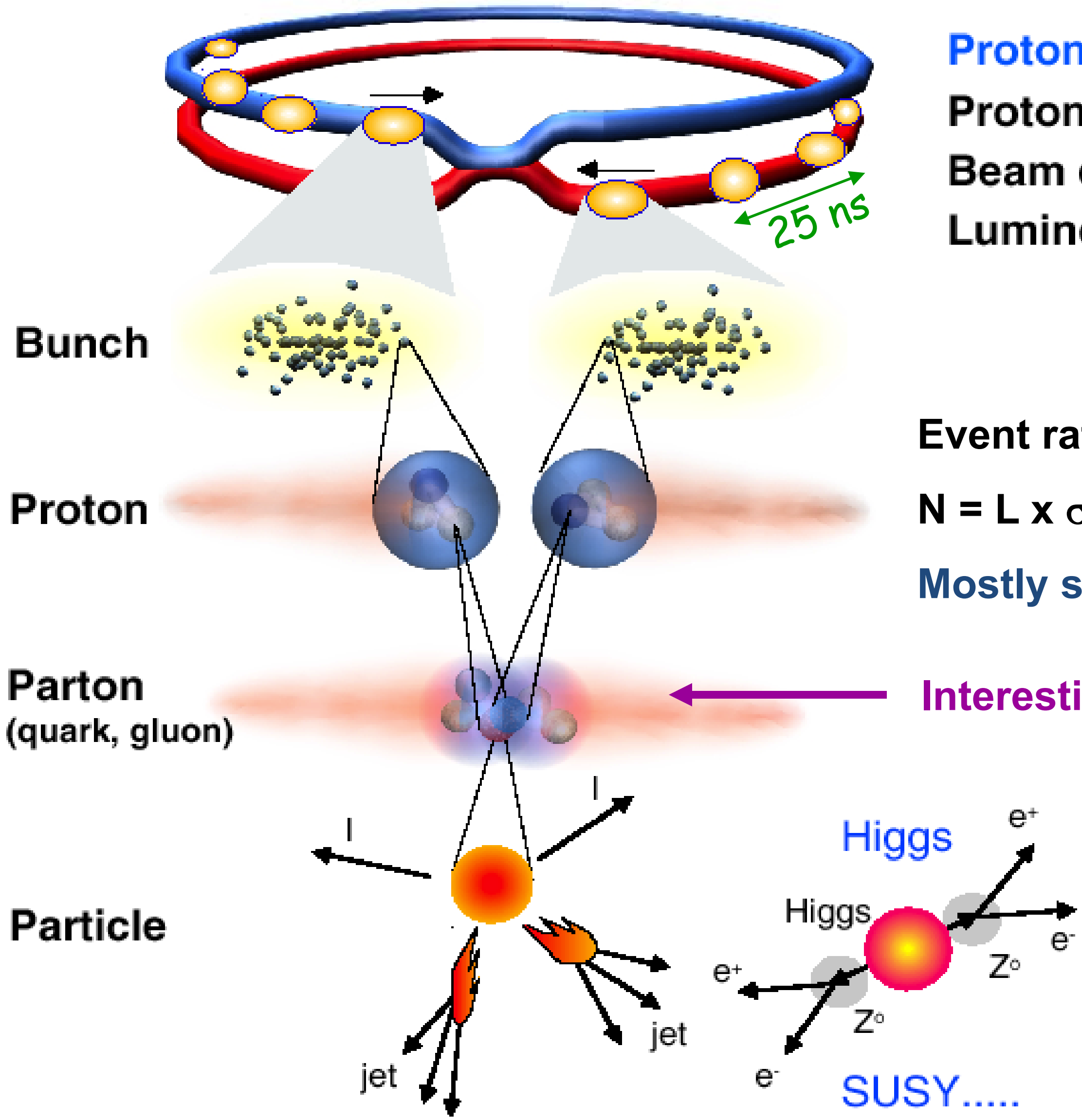
LHC Entering Operation:
An Overview of the LHC Project and its Status
(part II)

EISA – Corfu Summer Institute, Corfu, Greece
School and Workshop on Standard Model and Beyond, and Standard Cosmology
31st August 2009, Peter Jenni (CERN/ATLAS)

The LHC Experiments Entering Operation

Lecture II: Data Flow, Commissioning with Cosmic Rays, and a Few Examples of Physics Perspectives (much more to come in the dedicated physics talks by the CMS, ATLAS and LHCb speakers)

Collisions at LHC



Proton-Proton

Protons/bunch	**10^{11}**
Beam energy	**7 TeV (7×10^{12} eV)**
Luminosity	**10^{34} cm^{-2} s^{-1}**

Event rate:

N = L x σ (pp) $\approx$ 10^9 interactions/s

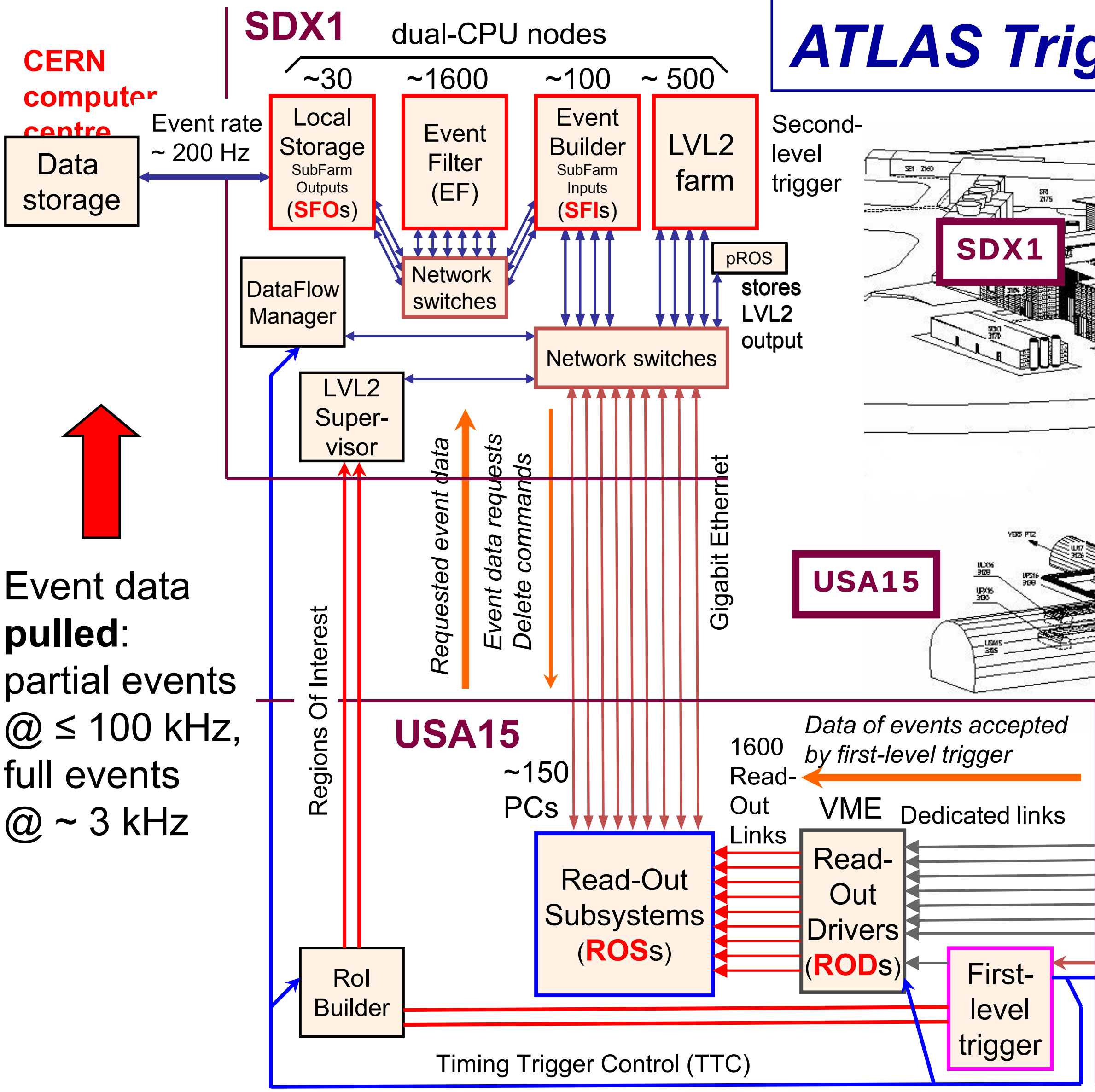
Mostly soft (low p_T) events

Interesting hard (high-p_T) events are rare

Selection of 1 in 10,000,000,000,000

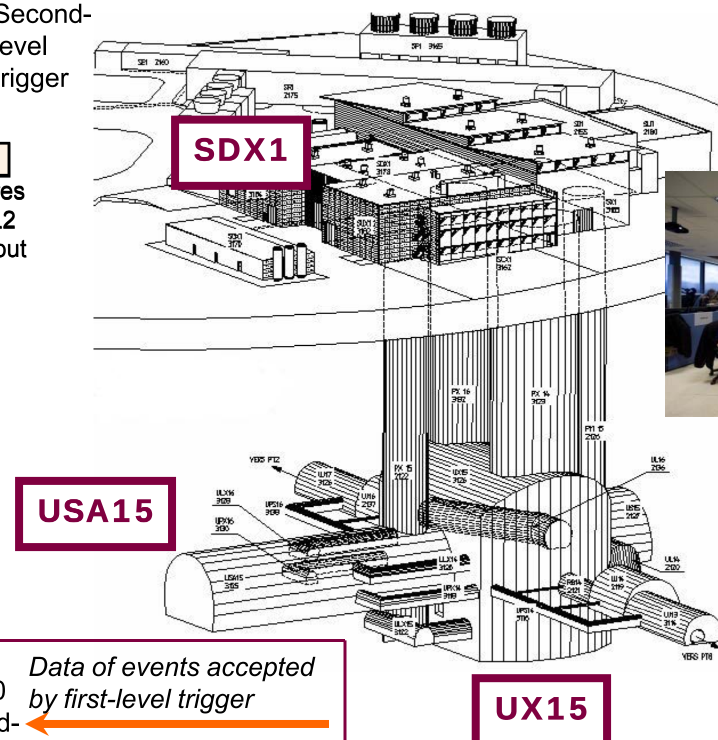
→ very powerful detectors needed

As an example: ATLAS Trigger / DAQ Data Flow



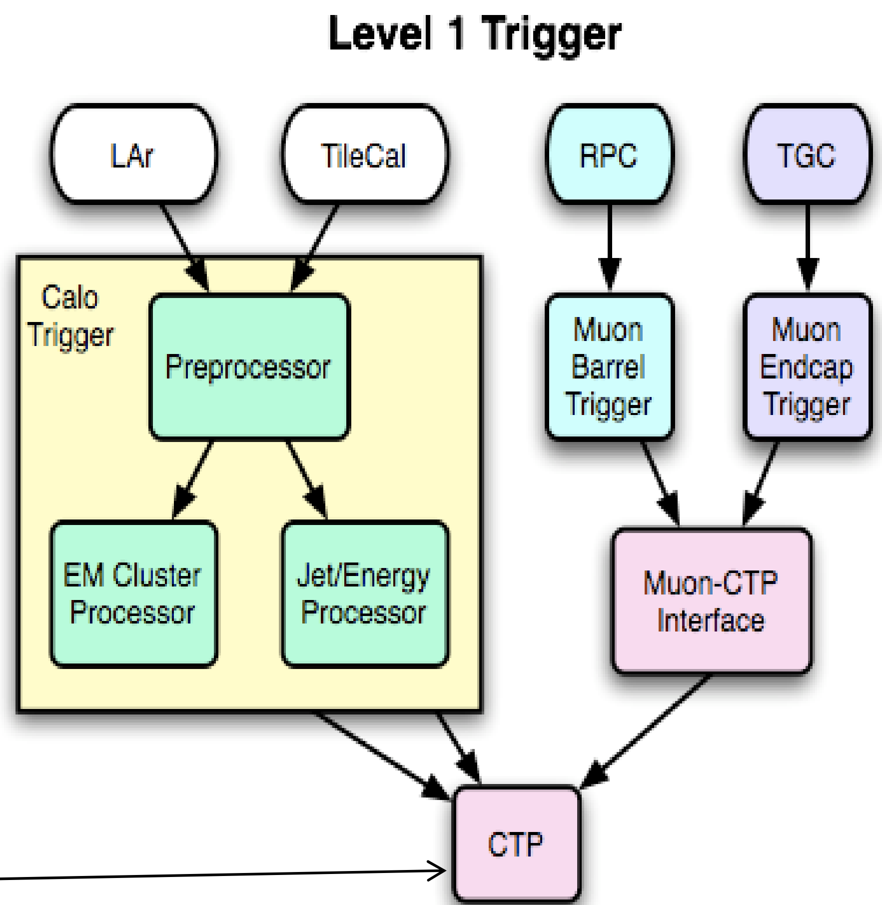
Event data **pulled**:
partial events @ ≤ 100 kHz,
full events @ ~ 3 kHz

Event data pushed @ ≤ 100 kHz,
1600 fragments of ~ 1 kByte each



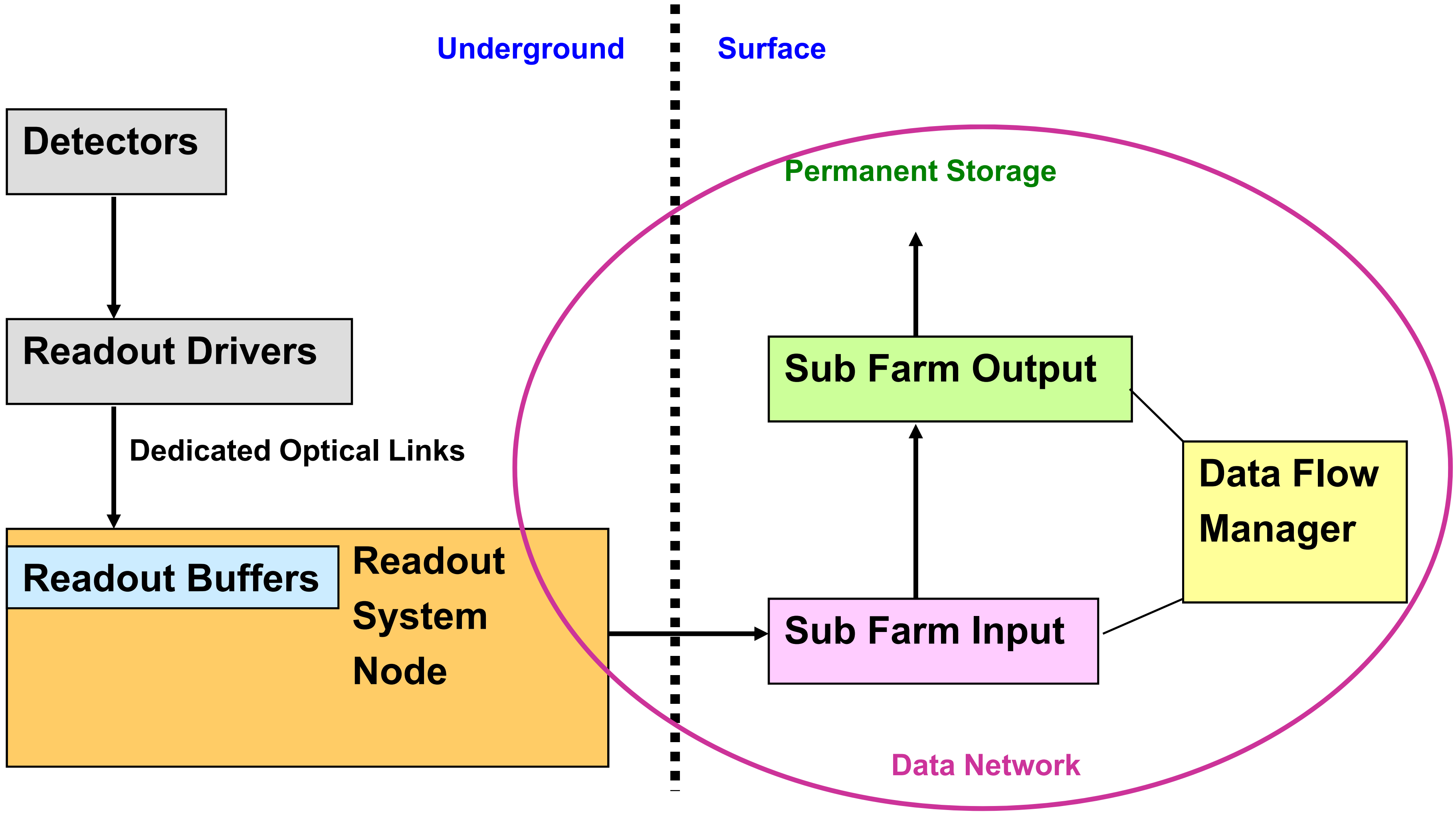
ATLAS Level-1 Trigger System

- **Three major systems**
  - **Calorimeter Trigger**
  - **Muon Trigger**
  - **Central Trigger Processor (CTP)**
- **Other triggers and signals also integrated by CTP**
  - **Minimum bias**
  - **Luminosity triggers**
  - **Beam Pick-up**
- **CTP distributes all timing information**



Beam pickups
Minimum-bias (MBTS)
LUCID, BCM, etc

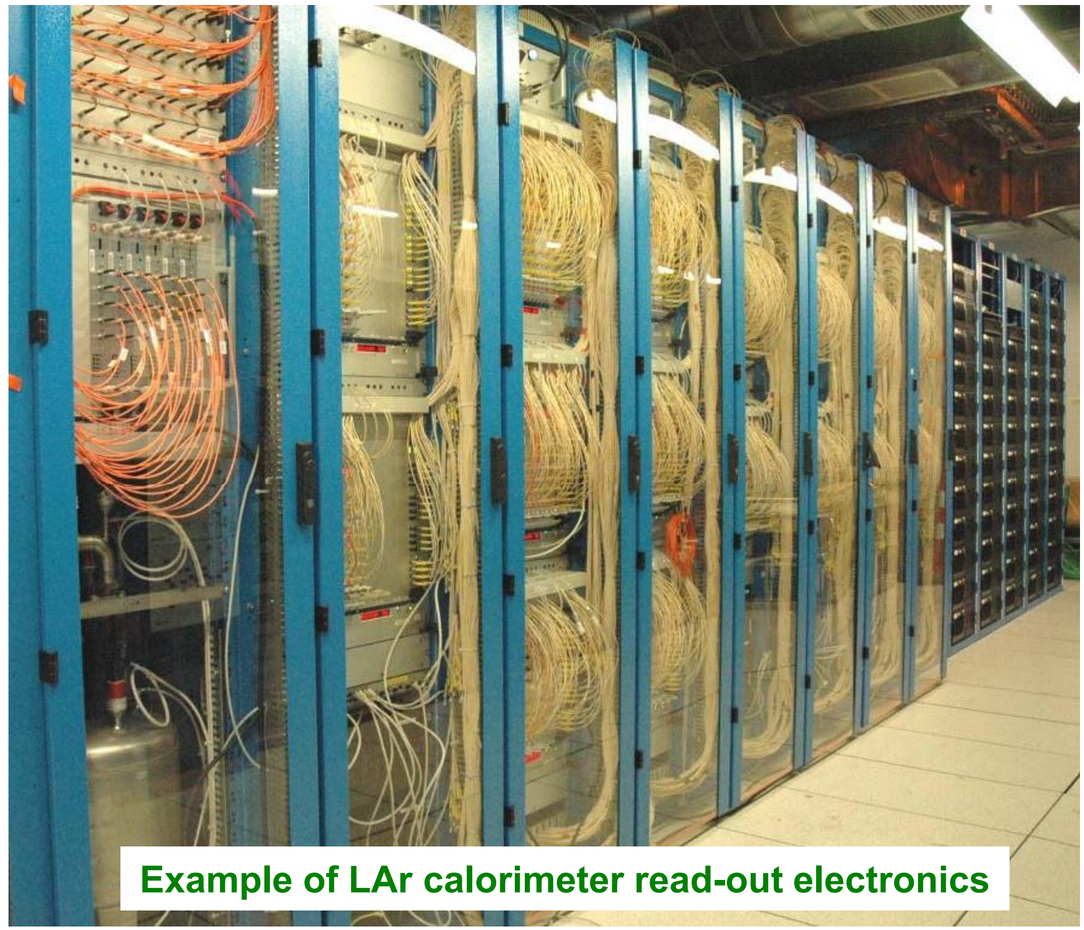
Dataflow view of Trigger and DAQ infrastructure:



The read-out electronics, trigger, DAQ and detector control systems have been brought into operation gradually over the past years, along with the detector commissioning with cosmics

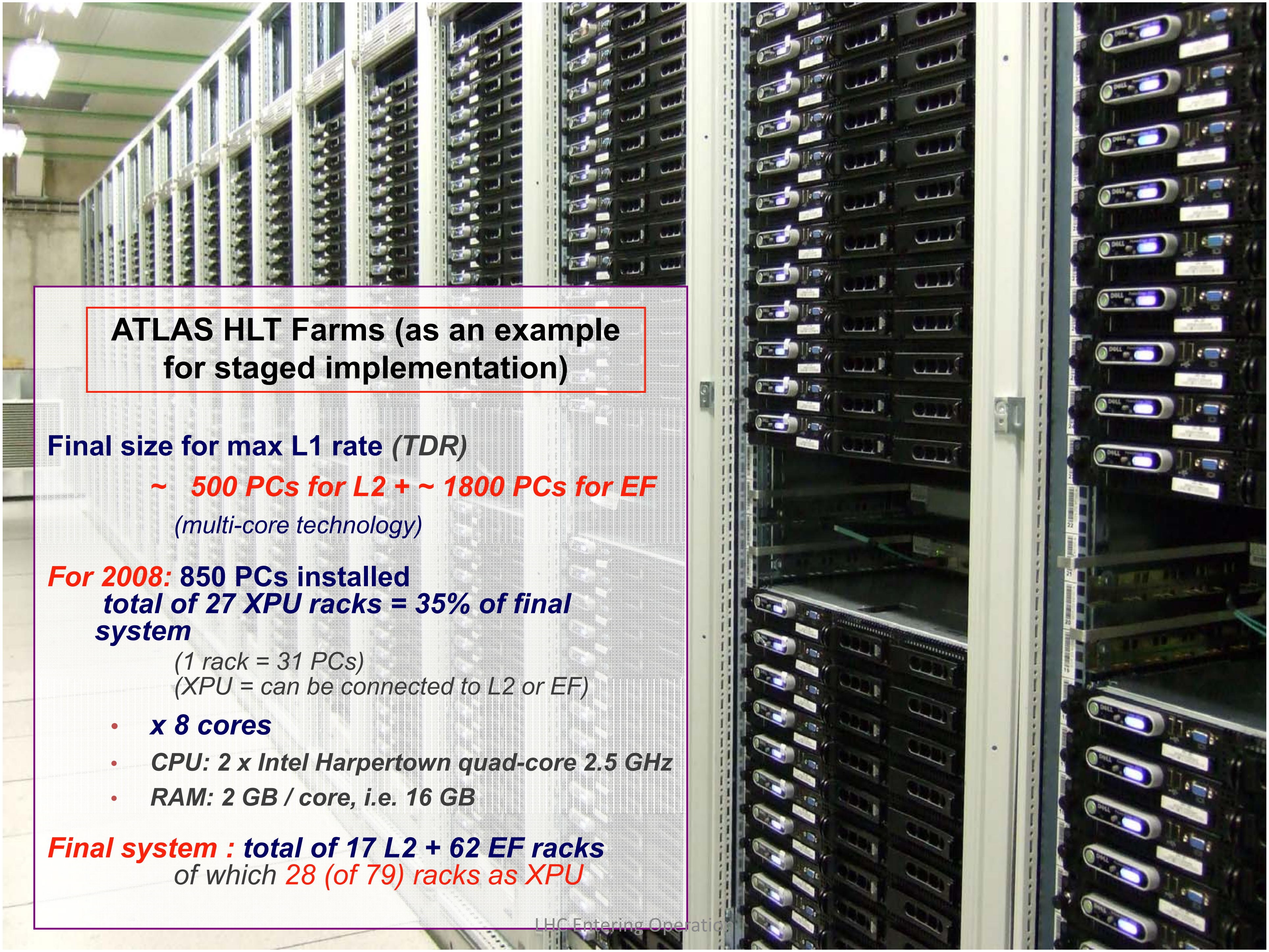
(Examples from ATLAS)

Example of Level-1 Trigger electronics



Example of LAr calorimeter read-out electronics

In total about 300 racks with electronics in the underground counting rooms



ATLAS HLT Farms (as an example for staged implementation)

Final size for max L1 rate ***(TDR)***

- ~ ***500 PCs for L2 + ~ 1800 PCs for EF***

  (multi-core technology)

For 2008: **850 PCs installed**

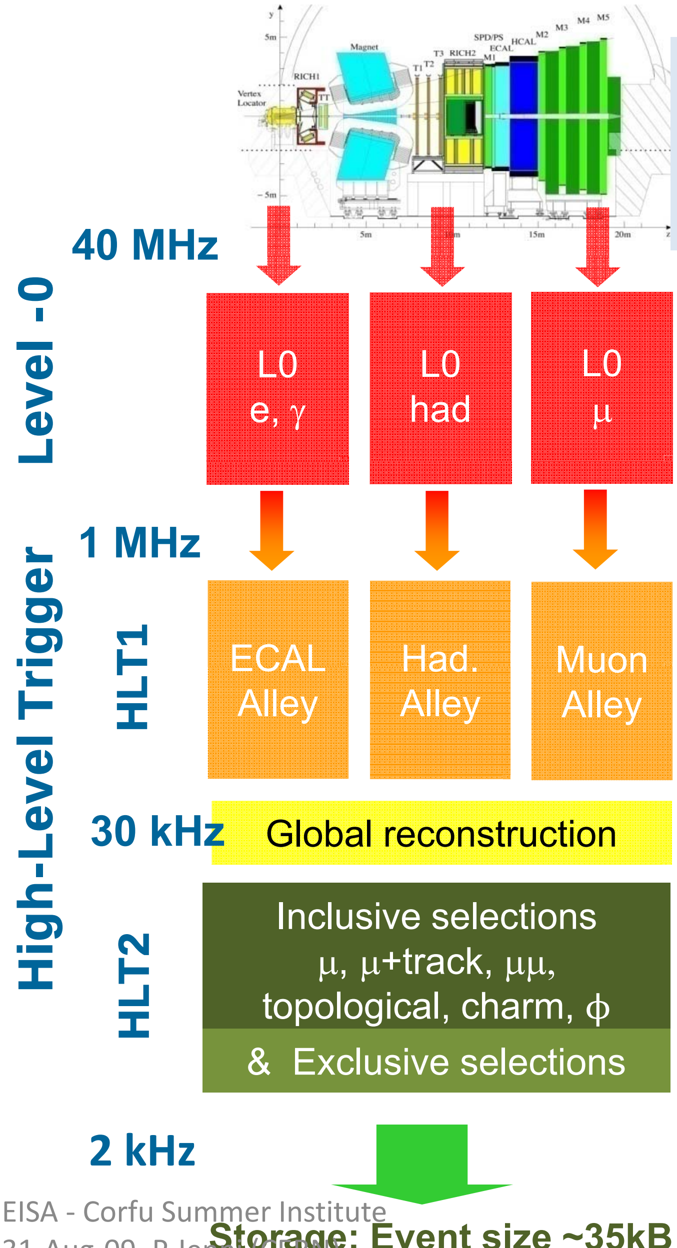
total of 27 XPU racks = 35% of final system

(1 rack = 31 PCs)
(XPU = can be connected to L2 or EF)

- ***x 8 cores***
- ***CPU: 2 x Intel Harpertown quad-core 2.5 GHz***
- ***RAM: 2 GB / core, i.e. 16 GB***

Final system : total of 17 L2 + 62 EF racks
of which 28 (of 79) racks as XPU

Another example: LHCb Trigger



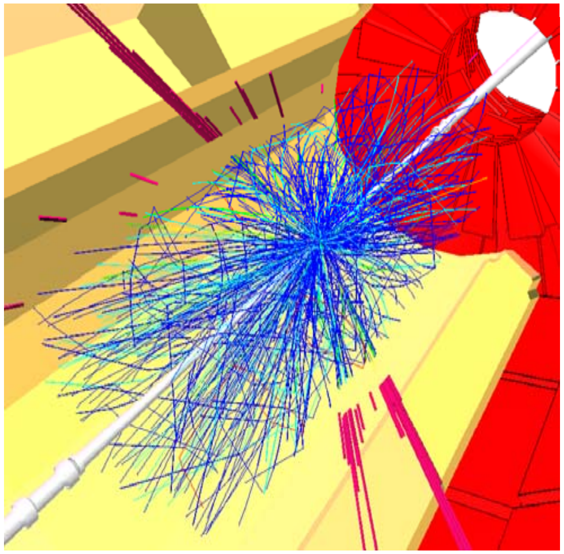
Trigger is crucial as σ_{bb} is less than 1% of total inelastic cross section and B decays of interest typically have BR < 10^{-5}

- **Hardware level (L0)**
  Search for high-p_T μ, e, γ and hadron candidates

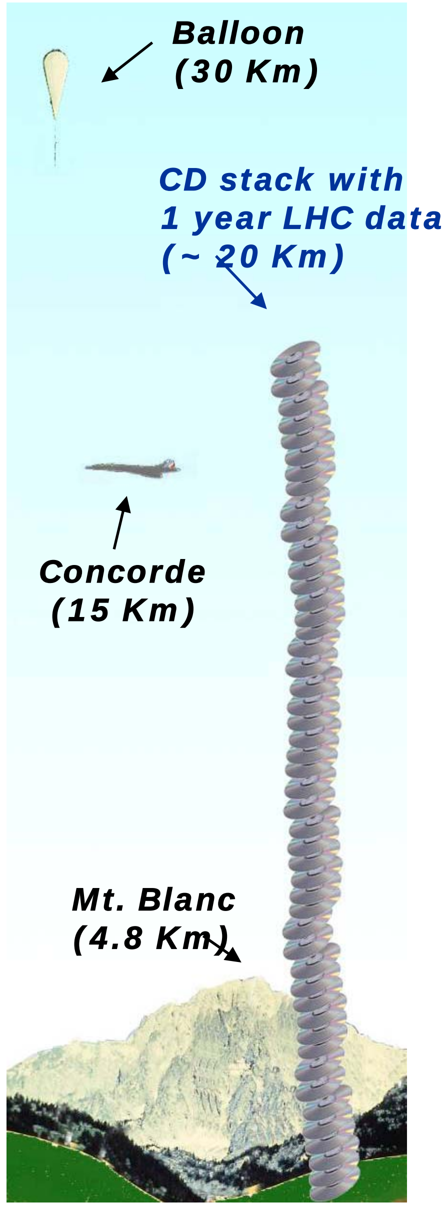
- **Software level (High Level Trigger, HLT)**
  *Farm with **O**(2000) multi-core processors*
  HLT1: Confirm L0 candidate with more complete info, add impact parameter and lifetime cuts
  HLT2: B reconstruction + selections

	ε(L0)	ε(HLT1)	ε(HLT2)
Electromagnetic	70 %		
Hadronic	50 %	> ~80 %	> ~90 %
Muon	90 %		

Worldwide LHC Computing Grid (wLCG)



WLCG is a worldwide collaborative effort on an unprecedented scale in terms of storage and CPU requirements, as well as the software project's size



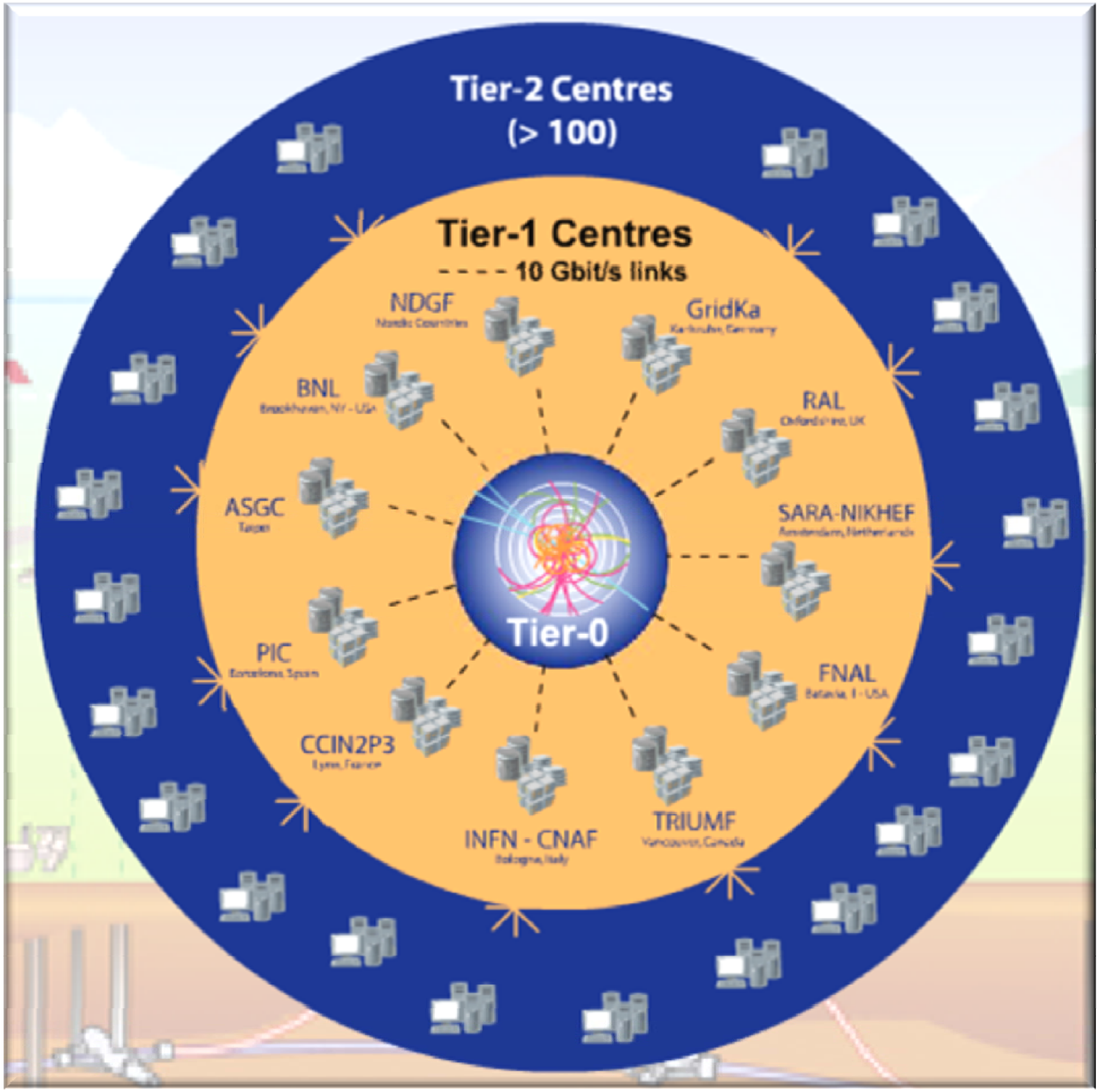
GRID computing developed to solve problem of data storage and analysis

LHC data volume per year:
10-15 Petabytes

One CD has ~ 600 Megabytes
1 Petabyte = 10^9 MB = 10^{15} Byte

(Note: the WWW is from CERN...)

The Worldwide LHC Computing Grid (wLCG)

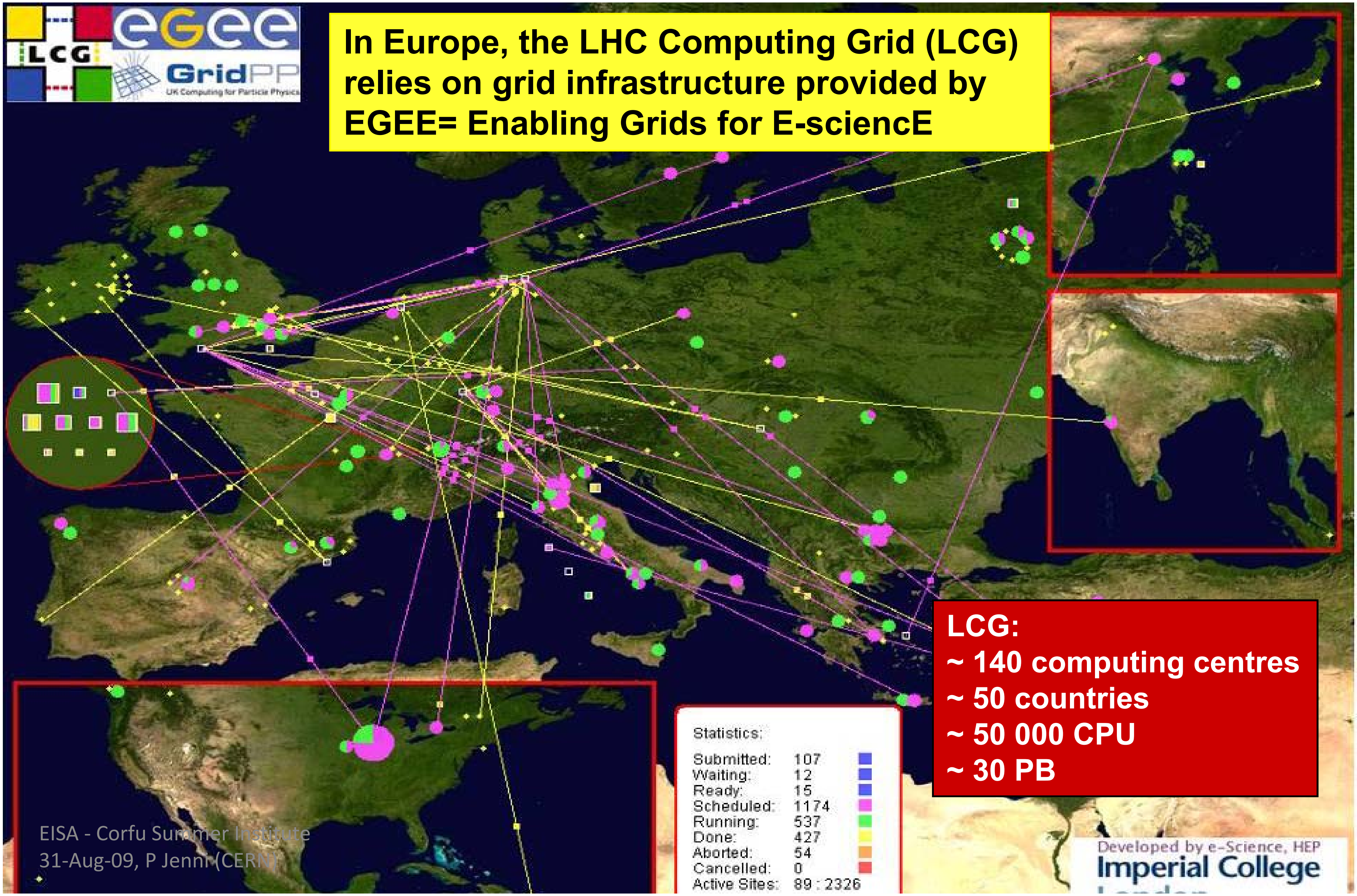


Tier-0 (CERN):
- Data recording
- Initial data reconstruction
- Data distribution

Tier-1 (11 centres):
- Permanent storage
- Re-processing
- Analysis

Tier-2 (federations of ~130 centres):
- Simulation
- End-user analysis

The Grid provides seamless access to computing power and data storage capacity distributed over the globe



In Europe, the LHC Computing Grid (LCG) relies on grid infrastructure provided by EGEE= Enabling Grids for E-sciencE

LCG:
- ~ 140 computing centres
- ~ 50 countries
- ~ 50 000 CPU
- ~ 30 PB

ATLAS Full Dress Rehearsal (FDR) 2008

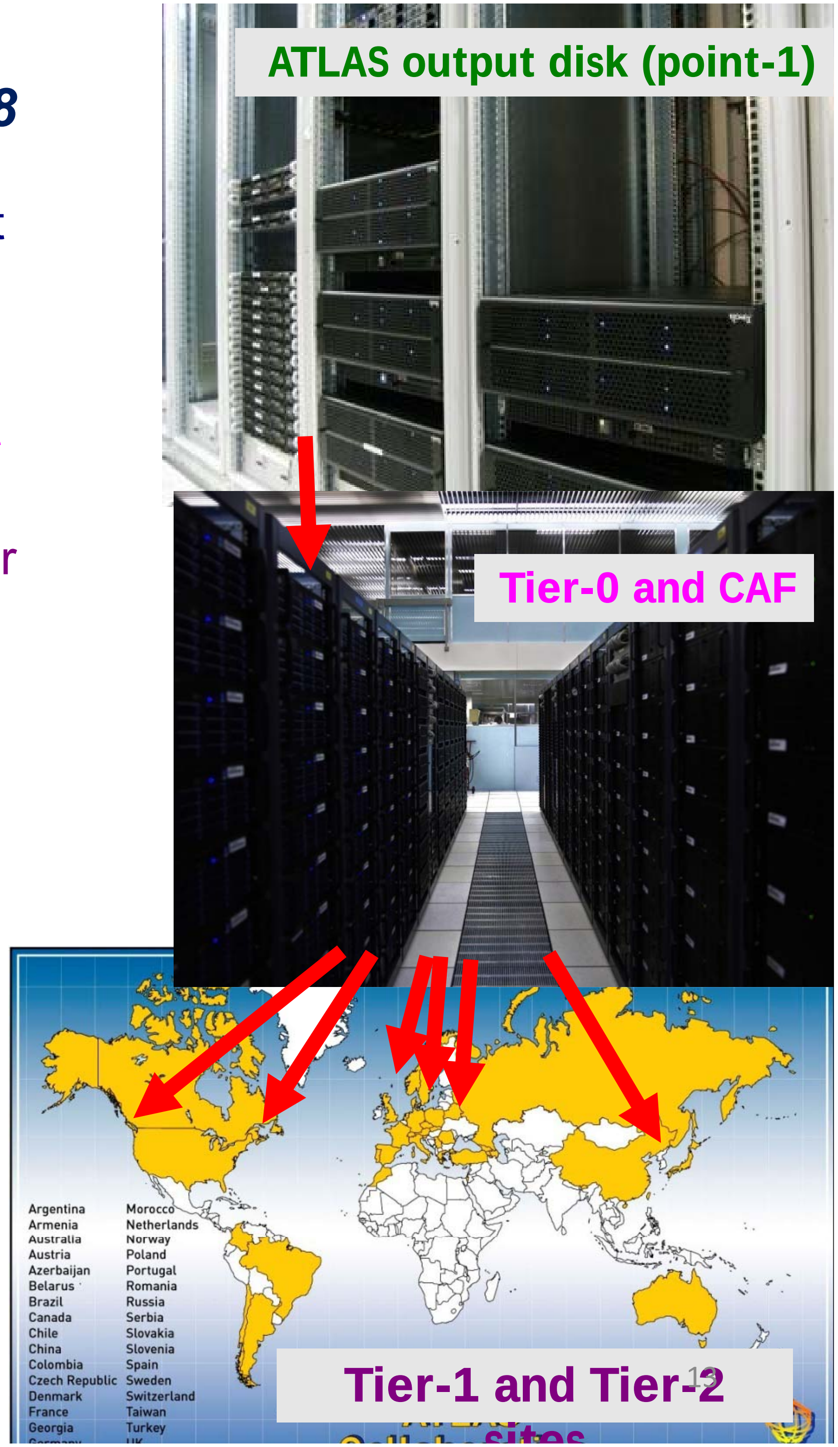
Played data through the computing system just as for real data from the LHC

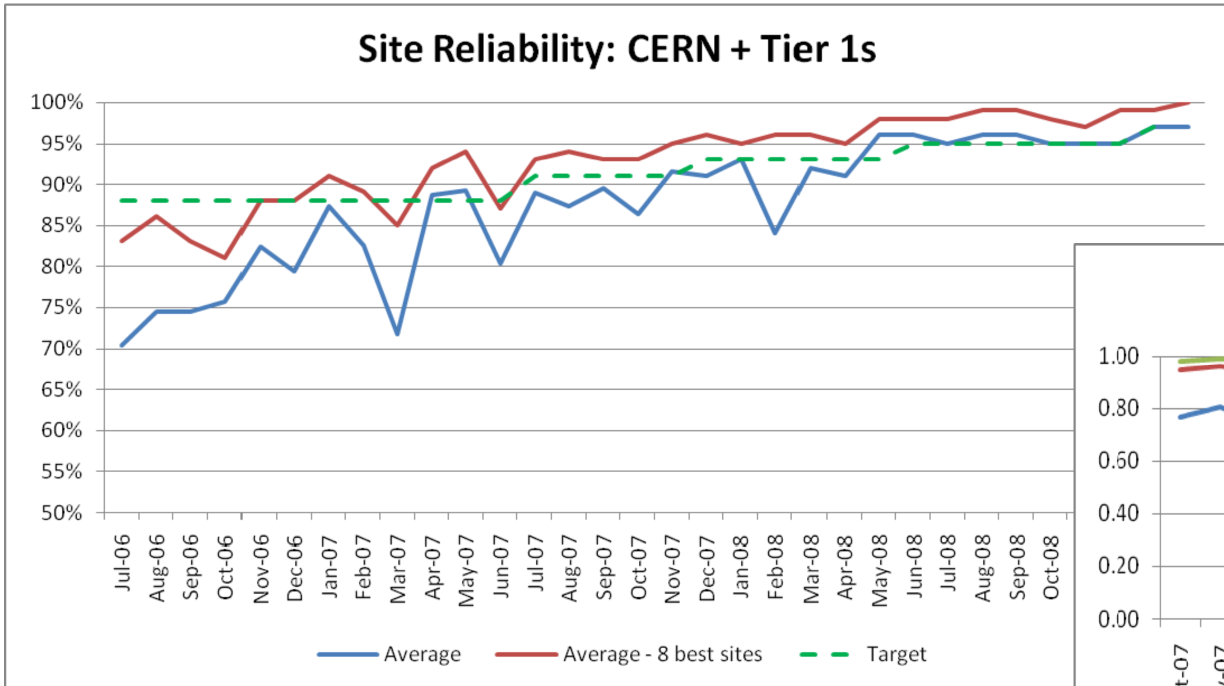
- started at point 1, as though real data
- processed data at CERN Tier-0, *various calibration & data quality steps*
- shipped out to the Tier-1s and Tier-2s for physics analysis

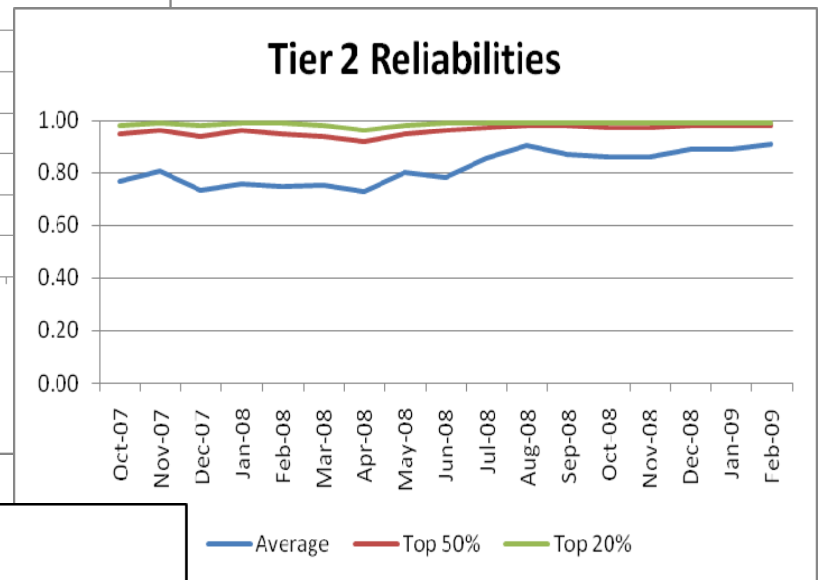
Complementary to “milestone runs” which test the real detector, but only with cosmic rays

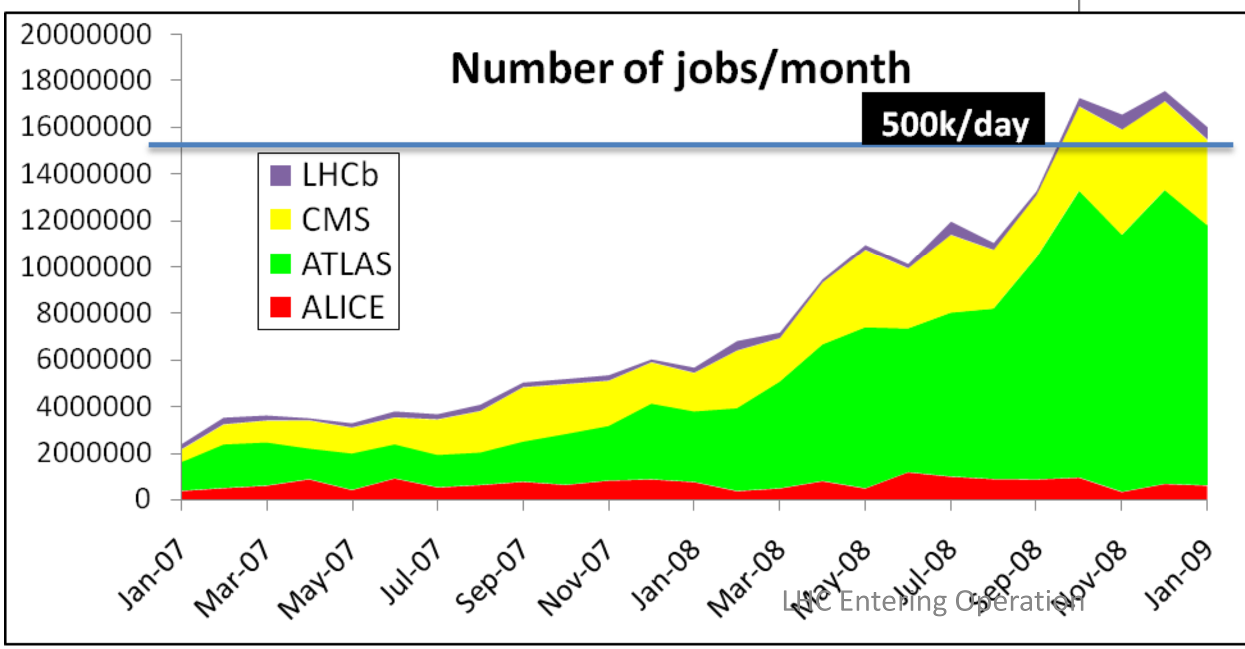
Two “FDR runs”
(February and June-July 2008)

Were a vital preparation for processing and analysing the first LHC data





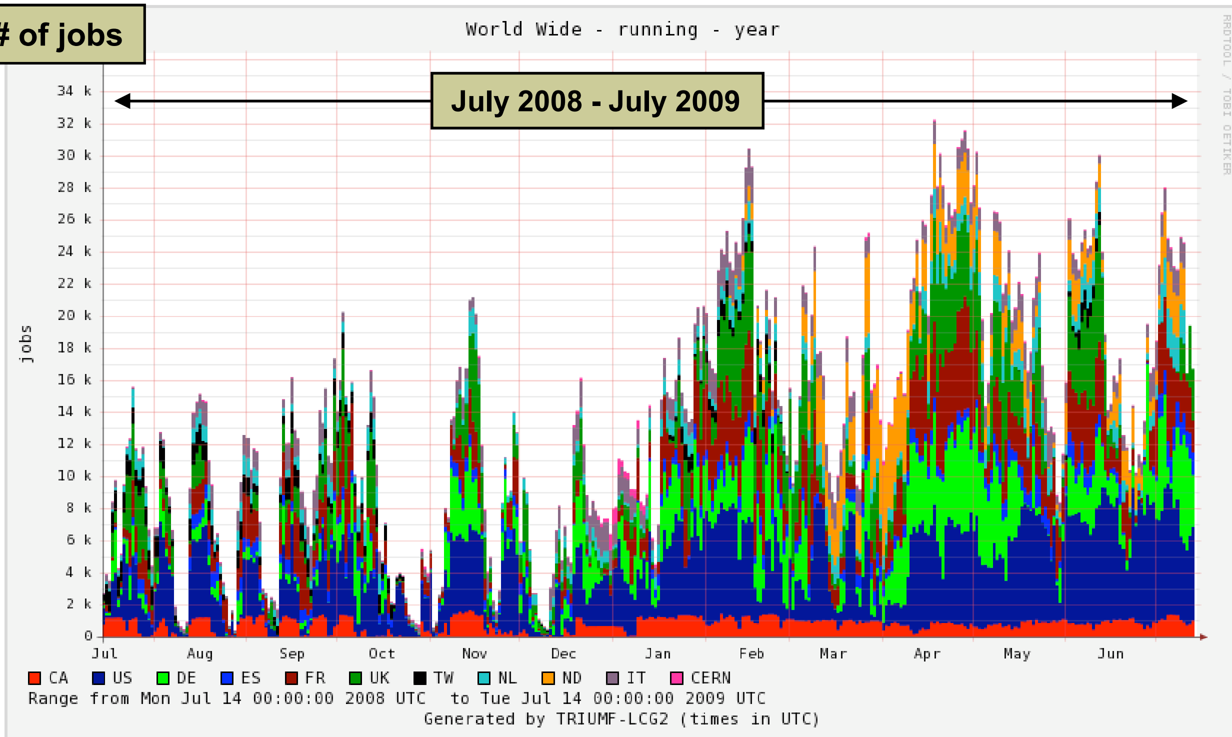




wLCG performances

ATLAS

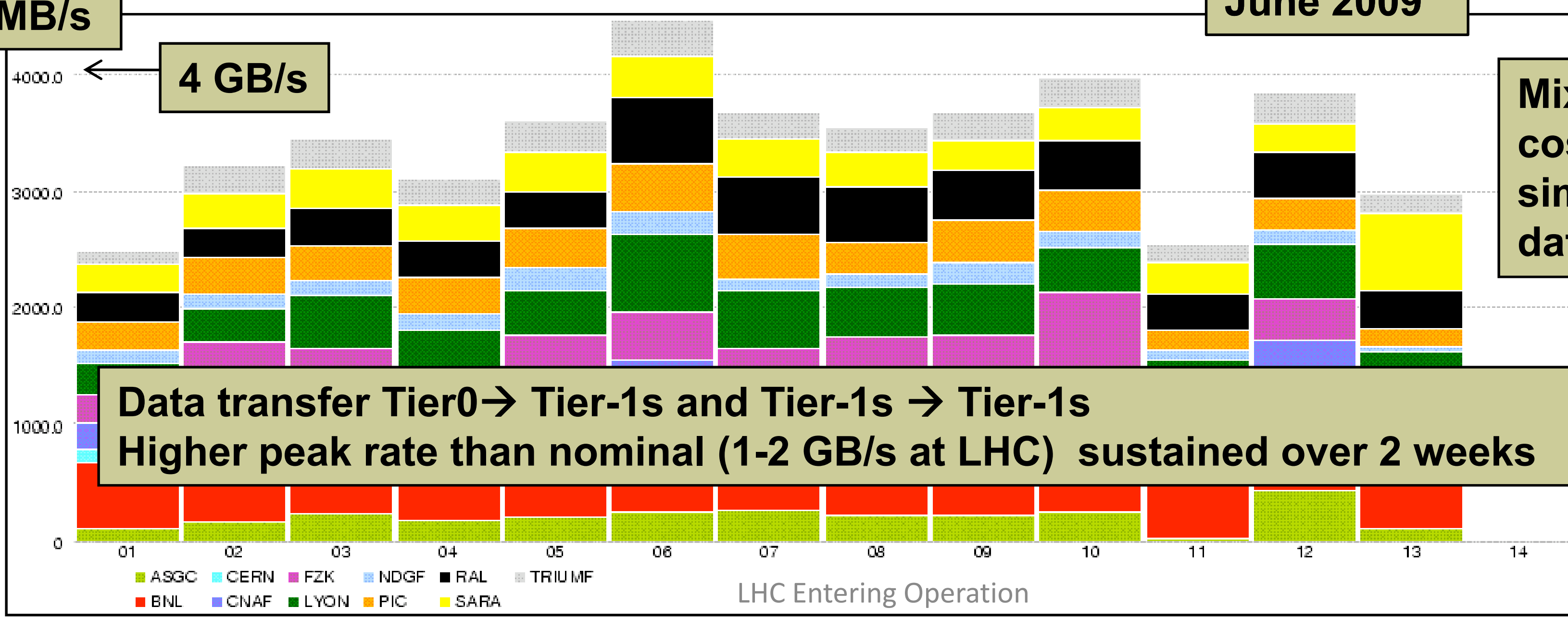
# of jobs



Production of MC samples for simulation studies.
>30 kjobs/day achieved

MB/s

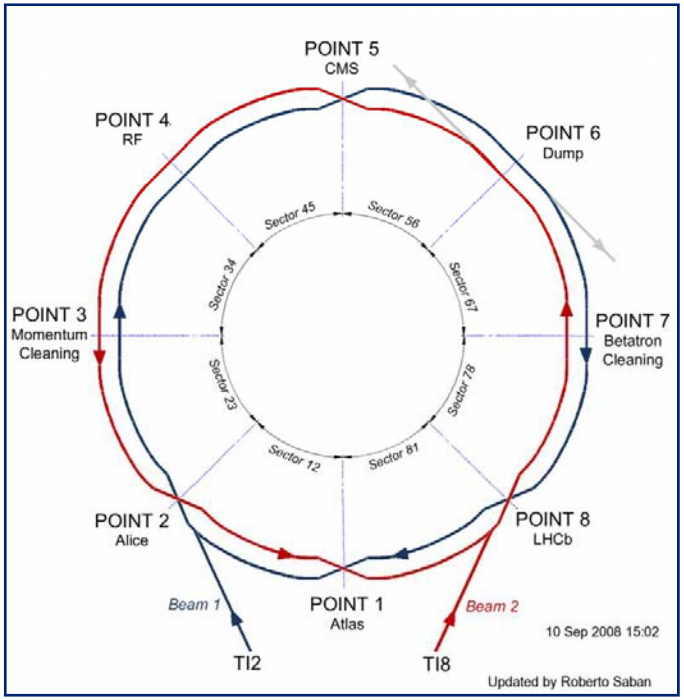
June 2009

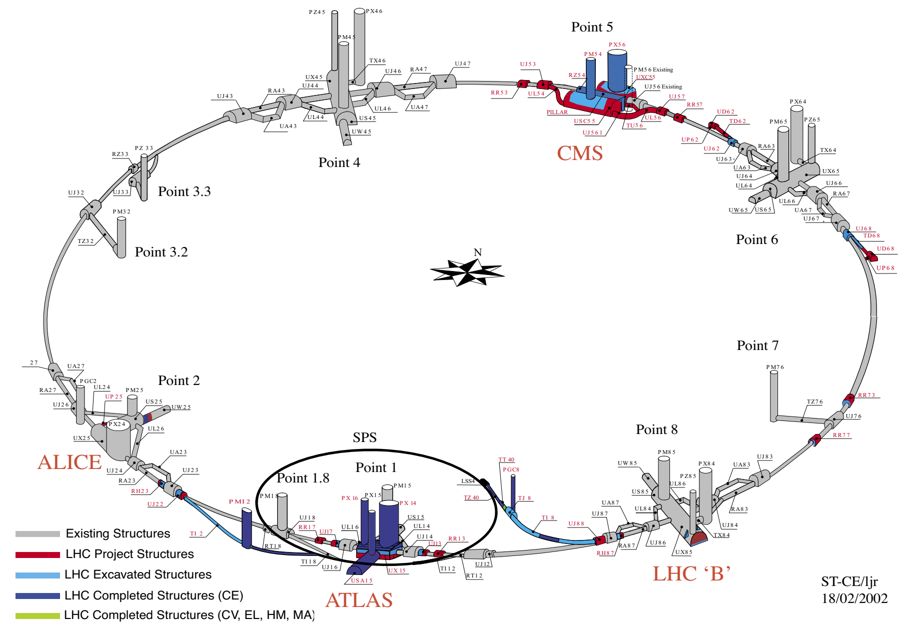


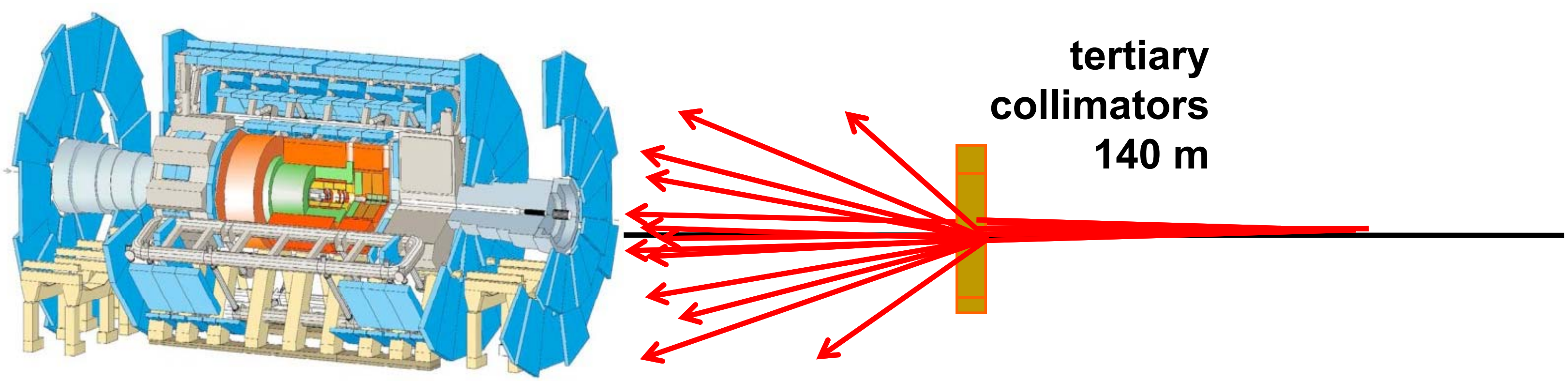
Mixture of cosmics and simulated data

Data transfer Tier0→ Tier-1s and Tier-1s → Tier-1s
Higher peak rate than nominal (1-2 GB/s at LHC) sustained over 2 weeks

First LHC Single Beam on 10th September 2008



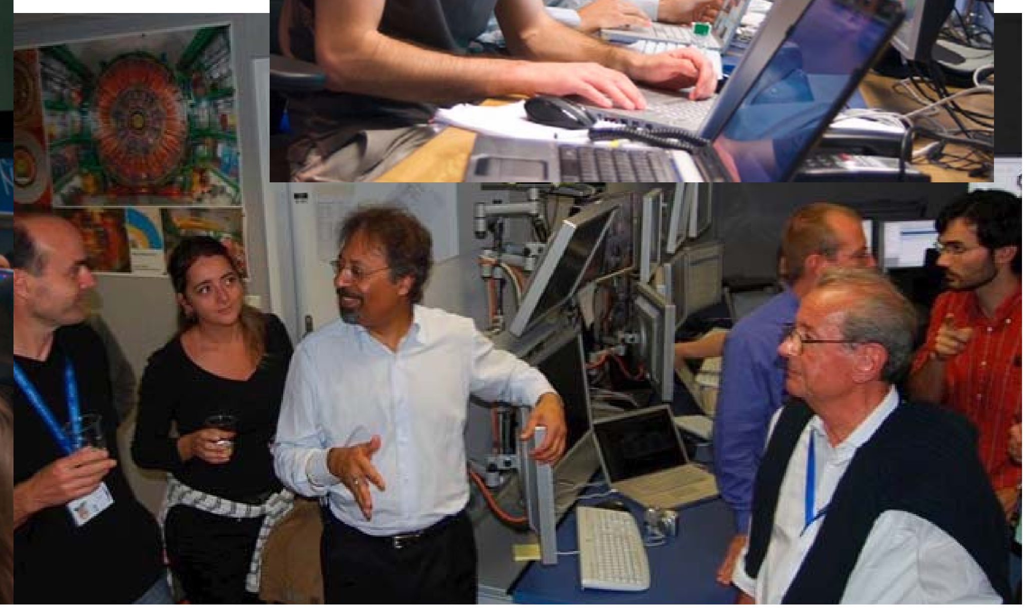




10th September 2008 in the CMS Control room



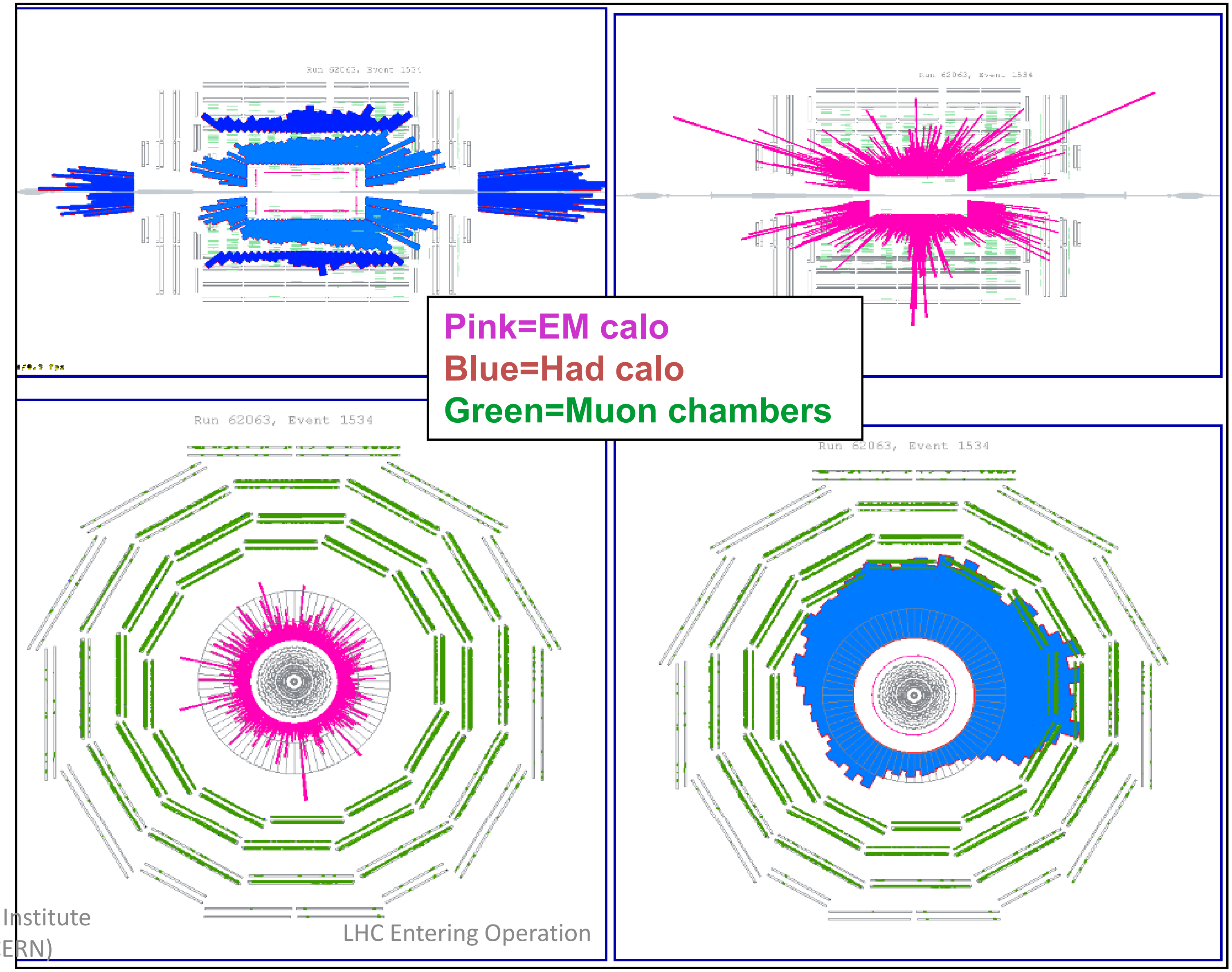




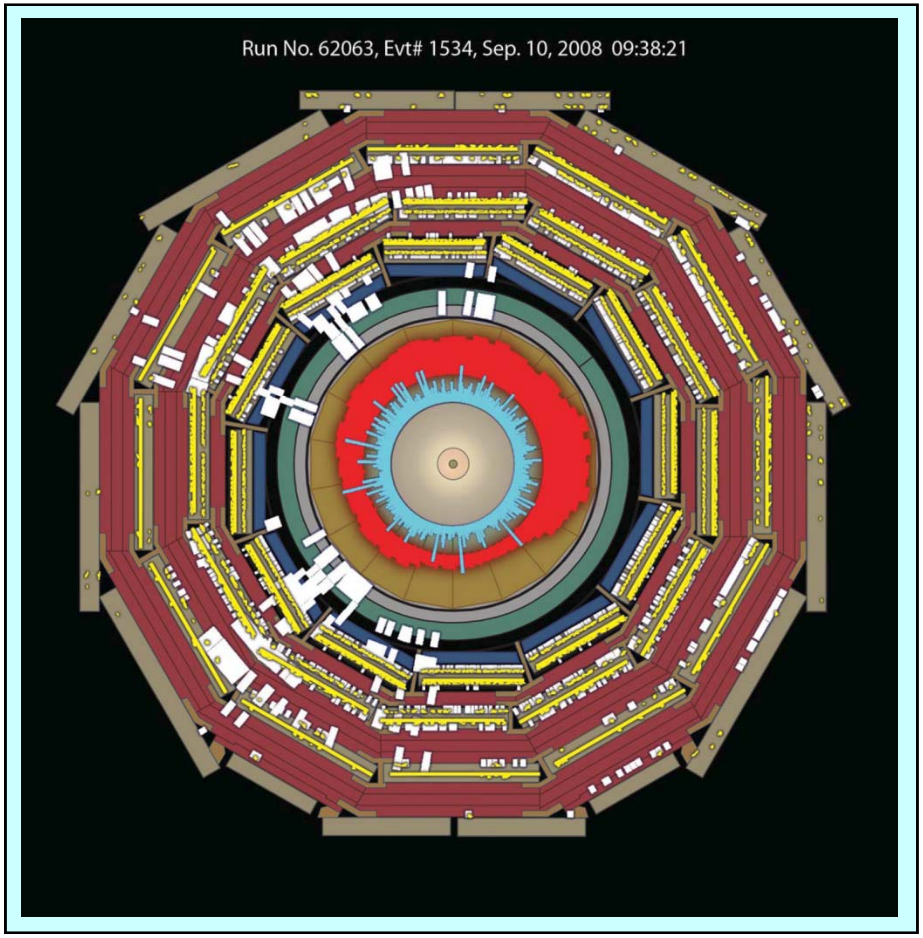
Beam "splash" in CMS from ~ 2×10^9 protons on collimators ~ 150 m upstream of the experiment in Point-5

> 80% channels fired

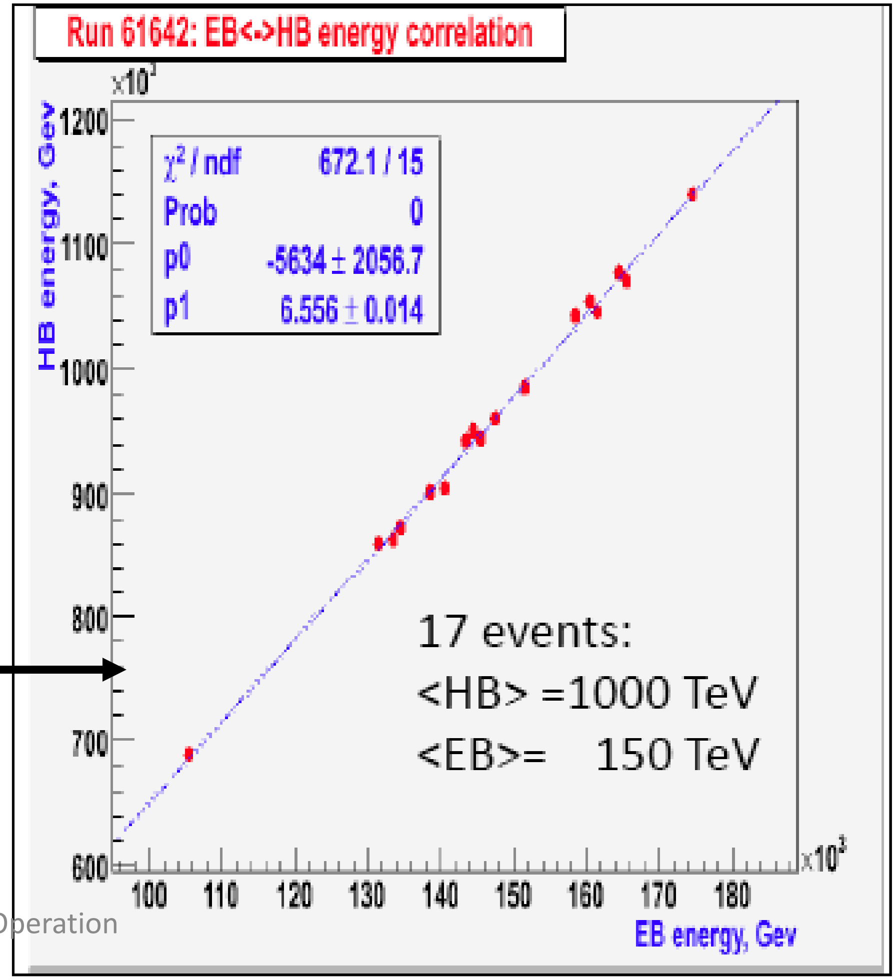
100-1000 TeV energy deposits



Event splash recorded on 10 September at 9:54

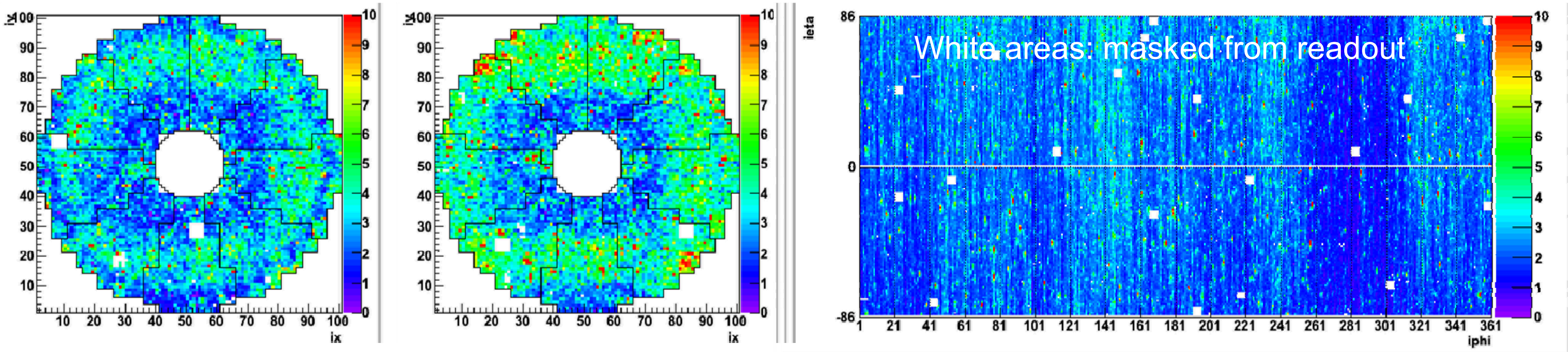


CMS preliminary



Correlation between the energies measured in the barrel EM and in the barrel HAD calorimeters in beam splash events.

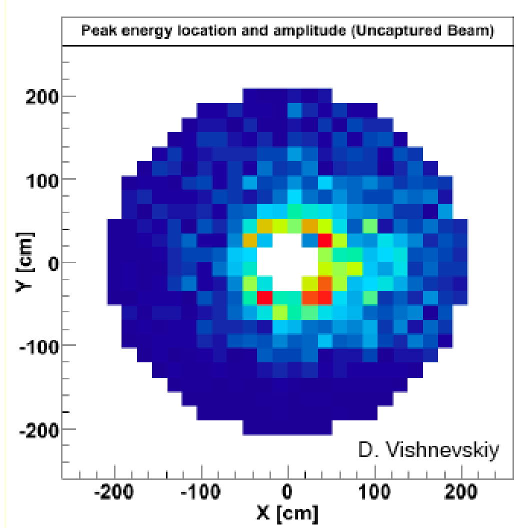
LHC Beam in CMS: Energy Deposit in Calorimeters

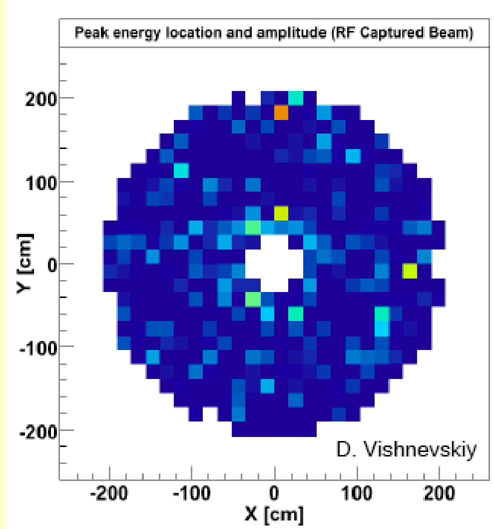


ECAL Endcaps (lhs), Barrel (rhs)

> 99% of ECAL channels alive, ~200 TeV energy deposited in EB+EE

Inter-crystals timing established (< 1ns), inter-crystal calibration EB (1.5-2.5% - test beam + cosmics), EE (~7% from splash events)

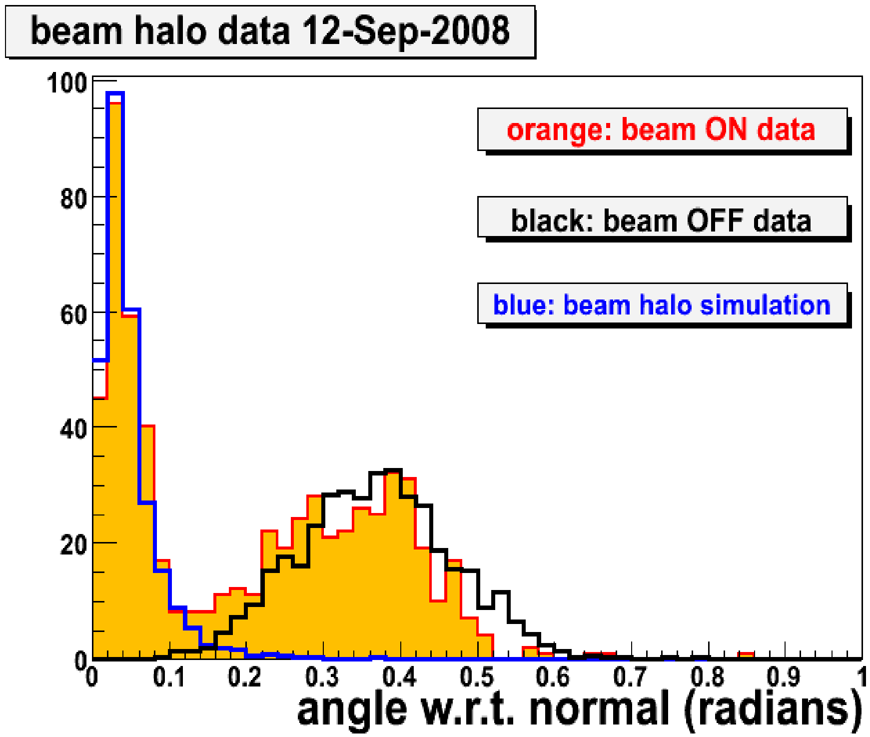


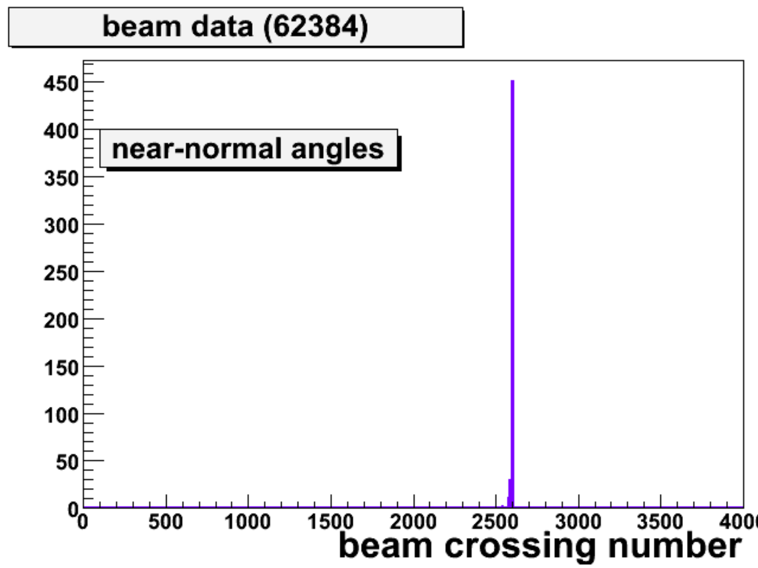


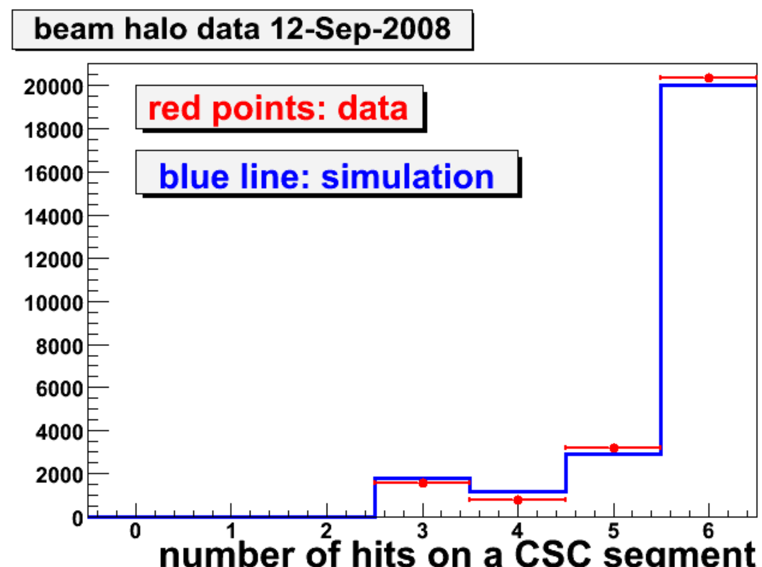
HCAL Endcap: un-captured (lhs) and captured circulating beam (rhs)

CMS Muon CSCs: Single Beam

Reconstructed track angle w.r.t. the transverse plane







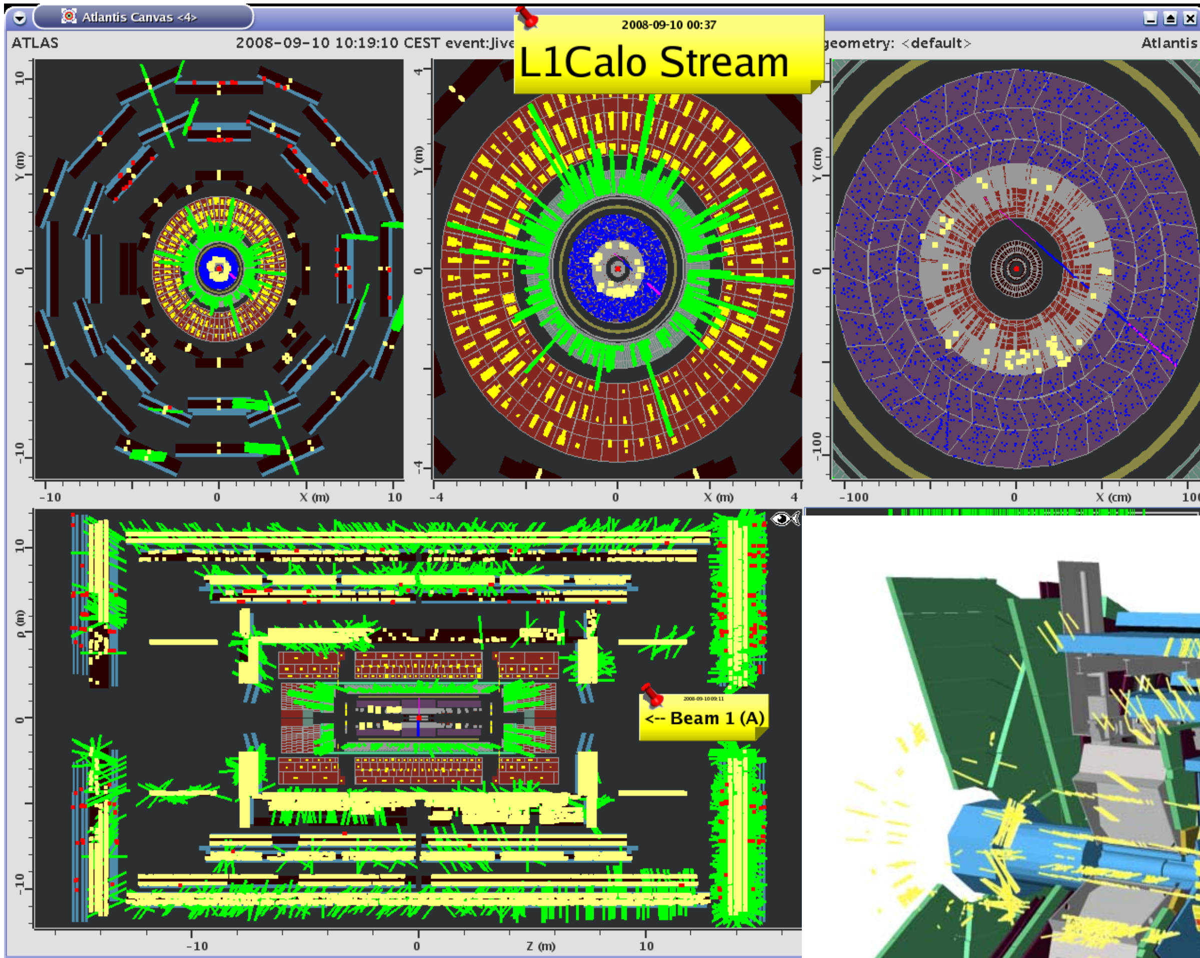
Reasonable description of beam ON data: a combination of

- **beam halo**
- **cosmic rays**

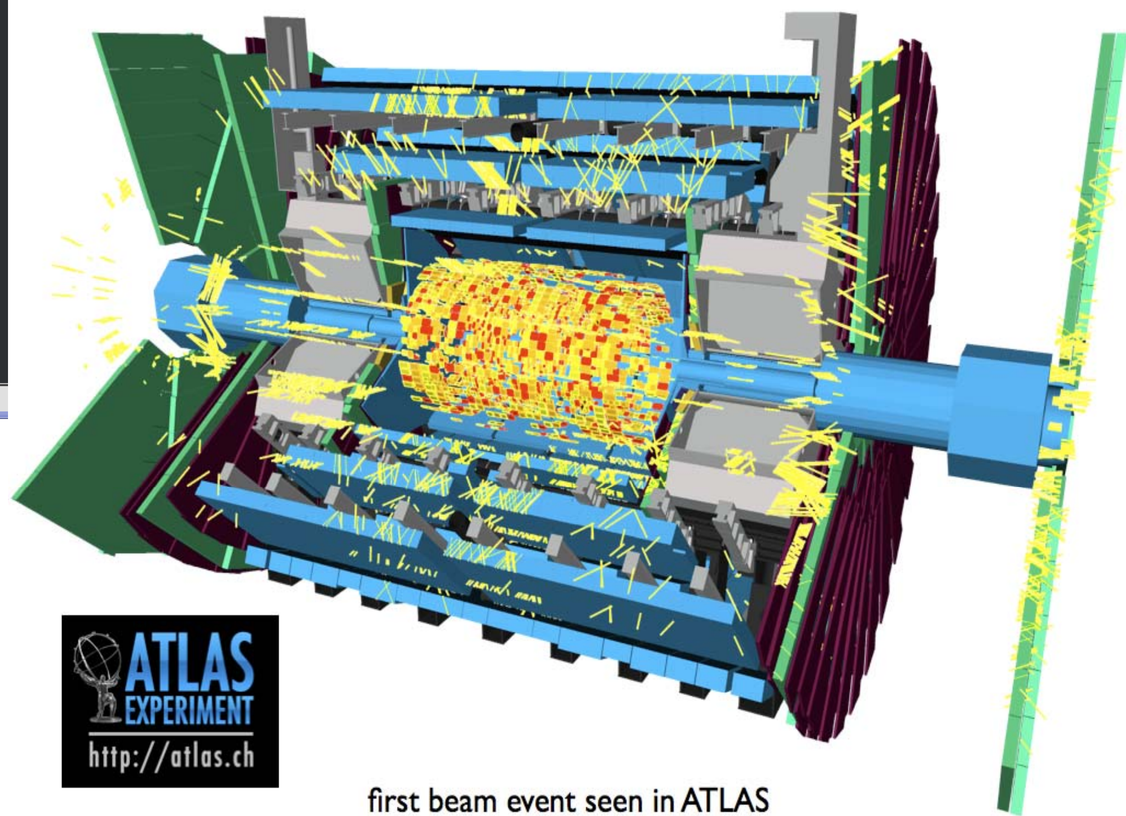
Excitement in the ATLAS Detector Control Room: The first LHC event on 10th September 2008

… as well as in the ATLAS Tier-0 and Data Quality Control Rooms: Reconstruction follow-up and analysis of the first LHC events

The very first beam-splash event from the LHC in ATLAS at 10:19, on 10th September 2008



Online display

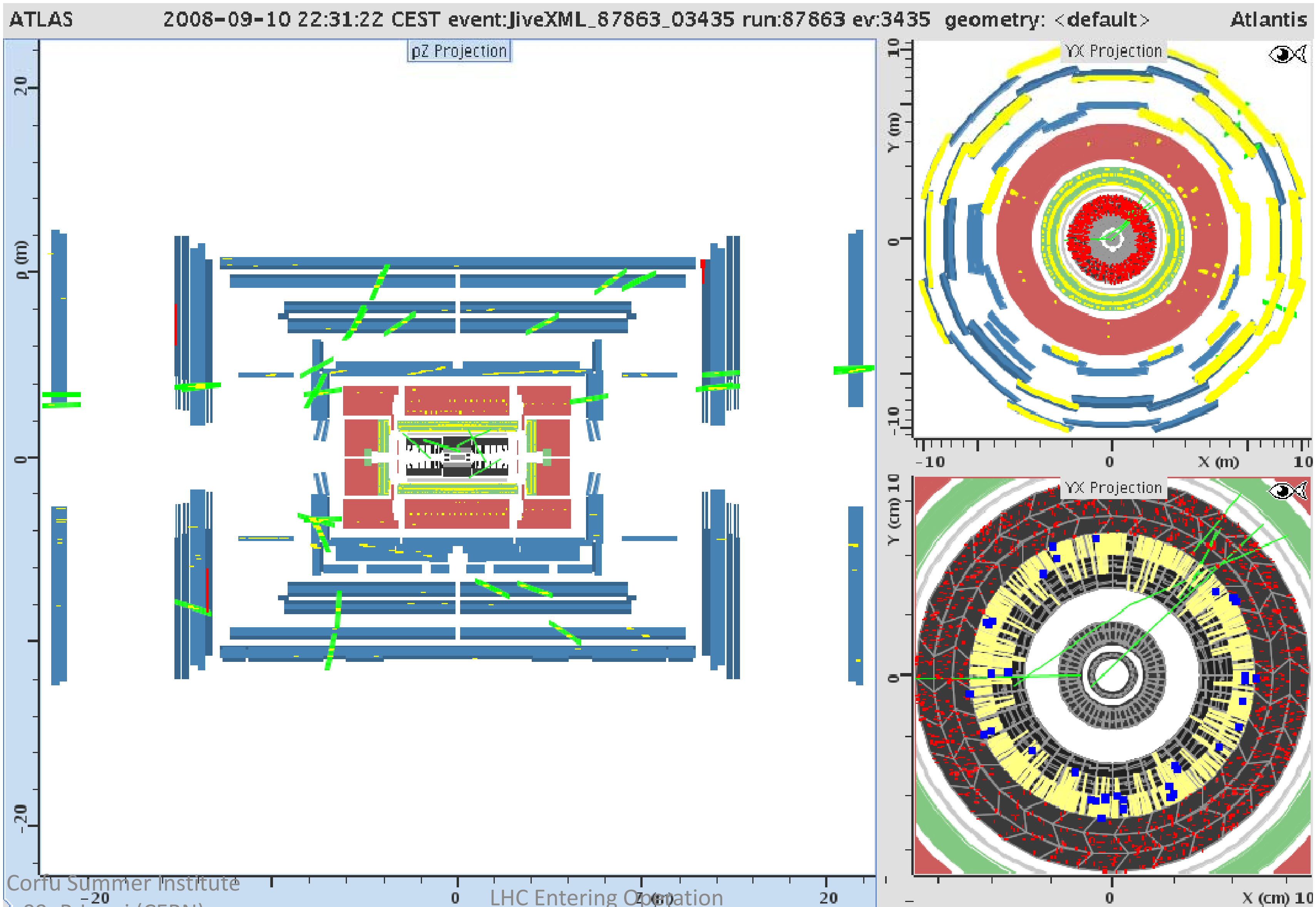


first beam event seen in ATLAS

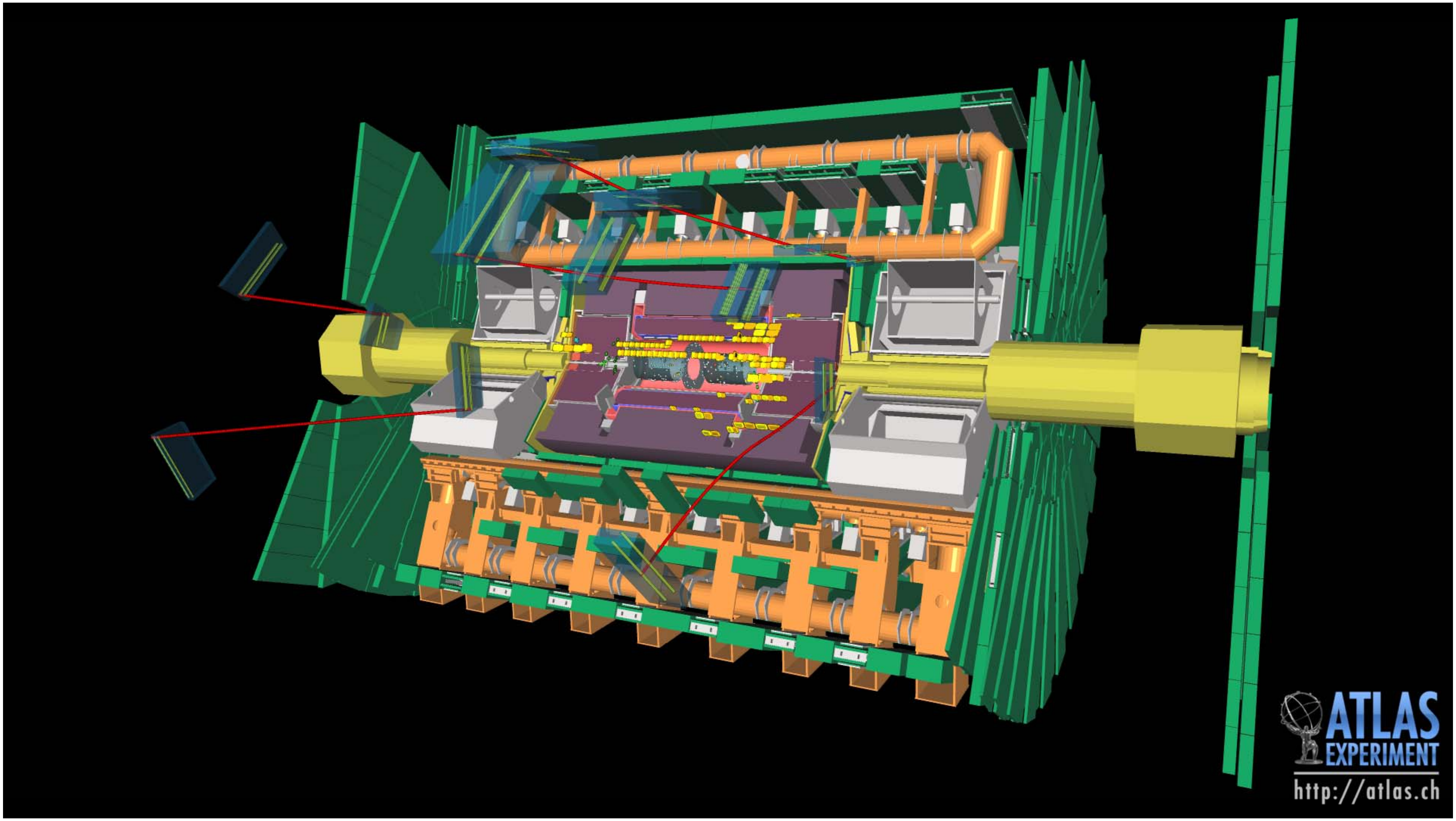
Offline display

ATLAS EXPERIMENT
http://atlas.ch

A busy beam-halo event with tracks bent in the Toroids from the start-up day (offline)



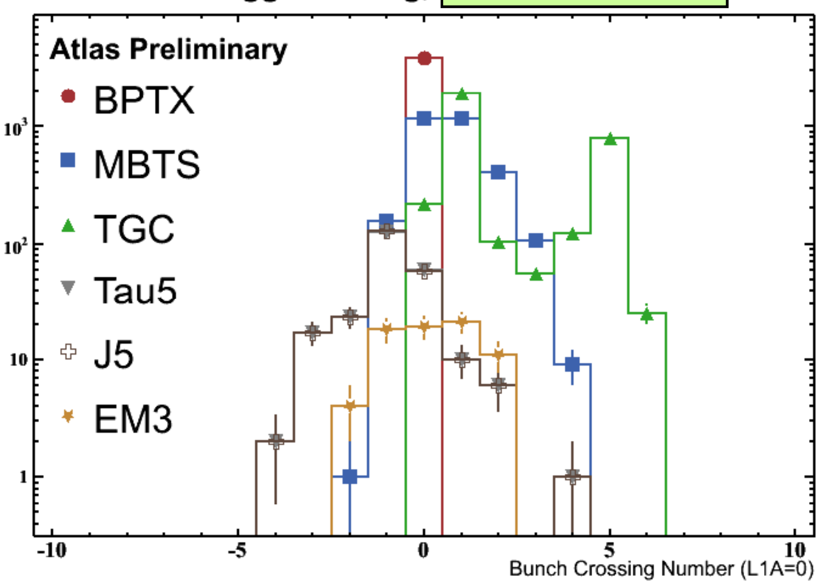
Another beam-halo event



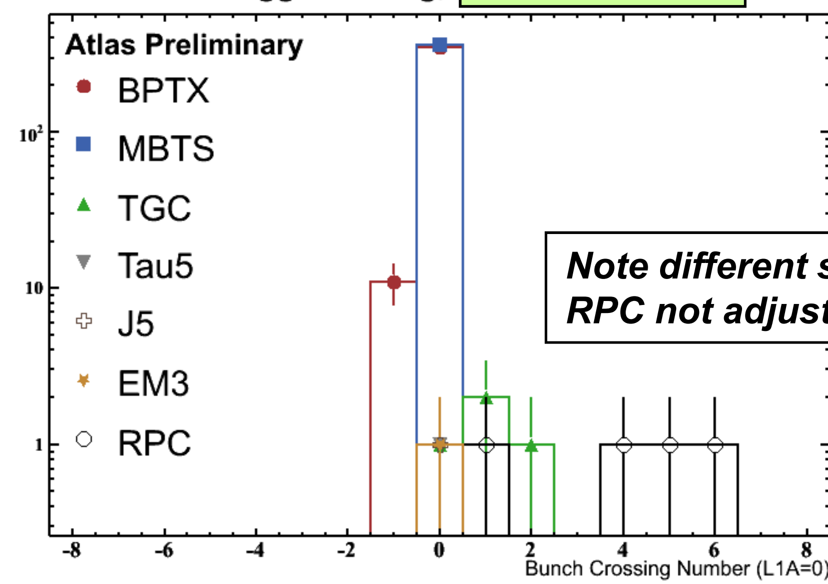
First beams on September 10-12 very useful to synchronize the various sub-detectors, in particular to start timing-in the trigger

- Timing of the various components (sub-detectors, trigger system) synchronized with respect to beam pick-ups (BPTX) reference
- Signal times of various triggers adjusted to match the BPTX reference
- Plots show improvement from 10 September to 12 September

Relative Trigger Timing, **10 September**



Relative Trigger Timing, **12 September**



Note different scale
RPC not adjusted

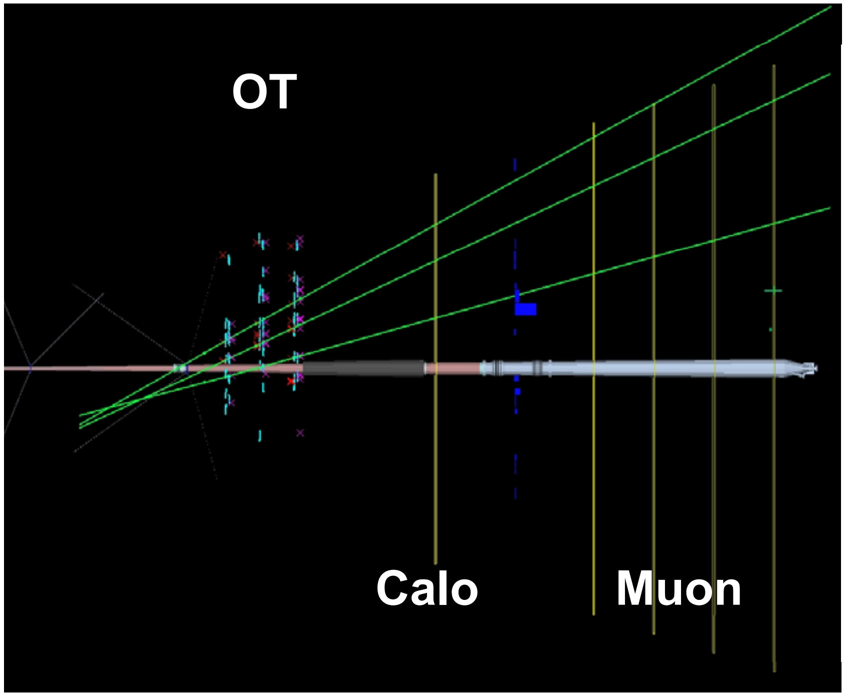
1 bunch crossing number = 25 ns

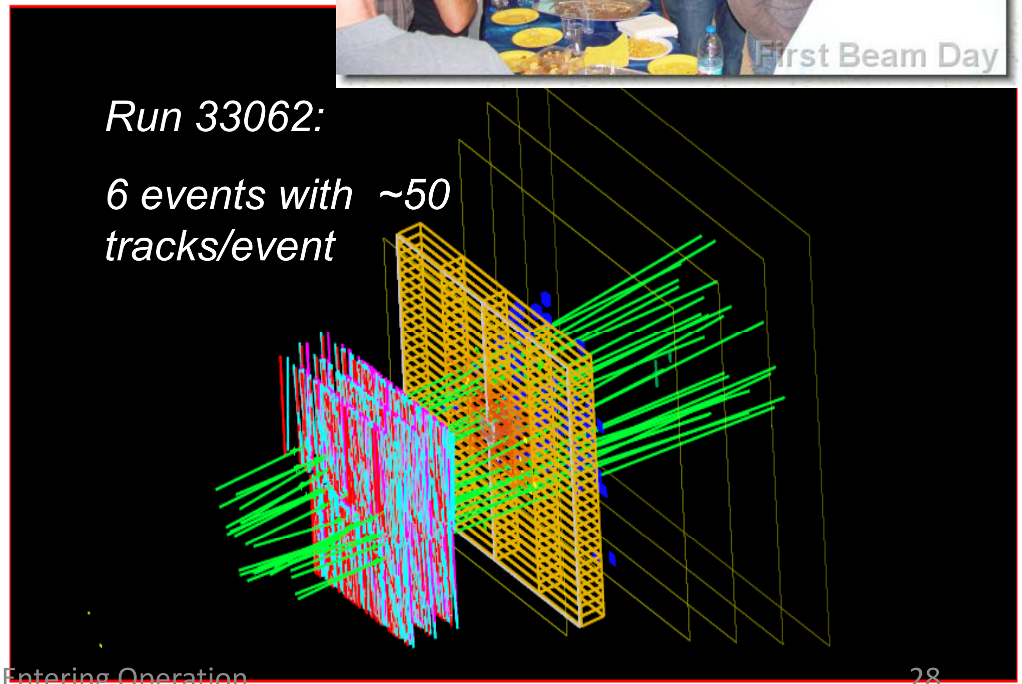
LHCb experience with first beam at LHC start-up

Contrary to what one wishes for the future, the splashes were highly desired events!

Allowed to commissioning

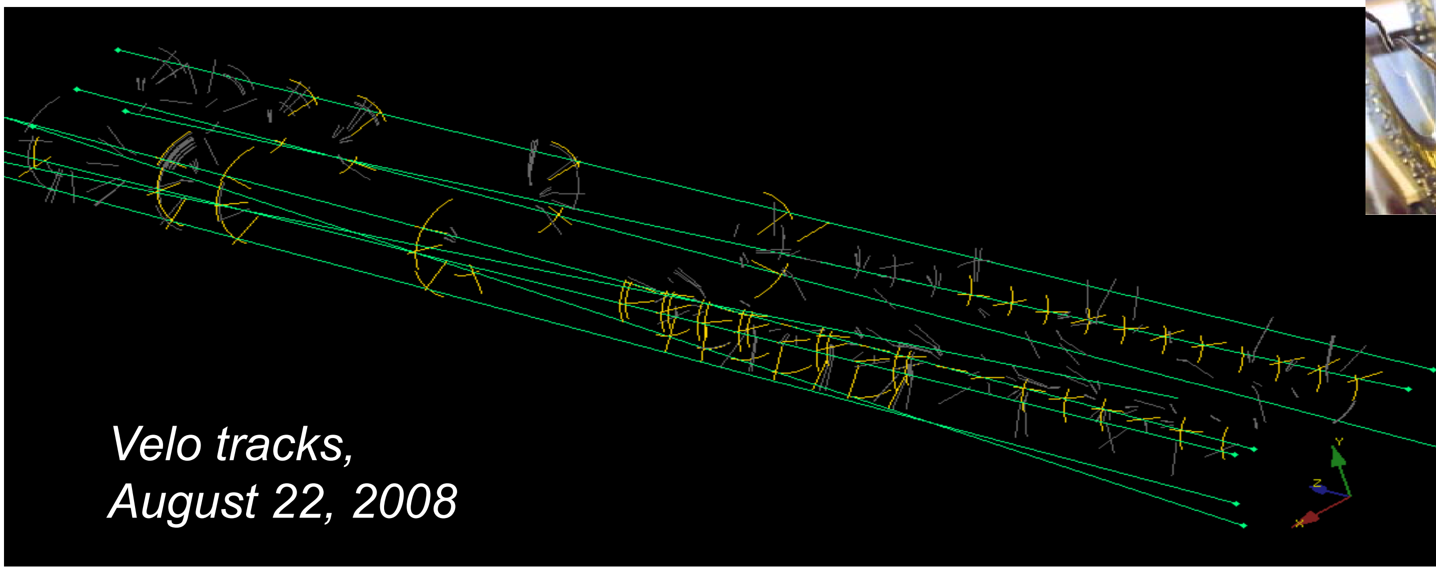
- **Software and hardware communication interfaces with LHC**
- **Monitoring of LHC instrumentation and beam conditions**



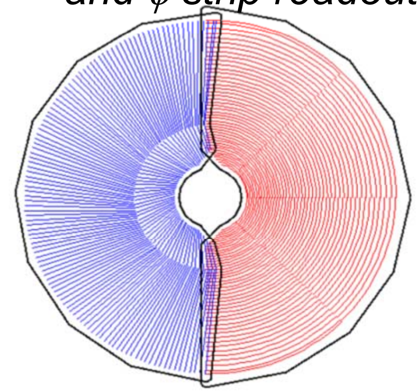


VELO alignment

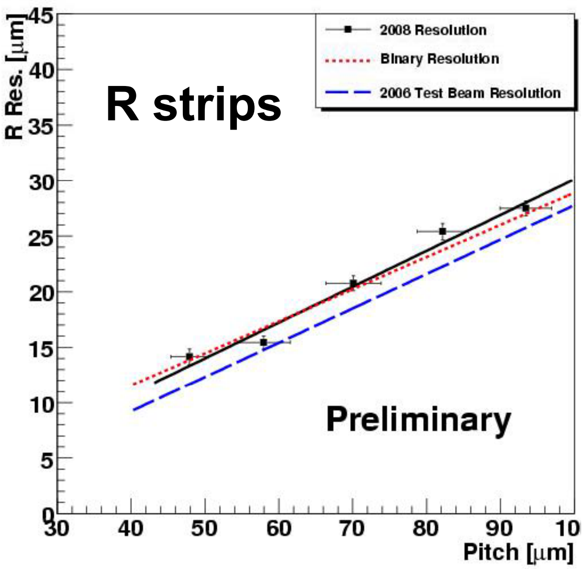
TED tracks perfect for VELO alignment: cross detector almost parallel to z-axis

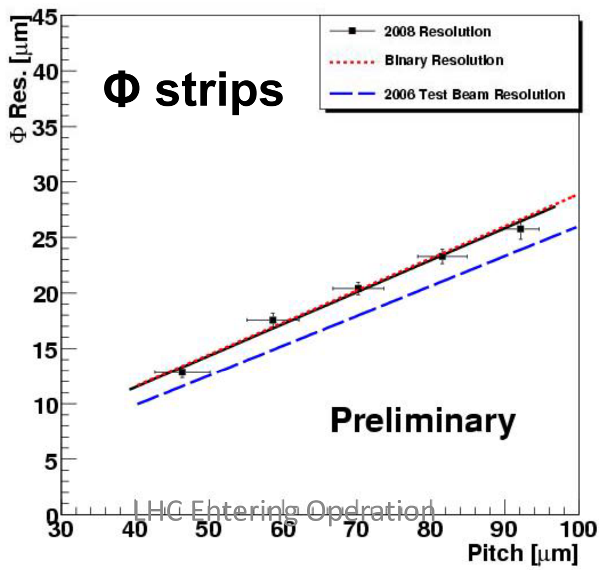


21 stations of Si wafer pairs with r and ϕ strip readout



resolution in μ

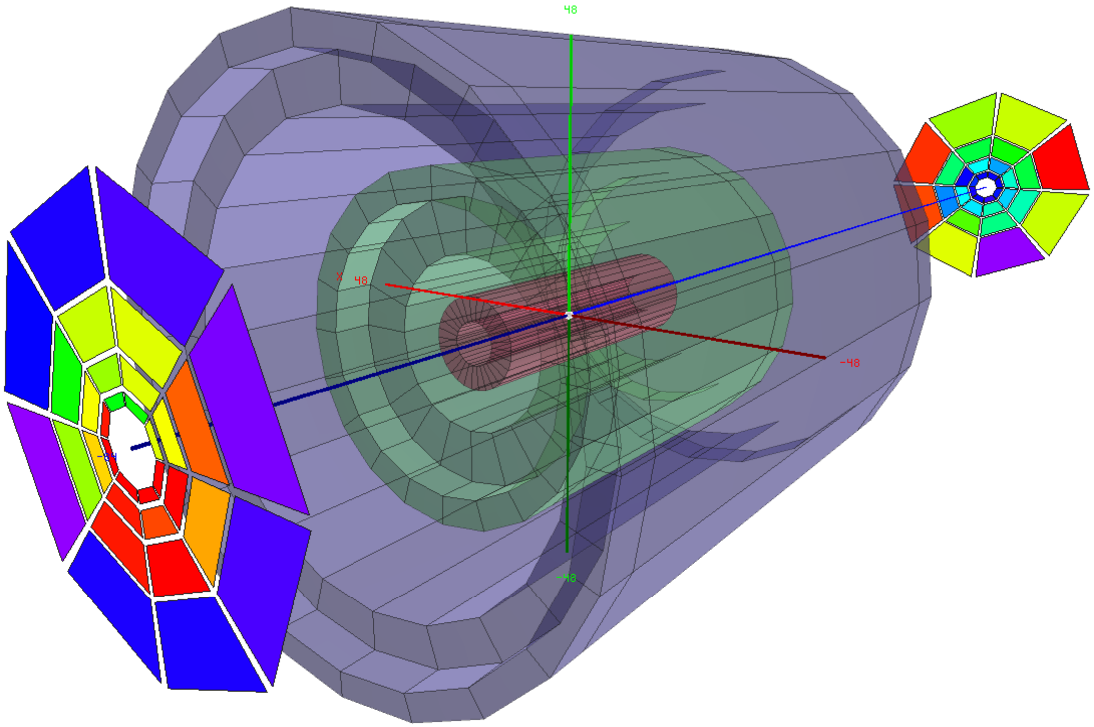




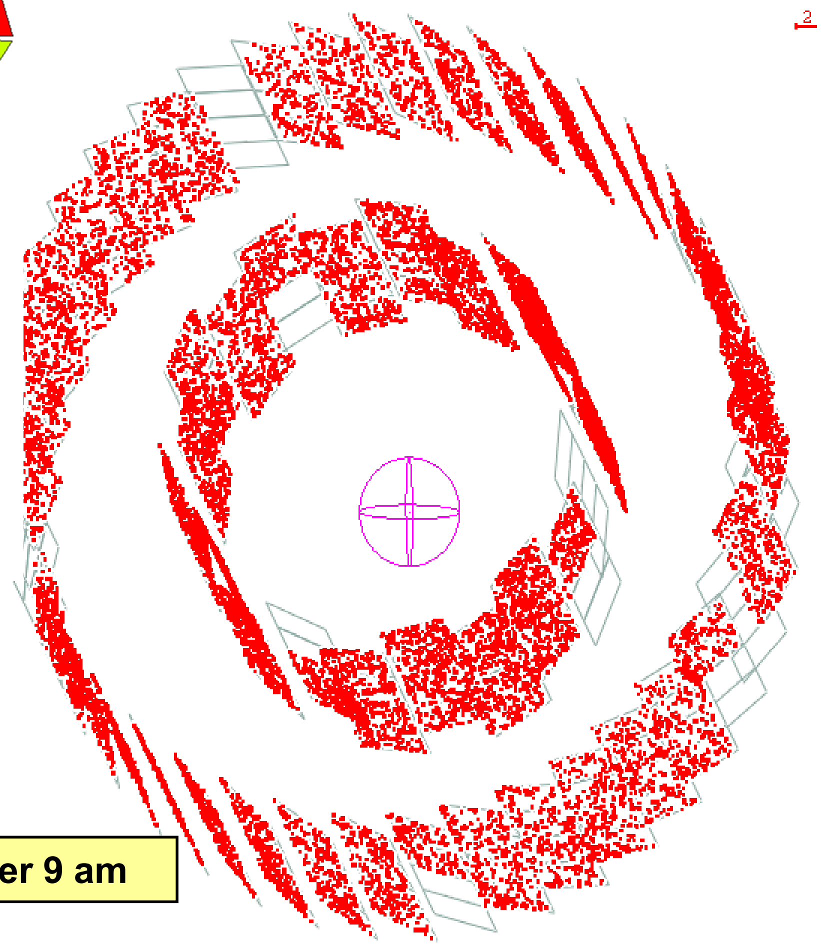
Resolution estimated from VELO hit residuals agrees well with expectations

Further improvement possible

First beam 10th September in ALICE

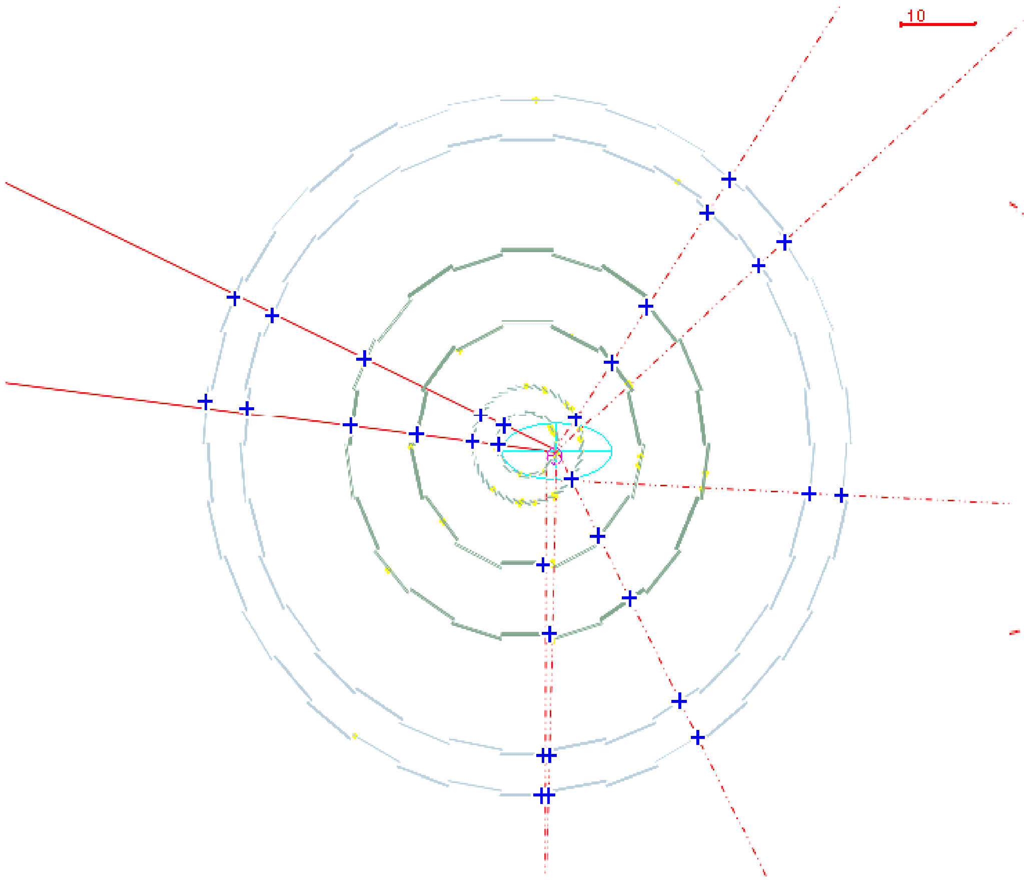


V0 hits on 10.9.2008, shortly after 9 am

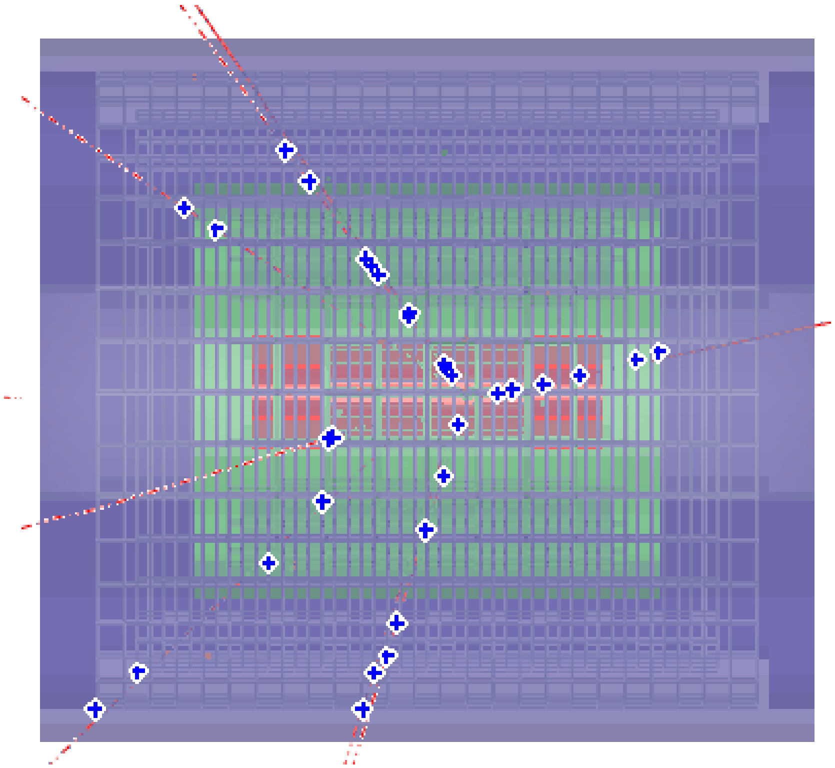


SPD hits on 10.9.2008, shortly after 9 am

First 'Interactions' in ALICE on 11th September



ITS tracks on 12.9.2008
7 reconstructed tracks, common vertex



Circulating beam 2:
stray particle causing an interaction in the ITS

Strategy toward physics

Before data taking starts:

- Strict quality controls of detector construction to meet physics requirements
- Test beams (a 15-year activity culminating with a combined test beam in 2004) to understand and calibrate (part of) detector and validate/tune software tools (e.g. Geant4 simulation)
- Detailed simulations of realistic detector "as built and as installed" (including misalignments, material non-uniformities, dead channels, etc.) $\rightarrow$ test and validate calibration/alignment strategies
- Experiment commissioning with cosmics in the underground cavern

With the first data:

- Commission/calibrate detector/trigger in situ with physics (min.bias, $Z \rightarrow ll$, …)
- "Rediscover" Standard Model, measure it at $\sqrt{s}$ = 10 TeV (minimum bias, W, Z, tt, QCD jets, …)
- Validate and tune tools (e.g. MC generators)
- Measure main backgrounds to New Physics (W/Z+jets, tt+jets, QCD-jets,…)

Prepare the road to discoveries …

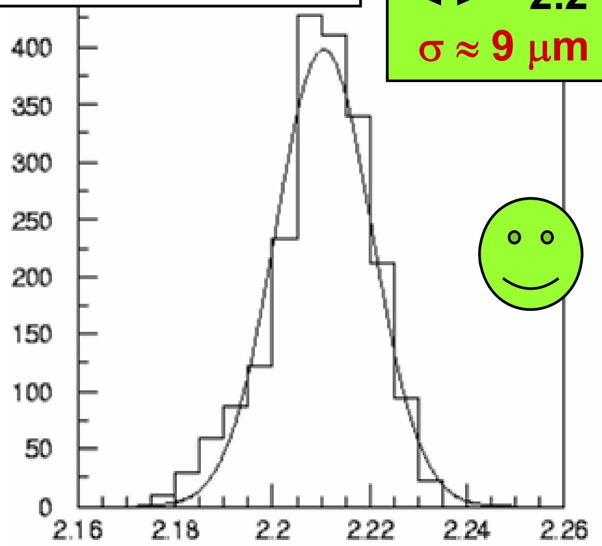
Example: ATLAS LAr em Accordion Calorimeter

Construction quality

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

End-cap: 1536 plates

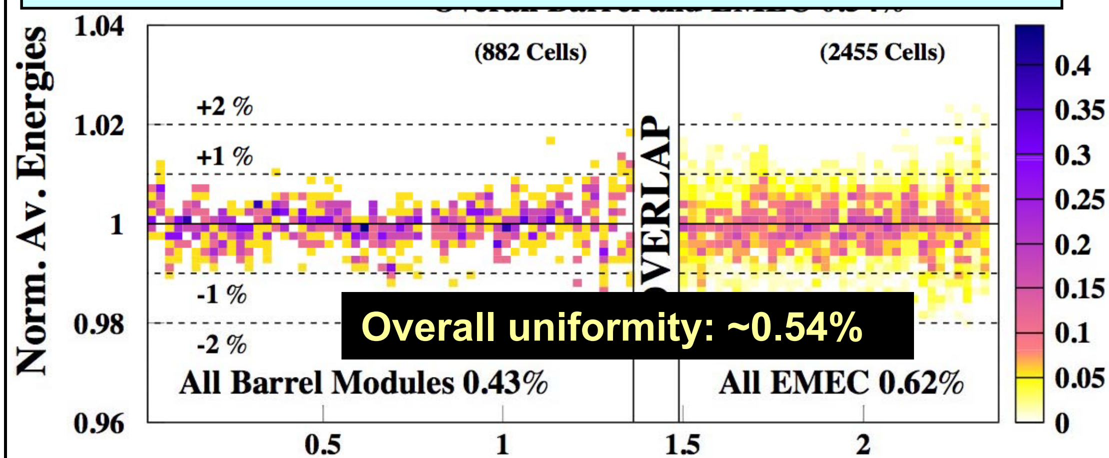
< > ~ 2.2 mm
σ ≈ 9 μm



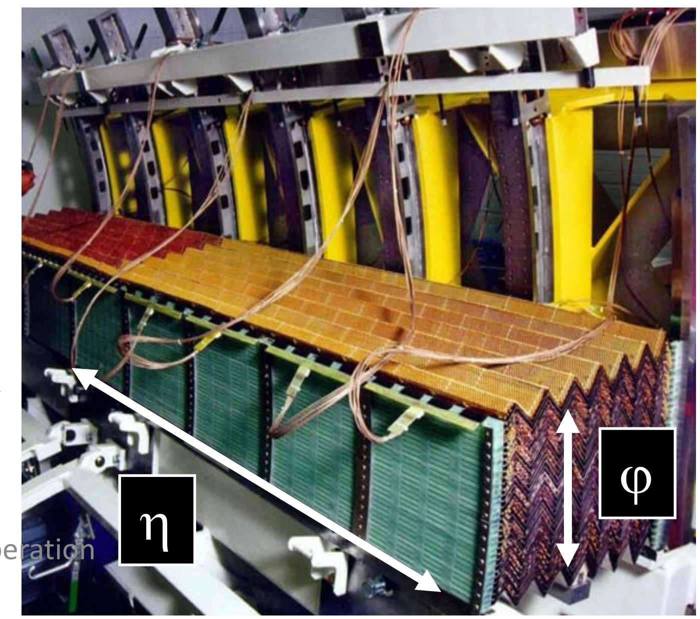
Test-beam measurements

4 (out of 32) barrel modules and 3 (out of 16) end-cap (EMEC) modules tested with beams

Scans with 120-245 GeV electrons (all 7 tested modules)

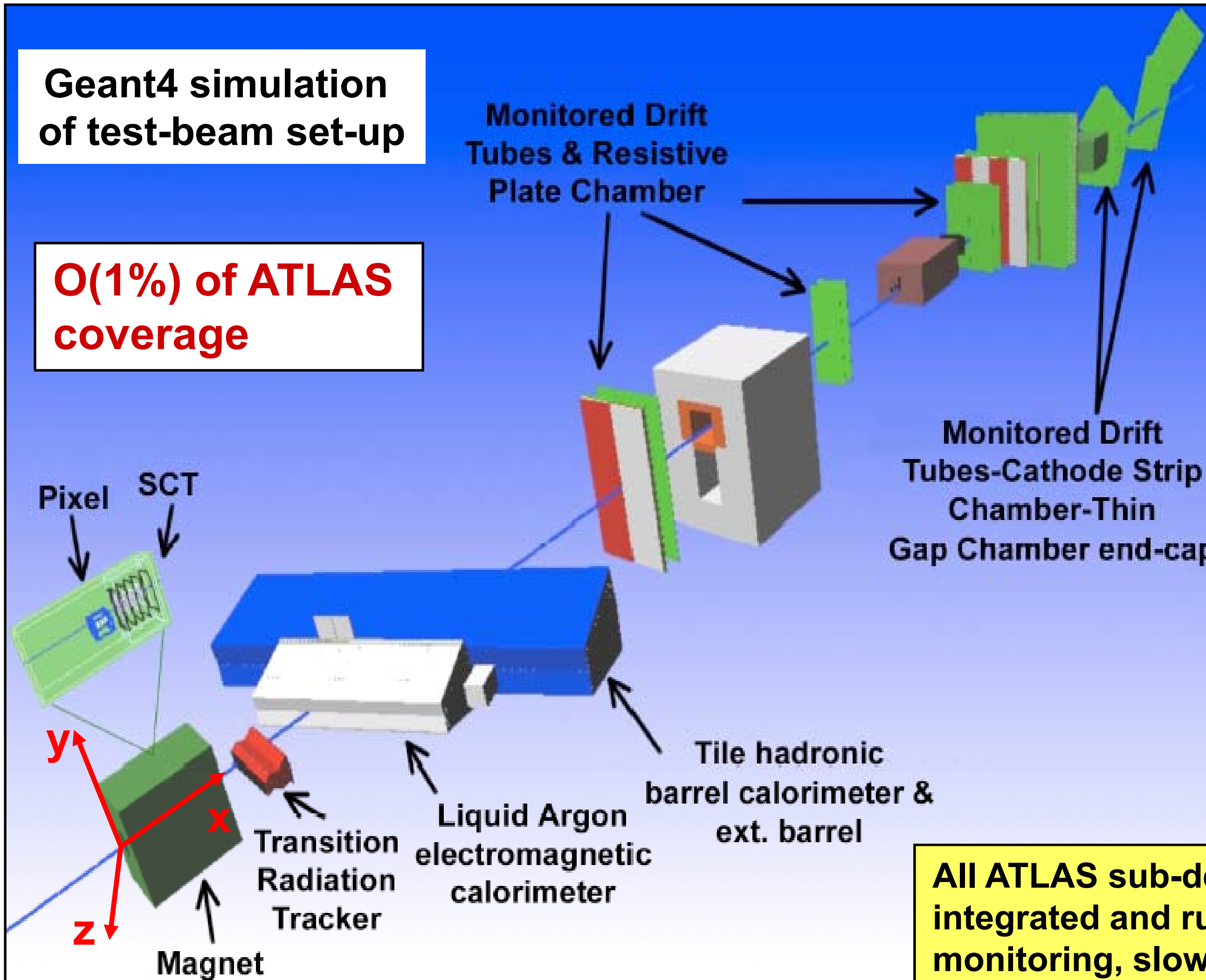


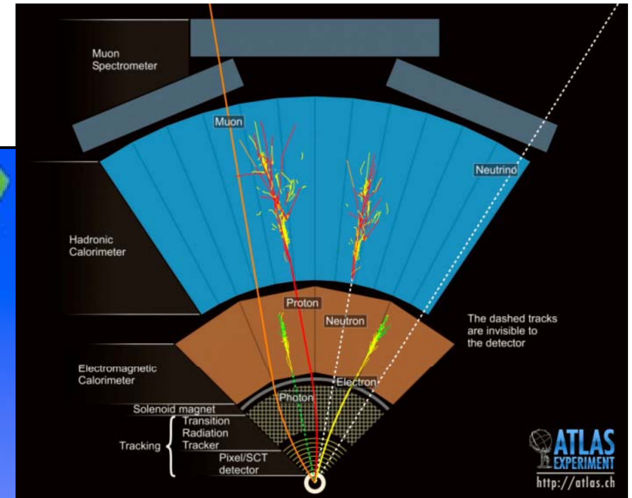
1 barrel module:
Δη x Δφ = 1.4 x 0.4
≈ 3000 channels



Example: 2004 ATLAS combined test beam

Full "vertical slice" of ATLAS tested in CERN H8 beam line



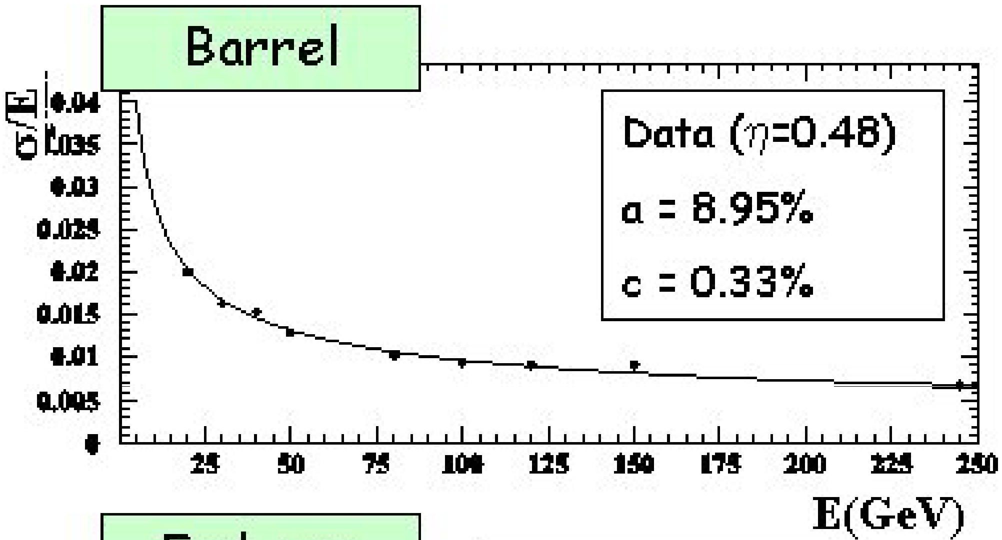


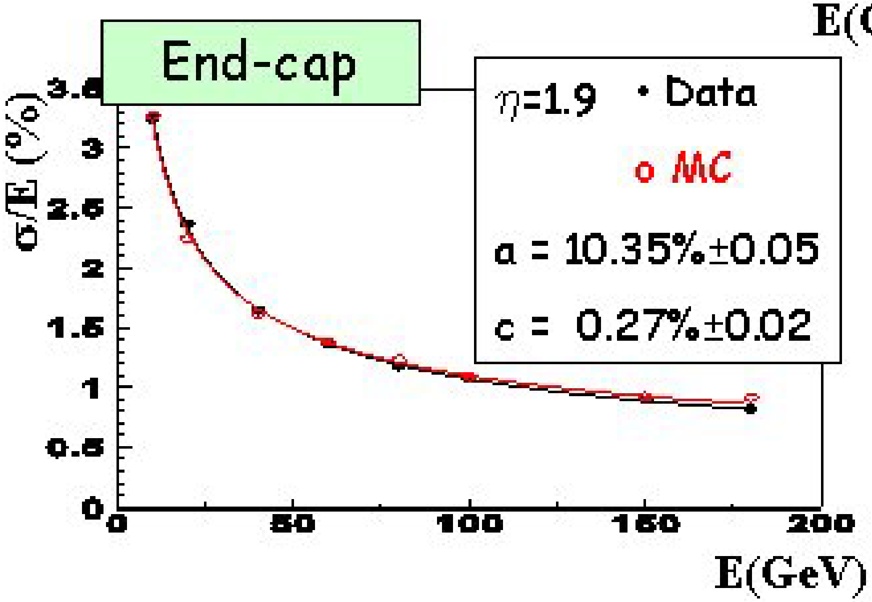
~ 90 million events collected
$e^{\pm}$, $\pi^{\pm}$ $1 \rightarrow 250$ GeV
$\mu^{\pm}$, $\pi^{\pm}$, p up to 350 GeV
γ 20-100 GeV
B-field = $0 \rightarrow 1.4$ T

Many configurations
(e.g. additional material in ID,
25 ns runs, …)

All ATLAS sub-detectors (and LVL1 trigger) integrated and run together with common DAQ, monitoring, slow-control.
Data analyzed with common ATLAS software.
Gained lot of global operation experience during ~ 6 month run.

ATLAS EM beam test results: Energy resolution





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

For every tested points:

Barrel	End-cap
a < 10%	a < 12.5%
c < 0.4%	c < 0.5%

- Within specifications
- Good agreement with MC

Impact on Higgs mass resolution in ATLAS

Simulations, m_H=130 GeV

✓ **H → γγ**

Resolution: 1% (low lum)

1.2% (high lum)

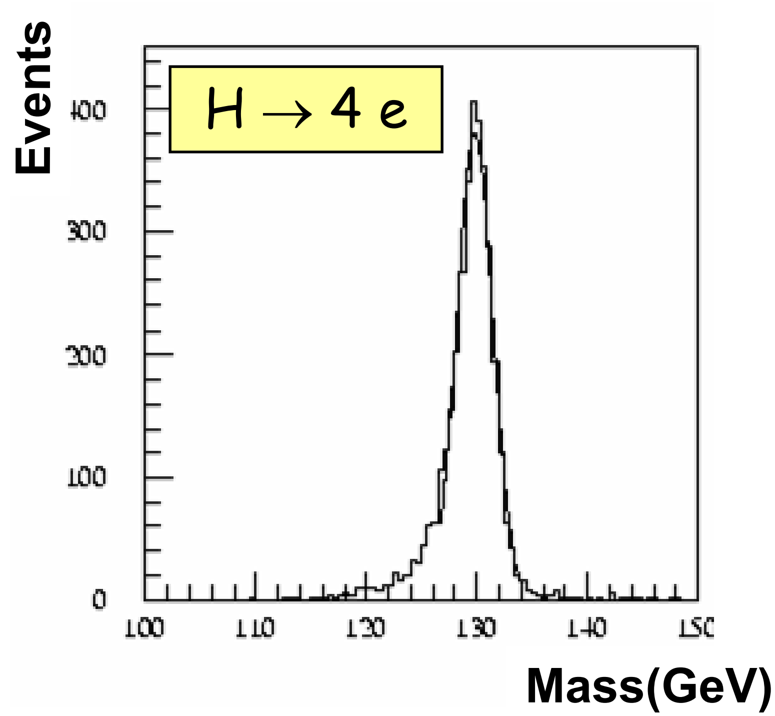
Acceptance: 80% within ±1.4 σ

✓ **H → 4e**

Resolution: 1.2% (low lum)

1.4% (high lum)

Acceptance: 84% within ±2 σ

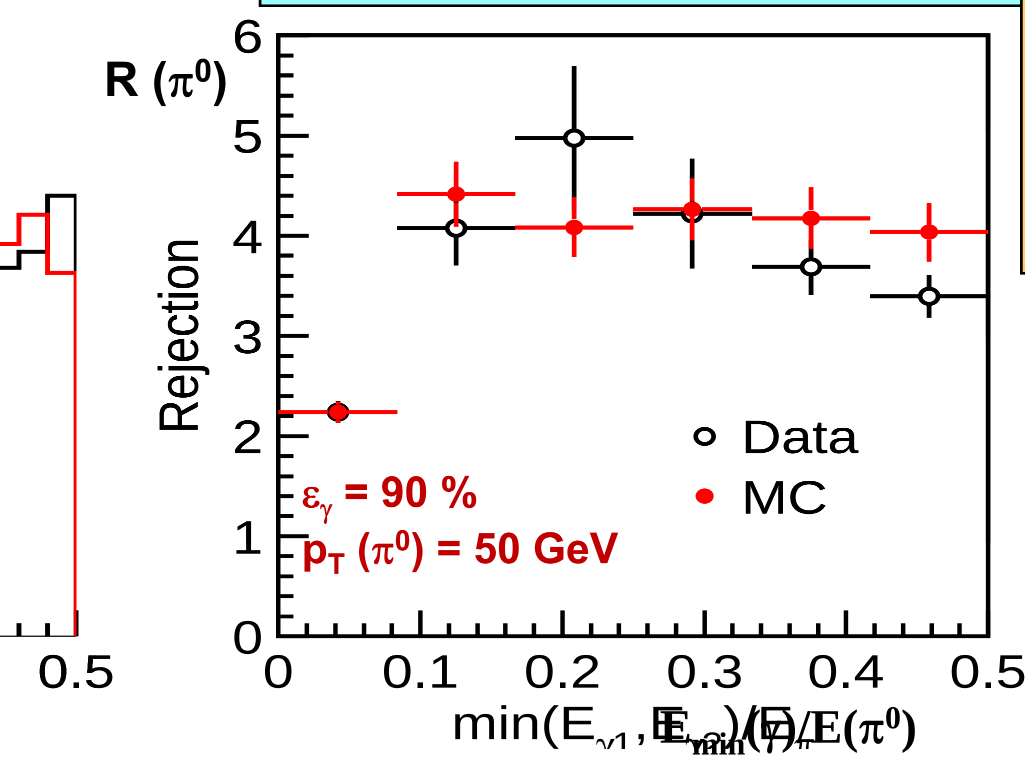


Particle identification

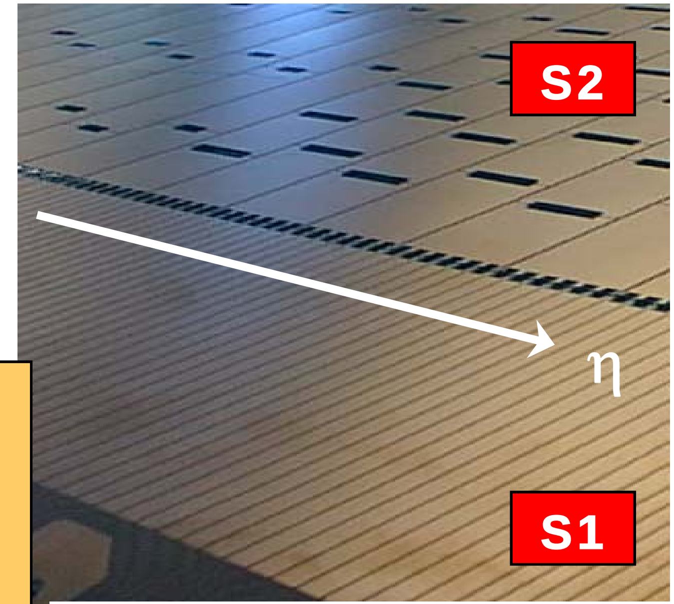
ATLAS

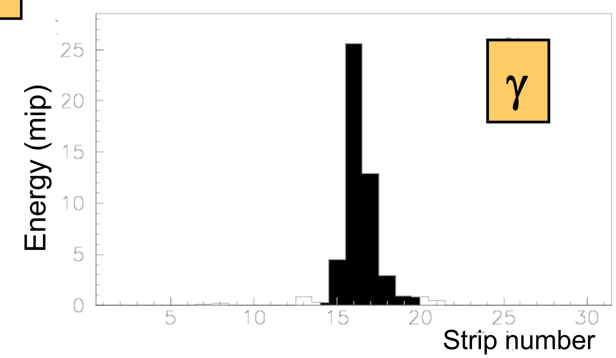
$R(\pi^0) \geq 3$ for $\varepsilon(\gamma) \sim 90\%$ needed
to reject $\gamma j + jj$ background to $H \to \gamma\gamma$

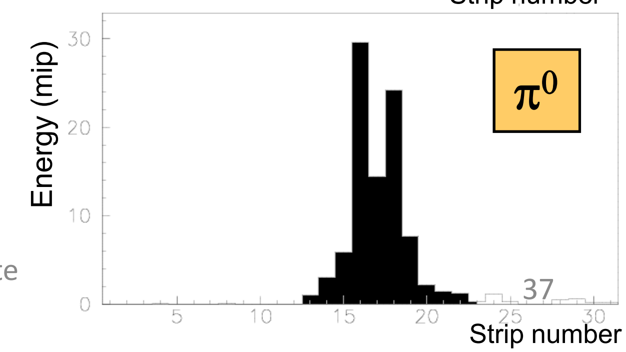
1999-2000 test-beam data
collected with special photon beam



γ/π^0 **separation based on 4mm** η**-strips in 1st calorimeter compartment**

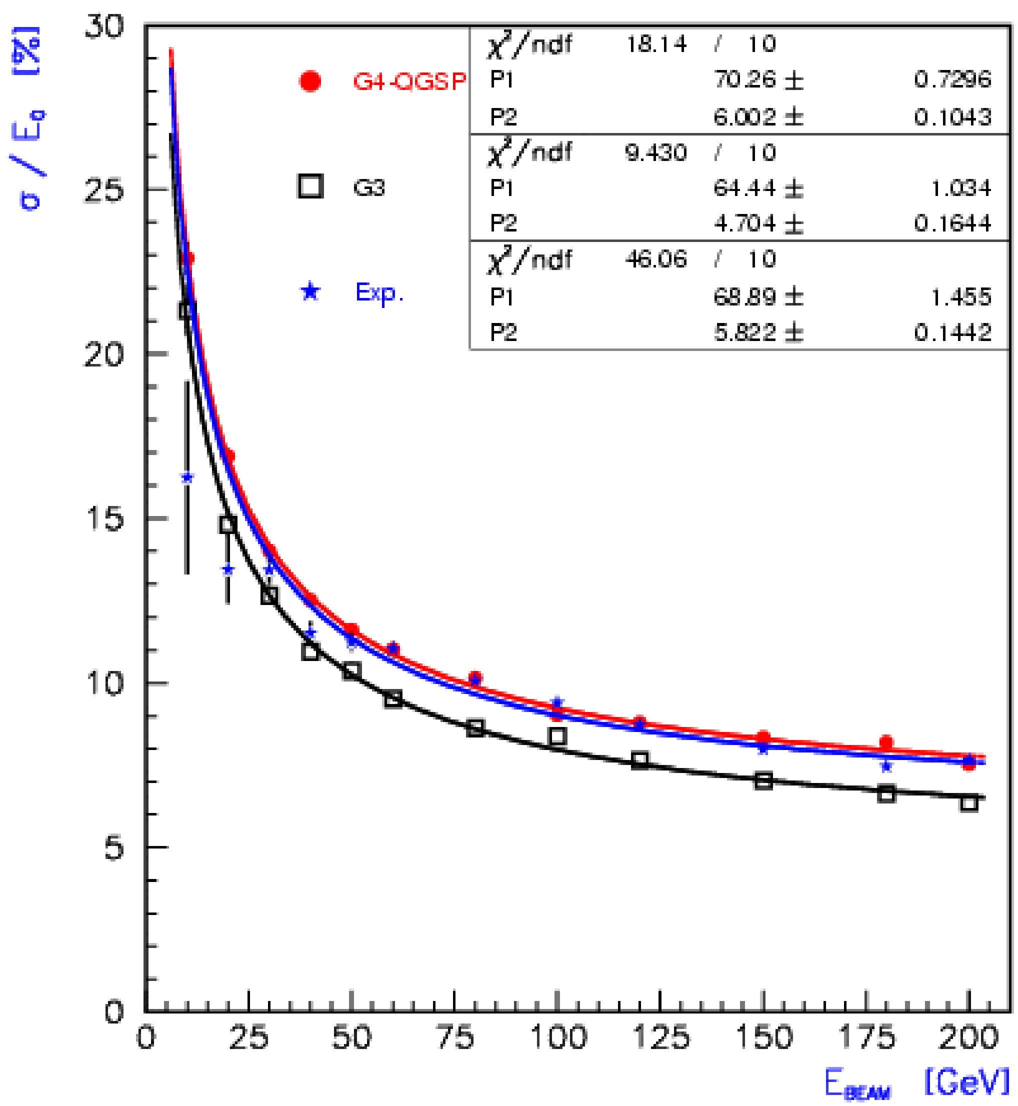






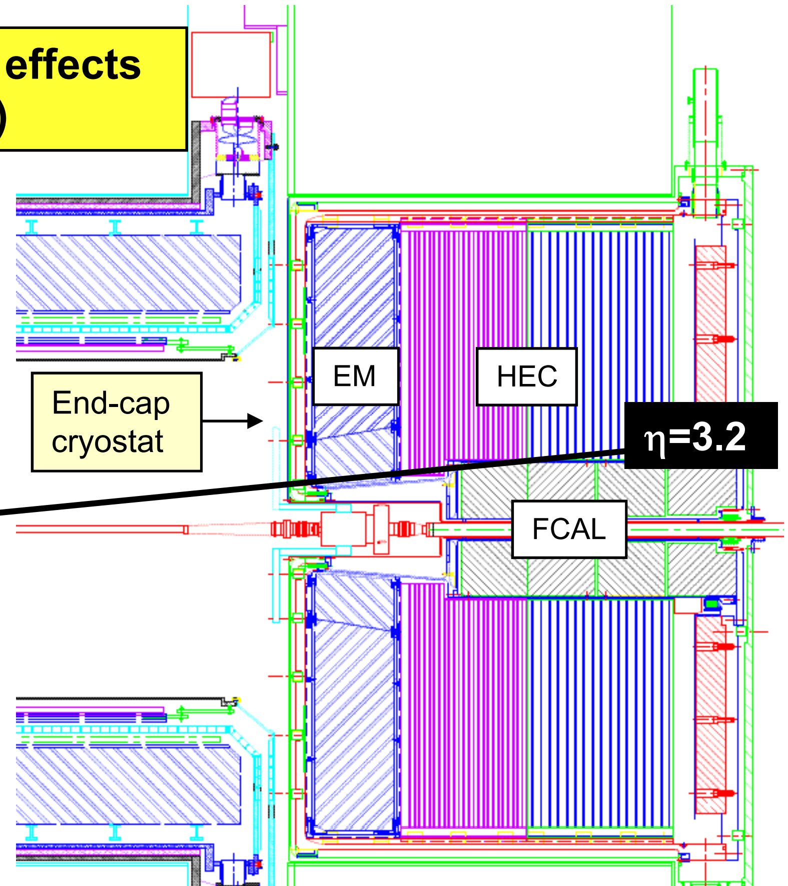
Data:	$\langle R(\pi^0) \rangle = 3.54 \pm 0.12$
MC:	$\langle R(\pi^0) \rangle = 3.66 \pm 0.10$

$\pi^{\pm}$ **E-resolution from the ATLAS had. calorimeter test beam data: ~ 70%/√E**

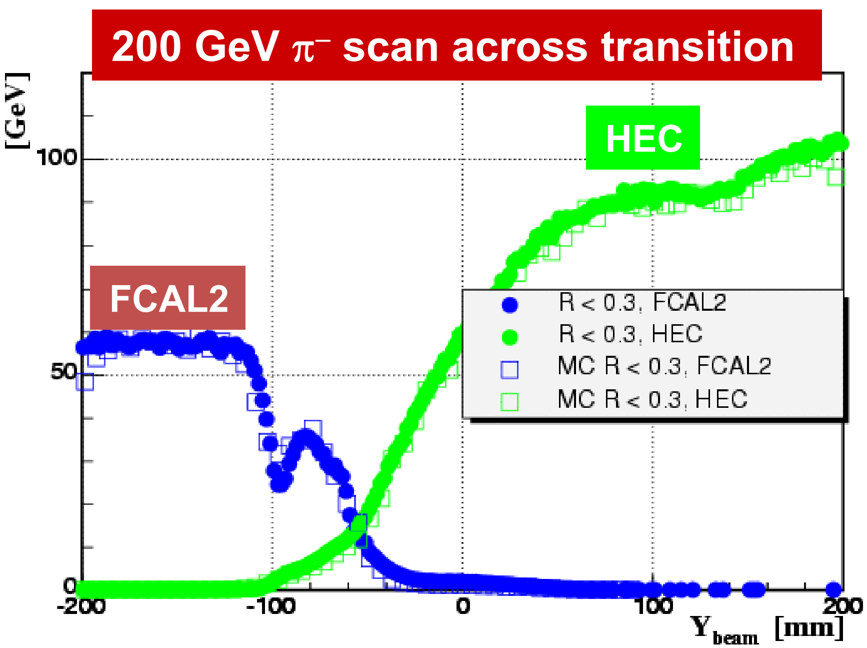


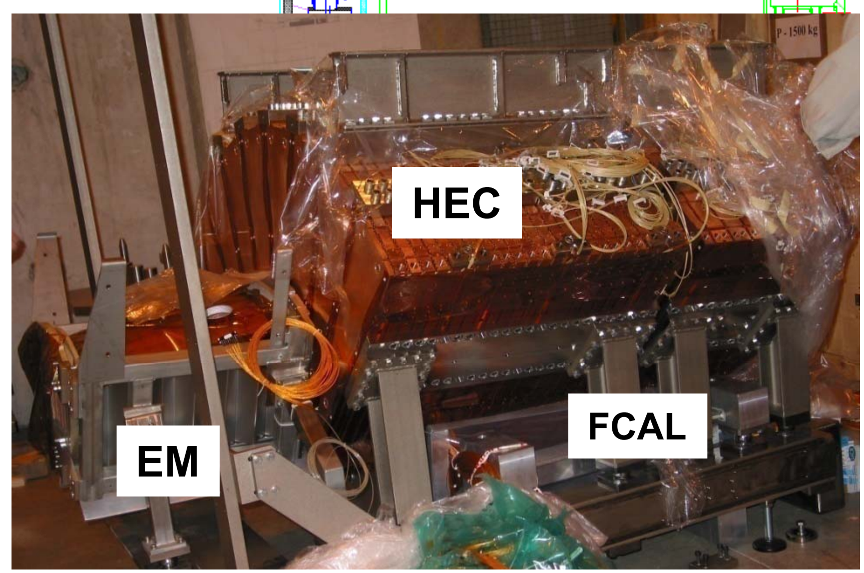
Background study: fake E_T^{miss} tails from instrumental effects (calorimeter non-compensation, resolution, cracks, …)

Transition between end-cap **(EM, hadronic/HEC)** and forward **(FCAL)** calorimeters at η=3.2 studied with dedicated combined test-beam in H6 beam in 2004

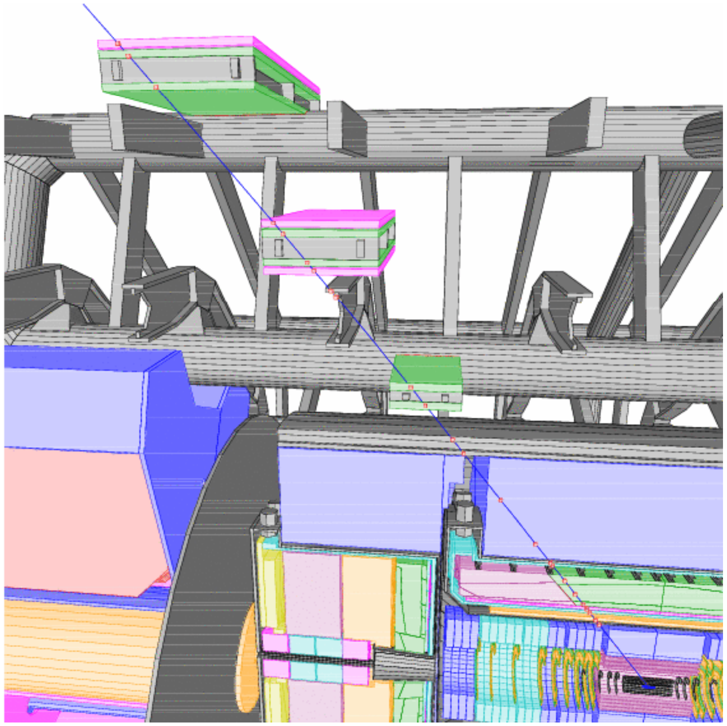


Data described well by MC in complex region with 3 different calorimeters and a lot of material



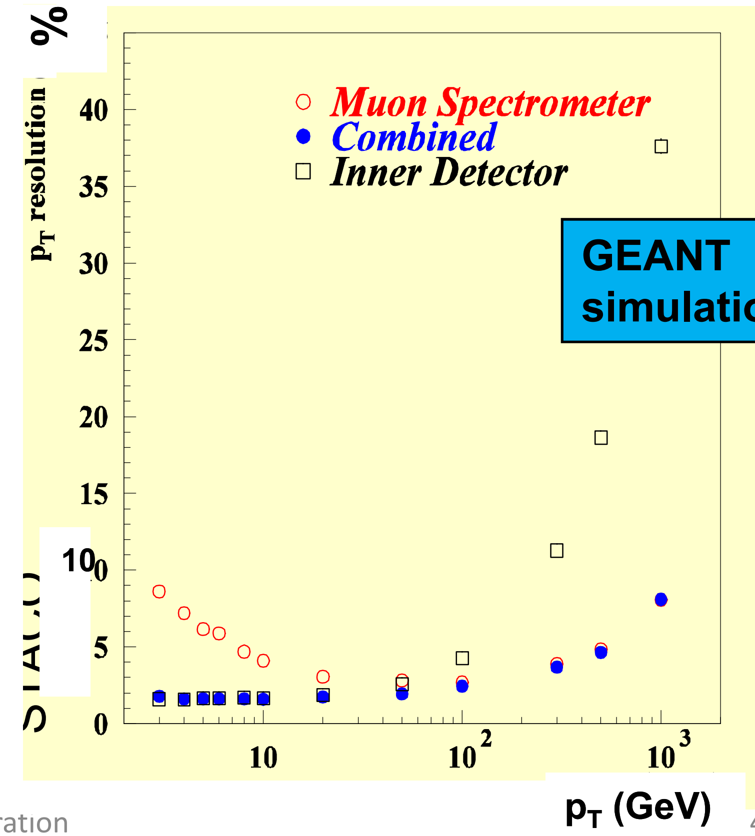


Another example: ATLAS Muon Spectrometer resolution



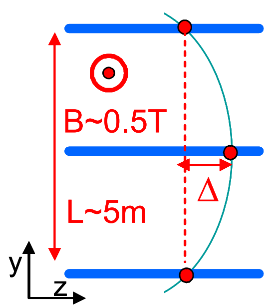
$\sigma/p < 10\%$ for $E_{\mu} \sim$ TeV **needed to observe a possible new resonance** $X \rightarrow \mu\mu$ **as "narrow" peak**

ATLAS Muon momentum resolution

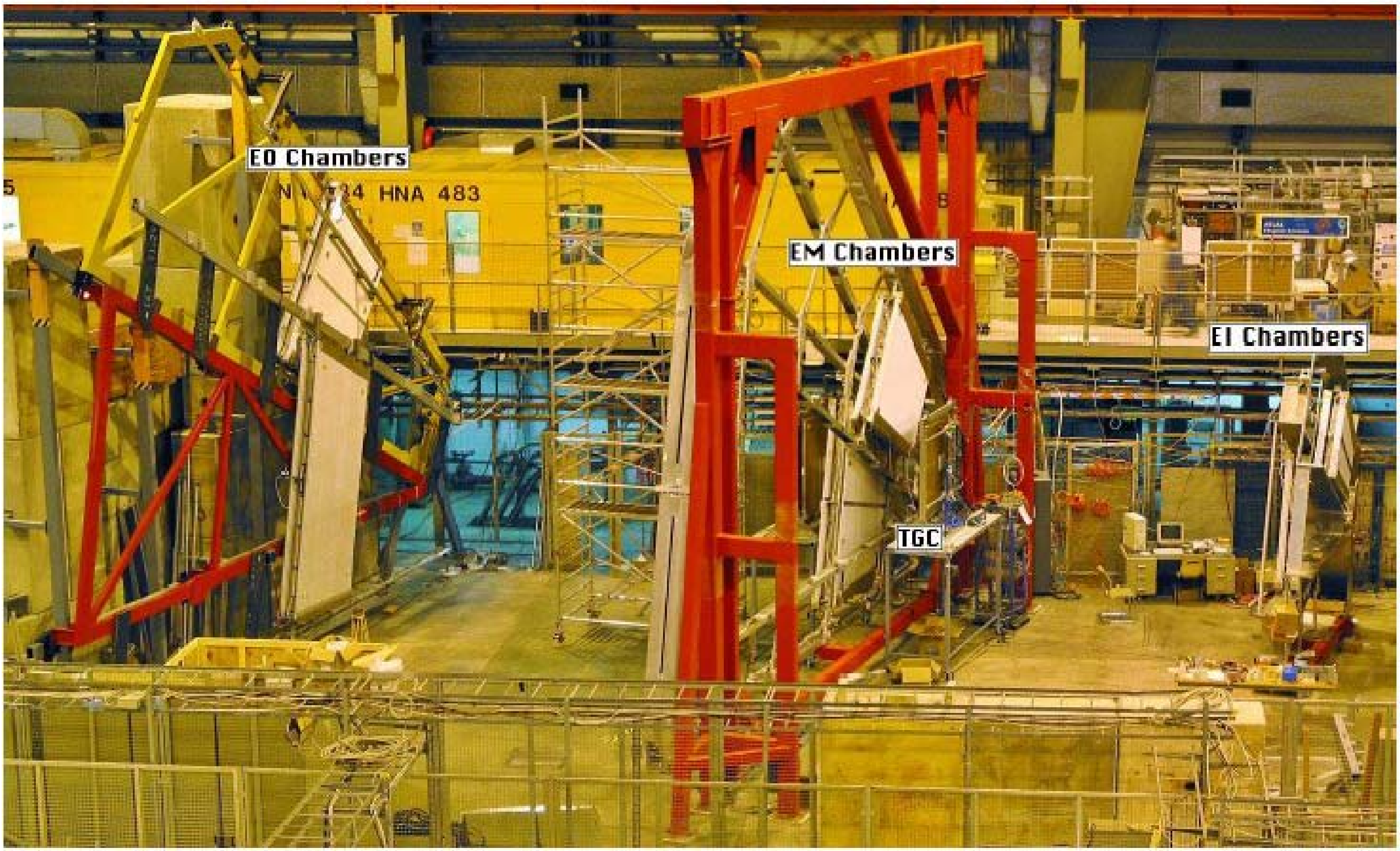


ATLAS Muon Spectrometer:
$E_{\mu} \sim 1$ TeV $\Rightarrow \Delta \sim 500\ \mu m$

– $\sigma/p \sim 10\%$ $\Rightarrow$ $\delta\Delta \sim 50\ \mu m$
- alignment accuracy to $\sim 30\ \mu m$

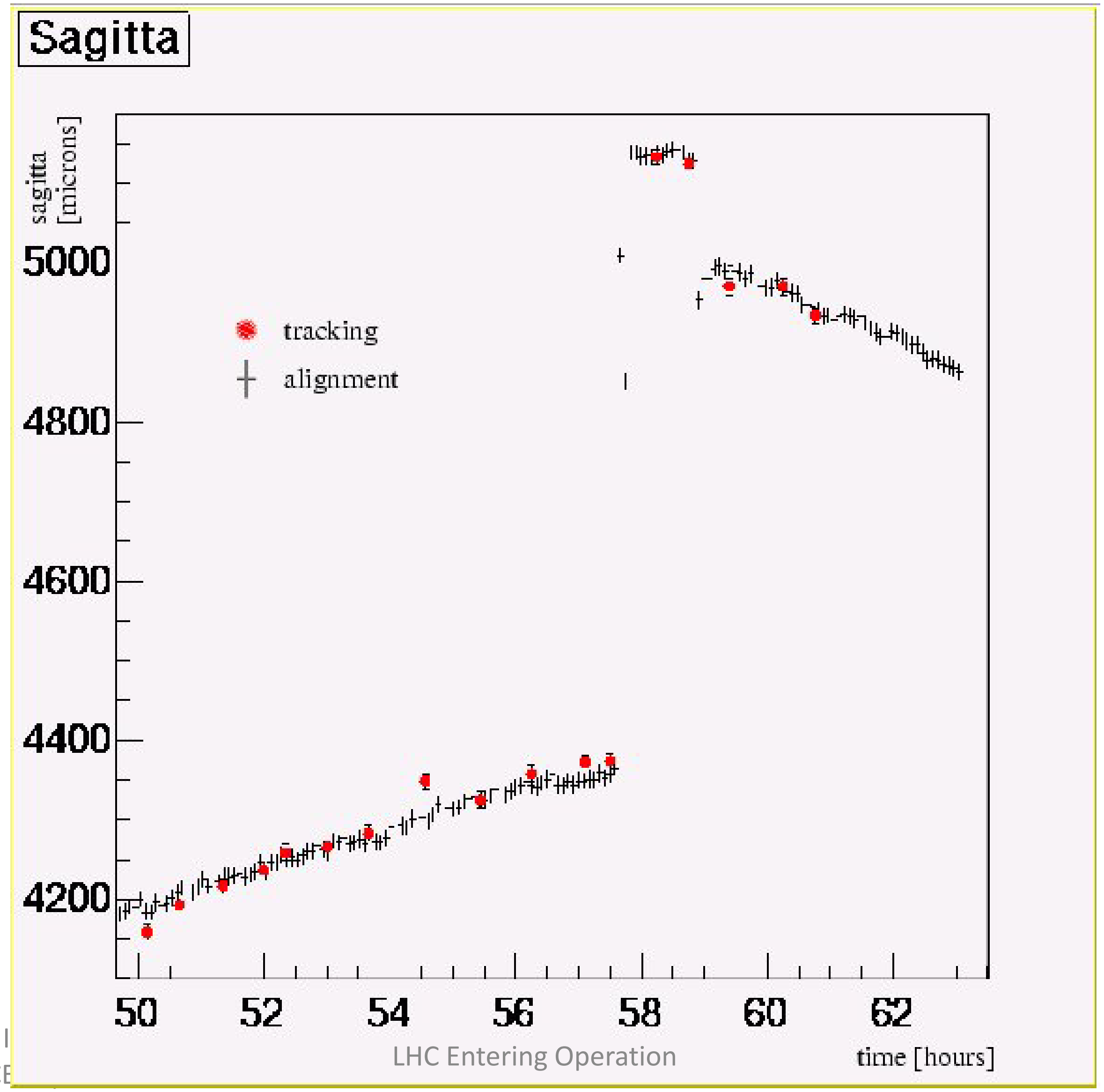


A large-scale system test facility for alignment, mechanical, and many other system aspects, with sample series chamber station in the SPS H8 beam



Shown in this picture is the end-cap set-up, it is preceded in the beam line by a barrel sector

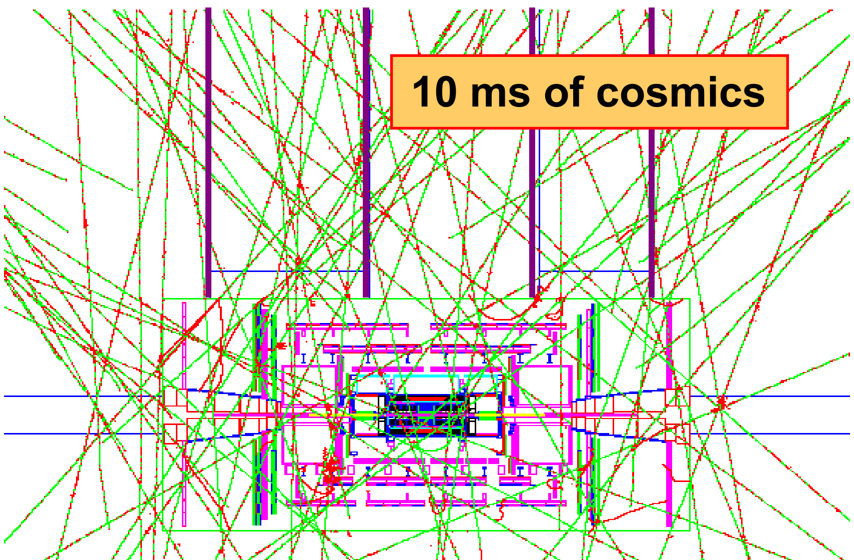
Example of tracking the sagitta measurements, following the day-night variation due to thermal variations of chamber and structures, and two forced displacements of the middle chamber → movements well tracked within the required precision of ~ 10 microns



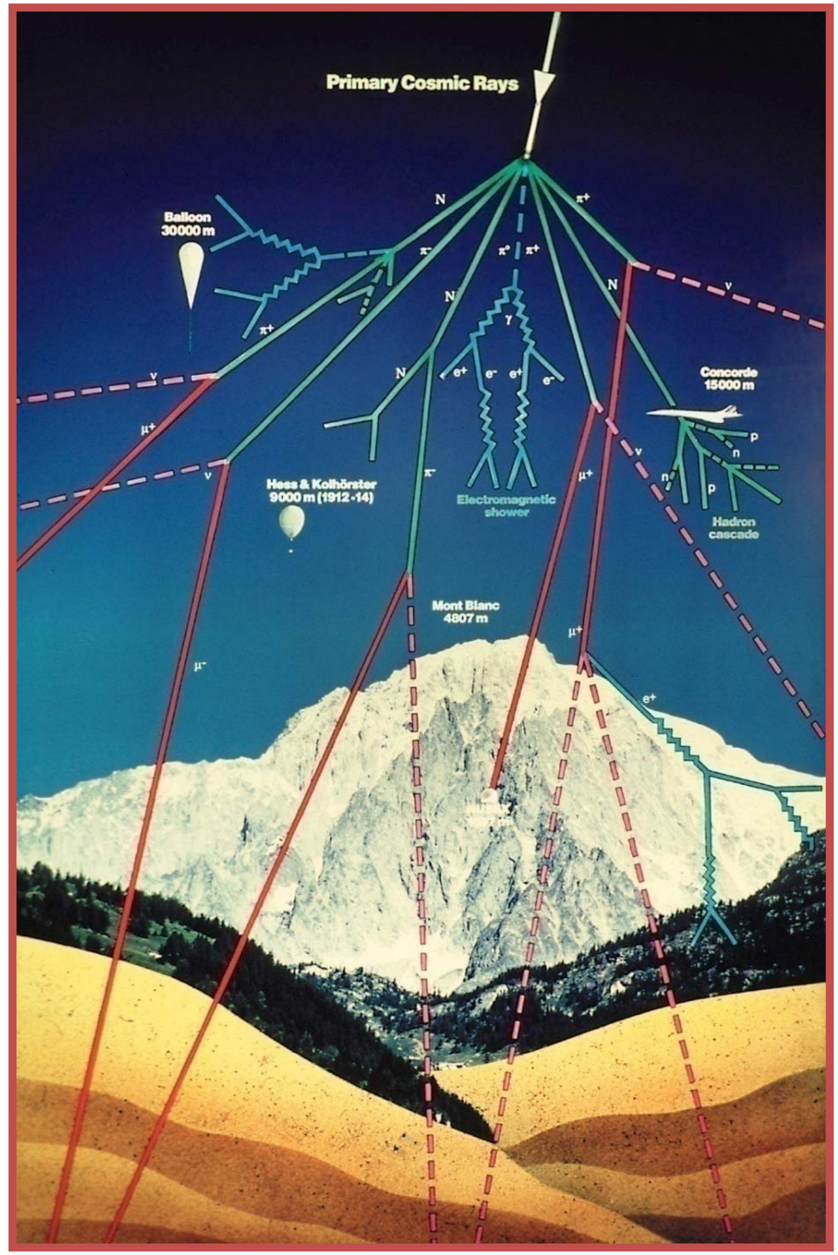
Commissioning with cosmics in the underground cavern
(the first real data in situ …)

Started about three years ago. Very useful to:

- **Run an increasingly more complete detector with final trigger, data acquisition and monitoring systems.** **Data analyzed with final software**
- **Shake-down and debug the experiment in its final position** $\rightarrow$ **fix problems**
- **Perform first calibration and alignment studies**
- **Gain global operation experience in situ before collisions start**



Rate of cosmics in ATLAS: 0.5-100 Hz
(depending on sub-detector size and location)



Continuous Operation of CMS

CRAFT: 'Cosmics Run at Four Tesla'

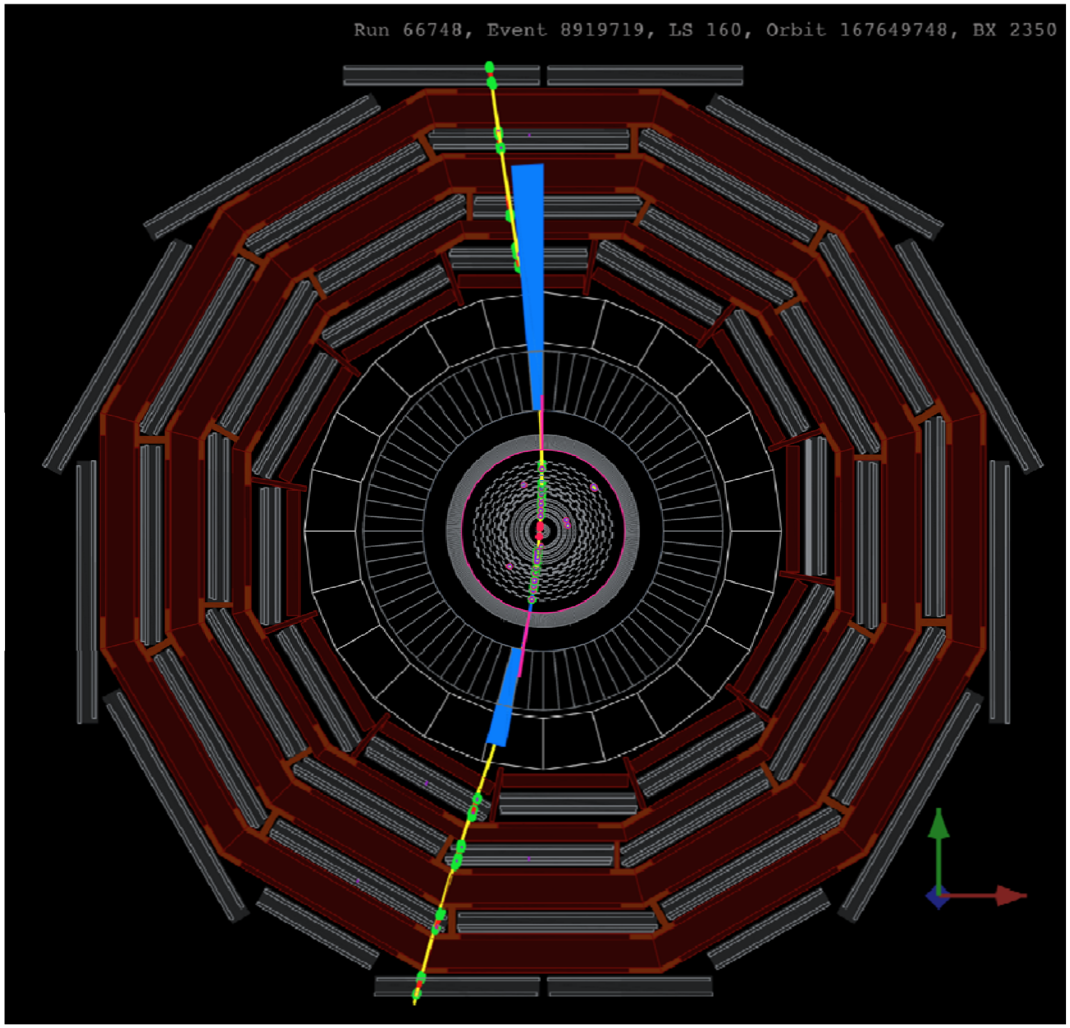
CMS ran for 6 weeks (Oct/Nov 08) continuously to gain operational experience

Collected 300M cosmic events with tracking detectors and field (≈ 70% live-time). About 400 TB of data distributed widely.

87% have a standalone muon track reconstructed

3% have a global muon track with strip tracker hits (~7M trks)

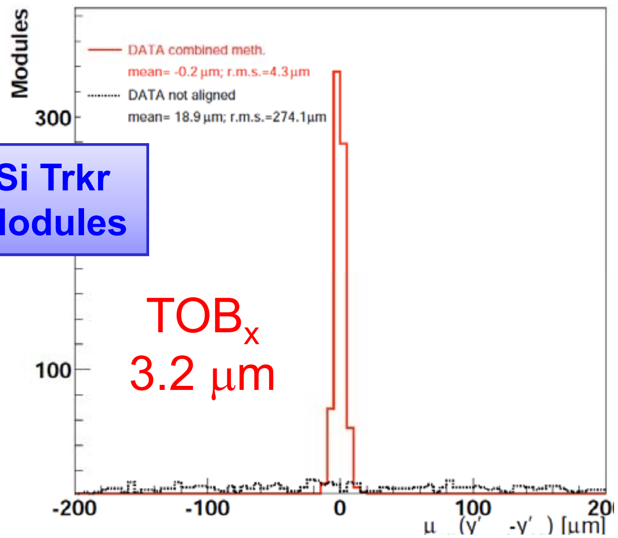
3-4 x 10^{-4} have a track with pixel hits (~70k trks)

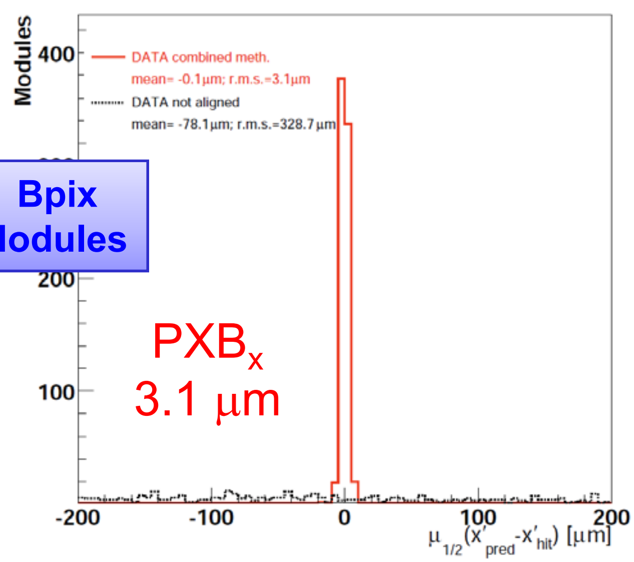


CMS CRAFT Results: Some Examples

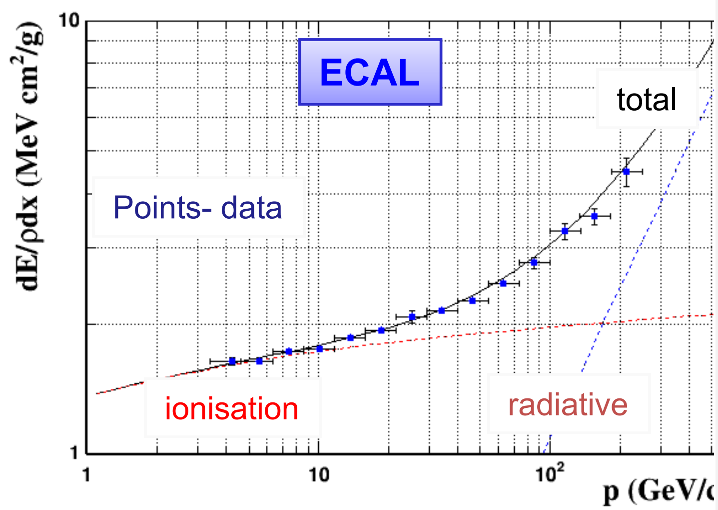
Alignment in Inner Tracker

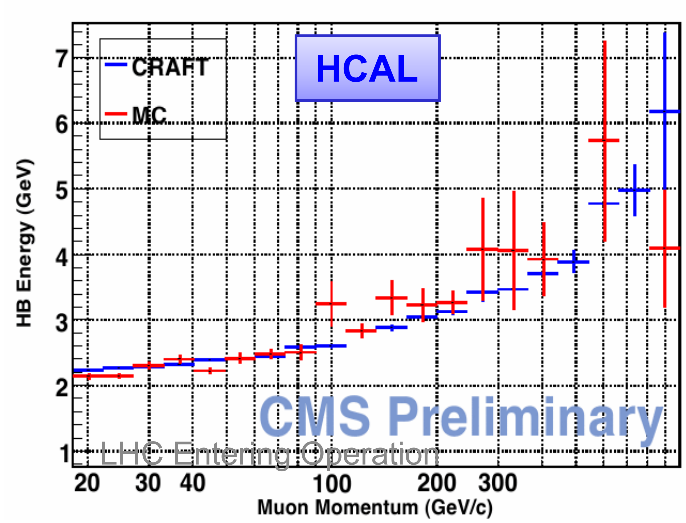
Distn of Mean Residuals



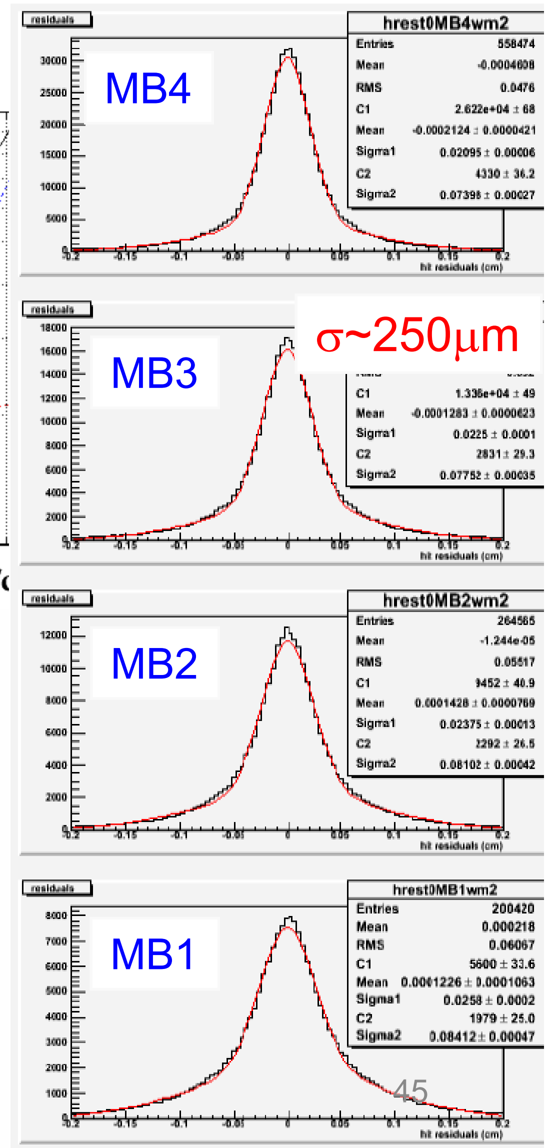


Energy deposited by muons



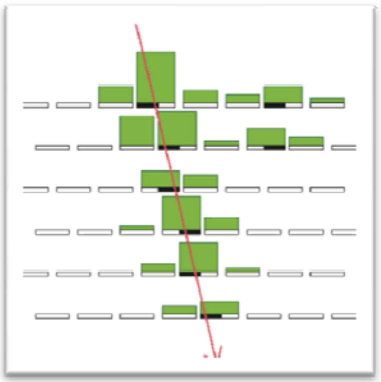


Muon Chambers Point Resolution

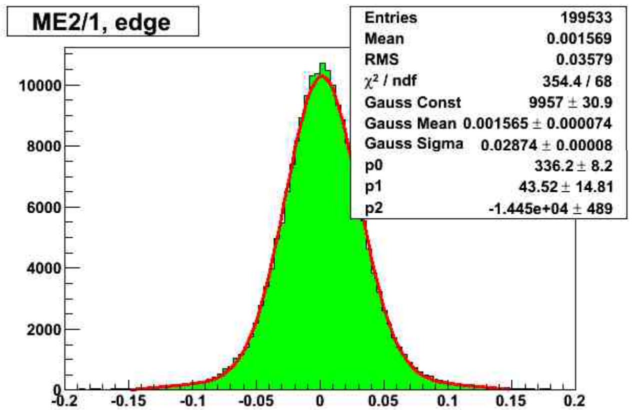


CMS CRAFT: Muon Resolution

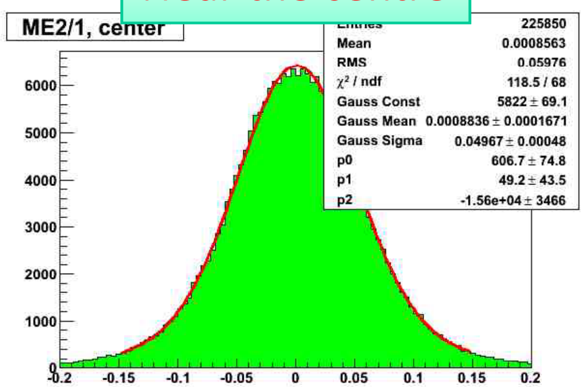
CSC chambers
6 Staggered
planes of strips

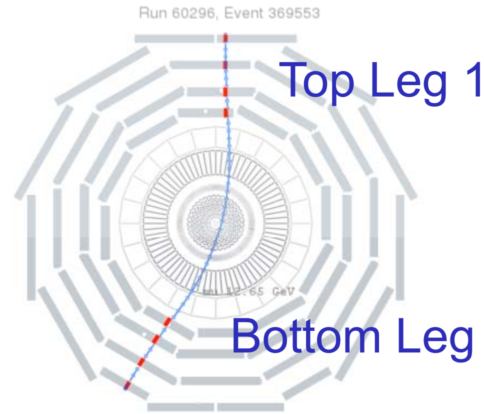


Near the strip edges

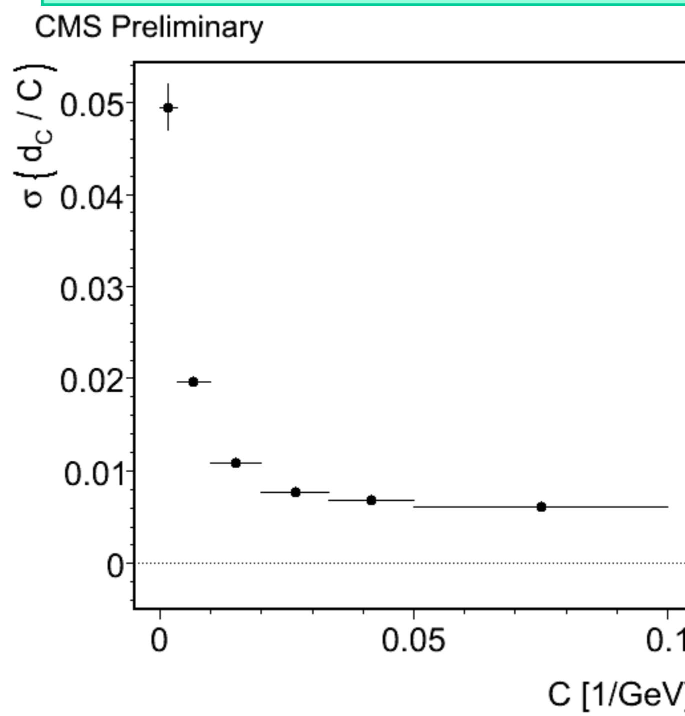


Near the centre





Momentum Resolution <2-leg>



$$1/\sigma^2\,(\text{chamber}) = 3/\sigma_1^2 + 3/\sigma_2^2$$

σ(ME2/1) = 161μm (TDR = 150μm)

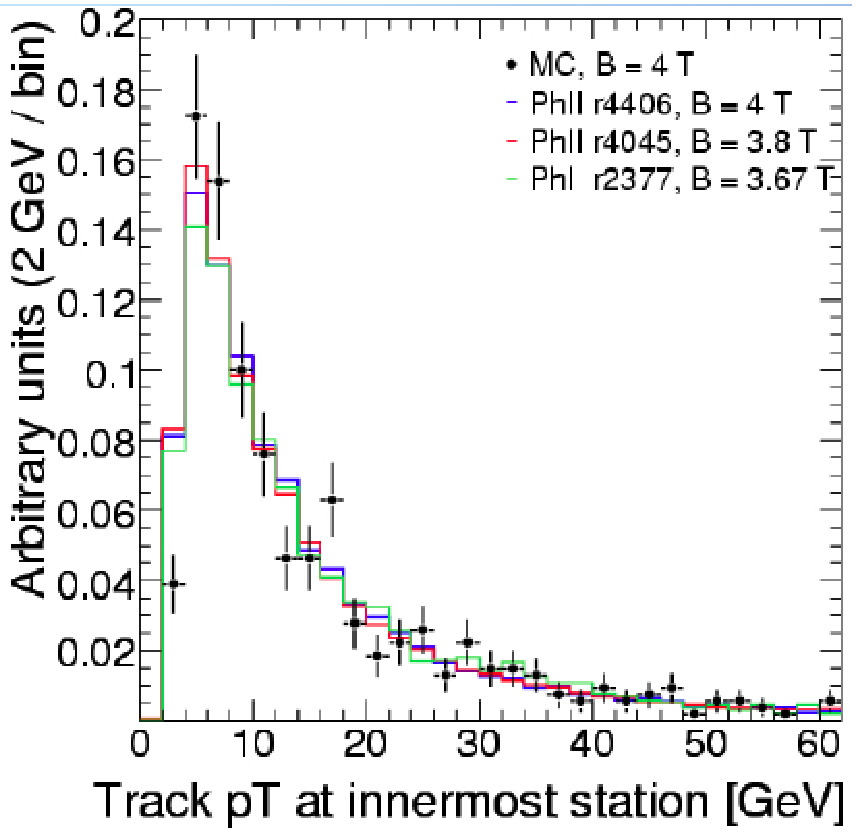
A CMS physics measurement …

CMS preliminary
Results from cosmics data

Data collected on the surface with solenoid on

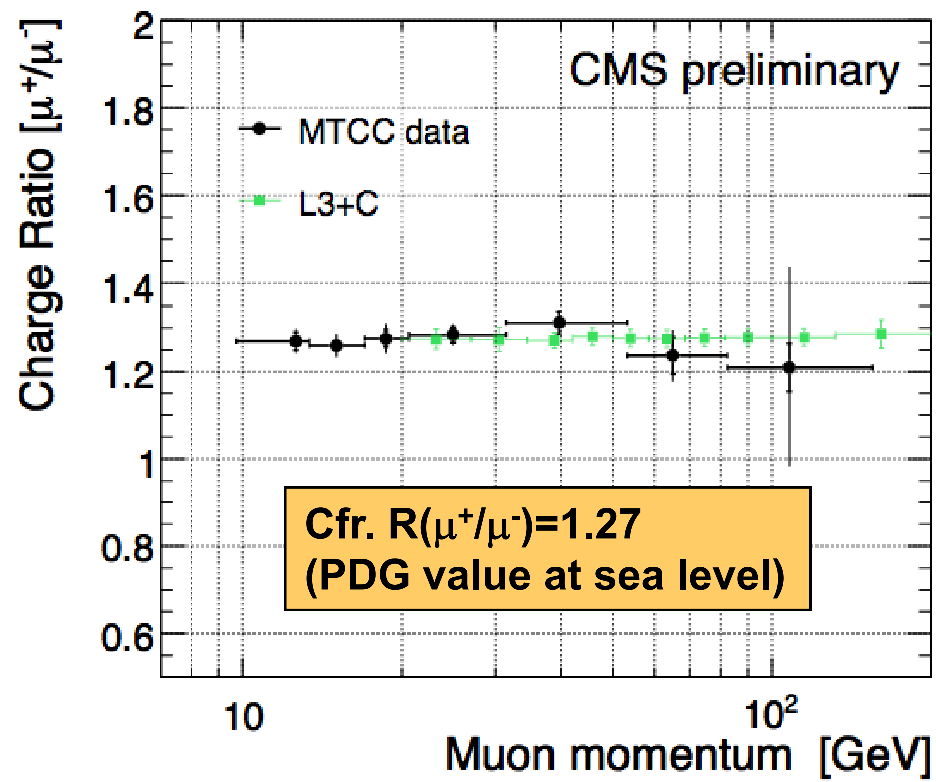
Cosmic muons momentum distribution

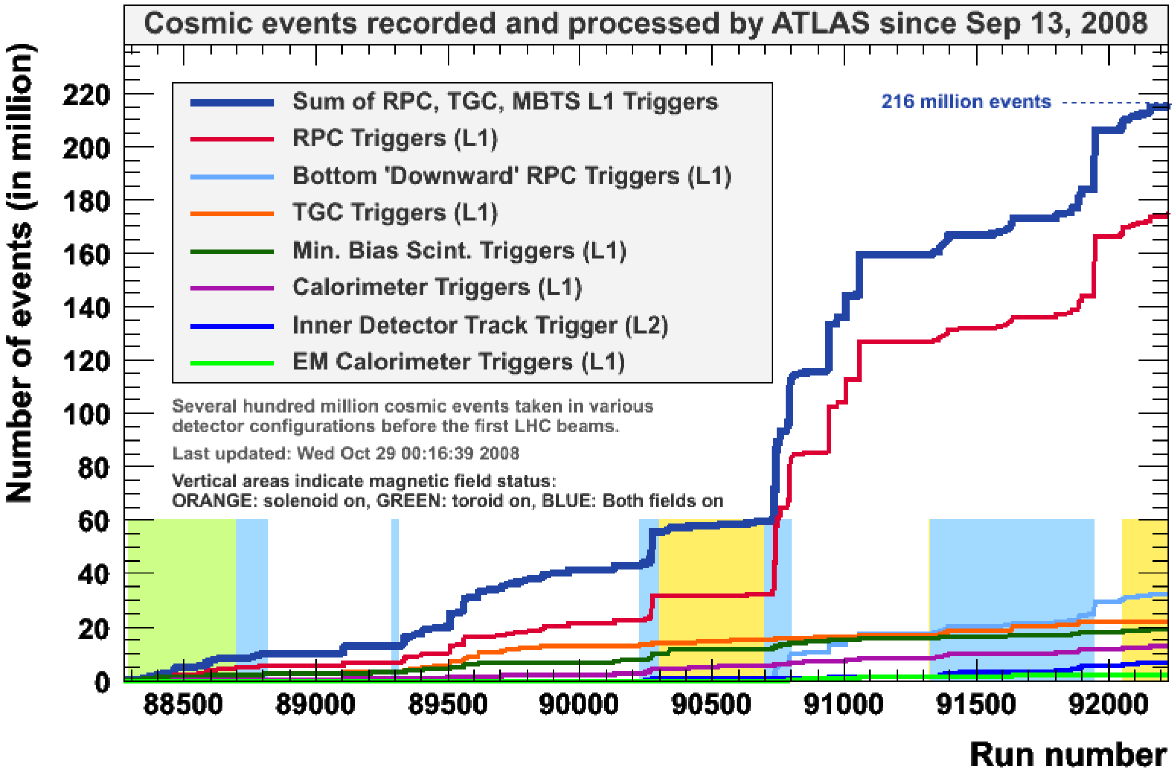
(For several values of the B-field)



Cosmic muons charge ratio (μ^+/μ^-)

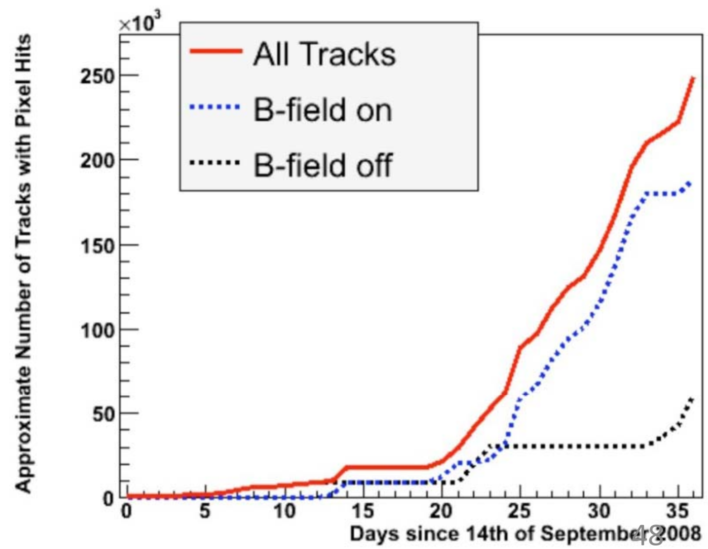
(Awaiting definitive alignment constants)



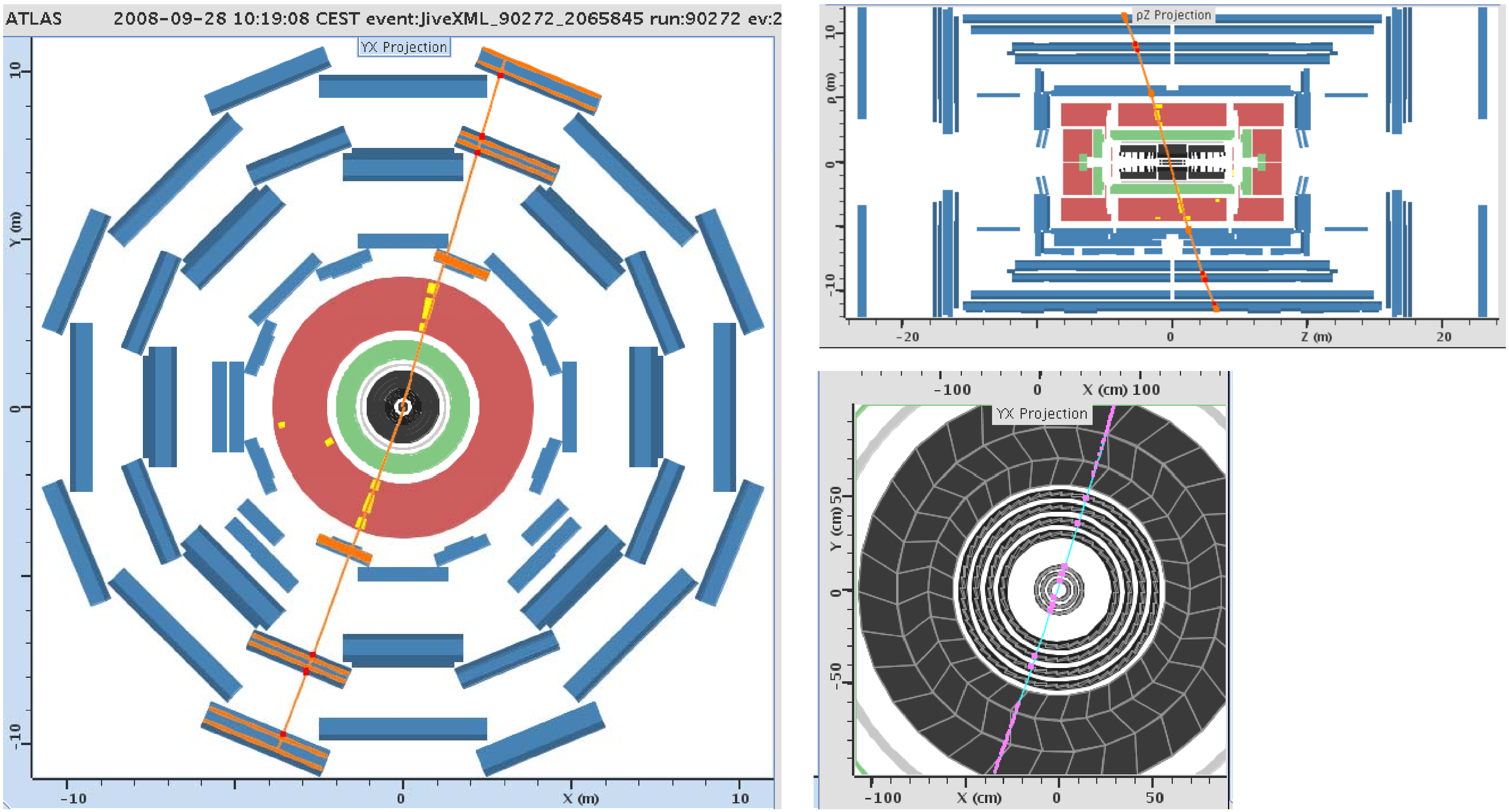


ATLAS

After the LHC incident, a few hundred millions of cosmic ray triggers were recorded in total (left), as well as several 100'000 tracks also in the smallest volume detector, the Pixels (below)

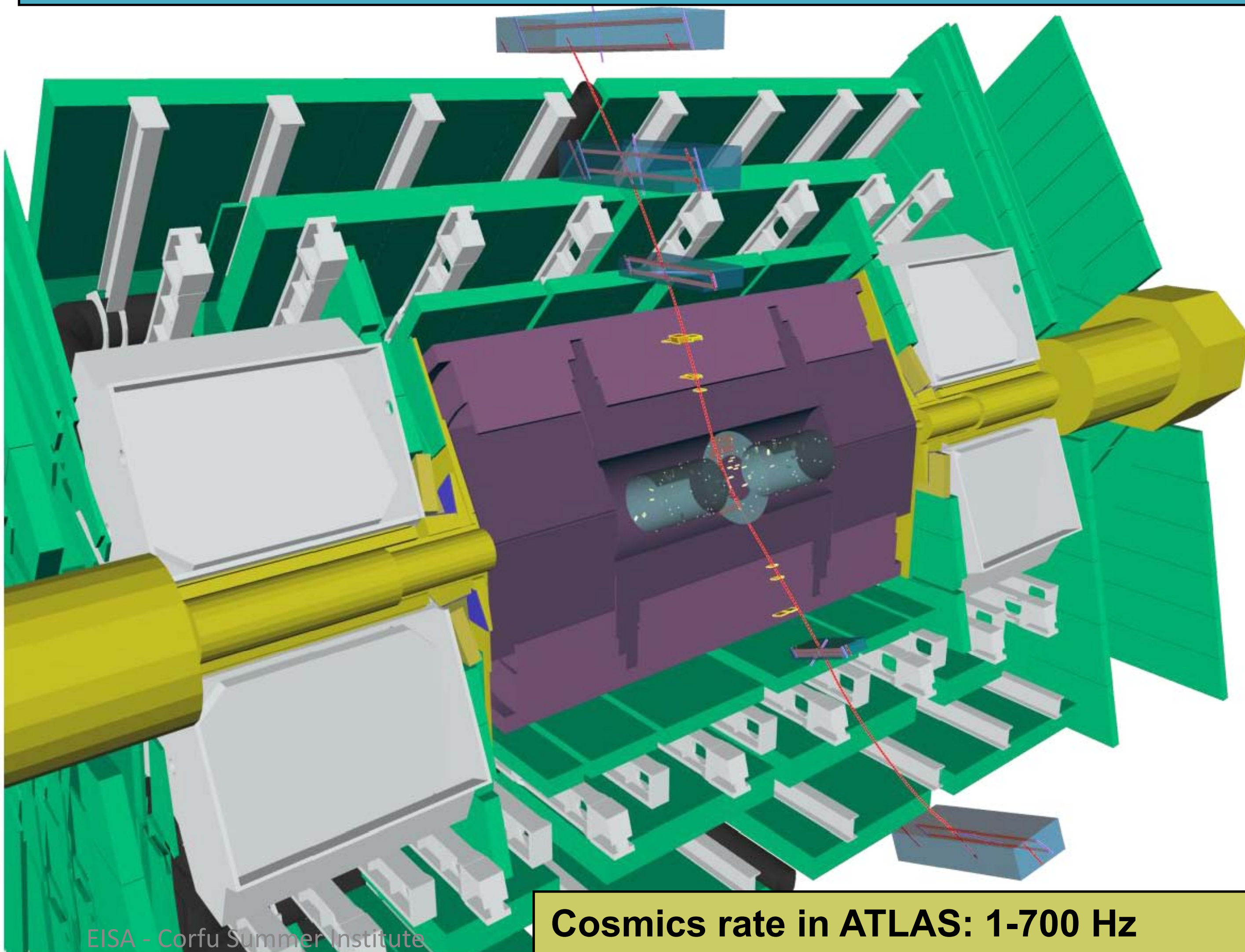


A nice cosmic muon through the whole ATLAS detector…



Commissioning with cosmics in the underground cavern has been very useful to:

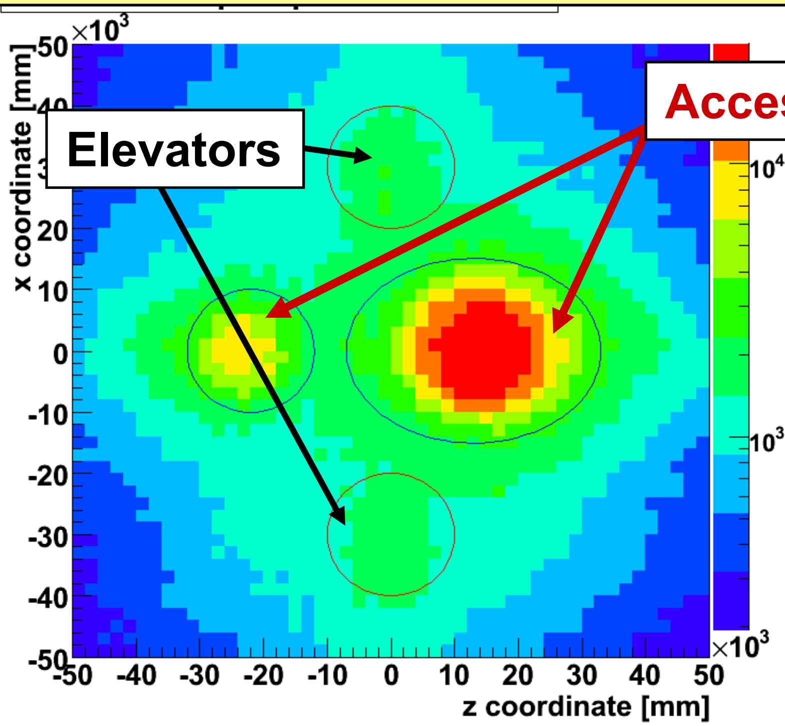
- **Shake-down and debug the experiment in its final position → fix problems**
- **First calibration and alignment studies:**
  achieved precisions far better than expectations at this stage
- **Gain global operation experience in situ**

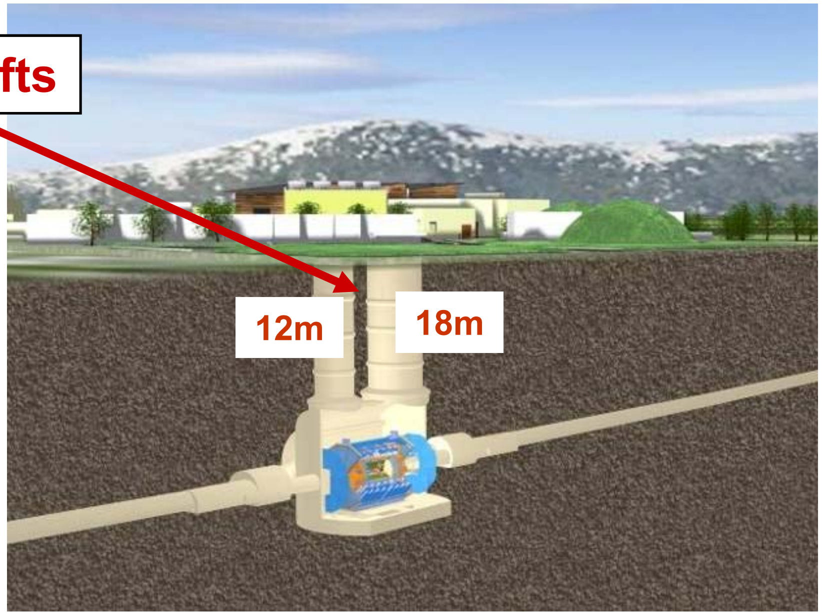


A cosmic muon traversing the whole detector, recorded on 18/10/2008

Cosmics rate in ATLAS: 1-700 Hz (depending on the sub-detector size and location)

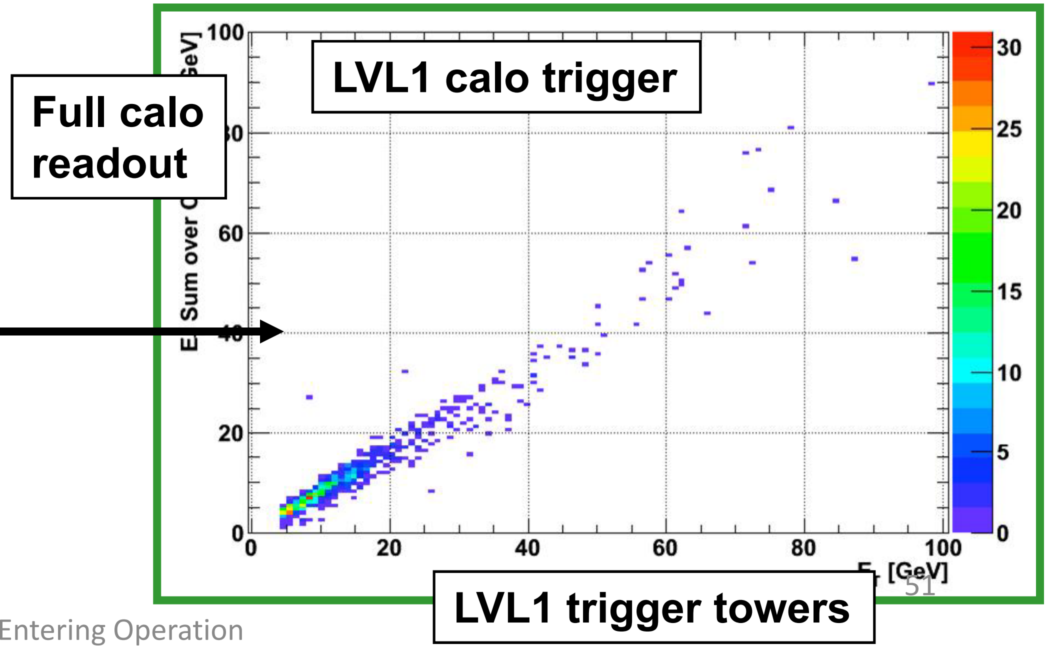
Extrapolation to the surface of cosmic muon tracks reconstructed by RPC trigger chambers



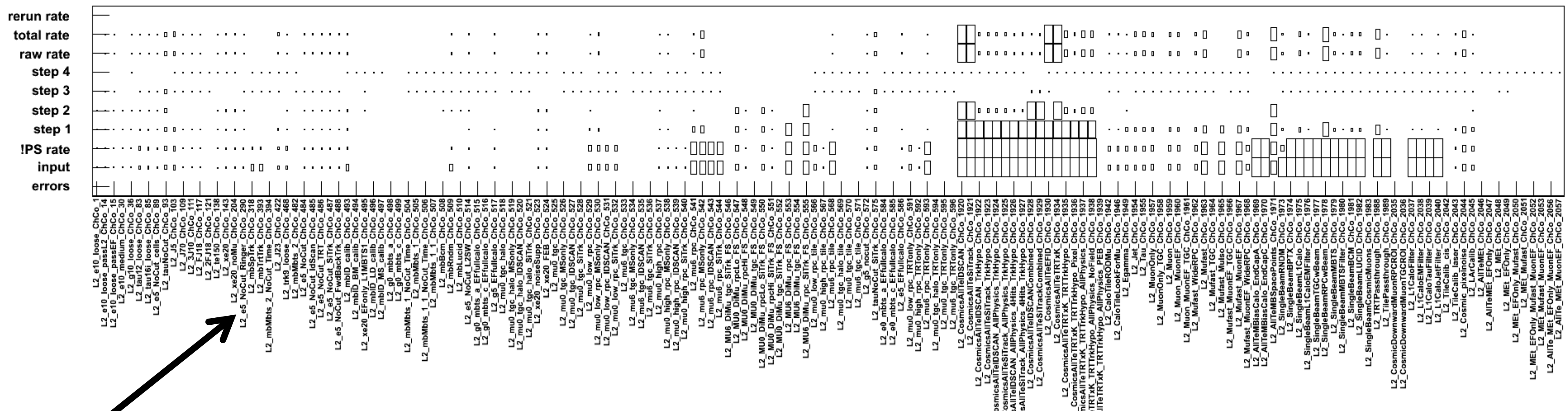


Muon (shower) energy measured with full calorimeter readout vs energy measured in trigger towers ($\eta \times \phi = 0.1 \times 0.1$) by level-one calorimeter trigger

With initial calibration (final calibration will reduce the spread)

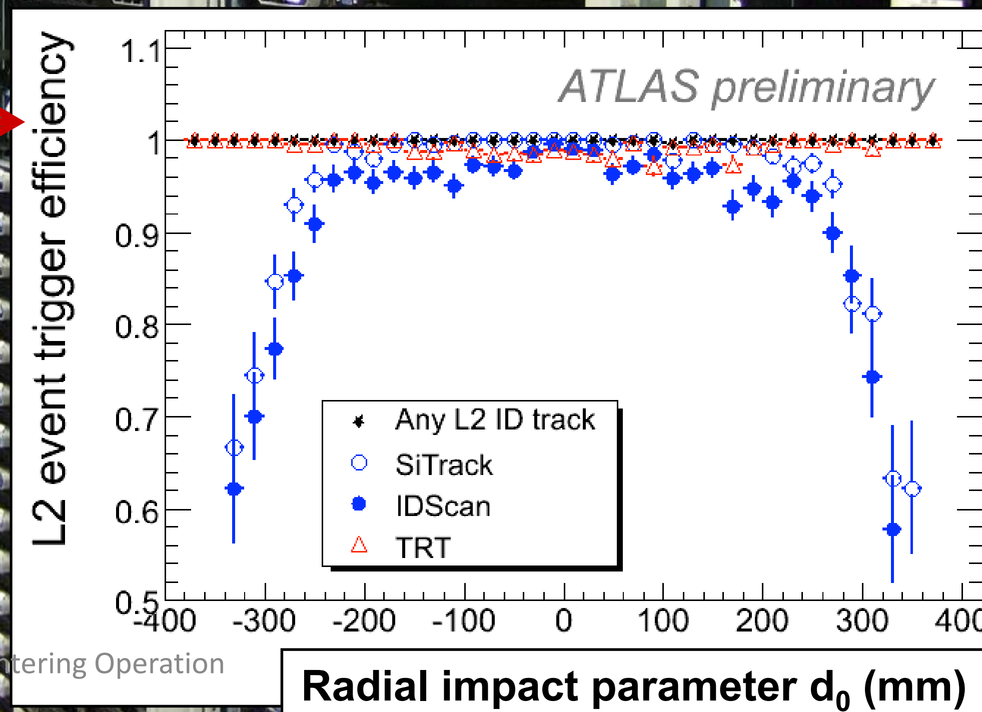


Raw acceptance of signatures in L2 Run Summary



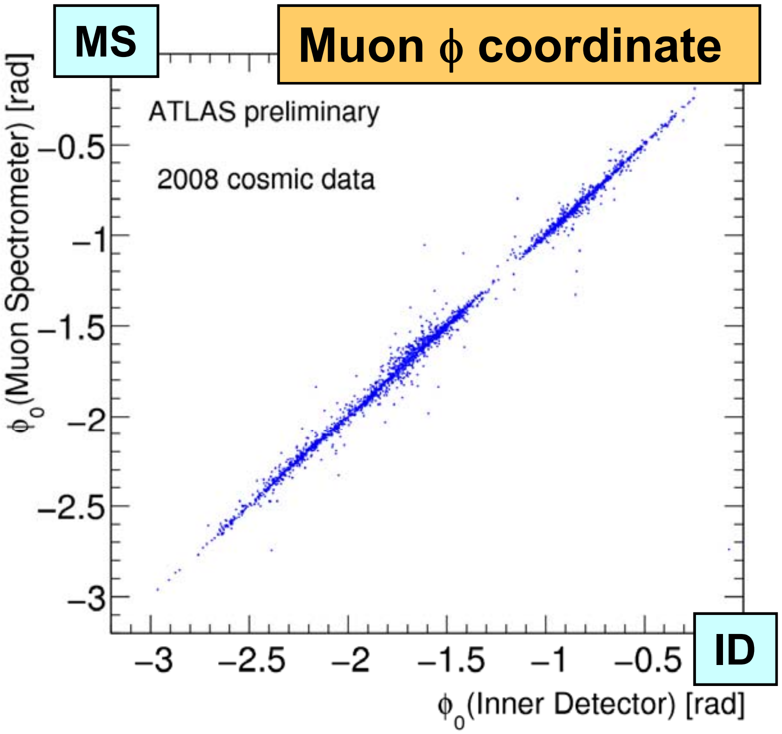
~ Each one of these unreadable lines is a chain run in the HLT during cosmics data-taking

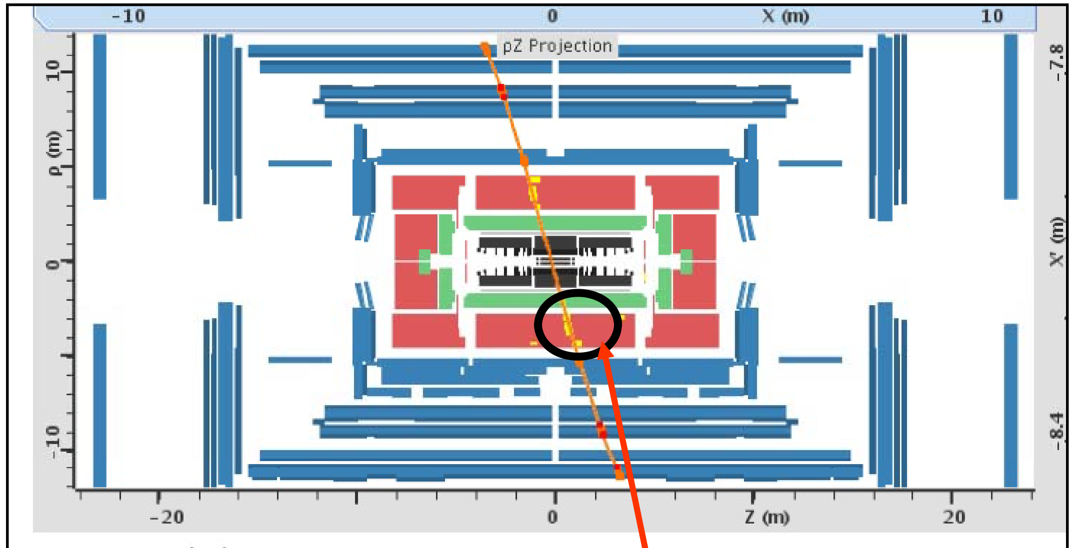
Efficiency of the track trigger at level-two vs track impact parameter
~ 5 M cosmics events selected by this trigger



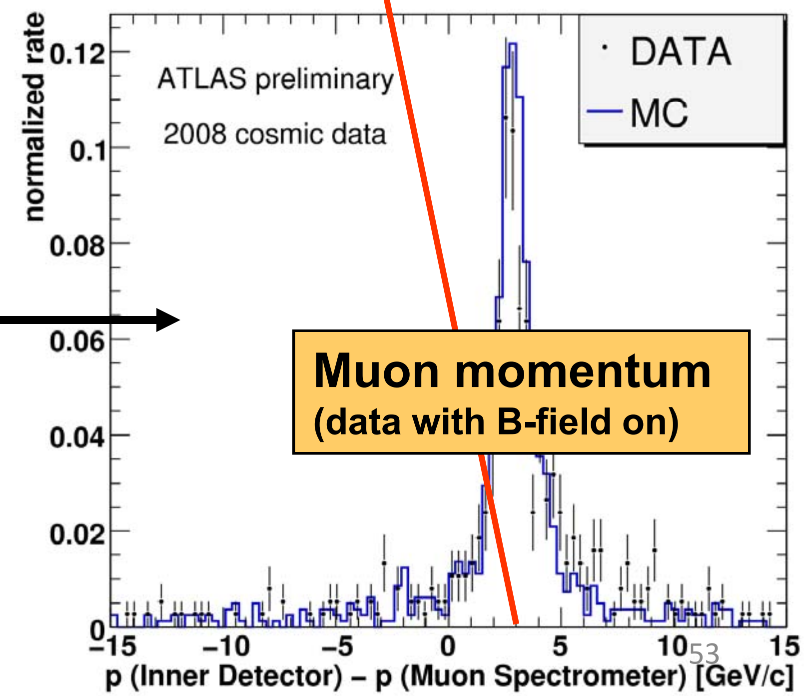
Curves reflect the different geometrical acceptance of the various sub-detectors

Correlation between measurements in the ATLAS Inner Detector and Muon Spectrometer



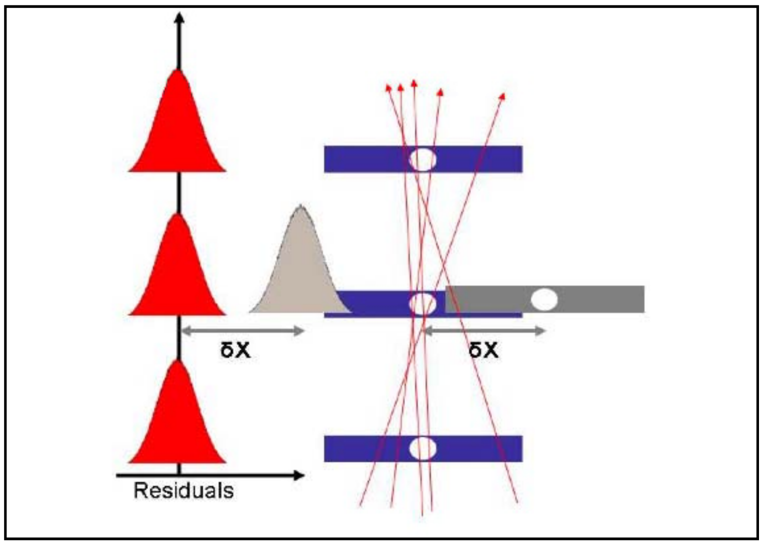


Difference between the muon momentum measured in the ID and in the MS for tracks in the bottom part of the detector (~ 3 GeV energy loss in the calorimeter)



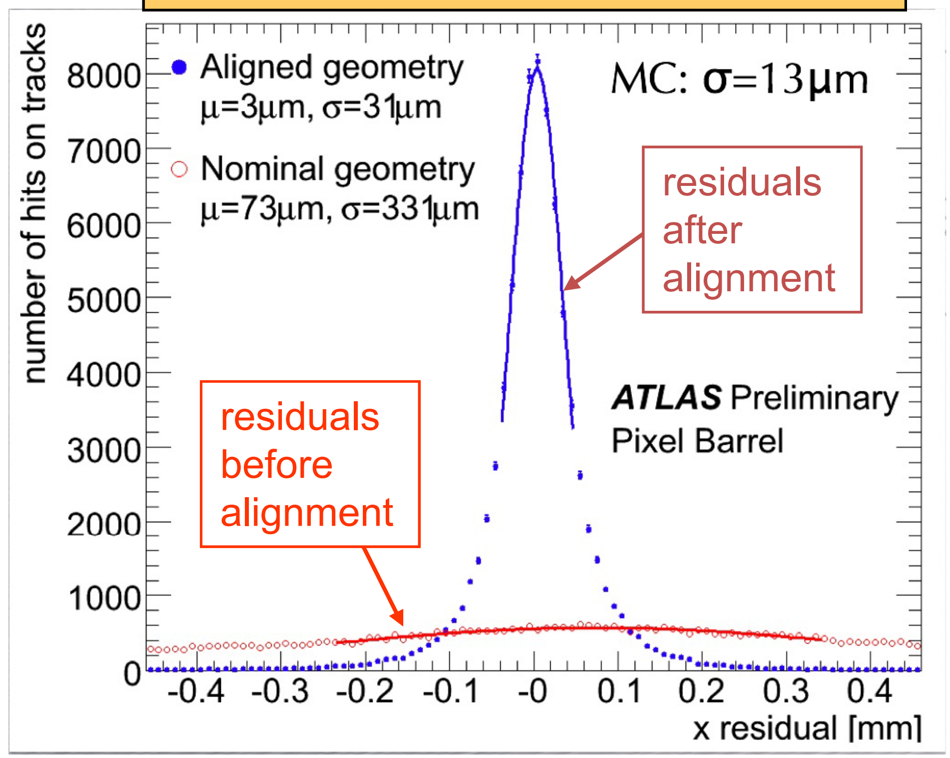
The positions ("alignment") of the Pixels and SCT detector modules must be known to a few microns for a precise reconstruction of the track parameters

The detector alignment is performed using tracks (from cosmics now, pp collisions later) and an iterative procedure that minimizes the hit residuals globally
~ 36000 degrees of freedom: 6000 detector modules x 6 unknown (3 position coordinates + 3 rotation angles per module)



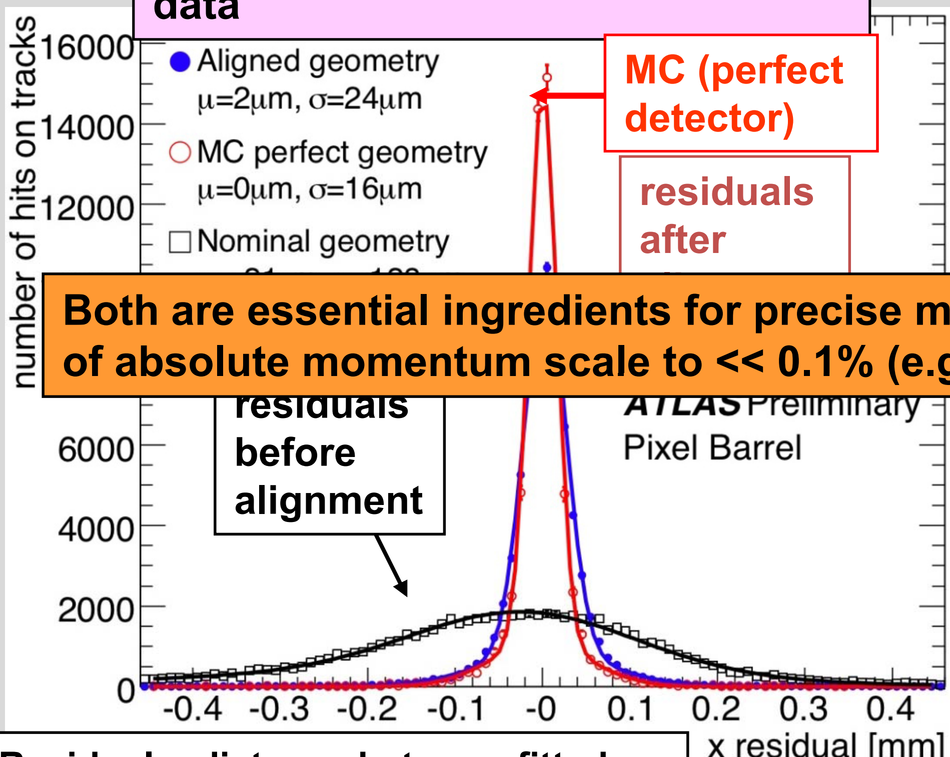
Residuals: distance between the fitted track and the hits in the individual layers. After alignment: distribution of residuals peaks at zero with σ compatible with detector resolution

Pixels alignment with cosmics data



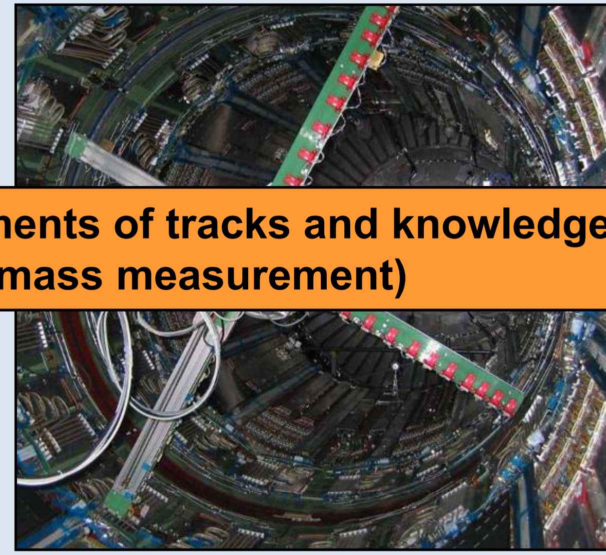
Precision studies towards LHC physics: Inner Detector alignment and B-field measurement

Pixels alignment with cosmics data



Residuals: distance between fitted track and hits in the individual layers

Solenoid B-field mapping campaign 2006: precision of 2×10^{-4} (4 Gauss) achieved

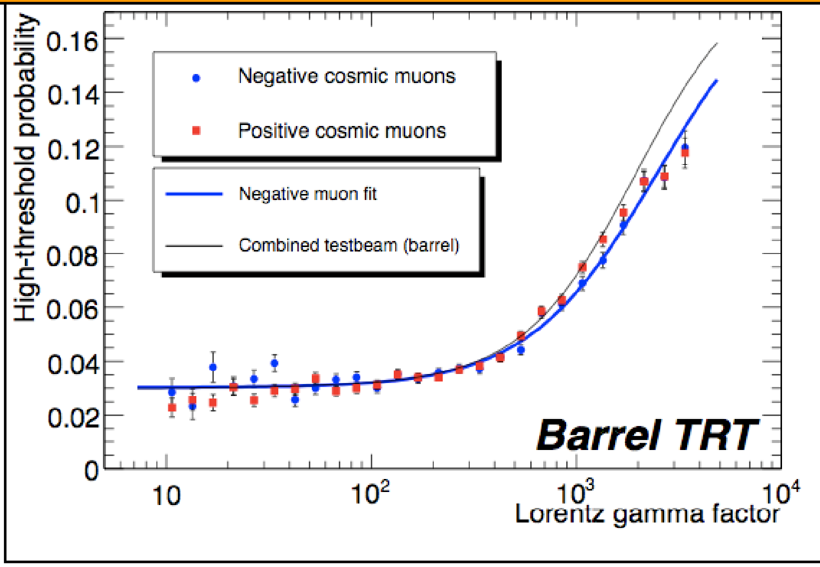


Both are essential ingredients for precise measurements of tracks and knowledge of absolute momentum scale to << 0.1% (e.g. for W-mass measurement)

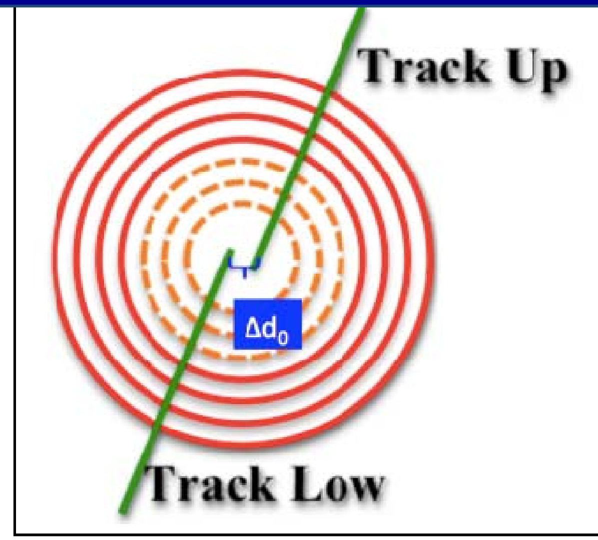
Field mapping machine inside solenoid volume: 250 000 points measured (5 currents)

Pixels, SCT: achieved with cosmics:
- **alignment precision: ~ 20 μm (ultimate goal 5-10 μm)**
- **alignment stability Oct-2008-June-2009: few microns**
- **layer hit efficiency: > 99% ; occupancy: 10^{-10}**

Transition radiation intensity is proportional to particle γ-factor: onset at high γ (E~100 GeV for muons)



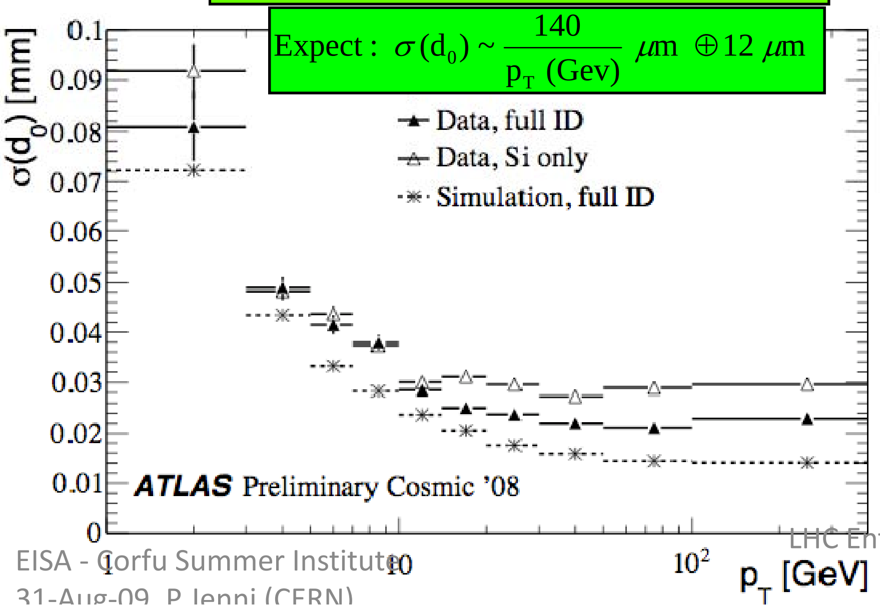
Tracks are split in the center and refit separately → can measure resolutions and biases from data



Split tracks

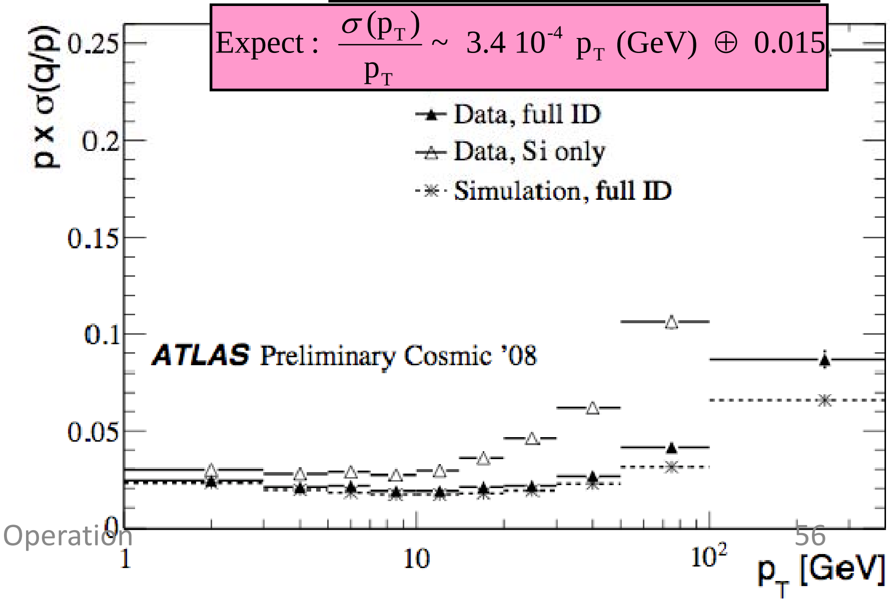
Impact parameter resolution

Expect : $\sigma(d_0) \sim \dfrac{140}{p_T\ (\mathrm{Gev})}\ \mu m \oplus 12\ \mu m$



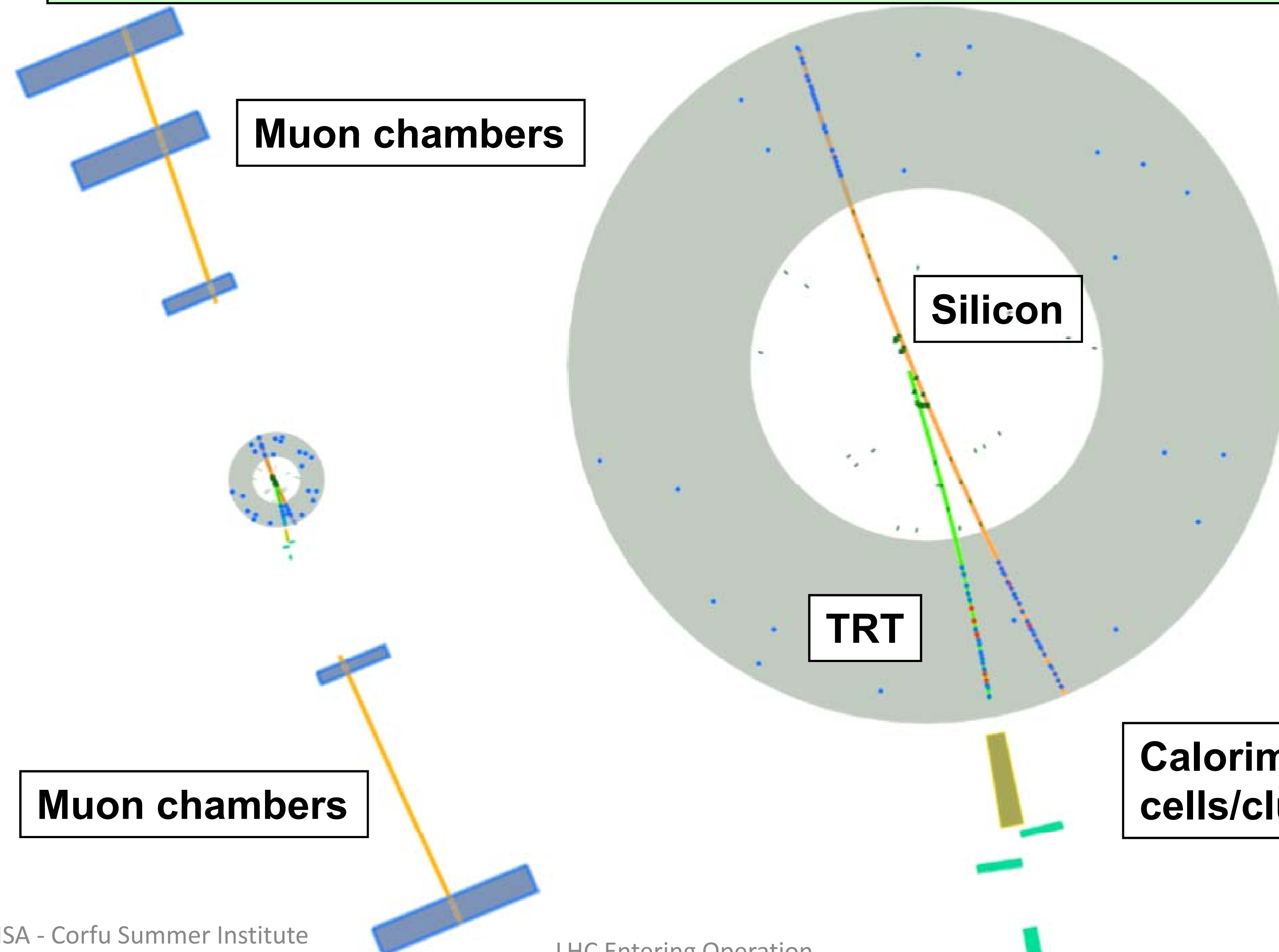
Momentum resolution

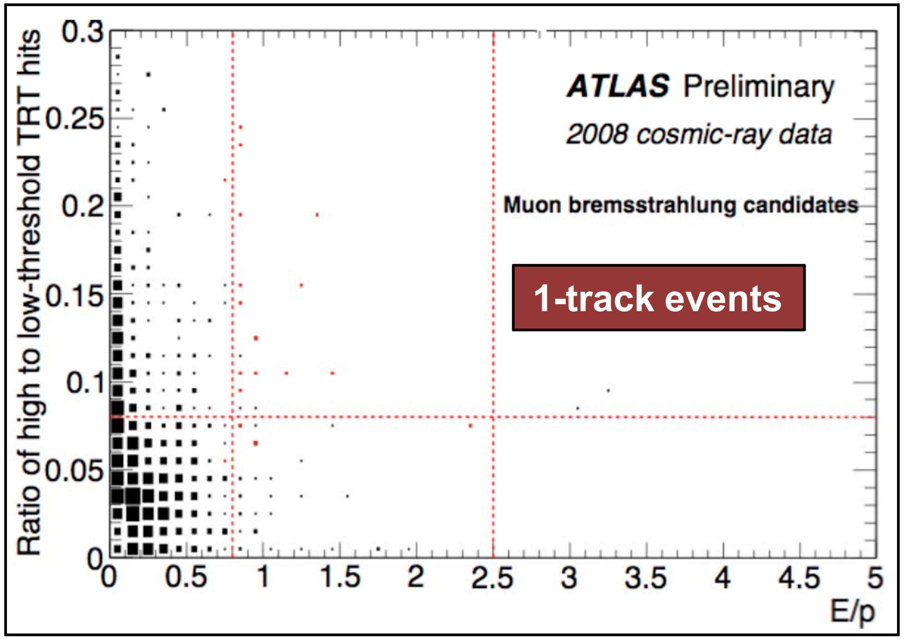
Expect : $\dfrac{\sigma(p_T)}{p_T} \sim 3.4\ 10^{-4}\ p_T\ (\mathrm{GeV}) \oplus 0.015$

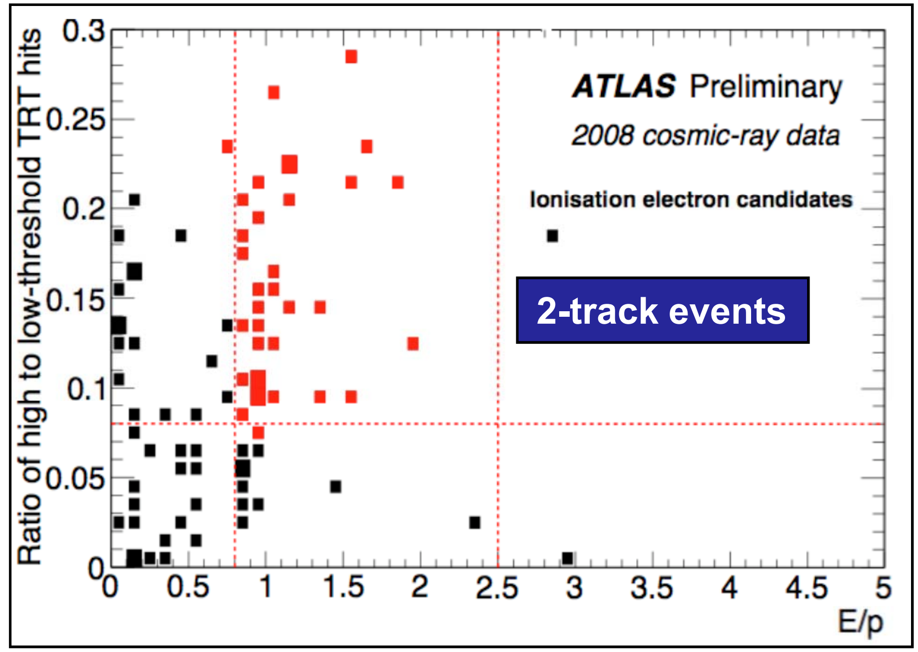


First electrons observed in ATLAS: from ionization of cosmics muons

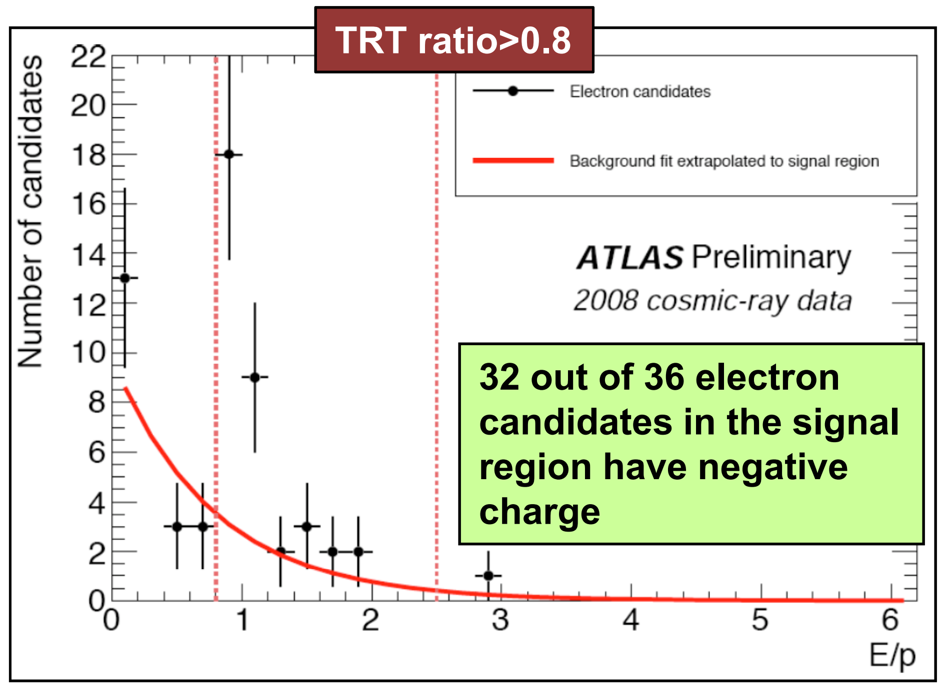
Event display of one of the electron candidates, recorded on 28/9/2008





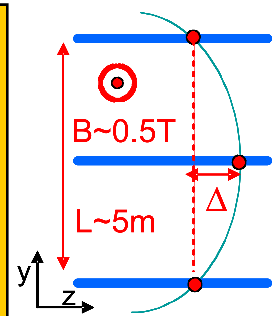


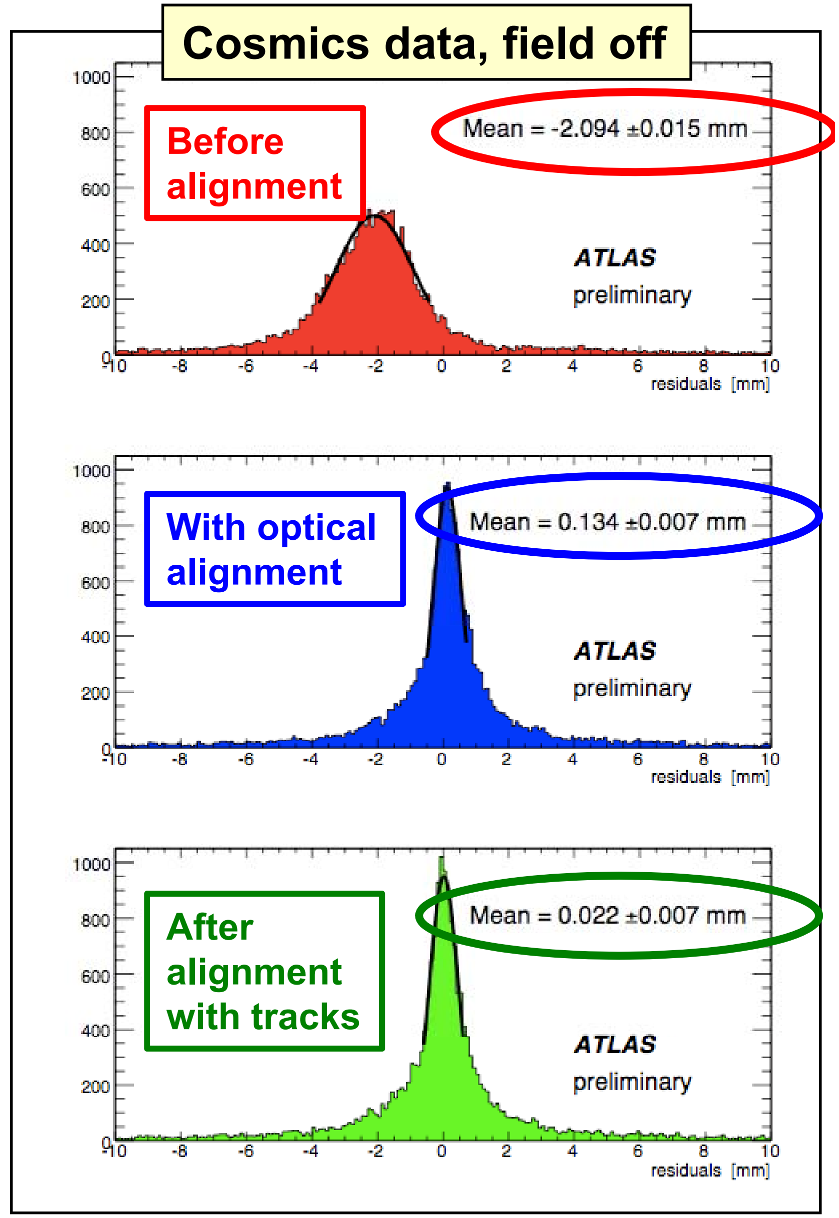
- Electrons produced by ionization (δ-rays)
- Input: 3.5 M events selected by level-two track trigger. Loose association required: track - EM cluster with E>3 GeV
- Resulting samples:
  electron "signal": events with 2 tracks
  background: events with 1 track
  (γ Bremsstrahlung by muons)
- Discrimination based mainly on TRT signal and E(calorimeter)/p(tracker) ratio



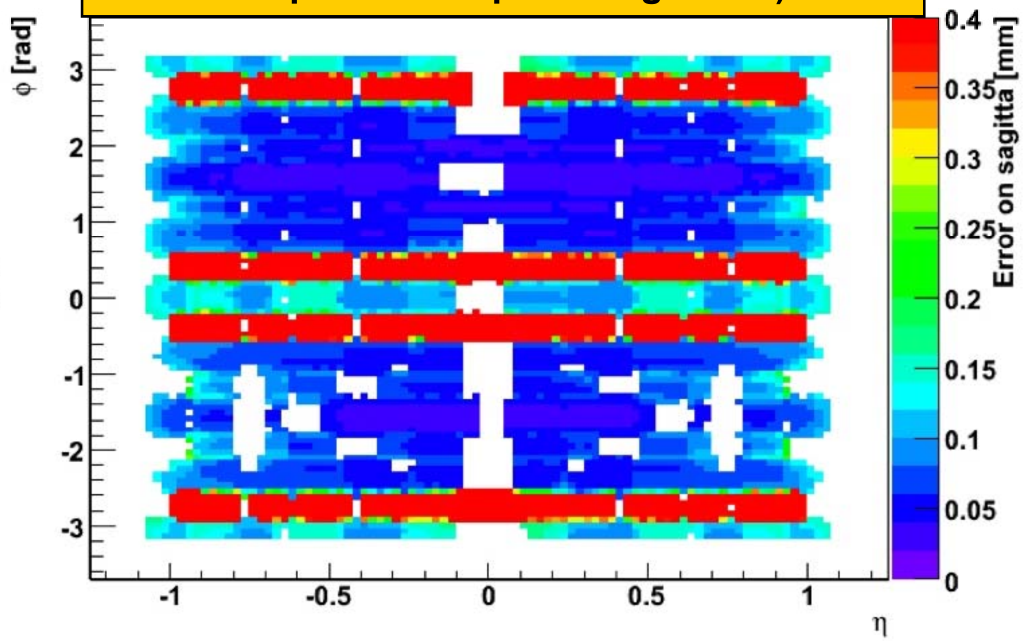
To observe new heavy resonance X→ μμ as "narrow" peak → σ/p<10% for E_μ~ 1 TeV

ATLAS Muon Spectrometer:
E_μ~ 1 TeV ⇒ sagitta Δ~500 μm
⬇
- **s/p ~10% ⇒ δΔ~50 μm**
- **alignment accuracy to ~40 mm**

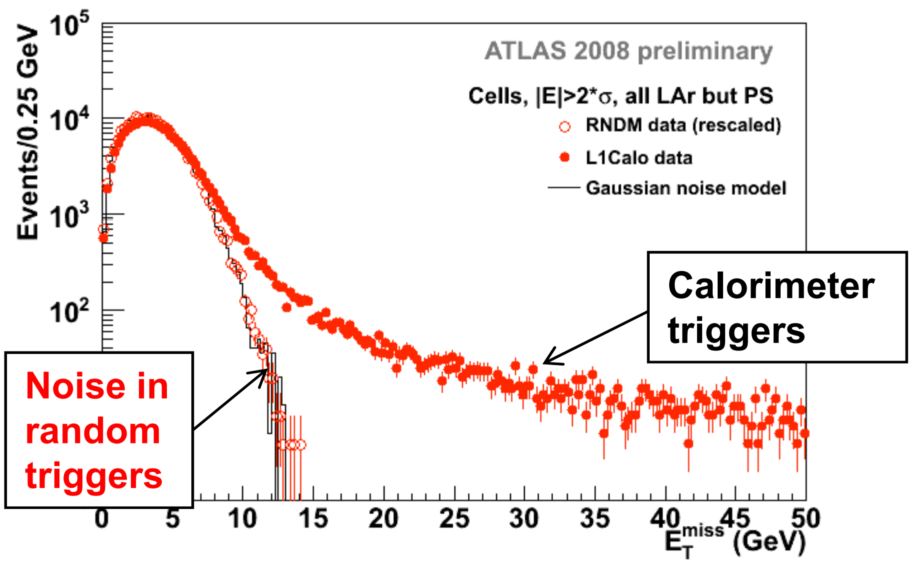




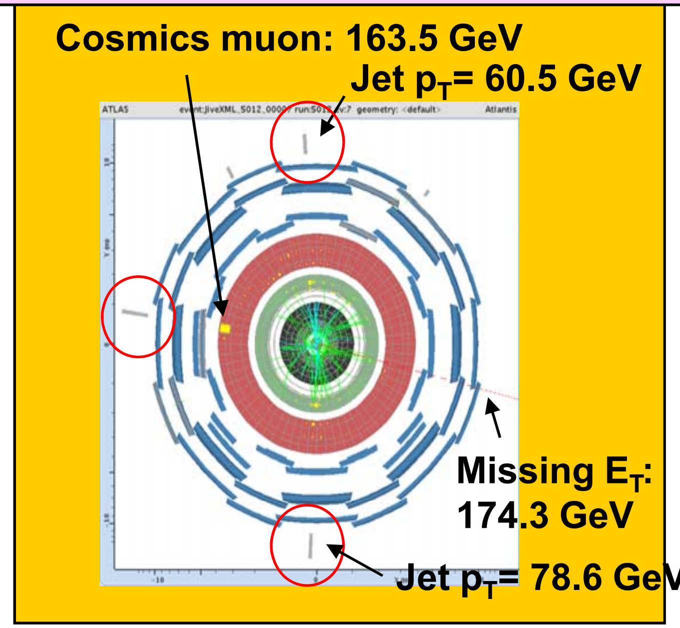
Expected alignment accuracy on "Day-1" (first collisions) combining cosmics and optical alignment (red regions are sectors on horizontal plane w/o optical alignment)

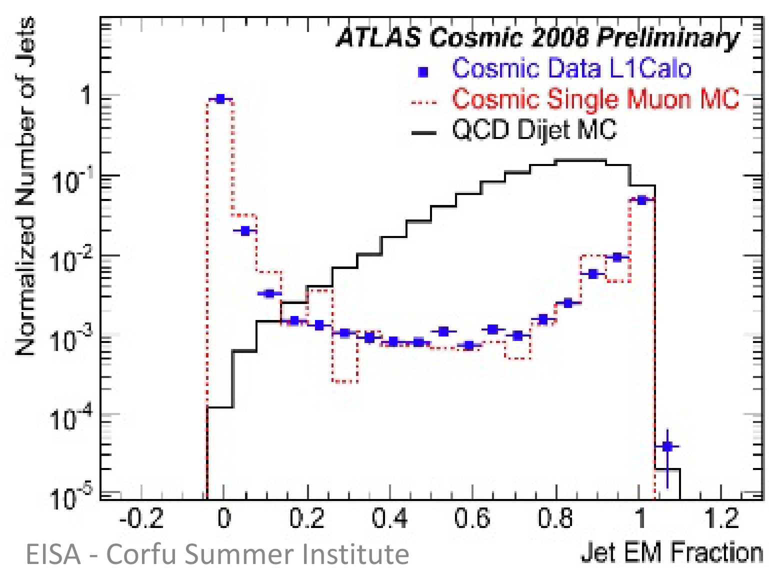


Background of fake missing energy from calorimeter noise and cosmics events being studied with cosmics data



Simulation of a cosmic muon overlap with a pp → jet-jet event

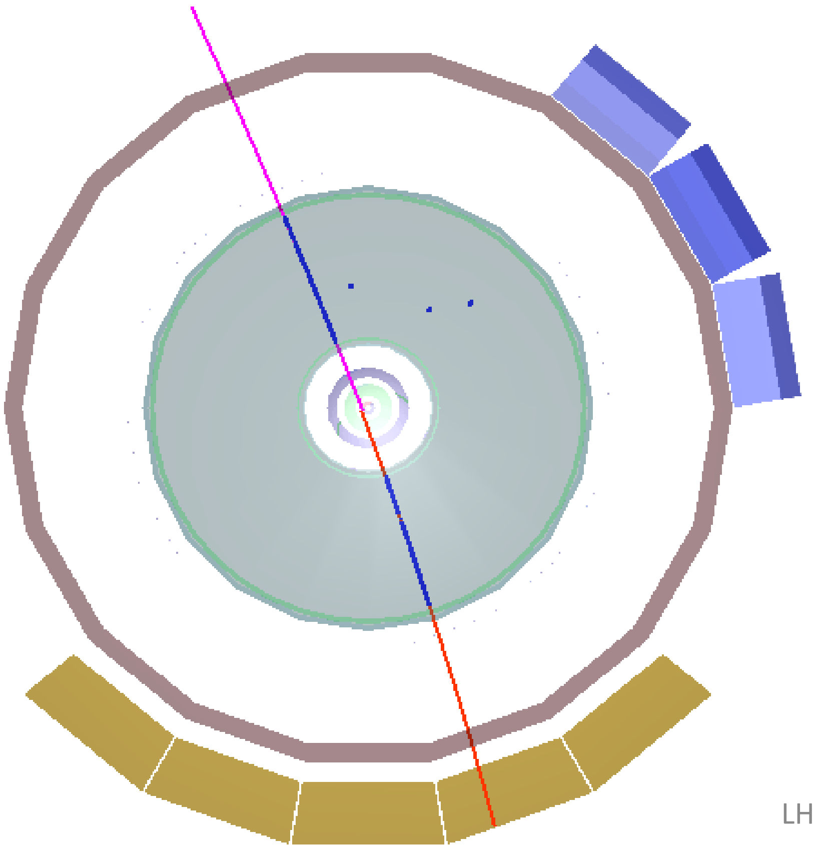


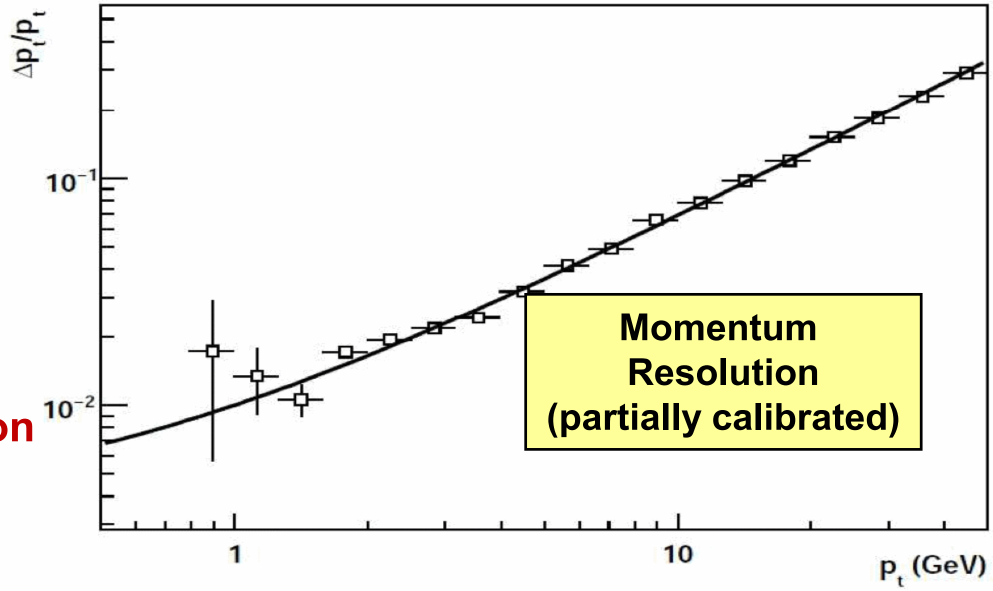


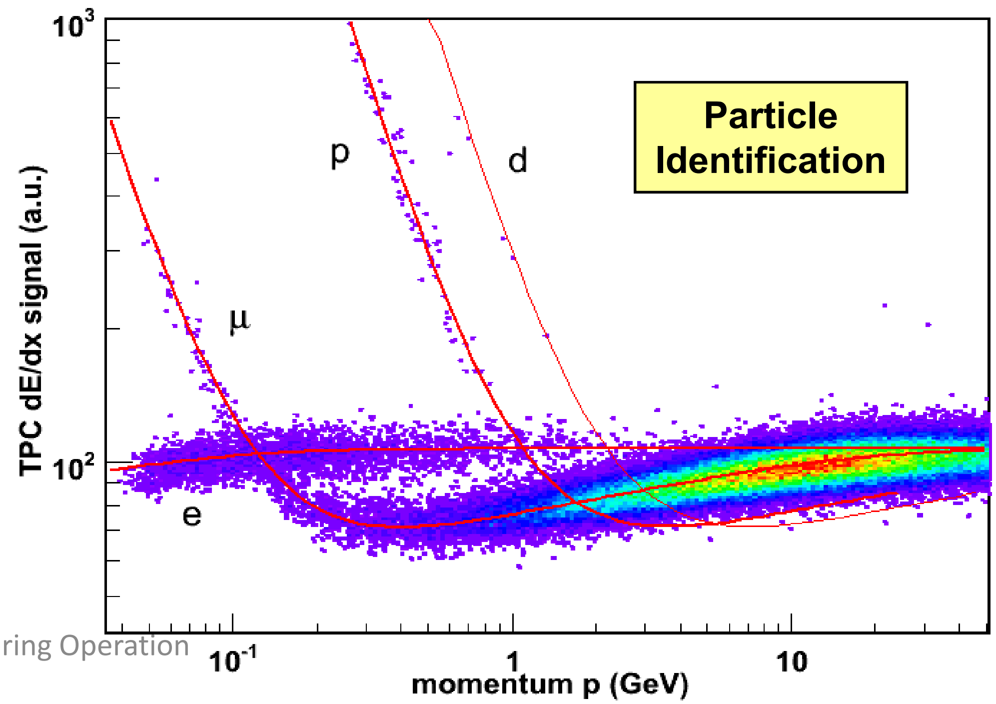
Variables to reject cosmics events (e.g. "jet" shapes) being studied

An example from ALICE: TPC Performance

- First preliminary results from cosmics
  - dE/dx resolution (goal: ~ 5.5%)
    - < 6%
  - p_t resolution (goal: ~ 5% @ 10 GeV)
    - < 7% @ 10 GeV partial calibration







Strategy toward physics

Before data taking starts:

- Strict quality controls of detector construction to meet physics requirements ✓
- Test beams (a 15-year activity culminating with a combined test beam in 2004) to understand and calibrate (part of) detector and validate/tune software tools (e.g. Geant4 simulation) ✓
- Detailed simulations of realistic detector "as built and as installed" (including misalignments, material non-uniformities, dead channels, etc.) $\rightarrow$ test and validate calibration/alignment strategies ✓
- Experiment commissioning with cosmics in the underground cavern ✓

With the first data:

- Commission/calibrate detector/trigger in situ with physics (min.bias, $Z \rightarrow ll$, …)
- "Rediscover" Standard Model, measure it at $\sqrt{s}$ = 10 TeV (minimum bias, W, Z, tt, QCD jets, …)
- Validate and tune tools (e.g. MC generators)
- Measure main backgrounds to New Physics (W/Z+jets, tt+jets, QCD-jets,…)

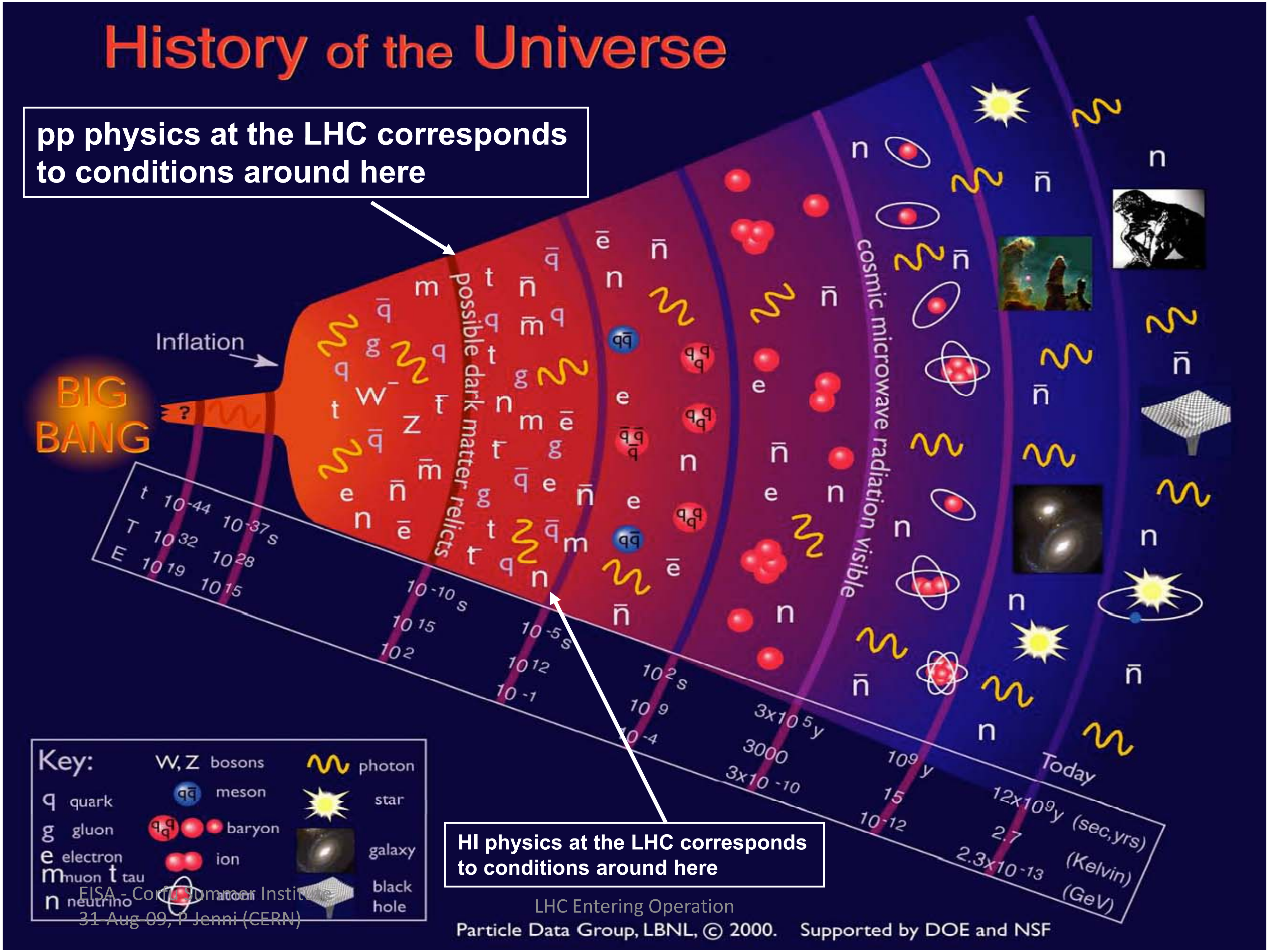
Prepare the road to discoveries …

LHC physics goals

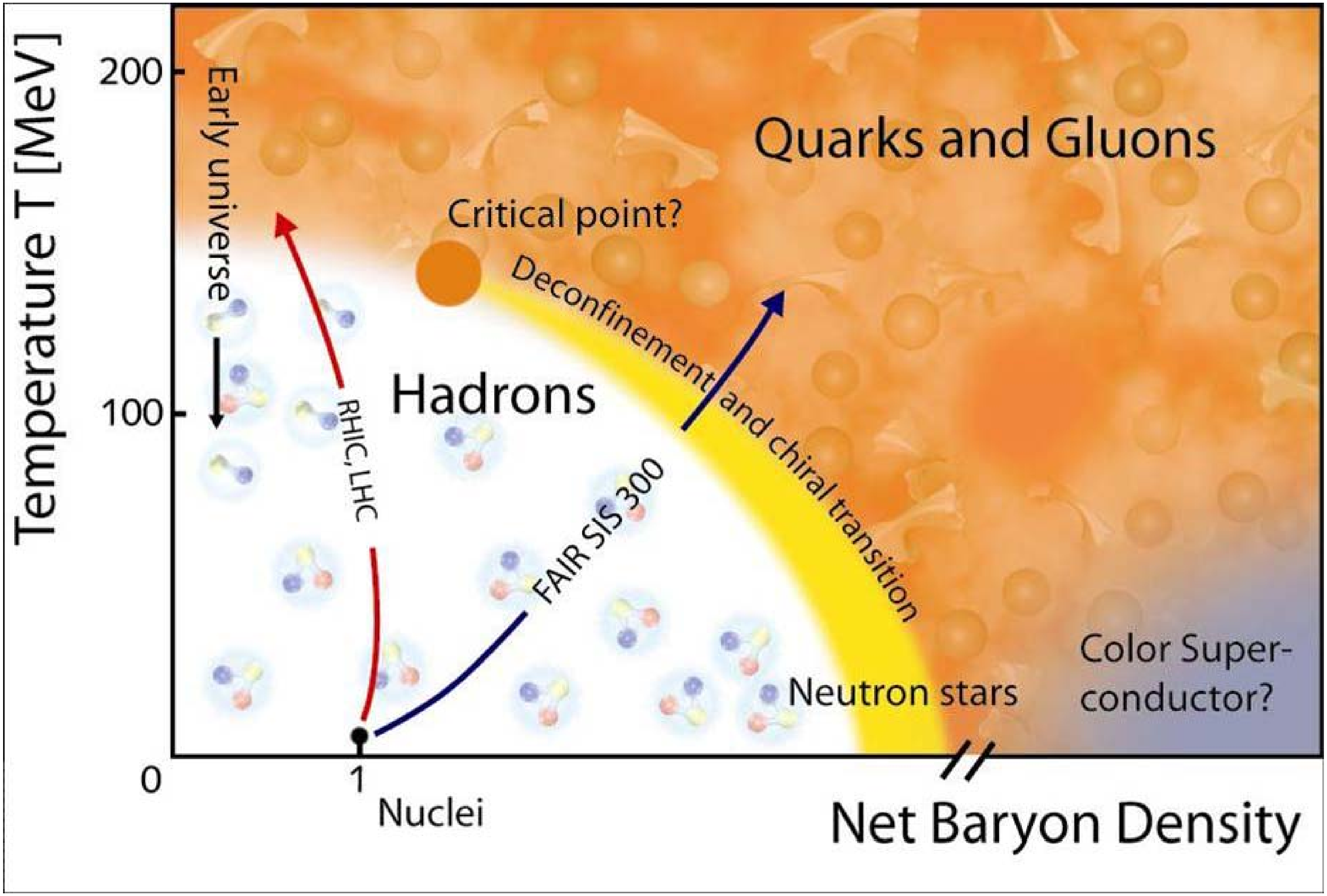
Search for the Standard Model Higgs boson over ~ $115 < m_H < 1000$ GeV.
Explore the highly-motivated TeV-scale, looking for physics beyond the SM
(Supersymmetry, Extra-dimensions, q/l compositness, leptoquarks, W'/Z', heavy q/l,..)
Measure CP-violation in B-decays
Measure transition from hadronic matter to quark-gluon plasma

What is the origin of the particle masses ?	ATLAS, CMS
What is the nature of the Universe dark matter ?	ATLAS, CMS
What is the origin of the Universe matter-antimatter asymmetry ?	LHCb, ATLAS, CMS
What were the constituents of the Universe primordial plasma ~10 μs after the Big Bang ?	ALICE, ATLAS, CMS
What happened in the first instants of the Universe life (10^{-10} s after the Big Bang) ?	ATLAS, CMS

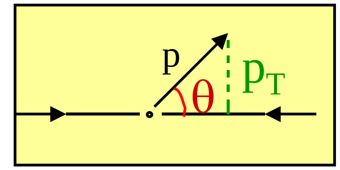
Etc. etc.

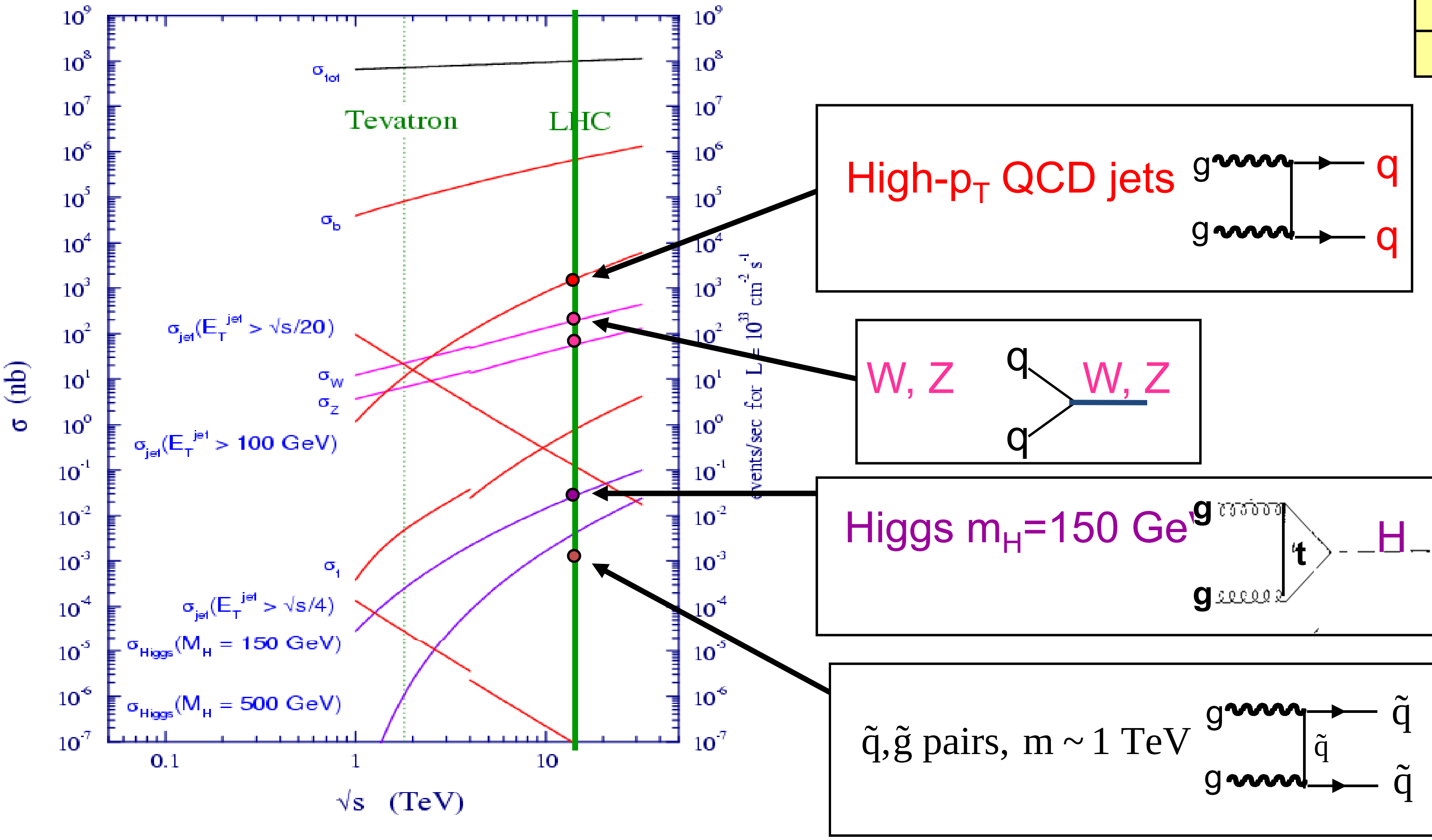

History of the Universe
pp physics at the LHC corresponds to conditions around here
Inflation
BIG BANG
possible dark matter relicts
cosmic microwave radiation visible
t 10-44 10-37 s
T 10 32 10 28
E 10 19 10 15
10 -10 s
10 15
10 2
10 -5 s
10 12
10 -1
10 2 s
10 9
10 -4
3x10 5 y
3000
3x10 -10
10 9 y
15
10 -12
Today
12x10 9 y (sec,yrs)
2.7 (Kelvin)
2.3x10 -13 (GeV)
Key:
q quark
g gluon
e electron
m muon t tau
n neutrino
W, Z bosons
meson
baryon
ion
atom
photon
star
galaxy
black hole
HI physics at the LHC corresponds to conditions around here
Particle Data Group, LBNL, © 2000. Supported by DOE and NSF

Quark-Gluon Plasma Physics in Heavy Ion Collisions at LHC



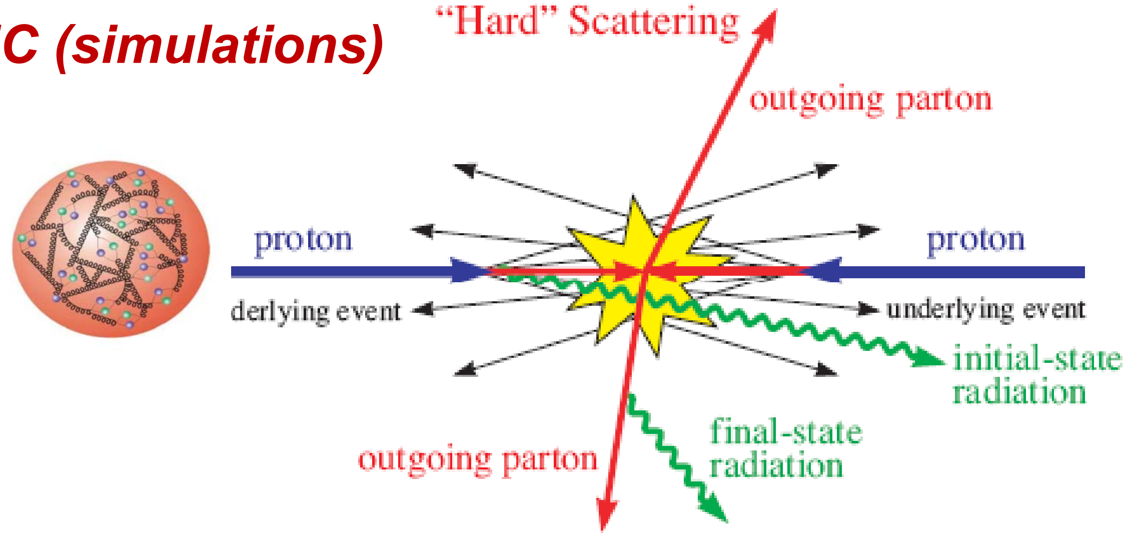
Huge (QCD) backgrounds (consequence of high pp energy …)

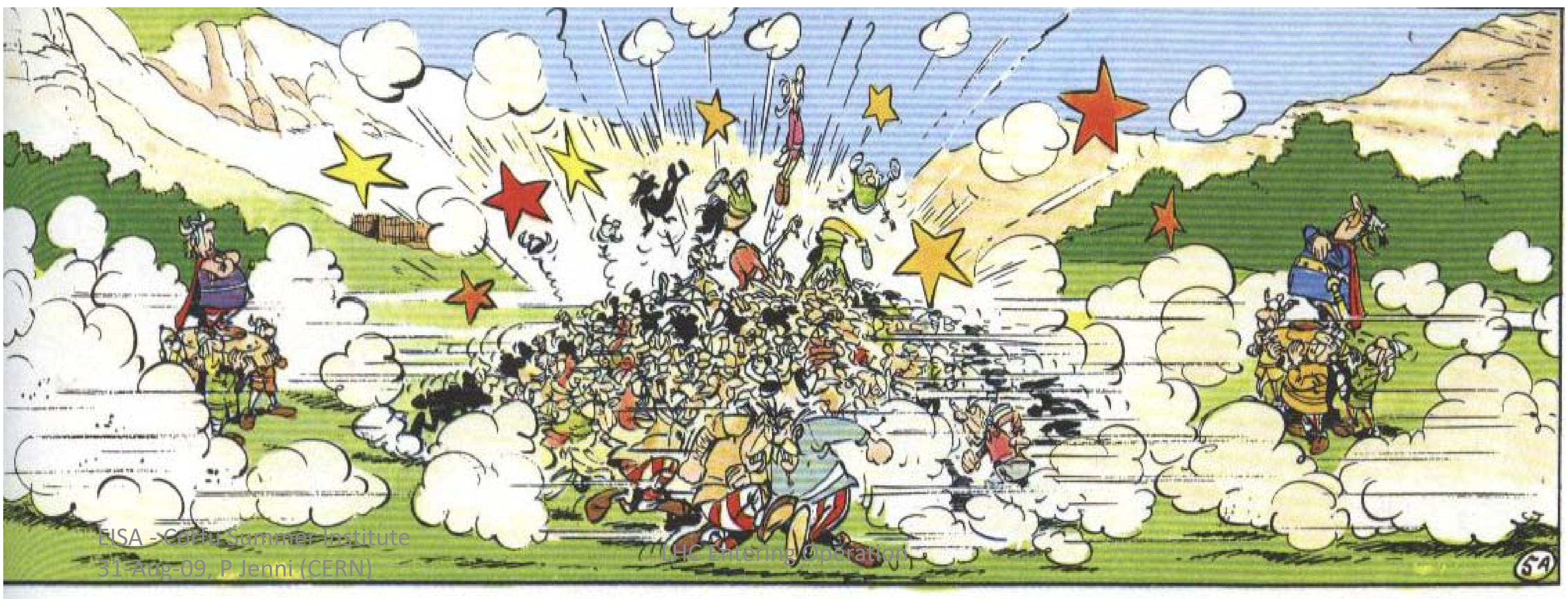




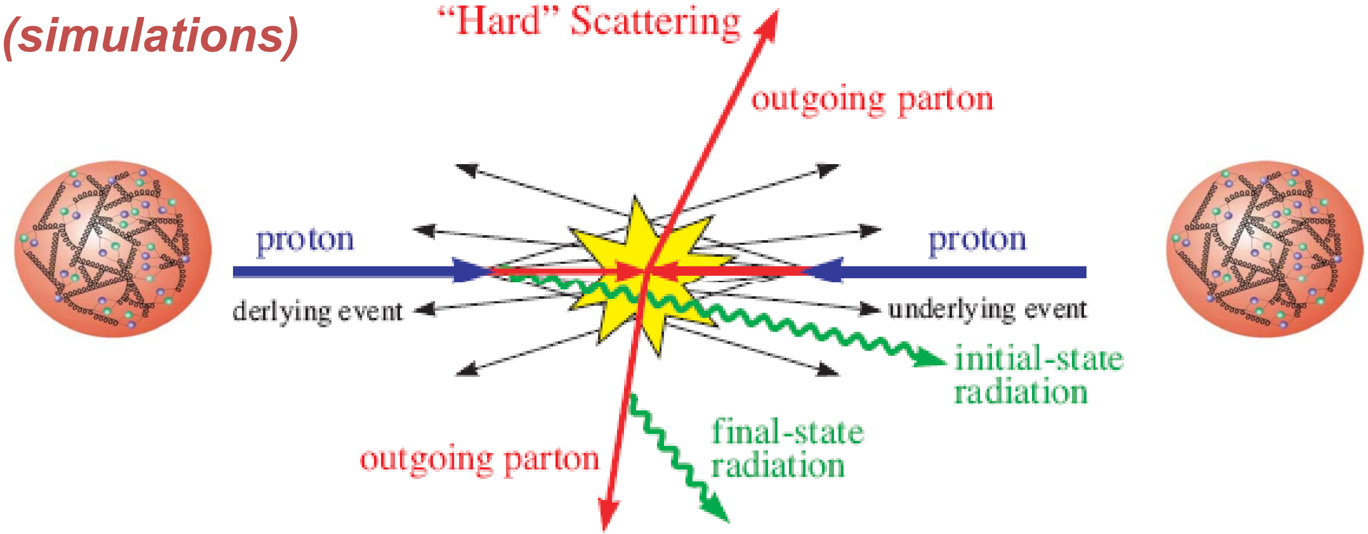
- **No hope to observe light objects (W, Z, H ?) in fully-hadronic final states → rely on l, γ**
- **Mass resolutions of ~ 1% (10%) needed for l, γ (jets) to extract tiny signals from backgrounds, and excellent particle identification (e.g. e/jet separation)**
- **Signal (EW) /Background (QCD) for "light" objects larger at Tevatron than at LHC**

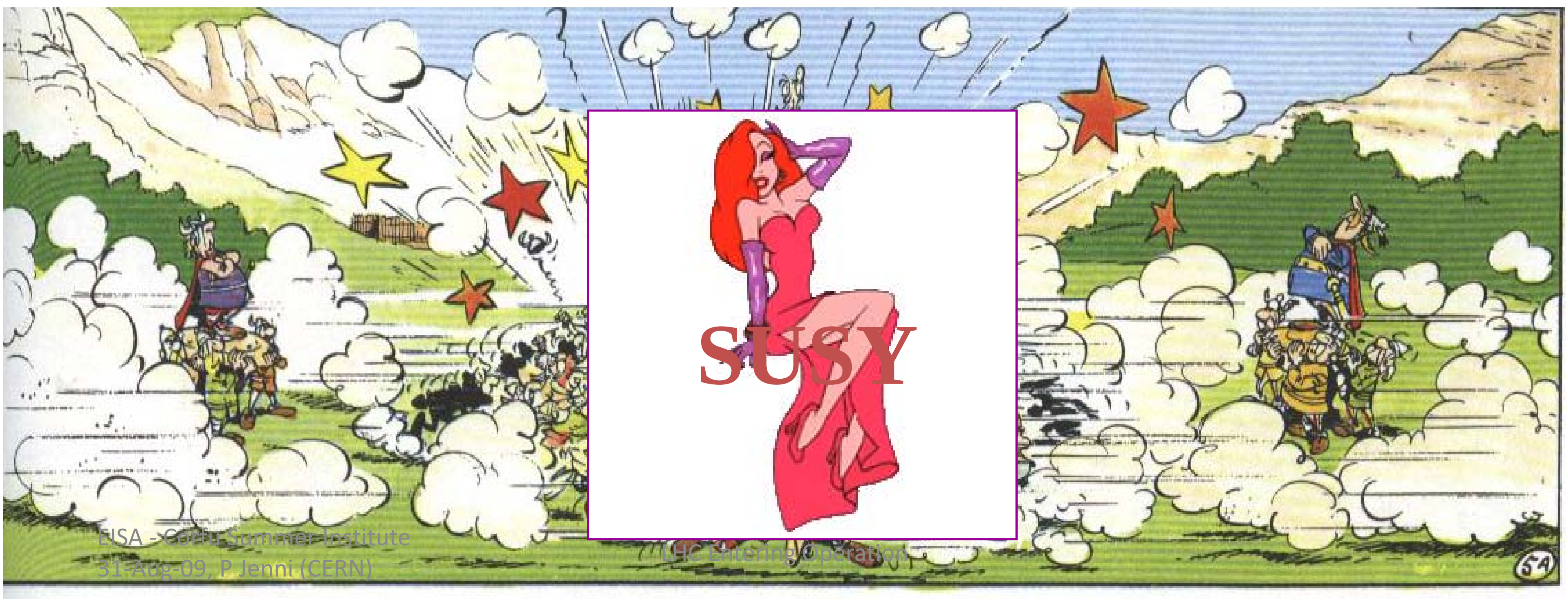
Examples of physics discoveries hoped for at the LHC (simulations)





Examples of physics discoveries hoped for at the LHC (simulations)





Expected data samples (examples) with 100 pb^{-1}

Note: expect up to 200 pb^{-1} after first physics run at high energy

Channels (examples ...)	Expected events in ATLAS after cuts $\sqrt{s}$= 10 TeV, 100 pb^{-1}
$J/\psi \to \mu\mu$	~ 10^6
$\Upsilon \to \mu\mu$	~ 5 10^4
$W \to \mu\nu$	~ 3 10^5
$Z \to \mu\mu$	~ 3 10^4
$tt \to WbWb \to \mu\nu + X$	~ 350
QCD jets p_T > 1 TeV	~ 500
$\tilde{g},\tilde{q}$ m ~ 1 TeV	~ 5

Goals in 2010:

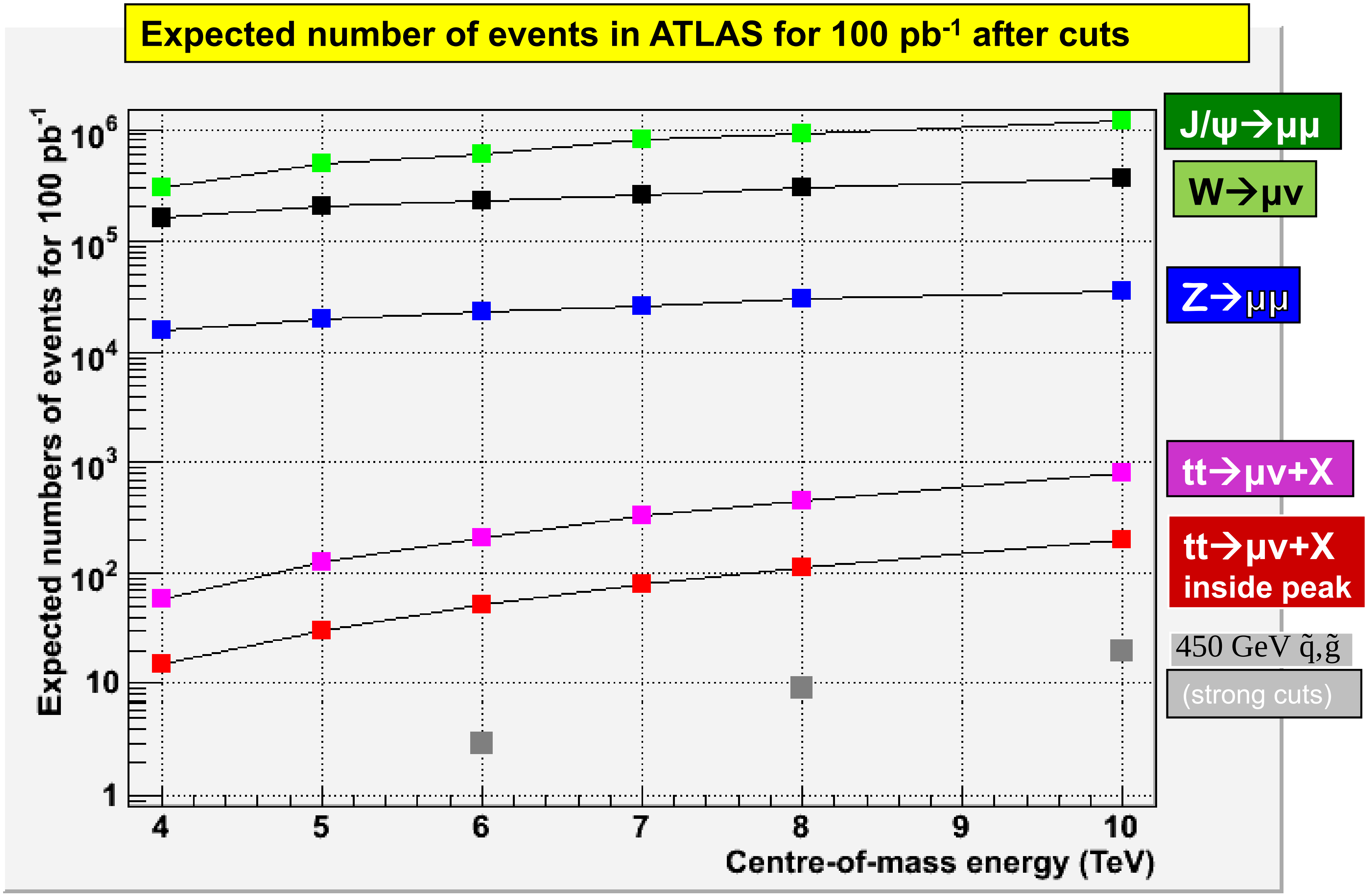
1) Commission and calibrate the detector in situ using well-known physics samples
   e.g. - $Z \to ee, \mu\mu$ tracker, ECAL, Muon chamber calibration and alignment, etc.
   - $tt \to bl\nu\, bjj$ jet scale from $W \to jj$, b-tag performance, etc.

2) "Rediscover" and measure Standard Model at $\sqrt{s}$ ~ 10 TeV: W, Z, tt, QCD jets …
   (also because omnipresent backgrounds to New Physics)

3) Early discoveries ? Potentially accessible: Z', SUSY, …. surprises ?

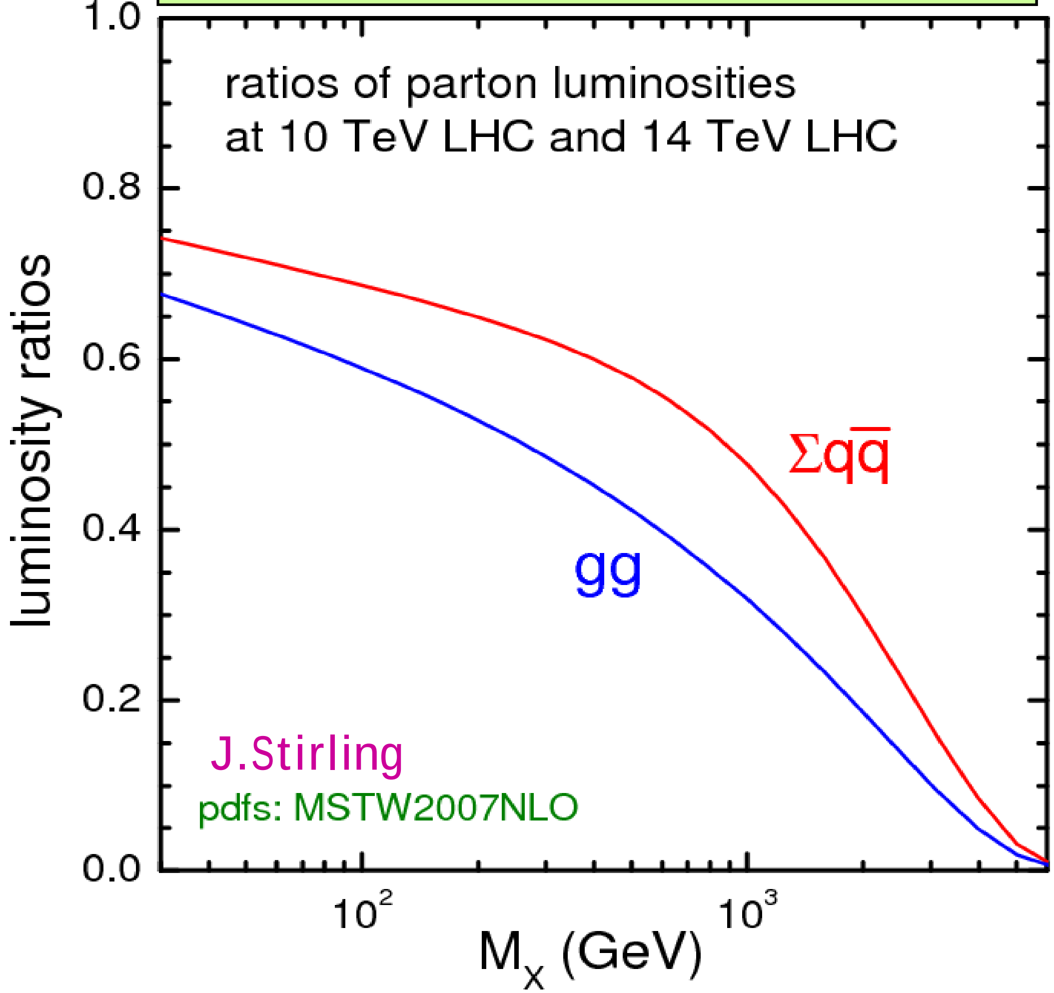
will take time … but necessary steps before claiming discoveries ….

ATLAS preliminary



A parenthesis: 10 TeV vs 14 TeV...

Ratios of cross-sections at 10/14 TeV for processes induced by gg and qq



At 10 TeV, more difficult to produce high mass objects...

Below about 300 GeV, this suppression is < 50% (process-dependent, e.g. tt ~ factor 2 lower cross-section)

Above ~ 1 TeV the effects are more marked

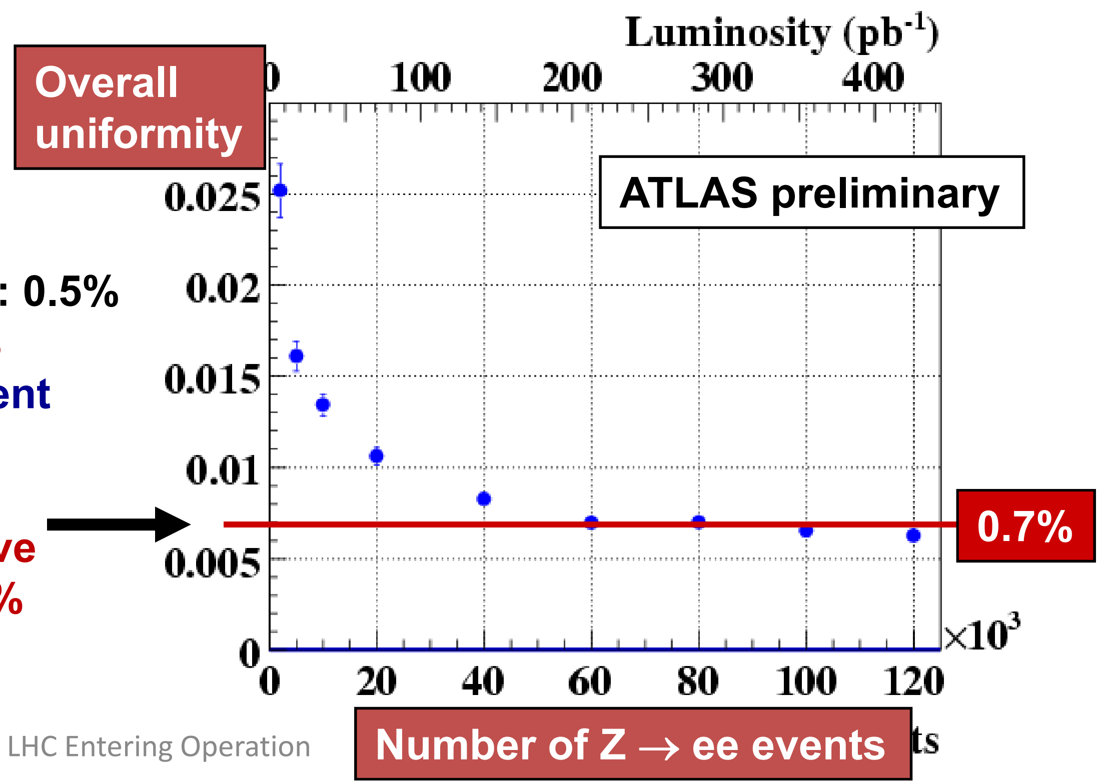
Example: Expected ATLAS performance on “Day-1”
(based on test-beam, simulation, and cosmics results)

	Initial Day-1	Ultimate goal	Data samples to improve (examples)
ECAL uniformity	~2.5%	0.7%	Isolated electrons, Z→ee
e/γ E-scale	2-3%	<0.1%	J/ψ, Z → ee, E/p for electrons
Jet E-scale	5-10%	1%	γ/Z + 1j, W → jj in tt eventsID
ID alignment	20-200 μm	5 μm	Generic tracks, isolated μ, Z → μμ
Muon alignment	40-1000 μm	40 μm	Straight m, Z → μμ

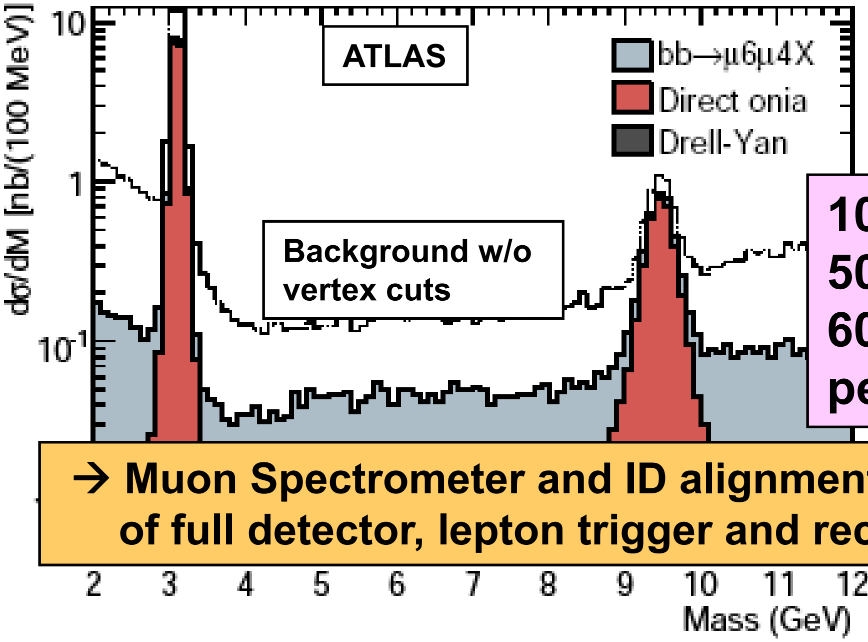
<u>**ECAL uniformity:**</u>

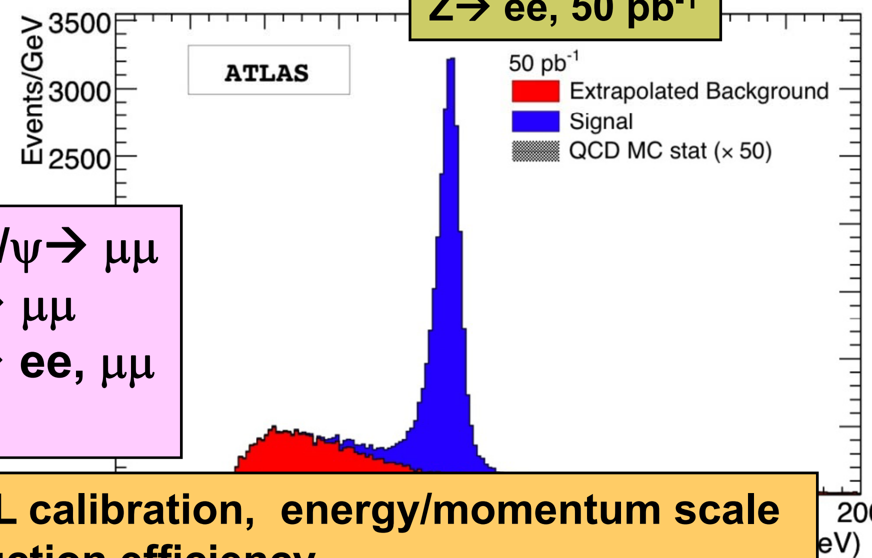
- local uniformity by construction/test: 0.5%
- residual long-range non-uniformities (upstream material, etc.): ~ few percent

→ use Z-mass constraint to correct
~ 10^5 Z → ee events enough to achieve the goal response uniformity of ~ 0.7%



SM "candles": J/ψ, Y, W, Z, top



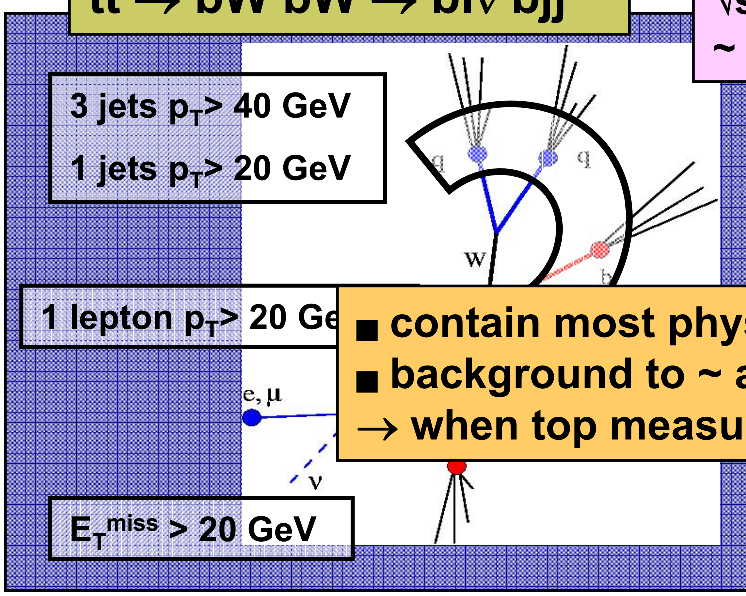


$Z \to ee$, 50 pb^{-1}

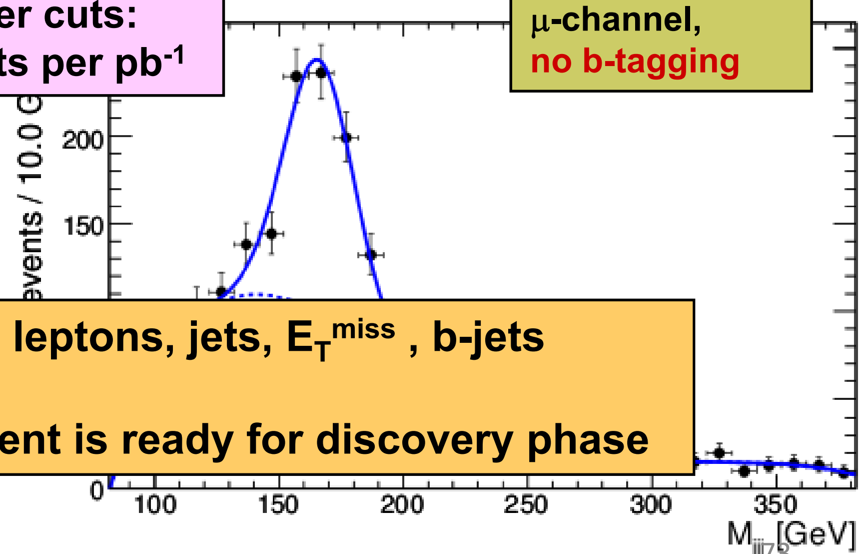
10000 $J/\psi \to \mu\mu$
500 Y $\to \mu\mu$
600 Z $\to$ ee, $\mu\mu$
per pb^{-1}

→ Muon Spectrometer and ID alignment, ECAL calibration, energy/momentum scale of full detector, lepton trigger and reconstruction efficiency, …

$t\bar{t} \to bW\,bW \to bl\nu\,bjj$



$\sqrt{s}$ = 10 TeV, after cuts:
~ 15 l=e,μ events per pb^{-1}



14 TeV, 100 pb^{-1}
μ-channel,
no b-tagging

- **contain most physics objects: leptons, jets, E_T^{miss}, b-jets**
- **background to ~ all searches**

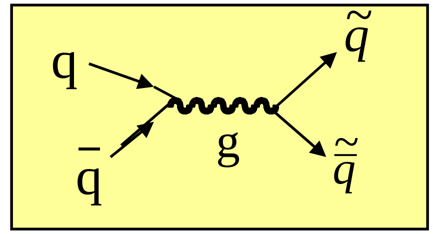
→ when top measured, experiment is ready for discovery phase

First discoveries: Supersymmetry ?

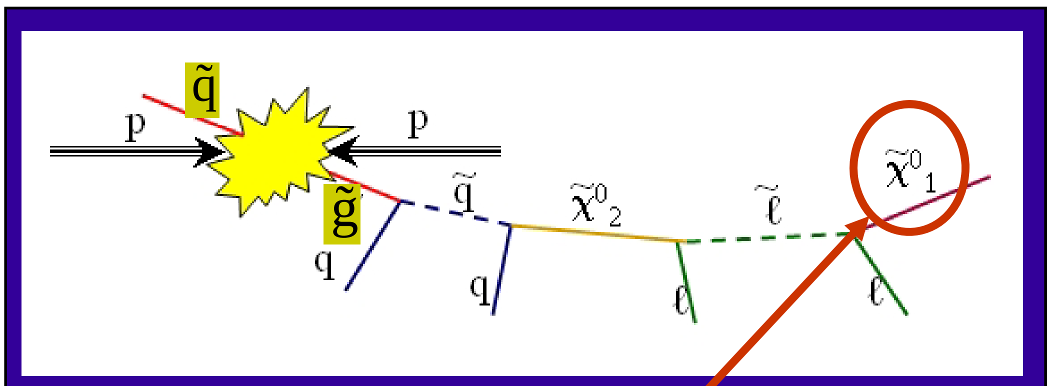
If it is at the TeV mass scale, it should be found "quickly" …. thanks to:

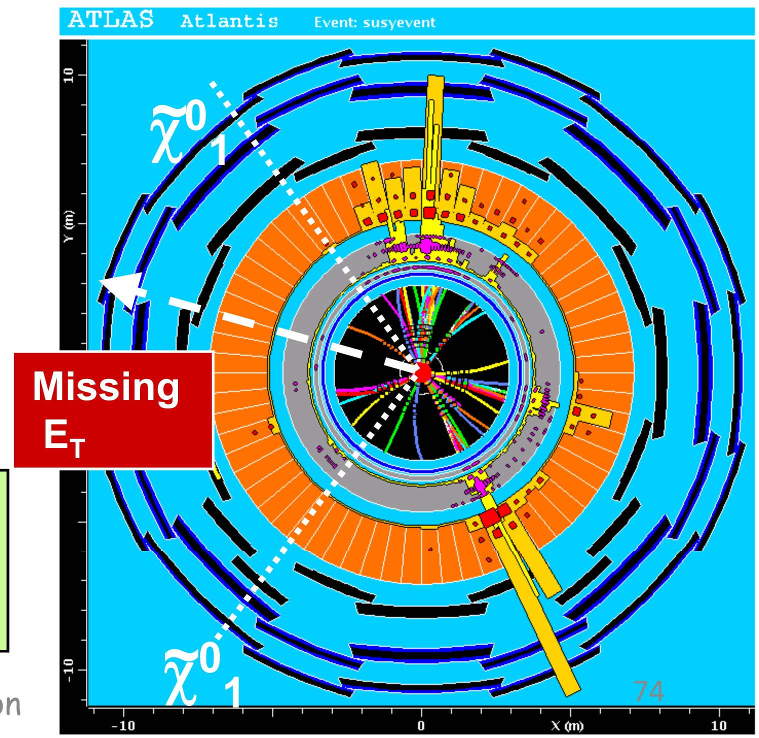
- **Huge production rate for** $\boxed{\tilde{q}\tilde{q}, \tilde{g}\tilde{q}, \tilde{g}\tilde{g} \text{ production}}$

  For $m(\tilde{q},\tilde{g}) \sim 1$ TeV
  expect 1 event/day at $L=10^{31}\ cm^{-2}\ s^{-1}$



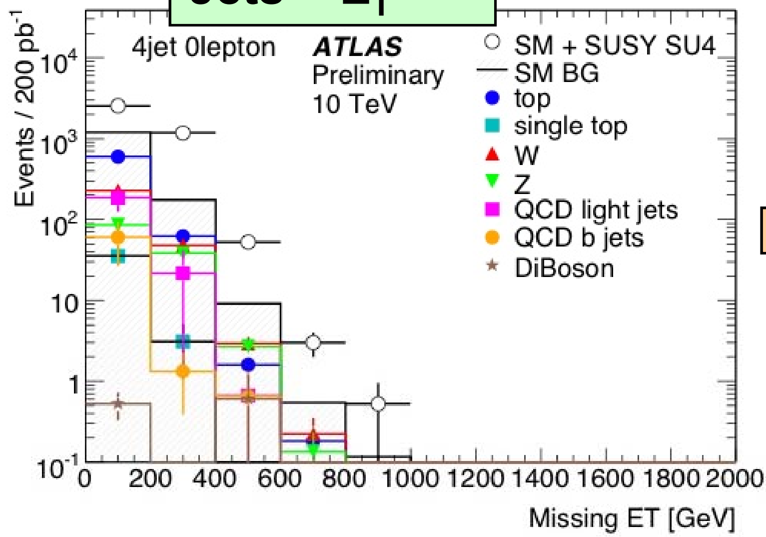
- **Spectacular final states (many jets, leptons, missing transverse energy)**





This particle (lightest neutralino) is stable, neutral and weakly interacting → escapes detection (like ν) → apparent missing energy in the final state

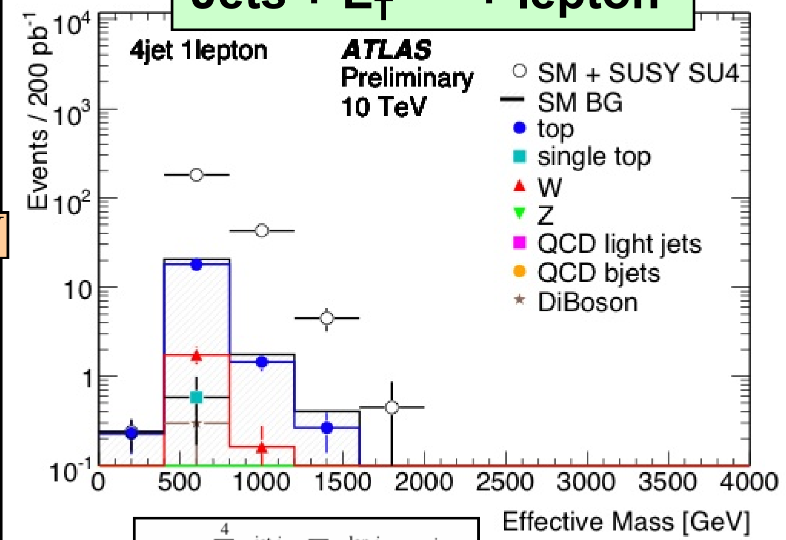
Jets + E_T^{miss}



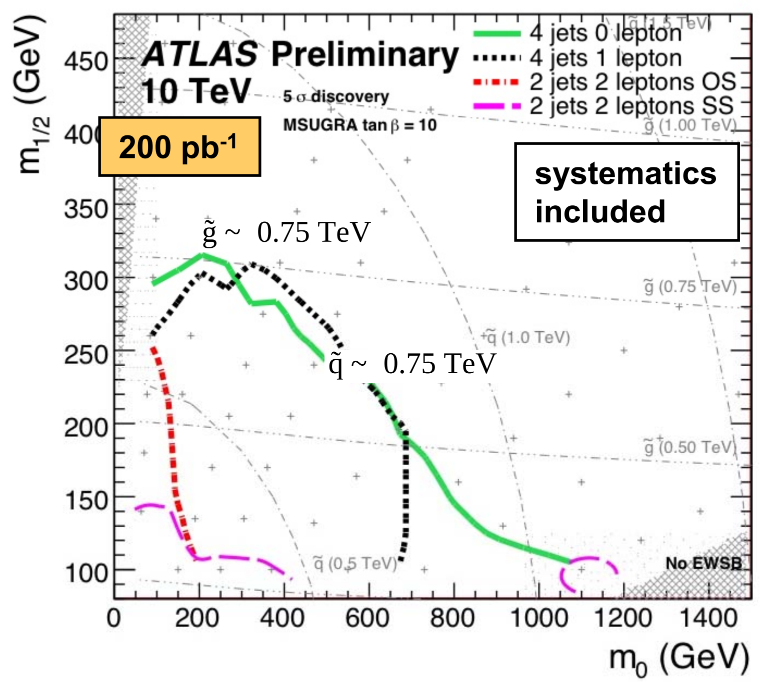
$\sqrt{s}$ = 10 TeV
200 pb^{-1}

$m(\tilde{q},\tilde{g}) \sim 410$ GeV

Jets + E_T^{miss} + lepton



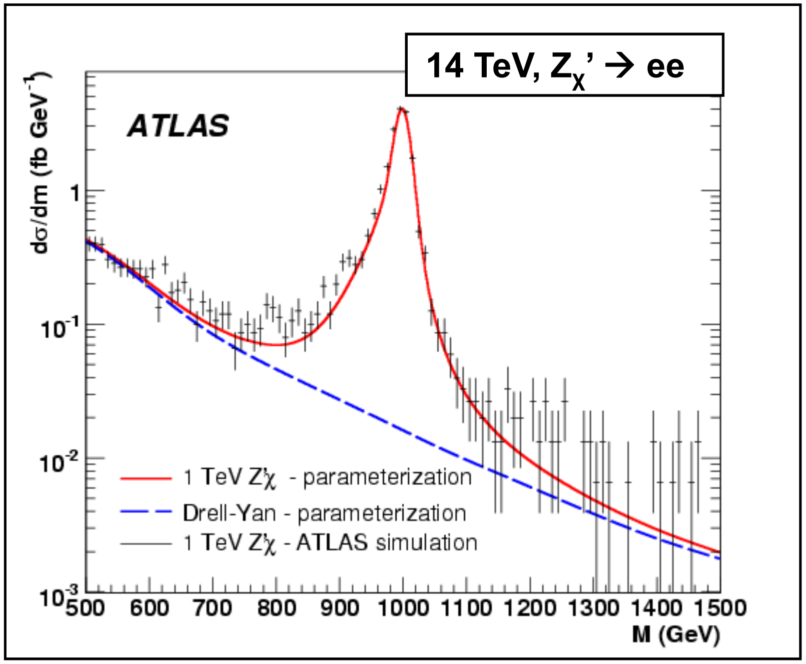
$$M_{\rm eff} \equiv \sum_{i=1}^{4} p_T^{{\rm jet},i} + \sum_{i=1} p_T^{{\rm lep},i} + E_T^{\rm miss}$$



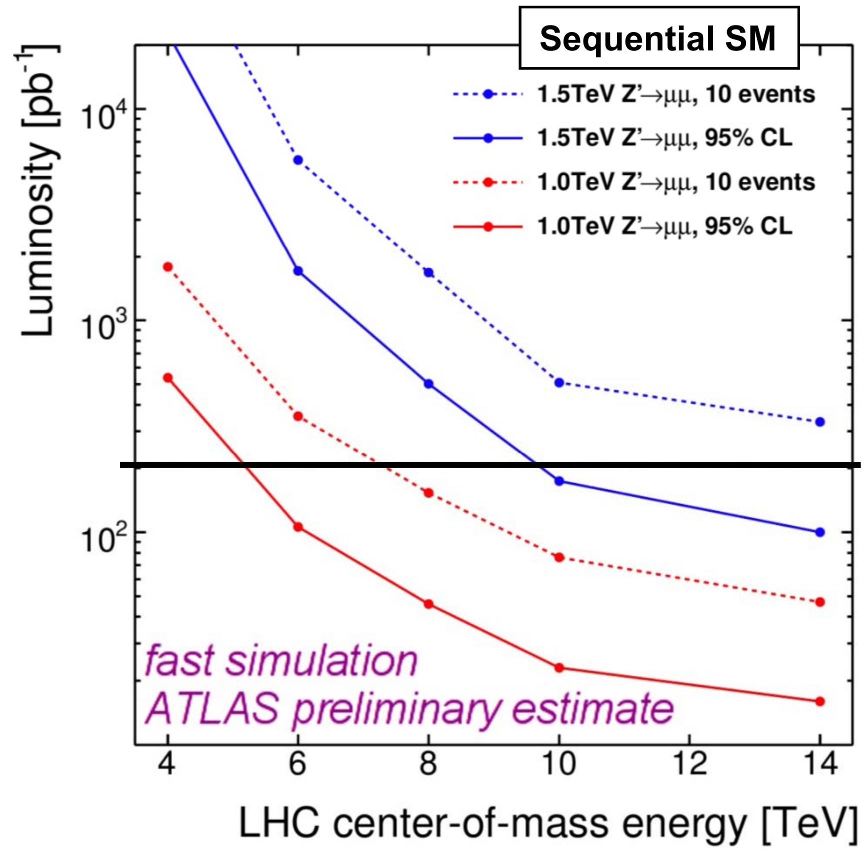
Jets + E_T^{miss} channel: highest reach
1-lepton channel: more robust against B uncertainties

- **Discovery up to m ~ 750 GeV with 200 pb^{-1} at $\sqrt{s}$ =10 TeV**
- **With 200 pb^{-1}, ATLAS discovery reach beyond Tevatron expected exclusion (~400 GeV) for $\sqrt{s} \geq 7$ TeV**
- **However: understanding the (tricky) backgrounds, in particular fake missing transverse energy coming from instrumental effects (noise, cracks, ..), will take time**
- **Ultimate LHC reach:** $m(\tilde{q},\tilde{g}) \sim 3$ TeV

An "easier" case : Z' $\rightarrow$ ll, mass ~ 1 TeV

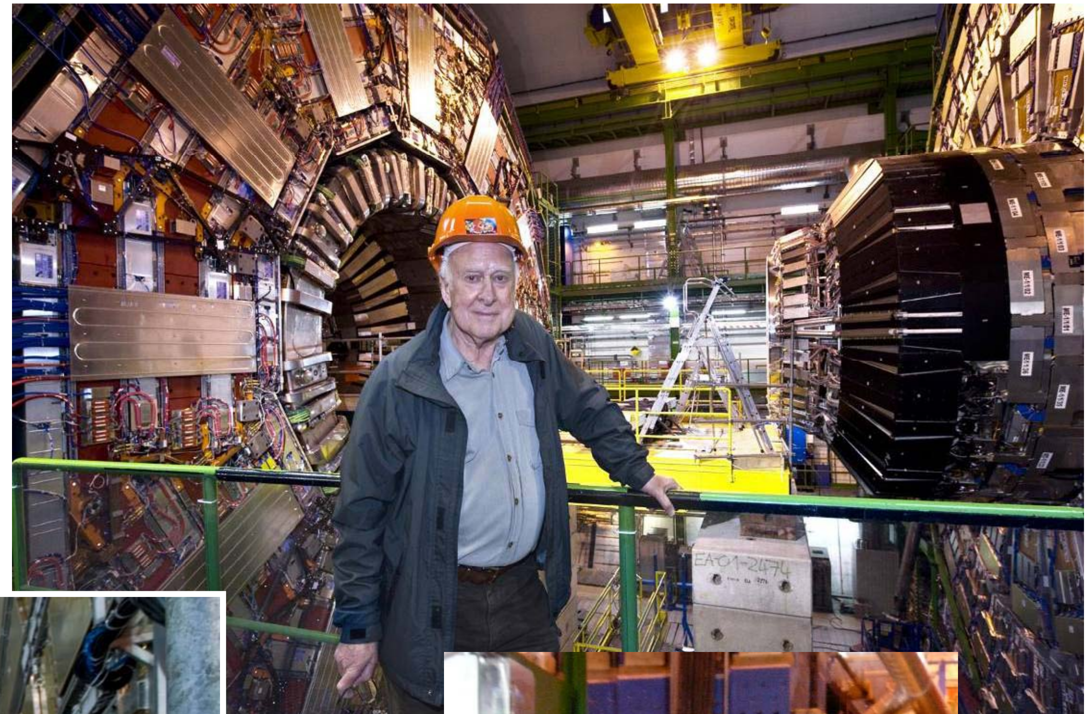


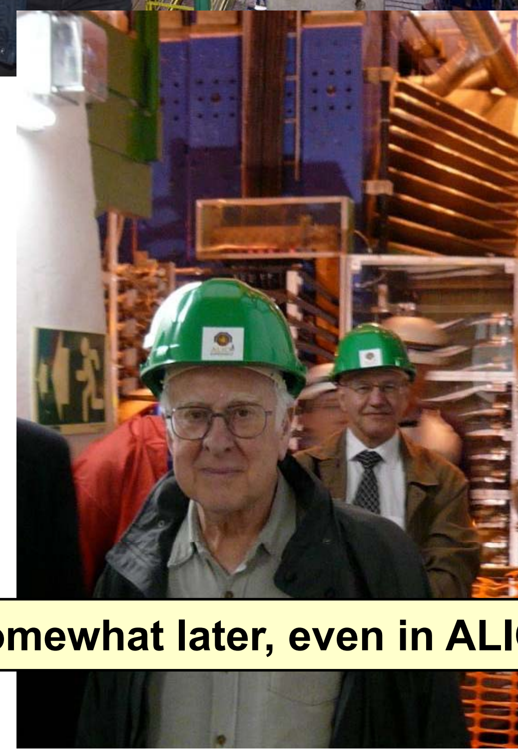
Is this a manifestation of new forces or new dimensions ?
From angular distribution of leptons can disentangle Z' (spin=1) from G (spin=2).
Requires more data …



- Signal is (narrow) mass peak above small and smooth SM background
- Does not require ultimate EM calorimeter performance
- Discovery beyond Tevatron exclusion reach (m ~ 1 TeV) possible with 200 pb^{-1} and $\sqrt{s} \geq 7$ TeV (100 pb^{-1} at 10 TeV)
  → perhaps sometime in 2010 ?

The first “Higgs” events observed jointly in CMS and ATLAS … (April 2008)





somewhat later, even in ALICE…

- The LHC is one of the most ambitious, challenging and motivated projects in science ever

- After a very successful inauguration of the accelerator and experiments on 10 September 2008, operation has been interrupted by an incident provoked by a faulty electrical connection between two magnets

- Repairs are progressing well, and the revised schedule foresees first beams again in November 2009 leading into a physics run at 7 TeV, and rising later in 2010 towards 10 TeV

- Commissioning of the experiments in the underground caverns with cosmics has been going on since a long time. It has demonstrated excellent detector quality and has allowed important alignment, calibration and timing studies to be made in situ with the final detectors

  → the experiments are ready to do good physics with first collision data

With more time and more data ….

The LHC will explore in detail the highly-motivated TeV-scale with a direct discovery potential up to m ≈ 5-6 TeV

→ if New Physics is there, the LHC should find it

→ it will say the final word about the SM Higgs mechanism and many TeV-scale predictions

→ it may add crucial pieces to our knowledge of fundamental physics → impact also on astroparticle physics and cosmology

→ most importantly: it will most likely tell us which are the right questions to ask, and how to go on

Thank you for your attention!

And many thanks to several colleagues from whom I ‘borrowed’ slides: in the first place to Fabiola Gianotti, the Spokesperson of ATLAS; to Karl Jakobs and Karlheinz Meier, as well as to my CMS, Alice and LHCb colleagues Jim Virdee, Juergen Schukraft and Andrey Golutvin; and last but not least to the LHC machine team