Commissioning and Early Physics Analysis at the[*] LHC

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[*]Concentrate on high-p_T commissioning and physics with ATLAS and CMS - apologies to the other experiments !

Lecture Themes

I. Setting the Stage … Motivation for a Huge Machine

II. The Large Hadron Collider (LHC)

III. The ATLAS and CMS Experiments

IV. Commissioning with test beam, cosmic ray and single-beam data

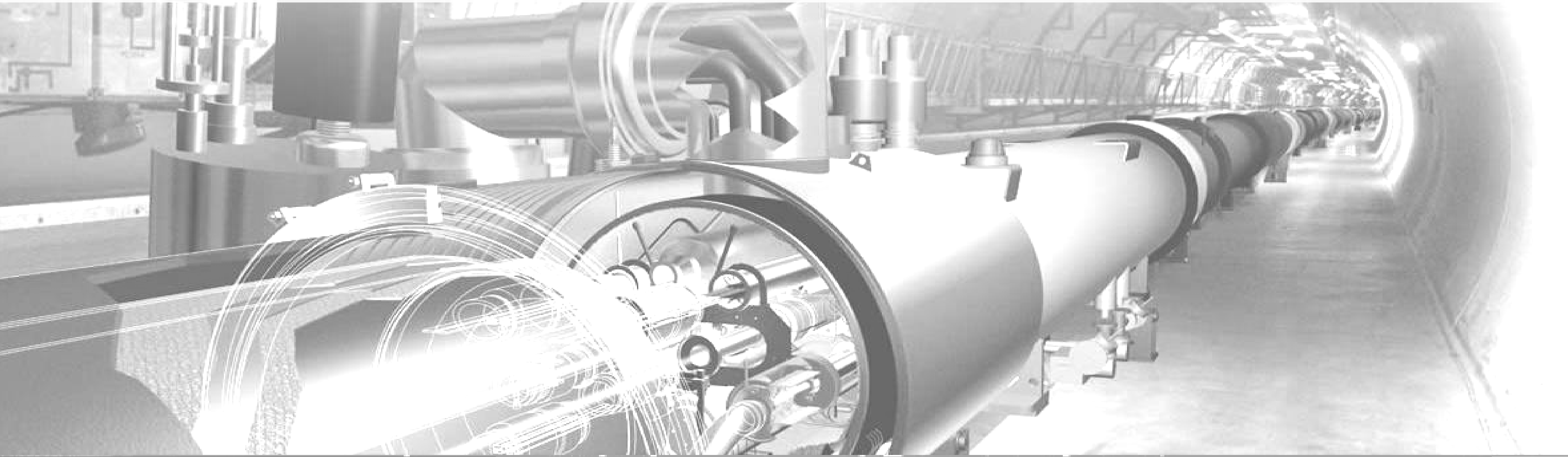
V. Early physics commissioning and analysis with ATLAS and CMS

VI. Physics potential at varying LHC energies

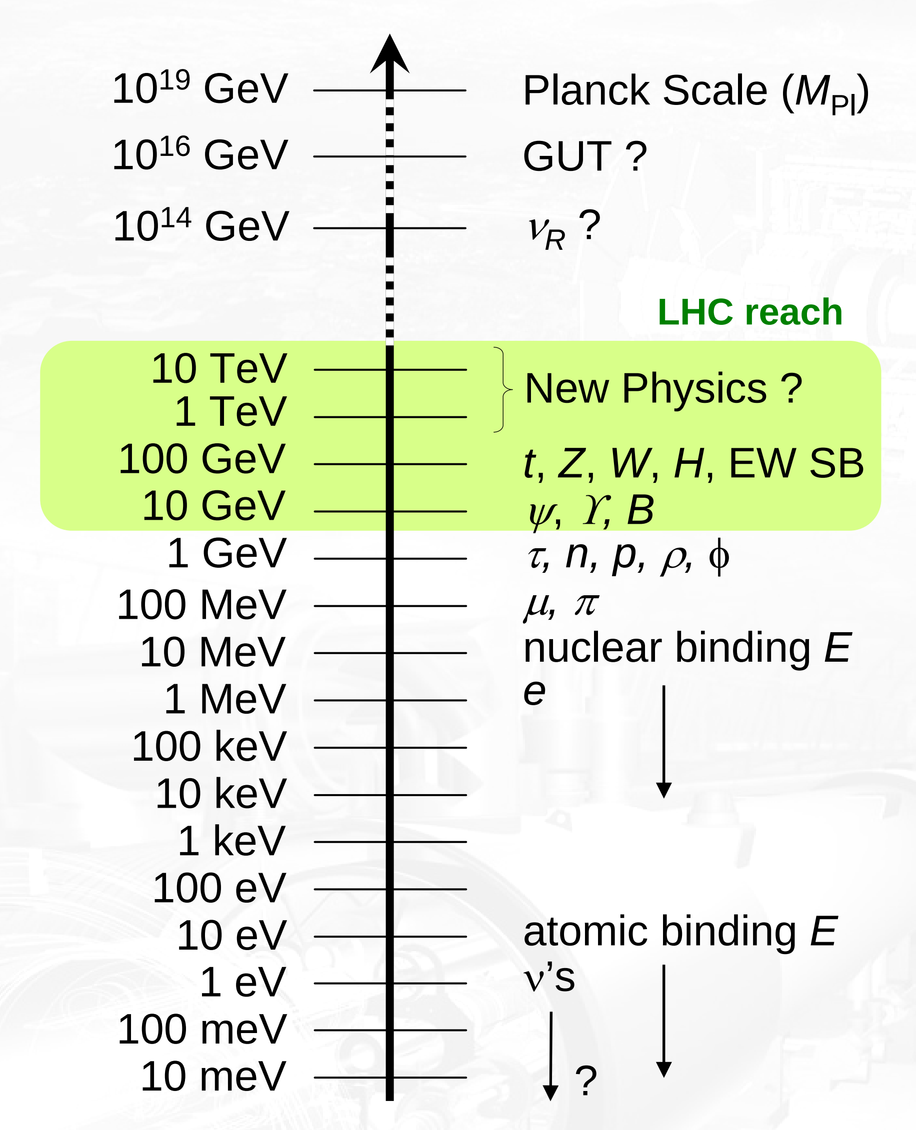
VII. Outlook

Setting the Stage

Motivation for a Huge Machine



Scales …


10^{19} GeV
Planck Scale (M_{Pl})
10^{16} GeV
GUT ?
10^{14} GeV
ν_R ?
LHC reach
10 TeV
1 TeV
New Physics ?
100 GeV
t, Z, W, H, EW SB
10 GeV
ψ, Υ, B
1 GeV
τ, n, p, ρ, ϕ
100 MeV
μ, π
10 MeV
nuclear binding E
1 MeV
e
100 keV
10 keV
1 keV
100 eV
10 eV
atomic binding E
1 eV
ν's
100 meV
10 meV
?

The Standard Model (SM)

During the last 35 years, the SM has been experimentally verified to extreme precisions

Muon spin precession frequency in magnetic field measured at Brookhaven

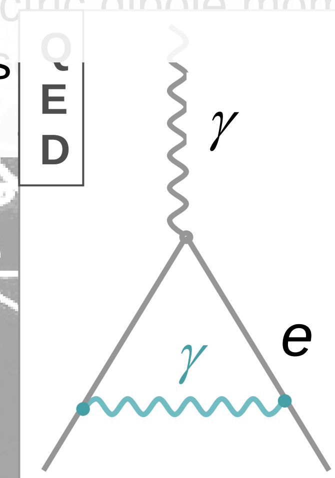
The predicted electron and muon magnetic moments have been verified to the parts

level

electric dipole moment

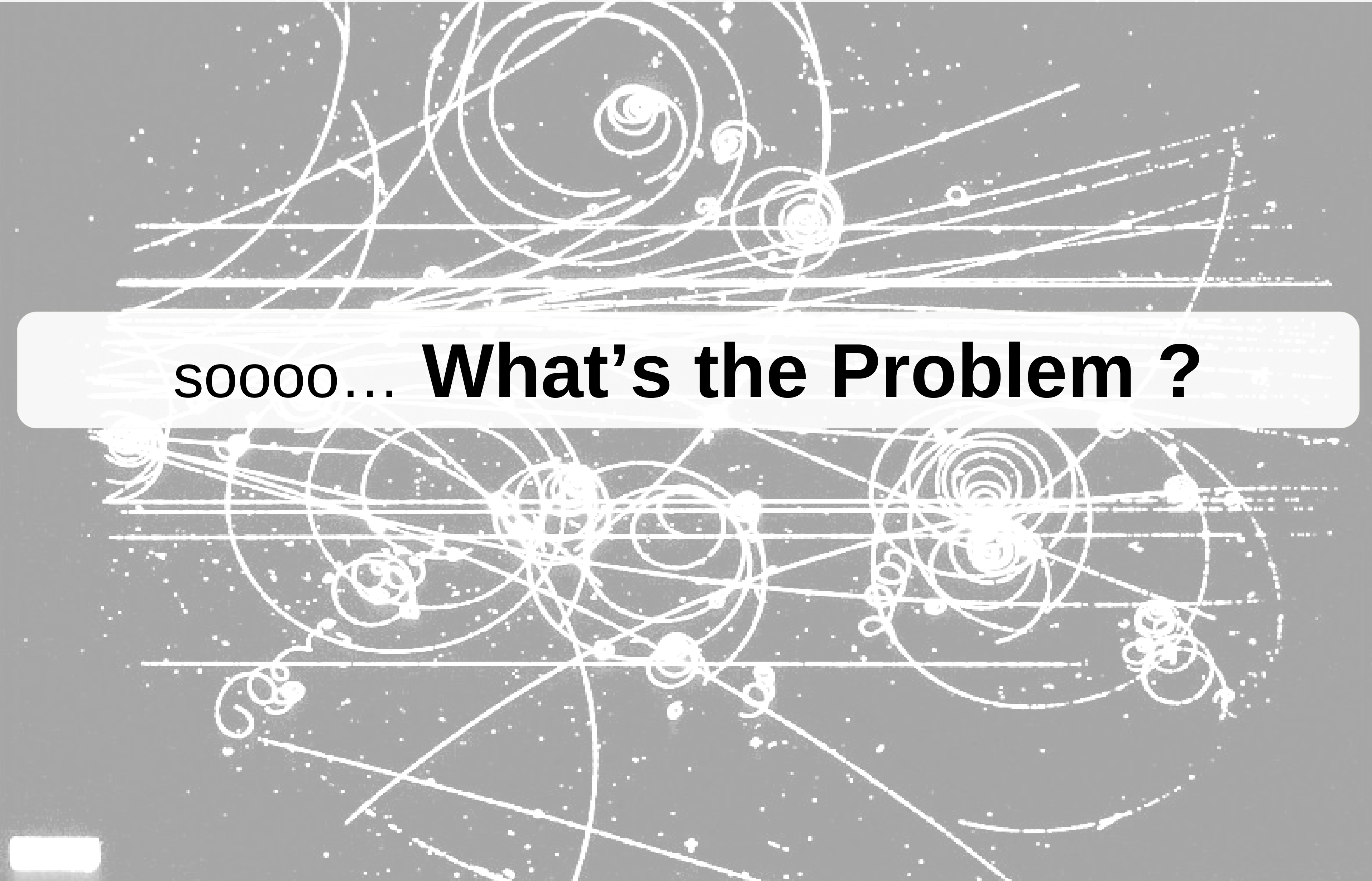
has

the



Many, many more successful tests ….

The Standard Model (SM)



soooo... **What’s the Problem ?**

The Problem is ...

- The Higgs is not yet discovered !
- The Higgs is the only fundamental scalar
- What is the origin of the huge mass hierarchy between matter particles ?

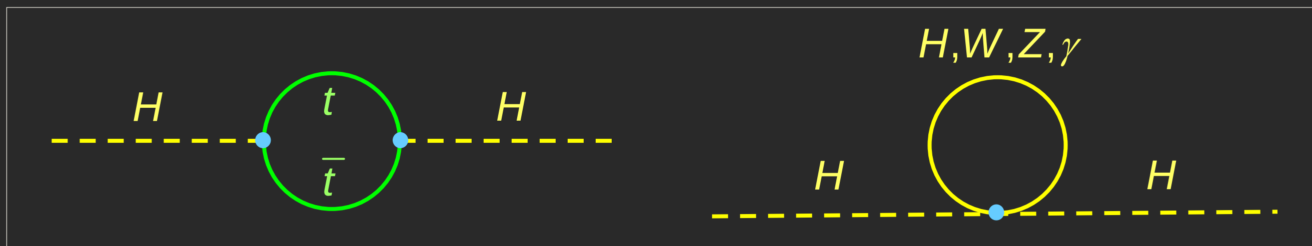
... and:

- Dark matter (and, perhaps, dark energy)
- Baryogenesis and Leptogenesis (Matter-Antimatter asymmetry)
- Grand Unification of the forces (related to baryon decay)
- The gauge hierarchy Problem
- The strong *CP* Problem (why is $\theta \sim 0$?)
- Neutrino masses
- Gravitation

Neutrino masses and inclusion of **gravity** in the SM require new physics at the scales ~10^{14} GeV and ~10^{19} GeV, respectively !

The Mass of the Scalar is Unprotected

- **If a Higgs boson with mass < 1 TeV is discovered, the Standard Model is complete !**
- However, when computing radiative corrections to the bare Higgs mass a problem occurs:



Higgs radiative corrections

$$\Rightarrow \quad m_H^2 = m_0^2 + \delta m_H^2 \quad \text{where:} \quad \underbrace{\delta m_H^2 \propto \int_0^\infty d^4k \frac{k^2 + m_f^2}{\left(k^2 + m_f^2\right)^2}}_{\text{Integral quadratically divergent}} + \ldots$$

- The cut-off sets the scale where new particles and physical laws must come in
- Above the EW scale we only know of two scales: GUT (~10^{16} GeV) and Planck (~10^{19} GeV)
- Such a cut-off would require an incredible amount of finetuning to keep m_H light and stable

$$m_H^2 \overset{?}{=} (120\ \text{GeV})^2 = m_0^2 + C \cdot \Lambda_{\text{cut-off}}^2$$

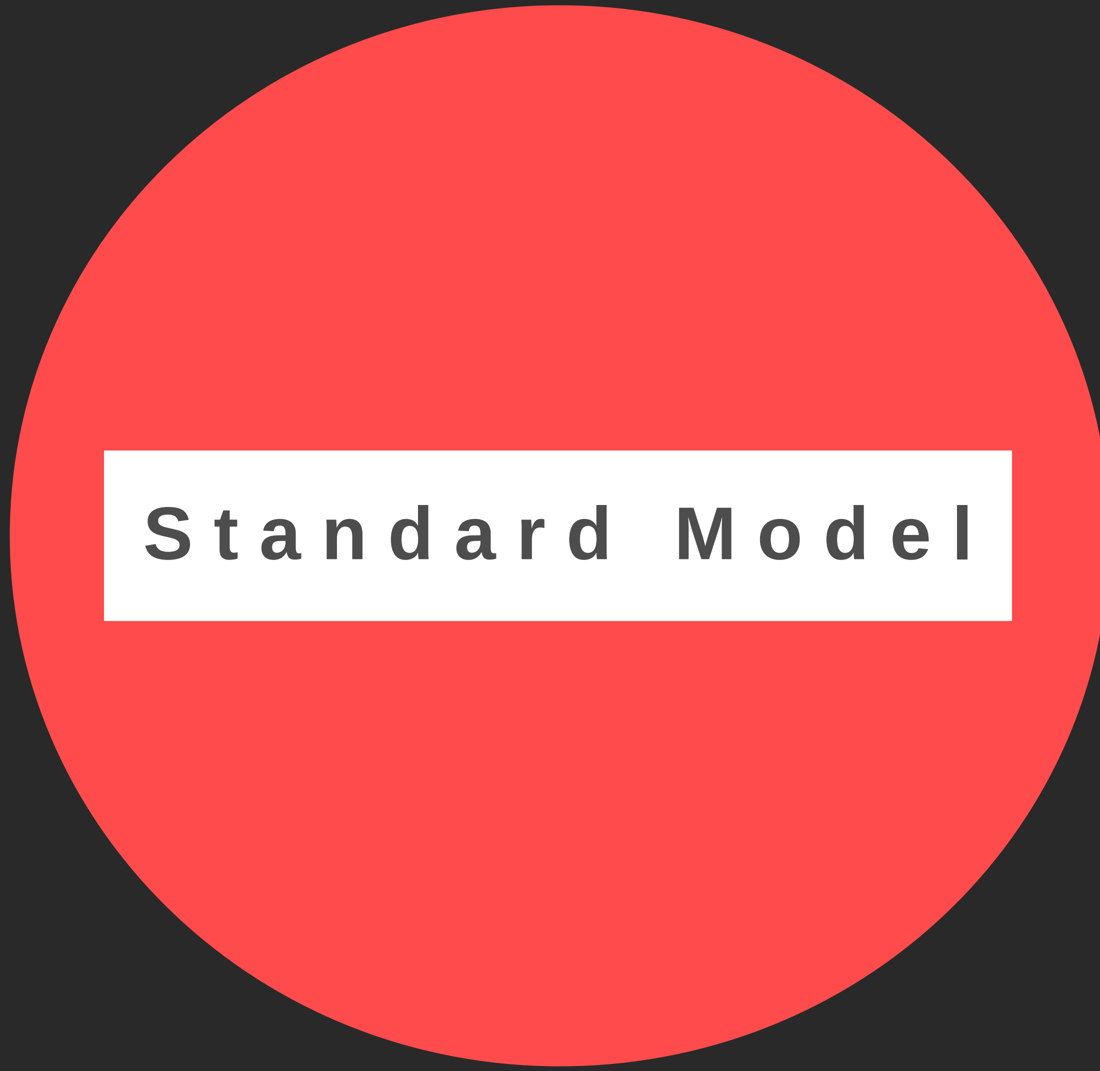
The “Hierarchy” Problem

The Gauge Hierarchy Problem…

- …denotes this finetuning of parameters, and the stro
weak scale on the physics at (presumably) much hig
- If the Higgs radiative corrections are cut off at the sc
electroweak symmetry breaking so different from the
- Equivalently, why is gravity so weak? $G_F = \frac{g^2}{4\sqrt{2}m_W^2}$

Possible solutions to the hierarchy problem:

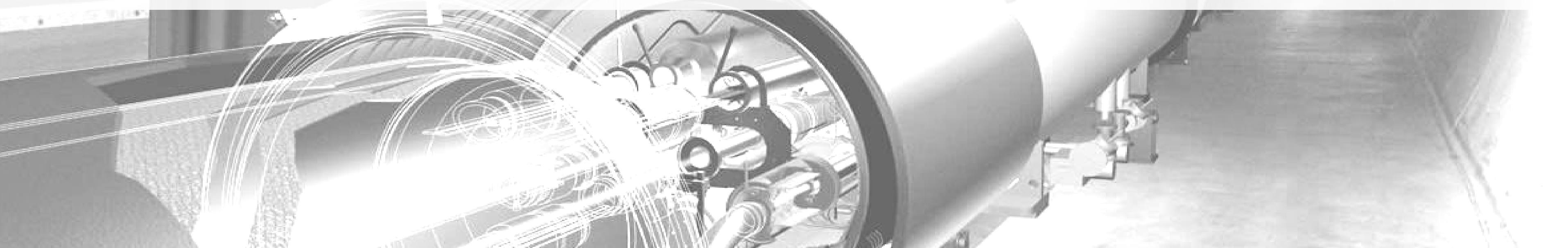
- New physics appears not much above the EW scale and regularises the quadratic divergences


Standard Model

Motivation for a Huge Machine

Most SM extensions solve the hierarchy problem and provide dark matter candidates by introducing **new particles at the TeV scale**

To find these, we need a new, huge collider providing hard parton collisions with centre-of-mass energy well above 1 TeV

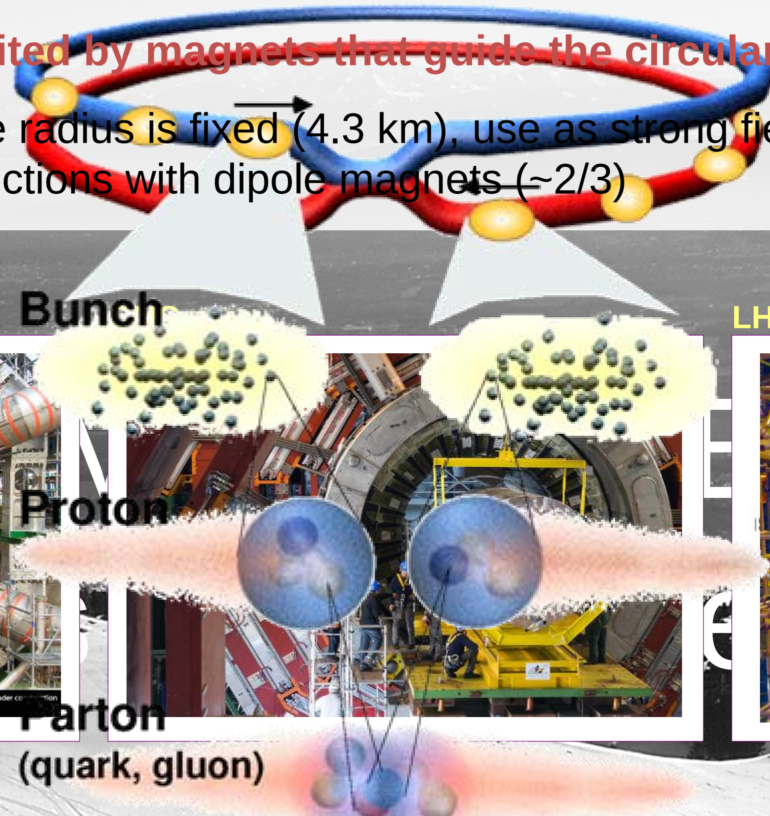


CERN, the LHC and ATLAS

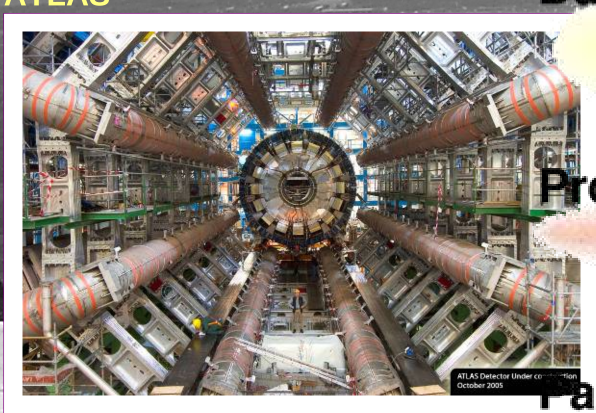
Experimental Challenges

LHC: The Accelerator Challenge

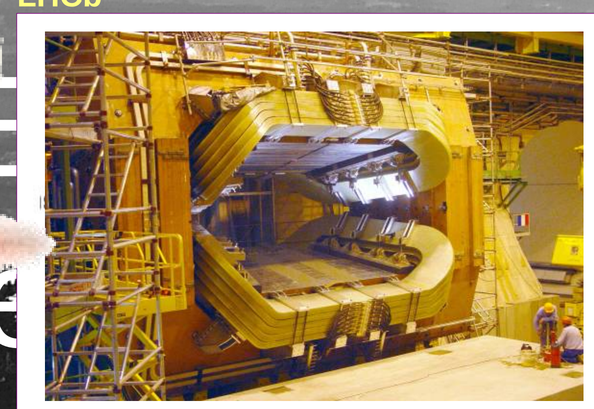
- The search for new phenomena exploits **ever smaller distances → ever larger energies**
- The LHC collides protons at E_{CM} = 14 TeV → probing a distance of 1.4 10^{-20} m ?
  … not quite, since protons are composites: the energy is distributed among its partons
- Want to produce **rare new particles → need high intensity beams**
- **Proton energy is limited by magnets that guide the circular beams**
- $E_{proton} \sim 0.3 \cdot B \cdot r$: since radius is fixed (4.3 km), use as strong fields as possible (> 8 T), and fill all free LHC sections with dipole magnets (~2/3)



ATLAS



LHCb



… and also ALICE !

Accelerators for the LHC

7 TeV

↑ LHC

450 GeV

↑ SPS

26 GeV

↑ PS

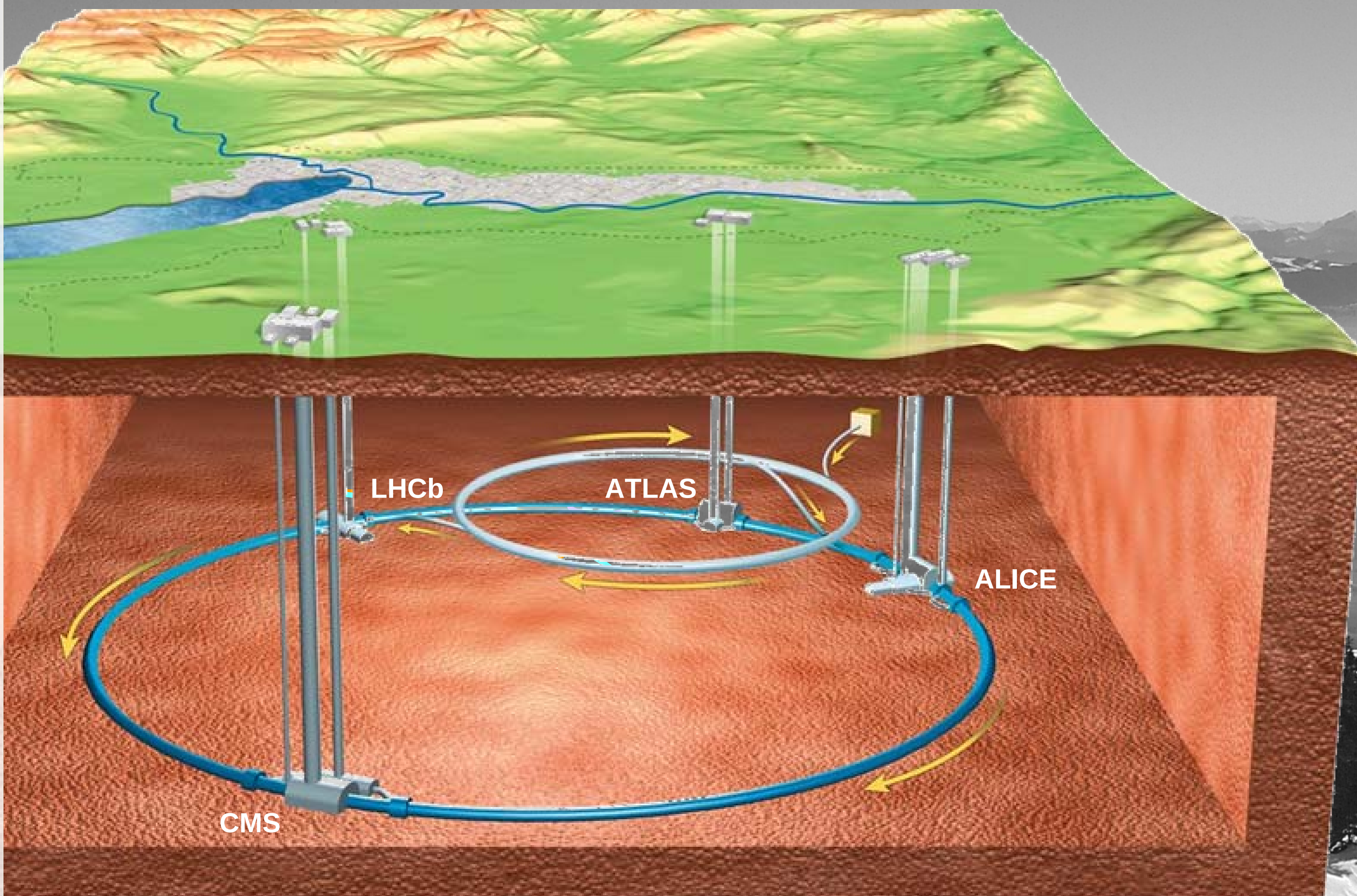
1.4 GeV

↑ BOO-
STER

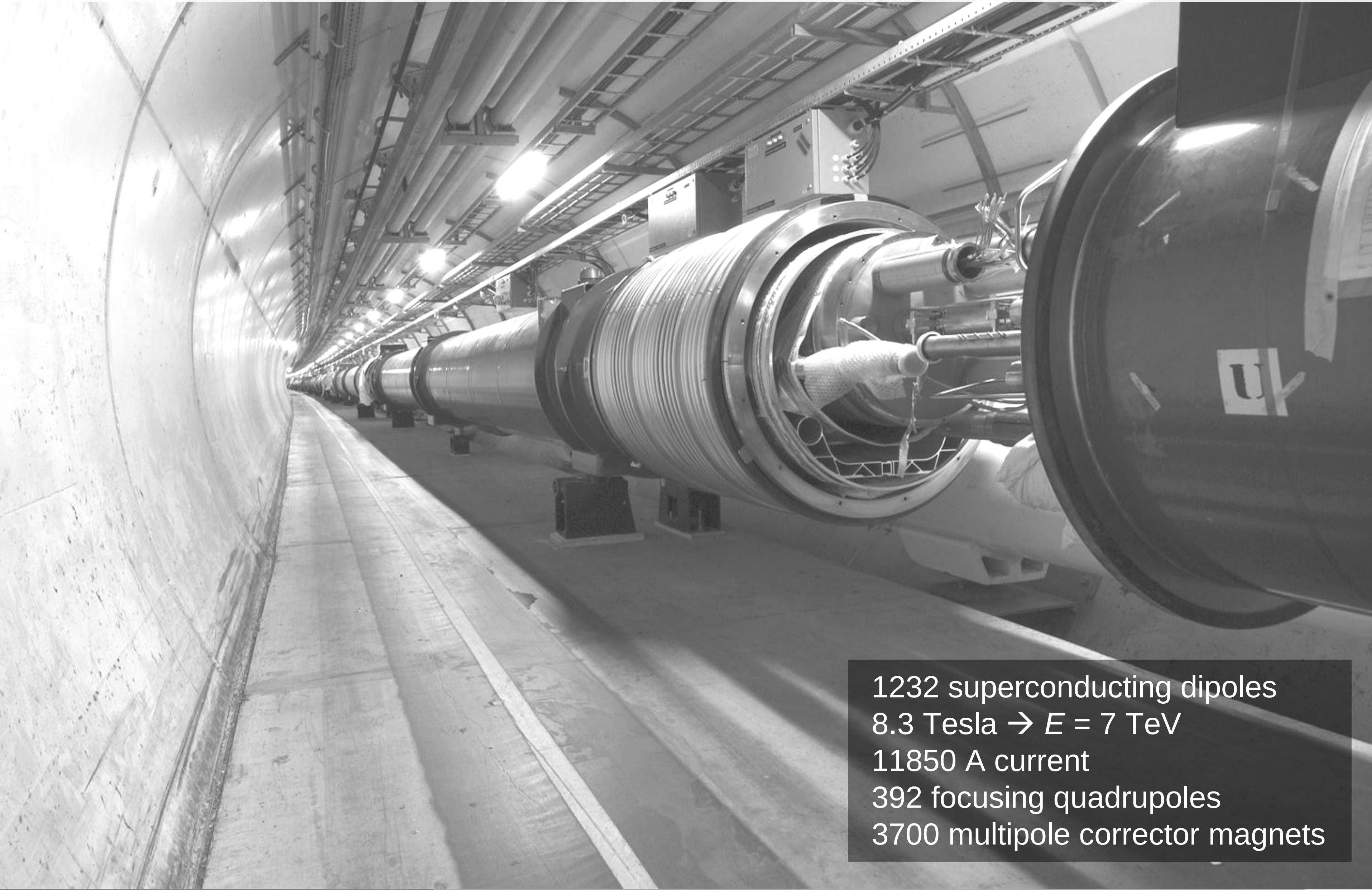
50 MeV

↑ LIN-
AC2

LHC has 4 large experiments: ATLAS, CMS, LHCb, ALICE



The LHC – Dipole Section



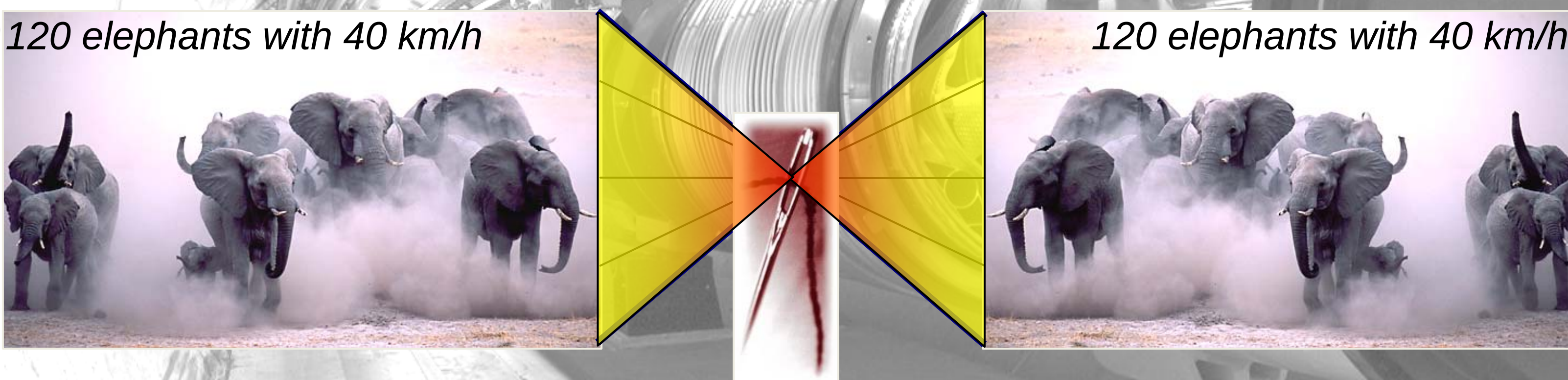
1232 superconducting dipoles
8.3 Tesla → E = 7 TeV
11850 A current
392 focusing quadrupoles
3700 multipole corrector magnets

The LHC – Stored Energy

2808 bunches filled with 10^{11} protons à 7 TeV per bunch

➧ 360 MJ stored energy per proton beam

Equivalent to Colliding 2×120 Elephants



Big challenge to control (and dump) the stored energy and to avoid damage

Eye of a needle: 0.3 mm diameter

Proton beams at interaction point are 20 x smaller: **16 μm diameter**

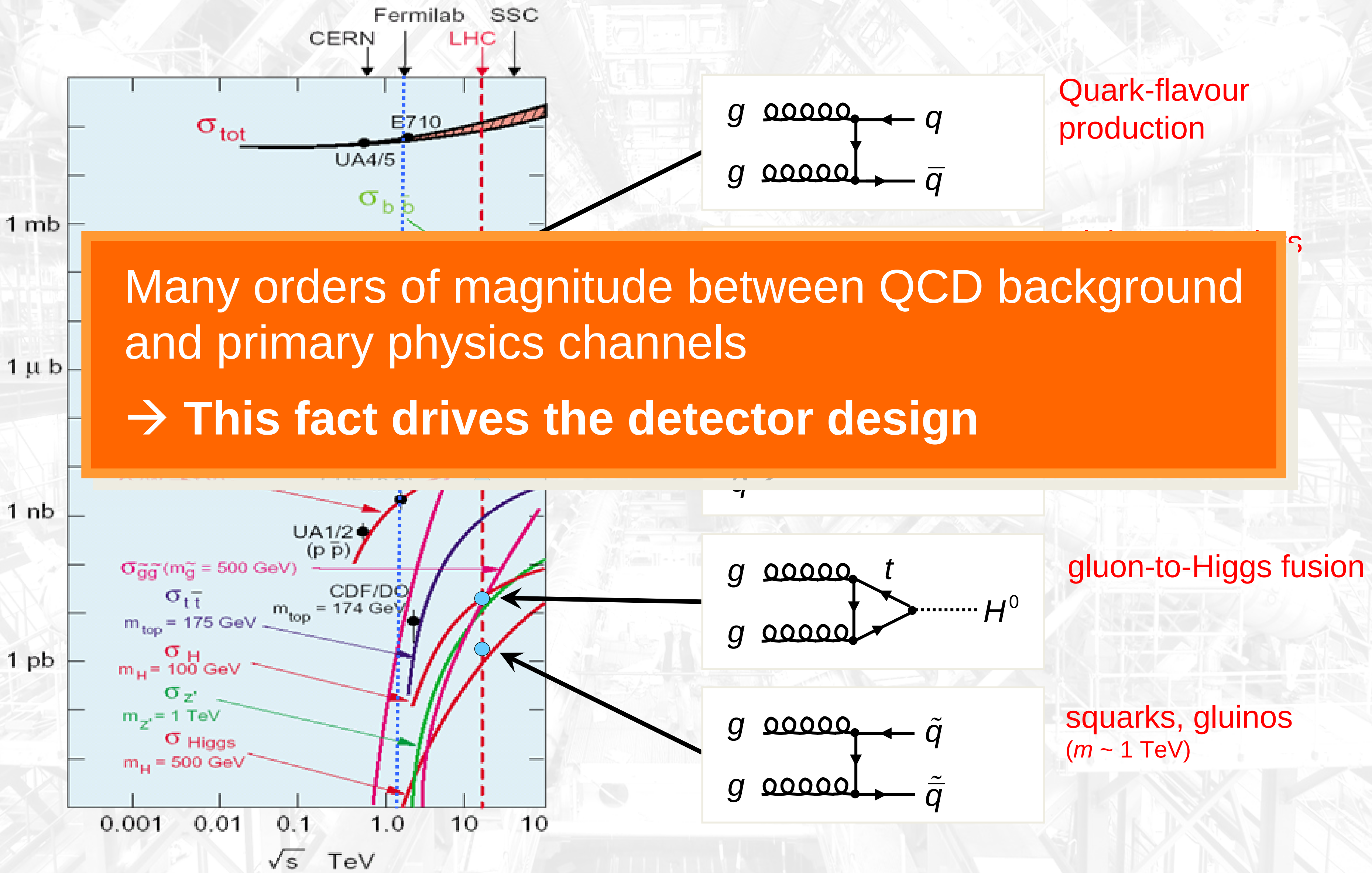
The LHC – Pictures

The High–p_T LHC Detectors

ATLAS and CMS are “general purpose detectors”, capable of adequately covering the entire physics programme reachable with high-luminosity 14 TeV *pp* collisions

- From charm and beauty physics at lowest transverse momenta (~3 GeV) …
- … to new physics searches up to the highest reachable scales (~4 TeV)

Cross Sections



Many orders of magnitude between QCD background and primary physics channels

→ **This fact drives the detector design**

Requirements from LHC Conditions

LHC and data conditions:	Design challenges:
40 MHz bunch crossing rate (25ns = 7.5m bunch spacing)	**Fast trigger, precise timing** **and** **“pipeline” electronics: Level-1 latency < 2.5μs**
~1 GHz interaction rate at *L* = 10^{34} $cm^{-2}s^{-1}$ (~25 ias. per bunch crossing)	**Efficient pattern recognition to reduce:** GHz → **L1** → 75 kHz → **HLT** → 200 Hz → Disk
~300 Mbytes/seconds data rate (200 Hz × *O*(1.5 MB/event))	**Powerful data processing farms**: distribute data analysis to computing centres worldwide
Irradiation rate / 10 LHC years: 5×10^{14} n_{eq}/cm^2 (300 kGray [= J/kg])	**Radiation hard inner tracker** (pixel with large *S*/*B*) **and forward calorimeter technology**
High charged multiplicity (*O*(1000) tracks per event, 10^{12} / sec)	**High-granular pixel/silicon** or **fine-grained straw tracker** technologies
High background rates (beam halo muons, neutrons, beam-gas collisions)	**Precise muon timing**, redundant pattern recognition, radiation hardness

Requirements from Physics Programme

- Some benchmark analyses
  - $B_{s(d)} \to \mu\mu$ and $B_s \to J/\psi\,\phi$
  - W mass
  - top mass
  - $H \to \gamma\gamma$, $4e$, 4μ, $\tau\tau$ (WBF)
  - SUSY with R-parity, SUSY Higgs
  - RS KK modes

- Design challenges:

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d B mass)

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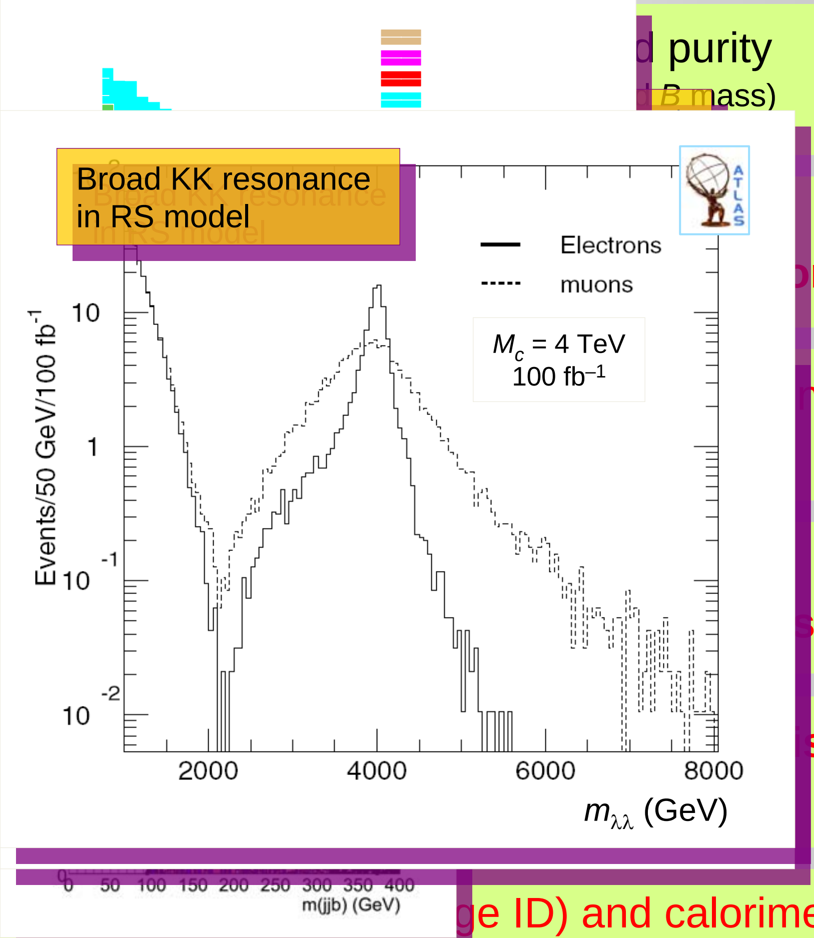
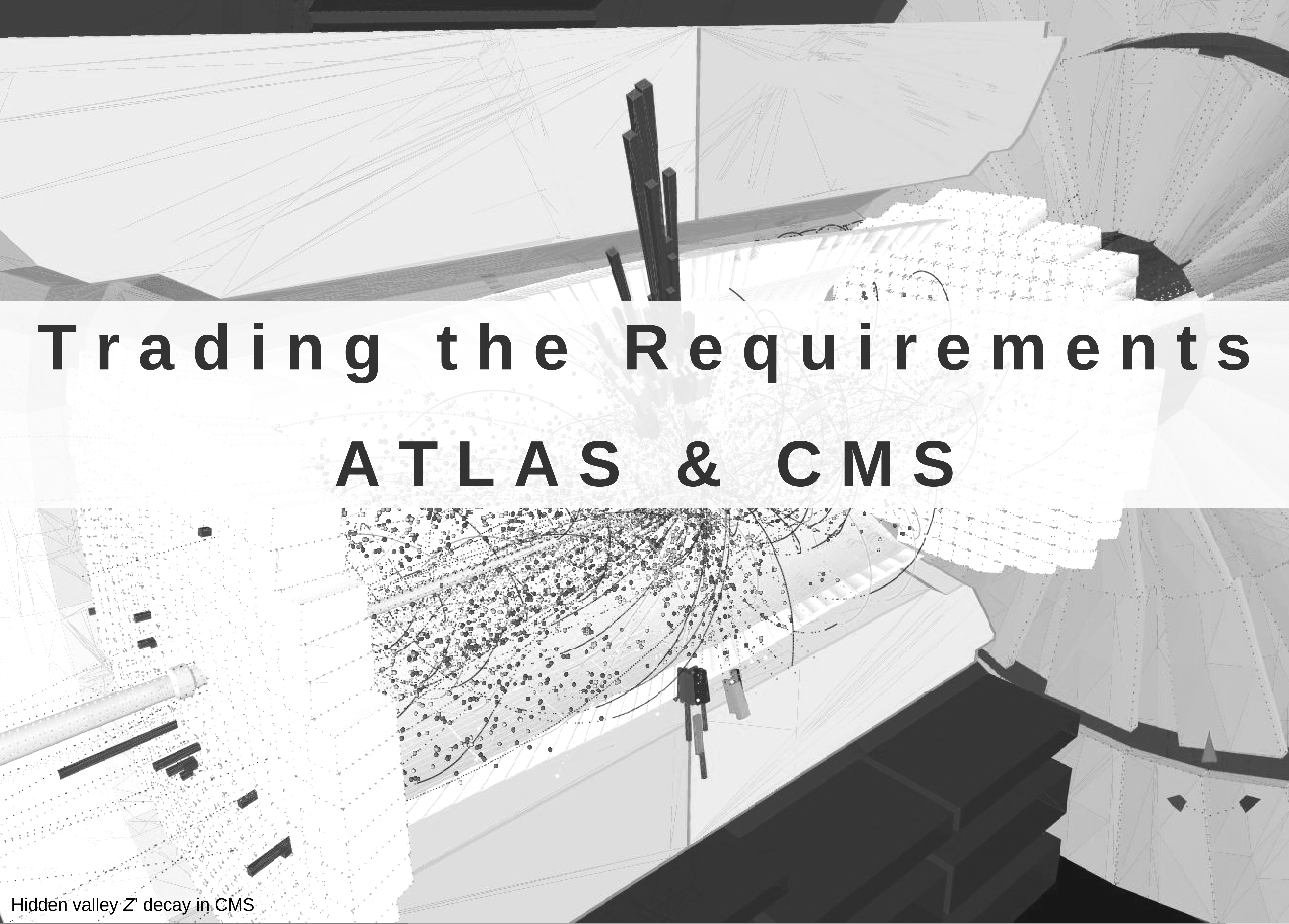


ge ID) and calorimeter resolution at O(TeV), little calo saturation

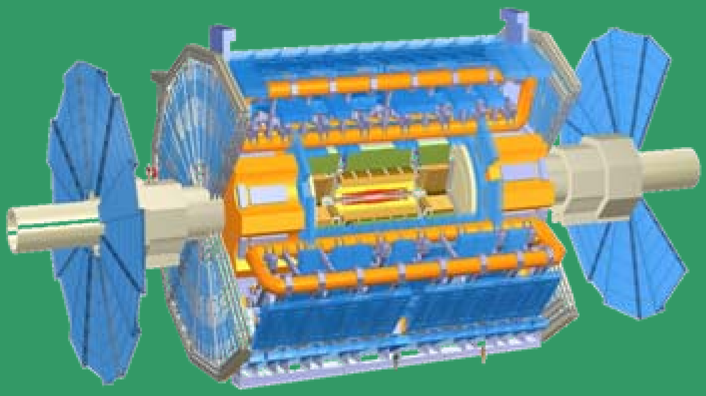


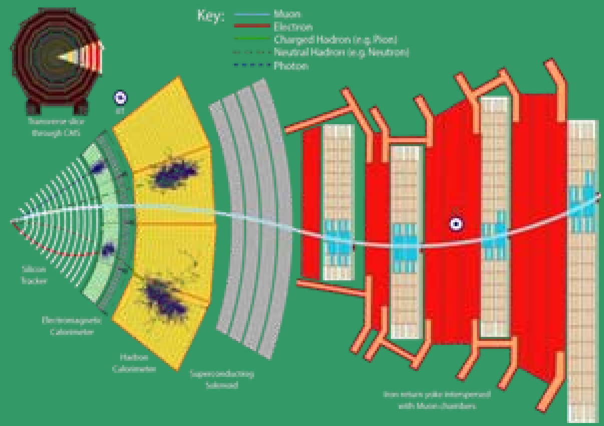
Trading the Requirements

ATLAS & CMS

Hidden valley Z' decay in CMS

ATLAS & CMS: Design & Performance Overview





ATLAS: emphasis on excellent jet and missing-E_T resolution, particle identification, and standalone muon measurement

CMS: emphasis on excellent electron/photon and tracking (muon) resolution

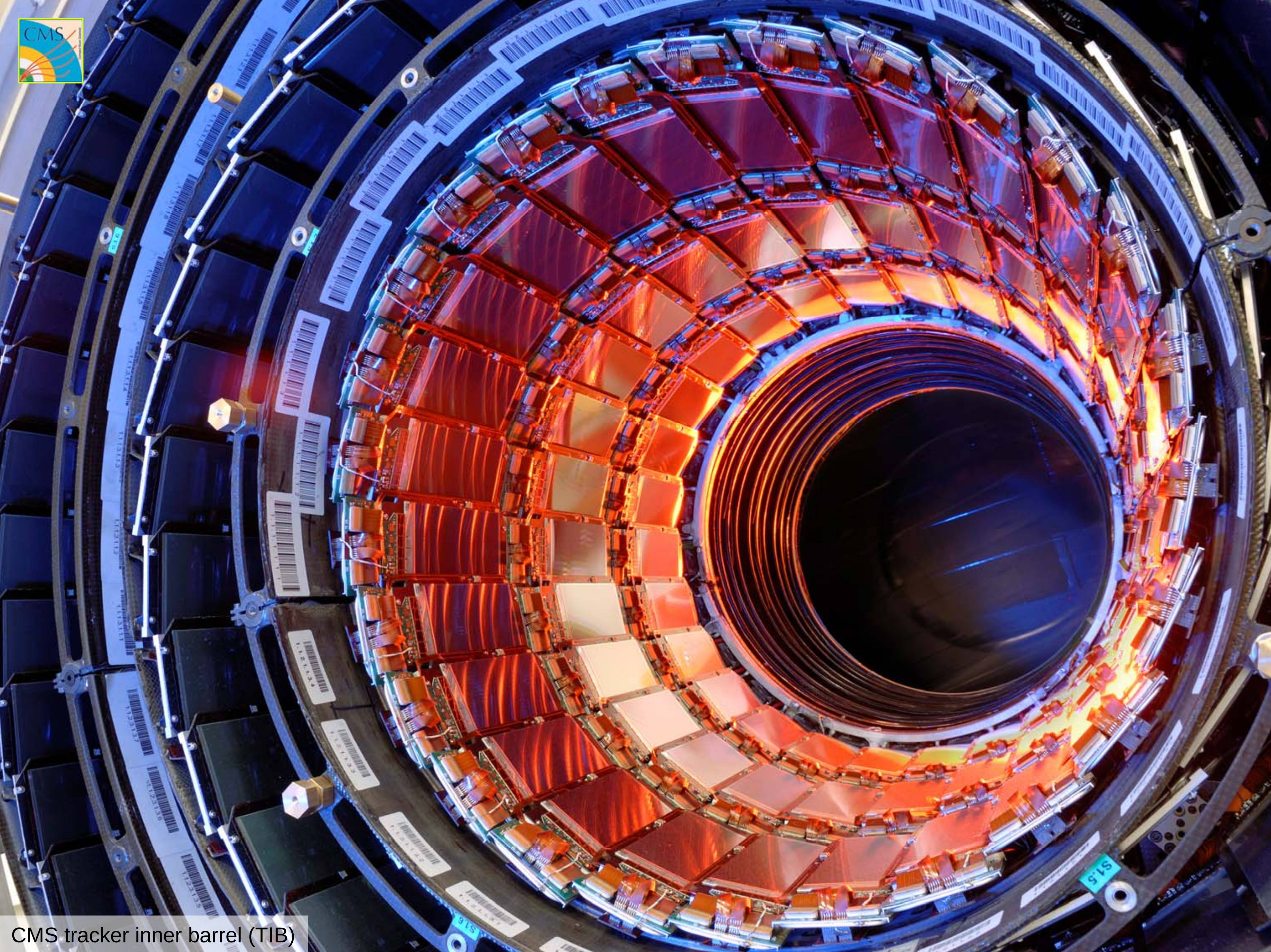
Both: excellent hermeticity – very few "cracks"

MUON	• $\sigma(p_T)$ ~ 10.5% / 10.4% (1 TeV, η = 0) (standalone / combined with tracker)	• $\sigma(p_T)$ ~ 13% / 4.5% (1 TeV, η = 0) (standalone / combined with tracker)

Source: F

Detector Commissioning

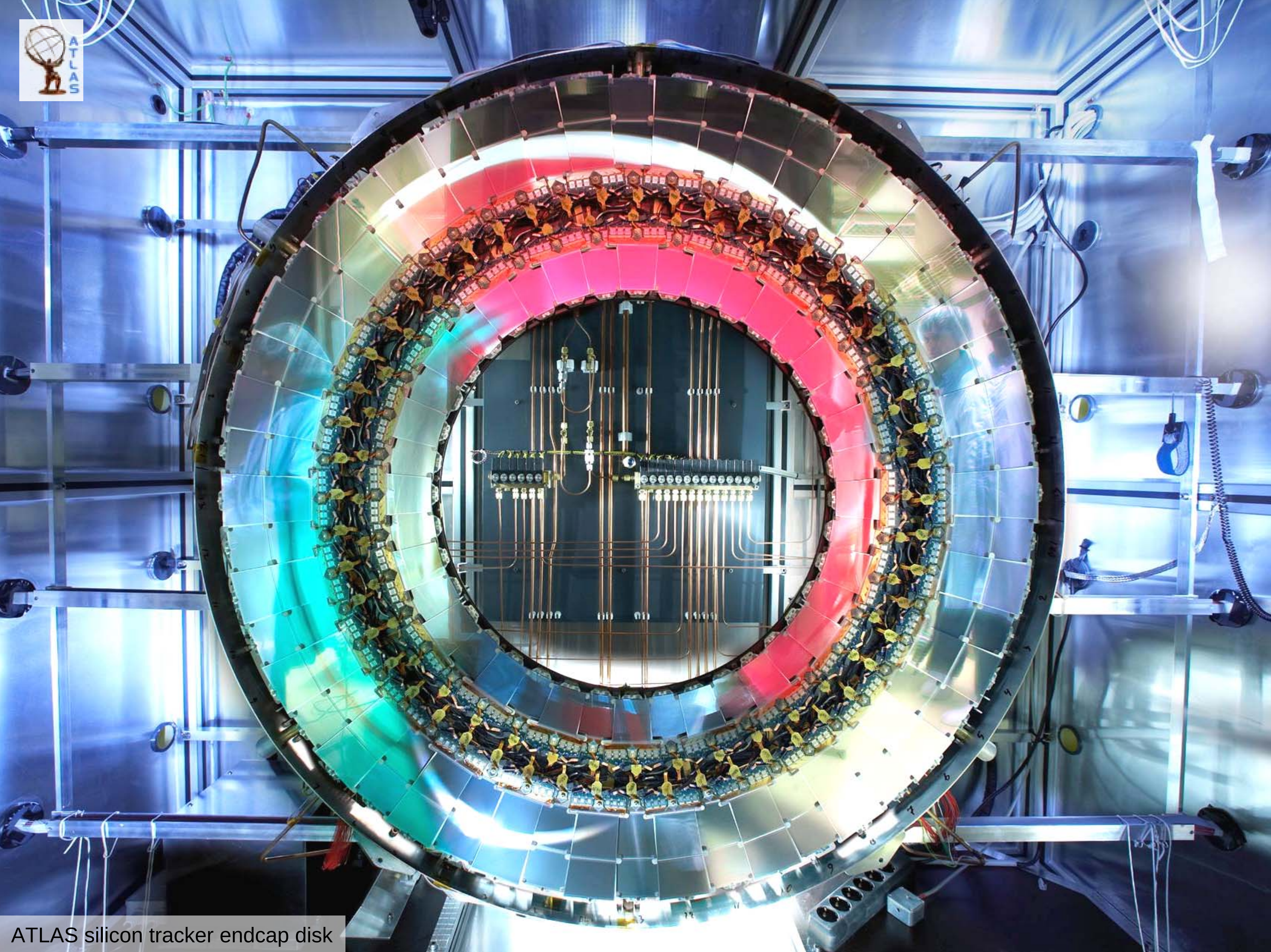
ATLAS barrel toroid magnets



CMS tracker inner barrel (TIB)

ATLAS electromagnetic calorimeter

CMS ECAL crystals



ATLAS silicon tracker endcap disk

Start-up Detector Commissioning (I)

Need to early and fully commission the experiments to reach performance goals

Before LHC collisions:

- Perform and maximally exploit test-beam measurements to understand detector components and tune simulation
- Perform realistic dress rehearsals to test acquisition, streaming and distribution of data
- Test calibration and alignment procedures with "as-installed" simulation samples
- Precisely map *B*-fields with survey data from magnetic probes
- Electronics channels are calibrated and mapped as dead or noisy with charge and/or external source injections, and cosmic ray events
- Collect large cosmic ray muon samples for initial detector alignment (barrel), and to provide reference for precise optical alignment system of muon spectrometer
- Use beam halo events for initial end-cap alignment

Start-up Detector Commissioning (II)

With LHC collisions:

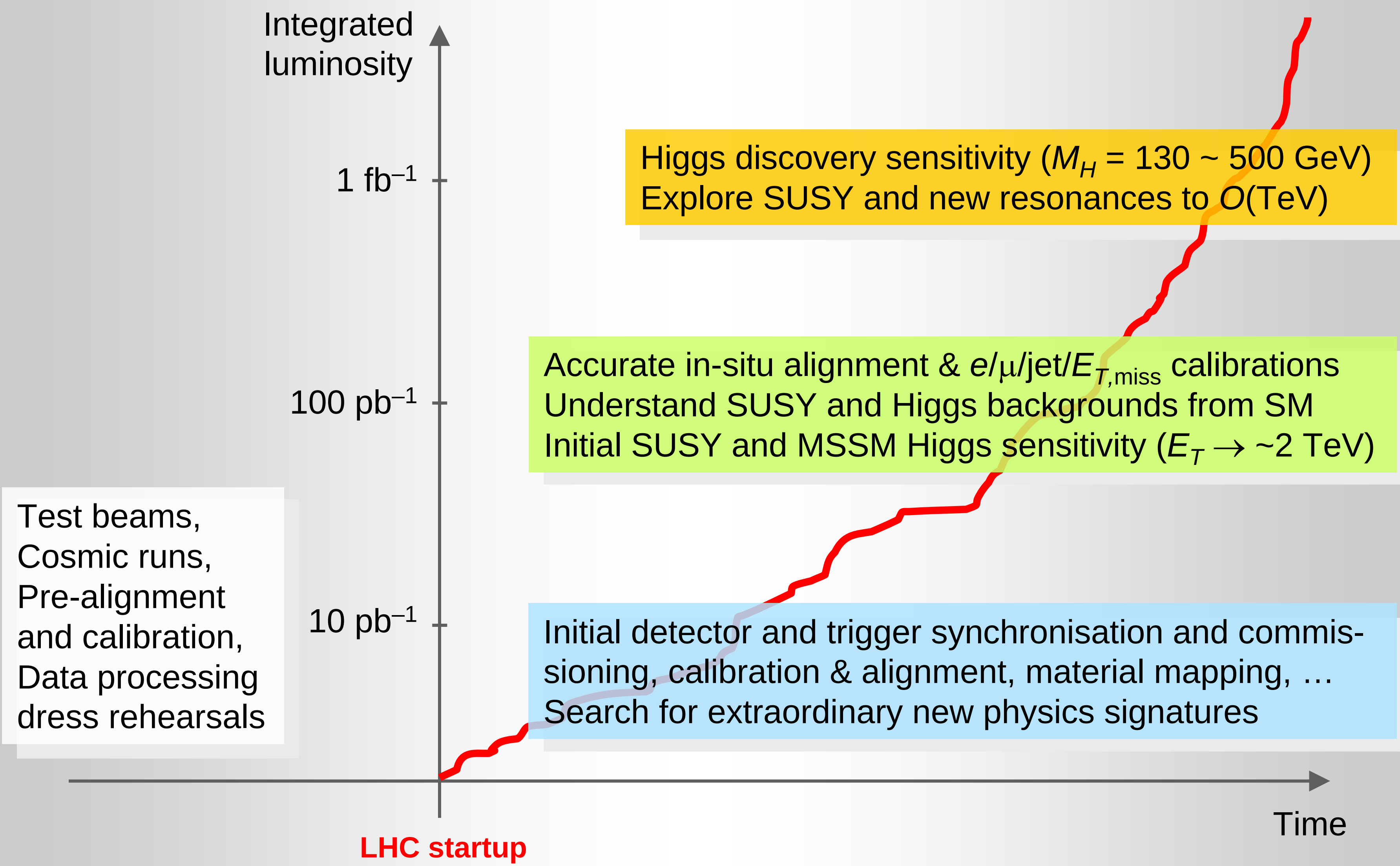
- Time-in detector components with LHC bunches and trigger signal
- Subsequently operate hardware and software triggers with min. bias events; first commission single-object triggers, followed by topological signatures, isolation and $E_{T,\mathrm{miss}}$
- Copious isolated tracks used to improve inner tracker alignment; use additional information from E/p of tracks with opposite charge, and K^0, Λ_b mass and lifetimes
- Initial monitor of uniformity (azimuthally and $\pm\eta$) of calorimeter response
- Initial checks of calorimeter simulation by comparing track E/p and jet shower shapes
- Collect low-p_T leptons from c, b and J/ψ, $\Upsilon \to \mu\mu$ decays (>100k registered J/ψ /pb^{-1})
- Collect high-p_T leptons from W and Z decays (~7k/pb^{-1} and ~2k/pb^{-1})
- Map pre-calorimeter material to $O(1\%)$ with photon conversions, bremsstrahlung, also use momentum dependence of invariant mass reconstruction of light resonances

Start-up Detector Commissioning (III)

With LHC collisions:

- EM inter-calibration with inclusive electrons, later with Z $\rightarrow$ *ee* (~100 pb^{-1} for 0.7% EM uniformity), also for global EM energy scale (similar: μ scale with Z $\rightarrow \mu\mu$)
- Hadronic track and jet inter-calibration with *E*/*p*, E_T balancing in di-jet, γ-jet, *Z*-jet events; global jet energy scale to < 5% after few months
- Jet calibration with $tt_{\rm bar}$ events, with $W \rightarrow jj$ & $W \rightarrow$ e/$\mu\nu$ (~250/pb^{-1}); calibrate *b*-tagging
- $E_{T,\rm miss}$ reconstruction requires event cleaning from beam halo, beam-gas collisions, cavern bkg, cosmics, and accurate mapping of instrumental deficiencies
- Study of $E_{T,\rm miss}$ tails with min. bias ($E_{T,\rm miss}$ vs ΣE_T), *Z*, *W* events → ~5% scale accuracy with 100 pb^{-1}
- Measure *e* and μ efficiencies and fake rates from $Z \rightarrow ee,\mu\mu$ "tag-and-probe" method
- Measure first differential and total cross sections for SM processes, study underlying event, verify PDFs, search for extraordinary physics, …

Start-up Programme in a Nutshell



Before Beam: **Test Beams**

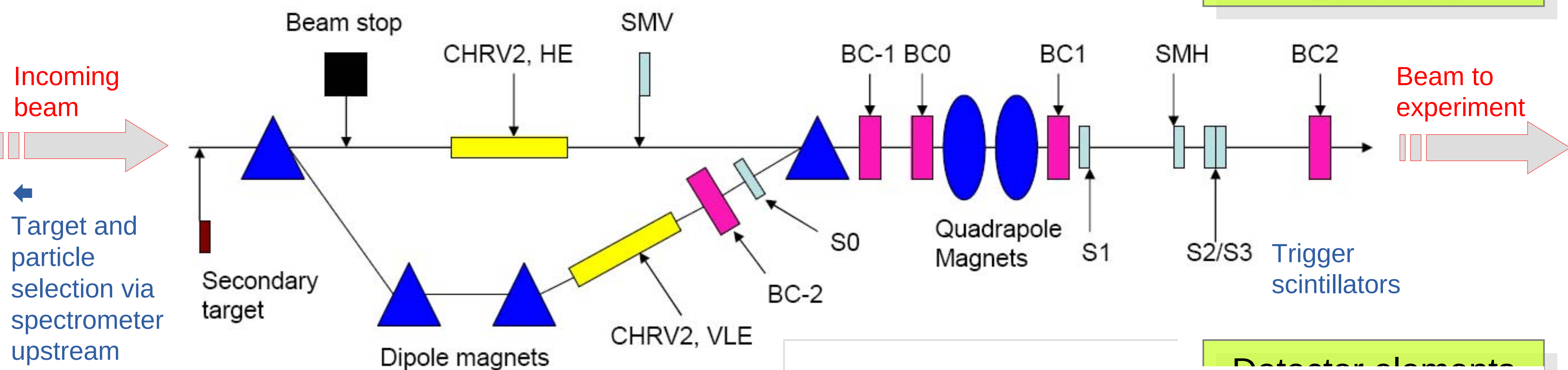
Both ATLAS and CMS have performed a series of measurements with test beams of known energies, and different particle types. Electrons, photons, muons, pions, protons with energies between 2 and 250 GeV and varying magnetic field configurations were collected.

Aims: test tracking efficiency, alignment and particle ID, (inter-)calibrate electromagnetic and hadronic calorimeters, test muon trigger efficiency, tune Monte Carlo simulation, …

“H8” Beam Line for ATLAS 2004 Test Beam

Beam line produces hadrons, electrons, muons from 1 to 350 GeV from initial SPS protons

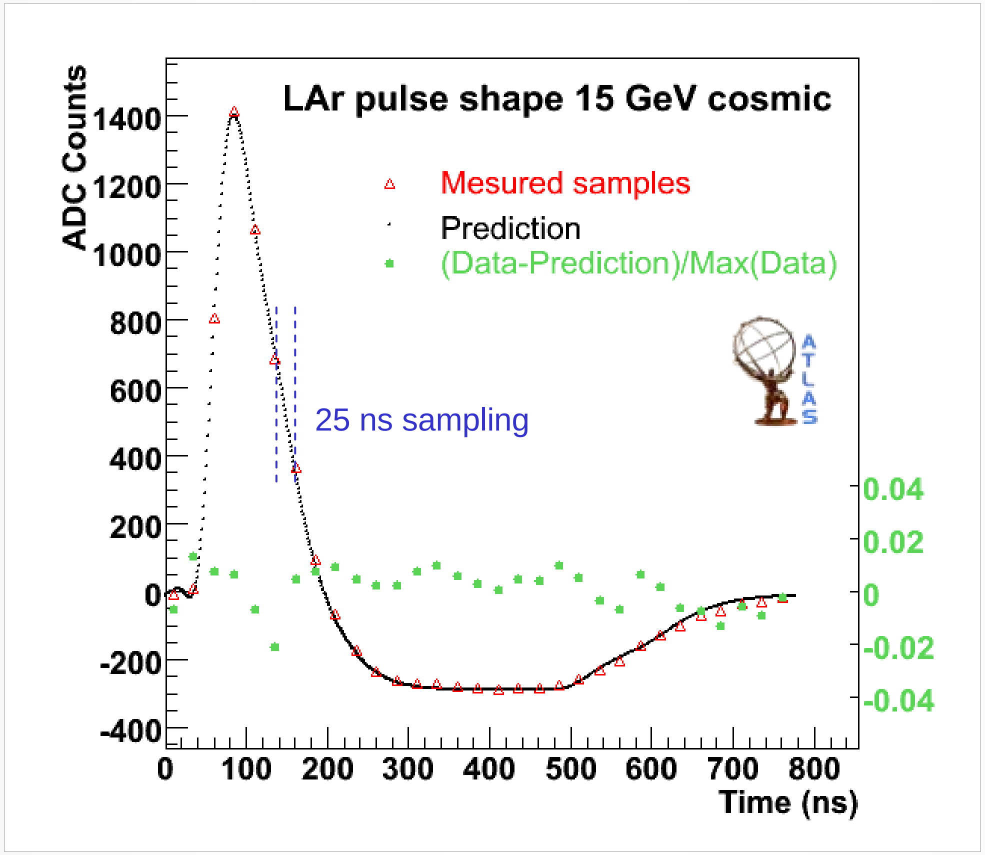
Beam line



Spectrometer for low-energy particles (1–9 GeV) created in secondary target

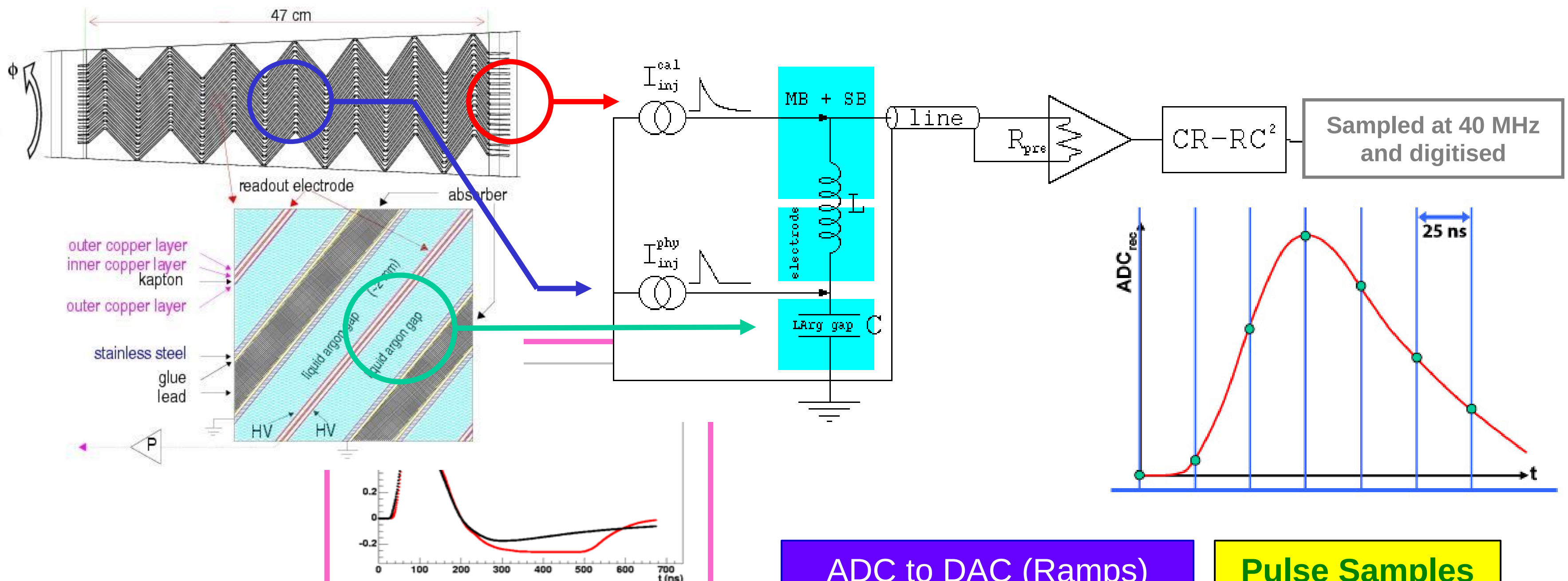
ATLAS EM Energy Reconstruction

- The Liquid-Argon sampling calorimeter measures shaped pulse shapes
  - With collisions: 5 samples around peak are sent from FEB → ROD where EM energy is computed
  - For cosmics: peak position unknown → send up to 32 samples offline and fit pulseshape



How to transform measured ADC counts into Energy ?

ATLAS EM Energy Reconstruction



ADC to DAC (Ramps)

Pulse Samples

$$E_{\text{cell}} = F_{\mu\text{A}\rightarrow\text{MeV}} \cdot F_{DAC\rightarrow\mu\text{A}} \cdot \frac{1}{\frac{\text{M}_{\text{phys}}}{\text{M}_{\text{cali}}}} \cdot R \left[\sum_{j=1}^{N_{\text{samples}}} a_j \left(s_j - p \right) \right]$$

Cell energy

Sampling fraction

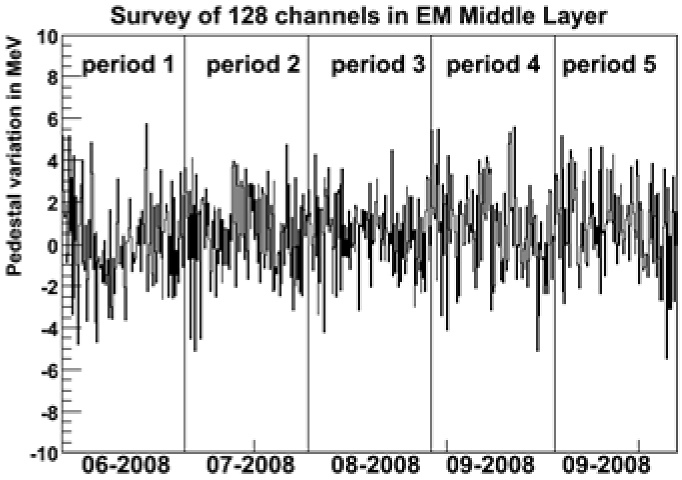
Calibration board

"Optimal Filtering" Coefficients

Pedestals

ATLAS EM Energy Reconstruction

Pedestals, noise, autocorrelation: obtained regularly from random triggers in physics events (use filled bunches to subtract physics background) – *performed after each LHC fill*



Pedestal measurements versus time

Pulse Samples

$$E_{\text{cell}} = F_{\mu A \to \text{MeV}} \cdot F_{DAC \to \mu A} \cdot \frac{1}{\frac{M_{\text{phys}}}{M_{\text{cali}}}} \cdot R \left[\sum_{j=1}^{N_{\text{samples}}} a_j \left(s_j - p \right) \right]$$

Cell energy

Pedestals

ATLAS EM Energy Reconstruction

Ramps: dedicated electronics calibration runs, injecting known charge and measuring ADC output (~linear dependence)

This procedure provides the EM energy scale

Physics events will be used to achieve absolute EM calibration

For hadrons and jets, one needs to account for hadronic shower corrections → pass from the EM to the hadronic scale

$$E_{\text{cell}} = F_{\mu A \to \text{MeV}} \cdot F_{DAC \to \mu A} \cdot \frac{1}{\frac{M_{\text{phys}}}{M_{\text{cali}}}} \cdot R \left[\sum_{j=1} a_j (s_j - p) \right]$$

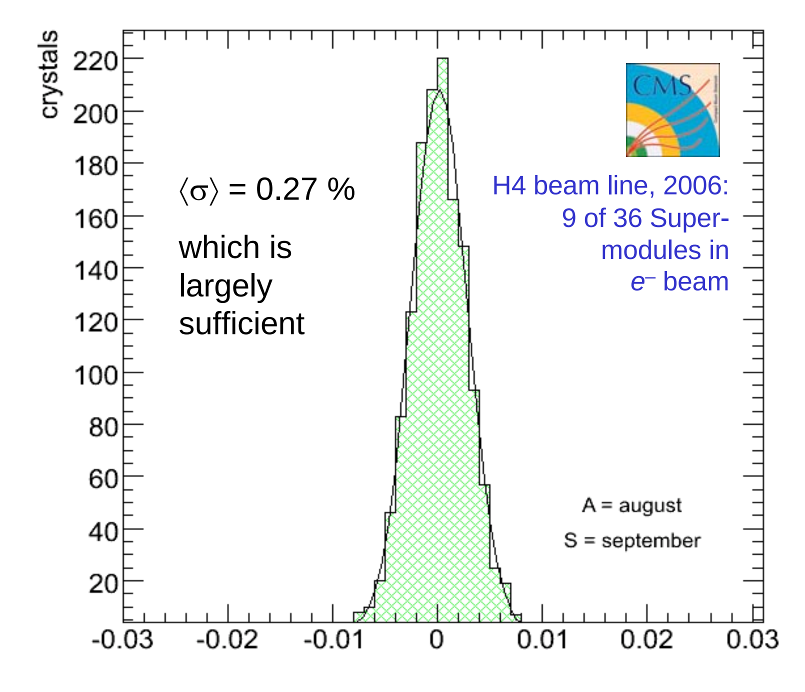
Cell energy

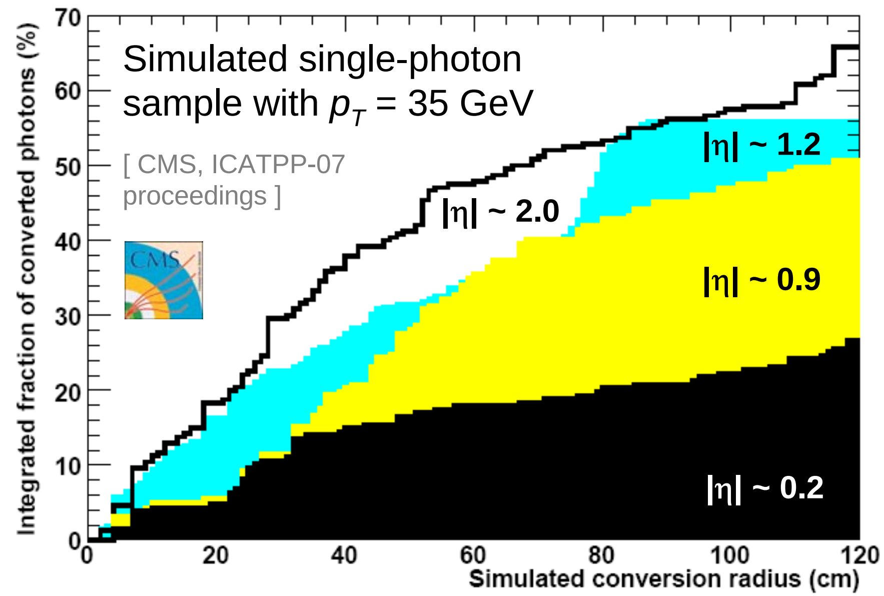
Sampling fraction

Calibration board

"Optimal Filtering" Coefficients

Electromagnetic Energy Resolution & Uniformity





Back-on-the-envelope for $H \to \gamma\gamma$:

$$\sigma_{M_H}(E_\gamma)\Big|_{p_H=0} \propto \frac{M_H}{\sqrt{2}}\frac{\sigma_{E_\gamma}}{E_\gamma} \underset{M_H=120\ \text{GeV}}{\approx} \begin{cases} 1.2\ \text{GeV}\ \ (\text{ATLAS}) \\ 0.7\ \text{GeV}\ \ (\text{CMS}) \end{cases}$$

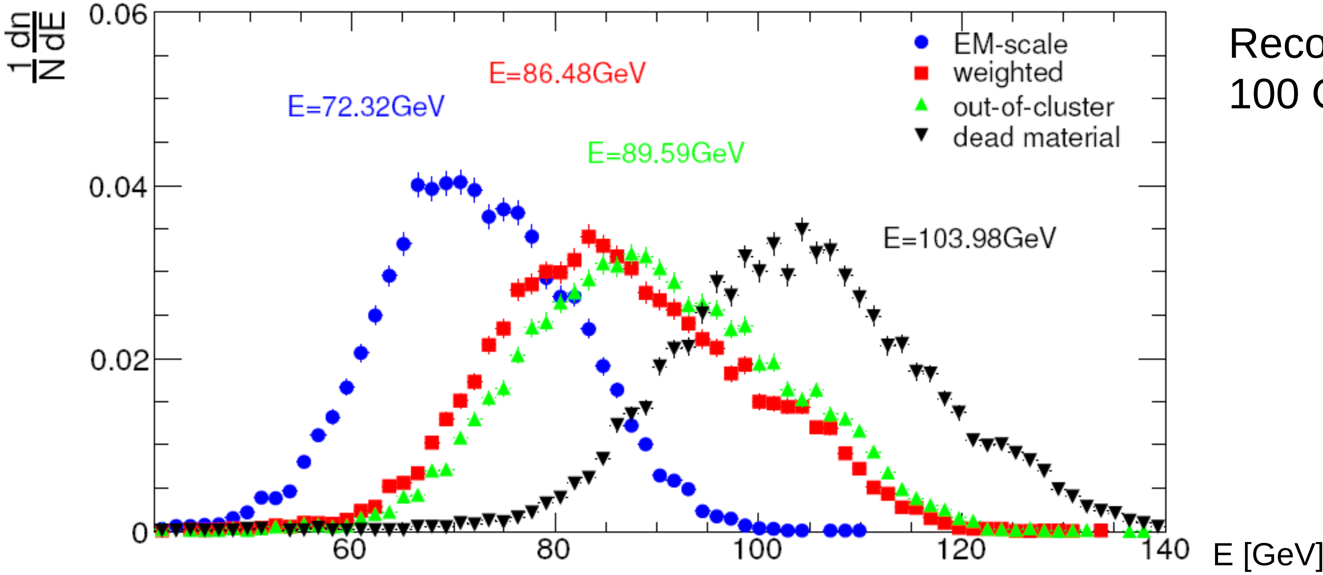
But: full picture must include error on opening anlge ($\theta_{\gamma\gamma}$), and $\gamma \to e^-e^+$ conversions (20–50%)

Electronics noise
(pile-up also contributes)

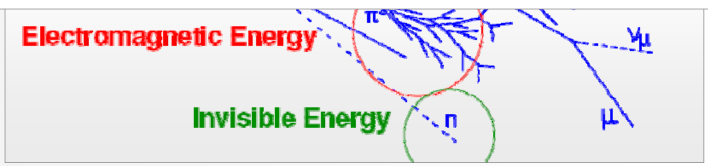
"Constant term"

Non-uniformities in calorimeter response due to inhomogeneities, non-linearities

Hadronic (Pion) Energy Reconstruction



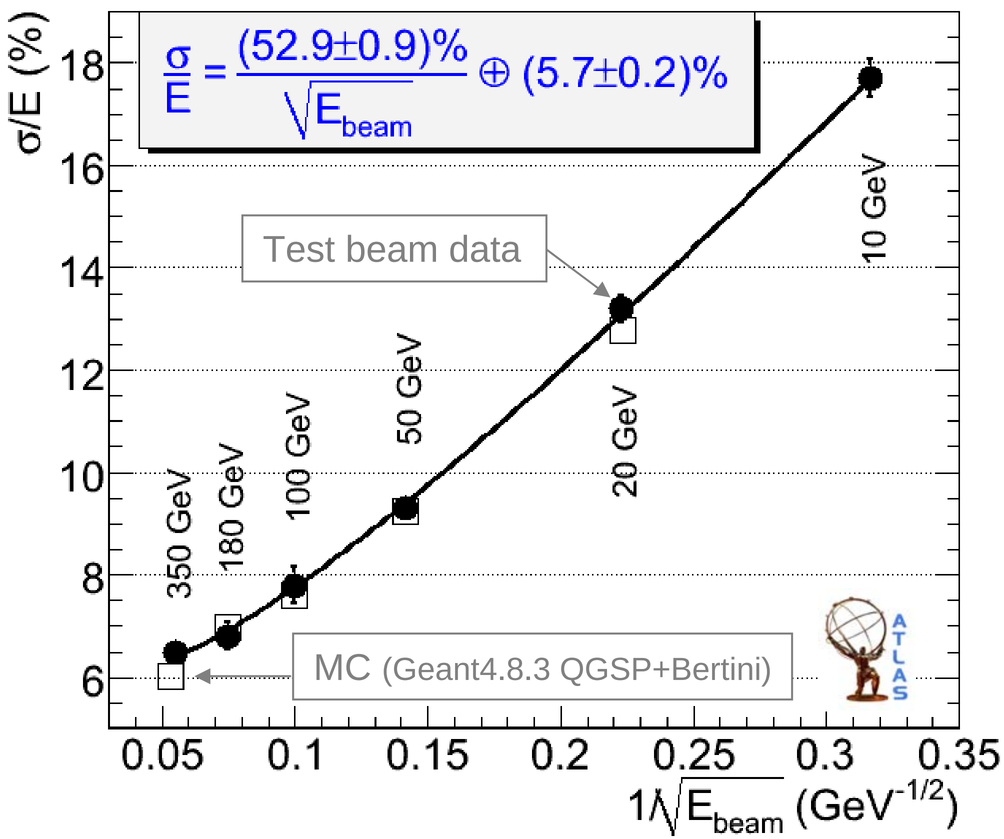
Reconstructed energy for 100 GeV pion beams



neutrons) O(25%) → causes worse HAD E resolution

- Escaped energy (*e.g.* neutrinos) O(2%)

Hadronic (Pion) Energy Reconstruction



Energy resolution from test beam data

- Hadrons: stochastic: ~53 %, constant: ~3 %, noise: ~0.5 GeV
- Jets (central, MC): stochastic: ~60 %, constant: ~3 %, noise: ~0.5 GeV
- Missing transverse energy: $\sigma(E_{T,miss}) / \Sigma E_T \approx 55\ \%$

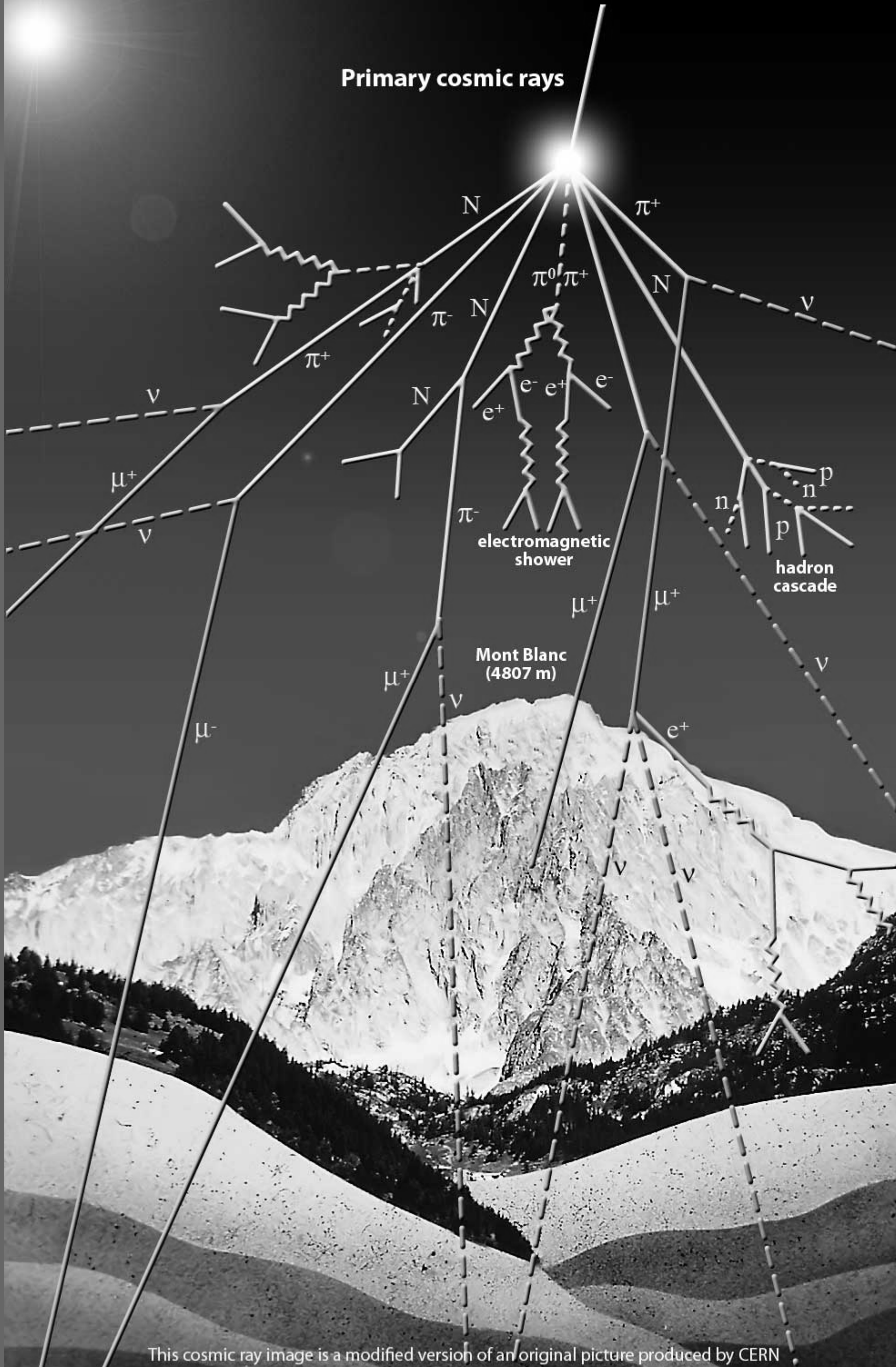
Before Beam: **Cosmic Rays**

Both ATLAS and CMS have performed large campaigns of cosmic ray data taking, initially with individual systems, later the whole detectors.

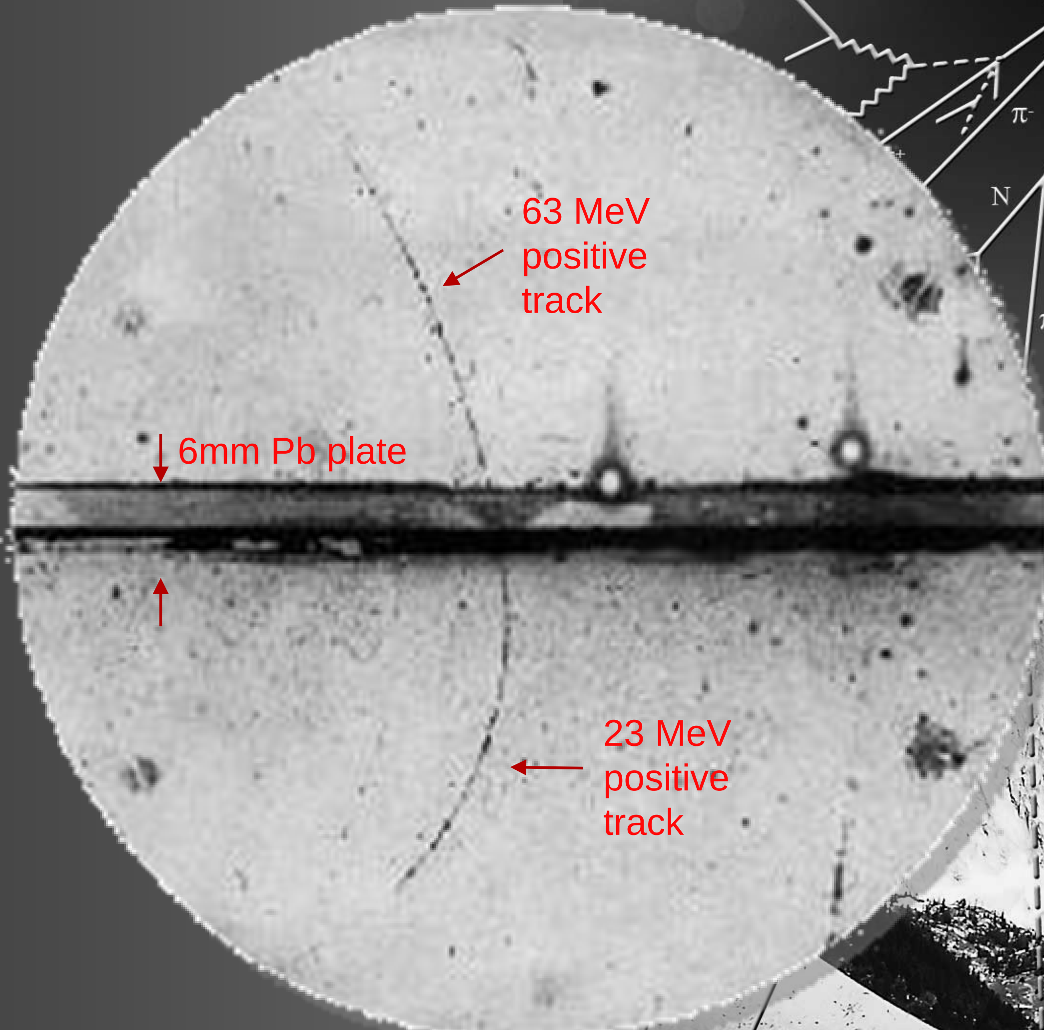
Aims: tracking alignment (with and without magnetic field), test for dead channels, test muon trigger efficiency, measure calorimeter pulse shapes, tune Monte Carlo simulation, …

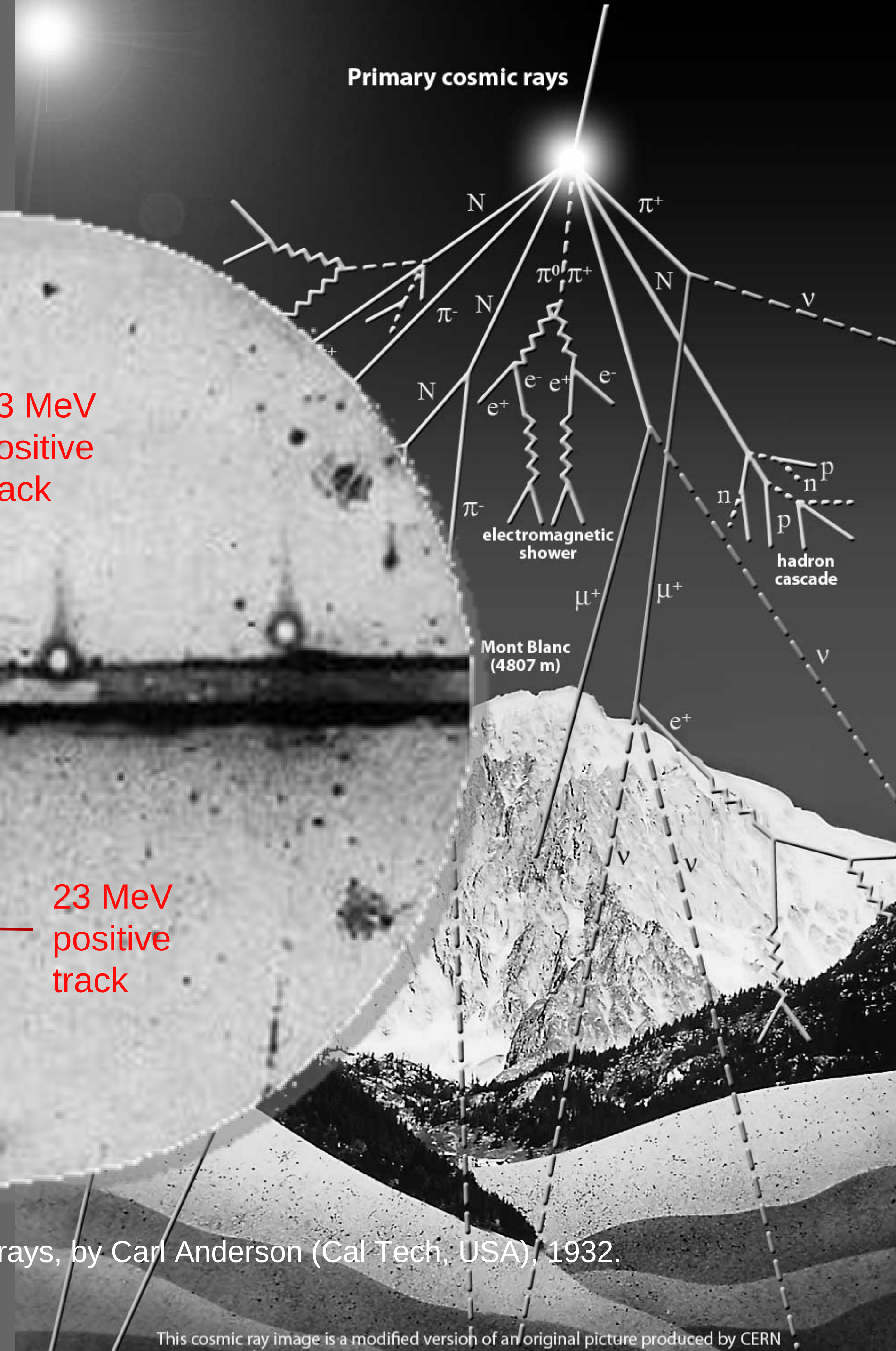
Cosmic Rays

Cosmic nuclei (90% protons) interact strongly with the earth’s atmosphere, creating hadrons that decay to minimum ionising relativistic muons, which reach see level on earth.



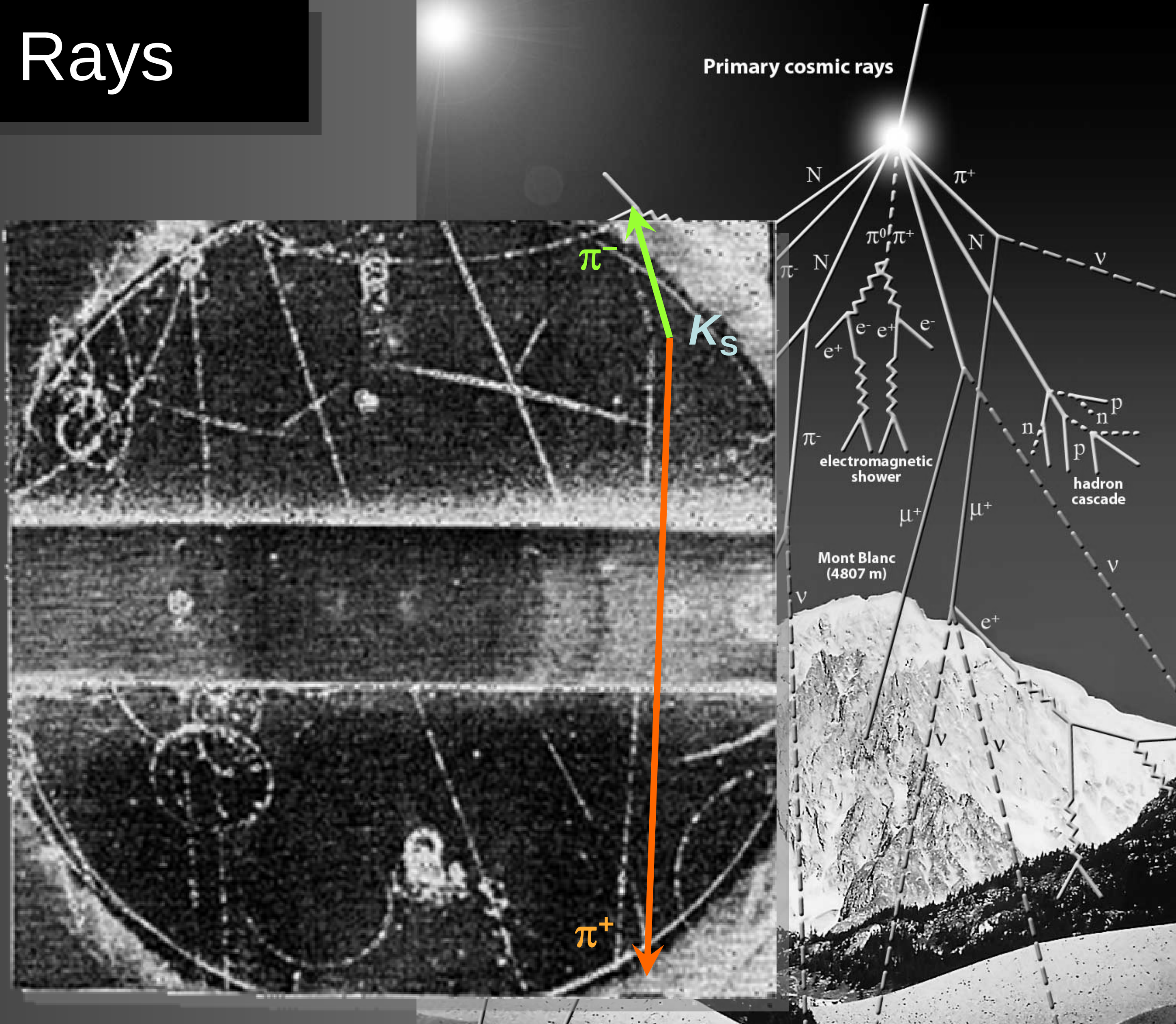
Cosmic Rays





Discovery of anti-electron (positron) in cosmic rays, by Carl Anderson (Cal Tech, USA), 1932.

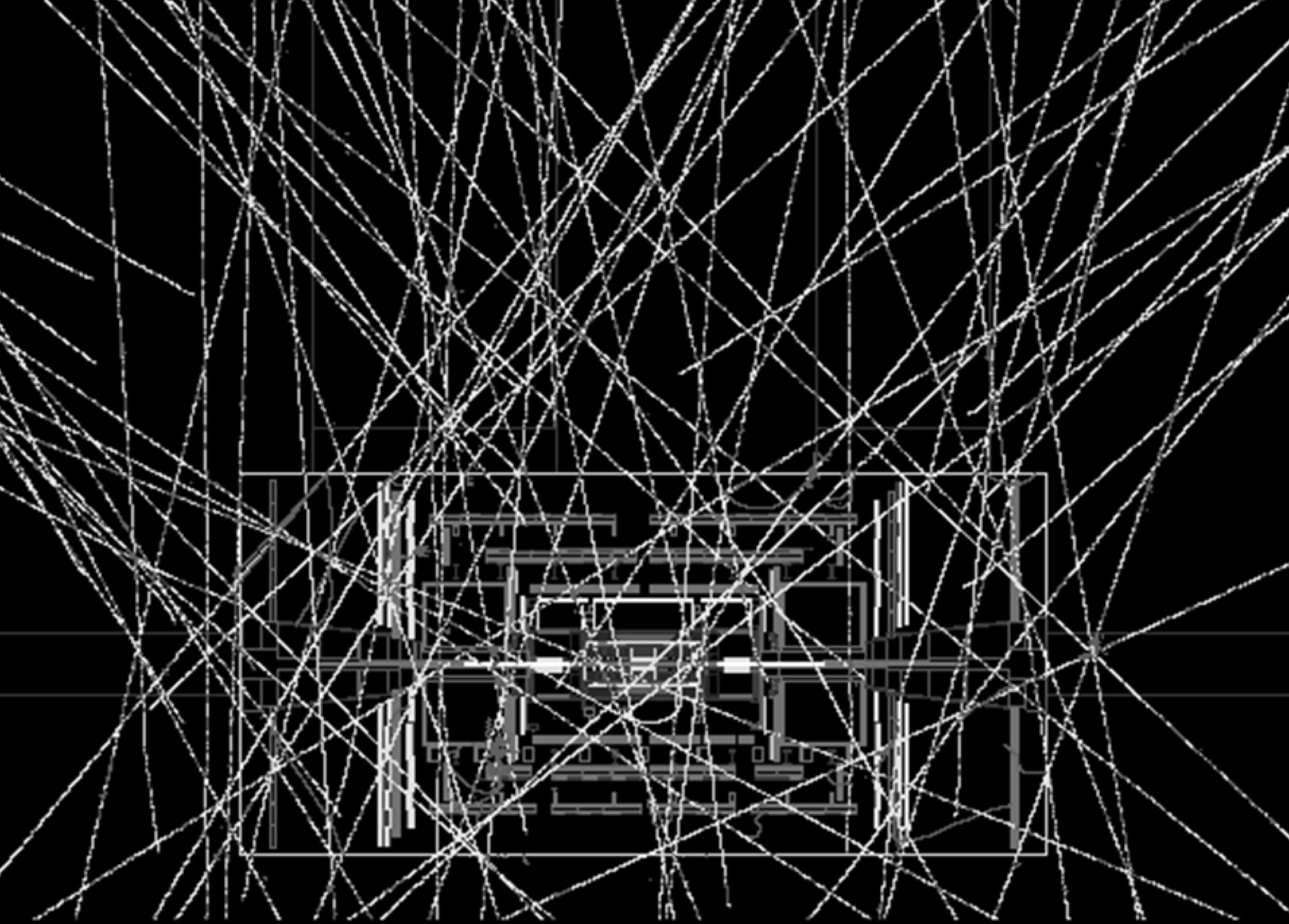
Cosmic Rays



Discovery of strange particles:

In 1946, Rochester and Butler (Manchester) observe two tracks “out of nothing”, i.e. from a decay of a neutral particle.

This cosmic ray image is a modified version of an original picture produced by CERN


Simulated cosmic flux in ATLAS cavern: integration over 10 msec

Muon flux at surface:

~130 Hz / m^2 for E_μ > 1 GeV

average energy ~4 GeV

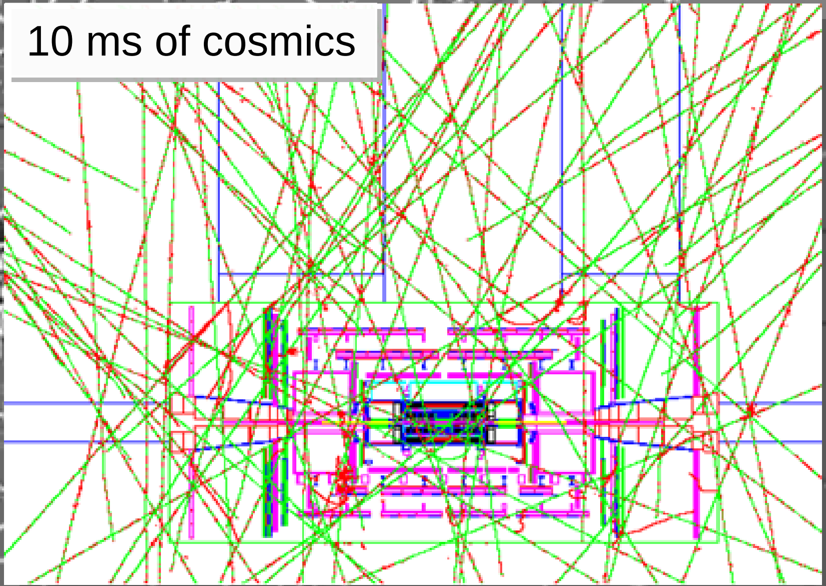
Muon flux in ATLAS detector (simulation):

~4 kHz in muon fiducial volume

~15 Hz in TRT barrel

Charge ratio: $\mu^+ / \mu^- \sim 1.27$

[T. Hebbeker, C. Timmermans, hep-ph/0102042]



Simulated cosmic flux in ATLAS cavern: integration over 10 msec

Muon flux at surface:

~130 Hz / m^2 for E_μ > 1 GeV

average energy ~4 GeV

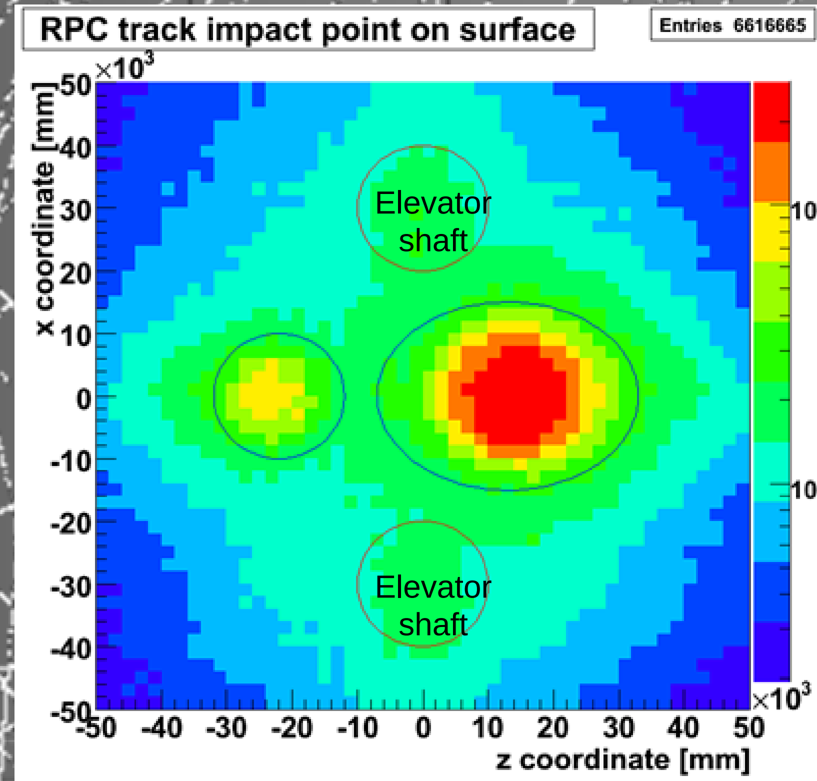
Muon flux in ATLAS detector (simulation):

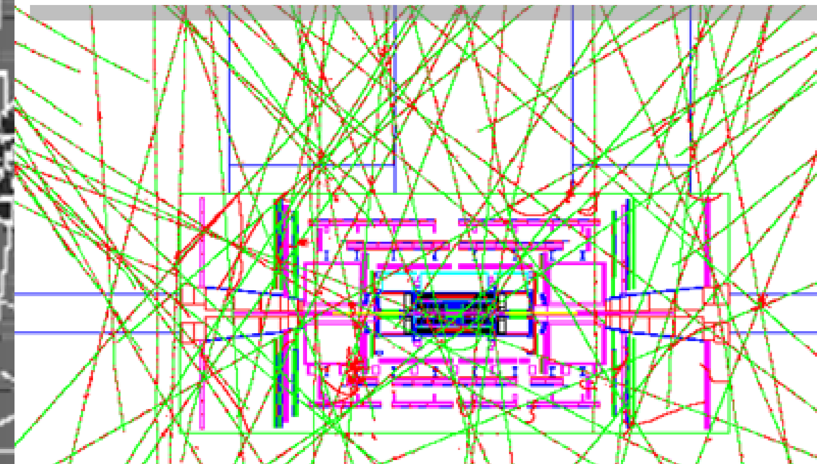
~4 kHz in muon fiducial volume

~15 Hz in TRT barrel

Charge ratio: $\mu^+ / \mu^- \sim 1.27$

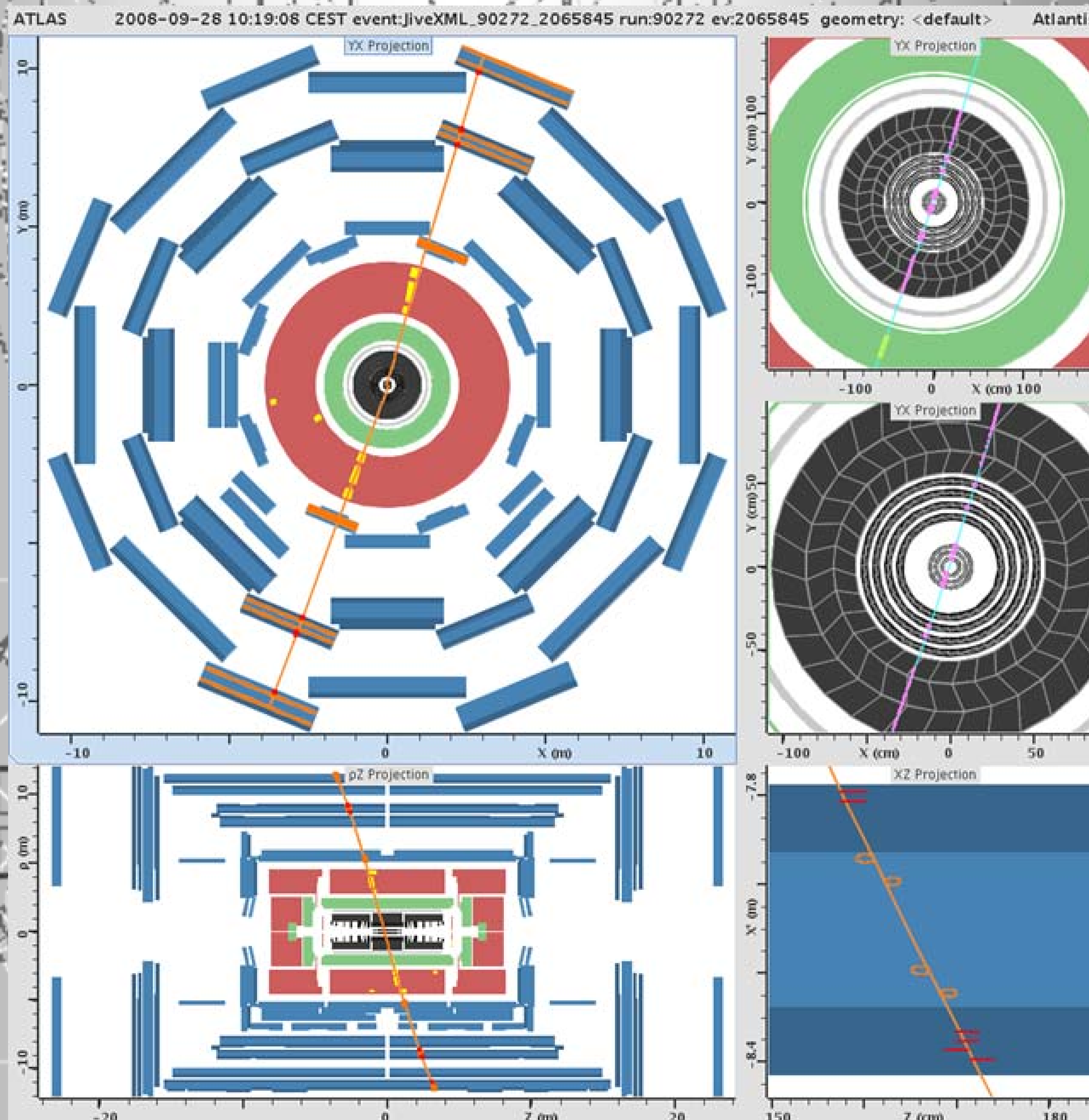
[T. Hebbeker, C. Timmermans, hep-ph/0102042]



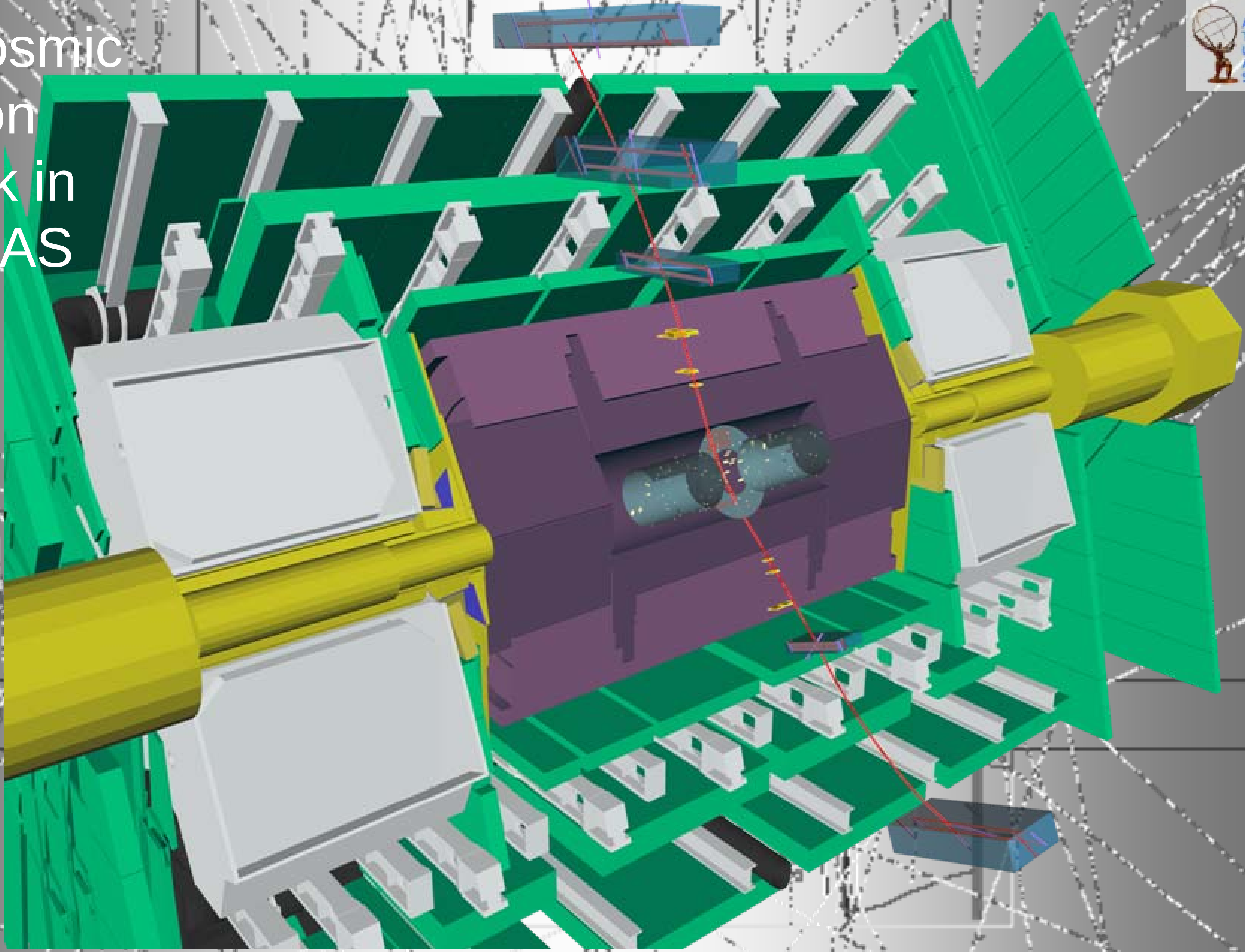


Simulated cosmic flux in ATLAS cavern: integration over 10 msec

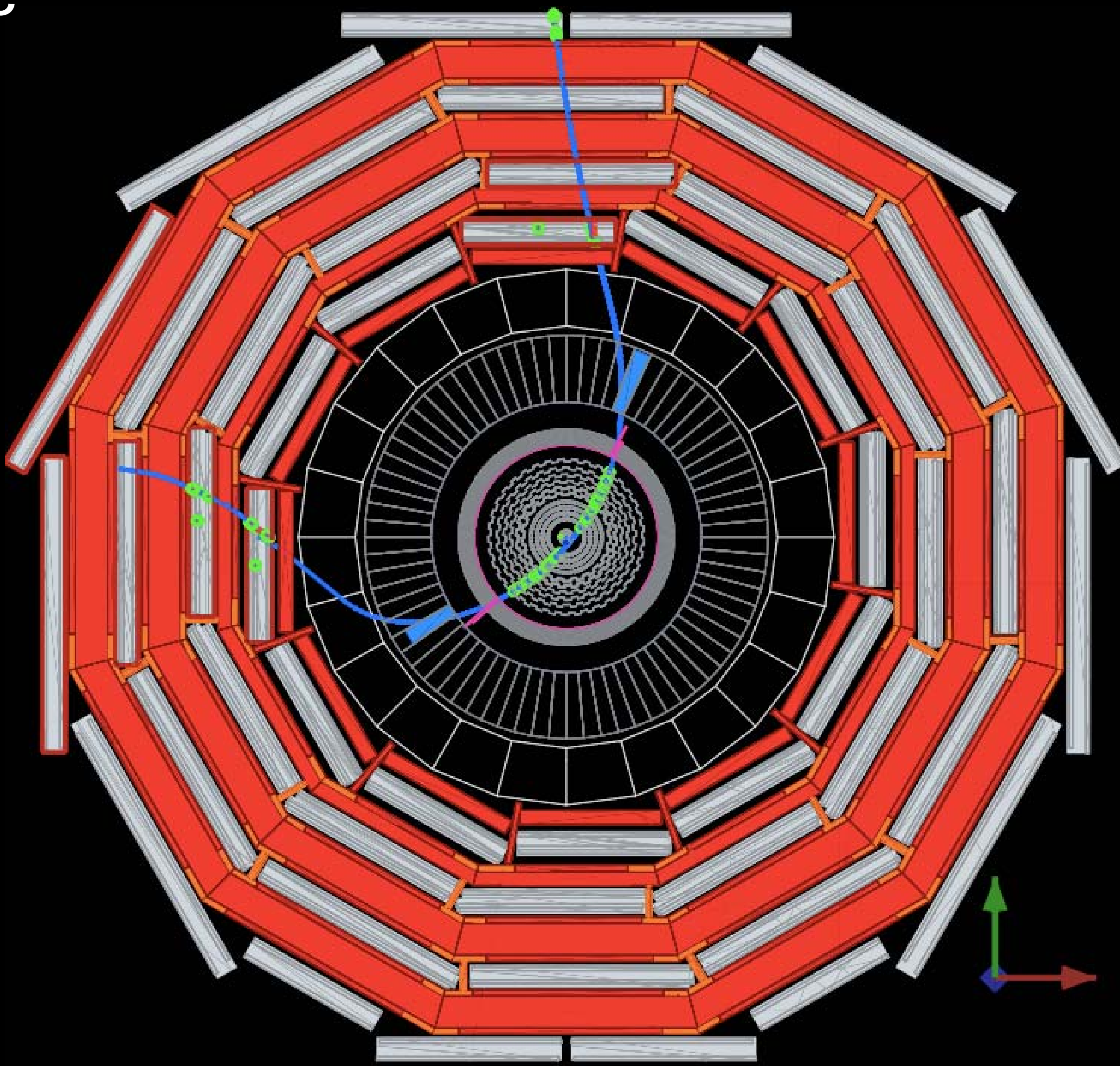
A cosmic muon track in ATLAS



A cosmic muon track in ATLAS

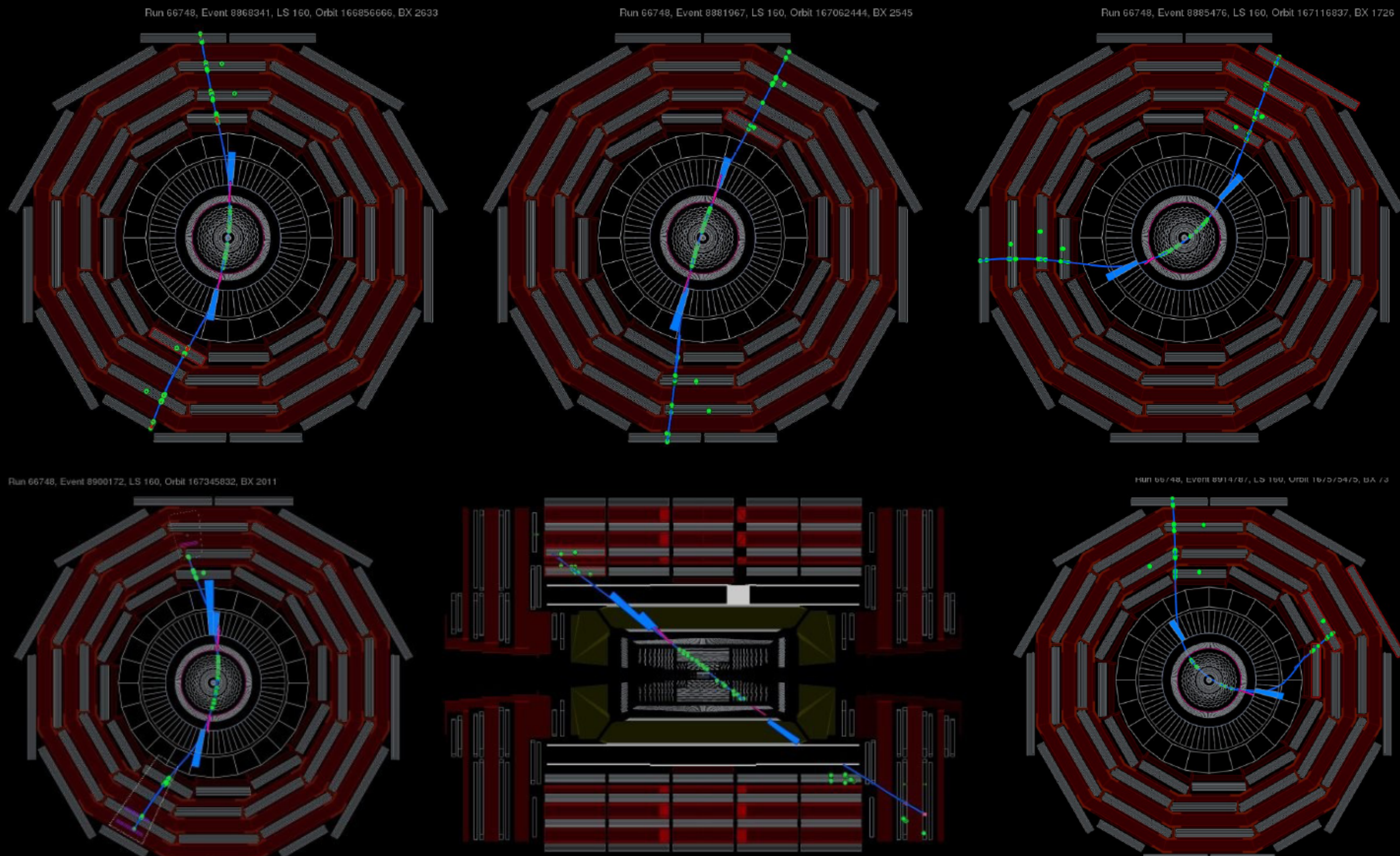


A cosmic muon track in CMS



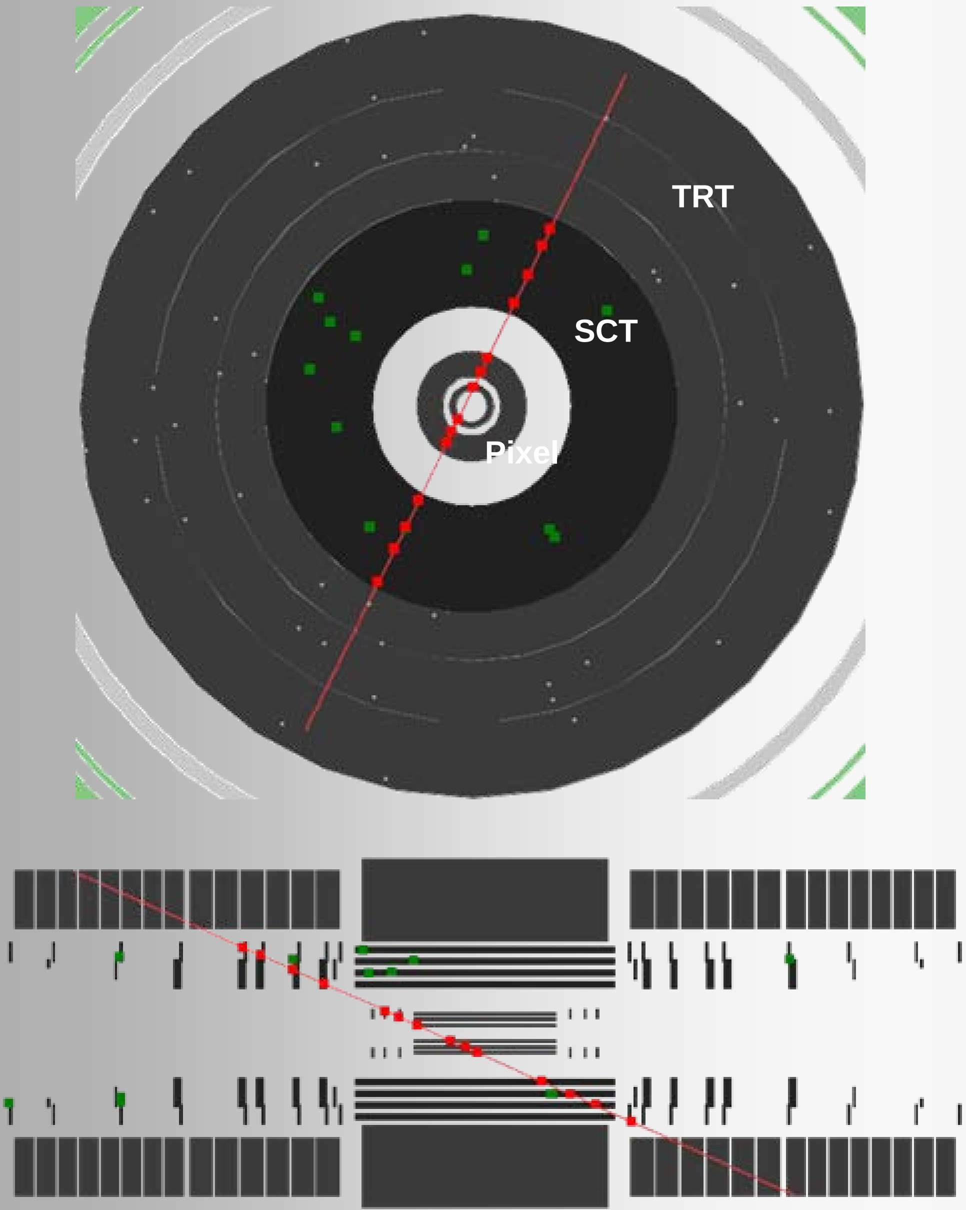
ECAL in magenta, HCAL in blue, tracker and muon hits in green

More Cosmic Muons (both charges!) …



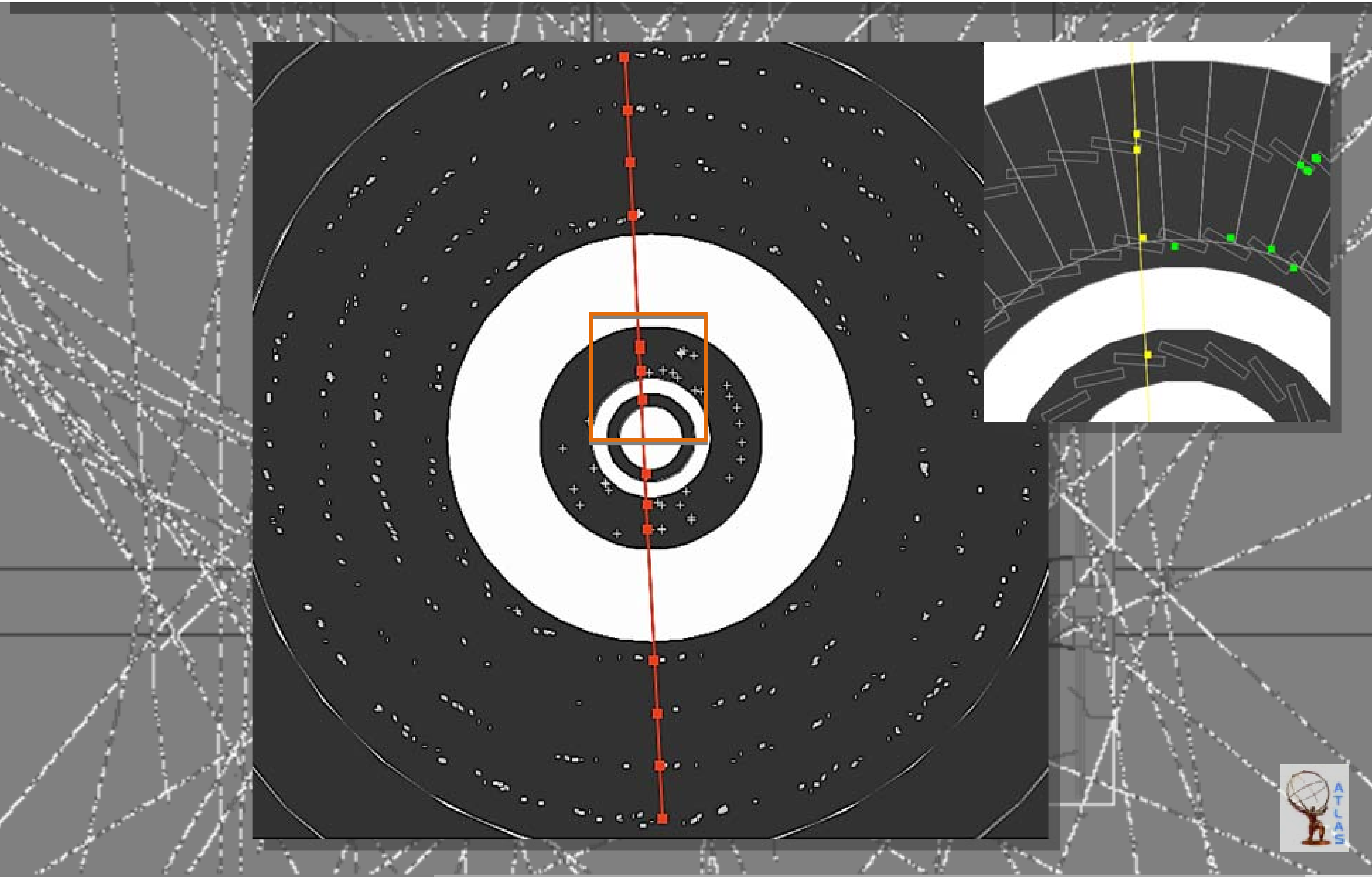
Through barrel and endcap muon detectors

No solenoid field



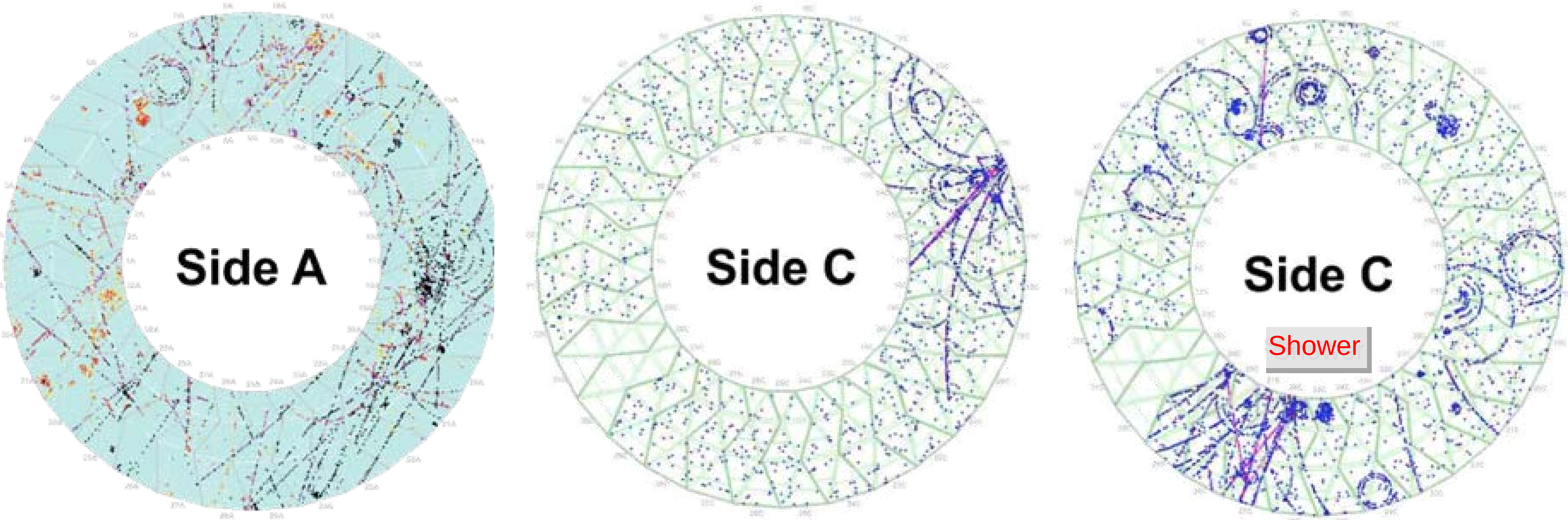
With 2T solenoid field

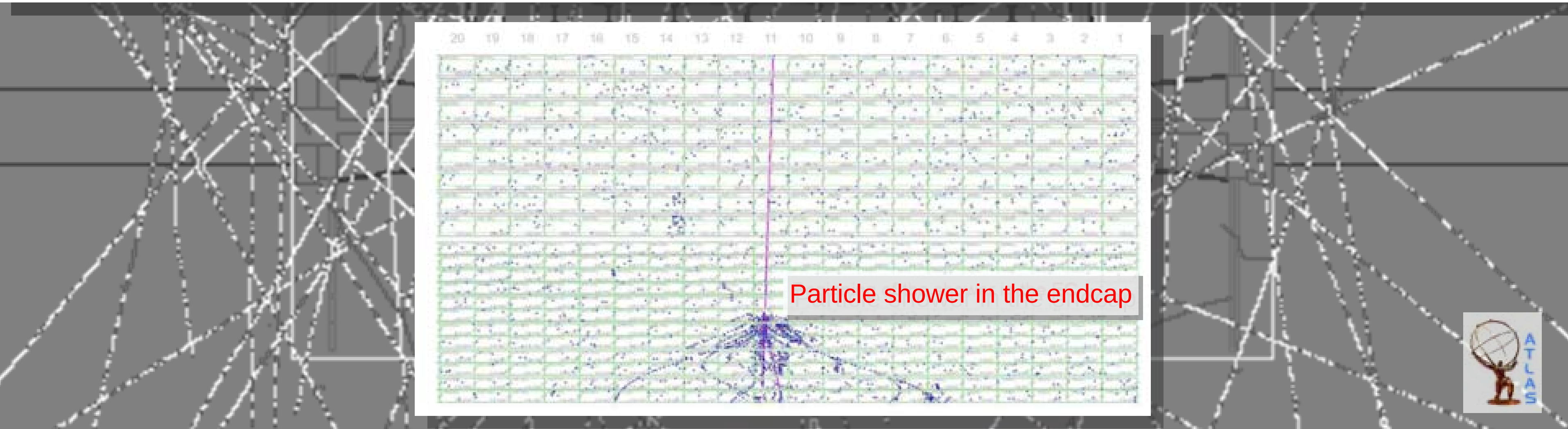
Cosmic Tracks in Silicon Detectors



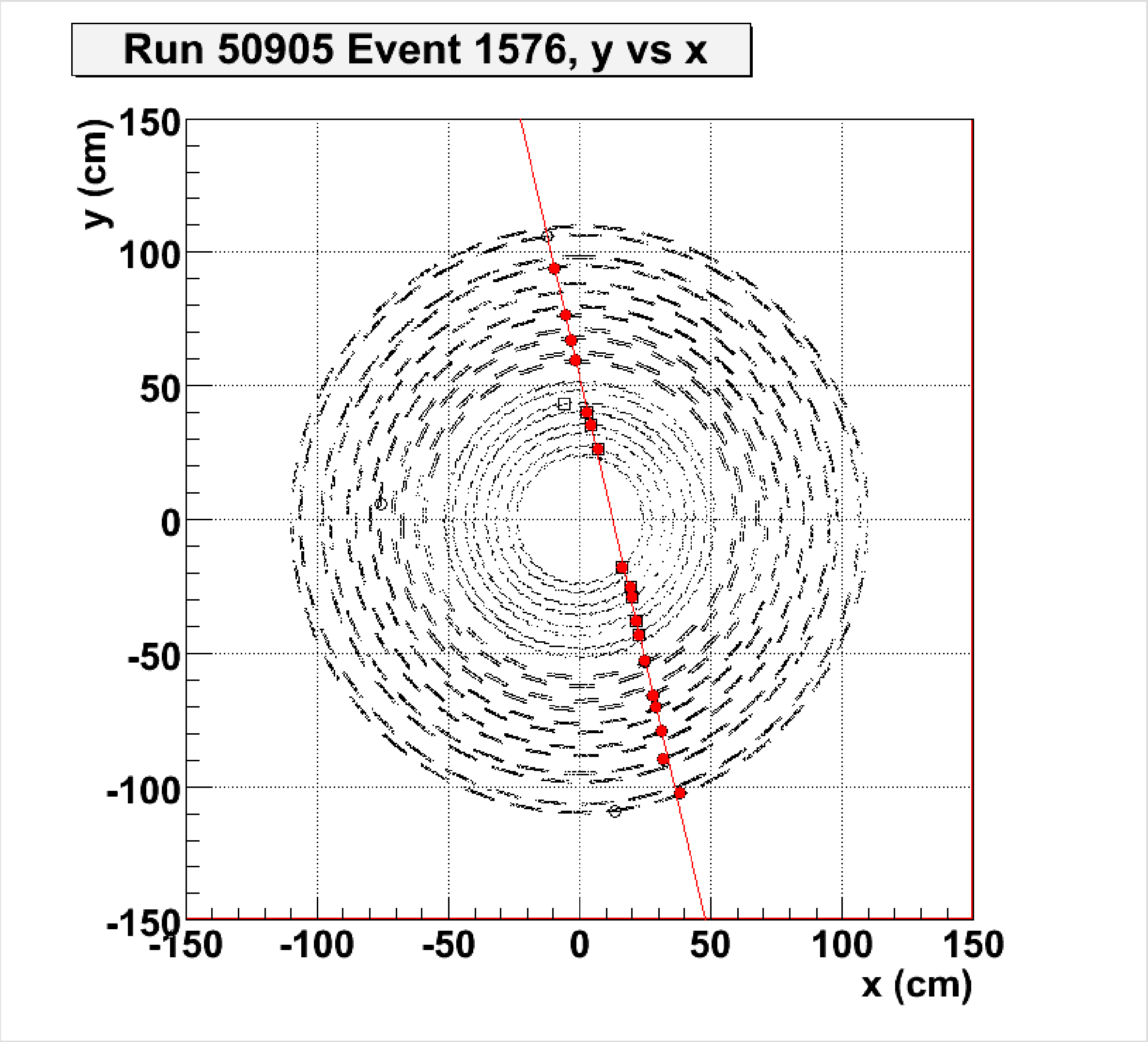
Cosmic Tracks in Transition Radiation Tracker

Cosmics run with solenoid, 22-25 Aug



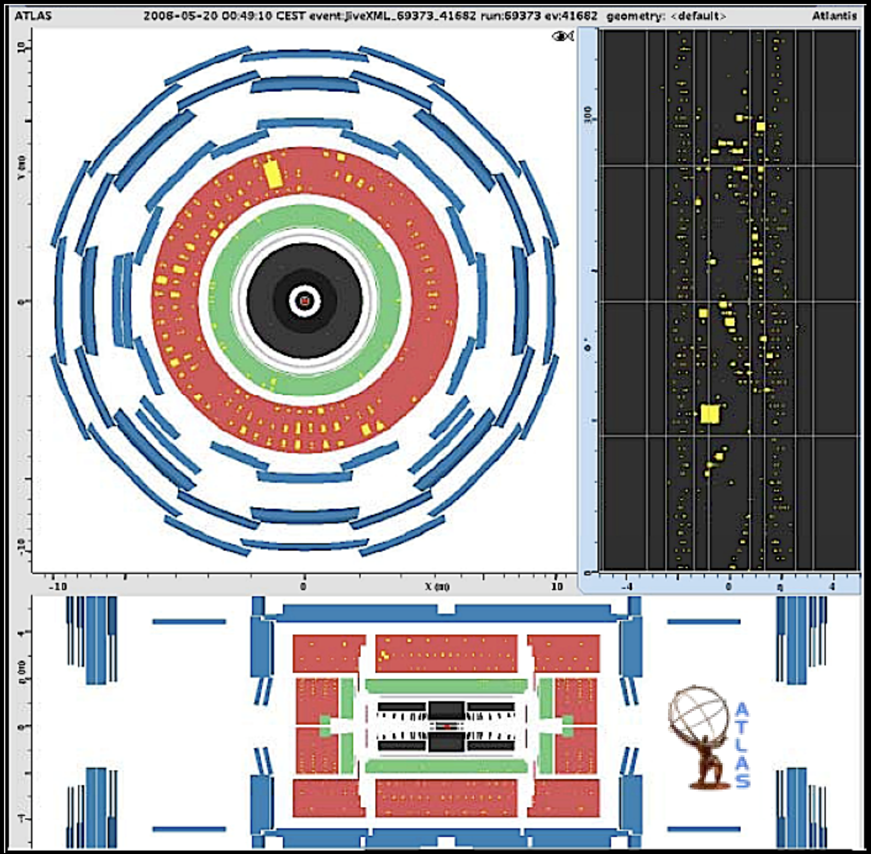


Cosmic Muon Movie

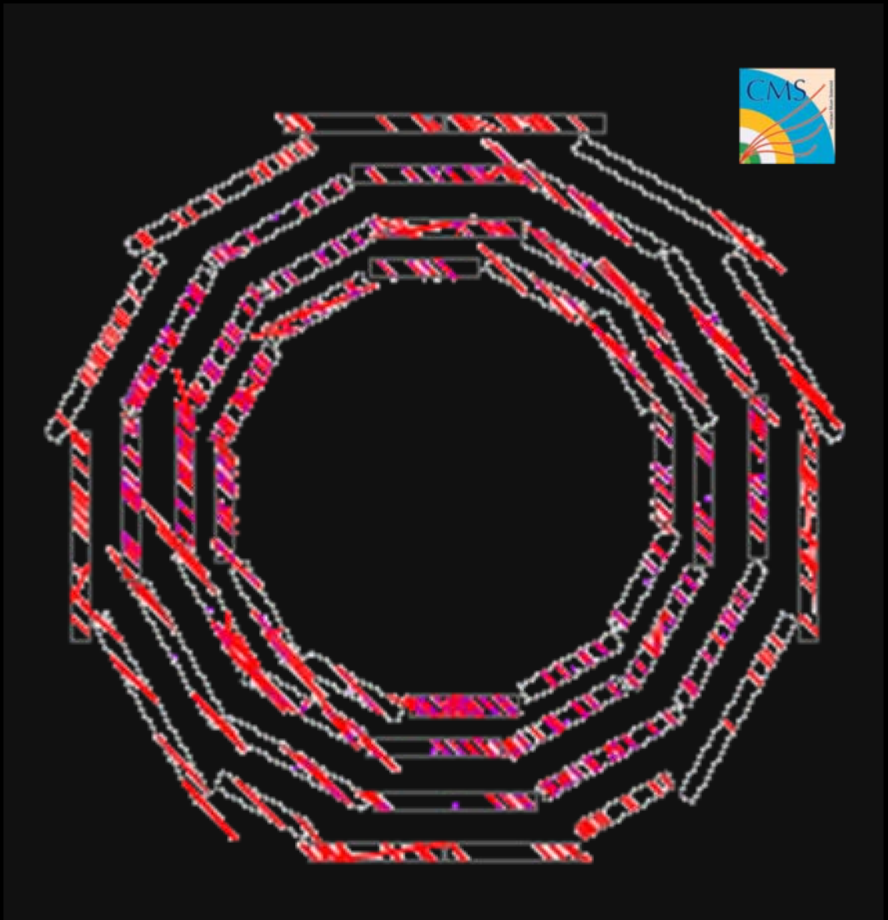


Cosmic Rays Can Shower and Produce Jets

Run: 69373, Event: 41682, May 20, 2008



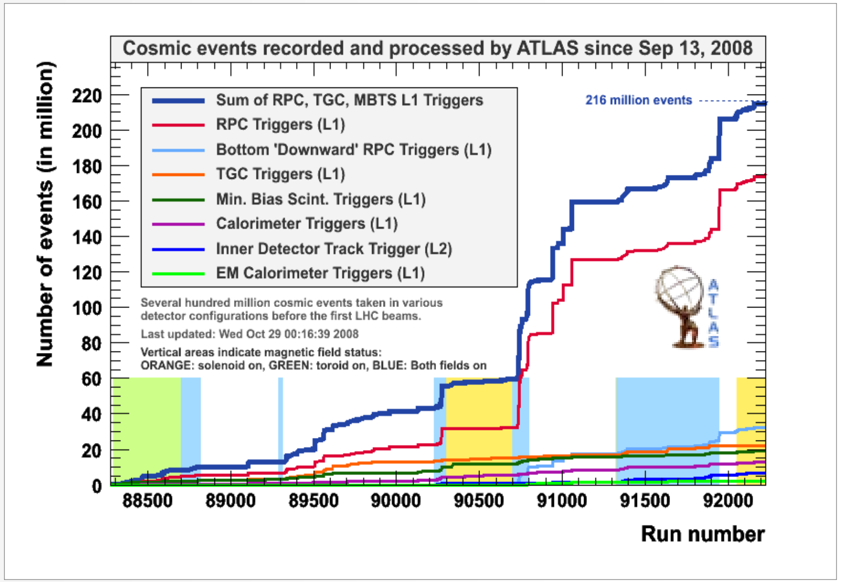
Cosmic event with many jets
(6 jets with E_T > 20 GeV observed; probably air shower)

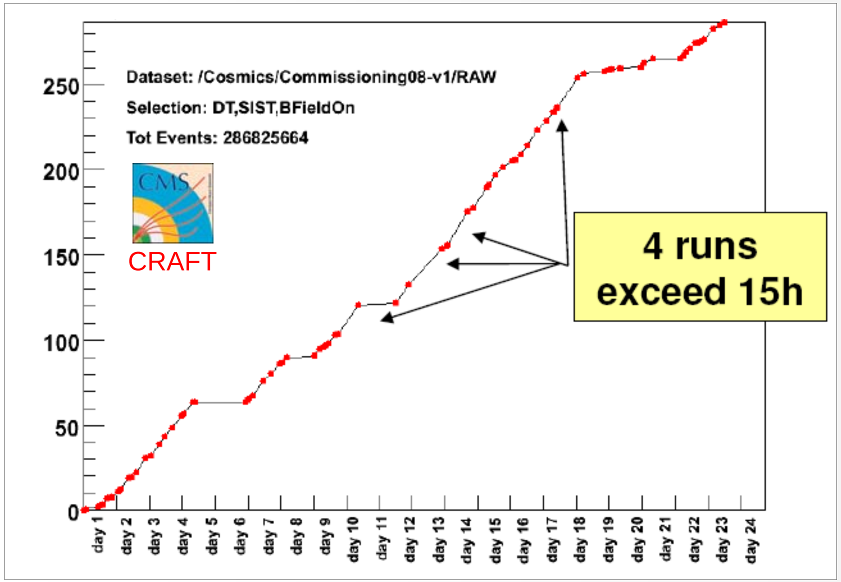


Cosmic Air shower in CMS, O(10-100) muons

Cosmic Ray Data Collection

- ATLAS and CMS took years of cosmic ray commissioning data with increasingly complex detector systems: full detector runs since Sep 2008





ATLAS: 216 million cosmic ray events recorded between Sep 13 and Oct 29, 2008 with full detector

CMS: 370 million cosmic ray events recorded between Oct 13 and Nov 11, 2008 with full detector

Tracking Alignment

Both ATLAS and CMS have huge muon systems and positioning requirements of O(10th of μm) to measure momenta and charges in TeV range.

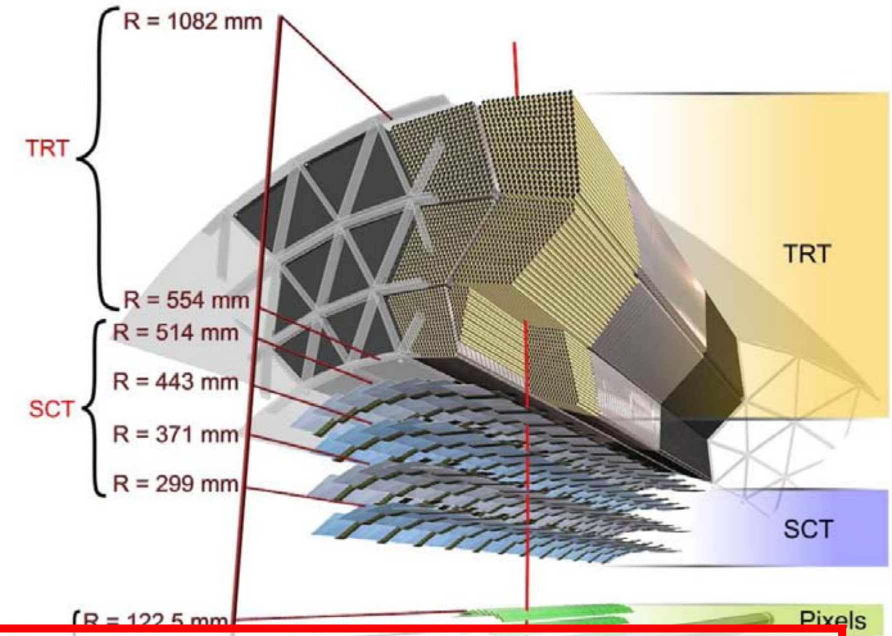
Although the detectors are placed with greatest care, the knowledge of the actual position is insufficient.

Alignment signifies to measure the real detector positions and orientations and correct the reconstruction software accordingly. Several methods and layers exist.

Inner Tracker Alignment

Resolution (barrel numbers)**:**

- **Pixel:** 10 μm [$r\phi$], 115 μm [z], 1744 modules
- **SCT:** 17 μm [$r\phi$], 580 μm [z], 4088 modules
- **TRT:** 130 μm [$r\phi$] / straw, 2688 modules

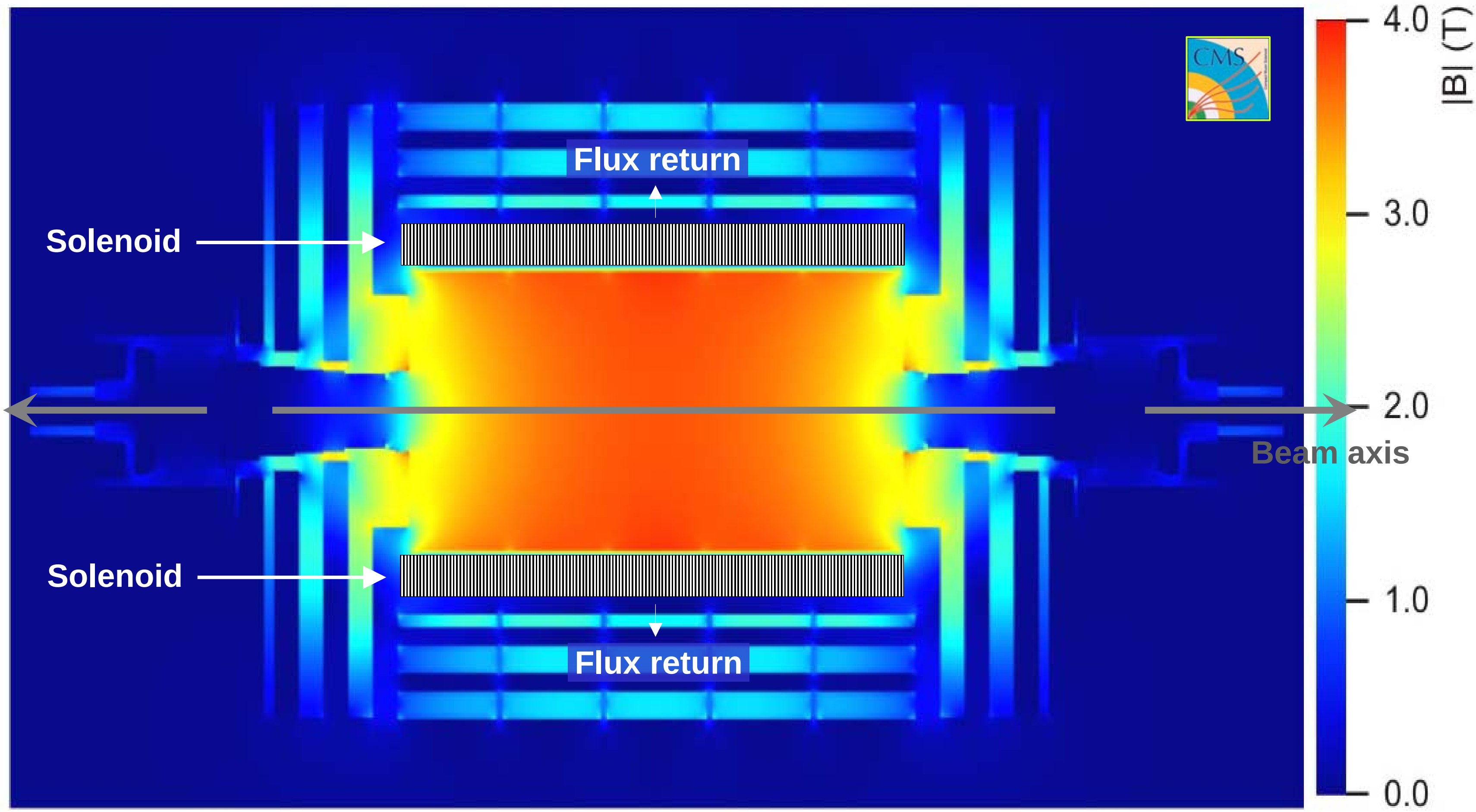


Challenge: track degradation due to misalignment < 20% of resolution

Source of information for alignment:

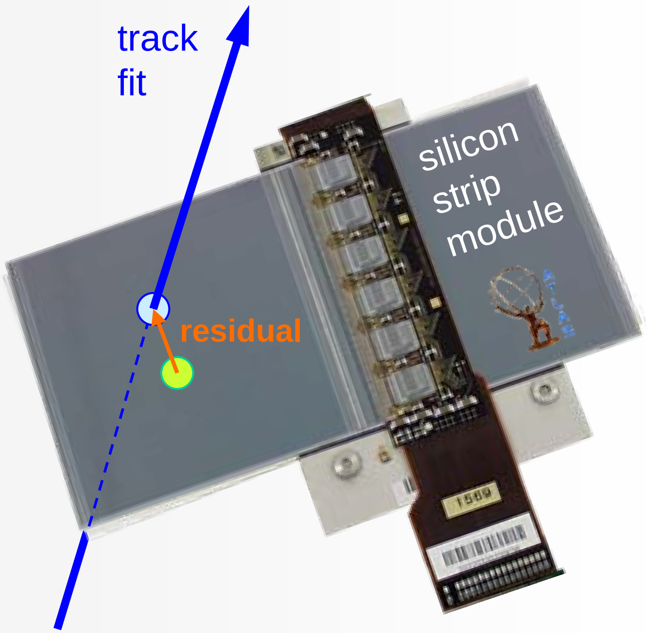
- Assembly knowledge: construction precision and survey, for initial precision corrections and errors
- Online monitoring and alignment: lasers, cameras, before and during run
- Offline track-based alignment: using physics and track residual information
- Offline monitoring: using physics, tracks and particle ID parameters

Momentum Measurement in Tracking Device



Track-Based Alignment

- Minimise track residuals by fitting detector positions (layers and modules)



Magnetic field	OFF	ON
All Tracks	4.9 M	2.7 M
SCT Tracks	1.2 M	880 k
Pixel Tracks	230 k	190 k

ATLAS track statistics since Sep 2008

- Global χ^2 minimisation of *N* linear equations

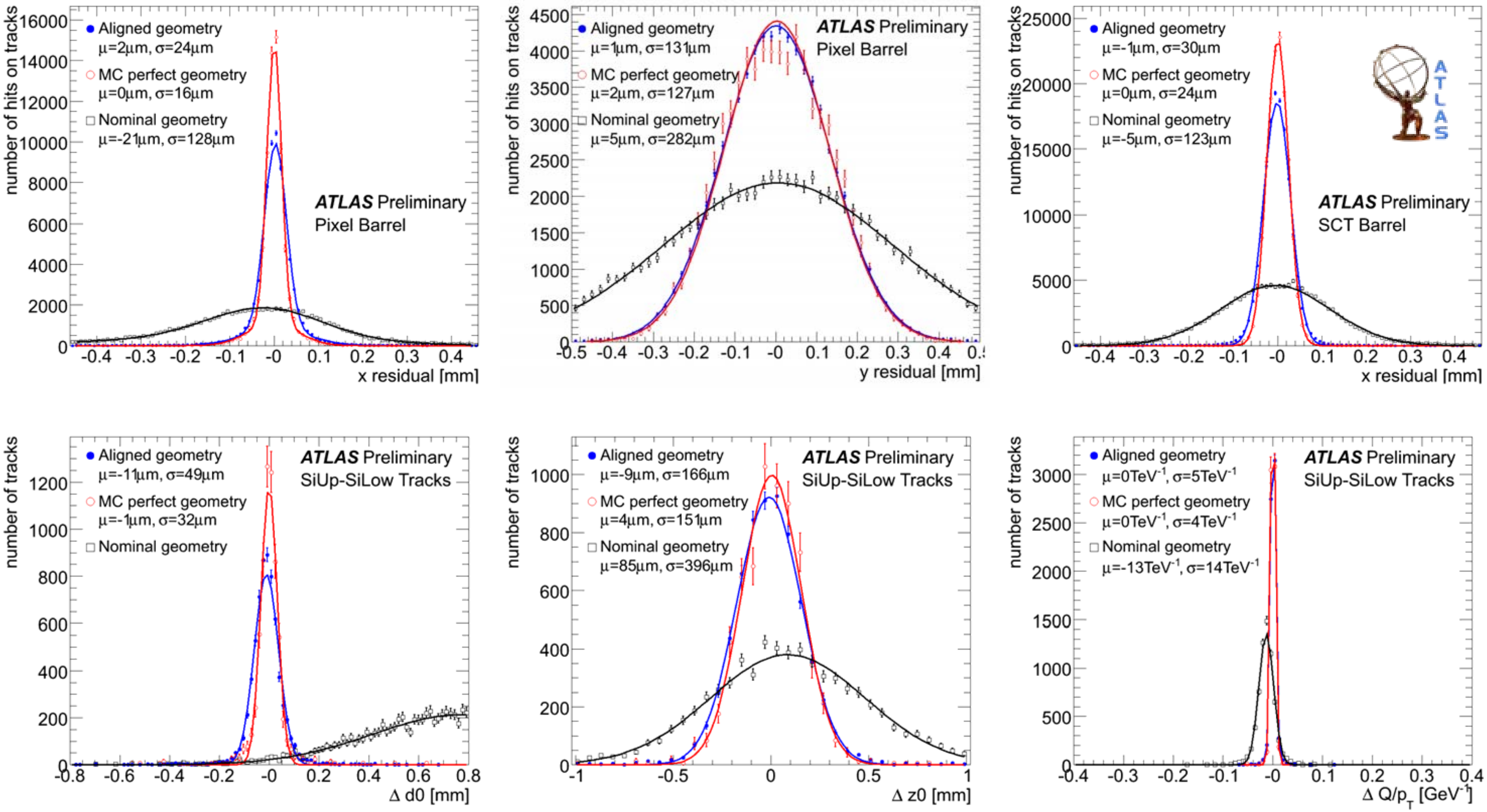
$$\chi^2 = \sum_{i \in \{\text{hits}\}} \left(\frac{m(\vec{\alpha}) - h_i}{\sigma_i} \right)^2$$

  m – model (track), α are track parameters

  ***h**$_i$* – measured hit and error σ_i

- 3 translations + 3 rotations → 6 DoF / module
- Total of ~40,000 DoF constrained by hits
- Depending of level of alignment (whole barrel/endcap, layers/disks, modules) different solving techniques can be used
- The correlations between fit parameters are important to help the fit converge rapidly

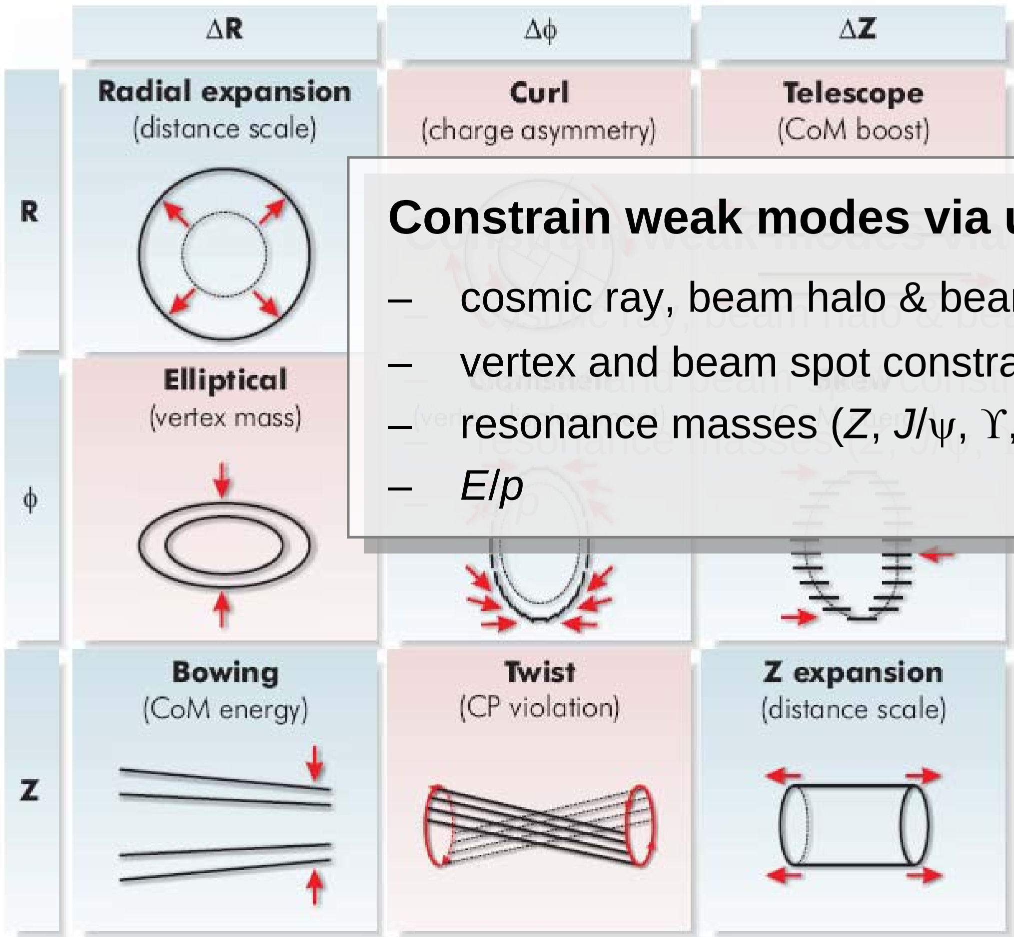
Results with Cosmic Muon Tracks



But… does this really mean it's all good ?

"Weak Modes"

- Residuals insensitive against some types of misalignment → effect on physics !



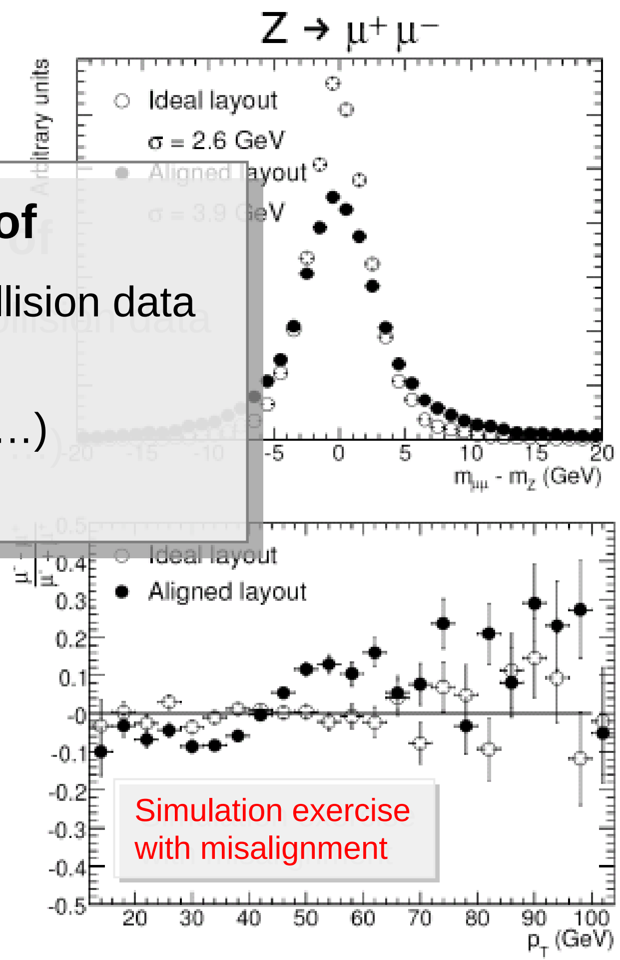
Constrain weak modes via use of

– cosmic ray, beam halo & beam collision data

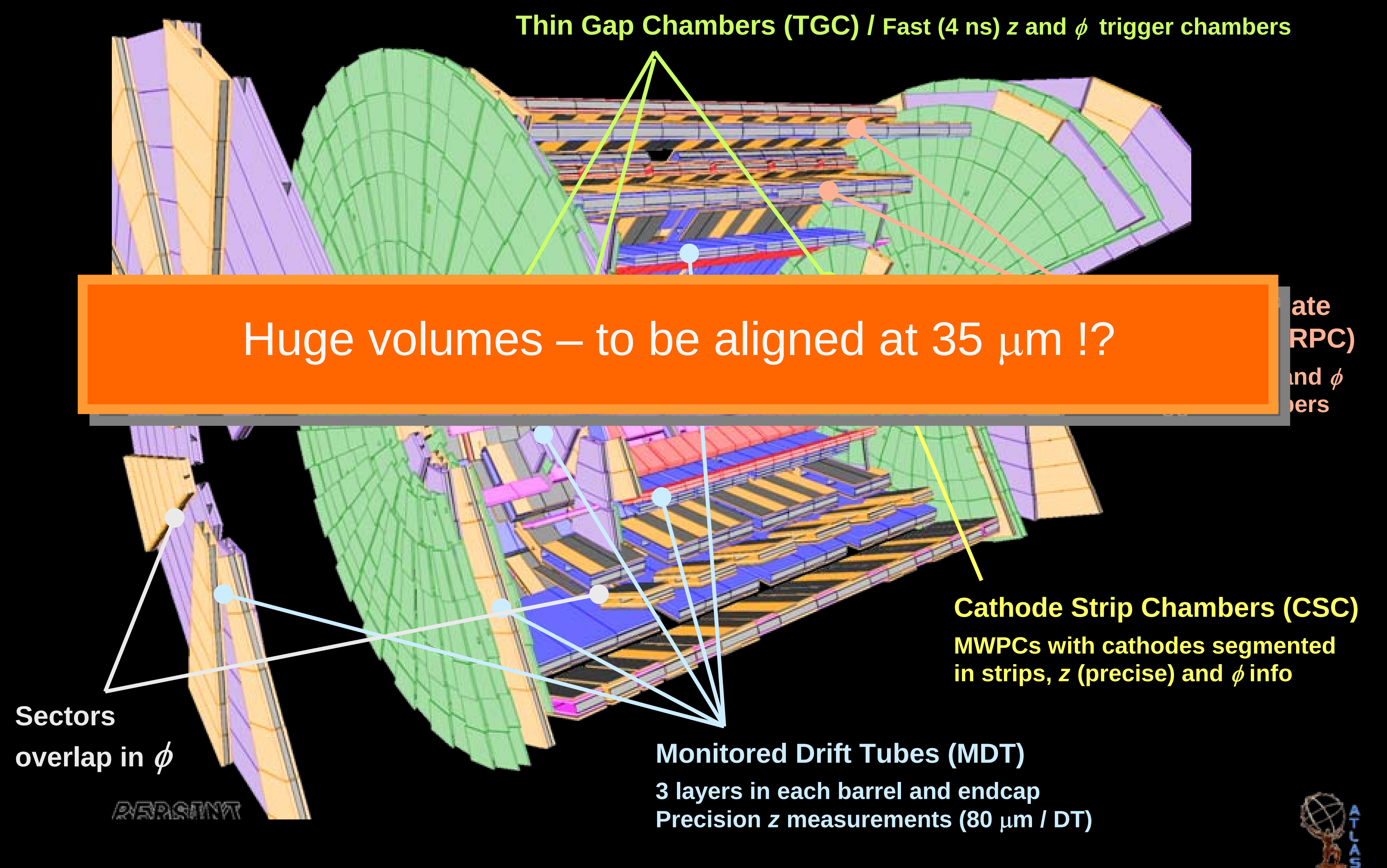
– vertex and beam spot constraints

– resonance masses (Z, J/ψ, Υ, K^0, …)

– E/p



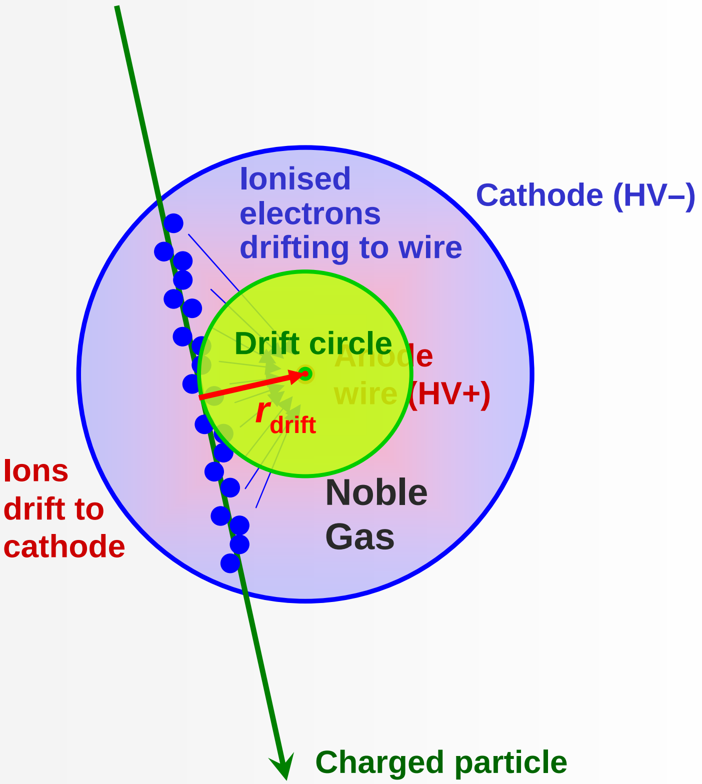
ATLAS Muon System – Active Material



Huge volumes – to be aligned at 35 μm !?

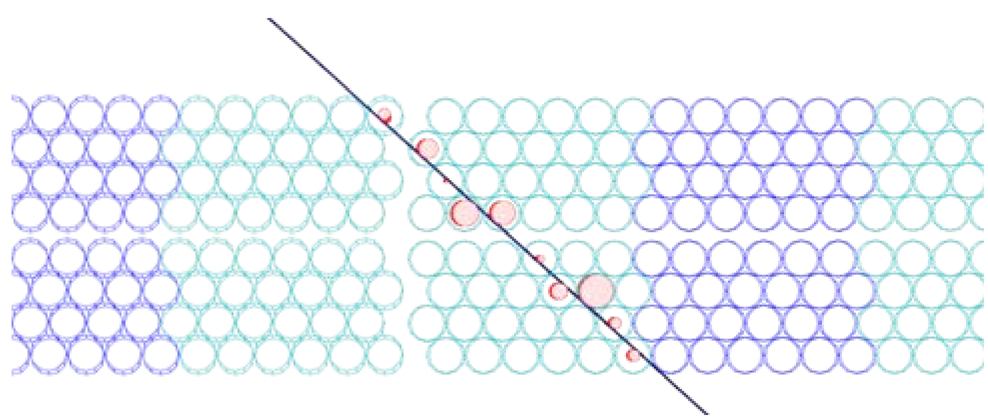
Alignment Requirements: ATLAS Muons

- Drift tubes: detection technique for charged particles based on gas ionisation and drift time measurement



TRT : Kapton tubes, ∅ = 4 mm
DT : Aluminium tubes, ∅ = 3/4 cm (ATLAS/CMS)

Example: simulated muon in MDTs **(aligned !)**



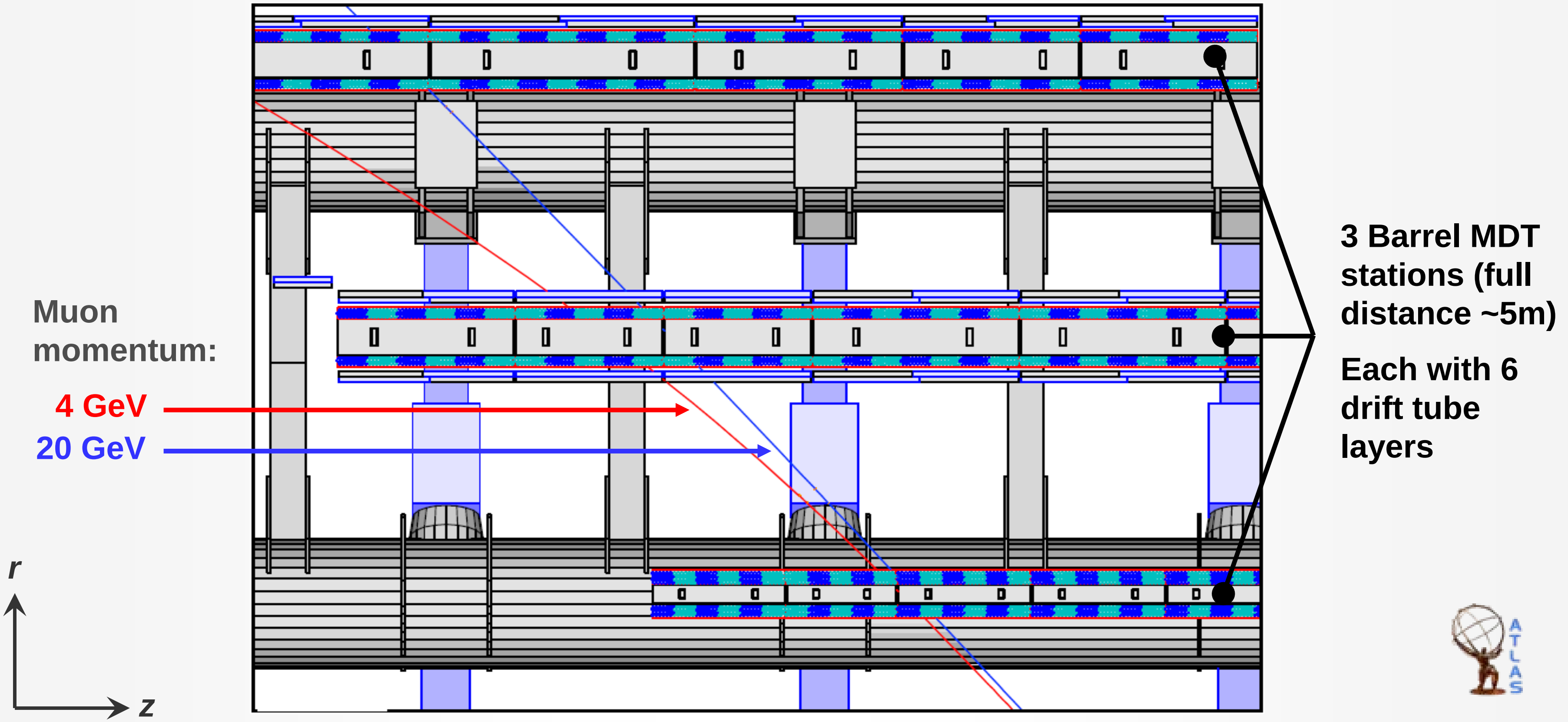
If the alignment (chamber position) shall not limit momentum (and charge!) measurement
→ it needs to be **better than 35 μm**

Alignment Requirements: ATLAS Muons

- Toroid fields bend tracks in ***z* direction**, instead of r -ϕ as in the inner detector

  $\sigma(z)$ = 35 μm per chamber → $\sigma(s) \approx (3/2)^{1/2} \cdot \sigma(z)$ = 43 μm

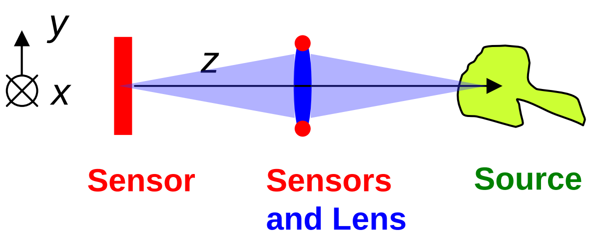
  → 1 TeV track has s = 500 μm at $\eta \approx 0$ → < 10 % precision on momentum measurement

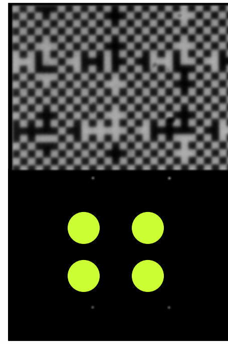


ATLAS Optical Alignment System – Layout

Main ingredients:

3 point system: CCD, lens, source





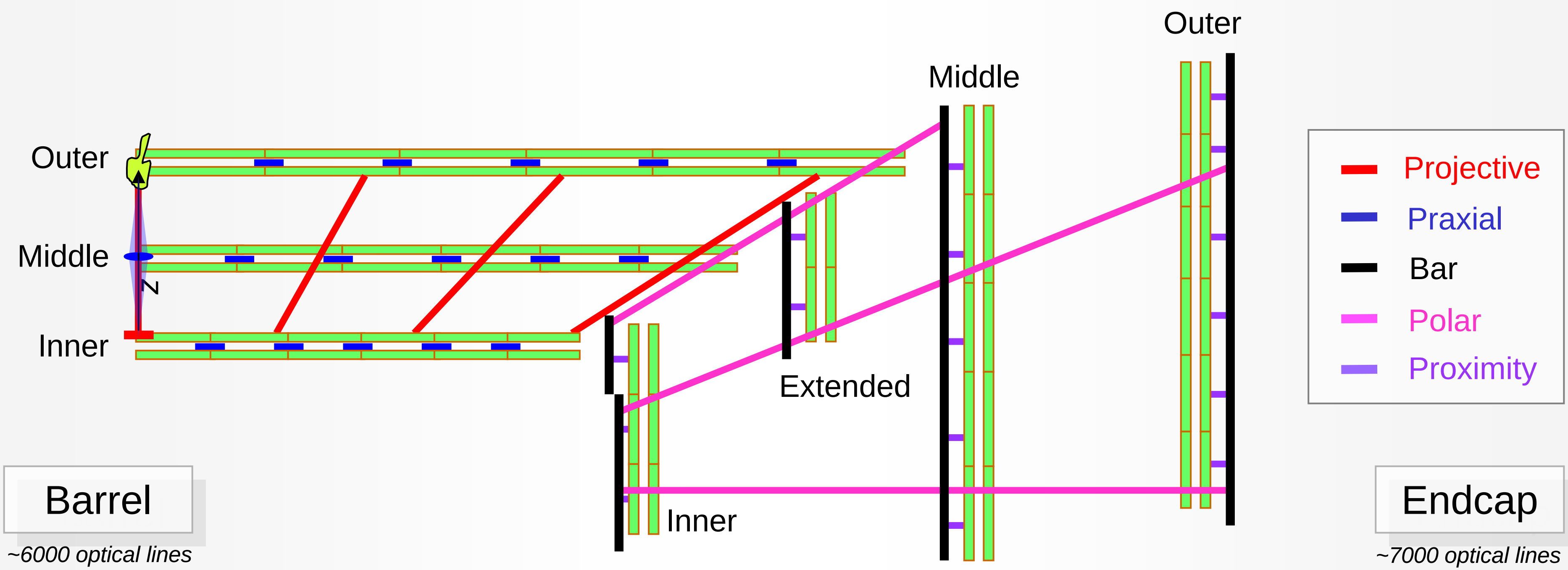
Chess pattern

2 source types in ATLAS

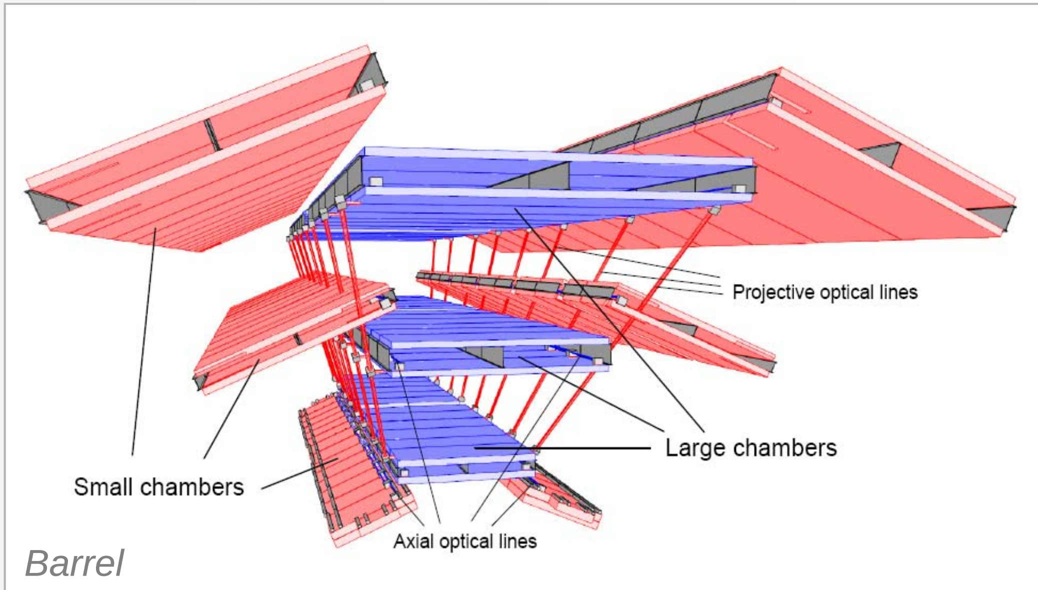
1-4 Led targets

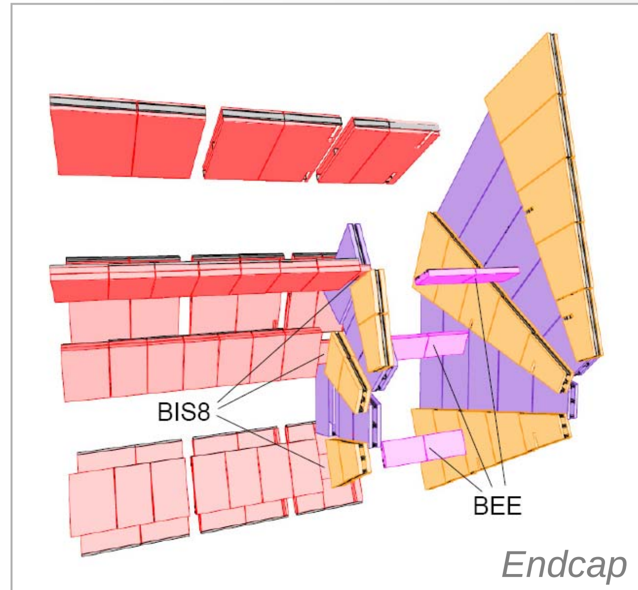
Outputs:

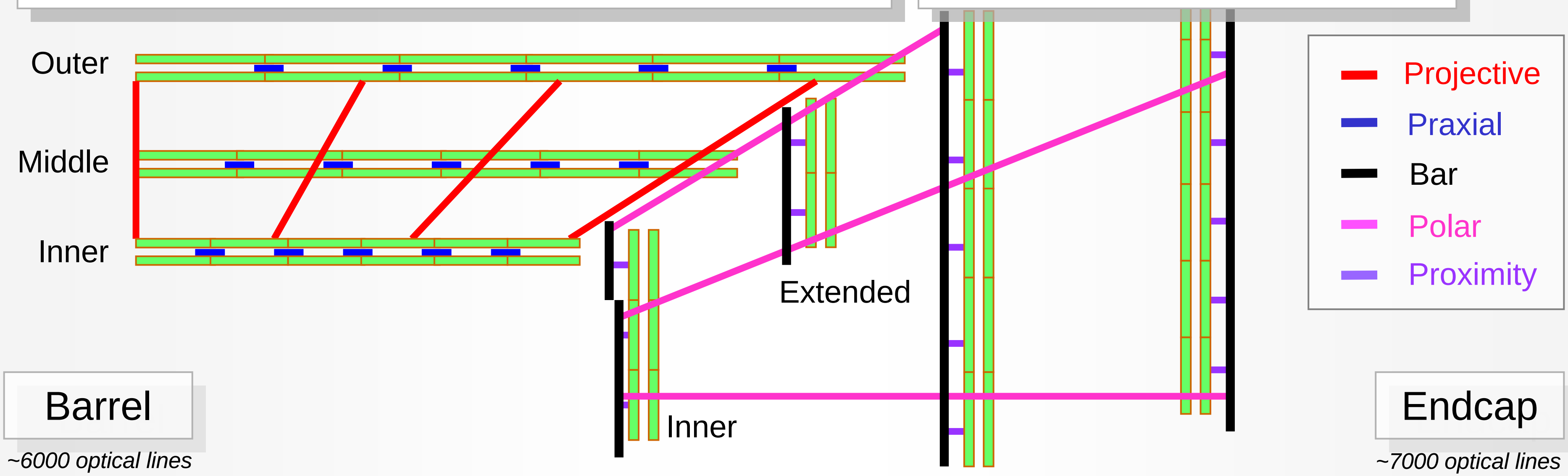
- *Translation in x, y*
- *Rotation around optical axis*
- *Magnification*



ATLAS Optical Alignment System – Layout

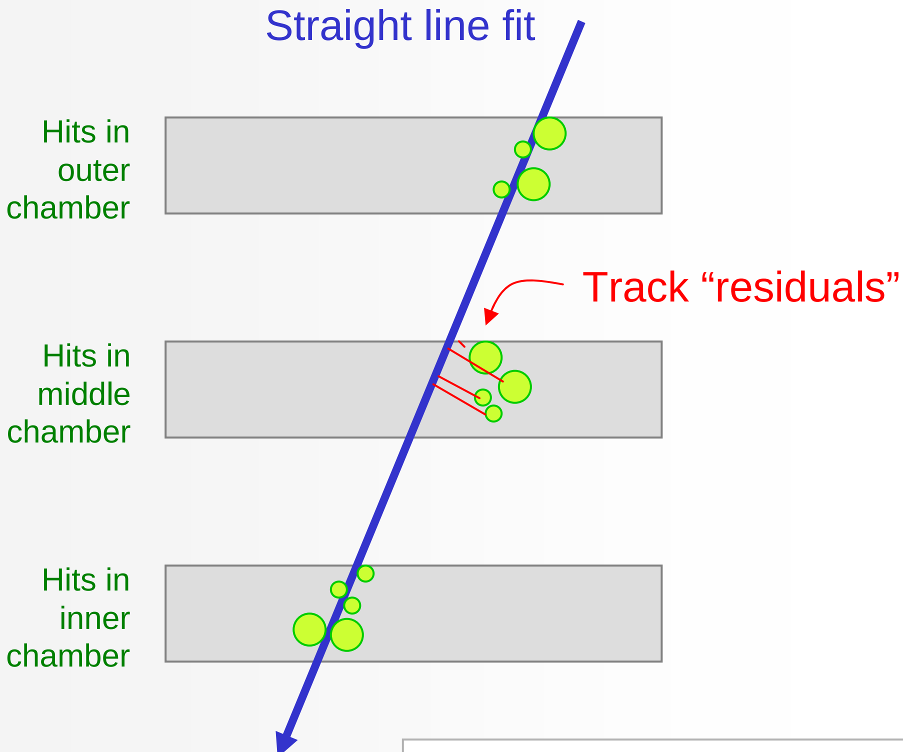


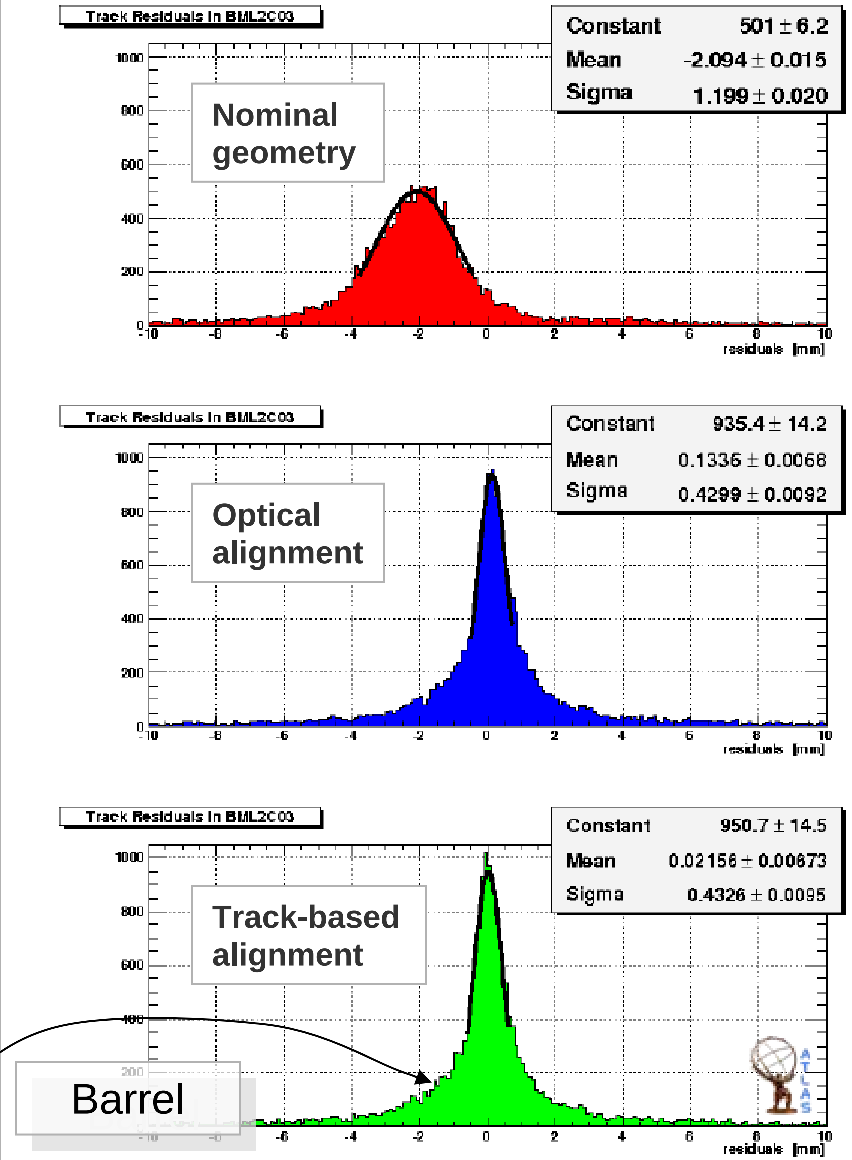




Muon Alignment Also Uses (Straight) Tracks

- Compare residuals for straight cosmic tracks

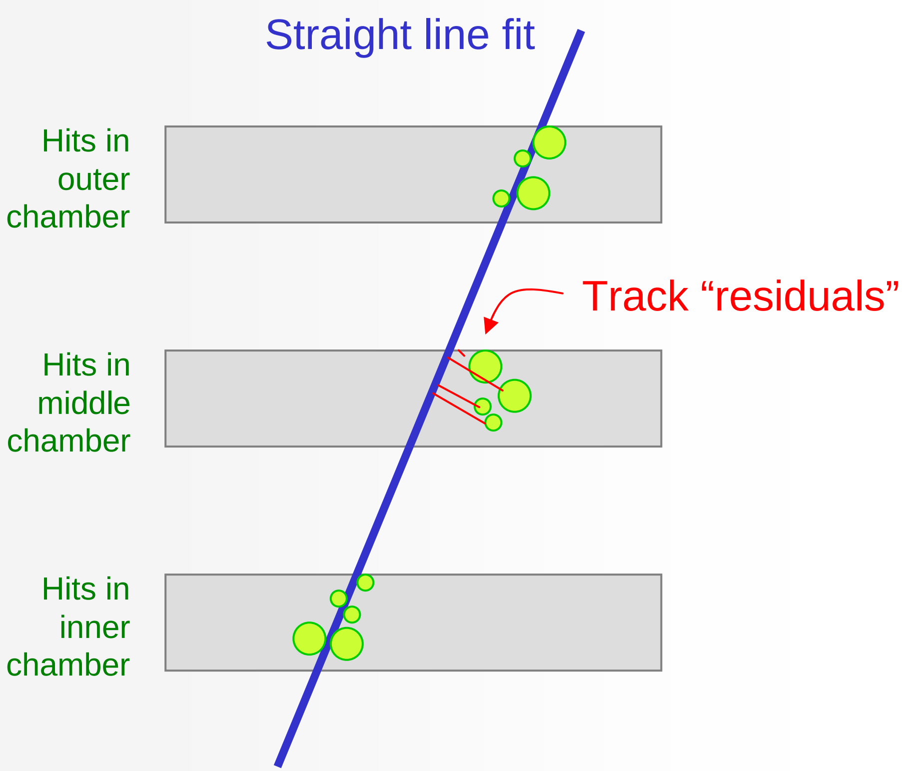


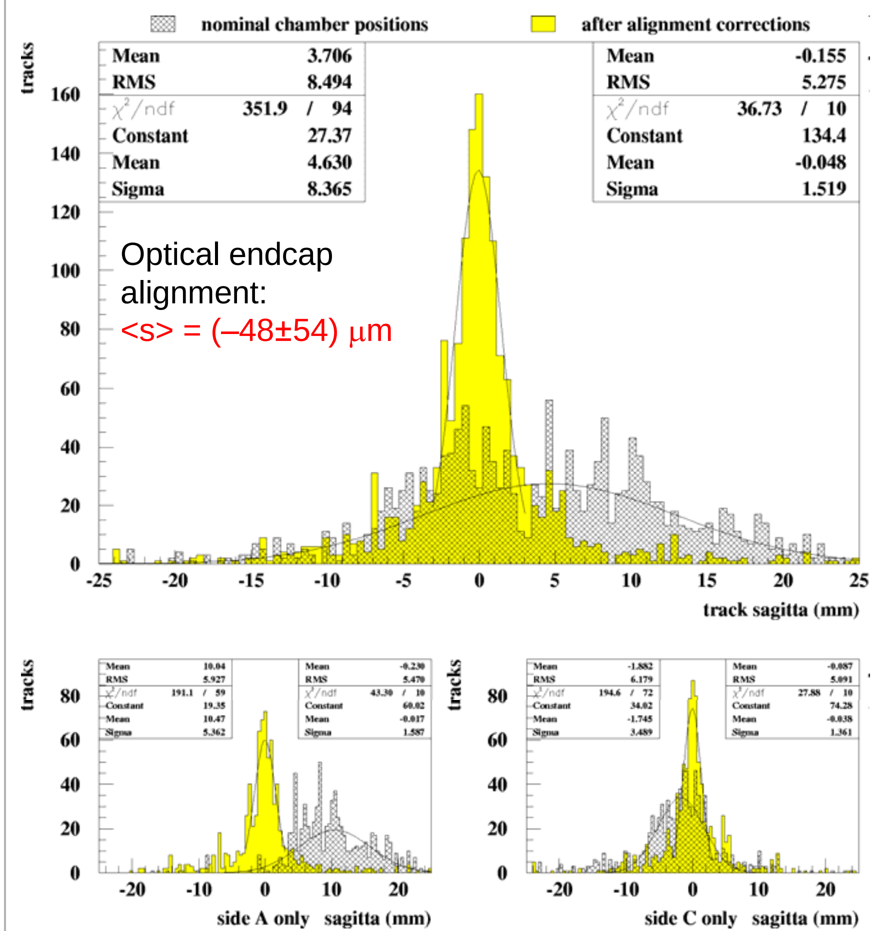


Low-momentum muons, tails dominated by multiple scattering

Muon Alignment Also Uses (Straight) Tracks

- Compare residuals for straight cosmic tracks for different alignment setups





Endcap

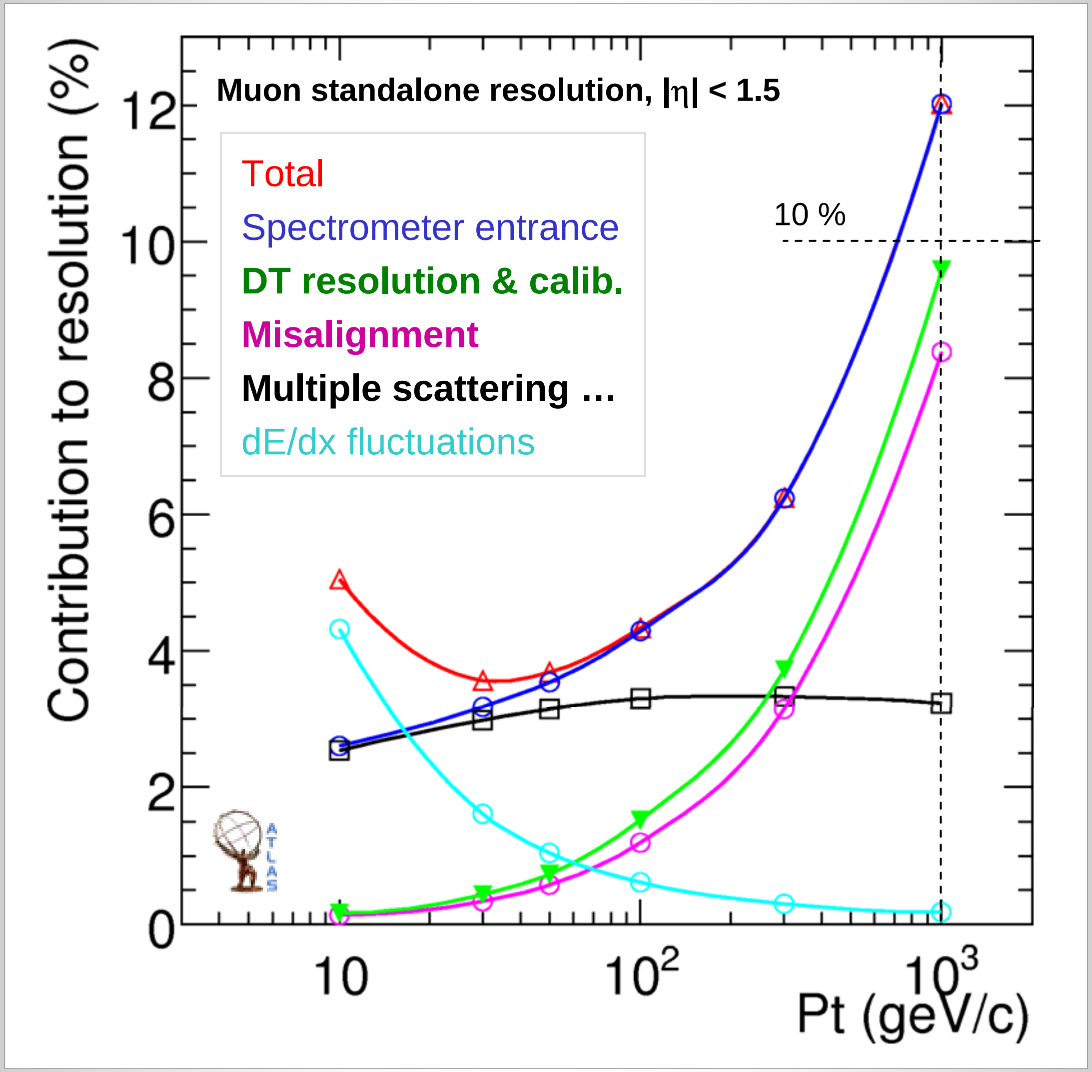
Multiple Scattering

Charged particles traversing a medium are deflected by successive small-angle scatters

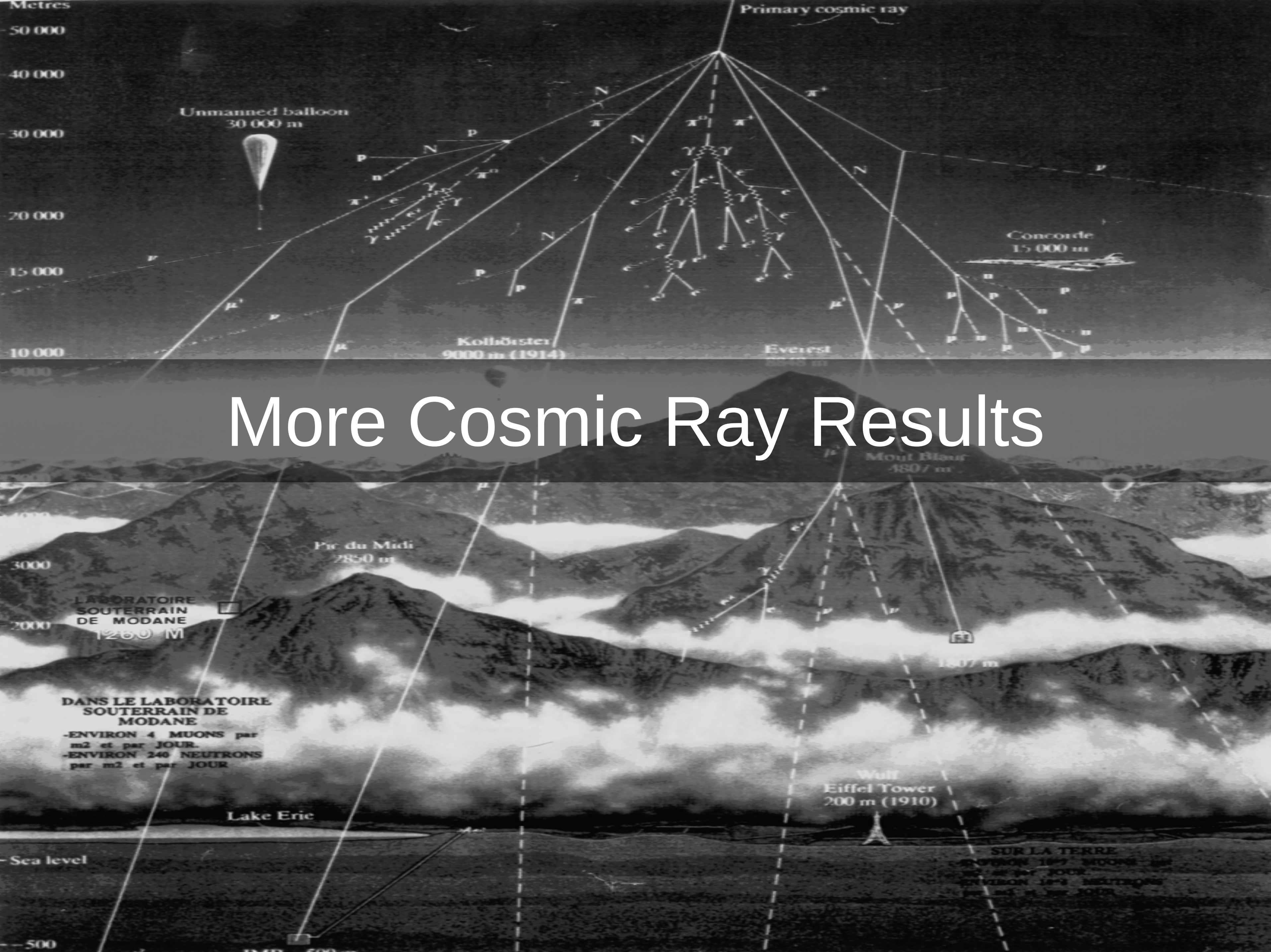
Angular distribution ~Gaussian, $\sigma_{MS} \sim (L/X_0)^{1/2}/p$, but also large angles from Rutherford scattering ~$\sin^{-4}(\theta/2)$

→ Complicates track fitting, limits momentum measurement

ATLAS Muons Spectrometer Resolution



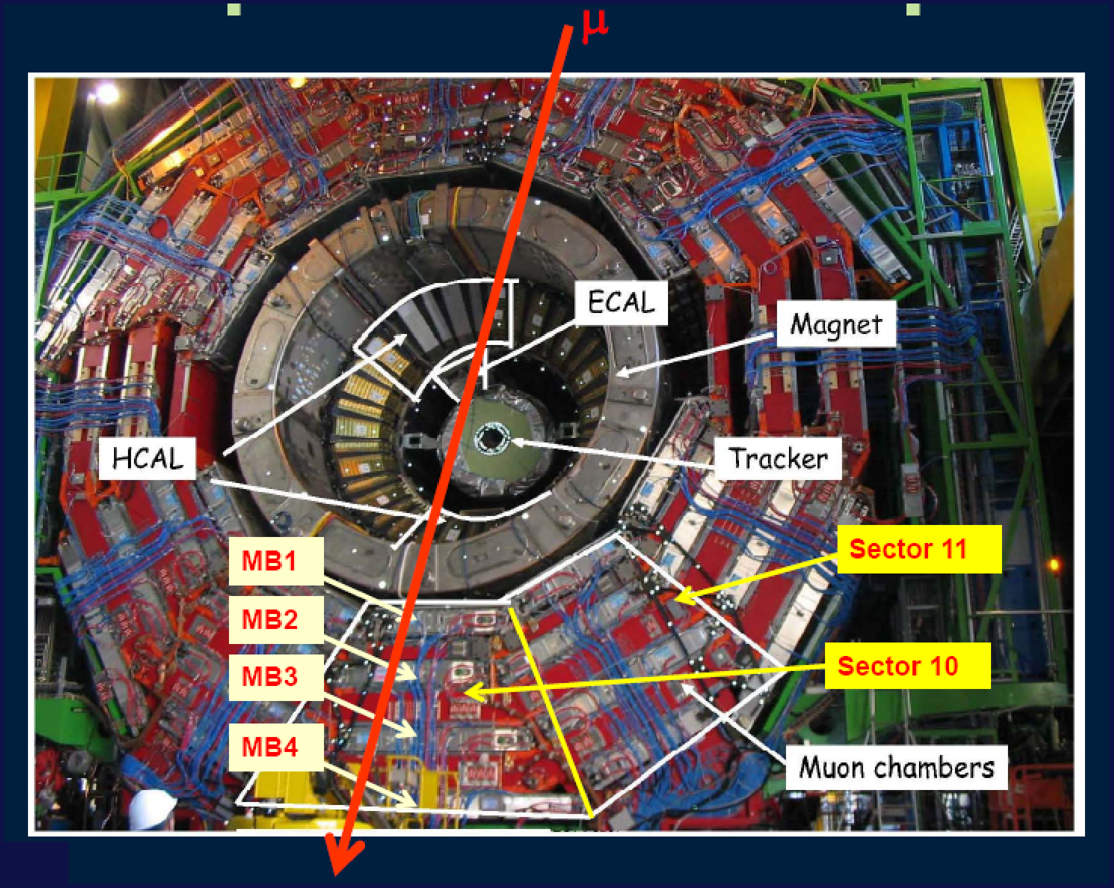
More Cosmic Ray Results



Tracking and Cosmics

Muon Momentum and Charge Ratio

- CMS measurement on surface using slice of muon DTs at B ~ 4 T, selecting high quality tracks with hits in at least 3 barrel stations, 2008 (MTCC)



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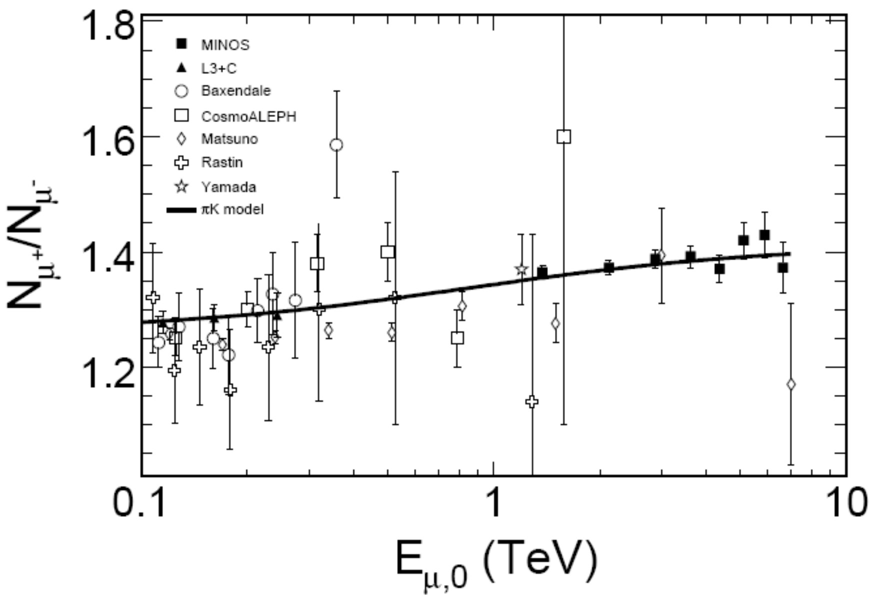
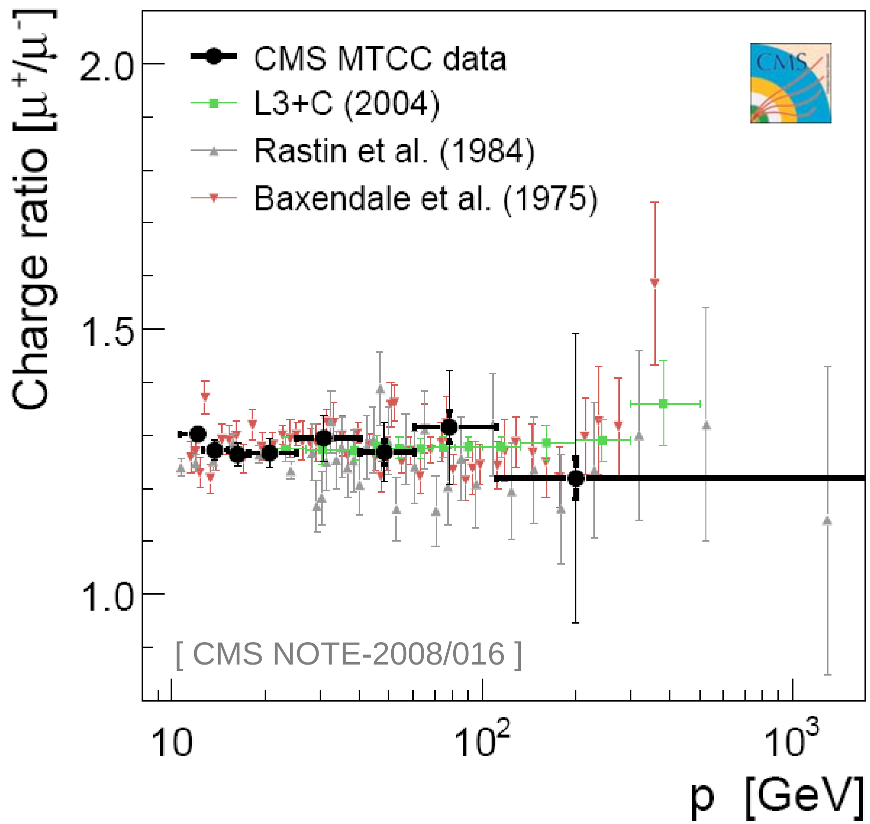
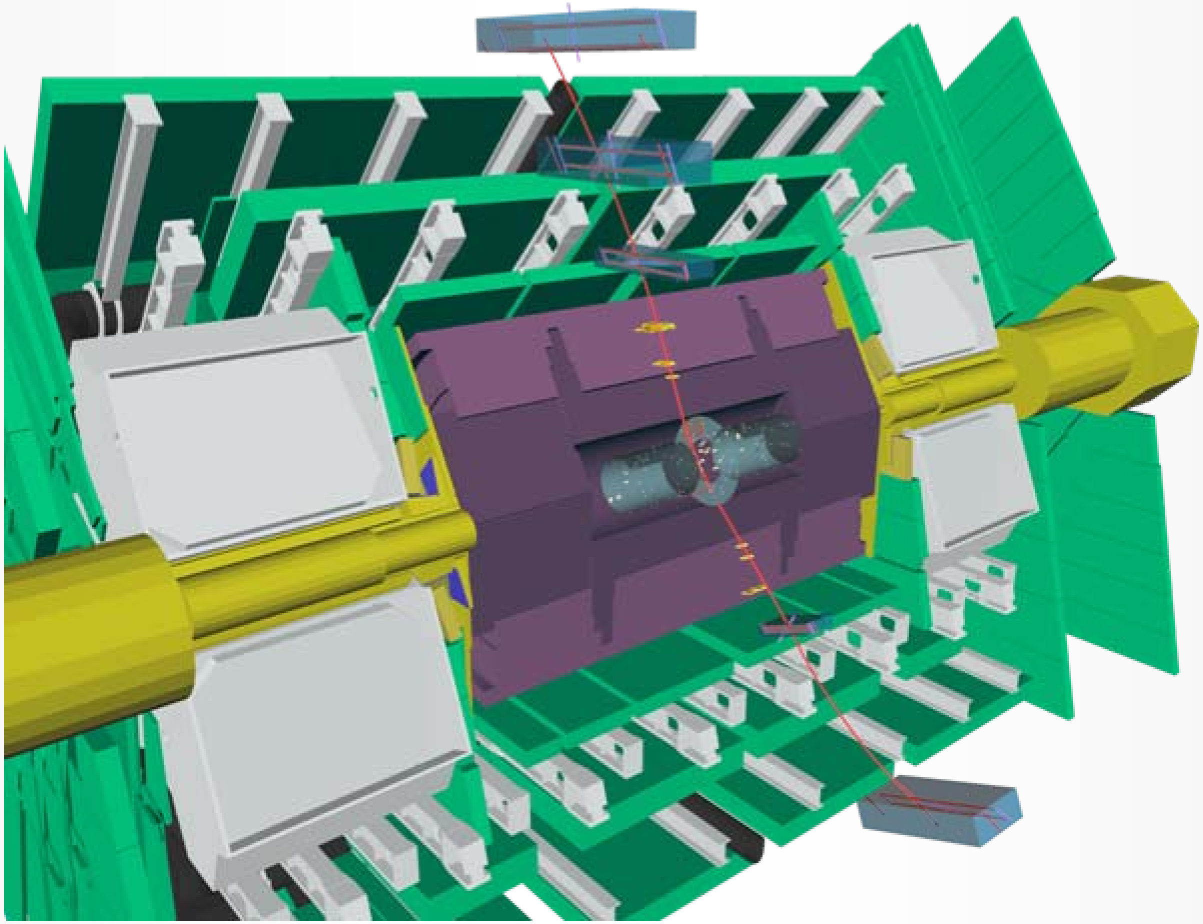
[MINOS, Phys. Rev. D76, 052003 (2007)]





Comparing Muon Spectrometer and Inner Tracker

- Standalone measurements of cosmic muon tracks between muons spectrometer and inner detector allow interesting comparisons



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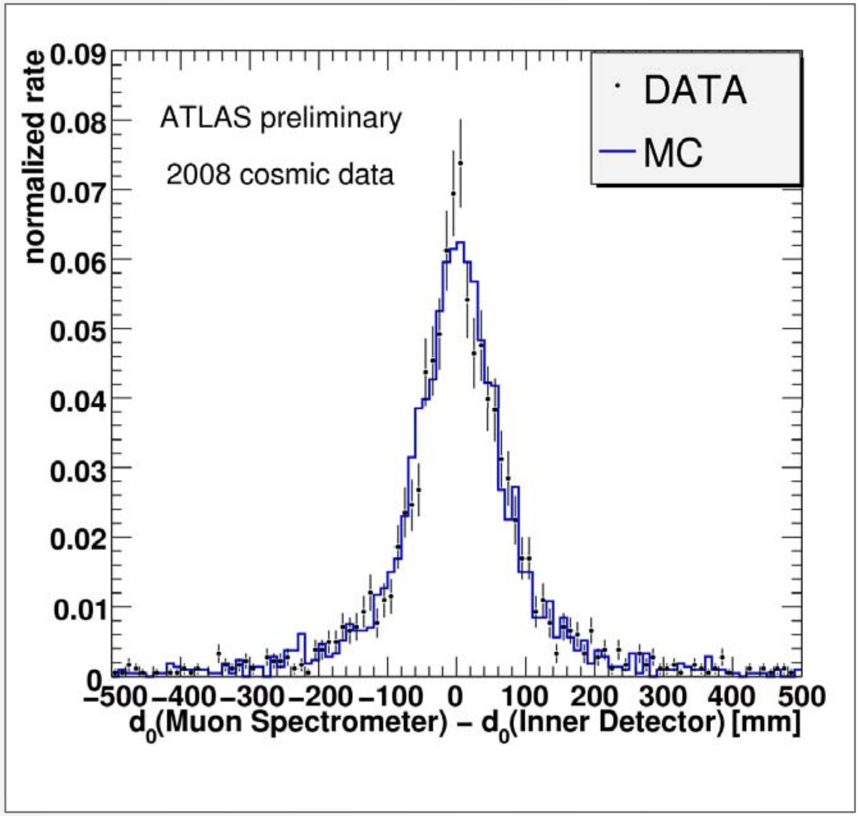
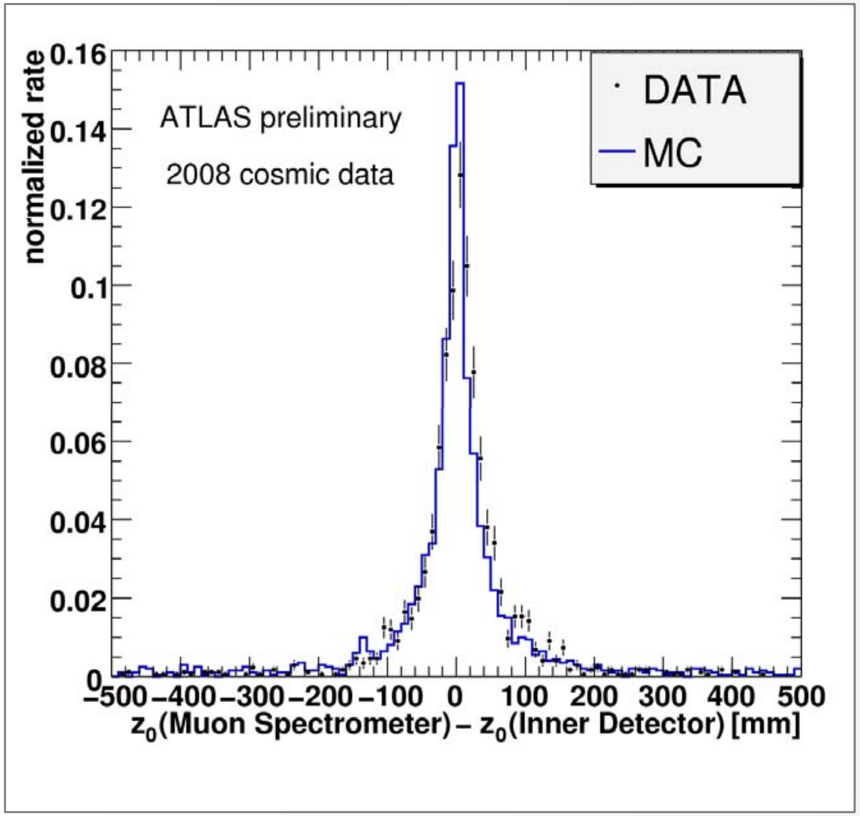




Comparing Muon Spectrometer and Inner Tracker

- But – the tracks loose momentum by (mostly) ionisation when traversing the thick calorimeters and the solenoid …

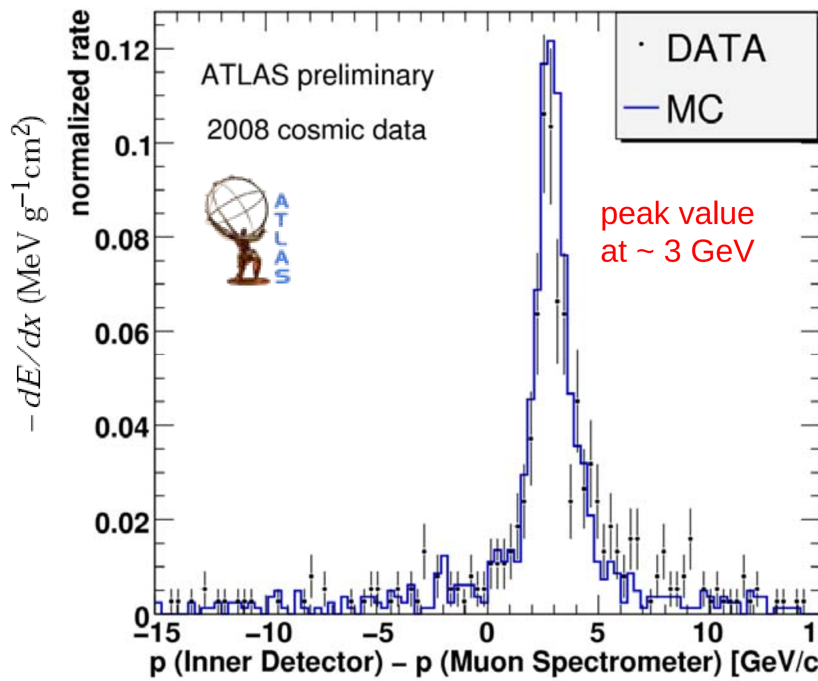
Back-on-the-envelope:

$$\text{HAD cal: } 200\text{cm}\cdot\left(0.4\cdot\left.\frac{dE}{dx}\right|_{\text{Fe}}\cdot 11.8\frac{\text{g}}{\text{cm}^3}+0.6\left.\frac{dE}{dx}\right|_{\text{C}}\cdot 2\frac{\text{g}}{\text{cm}^3}\right)=2.1\,\text{GeV}$$

$$\text{EM cal: } 100\text{cm}\cdot\left(0.4\cdot\left.\frac{dE}{dx}\right|_{\text{Pb}}\cdot 16.9\frac{\text{g}}{\text{cm}^3}\right)=1.0\,\text{GeV}$$

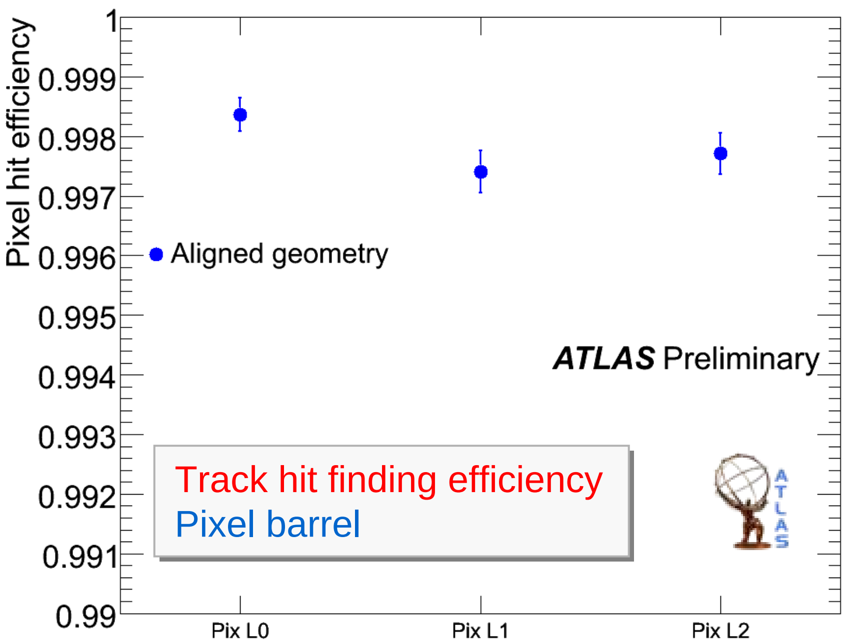
$$\text{Solenoid: } 5\text{cm}\cdot\left(\left.\frac{dE}{dx}\right|_{\text{Cu}}\cdot 8.9\frac{\text{g}}{\text{cm}^3}\right)=0.1\,\text{GeV}$$

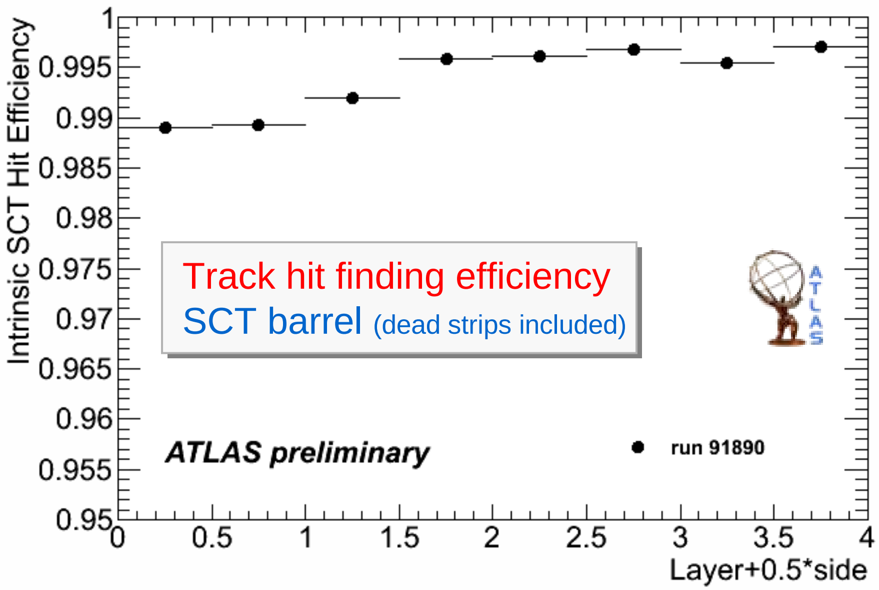
~ 3.2 GeV muon energy loss



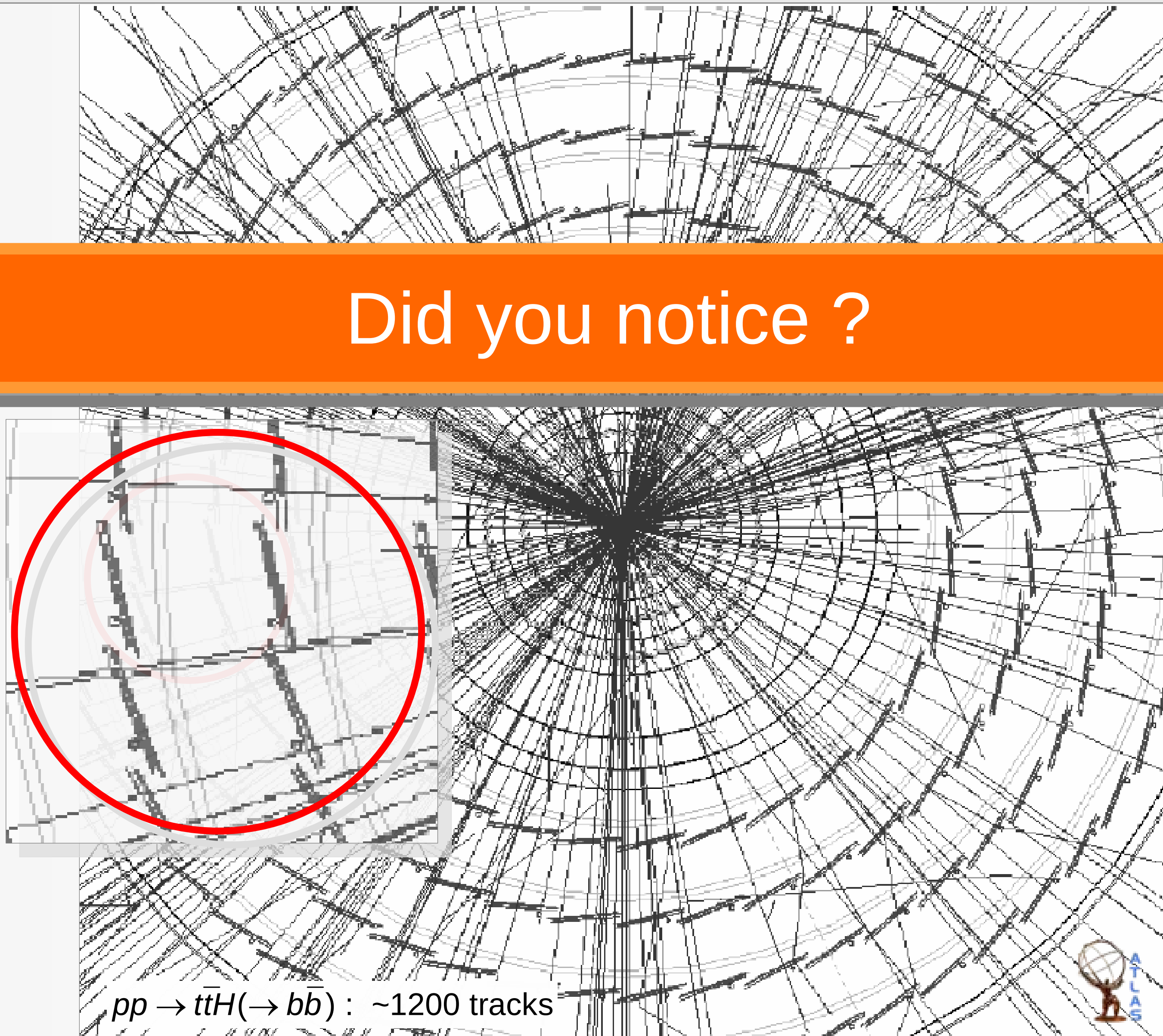
Silicon Tracker Hit Efficiencies

- Tracks from cosmic rays allow to determine hit efficiencies for the tracking devices
  1. Select tracks of good quality (large number of silicon hits, good χ^2/ndof, small incident angle)
  2. Exclude *i*-th layer hits (if there were)
  3. Refit track without *i*-th layer hits
  4. Calculate *i*-th layer hit efficiency within narrow road





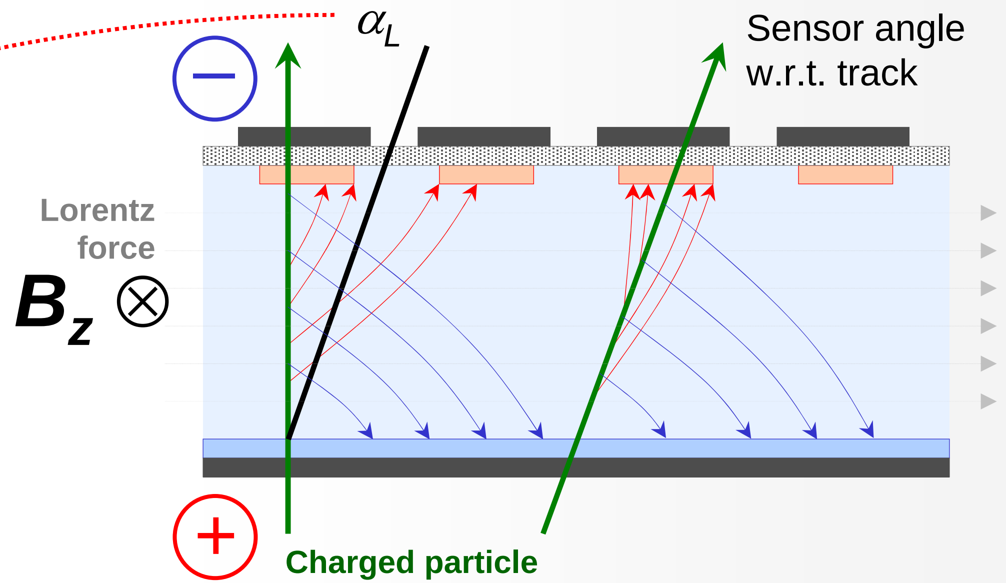
Silicon Detectors: Lorentz Angle



Did you notice ?

Lorentz Angle

- The sensors are tilted relative to the pointing axis: SCT (11º) and Pixel (20º) (*)
  - The charges travelling through the Si substrate are deviated by 2T *B* field (Hall effect)

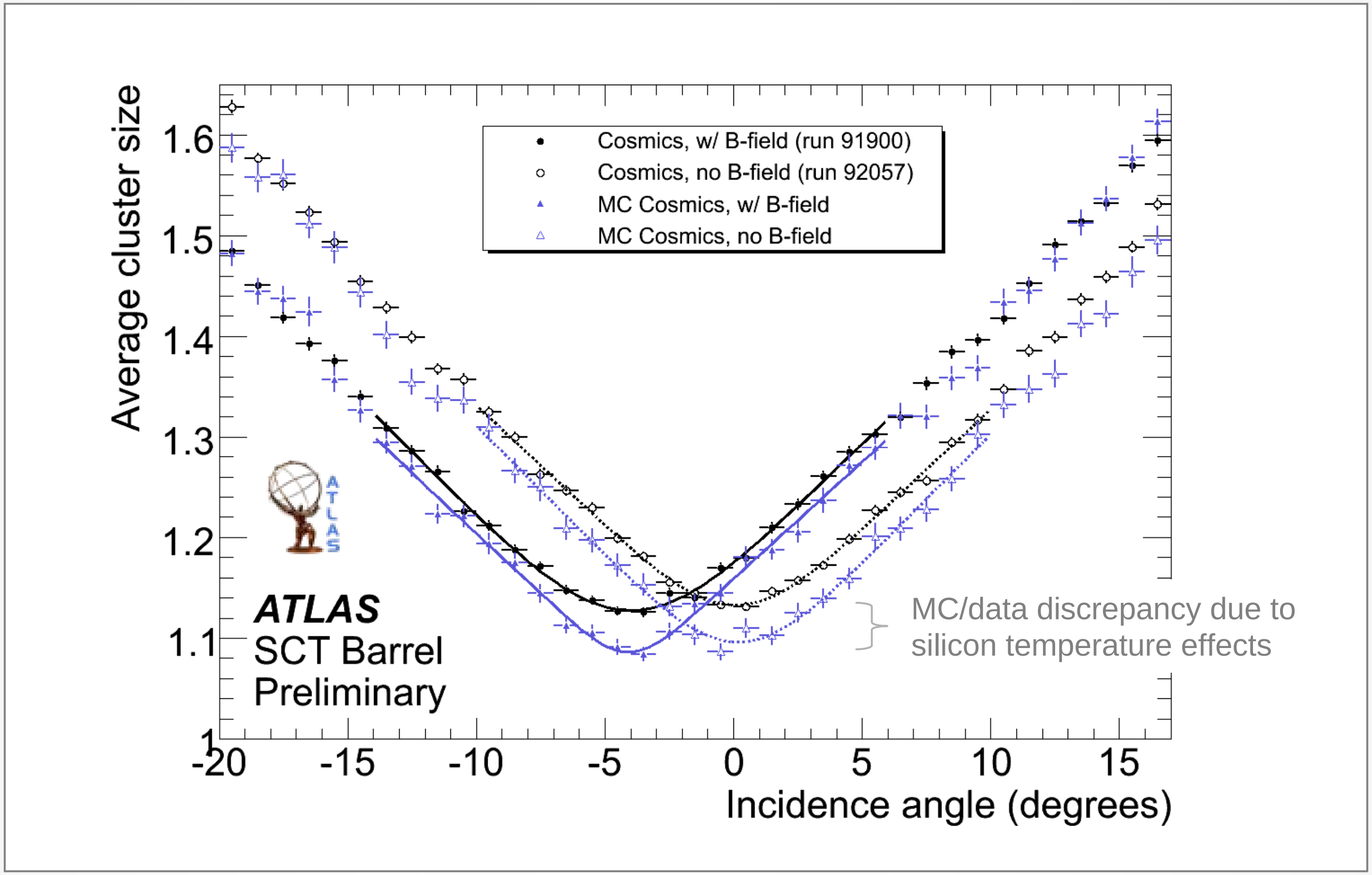


- Lorentz angle determined empirically by **minimising cluster width**
- $\alpha_L = f(V_{depl})$ → as bias voltage increases to cope with irradiation, α_L decreaes

(*) The actual Pixel and SCT Lorentz angles are 13º and 4º (no irradiation), and with opposite signs. The tilts chosen are due to technical reasons.

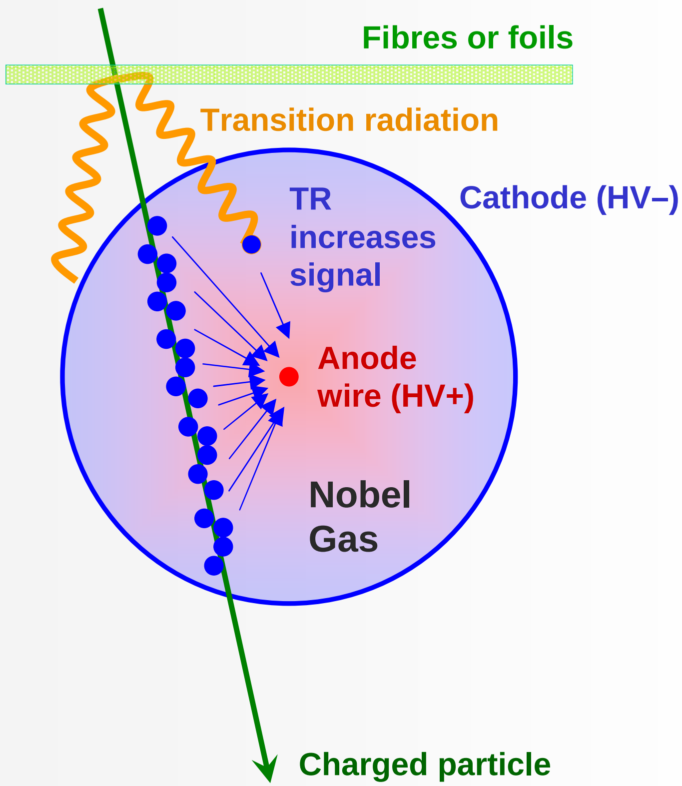
Lorentz Angle Measurement

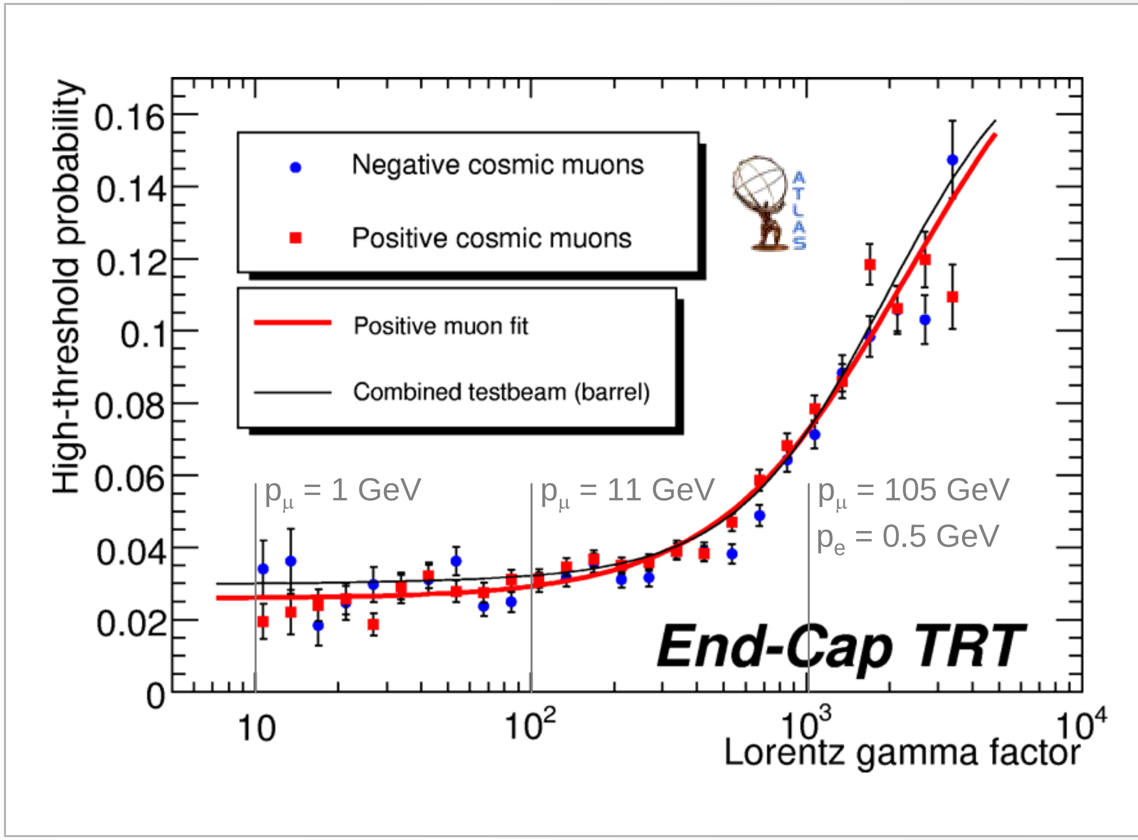
- The Lorentz angle can be determined from cosmic ray tracks
  - Plot cluster width versus incident angle with respect to module normal



Particle Identification with the ATLAS TRT

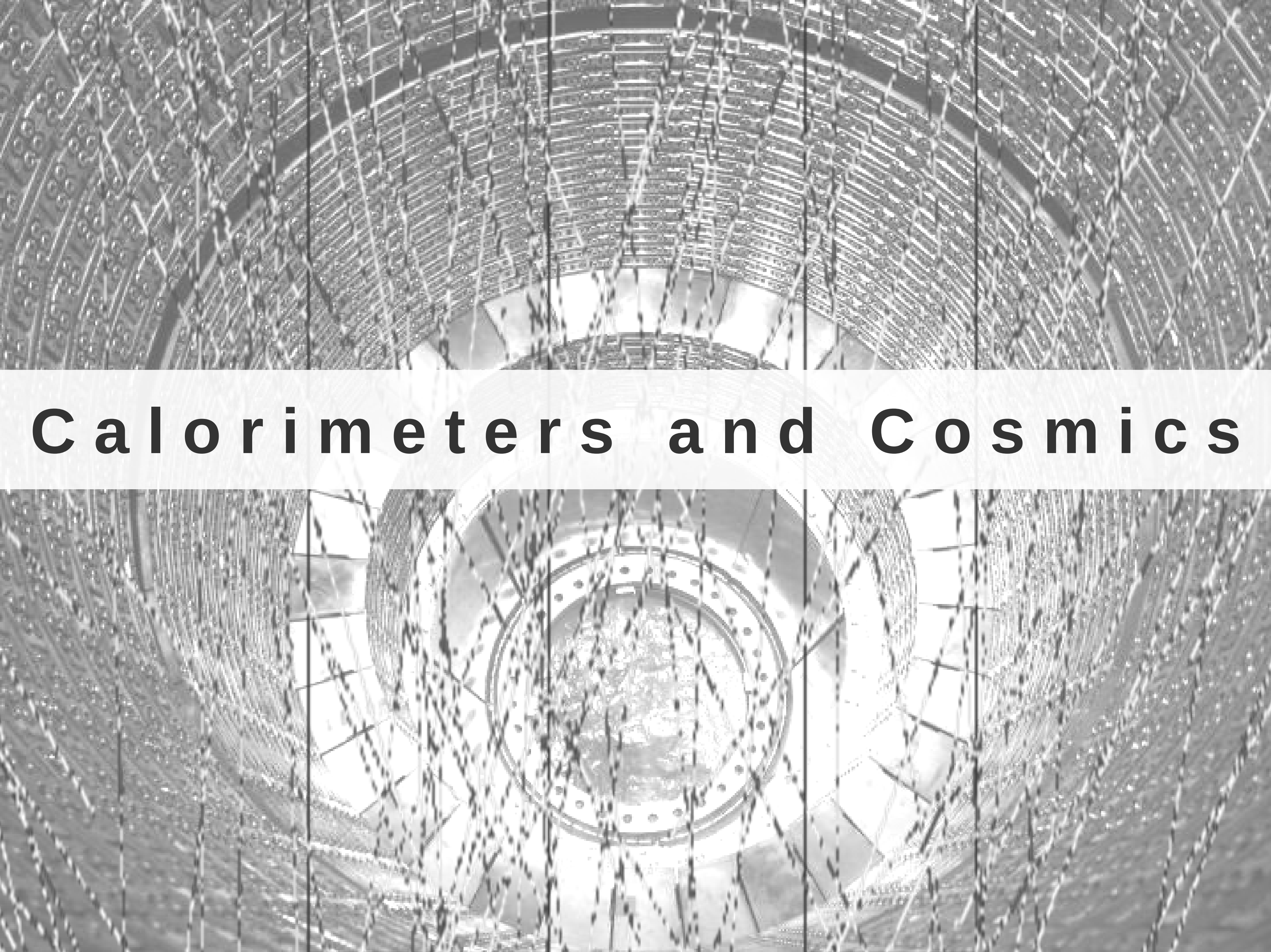
- e/π separation via transition radiation: polymer (PP) fibres/foils interleaved with DTs





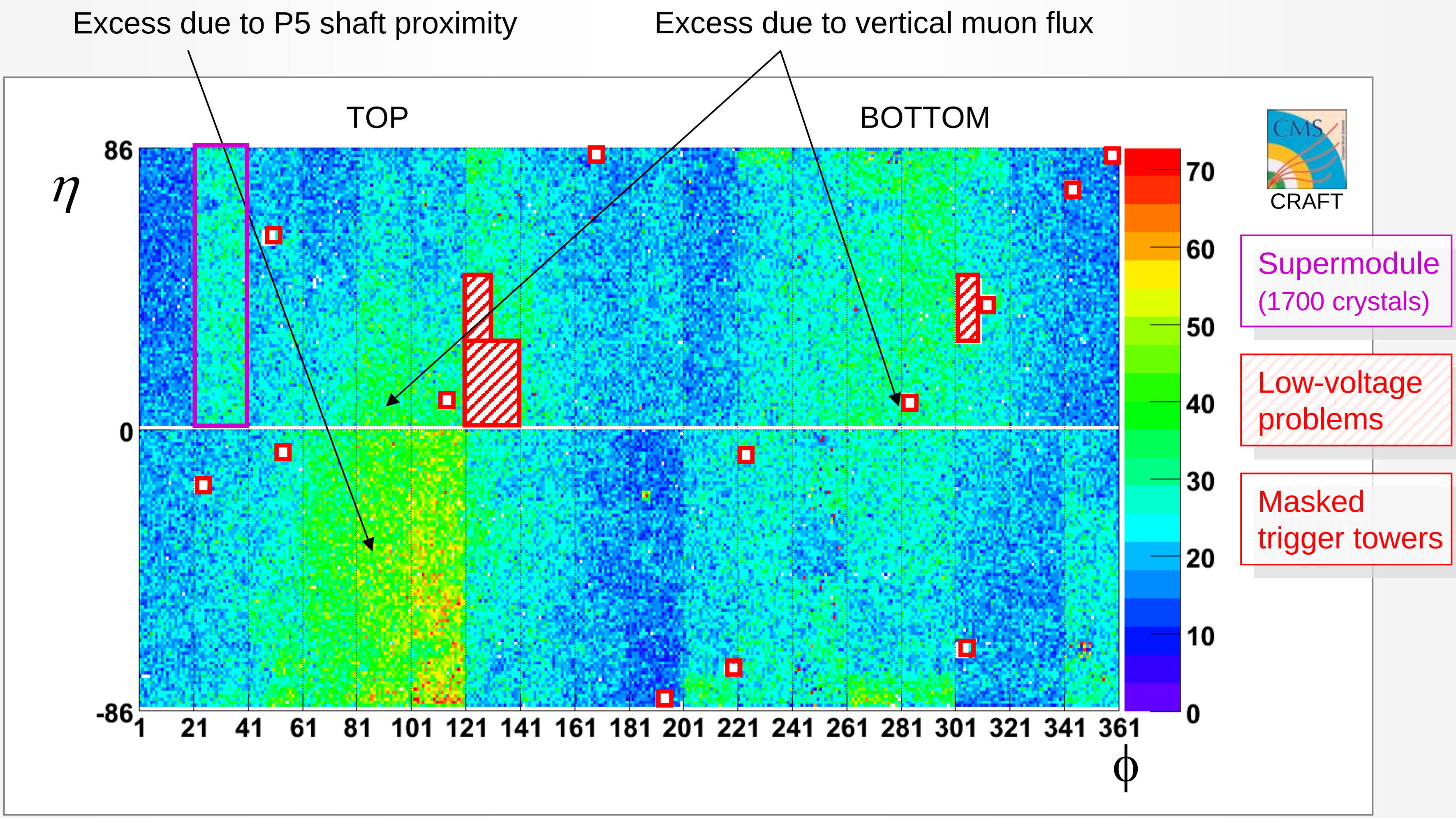
Electrons radiate more → higher signal; PID info by counting high threshold hits

Calorimeters and Cosmics



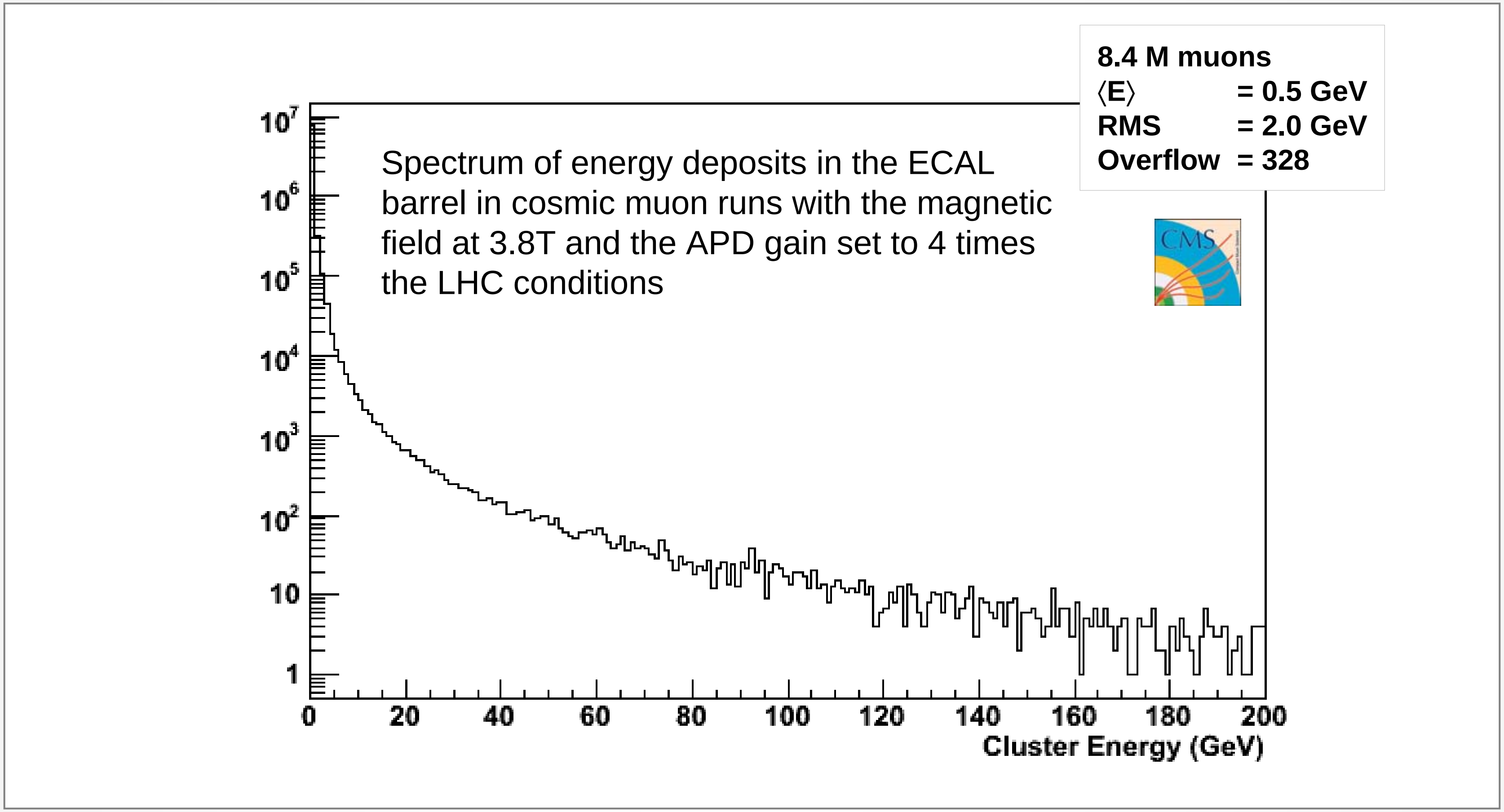
Calorimeter Response with Cosmic Muons

- Occupancy distribution of cosmic clusters in CMS Barrel ECAL (1.4 M cosmic rays)



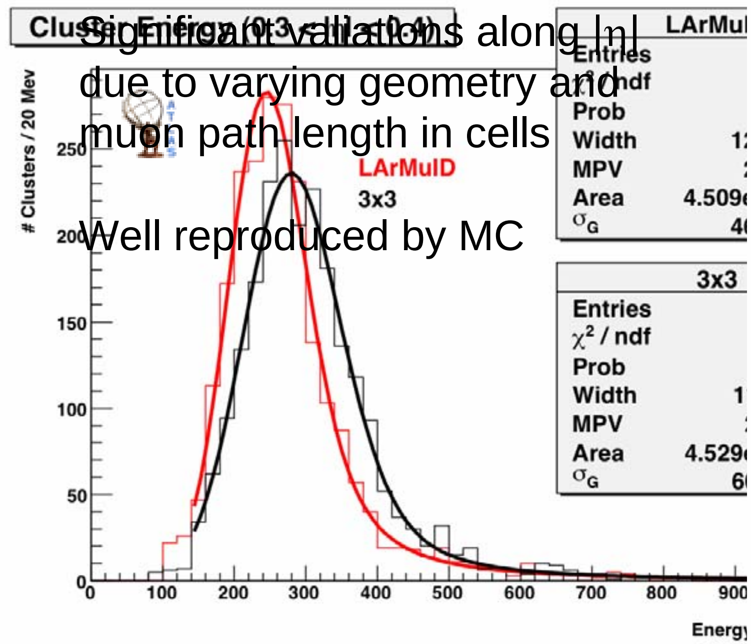
Muon ECAL Energy Distributions Data / MC

- Although muons are MIPs, sometimes they leave significant energy in the calorimeters…



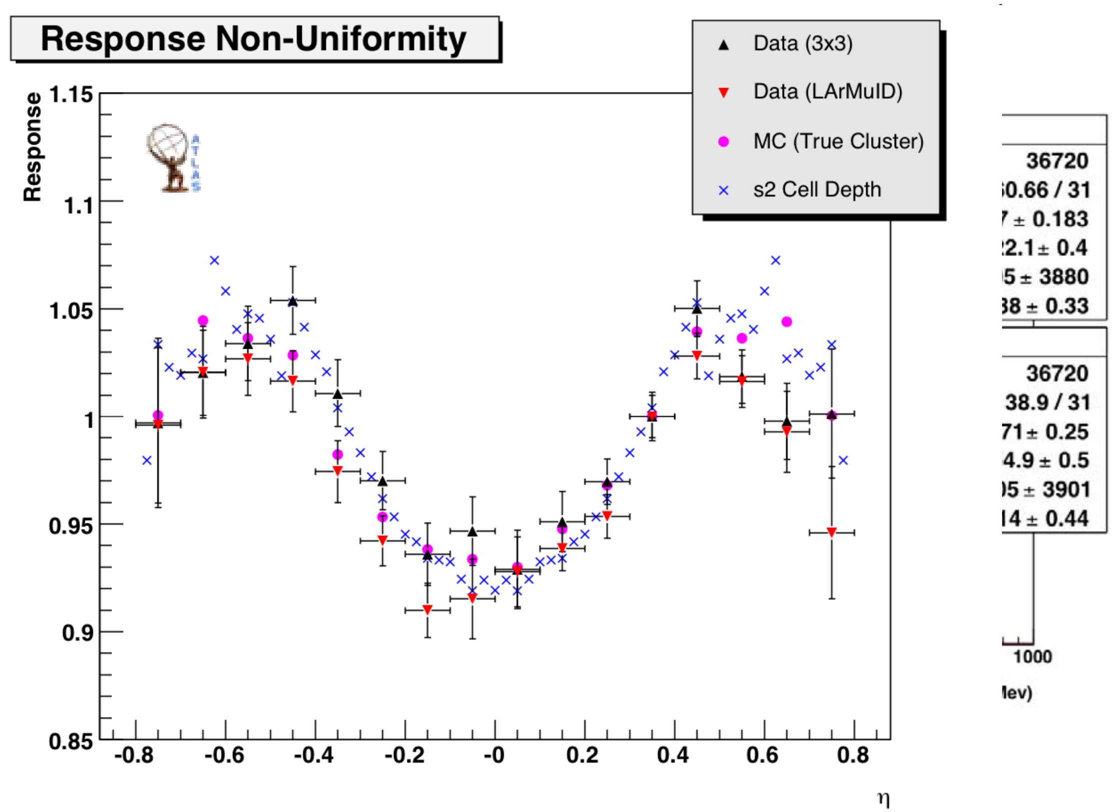
Muon Energy Distributions Data / MC

- Compare muon energy release in EM calorimeter between data and MC



Significant variations along |η| due to varying geometry and muon path length in cells

Well reproduced by MC



- Average muon energy per cluster can be used to ***intercalibrate*** the calorimeter

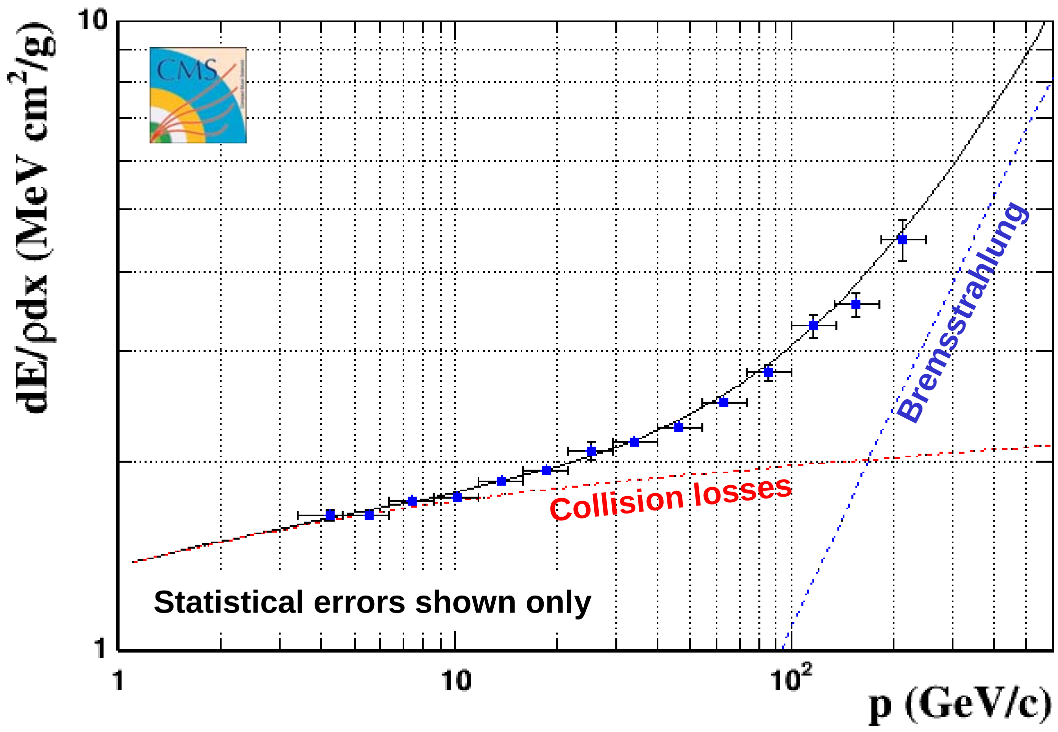
Comparing Muon Spectrometer and Inner Tracker

- But – the tracks loose momentum by (mostly) ionisation when traversing the thick calorimeters and the solenoid …

Measurement of muon *dE*/*dx*

ECAL energy deposit (dots) versus muon momentum compared to expectation from $PbWO_4$ (solid line)

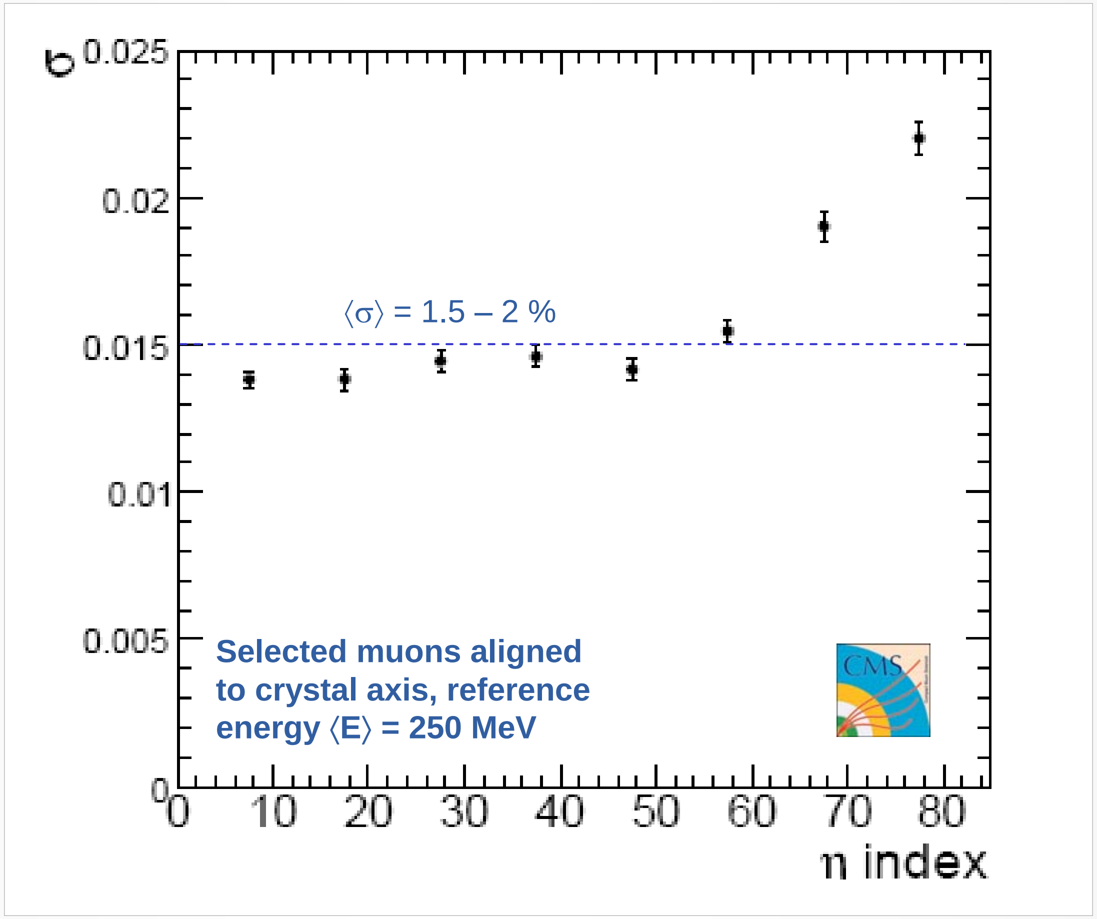
Results indicate the correctness of the tracker momentum scale and of the energy scale in ECAL calibrated with electron at test beams.



ECAL Intercalibration with Cosmic Muons

- Energy response channel-by-channel variations – acceptable performance for startup required, then improved with physics calibration procedures (see later)

Intercalibration with cosmic muons:

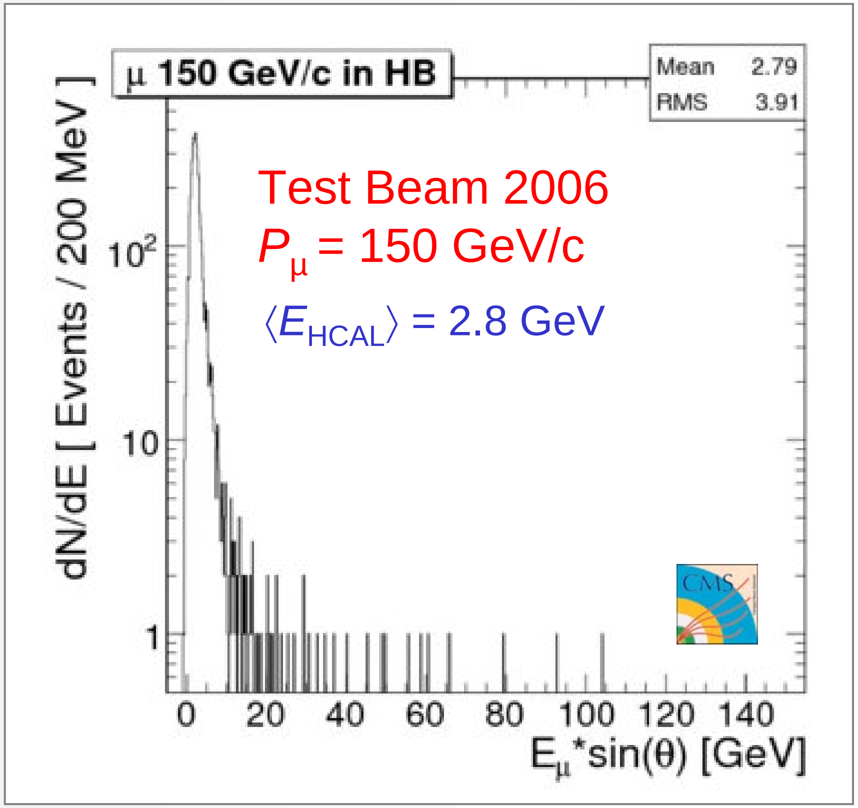


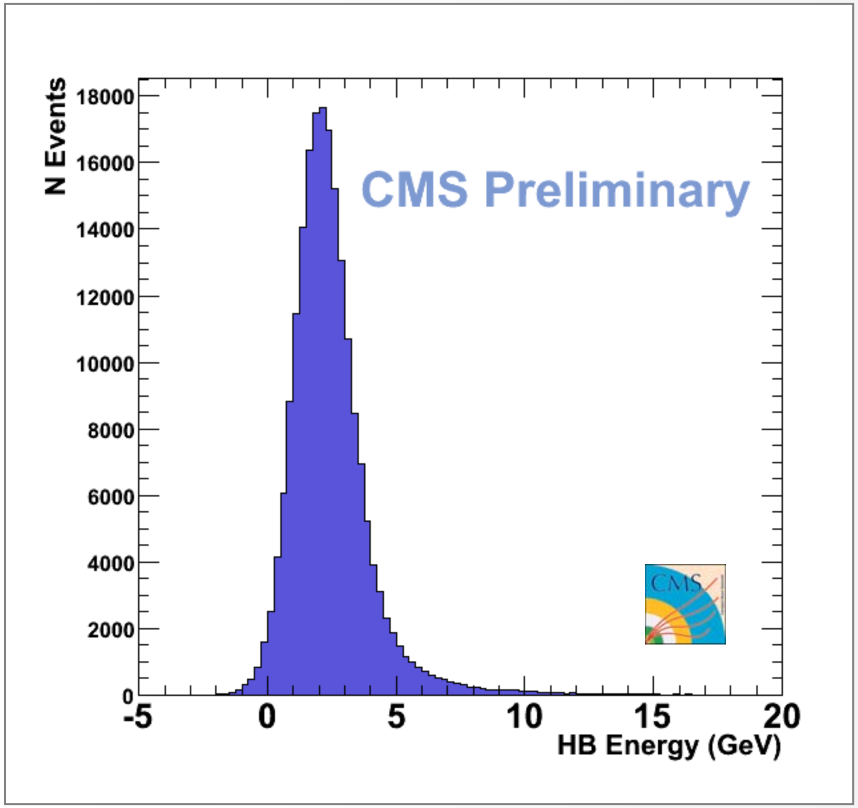
36 Supermodules (100%) intercali-brated with cosmics

9 Supermodules (25%) intercali-brated with electron beam

Hadronic Calorimeter Response

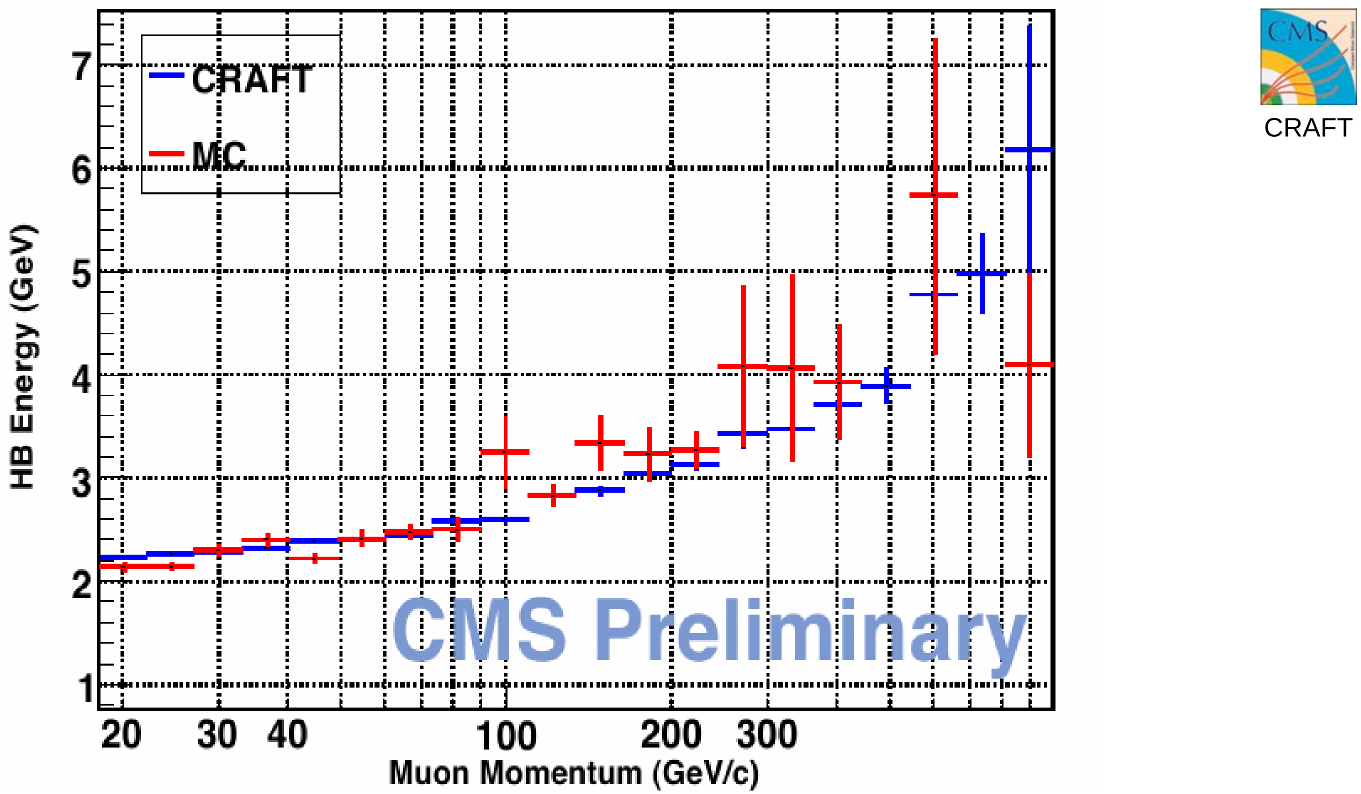
- About 10 times larger measured muon energy in Had than in EM calorimeter





Hadronic Calorimeter Response

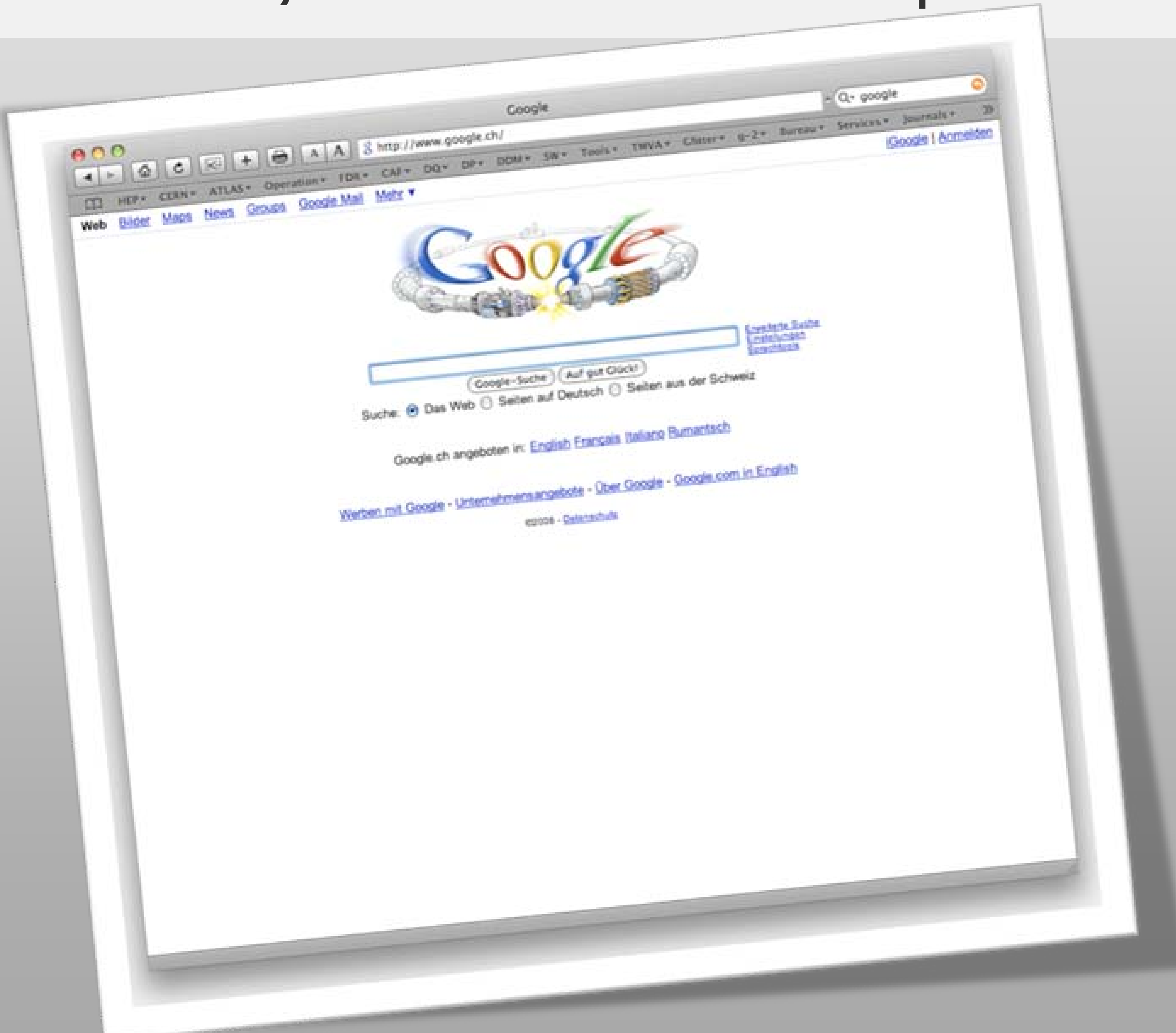
- HCAL (barrel) measured energy in data and MC for selected muons with tracks in DT and Inner Tracker ($20 < p_\mu < 1000$ GeV)



Single Beam

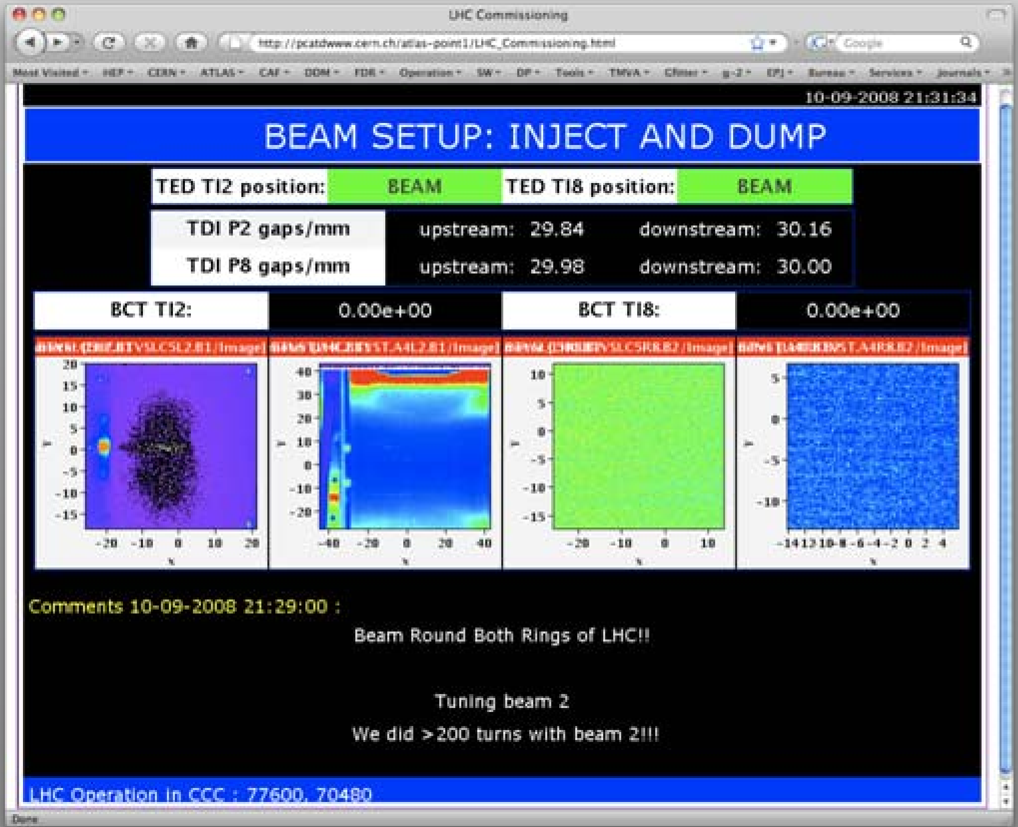
A lucky period from Sep 10 to Sep 13 (CMS: Sep 15?), 2008 with single beam of 900 GeV in both directions of the LHC, a single bunch of ~3 billion protons – RF captured and not, with closed and open collimators, stable beam and beam losses …

September 10th, 2008 – LHC Startup

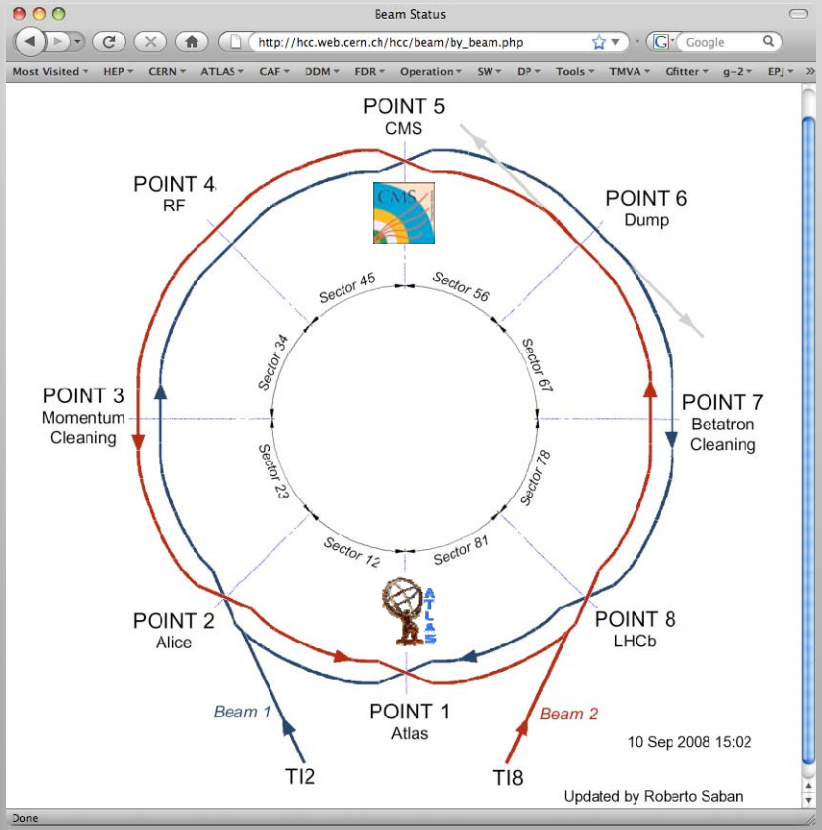


September 10th, 2008 – LHC Startup

LHC operation information



Following the growing beam path



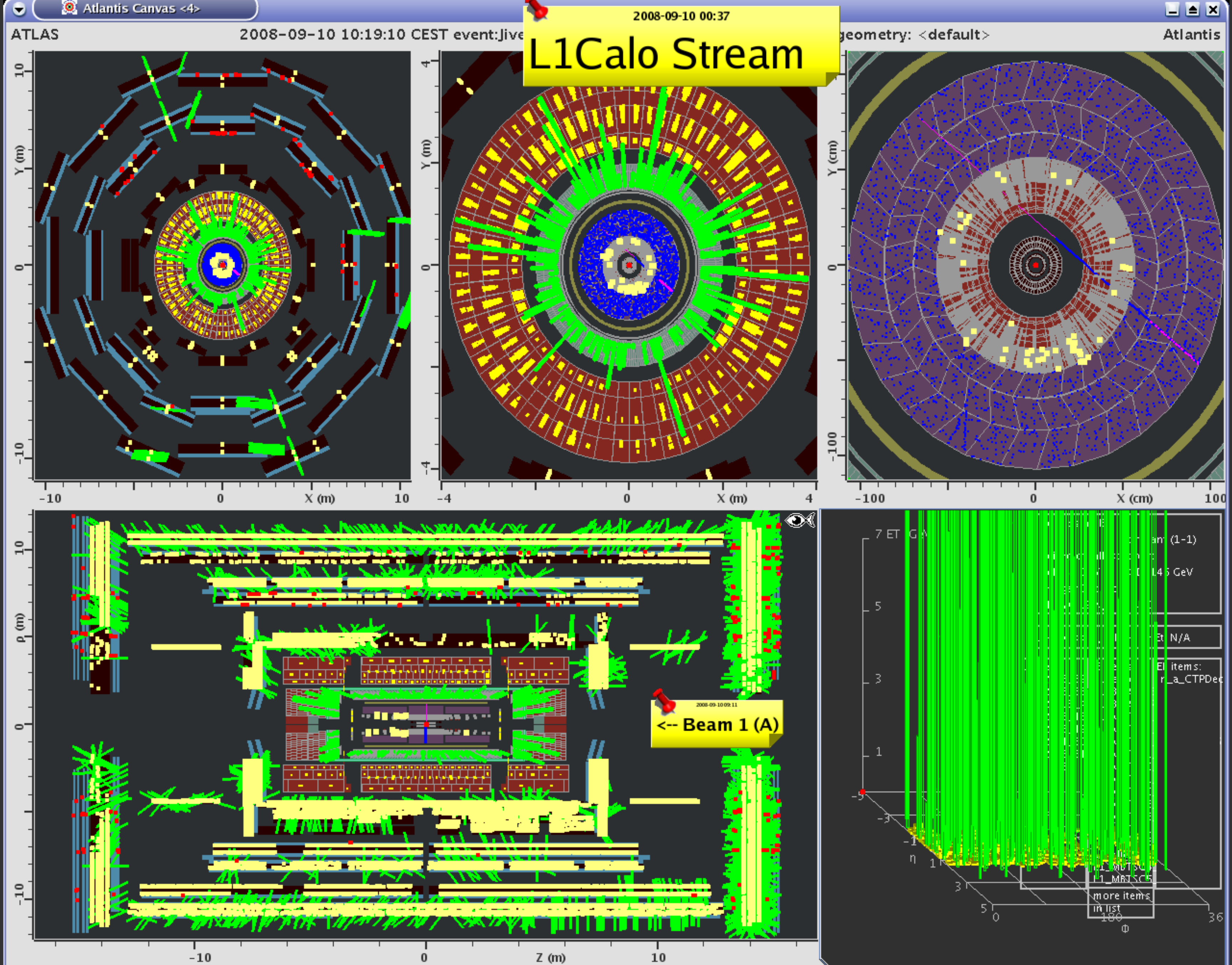
September 10th – LHC Perspective (“*The LHC is the Star*”)

LHC “CCC” with operators, DG and press

September 10th – ATLAS Perspective

September 10th – CMS Perspective

September 10th – LHCb Perspective


Atlantis Canvas <4>
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Y (m)
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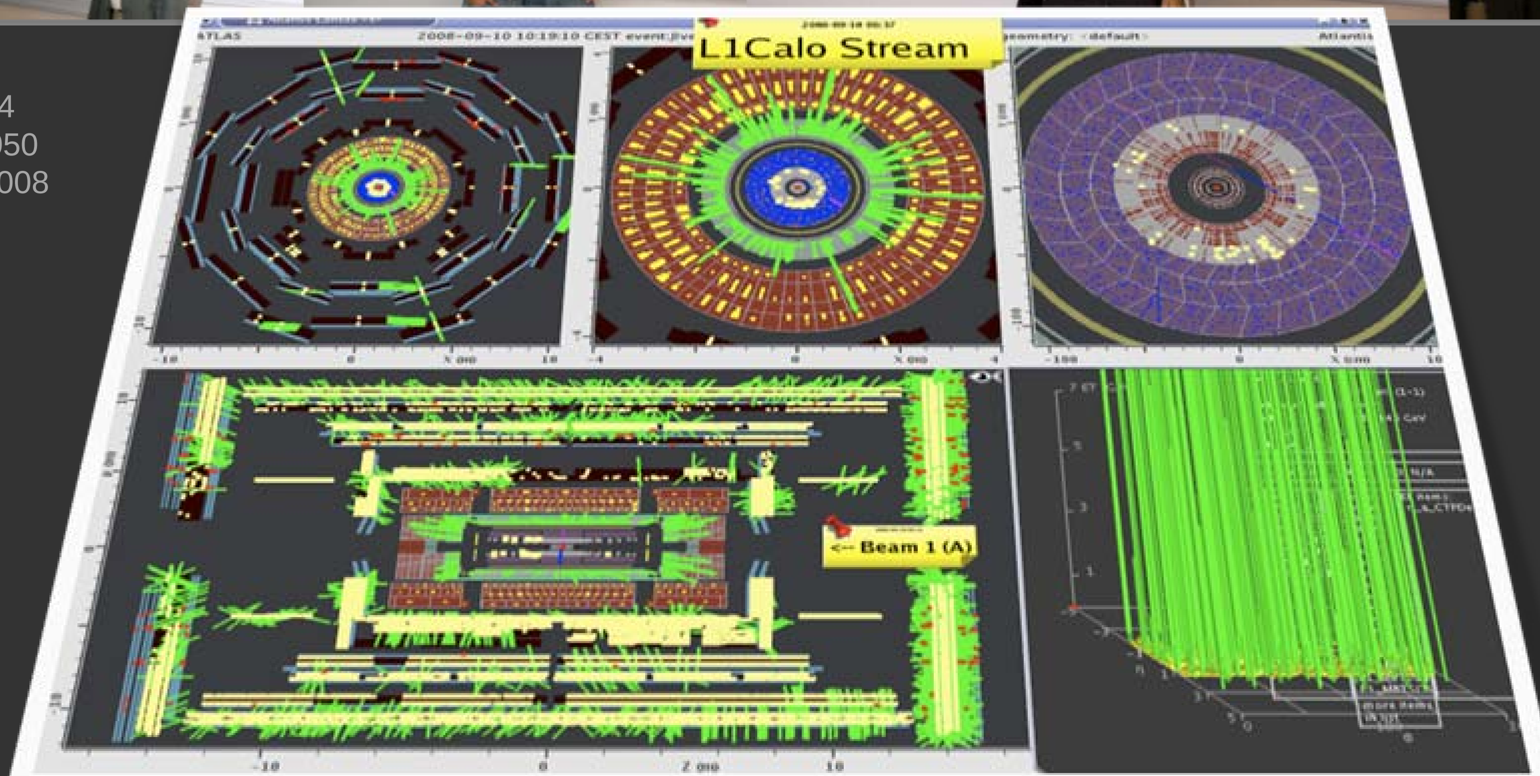
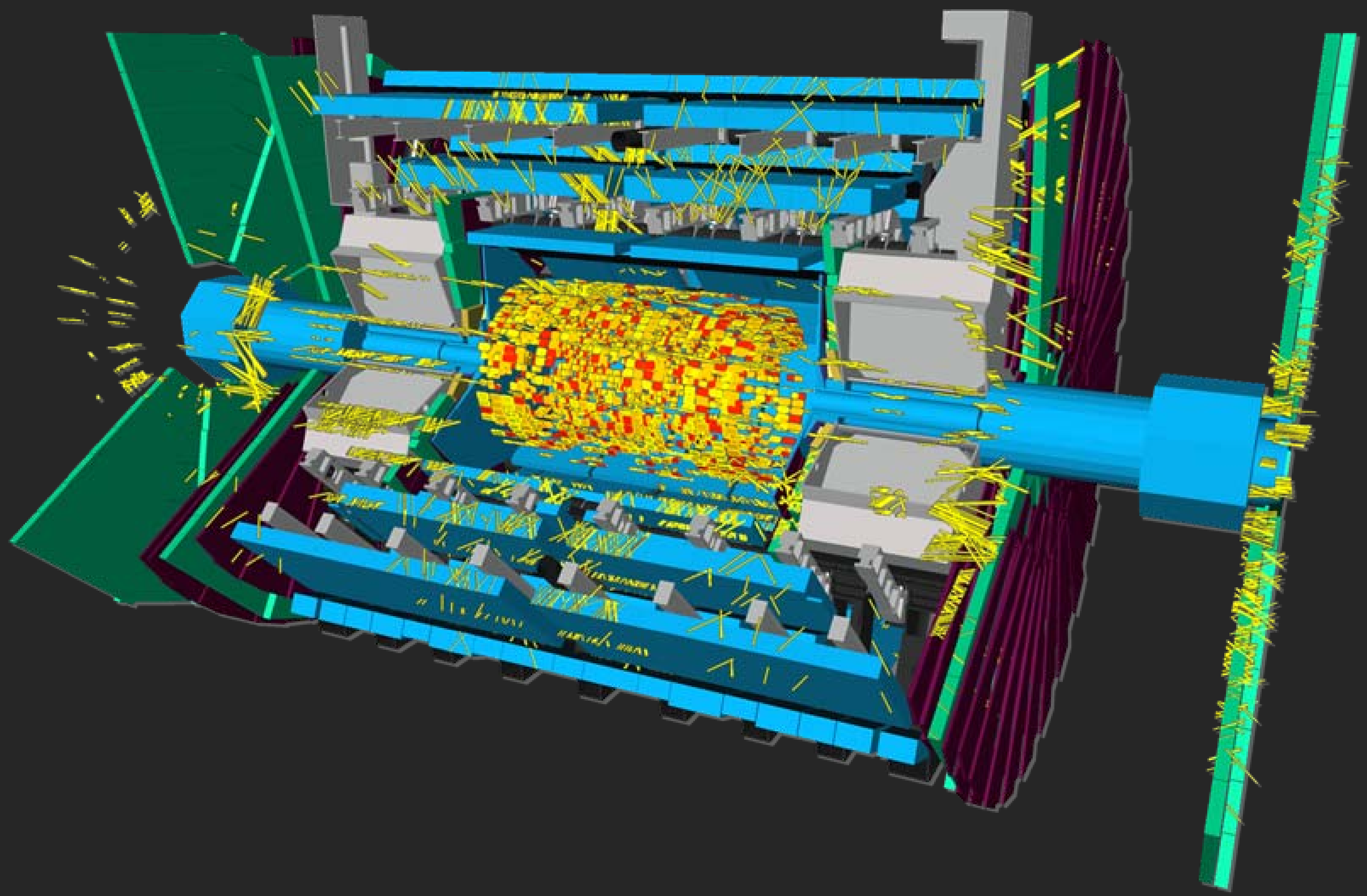
ATLAS
Run 87764
Event 40050
Sep 10, 2008



Most spectacular: collimator “splash” event in **ATLAS**

“Splash” event in ATLAS 3D display

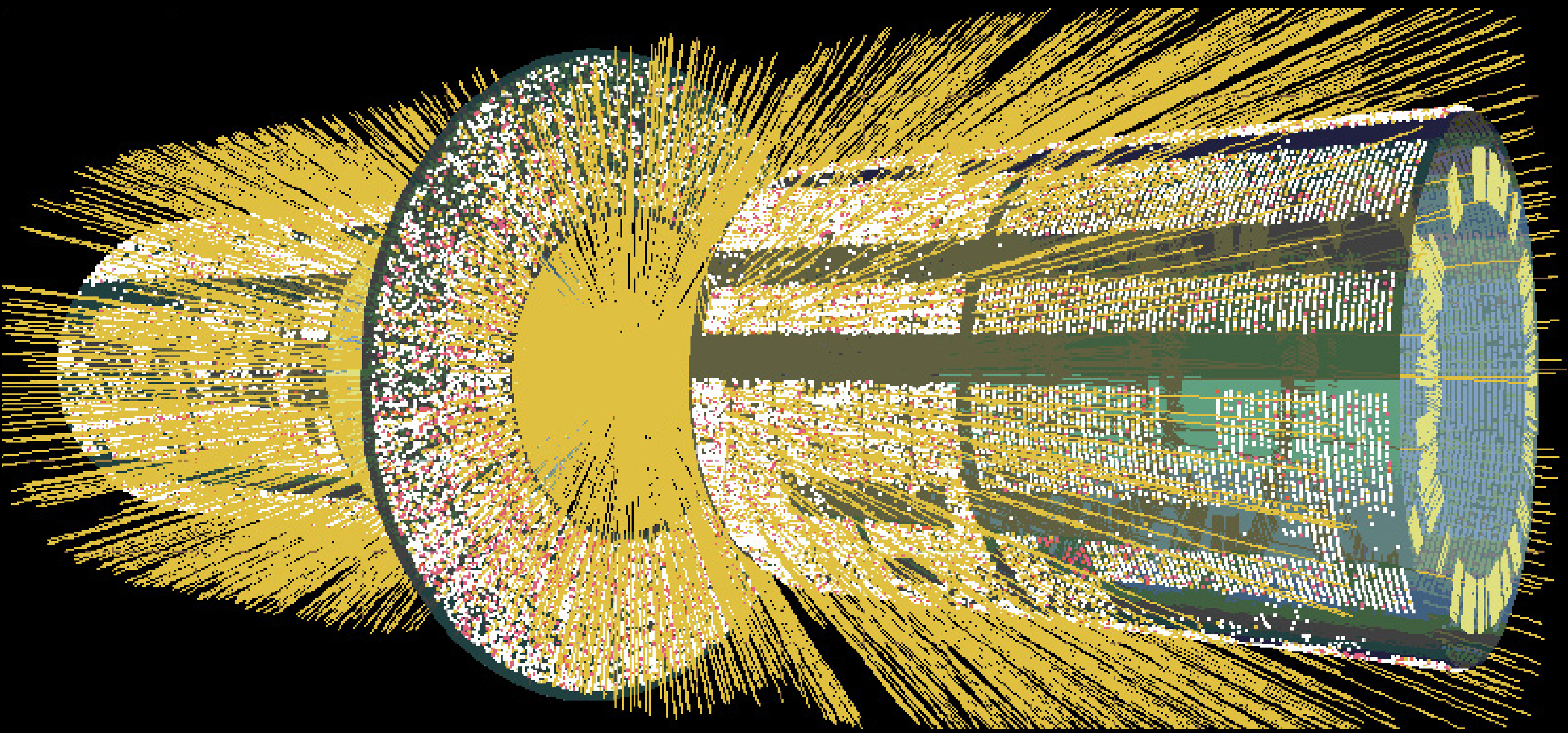
Runs 87764, Event 40050, Sep 10, 2008



Most spectacular: collimator “splash” event in **ATLAS**

“Splash” event in ATLAS 3D display

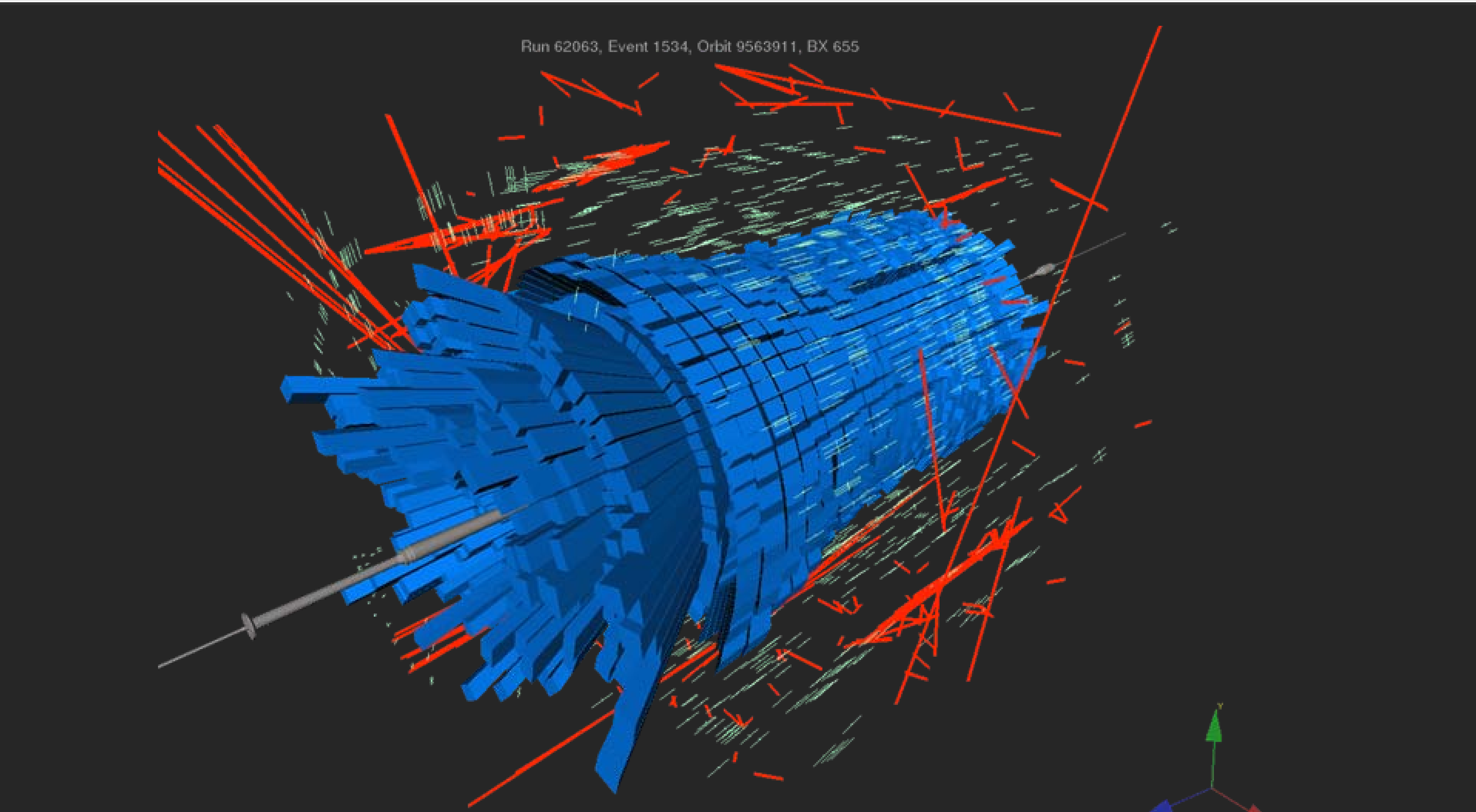
Runs 87863, Event 2627, Sep 10, 2008



Splash event in ATLAS Transition Radiation Tracker

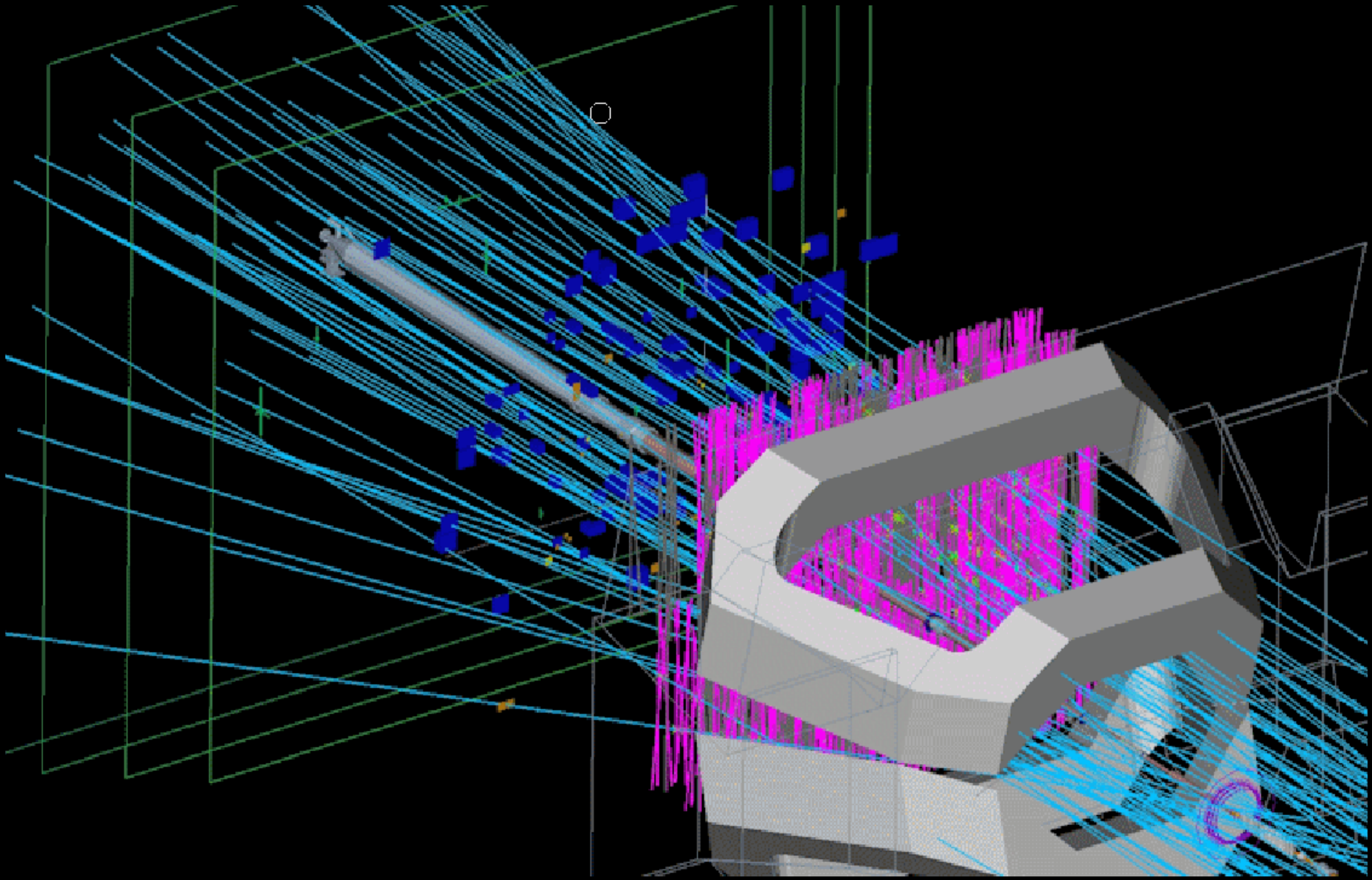
Beam also stopped in front of, and passed by **CMS** !

"Splash" event taken from: http://cmsdoc.cern.ch/cms/performance/FirstBeam/cms-e-commentary.htm



Blue is energy in HCAL, green are RPC hits, and red are muon DT hits

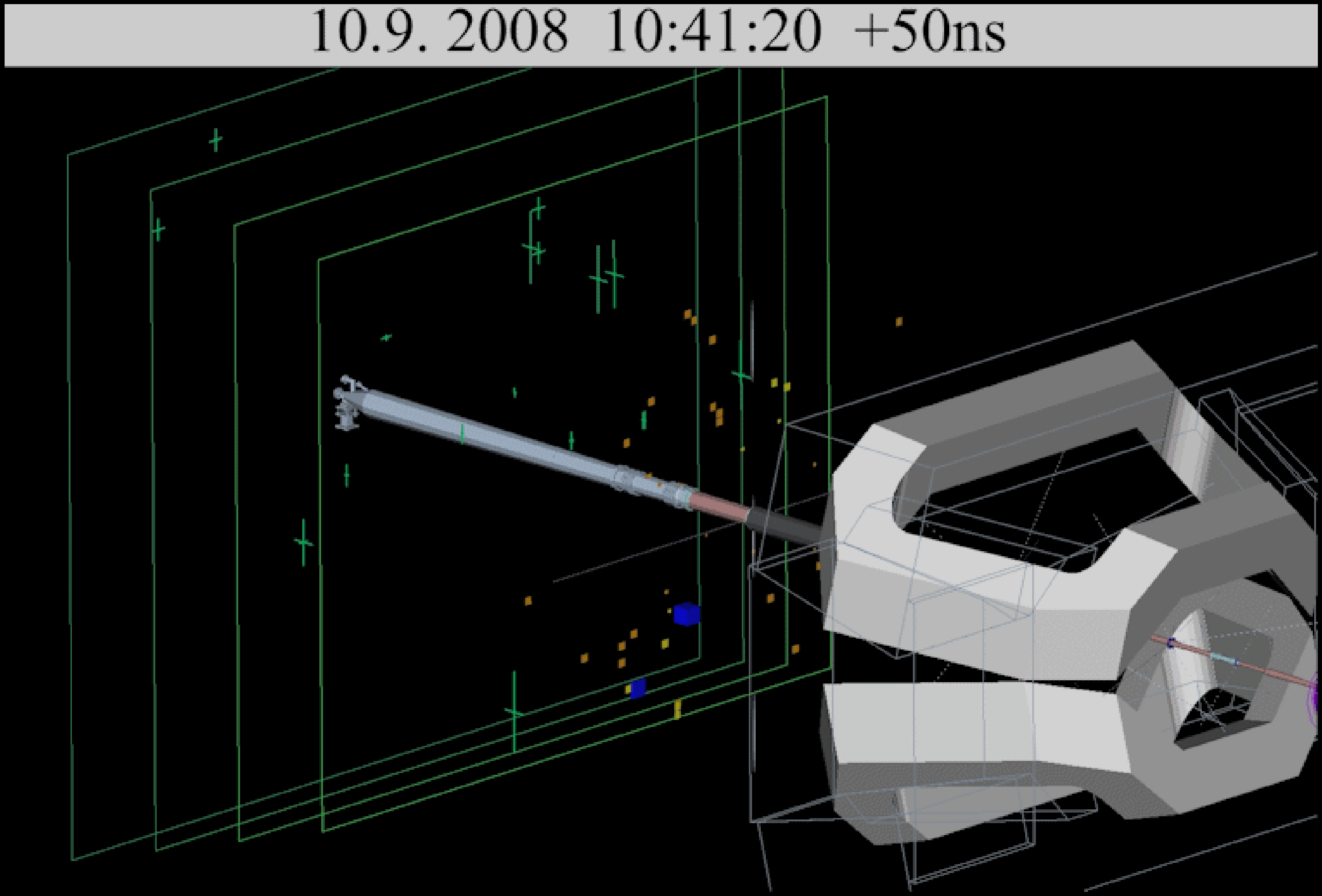
Beam also stopped in front of, and passed by **LHCb** – here, only beam-1 is useful !



Inner tracking devices off, but outer tracker, calorimeters, RICH detectors and muon chambers recording

Beam also stopped in front of, and passed by **LHCb** – here, only beam-1 is useful !

Collimator “splash” event read out with calorimeter and muon chambers



LHCb is capable of triggering and reading out up to 16 consecutive bunch crossings (every 25ns)