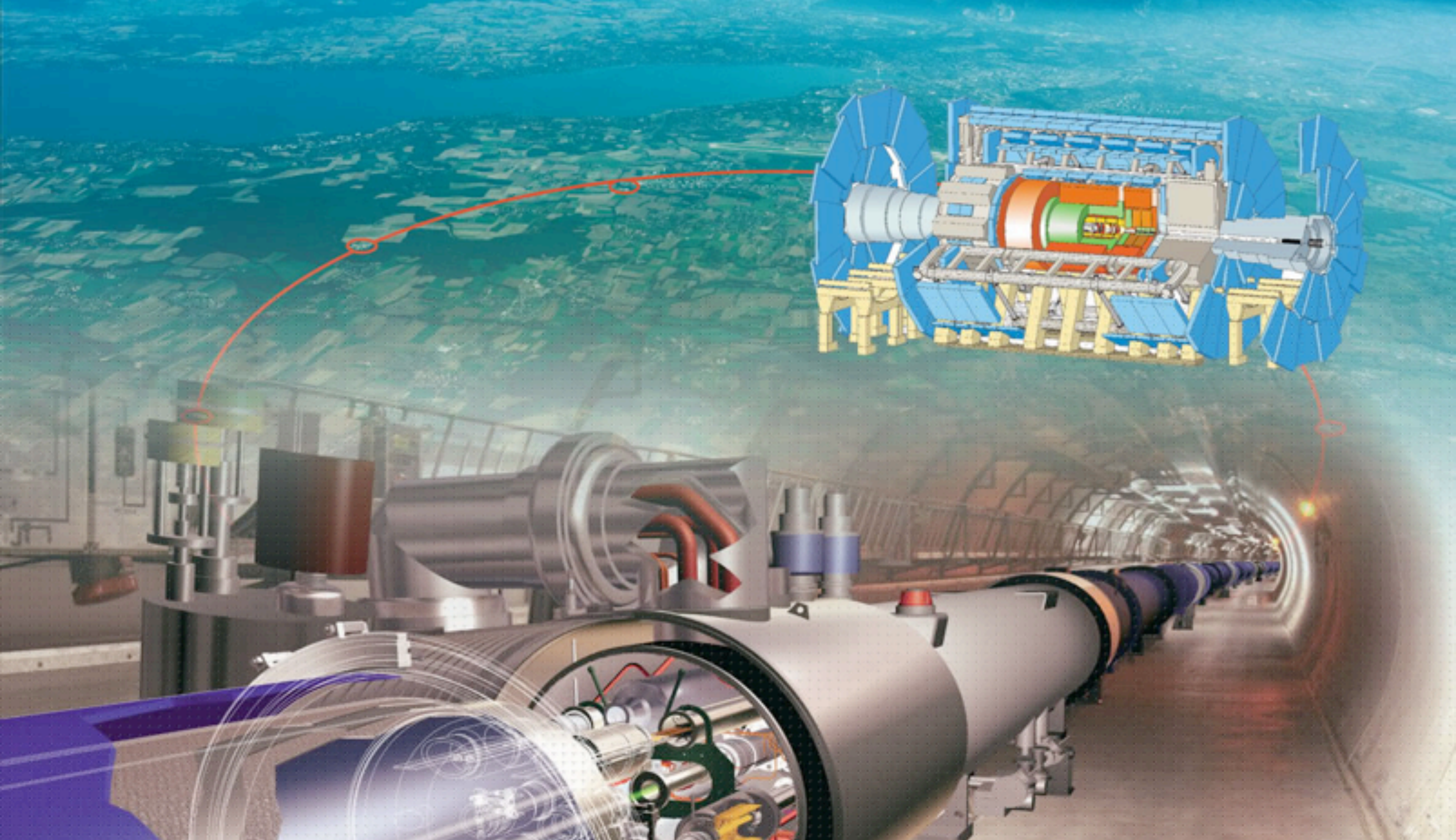
# Initial Performance of the ATLAS Detector at the LHC

P. Krieger, Dept. of Physics, U of T

April 1, 2010



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## World's largest atom smasher sets high-energy collisions

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## Cern LHC sees high-energy success


The New York Times

Science

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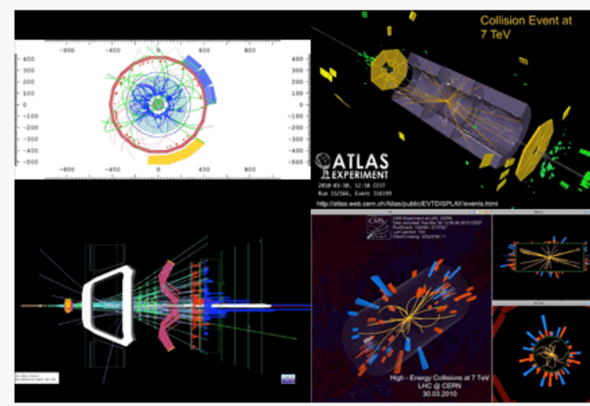
## Large Hadron Collider Finally Smashing Properly

Fabrice Coffrini/Agence France-Presse — Getty Images

Physicists at the European Center for Nuclear Research celebrated on Tuesday.

30 March 2010

## LHC First Physics




7 TeV collision events seen today by the LHC's four major experiments (clockwise from top-left: ALICE, ATLAS, CMS, LHCb). More LHC First Physics images »

LHC research programme gets underway

# Hadron Colliders vs Electron Positron Colliders

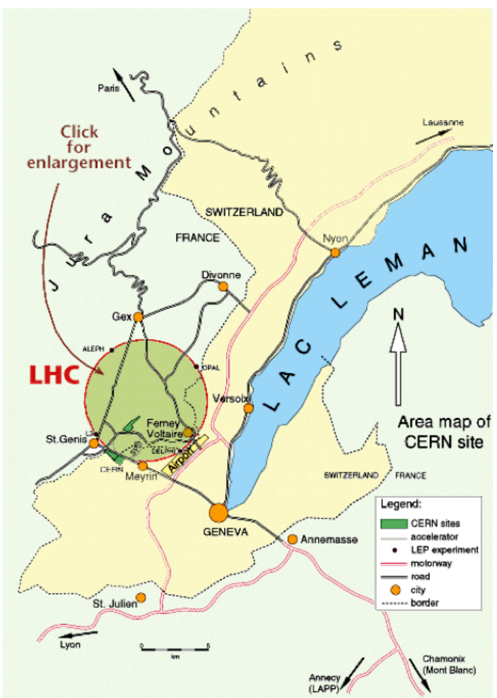
Bending a charged particle in a magnetic field

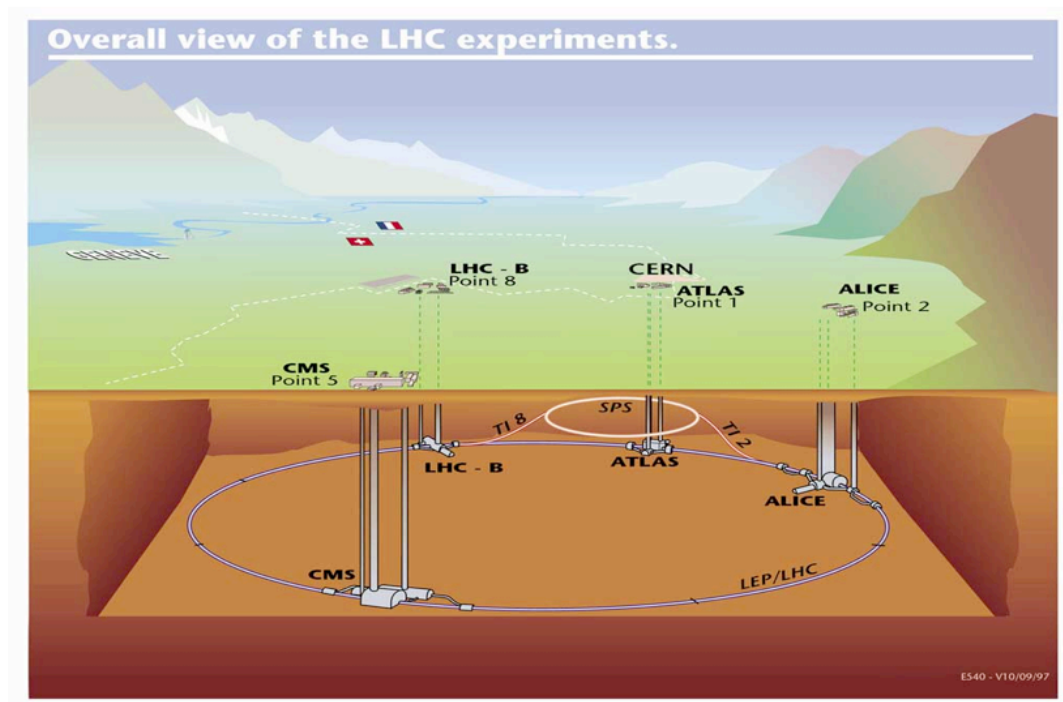
→ energy loss from synchrotron radiation:

$$\Delta E = \frac{4\pi}{3} \cdot \frac{e^2\beta^2\gamma^4}{\rho} \propto \frac{1}{m^4} \quad \text{or} \quad E^4$$

$$\left(\frac{m_e}{m_p}\right)^4 \approx 10^{-13}$$

This represent the energy loss per orbit around the circular ring.



# Hadron Colliders vs Electron Positron Colliders

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This represent the energy loss per orbit around the circular ring.

For fixed radius machine (i.e. in the LEP tunnel at CERN with $\rho$ = 6.28km) synchrotron radiation loss for protons is less that that for electrons by 13 orders of magnitude

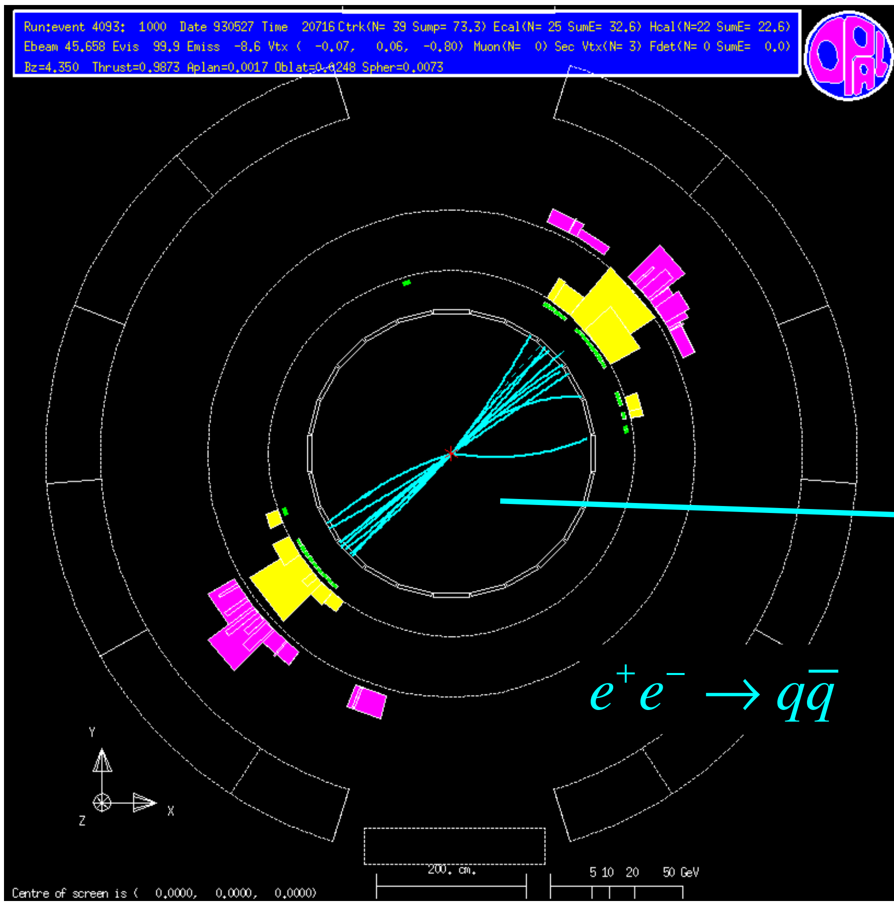
Cannot (feasibly) build electron synchrotrons of arbitrarily high energy. To explore the high-energy frontier, need either:

- ✓ a large hadron collider
- ✓ linear electron positron collider

With existing technology at a given time, the highest energies are always achieve with a hadron collider rather than a lepton collider. Hadron colliders are discovery machines. Lepton colliders are used for precision studies once the technology exists to build them at the required $E_{CM}$. (e.g. CERN SPS → LEP)

# Electron-positron Colliders

- Electron-positron collisions are usually in CM frame.
  - Longitudinal and transverse energy must balance.
  - All of the initial-state energy can go into new particle production.

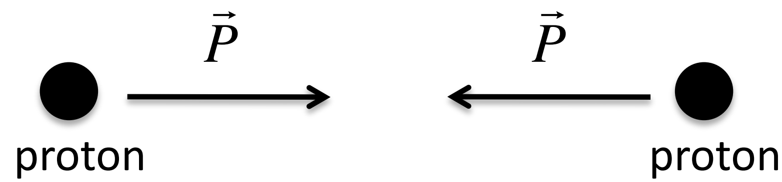



Event displayed is $e^+e^- \to q\bar{q}$ from the OPAL detector at LEP.

Jets (quarks do not exist freely)

# Hadron Colliders

The energy and momentum carried by a proton is shared amongst the various constituents – quarks, gluons, anti-quarks. About 50% is actually carried by gluons.



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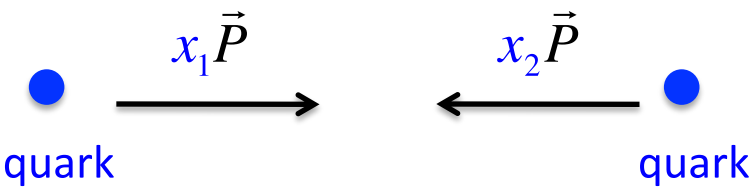
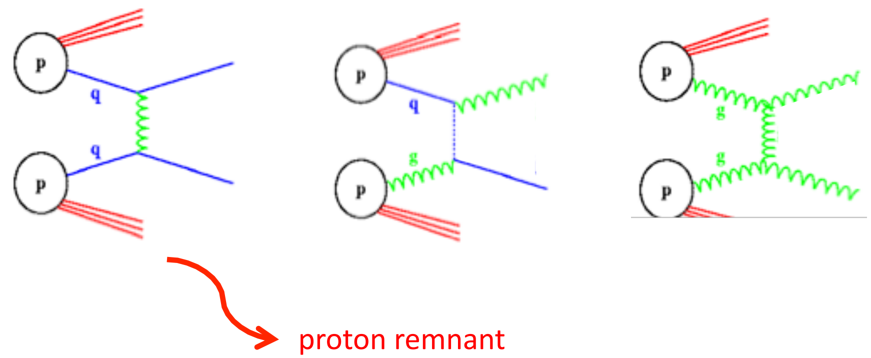
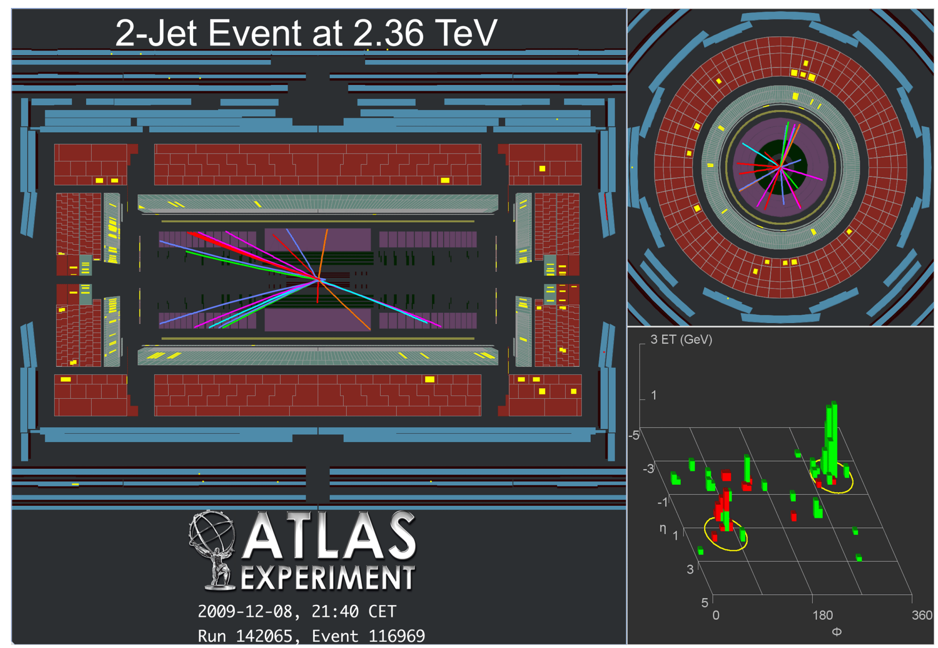


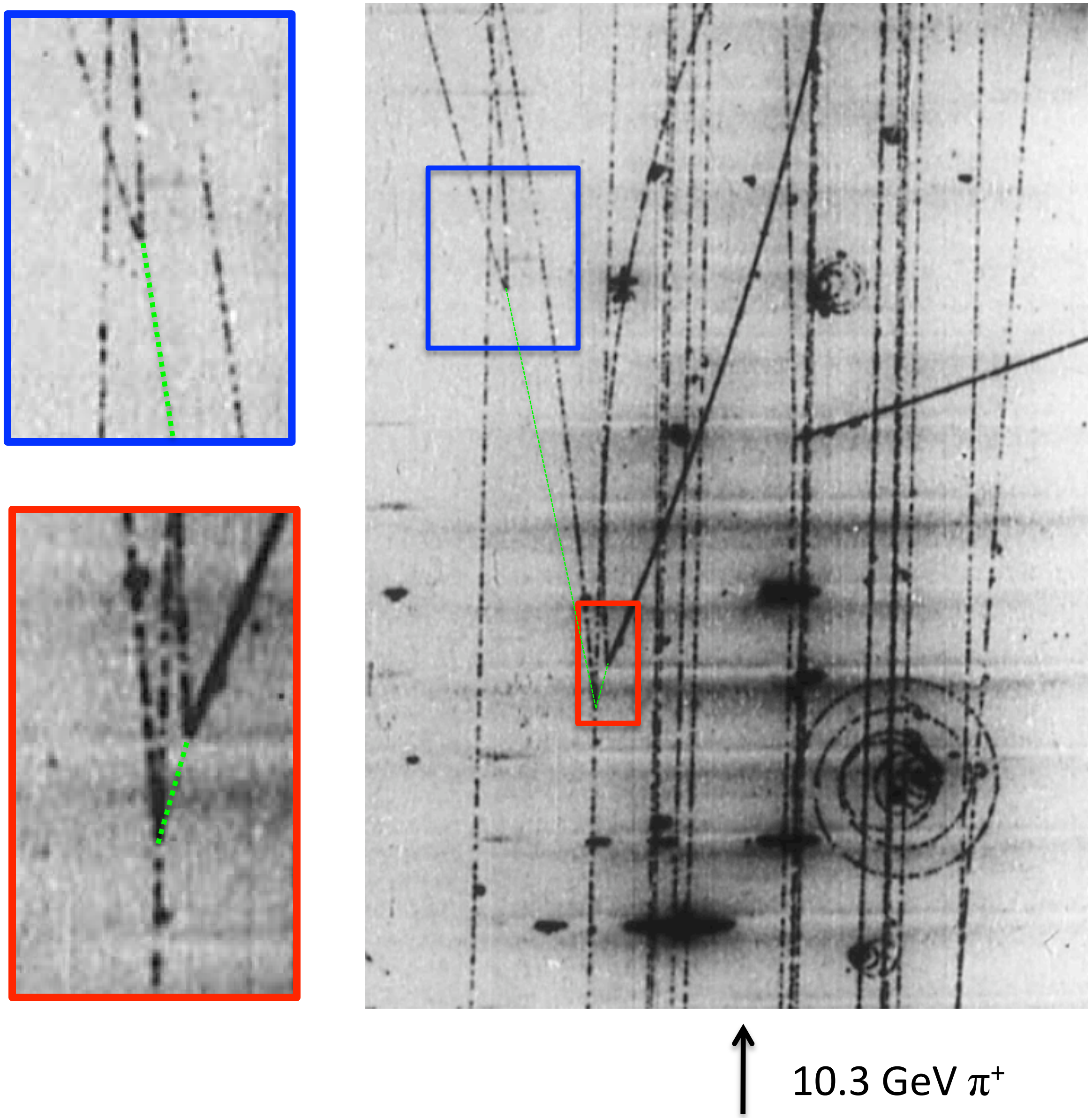

Typically $x_1 \neq x_2$ so:

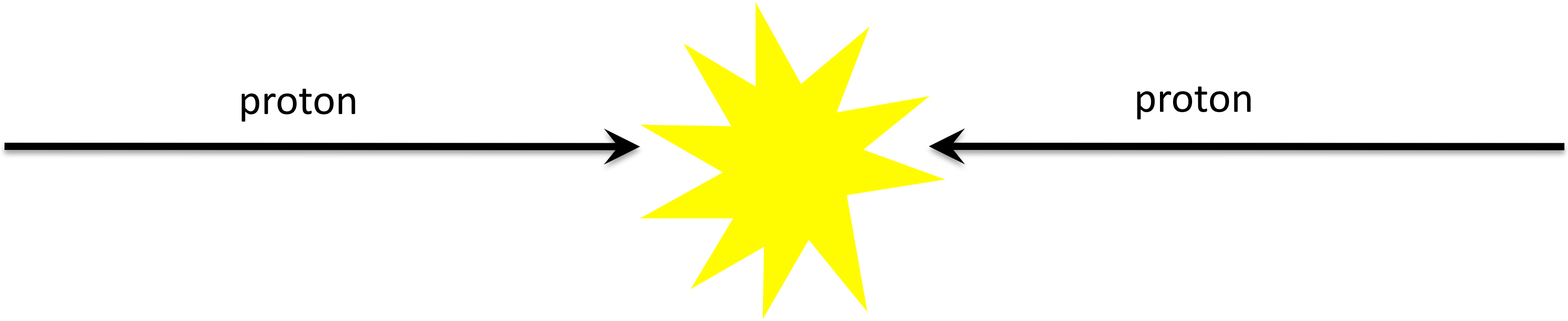
Net longitudinal momentum in initial/final state $|x_1 - x_2|\vec{P}$

Collision energy ~ $E_{CM}(pp)\sqrt{x_1 \cdot x_2}$



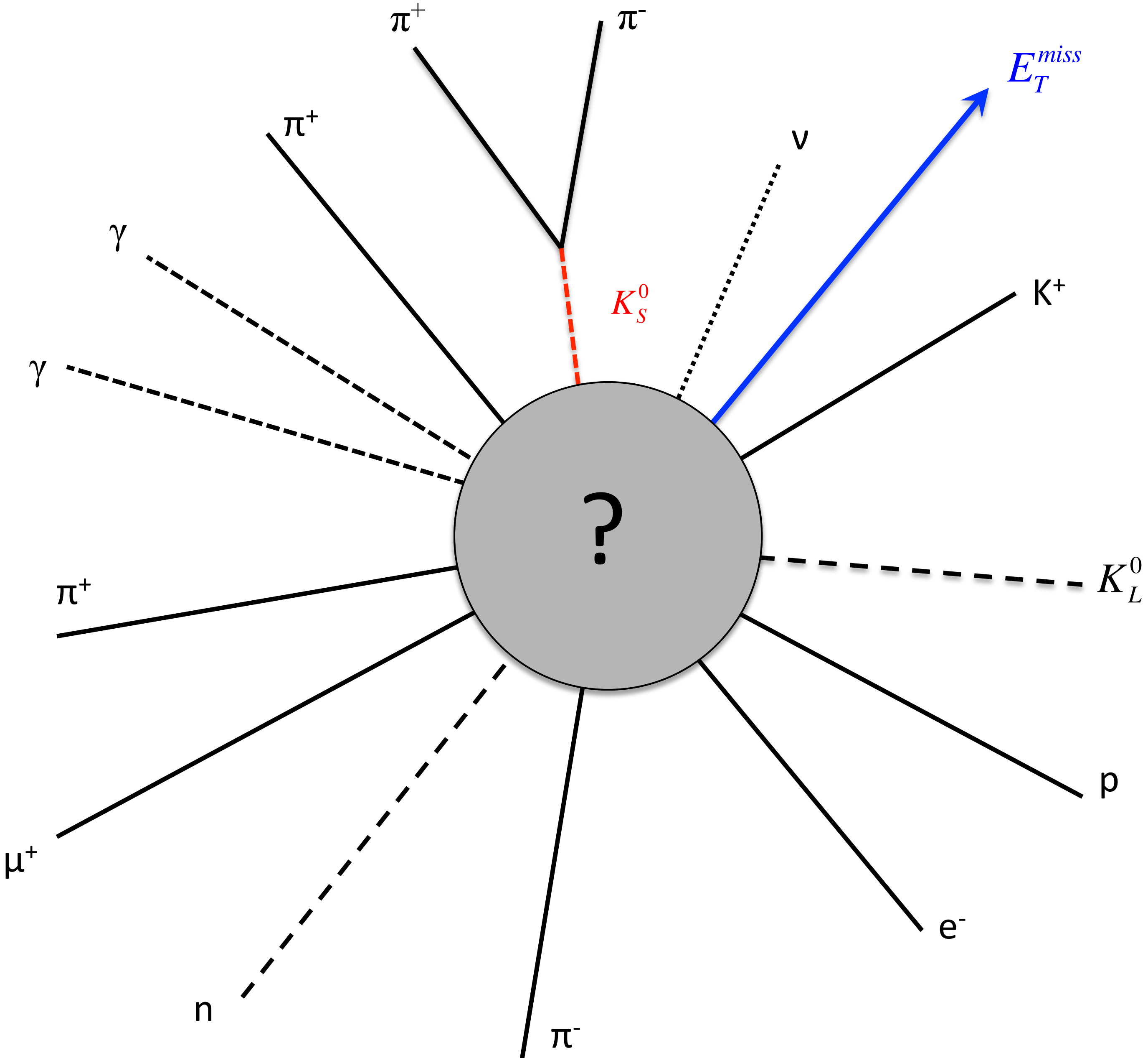
# Hadronic Collisions (here $\pi^+p$)




proton
proton

Higgs, SUSY particles, gravitinos, or your favorite BSM particle, or just boring Standard Model particles

BSM = Beyond the Standard Model (e.g. something new)

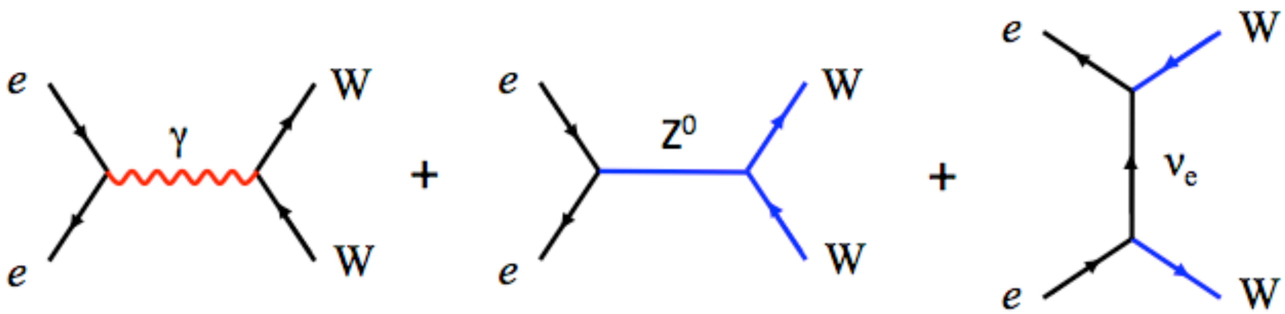



What you see (in the detector) is what you get……

# Some Basic Collider Physics

How does one calculate the rate for some physics process at a collider?

Quantum-mechanical amplitude $\mathcal{M}$ = sum of all contributing processes, here for $e^+e^- \rightarrow W^+W^-$




Define cross-section σ = kinematic factor * $|\mathcal{M}|^2$ units of (length)$^2$

Define luminosity $\mathcal{L} \approx N_1 N_2 \frac{f}{A}$

bunch crossing frequency

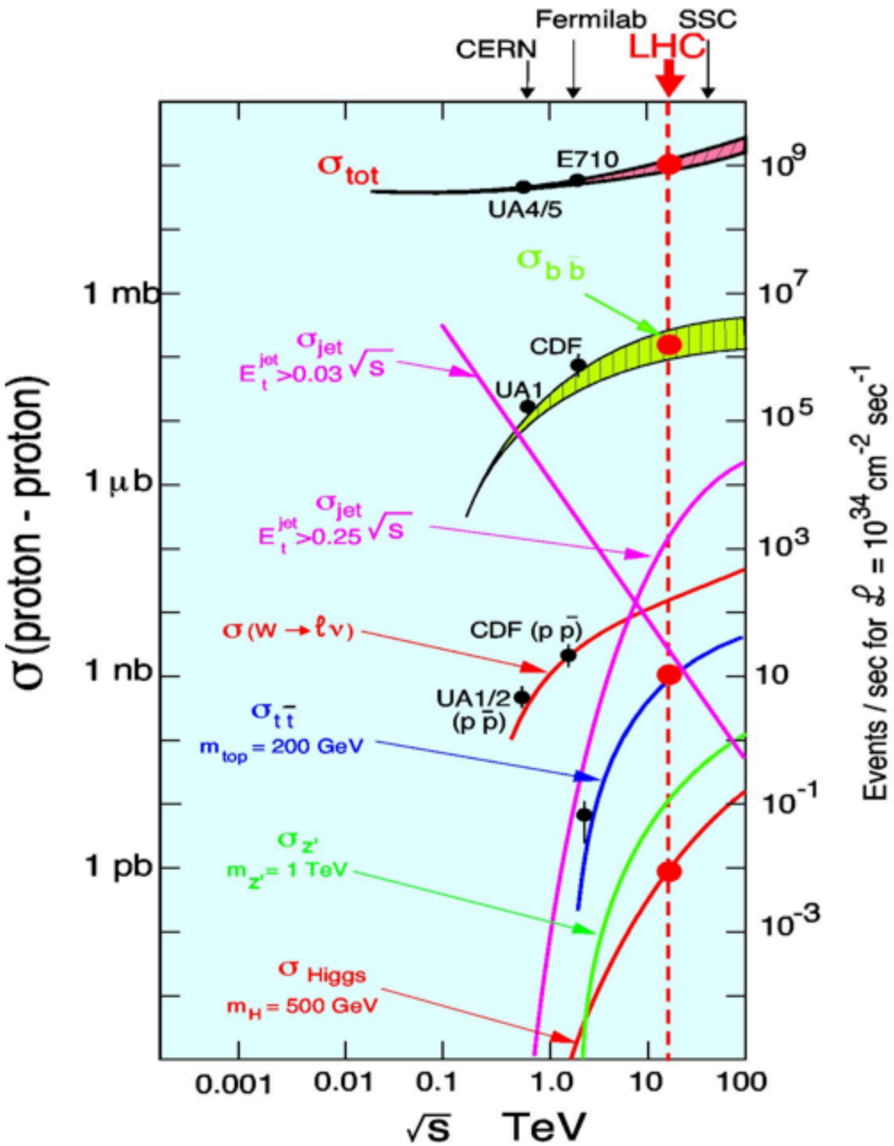
Number of particle bunches times numbers of particles in each bunch, for each beam

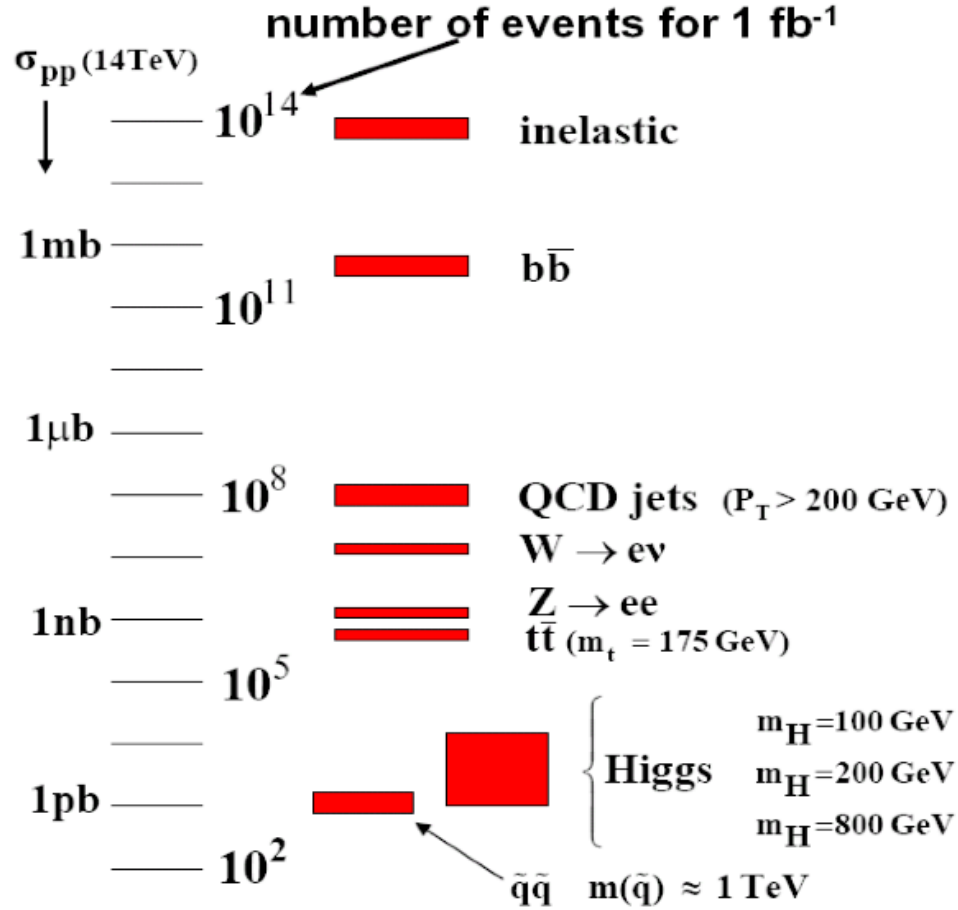
~ cross-sectional size of the beams

units are cm$^{-2}$s$^{-1}$

**Instantaneous production rate for any process is $N = \mathcal{L}\,\sigma$**

# Production cross-sections at the LHC



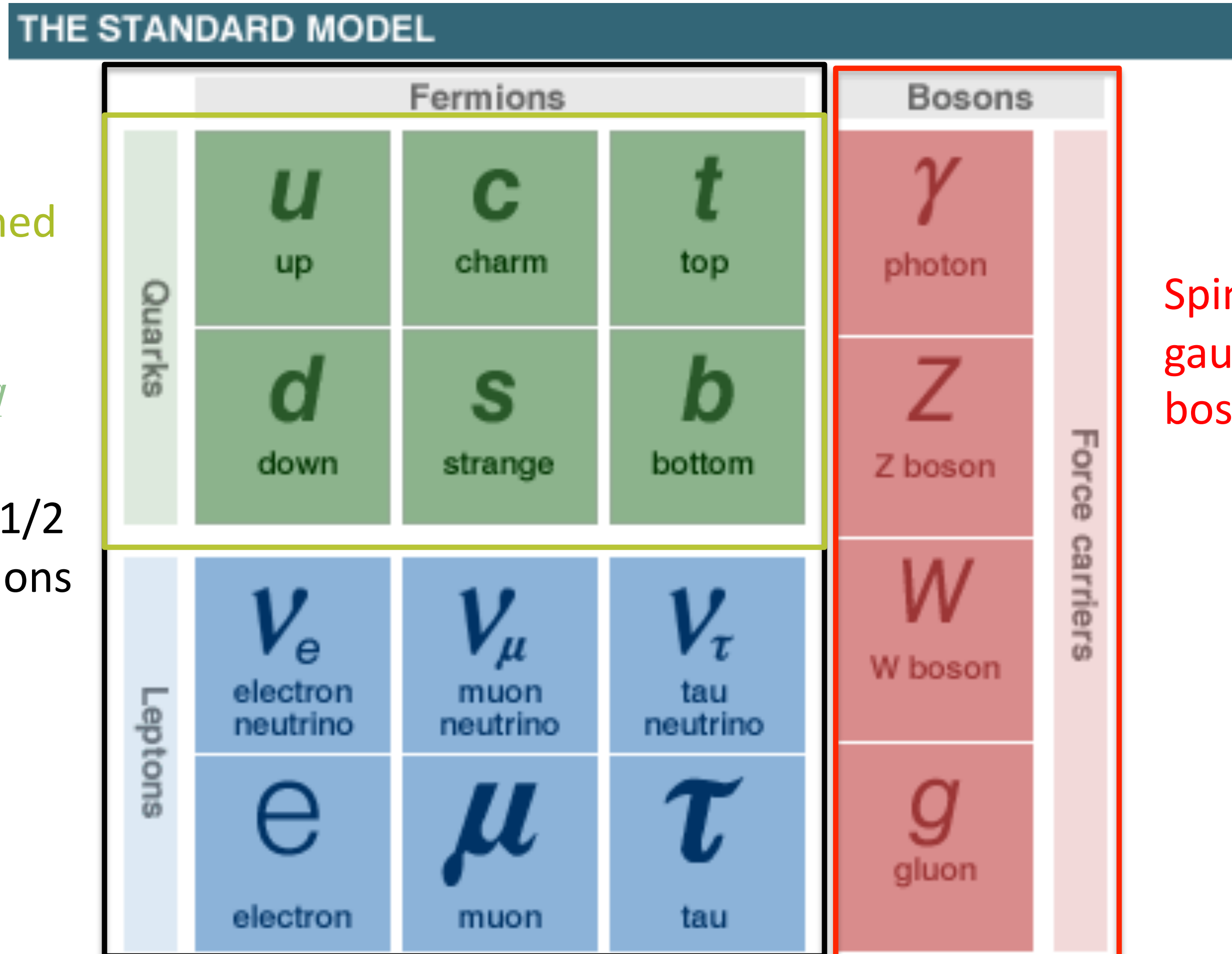

**Goal for 2010-11 run is 1 fb$^{-1}$**

**LHC goal is several hundred fb$^{-1}$**

# The Standard Model of Particle Physics

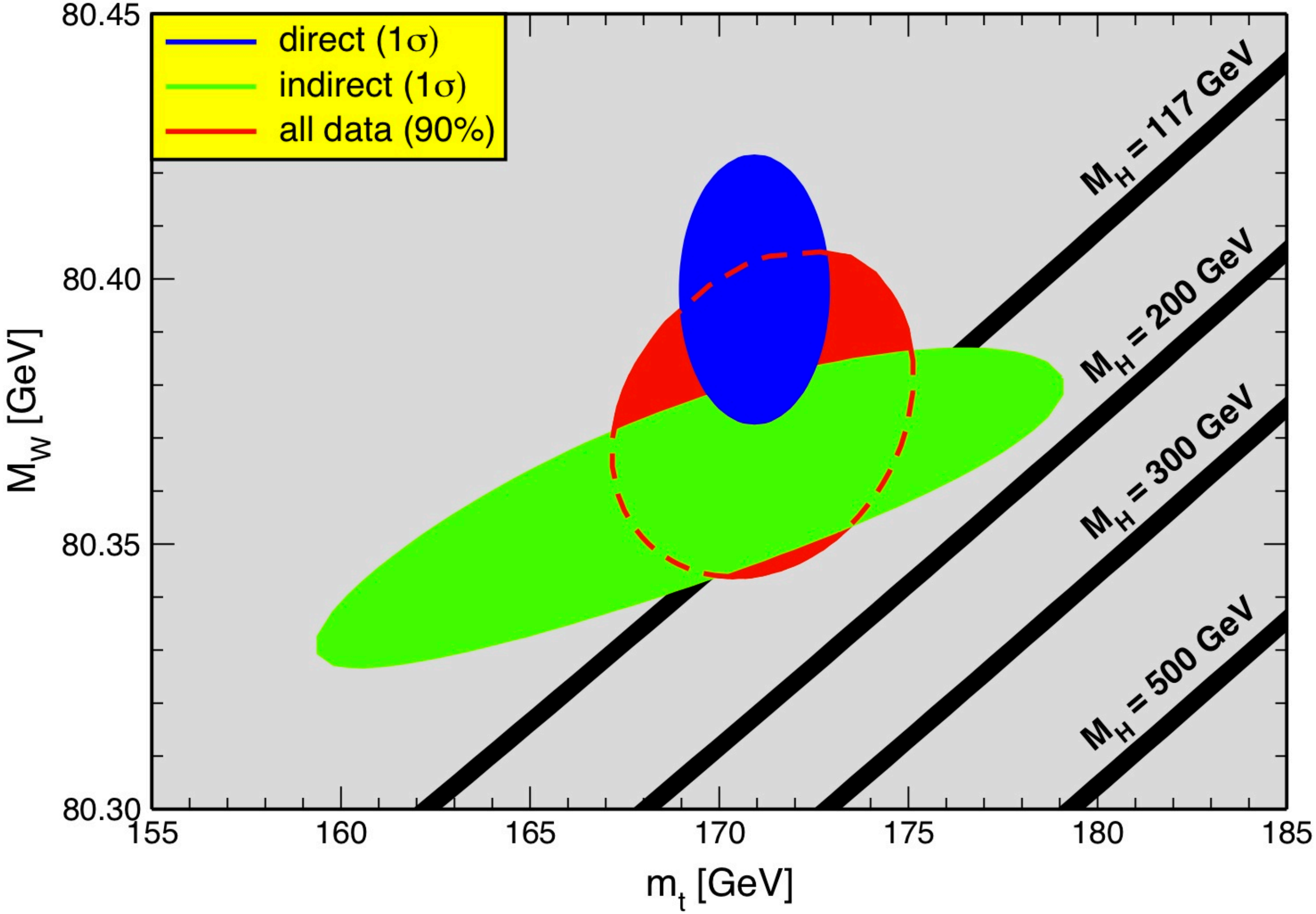
Hadrons formed by quarks:
Mesons $q\bar{q}$
Baryons $qqq$

Spin-1/2 fermions




Spin-1 gauge bosons

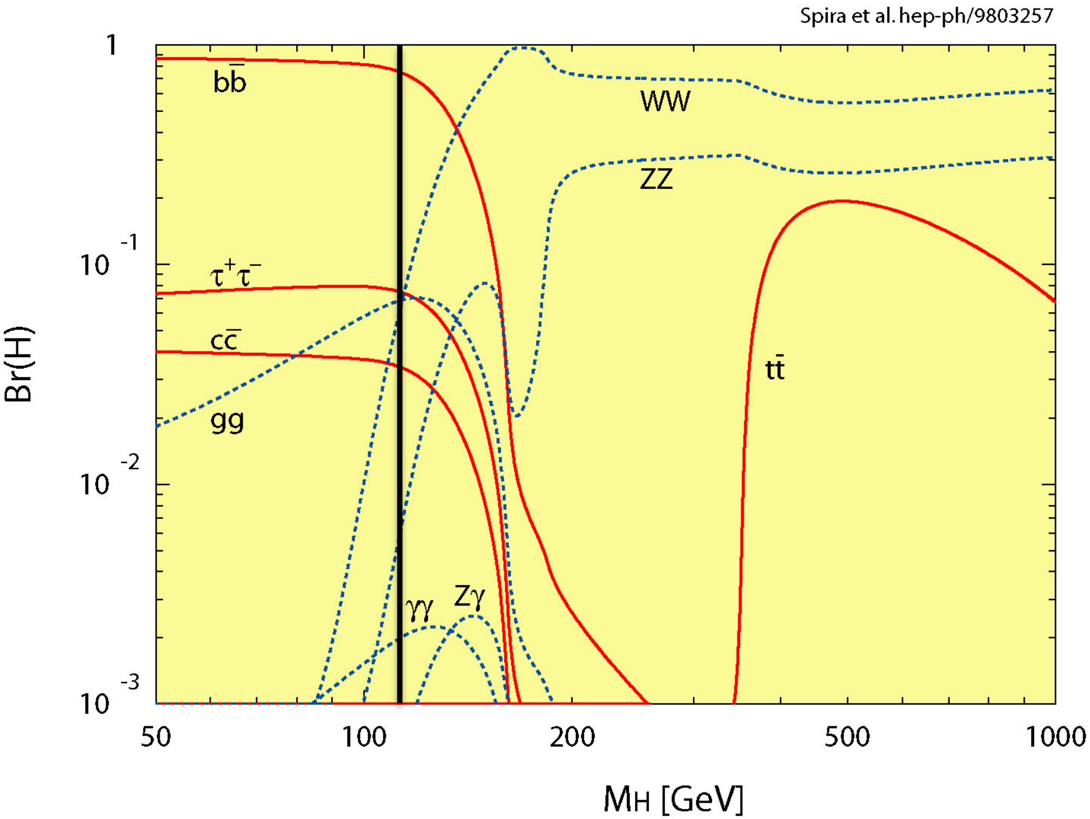
# Status of the Standard Model Higgs Boson




**Precision electroweak measurements favour light Higgs**

**Direct searches at LEP yield no Higgs signal: limit > 114 GeV @ 95% CL**

# Higgs Boson Branching Fractions vs $M_H$




In terms of discovery potential, $M_H$ matters a lot.

Low mass is tricky due to huge QCD backgrounds.

$H^0 \to b\bar{b}, \tau^+\tau^-, c\bar{c}, gg$ all look like events with QCD jets !!

Cleanest final state has lowest rate:

$$H^0 \to \gamma\gamma$$

Calculate the invariant mass of the system:

$$M_{\gamma_1\gamma_2} = \frac{1}{c}\sqrt{2E_1E_2\left(1-\cos\theta_{12}\right)}$$

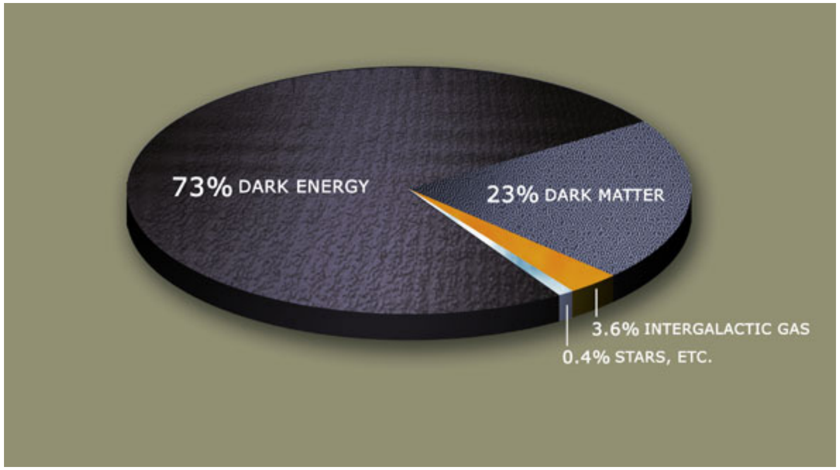
For good resolution on $M_{\gamma\gamma}$, need good resolution on both the energies and directions of the two photons.

# Missing Transverse Energy

- Many BSM theories predict stable massive weakly interacting particles with masses of at least 100 GeV.

- e.g. LSP of Supersymmetric theories (Cold Dark Matter).

- At LHC sensitive only to the missing energy in the transverse plane:



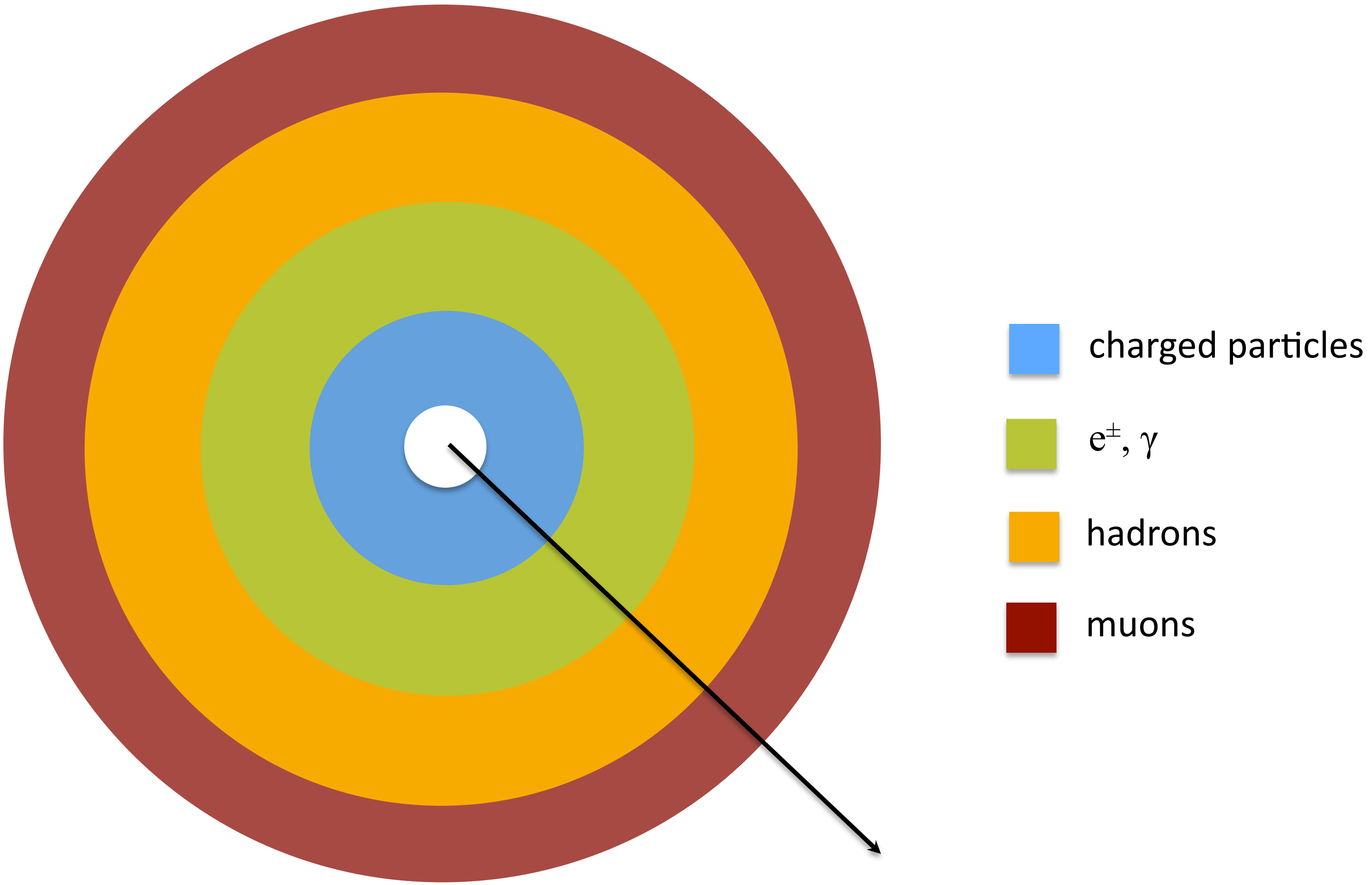

$$E_x^{miss} = \sum_i E_i \sin\theta_i \cos\phi_i$$

$$E_y^{miss} = \sum_i E_i \sin\theta_i \sin\phi_i$$

$$E_T^{miss} = \sqrt{\left(E_x^{miss}\right)^2 + \left(E_y^{miss}\right)^2}$$

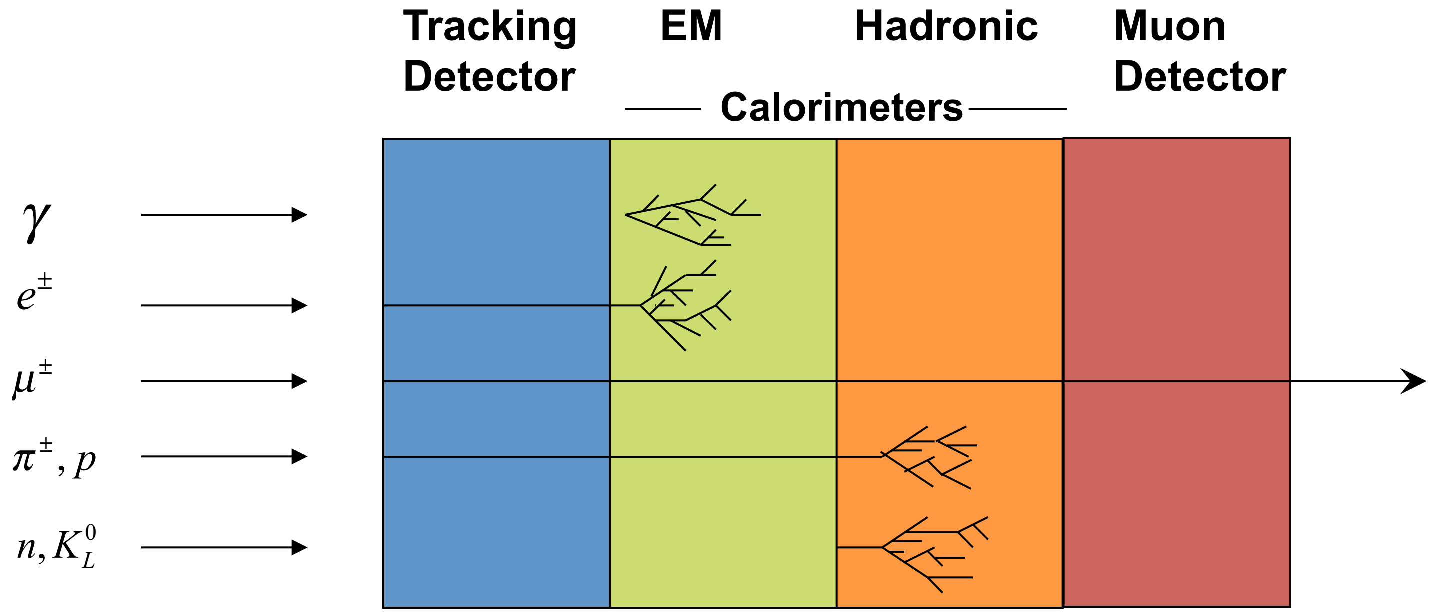
Want the sum to be over all particles produced in the event. In practice, this means summing over all calorimeter cells, or all cells associated with reconstructed objects (clusters)

# Collider Detectors (1)



# Collider Detectors (2)

Events are reconstructed based on particles stable enough to be detected (e.g. to make it to the instrumented region of the detector, staring at $r$ = 5cm)




$e^{\pm}, \gamma$

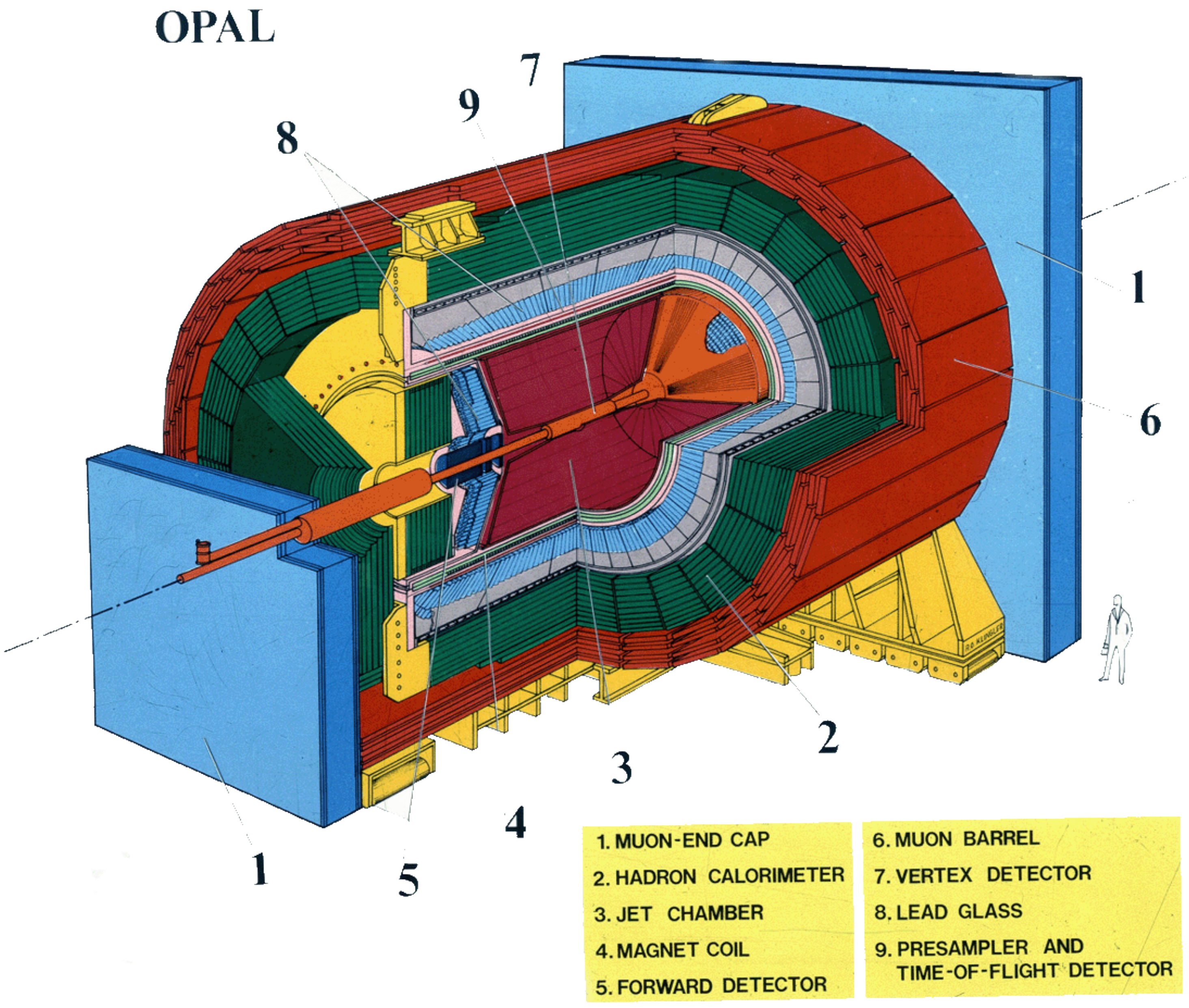
muons

Charged particle momentum, particle ID, vertex reconstruction

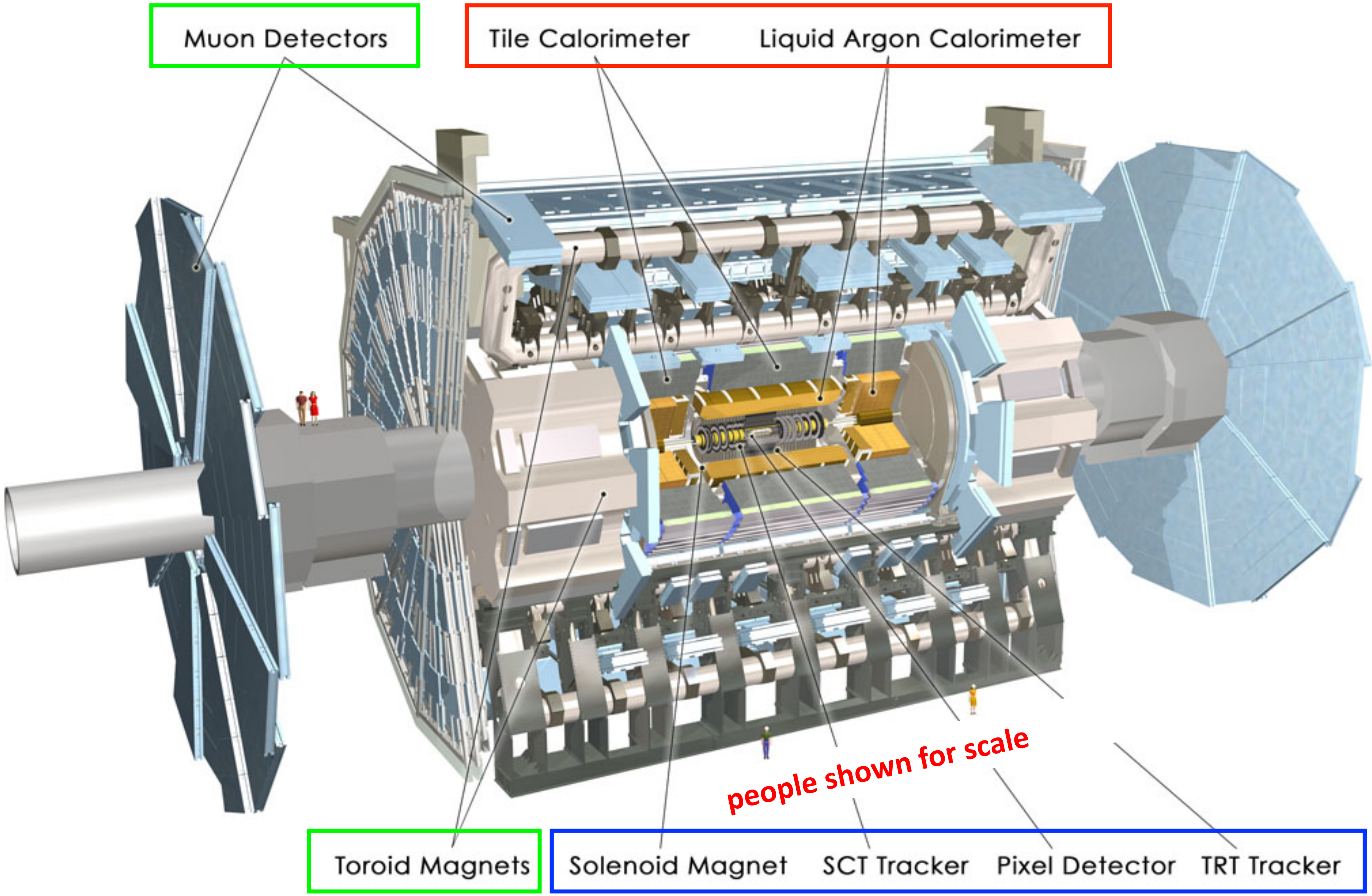
---------Hadrons, jets-------------

Measurement of energies of particles (charged and neutral) or jets

# The OPAL Detector at the Large Electron Positron Collider



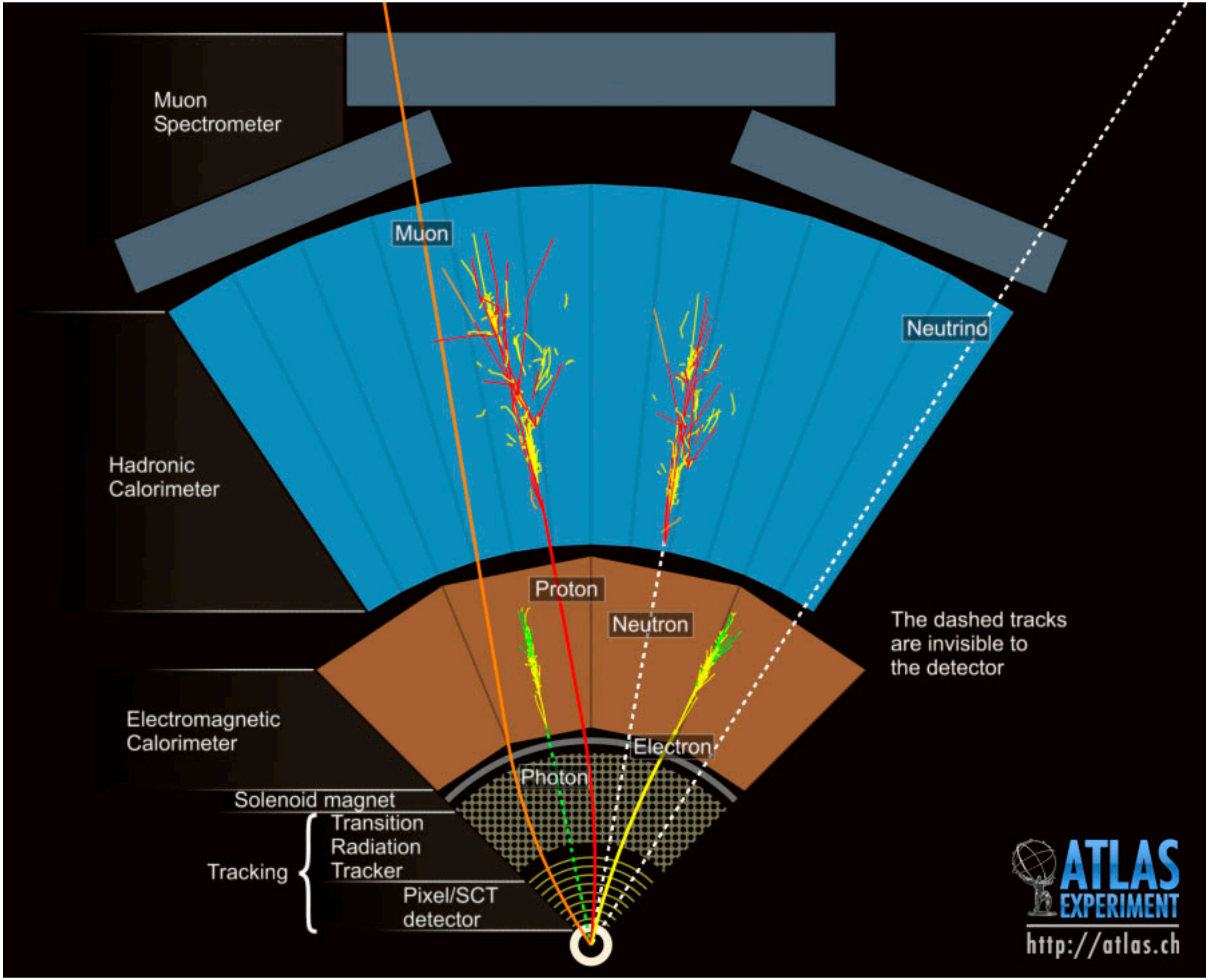
# The ATLAS Detector



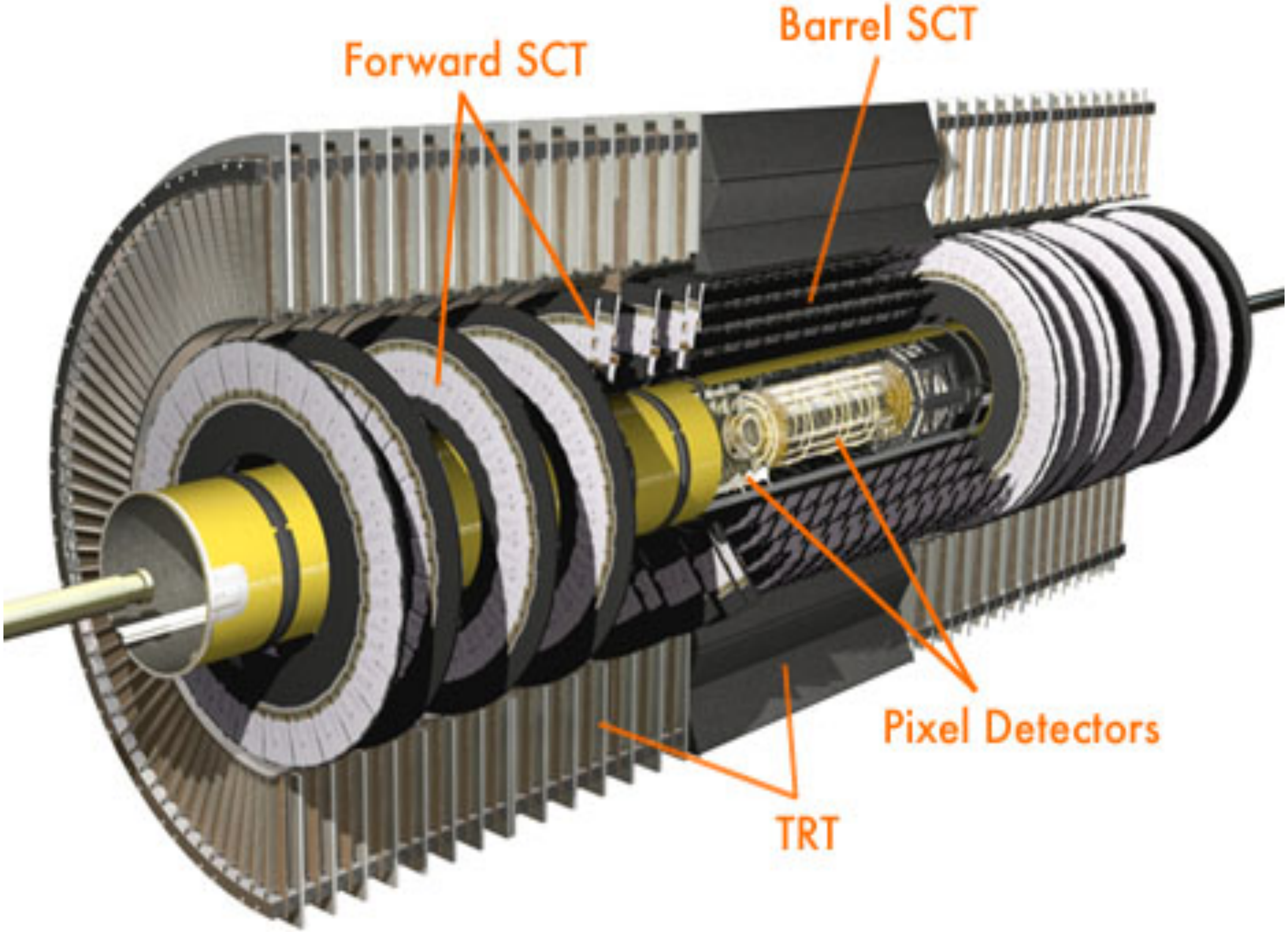
# Detector Status

| Subdetector | Number of Channels | Approximate Operational Fraction |
|---|---|---|
| Pixels | 80 M | 97.5% |
| SCT Silicon Strips | 6.3 M | 99.3% |
| TRT Transition Radiation Tracker | 350 k | 98.2% |
| LAr EM Calorimeter | 170 k | 98.6% |
| Tile calorimeter | 9800 | 98.0% |
| Hadronic endcap LAr calorimeter | 5600 | 99.9% |
| Forward LAr calorimeter | 3500 | 100% |
| LVL1 Calo trigger | 7160 | 99.5% |
| MDT Muon Drift Tubes | 350 k | 99.7% |
| CSC Cathode Strip Chambers | 31 k | 98.5% |
| RPC Barrel Muon Trigger | 370 k | 99.5% |
| TGC Endcap Muon Trigger | 320 k | 100% |

# ATLAS Event Slice

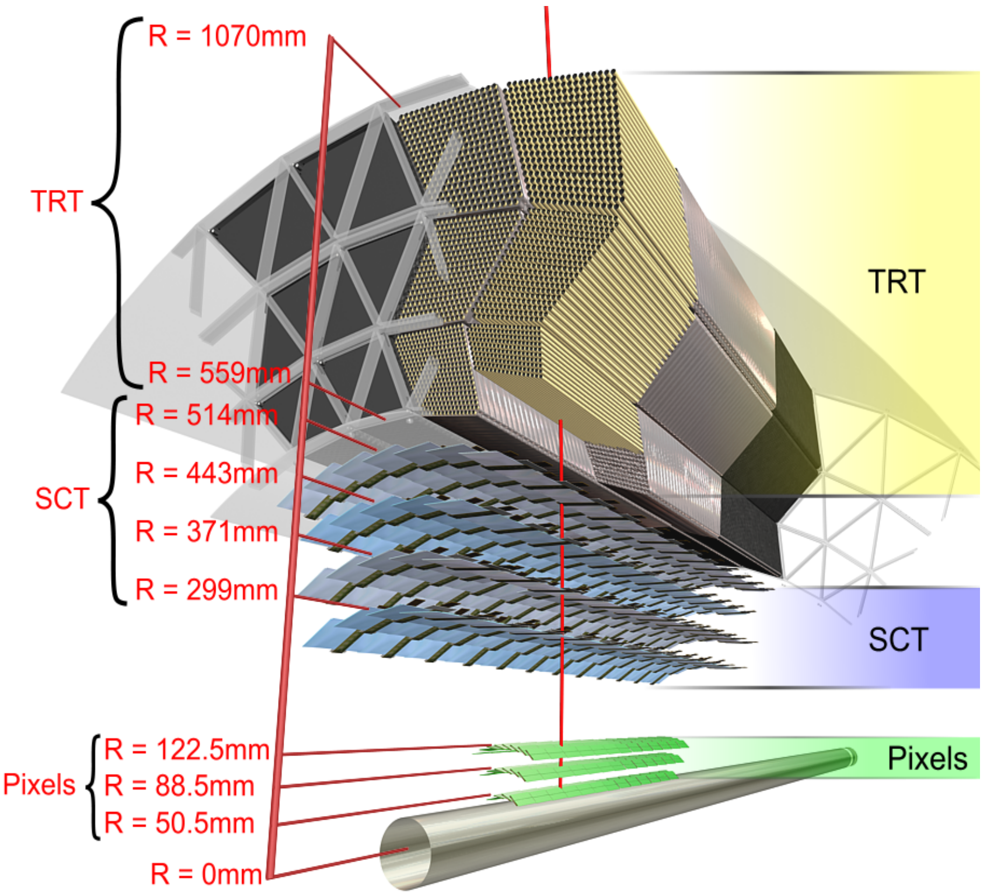


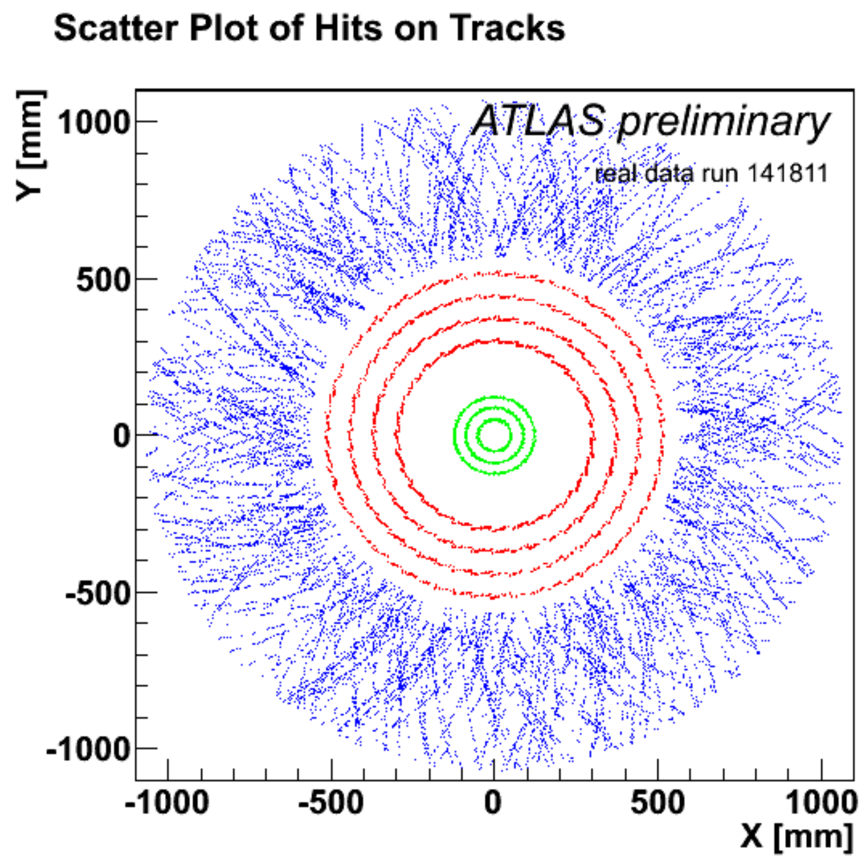
# The ATLAS Inner Detector




Located within 2T solenoidal magnetic field

# The ATLAS Inner Detector



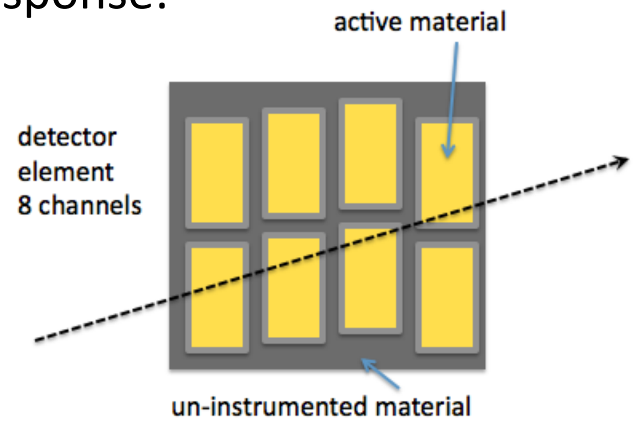



# Simulated Events in ATLAS

Simulation results shown in this talk rely on detailed modeling of:

– The physics of pp collisions at these energies (theory community)

– A very detailed simulation of the detector response:



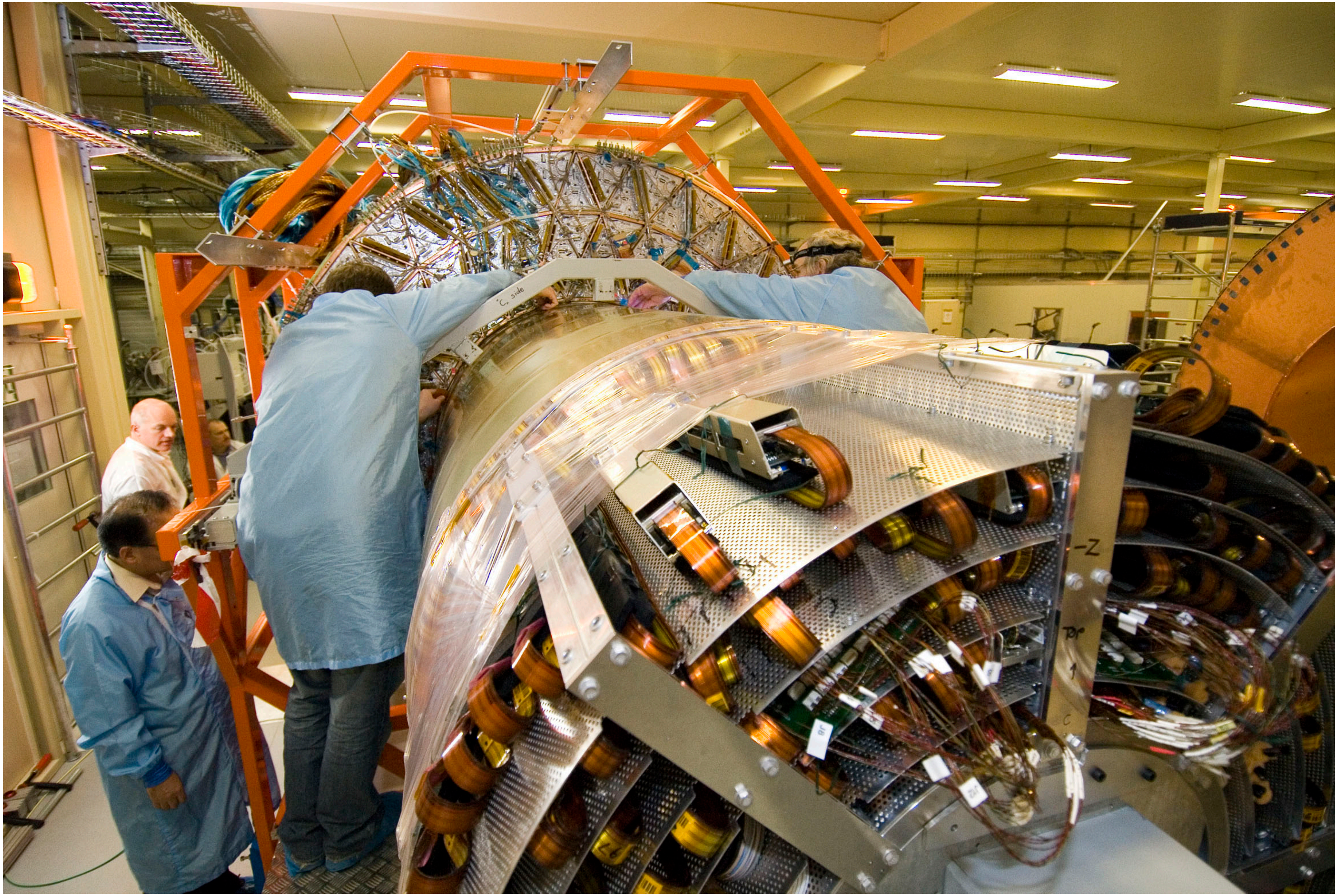

- Position/alignment of detector elements
- Energy deposits in active and inactive regions
- Modeling of electronic readout, including noise and bad / fault channels
- Magnetic field maps
- etc………

– At this stage, this is how we investigate our understanding of the detector performance

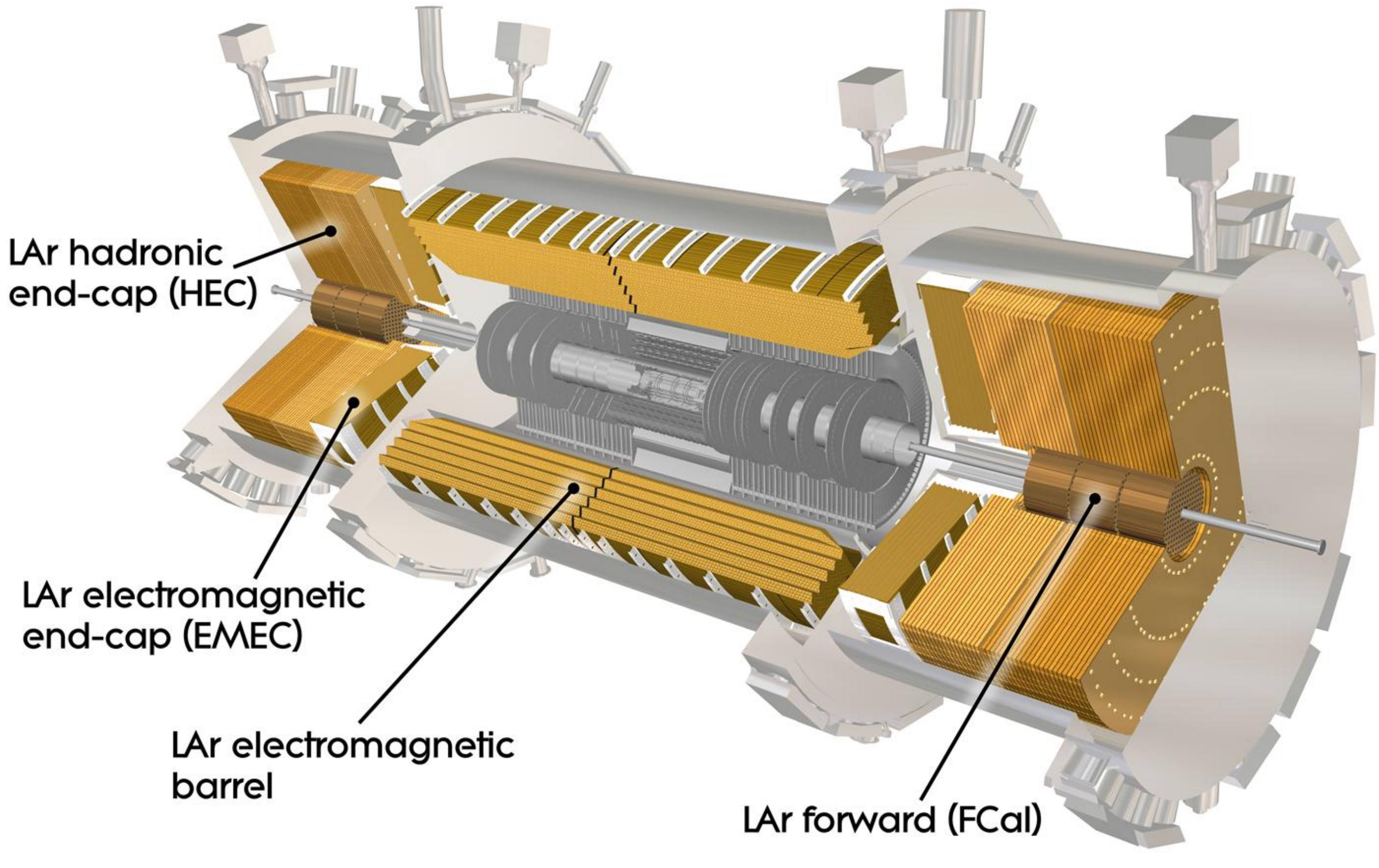
– Needs lots and lots of computing power

**ATLAS Group part of SCINET: actively using these resources for data analysis / simulations**

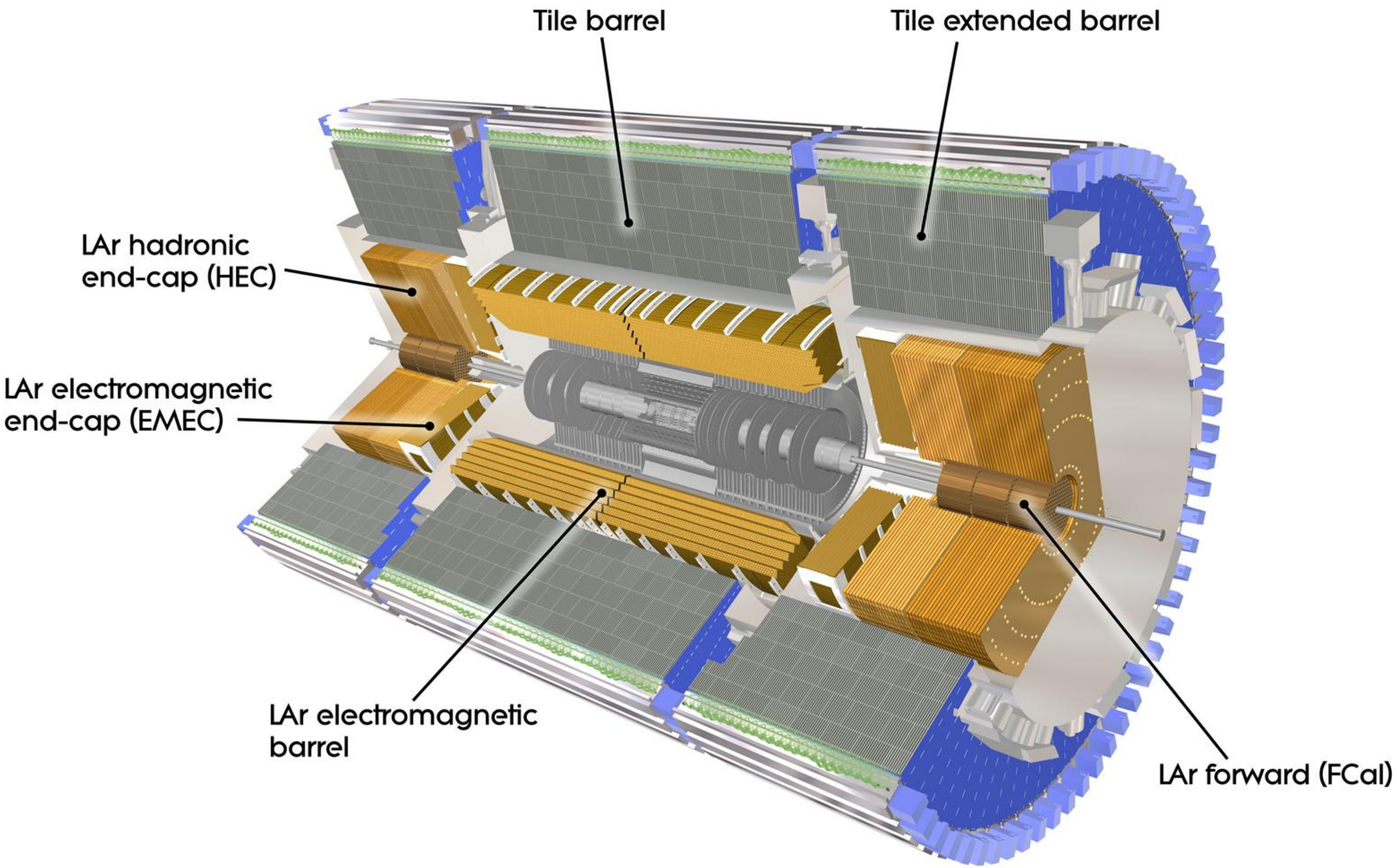
# Installation of SCT into TRT



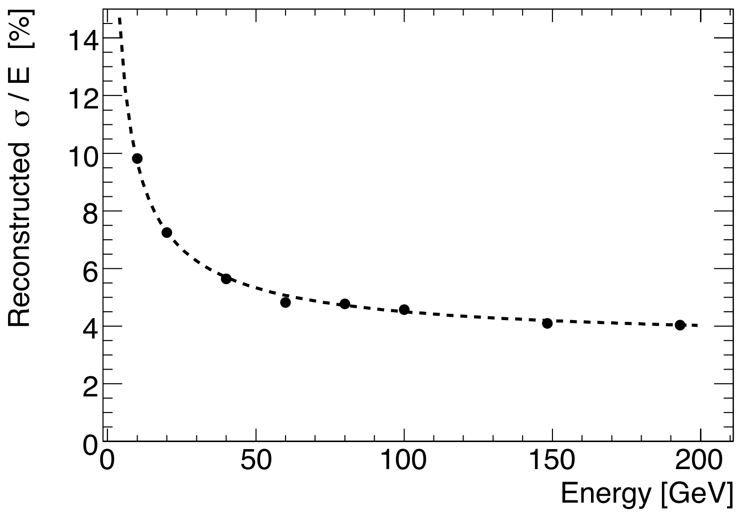
# The Liquid Argon Calorimeter



# The ATLAS Calorimeter (Liquid Argon + Tile)



# Calorimeter Energy Resolution (briefly)




$$\frac{\sigma}{E} = \frac{a}{E} \oplus \frac{b}{\sqrt{E}} \oplus c$$

- $a$ → noise term
- $b/\sqrt{E}$ → sampling term
- $c$ → constant term

---

## sampling term

- Choice of absorber
- Choice of active material
- Thickness of sampling layers
- …..

**Typically most important in 10-100 GeV energy range**

## constant term

- **depth of detector** $(X_0, \lambda_I)$
- **detector non-uniformities**
- **cracks**
- **dead material …….**

**Dominates at high energy**

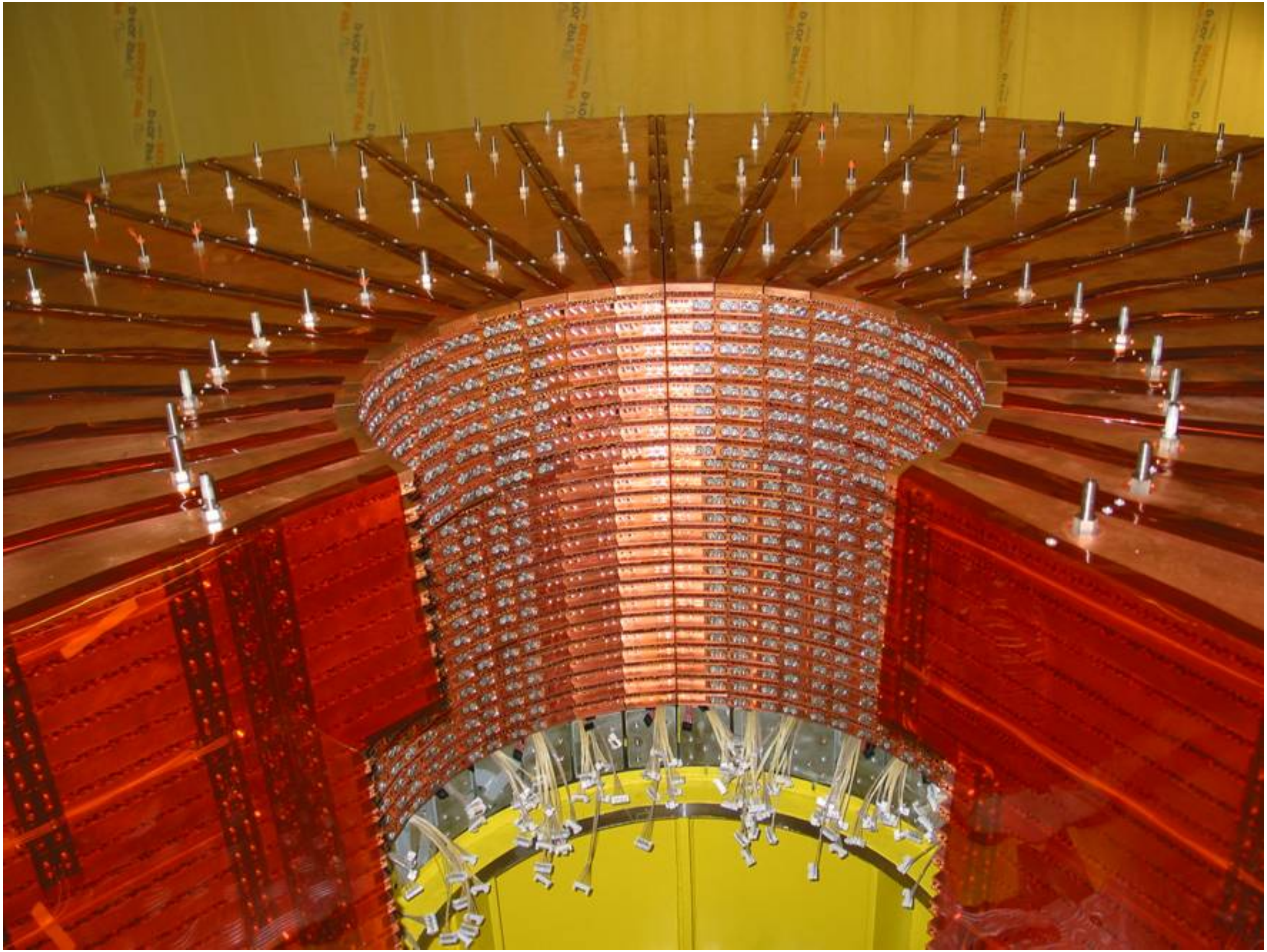
## noise term

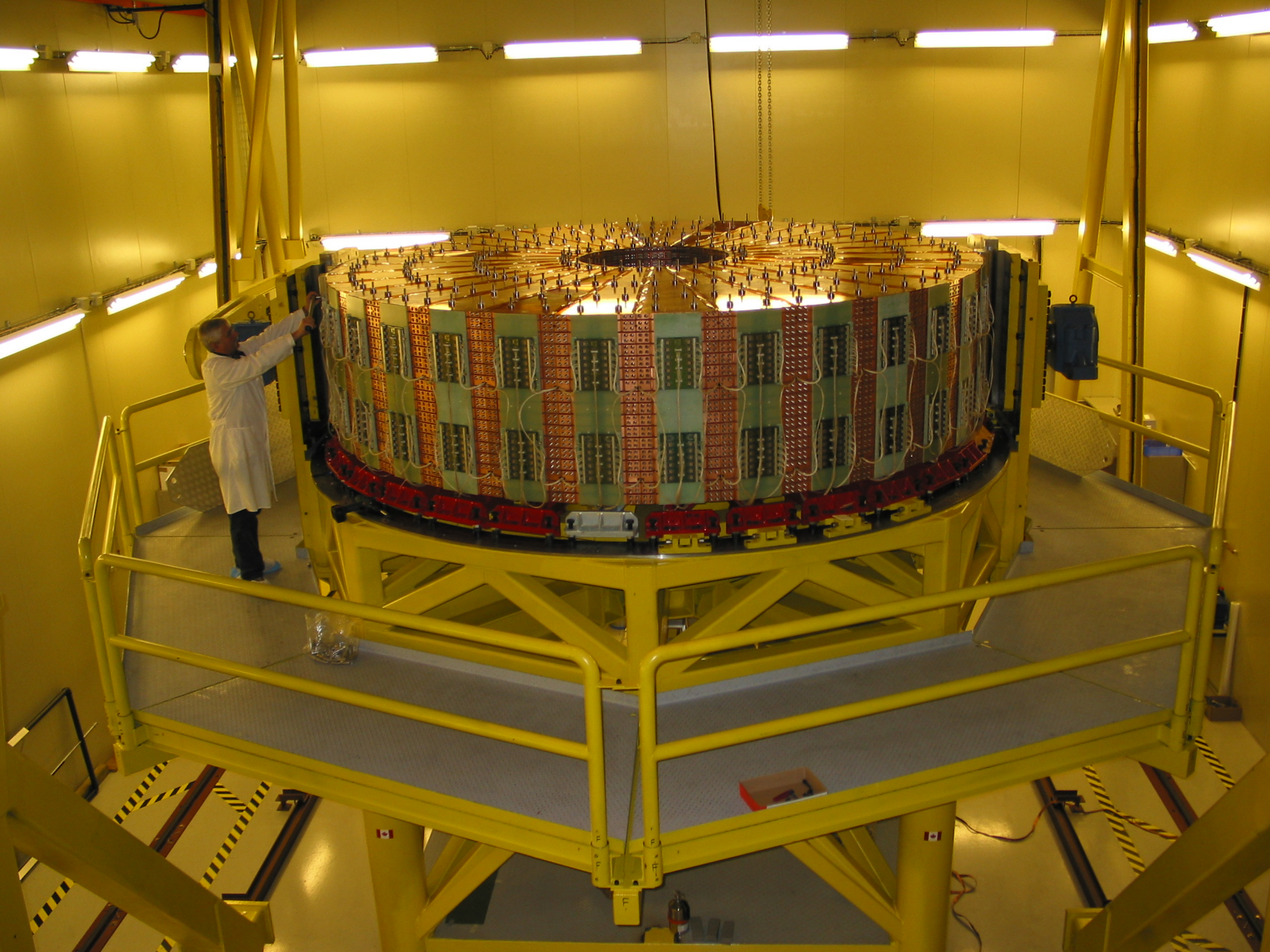
- **electronic noise**
- **signal pileup**

**Dominates at low energy**

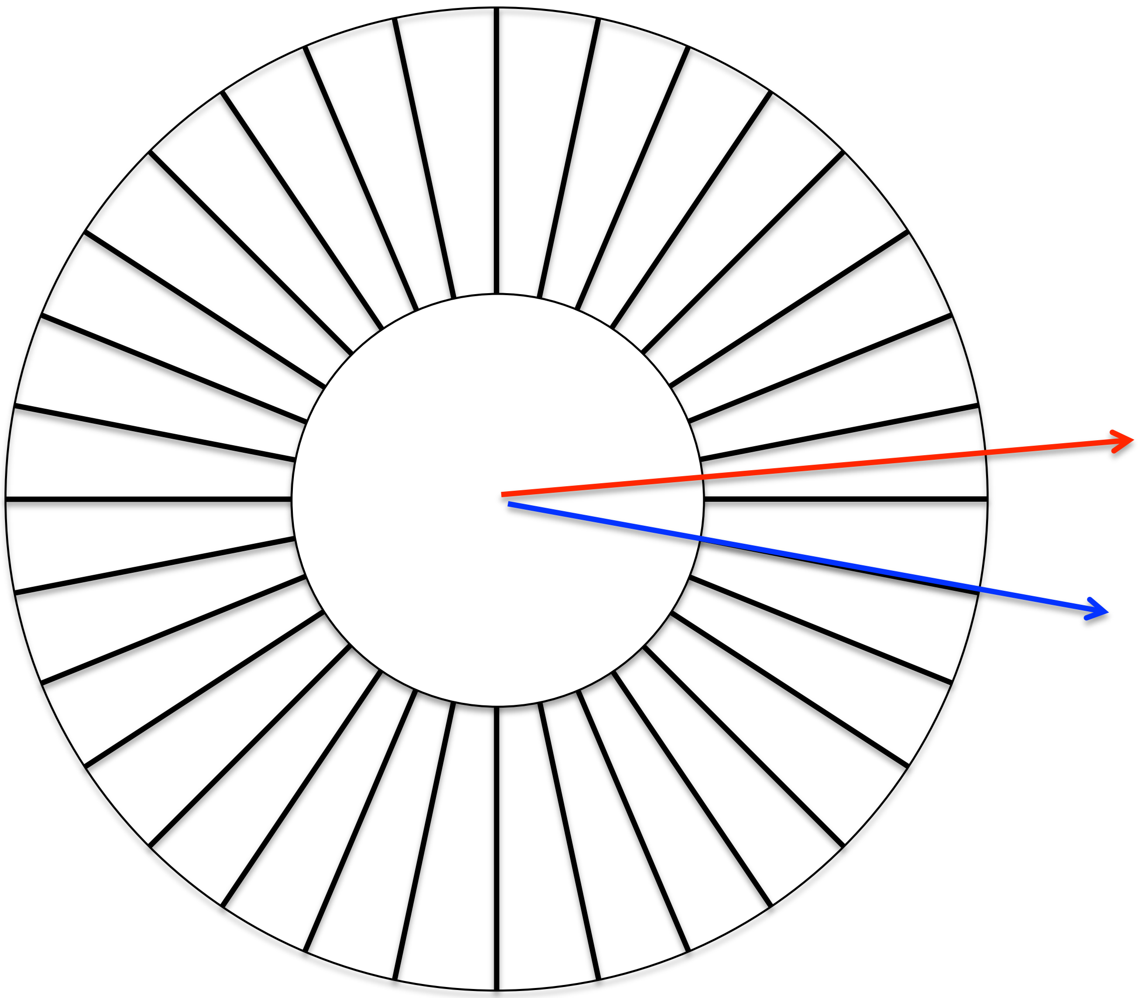

SIMIC spa
CAMERANIA
A Side

# ATLAS Hadronic Endcap Calorimeter





# Uniformity of Calorimeter Response



Tile Calorimeter built from 64 azimuthal slices (steel and scintillating tile)

Hadronic Endcap Calorimeter built from 32 azimuthal slices (copper and liquid argon)

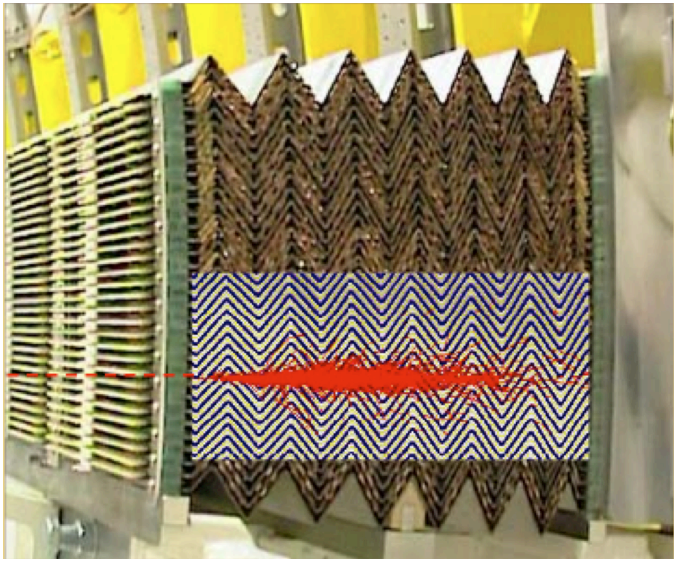
Good energy containment in middle of module

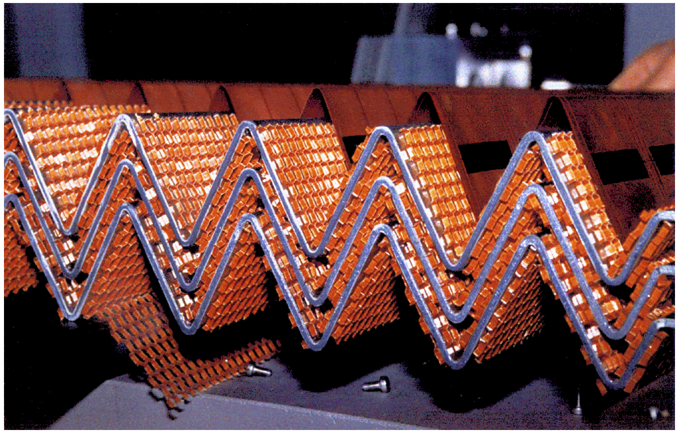
Some losses for energy deposits near module boundaries

Presence of un-instrumented regions contributes to constant term in the resolution function.

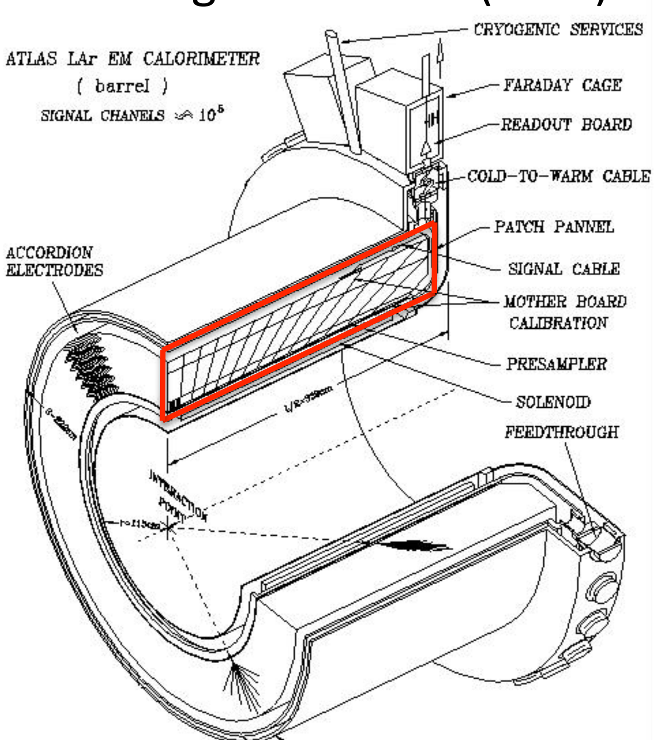
Want to avoid this problem for precision EM calorimetry (in order to minimize the resolutions at high-energies, e.g. the constant term: required for $H^0 \to \gamma\gamma$ ).

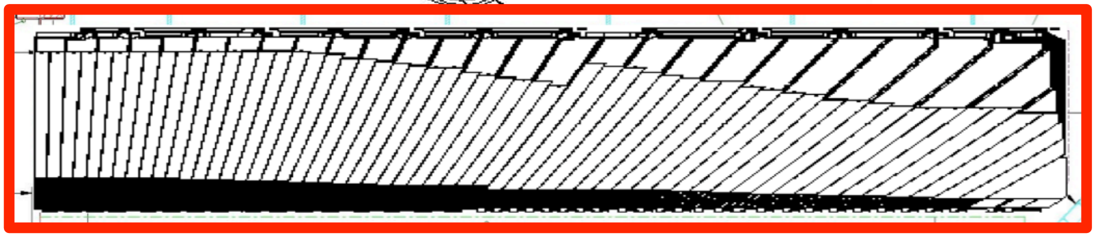
# ATLAS EM Accordion Calorimeter





Electromagnetic Barrel (EMB)

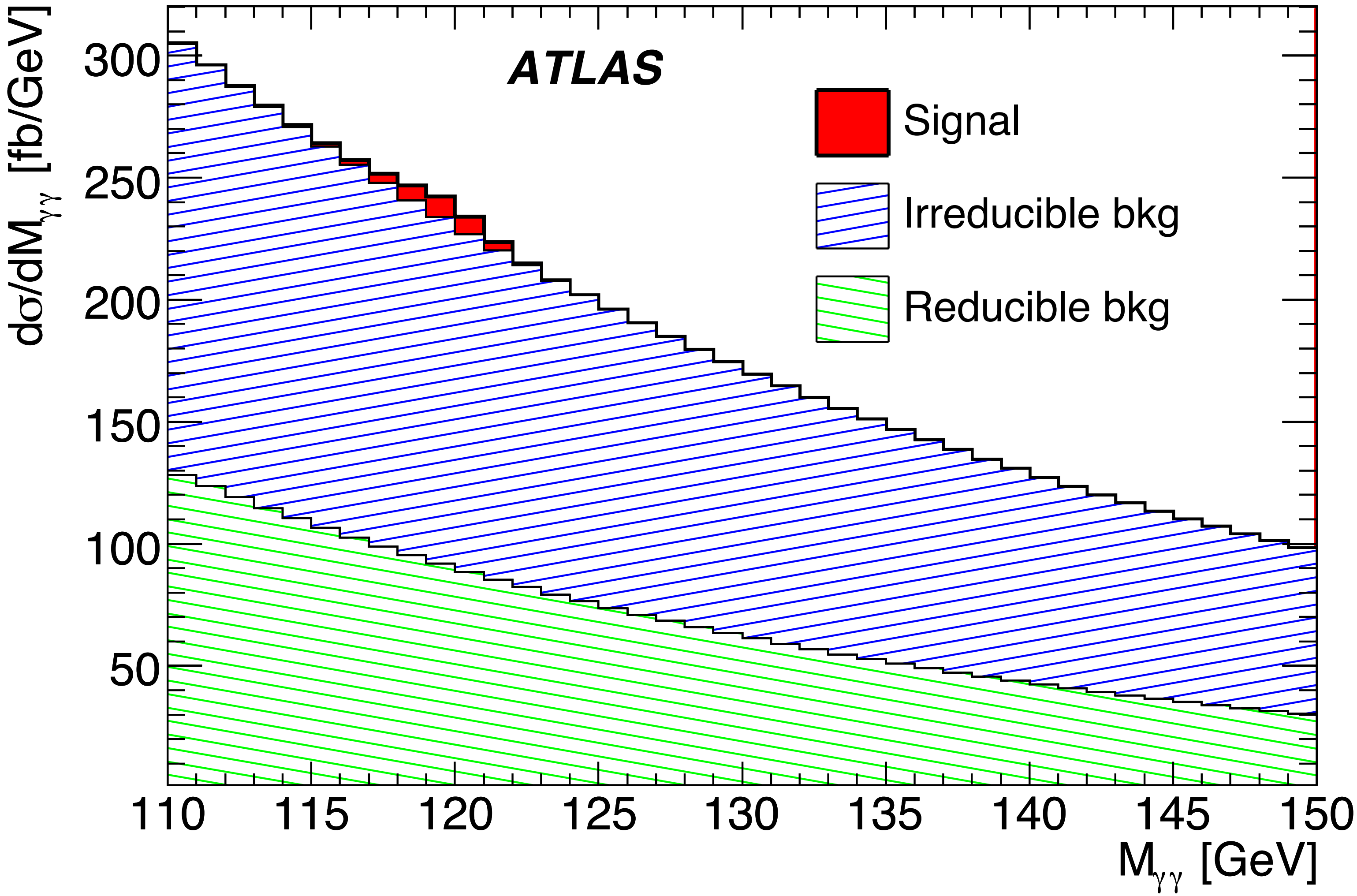


Very fine granularity in first layer

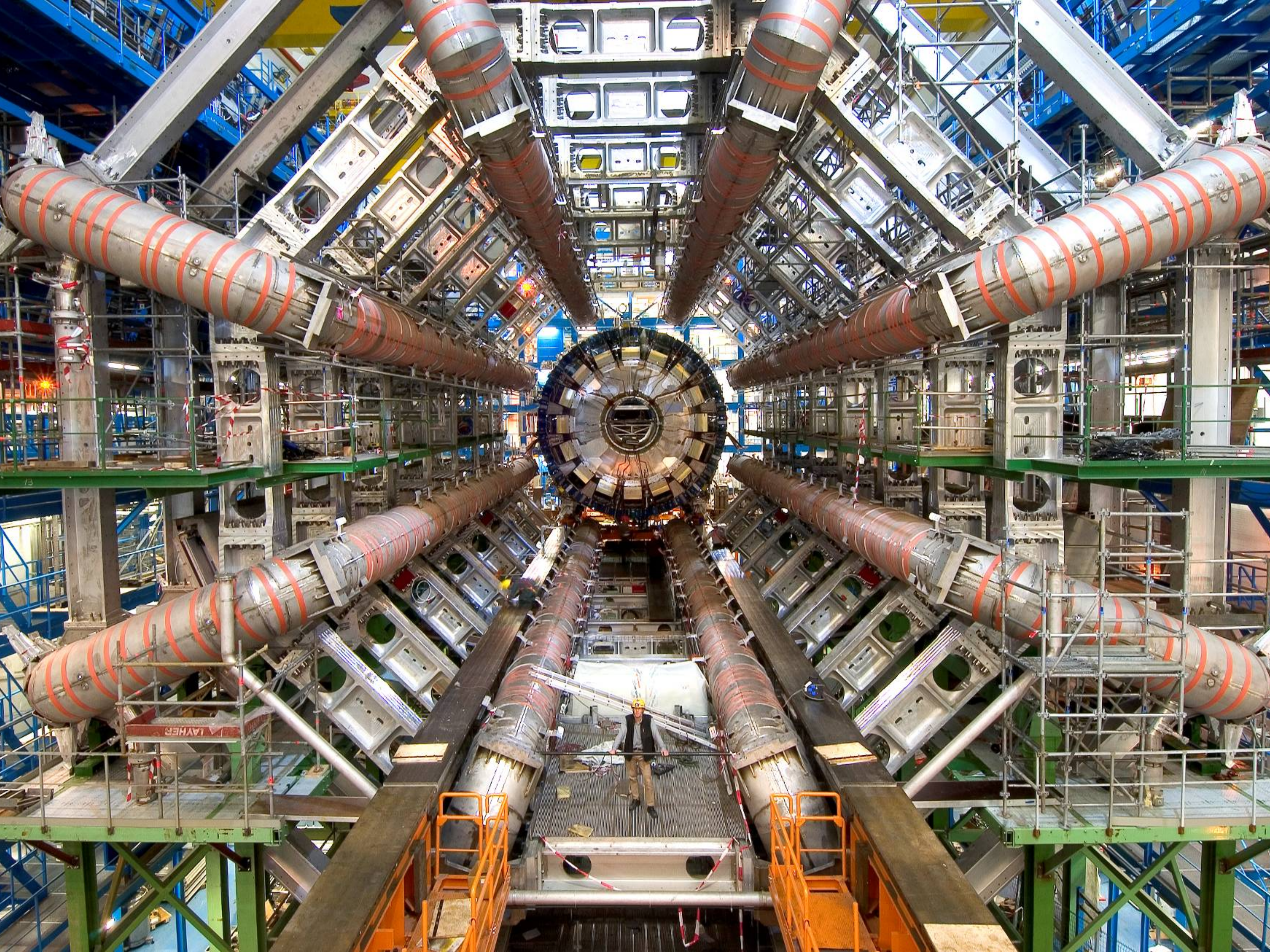
“Accordion” design eliminates azimuthal cracks to improve uniformity of the response

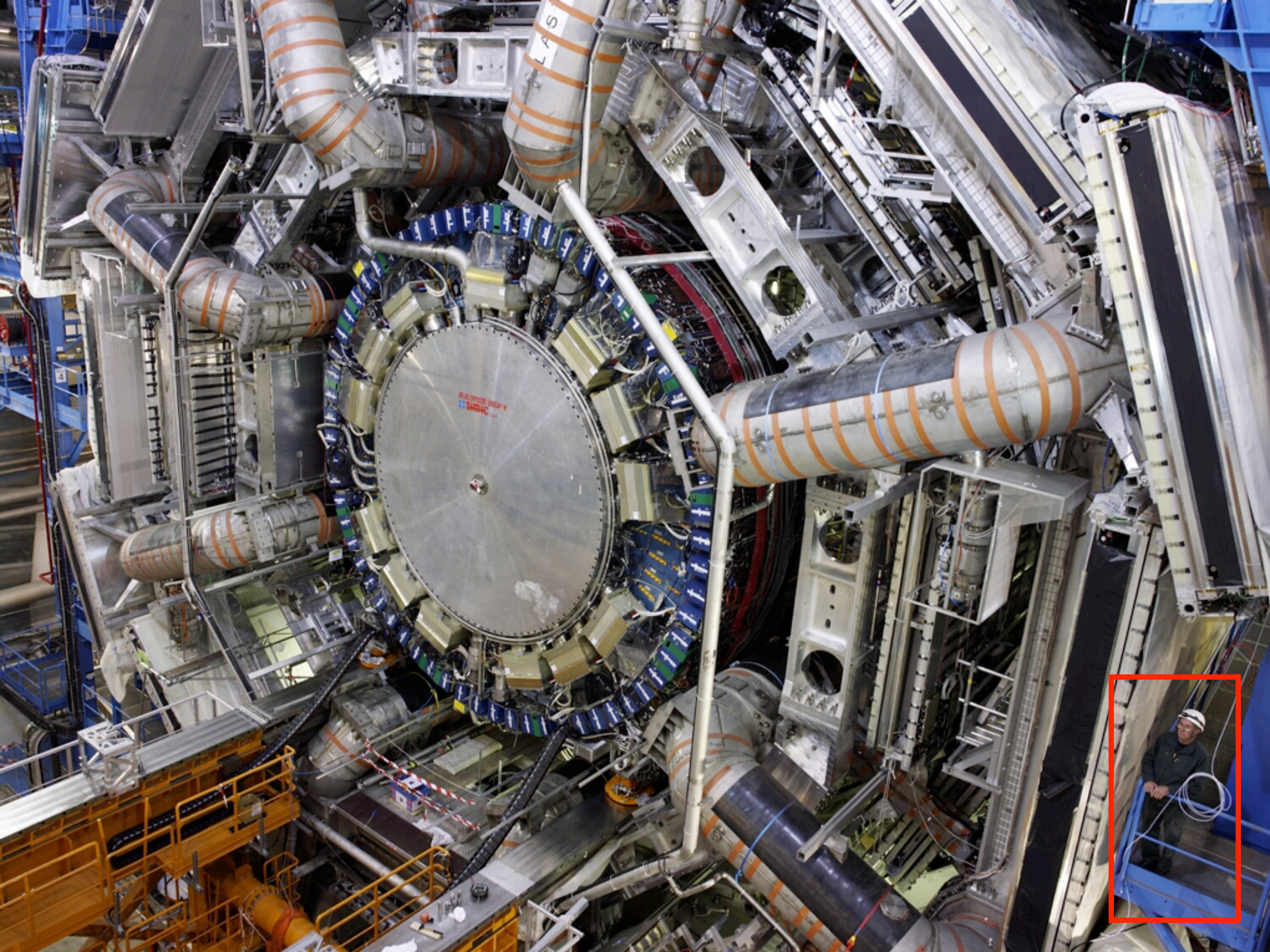
# Higgs to Gamma Gamma in Simulation




**Mass resolution clearly critical**

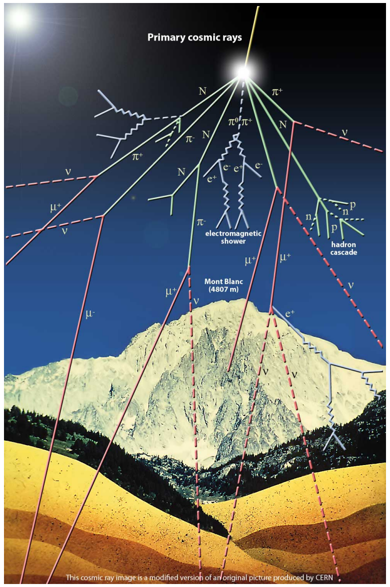
# ATLAS Barrel Cryostat (October 2004)

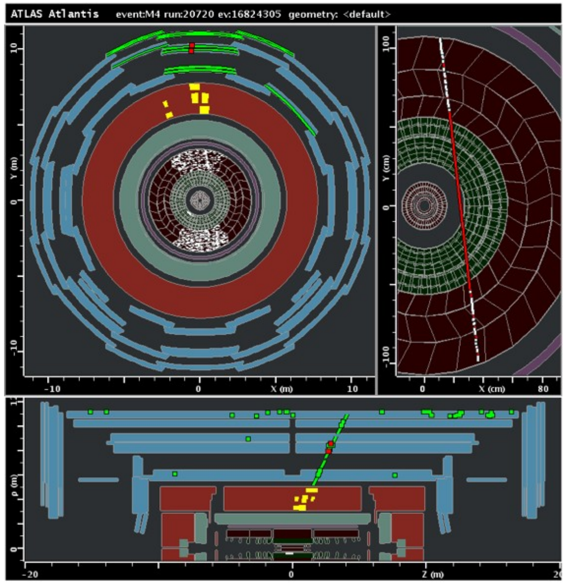



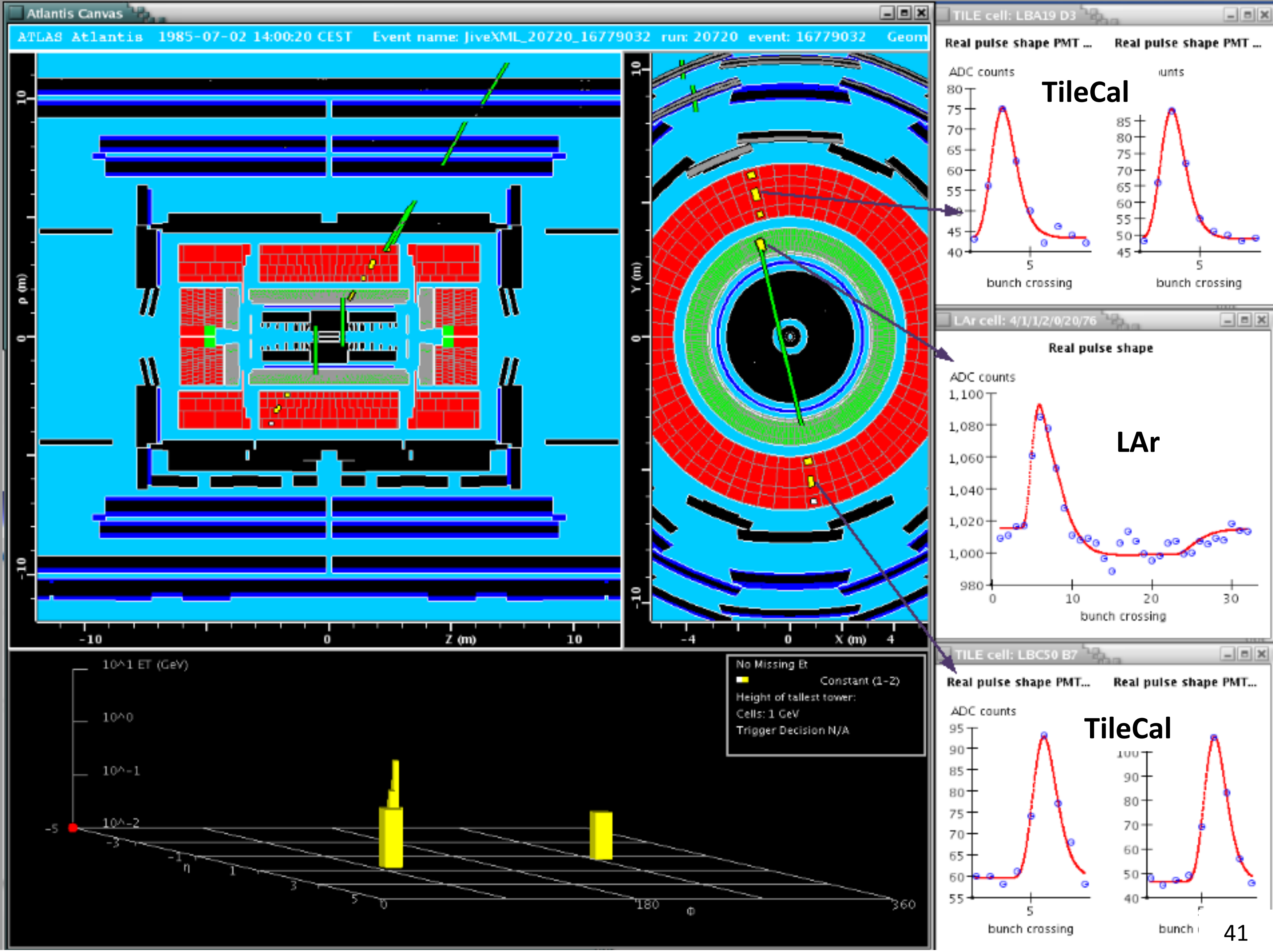


# Commissioning with Cosmic Ray Events

- Cosmic ray data taking has been extensively used for detector commissioning for some years.
- Full detector runs in 2008, 2009. Useful for
  - Exercising the data acquisition, training of shifters
  - Exercising reconstruction software, data handling infrastructure
  - Many detector performance studies (pulse shapes, timing studies, noise)
  - Development of cosmic ray event rejection criteria (for physics running)




Atlantis Canvas
ATLAS Atlantis 1985-07-02 14:00:20 CEST Event name: JiveXML_20720_16779032 run: 20720 event: 16779032
ρ (m)
Z (m)
Y (m)
X (m)
10^1 ET (GeV)
η
Φ
No Missing Et
Constant (1-2)
Height of tallest tower:
Cells: 1 GeV
Trigger Decision N/A
TILE cell: LBA19 D3
Real pulse shape PMT ...
ADC counts
bunch crossing
TileCal
LAr cell: 4/1/1/2/0/20/76
Real pulse shape
LAr
TILE cell: LBC50 B7
Real pulse shape PMT...
TileCal

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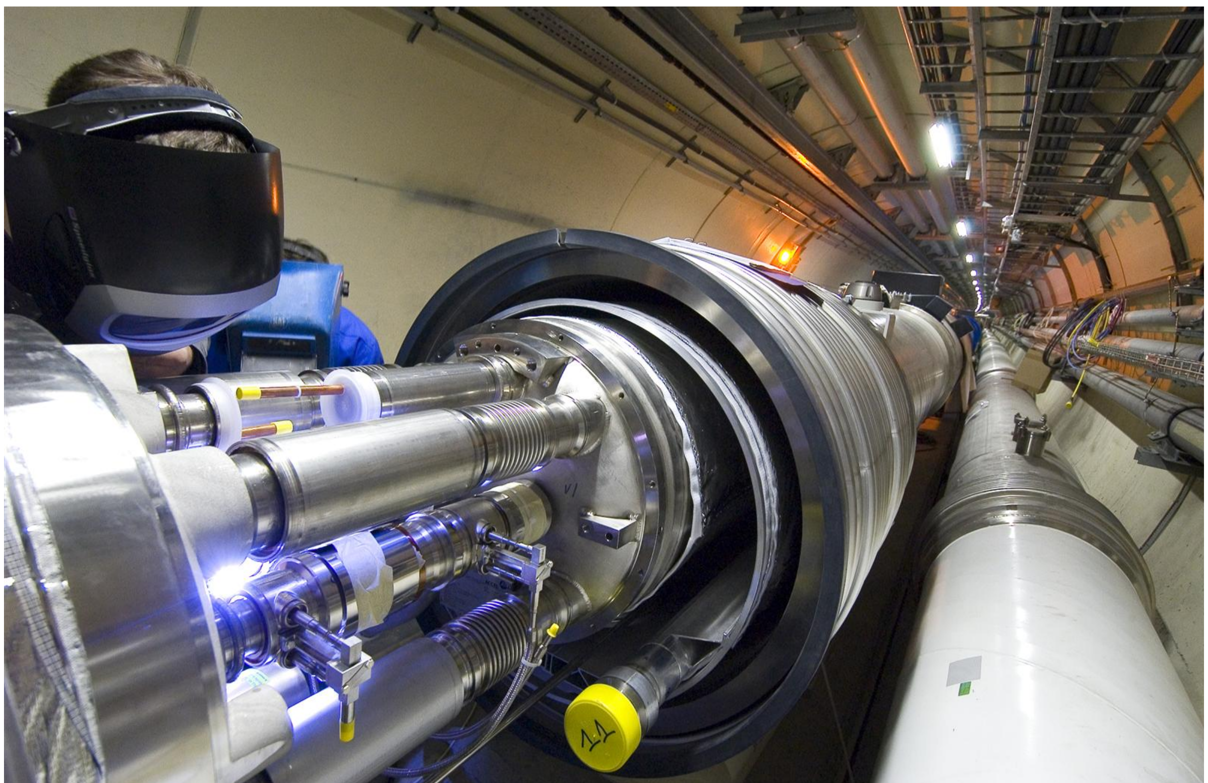
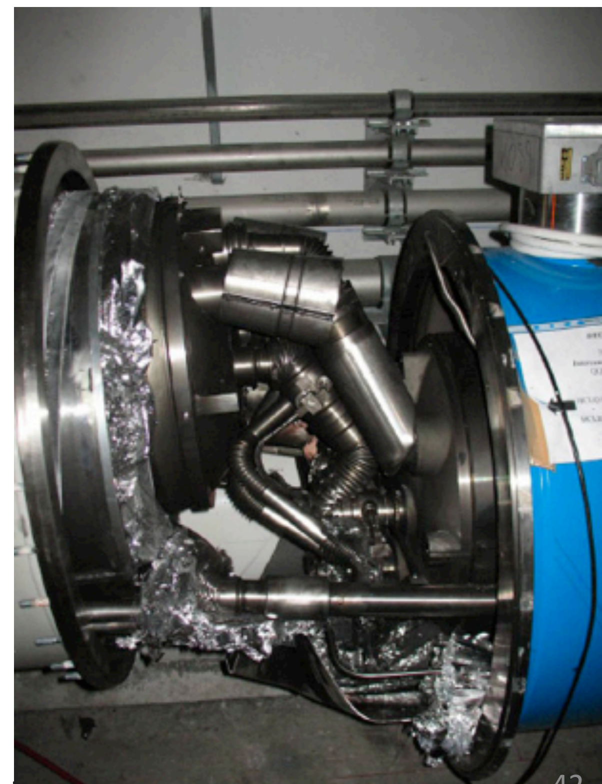
# Electrical Glitch Delays Large Hadron Collider

Monday, September 22, 2008 - 17:49 in Physics & Chemistry

Learn more about: atom smasher glitch delays helium leak superconducting magnets





# LHC Magnet Repairs Completed April 2009

## Final LHC magnet goes underground

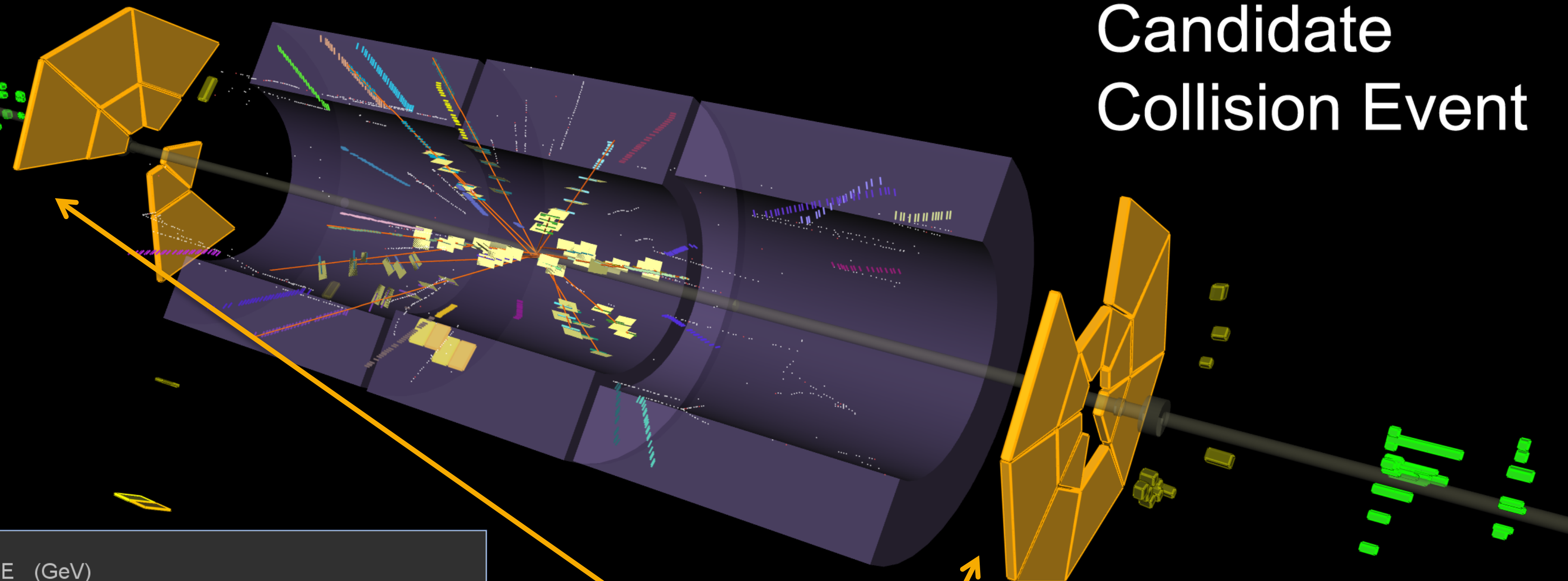
PR06.09
30.04.2009

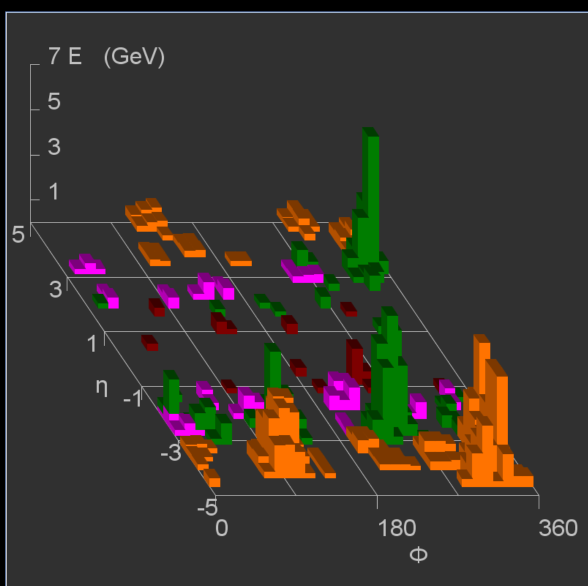
Geneva, 30 April 2009. The 53rd and final replacement magnet for CERN's[1] Large Hadron Collider (LHC) was lowered into the accelerator's tunnel today, marking the end of repair work above ground following the incident in September last year that brought LHC operations to a halt. Underground, the magnets are being interconnected, and new systems installed to prevent similar incidents happening again. The LHC is scheduled to restart in the autumn, and to run continuously until sufficient data have been accumulated for the LHC experiments to announce their first results.

A quadrupole magnet in the LHC tunnel


!!! BEAM AT ATLAS !!!
20-11-09 20:47
14 month long months later

# Nov. 23, 2010: First $\sqrt{s}$ = 900 GeV Collisions in ATLAS



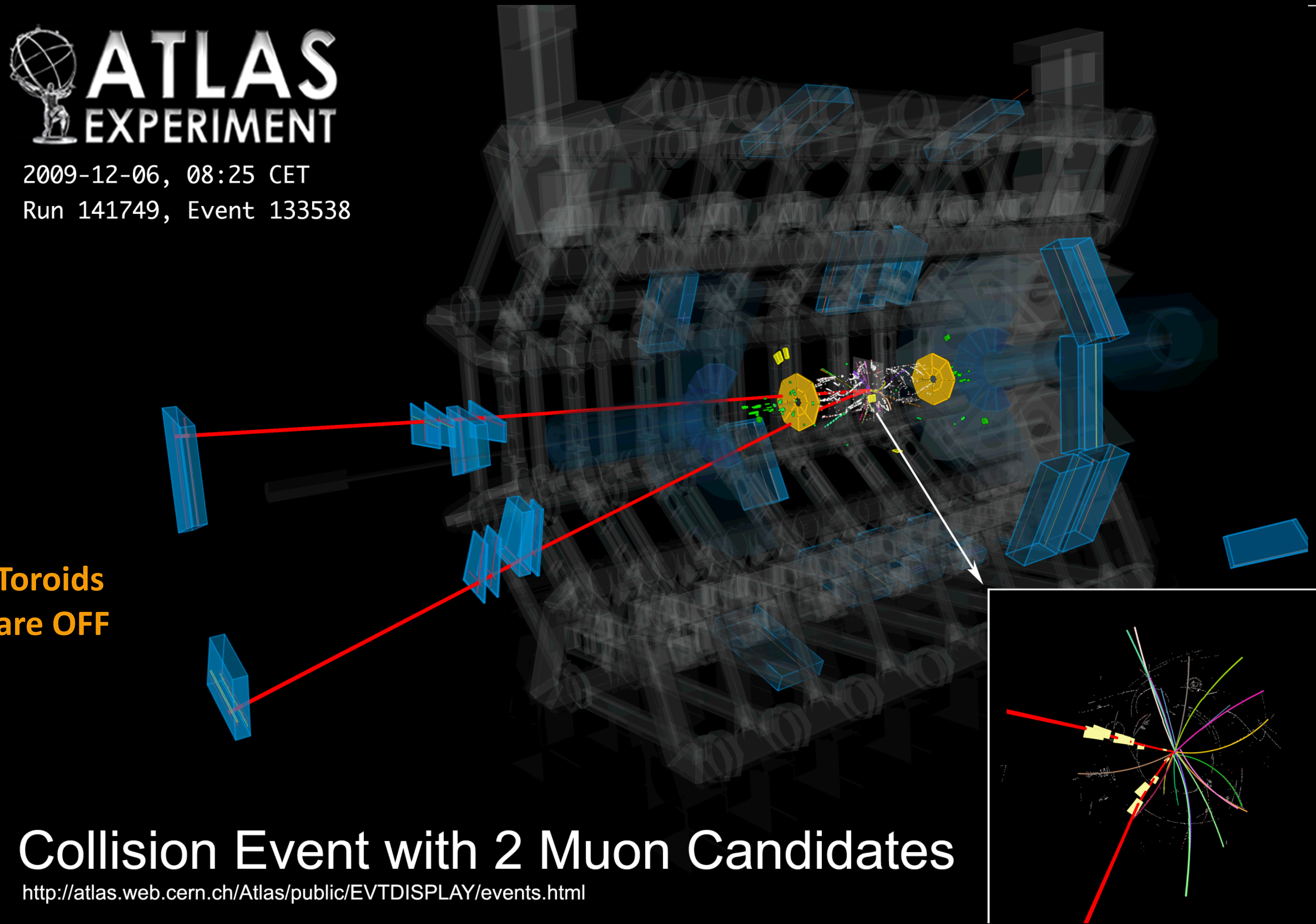




ATLAS EXPERIMENT

2009-11-23, 14:22 CET
Run 140541, Event 171897

http://atlas.web.cern.ch/Atlas/public/EVTDISPLAY/events.html

# December 6: first collisions at √s = 2.36 TeV

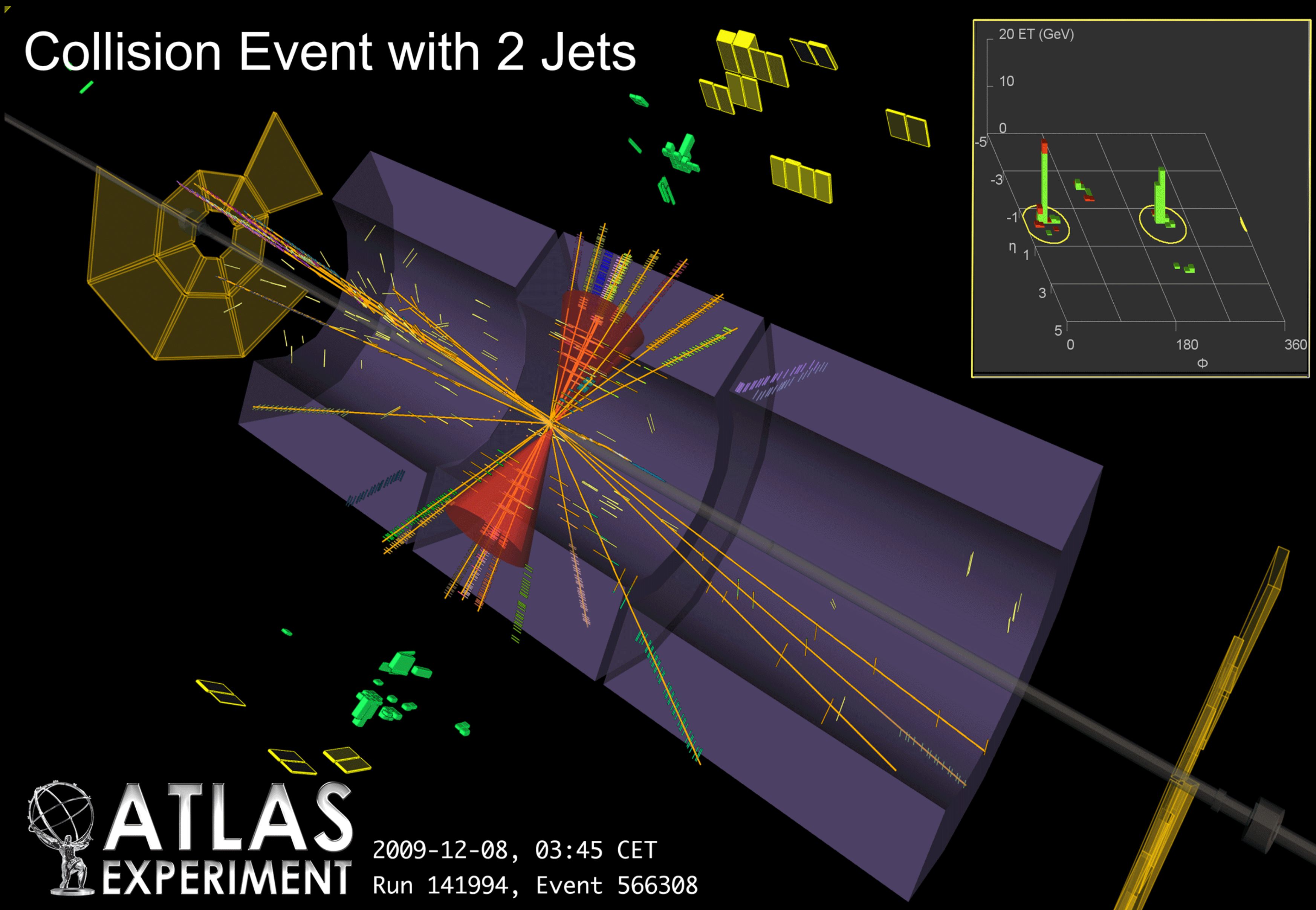


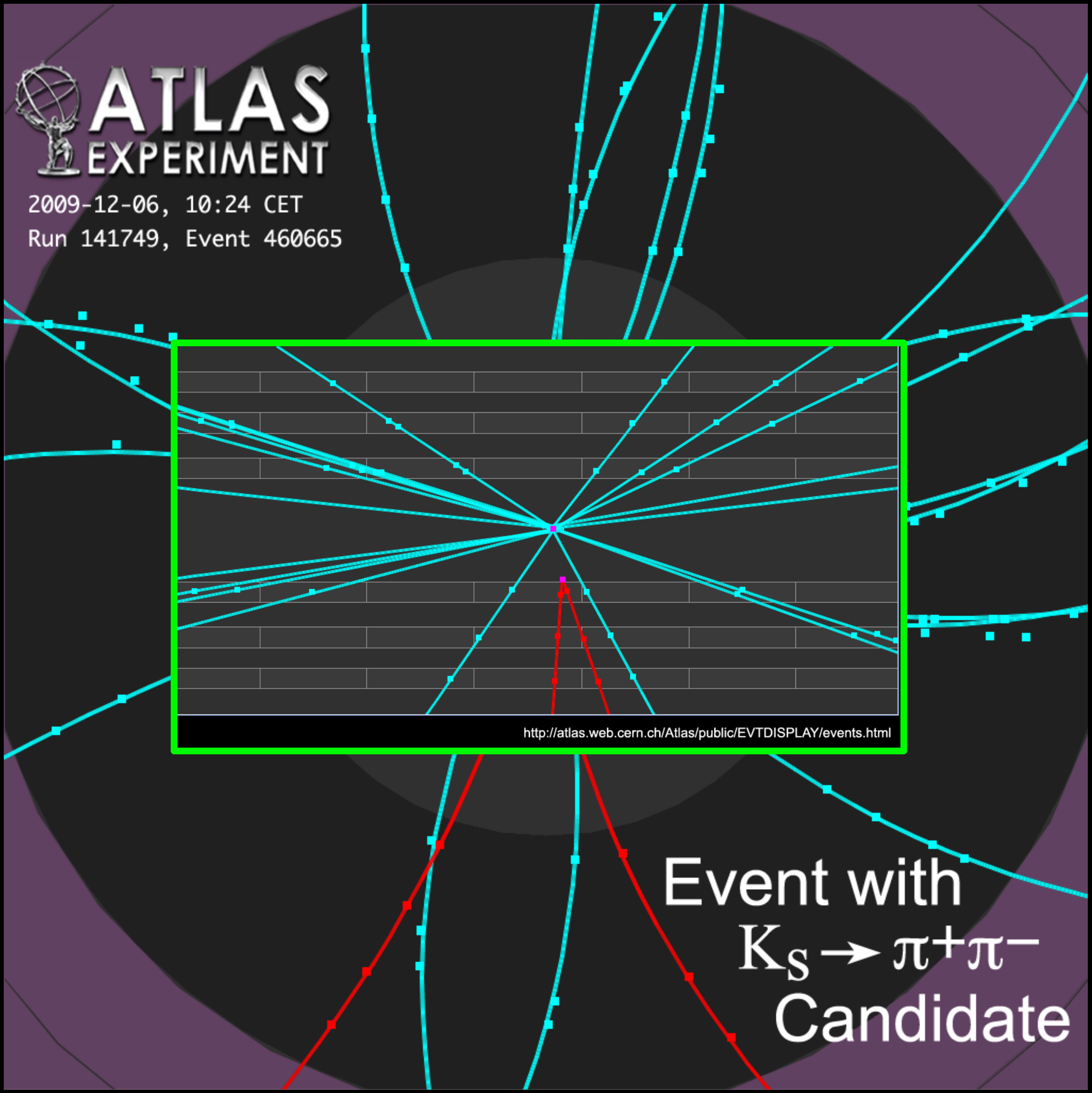

**Toroids are OFF**

Collision Event with 2 Muon Candidates

http://atlas.web.cern.ch/Atlas/public/EVTDISPLAY/events.html

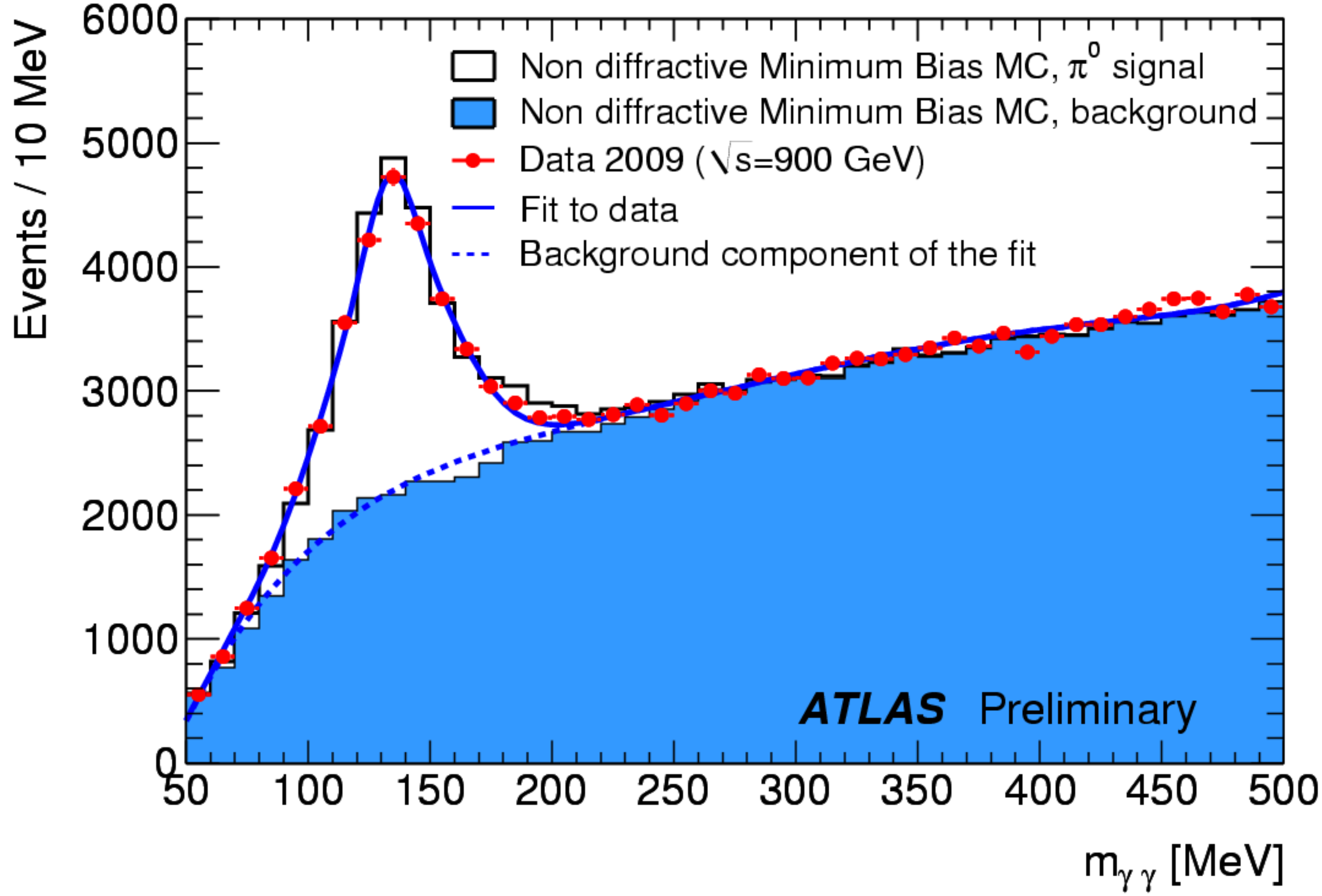
# Collisions at √s = 2.36 TeV: Jets in ATLAS



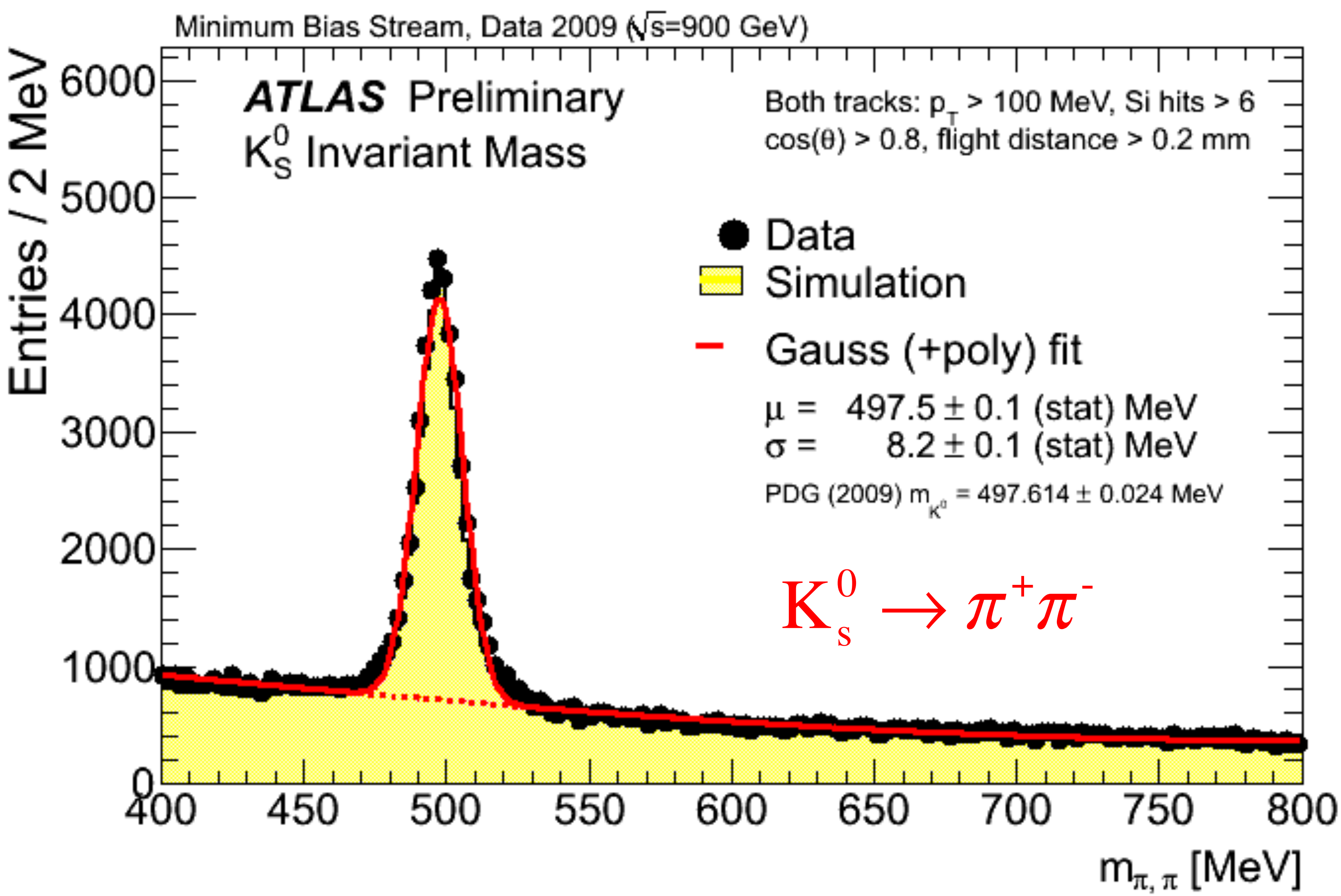

ATLAS EXPERIMENT
2009-12-06, 10:24 CET
Run 141749, Event 460665
http://atlas.web.cern.ch/Atlas/public/EVTDISPLAY/events.html
Event with
$K_S \rightarrow \pi^+\pi^-$
Candidate

# Reconstruction of Neutral Pions in the EM Calorimeter

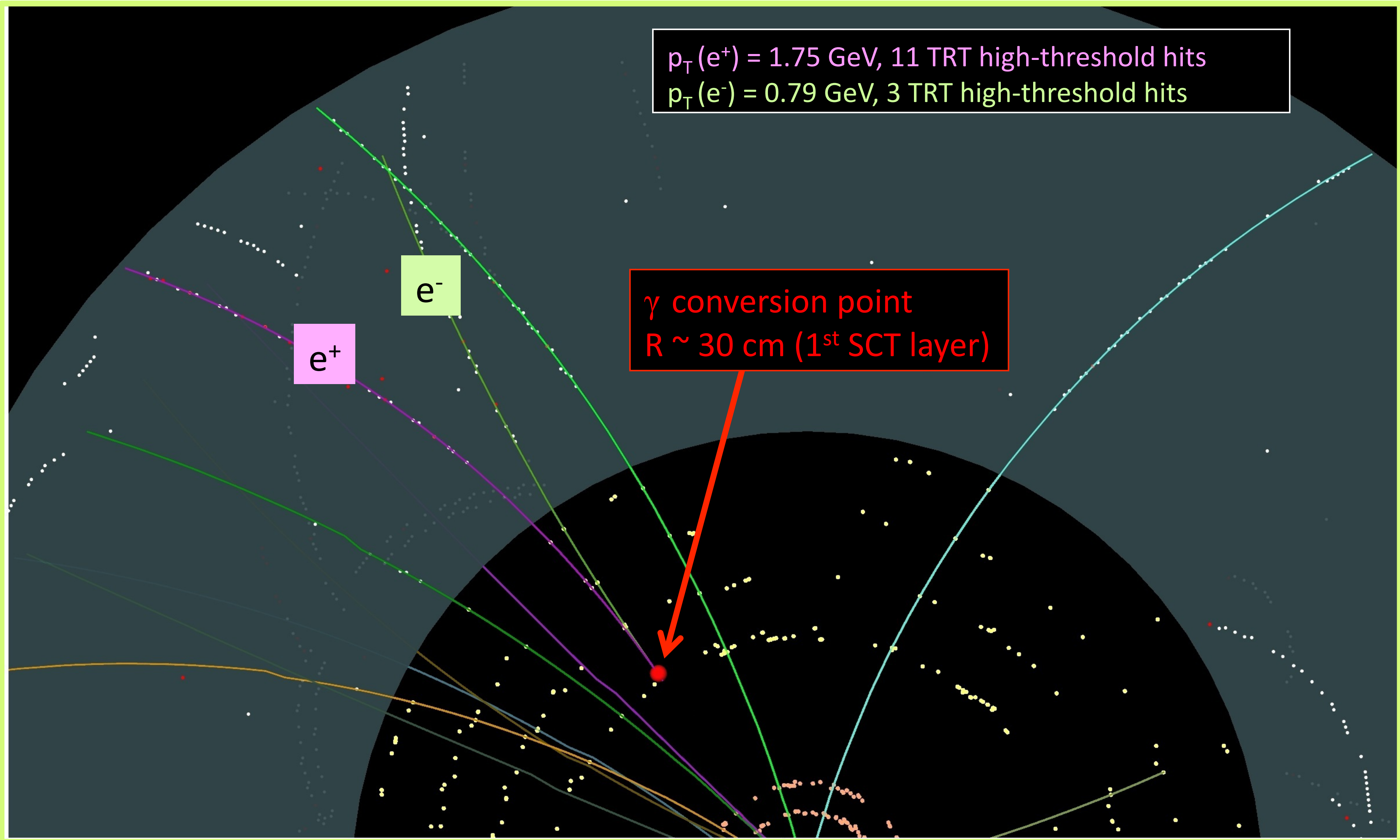
$$\pi^0 \rightarrow \gamma\gamma$$



# Reconstruction of Hadronic Decays (Tracking)

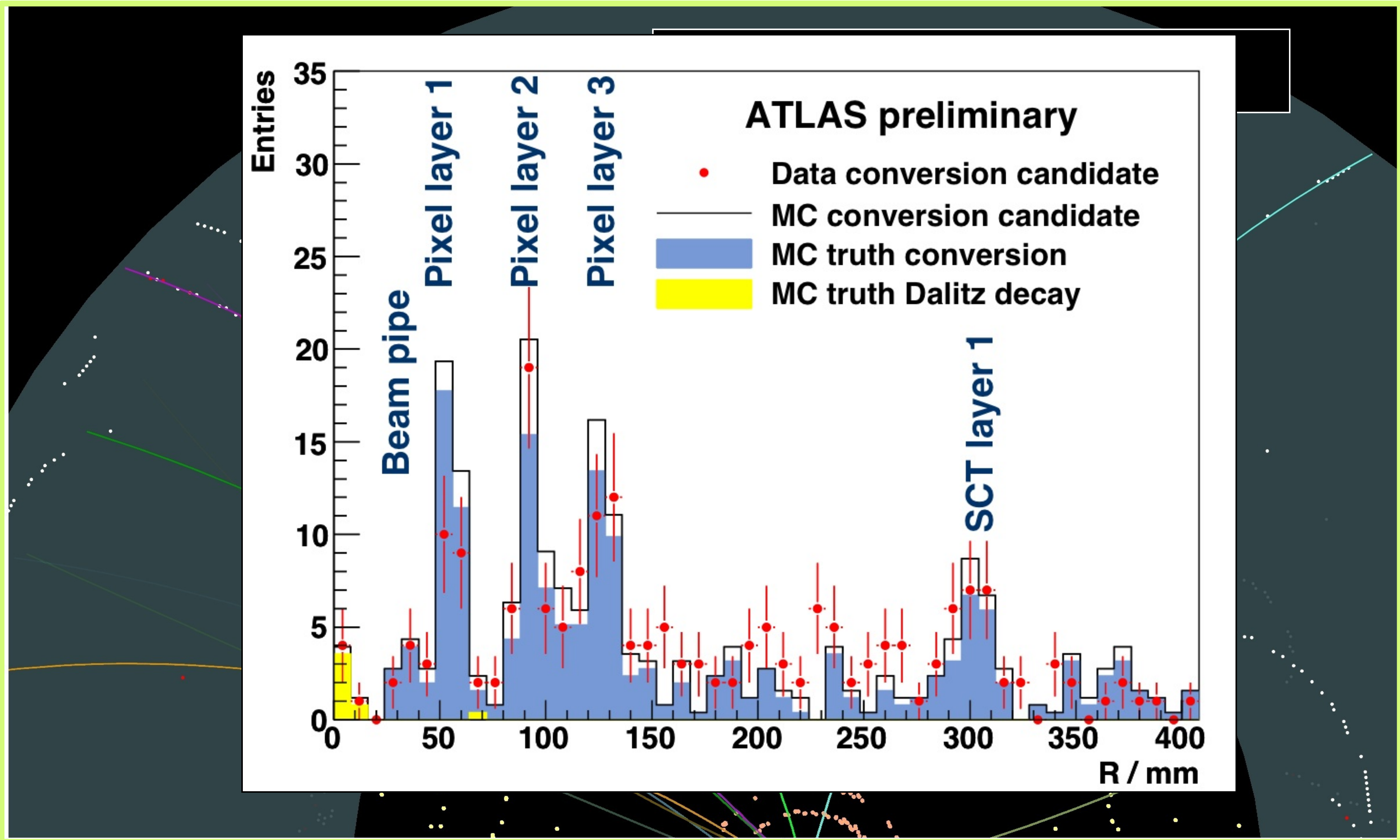


# Material Mapping with Photon Conversions



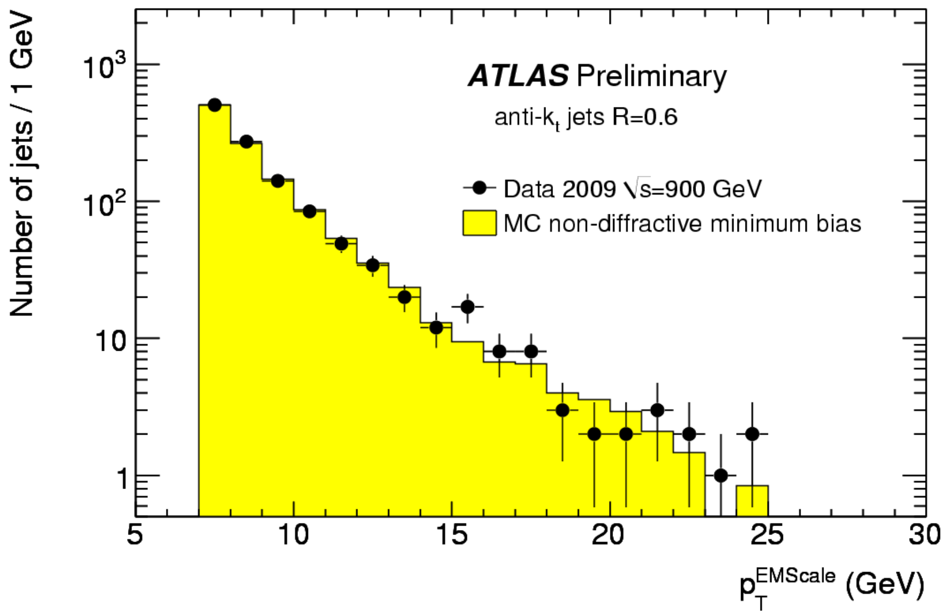

Reconstruction of photon conversions allows one to map the material in the detector, which is important for validating the material description in the detector simulation.

# Material Mapping with Photon Conversions

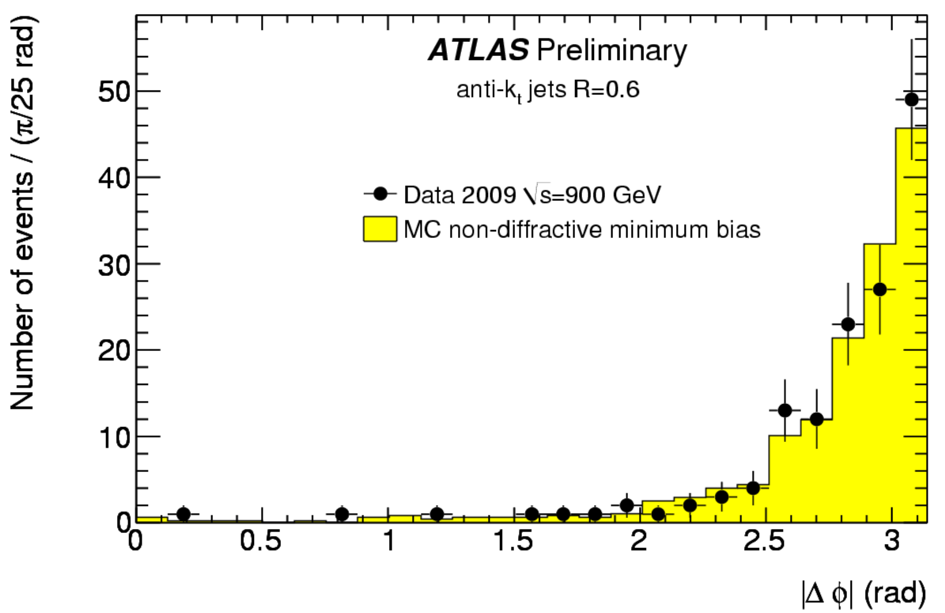



Reconstruction of photon conversions allows one to map the material in the detector, which is important for validating the material description in the detector simulation.

# Jet Kinematic Distributions from 900 GeV Data

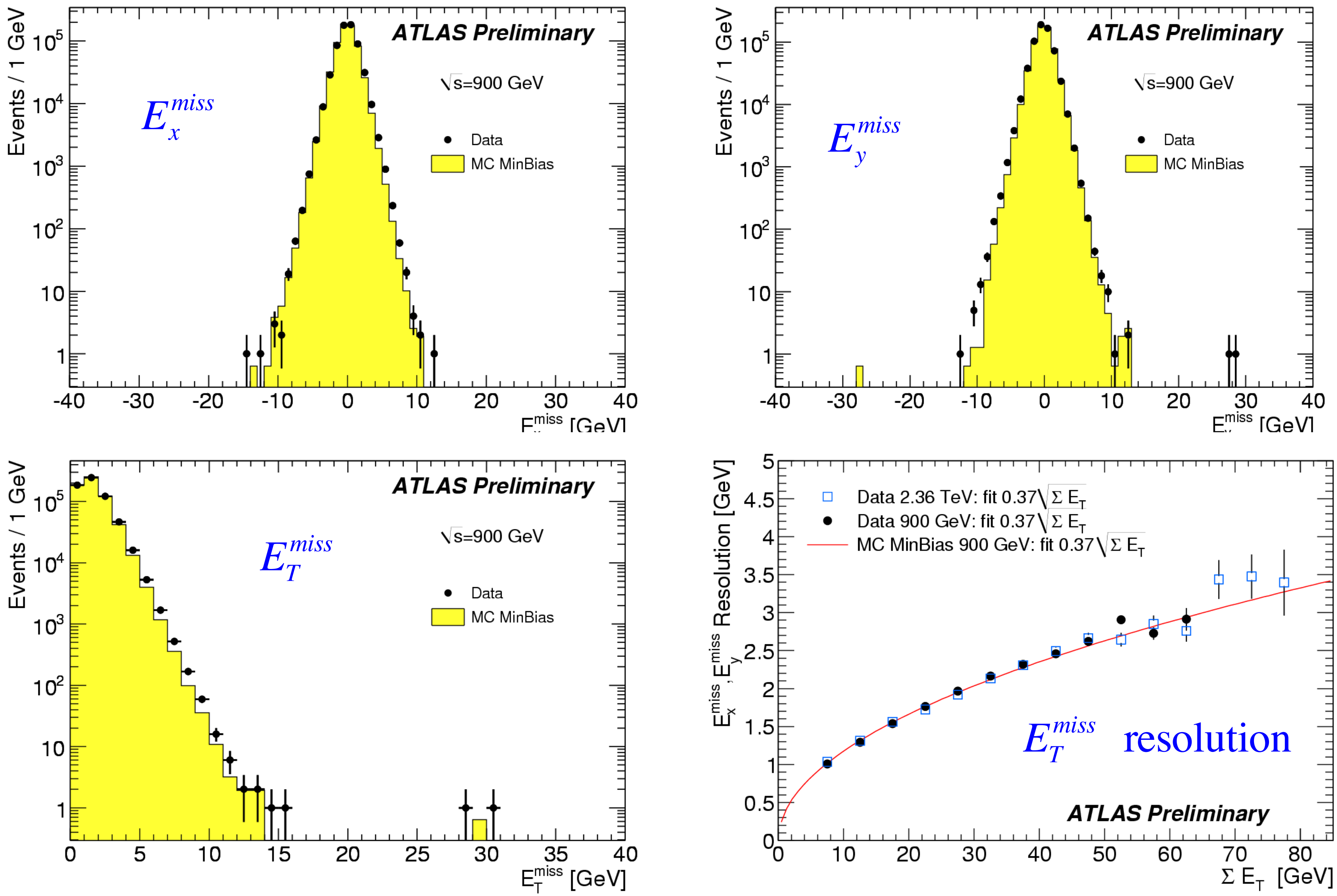



Jet transverse momentum

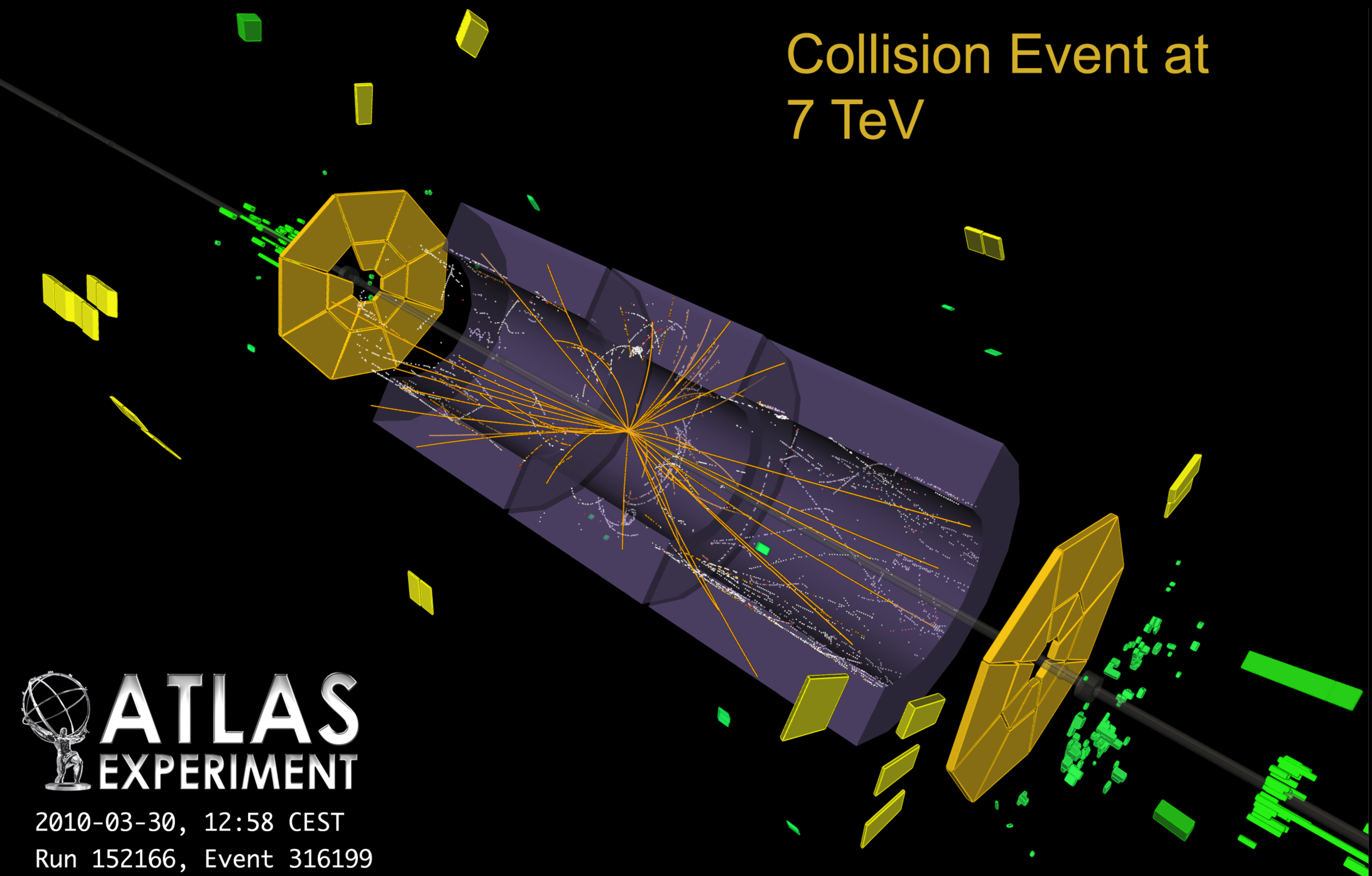



Jet azimuthal separation

# Performance for Missing Transverse Energy

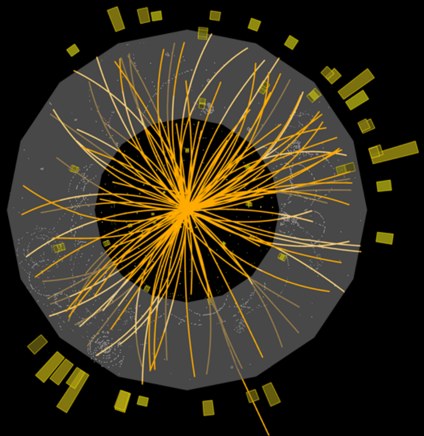


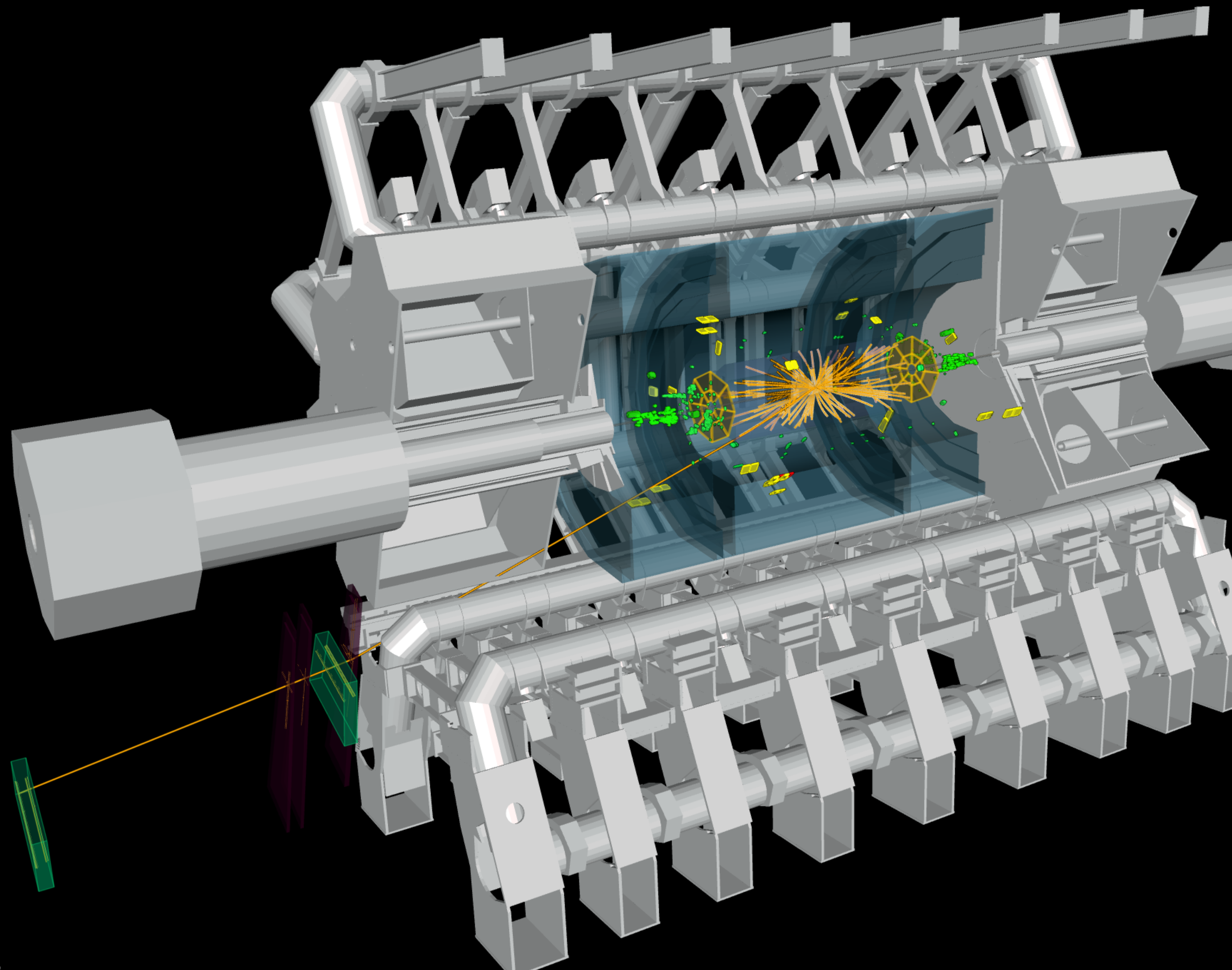
# March 30, 2010: LHC pp Collisions at $E_{CM}$=7TeV




http://atlas.web.cern.ch/Atlas/public/EVTDISPLAY/events.html

# Collision Event at 7 TeV with Muon Candidate

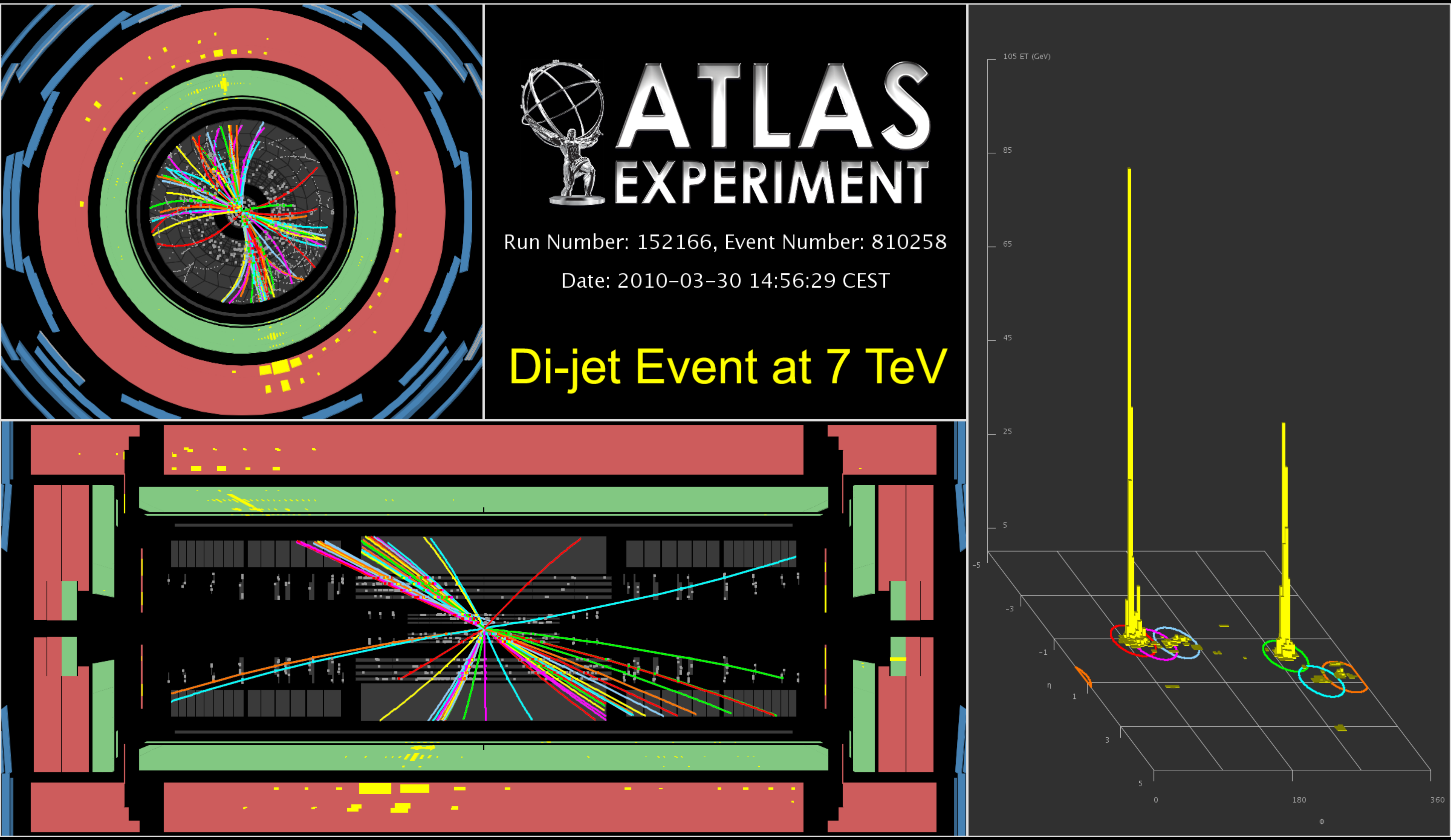




ATLAS EXPERIMENT

2010-03-30, 12:59 CEST
Run 152166, Event 322215

http://atlas.web.cern.ch/Atlas/public/EVTDISPLAY/events.html


ATLAS
EXPERIMENT
Run Number: 152166, Event Number: 810258
Date: 2010-03-30 14:56:29 CEST
Di-jet Event at 7 TeV
105 ET (GeV)
85
65
45
25
5
-5
-3
-1
η
1
3
5
0
180
360
Φ

# Outlook

- March 30: began running with collisions at $E_{CM}$ = 7 TeV (3.5 TeV/beam)
- Run at this energy until 1$fb^{-1}$ of integrated luminosity collected (fall 2011)
- Understanding of detector based on collision data is progress, but already impressive.
- Plan to shut down in 2012 for major work on LHC equipment to ensure that we can run safely at higher energies.
- First ATLAS publication on physics data has been submitted to PLB.