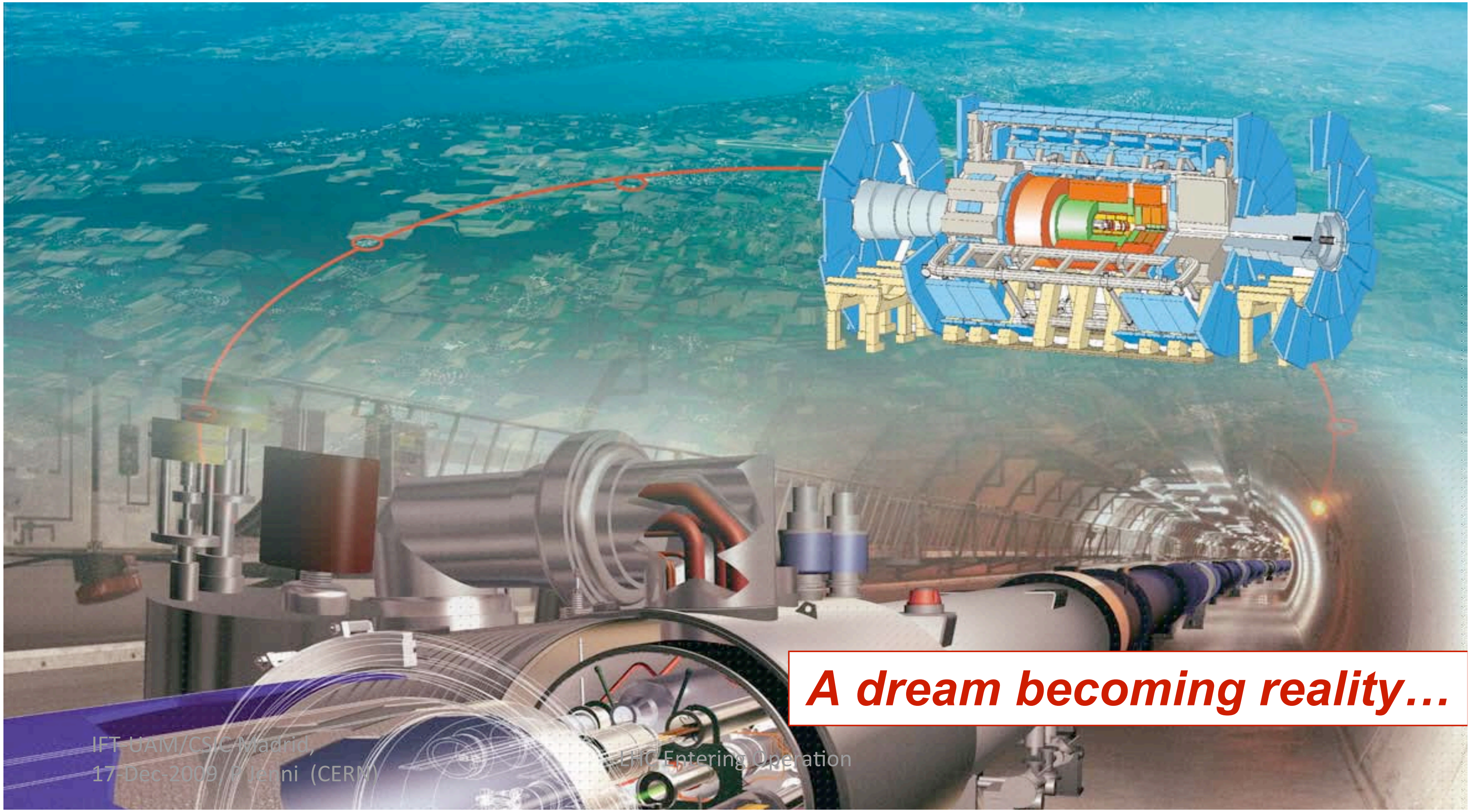
The Large Hadron Collider Finally Entering Operation

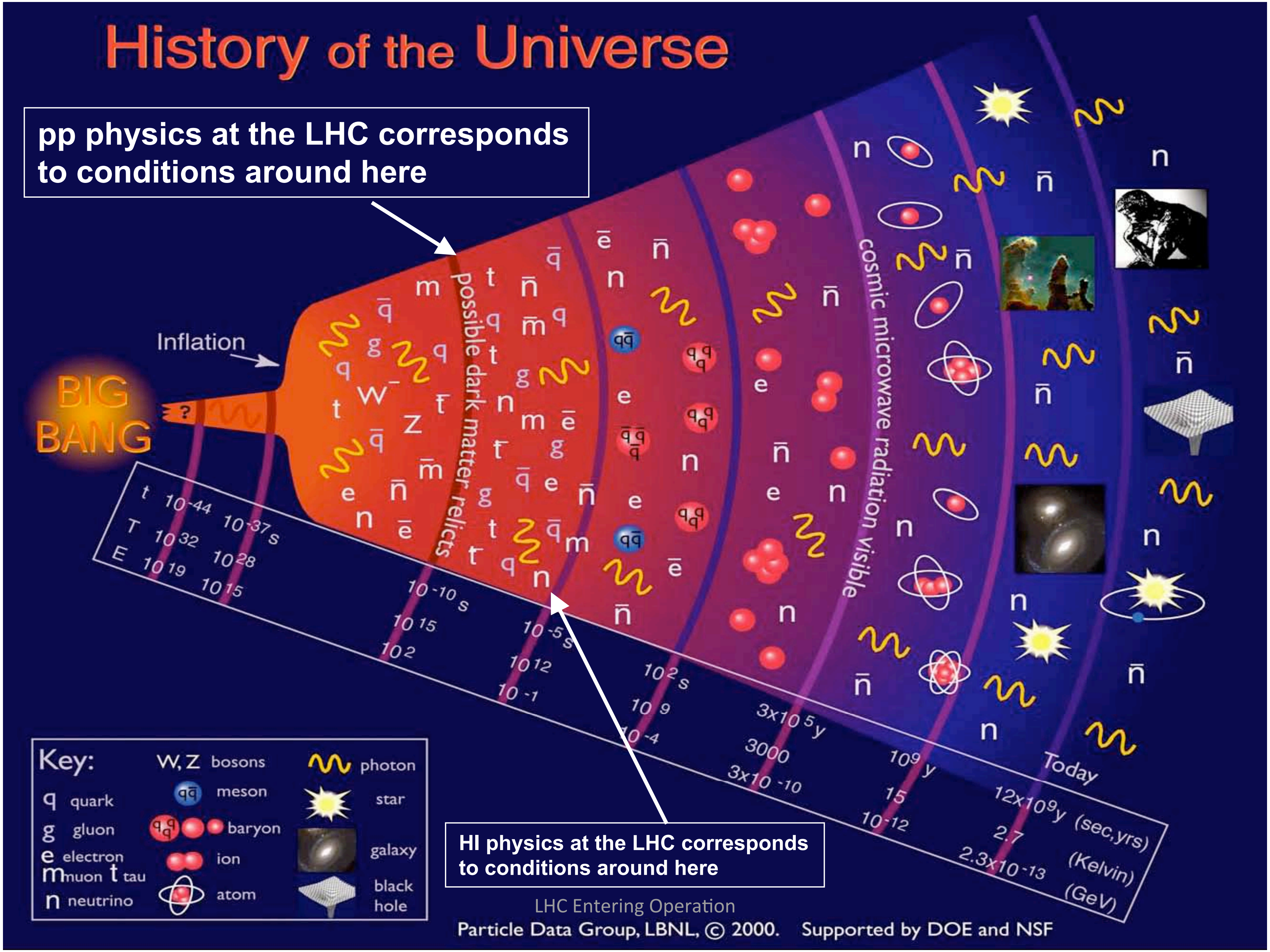
An Overview of the LHC Project and its Status

XV IFT-UAM/CSIC Christmas Workshop
Madrid, 16-18 December 2009, Peter Jenni (CERN/ATLAS)

ift XV Christmas Workshop
Windows on the Unknown
Madrid, 16-18 December 2009

The Large Hadron Collider Project:
A Journey to Discover the Physics Shortly After the Big Bang

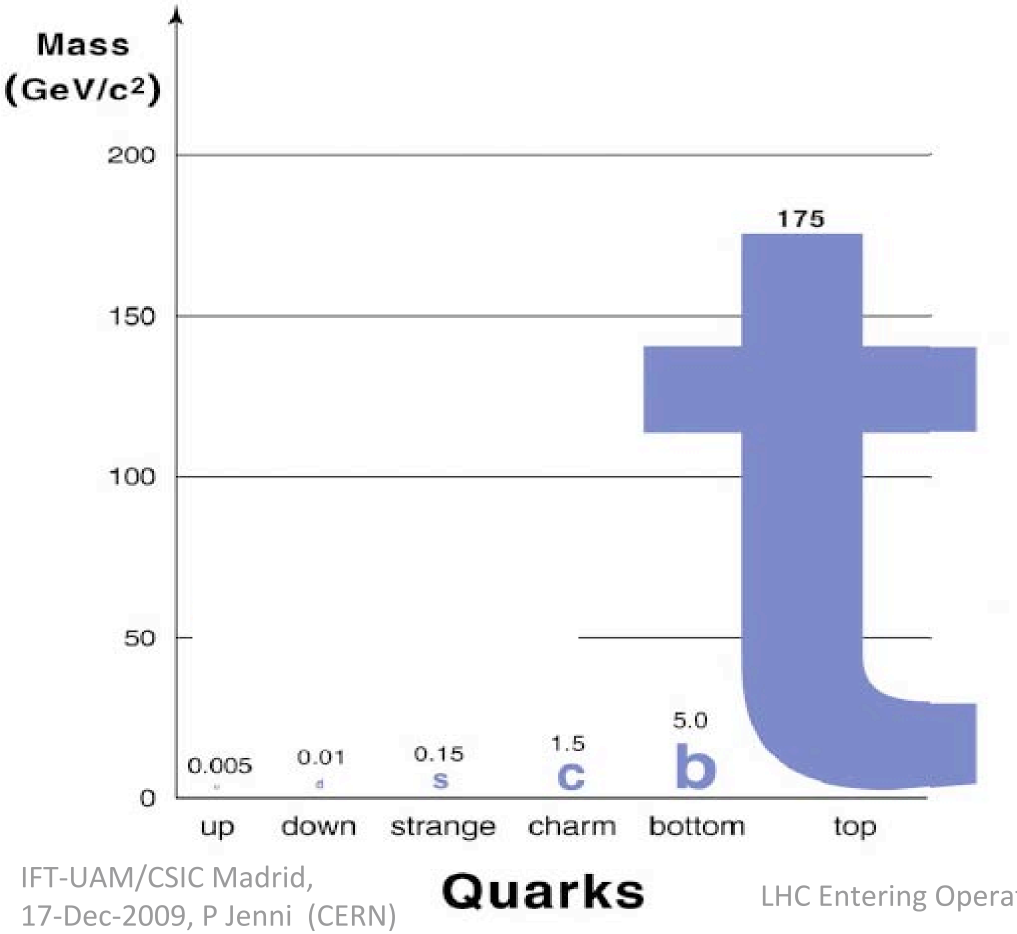



History of the Universe
pp physics at the LHC corresponds to conditions around here
HI physics at the LHC corresponds to conditions around here
BIG BANG
Inflation
possible dark matter relicts
cosmic microwave radiation visible
t 10-44 10-37 s
T 1032 1028
E 1019 1015
10-10 s
1015
102
10-5 s
1012
10-1
102 s
109
10-4
3x105 y
3000
3x10-10
109 y
15
10-12
Today
12x109 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
LHC Entering Operation
Particle Data Group, LBNL, © 2000. Supported by DOE and NSF

A most basic question is why particles (and matter) have masses (and so different masses)

The mass mystery could be solved with the 'Higgs mechanism' which predicts the existence of a new elementary particle, the 'Higgs' particle (theory 1964, P. Higgs, R. Brout and F. Englert)

Peter Higgs



The Higgs (H) particle has been searched for since decades at accelerators, but not yet found…

The LHC will have sufficient energy to produce it for sure, if it exists

Francois Englert

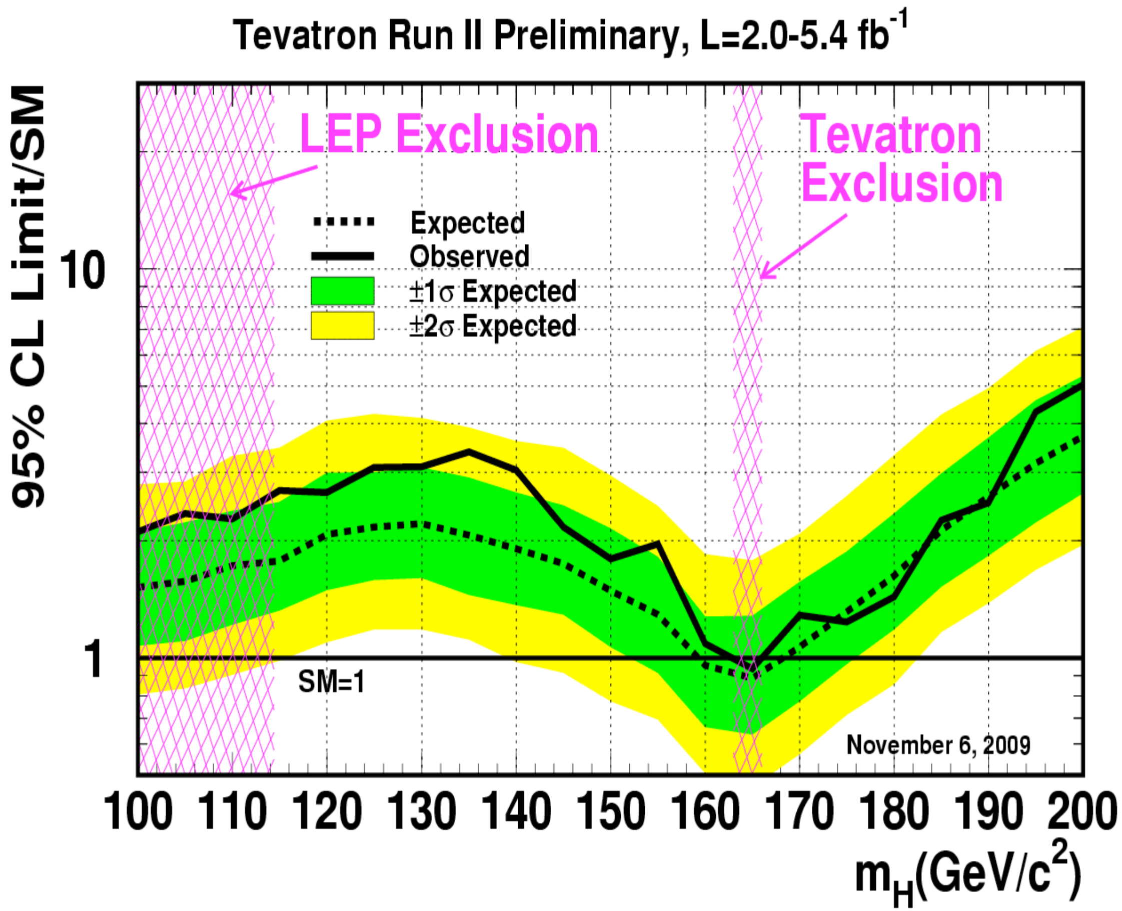
CDF/D0 Conclusion at HCP2009:

- Great results from both experiments in both low and high mass sectors

- SM Higgs exclusion in the range 163-166 GeV @95% CL
- Expected exclusion range 159-168 GeV

- Better than 2.2xSM sensitivity at all masses below 185 GeV

- Stay tuned for further Tevatron improvements in Higgs searches



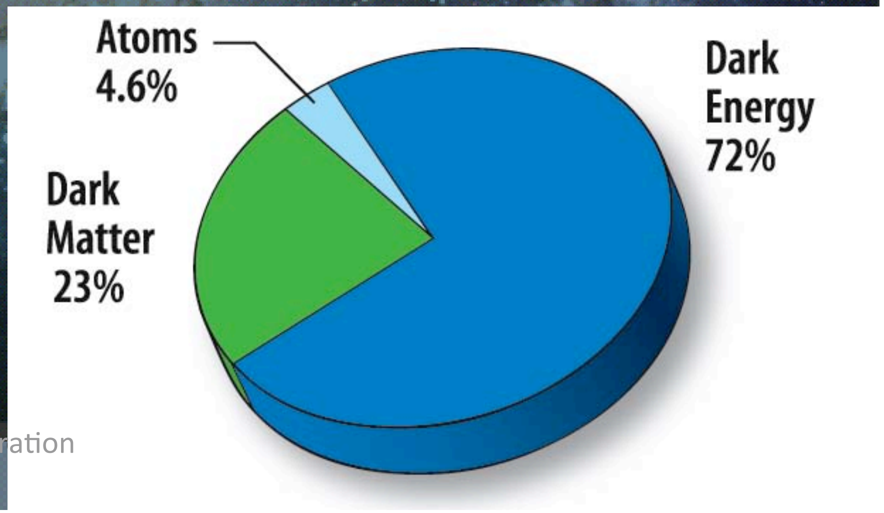
Dark Matter in the Universe

Astronomers say that most of the matter in the Universe is invisible Dark Matter

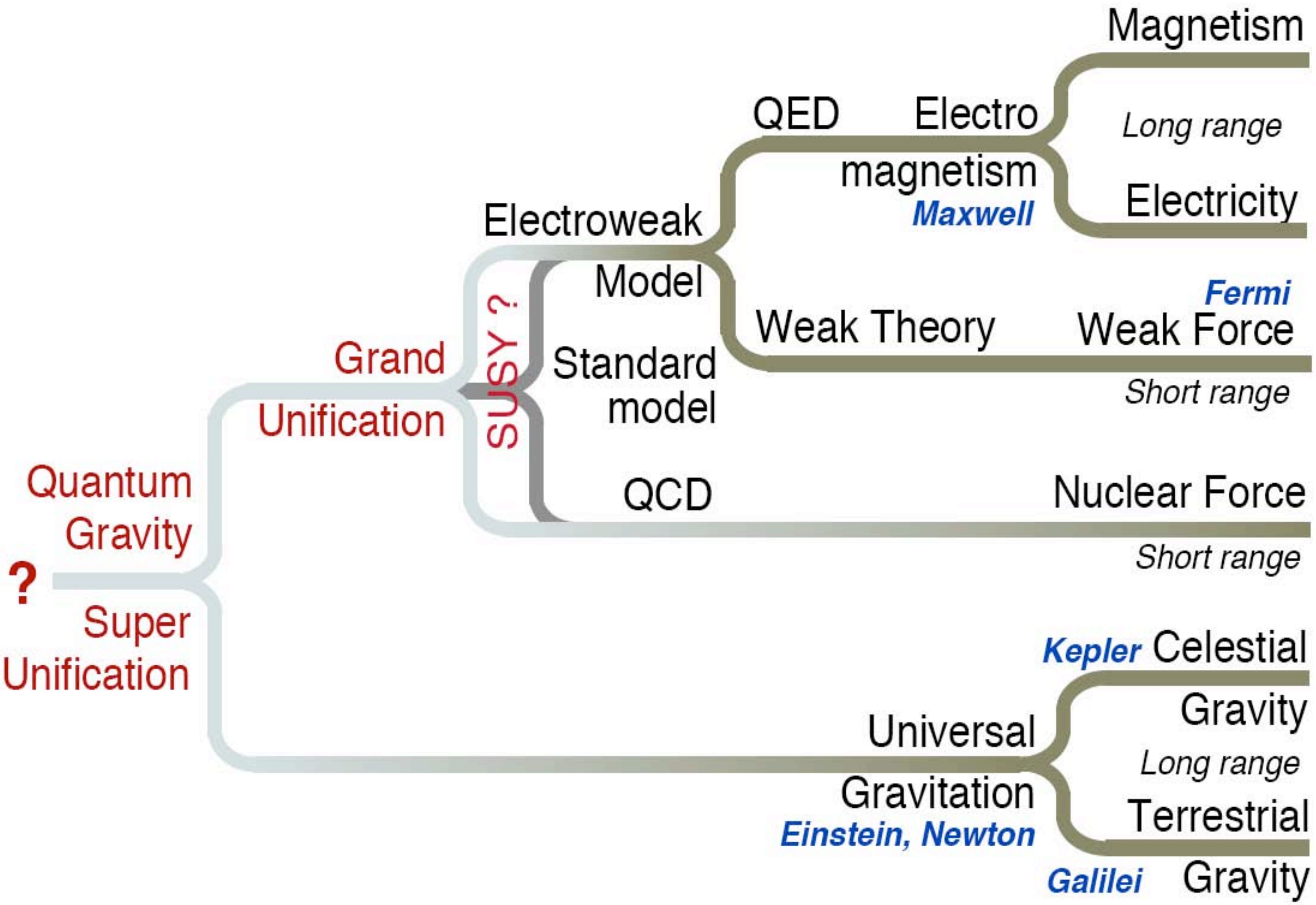
'Supersymmetric' particles ?

We shall look for them with the LHC

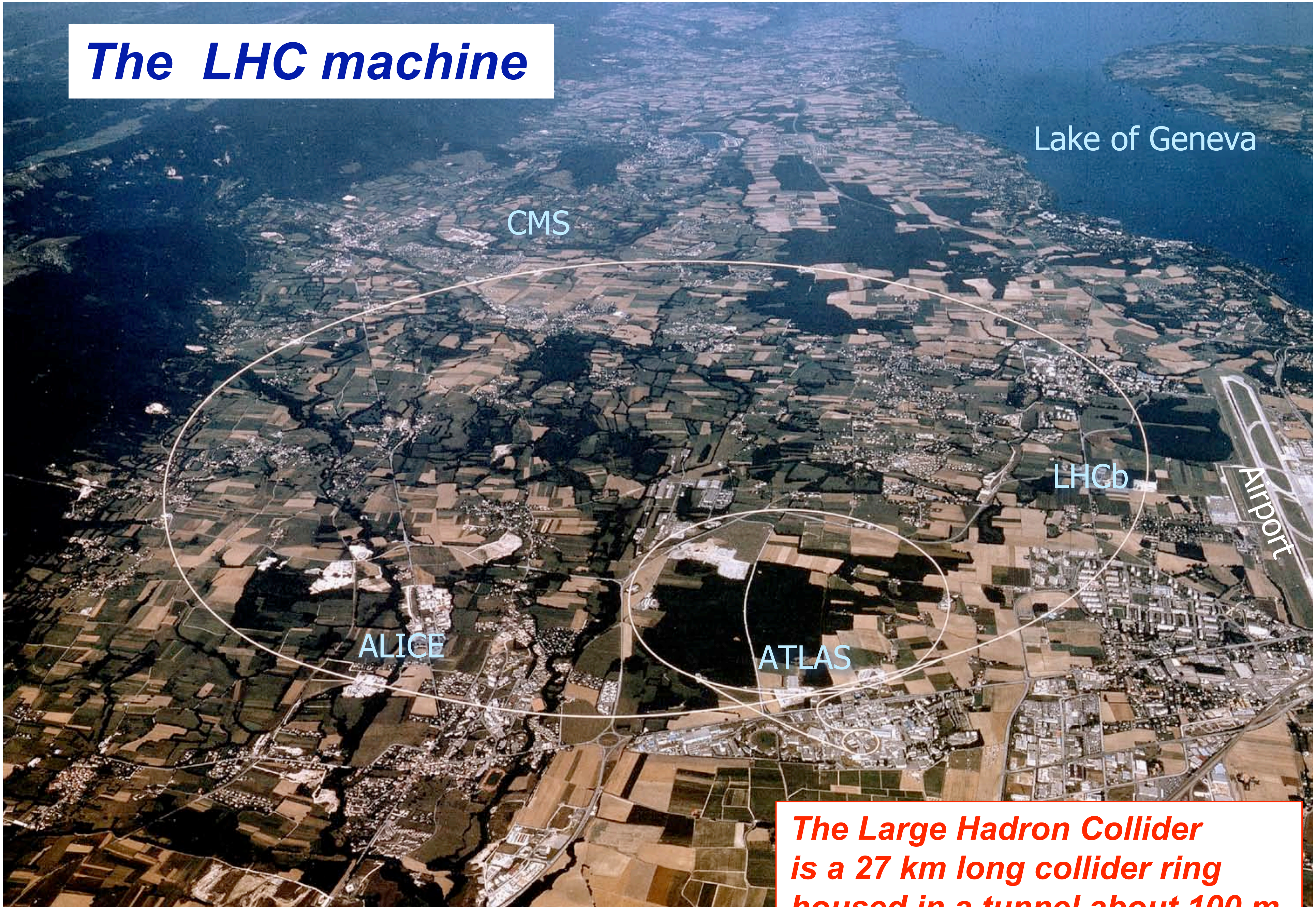
F. Zwicky 1898-1974



Unification of Forces



The LHC machine



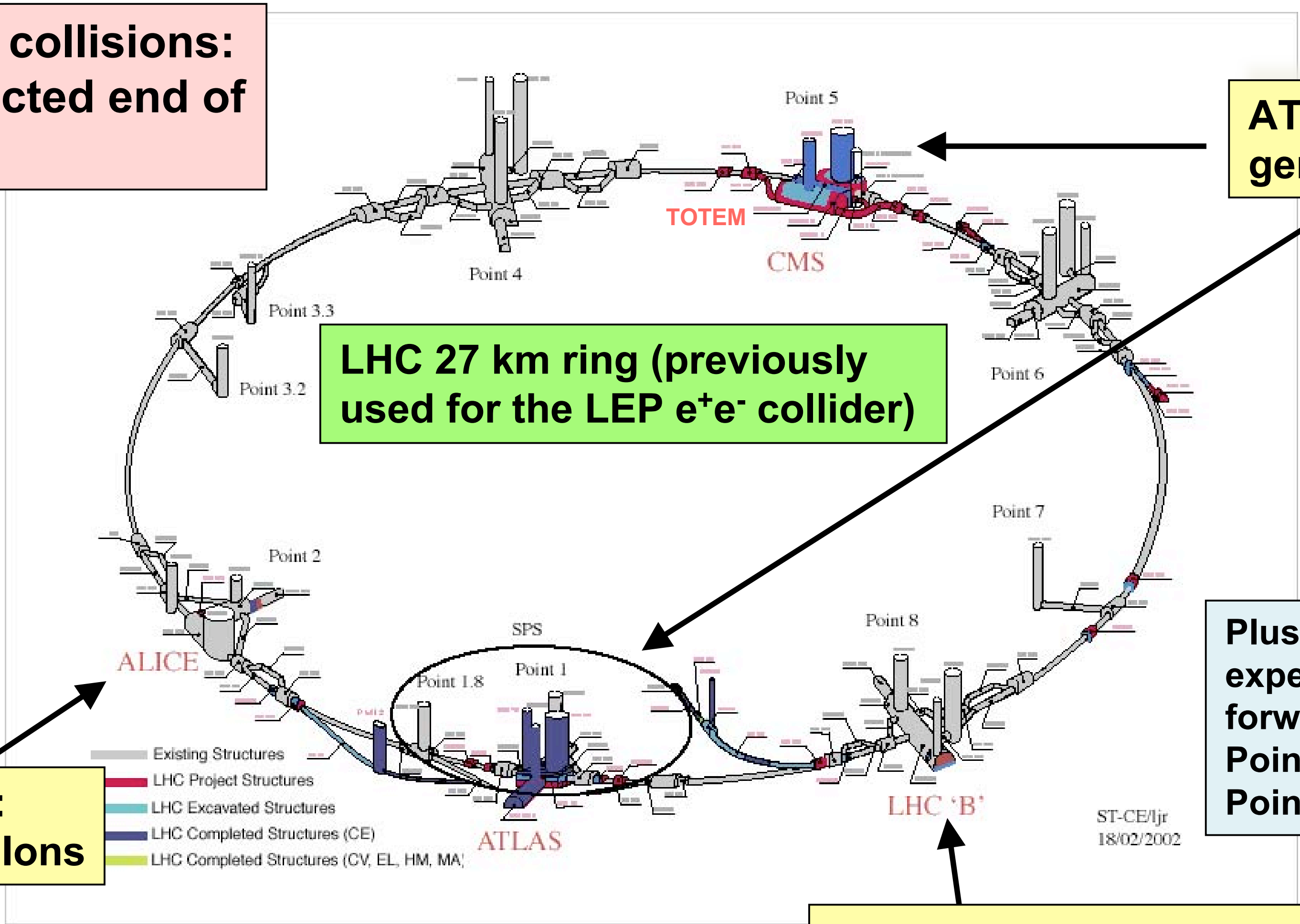
The Large Hadron Collider is a 27 km long collider ring housed in a tunnel about 100 m underground near Geneva

pp $\sqrt{s}$ = 14 TeV $L_{design} = 10^{34}\ cm^{-2}\ s^{-1}$ (after 2012/3)

7-14 TeV $L_{initial}$ < few x $10^{33}\ cm^{-2}\ s^{-1}$ (before)

Heavy ions (e.g. Pb-Pb at ~ 1150 TeV)

First collisions: expected end of 2009



LHC 27 km ring (previously used for the LEP e^+e^- collider)

ATLAS and CMS: general purpose

ALICE: Heavy Ions

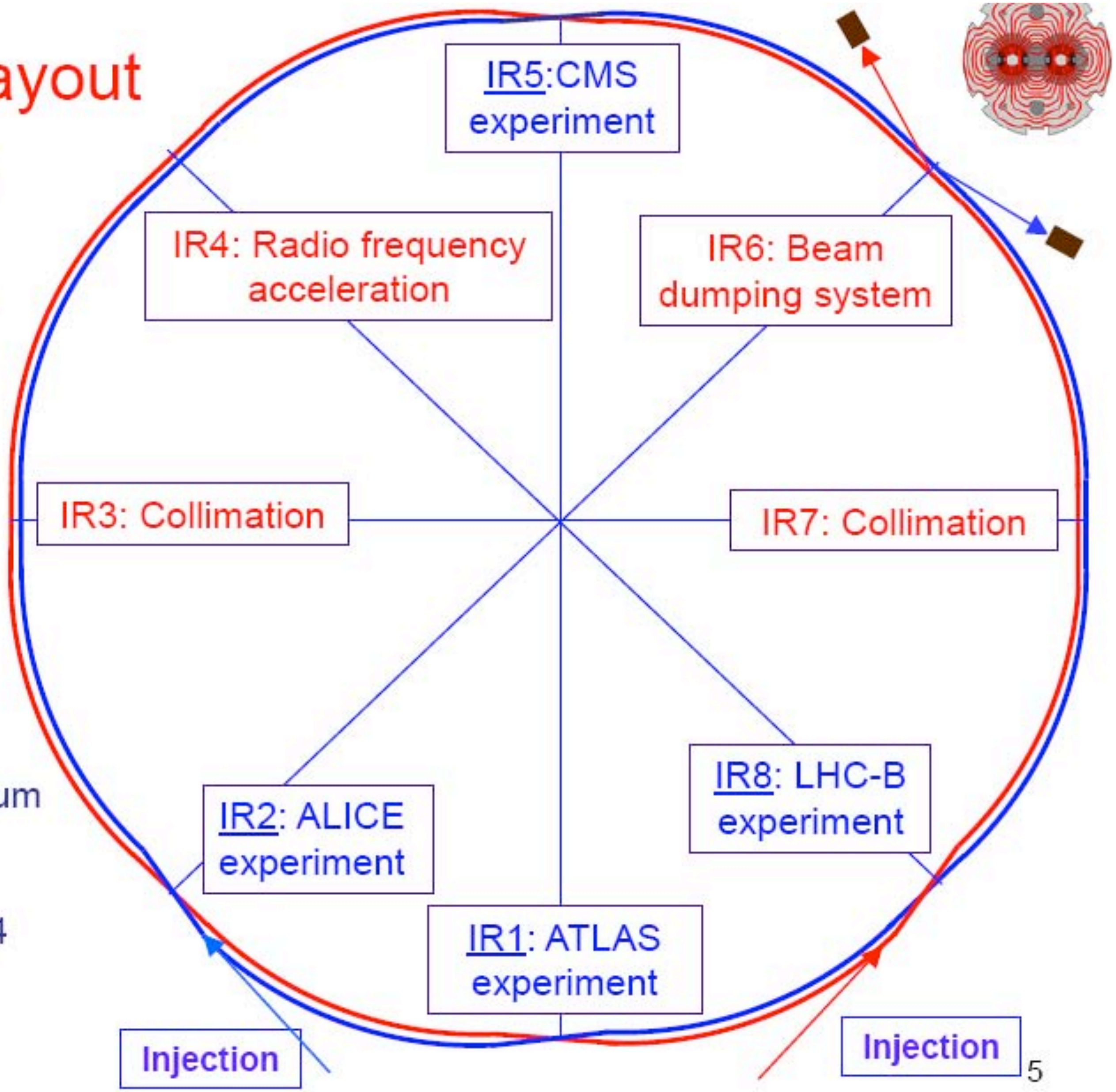
LHCb: B-physics, CP-violation

Plus two much smaller experiments with very forward detectors at
Point-1: LHCf
Point-5: Totem

LHC Layout

- 8 arcs (sectors)
- 8 long straight sections (700 m long):

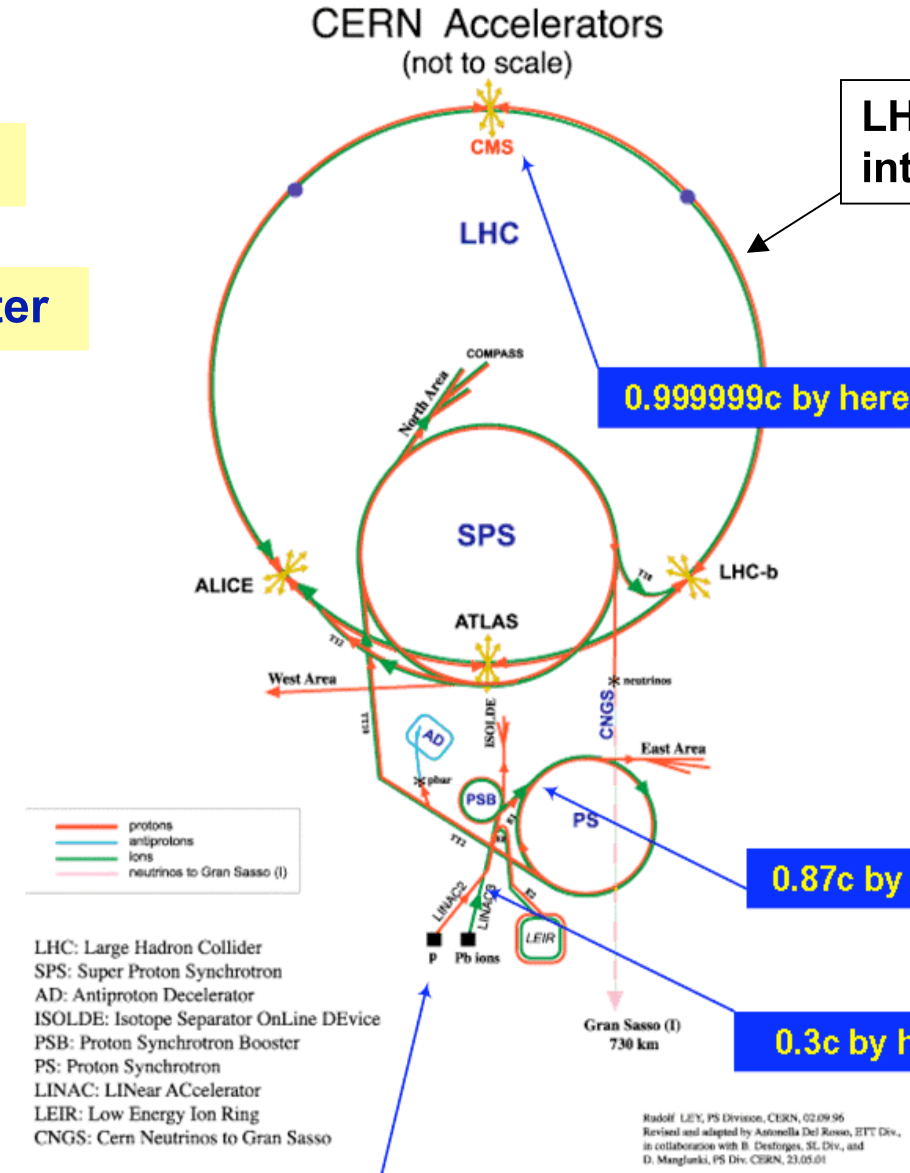
  IR1 to IR8



- 2 separate vaccum chambers
- beams cross in 4 points

The full LHC accelerator complex

Linac
↓
Booster
↓
PS
↓
SPS
↓
LHC



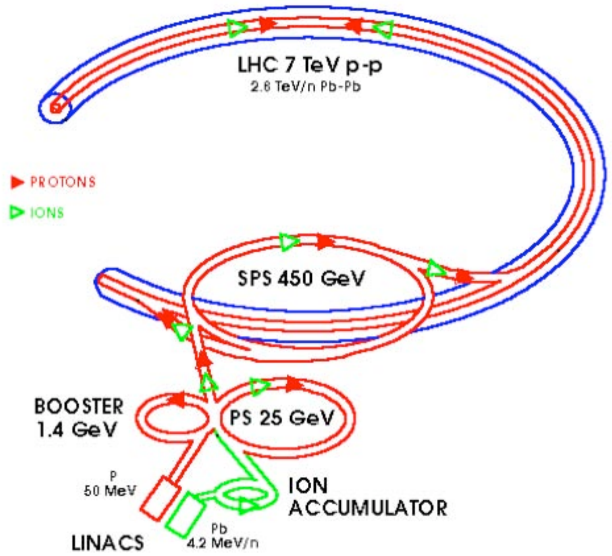
LHC ring is divided into 8 sectors

0.999999c by here

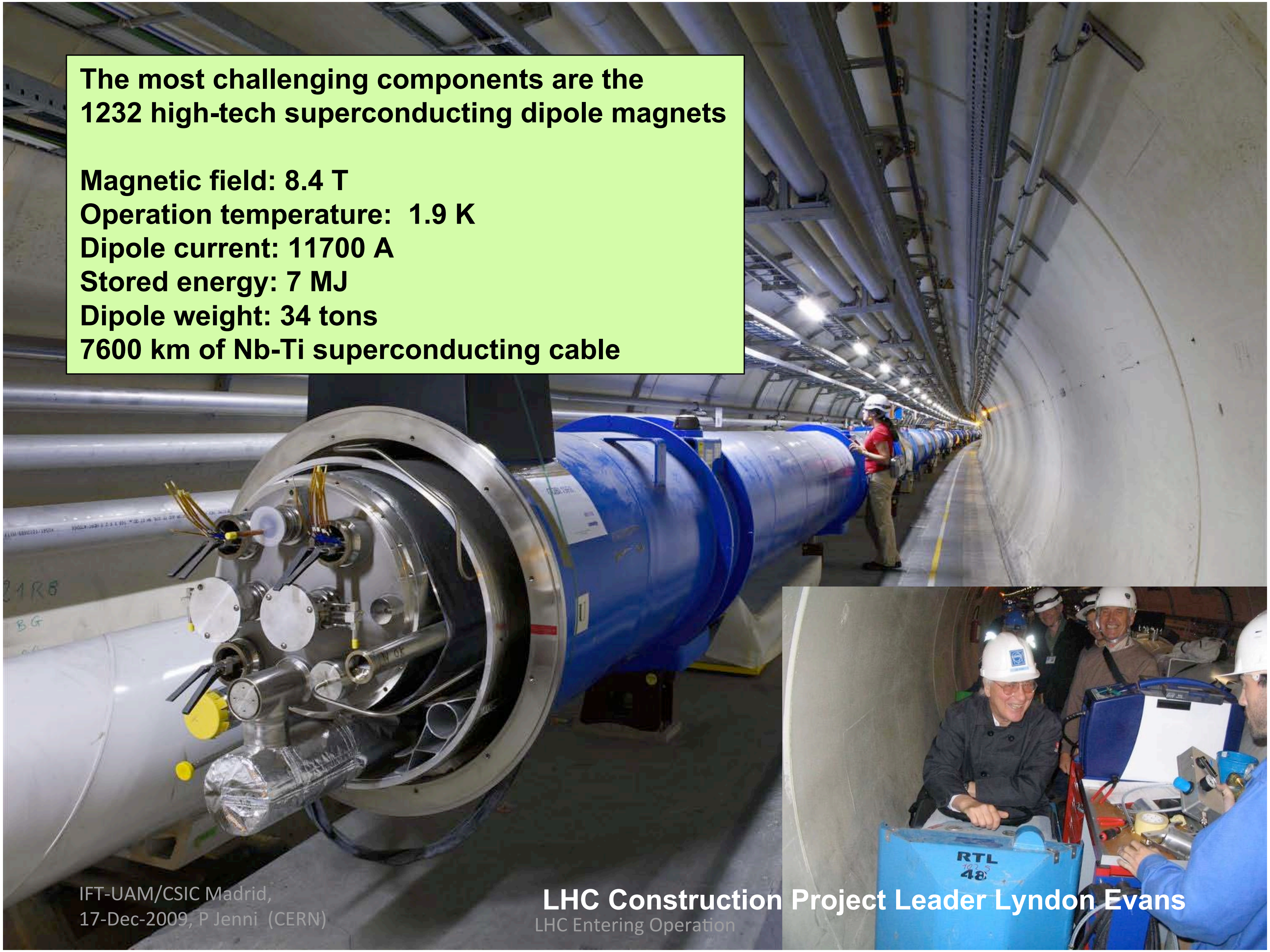
0.87c by here

0.3c by here

Start the protons out here



> 50 years of CERN history still alive and operational

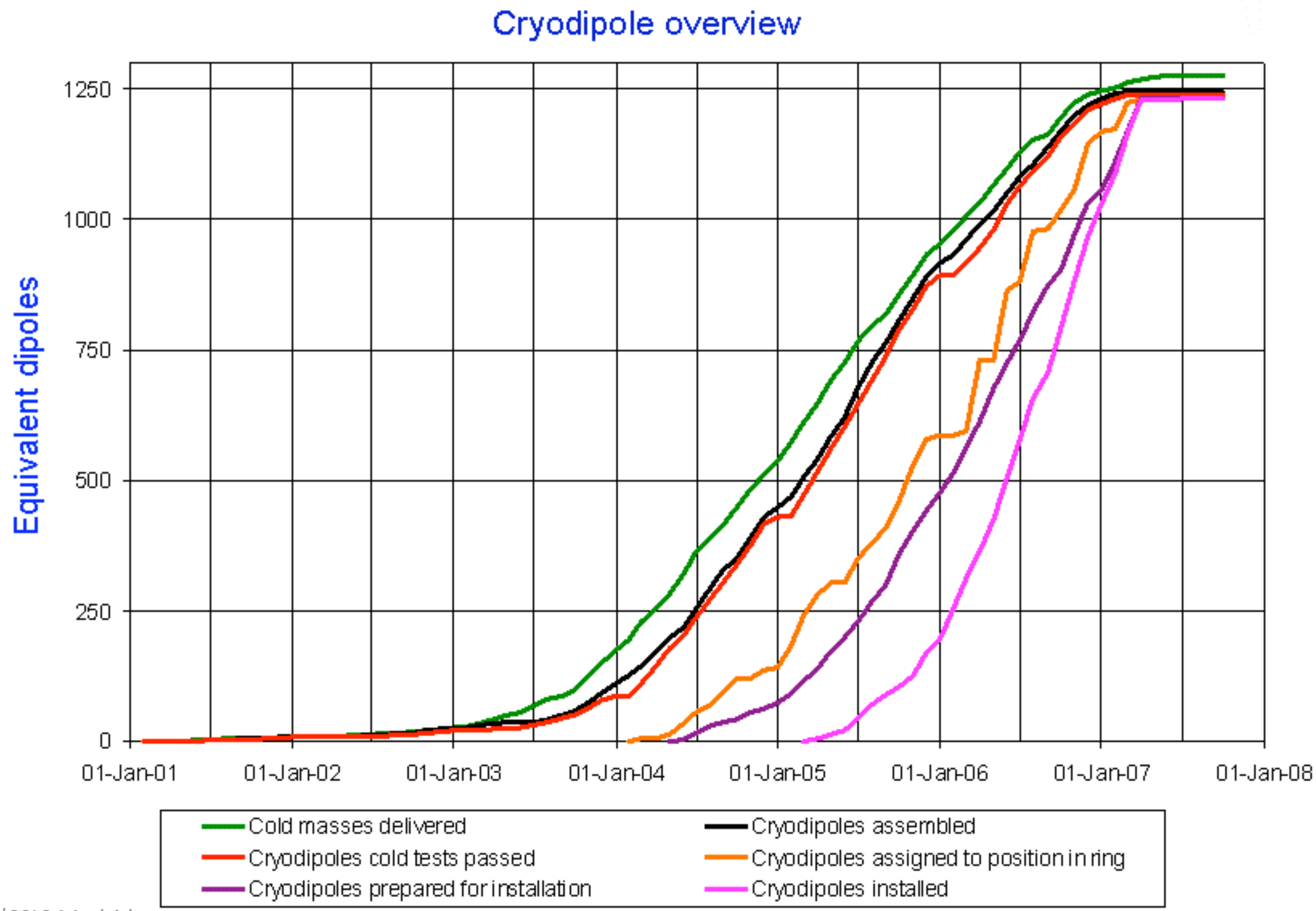


The most challenging components are the 1232 high-tech superconducting dipole magnets

- Magnetic field: 8.4 T
- Operation temperature: 1.9 K
- Dipole current: 11700 A
- Stored energy: 7 MJ
- Dipole weight: 34 tons
- 7600 km of Nb-Ti superconducting cable

LHC Construction Project Leader Lyndon Evans

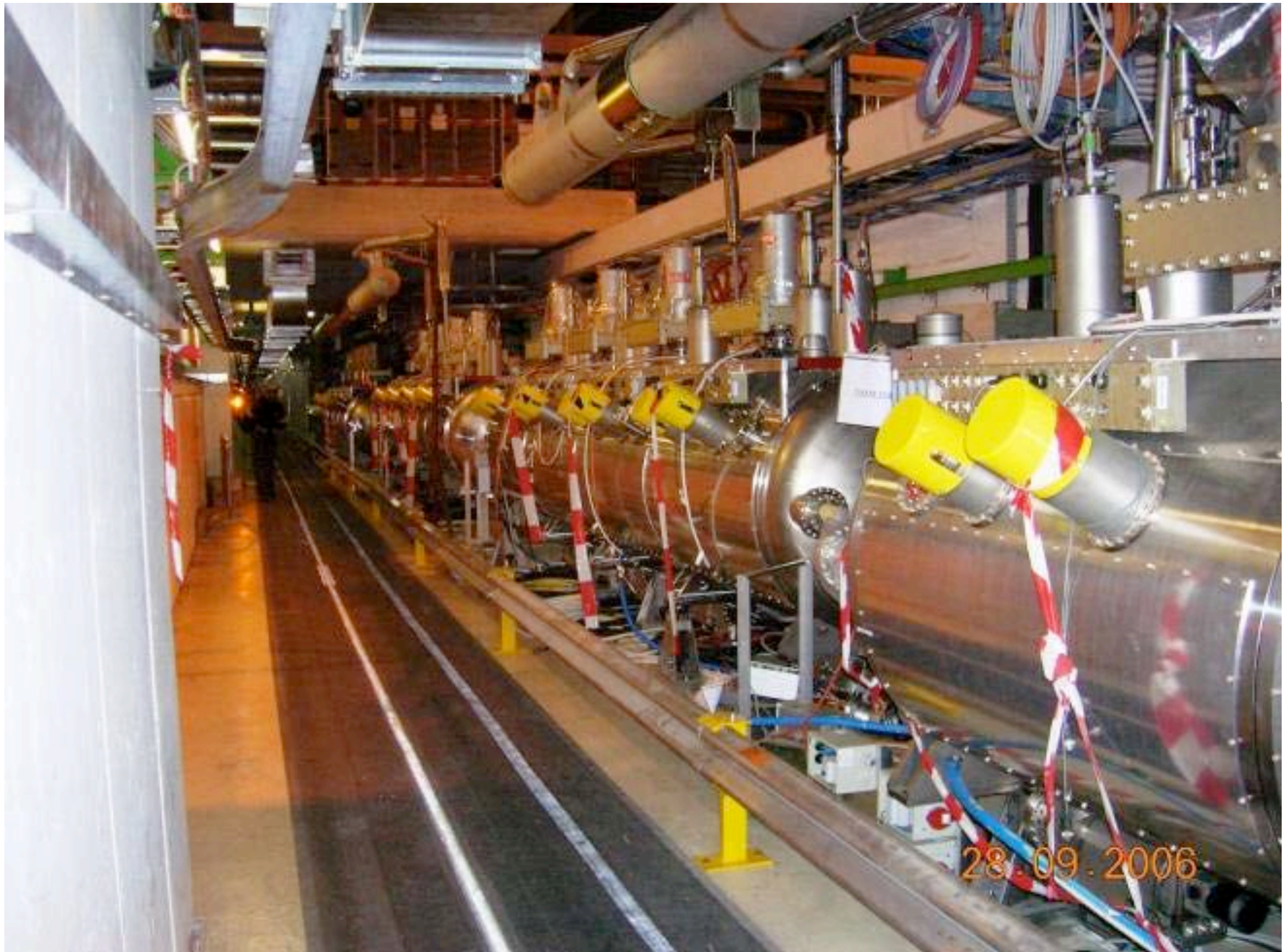
History of the dipole magnet construction and installation

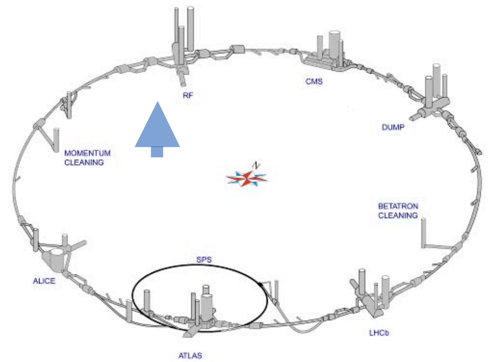


Updated 30 September 2007

Data provided by D. Tommasini AT-MCS, L. Bottura AT-MTM

The particle beams are accelerated by superconducting Radio-Frequency (RF) cavities

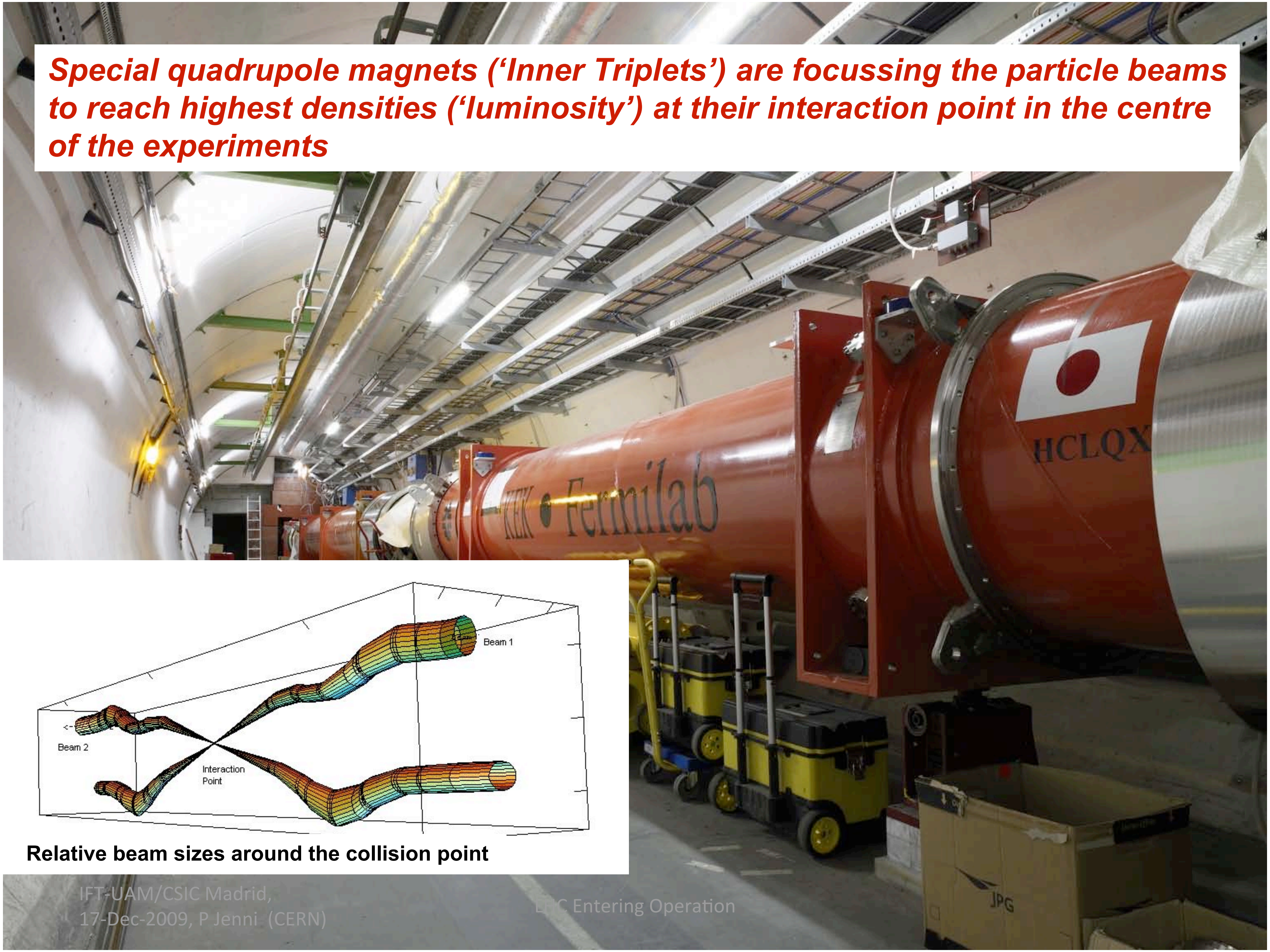




	LHC at 7 TeV	LEP at 100 GeV
Synchrotron radiation loss	6.7 keV/turn	3 GeV/turn
Peak accelerating voltage	16 MV/beam	3600 MV/beam

Note: The acceleration is not such a big issue in pp colliders (unlike in e^+e^- colliders), because of the ~ $1/m^4$ behaviour of the synchrotron radiation energy losses [~ E^4_{beam}/Rm^4]

Special quadrupole magnets ('Inner Triplets') are focussing the particle beams to reach highest densities ('luminosity') at their interaction point in the centre of the experiments



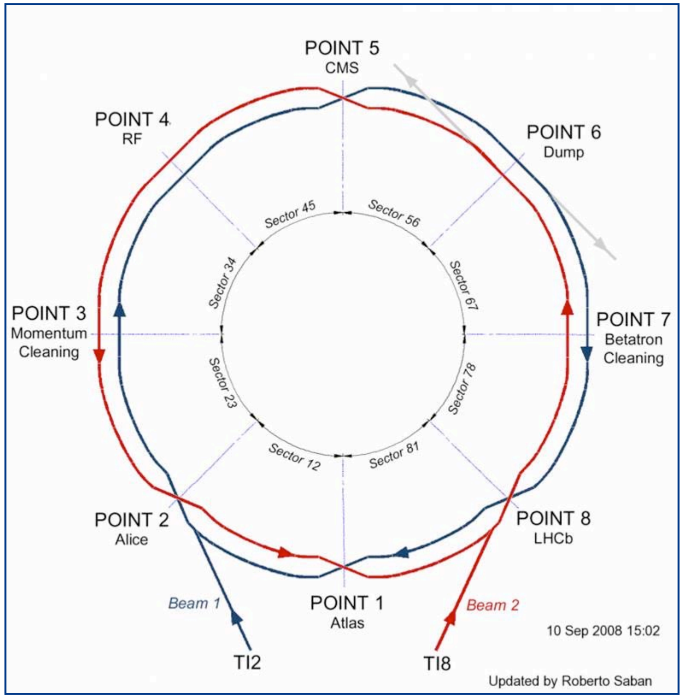
Relative beam sizes around the collision point

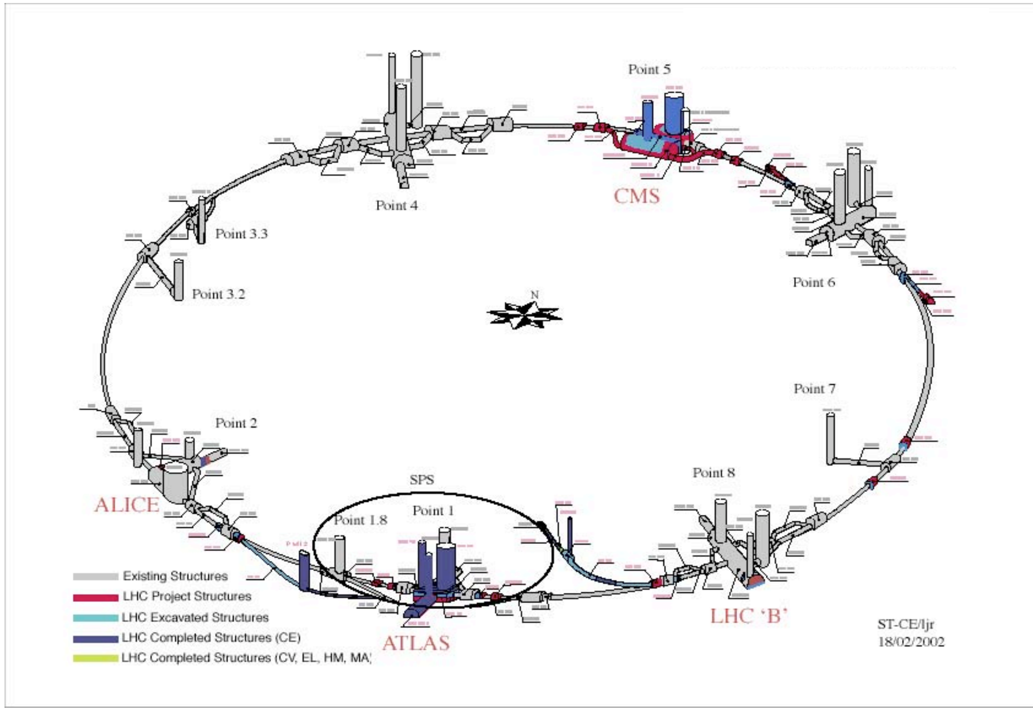
10 September 2008: LHC inauguration day

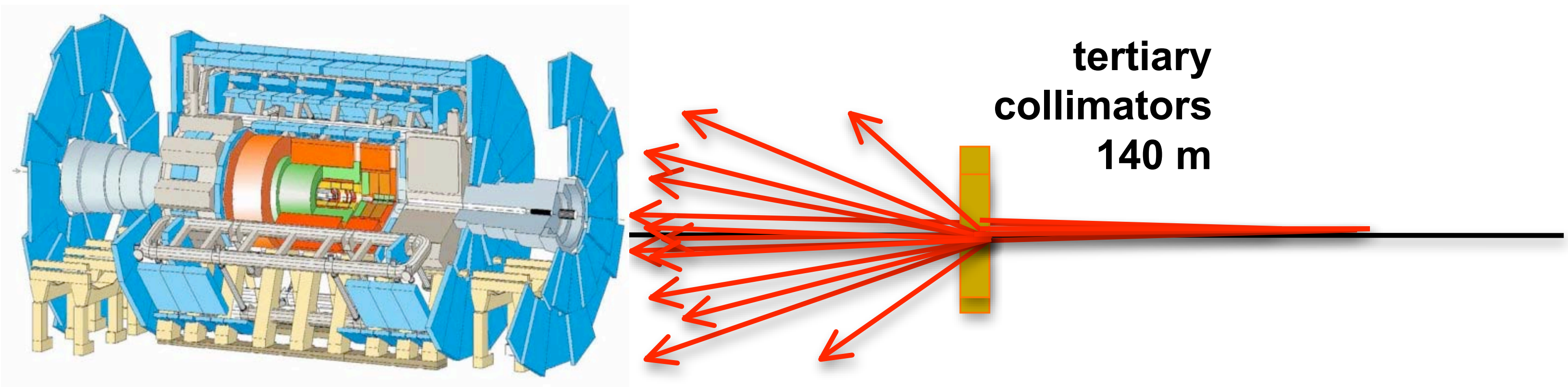
First (single) beams circulating in the machine

Five CERN DGs, from conception to realization: Schopper, Rubbia, Llewellyn Smith, Maiani, Aymar (from right to left)

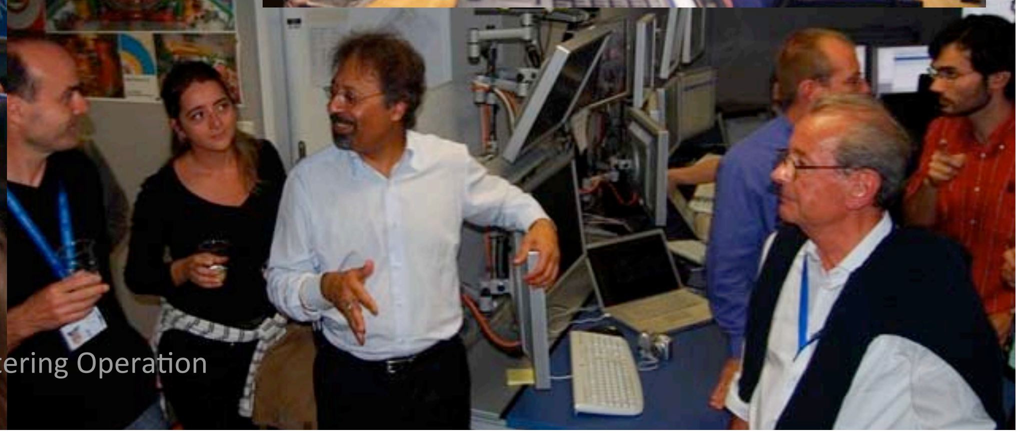
First LHC Single Beam on 10th September 2008



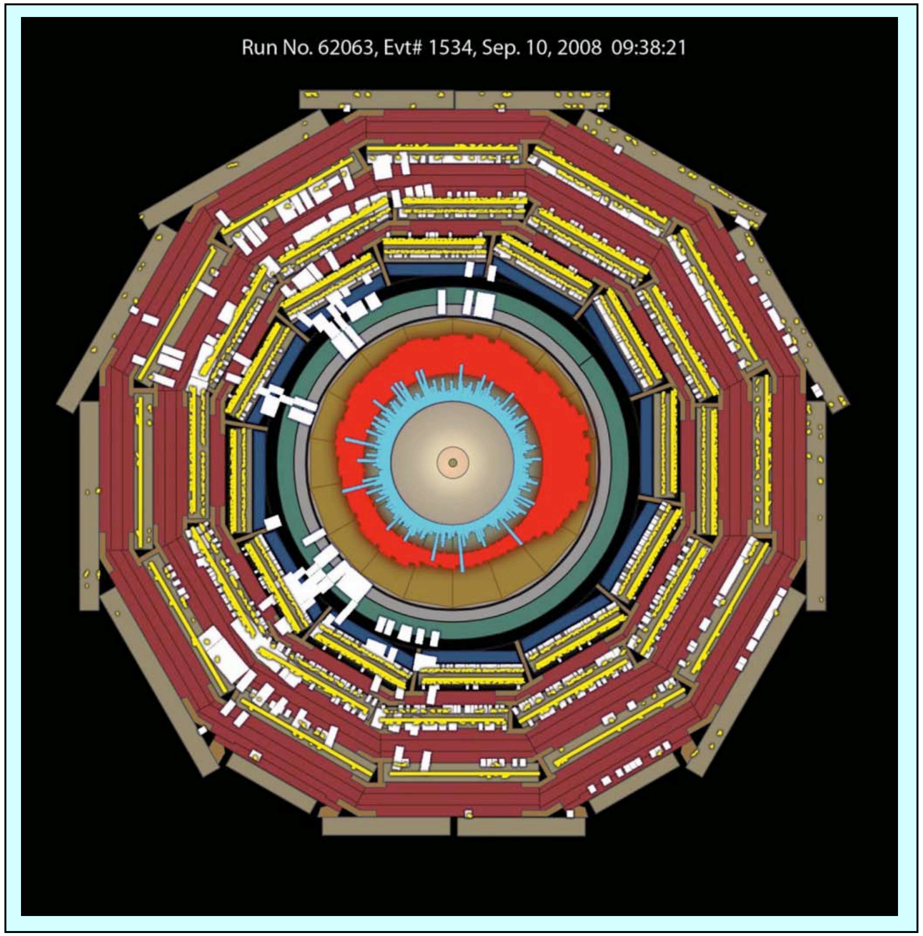




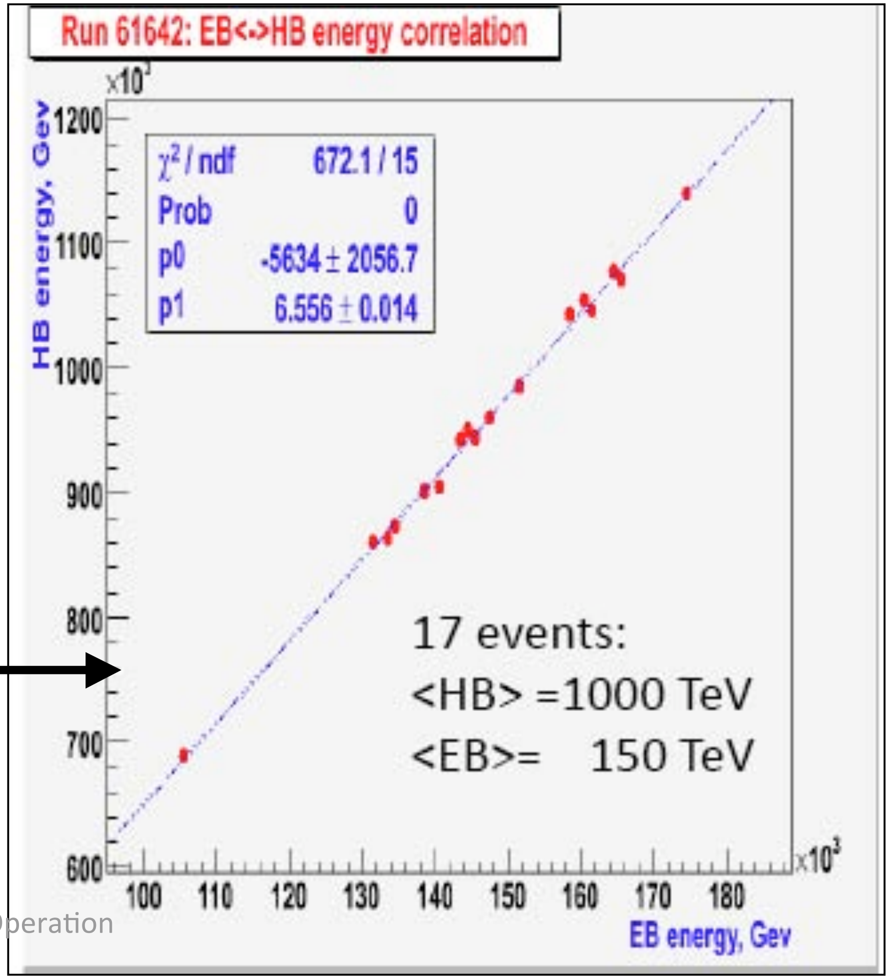
10th September 2008 in the CMS Control room



Event splash recorded on 10 September at 9:54



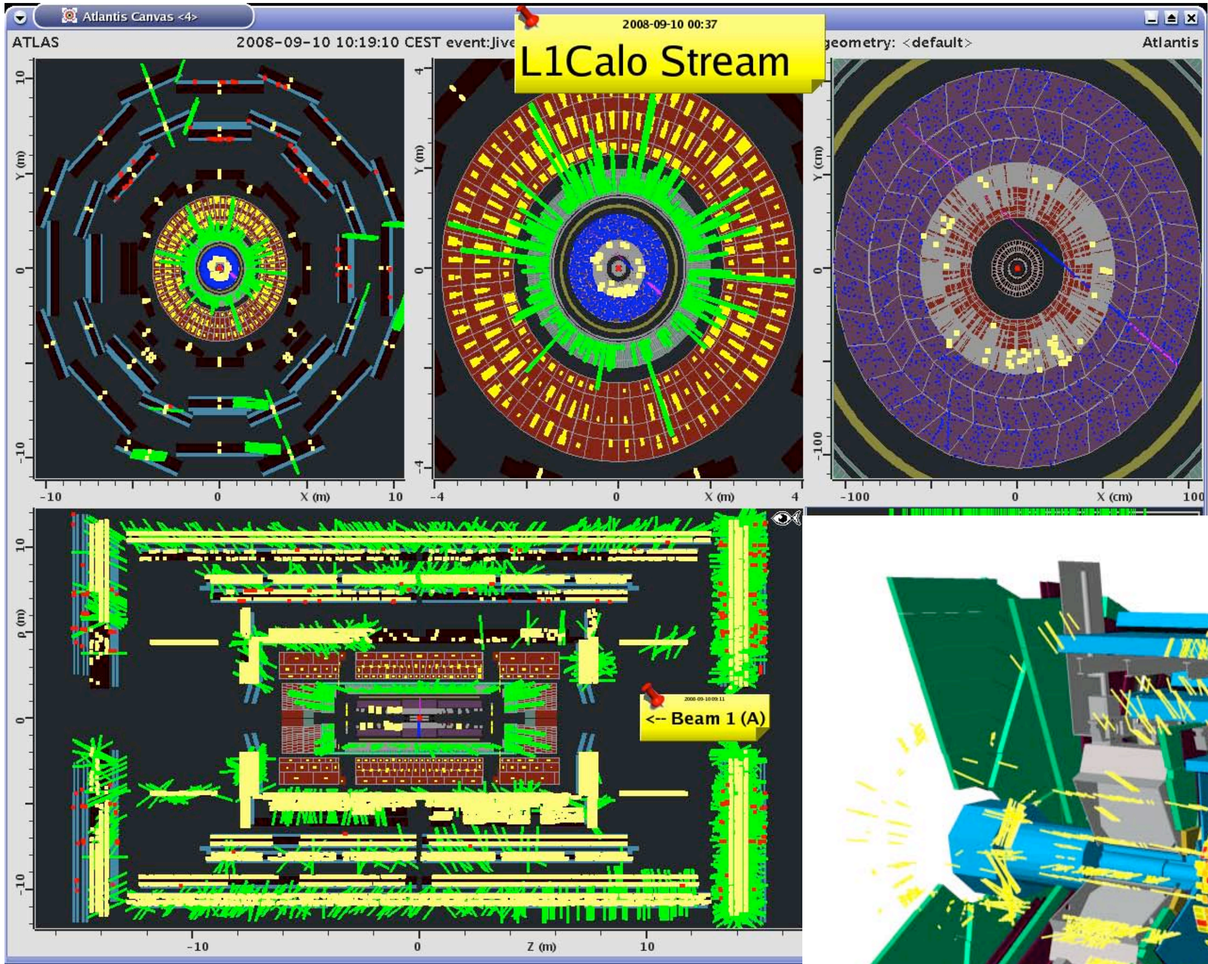
CMS preliminary



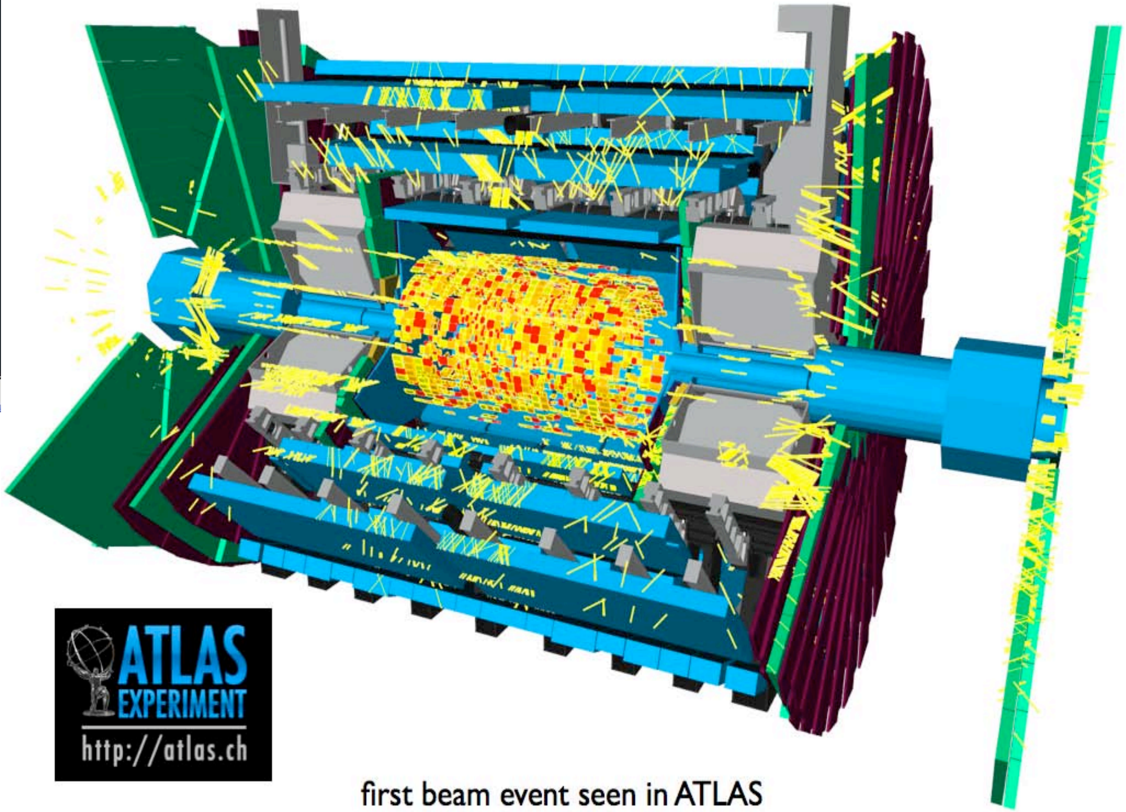
Correlation between the energies measured in the barrel EM and in the barrel HAD calorimeters in beam splash events.

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

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



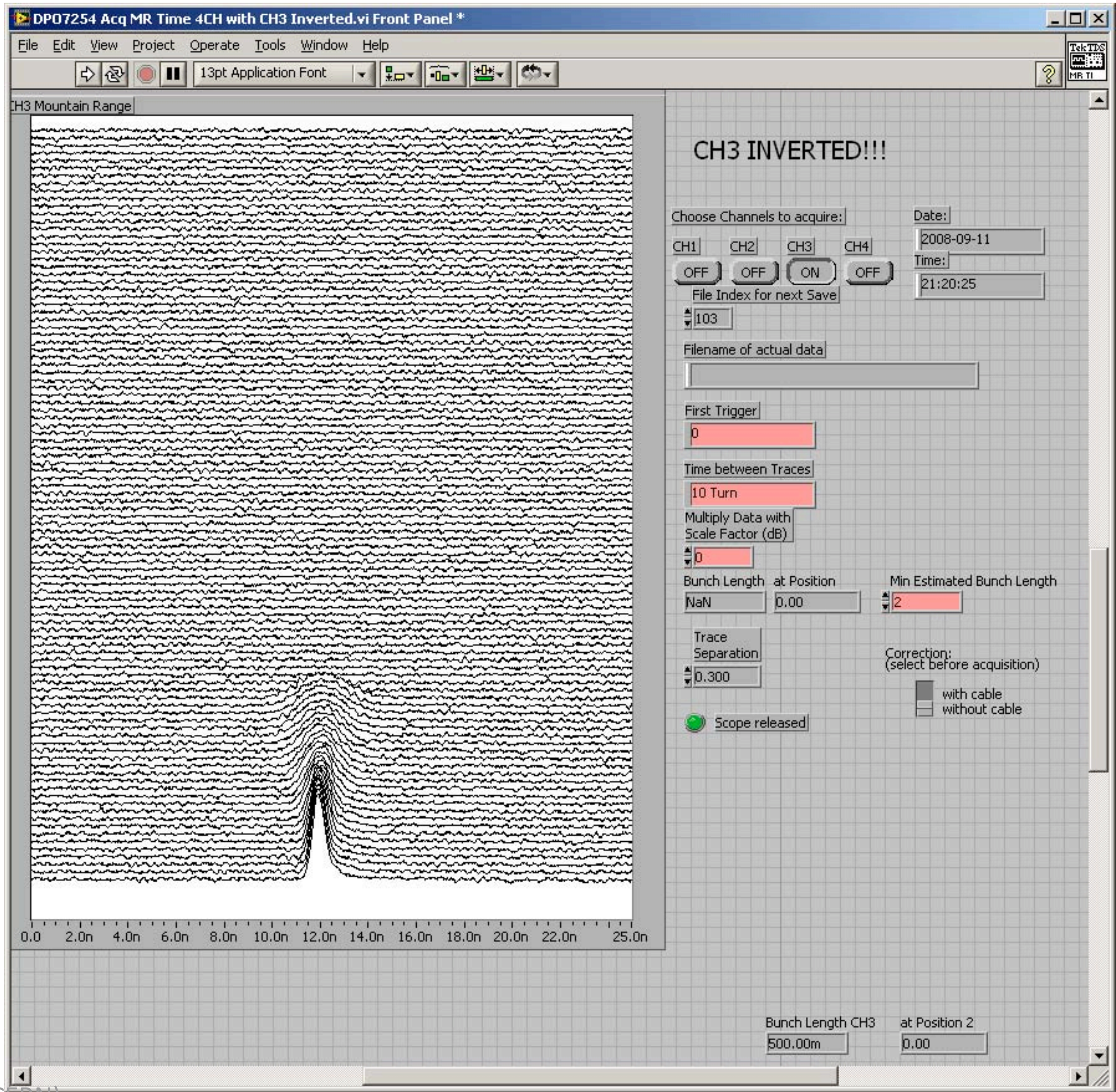
Online display



first beam event seen in ATLAS

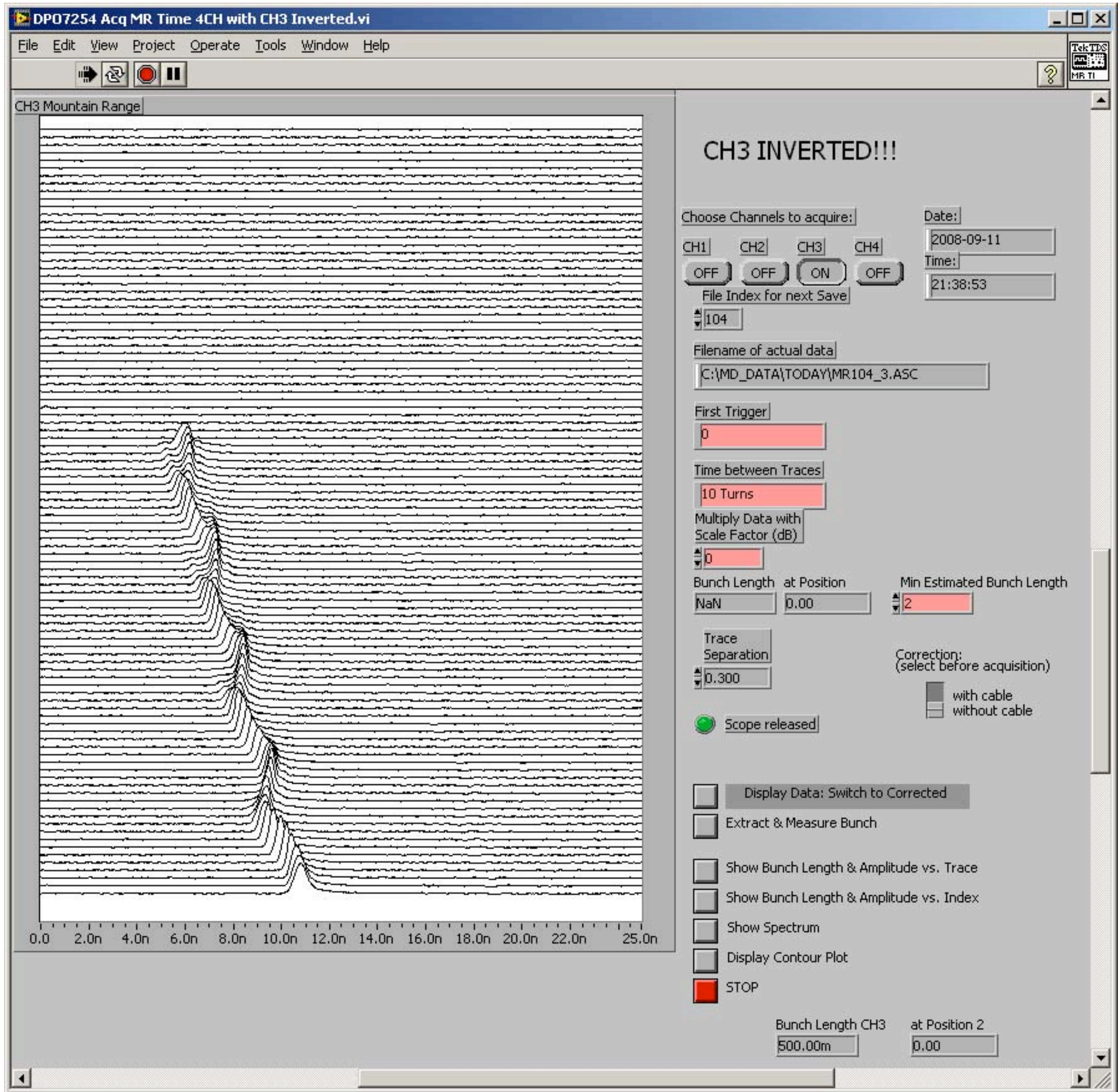
Offline display

No RF, debunching in ~ 25*10 turns, i.e. roughly 25 ms



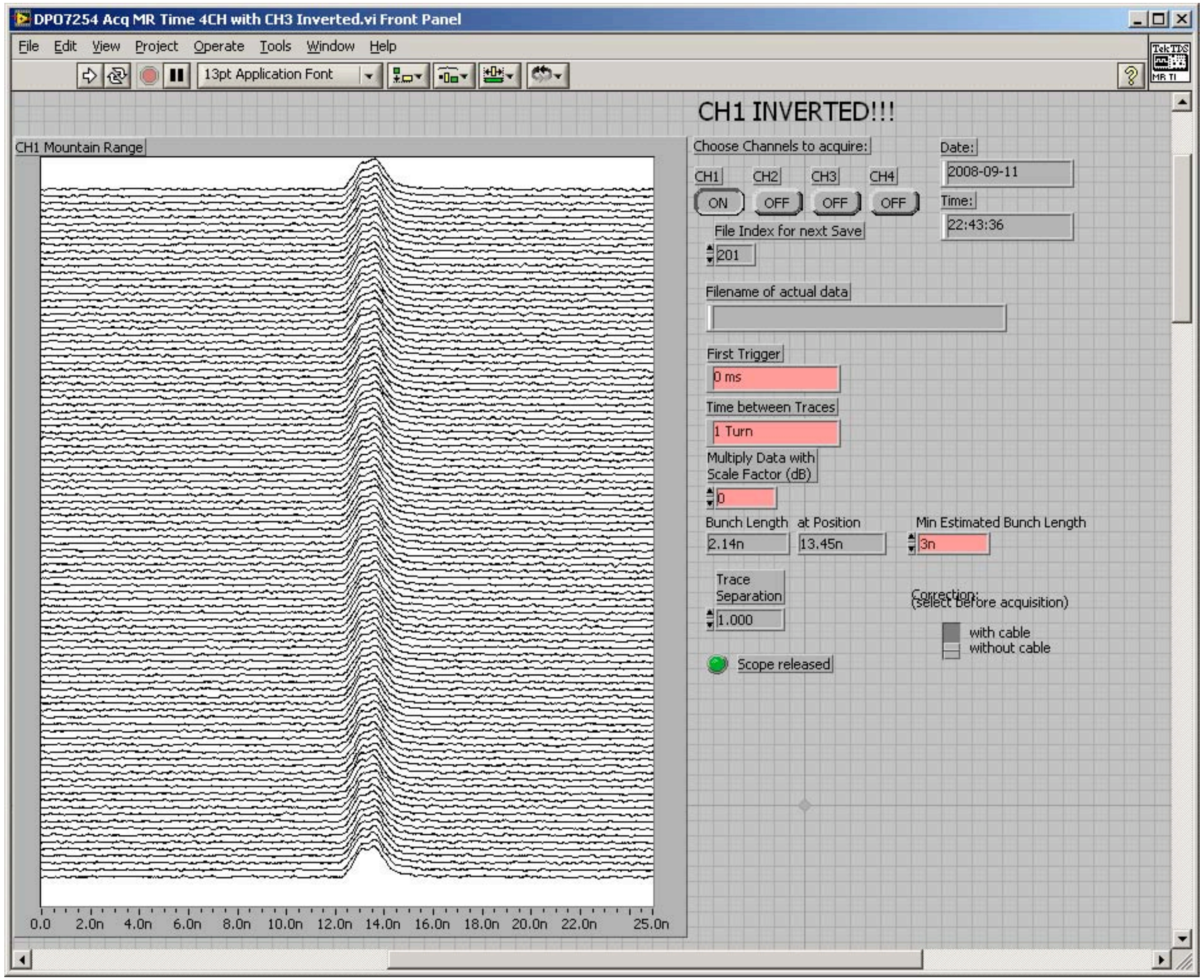
Courtesy E. Ciapala

Capture with first order corrected injection phasing



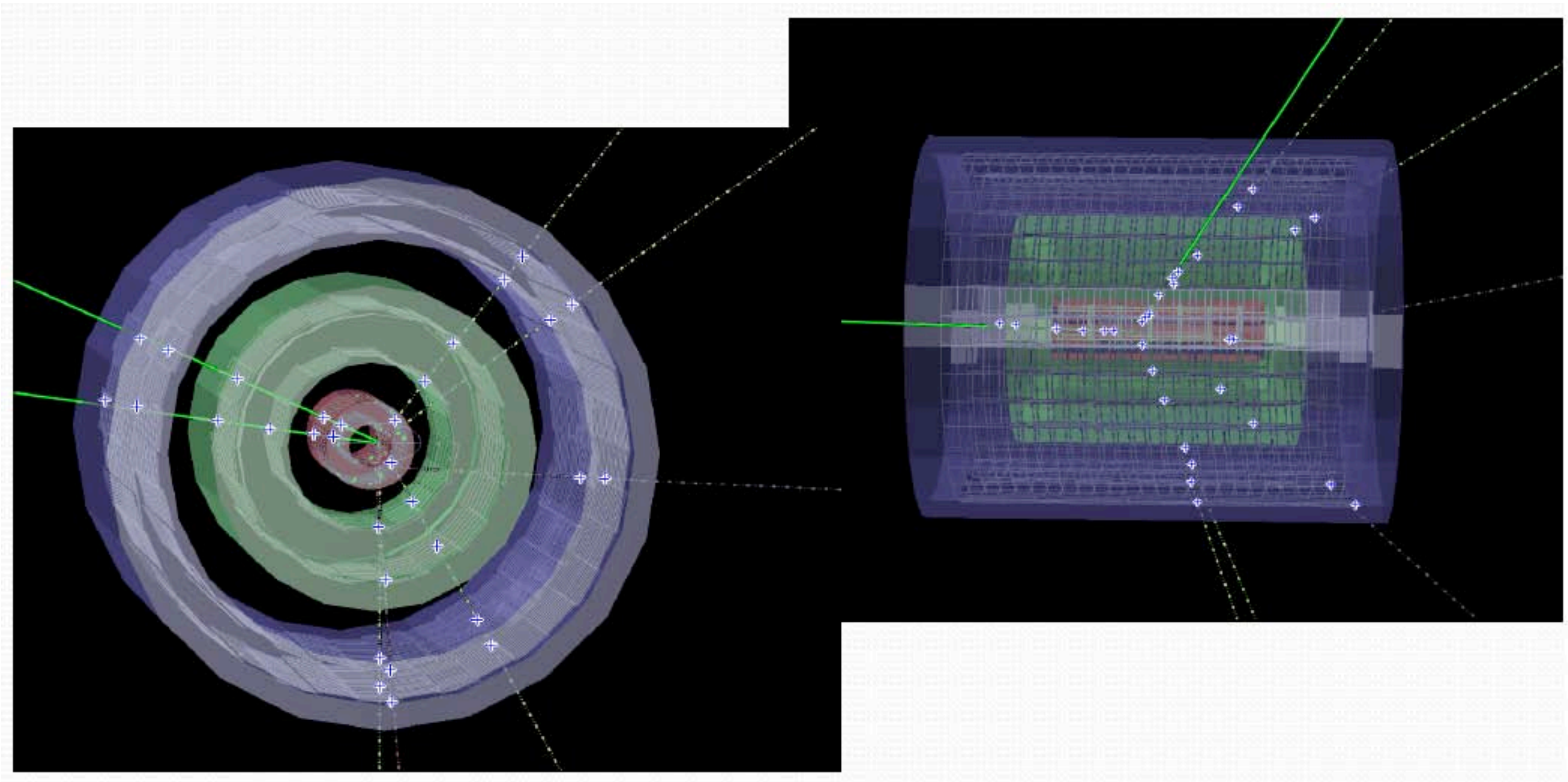
Courtesy E. Ciapala

Capture of the first LHC beam with optimum injection phasing, correct reference



Courtesy E. Ciapala

First 'interaction' (in ALICE beam pipe…) 12th Sept. 2008



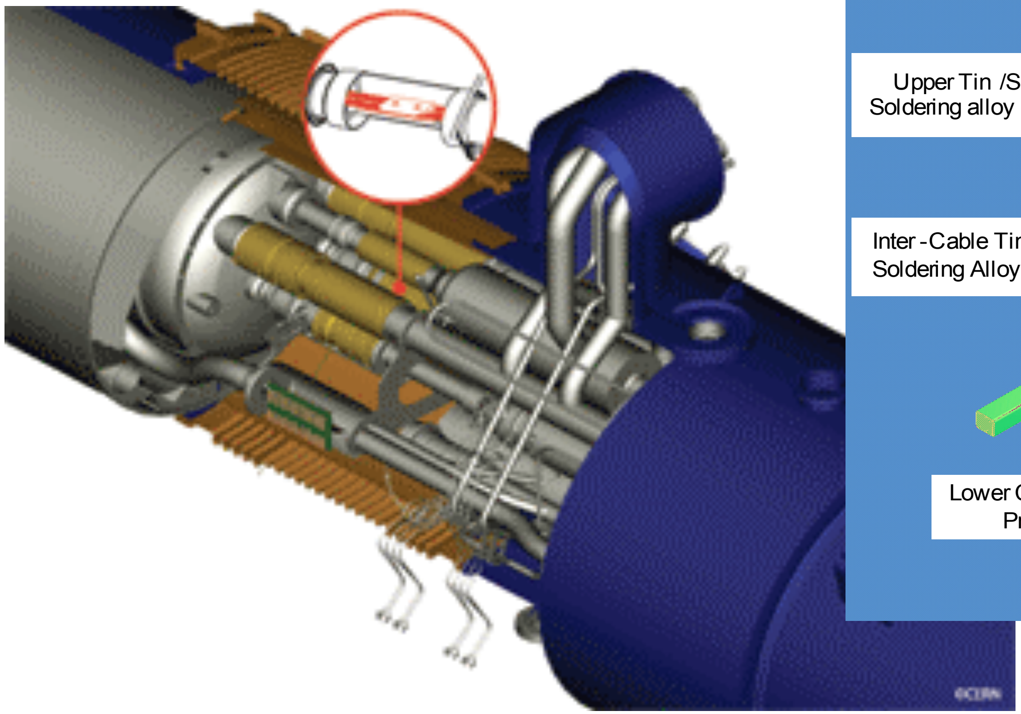
ITS tracks on 12.9.2008
7 reconstructed tracks, common vertex

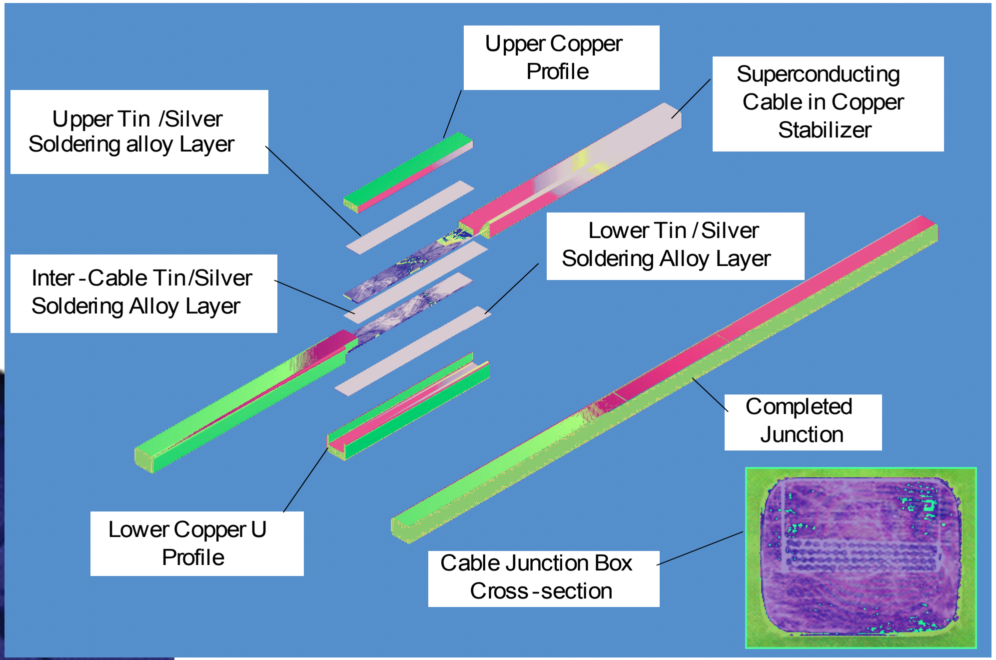
Circulating beam 2:
stray particle causing an interaction in the ITS

Incident on 19th September 2008

The LHC decided to use a few days of down-time due to a 'standard' power converter fault to finish work on missing powering tests in sector 3-4 (all other sectors were tested to 5.5 TeV equivalent currents)

At 8.7 kA (corresponding to ~ 5.1 TeV), a resistive zone appeared in the superconducting busbar between quadrupole Q24 and the neighboring dipole (due to a bad welding 'splice')



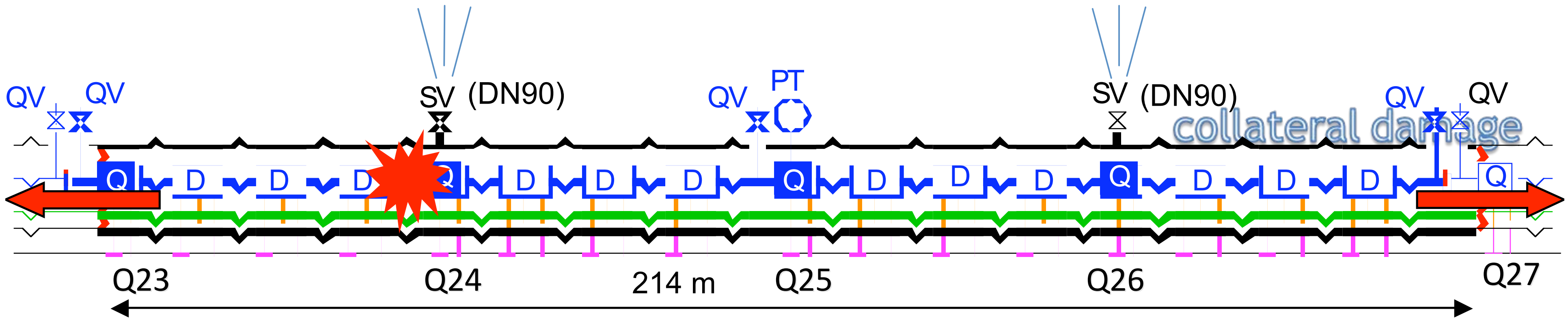


Interconnections of two magnets

Most likely, an electrical arc developed, which punctured the Helium enclosure

Large amounts of Helium gas were released into the insulating vacuum of the cryostat:

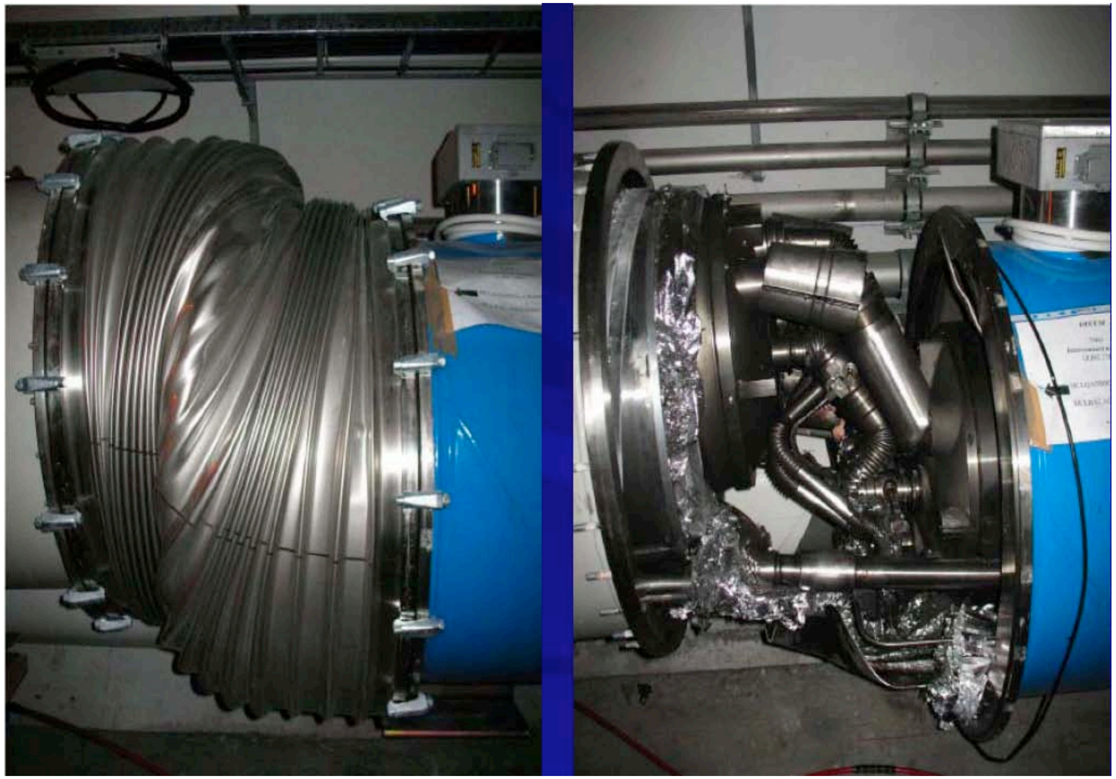
- **Self actuating relief valves opened, releasing large amount of He in the tunnel, but could not handle huge pressure**
- **Hence, large pressure waves traveled along the accelerator both ways**
- **Large forces exerted on the vacuum barriers located every 2 machine cells**
- **These forces displaced several quadrupoles by up to ~50 cm**
- **Beam pipes broke as well, vacuum contaminated**



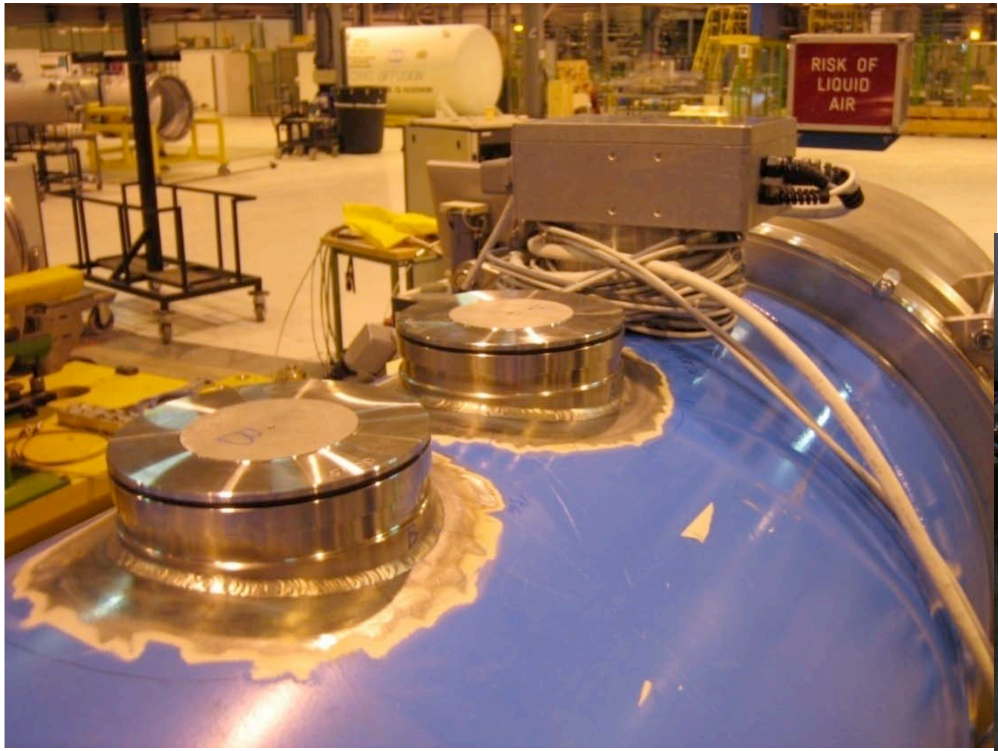
Examples of collateral damage

High pressure build-up damaged the magnet interconnects and the super-insulation

Perforation of the beam tubes resulted in pollution of the vacuum system with soot from the vaporization and with debris from the super insulation.

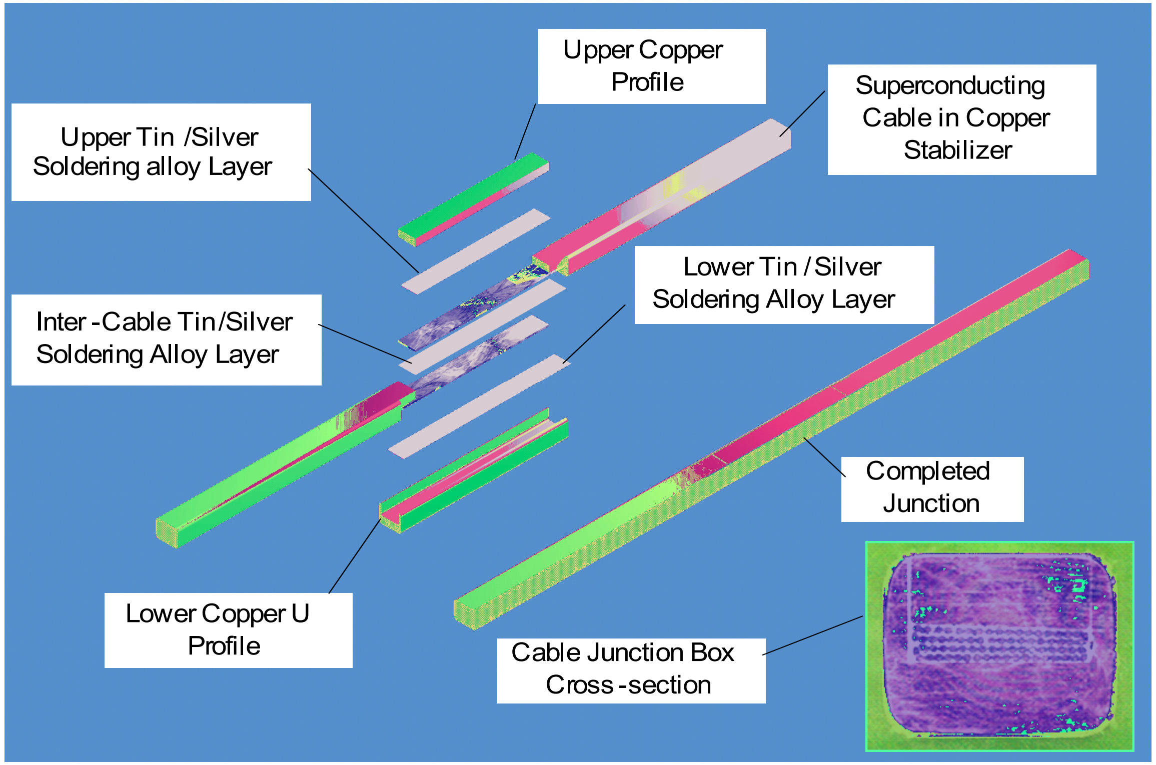


Illustrating some of the preventive measures

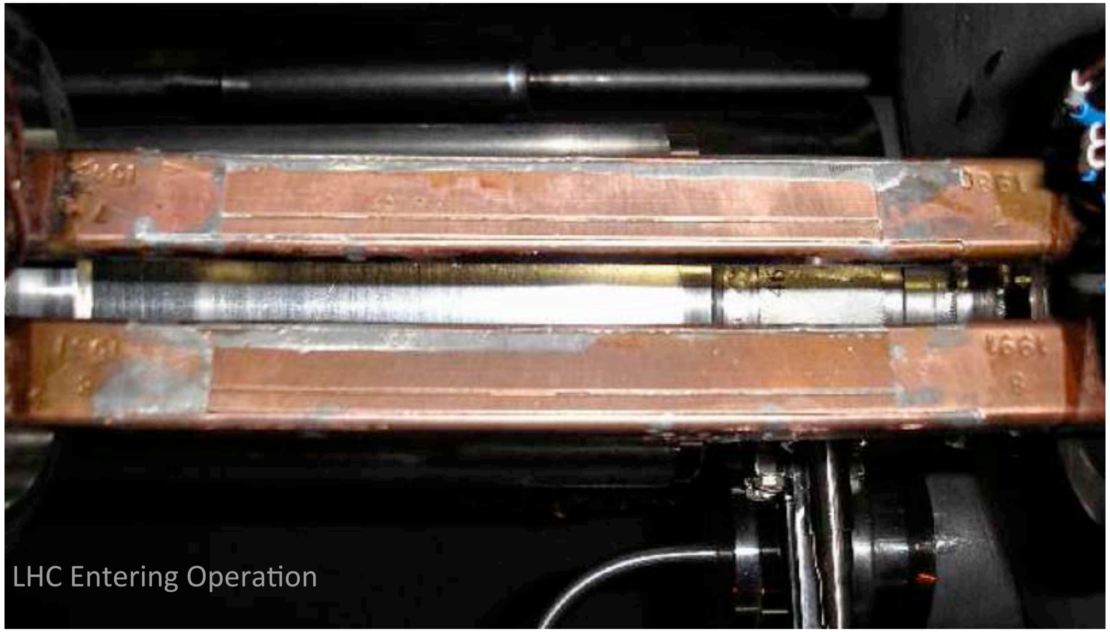


Pressure relieve valves on dipoles

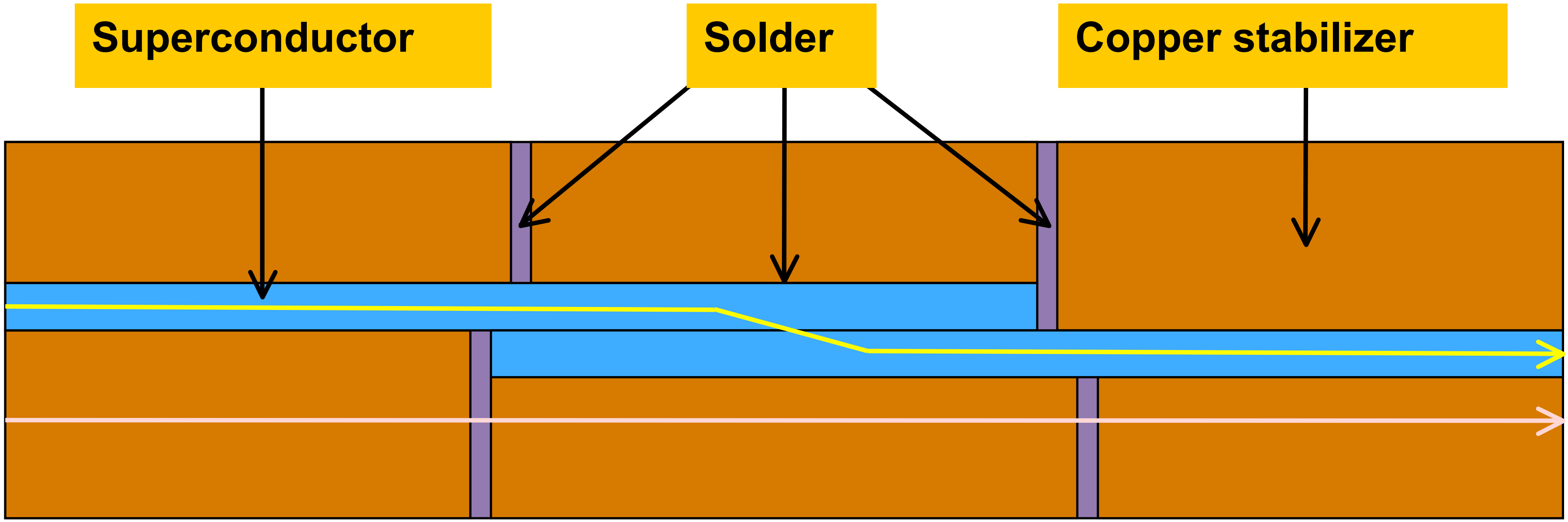
New additional anchoring system

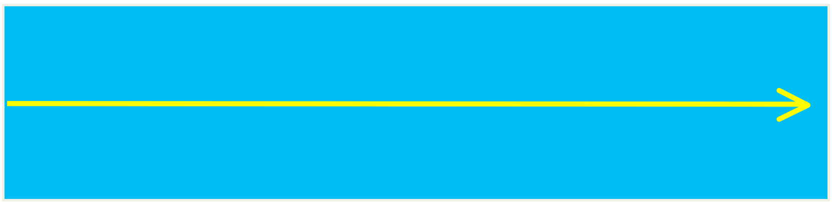


Busbar splices



Energy presently dictated by LHC Interconnects





Current flow at 1.9K

Good joint resistance < 1 nΩ

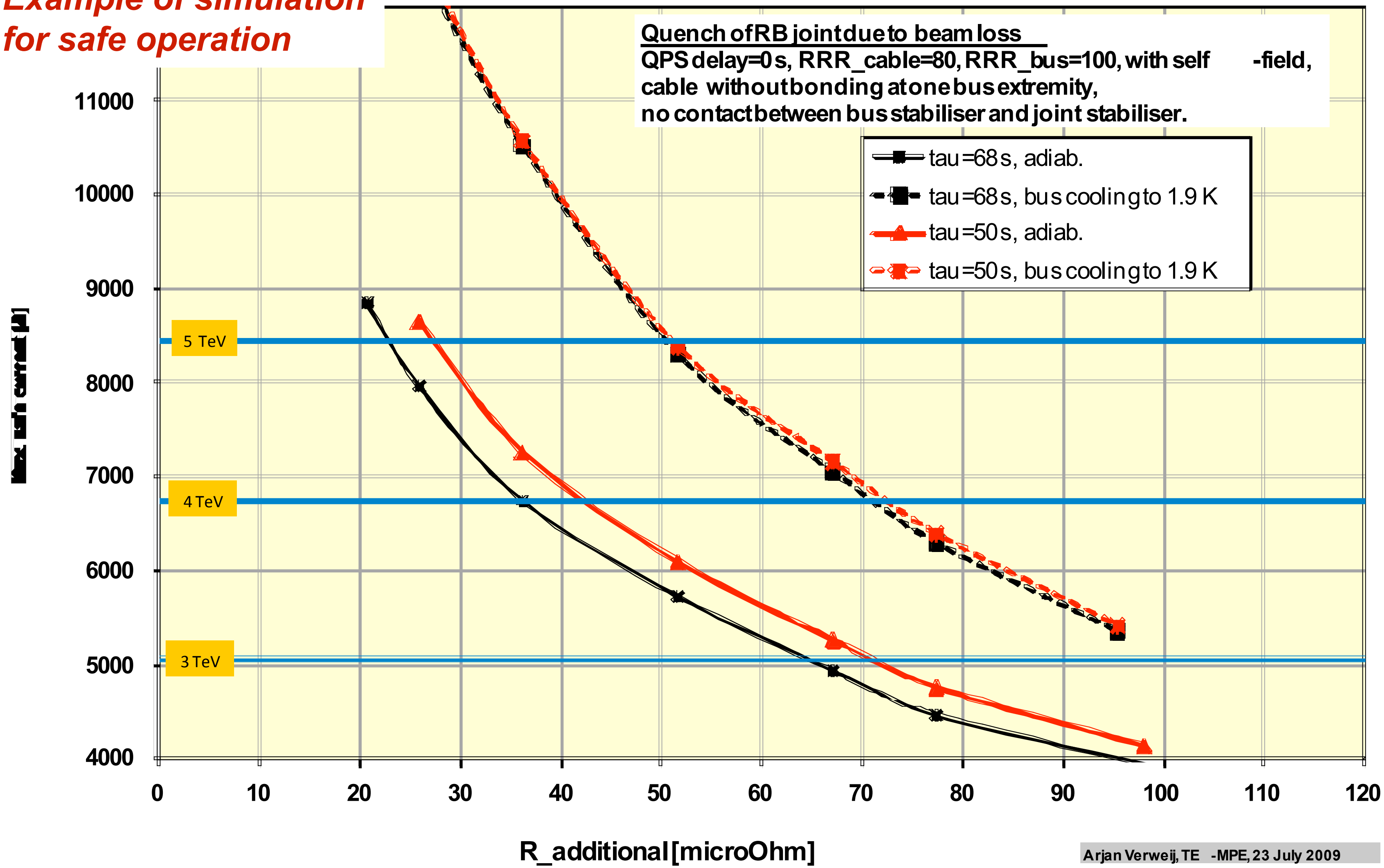
Current flow after a quench

Good joint resistance < 10 μΩ

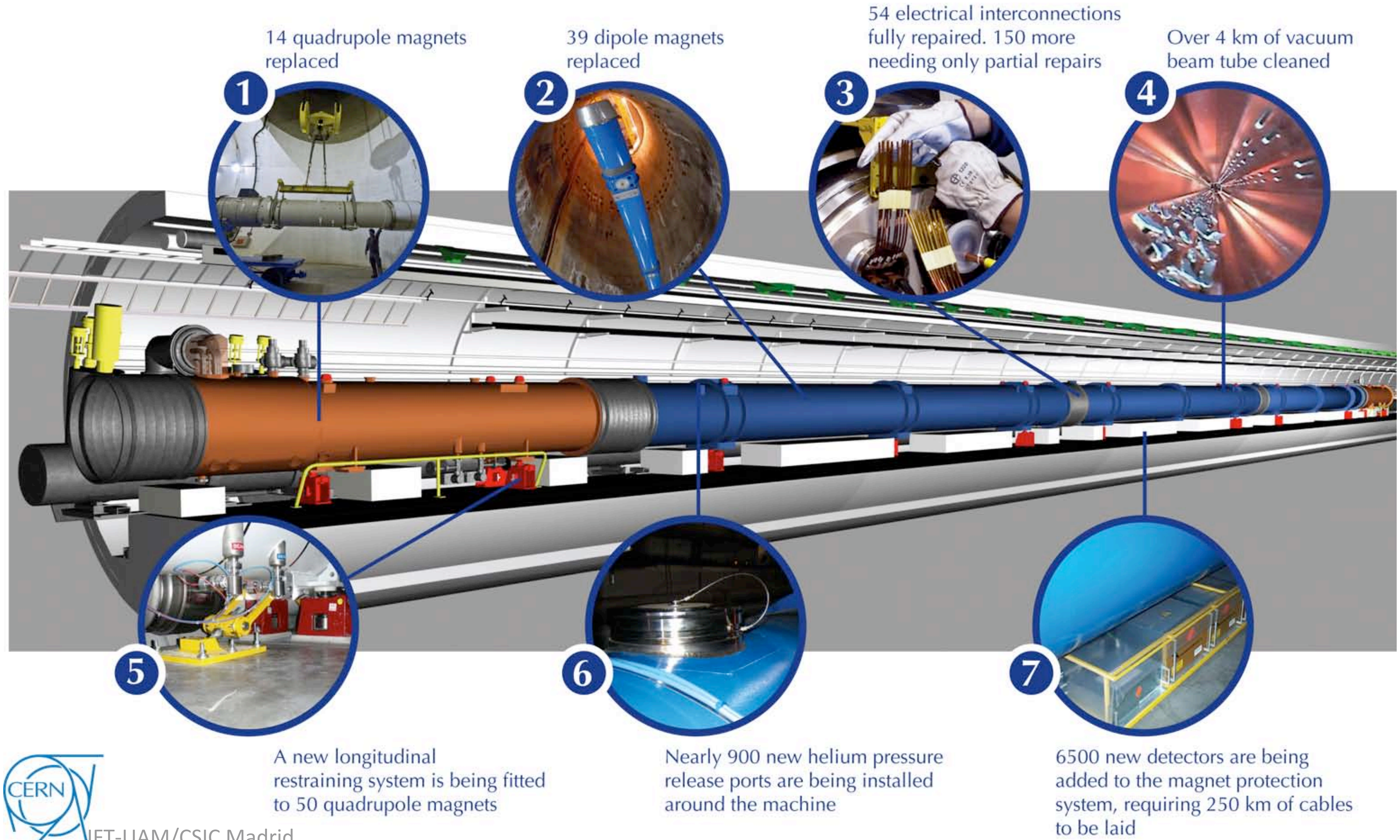
Simulations: Maximum safe currents vs copper joint resistance

RB: case 1 (quench in 1.9 K environment)

Example of simulation for safe operation



The LHC repairs in detail



Energy 2009 - 2010

- **During commissioning of new Quench Protection System Q4 2009**
  - **Breakdown at operational voltage – traced to connector quality**
  - **Obliged to run at lower voltage**
  - **OK for 3.5TeV (but with limited safety margin)**
  - **Need to change thousands of connectors**

- **Incurred delays in commissioning circuits to 6kA (for 3.5 TeV beam)**
  - **Target for 2009 2kA (allows to get to 1.18 TeV beam with small margin)**

- **Result**
  - **Beam energy 2009 1.18 TeV**
    - **Commissioning with beam (450 GeV collisions and ramp to 1.18 TeV)**
  - **Fix (some of) connectors and commission circuits to 3.5 TeV beam** **January**
  - **Beam energy first part of 2010 3.5 TeV**
    - **Physics at 7 TeV (few months)**
  - **Fix (rest of) connectors and commission circuits to 5TeV beam** **Summer**
  - **Beam energy second part of 2010 5 TeV**
    - **Physics at 10 TeV (few months)**

Higher Energies

- **Route to energies > 5 TeV blocked by 3 things**
  - **Pressure relief valves needed on dipoles in sectors 23 45 78 81**
  - **Interconnects**
    - **Only 3.5 TeV is sure**
    - **5 TeV is likely in 2010**
    - **Intervention needed to go higher**

Task force launched end of October
Define how to get to 7 TeV
Conclude by mid 2010

  - **Retraining of dipole magnets**
    - **All magnets reached 7 TeV in the SM18 tests**
    - **Installed sectors (with one notable exception!) all reached 5TeV**
    - **Detraining seen when pushing to higher fields in 2008 (sector 56)**
      - **Storage ?**
      - **Transport ?**
      - **Thermal cycle ?**
      - **Interconnections ?**

Can't investigate empirically until interconnects are sorted out

    - **Status (Chamonix 2009)**
      - **6 TeV looks easy (~10 quenches)**
      - **6.5 TeV looks harder (~100 quenches)**
      - **7 TeV looks harder still (~1000 quenches)**

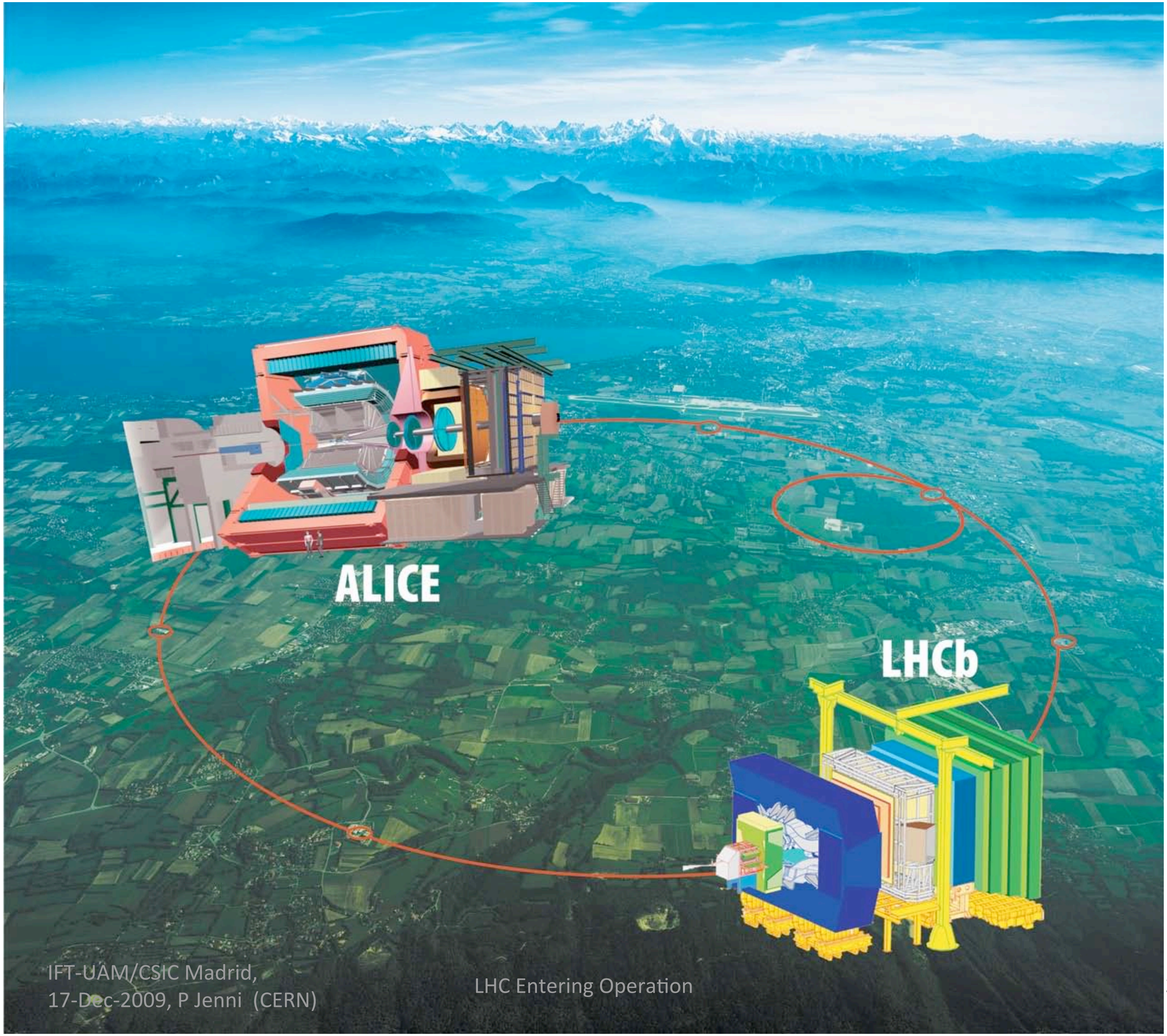
The LHC World of CERN

CMS
2900 Physicists
184 Institutions
38 countries
550 MCHF

ALICE
1000 Physicists
105 Institutions
30 countries
150 MCHF

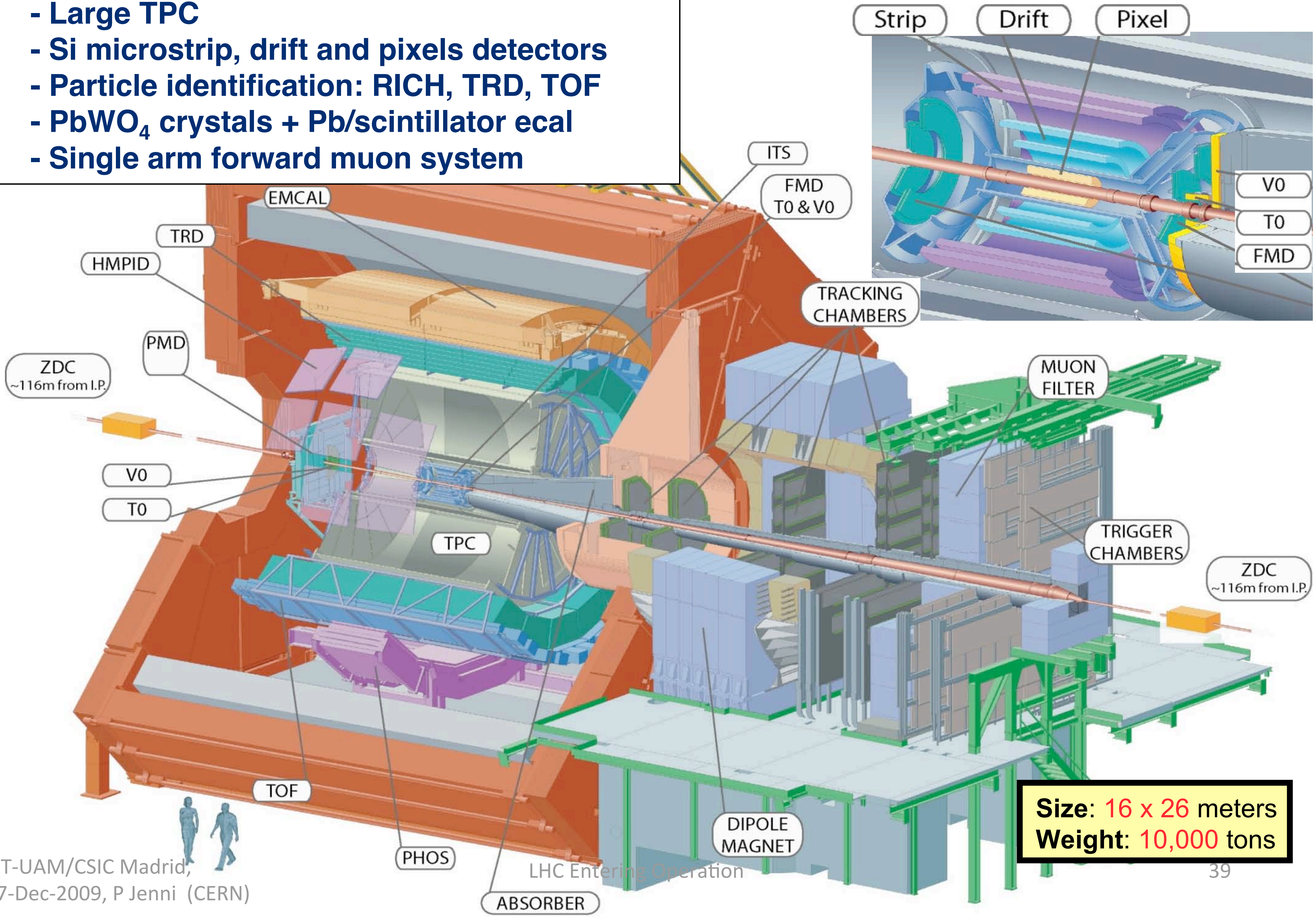
LHCb
700 Physicists
52 Institutions
15 countries
75 MCHF

ATLAS
2900 Physicists
172 Institutions
37 countries
550 MCHF

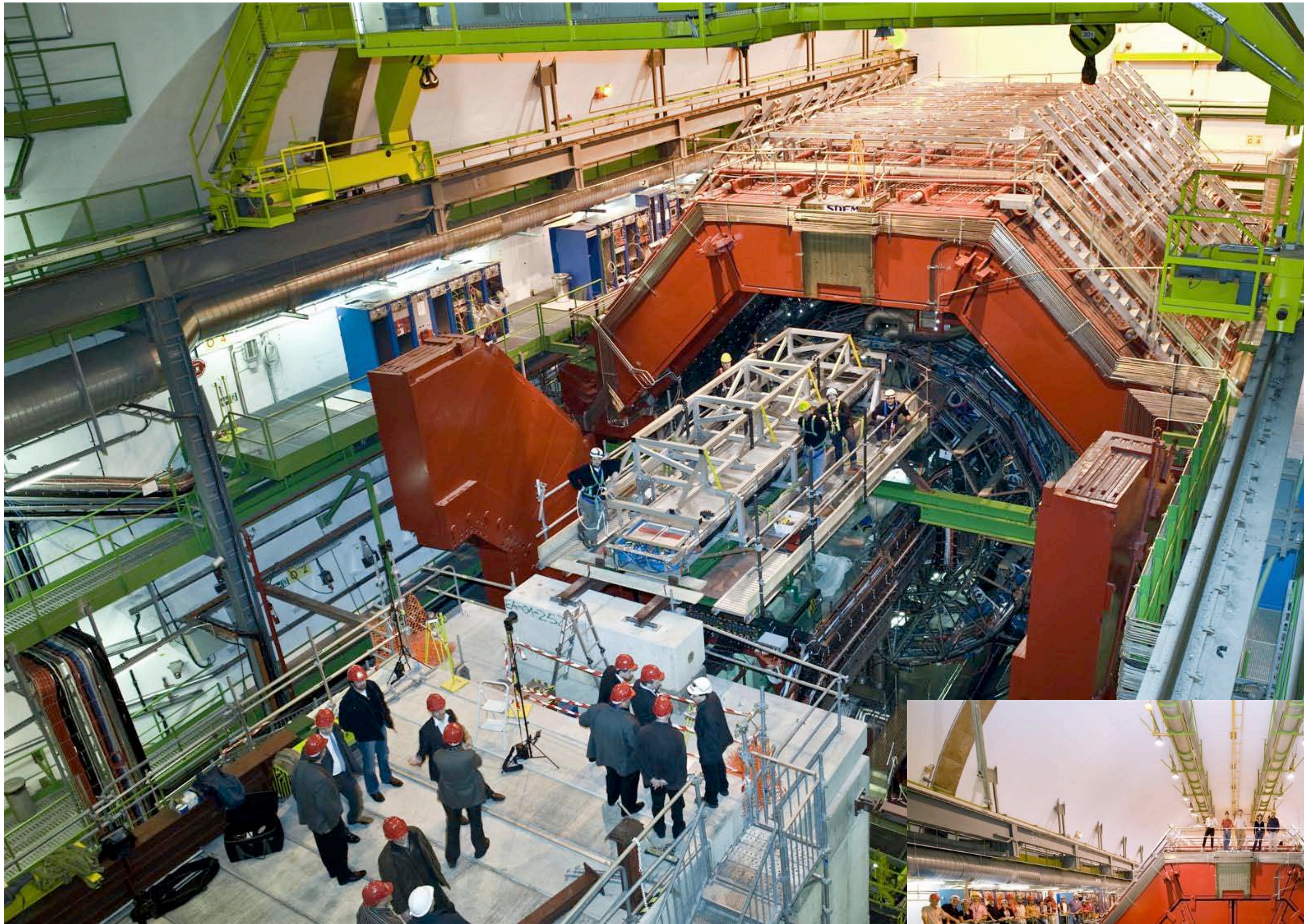

ALICE
LHCb

ALICE: study of quark-gluon plasma

- L3 solenoid
- Large TPC
- Si microstrip, drift and pixels detectors
- Particle identification: RICH, TRD, TOF
- $PbWO_4$ crystals + Pb/scintillator ecal
- Single arm forward muon system



Size: 16 x 26 meters
Weight: 10,000 tons

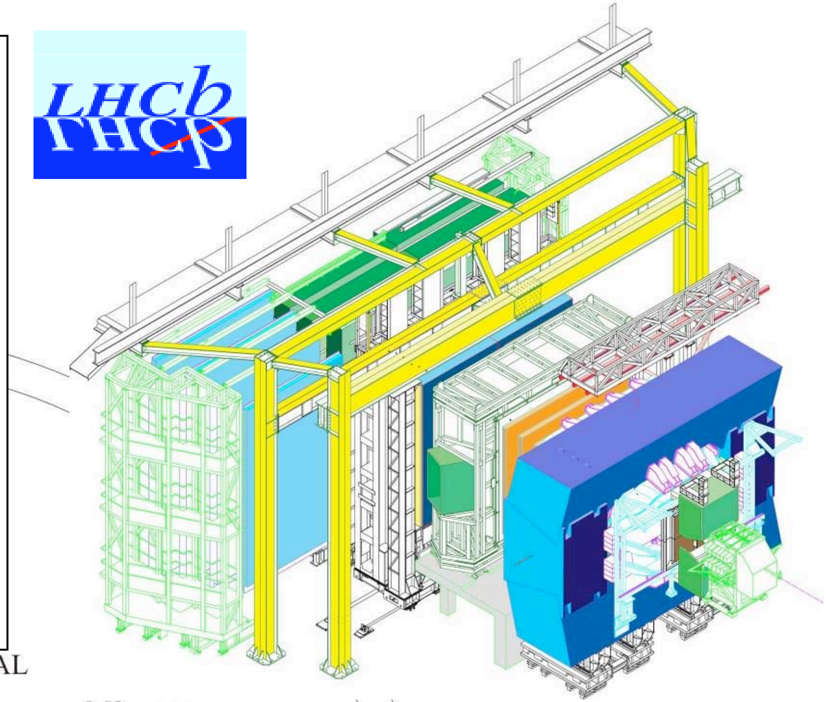


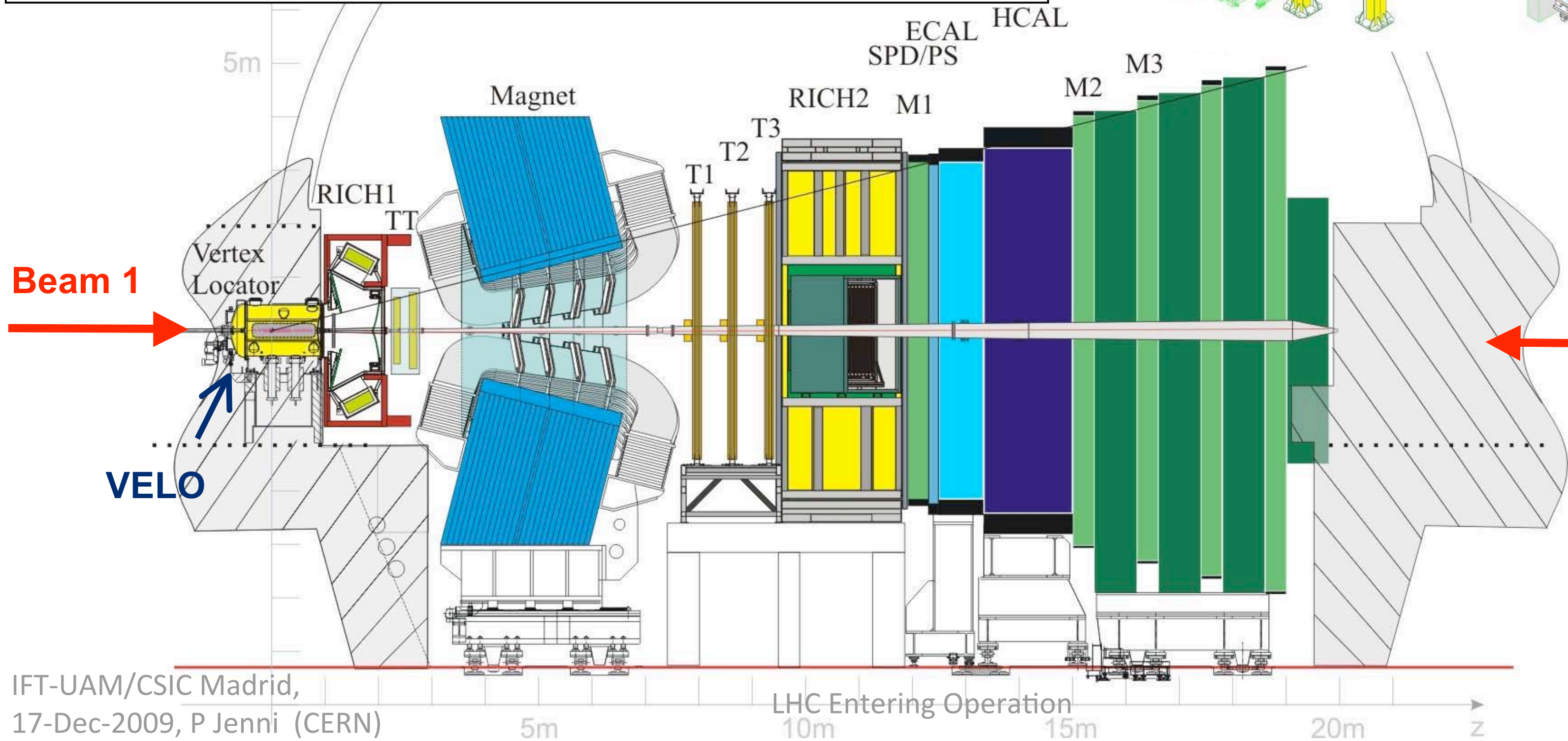
Installation of a ALICE TOF module May 2008

Formal end of ALICE installation July 2008

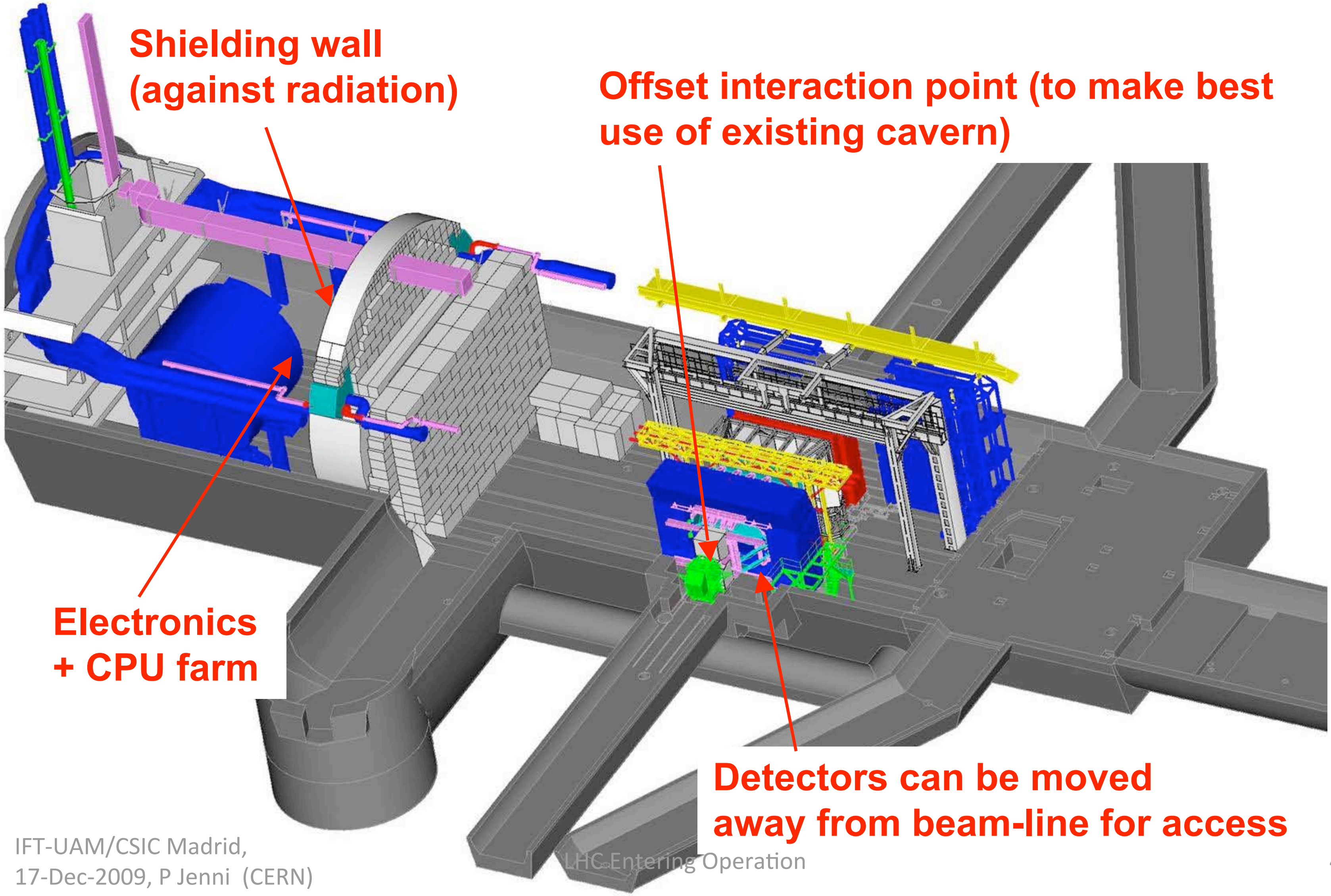
LHCb:
Study of B decays and CP Violation
(indirect search for New Physics)

- Dipole magnet (4 T.m)
- Particle Identification (2 RICH)
- 21 layer of Si microstrip vertex locator (VELO)
- Tracking: Silicon + long straw tubes
- Shashlik (Pb/scint) em calorimeter
- HCAL (Fe/scint),
- MWPC muon system

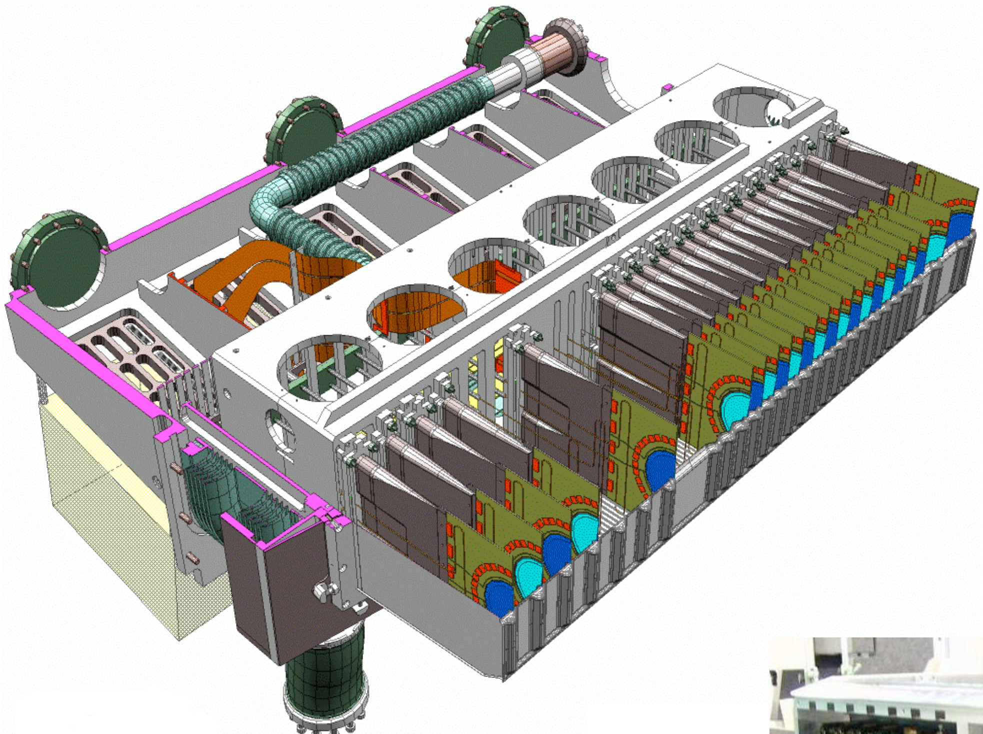


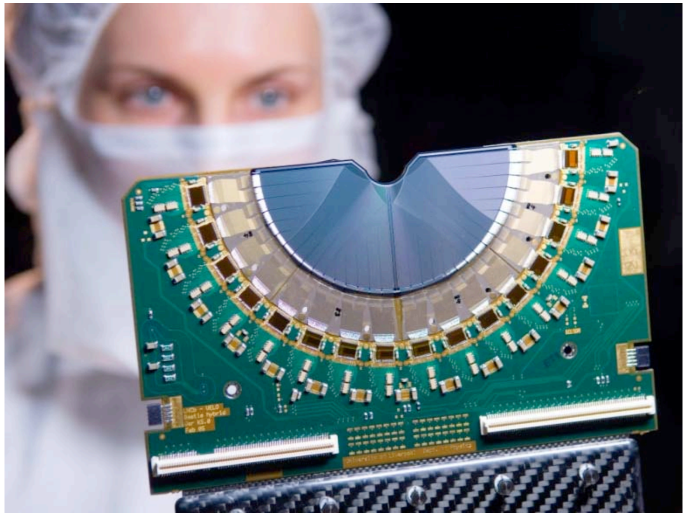


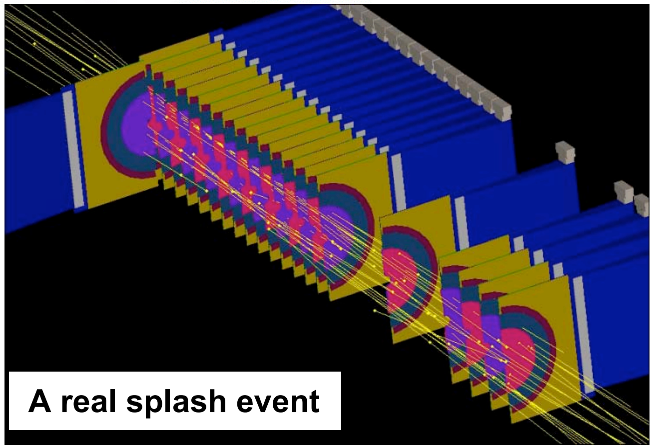
LHCb in its cavern (~100 m deep)

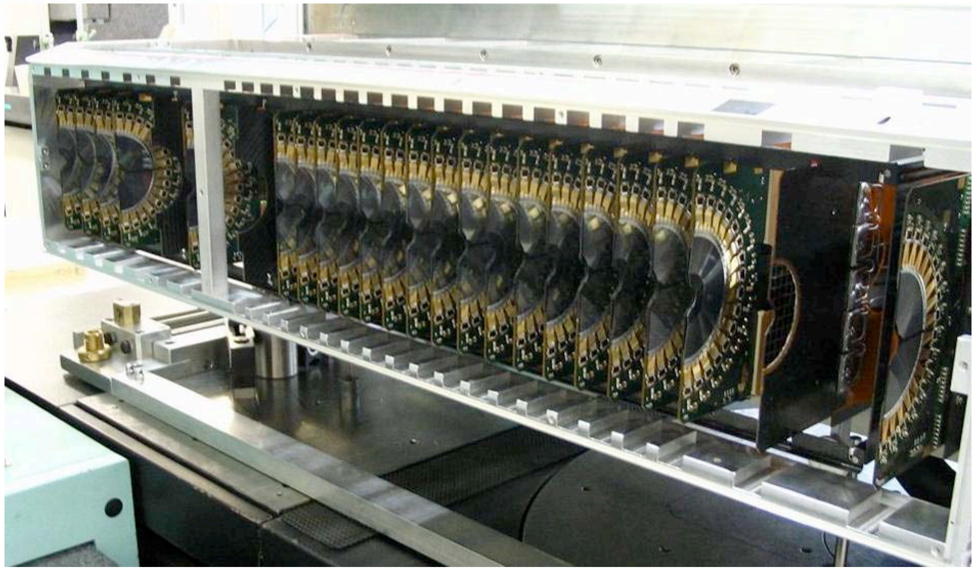


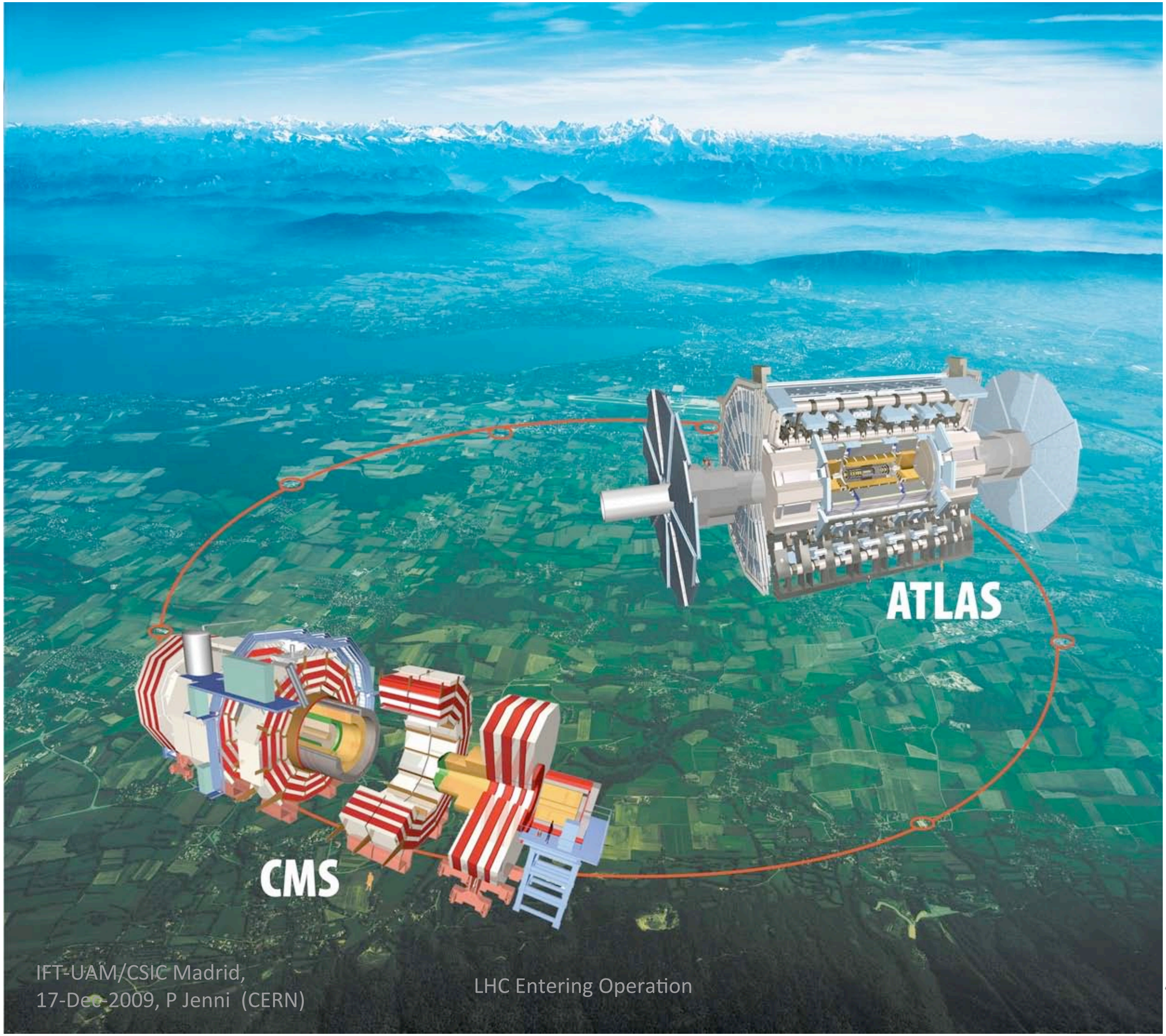
LHCb Vertex Locator (VELO)










ATLAS
CMS

CMS Detector

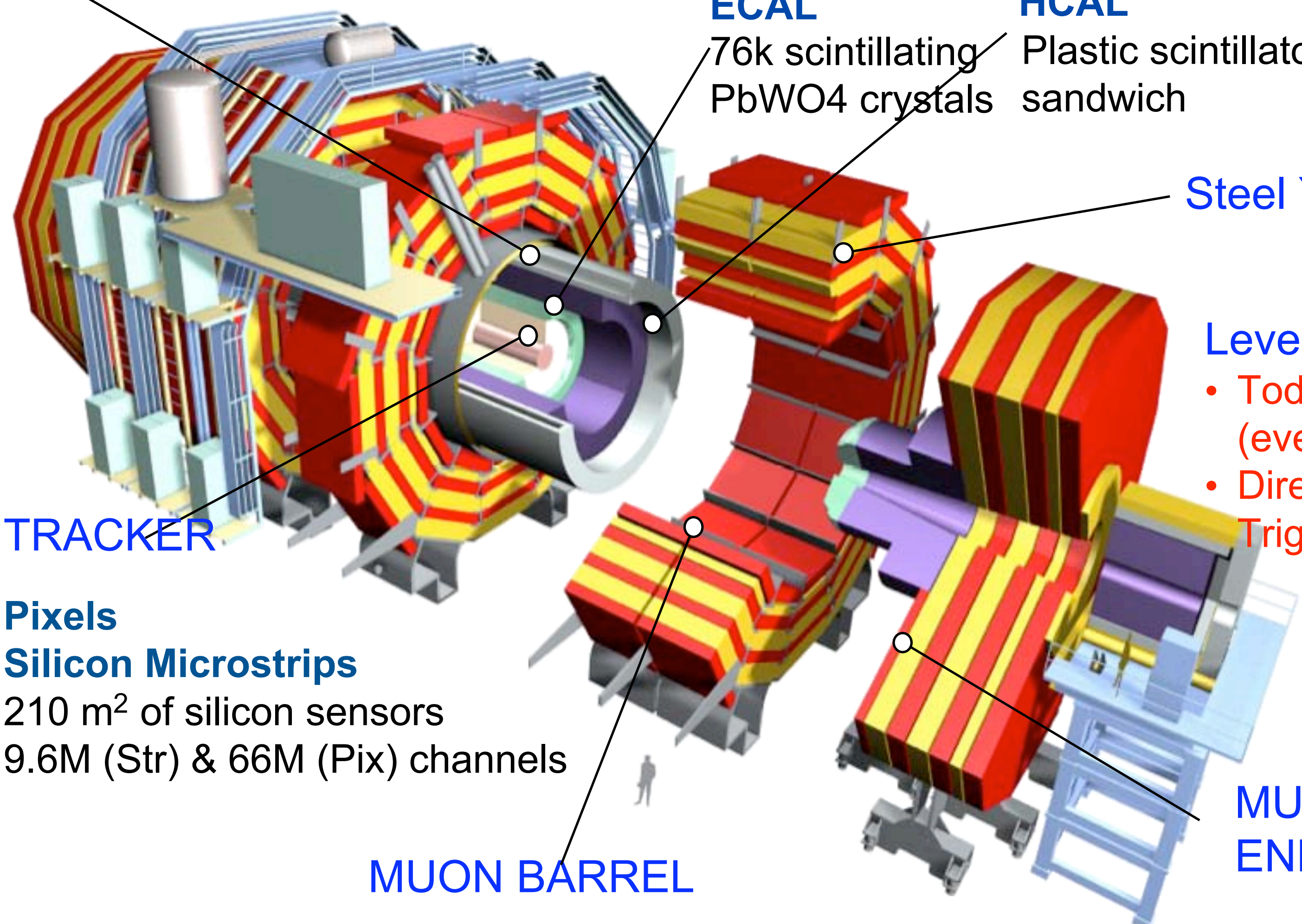
Superconducting Coil, 4 Tesla

CALORIMETERS

ECAL
76k scintillating PbWO4 crystals

HCAL
Plastic scintillator/brass sandwich

Steel YOKE



Level-1 Trigger Output
- Today: 50 kHz (eventually100 kHz)
- Directly feeds Higher Level Trigger CPU farm

TRACKER

Pixels
Silicon Microstrips
210 m^2 of silicon sensors
9.6M (Str) & 66M (Pix) channels

MUON BARREL

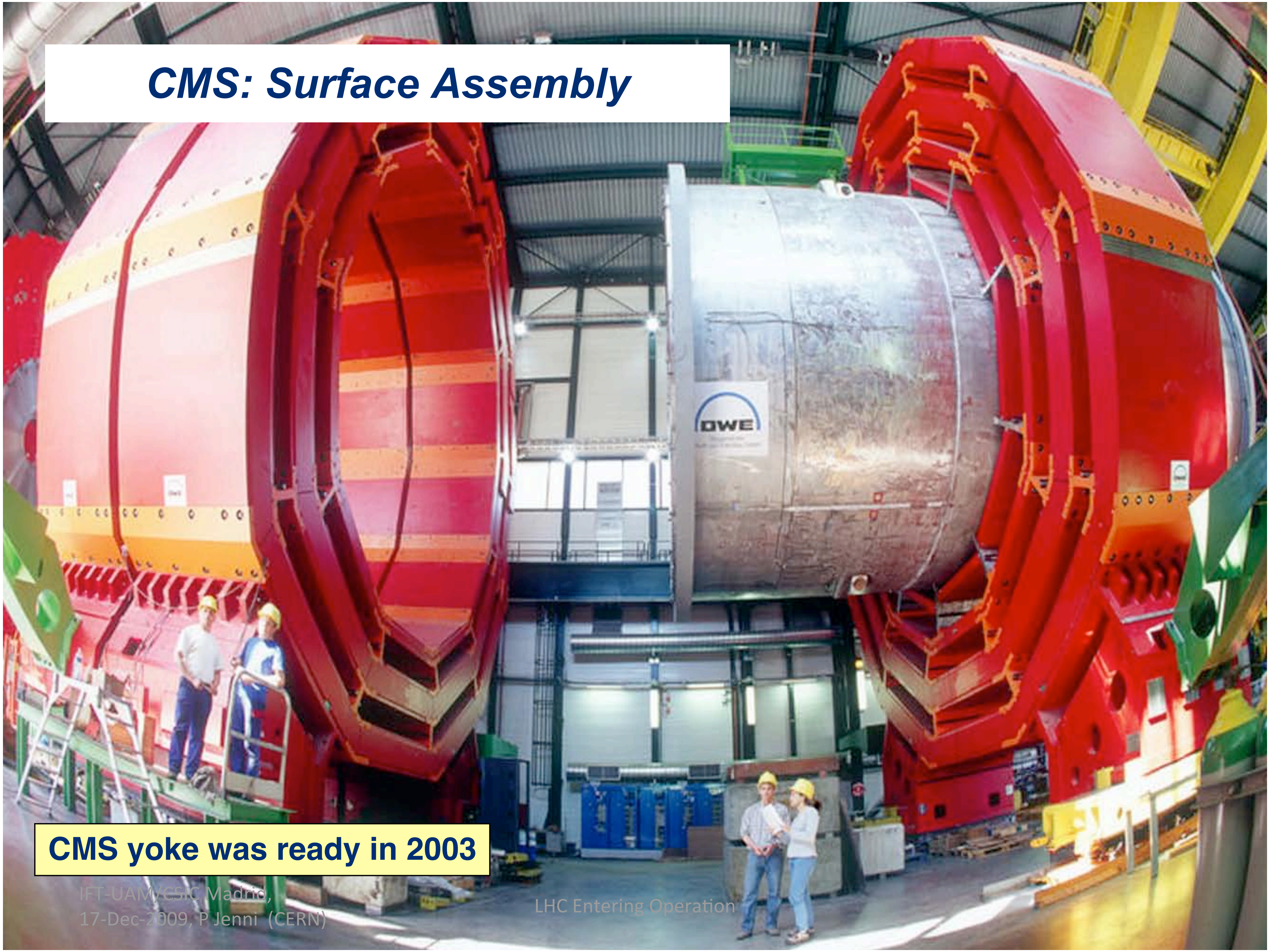
Drift Tube Chambers (DT)

Resistive Plate Chambers (RPC)

MUON ENDCAPS

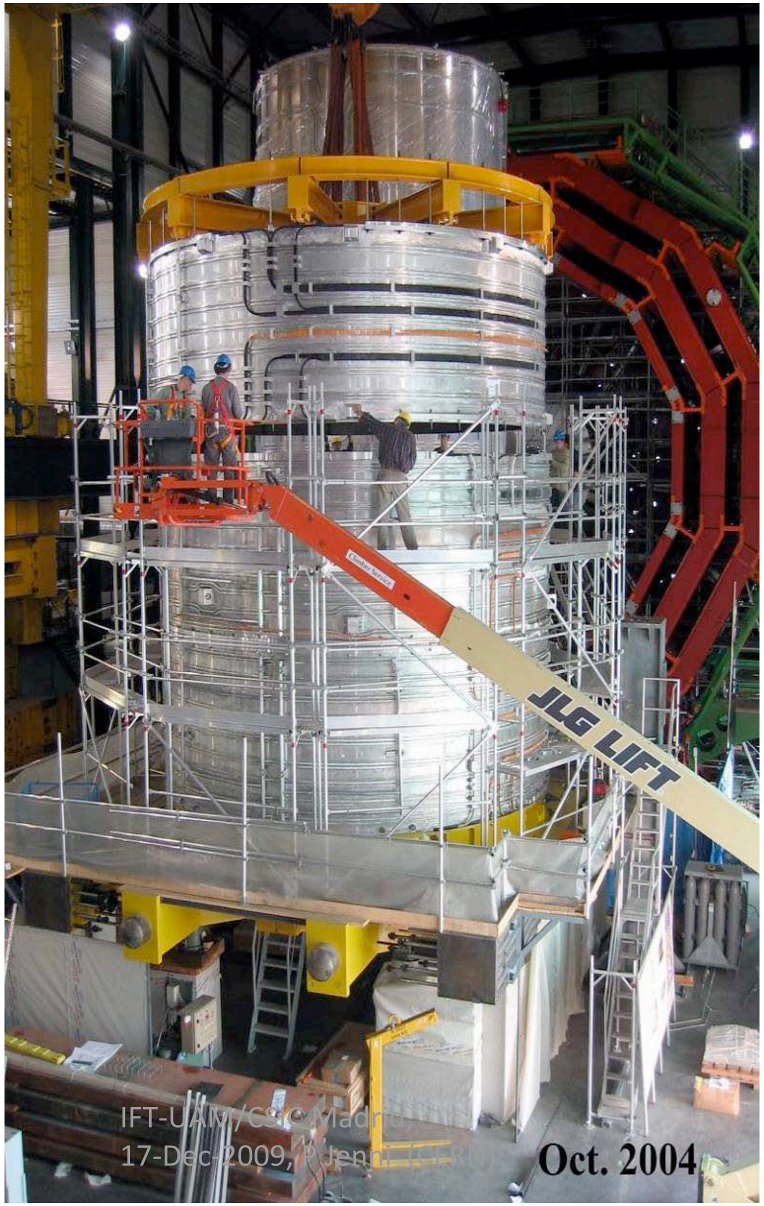
Cathode Strip Chambers (CSC)
Resistive Plate Chambers (RPC)

CMS: Surface Assembly



CMS yoke was ready in 2003

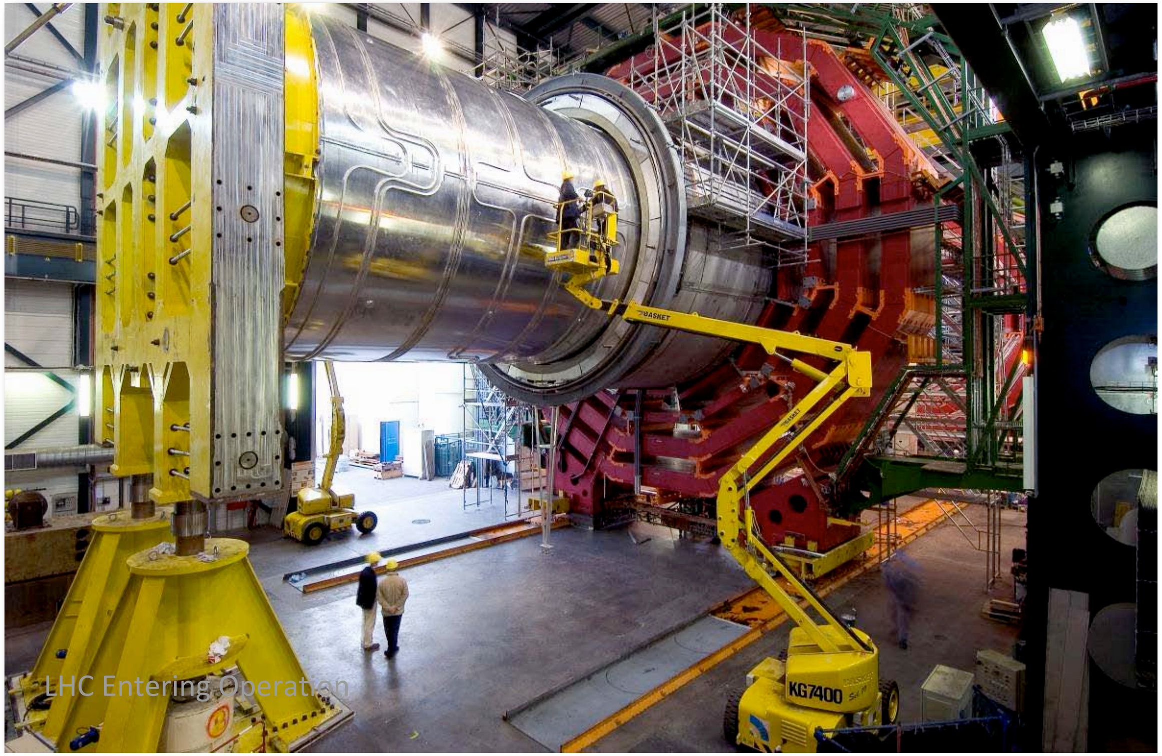
Example of an Engineering Challenge: CMS Solenoid



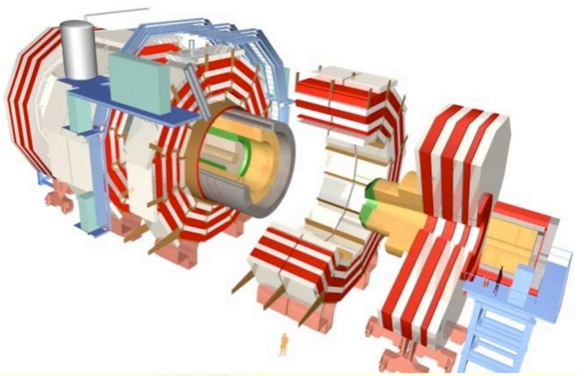
CMS solenoid:

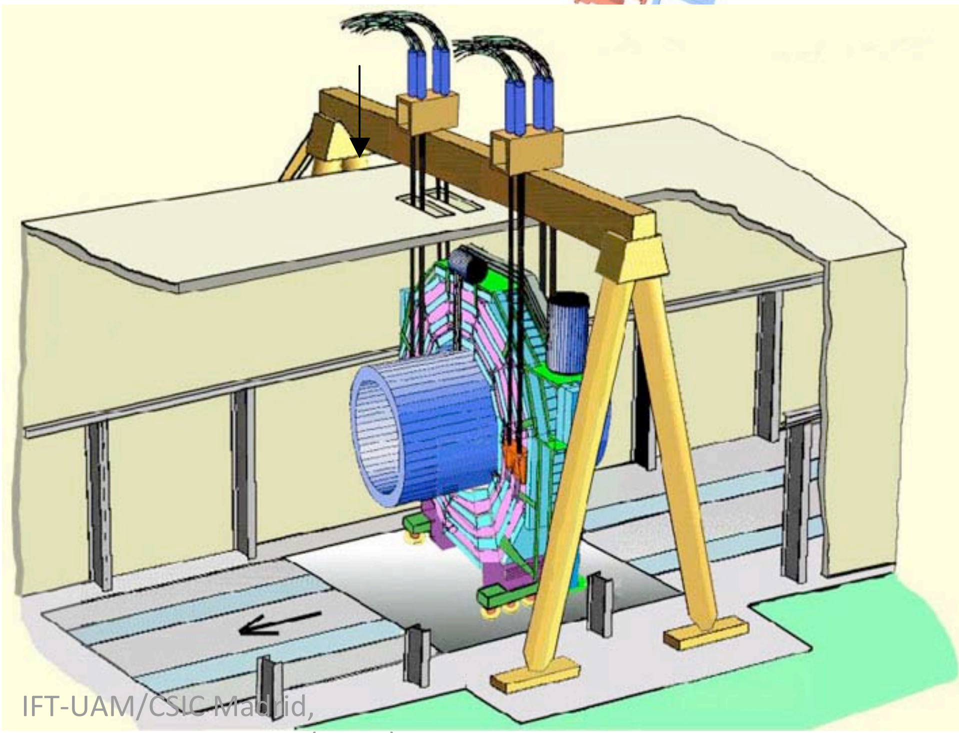
Magnetic length	**12.5 m**
Diameter	**6 m**
Magnetic field	**4 T**
Nominal current	**20 kA**
Stored energy	**2.7 GJ**

Tested at full current in Summer 2006



The central, heaviest slice (2000 tons) including the solenoid magnet lowered in the underground cavern in Feb. 2007

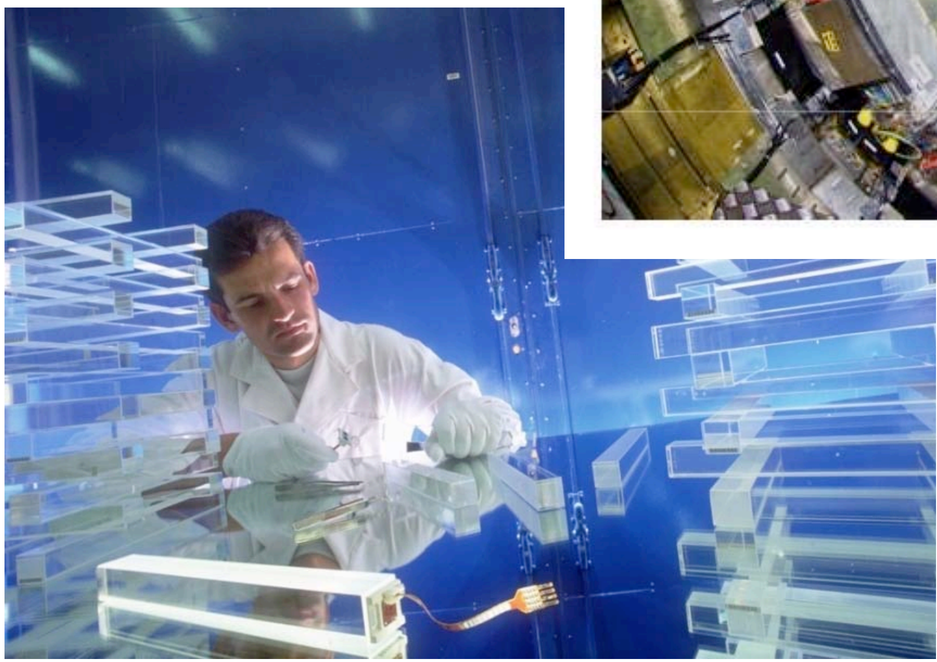


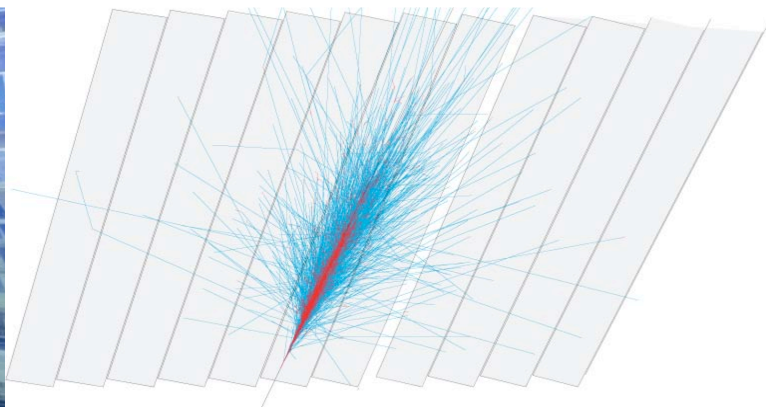


In total 15 slices were installed in this way

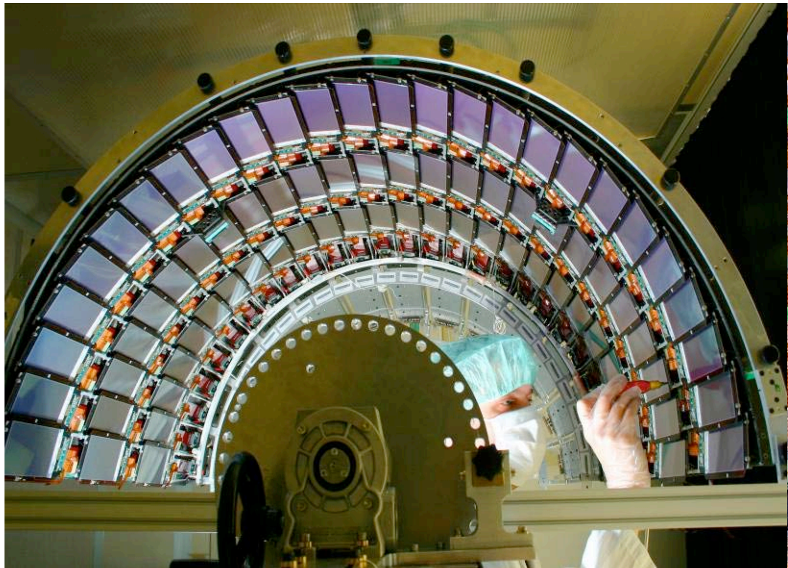
CMS Electron and Photon calorimeter: 76 000 $PbW0_4$ crystals

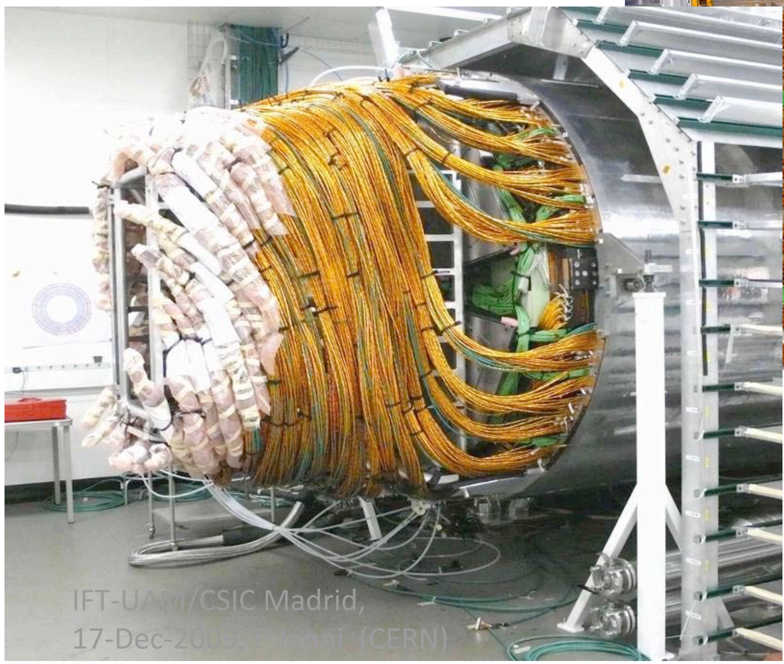
The End-cap was on the critical path for many years, but it was completed just in time before final closure, a major achievement by CMS

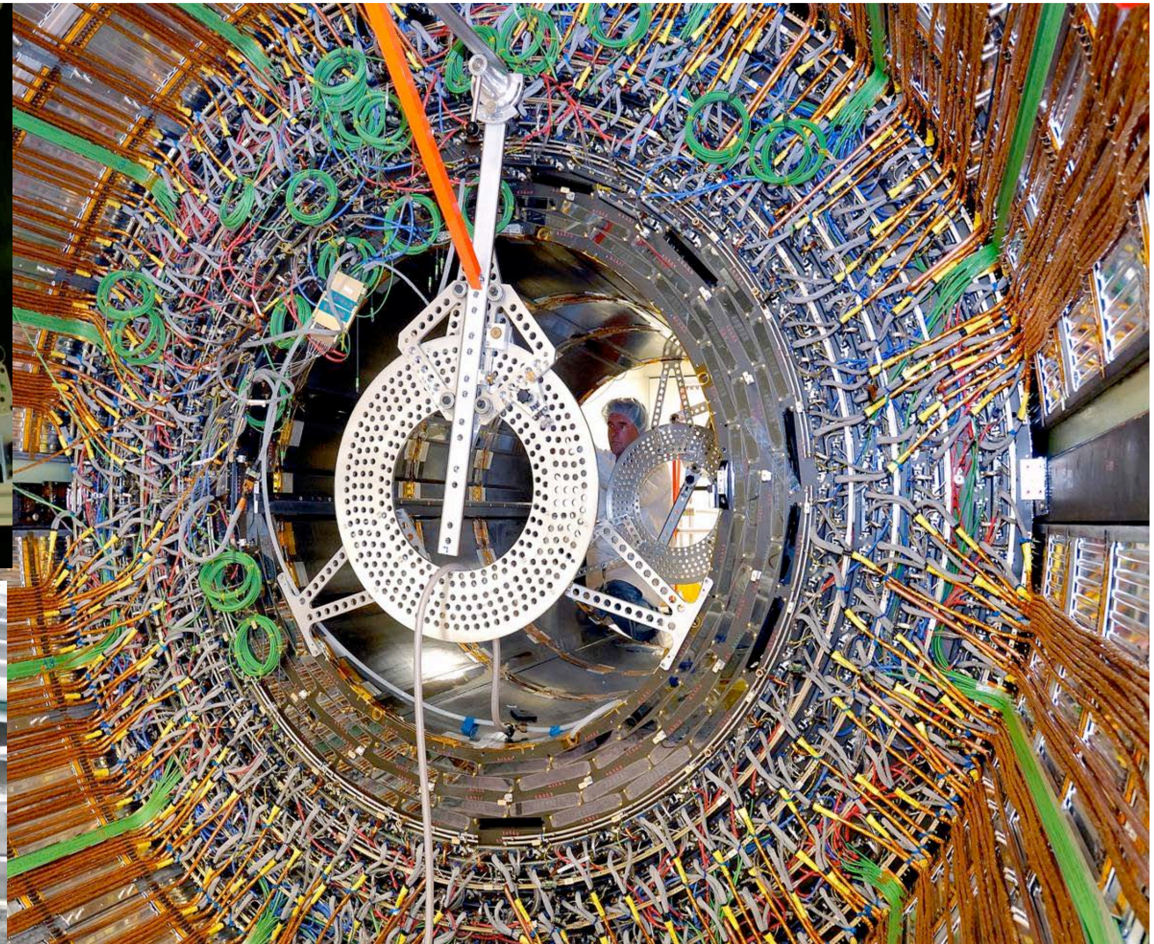




CMS Silicon Tracker







The Silicon tracker (200m^2) has 10 M channels
- Commissioned at operating temperature (-15°C)
- ~ 5 M cosmic rays recorded on the surface

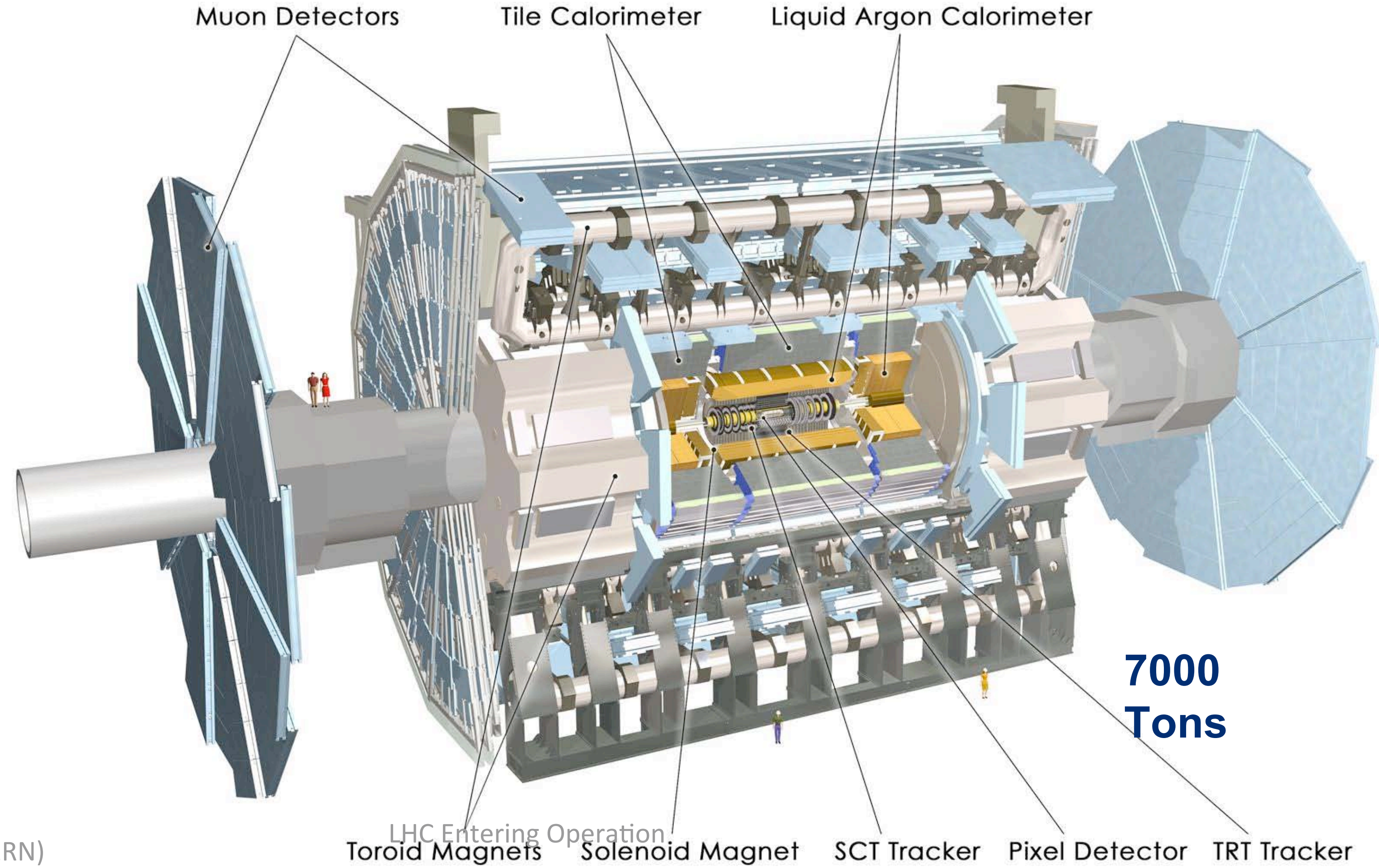
CMS before closure

ATLAS Detector

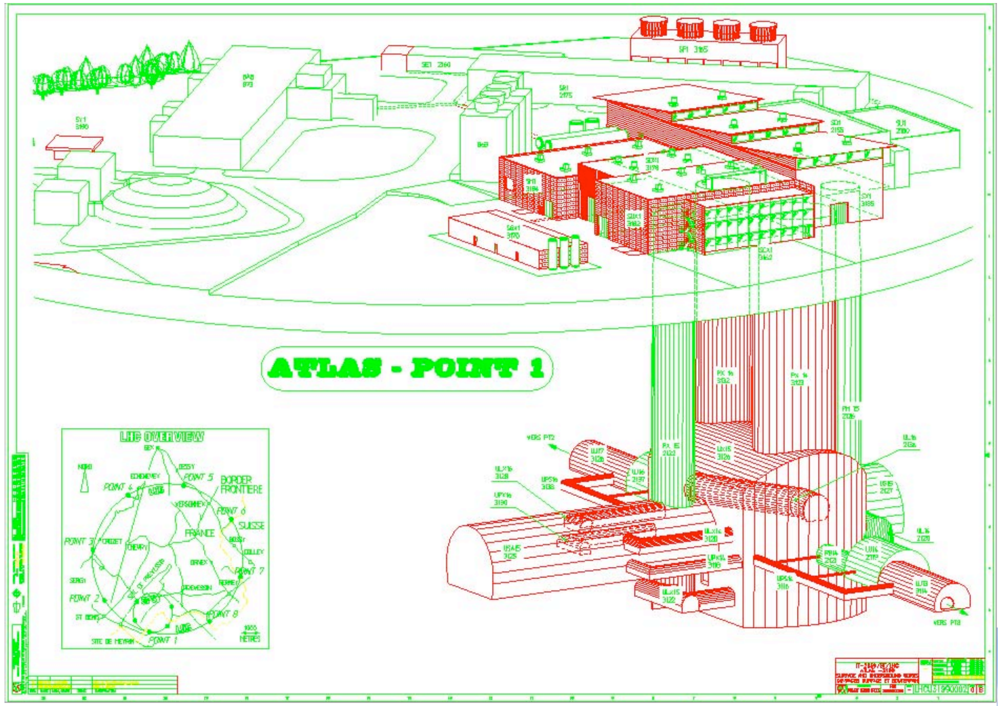
ATLAS superimposed to the 5 floors of building 40

45 m

24 m

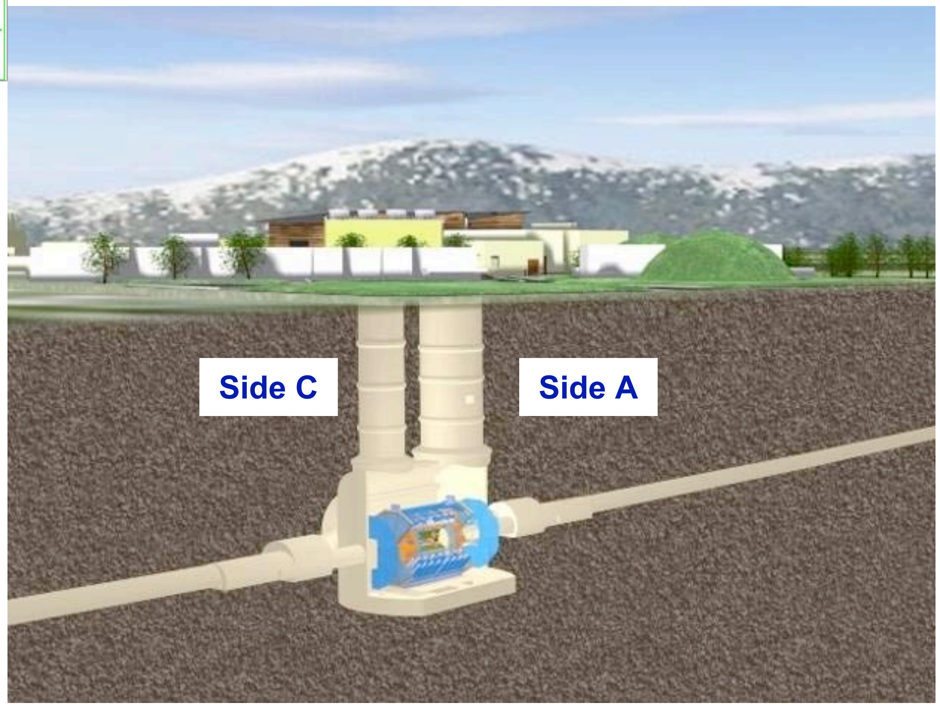


7000 Tons

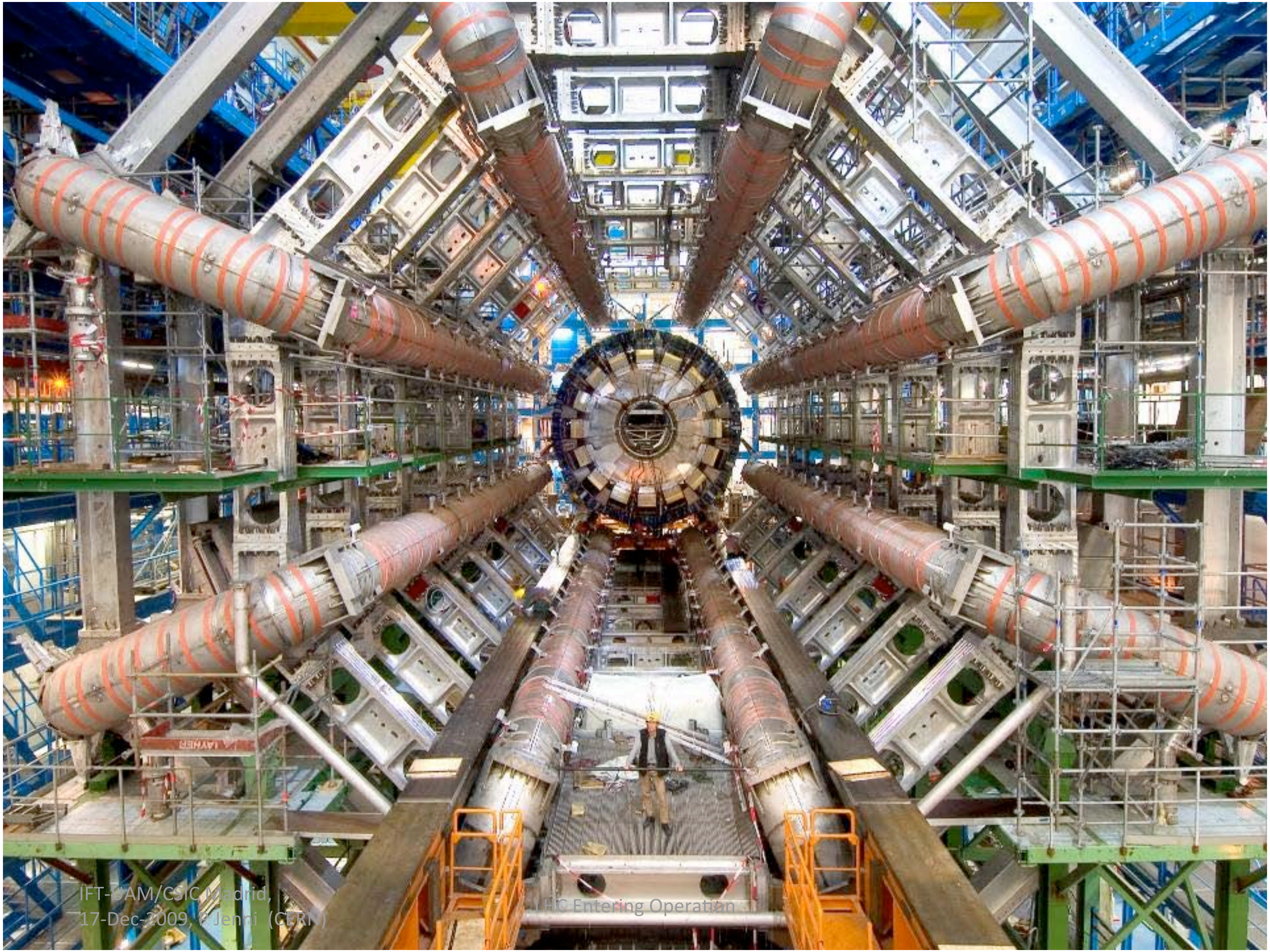


The Underground Cavern at Point-1 for the ATLAS Detector

Length	= 55 m
Width	= 32 m
Height	= 35 m

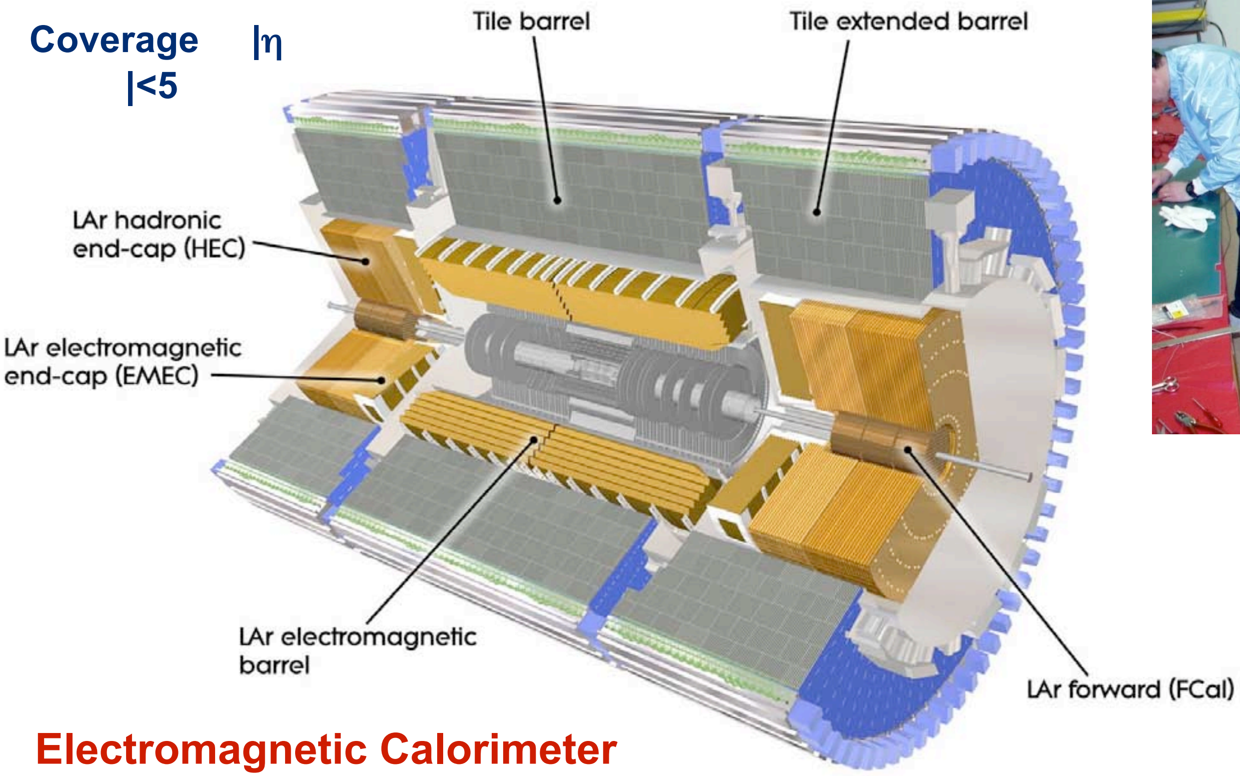


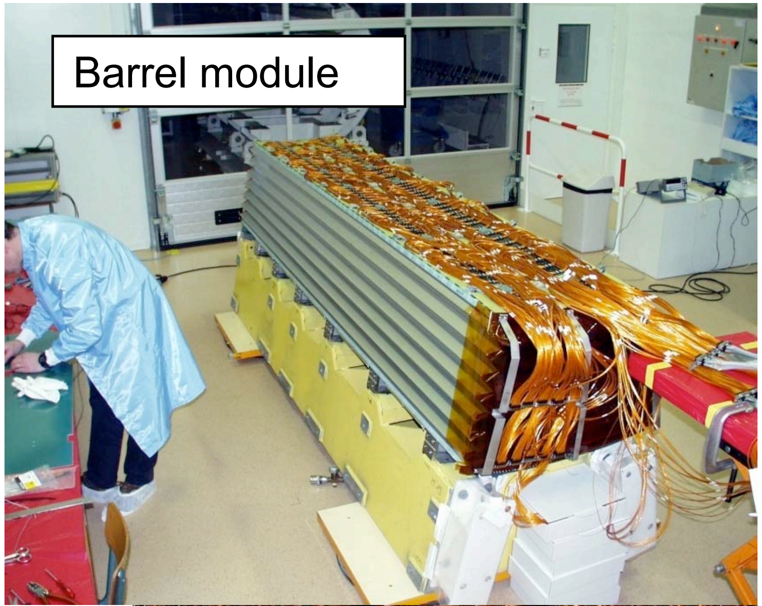
The underground cavern was finished in June 2003

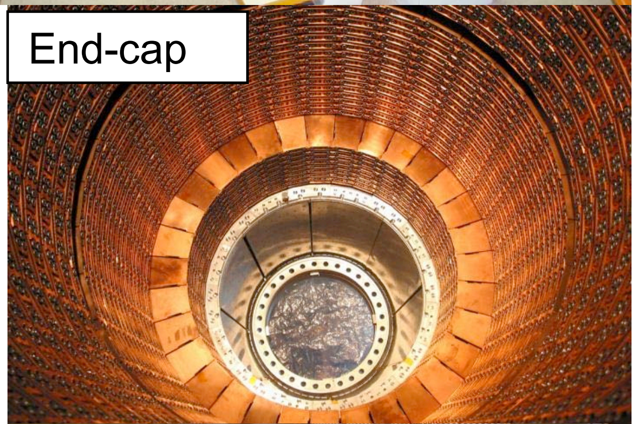


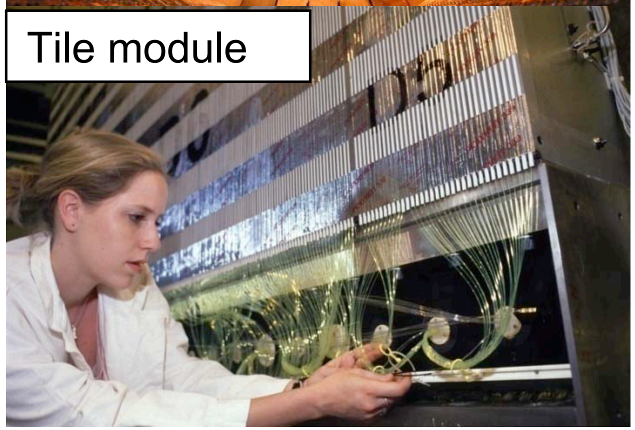
Calorimetry

Coverage |η|<5







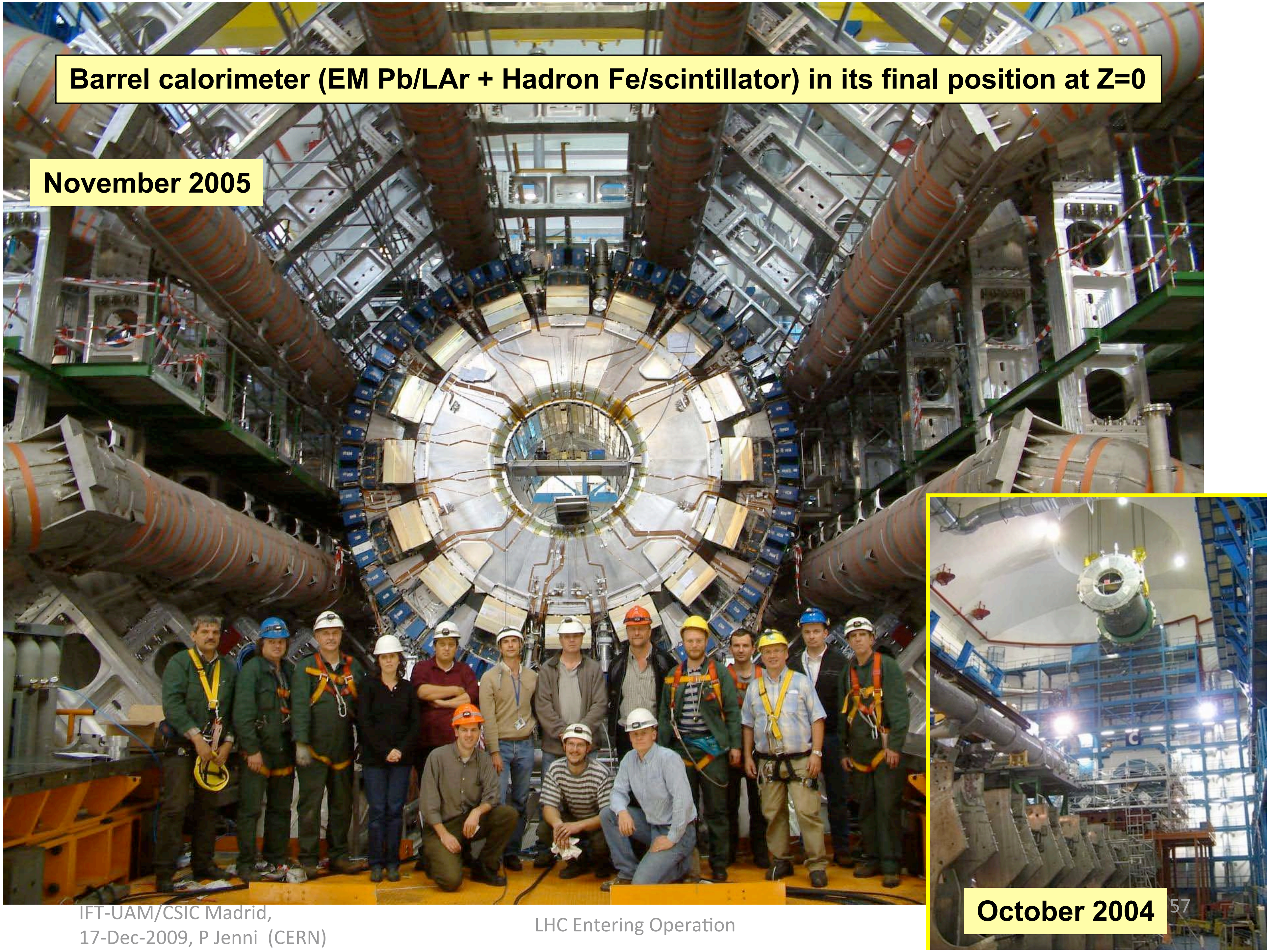


Electromagnetic Calorimeter
barrel, end-cap: Pb-LAr
~10%/√E energy resolution e/γ
180’000 channels: longitudinal segmentation

Hadron Calorimeter
barrel Iron-Tile, EC/Fwd Cu/W-LAr (~20000 channels)
$\sigma/E \sim 50\%/\sqrt{E} \oplus 0.03$ pion (10 λ)

Trigger for e/γ , jets, missing E_T ,etc

Barrel calorimeter (EM Pb/LAr + Hadron Fe/scintillator) in its final position at Z=0

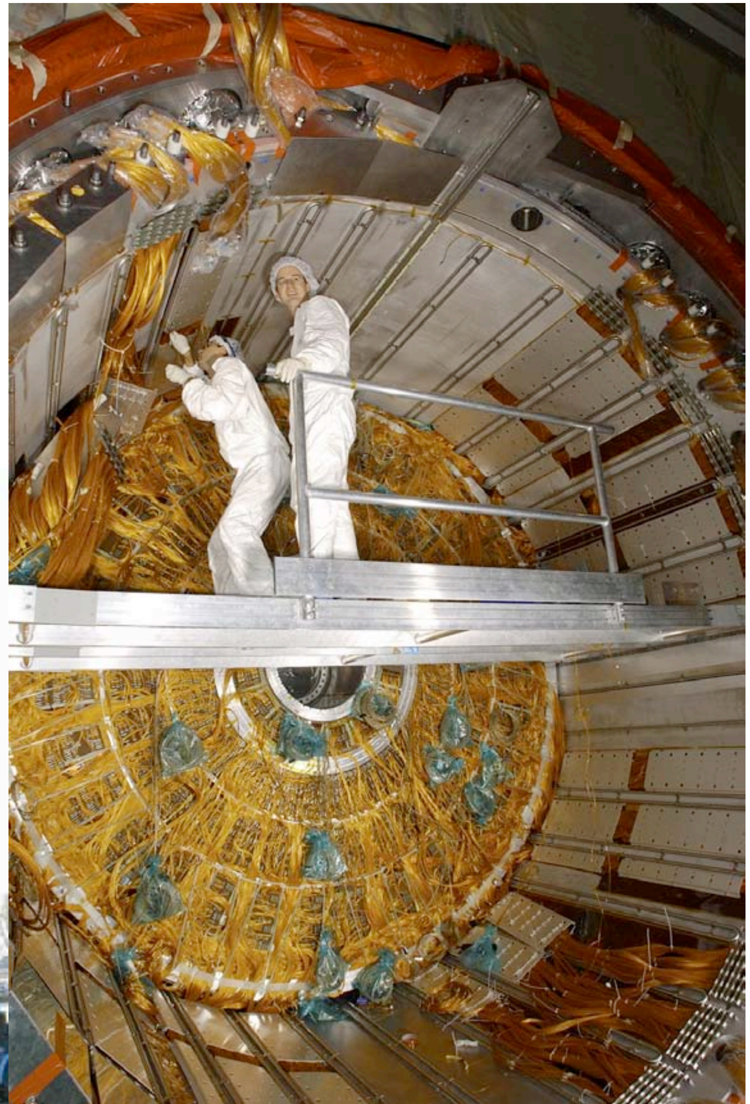


November 2005

October 2004

An outstanding construction job done by the HEP group at UAM !

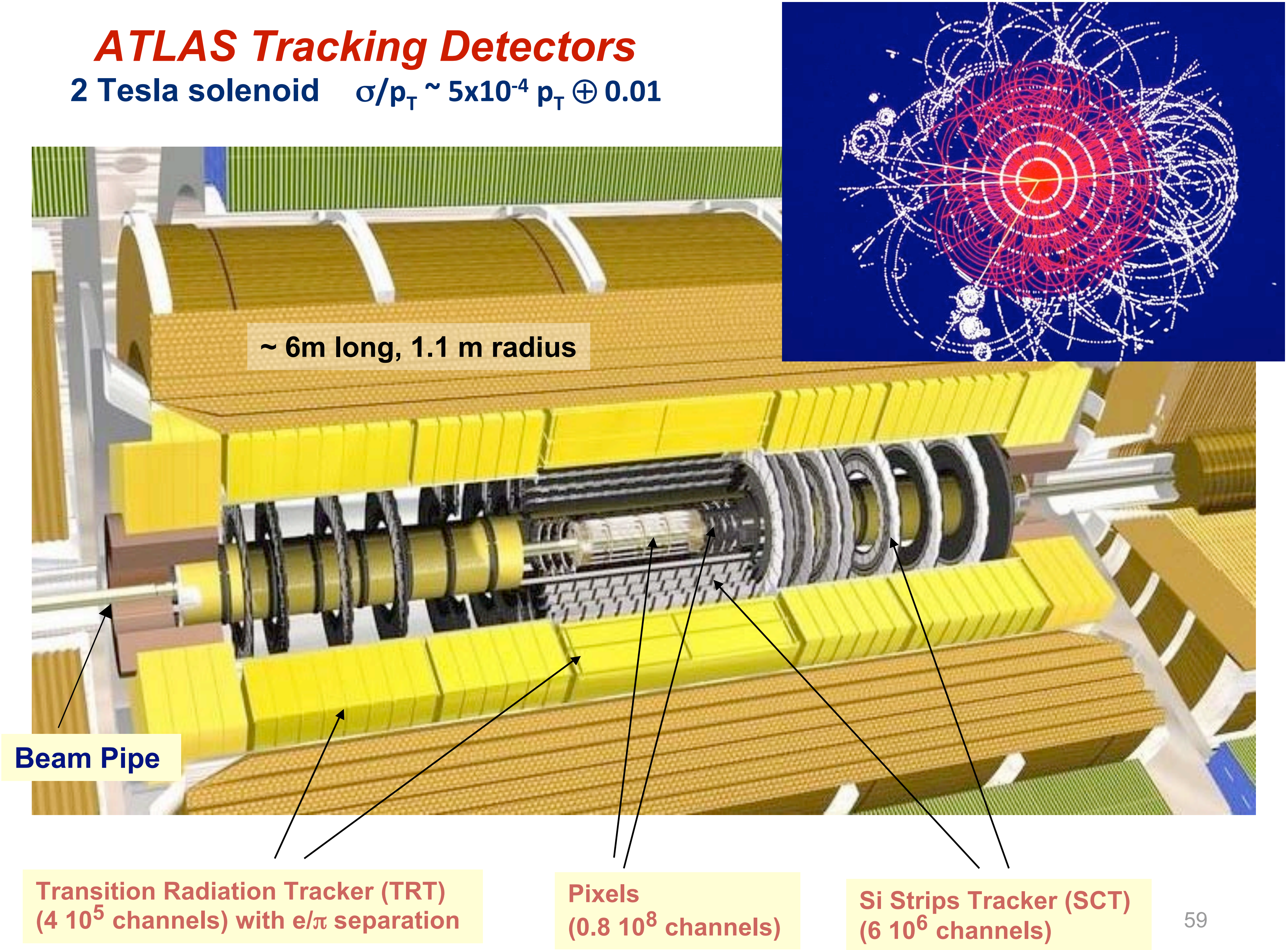
Transport of one of the two ATLAS LAr End-Cap Calorimeters to the pit (Dec 2005)



LAr EM calorimeter inserted in the cryostat

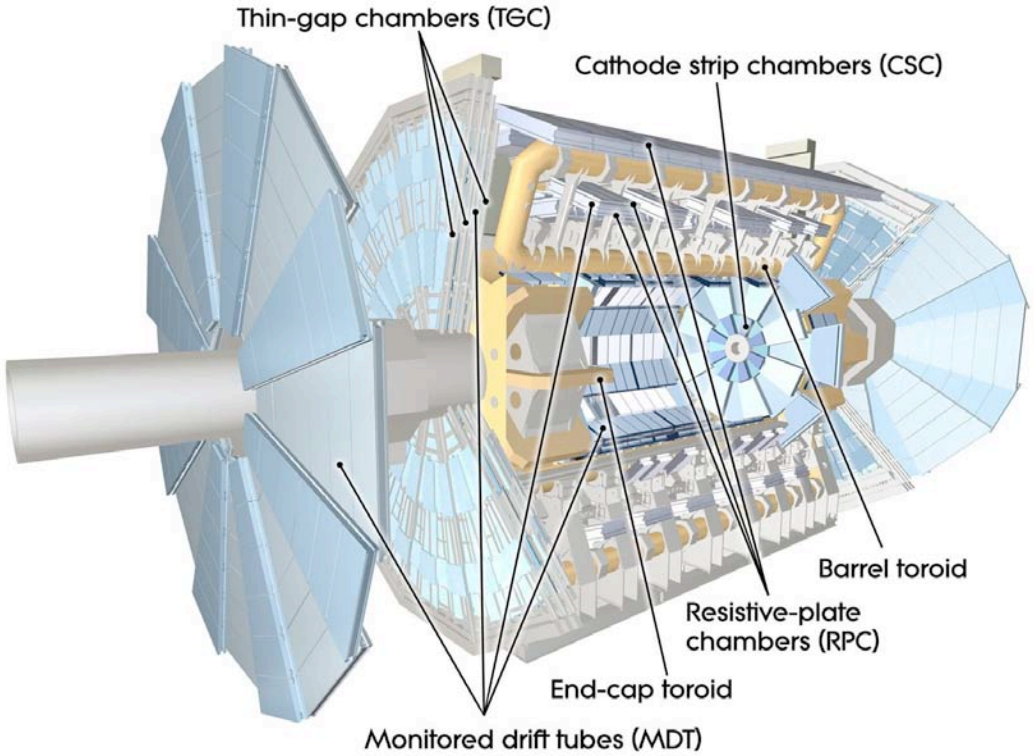
ATLAS Tracking Detectors

2 Tesla solenoid $\sigma/p_T \sim 5\mathrm{x}10^{-4}\, p_T \oplus 0.01$



Installation of the ATLAS barrel tracker (Aug 2006)

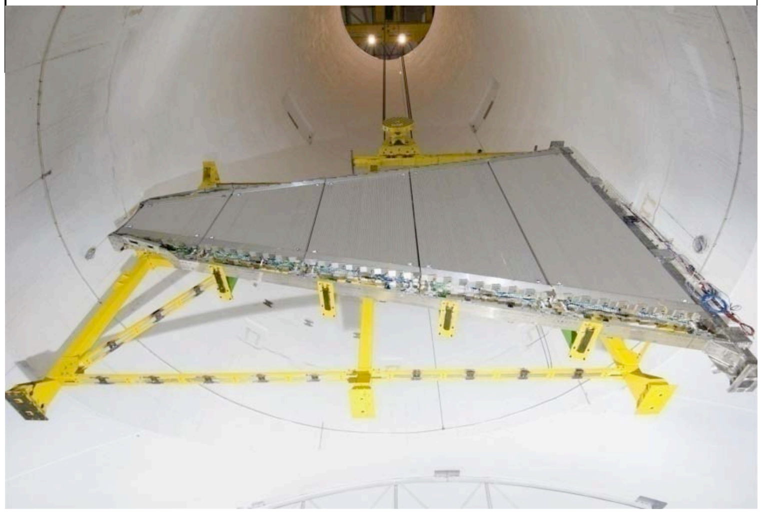
Muon System

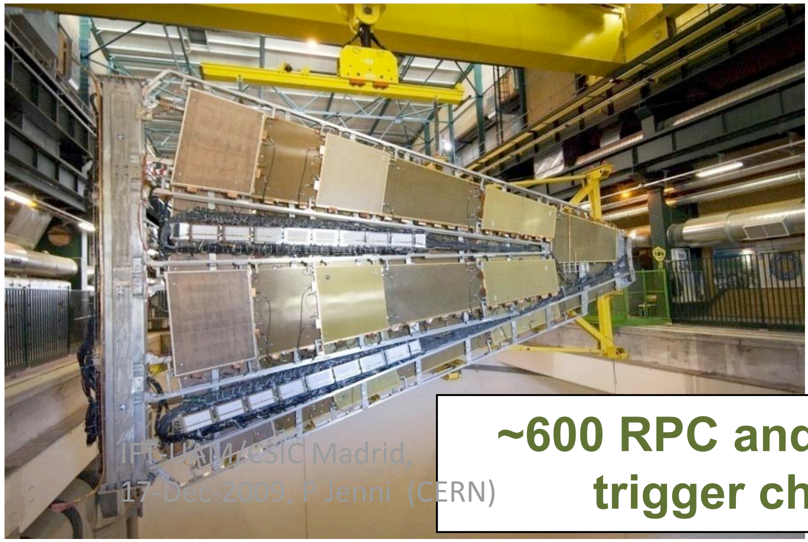


Stand-alone momentum resolution
ΔpT/pT < 10% up to 1 TeV

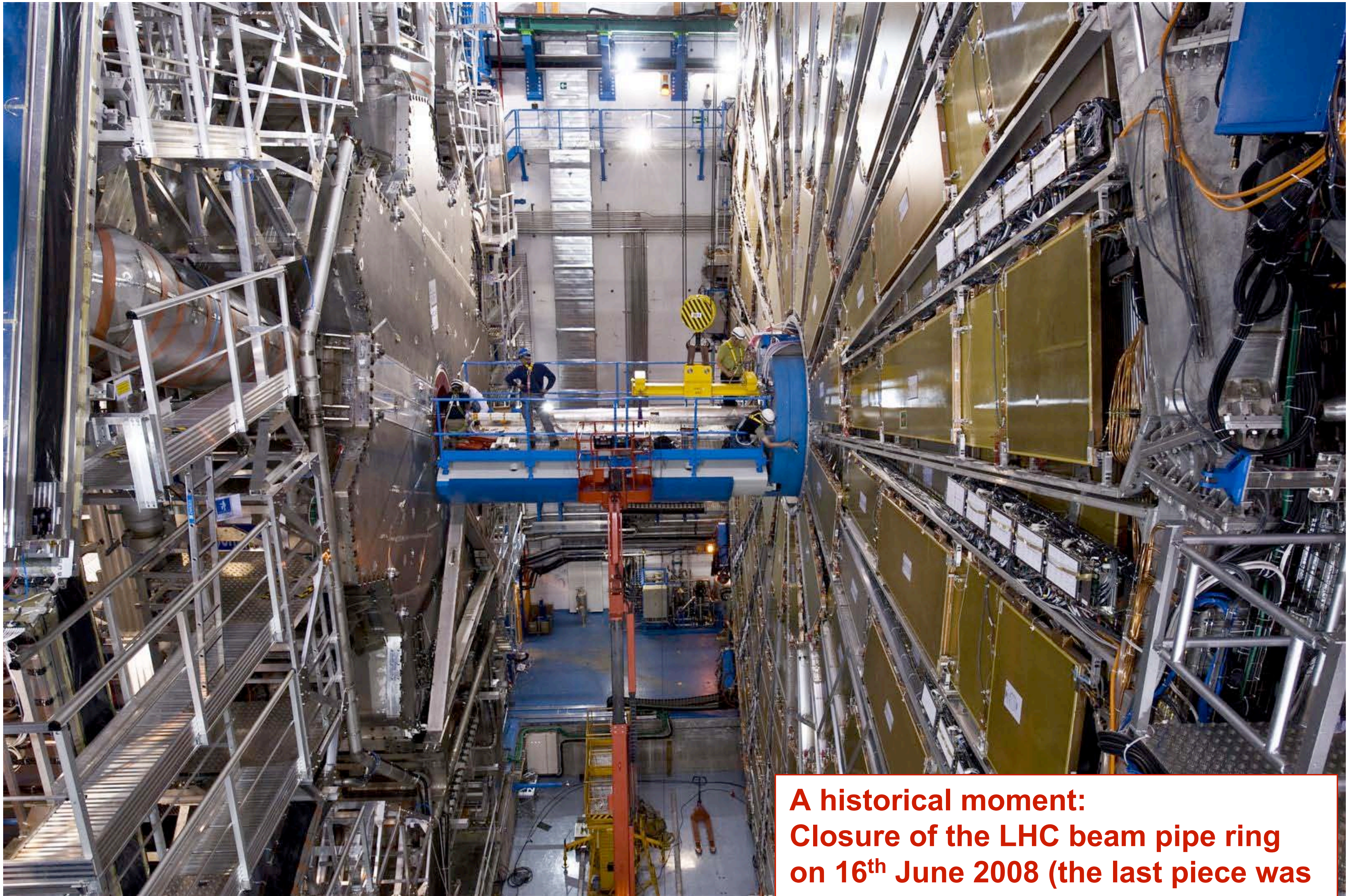
2-6 Tm |η|<1.3   4-8 Tm 1.6<|η|<2.7

~1200 MDT precision chambers for track



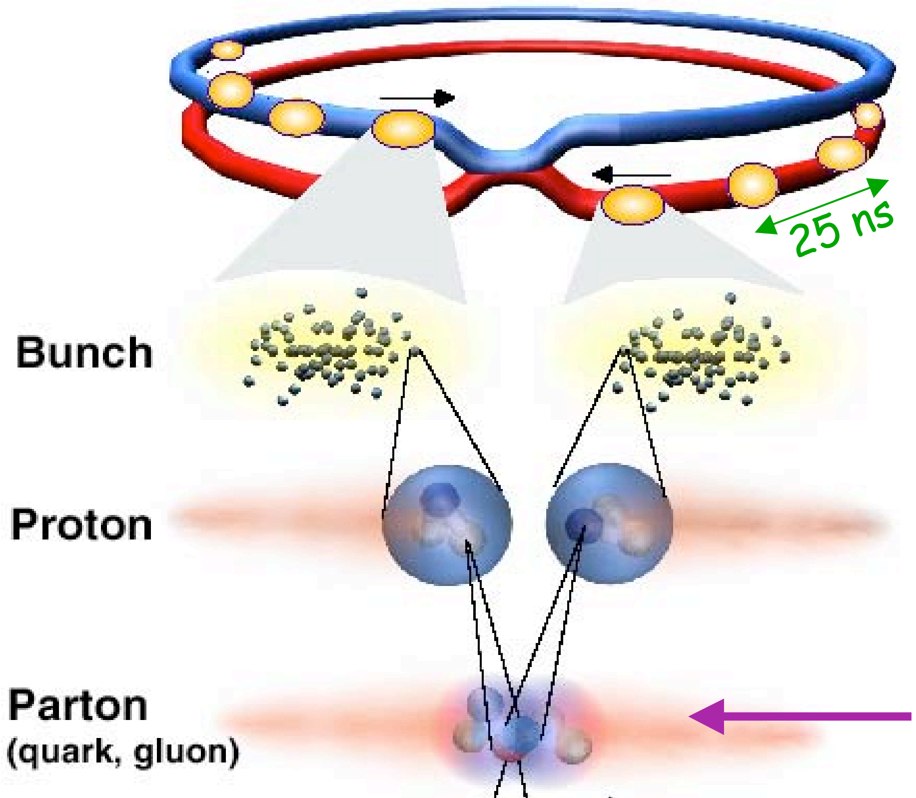


~600 RPC and ~3600 TGC trigger chambers



A historical moment:
Closure of the LHC beam pipe ring on 16th June 2008 (the last piece was the one shown here in ATLAS side A)

Collisions at LHC



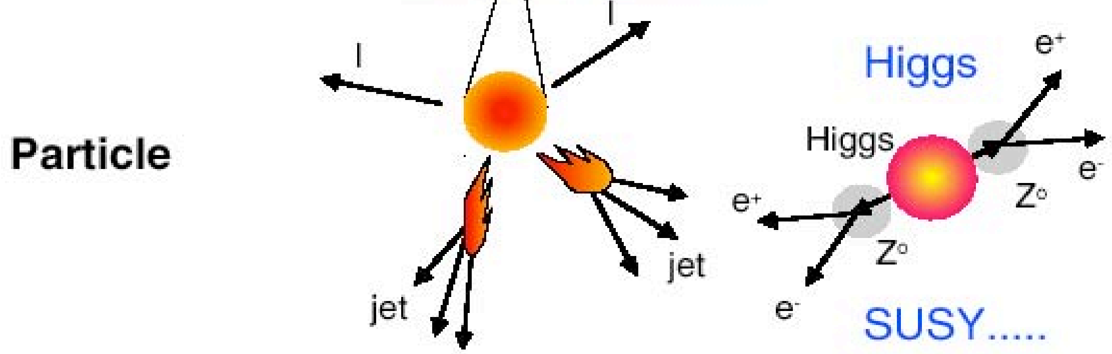
Proton-Proton	
Protons/bunch	10^{11}
Beam energy	7 TeV (7×10^{12} eV)
Luminosity	10^{34} cm^{-2} s^{-1}

Event rate:

$N = L \times \sigma$ (pp) ≈ 10^9 interactions/s

Mostly soft (low p_T) events

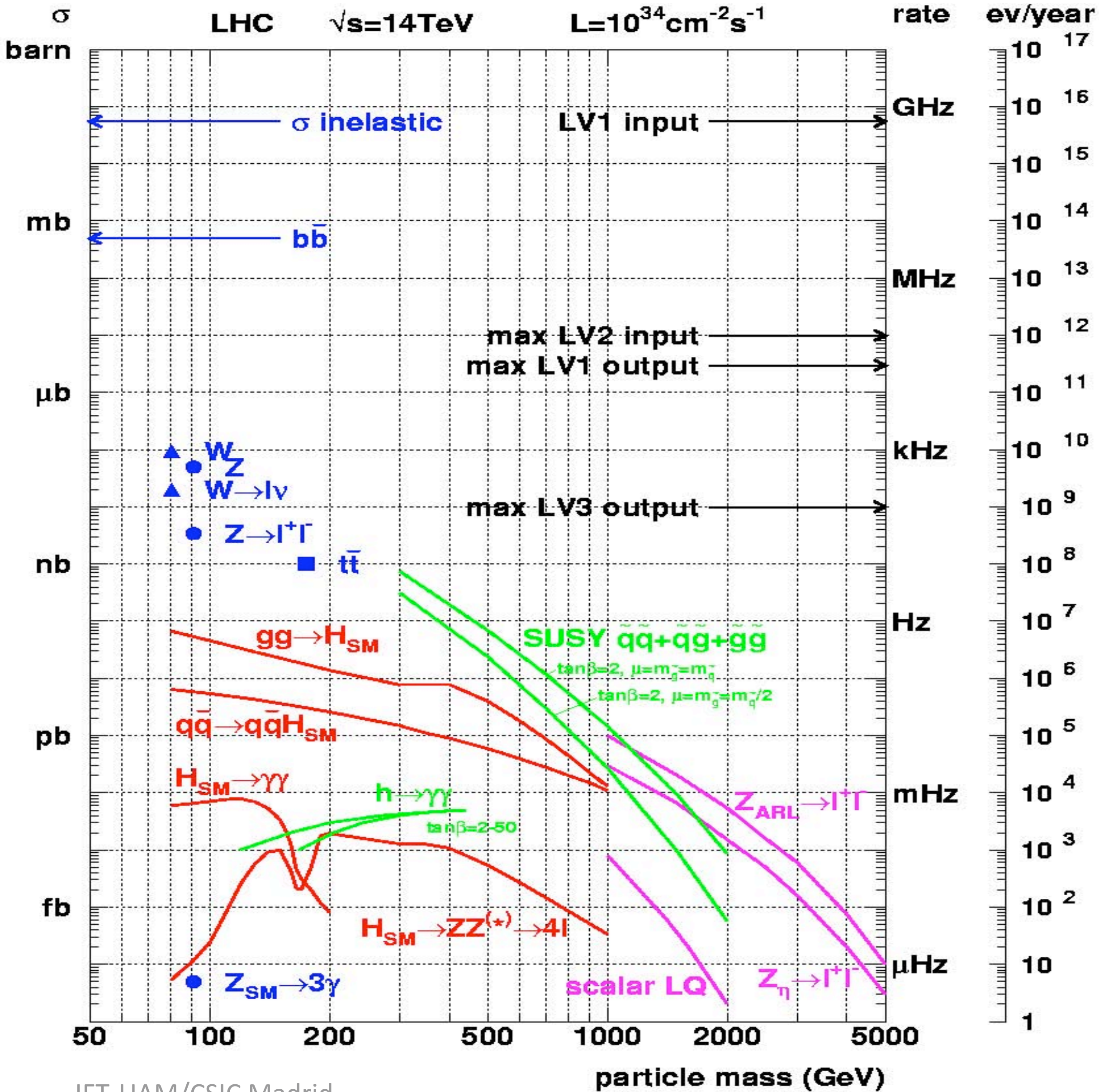
Interesting hard (high-p_T) events are rare



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

→ very powerful detectors needed

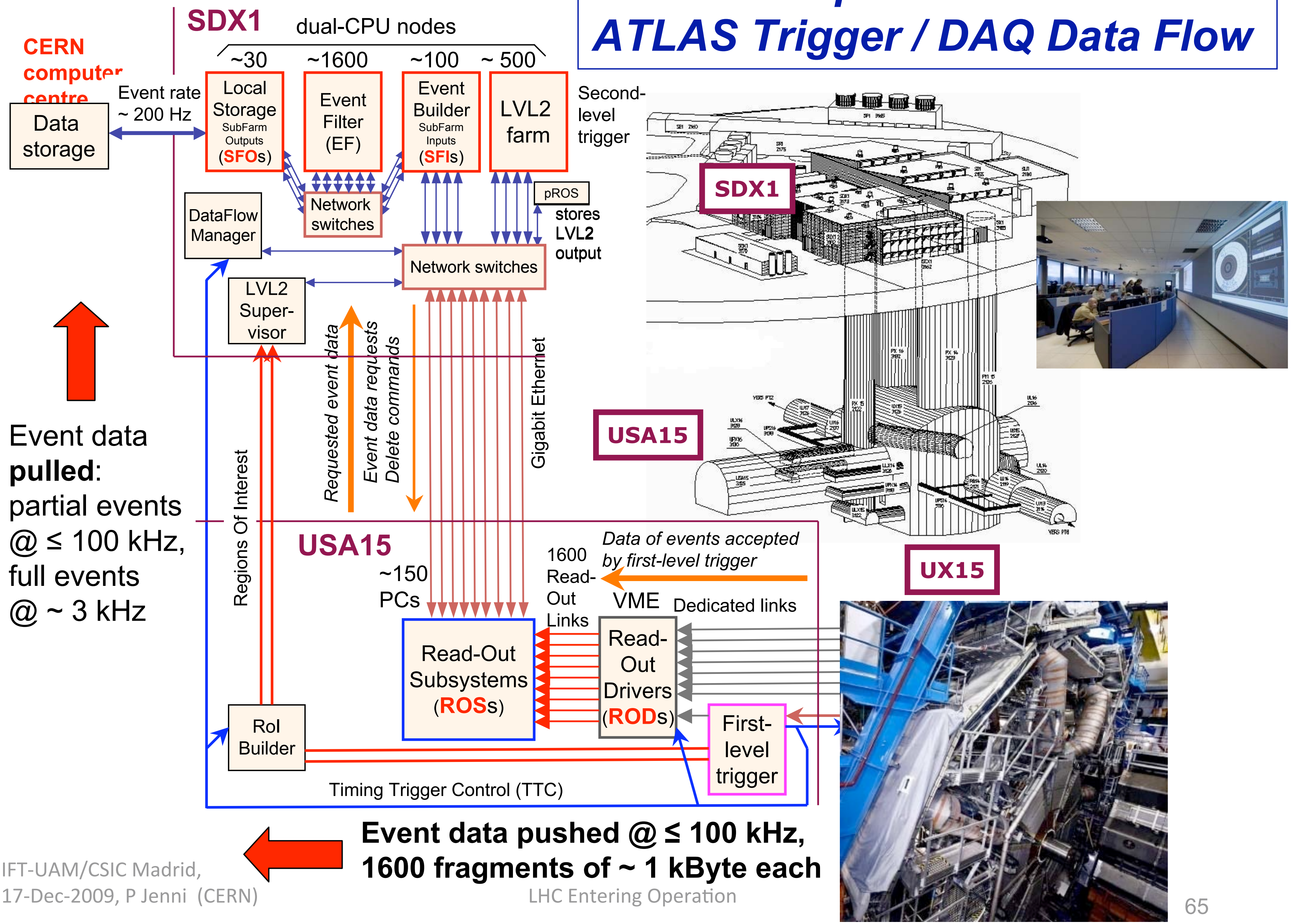
Cross Sections and Production Rates



"Well known" processes, don't need to keep all of them …

New Physics
This we want to keep!

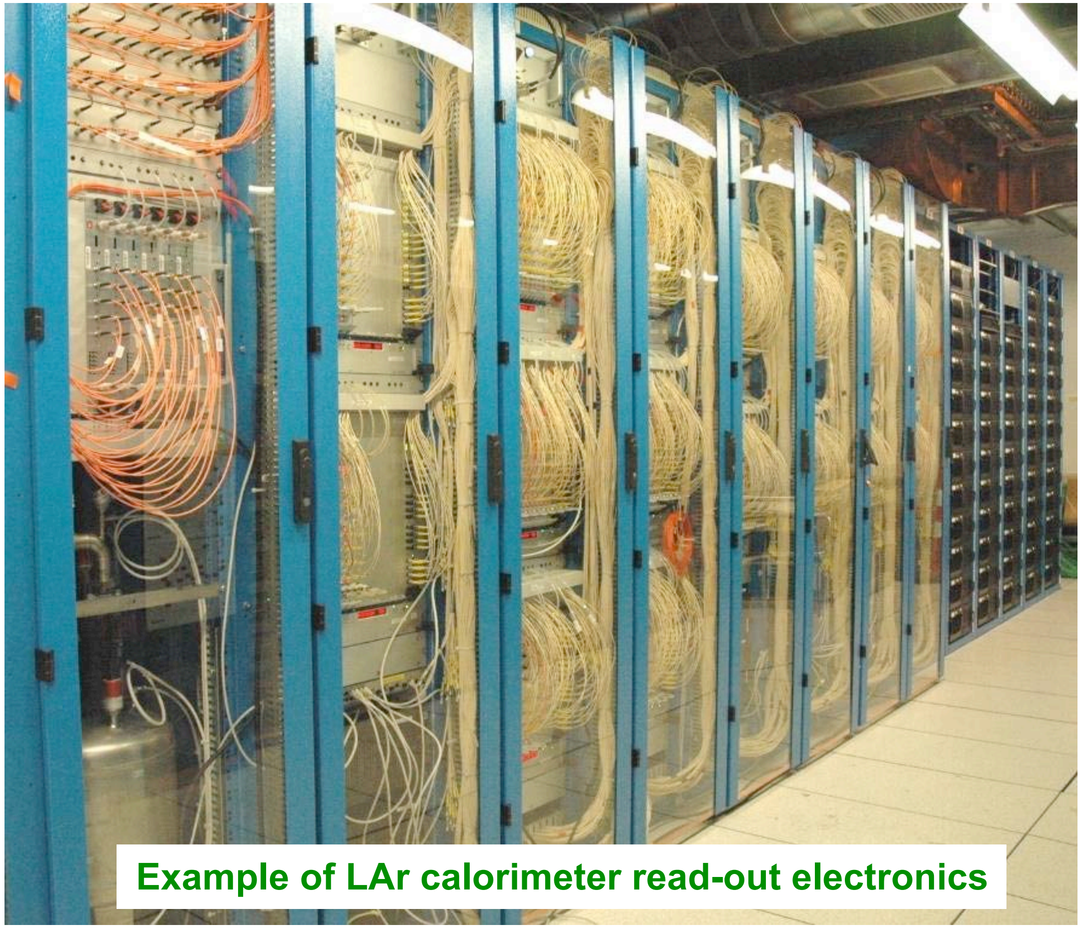
As an example:
ATLAS Trigger / DAQ Data Flow



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

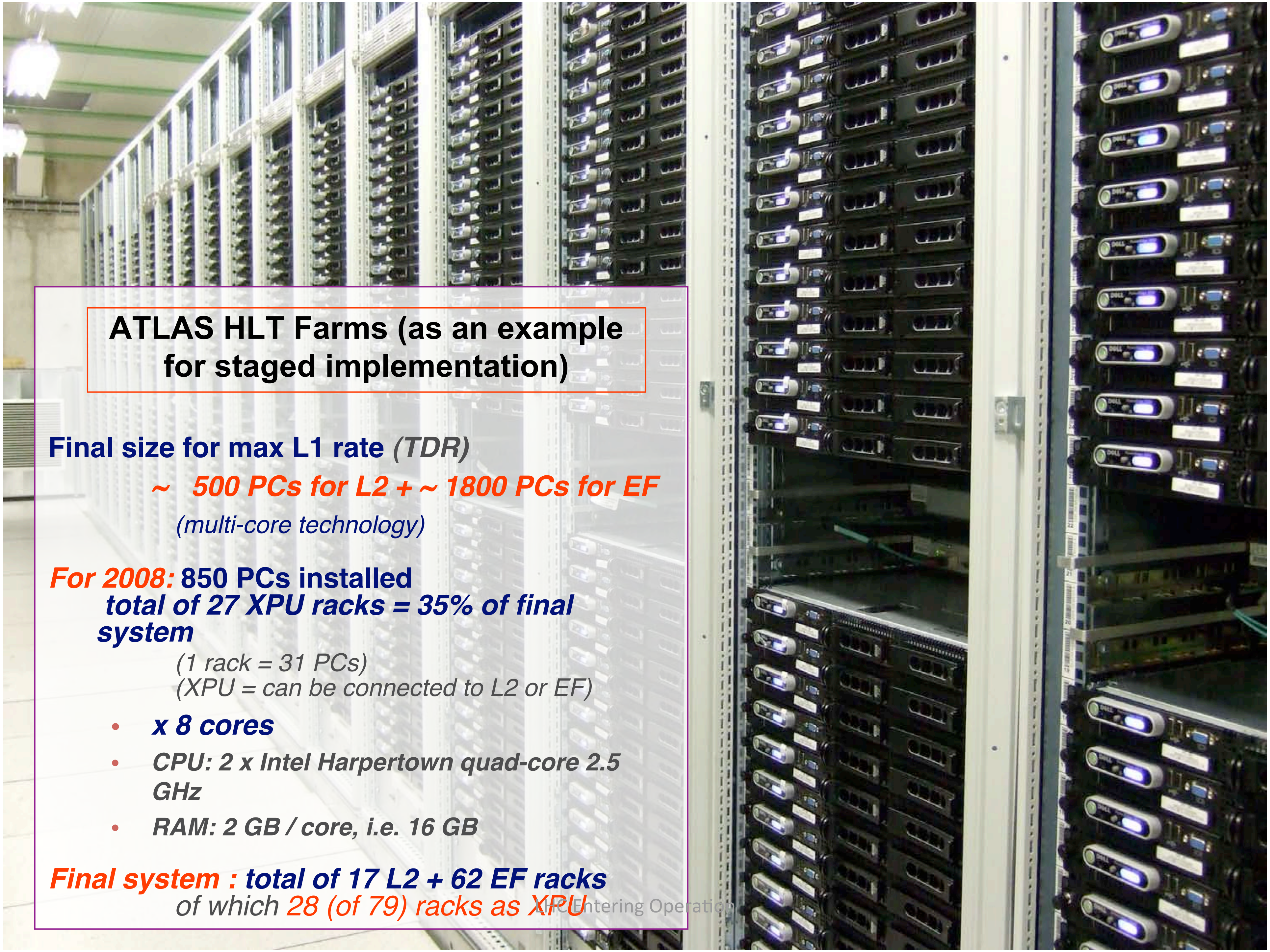
(Examples from ATLAS)

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**

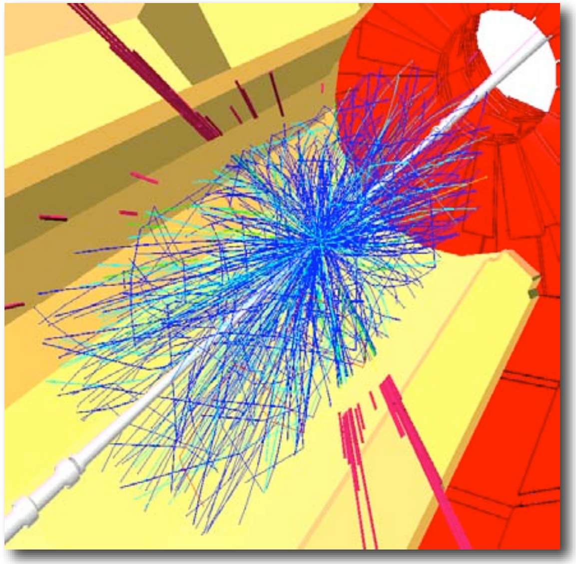
total of 27 XPU racks = 35% of final system

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

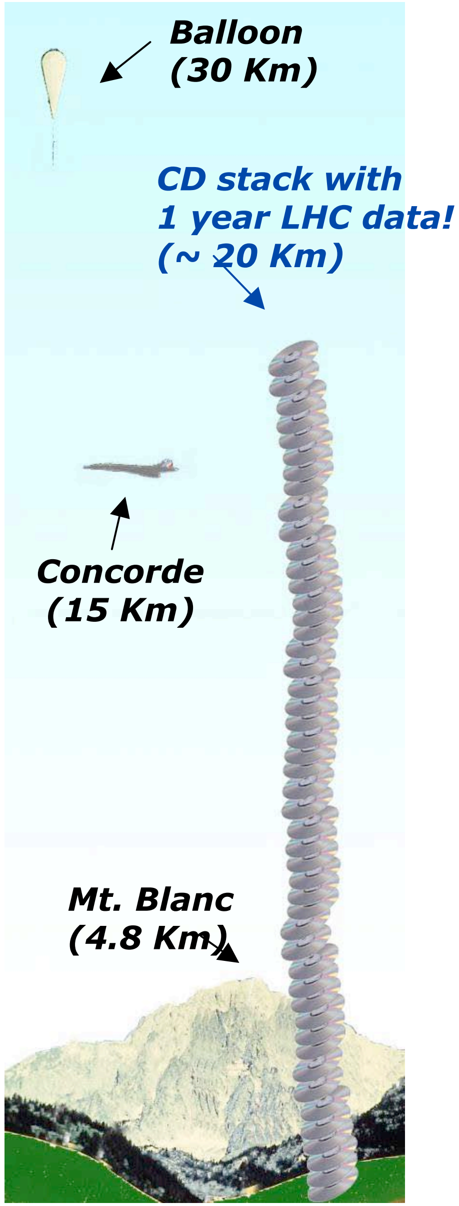
- ***x 8 cores***
- ***CPU: 2 x Intel Harpertown quad-core 2.5 GHz***
- ***RAM: 2 GB / core, i.e. 16 GB***

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

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



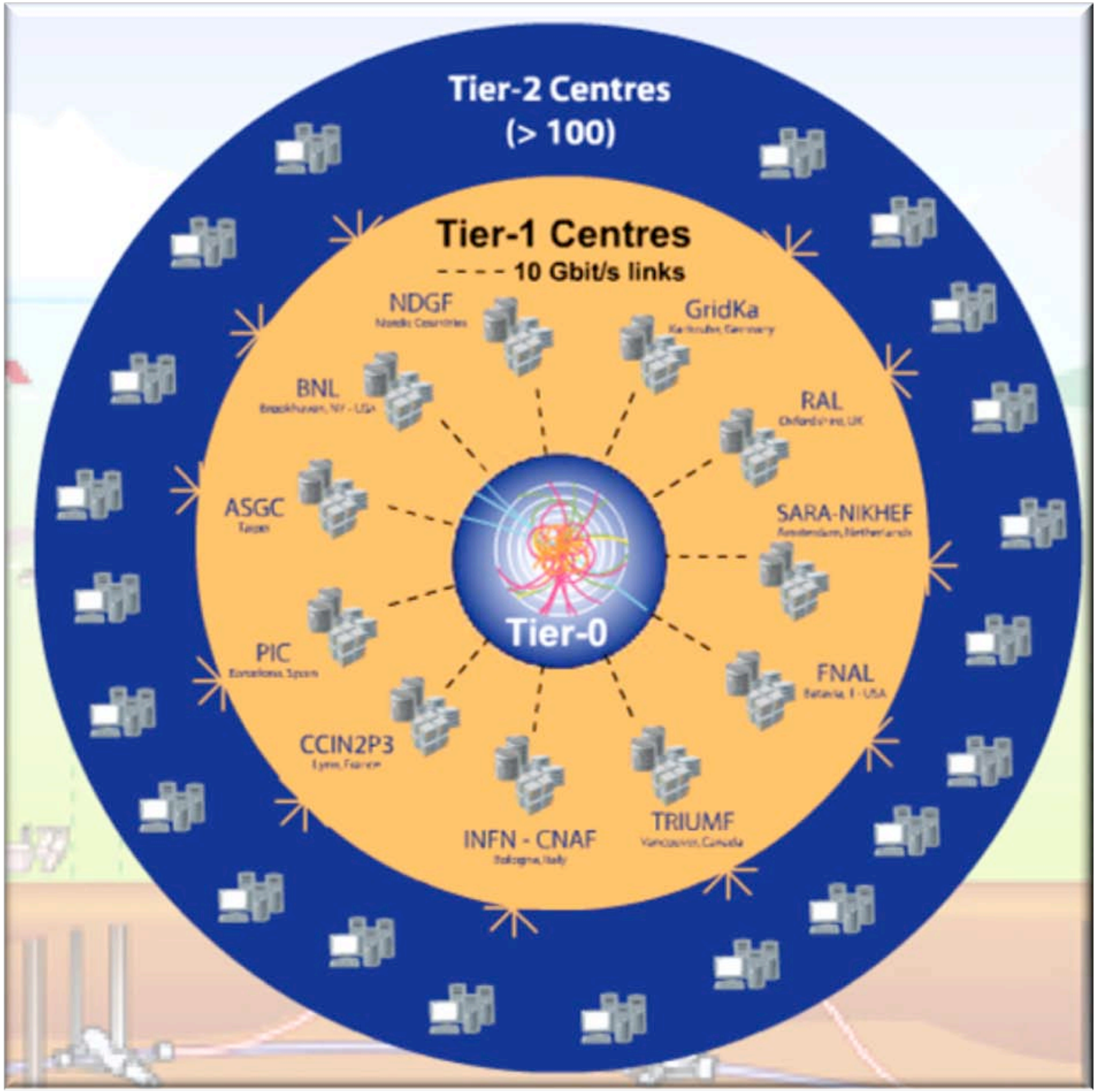
GRID computing developed to solve problem of data storage and analysis

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)



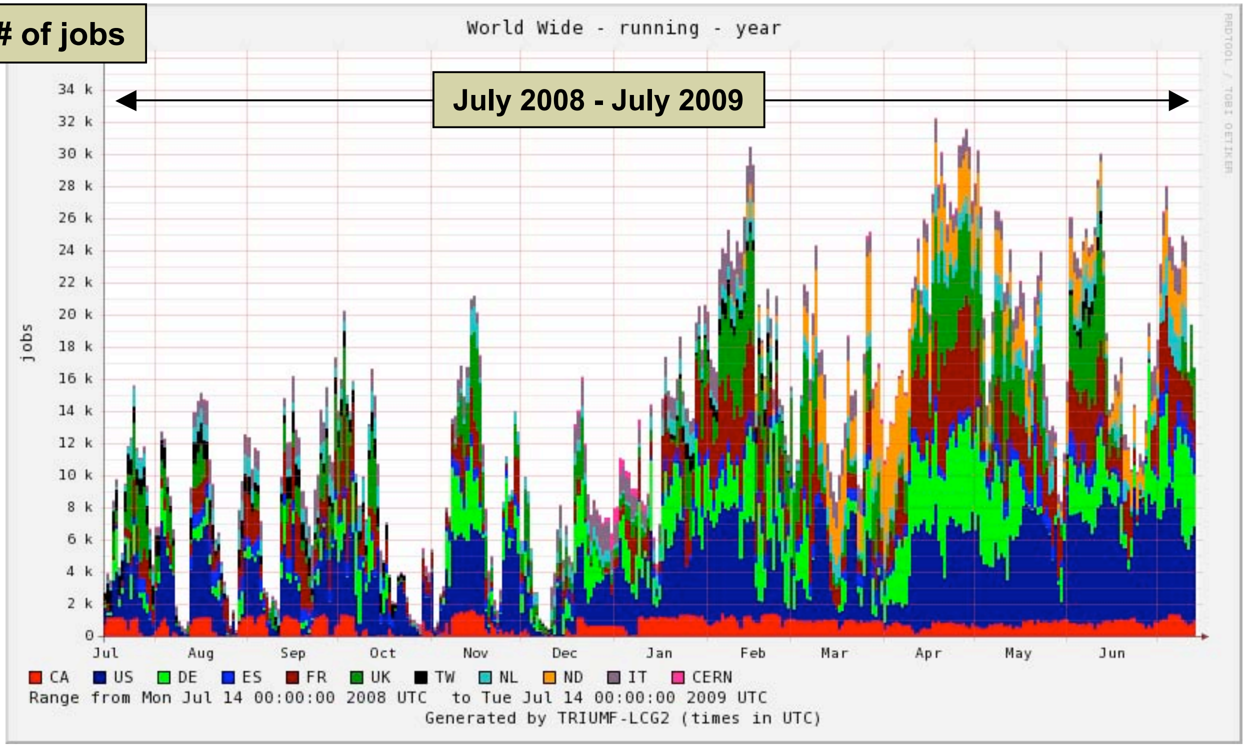
Tier-0 (CERN):
- Data recording
- Initial data reconstruction
- Data distribution

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

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

ATLAS

of jobs

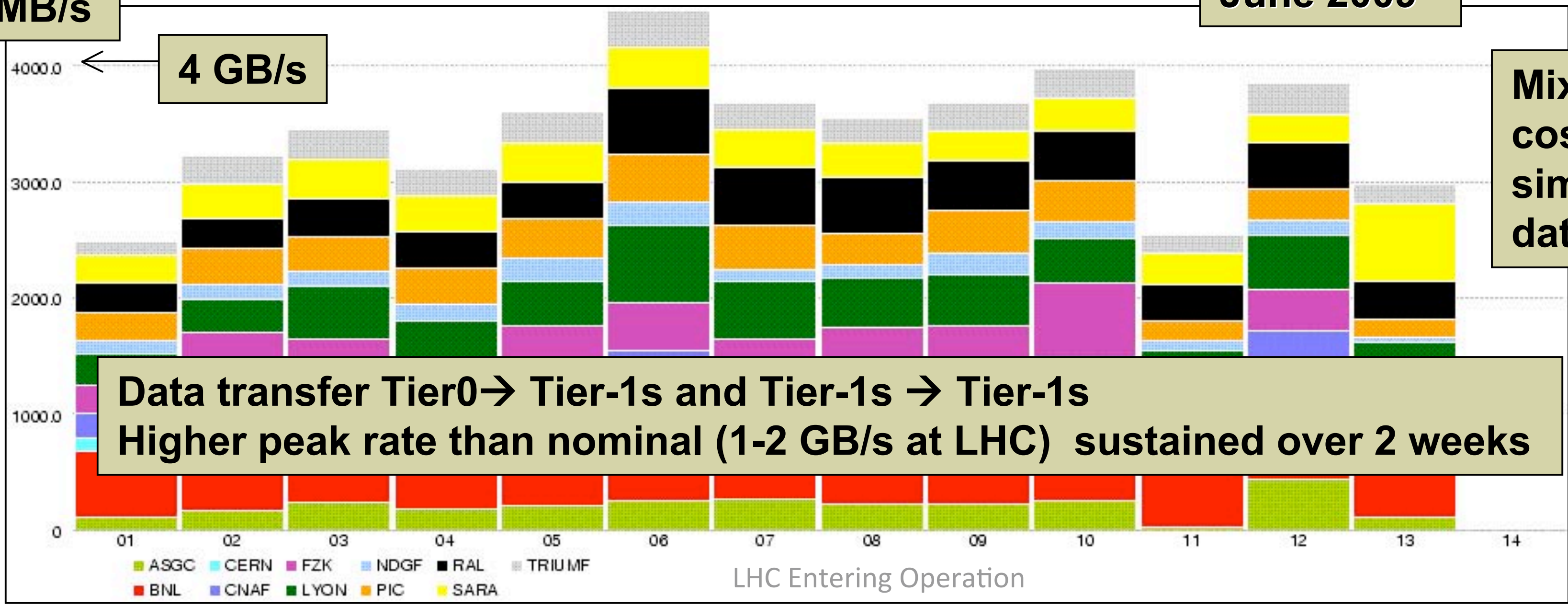


Number of production jobs running instantaneously on the ATLAS Grid

> 100k jobs per day

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

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.) → 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→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 …

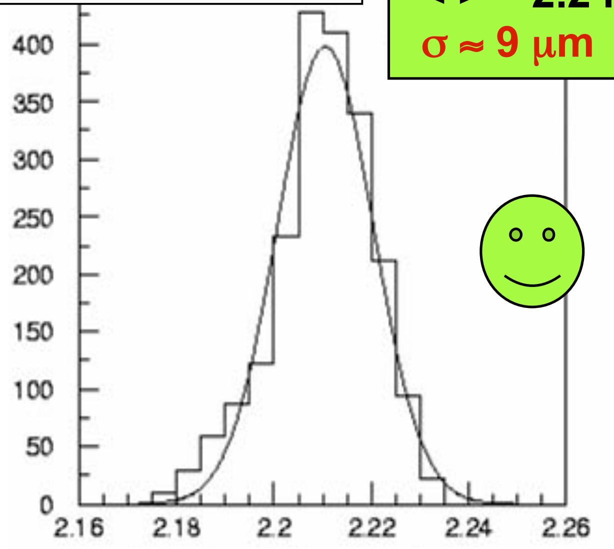
Example: ATLAS LAr em Accordion Calorimeter

Construction quality

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

End-cap: 1536 plates

< > ~ 2.2 mm
σ ≈ 9 μm

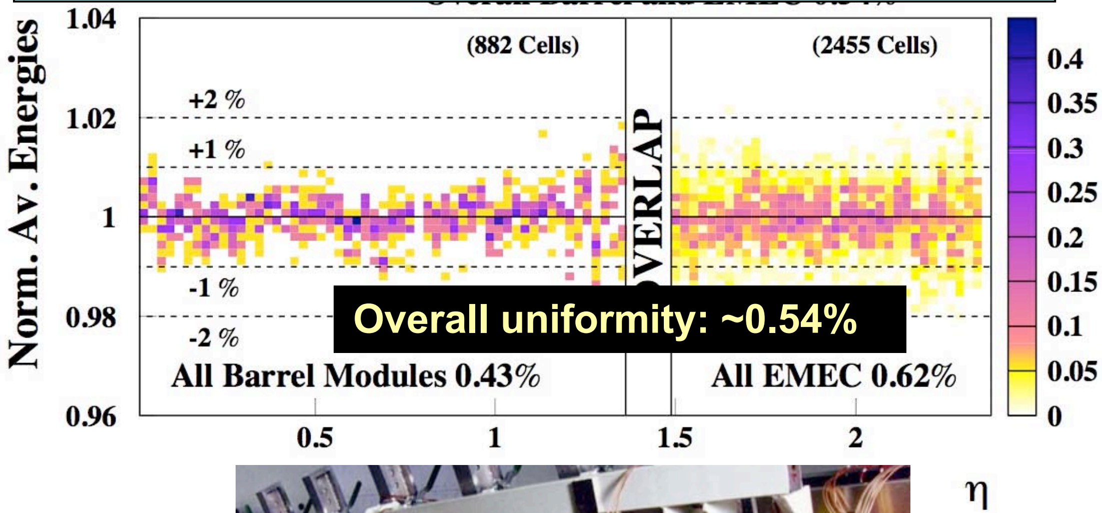


Absorber thickness (mm)

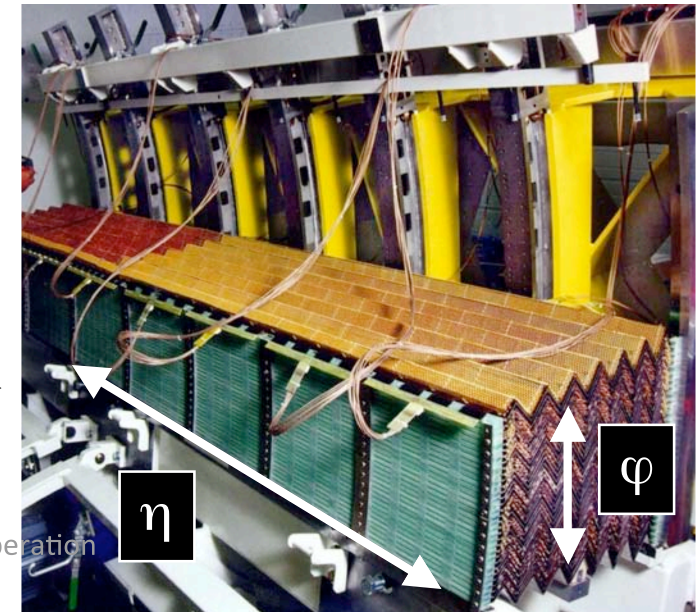
Test-beam measurements

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)



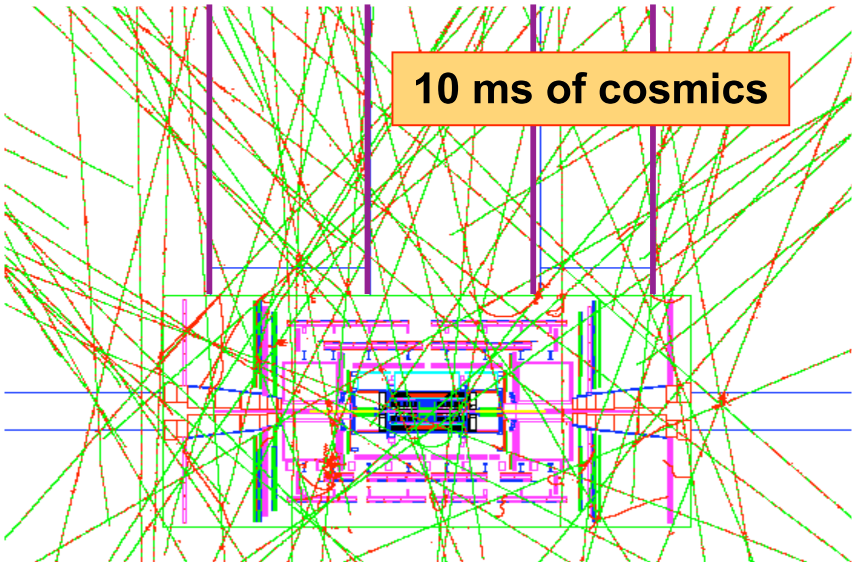
1 barrel module:
$\Delta\eta \times \Delta\varphi = 1.4 \times 0.4$
≈ 3000 channels



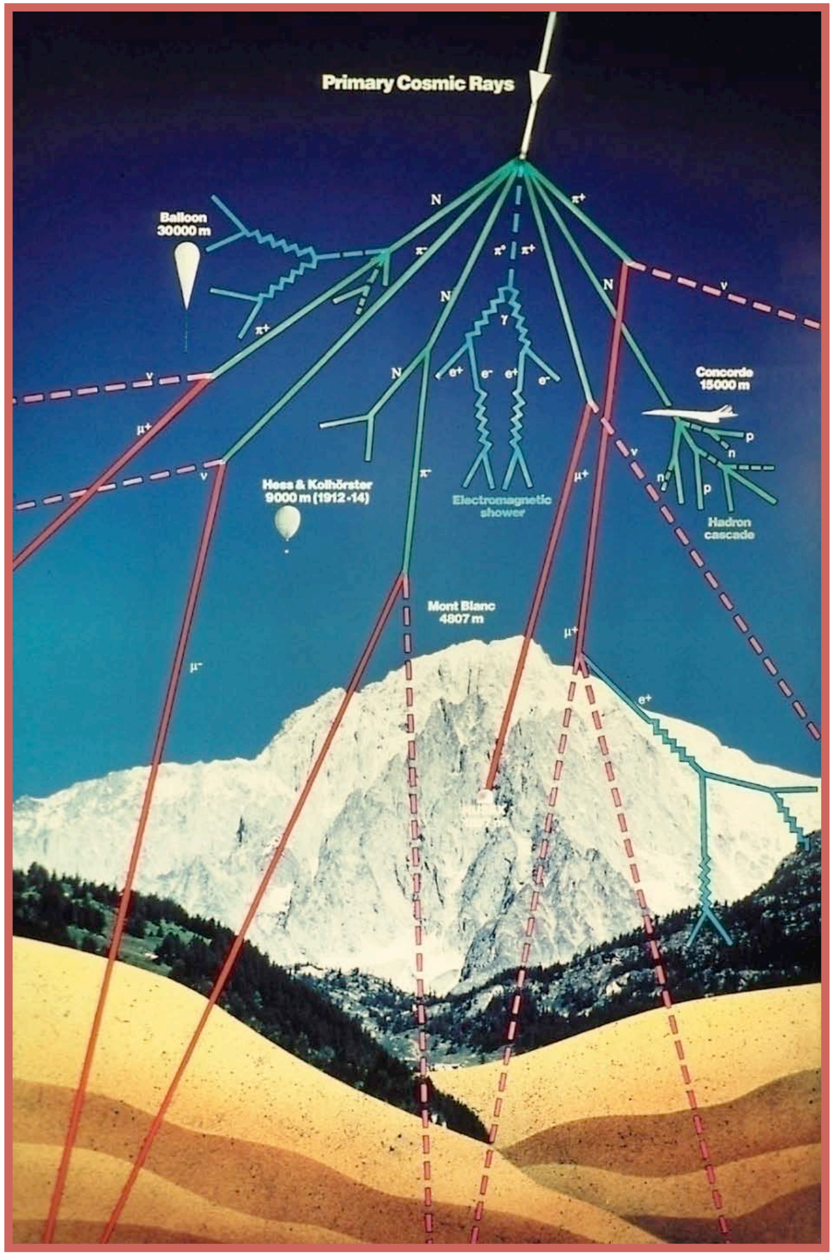
Commissioning with cosmics in the underground caverns
(the first real data in situ …)

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 → 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'

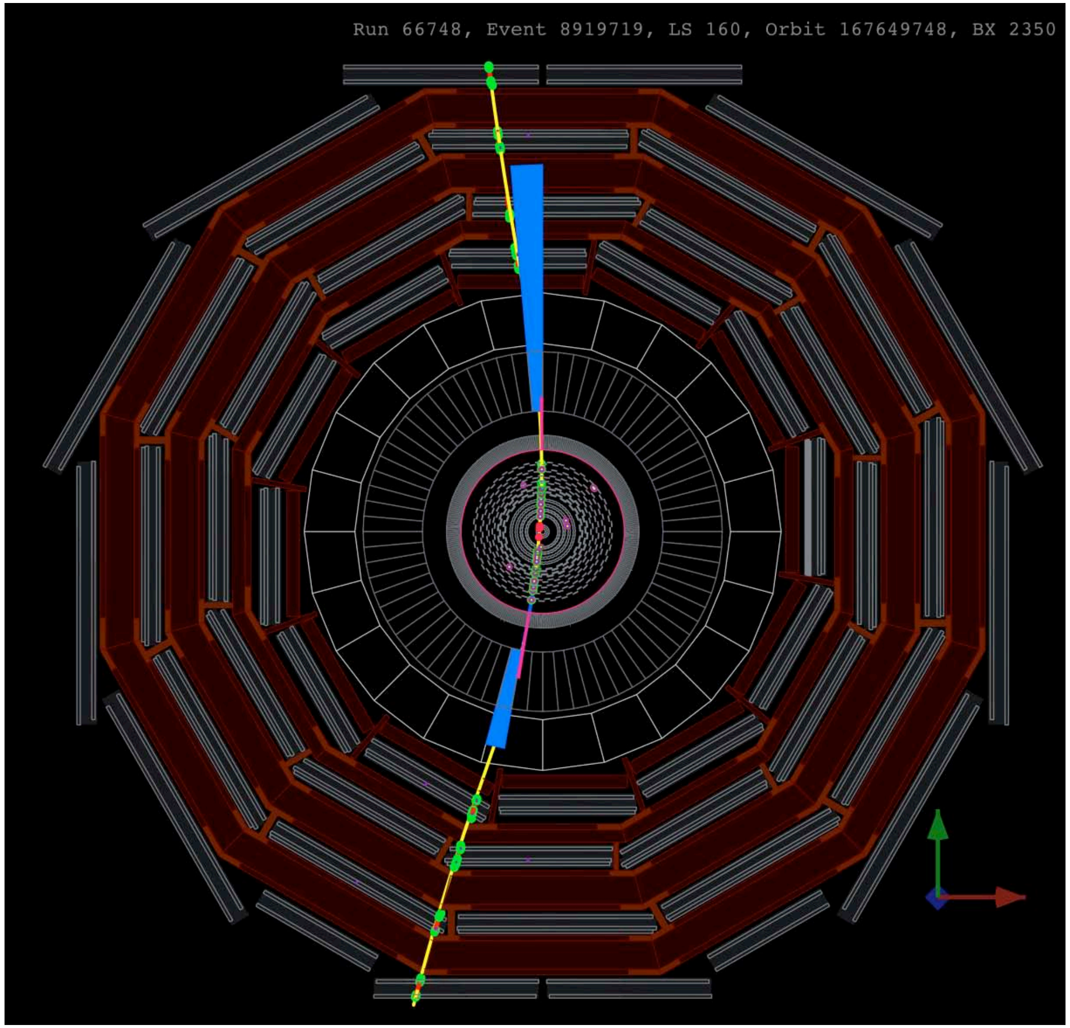
CMS ran for 6 weeks (Oct/Nov 08) continuously to gain operational experience

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)

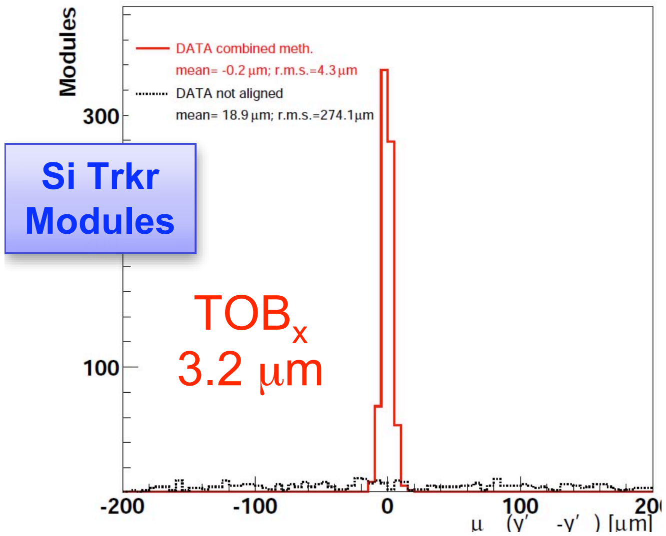
3-4 x 10^{-4} have a track with pixel hits (~70k trks)

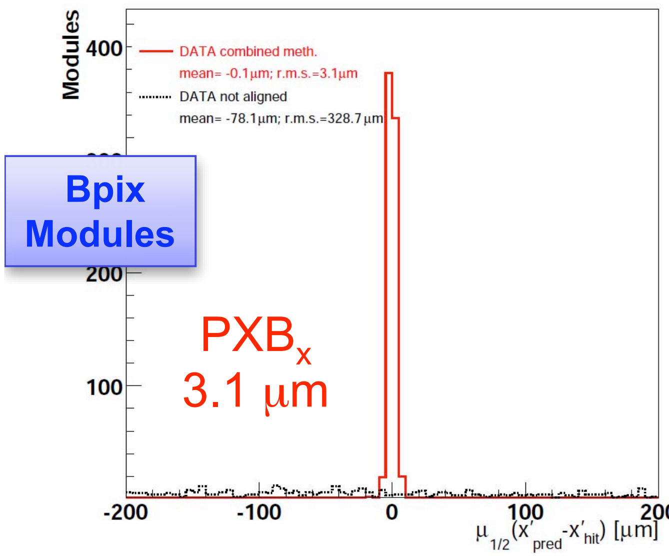


CMS CRAFT Results: Some Examples

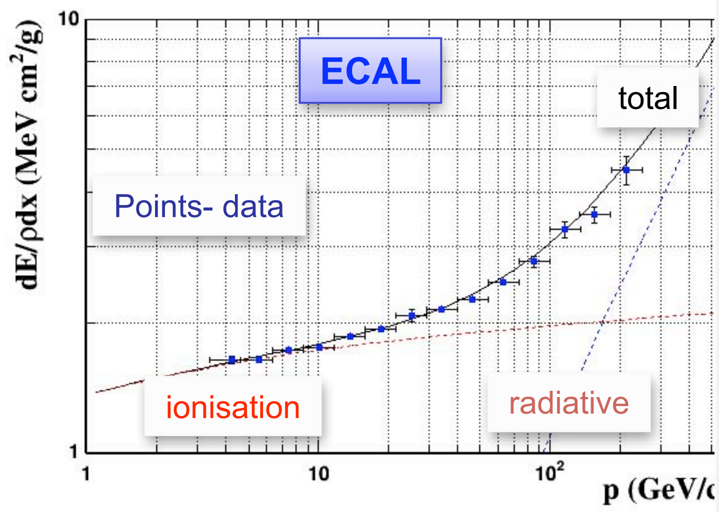
Alignment in Inner Tracker

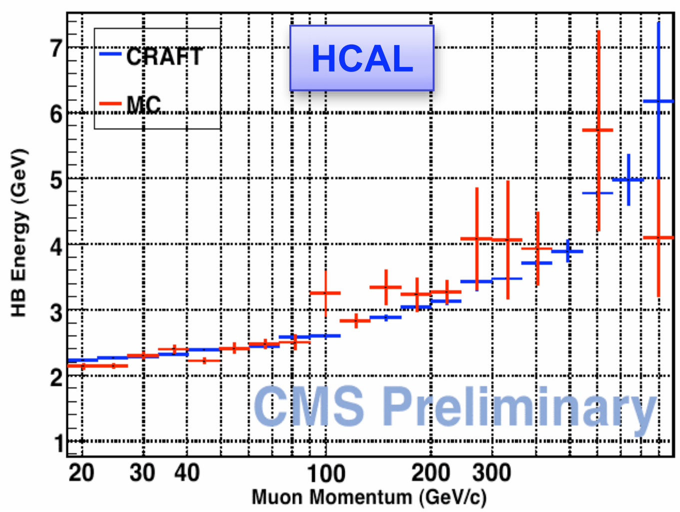
Distn of Mean Residuals



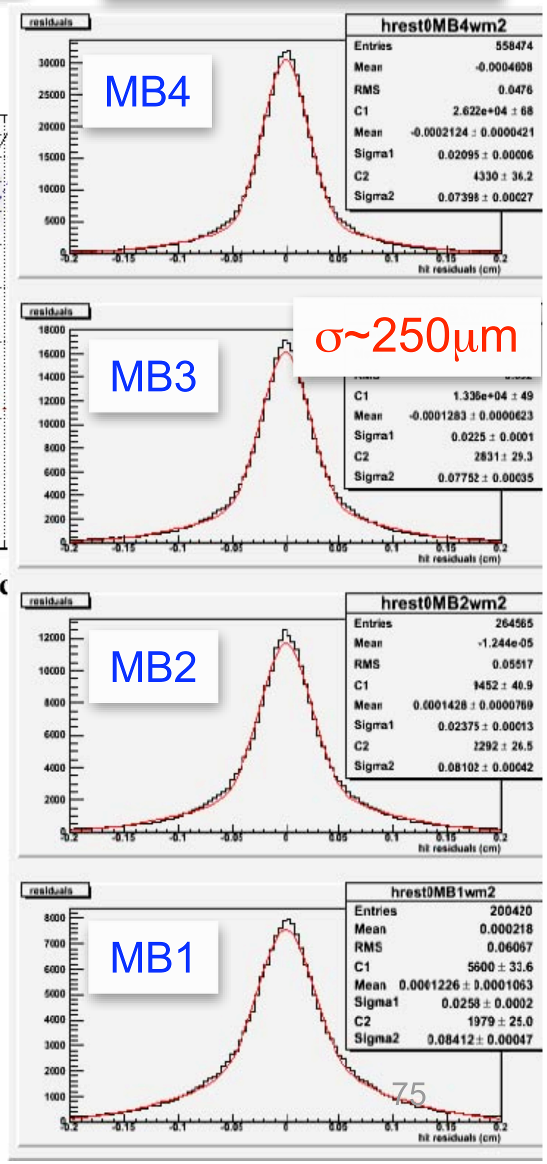


Energy deposited by muons

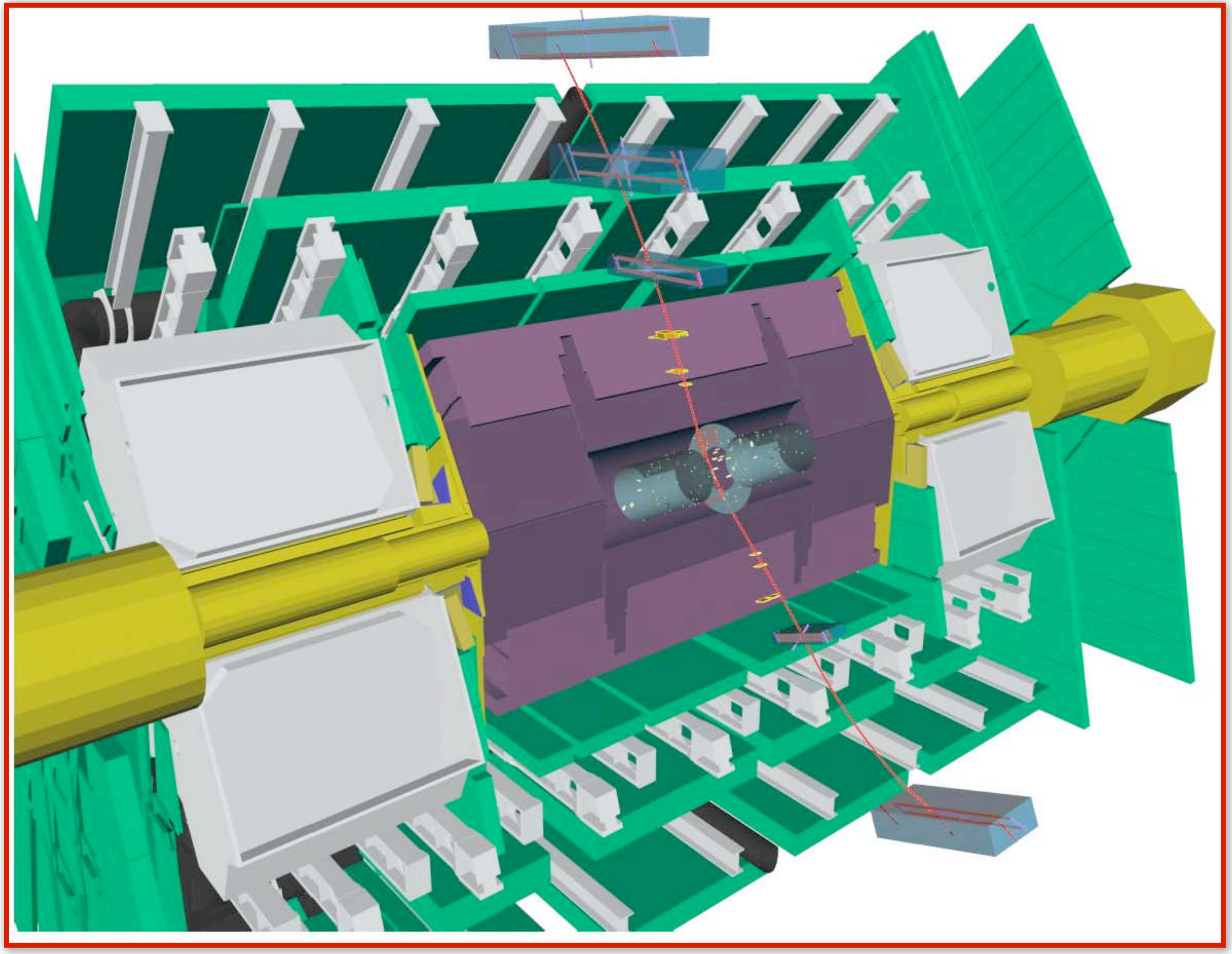




Muon Chambers Point Resolution

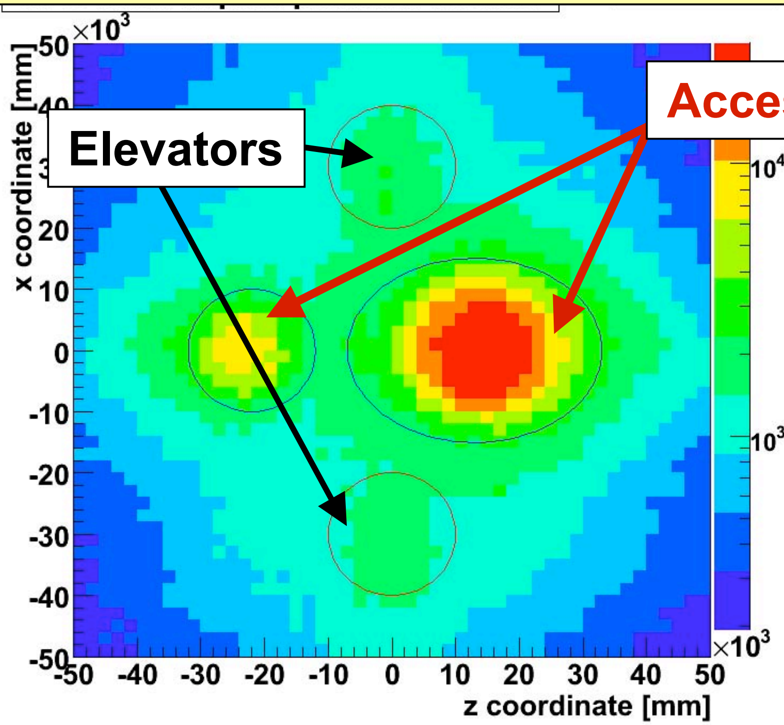


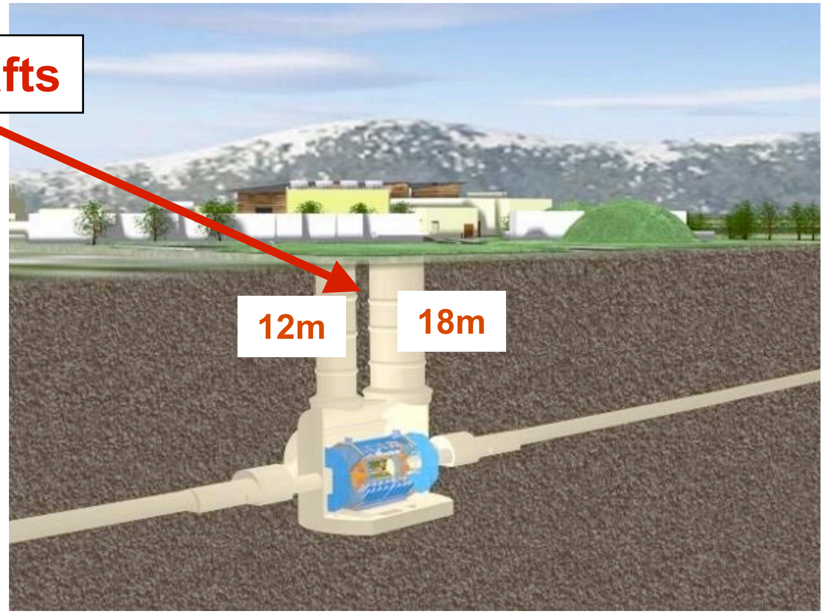
A cosmic muon traversing the whole ATLAS detector, recorded on 18/10/2008



Rate of cosmics events in ATLAS: 1-700 Hz (depending on the sub-detector size and location)

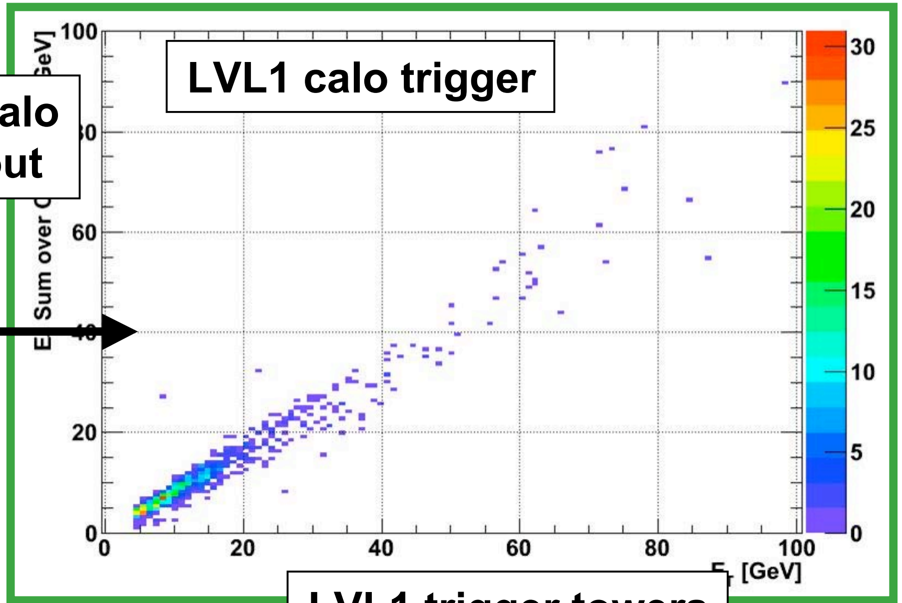
Extrapolation to the surface of cosmic muon tracks reconstructed by RPC trigger chambers



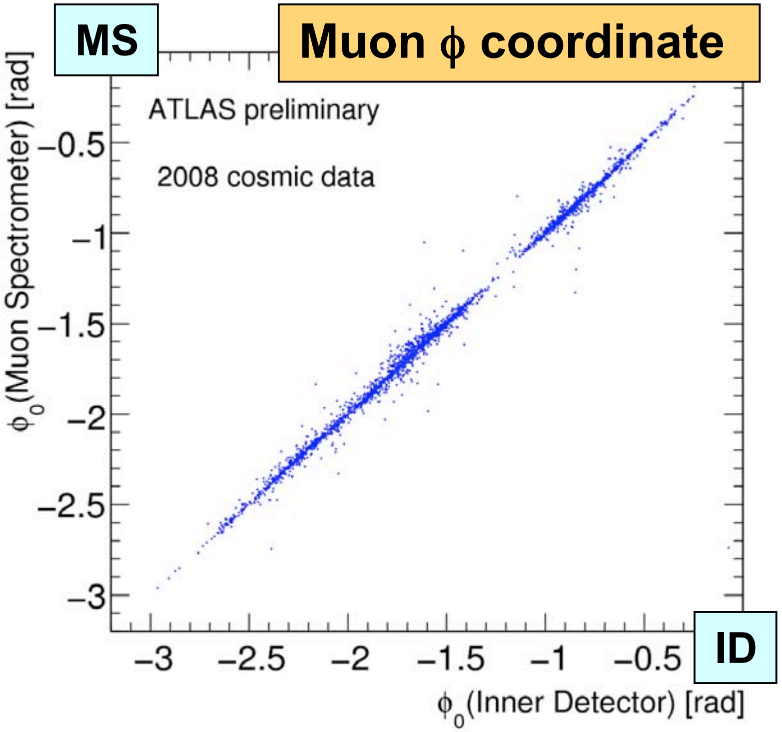


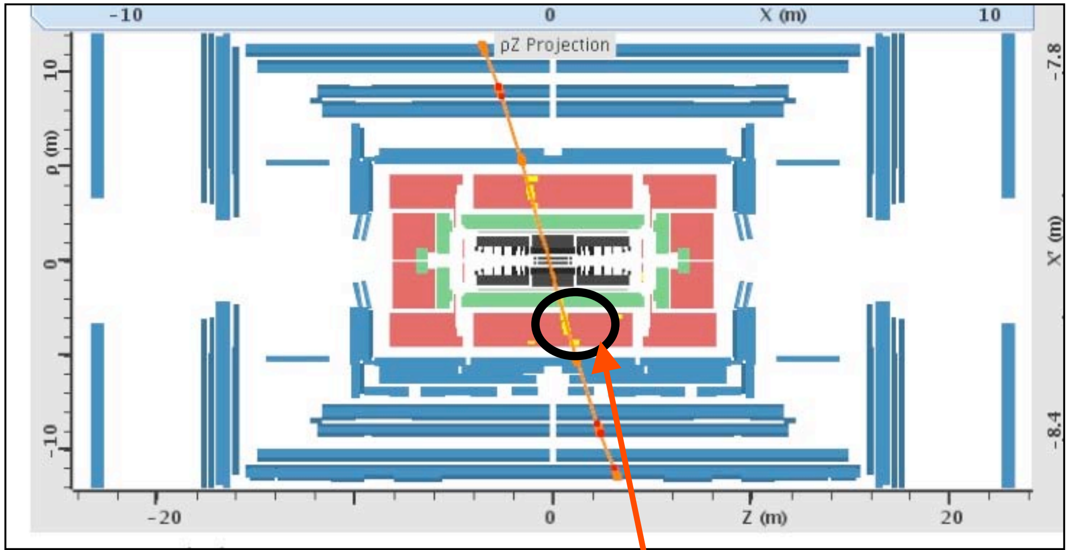
Muon (shower) energy measured with full calorimeter readout vs energy measured in trigger towers (ηxϕ =0.1x0.1) by level-one calorimeter trigger

With initial calibration (final calibration will reduce the spread)

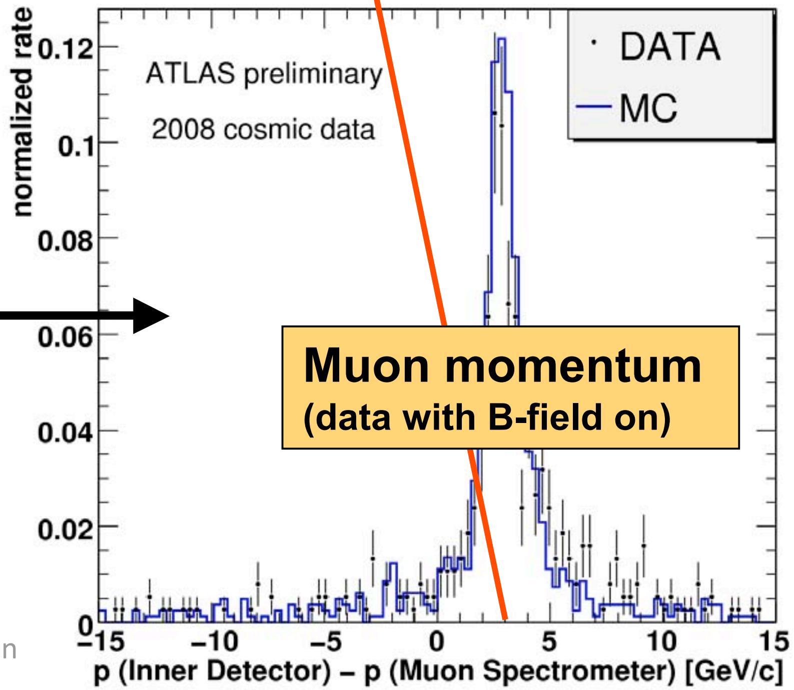


Correlation between measurements in the ATLAS Inner Detector and Muon Spectrometer





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)

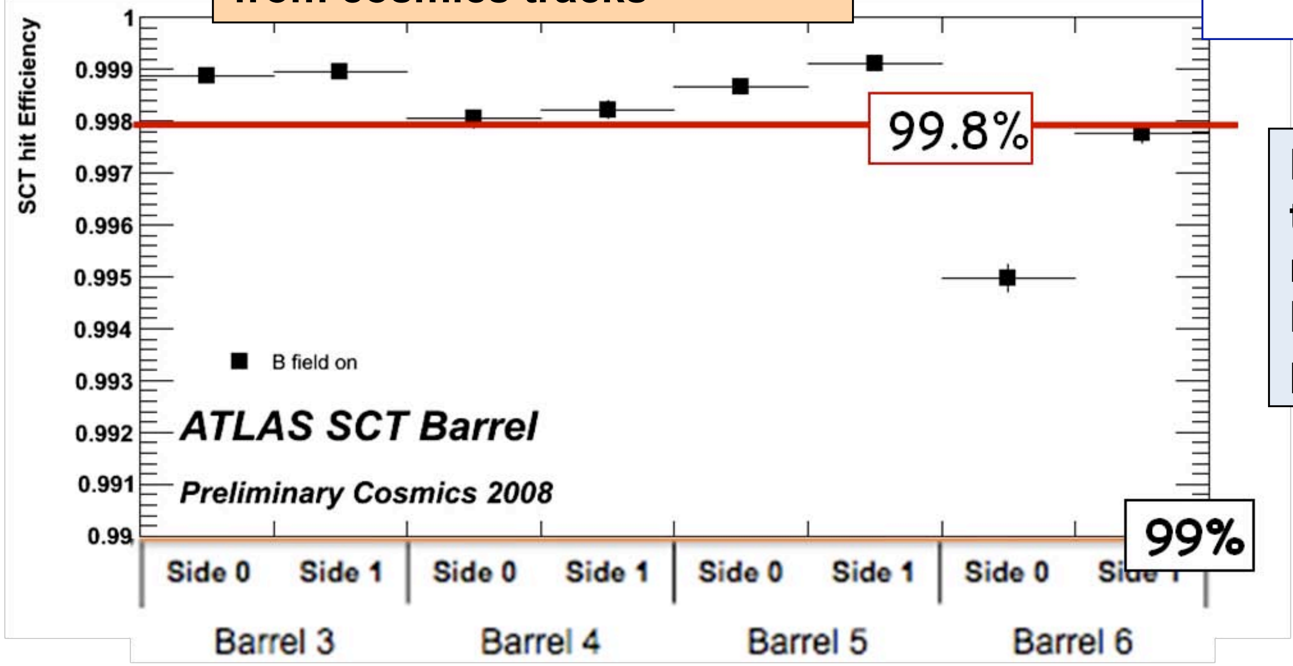


Inner Detector

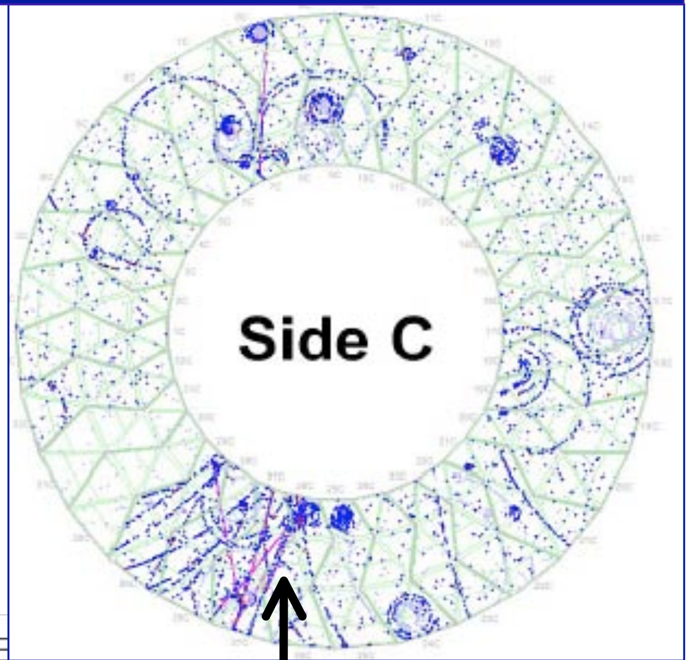
Silicon detectors (Pixels, SCT):

- achieved alignment precision with cosmics: ~ 20 μm (ultimate goal 5-10 μm)
- alignment stability Oct 2008-Jun 2009: few microns
- layer hit efficiency: > 99.5%
- noise occupancy: 10^{-10} (Pixels), $<10^{-4}$ (SCT)

SCT hit efficiency vs layer from cosmics tracks

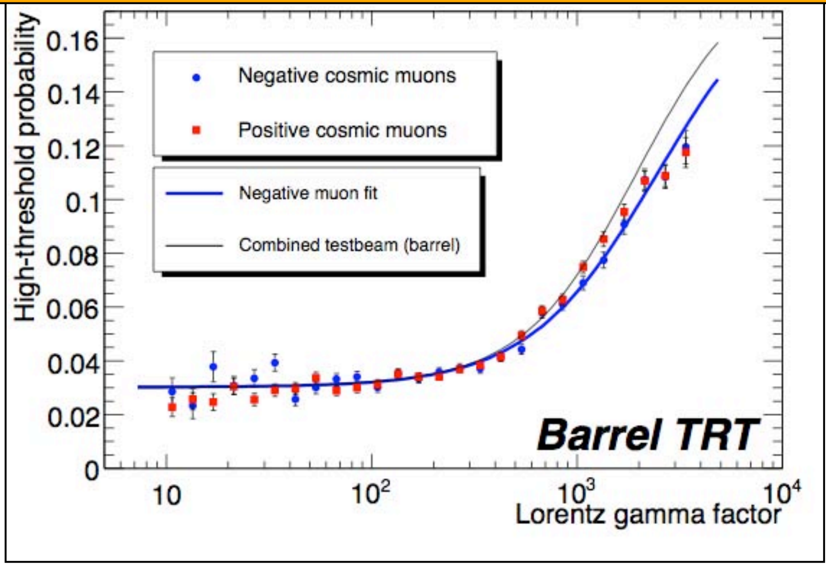


Cosmics-ray shower recorded in barrel TRT

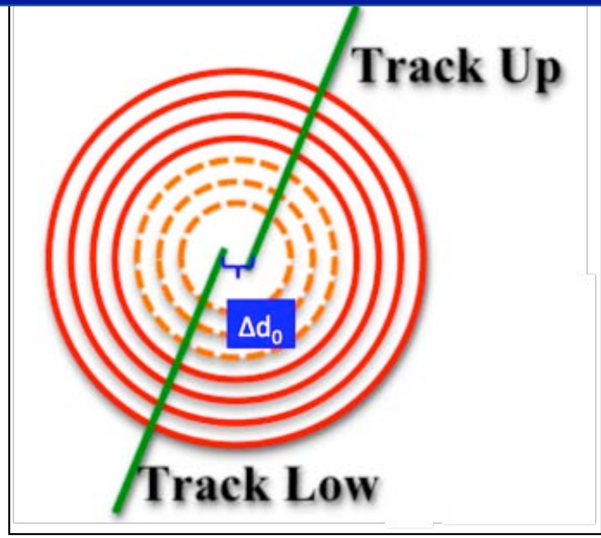


Bubble-chamber quality tracking plus transition radiation (red points) for high Lorentz γ−factor particles (typically electrons)

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



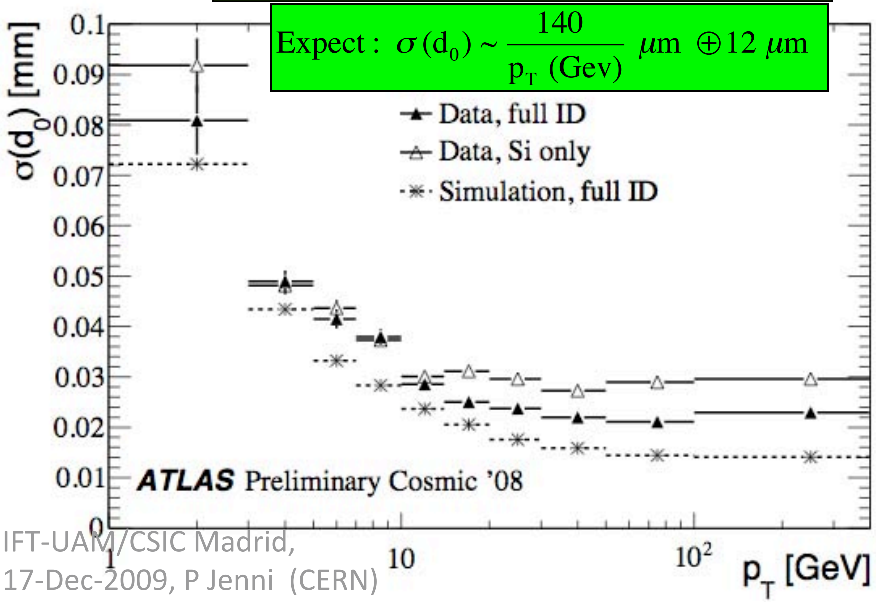
Tracks are split in the center and refit separately → can measure resolutions and biases from data



Split tracks

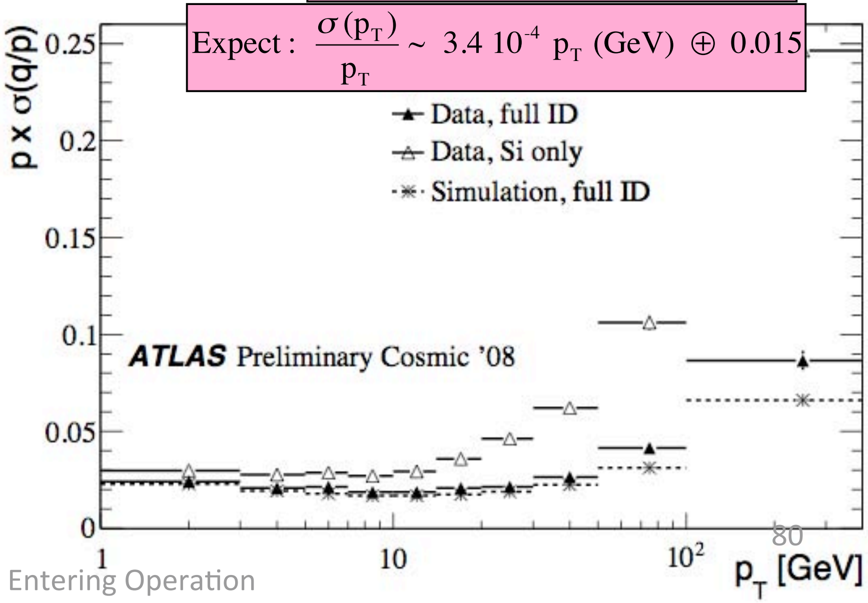
Impact parameter resolution

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



Momentum resolution

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

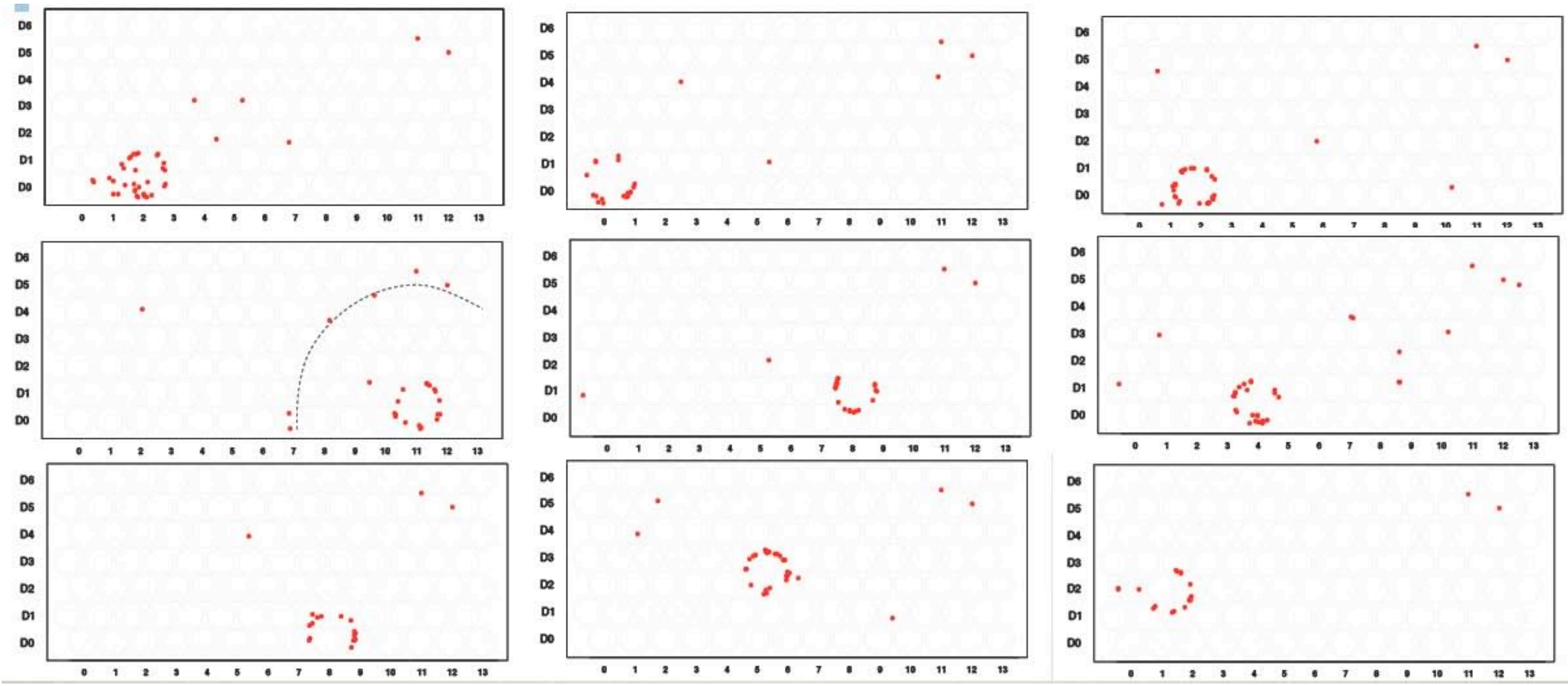


LHCb example: Seeing RICH1 rings from cosmics

RICH optics assumes particles ~horizontal and from IP → using cosmics is tricky!

Solution: use scintillators as auxiliary triggers and a lot of patience

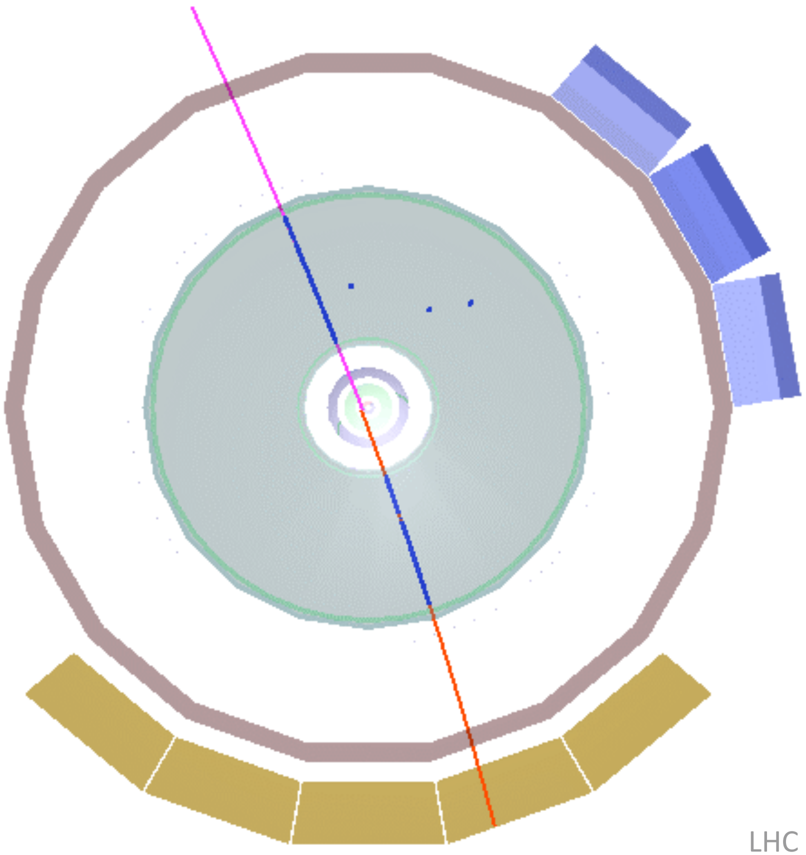
(~2 triggers/minute)

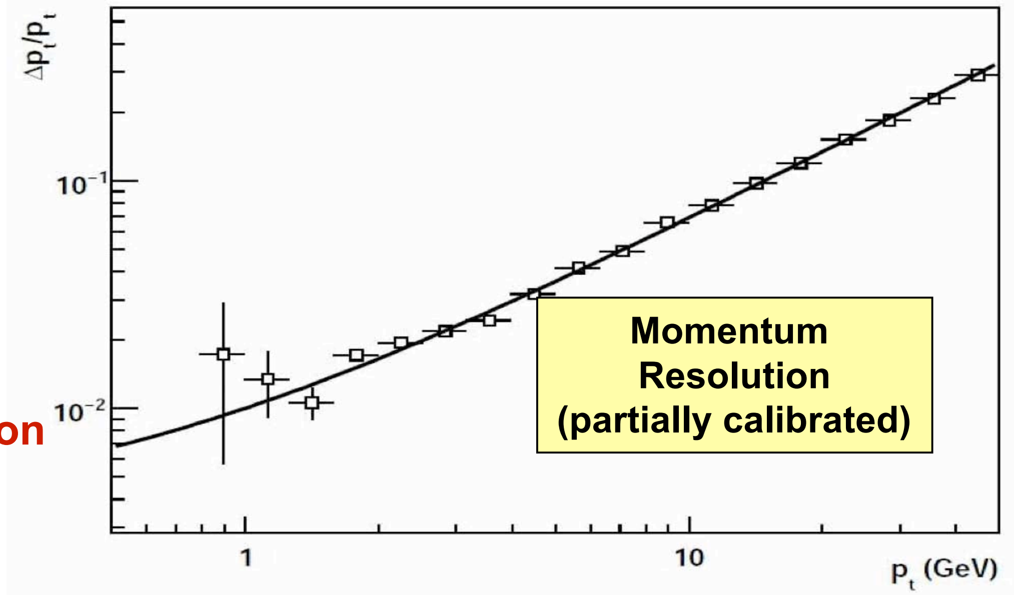


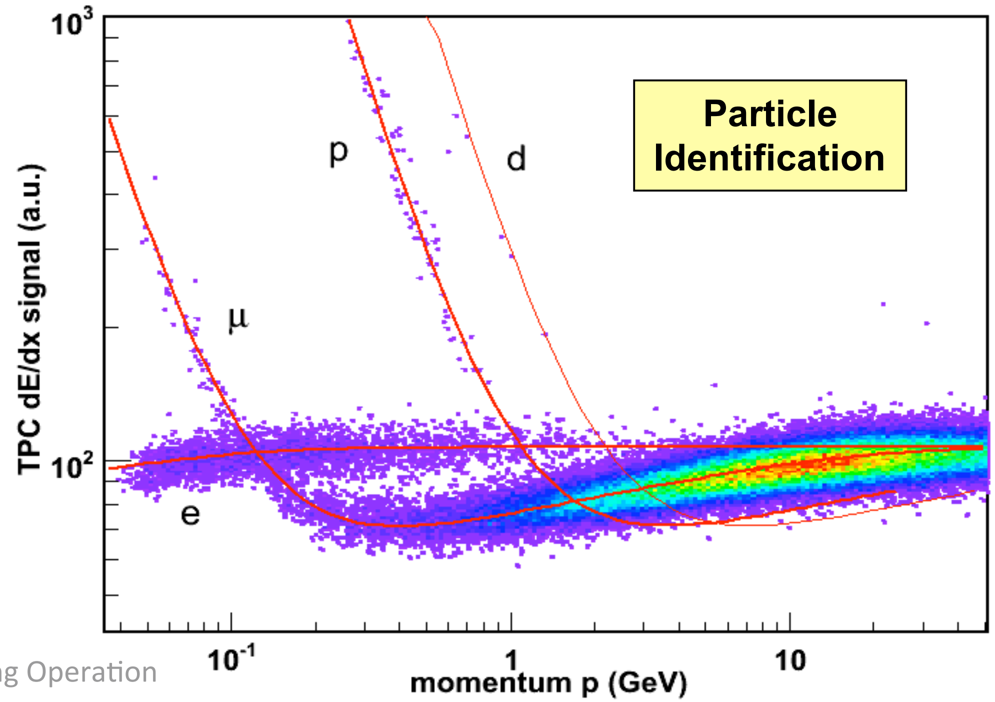
Several rings observed!

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.)
  → 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 …

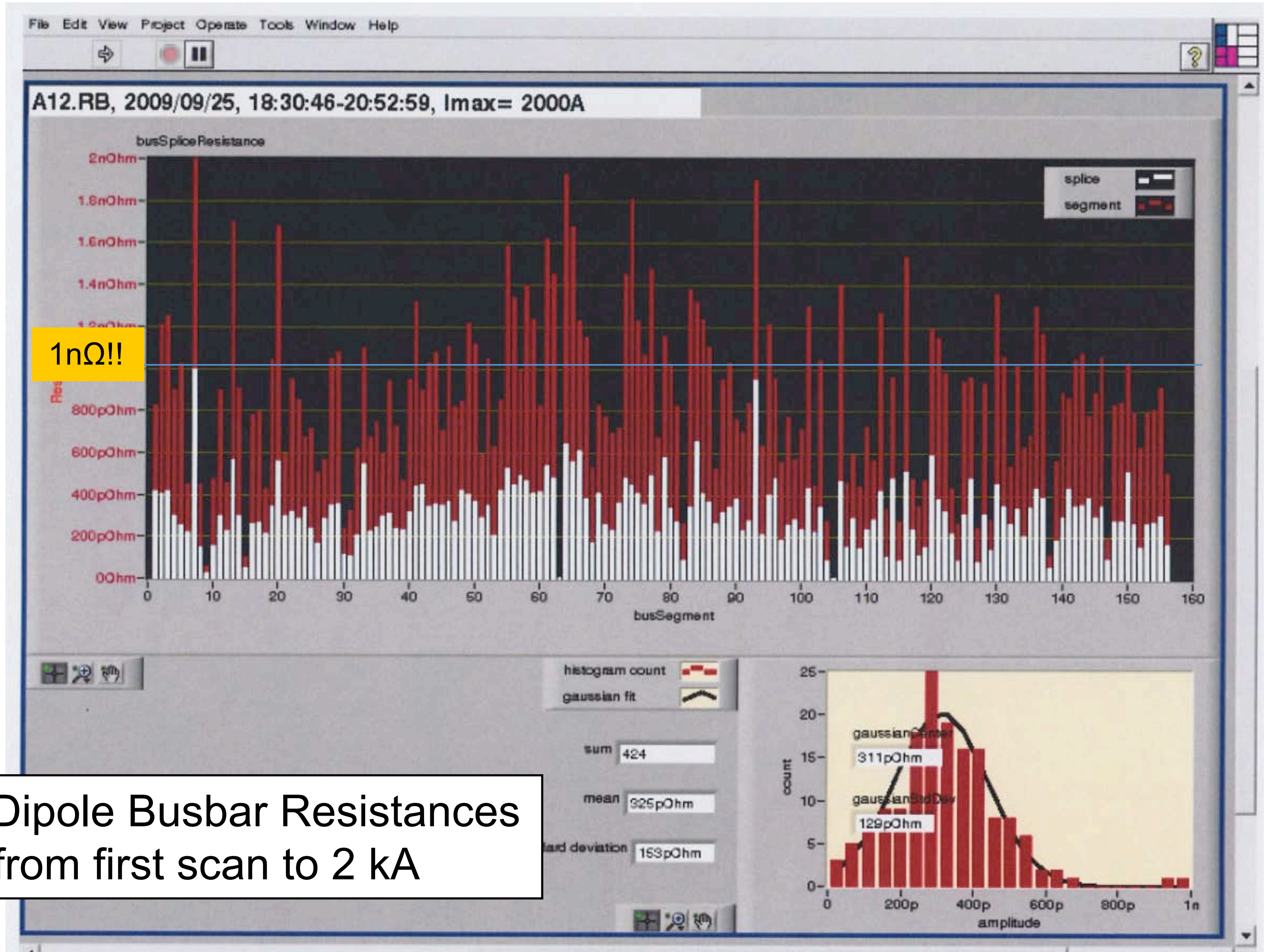
Steve Myers, CERN 26th November 2009:

LHC is back!

‘From the dark days after September 19, 2008 to the bright days of late November 2009’

Splice Mapping of Dipoles

QPS team



1nΩ!!

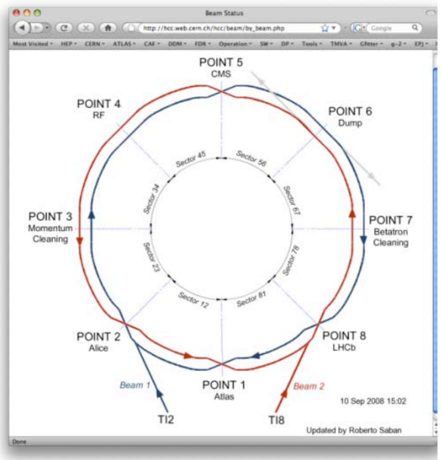
First Dipole Busbar Resistances from first scan to 2 kA

Friday November 20th, 2009

18:30 Beam 1

- 19.00 beam through CMS (23, 34, 45)
  - beam1 through to IP6 19.55 Starting again injection of Beam1
  - corrected beam to IP6, 7, 8, 1
- 20.40 Beam 1 makes 2 turns
  - Working on tune measurement, orbit, dump and RF
  - Beam makes several hundred turns (not captured)
    - Integers 64 59, fractional around .3 (Qv trimmed up .1)
- 20.50 Beam 1 on beam dump at point 6
- 21.50 Beam 1 captured

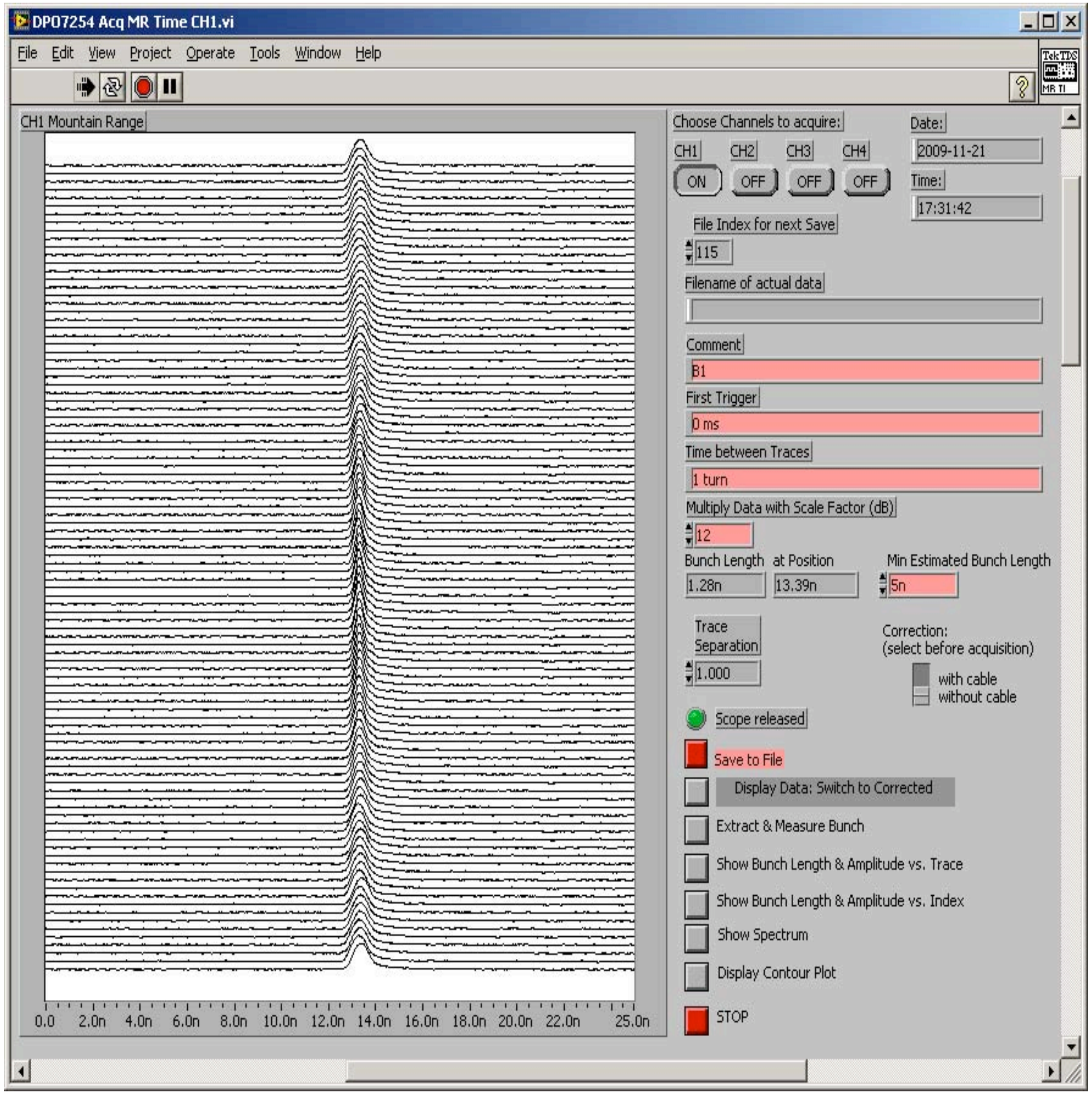
2h10 for 27km: 12.5km/h average speed



22:15 Beam2

- 23.10 Start threading Beam2
  - Round to 7 6 5 2 1
- 23.40 First Turn Beam2
  - Working on tune measurement, orbit, dump and RF
  - Beam makes several hundred turns (not captured)
    - Integers 64 59, fractional around .3 (Qv trimmed up .05)
- 24.10 Beam 2 captured

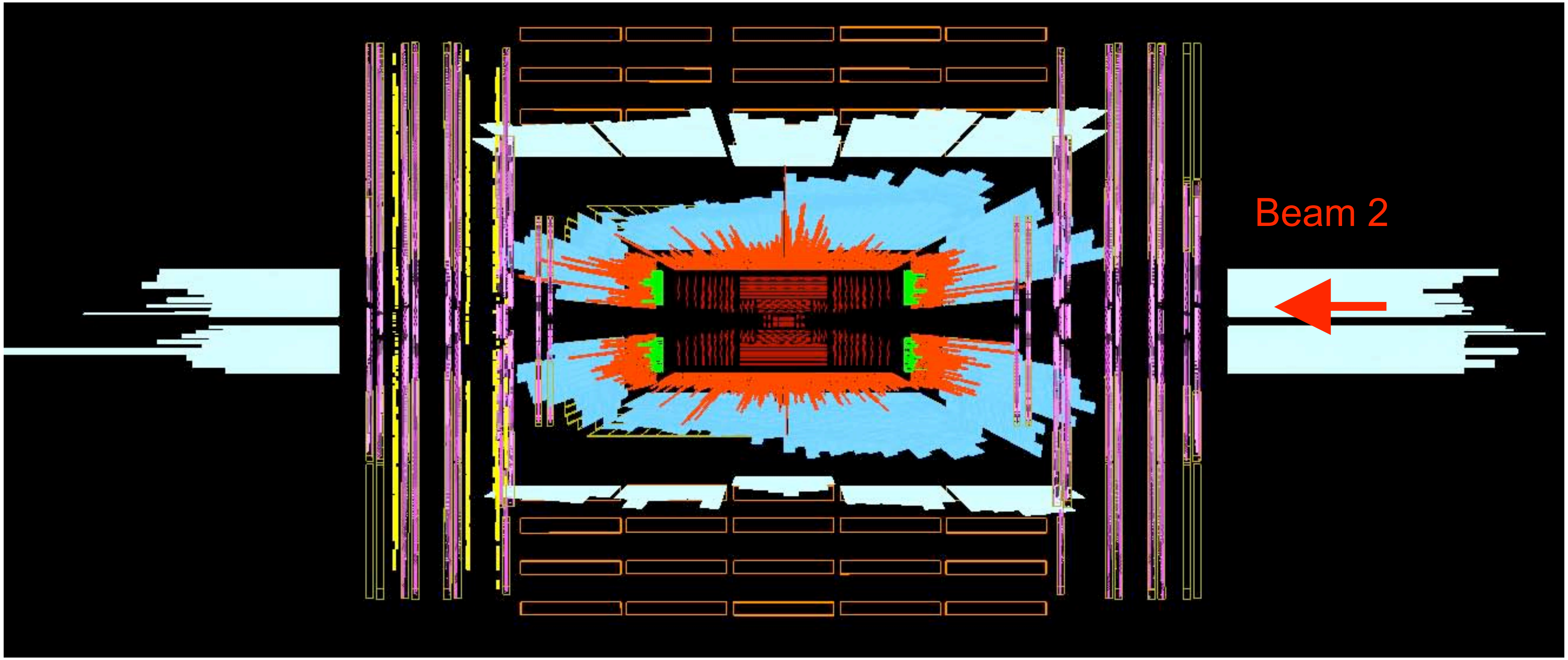
1h25 for 27km: a bit faster



Beam is circulating and stable

- **magnets**
- **power supplies**
- **vacuum**
- **RF**
- **cryogenics**
- **all infrastructure**
- **optics**
- **injection**

CMS Splash '09 Event Display



ECAL energy deposits in red, Preshower in green,
HCAL energy deposits in blue (light blue for HF and HO),
RPC muon hits are in yellow,
and CSC muon hits are in magenta.

1st Beam Splash
from Beam-2

ATLAS beam-splash events

Avalanche of scattered particles from beam-on-collimator hits

Detectors fully lit, typically

•300,000 SCT hits

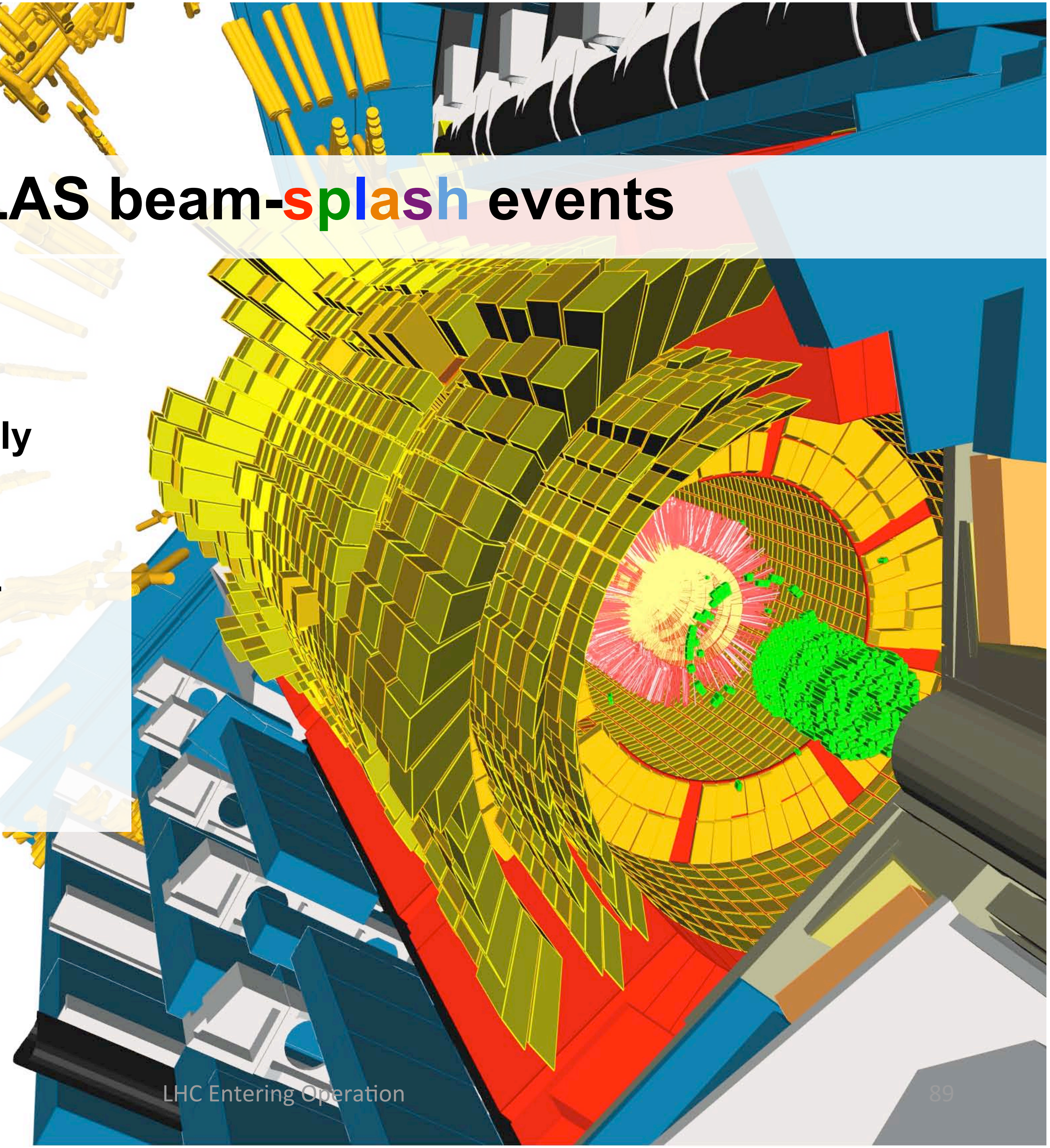
•350,000 TRT hits
(~all passing high-threshold)

•3000 TeV calo energy sum

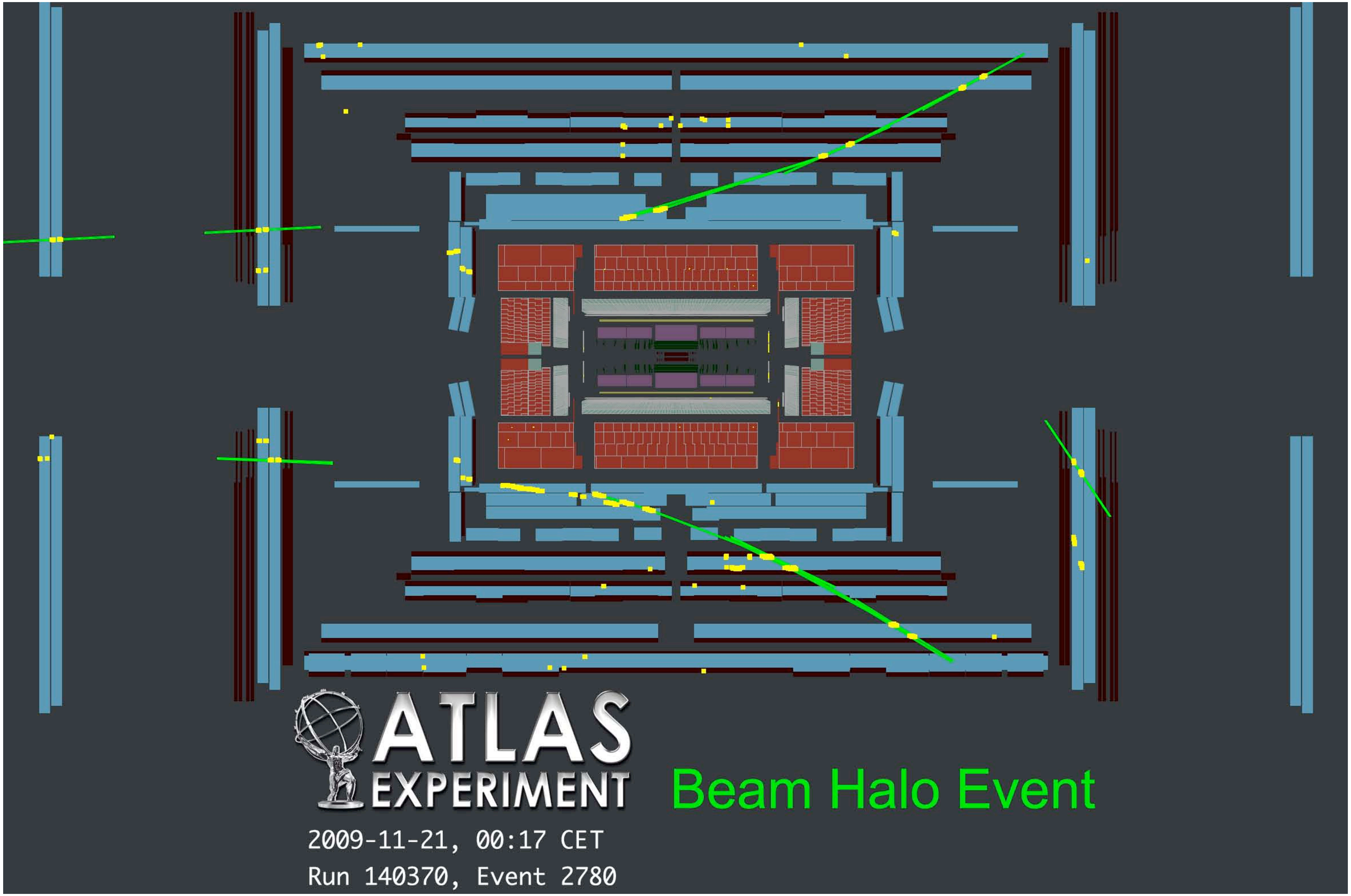
•490,000 MDT hits

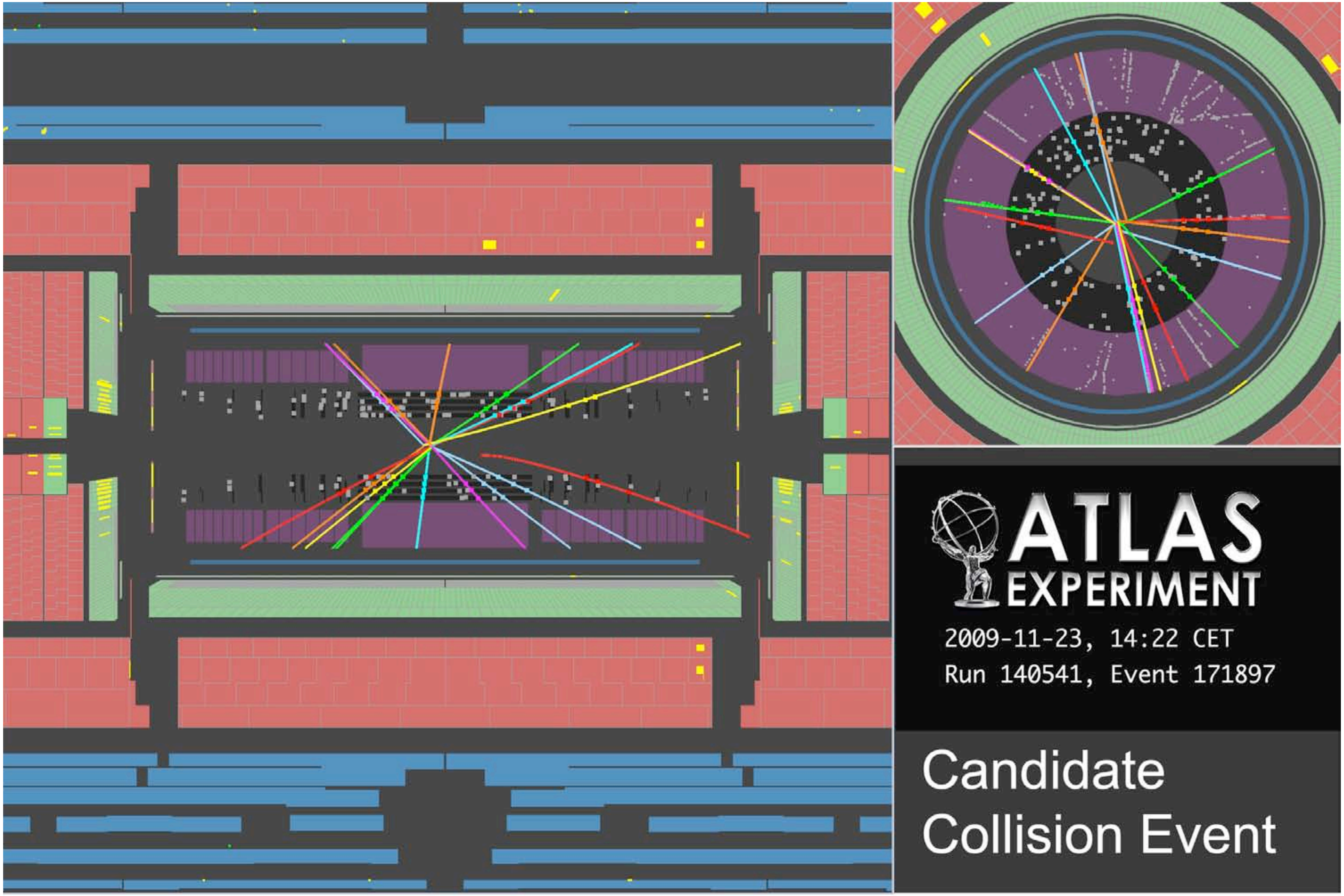
•320,000 RPC hits

•65,000 TGC hits



2009-11-20, 23:32 CET
Run 140370, Event 2666

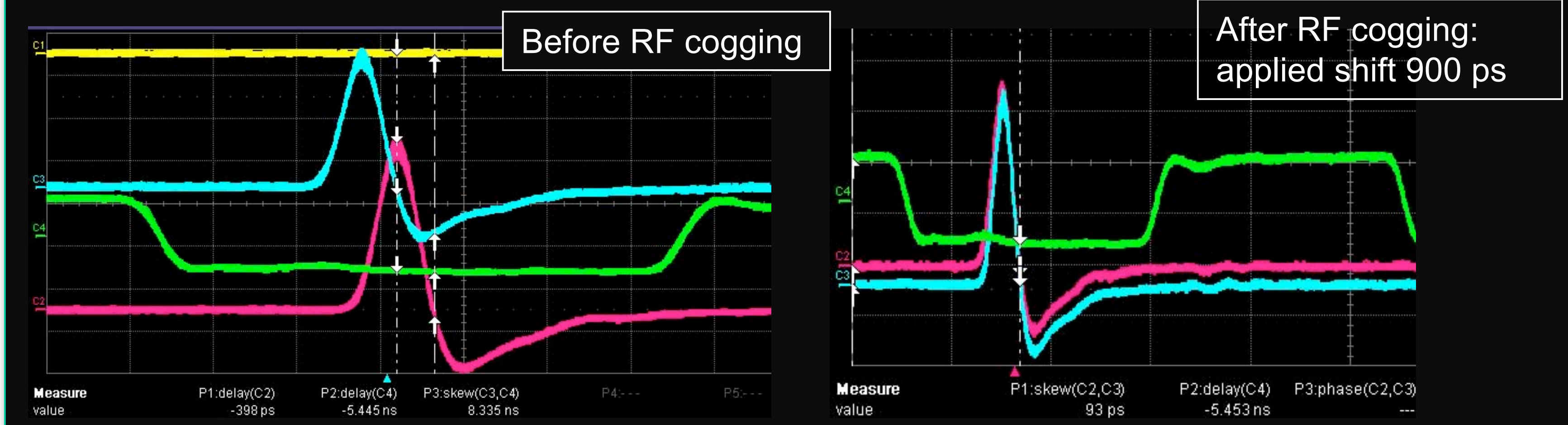

ATLAS
EXPERIMENT
Beam Halo Event
2009-11-21, 00:17 CET
Run 140370, Event 2780



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

**Examples of early optimization work …
and “handshake” between
ATLAS and LHC operation team**

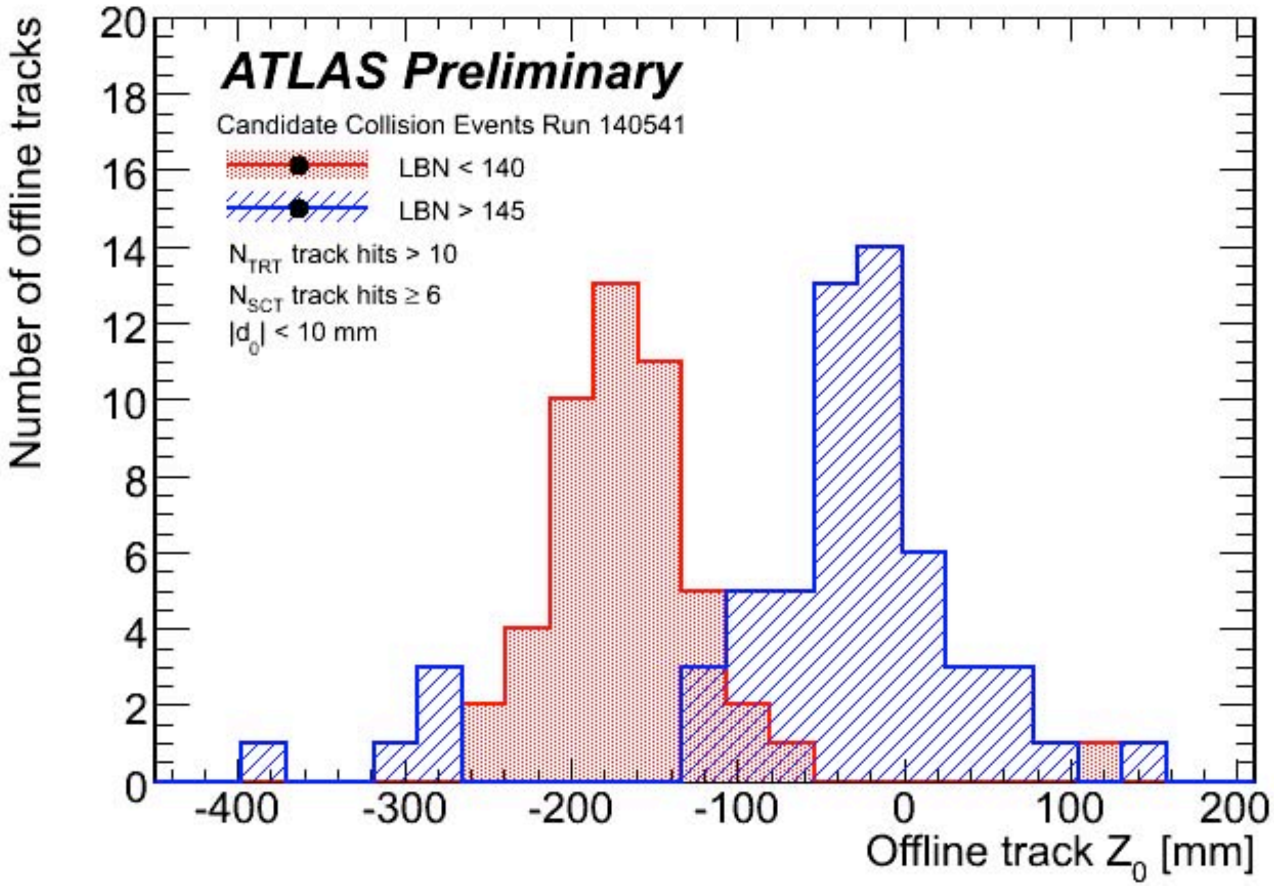
**First collision events on 23 November:
ATLAS beam pickups showed phase shift of
900 ps, causing the primary vertex
to be shifted by -13.5 cm in Z → based on this
information, the machine team corrected the RF cogging**



Beam pickup scope shots, beam 1 & 2

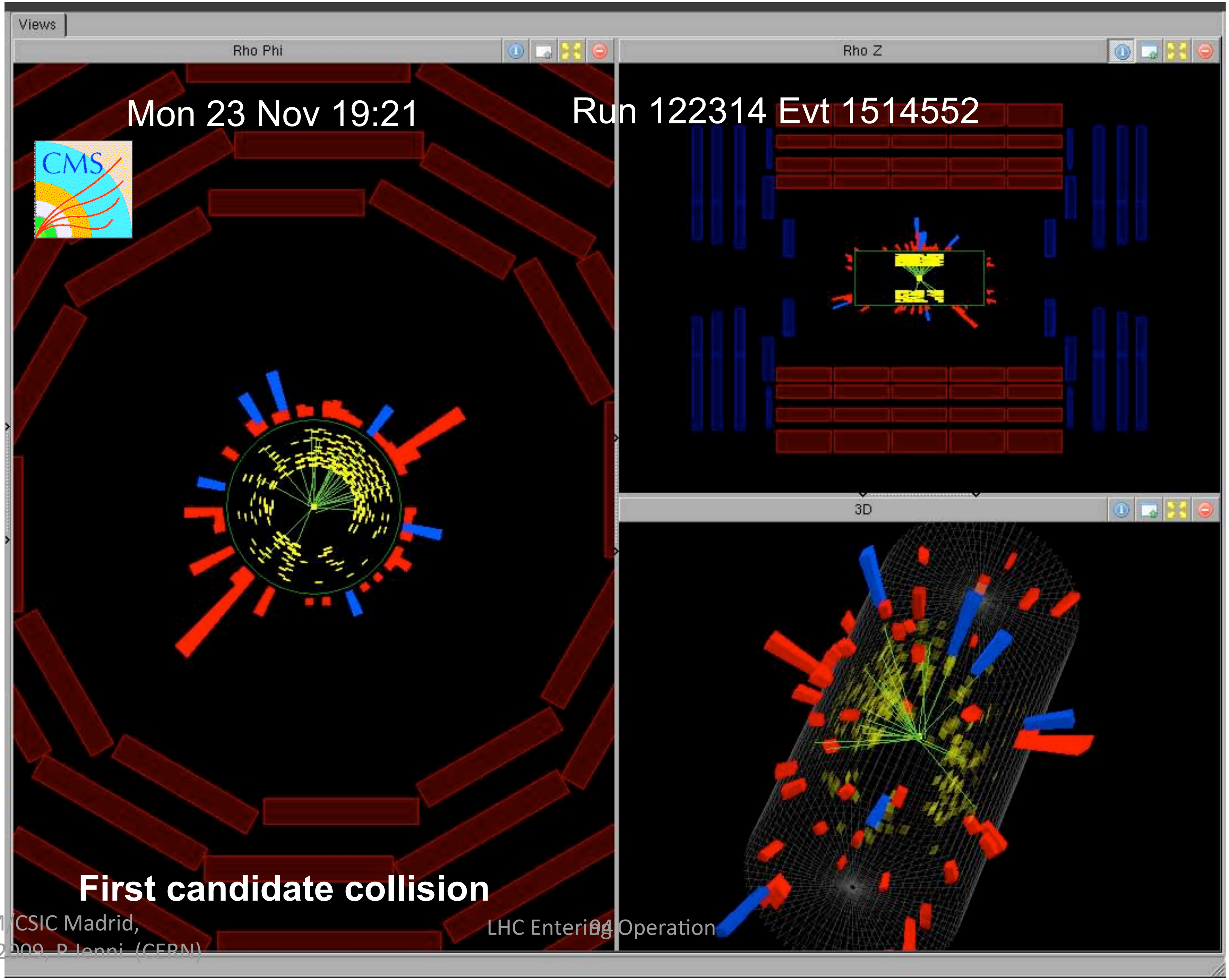
Bunches stable within 20 ps (rms)

Track *Z* distribution of collision candidate events as obtained before and after RF cogging. Observed shift: ~ +12 cm

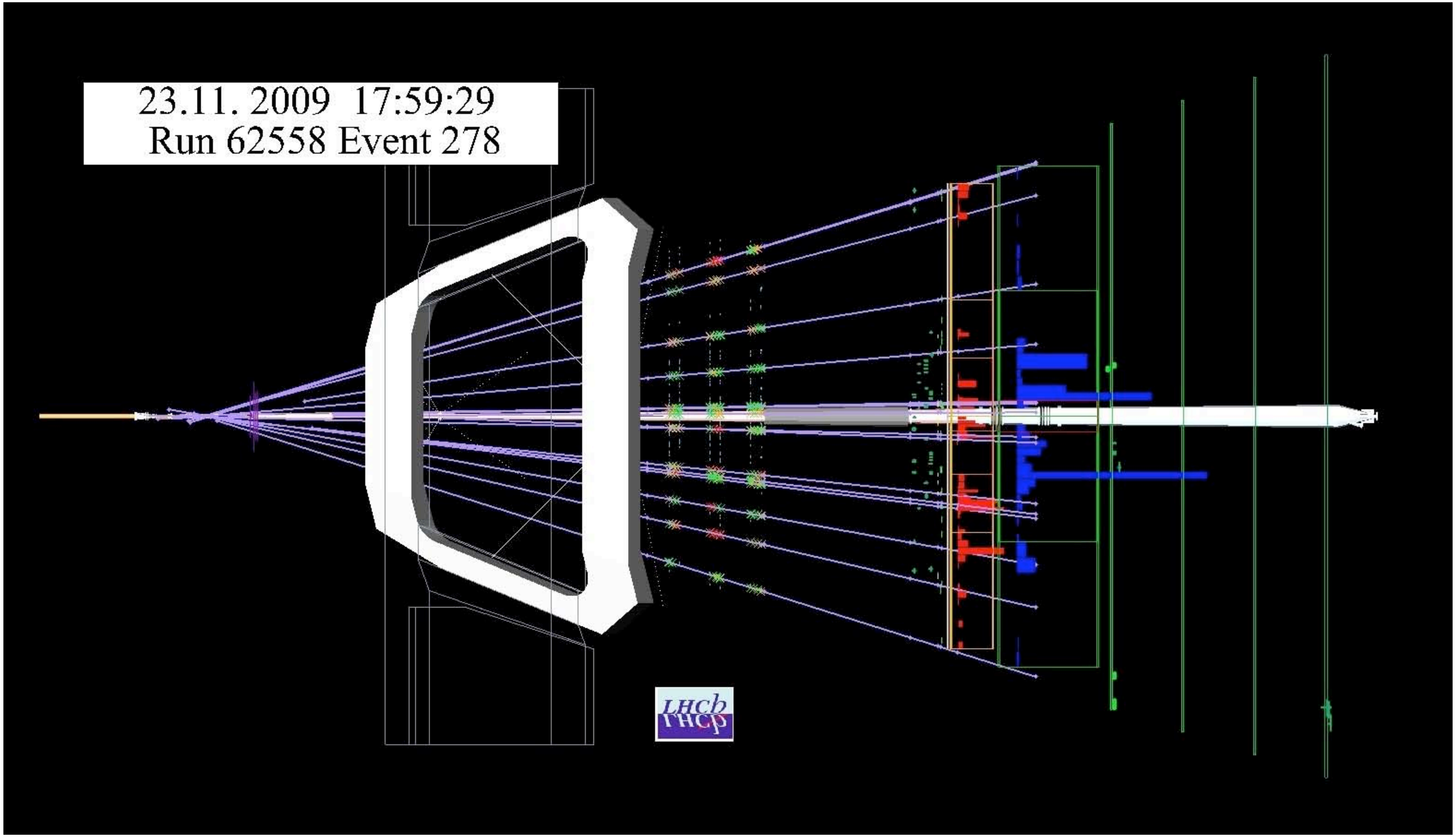


Note: beams were not yet stable → Pixels off and SCT at reduced voltage

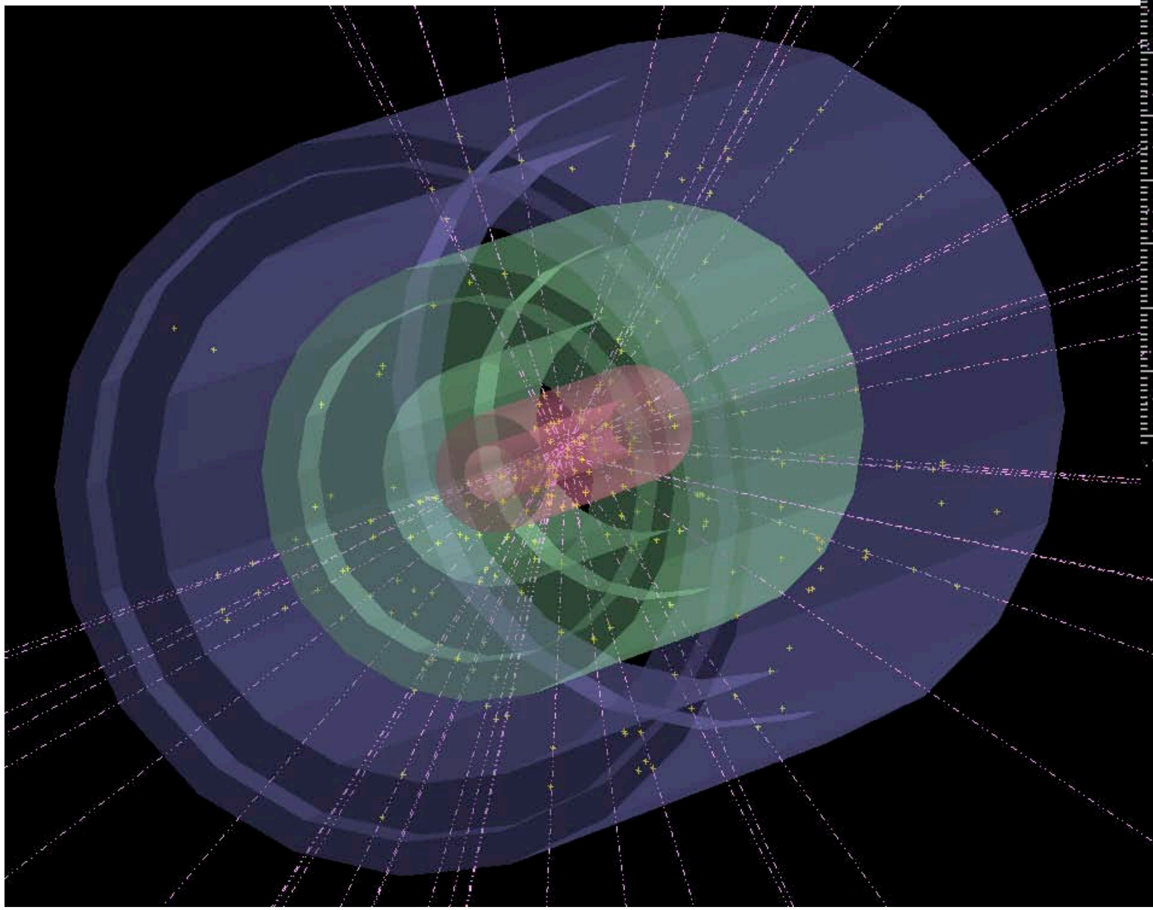
CMS event from the Evening Fill

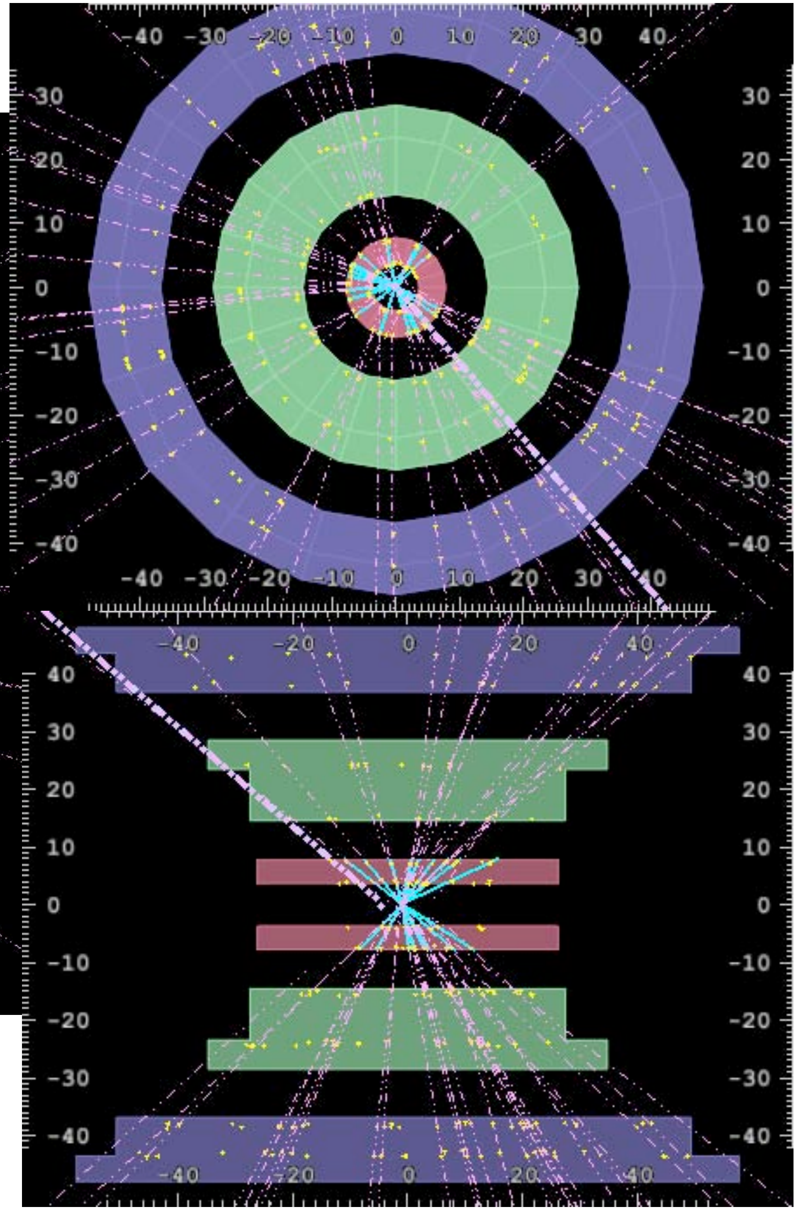


LHCb events have nice vertices (extrapolating OT tracks)

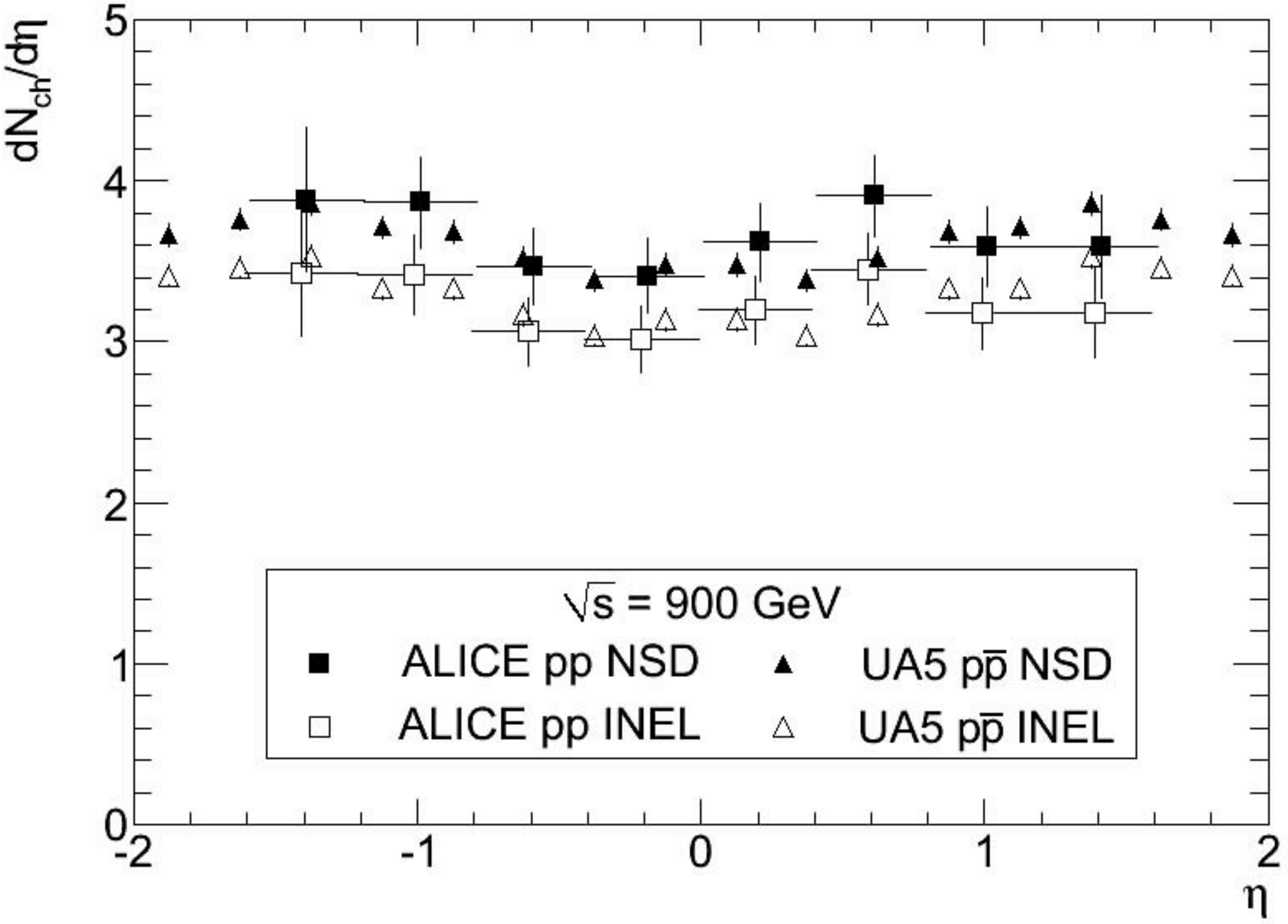


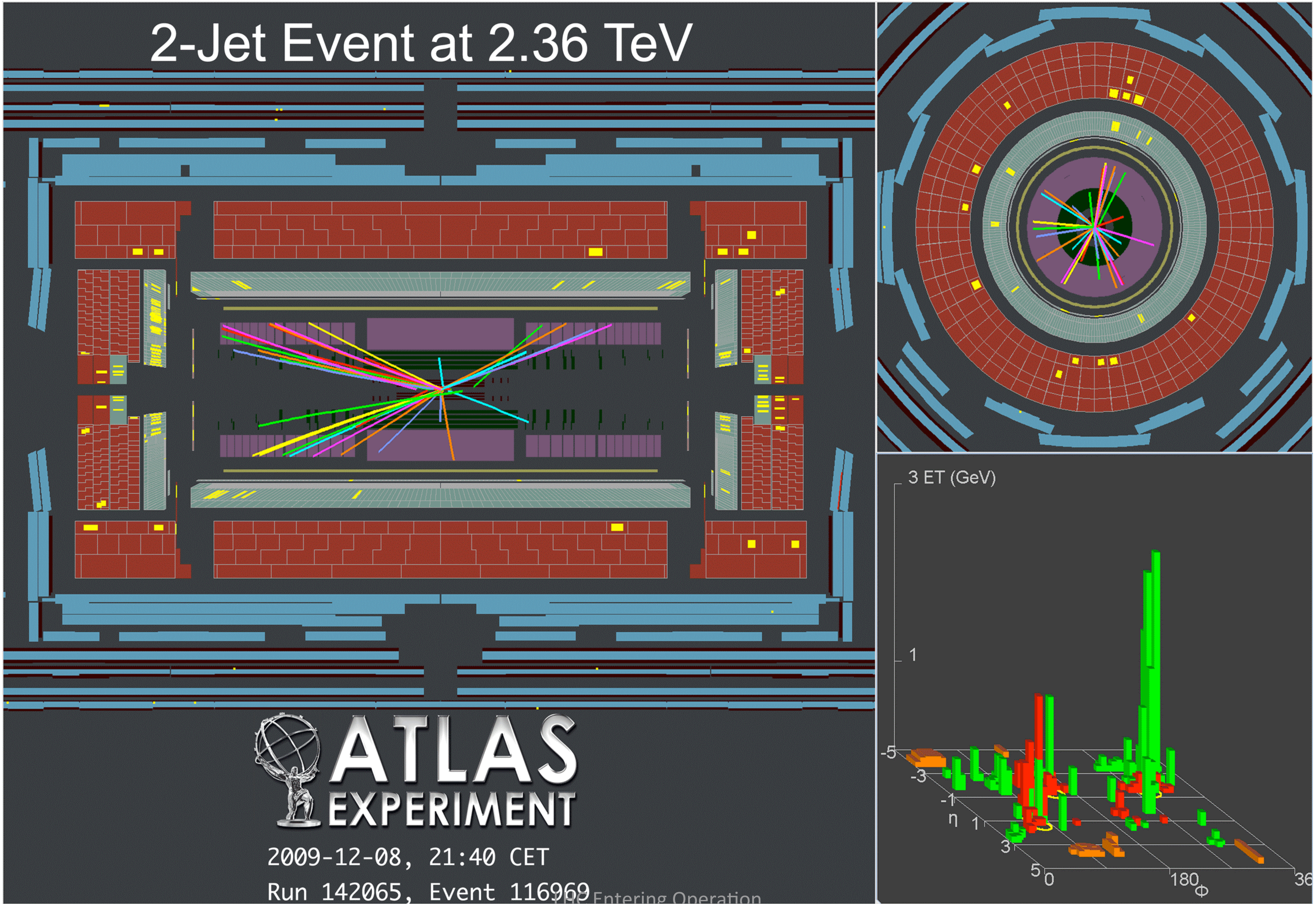
A high multiplicity Alice event…

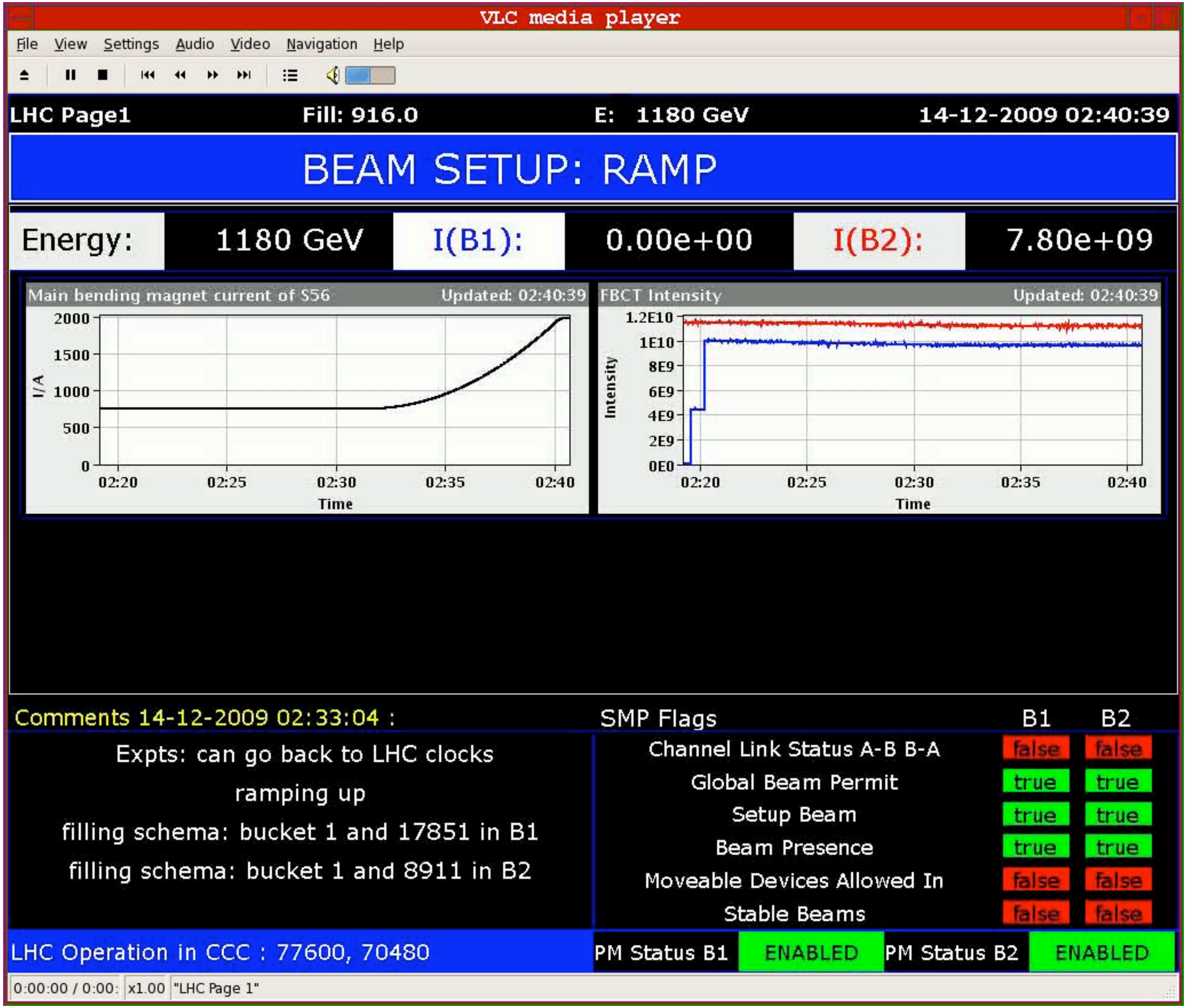


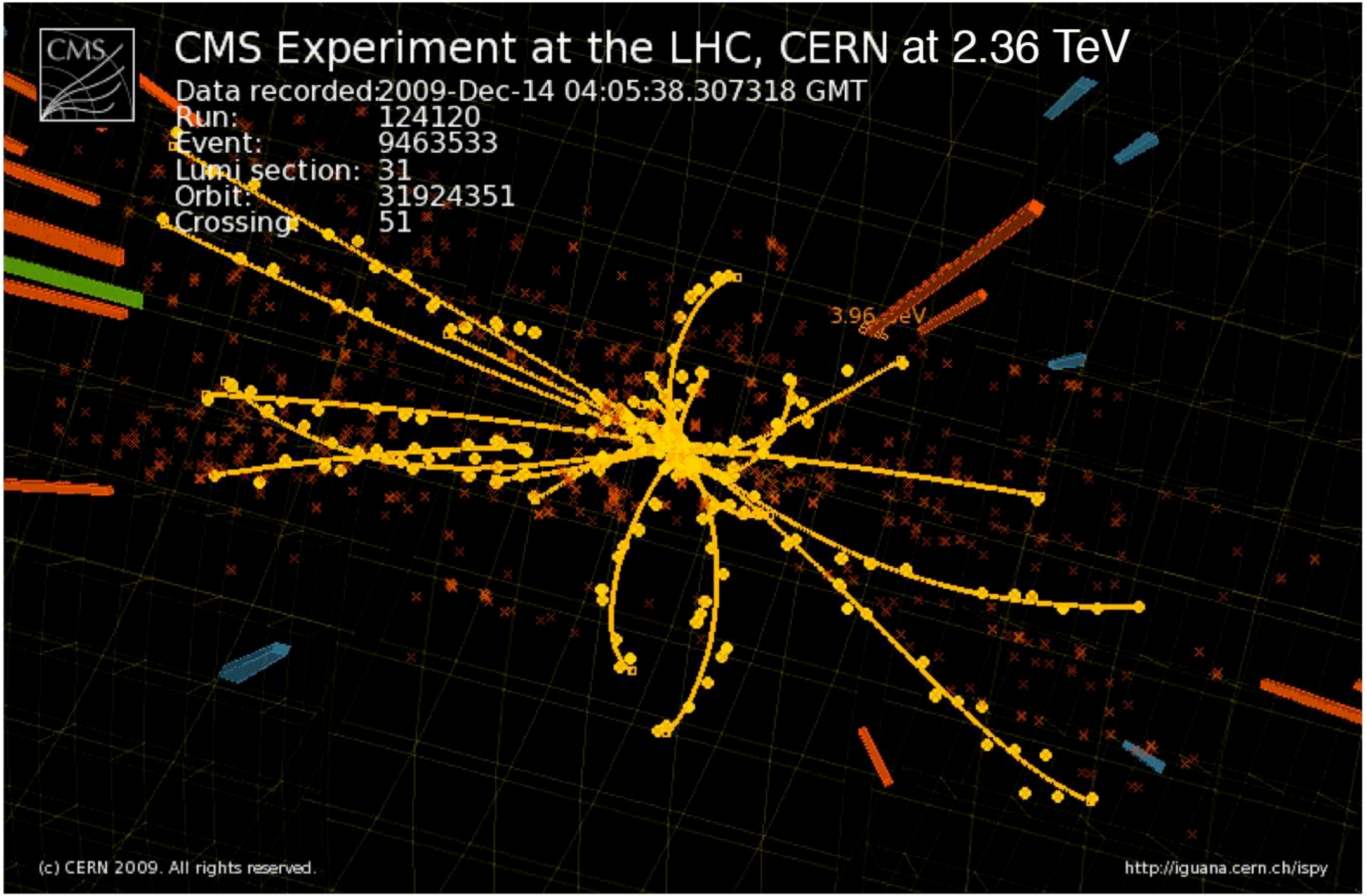


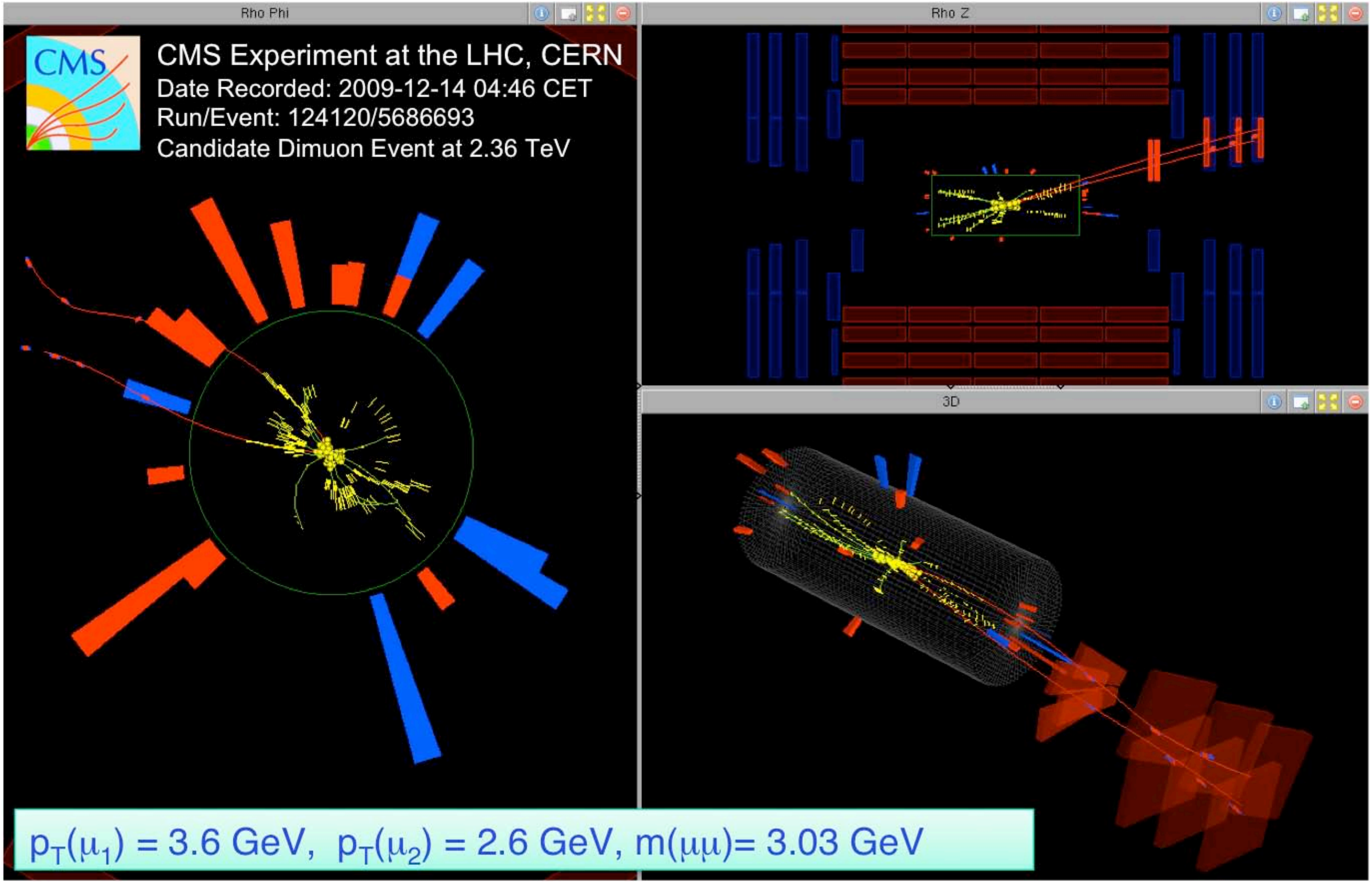
ALICE (paper accepted by EPJ C)



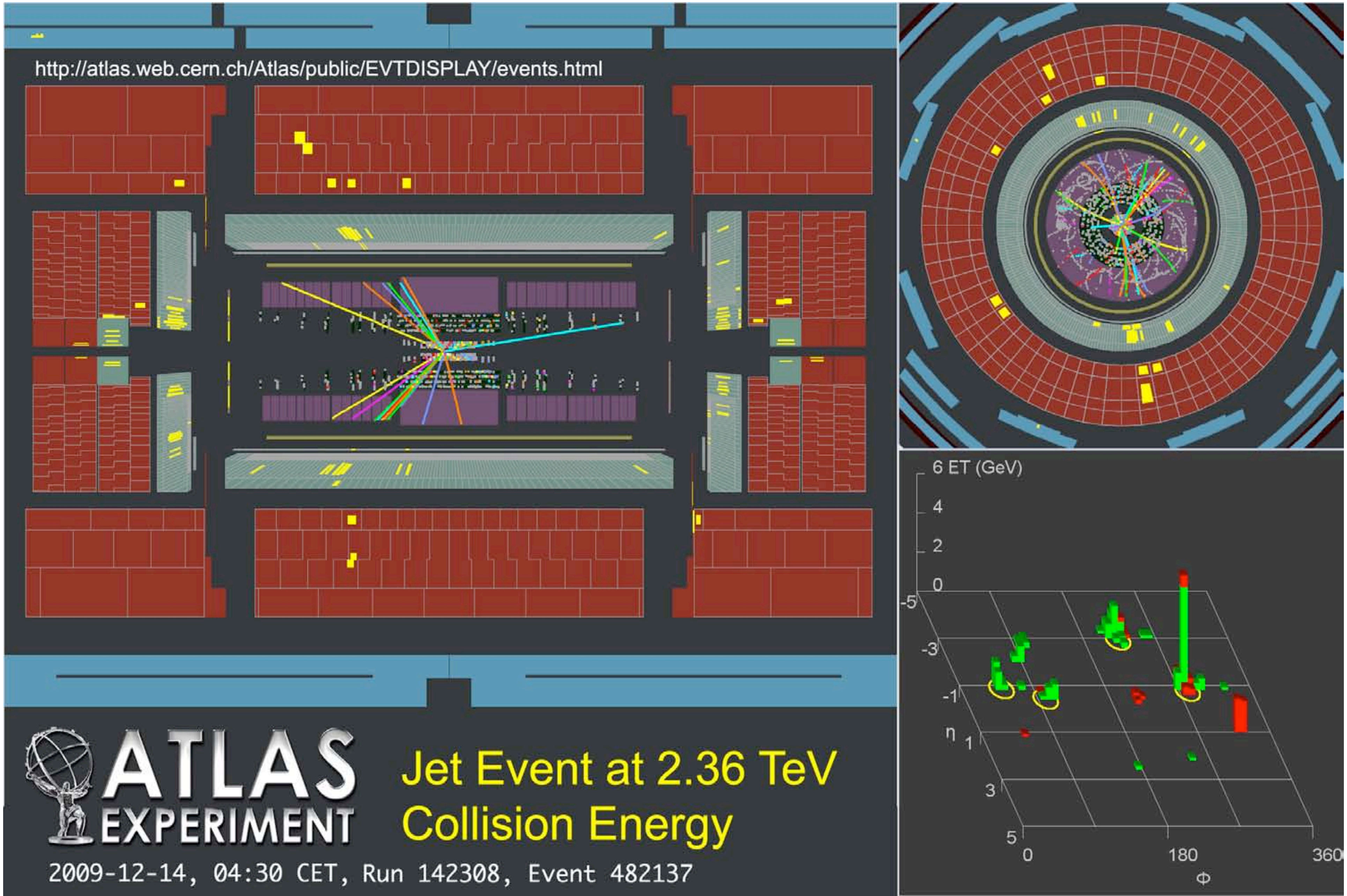

2-Jet Event at 2.36 TeV
ATLAS
EXPERIMENT
2009-12-08, 21:40 CET
Run 142065, Event 116969
3 ET (GeV)
1
-5
-3
-1
η
1
3
5
0
180
Φ
36

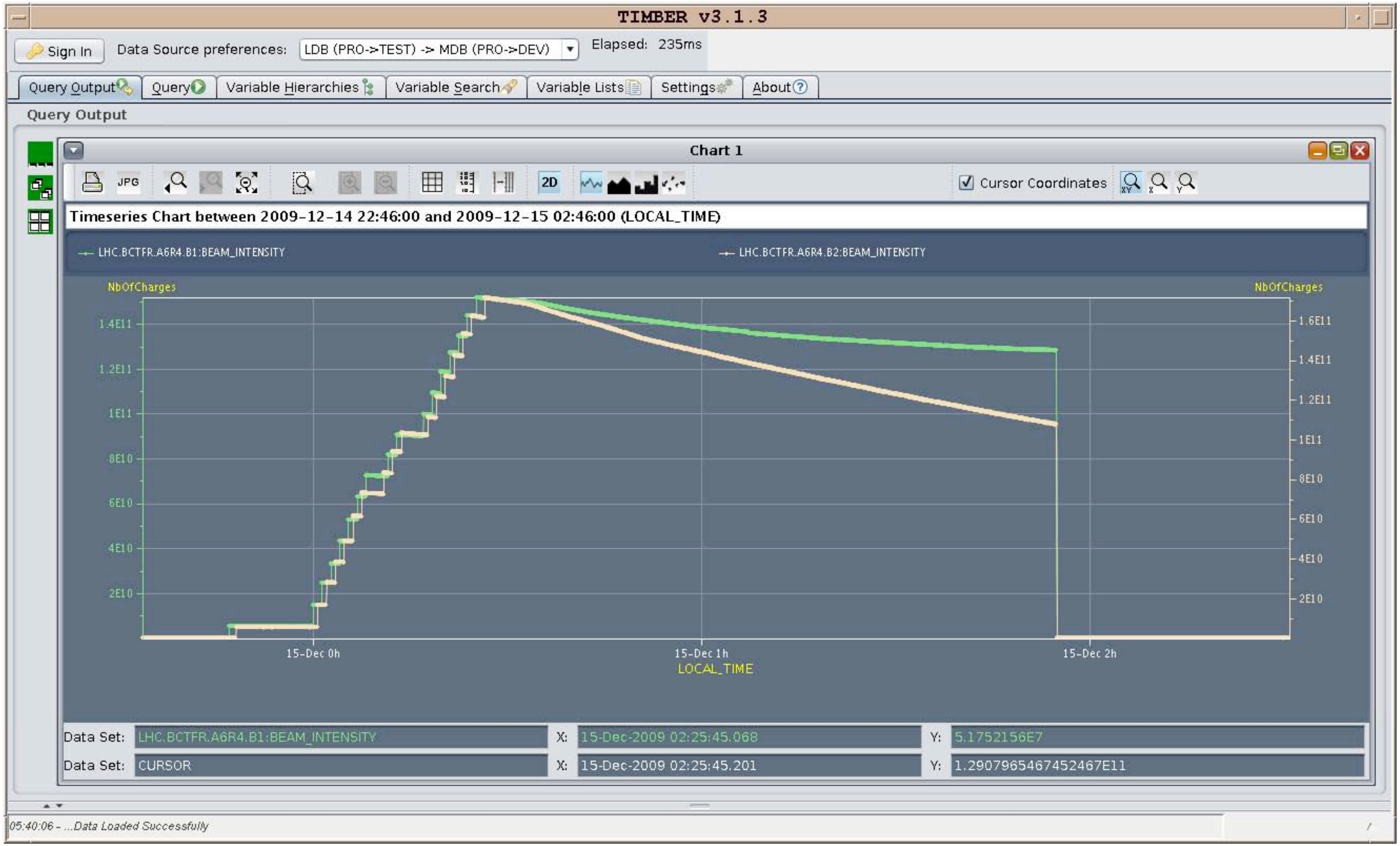

VLC media player
File View Settings Audio Video Navigation Help
LHC Page1
Fill: 916.0
E: 1180 GeV
14-12-2009 02:40:39
BEAM SETUP: RAMP
Energy:
1180 GeV
I(B1):
0.00e+00
I(B2):
7.80e+09
Main bending magnet current of S56
Updated: 02:40:39
I / A
2000
1500
1000
500
0
02:20
02:25
02:30
02:35
02:40
Time
FBCT Intensity
Updated: 02:40:39
Intensity
1.2E10
1E10
8E9
6E9
4E9
2E9
0E0
02:20
02:25
02:30
02:35
02:40
Time
Comments 14-12-2009 02:33:04 :
Expts: can go back to LHC clocks
ramping up
filling schema: bucket 1 and 17851 in B1
filling schema: bucket 1 and 8911 in B2
SMP Flags
B1
B2
Channel Link Status A-B B-A
false
false
Global Beam Permit
true
true
Setup Beam
true
true
Beam Presence
true
true
Moveable Devices Allowed In
false
false
Stable Beams
false
false
LHC Operation in CCC : 77600, 70480
PM Status B1
ENABLED
PM Status B2
ENABLED
0:00:00 / 0:00:
x1.00
"LHC Page 1"


CMS
CMS Experiment at the LHC, CERN at 2.36 TeV
Data recorded:2009-Dec-14 04:05:38.307318 GMT
Run: 124120
Event: 9463533
Lumi section: 31
Orbit: 31924351
Crossing: 51
(c) CERN 2009. All rights reserved.
http://iguana.cern.ch/ispy



$p_T(\mu_1) = 3.6$ GeV, $p_T(\mu_2) = 2.6$ GeV, $m(\mu\mu) = 3.03$ GeV


http://atlas.web.cern.ch/Atlas/public/EVTDISPLAY/events.html
ATLAS
EXPERIMENT
Jet Event at 2.36 TeV
Collision Energy
2009-12-14, 04:30 CET, Run 142308, Event 482137
6 ET (GeV)
4
2
0
-5
-3
-1
η
1
3
5
0
180
360
Φ

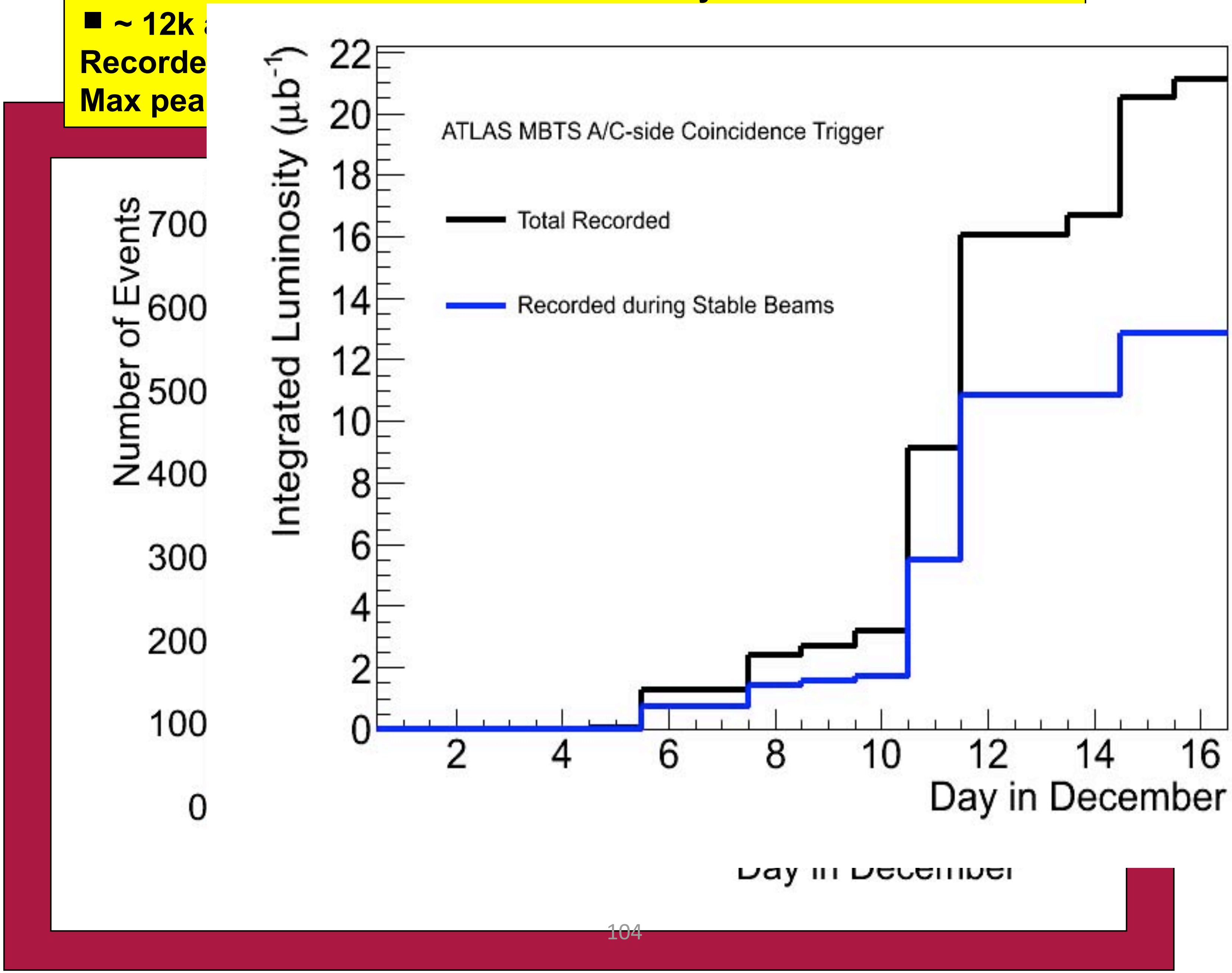

TIMBER v3.1.3
Sign In
Data Source preferences:
LDB (PRO->TEST) -> MDB (PRO->DEV)
Elapsed: 235ms
Query Output
Query
Variable Hierarchies
Variable Search
Variable Lists
Settings
About
Query Output
Chart 1
JPG
2D
Cursor Coordinates
Timeseries Chart between 2009-12-14 22:46:00 and 2009-12-15 02:46:00 (LOCAL_TIME)
LHC.BCTFR.A6R4.B1:BEAM_INTENSITY
LHC.BCTFR.A6R4.B2:BEAM_INTENSITY
NbOfCharges
NbOfCharges
1.4E11
1.2E11
1E11
8E10
6E10
4E10
2E10
1.6E11
1.4E11
1.2E11
1E11
8E10
6E10
4E10
2E10
15-Dec 0h
15-Dec 1h
15-Dec 2h
LOCAL_TIME
Data Set: LHC.BCTFR.A6R4.B1:BEAM_INTENSITY X: 15-Dec-2009 02:25:45.068 Y: 5.1752156E7
Data Set: CURSOR X: 15-Dec-2009 02:25:45.201 Y: 1.2907965467452467E11
05:40:06 - ...Data Loaded Successfully

Total number of collisions recorded: ~700k

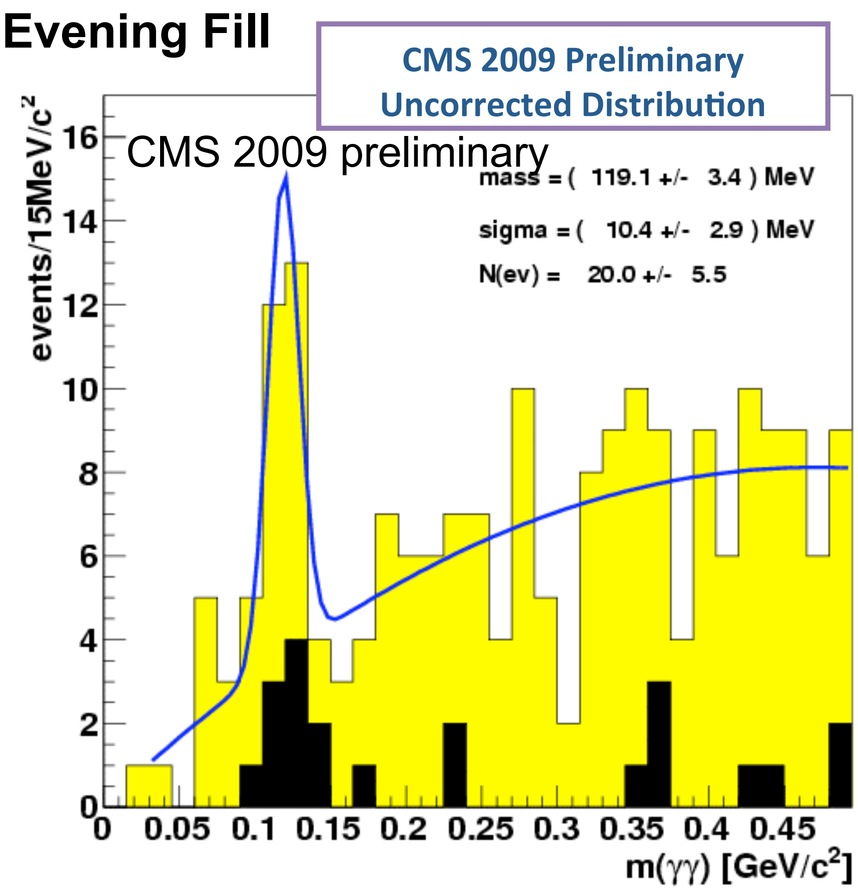
- **~450k with stable beams → tracker fully on**
- **~ 12k**

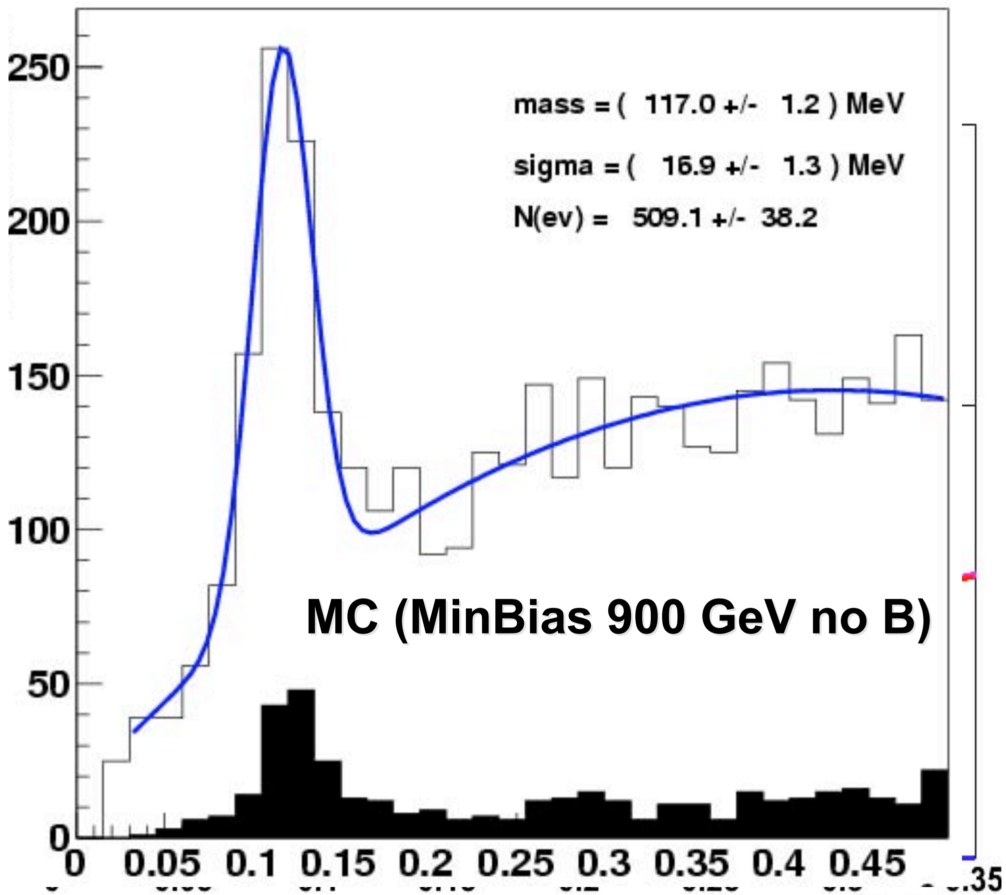
Recorde

Max pea



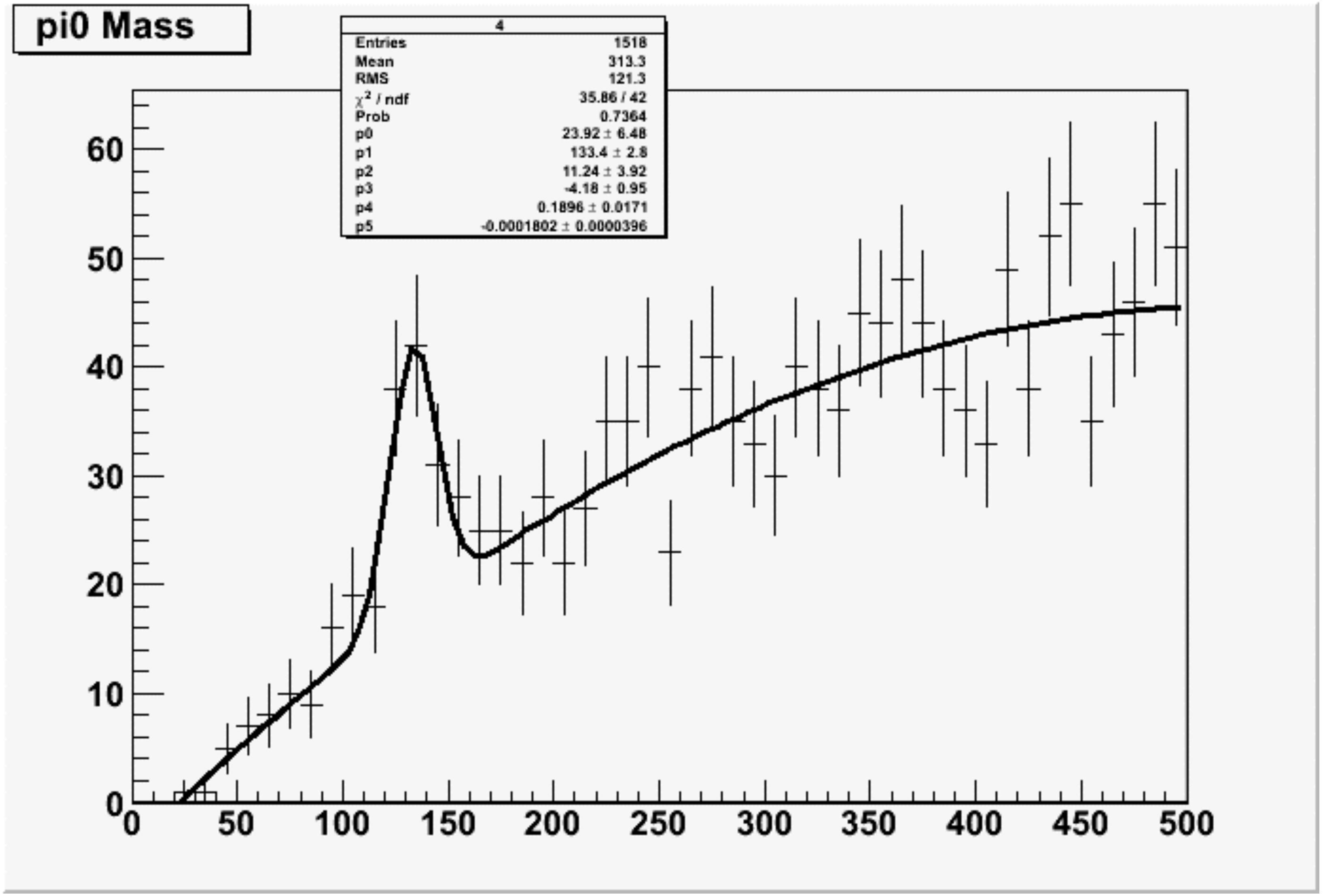
First Di-photon Distribution in CMS





- $M(\pi^0)$ is lower in both data and MC
- Mostly due to the readout threshold (100 MeV/Crystal).
- Conversions: part of the energy is deposited upstream of ECAL.
- Event timing is consistent

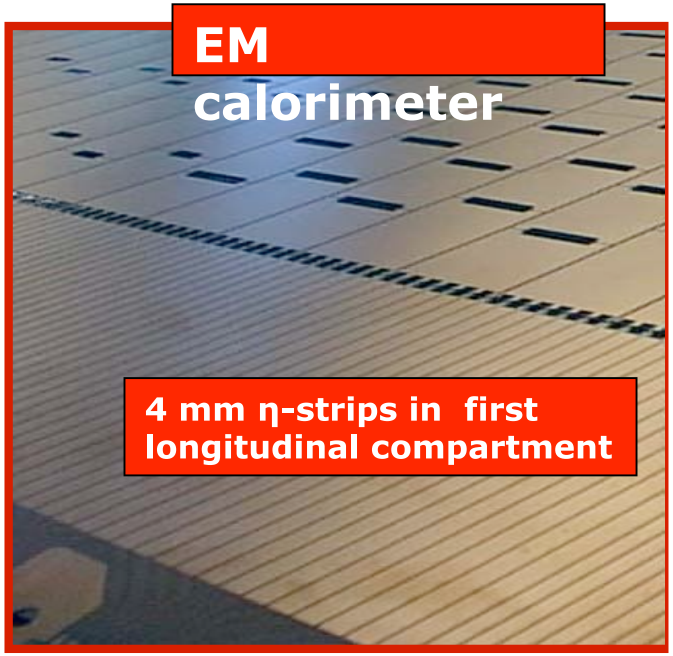
LHCb π^0 have been reconstructed in the calorimeter

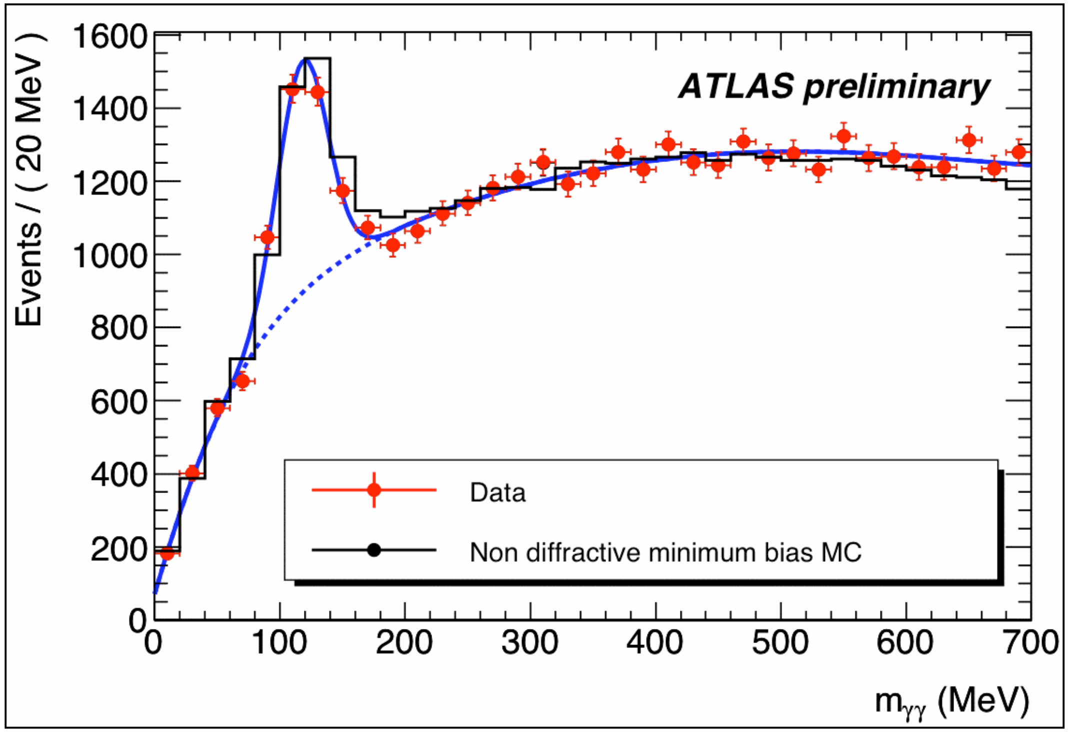


ATLAS $\pi^0 \rightarrow \gamma\gamma$

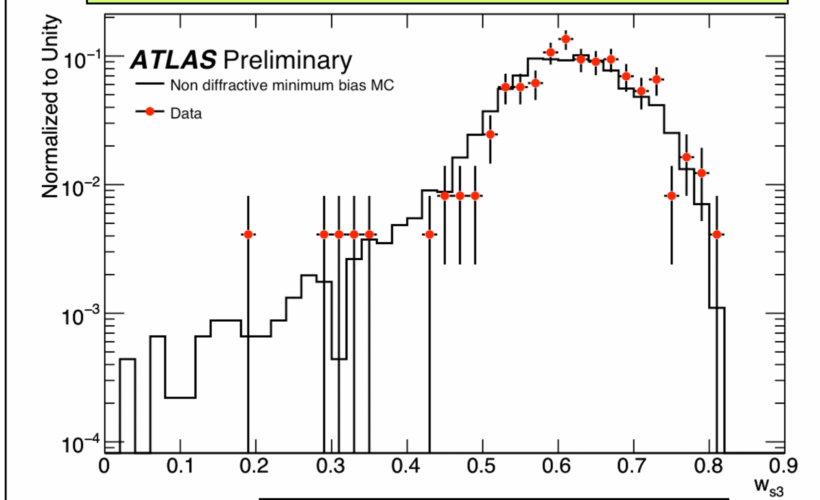
- 2 photons with $E_T(\gamma) > 300$ MeV
- $E_T(\gamma\gamma) > 900$ MeV
- shower shapes compatible with photons

All combinations plotted.
No correction for upstream dead material (~ 2.5 X_0 at $\eta=0$)
Data and MC normalised to the same area





Very good data-MC agreement for (very soft !) photon showers

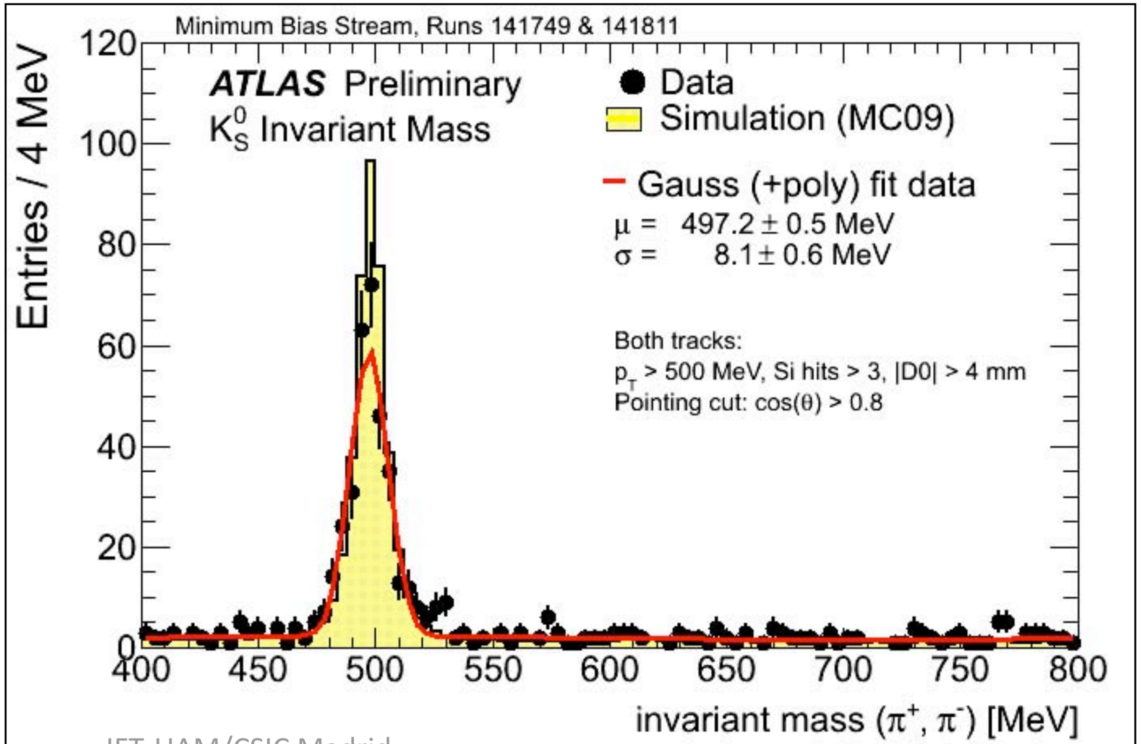


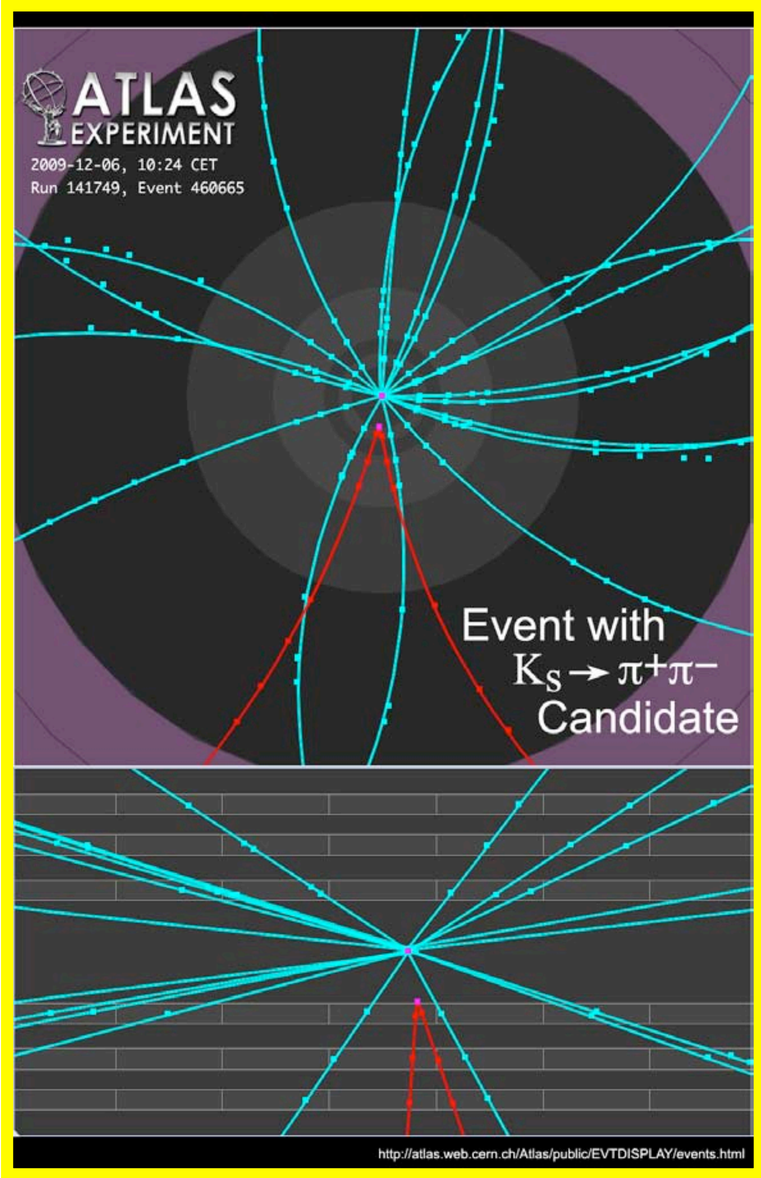
Shower width (strip unit)

ATLAS $K^0_s \rightarrow \pi^+\pi^-$

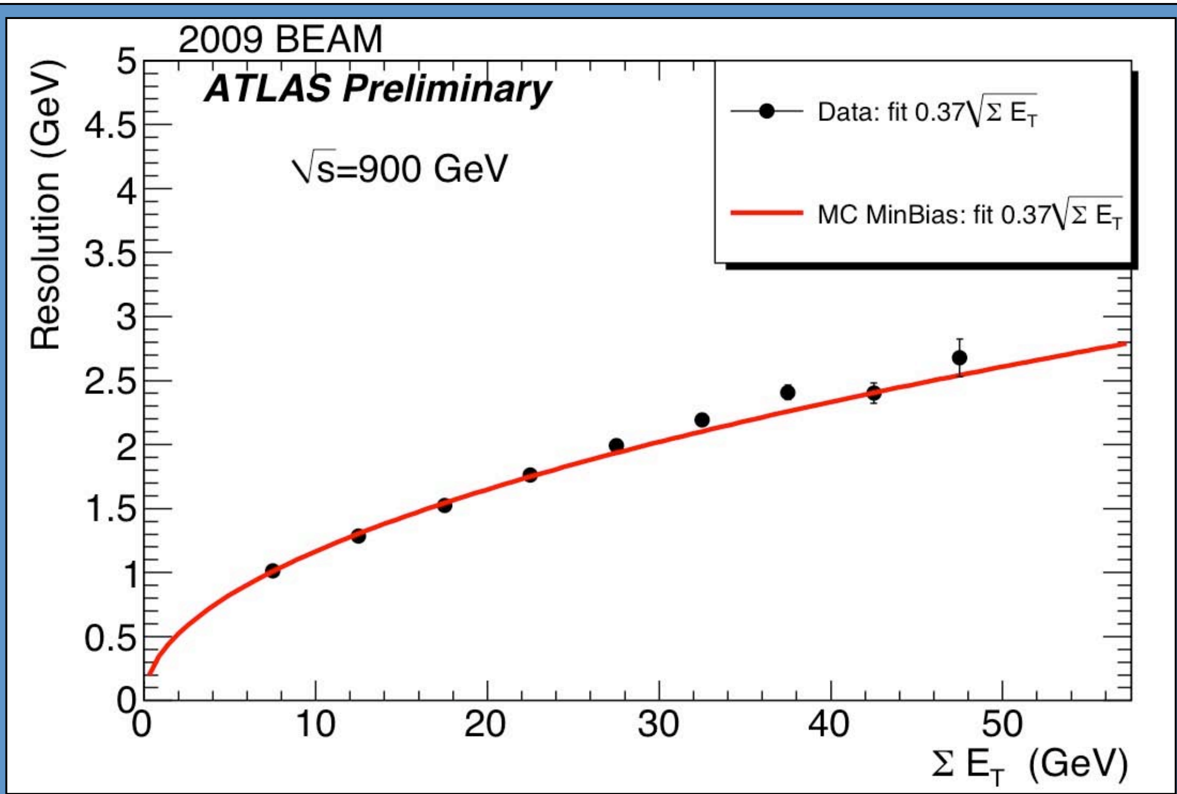
2 opposite-sign tracks:
- **p_T >500 MeV**
- **originating from common vertex**
- **impact parameter d_0 > 4 mm**
- **momentum sum along flight direction**

Data and MC normalized to the same area



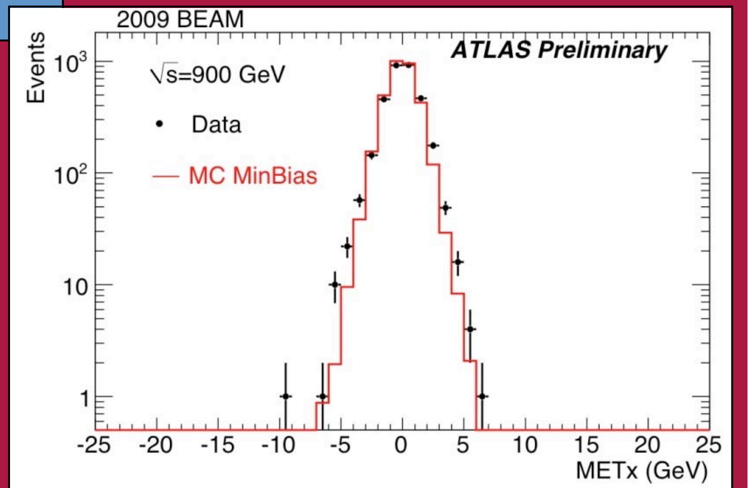


ATLAS missing transverse energy resolution



Energy resolution of the two components (METx, METy) of the missing E_T vector vs the total transverse energy in the calorimeters

- **Measurement over full calorimeter coverage, $|\eta| < 5$, ~ 200000 cells**
- **Calculated using clusters at EM-scale**
- **Noise contribution (from random triggers): 0.5 GeV**



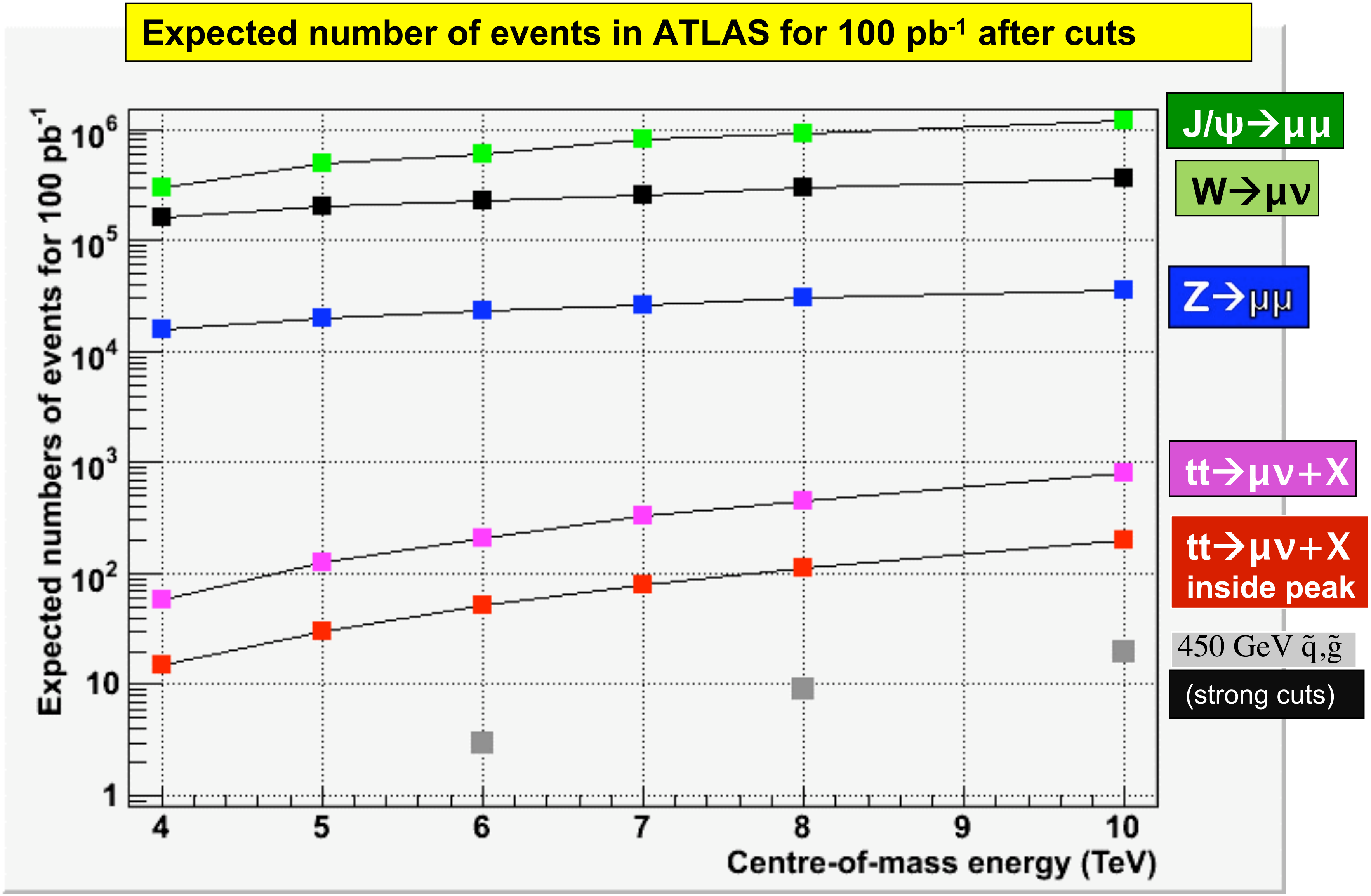
LHC physics goals

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.

ATLAS preliminary



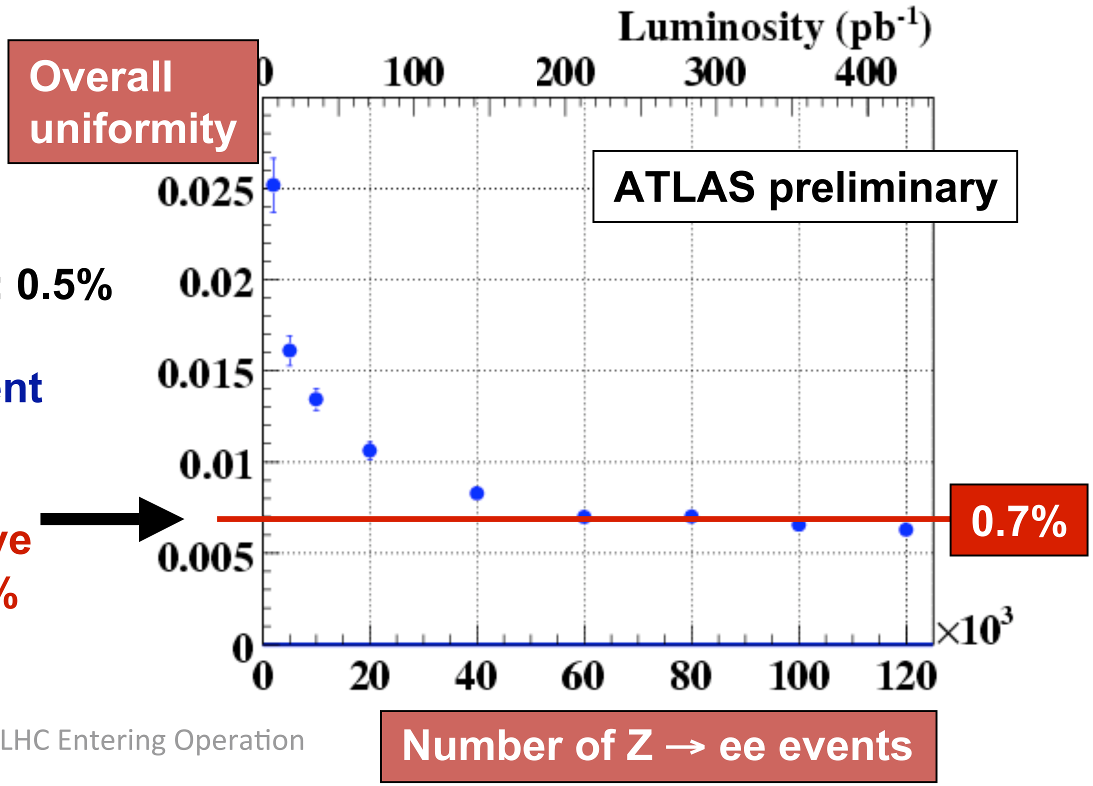
Example: Expected ATLAS performance on "Day-1"
(based on test-beam, simulation, and cosmics results)

	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%



QCD jet spectrum

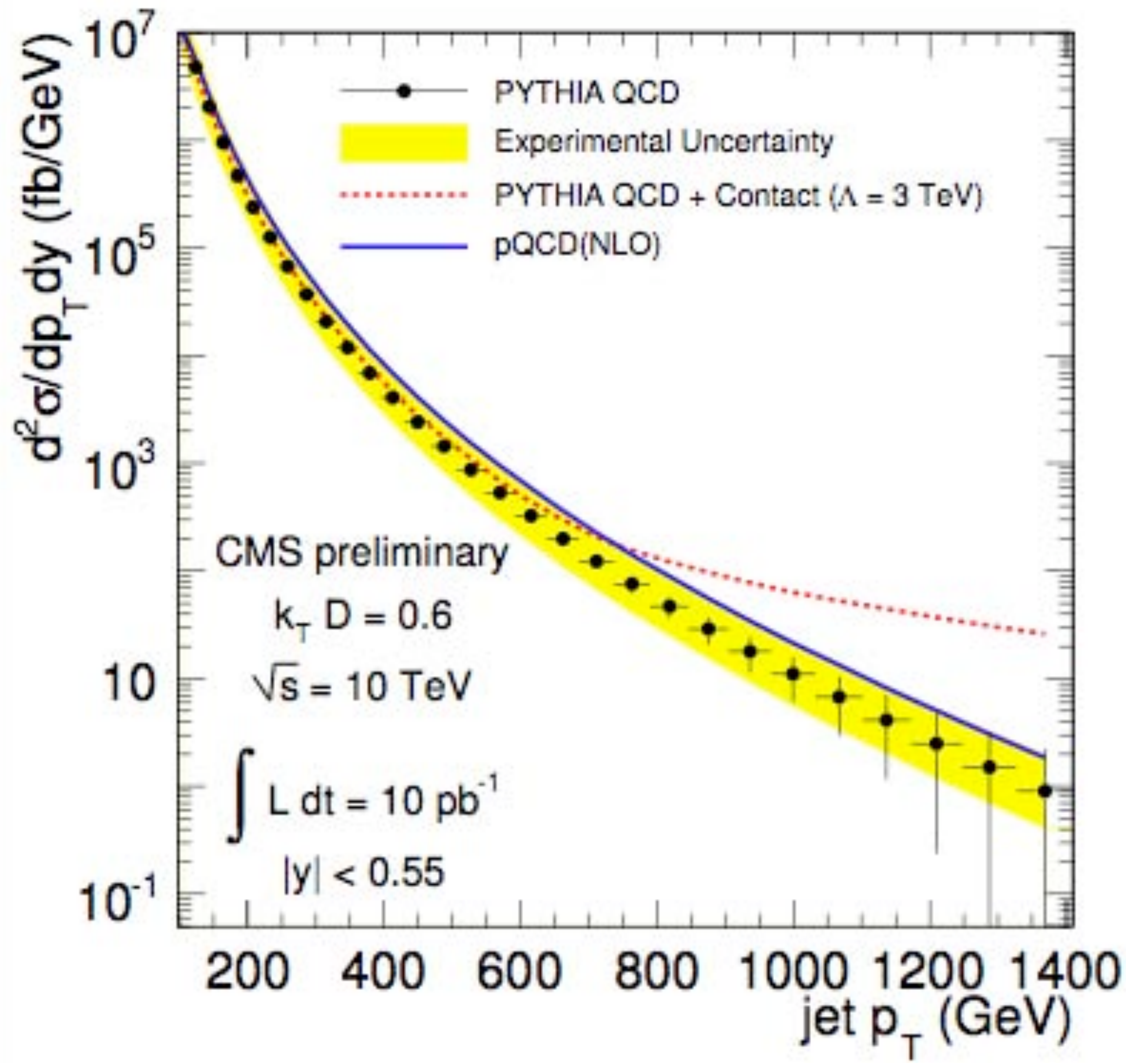
From the first 10 pb^{-1} of data, the differential inclusive cross-section can be measured

- **100 GeV < p_T^{jet} < 1.4 TeV**
- **central rapidity**

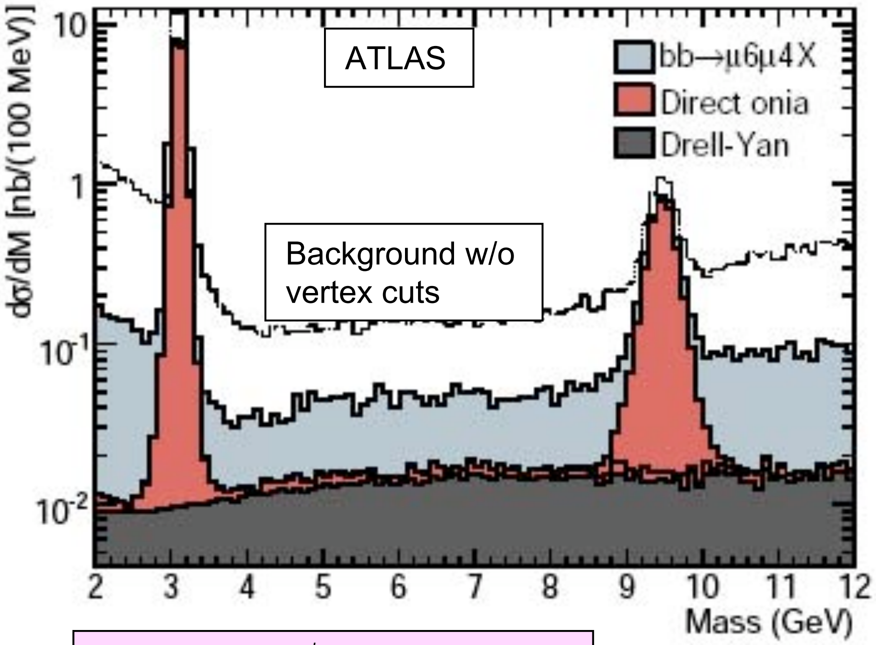
Systematic errors will go down as more events are collected

Any large deviation from QCD prediction

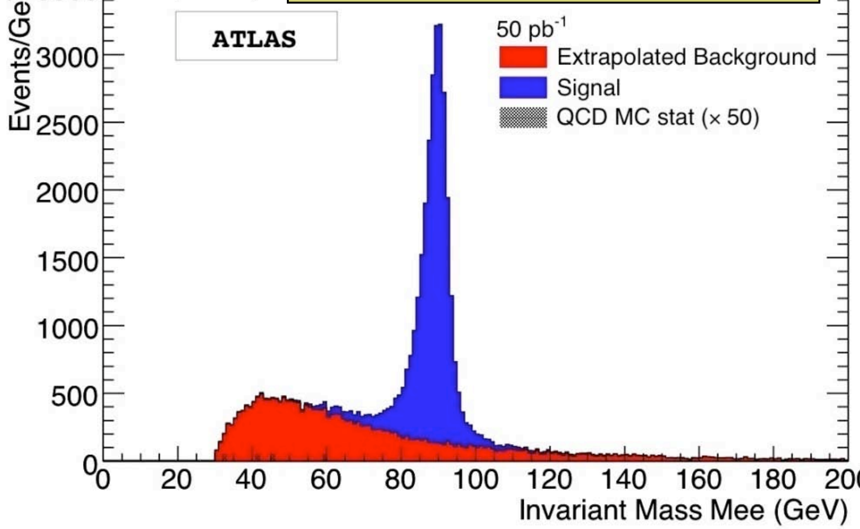
- ***will be studied carefully***
- ***may be sign for new physics***



SM "candles": J/ψ, Υ, W, Z, top

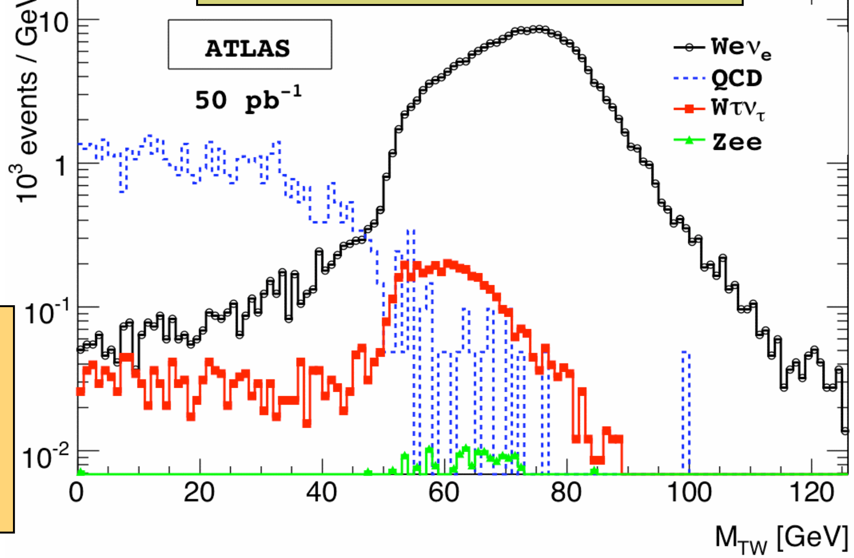


Z→ ee, 50 pb^{-1},14 TeV



100 pb^{-1} , $\sqrt{s}$ = 4-10 TeV:
~ 3-12 10^5 J/ψ→ μμ
~ 3-7 10^5 W → μν,eν
~ 3-7 10^4 Z → ee, μμ

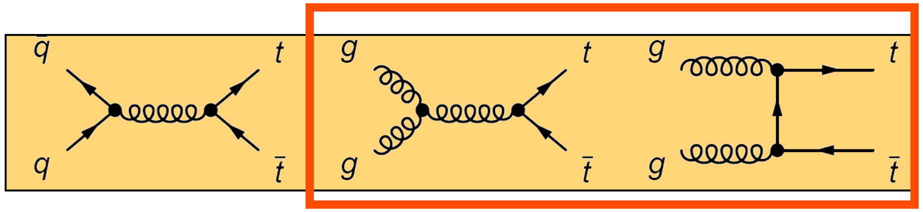
W→ eν, 50 pb^{-1},14 TeV



- → **Muon Spectrometer and ID alignment, ECAL calibration, detector energy/momentum scale, lepton trigger and reconstruction efficiency, …**
- → **First SM measurements and MC tuning**

Precision on σ (Z→μμ) with 100 pb^{-1}:
~ 4% (experimental error, dominated by systematics), ~10-20% (luminosity)

Early top measurements



10 TeV:
σ_{tt} ≈ 140 pb for tt → bW bW → blν bjj
σ_{tt}(LHC)/σ_{tt}(Tevatron)~50

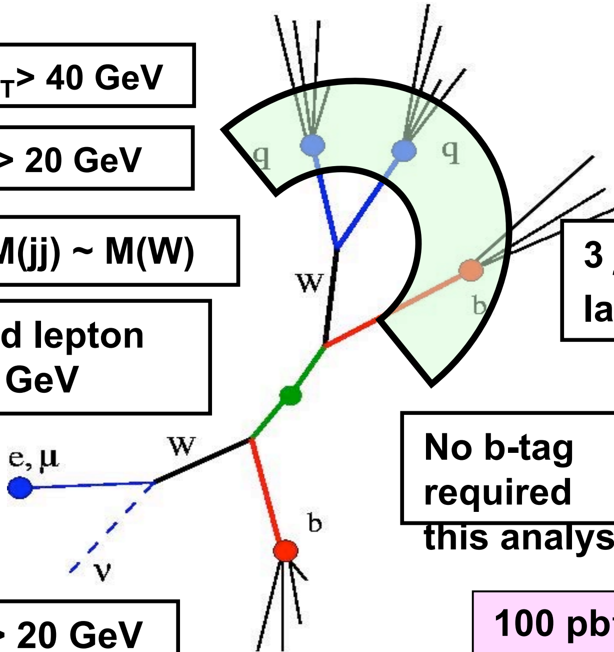
3 jets p_T> 40 GeV

1 jet p_T> 20 GeV

2 jets M(jj) ~ M(W)

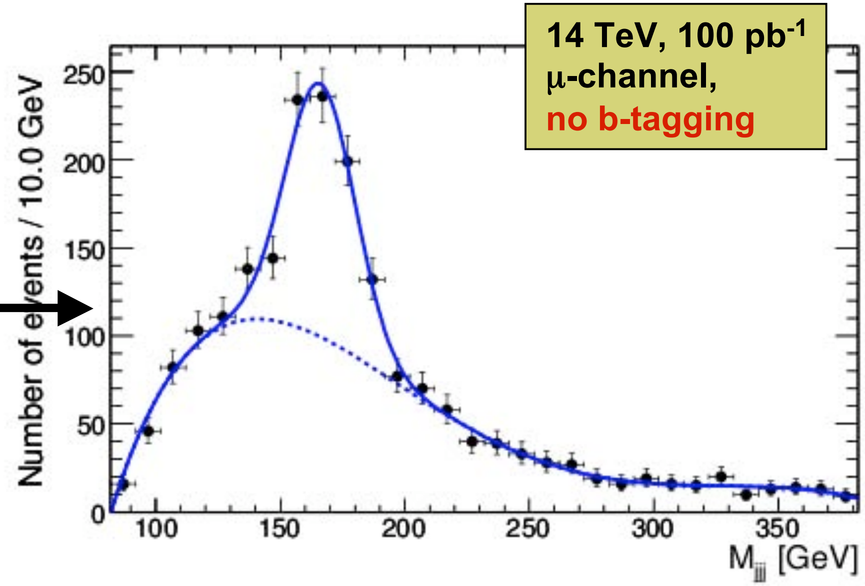
Isolated lepton p_T> 20 GeV

E_T^{miss} > 20 GeV



3 jets with largest ∑ p_T

No b-tag required in this analysis



100 pb^{-1}, √s = 4-10 TeV, after cuts: ~ 200-3000 events tt→ bjj blν
→ Top signal observable with O(10 pb^{-1}), no b-tagging and simple analysis even at intermediate energy steps as low as 4 TeV

- S/B ~2-3, large enough to see clean peak. However, pure sample for detector commissioning (~
- tt final states contain most physics objects: leptons, jets, E_T , b-jets
- tt is background to ~ all searches → essential milestone in the path to discoveries

→ when top measured, the experiment is ready for discovery phase

Prospects for most competitive LHCb measurements in 2010

$B_s \rightarrow \mu\mu$

Small BR in SM: $(3.6 \pm 0.3) \times 10^{-9}$

(Buras arXiv:0904.4917v1)

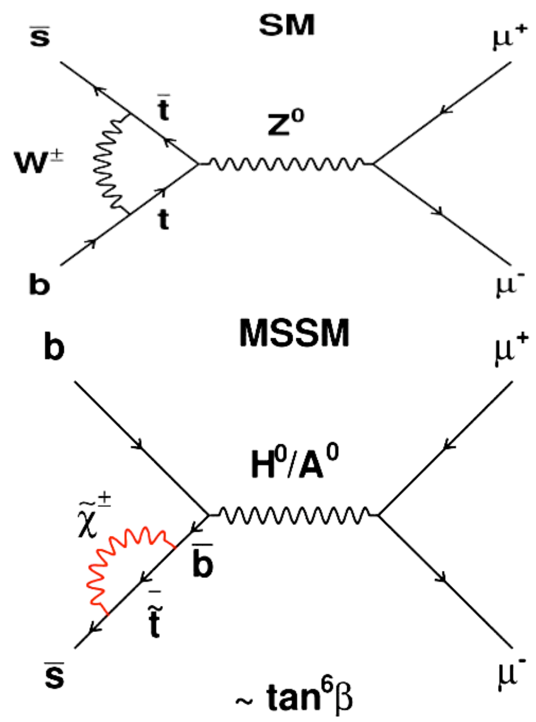
Sensitive to NP

- could be strongly enhanced in SUSY
  - In MSSM scales like ~$\tan^6\beta$

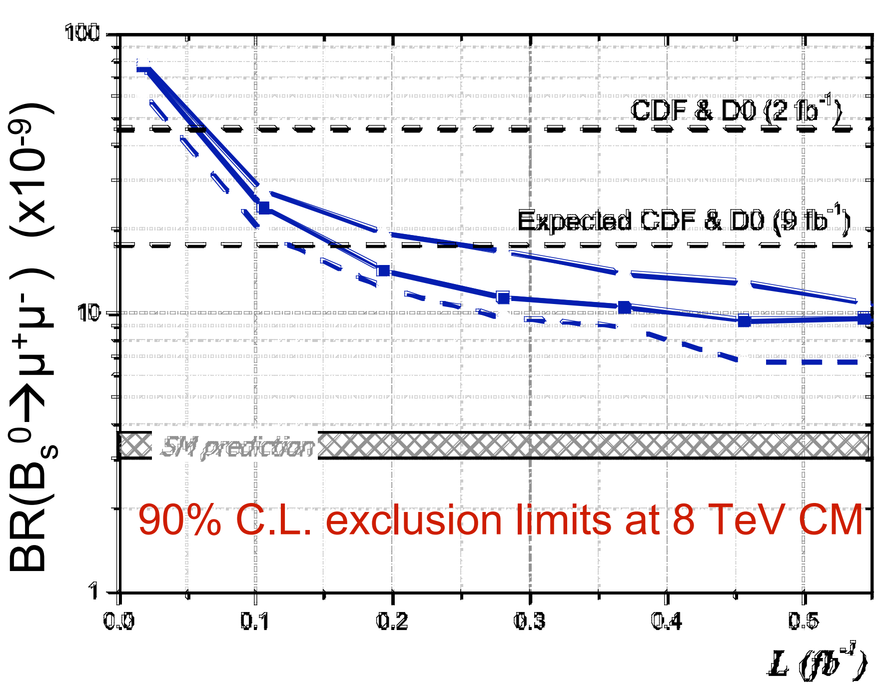
Current (unofficial) Tevatron limit (G.Punzi, EPS'09):

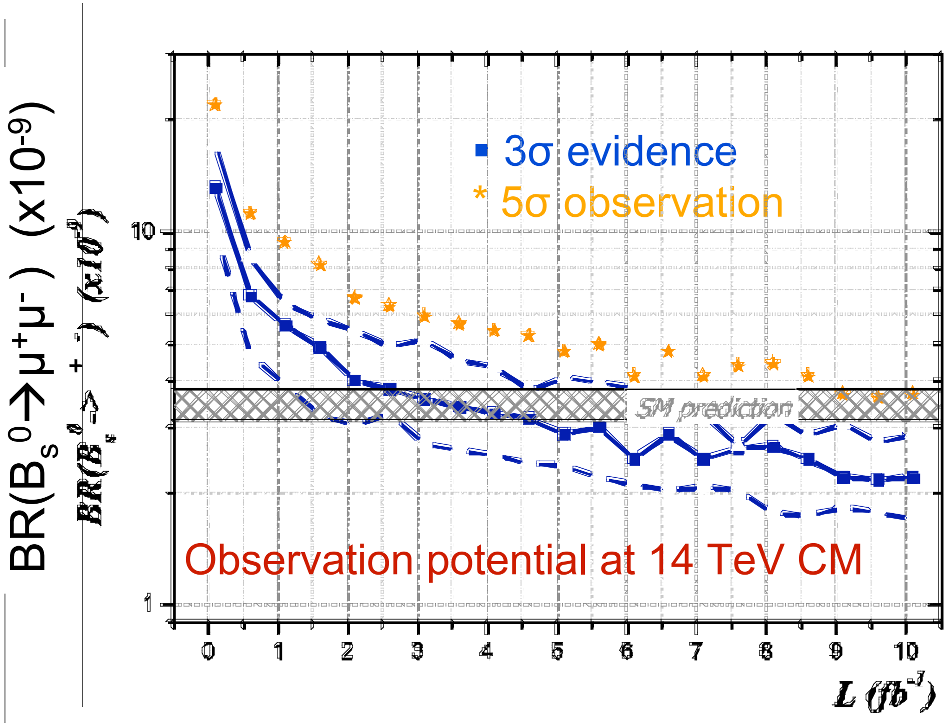
$< 45 \times 10^{-9}$ with $2 fb^{-1}$ (13xSM)

- CDF and D0 expect ~2 SM $B_s \rightarrow \mu\mu$ events in their current samples
- Making a dent in the final factor of 10 from the SM !



Physics reach for BR($B_s^0 \rightarrow \mu^+\mu^-$) as function of integrated luminosity (and comparison with Tevatron)





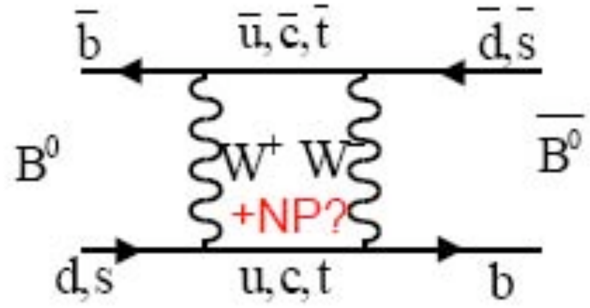
→ **With ~0.3 fb^{-1} LHCb should improve on expected Tevatron limit with 9 fb^{-1}**

→ **Collect ~3 fb^{-1} for 3σ evidence of SM value and ~10 fb^{-1} for 5σ observation of SM**

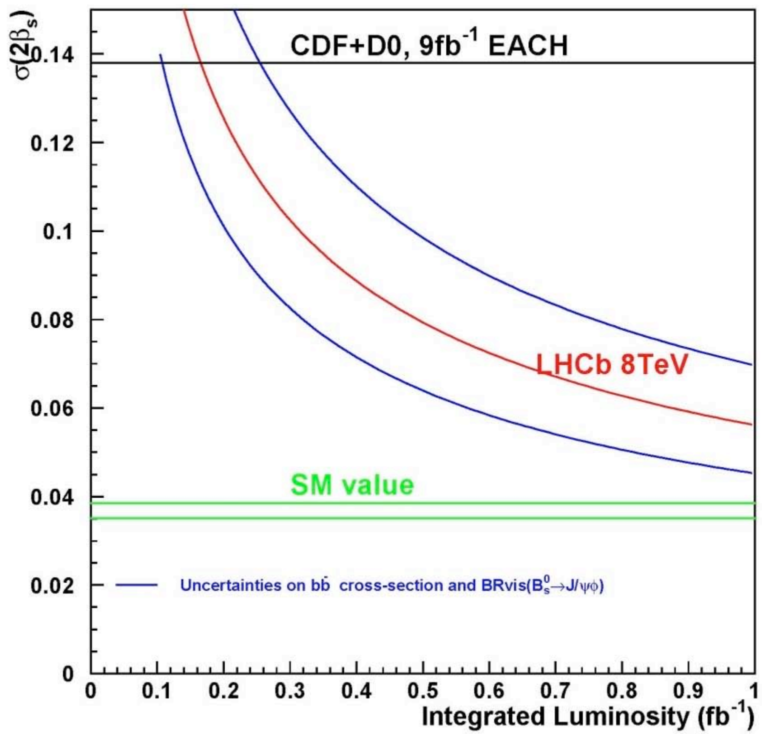
(Note: ATLAS/CMS will be competitive)

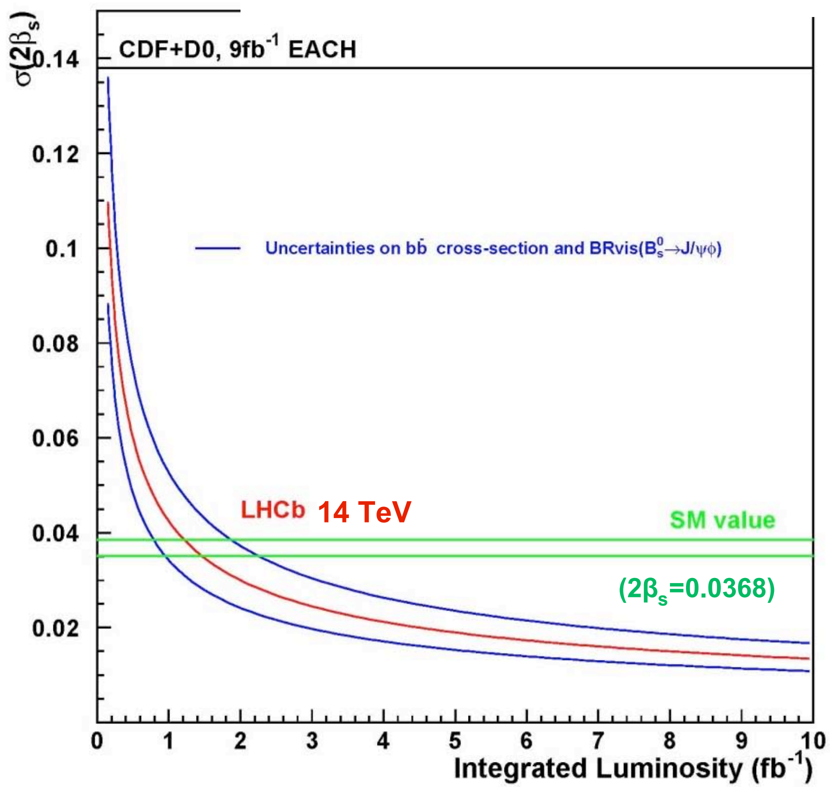
B_s-$\bar{B}_s$ mixing phase ϕ_s (from $B_s \rightarrow J/\psi\ \phi$)

Sensitive to New Physics effects in box diagrams



- $\phi_s = \phi_{s(SM)} + \phi_{s\ (NP)}$
- $\phi_{s(SM)} = -\ 2\beta_s = -2\lambda^2\eta \sim -0.04$





→ ***With ~0.2 fb^{-1} LHCb should improve on expected Tevatron limit***

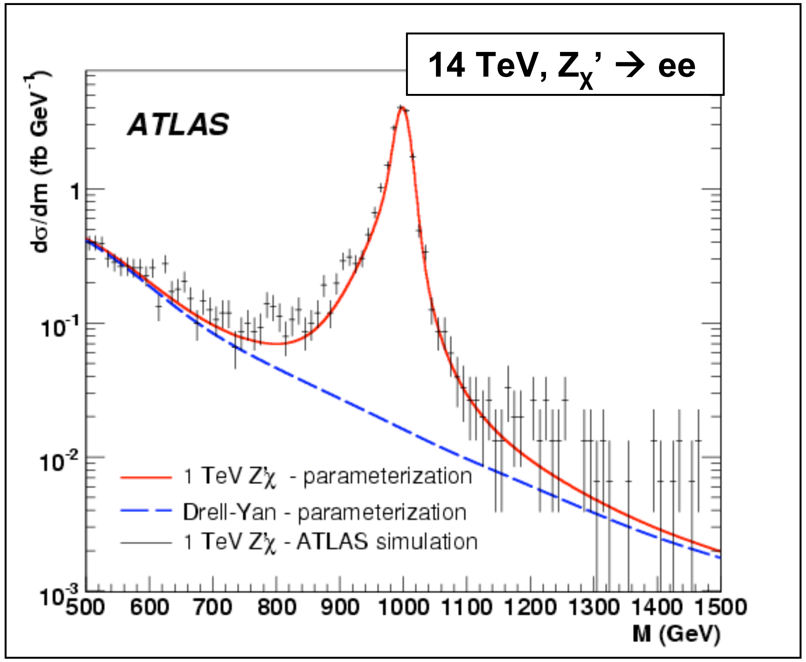
What about discoveries ?

(coming back to ATLAS and CMS)

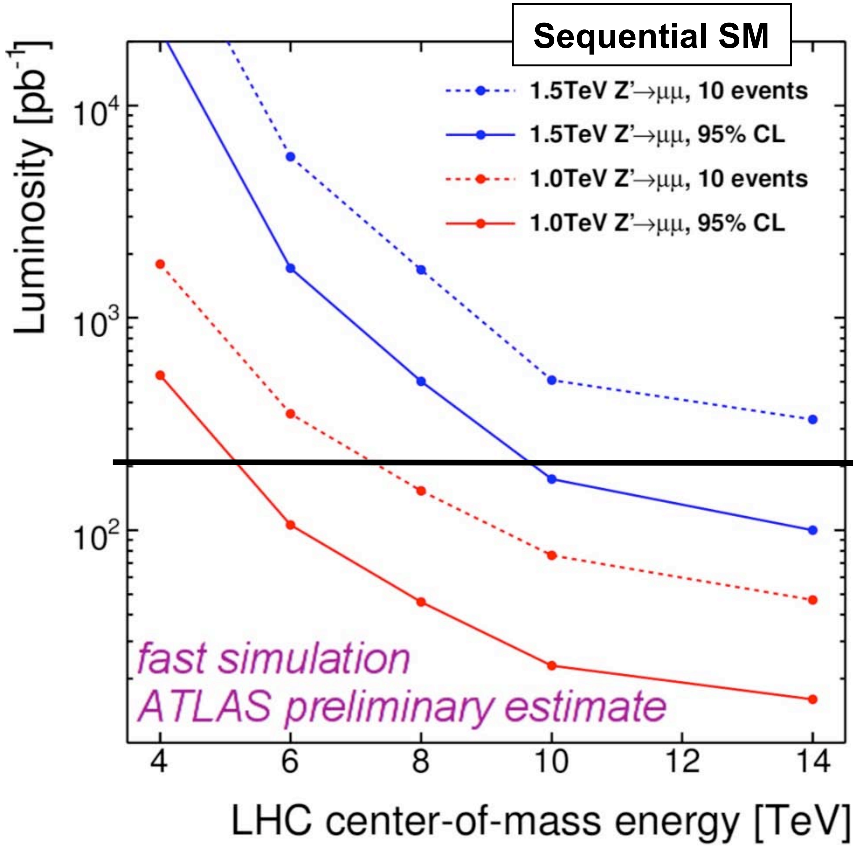
Three cases are usually considered for illustration (luminosities shown here refer to $\sqrt{s} \sim 10$ TeV)

■ ~ 1 TeV new resonance $X \rightarrow ll$	needs ~ 100 pb^{-1}	new forces ? new dimensions ?
■ Supersymmetry (~ 1 TeV $\tilde{q}, \tilde{g}$)	needs few 100 pb^{-1}	dark matter ?
■ Light Higgs boson	1 - few fb^{-1}	origin of mass

An "easier" case : Z' → 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 …



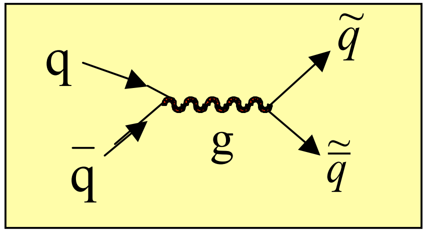
- Signal is (narrow) mass peak above small and smooth SM background
- Does not require ultimate EM calorimeter performance
- Discovery beyond Tevatron exclusion reach (m ~ 1 TeV) possible with 200 pb^{-1} and $\sqrt{s} \geq 7$ TeV (100 pb^{-1} at 10 TeV)
  → perhaps sometime in 2010 ?

First discoveries: Supersymmetry ?

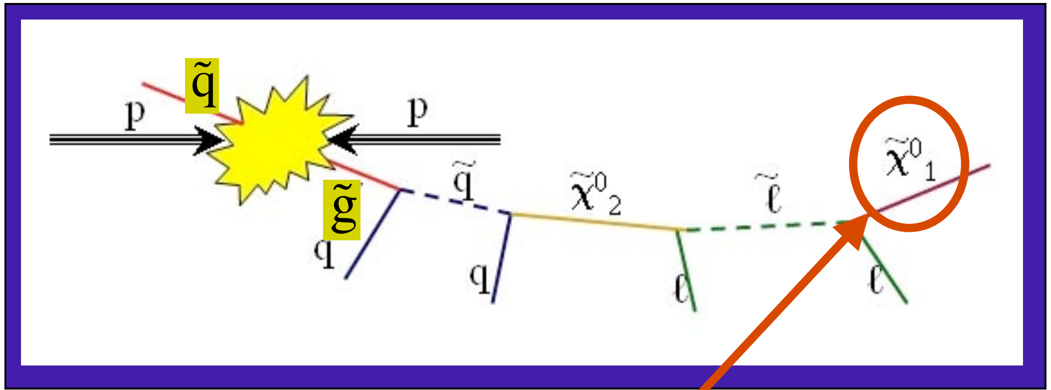
If it is at the TeV mass scale, it should be found "quickly" …. thanks to:

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

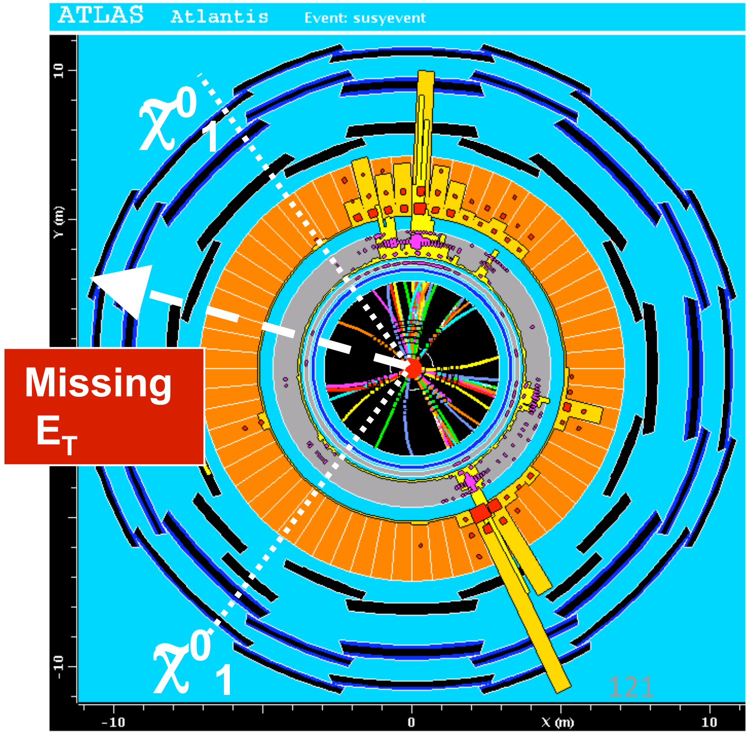
  For $m(\tilde{q},\tilde{g}) \sim 1$ TeV
  expect 1 event/day at L=10^{31} cm^{-2} s^{-1}



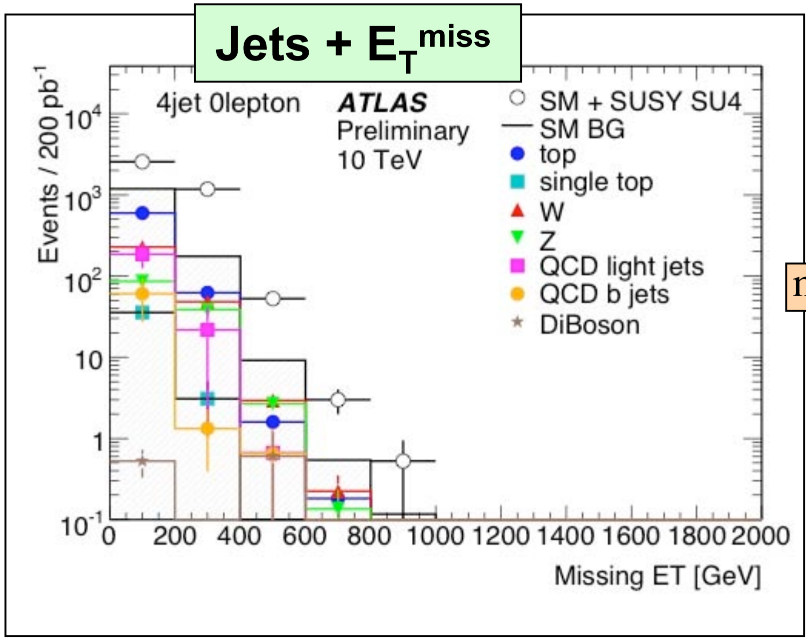
- **Spectacular final states (many jets, leptons, missing transverse energy)**



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



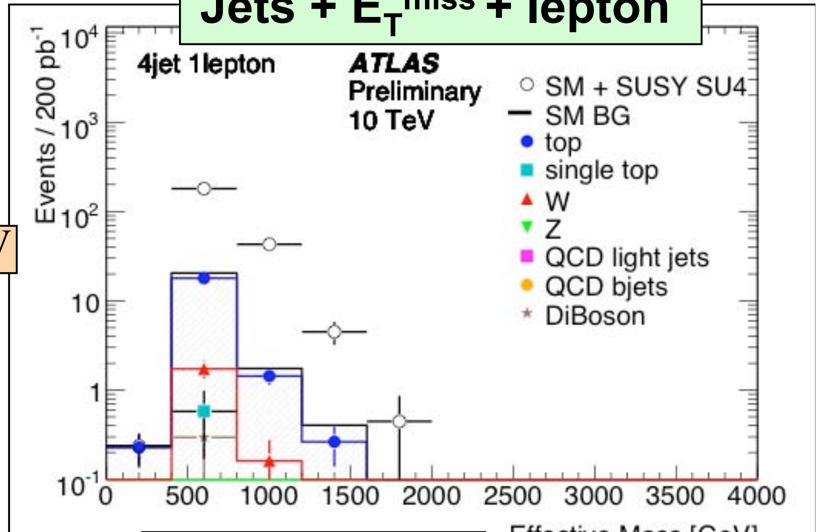
Jets + E_T^{miss}



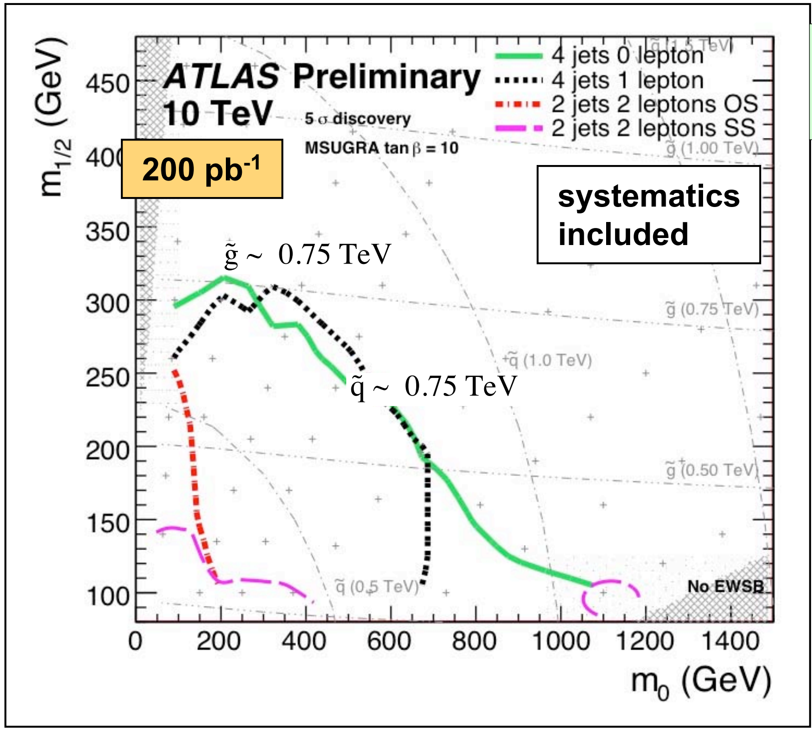
$\sqrt{s}$ = 10 TeV
200 pb^{-1}

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

Jets + E_T^{miss} + lepton



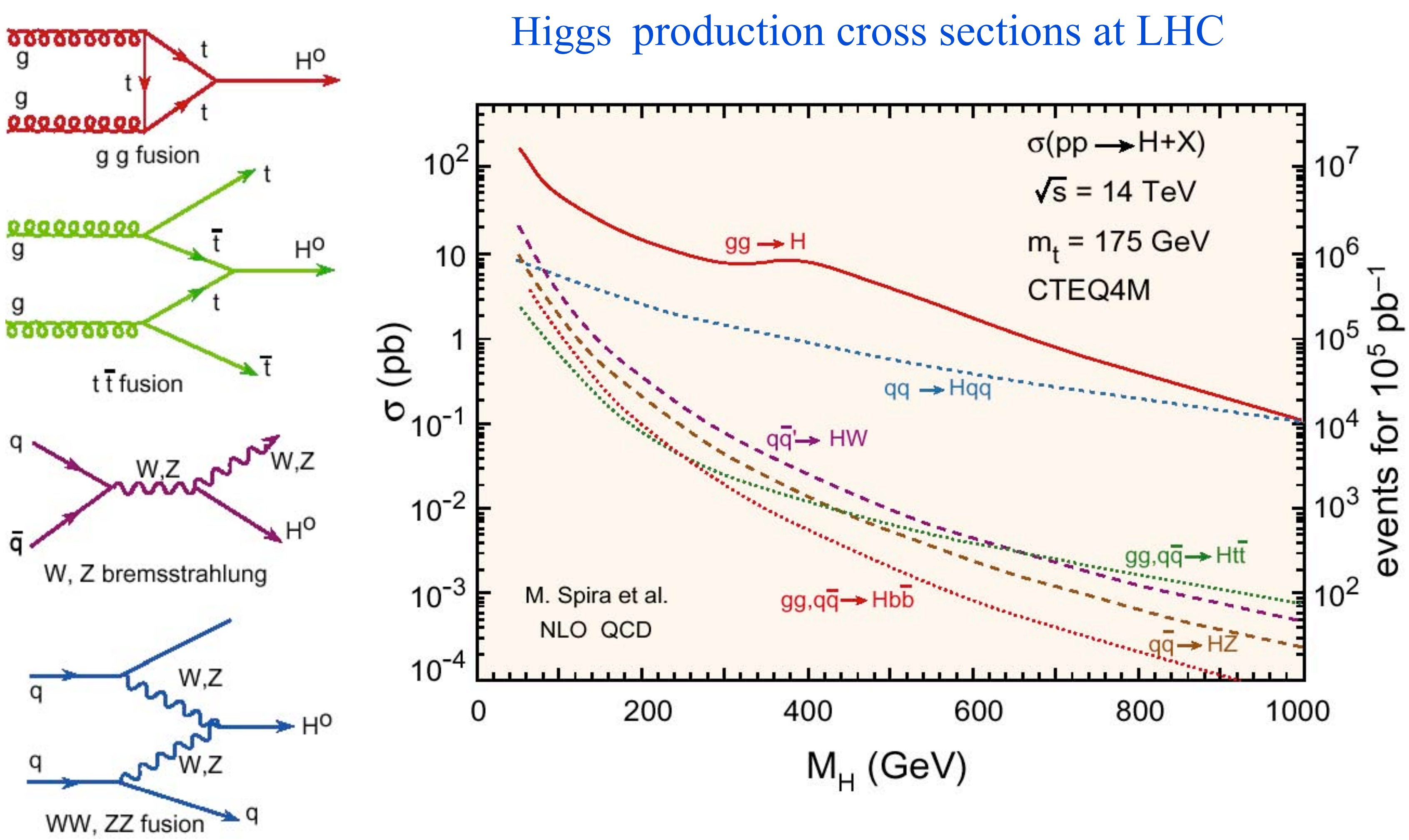
$$M_{\rm eff} \equiv \sum_{i=1}^{4} p_T^{{\rm jet},i} + \sum_{i=1} p_T^{{\rm lep},i} + E_T^{\rm miss}$$



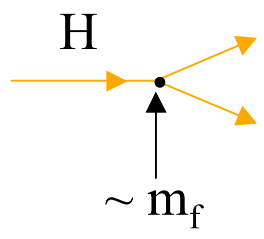
Jets + E_T^{miss} channel: highest reach
1-lepton channel: more robust against bg. uncertainties

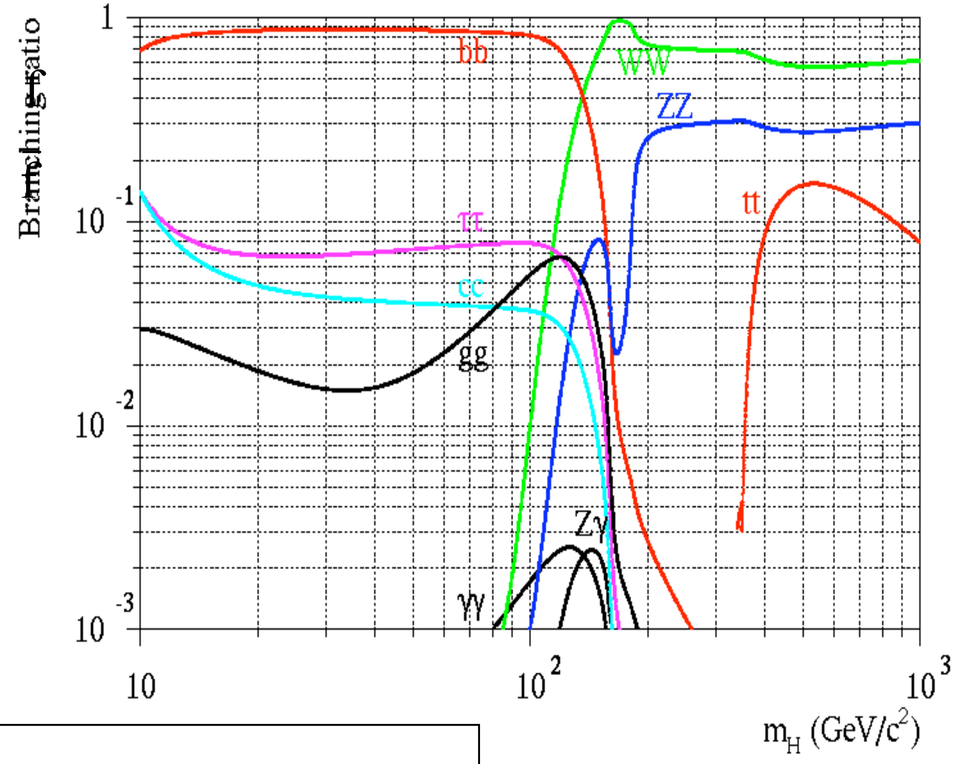
- Discovery up to m ~ 750 GeV with 200 pb^{-1} at $\sqrt{s}$ =10 TeV
- With 200 pb^{-1}, ATLAS or CMS discovery reach beyond Tevatron expected exclusion (~400 GeV) for $\sqrt{s} \geq 7$ TeV
- However: understanding the (tricky) backgrounds, in particular fake missing transverse energy coming from instrumental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

The Higgs Hunt



Higgs decay modes





Remember: light fully-hadronic final states cannot be extracted from QCD background at hadron colliders

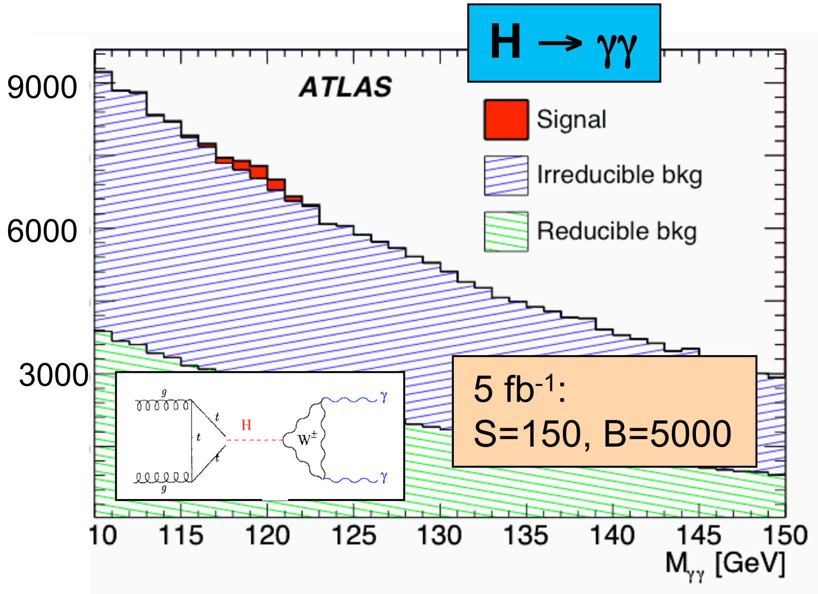
m_H < 130 GeV : H → bb, ττ dominate
→ best search channels at the LHC : qqH→qq ττ, ttH → bb l+X (?)
H → γγ (rare decay mode)
This is the most difficult region (S/B <<1) !

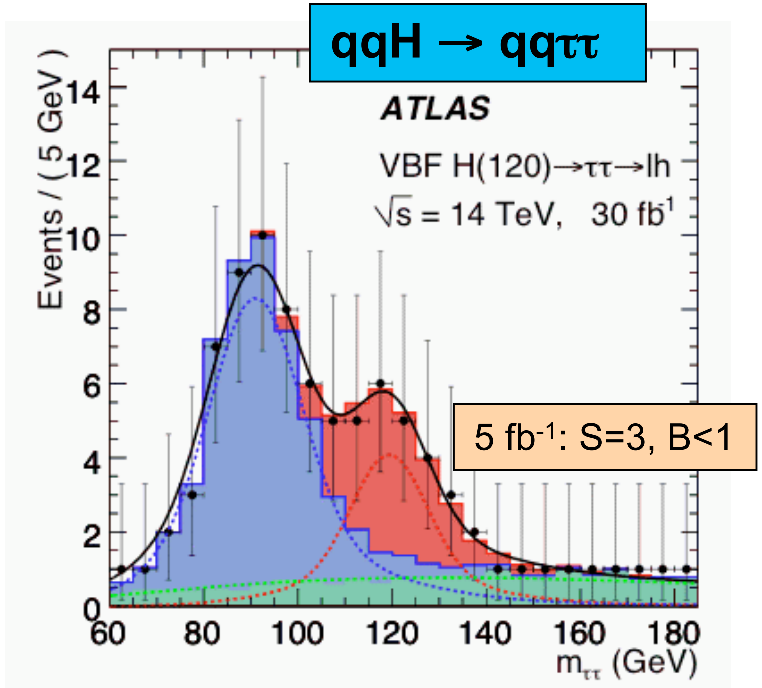
m_H > 130 GeV : H → $WW^{(*)}$, $ZZ^{(*)}$ dominate
→ best search channels at the LHC : H → $ZZ^{(*)}$ → 4l (gold-plated)
H → $WW^{(*)}$ → lν lν

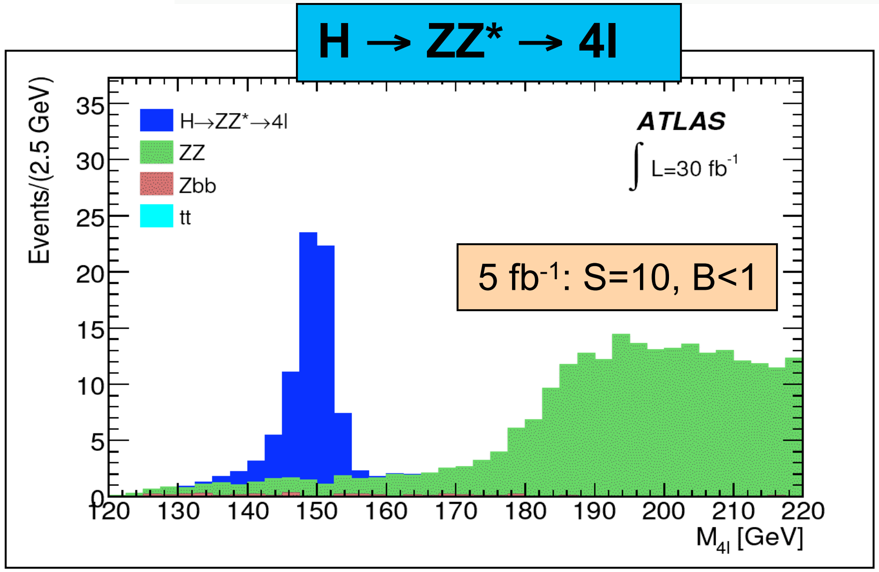
Especially in the region m_H<130 GeV, excellent detector performance needed to suppress the huge backgrounds: b-tag, l/γ E-resolution, γ/j separation, missing E_T resolution, forward jet tag, etc.
→ Higgs searches used as benchmarks for ATLAS and CMS detector design

Light Higgs

30 fb^{-1}





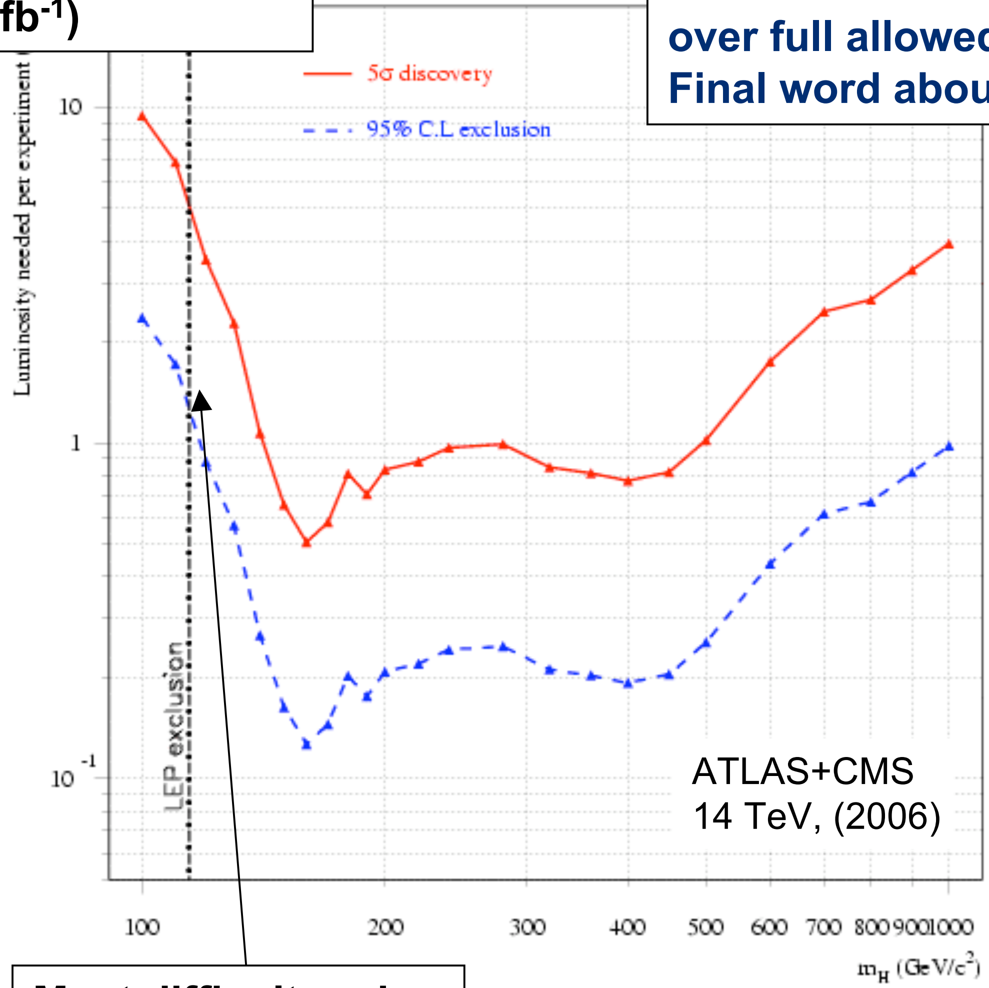


- **m_H < 130 GeV: most difficult region: need to combine many channels with small S or S/B**
- **m_H > 130 GeV: discovery easier with H → 4l (narrow mass peak, small B)**
- **H → WW → lνlν (dominant for 160-185 GeV) is a counting experiment (no mass peak)**

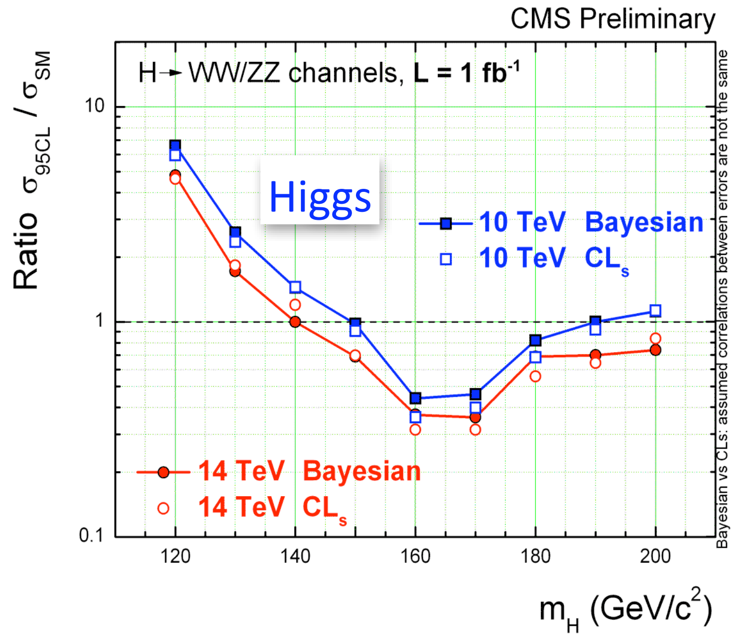
Summary of Higgs discovery potential at the LHC

Needed ∫Ldt per experiment (fb^{-1})

With
1 fb^{-1}: 95% C.L. exclusion
5 fb^{-1}: 5σ discovery
over full allowed mass range
Final word about Higgs mechanism by 2013 ?

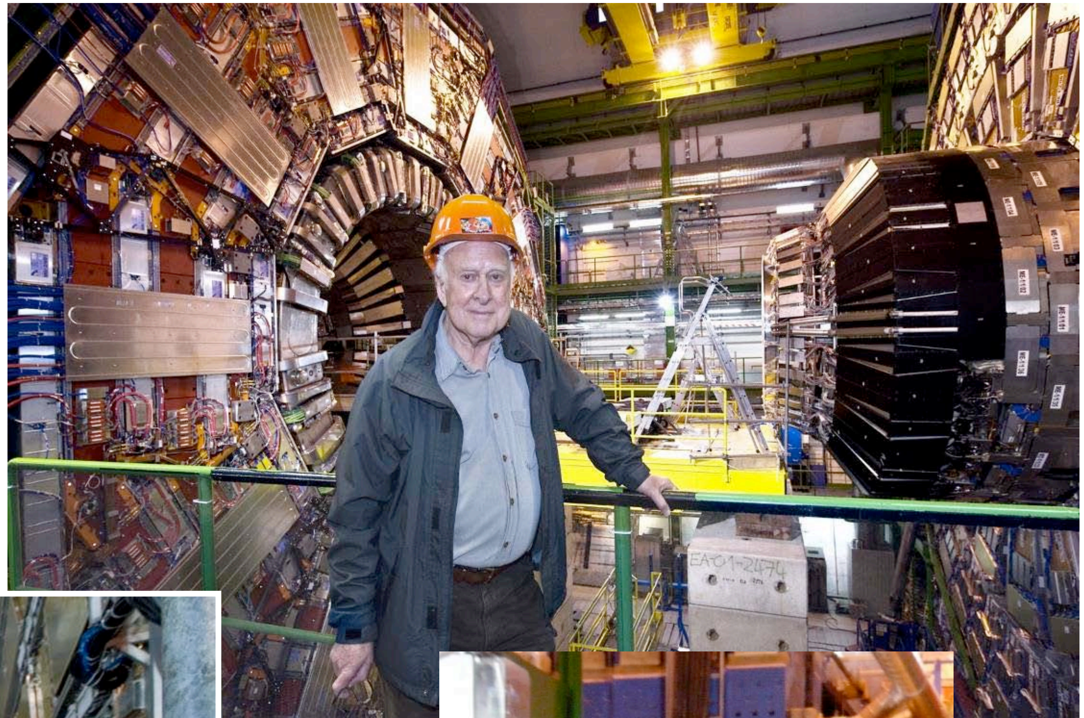


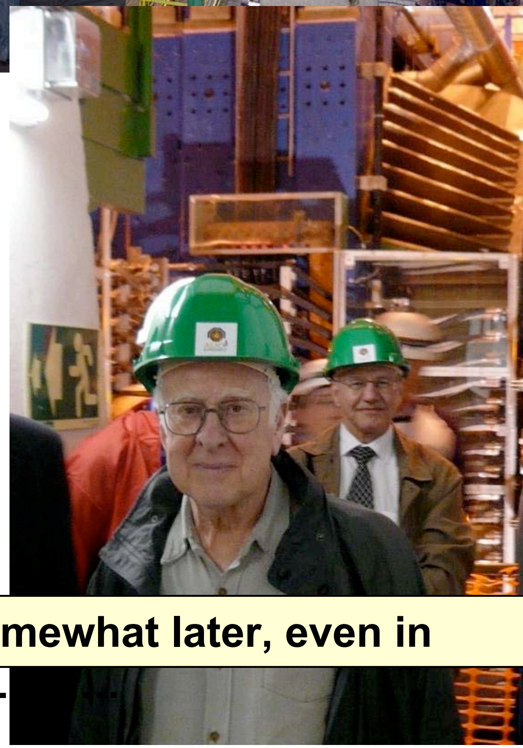
Most difficult region



With 200 pb^{-1}, reach current Tevatron sensitivity for Higgs

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

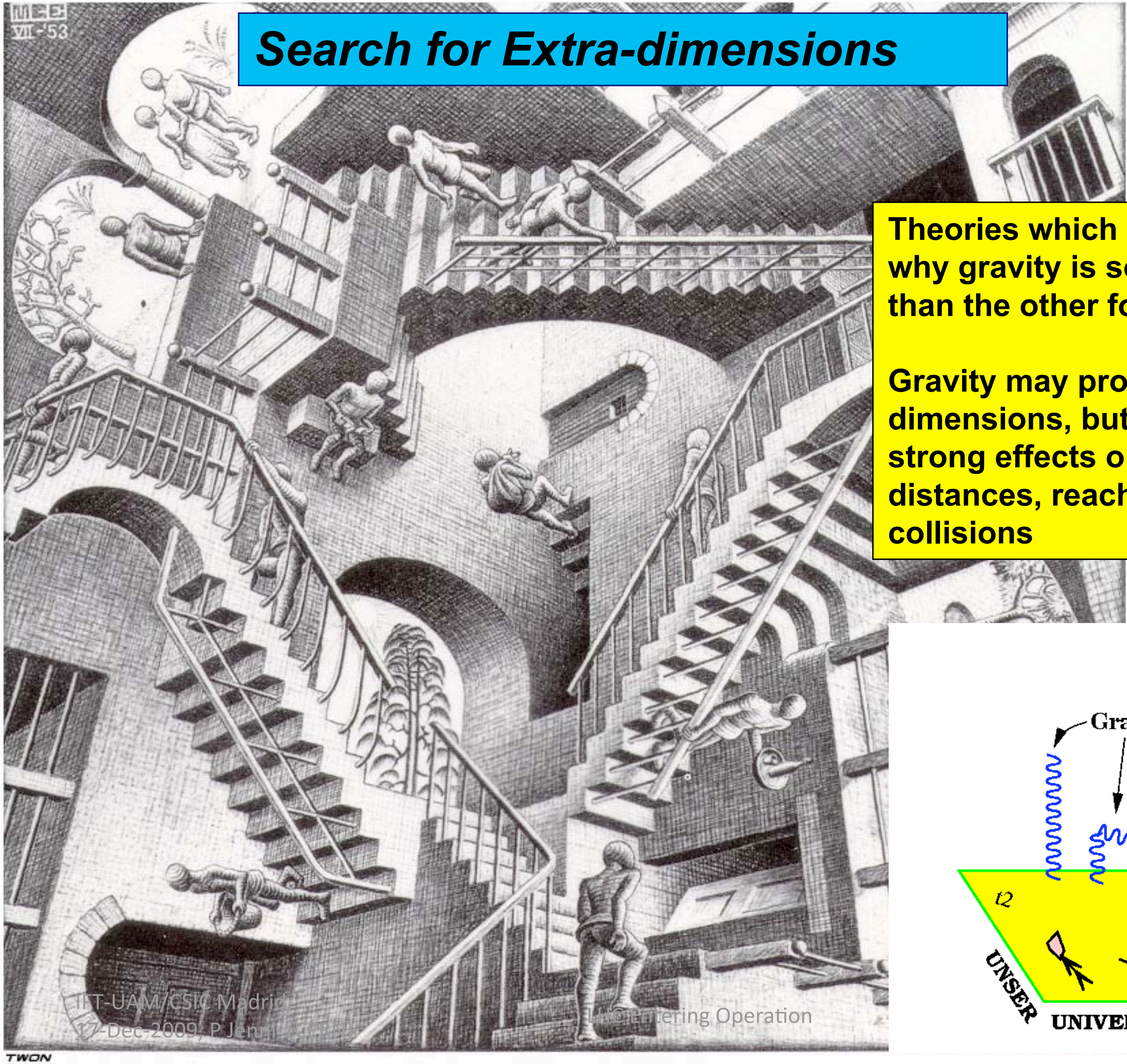




somewhat later, even in

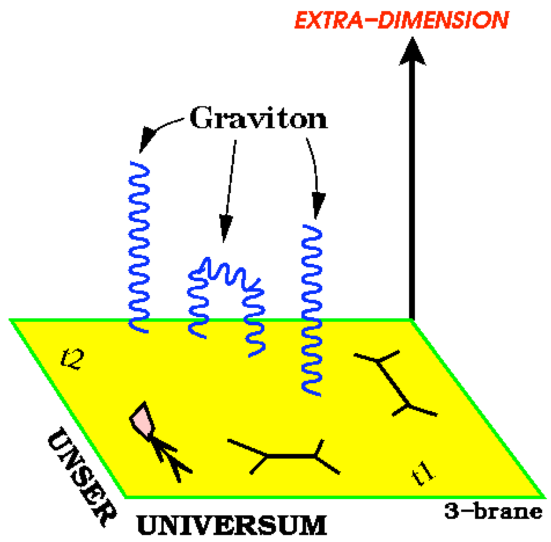
AL

Search for Extra-dimensions

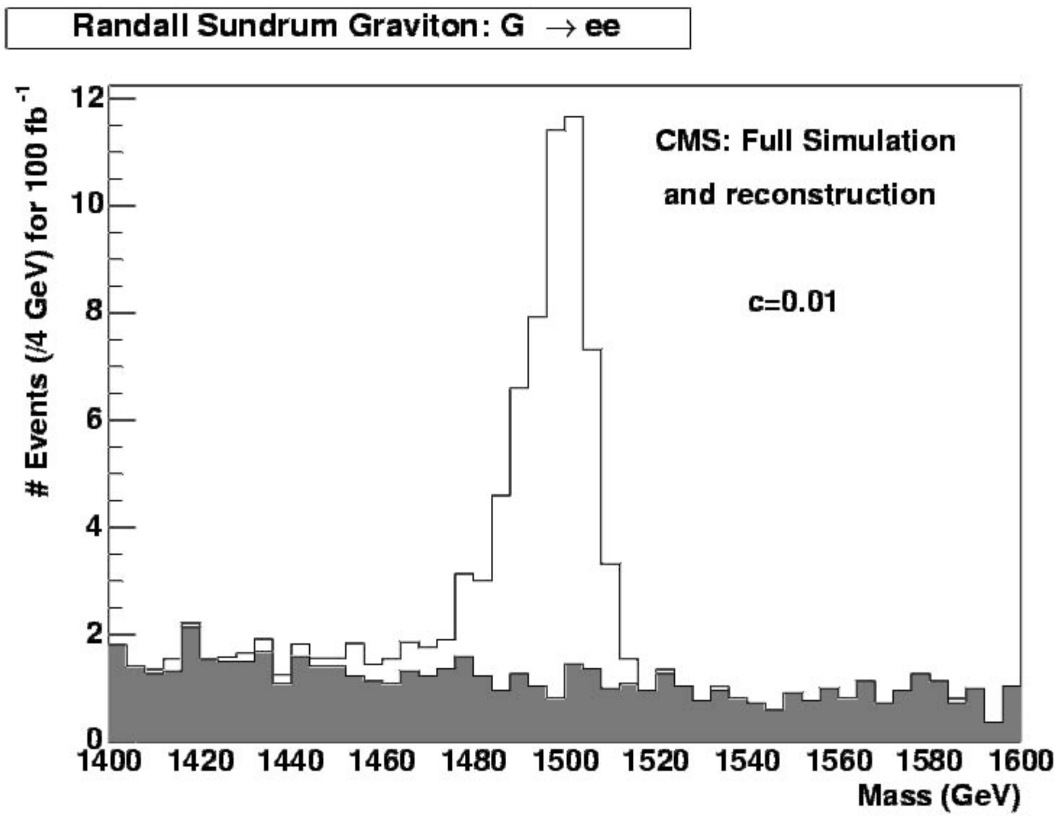


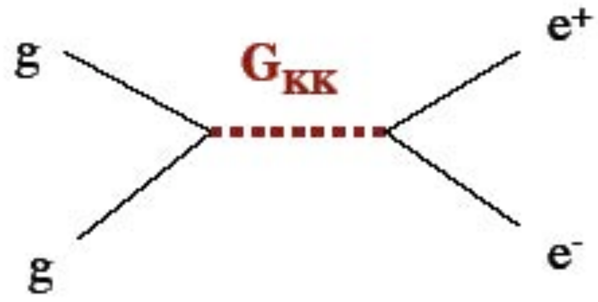
Theories which try to explain why gravity is so much weaker than the other forces

Gravity may propagate in 4+n dimensions, but we could see strong effects only at very small distances, reachable in pp LHC collisions



Warped Extra-dimensions (Randall-Sundrum models): production of narrow Graviton resonances





Signature: a resonance in the di-electron or di-muon final state a priori easy for the experiments

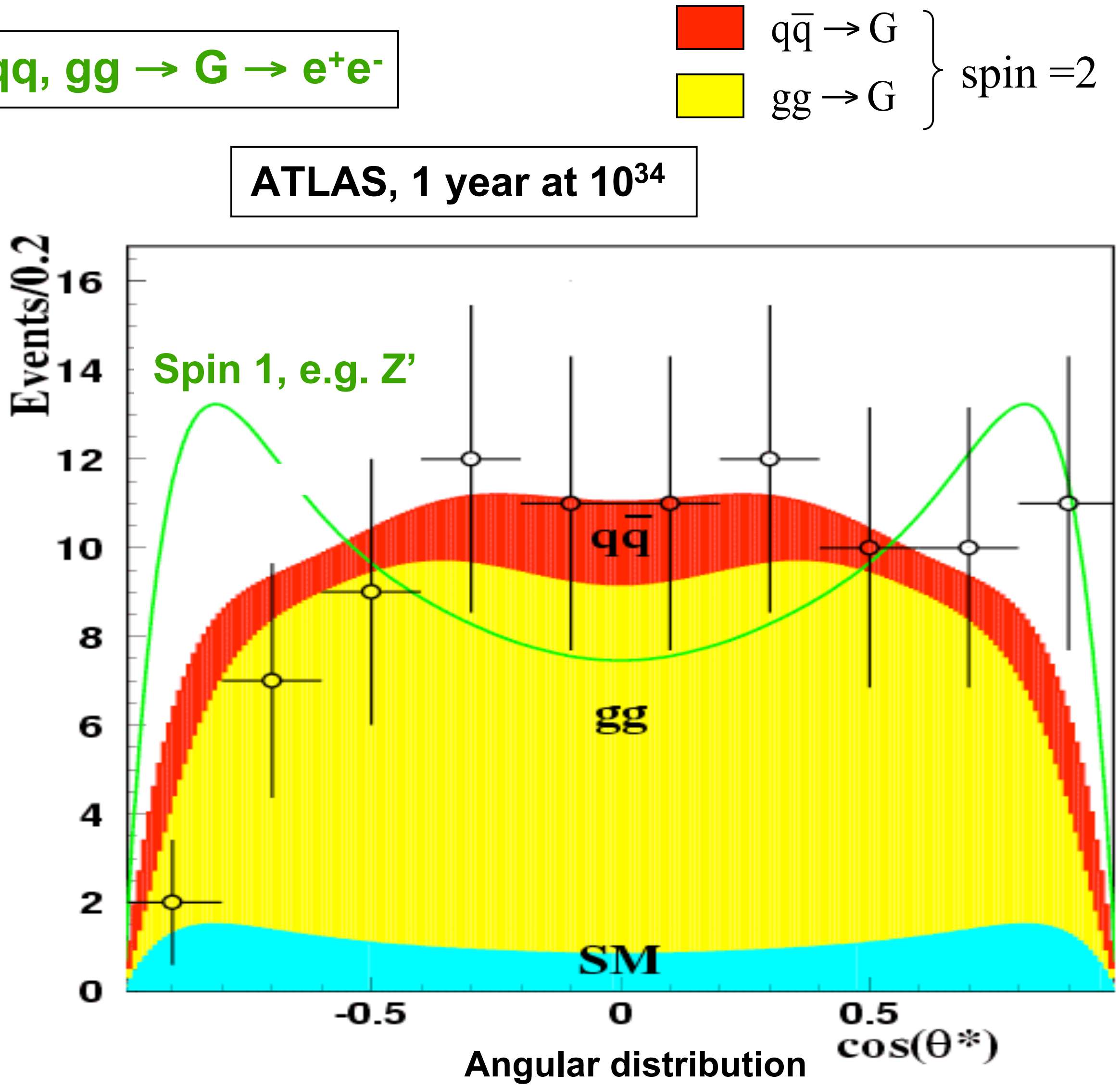
Caveat: new developments suggest that G_{KK} would couple dominantly to top anti-top…

Warped Extra-dimensions (Randall-Sundrum models): production of narrow Graviton resonances

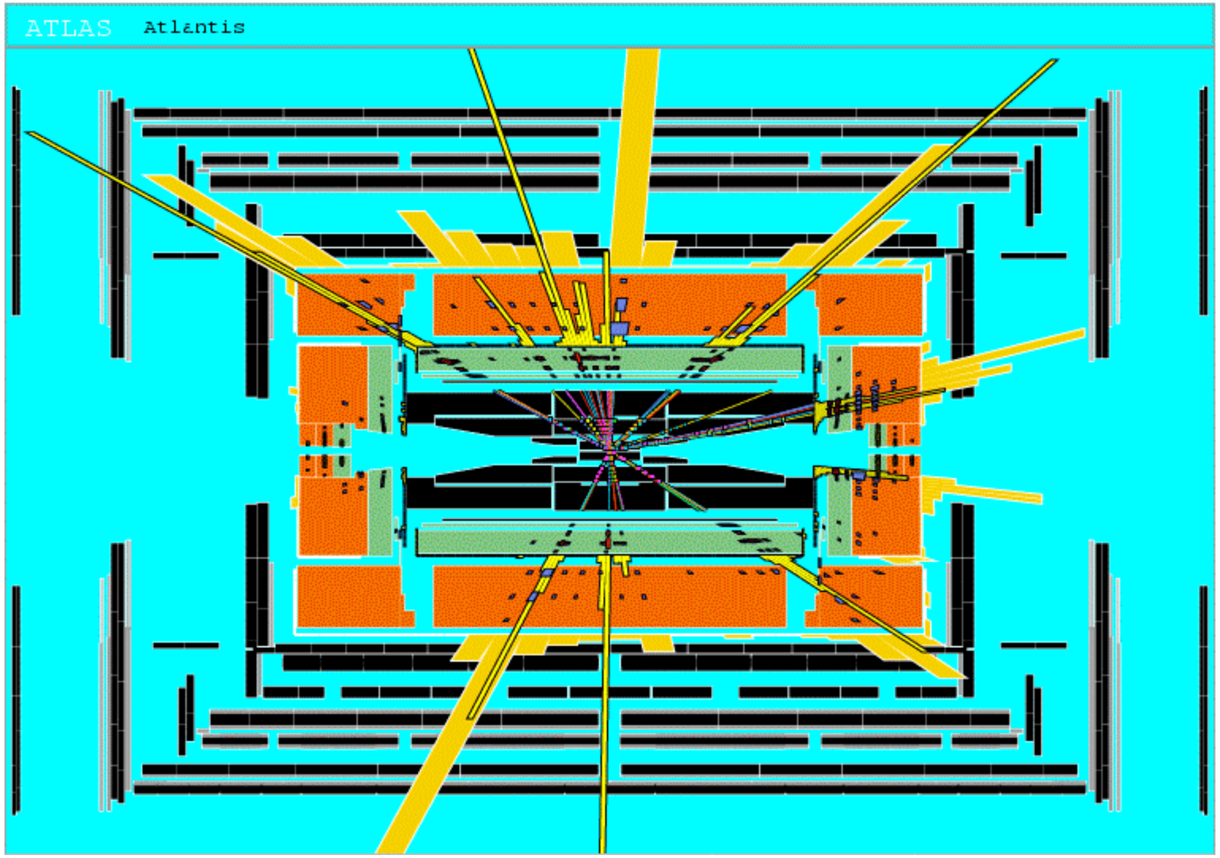
discovery channel : $qq, gg \rightarrow G \rightarrow e^+e^-$

ATLAS, 1 year at 10^{34}

Lisa Randall visiting ATLAS



If theories with Extra-dimensions are true, microscopic black holes could be abundantly produced and observed at the LHC



Simulation of a black hole event with M_{BH} ~ 8 TeV in ATLAS

They decay immediately through Stephen Hawking radiation

Finally the LHC Project is in Operation

All experiments have collected successfully first LHC collision data

The experiments operated remarkably well, from data taking to data transfer worldwide, and produced first results that confirm initial hopes to reach the expected performances

→ *All hopes are permitted for the physics to come!*

The machine turned on in an extraordinary manner, and all compliments have to go to the LHC team

It is also clear that the machine and the experiments have still a long way to go, but the enthusiasm is great to do so

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' material: in the first place to Fabiola Gianotti, the Spokesperson of ATLAS, to Karl Jakobs, Karlheinz Meier, as well as to CMS, Alice and LHCb colleagues, and last but not least to the LHC machine team