Physics at the LHC
Lecture 1: Machine and Experiments

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Wintersemester 2010/2011

Vorlesungsübersicht

- 1. VL 29.10.2010
  10.00 KM: **Die LHC Experimente**
  12.30 KM: **Das Standardmodell am LHC (I)**
- 2. VL 12.11.2010
  10.00 SM: **Das Standardmodell am LHC (Theorie)**
- 3. VL 26.11.2010
- 4. VL 10.12.2010
- 5. VL 07.01.2011
- 6. VL 21.01.2011
- 7. VL 04.02.2011
- 8. VL 18.02.2011

Web-Page:

`http://www-zeuthen.desy.de/ATLAS/lectures/hub_ws1011/physics@lhc/`

Why proton accelerators?

Reason to build LHC:
Want to reach high energies to discover new physics at TeV scale

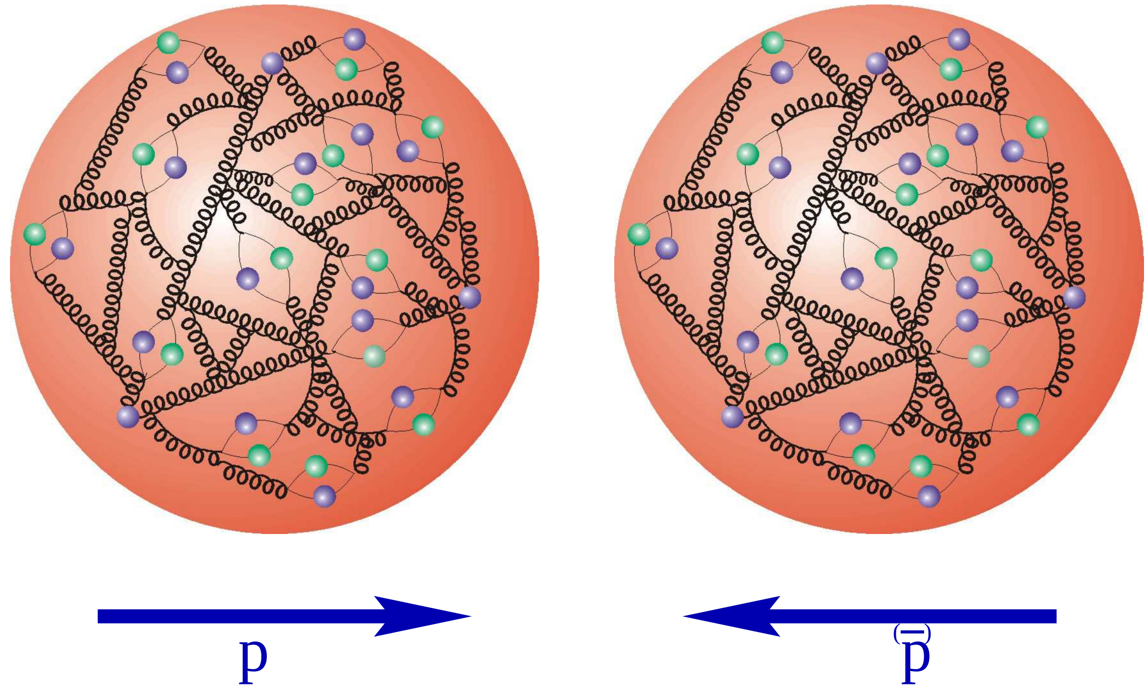
Must accelerate stable charged particles!

Electrons:

- Point-like:
  - well known initial state, including polarisation if needed
  - whole energy goes into interaction
  - full event in detector ➠ can use energy-momentum constraint
- No strong interactions:
  - relatively small cross sections
  - relatively equal cross sections for all processes ➠ no large backgrounds
- Electrons are light;
  - synchrotron radiation $\propto \left(\frac{E}{m}\right)^4 / r$ ➠ limits energy in accelerator

Protons:

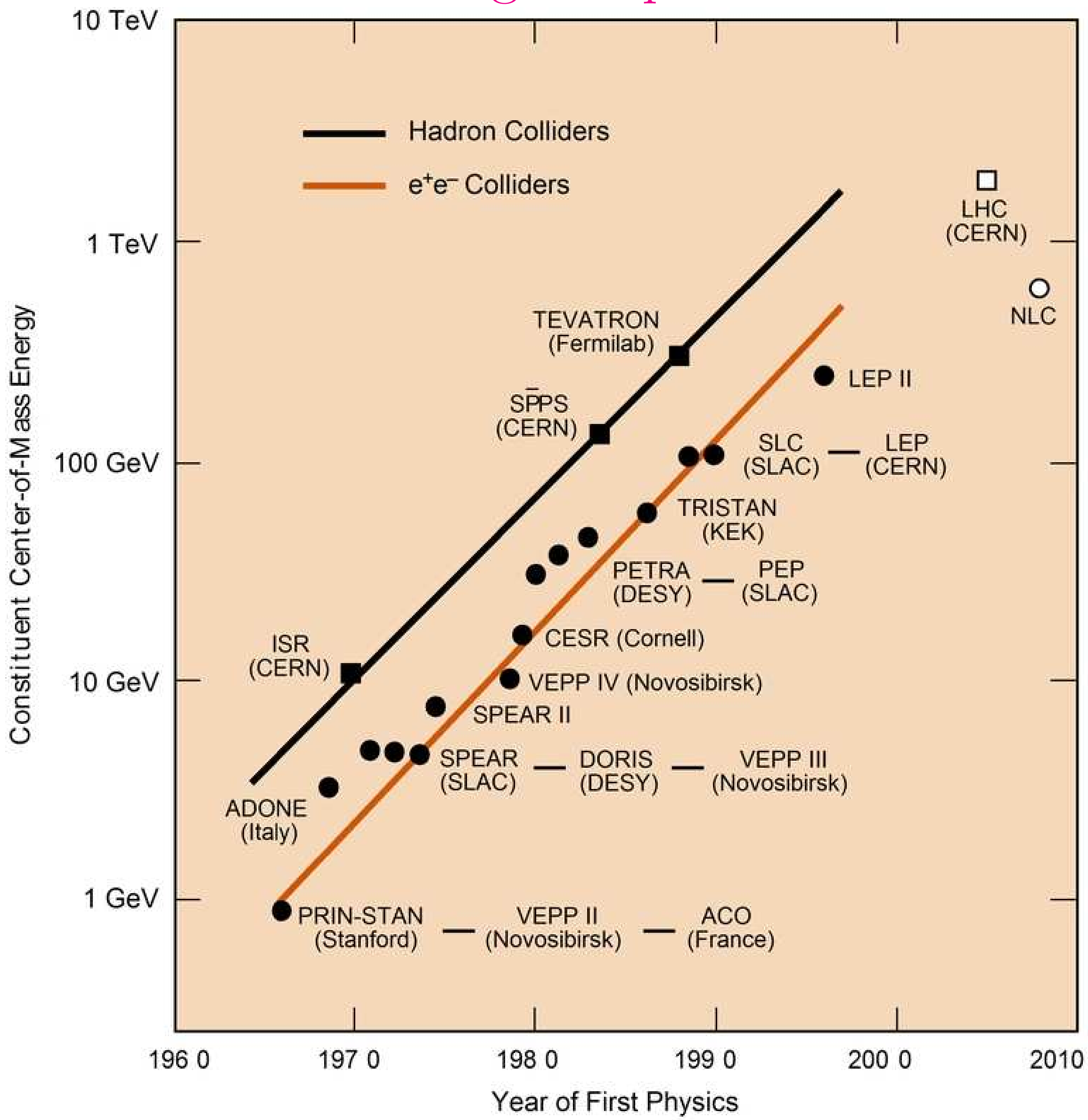
- Protons are composite
  - interaction unknown at parton level
  - interaction energy ≪ proton energy



  - proton remnants disappear in the beampipe ➟ kinematics must be reconstructed from the decay products
- Protons have strong interactions
  - cross sections for production of strongly interacting particles are large
  - useful for some signals
  - huge QCD backgrounds
- Protons are heavy
  - no significant energy loss

Energy Frontier Accelerators in the Past

“Livingston plot”



Last e^+e^- accelerator:

LEP (CERN, up to 2000)

- 26 km circumference
- $\sqrt{s} \approx 200\,\mathrm{GeV}$
- definite end of circular technology for electrons

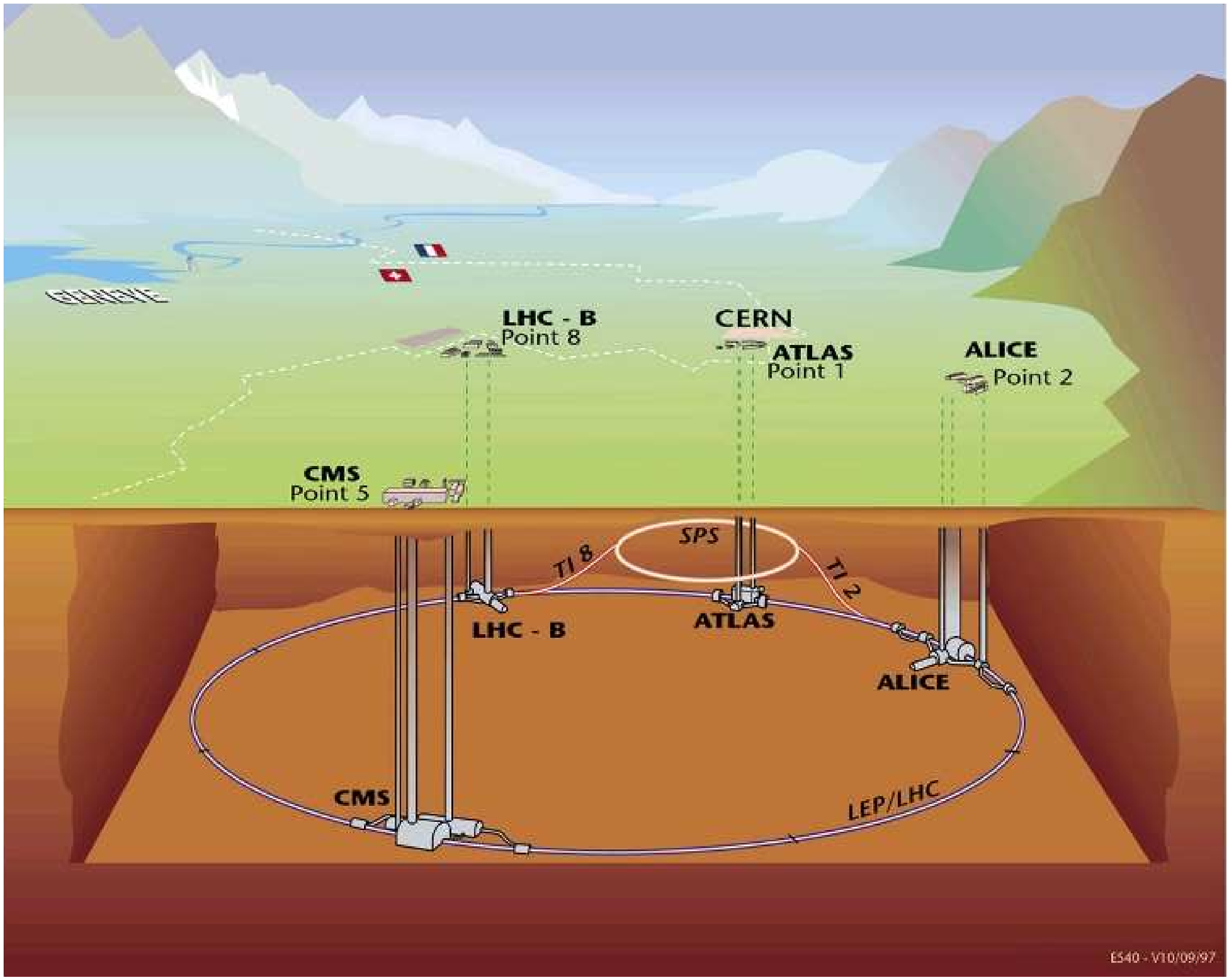
Last $p\bar{p}$ accelerator:

Tevatron (FNAL, still running)

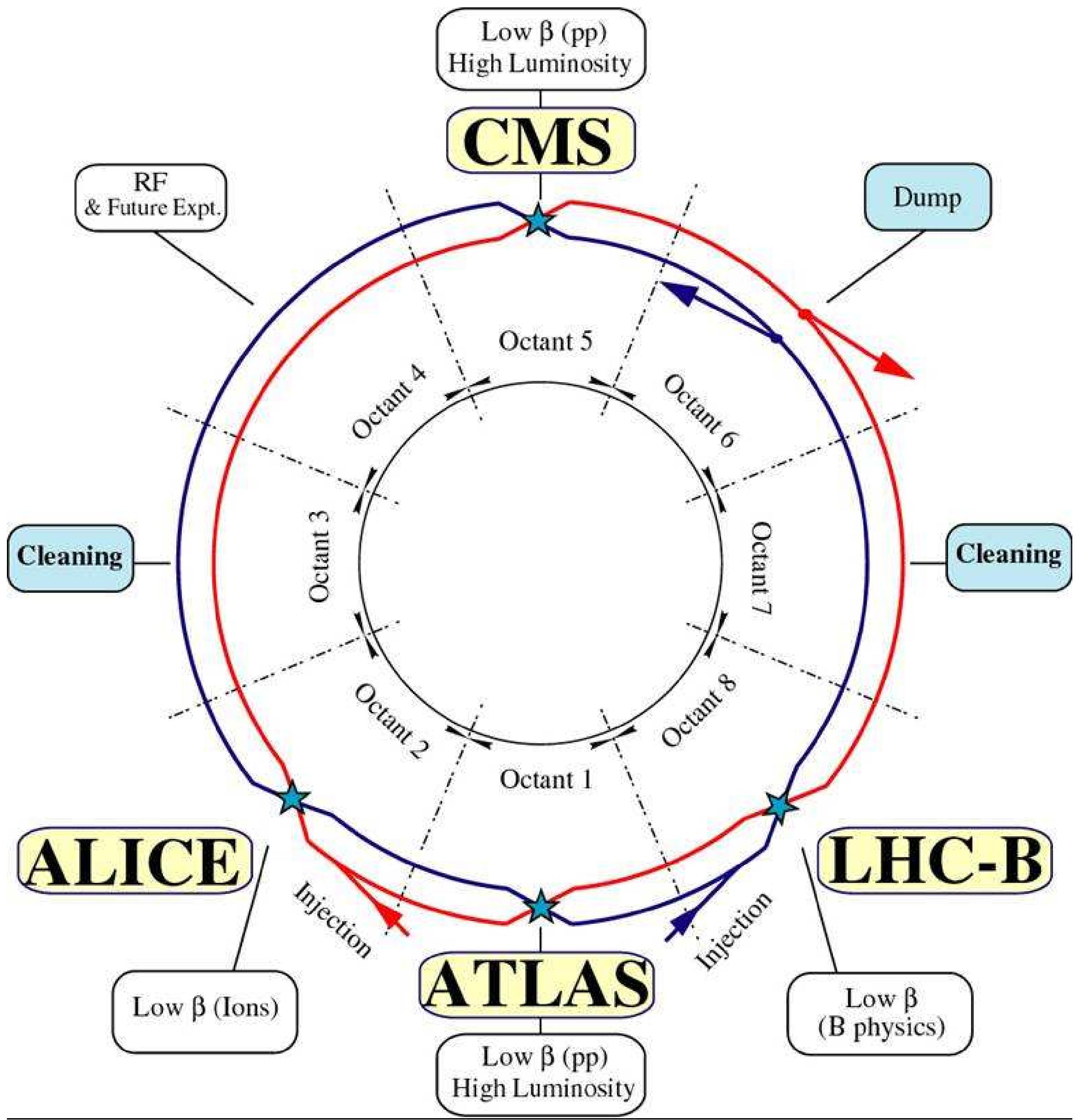
- 6 km circumference
- $\sqrt{s} = 2\,\mathrm{TeV}$

The LHC

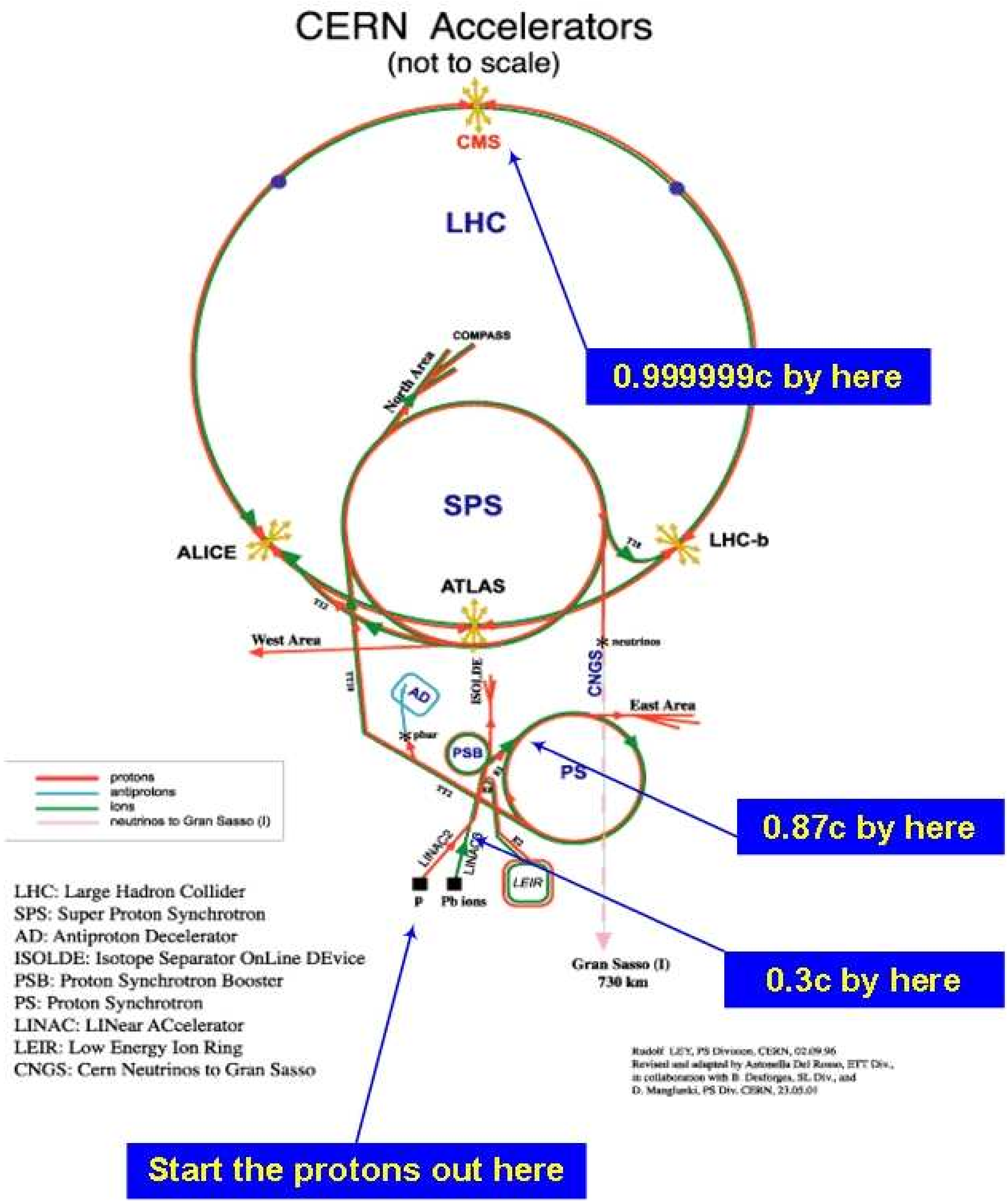
- pp-collider in the LEP tunnel at CERN (l=27 km)
- $\sqrt{s} \approx 14\,\mathrm{TeV}$
- Luminosity up to $\mathcal{L} = 10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$



Detailed layout of the LHC

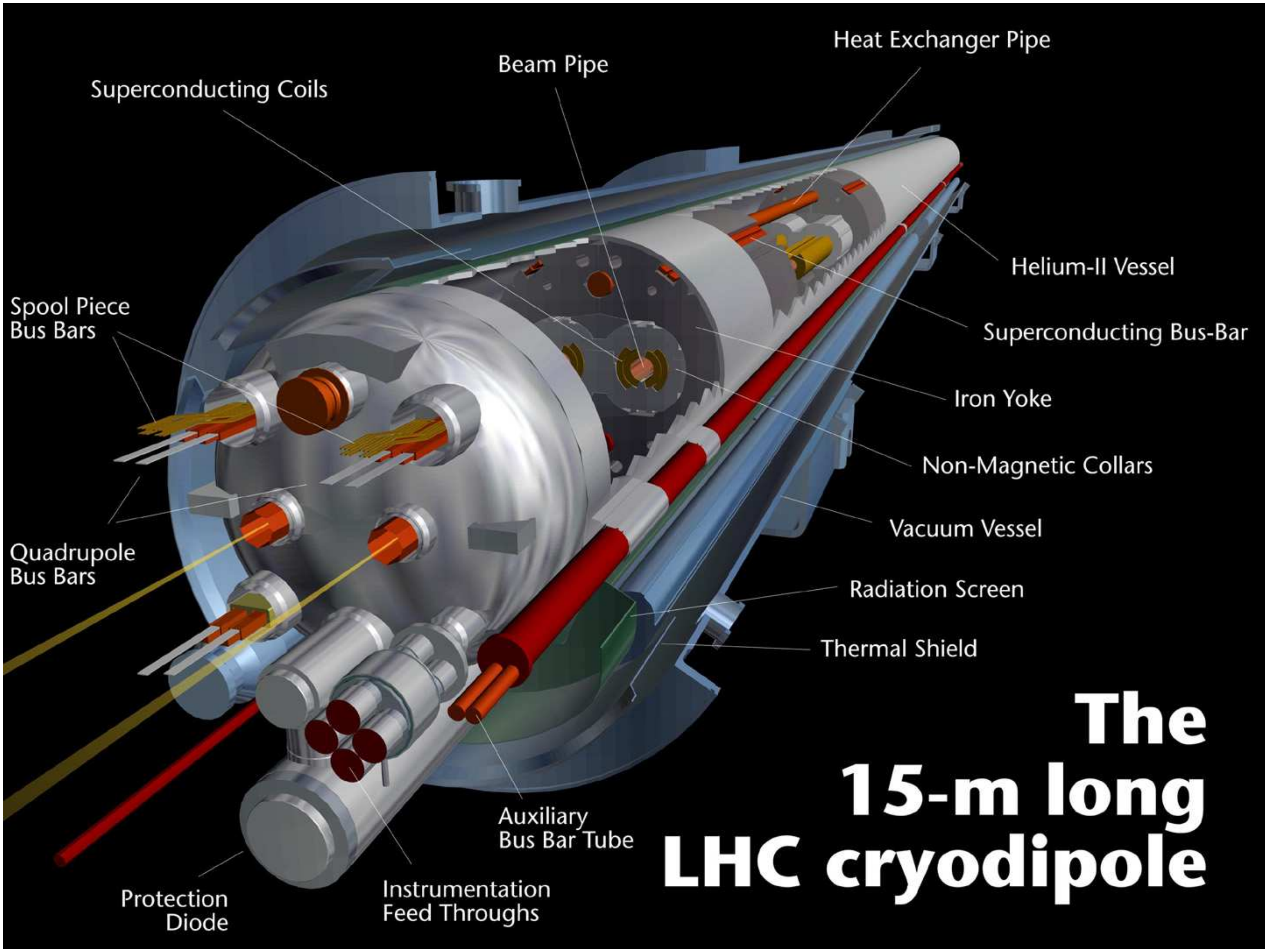


LHC receives its beams from the CERN accelerator complex



Main challenge: need 9 T magnets to reach desired energy

Solution: superconducting "2 in 1" magnets to save cost



The LHC beams

- Two proton beams of E=7 TeV each (now 3.5 TeV)

- 2800 bunches/beam (now 300)

- $1.2 \cdot 10^{11}$ protons per bunch (almost reached)

➠ The total stored energy is 360 MJ per beam (now 19)
(This corresponds to a British aircraft carrier at 12 knots or a luxury car at 2000 km/h)
However the energy of two colliding protons corresponds to the energy of two colliding mosquitoes

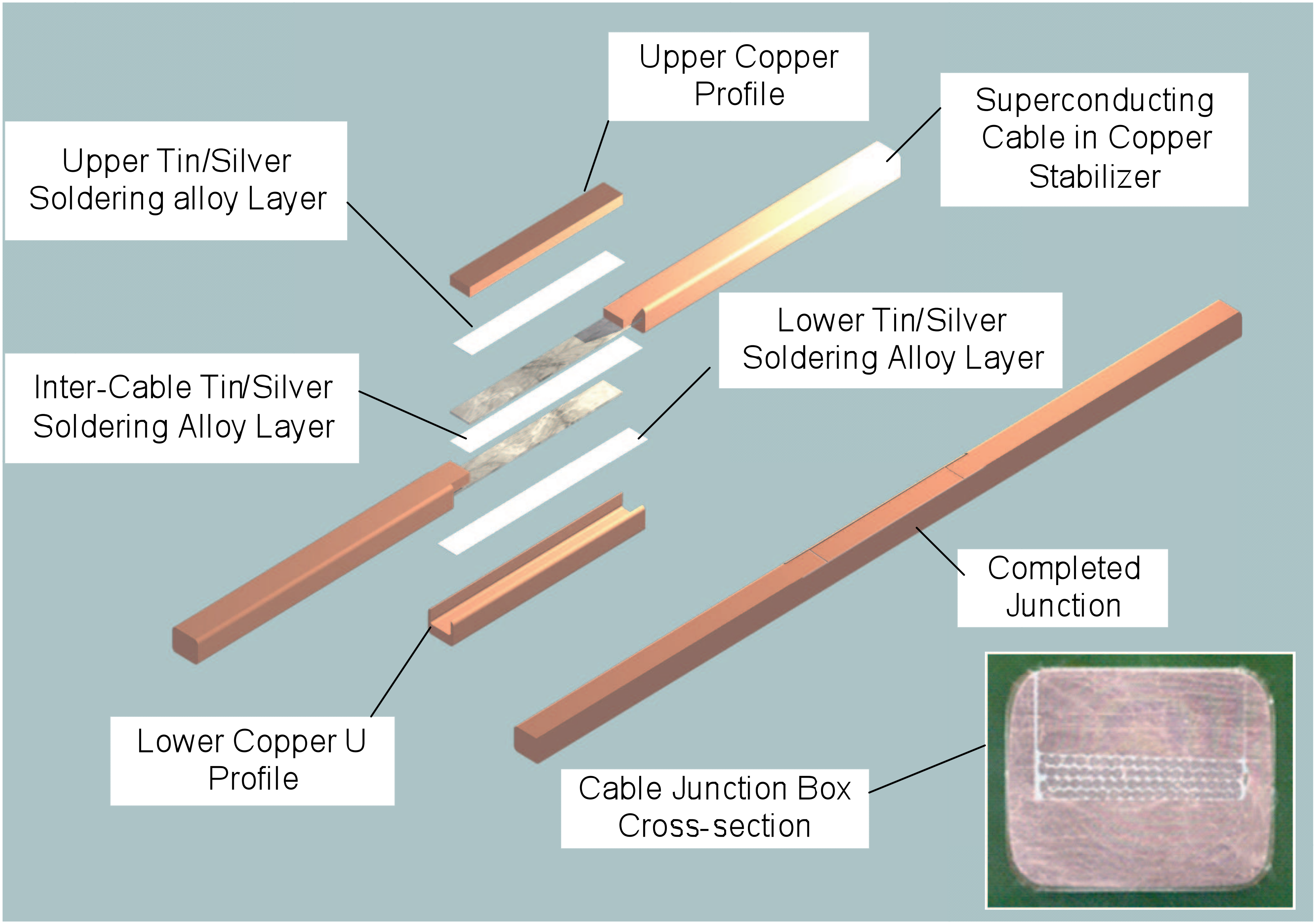
- Beam size at IP: few cm long, 16μm wide

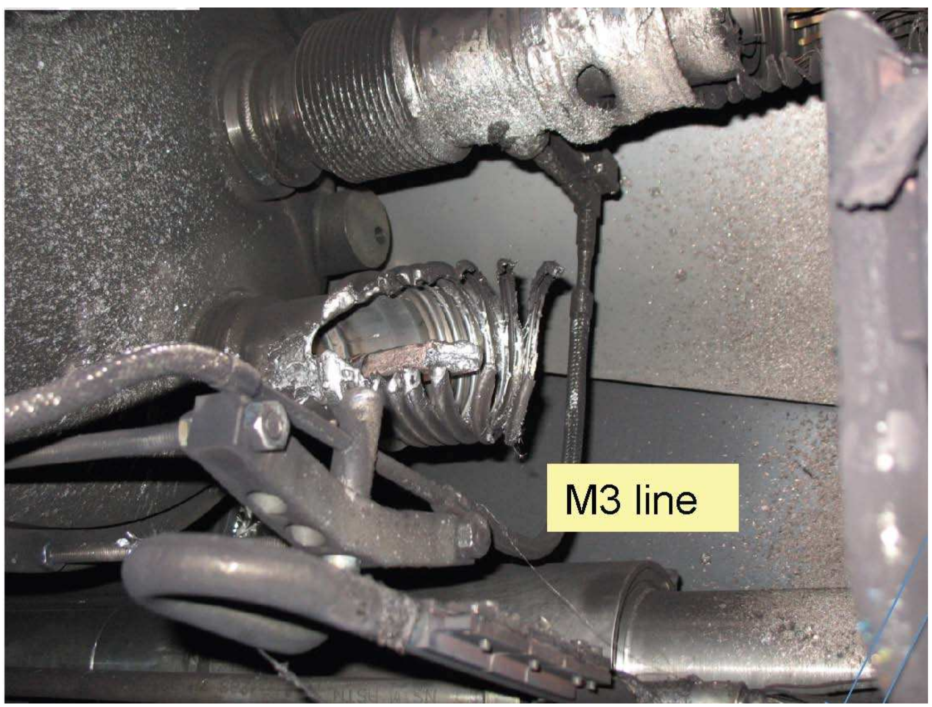
The LHC timescale

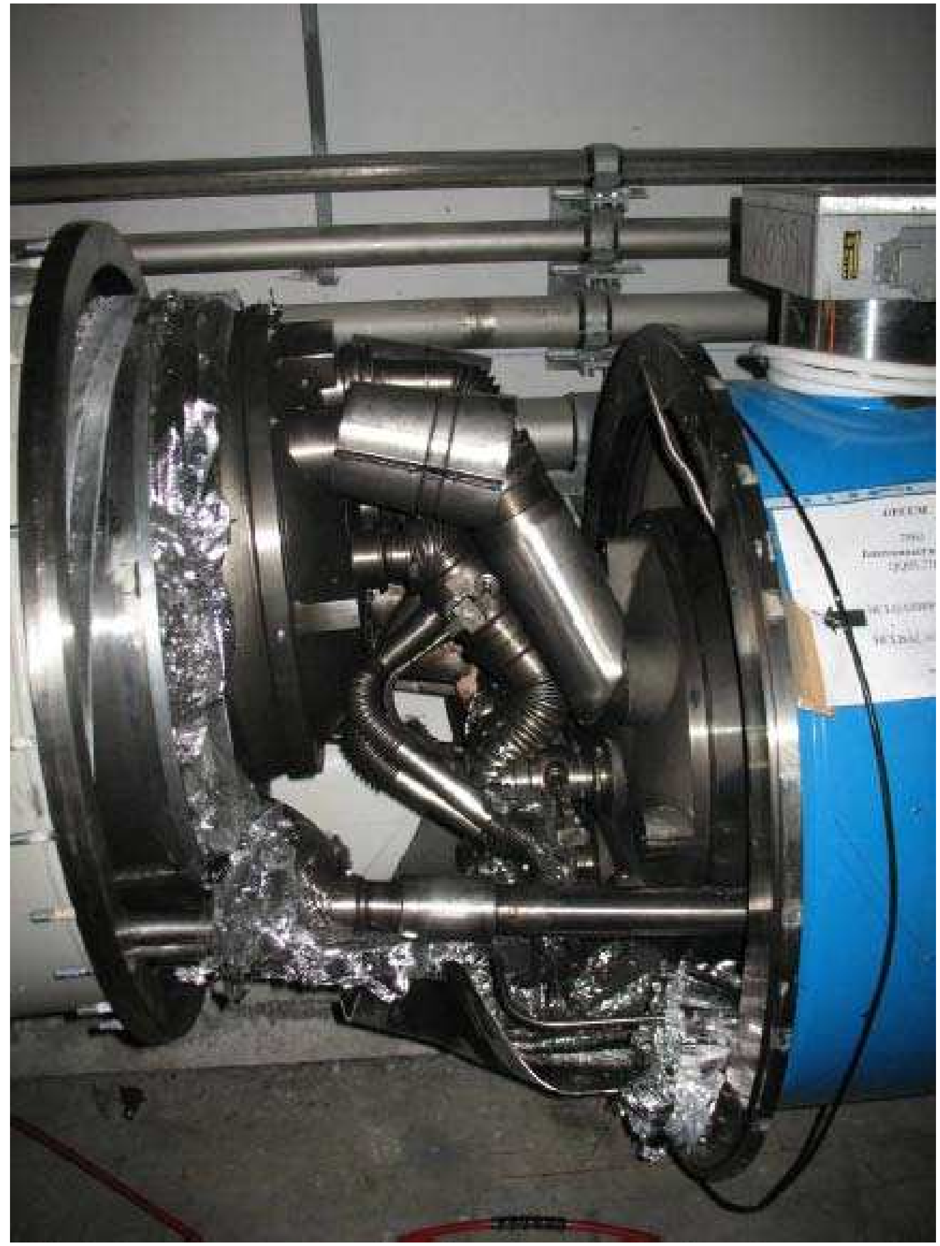
- First discussions on the project: 1984
- Constructed in the LEP tunnel since 2001
- Late 2009: first collisions at $\sqrt{s} = 0.8\,\text{TeV}$
- 2010 – 2011 Collisions at $\sqrt{s} = 7 - 8\,\text{TeV}$
- 2012 Upgrade to 14 TeV (maybe delayed to 2013)
- 2013 – 2019: Run with $\sqrt{s} = 14\,\text{TeV}$ and luminosity from $\mathcal{L} = 10^{33}\text{cm}^{-2}\text{s}^{-1}$ to $\mathcal{L} = 10^{34}\text{cm}^{-2}\text{s}^{-1}$
  (one long shutdown (2016?) forseen for detector upgrades)
- $\sim$ 2020: luminosity upgrade to $\mathcal{L} \sim 10^{35}\text{cm}^{-2}\text{s}^{-1}$

The LHC problem(s)

- The magnets are powered in series with a splice connection between the magnets
- The splices could only be connected in the tunnel and could not be tested
- On September 19, 2008 a splice connection between two magnets quenched
- This caused an electrical arc in the connection
- The arc boiled the local helium
- The gaseous helium could not be extracted fast enough and the shock-wave caused some destruction at about 50 magnets
- All magnets repaired
- A new quench protection system can measure $n\Omega$ resistence in the splices to avoid this problem in future


Upper Copper Profile
Superconducting Cable in Copper Stabilizer
Upper Tin/Silver Soldering alloy Layer
Lower Tin/Silver Soldering Alloy Layer
Inter-Cable Tin/Silver Soldering Alloy Layer
Completed Junction
Lower Copper U Profile
Cable Junction Box Cross-section


M3 line



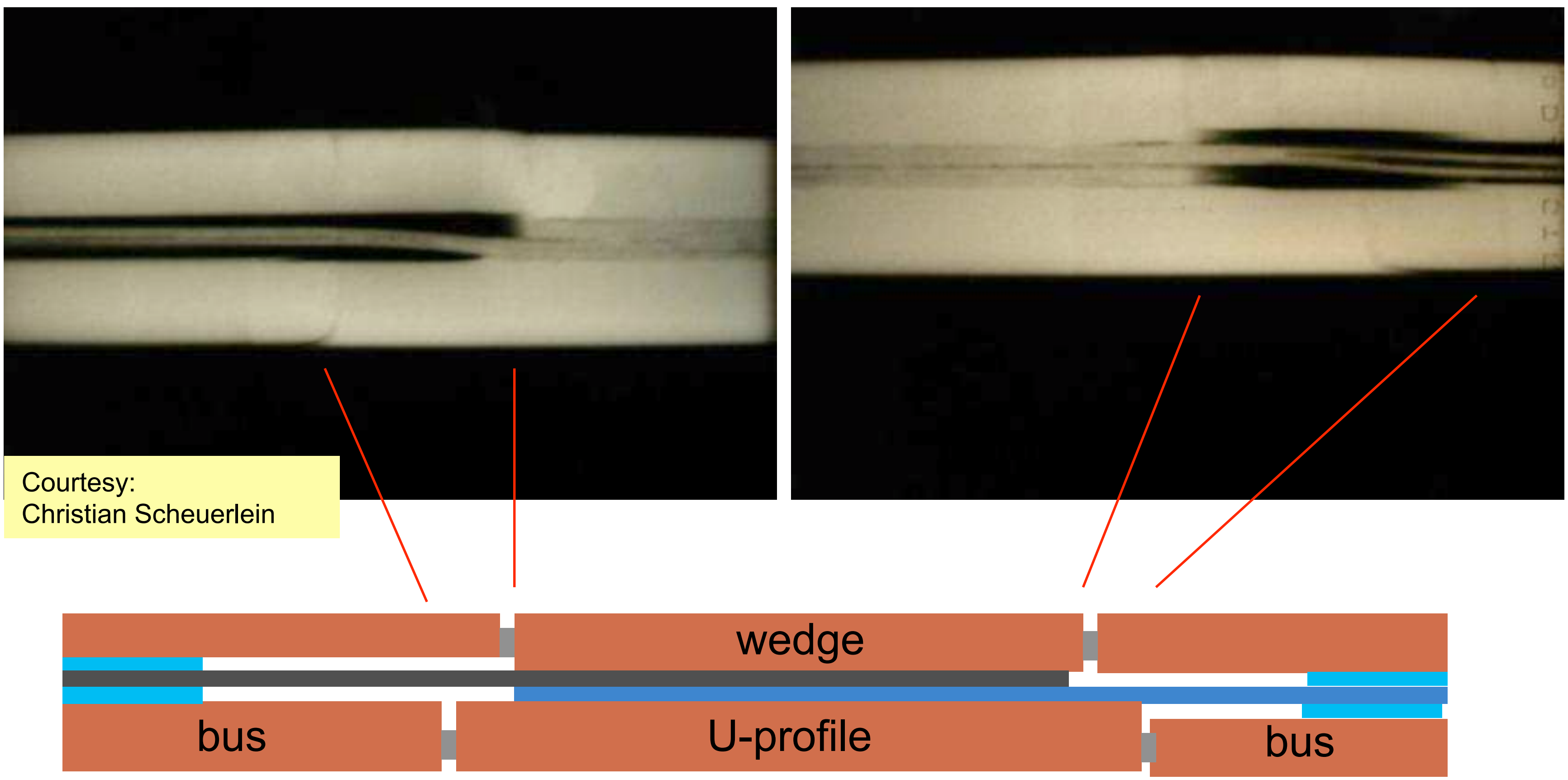
Remaining Problem: Bad connection between copper parts in the busbars

- In case of quench the current cannot completely flow through the copper

➠ Danger for the superconducting cable

- At present limits the beam energy to 3.5 TeV
- For 7 TeV new clamp connections may be needed ⇒ long shutdown

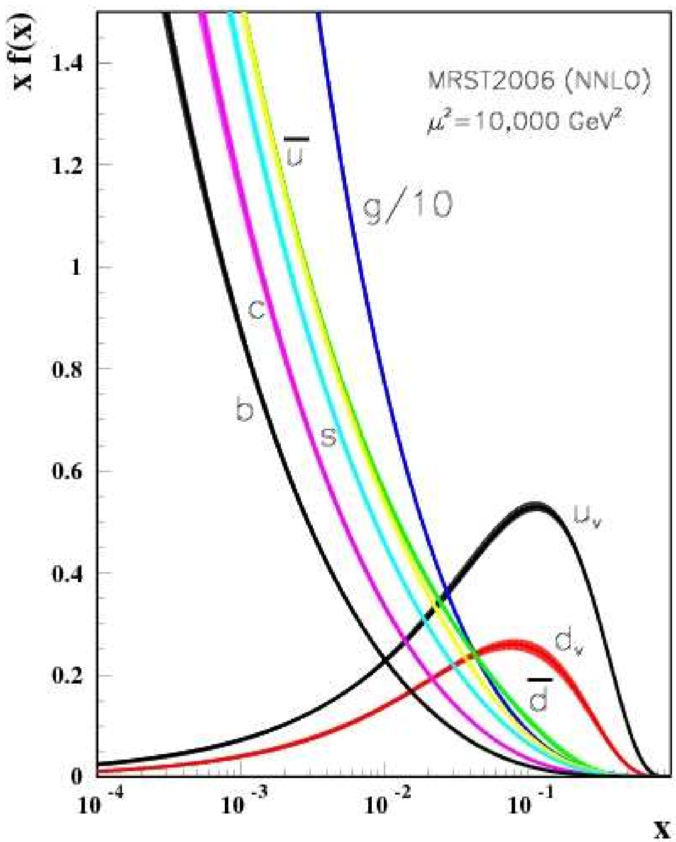
Gamma rays QBBI.B25R3-M3 before disconnection (QRL connection & QRL lyra sides)

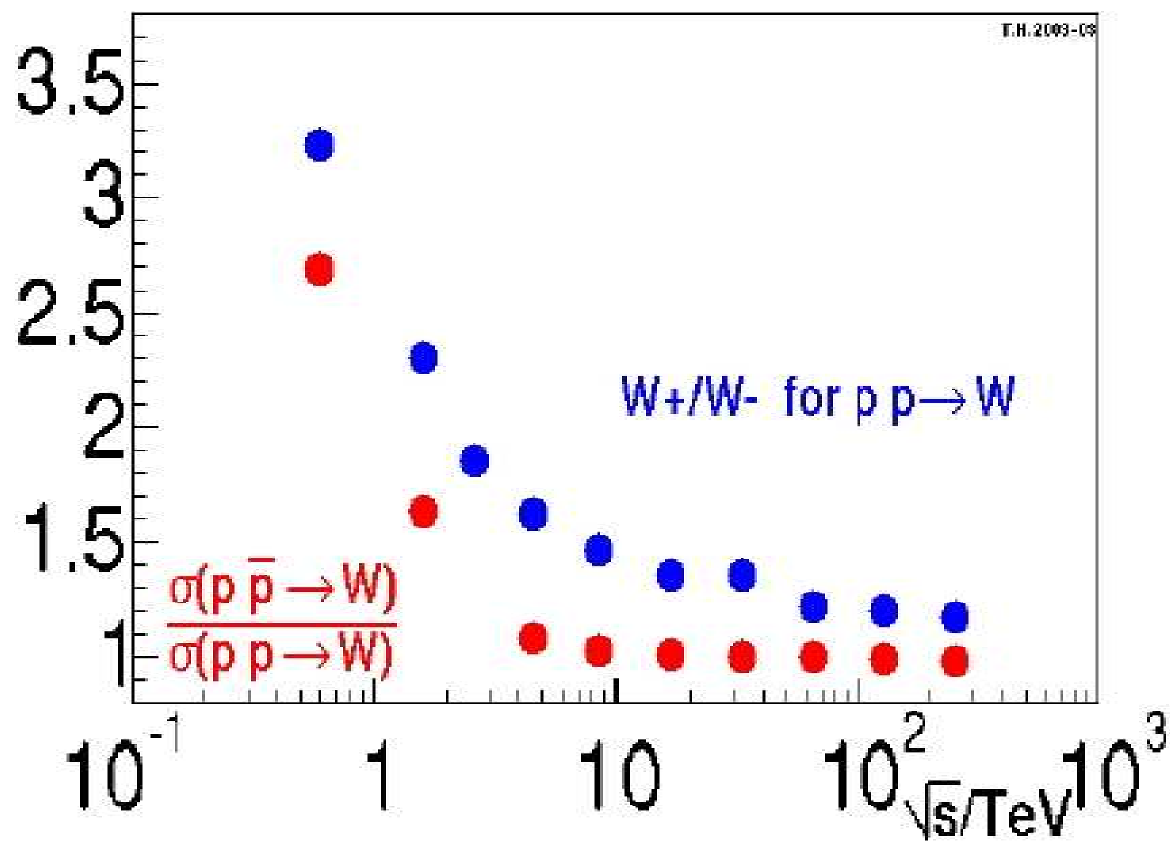


Why pp?

- In principle want to annihilate particles with antiparticles
- Generation of antiprotons is very expensive and limits luminosity
- At high energy PDFs anyway dominated by gluon and sea-quarks

➠ (almost) no difference between pp and p$\bar{\text{p}}$ cross sections

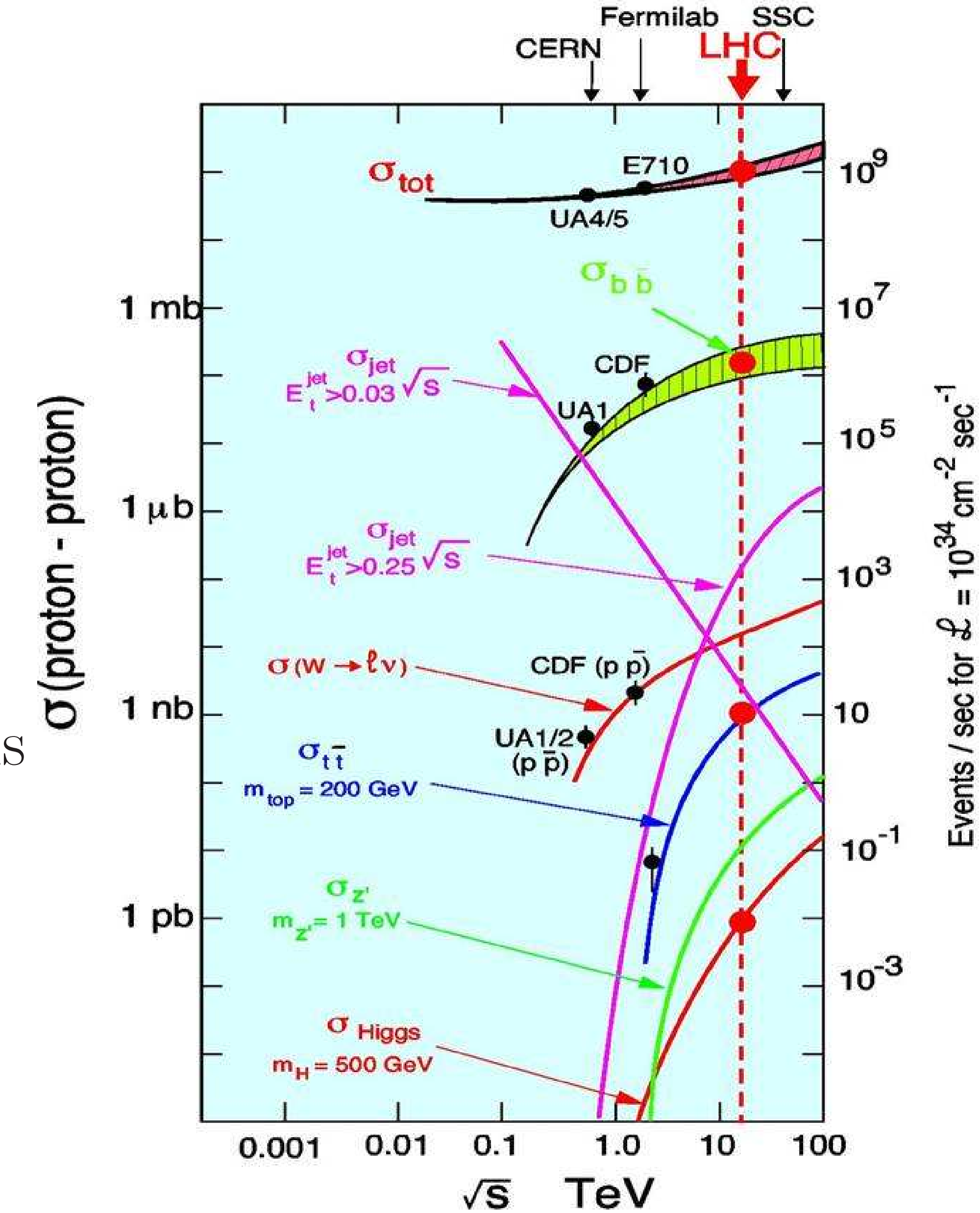




Cross sections at the LHC

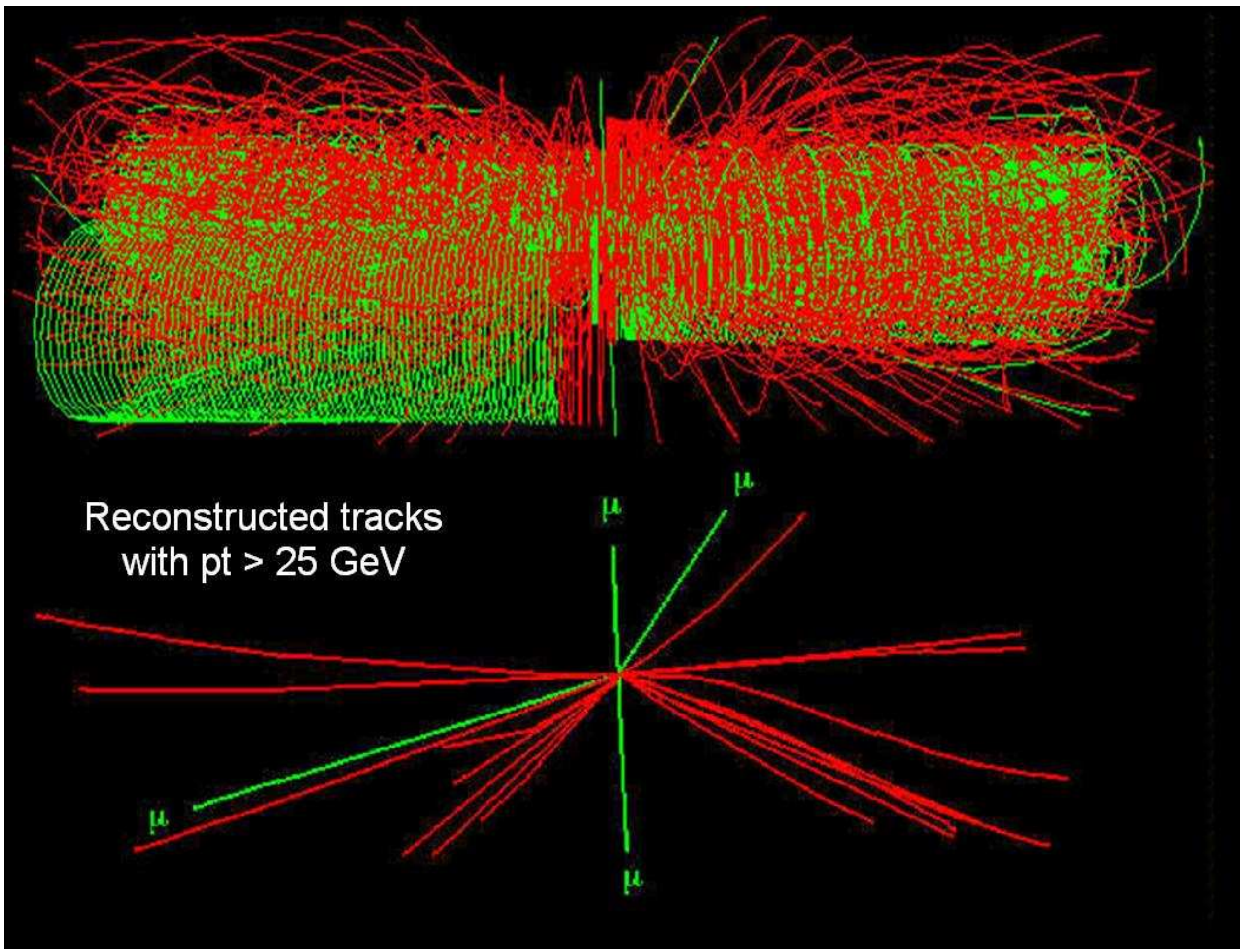
- Huge signal cross sections
  - 150 $W \rightarrow e\nu$/s
    15 $Z \rightarrow \mathrm{e}^+\mathrm{e}^-$/s
  - 8 $\mathrm{t\bar{t}}$/s
  - 0.2 Higgs (150 GeV)/s
  - 0.03 SUSY particles /s
- However also huge backgrounds
  - 10^9 inelastic pp interactions (minimum bias)/s
    = 25/bunch crossing
  - thousands of jet events/s

Triggering is a challenge!



Pileup

- 25 pileup events/bunch crossing at high luminosity
- This means hundreds of tracks per bunch crossing
- Reconstruction program must filter out the interesting ones



Kinematic variables

- Every particle can be characterised by 3 variables e.g. (p,θ, ϕ)
- pp collisions: longitudinal boost because of parton momentum differences

  ➠ need longitudinal variable that gets only a constant shift:

  – Rapidity: $y = \frac{1}{2} \ln \left(\frac{E+p_\parallel}{E-p_\parallel} \right)$

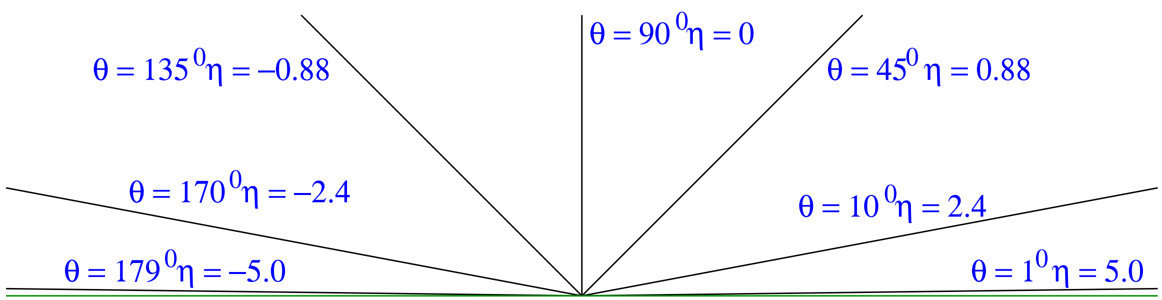
  – no particle id ➠ use pseudorapidity (m=0) $\eta = -\ln \left(\tan \frac{\theta}{2} \right)$

  ➠ no interest in longitudinal momentum

  – use p_t as estimator for hardness of interaction

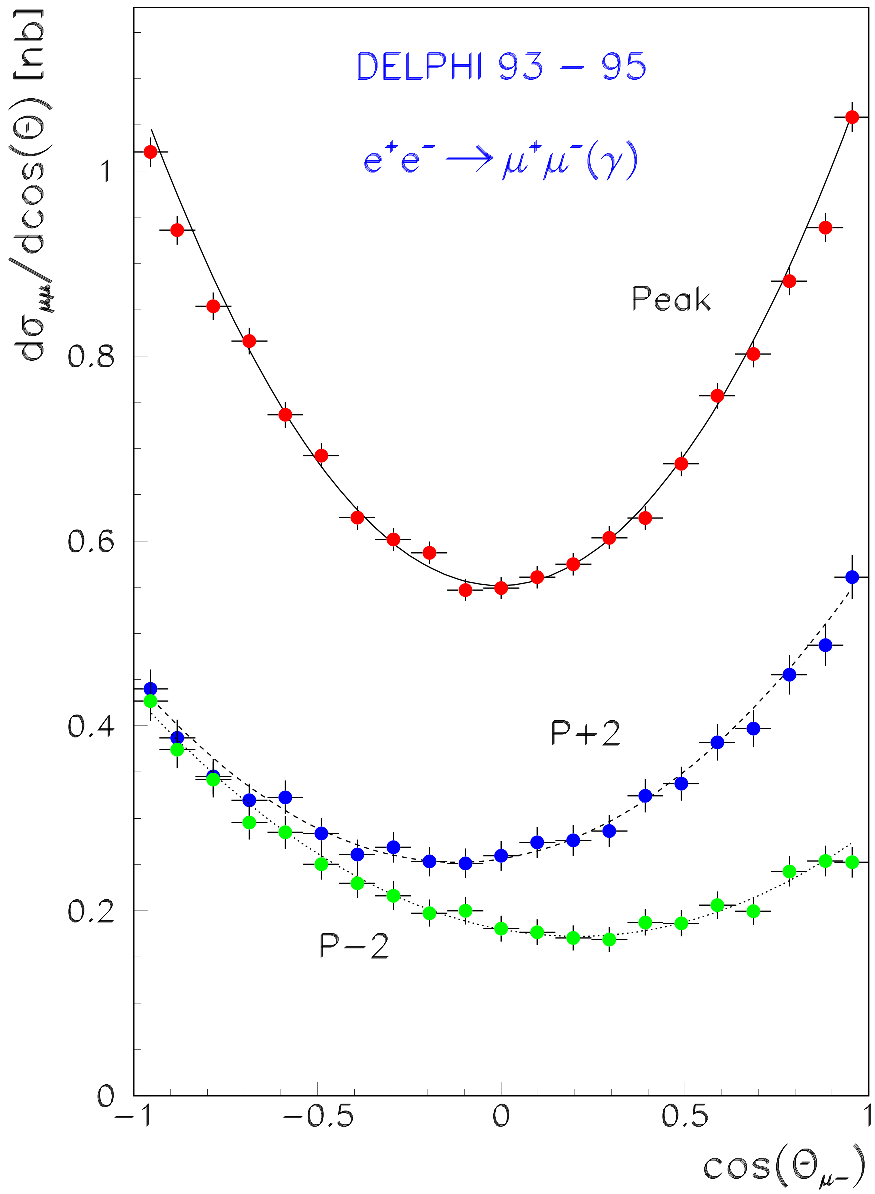
  – common slang: $E_t = p_t$ measured by calorimeters

- ϕ as azimuthal variable is ok.



Phase space is flat in $\cos\theta$

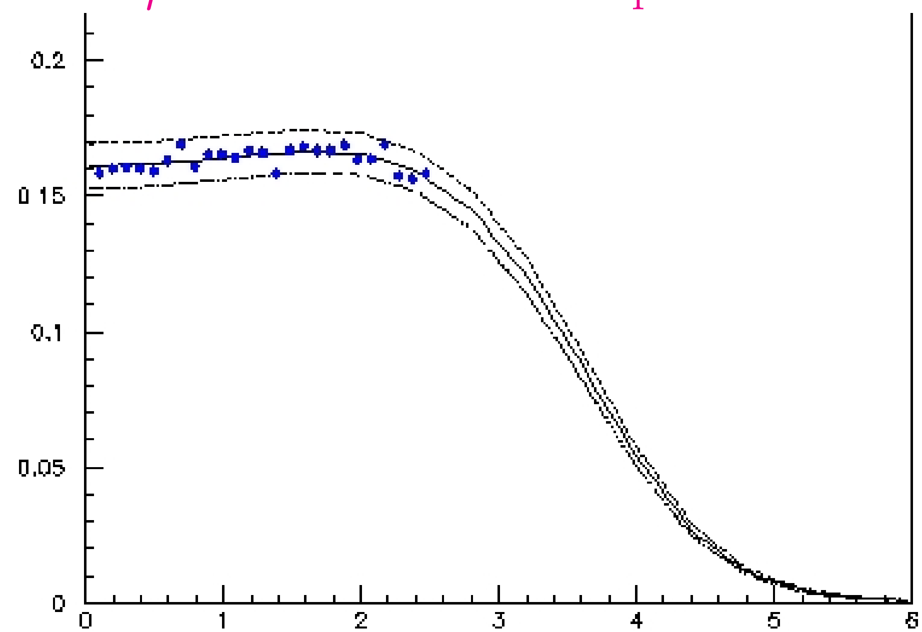
$\Rightarrow$ e^+e^- observables are usually shown in $\cos\theta$



Events at hadron colliders strongly forward peaked

$\Rightarrow \eta \sim$ flat between $\pm\eta_{\max}$

η of electrons from W production



Luminosity at the LHC

Luminosity defined as

$$\frac{dN}{dt} = \mathcal{L}\sigma$$

In terms of bunch sizes and charges $\mathcal{L}$ can be calculated as

$$\mathcal{L} = f_c N_b \frac{N^+ N^-}{4\pi\sigma_x\sigma_y}$$

$$\sigma_x \approx \sigma_y \approx 15\mu\mathrm{m} \quad N^+ \approx N^- \approx 10^{11} \quad f_c \approx 12000/s \quad N_b \approx 2800$$

- 2010: $\mathcal{L} < 10^{32}\mathrm{cm}^{-2}\mathrm{s}^{-1}$
- 2011: $\mathcal{L} \sim 10^{32}\mathrm{cm}^{-2}\mathrm{s}^{-1}$
- $\geq$2013: $\mathcal{L} < 10^{33} \rightarrow 10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$

Luminosity measurement

Relative measurement:

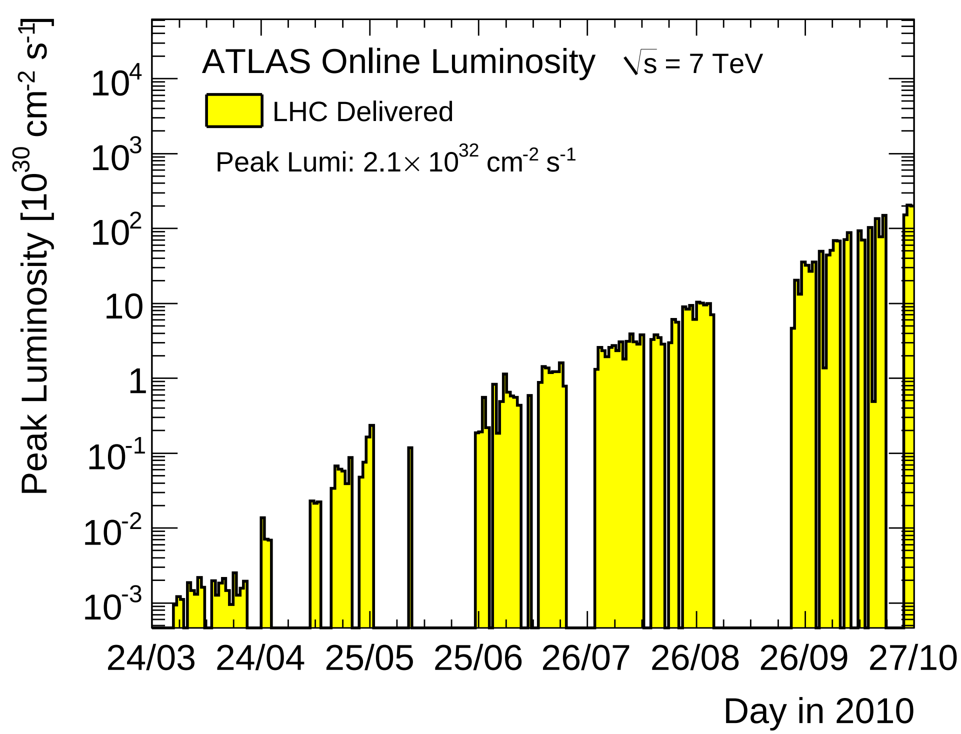
- Measure rate of minimum bias events with some subdetectors

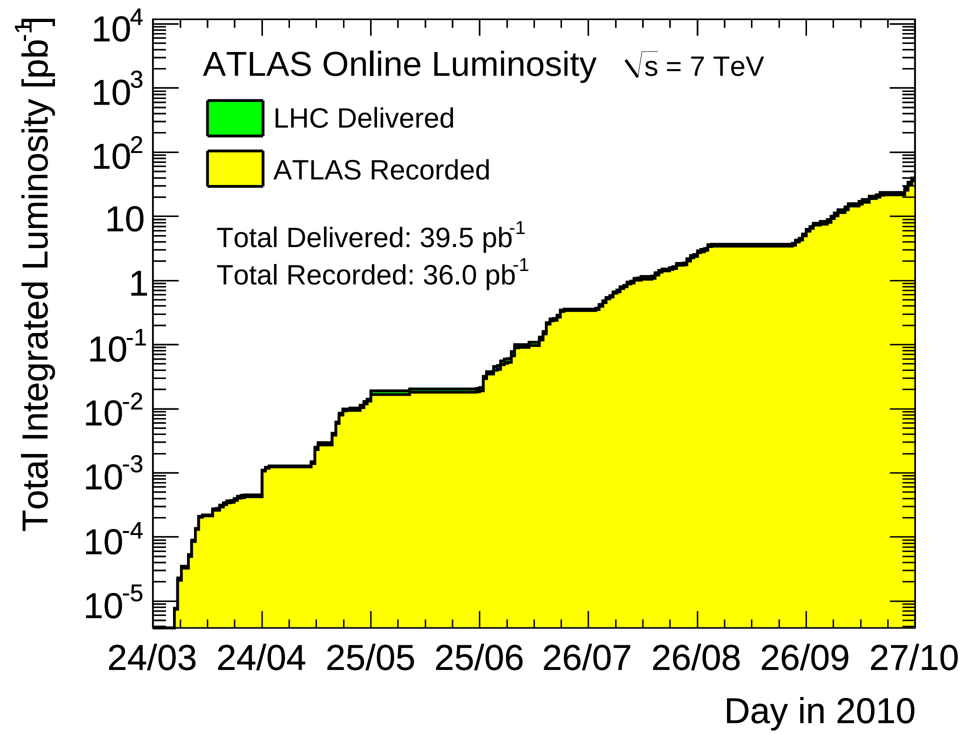
Absolute measurement:

- Always calibrate relative measurement in spacial run, then use this.
- In the beginning use Van der Meer scans
  - Scan beams wrt. each other to get beam size
  - Beam charge from current
  - At present 10% precision limited by charge measurement
- Next step Coulomb scattering
  - Cross section known from theory
  - Measure rate at very small scattering angles ($\sim$ 1 cm at 240 m) in runs with special optics
  - $\sim$ 3% precision possible

Performance of the LHC in 2010

- Machine started with few bunches and low current ($\mathcal{L} \sim 10^{27}\mathrm{cm}^{-2}\mathrm{s}^{-1}$) in March to protect machine $\rightarrow$ minimum bias physics
- Higher bunch charge and more single bunches in summer ($\mathcal{L} \sim 10^{30}\mathrm{cm}^{-2}\mathrm{s}^{-1}$) $\rightarrow$ physics with low energy jets without pileup
- Now at trains with $\sim$ 300 bunches and full current ($\mathcal{L} > 10^{32}\mathrm{cm}^{-2}\mathrm{s}^{-1}$) $\rightarrow \sim 2$ pileup events per bunch-crossing





Signatures for new physics at the LHC

- High p_t objects (jets)
  - LEP and Tevatron have excluded new physics up to $\gtrsim 100\,\mathrm{GeV}$
  - ➠ expect energy of decay products from new particles above half this energy
- Leptons
  - leptons have no strong interactions ➠ not produced in QCD background events
  - weak interactions are democratic ➠ leptons are a good indicator of weakly decaying particles
- b-quarks
  - b-quarks are suppressed in QCD jets which are largely gluons
  - b-quarks are abundantly produced in weak decays at the Z scale
  - every top decay contains a b-quark

- Missing energy
  - QCD events result only in visible particles (hadrons)
  - neutrinos from weak decays give moderate missing energy ($\mathcal{O}(50\,\mathrm{GeV})$)
  - if the decays of new particles involve the dark matter particle a huge amount of energy can be missing
  - since a very large energy from the proton remnants disappears in the beampipe only the missing transverse momentum (missing E_t) can be used as an indicator

$$E_t(\mathrm{miss}) = \sqrt{(\Sigma_i E_i \sin\theta_i \cos\phi_i)^2 + (\Sigma_i E_i \sin\theta_i \sin\phi_i)^2}$$

Experiments at the LHC

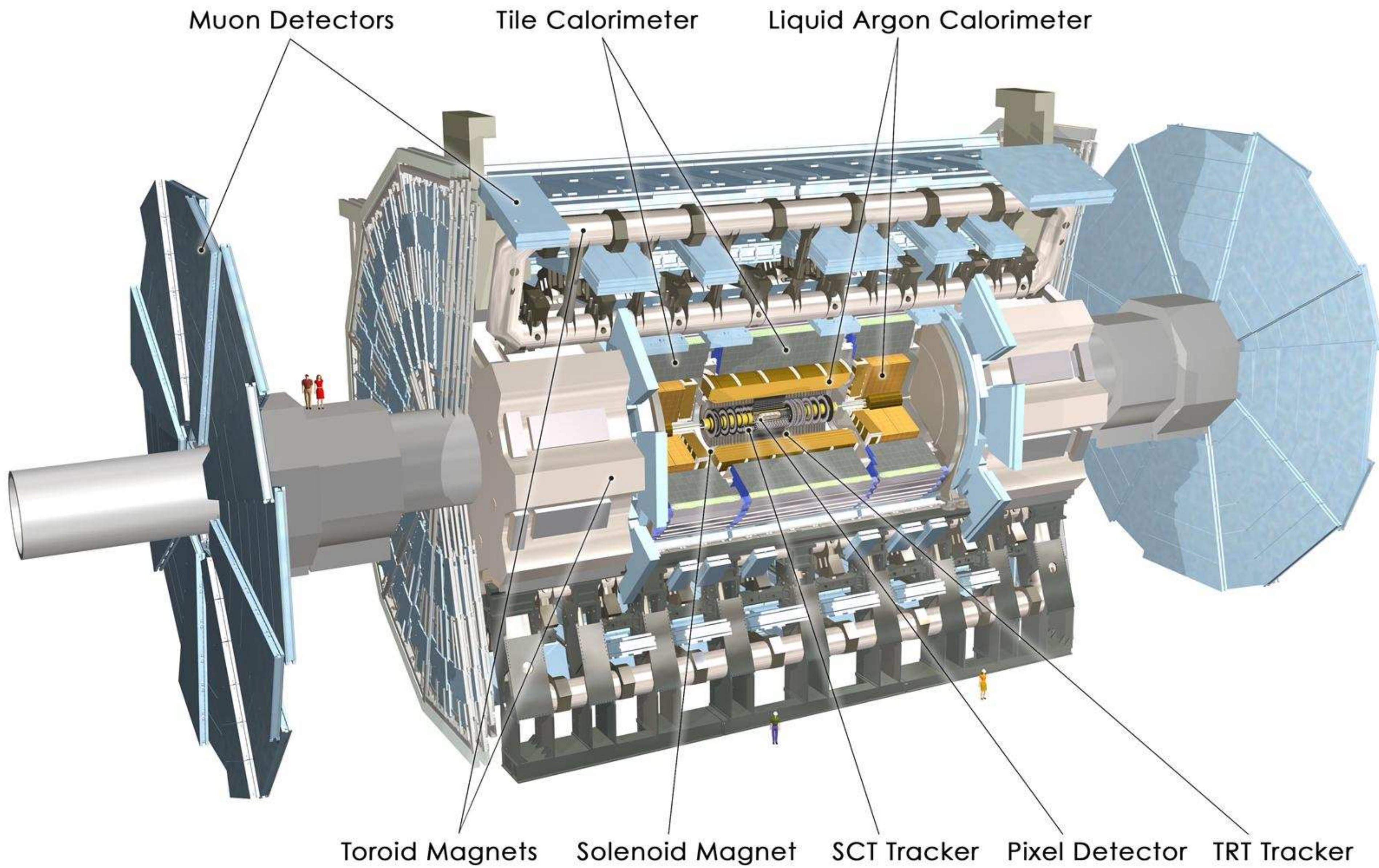
Four large experiments at LHC

- ATLAS: multi-purpose experiment, mainly for searches at the energy frontier
- CMS: same as ATLAS
- LHCb: B-physics (CP violation) experiment looking for forward production
- ALICE: Experiment to measure quark gluon plasma

Two small experiments

- Totem: Total Cross Section, Elastic Scattering and Diffraction Dissociation at the LHC, installed in the low angle region of CMS
- LHCf: Calorimetry in the very forward region of ATLAS to test hadronic interaction models for cosmic air-showers

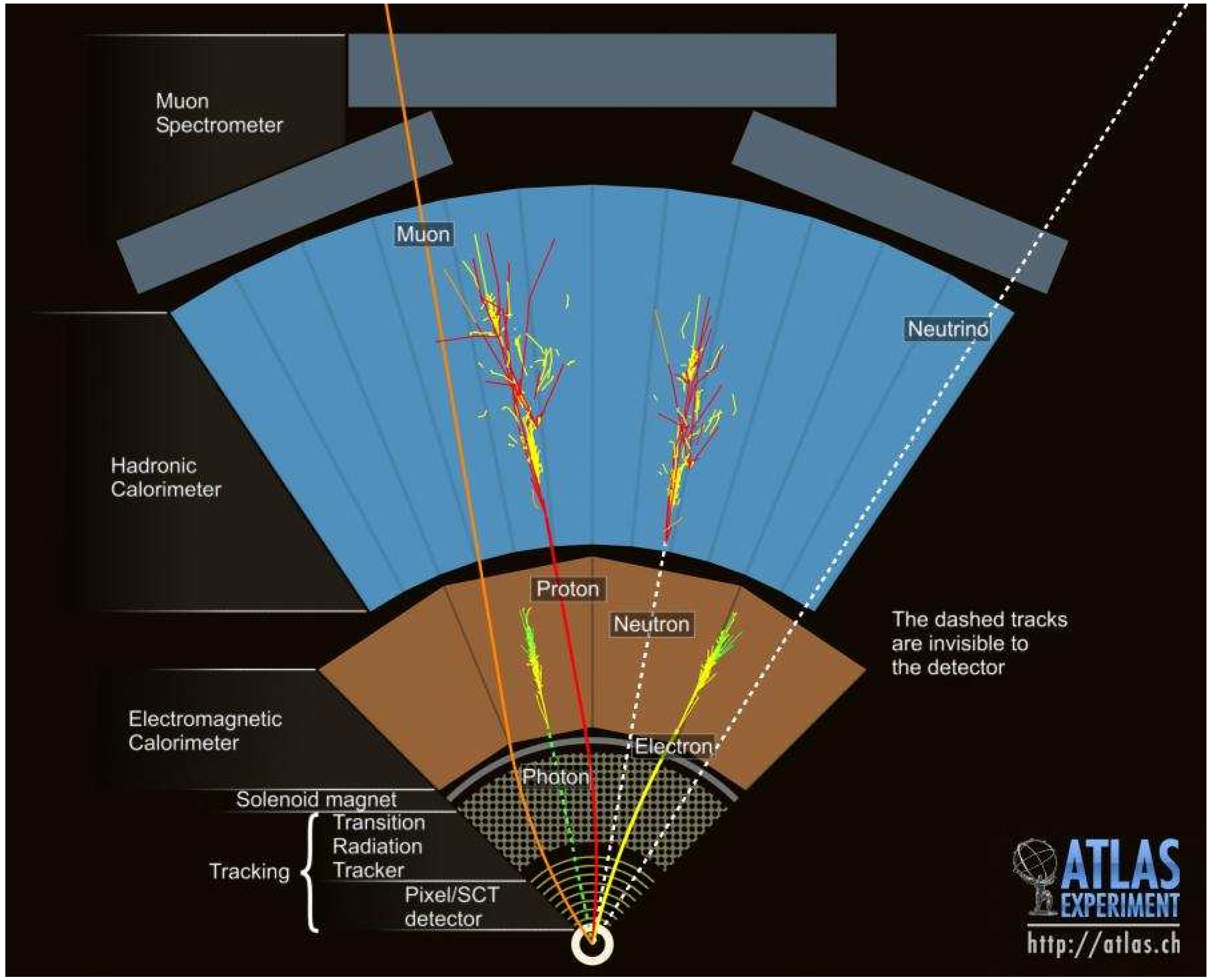
ATLAS



Muon Detectors
Tile Calorimeter
Liquid Argon Calorimeter
Toroid Magnets
Solenoid Magnet
SCT Tracker
Pixel Detector
TRT Tracker

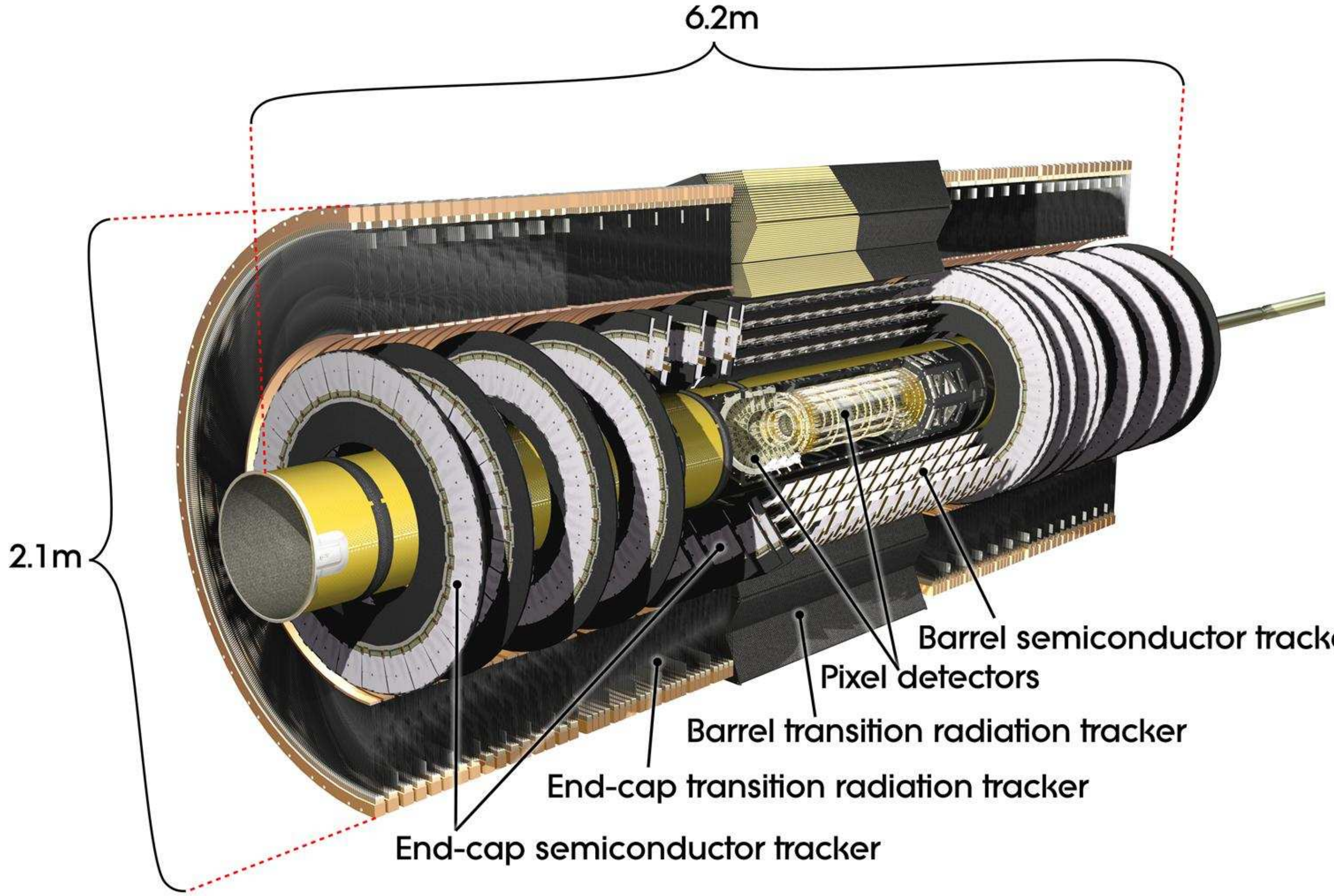
Standard collider detector with barrel and two endcaps:

- Inner tracker for charged particle momentum measurement
- Surrounded by superconducting coil with B=2T
- Liquid Argon electromagnetic calorimeter
- Scintillating tile hadronic calorimeter
- Toroid system with precision chambers for muon momentum measurement



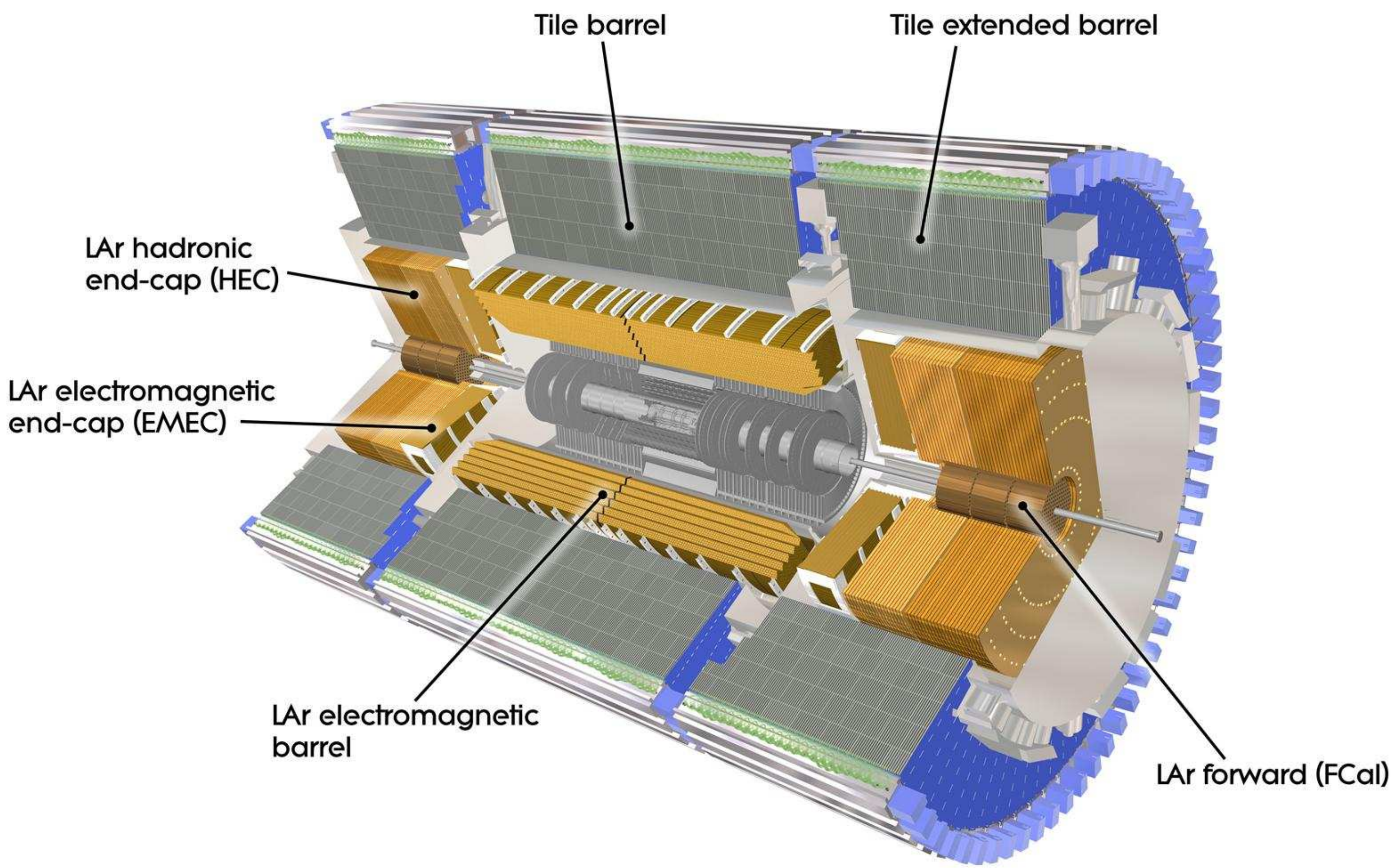
The ATLAS Tracker

- Pixel detectors close to beam pipe for b-tagging
- Silicon strips for precision tracking
- Transition radiation tracker for electron id and to improve momentum resolution



The ATLAS calorimeters

- Lead/liquid Argon for electromagnetic
- Fe/ scintillating tiles for hadronic
- Relatively good spacial resolution allows reweighting procedures

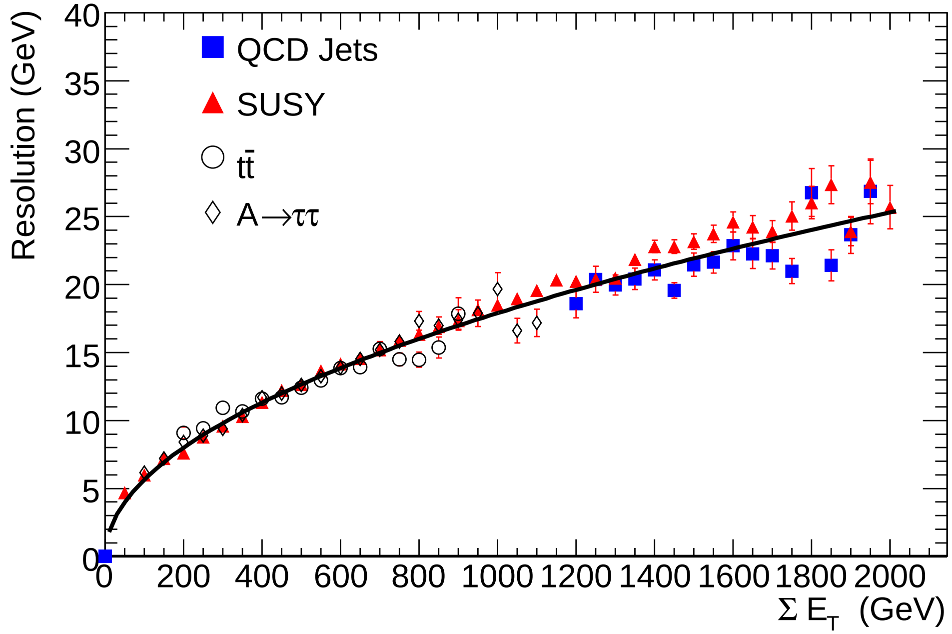


Some numbers on ATLAS

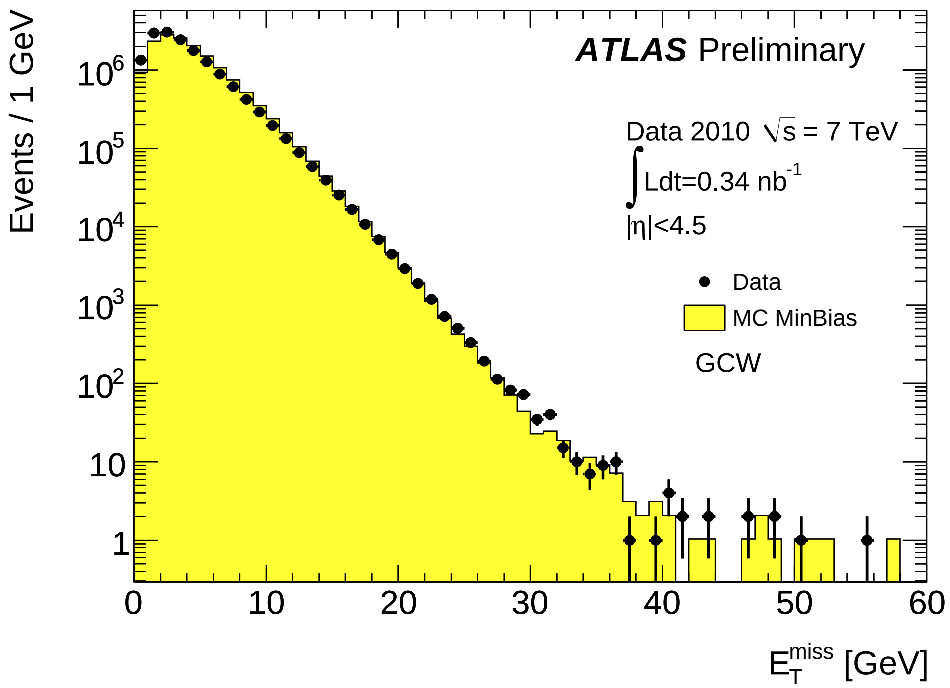
- Size: 25m $\times$ 25m $\times$ 46m
- Weight: 3000 t
- $>$ 100 million readout channels
- Angular coverage:
  - tracking $|\eta| < 2.5$ ($\theta > 9^\circ$)
  - calorimeters $|\eta| < 5$ ($\theta > 1^\circ$)

Some resolution plots

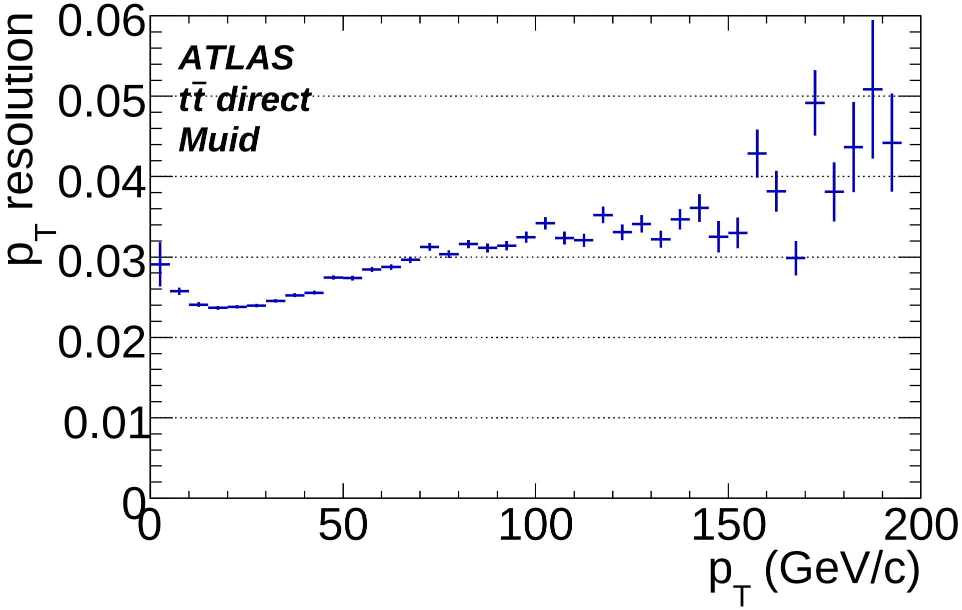
Resolution of total transverse energy



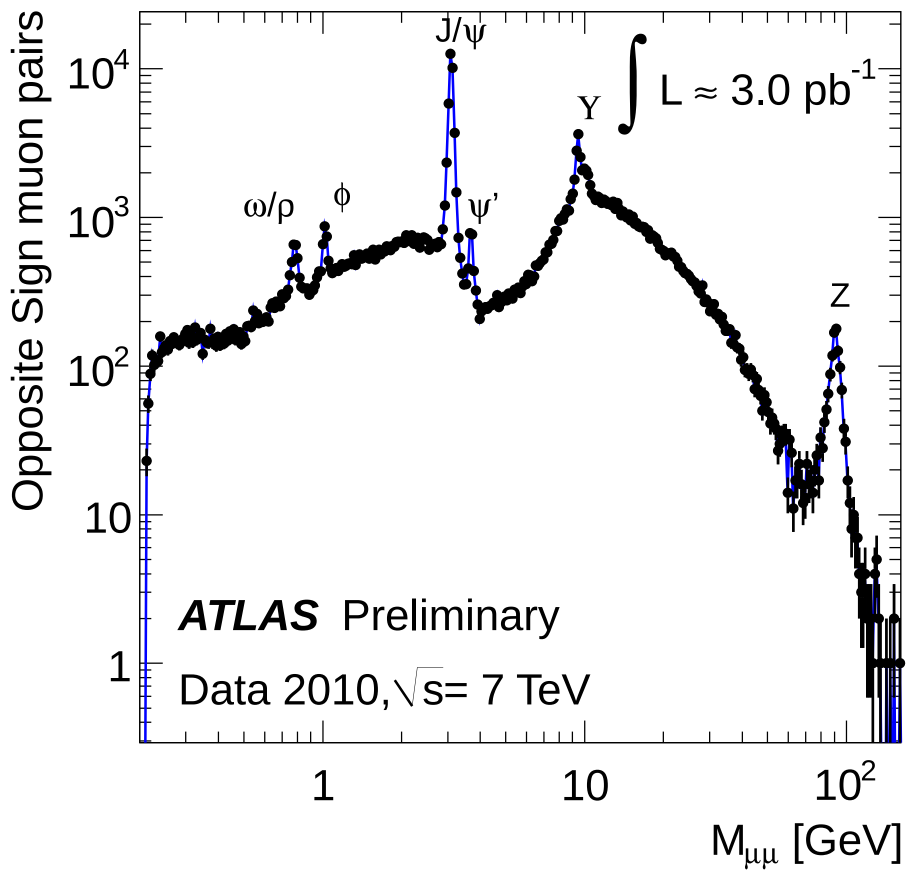
Data/MC comparison of missing energy resolution



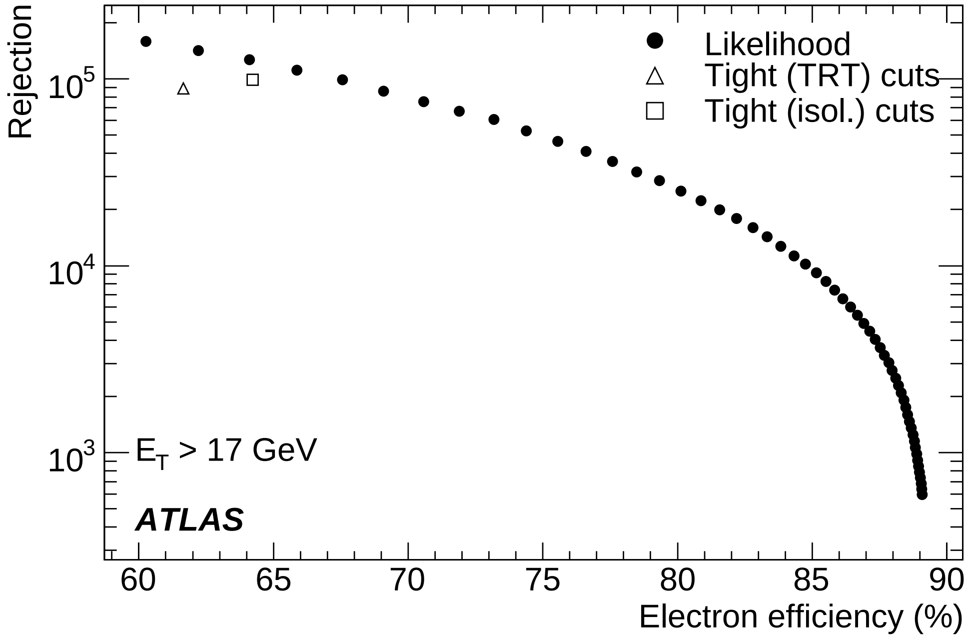
Momentum resolution for muons



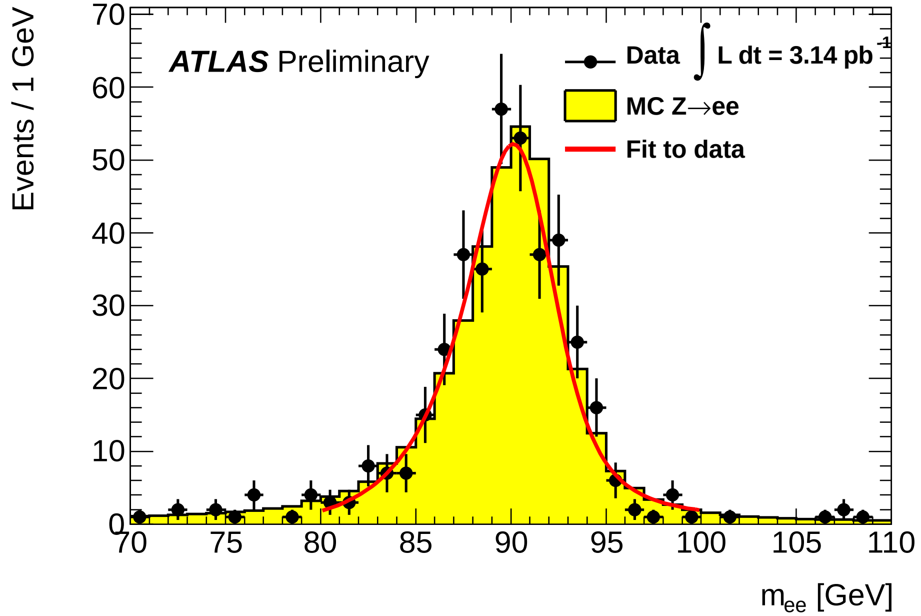
Dimuon mass spectrum



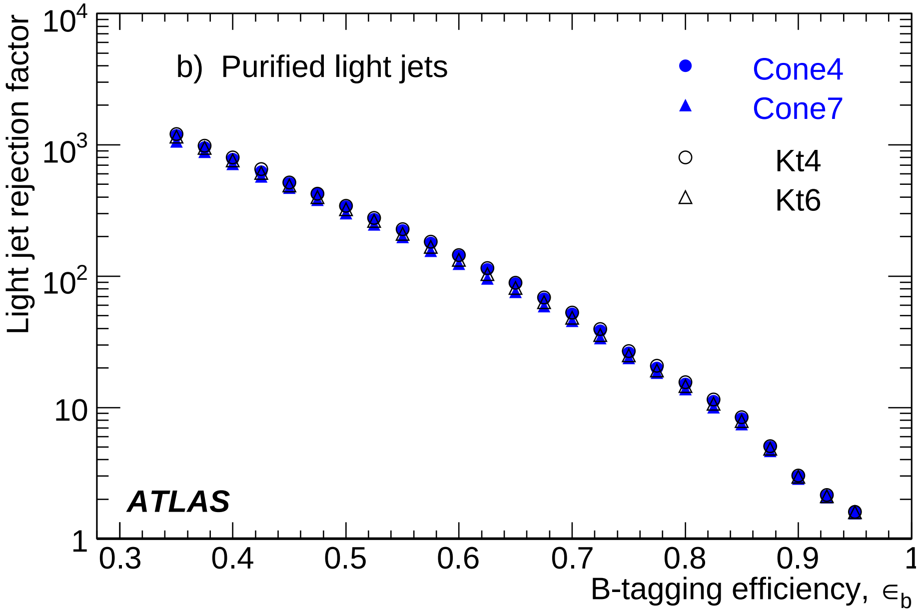
e id-efficiency vs bg. rejection



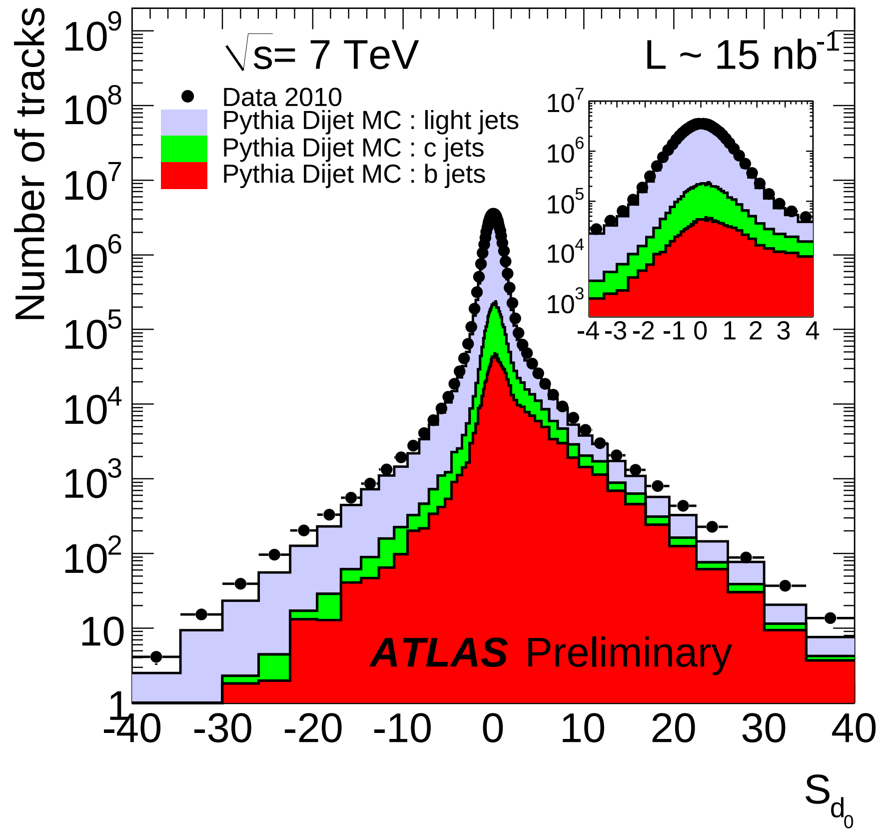
$Z \to e^+e^-$ mass spectrum



B-tagging efficiency vs bg. rejection



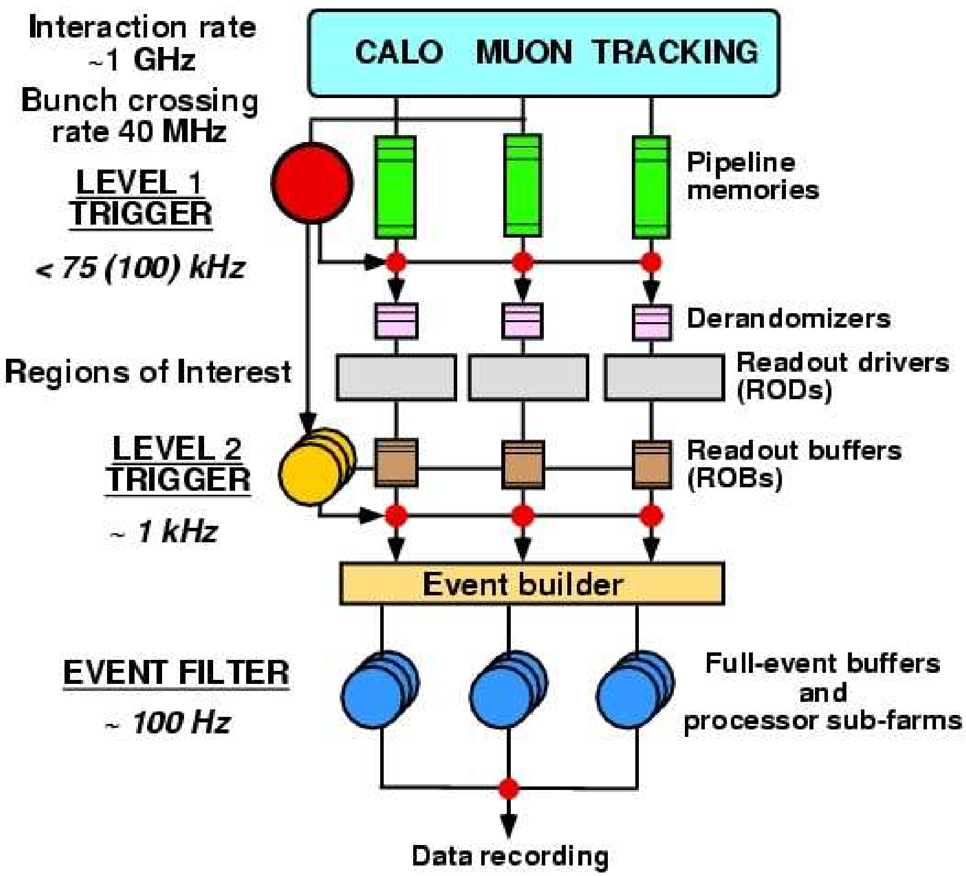
Impact parameter distribution in data and MC



The ATLAS trigger

Challenge:

- Bunch crossing rate 40 MHz
- Interaction rate 1 Hz
- Output rate ∼ 100 Hz



3-level trigger

- 1st level: special hardware
  - reduces rate to 100 kHz
  - defines regions of interest (ROI)
- 2nd level: standard PCs
  - gets data inside ROIs
  - processing time 10 ms
  - reduces rate to 1 kHz
- Event filter: standard PCs
  - access to full data
  - processing time 1 s
  - reduces rate to 100 Hz

Trigger chains

Atlas triggers on muons and calorimeters in L1 + tracker in HLT

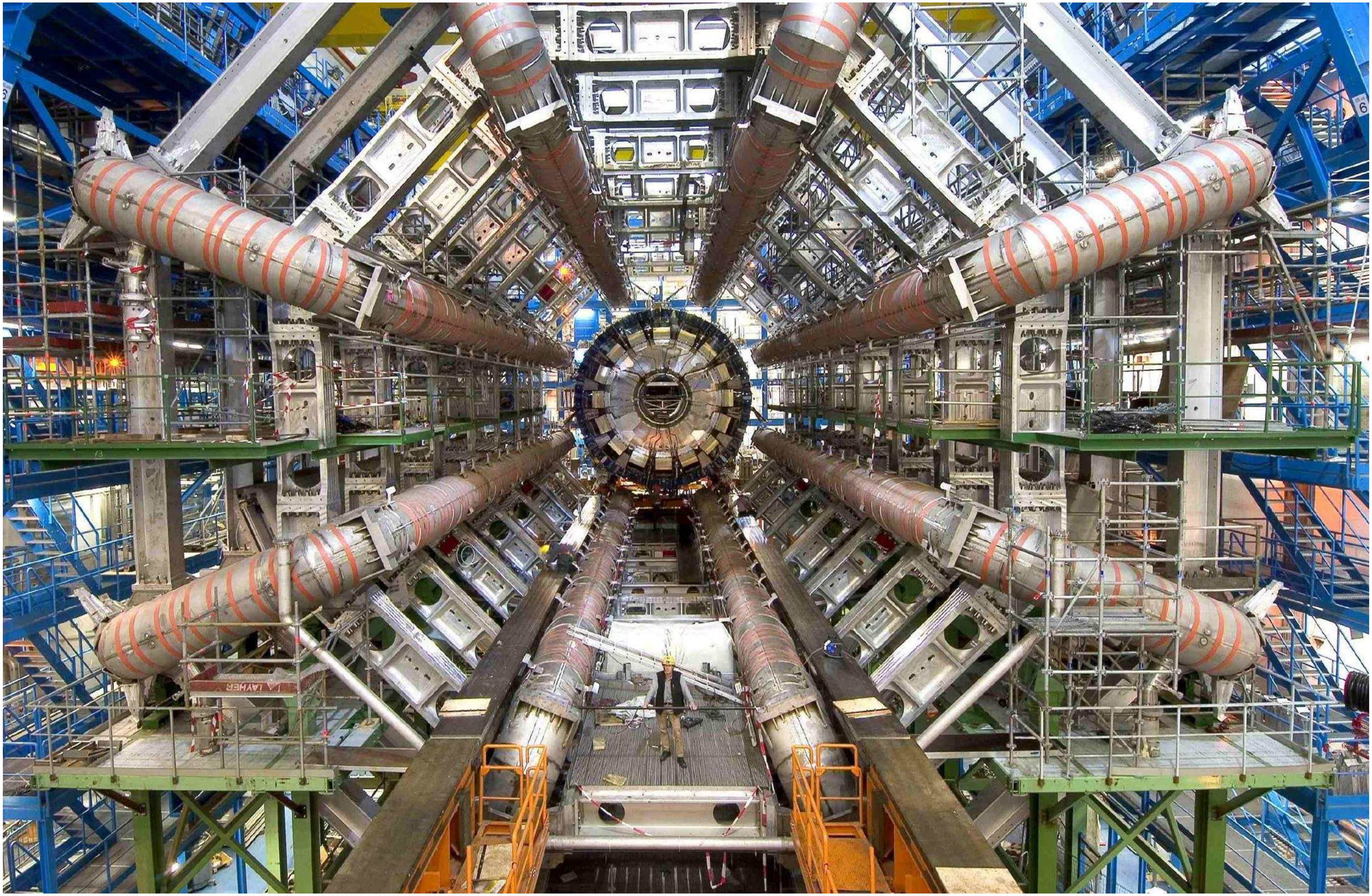
Standard Model triggers can have prescales to get rates down

Trigger slices (example for unprescaled triggers with $\mathcal{L} = 10^{33}\mathrm{cm}^{-2}\mathrm{s}^{-1}$)

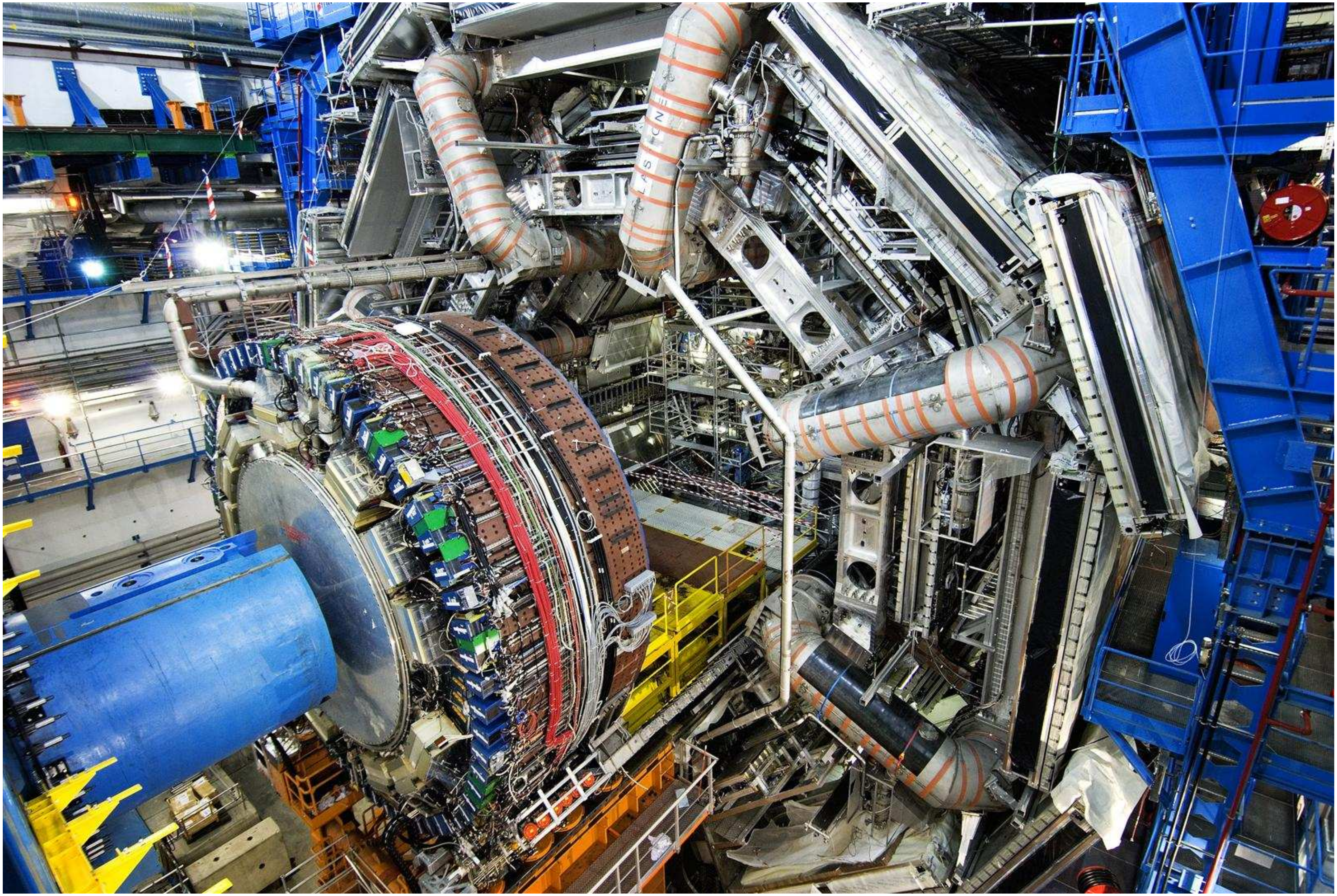
- muons
  - 2 muons with $p > 15\,\mathrm{GeV}$
  - 1 muon with $p > 20\,\mathrm{GeV}$
- egamma
  - 1 isolated e with $p > 25\,\mathrm{GeV}$
  - 2 isolated e with $p > 15\,\mathrm{GeV}$
  - 1 e with $p > 105\,\mathrm{GeV}$
  - 1 γ with $p > 150\,\mathrm{GeV}$

- jets
  - 1 jet with $E > 300\,\mathrm{GeV}$
  - 3 jets with $E > 100\,\mathrm{GeV}$
  - 4 jets with $E > 50\,\mathrm{GeV}$
  - total jet energy $> 500\,\mathrm{GeV}$
  - total energy $> 900\,\mathrm{GeV}$
- taus
  - 1 tau with $p > 150\,\mathrm{GeV}$
  - 2 isolated taus with $p > 45\,\mathrm{GeV}$
- missing E_t
  - missing energy $> 90\,\mathrm{GeV}$

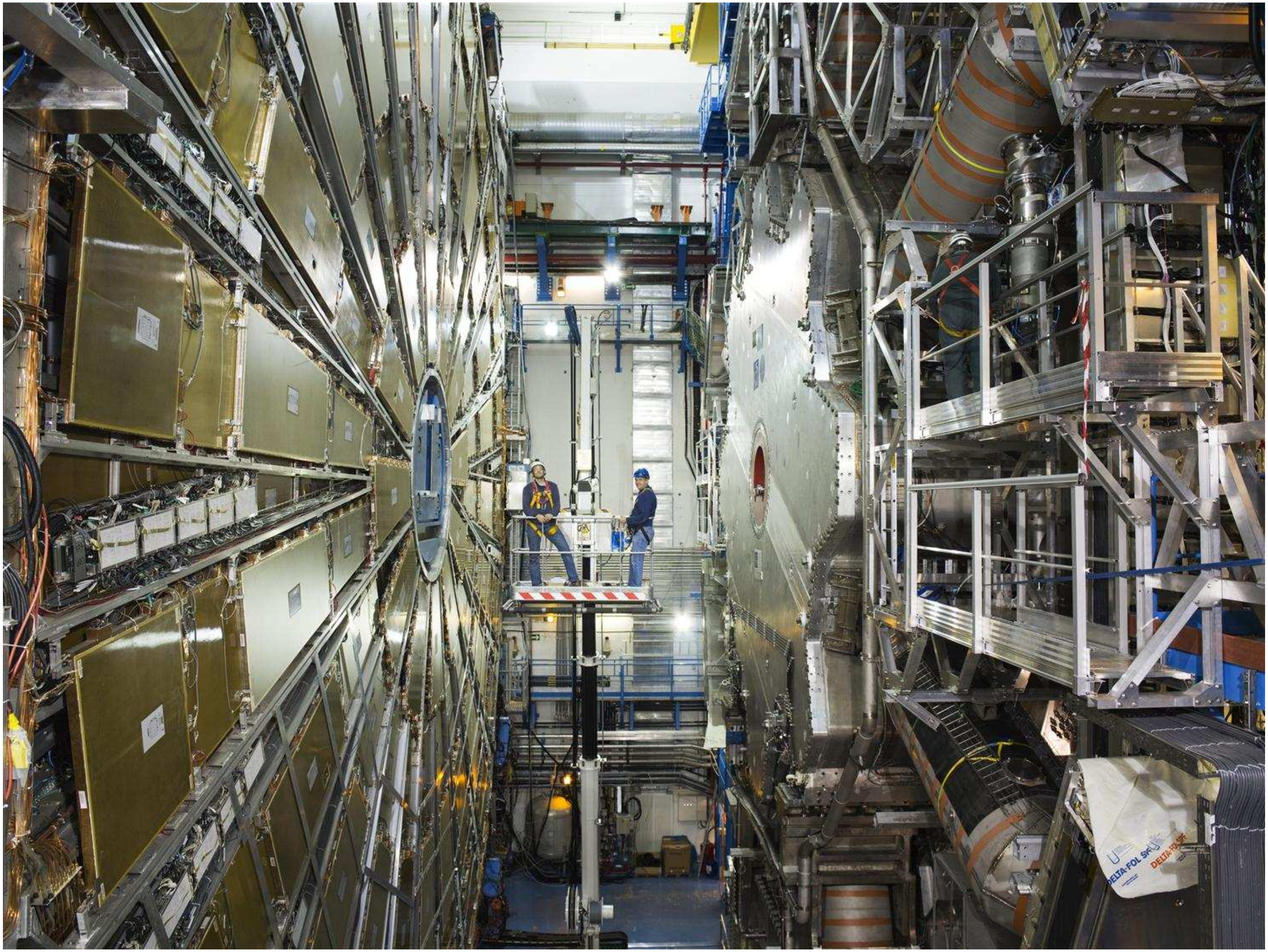
View inside the toroid



Installation of the forward calorimeters



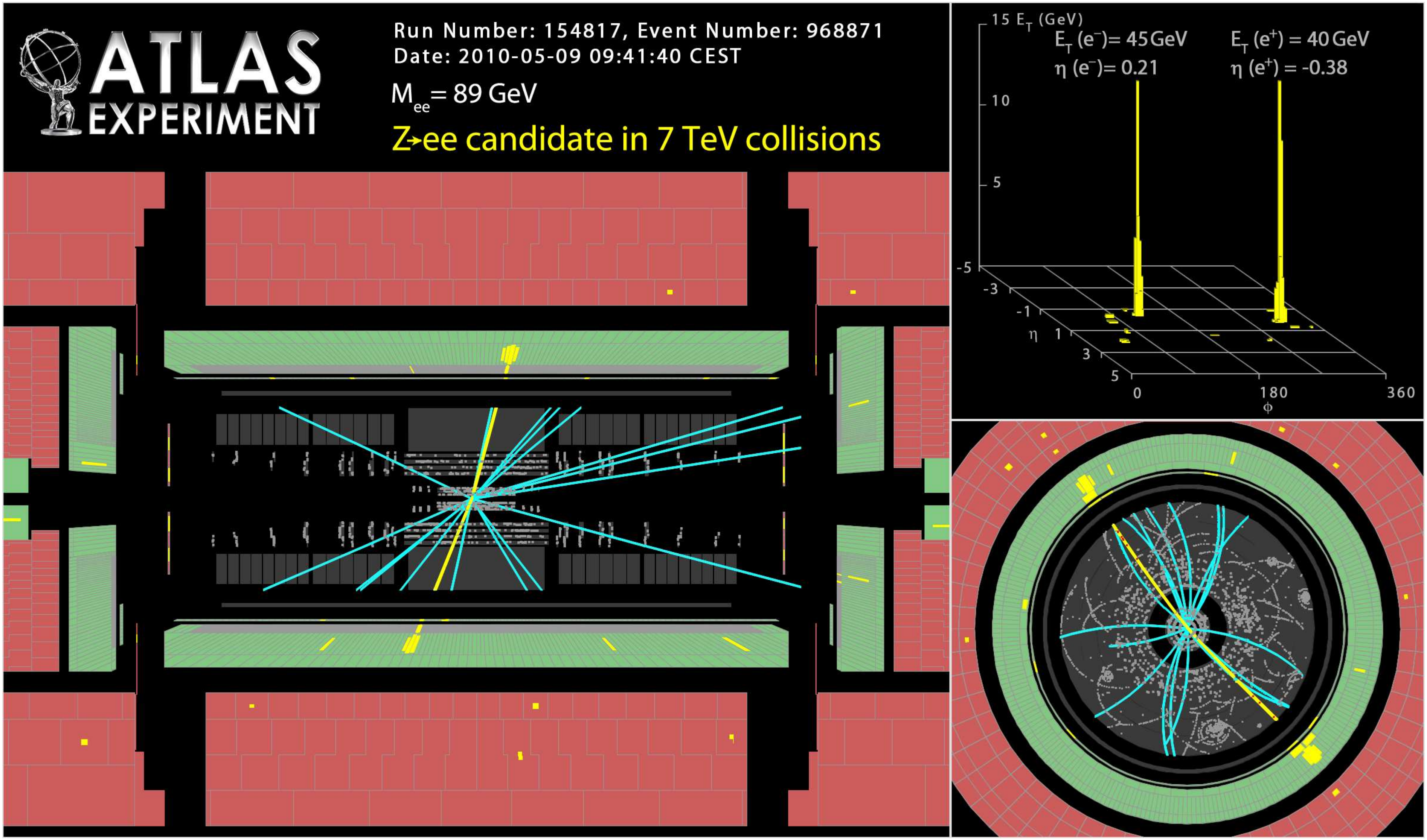
Endcap muon chambers and toroid



The ATLAS collaboration

- $\sim$ 2200 physicists
- from 170 institutes (Humboldt university, DESY HH and Zeuthen...)
- from 37 countries

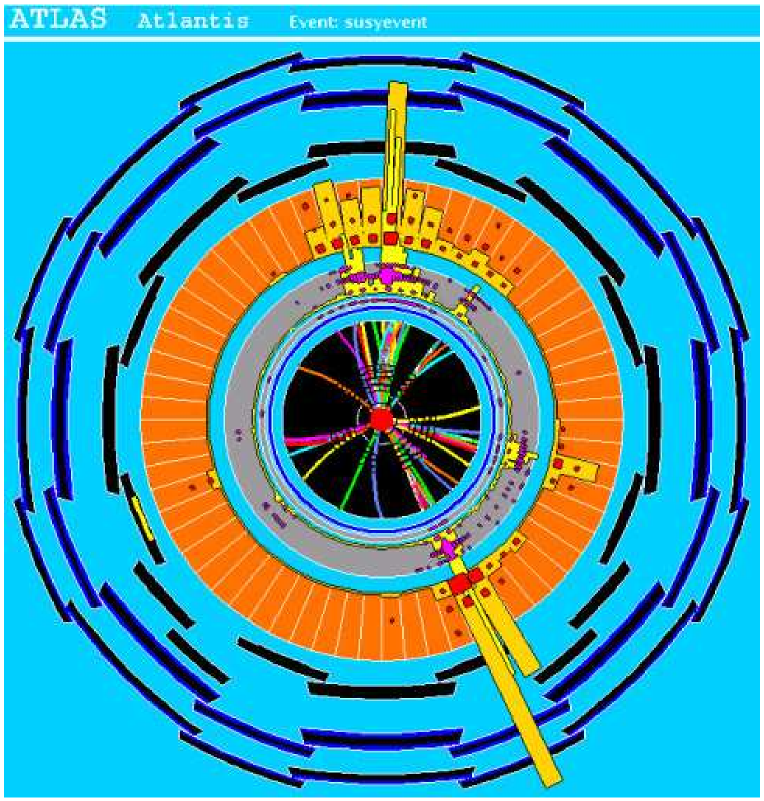
$Z \to e^+e^-$ event (data)

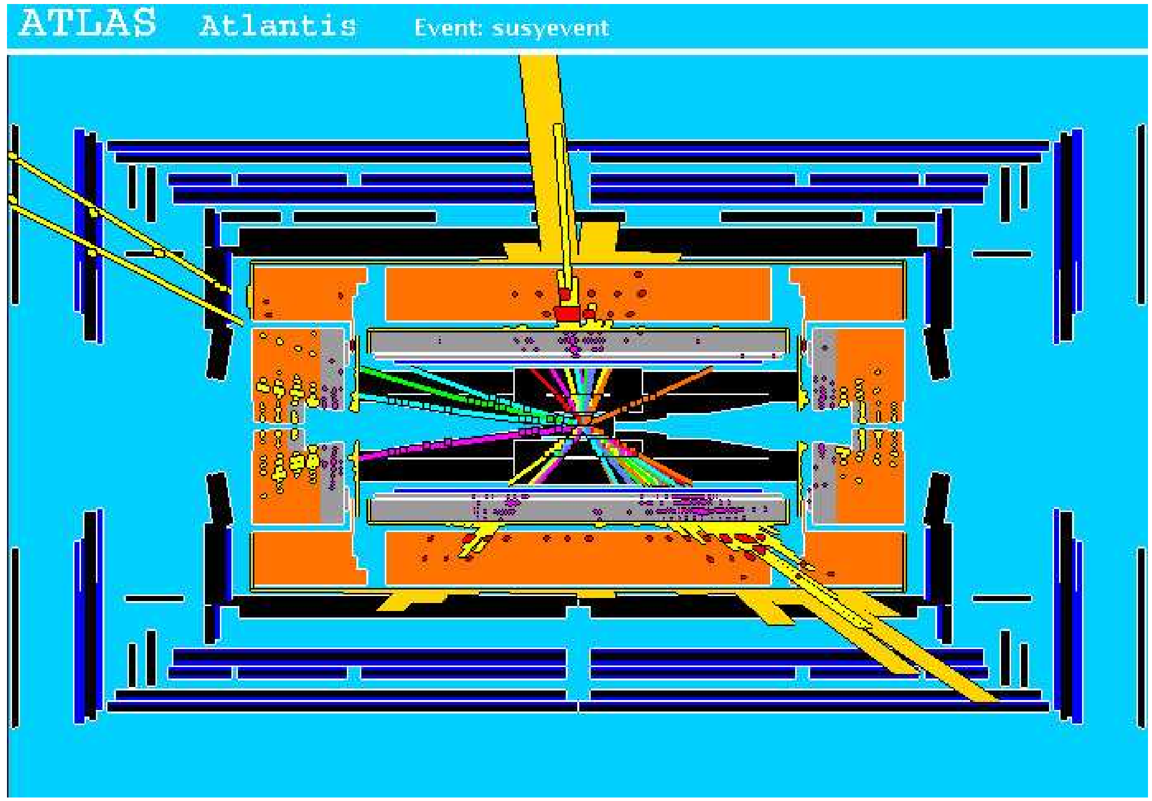


A SUSY event in ATLAS (MC)

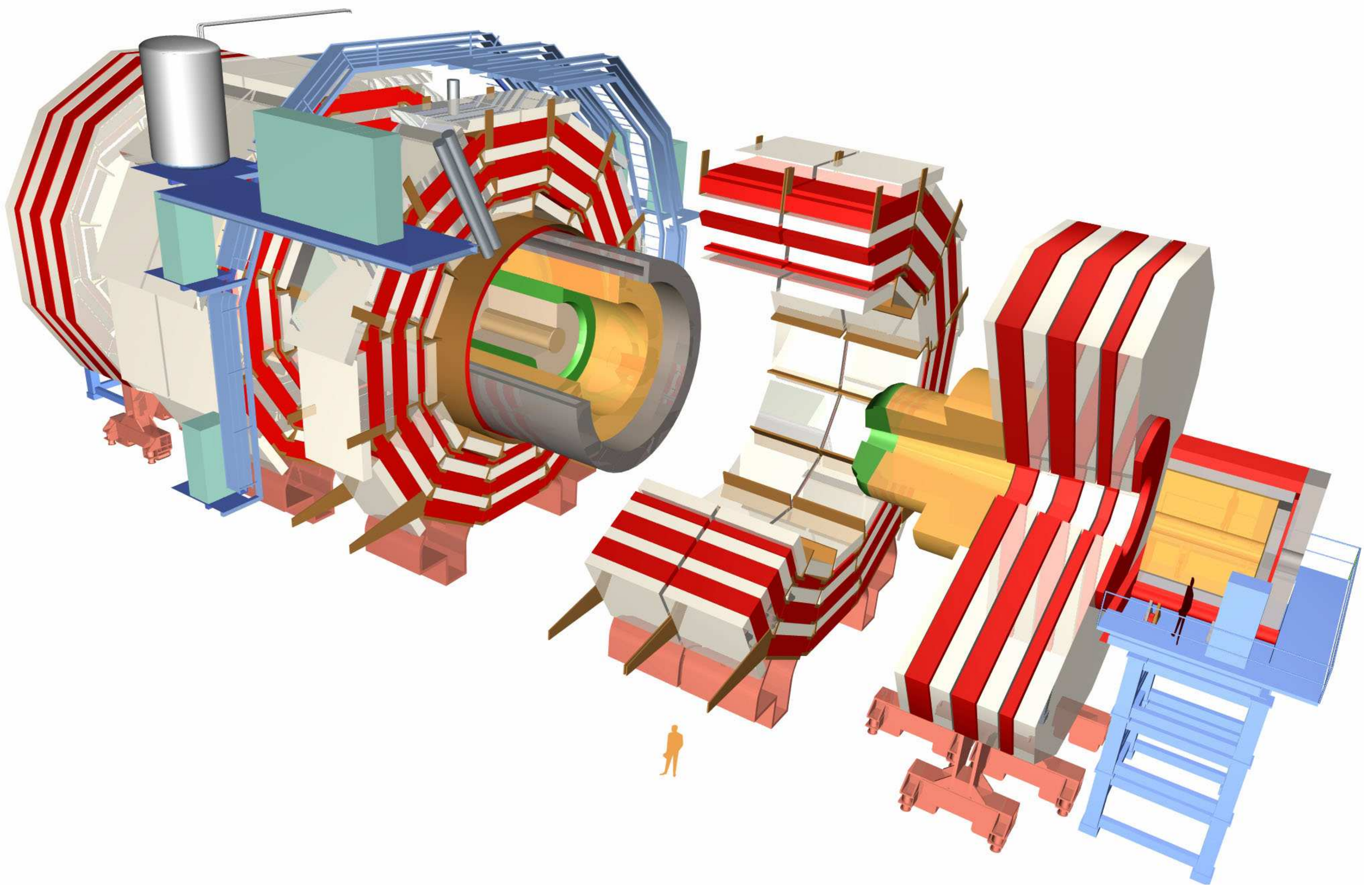
Example for a SUSY event

- six jets
- two muons
- 280 GeV missing transverse energy





CMS



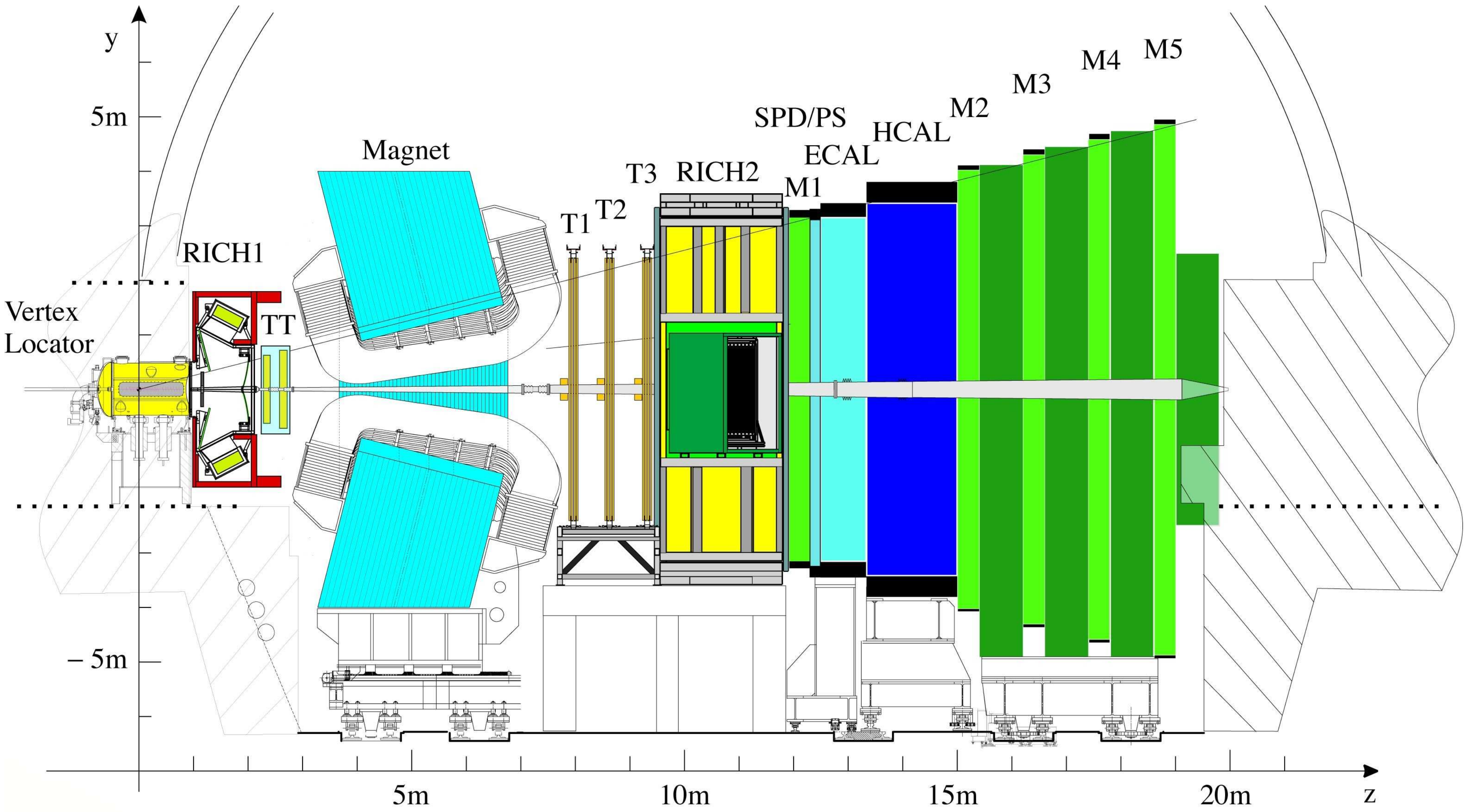
The concept is similar to ATLAS, however different in detail:

- All silicon tracker
- Larger coil with larger B-filed (4T)

➠ better momentum resolution in the inner tracker

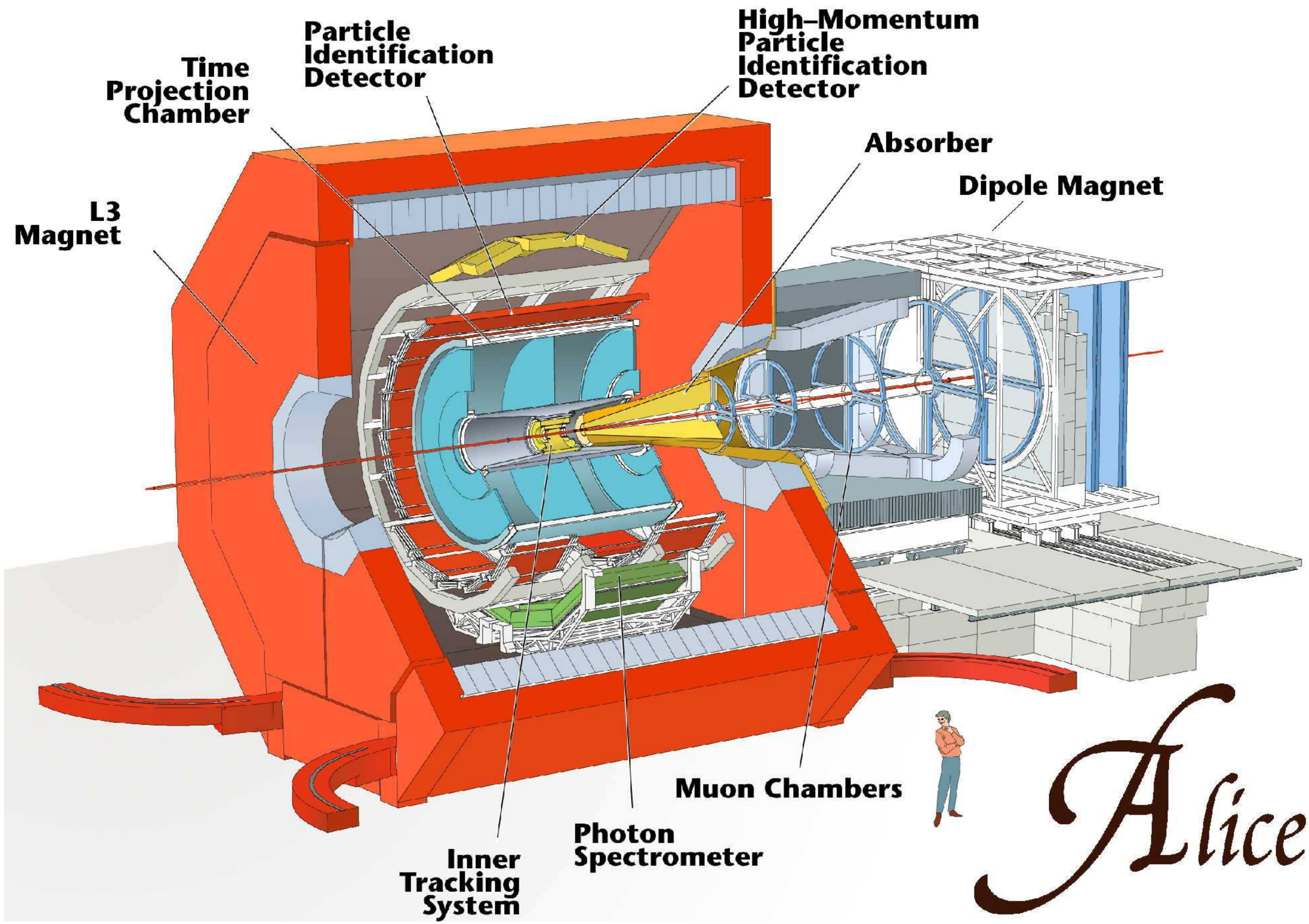
- Therefore no extra magnet for muons
- Crystal calorimeter with better energy and worse spacial resolution
- Hadron calorimeter with worse granularity doesn't allow reweighting

LHCb


y
5m
– 5m
Magnet
RICH1
Vertex
Locator
TT
T1
T2
T3
RICH2
M1
SPD/PS
ECAL
HCAL
M2
M3
M4
M5
5m
10m
15m
20m
z

- Huge b-cross section, mainly in forward region
- Can be used to study CKM matrix and CP violation
- Advantages compared to e^+e^- B-factories
  - access to heavier B-states like B_s
  - huge statistics gives access to rare decays like $B \to \mu^+\mu^-$
- Disadvantages compared to e^+e^- B-factories
  - large backgrounds form non-B events
  - hadronic B-decays cannot be triggered
- LHCb optimised for forward region coverage, particle id and lepton trigger

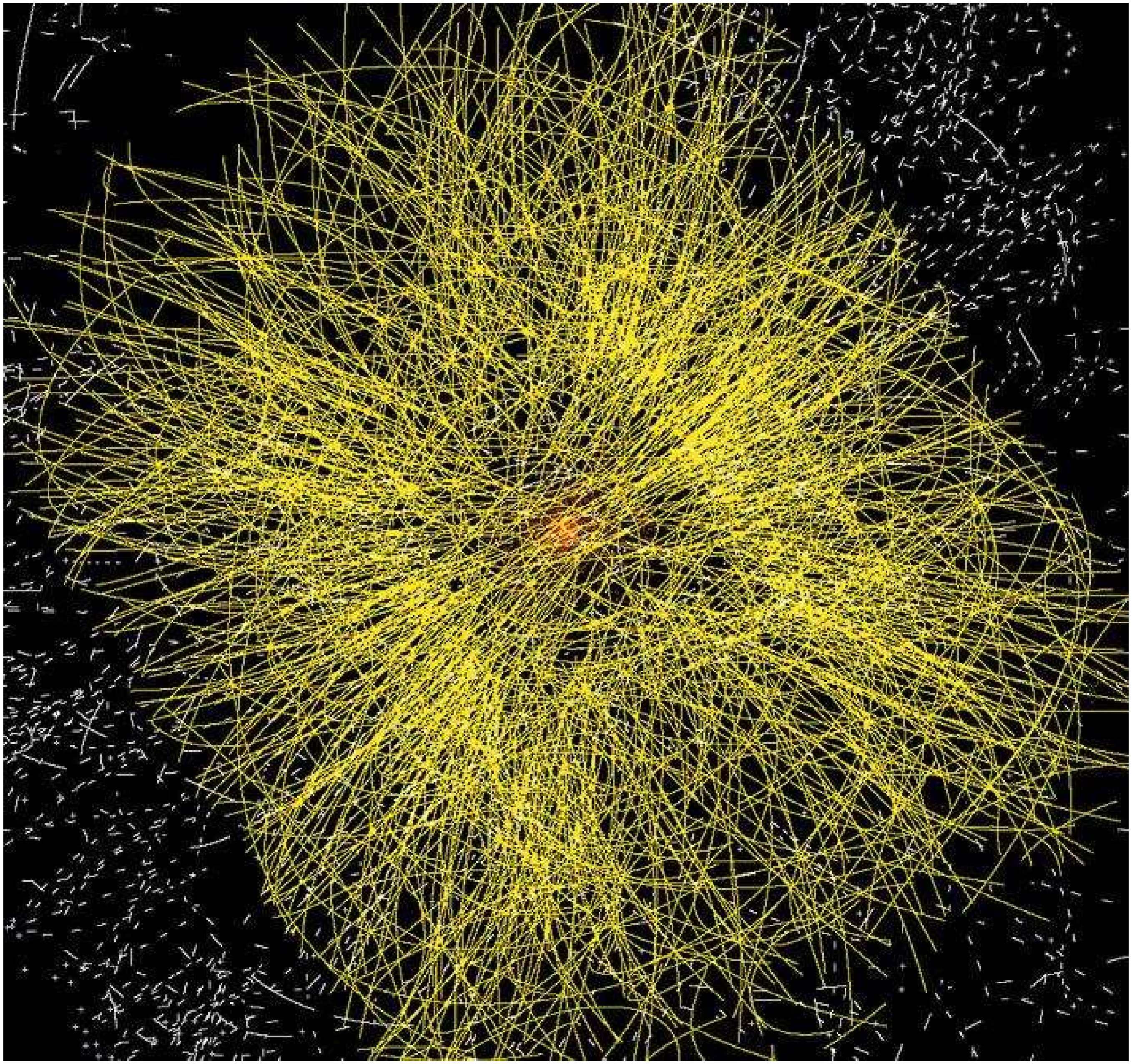
ALICE



Time Projection Chamber
Particle Identification Detector
High–Momentum Particle Identification Detector
Absorber
Dipole Magnet
L3 Magnet
Muon Chambers
Photon Spectrometer
Inner Tracking System
Alice

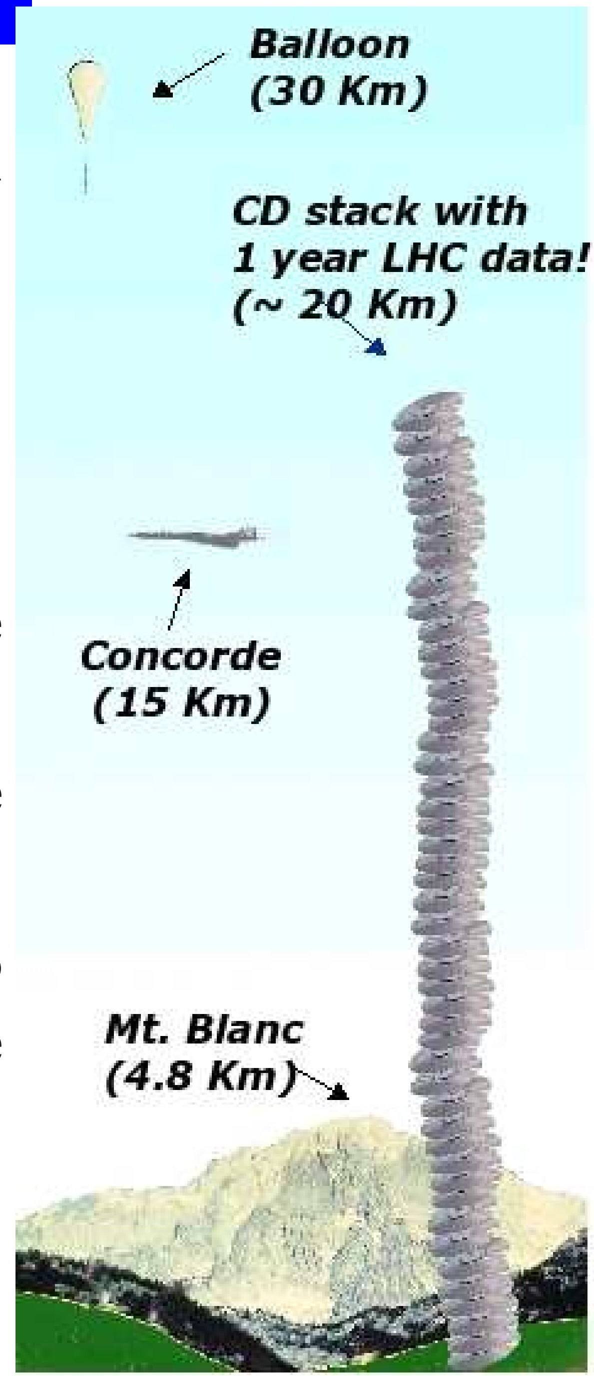
- The LHC can produce lead-lead collisions
- In the high energy density of the collision a quark-gluon plasma should form
- Its decay results in events with several thousand charged particles
- The analysis requires multiplicity measurement, lepton and photon ID and the measurement of the jet substructure
- ALICE contains a large TPC for charged particle identification plus some muon and photon detector and calorimetry
- Since mostly statistical properties are required no hermeticity is needed!

A typical event in ALICE



Computing at the LHC

- The experiments each write out events with 200 Hz resulting in 7 Pb/year each
- These data need to be reconstructed and analysed
- For this the Grid paradigm will be used:
  - Computing centres are distributed over the world
  - Submitted jobs are processed anywhere where the required resources are available
  - This resembles the power grid where I also don't know which power plant produced the electricity I use
- However for the large storage requirements a hierarchical structure is needed



Grid hierarchy

Tier0: at CERN, receives all raw data and does the first path reconstruction.

Tier1: 11 around the world (Karlsruhe for Germany), receive 20% of the raw data, mainly for reprocessing

Tier2: ~ 60 around the world, receive $\sim 1/3$ of the AODs each, responsible for data analysis and simulation

Tier3: local installations at the collaborating institutes