Experimental Particle Physics at the LHC

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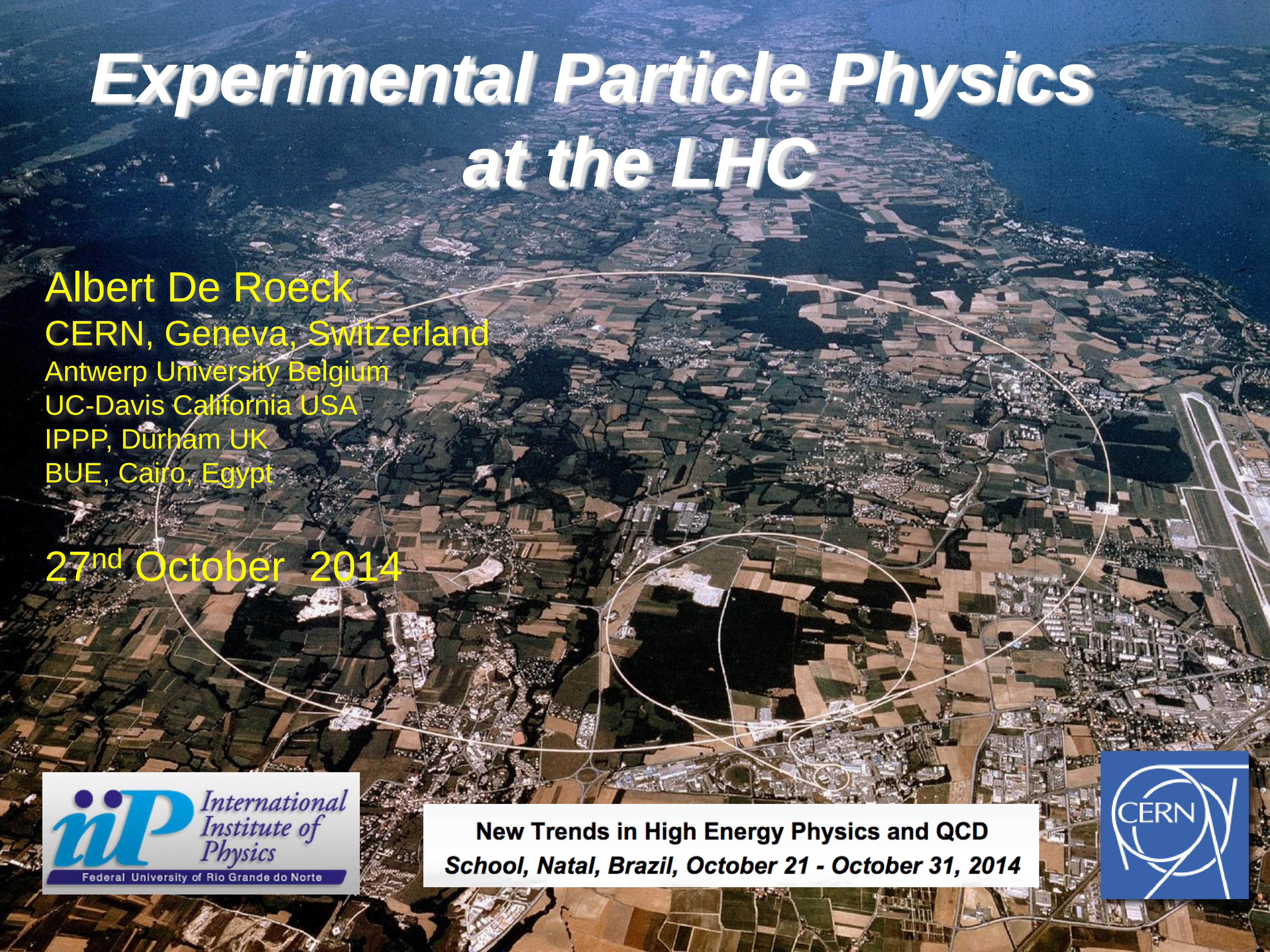
27nd October 2014



International Institute of Physics

Federal University of Rio Grande do Norte

New Trends in High Energy Physics and QCD

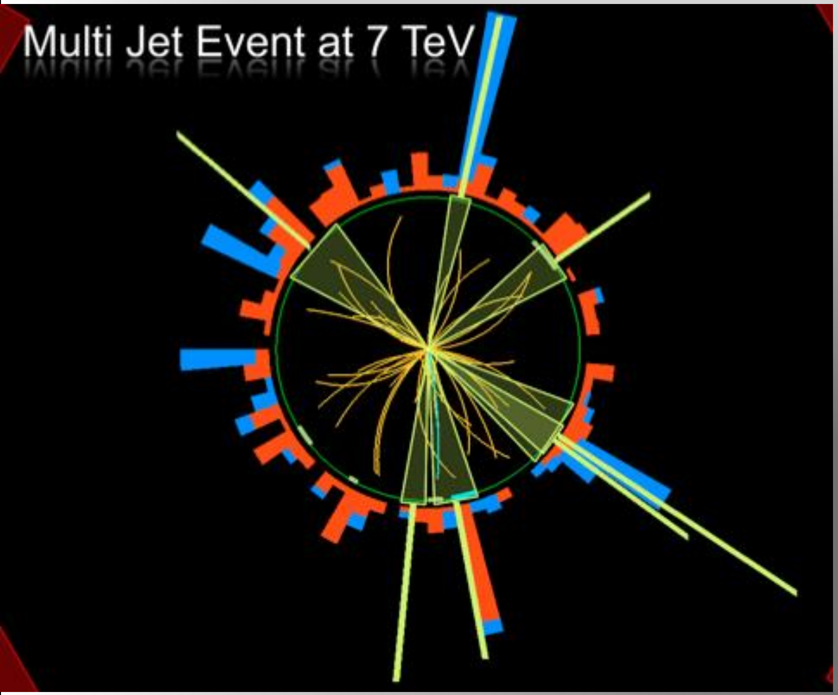
School, Natal, Brazil, October 21 - October 31, 2014

CERN

Lecture Plan

Overview of the 3 lectures in the next days

- Lecture 1: Introduction to Experimental Particle Physics at the LHC
- Lecture 2: Measurements and test of the Standard Model, (excluding the Higgs)
- Lecture 3: Searches beyond the Standard Model at the LHC



Outline Lecture I

- Introduction: Experimental Particle Physics
- The Large Hadron Colider
- Experiments at the LHC
- Experimental Challenges
- Experimental Objects
- Summary

Disclaimer:
ATLAS & CMS have very similar results
Typically one chosen for illustration

BUSSTEPP!

This is a School on Theoretical and Experiment in HEP

Theory is no doubt extremely important

- The Standard Model, our present Standard Theory is a triumph !!
- The BEH mechanism, through the discovery of the Higgs Boson underlines the power if theoretical insight!!
- If Supersymmetry will be discovered this will be an unmatched theoretical triumph!!

But none of the insight/believe in these theories would have happened without experimental data. No sign of Supersymmetry found yet!!

Moreover experiments have over the past given a lot of ‘surprises’ and new directions (particle generations, neutrino masses…)

Experimental Particle physics is (mostly) conducted at particle accelerators.
The most recent energy frontier instrument is the Large Hadron Collider LHC

Data and Theories

NOW!

Before LHC

With LHC

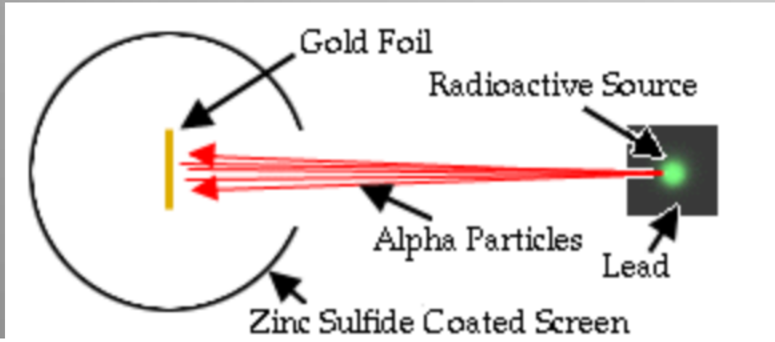
March 2010

"Data are coming! Data are coming!"

High Energy Physics Experiments

First High Energy Physics Experiments:

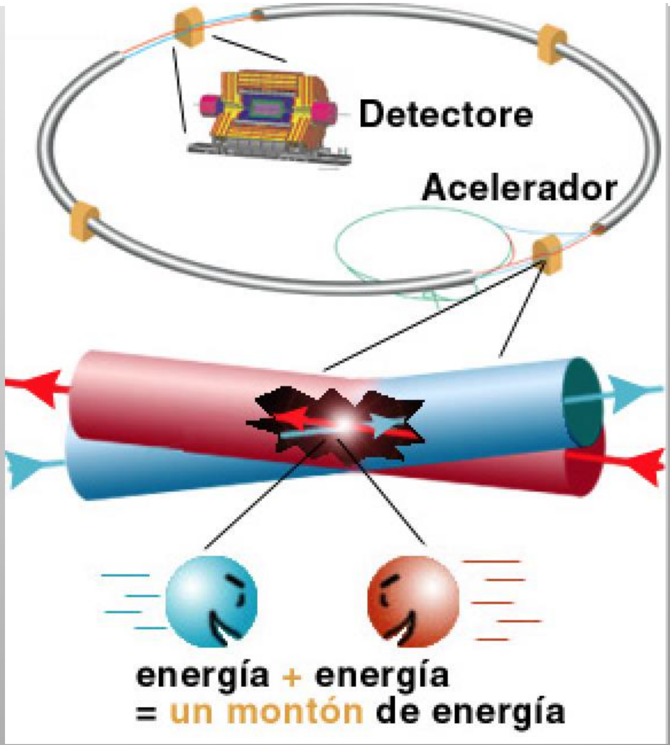
Beam on fixed target!



Rutherford experiment (1909)

High Energy Physics Experiments since mid 70's:

Colliding beams!



Centre of mass energy squared $s=E_1m_2$

Centre of mass energy squared $s=4E_1E_2$

…plus secondary beams such as neutrinos…

Recent High Energy Colliders

Highest energies can be reached with proton colliders

Machine	Year	Beams	Energy ($\sqrt{s}$)	Luminosity
SPPS (CERN)	1981	pp	630-900 GeV	$6.10^{30} cm^{-2}s^{-1}$
Tevatron (FNAL)	1987	pp	1800-2000 GeV	10^{31}-$10^{32} cm^{-2}s^{-1}$
SLC (SLAC)	1989	e^+e^-	90 GeV	$10^{30} cm^{-2}s^{-1}$
LEP (CERN)	1989	e^+e^-	90-200 GeV	10^{31}-$10^{32} cm^{-2}s^{-1}$
HERA (DESY)	1992	ep	300 GeV	10^{31}-$10^{32} cm^{-2}s^{-1}$
RHIC (BNL)	2000	pp / AA	200-500 GeV	$10^{32} cm^{-2}s^{-1}$
LHC (CERN)	2009	pp (AA)	7-14 TeV	10^{33}-$10^{34} cm^{-2}s^{-1}$

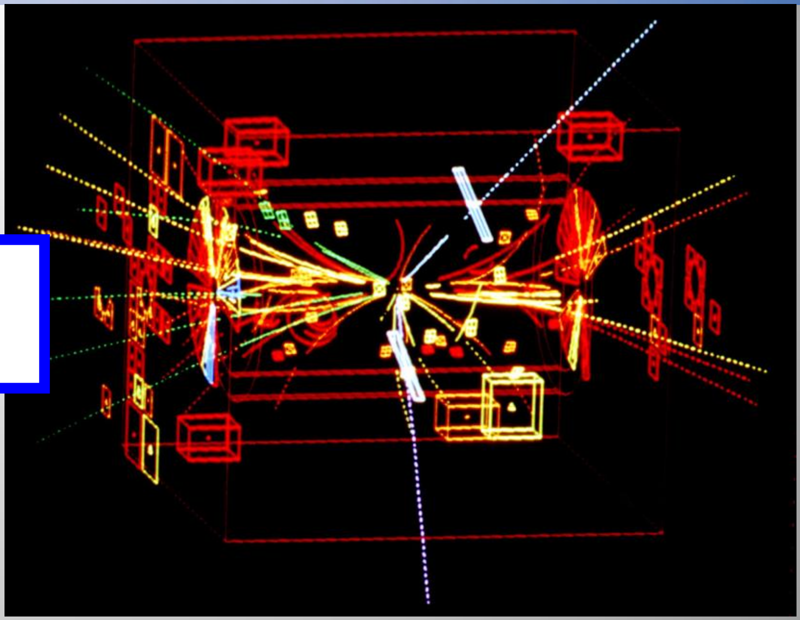
Luminosity = number of events/cross section/sec

- Limits on circular machines
  - Proton colliders: Dipole magnet strength $\rightarrow$superconducting magnets
  - Electron colliders: Synchrotron radiation/RF power

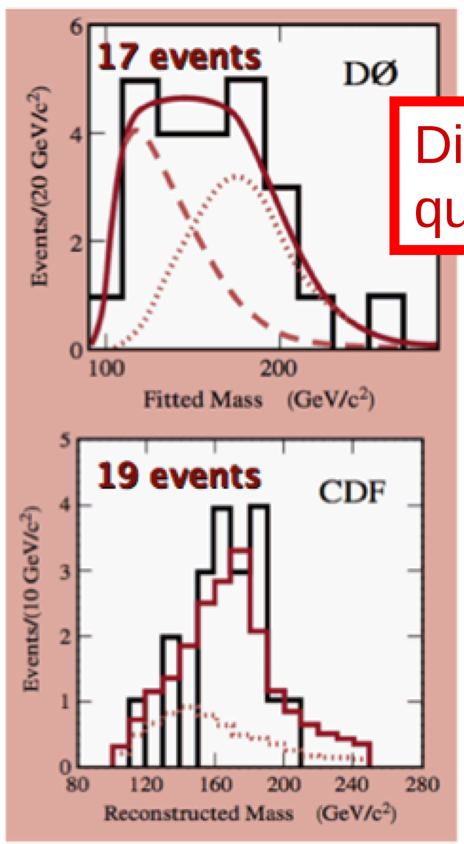
Some Discoveries/Measurements

Discovery of the Z and W bosons in UA1/UA2 (1983)

$pp \rightarrow Z + X$
$\rightarrow e^+e^- + X$



Discovery of the top quark in CDF/D0(1995)



1995, CDF and DØ experiments, Fermilab

Detailed Z-property measurements (1995)

- After 5 years at LEP1: per-mil precision

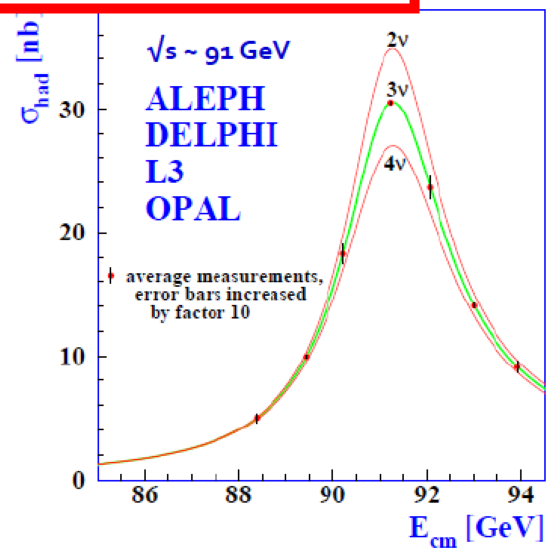
  $N_\nu = 2.984 \pm 0.008$

  (Note the 2σ deficit)

  $\Gamma_Z = 2495.2 \pm 2.3$ MeV

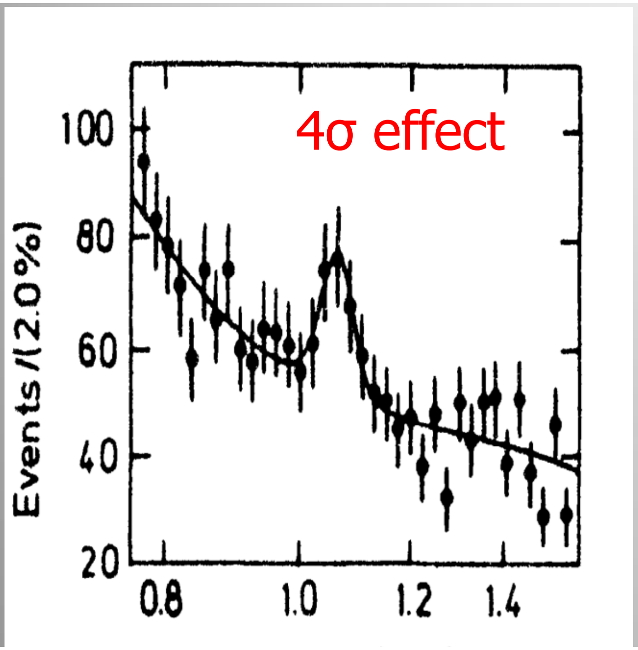
  $m_Z = 91187.5 \pm 2.1$ MeV

  $\alpha_S = 0.1190 \pm 0.0025$

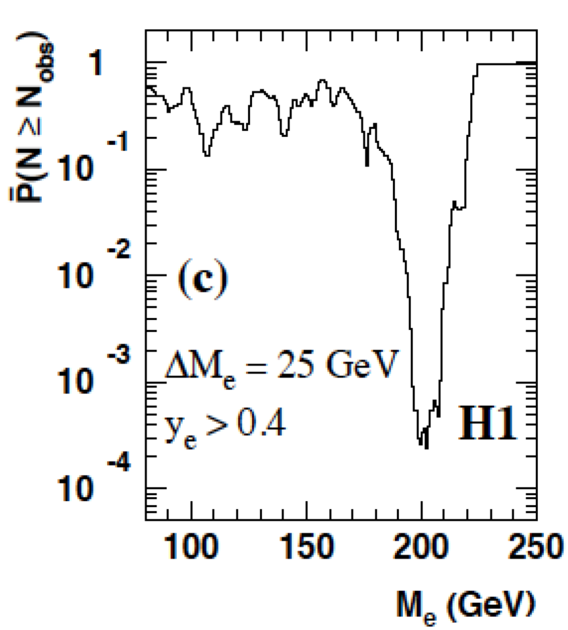


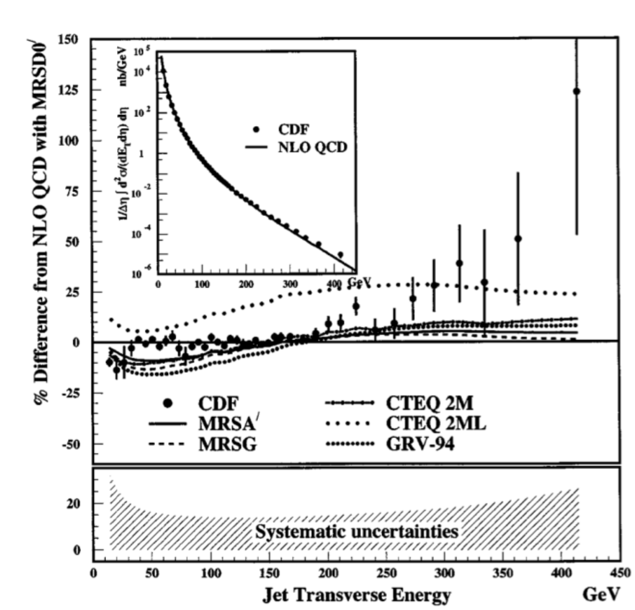
And Some NON-Discoveries

EVIDENCE FOR A MASSIVE STATE IN THE RADIATIVE DECAYS OF THE UPSILON



Is the X(8.31 GeV) the Higgs particle? A lot of excitement summer 1984





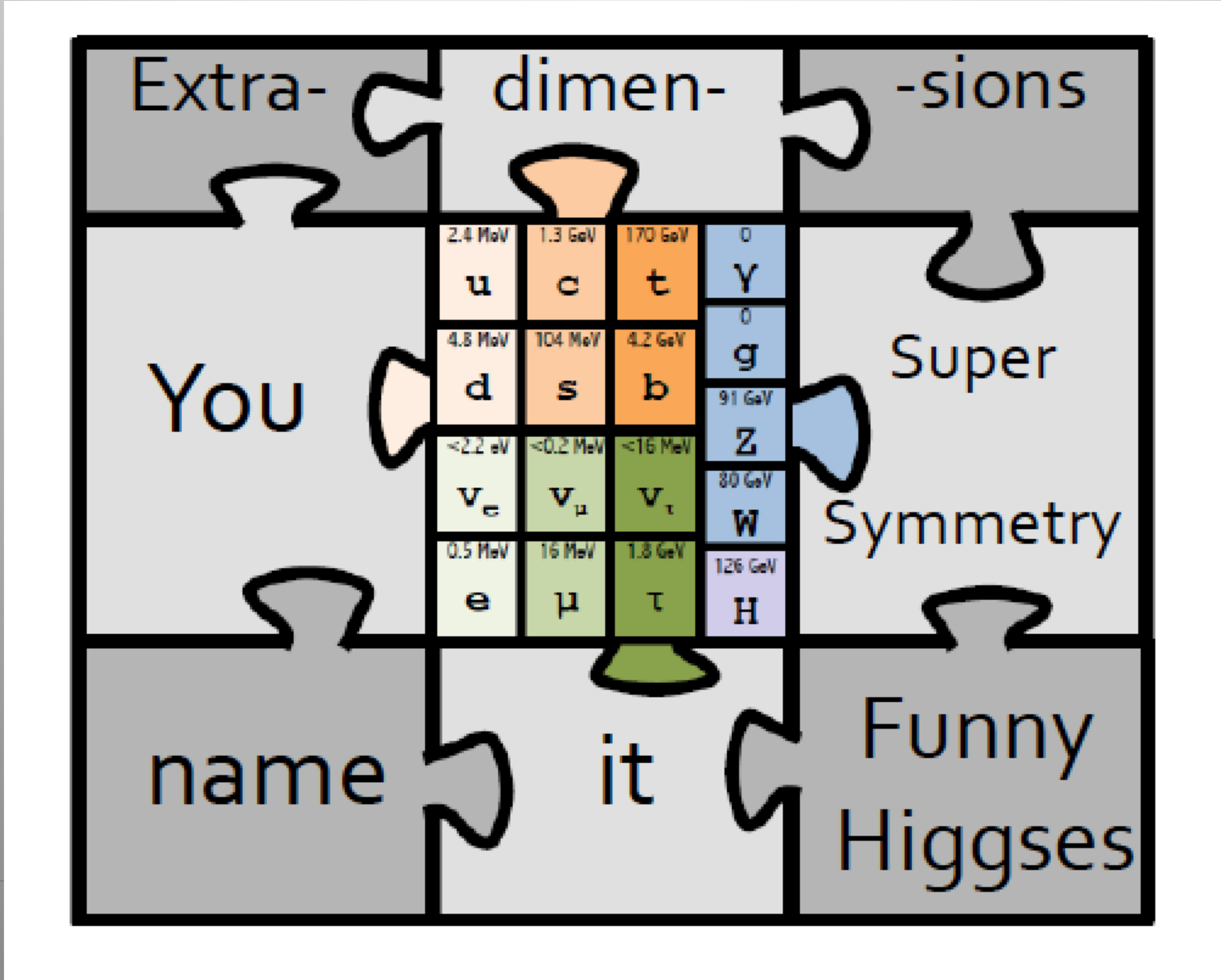
Excess in inclusive jet analysis

Excess of events at high Q^2 in ep DIS at HERA, mainly in H1:

- 7 events found with an electron-quark mass of ~200 GeV, expected ~1 event
- 4 events found with expected 2 events in ZEUS

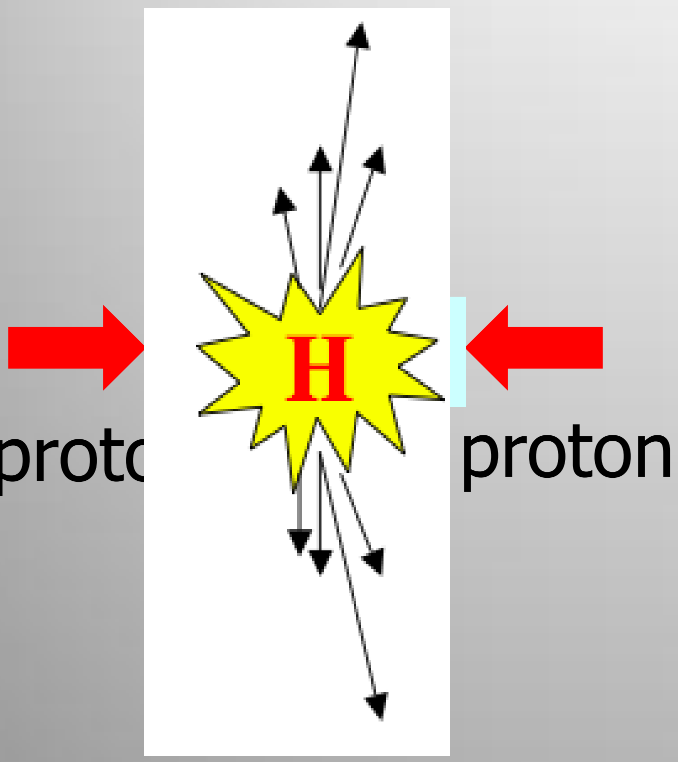
In All: The Standard Model…

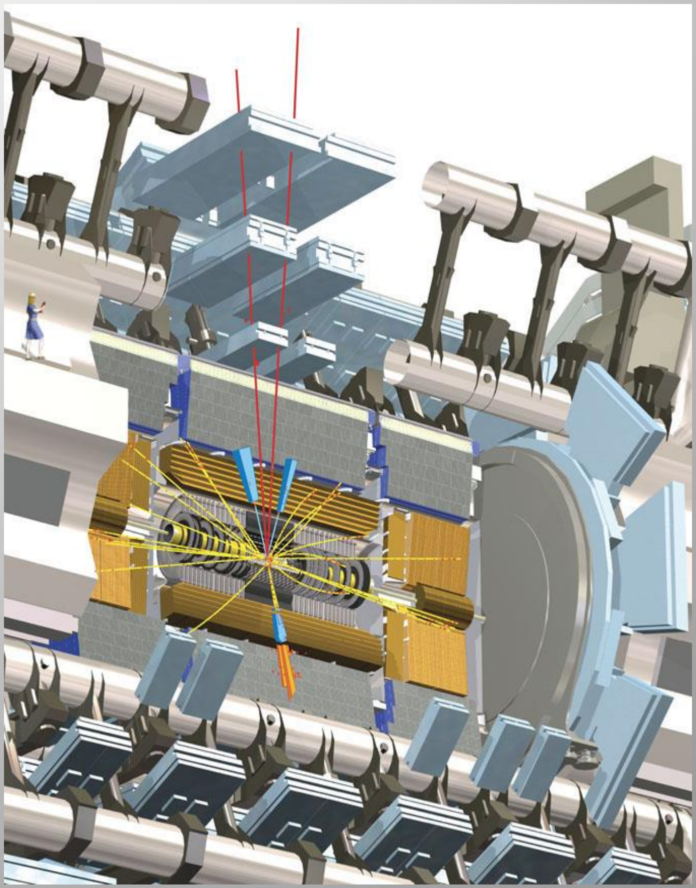
And beyond….???   The Experimentalist view ☺



Example: The Higgs Particle

Technique: Produce and detect Higgs Particles at Particle Colliders





Experimental view…

This Search Requires…….

1. Accelerators : powerful machines that accelerate particles to extremely high energies and bring them into collision with other particles

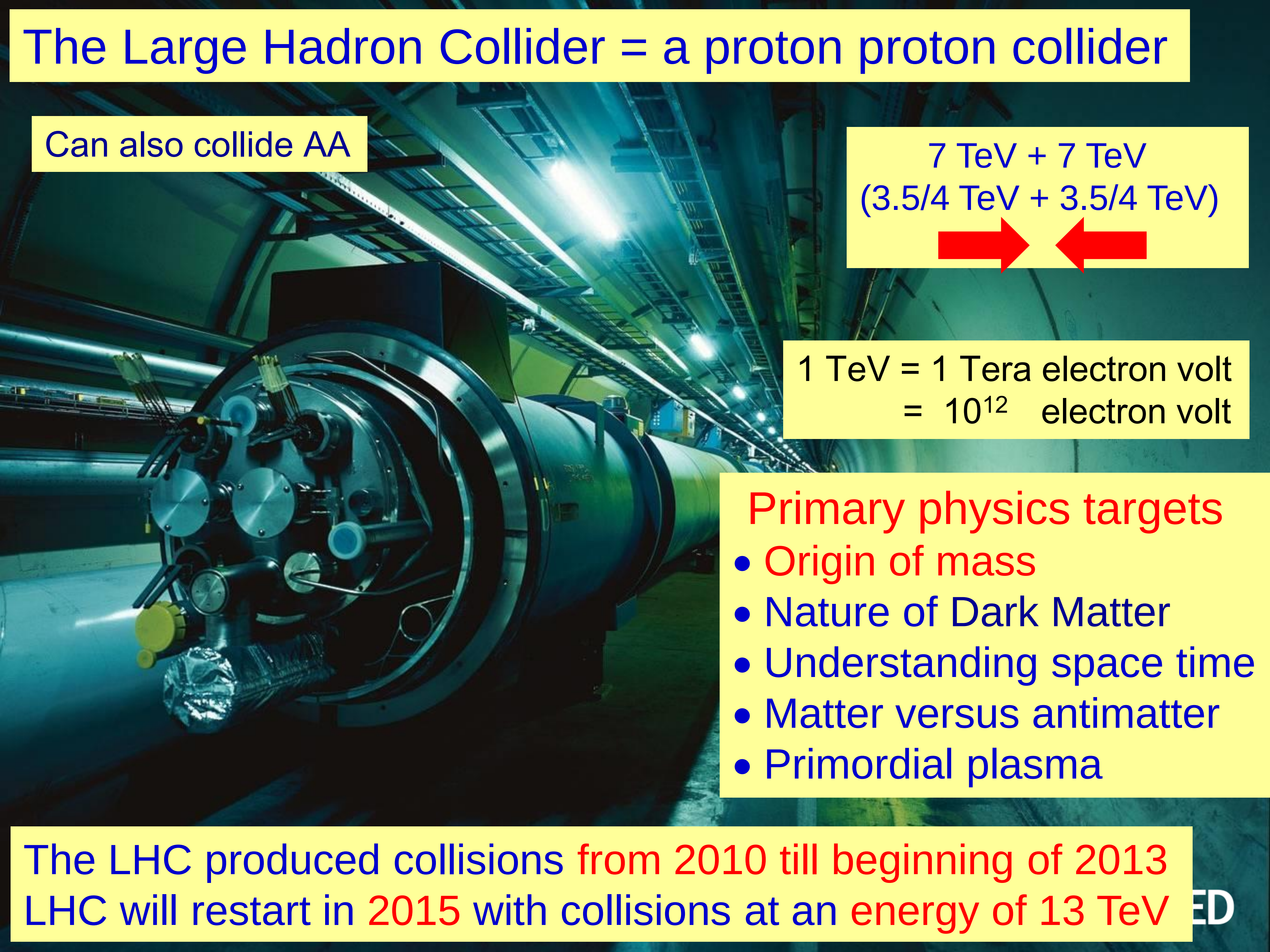
2. Detectors : gigantic instruments that record the resulting particles as they "stream" out from the point of collision.

3. Computing : to collect, store, distribute and analyse the vast amount of data produced by these detectors

4. Collaborative Science on Worldwide scale : thousands of scientists, engineers, technicians and support staff to design, build and operate these complex "machines".

The Large Hadron Collider…

The Large Hadron Collider = a proton proton collider



Can also collide AA

7 TeV + 7 TeV
(3.5/4 TeV + 3.5/4 TeV)

1 TeV = 1 Tera electron volt
= 10^{12} electron volt

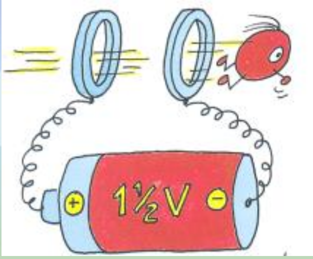
Primary physics targets

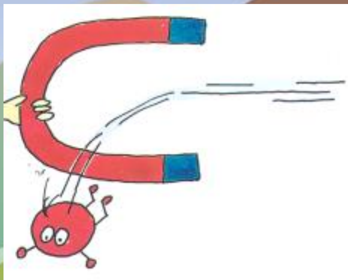
- Origin of mass
- Nature of Dark Matter
- Understanding space time
- Matter versus antimatter
- Primordial plasma

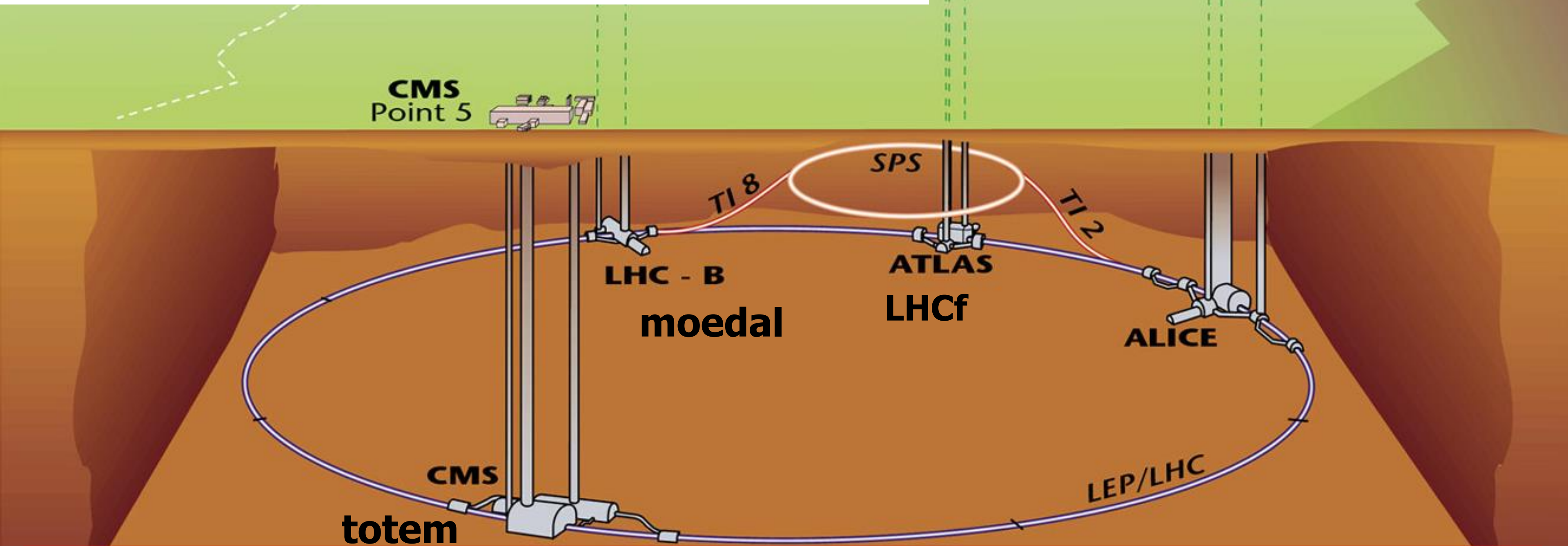
The LHC produced collisions from 2010 till beginning of 2013
LHC will restart in 2015 with collisions at an energy of 13 TeV

The LHC Machine and Experiments

LHC is 100m underground
LHC is 27 km long
Magnet Temperature is 1.9 Kelvin = -271 Celsius
LHC has ~ 9000 magnets
LHC: 40 million proton-proton collisions per second
LHC: Luminosity 10-100 fb^{-1}/year (after start-up phase)







- High Energy ⇒ factor 7 increase w.r.t. present accelerators
- High Luminosity (# events/cross section/time) ⇒ factor 100 increase

The LHC is an Extraordinary Machine

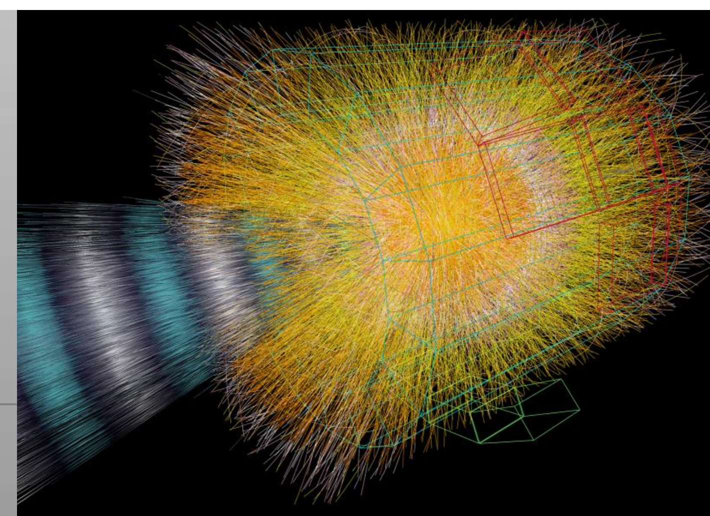
LHC facts

The LHC is …

Colder than the empty space in the Universe: 1.9K ie above absolute zero

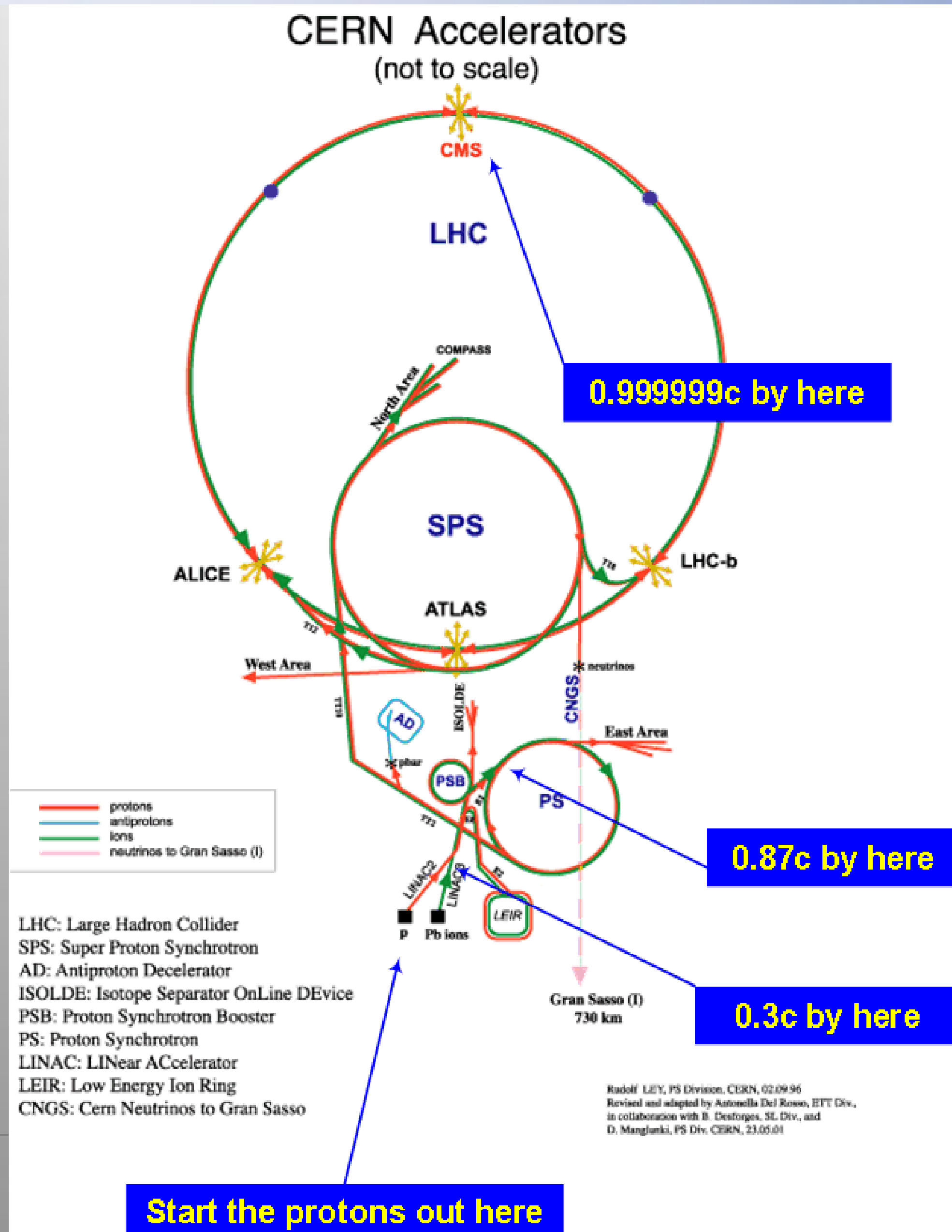
The emptiest place in our solar system. The vacuum is better than on the moon

Hotter than in the sun: temperature in the collisions is a billion times the one in the centre of the sun



The LHC is an Extraordinary Machine

Linac
↓
Booster
↓
PS
↓
SPS
↓
LHC



LHC Parameters (Design/14 Tev)

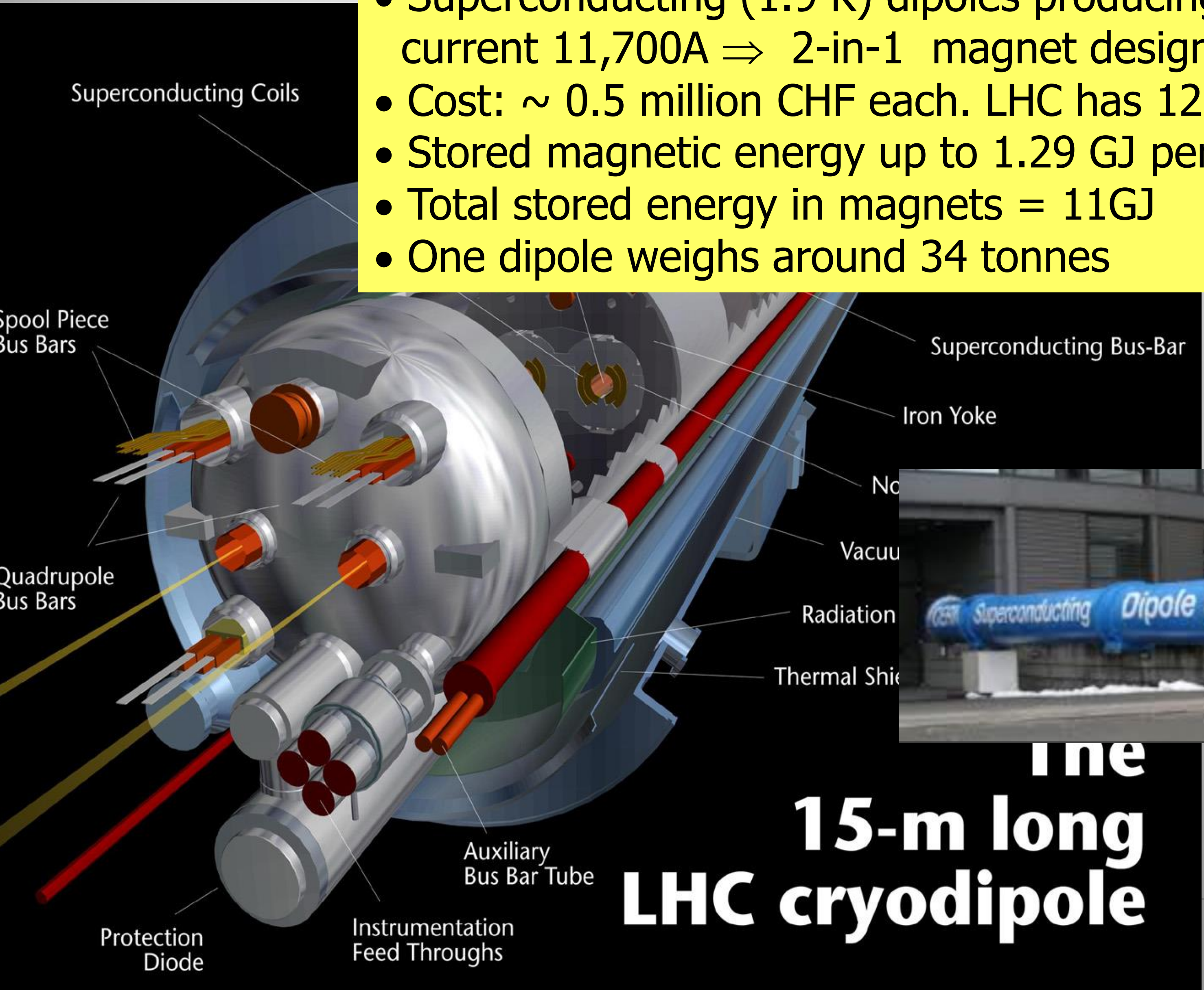
Bunch Intensity	1.15×10^{11}
Number of bunches	2808
emittance	5×10^{-10} m
β* fully squeezed	55 cm
beam size at IP	16 μm
Crossing angle	285 μrad
Bunch length	1.06 ns (7.5 cm)
Luminosity	10^{34} $cm^{-2}s^{-1}$
Total Beam energy	362 MJ per beam

Run-I: 7/8 TeV, less bunches per beam (factor 2),
higher bunch intensity (30%), lumi ~$8.10^{33} cm^{-2}s^{-1}$

Full list at: http://cern.ch/ab-div/Publications/LHC-DesignReport.html

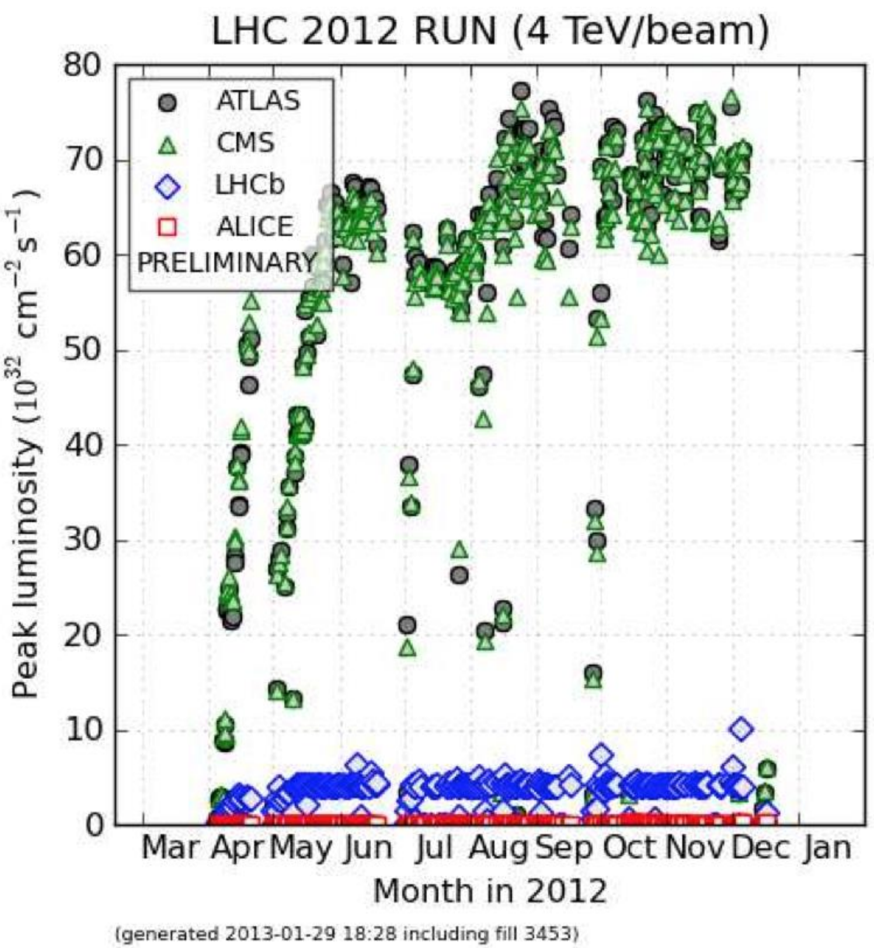
The Cryodipole Magnets

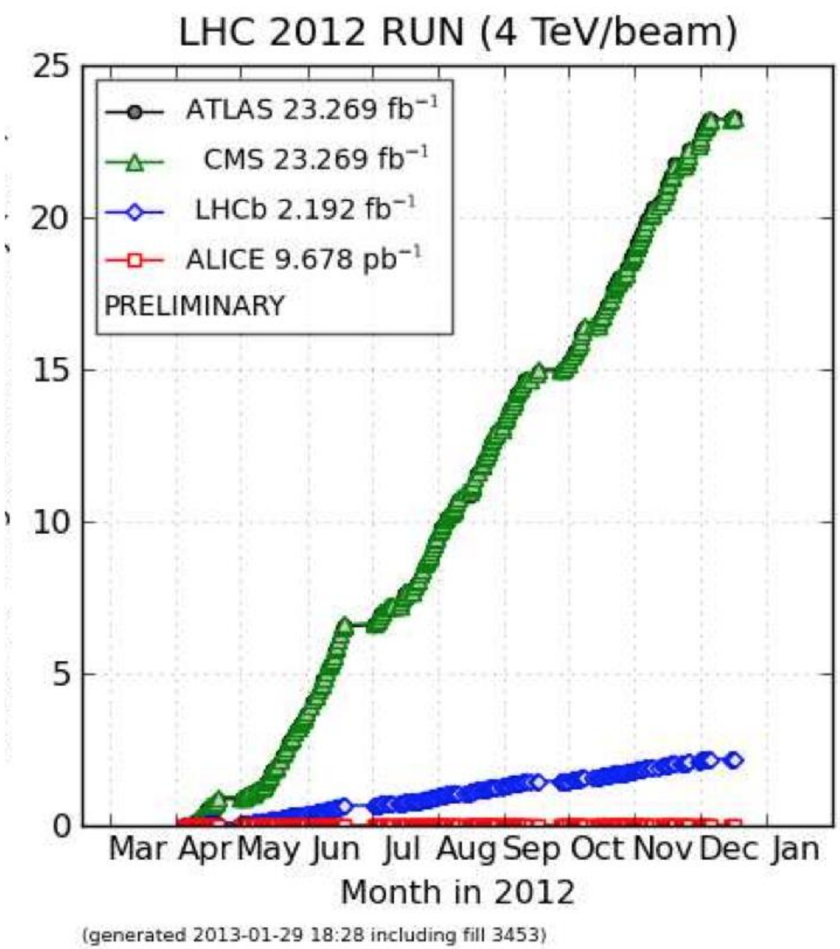
- Superconducting (1.9 K) dipoles producing a field of 8.4 T – current 11,700A ⇒ 2-in-1 magnet design
- Cost: ~ 0.5 million CHF each. LHC has 1232 of them
- Stored magnetic energy up to 1.29 GJ per sector.
- Total stored energy in magnets = 11GJ
- One dipole weighs around 34 tonnes



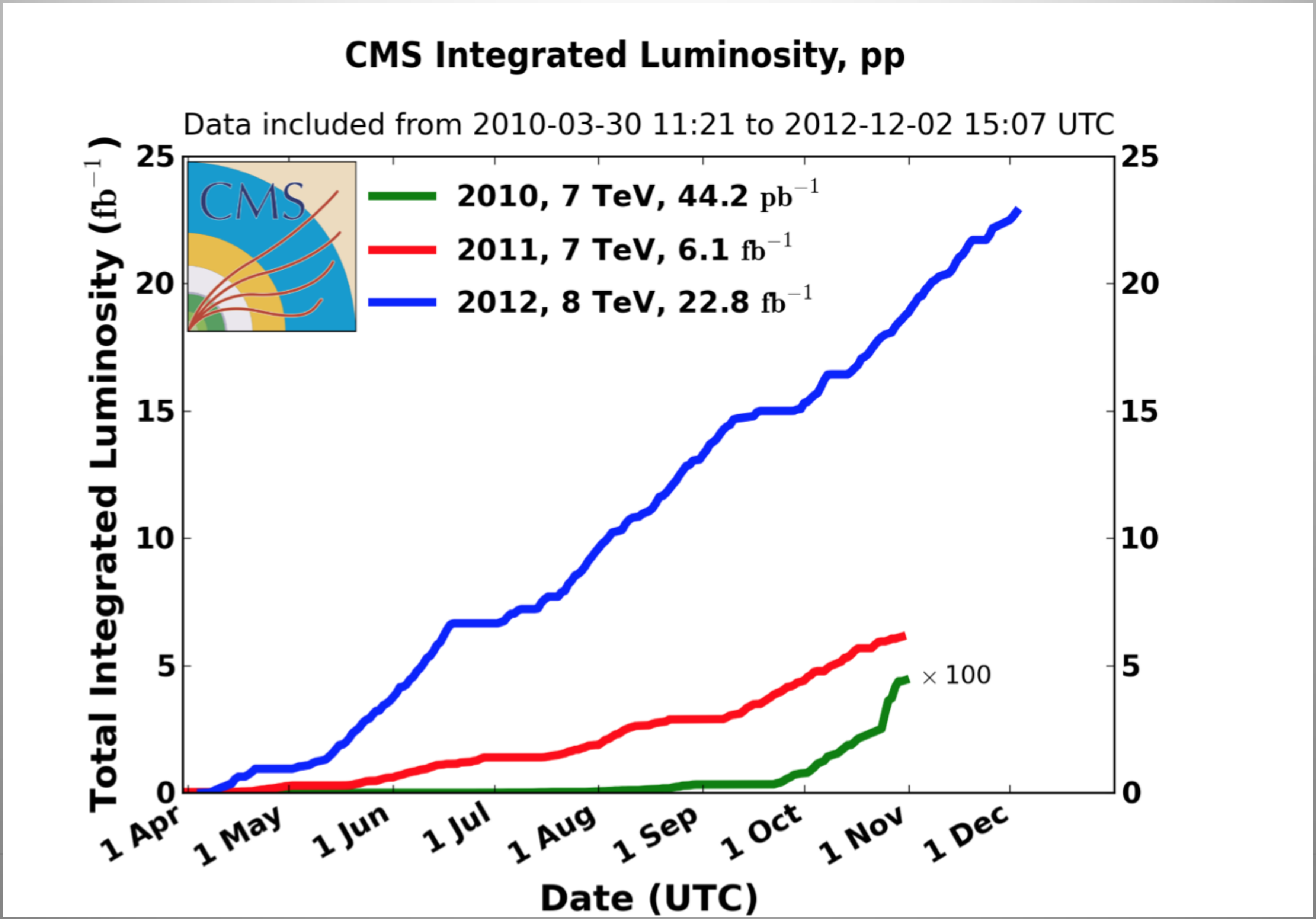
LHC Performance (2012)

For the record: Final p-p luminosity for 2012

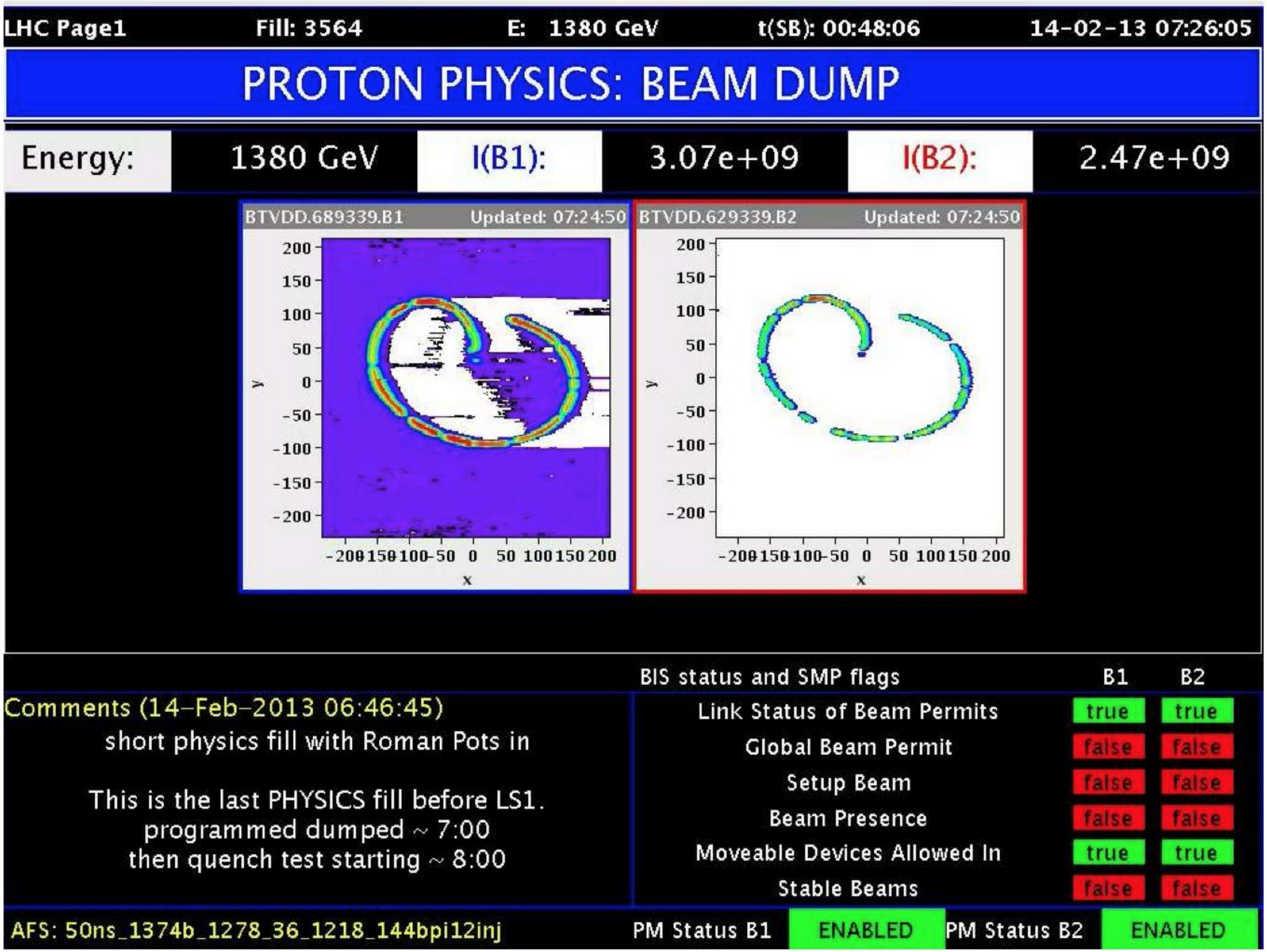




LHC Performance (2010-2012)



THE LAST PHYSICS BEAM OF LHC RUN 1 (2009 - 2013)



LHC being 'upgraded' and awakening as we speak… more in Lecture 3

Experiments at the LHC

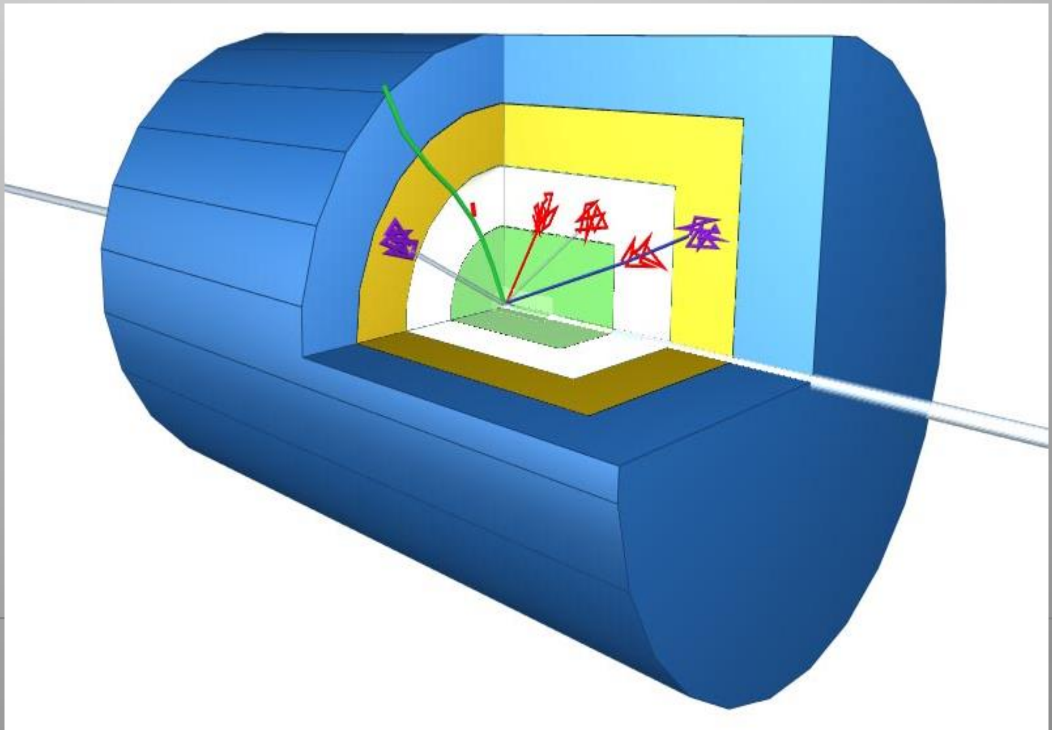
Schematic of a LHC Detector

Physics requirements drive the design!

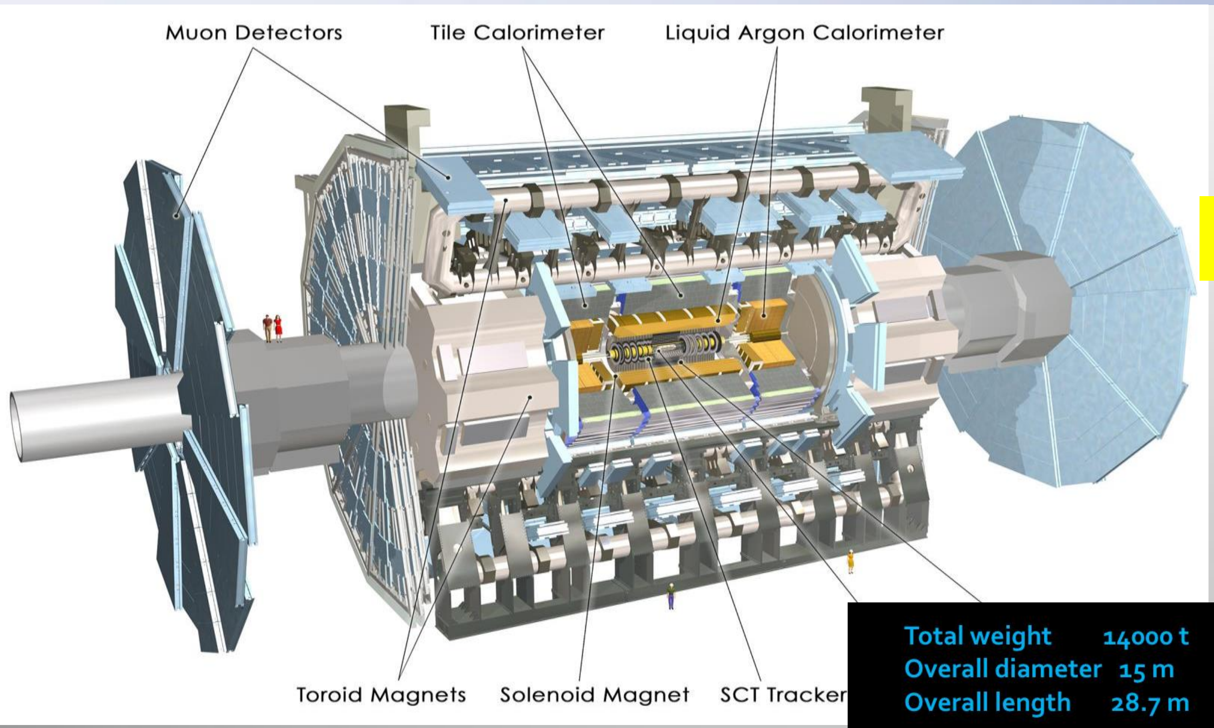
Analogy with a cylindrical onion:

Technologically advanced detectors comprising many layers, each designed to perform a specific task.
Together these layers allow us to identify and precisely measure the energies and directions of all the particles produced in collisions.

Such an experiment has ~ 100 Million read-out channels!!

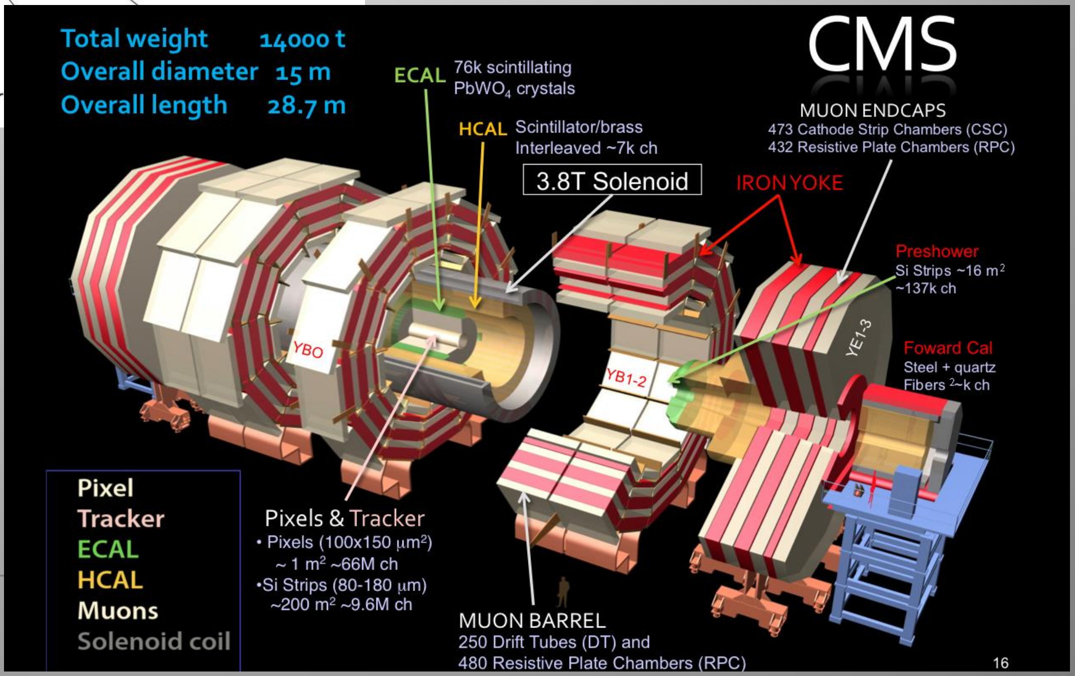


The Higgs Hunters @ the LHC



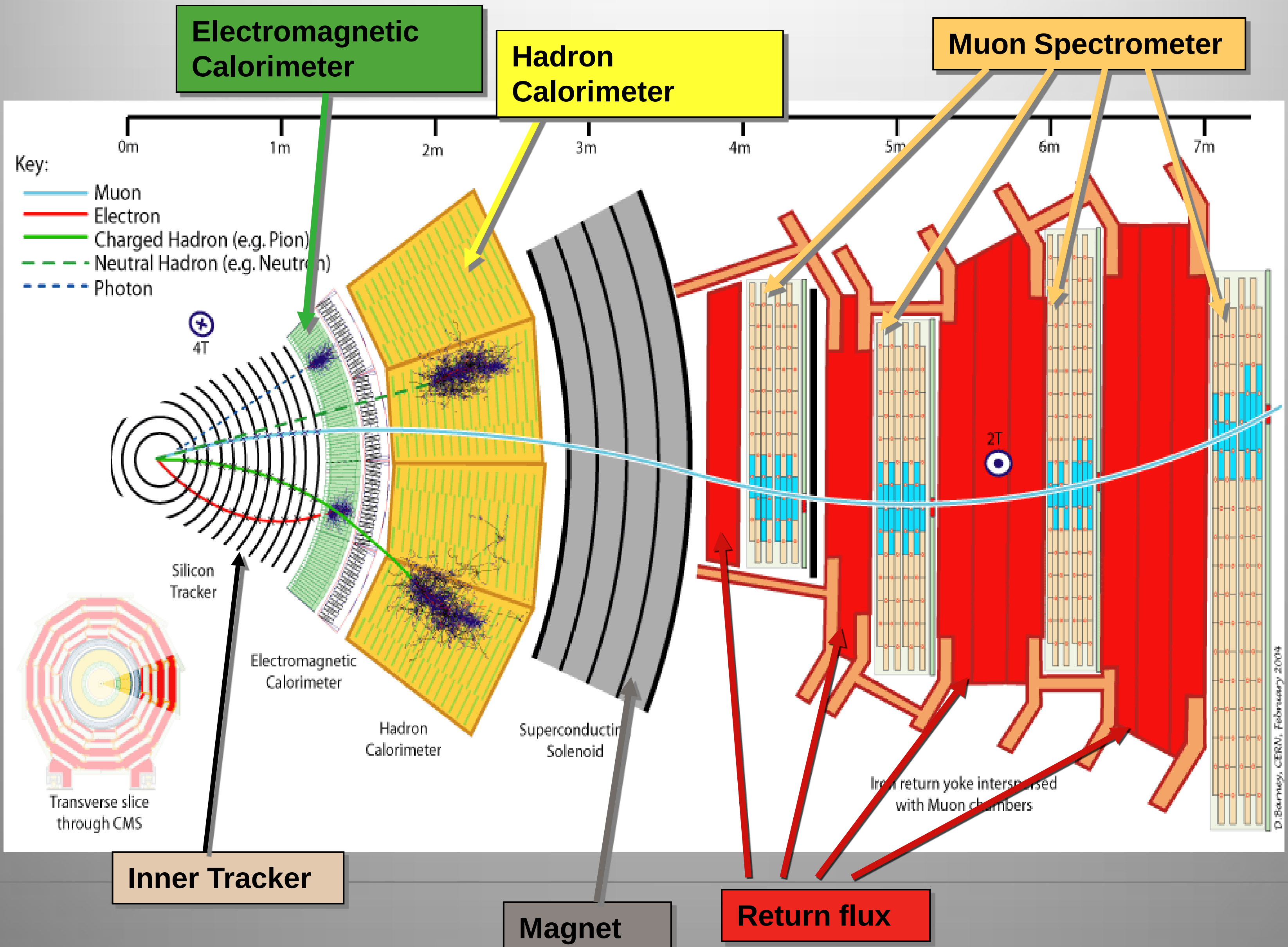
The ATLAS experiment

The CMS experiment



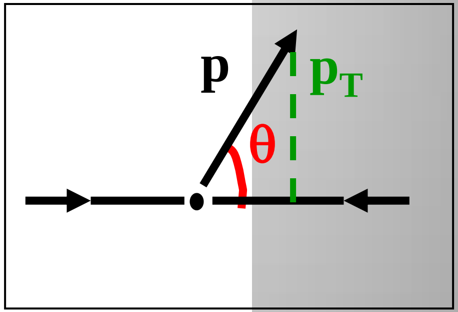
These experiments use different technologies for their detector components

Particles in Detectors



Kinematic Variables for pp Scattering

- Transverse momentum, p_T and $E_T = E \sin\theta$
  - Particles that escape detection (0) have $p_T=0$
  - Visible transverse momentum =0
    - Very useful variable!
- Longitudinal momentum and energy, p_z and E
  - Particles that escape detection have large p_z
  - Visible p_z is not conserved
    - Not so useful variable
- Angle:
  - Polar angle θ is not Lorentz invariant
  - Rapidity: y
  - Pseudorapidity: η

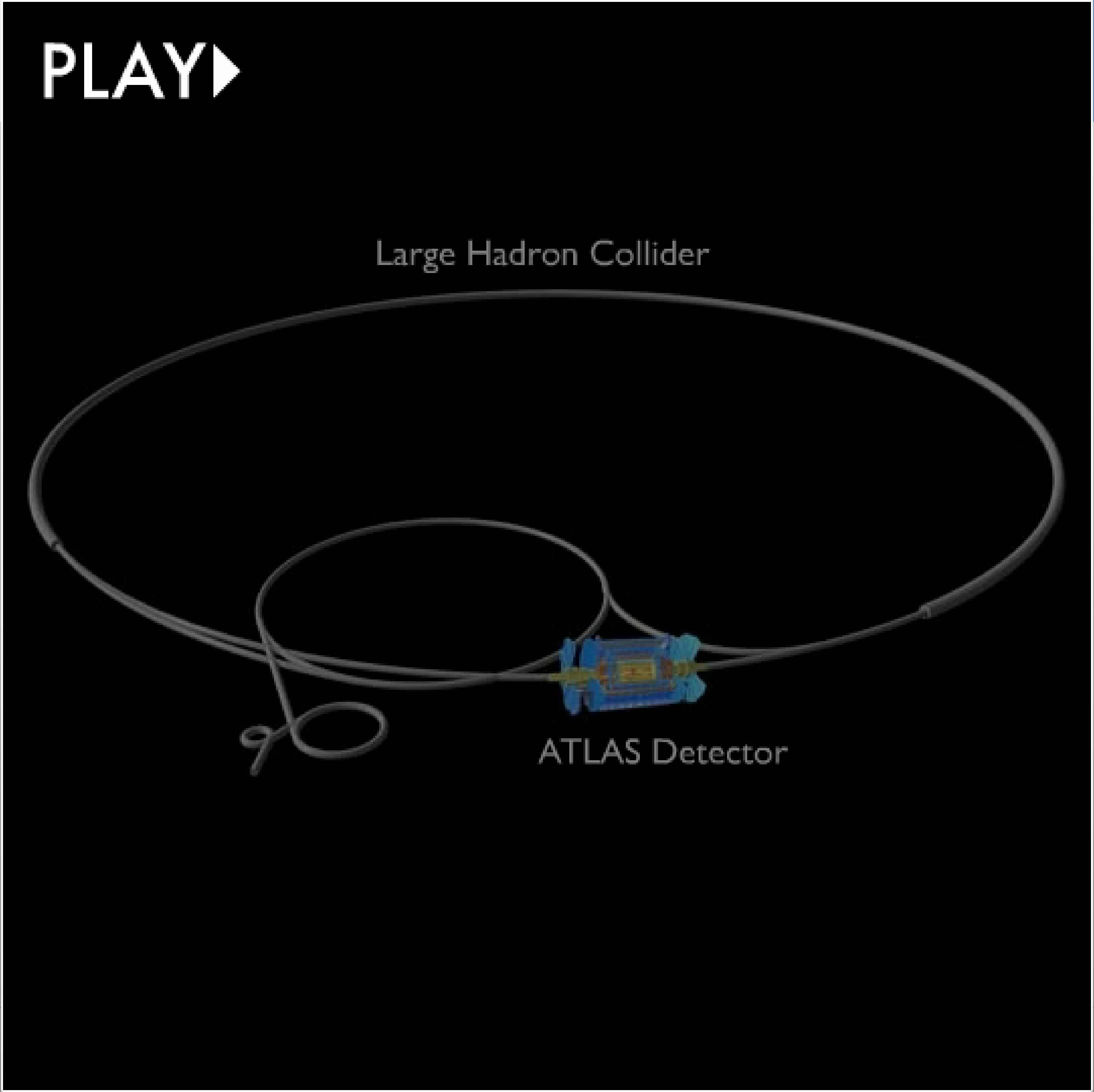


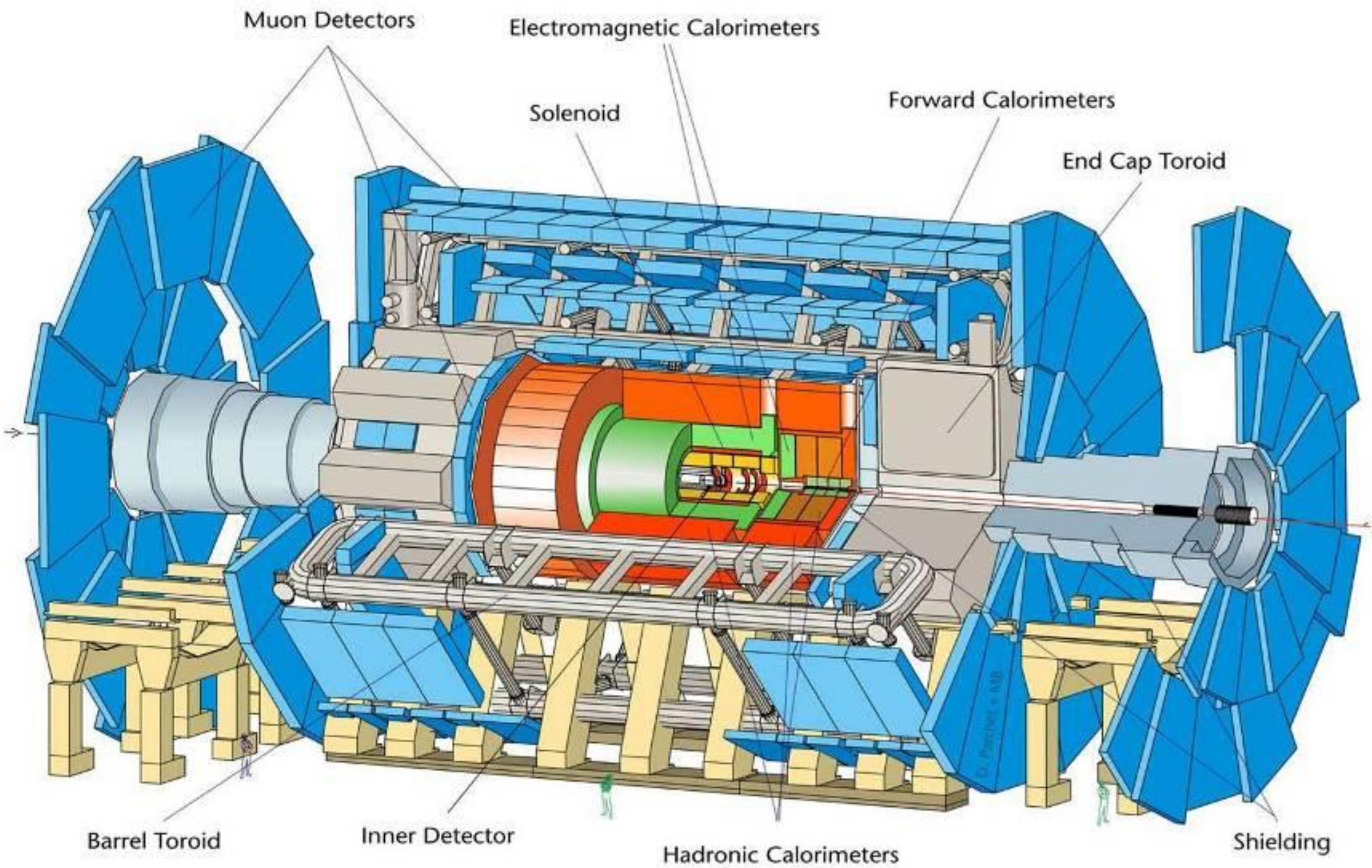
$$y = \frac{1}{2}\ln\frac{E+p_z}{E-p_z}$$

For M=0

$$y = \eta = -\ln(\tan\frac{\theta}{2})$$

- Missing E_T and P_T : Vectorial sum of all transverse momenta


PLAY
Large Hadron Collider
ATLAS Detector



Length = 55 m; Width = 32 m; Height = 35 m; but spatial precision ~ 100 μm

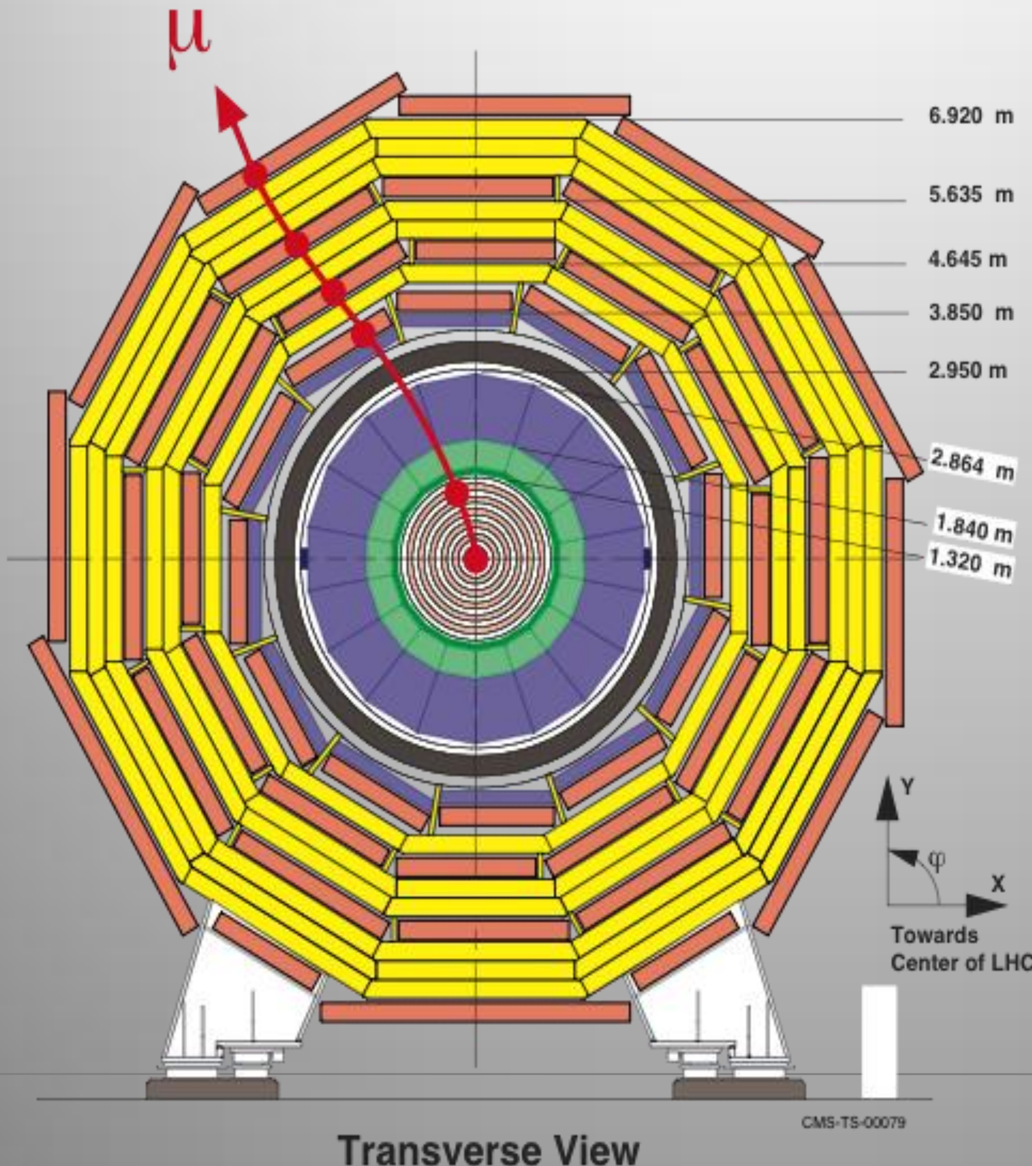
CMS Detector Design Priorities

Expression of Intent (EOI): Evian 1992

1. A robust and redundant Muon system
2. The best possible e/γ calorimeter consistent with 1.
3. A highly efficient Tracking system consistent with 1. and 2.
4. A hermetic calorimeter system.
5. A financially affordable detector.

Compact Muon Solenoid (CMS)

Letter of Intent (LOI): LHCC, TDR in 1994



Strong Field 4T

Compact design

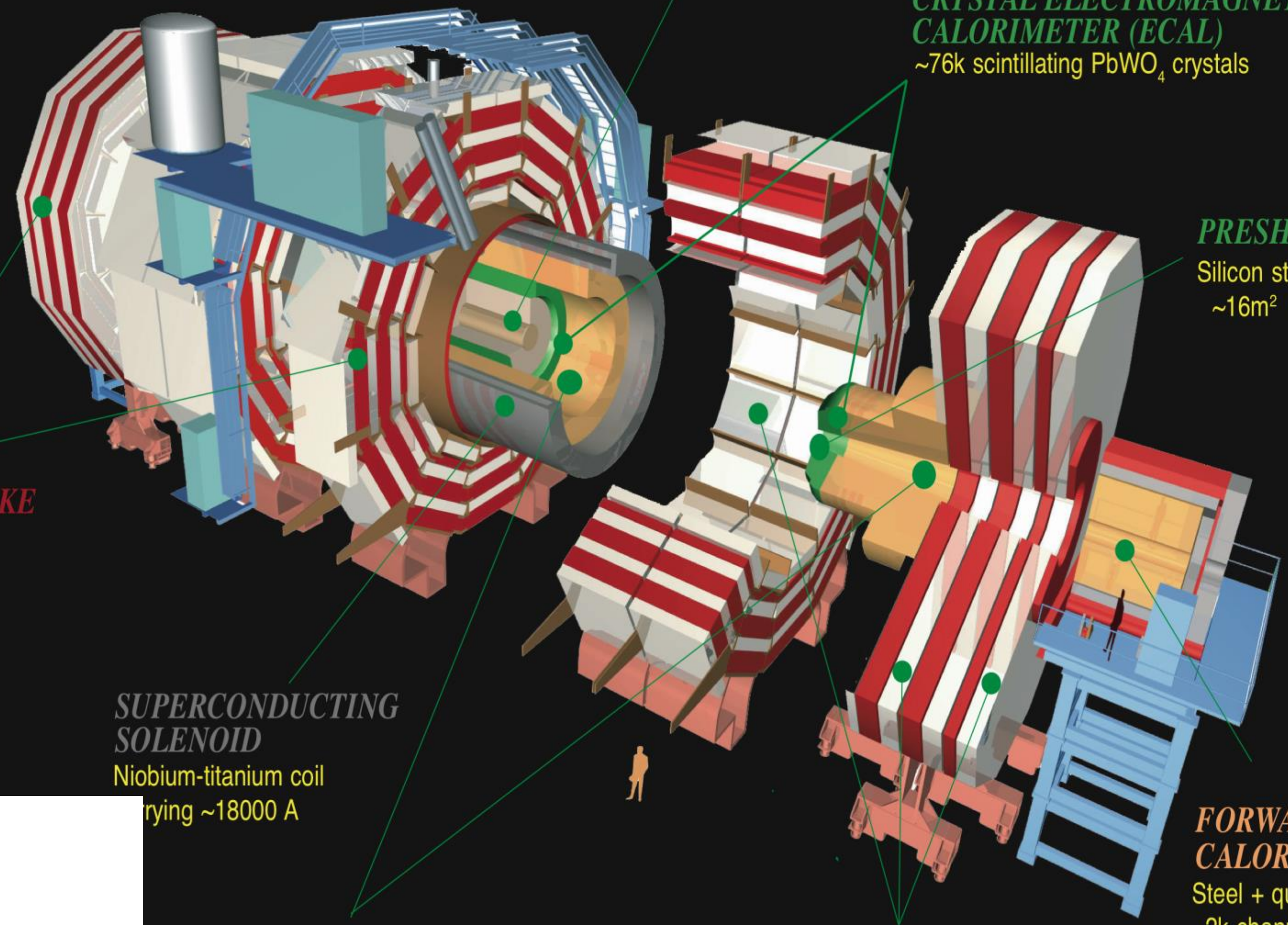
Solenoid for Muon P_T trigger in transverse plane

Redundancy: 4 muon stations with 32 R-phi measurements

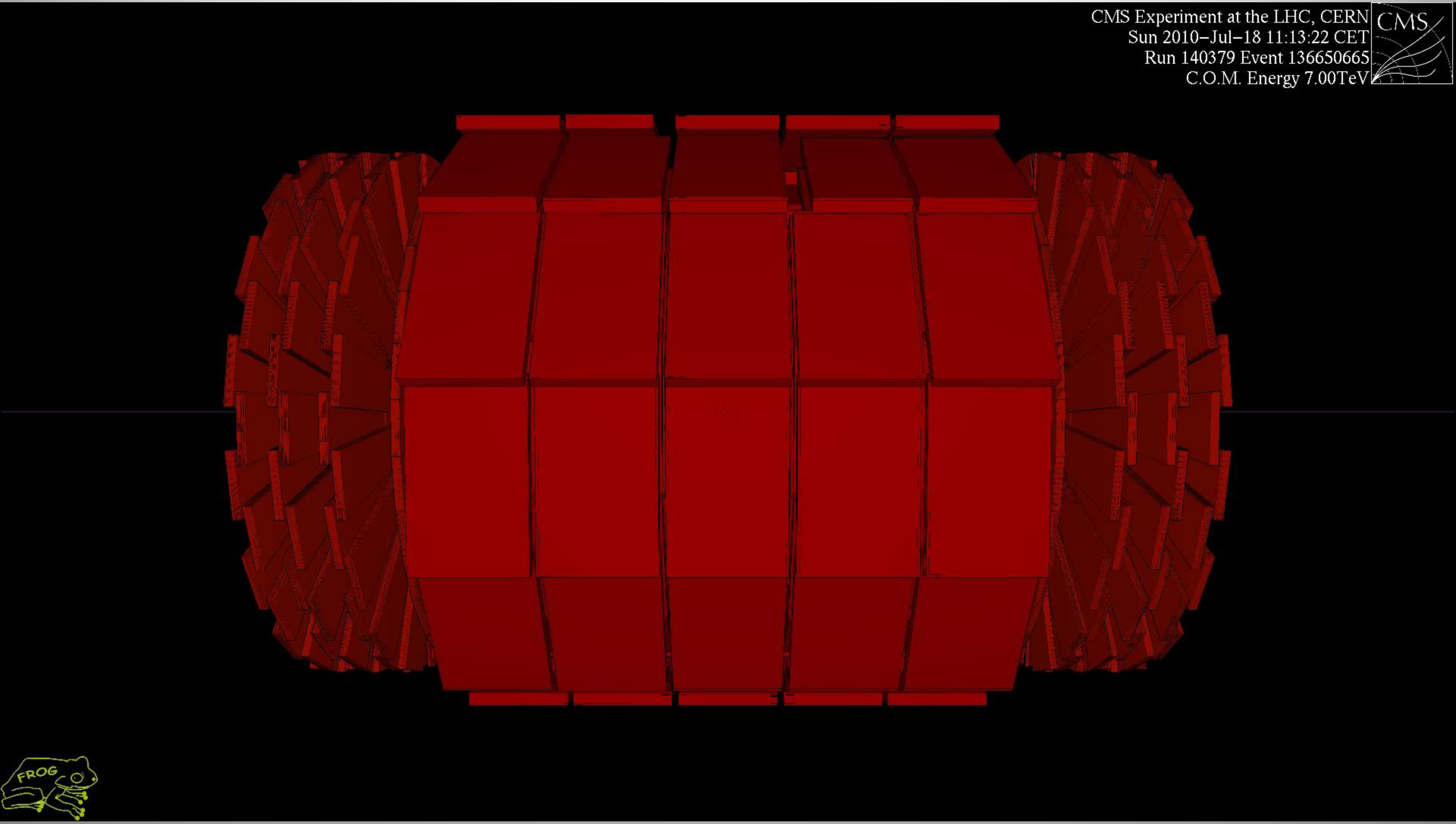
$\Delta P_t/P_t \sim 5\%$ @1TeV for reasonable space resolution of muon chambers (200μm)

CMS Detector

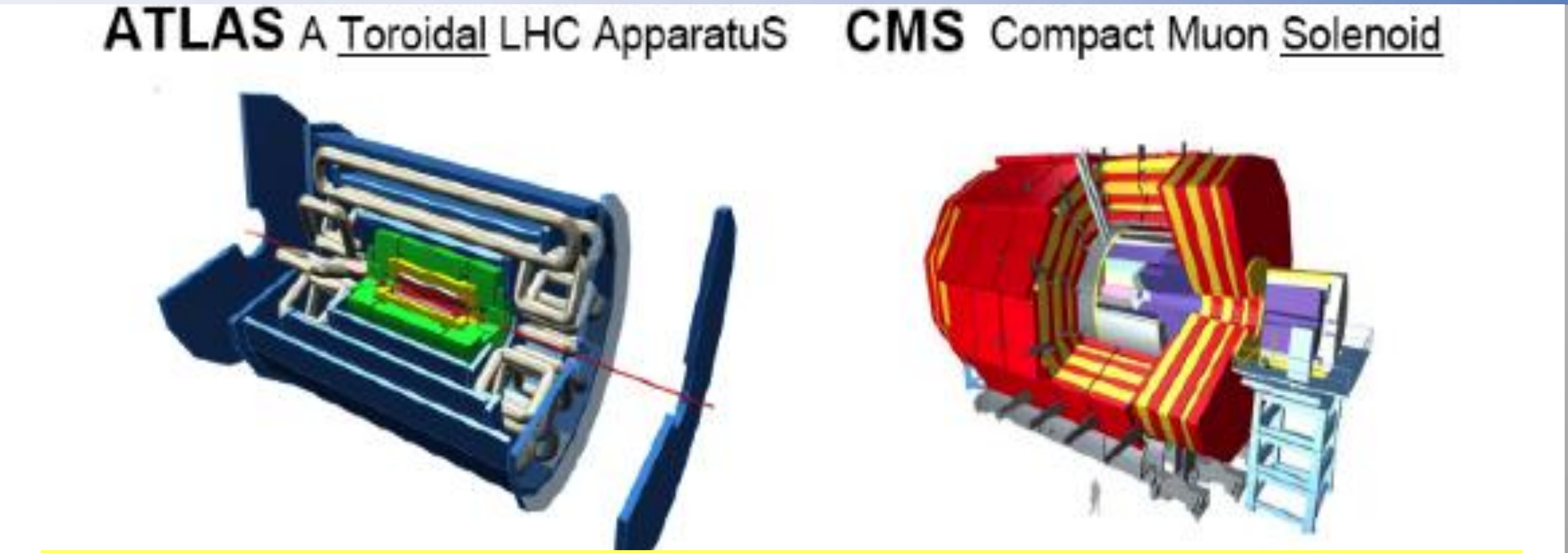
Compact Muon Solenoid



Total weight:
14000 tons
Overall diameter:
15 m
Overall length:
28.7m

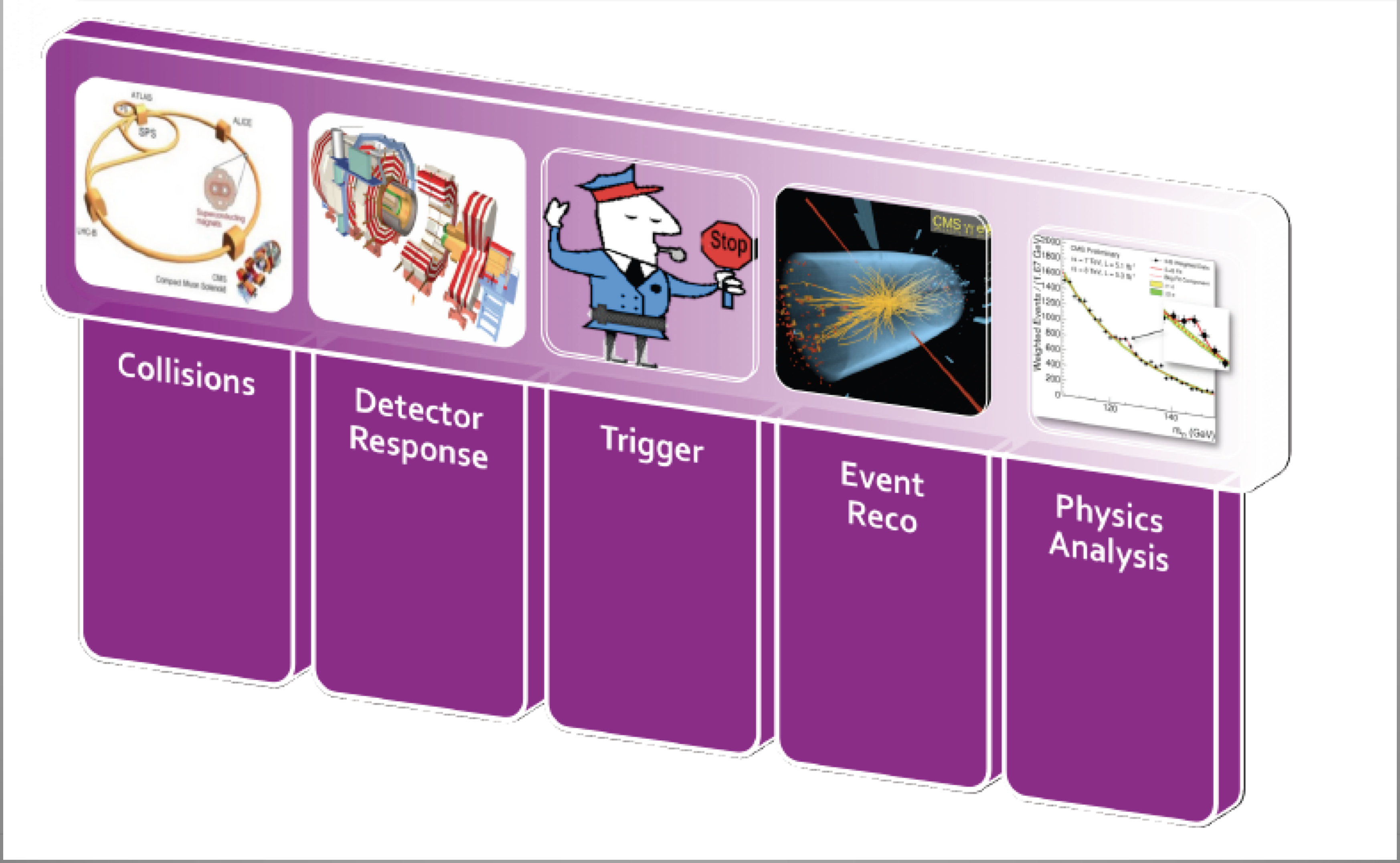

CMS Experiment at the LHC, CERN
Sun 2010–Jul–18 11:13:22 CET
Run 140379 Event 136650665
C.O.M. Energy 7.00TeV
CMS
FROG

General Purpose Detectors at LHC

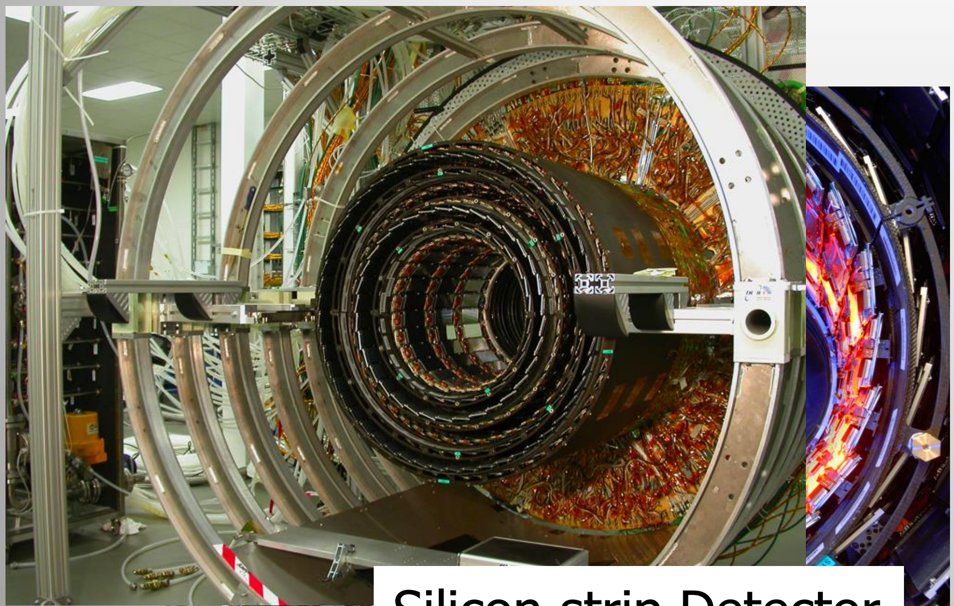


In total about
~100 000 000 electronic channels
Each channel checked
20 000 000 times per second (collision rate is 20 MHz, 40 MHz soon)
Amount of data of just one collision
>1 000 000 Bytes
Trigger (online event selection)
Reduce 20 MHz collision rate to ~300 Hz data recording rate
Readout to disk
Few 100 collisions/sec ⇒ petaBytes of data/year

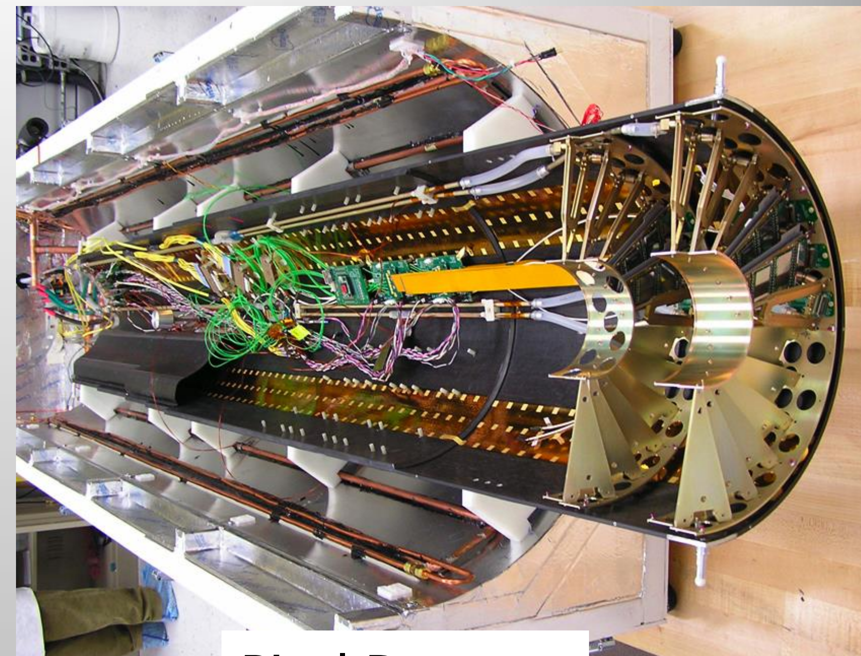
From Collisions to Papers…



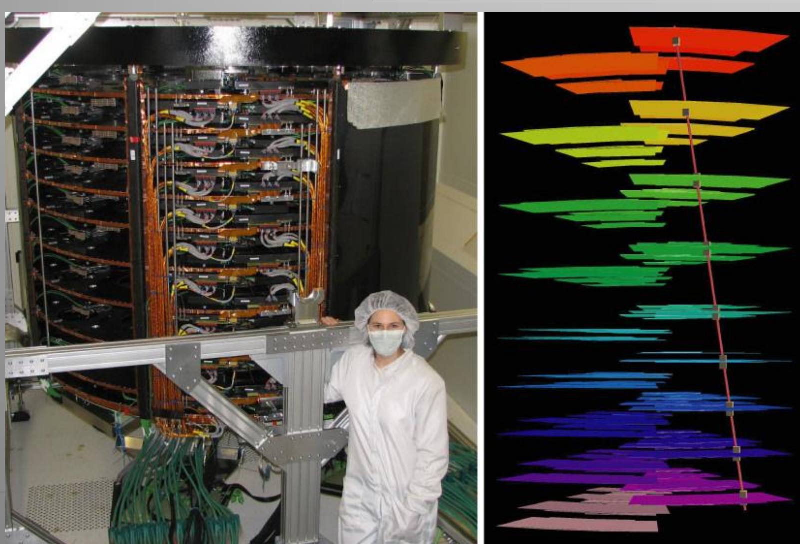
Example: CMS Central Tracker



Silicon strip Detector



Pixel Detector



- 200 m^2 silicon strip detectors

  (~ tennis court)

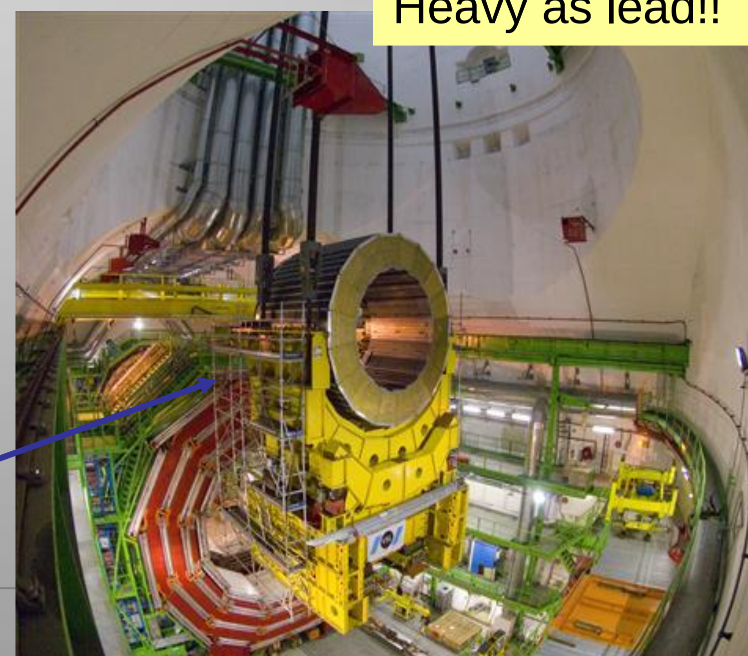
  ~ 10^7 read-out channels
- 70 million pixels for pixel detector

Example: The CMS Calorimeters

ECAL: Barrel 36 super modules/1700 crystals
Endcaps detectors completed in summer 2008
Total of ~70000 crystals for this detector

Lead tungstanate.
Transparent like glass
Heavy as lead!!

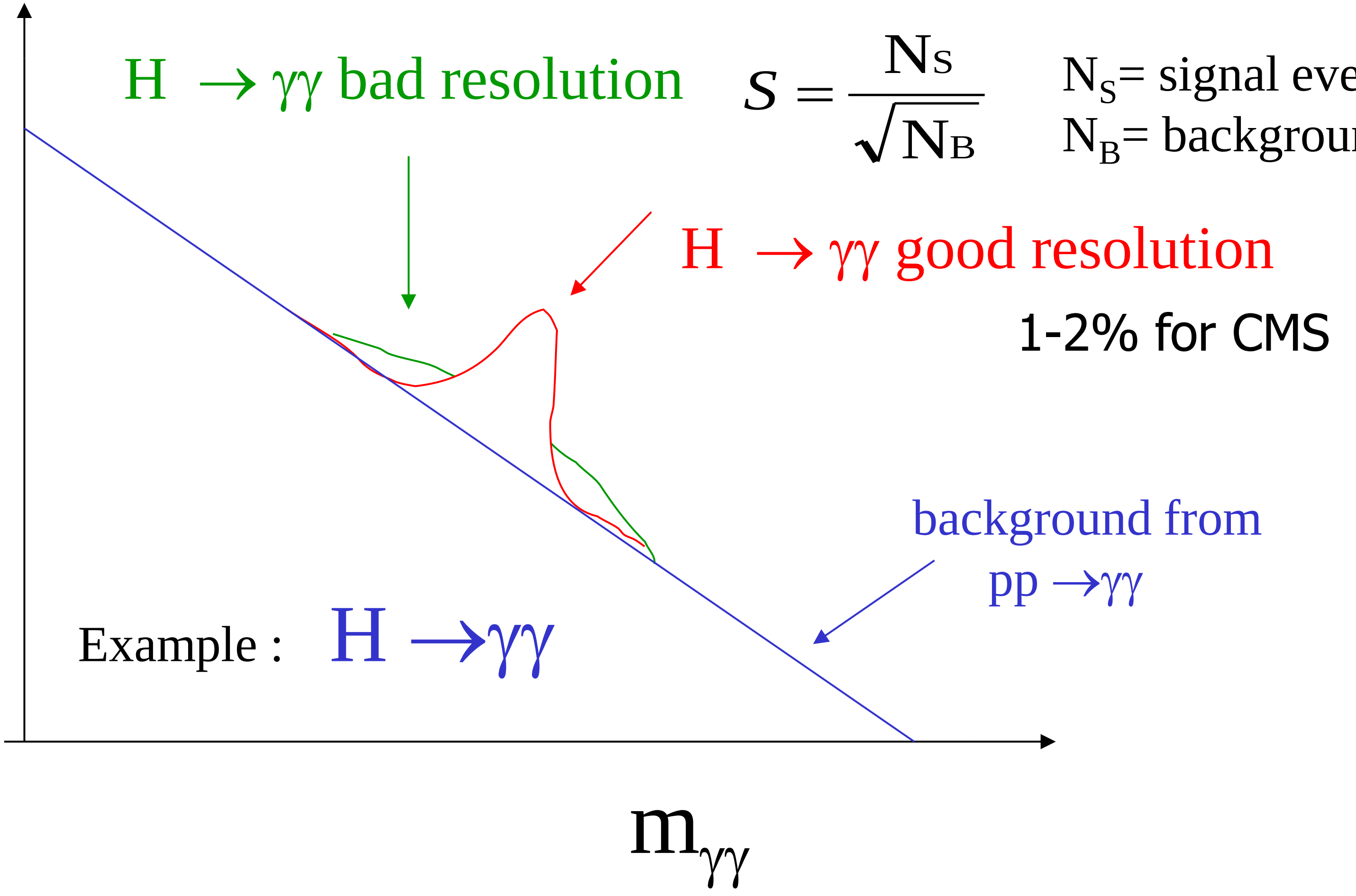
Central ECAL installation in CMS



Hadronic Calorimeter
(brass/scintillator) completed in 2006
Lowering in the experimental hall

Calorimeter Resolution: eg. Higgs

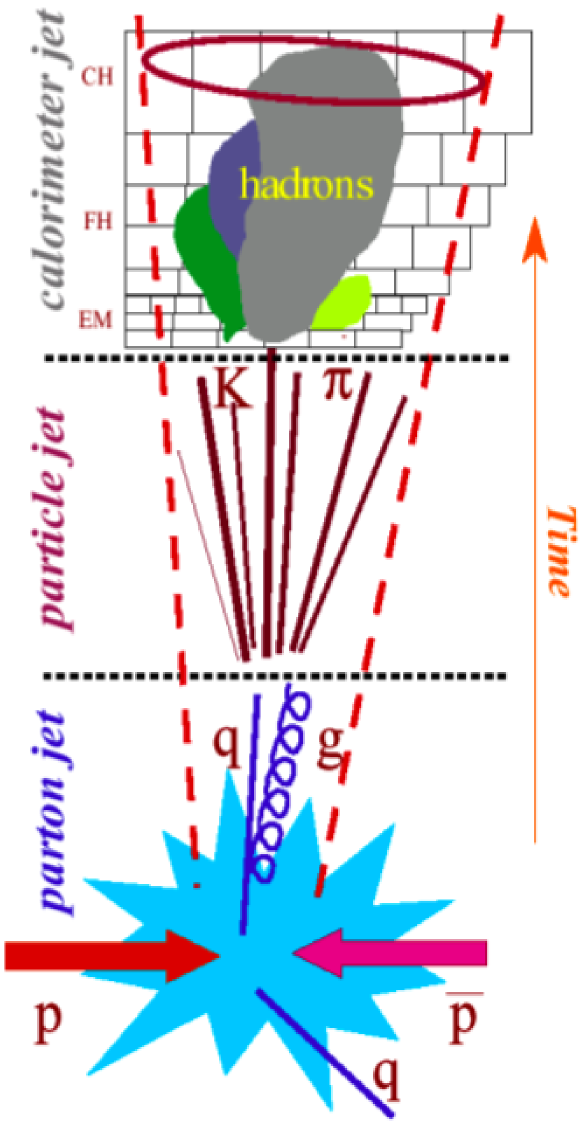
- Excellent energy resolution of EM calorimeters for e/γ and of the tracking devices for μ in order to extract a signal over the backgrounds.



$$S = \frac{N_S}{\sqrt{N_B}}$$

N_S= signal events
N_B= background events

Jet Finding



- **Calorimeter jet (cone)**
  - jet is a collection of energy deposits with a given cone *R*: $R = \sqrt{\Delta\varphi^2 + \Delta\eta^2}$
  - cone direction maximizes the total E_T of the jet
  - various clustering algorithms

→ correct for finite energy resolution
→ subtract underlying event
→ add out of cone energy

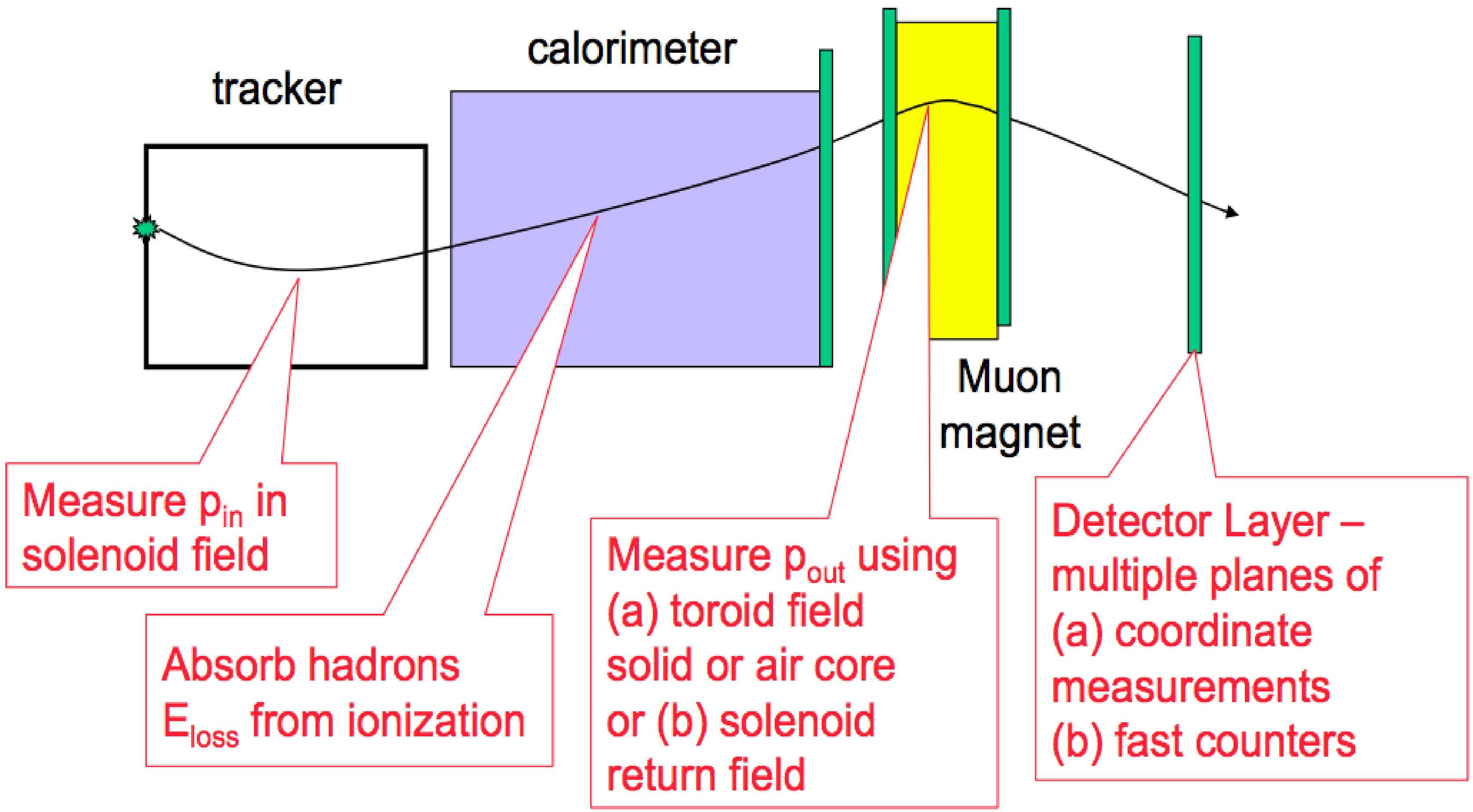
- **Particle jet**
  - a spread of particles running roughly in the same direction as the parton after hadronization

Example : CMS Muon Detectors

250 Drift tube chambers
172,000 channels
468 Cathode strip chambers
500,000 channels
912 Resistive plate chambers
160,000 channels
Total area ~ 6000 m^2 ie like a football field

Muon Measurement

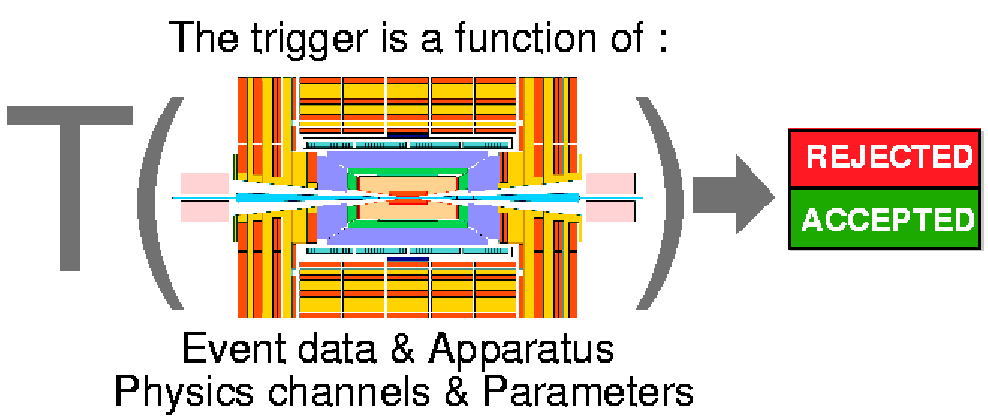
Elements of Muon Detection



CMS before closure

Event Filtering: the Trigger System

Bunch crossing rate is 20 MHz Event size ~1 Mbyte
2007 technology (and budget) allows only to write a few 100 Hz of events to tape → need a factor ~10^5 online filtering!!

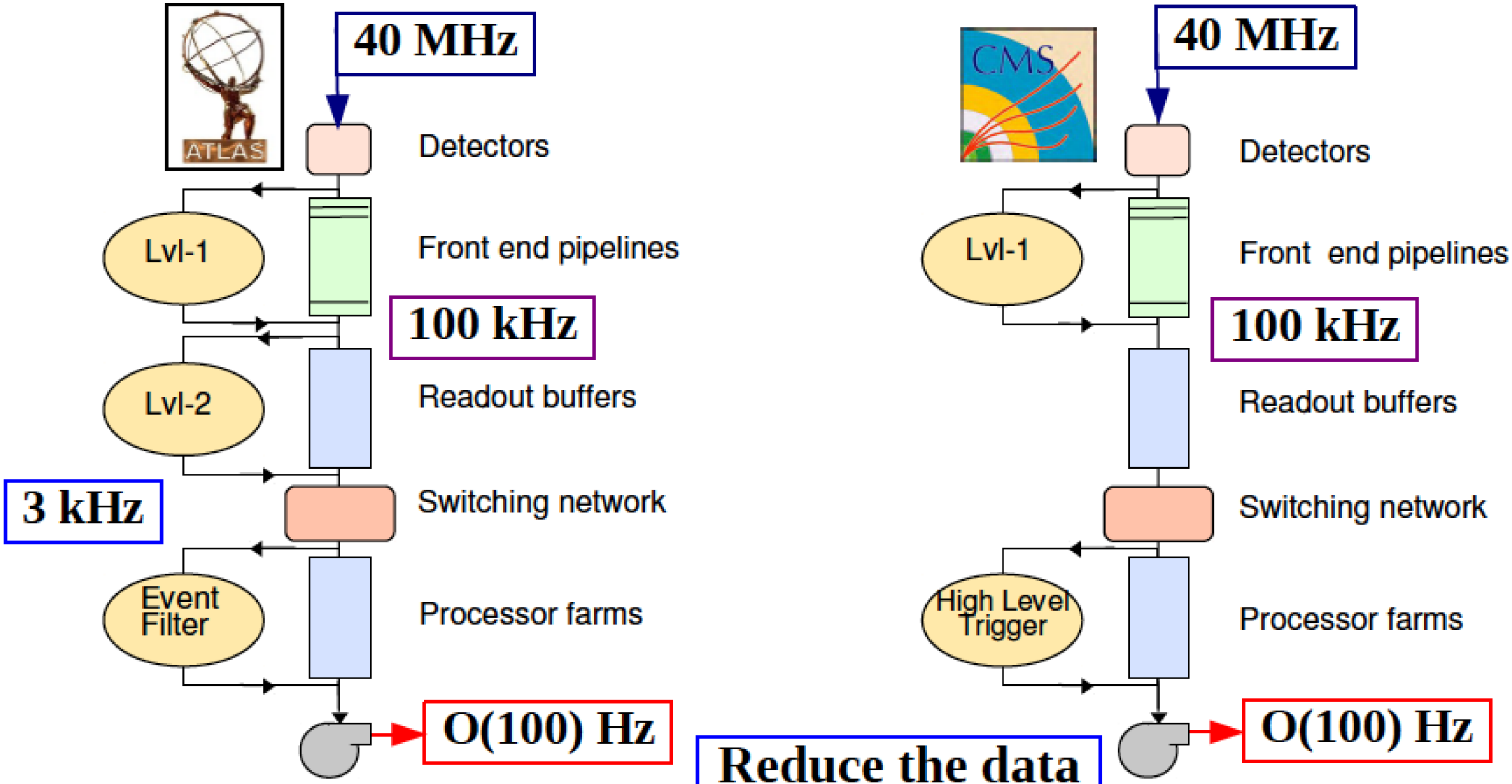


lost forever!!

written to disk for offline analysis

The event trigger is one of the biggest challenges at the LHC
⇒ Based on hard scattering signatures: jets, leptons, photons, missing E_T,…

Trigger in Detail



Reduce the data volume in stages

Somewhat outdated numbers here

The LHC Data Challenges

Experiments were anticipated to produce about **15 Million Gigabytes** of data each year (~20 million CDs!)

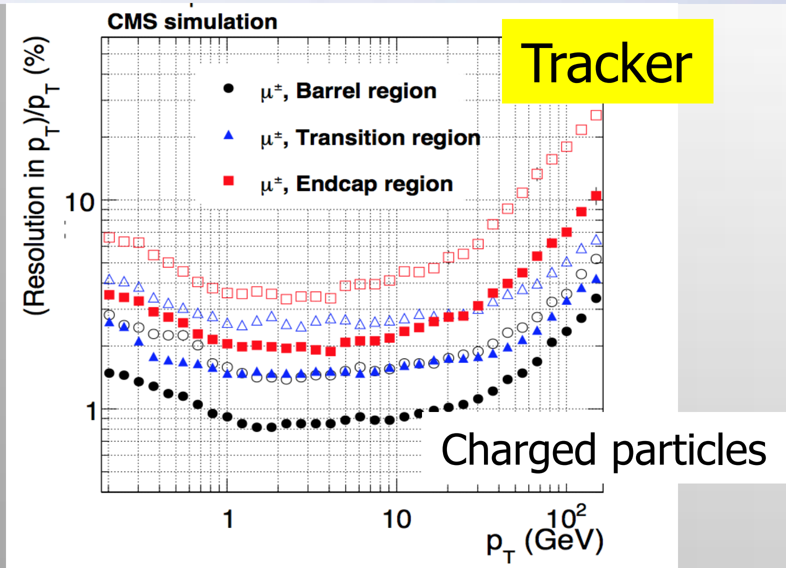
The total volume in eg ATLAS is 5 billion detector events and several billion Monte Carlo events amounting to 100 Million Gigabytes of data in 3 years

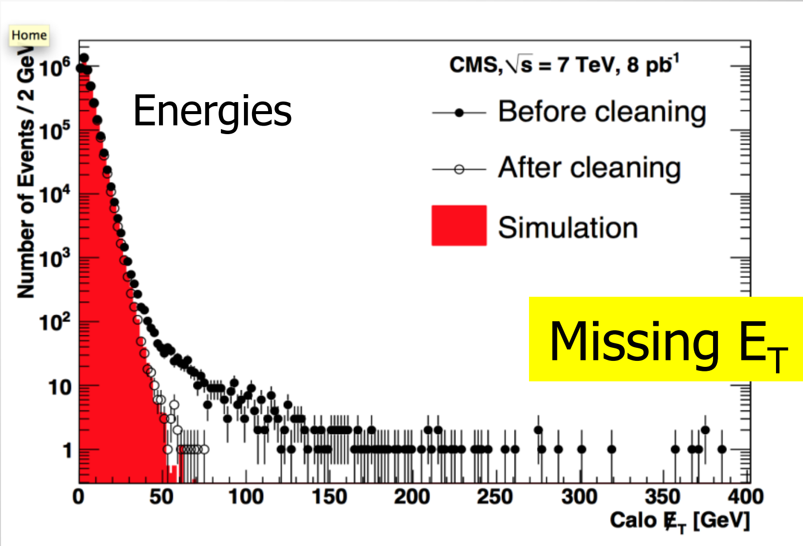
LHC data analysis requires a computing power equivalent to **~100,000 of today's fastest PC processors**

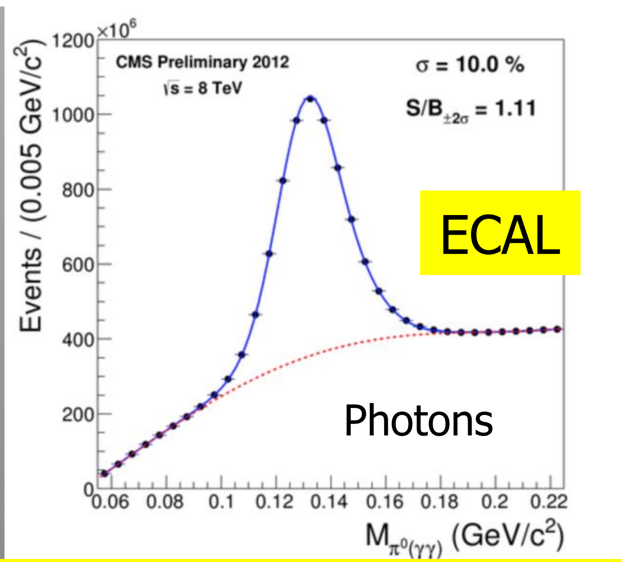
=> Requires many cooperating computer centres, as CERN can only provide ~20% of the capacity

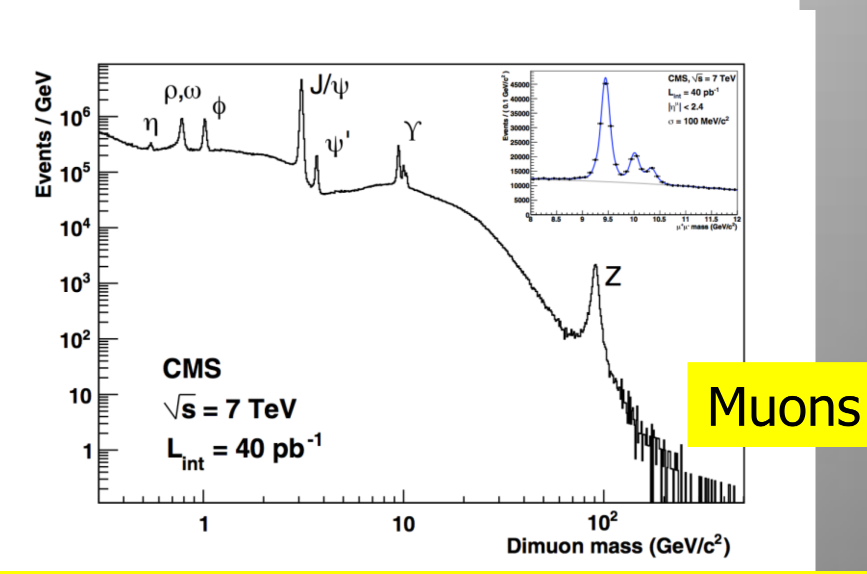
GRID Computing

Object Reconstruction: Examples





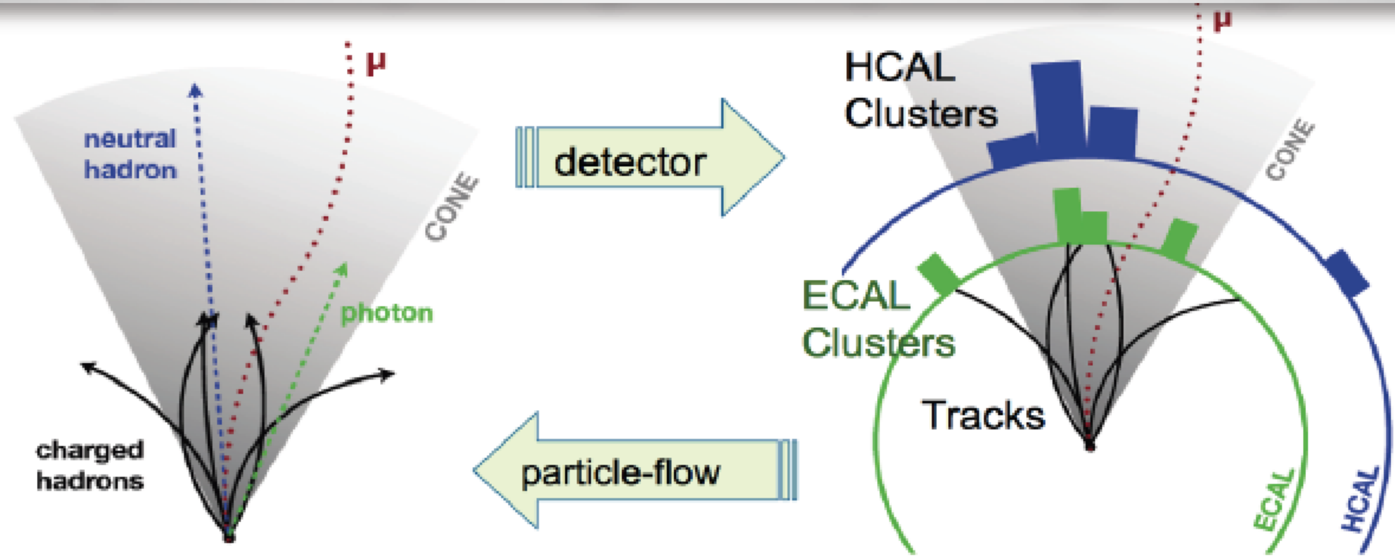




Important! Experiments are not like Monte Carlo Generators: often no unique assignment of particle type/fakes/backgrounds!!

Global Event Reconstruction

Using all information of the detector together for optimal measurement



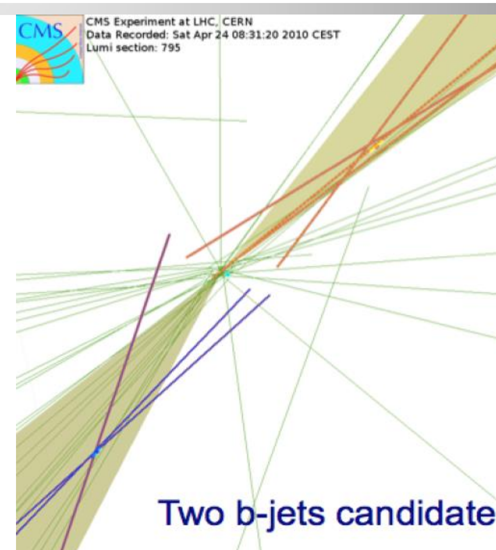
- Optimal combination of information from all subdetectors
- Returns a list of reconstructed particles
  - e,μ,γ, charged and neutral hadrons
    - Used in the analysis as if it came from a list of generated particles
    - Used as building blocks for jets, taus , missing transverse energy , isolation and PU particle identification

Adapted in CMS

B-quark Tagging

Generally: look for jets with displaced vertices (or leptons) from B-meson decays

b-tag efficiency

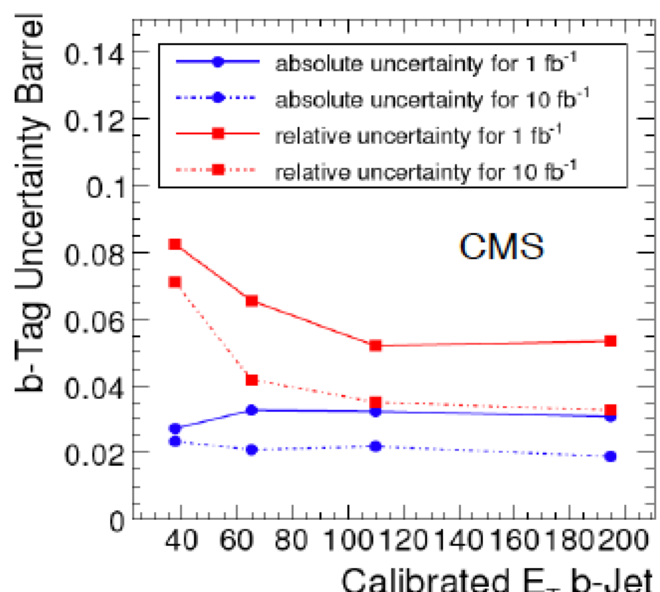


Select b-enriched samples using tt sample

- t → W b ~ 100% → tagging top = tagging b
- Select pure b sample by using tt event topologies
  - 1(2) high p_T leptons, E_{Tmiss}, m_W & m_t constraints
  - 70-80% b-purity after selection

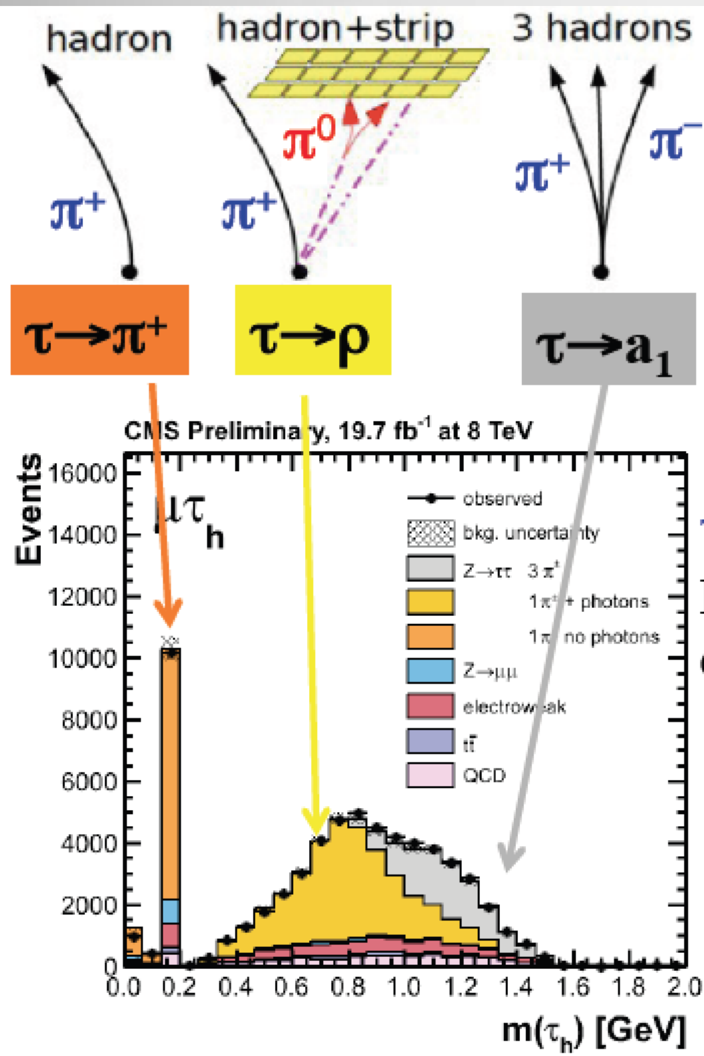
- CMS study 1(10) fb^{-1}
  - Efficiencies 40% to 60% (at $E_{Tb\text{-}Jet}$ > 100) GeV
  - Uncertainty 4-6% for large data samples

- ATLAS study 100 pb^{-1}
  - Similar efficiencies, purities
  - Estimated uncertainty ~10%

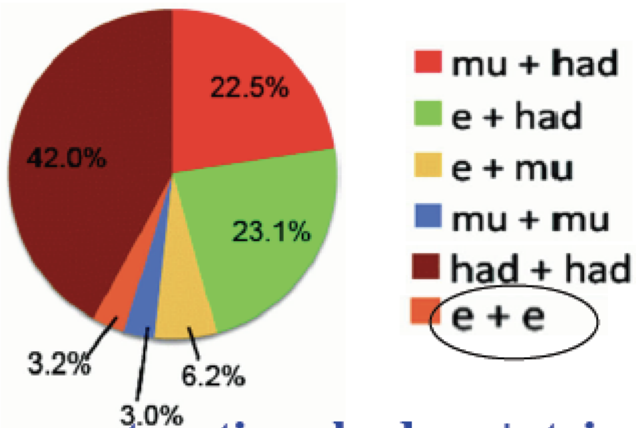


Tau-finding

Hadronic tau decays are narrow low multiplicity 'jets'



All di-tau final states used in Higgs search



Tau reconstruction: hadron+strip

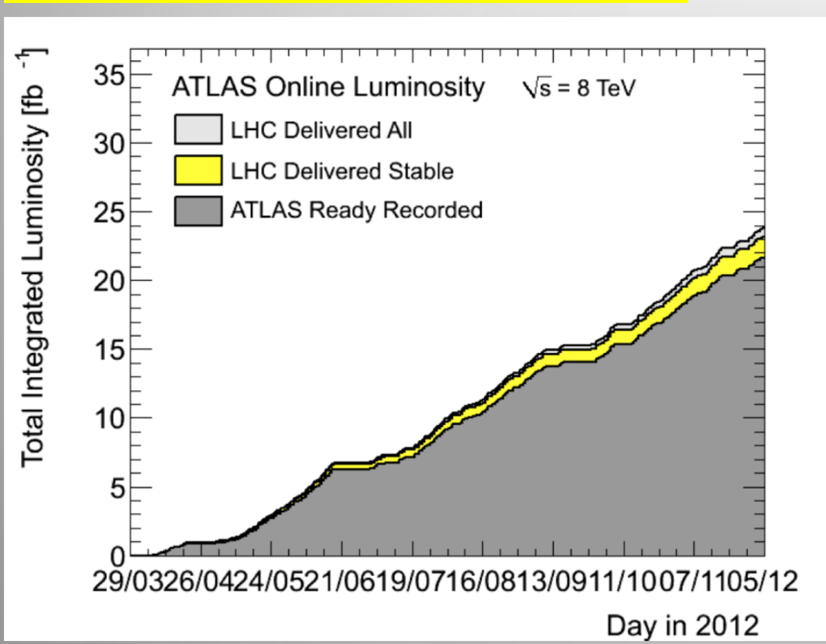
Particle-flow based algorithm to reconstruct different hadronic tau decay modes

τ_h identification: efficiency ~ 60%
fake rate ~ 1%

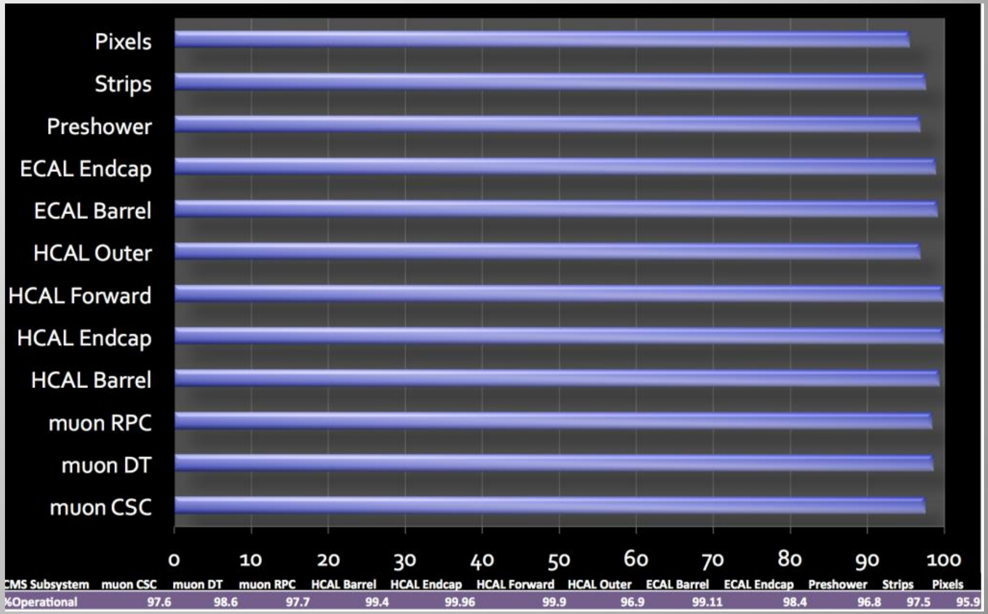
The τ_h mass distribution used to control the tau energy-scale within 3% & reconstruction of decay modes

Operation of the expriments

LHC: pp collisions Luminosity:
5 fb^{-1} @ 7 TeV
20 fb^{-1} @ 8 TeV



CMS: sub-detector operation



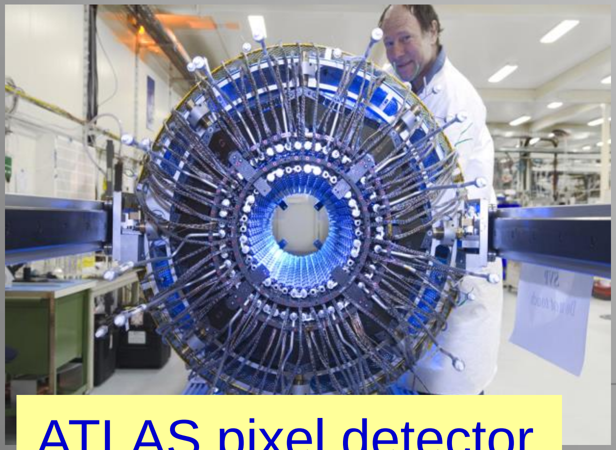
ATLAS: sub-detector operation efficiency in 2012

ATLAS p-p run: April-December 2012										
Inner Tracker			Calorimeters		Muon Spectrometer				Magnets	
Pixel	SCT	TRT	LAr	Tile	MDT	RPC	CSC	TGC	Solenoid	Toroid
99.9	99.4	99.8	99.1	99.6	99.6	99.8	100.	99.6	99.8	99.5
All good for physics: 95.8%										

Luminosity weighted relative detector uptime and good quality data delivery during 2012 stable beams in pp collisions at √s=8 TeV between April 4th and December 6th (in %) – corresponding to 21.6 fb^{-1} of recorded data.

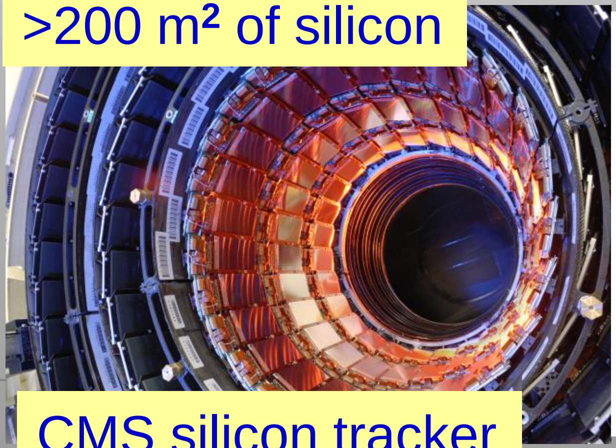
The LHC Detectors are Major Challenges

- CMS/ATLAS detectors have about 100 million read-out channels
- Collisions in the detectors happen every 25 nanoseconds
- ATLAS uses over 3000 km of cables in the experiment
- The data volume recorded at the front-end in CMS is 1 TB/second which is equivalent to the world wide communication network traffic
- Data recorded during the 10-20 years of LHC life will be about all the words spoken by mankind since its appearance on earth
- A worry for the detectors: the kinetic energy of the beam is that of a small aircraft carrier of 10^4 tons going 20 miles/ hour



ATLAS pixel detector

>200 m² of silicon

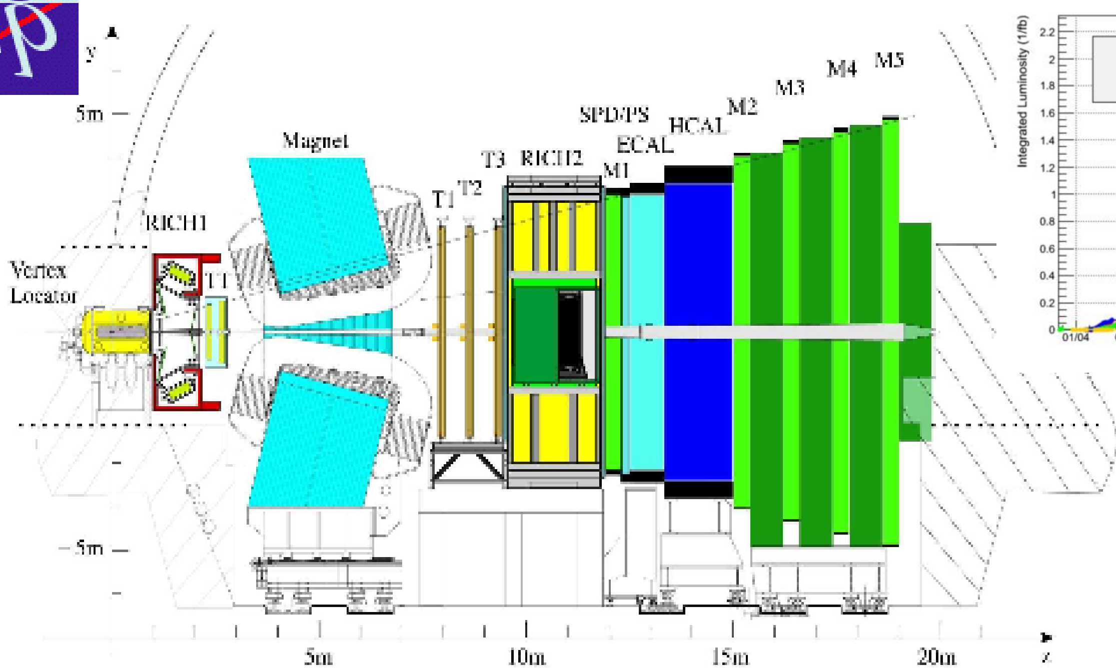


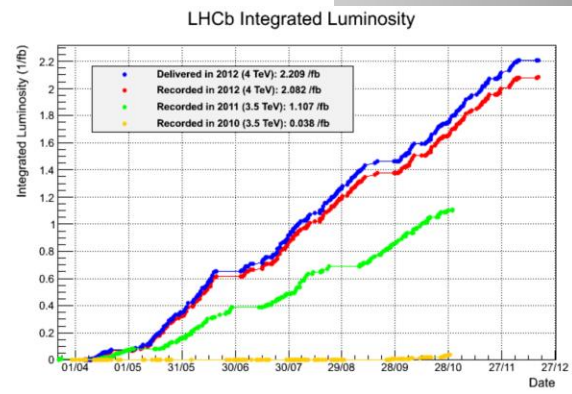
CMS silicon tracker

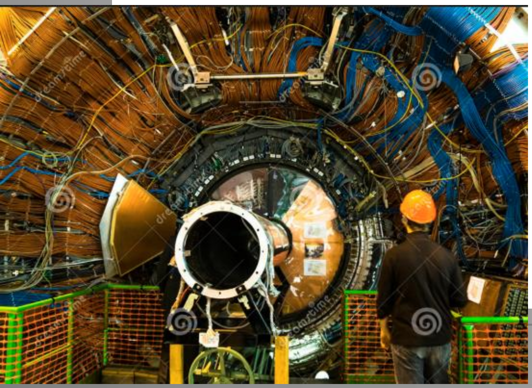
Object	Weight (tons)
Boeing 747 [fully loaded]	200
Endeavor space shuttle	368
ATLAS	7,000
Eiffel Tower	7,300
USS John McCain	8,300
CMS	12,500

Other Experiments at the LHC

LHCb: Bottom and Charm Physics

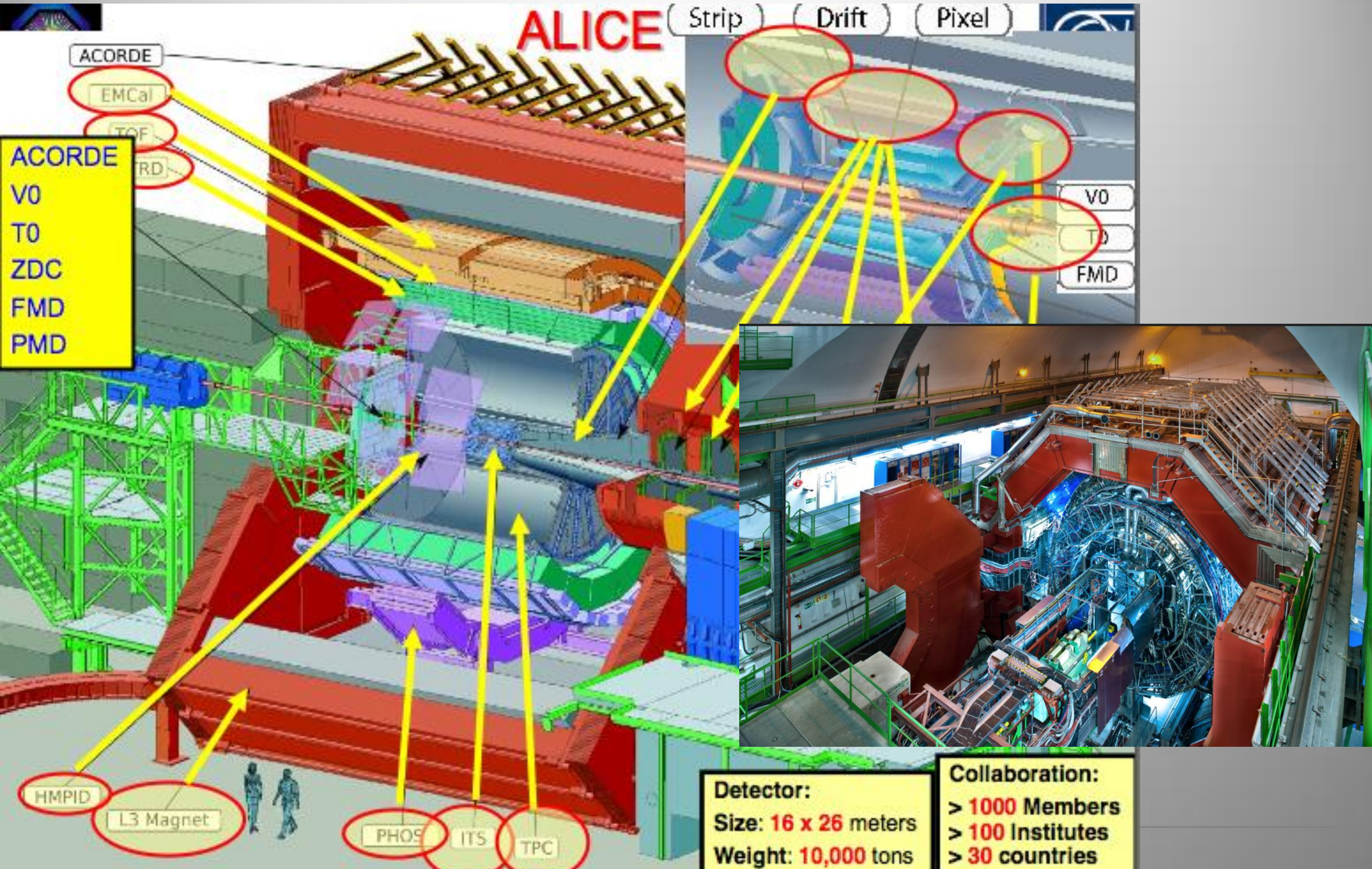






- Forward acceptance ($2 < \eta < 5$) and down to very low p_T
- Precise vertexing (VELO) – hit resolution of down to 4 μm achieved; measurements 8mm from beam-line
- RICH system providing hadron id between 2 and 100 GeV/c
- High performance muon system

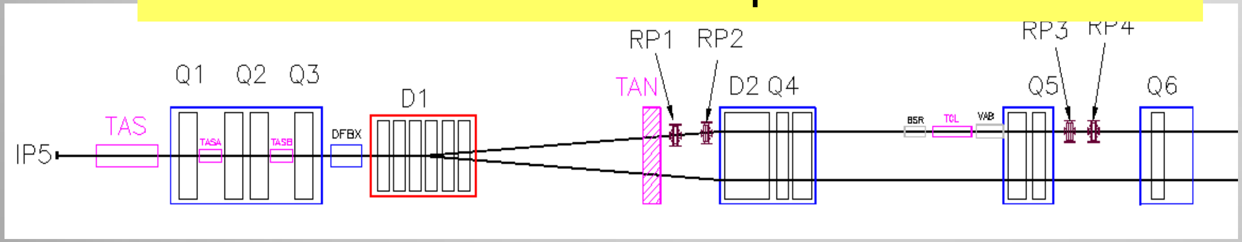
ALICE: Heavy Ion Physics at the LHC

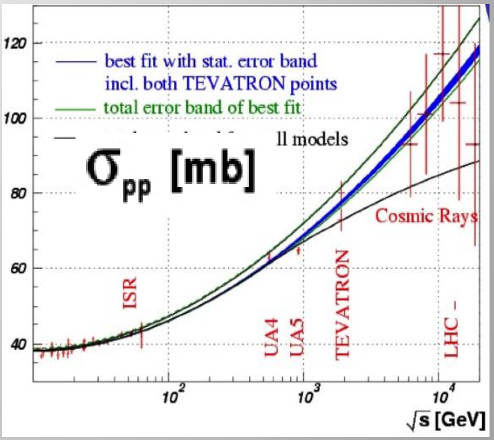


A Few Smaller Experiments: TOTEM & LHCf

TOTEM: measuring the total, elastic and diffractive cross sections
Add Roman pots (and inelastic telescope) to CMS interaction regions (200 m from IP)
Common runs with CMS planned

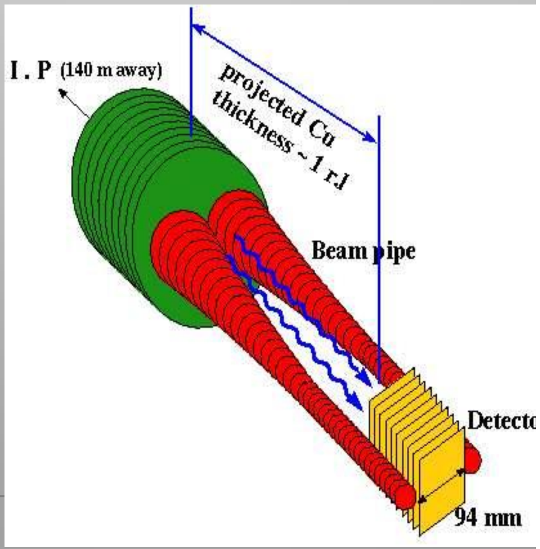
TOTal and Elastic cross section Measurement

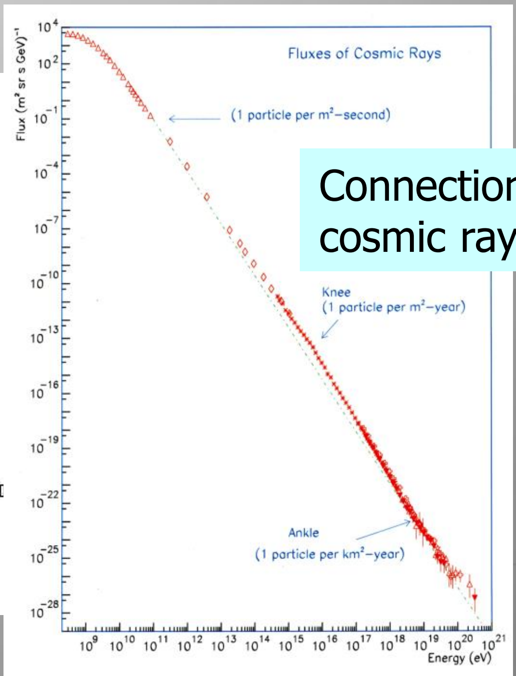




LHCf: measurement of photons and neutral pions in the very forward region of LHC

Add a EM calorimeter at 140 m from the Interaction Point (of ATLAS)

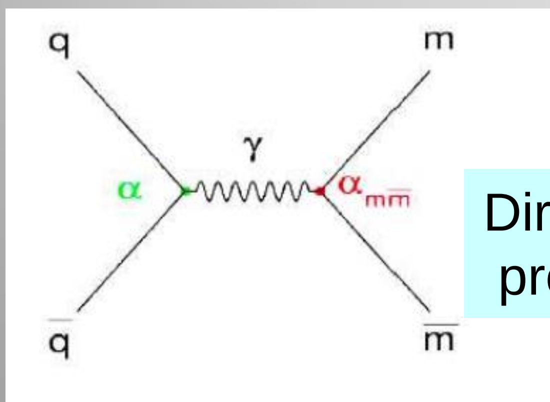




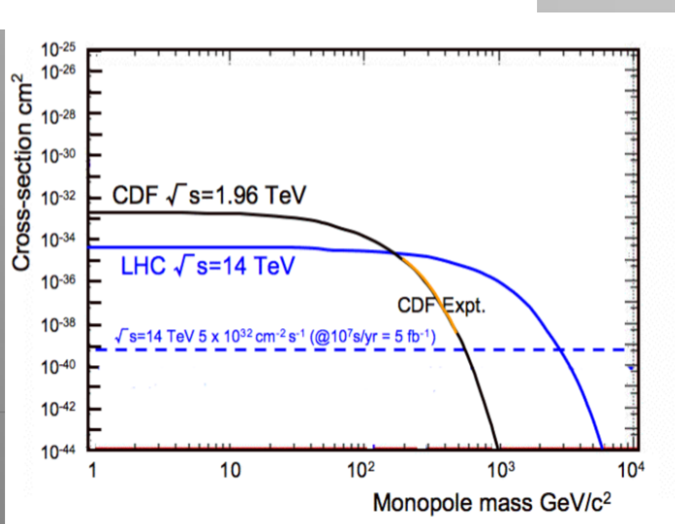
Connection with cosmic rays

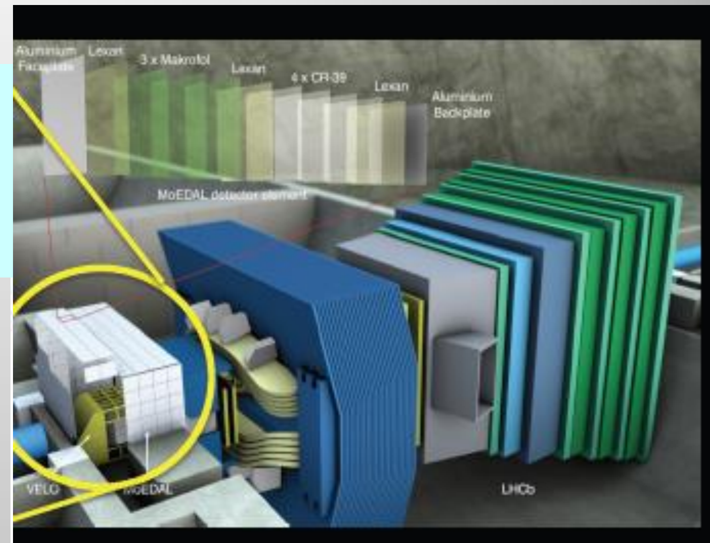
MoEDAL: Monopole and Exotics Detector at the LHC

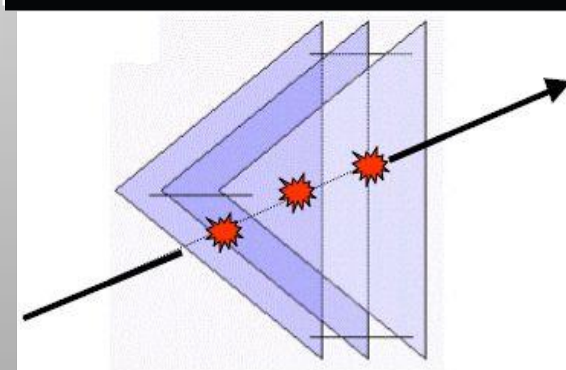
Heavy particles which carry "magnetic charge"
Could eg explain why particles have "integer electric charge"



Direct Monopole production







Remove the sheets after some running time and inspect for 'holes'

Summary: Challenges@ LHC

- High event rate and pile-up
  - High granularity: typically 10x more channels compared to detectors before the LHC
- Timing/synchronization of 10^8 channels is non trivial
- Event size (> 1 Mbyte)/Computing
  - Limit event rate to a few 100 Hz, use the Grid
- Trigger reduce event rate from 40MHz to 100 Hz
  - Multi-layered trigger system and pipelined electronics
- Detectors need excellent hermeticity (missing E_T), lepton identification, B & Tau identification, jet measurements…
- Detectors must be radiation hard and reliable for ~ 10-20 years…

We have these detectors: Let’s look at measurements in Lecture II