The Abdus Salam International Centre for Theoretical Physics

United Nations Educational, Scientific and Cultural Organization

IAEA International Atomic Energy Agency

1970-2

Signaling the Arrival of the LHC Era

8 - 13 December 2008

Current Status of CMS

Albert De Roeck
CERN
Switzerland

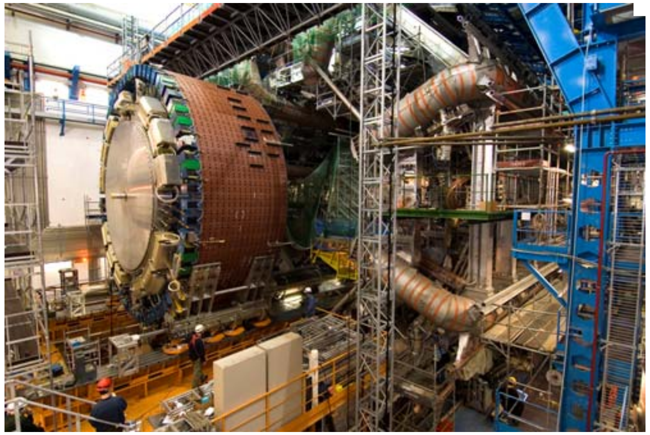
Status of CMS

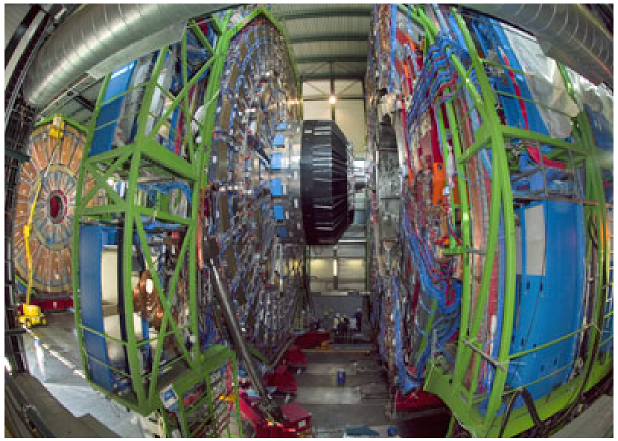
Albert De Roeck
CERN
and University of Antwerp
and the IPPP Durham

SIGNALING THE ARRIVAL OF THE LHC ERA

8 - 13 December 2008

Miramare, Trieste, Italy

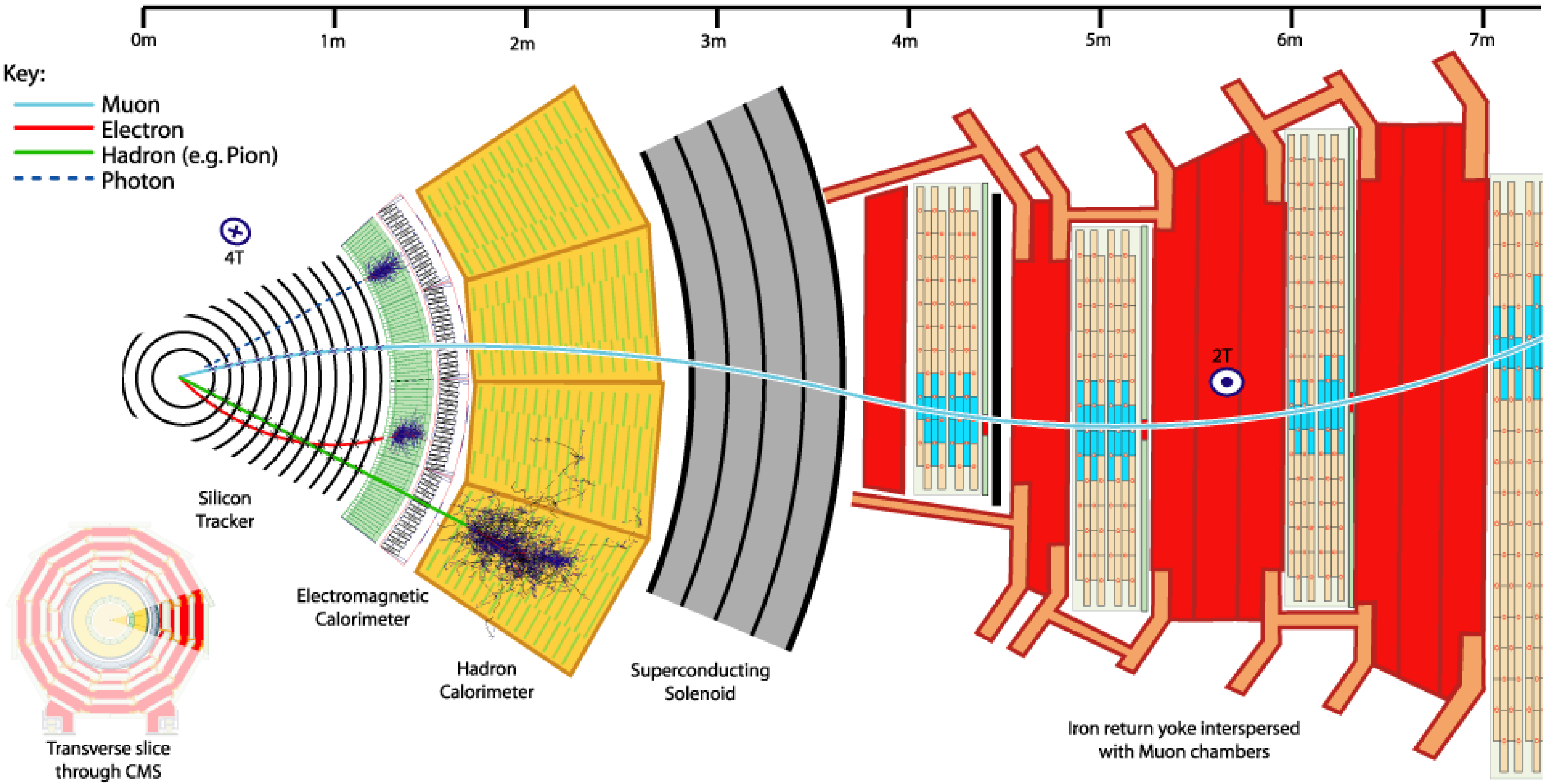




LHCf

Experiments at the LHC

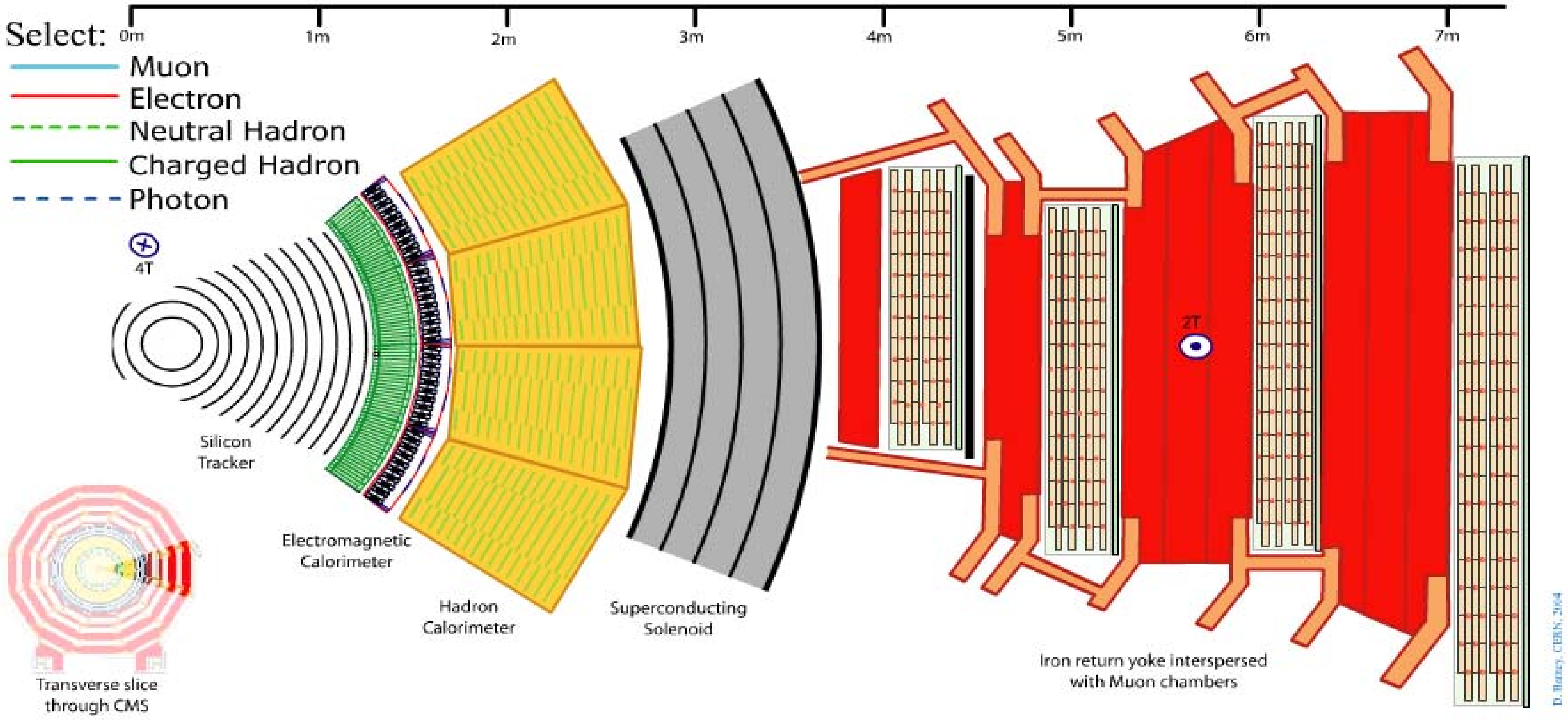
Particles in the detector



Transverse slice through CMS detector

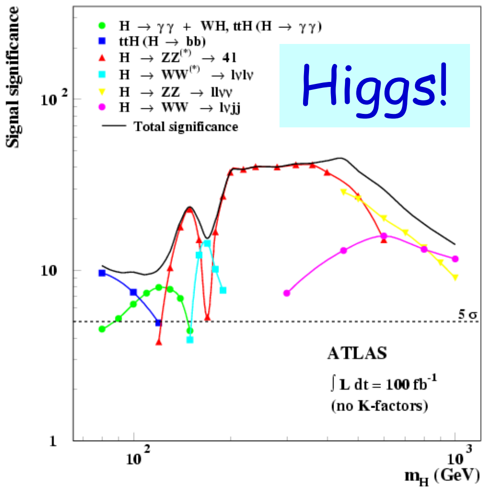
Click on a particle type to visualise that particle in CMS

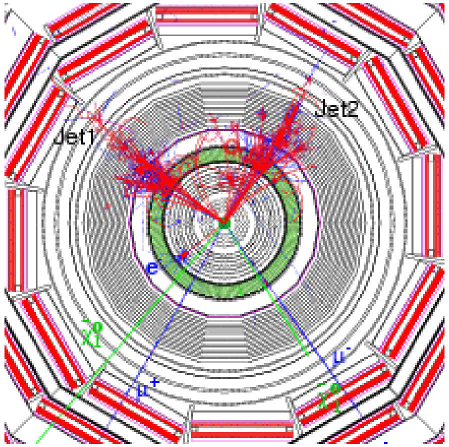
Press "escape" to exit



Physics at the LHC: pp @ 14 TeV

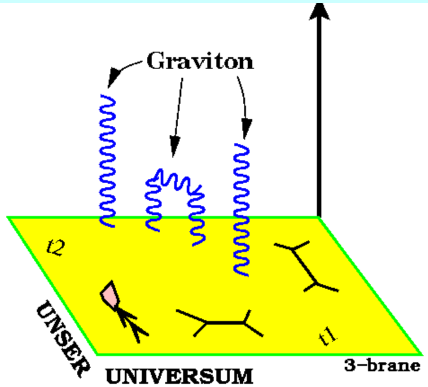
Higgs!



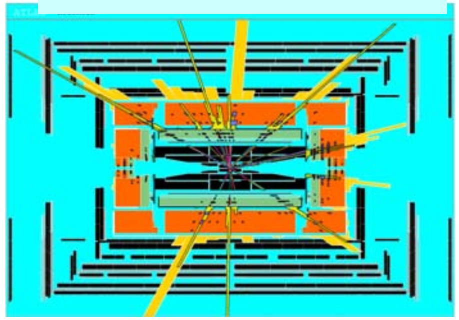


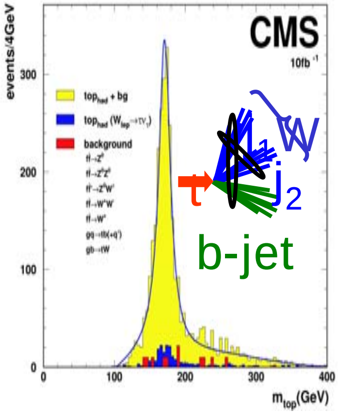
Supersymmetry?

Extra Dimensions?



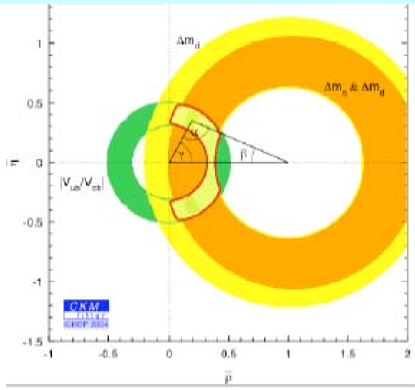
Black Holes???



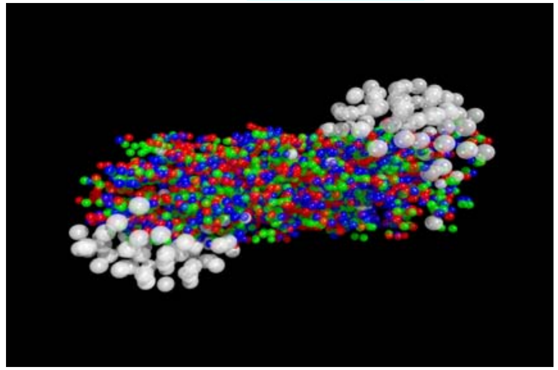


Precision measurements e.g top!

unitarity triangle!

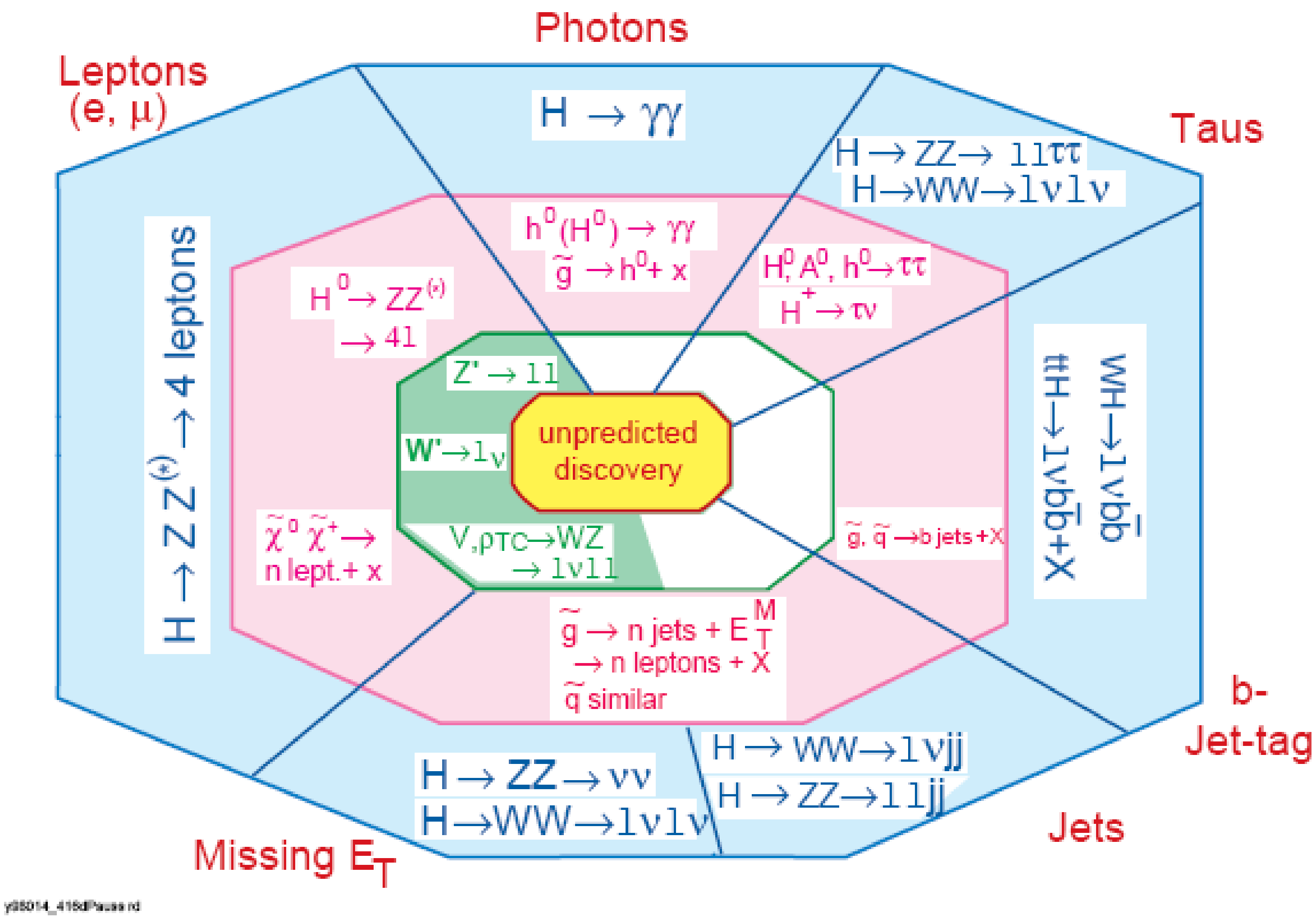


QGP?



The LHC will be the new collider energy frontier

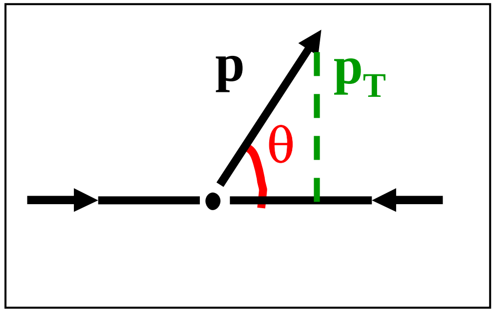
How to search for new particles?



T Han

Kinematic Variables for pp scattering

- Transverse momentum, p_T and E_T=E sinθ
  - 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

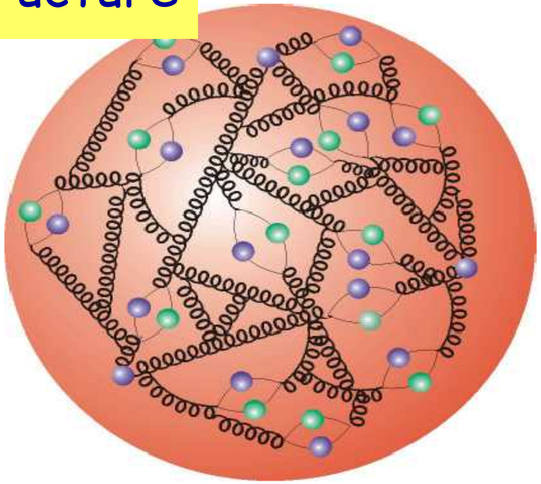
$$y = \eta = -\ln(\tan\frac{\theta}{2})$$

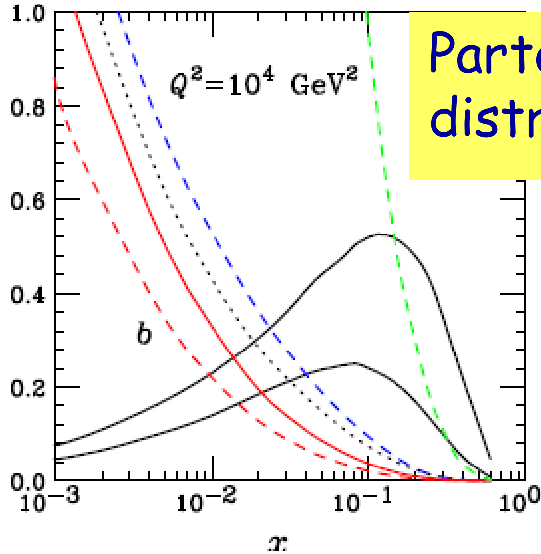
- Missing E_T and P_T

Challenges for Experiments at the LHC

pp Collisons : Complications

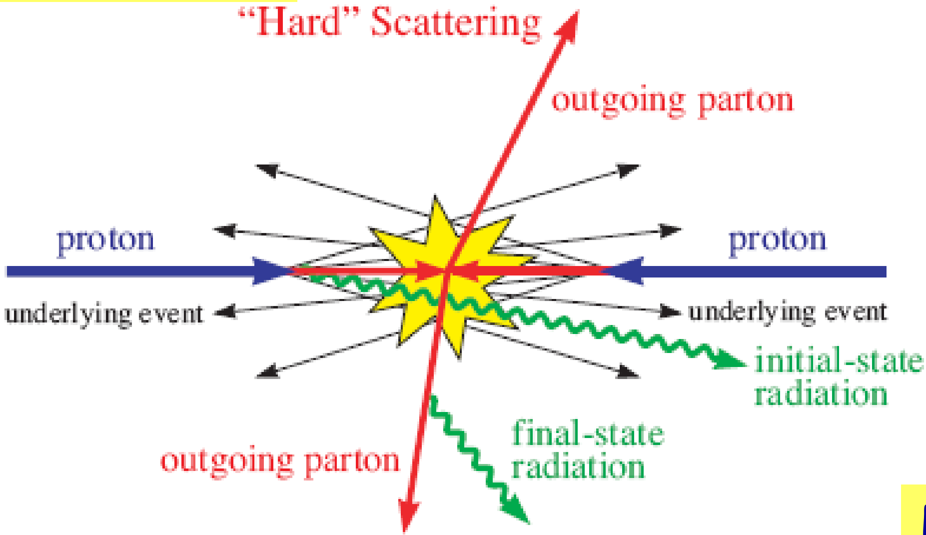
Protons have structure





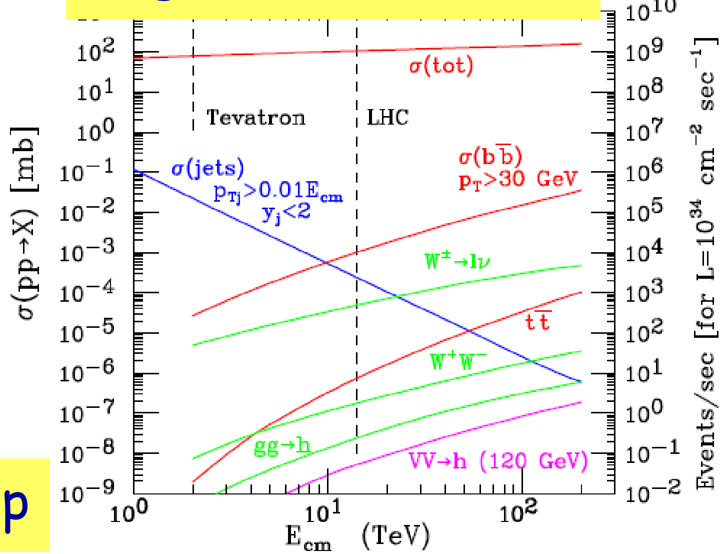
Parton distributions

Underlying event



Scattering cross sections for various SM processes:

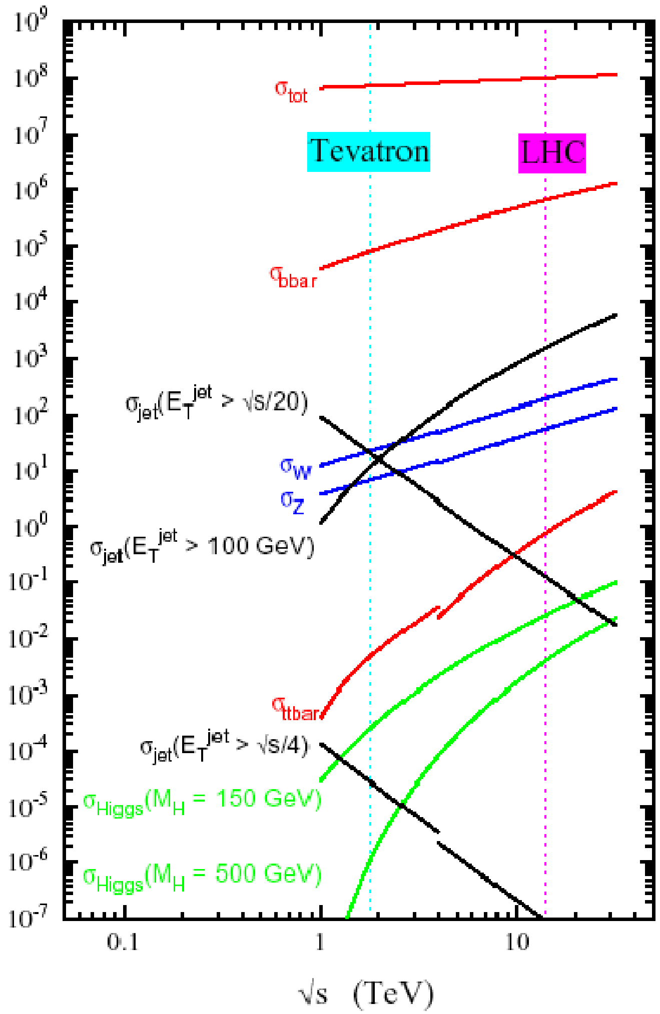
Huge cross sections



Pile-up

Event Rates for pp at $\sqrt{s}$=14 TeV

Process	Events/s	Events/year	Other machines
$W \rightarrow e\nu$	15	10^8	10^4 LEP / 10^7 Tev
$Z \rightarrow ee$	1.5	10^7	10^7 LEP
$t\bar{t}$	0.8	10^7	10^4 Tevatron
$b\bar{b}$	10^5	10^{12}	10^8 Belle/BaBar
$\tilde{g}\tilde{g}$ (m=1 TeV)	0.001	10^4	—
H (m=0.8 TeV)	0.001	10^4	—
Black Holes M_D=3 TeV n=4	0.0001	10^3	



Luminosity $10^{33}cm^{-2}s^{-1}$

In the first 3 minutes at $10^{33} cm^{-2}s^{-1}$
LHC will produce per experiment:

- ~5000 $W \rightarrow \mu\nu, e\nu$ decays
- ~ 500 $Z \rightarrow \mu\mu, ee$ decays
- ~2.10^7 bottom quark pairs
- ~150 top quark pairs
- ~10 Higgs particles (M_H=120 GeV)
- ~20 gluino pairs with mass 500 GeV
- A quantum black hole (M_D = 2TeV)
- ….

Startup luminosity at 14 TeV will be much lower, perhaps like 10^{31}-10^{32} $cm^{-2}s^{-1}$ (less bunches/current)

Data Recording ~ 20K events/30Gbyte

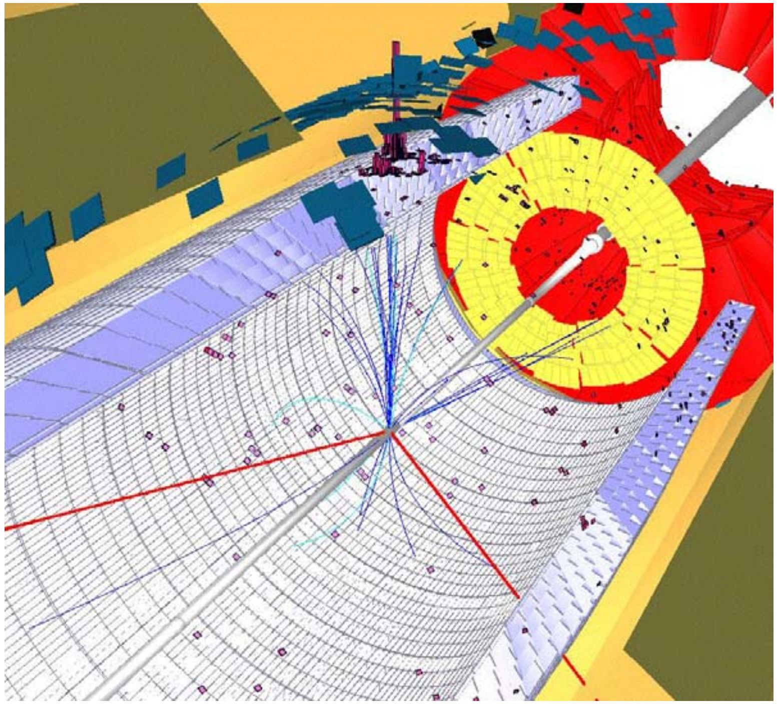
Pile-up at the LHC

Pile-up ⇒ additional -mostly soft- interactions per bunch crossing

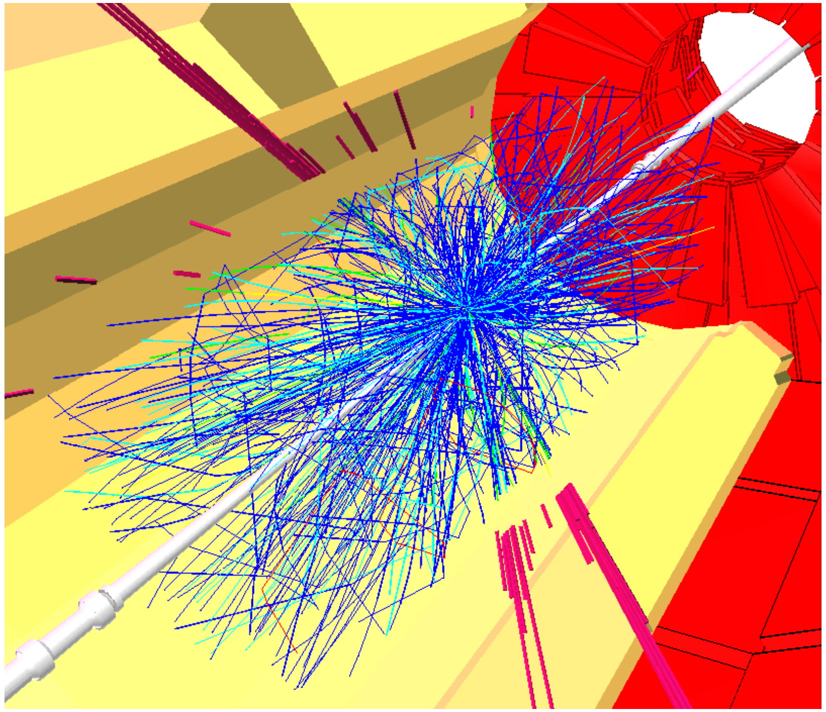
Startup luminosity $2 \bullet 10^{33} cm^{-2} s^{-1}$ ⇒~4 events per bunch crossing

High luminosity $10^{34} cm^{-2} s^{-1}$ ⇒ ~20 events per bunch crossing

Luminosity upgrade $10^{35} cm^{-2} s^{-1}$ ⇒ ~200 events per bunch crossing



SUSY event (no pileup)

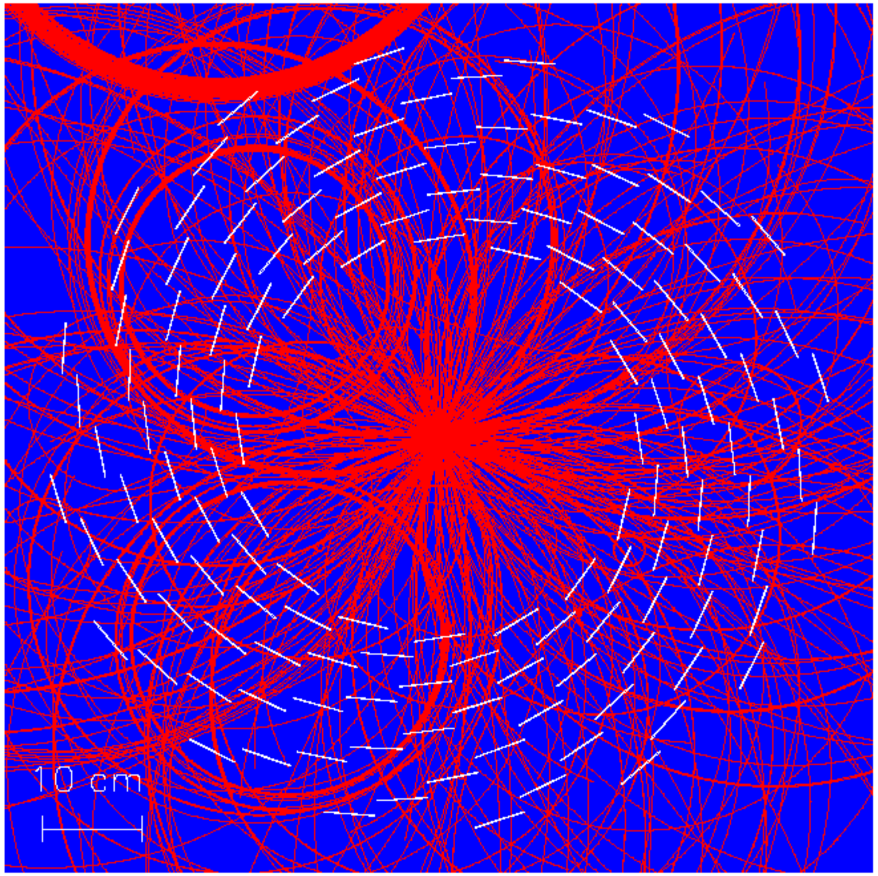


SUSY event ($10^{34} cm^{-2} s^{-1}$)

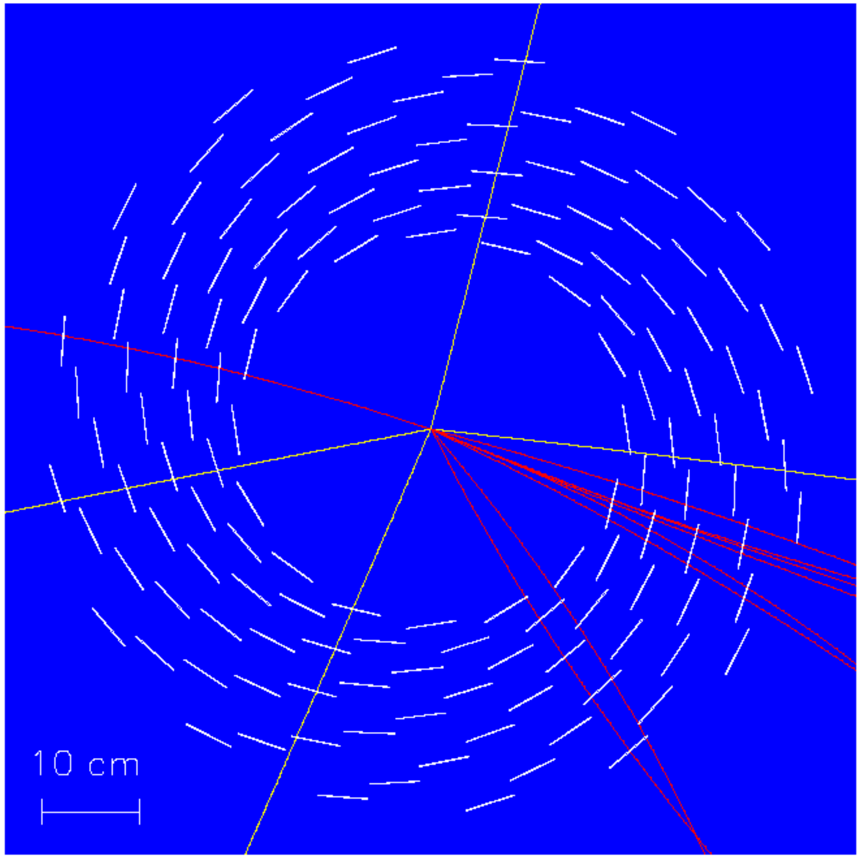
How to find the interesting signals

This event contains pp $\rightarrow H+X$, with $H \rightarrow ZZ \rightarrow \mu\mu\mu\mu$

$\Rightarrow$ X ~ 100 charged particles



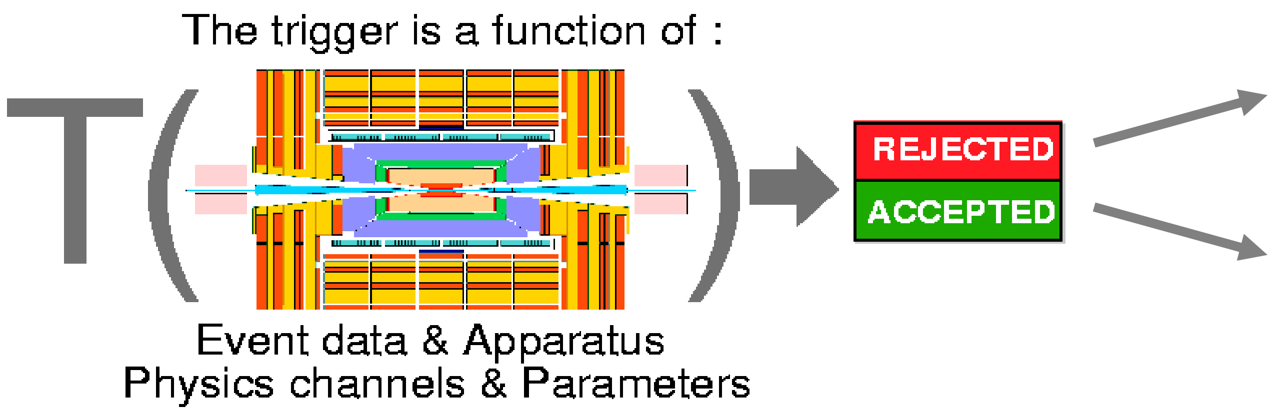
All tracks shown



Only tracks with transverse momentum > 2 GeV shown

Event filtering: the trigger system

Collision rate is 40 MHz   Event size ~1.5 Mbyte
2007 technology (and budget) allows only to write 100 Hz of events to tape → need a factor ~10^7 online filtering!!

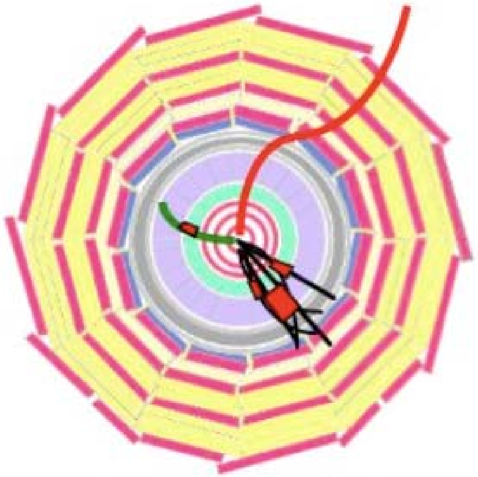


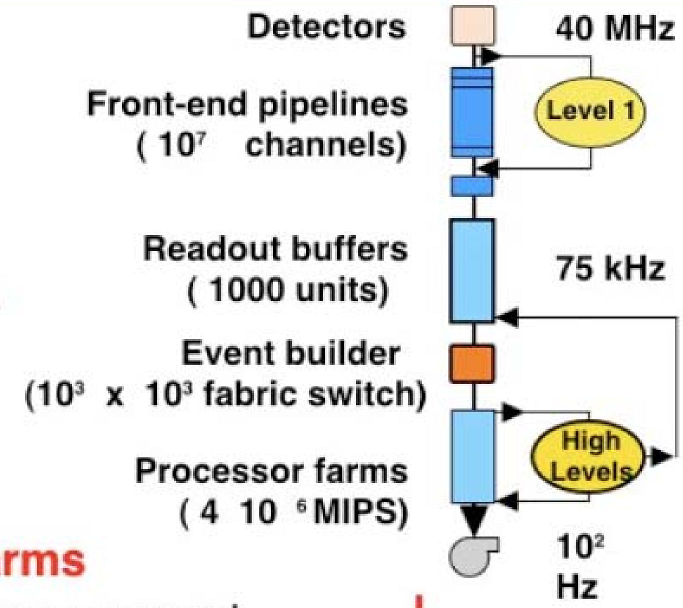
lost forever!!

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 Et,…

Example: CMS trigger





High level triggers. CPU farms

- Finer granularity precise measurement
- Clean particle signature (π^0-γ, isolation, ...)
- Kinematics. Effective mass cuts and topology
- Track reco and matching, b,τ-jet tagging
- Full event reconstruction and analysis

Successive improvements : background event filtering, physics selection

NB: Similar output rate at the Tevatron

17

Example: CMS HLT trigger table

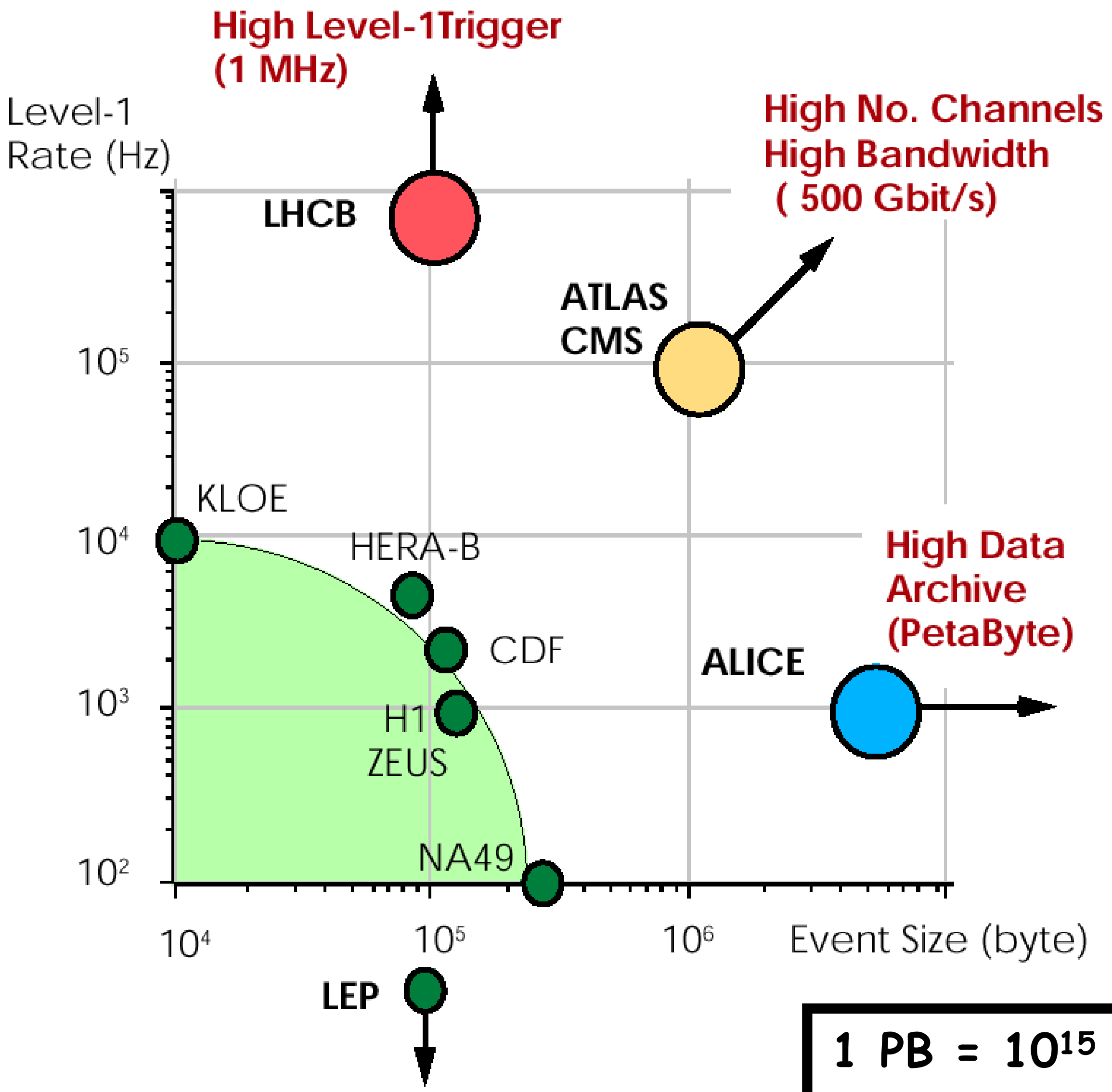
Trigger	Threshold (GeV or GeV/c)	Rate (Hz)	Cumulative Rate (Hz)
inclusive electron	29	33	33
di-electron	17	1	34
inclusive photon	80	4	38
di-photon	40, 25	5	43
inclusive muon	19	25	68
di-muon	7	4	72
τ-jet * $\not{E}_T$	86 * 65	1	73
di-τ-jets	59	3	76
1-jet * $\not{E}_T$	180 * 123	5	81
1-jet OR 3-jets OR 4-jets	657, 247, 113	9	89
electron * τ-jet	19 * 45	0.4	89.4
muon * τ-jet	15 * 40	0.2	89.6
inclusive b-jet	237	5	94.6
calibration and other events (10%)*		10	105
TOTAL			**105**

CMS DAQ TDR 2002

Similar numbers for ATLAS

More combined triggers as eg. jets + leptons or leptons + MET possible will be included as well

Comparison of LHC with other experiments



Huge computing Effort!

- >1 PB of raw data/year
- 3000 CPU's at CERN
  + >5000 in regional centers
- Data GRID project
  ⇒ LHC experiments are heavily involved

The grid will be important for LHC data analysis

1 PB = 10^{15} B =1 000 000 000 000 000 Bytes

The LHC Data Challenge

The LHC accelerator will run for 10-15 years

Experiments will produce about **15 Million Gigabytes** of data each year (about 20 million CDs!)

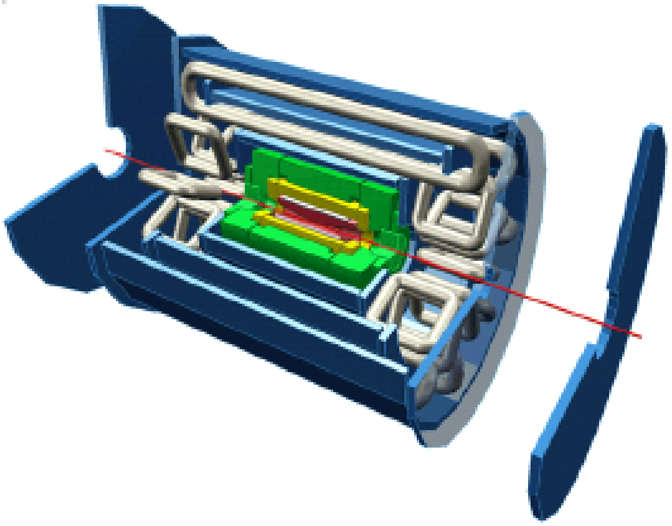
LHC data analysis requires a computing power equivalent to **~100,000 of today's fastest PC processors**

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

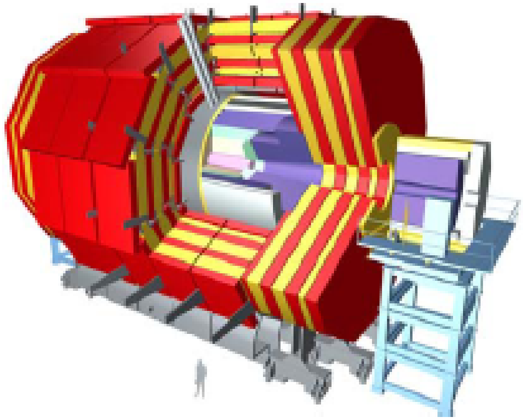
The CMS Detector

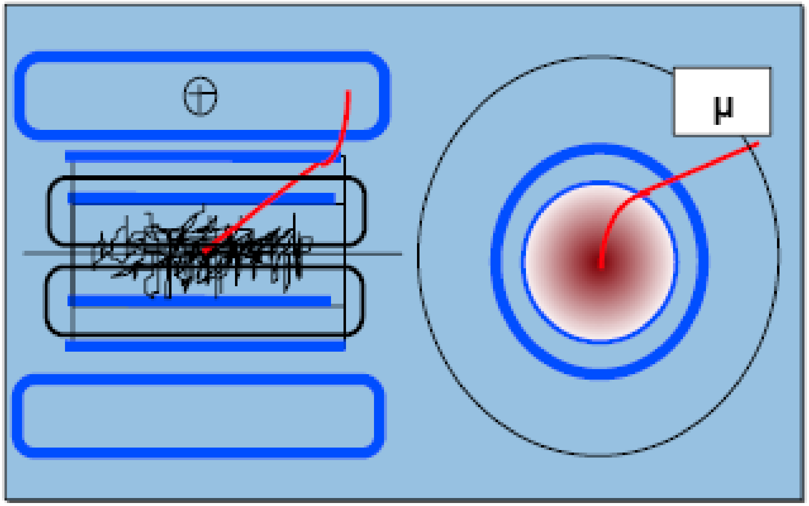
General Purpose Detectors at the LHC

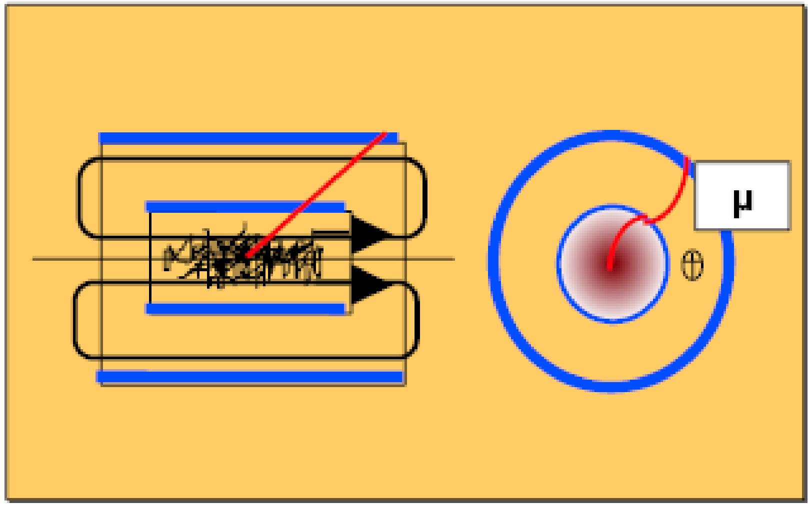
ATLAS A Toroidal LHC ApparatuS



CMS Compact Muon Solenoid







In total about

~100 000 000 electronic channels

Each channel checked

40 000 000 times per second (collision rate is 40 MHz)

Amount of data of just one collisions

>1 500 000 Bytes

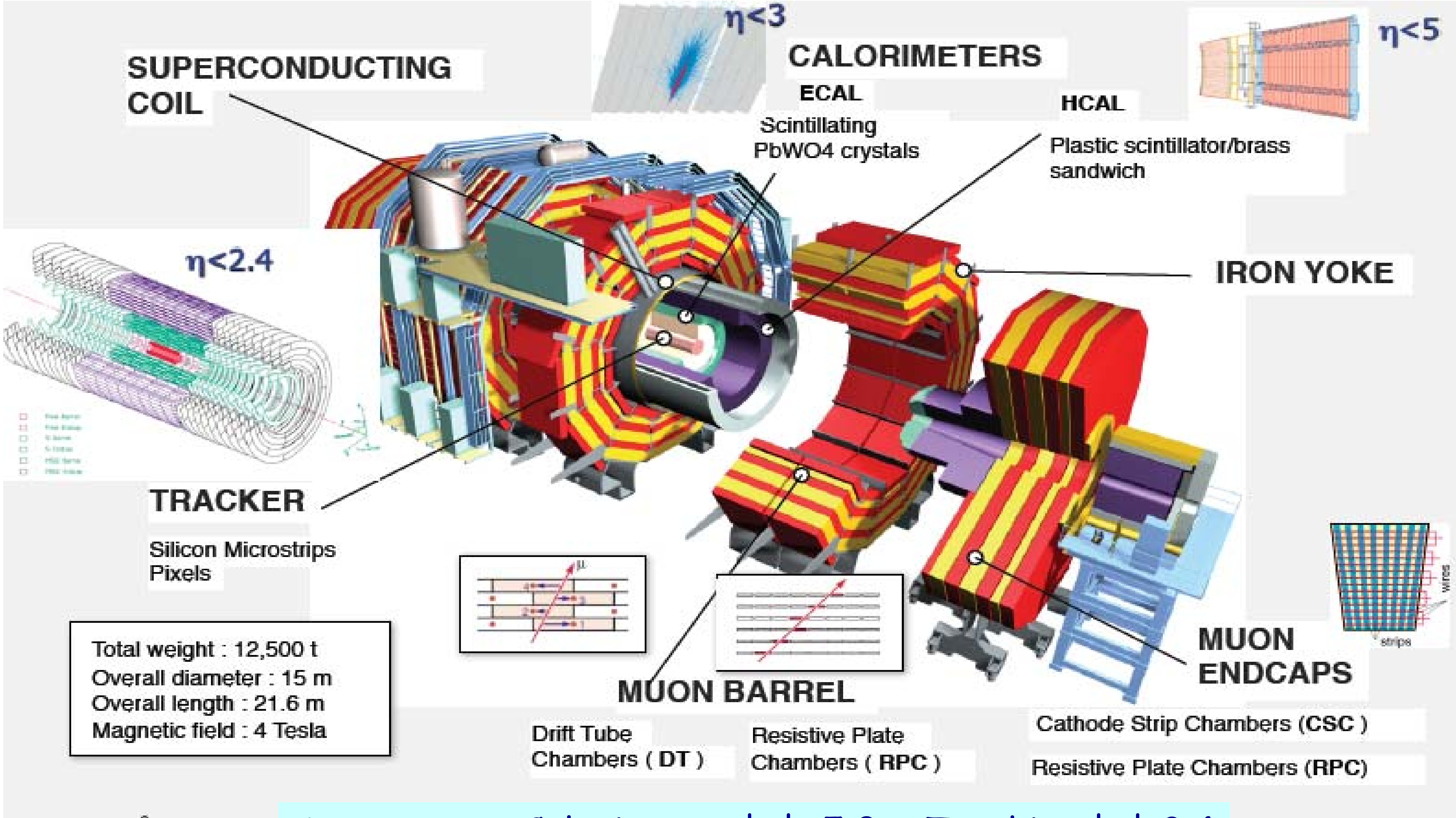
Trigger (online event selection)

Reduce 40 MHz collision rate to ~100 Hz data recording rate

Readout to disk

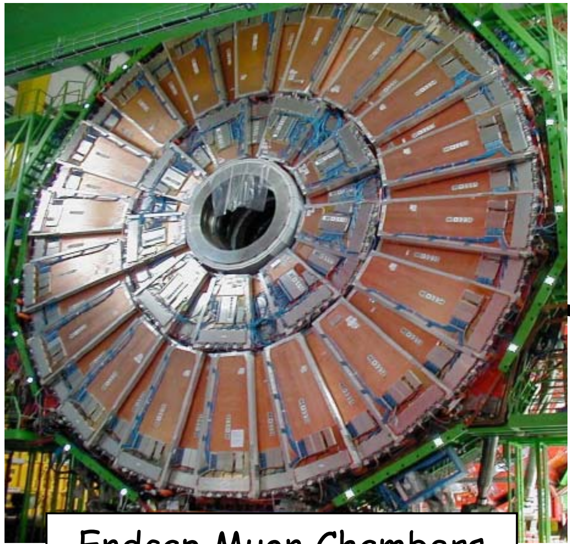
~200 collisions/sec ⇒ pentaBytes of data/year

The Modular Design of CMS

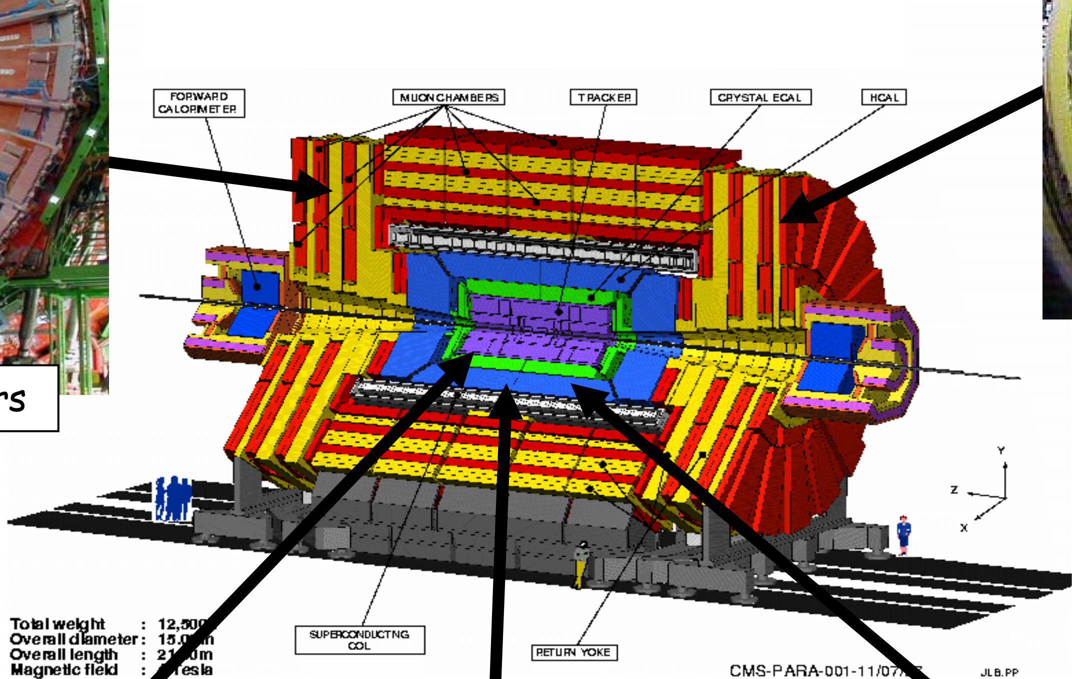


Acceptance: Calorimetry $|\eta| < 5.0$ Tracking $|\eta| < 2.4$

CMS



Endcap Muon Chambers

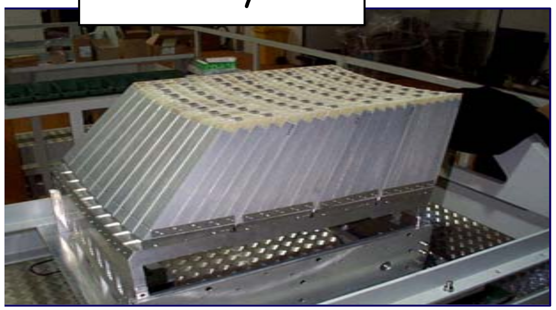


Coil + inner vacuum tank

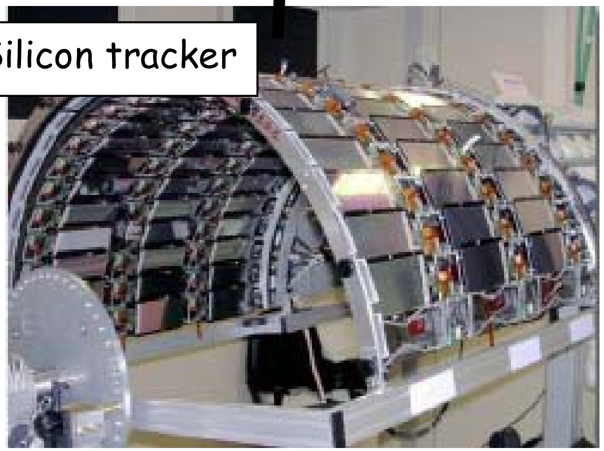
Length : ~20 m
Radius : ~7 m
Weight : ~ 13000 tons

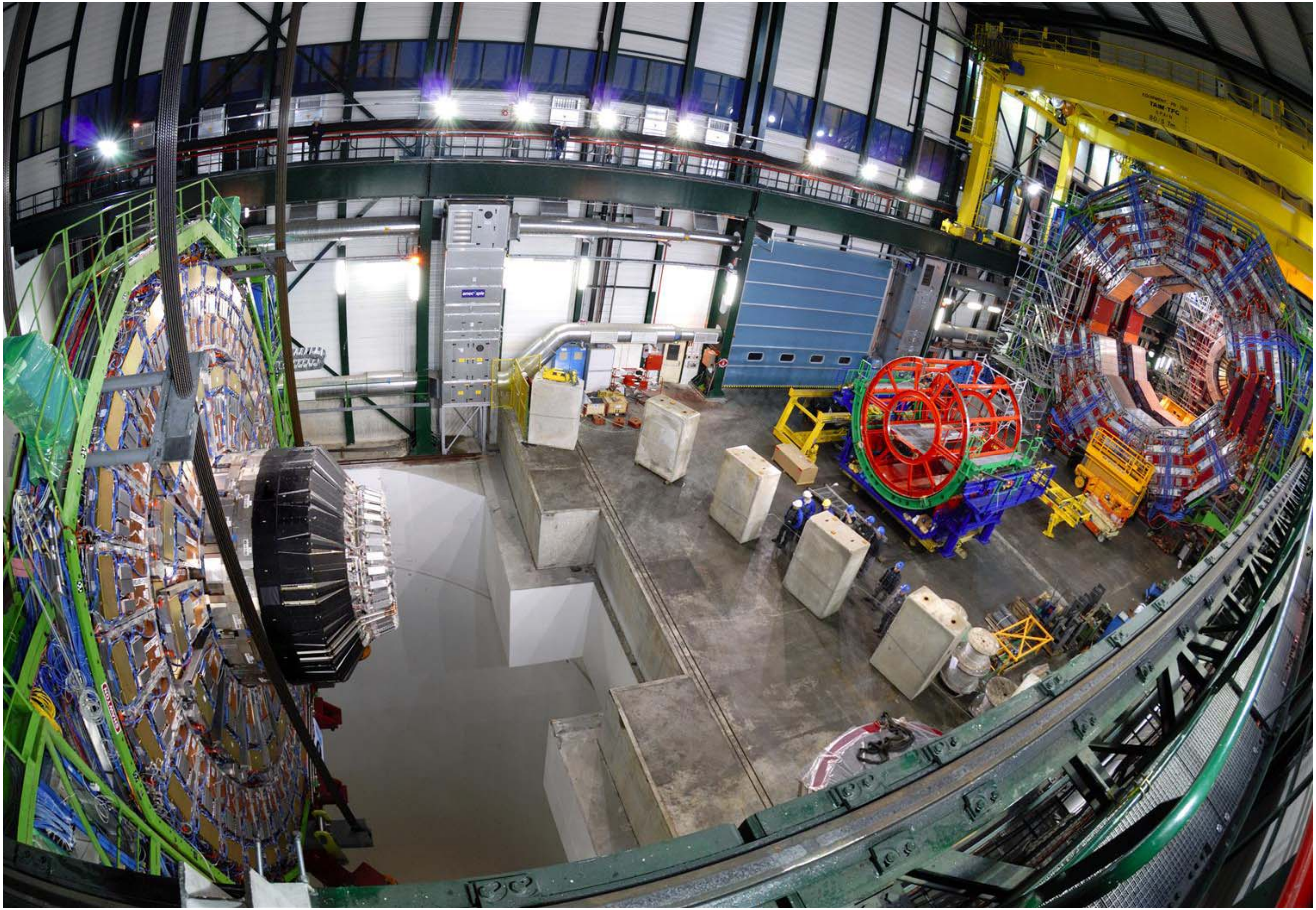
Barrel HCAL

ECAL crystals



Silicon tracker




TAIM-TFC
SPAIN

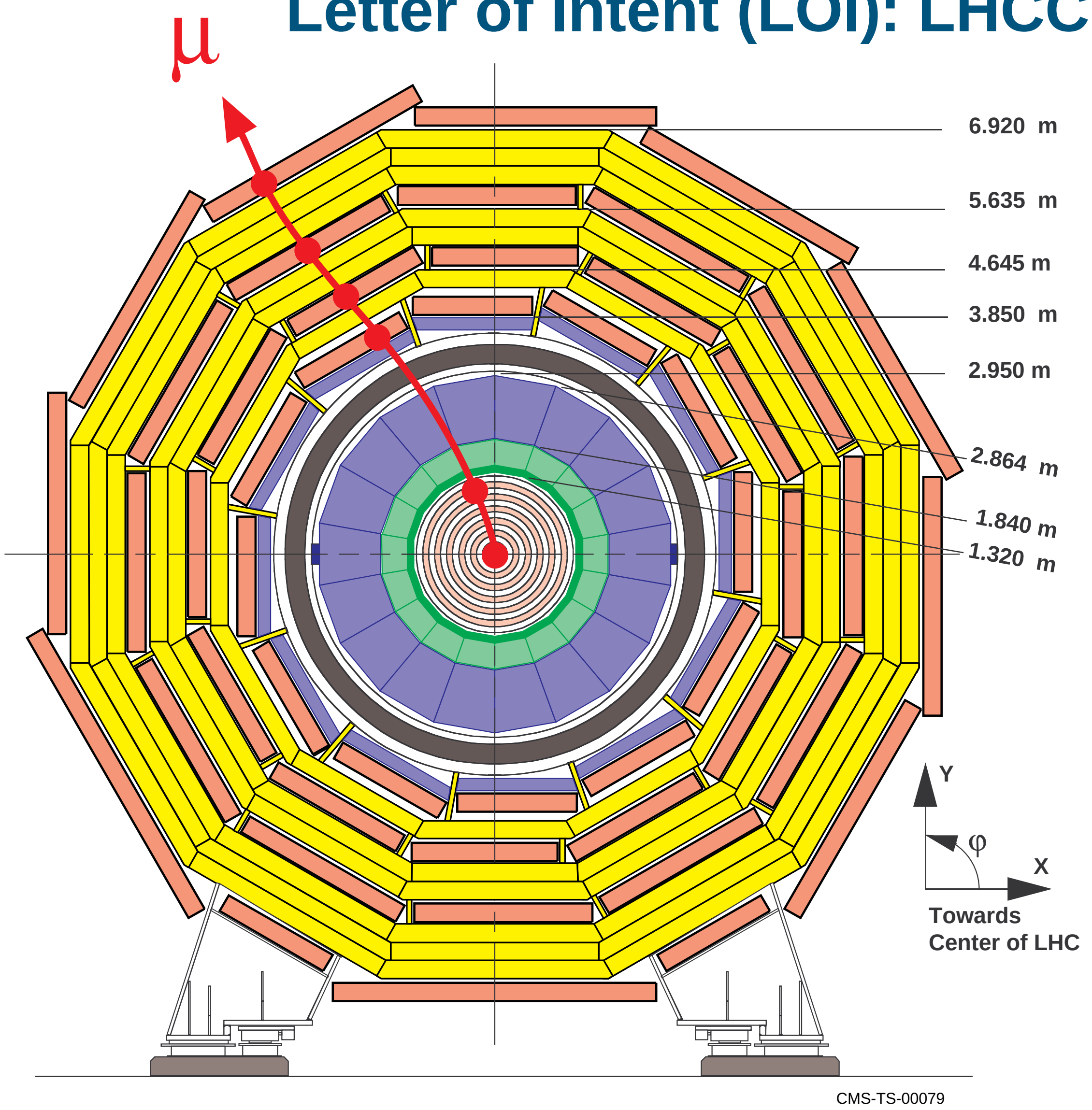
CMS Detector Design Priorities

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



Transverse View

Strong Field 4T

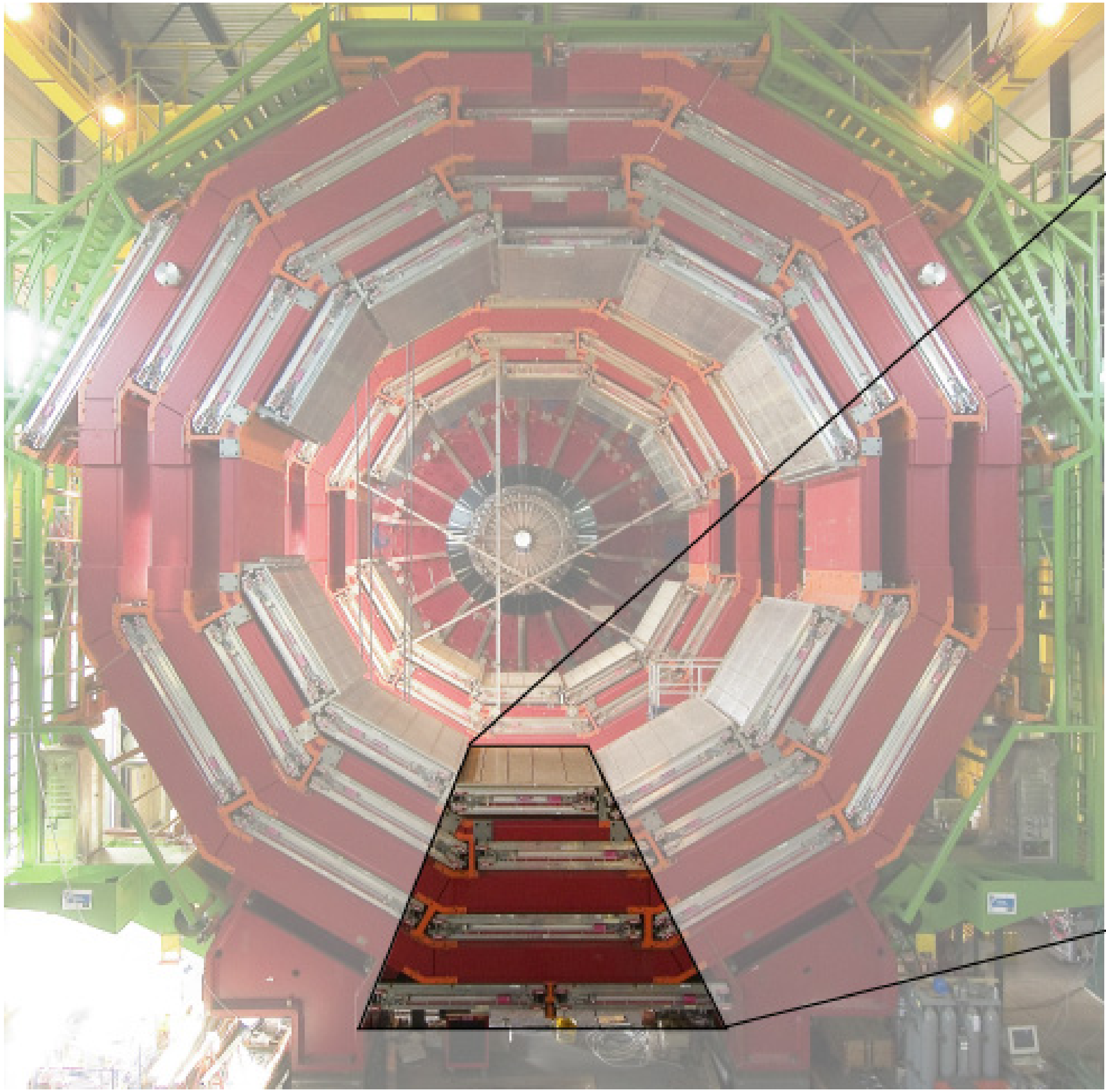
Compact design

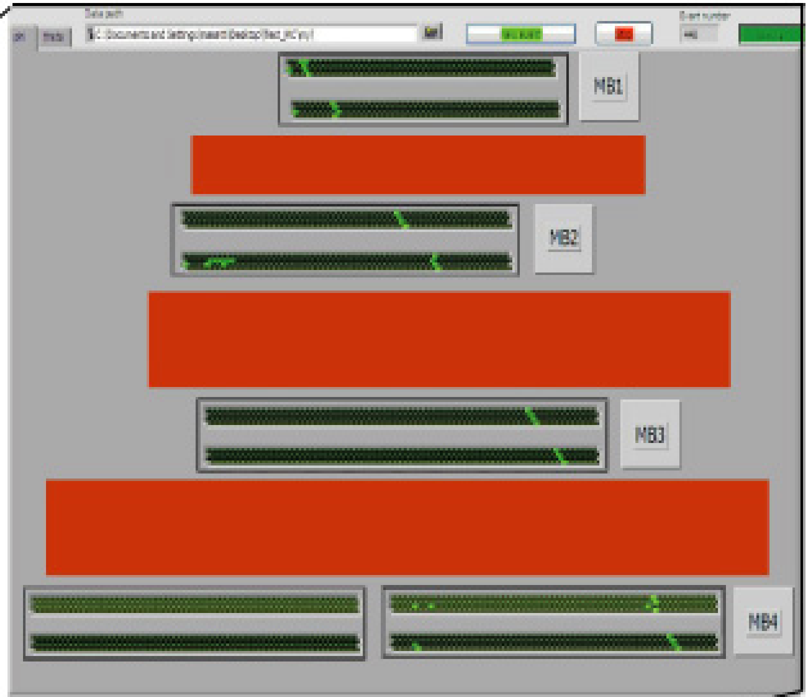
Solenoid for Muon P_t trigger in transverse plane

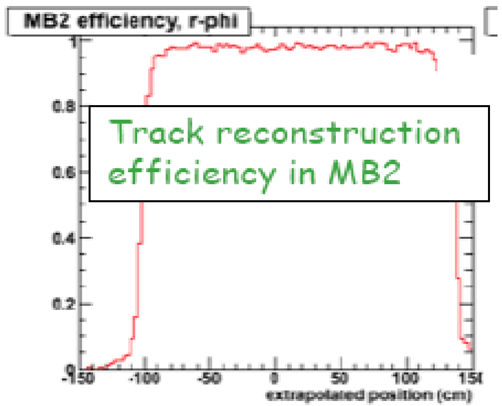
Redundancy: 4 muon stations with 32 r-phi measurements

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

December 2005
Cosmic Muons in CMS





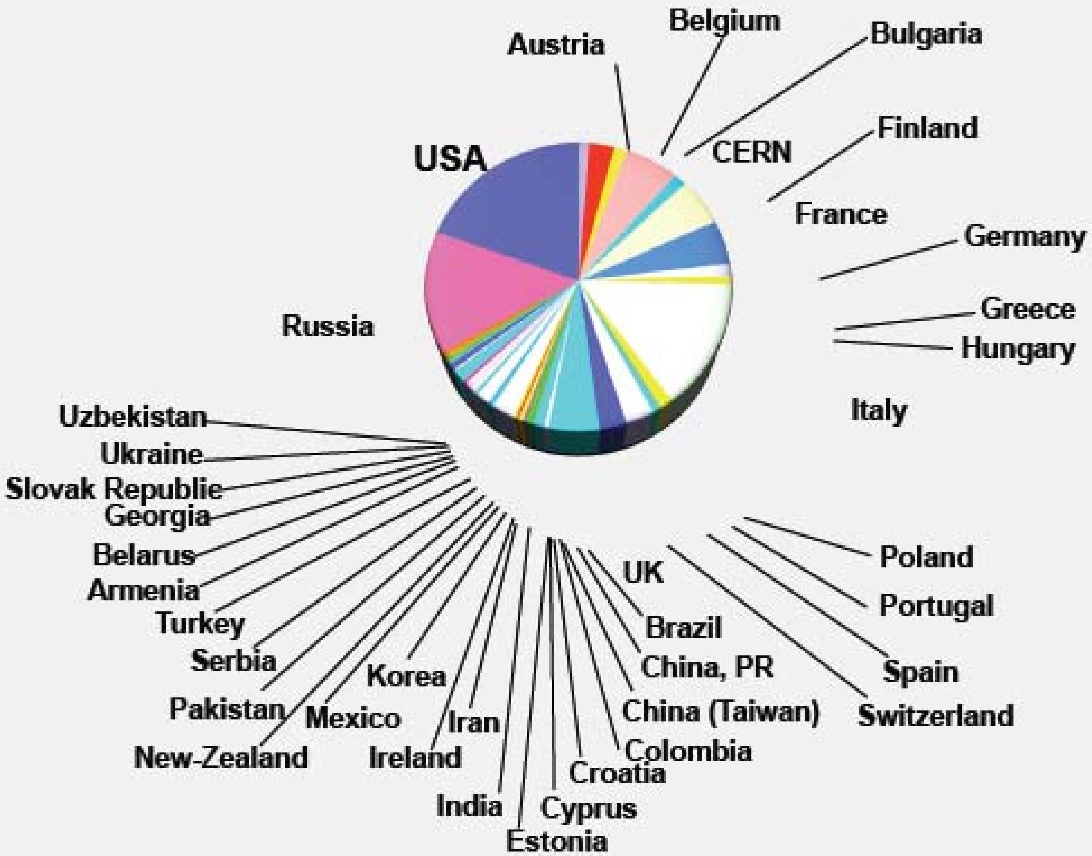


CMS Collaboration

	Institutions
Member States	61
Non-Mem. States	64
USA	49
Total	174

	Scientists
Member States	1055
Non-Mem. States	428
USA	547
Total	2030

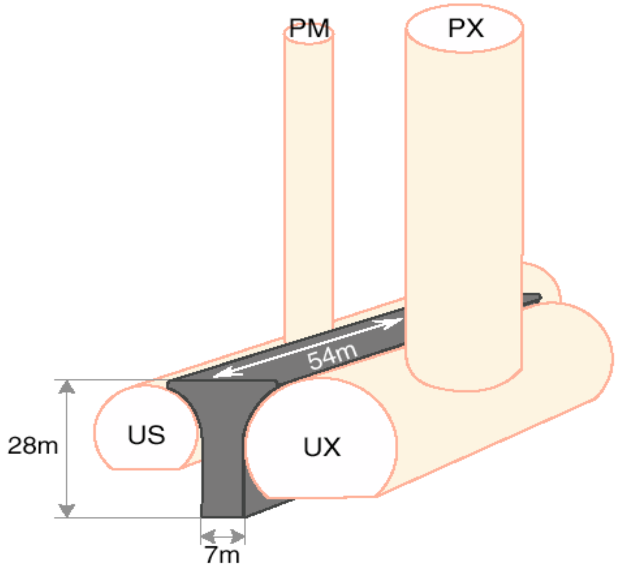
Associated Institutes	
Number of Scientists	46
Number of Laboratories	8



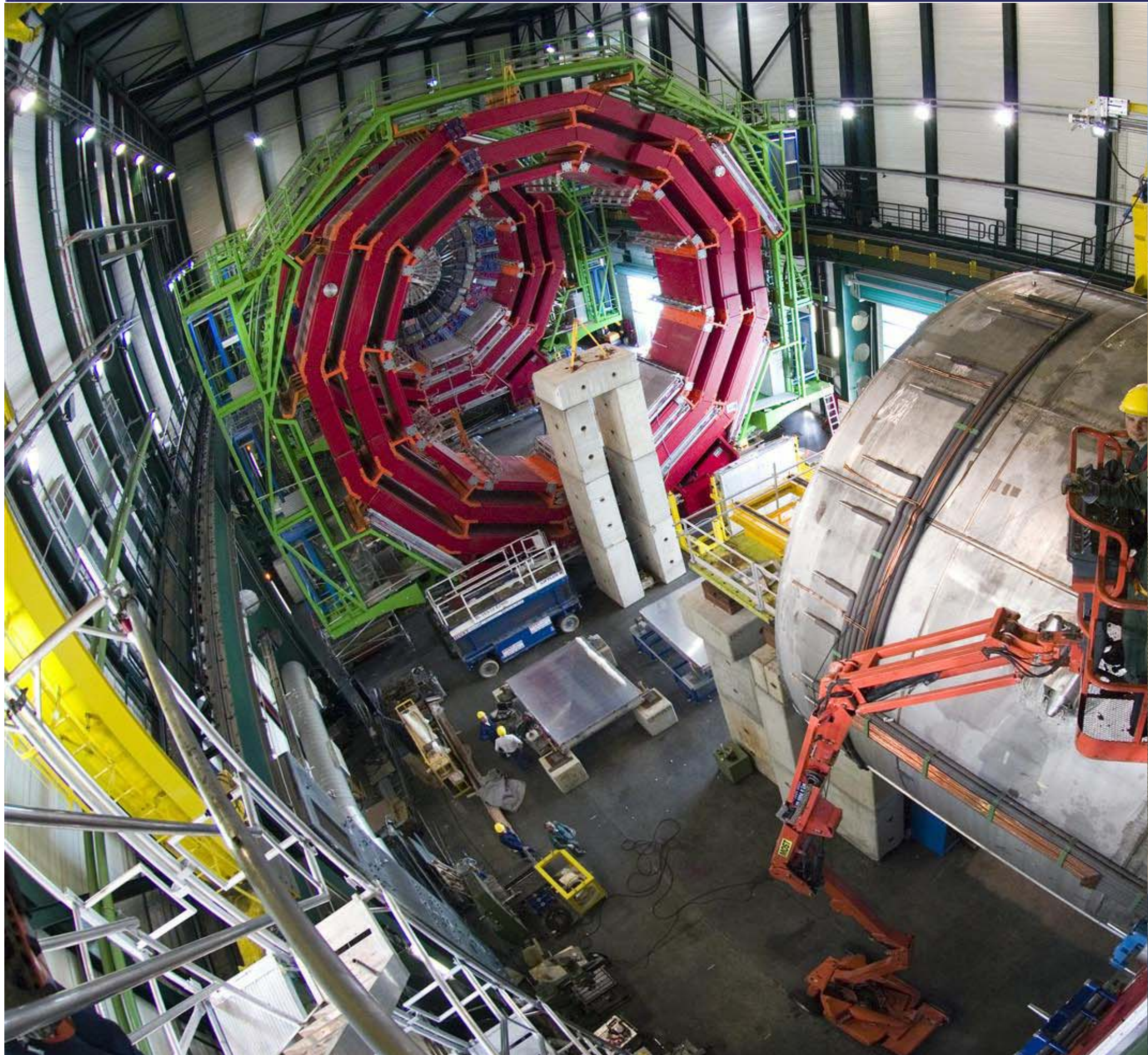
2030 Scientific Authors, 38 Countries, 174 Institutions

May, 04 2006/gm
http://cmsdoc.cern.ch/pictures/cmsorg/overview.html

CMS Experimental Site: Point 5 of the LHC



CMS built on the surface and lowered in the cavern 100m below
Piece by piece over three years



Hydraulic jacks and control tower used in CMS will be used
in Durban to lift the roof of the stadium for World Cup 2010

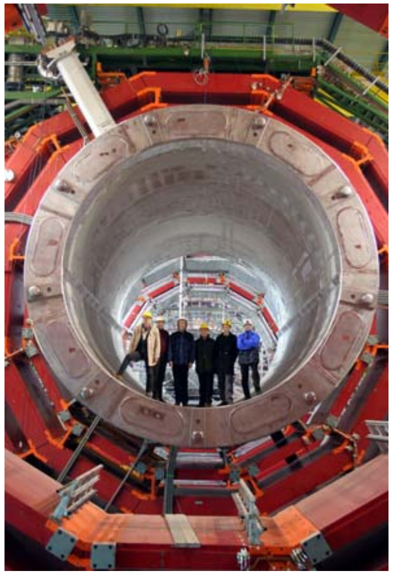
CMS Solenoid

Swivelling of coil 25 Aug

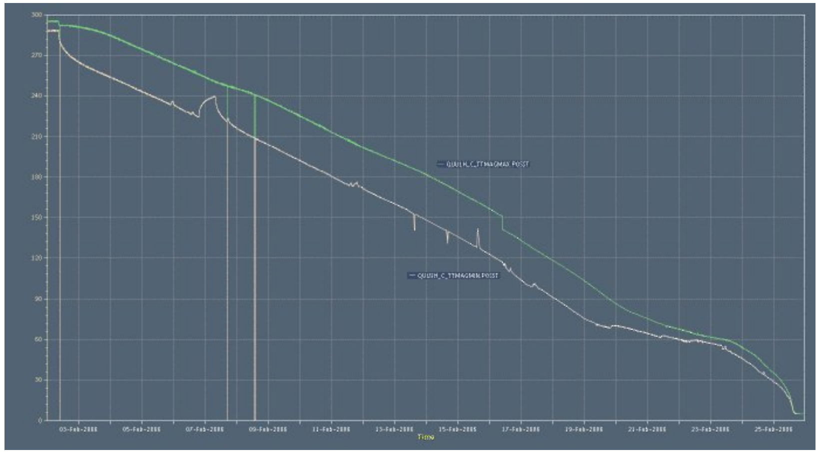
Magnetic length	12.5 m
Free bore diameter	6 m
Central magnetic induction	4 T
Nominal current	20 kA
Stored energy	2.7 GJ
Magnetic Radial Pressure	64 Atmospheres!
Reinforced Conductor	53 km (20 x 2.65 km)

Coil inserted 14 Sep.

Vacuum Tank welded (Nov - Jan)



Coil Cooled down to 4.5ºK in 25 days (Feb). Test on Surface (May-Aug)

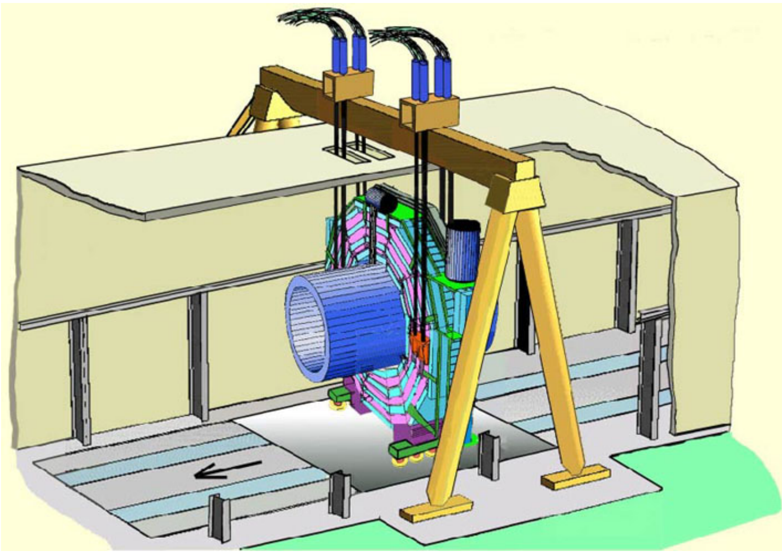


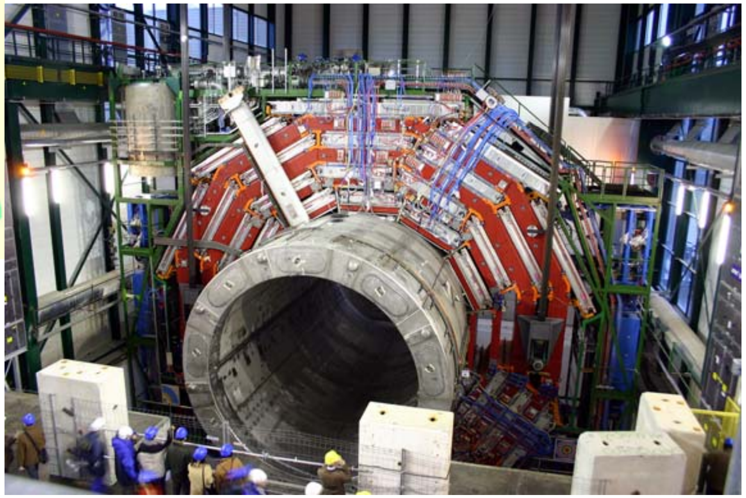
Big Milestone for CMS:
August 28 '06: 4Tesla field reached!!

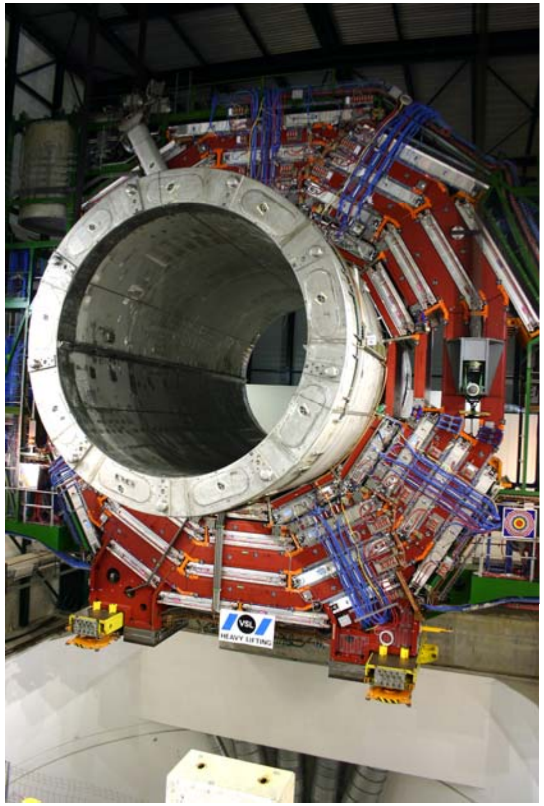
Lowering of the Solenoid

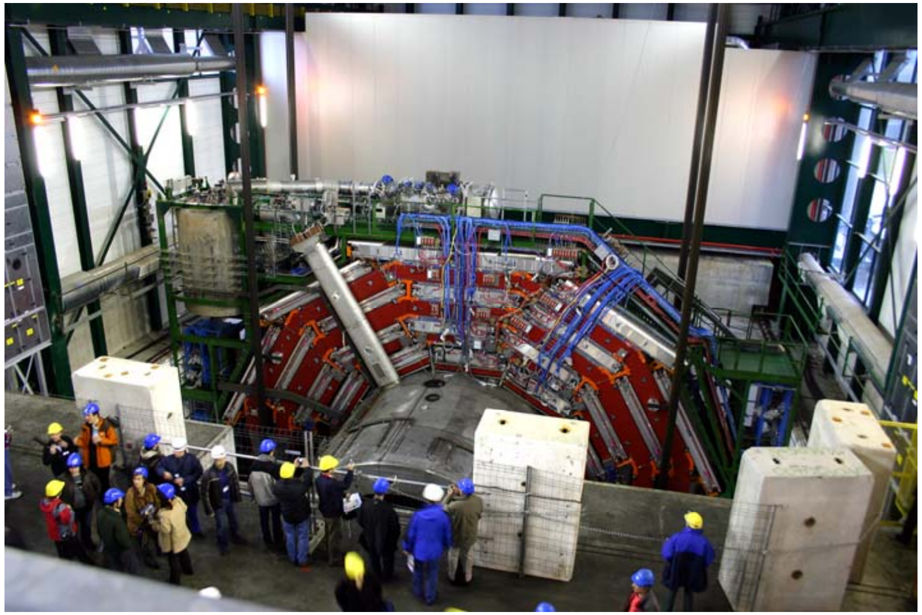
The Central piece of CMS
⇒The barrel wheel with the solenoid

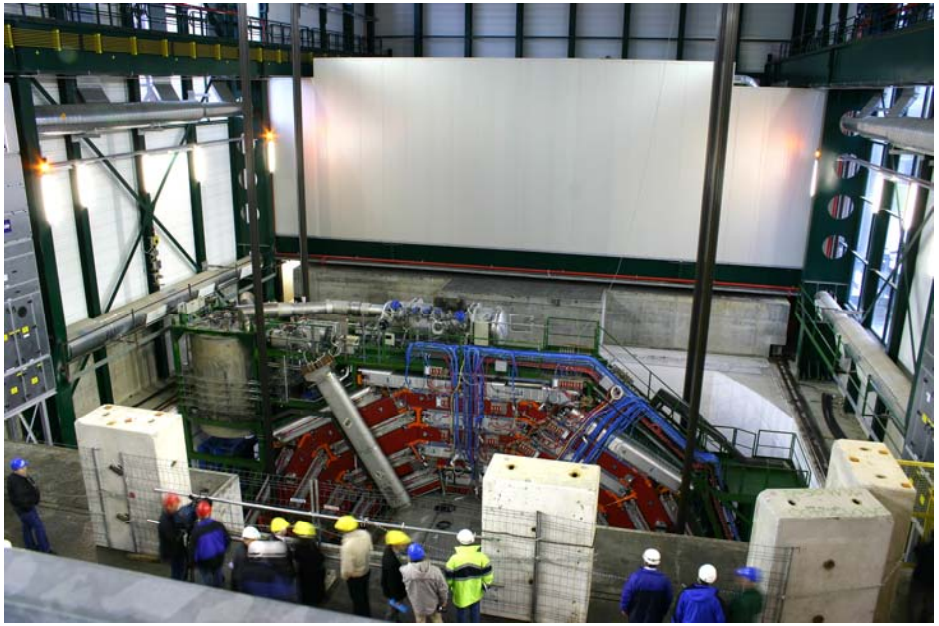
Total weight ~ 2Ktons
= 5 jumbo jets
Lowered February 28 (2007)

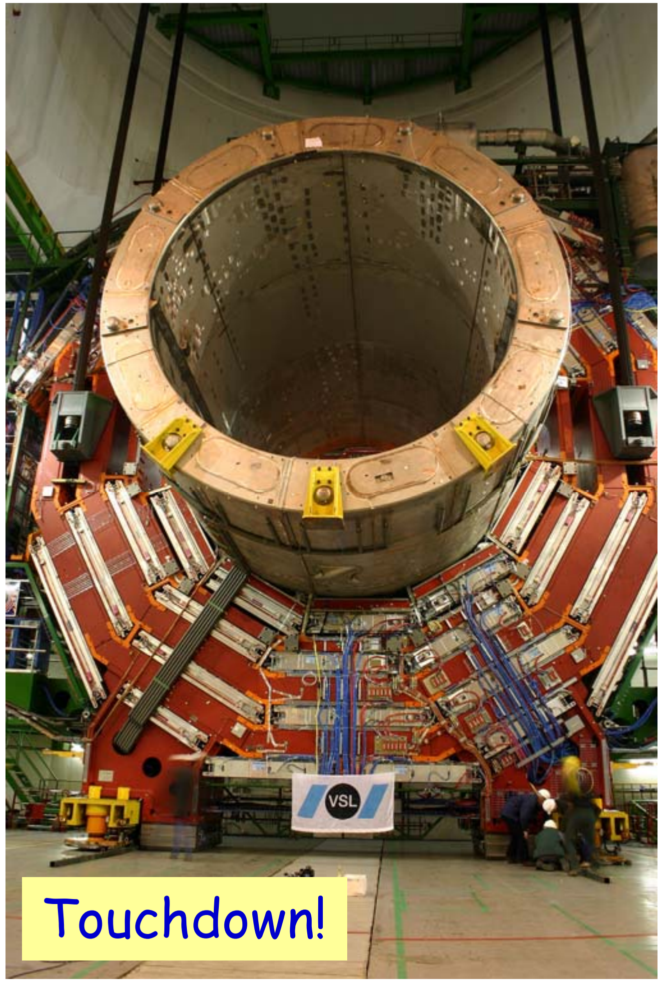











VSL
Touchdown!

Heavy lowering: CMS parts going 100m down

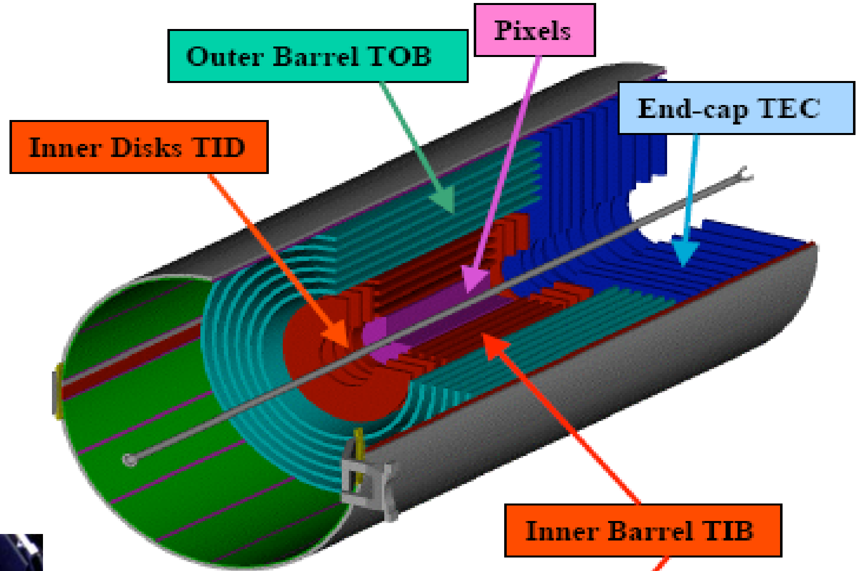
30 Nov: Y\\\E+3 leaves SX5 and 11 hours later touches down safely in UXC

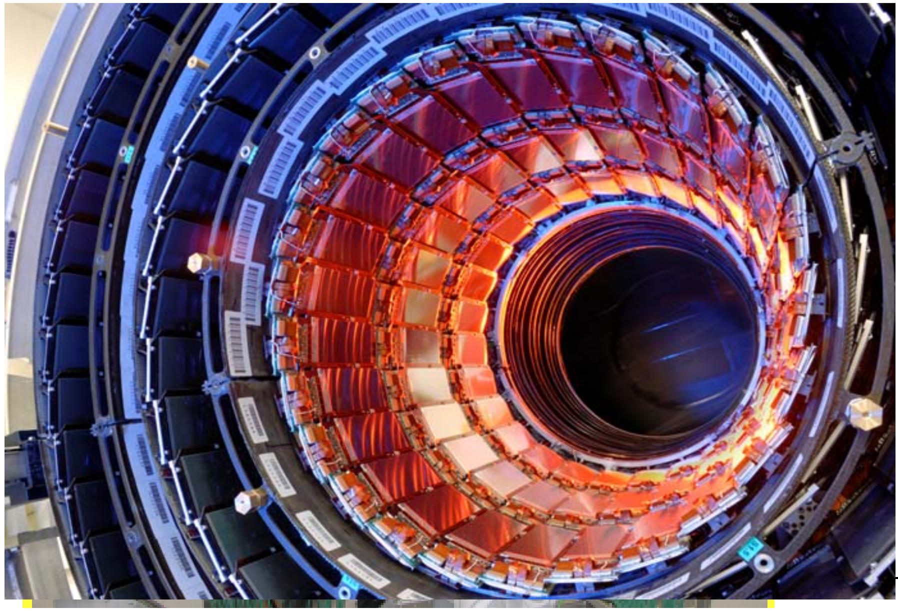
The first force studied carefully by CMS is Gravity

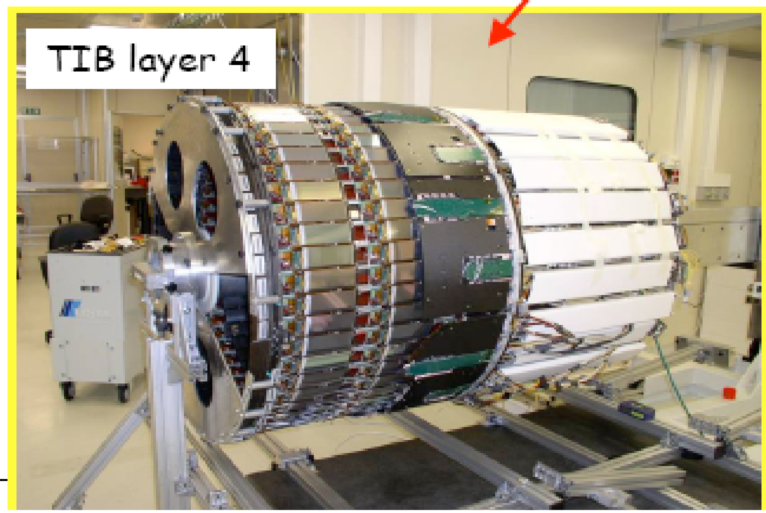
The Inner Tracker

About 220 m^2 of Si Sensors
$\Rightarrow 10^7$ Si strips
$\Rightarrow 6.5 \bullet 10^7$ pixels

All 16000 modules finished
Installation in IP5 in April 07

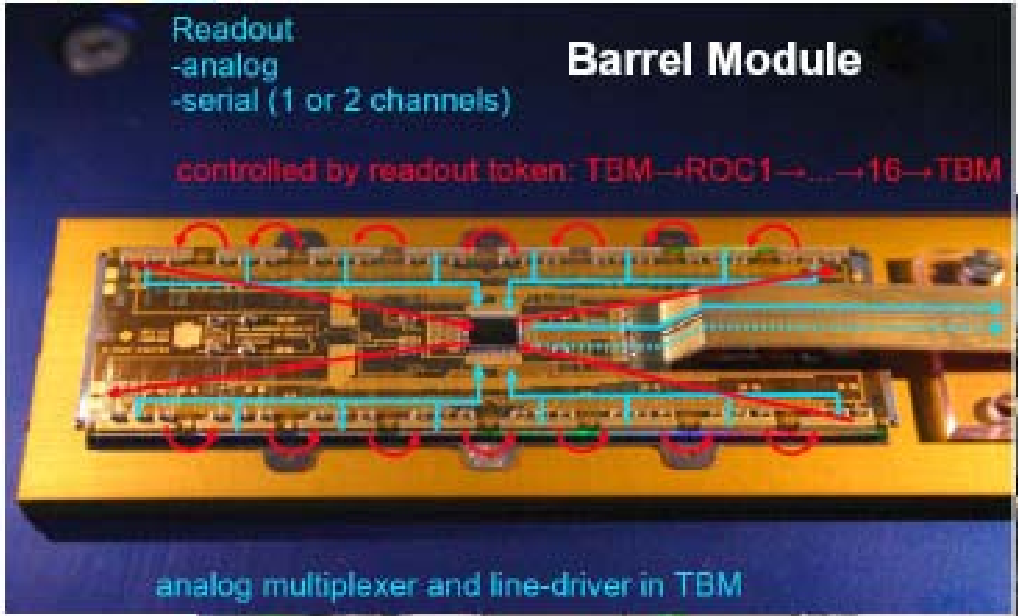






Function: Follow the particle tracjectories and measure their momentum

Pixels



Comparable to : 70 million pixels digital camera taking 40 million pictures per second!

Installation of the Central Tracker in CMS


December 2007

37

Electromagnetic Calorimeter (ECAL)

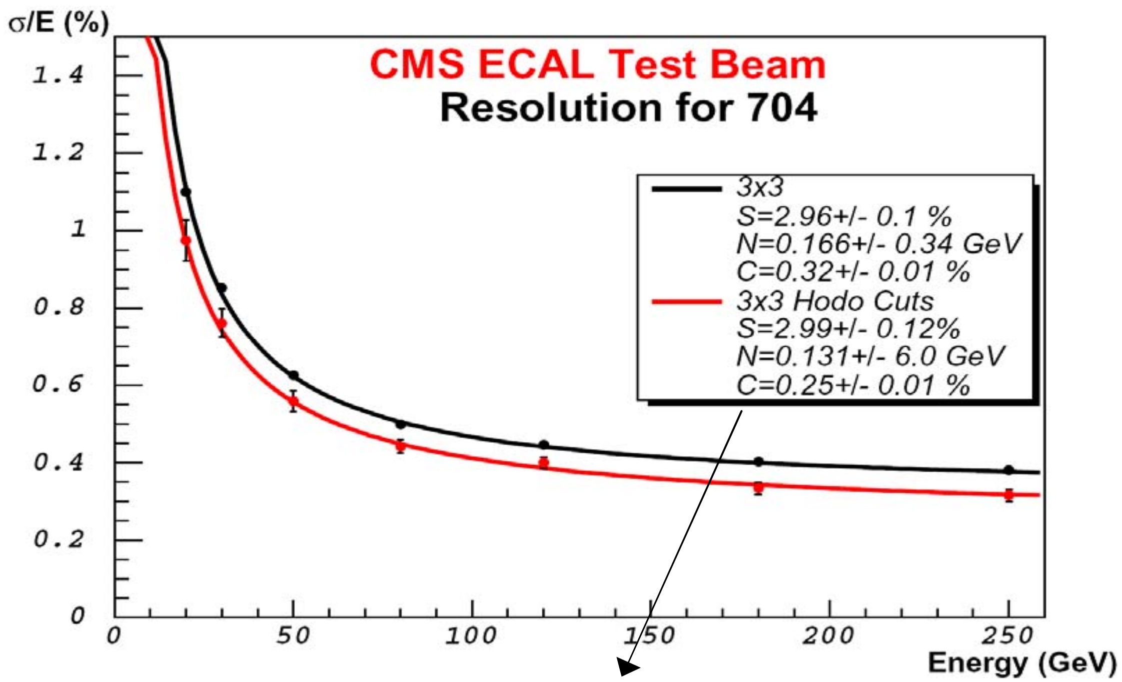
80000 crystals of $PbWO_4$
(lead tungstate)
« scintillate proportionately» when energetic particles go through..
Tranparent Lead!

A Russian factory in a former military complex took on the job of producing most of the crystals, whilst the remainder were produced in China. It took about ten years to grow all 78,000 crystals to stringent specifications, taking around two days to artificially grow each one.

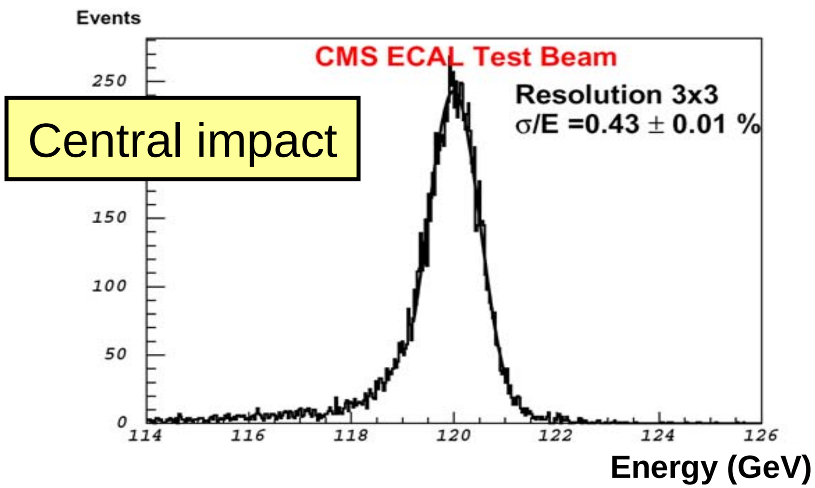
Function: Measure the energy of electrons, positrons & photons

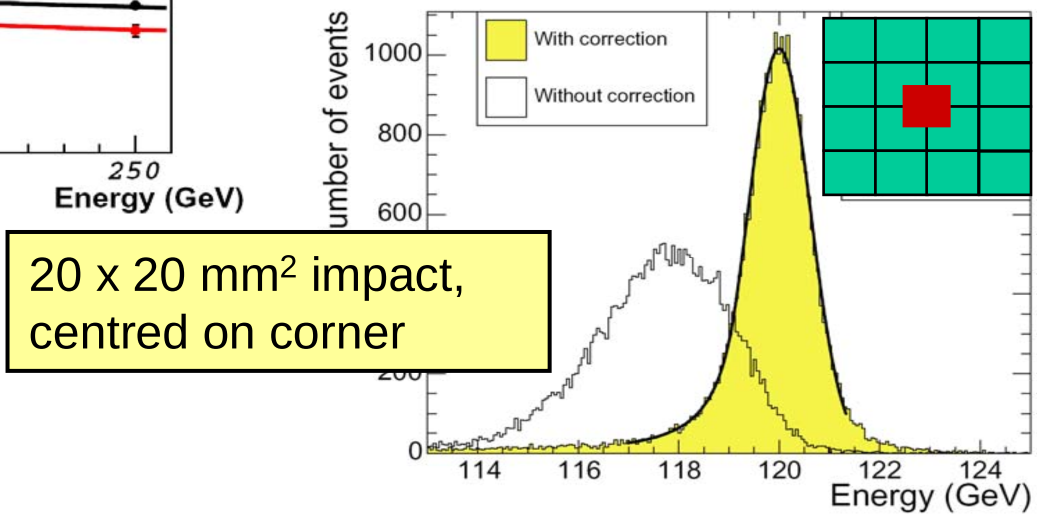
ECAL Test Beam Results

- Supermodule in H4 beam in 2004 (1700 Crystals)
- Demonstrate expected performance



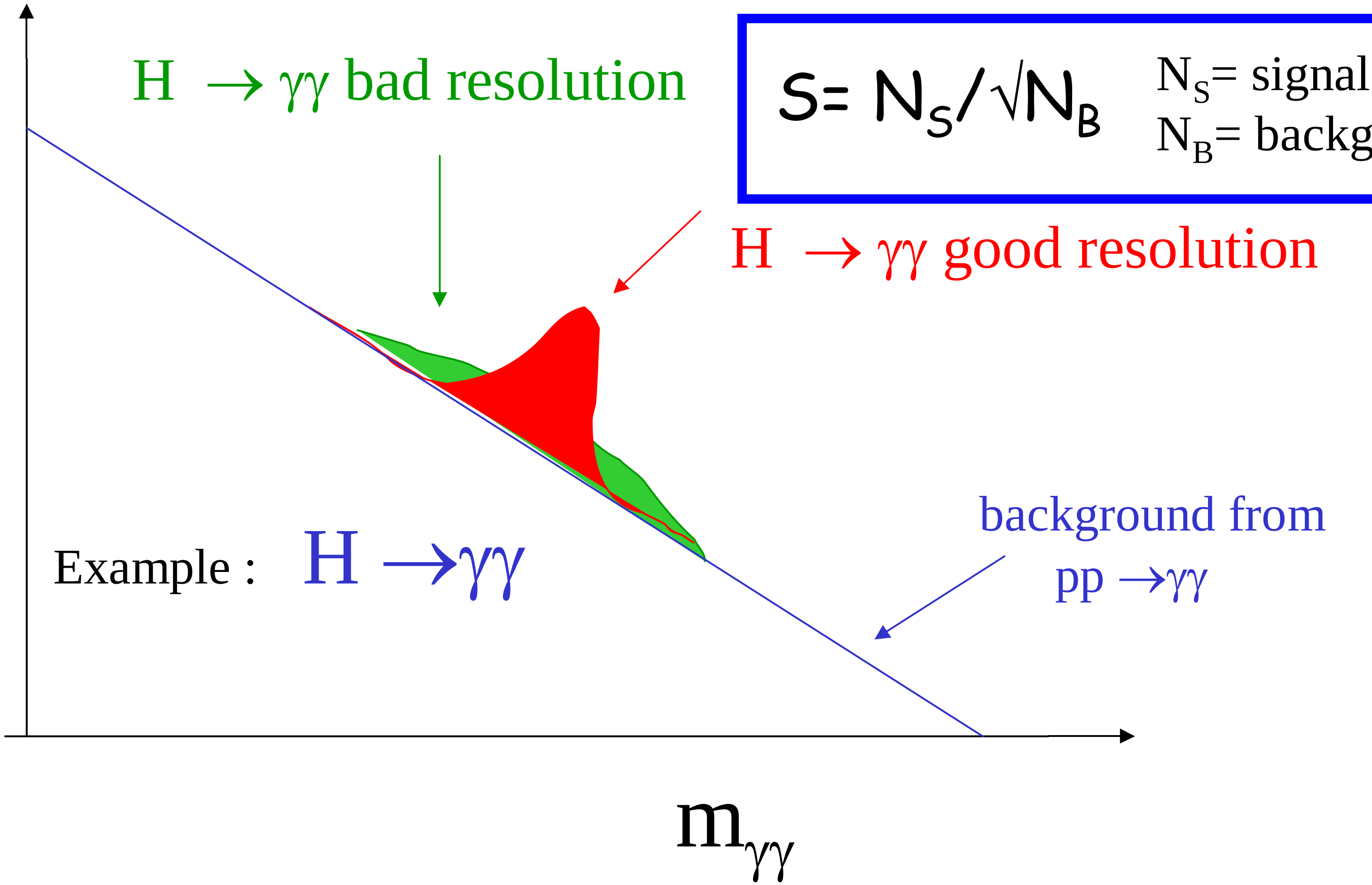
$$\left(\frac{\sigma}{E}\right)^2 = \left(\frac{S}{\sqrt{E}}\right)^2 + \left(\frac{N}{E}\right)^2 + C^2,$$





SM Higgs Search Strategy

- 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.

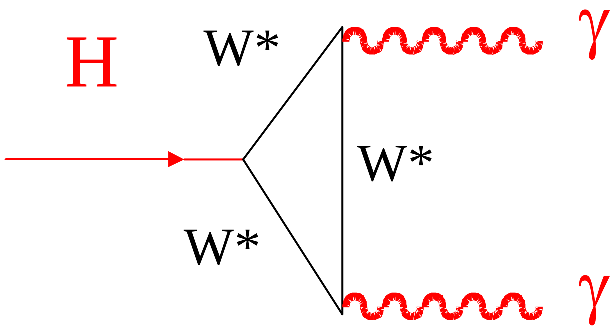


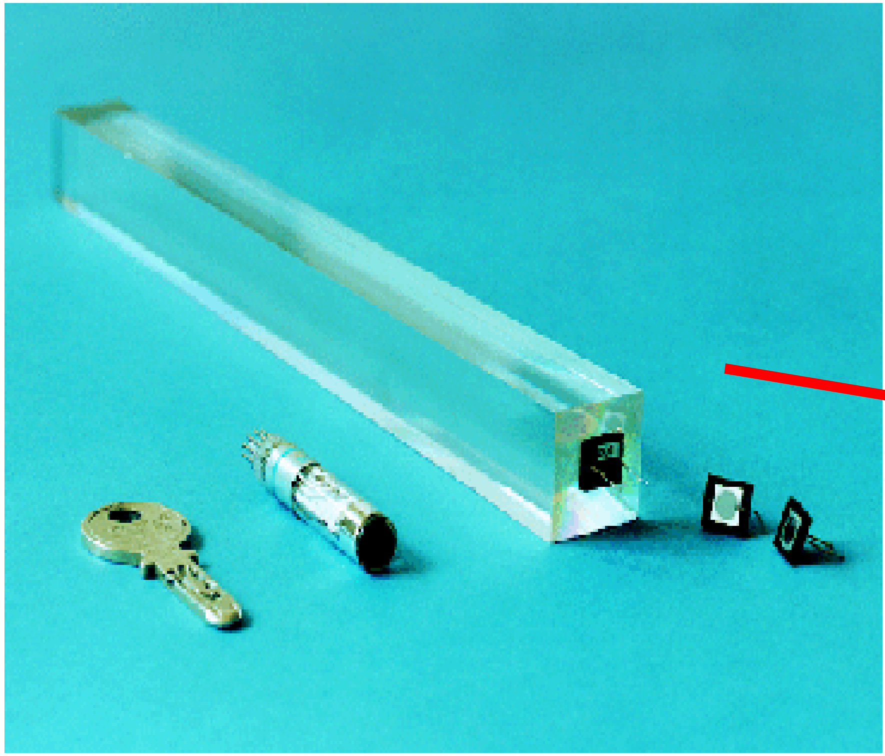
$S = N_S/\sqrt{N_B}$

N_S= signal events
N_B= background events

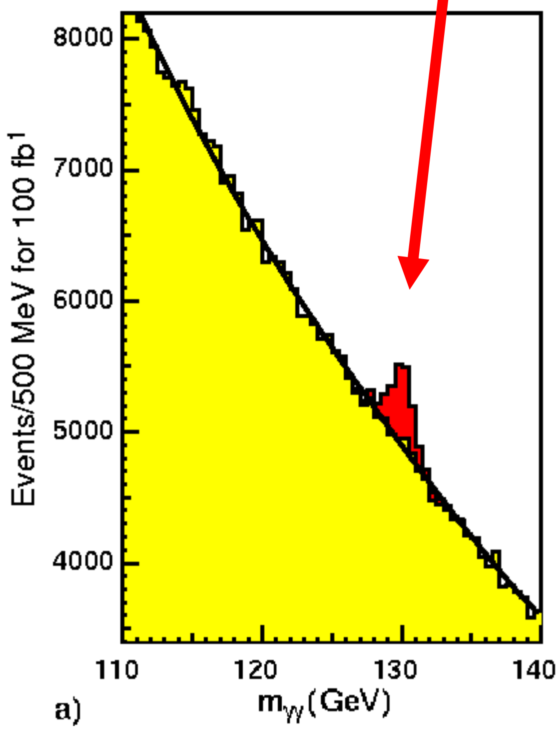
Measurements of a light Higgs

If the Higgs is light (115-120 GeV) then one of the most promising signals is $H \to \gamma\gamma$ (i.e. 2 photons)



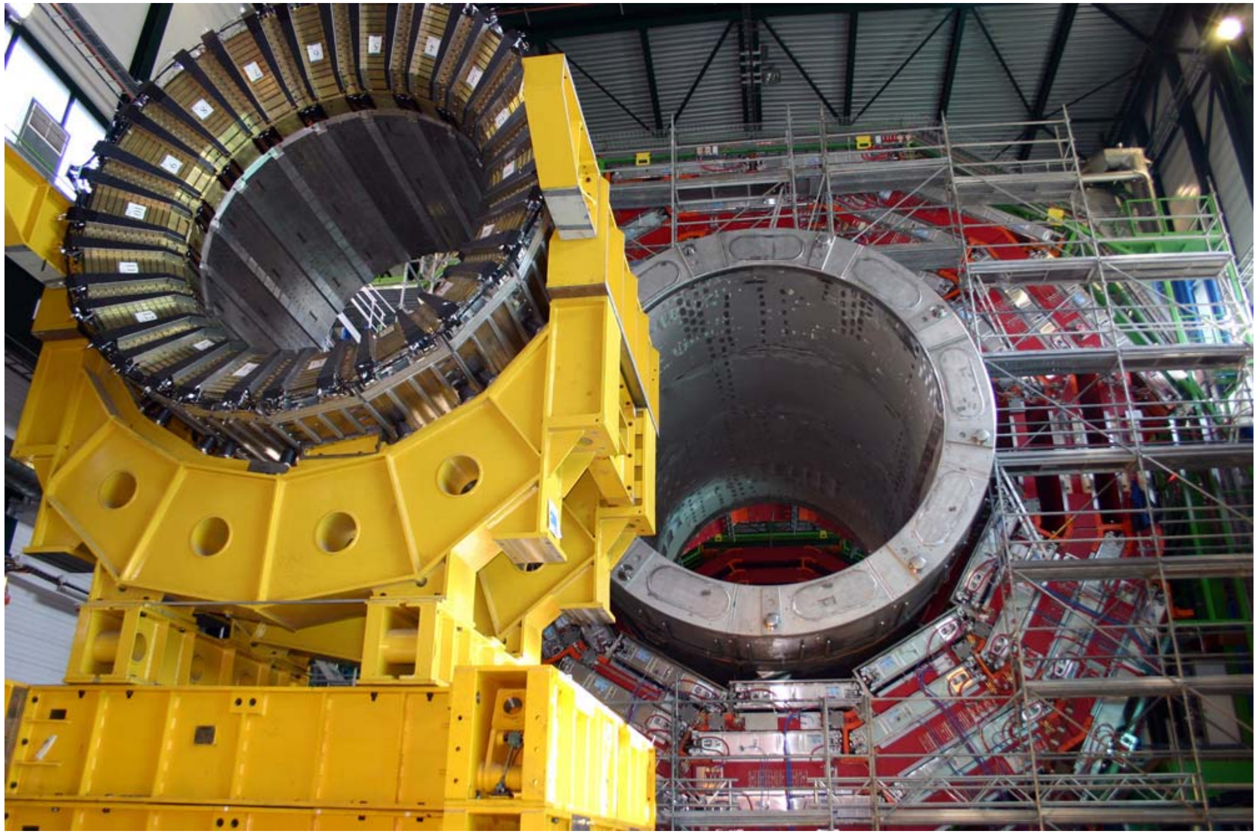


Excellent calorimetery needed ($PbWO_4$)



100 fb^{-1}

Hadron Calorimeter (HCAL)



Made of dense brass layers interspersed with
plastic scintilitaors

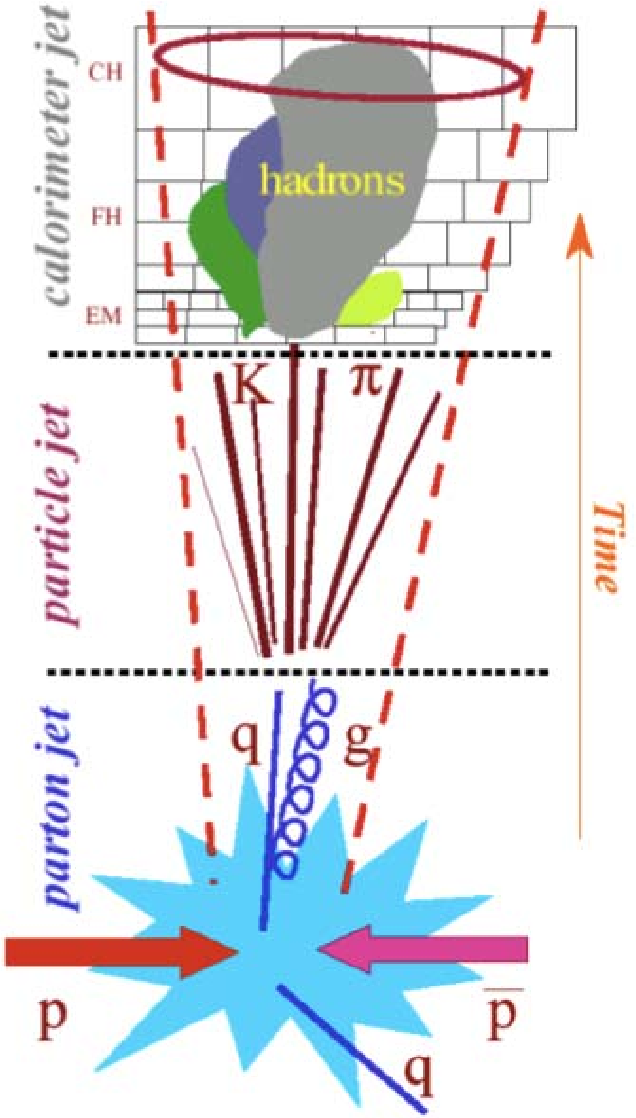
Used over a million World War II brass shell casements from the Russian Navy in making some of its detector components;
is made up of 36 wedges, each of which weighs as much as 6 African elephants;
contains over 400 “optical decoder” units, all of which were made by American high school students through the QuarkNet programme.

Function:

Measure energy of hadrons (protons, neutrons)




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

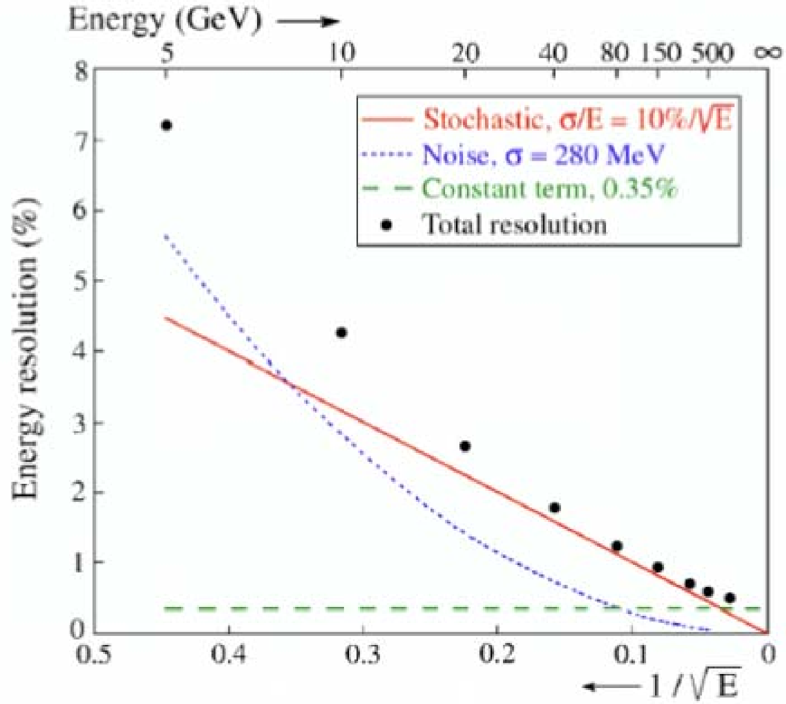
→ correct for finite energy resolution
→ subtract underlying event
→ add out of cone energy

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

Energy resolution

Usually parameterized by :

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



a : intrinsic resolution or stochastic term

→ given by technology choice

b : contribution of noise:

material, electronics, pile up, radioactivity

→ give by the electronics design

c : constant term: contains all the imperfection

response variation versus position (uniformity), time (stability), temperature….

→ Constraints on all aspects : mechanics, electronics….

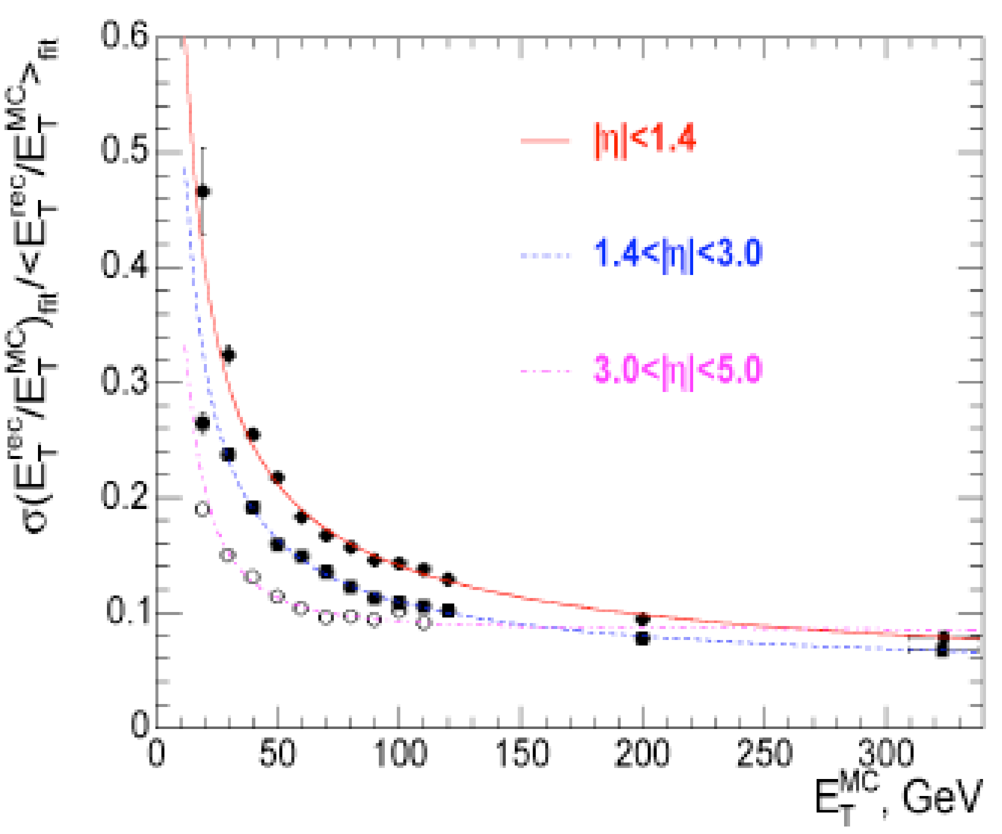
Homogenous calorimeters: noise and constant term dominate

Sampling calorimeters: stochastic term dominates

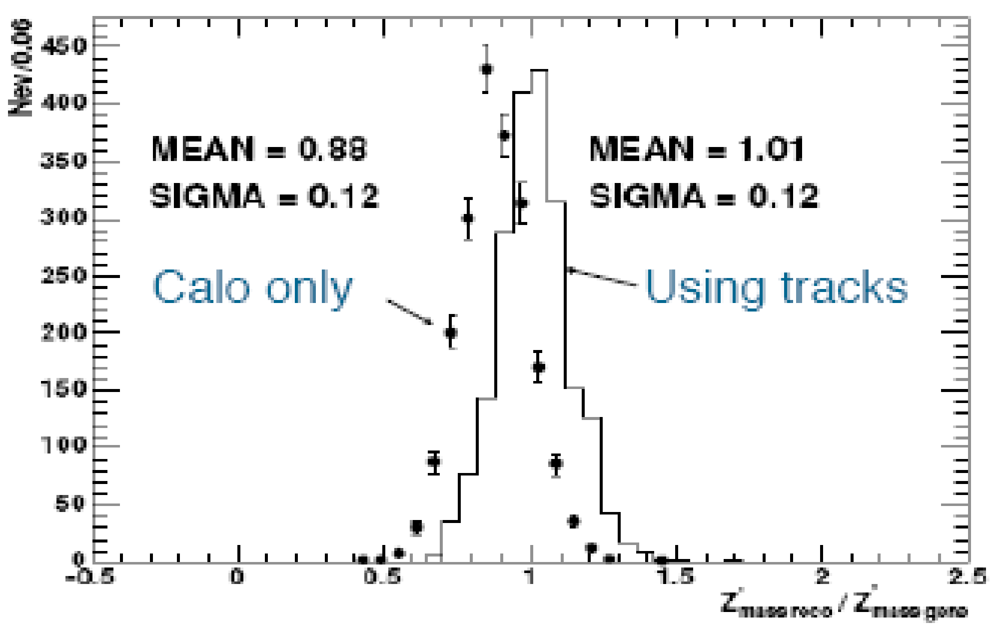
→ Energy resolution improves with energy compared to tracking detectors, where the momentum measurement degrades at high momentum (dp/p ∝ p)

Jet and Mass resolutions

Jet E_T resolution

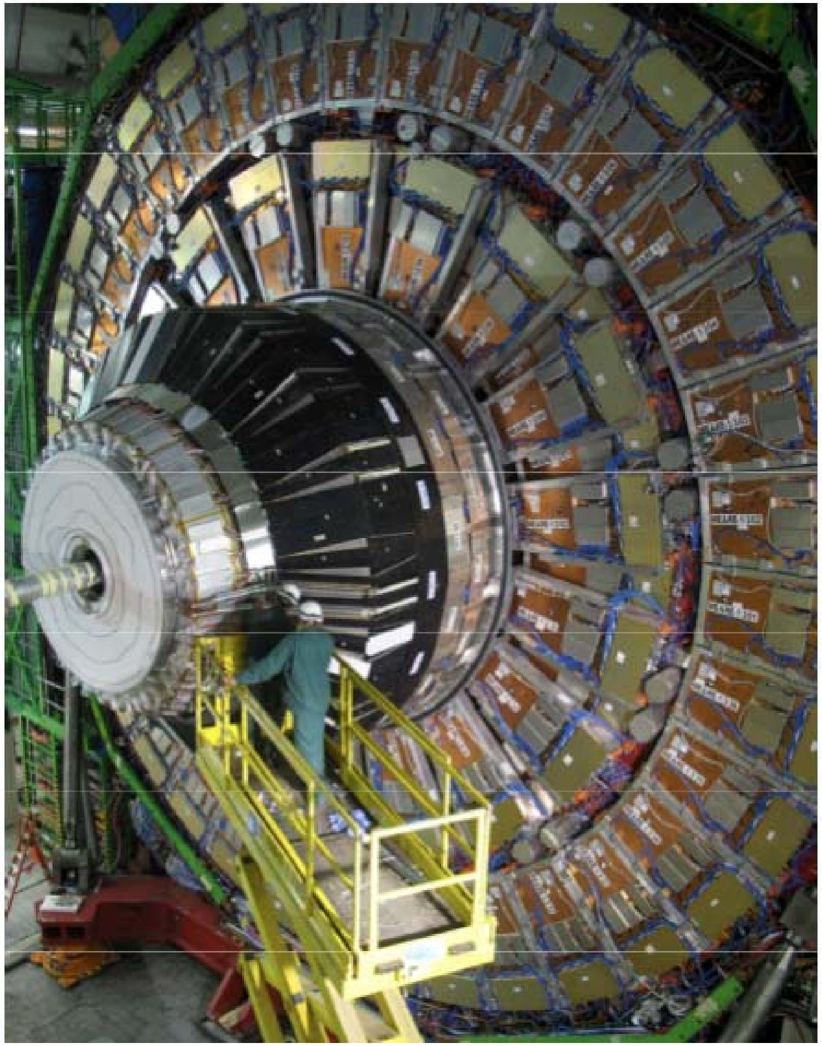


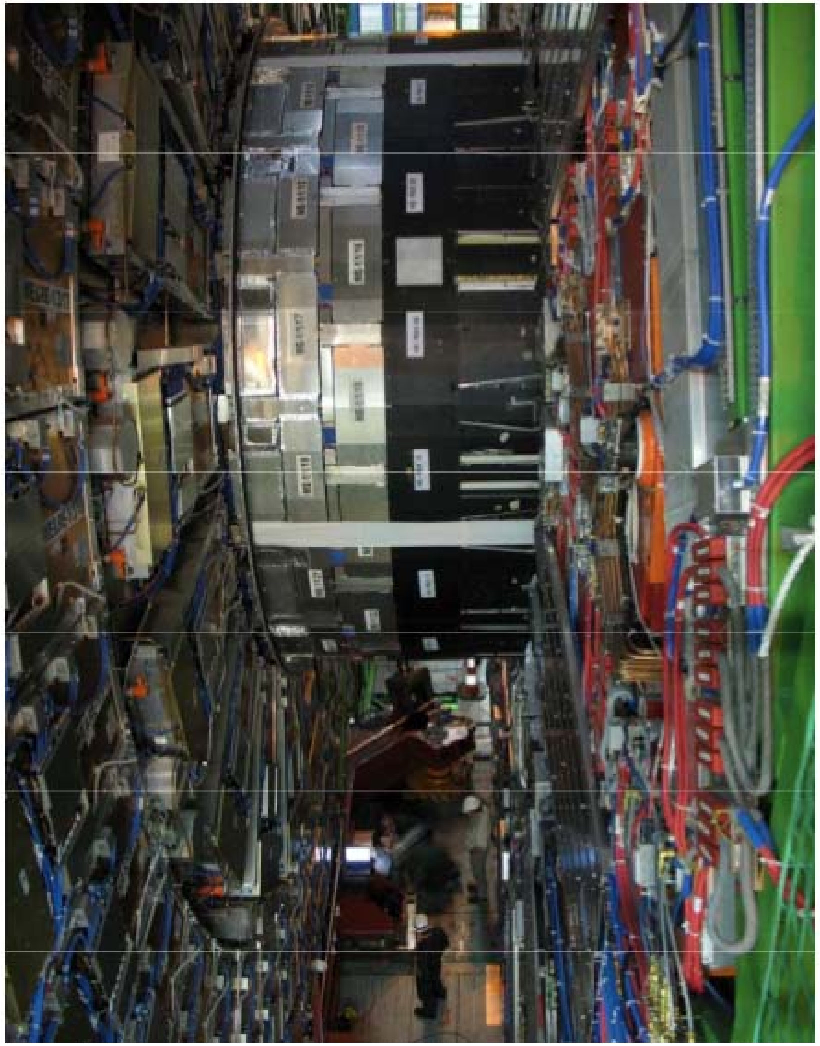
M_{jj} resolution at 120 GeV



M_{jj} resolution $\leq$ 15%

Muon System

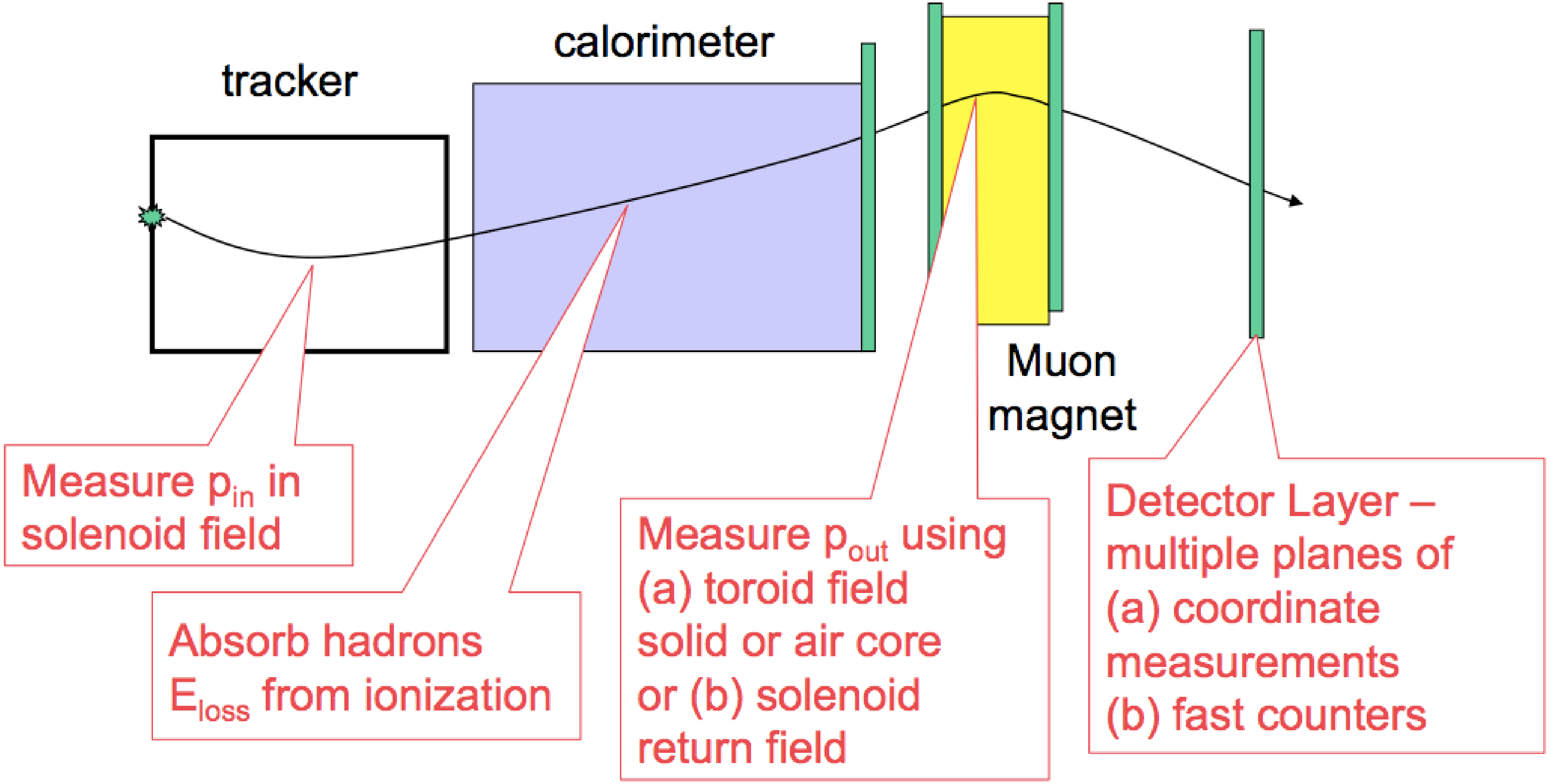




250 Drift tube chambers
  172,000 channels
468 Cathode strip chambers
  500,000 channels
912 Resistive plate chambers
  160,000 channels
Total area ~ 6000 m^2
ie like a
footbal field

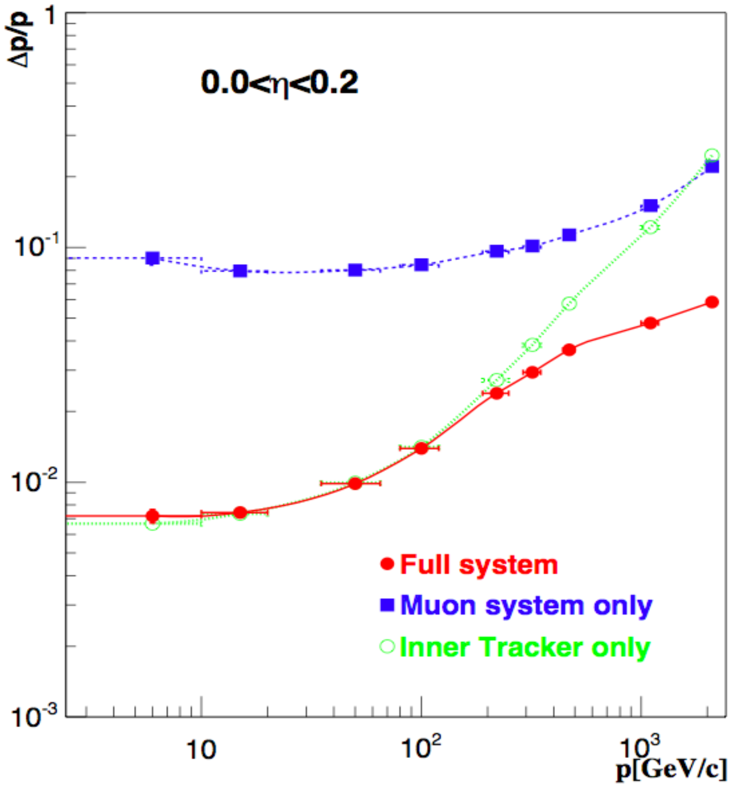
Purpose: identify muons and measure their momenta

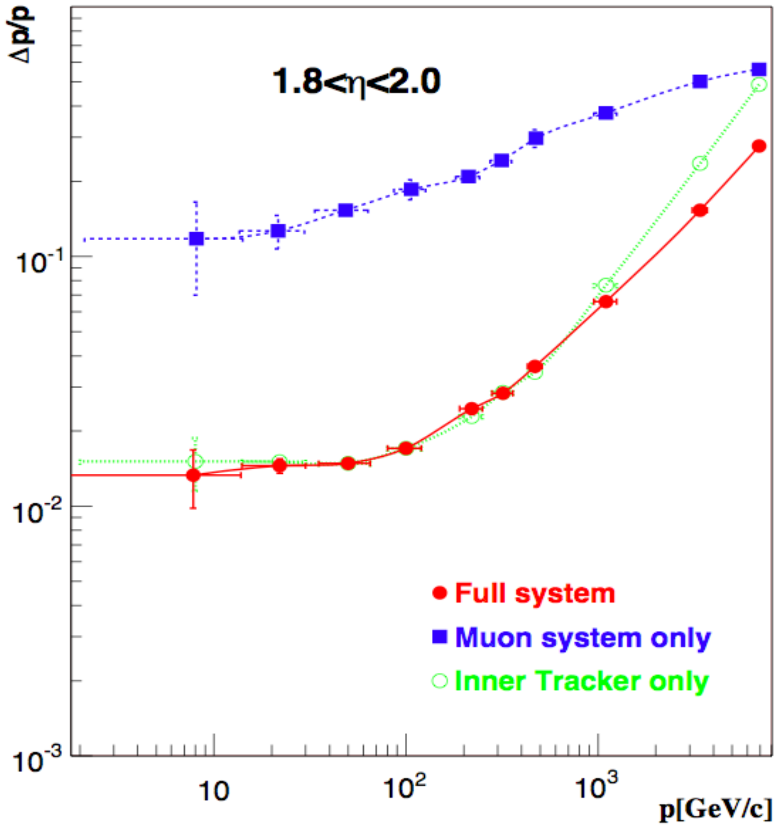
Elements of Muon Detection



Muon Reconstruction (Momentum Res.)

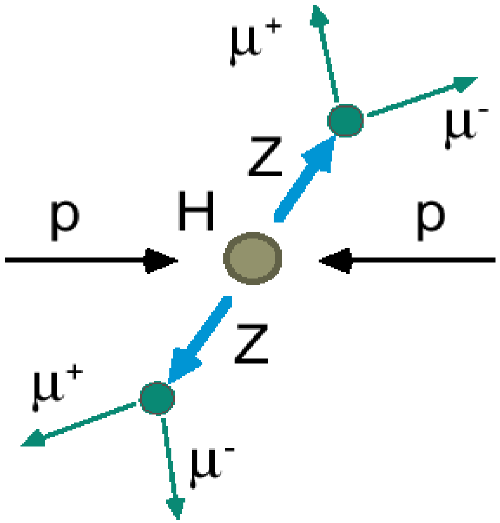
- Stand-alone Muon Reconstruction
  - Muon system only
- Global MuonReconstruction
  - Muon system + silicon tracker

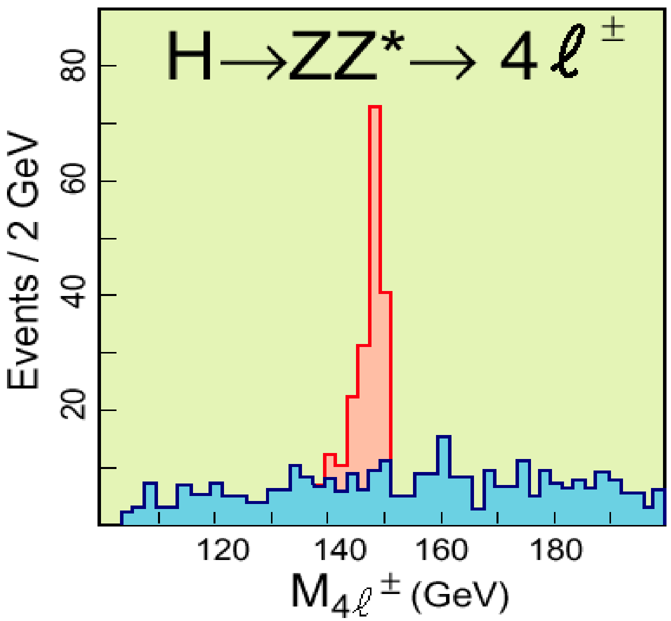


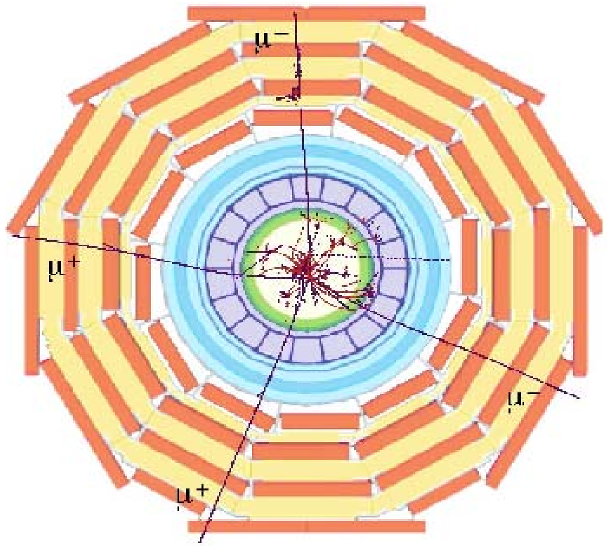


Example: Intermediate mass Higgs: ZZ*

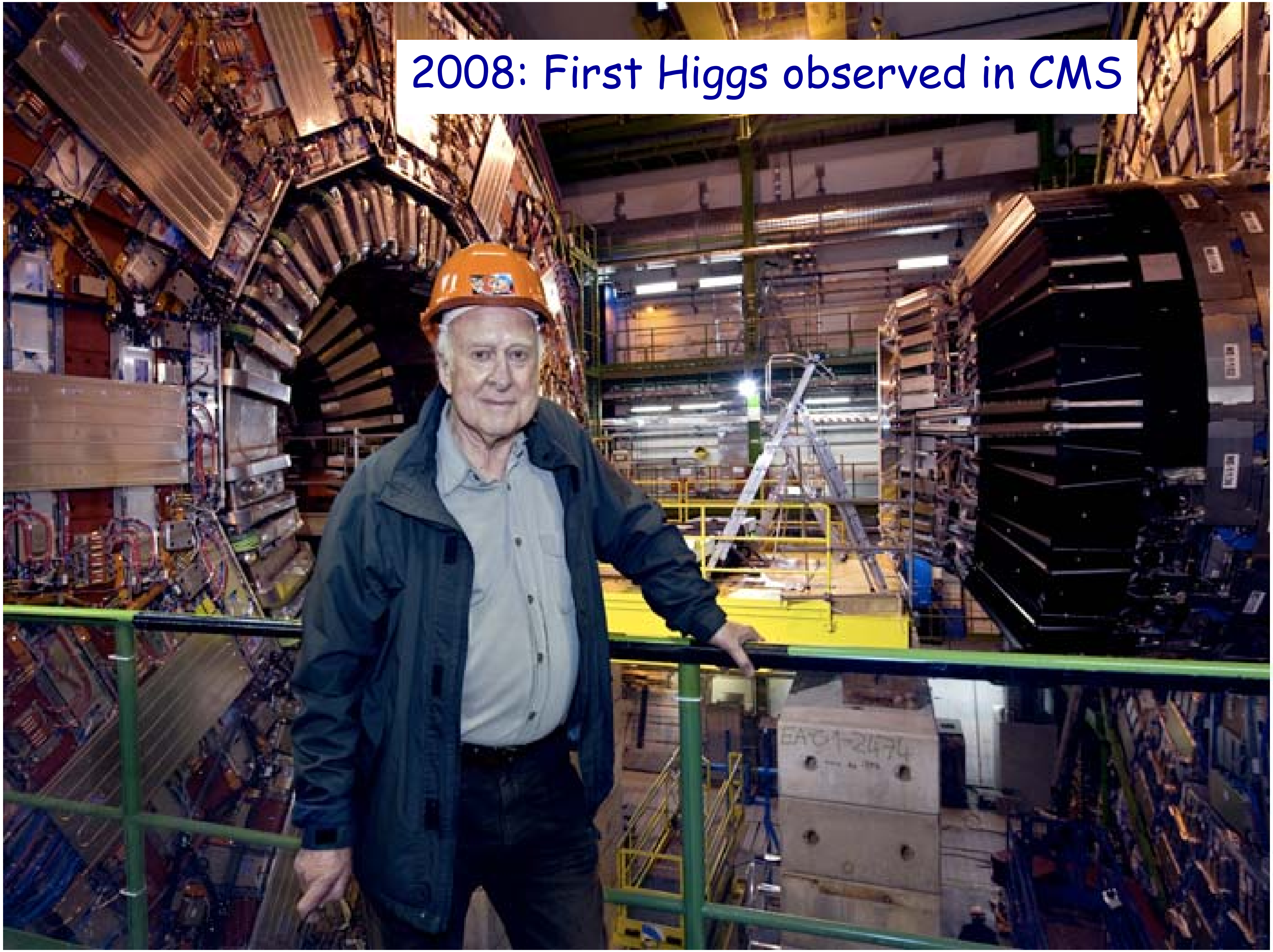
- $H \to ZZ \to l^+l^- \, l^+l^-$ ($l = e, \mu$)
  - Very clean
    - Resolution: better than 1 GeV
  - Valid for the mass range $130 < M_H < 500$ GeV/c^2





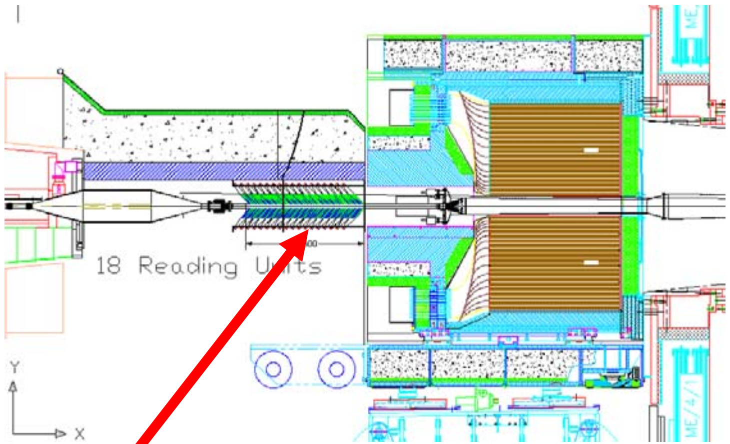


2008: First Higgs observed in CMS

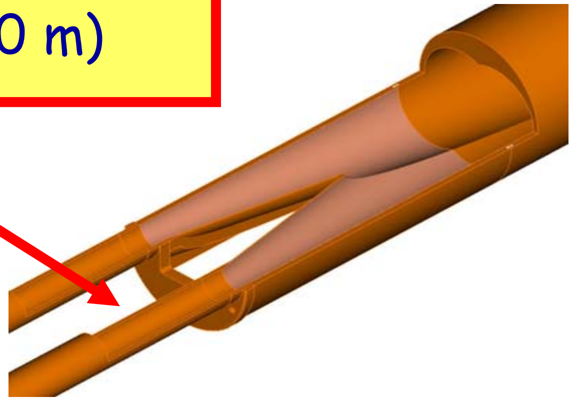


Forward Detectors (Diffraction, low-x…)

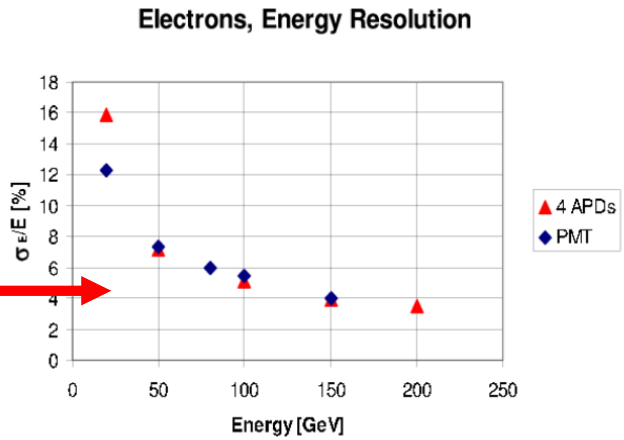
- CASTOR Calorimeter
- ZDC Calorimeter (at 140 m)



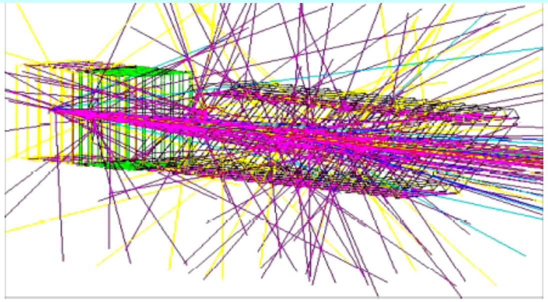
ZDC location
Tungsten/
quartz fibres



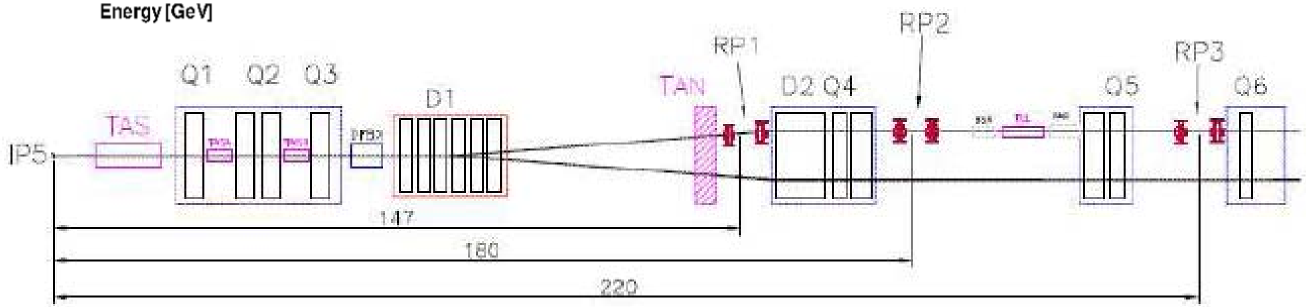
CASTOR 5.25<η <6.5
Tungsten/
quartz plates
Energy resolution



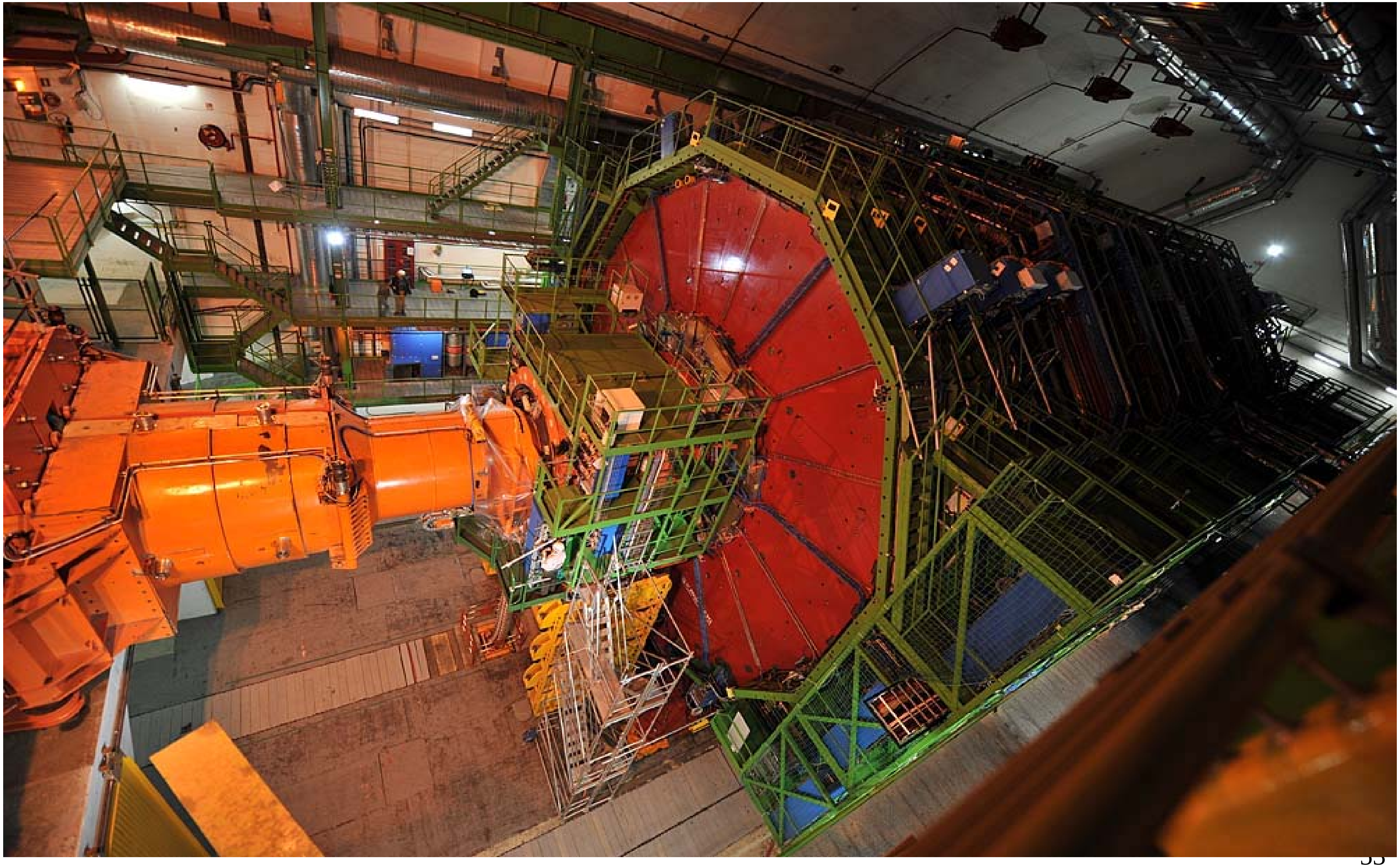
1 TeV neutron shower in ZDC



Common runs planned
with TOTEM:
Roman Pots and T1/T2

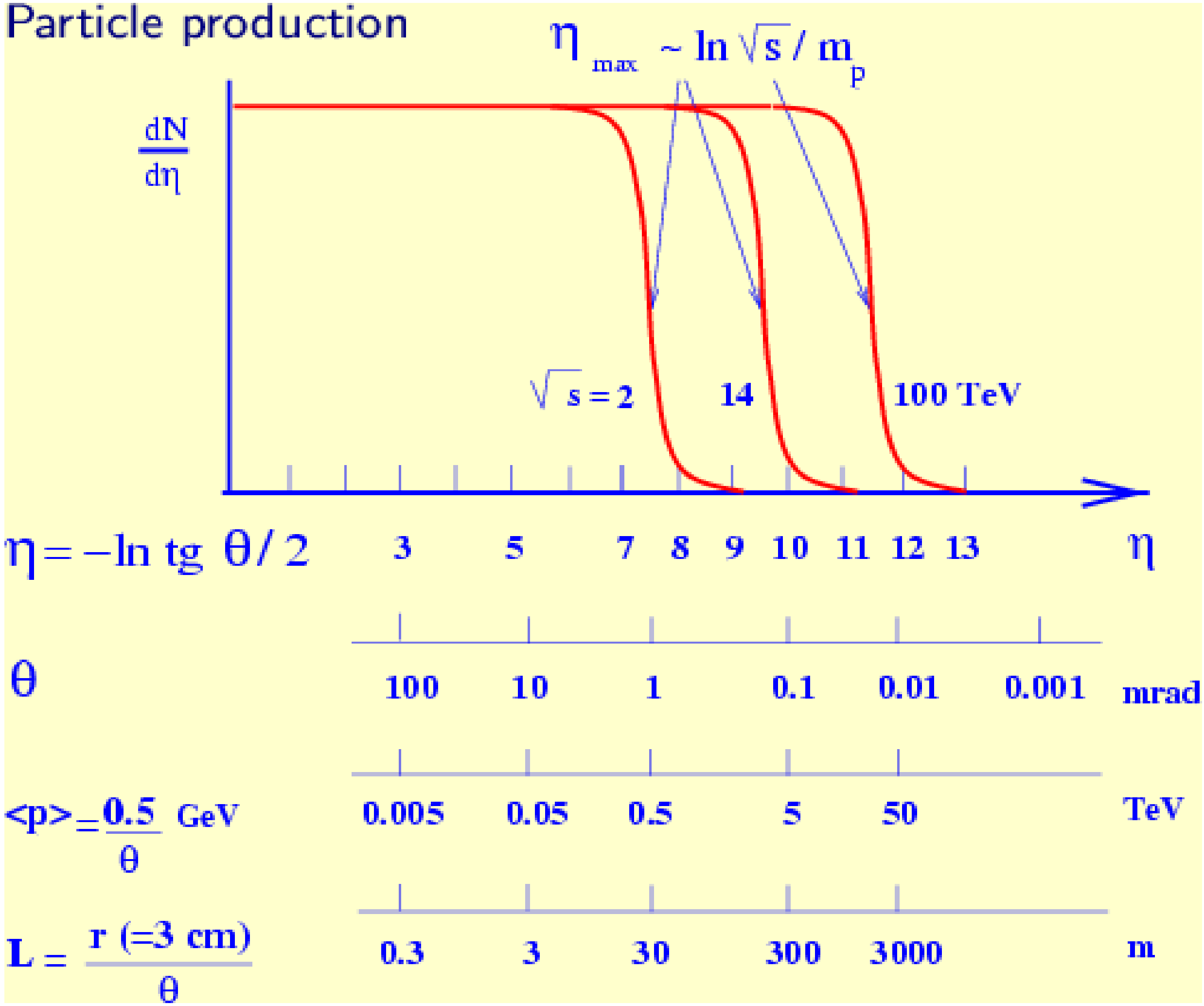


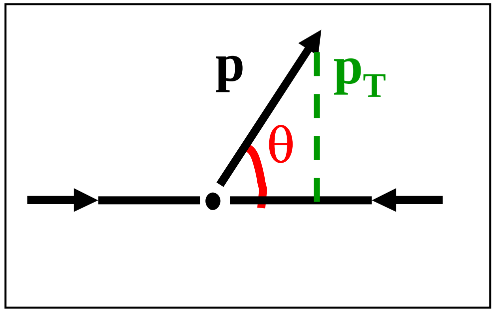
CMS Closed and ready… for LHC collisions



Beampipe installation

Forward Detectors





$d\sigma/dp_T dy$ is Lorentz-invariant

$\eta = y$ for $m \approx 0$

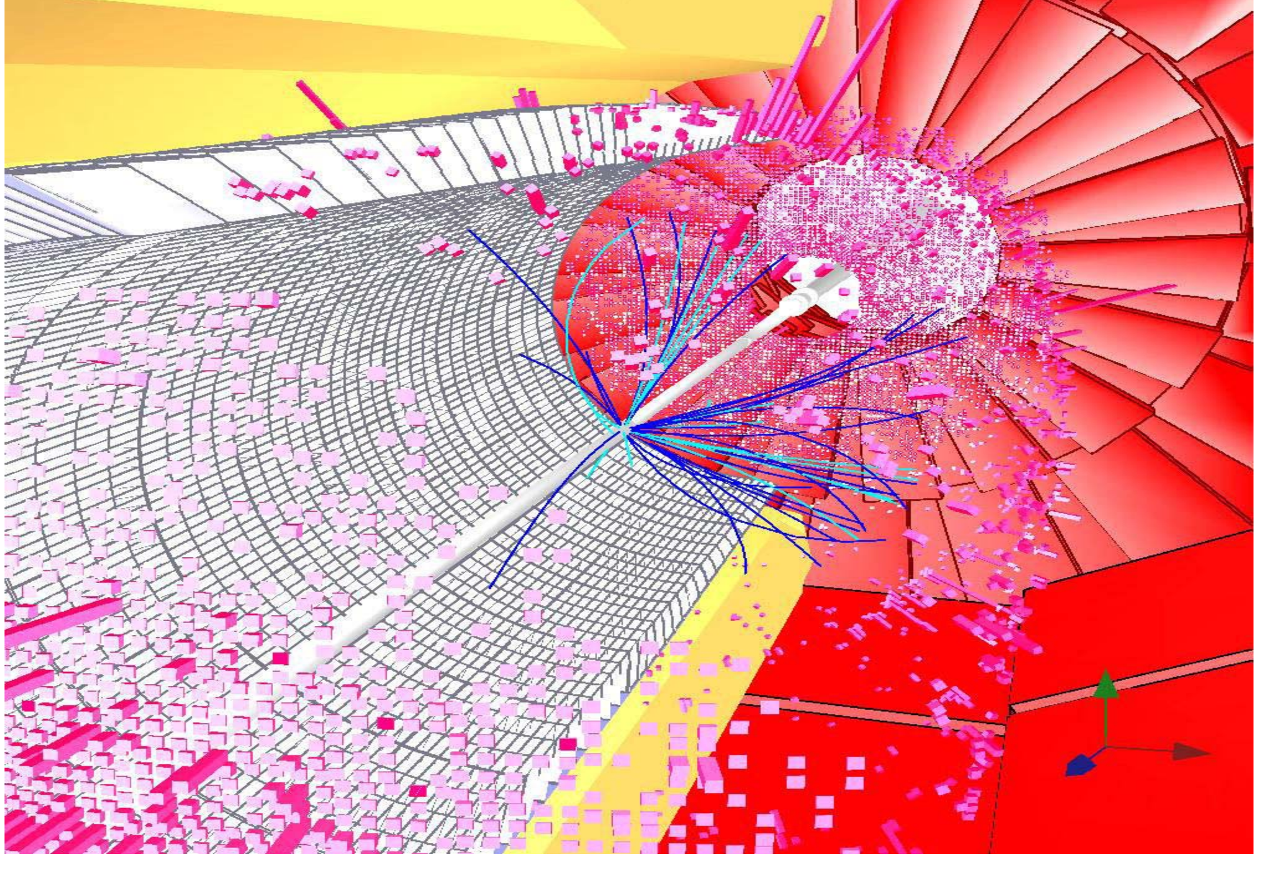
CMS/ATLAS detectors have about 100 million read-out channels

Collisions in the detectors happen every 25 nanoseconds

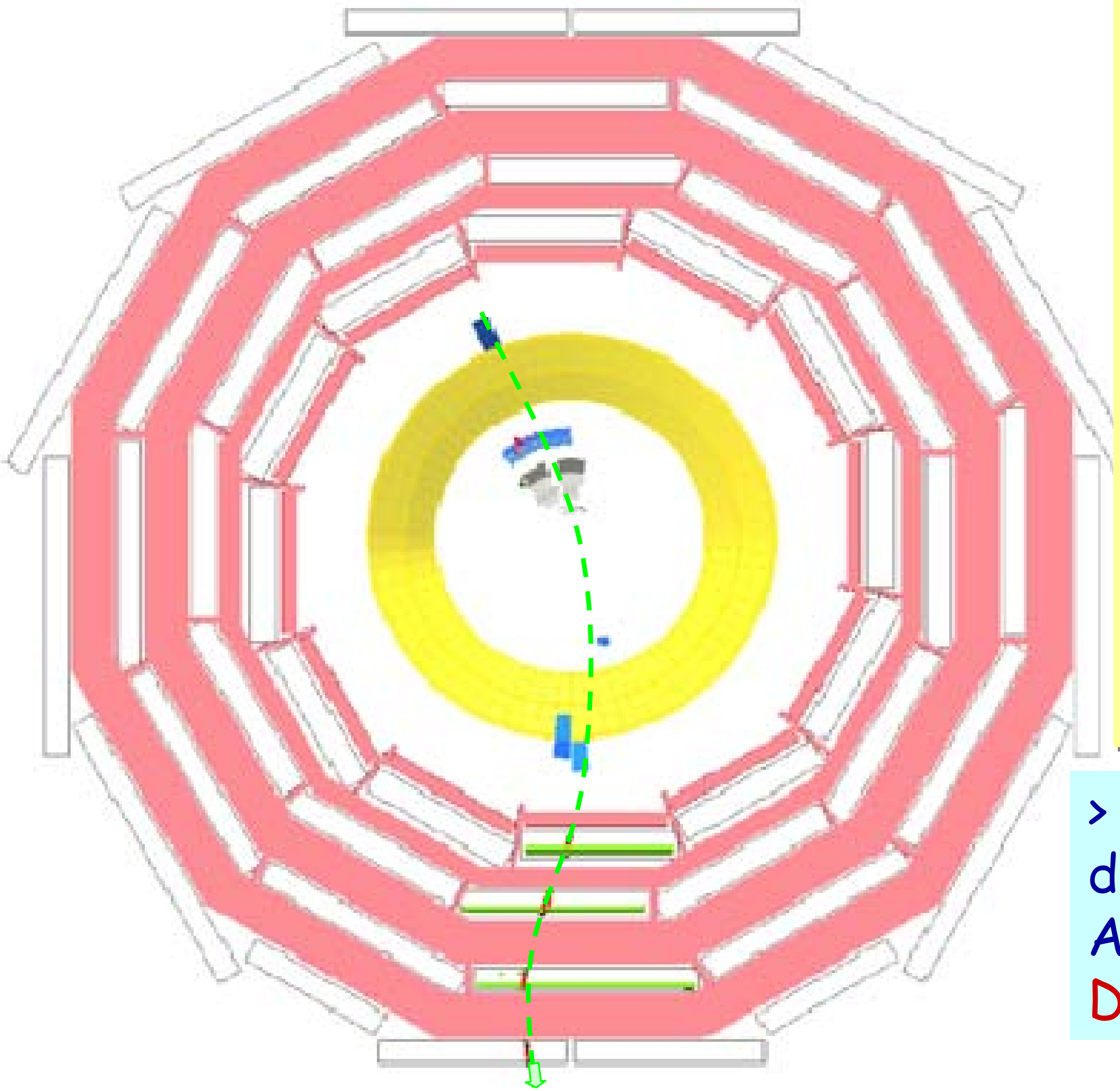
ATLAS uses over 3000 km of cables in the experiment

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



Magnet Test and Cosmic Data Challenge 2006



Full 4-Tesla field reached in August 2006!

The "gold plated" event going through all central detectors and read out by central DAQ

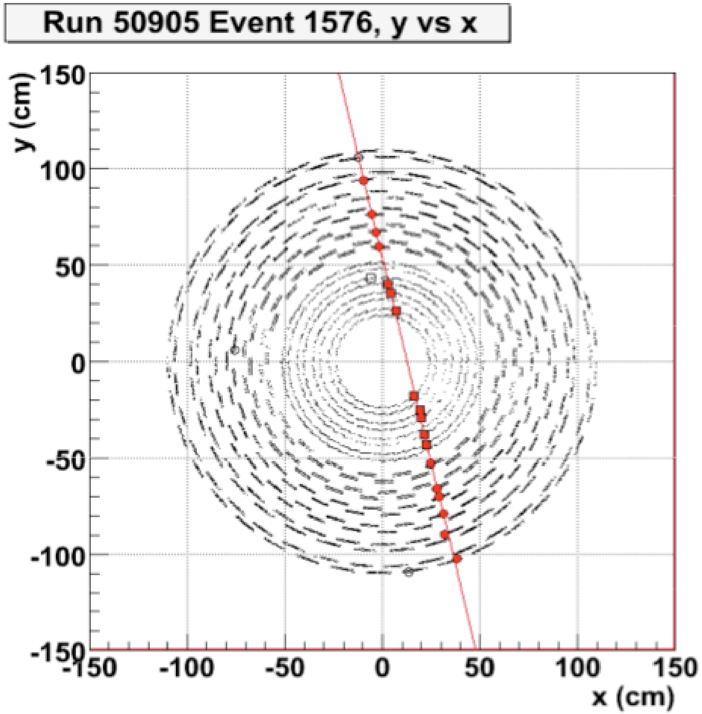
- ✓ tracker,
- ✓ HCAL (top and bottom),
- ✓ ECAL,
- ✓ Muon Chambers

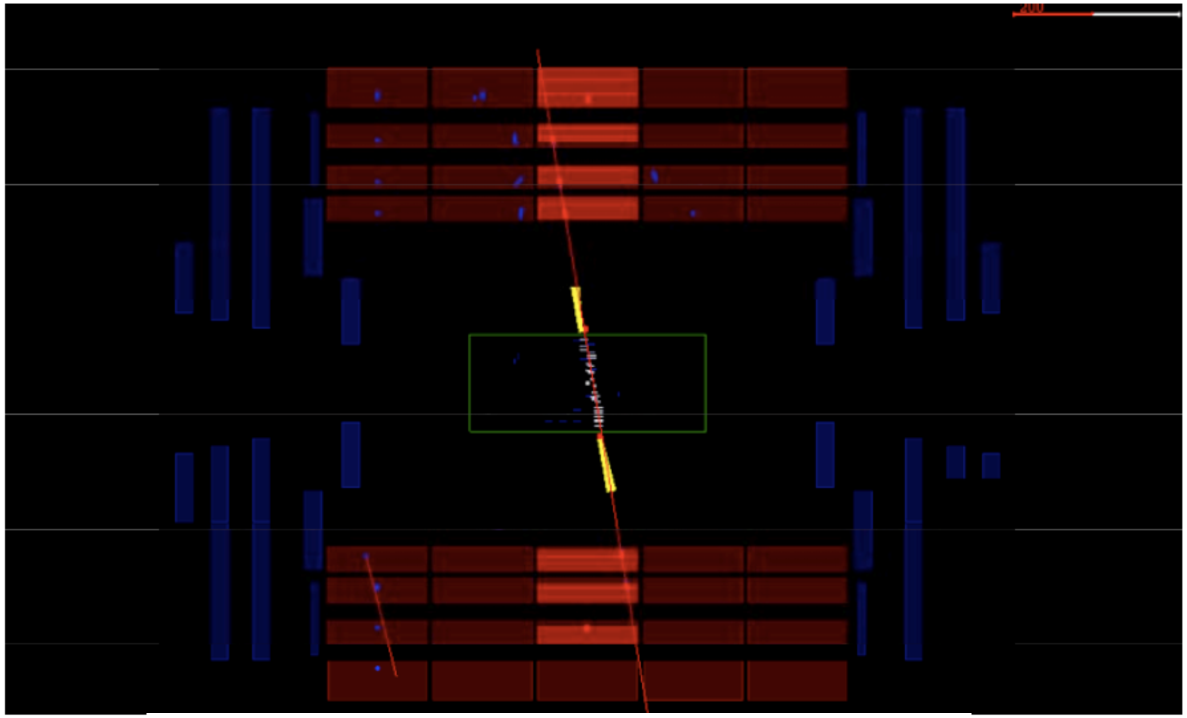
Few % of the full detector…

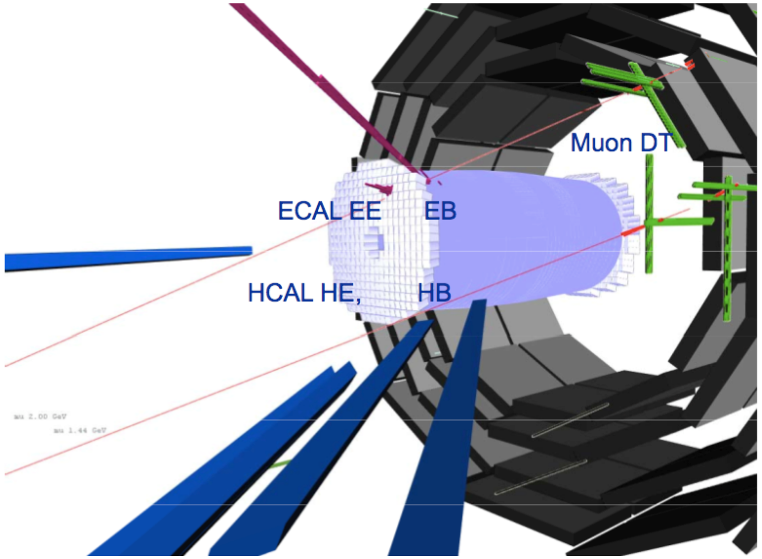
> 200•10⁶ cosmic muons taken during the cosmic challenge August-October

Detector worked very well!

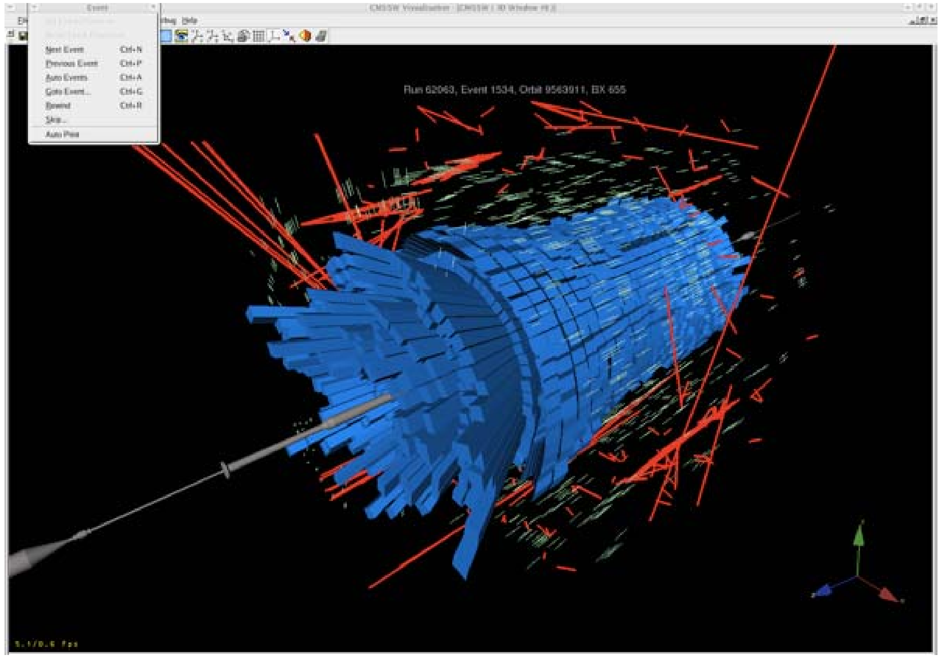
Cosmic events in situ summer 2008

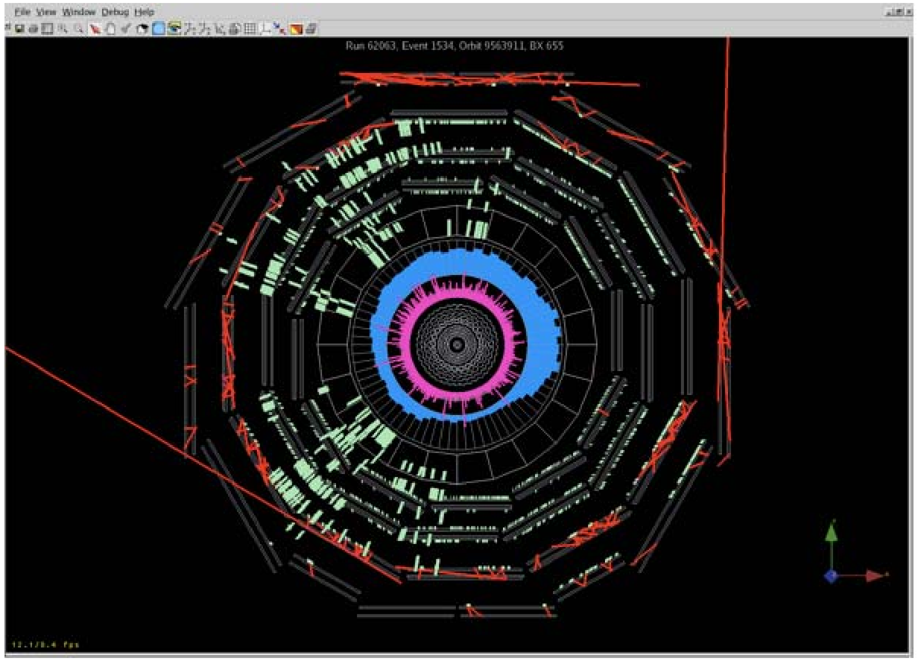






CMS Works …
… and for Particles from LHC…



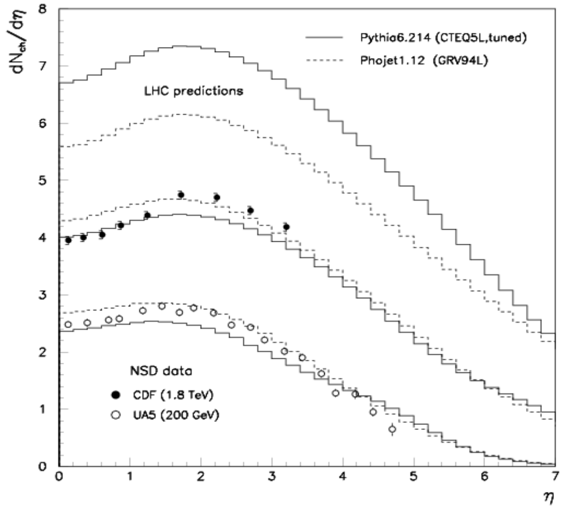


10 September 2008:
The start-up of the LHC

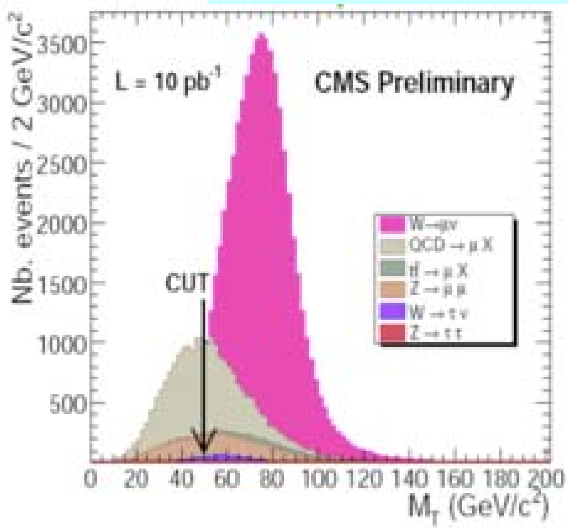
The first particle bunches injected in the LHC accelerator and the signals recorded by the CMS detector

First Physics (100 pb^{-1} or less)

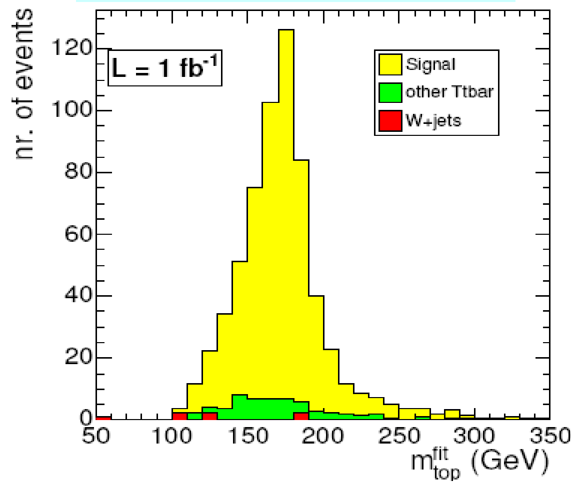
Soft collisions: particle distributions

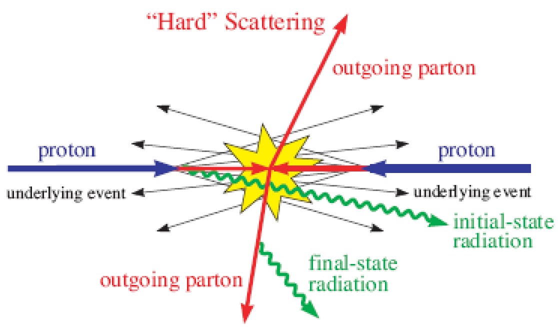


W & Z bosons

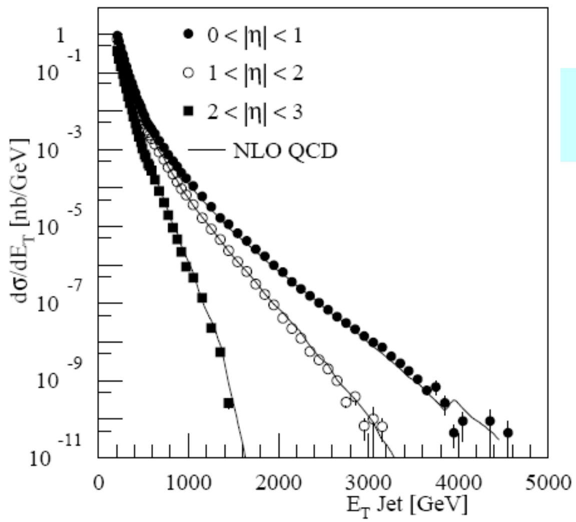


First top quarks in Europe





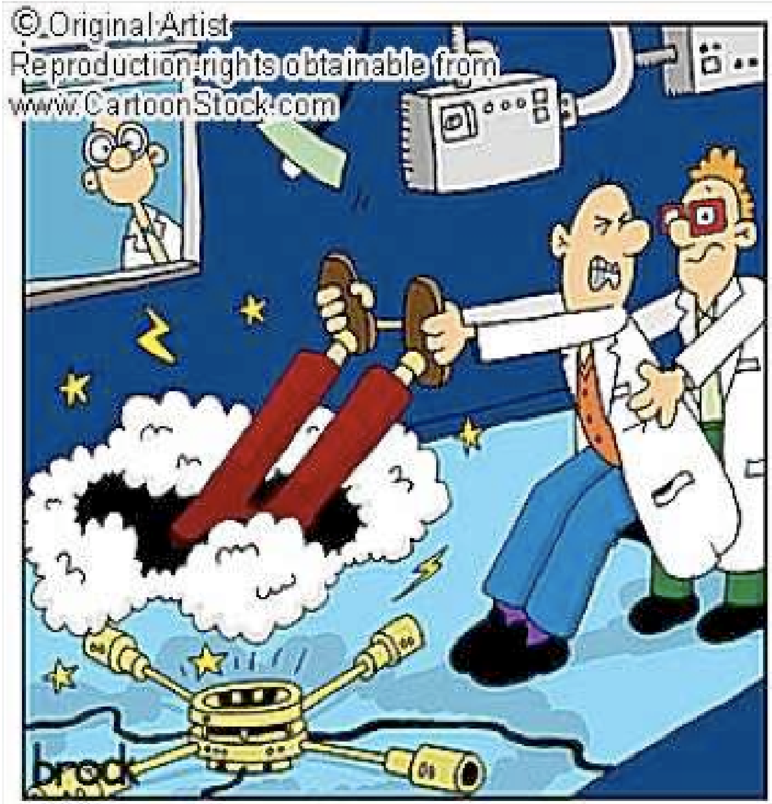
Underlying event



Jets

…and searches for New Physics

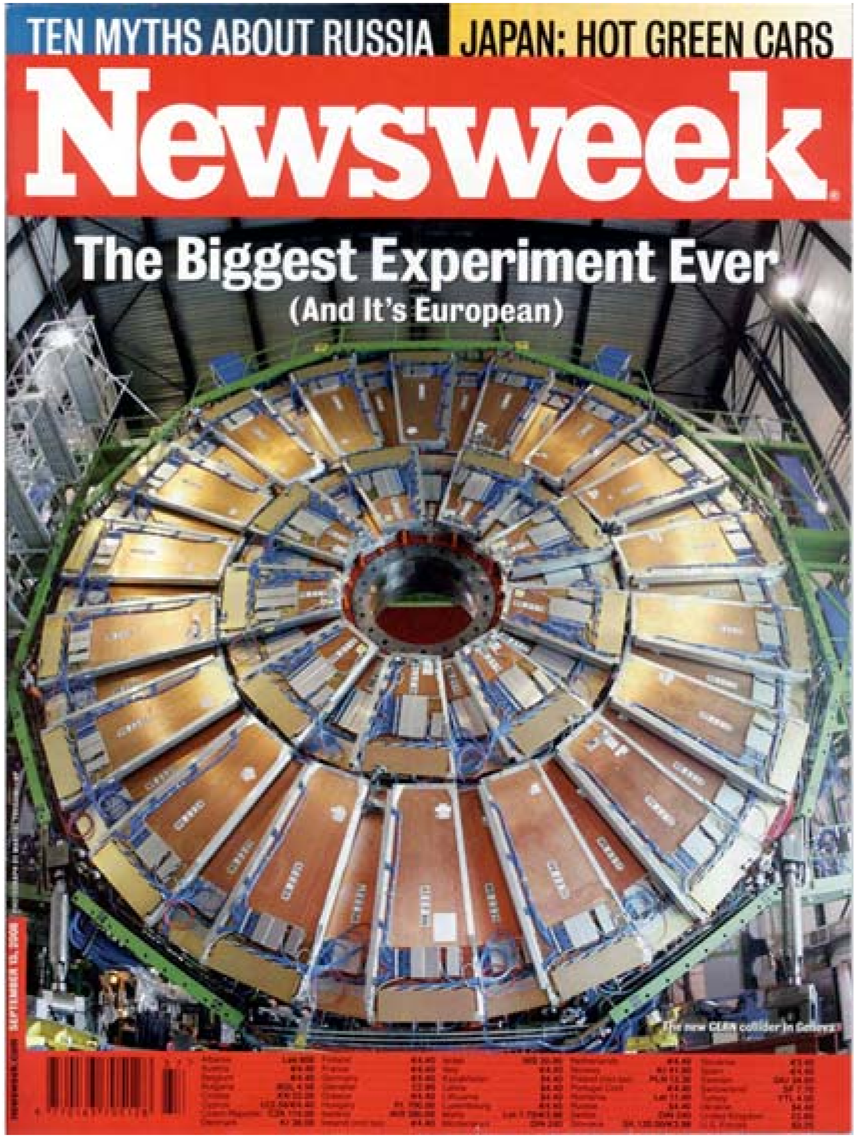
First Physics (100 pb^{-1} or less)



Professor Landsberg was fast regretting becoming the first man to successfully create a mini black hole in the laboratory.

Micro Black holes?
☺

LHC is Front Page News..

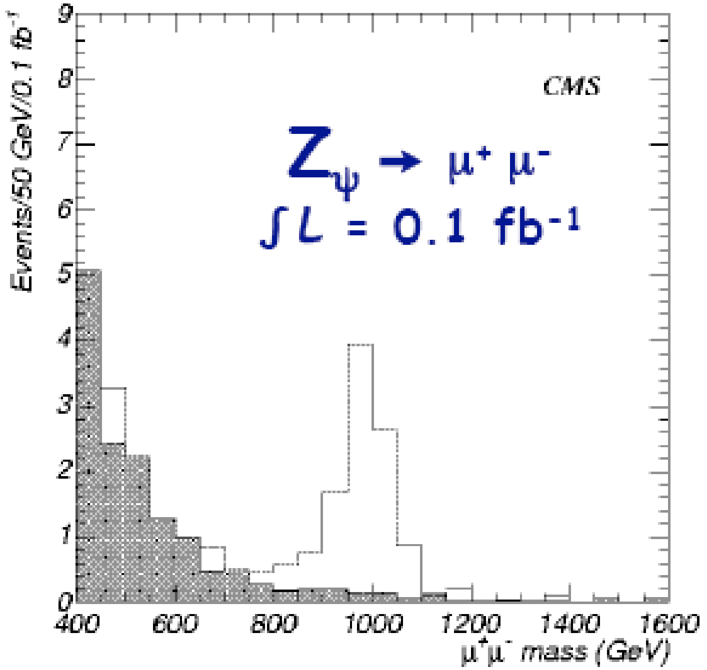


Summary

- Experimental challenges
  - The experimental challenges at the LHC are considerable
    - Pile-up, triggers, computing, (radiation)…
  - The experiments are facing these challenges
- This Lecture:
  - How CMS copes with these challenges
  - CMS is now completed and preparing for taking data
  - We take cosmics now (may even do physics with it)
  - A startup physics program for first collisions is in place…

Let the collisions come!!!

…and, who knows, end of 2009…



Backup

Standard Model Precision Measurements

Examples

- Measure ΔM_W down to 15 MeV
- Measure Triple Gauge Couplings →
- Precise Drell-Yan cross sections

  $\sin^2\theta_{eff}^{lept}$ to better than 10^{-4}
- Measure Top quarks

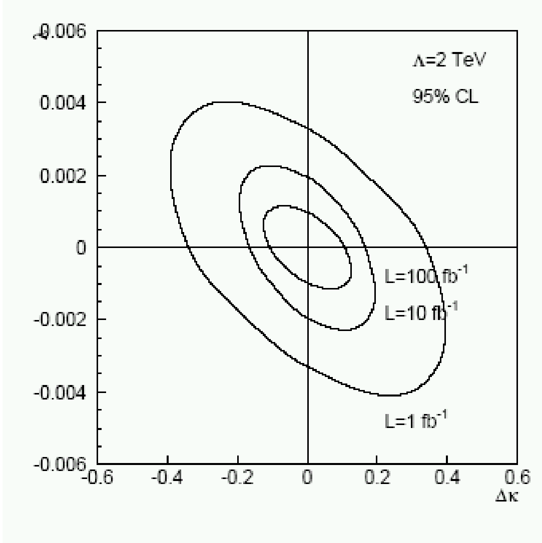
  -Δ M(top) down to better than 1 GeV

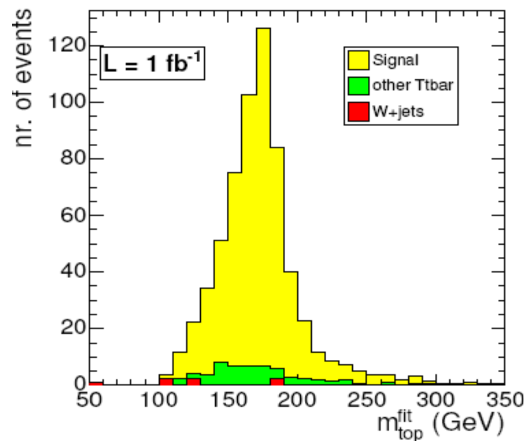
  -Top polarization

  -V_{tb} ~ 5-10% (single top production)

  -BR($t \rightarrow bH+$) ~ 3%

  -Rare decays: e.g. $t\rightarrow u\gamma$: ~ 10^{-4}



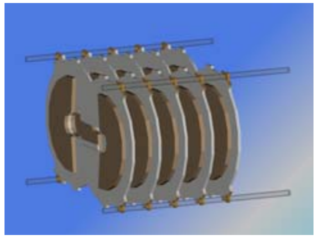


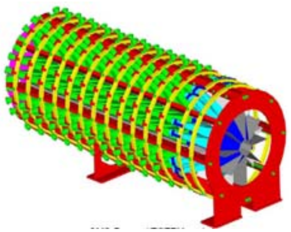
challenges

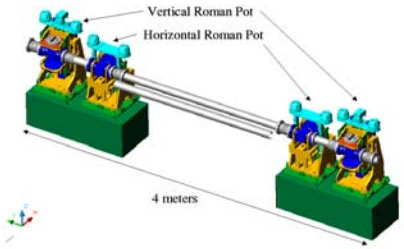
! It will be a though job ! Main challenges:
To keep the systematic errors under control

(New:) Forward detectors in ATLAS/CMS

TOTEM -T2 | CASTOR | ZDC/FwdCal | TOTEM-RP | FP420



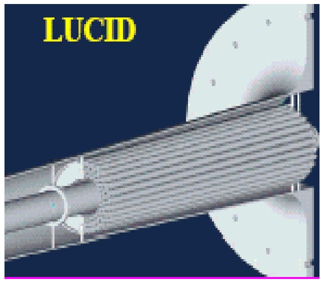


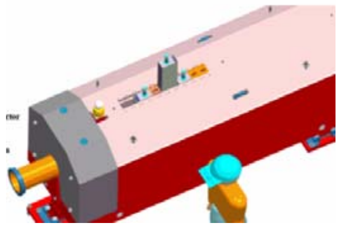


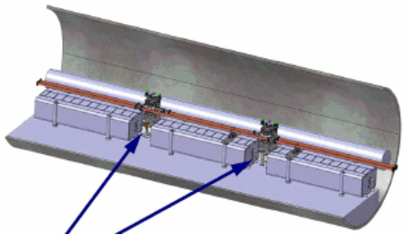
IP5

14 m | 16 m | 140 m | 147m - 220 m | 420 m

IP1



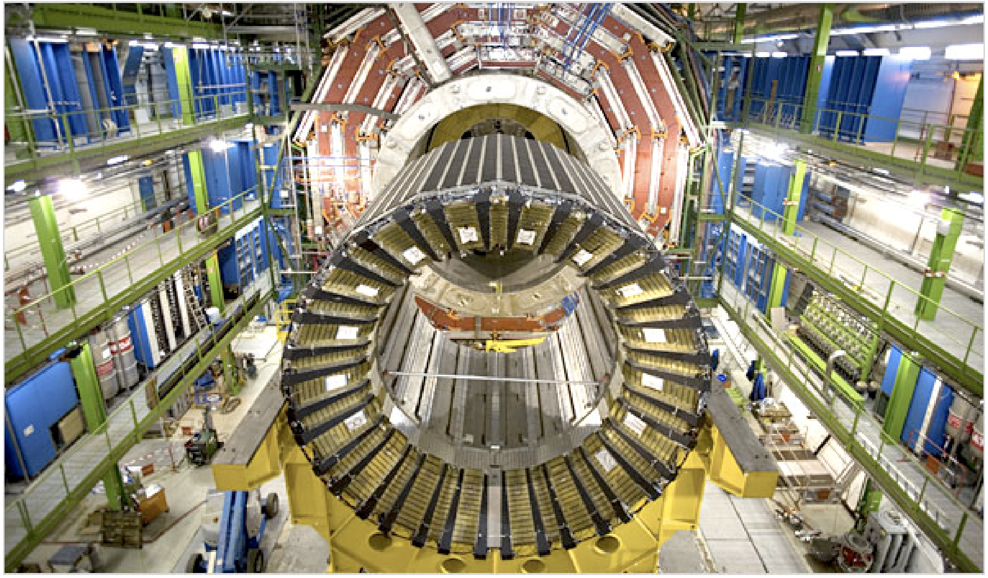




LUCID | ZDC | ALFA/RP220 | FP420

But… Saturday 29/3 New York Times..

Asking a Judge to Save the World, and Maybe a Whole Lot More



Valerio Mezzanotti for The New York Times

Part of a detector to study results of proton collisions by a particle accelerator that a federal lawsuit filed in Hawaii seeks to stop.

By DENNIS OVERBYE
Published: March 29, 2008

Stable black Hole production at the LHC:
A problem for the survival of mankind?
Giddings & Mangano: No! (probably)
Law suit against the LHC (Hawai)?

A few LHC numbers…

- Rate of pp interactions at 10^{34} : 10^9 events per second
- Energy of pp is about 7 times higher than that of the Tevatron at FNAL
- Weight of the CMS experiment: ~ 13000 tons (30% more than the Tour Eiffel)
- Amount of cables used in ATLAS : ~ 3000 km
- Data volume recorded at the front-end in CMS is 1 TB/second which corresponds to 10,000 Encyclopedia Britannica
- Data recorded during the 10-20 years of LHC life will be equivalent to all the words spoken by mankind since its appearance on earth
- A worry for the detectors: the kinetic energy the beam is of 1 small aircraft carrier of 10^4 tons going 20 miles/ hour
- Machine temperature : 1.9 K (largest cryogenic system in the world)
- Total cost of machine + experiments : ~ 5000 MCHF
- Total number of involved physicists : > 5000

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