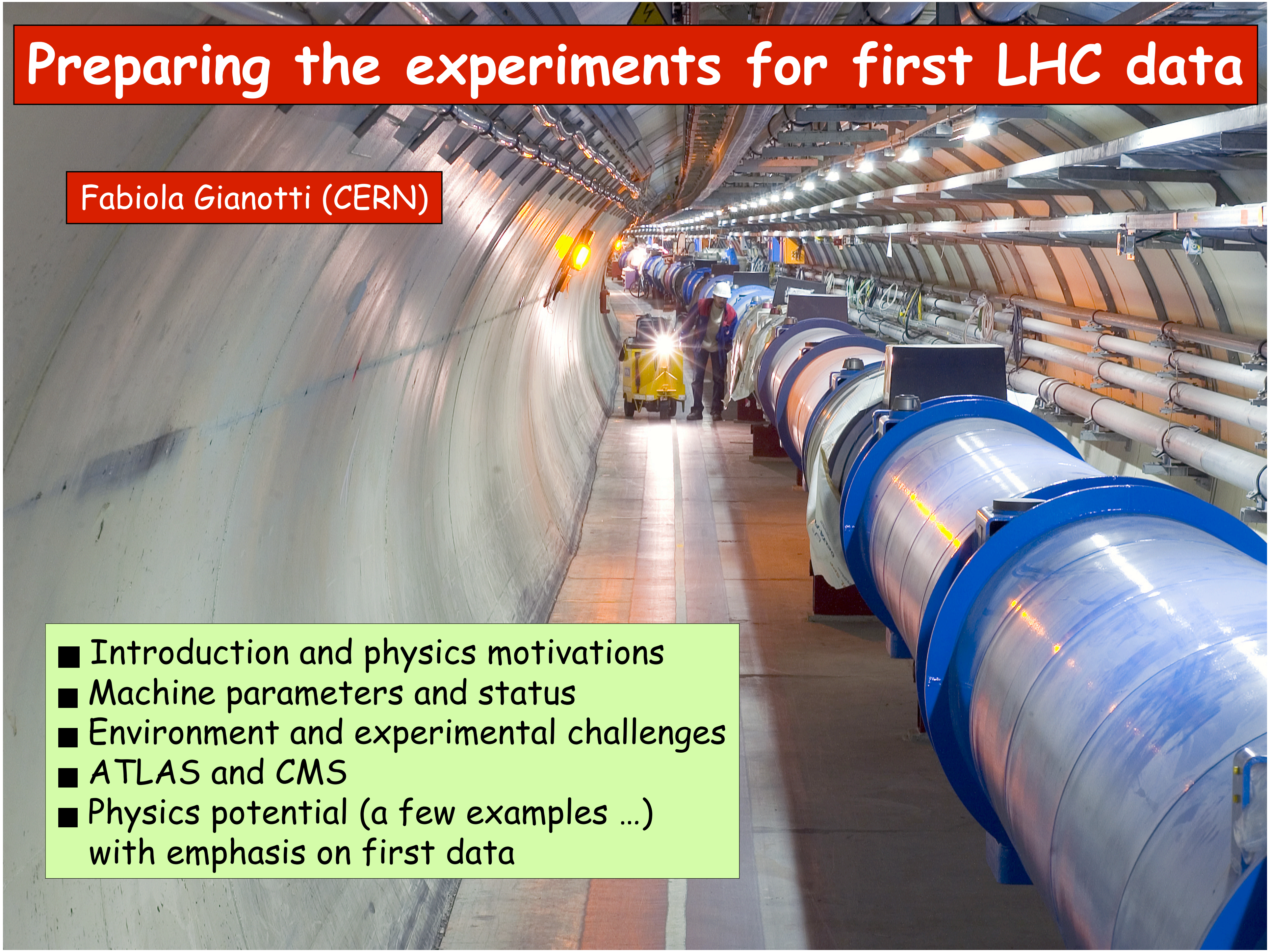
Preparing the experiments for first LHC data

Fabiola Gianotti (CERN)



- Introduction and physics motivations
- Machine parameters and status
- Environment and experimental challenges
- ATLAS and CMS
- Physics potential (a few examples …) with emphasis on first data

LHC history

The most ambitious project in high-energy physics ever, and one of the most ambitious in science more generally

1983 : $W^{\pm}/Z$ detected at SPS proton-antiproton collider
1984 : First studies for a high-energy pp collider in the LEP tunnel
1989 : Start of LEP e^+e^- collider operation at Z peak
1994 : Approval of the LHC by the CERN Council
1996 : Construction of machine and experiments start
1996 : LEP2 starts operation ($\sqrt{s}$ up to 200 GeV)
2000 : End of LEP2
2003 : Start of the accelerator and experiments installation

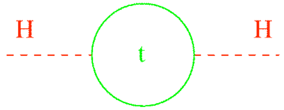
July 2008 : First collisions at $\sqrt{s}$ = 14TeV
Start a ~15-year long physics program

A 40-year project !!

WHY ???

Physics motivations for the LHC
(a brief reminder …)

What is wrong with the SM ?

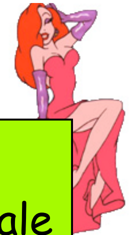
- Origin of particle masses → where is the Higgs boson ?
- "Naturalness" problem :
  radiative corrections 

  $\delta m_H^2 \sim \Lambda^2$ → $\Lambda \equiv$ scale up to which SM is valid
- "Hierarchy" problem : why $M_{EW}/M_{Planck} \sim 10^{-17}$? Is there anything in between ?
- Flavour/family problem, CP-violation, coupling unification, gravity incorporation, ν masses/oscillations, dark matter and dark energy, etc. etc., …. …..

All this calls for

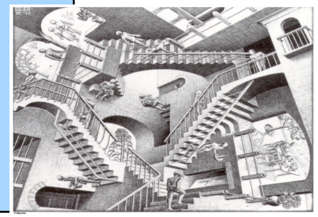
A more fundamental theory of which SM is low-E approximation ➡ New Physics

Difficult task : solve SM problems without contradicting (the very constraining) EW data



SUSY

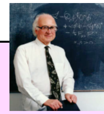
New particles at TeV scale stabilize m_H



Extra-dimensions

Additional dimensions $\rightarrow M_{gravity} \sim M_{EW}$

New states at TeV scale

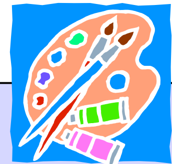


Little Higgs

SM embedded in larger gauge group

New particles at TeV scale, stable m_H

$\delta m_H \sim \Lambda \;\Rightarrow$ New Physics to stabilize m_H already needed at TeV scale



Technicolour

New strong interactions break EW symmetry

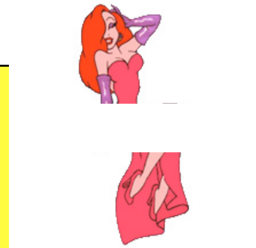
$\rightarrow$ Higgs (elementary scalar) removed

New particles at TeV scale

Split SUSY

Accept fine-tuning of m_H (and of cosm. constant) by anthropic arguments

Part of SUSY spectrum at TeV scale (for couplings unification and dark matter)

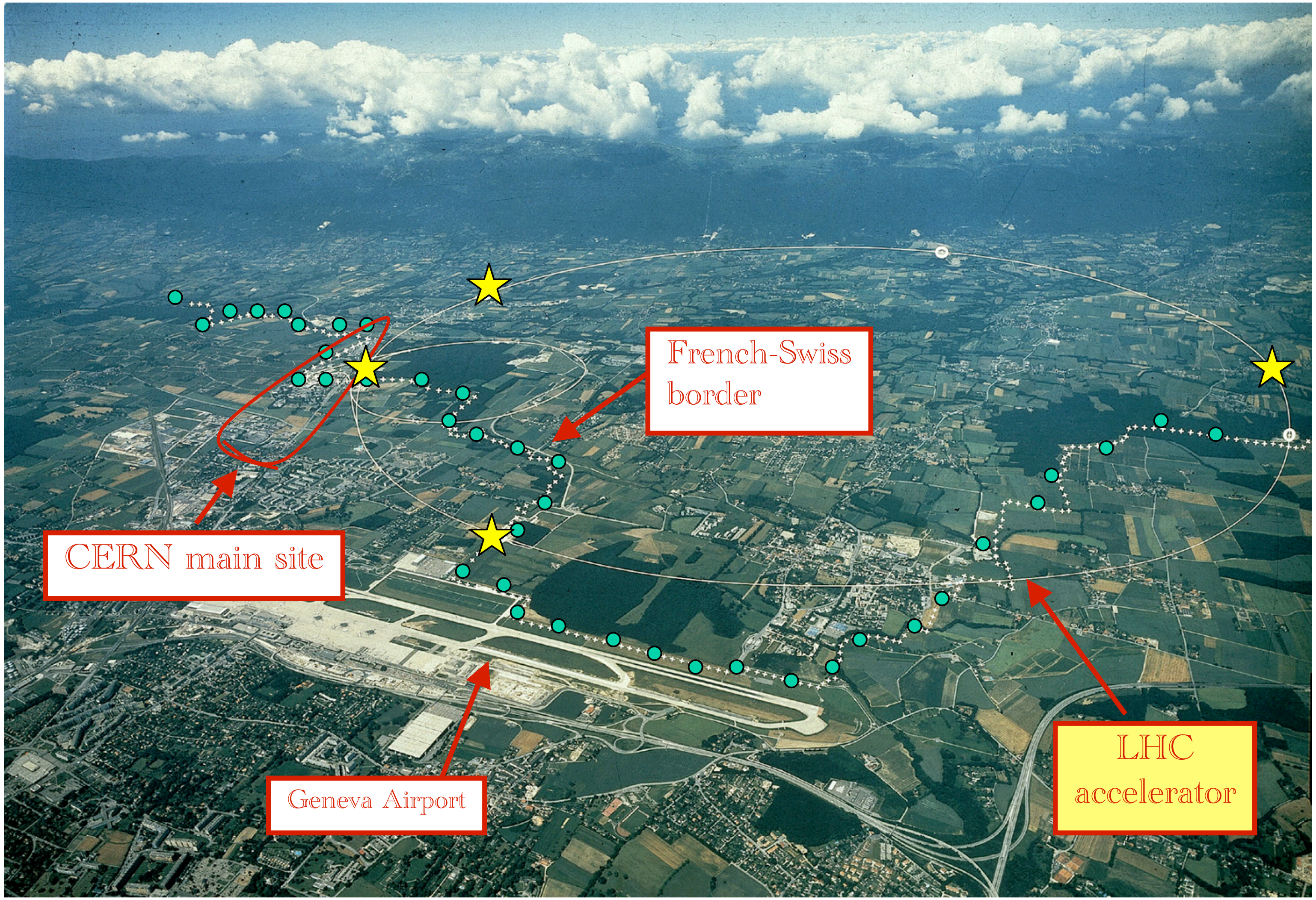


strong motivations for a machine able to explore the TeV-scale

⬇

LHC

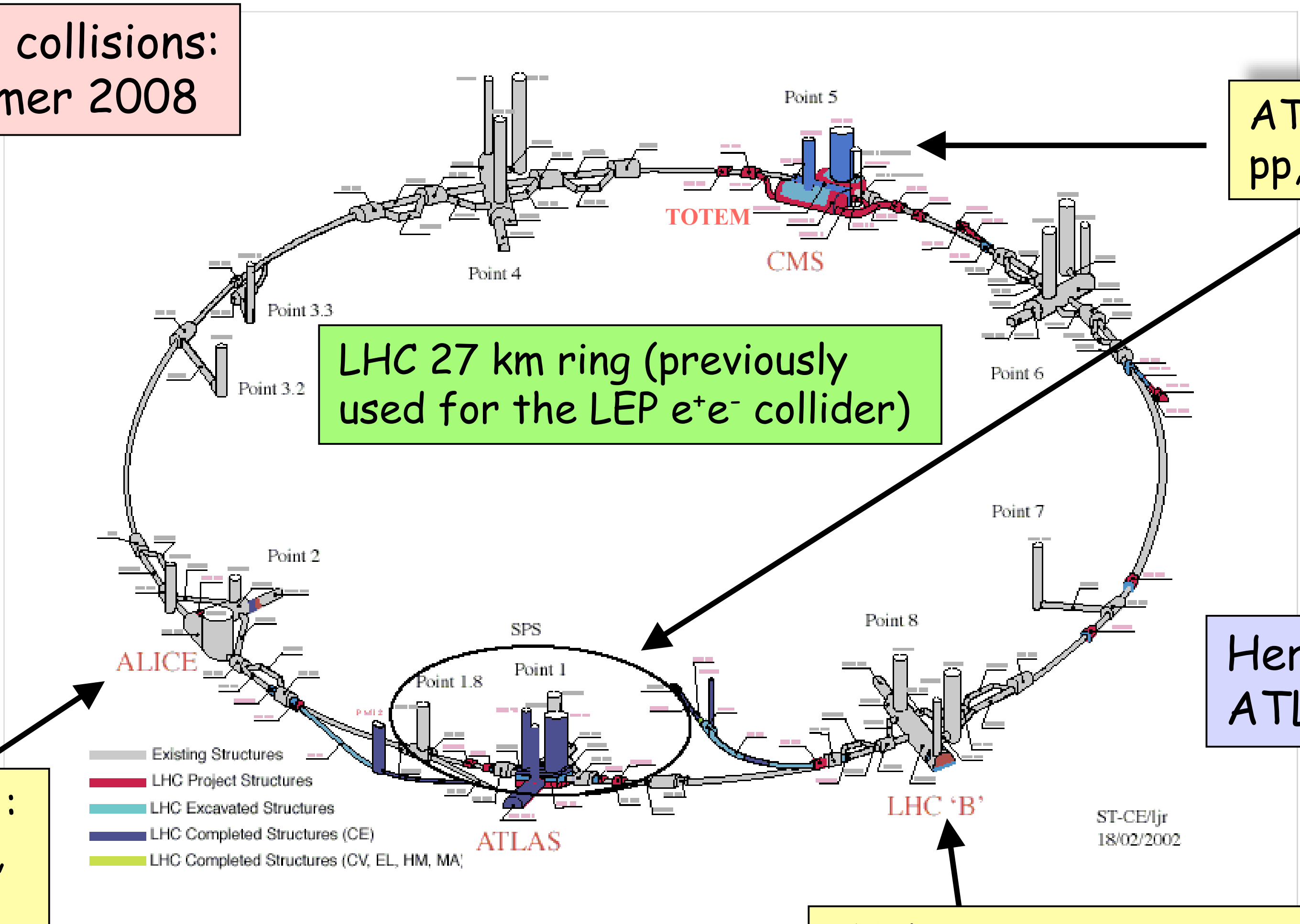
Machine main parameters and status



- pp $\sqrt{s}$ = 14 TeV $L_{design} = 10^{34}$ cm^{-2} s^{-1} (after 2010)
  $L_{initial}$ < few x 10^{33} cm^{-2} s^{-1} (before)

  Note: $\sqrt{s}$ is x7 Tevatron, L_{design} is x100 Tevatron
- Heavy ions (e.g. Pb-Pb at $\sqrt{s}$ ~ 1000 TeV)

First collisions: summer 2008



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

ATLAS and CMS : pp, general purpose

Here: mainly ATLAS and CMS

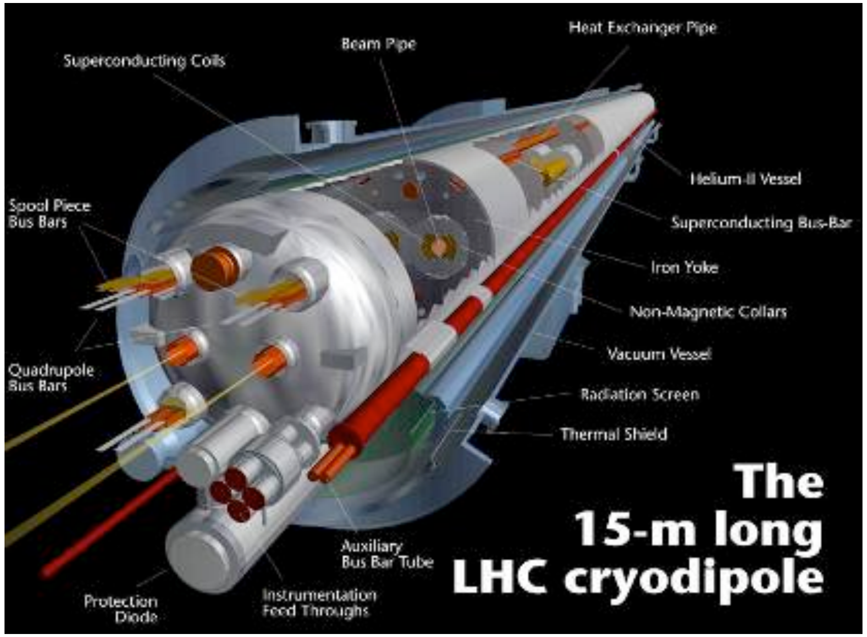
ALICE : ion-ion, p-ion

LHCb : pp, B-physics, CP-violation

$\sqrt{s}$: limiting factor is bending power needed to keep 7 TeV beams in 27 km ring:

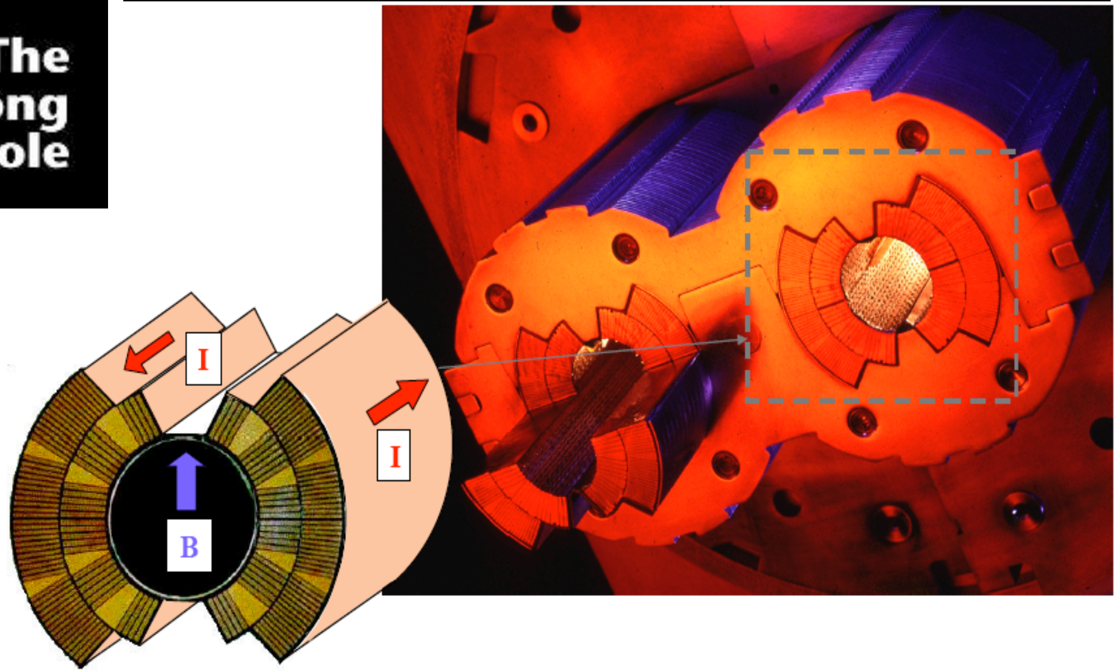
p(TeV) = 0.3 B(T) R(km)

with typical magnet packing factor of ~ 70%, need 1232 magnets providing B=8.4 T for 7 TeV beams



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

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



Note: in a pp collider, beam acceleration is not such a big issue as in an e^+e^- collider (see later)

Main parameters of the machine

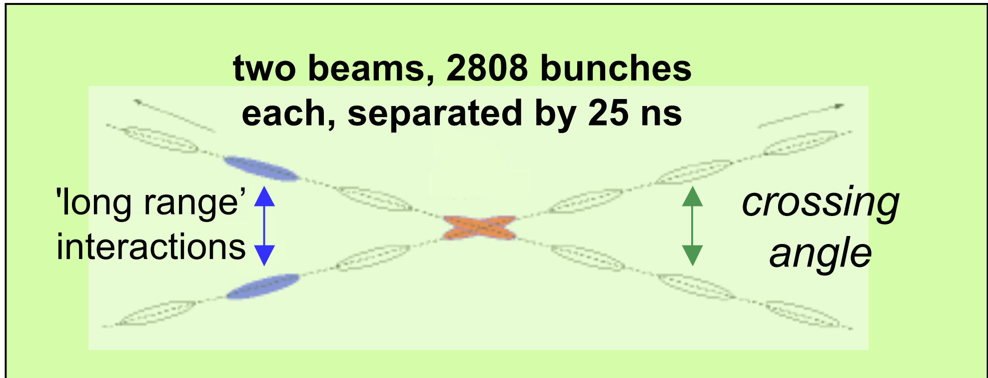
	Design operation	
Beam energy	7	TeV
Instantaneous luminosity L	10^{34}	$cm^{-2}s^{-1}$
Integrated luminosity/year	~ 100	fb^{-1}
Dipole field	8.4	T
Dipole current	11700	A
Circulating current/beam	0.53	A
Number of bunches	2808	
Bunch spacing	25	ns
Protons per bunch	10^{11}	
R.m.s. beam radius at IP1/5	16	μm
R.m.s. bunch length	7.5	cm
Stored beam energy	360	MJ
Crossing angle	300	μrad
Number of events per crossing	20	
Luminosity lifetime	10	hours

$$L = \frac{N^2 k_b f}{4\pi\sigma_x\sigma_y}$$

n. of protons per bunch (N); n. of bunches (k_b); n. of turns per second (f)

beam size at IP ($\sigma_{x,y}$ = 16 μm)

$$N = L \times \sigma\,(pp \rightarrow X)$$



x200 Tevatron

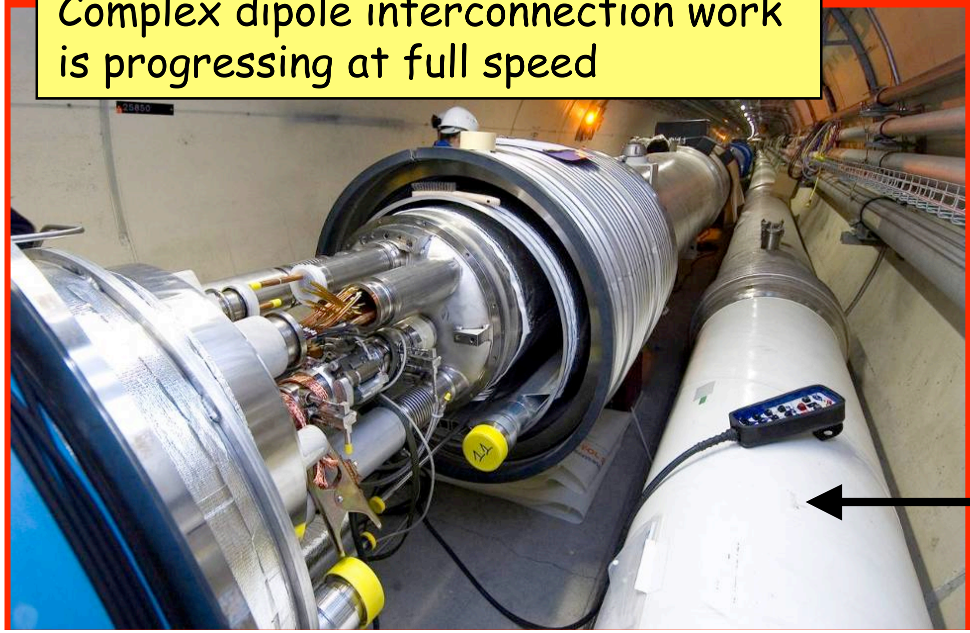
Aircraft carrier at 12 knots

All 1232 dipoles have been installed in the underground tunnel

Dipole quality
(from warm/cold tests)
is excellent

Electrical quality assurance

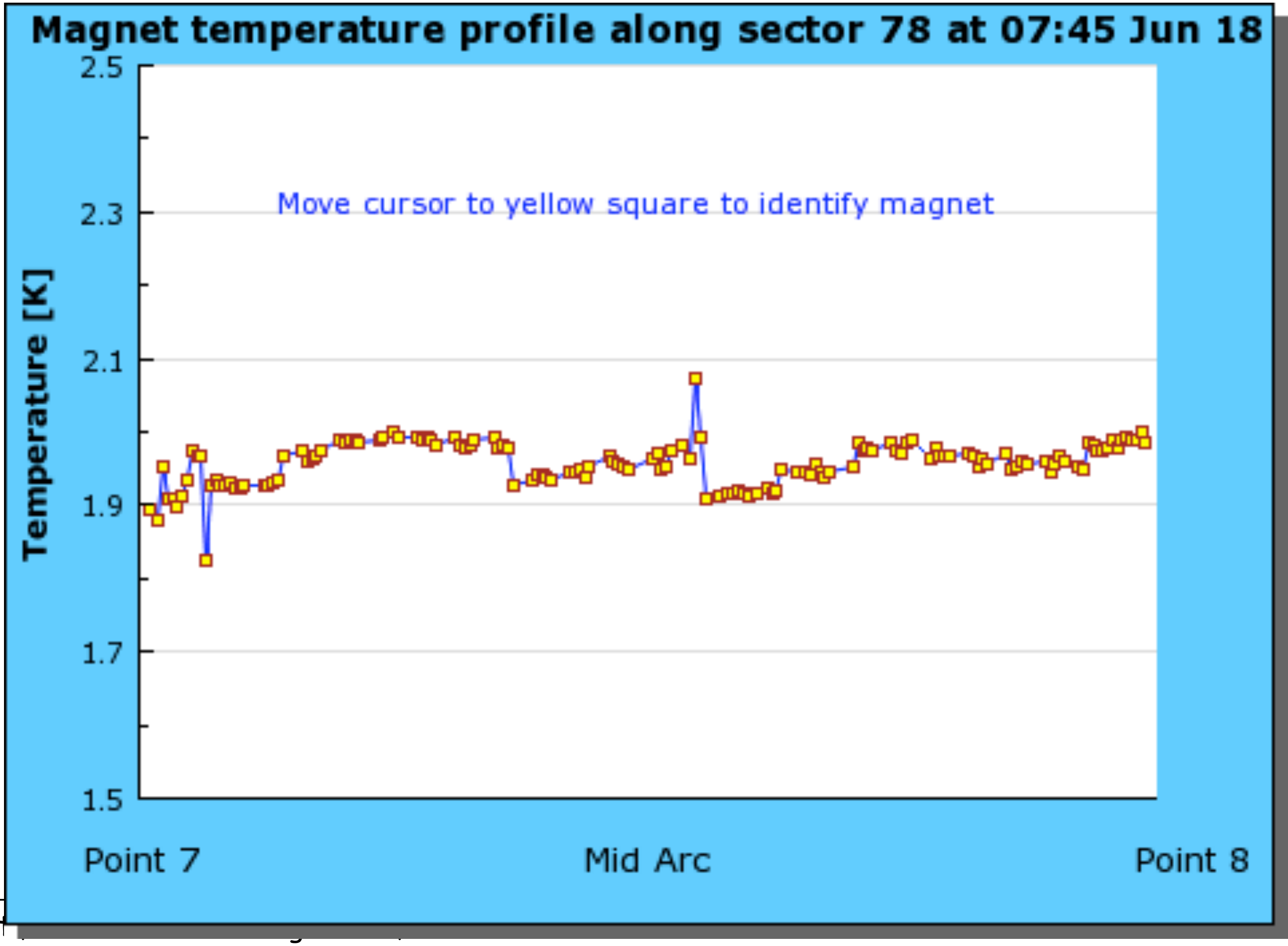
Complex dipole interconnection work is progressing at full speed



Cryogenic line

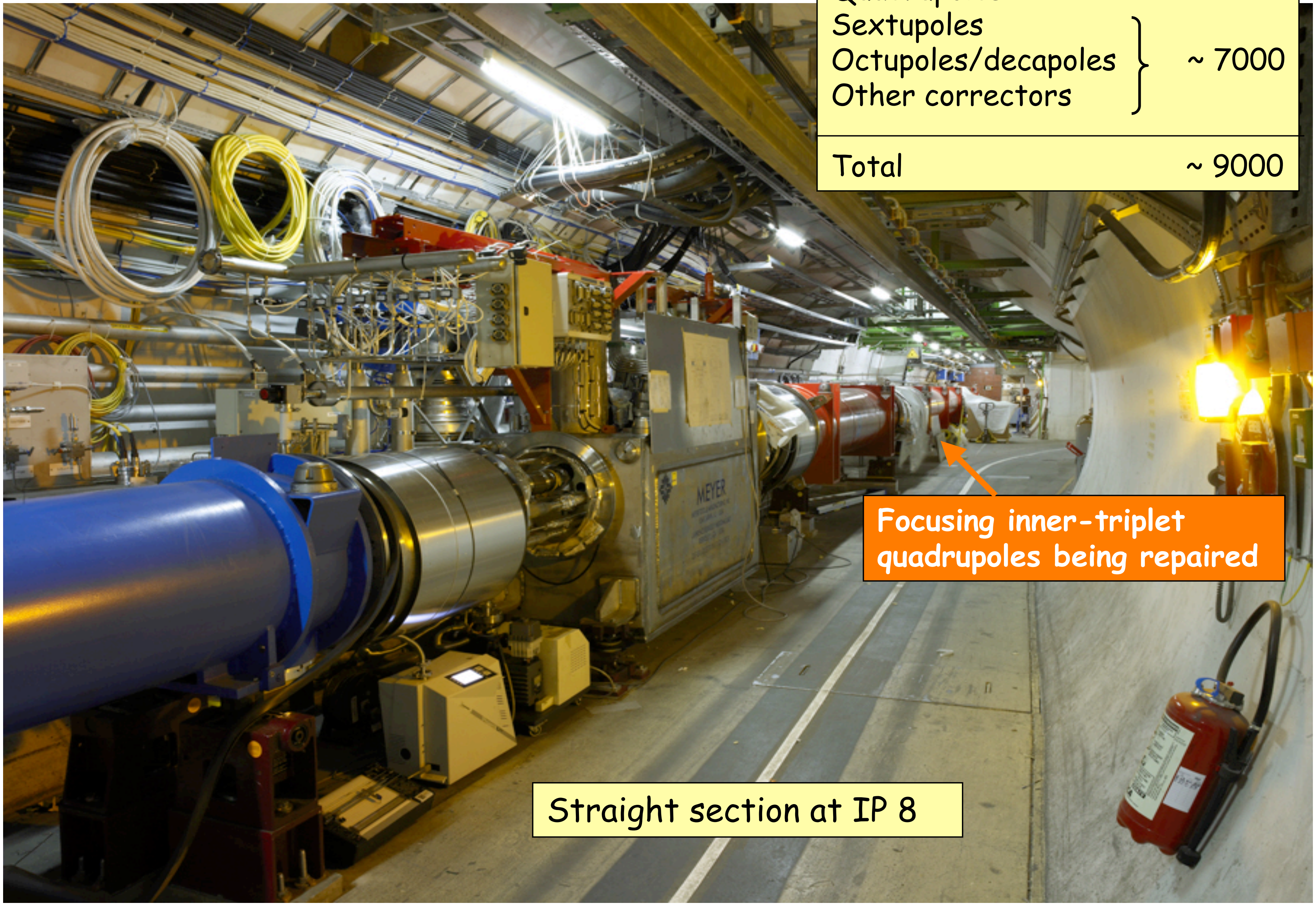
The first one of eight sectors (sector 7-8) was cooled down to the 1.9 K operation temperature in the first half of 2007
Cool-down of sector 4-5 starting

One sector: 3.3 km, 154 dipoles



Not only dipoles ….

Main dipoles	1232
Quadrupoles	~ 400
Sextupoles Octupoles/decapoles Other correctors	~ 7000
Total	~ 9000



Accelerating cavities

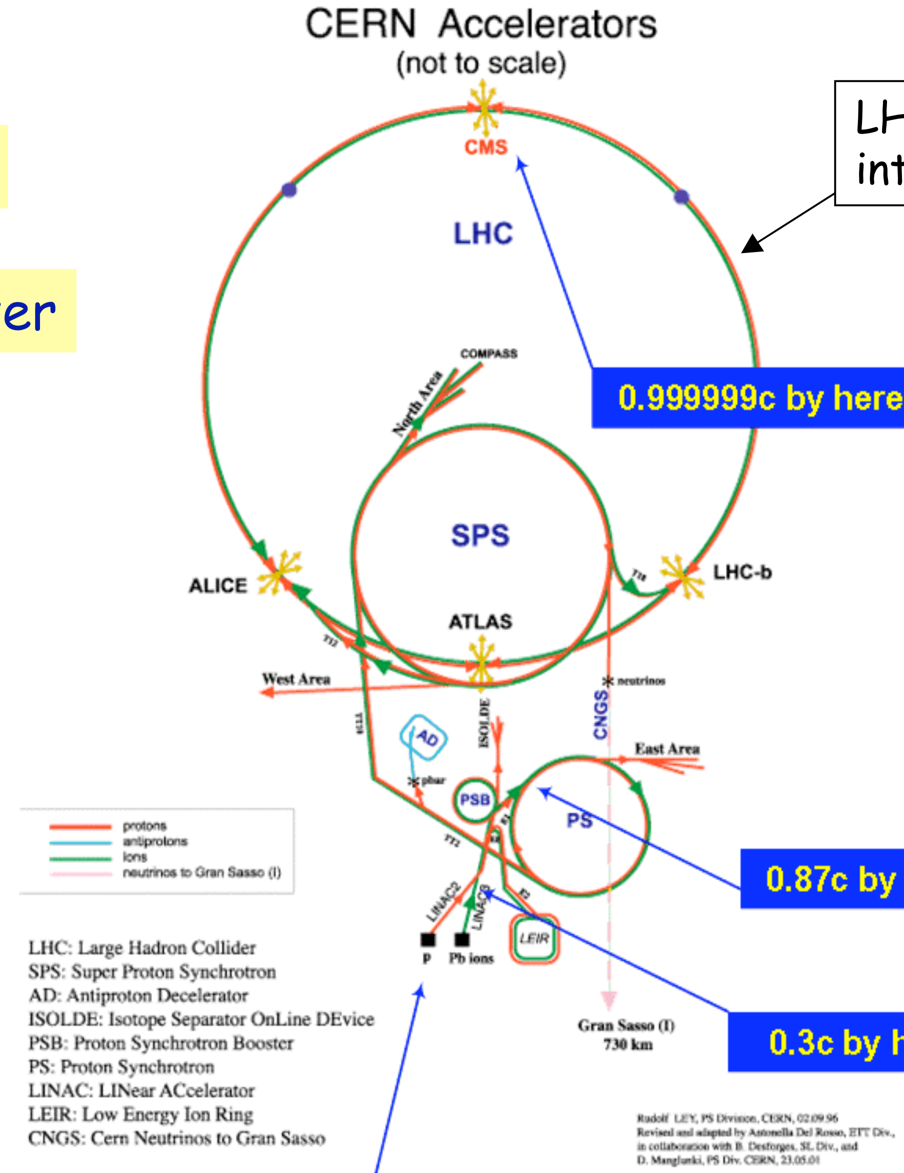
The LHC uses 8 superconducting cavities per beam, delivering 16 MV (an accelerating field of 5 MV/m) at 400 MHz.
The cavities will operate at 4.5 K.

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

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

The full accelerator complex

Linac
↓
Booster
↓
PS
↓
SPS
↓
LHC



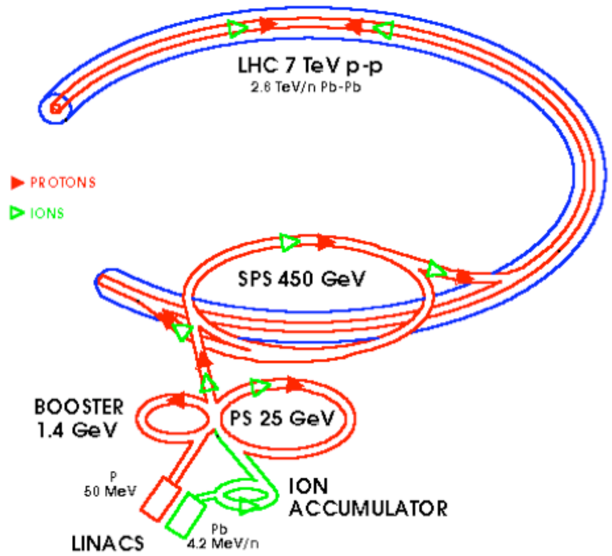
LHC ring is divided into 8 sectors

0.999999c by here

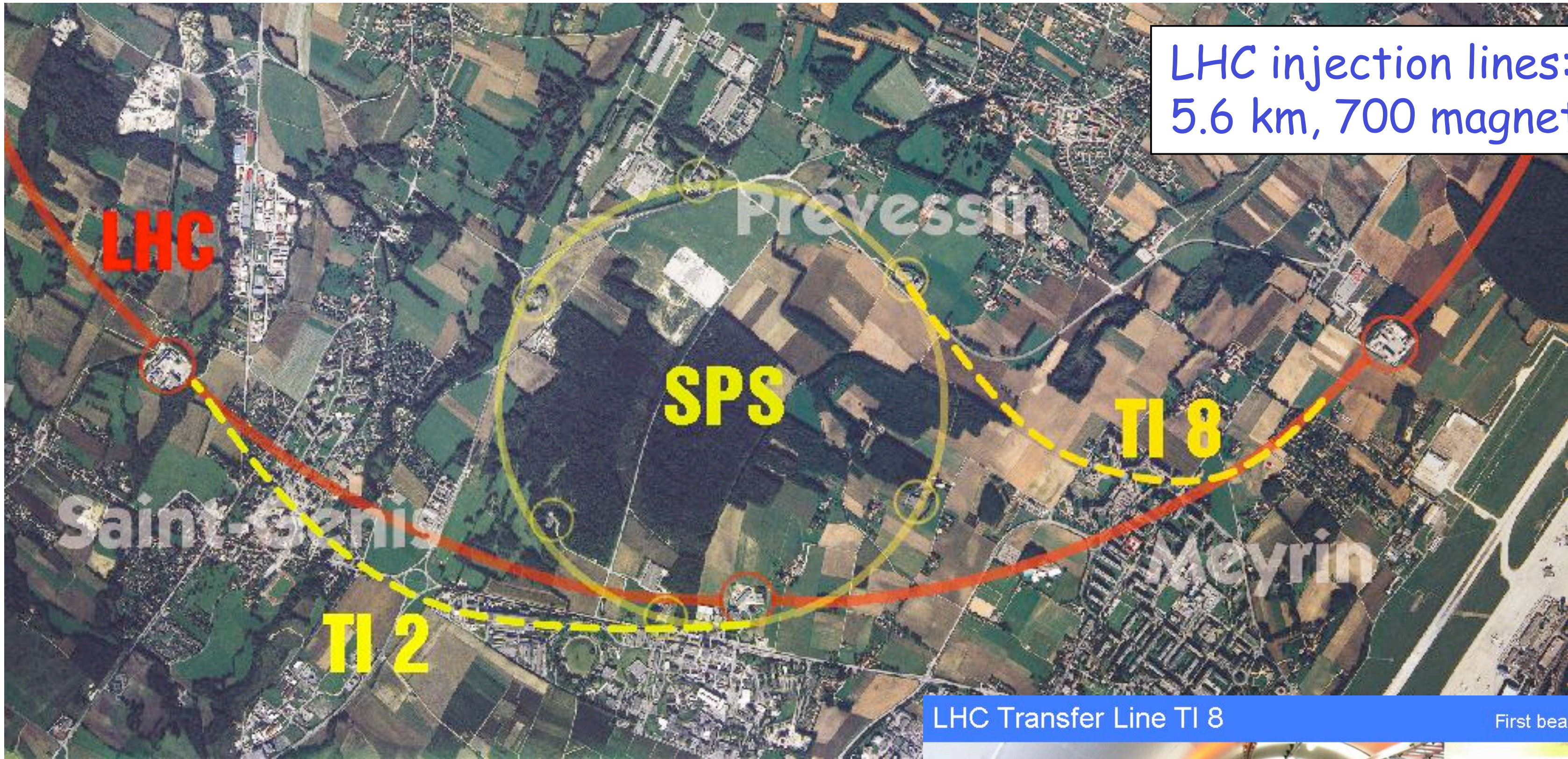
0.87c by here

0.3c by here

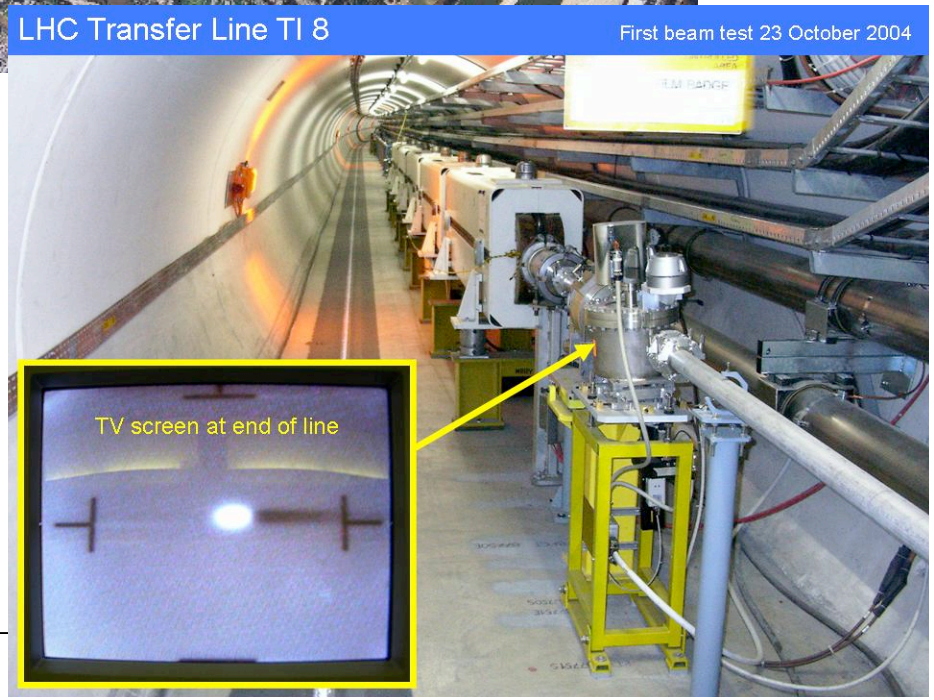
Start the protons out here



50 years of CERN history still alive and operational



LHC injection lines:
5.6 km, 700 magnets



October 2004: first beam injection test from SPS to LHC through TI8 transfer line

Lyn Evans
SPC 18-June-2007

General LHC Schedule

- Engineering run originally foreseen at end 2007 now precluded by delays in installation and equipment commissioning.
- 450 GeV operation now part of normal setting up procedure for beam commissioning to high-energy
- General schedule being reassessed, accounting for inner triplet repairs and their impact on sector commissioning

  -- All technical systems commissioned to 7 TeV operation, and machine closed April 2008

  -- Beam commissioning starts May 2008

  -- First collisions at 14 TeV c.m. July 2008

  -- Pilot run pushed to 156 bunches for reaching 10^{32} cm^{-2} s^{-1} by end 2008
- No provision in success-oriented schedule for major mishaps, e.g. additional warm-up/cooldown of sector

LHC General co-ordination schedule, EDMS 102509, 12 June 2007

Lyn Evans
SPC 18-June-2007

The various steps toward design luminosity

Jorg Wenninger
(machine team)

Beam commissioning will proceed in phases with increased complexity:

- Number of bunches and bunch intensity.
- Crossing angle (start without crossing angle !).
- Less focusing at the collision point (larger 'β*').
- It cannot be excluded that initially the LHC will operate at 6 TeV or so due to magnet 'stability'. Experience will tell...

It will most likely take YEARS

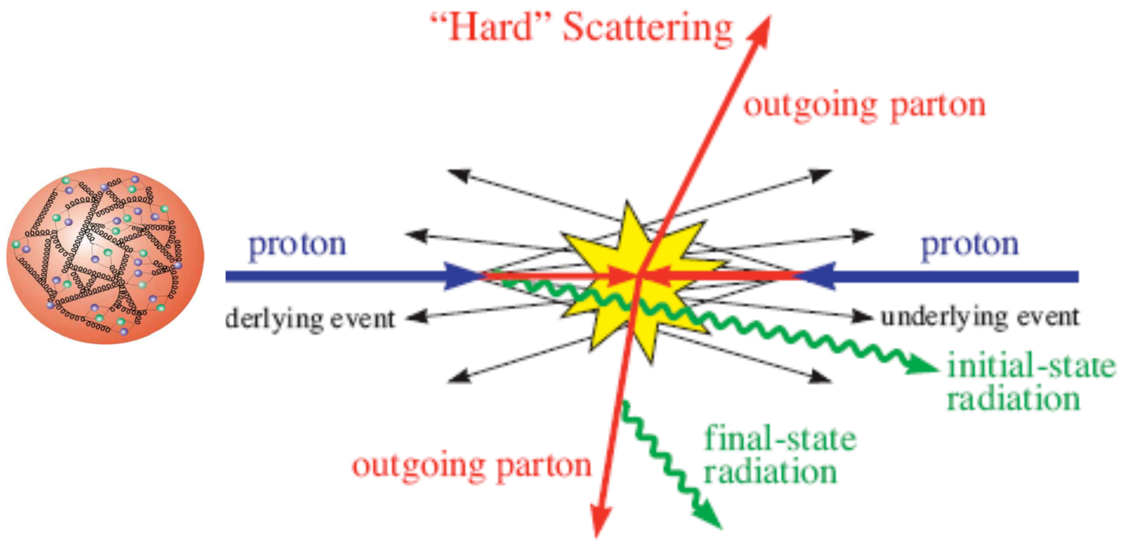
My guess: Total integrated luminosity
$\int Ldt$ O(100 pb^{-1}) in 2008 ?
$\int Ldt \sim$ 1-10 fb^{-1} in 2009 ?

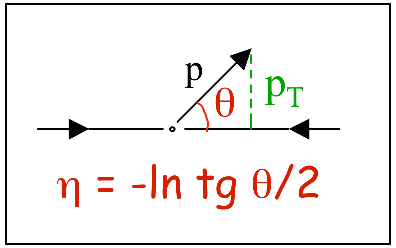
Parameter	Phase A	Phase B	Phase C	Nominal
k / no. bunches	43-156	936	2808	2808
Bunch spacing (ns)	2021-566	75	25	25
N (10^{11} protons)	0.4-0.9	0.4-0.9	0.5	1.15
Crossing angle (μrad)	0	250	280	280
$\sqrt{(\beta^*/\beta^*_{nom})}$	2	$\sqrt{2}$	1	1
σ* (μm, IR1&5)	32	22	16	16
L ($cm^{-2}s^{-1}$)	6×10^{30}-10^{32}	10^{32}-10^{33}	(1-2)$\times10^{33}$	10^{34}
Year (?)	2008	2009	2009-2010	> 2010

The environment and the experimental challenges

Backgrounds, pile-up, radiation, detector performance, trigger, computing …

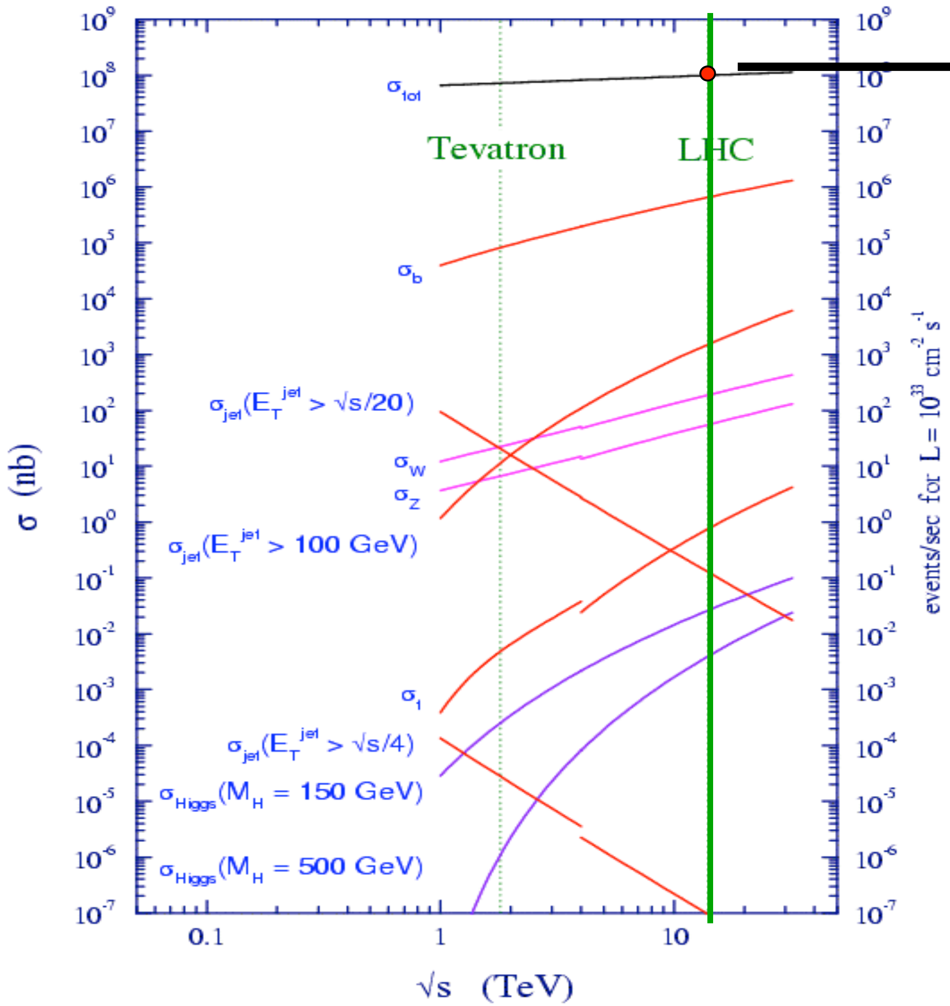
Phenomenology of pp interactions (short reminder)





- Most collisions are peripheral events where protons interact as a whole → small momentum transfer. These are called "minimum-bias" events (not so interesting....)
- In rarer cases: head-on collisions between incoming protons lead to interactions between their constituents (quarks and gluons) with large (transverse) momentum p_T transfer (scattering at large angle). These are called hard-scattering processes, and are the interesting events that can produce (new) heavy physics
- Since quarks and gluons carry a fraction of the proton momentum, the centre-of-mass energy of quark/gluon collisions is smaller than 14 TeV. Typically up to a few TeV

❶ Event rate and pile-up (consequence of machine high luminosity …)



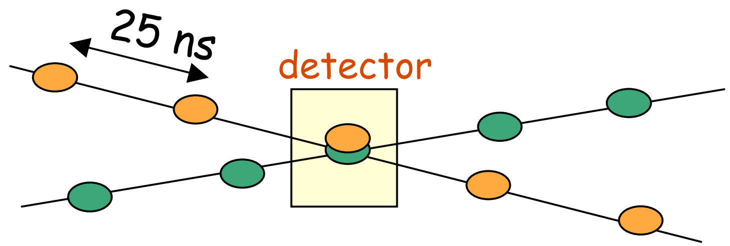
Event rate in ATLAS, CMS :

$N = L \times \sigma_{inelastic}(pp) \approx 10^{34}$ cm^{-2} s^{-1} $\times$ 70 mb

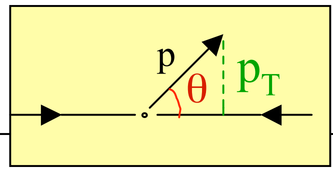
$\approx 10^9$ interactions/s

Proton bunch spacing : 25 ns

Protons per bunch : 10^{11}



~ 20 inelastic (low-p_T) events ("minimum bias") produced simultaneously in the detectors at each bunch crossing → pile-up

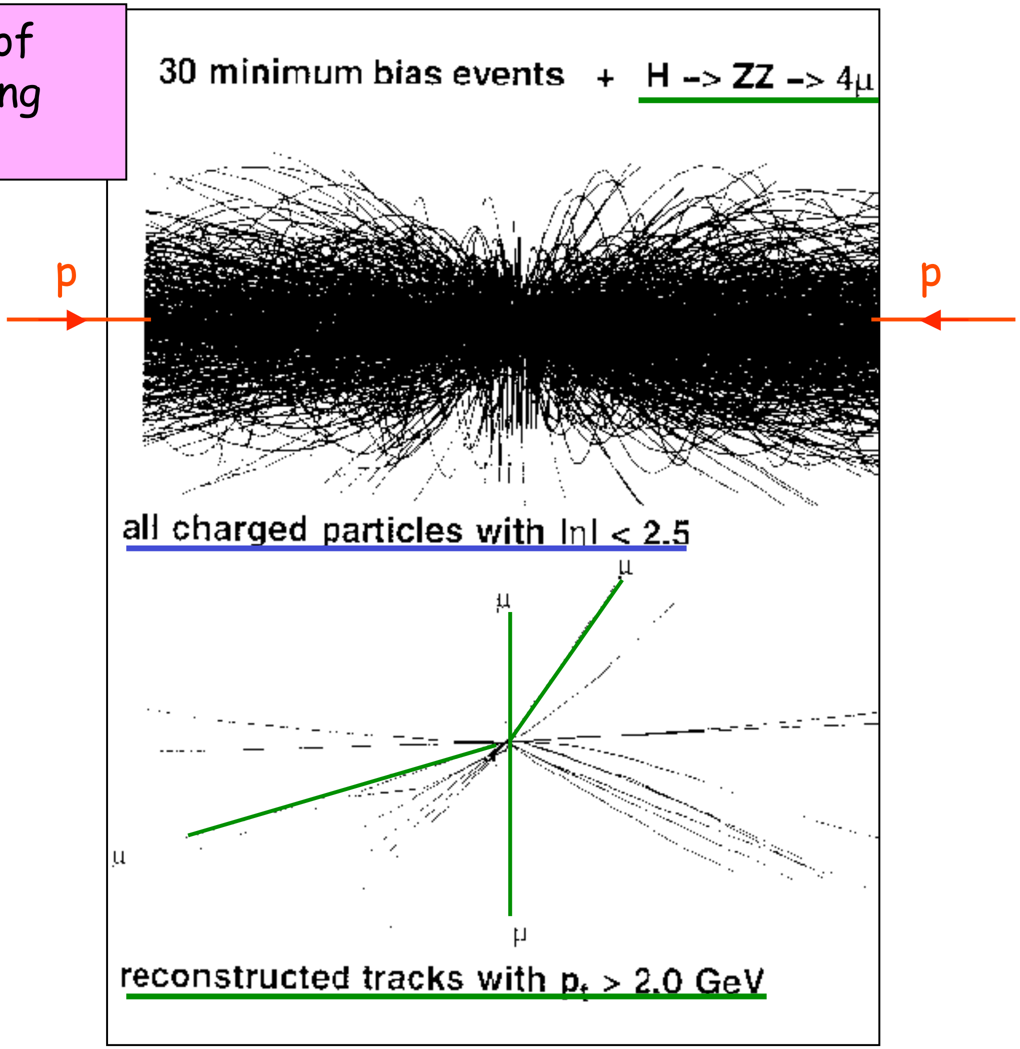


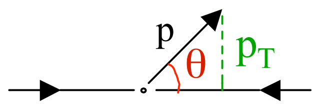
Simulation of CMS tracking detector

At each crossing : ~1000 charged particles produced over $|\eta| < 2.5$ $(10^0 < \theta < 170^0)$

However : $\langle p_T \rangle \approx 500$ MeV

→ applying p_T cuts allows extraction of interesting events





$\eta = -\ln tg\, \theta/2$

Impact of pile-up on detector requirements and performance:

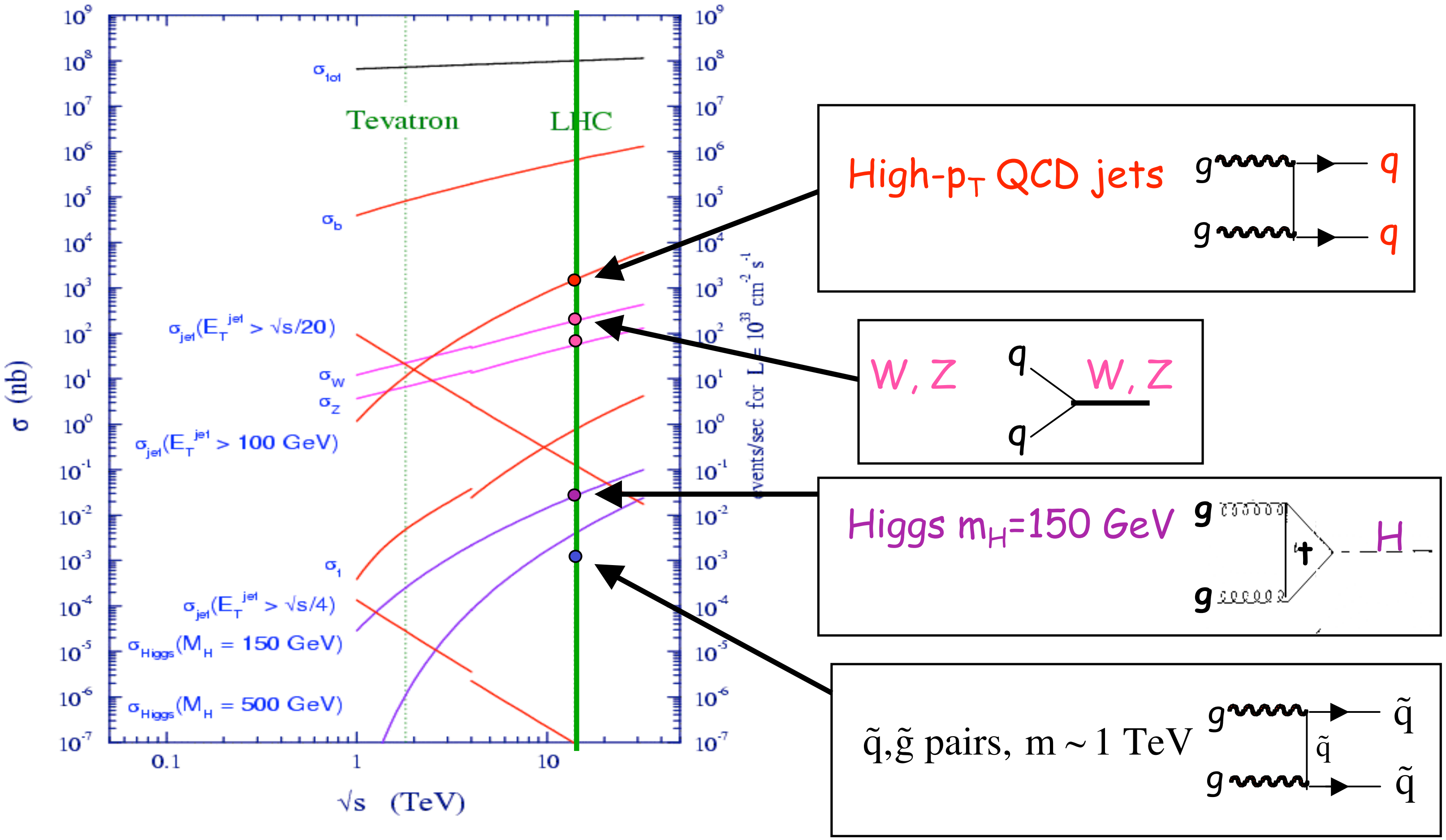
-- fast response : ~ 50 ns

-- granularity : $> 10^8$ channels

-- radiation resistance (up to 10^{16} n/cm^2/year in forward calorimeters)

-- event reconstruction much more challenging than at previous colliders

❷ Huge (QCD) backgrounds (consequence of high energy …)



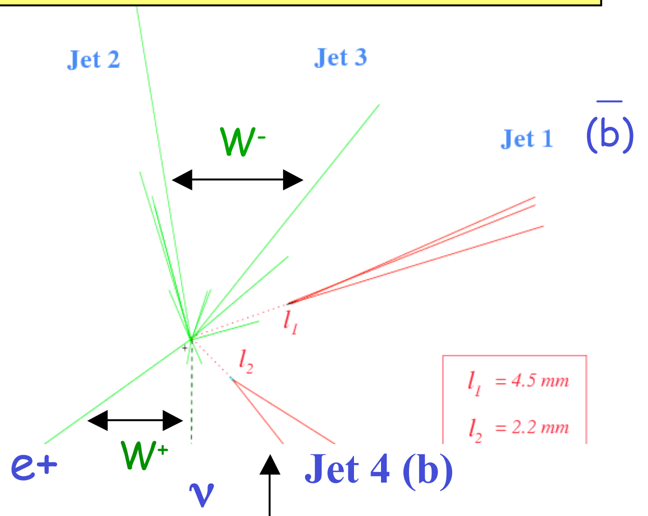
- No hope to observe light objects (W, Z, H ?) in fully-hadronic final states → rely on l, γ
- Mass resolutions of ~ 1% (10%) needed for l, γ (jets) to extract tiny signals from backgrounds, and excellent particle identification (e.g. e/jet separation)
- Fully-hadronic final states (e.g. q* → qg) can be extracted from backgrounds only with hard O(100 GeV) p_T cuts → works only for heavy objects
- S (EW) /B (QCD) larger at Tevatron than at LHC

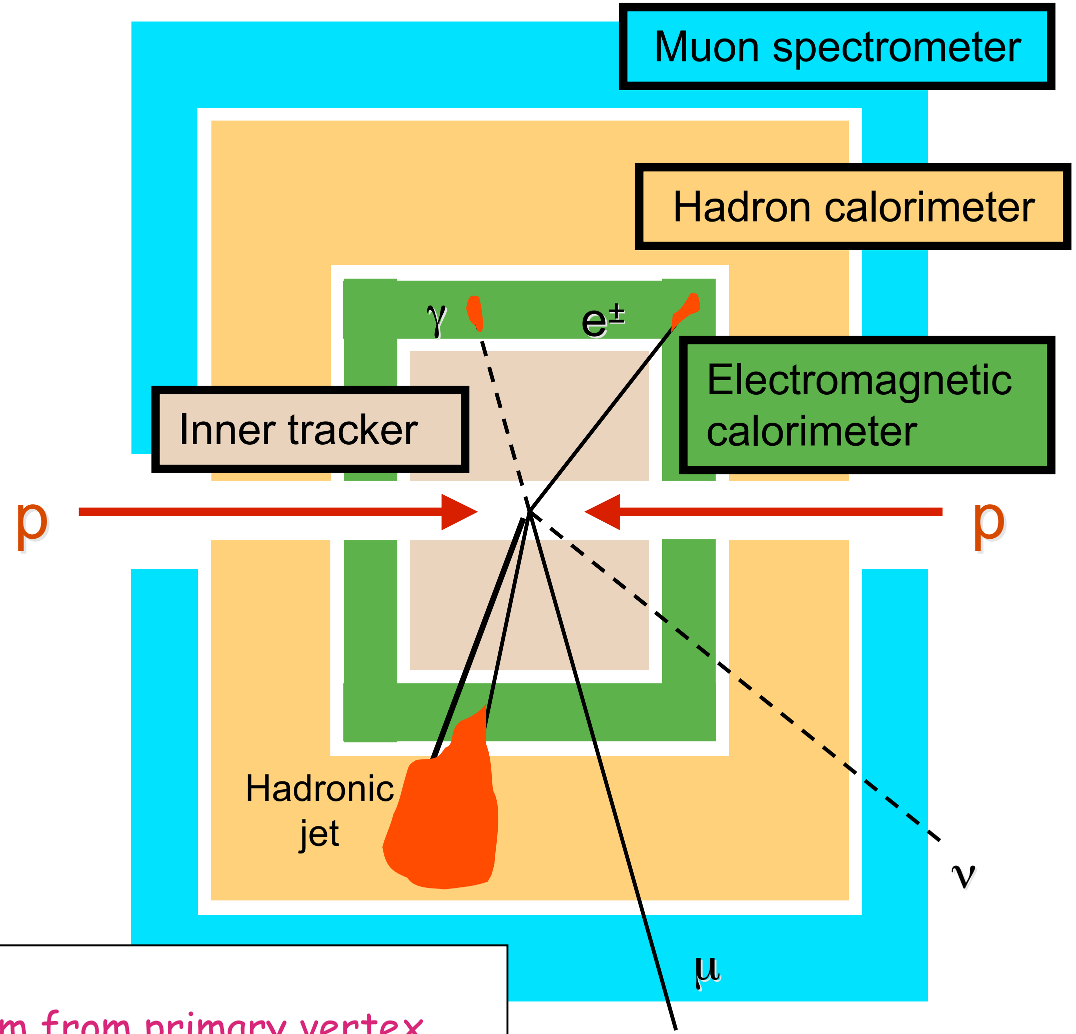
❸ Powerful high-performance experiments

Don' t know how New Physics will manifest → detectors must be able to detect as many particles and signatures as possible: e, μ, τ, ν, γ, jets, b-quarks, ...
→ ATLAS and CMS are general-purpose experiments.

Excellent performance over unprecedented energy range :
few GeV → few TeV

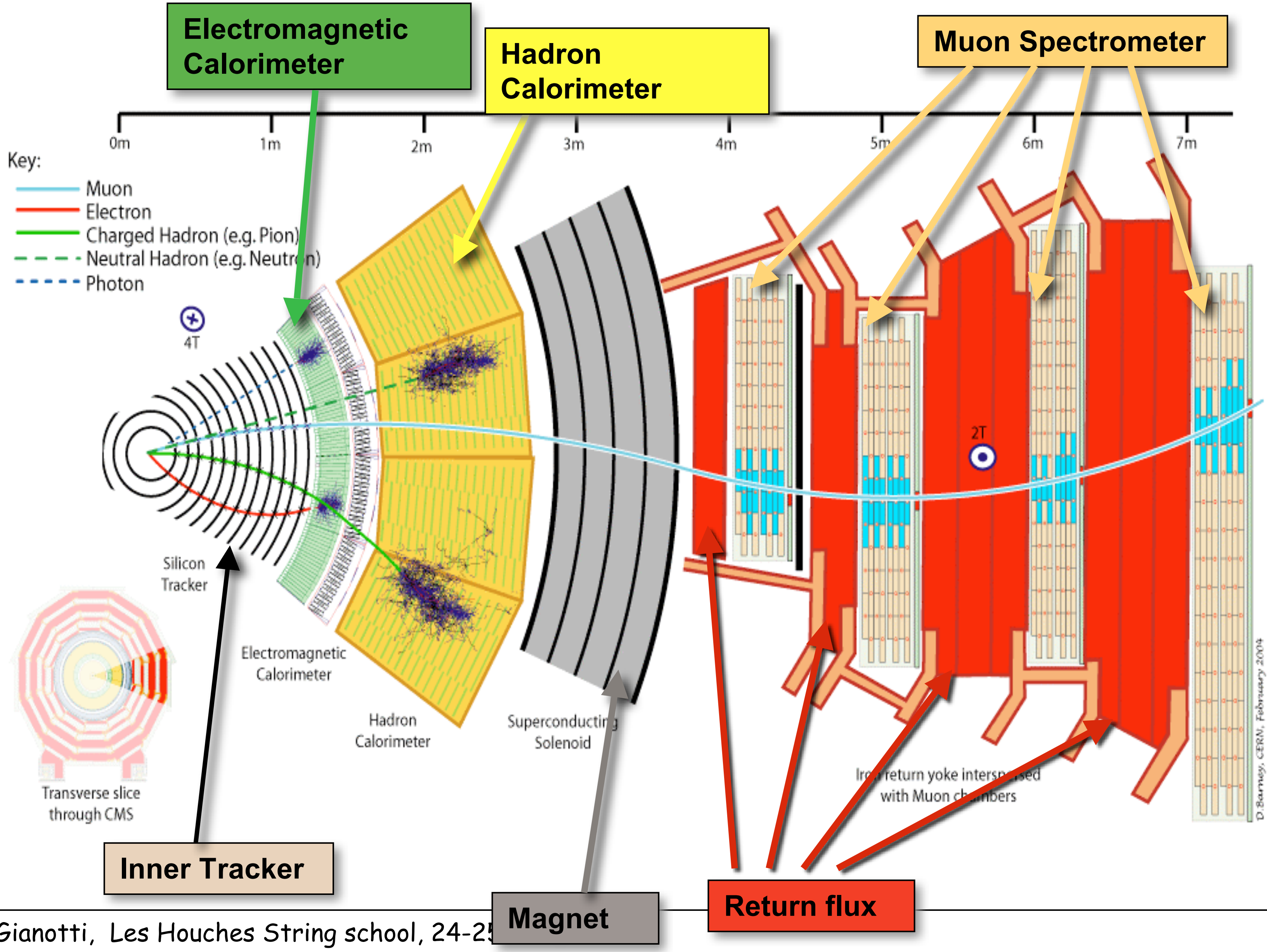
$t\bar{t} \rightarrow bW\,\bar{b}W \rightarrow bl\nu\,\bar{b}jj$ event from CDF data





b-tagging (secondary vertices)
τ (b-hadrons) ~ 1.5 ps → decay at few mm from primary vertex
→ detected with high-granularity Si detectors

With some more details (CMS case)

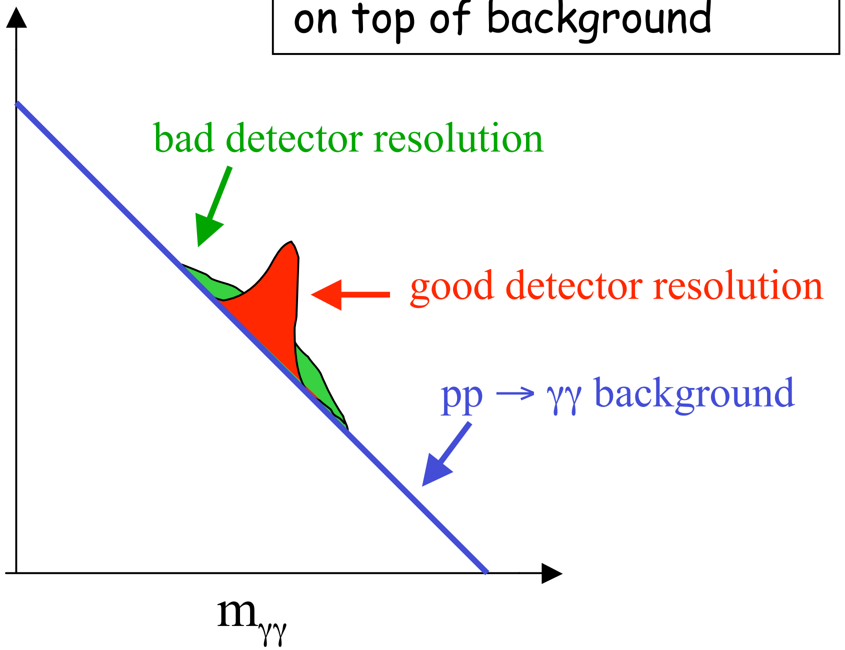


Examples of detector performance requirements

Lepton measurement: $p_T \approx$ GeV → 5 TeV (b → l+X, W'/Z', …)

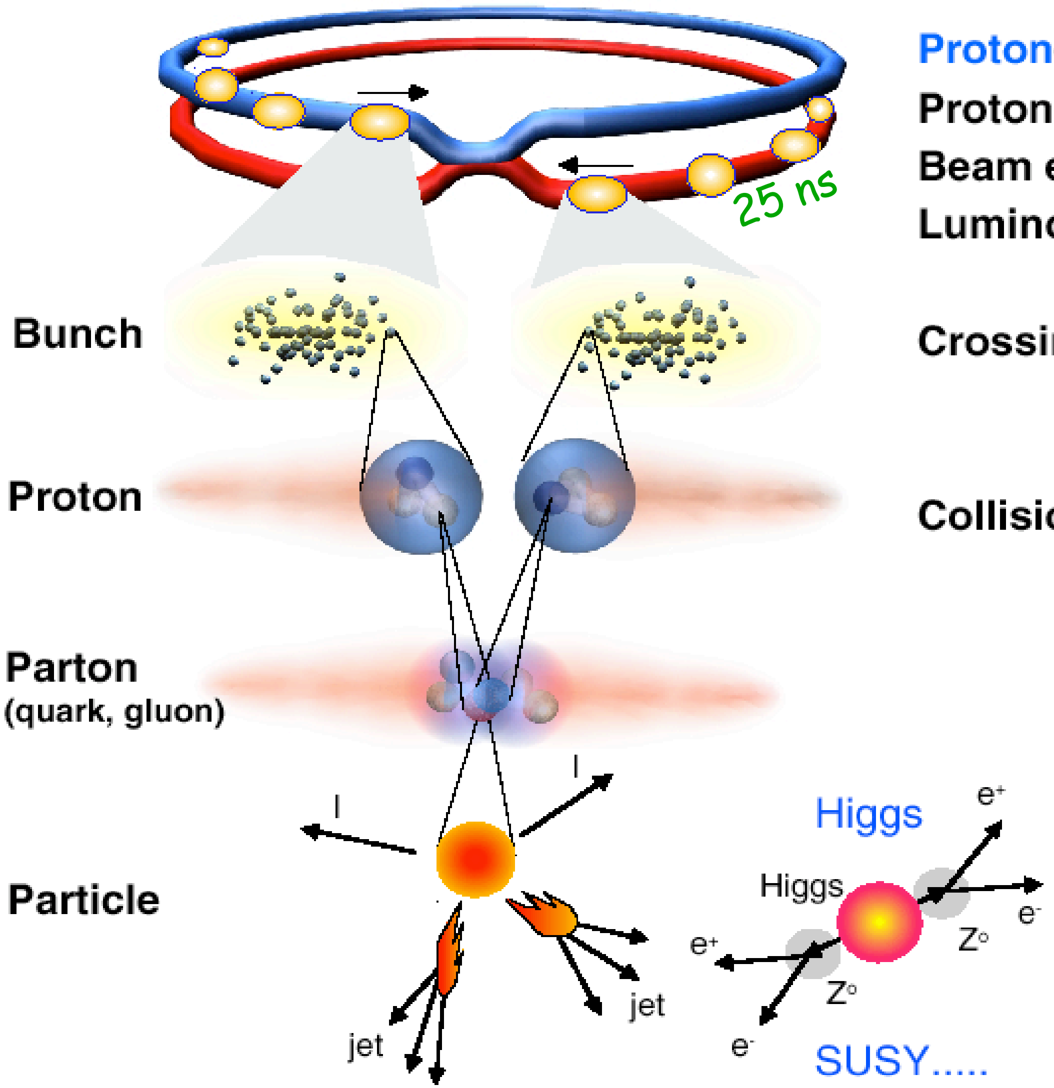
Mass resolutions:
- ≈ 1% decays into leptons or photons (Higgs, new resonances)
- ≈ 10% W → jj, H → bb (top physics, Higgs, …)

Hypothetical X → γγ signal on top of background



Particle identification:
- b/jet separation : ε (b) ≈ 50% R (jet) ≈ 100 (H → bb, SUSY, 3rd generation !!)
- τ/jet separation : ε (τ) ≈ 50% R(jet) ≈ 100 (A/H → ττ, SUSY, 3rd generation !!)
- γ/jet separation : ε (γ) ≈ 80% R(jet) > 10^3 (H → γγ)
- e/jet separation : ε (e) > 70% R(jet) > 10^5 (inclusive electron sample)

Very selective triggers (online event selection system):
10^9 Hz (interaction rate) → 200 Hz (affordable rate-to-storage)
1 Higgs event with H→ 4e every 10^{13} interactions

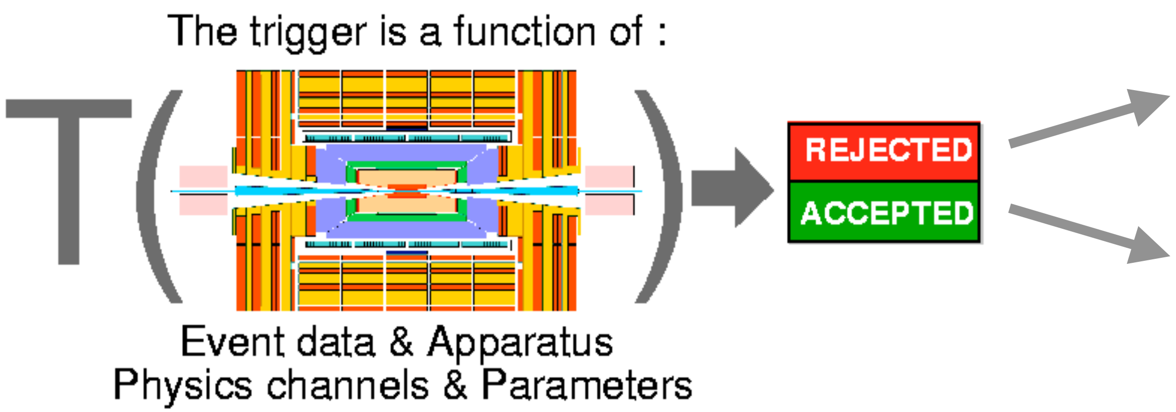


Proton-Proton	2808 bunch/beam
Protons/bunch	10^{11}
Beam energy	7 TeV (7×10^{12} eV)
Luminosity	10^{34} cm^{-2} s^{-1}
Crossing rate	40 MHz
Collisions ≈	10^7 - 10^9 Hz

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

Event filtering: the trigger system

Collision rate is 40 MHz
2007 technology (and budget) allows only to write 200 Hz of events to tape --> need a factor ~10^7 online filtering!!

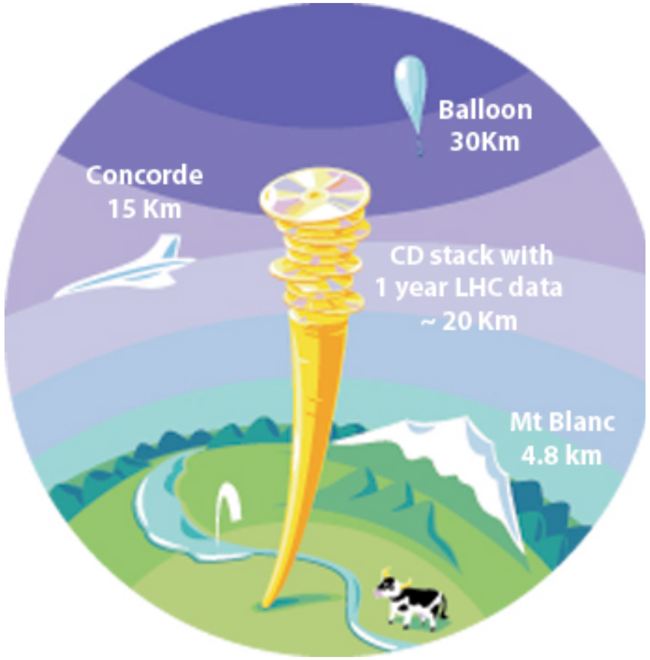


lost forever!!

written to disk for offline analysis

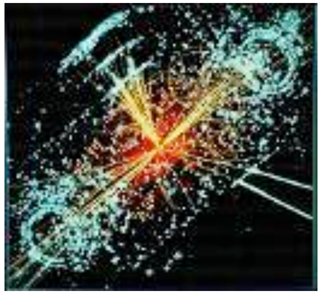
The event trigger is one of the biggest challenges at the LHC
⇒ Based on hard scattering signatures: jets, leptons, photons

Massive (distributed) computing resources (CPU, storage)



The LHC experiments will produce 10-15 PB
of data per year 1 PB=10^{15} Bytes
This corresponds to ~ 20 million CD (a 20 km stack ...)

Data analysis requires computing power
equivalent to ~100 000 today's
fastest PC processors.



The experiment international Collaborations
are spread all over the world → computing
resources must be distributed.

↓

Cooperation of many computer centres
all over the world is needed
(CERN provides ~20% of the resources) →

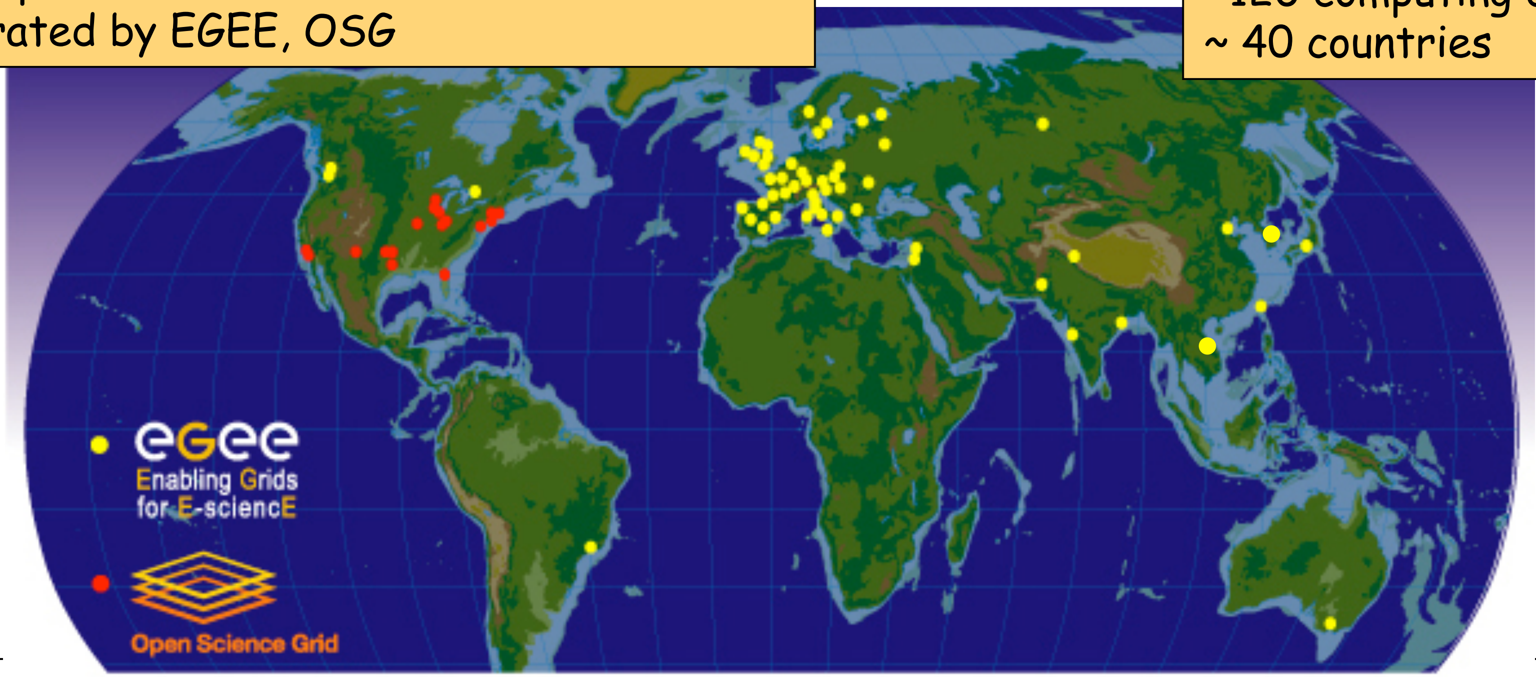
• The World Wide Web (invented at CERN) provides seamless access to information stored in many millions of different geographical locations

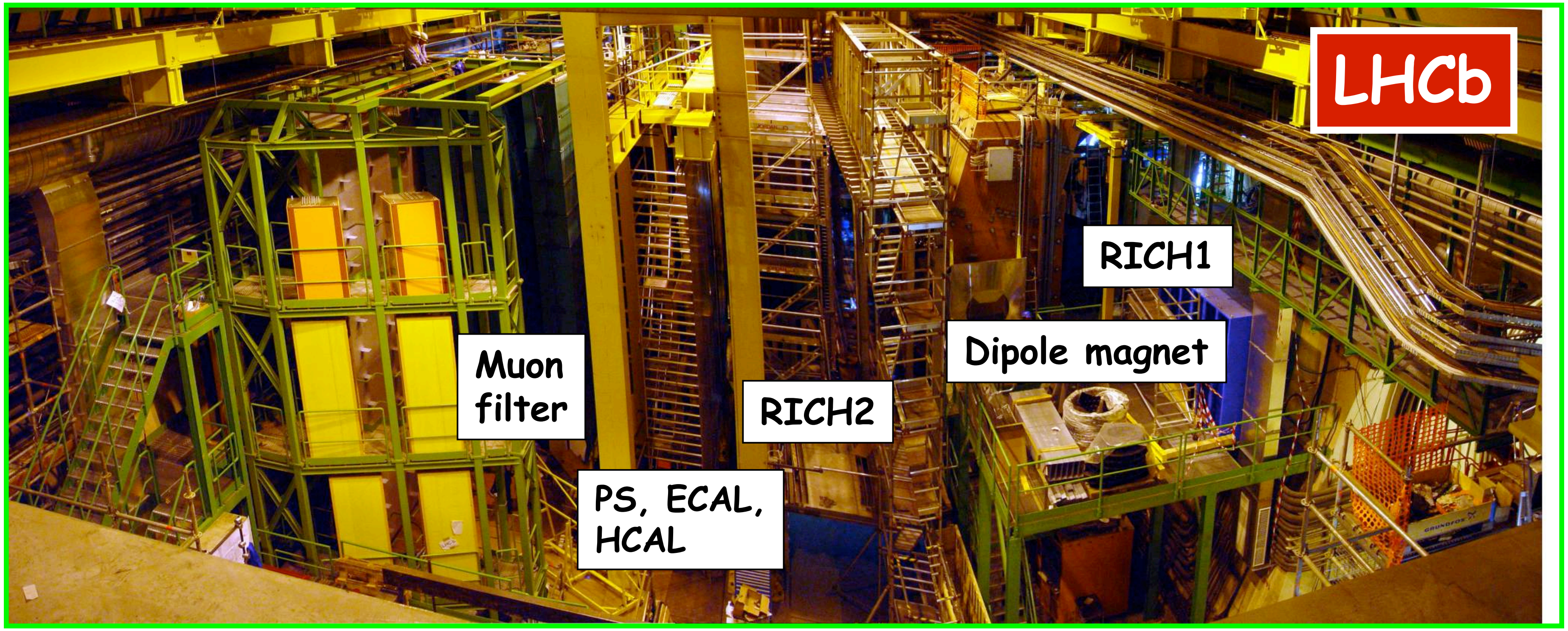
• The Grid provides seamless access to computing power and data storage capacity distributed over the globe.

• The LHC Computing Grid (LCG) relies on grid infrastructure provided by EGEE, OSG, Nordugrid

A map of the worldwide LCG infrastructure operated by EGEE, OSG

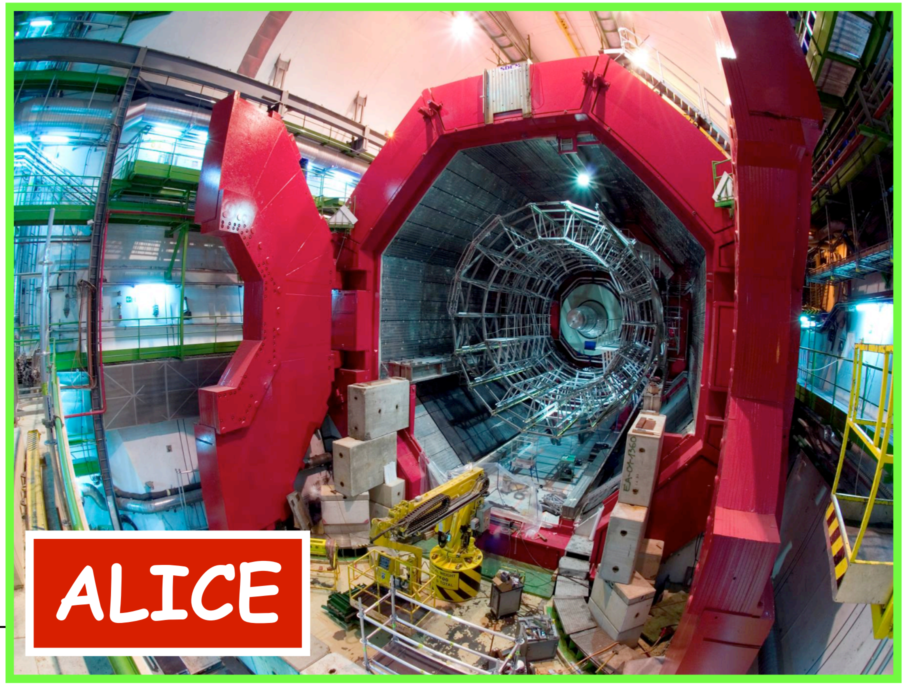
~120 computing centers
~ 40 countries



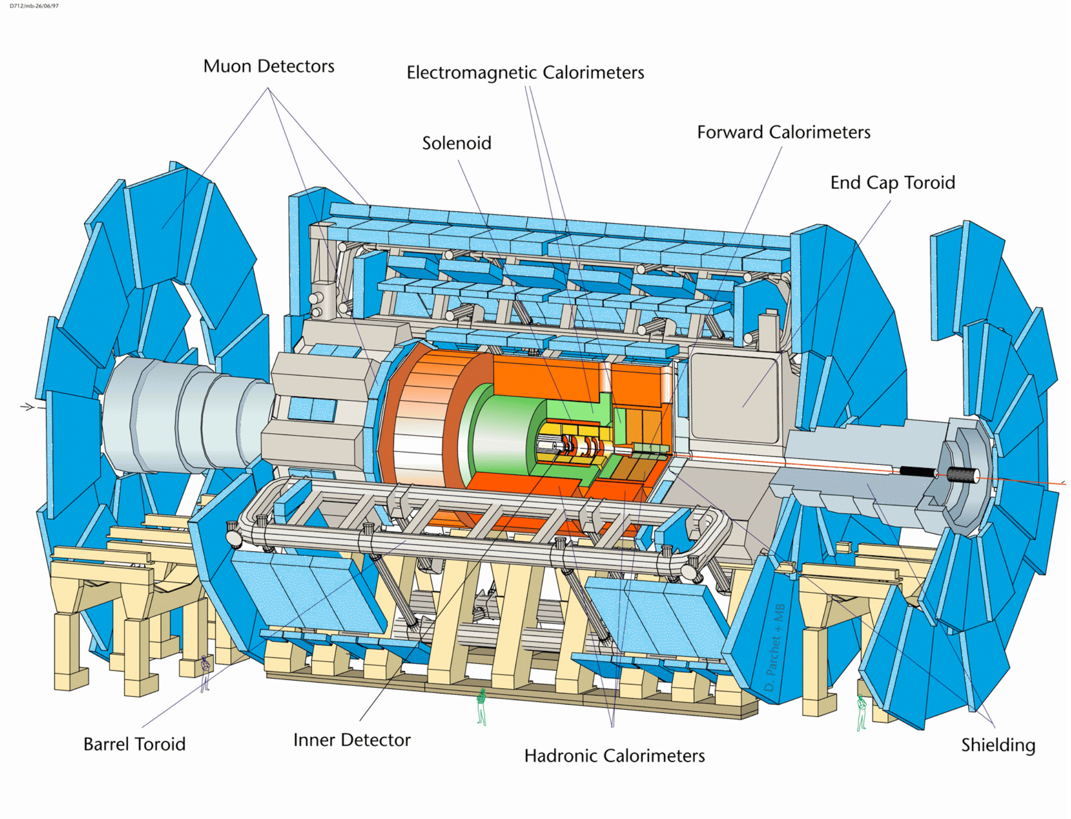


The general-purpose experiments: ATLAS and CMS

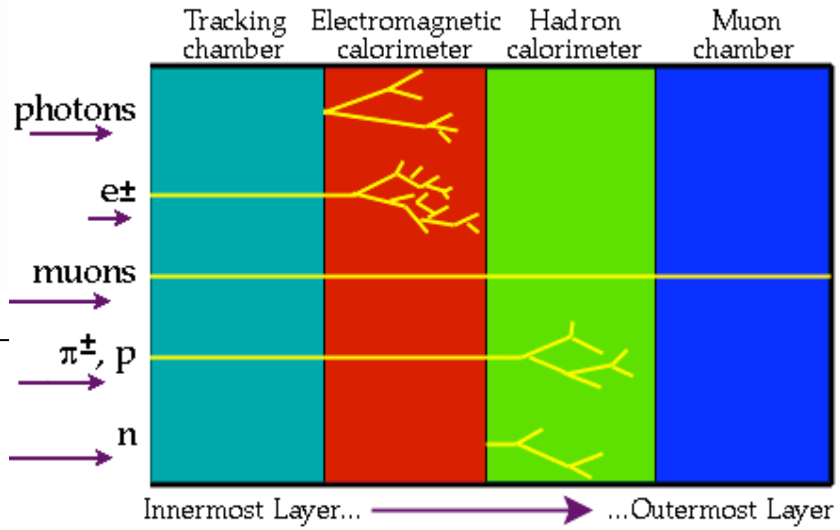
(ALICE and LHCb are also on track)



ATLAS



Length : ~46 m
Radius : ~12 m
Weight : ~ 7000 tons
~10^8 electronic channels

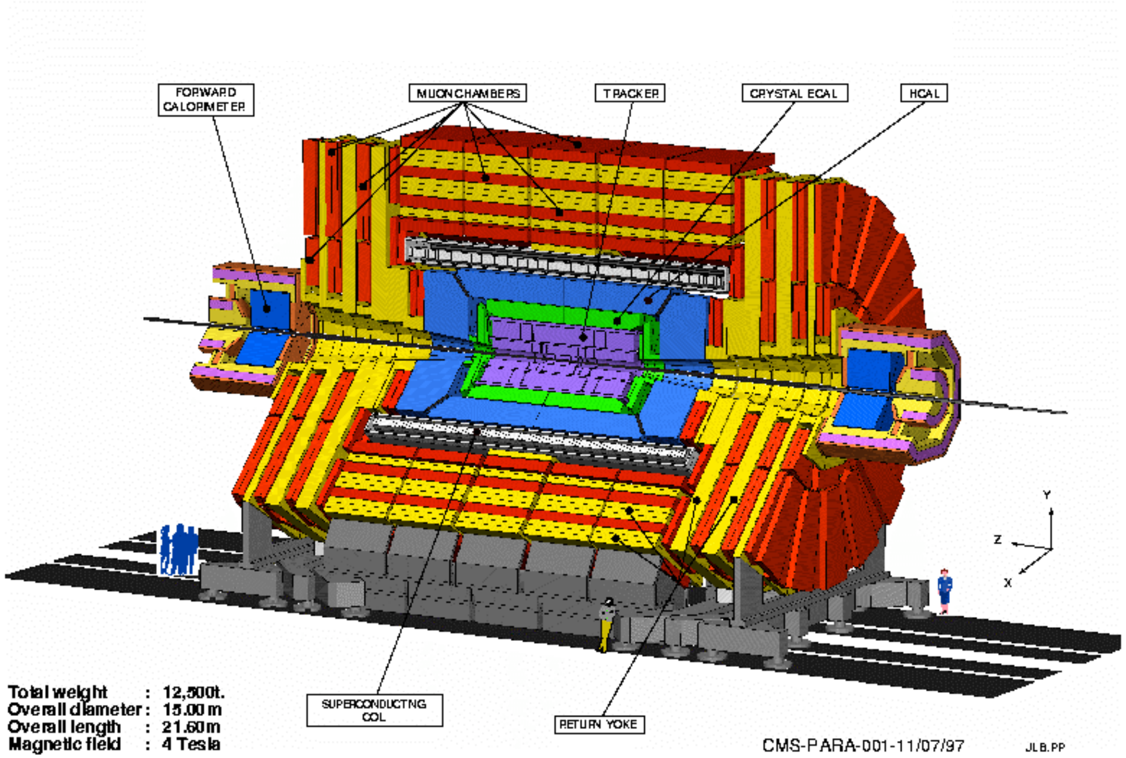


- Tracking (|η|<2.5, B=2T) :
  -- Si pixels and strips
  -- Transition Radiation Detector (e/π separation)

- Calorimetry (|η|<5) :
  -- EM : Pb-LAr
  -- HAD: Fe/scintillator (central), Cu/W-LAr (fwd)

- Muon Spectrometer (|η|<2.7) :
  air-core toroids with muon chambers

And .... 1900 physicists from
165 Institutions from 35 countries
from 5 continents

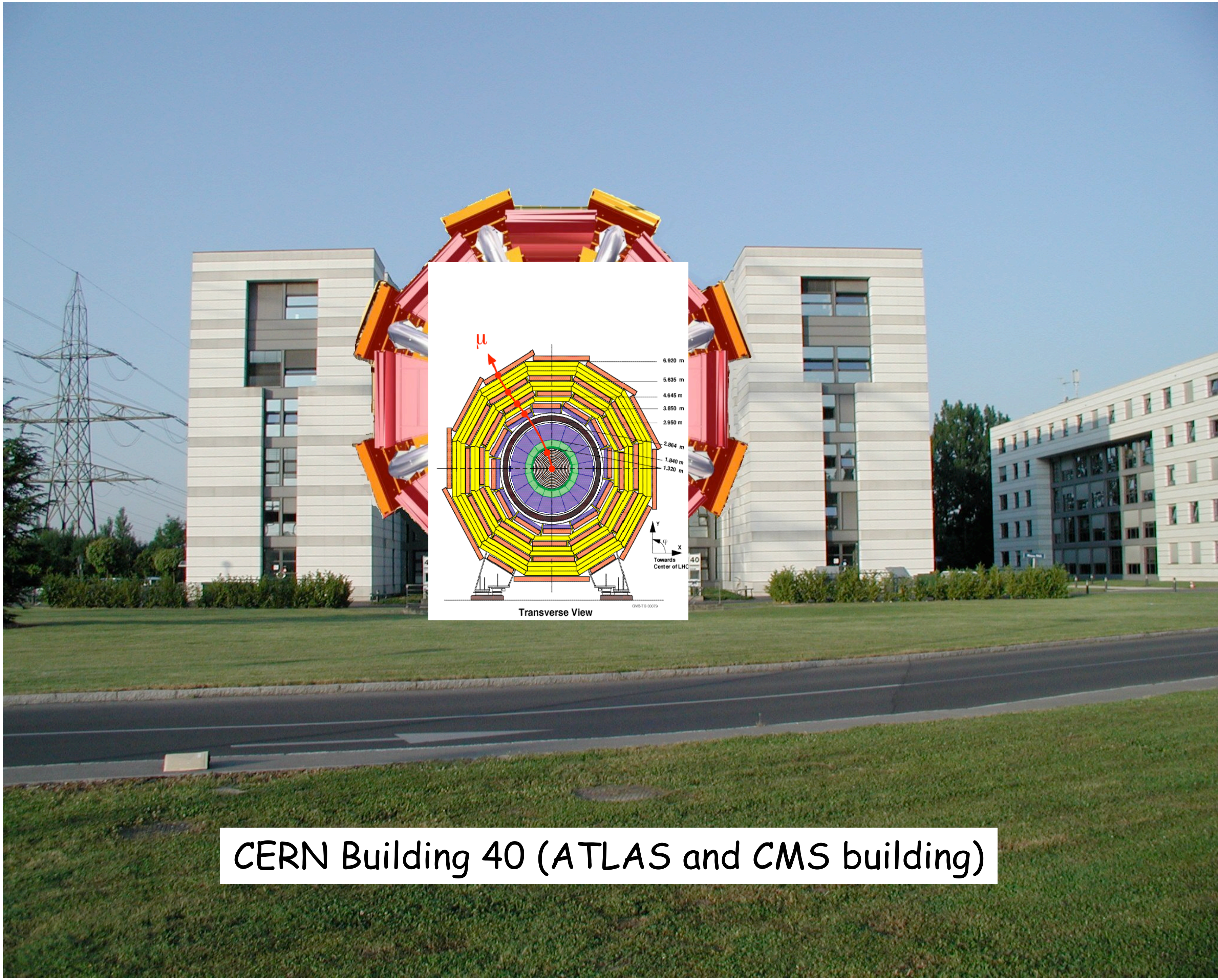


CMS

Length : ~22 m
Radius : ~7 m
Weight : ~ 12500 tons

And …. 2000 physicists from
174 Institutions from 38 countries
from 5 continents

- Tracking ($|\eta|<2.5$, B=4T) : Si pixels and strips
- Calorimetry ($|\eta|<5$) :
  -- EM : $PbWO_4$ crystals
  -- HAD: brass/scintillator (central+ end-cap),
  Fe/Quartz (fwd)
- Muon Spectrometer ($|\eta|<2.5$) : return yoke of solenoid instrumented with muon chambers



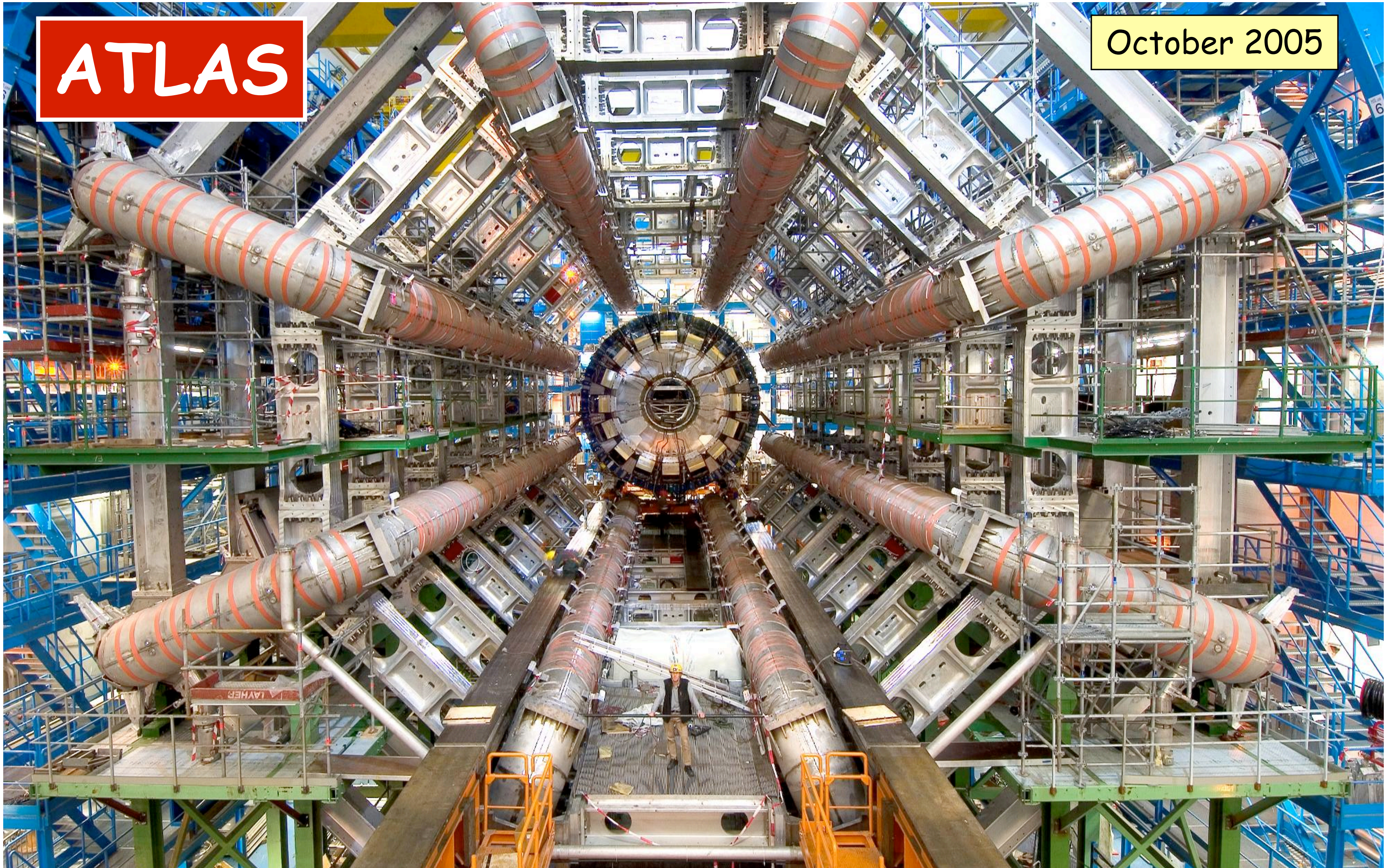
CERN Building 40 (ATLAS and CMS building)

	ATLAS ≡ A Toroidal LHC ApparatuS	CMS ≡ Compact Muon Solenoid
MAGNET (S)	Air-core toroids + solenoid in inner cavity 4 magnets Calorimeters in field-free region	Solenoid Only 1 magnet Calorimeters inside field
TRACKER	Si pixels+ strips TRT → particle identification B=2T $\sigma/p_T \sim 5\times10^{-4}\, p_T \oplus 0.01$	Si pixels + strips No particle identification B=4T $\sigma/p_T \sim 1.5\times10^{-4}\, p_T \oplus 0.005$
EM CALO	Pb-liquid argon $\sigma/E \sim 10\%/\sqrt{E}$ uniform longitudinal segmentation	$PbWO_4$ crystals $\sigma/E \sim 2\text{-}5\%/\sqrt{E}$ no longitudinal segm.
HAD CALO	Fe-scint. + Cu-liquid argon (10 λ) $\sigma/E \sim 50\%/\sqrt{E} \oplus 0.03$	Cu-scint. (> 5.8 λ +catcher) $\sigma/E \sim 100\%/\sqrt{E} \oplus 0.05$
MUON	Air → $\sigma/p_T \sim 7$ % at 1 TeV standalone	Fe → $\sigma/p_T \sim 5\%$ at 1 TeV only combining with tracker

Construction finished, installation well advanced, commissioning with cosmics started (these are also big challenges …)

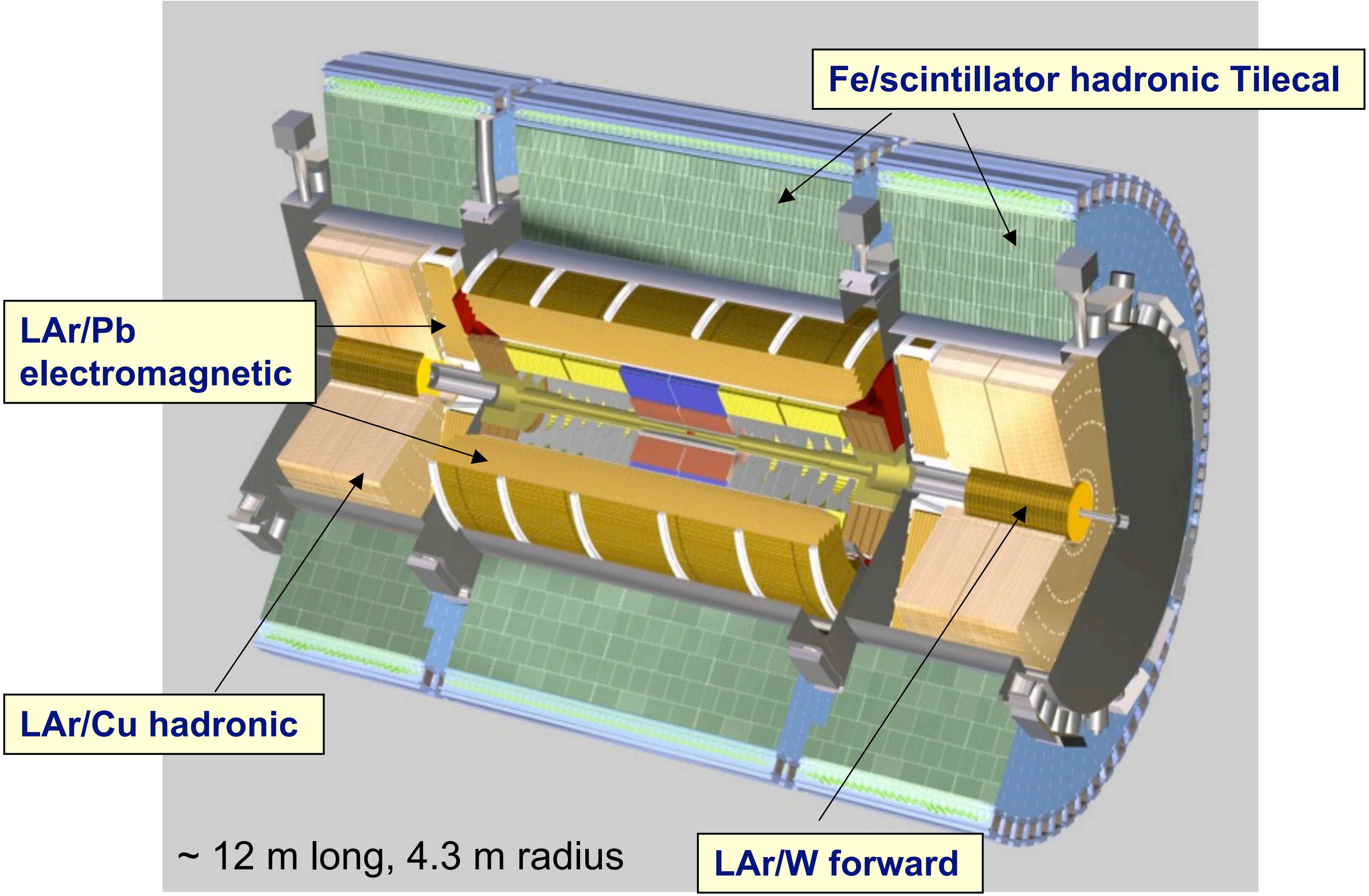
ATLAS

October 2005

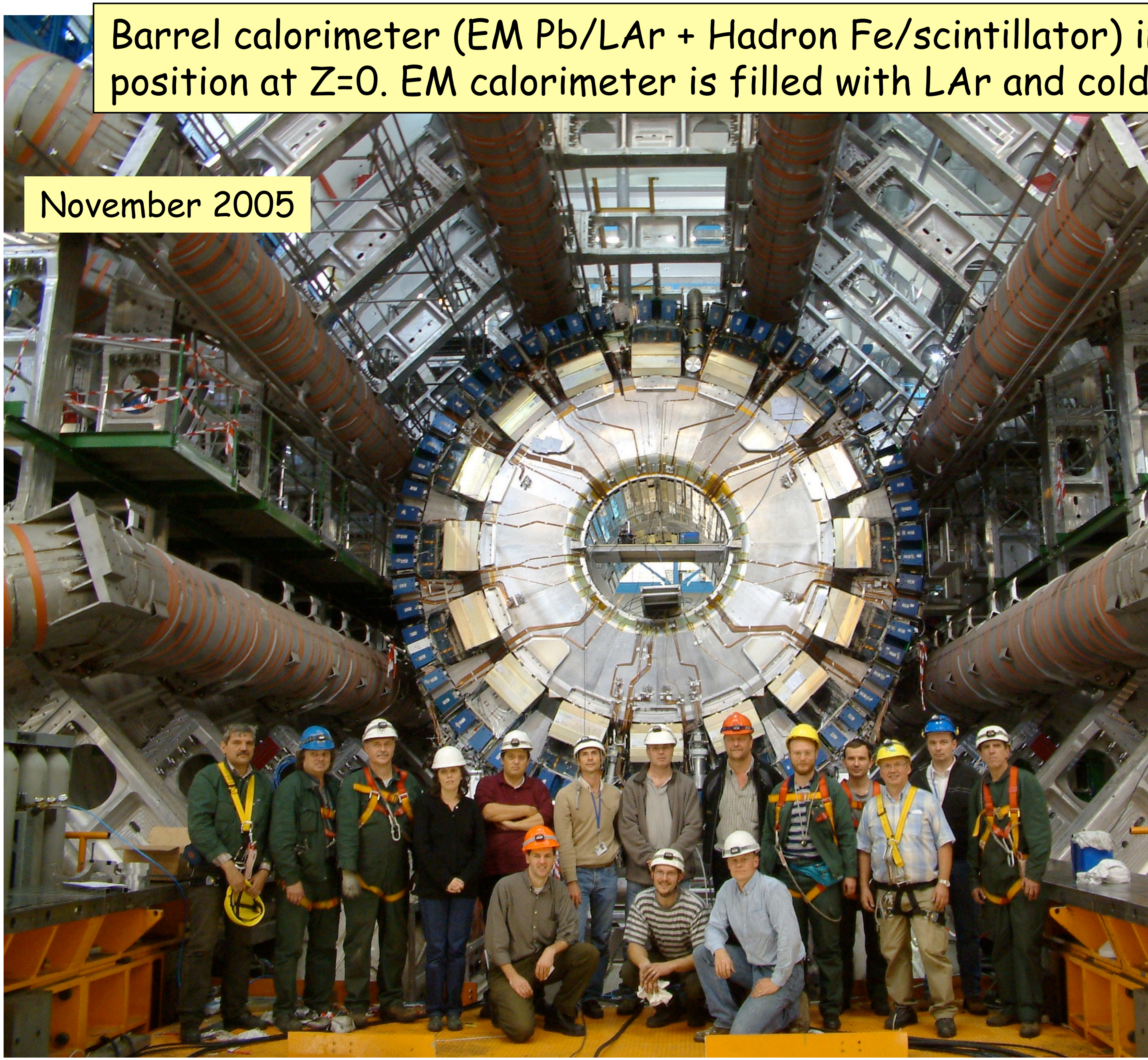


Barrel toroid system (eight 25m long-100 tons superconducting coils):
tested at full field (20 kA current) in November 2006.

Calorimeters

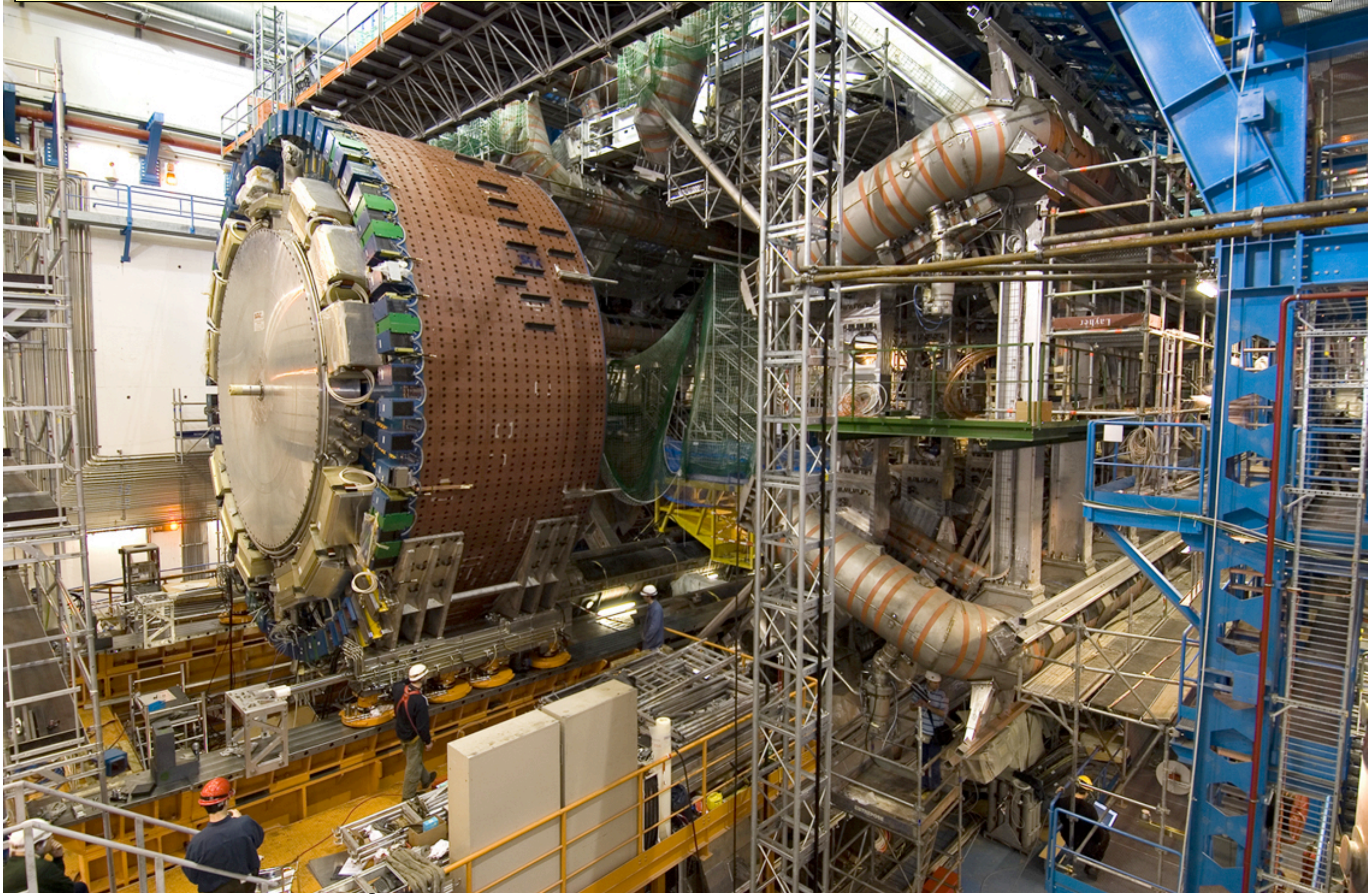


Barrel calorimeter (EM Pb/LAr + Hadron Fe/scintillator) in its final position at Z=0. EM calorimeter is filled with LAr and cold (87 K)


November 2005

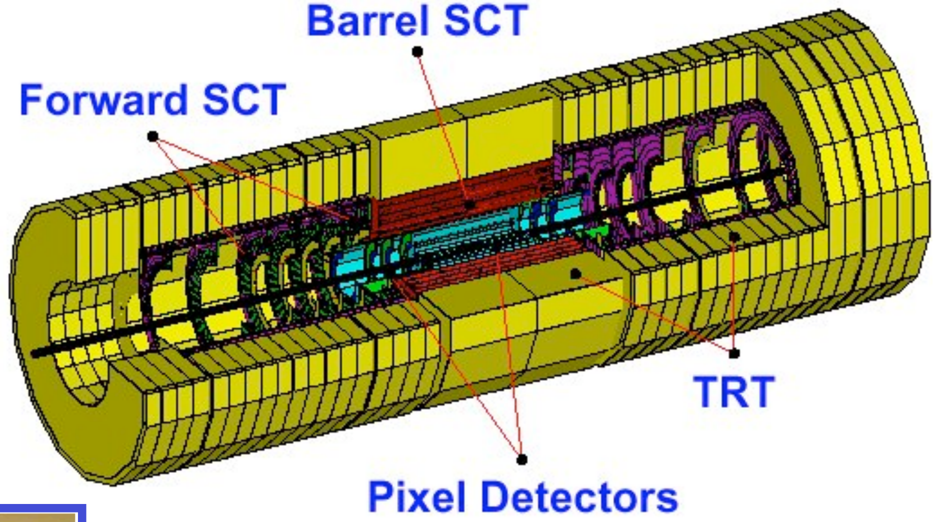

October 2004

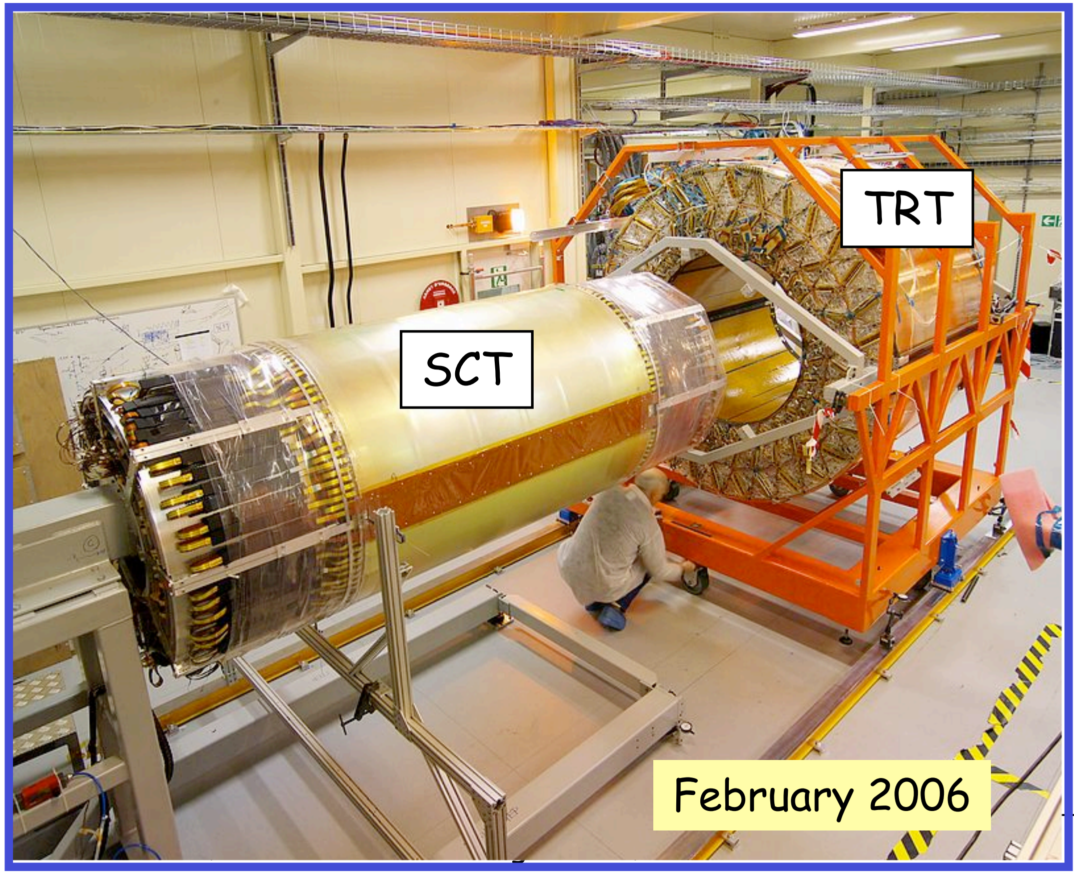
One end-cap calorimeter (LAr EM, LAr HAD, LAr Forward inside same cryostat, surrounded by HAD Fe/Scintillator Tilecal) being moved inside the barrel toroid



Inner tracker

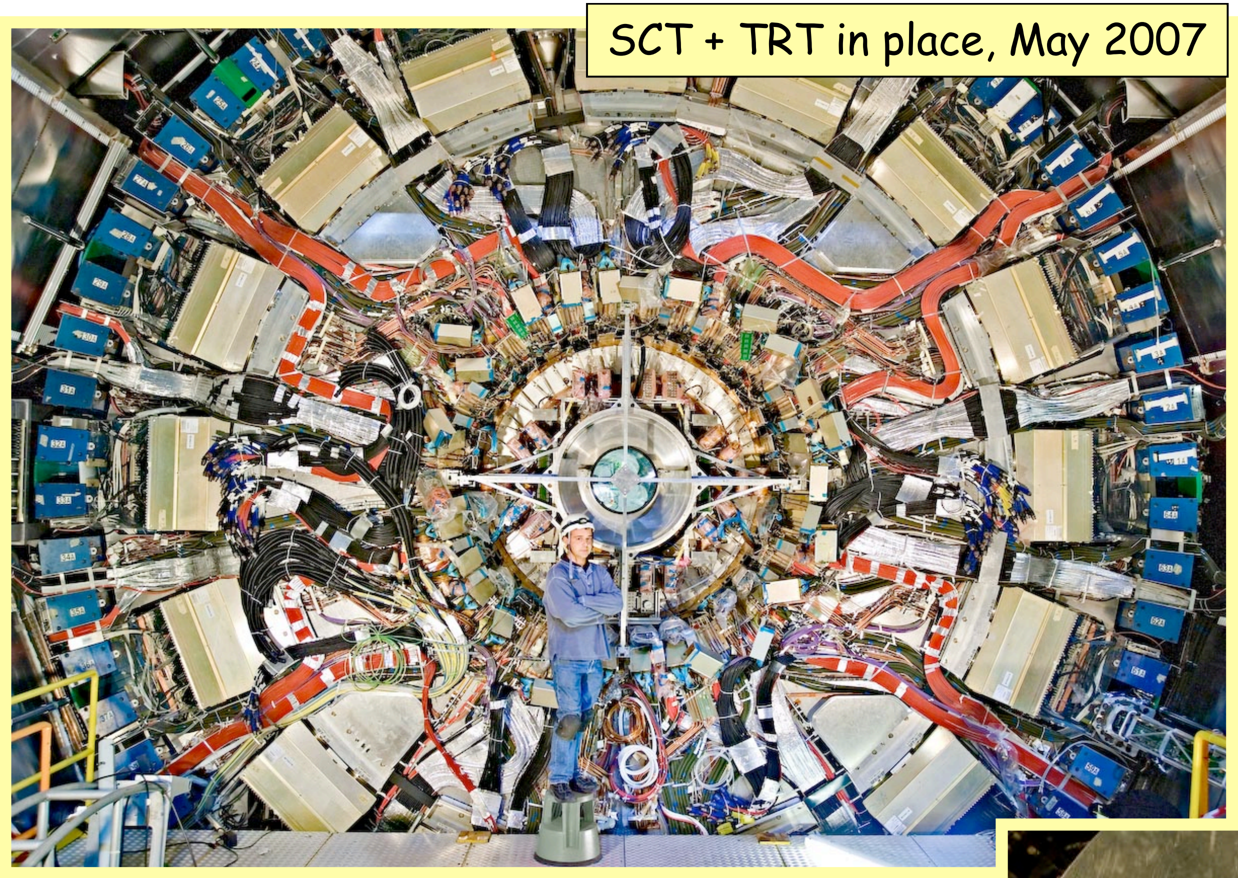
3 sub-systems:
Silicon pixels : 0.8 10^8 channels
Silicon strips (SCT) : 6 10^6 channels
Transition Radiation Tracker (TRT) :
straw tubes filled with gas, 4 10^5 channels



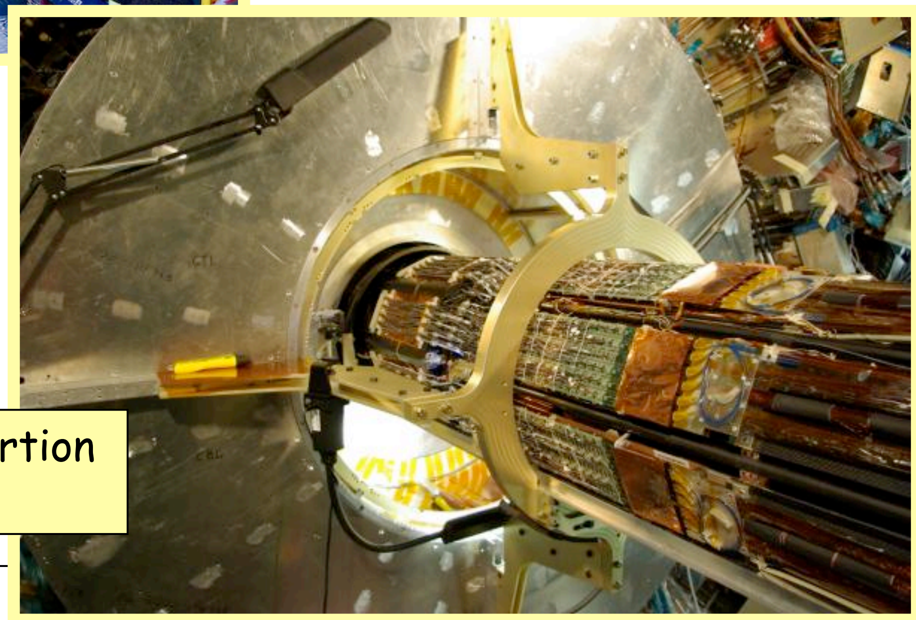


Cosmic muon recorded in the barrel TRT (in the assembly surface room)

SCT + TRT in place, May 2007



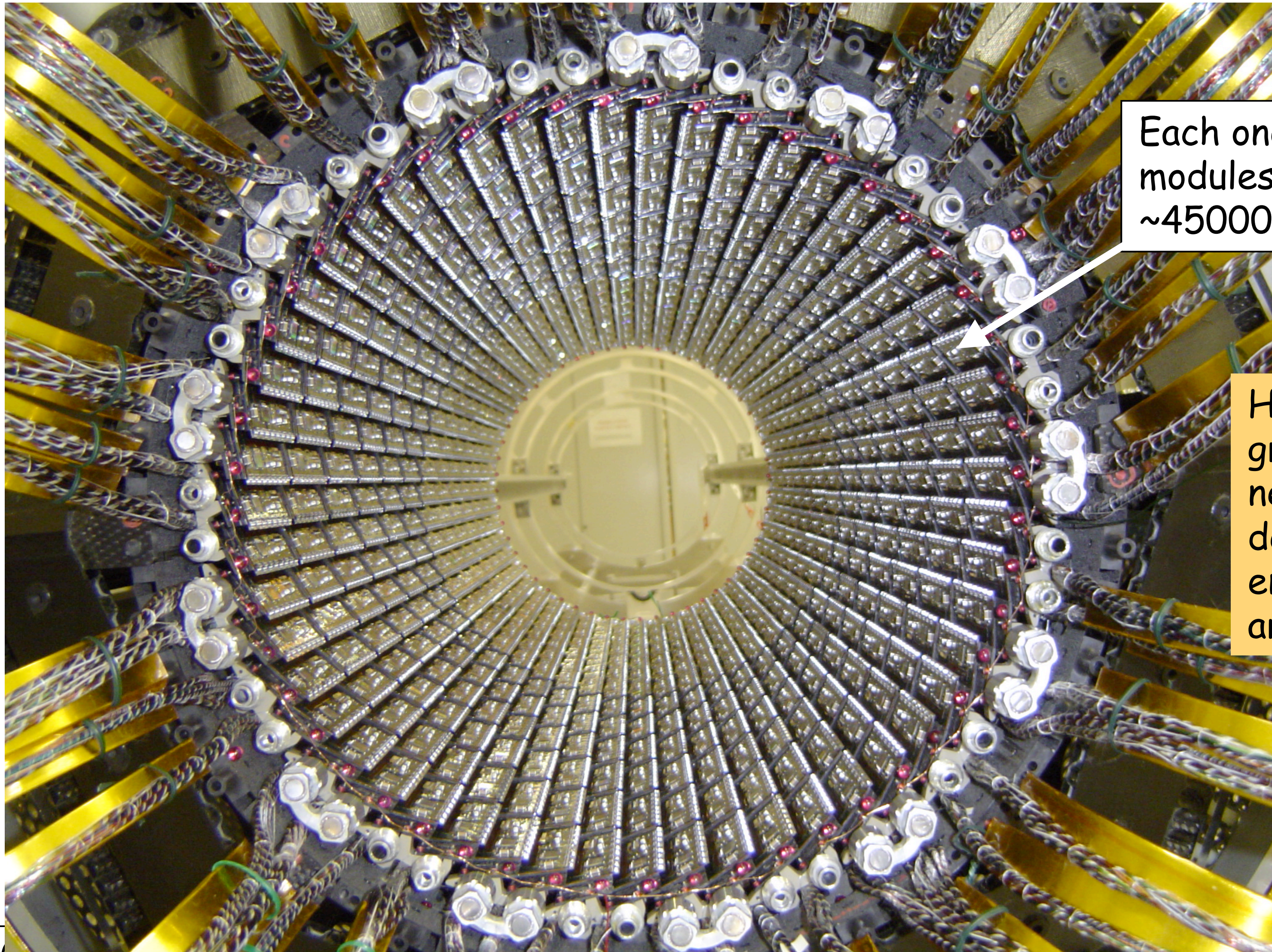
Inner Detector installation in underground cavern completed



Pixels (+ beam pipe) insertion
June 2007

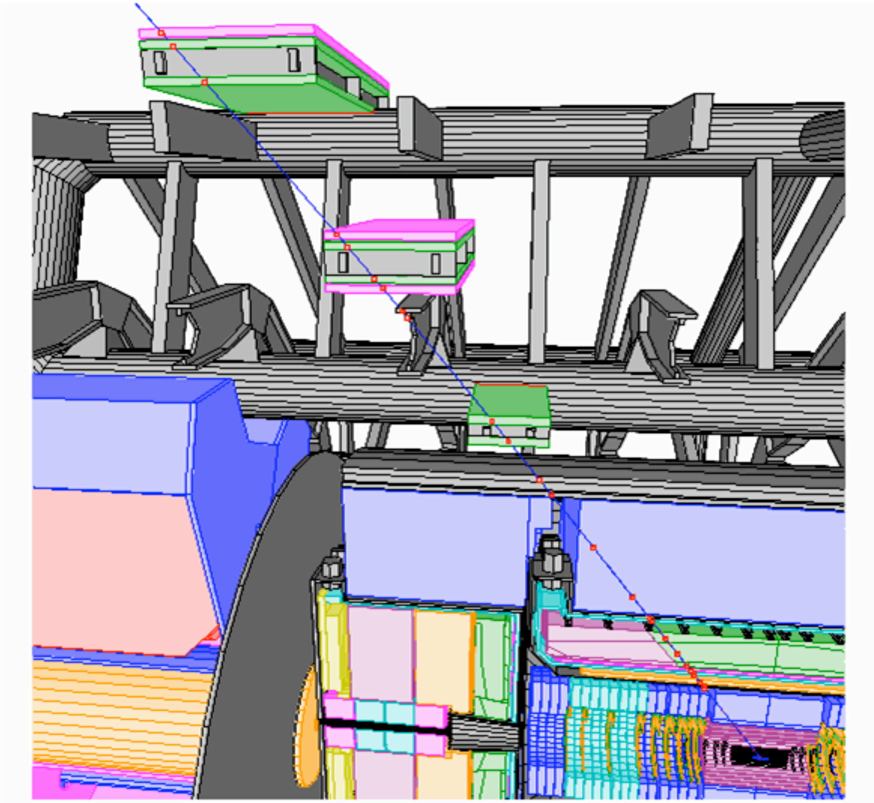
The core of ATLAS: the Pixel detector

- 3 layers at ~ 5cm, 10cm, 13cm from the beam line
- made of ~ 80 million high-tech Si pixels 50μm wide, 400μm long, 250μm thick

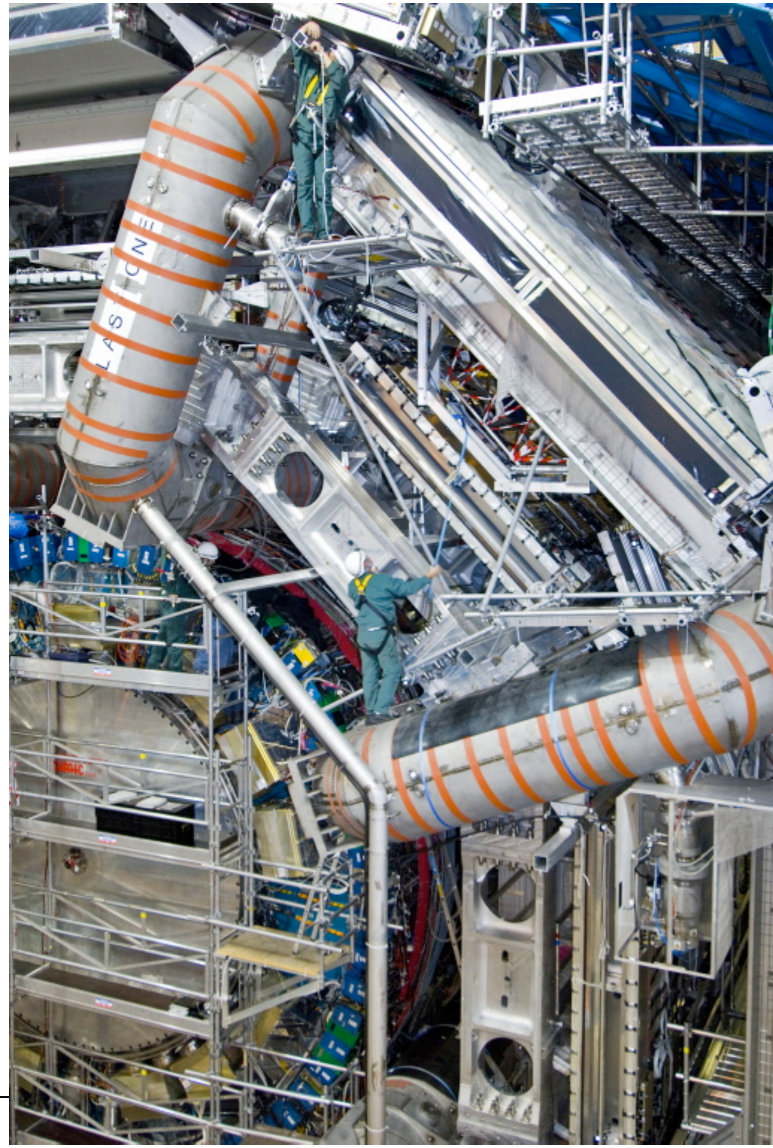


Each one of these modules contains ~45000 pixel sensors

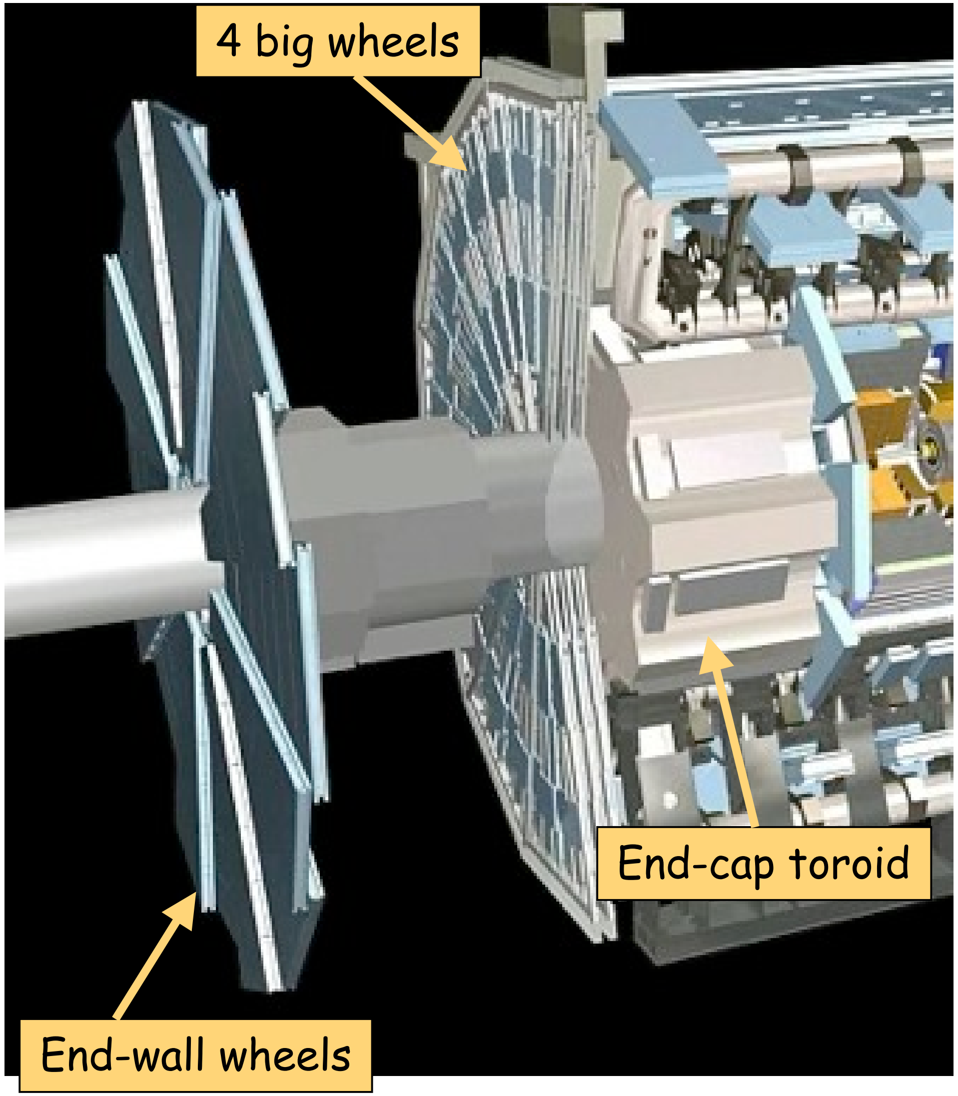
High detector granularity needed in very dense track environment around the beam

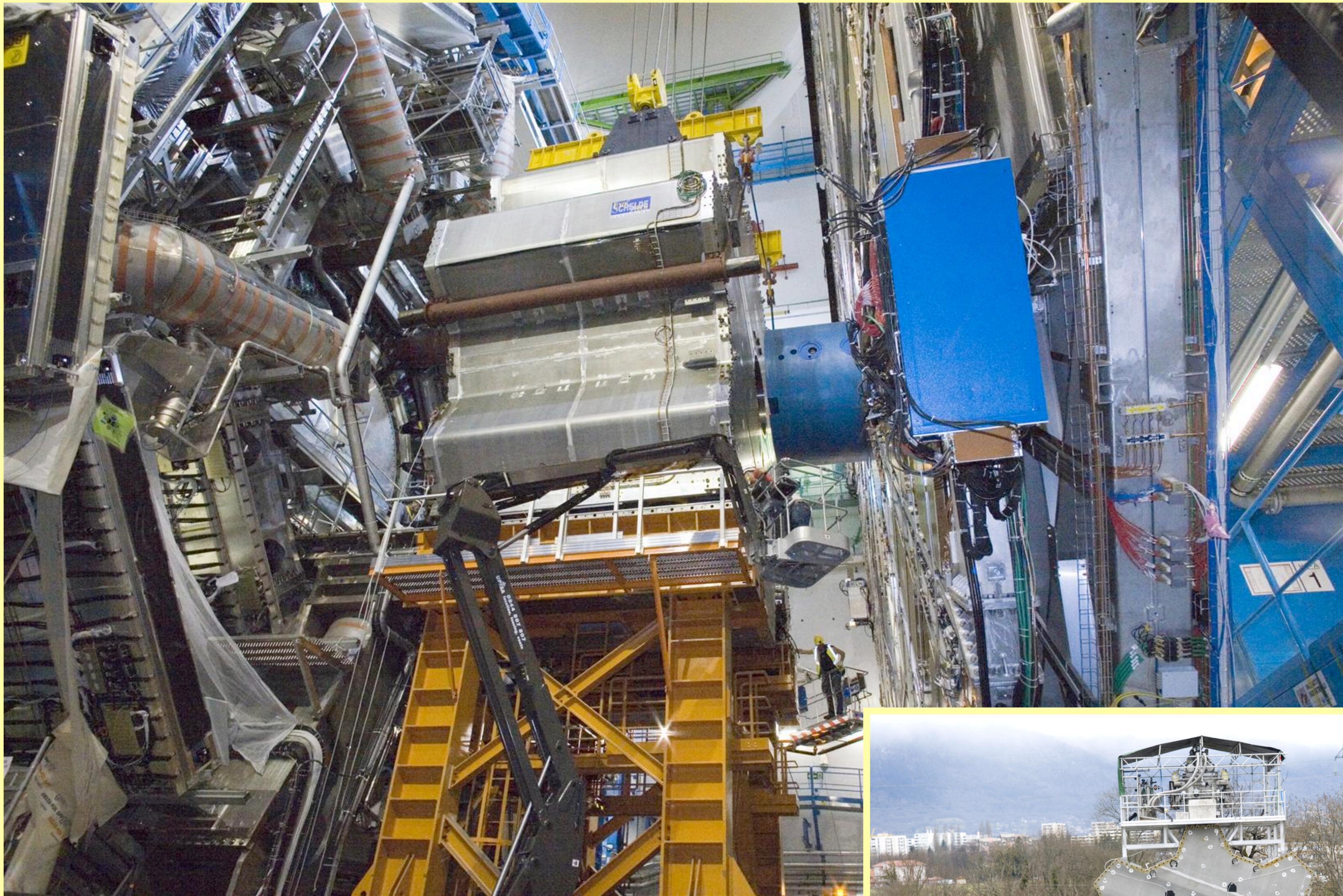


Installation of barrel muon chambers (~ 700 stations) started in December 2005 and is ~ completed.



Forward muon spectrometer: 6 out of 8 big wheels installed in the cavern

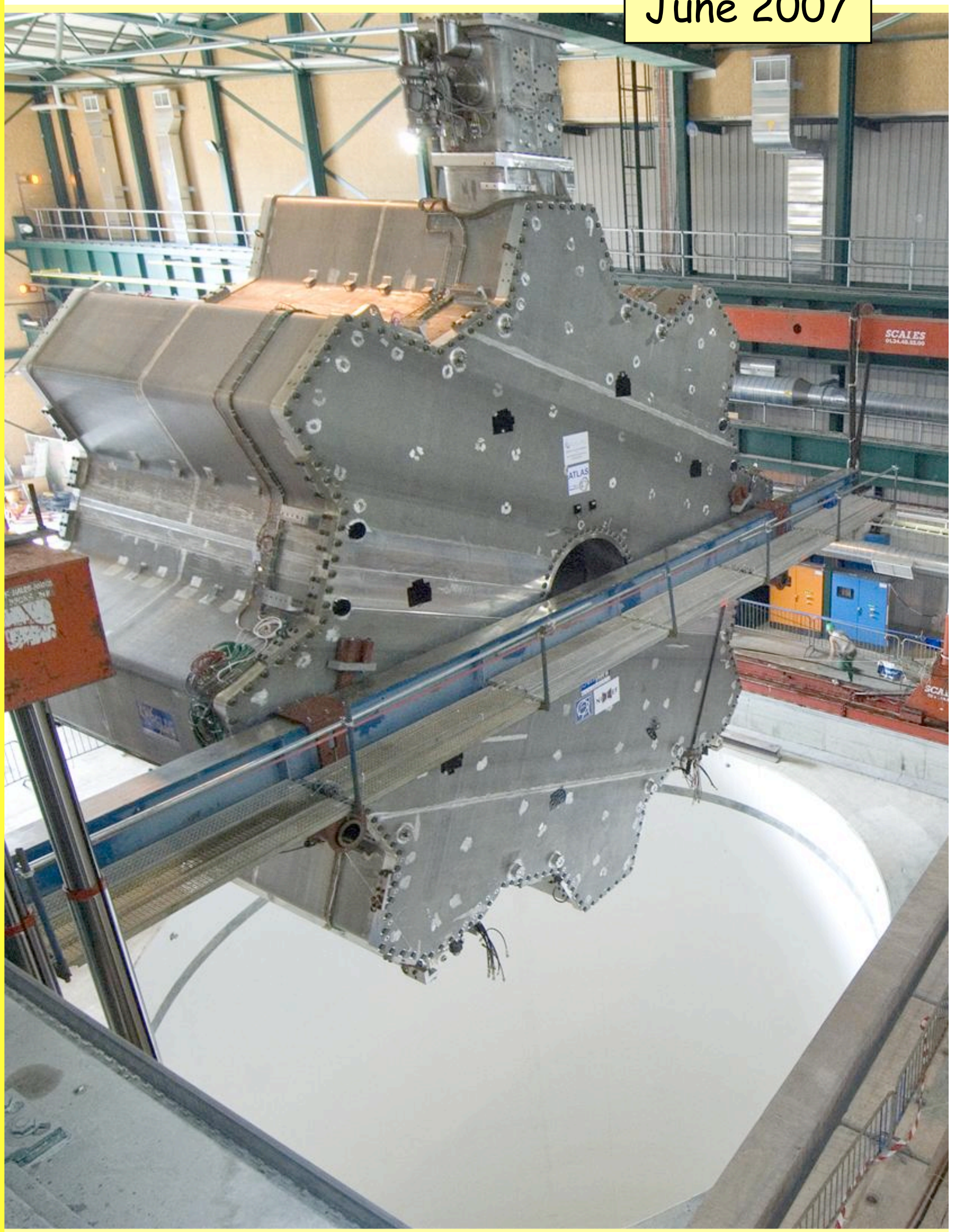




The two end-cap toroid magnets installed in June-July 2007

Spectacular operations …

October 2004



June 2007

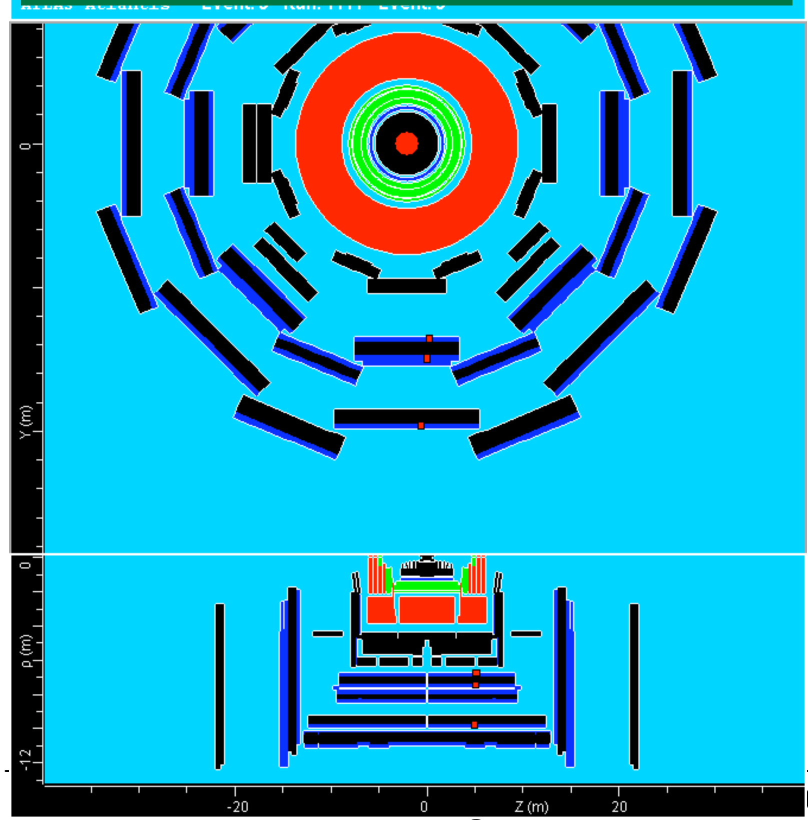
First data collected in the underground cavern: cosmic muons

Very useful to:

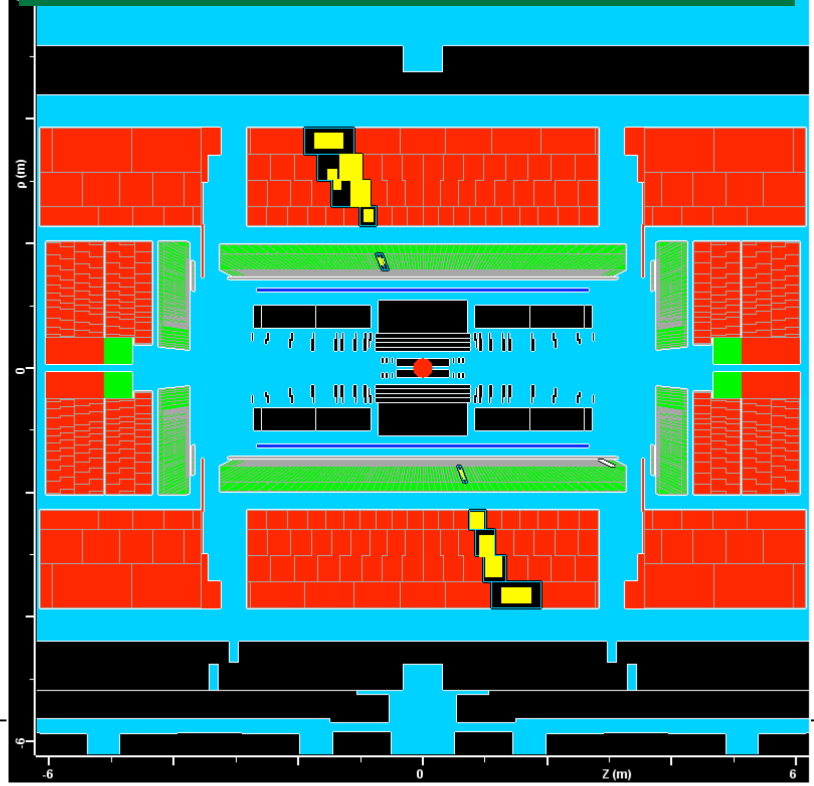
- run together several sub-detectors with common trigger, data acquisition and monitoring systems. Data analyzed with final software
- shake-down and debug the detector in its final position → fix problems
- gain global operation experience before collisions start

Rate (~100 m below ground): ~ O(10 Hz)

Cosmic muon in Muon Spectrometer

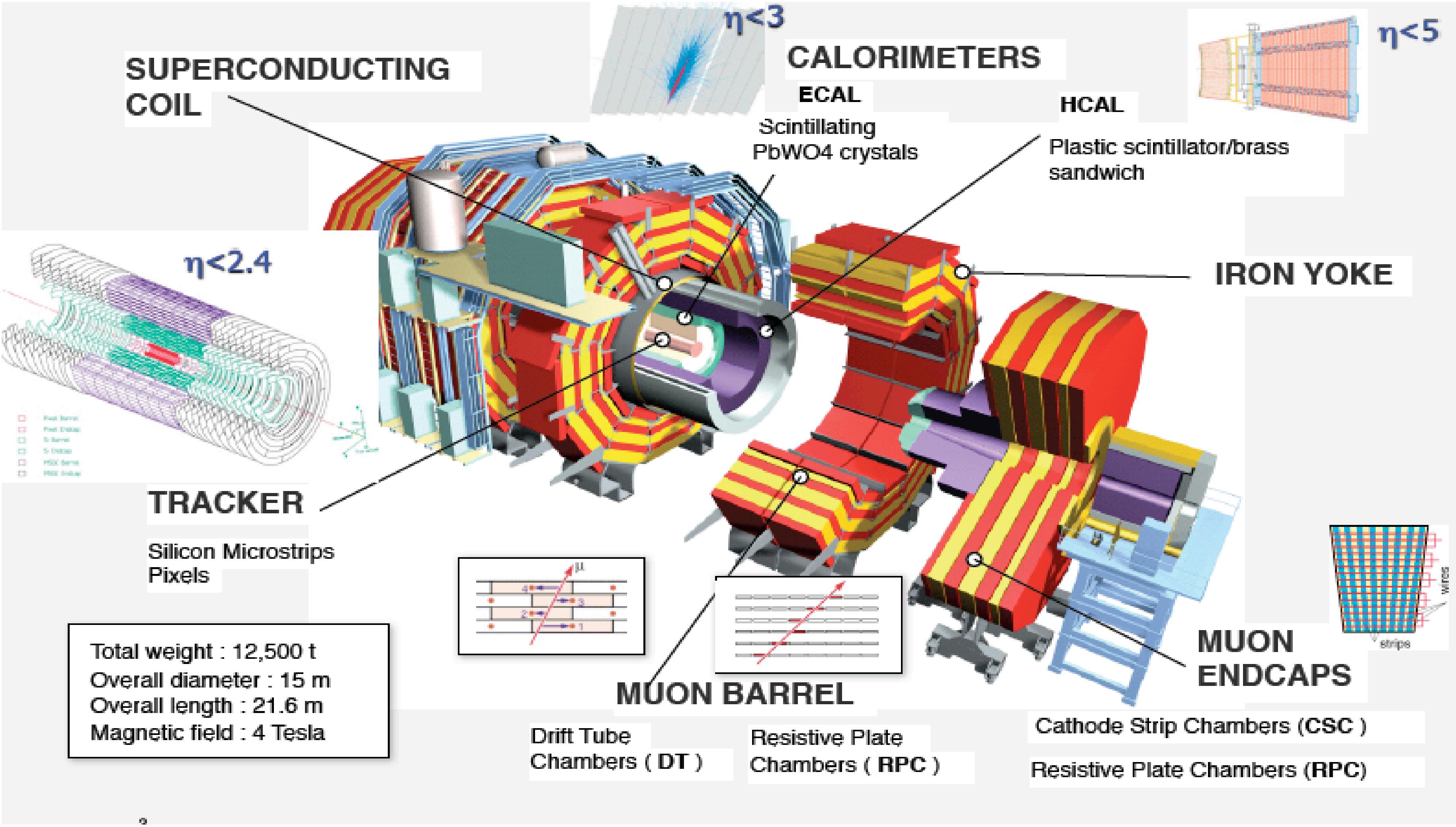


Cosmic muon in LAr EM calorimeter and Tile calorimeter

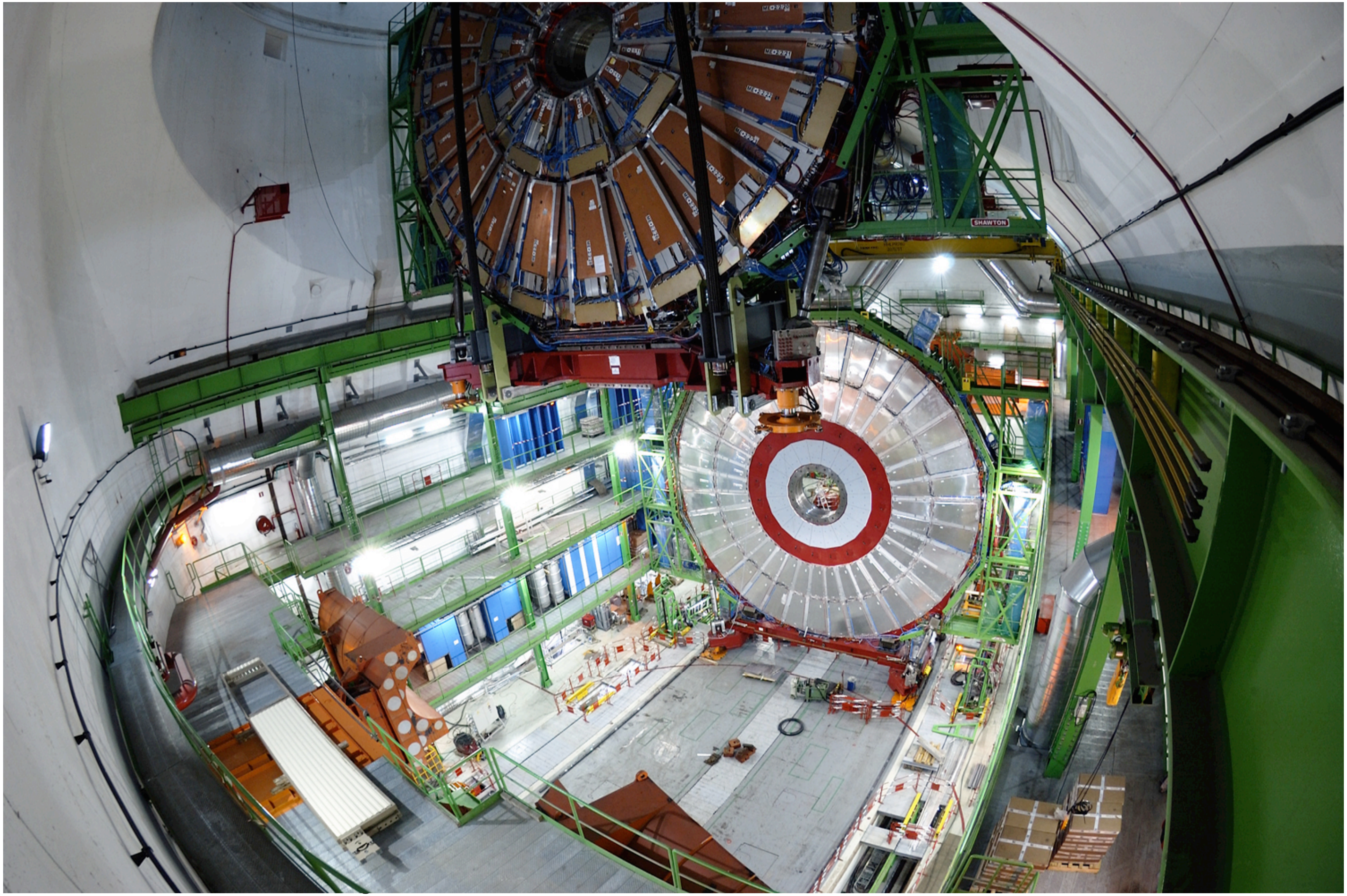


CMS

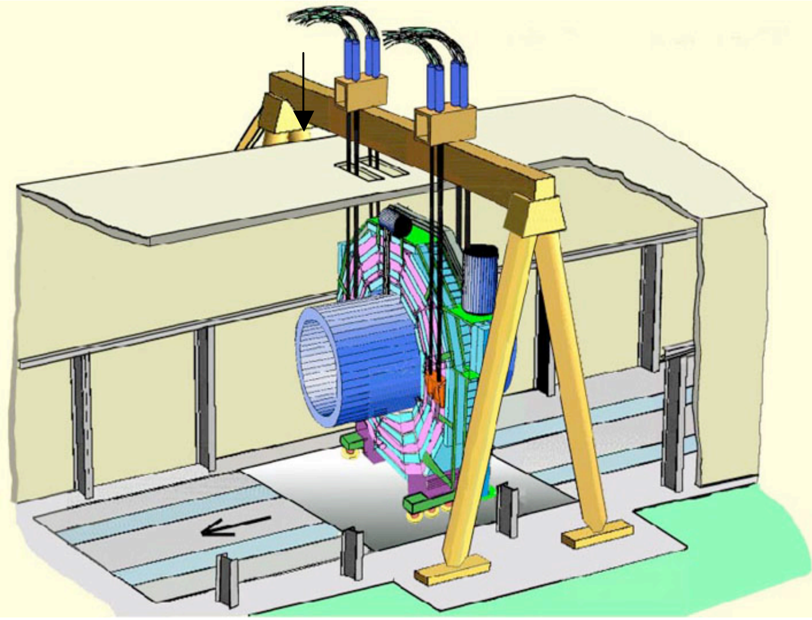
Compact and modular : assembled at the surface and lowered in the cavern slice by slice (11 in total)

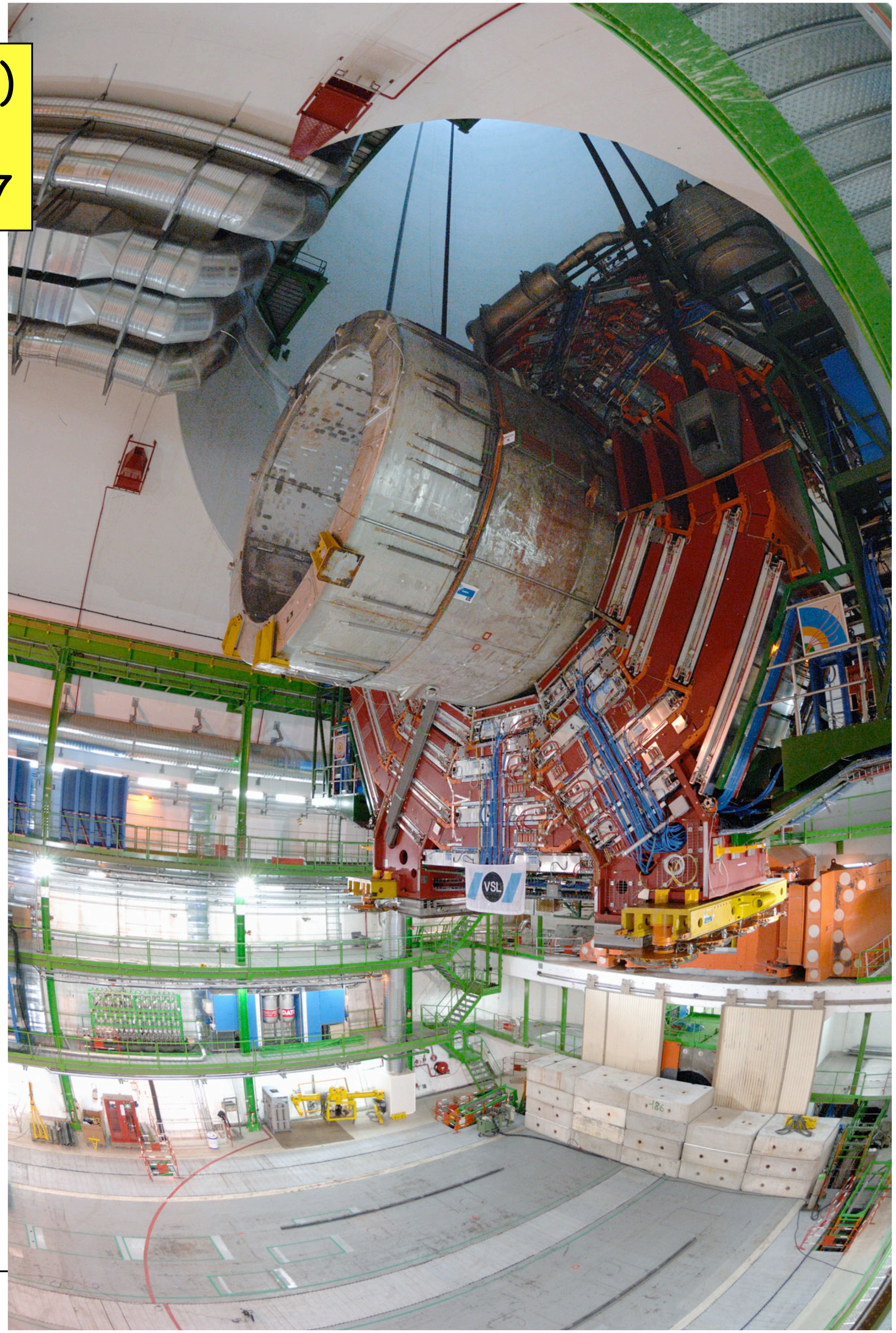


First slices going down end 2006, six out of eleven installed so far



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



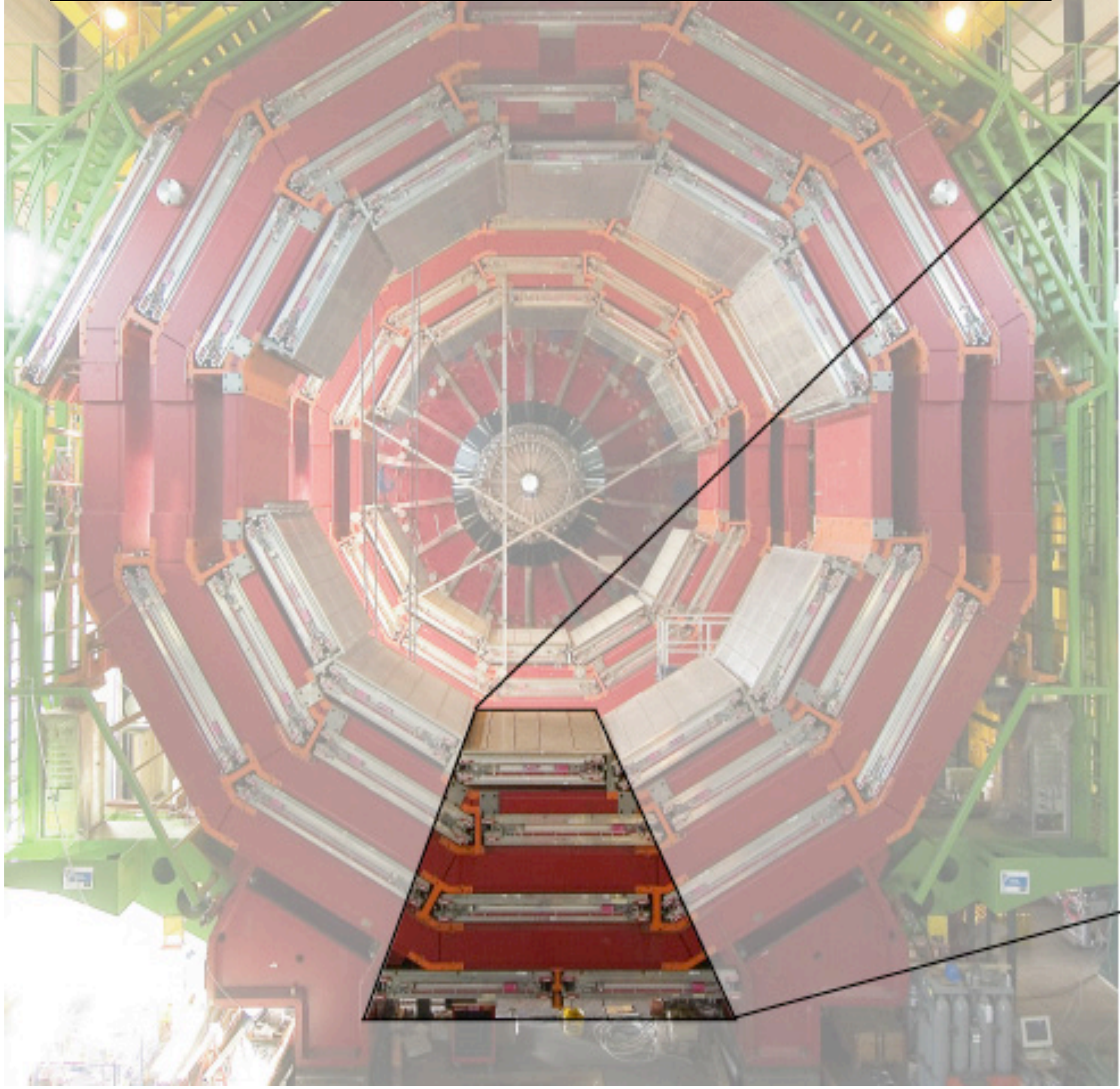


<u>CMS solenoid:</u>

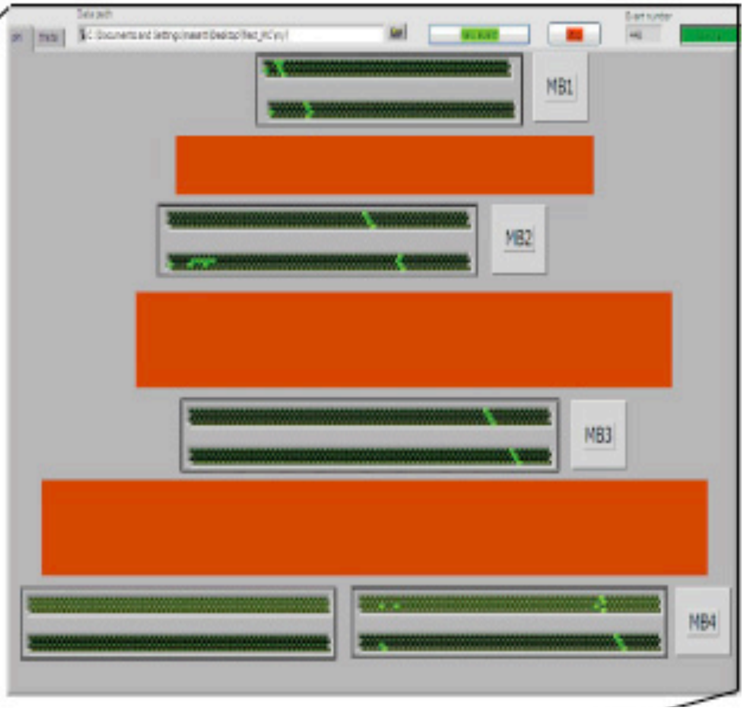
Magnetic length	12.5 m
Diameter	6 m
Magnetic field	4 T
Nominal current	20 kA
Stored energy	2.7 GJ

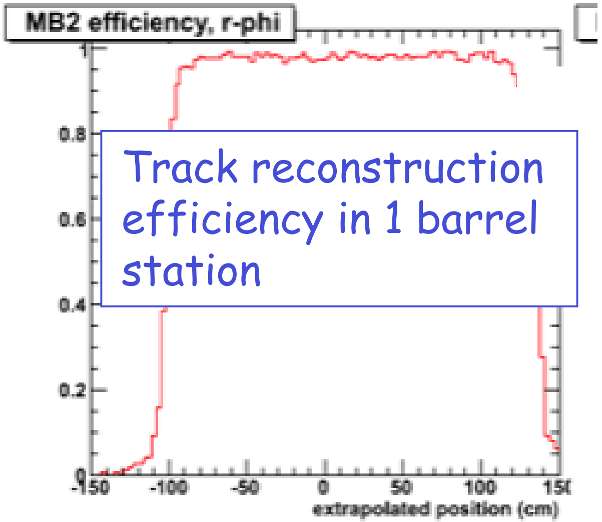
Tested at full current in Summer 2006

Muon stations installation ~ completed

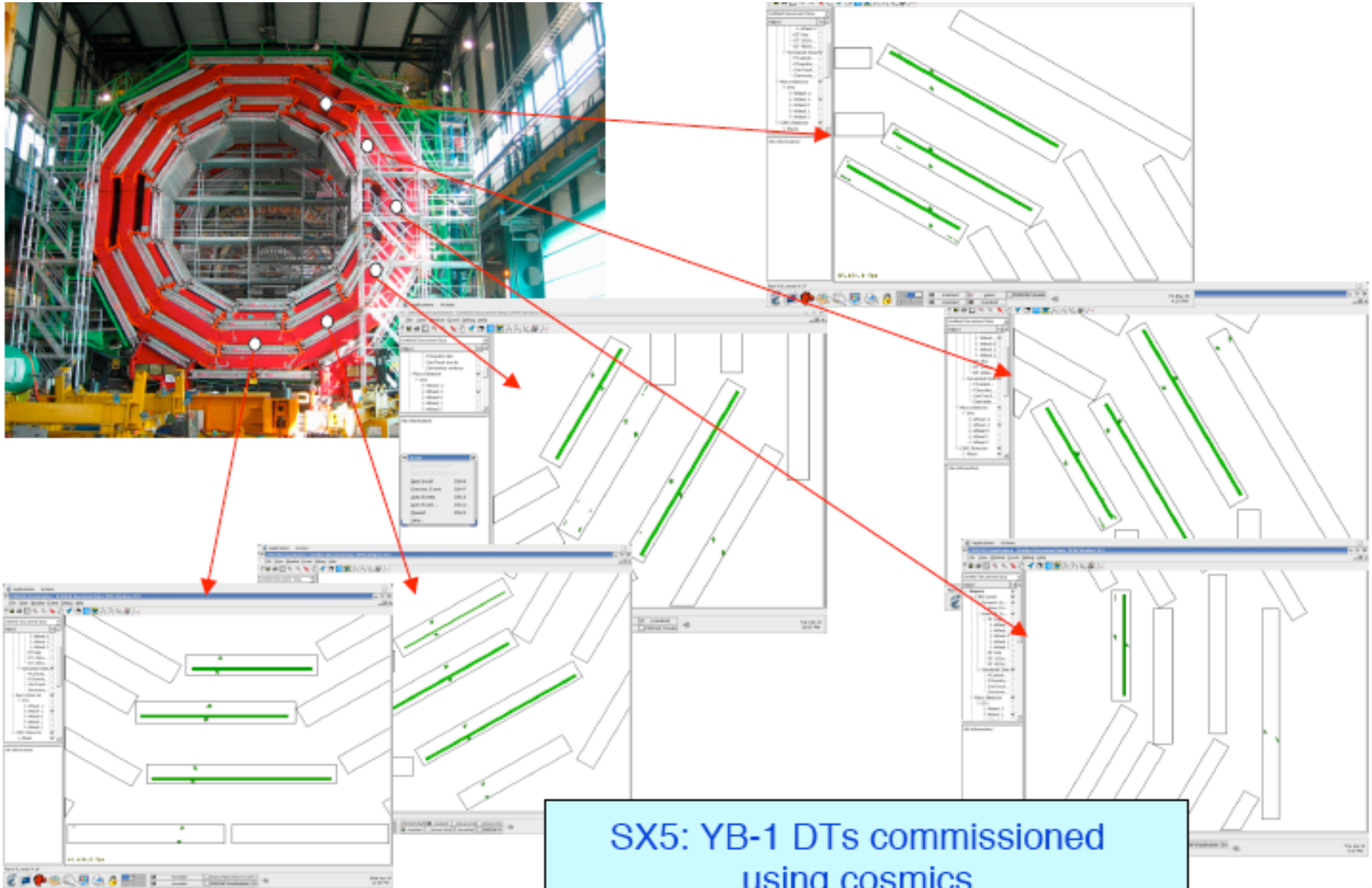


December 2005: cosmic muons in CMS (surface hall)





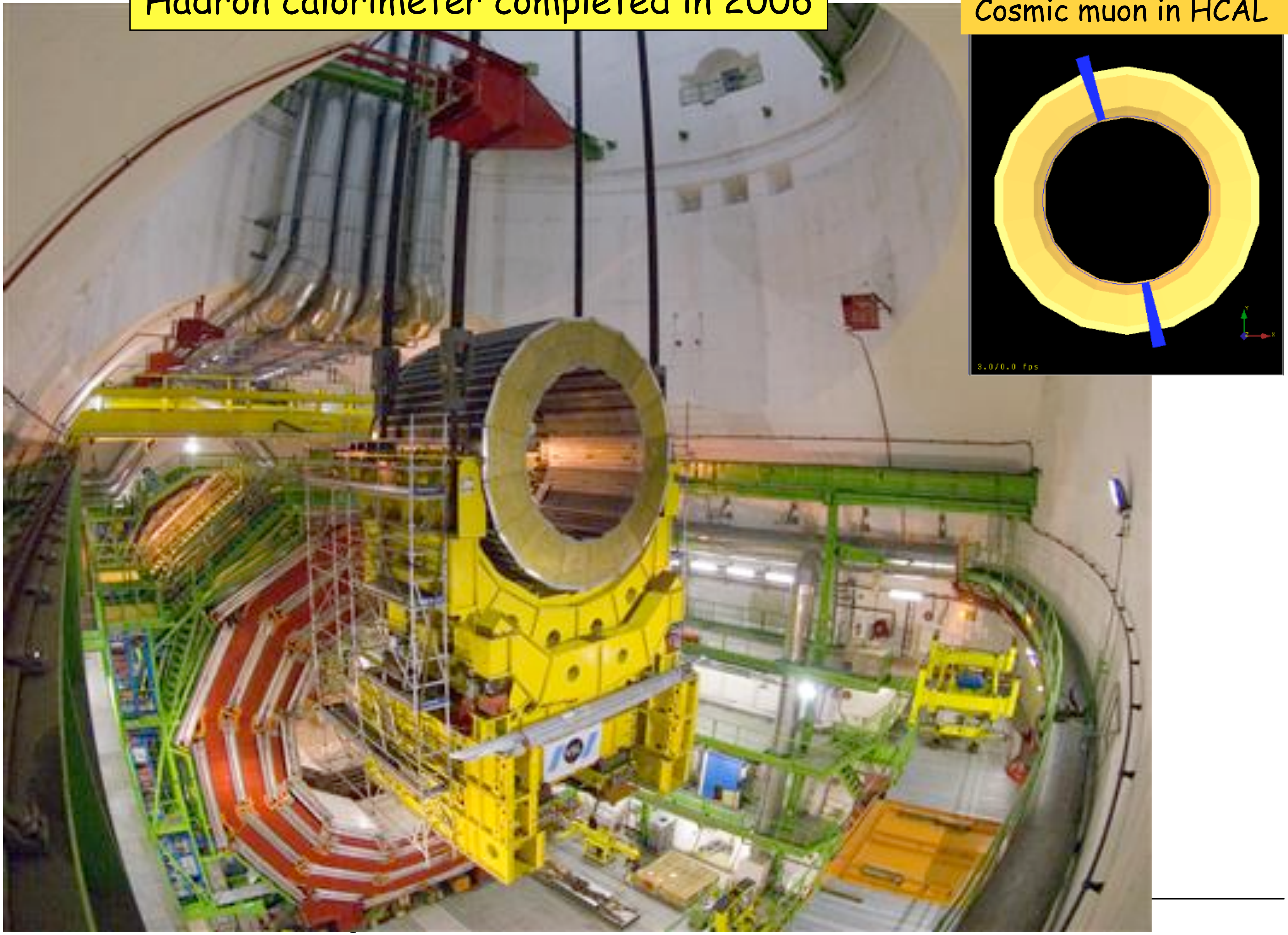
CMS muon chamber commissioning with cosmics



SX5: YB-1 DTs commissioned using cosmics

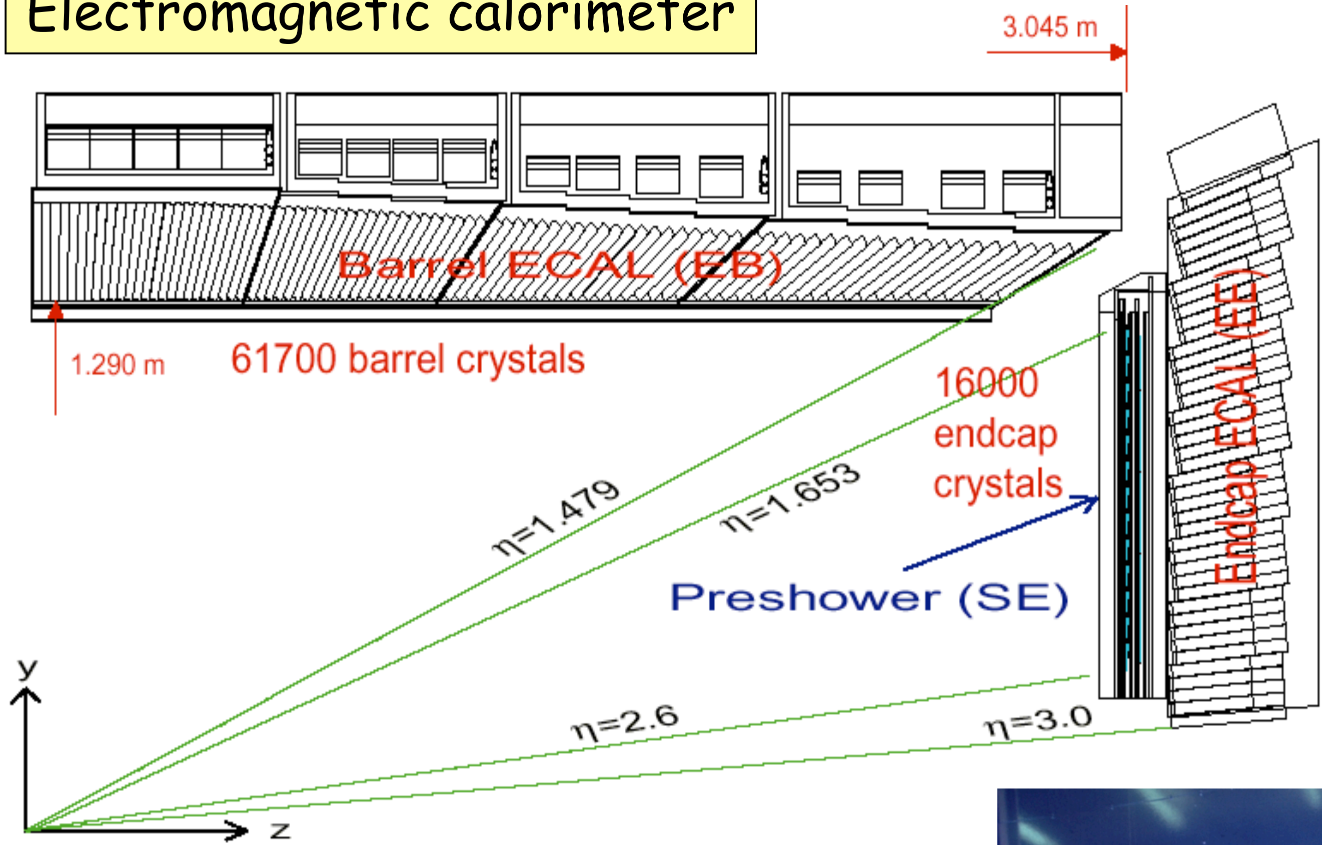
Hadron calorimeter completed in 2006

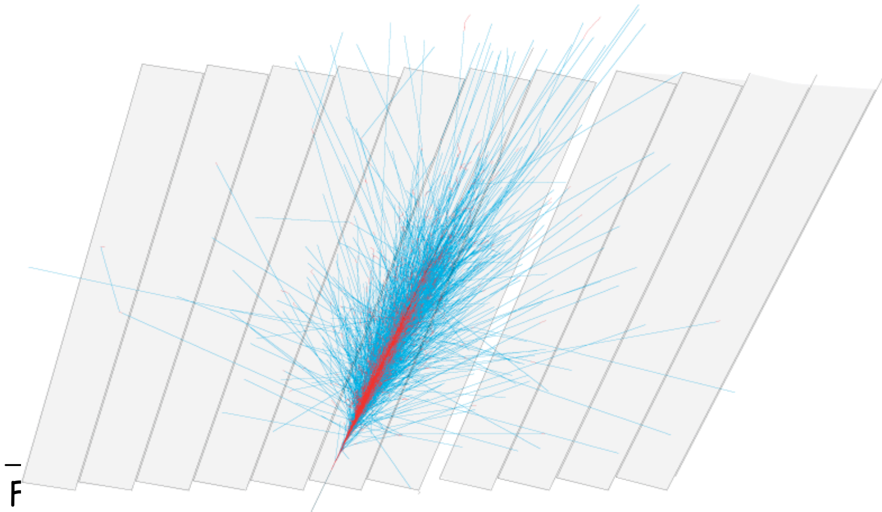
Cosmic muon in HCAL

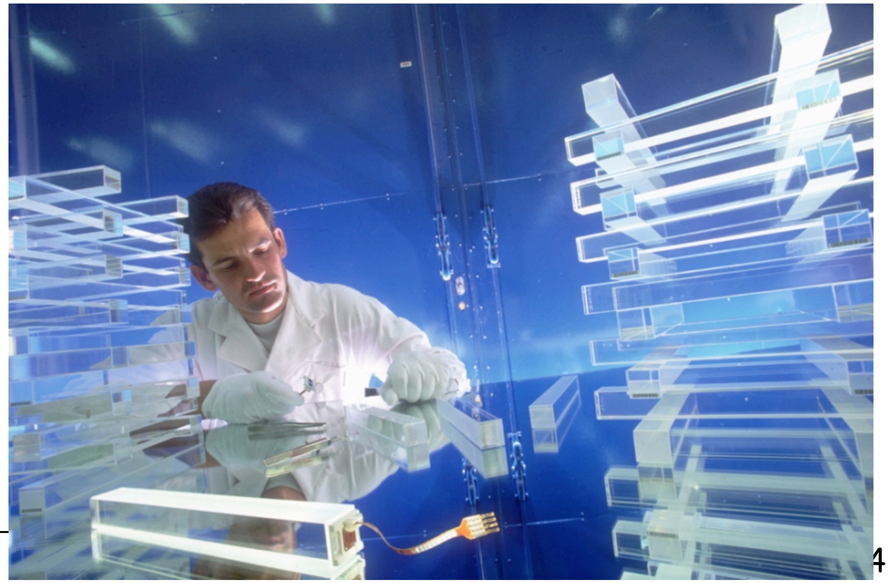


Electromagnetic calorimeter

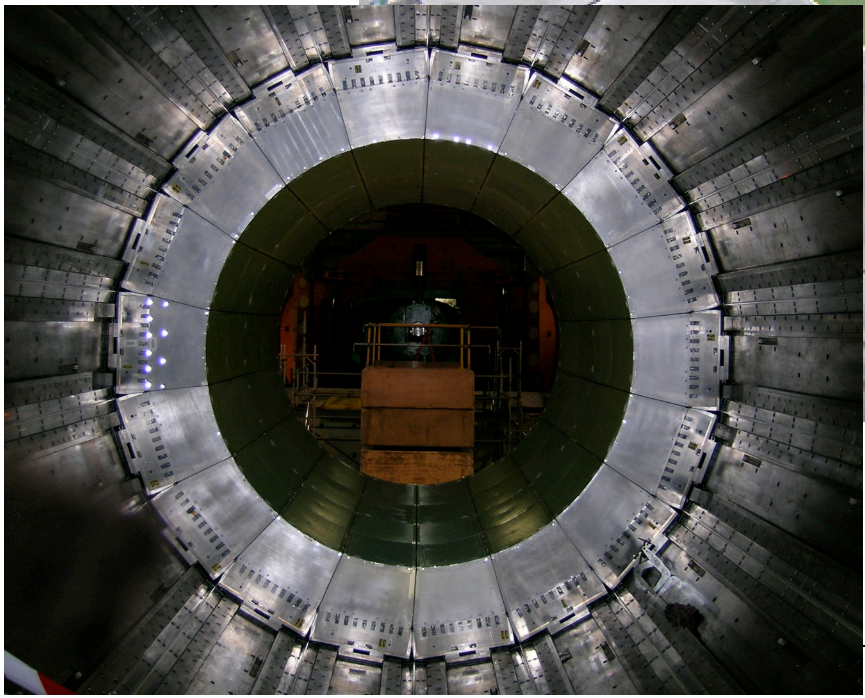
~ 80000 $PbWO_4$ crystals





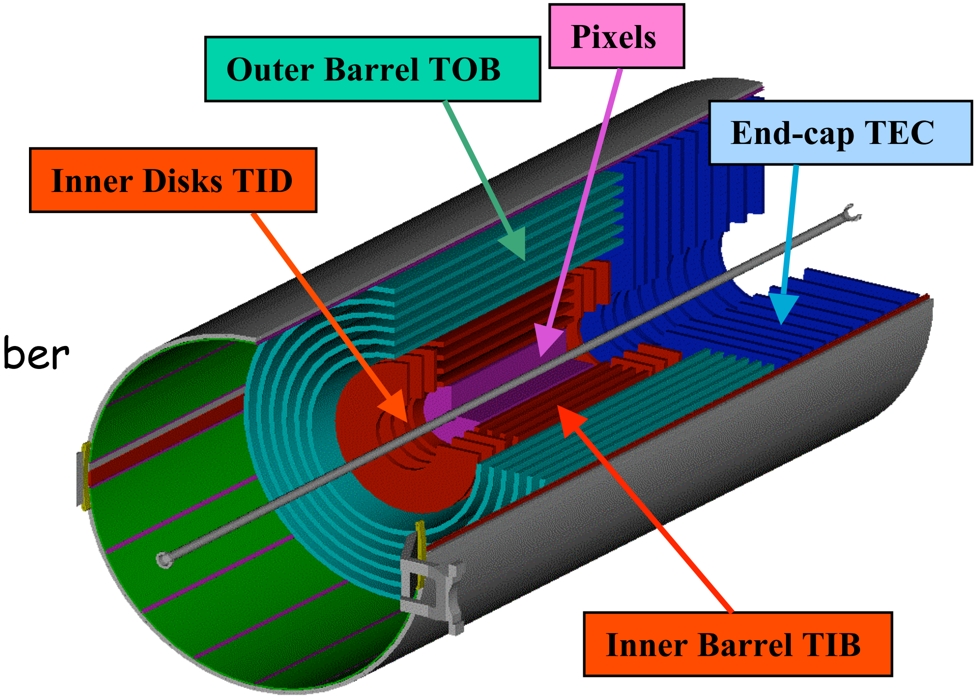


Half EM barrel calorimeter installed in May 2007



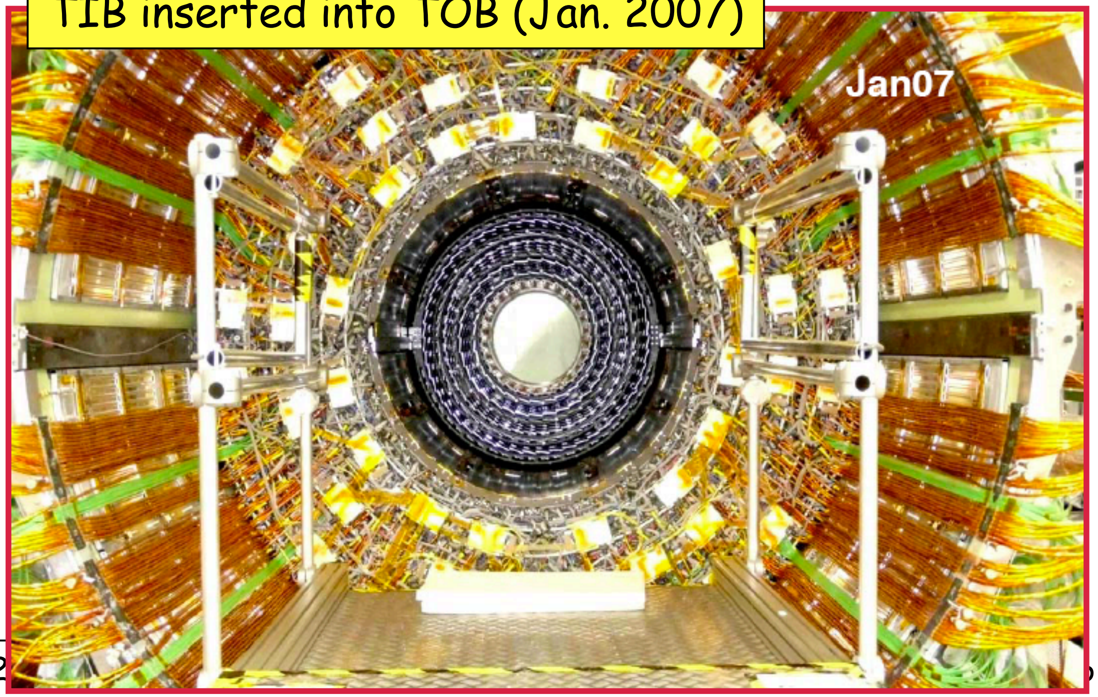
<u>CMS Inner tracker:</u>
~ 220 m^2 of Si sensors
10.6 million Si strips
65.9 million Pixels

Installation in underground cavern in September



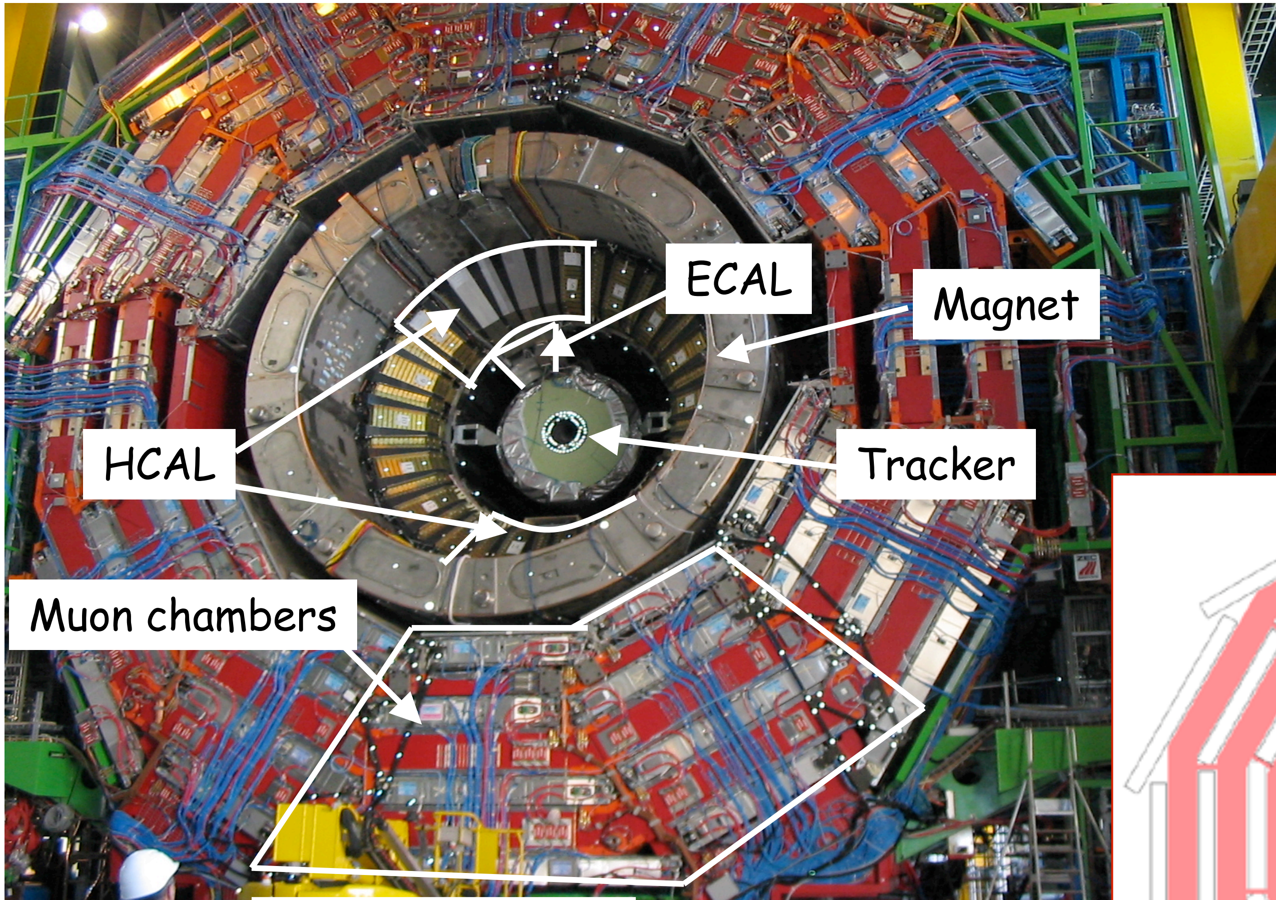
End-cap (TEC) disk

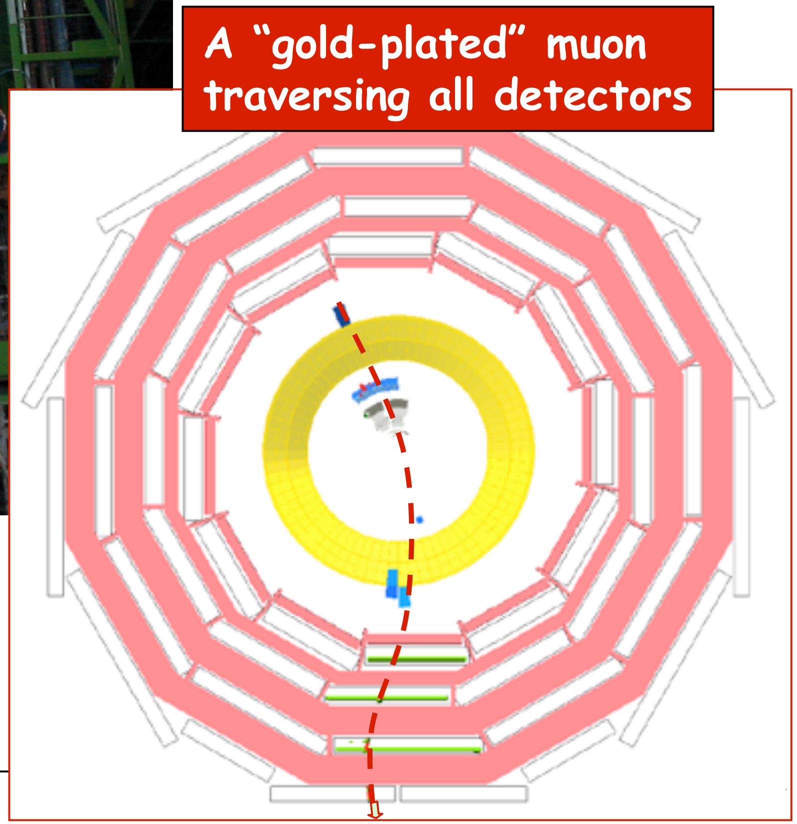
TIB inserted into TOB (Jan. 2007)



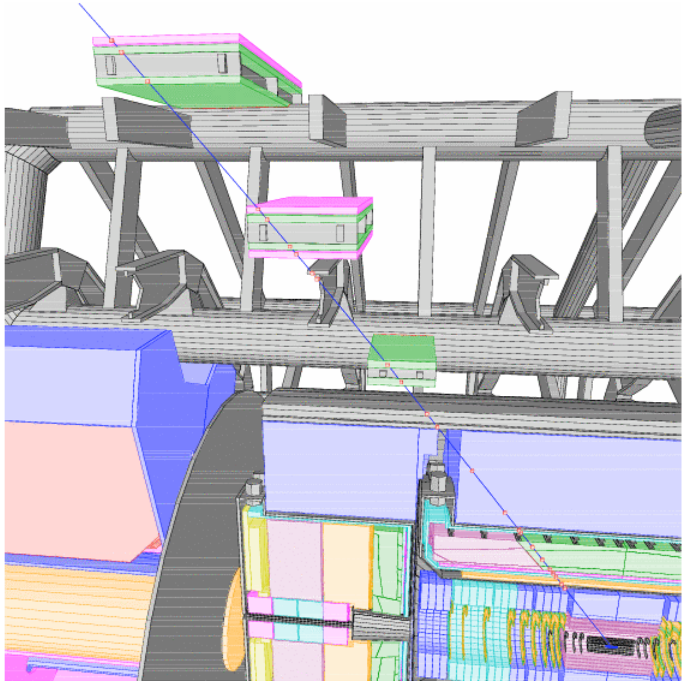
CMS Magnet Test and Cosmic Challenge in August-October 2006

Cosmics run of a ~ full detector slice (few percent of CMS coverage) inside 4T field.
200 million cosmic muons collected in the surface hall (rate is 0.5-1 kHz at surface)



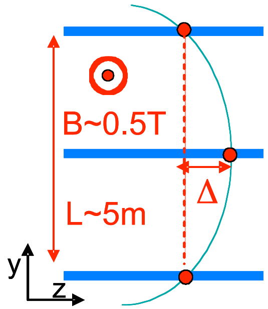


Expected performance: muon measurement

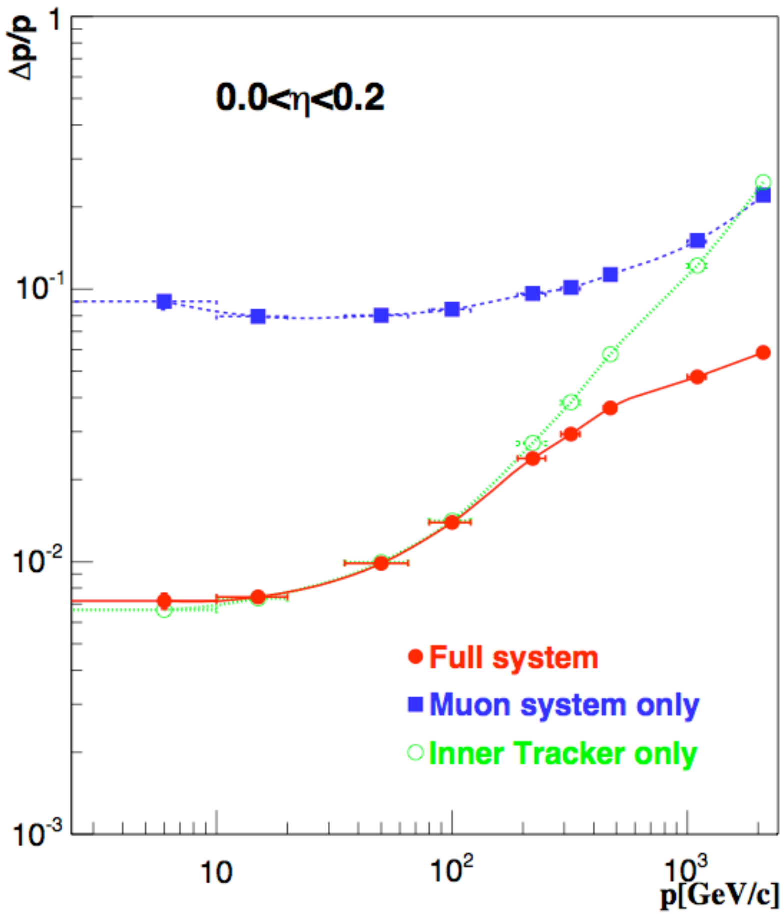


ATLAS Muon Spectrometer:
E_μ ~ 1 TeV $\Rightarrow$ Δ~500 μm

– σ/p ~10% $\Rightarrow$ $\delta\Delta$~50 μm
- alignment accuracy to ~20 μm

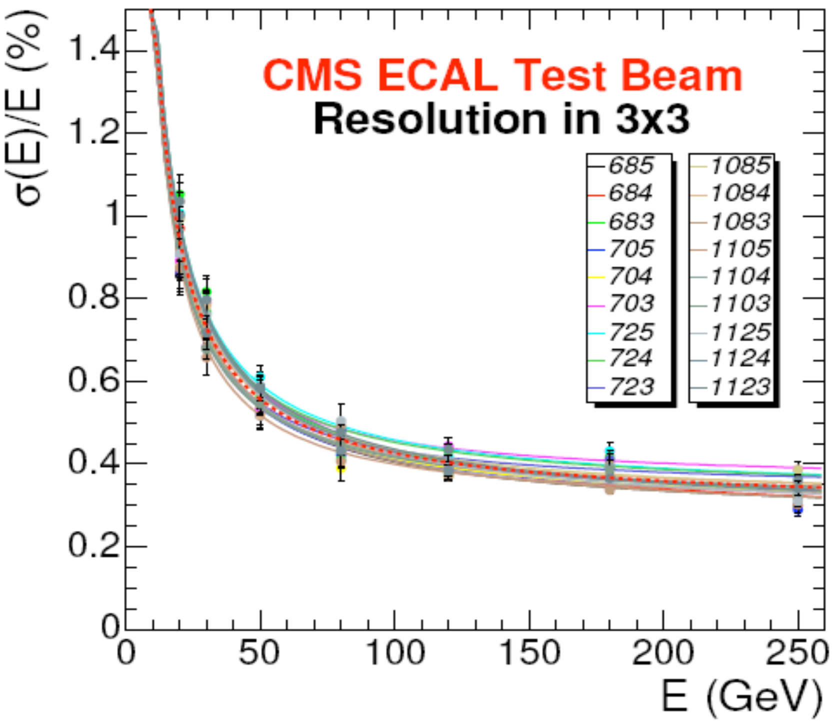


Muon momentum resolution in CMS



Electron measurement

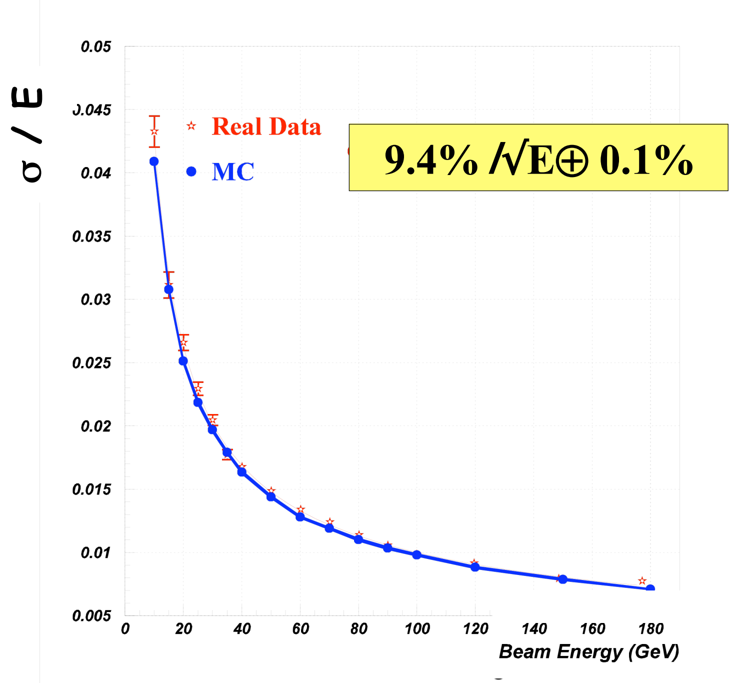
Electron E-resolution measured in beam tests of CMS EM calorimeter (crystals)

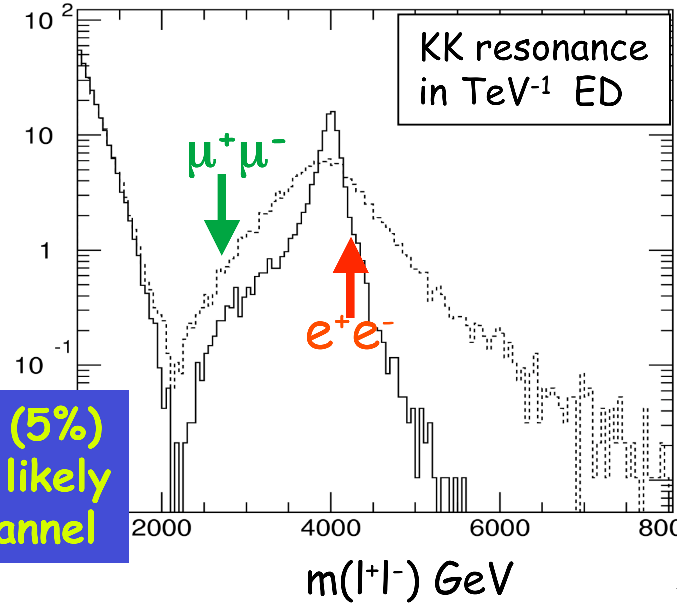


Mean Resolution (18 crystals):

$$\left(\frac{\sigma}{E}\right)^2 = \left(\frac{2.9\%}{\sqrt{E}}\right)^2 + \left(\frac{125(MeV)}{E}\right)^2 + (0.30\%)^2$$

Electron E-resolution measured in beam tests of ATLAS EM calorimeter (Pb/LAr)





1 TeV $e^\pm$ ($\mu^\pm$): σ (E)/E ≈ 0.5% (5%)
→ heavy narrow resonances will likely be discovered in the X → ee channel

A few more numbers .....

Number of turns of the LHC ring made by protons in one second: ~ 11000
Number of proton-proton interactions per second at design L: 1 billion

Number of particles produced per collision at design L: more than 1000

Machine temperature : 1.9 K (the largest cryogenic system in the world)

Total length of filaments of the dipole superconducting cable corresponds to 5 trips to the sun and back plus a few trips to the moon

Weight of CMS experiment: ~ 13000 tons (30% more than the Tour Eiffel)

Amount of cables used to transfer the detector signals in ATLAS : ~ 3000 km

Data collected by experiments in 1 year: 20 km of CD

Number of involved world-wide physicists : > 4000

Total cost (accelerator plus experiments) : ~ 5000 MCHF

Such a spectacular enterprise is justified by spectacular physics goals

Examples of open questions and mysteries that the LHC will address

What is the origin of the particle masses ? **ATLAS, CMS**

What is the nature of the Universe dark matter ? **ATLAS, CMS**

What is the origin of the Universe matter-antimatter asymmetry ? **LHCb** +ATLAS, CMS

What were the constituents of the Universe primordial plasma ~10 μs after the Big Bang ? **ALICE** +ATLAS, CMS

What happened in the first instants of the Universe life (10^{-10} s after the Big Bang) ? **ATLAS, CMS**

The LHC will help solve these and other mysteries … and .. determine the future course of high-energy physics

In more detail, the main LHC goals are:

Search for the Standard Model Higgs boson over ~ $115 < m_H < 1000$ GeV.

Explore the highly-motivated TeV-scale, search for physics beyond the SM (Supersymmetry, Extra-dimensions, q/l compositness, leptoquarks, W'/Z', heavy q/l, etc.)

Precise measurements :

-- W mass
-- top mass, couplings and decay properties
-- Higgs mass, spin, couplings (if Higgs found)
-- B-physics (mainly LHCb): CP violation, rare decays, B^0 oscillations
-- QCD jet cross-section and α_s
-- etc. ….

Study phase transition at high density from hadronic matter to quark-gluon plasma (mainly ALICE).

Etc. etc. …..

Here : focus on high-p_T physics (ATLAS and CMS)

Physics potential: a few examples with emphasis on first data

With the first physics data in 2008 ….

$1\ fb^{-1}$ ($100\ pb^{-1}$) ≡ 6 months (few days) at L= $10^{32}\ cm^{-2}s^{-1}$
with 50% data-taking efficiency
→ may collect a O($100\ pb^{-1}$) per experiment by end 2008

Channels (examples …)	Events to tape for $100\ pb^{-1}$ (per expt: ATLAS, CMS)	Total statistics from some of previous Colliders
$W \to \mu\nu$	$\sim 10^6$	$\sim 10^4$ LEP, $\sim 10^6$ Tevatron
$Z \to \mu\mu$	$\sim 10^5$	$\sim 10^6$ LEP, $\sim 10^5$ Tevatron
$tt \to WbWb \to \mu\nu + X$	$\sim 10^4$	$\sim 10^4$ Tevatron
QCD jets $p_T > 1$ TeV	$> 10^3$	---
$\tilde{g}\tilde{g}$ m = 1 TeV	~ 50	---

With these data:

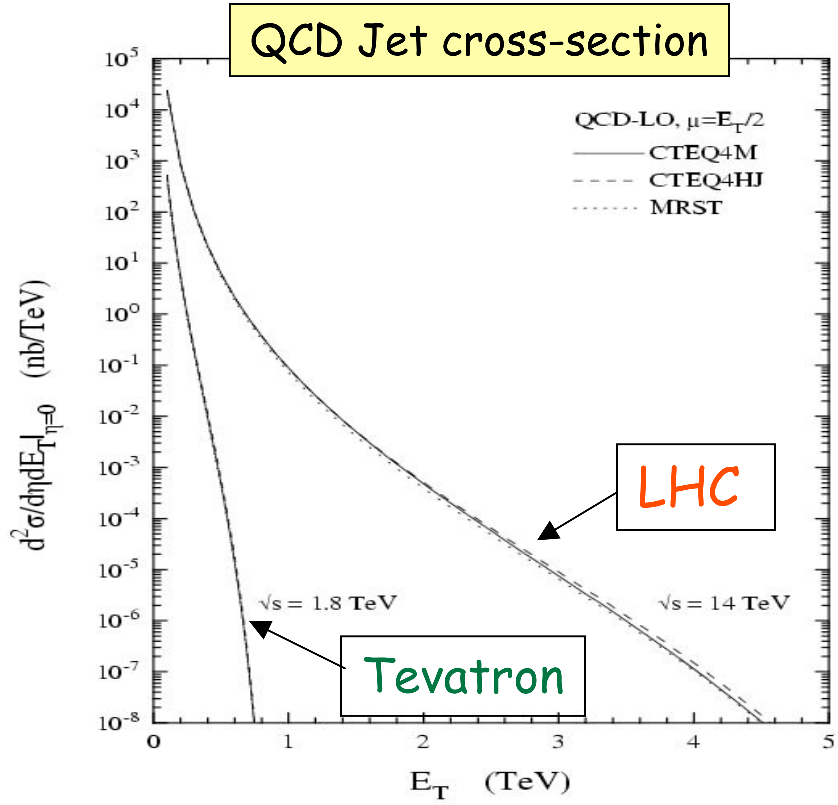
- Understand and calibrate detectors in situ using well-known physics samples
  e.g. - $Z \to ee, \mu\mu$ tracker, ECAL, Muon chambers calibration and alignment, etc.
  - $tt \to bl\nu\ bjj$ jet scale from $W \to jj$, b-tag performance, etc.

- "Rediscover" and measure SM physics at $\sqrt{s}$ = 14 TeV : W, Z, tt, QCD jets …
  (also because omnipresent backgrounds to New Physics)

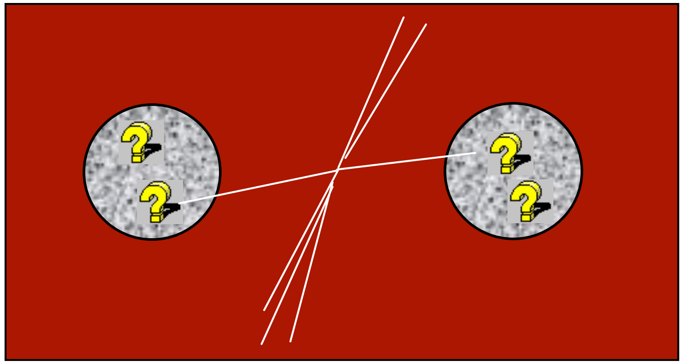
→ prepare the road to discoveries …… it will take time …

Jump in a new territory very soon …

- Explore E_T(jet) > 500 GeV after few weeks at $10^{31}cm^{-2}s^{-1}$
- Expect >10^3 events with E_T(jet) > 1 TeV with 100 pb^{-1} (end 2008 ?)
- Going fast beyond the Tevatron reach
- Early sensitivity to quark compositeness: $\Lambda \sim 5$ (8)TeV with 100 (1000) pb^{-1}



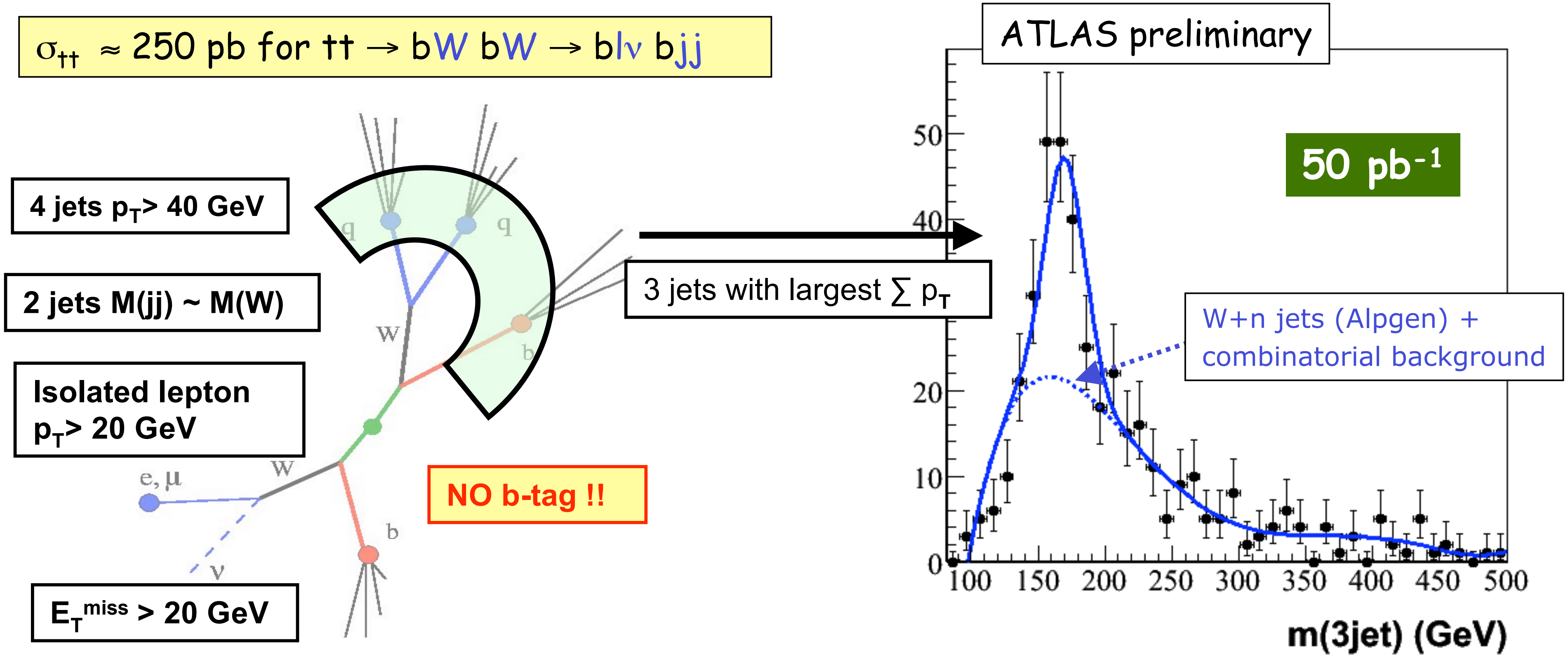
If quarks are composite : new $qq \rightarrow qq$ interactions with strength $\sim 1/\Lambda^2$, $\Lambda \equiv$ scale of New Physics.
$\Rightarrow$ expect excess of high-p_T jets compared to SM
The higher Λ the smaller the excess.
LHC ultimate sensitivity up to $\Lambda \approx 40$ TeV



Example of initial measurement: understanding detector and physics with top events

Can we observe an early top signal with limited detector performance ?
And use it to understand detector and physics ?

$\sigma_{tt} \approx 250$ pb for tt → bW bW → blν bjj



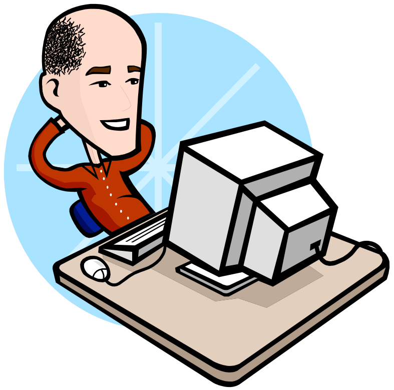
Top signal observable in early days with no b-tagging and simple analysis (100 ± 20 evts for 50 pb^{-1}) → measure σ_{tt} to 20%, m to 10 GeV with ~100 pb^{-1} ?

In addition, excellent sample to:

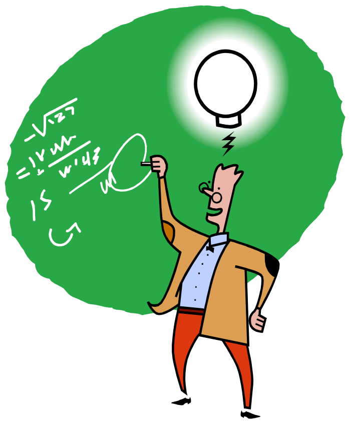
- **understand detector performance for e, μ, jets, b-jets, missing E_T, …**
- **understand / constrain theory and MC generators using e.g. p_T spectra**

What about early discoveries ? Three examples .....

An easy case : a new (narrow) resonance of mass ~ 1 TeV decaying into e+e-, e.g. a Z' or a Graviton



An intermediate case : SUSY

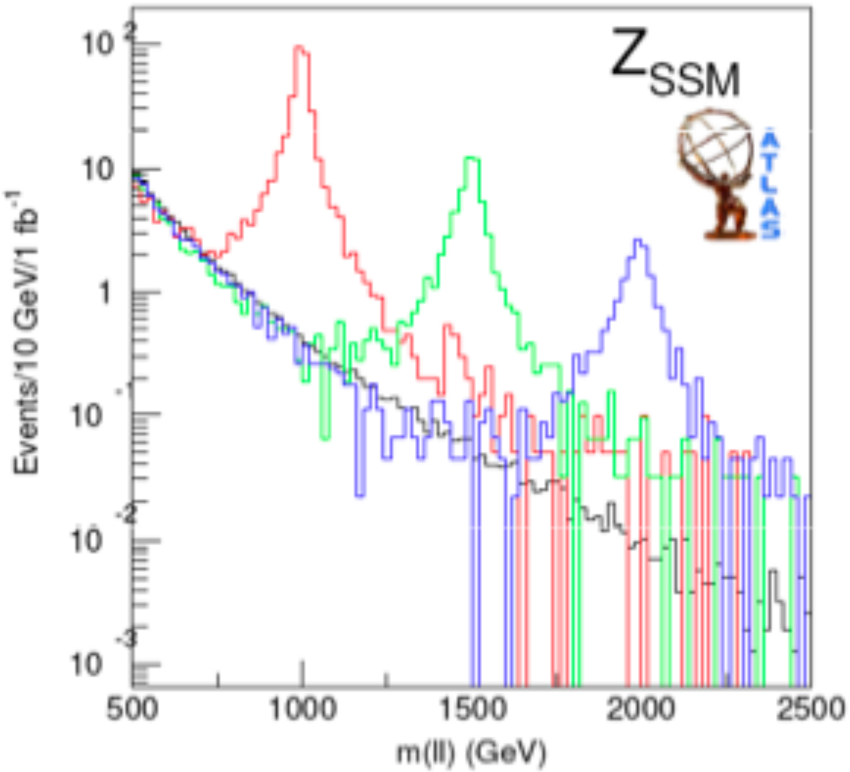


A difficult case : a light Higgs (m_H ~ 115 GeV)

An "easy case" : $Z' \rightarrow e^+e^-$, mass ~ 1 TeV with SM-like couplings (Z_{SSM})

Mass	Expected events for 1 fb^{-1} (after all analysis cuts)	Integrated luminosity needed for discovery (corresponds to 10 observed evts)
1 TeV	~ 160	~ 70 pb^{-1}
1.5 TeV	~ 30	~ 300 pb^{-1}
2 TeV	~ 7	~ 1.5 fb^{-1}

- large enough signal for discovery with ~100 pb^{-1} up to m > 1 TeV
- small SM background
- signal is (narrow) mass peak above background



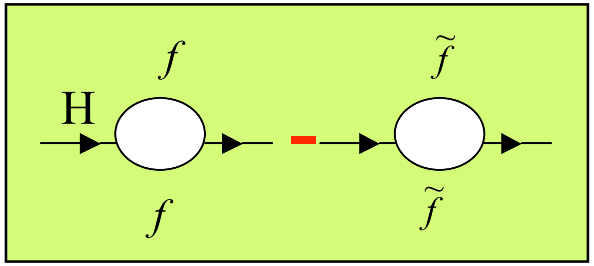
An "intermediate case" : SUPERSYMMETRY

The (minimal) model considered in experimental studies at colliders is the MSSM (Minimal Supersymmetric extension of the Standard Model):

MSSM particle spectrum

SM particle	SUSY partner		spin
l	sleptons	$\tilde{l}$	0
q	squarks	$\tilde{q}$	0
g	gluino	$\tilde{g}$	1/2
$W^{\pm}$ (+Higgs)	charginos	$\chi^{\pm}_{1,2}$	1/2
γ, Z (+Higgs)	neutralinos	$\chi^{0}_{1,2,3,4}$	1/2

+ 5 Higgs : h, H, A, $H^{\pm}$ $m_h < 135$ GeV



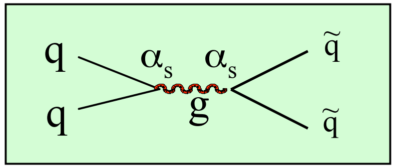
- No experimental evidence for SUSY → sparticles are heavy
- However: to stabilize Higgs mass need masses up to ~TeV → should not escape at LHC

- In models avoiding rapid proton decay (R-parity is conserved):

■ SUSY particles produced in pairs
■ Lighest Supersymmetric Particle (LSP) is stable
LSP ≡ χ^{0}_{1} weakly interacting ←→ excellent dark matter candidate
■ all SUSY particles decay to LSP

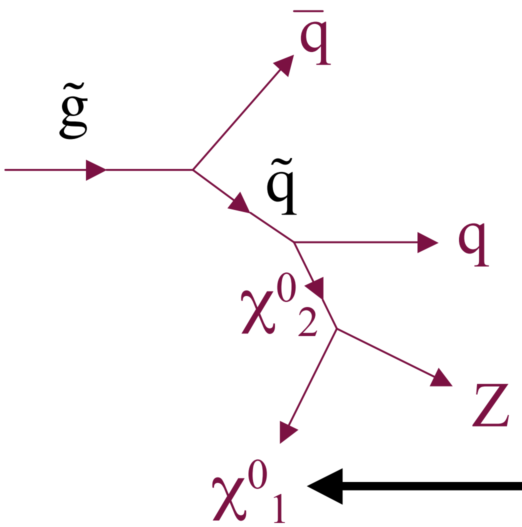
SUSY searches at LHC

- Dominant processes : $\tilde{q}\tilde{q}$, $\tilde{q}\tilde{g}$, $\tilde{g}\tilde{g}$ production
  strong production → huge cross-section

e.g. 

e.g. for $m(\tilde{q},\tilde{g}) \sim 1$ TeV ~ 100 events produced with 100 pb^{-1}

- $\tilde{q}, \tilde{g}$ heavy (present Tevatron limits: m > 280-380 GeV) → cascade decays

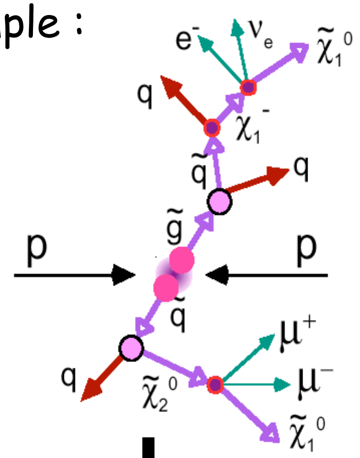


→ spectacular signatures with many jets, leptons + missing E

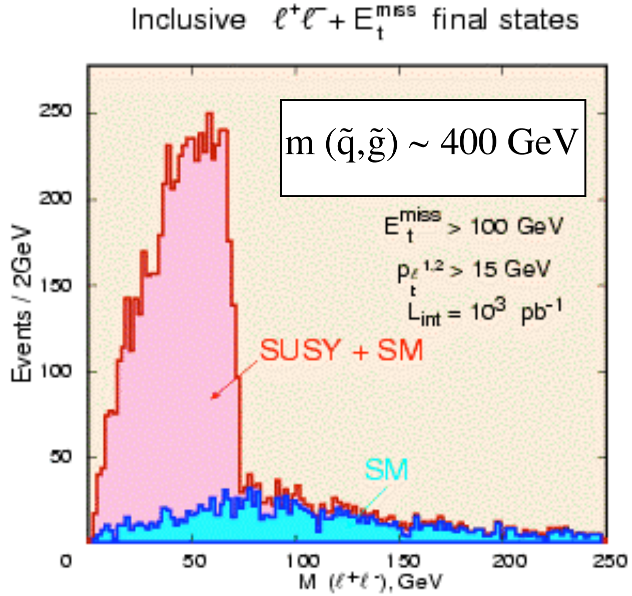
→ relatively easy to extract SUSY signal from SM backgrounds at LHC (in most cases…)

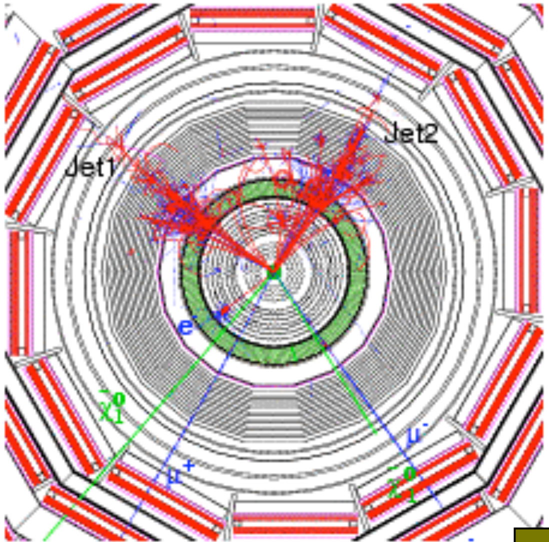
This particle (lightest neutralino) is stable, neutral and weakly interacting → escapes detection (like ν) → apparent missing energy in the final state

Example :



CMS





LHC discovery reach

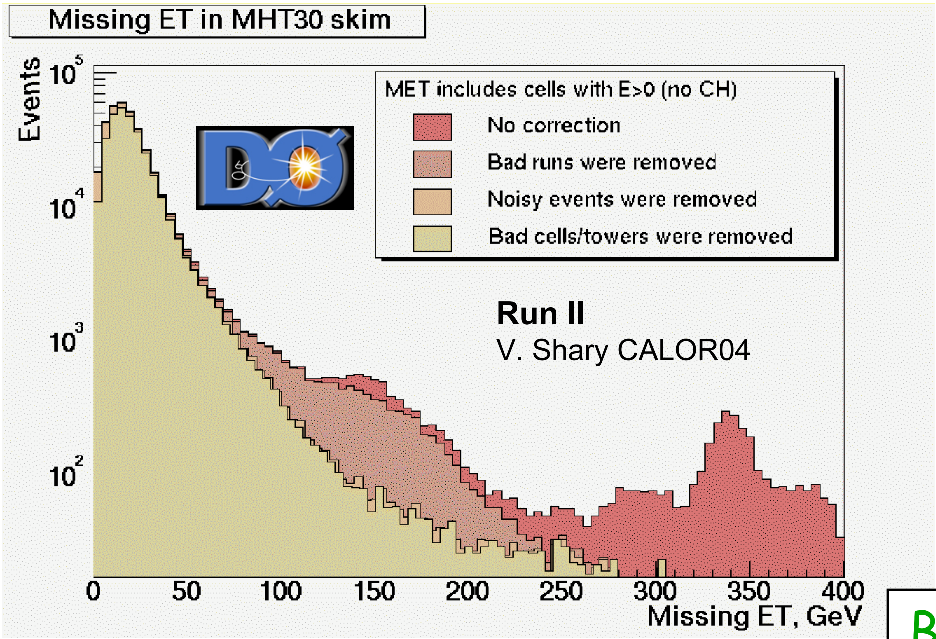
Needed ∫Ldt / time	Reach in gluino mass
100 pb^{-1} (end 2008 ?)	~ 1.3 TeV
1 fb^{-1} (mid 2009 ?)	~ 1.7 TeV
ultimate (300 fb^{-1})	up to ~ 3 TeV

- SUSY can be discovered quickly (in principle with 100 pb^{-1}) provided detectors and backgrounds well understood (this will take more time than in the previous/Z' case)
- If nothing found at LHC, (low-E) SUSY is likely dead

→ need another explanation for e.g. dark matter …

Main backgrounds to SUSY searches in jets + E_T^{miss} topology
(one of the most "dirty" signatures …) :

- W/Z + jets with $Z \to \nu\nu$, $W \to \tau\nu$; $t\bar{t}$; etc.
- QCD multijet events with fake E_T^{miss} from jet mis-measurements (calorimeter resolution and non-compensation, cracks, …)
- cosmics, beam-halo, detector problems overlapped with high-p_T triggers, …

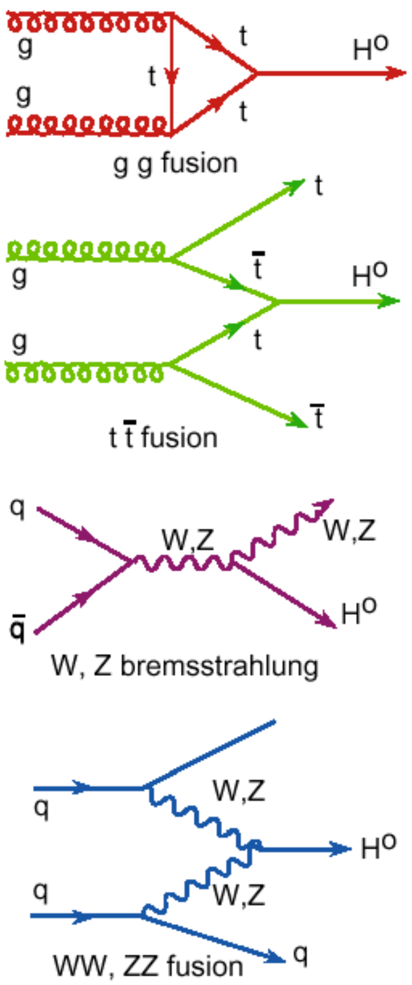


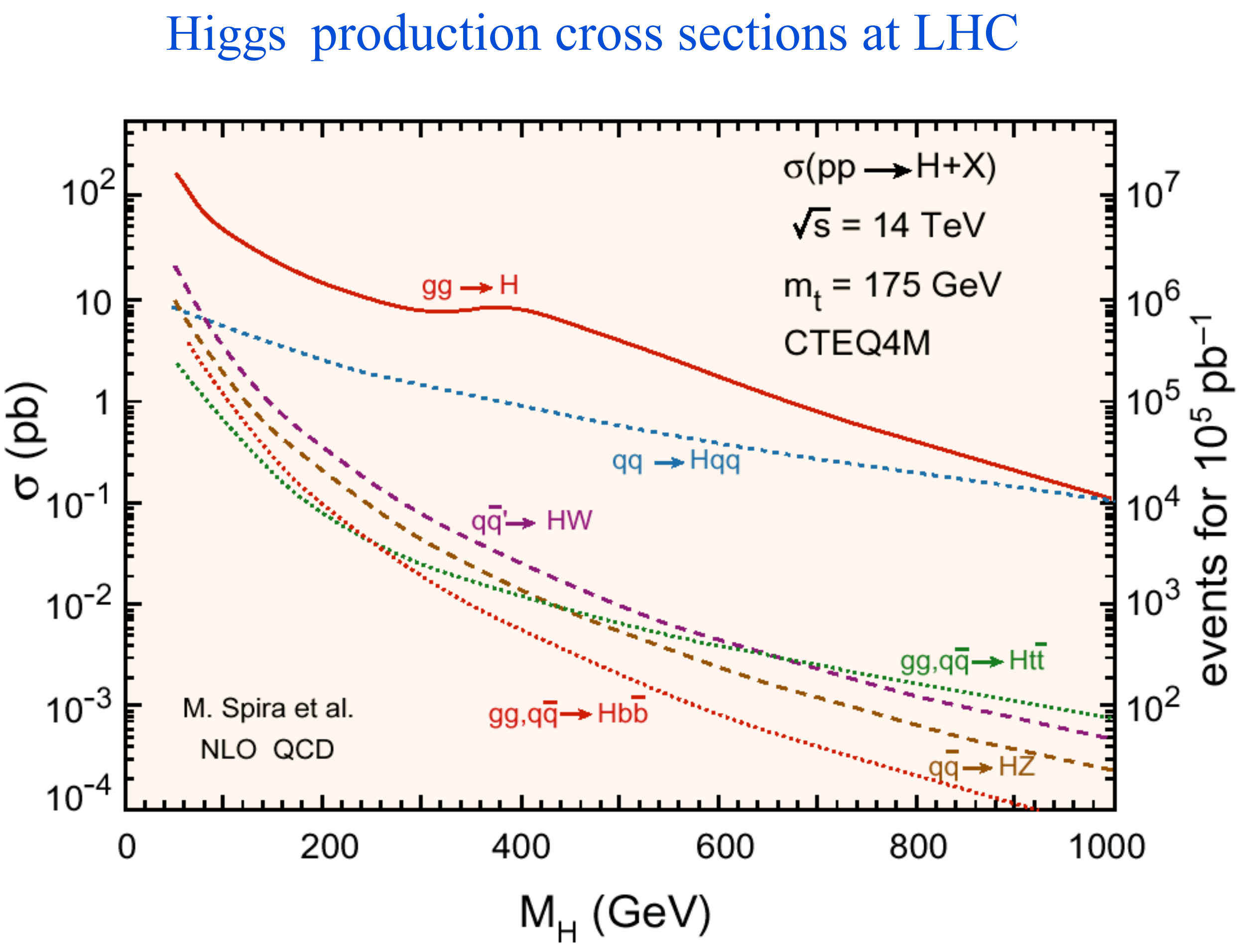
Understanding E_T^{miss} spectrum (and tails from instrumental effects) is one of most crucial and difficult experimental issues for SUSY searches at hadron colliders.
Note: can also use final states with leptons (cleaner …)

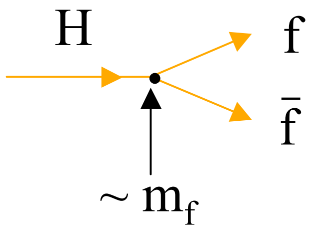
Background process (examples ….)	Control samples (examples ….)
$Z (\to \nu\nu)$ + jets	$Z (\to ee, \mu\mu)$ + jets
$W (\to \tau\nu)$ + jets	$W (\to e\nu, \mu\nu)$ + jets
$t\bar{t} \to bl\nu bjj$	$t\bar{t} \to bl\nu\, bl\nu$
QCD multijets	lower E_T sample

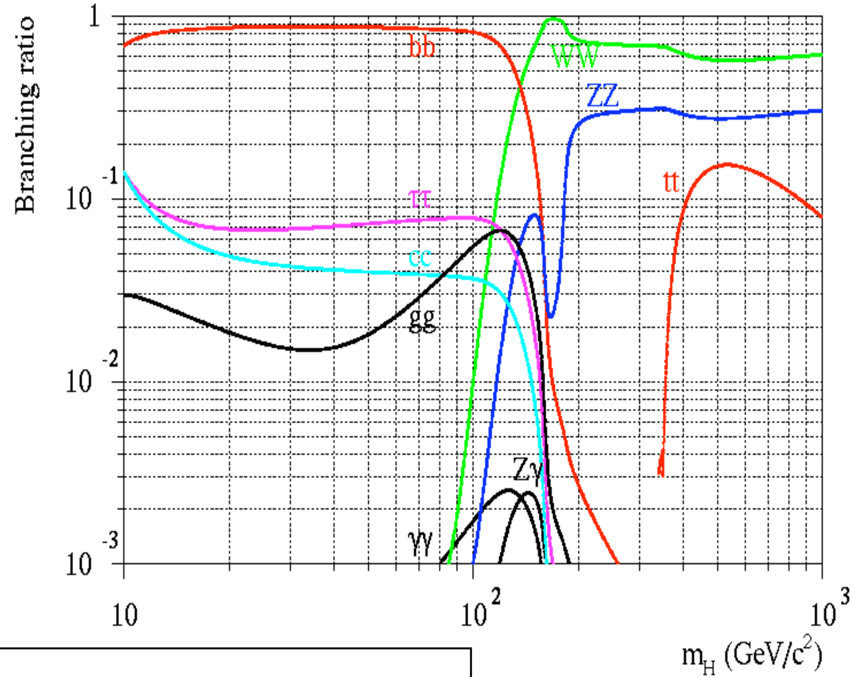
Estimate backgrounds using <u>as much as possible data (control samples)</u> and MC

A difficult case: a light Higgs (m_H ~ 115-150 GeV) ...









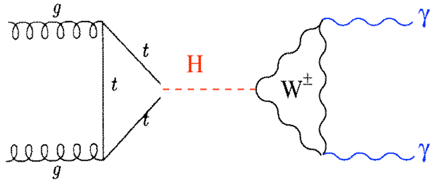
Remember: light fully-hadronic final states cannot be extracted from QCD background at hadron colliders

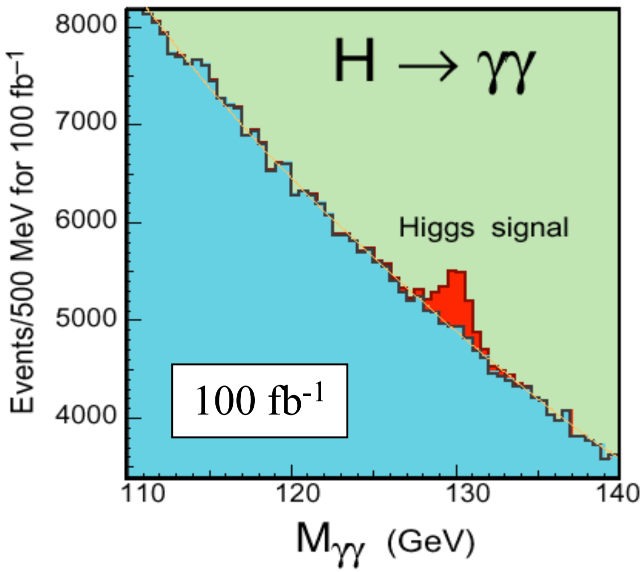
m_H < 130 GeV : H → bb, ττ dominate
→ best search channels at the LHC : ttH → bb l+X, qqH→qq ττ
H → γγ (rare decay mode)
This is the most difficult region (S/B <<1) !

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

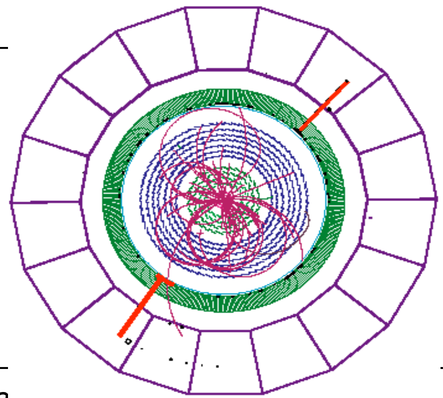
Especially in the region m_H<130 GeV, excellent detector performance needed to suppress the huge backgrounds: b-tag, l/γ E-resolution, γ/j separation, missing E_T resolution, forward jet tag, etc.
→ Higgs searches used as benchmarks for ATLAS and CMS detector design

$H \rightarrow \gamma\gamma$

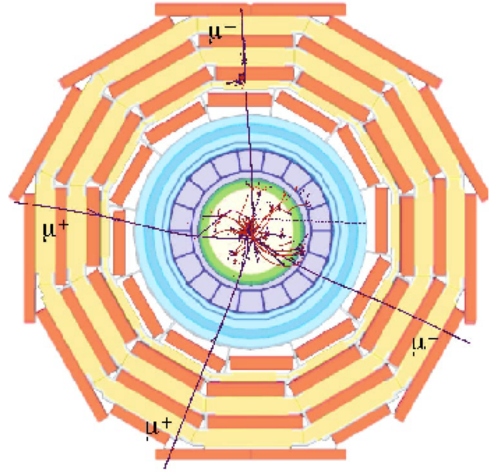


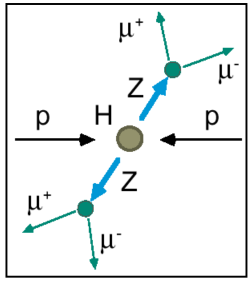


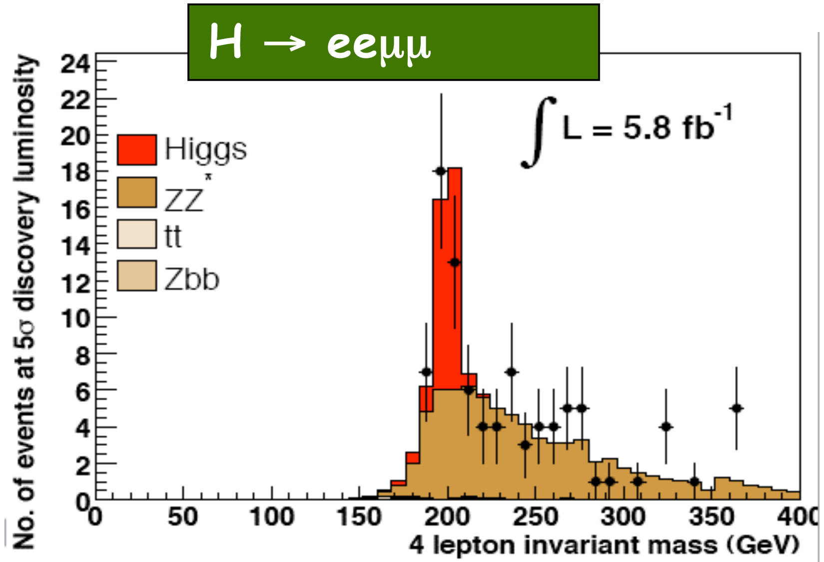
Requires excellent EM calorimetry
(E-resolution, γ/π^0 separation)



CMS



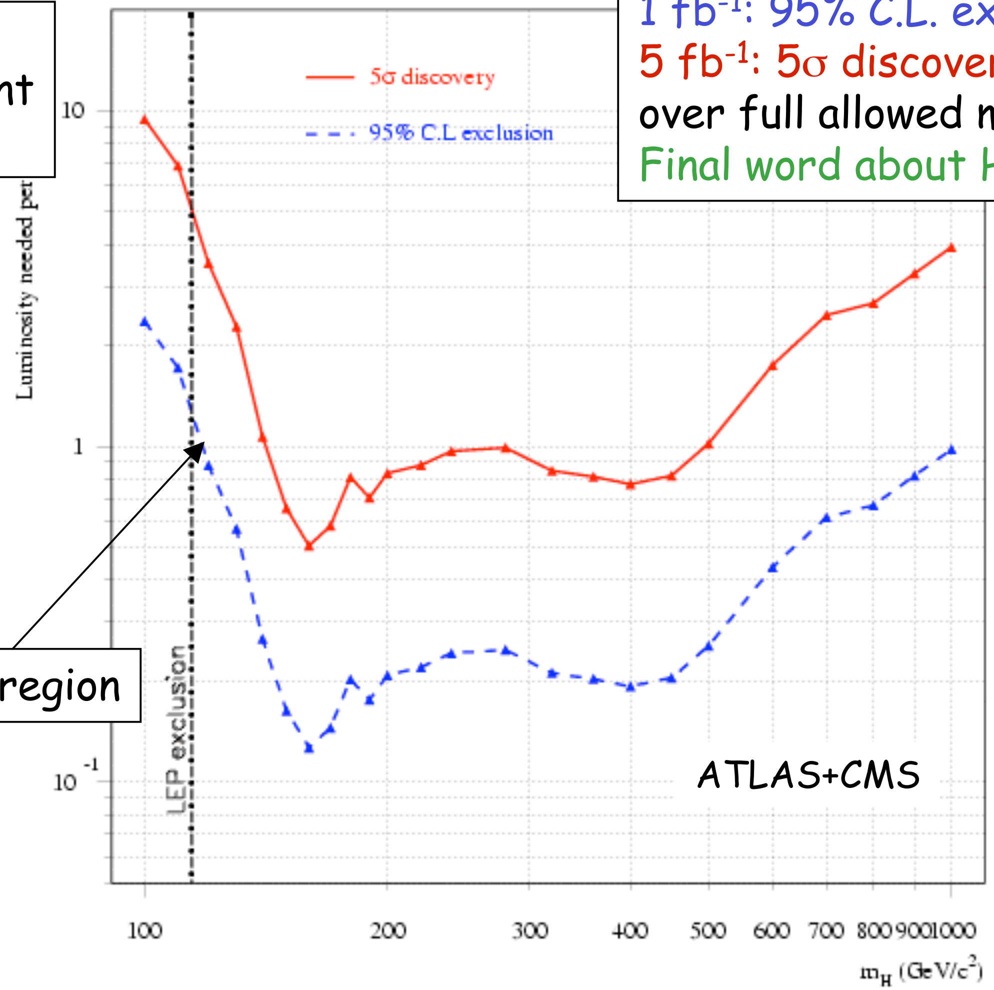




Gold-plated channel at LHC
(~ background free ...)

Summary of Higgs discovery potential at the LHC

Needed ∫Ldt per experiment (fb^{-1})

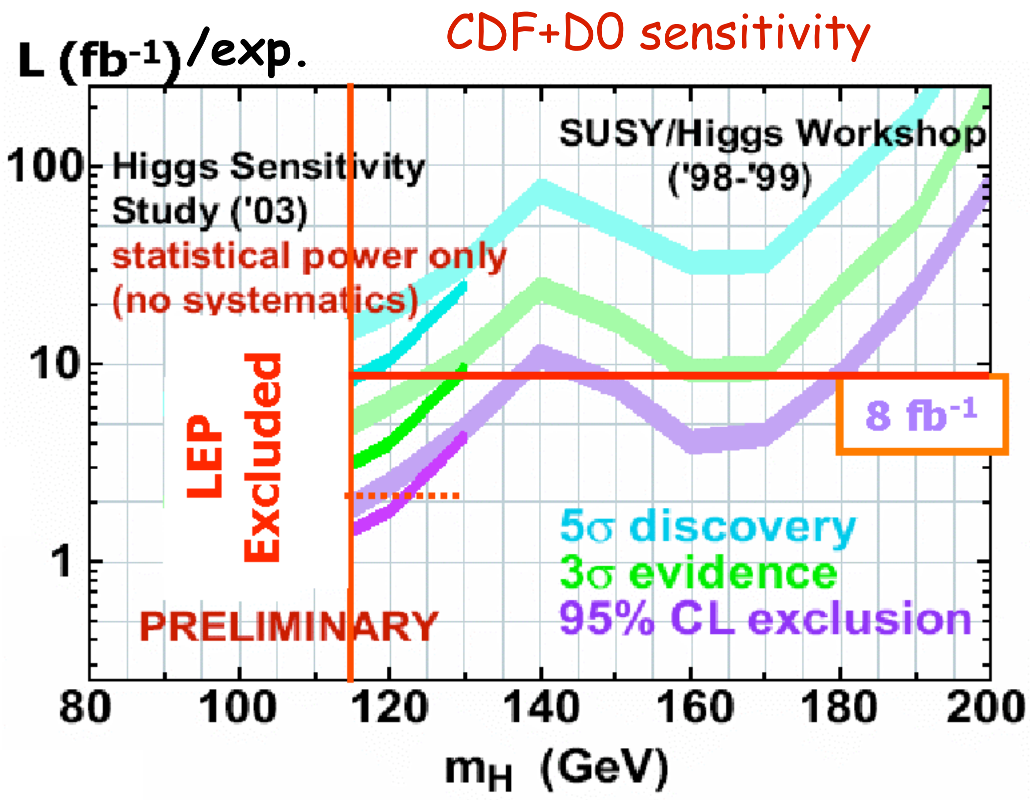


Most difficult region

With
1 fb^{-1}: 95% C.L. exclusion
5 fb^{-1}: 5σ discovery
over full allowed mass range
Final word about Higgs mechanism by 2009 ?

If Higgs found, mass can be measured to 0.1%, couplings to ~ 10-20%
→ major insight into electroweak symmetry breaking mechanism

What about the Tevatron ?



Today : ~ 3 fb^{-1} /experiment
2009: expect 6-7 fb^{-1} /experiment
Tevatron operation in 2010 being discussed

With 4 (8) fb^{-1}:
~no 5σ sensitivity
3σ evidence up to 120 (130) GeV
95% C.L. exclusion up to ~ 130 (180) GeV

competition between Tevatron and LHC in 2009 if m_H < 130 GeV ?

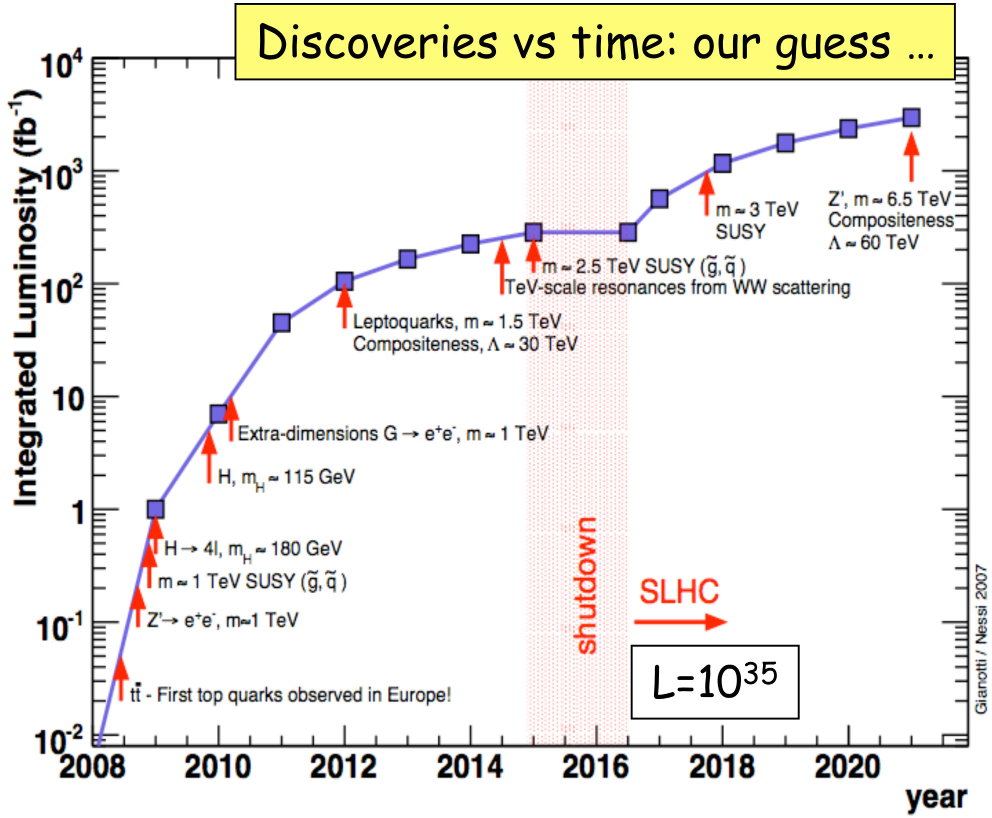
With more time and more data, the LHC can discover:

Excited quarks $q^* \to \gamma q$: up to $m \approx 6$ TeV
Leptoquarks: up to $m \approx 1.5$ TeV
Monopoles $pp \to \gamma\gamma pp$: up to $m \approx 20$ TeV
Compositeness: up to $\Lambda \approx 40$ TeV
$Z' \to ll, jj$: up to $m \approx 5$ TeV
$W' \to l\nu$: up to $m \approx 6$ TeV
etc.... etc....

Large number of scenarios studied
Main conclusions:

⇒ **LHC direct discovery reach up to m ~ 5-6 TeV**

⇒ **demonstrated detectors sensitivity to many signatures → robustness, ability to cope with unexpected scenarios**



Conclusions

- The LHC is one of the most ambitious and motivated projects in science ever …

- Construction is ~ finished and emphasis is now on installation and commissioning of a machine and detectors of unprecedented complexity, technology and performance

- All efforts are being made to deliver first collisions in Summer 2008
Experiments are on track toward this target

So, in about 1 year from now, particle physics will enter a new epoch, hopefully the most glorious and fruitful of its history.

We can anticipate a profusion of exciting results from a machine able to explore in detail the highly-motivated TeV-scale with a direct discovery potential up to m ≈ 5-6 TeV

→ if New Physics is there, the LHC should find it
(SUSY could be found quickly, light Higgs requires a bit more time, … and what about early surprises ?)

→ it will say the final word about the SM Higgs mechanism and many TeV-scale predictions

→ it may add crucial pieces to our knowledge of fundamental physics → impact also on astroparticle physics and cosmology

→ most importantly, it will tell us how to go on …