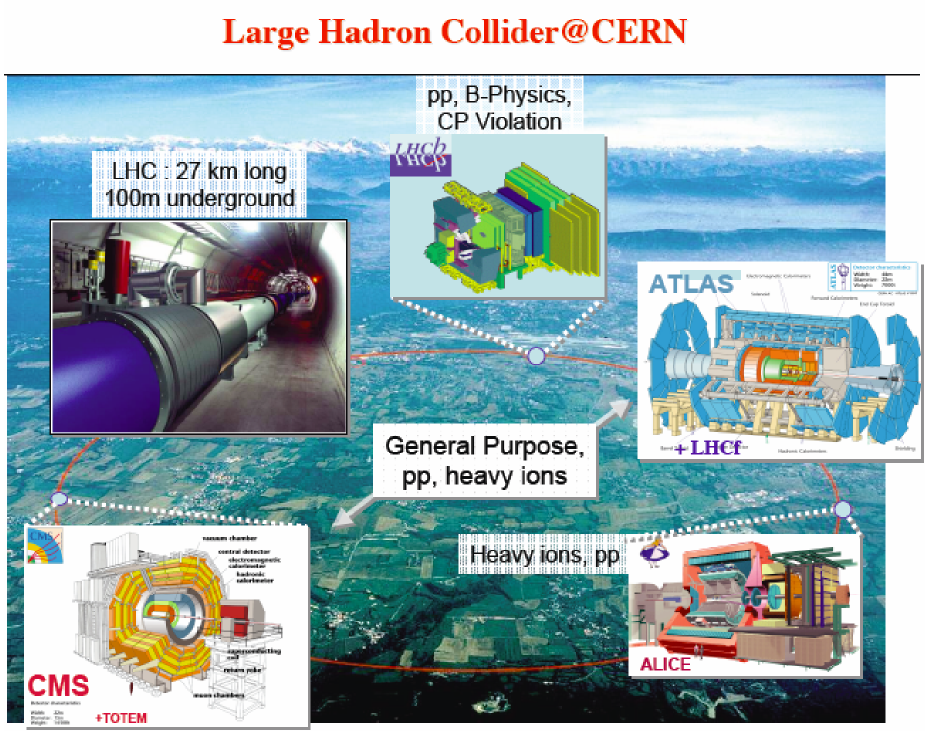
Lecture 1

Physics Program

of the experiments at

Large Hadron Collider



Outline of this course

1. Introduction to LHC, its experiments, physics programme and experimental challenges?
2. ATLAS detector, requirements and expected physics performance
3. The SM precision measurements : m_W, m_t, couplings
4. The SM and MSSM Higgs
5. Supersymmetry
6. Extra dimensions and exotics
7. B-physics programme
8. Heavy ion programme

http://hibiscus.if.uj.edu.pl/~erichter/Dydaktyka2008/LHCPhysics-2008

Many thanks to colleagues from LHC collaborations for making available large parts of material shown here.

Outline of this lecture

What is CERN and brief history toward the LHC?
What is the LHC ?
Why the LHC ?
The general purpose experiments: ATLAS and CMS
Brief overview of the physics programme
Experimental challenges

LHC at CERN laboratory

CERN: the world's largest particle physics laboratory

- international organisation created in 1953/1954, initial membership: 12 countries
- Poland is a member starting from year 1991
- About 10 000 active physicisists, computing scientists, engineers

situated between
Jura mountains and Geneva
(France/Swiss)

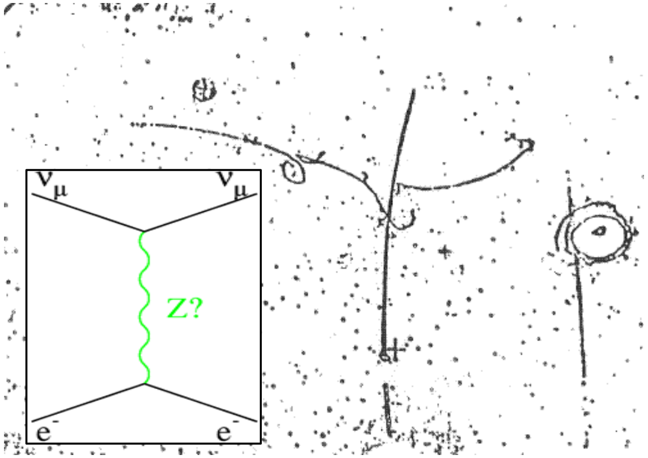
http://public.web.cern.ch

A brief historical overview: toward LHC

1964: First formulation of Higgs mechanism (P.W.Higgs)

1967: Electroweak unification, with W, Z and H (Glashow, Weinberg, Salam)

1973: Discovery of neutral currents in ν_μe scattering (Gargamelle, CERN)



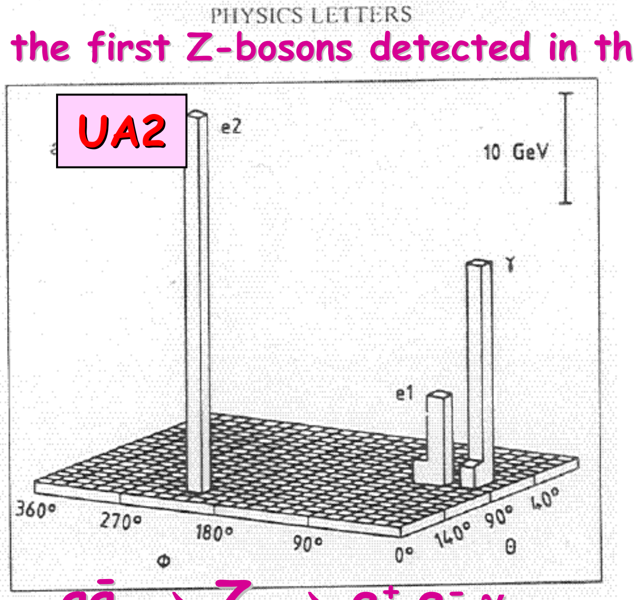
1974: Complete formulation of the standard model with $SU(2)_W \times U(1)_Y$ (Iliopoulos)

1981: The CERN SpS becomes a proton-antiproton collider

LEP and SLC are approved before W/Z boson discovery

1983: LEP and SLC construction starts W and Z discovery (UA1, UA2)

One of the first Z-bosons detected in the world



$q\bar{q} \to Z \to e^+ e^- \gamma$

A brief historical overwiew: toward LHC

1984: Glimmerings of LHC and SSC

1987: First comparative studies of physics potential of hadron colliders (LHC/SSC) and e^+e^- linear colliders (CLIC)

1989: First collisions in LEP and SLC
Precision tests of the SM and search for the Higgs boson begin in earnest
R&D for LHC detectors begins

1993: Demise of the SSC

1994: LHC machine is approved (start in 2005)

1995: Discovery of the top quark at Fermilab by CDF (and D0)
Precision tests of the SM and search for the Higgs boson continue at LEP2

Approval of ATLAS and CMS

2000: End of LEP running

2001: LHC schedule delayed by two more years

During the last 15 years, three parallel activities have been ongoing, all with impressive results:

1) Physics at LEP with a wonderful machine
2) Construction of the LHC machine
3) Construction of the LHC detectors after an initial very long R&D period

LHC

- pp machine (mainly):

$\sqrt{s}$ = 14 TeV   7 times higher than present highest energy machine (Tevatron/Fermilab: $\sqrt{s}$ = 2 TeV)

→ search for new massive particles up to m ~ 5 TeV

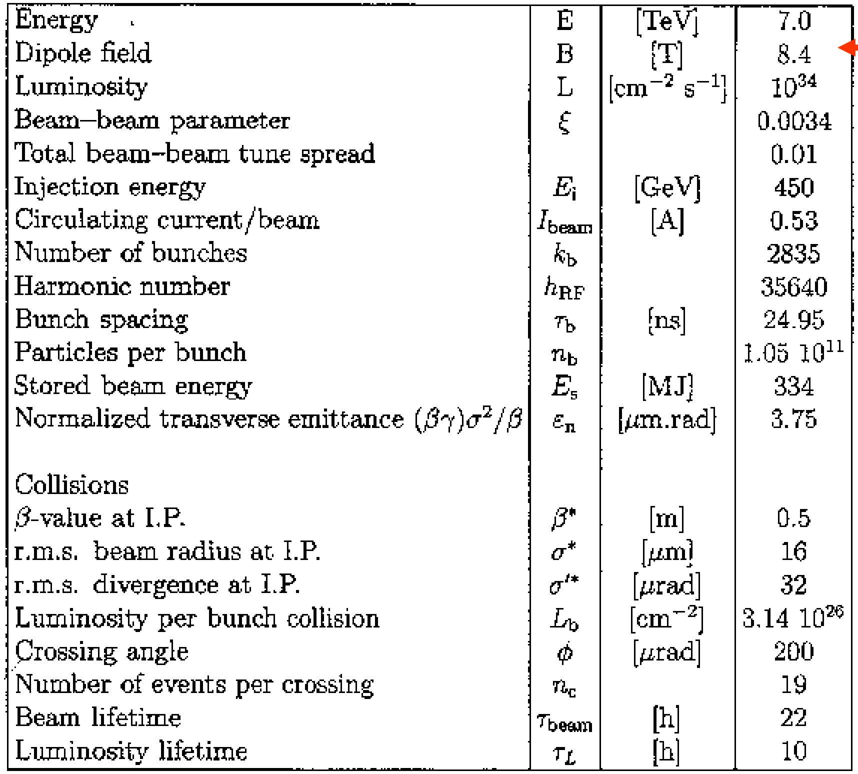
Note : $\sqrt{s}$ limited by needed bending power.
LHC : 1232 superconducting dipoles with B = 8.4 T
working at 1.9 Kelvin (biggest cryogenic system in the world)

$$L \propto \frac{N_1 \; N_2}{\delta x \; \delta y} = 10^{34}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$$

~ 10^3 larger than LEP2, Tevatron

→ search for rare processes with small σ ($N = L\sigma$)

A few machine parameters



Energy	E	[TeV]	7.0
Dipole field	B	[T]	8.4
Luminosity	L	$[\mathrm{cm}^{-2}\ \mathrm{s}^{-1}]$	10^{34}
Beam–beam parameter	ξ		0.0034
Total beam–beam tune spread			0.01
Injection energy	E_i	[GeV]	450
Circulating current/beam	I_{beam}	[A]	0.53
Number of bunches	k_b		2835
Harmonic number	h_{RF}		35640
Bunch spacing	τ_b	[ns]	24.95
Particles per bunch	n_b		$1.05\ 10^{11}$
Stored beam energy	E_s	[MJ]	334
Normalized transverse emittance $(\beta\gamma)\sigma^2/\beta$	ε_n	$[\mu\mathrm{m.rad}]$	3.75
Collisions			
β-value at I.P.	β^*	[m]	0.5
r.m.s. beam radius at I.P.	σ^*	$[\mu\mathrm{m}]$	16
r.m.s. divergence at I.P.	σ'^*	$[\mu\mathrm{rad}]$	32
Luminosity per bunch collision	L_b	$[\mathrm{cm}^{-2}]$	$3.14\ 10^{26}$
Crossing angle	ϕ	$[\mu\mathrm{rad}]$	200
Number of events per crossing	n_c		19
Beam lifetime	τ_{beam}	[h]	22
Luminosity lifetime	τ_L	[h]	10

Limiting factor for √s :
bending power needed to fit ring
in 27 km circumference LEP tunnel:

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

= 7 TeV   = 4.3 km

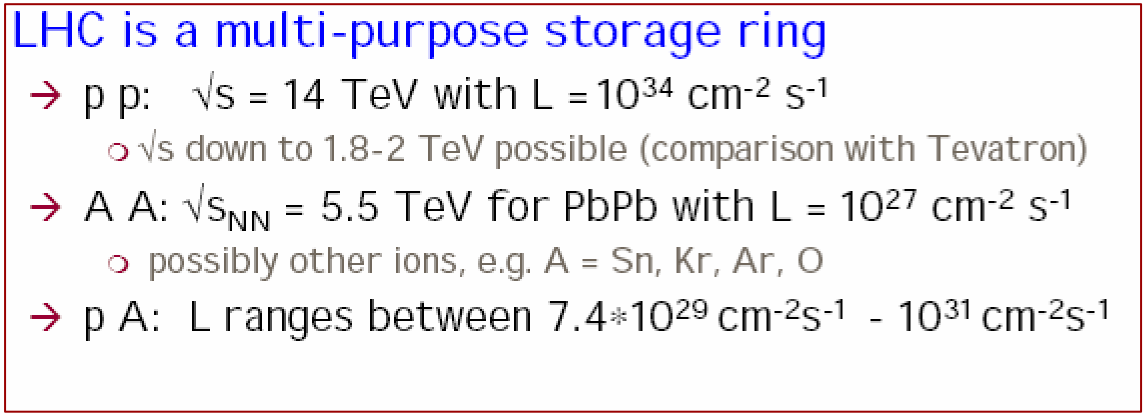
LHC :
B=8.4 T : ~ 1300 superconducting dipoles working at 1.9 K
(biggest cryogenic system in the world)

LHC

- under construction, first beam 10 September 2008
- is being installed in the existing LEP tunnel
- two phases:

  2008 – 20?? : $L \sim 10^{33}\ \mathrm{cm^{-2}\ s^{-1}}$, $\int L dt \approx 10\ \mathrm{fb^{-1}}$ (1 year)
  “low luminosity”
  20?? - 20xx : $L \sim 10^{34}\ \mathrm{cm^{-2}\ s^{-1}}$, $\int L dt \approx 100\ \mathrm{fb^{-1}}$ (1 year)
  “high luminosity
  ultimate: 300 $\mathrm{fb^{-1}}$

•RND for Super LHC already started



LHC is a multi-purpose storage ring

→ p p: $\sqrt{s} = 14$ TeV with $L = 10^{34}\ \mathrm{cm^{-2}\ s^{-1}}$
  - $\sqrt{s}$ down to 1.8-2 TeV possible (comparison with Tevatron)

→ A A: $\sqrt{s_{NN}} = 5.5$ TeV for PbPb with $L = 10^{27}\ \mathrm{cm^{-2}\ s^{-1}}$
  - possibly other ions, e.g. A = Sn, Kr, Ar, O

→ p A: L ranges between $7.4 * 10^{29}\ \mathrm{cm^{-2}s^{-1}}$ - $10^{31}\ \mathrm{cm^{-2}s^{-1}}$

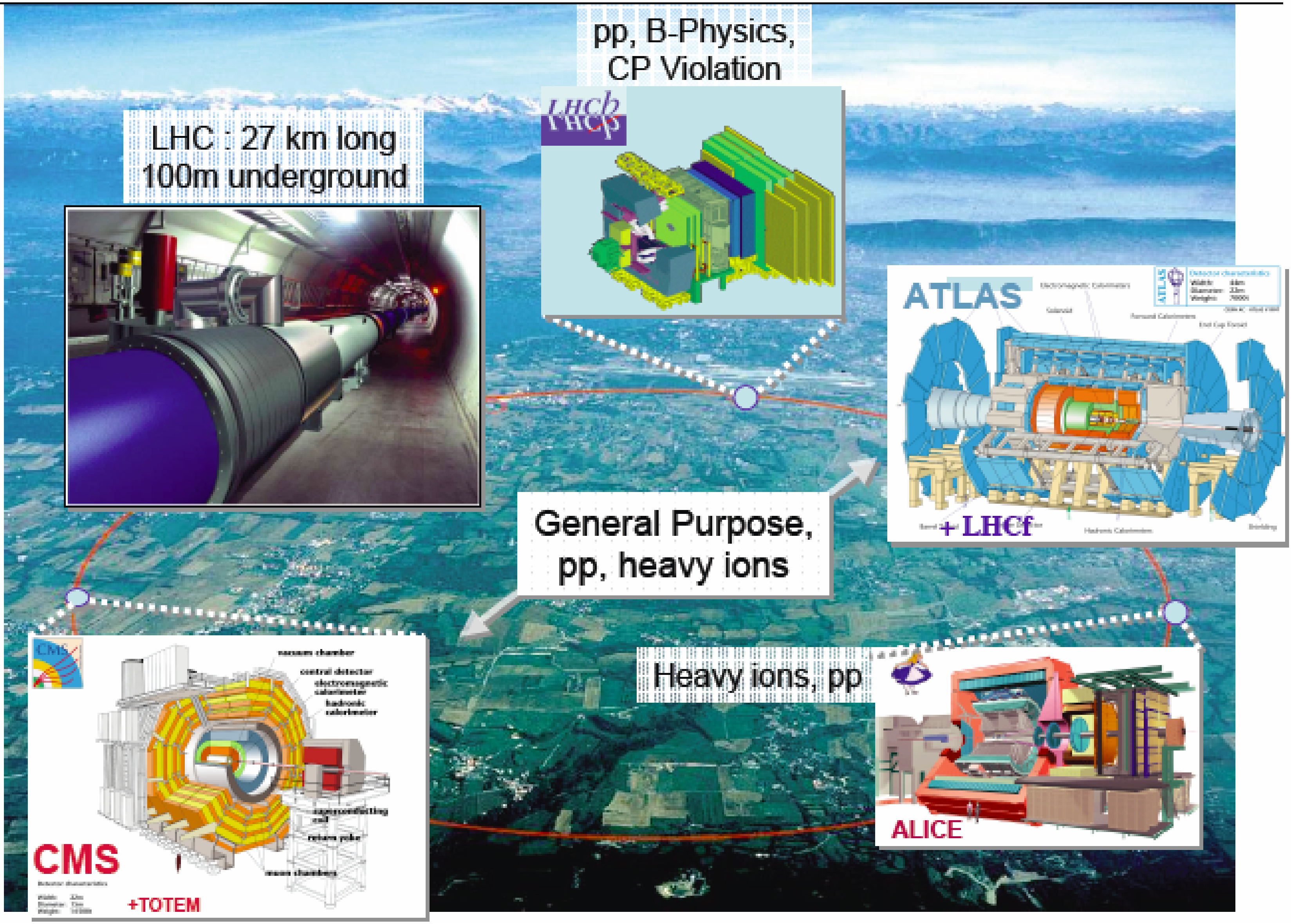
Experiments

Four (six) large-scale experiments:

Cracow IFJ-PAN
-> ATLAS, ALICE, LHCb

ATLAS CMS	general-purpose pp experiments
LHCb	pp experiment dedicated to b-quark physics and CP violation
ALICE	heavy-ion experiment (Pb-Pb collisions) at 5.5 TeV/nucleon → $\sqrt{s} \cong 1000$ TeV Quark-gluon plasma studies.
TOTEM (in CMS cavern)	Total Cross-Section, Elastic Scattering and Diffraction Dissociation

Large Hadron Collider@CERN



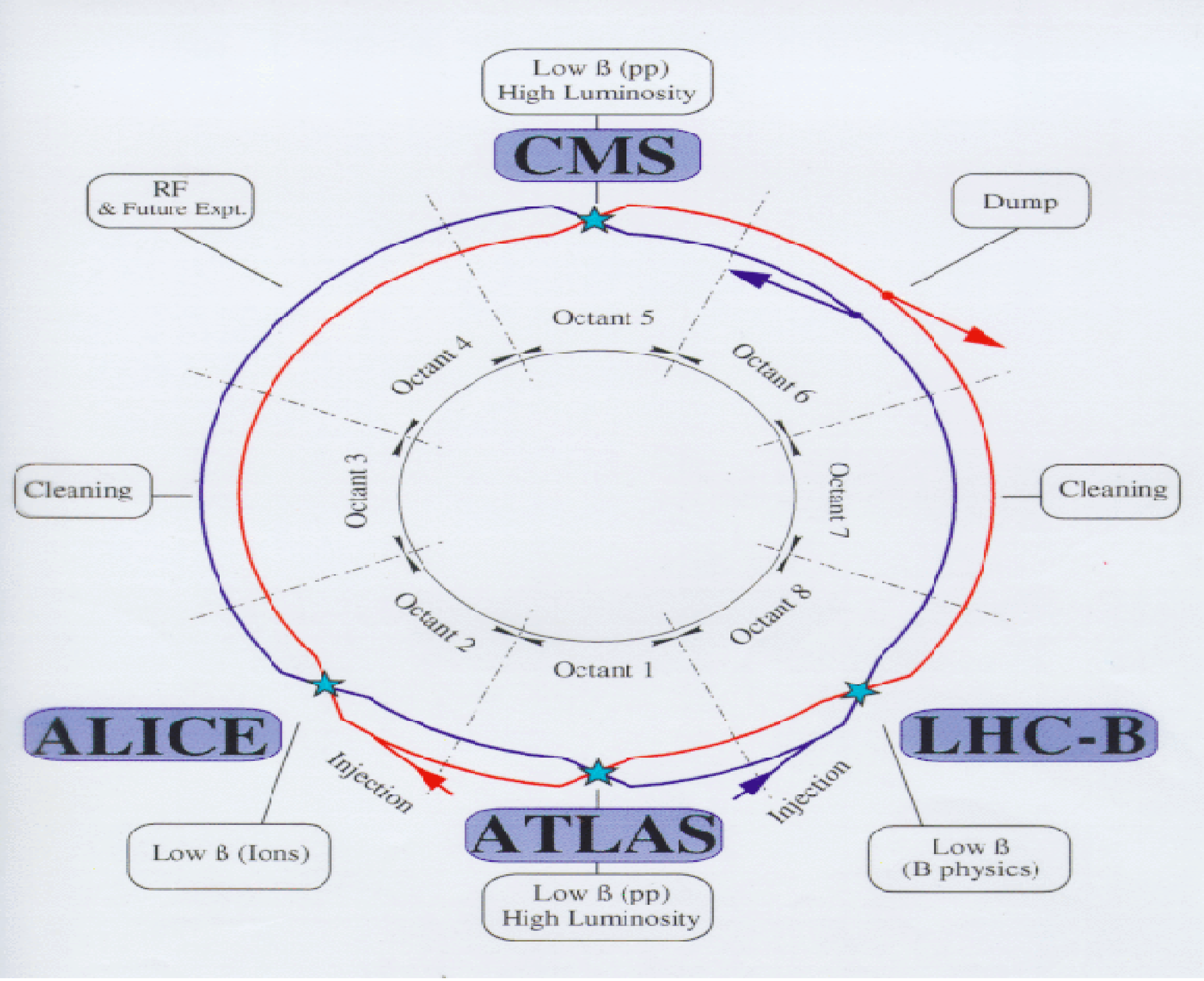
pp, B-Physics,
CP Violation

LHC : 27 km long
100m underground

General Purpose,
pp, heavy ions

Heavy ions, pp

Experiments



LHC is an unprecedented machine

- Energy

- Luminosity

- Cost : > 4000 MCHF (machine + experiments)

- Size/complexity of experiments :
  ~ 1.3-2 times bigger than present collider experiments
  ~ 10 times more complex

- Human resources : > 4000 physicists in the experiments

WHY ?

Motivations for LHC

Motivation 1 : Origin of particle masses

Standard Model of electroweak interactions verified with precision 10^{-3} - 10^{-4} by measurements at LEP at $\sqrt{s} \geq m_Z$ and at the Tevatron at $\sqrt{s} = 1.8$ TeV

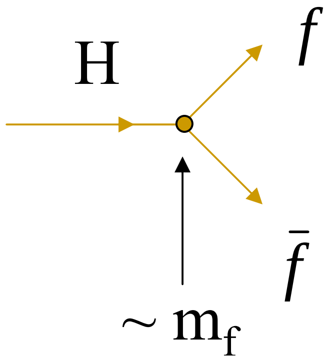
discovery of top quark in '94,
$m_{top} \cong 174$ GeV

However: origin of particle masses not known.

Ex. : $m_\gamma = 0$
$m_{W,Z} \approx 100$ GeV

Motivation for LHC

SM : Higgs mechanism gives mass to particles
(Electroweak Symmetry Breaking)



$m_H < 1$ TeV from theory

However:

-- Higgs not found yet: only missing (and essential) piece of SM
-- present limit : $m_H > 114.4$ GeV (from LEP)
-- Tevatron may go beyond (depending on luminosity)

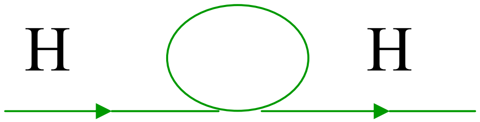
$\Rightarrow$ need a machine to discover/exclude

Higgs from ≈ 115 GeV to 1 TeV

Motivation for LHC

Motivation 2 : Is SM the "ultimate theory" ?

- Higgs mechanism is the weakest part of the SM:
  - -- "ad hoc" mechanism
  - -- due to radiative corrections



Λ : energy scale up to which SM is valid (can be very large).

$\Delta m_H^2 \sim \Lambda^2$

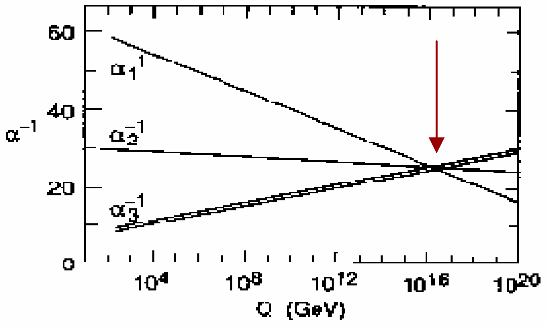
$\Rightarrow$ radiative corrections can be very large ("unnatural")
and Higgs mass can diverge unless "fine-tuned"
cancellations → " bad behaviour " of the theory

Motivation for LHC

Motivation 2 : Is SM the "ultimate theory" ?

•Hints that forces could unify at high energy

$$\left.\begin{array}{l}\alpha_{EM} \equiv \alpha_1 \approx 1/128 \approx 0.008 \\ \alpha_{WEAK} \equiv \alpha_2 \approx 0.03 \\ \alpha_S \equiv \alpha_3 \approx 0.12\end{array}\right\} \quad \sqrt{s} = 100 \text{ GeV}$$



- E-dependence of coupling constants proven experimentally
- Grand Unified Theories: EM/Weak/Strong forces unify at E ~ 10^{16} → beyond physics become simple (one force with strength α_G)

Motivation for LHC

- SM is probably low-energy approximation of a more general theory

- Need a high-energy machine to look for manifestations of this theory

- e.g. Supersymmetry : $m_{SUSY} \sim$ TeV
  Many other theories predict New Physics at the TeV scale

Motivation for LHC

Motivation 3 : Many other open questions

- Are quarks and leptons really elementary ?
- Why 3 fermion families ?
- Are there additional families of (heavy) quarks and leptons ?
- Are there additional gauge bosons ?
- What is the origin of matter-antimatter asymmetry in the universe ?
- Can quarks and gluons be deconfined in a quark-gluon plasma as in early stage of universe ?
- …. etc. …...

Motivation for LHC

Motivation 4 : The most fascinating one …

Unexpected physics ?

Motivation 5 : Precise measurements

Two ways to find new physics:

-- discover new particles/phenomena

-- measure properties of known particles
as precisely as possible ⇒ find deviations
from SM

Motivation for LHC

LHC: known particles (W, Z, b, top, …) produced with enormous rates thanks to high energy (→ high σ) and L (→ high rate)

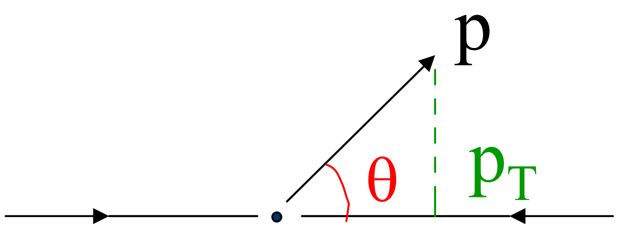
Ex. : 1 year at low luminosity

$5\ 10^8$ $W \to l\nu$
$5\ 10^7$ $Z \to ll$
10^7 tt pairs
10^{12} bb pairs

→ many precision measurements possible thanks to large statistics (stat. error ~ $1/\sqrt{N}$)

Note : measurements of Z parameters performed at LEP and SLD, however precision can be improved for :
-- W physics
-- Triple Gauge Couplings WWγ, WWZ
-- b-quark physics
-- top-quark physics

Phenomenology of pp collisions



Transverse momentum

(in the plane perpendicular to the beam) :

$p_T = p \sin\theta$

Rapidity: $\eta = -\log\left(\mathrm{tg}\,\frac{\theta}{2}\right)$

$\theta = 90^o \rightarrow \eta = 0$
$\theta = 10^o \rightarrow \eta \cong 2.4$
$\theta = 170^o \rightarrow \eta \cong -2.4$

Total inelastic cross-section:

$\sigma_{tot}(pp) = 70$ mb $\sqrt{s} = 14$ TeV

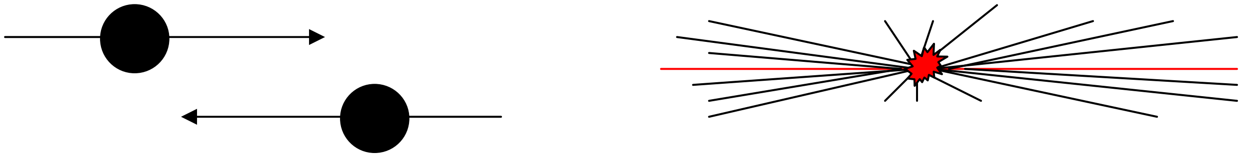
Rate = $\frac{\text{n. events}}{\text{second}} = L \times \sigma_{tot}(pp) = 10^9$ interactions/s

10^{34} cm^{-2} s^{-1}

Phenomenology of pp collisions

Class 1:

Most interactions due to collisions at large distance between incoming protons where protons interact as " a whole " → small momentum transfer ($\Delta p \approx 1/\Delta x$) → particles in final state have large longitudinal momentum but small transverse momentum (scattering at large angle is small)



$< p_T > \approx$ 500 MeV of charged particles in final state

charged particles uniformly distributed in ϕ

$$\frac{dN}{d\eta} \approx 7$$

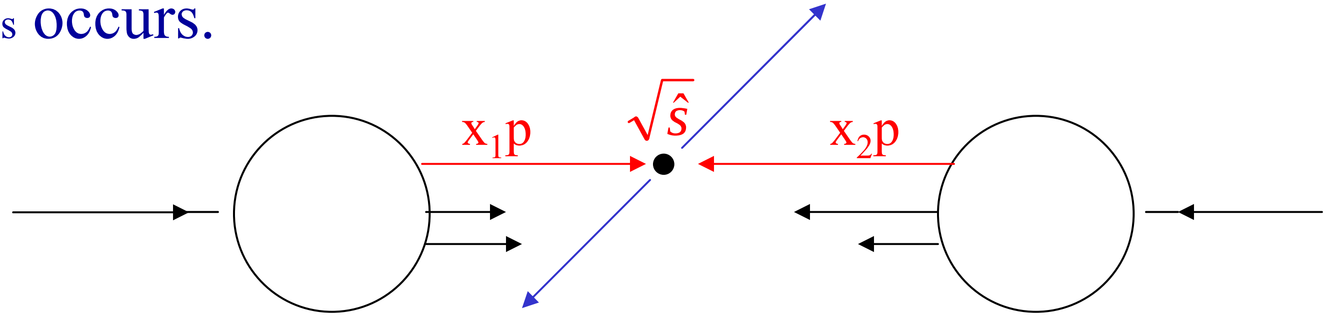
Most energy escapes down the beam pipe.

These are called minimum-bias events (" soft " events).
They are the large majority but are not very interesting.

Phenomenology of pp collisions

Class 2:

Monochromatic proton beam can be seen as beam of quarks and gluons with a wide band of energy. Occasionally hard scattering (“ head on”) between constituents of incoming protons **occurs.**



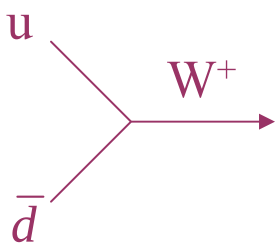
p ≡ momentum of incoming protons = 7 TeV

Interactions at small distance → large momentum transfer → massive particles and/or particles at large angle are produced.

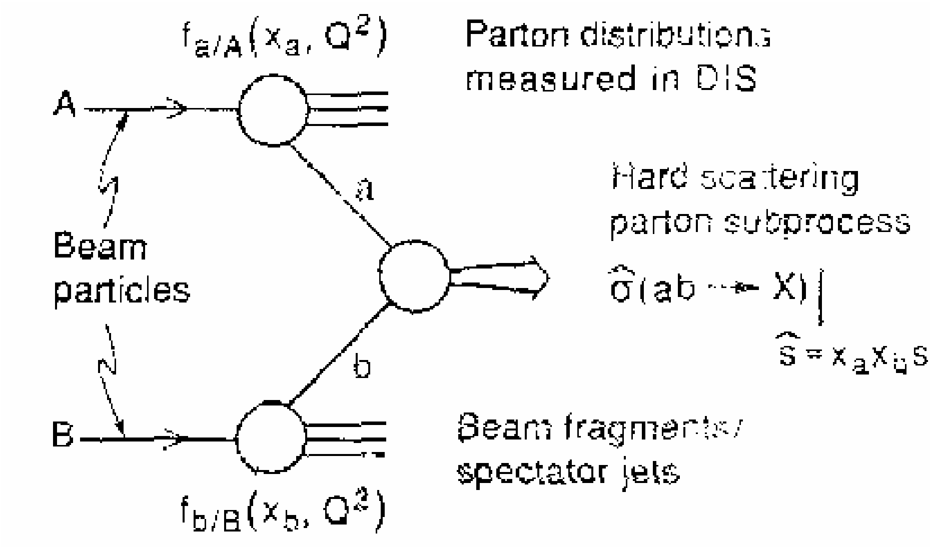
These are interesting physics events but they are rare.

Ex. $u + \bar{d} \rightarrow W^+$

$\sigma\,(pp \rightarrow W) \approx 150\text{ nb} \approx 10^{-6}\,\sigma_{tot}\,(pp)$



Unlike at e^+e^- colliders



- effective centre-of-mass energy $\sqrt{\hat{s}}$ smaller than $\sqrt{s}$ of colliding beams:

→ to produce m ≈ 100 GeV $x \sim 0.01$
to produce m ≈ 5 TeV $x \sim 0.35$

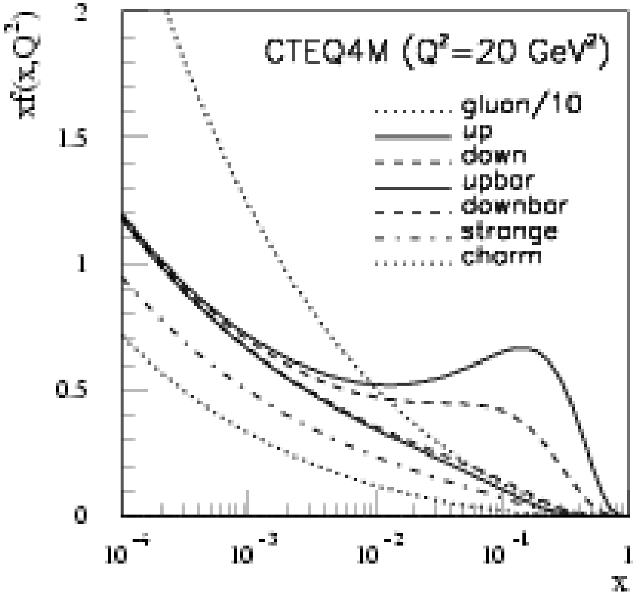
$$\left.\begin{aligned} \vec{p}_a &= x_a \vec{p}_A \\ \vec{p}_b &= x_b \vec{p}_B \end{aligned}\right\} \quad p_A = p_B = 7\ \text{TeV} \qquad \sqrt{\hat{s}} = \sqrt{x_a x_b s} \approx x\sqrt{s}$$

if $x_a \approx x_b$

Unlike at e+e$^-$ colliders

•cross-section :

$$\sigma = \sum_{a,b} \int dx_a \, dx_b \, f_a(x_a, Q^2) \, f_b(x_b, Q^2) \, \hat{\sigma}_{ab}(x_a, x_b)$$



$\hat{\sigma}_{ab}$ ≡ hard scattering cross-section

$f_i(x, Q^2)$ ≡ parton distribution function

p ≡ uud

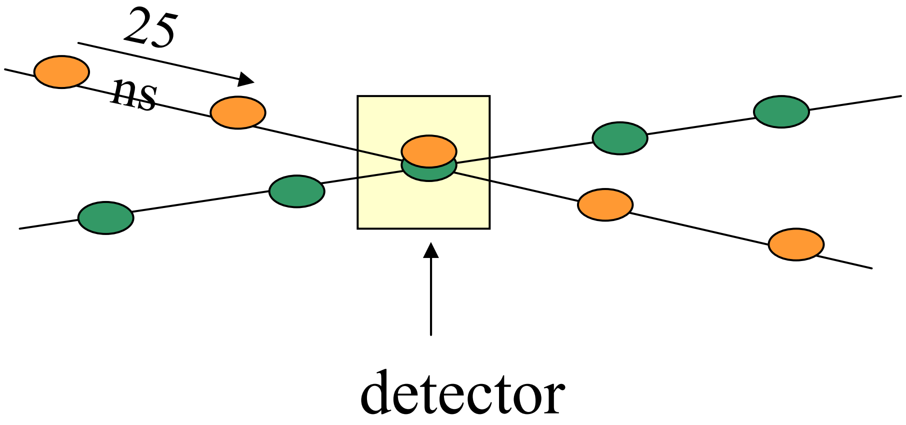
Two main difficulties: pile-up

Typical of LHC:

$R = L\sigma = 10^9$ interactions / second

Protons are grouped in bunches (of $\approx 10^{11}$ protons)

colliding at interaction points every 25 ns



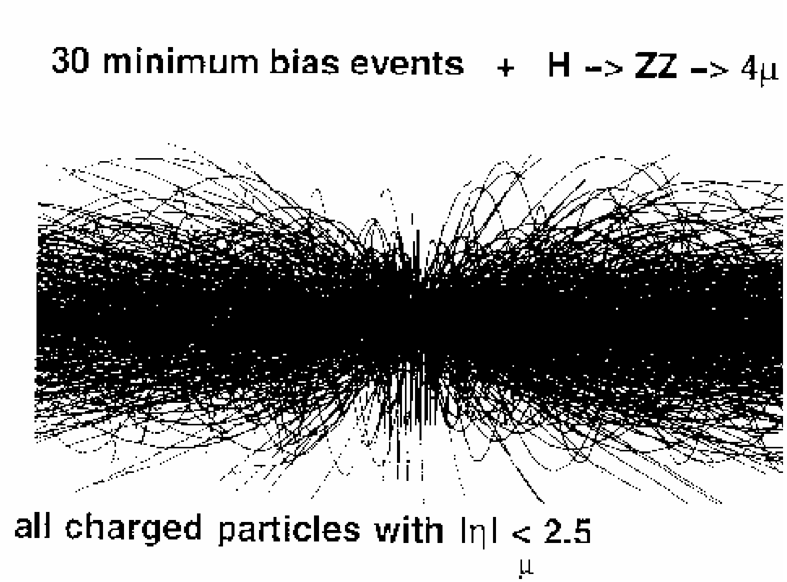
⇒ At each interaction on average $\approx$ 25 minimum-bias events are produced. These overlap with interesting (high p_T) physics events, giving rise to so-called pile-up

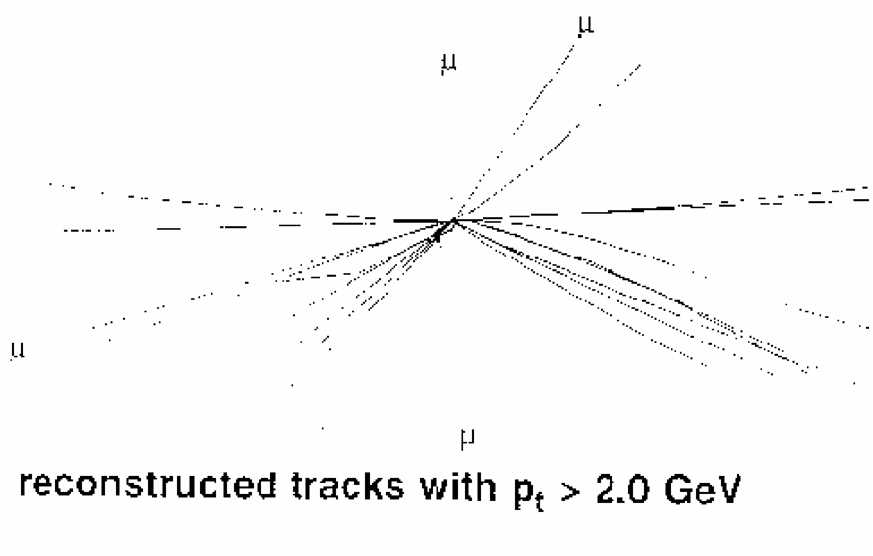
~1000 charged particles produced over $|\eta| < 2.5$ at each crossing. However $< p_T > \approx 500$ MeV (particles from minimum-bias).

→ applying p_T cut allows extraction of interesting particles

Two main difficulties: pile-up

$H \to ZZ \to 4\mu$





Two main difficulties: pile-up

Pile-up is one of the most serious experimental difficulty at LHC.

Large impact on detector design:

- LHC detectors must have fast response, otherwise integrate over many bunch crossings → too large pile-up

  Typical response time : 20-50 ns

  → integrate over 1-2 bunch crossings → pile-up of 25-50 minimum bias

  ⇒ very challenging readout electronics

- LHC detectors must be highly granular to minimise probability that pile-up particles be in the same detector element as interesting object (e.g. γ from $H \to \gamma\gamma$ decays)

  → large number of electronic channels

  ⇒ high cost

- LHC detectors must be radiation resistant: high flux of particles from pp collisions → high radiation environment

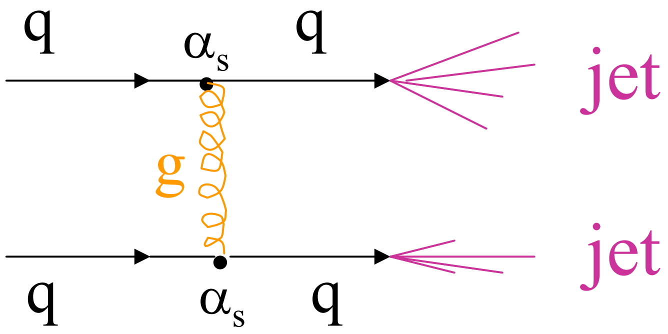
E.g. in forward calorimeters: up to 10^{17} n / cm^2
(10 years of LHC operation) up to 10^7 Gy

Note : 1 Gy =
unit of absorbed energy =
1 Joule/Kg

Two main difficulties: QCD background

Common to all hadron colliders:

high-p_T events dominated by QCD jet production



- Strong production → large cross-section
- Many diagrams contribute: qq → qq, qg → qg, gg → gg, etc.
- Called " QCD background "

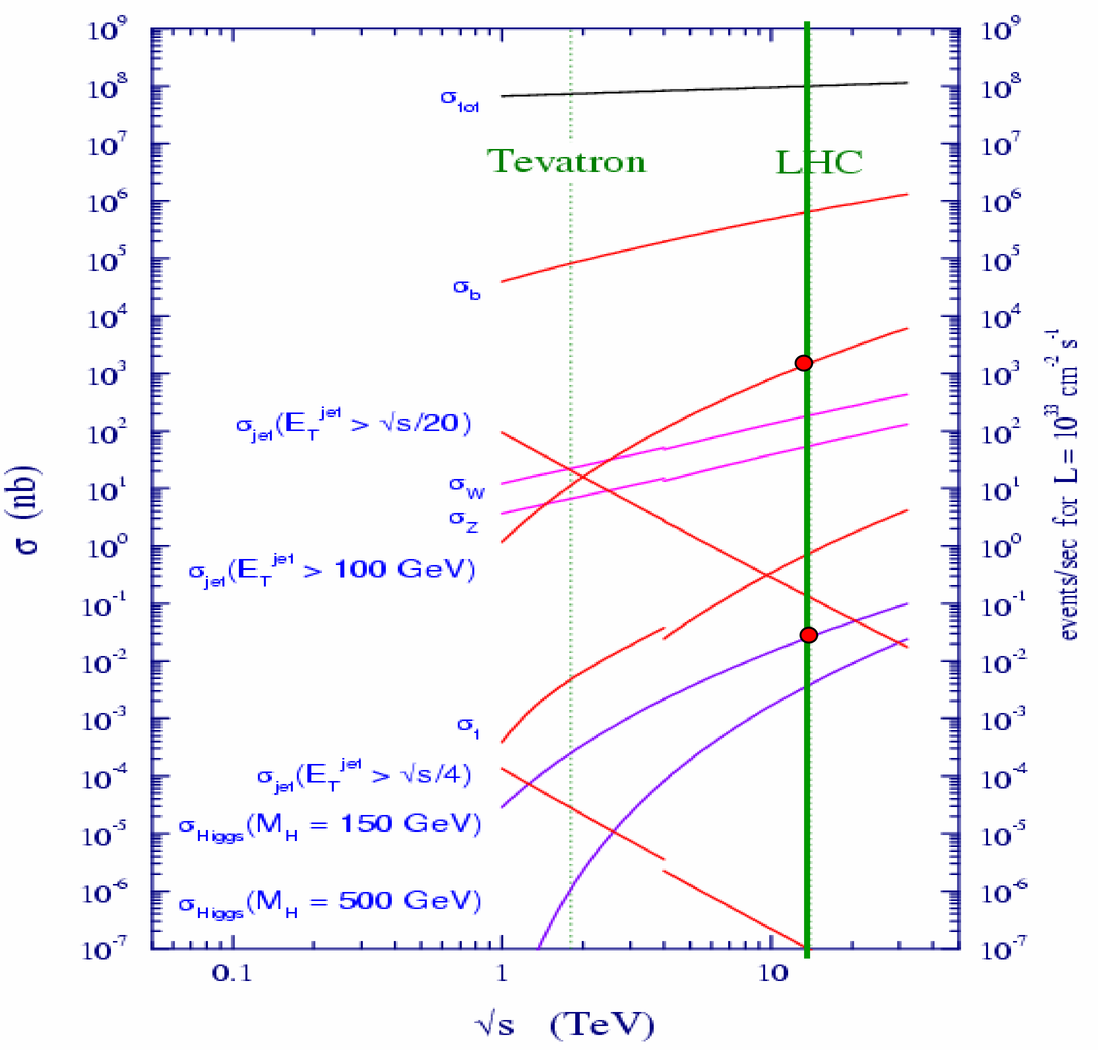
Most interesting are rare processes:

- involve heavy particles
- weak-force mediated production mechanisms (e.g. W production)

Proton - (anti) proton cross-section

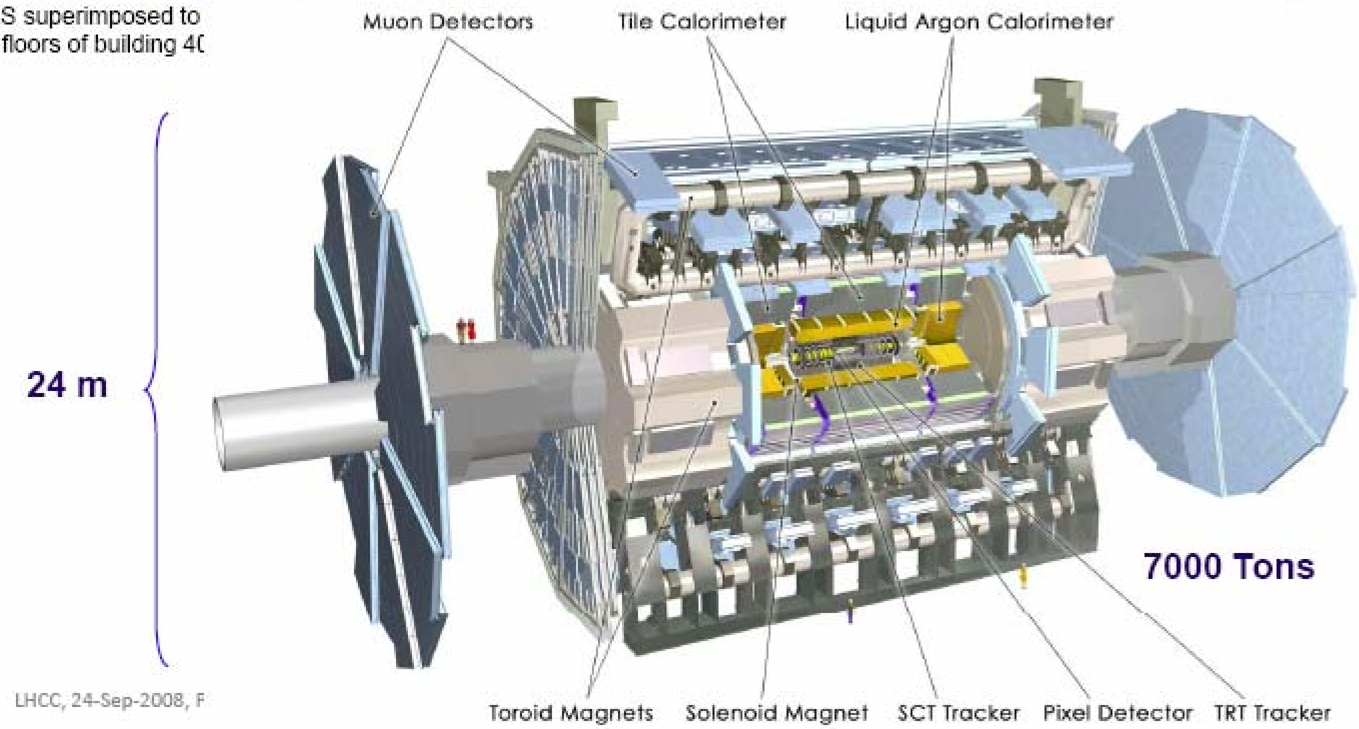
To extract signal over QCD jet background must look at decays to photons and leptons
→ pay a prize in branching ratio

Ex. BR (W → jet jet) ≈ 70%
BR (W → lν) ≈ 30%



ATLAS Detector

ATLAS superimposed to the 5 floors of building 4



LHCC, 24-Sep-2008, F

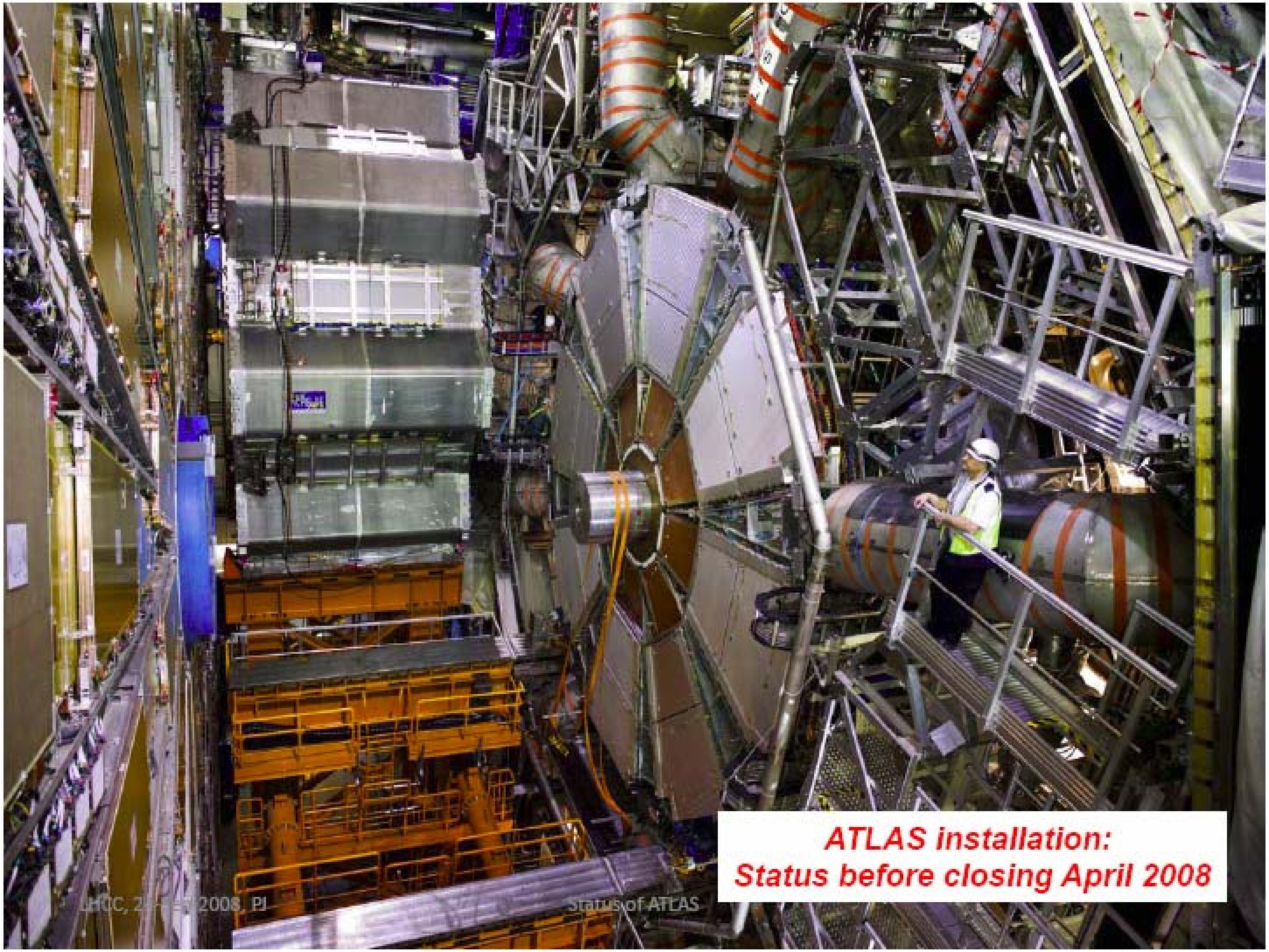
Status of construction

2006

2004

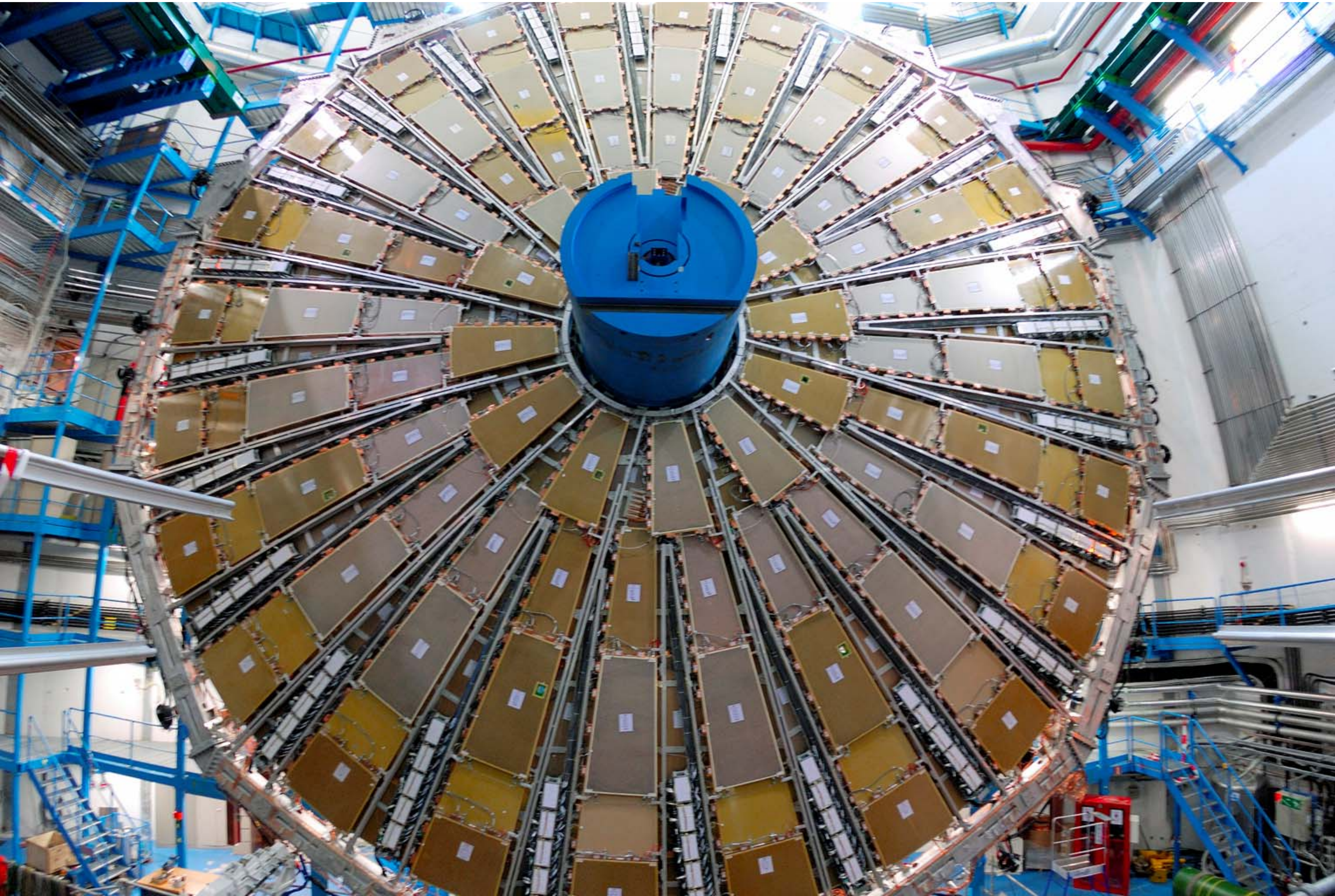
ATLAS cavern

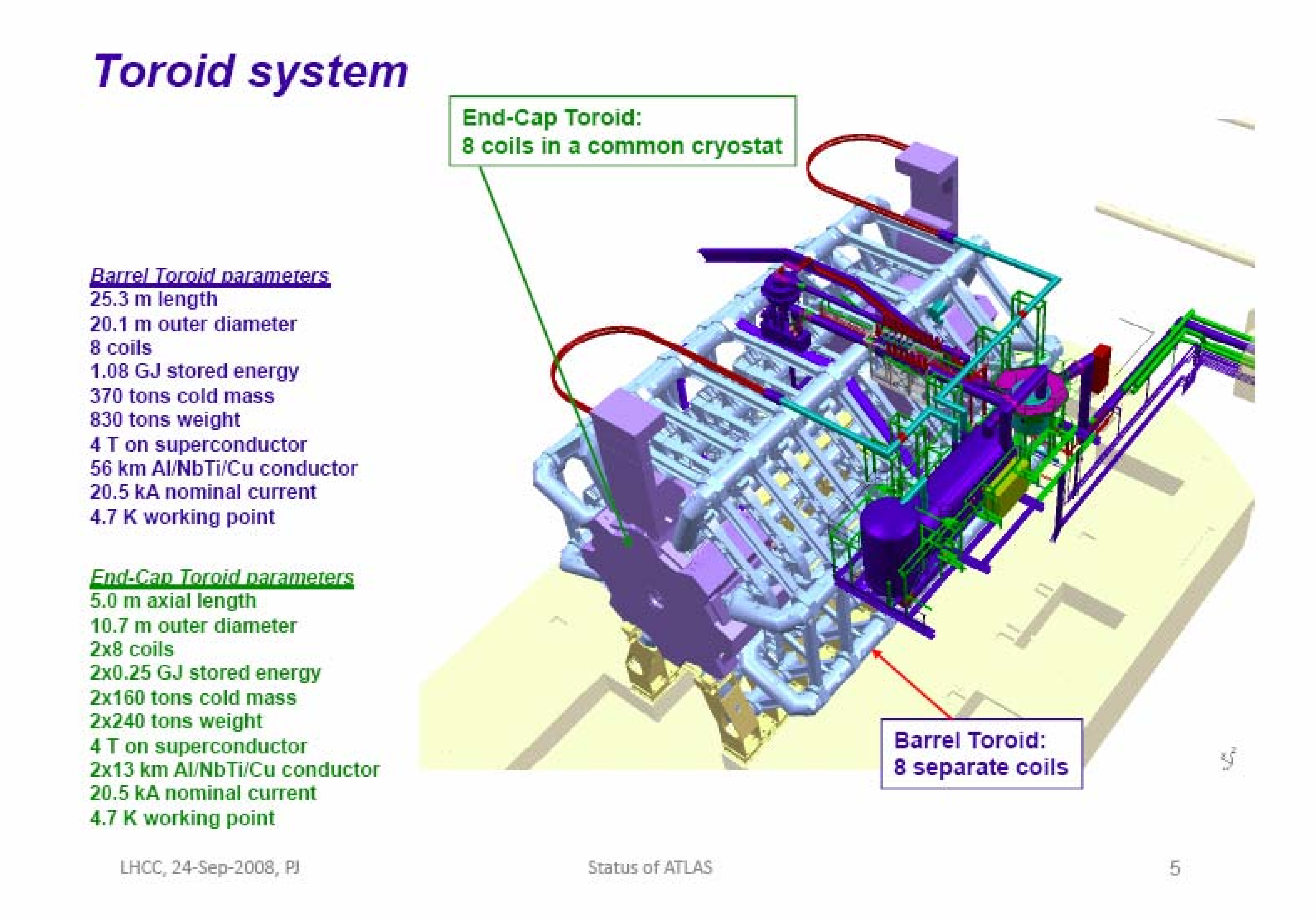
Barrel calorimeter
(EM liquid-argon + HAD Fe/scintillator Tilecal)
in final position at Z=0. Barrel cryostat cold and
filled with Ar.



ATLAS installation:
Status before closing April 2008

One more view of the first installed TGC Big Wheel





Toroid system

End-Cap Toroid:
8 coils in a common cryostat

Barrel Toroid:
8 separate coils

Barrel Toroid parameters

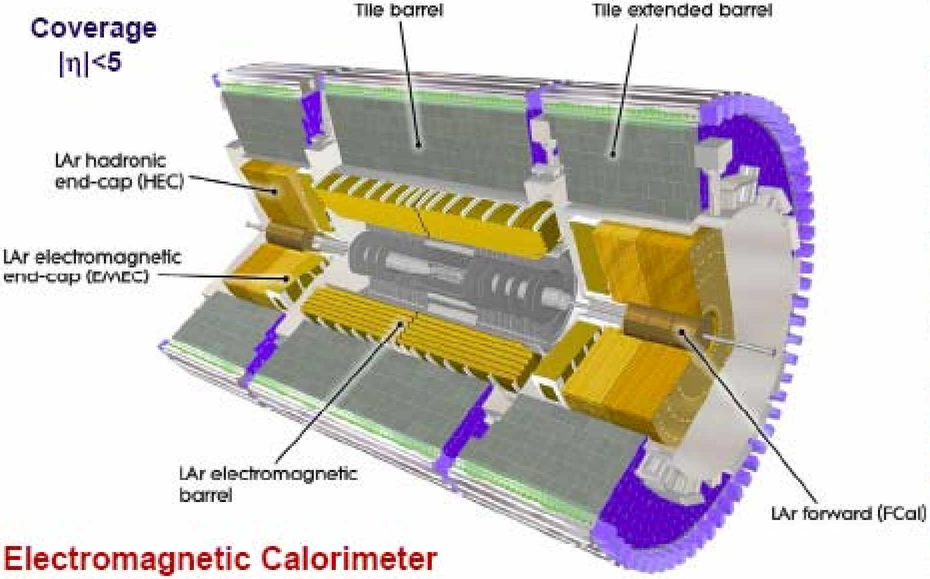
25.3 m length
20.1 m outer diameter
8 coils
1.08 GJ stored energy
370 tons cold mass
830 tons weight
4 T on superconductor
56 km Al/NbTi/Cu conductor
20.5 kA nominal current
4.7 K working point

End-Cap Toroid parameters

5.0 m axial length
10.7 m outer diameter
2x8 coils
2x0.25 GJ stored energy
2x160 tons cold mass
2x240 tons weight
4 T on superconductor
2x13 km Al/NbTi/Cu conductor
20.5 kA nominal current
4.7 K working point

LHCC, 24-Sep-2008, PJ Status of ATLAS 5

Calorimetry



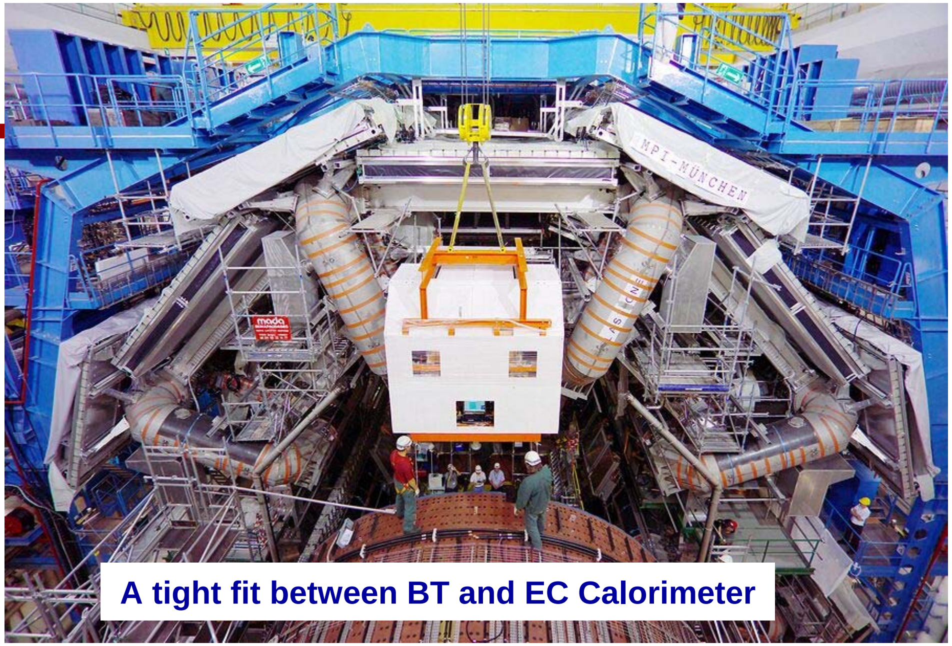
Electromagnetic Calorimeter
barrel, end-cap: Pb-LAr
~10%/√E energy resolution e/γ
180'000 channels: longitudinal segmentation

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

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

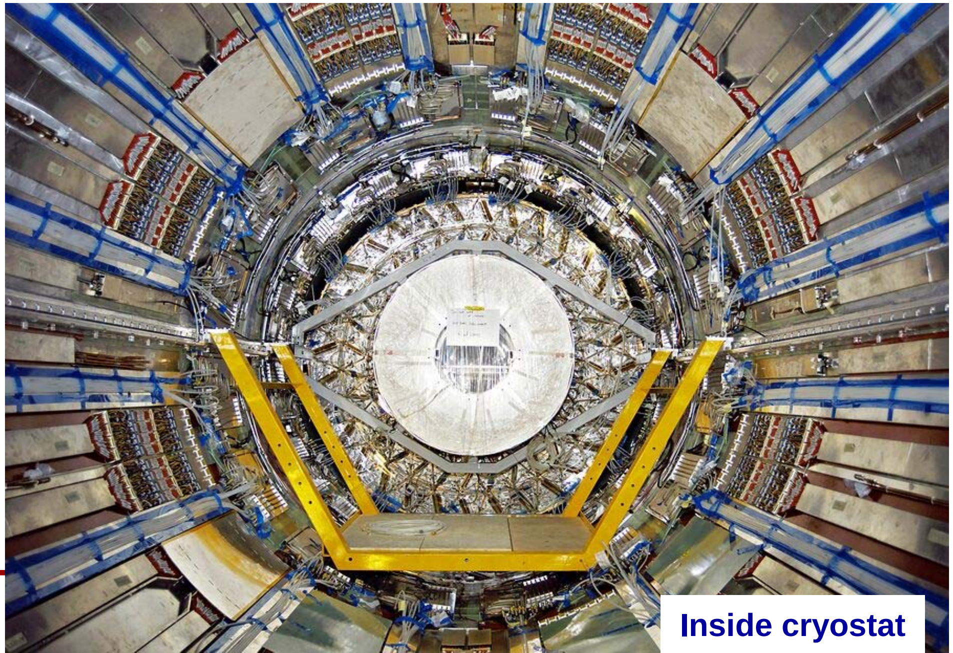
TRT+SCT barrel travelled to the pit, 24th Aug 2006

Through the parking area

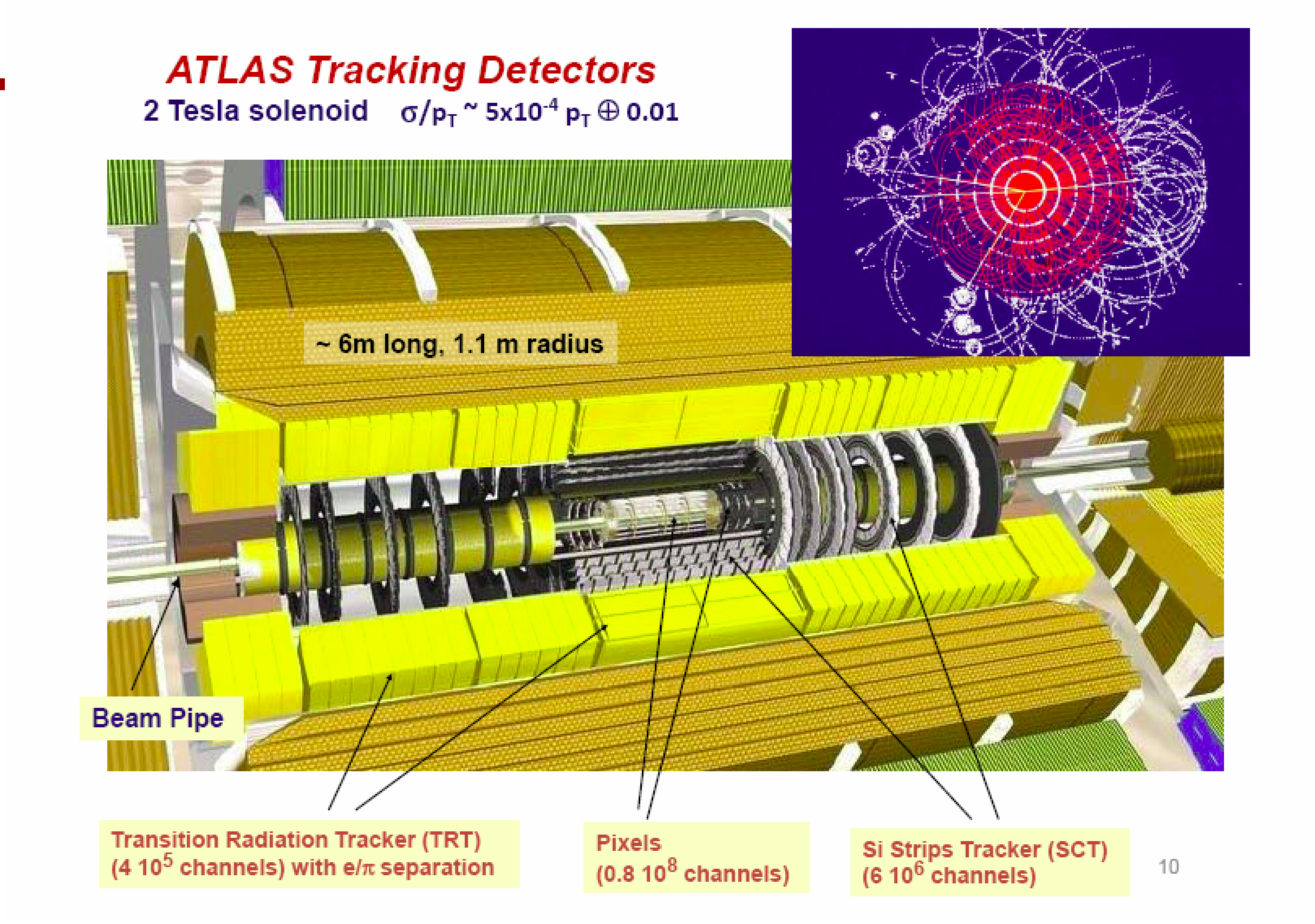


A tight fit between BT and EC Calorimeter

From the trolley to the support rails



Inside cryostat



ATLAS Tracking Detectors

2 Tesla solenoid $\sigma/p_T \sim 5\times10^{-4}\, p_T \oplus 0.01$

~ 6m long, 1.1 m radius

Beam Pipe

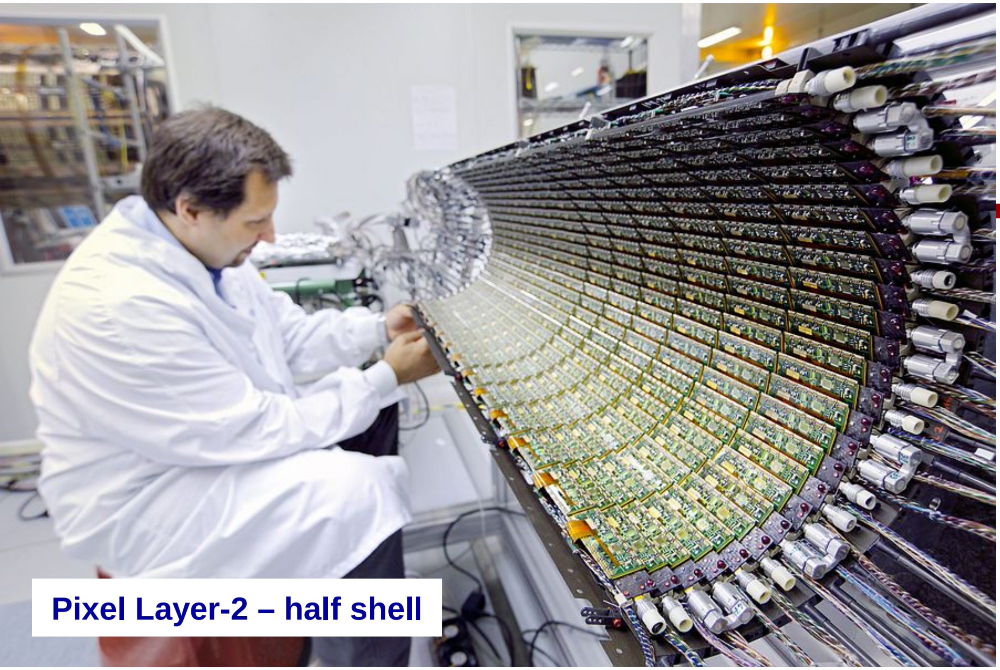
Transition Radiation Tracker (TRT)
($4\ 10^5$ channels) with e/π separation

Pixels
($0.8\ 10^8$ channels)

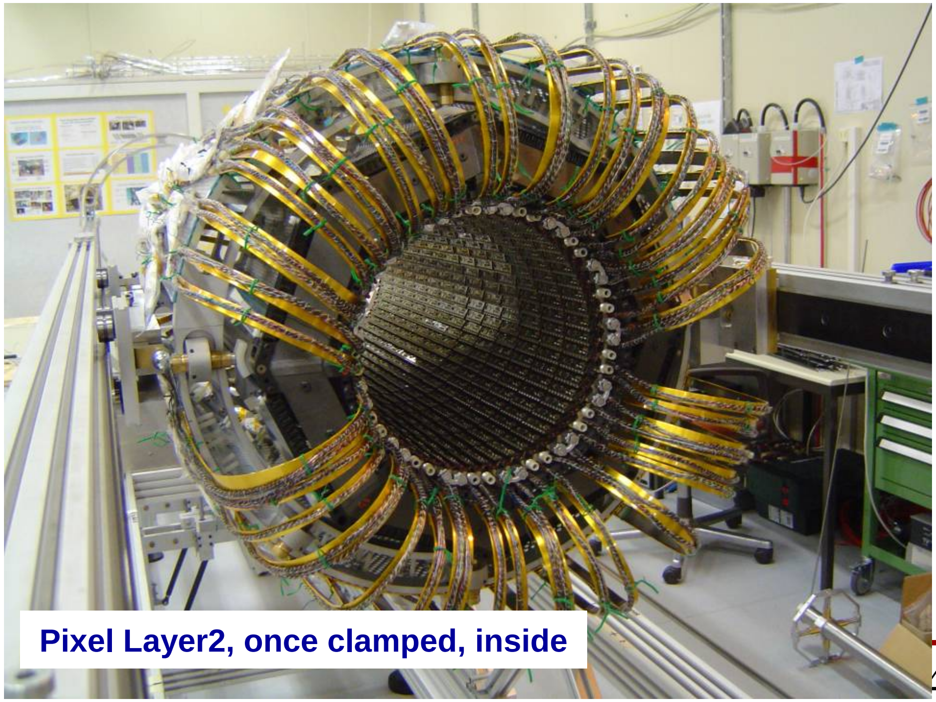
Si Strips Tracker (SCT)
($6\ 10^6$ channels)

10

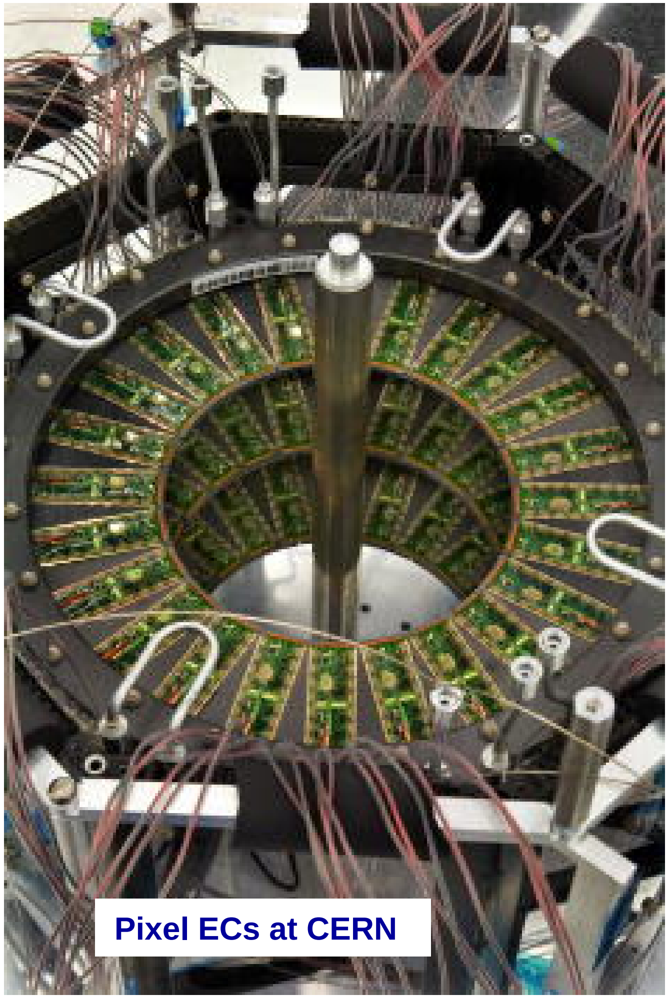
Lot of progress on the Pixels!



Pixel Layer-2 – half shell



Pixel Layer2, once clamped, inside

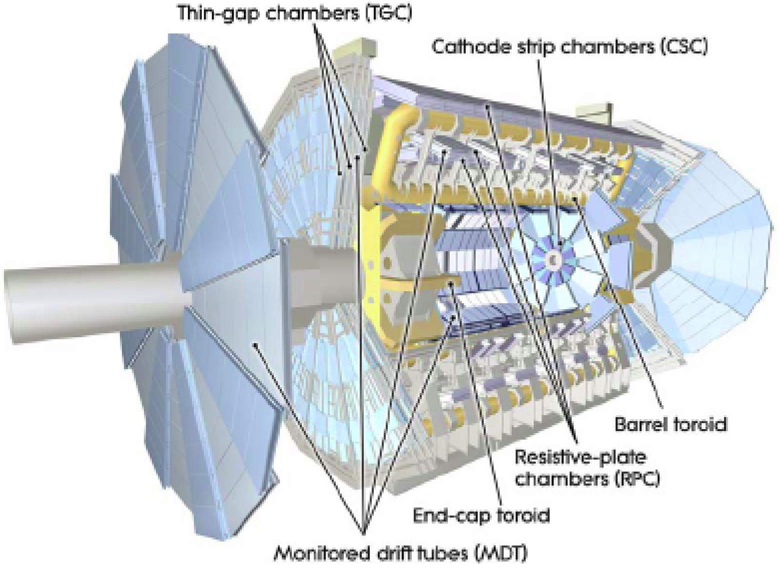


Pixel ECs at CERN

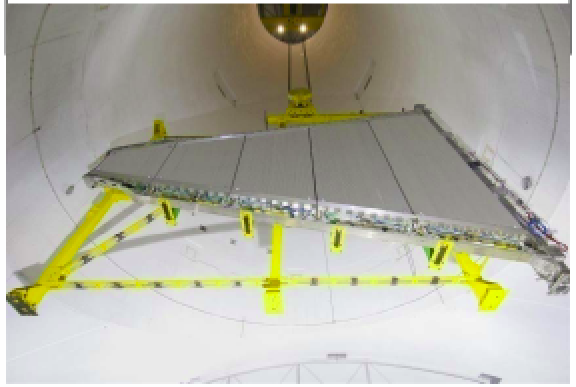
Muon System

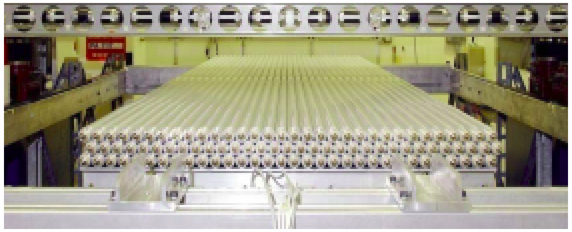
Stand-alone momentum resolution
ΔpT/pT < 10% up to 1 TeV

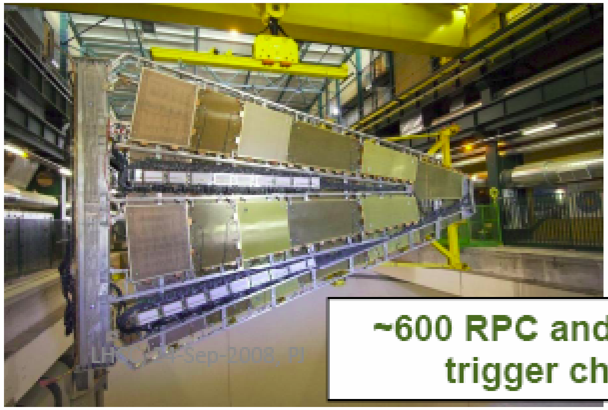
2-6 Tm $|\eta|<1.3$ 4-8 Tm $1.6<|\eta|<2.7$



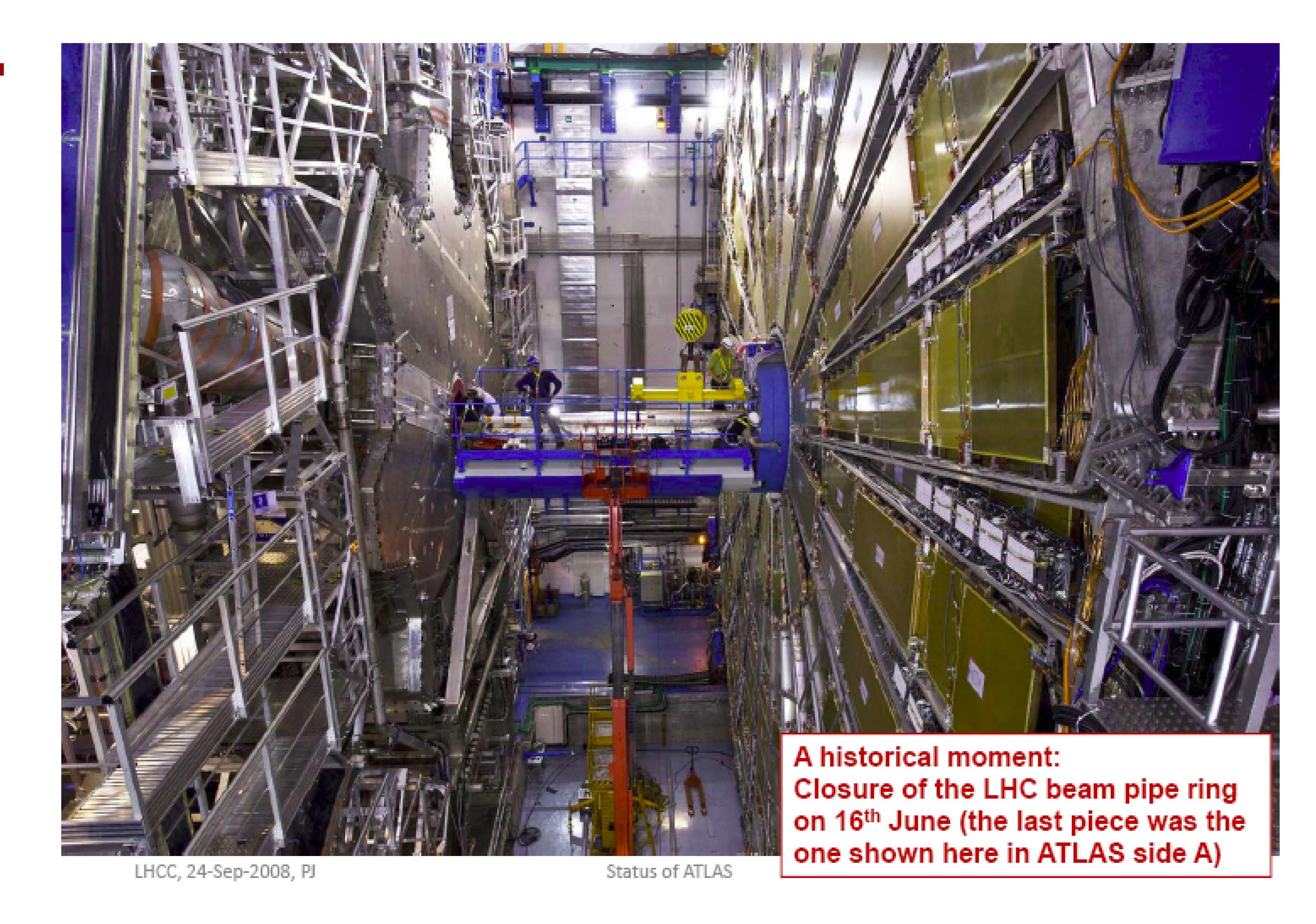
~1200 MDT precision chambers for track







~600 RPC and ~3600 TGC trigger chambers

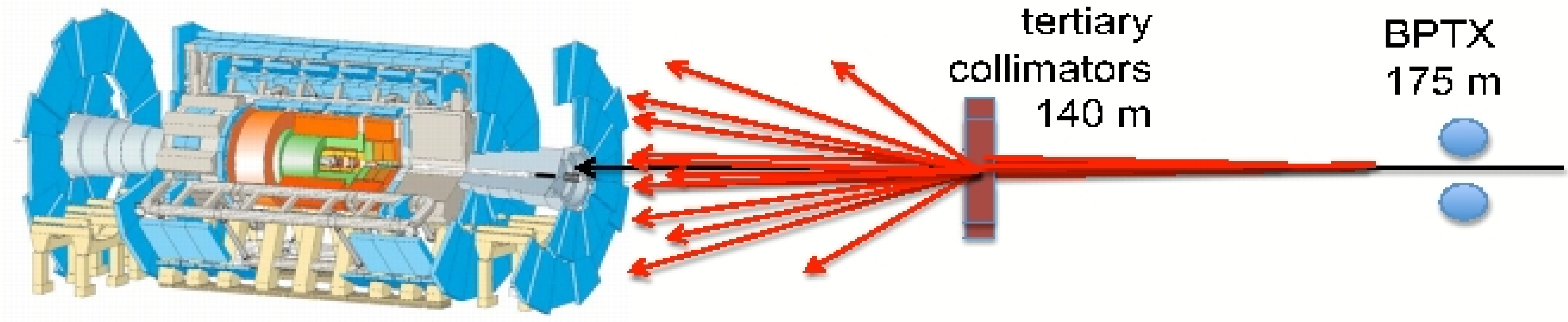


A historical moment:
Closure of the LHC beam pipe ring on 16th June (the last piece was the one shown here in ATLAS side A)

LHCC, 24-Sep-2008, PJ

Status of ATLAS

Going into beam op. Sep 10th

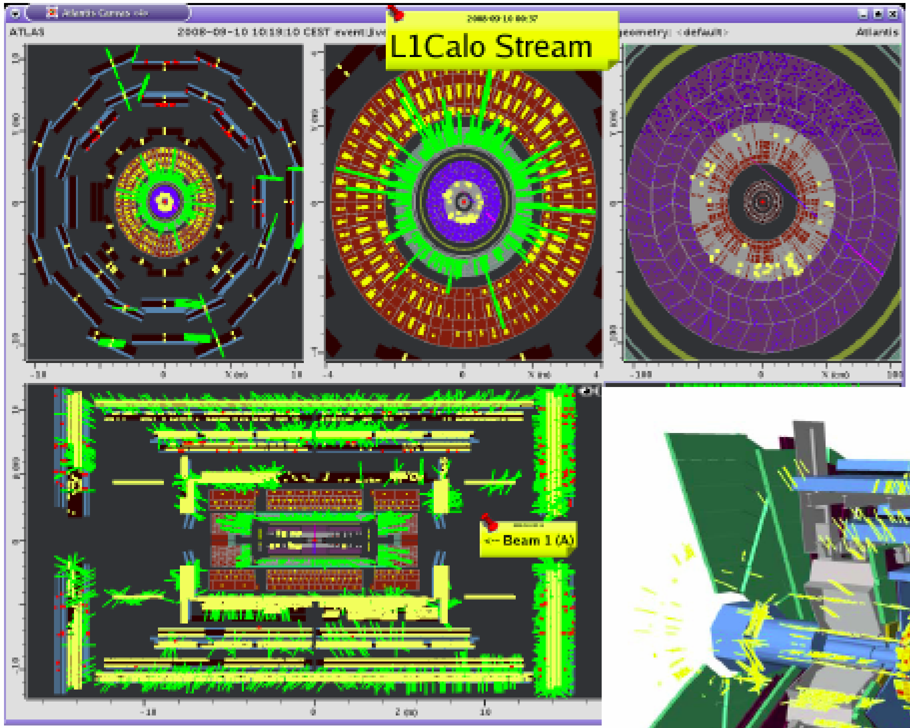


ATLAS was ready for first beam:

- Muon system (MDT, RPC, TGC) on at reduced HV
- LAr (-FCAL HV), Tile on
- TRT on, SCT reduced HV, Pixel off
- BCM, LUCID, MinBias Scint. (MBTS), Beam pickups (BPTX)
- L1 trigger processor, DAQ up and running, HLT available (but used for streaming only)

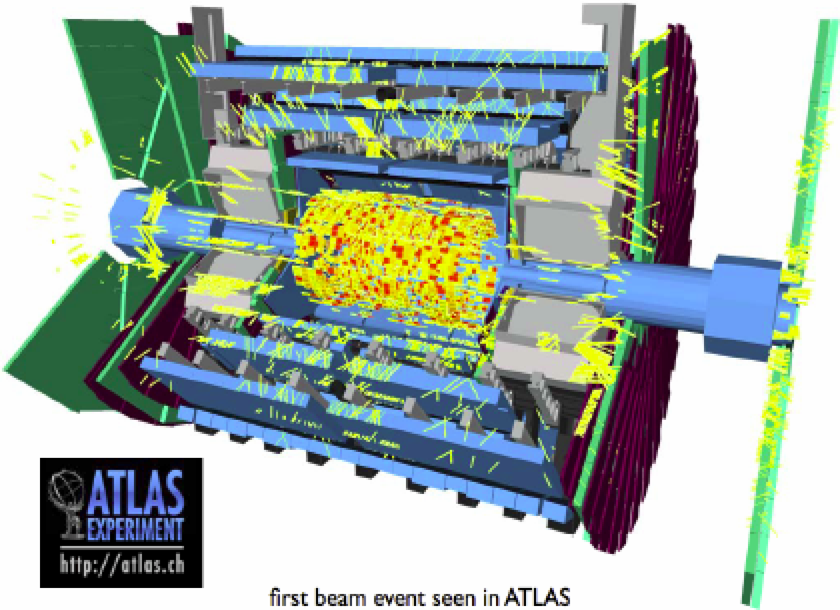
Two LHC start-up scenarios:

1. Open all collimators, go around as far as beam goes, correct as needed
   - Little activity expected except for accidents
2. Go step-by-step, stopping beam on collimators, re-align with centre, open collimator, keep going
   - Splash event from collimators for each beam shot



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

Online display



first beam event seen in ATLAS

ATLAS EXPERIMENT http://atlas.ch

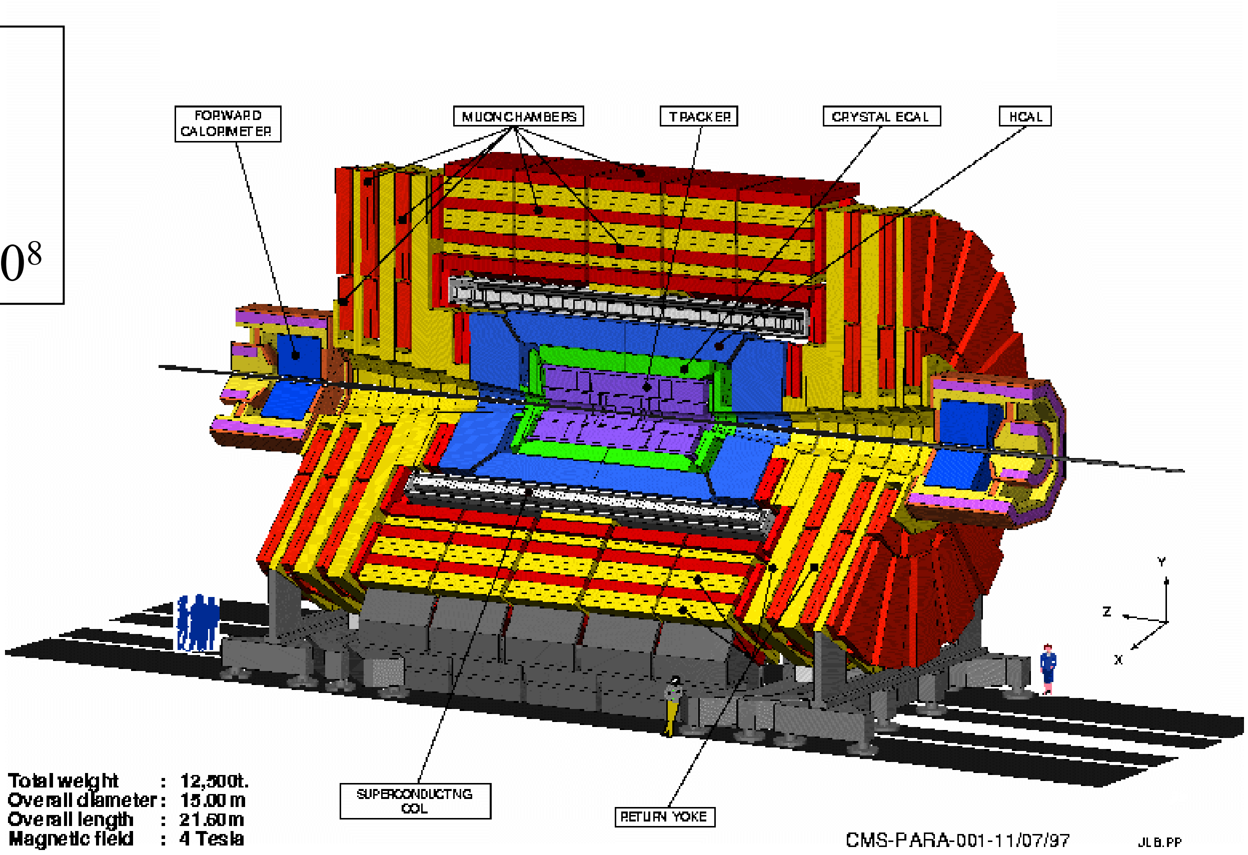
Offline display

LHCC, 24-Sep-2008, PJ

Status of ATLAS

CMS (Compact Muon Solenoid)

Length : 20 m
Radius : 7 m
Weight : 14000 tons
Electronics channels : 10^8



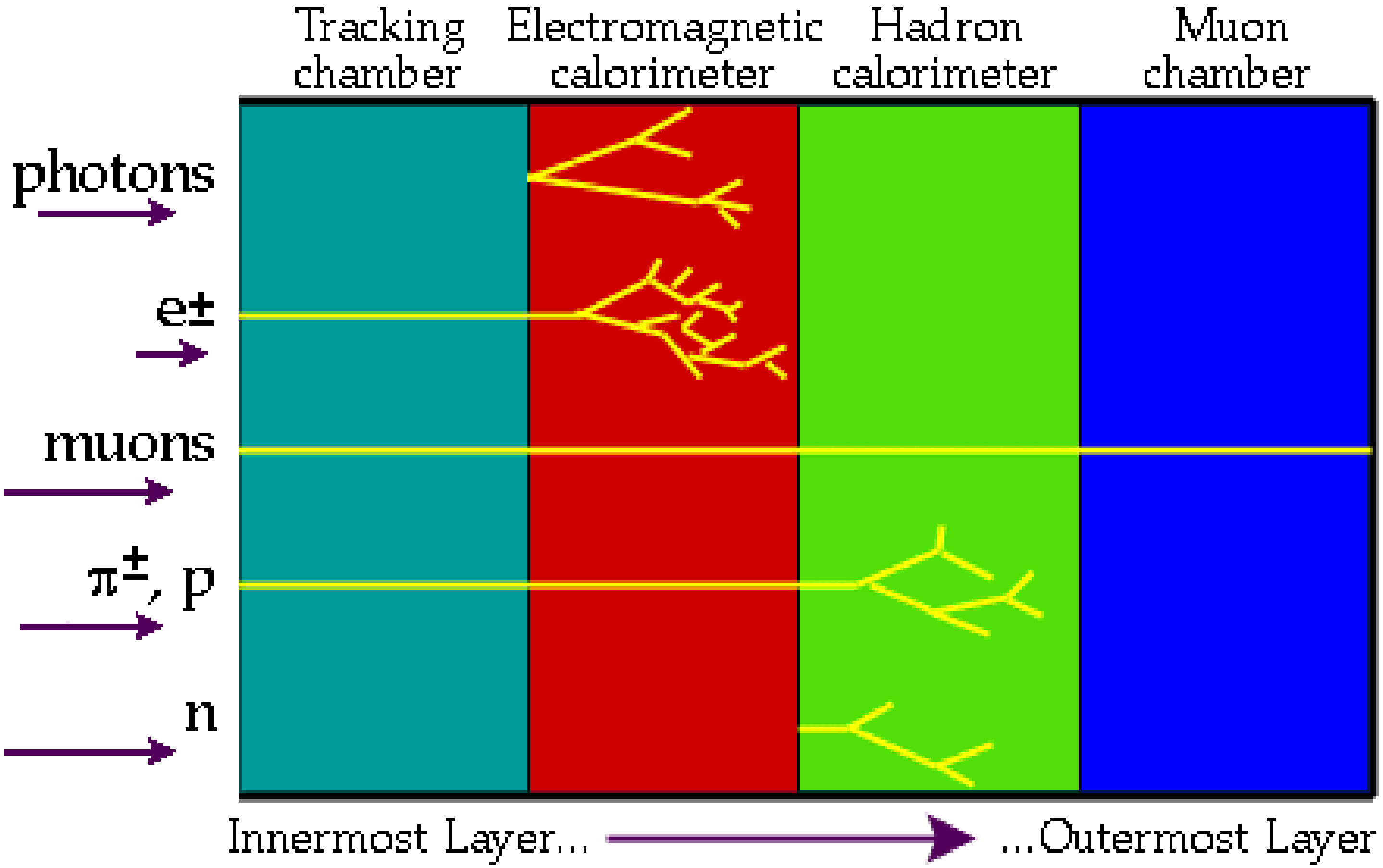
CMS and ATLAS detectors

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, ….
→ " multi-purpose" experiments.

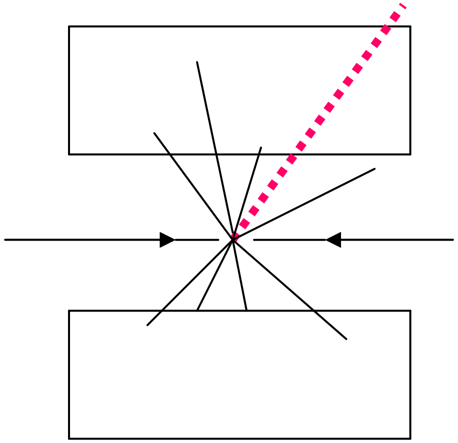
- Momentum / charge of tracks and secondary vertices (e.g. from b-quark decays) measured in central tracker. Excellent momentum and position resolution required.
- Energy and position of electrons and photons measured in electromagnetic calorimeters. Excellent resolution and particle identification required.
- Energy and position of hadrons and jets measured mainly in hadronic calorimeters. Good coverage and granularity are required.
- Muons identified and momentum measured in external muon spectrometer (+ central tracker). Excellent resolution over ~ 5 GeV $< p_T < \sim$ TeV required.
- Neutrinos "detected and measured" through measurement of missing transverse energy E_T^{miss}. Calorimeter coverage over $|\eta| < 5$ needed.

ATLAS and CMS detectors



ATLAS and AMS detectors

Detection and measurement of neutrinos



- Neutrinos traverse the detector without interacting
  → not detected directly
- Can be detected and measured asking energy-momentum conservation:

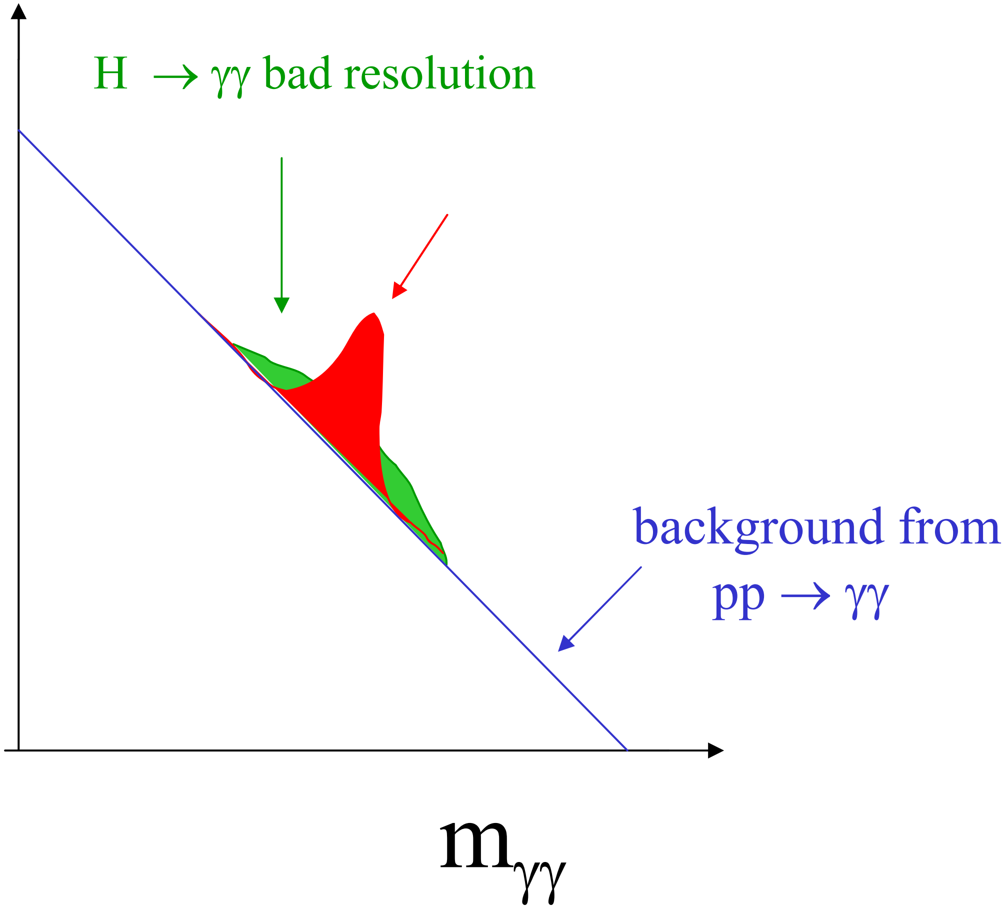
Hadron colliders: energy and momentum of initial state (energy and momentum of interacting partons) not known.
However: transverse momentum of the system = 0

if a neutrino produced $p_T^f \neq 0$
→ missing transverse momentum and $p_T^\nu = p_T^f = E_T^{miss}$

Examples of performance requirements

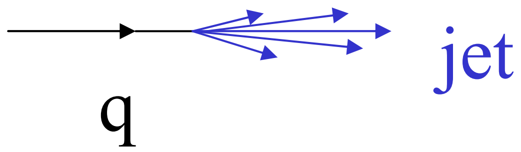
Excellent energy resolution
of EM calorimeters for e/γ and of the tracking devices for μ in order to extract a signal over the backgrounds.

Example : $H \rightarrow \gamma\gamma$

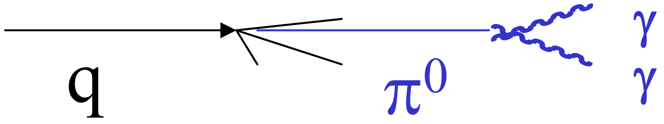


Examples of performance requirements

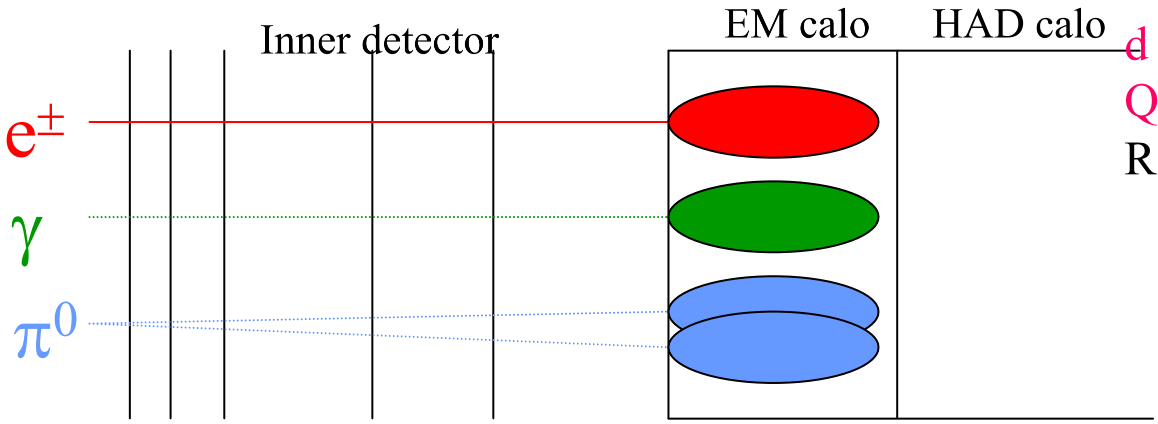
Excellent particle identification capability e.g. e/jet , γ/jet separation



number and p_T of hadron in a jet have large fluctuations



in some cases: one high-p_T π^0; all other particles too soft to be detected



d (γγ) < 10 mm in calorimeter → QCD jets can mimic photons.

Rare cases, however:

$$\frac{\sigma_{jj}}{\sigma(H \to \gamma\gamma)} \sim 10^8$$

$m_{\gamma\gamma} \sim 100$ GeV

need detector (calorimeter) with fine granularity to separate overlapping photons from single photons

Examples of performance requirements

Trigger : much more difficult than at e^+e^- machines

Interaction rate: ~ 10^9 events/second

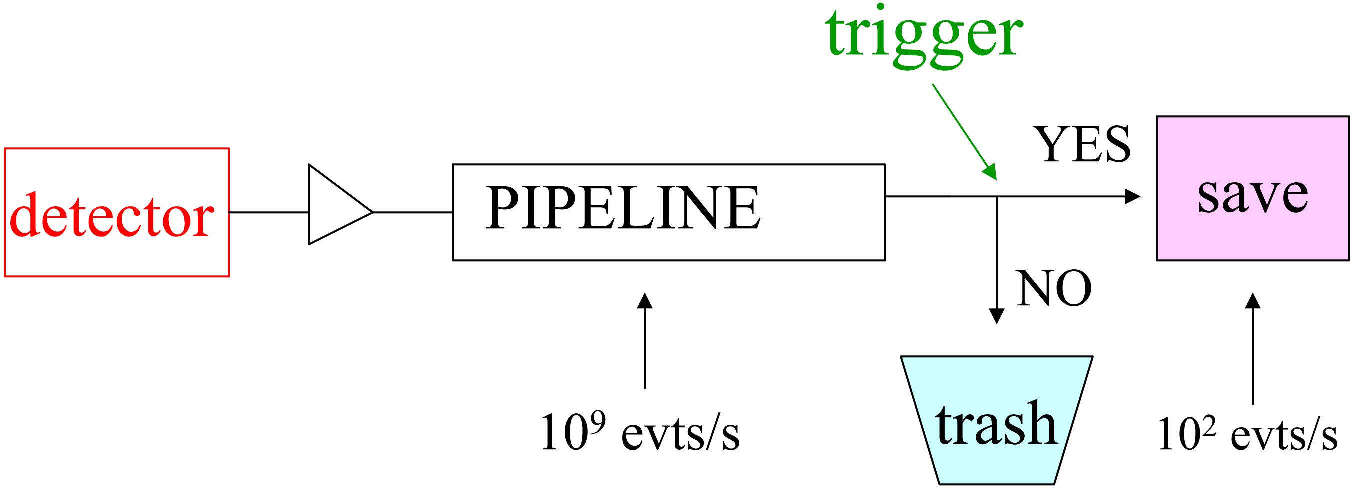
Can record ~ 100 events/second

(event size 1 MB)

⇒ trigger rejection ~ 10^7

Trigger decision ≈ μs → larger than interaction rate of 25 ns

store massive amount of data in pipelines while trigger performs calculations



Summary

LHC:
pp machine (also Pb-Pb)
$\sqrt{s} = 14$ TeV
$L = 10^{33}$-10^{34} cm^{-2} s^{-1}
Start-up : 2007

Four large-scale experiments:

ATLAS, CMS	pp multi-purpose
LHCb	pp B-physics
ALICE	Pb-Pb

\+ dedicated small experiment
TOTEM

Very broad physics programme thanks to energy and luminosity: mass reach : ≤ 5 TeV

Summary

Very difficult environment:

- -- pile-up : ~ 25 soft events produced at each crossing.
  Overlap with interesting high-p_T events.
- -- large background from QCD processes (jet production): typical of hadron colliders

Very challenging, highly-performing and expensive detectors:

- -- radiation hard
- -- fast
- -- granular
- -- excellent energy resolution and particle identification capability
- -- complicated trigger