The Abdus Salam
International Centre for Theoretical Physics

United Nations
Educational, Scientific
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International Atomic
Energy Agency

SMR 1773 - 14

SCHOOL ON PHYSICS AT LHC: "EXPECTING LHC"
11 - 16 September 2006

LHC: Machine and Detectors (LHC Collider and Experiments) Part I

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These are preliminary lecture notes, intended only for distribution to participants.

LHC Collider and Experiments

Albert De Roeck/CERN
ICTP 11-16/09/06

LHC@ICTP 2006

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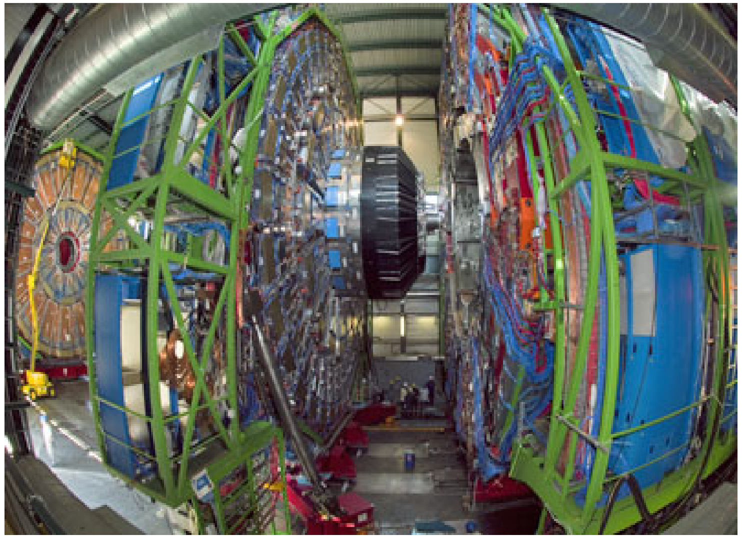
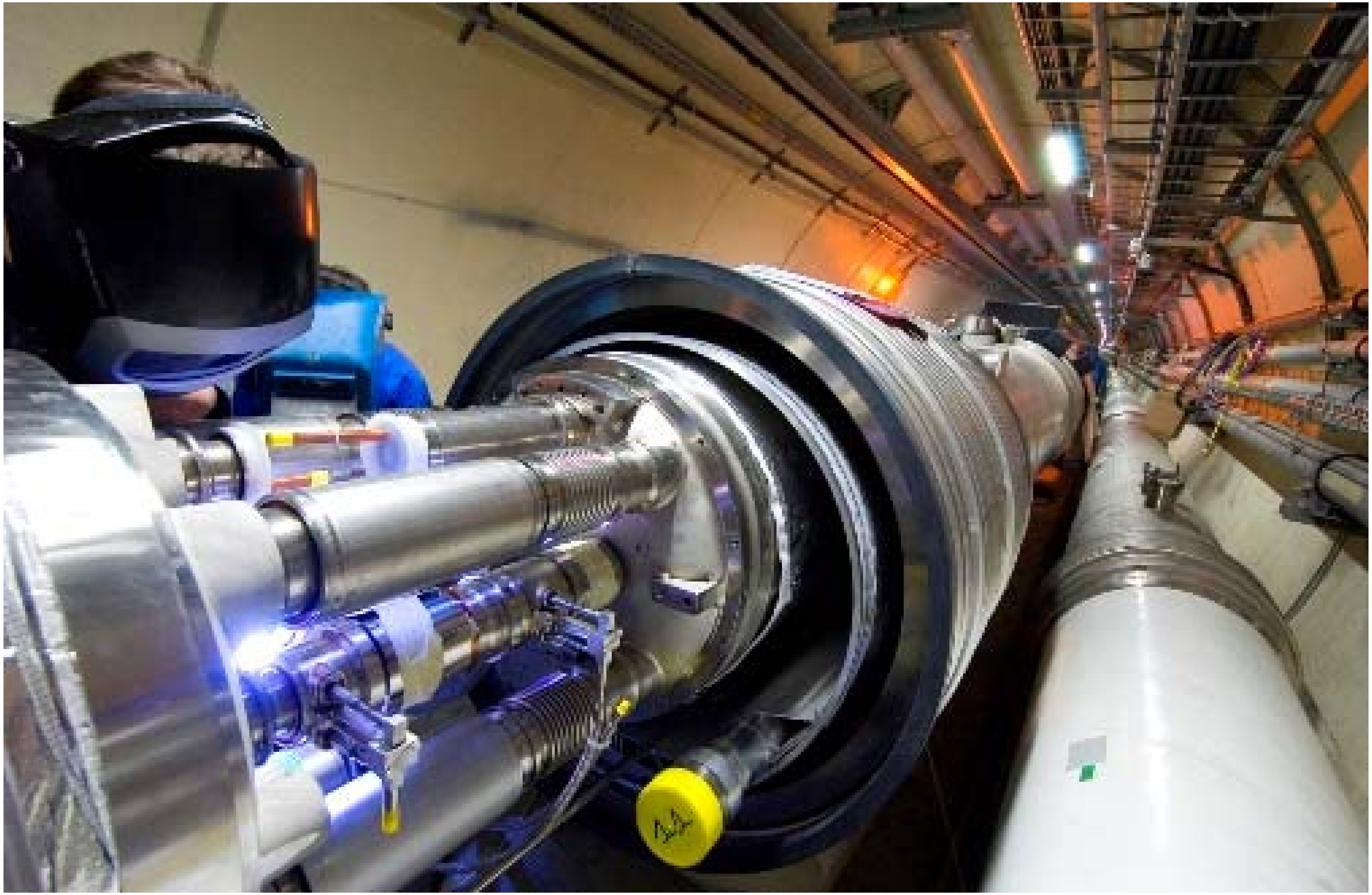


The LHC is Coming!



Lecture Plan

- The LHC Collider
  - Introduction to the LHC
  - Experimental challenges
- The ATLAS and CMS experiments
- The specialised experiments
  - The LHCb experiment
  - The ALICE experiment
  - The forward experiments (TOTEM, LHCf) and MOEDAL
- Startup scenarios and first physics at the LHC

High Energy Accelerators

- Accelerators are the tools in HEP to probe the structure of matter and fundamental interactions
- Up to now: acceleration of stable particles (& anti particles)

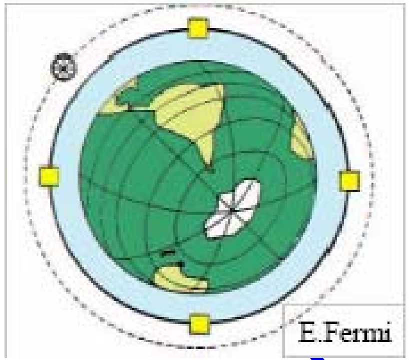
  Protons and electrons

  (pion, neutrino etc. beams are secondary beams)
- Mostly circular machines, to use the beams for long time (hours…)
- Proton: limited by bending power of dipole magnets in the ring
  - Stronger magnets (superconducting)→ higher energies reachable
- Electrons: limited by synchrotron radiation = energy loss on circular path
  - loss per turn ~ 88.5 E^4/Radius KeV (E in GeV, R in meters)
  - LEP = 27.5 circumference → Max 100 GeV beams
- Future for leptons
  - Linear colliders → beams up to 1 –2 TeV
  - Muon colliders? Energy loss per turn is $(m_e/m_\mu)^4$ smaller!

High Energy Accelerators

Highest energies can be reached with proton colliders

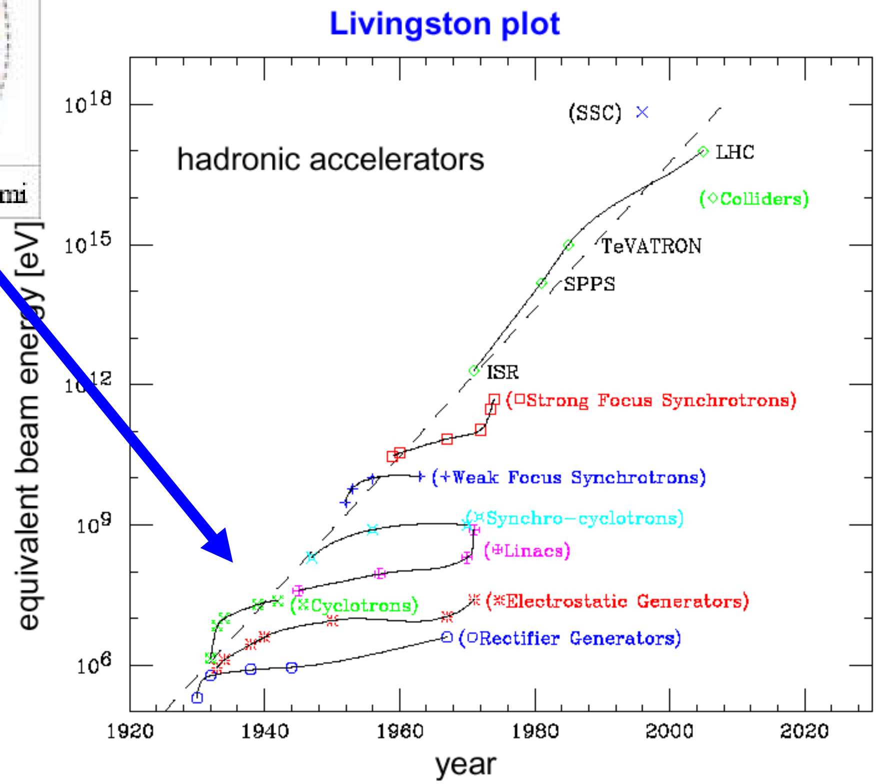
Historical note:
1954 APS meeting →
E. Fermi considered a proton accelerator around the earth with 2T field magnets



The fixed target energy would be E_{max}=5.10^{15} eV, and the price 170 billion $, reached in 1994.

Actually the Tevatron (Fermilab) collider reached E_{max}=2.10^{15} eV in 1987 but with a radius of 1 km

LHC will reach E_{max}=1.10^{17} eV in 2007 for about 4 billion CHF



Innovative accelerator R&D needed

Recent Accelerators

Highest energies can be reached with proton colliders

Machine	Year	Beams	Energy ($\sqrt{s}$)	Luminosity
SPPS (CERN)	1981	pp	630-900 GeV	$6.10^{30}cm^{-2}s^{-1}$
Tevatron (FNAL)	1987	pp	1800-2000 GeV	10^{31}-$10^{32}cm^{-2}s^{-1}$
SLC (SLAC)	1989	e^+e^-	90 GeV	$10^{30}cm^{-2}s^{-1}$
LEP (CERN)	1989	e^+e^-	90-200 GeV	10^{31}-$10^{32}cm^{-2}s^{-1}$
HERA (DESY)	1992	ep	300 GeV	10^{31}-$10^{32}cm^{-2}s^{-1}$
RHIC (BNL)	2000	pp / AA	200-500 GeV	$10^{32}cm^{-2}s^{-1}$
LHC (CERN)	2007/8	pp (AA)	14000 GeV	10^{33}-$10^{34}cm^{-2}s^{-1}$

Luminosity = number of events/cross section/sec

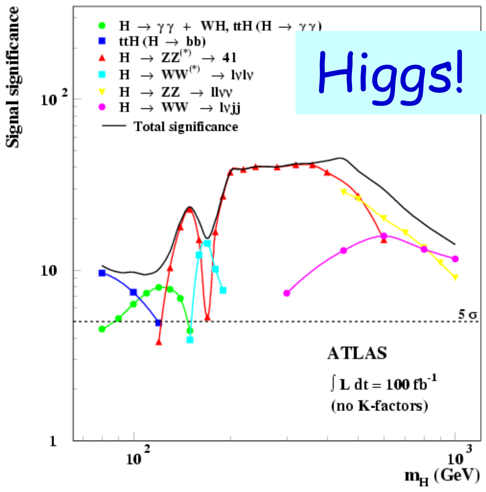
- Limits on circular machines
  - Proton colliders: Dipole magnet strength →superconducting magnets
  - Electron colliders: Synchrotron radiation/RF power

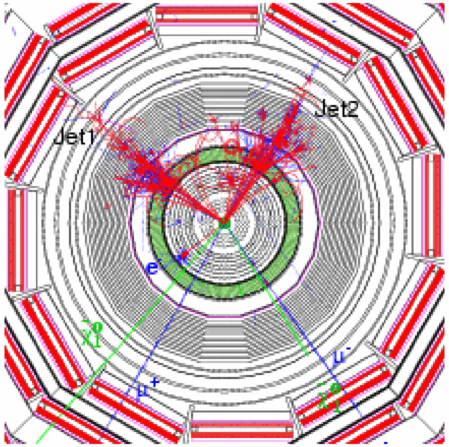
LHC Physics Program

- Discover or exclude the Higgs in the mass region up to 1 TeV. Measure Higgs properties
- Discover Supersymmetric particles (if exist) up to 2-3 TeV
- Discover Extra Space Dimensions, if these are on the TeV scale, and black holes?
- Search other new phenomena (e.g. strong EWSB, new gauge bosons, Little Higgs model, Split Supersymmetry)
- Study CP violation in the B sector,B physics
- Precision measurements of m_{top}, m_W, anomalous couplings…
- Heavy ion collisions and search for quark gluon plasma
- QCD and diffractive (forward) physics in a new regime
- …

Physics at the LHC: pp @ 14 TeV

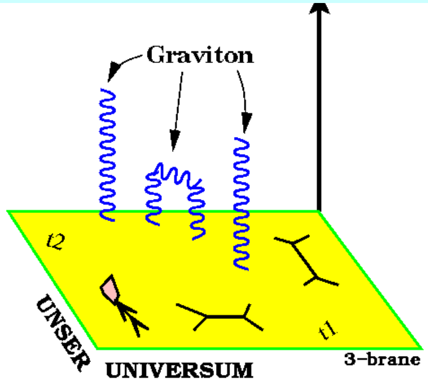
Higgs!



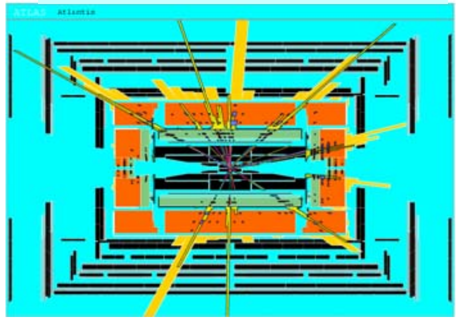


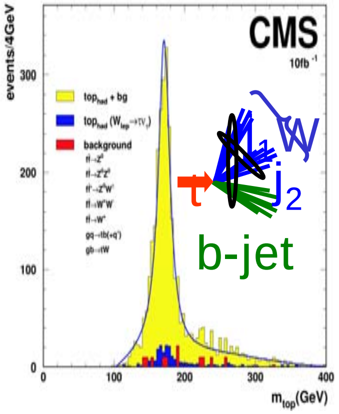
Supersymmetry?

Extra Dimensions?



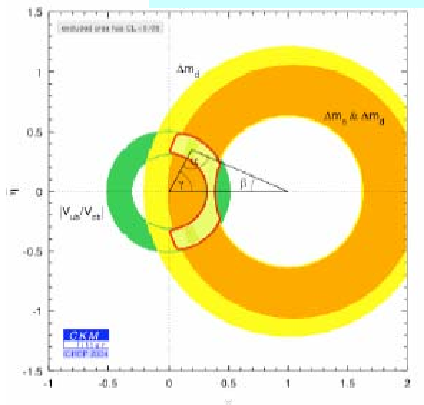
Black Holes???



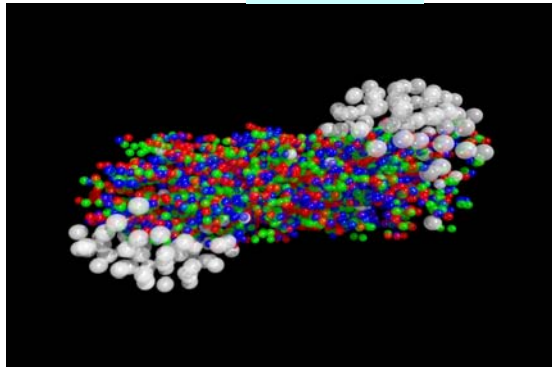


Precision measurements e.g top!

CP triangle!



QGP?



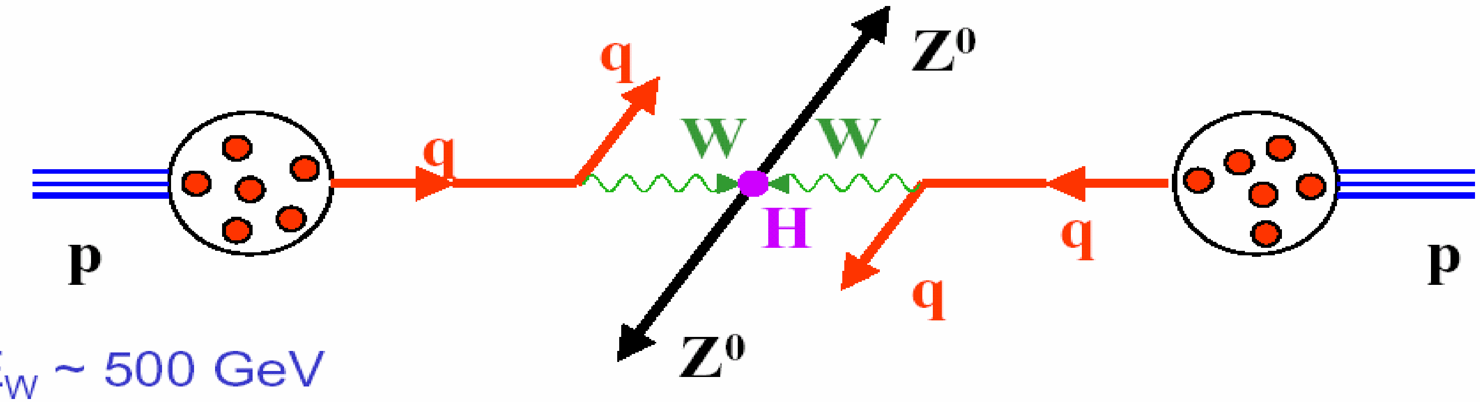
The LHC will be the new collider energy frontier

Requirements for a new collider

Example: Higgs particle production

Hadron colliders are broad-band exploratory machines

May need to study W_L-W_L scattering at a cm energy of ~ 1 TeV



⇨ E_W ~ 500 GeV

⇨ E_{quark} ~ 1 TeV

⇨ E_{proton} ~ 6 TeV

⇨ **pp collisions at 7 + 7 TeV** → **14 TeV collider**

→ **$L \sim 10^{34}$ cm^{-2} s^{-1}**

Event Rate = L.σ.BR

e.g. H(1 TeV) → ZZ → 2e+2μ or 4e or 4μ

For L ~10^{34} , Evts/yr = **10^{34}** $10^{-37}.10^{-3}.10^{7}$ ~ 10 /yr !!

The Large Hadron Collider LHC

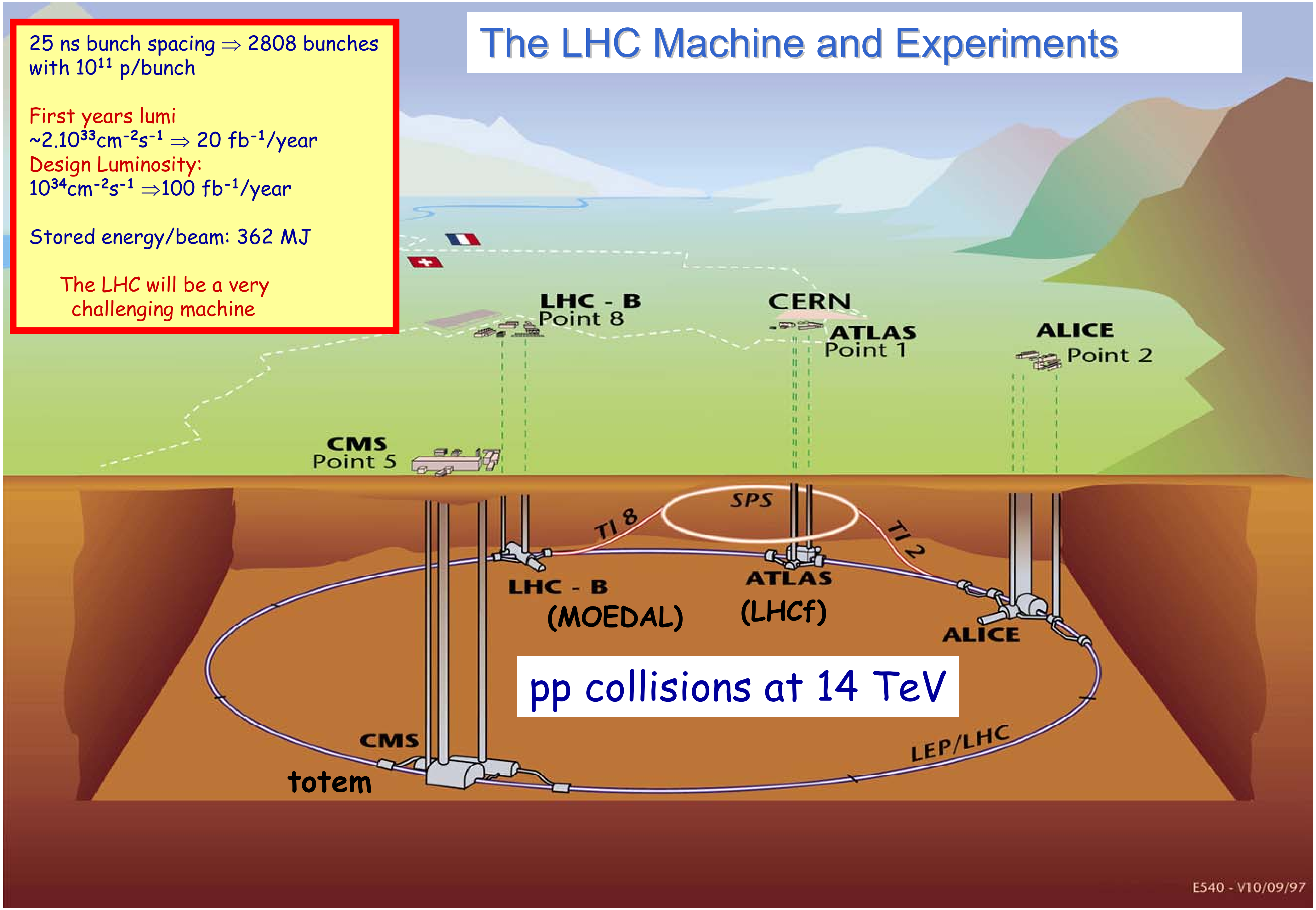
The LHC Machine and Experiments

25 ns bunch spacing ⇒ 2808 bunches with 10^{11} p/bunch

First years lumi
~$2.10^{33} cm^{-2}s^{-1}$ ⇒ 20 fb^{-1}/year
Design Luminosity:
$10^{34} cm^{-2}s^{-1}$ ⇒100 fb^{-1}/year

Stored energy/beam: 362 MJ

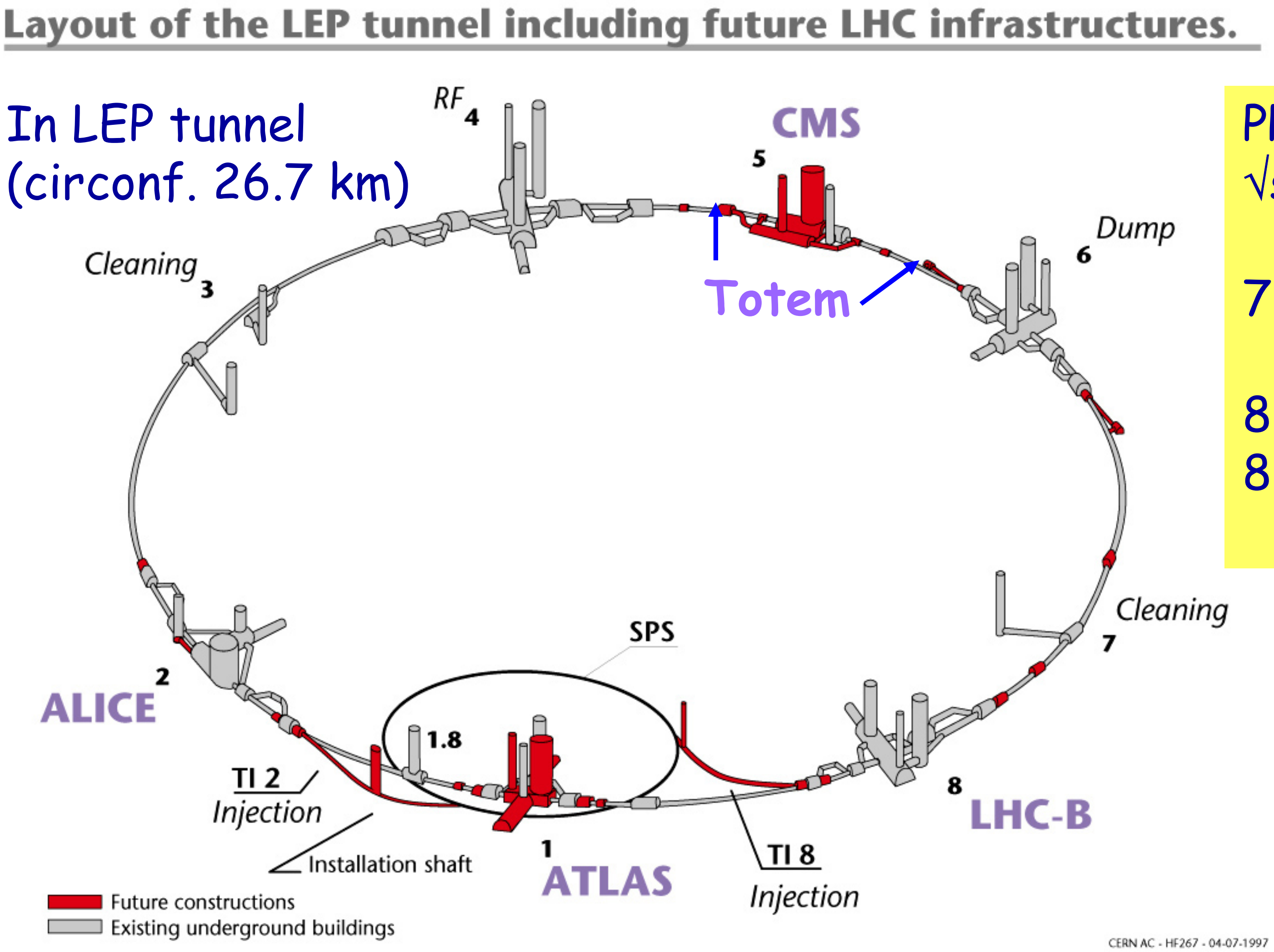
The LHC will be a very challenging machine



pp collisions at 14 TeV

The Large Hadron Collider (LHC)

In LEP tunnel
(circonf. 26.7 km)



PP collisions at
$\sqrt{s}$ = 14 TeV

7 experiments

8 straight sections +
8 arcs (cold magnets)

The Accelerator scheme

Linac

↓

Booster

↓

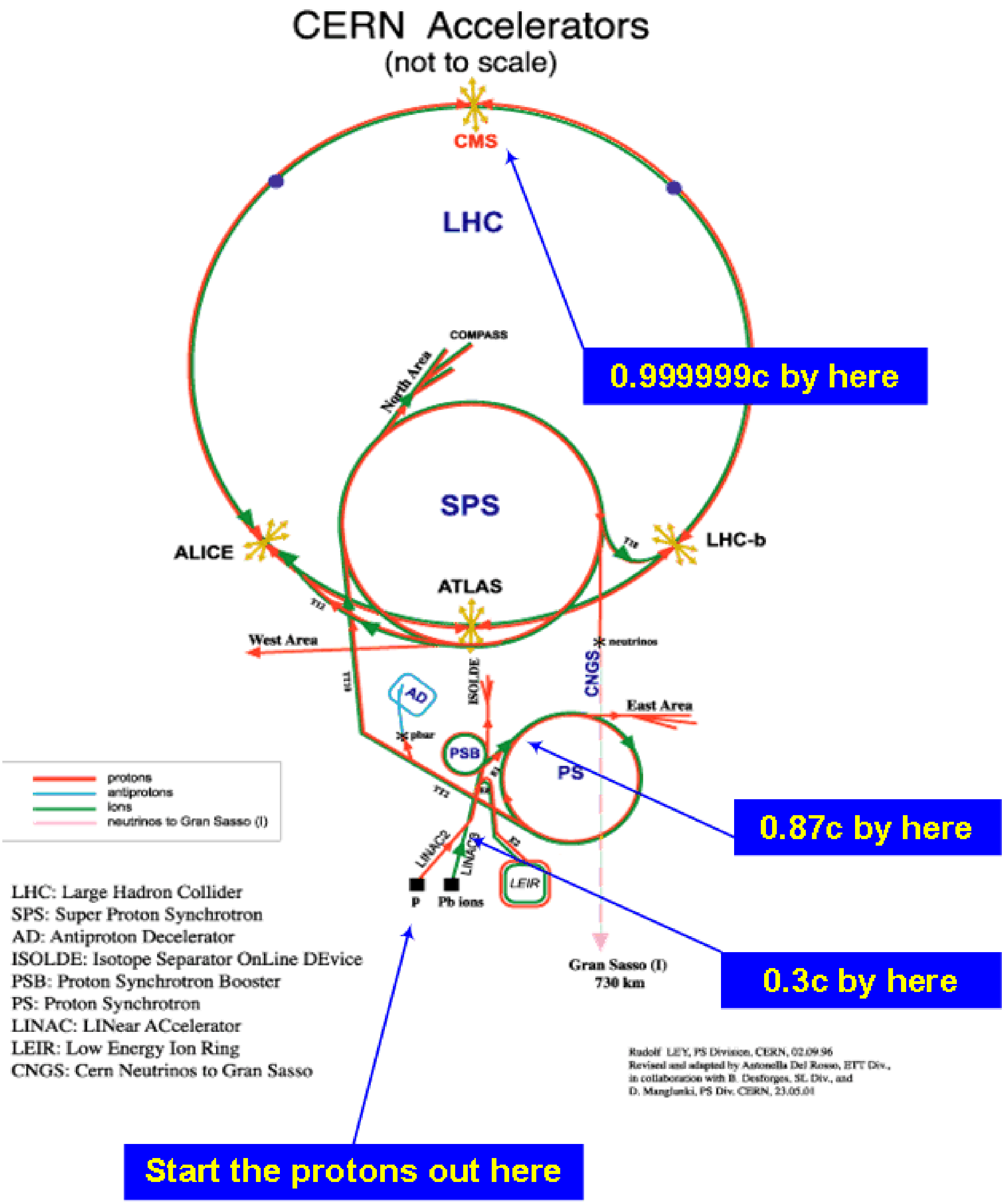
PS

↓

SPS

↓

LHC



LHC Parameters

LHC design report

Table 2.1: LHC beam parameters relevant for the peak luminosity

		Injection	Collision
Beam Data			
Proton energy	[GeV]	450	7000
Relativistic gamma		479.6	7461
Number of particles per bunch		1.15×10^{11}	
Number of bunches		2808	
Longitudinal emittance (4σ)	[eVs]	1.0	2.5[a]
Transverse normalized emittance	[μm rad]	3.5[b]	3.75
Circulating beam current	[A]	0.582	
Stored energy per beam	[MJ]	23.3	362
Peak Luminosity Related Data			
RMS bunch length[c]	cm	11.24	7.55
RMS beam size at the IP1 and IP5[d]	μm	375.2	16.7
RMS beam size at the IP2 and IP8[e]	μm	279.6	70.9
Geometric luminosity reduction factor F[f]		-	0.836
Peak luminosity in IP1 and IP5	[$cm^{-2}sec^{-1}$]	-	1.0×10^{34}
Peak luminosity per bunch crossing in IP1 and IP5	[$cm^{-2}sec^{-1}$]	-	3.56×10^{30}

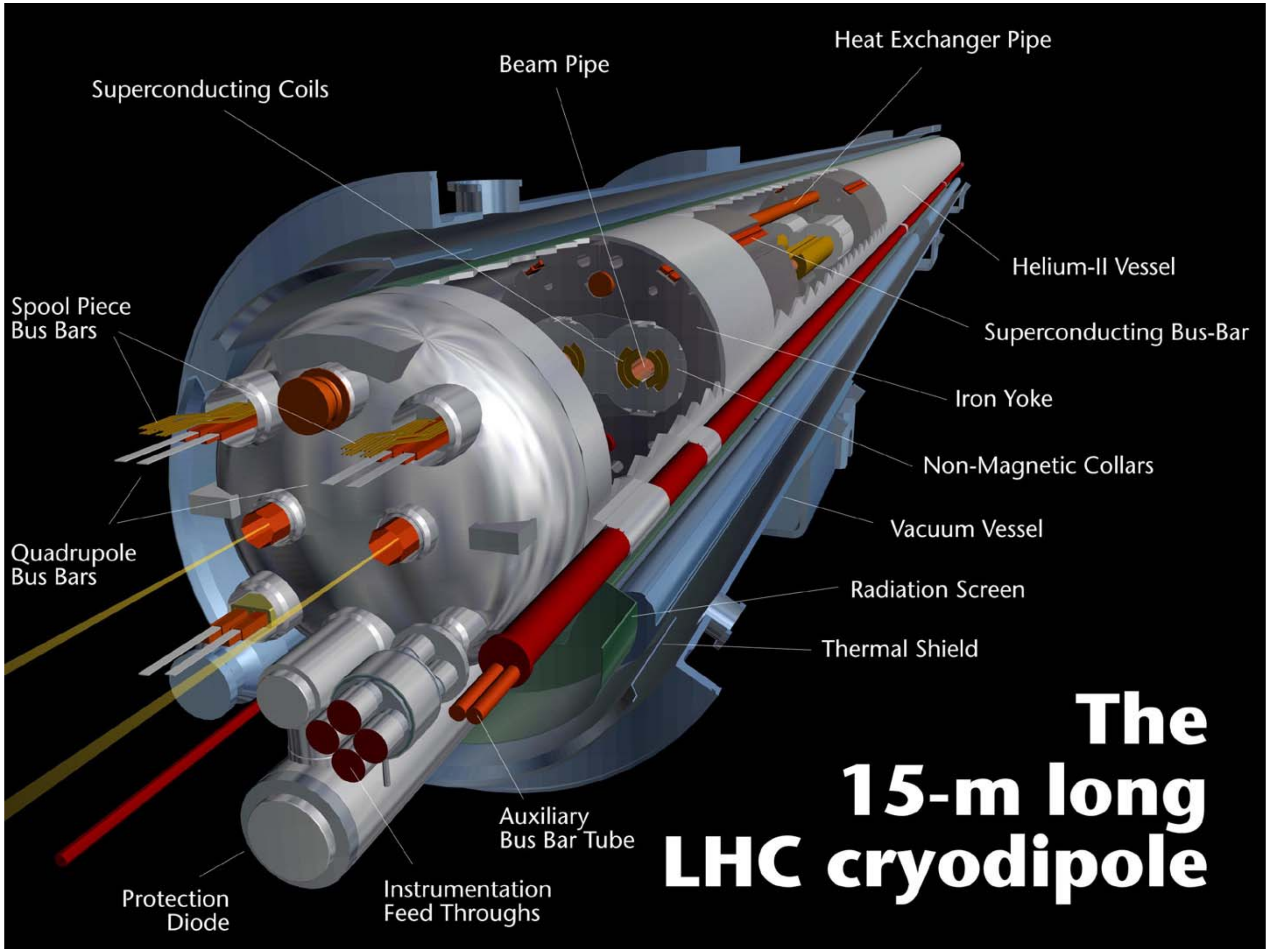
Magnets for the LHC (part of them)

		No. of Magnets	Aperture
Dipole	MB	1232	twin
Lattice quadrupoles	MQ	392	twin
Lattice sextupoles	MS	688	single
Lattice Octupoles	MO	168	twin
Skew quad	MQS	32	twin
Arc skew sext	MSS	64	single
Tuning trim quad	MQT	160	twin
Octupole spool pieces	MCO	1232	single
Decapole spool pieces	MCD	1232	single
Sextupole corrector (b3) in MBA & MBB (spool piece corrector)	MCS	2464	single
Insertion region long trim quads	MQTLI	36	twin
Arc dipole corrector	MCBH	376	single
Arc dipole corrector	MCBV	376	single
Twin aperture separation dipole in IR (194mm). D4	MBRB		twin
Twin Aperture Separation dipole in IR(188mm). D2	MBRC	8	twin

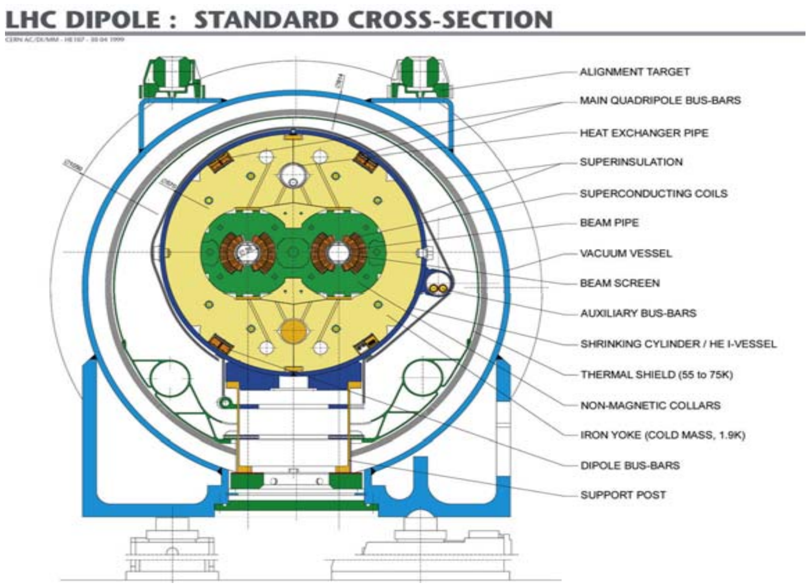
About 9000 magnets of which 1232 are the cryodipoles

The Cryodipole Magnets

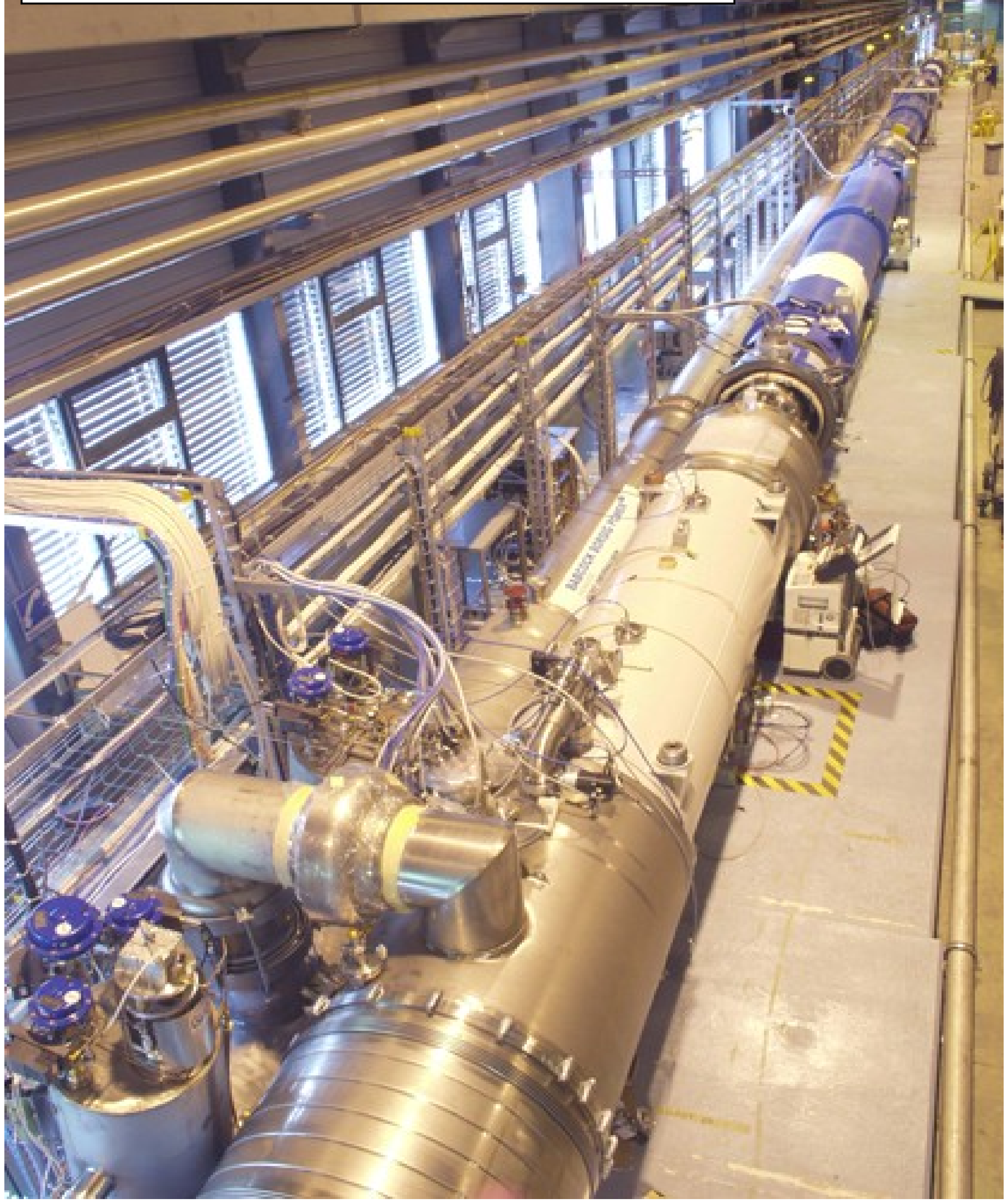
- Superconducting (1.9 K) dipoles producing a field of 8.4 T – current 11,700A ⇒ 2-in-1 magnet design
- Cost: ~ 0.5 million CHF each. Need 1232 of them
- Stored magnetic energy up to 1.29 GJ per sector.
- Total stored energy in magnets = 11GJ
- One dipole weighs around 34 tonnes



The Cryodipoles



First full LHC cell (~ 120 m long) :
6 dipoles + 4 quads
1 dipole = 15m and weights 34 tons!



Cryogenics

The QRL Cryoline problems caused a lot of headaches in 2004.

Dipoles: Waiting to be lowered after QRL repair
Parking space @ CERN was getting sparse

Cryogenics

LHC uses superfluid helium, which has unusually efficient heat transfer properties, allowing kilowatts of refrigeration to be transported over more than a kilometer with a temperature drop of less than 0.1 K.
LHC superconducting magnets will sit in a 1.9 K bath of superfluid helium at atmospheric pressure. In all, LHC cryogenics will need 40,000 leak-tight pipe junctions, 12 million litres of liquid

Conclusions from Lyn Evans' recent presentation at the CERN Scientific Policy Committee, on 12th December 2005

(Available via the official LHC Web: http://lhc.web.cern.ch/lhc/)

All key objectives have been reached for the end of 2005

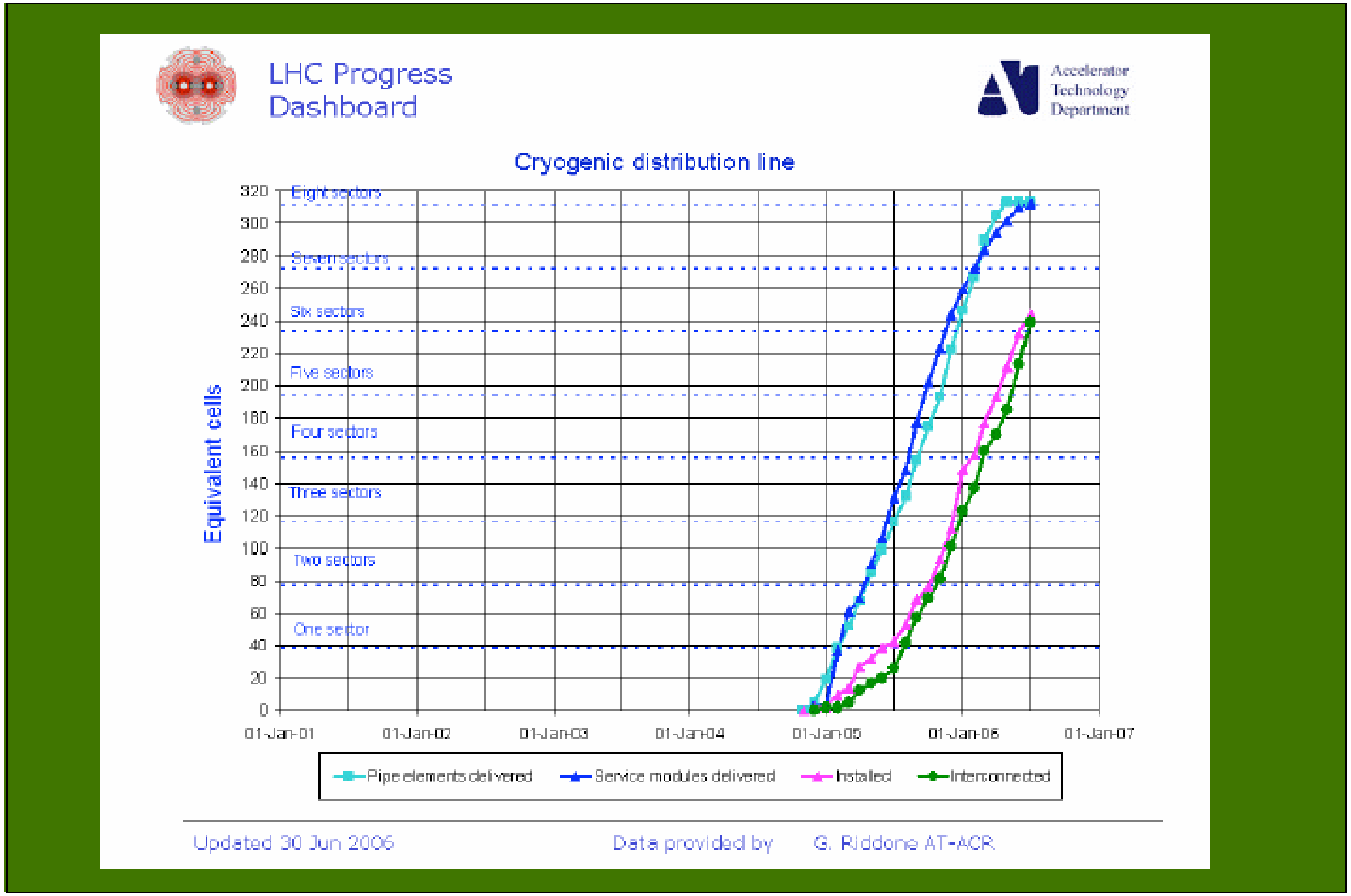
- End of repair of QRL, reinstallation of sector 7-8 and cold test of sub -sectors A and B
- Cool-down of full sector 8-1
- Pressure test of sector 4-5
- Endurance test of full octant of power converters

Magnet installation rate is now close to 20/week, with more than 200 installed

This, together with interconnect work, will remain the main bottleneck until the end of installation

Cryoline tests

First 600 m of cryoline (QRL) successfully cooled down on 14/9/2005, followed by cool-down of full cryoline sector 8-1 and pressure test of sector 4-5.



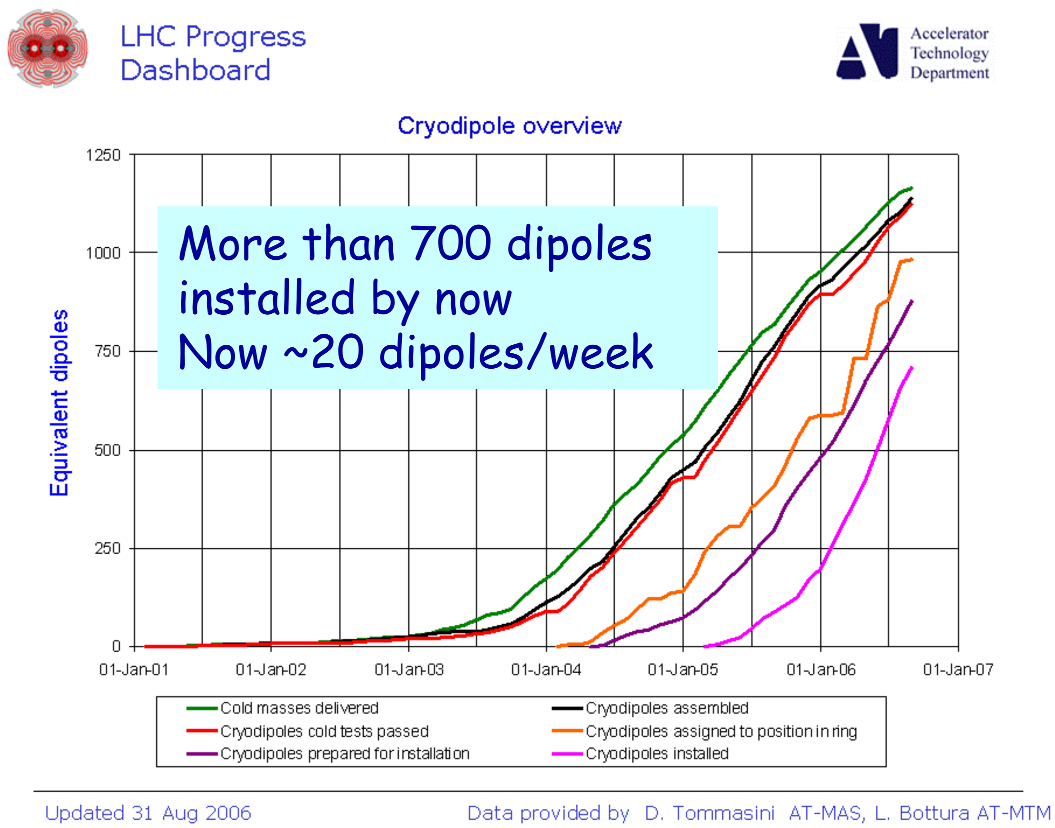
Instaling of the Dipoles

- First dipole lowered in March 2005
- The 616th dipole out of a total of 1232 was installed at 3 a.m on Wednesday 12 July 06. Half way!
- Octant 7-8 will be cooled down and tested before the end of the year

Around the clock activity

The LHC Progress & Schedule

Crucial part: 1232 superconducting dipoles
Can follow progress on the LHC dashboard
http://lhc-new-homepage.web.cern.ch/lhc-new-homepage/



The LHC Schedule(*)

- LHC will be closed and set up for beam on 1 September 2007
  - LHC commissioning will take time!
- First collisions expected in November 2007
  - Followed by a short pilot run
  - Collisions will be at injection energy ie cms of 0.9 TeV
- First physics run in 2008
  - ~1 fb^{-1}? 14TeV!
- Physics run in 2009 +…
  - 10-20 fb^{-1}/year $\Rightarrow$100 fb^{-1}/year

More details on the schedule in the last lecture

(*) eg. M. Lamont et al, April 2005.
Achtung! Lumi estimates are mine, not from the machine
Includes updates from Jujne 06

(Revised) LHC schedule

as presented to CERN Council on 23 June 2006

- Last magnet installed : March 2007
  Machine and experiments closed : 31 August 2007
- First collisions ($\sqrt{s}$ = 900 GeV, L~10^{29} cm^{-2} s^{-1}) : November 2007
  Commissioning run at injection energy until end 2007, then shutdown (3 months ?)
- First collisions at $\sqrt{s}$=14 TeV (followed by first physics run): Spring 2008

Goal : deliver integrated luminosity of few fb^{-1} by end 2008

L. Evans,
CERN Council,
23/6/2006

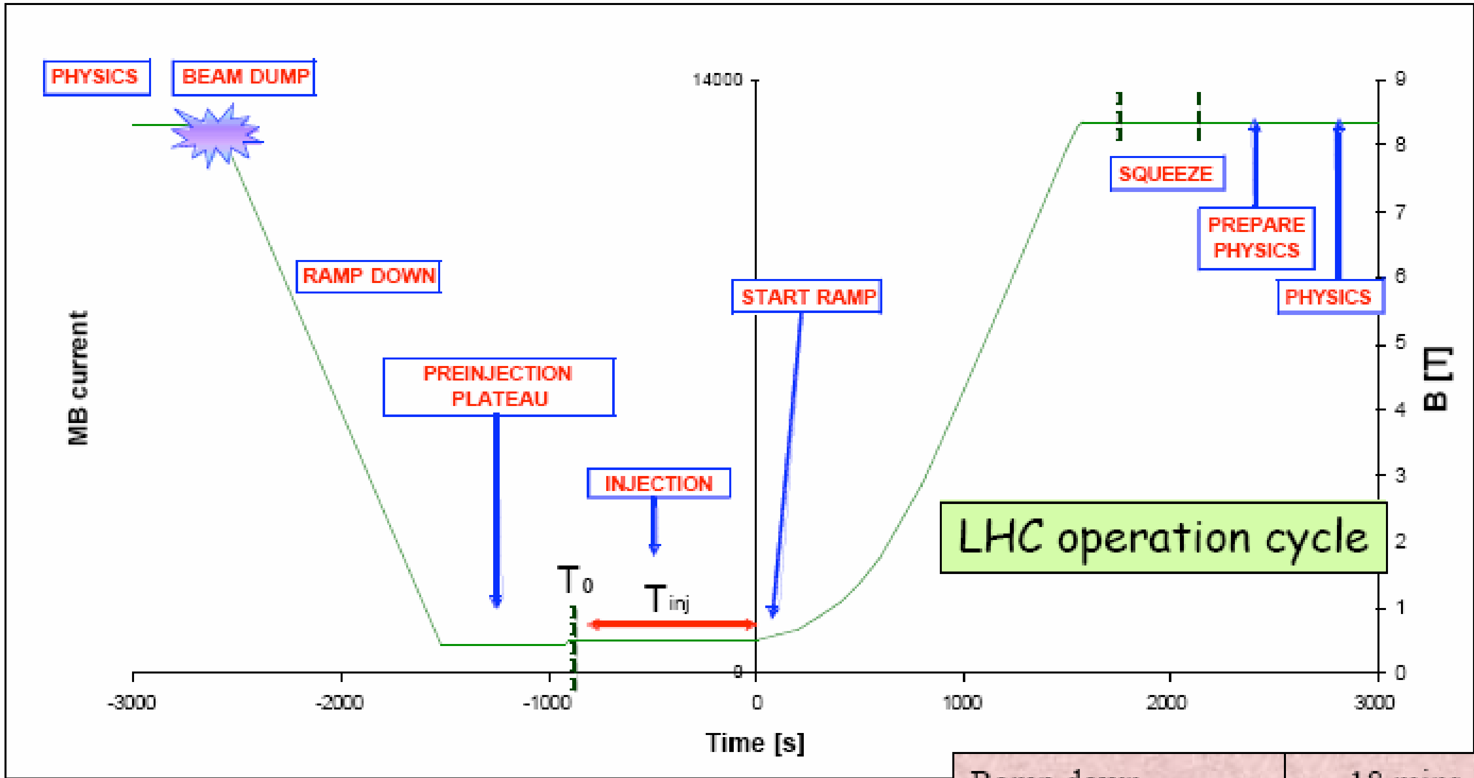
- Sectors 7-8 and 8-1 will be fully commissioned up to 7 TeV in 2006-2007.
  If we continue to commission the other sectors up to 7 TeV,
  we will not get circulating beam in 2007.
- The other sectors will be commissioned up to the field needed for de-Gaussing.
- Initial operation will be at 900 GeV (CM) with a static machine (no ramp, no squeeze) to debug machine and detectors.
- Full commissioning up to 7 TeV will be done in the winter 2008 shutdown

7

F. Gianotti
ICHEP06

More details on the schedule in the last lecture

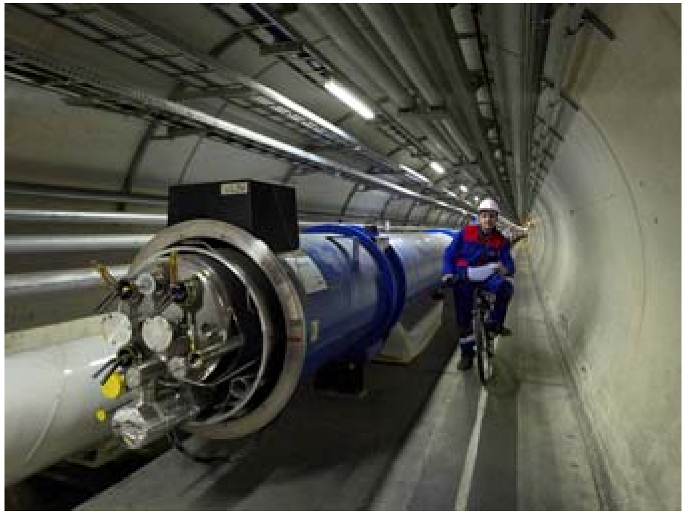
Expected LHC operation Cycle



Ramp down	≈ 18 mins
Pre-injection plateau	15 mins
Injection	≈ 15 mins
Ramp	≈ 28 mins
Squeeze	< 5 mins
Prepare physics	≈ 10 mins
Physics	**10-20 hours**

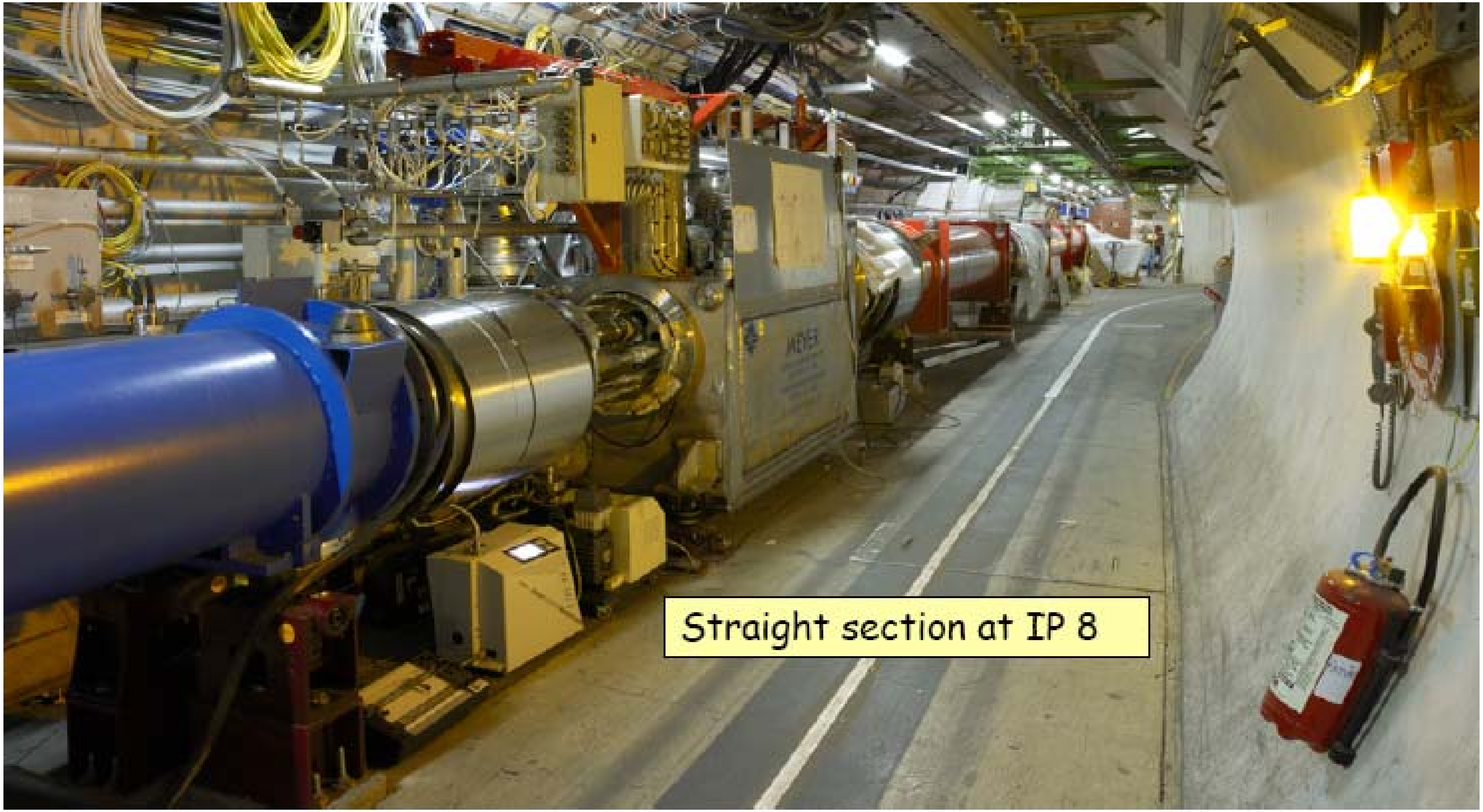
Some Impressions

Top speed
3km/h



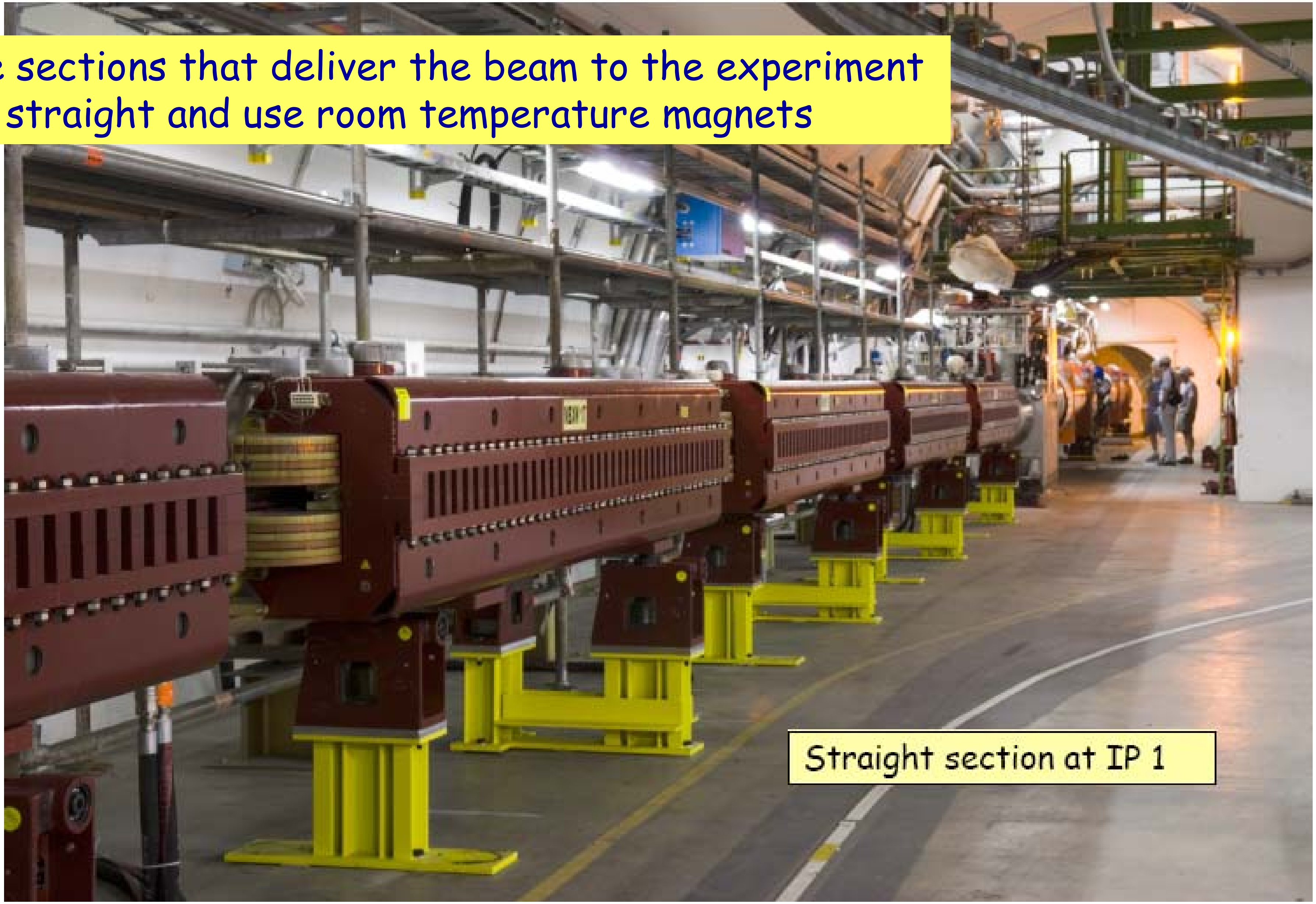
Dipole interconnection is a tedious and time consuming job

LHC is more than just dipoles…



Straight Sections

The sections that deliver the beam to the experiment are straight and use room temperature magnets



Straight section at IP 1

LHCb

TOTEM

LHCf

CMS
Compact Muon Solenoid

Experiments at the LHC

ATLAS

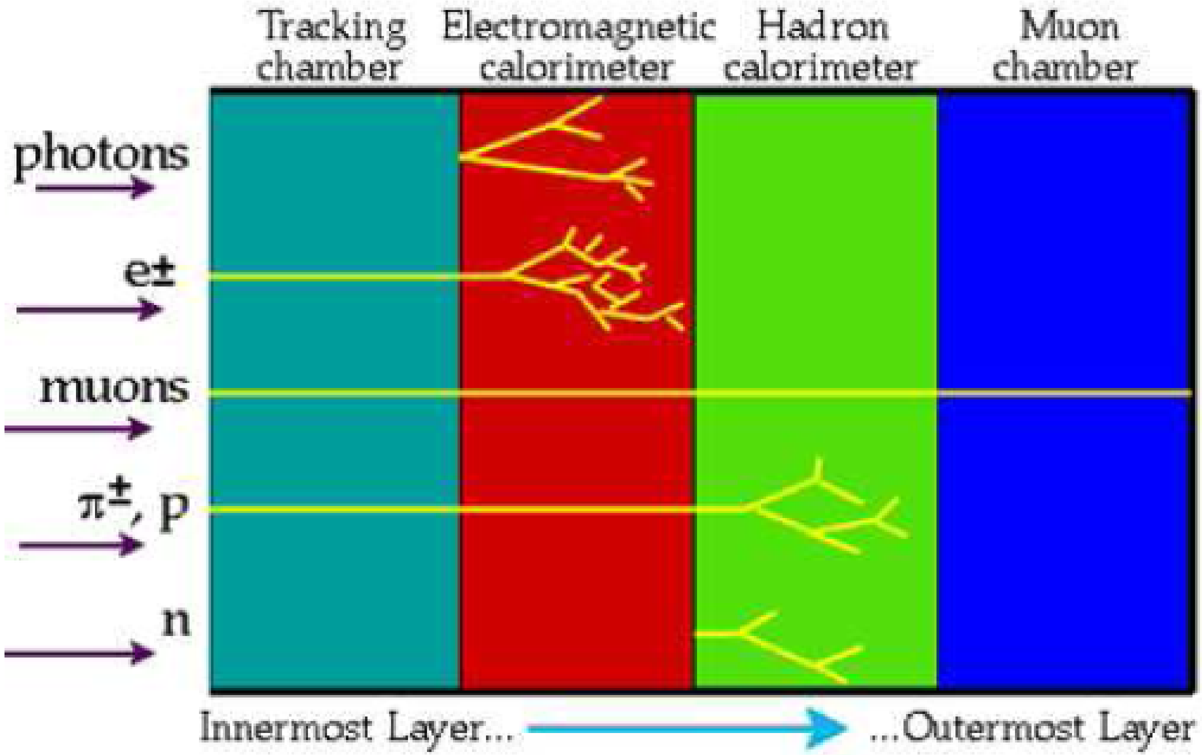
moedal

ALICE

Detectors at Accelerators

Particle Detection: What we "see" as particles:

For "stable particles" of life time $\geq 10^{-10}$ s:

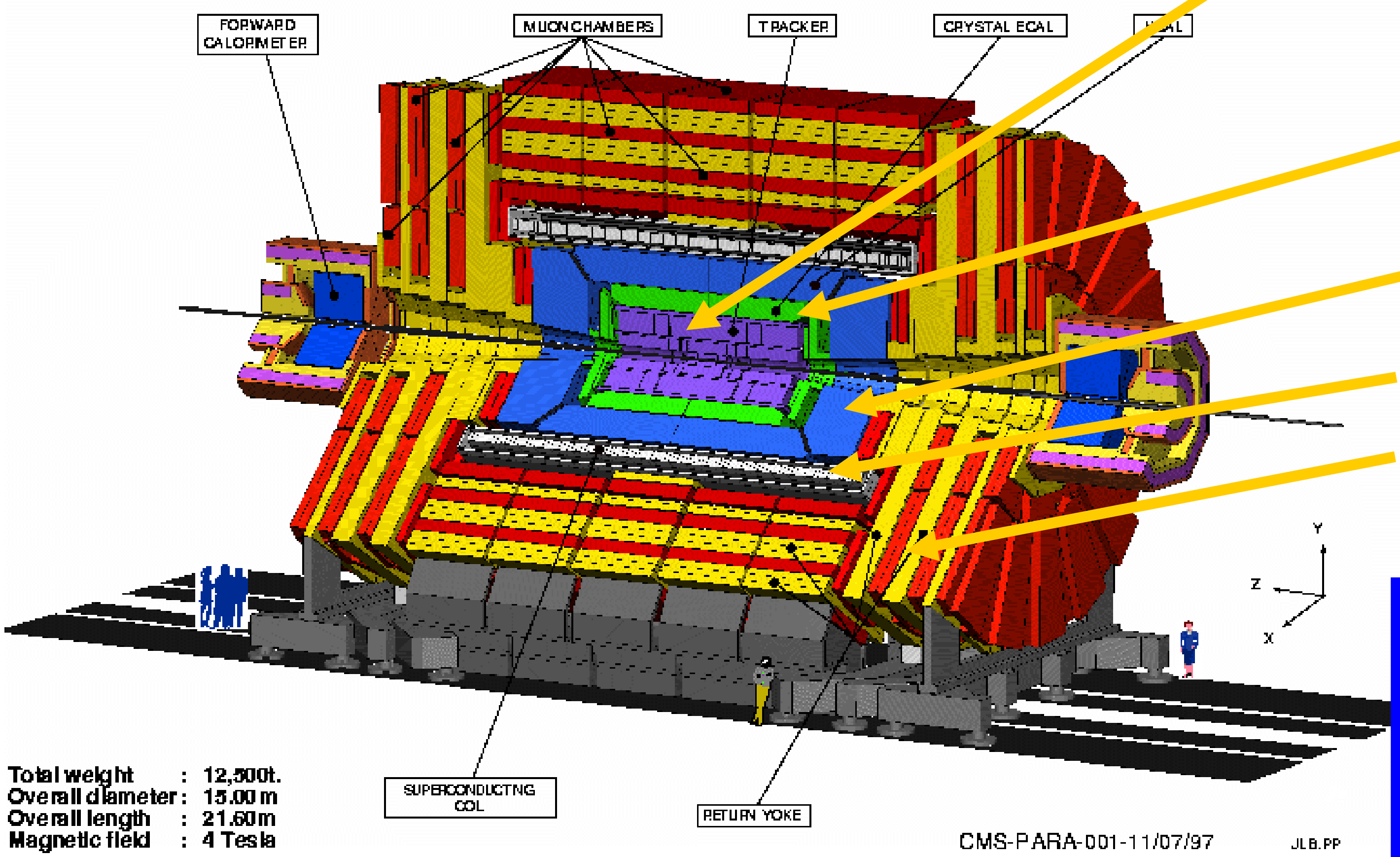


For charged tracks : $\Delta p/p \propto p$,

for calorimetry : $\Delta E/E \propto \frac{1}{\sqrt{E}}$.

Example: The CMS experiment

~2300 people/~150 institutes

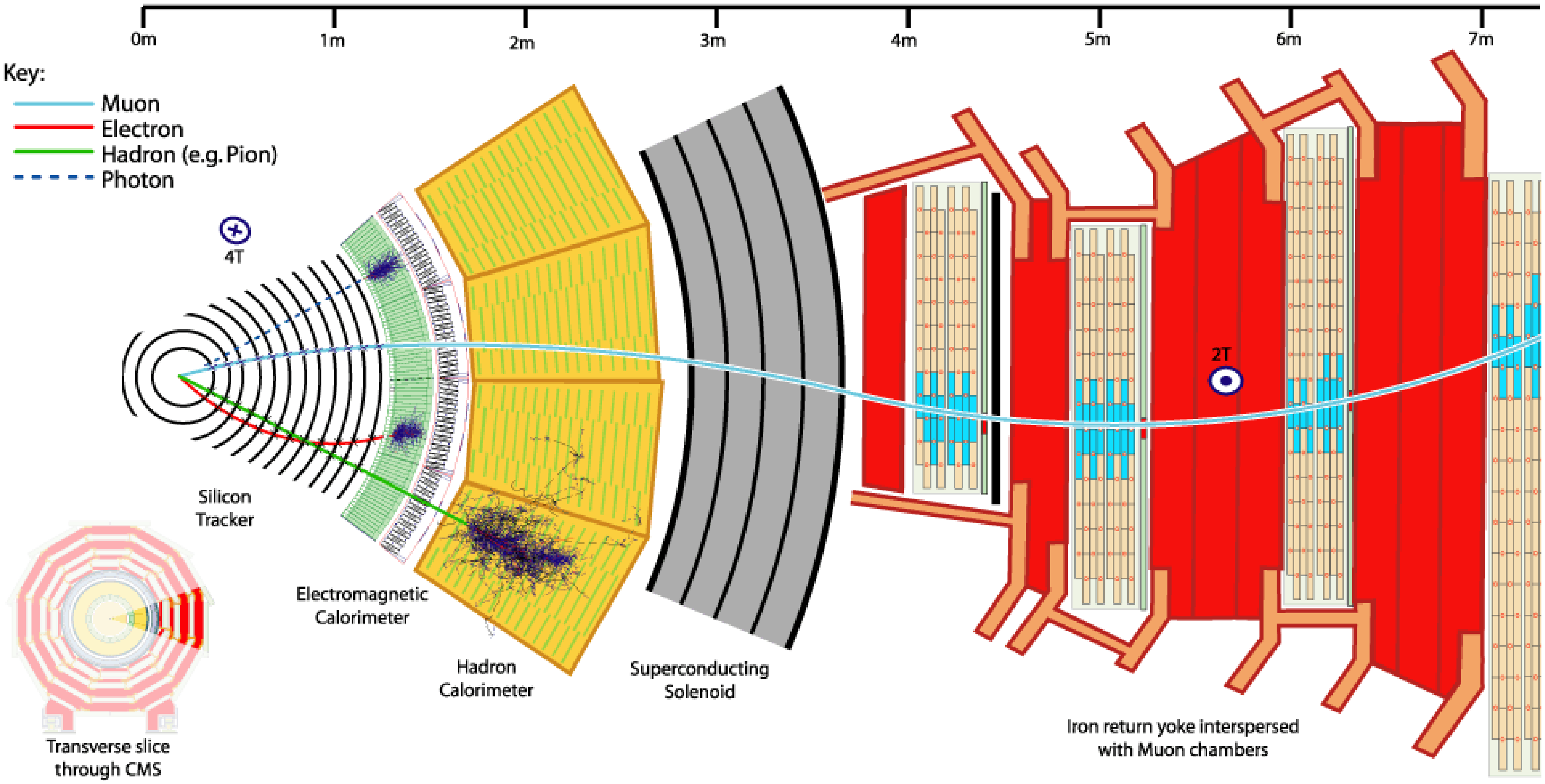


- Tracking
  - Silicon pixels
  - Silicon strips
- Calorimeters
  - PbW04 crystals for Electro-magn.
  - Scintillator/steel for hadronic part
- 4T solenoid
- Instrumented iron for muon detection

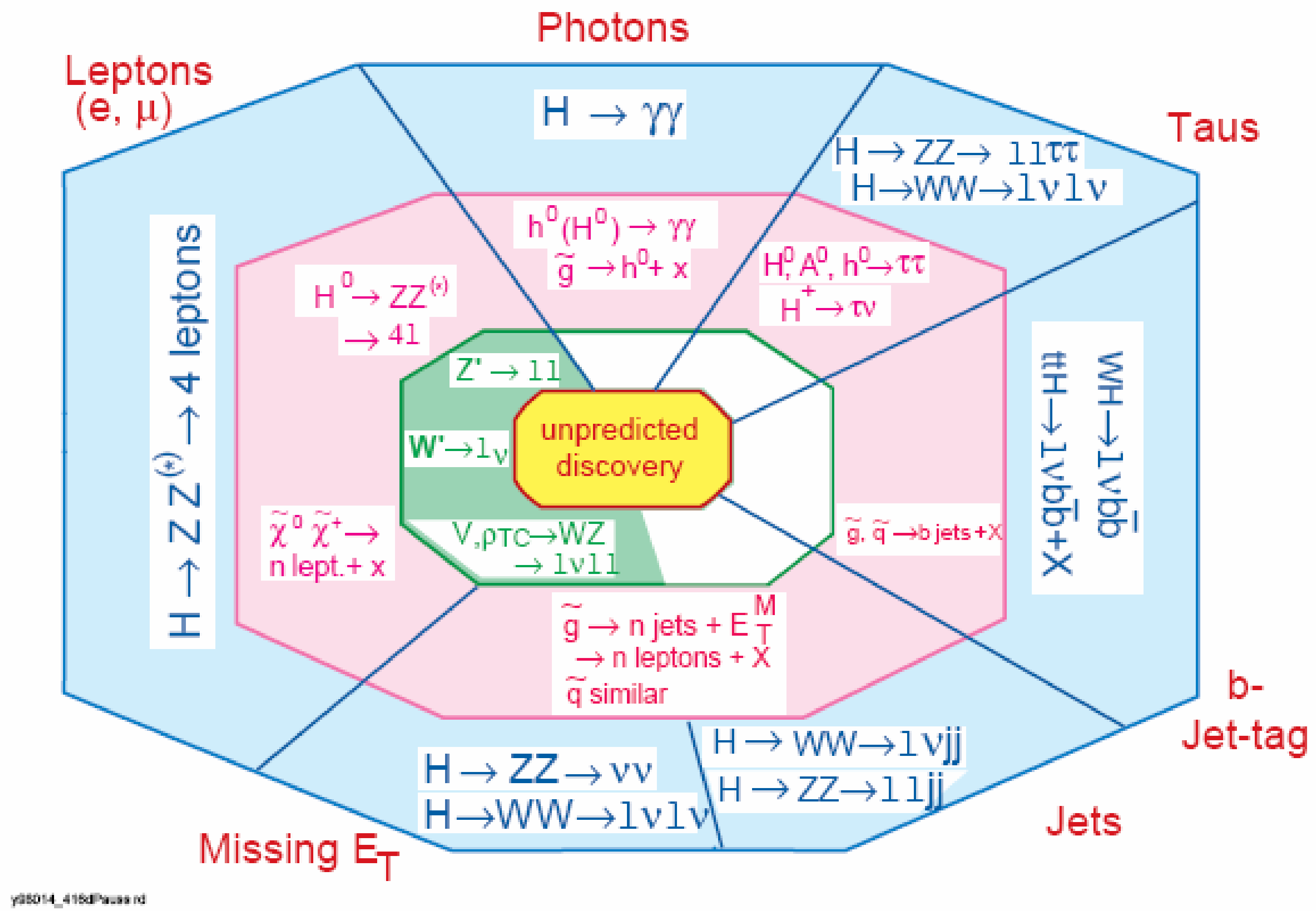
A Huge Enterprise !

- In total about 98 000 000 channels
- Size of 1 event 1 000 000 Bytes
- Readout to disk 100 events/sec

Particles in the detector



How to search for new particles?



T Han

Kinematic Variables for pp and ep (ee)

- 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

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

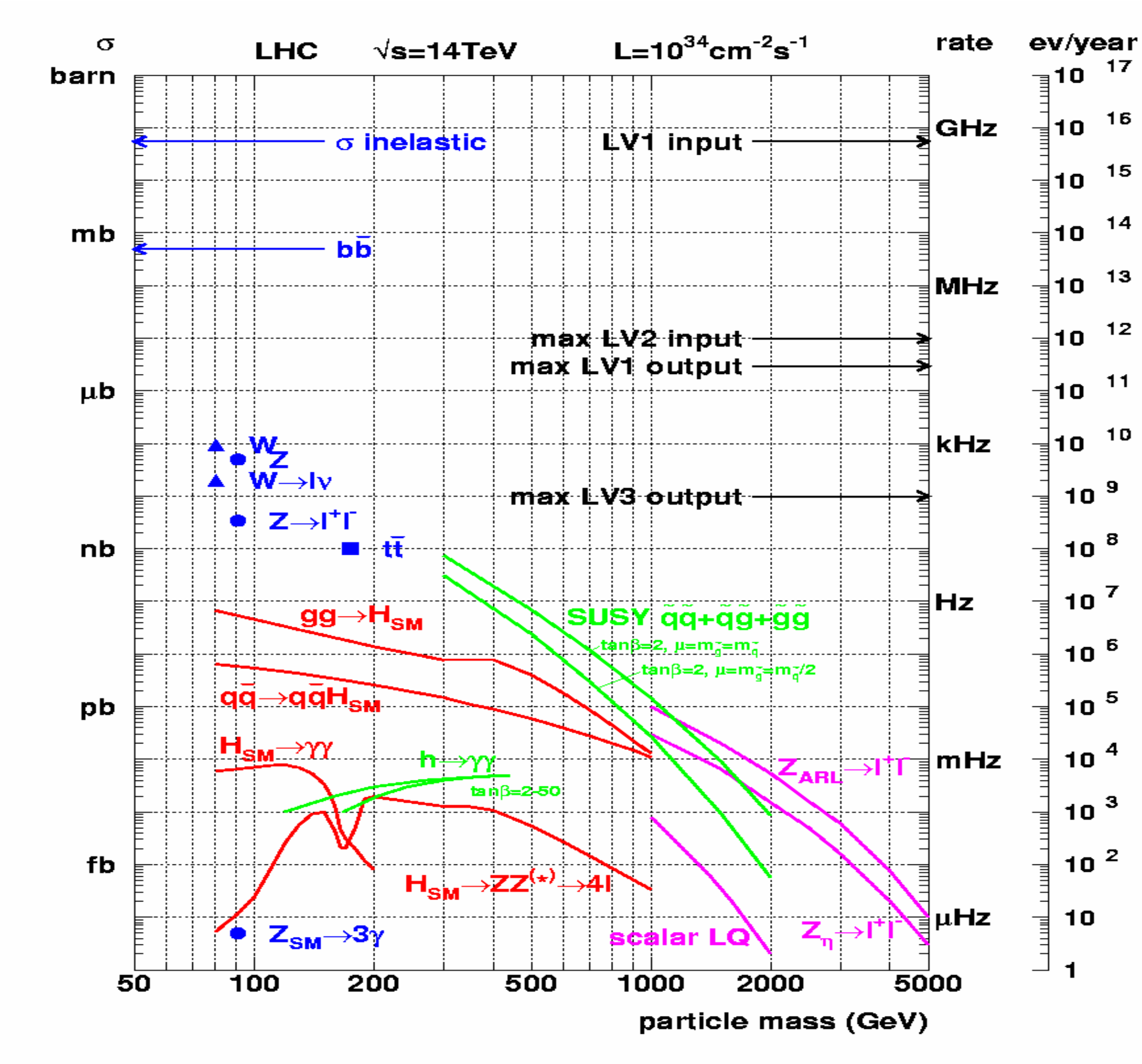
For M=0

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

- Missing E_T and P_T

Challenges for Experiments at the LHC

Cross sections at the LHC



"Well known" processes, don't need to keep all of them …

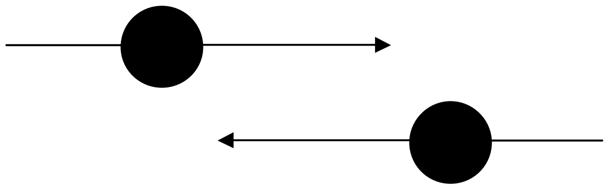
New Physics!!

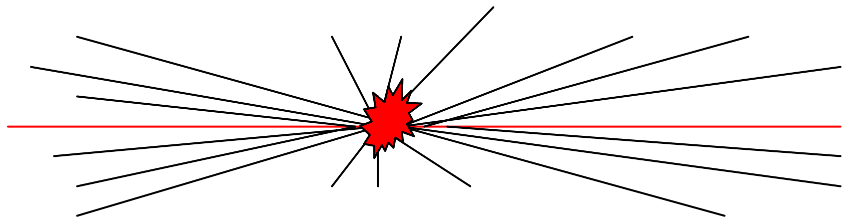
This we want to keep!!

Proton-proton collisions

Most interactions due to collisions at large distance between incoming protons where protons interact as " a whole "
→ small momentum transfer ($\Delta p \approx \hbar / \Delta x$)

→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

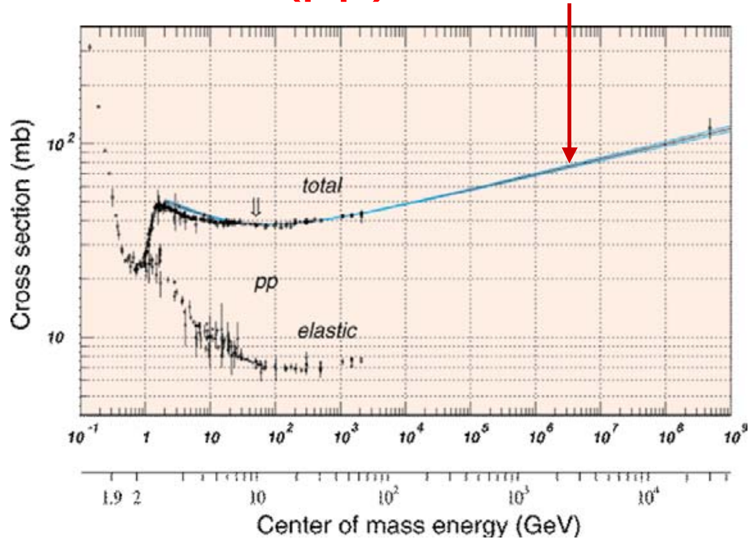
Most energy escapes down the beam pipe.

These are called minimum-bias events (" soft " events)..

pp cross section and min. bias

- # of interactions/crossing:
  - Interactions/s:
    - Lum = 10^{34} $cm^{-2}s^{-1}$=$10^7 mb^{-1}$Hz
    - $\sigma(pp)$ = 70 mb
    - Interaction Rate, R = 7×10^8 Hz
  - Events/beam crossing:
    - Δt = 25 ns = 2.5×10^{-8} s
    - Interactions/crossing=17.5
  - Not all p bunches are full
    - Approximately 4 out of 5 (only) are full
    - Interactions/"active" crossing = 17.5 x 3564/2808 = 23

$\sigma(pp)\approx$70 mb(*)



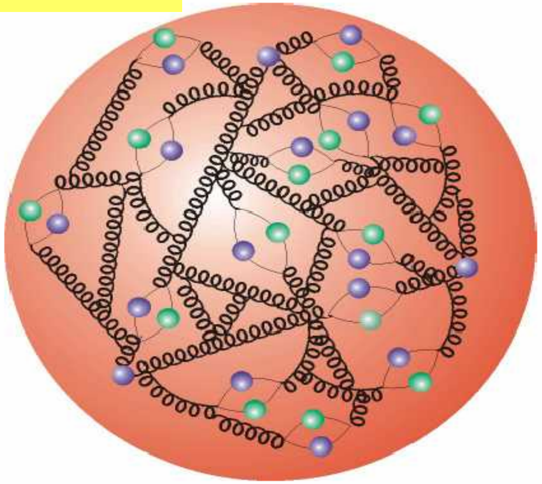
Operating conditions (summary):

1) A "good" event containing a Higgs decay +
2) ≈ 20 extra "bad" (minimum bias) interactions

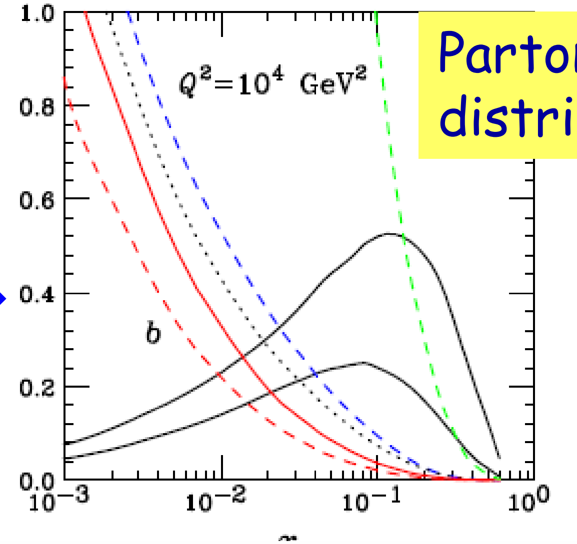
(*)Non-diffractive cross section

pp collisons : complications

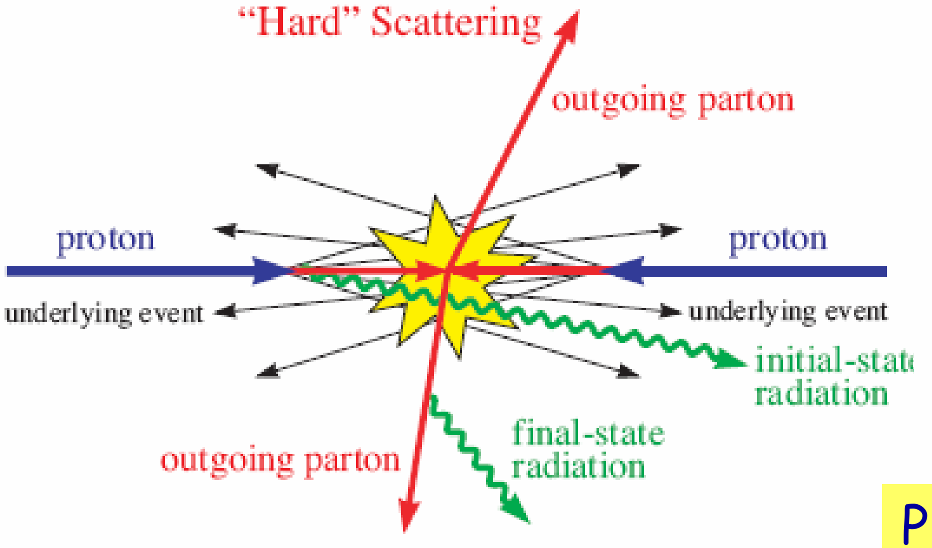
Protons have structure



Parton distributions

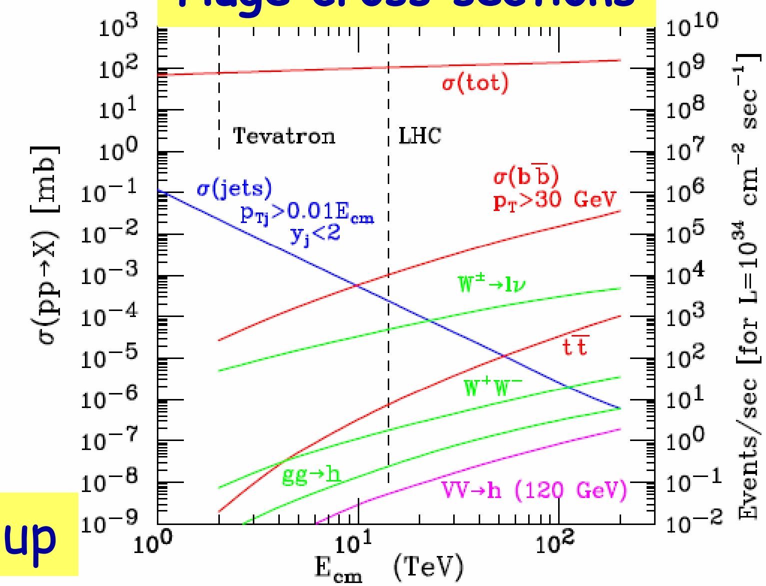


Underlying event



Scattering cross sections for various SM processes:

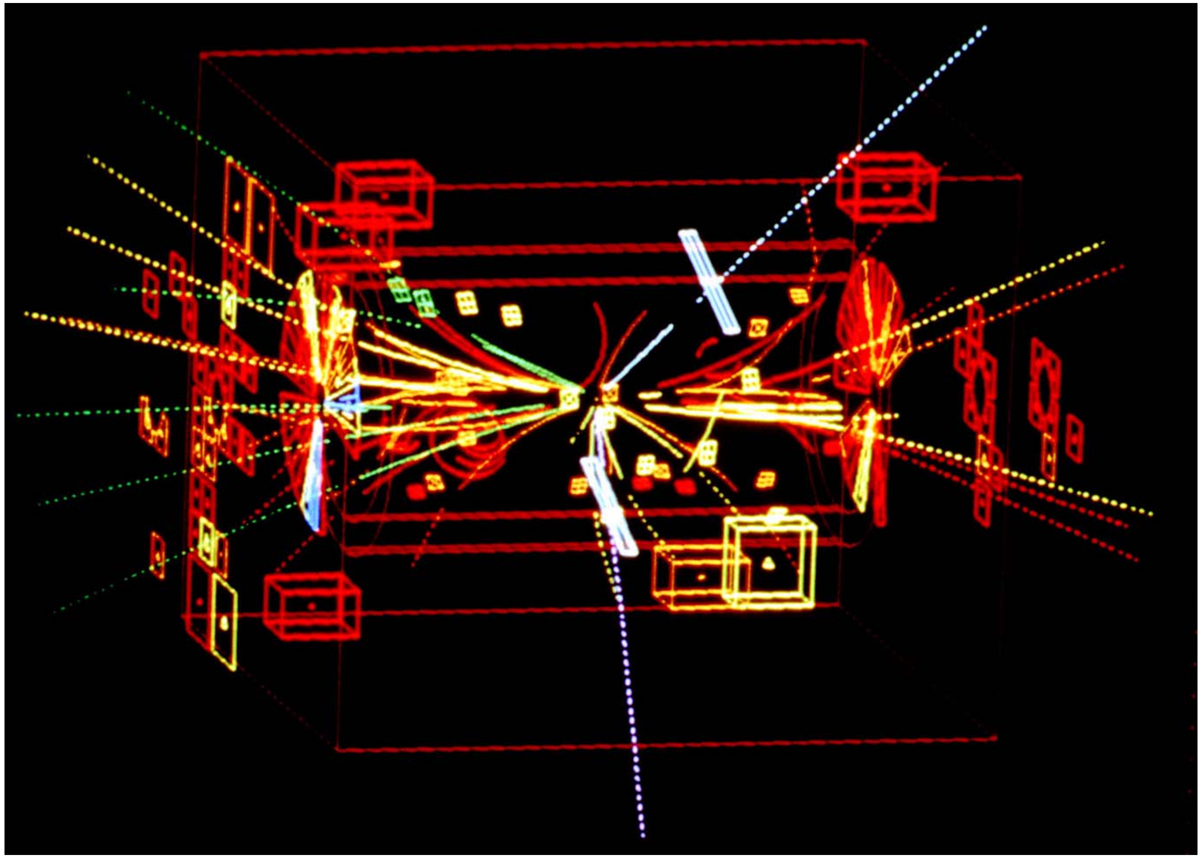
Huge cross sections



Pile-up

Proton –(anti) Proton colliders
Discoveries are possible

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



Collaboration includes Helsinki Univ.

'Picture' of the first

$p\bar{p} \rightarrow Z + X$
$\rightarrow e^+e^- + X$

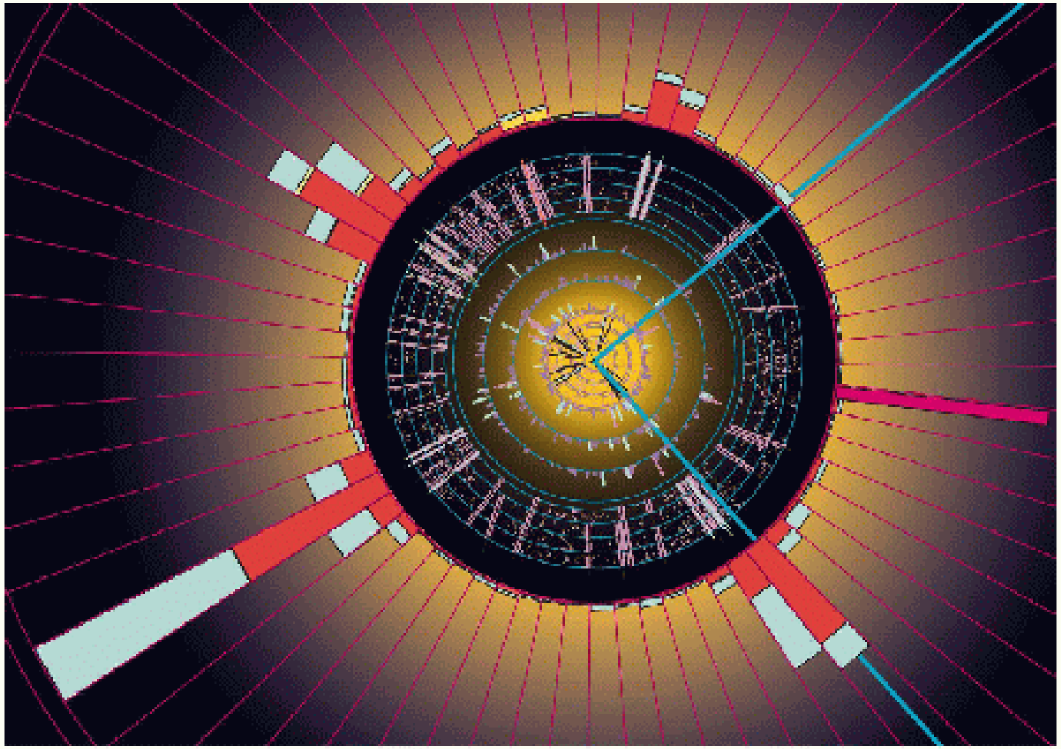
event in the UA1 detector at the SppS, for a centre of mass energy ($\sqrt{s}$) = 630 GeV

(30/4/1983)
Success story of the SppS machine at CERN rebuilt from a fixed target machine to a collider

Discovery of the Top Quark

Recent Steps

The Last Quark



Top Quark discovered at Fermilab

1994
Top mass
174 +/- 5 GeV

i.e. this quark is as heavy as a gold nucleus

In 2000: also the Tau-neutrino was seen directly
(DONUT exp. at FNAL)

All 3 families in the SM are now complete

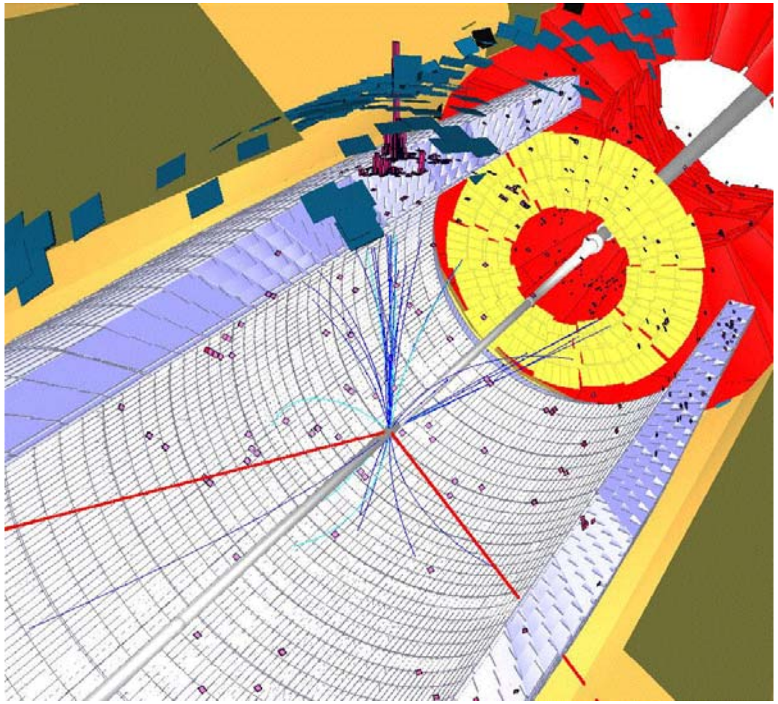
Pile-up at the LHC

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

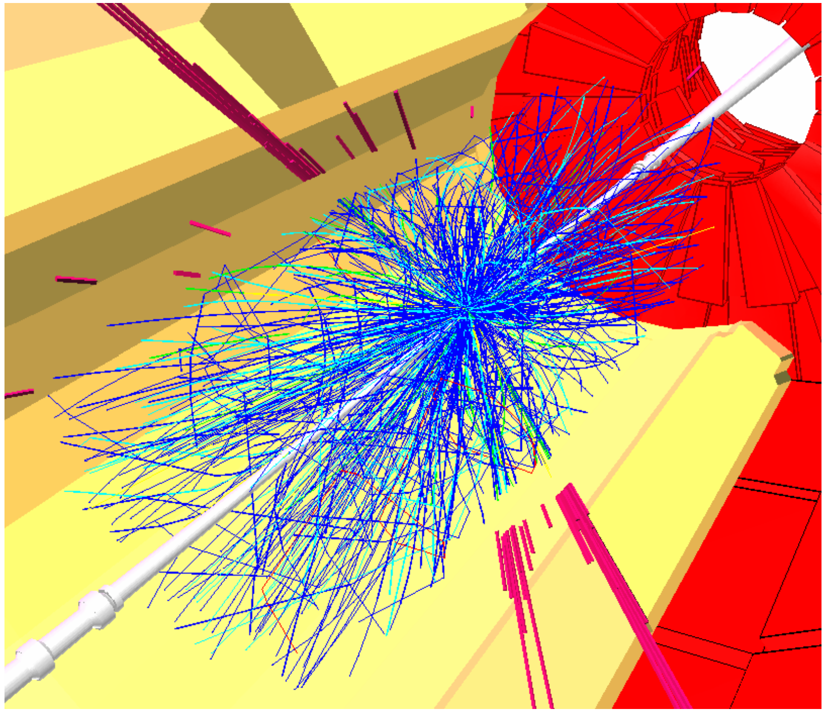
Startup luminosity $2 \bullet 10^{33} cm^{-2} s^{-1}$ ⇒ 4 events per bunch crossing

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)

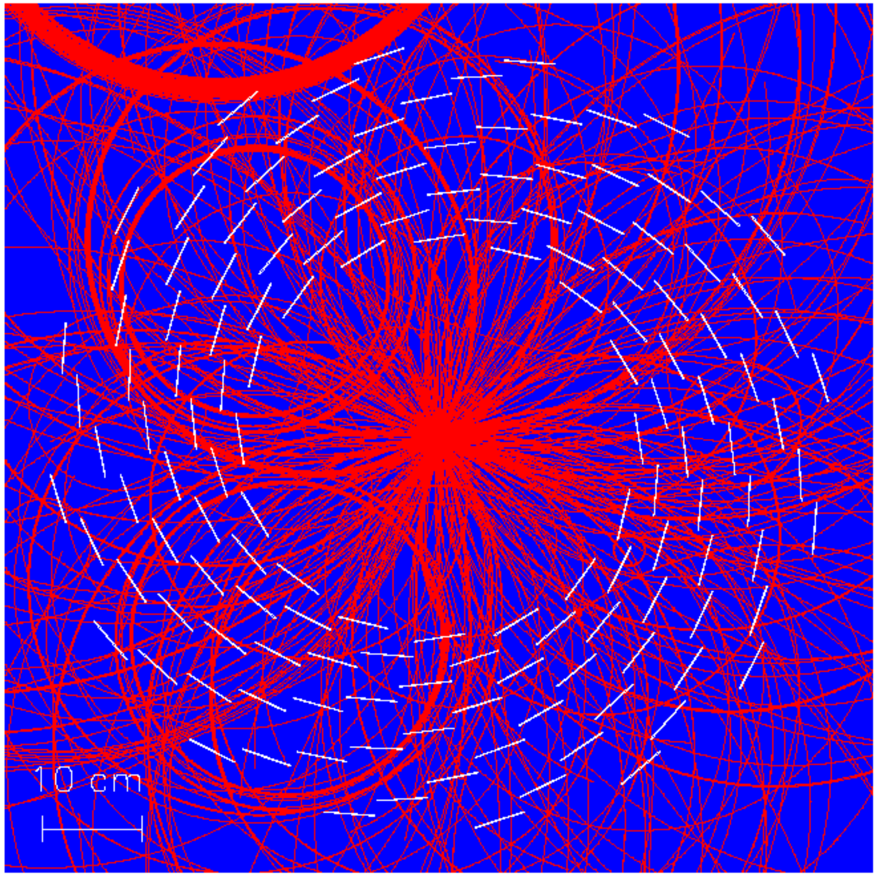


SUSY event ($10^{34} cm^{-2} s^{-1}$)

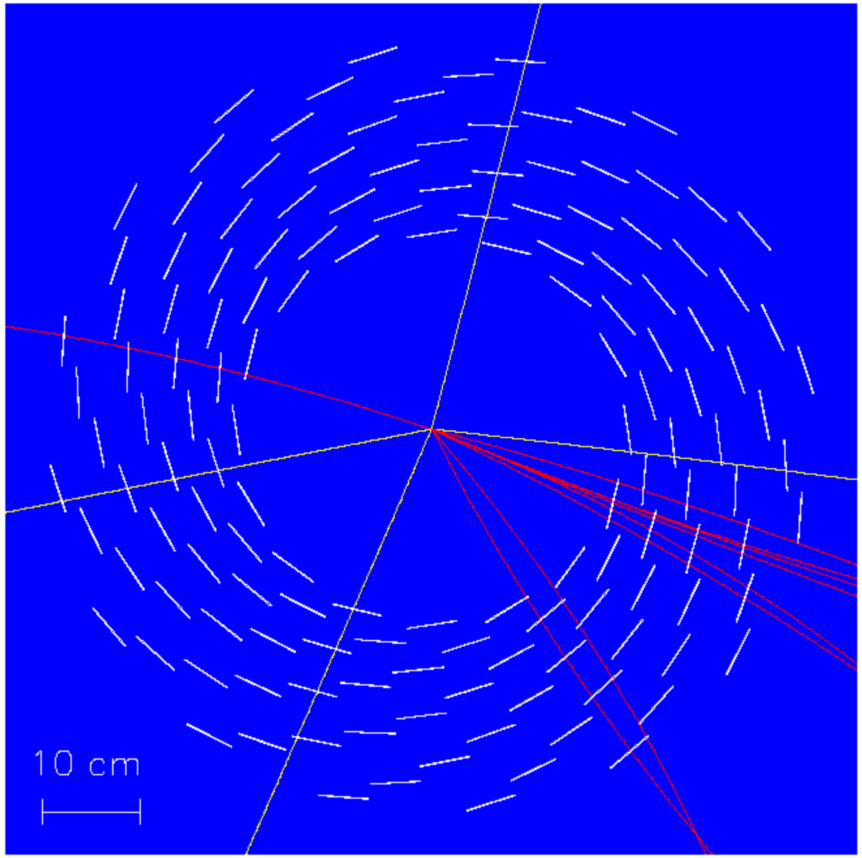
How to find the interesting signals

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

↳ X ~ 100 charged particles



All tracks shown



Only tracks with transverse momentum > 2 GeV shown

Large Event rates

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	—
QCD jets $p_T > 200$ GeV	10^2	10^9	10^7

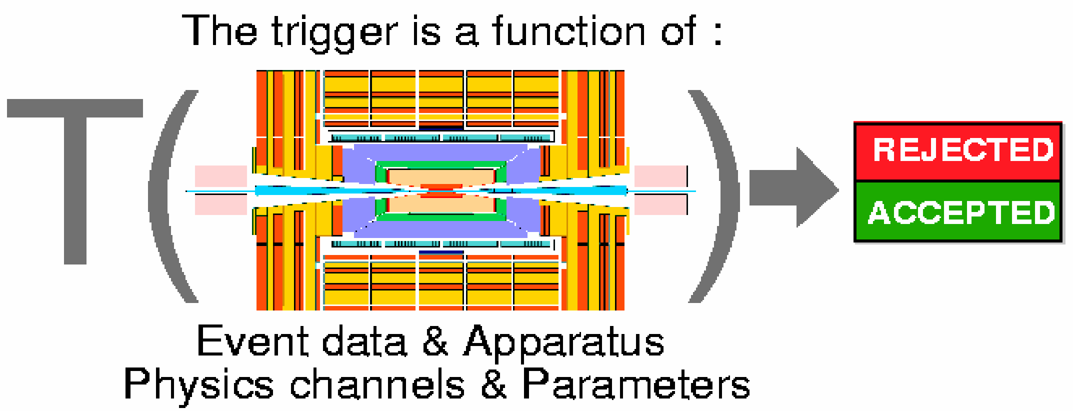
Huge event rates:
($10^{33} cm^{-2} s^{-1}$)

The LHC will be a W-factory, a Z-factory, a top factory, a Higgs factory etc..

Precision EW physics will be limited by systematics

Event filtering: the trigger system

Collision rate is 40 MHz   Event size ~1 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 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

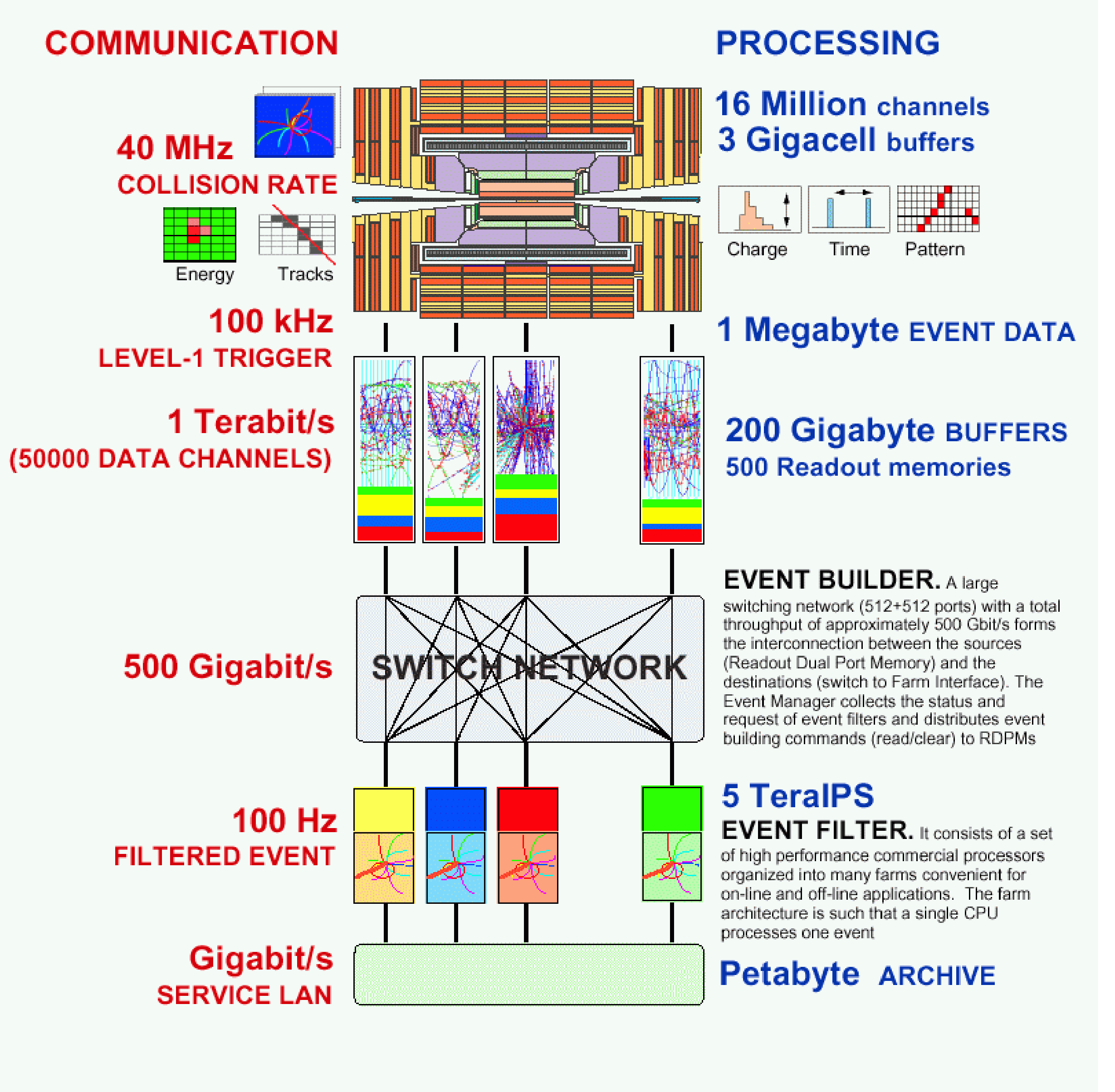
Similar numbers for ATLAS

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

“Typical data at the LHC”

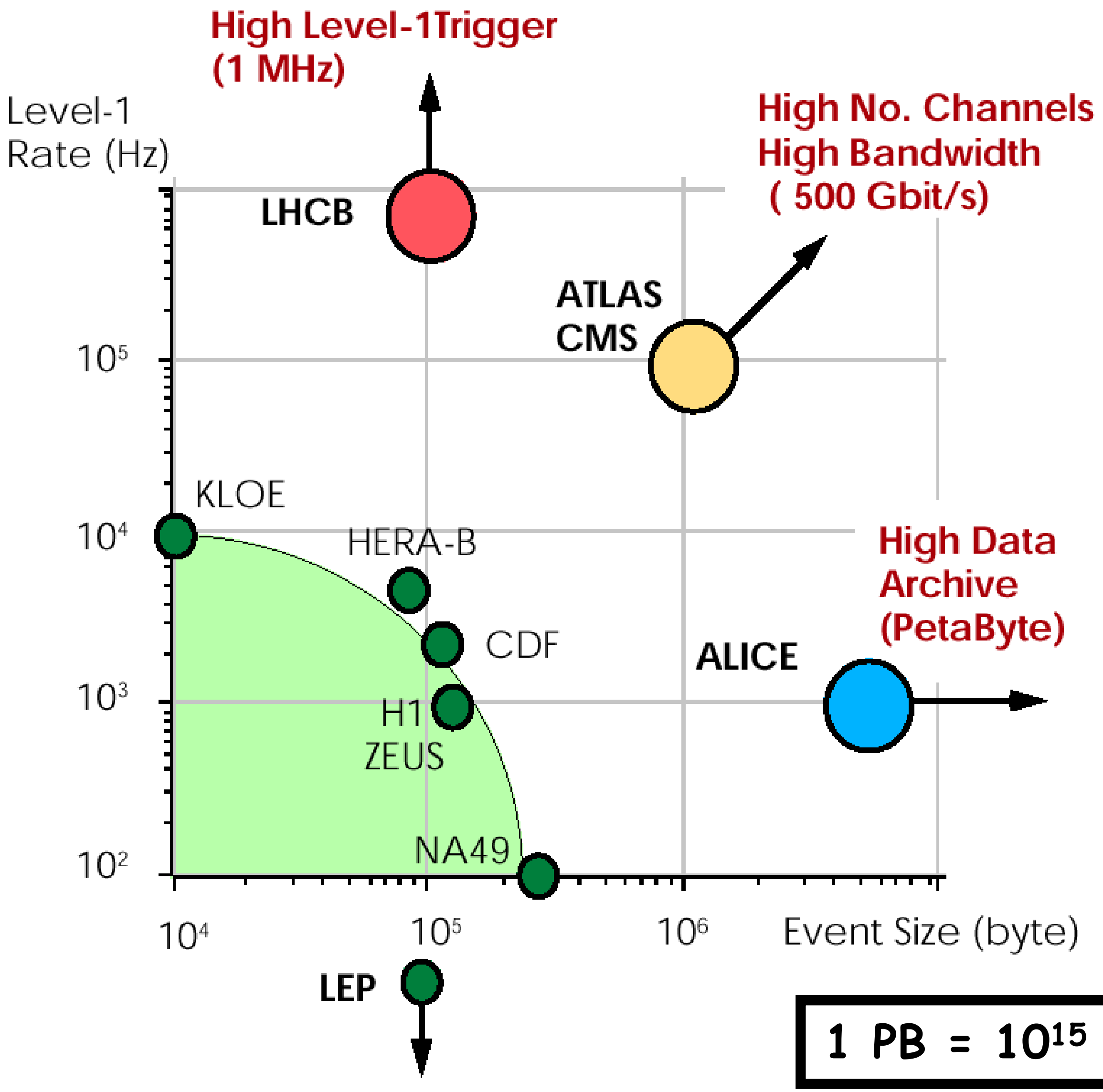
detector	channels	occupancy	event size
pixels	80 000 000	0.01 %	100 kB
microstrips	16 000 000	3 %	700 kB
preshower	512 000	10 %	50 kB
calorimeter	125 000	5 %	50 kB
muon detector	1 000 000	0.1 %	10 kB
Total event size			1 MB

Trigger/DAQ schemes: a challenge



Tera : 10^{12}; Peta 10^{15}; IPS : Instruction Per Second; LAN : Local Area Network

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

GRID Computing

Interconnecting computing power

A complex problem by itself

Example EGEE
Others: Nordic Grid, US grid,...

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

….

Summary of Lecture 1

- LHC is getting completed
  - Expect operation starting in 2007
    - November 2007 collisions at 900 GeV CMS
    - Spring/summer 2008 collisions at 14 TeV
  - The LHC will be a challenging machine to operate.
- Experimental challenges
  - The experimental challenges at the LHC are considerable
  - Pile-up, triggers, computing, (radiation)…
  - Experiments are facing these challenges and are nearing completion
  - Tomorrow: How CMS and ATLAS are dealing with these challenges…