Early Physics at the LHC

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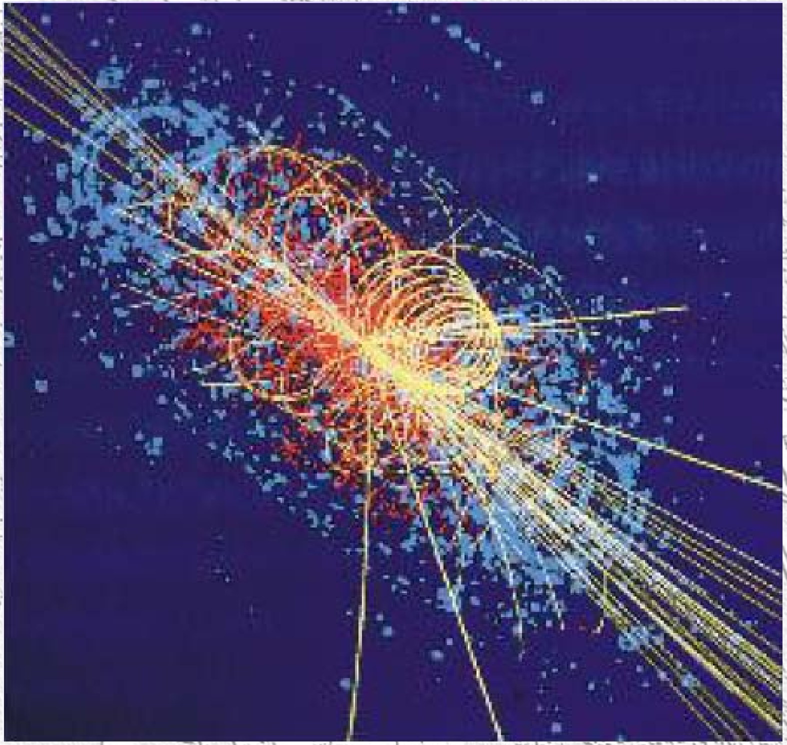
Outline

- Lecture 1:
  Physics at proton colliders
  Status of LHC & experiments

- Lecture 2:
  Standard Model physics

- Lecture 3:
  Searches for new particles & phenomena
  e.g. Higgs and SUSY



Today's Questions and Problems

- Are quarks and leptons really elementary?
  e.g. structureless, pointlike objects?
- Why are there 3 families?
- Are there additional forces and gauge bosons?
- What is the origin of the matter-antimatter asymmetry in the universe?
  What is the origin of CP violation?
- What is dark matter (≈ 20% of the universe) and dark energy (≈ 75%)?
- …
- Answers to these questions need
  - experiments at high energy
  - and with high precision

Future Experiments

- **Discoveries**
  - Increase collision energy to explore TeV region
    - explore the allowed Higgs mass range
    - search for Supersymmetry
    - and other new physics phenomena
    - be prepared for the unexpected

    → LHC

- **Precision measurements and tests of the SM**
    - measure SM parameters m_W, m_t
    - measure properties of new particles (Higgs, SUSY)
    - and check consistency of the model

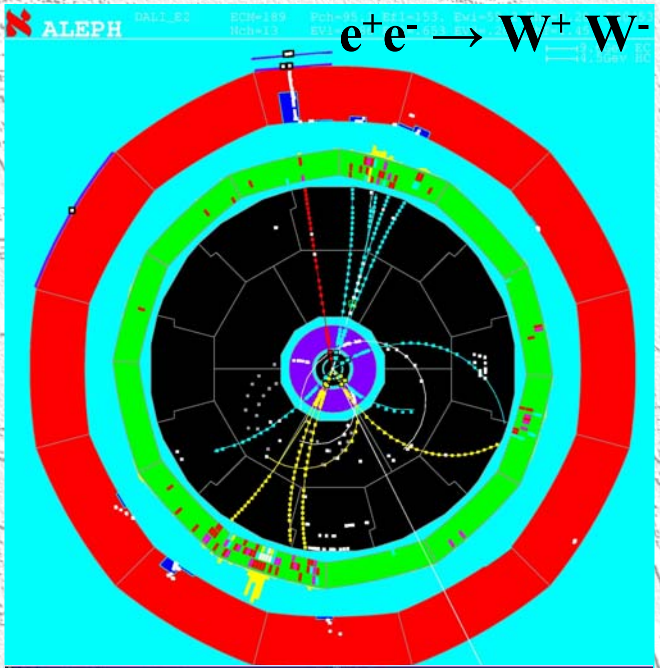
    → LHC & ILC

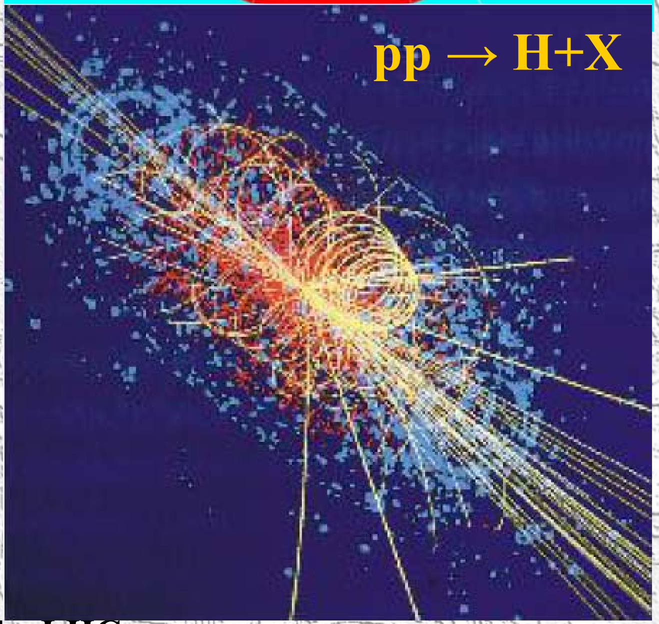
Proton Collider

- **Why a proton collider like the LHC?**

  e^+e^- machines like LEP are ideal machines for precision emasurements:
  - **e^+/e- are point-like, no substructure → very clean events**
  - **centre-of-mass system**
  - **event kinematics completely fixed**

Events at proton collider are much more complex:
- **protons are not elementary**
- **hard scattering of partons (quarks & gluons)**
- **underlying event**
- **use only part of the beam energy**
- **event kinematics only partially constraint**





Problem of Electron Storage Rings

Drawback of circular electron colliders like LEP:
Energy loss due to synchrotron radiation
(Accelerated charge does radiate photons!)

- Radiated power P (in synchrotron photons) ring with radius R and energy E

$$P = \frac{2\, e^2\, c}{3\, R^2} \left(\frac{E}{mc^2} \right)^4$$

- Energy loss per turn

$$-\Delta E \approx \frac{4\, \pi\, e^2}{3\, R} \left(\frac{E}{mc^2} \right)^4$$

- Ratio of energy loss between electrons and protons

$$\frac{\Delta E(e)}{\Delta E(p)} = \left(\frac{m_p}{m_e} \right)^4 \sim 10^{13}$$

To reach higher energies at future colliders:

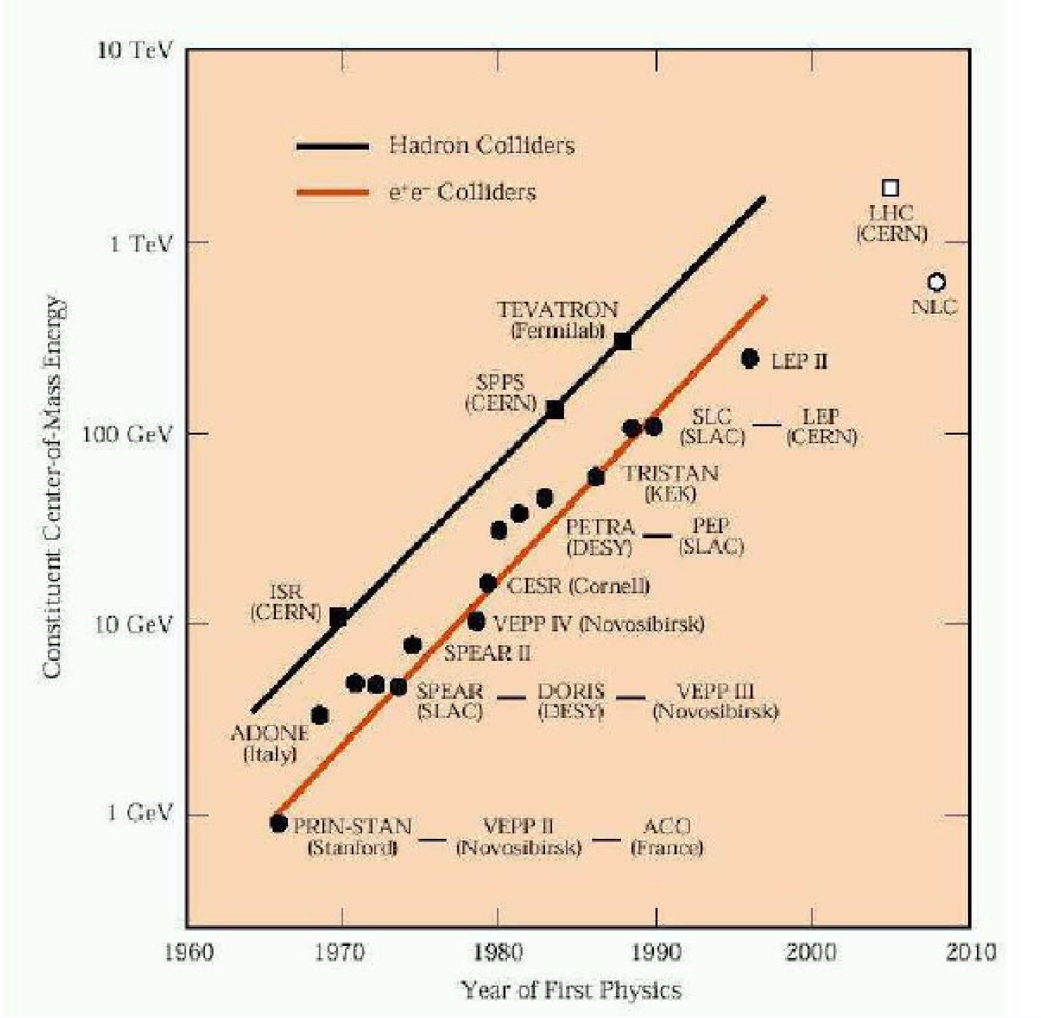
a) Linear electron-positron colliders (→ ILC)

b) Proton colliders (→ LHC)

LHC uses existing LEP tunnel!

History of Colliders

Comparison of past and future electron and proton colliders:



The Tevatron Collider at Fermilab

Proton-Antiproton Collider

- **1992 - 1996**
  Run I with 2 experiments CDF and D0
  $\sqrt{s}$ = 1.8 TeV
  $\int L dt = 125\ pb^{-1}$

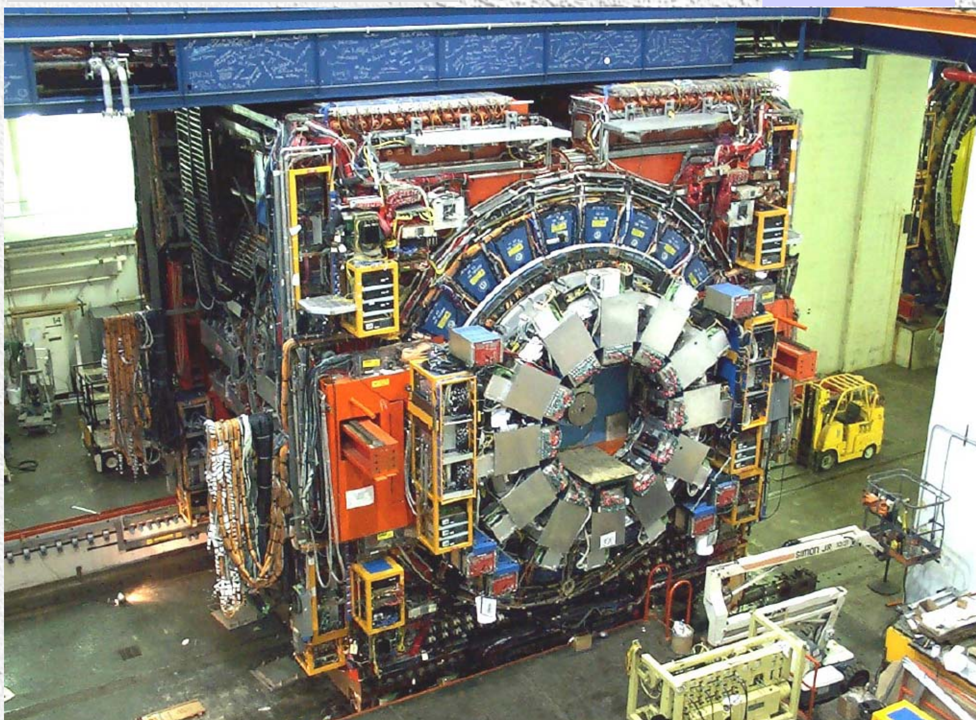
- **1996 – 2001 Upgrade**
  - new injector, antiproton recycler
    → higher luminosity
  - detector improvements

- **since March 2001**
  Run II, $\sqrt{s}$ = 1.96 TeV

Both experiments are running collecting & analysing data

Experiments at the Tevatron

The CDF detector

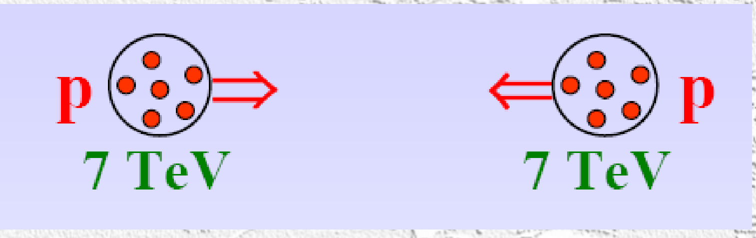


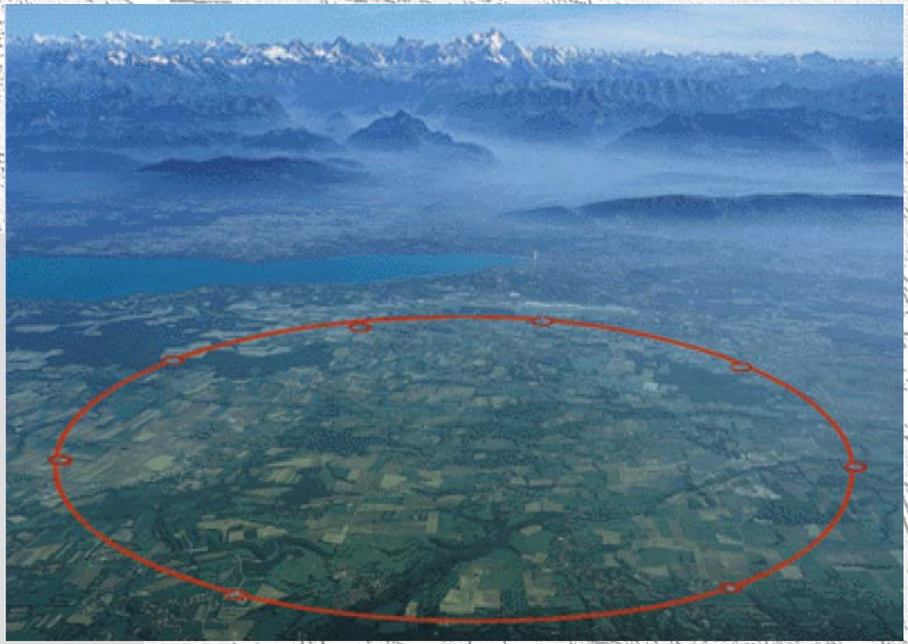
The D0 detector

≈ 700 physicists/collaboration

The Large Hadron Collider (LHC) at CERN

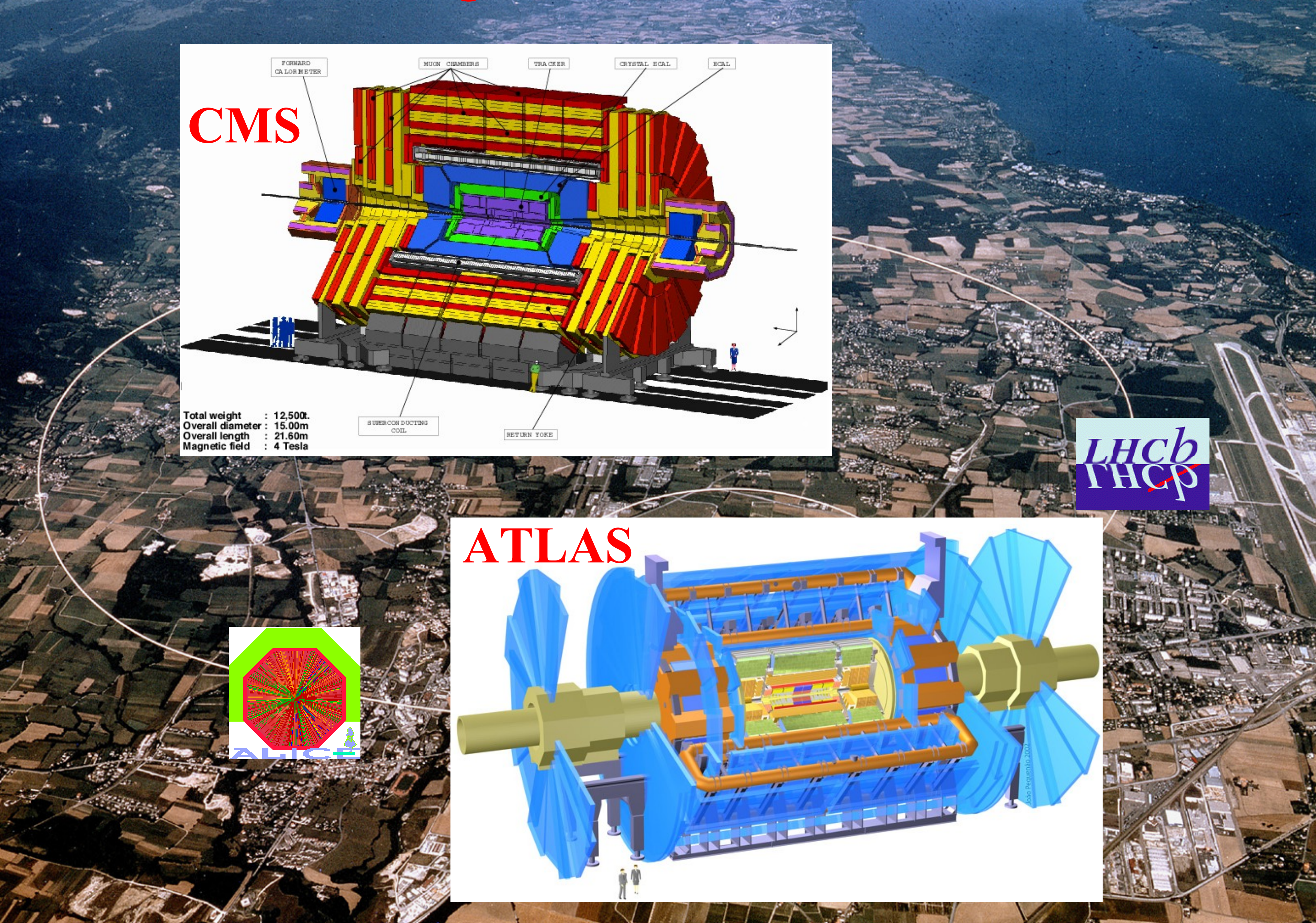
- Proton-proton collider in the former LEP tunnel at CERN (Geneva)





- Highest ever energy per collision
  14 TeV in the pp-system
- Conditions as $10^{-13} - 10^{-14}$ s after the Big Bang
- 4 experiments:
  ATLAS
  CMS
  LHC-B specialised on b-physics
  ALICE specialised for heavy ion collisons
- Constructed in worldwide collaborations
- Start planned for 2008

The Large Hadron Collider LHC



Challenges for the LHC

- Superconducting dipole magnets to keep 7 TeV protons on circular path (r ≈ 3 km)

  |B| = 8.33 Tesla

- 1232 dipole magnets are needed
  (+ quadrupole, sextupoles etc.)
  each dipole is 15 m long

- 1.9 K operating temperature
  supraliquid He
  largest cyrogenic facility in the world

- Quench protection
  stored energy in one dipole: 8 MJ

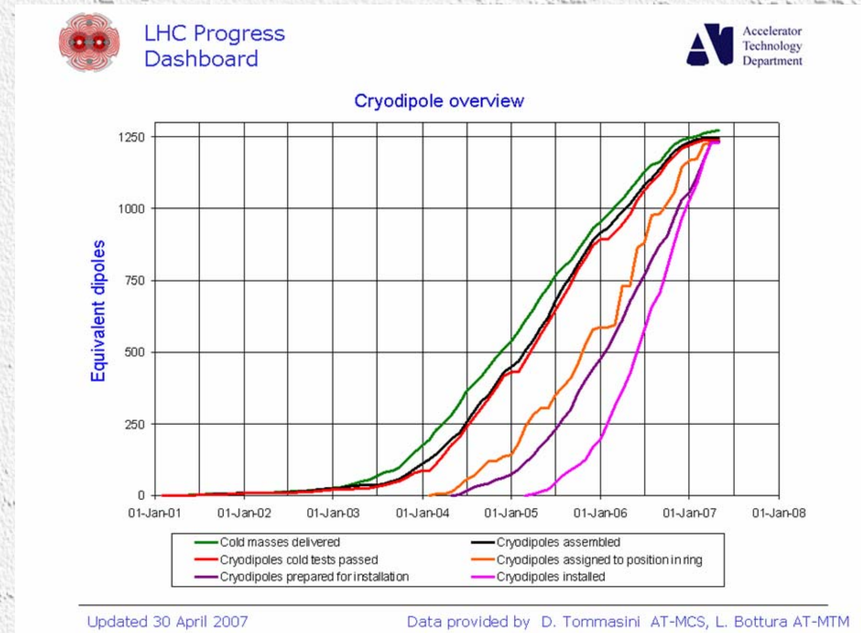
  corresponds to a
  40 t truck at 50 km/h!

- LHC dipole design
  incoporates reversed field for oppositely rotating proton beam

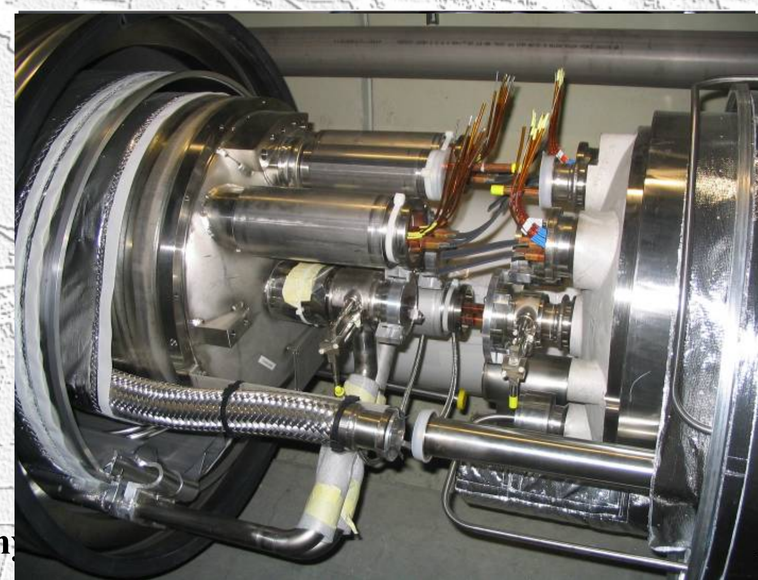
BTW:
the stored energy in the LHC proton beams is 350 MJ
enough to melt 500 kg of copper!

Status of the LHC

- Example dipoles:
  all 1232 dipoles built and installed



- Last dipole lowered on April 26, 2007



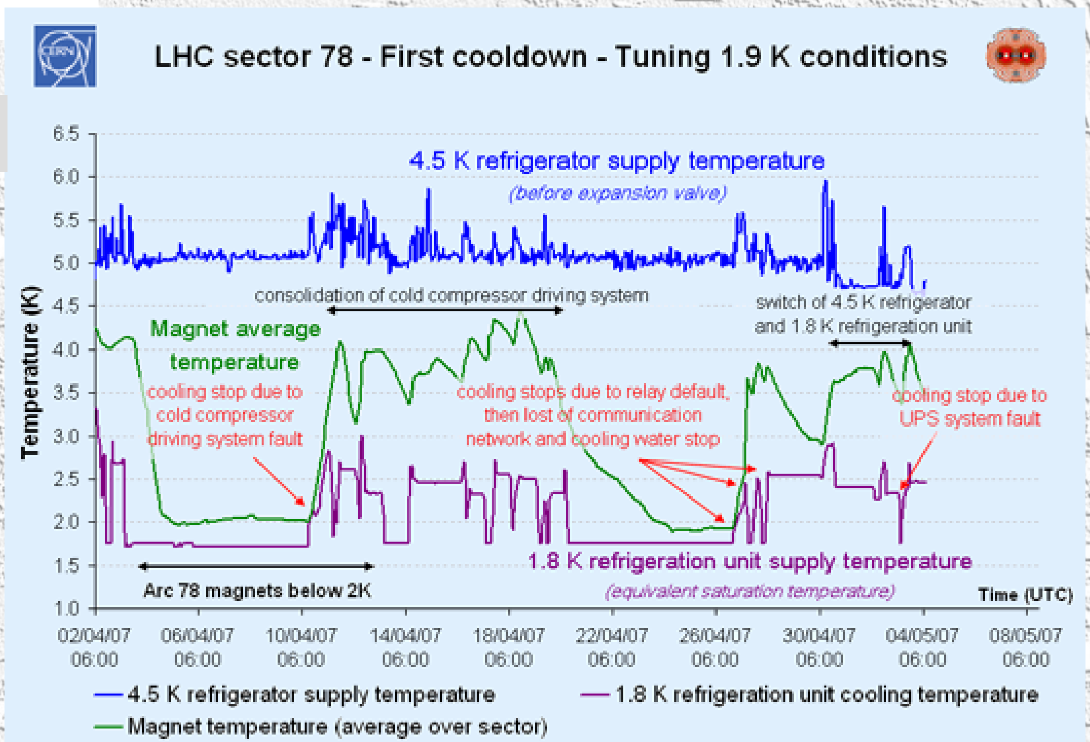
- All magnets prepared on schedule
- Interconnections on-going in 6 sectors
  - sector 7-8 ready
  - closure of 4-5 and 8-1 upcoming

LHC schedule: first beam in 2008

Status of the LHC

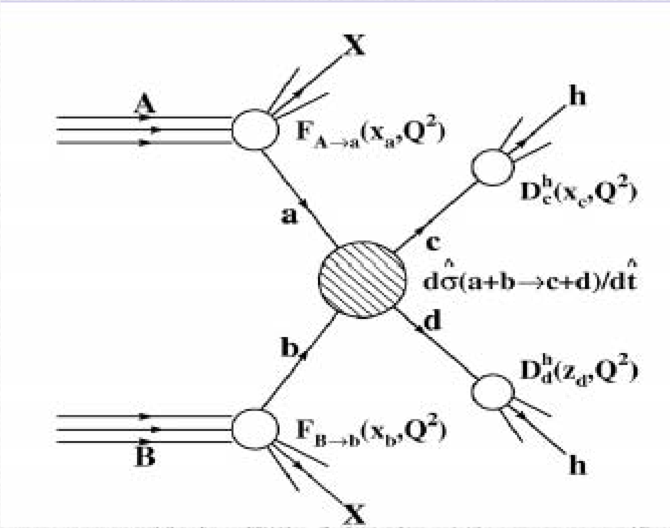
- **Cryogenics complete**

- **First cooldown April 2007:**



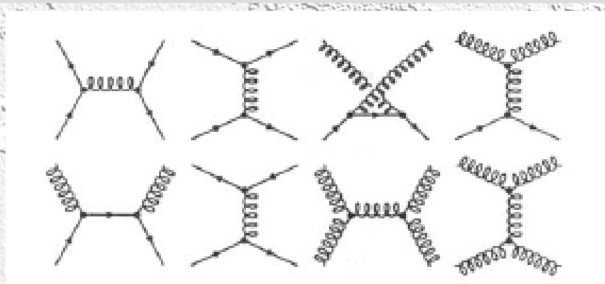
- **1.9 K: The coldest place in the universe!**

Physics at Proton Colliders



- **Protons are composite, complex objects**
  - partonic substructure
  - quarks and gluons

- **Interesting hard scattering processes**
  quark-(anti)quark
  quark-gluon
  qluon-gluon

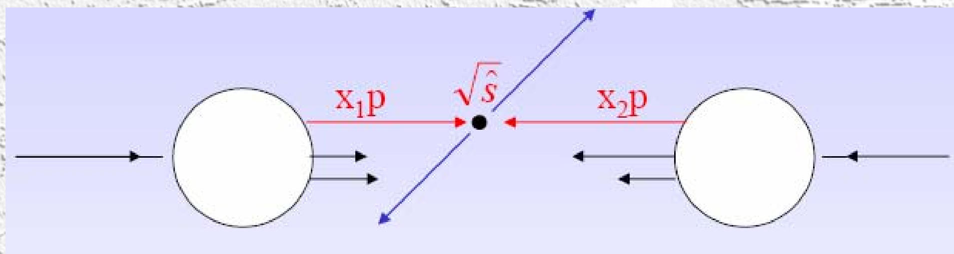


However, hard scattering (high momentum transfer) processes are only a small fraction of the total cross section

- total inelastic cross section ≈ 70 mb (huge!)
- dominated by events with small momentum transfer

Proton-Proton Collisions

- Proton beam can be seen as beam of quarks and gluons with a wide band of energies
- The proton constituents (partons) carry only a fraction $0 \leq x \leq 1$ of the proton momentum



- The effective centre-of-mass energy $\sqrt{\hat{s}}$ is smaller than $\sqrt{s}$ of the incoming protons

$$\left.\begin{aligned} p_1 &= x_1\, p_A \\ p_2 &= x_2\, p_B \\ p_A = p_B &= 7\ \text{TeV} \end{aligned}\right\} \quad \sqrt{\hat{s}} = \sqrt{x_1\, x_2\, s} = x\sqrt{s}$$

$$(\text{if } x_1 = x_2 = x)$$

Note:

- the component of the parton momentum parallel to the beam can vary from 0 to the proton momentum ($0 \leq x \leq 1$)
- the variation of the transverse component is much smaller (of order the proton mass)

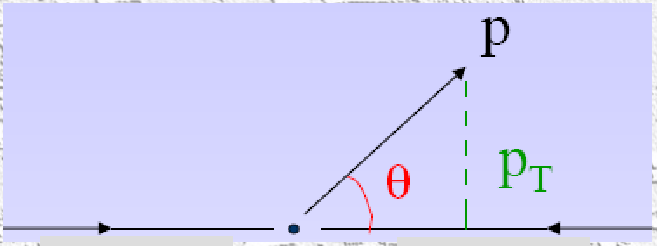
To produce a particle of mass		
mass	LHC	Tevatron
100 GeV	$x \approx 0.007$	$x \approx 0.05$
5 TeV	$x \approx 0.36$	---

Variables in pp Collisions

Kinematics fully defined only in transverse plane

Transverse momentum p_T

$p_T = p \sin\theta$



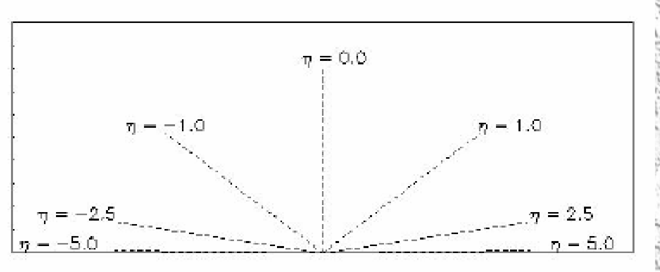
proton **proton**

Rapidity: $$y = \frac{1}{2}\ln\frac{E+p_L}{E-p_L}$$

Differences in y are invariant under Lorentz boosts

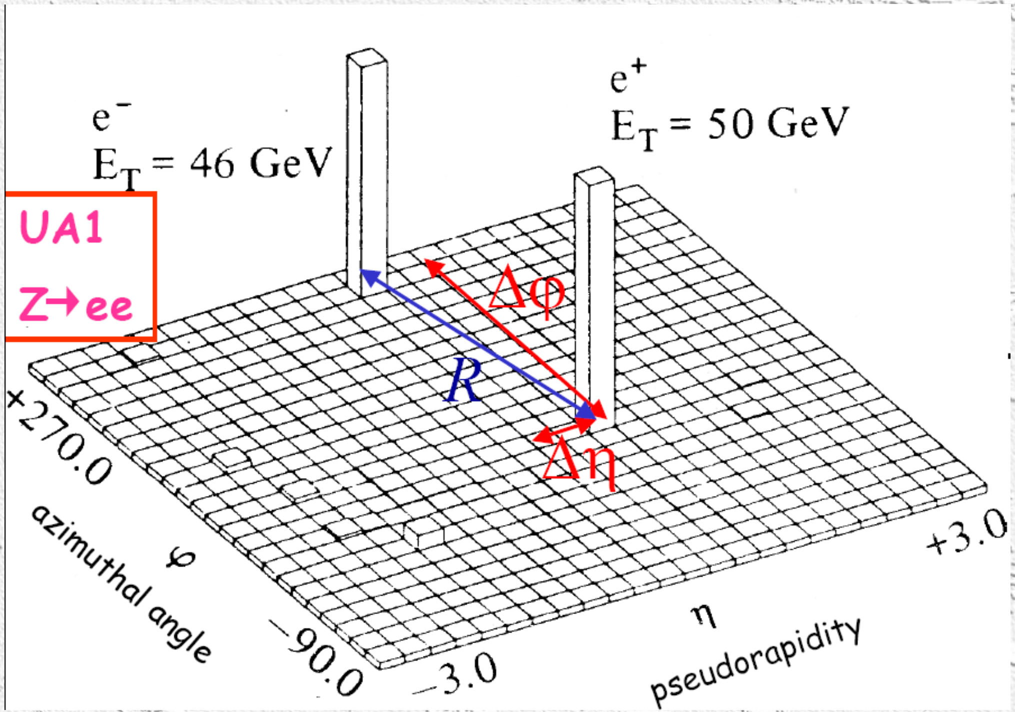
Pseudo-rapidity: $$\eta = -\ln\tan\frac{\theta}{2}$$

handy approximation, do not need to know the particle mass



θ = 90°	η = 0
θ = 10°	η ≈ 2.4

Rapidity and Pseudo-Rapidity



distance measure:

$$R^2 = (\Delta\phi)^2 + (\Delta\eta)^2$$

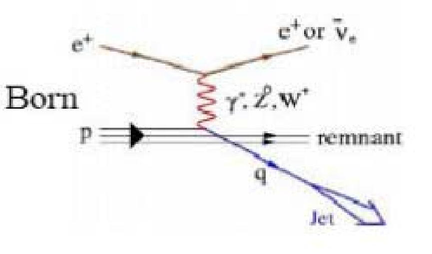
$$\Delta\phi = \phi_1 - \phi_2$$

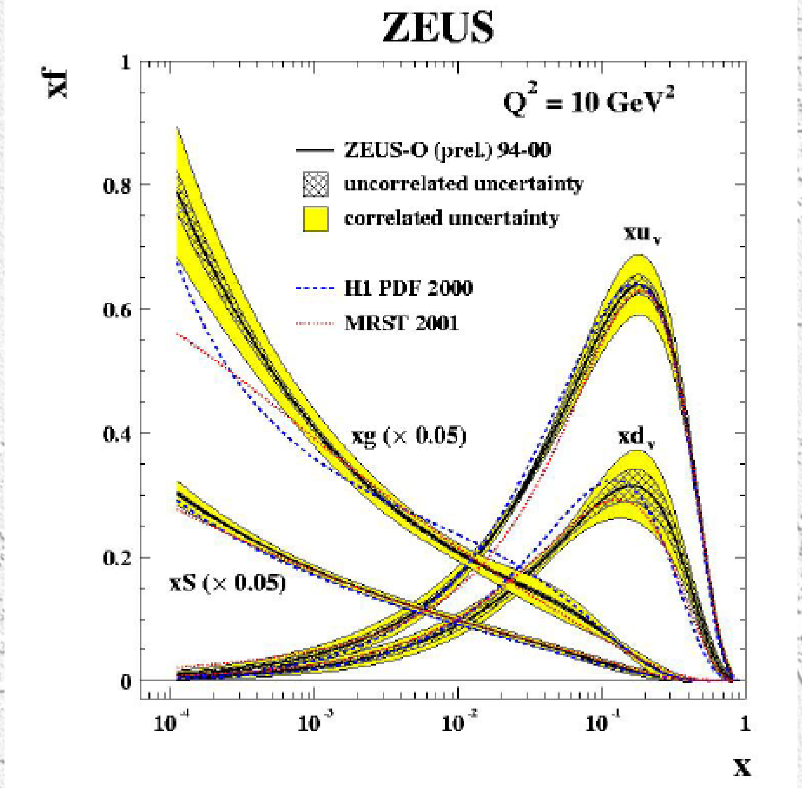
$$\Delta\eta = \eta_1 - \eta_2$$

rotation: $\Delta\eta$ = constant
boost: $\Delta\varphi$ = constant

Parton Density Functions

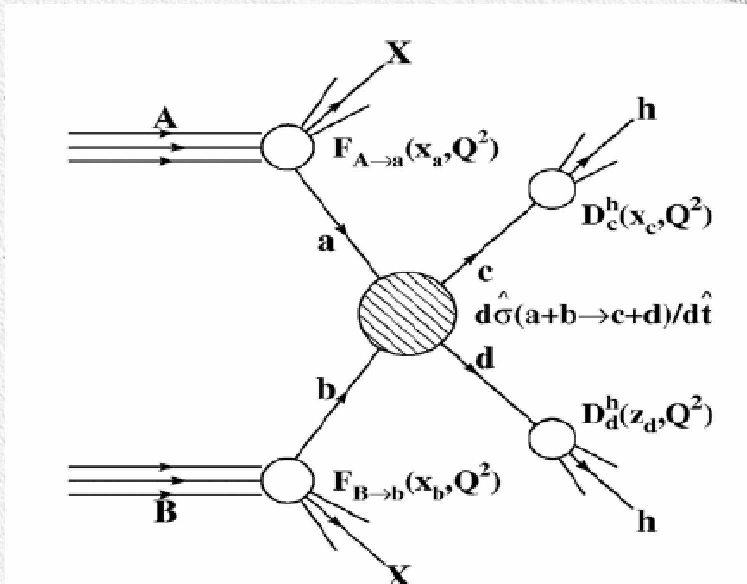
How do the distributions of the *x*-values look like?
Measured at HERA in ep-scattering, e.g.:





- **u- and d-quarks at large x-values**
- **gluons dominate at small x**
- **large uncertainties for gluons**

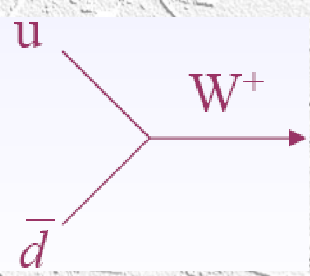
Cross Section Calculation



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

- **sum over initial states a,b**
- **$f_i(x_i,Q^2)$ = parton density functions**

- **Example: W production in leading order**



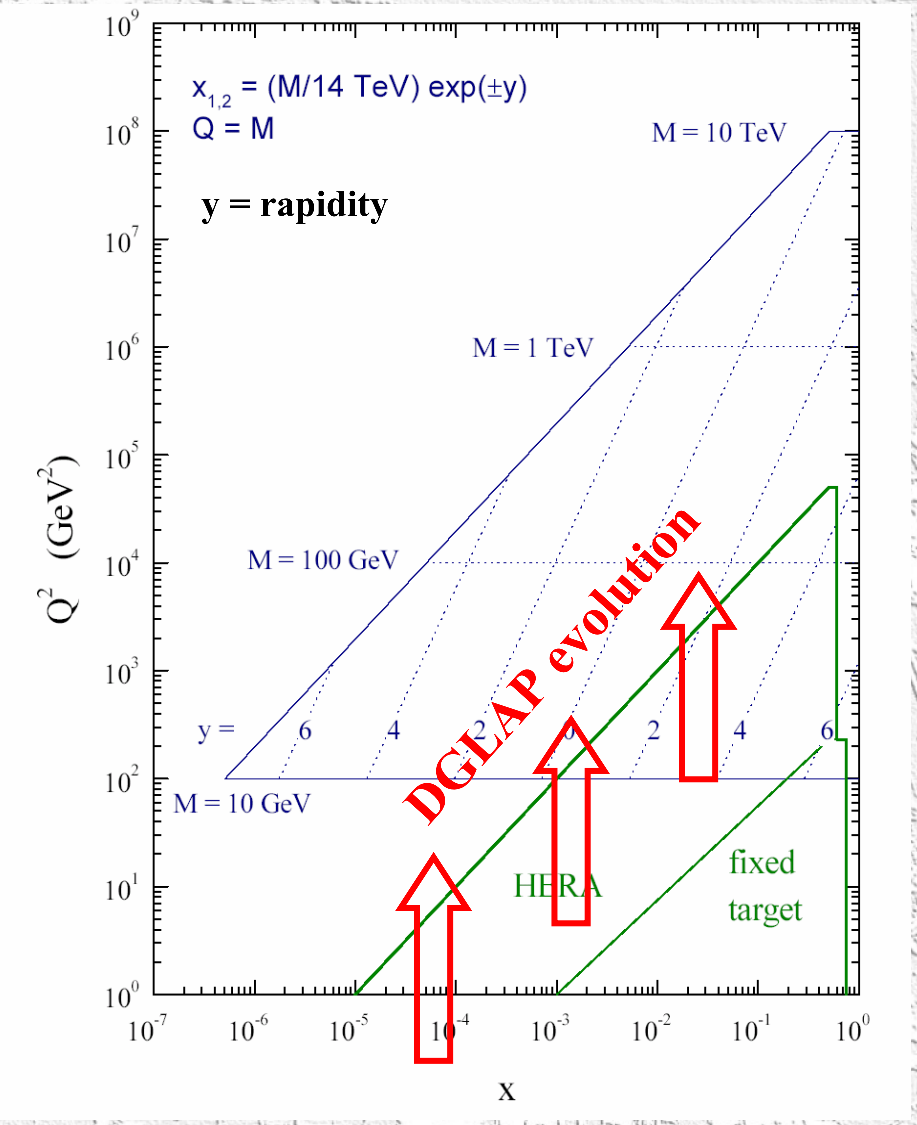
$\sigma(pp\to W) \approx 150$ nb $\approx 2\cdot 10^{-6}\, \sigma_{tot}$

Parton Density Functions at the LHC

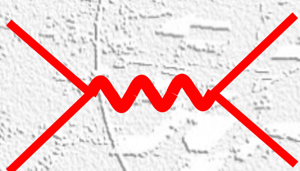
LHC is a proton-proton collider

But fundamental processes are the scattering of

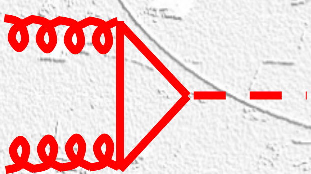
- **Quark – Antiquark**
- **Quark – Gluon**
- **Gluon – Gluon**



Examples:



$q\bar{q}$ → W → lν



gg → H

⇒ need precise PDF(x,Q²)
+ QCD corrections (scale)

Luminosity

Rate of produced events for a given process

$$N = \sigma L$$

σ cross section [barn = 10^{-24} cm^2]
L luminosity [1/cm^2/s]

- luminosity depends on machine parameters: number of protons stored, beam focus at the interaction point, …
- luminosity should be high to achieve acceptable rates for rare processes

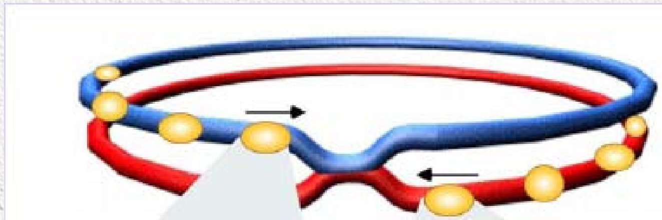
Comparison of colliders:

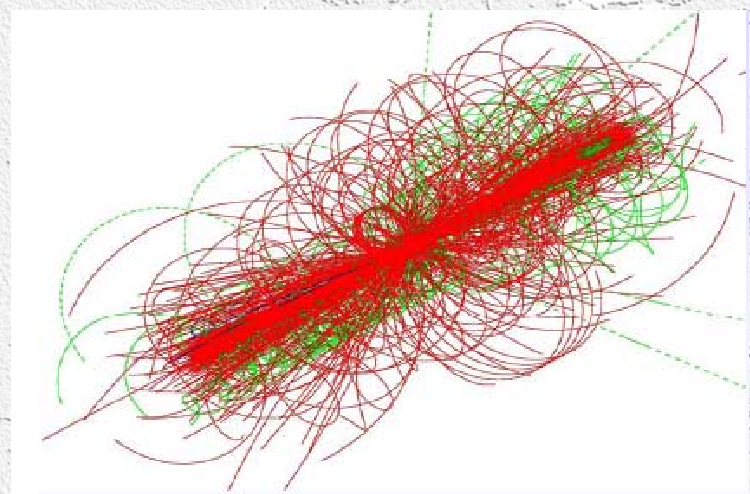
- 10^{31}/cm^2/s	LEP
- $2\cdot10^{32}$/cm^2/s	Tevatron Run II design
- 10^{33}/cm^2/s	LHC initial phase (≈ 3 years)
- 10^{34}/cm^2/s	LHC design luminosity (> 2010)

1 experimental year is about 10^7 s

- 10 fb^{-1} per year in the initial LHC phase
- 100 fb^{-1} per year later

Proton-Proton Collisions at the LHC





- 2835 + 2835 proton bunches
  separated by 7.5 m

→ collisions every 25 ns
  = 40 MHz crossing rate

- 10^{11} protons per bunch

- at $10^{34}/cm^2/s$
  ≈ 35 pp interactions per crossing
  pile-up

→ ≈ 10^9 pp interactions per second !!!

- in each collision
  ≈ 1600 charged particles produced

enormous challenge for the detectors

Cross Section of Various SM Processes

⇒ Low luminosity phase

$10^{33}/cm^2/s = 1/nb/s$

approximately

- 10^8 pp interactions
- 10^6 bb events
- 200 W-bosons
- 50 Z-bosons
- 1 tt-pair

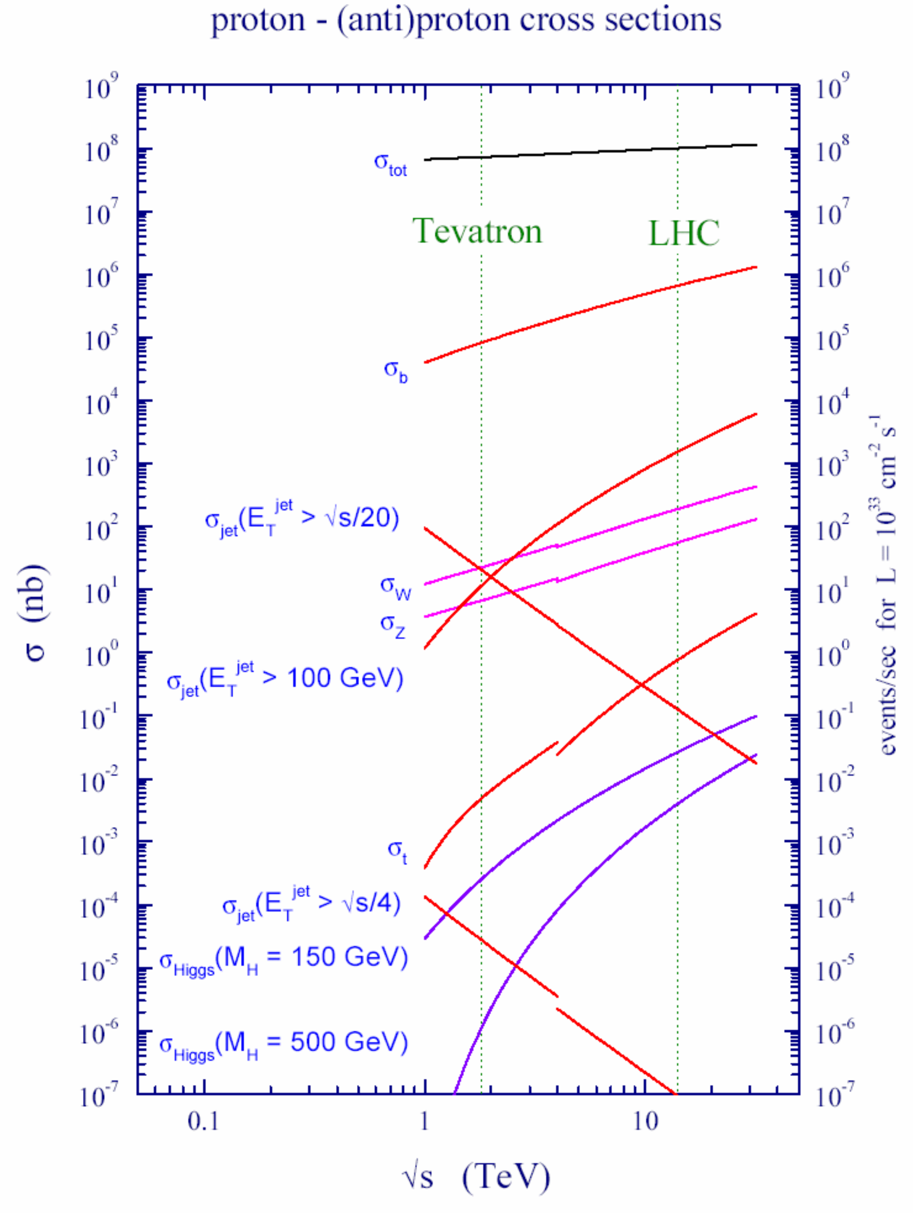
will be produced per second and

- 1 light Higgs

per minute!

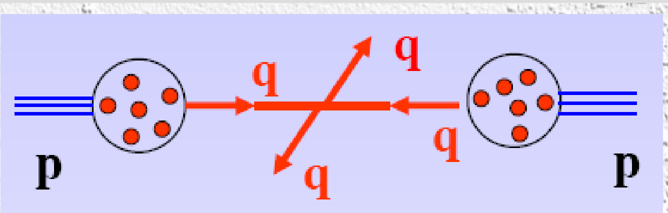
The LHC is a b, W, Z, top, Higgs, … factory!

The problem is to detect the events!



Experimental Signatures

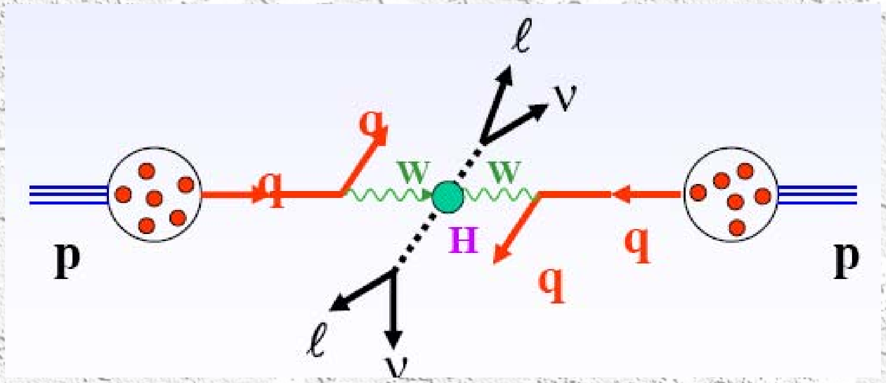
1. Hadronic final states, e.g. quark-quark



no high p_T leptons or photons in the final state

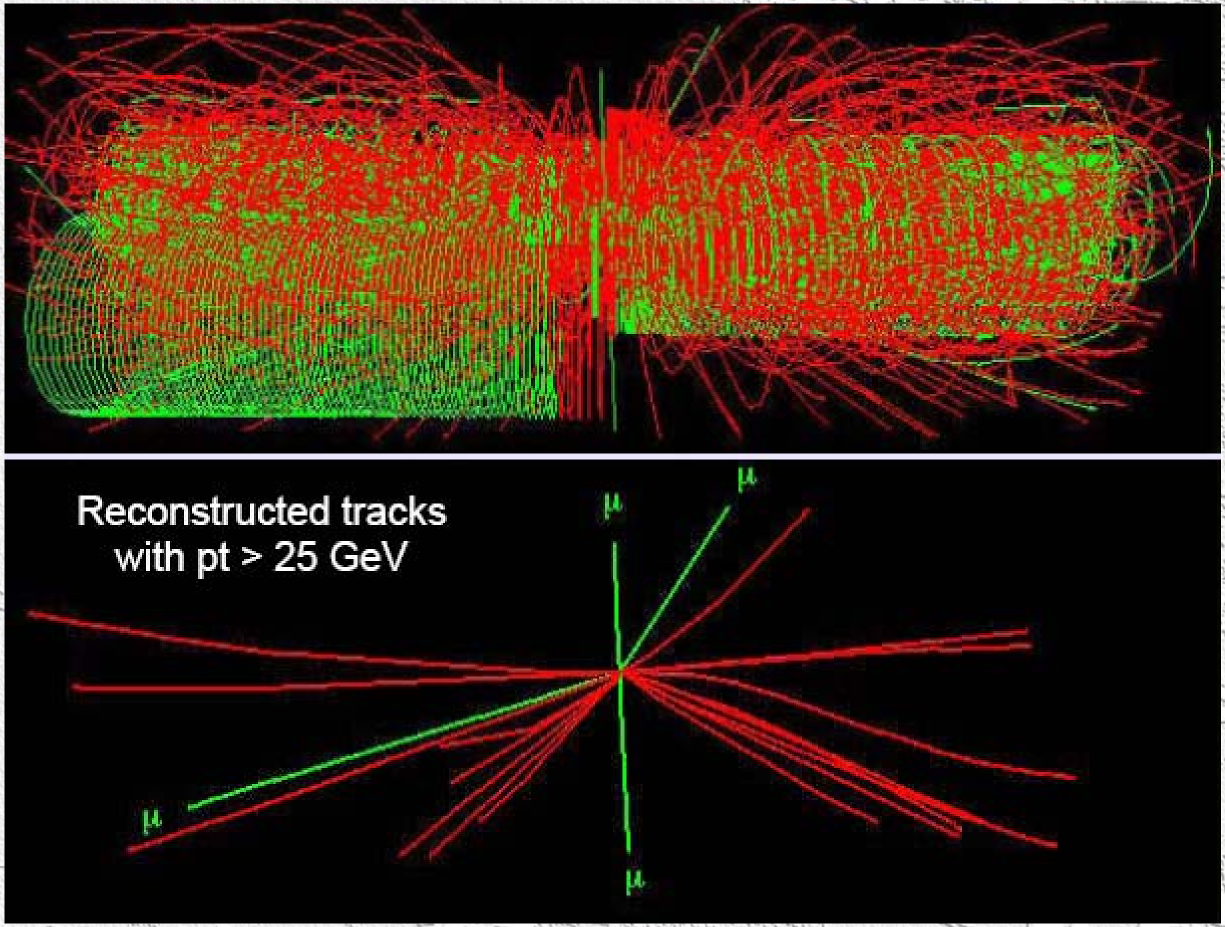
holds for the bulk of the total cross section

2. Lepton/photons with high p_T,
   example Higgs production and decay



Important signatures for interesting events:
- leptons and photons
- missing transverse energy

Suppression of Background



with 25 pile-up events

removing tracks with p_T < 25 GeV

- requires high granularity (many channels)
- good position, momentum and energy resolution

Detector Design Aspects

- good measurement of leptons (high p_T)
  muons: large and precise muon chambers
  electrons: precise electromagnetic calorimeter and tracking

- good measurement of photons

- good measurement of missing transverse energy (E_T^{miss})
  requires in particular good hadronic energy measurements
  down to small angles, i.e. large pseudo-rapidities ($\eta \approx 5$, i.e. $\theta \approx 1°$)

- in addition identification of b-quarks and τ-leptons
  precise vertex detectors (Si-pixel detectors)

Very important: radiation hardness
e.g. flux of neutrons in forward calorimeters
10^{17} n/cm^2 in 10 years of LHC operation

Online Trigger

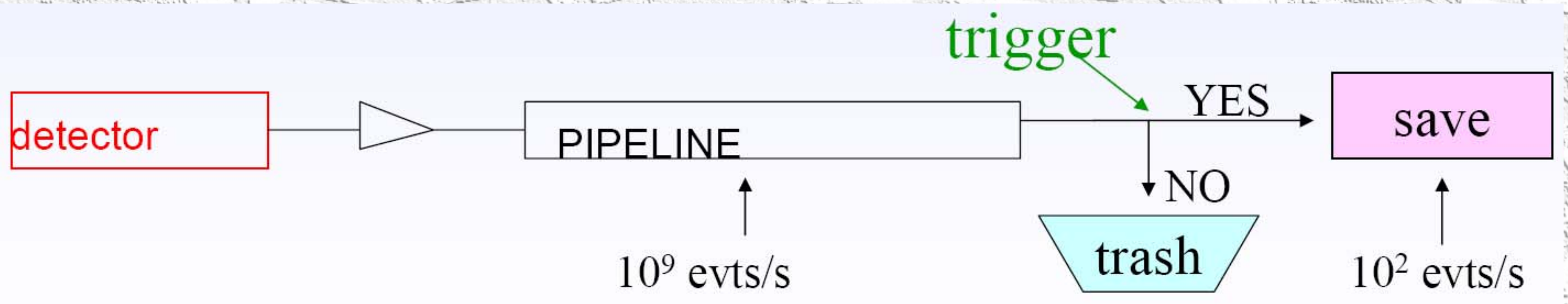
Trigger of interesting events at the LHC is much more complicated than at e^+e^- machines

- interaction rate: $\approx 10^9$ events/s
- max. record rate: ≈ 100 events/s   event size ≈ 1 MByte ⇒ 1000 TByte/year of data

⇒ trigger rejection $\approx 10^7$

- collision rate is 25 ns (corresponds to 5 m cable delay)
- trigger decision takes ≈ a few μs

⇒ store massive amount of data in front-end pipelines
while special trigger processors perform calculations



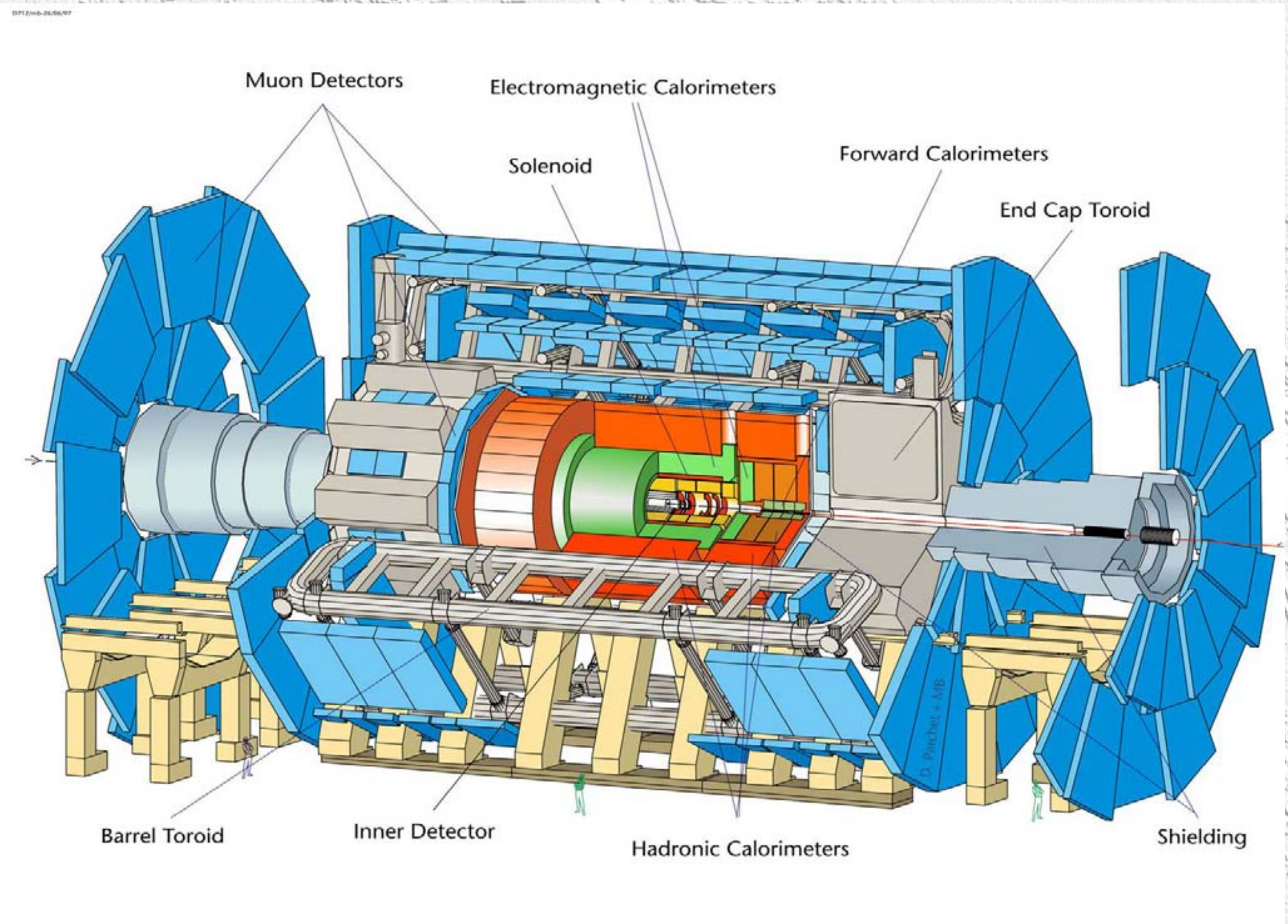
The ATLAS experiment

A Toroidal LHC ApparatuS

ATLAS in a nutshell:
- Large air toroid with μ chambers
- HCAL: steel & scintillator tiles
- ECAL: LAr
- Inner solenoid (2 T)
- Tracker: Si-strips & straw tubes (TRD)
- Si-pixel detector

10^8 channels

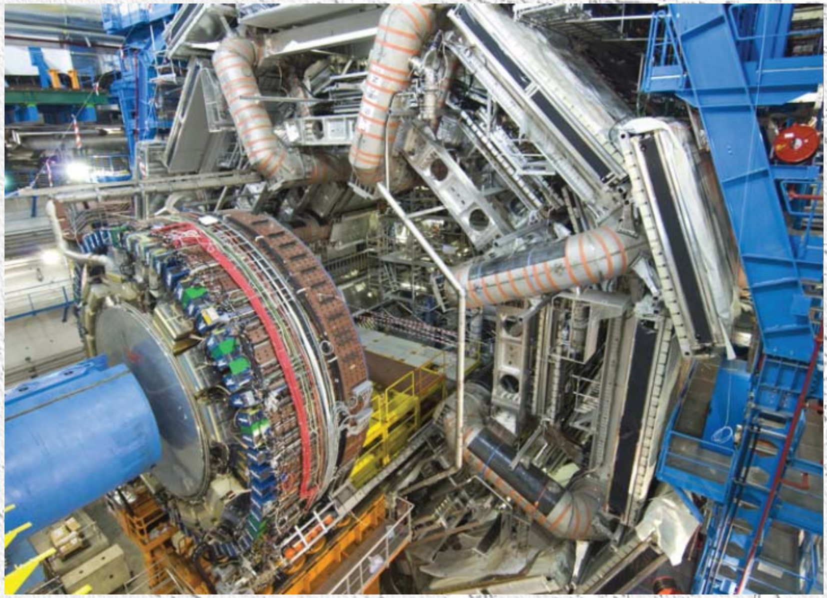
15 μm resolution



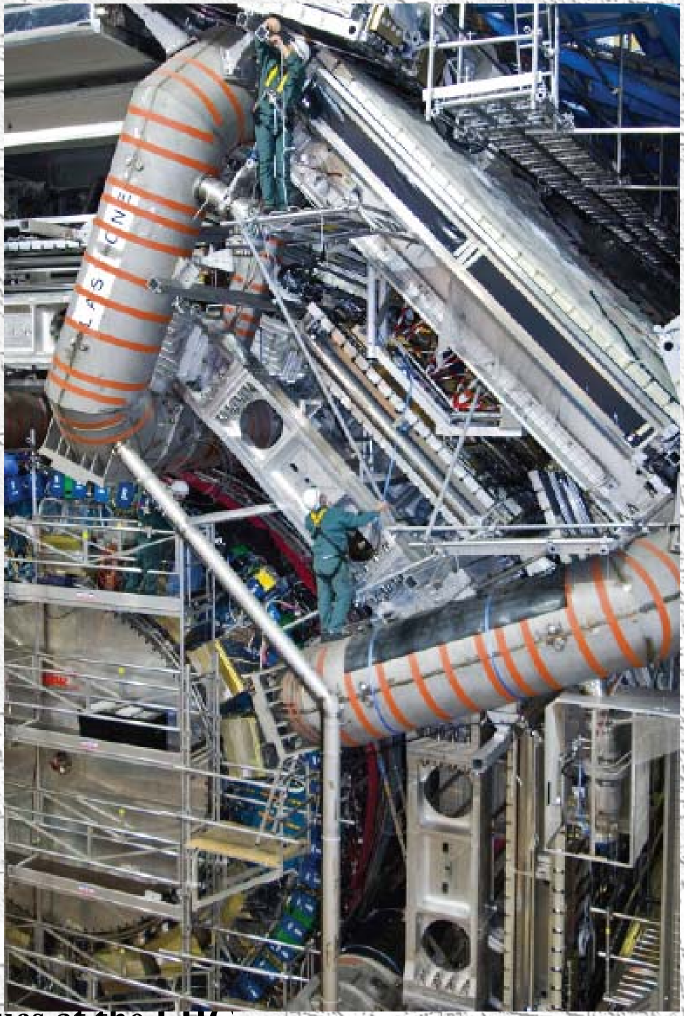
Status of ATLAS

Major structures assembled underground

- all calorimeters installed



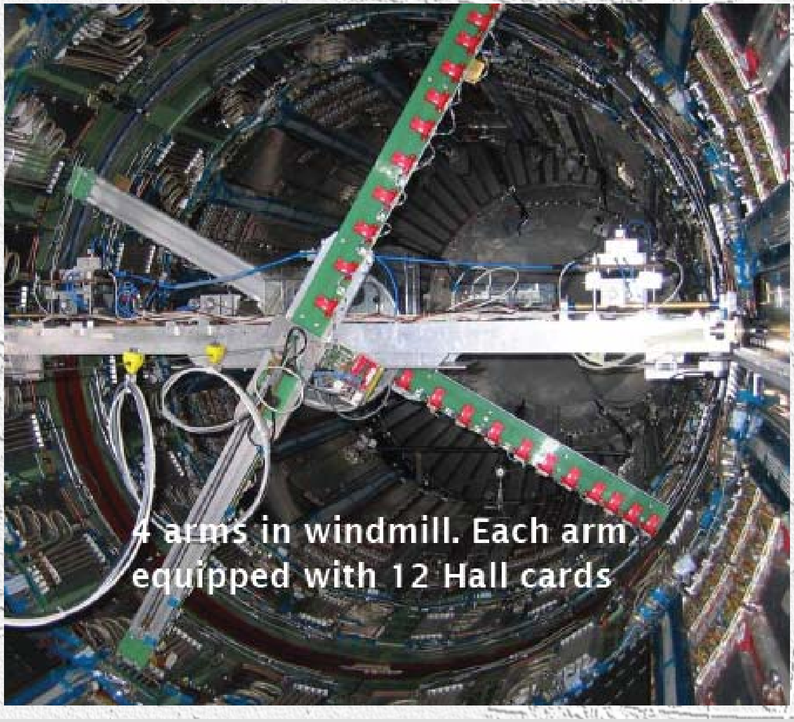
- 99% of barrel μ chambers installed



ATLAS: on track for LHC physics

Status of ATLAS

- Magnets
  - barrel toroid tested sucesfully (11/06)
  - inner solenoid:
    tested & field map taken

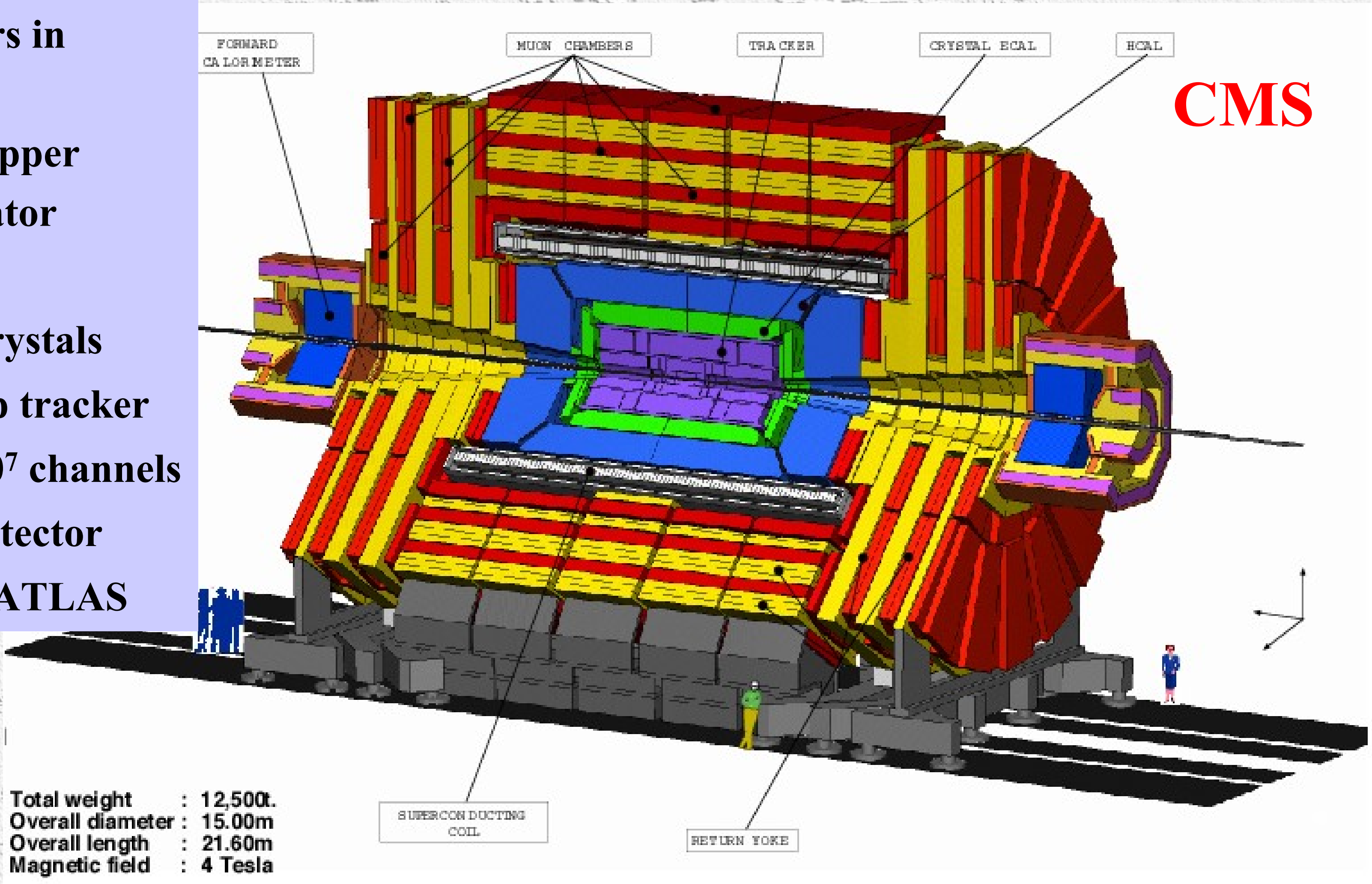


- 1 endcap toroid sucessfully tested (03/07)
  moved to IP1
- 2nd followed in June

The CMS experiment

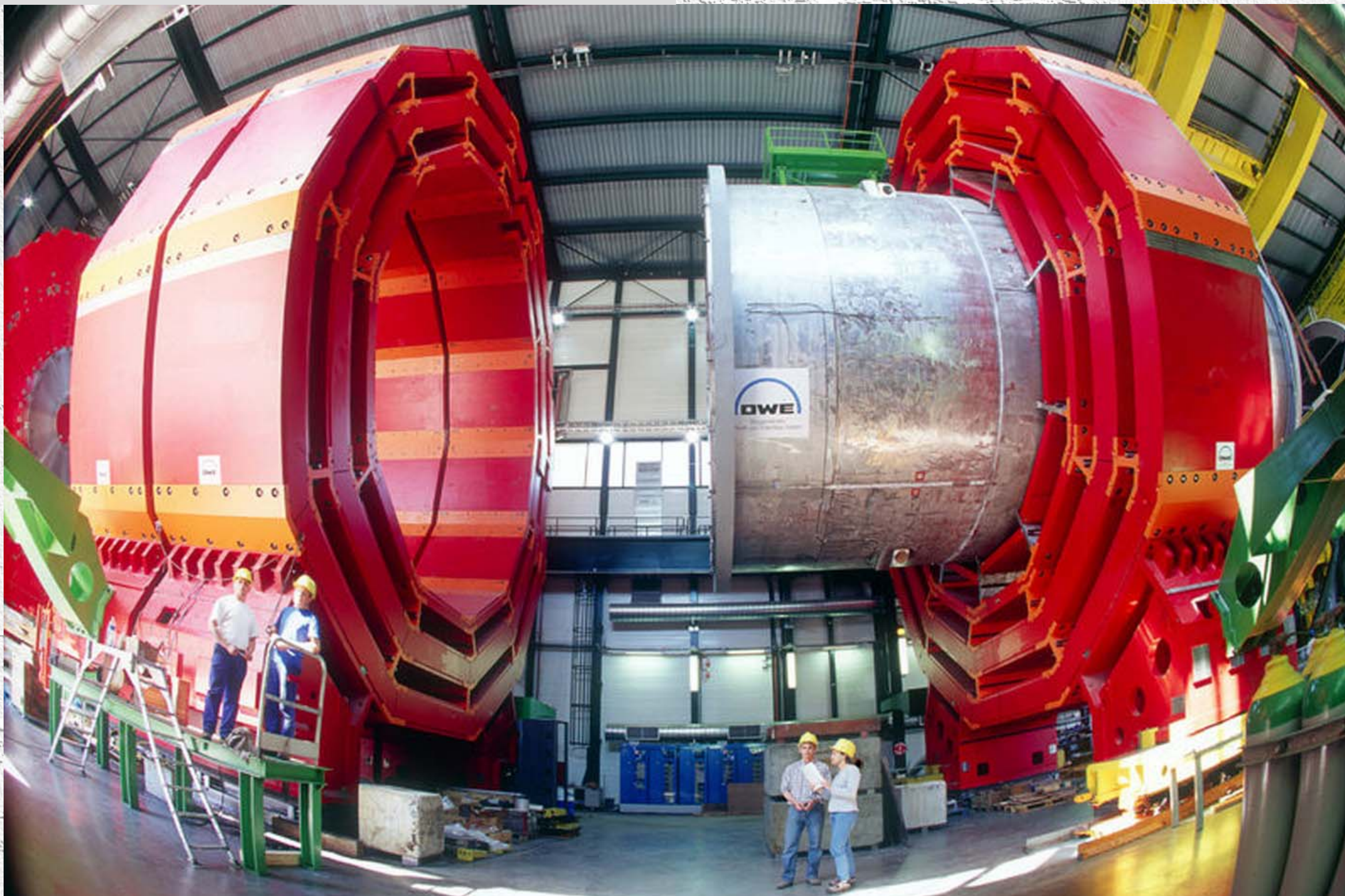
Compact Muon Solenoid

CMS in a nutshell:
- 4 T solenoid
- μ chambers in iron yoke
- HCAL: copper & scintillator
- ECAL: $PbWO_4$ crystals
- All Si-strip tracker 220 m², 10^7 channels
- Si-pixel detector similar to ATLAS



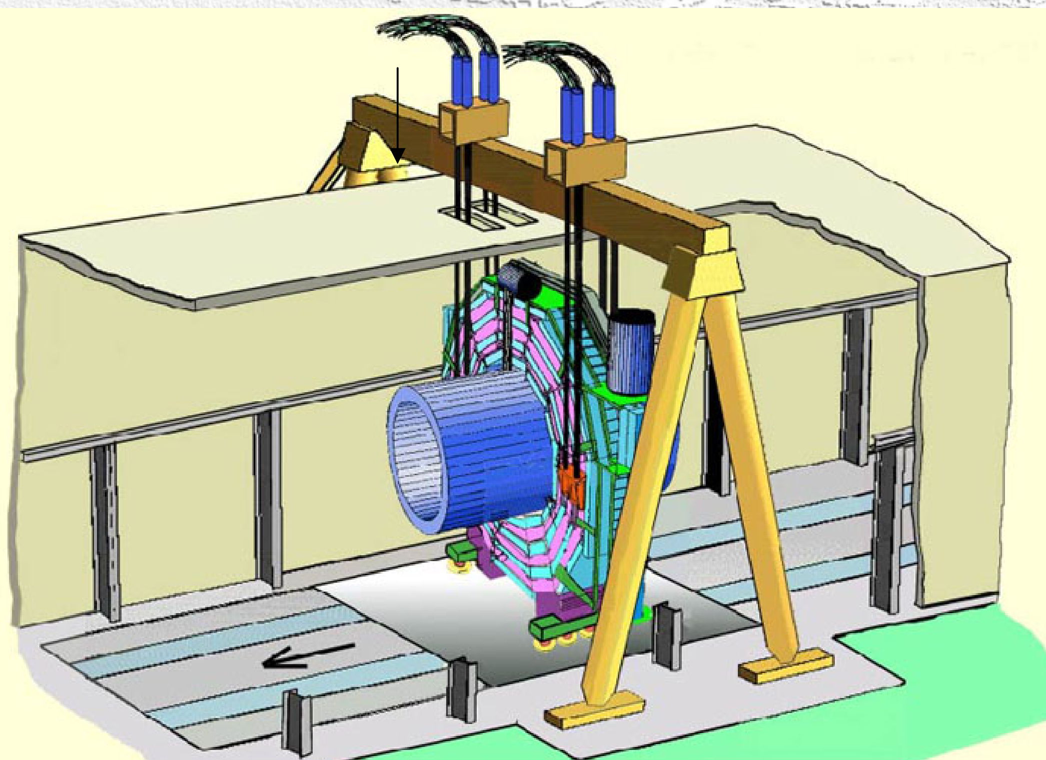
Layout of CMS

- 11 slices: 5 barrel and 2*3 endcaps



Lowering of CMS

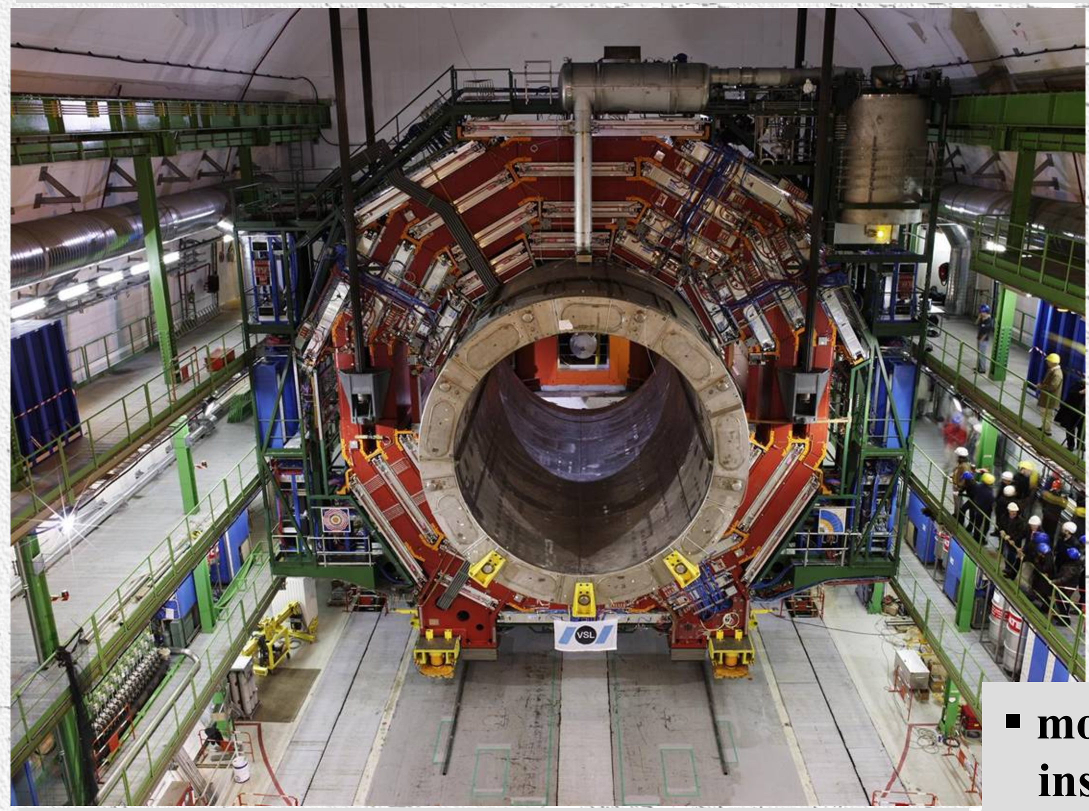
- Crane installed
- Lowering starts in autumn 2006



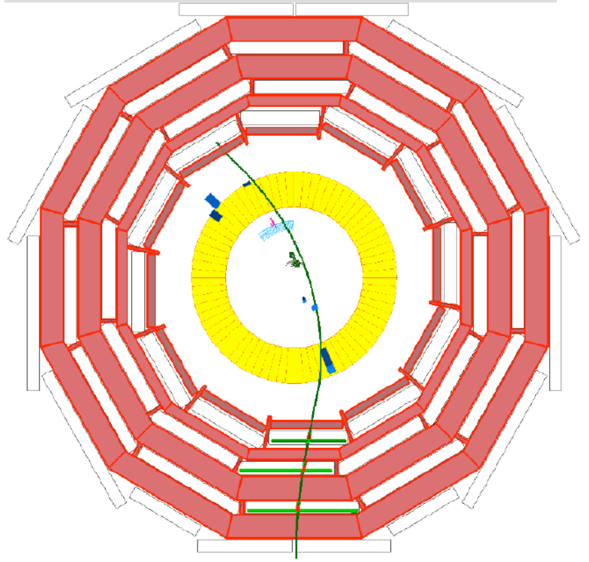
Status of CMS

CMS: major structures assembled on surface

- solenoid sucessfully operated at 4 Tesla (11/06), field map
- lowering of central magnet slice (YB0) on February 28th



Cosmic from magnet test



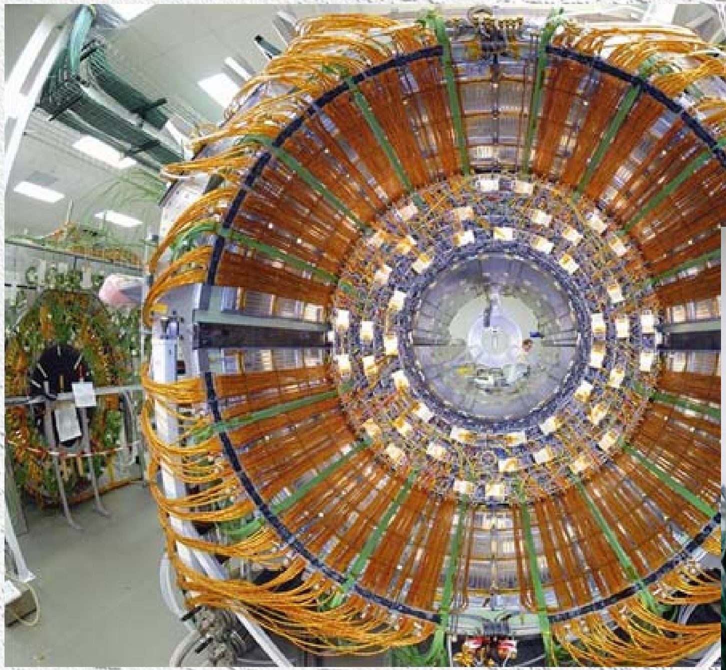
- most μ chambers installed

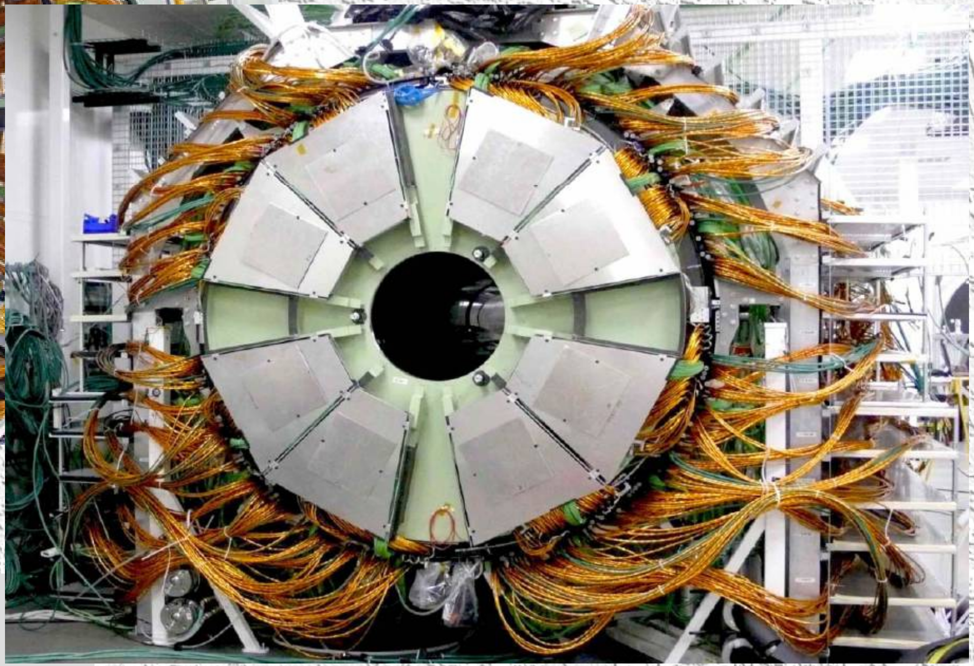
- 5/13 heavy pieces still to be lowered but all of known type
- 2nd endcap cabled, tested & commissioned on surface

Status of CMS

- Silicon tracker ready
  - under test at surface
  - to be installed in August 2007

CMS tracker:
- ≈ 220 m^2 of Si sensors
- 10.6 million Si strips
- 65.9 million Si pixel





- Pixel detector:
  - 2/3 of modules produced
  - ready for installation end 2007

CMS: on track for LHC physics

Comparison of ATLAS and CMS

	ATLAS	CMS
length	≈ 46 m	≈ 22 m
diameter	≈ 25 m	≈ 15 m
weight	≈ 7000 t	≈ 12000 t

Comparison of ATLAS and CMS

Physics performance:
comparison in terms of mass resolutions

Table 8
Mass resolution for various states in the different experiments (at a luminosity of 2×10^{33} cm^{-2} s^{-1} in the case of ATLAS and CMS)

	ATLAS (GeV c^{-2})	CMS (GeV c^{-2})	LHCb (GeV c^{-2})	ALICE (GeV c^{-2})
$B \to \pi\pi$	0.070	0.031	0.017	—
$B \to J/\psi K^0_S$	0.019	0.016	0.010	—
$\Upsilon \to \mu\mu$	0.152	0.050	—	0.107
$H(130\,\text{GeV}\,c^{-2}) \to \gamma\gamma$	1.55	0.90	—	—
$H(150\,\text{GeV}\,c^{-2}) \to ZZ^* \to 4\mu$	1.60	1.35	—	—
$A(500\,\text{GeV}\,c^{-2}) \to \tau\tau$	50.0	75.0	—	—
$W \to$ jet jet	8.0	10.0	—	—
$Z'(3\,\text{TeV}\,c^{-2}) \to \mu\mu$	240	170	—	—
$Z'(1\,\text{TeV}\,c^{-2}) \to ee$	7.0	5.0	—	—

From T. Virdee, Phys. Rep. 403-404 (2004) 401

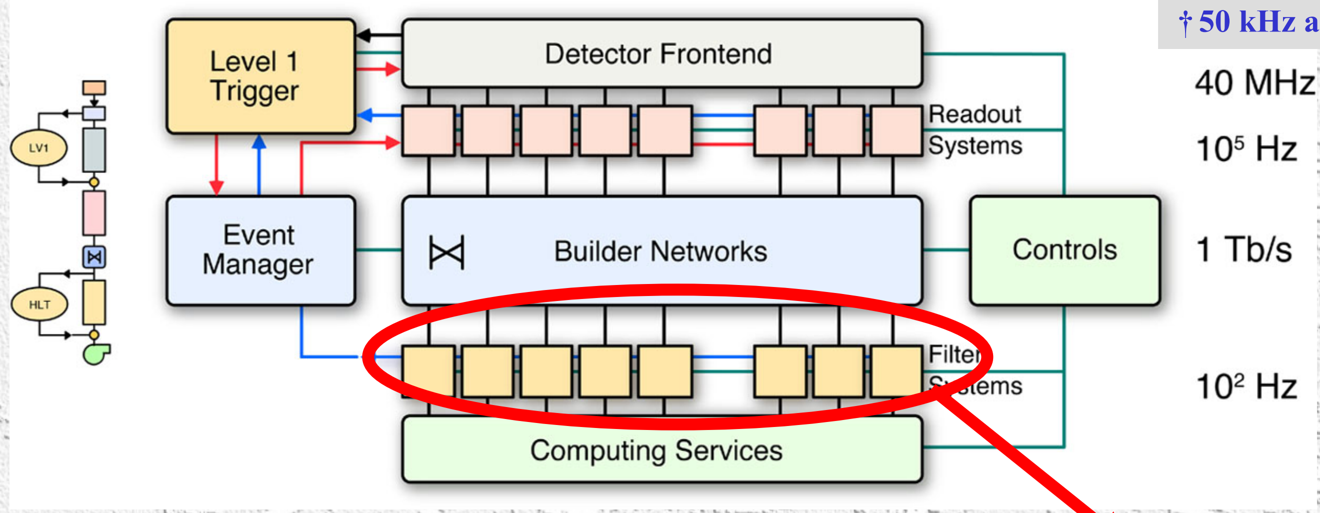
Trigger & DAQ system

Similar design for ATLAS & CMS

Example CMS:

Collision rate	40 MHz
Level-1 max. trigger rate	100 kHz†
Average event size	≈ 1 Mbyte

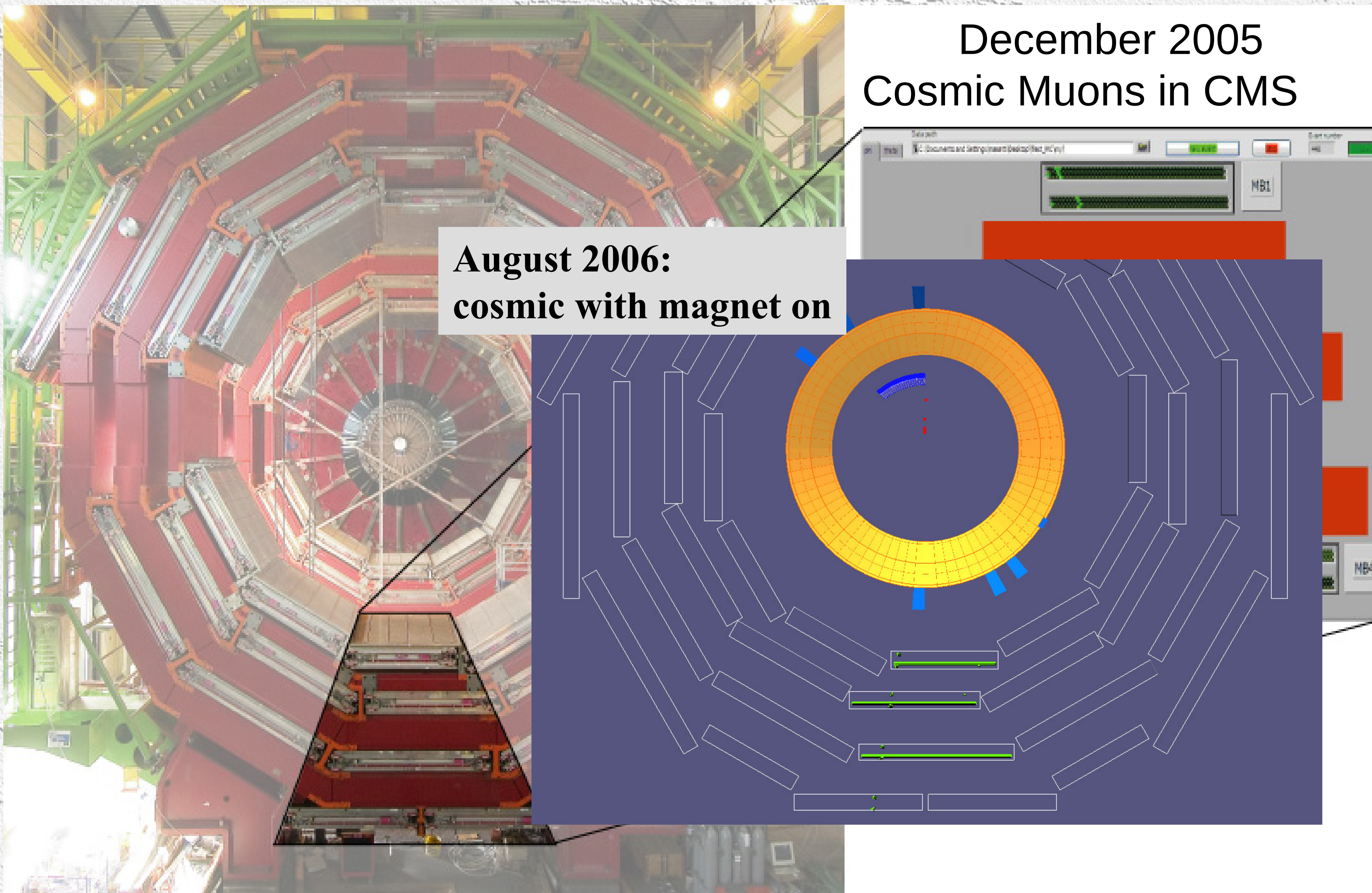
† 50 kHz at startup (DAQ staging)



Filter farm:
- approx. 2000 CPUs
- easily scaleable
- staged (lower lumi & saves money)
- uses offline software

The longest journey starts with the first step…

- **Cosmic data taking with assembled detector components…**



Possible LHC Schedule

- **2008 first physics year**
  - machine closure April
  - first collisions in summer at 7 TeV proton energy
  - try to reach $10^{32}/cm^2/s$ $\int L dt \leq 1\ fb^{-1}$
- **2009 – 2010/11 two or three years at $1 - 2 \cdot 10^{33}/cm^2/s$**
  - $\geq 30\ fb^{-1}$ in total
  - important for precision physics and discoveries
- **$\geq$ 2011 high luminosity running at $10^{34}/cm^2/s$**
  - $100\ fb^{-1}$ per year
- **2015 Upgrade to Super LHC $10^{35}/cm^2/s$**
  - under discussion
  - requires major machine and detector upgrades

End of Lecture 1