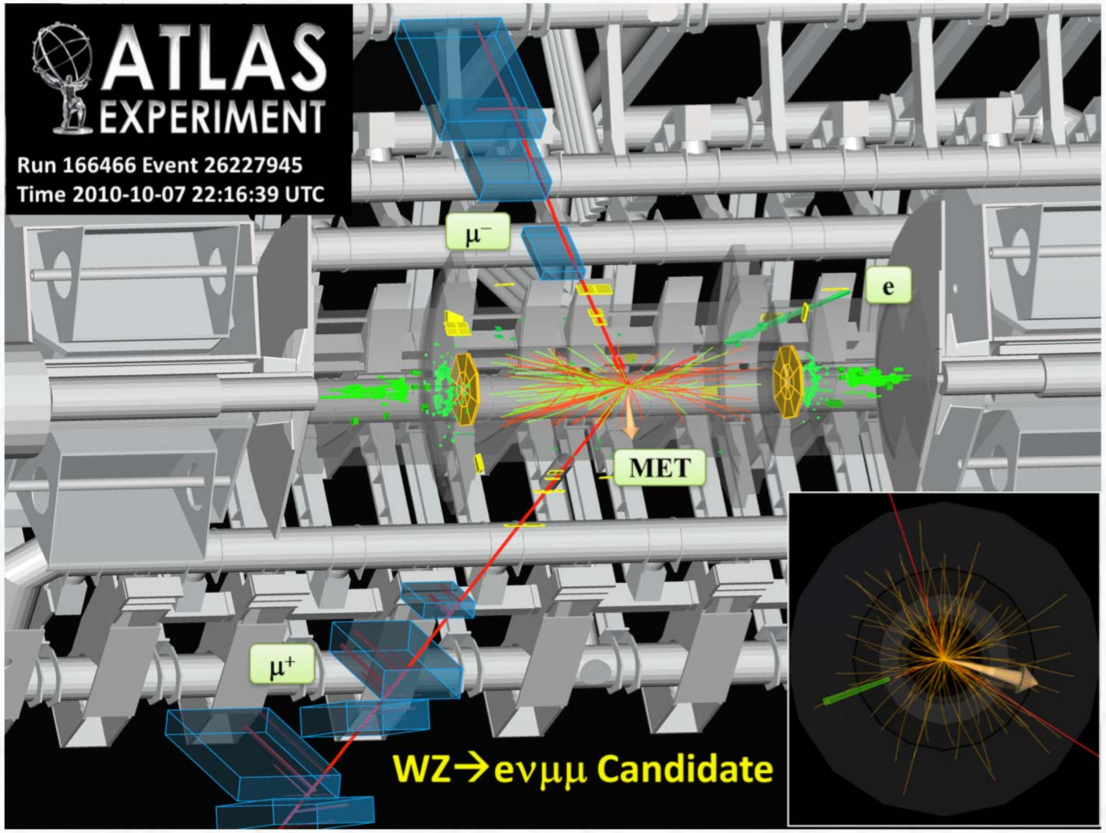
Physics at the LHC

- From the Standard Model to searches for new physics-



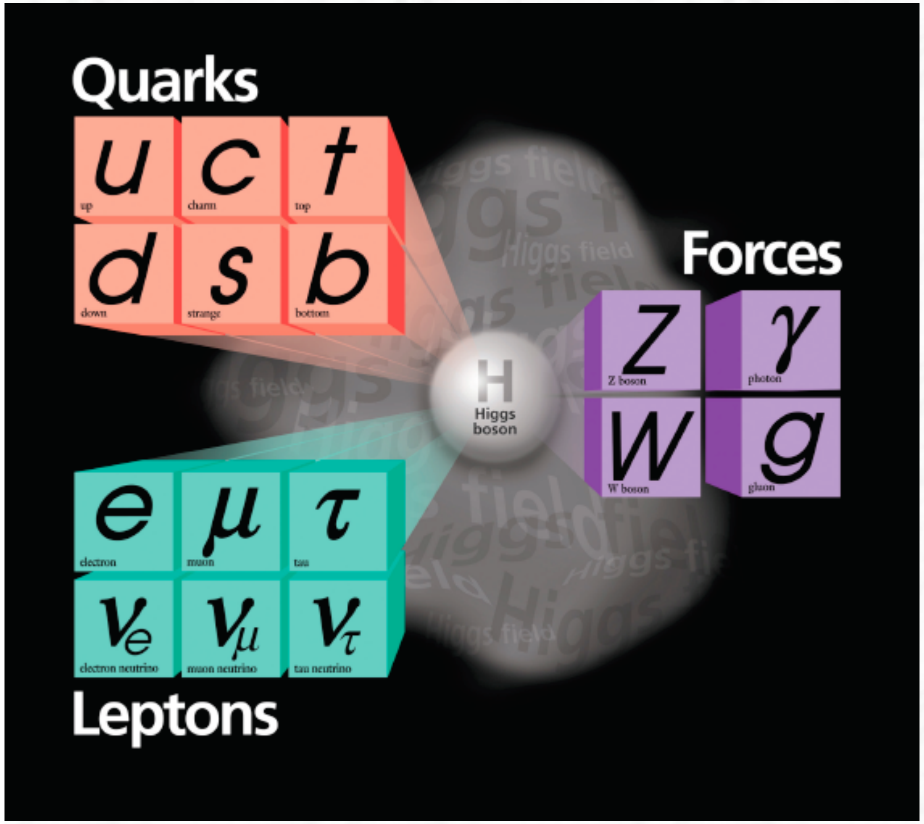
Prof. Karl Jakobs
Physikalisches Institut
Universität Freiburg

Outline of the lectures:

1. Introduction
2. The accelerator and experiments
3. Test of the Standard Model
4. Search for the Higgs Boson
5. Search for New Phenomena

Disclaimer: I will try to highlight important first physics measurements and results on searches for new physics. The coverage is not complete, i.e. not all results available will be presented; Results from both general purpose experiments, ATLAS and CMS, are shown, but there might still be a bias towards the experiment I am working on. This bias is not linked to the scientific quality of the results.

Building blocks of the Standard Model



- **Matter**

  made out of fermions
  (Quarks and leptons)

- **Forces**

  electromagnetism, weak and strong force
  + gravity
  (mediated by bosons)

- **Higgs field**

  needed to break (hide) the electroweak symmetry and to give mass to weak gauge bosons and fermions

$\rightarrow$ Higgs particle

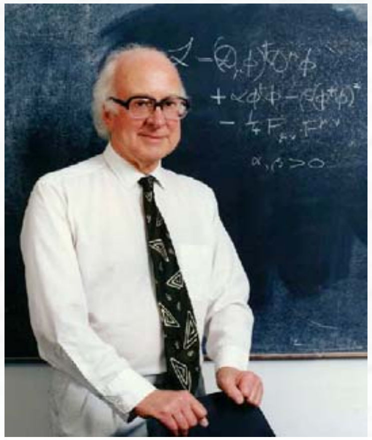
Theoretical arguments: $m_H < \sim 1000$ GeV/c^2

Where do we stand today?

e^+e^- colliders LEP at CERN and SLC at SLAC + the Tevatron pp collider
+ HERA at DESY + many other experiments (fixed target…….)
have explored the energy range up to **~100 GeV** with incredible precision

- The Standard Model is consistent with all experimental data !
- No Physics Beyond the SM observed
  (except clear evidence for neutrino masses)
- No Higgs seen (yet)

Direct searches: (95% CL limits)
m_H > 114.4 GeV/c^2
m_H < 158 GeV/c^2 or m_H > 173 GeV/c^2

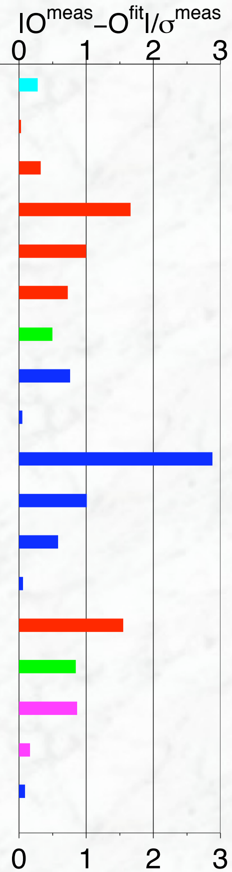


Only unambiguous example of observed Higgs

(P. Higgs, Univ. Edinburgh)

Summer 2010

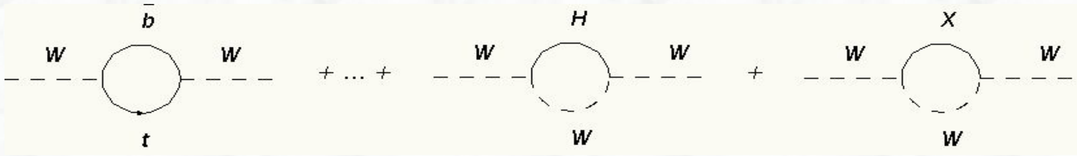
	Measurement	Fit
$\Delta\alpha^{(5)}_{had}(m_Z)$	0.02758 ± 0.00035	0.02768
m_Z [GeV]	91.1875 ± 0.0021	91.1874
Γ_Z [GeV]	2.4952 ± 0.0023	2.4959
σ^0_{had} [nb]	41.540 ± 0.037	41.479
R_l	20.767 ± 0.025	20.742
$A^{0,l}_{fb}$	0.01714 ± 0.00095	0.01645
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1481
R_b	0.21629 ± 0.00066	0.21579
R_c	0.1721 ± 0.0030	0.1723
$A^{0,b}_{fb}$	0.0992 ± 0.0016	0.1038
$A^{0,c}_{fb}$	0.0707 ± 0.0035	0.0742
A_b	0.923 ± 0.020	0.935
A_c	0.670 ± 0.027	0.668
A_l(SLD)	0.1513 ± 0.0021	0.1481
$\sin^2\theta^{lept}_{eff}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.399 ± 0.023	80.379
Γ_W [GeV]	2.085 ± 0.042	2.092
m_t [GeV]	173.3 ± 1.1	173.4

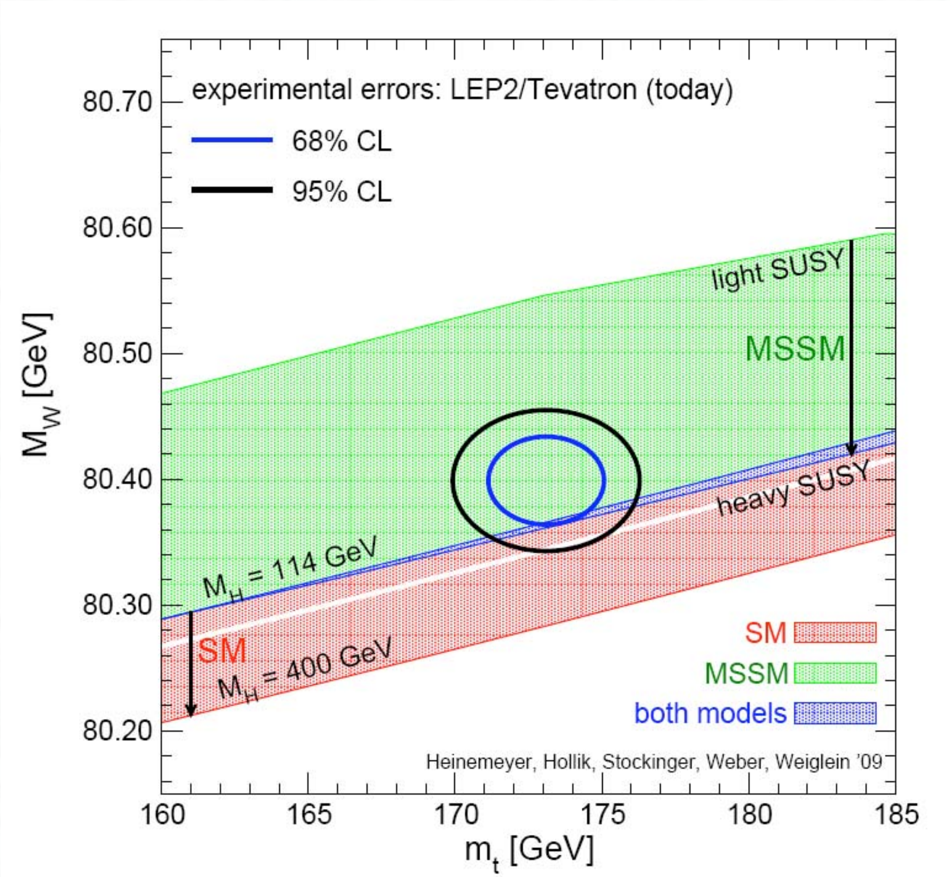


July 2010

Consistency with the Standard Model

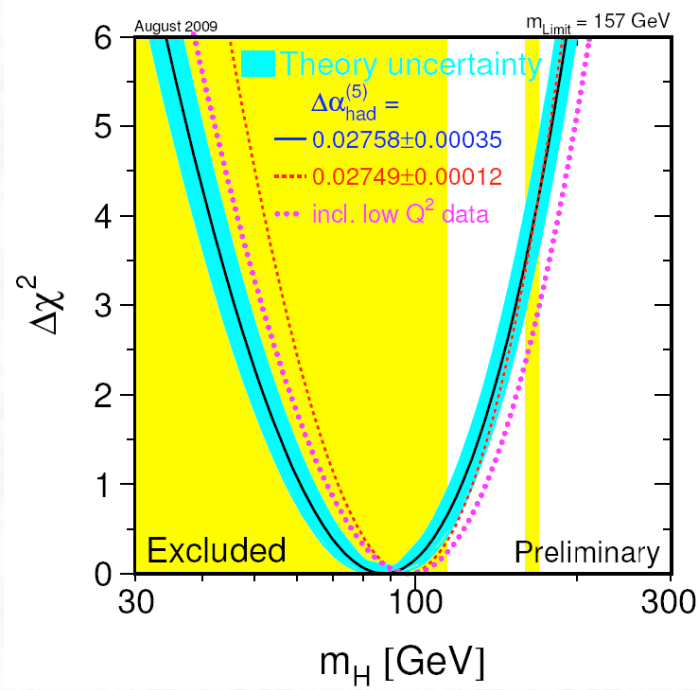
Sensitivity to the Higgs boson and other new particles via quantum corrections:





Interpretation within the Standard Model

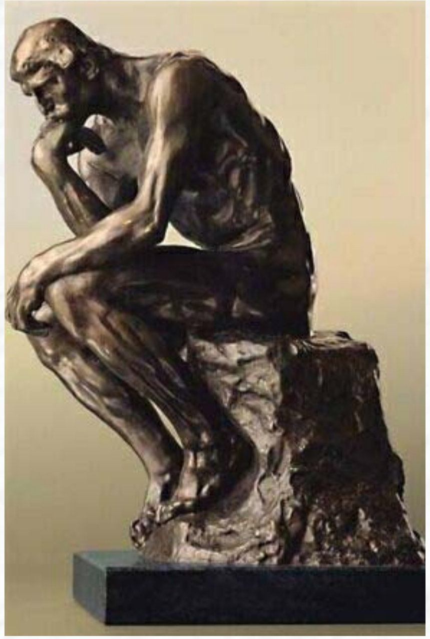
(incl. new (2010) m_W and m_t measurements)



m_H = 89 (+35) (-26) GeV/c^2

m_H < 158 GeV/c^2 (95 % CL)

The Open Questions



Key Questions of Particle Physics

1. Mass: What is the origin of mass?

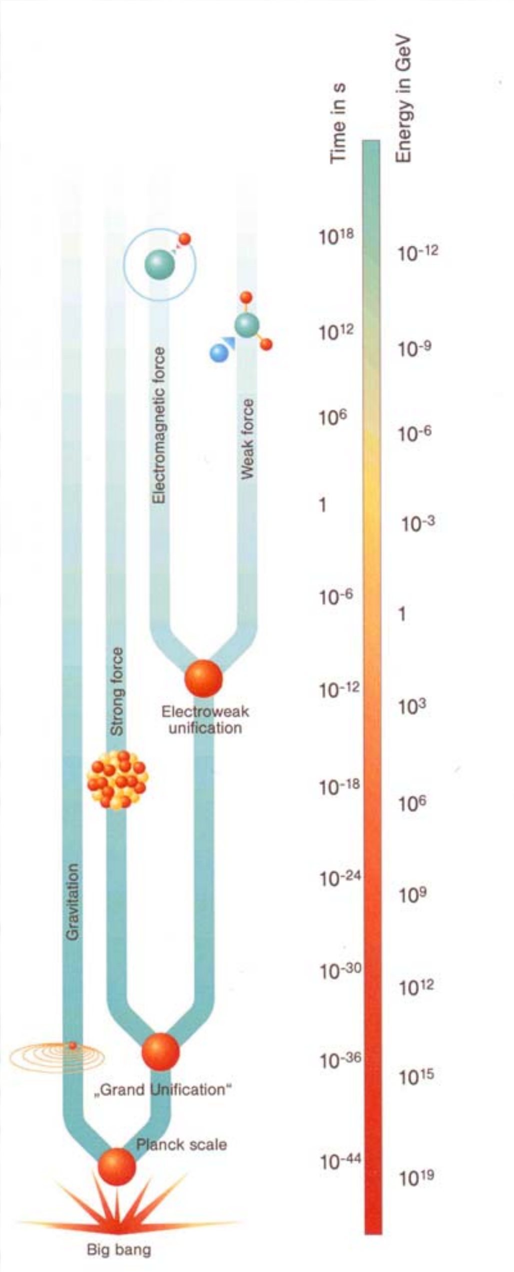
- How is the electroweak symmetry broken ?
- Does the Higgs boson exist ?

2. Unification: **What is the underlying fundamental theory ?**

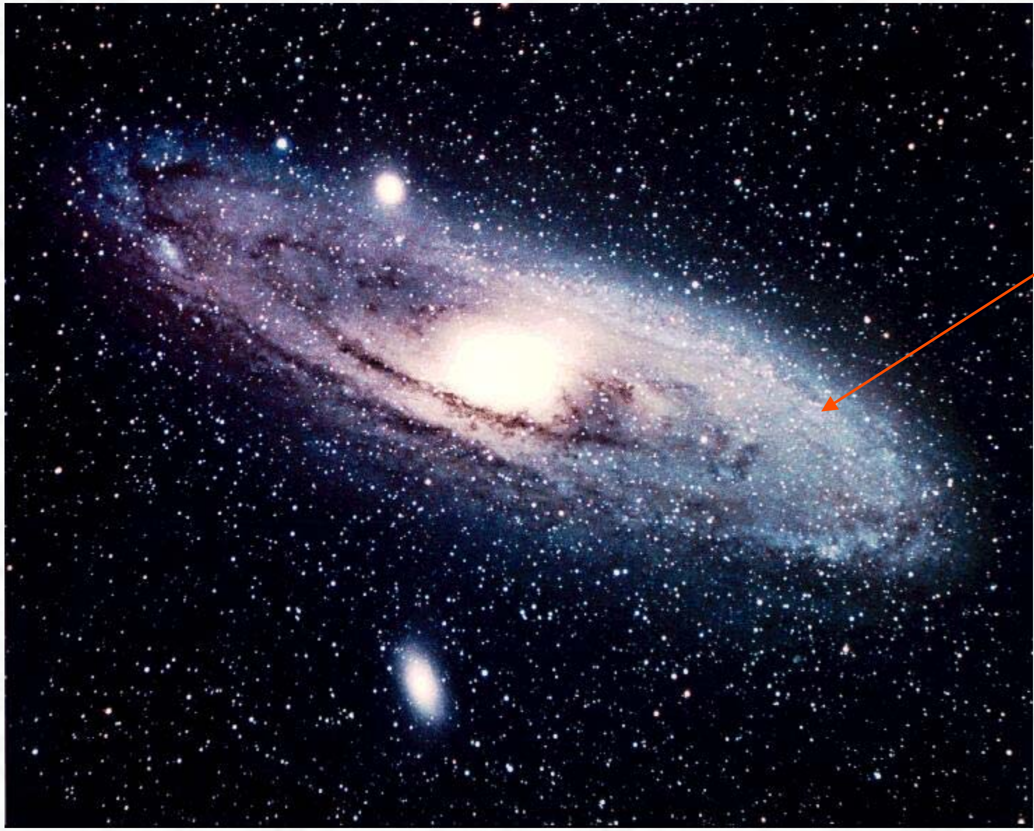
- Can the interactions be unified at larger energy?
- How can gravity be incorporated ?
- Is our world supersymmetric ?
- ….

3. Flavour: **or the generation problem**

- Why are there three families of matter?
- Neutrino masses and mixing?
- What is the origin of CP violation?



Problems at a larger scale



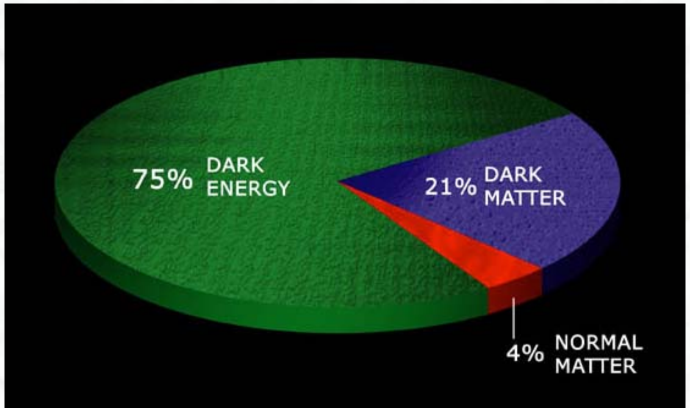
We are here

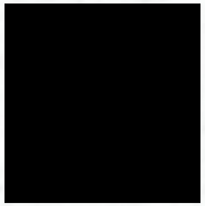
Surrounded by

- Mass
  (planets, stars, ….,hydrogen gas)

- **Dark Matter**

- **Dark Energy**





The role of the LHC

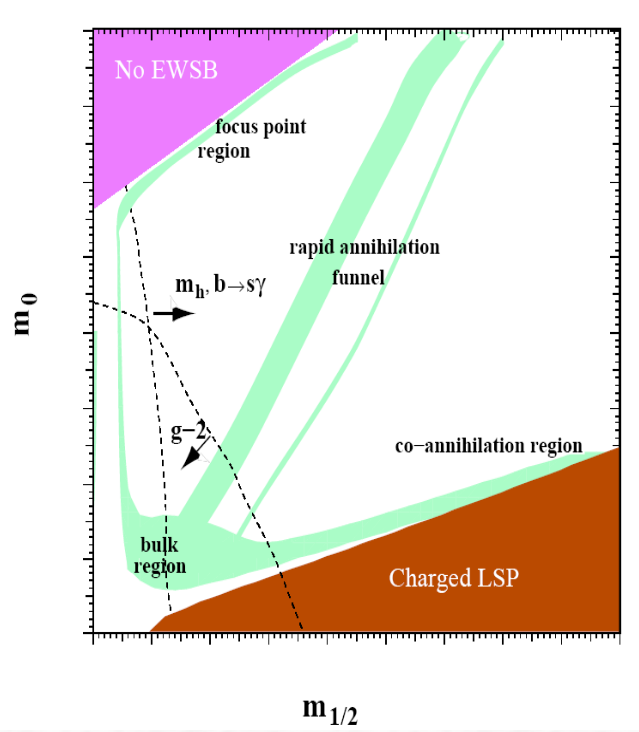
1. Explore the TeV mass scale

- What is the origin of the electroweak symmetry breaking ?
- The search for "low energy" supersymmetry

  Can a link between SUSY and dark matter be established?
- Other scenarios beyond the Standard Model
- ....

Look for the "expected", but we need to be open for surprises

The link between SUSY and Dark Matter ?



M. Battaglia, I. Hinchliffe, D.Tovey, hep-ph/0406147

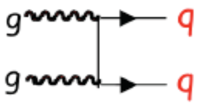
2. Precise tests of the Standard Model

- There is much sensitivity to physics beyond the Standard Model in the precision area
- Many Standard Model measurements can be used to test and to tune the detector performance

Theoretical models for physics Beyond the Standard Model

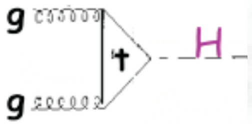
How can interesting objects be produced?

High-p_T QCD jets

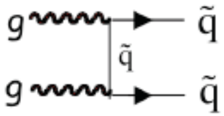


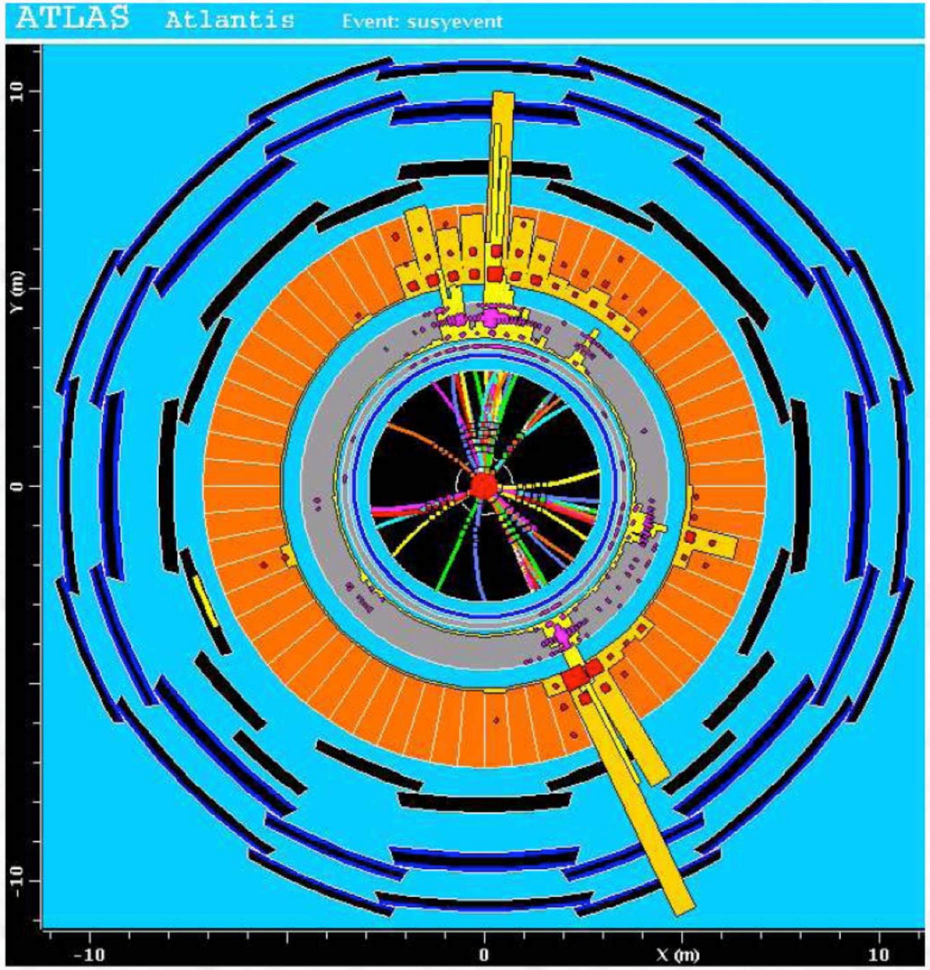
W, Z

Higgs m_H=150 GeV



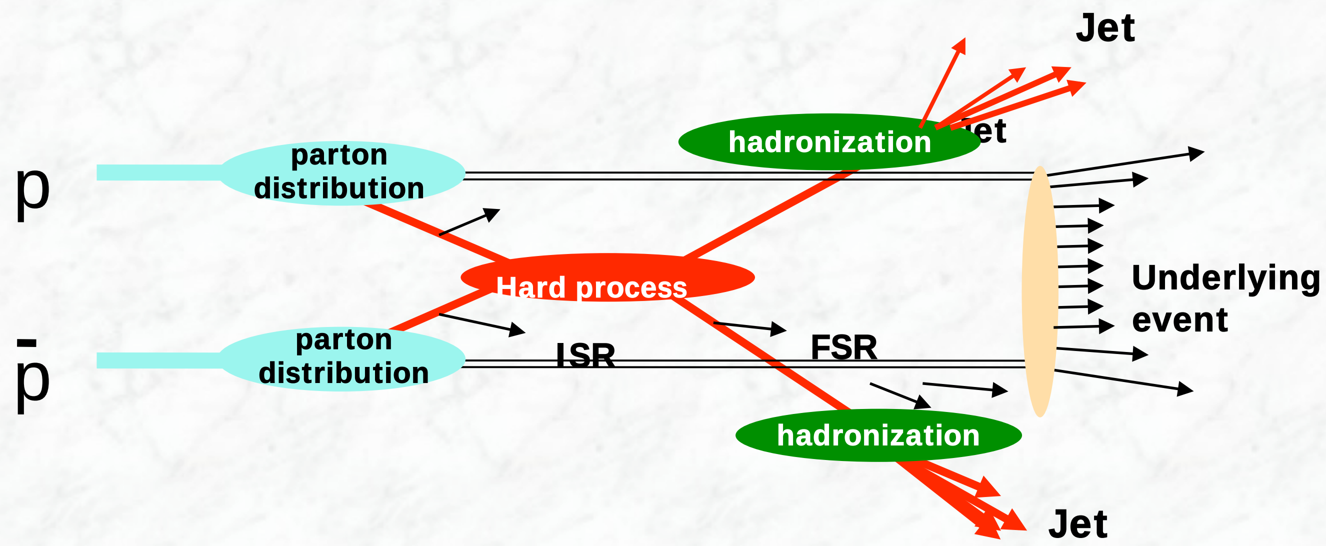
$\tilde{q}$,$\tilde{g}$ pairs, m ~ 1 TeV





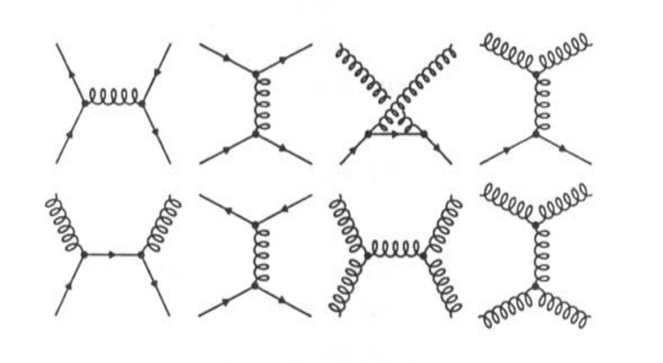
Quarks and gluons in the initial state

Hard Scattering Processes ….or QCD jet production

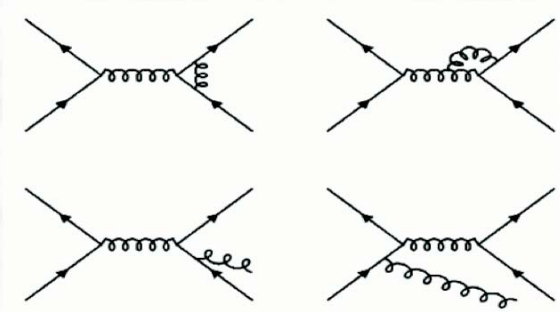


Dominant hard scattering processes: qq, qg and gg "scattering"

Leading order

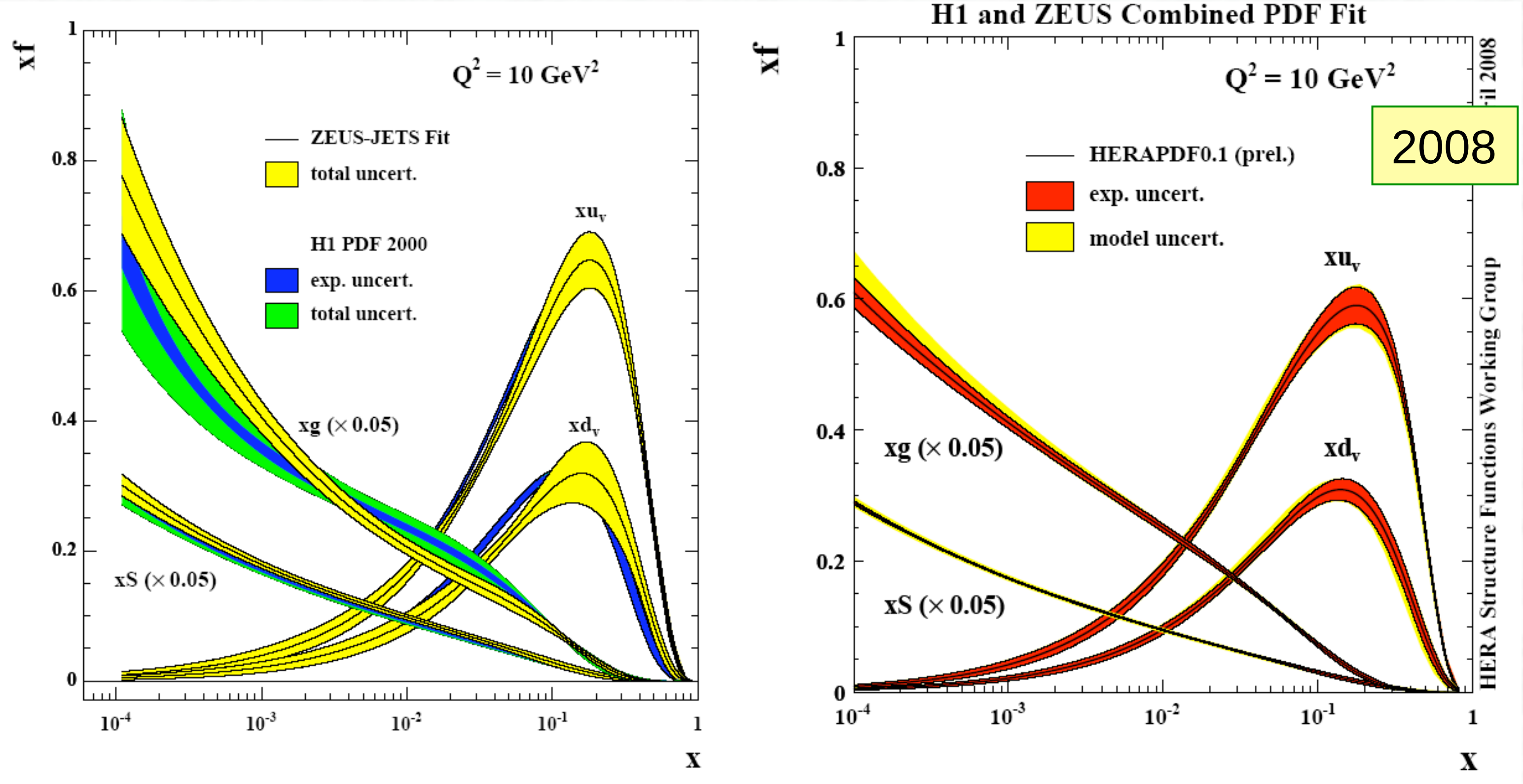


…some NLO contributions



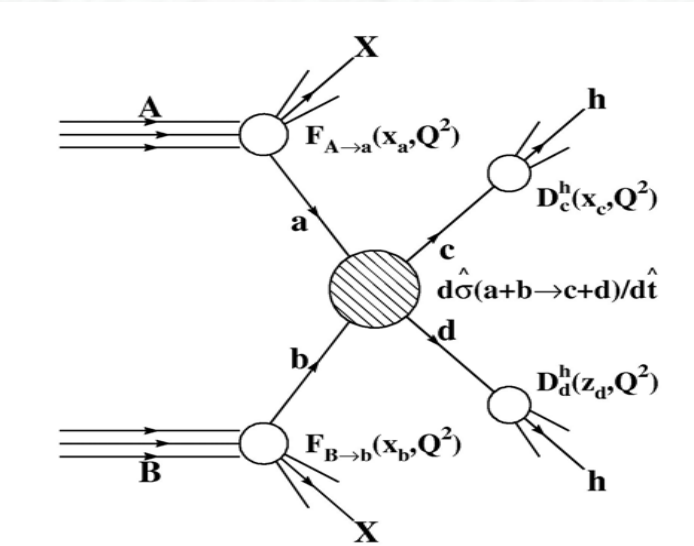
Results from HERA on the proton structure

- Large data sets and combination of the two HERA experiments (H1 and ZEUS) improve the precision on the parton distribution functions



- Very important to reduce cross section uncertainties at hadron colliders; but still not good enough ….. (~ 10% errors for LHC cross sections)

Calculation of cross sections



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

Sum over initial partonic states a,b

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

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

… + higher order QCD corrections (perturbation theory)

which for some processes turn out to be large
(e.g. Higgs production via gg fusion)

usually introduced as K-factors: $K_{[n]} = \sigma_{[n]} / \sigma_{[LO]}$

a few examples: Drell-Yan production of W/Z: $K_{NLO} \sim 1.2$
Higgs production via gg fusion: $K_{NLO} \sim 1.8$

Luminosity

The rate of events produced for a given physics process is given by:

$$N = L \cdot \sigma$$

L = Luminosity
σ = cross section

dimensions: $s^{-1} = cm^{-2}\, s^{-1} \cdot cm^{2}$

Luminosity depends on the machine:
important parameters: number of protons stored, beam focus at interaction region,….

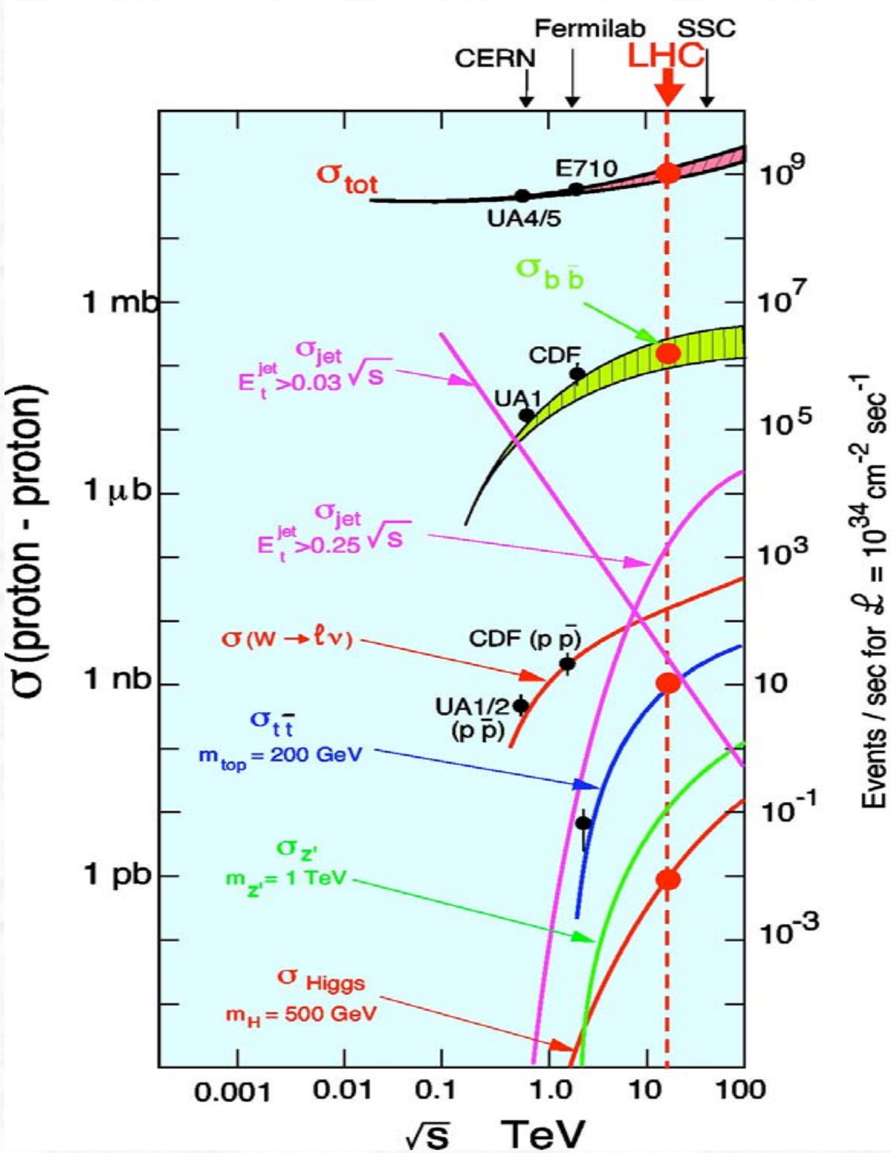
In order to achieve acceptable production rates for the interesting physics processes, the luminosity must be high !

$L = 2 \cdot 10^{32}\ cm^{-2}\, s^{-1}$ design value for Tevatron Run II
$L = 10^{33}\ cm^{-2}\, s^{-1}$ planned for the initial phase of the LHC (1-2 years)
$L = 10^{34}\ cm^{-2}\, s^{-1}$ LHC design luminosity, very large !!
(1000 x larger than LEP-2, 50 x Tevatron Run II design)

One experimental year has ~ 10^{7} s →

Integrated luminosity at the LHC: 10 fb^{-1} per year, in the initial phase
100 fb^{-1} per year, later, design

Cross Sections and Production Rates



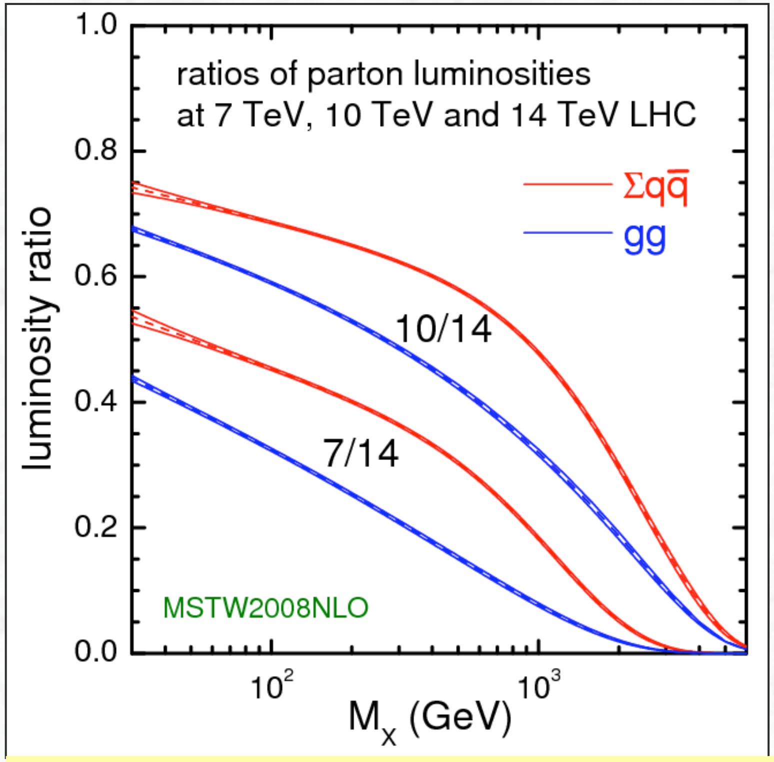
Rates for $L = 10^{34}$ cm^{-2} s^{-1}: (LHC)

• Inelastic proton-proton reactions:	10^9 / s
• bb pairs • tt pairs	$5\ 10^6$ / s 8 / s
• W → e ν • Z → e e	150 / s 15 / s
• **Higgs (150 GeV)** • **Gluino, Squarks (1 TeV)**	**0.2 / s** **0.03 / s**

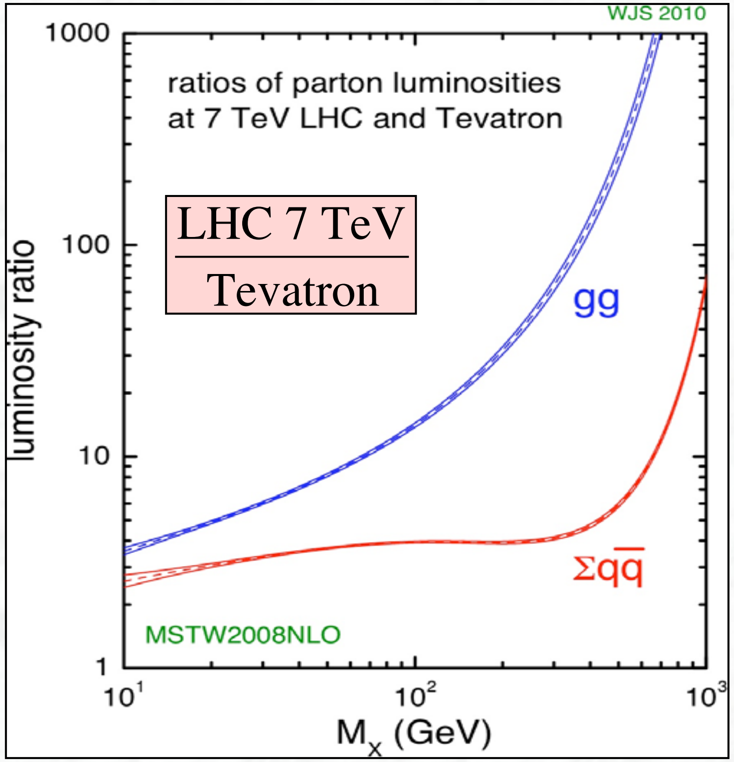
LHC is a factory for:
top-quarks, b-quarks, W, Z, …,Higgs, …

Impact of reduced beam energy

- Ratio of parton luminosities for 7/14 and 10/14 TeV …



J.Stirling
http://projects.hepforge.org/mstwpdf/plots/plots.html



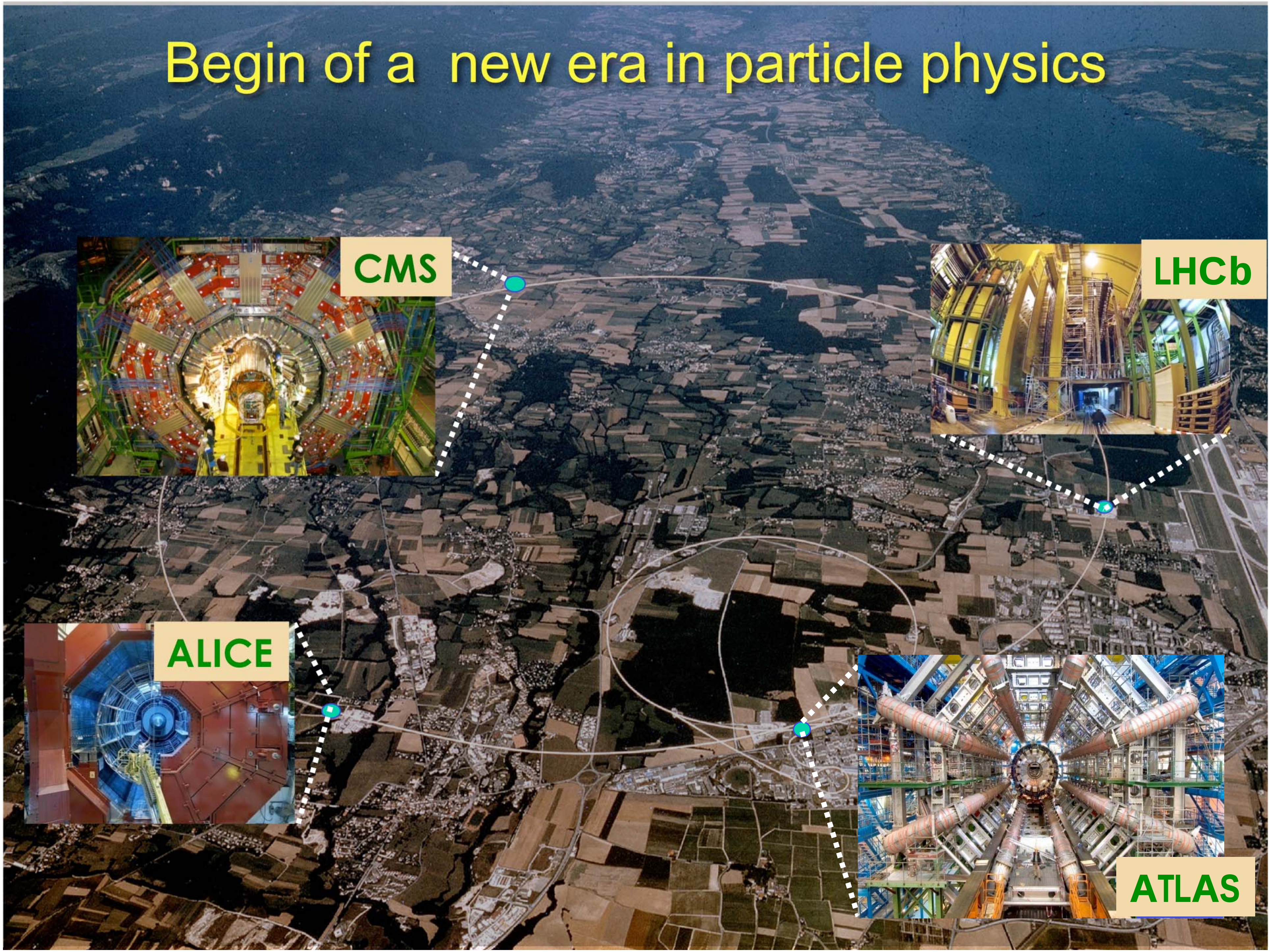
ttbar:
7/14 = 0.2

W' (1.5 TeV):
7/14 = 0.1

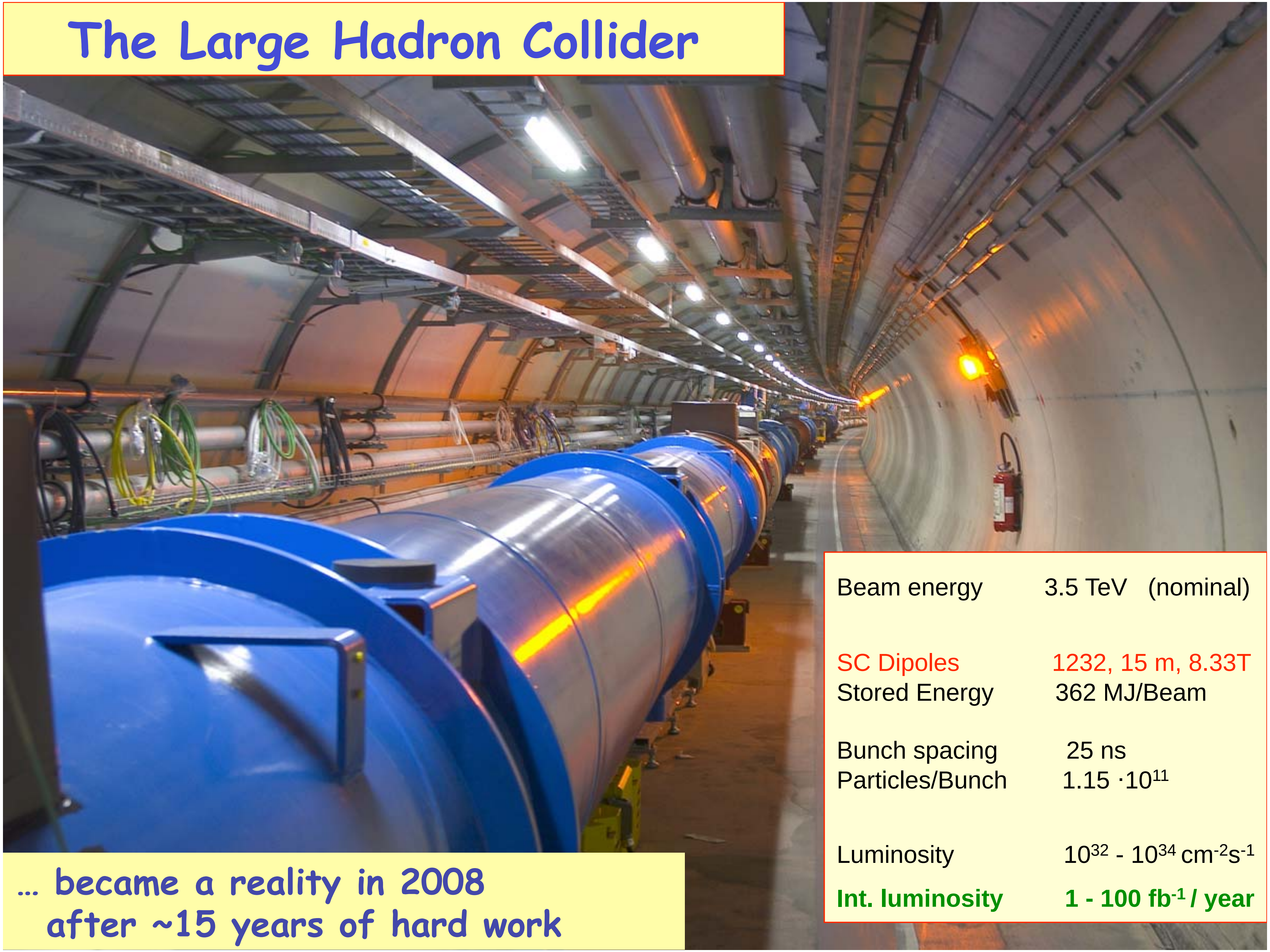
W' (1 TeV):
7(pp) / 2(ppbar) ~ 60

...but still large factor compared to the Tevatron ($\sqrt{s}$ =1.96 TeV)


The Large Hadron Collider (LHC)


Begin of a new era in particle physics
CMS
LHCb
ALICE
ATLAS

The Large Hadron Collider



Beam energy	3.5 TeV (nominal)
SC Dipoles	1232, 15 m, 8.33T
Stored Energy	362 MJ/Beam
Bunch spacing	25 ns
Particles/Bunch	$1.15 \cdot 10^{11}$
Luminosity	10^{32} - 10^{34} $cm^{-2}s^{-1}$
Int. luminosity	**1 - 100 fb^{-1} / year**

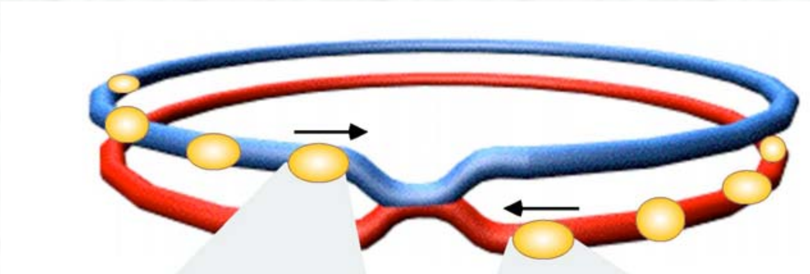
… became a reality in 2008
after ~15 years of hard work

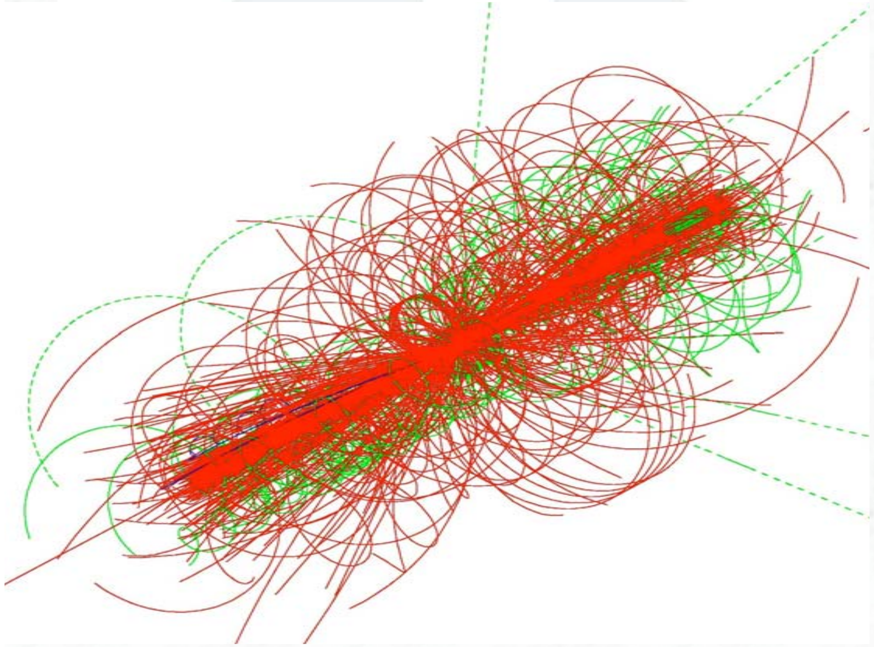
Comparison of the LHC and Tevatron machine parameters

	LHC (design)	**Tevatron (achieved)**
Centre-of-mass energy	**14 TeV**	**1.96 TeV**
Number of bunches	**2808**	**36**
Bunch spacing	**25 ns**	**396 ns**
Energy stored in beam	**360 MJ**	**1 MJ**
Peak Luminosity	**10^{33}-10^{34} $cm^{-2}s^{-1}$**	**3.5 x 10^{32} $cm^{-2}s^{-1}$**
Integrated Luminosity / year	**10-100 fb^{-1}**	**~ 2 fb^{-1}**

- 7 times more energy (after initial 3.5 and 5 TeV phases)
- Factor 3-30 times more luminosity
- Physics cross sections factor 10-100 larger

Proton proton collisions at the LHC





Proton – proton:

2835 x 2835 bunches
Separation: 7.5 m (25 ns)

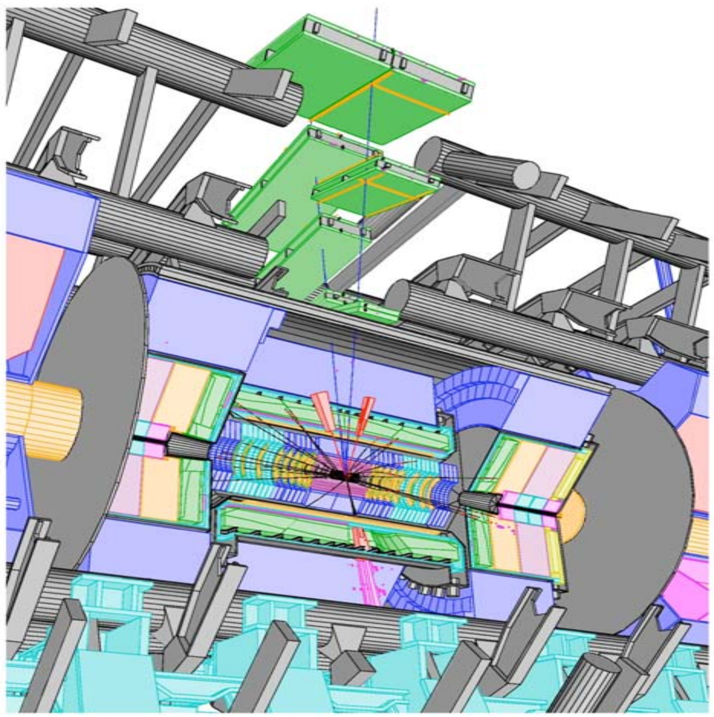
10^{11} protons / bunch
Crossing rate of p-bunches: 40 Mio. / s
Luminosity: L = 10^{34} cm^{-2} s^{-1}

~10^{9} pp collisions / s
(superposition of 23 pp-interactions
per bunch crossing: **pile-up**)

~1600 charges particles in the detector

⇒ high particle densities
high requirements for the detectors

Detector requirements from physics

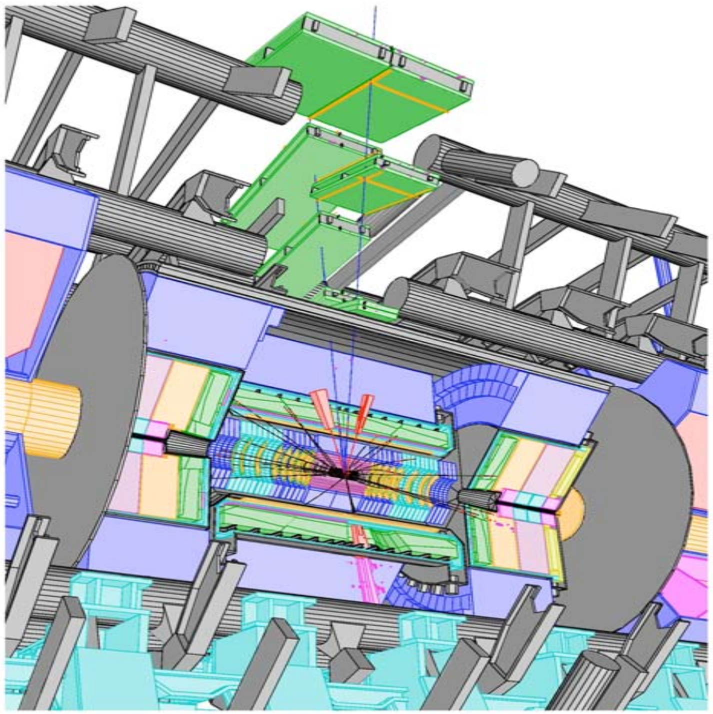


- Good measurement of leptons and photons with large transverse momentum P_T

- Good measurement of missing transverse energy (E_T^{miss})
  and
  energy measurements in the forward regions
  $\Rightarrow$ calorimeter coverage down to $\eta \sim 5$

- Efficient b-tagging and τ identification (silicon strip and pixel detectors)

Detector requirements from the experimental environment (pile-up)



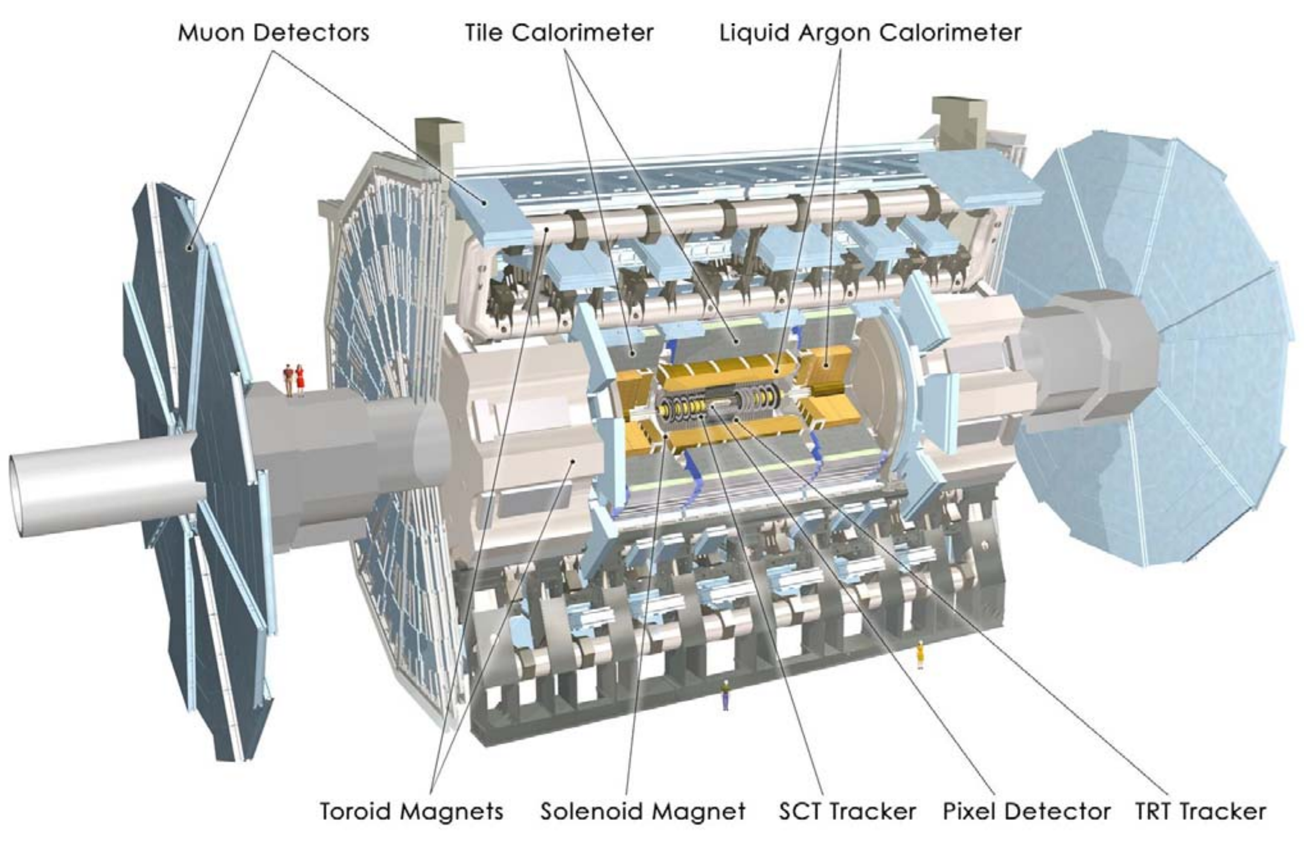
- LHC detectors must have **fast response**, otherwise integrate over many bunch crossings → too large pile-up

  Typical response time : 20-50 ns
  → integrate over 1-2 bunch crossings
  → pile-up of 25-50 minimum bias events
  ⇒ very challenging readout electronics

- **High granularity** to minimize probability that pile-up particles be in the same detector element as interesting object
  → 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 in 10 years of LHC operation

The ATLAS experiment



- Solenoidal magnetic field (2T) in the central region (momentum measurement)

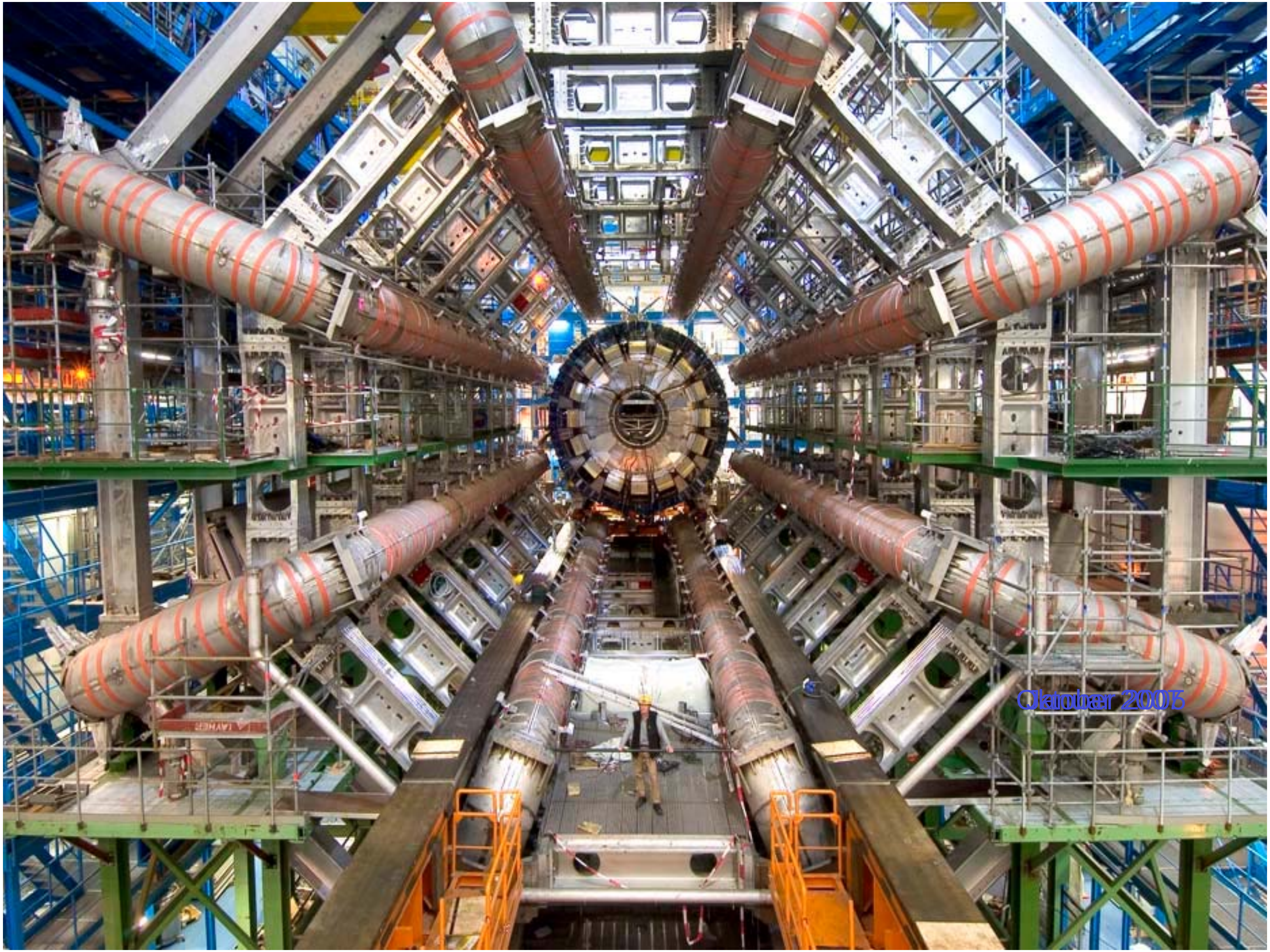
  High resolution silicon detectors:
  - 6 Mio. channels (80 μm x 12 cm)
  - 100 Mio. channels (50 μm x 400 μm)

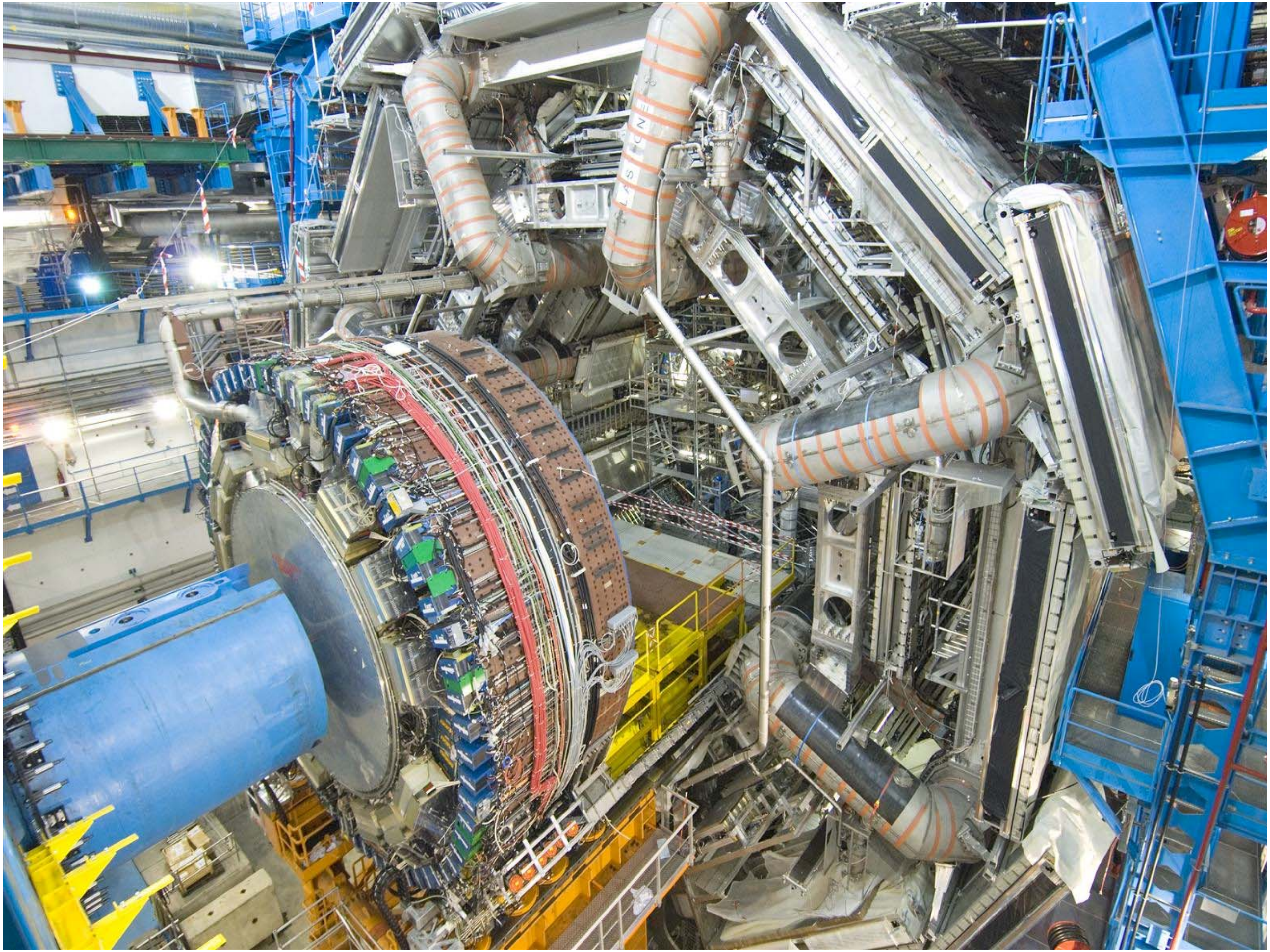
  space resolution: ~ 15 μm

- Energy measurement down to 1° to the beam line

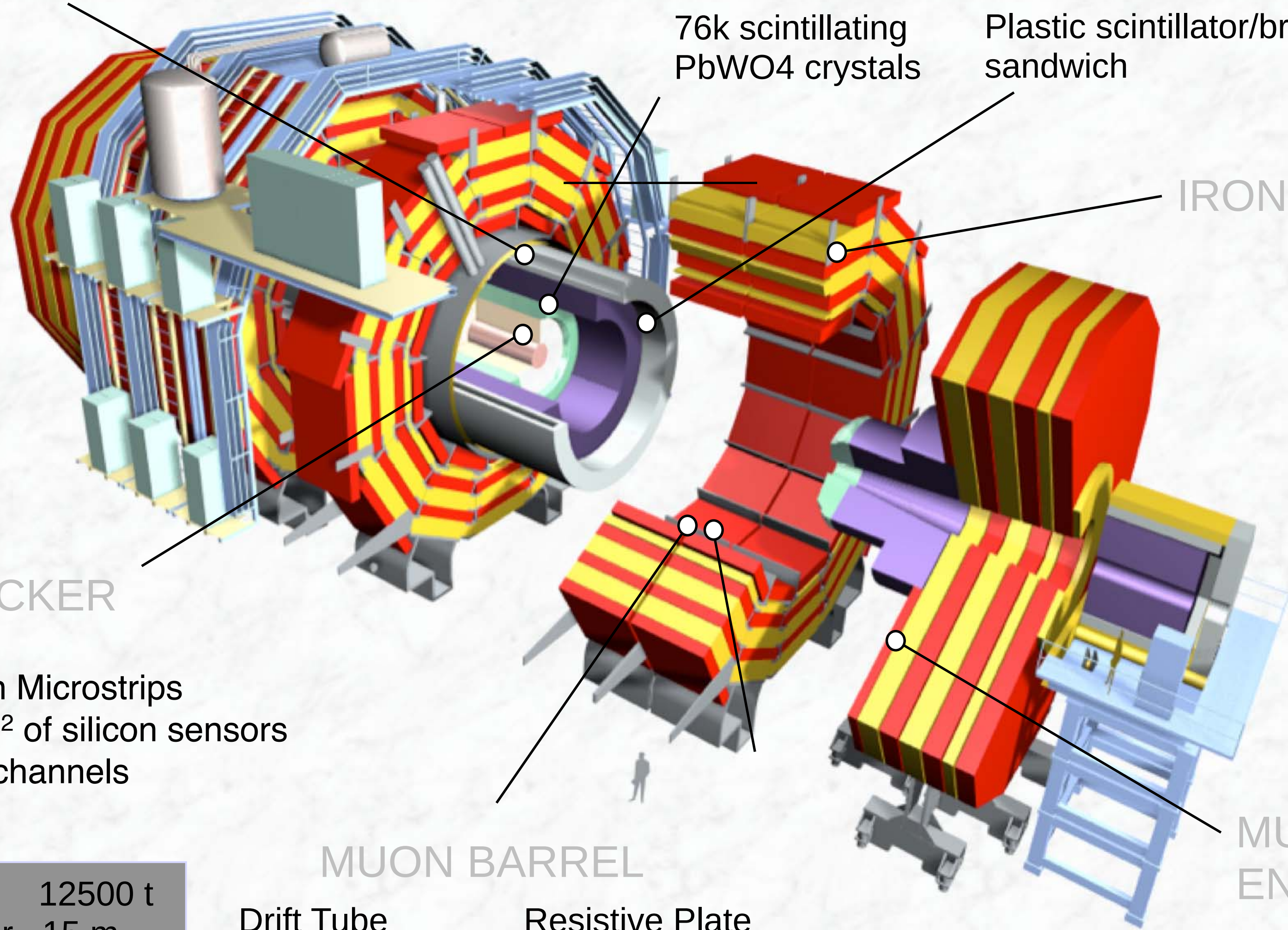
- Independent muon spectrometer (supercond. toroid system)

Diameter	25 m
Barrel toroid length	26 m
End-cap end-wall chamber span	46 m
Overall weight	7000 Tons


Oktober 2005
Januar 2007



CMS



Superconducting Coil, 4 Tesla

CALORIMETERS

ECAL
76k scintillating PbWO4 crystals

HCAL
Plastic scintillator/brass sandwich

IRON YOKE

TRACKER

Pixels
Silicon Microstrips
210 m^2 of silicon sensors
9.6M channels

MUON BARREL

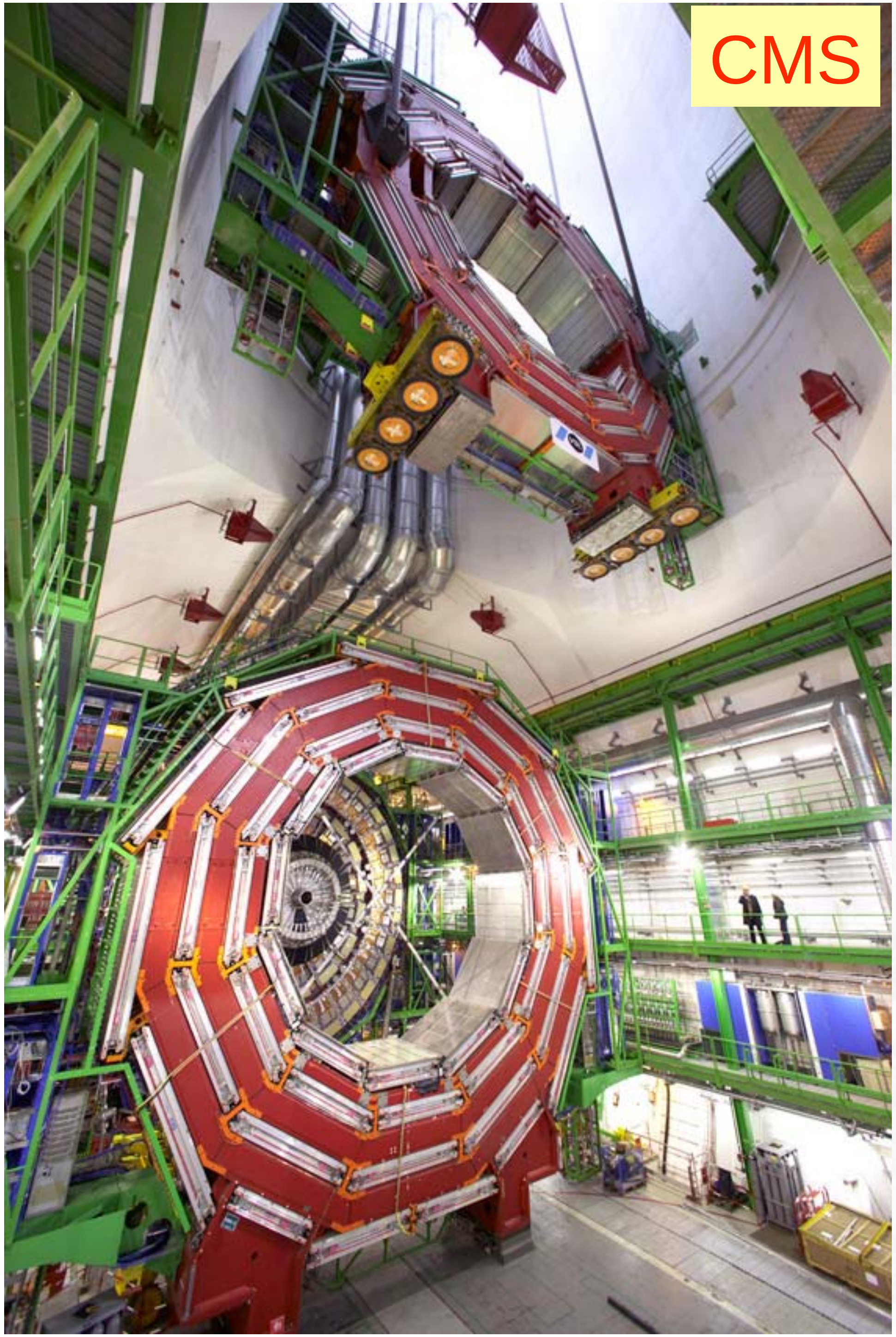
Drift Tube Chambers (**DT**)

Resistive Plate Chambers (**RPC**)

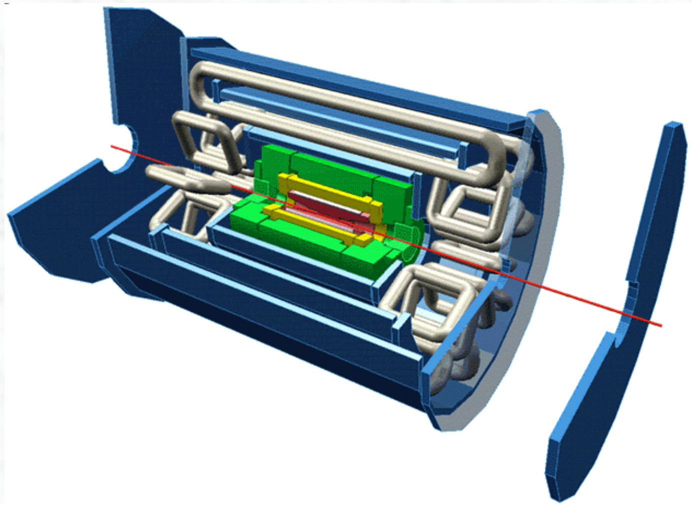
MUON ENDCAPS

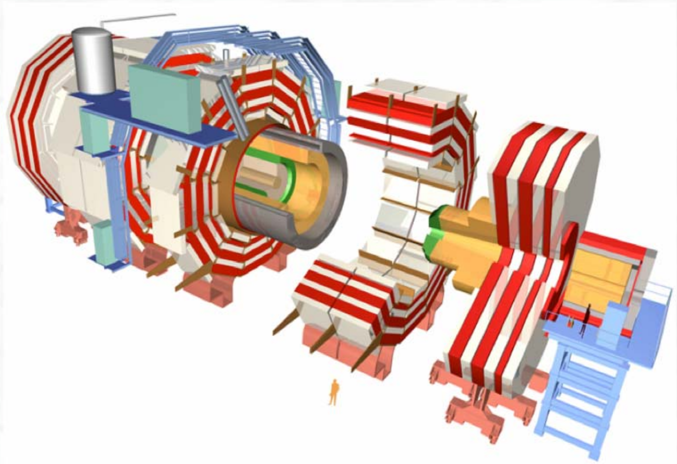
Cathode Strip Chambers (**CSC**)
Resistive Plate Chambers (**RPC**)

Total weight	12500 t
Overall diameter	15 m
Overall length	21.6 m


CMS

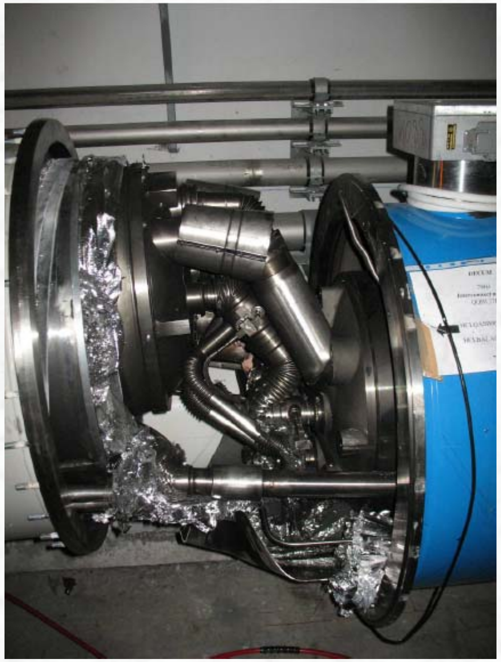
	ATLAS	CMS
Magnetic field	2 T solenoid + toroid: 0.5 T (barrel), 1 T (endcap)	4 T solenoid + return yoke
Tracker	Silicon pixels and strips + transition radiation tracker $\sigma/p_T \approx 5 \cdot 10^{-4} p_T + 0.01$	Silicon pixels and strips (full silicon tracker) $\sigma/p_T \approx 1.5 \cdot 10^{-4} p_T + 0.005$
EM calorimeter	Liquid argon + Pb absorbers $\sigma/E \approx 10\%/\sqrt{E} + 0.007$	$PbWO_4$ crystals $\sigma/E \approx 3\%/\sqrt{E} + 0.003$
Hadronic calorimeter	Fe + scintillator / Cu+LAr (10λ) $\sigma/E \approx 50\%/\sqrt{E} + 0.03$ GeV	Brass + scintillator (7 λ + catcher) $\sigma/E \approx 100\%/\sqrt{E} + 0.05$ GeV
Muon	$\sigma/p_T \approx$ 2% @ 50GeV to 10% @ 1TeV (Inner Tracker + muon system)	$\sigma/p_T \approx$ 1% @ 50GeV to 10% @ 1TeV (Inner Tracker + muon system)
Trigger	L1 + HLT (L2+EF)	L1 + HLT (L2 + L3)





An excellent LHC start: first beams – Sept 10, 2008

Incident on 19th Sep. 2008, repair, comeback…..



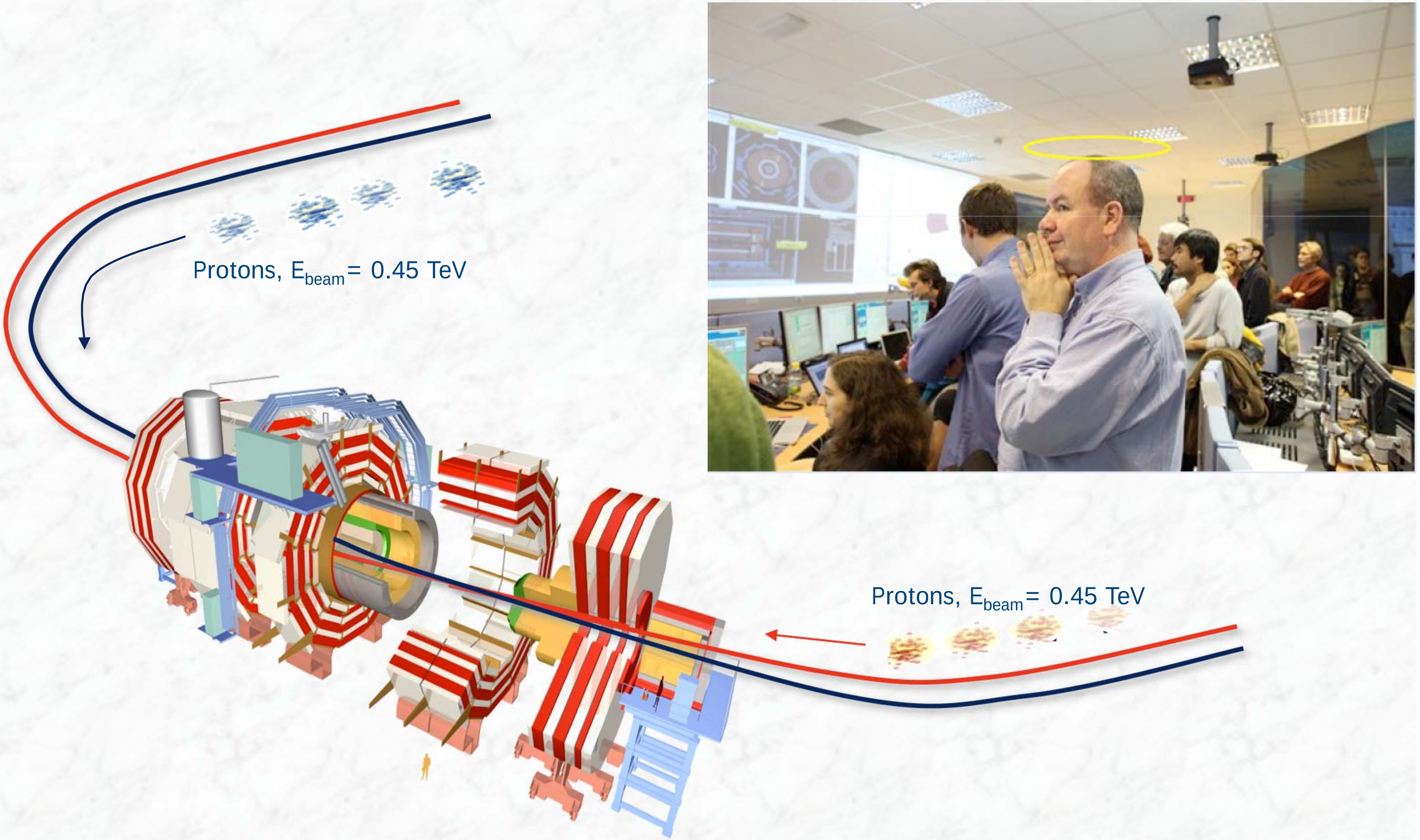
- A resistive zone developed in an electrical bus bar connection
- Electrical arc → punctured the helium enclosure
- Helium release under high pressure
- Relief discs unable to maintain the pressure rise below 0.15 MPa → large pressure forces

- Lot of repair work during 2009

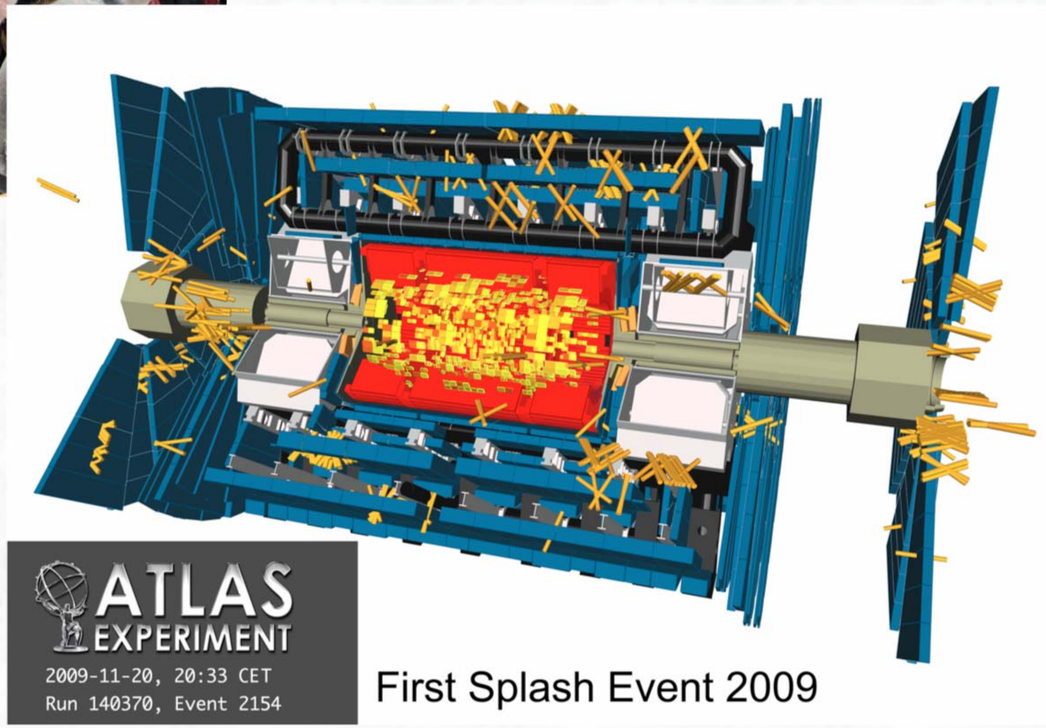
  (14 quadrupole and 39 dipole magnets replaced, electrical interconnections repaired, larger helium pressure release ports installed,…..)

- **A very successful re-start in Nov. 2009**

LHC re-start in Nov. 2009



The first signals in the ATLAS experiment, 20. Nov 2009



First Splash Event 2009

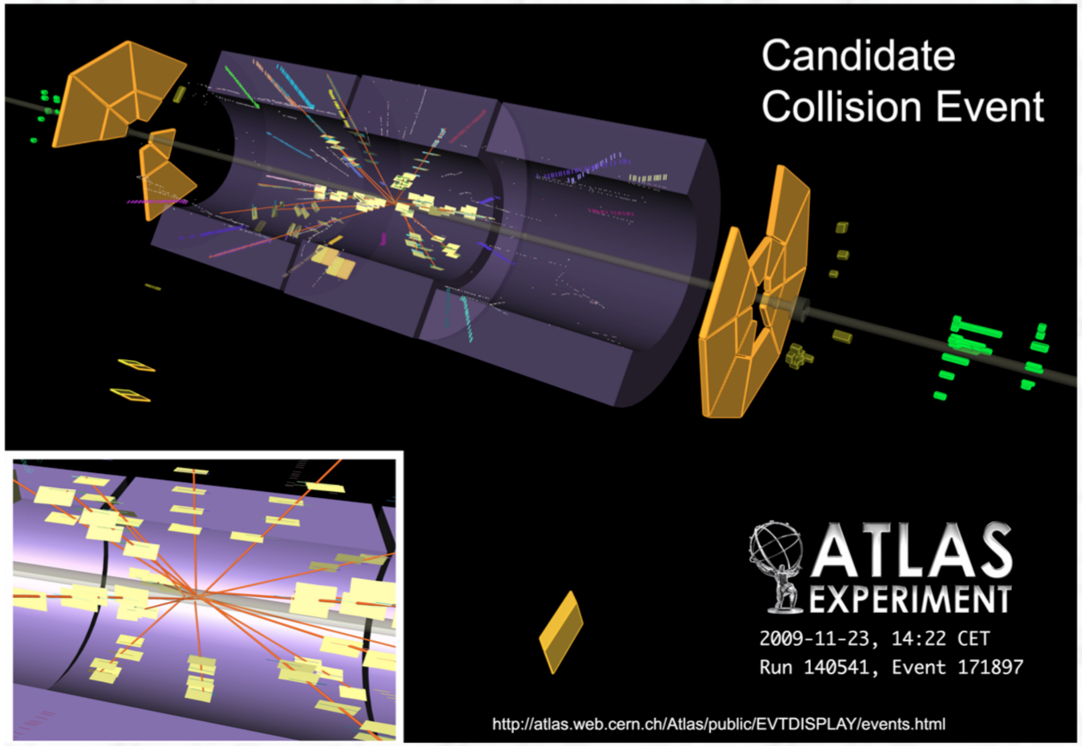
CMS in the BBC news

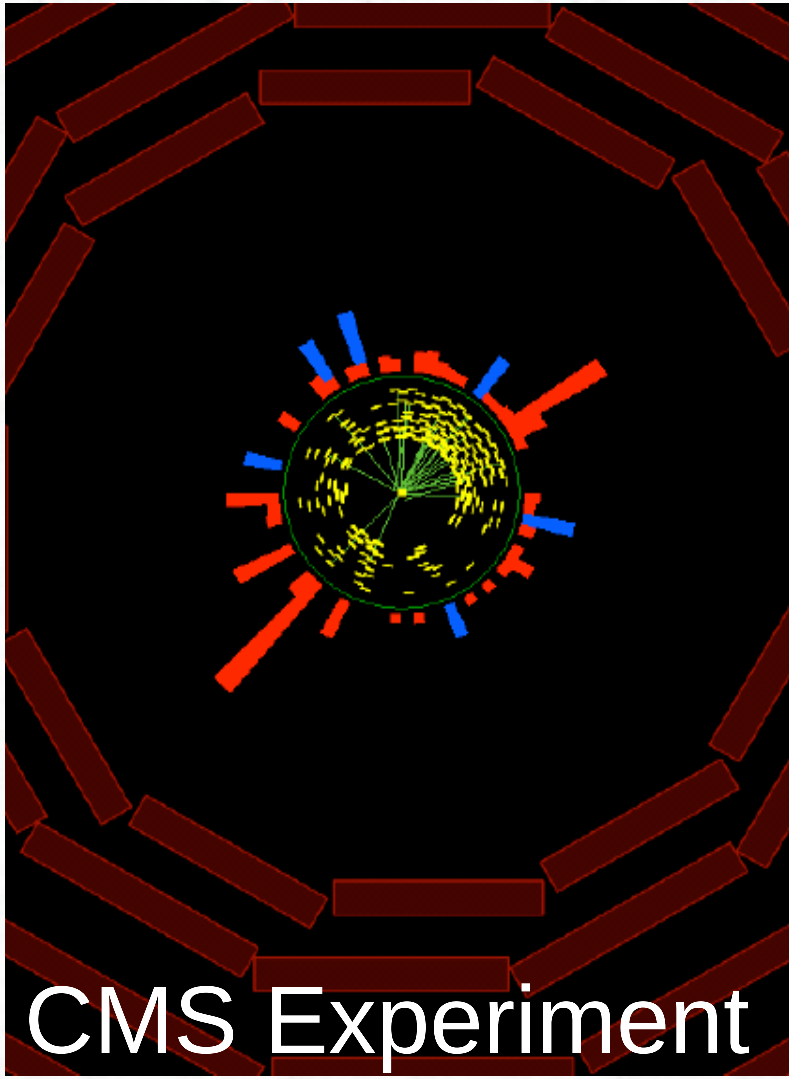
November 21, 2009

BBC NEWS

Scientists at Cern in Geneva have restarted the Large Hadron Collider (LHC) experiment, which hopes to shed light on the origins of the universe.

23. Nov 2009: First collisions at 900 GeV

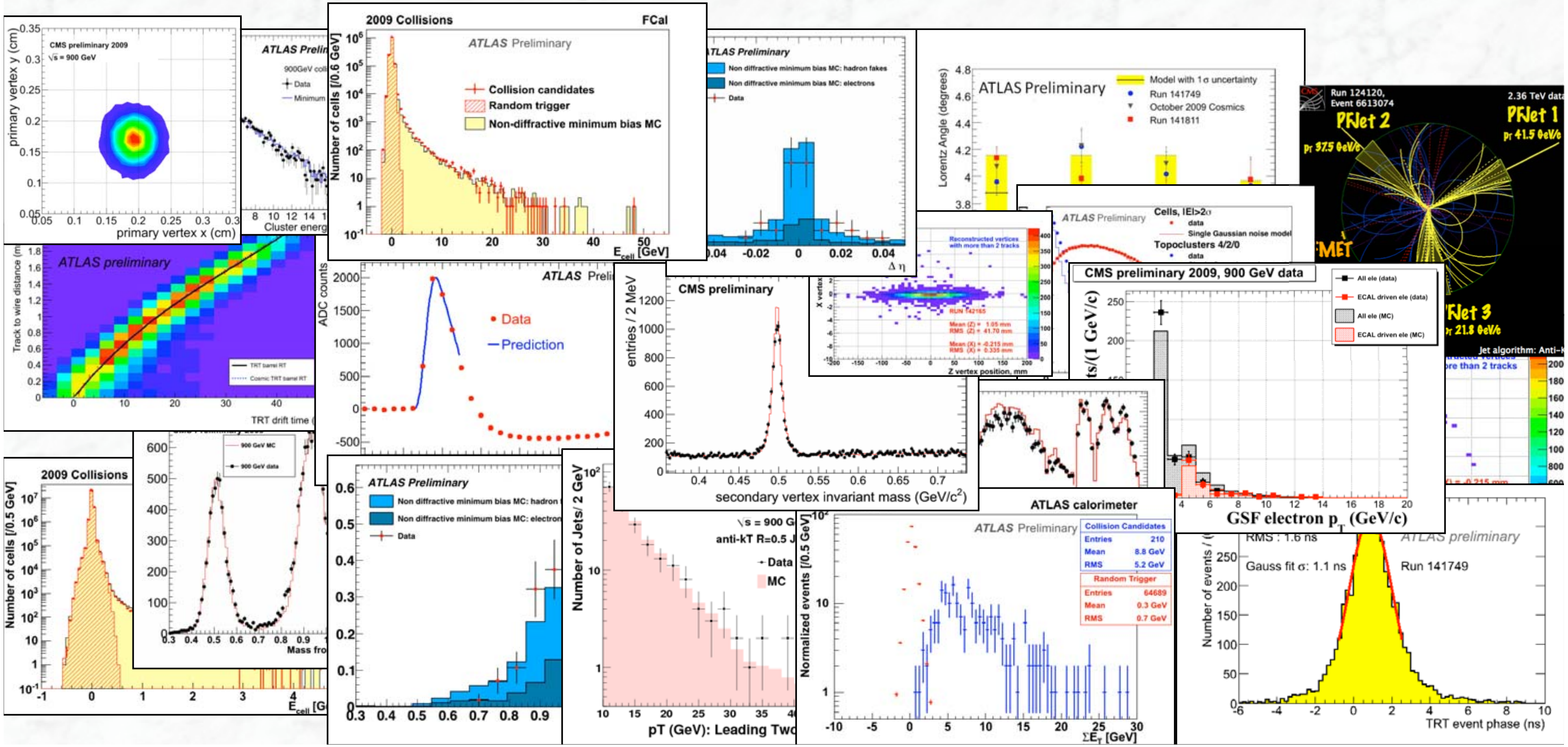




23rd Nov 2009

First results
on detector performance after only a few days / weeks

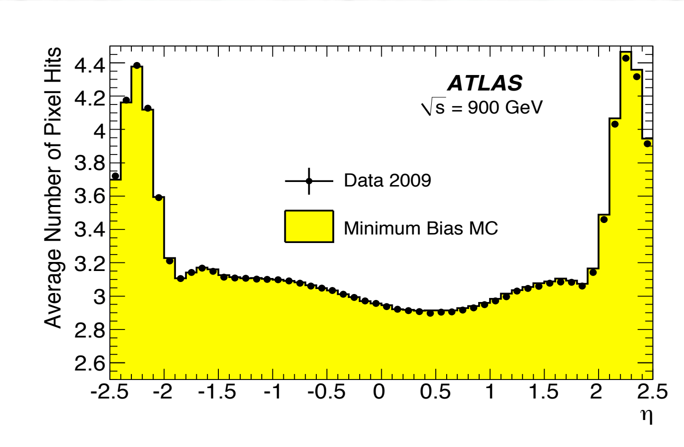
First publications of physics results in Feb/March 2010

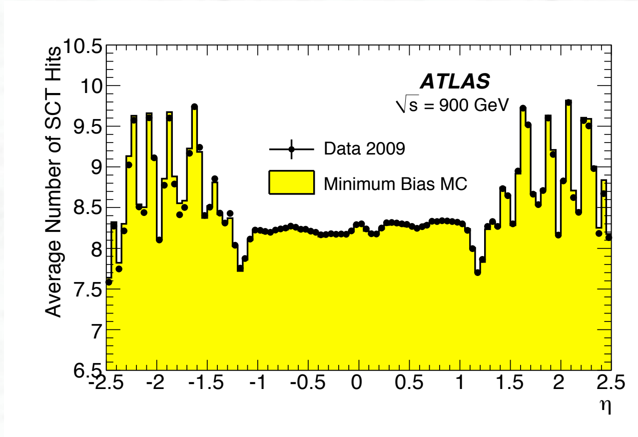


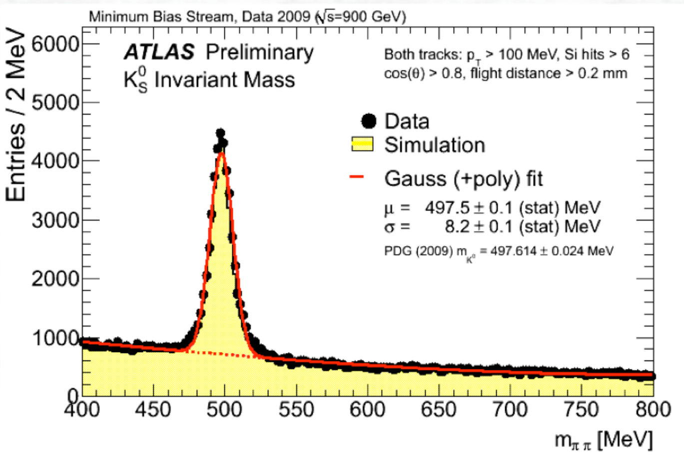
Inner Detector performance: hits, tracks, resonances,...

- Very good agreement for the average number of hits on tracks in the silicon pixel and strip detectors

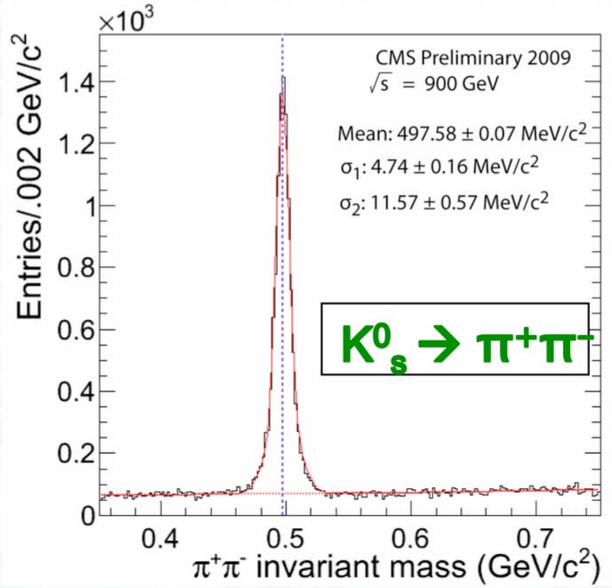
- Material distribution in the inner detector is well described in Monte Carlo

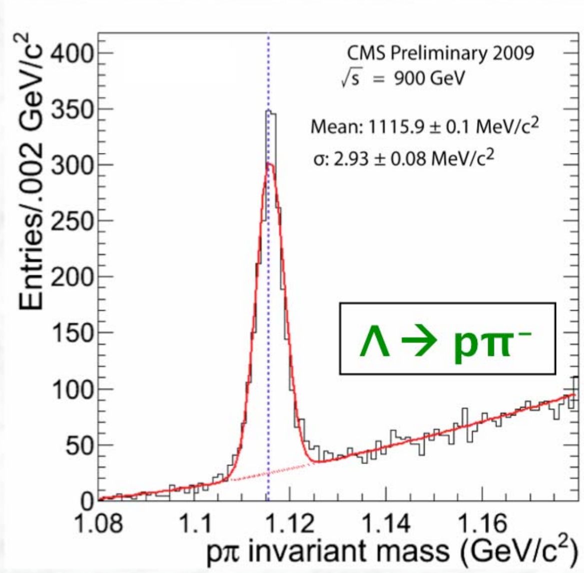


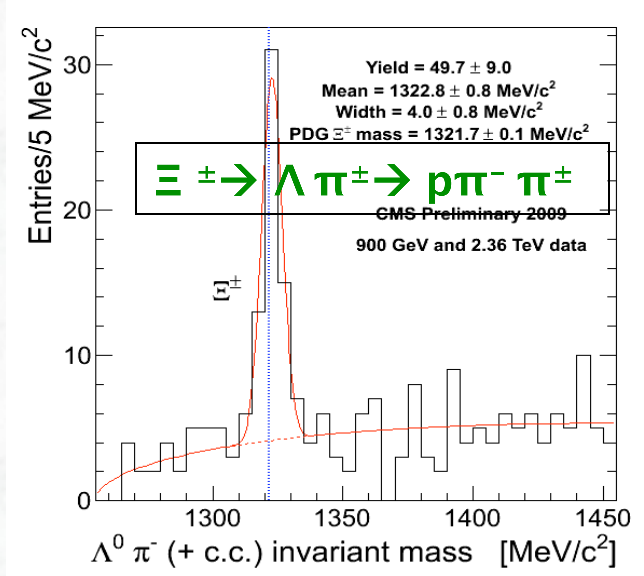


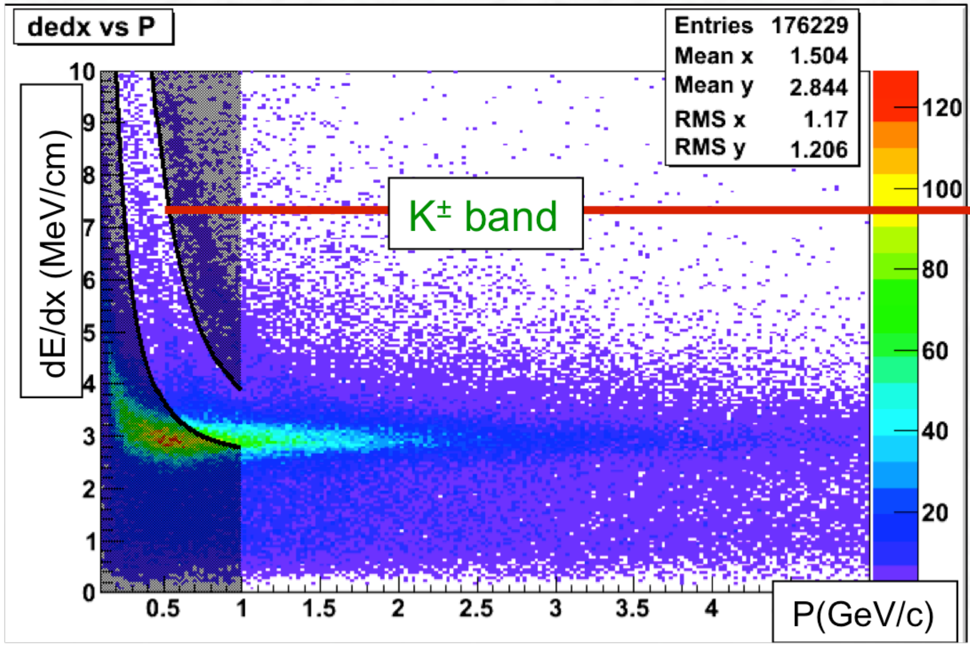


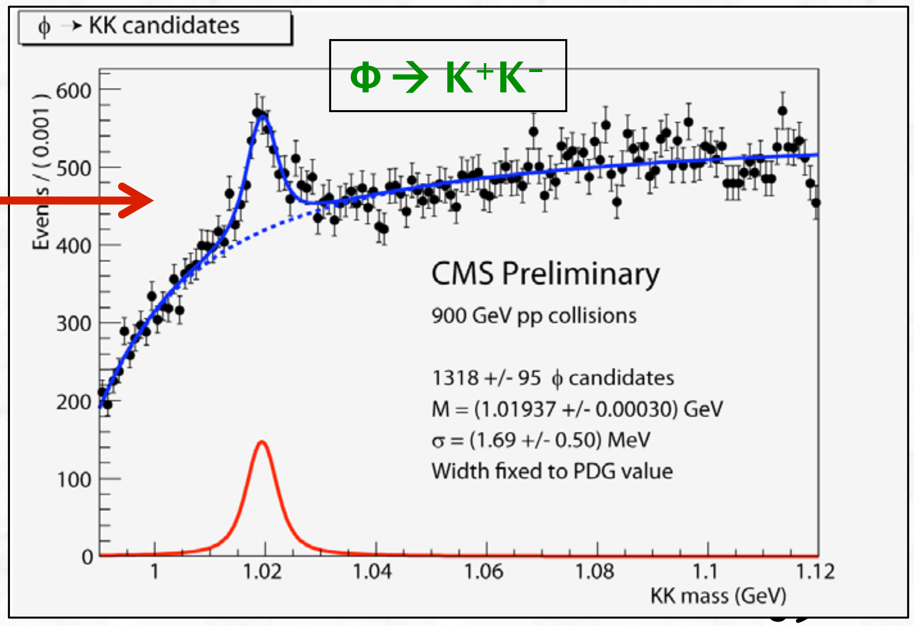
Resonances: CMS tracking detector





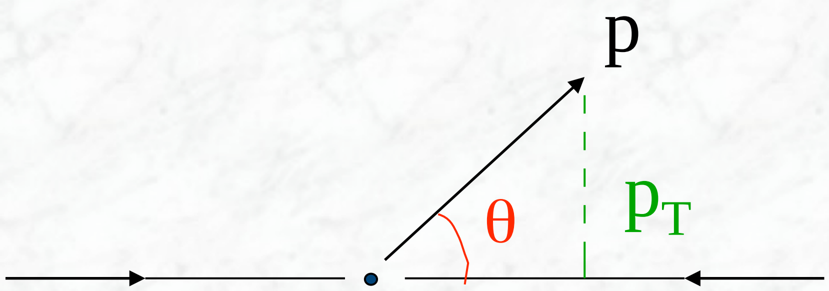






First Physics

Variables used in the analysis of pp collisions

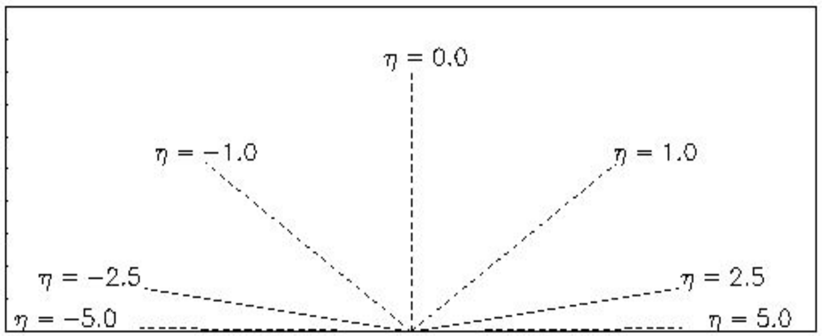


Transverse momentum
(in the plane perpendicular to the beam)

$p_T = p \sin\theta$

(Pseudo)-rapidity: $\eta = -\ln \tan \frac{\Theta}{2}$

[$d\sigma / dp_T \, d\eta$ is Lorentz-invariant]



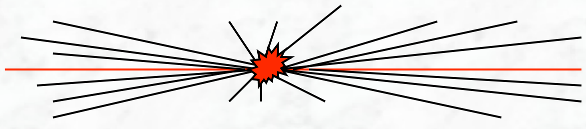
$\theta = 90^o \rightarrow \eta = 0$

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

$\theta = 1^o \rightarrow \eta \cong 5.0$

Inelastic low-p_T pp collisions

Most interactions are due to interactions at large distance between incoming protons
→ small momentum transfer, particles in the final state have large longitudinal, but small transverse momentum

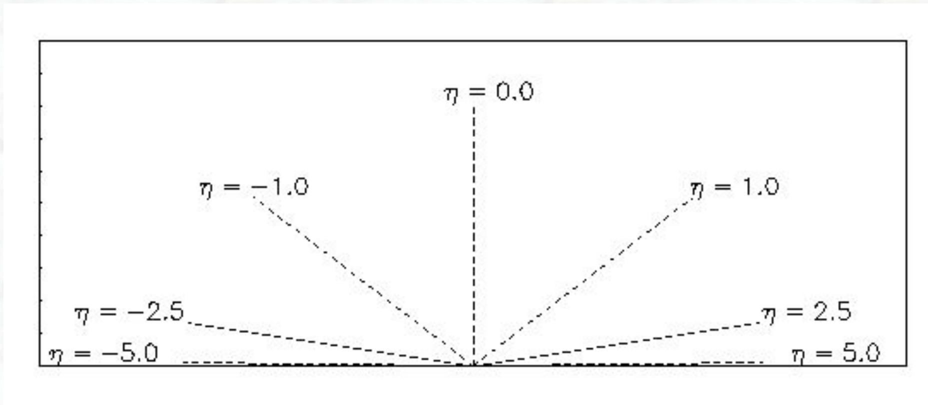


$< p_T > \approx 500$ MeV (of charged particles in the final state)

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

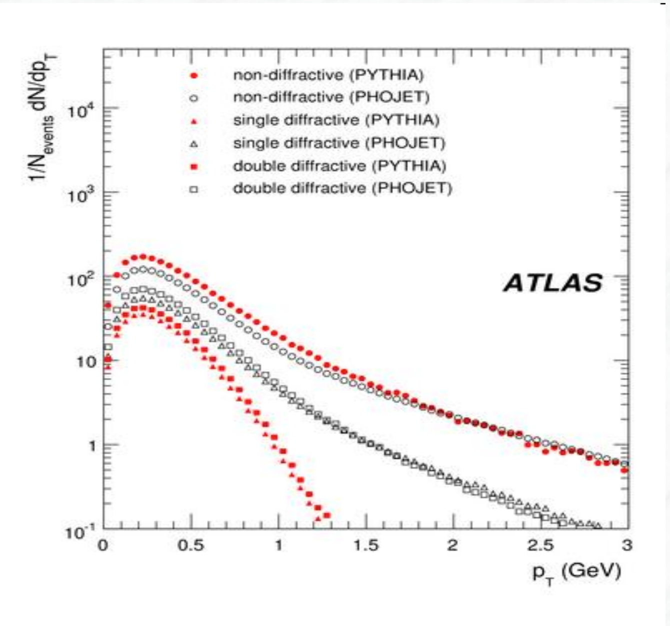
- about 7 charged particles per unit of pseudorapidity in the central region of the detector
- uniformly distributed in ϕ

These events are usually referred to as "minimum bias events"

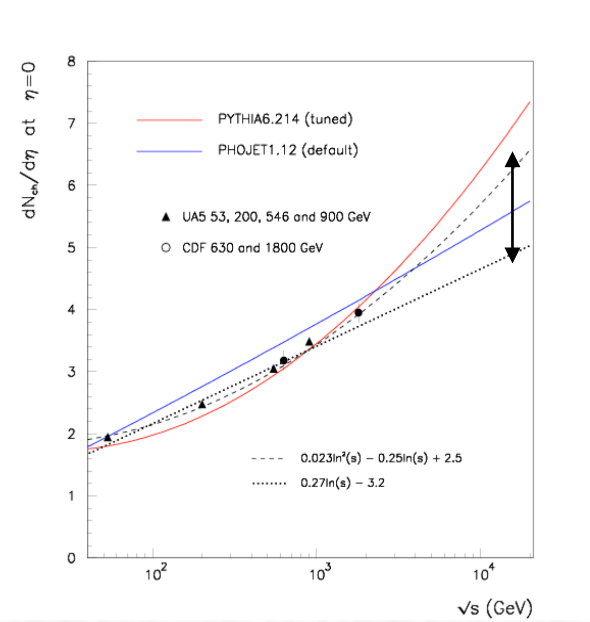


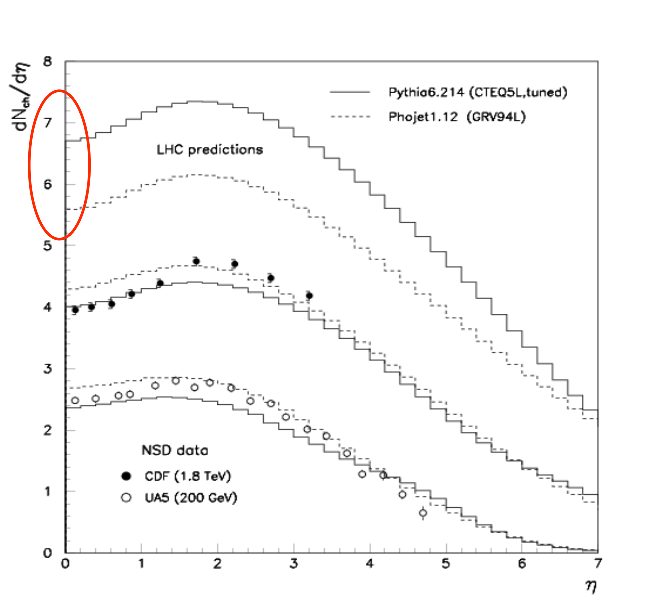
Some features of soft inelastic pp collisions

- Features of soft inelastic collisions cannot be calculated in perturbative QCD
- Experimental measurements / input needed
- Models / parametrizations are used to extrapolate from previous colliders (energies) to the LHC energy regime $\rightarrow$ large uncertainties
- Needed to model other interesting physics (superposition of events,…)



$\langle p_T \rangle$ (η =0): 550 – 640 MeV (15%)





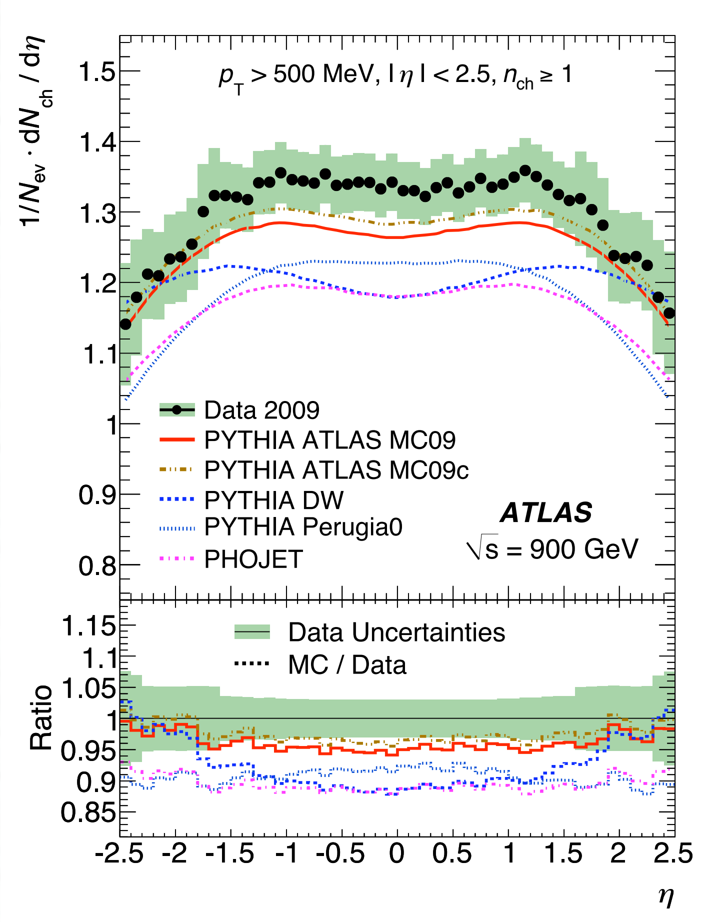
$dN_{ch}/d\eta$ (η=0): 5-7 (~ 33%)

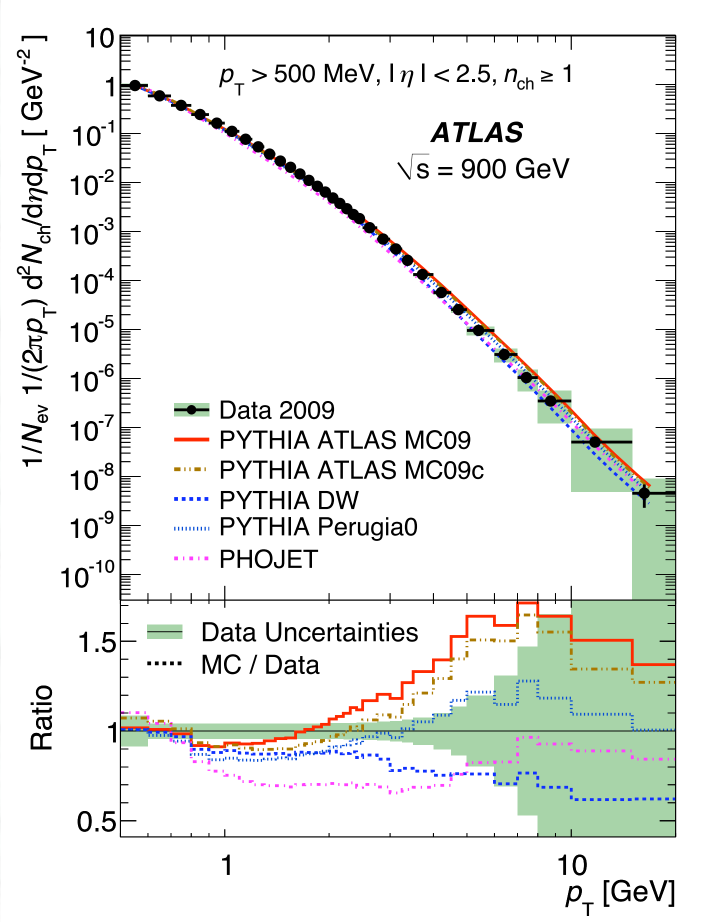
Charged particle density versus η and p_T

N_{ch}: number of primary charged particles corrected to particle level, normalized to the number of selected events N_{ev}

p_T > 500 MeV
$|\eta|$ < 2.5
$N_{ch} \geq 1$

900 GeV data
March 2010

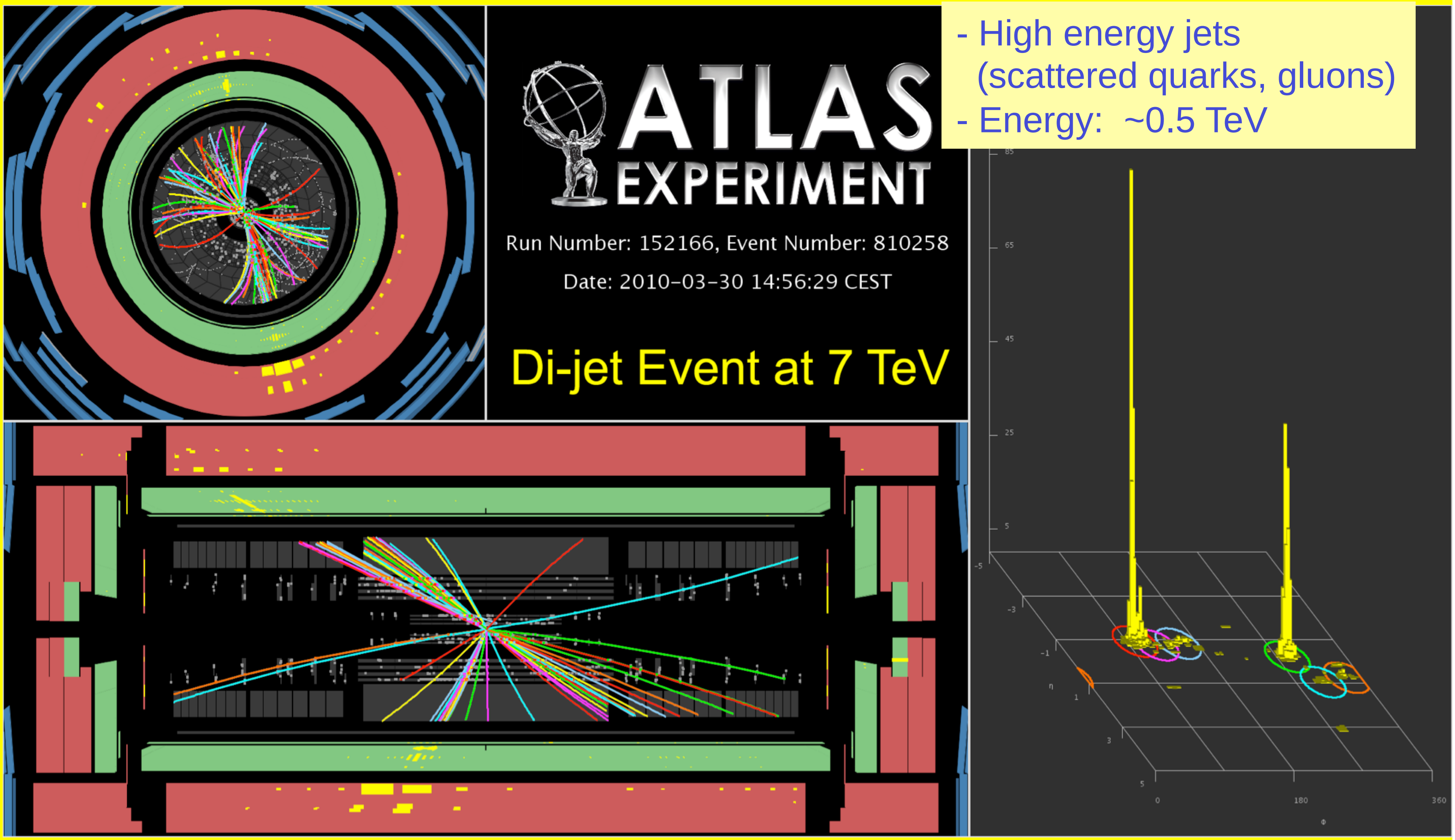




Various Monte Carlo models fail to describe the ATLAS data

Since 30. March 2010: collisions at 7 TeV

(.... first interesting results appeared soon)



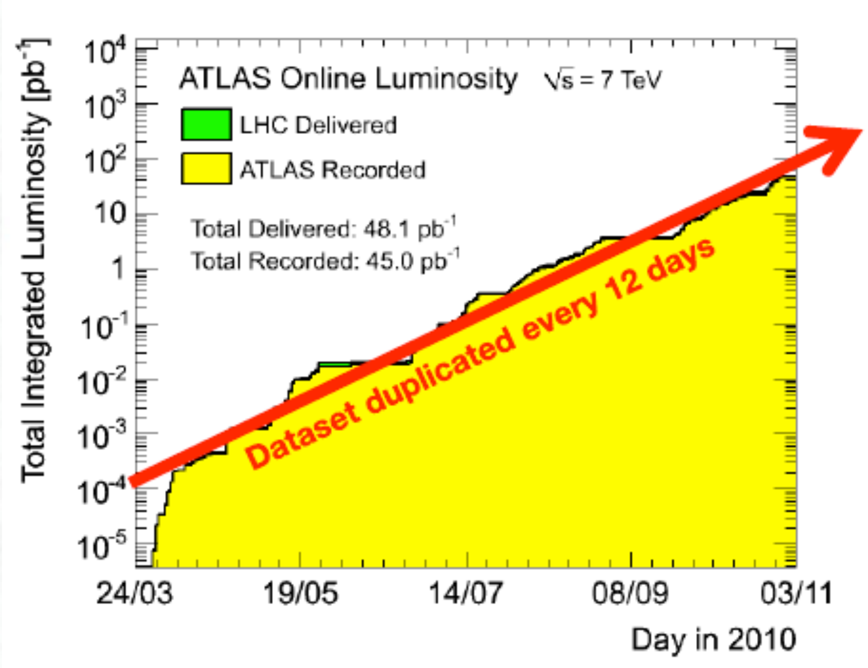
- High energy jets
  (scattered quarks, gluons)
- Energy: ~0.5 TeV

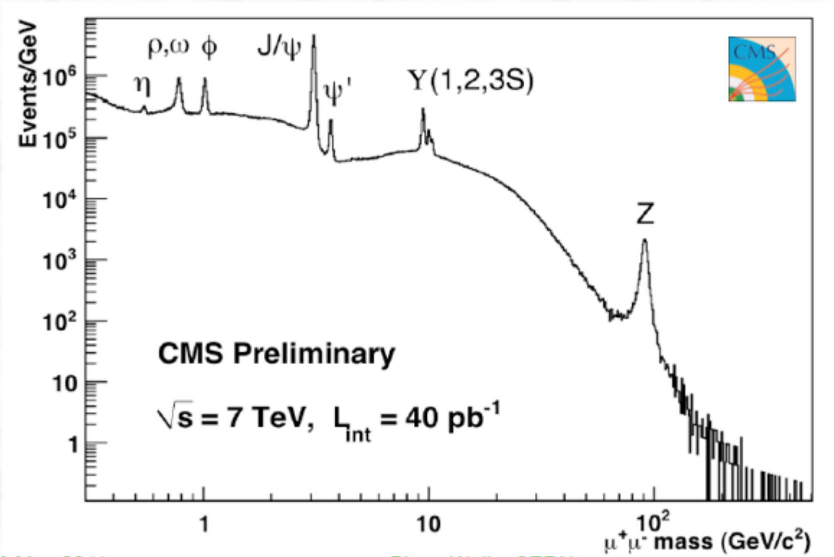
Collected data in 2010:

~40 pb^{-1} recorded
~36 pb^{-1} used in analysis
(good quality)

Both experiments have a very high data taking efficiency !

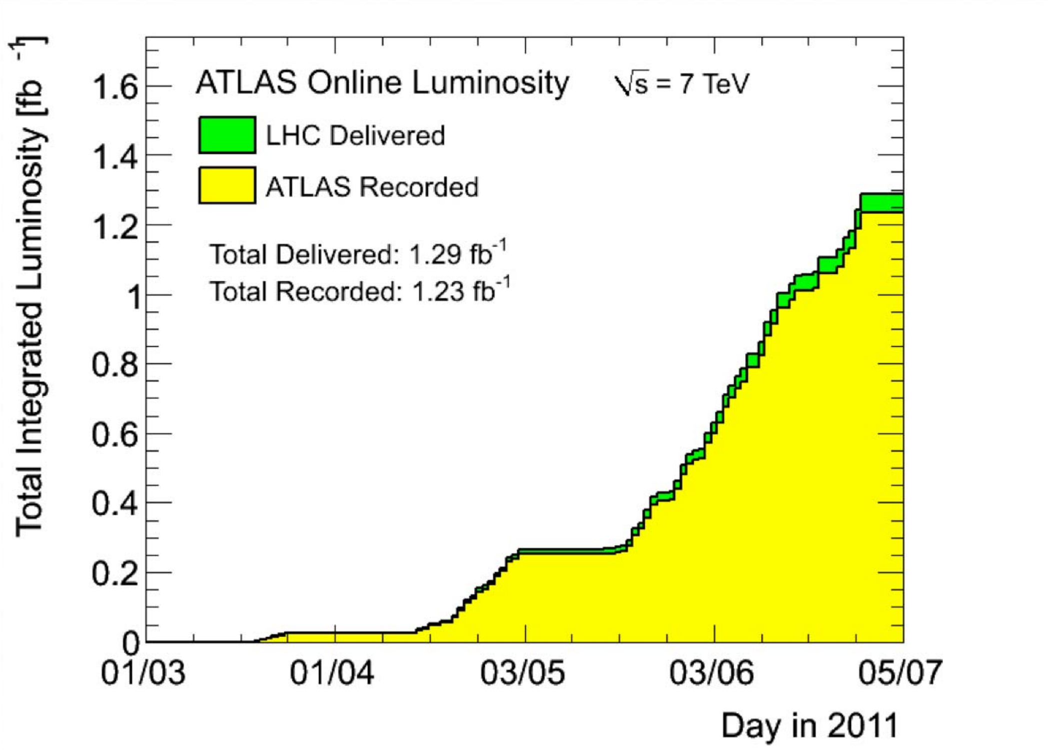
Well known resonances appeared "online"





Data taking in 2011

Original goal to collect 1 fb^{-1} already surpassed in June 2011



- World record on instantaneous luminosity on 22. April 2011: 4.67 10^{32} cm^{-2} s^{-1} (Tevatron record: 4.02 10^{32} cm^{-2} s^{-1})
- 1 fb^{-1} line passed in June 2011
- Collect per day as much luminosity as in 2010
- Data taking efficiency is high
- Pile-up is high (high intensity bunches)