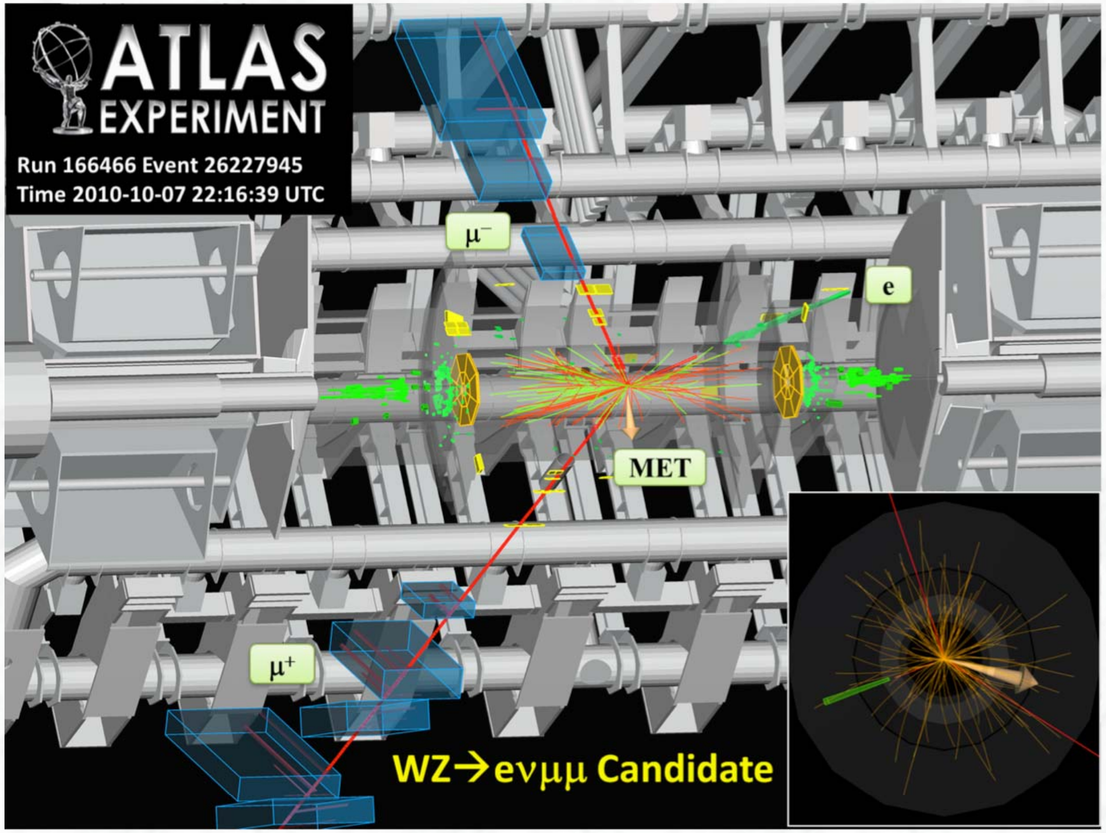
# Physics at the LHC

## *- From the Standard Model to searches for new physics-*

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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

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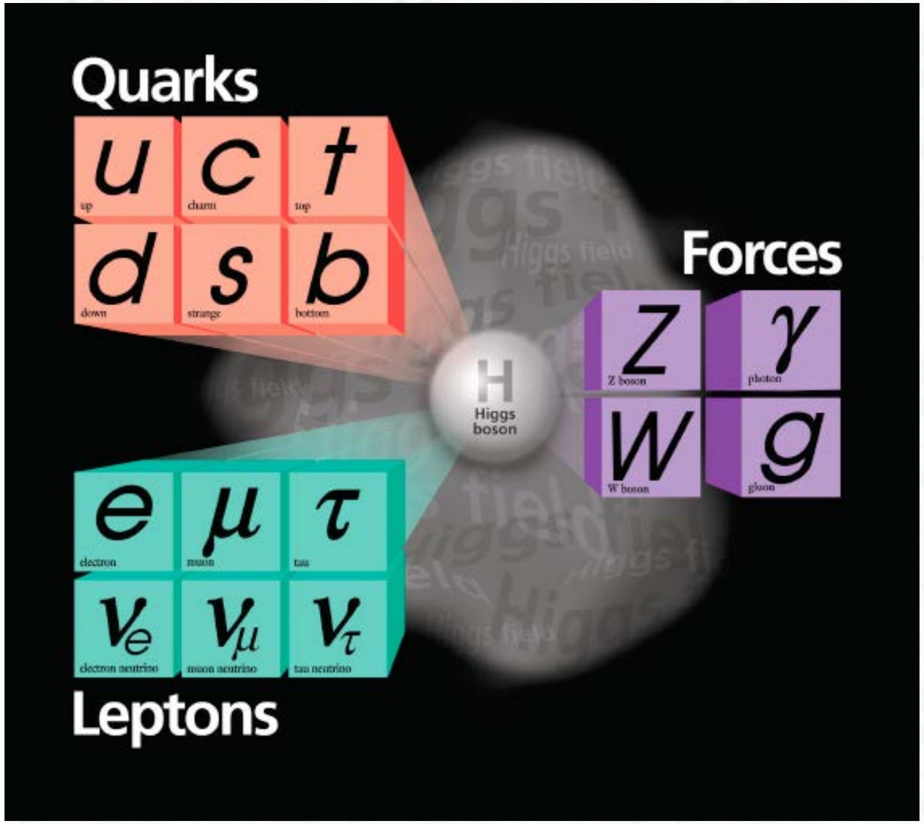
Disclaimer: I will try to highlight important first physics measurements and results on searches for new physics. The coverage is not complete, i.e. not all results available will be presented; Results from both general purpose experiments, ATLAS and CMS, are shown, but there might still be a bias towards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

→ Higgs particle

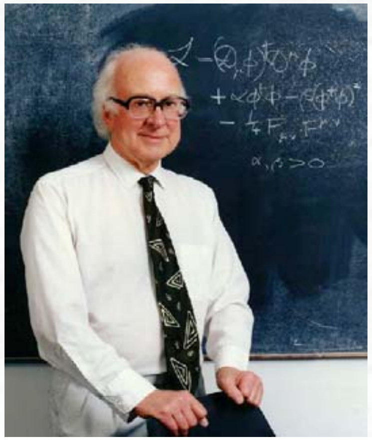
Theoretical arguments: $m_H < \sim 1000$ GeV/$c^2$

# 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$^2$**

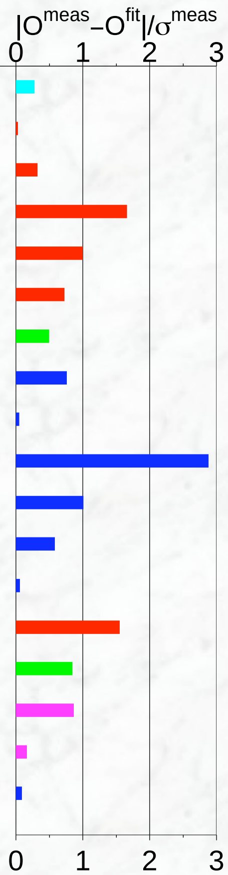


**Only unambiguous example of observed Higgs**

**(P. Higgs, Univ. Edinburgh)**

Summer 2010

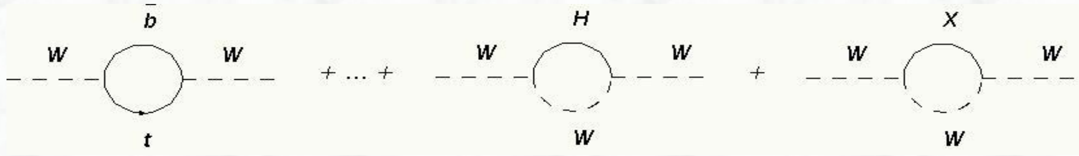
| | Measurement | Fit |
|---|---|---|
| $\Delta\alpha^{(5)}_{had}(m_Z)$ | 0.02758 ± 0.00035 | 0.02768 |
| $m_Z$ [GeV] | 91.1875 ± 0.0021 | 91.1874 |
| $\Gamma_Z$ [GeV] | 2.4952 ± 0.0023 | 2.4959 |
| $\sigma^0_{had}$ [nb] | 41.540 ± 0.037 | 41.479 |
| $R_l$ | 20.767 ± 0.025 | 20.742 |
| $A^{0,l}_{fb}$ | 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 |
| $\Gamma_W$ [GeV] | 2.085 ± 0.042 | 2.092 |
| $m_t$ [GeV] | 173.3 ± 1.1 | 173.4 |

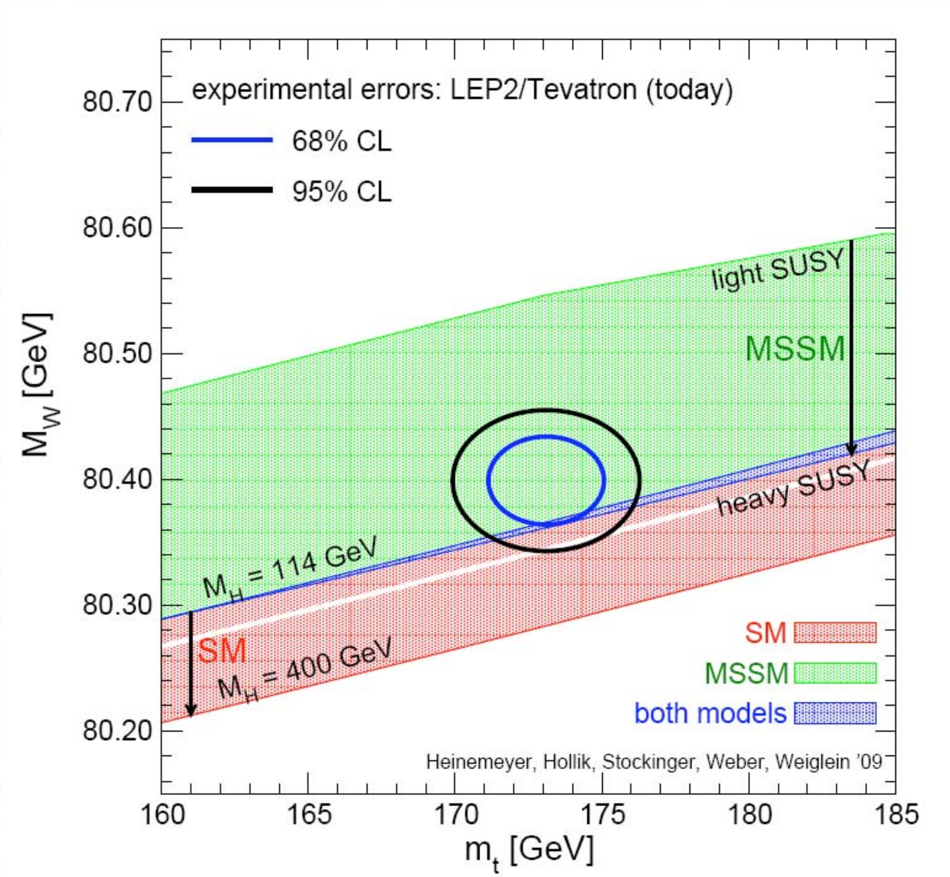



July 2010

# Consistency with the Standard Model

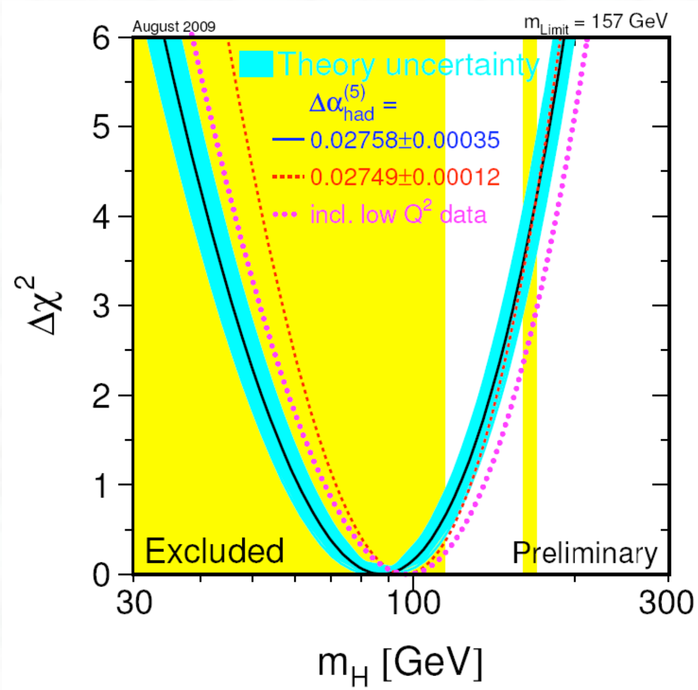
Sensitivity to the Higgs boson and other new particles via quantum corrections:




Interpretation within the Standard Model

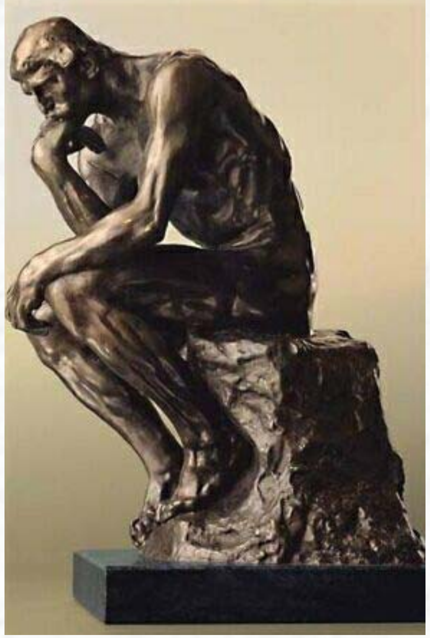
(incl. new (2010) $m_W$ and $m_t$ measurements)




**$m_H$ = 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?**

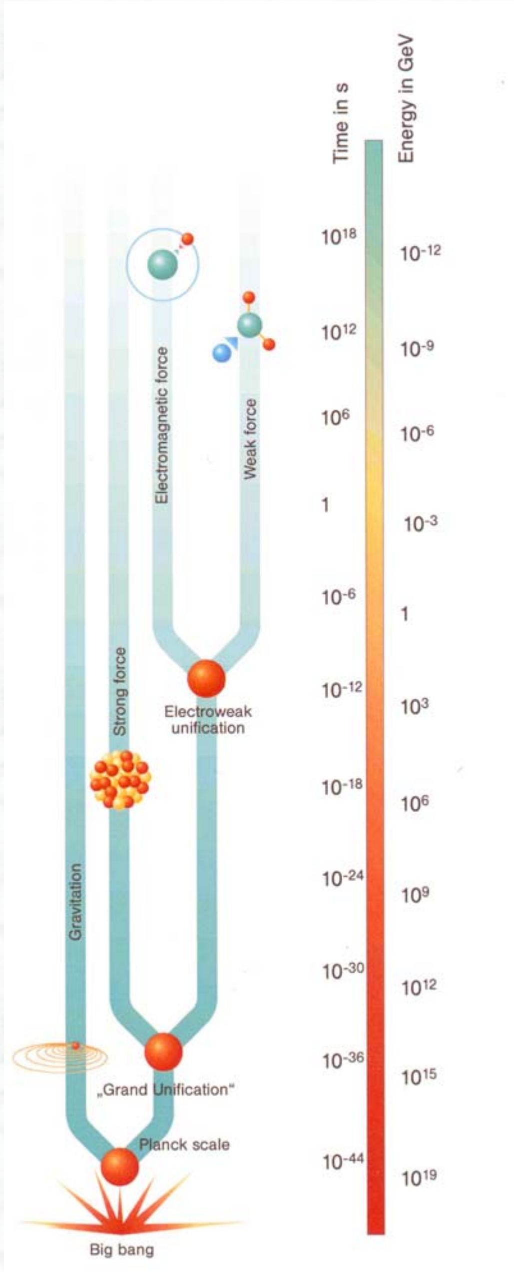
- How is the electroweak symmetry broken ?
- Does the Higgs boson exist ?

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

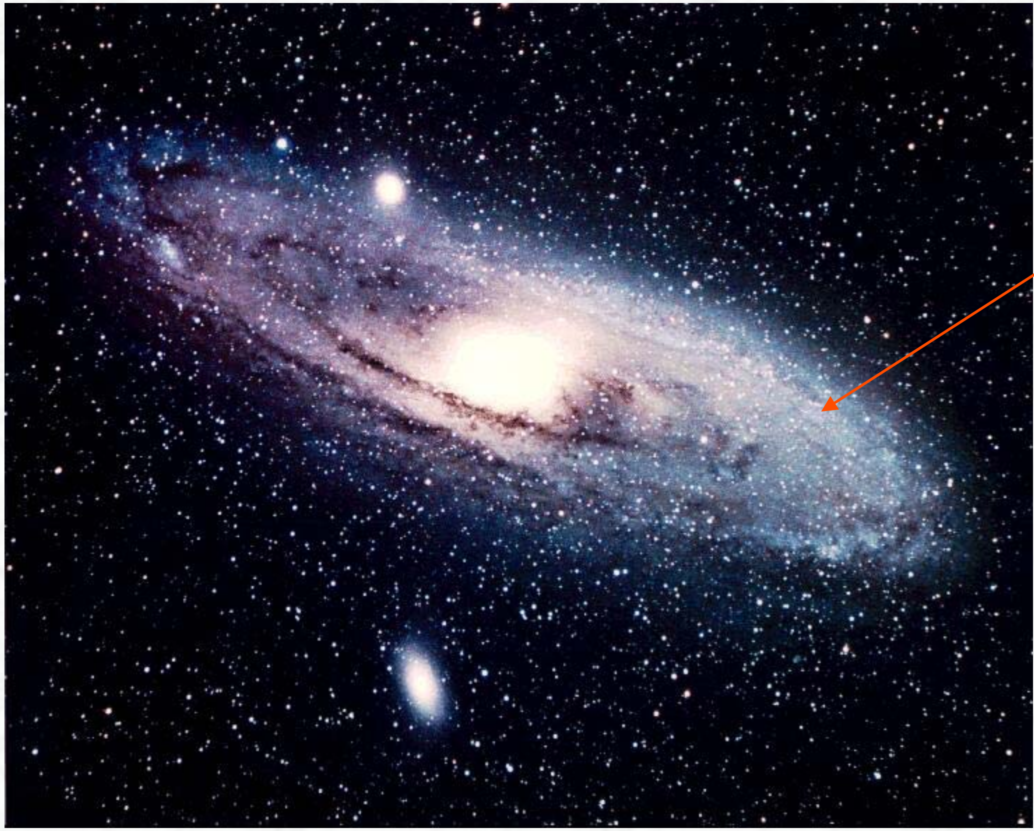
- Can the interactions be unified at larger energy?
- How can gravity be incorporated ?
- Is our world supersymmetric ?
- ….

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

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



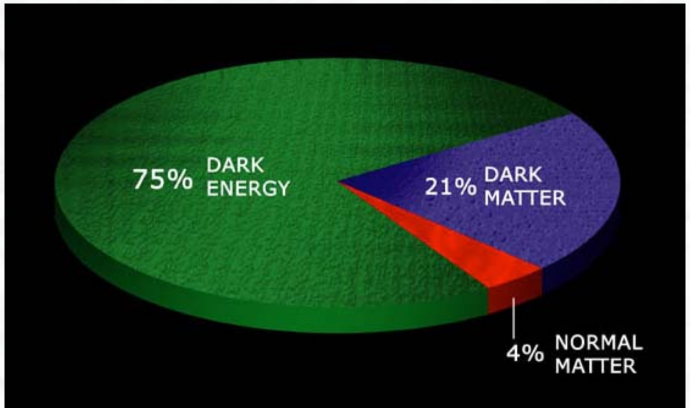
# Problems at a larger scale



We are here

Surrounded by

- Mass
  (planets, stars, ….,hydrogen gas)
- **Dark Matter**
- **Dark Energy**




© Rocky Kolb

# The role of the LHC

## 1. Explore the TeV mass scale

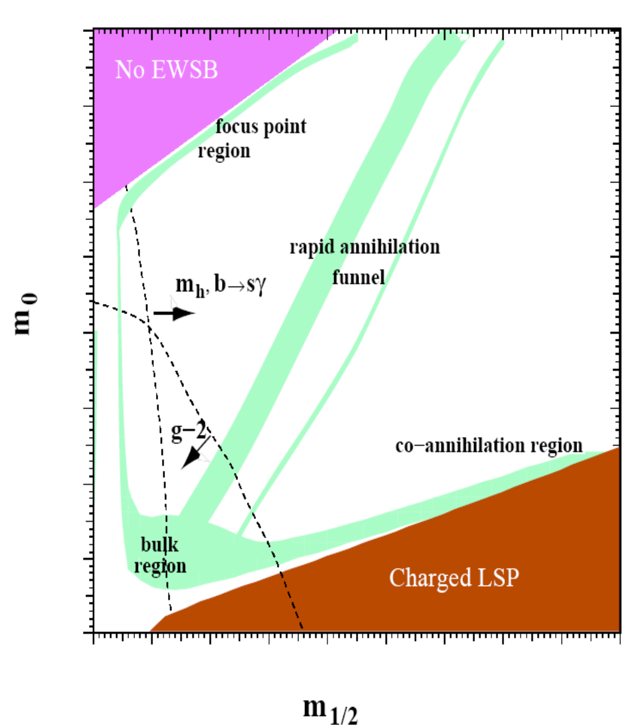
- What is the origin of the electroweak symmetry breaking ?

- 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

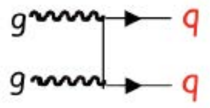
## 2. Precise tests of the Standard Model

- 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

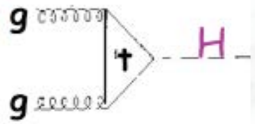
# How can interesting objects be produced?

High-$p_T$ QCD jets

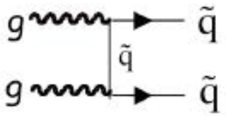


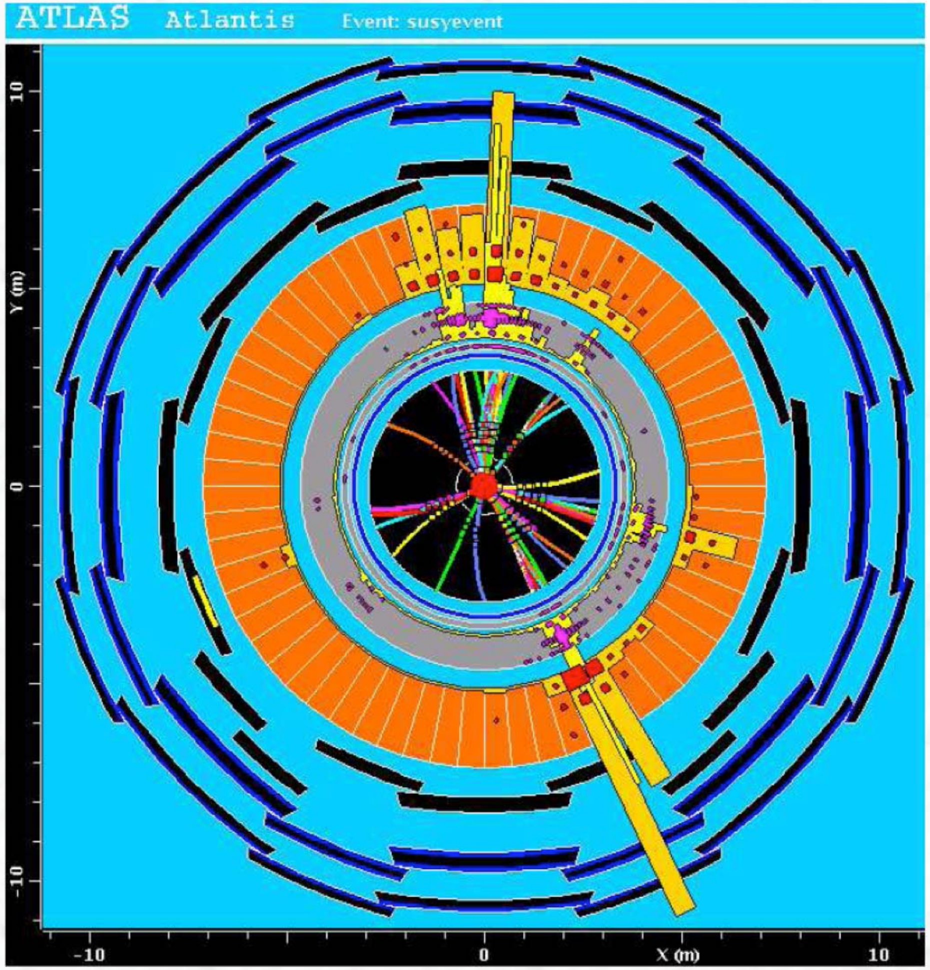

W, Z


Higgs $m_H$=150 GeV



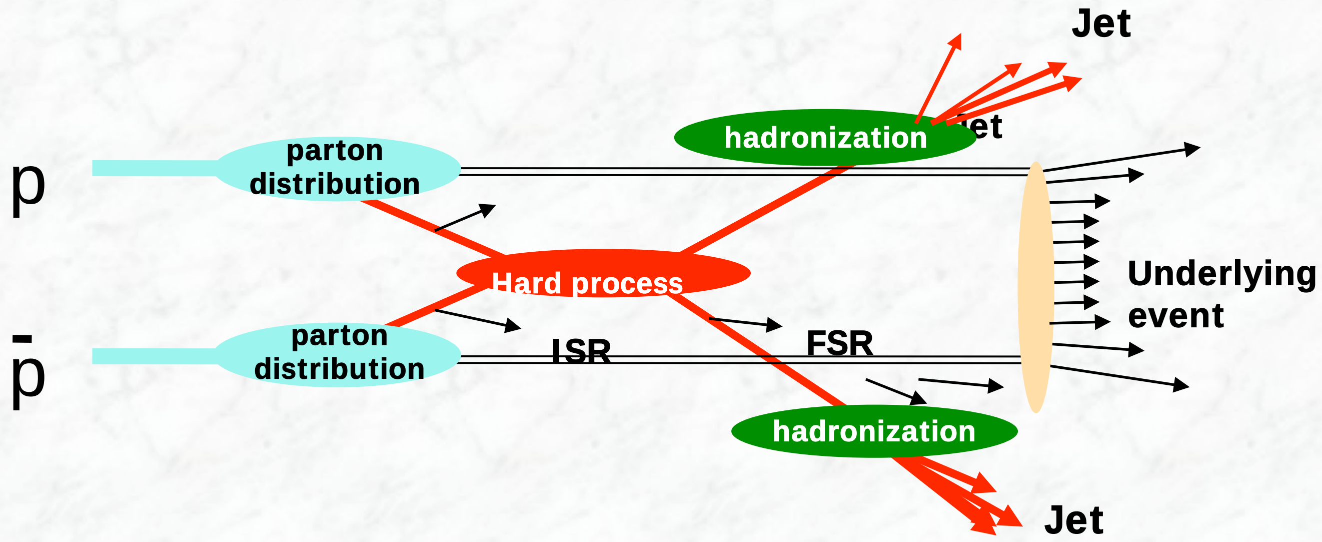

$\tilde{q}, \tilde{g}$ pairs, m ~ 1 TeV



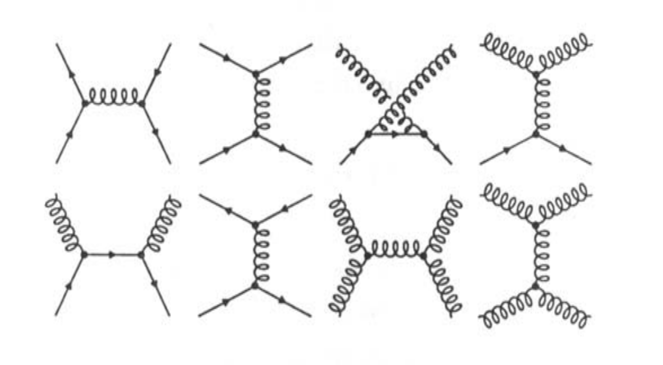

**Quarks and gluons in the initial state**

# Hard Scattering Processes ….or QCD jet production

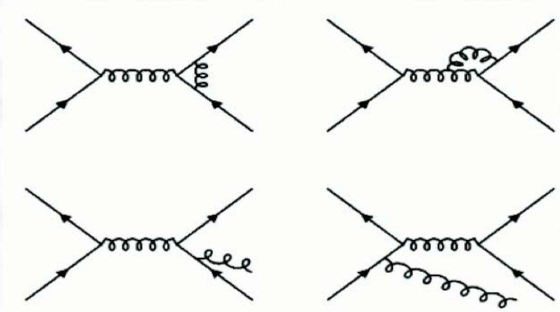



Dominant hard scattering processes: qq, qg and gg “scattering”

Leading order

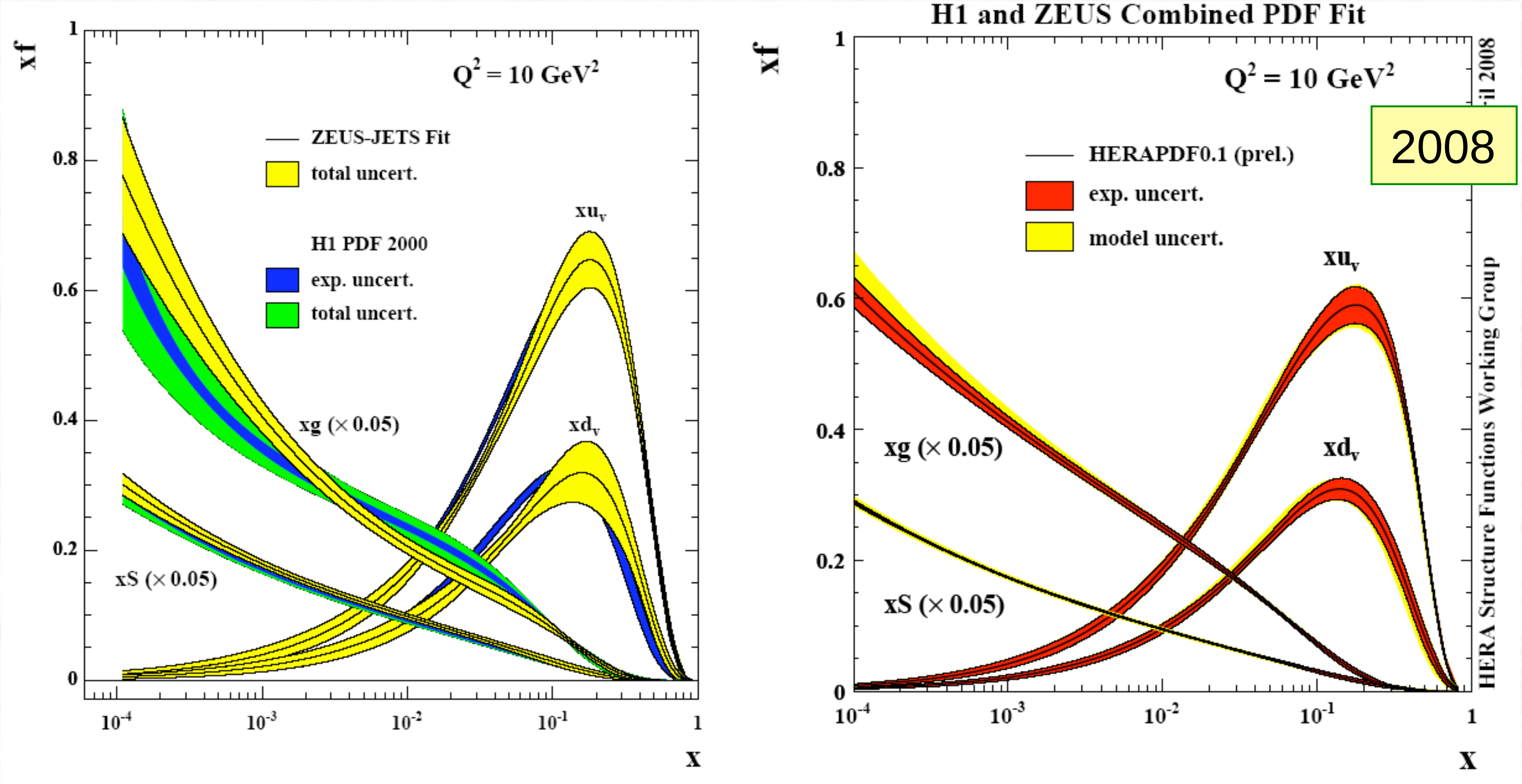


…some NLO contributions



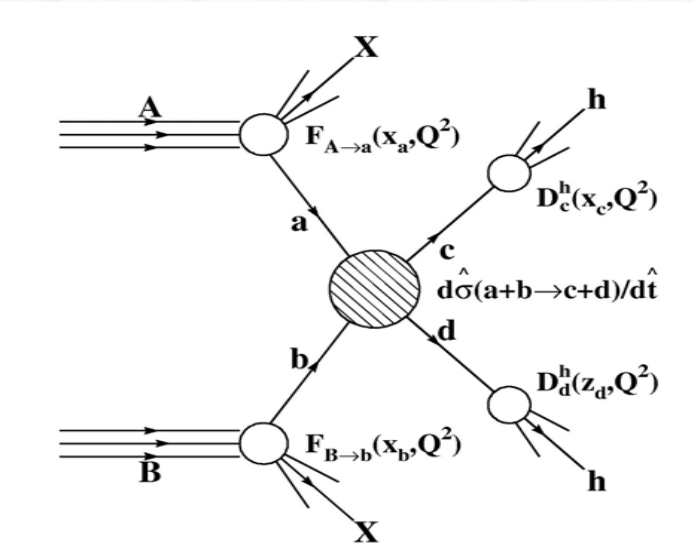
# Results from HERA on the proton structure

- 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: $K_{NLO}$ ~ 1.2
Higgs production via gg fusion: $K_{NLO}$ ~ 1.8

# Luminosity

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

$$N = L \cdot \sigma$$

L = Luminosity
$\sigma$ = 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,….

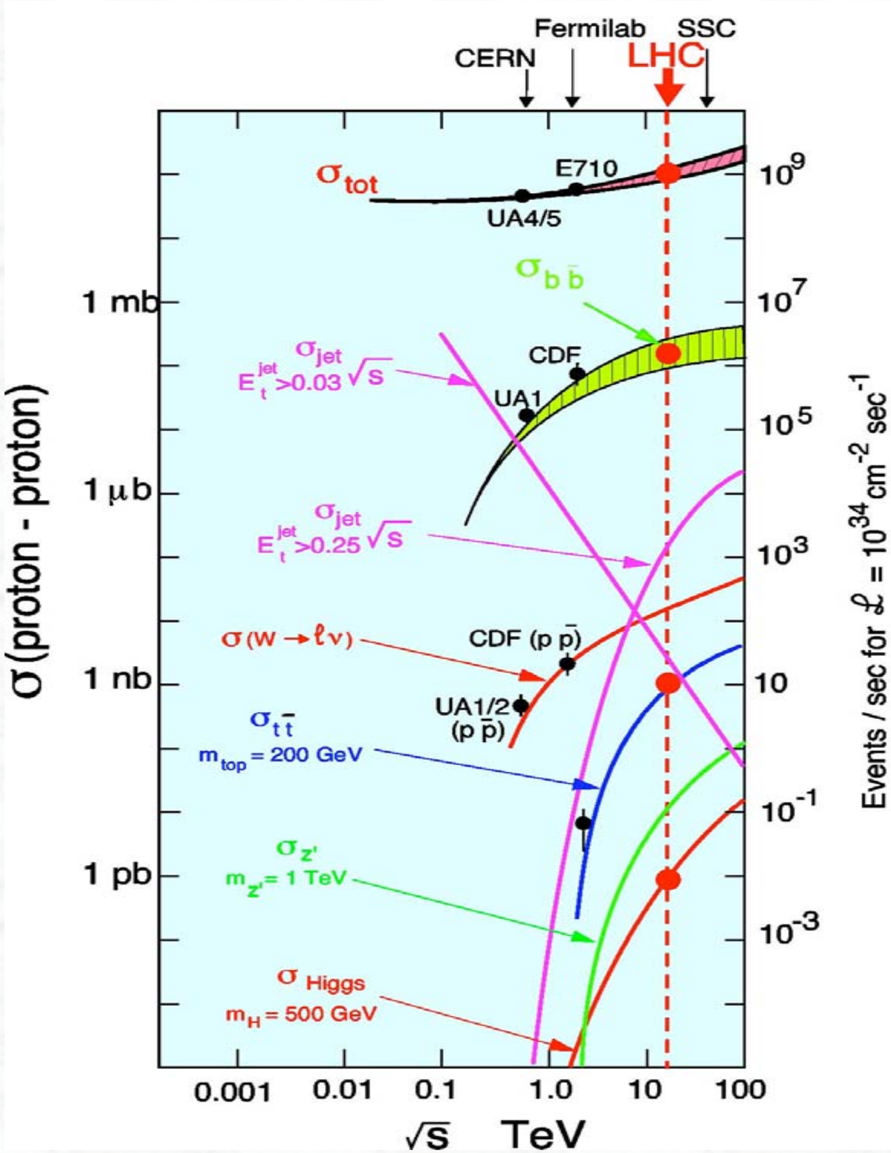
In order to achieve acceptable production rates for the interesting physics processes, the luminosity must be high !

$L = 2 \cdot 10^{32}$ $cm^{-2}\, s^{-1}$ 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 $\rightarrow$

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



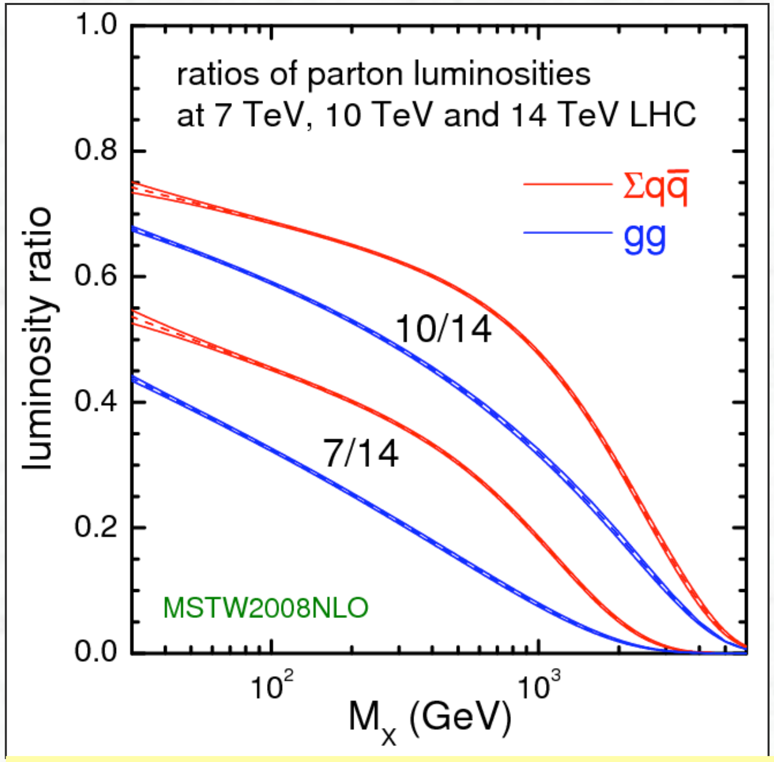

Rates for L = $10^{34}$ $cm^{-2}$ $s^{-1}$: (LHC)

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

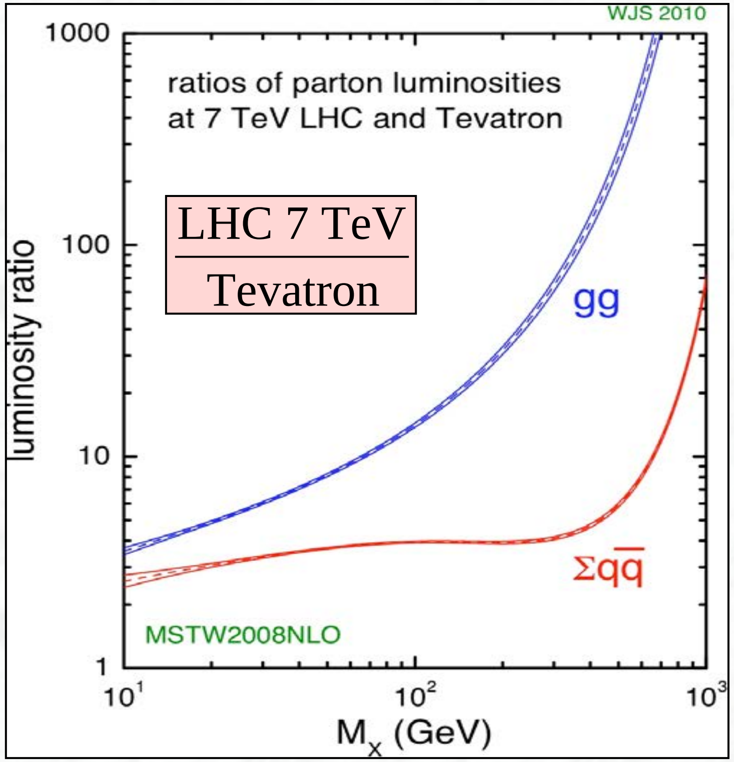
LHC is a factory for:
top-quarks, b-quarks, W, Z, …,Higgs, …

# 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

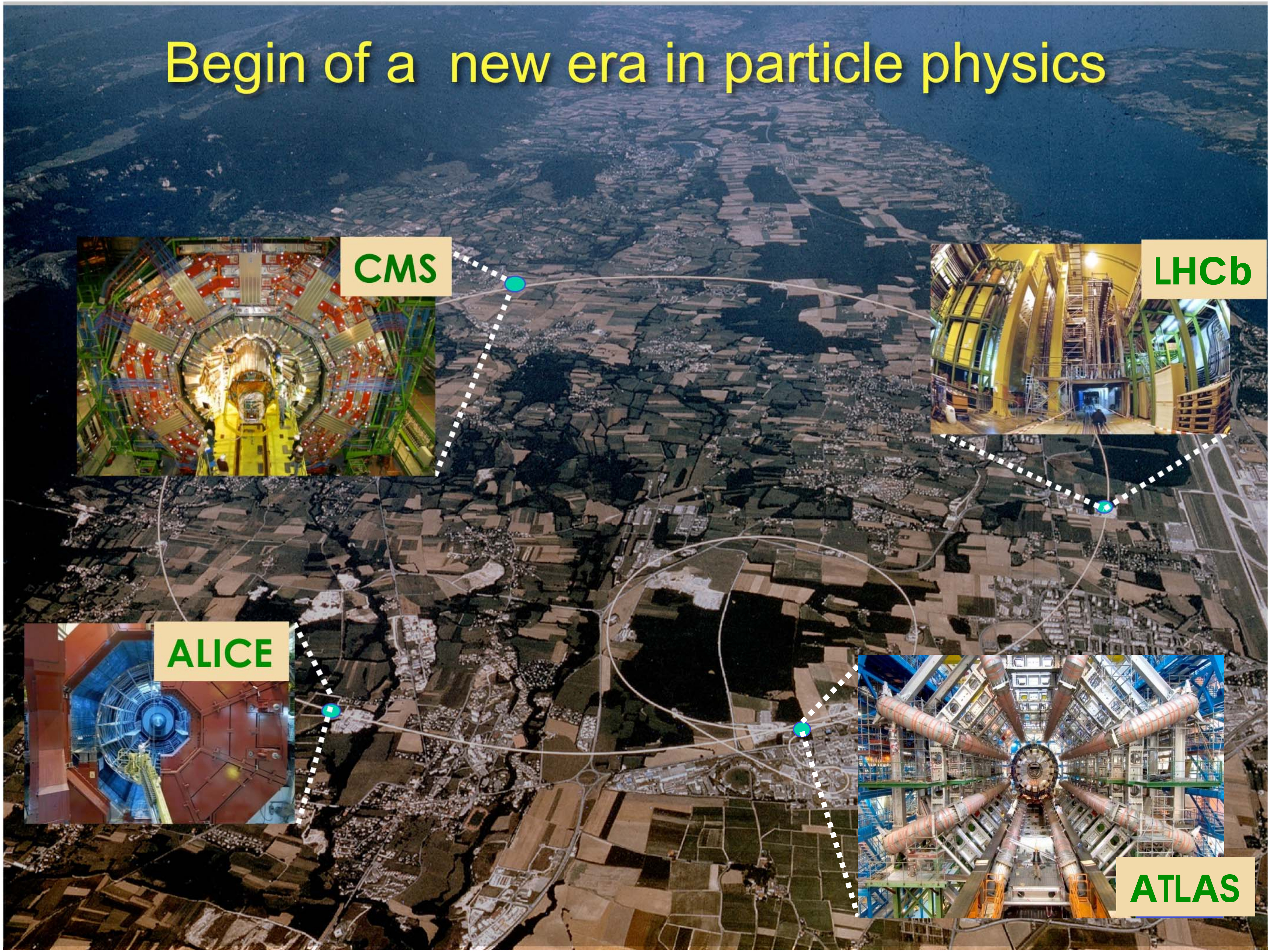
W' (1.5 TeV):
7/14 = 0.1

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

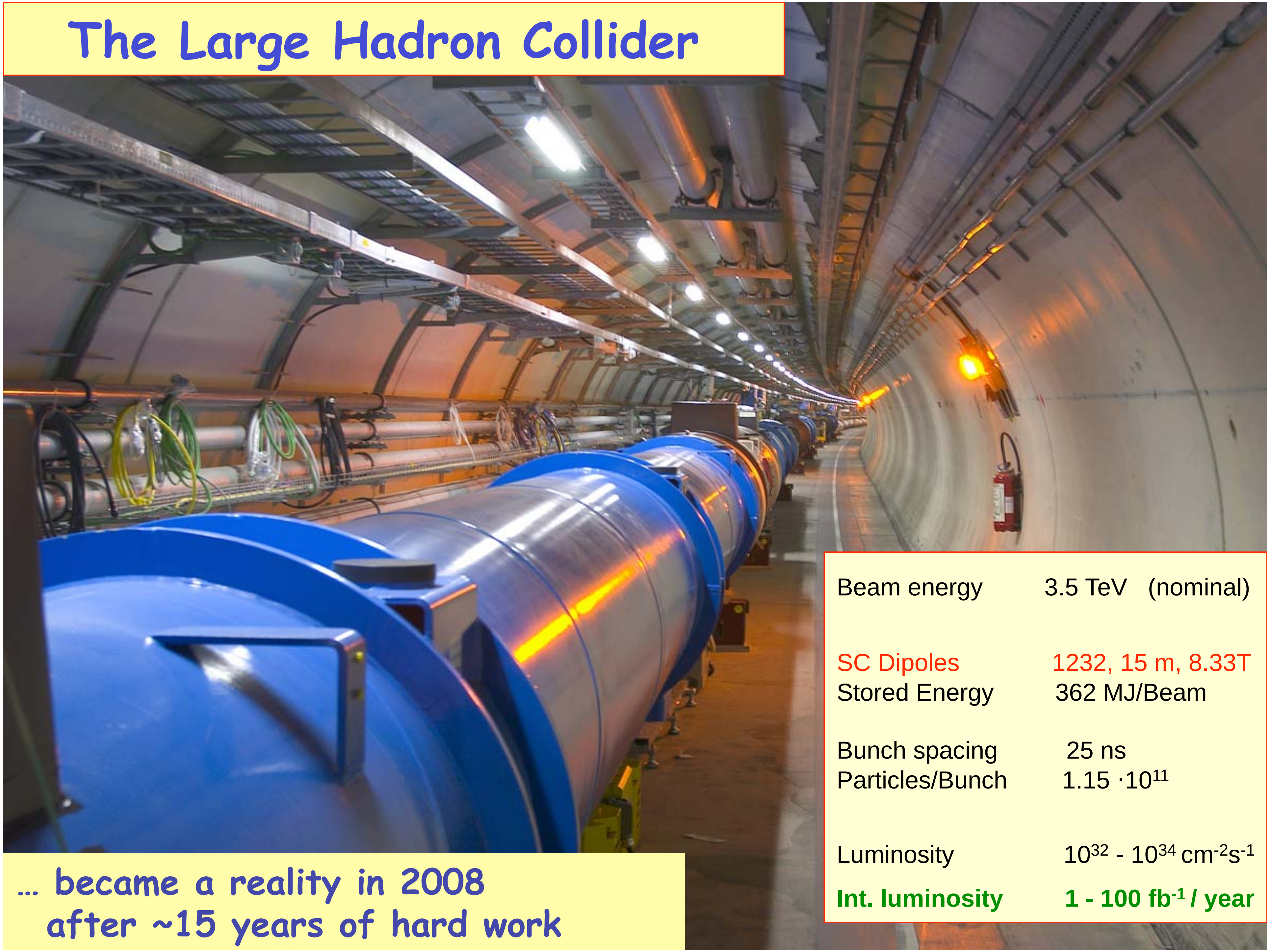
...but still large factor compared to the Tevatron ($\sqrt{s}$ =1.96 TeV)

# The Large Hadron Collider (LHC)

# Begin of a new era in particle physics



# 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** |

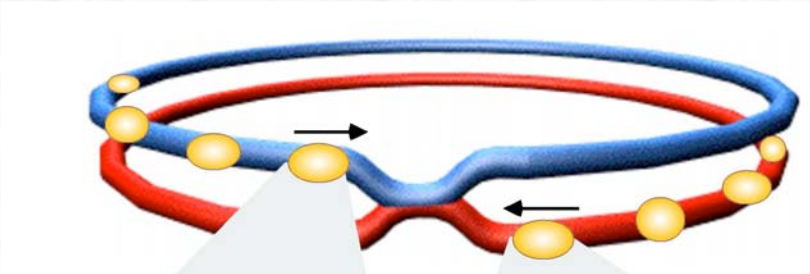
… became a reality in 2008
after ~15 years of hard work

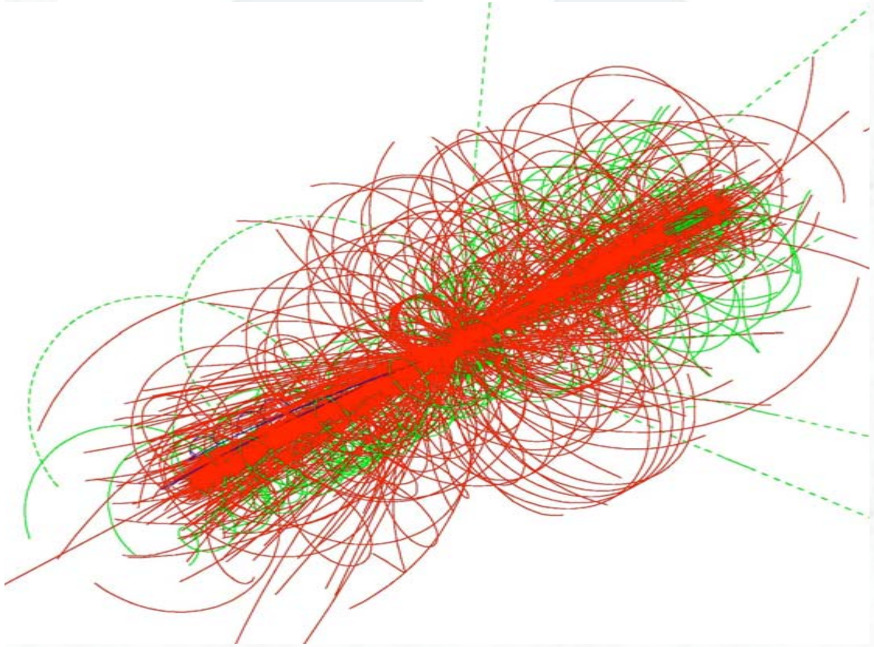
# Comparison of the LHC and Tevatron machine parameters

| | 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)

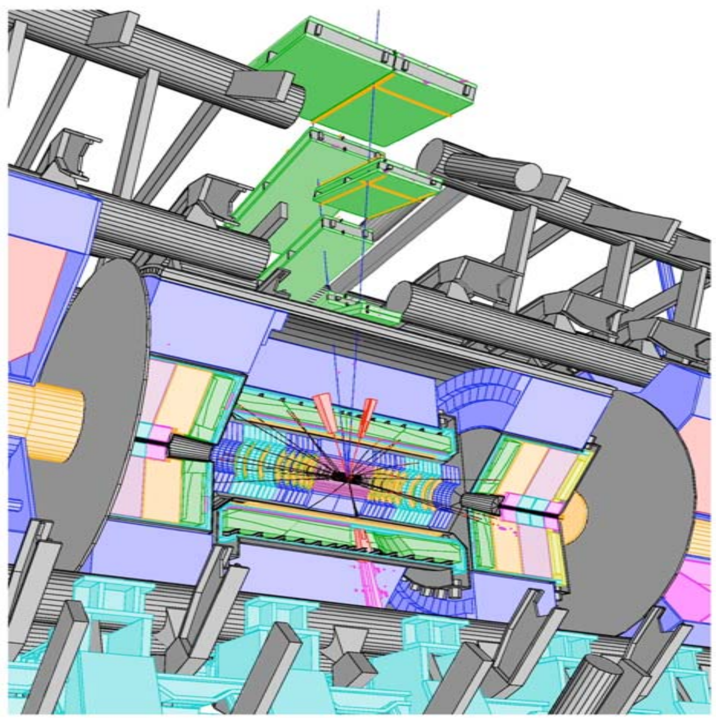
$10^{11}$ protons / bunch
Crossing rate of p-bunches: 40 Mio. / s
Luminosity: $L = 10^{34}\ cm^{-2}\ s^{-1}$

~$10^9$ 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 ($E_T^{miss}$)

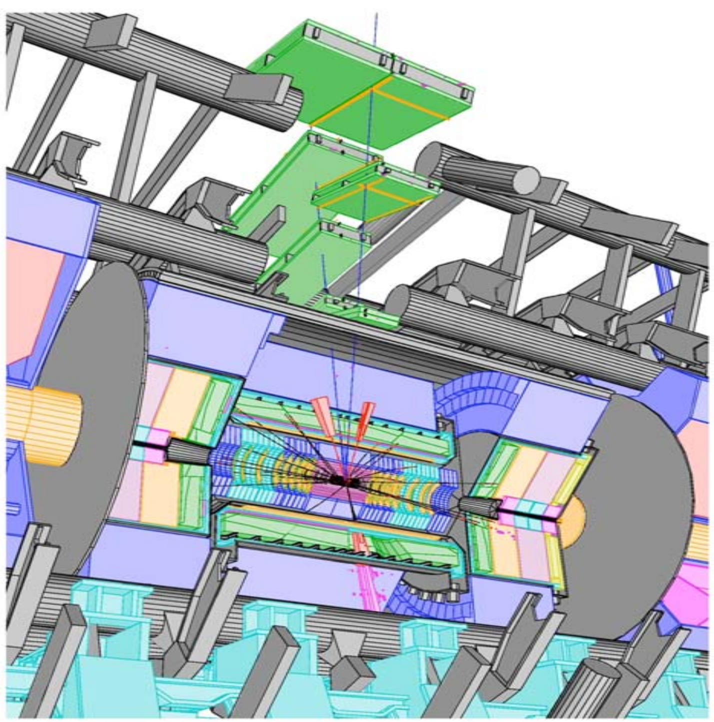
  and

  energy measurements in the forward regions

  $\Rightarrow$ calorimeter coverage down to $\eta \sim 5$

- Efficient b-tagging and $\tau$ identification (silicon strip and pixel detectors)

# Detector requirements from the experimental environment (pile-up)



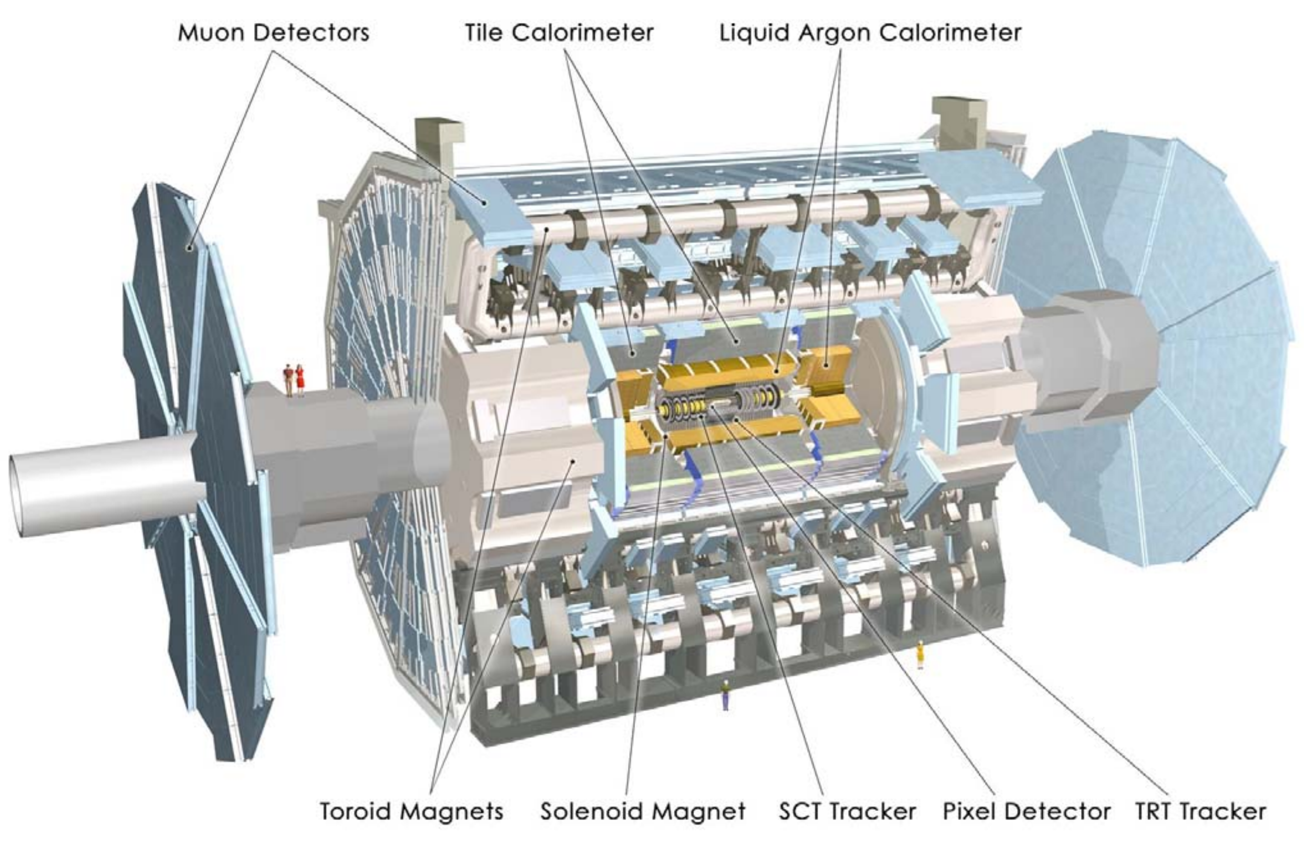
- LHC detectors must have **fast response**, otherwise integrate over many bunch crossings → too large pile-up

  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)

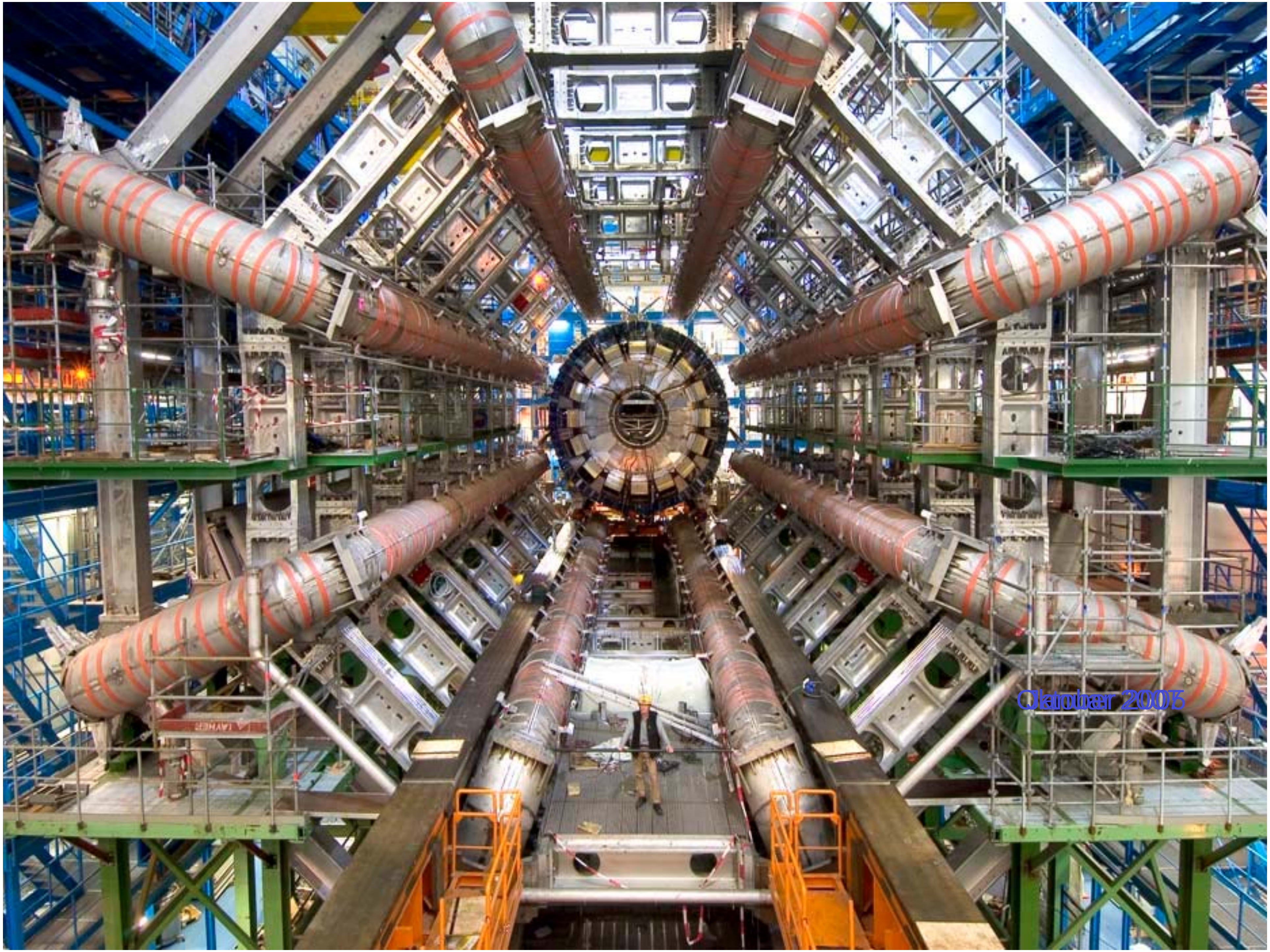
  High resolution silicon detectors:
  - 6 Mio. channels (80 μm x 12 cm)
  - 100 Mio. channels (50 μm x 400 μm)

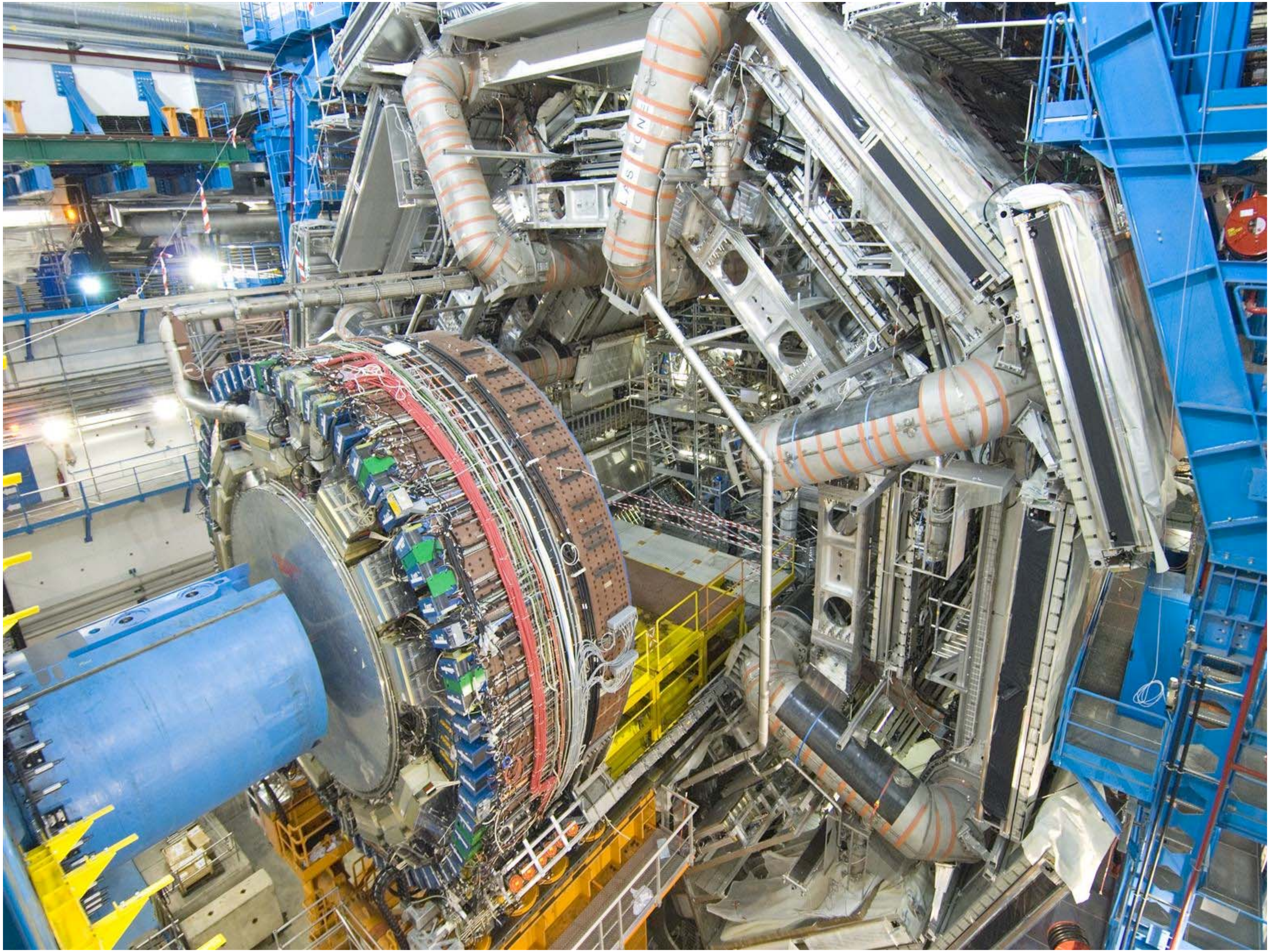
  space resolution: ~ 15 μm

- Energy measurement down to 1º to the beam line

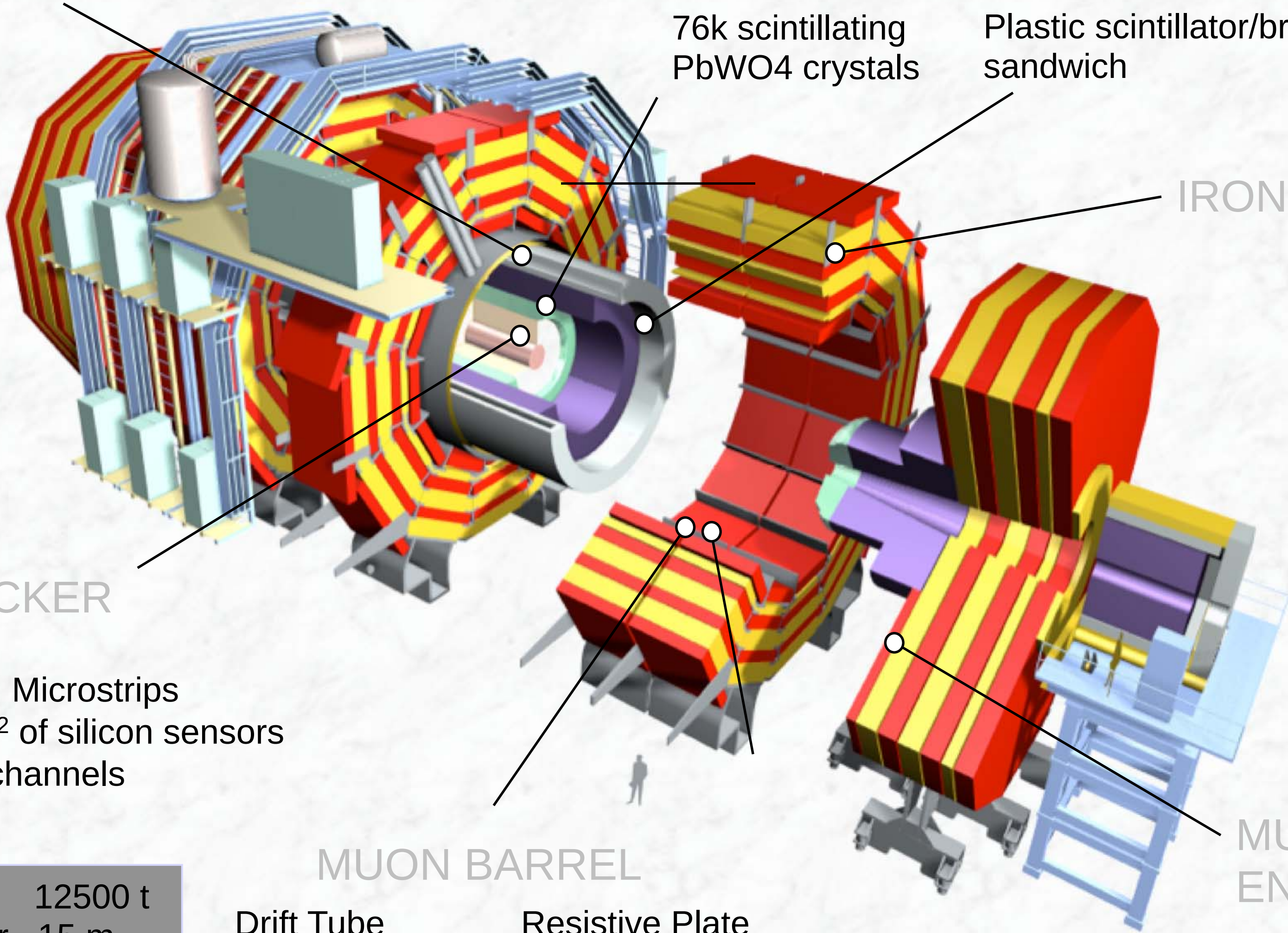
- Independent muon spectrometer (supercond. toroid system)

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





# 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

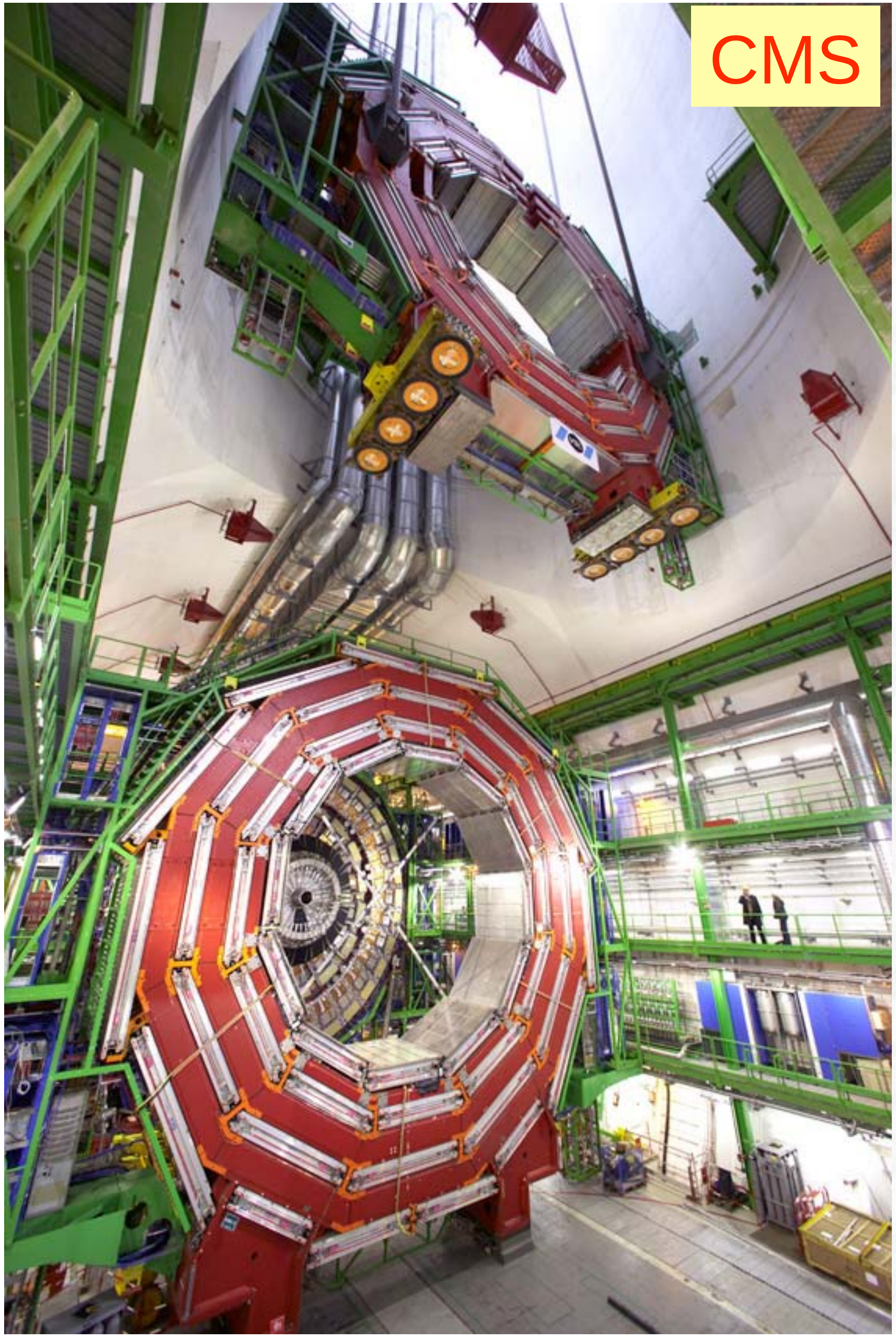
Drift Tube
Chambers (**DT**)

Resistive Plate
Chambers (**RPC**)

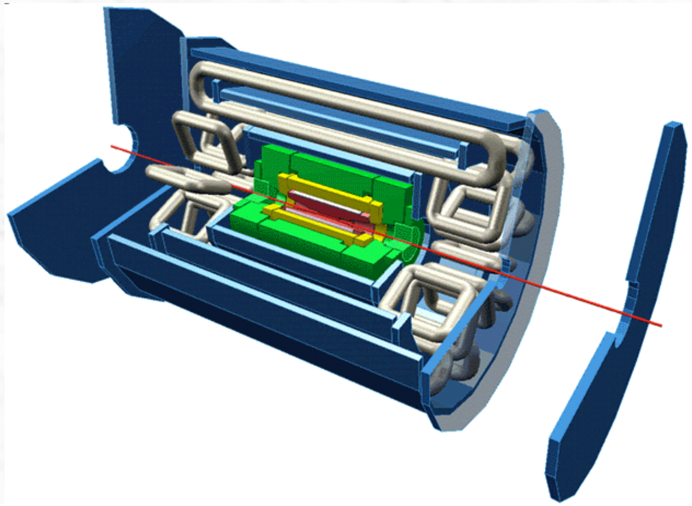
MUON
ENDCAPS

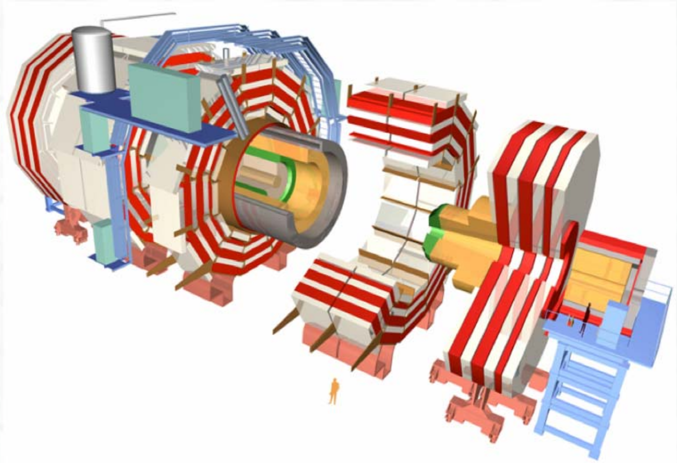
Cathode Strip Chambers (**CSC**)
Resistive Plate Chambers (**RPC**)

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


CMS

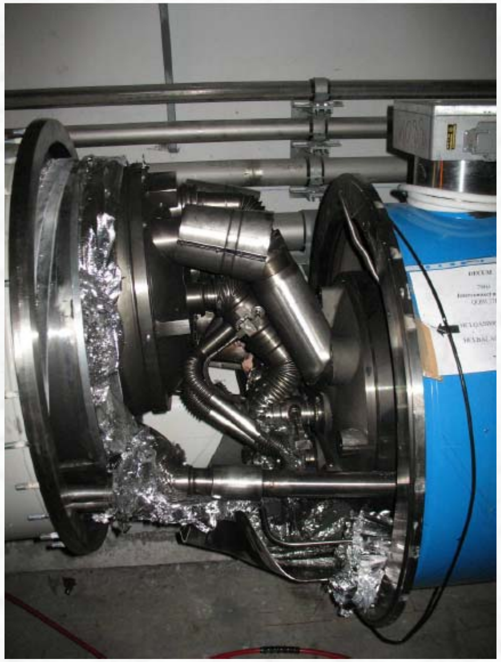
| | ATLAS | CMS |
|---|---|---|
| Magnetic field | 2 T solenoid<br>+ toroid: 0.5 T (barrel), 1 T (endcap) | 4 T solenoid + return yoke |
| Tracker | Silicon pixels and strips<br>+ transition radiation tracker<br>$\sigma/p_T \approx 5 \cdot 10^{-4} p_T + 0.01$ | Silicon pixels and strips<br>(full silicon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

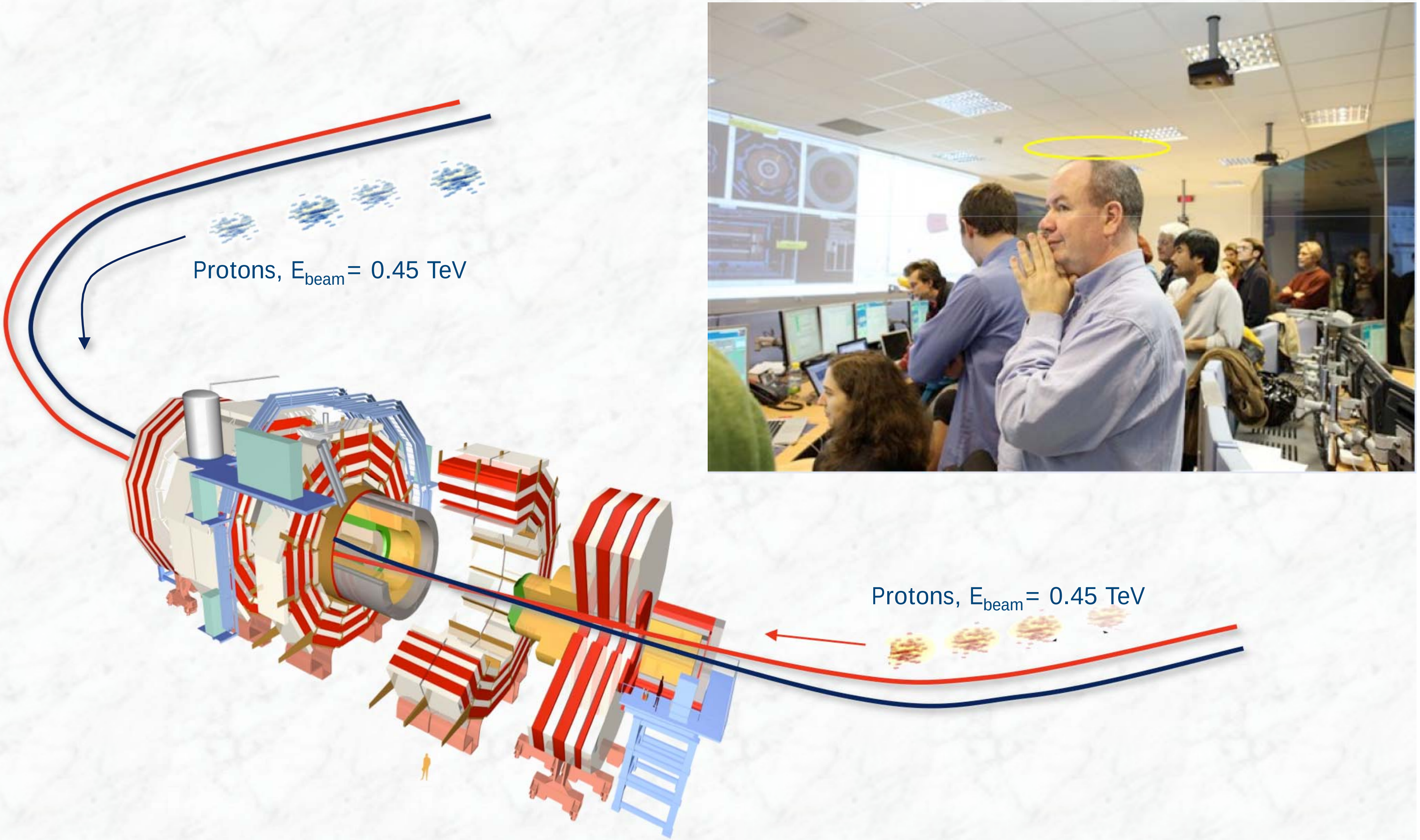


- A resistive zone developed in an electrical bus bar connection
- Electrical arc → punctured the helium enclosure
- Helium release under high pressure
- Relief discs unable to maintain the pressure rise below 0.15 MPa → large pressure forces

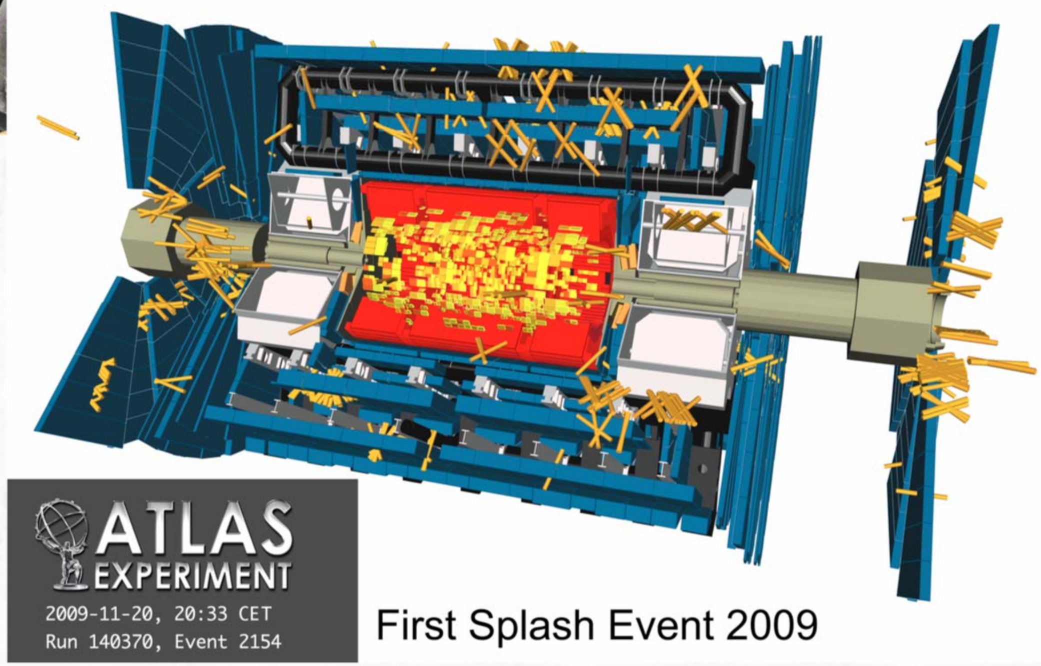
- Lot of repair work during 2009
  (14 quadrupole and 39 dipole magnets replaced, electrical interconnections repaired, larger helium pressure release ports installed,…..)

- **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

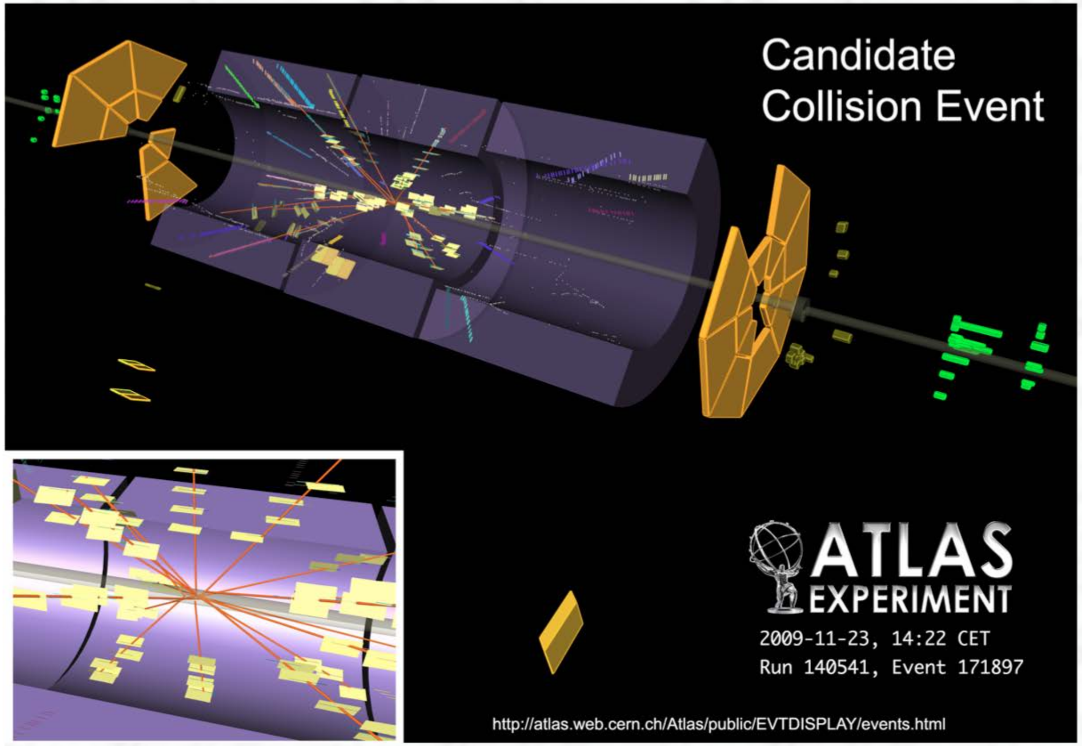
# CMS in the BBC news

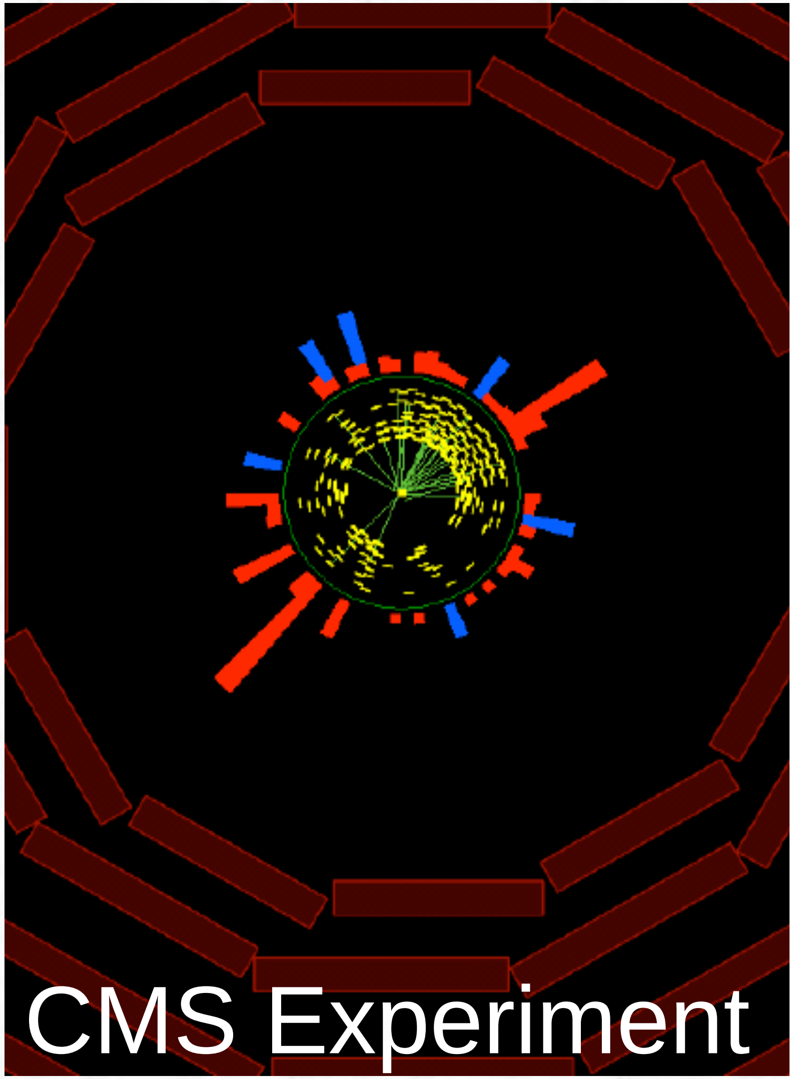
**November 21, 2009**

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

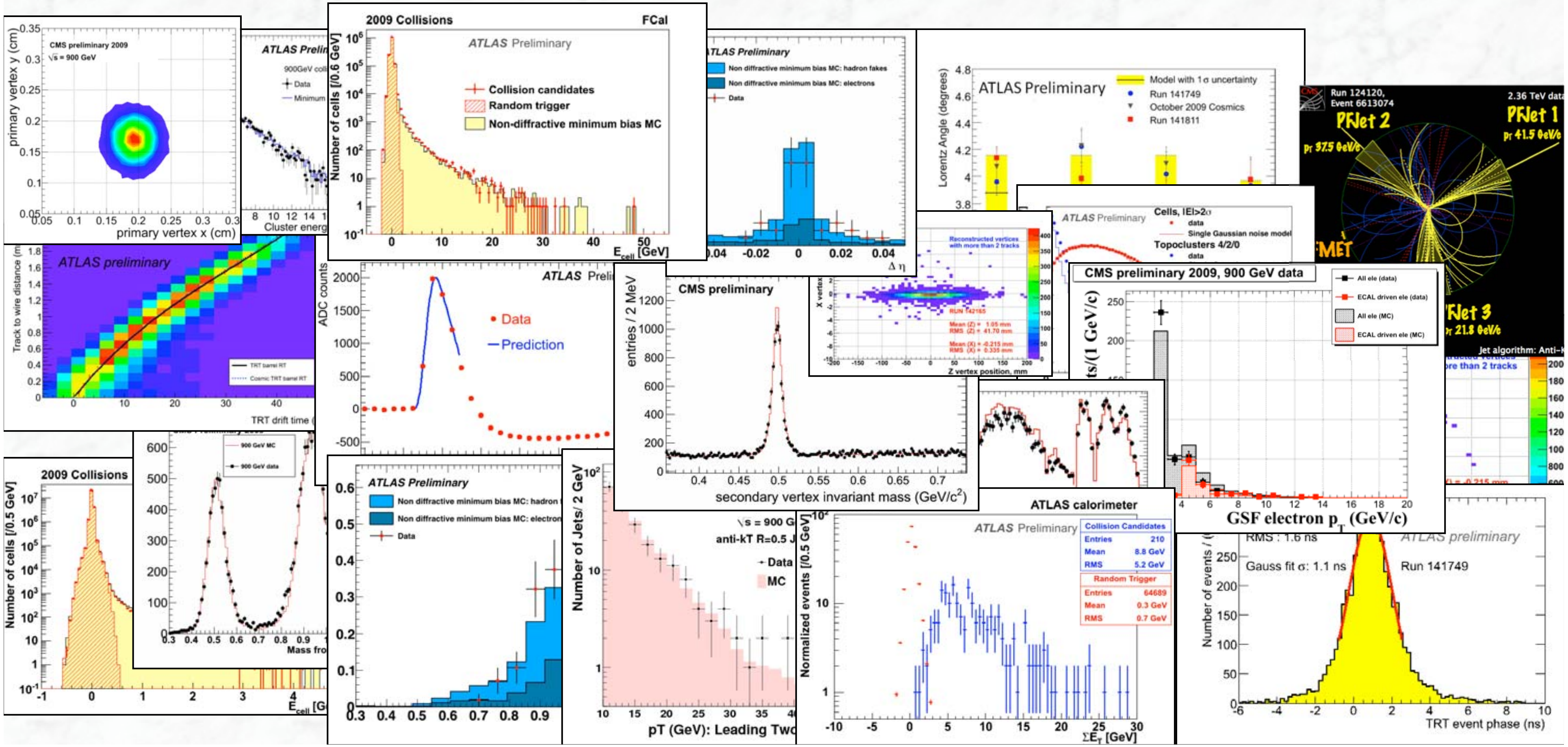



23rd Nov 2009

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

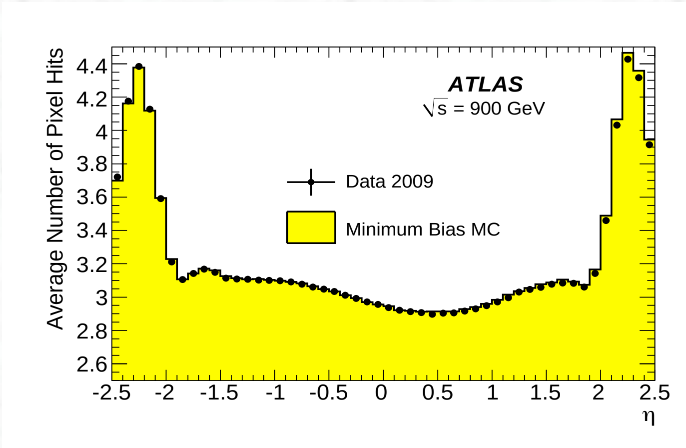
# First publications of physics results in Feb/March 2010

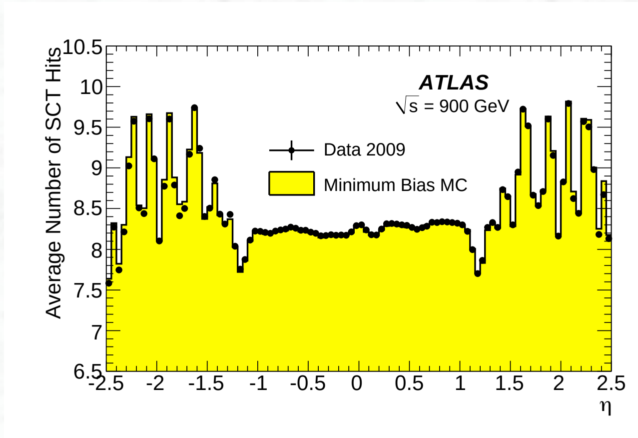


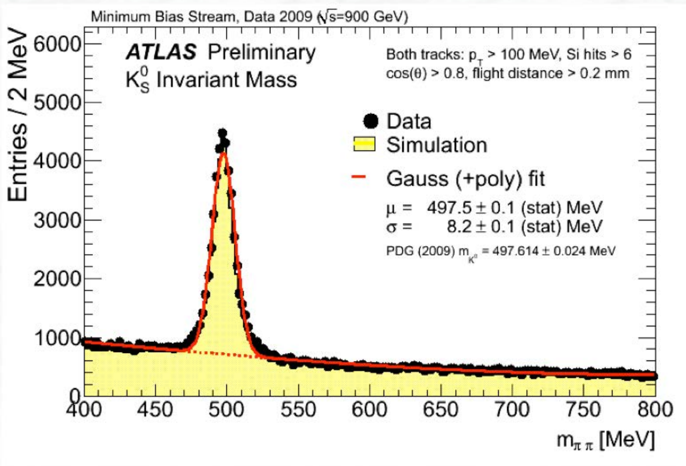
# Inner Detector performance:  hits, tracks, resonances,...

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

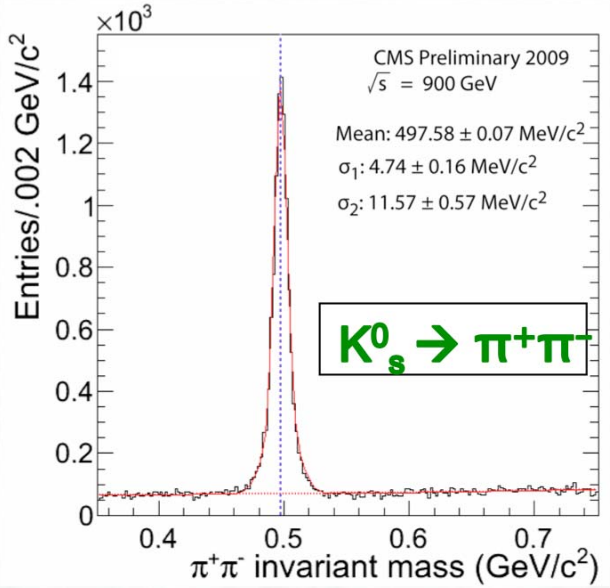
- Material distribution in the inner detector is well described in Monte Carlo

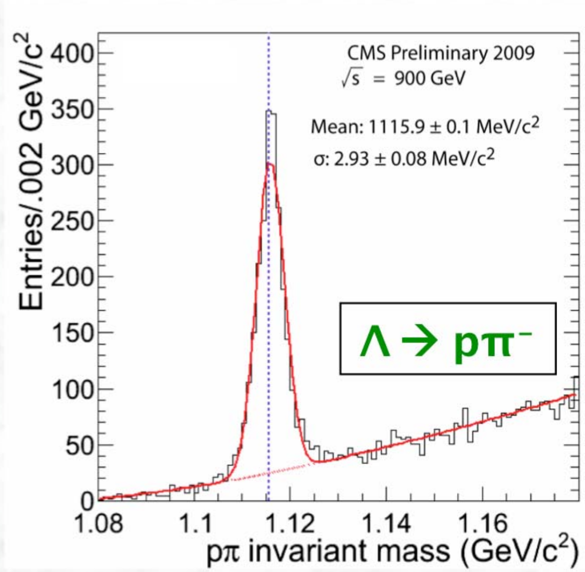


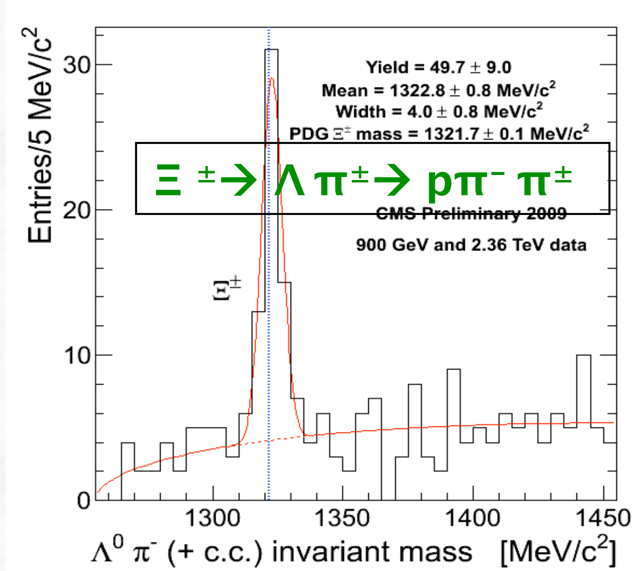



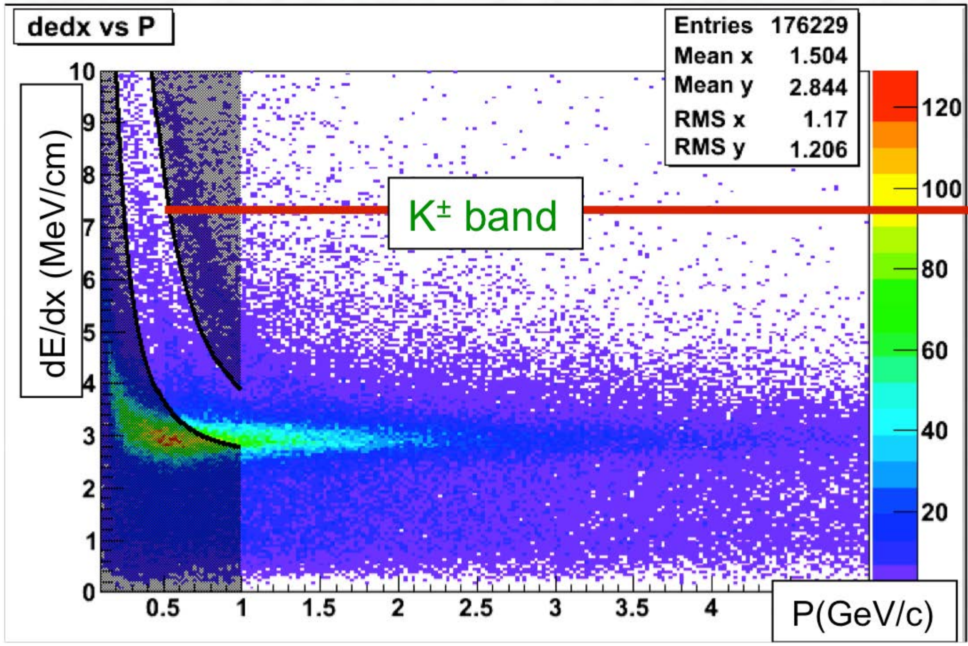



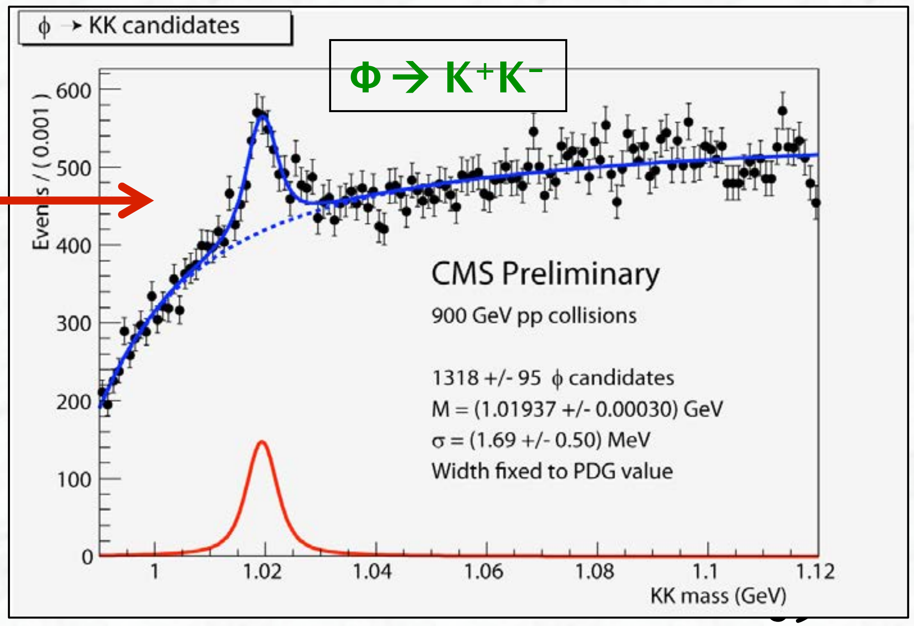
# Resonances: CMS tracking detector



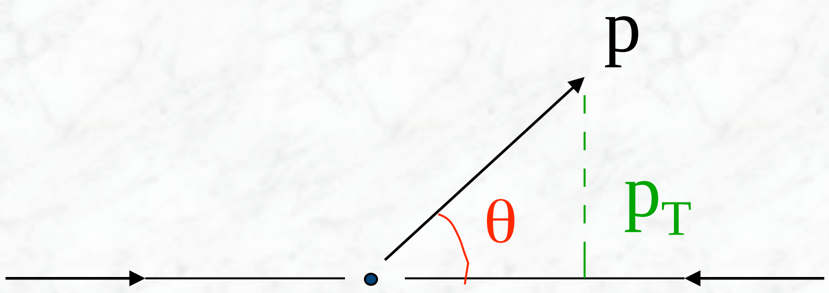



# First Physics

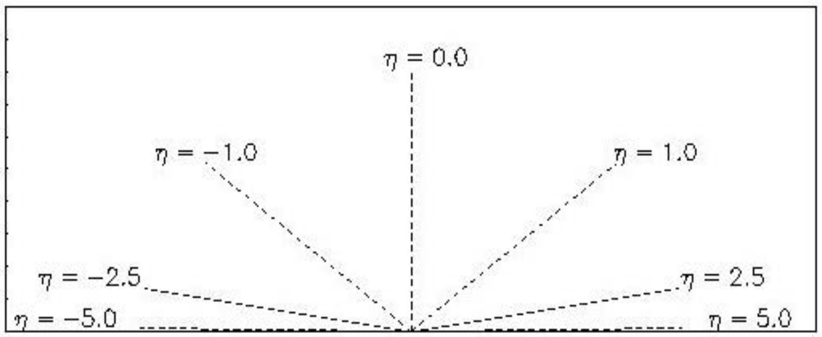
# Variables used in the analysis of pp collisions




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]

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

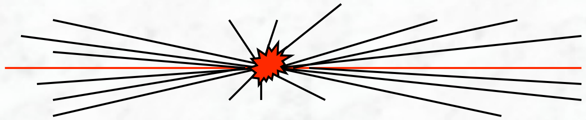
$\theta = 10^o \rightarrow \eta \cong 2.4$
$\theta = 170^o \rightarrow \eta \cong -2.4$

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

# 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

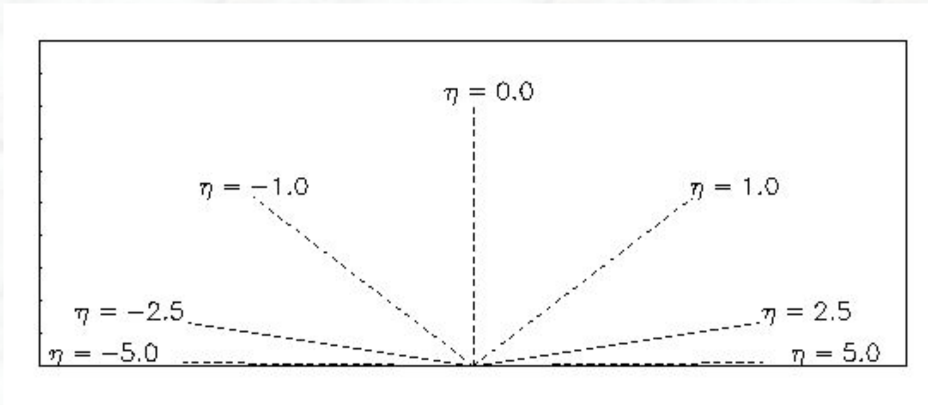


$< p_T > \approx 500$ MeV (of charged particles in the final state)

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

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

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



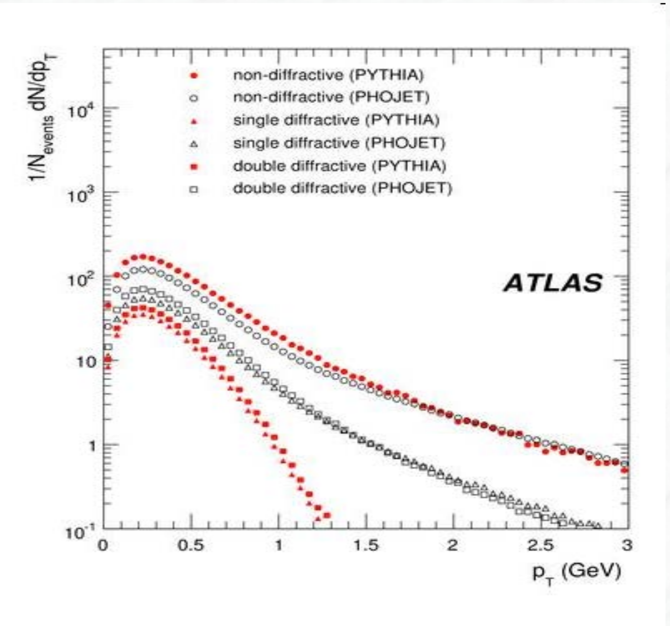
# Some features of soft inelastic pp collisions

- Features of soft inelastic collisions cannot be calculated in perturbative QCD

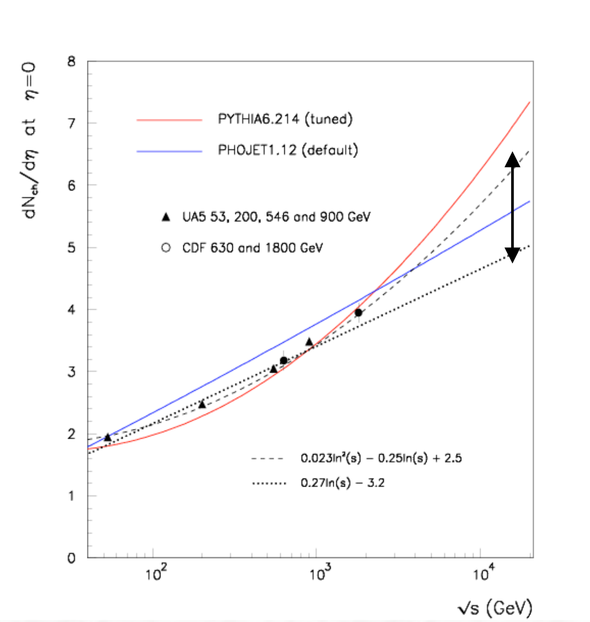
- Experimental measurements / input needed

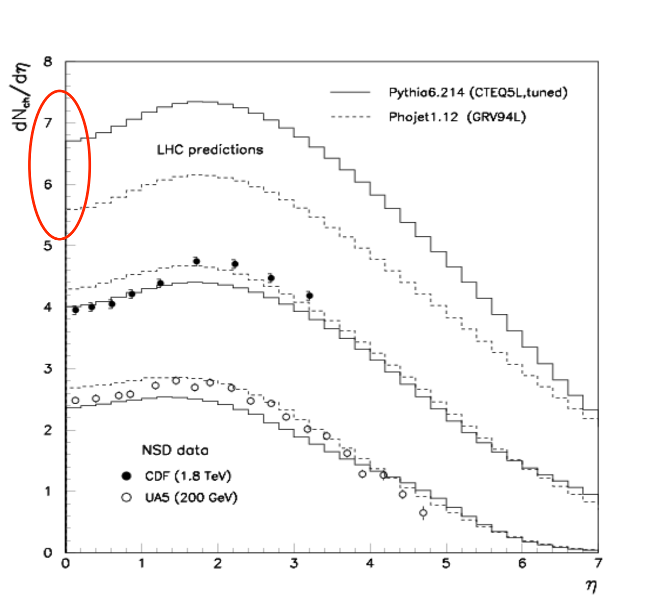
- Models / parametrizations are used to extrapolate from previous colliders (energies) to the LHC energy regime → large uncertainties

- Needed to model other interesting physics (superposition of events,…)




$<p_T>$ ($\eta$ =0): 550 – 640 MeV (15%)



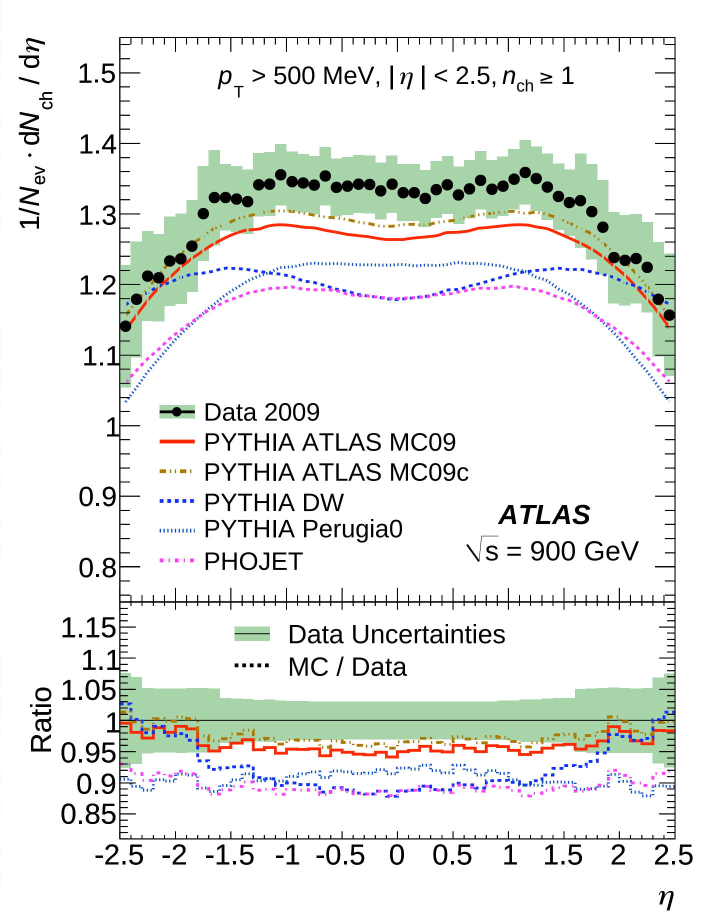

$dN_{ch}/d\eta$ ($\eta$=0): 5-7 (~ 33%)

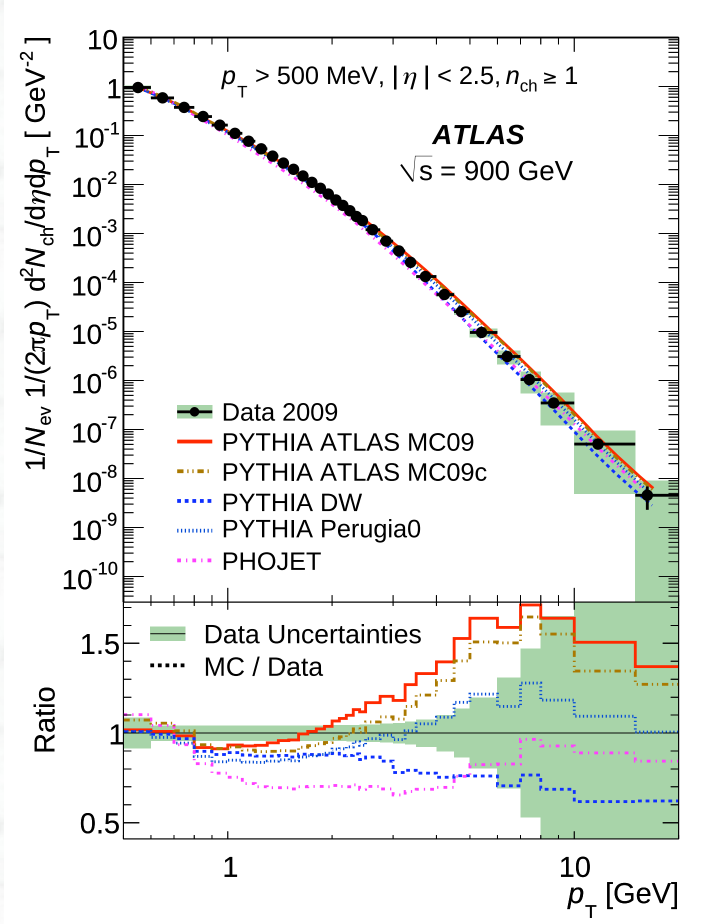
# Charged particle density versus η and $p_T$

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

$p_T$ > 500 MeV
|η| < 2.5
$N_{ch}$ ≥ 1

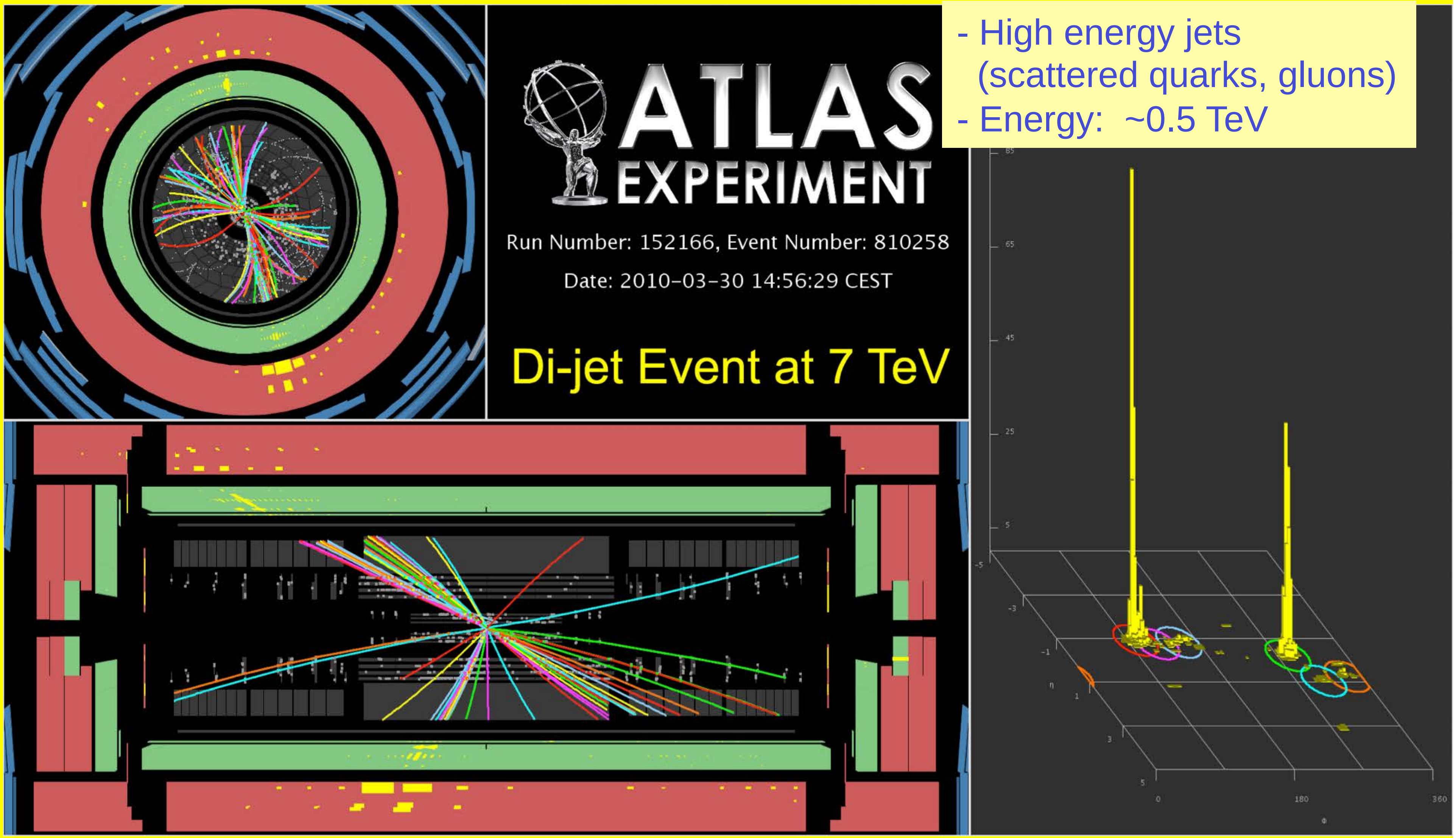
900 GeV data
March 2010




Various Monte Carlo models fail to describe the ATLAS data

## Since 30. March 2010: collisions at 7 TeV
(.... first interesting results appeared soon)



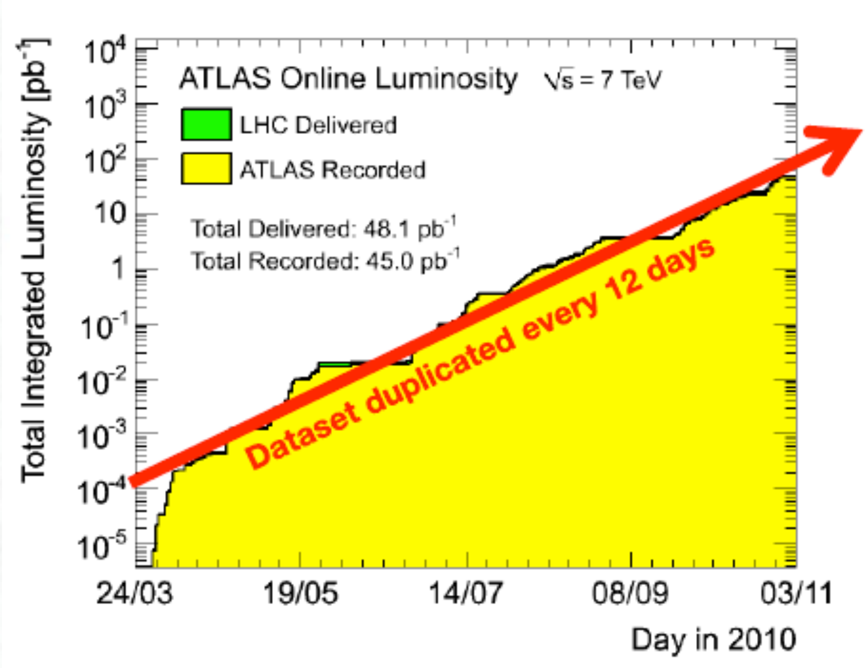

- High energy jets
  (scattered quarks, gluons)
- Energy: ~0.5 TeV

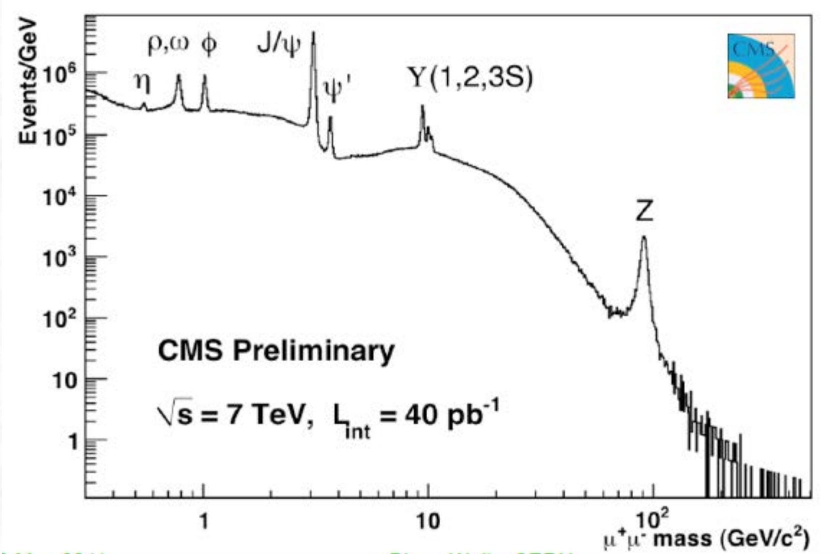
# Collected data in 2010:

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

Both experiments have a very high data taking efficiency !

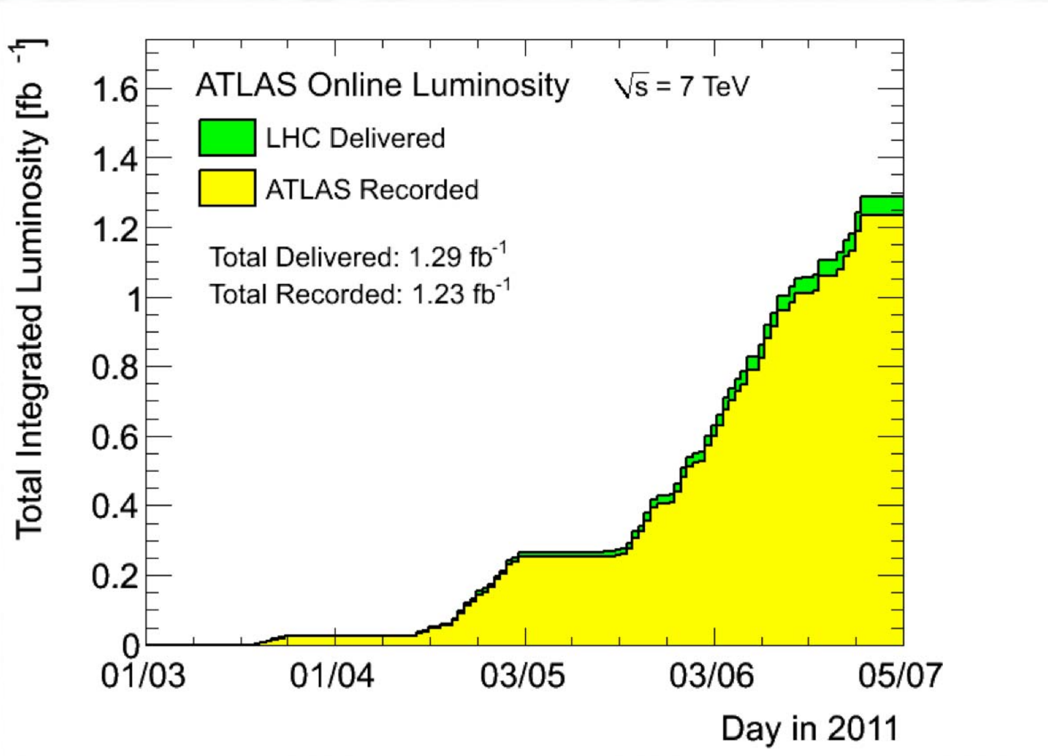
Well known resonances appeared "online"



# 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)