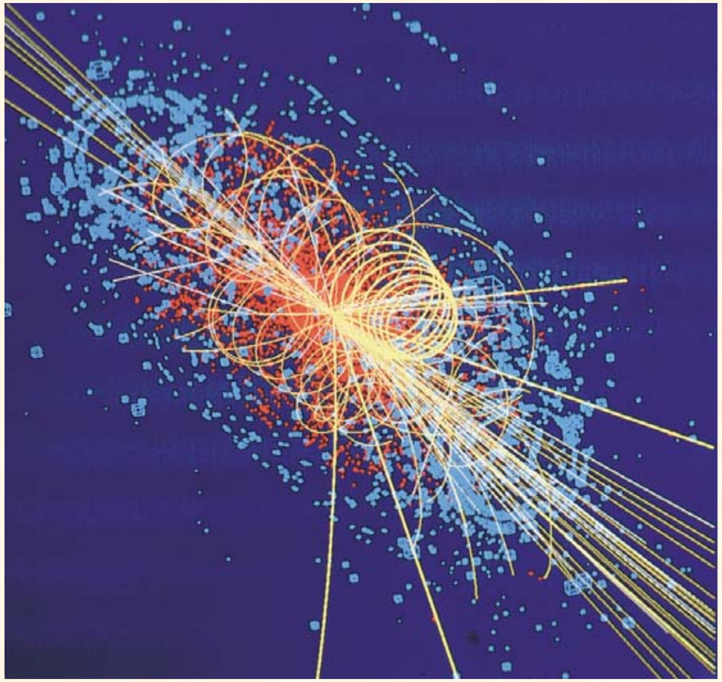
Physics at Hadron Colliders

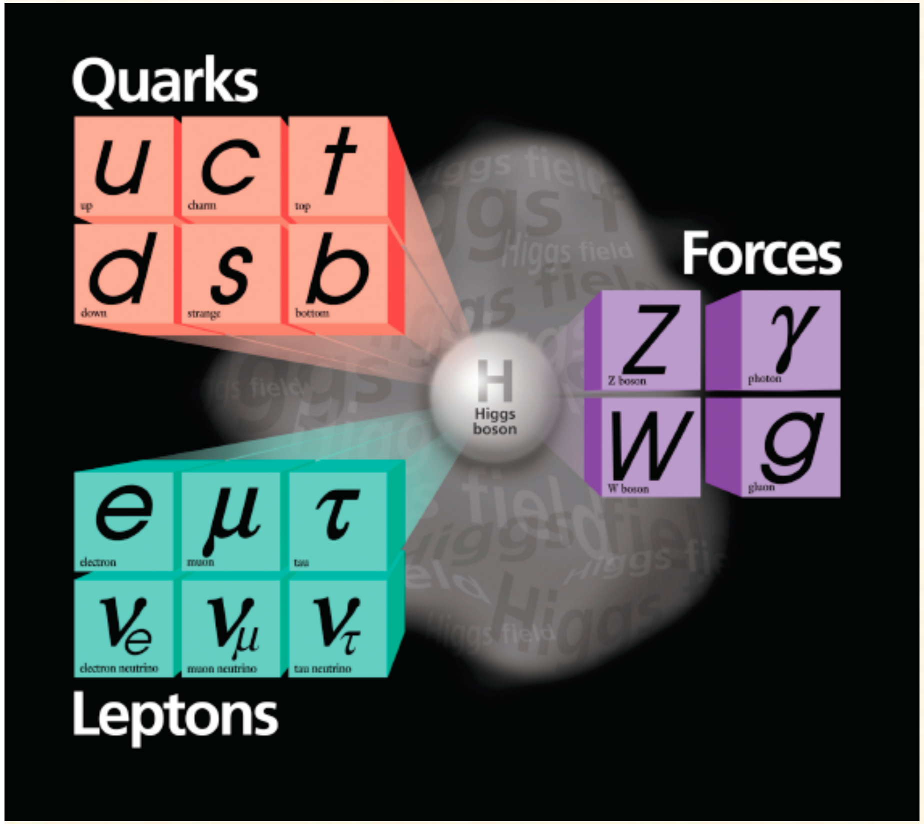
-From the Tevatron to the LHC-



- **Introduction to Hadron Collider Physics**
- **The present Hadron Colliders**
  - The Tevatron and the LHC
  - First collisions at the LHC in 2009
- **Test of the Standard Model**
  - QCD: Jet, W/Z, top-quark production
  - W and top-quark mass measurements
- **Search for the Higgs Boson**
- **Search for New Phenomena**

Karl Jakobs
Physikalisches Institut
Universität Freiburg / Germany

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

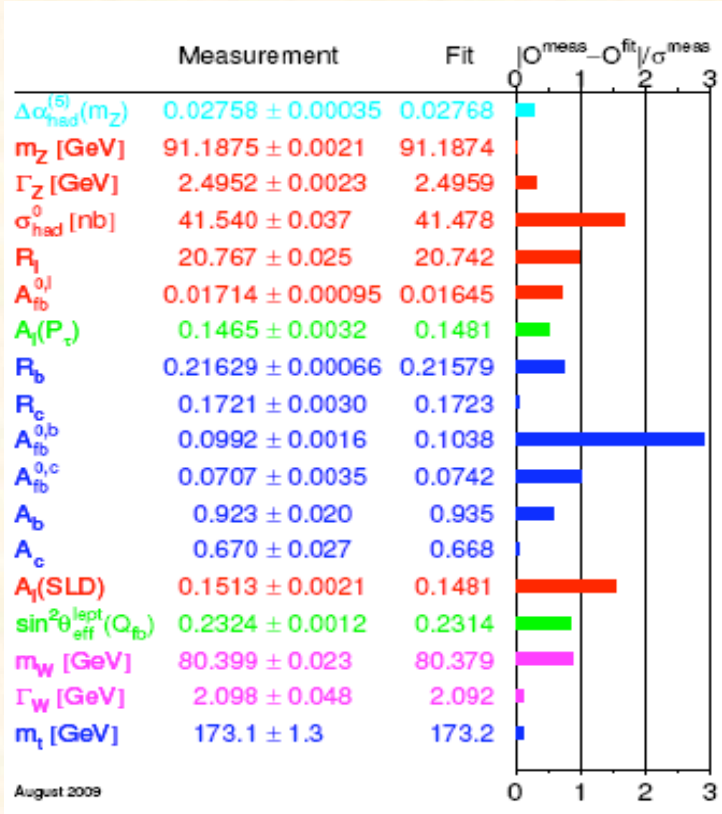
Where do we stand today?

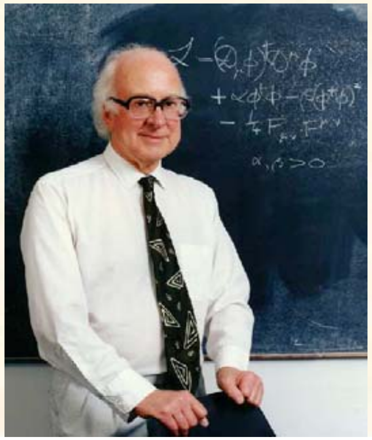
e^+e^- colliders LEP at CERN and SLC at SLAC + the Tevatron pp collider
+ HERA at DESY + many other experiments (fixed target…….)
have explored the energy range up to **~100 GeV** with incredible precision

- 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 < 163 GeV/c^2 or m_H > 166 GeV/c^2

Summer 2009



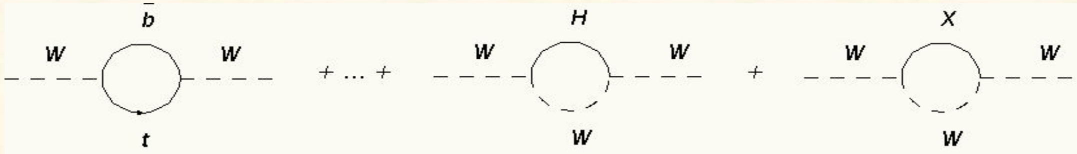


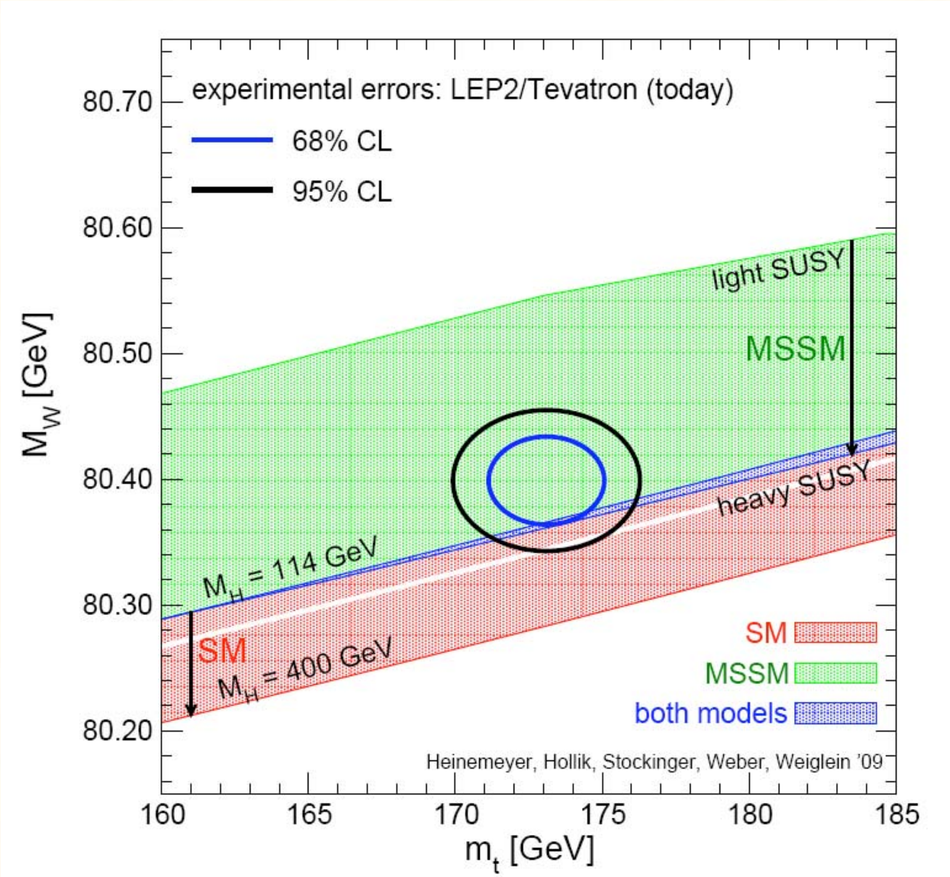
Only unambiguous example of observed Higgs

(P. Higgs, Univ. Edinburgh)

Consistency with the Standard Model

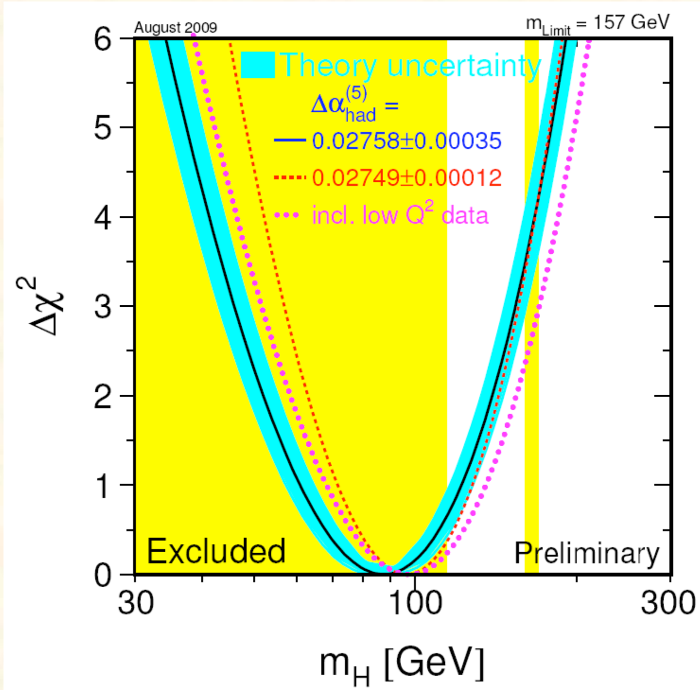
Sensitivity to the Higgs boson and other new particles via quantum corrections:





Interpretation within the Standard Model

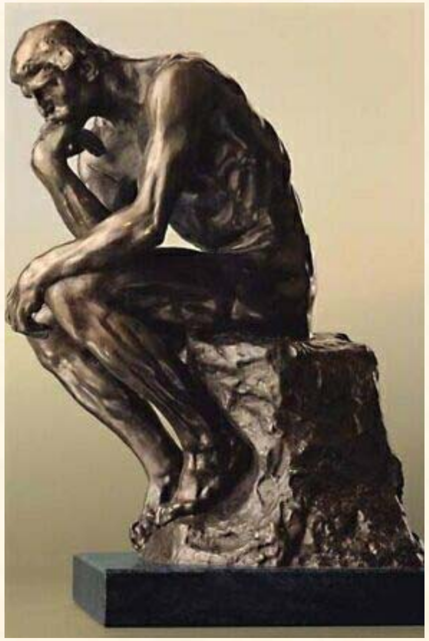
(incl. new (2009) m_W and m_t measurements)



m_H = 87 (+35) (-26) GeV/c^2

m_H < 157 GeV/c^2 (95 % CL)

The Open Questions

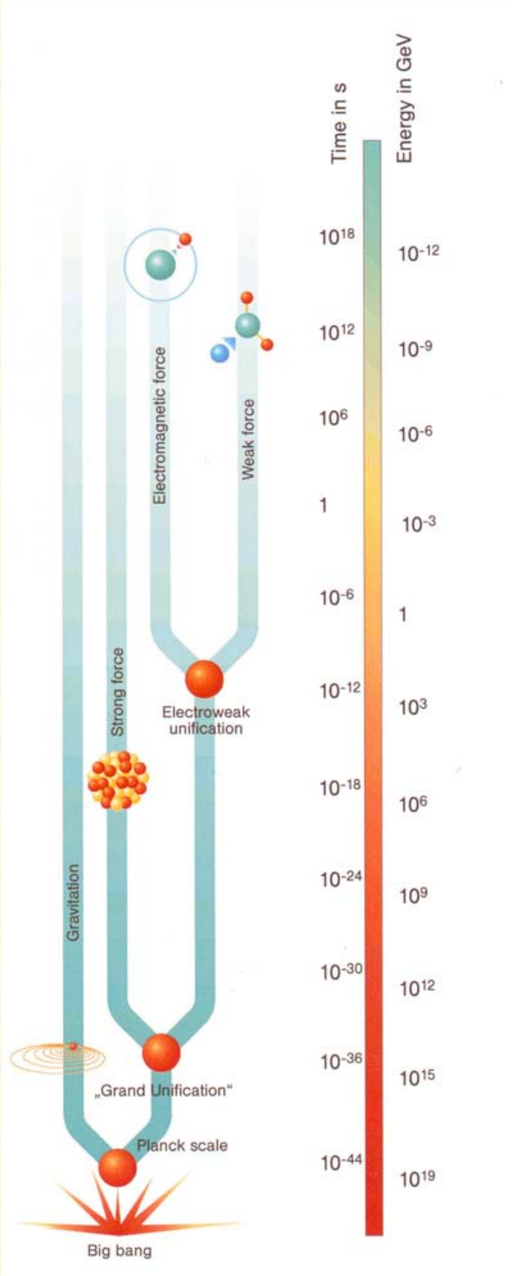


Key Questions of Particle Physics

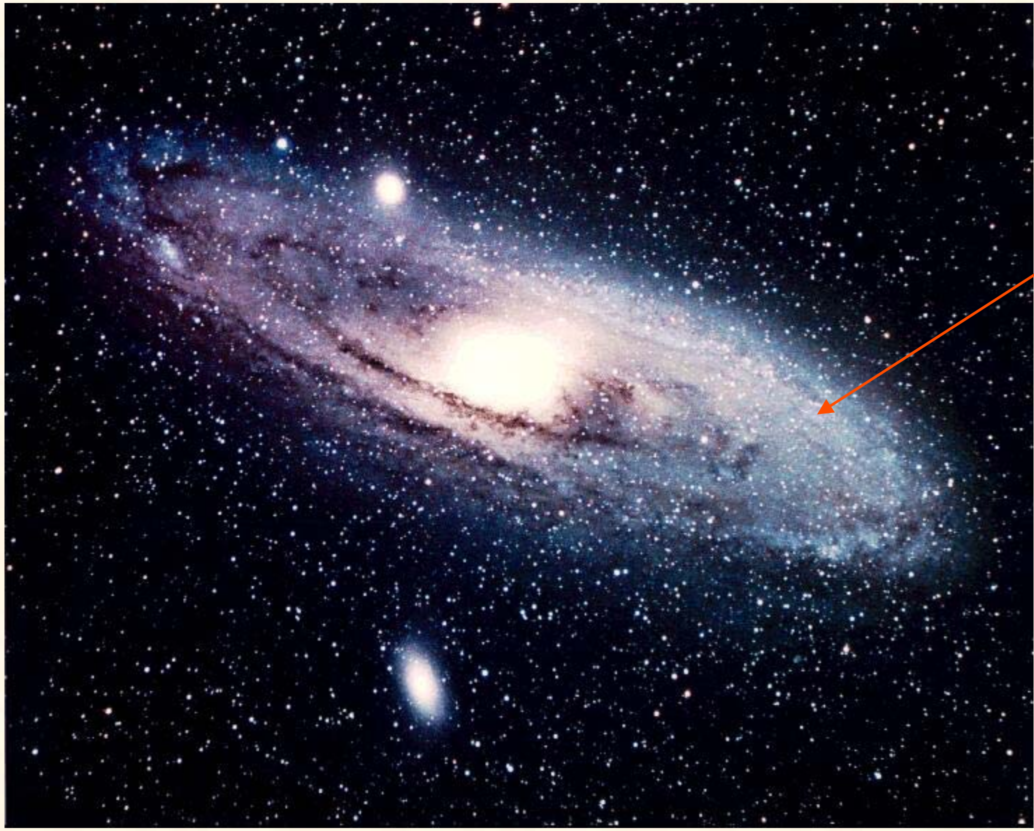
1. Mass: What is the origin of mass?
- How is the electroweak symmetry broken ?
- Does the Higgs boson exist ?

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?



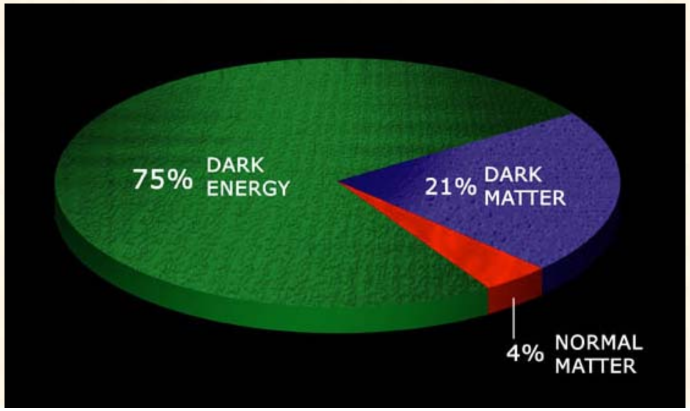
Problems at a larger scale

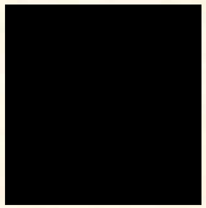


We are here

Surrounded by

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





The role of the present Hadron Colliders

1. Explore the TeV mass scale

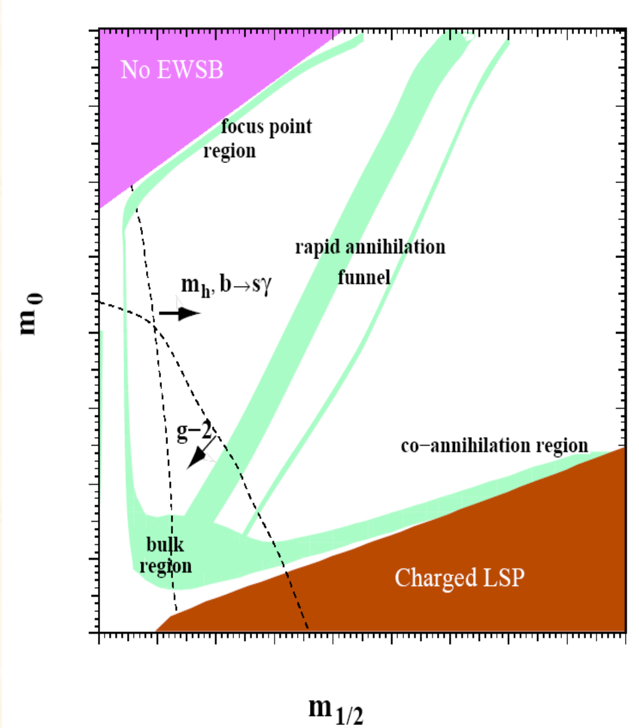
- What is the origin of the electroweak symmetry breaking ?

- 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

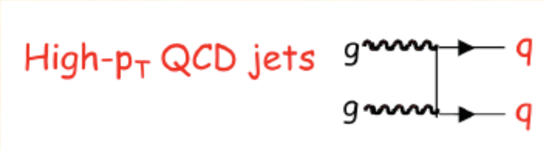
2. Precise tests of the Standard Model

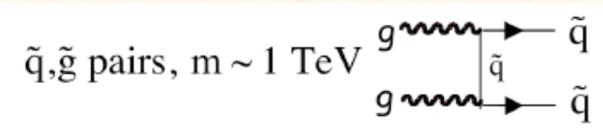
- There is much sensitivity to physics beyond the Standard Model in the precision area
- Many Standard Model measurements can be used to test and to tune the detector performance

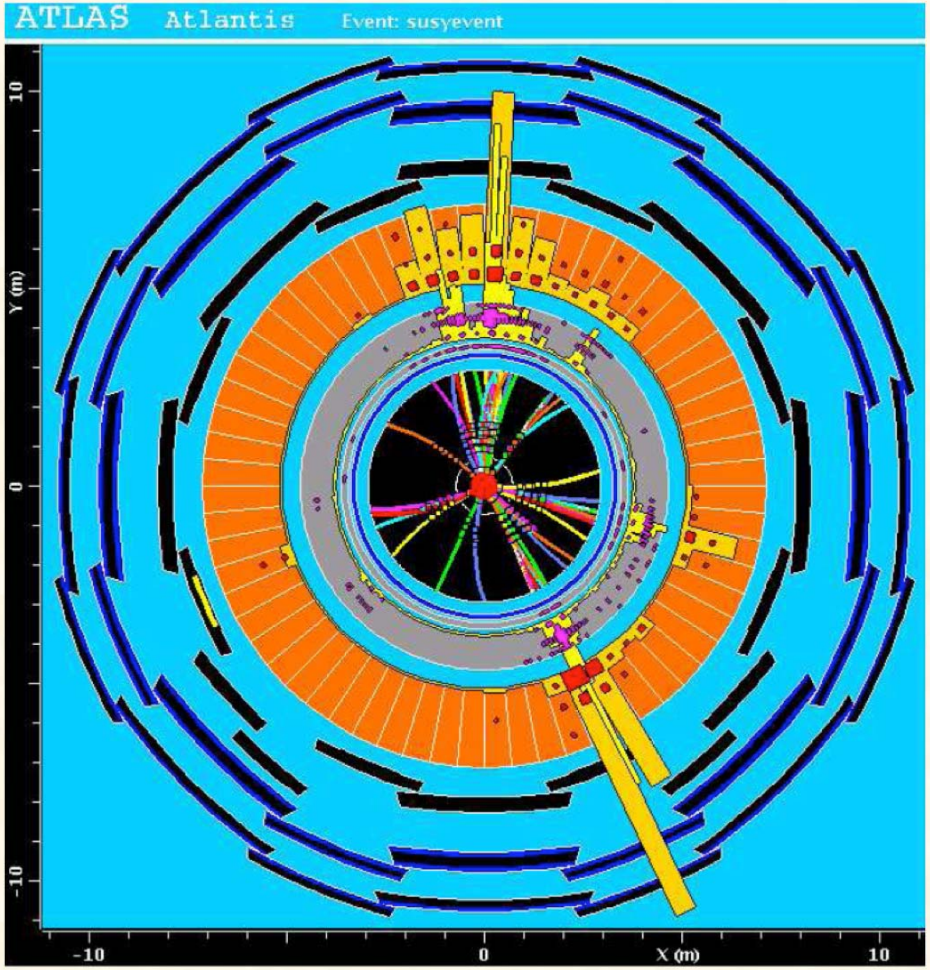
- Supersymmetry
- Extra dimensions
- ....
- Composite quarks and leptons
- ....

- New gauge bosons
- Leptoquarks
- Little Higgs Models
- ....
- Invisibly decaying Higgs bosons

How can interesting objects be produced?

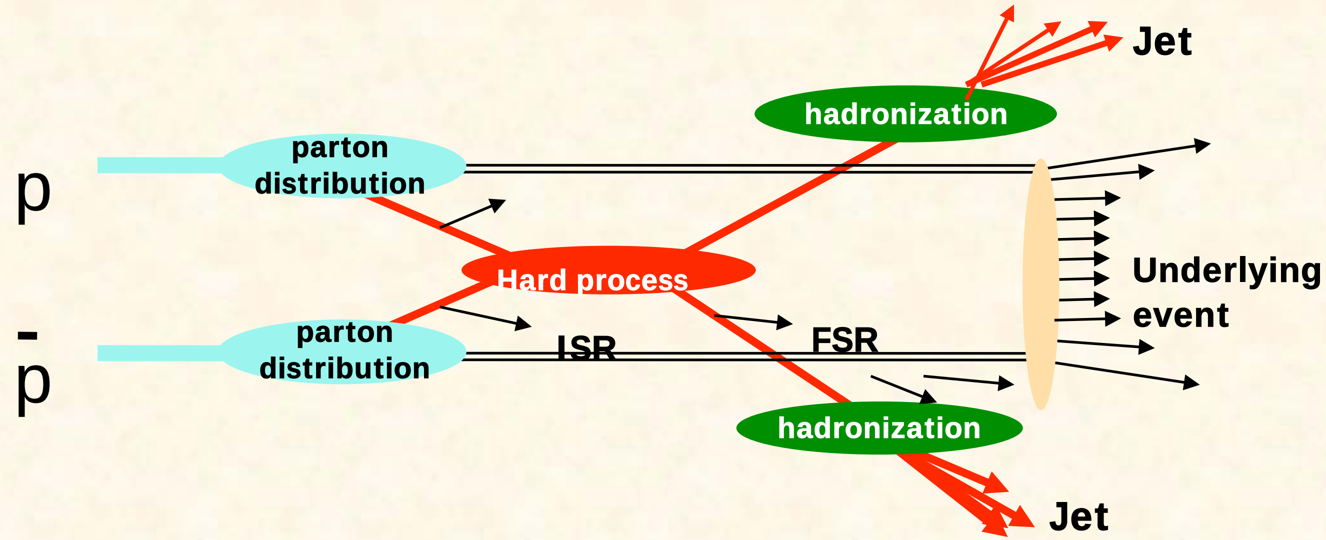




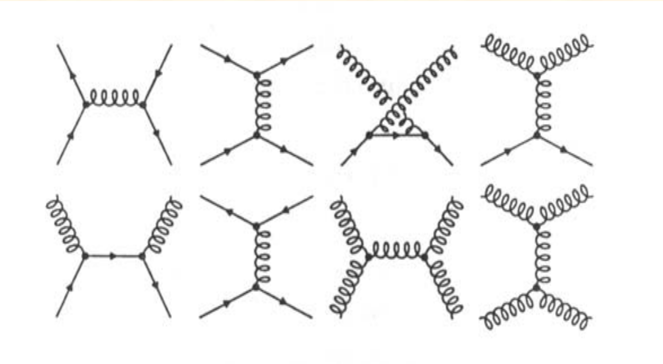


Quarks and gluons in the initial state

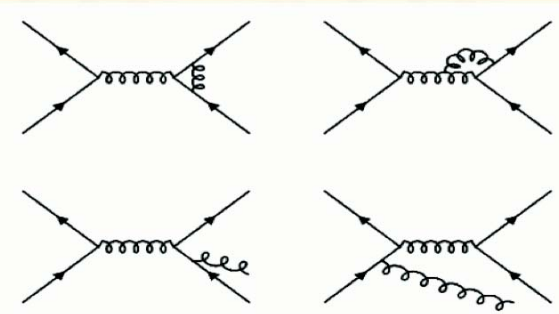
Hard Scattering Processes ….or QCD jet production



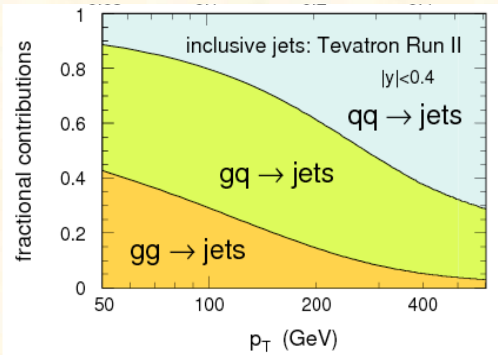
Leading order



…some NLO contributions



- Large momentum transfer, high p_T in final state; qq, qg, gg scattering or annihilation

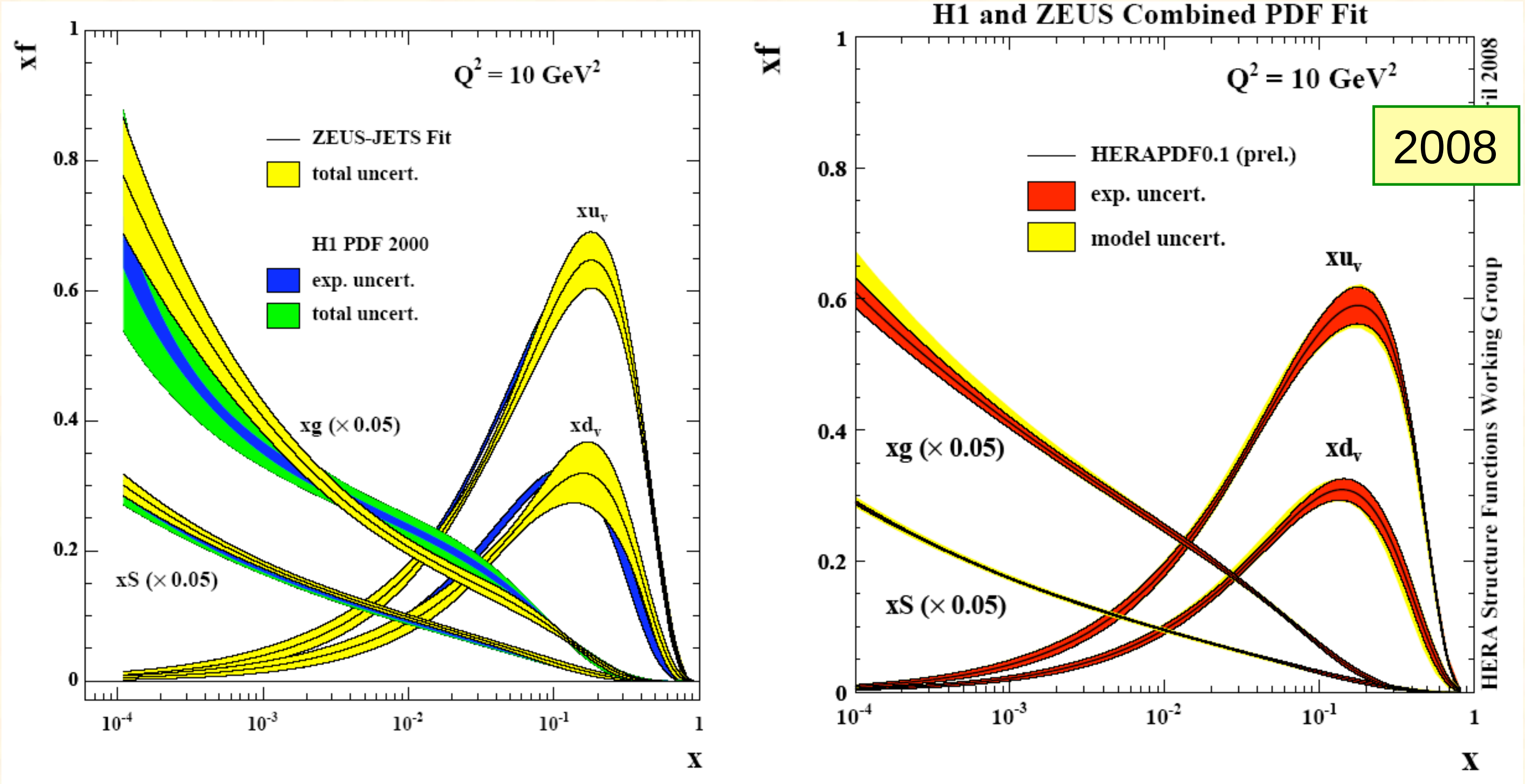


Tevatron,
ppbar, $\sqrt{s}$ = 1.96 TeV,
central region $|\eta| < 0.4$

- Calculable in perturbative QCD
  → test of QCD (search for deviations)
- Constraints on the proton structure possible (parton distribution functions of the proton)

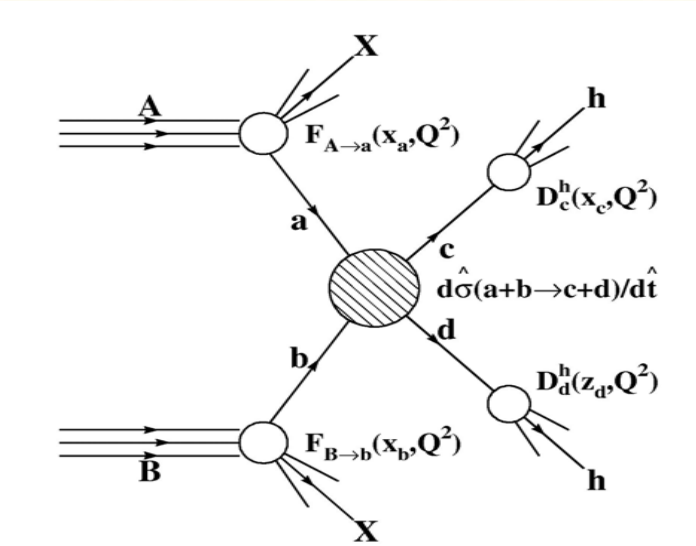
Results from HERA on the proton structure

- 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

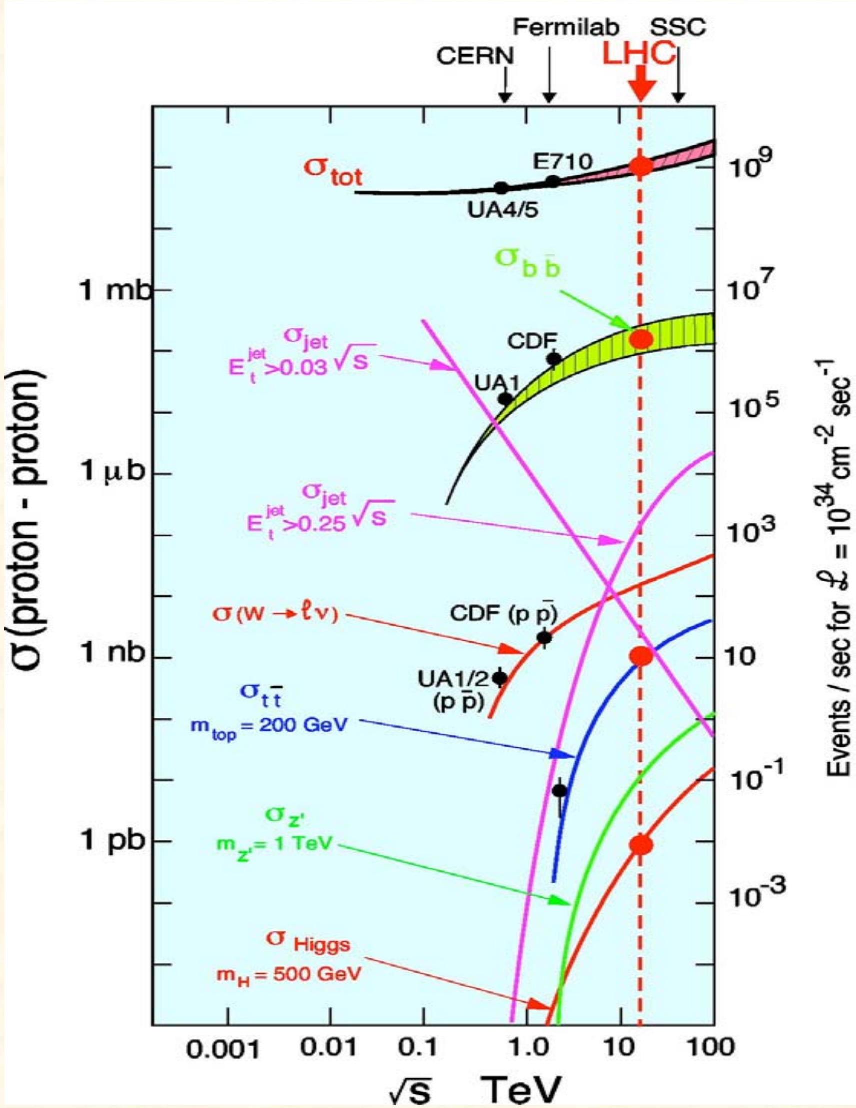
… + higher order QCD corrections (perturbation theory)

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

Cross Sections and Production Rates

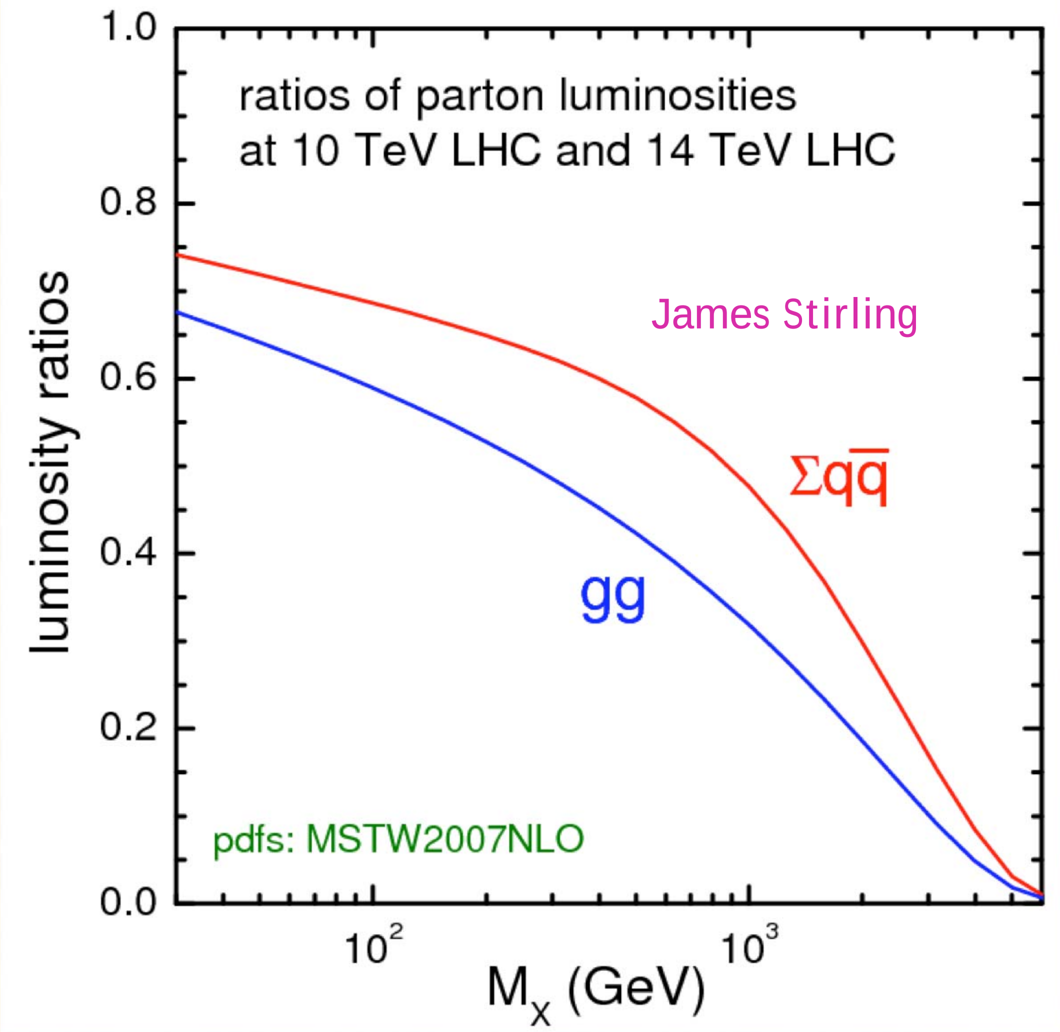


Rates for L = 10^{34} cm^{-2} s^{-1}: (LHC)

• 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, ……

Physics implications of 10 vs 14 TeV



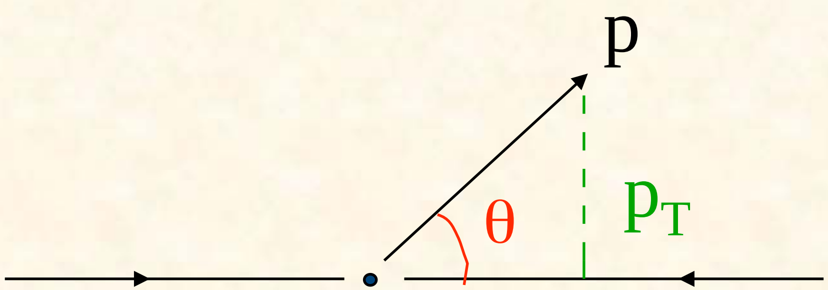
- At 10 TeV, more difficult to create high mass objects...
- Below about 200 GeV, this suppression is <50% (process dependent)

	√s [TeV]	Cross section
W-> lν	14	20.5 nb
	10	14.3 nb
Z-> ll	14	2.02 nb
	10	1.35 nb
ttbar	14	833 pb
	10	396 pb

- Above ~2-3 TeV the effect is more marked

14 TeV simulation results will be shown throughout the lectures, unless stated otherwise

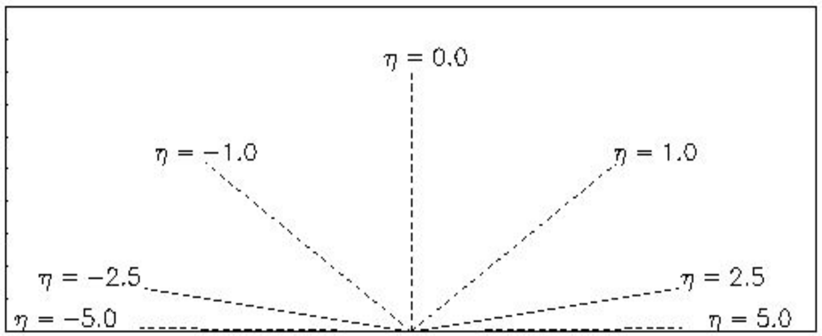
Variables used in the analysis of pp collisions



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]

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

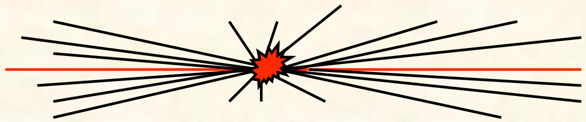
$\theta = 10^o \rightarrow \eta \cong 2.4$
$\theta = 170^o \rightarrow \eta \cong -2.4$

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

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



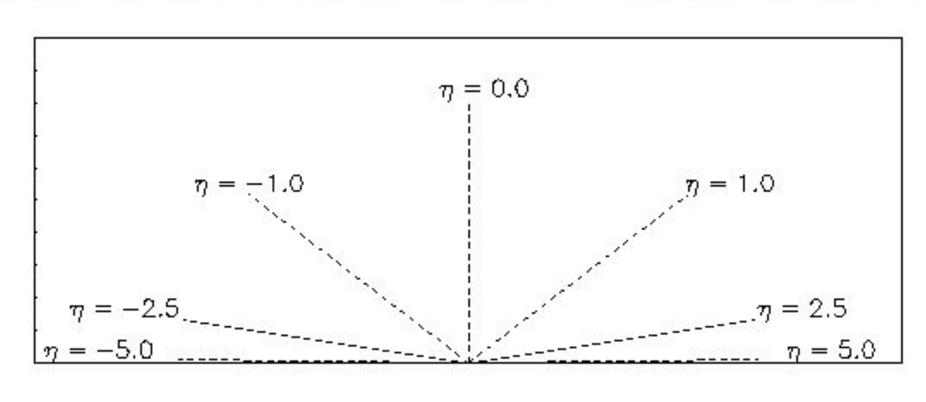
$< p_T > \approx 500$ MeV (of charged particles in the final state)

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

- 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"

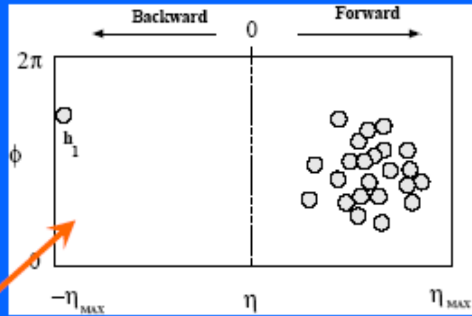
(more precise definition follows)



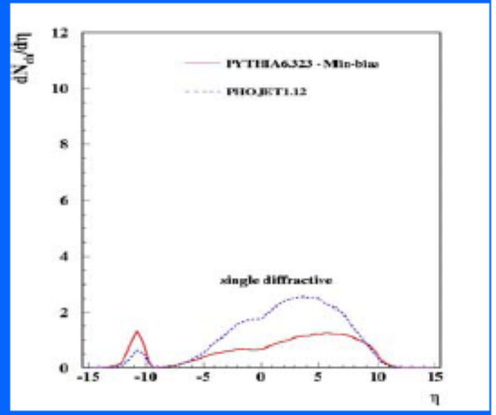
Soft pp collisions

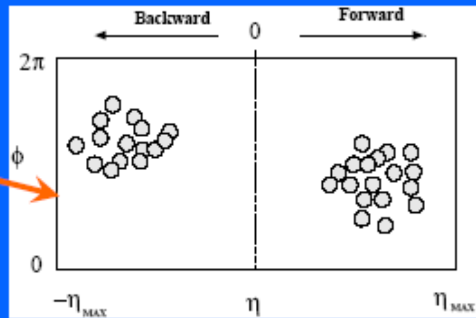
pp collisions at $\sqrt{s}$ = 14TeV	PYTHIA6.323	PHOJET1.12
σ_{tot}	101.5 mb	119.1 mb
σ_{elas}	22.2 mb	34.5mb
$2^*\sigma_{SD}$	14.4mb	11.0mb
σ_{DD}	10.3mb	4.1mb
σ_{ND}	54.7mb	69.5mb

Minimum bias
Made up of
combination of
non-diffractive
and diffractive

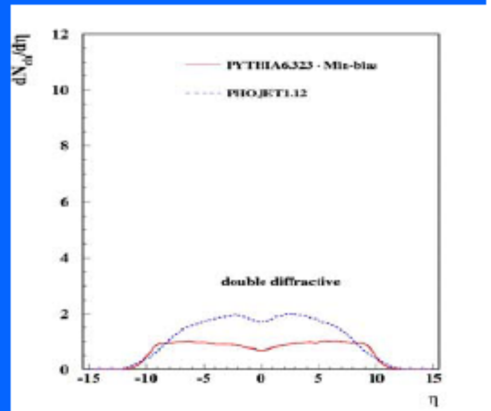


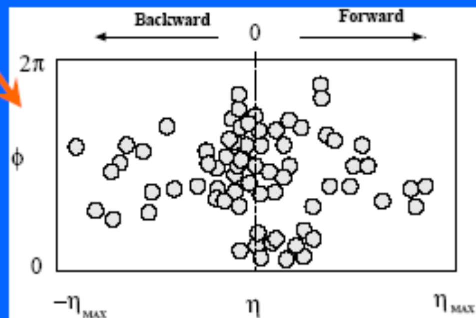
Single diffractive SD



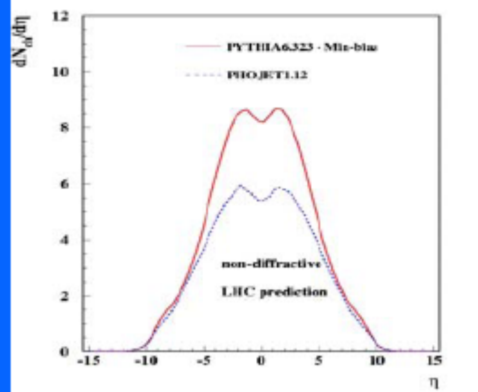


Double diffractive DD



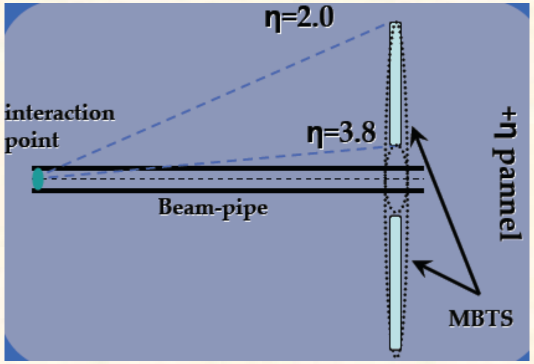


Non-diffractive ND



C. Buttar, DIS09

“Minimum bias events”



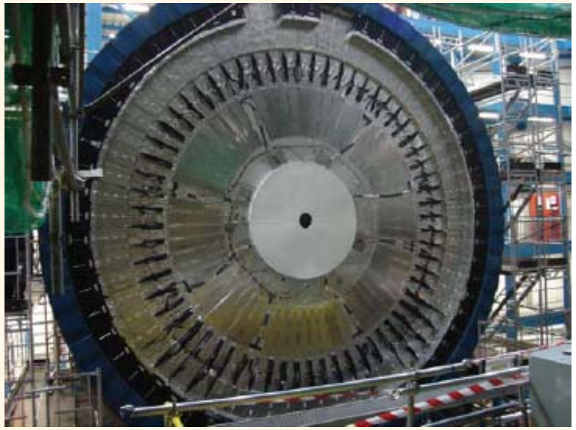
- Minimum bias is an experimental definition, defined by experimental trigger selection and analysis

- Relation to Physics:

$$\sigma_{measured} = f_{sd}\,\sigma_{sd} + f_{dd}\,\sigma_{dd} + f_{nd\text{-}inelestic}\sigma_{nd\text{-}inelastic}$$

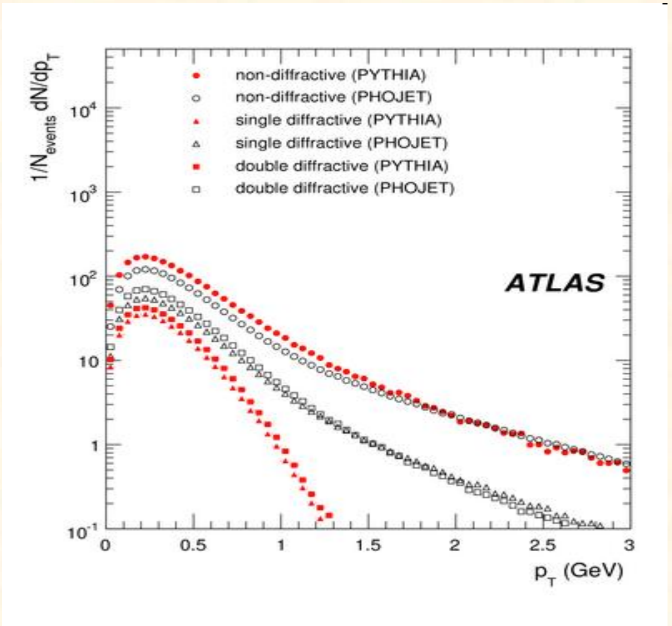
where f_i are the efficiencies for different physics processes determined by the trigger

NB: need to understand what is measured
to allow comparison to previous results,
often presented for non-single diffractive events

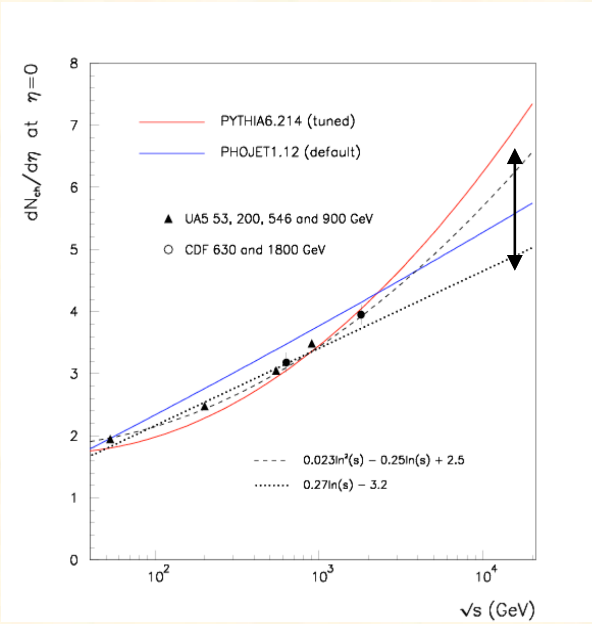


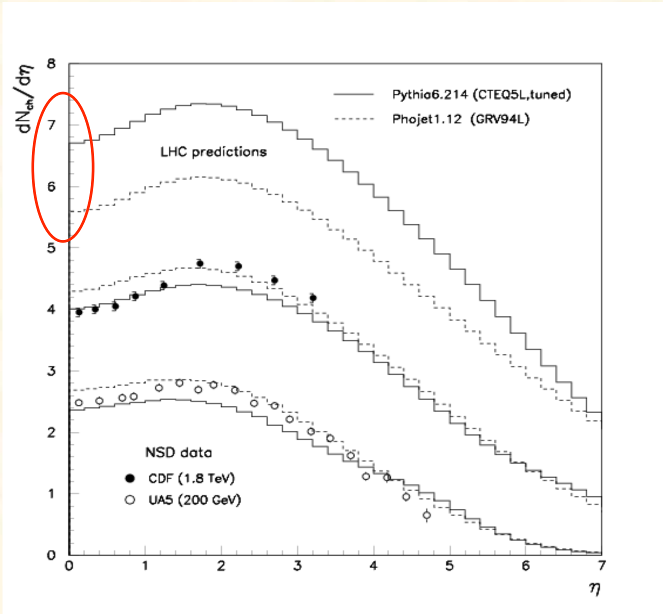
Some features of minimum bias events

- Features of minimum bias events cannot be calculated in perturbative QCD
- Experimental measurements / input needed
- Models / parametrizations are used to extrapolate from existing colliders (energies) to the LHC energy regime → large uncertainties
- Will be one of the first physics measurements at the LHC
- Needed to model other interesting physics (superposition of events,…)



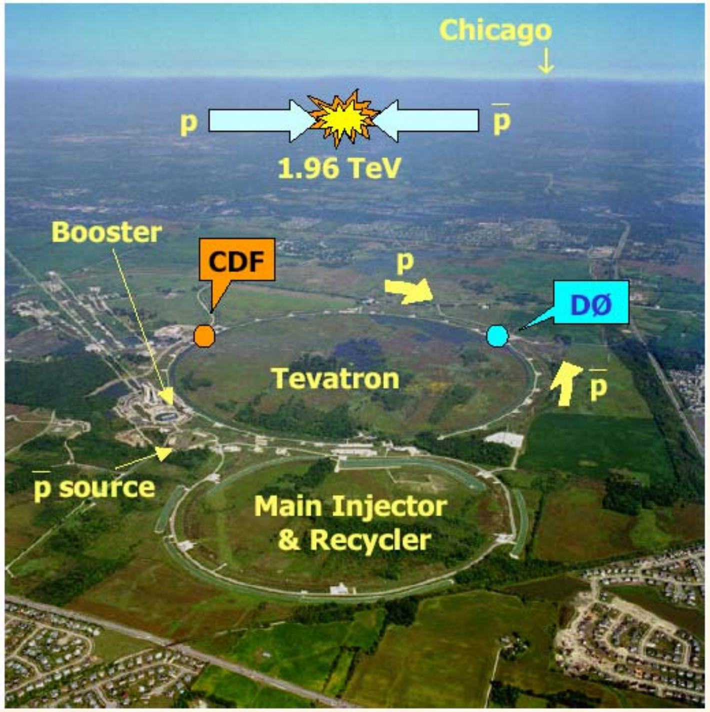
$<p_T>$ (η =0): 550 – 640 MeV (15%)

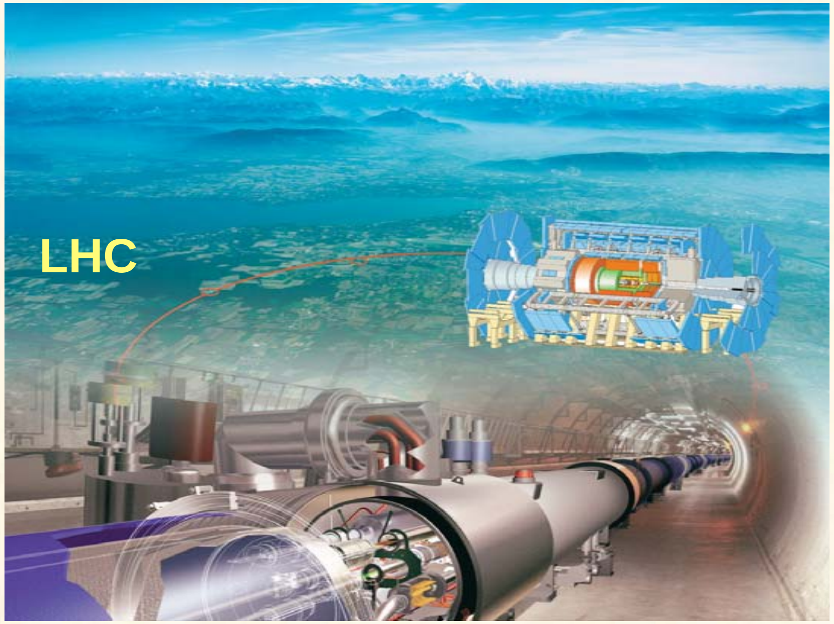


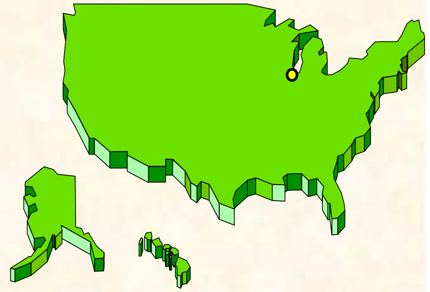


$dN_{ch}/d\eta$ (η=0): 5-7 (~ 33%)

The accelerators







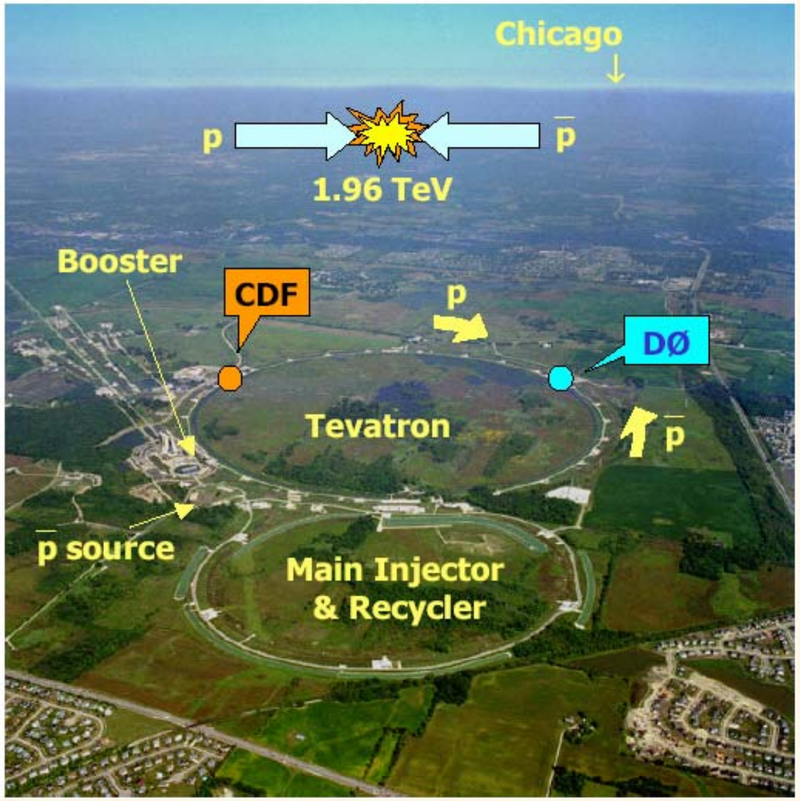
The Tevatron Collider at Fermilab

- **<u>Proton antiproton collider</u>**

  - 6.5 km circumference

  - Beam energy 0.98 TeV, **$\sqrt{s}$ = 1.96 TeV**

  - 36 bunches, 396 ns separation
  (time between crossings)



- **<u>2 Experiments</u>: CDF and DØ**

- **Main challenges:**

  - Antiproton production and storage

  → luminosity, stability of operation

Collider is running in so called Run II (since 2001)

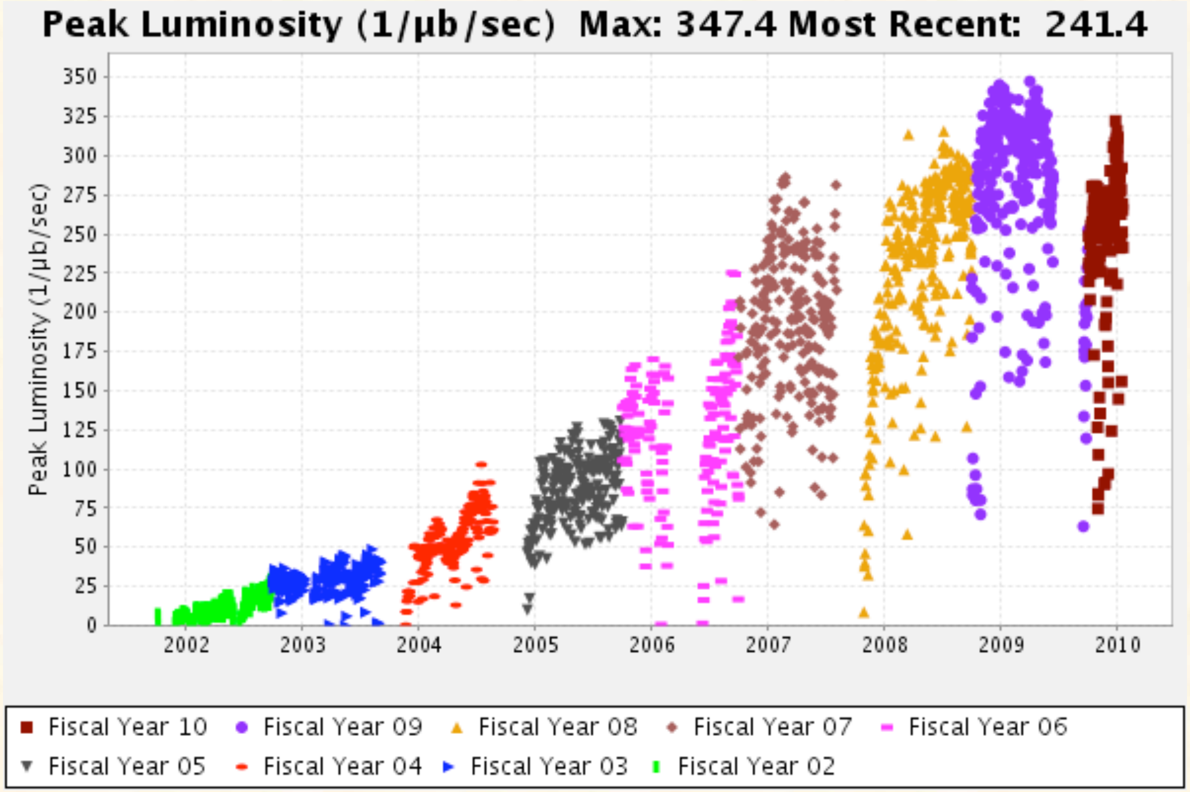
[Run I from 1990 – 1996, int. luminosity: 0.125 fb^{-1}, Top quark discovery]

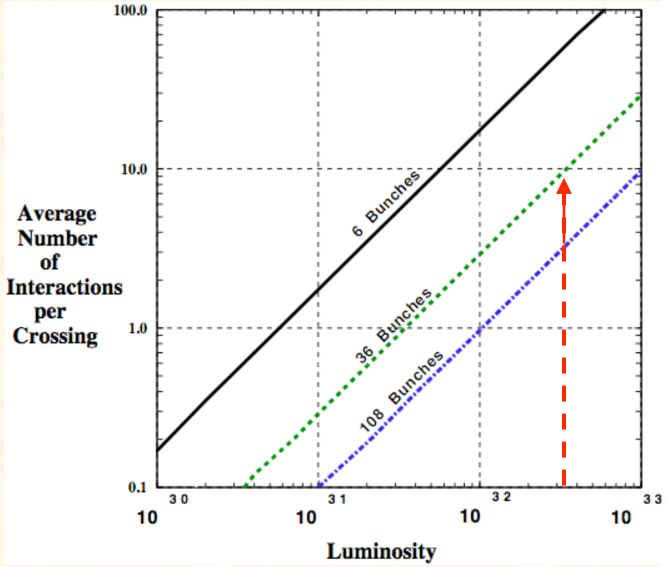
Real Data

- **March 2001 – Feb 2006: Run II a, $\int L\,dt$ = 1.2 fb^{-1}**
- **July 2006 - 2010 (11 / 12)?: Run II b, $\int L\,dt$ = 10 -12 fb^{-1}**

Tevatron performance

Peak luminosities of the machine as a function of time

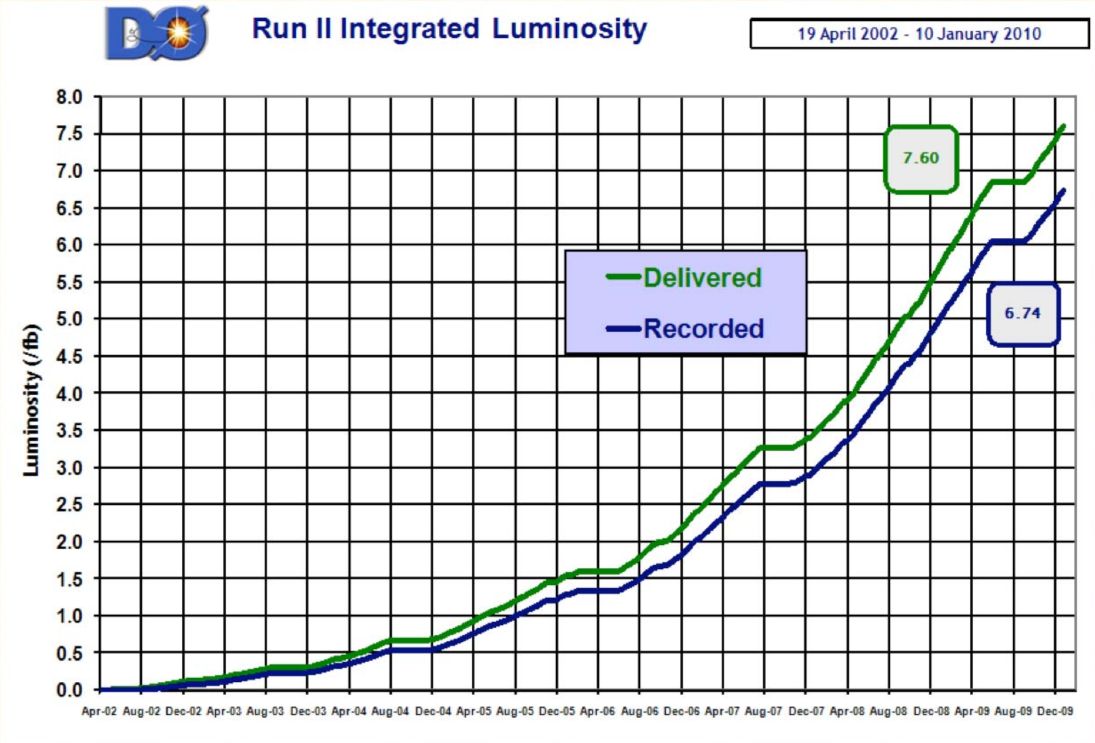




- Peak luminosity of 3.47 $\cdot 10^{32}$ cm^{-2} s^{-1}
- Corresponds to ~10 interactions per bunch crossing
  (superposition of minimum bias events on hard collision)

The integrated Tevatron luminosity (until Jan 2010)

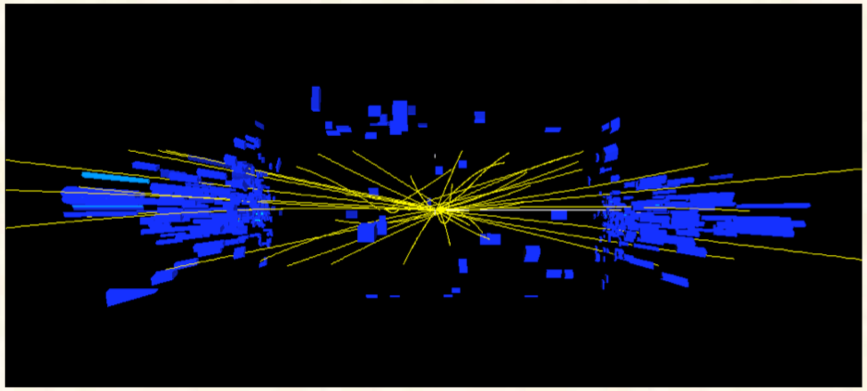
- After a slow start-up (2001 – 2003), the Tevatron accelerator has reached an excellent performance
- Today, Tevatron delivers a data set equal to Run I (~100 pb^{-1}) every 2 weeks
- Integrated luminosity delivered to the experiments so far ~ 7.6 fb^{-1}
- Anticipate an int. luminosity of ~10 fb^{-1} until end of 2010, with a potential increase to 12 - 13 fb^{-1}, if Tevatron will run until end of 2011

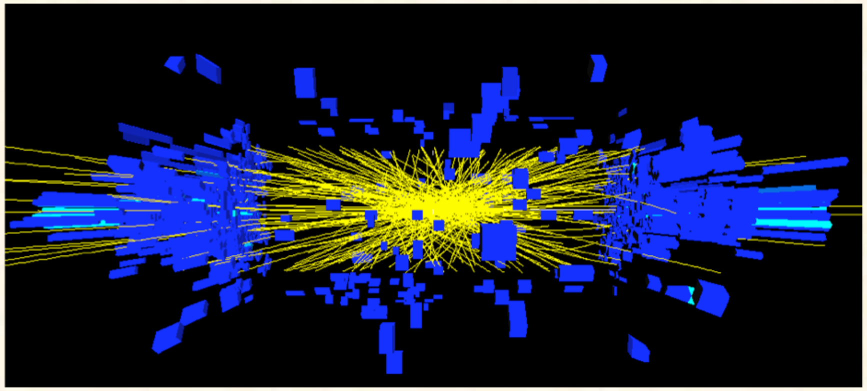


Data corresponding to an int. luminosity of up to 5.4 fb^{-1} analyzed…

Challenges with high luminosity

Min. bias pileup at the Tevatron, at $0.6 \cdot 10^{32}$ cm^{2}s^{-1} ... and at $2.4 \cdot 10^{32}$ cm^{2}s^{-1}

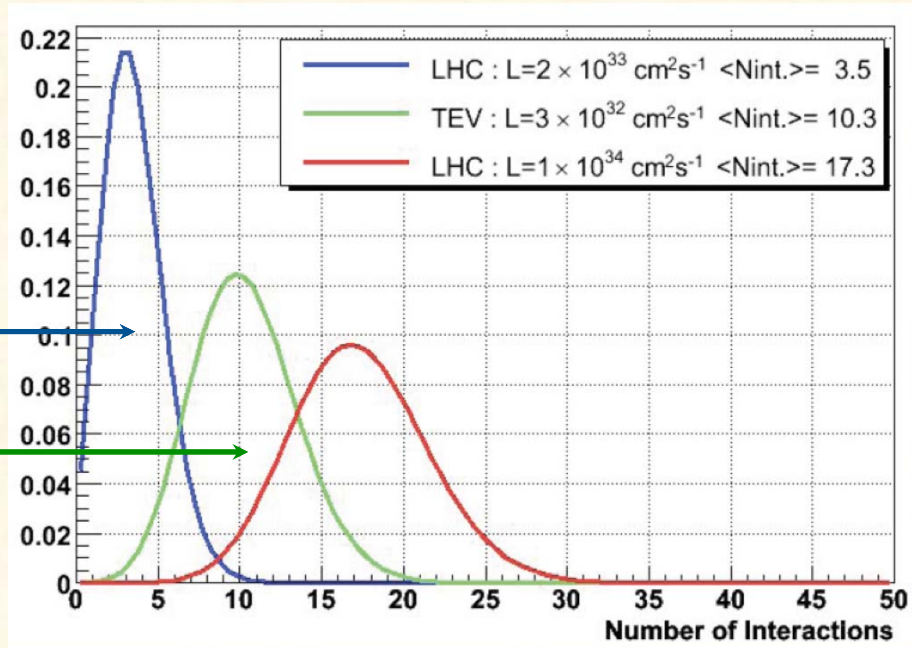




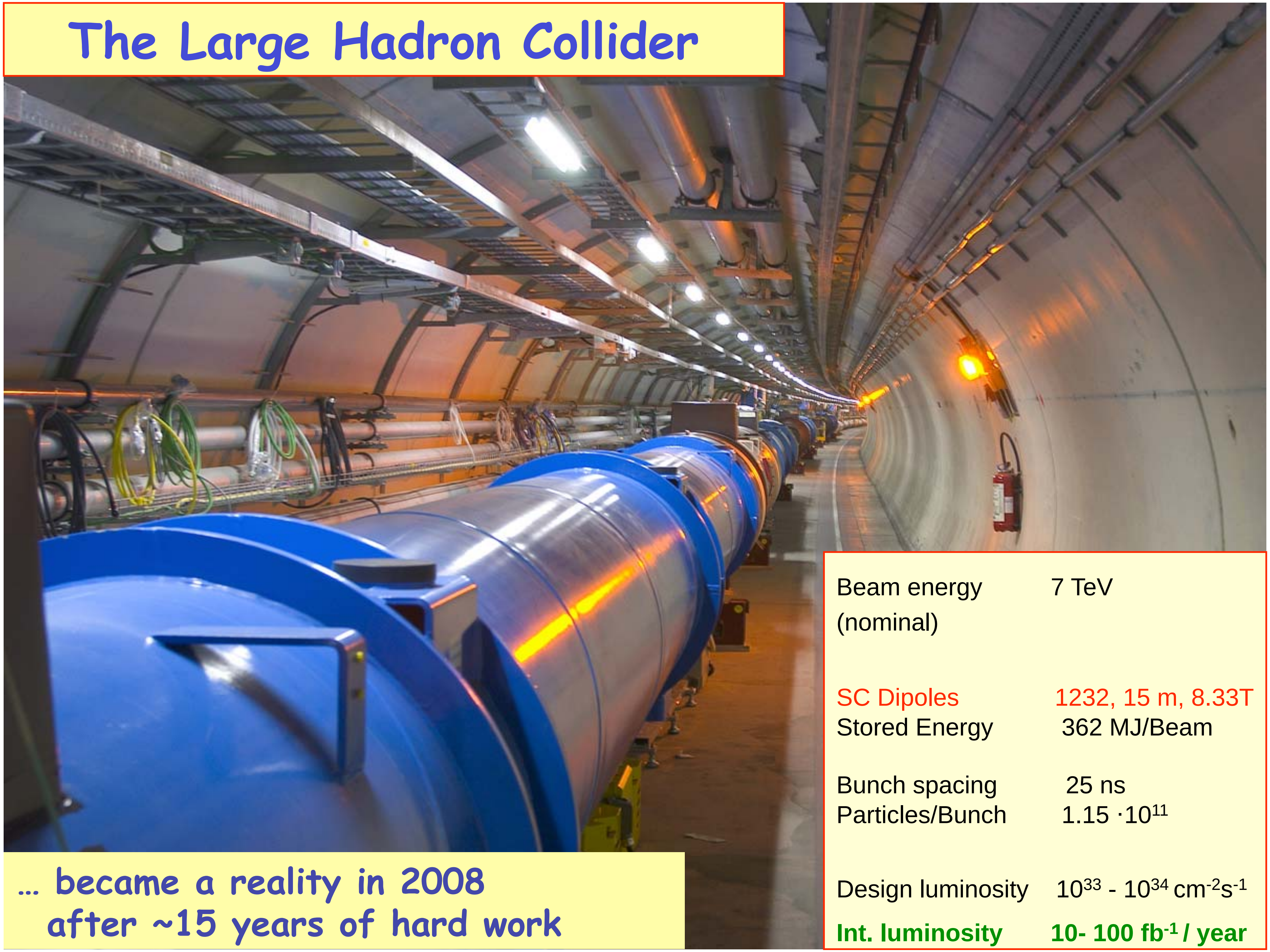
Average number of interactions:

LHC: initial “low” luminosity run
(L=2 $\cdot 10^{33}$ cm^{2}s^{-1}): <N>=3.5

TeV: (L=3 $\cdot 10^{32}$ cm^{2}s^{-1}): <N>=10



The Large Hadron Collider



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

Beam energy (nominal)	7 TeV
SC Dipoles	1232, 15 m, 8.33T
Stored Energy	362 MJ/Beam
Bunch spacing	25 ns
Particles/Bunch	$1.15 \cdot 10^{11}$
Design luminosity	10^{33} - 10^{34} $cm^{-2}s^{-1}$
Int. luminosity	**10- 100 fb^{-1} / year**

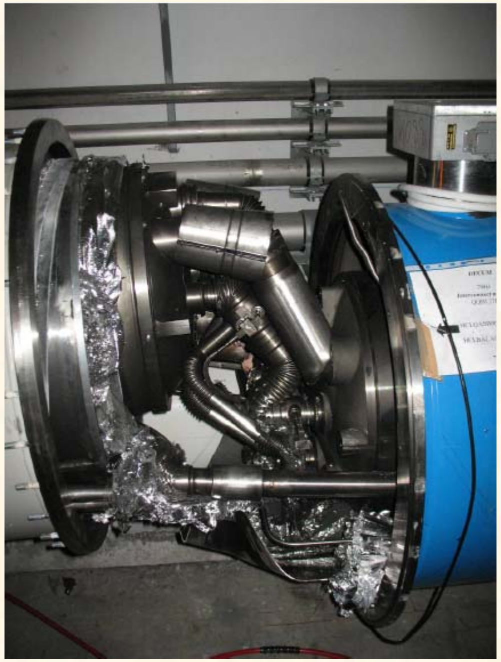
Comparison of the LHC and Tevatron machine parameters

	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

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

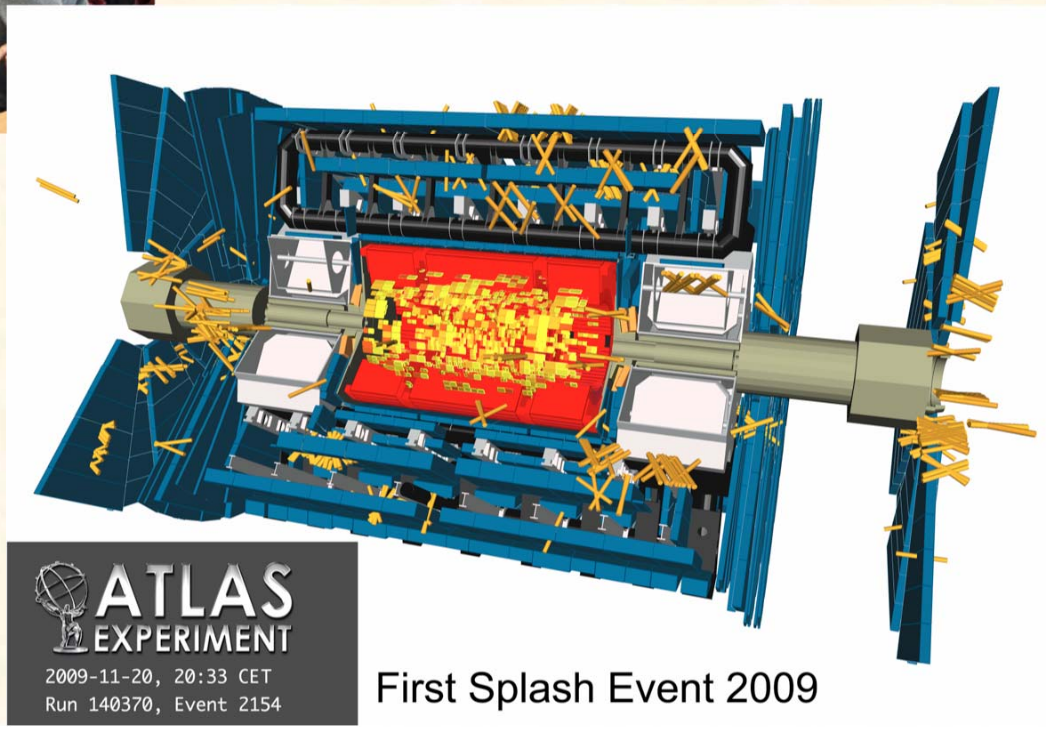
  → large pressure forces

- Lot of repair work during 2009

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

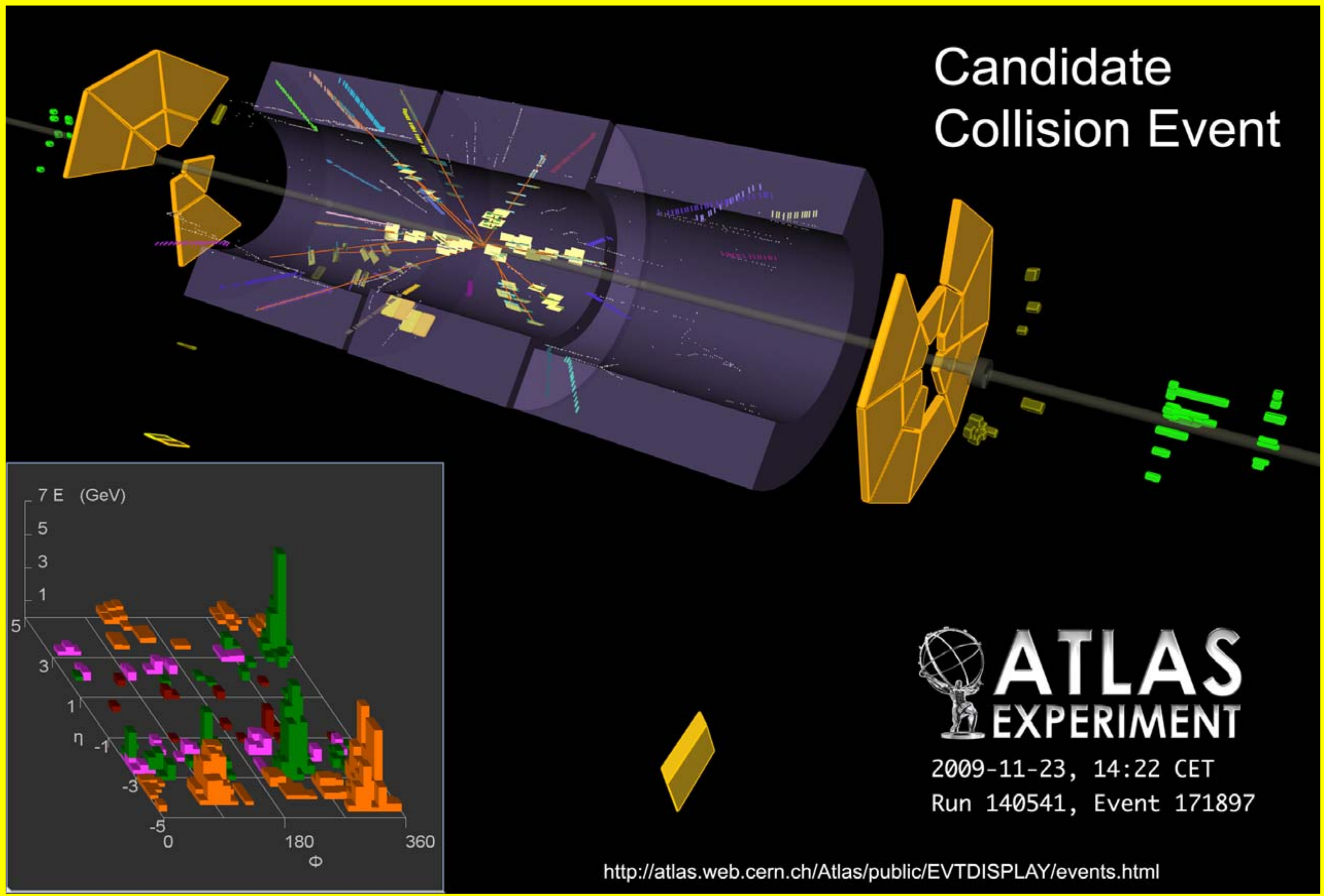
- **A very successful re-start in Nov. 2009**

Re-start on 20. Nov. 2009, ATLAS control room



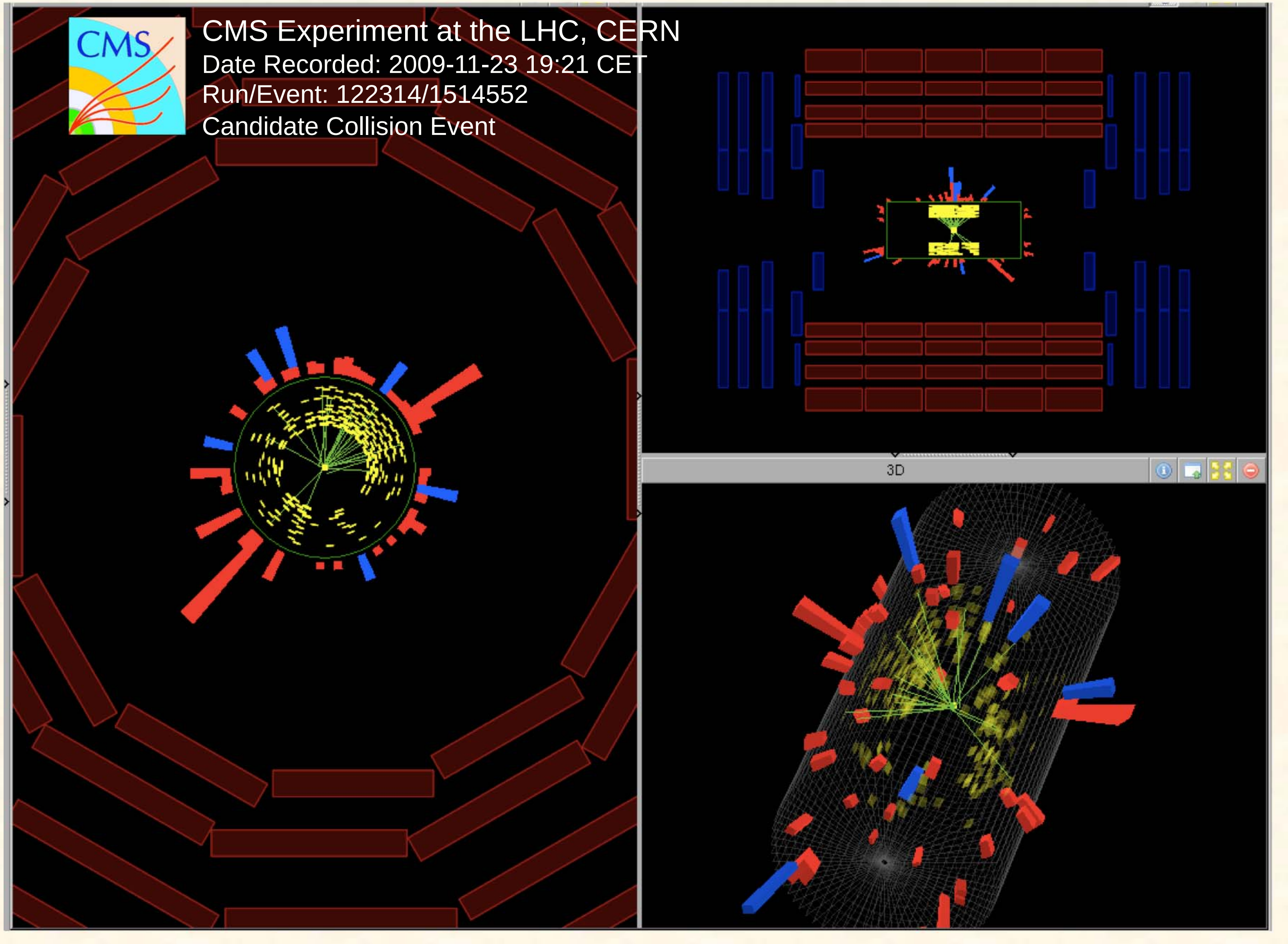
First Splash Event 2009

23. Nov. 2009: First collisions at 900 GeV



Start of the LHC: First Collisions

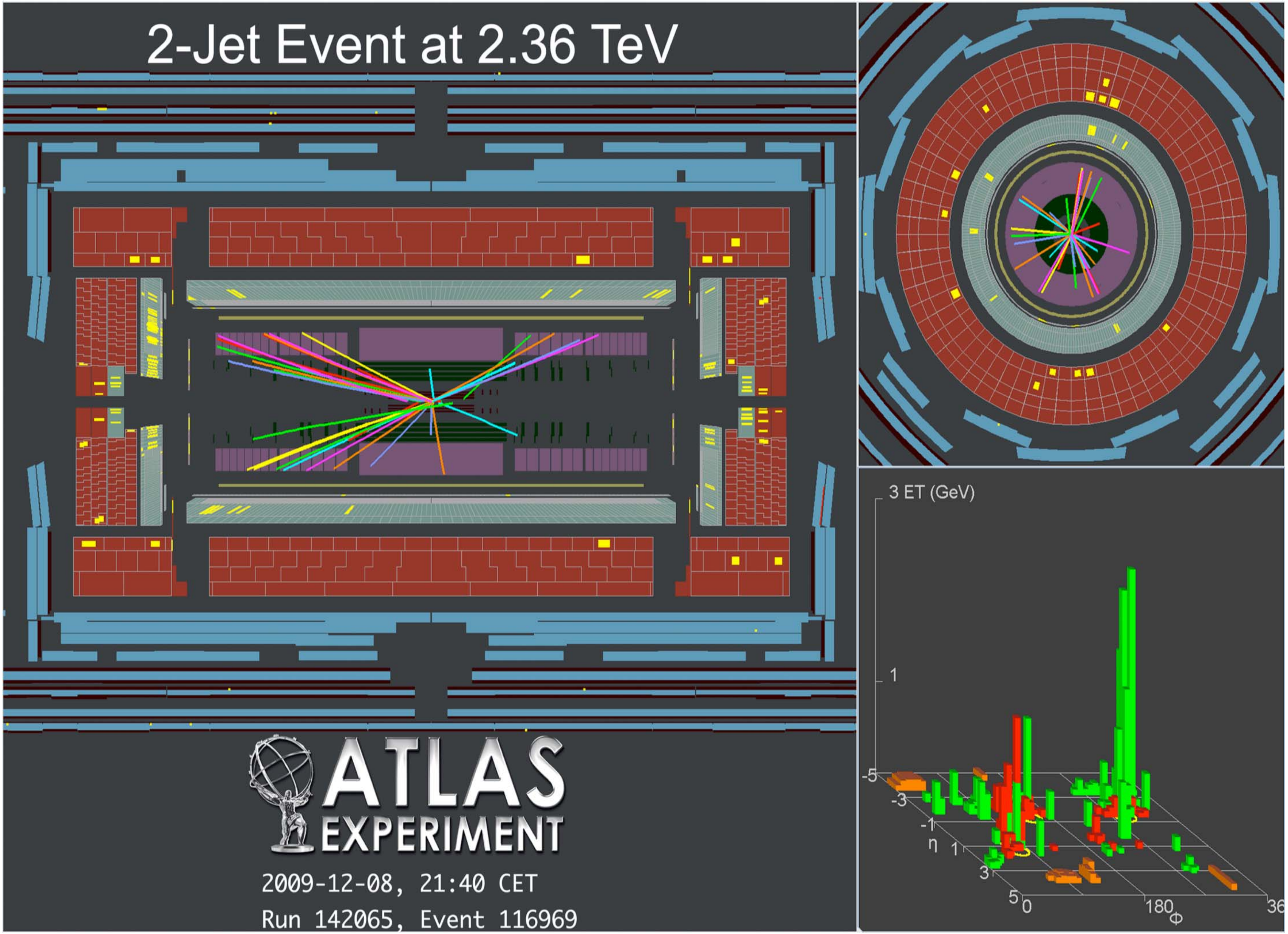
Monday 23rd November



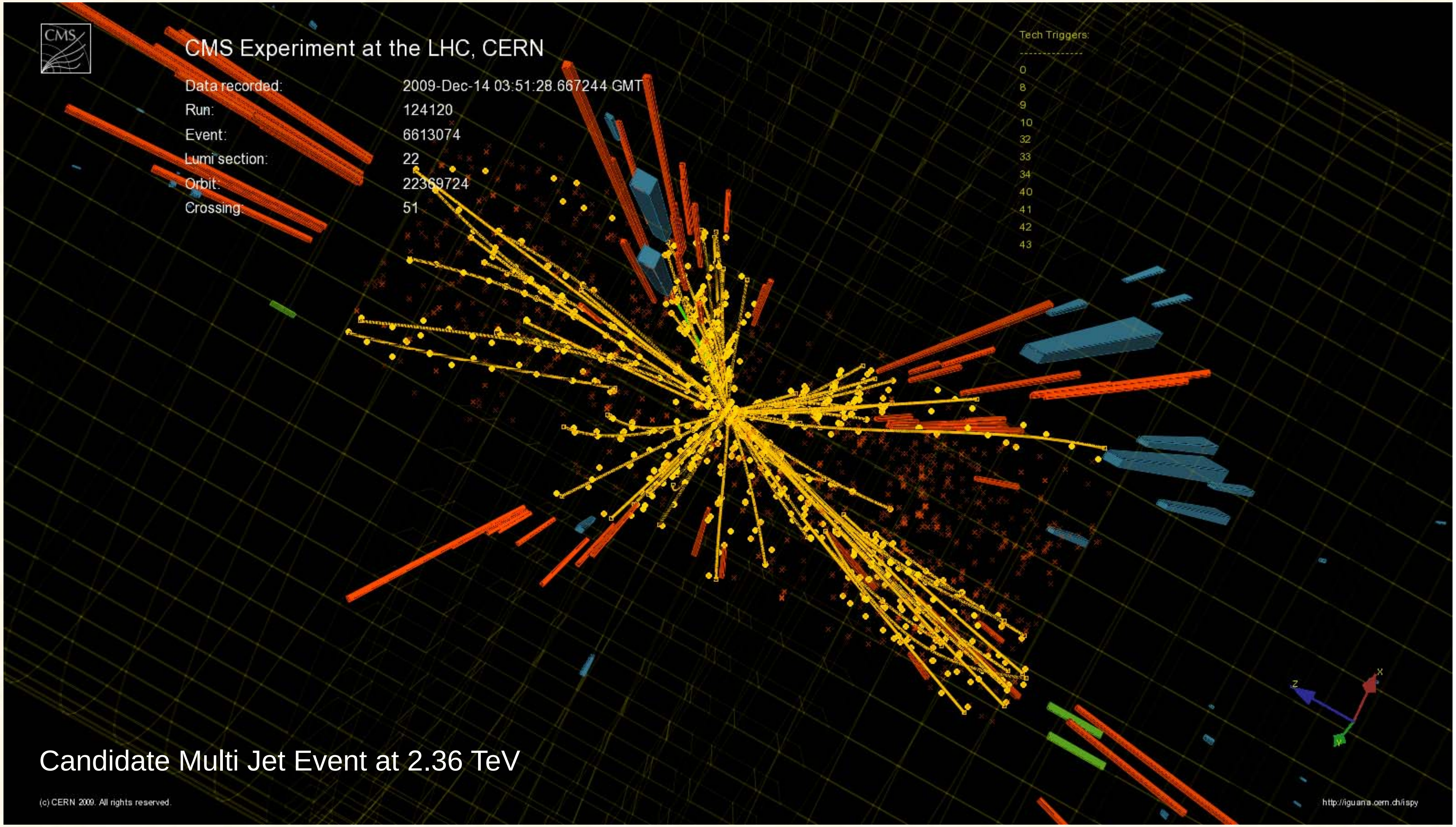
LHC sets new world record

Scenes of joy in the CERN Control Centre more photos »

Geneva, 30 November 2009. CERN's Large Hadron Collider has today become the world's highest energy particle accelerator, having accelerated its twin beams of protons to an energy of 1.18 TeV in the early hours of the morning. This exceeds the previous world record of 0.98 TeV, which had been held by the US Fermi National Accelerator Laboratory's Tevatron collider since 2001. It marks another important milestone on the road to first physics at the LHC in 2010.


2-Jet Event at 2.36 TeV
ATLAS
EXPERIMENT
2009-12-08, 21:40 CET
Run 142065, Event 116969
3 ET (GeV)
1
-5
-3
-1
η
1
3
5
0
180
Φ
36

A candidate multi jet event at 2.36 TeV in CMS



Detector requirements from physics

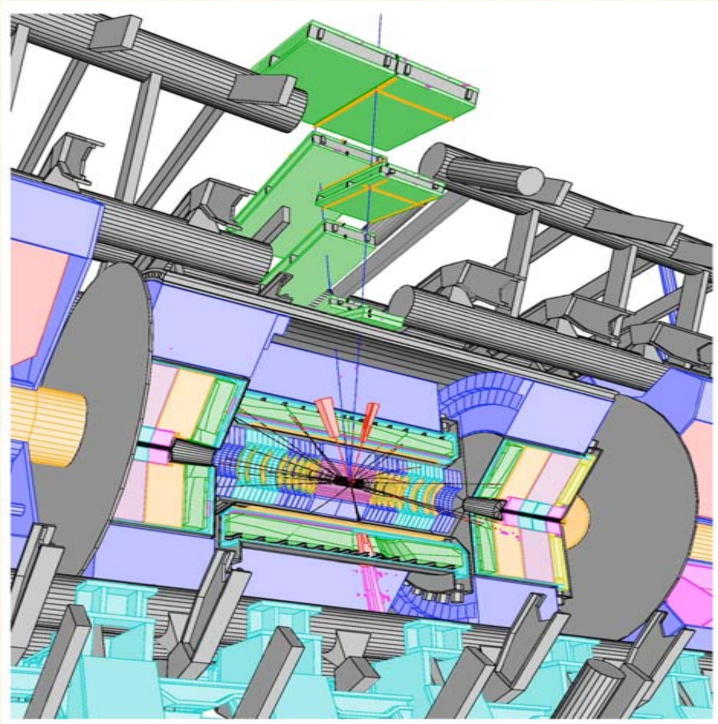
- Good measurement of leptons and photons with large transverse momentum P_T

- Good measurement of missing transverse energy (E_T^{miss})

  and

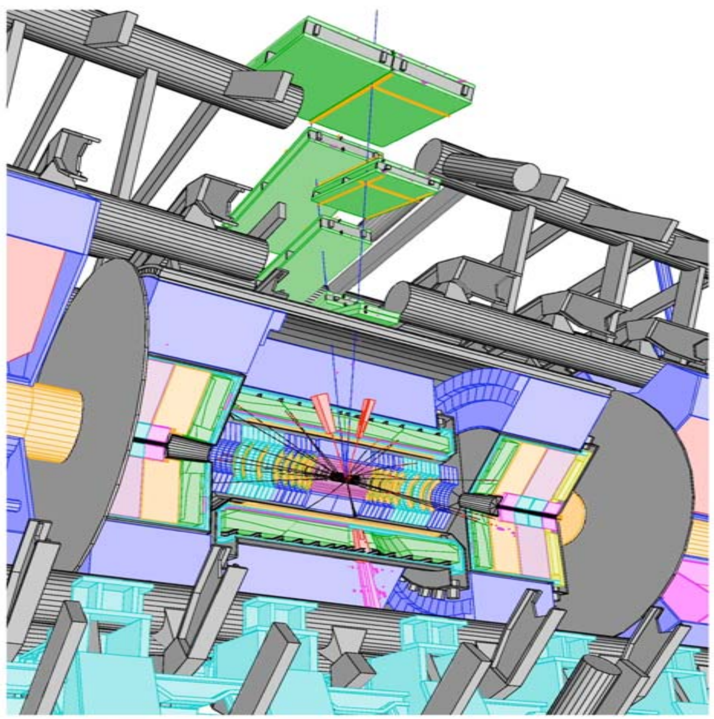
  energy measurements in the forward regions

  $\Rightarrow$ calorimeter coverage down to η ~ 5



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

Detector requirements from the experimental environment (pile-up)



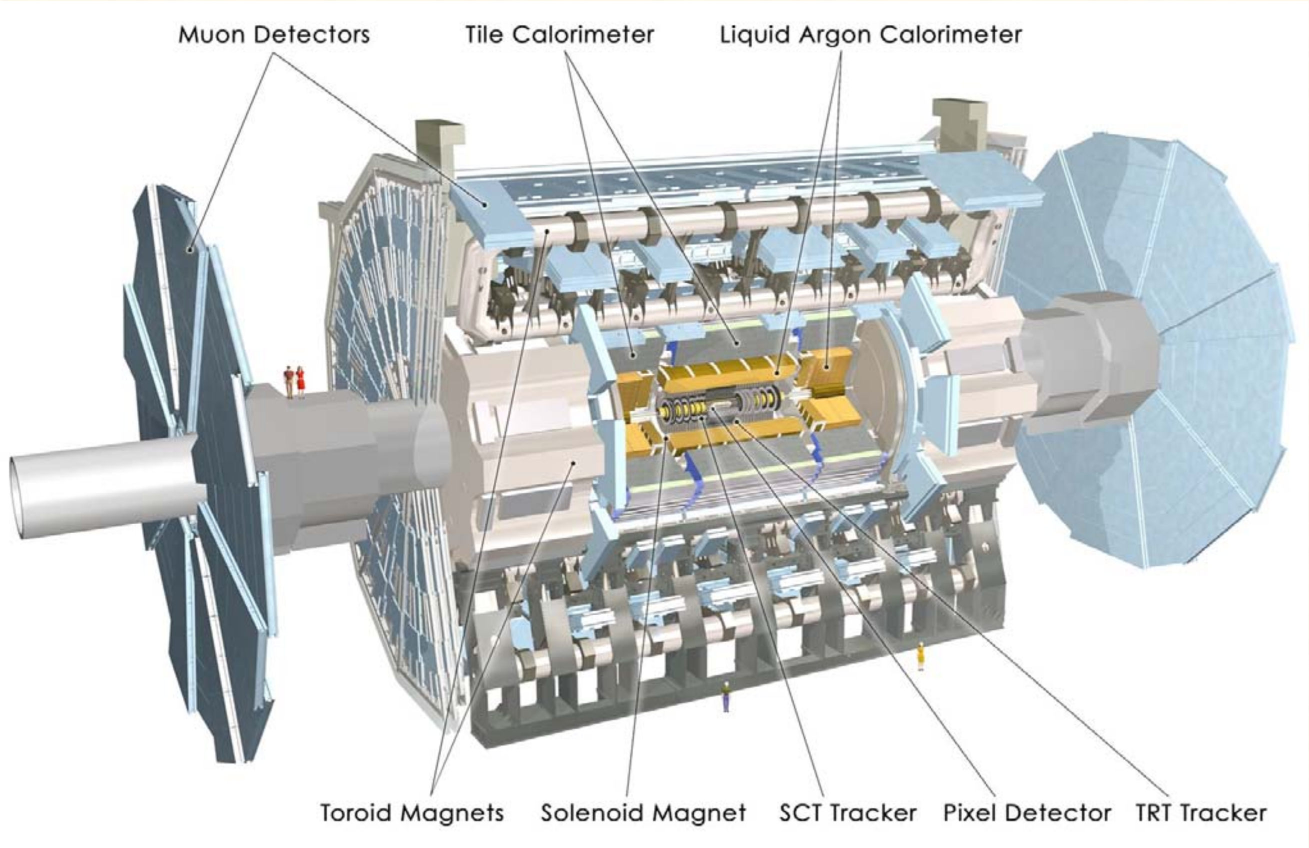
- LHC detectors must have **fast response**, otherwise integrate over many bunch crossings → too large pile-up

  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)

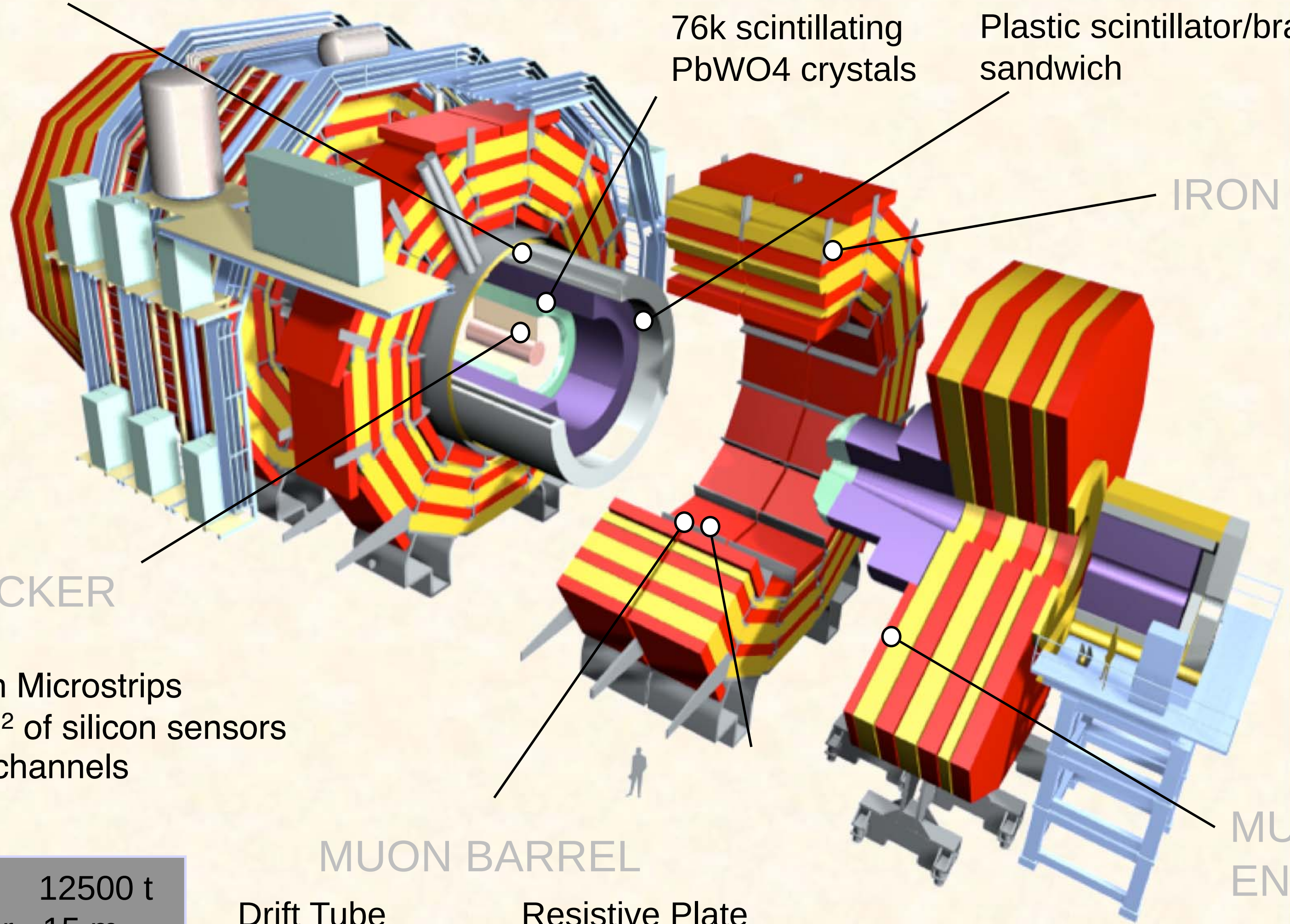
  space resolution: ~ 15 µm

- Energy measurement down to 1^{o} to the beam line

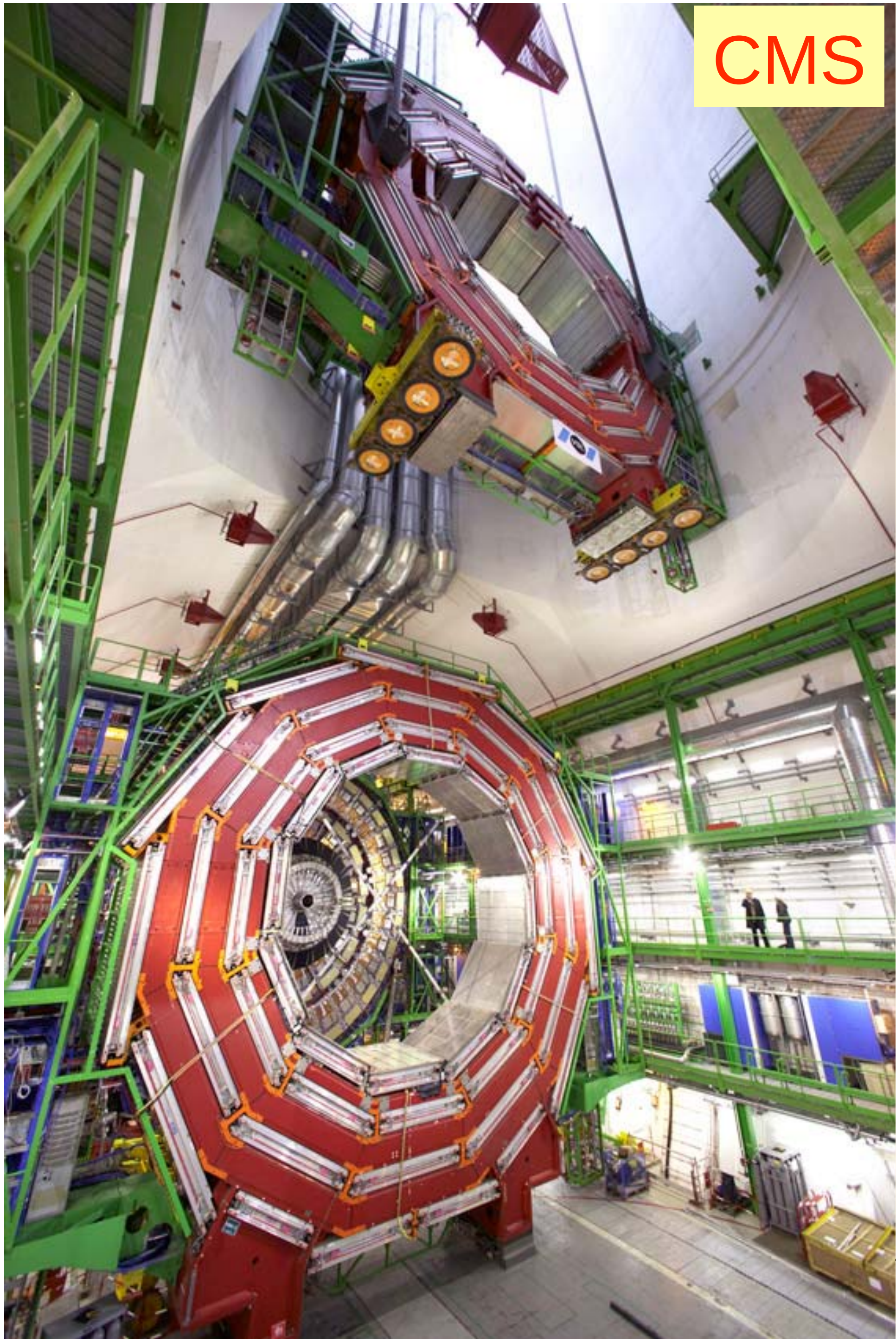
- Independent muon spectrometer (supercond. toroid system)

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

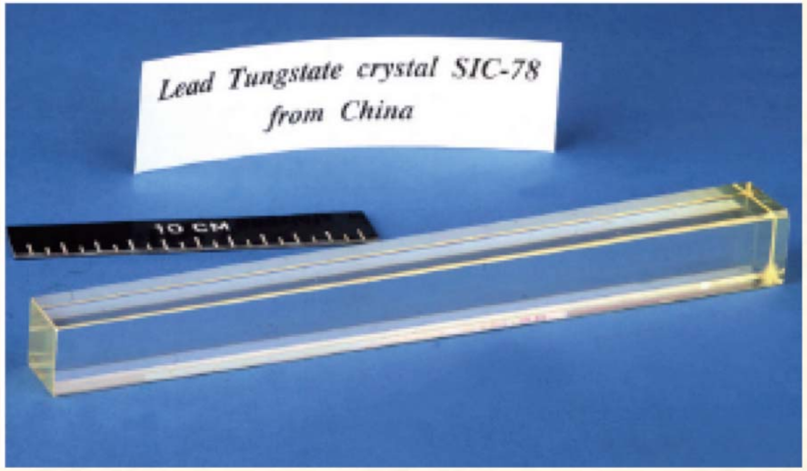
CMS



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


CMS

Important differences I:

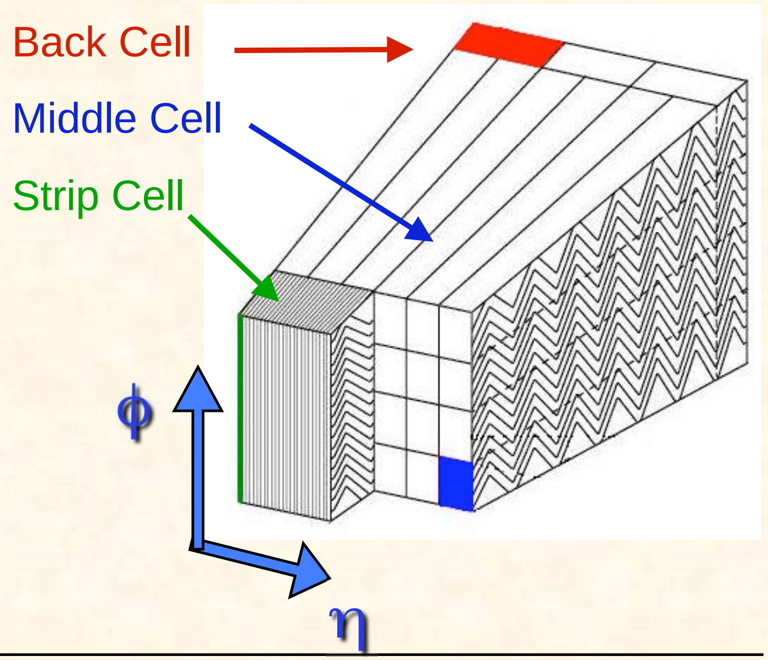


- In order to maximize the sensitivity for **H → γγ decays**, the experiments need to have an excellent e/γ identification and resolution

---

- CMS: has opted for a high resolution $PbWO_4$ crystal calorimeter
  - higher intrinsic resolution

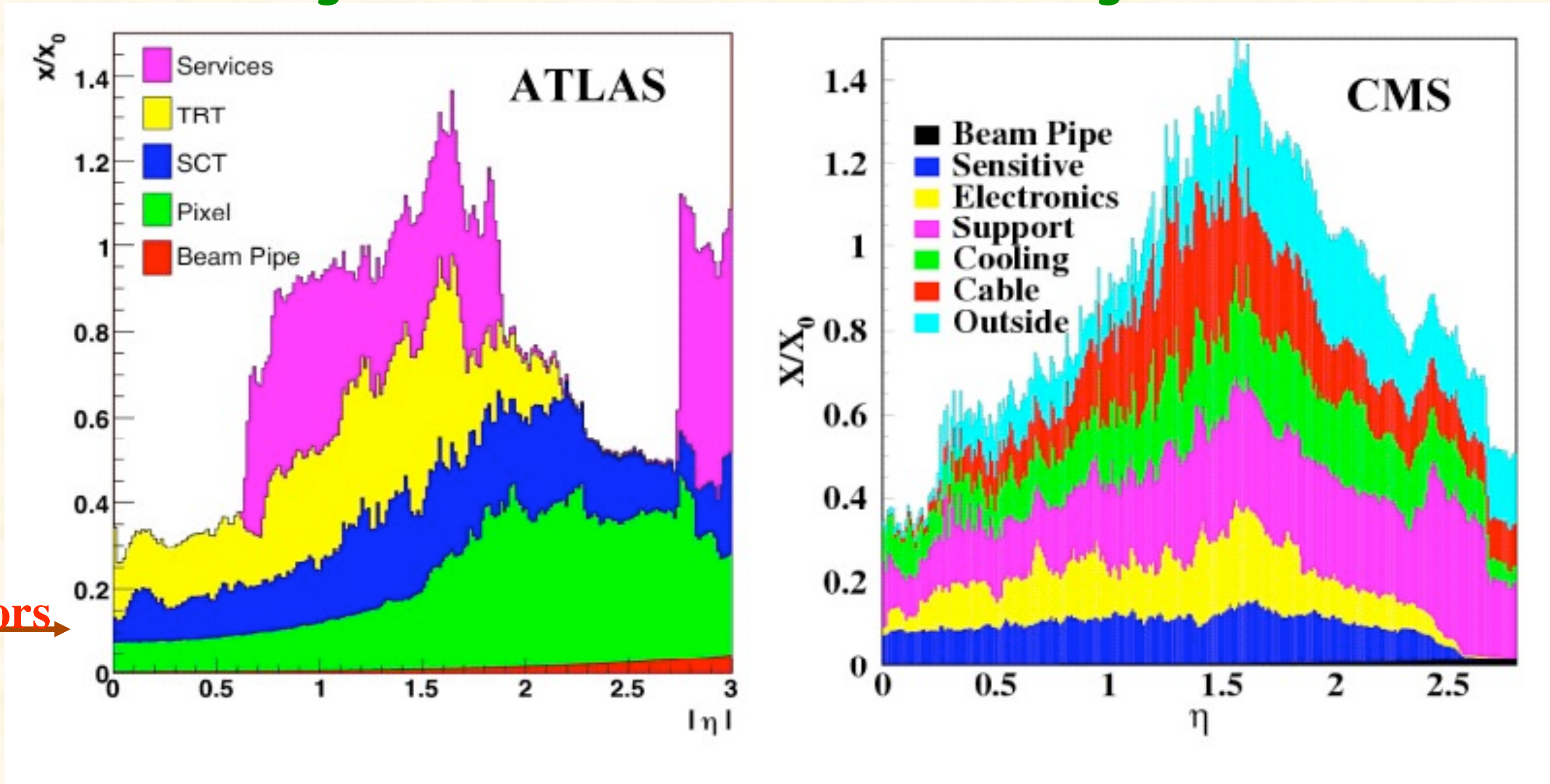
- ATLAS: Liquid argon calorimeter
  - high granularity and longitudinally segmentation (better e/γ ID)
  - electrical signals, high stability in calibration & radiation resistant



Amount of material in ATLAS and CMS inner trackers

Weight: 4.5 tons

Weight: 3.7 tons



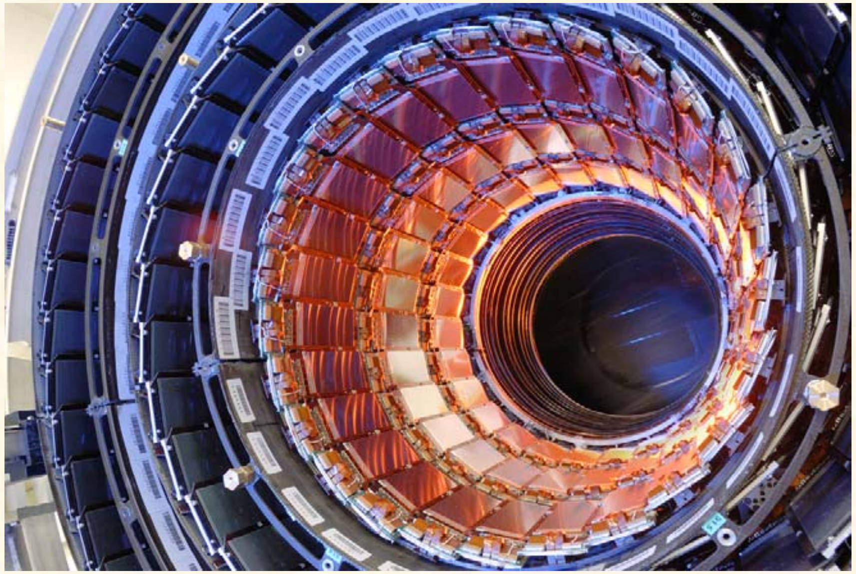
LEP detectors

- Active sensors and mechanics account each only for ~ 10% of material budget
- Need to bring 70 kW power into tracker and to remove similar amount of heat
- Very distributed set of heat sources and power-hungry electronics inside volume: this has led to complex layout of services, most of which were not at all understood at the time of the TDRs

Important differences II:

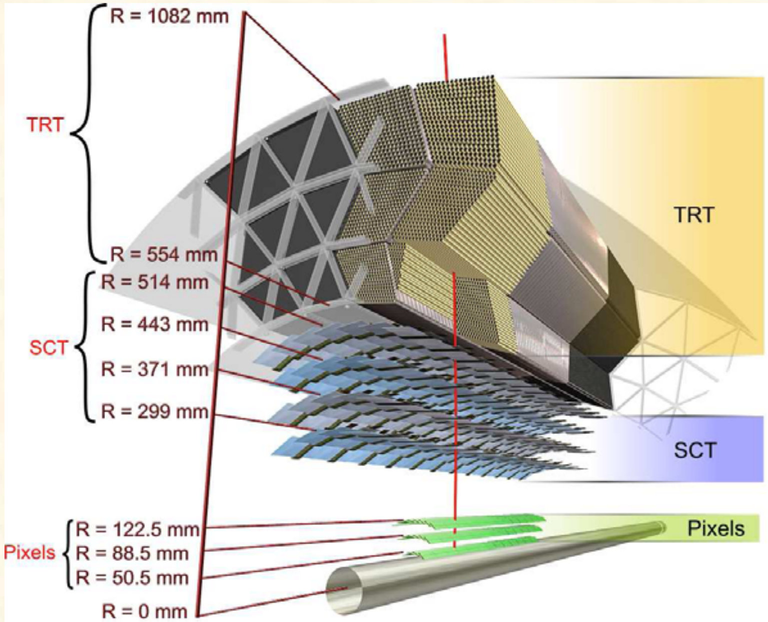
• Inner detectors / tracker

Both use solenoidal fields
ATLAS: 2 Tesla
CMS: 4 Tesla



• CMS: full silicon strip and pixel detectors
- high resolution, high granularity

• ATLAS: Silicon (strips and pixels)
+ Transition Radiation Tracker
- high granularity and resolution close to interaction region
- "continuous" tracking at large radii



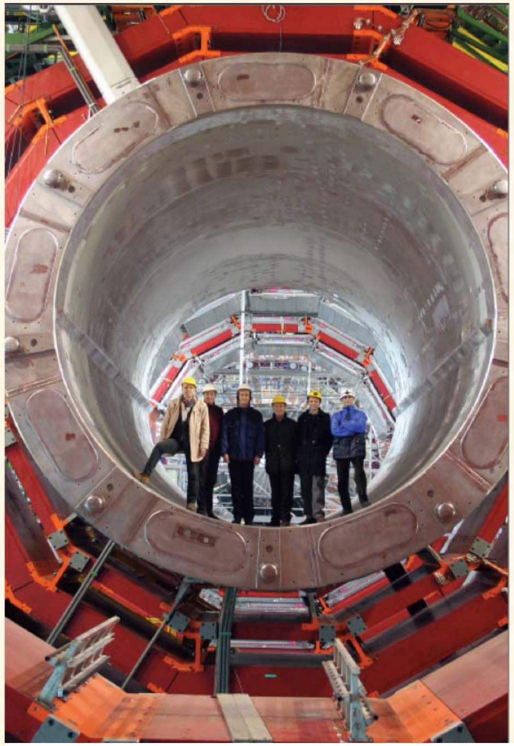
Important differences III:

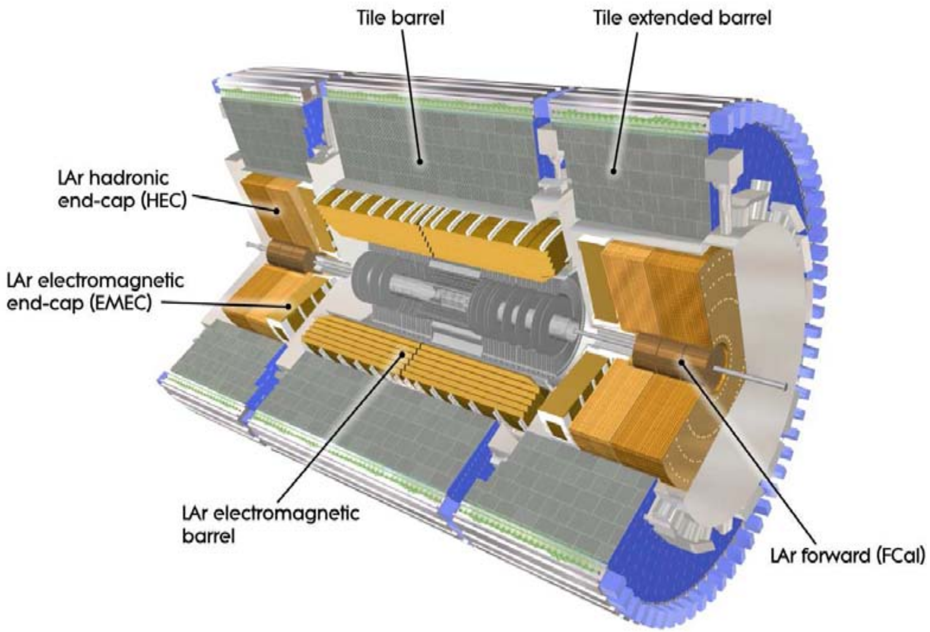
• Coil / Hadron calorimeters

• CMS: electromagnetic calorimeter
and part of the hadronic calorimeter
(7λ) inside the solenoidal coil
+ tail catcher, return yoke

good for e/γ resolution
bad for jet resolution

• ATLAS:
calorimetry outside coil



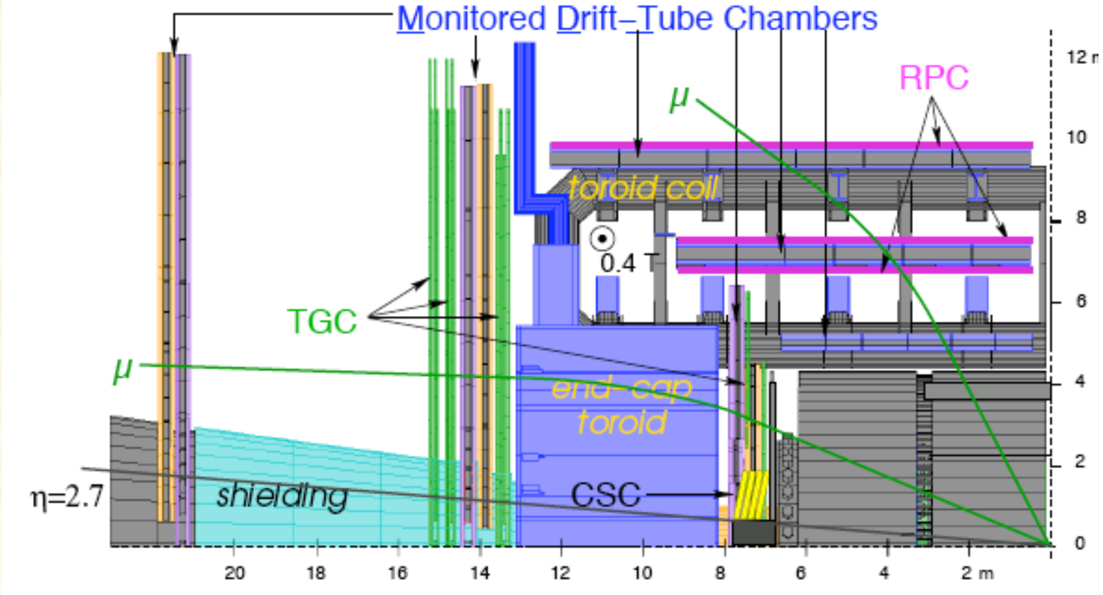


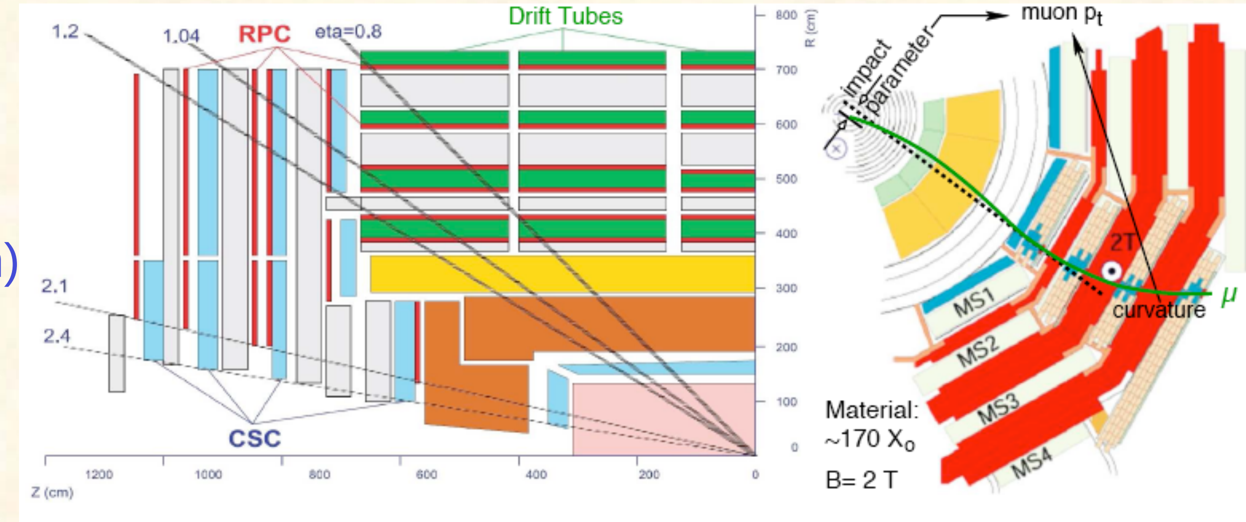
Important differences IV:

- Muon spectrometer

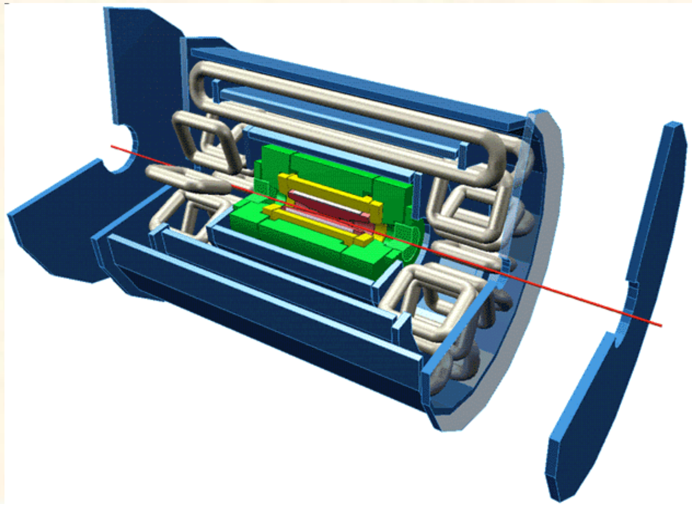
- ATLAS: independent muon spectrometer; → excellent stand-alone capabilities

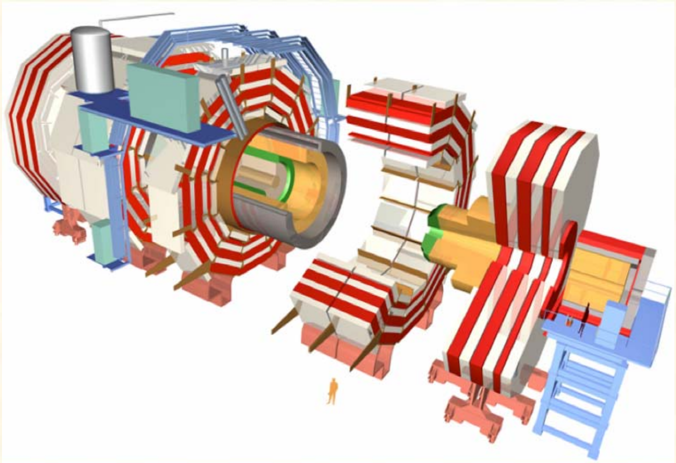
- CMS: superior combined momentum resolution in the central region; limited stand-alone resolution and trigger capabilities (multiple scattering in the iron)





	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)



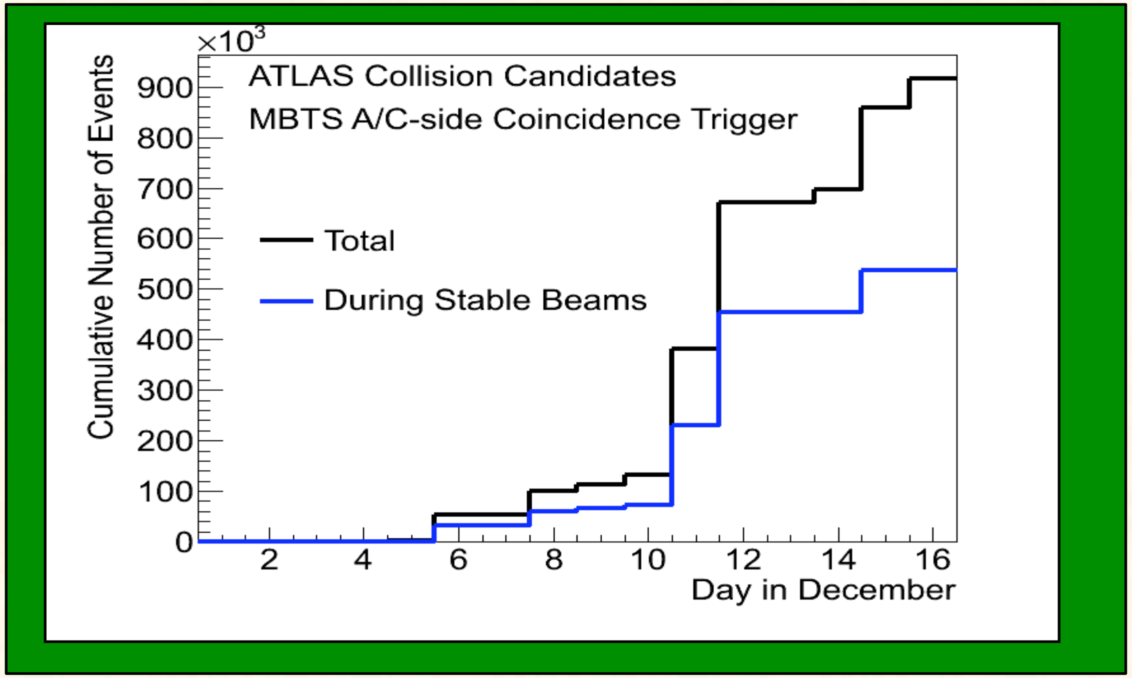


A first look at the collision data

Based on presentations by the four experiments on
18. Dec. 2009 at CERN

(J. Schukraft (ALICE), F. Gianotti (ATLAS),
T. Virdee (CMS), A. Gloutvin (LHCb))

Recorded events, efficiencies, ...

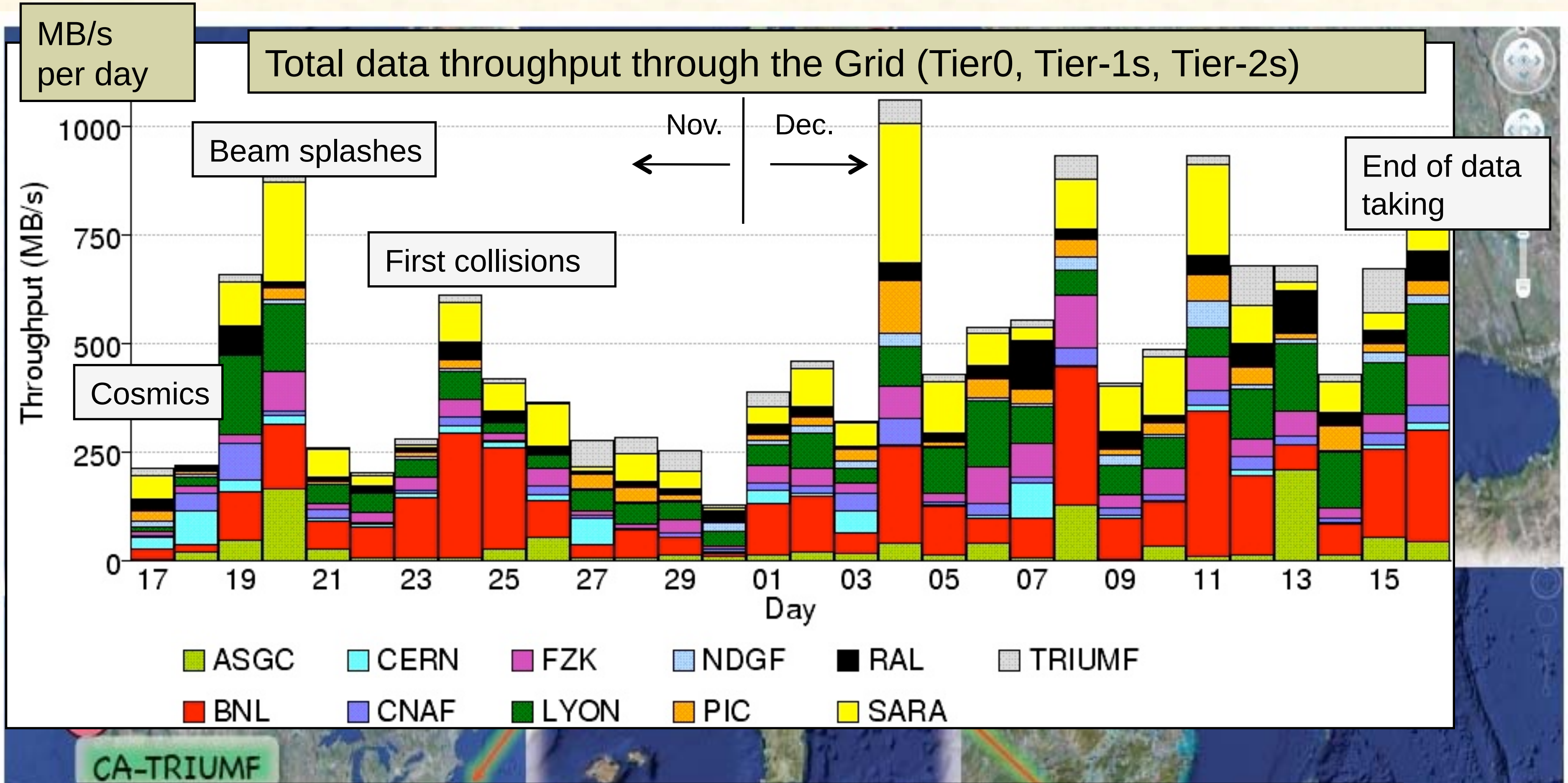


Max peak luminosity seen by ATLAS : ~ 7 x 10^{26} cm^{-2} s^{-1}

Recorded data samples	Number of events	Integrated luminosity (< 30% uncertainty)
Total	~ 920k	~ 20 μb^{-1}
With stable beams (→ tracker fully on)	~ 540k	~ 12 μb^{-1}
At $\sqrt{s}$=2.36 TeV (flat top)	~ 34k	≈ 1 μb^{-1}

Average data-taking efficiency: ~ 90%

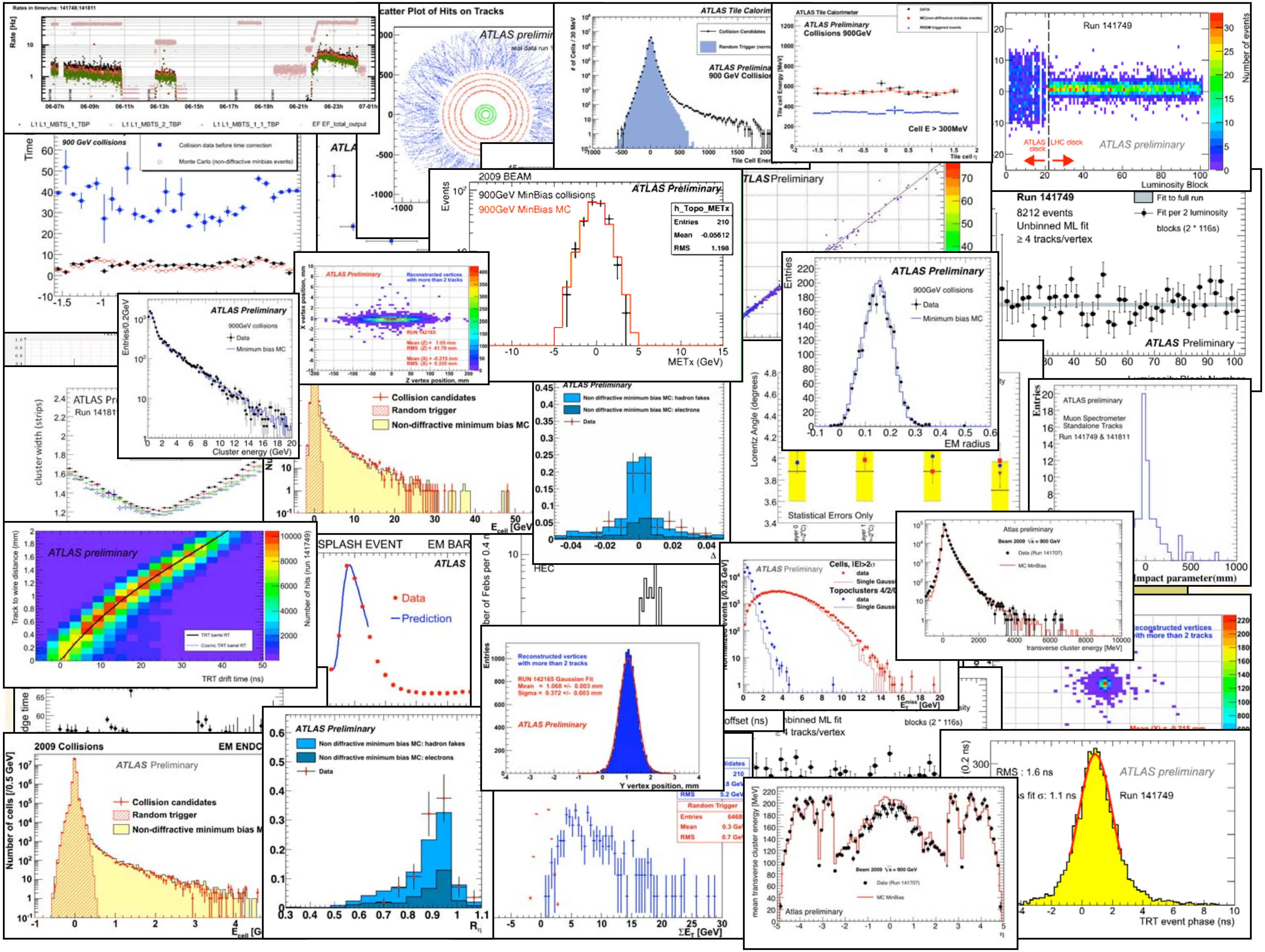
Worldwide data distribution and analysis



- ~ 0.2 PB of data stored since 20th November
- ~ 8h between Data Acquisition at the pit and data arrival at Tier2 (including reconstruction atTier0)
- increasing usage of the Grid for analysis

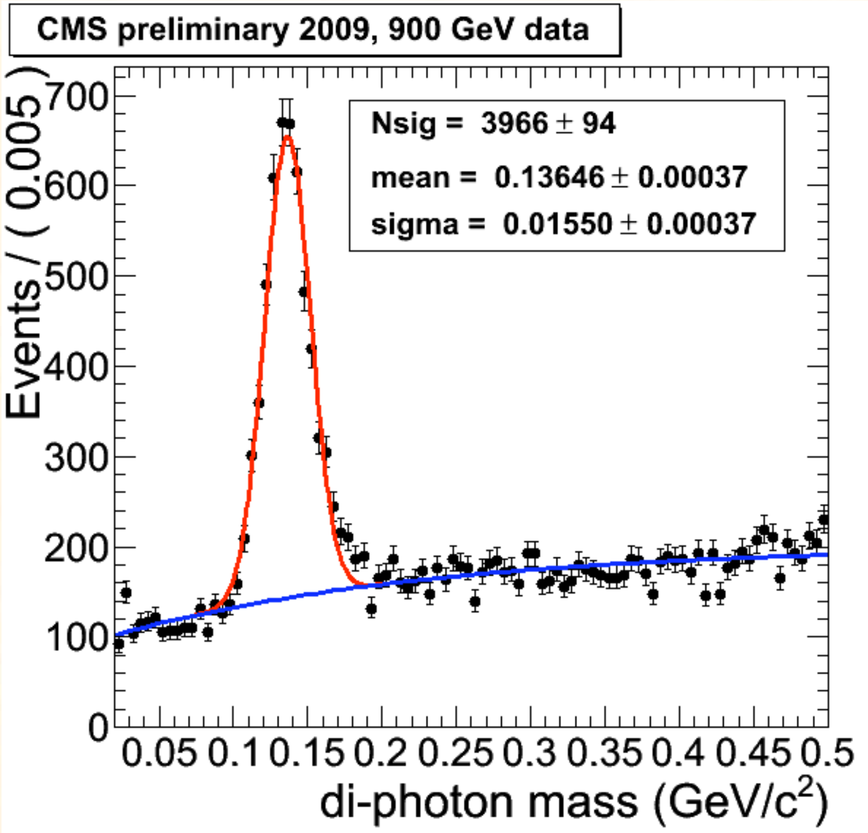
WLCG

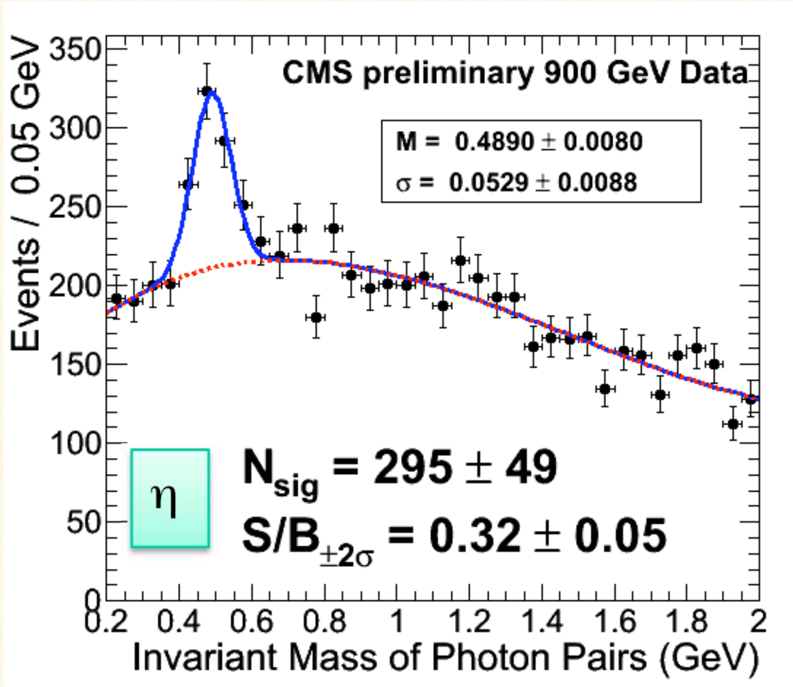
A lot of analysis activity started immediately ....



Rates in timeruns: 141748:141811
Rate [Hz]
L1 L1_MBTS_1_TBP
L1 L1_MBTS_2_TBP
L1 L1_MBTS_1_1_TBP
EF EF_total_output
catter Plot of Hits on Tracks
ATLAS prelimi
ATLAS Tile Calorim
Collision Candidates
Random Trigger
ATLAS Preliminary
900 GeV Collision
Tile Cell Ener
ATLAS Tile Calorimeter
ATLAS Preliminary
Collisions 900GeV
Cell E > 300MeV
Tile cell η
Run 141749
ATLAS clock
LHC clock
ATLAS preliminary
Luminosity Block
Number of events
900 GeV collisions
Collision data before time correction
Monte Carlo (non-diffractive minbias events)
Time
2009 BEAM
900GeV MinBias collisions
900GeV MinBias MC
ATLAS Preliminary
h_Topo_METx
Entries 210
Mean -0.05612
RMS 1.198
METx (GeV)
Events
Run 141749
8212 events
Unbinned ML fit
≥ 4 tracks/vertex
Fit to full run
Fit per 2 luminosity blocks (2 * 116s)
ATLAS Preliminary
ATLAS Preliminary
Reconstructed vertices with more than 2 tracks
Z vertex position, mm
X vertex position, mm
ATLAS Preliminary
900GeV collisions
Data
Minimum bias MC
Cluster energy (GeV)
Entries/0.2GeV
ATLAS Preliminary
900GeV collisions
Data
Minimum bias MC
EM radius
Entries
Collision candidates
Random trigger
Non-diffractive minimum bias MC
ATLAS Preliminary
Non diffractive minimum bias MC: hadron fakes
Non diffractive minimum bias MC: electrons
Data
Lorentz Angle (degrees)
Statistical Errors Only
ATLAS preliminary
Muon Spectrometer Standalone Tracks
Run 141749 & 141811
Impact parameter(mm)
Entries
cluster width (strips)
ATLAS preliminary
TRT barrel RT
Cosmic TRT barrel RT
TRT drift time (ns)
Track to wire distance (mm)
Number of hits (run 141749)
SPLASH EVENT
EM BAR
ATLAS
Data
Prediction
HEC
Reconstructed vertices with more than 2 tracks
RUN 142165 Gaussian Fit
Mean = 1.068 +/- 0.003 mm
Sigma = 0.372 +/- 0.003 mm
ATLAS Preliminary
Y vertex position, mm
ATLAS Preliminary
Cells, |E|>2σ
data
Single Gauss
Topoclusters 4/2/0
data
Single Gauss
Atlas preliminary
Beam 2009 √s = 900 GeV
Data (Run 141707)
MC MinBias
transverse cluster energy [MeV]
2009 Collisions
EM ENDC
ATLAS Preliminary
Collision candidates
Random trigger
Non-diffractive minimum bias M
Number of cells [/0.5 GeV]
ATLAS Preliminary
Non diffractive minimum bias MC: hadron fakes
Non diffractive minimum bias MC: electrons
Data
Random Trigger
Entries
Mean
RMS
ΣE_T [GeV]
offset (ns)
Unbinned ML fit
≥ 4 tracks/vertex
blocks (2 * 116s)
mean transverse cluster energy [MeV]
Beam 2009 √s = 900 GeV
Data (Run 141707)
MC MinBias
Atlas preliminary
RMS : 1.6 ns
fit σ: 1.1 ns
ATLAS preliminary
Run 141749
TRT event phase (ns)

First Di-photon distributions in CMS



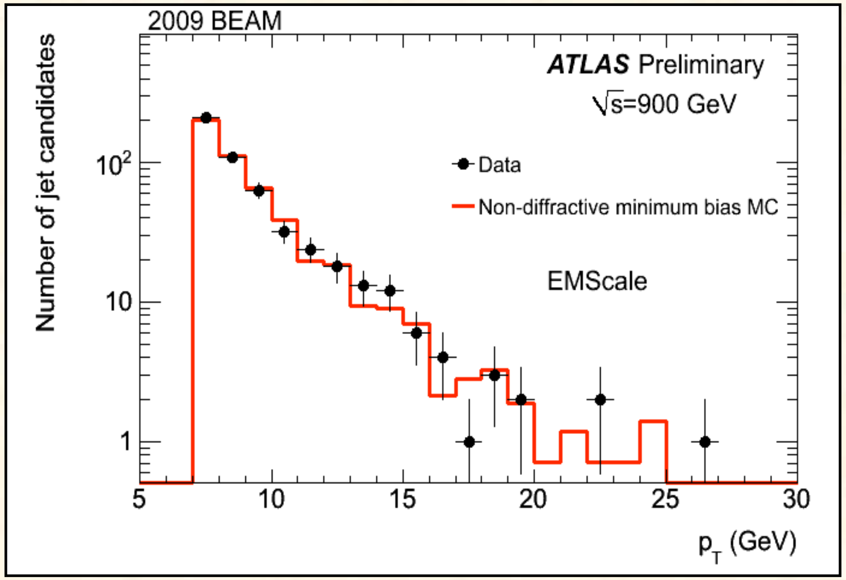


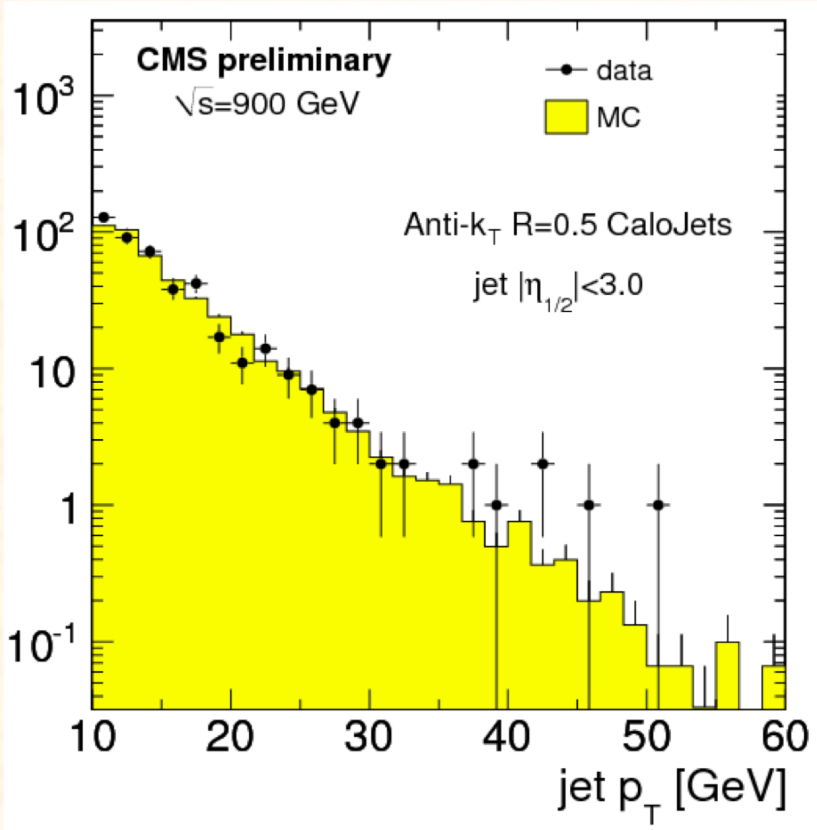
Using "out of the box" corrections

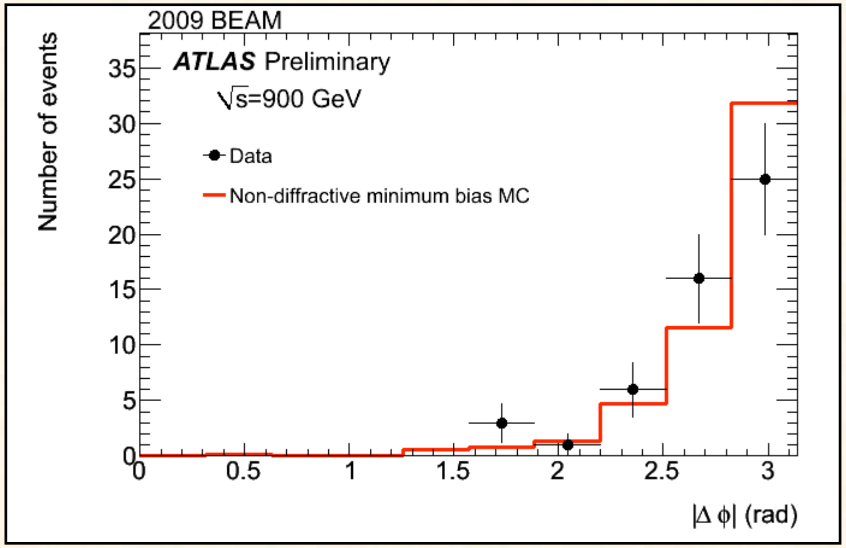
Data: $N(\eta)/N(\pi^0) = 0.020 \pm 0.003$

MC: $N(\eta)/N(\pi^0) = 0.021 \pm 0.003$

First energy distributions / jets in the calorimeters



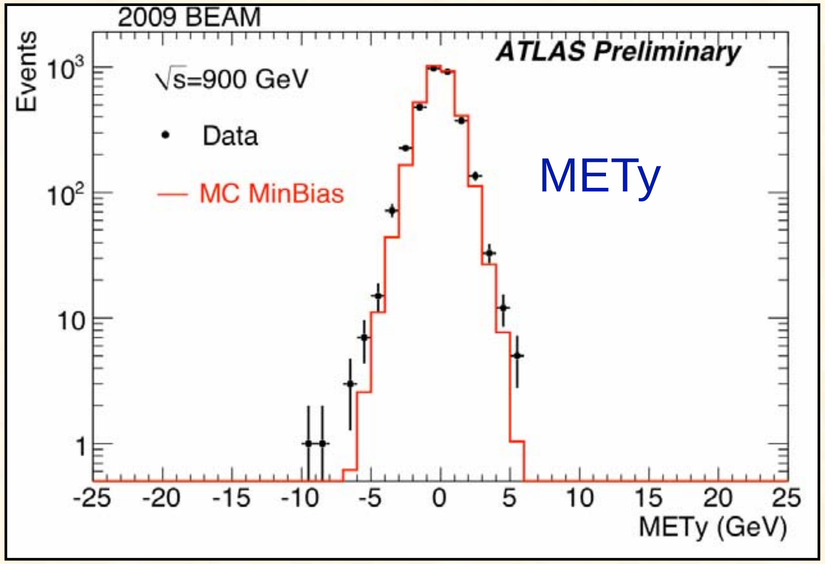




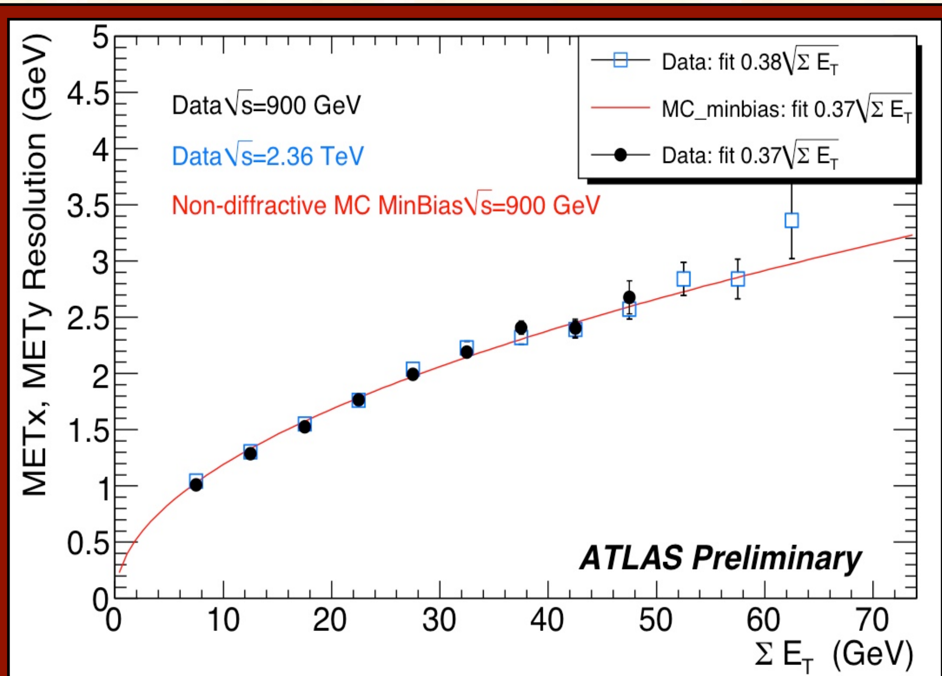
Uncalibrated, EM scale,
Monte Carlo normalized to number of events in data

Missing transverse energy

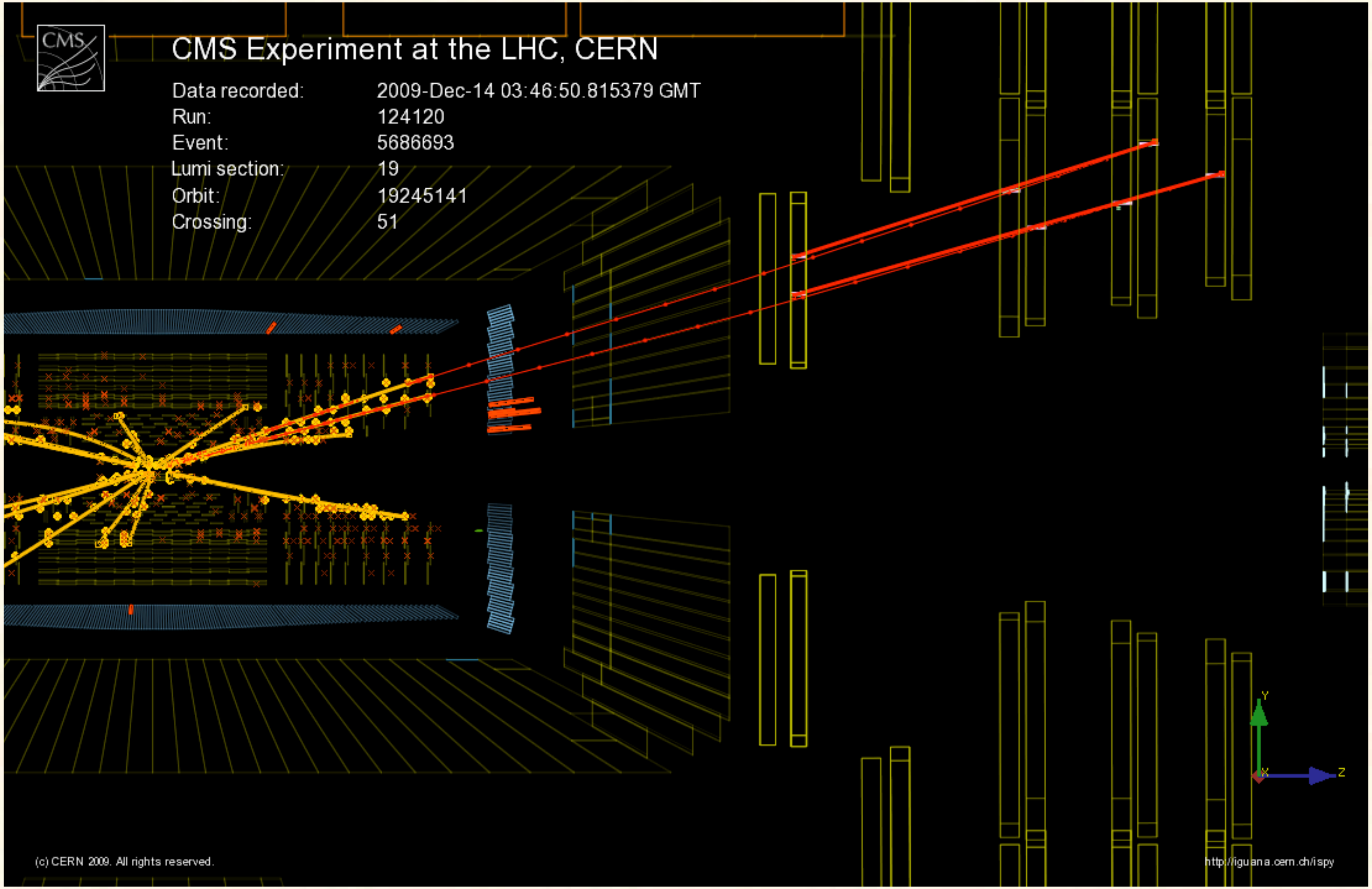
- Sensitive to calorimeter performance (noise, coherent noise, dead cells, mis-calibrations, cracks, etc.) and backgrounds from cosmics, beams, …
- Measurement over full calorimeter coverage (360^0 in φ, |η| < 5, ~ 200000 cells)



METx / METy indicate x/y components of missing E_T vector



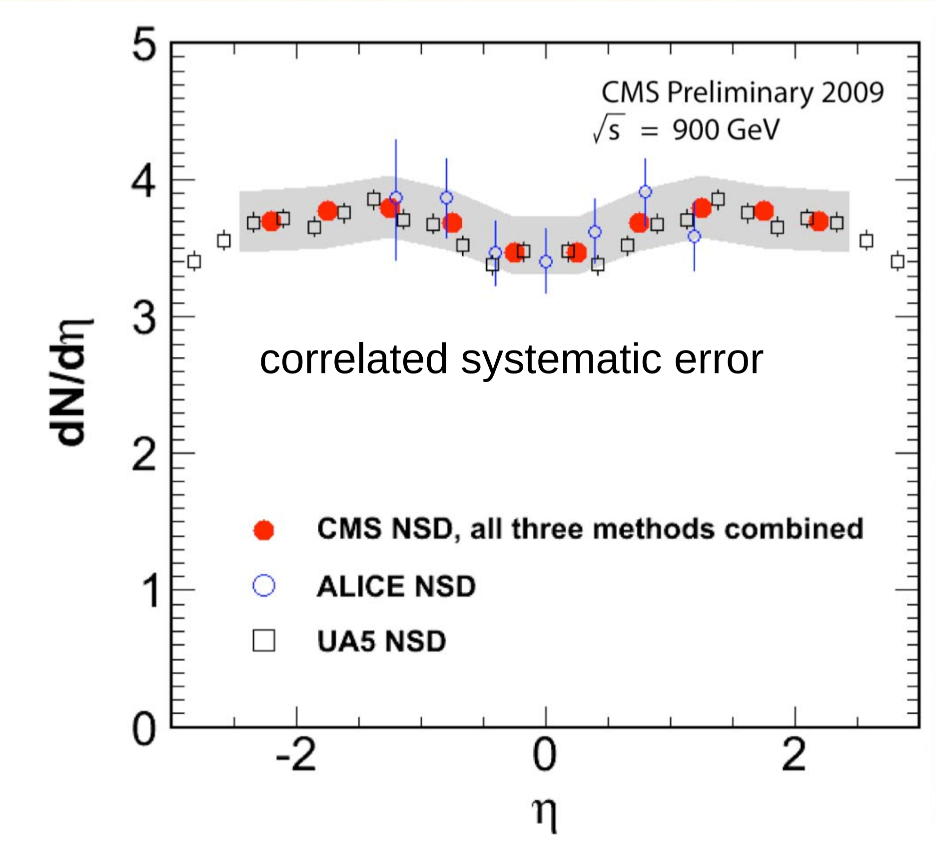
Muons: A Dimuon Event at 2.36 TeV



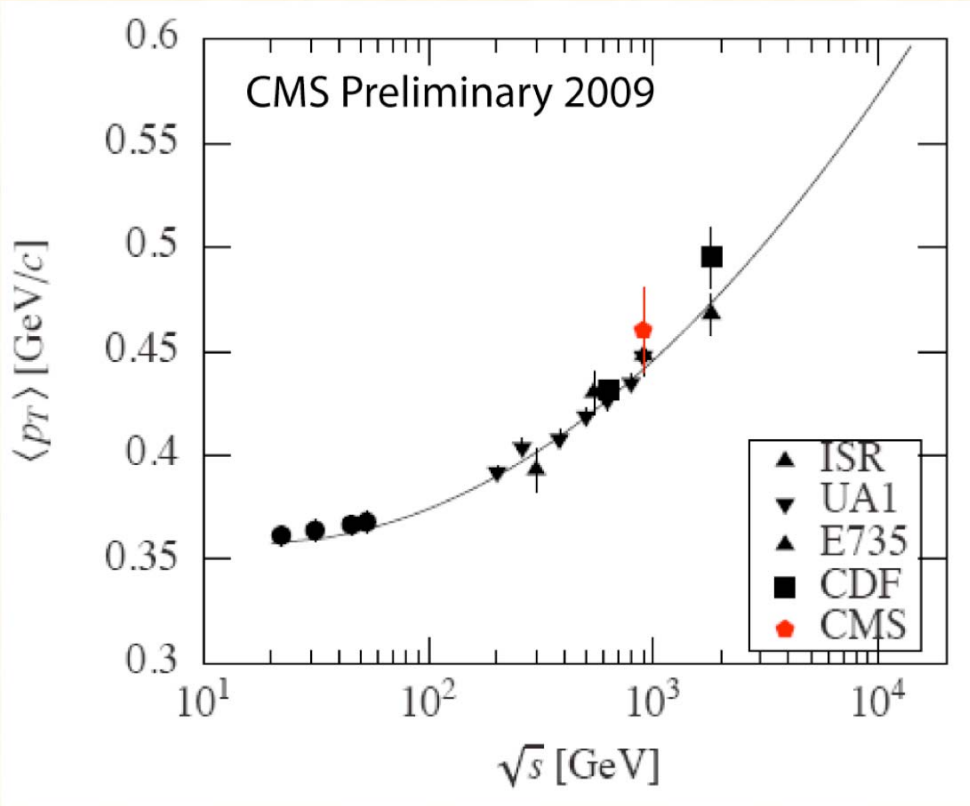
$p_T(\mu_1)$ = 3.6 GeV, $p_T(\mu_2)$ = 2.6 GeV, $m(\mu\mu)$= 3.03 GeV

First Physics Distributions

Charged Particle Multiplicity



Average p_T



Conclusions from the 2009 LHC run

- All experiments have successfully collected first LHC collision data.
- They operated efficiently and fast, from data taking at the pit, to data transfer worldwide, to the production of first results
(on a very short time scale … few days).
- First LHC data indicate that the performance of the detector, simulation and reconstruction (including the understanding of material and control of instrumental effects) is far better than expected at this (initial) stage of the experiment.
- Years of test beam activities, increasingly realistic simulations, and commissioning with cosmics to understand and optimize the detector performance and validate the software tools were fundamental to achieve these results.
- The enthusiasm and the team spirit in the collaborations are extraordinary.