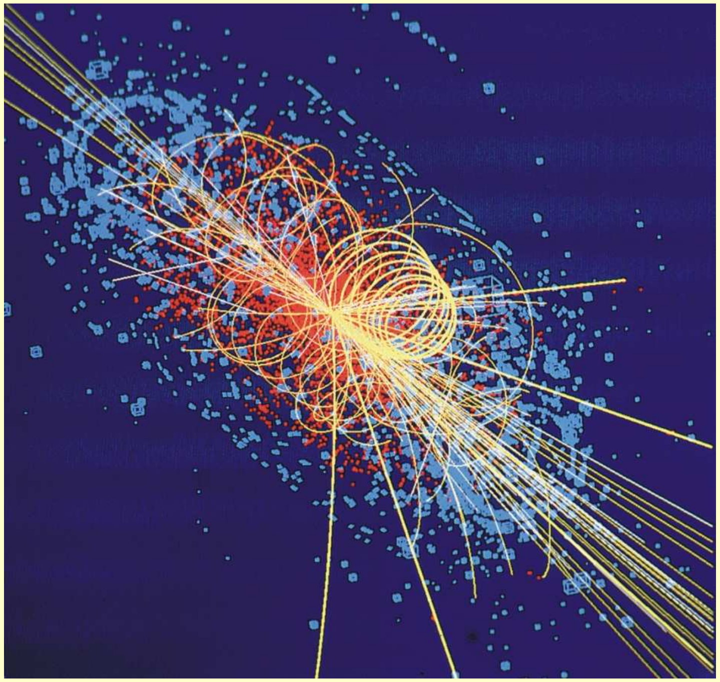
Physics at Hadron Colliders

-From the Tevatron to the LHC-



- **Introduction to Hadron Collider Physics**

- **The present Hadron Colliders**
  - The Tevatron and the LHC
  - The experiments
  - Experimental issues (particle ID, ….)

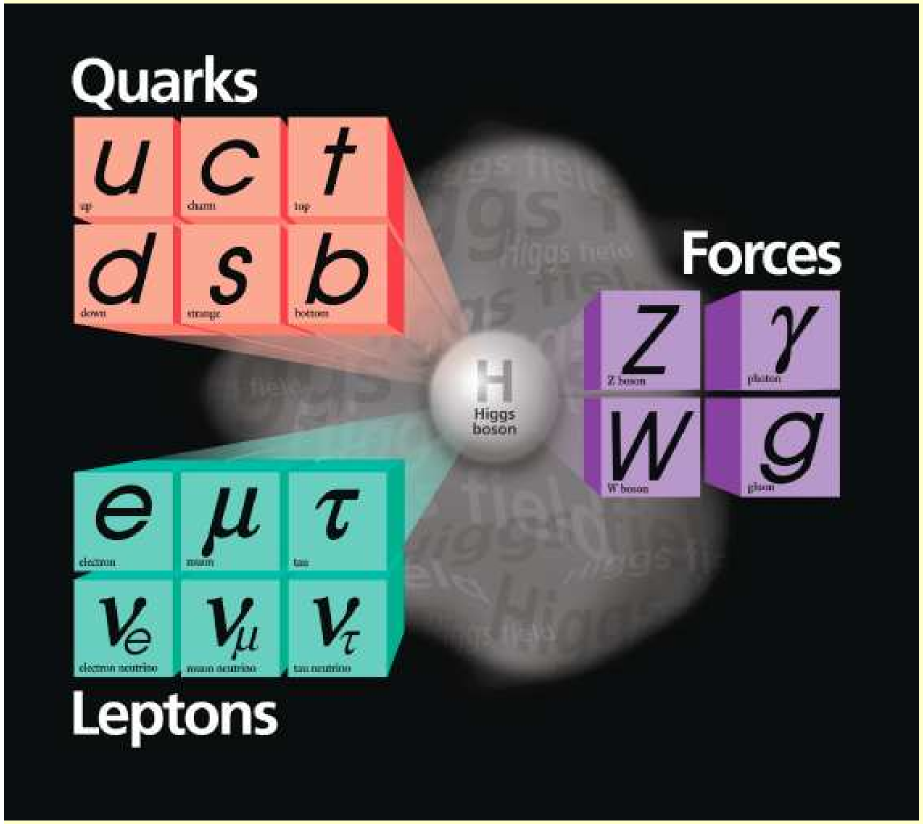
- **Test of the Standard Model**
  - QCD: Jet, W/Z, top-quark production
  - W and top-quark mass measurements

- **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

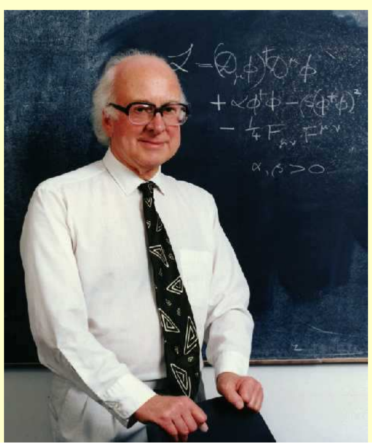
Theoretical arguments: $m_H < \sim 1000$ GeV/c^2

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
$m_H < 160$ GeV/c^2 or $m_H > 170$ GeV/c^2



Only unambiguous example of observed Higgs

(P. Higgs, Univ. Edinburgh)

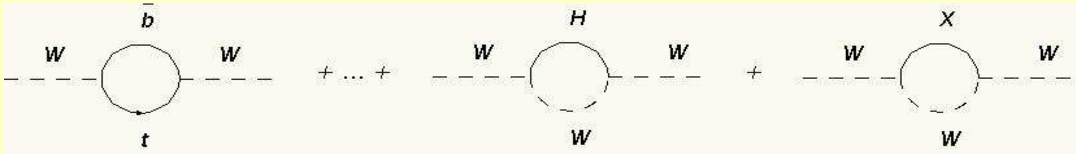
Summer 2009

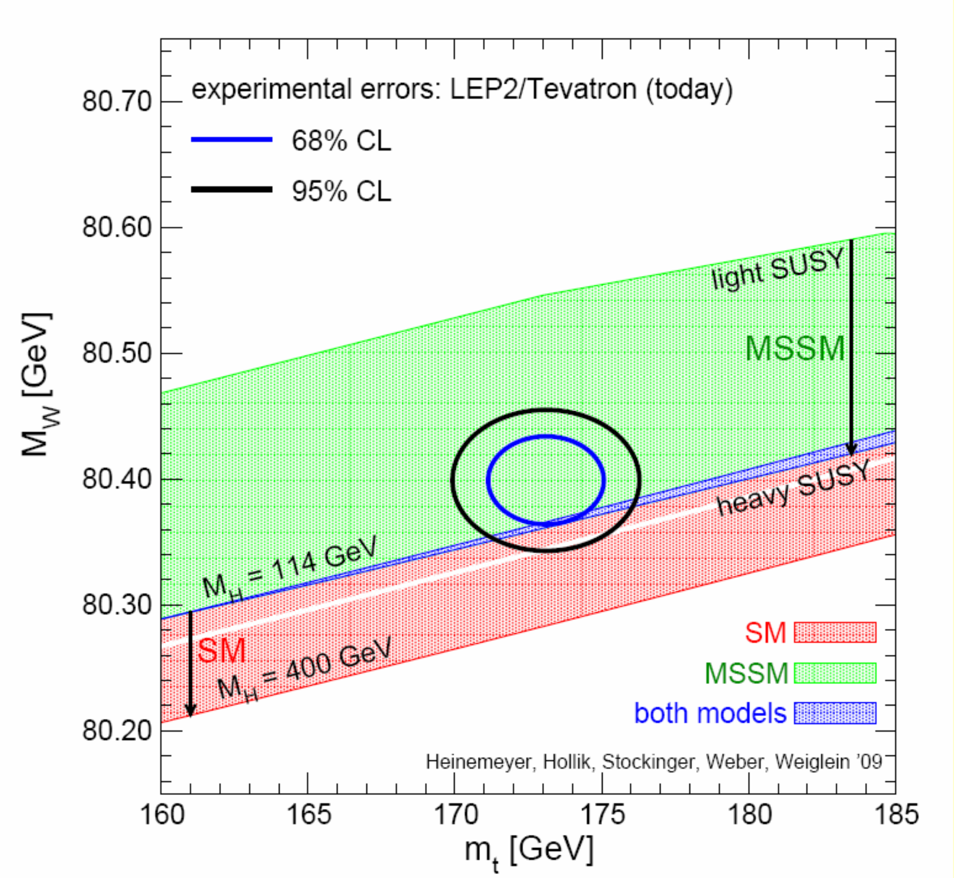
	Measurement	Fit	$\lvert O^{meas}-O^{fit}\rvert/\sigma^{meas}$
$\Delta\alpha^{(5)}_{had}(m_Z)$	0.02758 ± 0.00035	0.02768	
m_Z [GeV]	91.1875 ± 0.0021	91.1874	
Γ_Z [GeV]	2.4952 ± 0.0023	2.4959	
σ^0_{had} [nb]	41.540 ± 0.037	41.478	
R_l	20.767 ± 0.025	20.742	
$A^{0,l}_{fb}$	0.01714 ± 0.00095	0.01645	
$A_l(P_\tau)$	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]	2.098 ± 0.048	2.092	
m_t [GeV]	173.1 ± 1.3	173.2	

August 2009

Consistency with the Standard Model

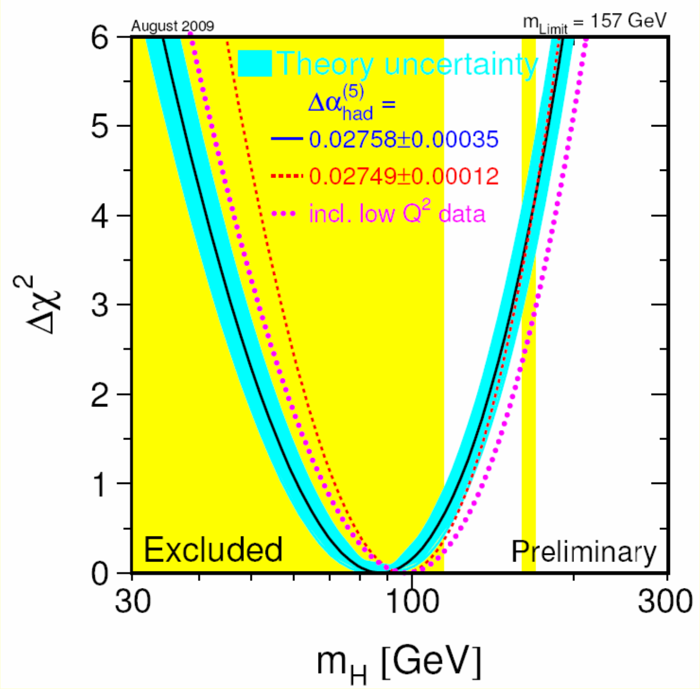
Sensitivity to the Higgs boson and other new particles via quantum corrections:





Interpretation within the Standard Model

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

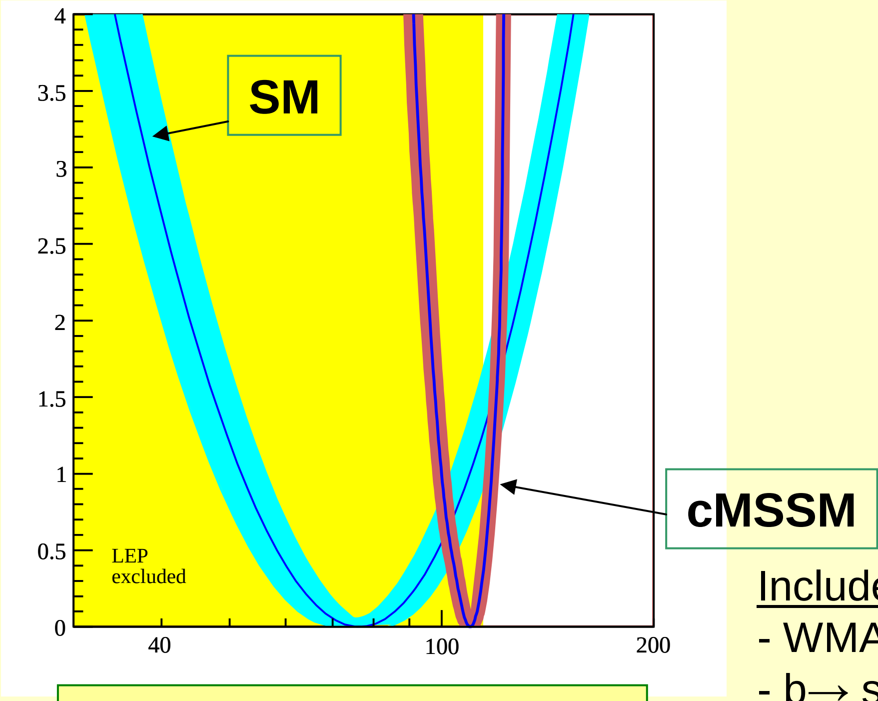


m_H = 87 (+35) (-26) GeV/c^2

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

Constraints on the Higgs mass in a supersymmetric theory

O. Buchmüller et al., arXiv:0707.3447



m_h = 110 (+8) (-10) ± 3 (theo) GeV/c^2

….watch the low mass region !

Includes:
- WMAP
- $b \rightarrow s\gamma$
- a_μ

The role of the present Hadron Colliders

1. Explore the TeV mass scale

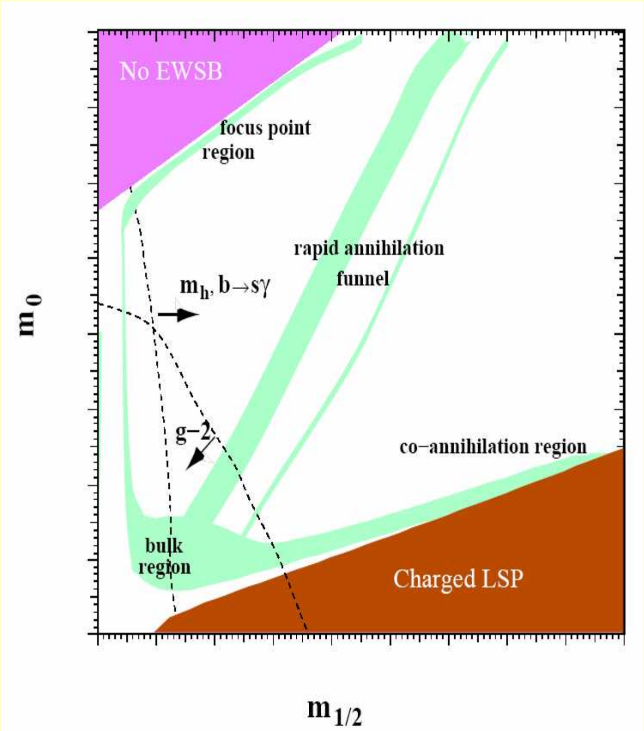
- What is the origin of the electroweak symmetry breaking ?

- 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

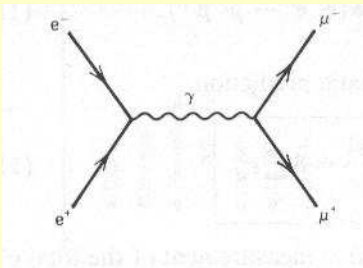
….and they have still not finished

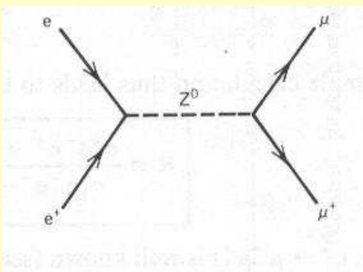
[Hitoshi Murayama]

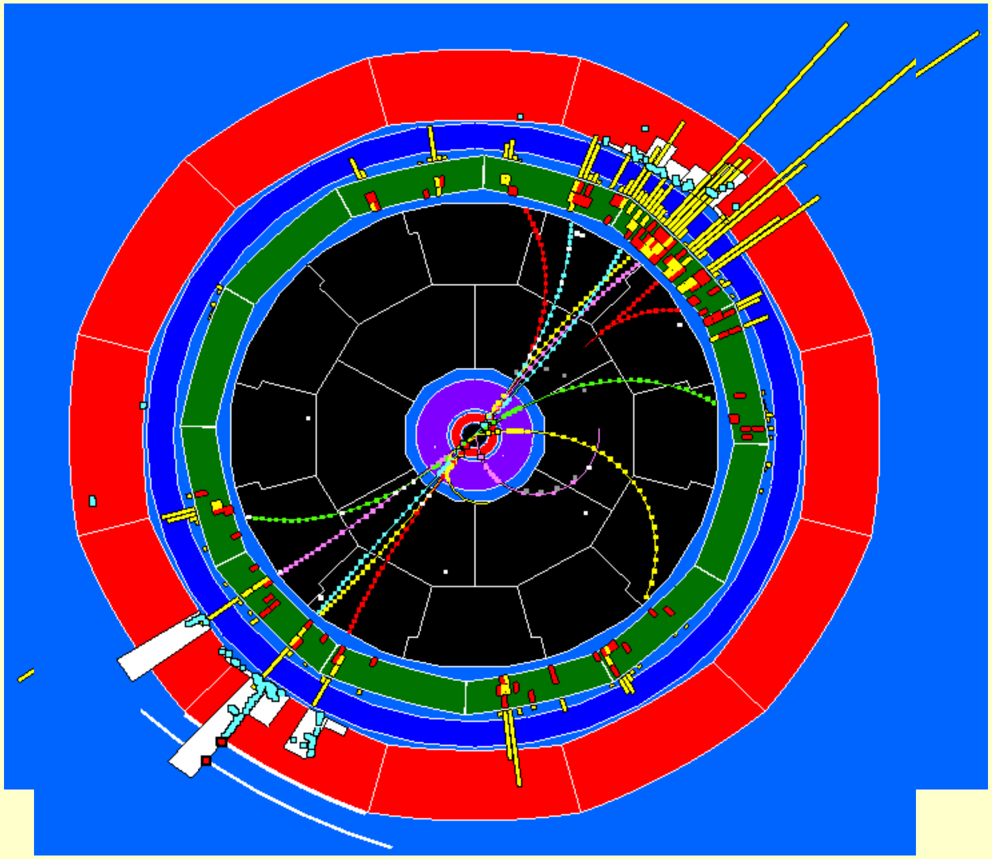
Why a hadron collider ?

e^+e^- colliders are excellent machines for precision physics !!

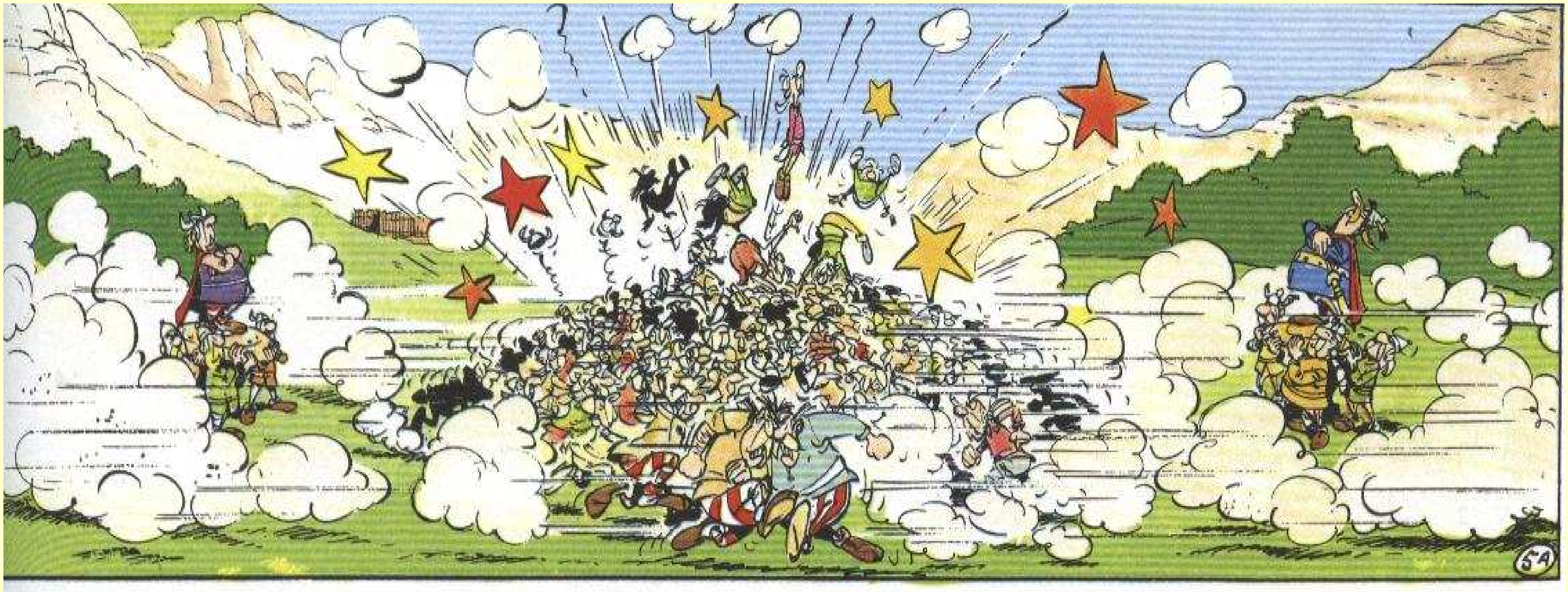
- e^+ e^- are point-like particles, no substructure → clean events
- complete annihilation, centre-of-mass system, kinematic fixed







Proton proton collision are more complex



Main drawbacks of e^+e^- circular accelerators:

1. Energy loss due to synchrotron radiation
   (basic electrodynamics: accelerated charges radiate,
   x-ray production via bremsstrahlung, synchrotron radiation……)

   - Radiated power (synchrotron radiation):
     (ring with radius R and energy E)

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

   - Energy loss per turn:

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

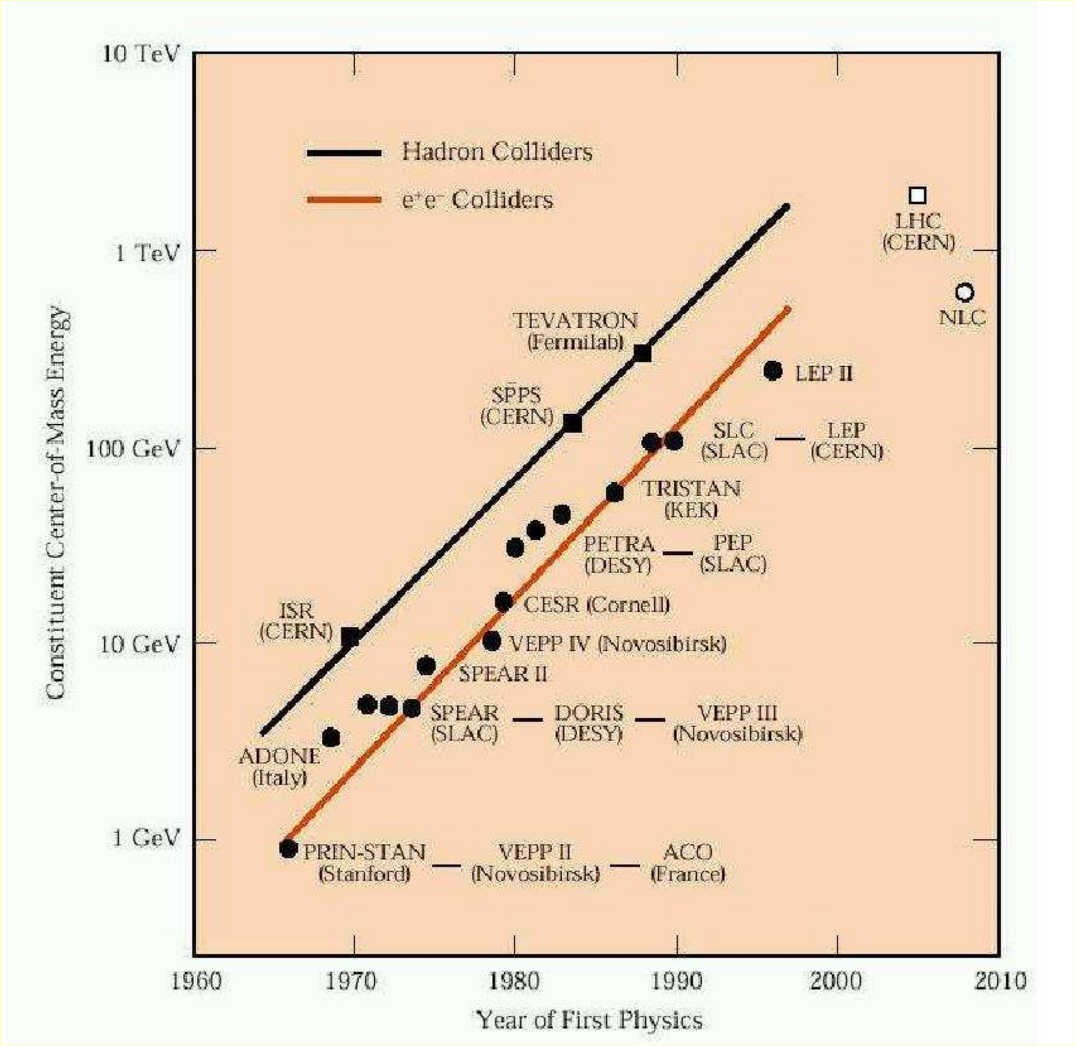
   - Ratio of the energy loss between protons and electrons:

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

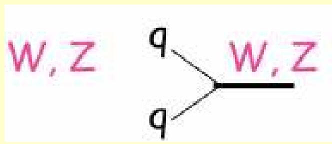
Future accelerators:

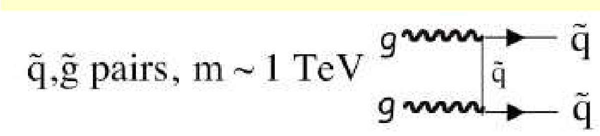
- pp ring accelerators (LHC, using existing LEP tunnel)
- or e^+e^- linear accelerators, International Linear Collider ILC or CLIC (under study / planning)

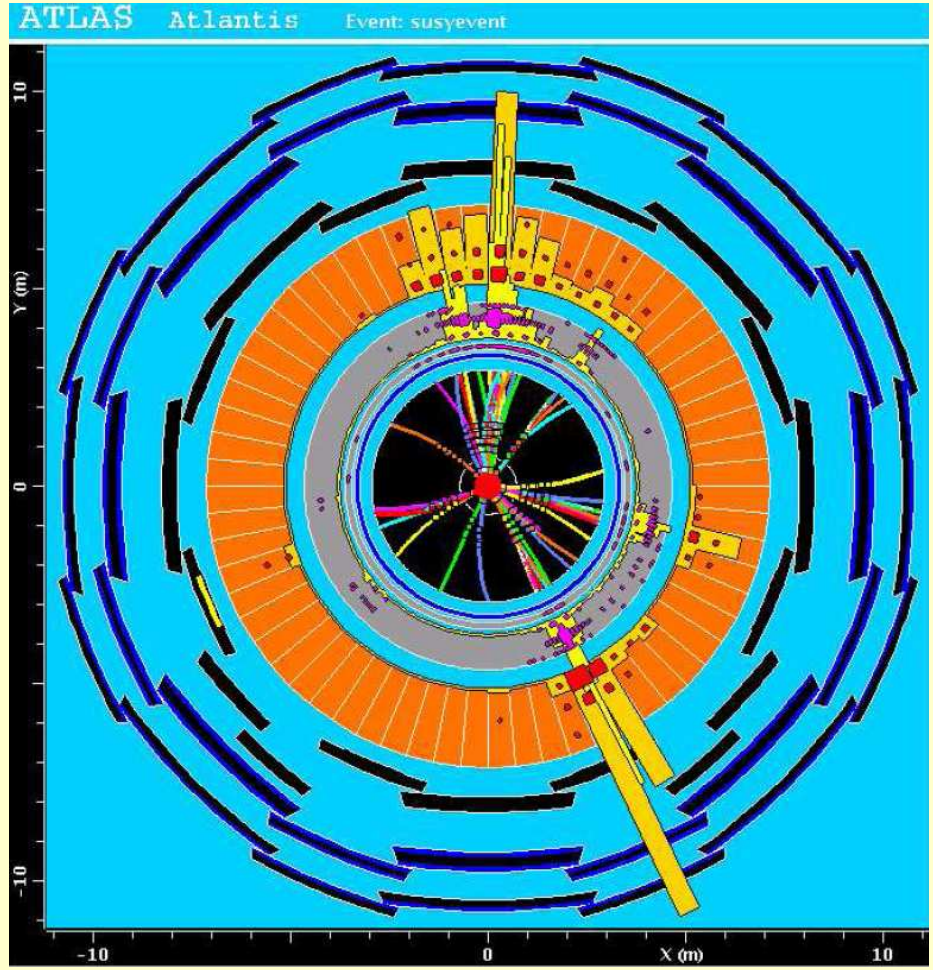
2. Hard kinematic limit for e^+e^- center-of-mass energy from the beam energy: $\sqrt{s} = 2\ E_{beam}$



How can interesting objects be produced?







Quarks and gluons in the initial state

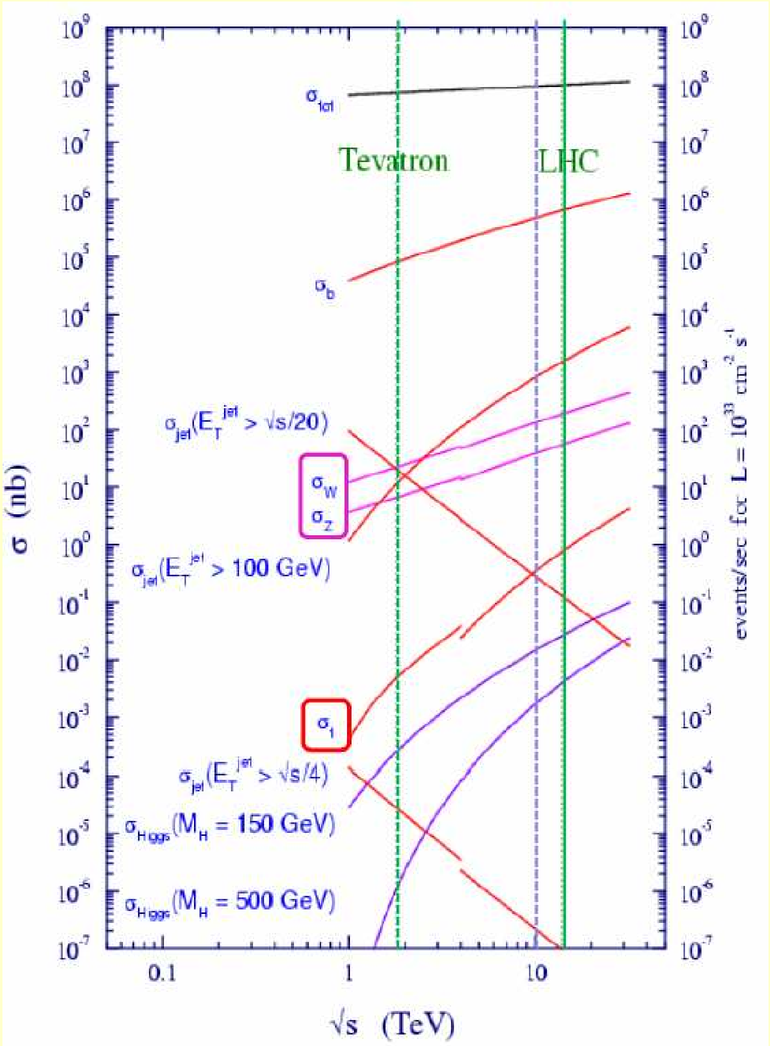
Cross Sections

as a function of √s

Accelerators:

(1) Proton-Antiproton Collider
Tevatron at Fermilab,
$\sqrt{s}$ = 1.96 TeV

(2) Large Hadron Collider (**LHC**)
pp collider at CERN
$\sqrt{s}$ = 7, 10 – 14 TeV



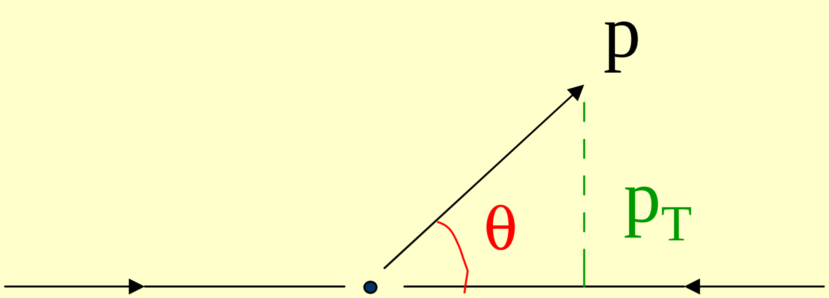
$N_{event} = \sigma \cdot L \cdot \varepsilon$ (efficiency · acceptance)

Physics — *Accelerator* — *Experiment*

(data taking, detector acceptance, reconstruction efficiency, selection cuts, ananlysis,…)

$[s^{-1}] = [cm^2] \cdot [cm^{-2}\, s^{-1}]$

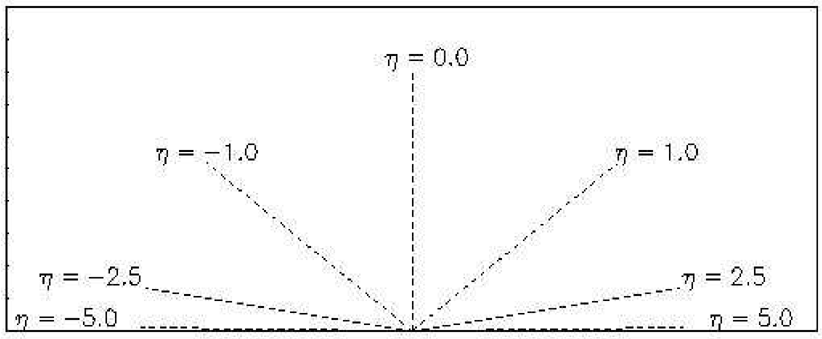
Variables used in the analysis of pp collisions



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]

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

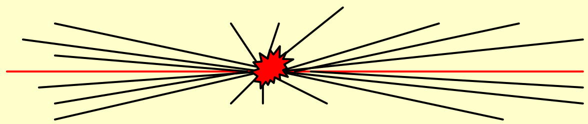
$\theta = 10^o \rightarrow \eta \cong 2.4$
$\theta = 170^o \rightarrow \eta \cong -2.4$

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

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



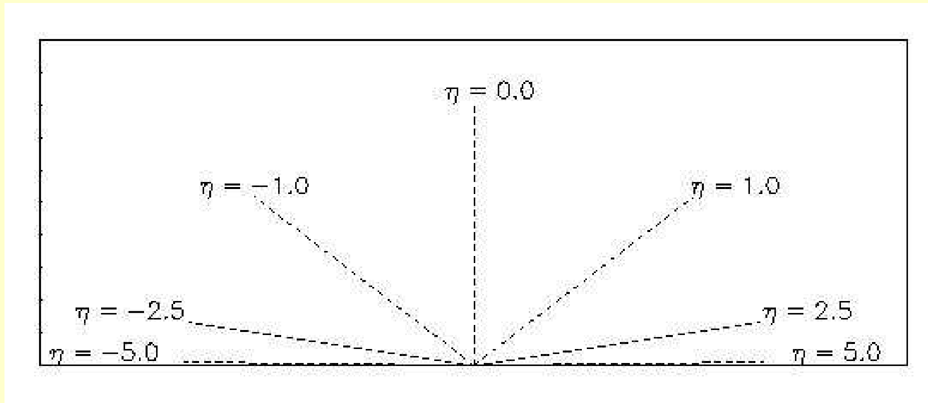
$< p_T > \approx 500\ \mathrm{MeV}$ (of charged particles in the final state)

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

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

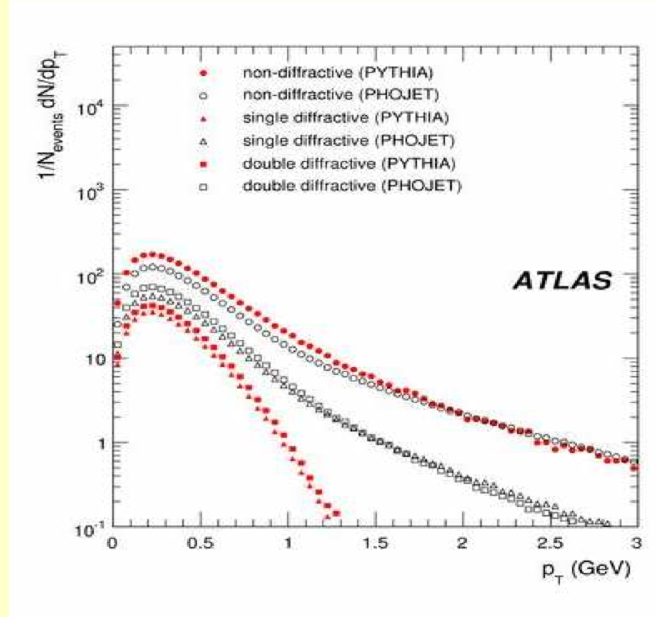
These events are usually referred to as "minimum bias events"

(more precise definition this afternoon)

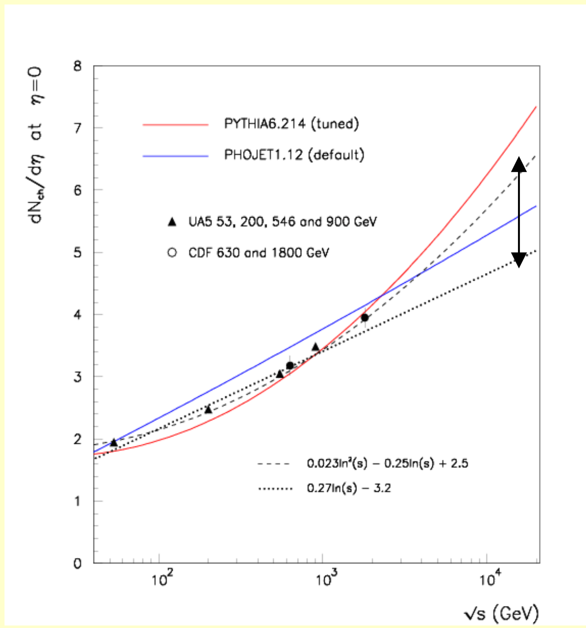


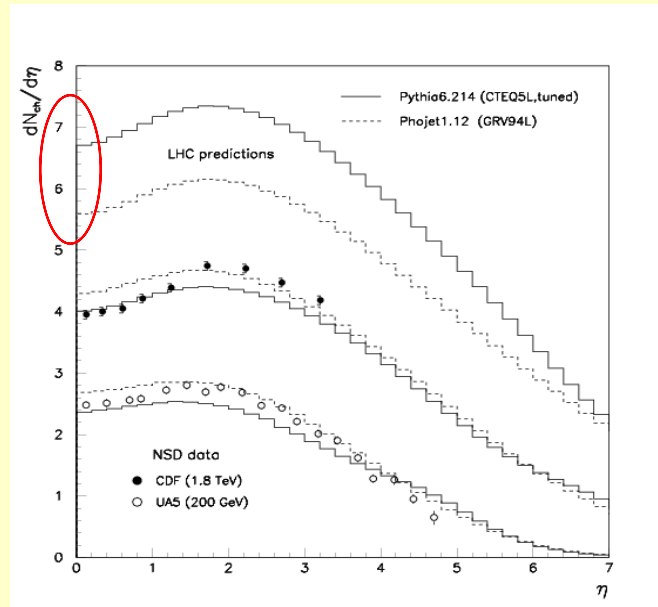
Some features of minimum bias events

- 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,…)



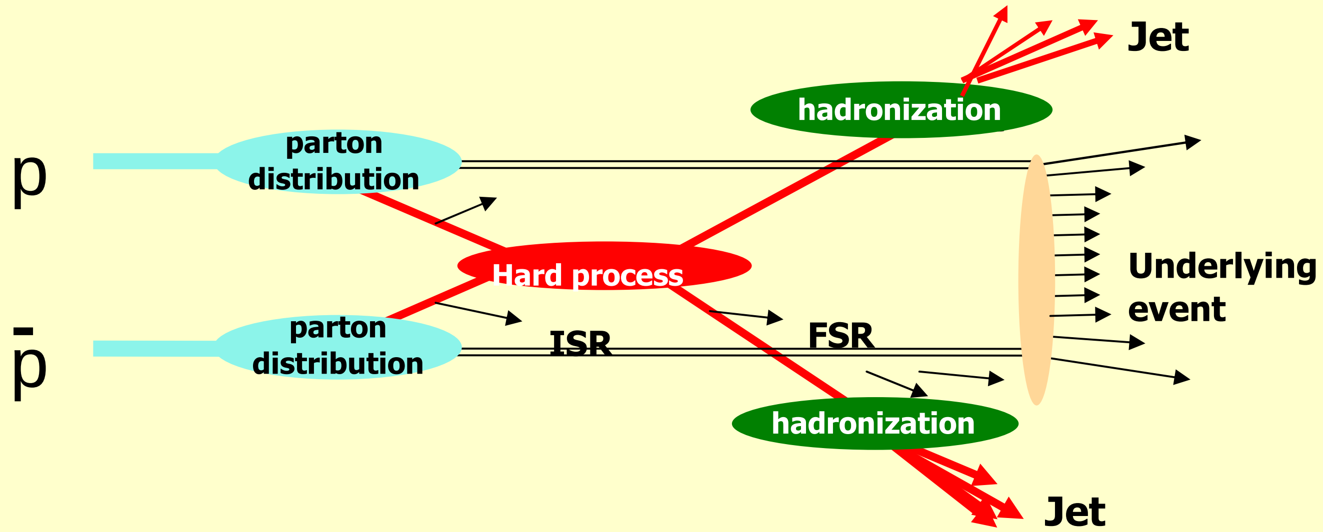
$<p_T>$ (η =0): 550 – 640 MeV (15%)



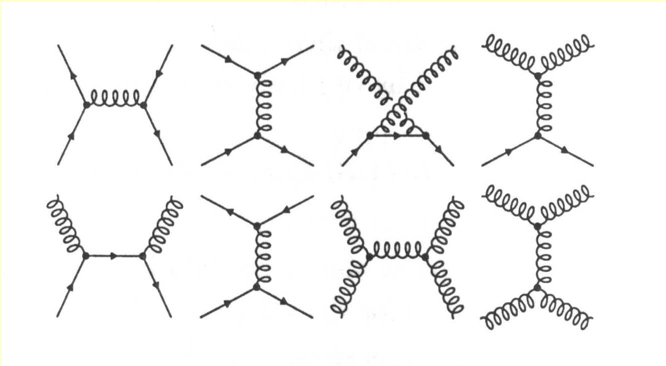


$dN_{ch}/d\eta$ (η=0): 5-7 (~ 33%)

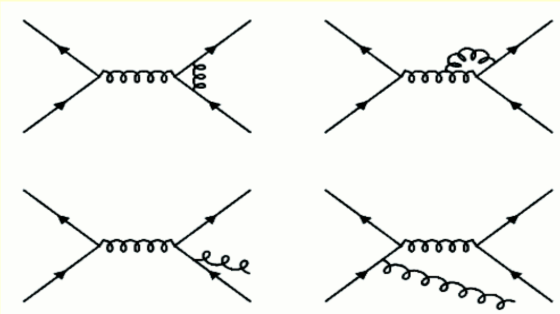
Hard Scattering Processes ….or QCD jet production



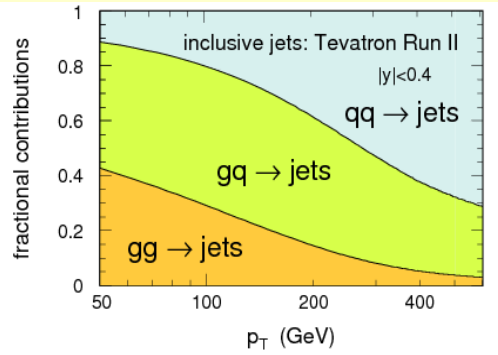
Leading order



…some NLO contributions



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

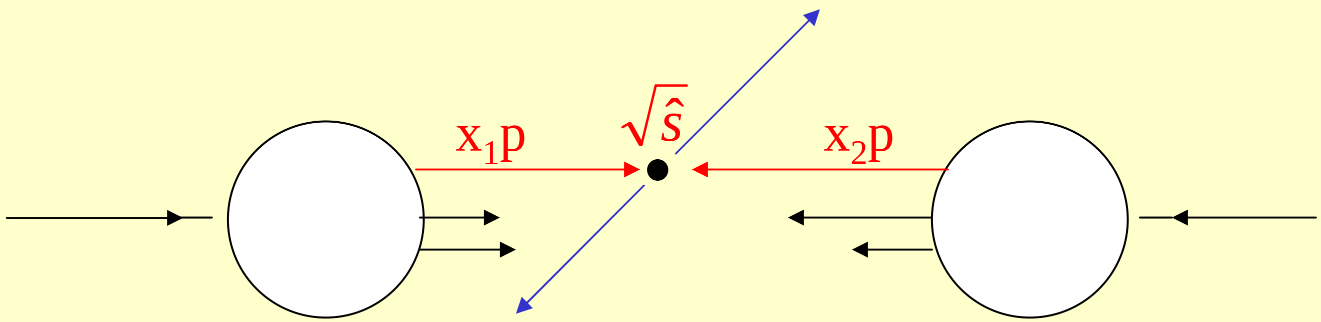


Tevatron,
ppbar, $\sqrt{s}$ = 1.96 TeV,
central region $|\eta| < 0.4$

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

More details on the hard scattering process:

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



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

$$p_1 = x_1 p_A$$

$$p_2 = x_2 p_B$$

$$p_A = p_B = 7 \text{ TeV}$$

$$\sqrt{\hat{s}} = \sqrt{x_1 x_2 s} = x\sqrt{s}$$

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

To produce a mass of:

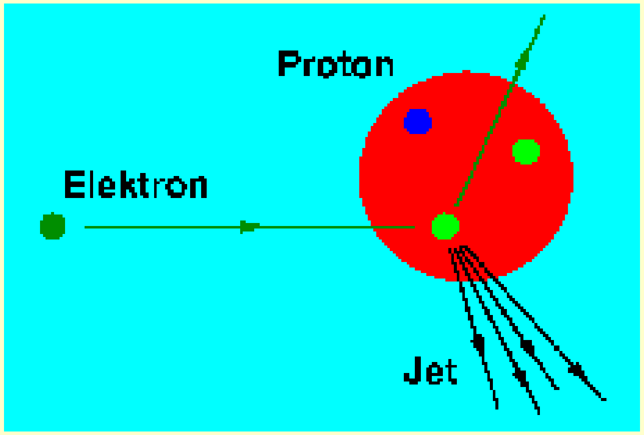
	LHC	Tevatron
100 GeV:	x ~ 0.007	0.05
5 TeV:	x ~ 0.36	--

Where do we know the x-values from?

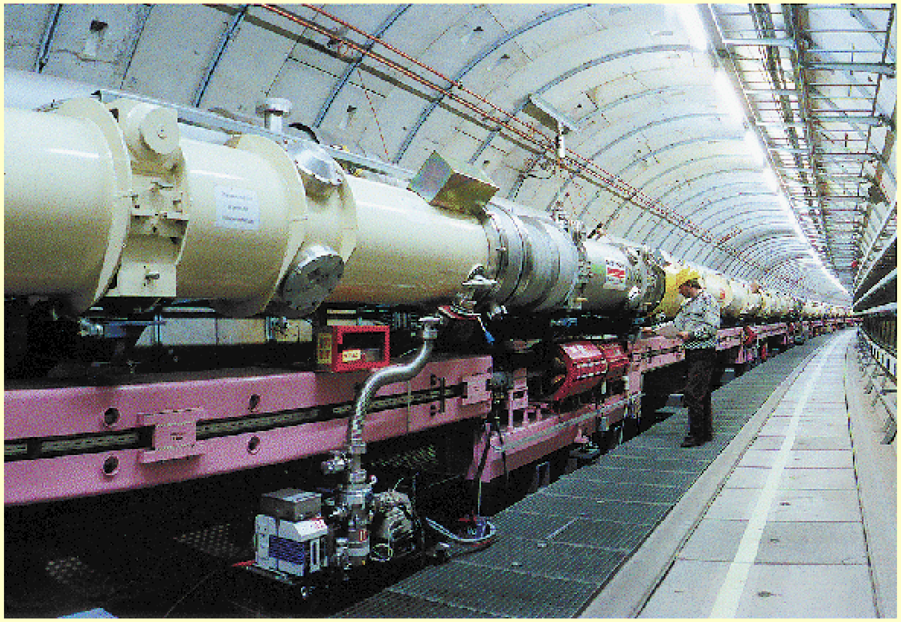
The structure of the proton is investigated in *Deep Inelastic Scattering* experiments:

Highest energy machine was the HERA ep collider at DESY/Hamburg
(stopped operation in June 2007)

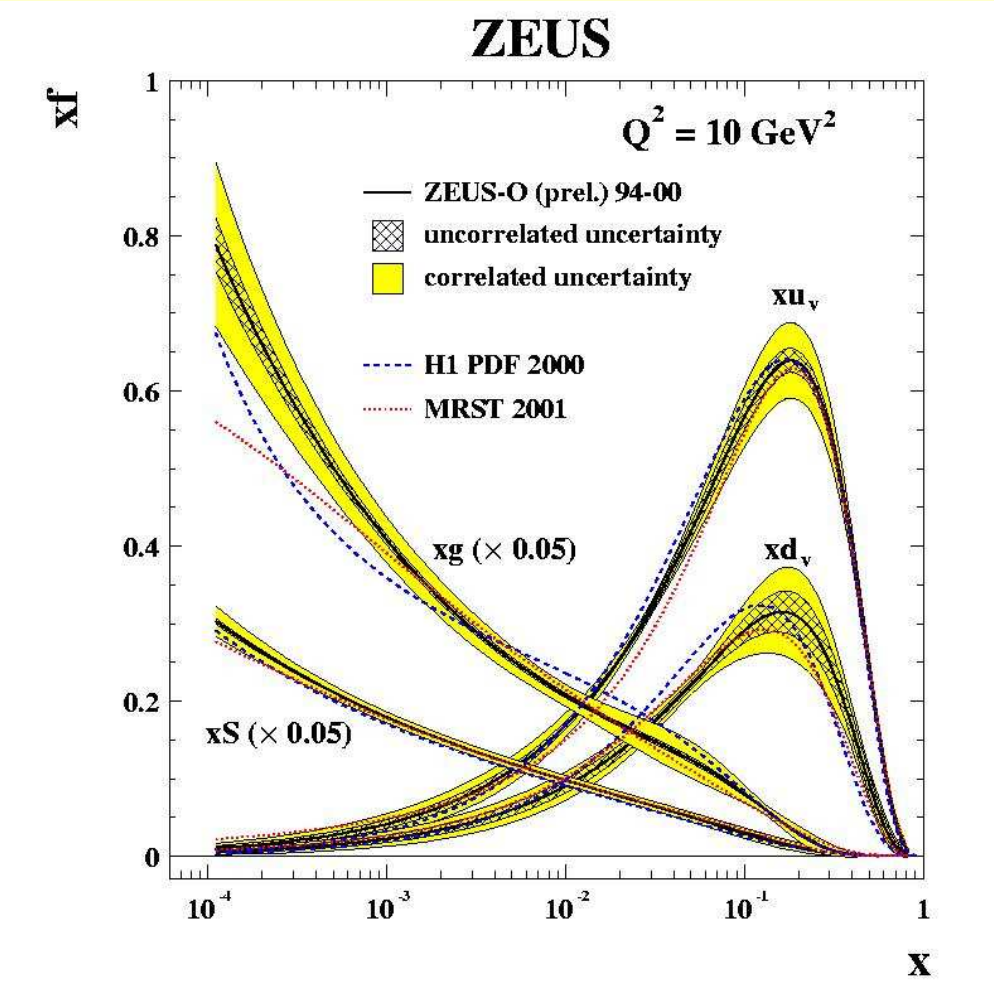
Scattering of 30 GeV electrons on 900 GeV protons:
→ Test of proton structure down to 10^{-18} m

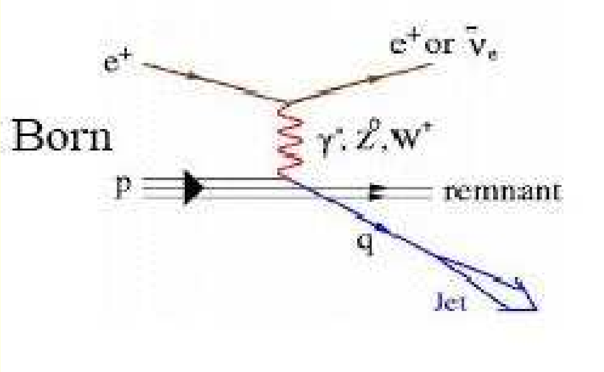


HERA ep accelerator, 6.3 km circumference



How do the x-values of the proton look like?





Parton density functions (pdf):

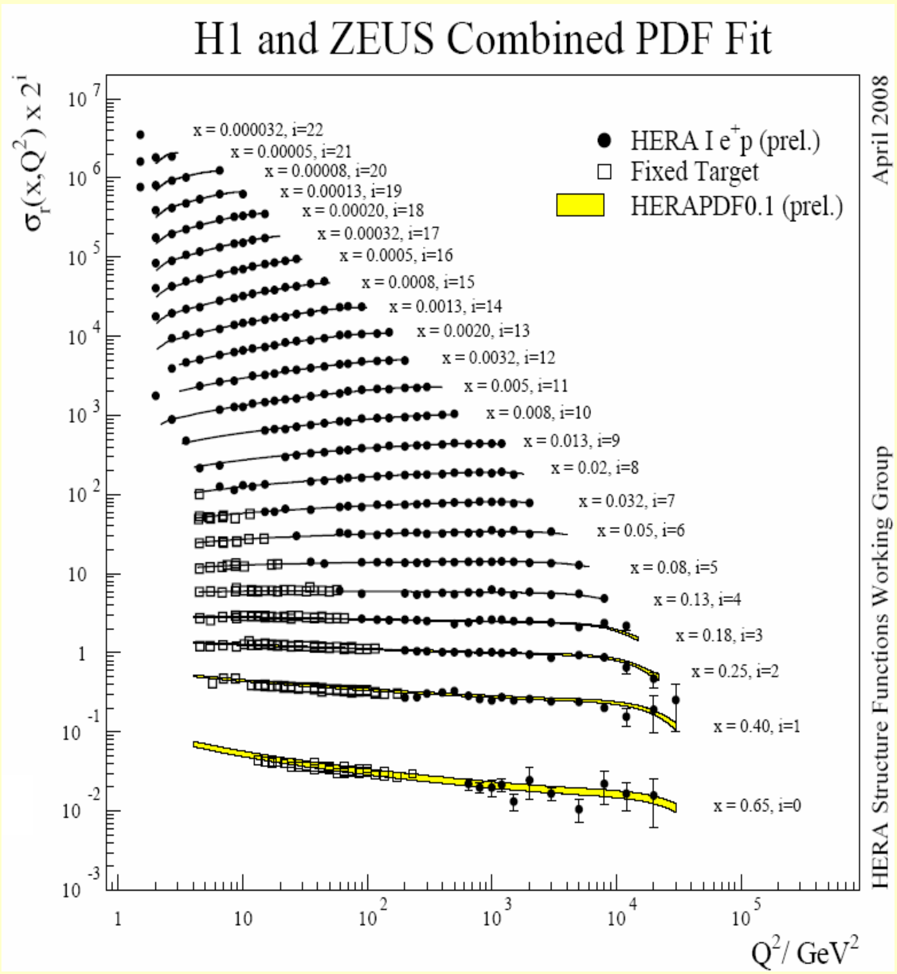
u- and d-quarks at large x-values

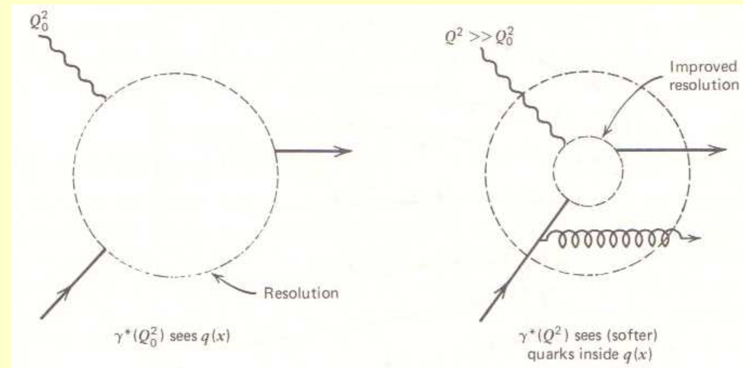
Gluons dominate at small x !!

Uncertainties in the pdfs,
in particular on the gluon distribution
at small x

Parton densities depend on x and momentum transfer (energy scale) Q^2

Impressive results achieved at HERA over the past years;
Measurements of ep scattering cross sections (proton structure function $F_2(x,Q^2)$)



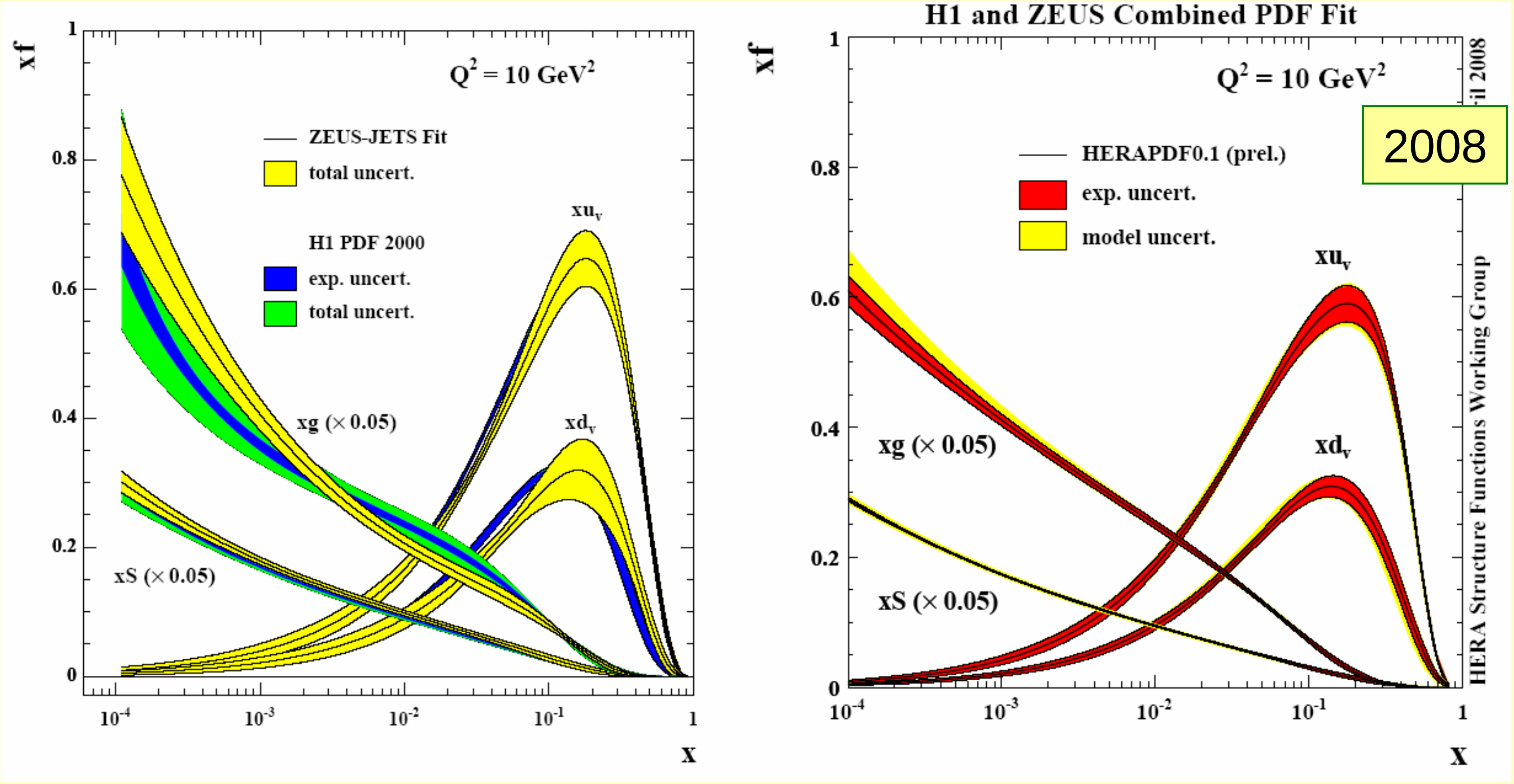


Evolution (Q^2 dependence)
predicted by QCD
(Altarelli-Parisi or DGLAP equation):

$$\frac{d}{d\log Q^2} q(x,Q^2) = \frac{\alpha_s}{2\pi} \int_x^1 \frac{dy}{y} q(y,Q^2)\, P_{qq}\left(\frac{x}{y}\right).$$

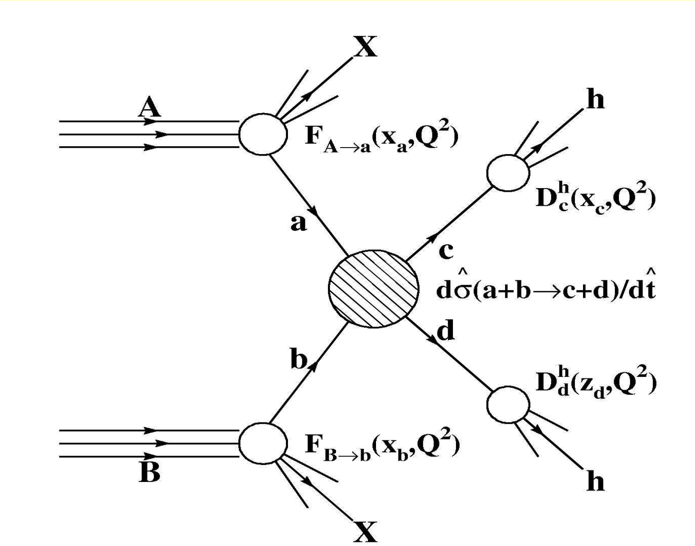
Results from HERA

- 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

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

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

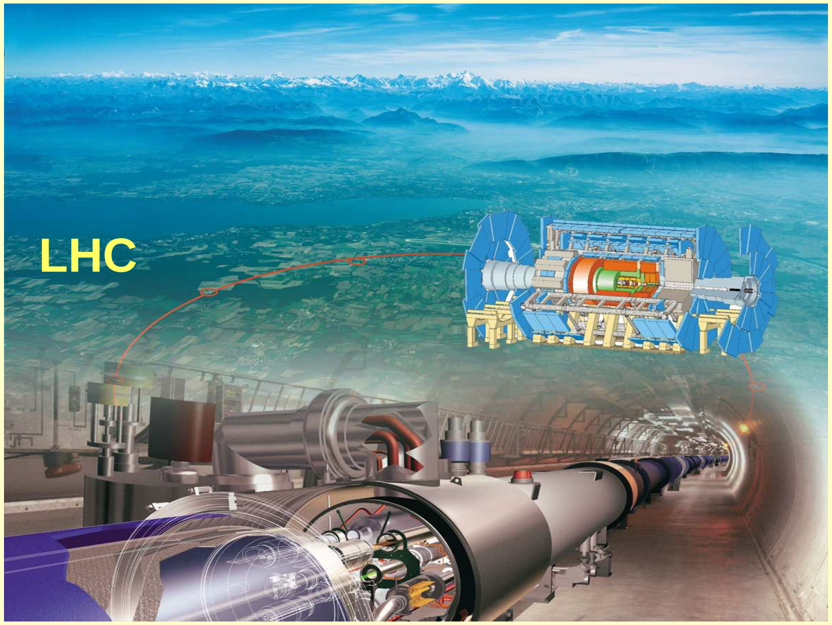
… + higher order QCD corrections (perturbation theory)

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

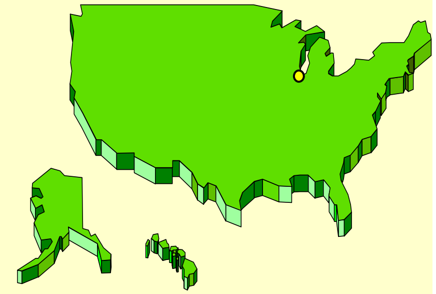
usually introduced as K-factors: $K_{[n]} = \sigma_{[n]} / \sigma_{[LO]}$

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

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)

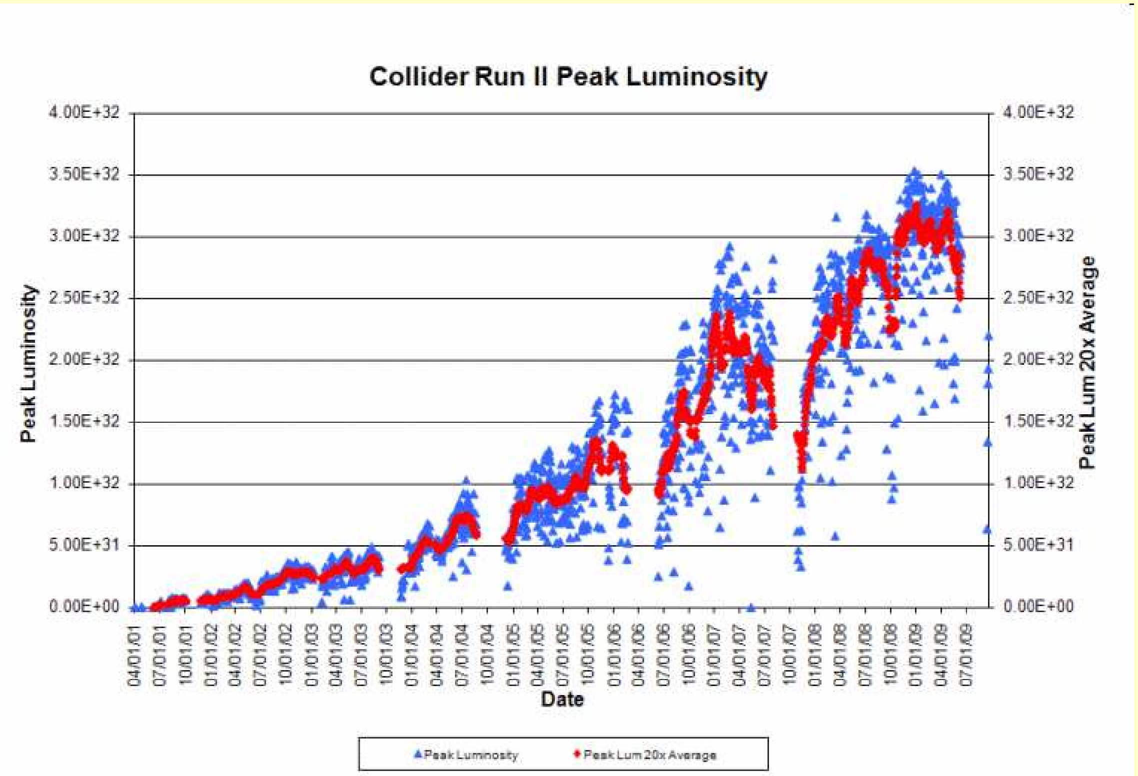
[Run I from 1990 – 1996, int. luminosity: 0.125 fb^{-1}, Top quark discovery]

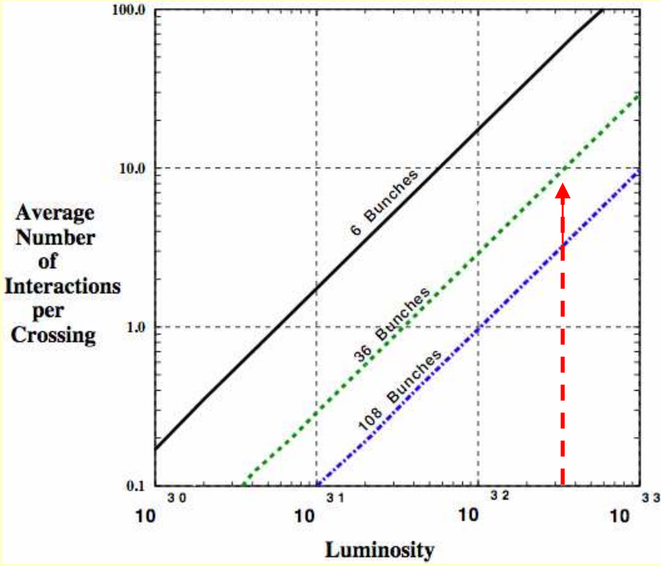
Real Data

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

Tevatron performance

Peak luminosities of the machine as a function of time

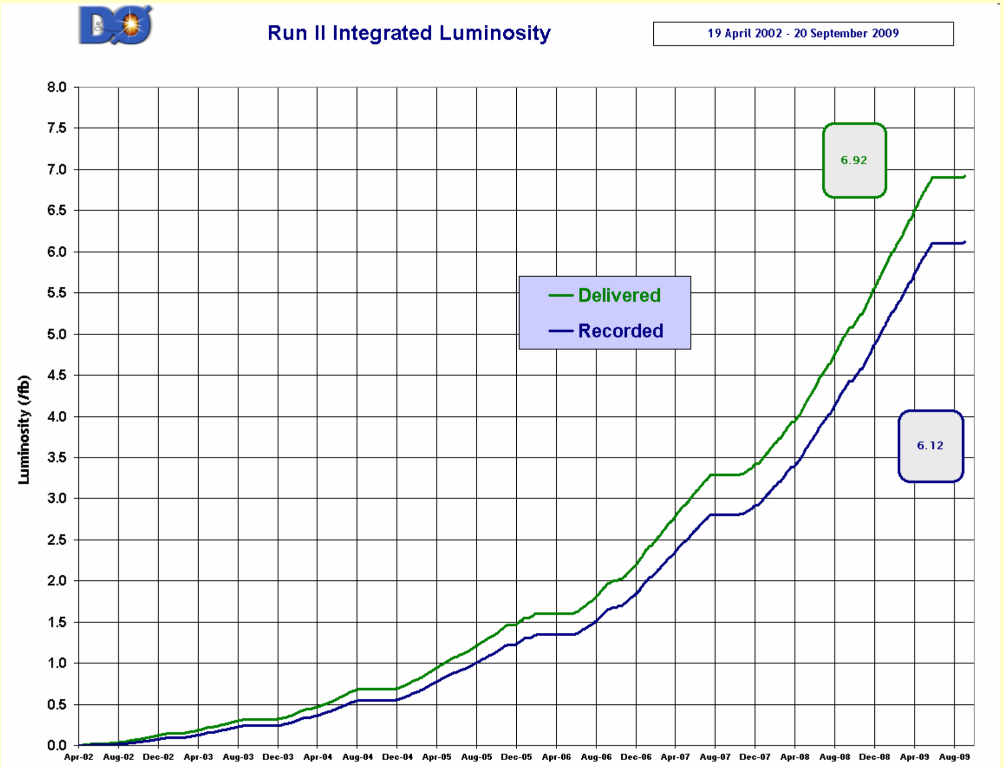


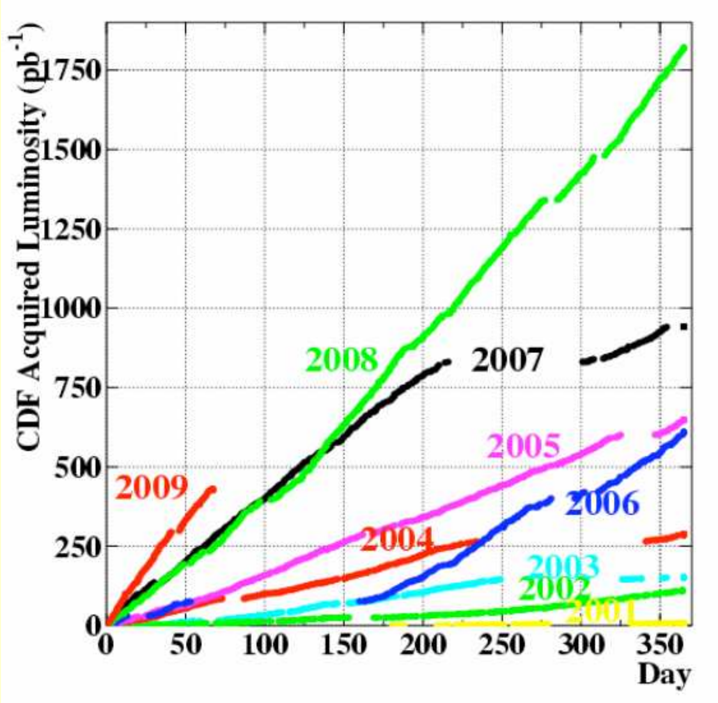


- Peak luminosity of $3.5 \cdot 10^{32}$ cm^{-2} s^{-1}
- Corresponds to ~10 interactions per bunch crossing
  (superposition of minimum bias events on hard collision)

The integrated Tevatron luminosity (until July 2009)

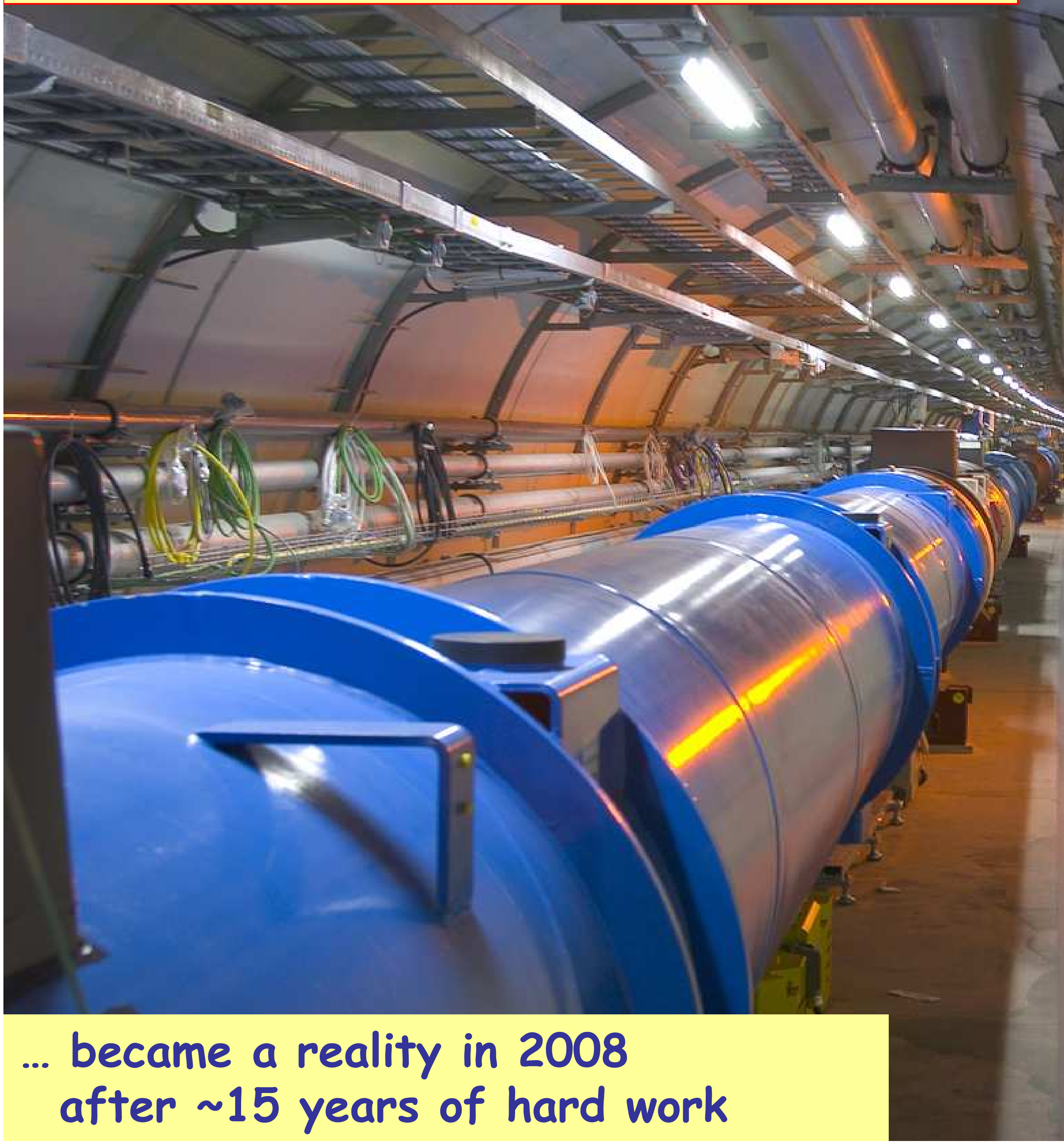
- After a slow start-up (2001 – 2003), the Tevatron accelerator has reached an excellent performance
- Today, Tevatron delivers a data set equal to Run I (~100 pb^{-1}) every 2 weeks
- Integrated luminosity delivered to the experiments so far ~ 6.9 fb^{-1}
- Anticipate an int. luminosity of ~10 fb^{-1} 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 4.8 fb^{-1} analyzed…

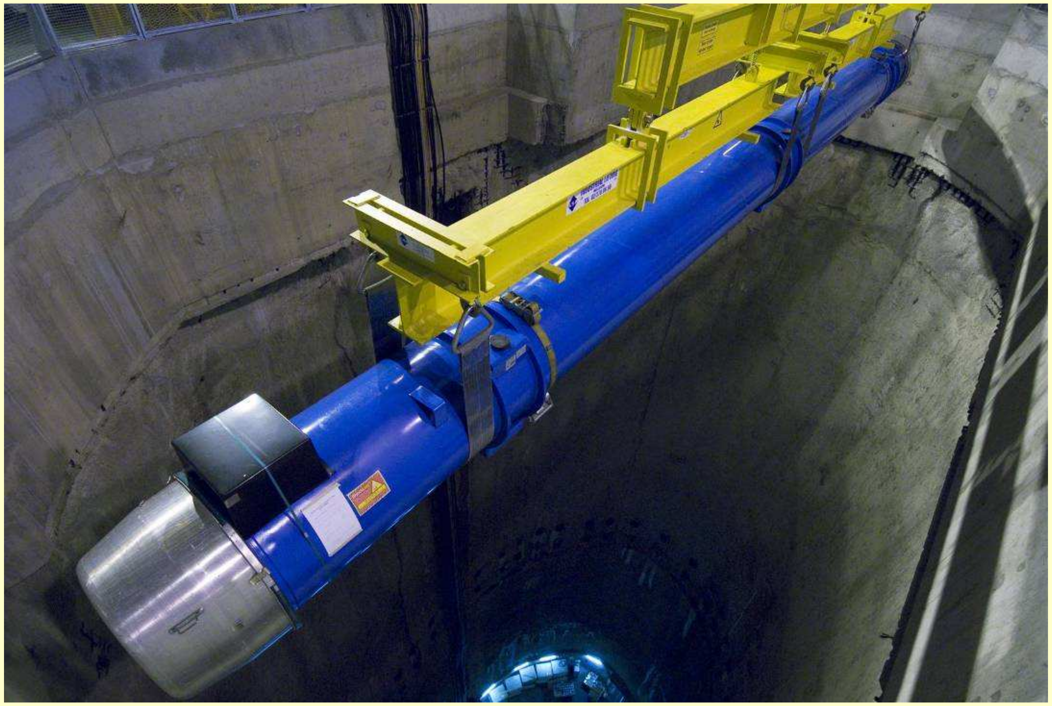
The Large Hadron Collider



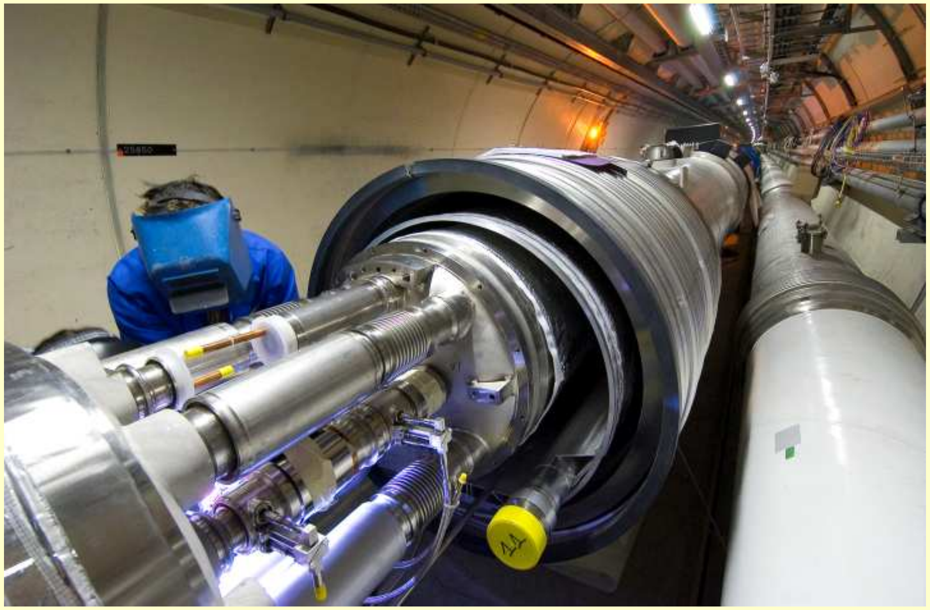
… became a reality in 2008
after ~15 years of hard work

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**

Descent of the last magnet, 26 April 2007

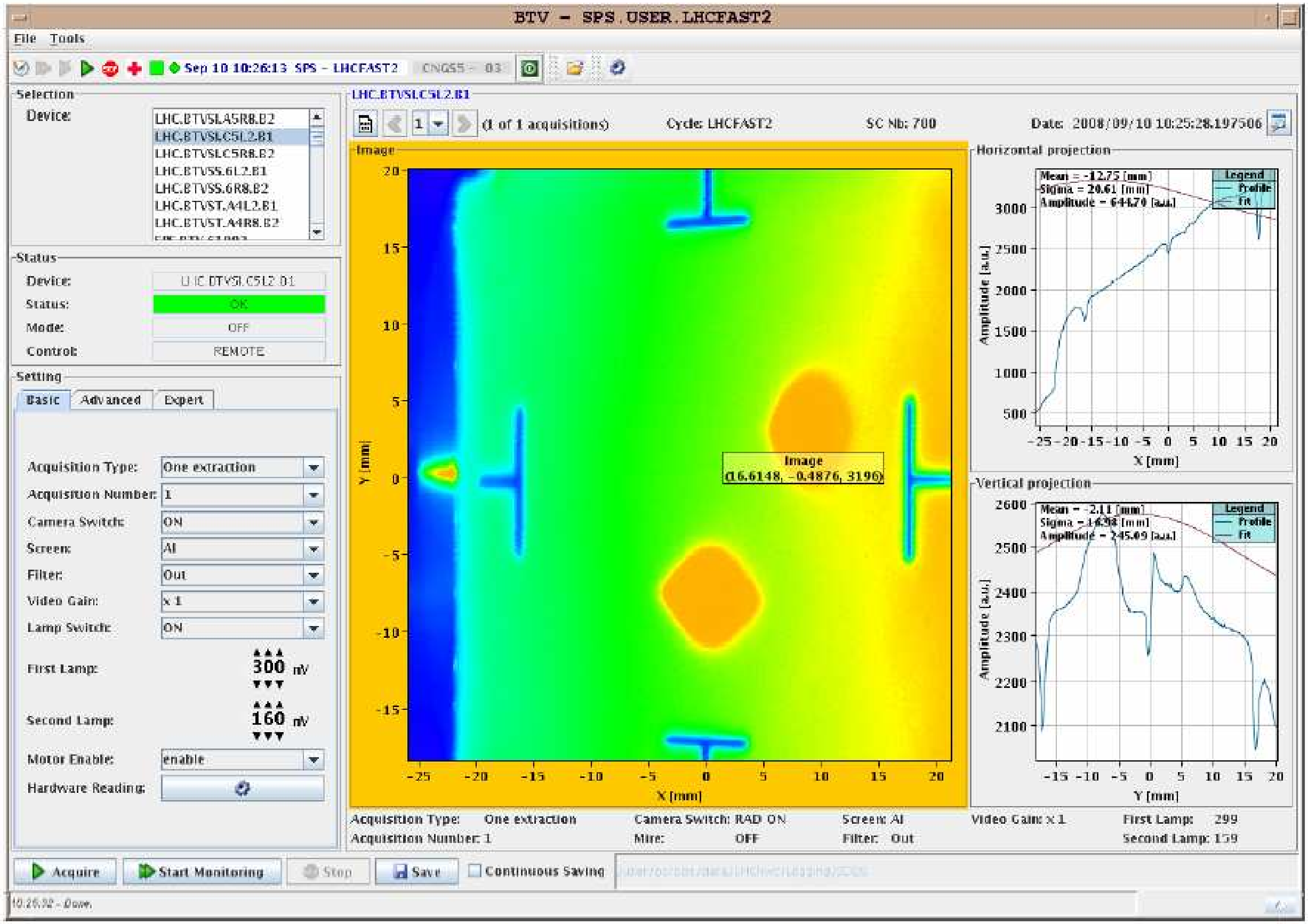


Work on installation, interconnection and testing underground



An excellent start: first beams – September 10, 2008

Beam on turns 1 and 2



After September 10

- Successful continuation of commissioning with beam

  (low intensity, 10^9 protons)

  Sept 11:

  Switched on RF for beam 2 circulating beam for 10 min

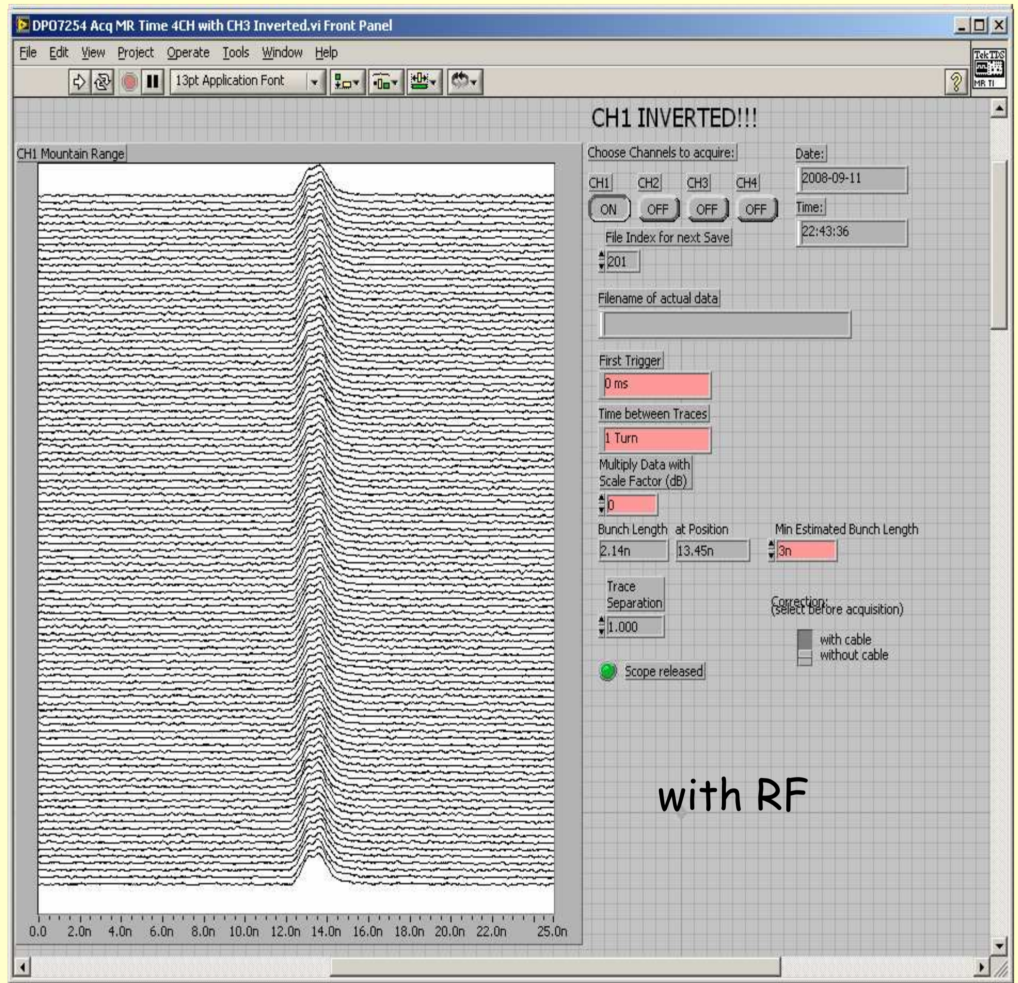
  Many tests (orbit, dump,…)

  Sept 12:

  Measure horizontal beam profile with wire scanner

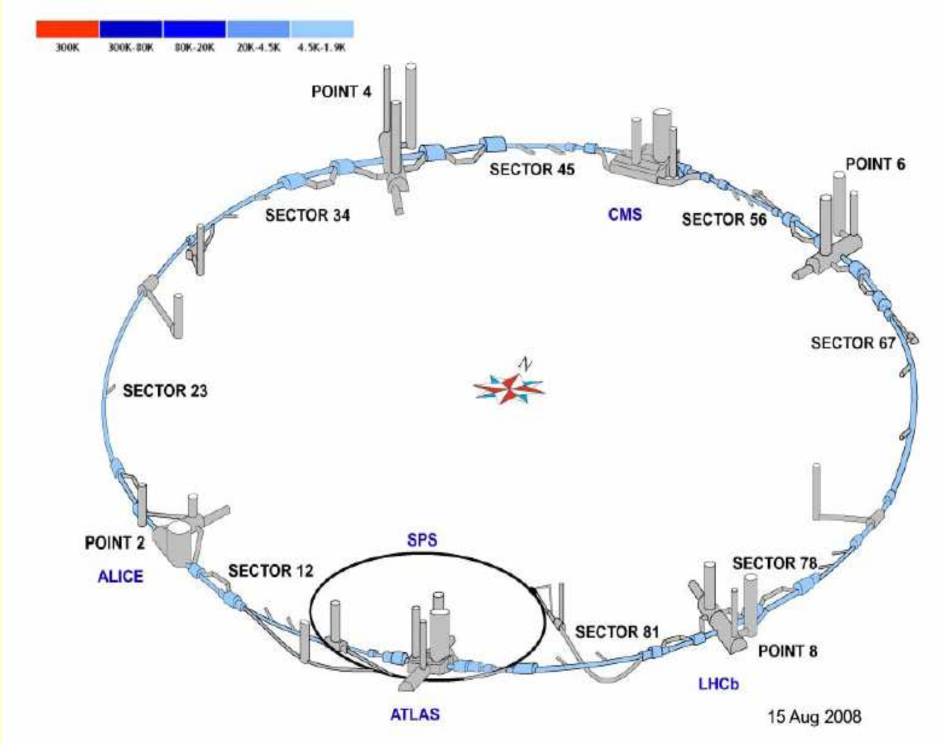
  ……

  everything worked impressively well



The Event on 19. Sep 2008

- the present understanding
- repair work
- plans for 2009/2010



...or 34: the event which started the incident

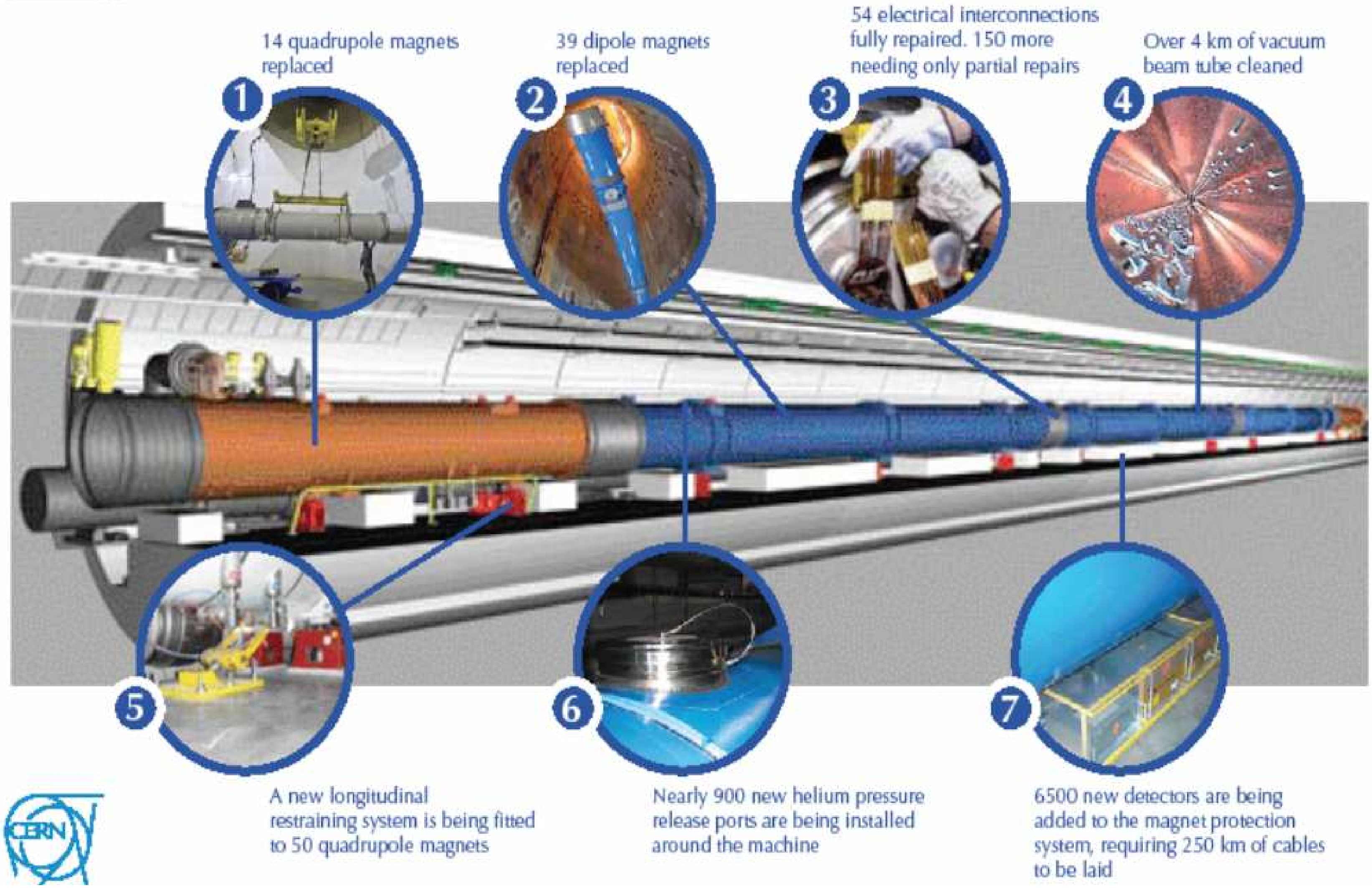
Interim Summary Report on the analysis of the 19th September 2008 incident at the LHC

had been fully commissioned to their nominal currents (corresponding to ...fore 10th Sep. The dipole circuits of sector 34 had only been powered up ...al 9.3 kA) prior to 10th Sep 2008.

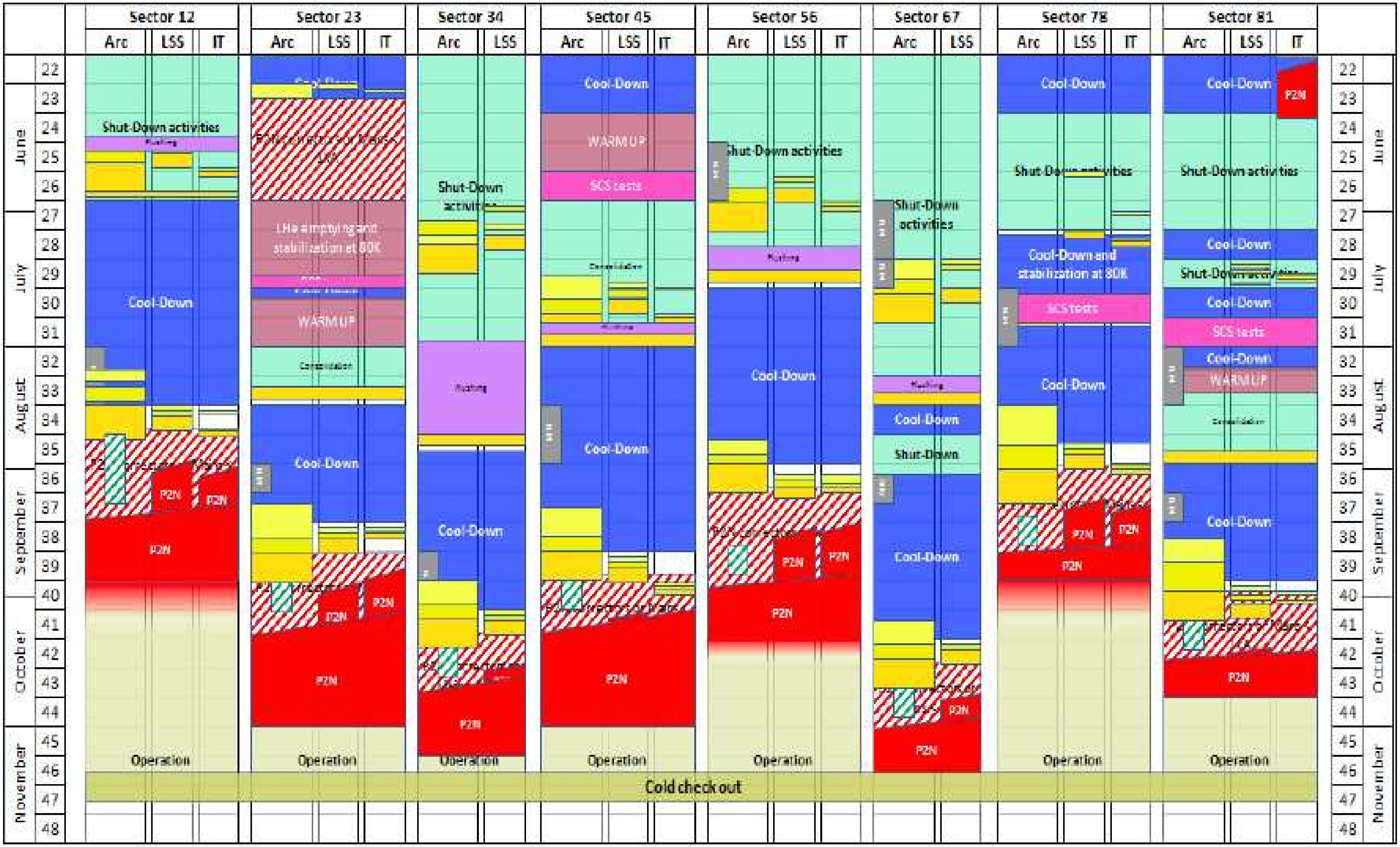
...ch precluded further beam operation for 2-3 days, commissioning of this ...ep. During ramp-up of the current a resistive zone developed in the ... region between a dipole and a quadrupole (at a current of 8.7 kA). ...ge had grown to 1 V and the power converter, unable to maintain the ...discharge mode). The current started to decrease in the circuit and at 0.86 s, the energy discharge switch opened, inserting dump resistors in the circuit to produce a fast power abort.

- Within the first second, an electrical arc developed and punctured the helium enclosure, leading to release of helium into the insulation vacuum of the cryostat.
- Relief discs on the vacuum enclosure opened when the pressure exceeded atmospheric. They were however unable to contain the pressure rise below the nominal 0.15 MPa absolute in the vacuum enclosures of subsector 23-25, thus resulting in large pressure forces acting on the vacuum barriers separating neighboring subsectors.
- These forces displaced dipoles in the subsectors affected from their cold internal supports, and knocked the Short Straight Section cryostats housing the quadrupoles and vacuum barriers from their external support jacks.

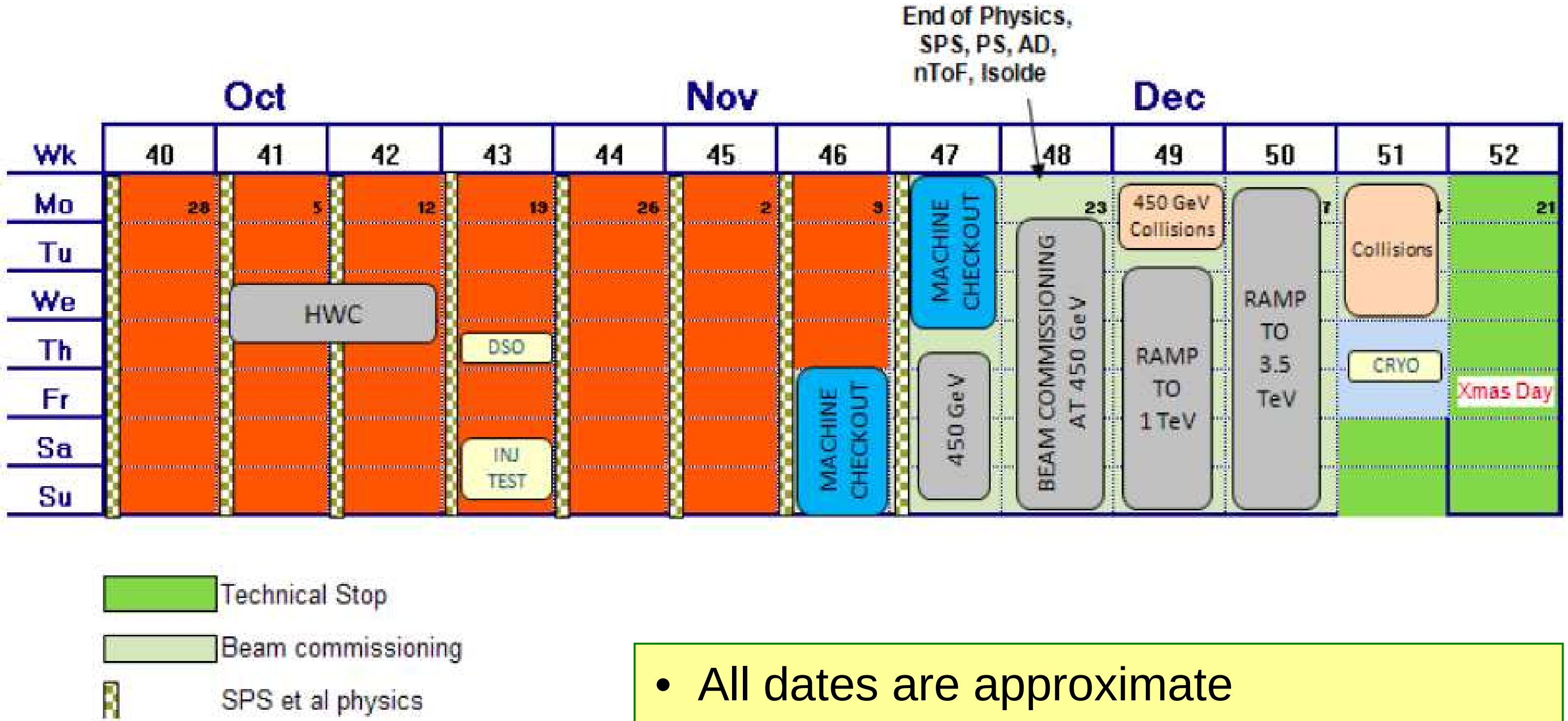
The LHC repairs in detail



Recent news from the machine   (“a piece of art”)

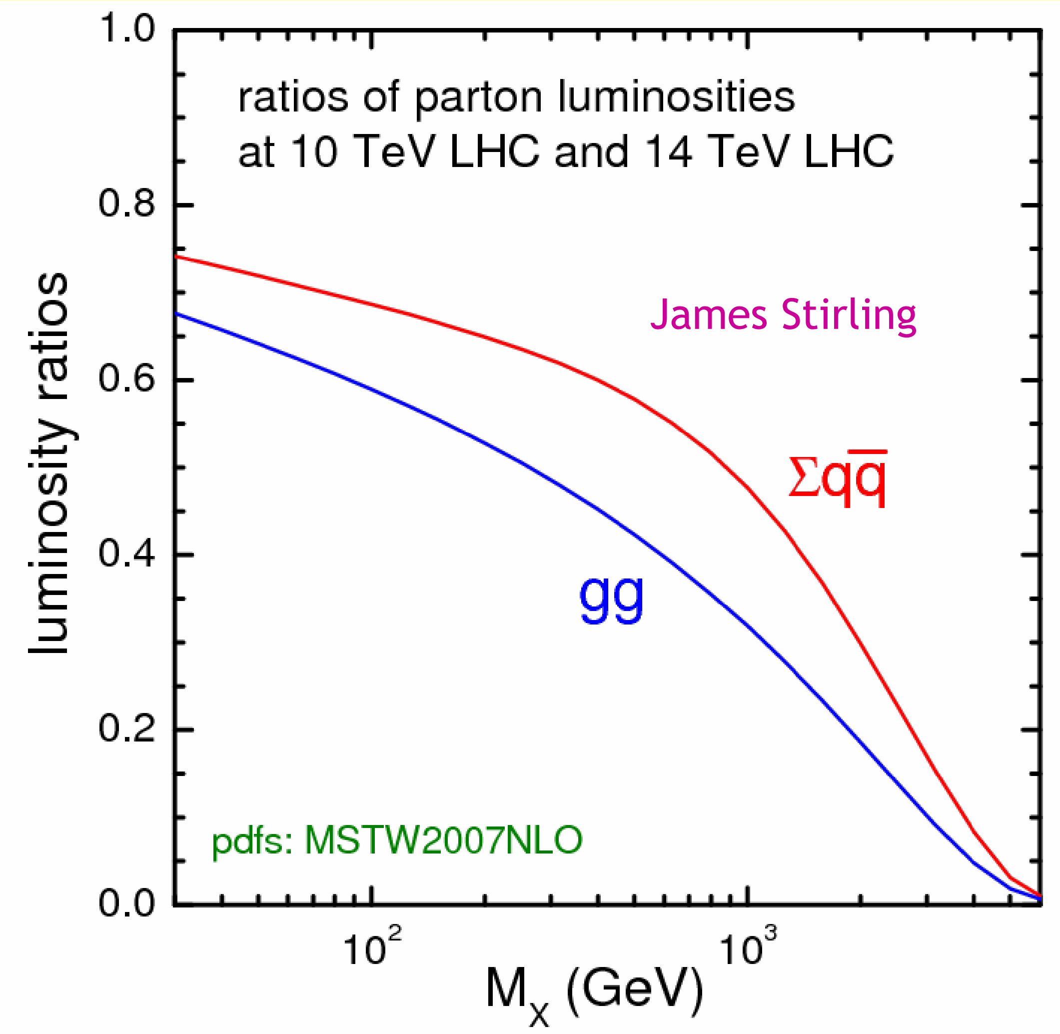


Recent news from the machine (cont.)



- All dates are approximate
- **Plans for 2010:**
  - machine commissioning
  - physics run at 3.5 TeV
  - possible ramp up to 5 TeV (depends on many issues…….)
  - plan to reach 200 – 300 pb^{-1}
  - heavy ion run (1 month, end of the year)

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

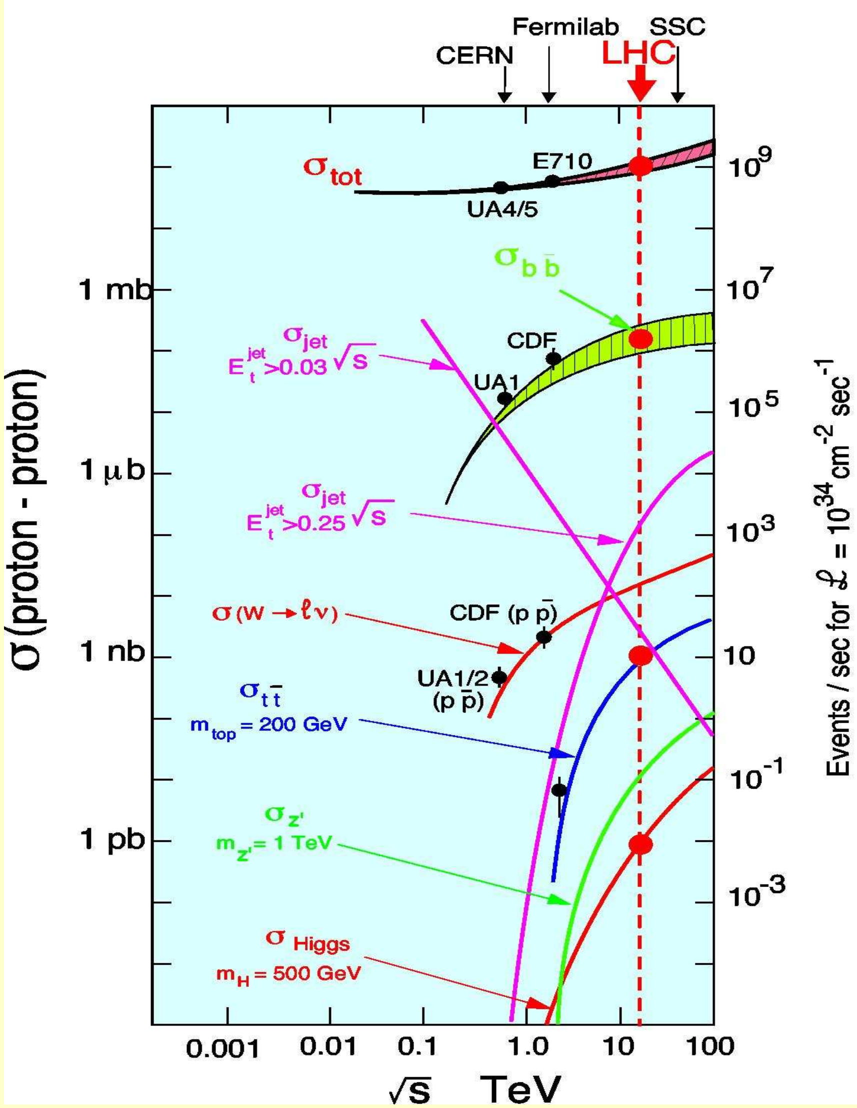
14 TeV simulation results will be shown throughout the lectures, unless stated otherwise

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} $cm^{-2}s^{-1}$	3.5×10^{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

Cross Sections and Production Rates



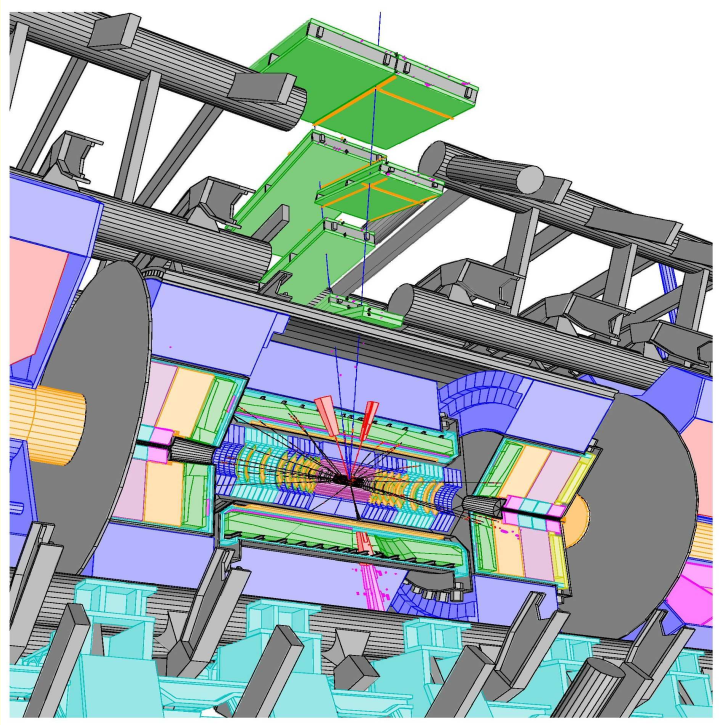
Rates for $L = 10^{34}$ cm^{-2} s^{-1}: (LHC)

• Inelastic proton-proton reactions:	10^9 / s
• bb pairs • tt pairs	5 10^6 / s 8 / s
• W $\rightarrow$ e ν • Z $\rightarrow$ 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, ……

The only problem: you have to detect them !

Detector requirements from physics



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

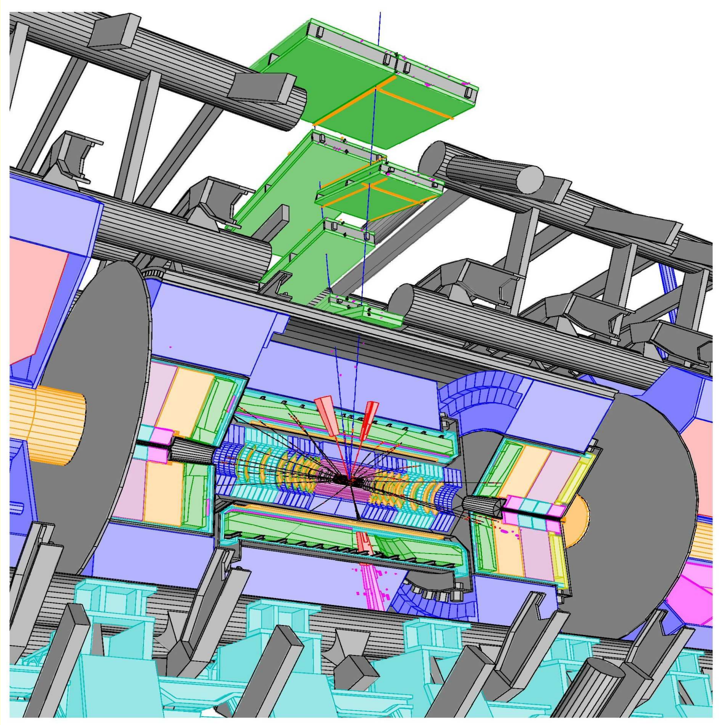
- Good measurement of missing transverse energy (E_T^{miss})

  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)



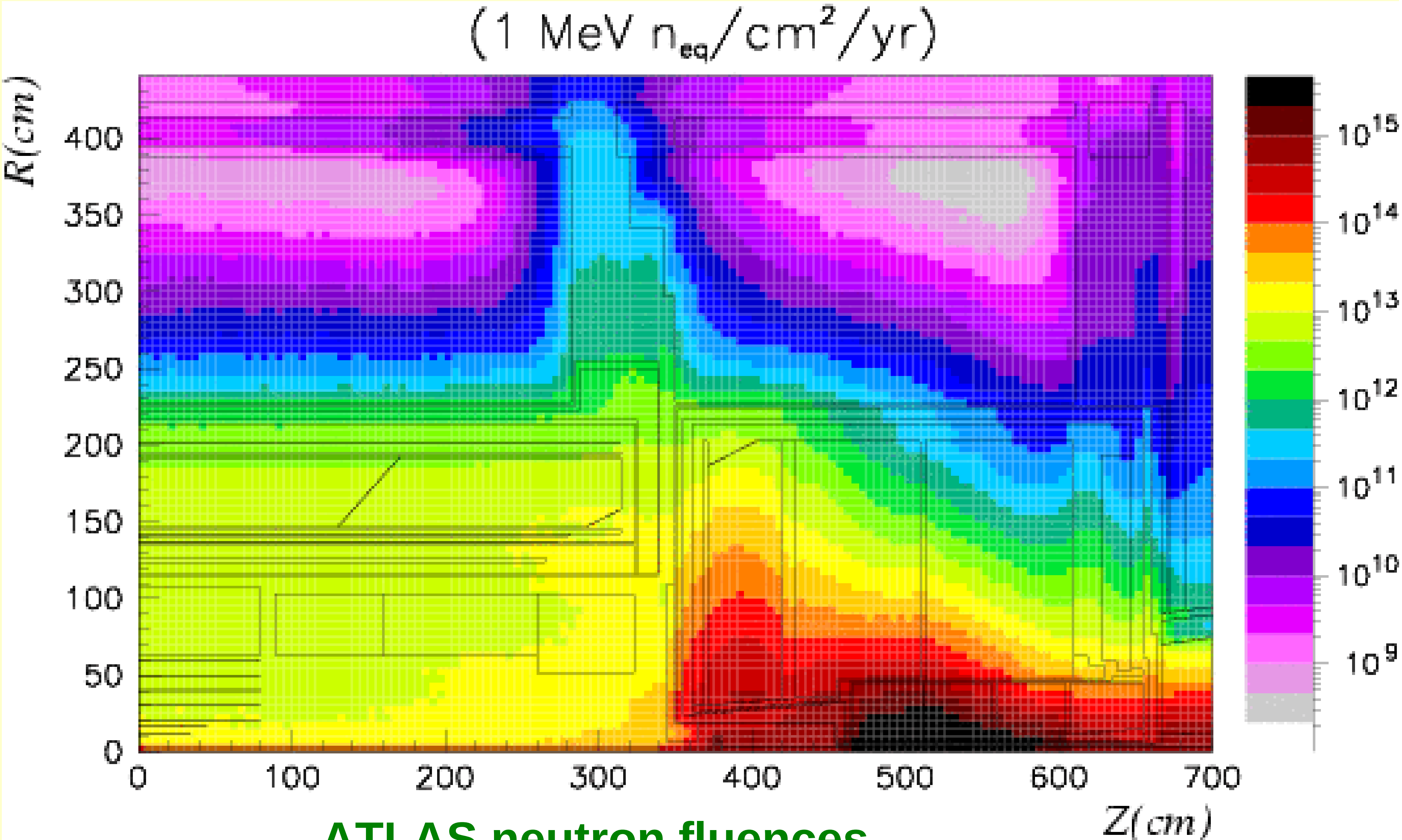
• LHC detectors must have **fast response**, otherwise integrate over many bunch crossings $\rightarrow$ too large pile-up

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

• **High granularity** to minimize probability that pile-up particles be in the same detector element as interesting object
$\rightarrow$ large number of electronic channels, high cost

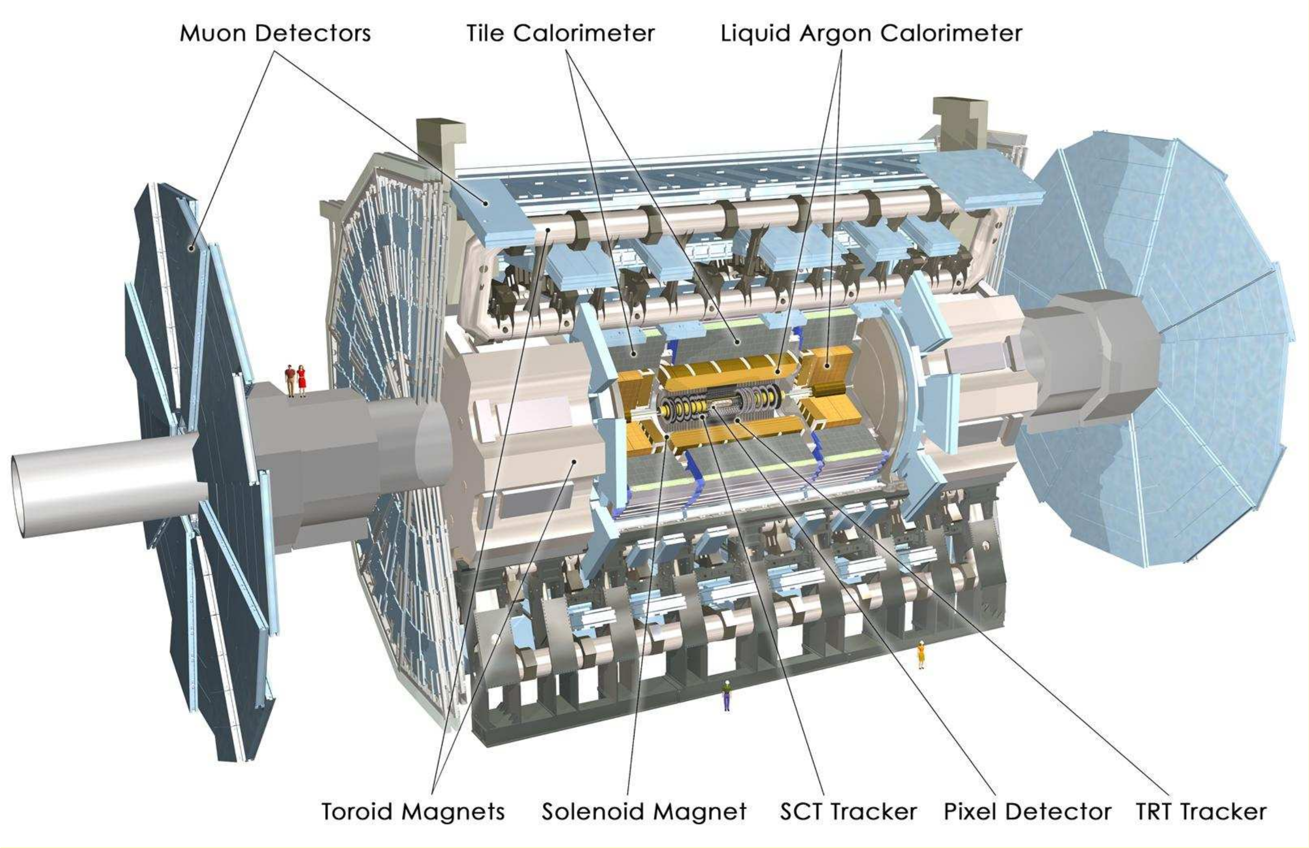
• LHC detectors must be **radiation resistant**: high flux of particles from pp collisions $\rightarrow$ high radiation environment
e.g. in forward calorimeters: up to 10^{17} n / cm^2 in 10 years of LHC operation

Experimental environment (radiation resistance of detectors)



ATLAS neutron fluences

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)

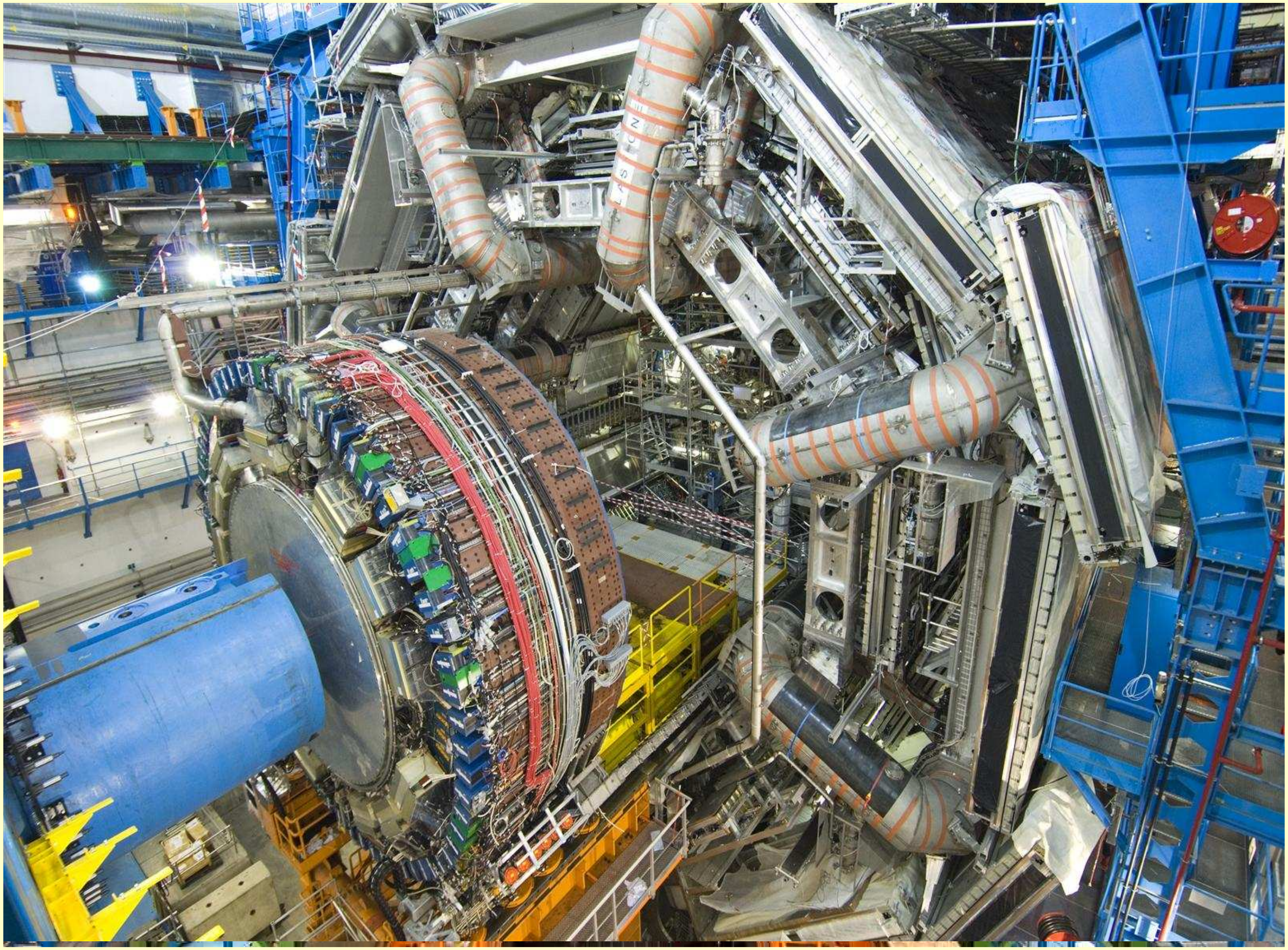
  space resolution: ~ 15 μm

- Energy measurement down to 1º to the beam line

- Independent muon spectrometer (supercond. toroid system)

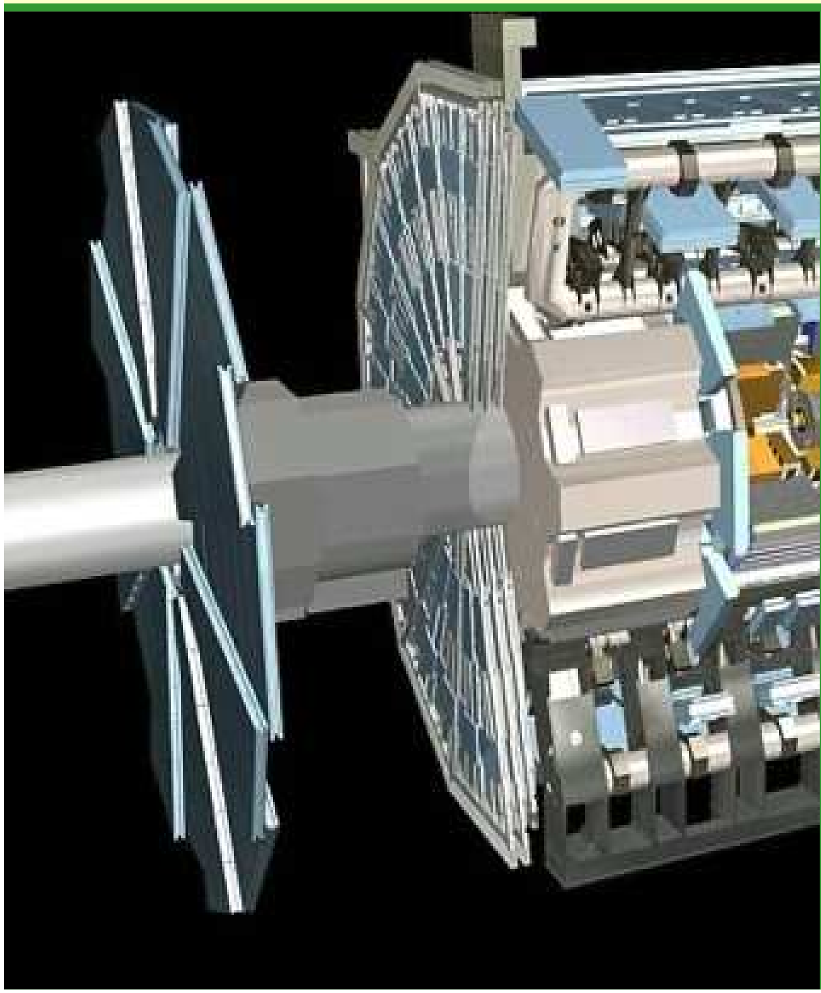
Diameter	25 m
Barrel toroid length	26 m
End-cap end-wall chamber span	46 m
Overall weight	7000 Tons

ATLAS Installation

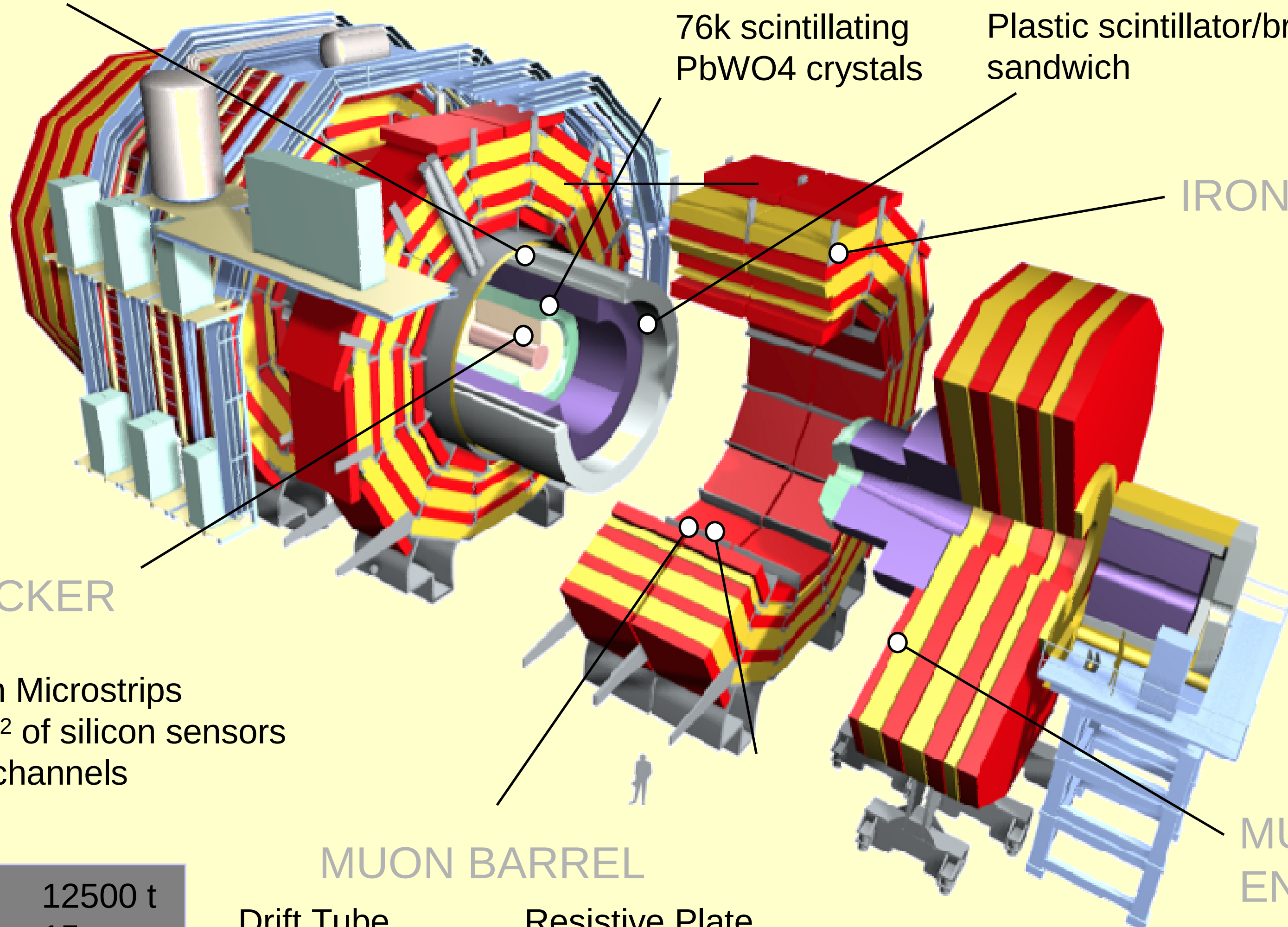


October 2006

Muon detector system
In the forward region



CMS

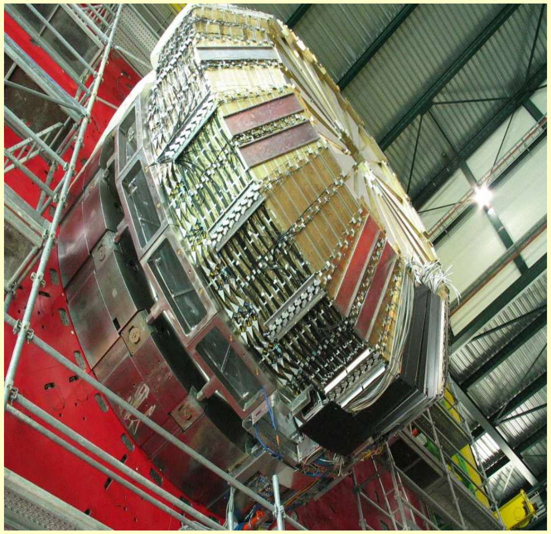


Total weight	12500 t
Overall diameter	15 m
Overall length	21.6 m

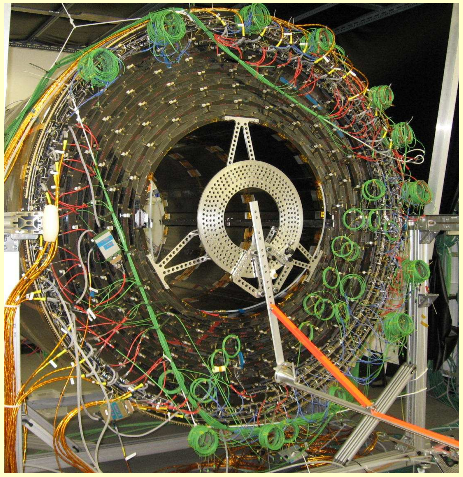
CMS Installation

Coil inserted, 14. September 2005

Cathode Strip chambers and yoke endcaps

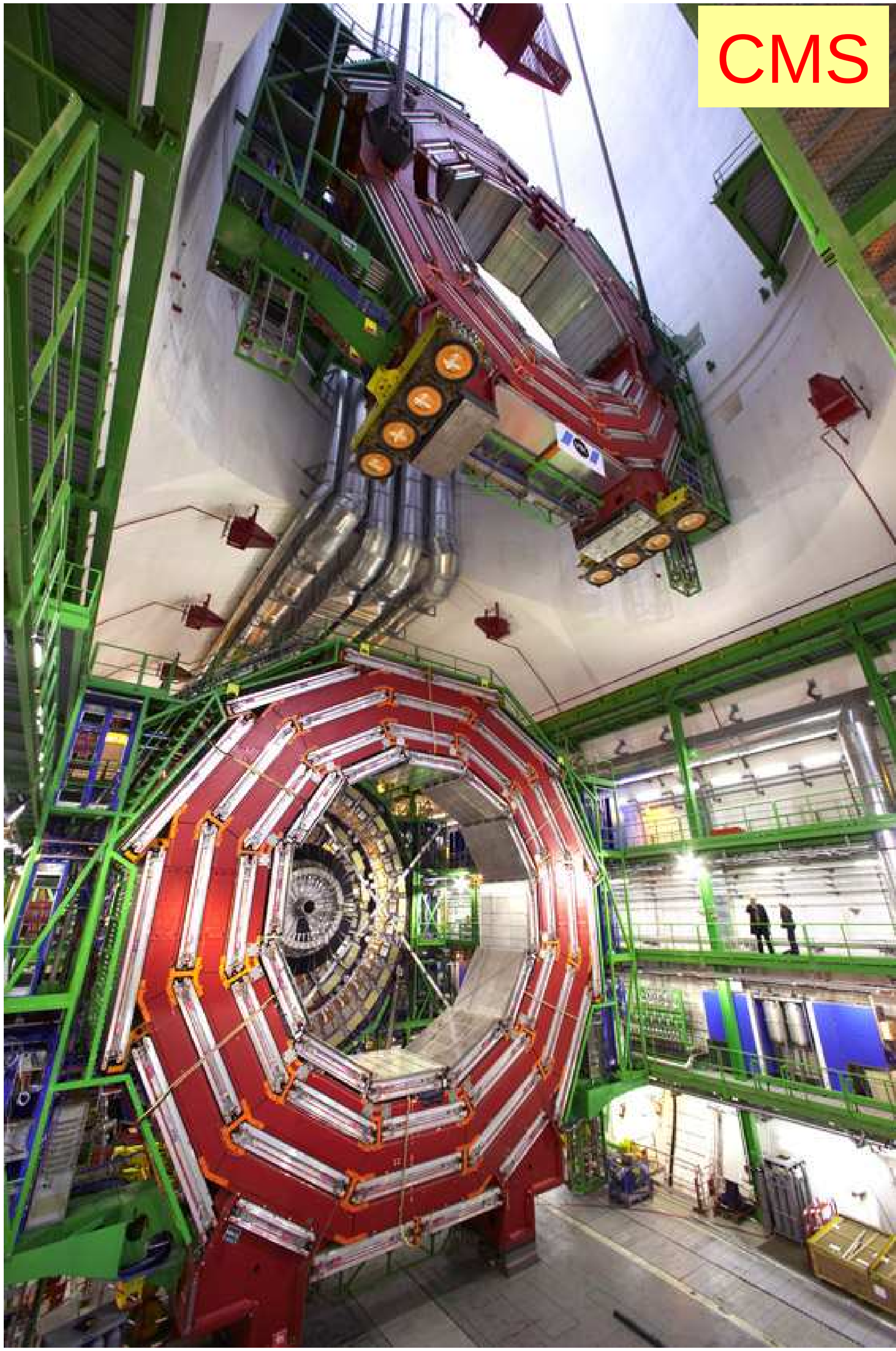


Hadronic calorimeter, endcap



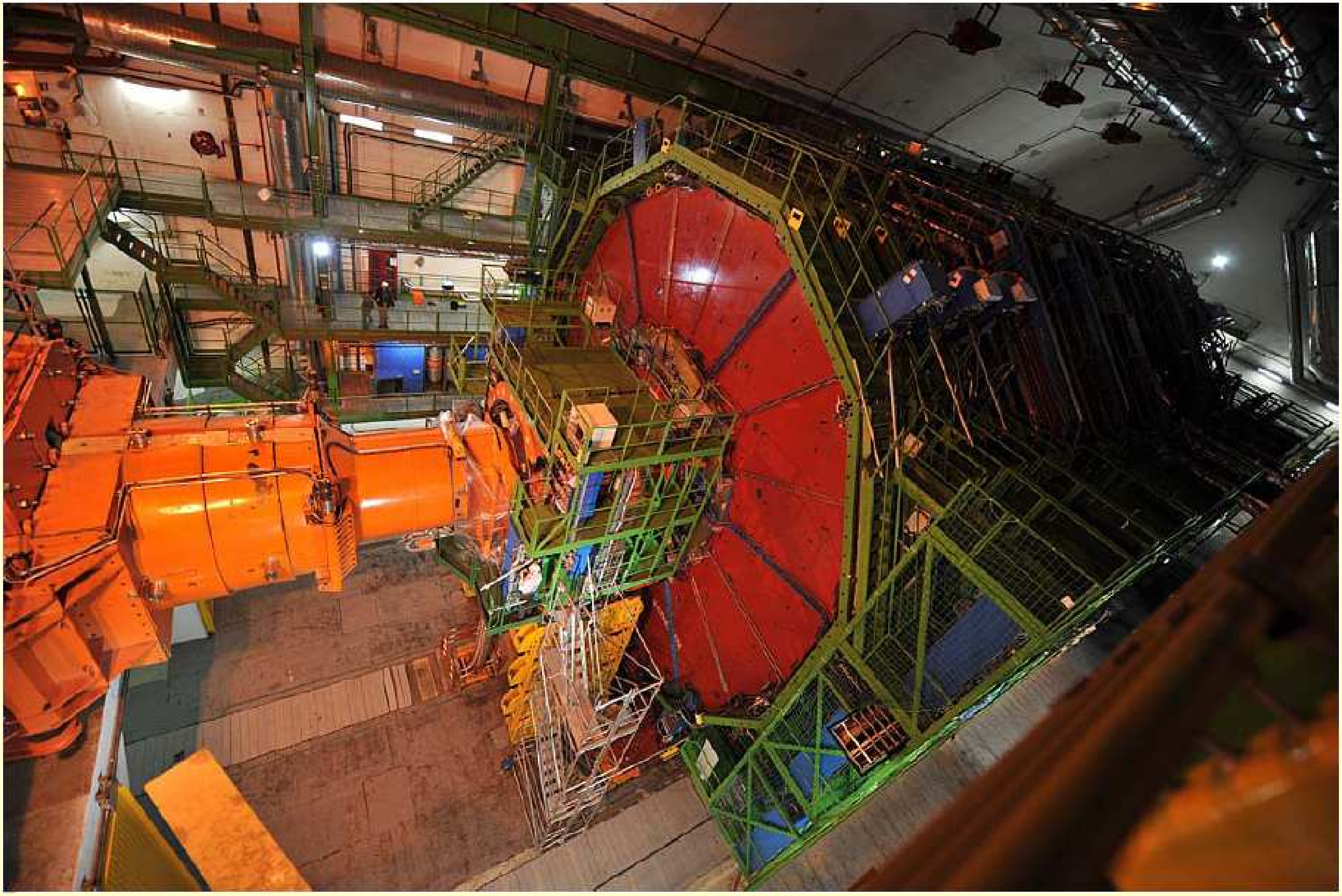
Tracker, outer barrel

CMS



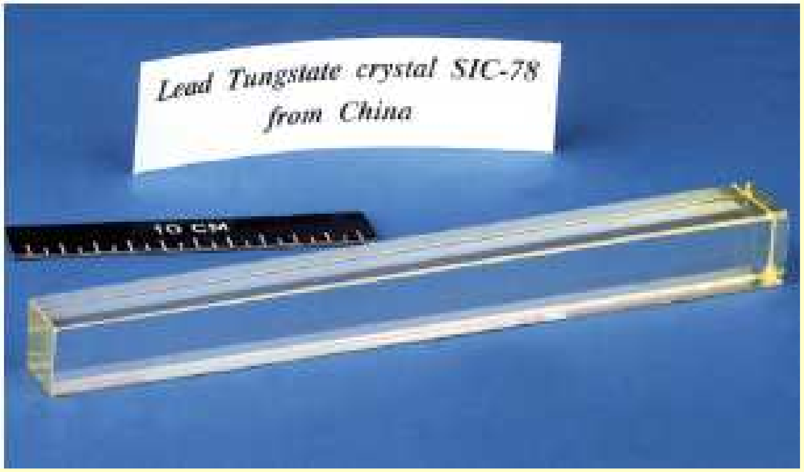
re

CMS Detector closed for 10th Sep.



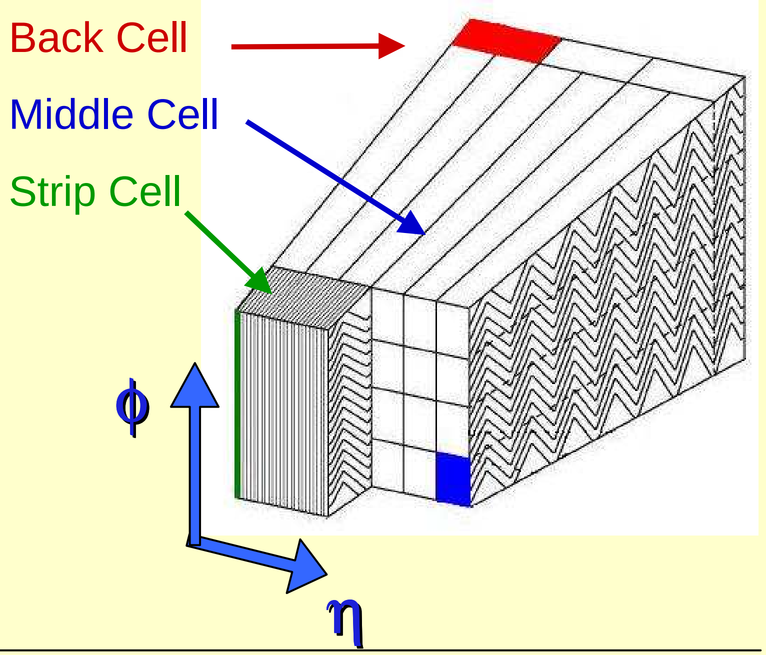
Important differences I:

- In order to maximize the sensitivity for **$H \rightarrow \gamma\gamma$ decays**, the experiments need to have an excellent e/γ identification and resolution



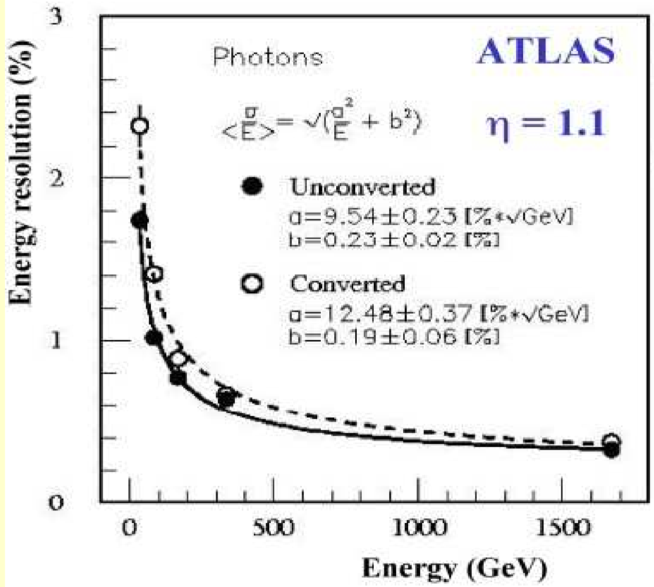
- CMS: has opted for a high resolution $PbWO_4$ crystal calorimeter
  - higher intrinsic resolution

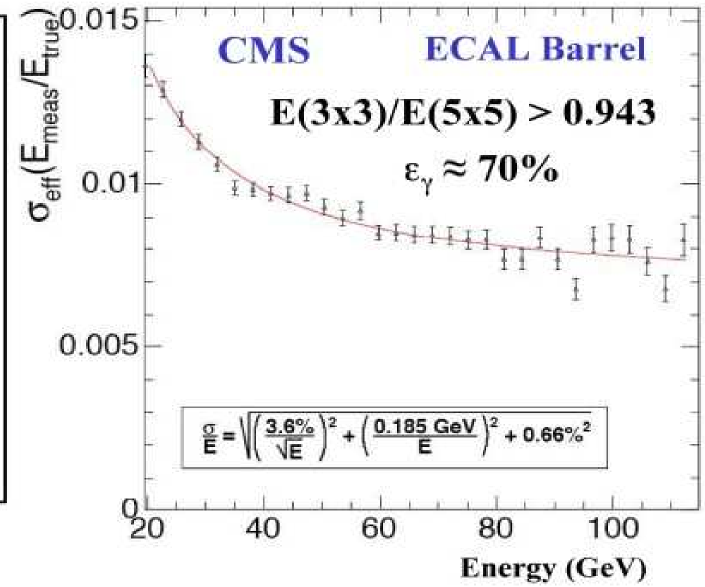
- ATLAS: Liquid argon calorimeter
  - high granularity and longitudinally segmentation (better e/γ ID)
  - electrical signals, high stability in calibration & radiation resistant



ATLAS/CMS: e/γ resolutions

Actual performance expected in real detector quite different!!

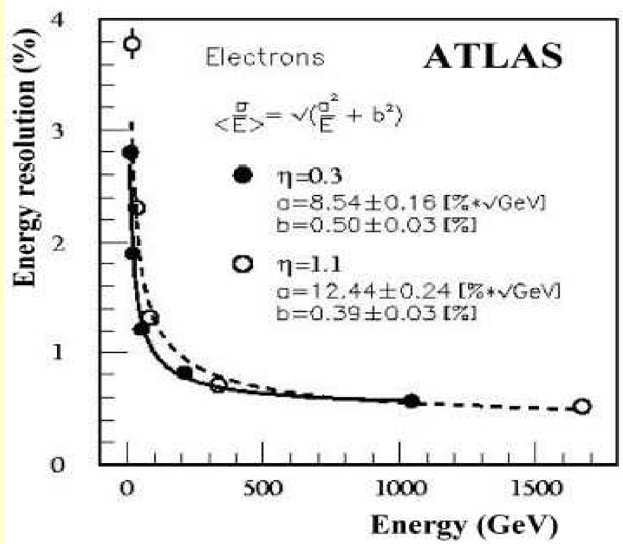


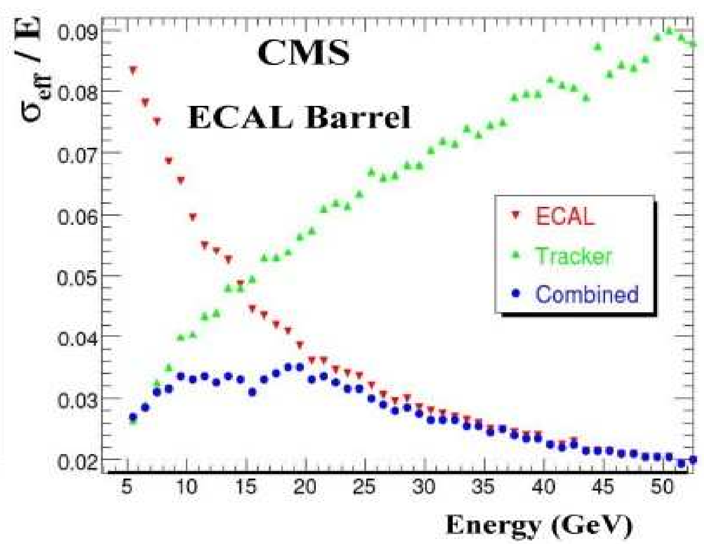


Photons at 100 GeV

ATLAS: 1-1.5% energy resol. (all γ)

CMS: 0.8% energy resol. (ε_γ ~ 70%)





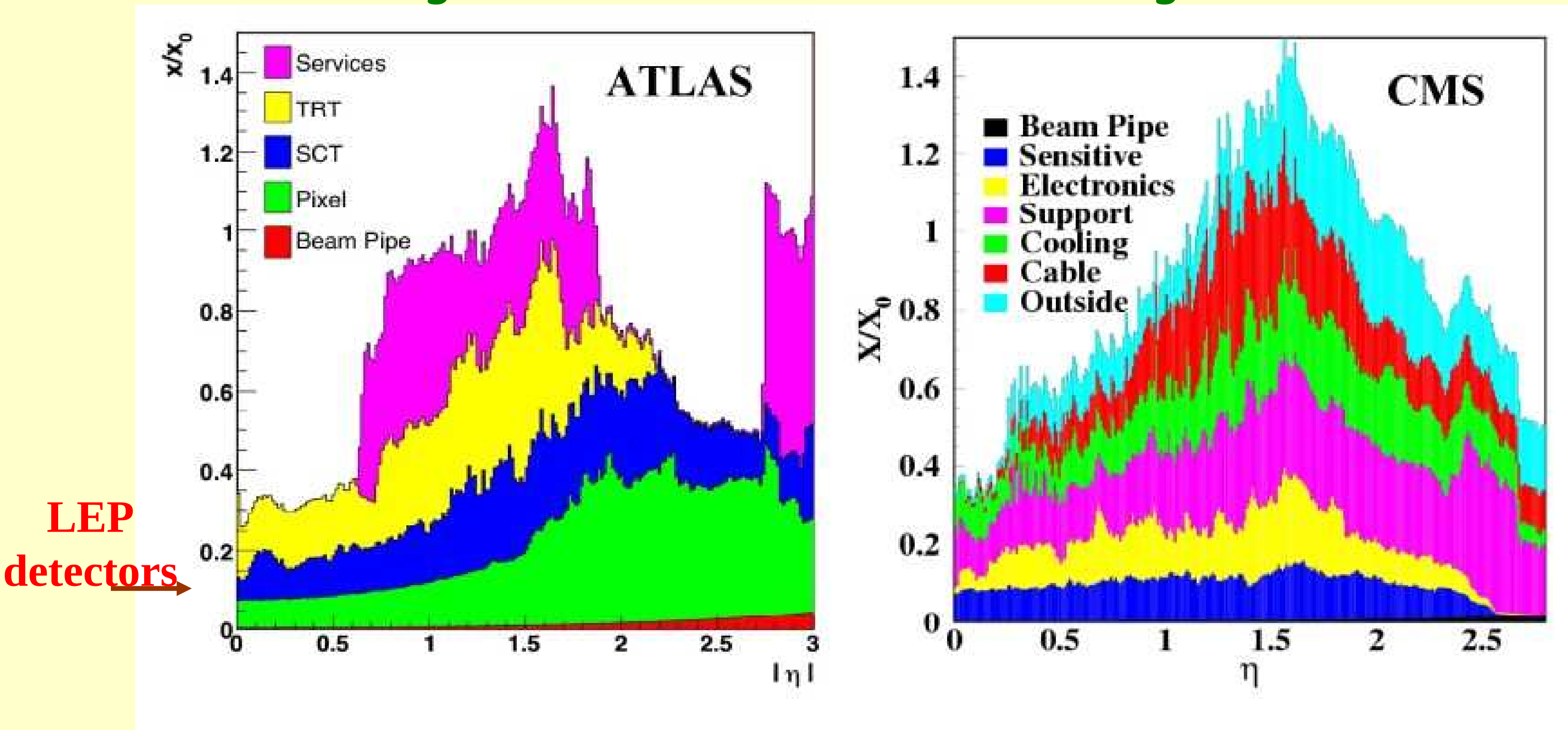
Electrons at 50 GeV

ATLAS: 1.3-2.3% energy resol. (use EM calo only)

CMS: ~ 2.0% energy resol. (combine EM calo and tracker)

Amount of material in ATLAS and CMS inner trackers

Weight: 4.5 tons **Weight: 3.7 tons**



- 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

Evolution of the amount of material expected in the ATLAS and CMS trackers from 1994 to 2006

Date	ATLAS $\eta \approx 0$	$\eta \approx 1.7$	CMS $\eta \approx 0$	$\eta \approx 1.7$
1994 (Technical Proposals)	0.20	0.70	0.15	0.60
1997 (Technical Design Reports)	0.25	1.50	0.25	0.85
2006 (End of construction)	0.35	1.35	0.35	1.50

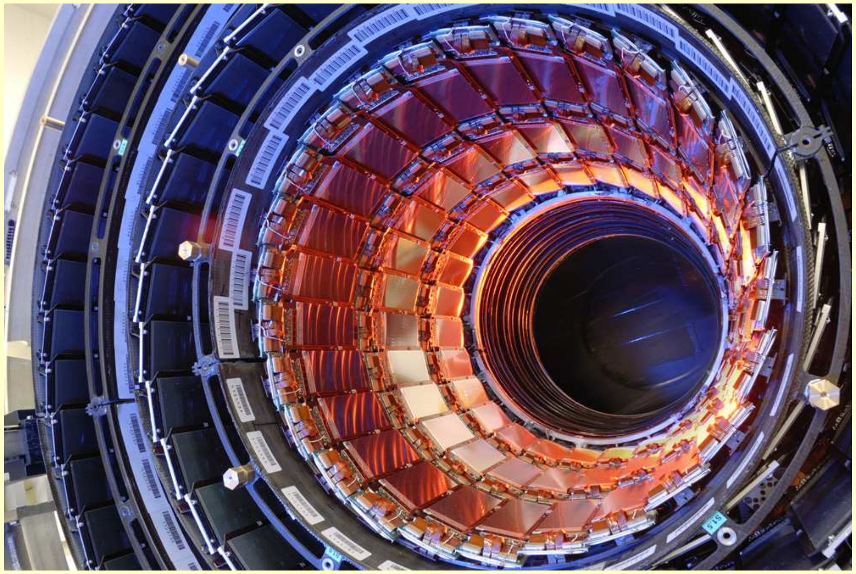
The numbers are given in fractions of radiation lengths (X/X_0). Note that for ATLAS, the reduction in material from 1997 to 2006 at $\eta \approx 1.7$ is due to the rerouting of pixel services from an integrated barrel tracker layout with pixel services along the barrel LAr cryostat, to an independent pixel layout with pixel services routed at much lower radius and entering a patch panel outside the acceptance of the tracker (this material appears now at $\eta \approx 3$). Note also that the numbers for CMS represent almost all the material seen by particles before entering the active part of the crystal calorimeter, whereas they do not for ATLAS, in which particles see in addition the barrel LAr cryostat and the solenoid coil (amounting to approximately $2X_0$ at $\eta = 0$), or the end-cap LAr cryostat at the larger rapidities.

- Material increased by ~ factor 2 from 1994 (approval) to now (end of construction)
- Electrons lose between 25% and 70% of their energy before reaching the EM calorimeter
- Between 20% and 65% of photons convert into e^+e^- pairs before they reach the EM calorimeter
- Need to know material to ~ 1% X_0 for precision measurement of m_W (< 10 MeV)!

Important differences II:

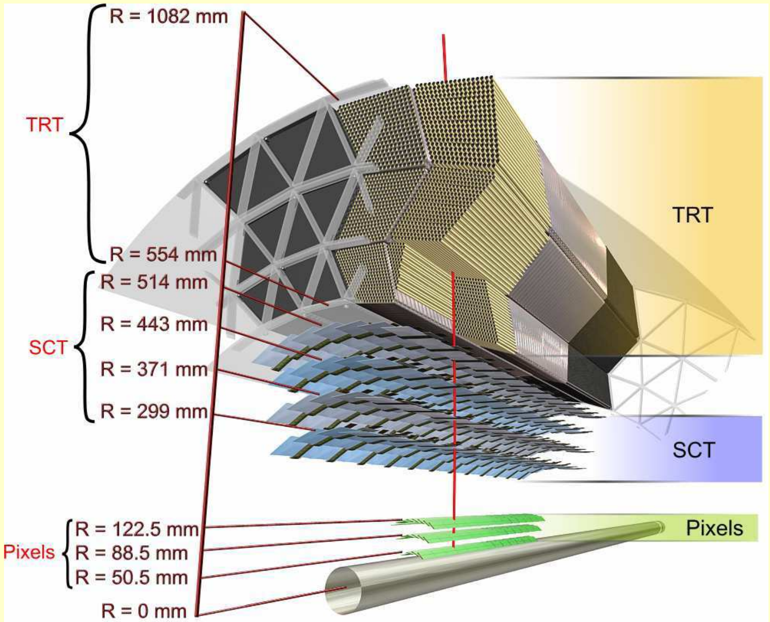
• Inner detectors / tracker

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



Main performance characteristics of the ATLAS and CMS trackers

	ATLAS	CMS
Reconstruction efficiency for muons with $p_T = 1$ GeV	96.8%	97.0%
Reconstruction efficiency for pions with $p_T = 1$ GeV	84.0%	80.0%
Reconstruction efficiency for electrons with $p_T = 5$ GeV	90.0%	85.0%
Momentum resolution at $p_T = 1$ GeV and $\eta \approx 0$	1.3%	0.7%
Momentum resolution at $p_T = 1$ GeV and $\eta \approx 2.5$	2.0%	2.0%
Momentum resolution at $p_T = 100$ GeV and $\eta \approx 0$	3.8%	1.5%
Momentum resolution at $p_T = 100$ GeV and $\eta \approx 2.5$	11%	7%
Transverse i.p. resolution at $p_T = 1$ GeV and $\eta \approx 0$ (µm)	75	90
Transverse i.p. resolution at $p_T = 1$ GeV and $\eta \approx 2.5$ (µm)	200	220
Transverse i.p. resolution at $p_T = 1000$ GeV and $\eta \approx 0$ (µm)	11	9
Transverse i.p. resolution at $p_T = 1000$ GeV and $\eta \approx 2.5$ (µm)	11	11
Longitudinal i.p. resolution at $p_T = 1$ GeV and $\eta \approx 0$ (µm)	150	125
Longitudinal i.p. resolution at $p_T = 1$ GeV and $\eta \approx 2.5$ (µm)	900	1060

- Performance of CMS tracker is undoubtedly superior to that of ATLAS in terms of momentum resolution.
- Vertexing and b-tagging performances are similar.
- However, impact of material and B-field already visible on efficiencies.

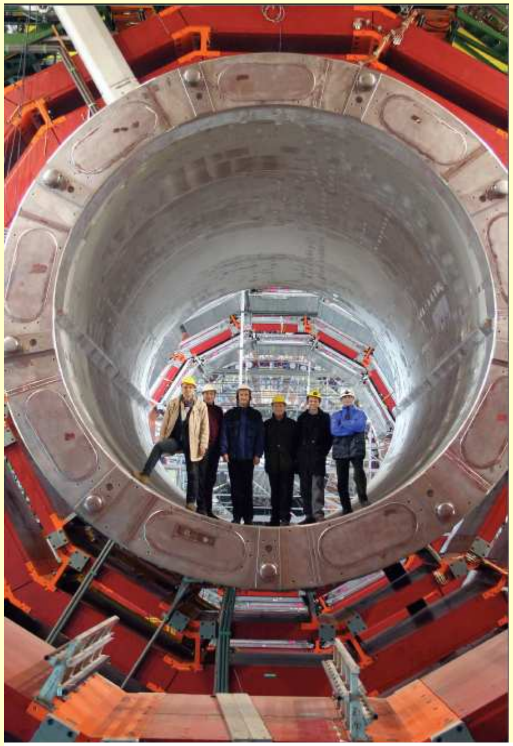
Important differences III:

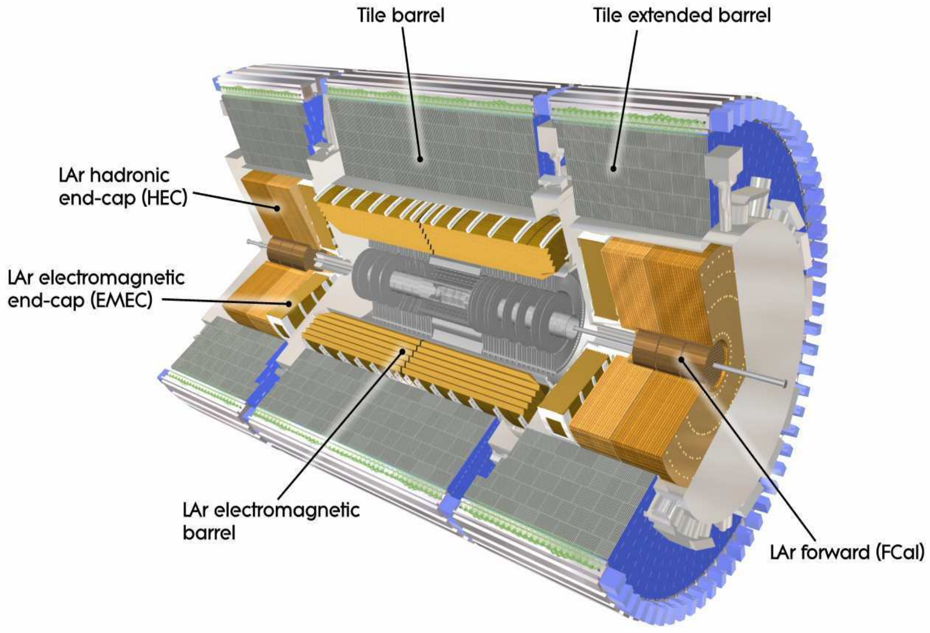
• Coil / Hadron calorimeters

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

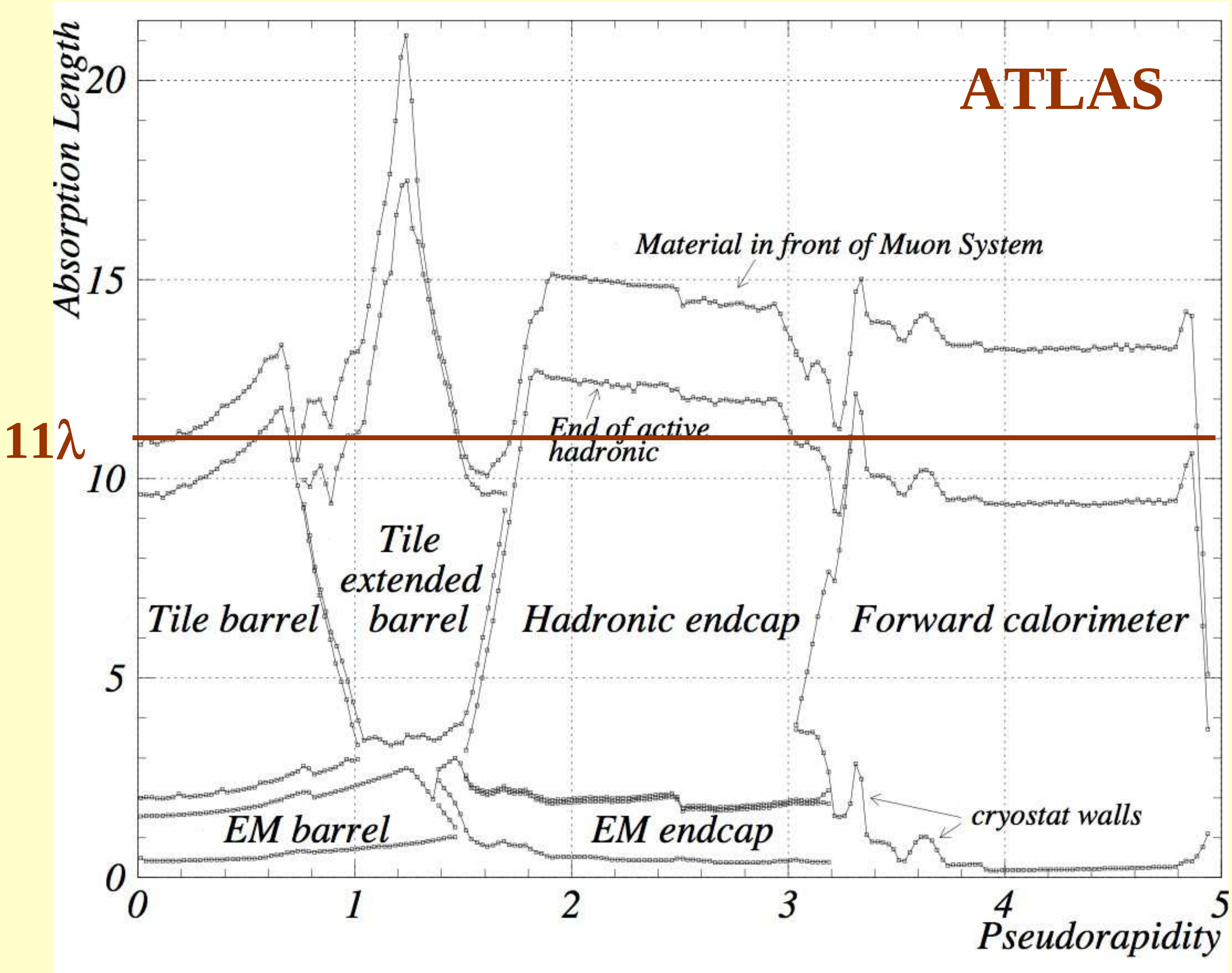
good for e/γ resolution
bad for jet resolution

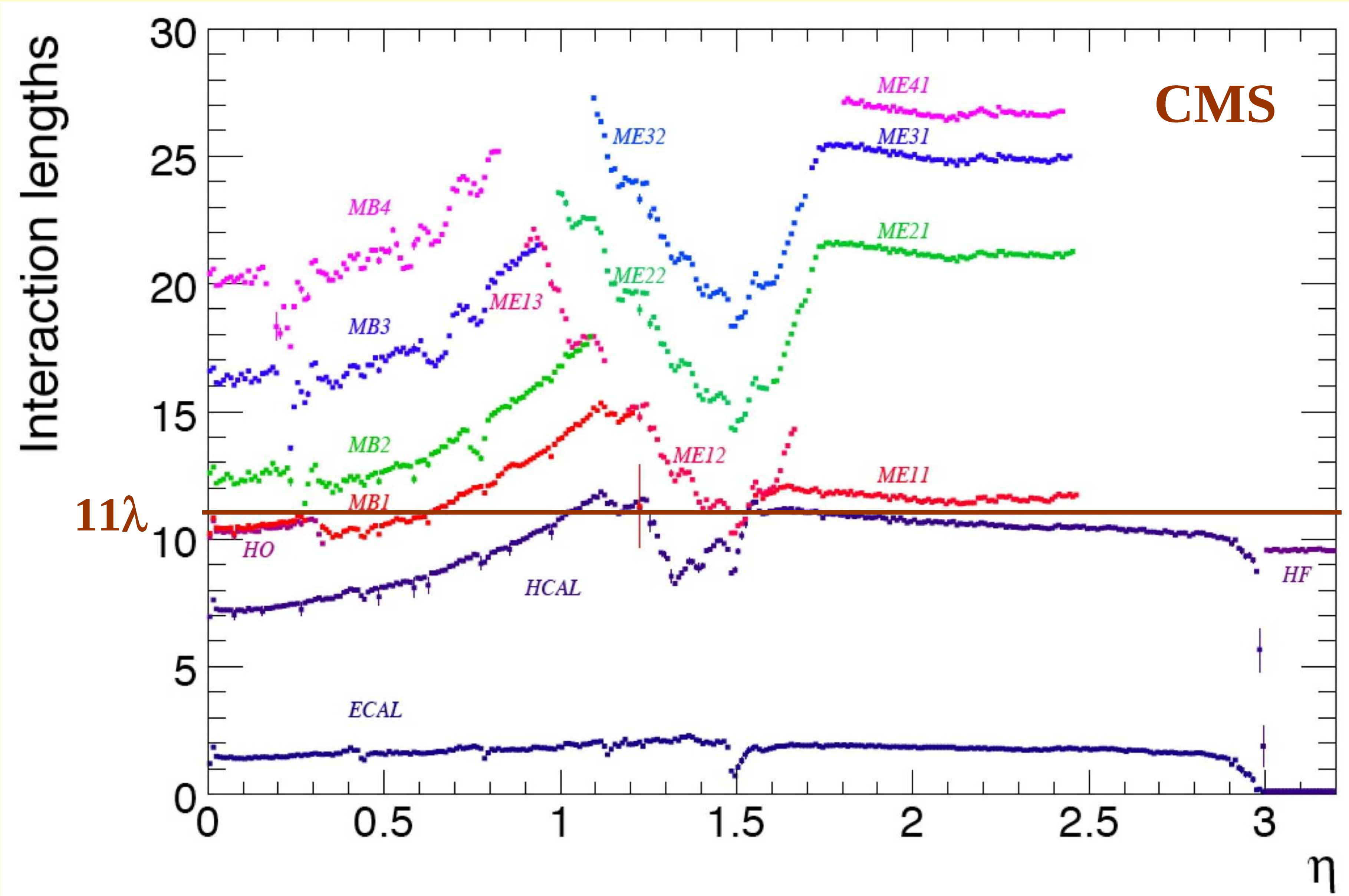
• ATLAS:
calorimetry outside coil





Hadronic absorption length of the calorimeters





Interaction lengths
30
25
20
15
10
5
0
0
0.5
1
1.5
2
2.5
3
η
CMS
11λ
MB4
MB3
MB2
MB1
HO
HCAL
ECAL
ME13
ME32
ME22
ME12
ME41
ME31
ME21
ME11
HF

Main performance parameters of the different hadronic calorimeter components of the ATLAS and CMS detectors, as measured in test beams using charged pions in both stand-alone and combined mode with the ECAL

	ATLAS				CMS	
	Barrel LAr/Tile		End-cap LAr			
	Tile	Combined	HEC	Combined	Had. barrel	Combined
Electron/hadron ratio	1.36	1.37	1.49			
Stochastic term	$45\%/\sqrt{E}$	$55\%/\sqrt{E}$	$75\%/\sqrt{E}$	$85\%/\sqrt{E}$	$100\%/\sqrt{E}$	$70\%/\sqrt{E}$
Constant term	1.3%	2.3%	5.8%	$< 1\%$		8.0%
Noise	Small	3.2 GeV		1.2 GeV	Small	1 GeV

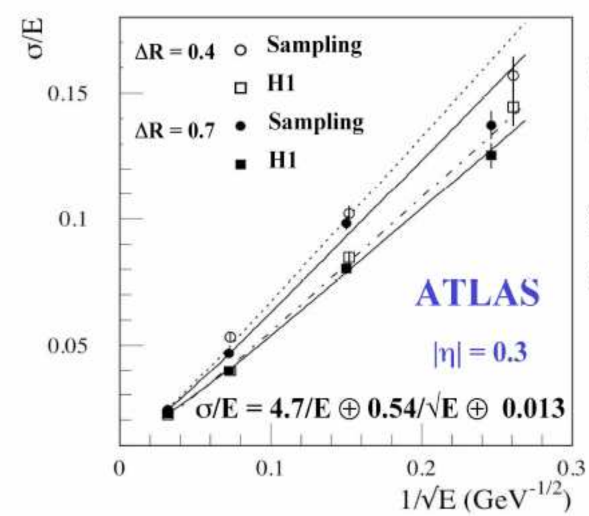
The measured electron/hadron ratios are given separately for the hadronic stand-alone and combined calorimeters when available, and for the contributions (added quadratically except for the stand-alone ATLAS tile calorimeter) to the pion energy resolution from the stochastic term, the local constant term, and the noise are also shown, when available from published data.

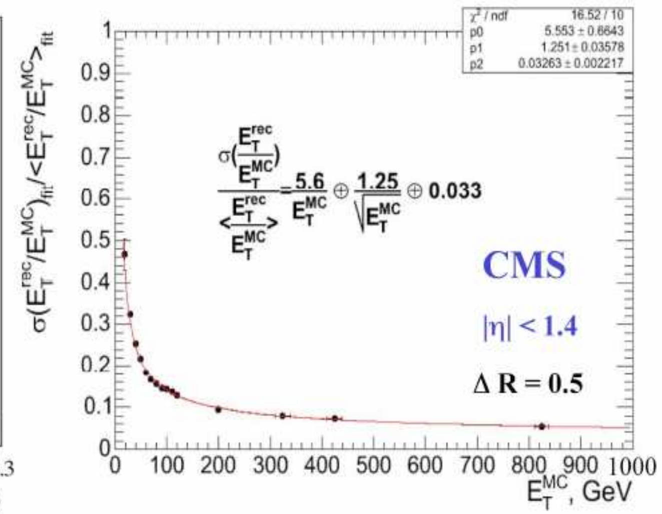
Biggest difference in performance perhaps for hadronic calorimetry

Jets at 1000 GeV

ATLAS: ~ 2%
energy resolution
CMS: ~ 5%
energy resolution,

But expect sizable improvement using tracks (especially at lower E)



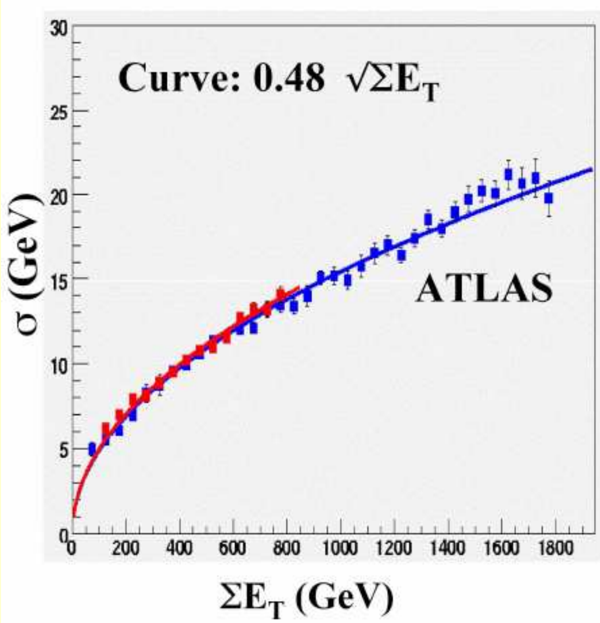


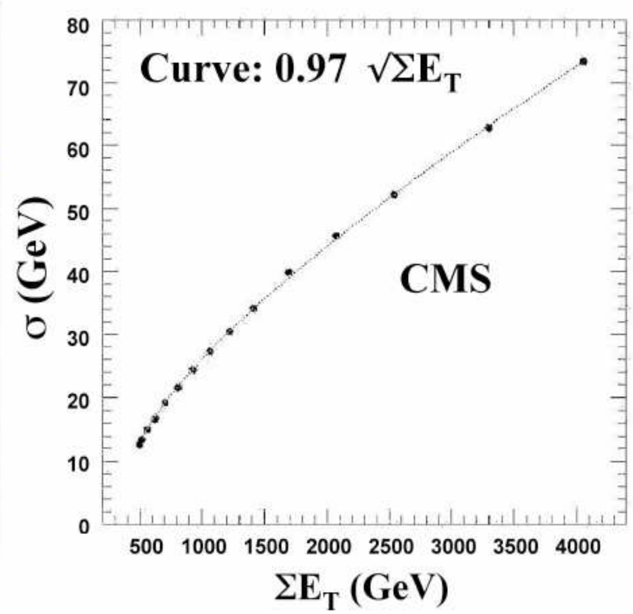
E_T^{miss} at ΣE_T = 2000 GeV

ATLAS: σ ~ 20 GeV

CMS: σ ~ 40 GeV

This may be important for high mass H/A $\rightarrow \tau\tau$





How much can be recovered using energy-flow algorithms?

Jets in 20-100 GeV range are particularly important for searches (e.g. H $\rightarrow$ bb)

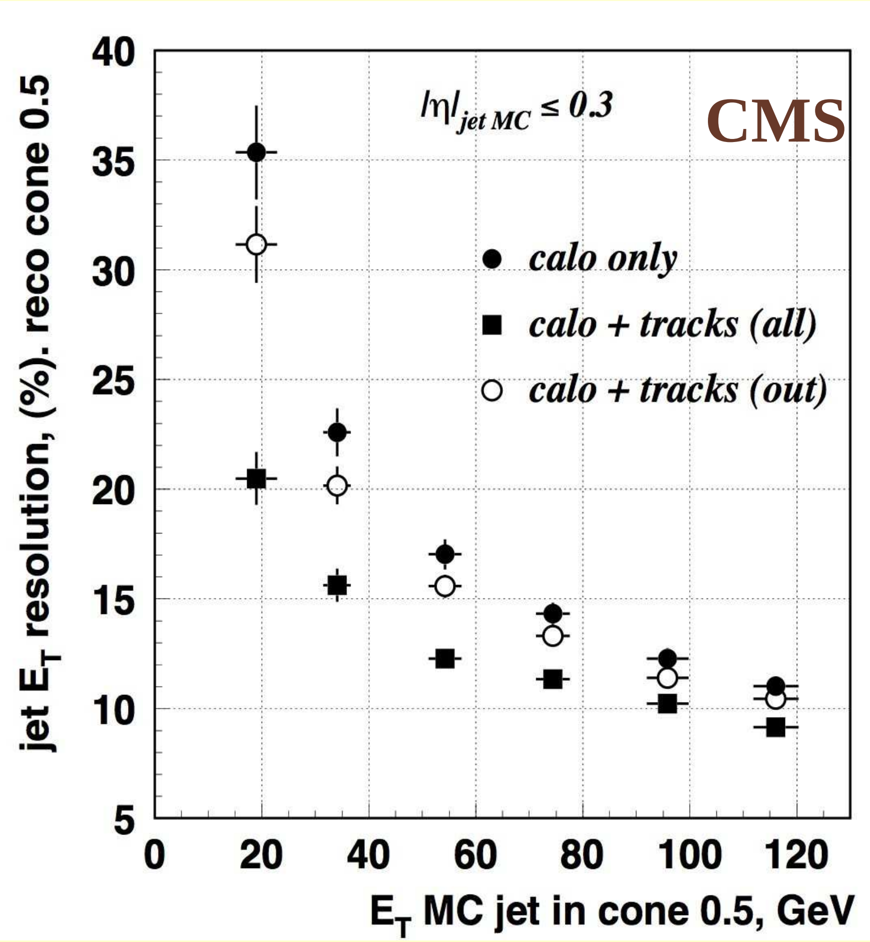
For E_T ~ 50 GeV in barrel:
ATLAS: ~ 10% energy resolution

CMS:
~ 19% energy resolution (calo only)
~ 14% energy resolution (calo + tracks)

Some words of caution though:
- Danger from hadronic interactions in the tracker material
  $\rightarrow$ non-Gaussian tails in response

- Gains smaller at large η (material) and at high energy

- Linearity of response at low energy important



One word about neutrinos in hadron colliders:

✓ since most of the energy of the colliding protons escapes down the beam pipe, one can only use the energy-momentum balance in the transverse plane

$\rightarrow$ concepts such as $\mathbf{E_T^{miss}}$ (missing transverse energy/momentum) and **transverse mass** are often used (only missing component is E_z^{miss})

$\rightarrow$ reconstruct "fully" certain topologies with neutrinos, e.g. $W \rightarrow \ell\nu$ and even better $H \rightarrow \tau\tau \rightarrow \ell\nu_\ell\nu_\tau\ h\nu_\tau$

✓ the detector must therefore be quite hermetic

$\rightarrow$ transverse energy flow fully measured with reasonable accuracy

$\rightarrow$ no neutrino/weakly interacting particle escapes "undetected"

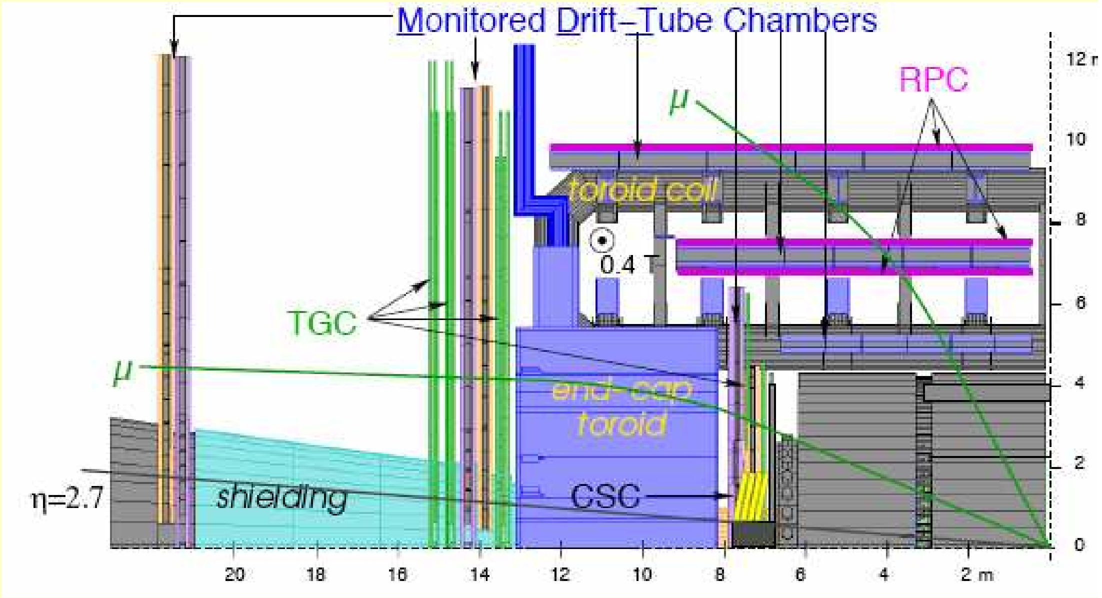
$\rightarrow$ [no human enters without major effort (fast access to some parts of ATLAS/CMS quite difficult)]

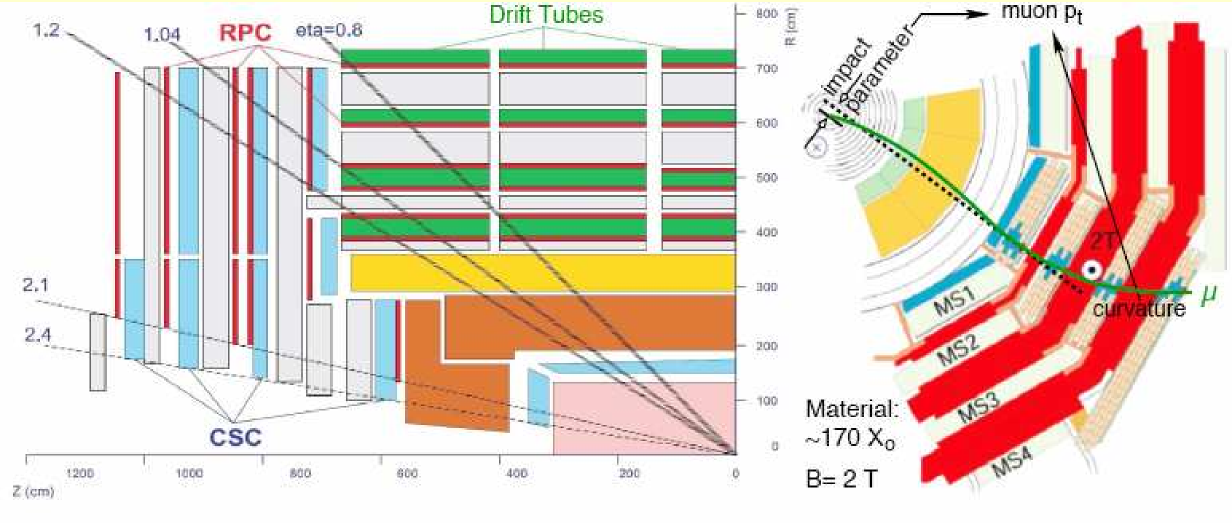
Important differences IV:

- 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)



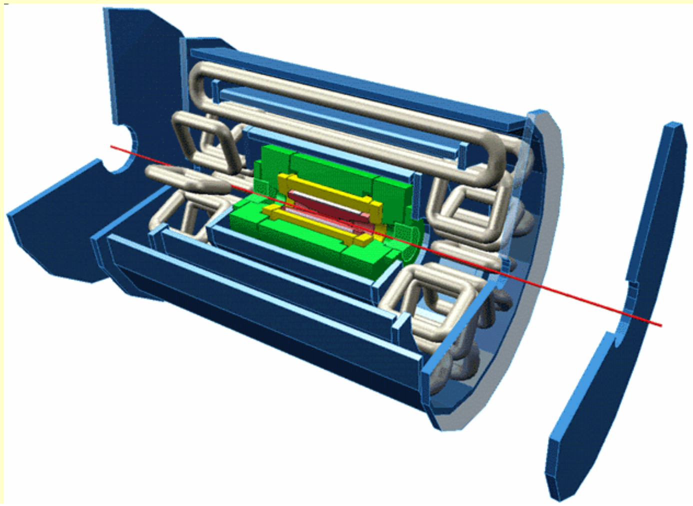


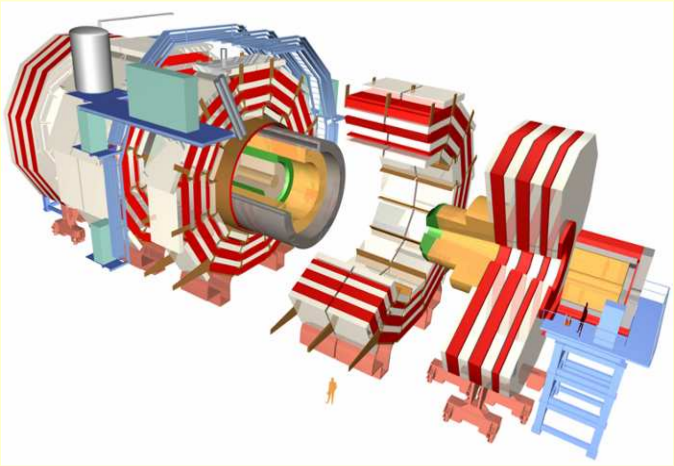
Main parameters of the ATLAS and CMS muon measurement systems as well as a summary of the expected combined and stand-alone performance at two typical pseudorapidity values (averaged over azimuth)

Parameter	**ATLAS**	**CMS**
Pseudorapidity coverage		
-Muon measurement	$\|\eta\| < 2.7$	$\|\eta\| < 2.4$
-Triggering	$\|\eta\| < 2.4$	$\|\eta\| < 2.1$
Dimensions (m)		
-Innermost (outermost) radius	5.0 (10.0)	3.9 (7.0)
-Innermost (outermost) disk (*z*-point)	7.0 (21–23)	6.0–7.0 (9–10)
Segments/superpoints per track for barrel (end caps)	3 (4)	4 (3–4)
Magnetic field B (T)	0.5	2
-Bending power (BL, in T· m) at $\|\eta\| \approx 0$	3	16
-Bending power (BL, in T· m) at $\|\eta\| \approx 2.5$	8	6
Combined (stand-alone) momentum resolution at		
-p = 10 GeV and $\eta \approx 0$	1.4% (3.9%)	0.8% (8%)
-p = 10 GeV and $\eta \approx 2$	2.4% (6.4%)	2.0% (11%)
-p = 100 GeV and $\eta \approx 0$	2.6% (3.1%)	1.2% (9%)
-p = 100 GeV and $\eta \approx 2$	2.1% (3.1%)	1.7% (18%)
-p = 1000 GeV and $\eta \approx 0$	10.4% (10.5%)	4.5% (13%)
-p = 1000 GeV and $\eta \approx 2$	4.4% (4.6%)	7.0% (35%)

CMS muon performance driven by tracker: better than ATLAS at η ~ 0;
ATLAS muon stand-alone performance excellent over whole η range

	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)





How huge are ATLAS and CMS?

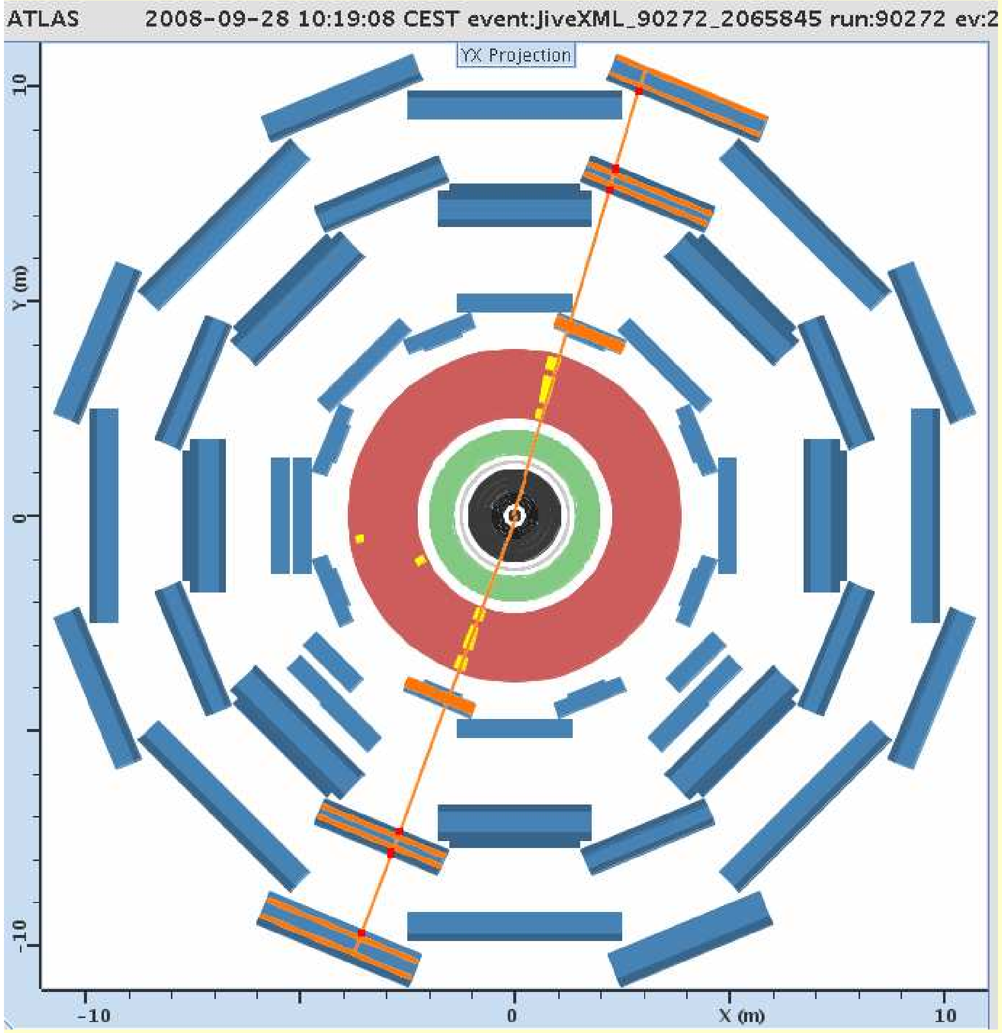
Size of detectors:

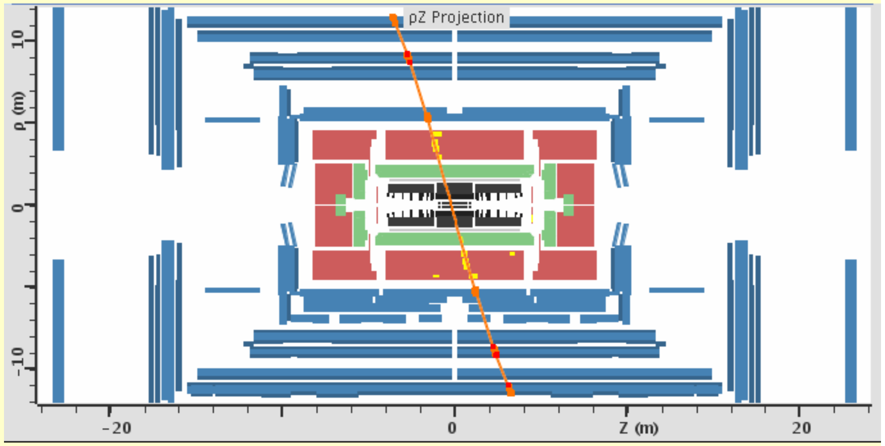
- Volume: 20 000 m^3 for ATLAS
- Weight: 12 500 tons for CMS
- 66 to 80 million pixel readout channels near vertex
- 200 m^2 of active silicon for CMS tracker
- 175 000 readout channels for ATLAS LAr EM calorimeter
- 1 million channels and 10 000 m^2 area of muon chambers
- Very selective trigger/DAQ system
- Large-scale offline software and worldwide computing (GRID)

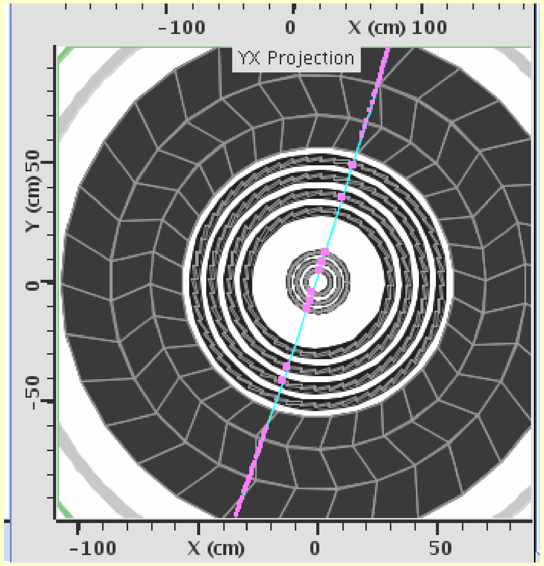
Time-scale:

Will have been > 25 years from first conceptual studies (Lausanne 1984) to solid physics results confirming that LHC will have taken over the high-energy frontier from Tevatron

ATLAS Commissioning

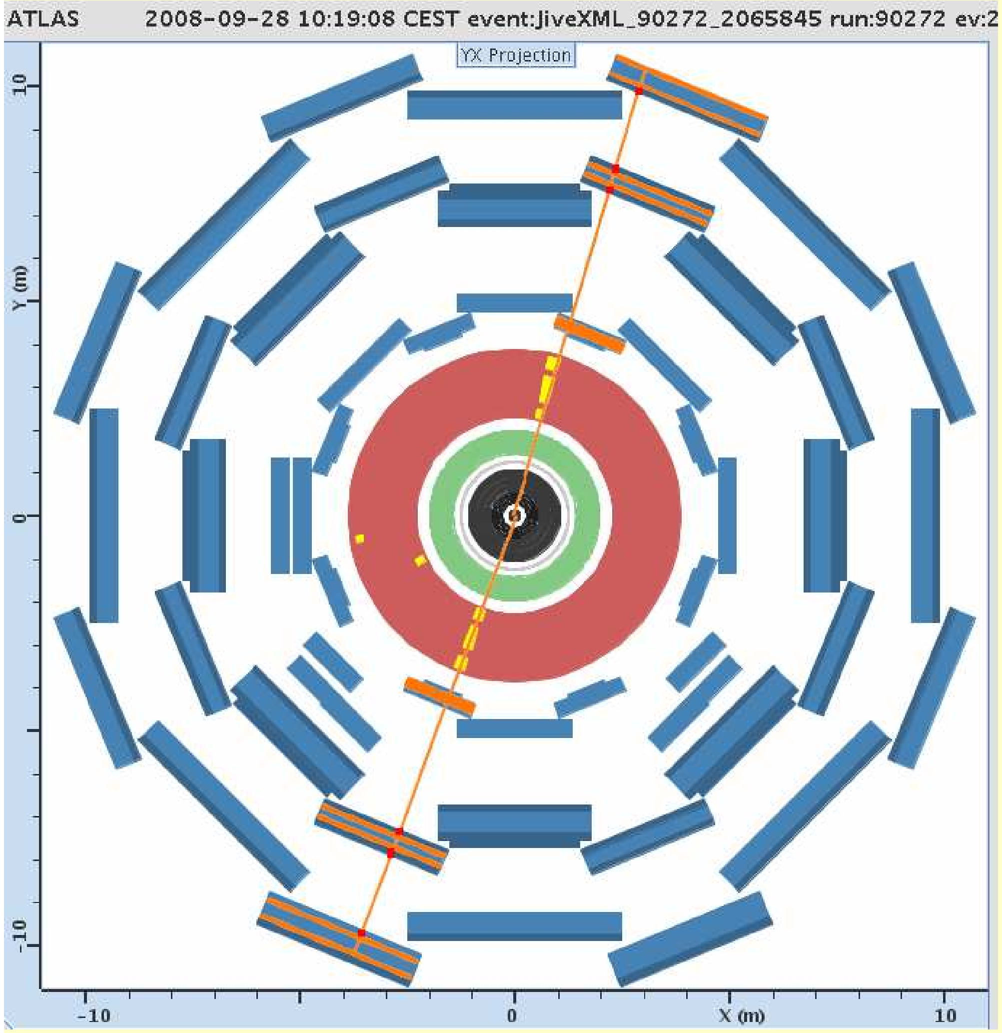


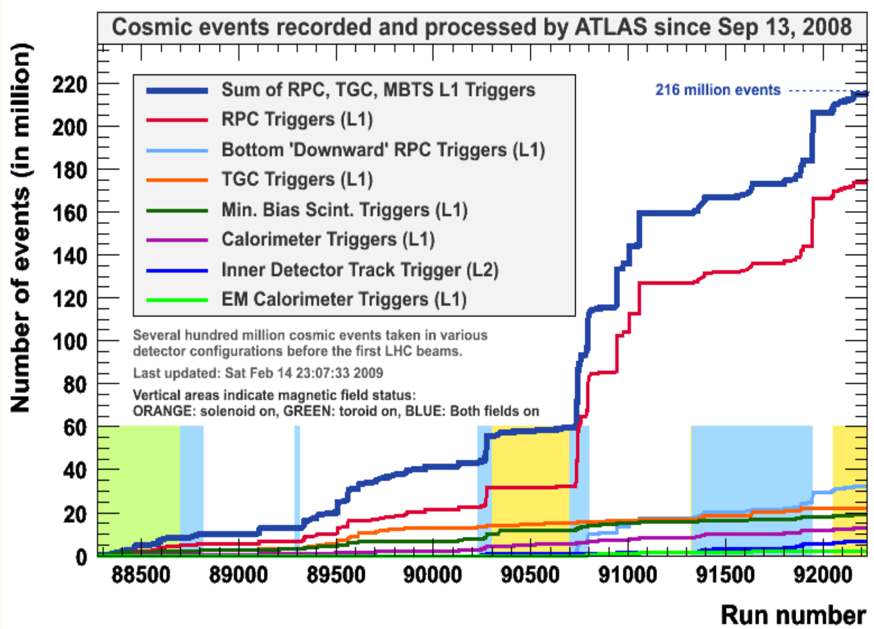




with cosmic rays.....

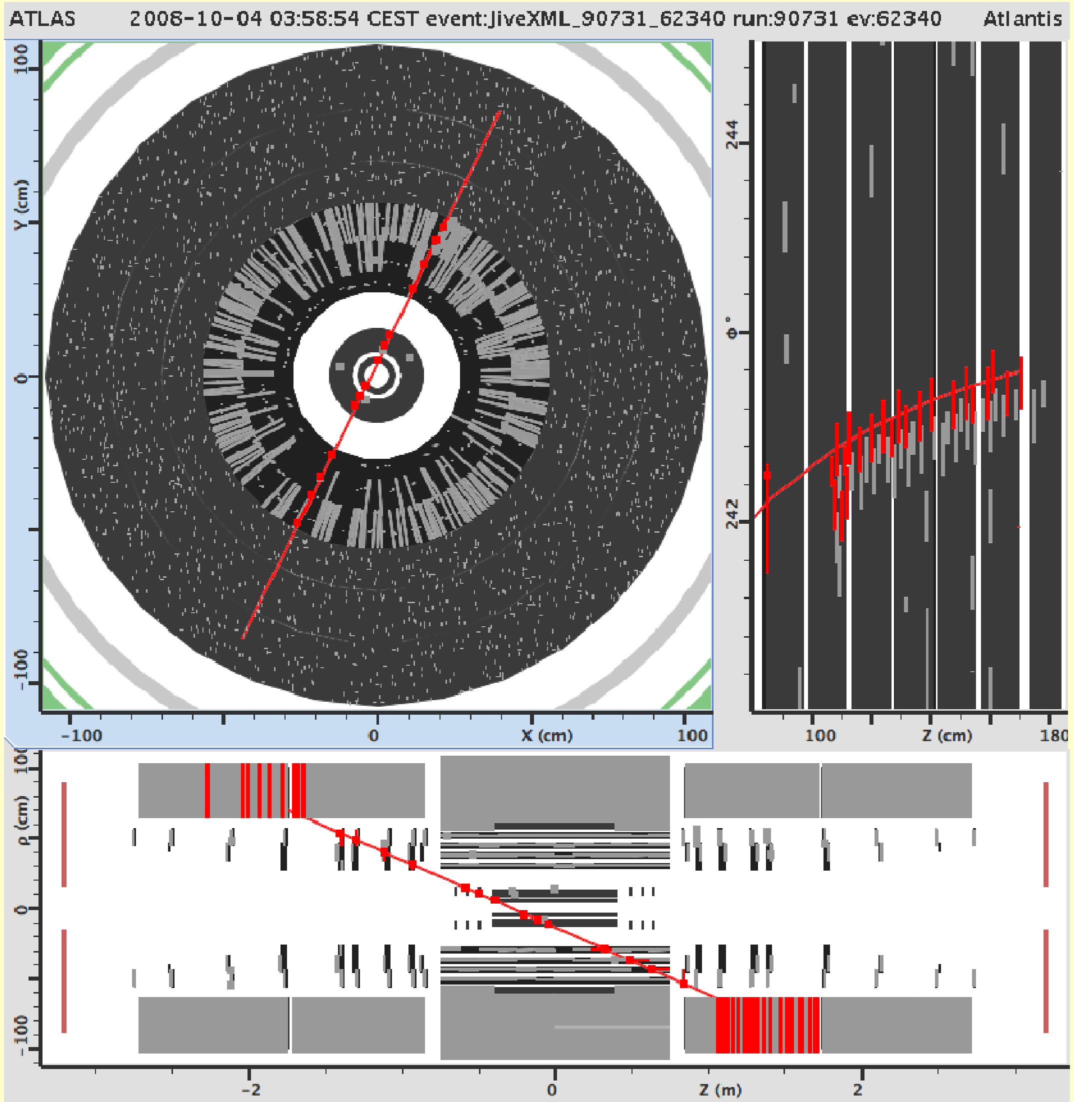
Commissioning with cosmics





more than 200 M events recorded since Oct. 08

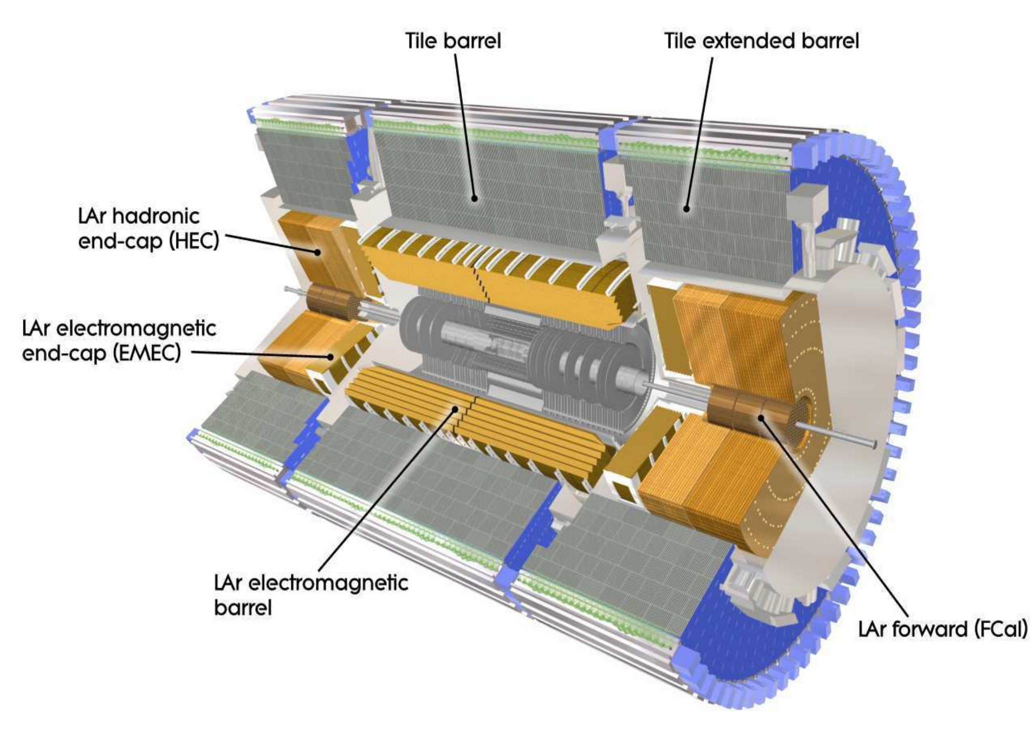
A combined barrel + endcap track



- Hits in:
  - TRT (endcap)
  - SCT (endcap and barrel)
  - Pixels (endcap and barrel)

- Very useful for alignment

The Calorimeters



- Fine granularity in region of Inner Detector acceptance, $|\eta| < 2.5$:
  - $\sigma/E \sim 10\%/\sqrt{E} \oplus 0.7\%$
  - Linearity to ~0.1%

- Coarser granularity in the other regions sufficient for jet reconstruction and E_T^{miss} measurements
  - $\sigma/E \sim 50\% / \sqrt{E} \oplus 3\%$ (barrel / endcap)
  - $\sigma/E \sim 100\%/\sqrt{E} \oplus 10\%$ (forward)

Commissioning since ~3 years

- Good performance, small number of "dead channels":

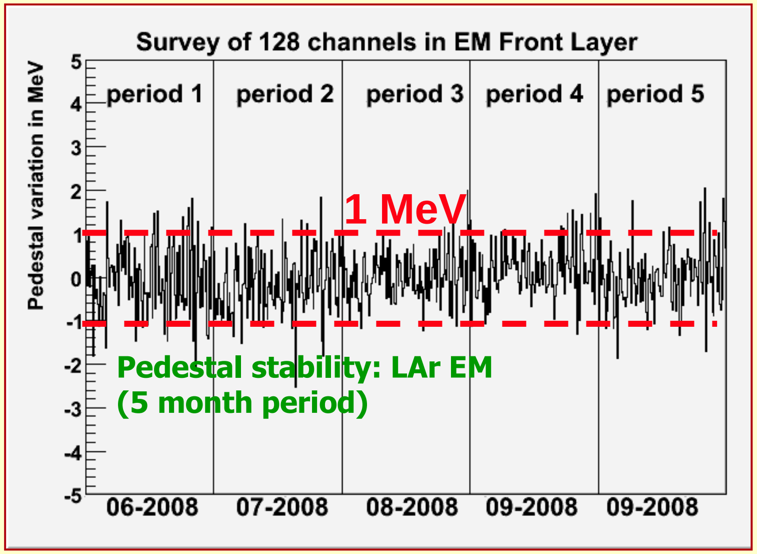
  - EM: ~0.01%
  - HEC: ~0.1%
    (+ Low voltage power supply problems, impacting ¼ of an endcap)
  - FCal: none
  - Tile Calorimeter: ~1.5%

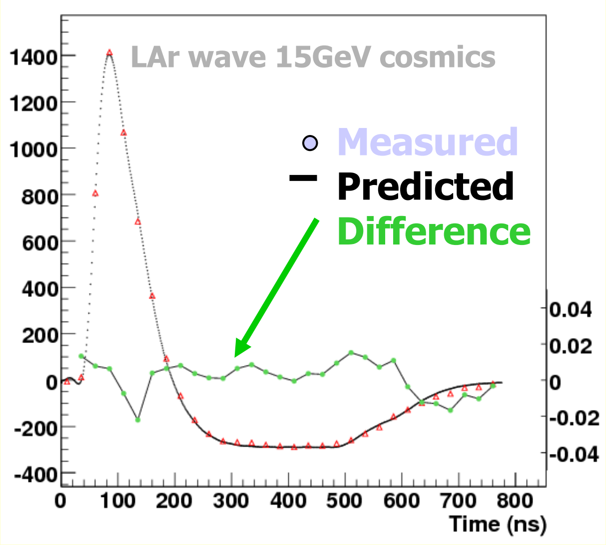
  Most of them recovered during the shutdown

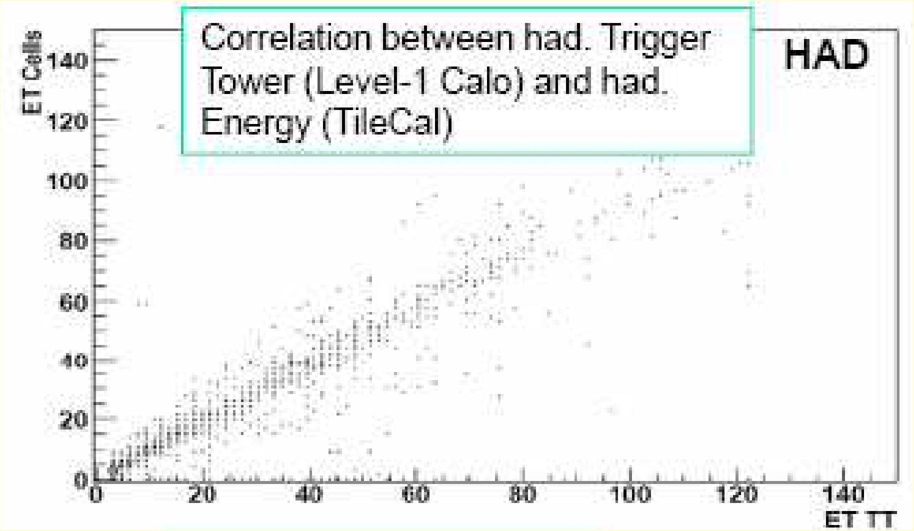
- Effort is now more focussed on:

  * Long term stability
  * Prediction of the signal
  * Extraction of calibration constants

Some calorimeter commissioning results

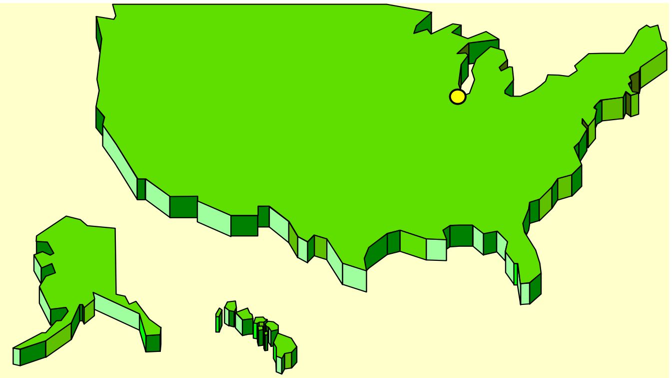




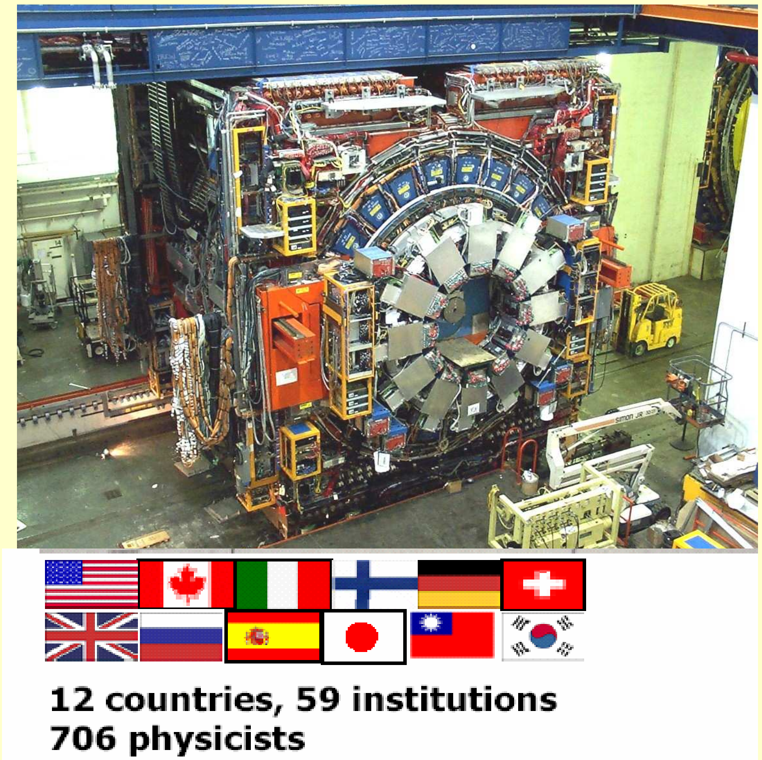


Precise knowledge is very important
for an accurate calibration

Back to the Tevatron



The CDF experiment

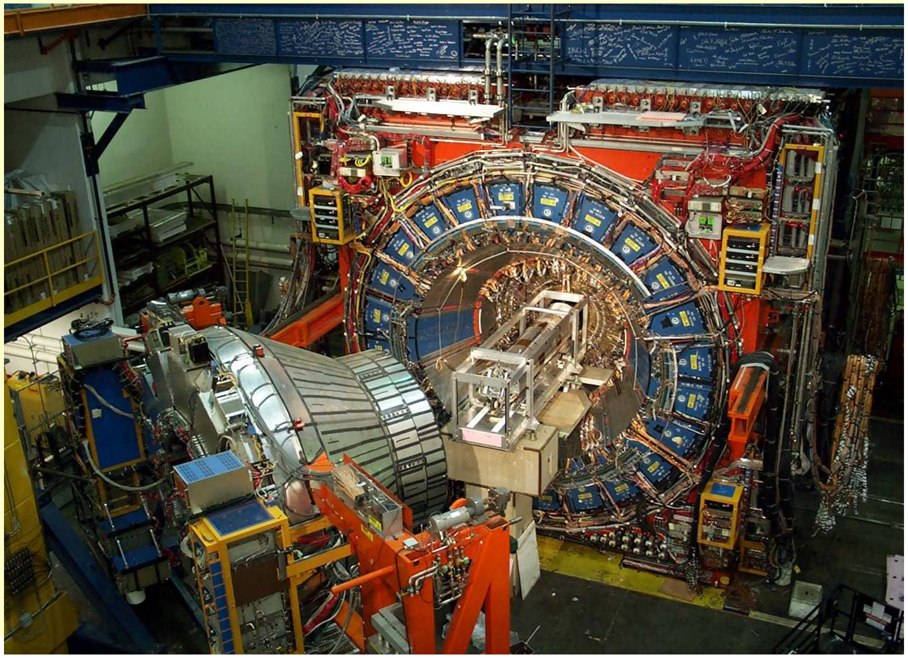


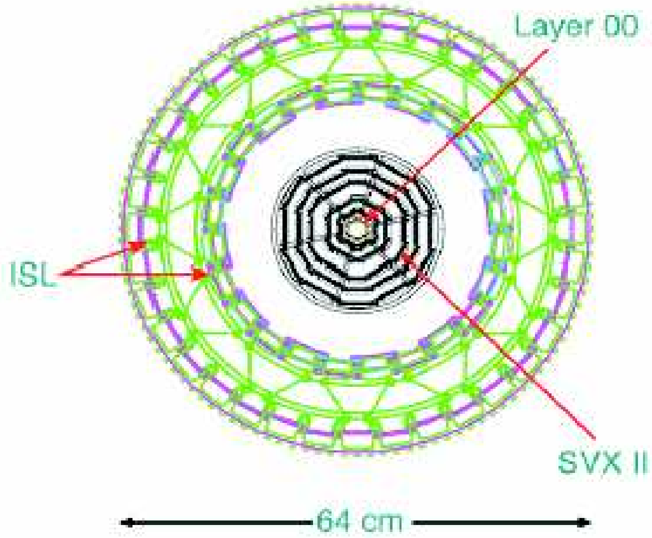
The DØ collaboration

19 countries, 83 institutions
664 physicists

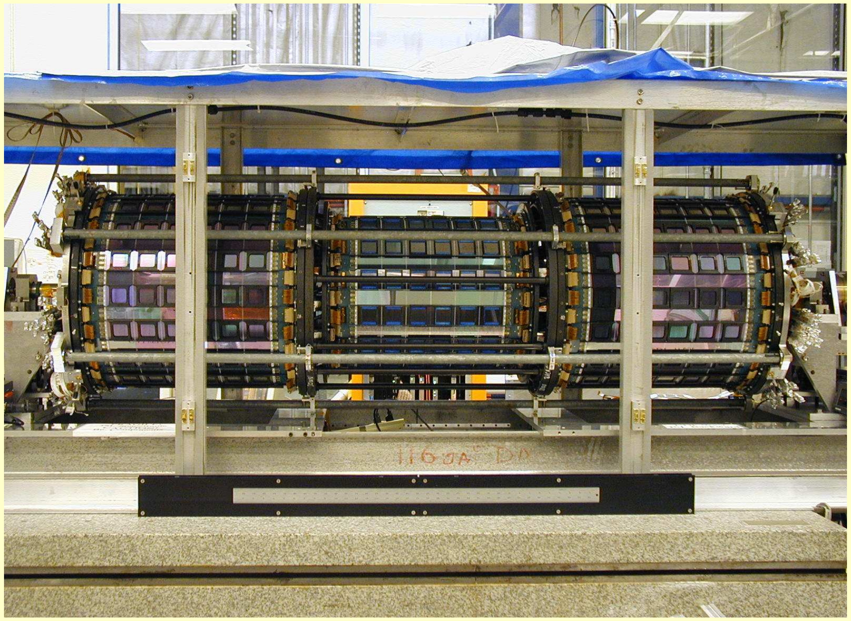
The CDF detector in Run II

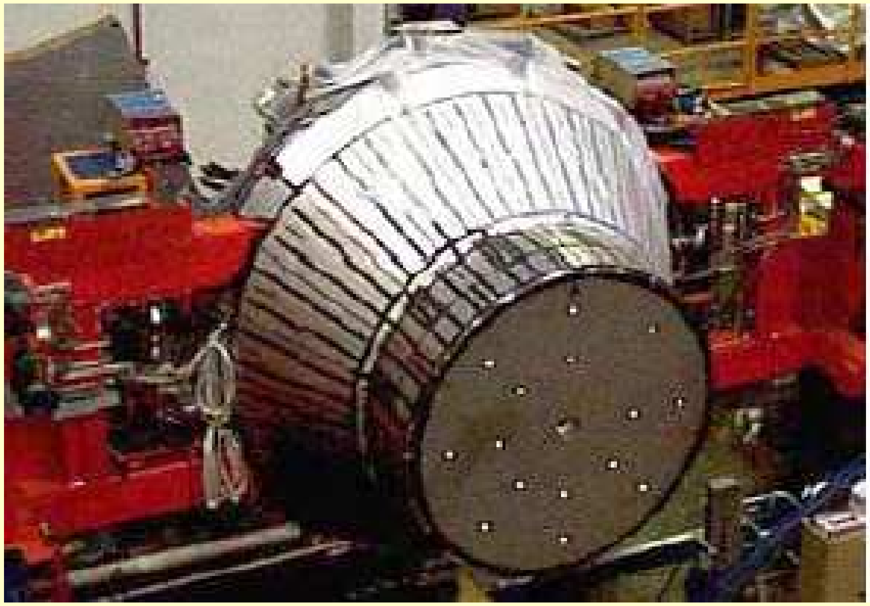
- Core detector operates since 1985:
  - Central Calorimeters
  - Central muon chambers
- Major upgrades for Run II:
  - Drift chamber (central tracker)
  - **Silicon tracking detector**:
    SVX, ISL, Layer 00
    - 8 layers
    - 700k readout channels
    - 6 m^2
    - material:15% X_0
  - Forward calorimeters
  - Forward muon system
  - Time-of-flight system
  - Trigger and DAQ
  - Front-end electronics



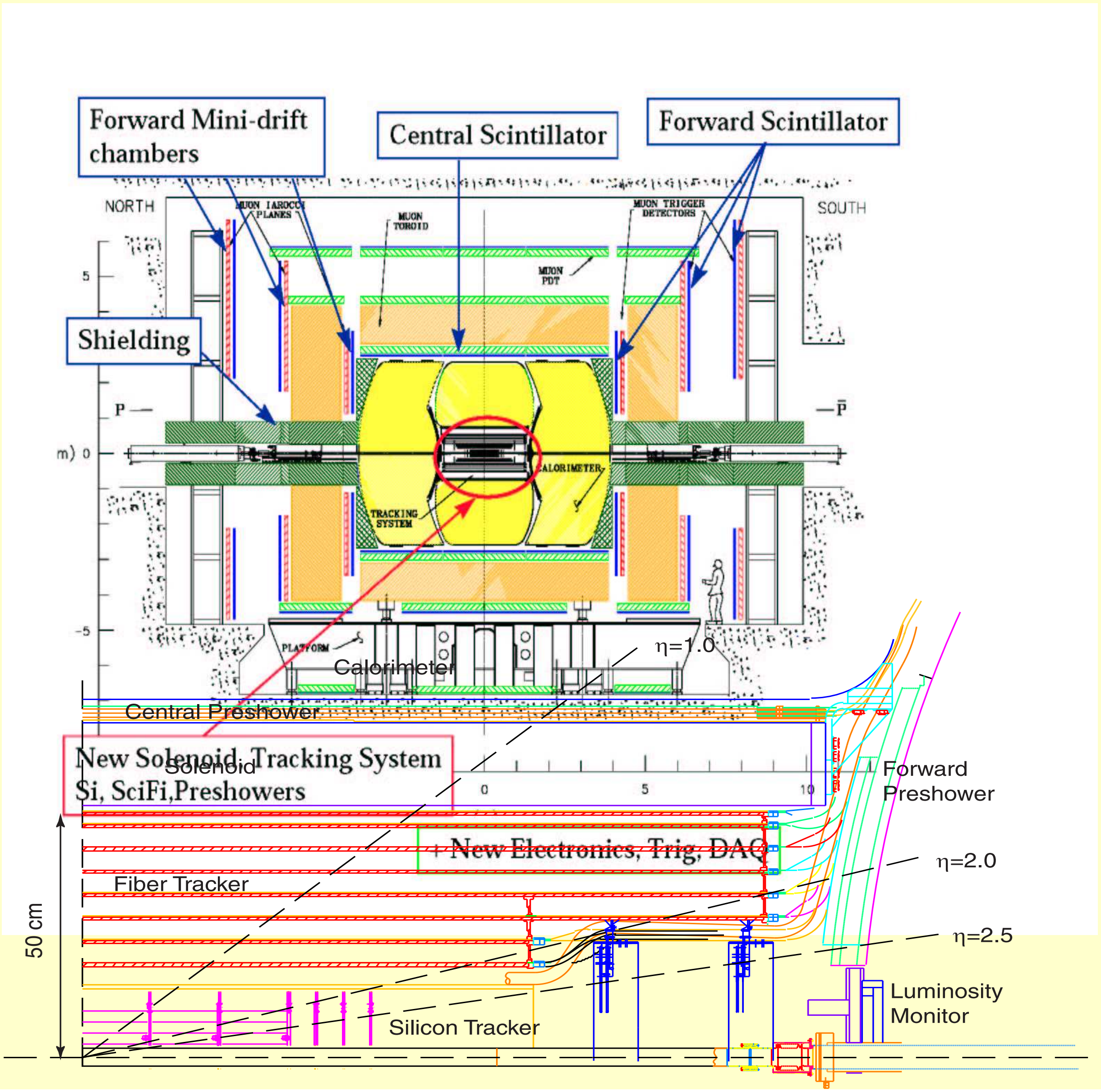


Some new CDF subdetectors





The DØ Run II Detector



Retained from Run I

- LAr calorimeter
- Central muon detector
- Muon toroid

New for Run II

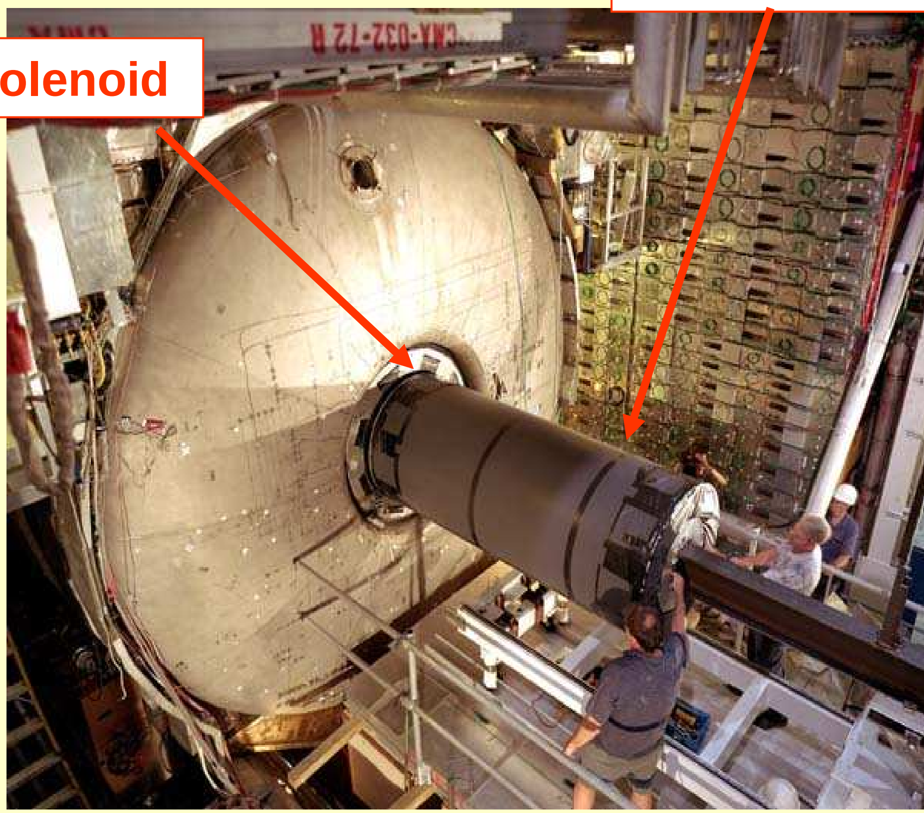
Inner detector (tracking)

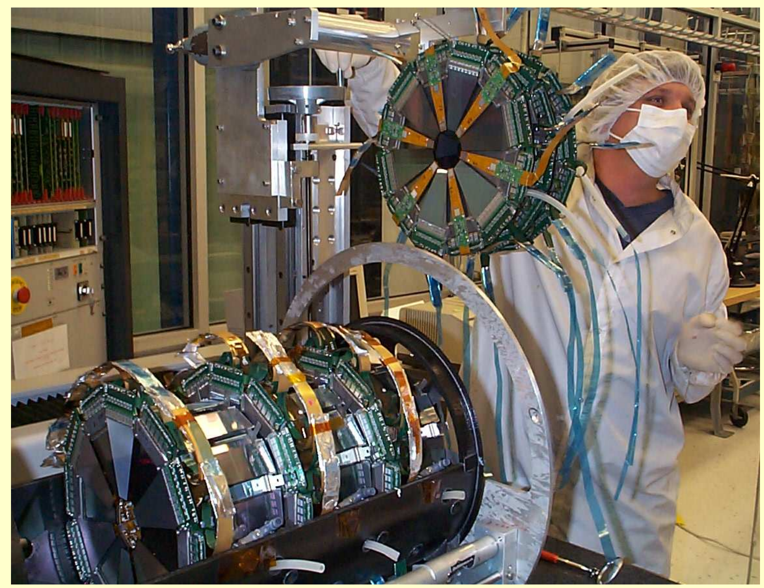
Magnetic field added

- Preshower detectors
- Forward muon detector
- Front-end electronics
- Trigger and DAQ

In addition: Inner B-layer (similar to CDF)

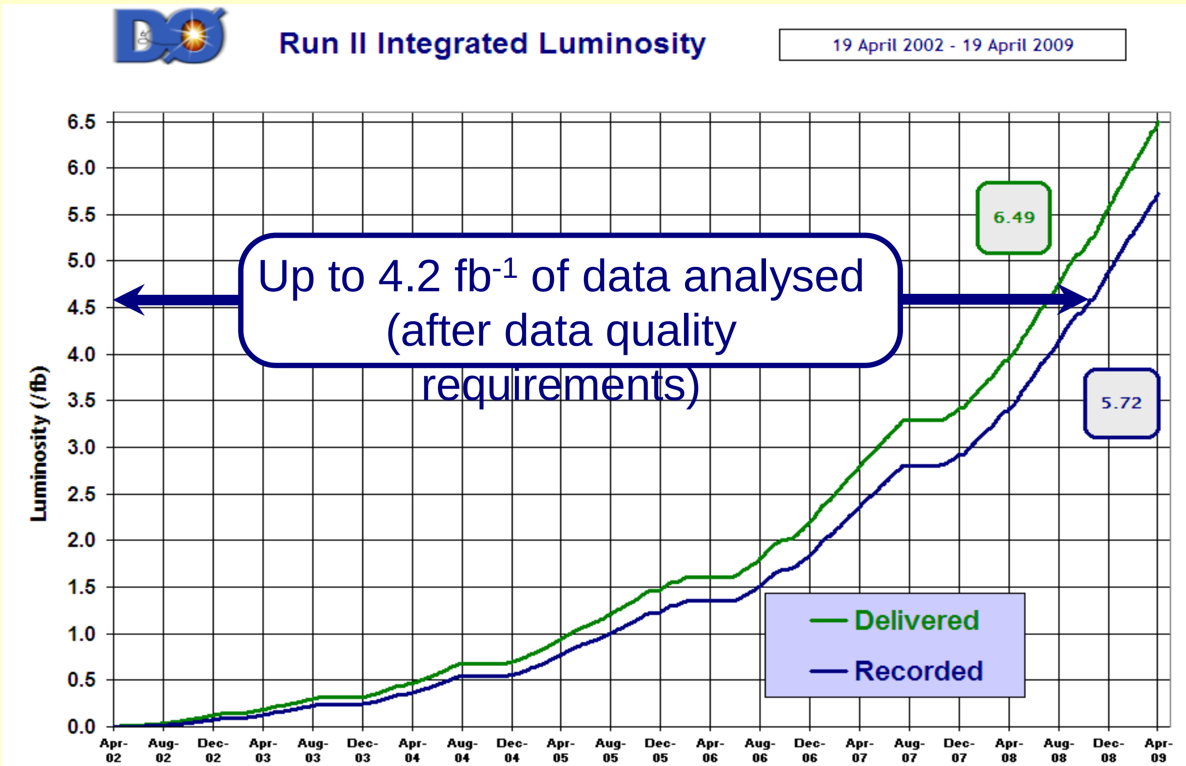
DØ Detector





Data set

Tevatron delivers a data set equal to Run I (~100 pb^{-1}) every 2 weeks
+ Well understood detectors with data taking efficiencies of ~90%



Similar for CDF

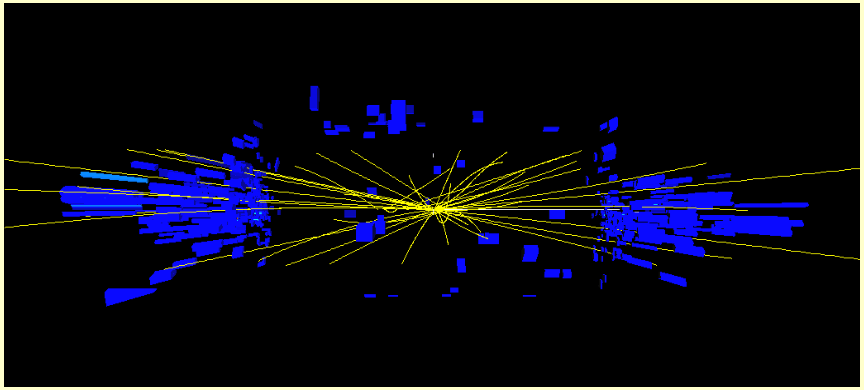
$$N_{event}\ [1/s] = \sigma \cdot L \cdot \varepsilon\ (\text{efficiency} \cdot \text{acceptance})$$

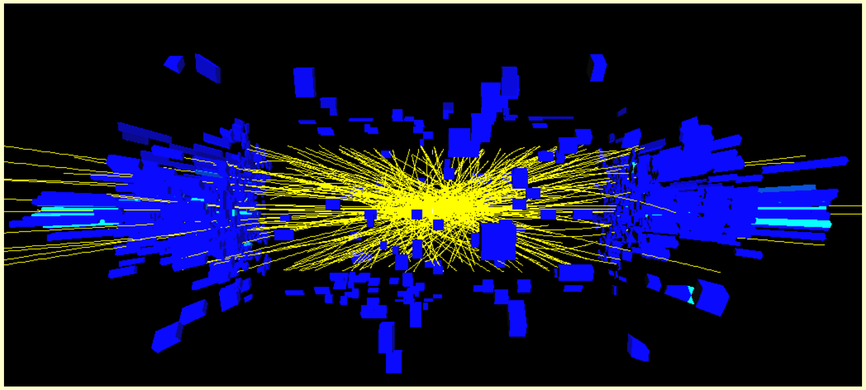
Physics *accelerator* *experiment*

(data taking, detector acceptance, reconstruction efficiency)

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}

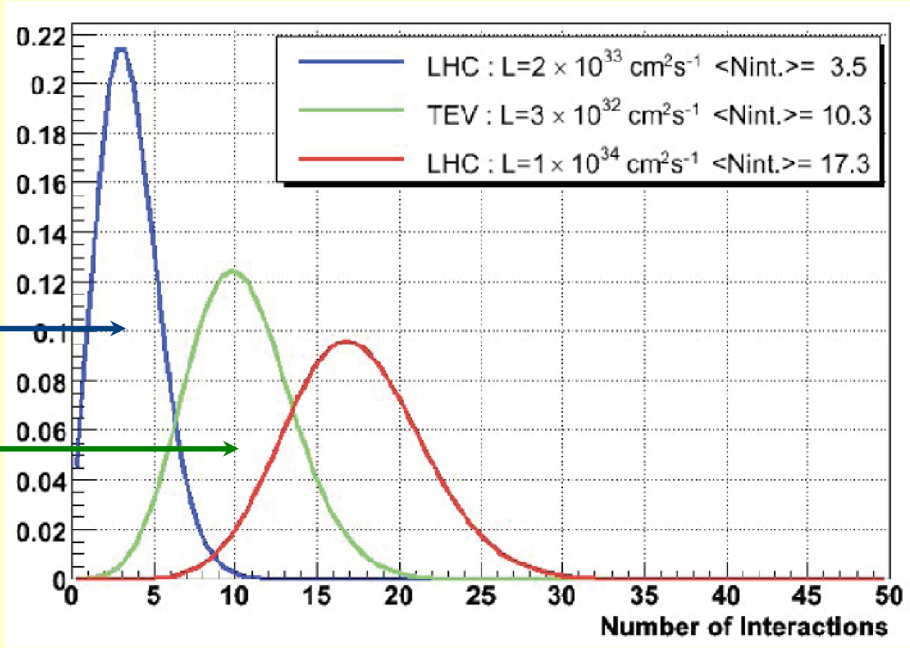




Average number of interactions:

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



How are the interesting events selected ?

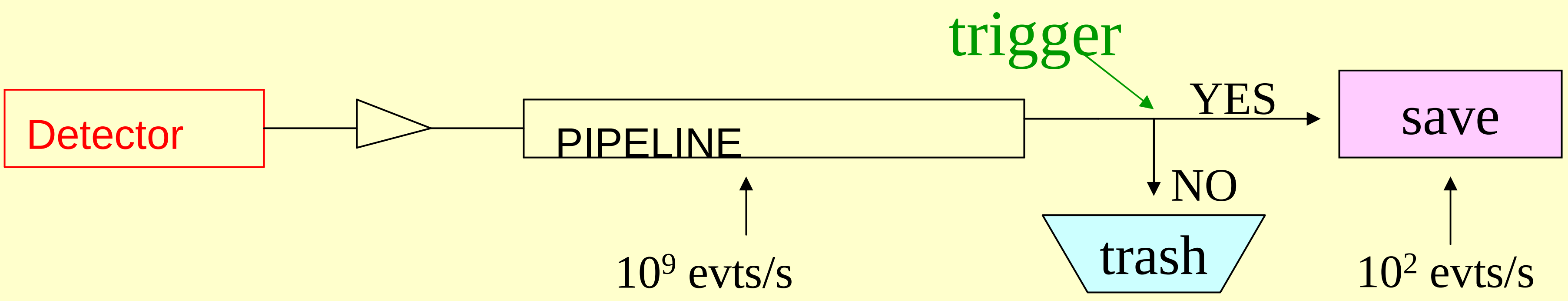
TRIGGER: much more difficult than at e^+e^- machines

Interaction rate: ~ 10^9 events/s
Can record ~ 200 events/s (event size 1 MB)

$\Rightarrow$ **trigger rejection ~ 10^7**

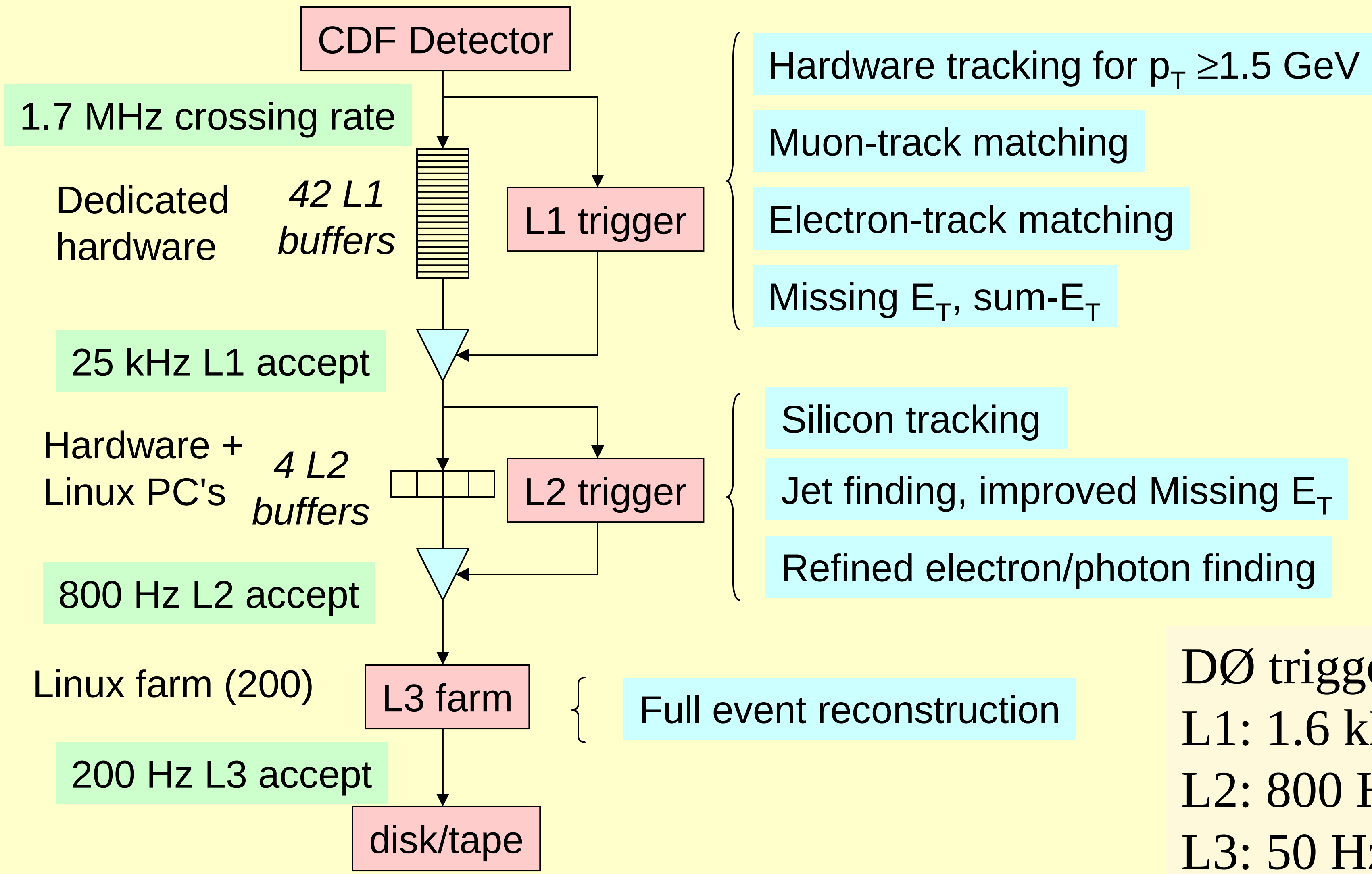
Trigger decision $\approx \mu s \rightarrow$ larger than interaction rate of 25 ns

store massive amount of data in **pipelines**
while special trigger processors perform calculations



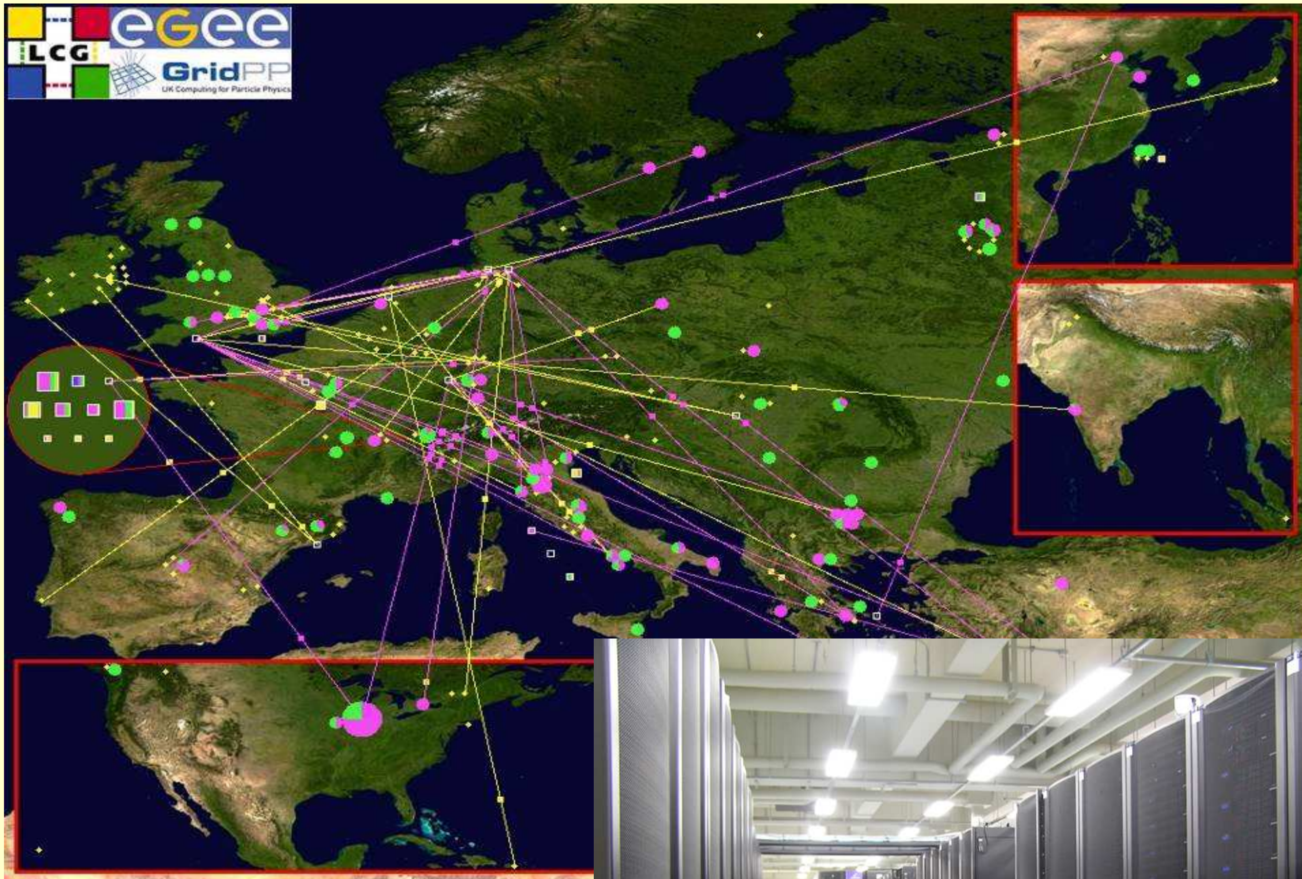
Triggering at hadron colliders

The trigger is the key at hadron colliders



DØ trigger:
L1: 1.6 kHz
L2: 800 Hz
L3: 50 Hz

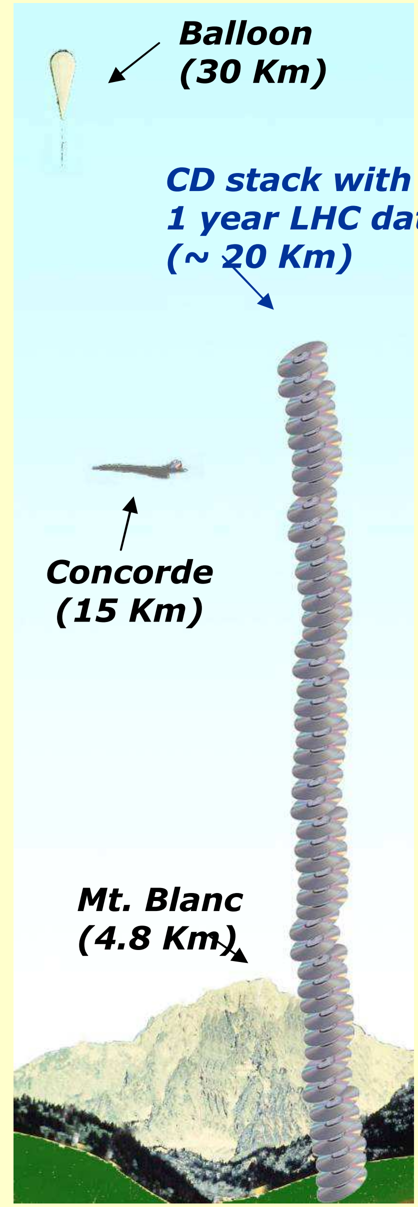
LHC data handling, GRID computing



Trigger system selects
~200 “collisions” per sec.

LHC data volume per year:
10-15 Petabytes
= 10-15 $\cdot 10^{15}$ Byte

A typical Tier-2 GRID center
(example: Tokyo University)



Towards Physics:

some aspects of reconstruction of physics objects

• As discussed before, key signatures at Hadron Colliders are

Leptons: e (tracking + very good electromagnetic calorimetry)
μ (dedicated muon systems, combination of inner tracking and muon spectrometers)
τ hadronic decays: $\tau \rightarrow \pi^+ + n\,\pi^0 + \nu$ (1 prong)
$\rightarrow \pi^+\pi^-\pi^+ + n\,\pi^0 + \nu$ (3 prong)

Photons: γ (tracking + very good electromagnetic calorimetry)

Jets: electromagnetic and hadronic calorimeters
b-jets identification of b-jets (b-tagging) important for many physics studies

Missing transverse energy: inferred from the measurement of the total energy in the calorimeters; needs understanding of all components… response of the calorimeter to low energy particles

Requirements on e/γ Identification in ATLAS/CMS

- Electron identification
- Isolated electrons: e/jet separation
  - R_{jet} ~ 10^5 needed in the range p_T > 20 GeV
  - R_{jet} ~ 10^6 for a pure electron inclusive sample (ε_e ~ 60-70%)
- Soft electron identification – e/π separation
  - B physics studies (J/ψ)
  - Soft electron b-tagging (WH, ttH with H $\rightarrow$ bb)

- Photon identification
- γ/jet and γ/π^0 separation
  - Main reducible background to H $\rightarrow \gamma\gamma$ comes from jet-jet and is ~ 2 $\cdot 10^6$ larger than signal
  - R_{jet} ~5000 in the range E_T >25 GeV
  - R (isolated high-p_T π^0) ~3
- Identification of conversions

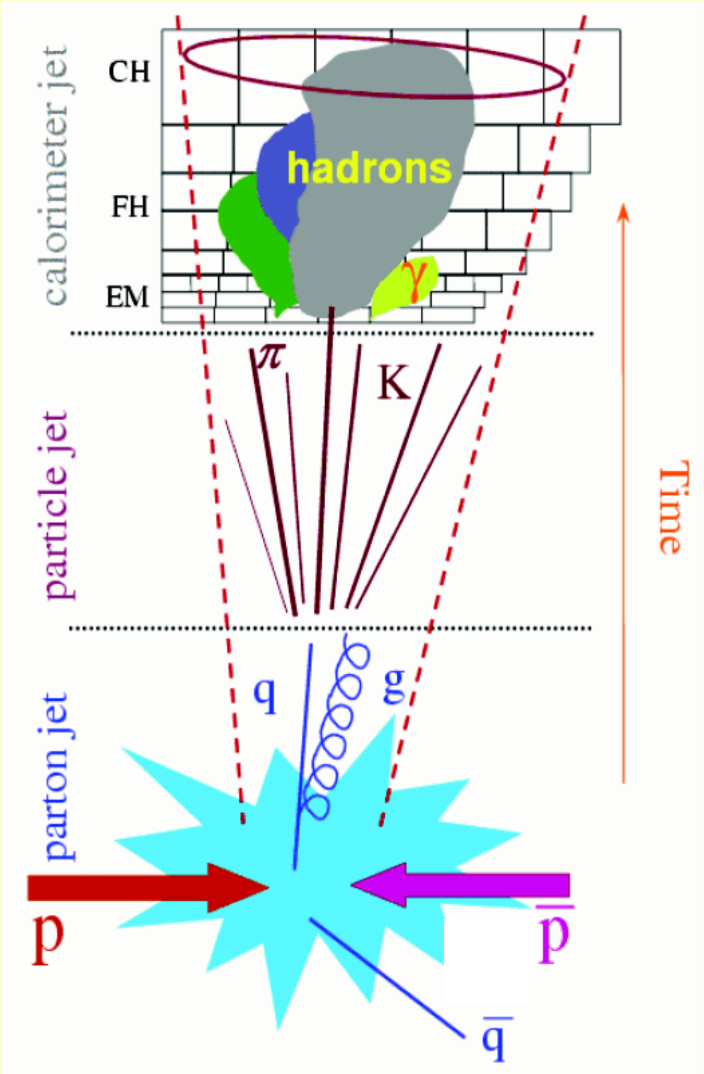
Jet reconstruction and energy measurement

- A jet is NOT a well defined object
  (fragmentation, gluon radiation, detector response)

- The detector response is different for particles interacting electromagnetically (e,γ) and for hadrons
  → for comparisons with theory, one needs to correct back the calorimeter energies to the „particle level“ (particle jet)
  Common ground between theory and experiment

- One needs an algorithm to define a jet and to measure its energy
  conflicting requirements between experiment and theory (exp. simple, e.g. cone algorithm, vs. theoretically sound (no infrared divergencies))

- Energy corrections for losses of fragmentation products outside jet definition and underlying event or pileup energy inside

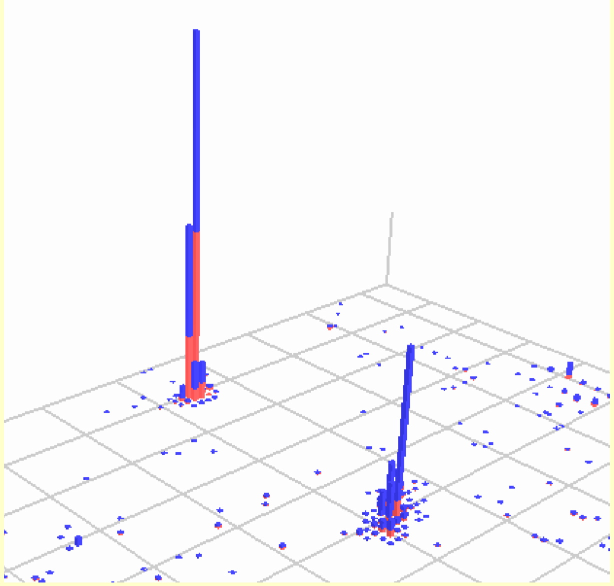


Main corrections:

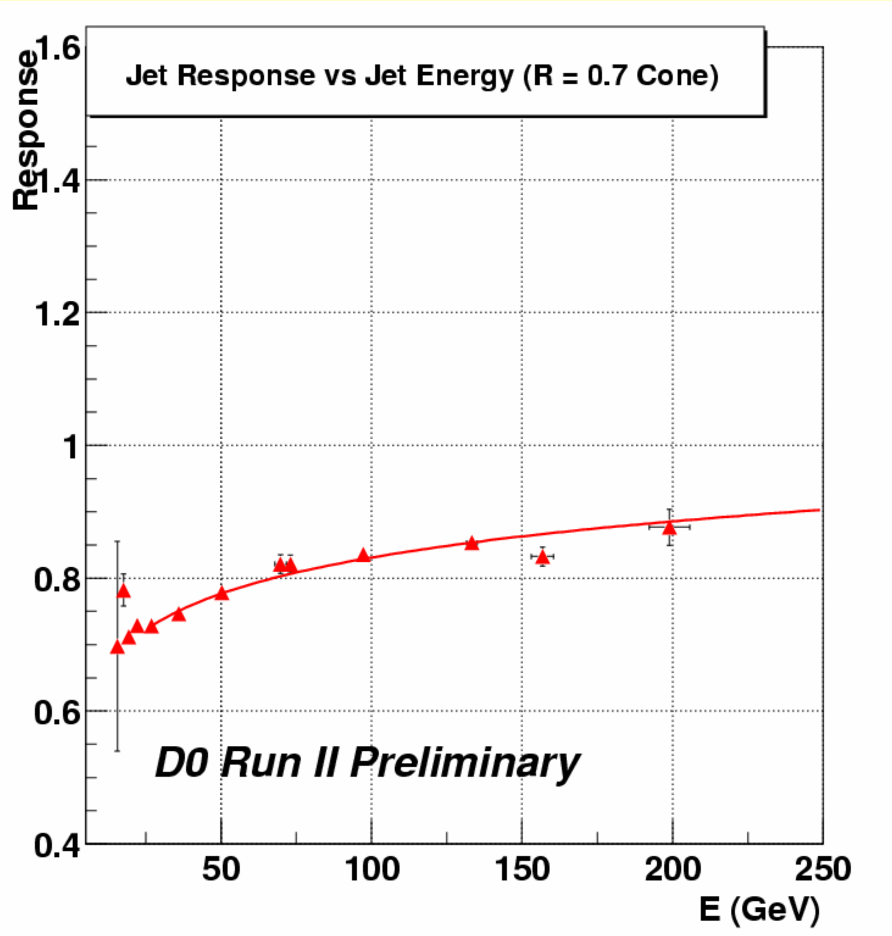
- In general, calorimeters show different response to electrons/photons and hadrons

- Subtraction of offset energy not originating from the hard scattering
 (inside the same collision or pile-up contributions, use minimum bias data
 to extract this)

- Correction for jet energy out of cone
 (corrected with jet data + Monte Carlo simulations)

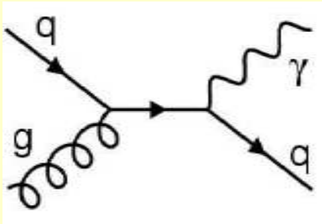


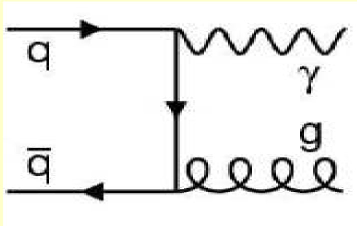
Jet Energy Scale



Jet response correction in DØ:

- Measure response of particles making up the jet
- Use photon + jet data - calibrate jets against the better calibrated photon energy





- Achieved jet energy scale uncertainty:

DØ: $\Delta E / E$ ~1-2%
(excellent result, a huge effort)

Jet energy scale at the LHC

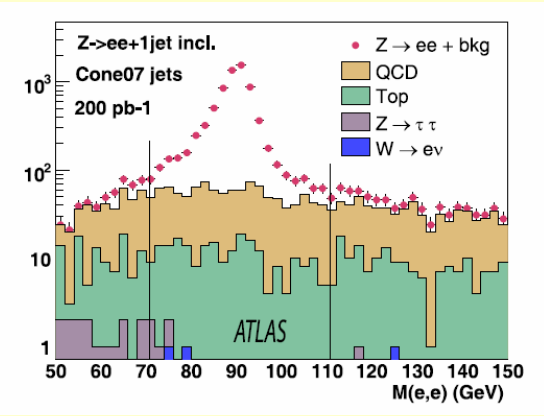
- A good jet-energy scale determination is essential for many QCD measurements (arguments similar to Tevatron, but kinematic range (jet p_T) is larger, ~20 GeV – ~3 TeV)

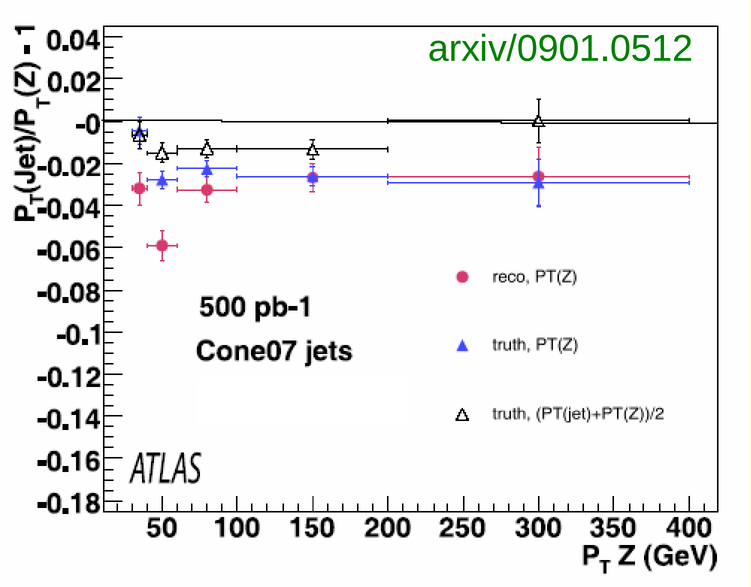
- Propagate knowledge of the em scale to the hadronic scale, but several processes are needed to cover the large p_T range

Measurement process	**Jet p_T range**
Z + jet balance	$20 < p_T < 100 – 200$ GeV
γ + jet balance	$50 < p_T < 500$ GeV (trigger, QCD background)
Multijet balance	$500 \text{ GeV} < p_T$

Reasonable goal: 5-10% in first runs (1 fb^{-1})
1- 2% long term

Example: Z + jet balance





Stat. precision (500 pb^{-1}): 0.8%
Systematics: 5-10% at low p_T, 1% at high p_T