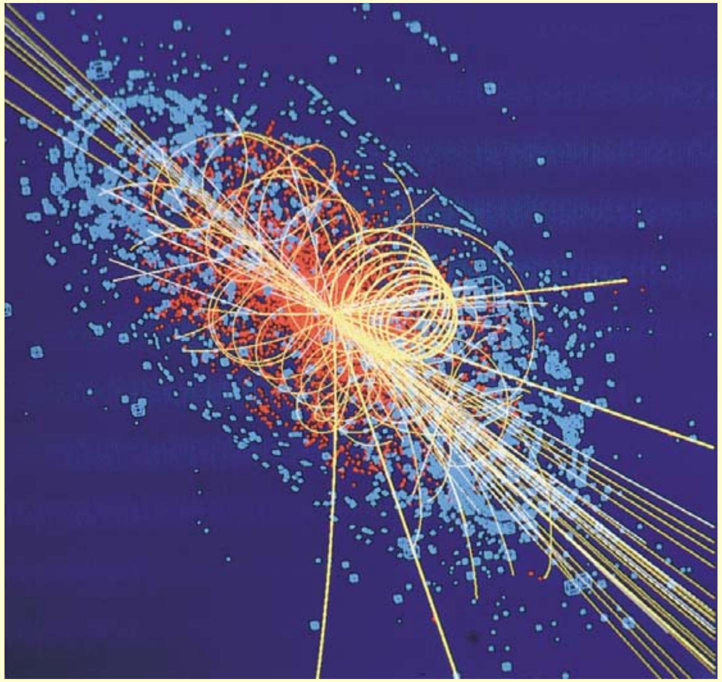
Physics at Hadron Colliders

-From the Tevatron to the LHC-



- **Introduction to Hadron Collider Physics**

- **The present Hadron Colliders**
  - The Tevatron and the LHC
  - The experiments

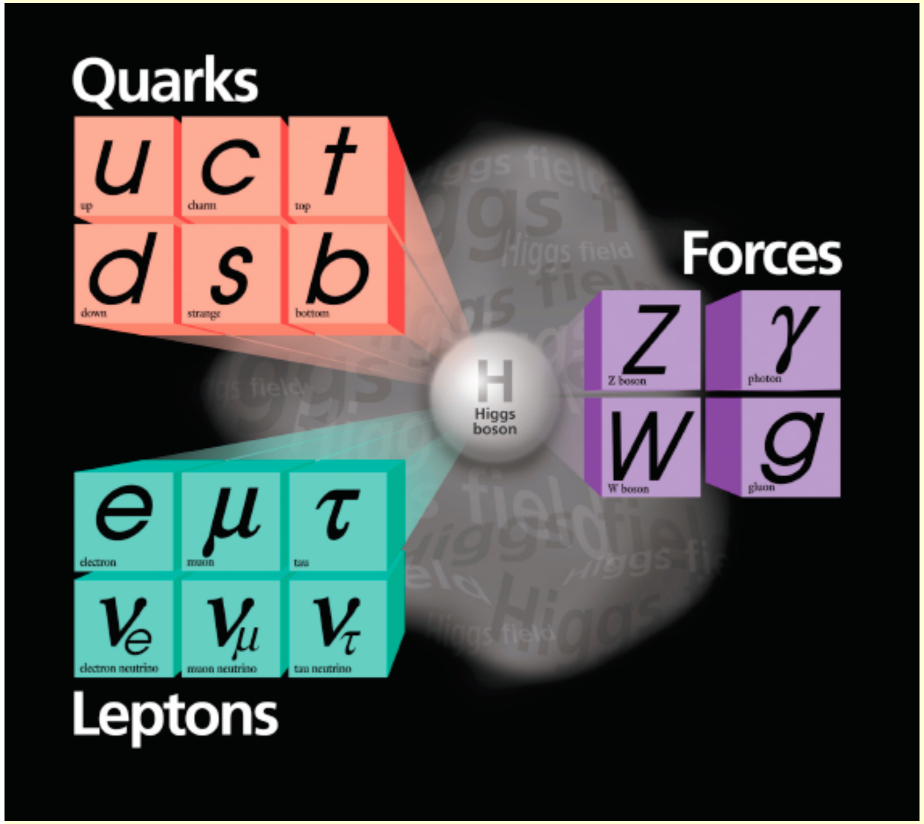
- **Test of the Standard Model**
  - QCD: Jet, W/Z, top-quark production
  - W and top-quark mass measurements

- **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

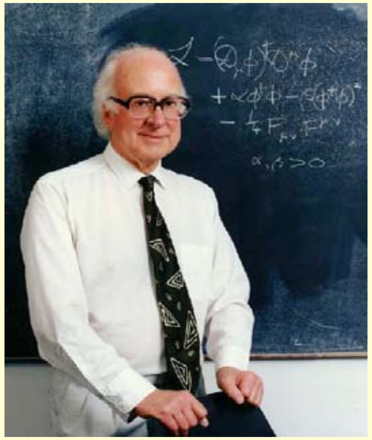
→ Higgs particle (see lecture by C. Grojean)

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

Where do we stand today?

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

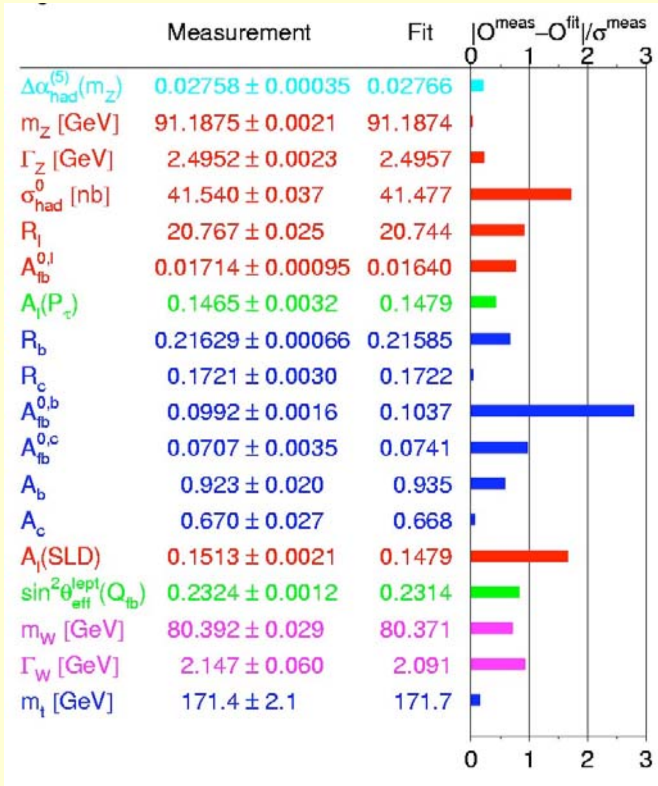
- The Standard Model is consistent with all experimental data !
- No Physics Beyond the SM observed
- No Higgs seen (yet)



Only unambiguous example of observed Higgs

(P. Higgs, Univ. Edinburgh)

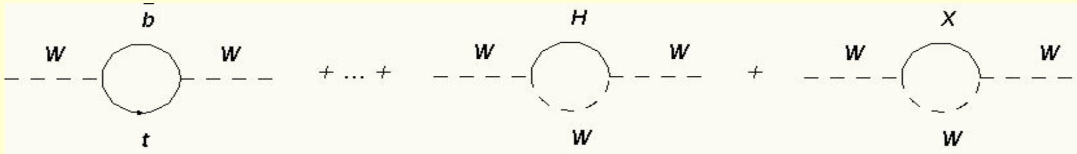
Summer 2007

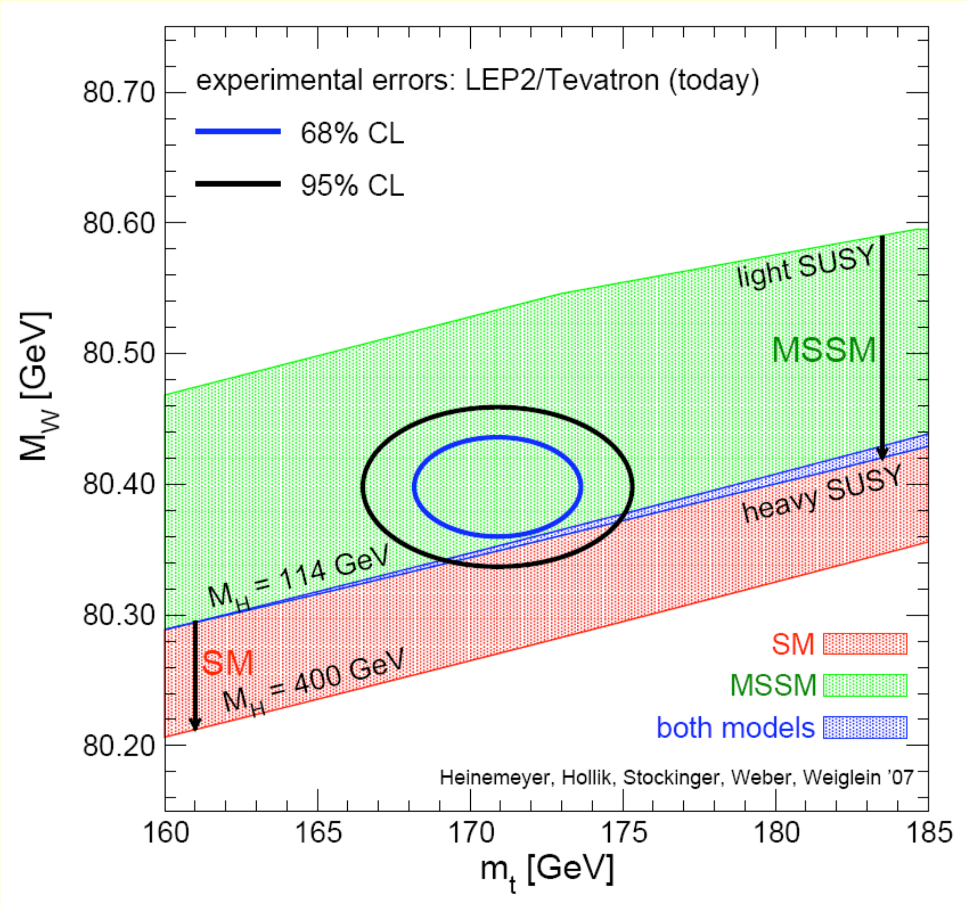


Direct searches at LEP: m_H > 114.4 GeV/c^2 (95% CL)

Consistency with the Standard Model

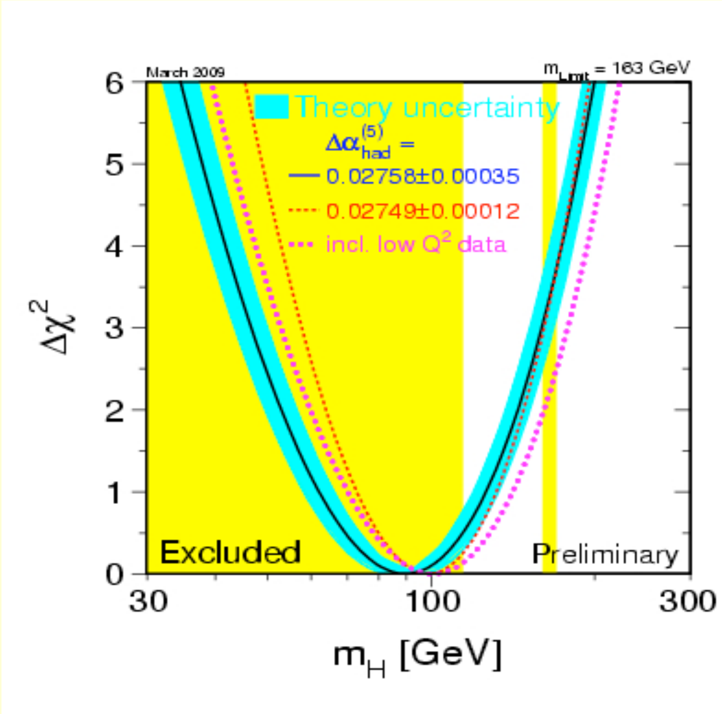
Sensitivity to the Higgs boson and other new particles via quantum corrections:





Interpretation within the Standard Model

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

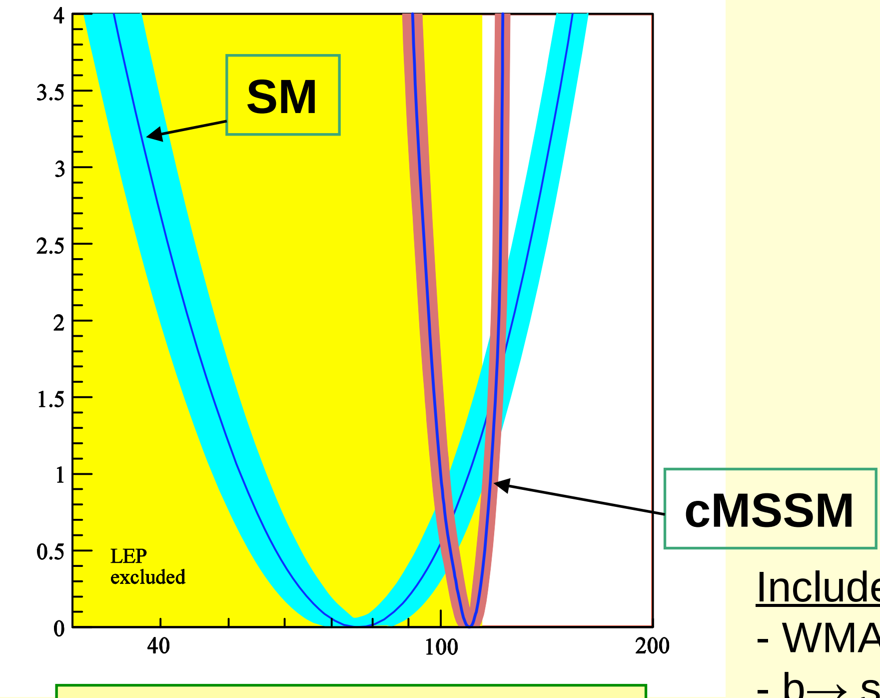


m_H = 90 (+36) (-27) GeV/c^2

m_H < 163 GeV/c^2 (95 % CL)

Constraints on the Higgs mass in a supersymmetric theory

O. Buchmüller et al., arXiv:0707.3447

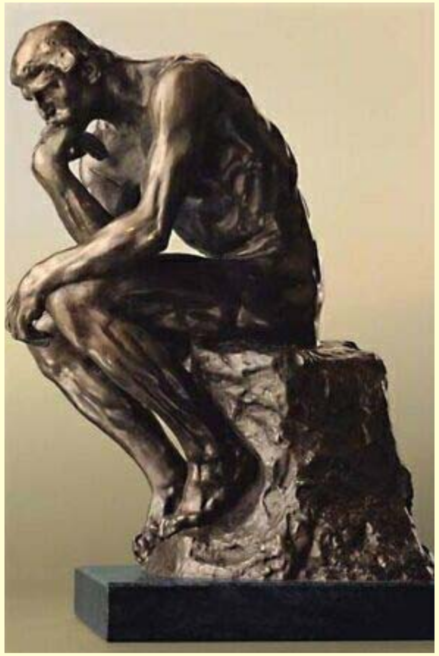


m_h = 110 (+8) (-10) ± 3 (theo) GeV/c^2

….watch the low mass region !

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

The Open Questions



Key Questions of Particle Physics

1. Mass: What is the origin of mass?

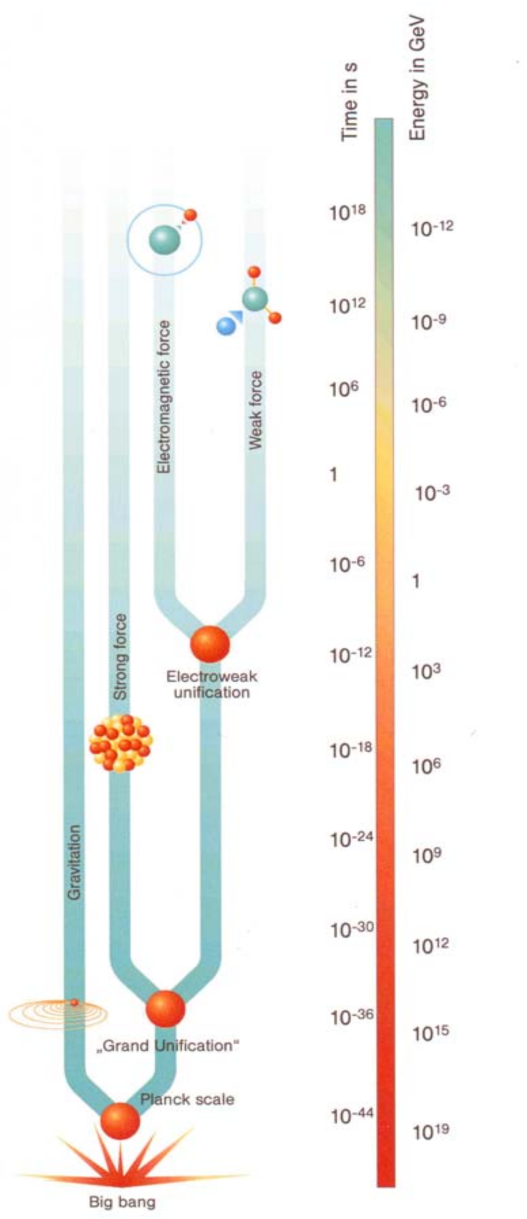
- How is the electroweak symmetry broken ?
- Does the Higgs boson exist ?

2. Unification: What is the underlying fundamental theory ?

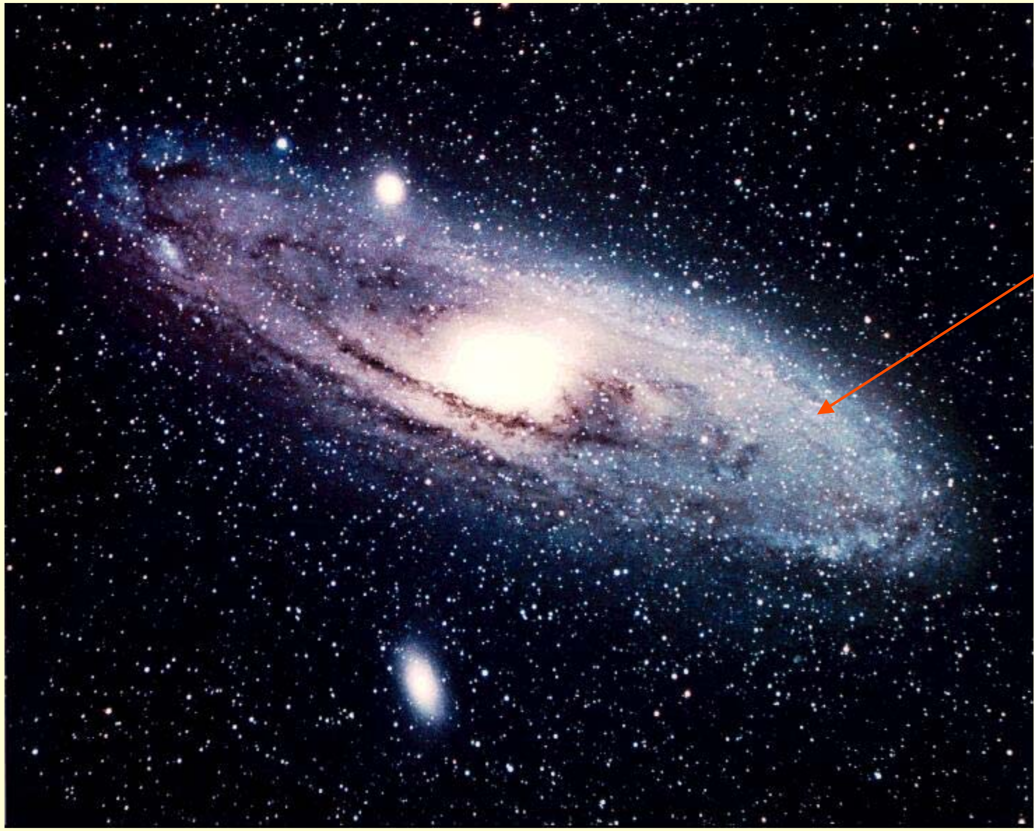
- Can the interactions be unified at larger energy?
- How can gravity be incorporated ?
- Is our world supersymmetric ?
- ....

3. Flavour: or the generation problem

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



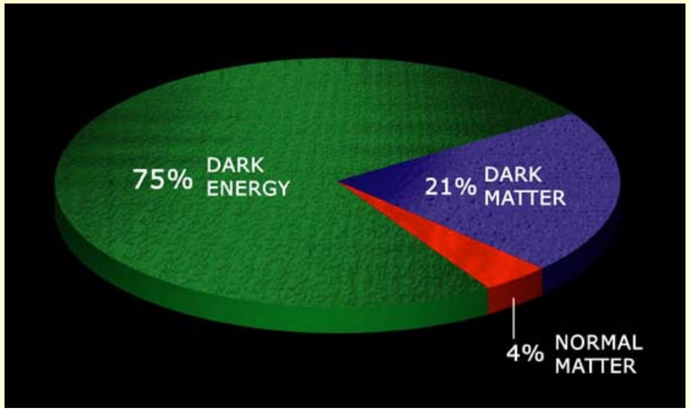
Problems at a larger scale

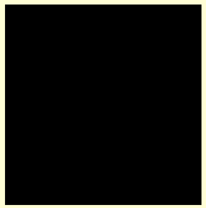


We are here

Surrounded by

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





- 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]

The role of the present Hadron Colliders

1. Explore the TeV mass scale

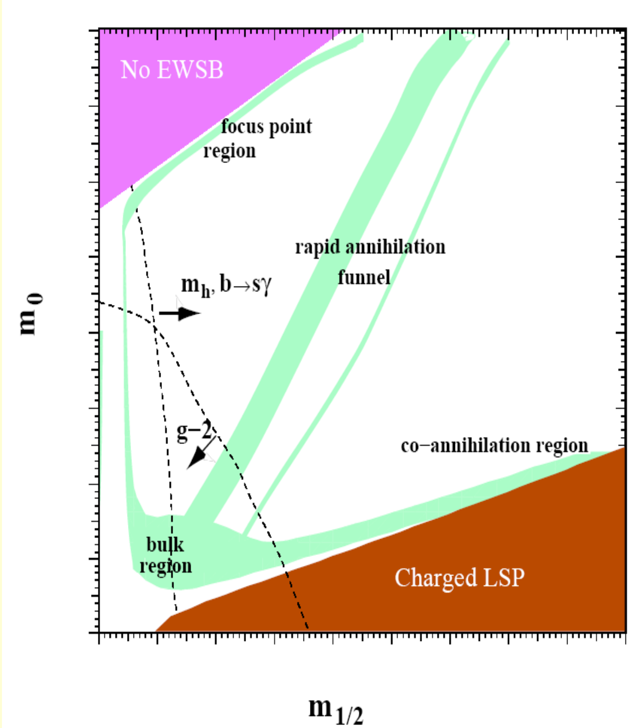
- What is the origin of the electroweak symmetry breaking ?

- 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

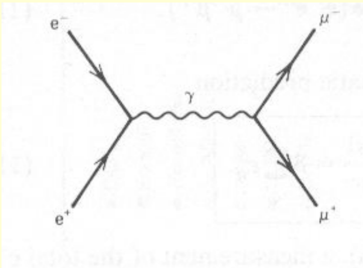
- There is much sensitivity to physics beyond the Standard Model in the precision area

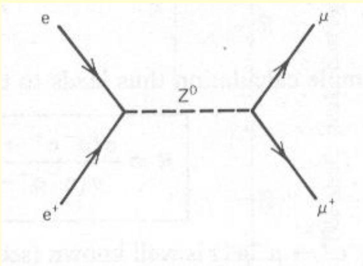
- Many Standard Model measurements can be used to test and to tune the detector performance

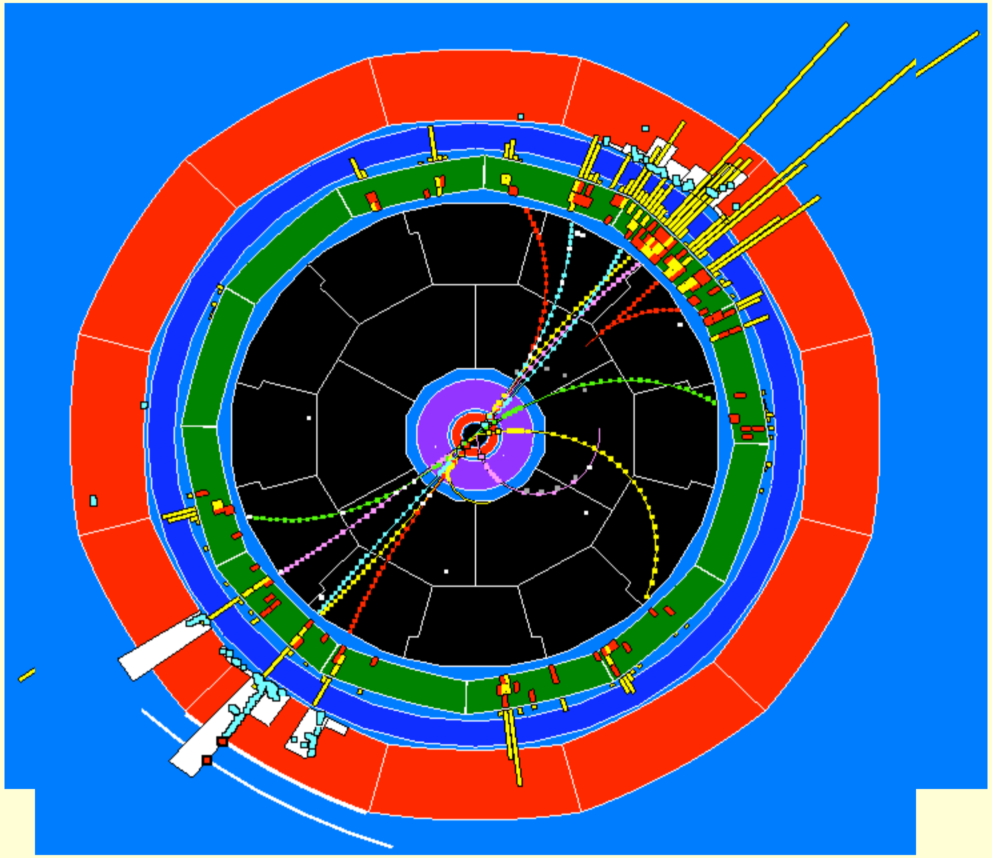
Why a hadron collider ?

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

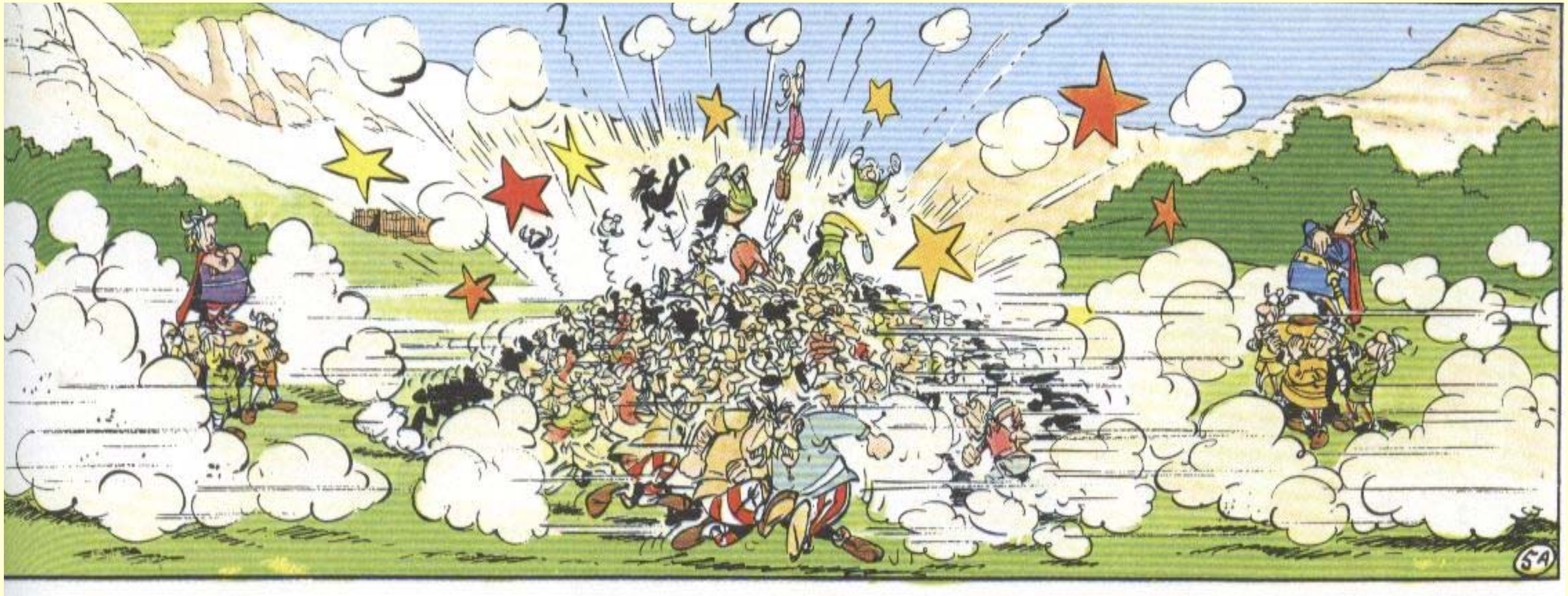
- e^+ e^- are point-like particles, no substructure → clean events
- complete annihilation, centre-of-mass system, kinematic fixed







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,
dipole, 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:

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

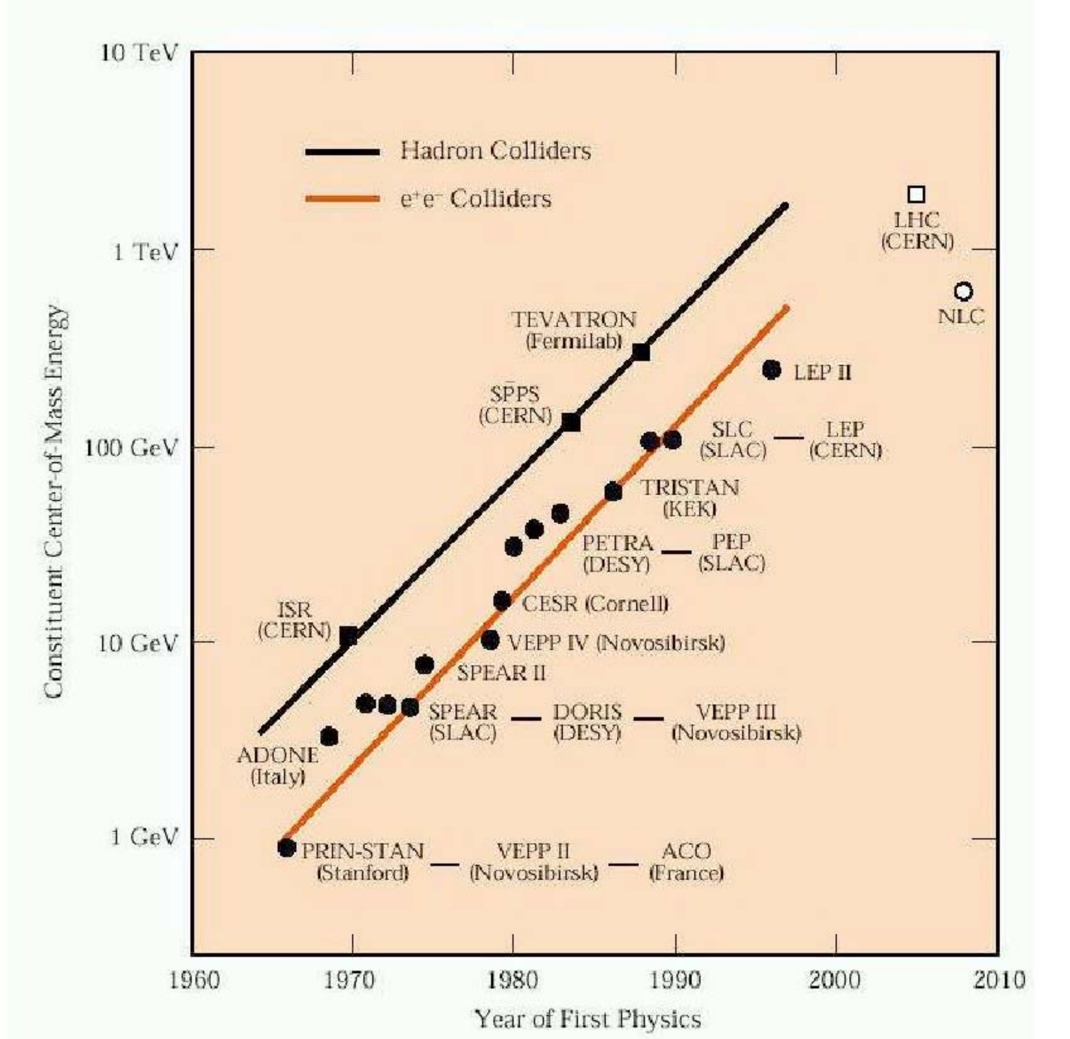
- Ratio of the energy loss between protons and electrons:

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

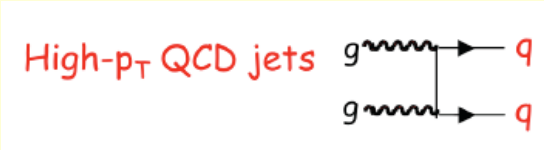
Future accelerators:

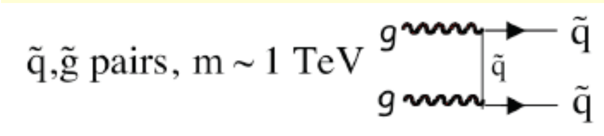
- pp ring accelerators (LHC, using existing LEP tunnel)
- or e^+e^- linear accelerators, International Linear Collider ILC or CLIC
(under study / planning)

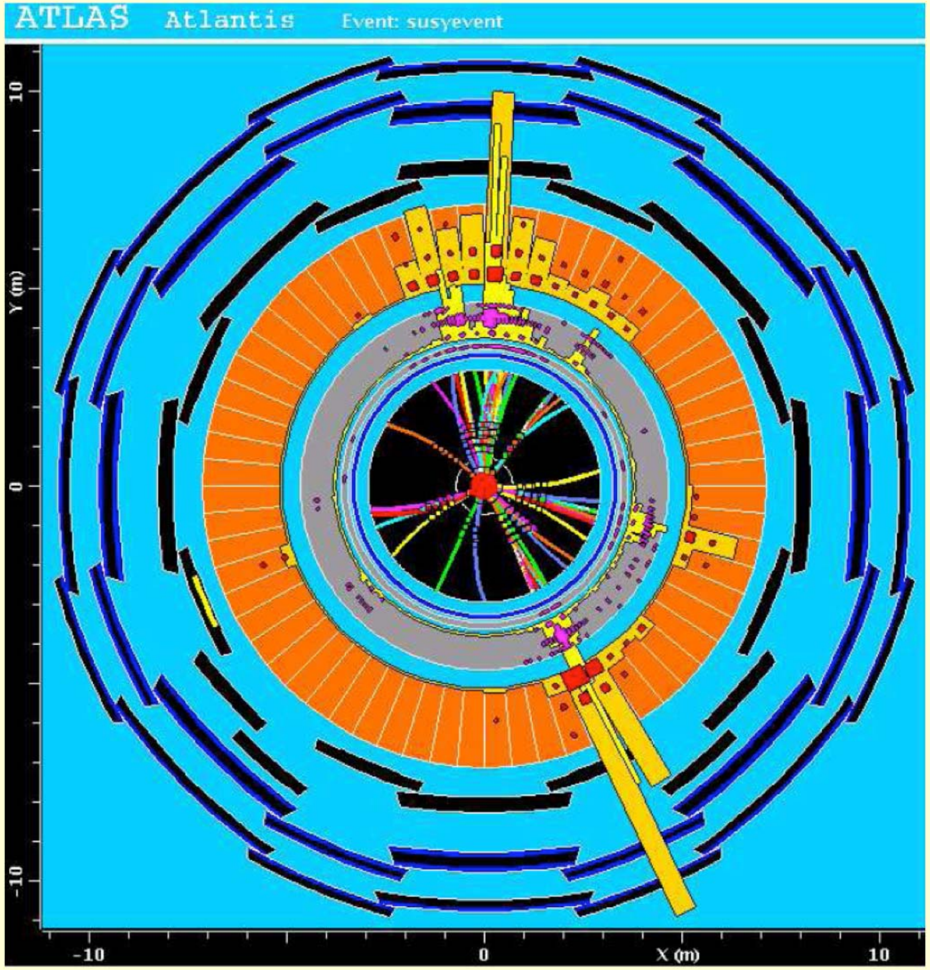
2. Hard kinematic limit for e^+e^- center-of-mass energy from the beam energy: $\sqrt{s} = 2\,E_{beam}$



How can interesting objects be produced?







Quarks and gluons in the initial state

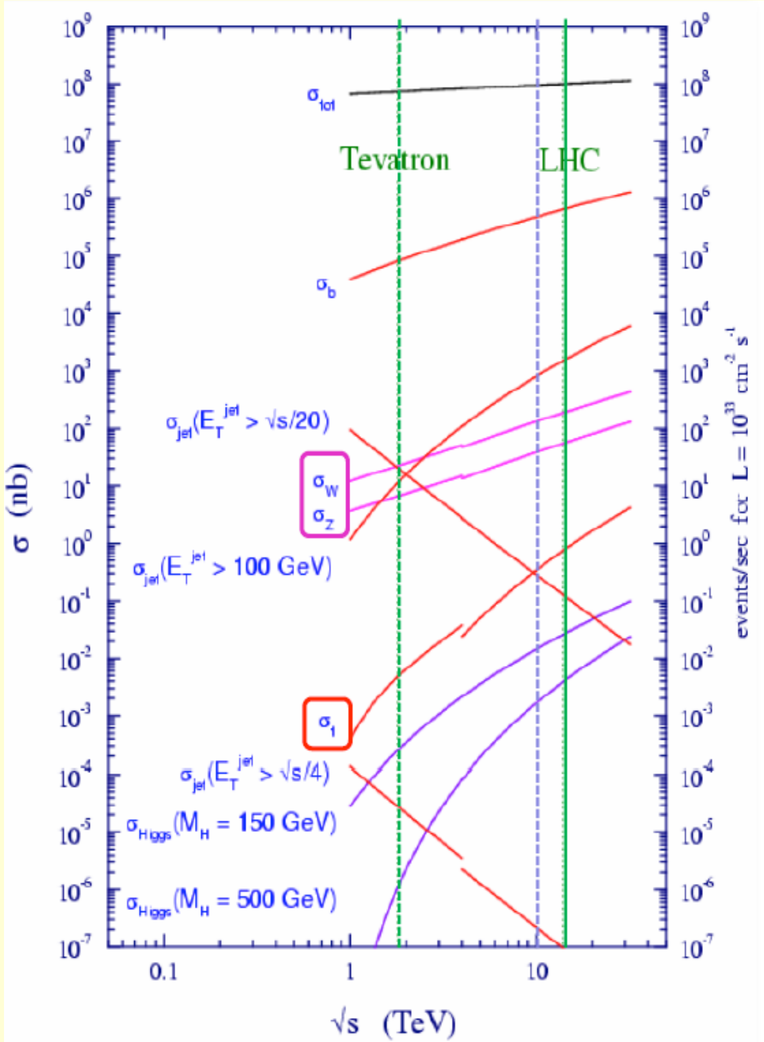
Cross Sections

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
$\sqrt{s}$ = 10 – 14 TeV



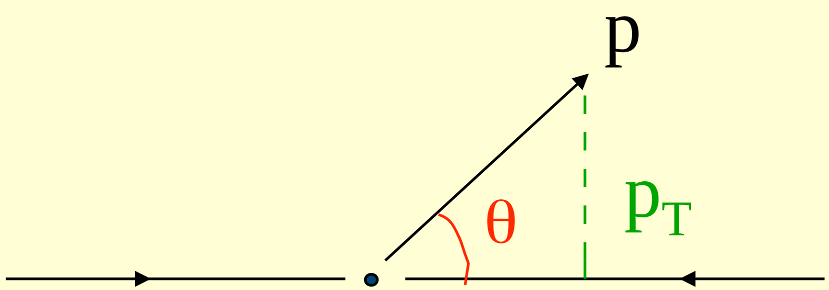
N_{event} = σ · L · ε (efficiency · acceptance)

Physics ***Accelerator*** ***Experiment***

(data taking, detector acceptance, reconstruction efficiency, selection, analysis, ...)

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

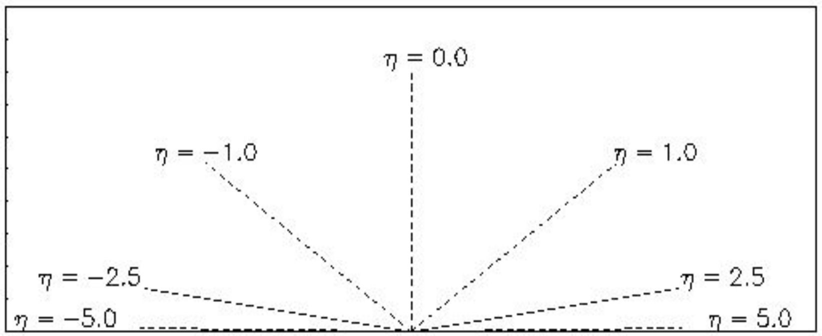
Variables used in the analysis of pp collisions



Transverse momentum
(in the plane perpendicular to the beam)

$$p_T = p \sin\theta$$

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



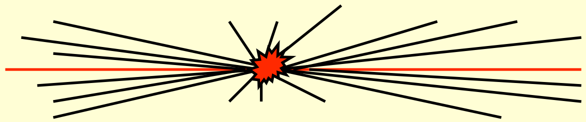
$\theta = 90^o \rightarrow \eta = 0$

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

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

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

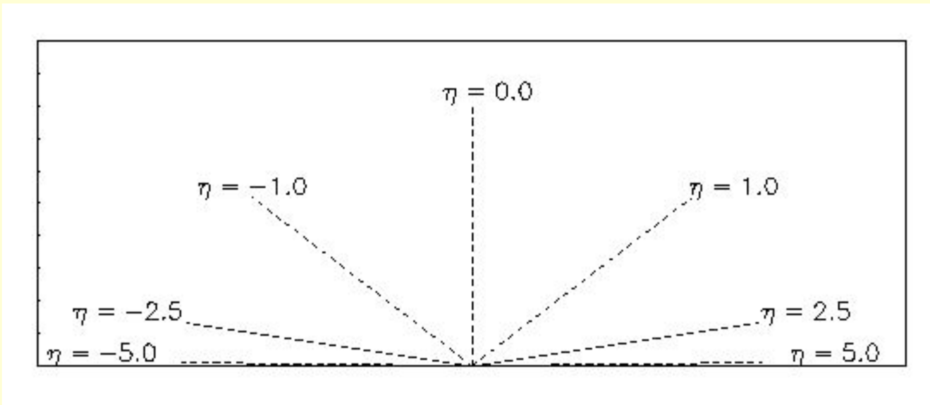


$< p_T > \approx 500$ MeV (of charged particles in the final state)

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

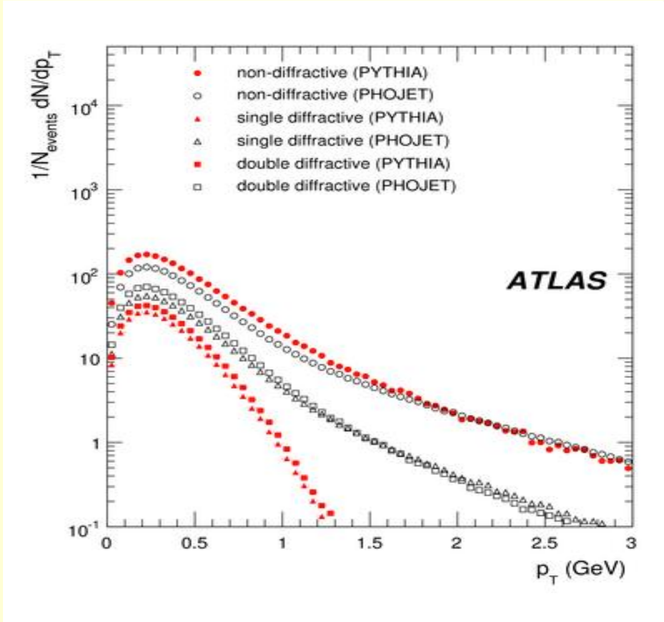
- about 7 charged particles per unit of pseudorapidity in the central region of the detector
- uniformly distributed in Φ

These events are called
"Minimum-bias events"



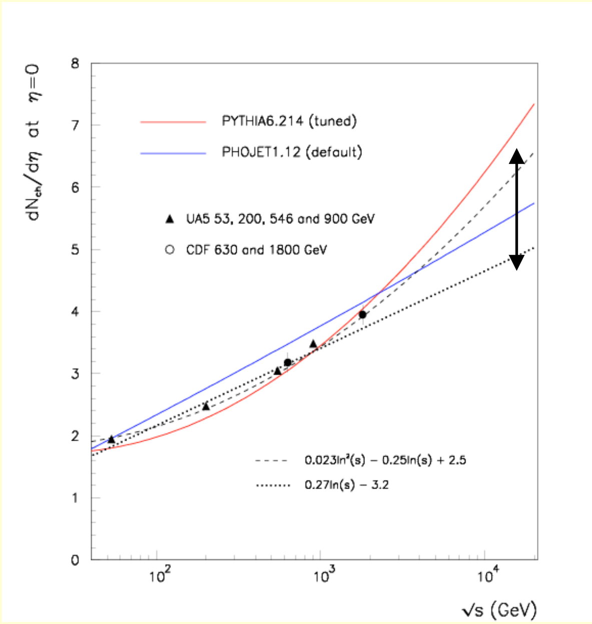
Some features of minimum bias events

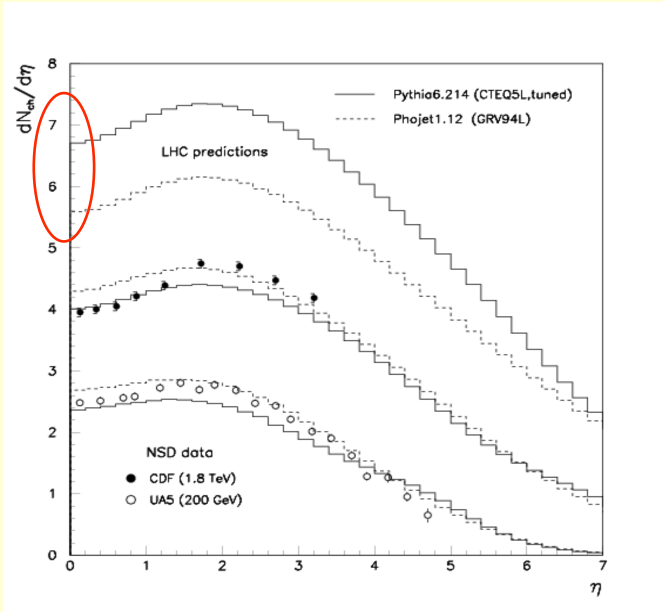
- Features of minimum bias events cannot be calculated in perturbative QCD
- Experimental measurements / input needed
- Models / parametrizations are used to extrapolate from existing colliders (energies) to the LHC energy regime $\rightarrow$ large uncertainties



$<p_T>$ (η =0): 550 – 640 MeV (15%)

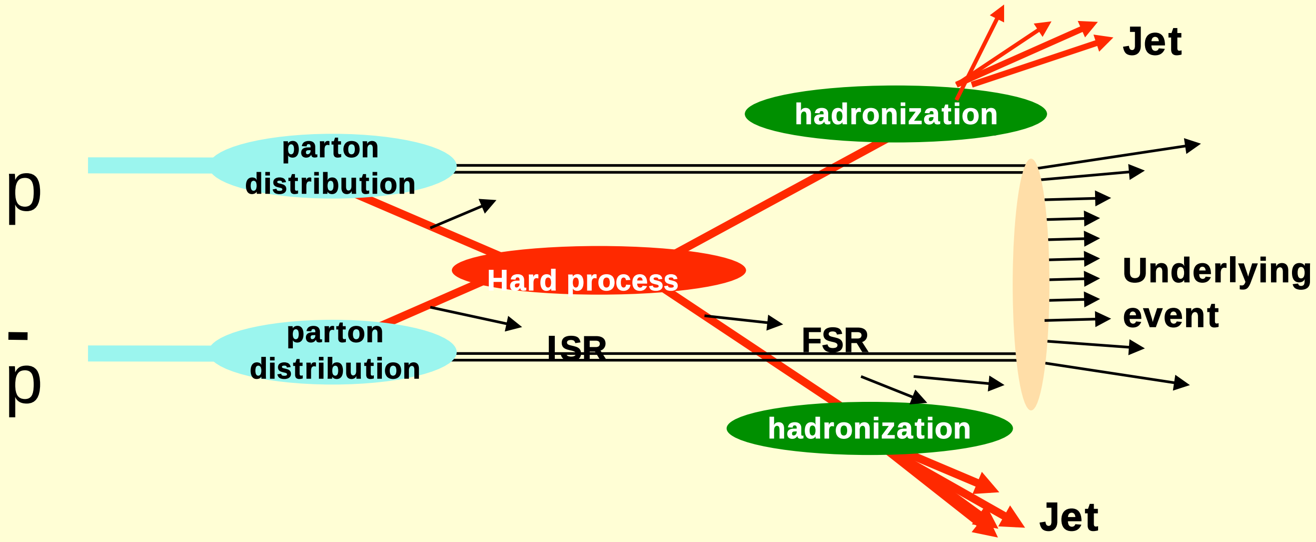
- Will be one of the first physics measurements at the LHC
- Needed to model other interesting physics (superposition of events,…)



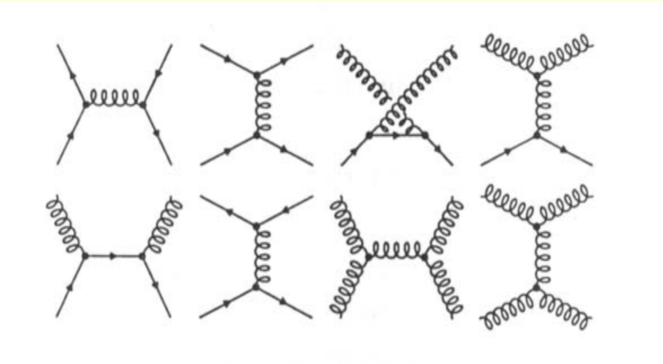


$dN_{ch}/d\eta$ (η=0): 5-7 (~ 33%)

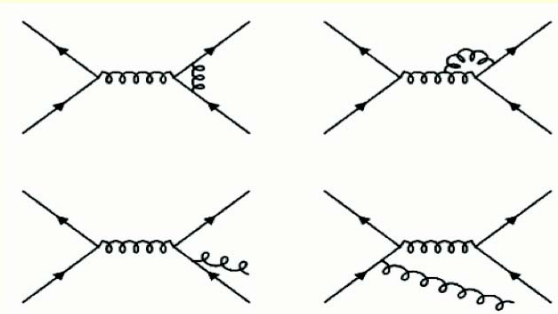
Hard Scattering Processes ….or QCD jet production



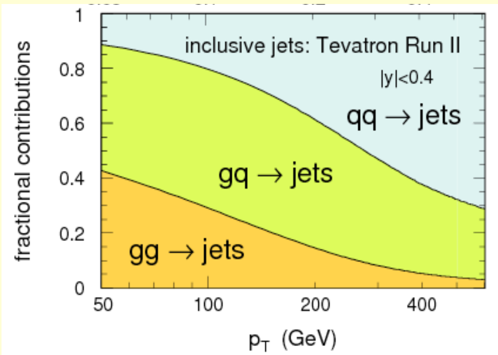
Leading order



…some NLO contributions



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

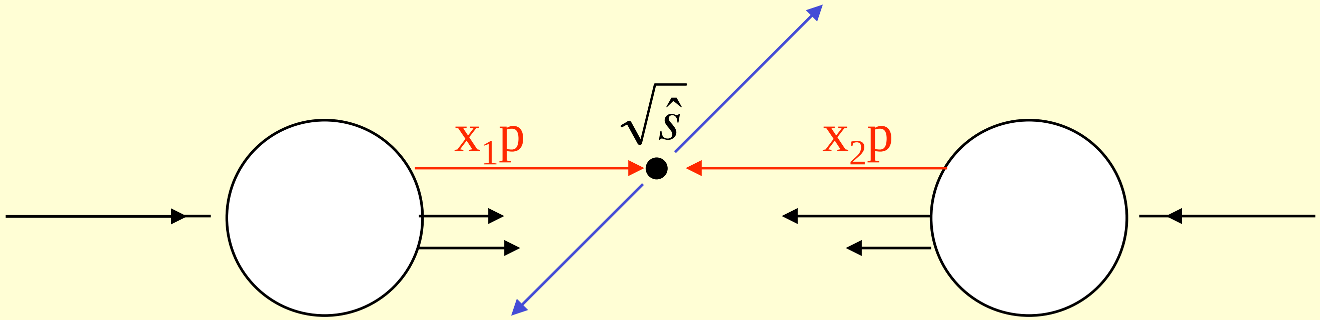


Tevatron,
ppbar, √s = 1.96 TeV,
central region |η| < 0.4

- 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 $\sqrt{s}$ of the incoming protons

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

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

To produce a mass of:

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

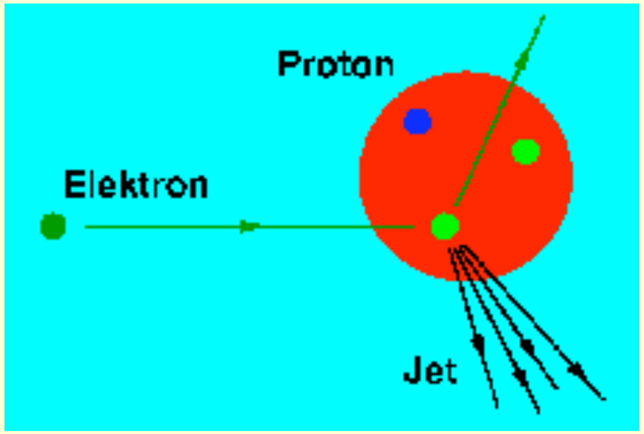
Where do we know the x-values from?

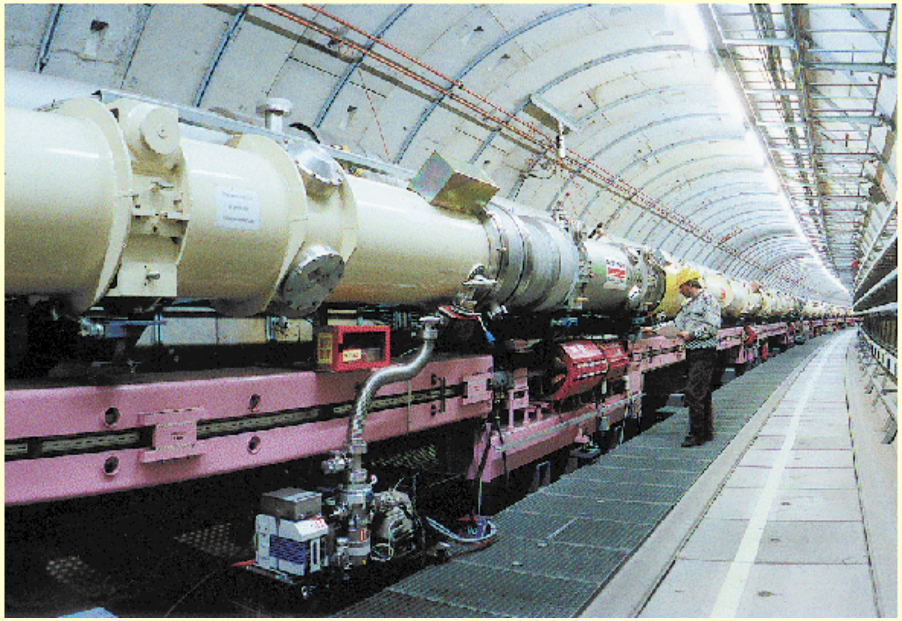
The structure of the proton is investigated in *Deep Inelastic Scattering* experiments:

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

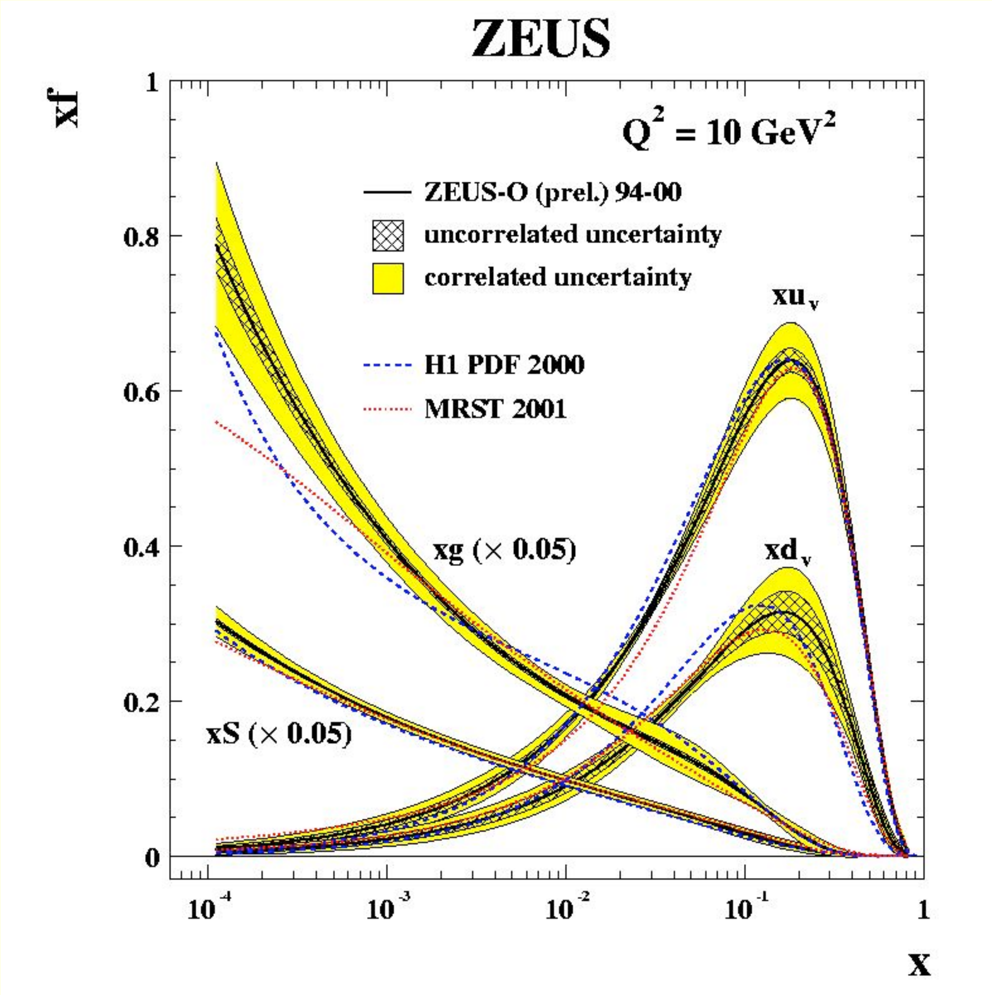
Scattering of 30 GeV electrons on 900 GeV protons:
→ Test of proton structure down to 10^{-18} m

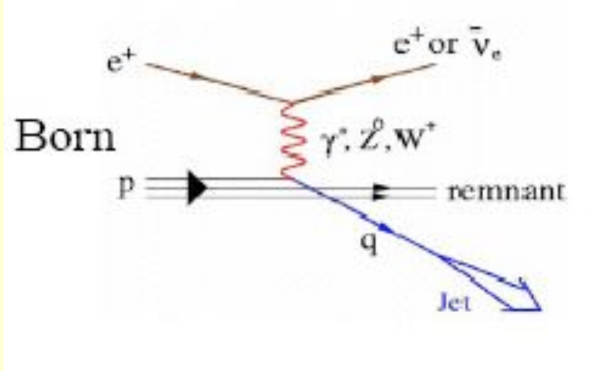
HERA ep accelerator, 6.3 km circumference





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





Parton density functions (pdf):

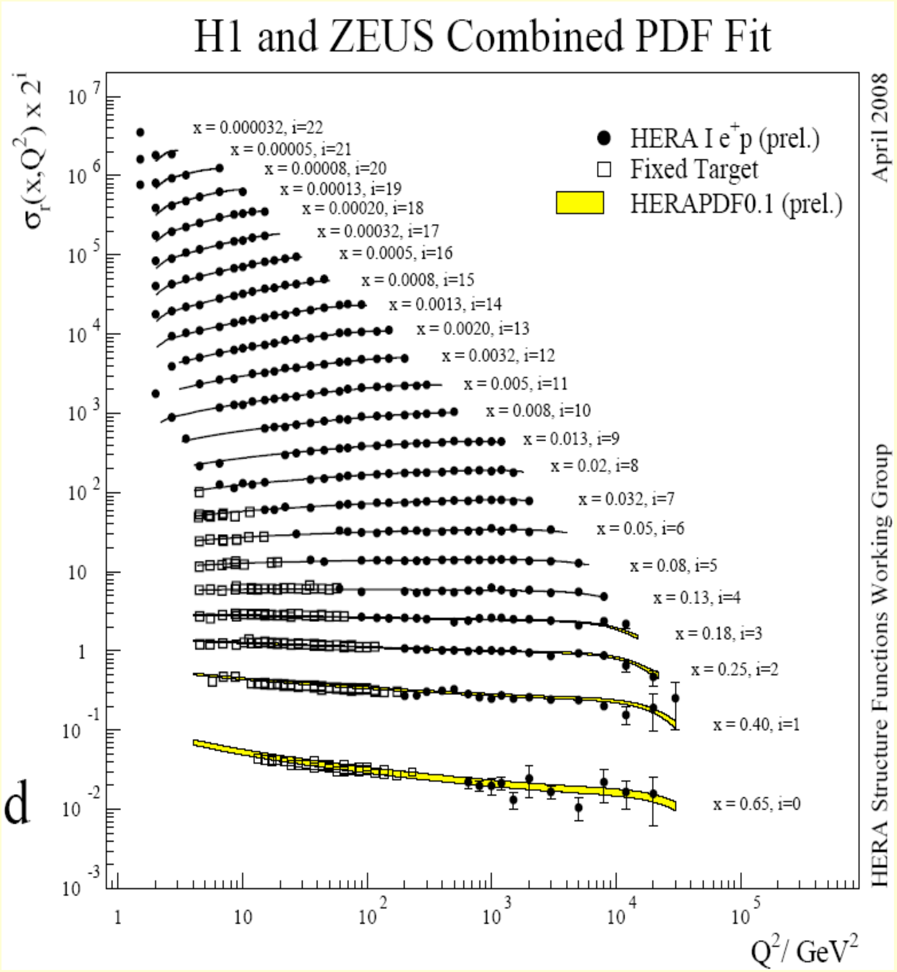
u- and d-quarks at large x-values

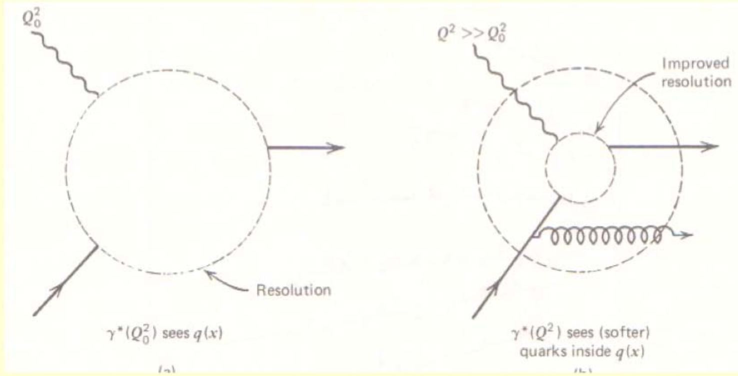
Gluons dominate at small x !!

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 $F_2(x,Q^2)$)



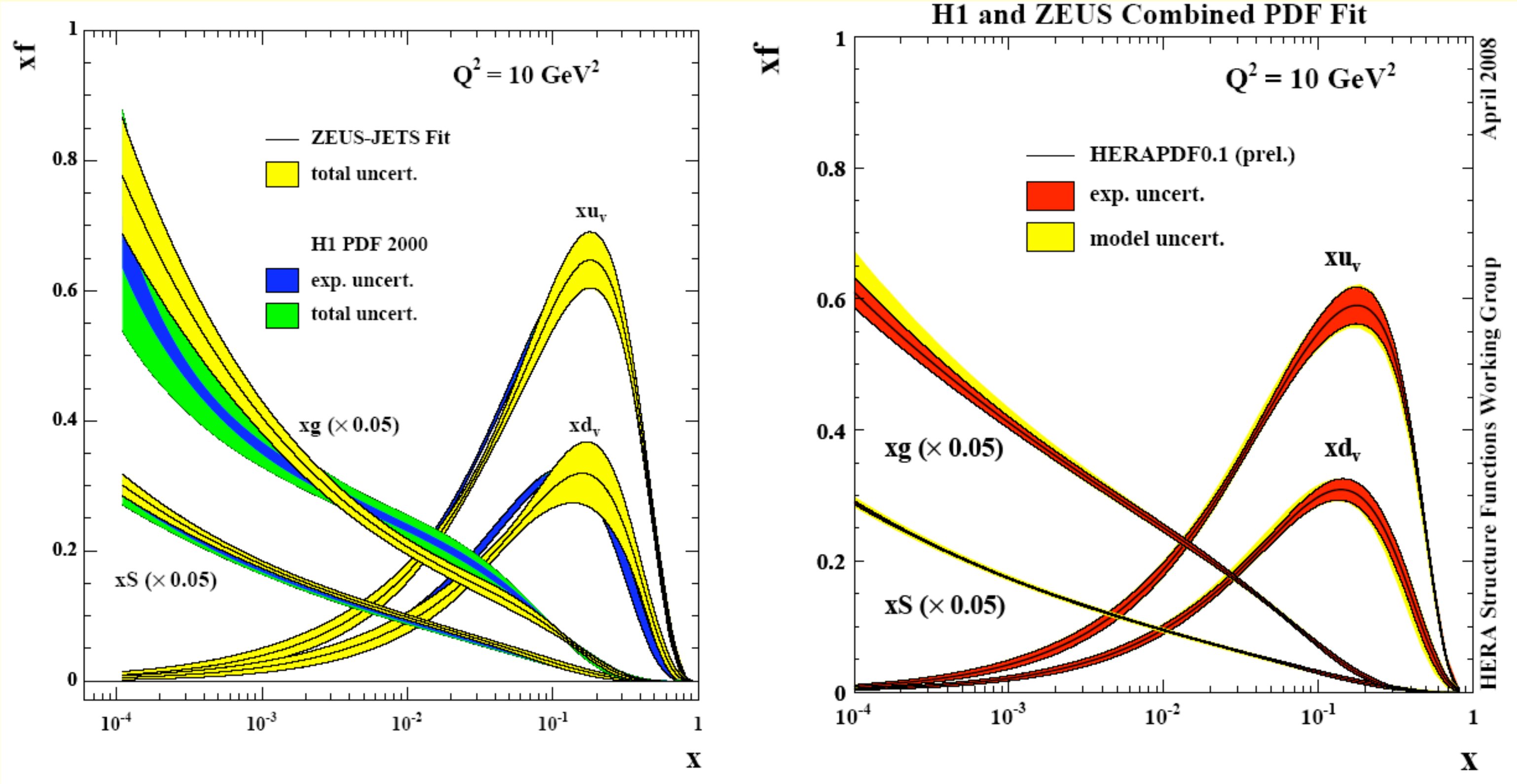


Evolution (Q^2 dependence)
predicted by QCD
(Altarelli-Parisi or DGLAP equation):

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

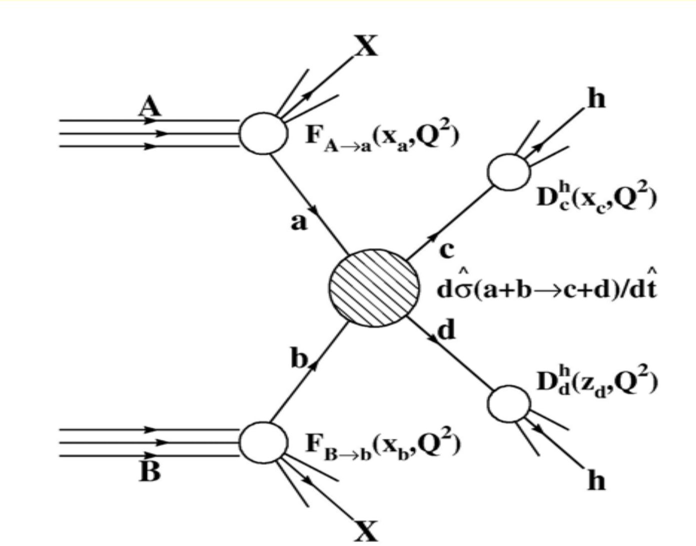
Results from HERA

- 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

Calculation of cross sections



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

Sum over initial partonic states a,b

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

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

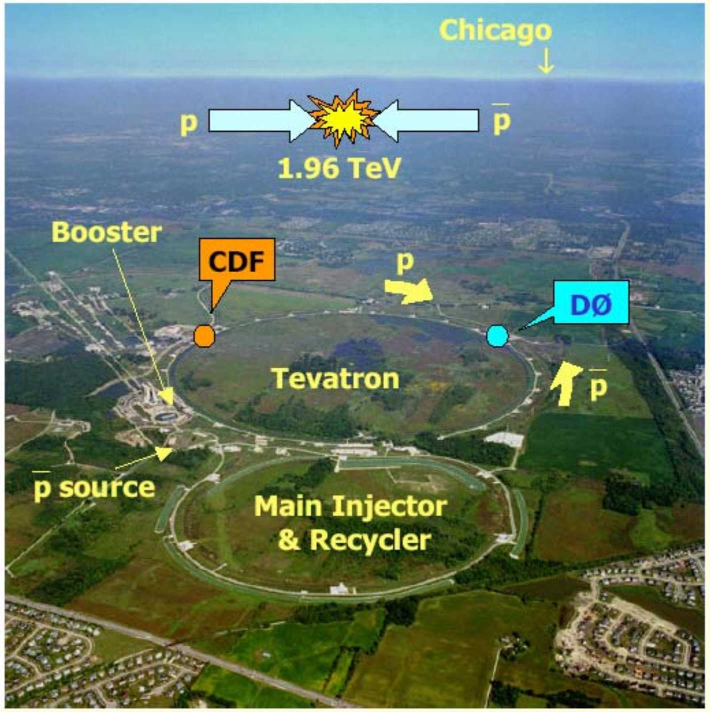
… + higher order QCD corrections (perturbation theory)

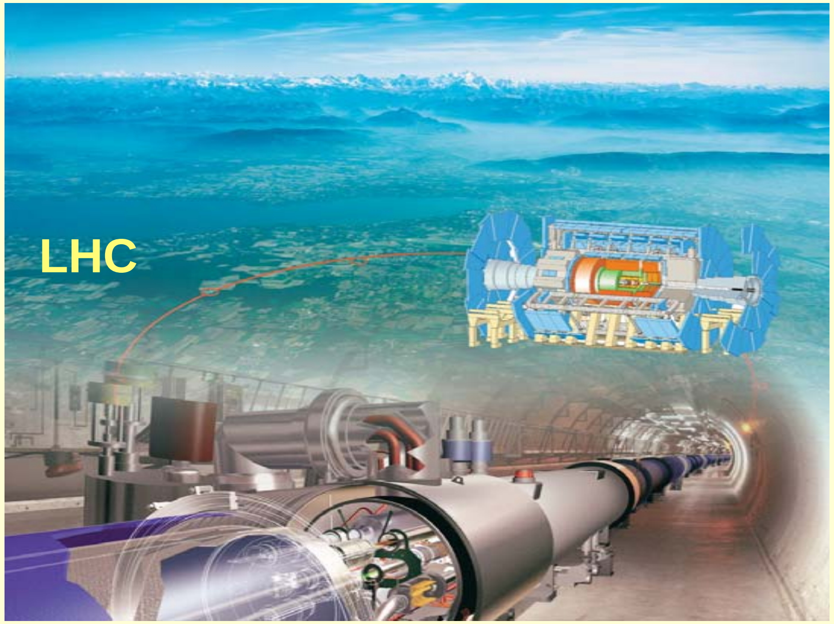
which for some processes turn out to be large
(e.g. Higgs production via gg fusion)

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

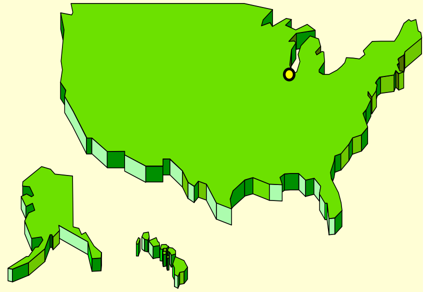
a few examples: Drell-Yan production of W/Z: $K_{NLO} \sim 1.2$
Higgs production via gg fusion: $K_{NLO} \sim 1.8$

The accelerators

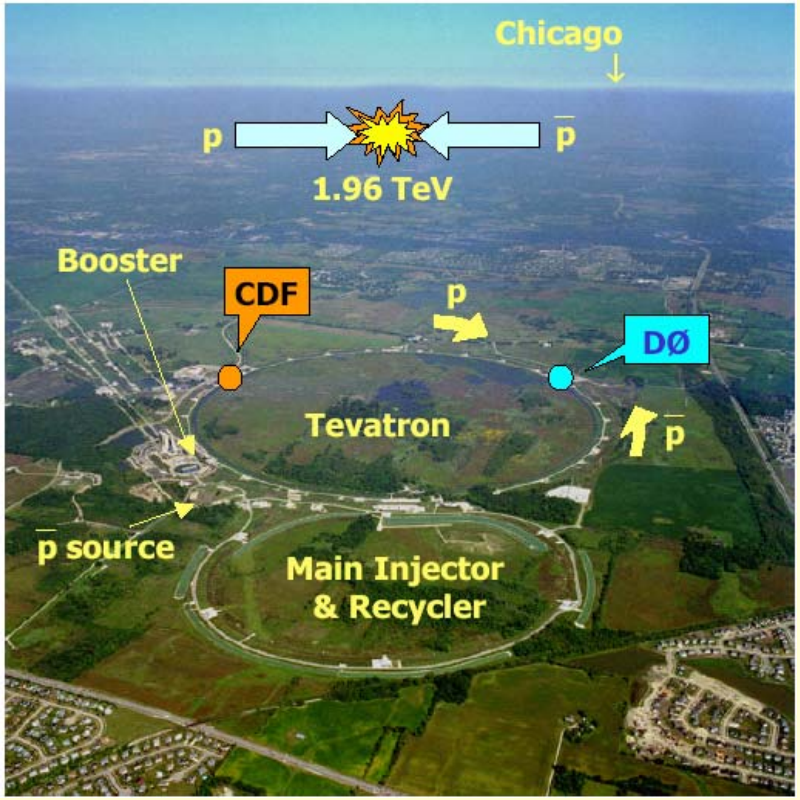




The Tevatron Collider at Fermilab



- **Proton antiproton collider**
  - **- 6.5 km circumference**
  - **- Beam energy 0.98 TeV,** **$\sqrt{s}$ = 1.96 TeV**
  - **- 36 bunches, 396 ns separation (time between crossings)**



- **2 Experiments: CDF and DØ**

- **Main challenges:**
  - **- Antiproton production and storage**
  - **→ luminosity, stability of operation**

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

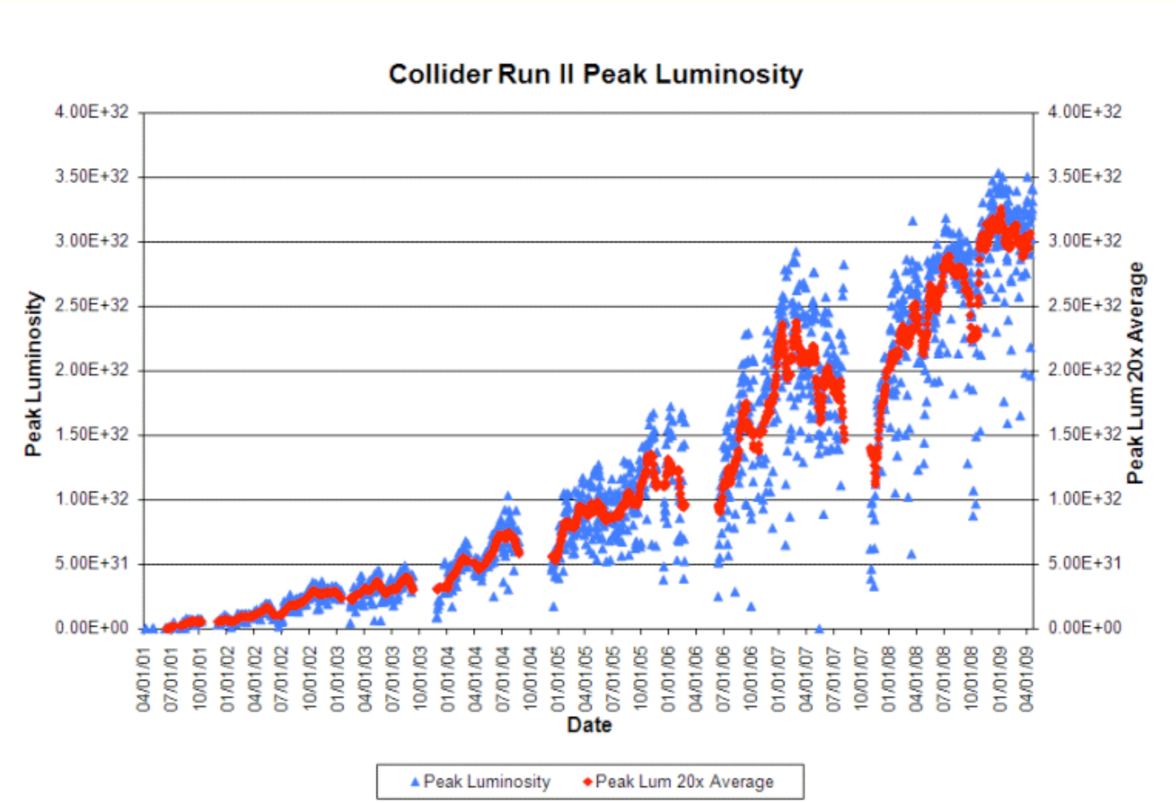
[Run I from 1990 – 1996, int. luminosity: 0.125 fb^{-1}, Top quark discovery]

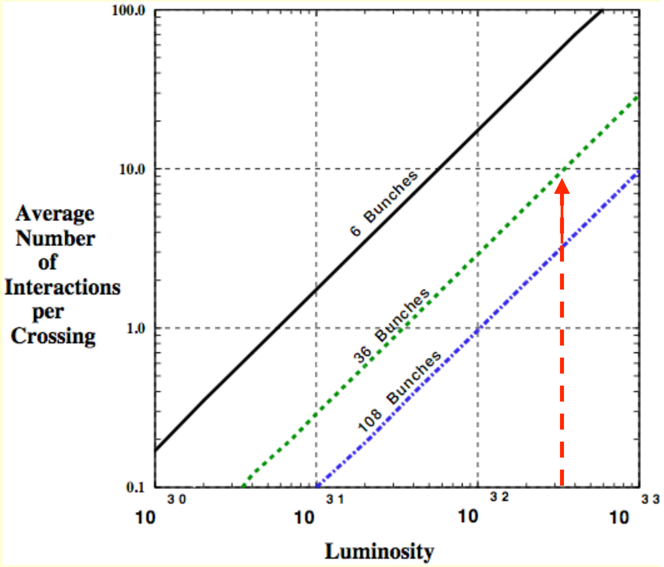
Real Data

- **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

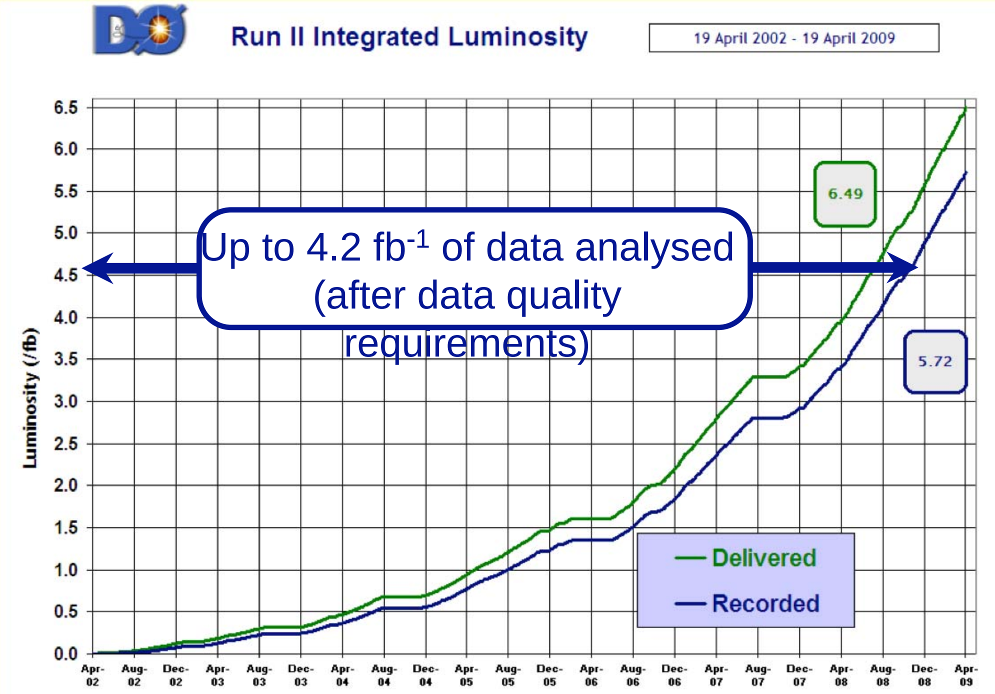


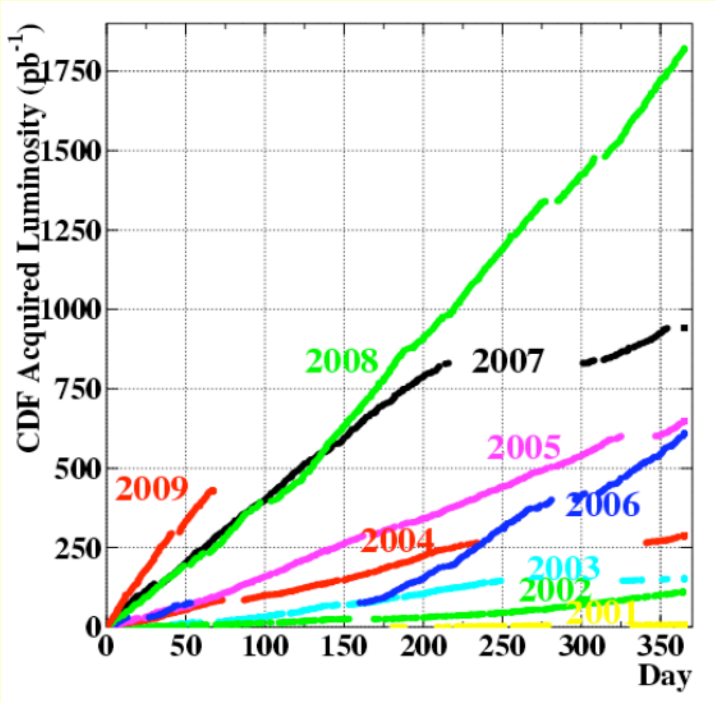


- Peak luminosity of $3.5 \cdot 10^{32}$ cm^{-2} s^{-1}
- Corresponds to ~10 interactions per bunch crossing
  (superposition of minimum bias events on hard collision)

The integrated Tevatron luminosity (until Apr. 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 ~ 6.5 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



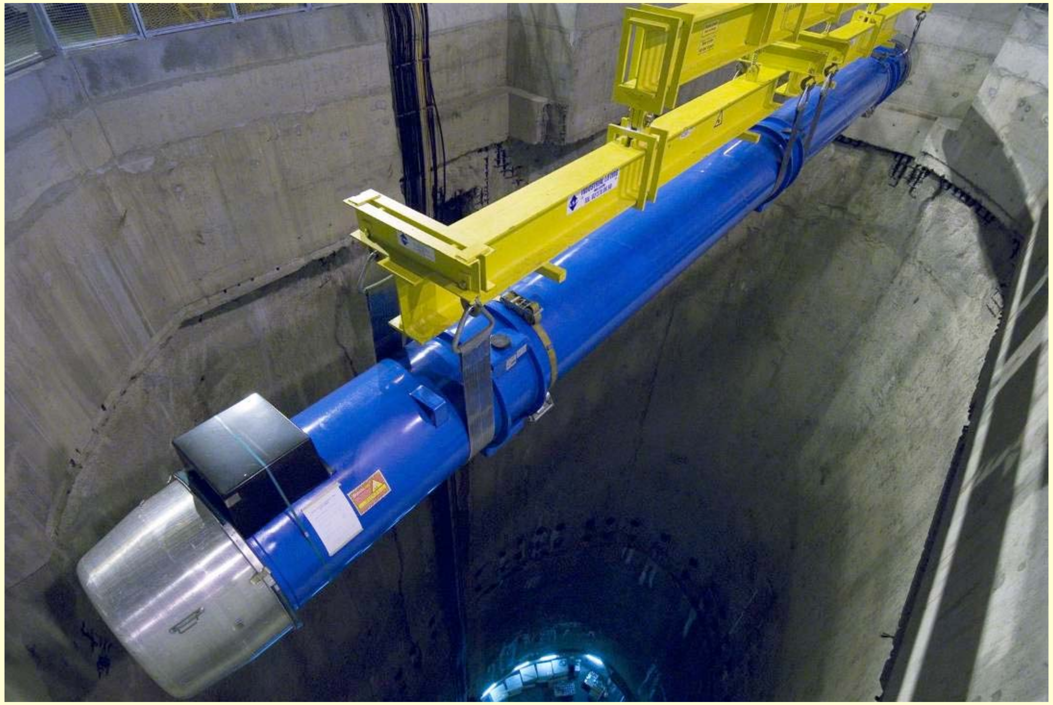


The Large Hadron Collider

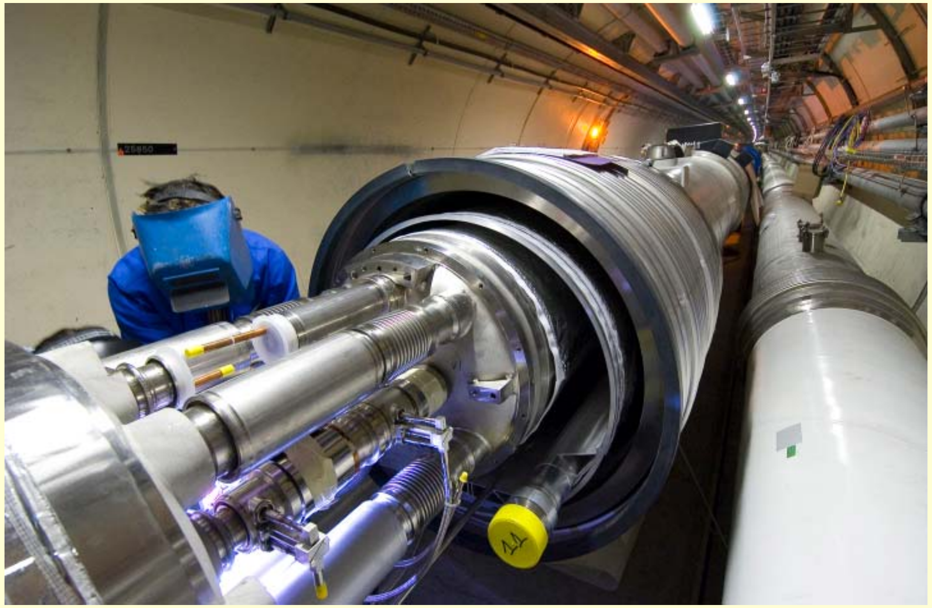
Beam energy (nominal)	7 TeV
SC Dipoles	1232, 15 m, 8.33T
Stored Energy	362 MJ/Beam
Bunch spacing	25 ns
Particles/Bunch	$1.15 \cdot 10^{11}$
Design luminosity	10^{33} - 10^{34} $cm^{-2}s^{-1}$
Int. luminosity	**10- 100 fb^{-1} / year**

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

Descent of the last magnet, 26 April 2007

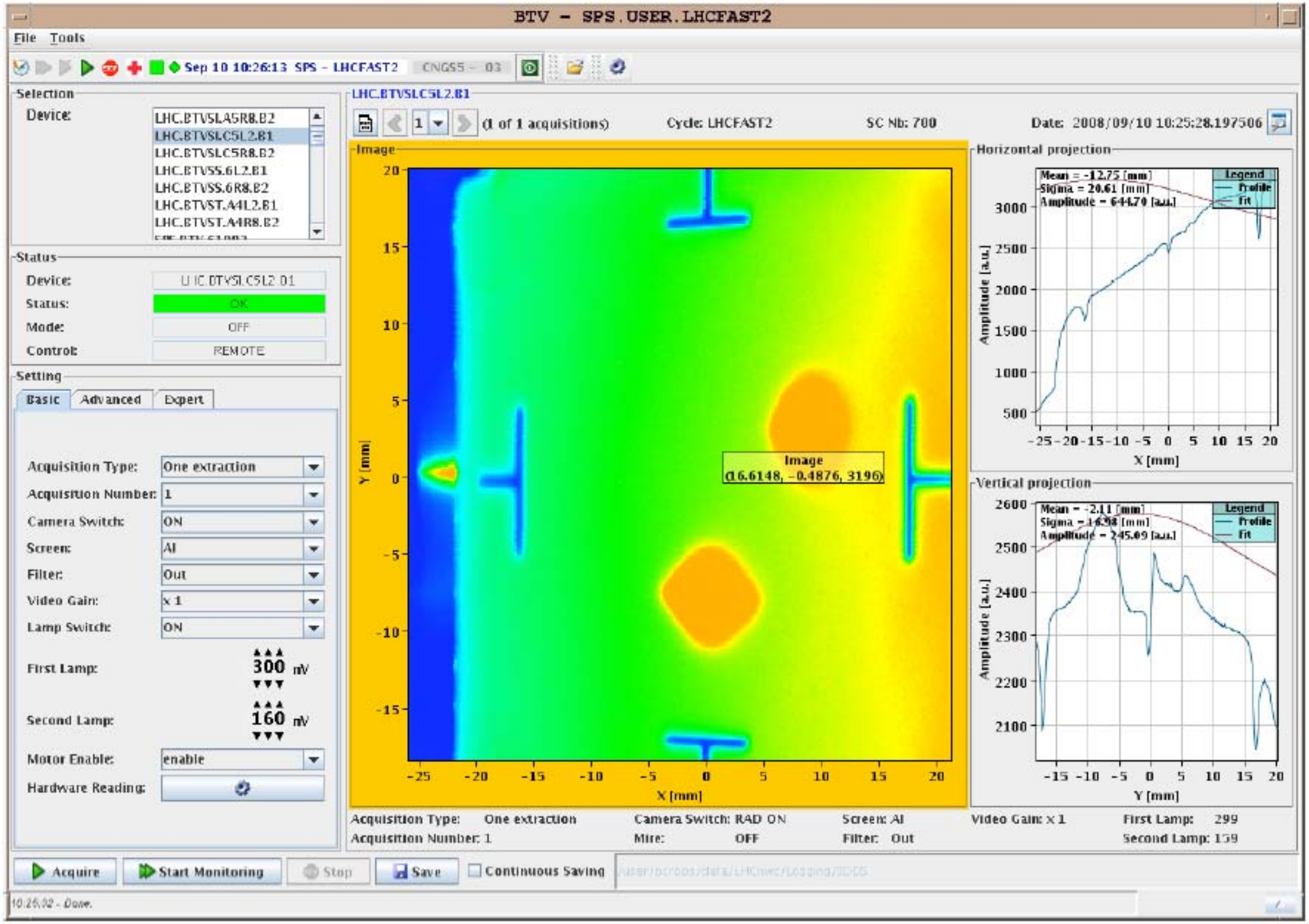


Work on installation, interconnection and testing underground



An excellent start: first beams – September 10, 2008

Beam on turns 1 and 2



First beams at CERN – and everywhere else…

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

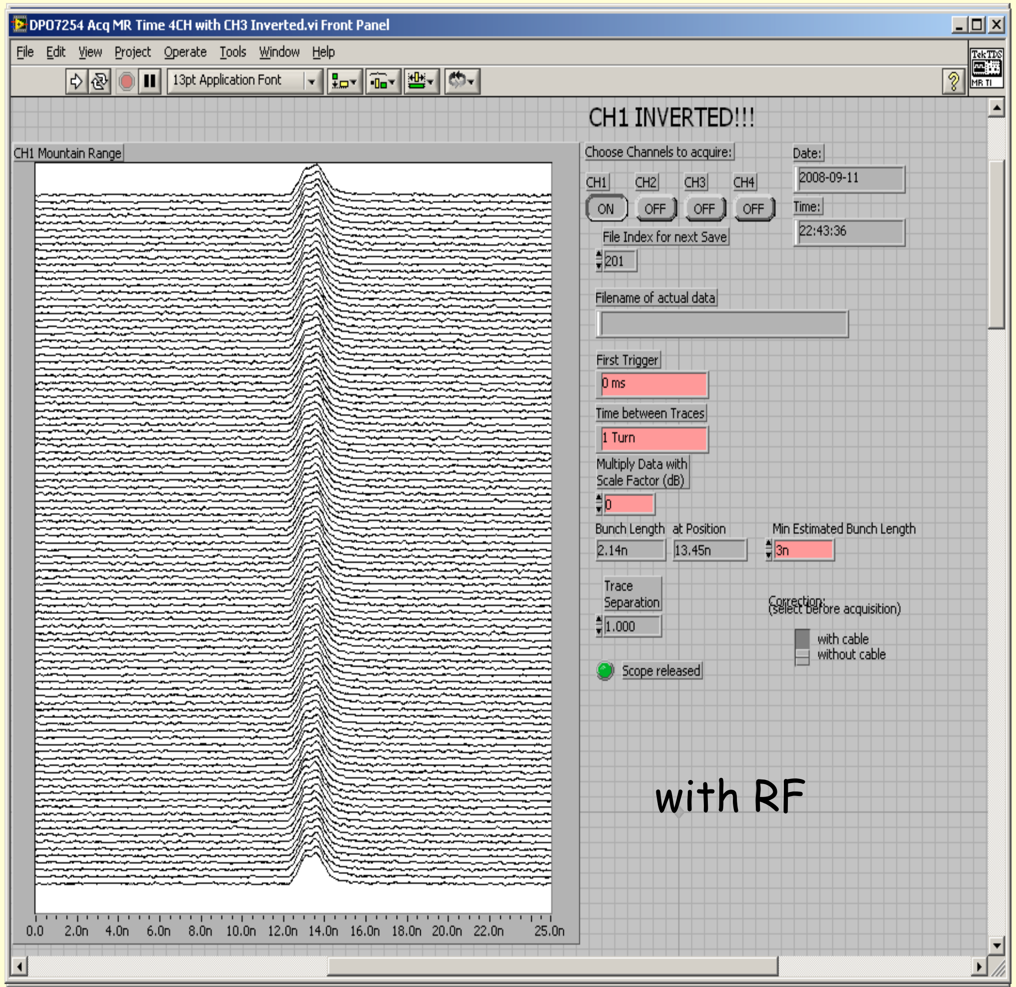
  Many tests (orbit, dump,…)

  Sept 12:

  Measure horizontal beam profile with wire scanner

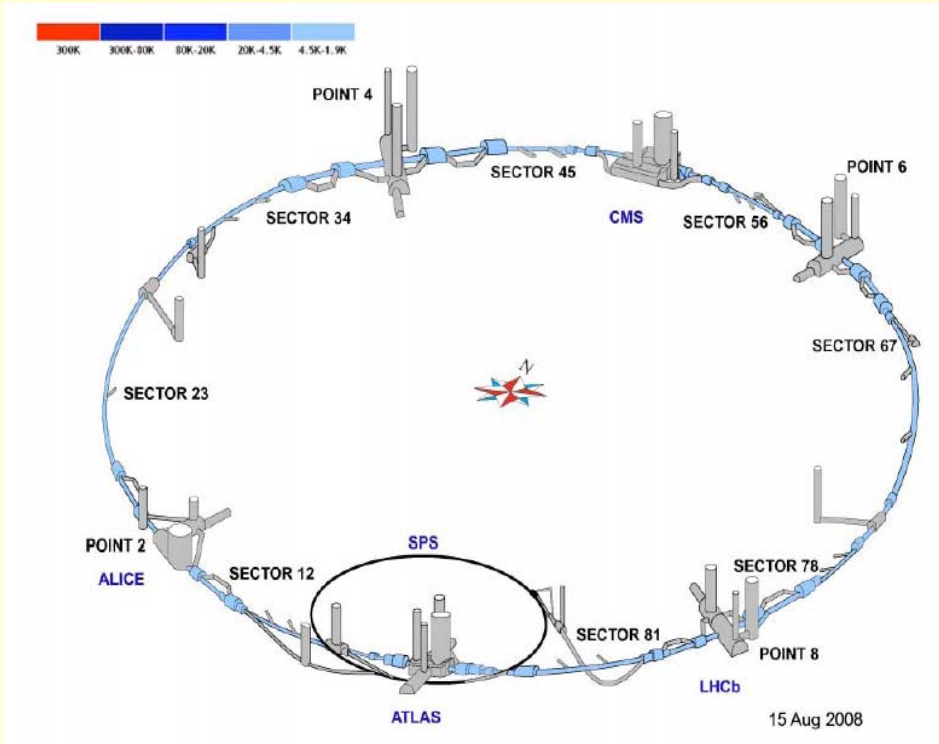
  ……

  everything worked impressively well



The Event on 19. Sep 2008

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



Sector 34: the event which started

Actions ongoing and time schedule

- Repair work is well underway
  (all magnets in the incident area and in a buffer zone around have been removed, repaired and meanwhile lowered down in the tunnel again)

- Quench detection system has been improved to generate both early warnings and interlocks and to encompass magnets, bus bars and interconnects;
  Relief devices on the cryostat vacuum vessels increased in discharge capacity (in the sectors that were warm).

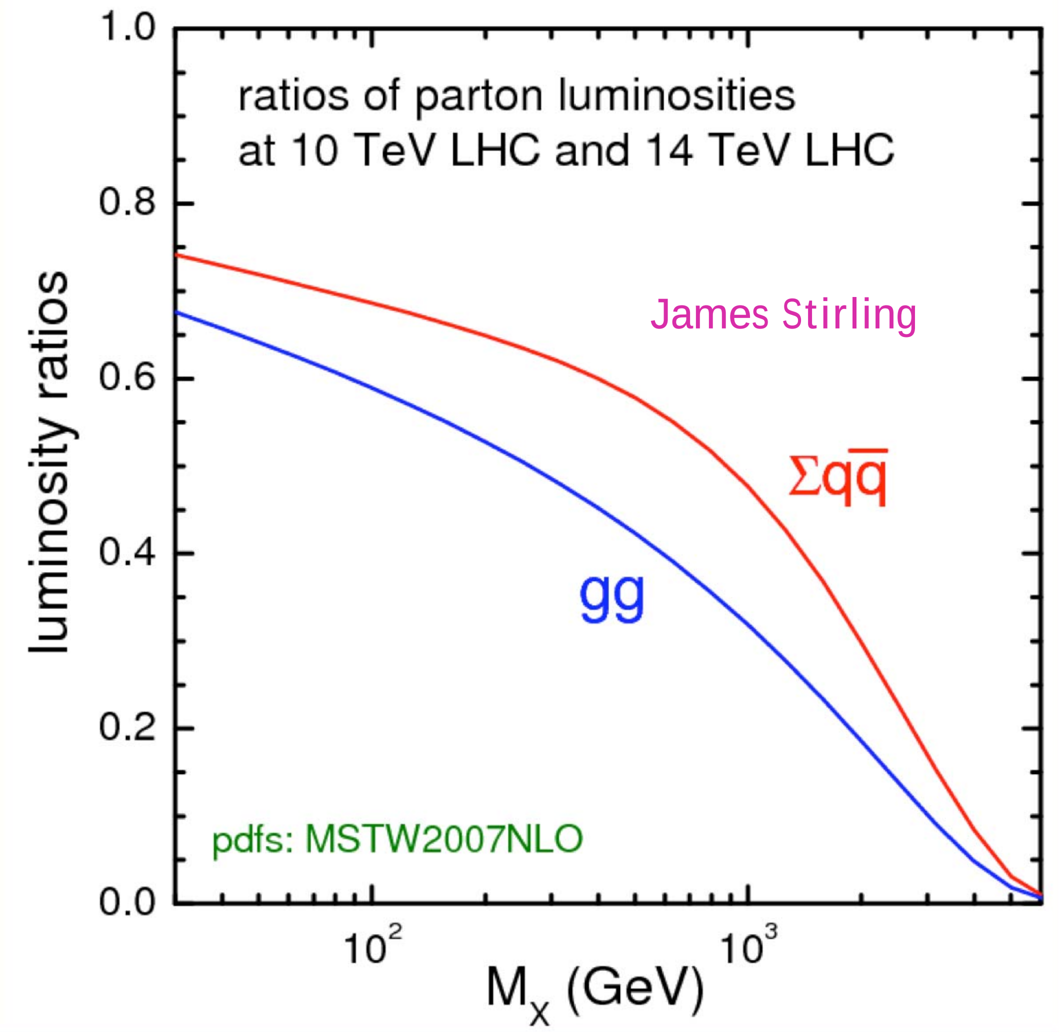
- Powerful techniques have been developed to spot resistive splices at low current;
  All sectors have been systematically verified to spot eventual defects.

- It is expected that machine operation will be resumed in Oct. 2009, with first collisions towards the end of the year

- **Physics run with beam energy of 5 TeV**

- **Start with low number of bunches / intensity, expect to deliver a few hundreds of pb^{-1} until end of 2010**

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

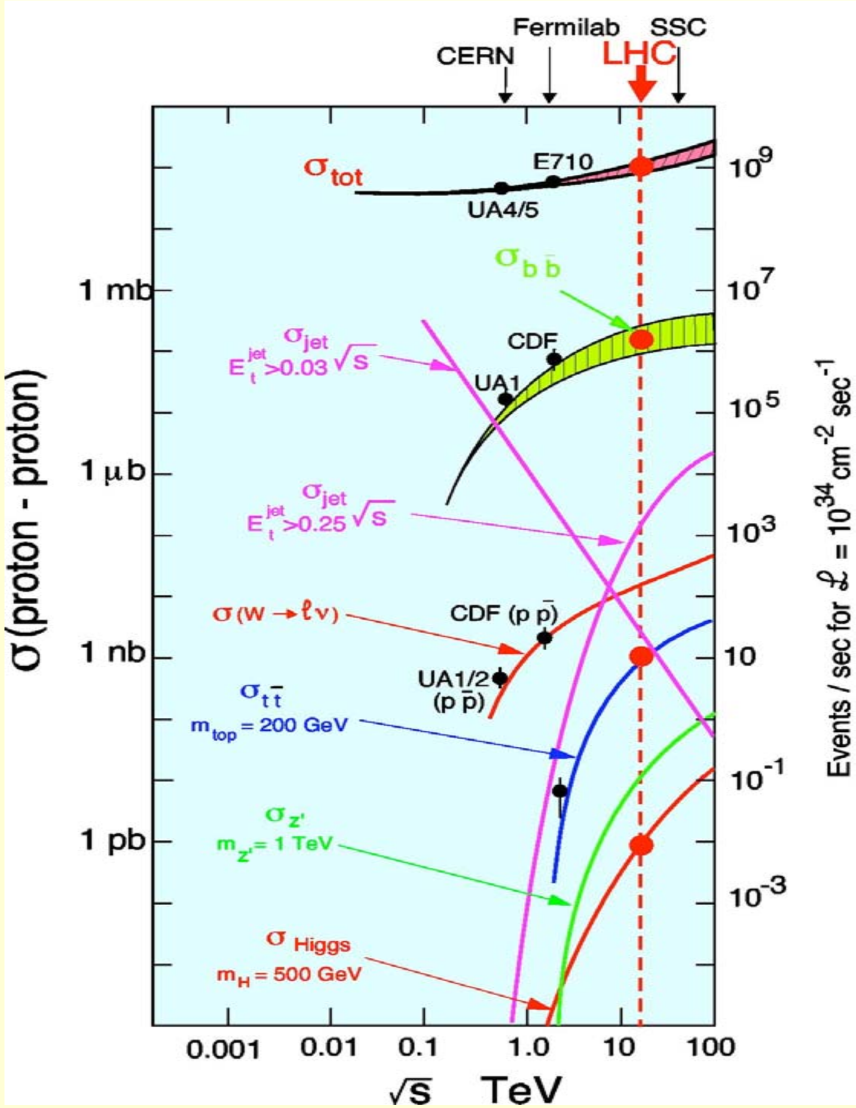
14 TeV simulation results will be shown throughout the lectures, unless stated otherwise

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 x 10^{32} $cm^{-2}s^{-1}$**
Integrated Luminosity / year	**10-100 fb^{-1}**	**~ 2 fb^{-1}**

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

Cross Sections and Production Rates



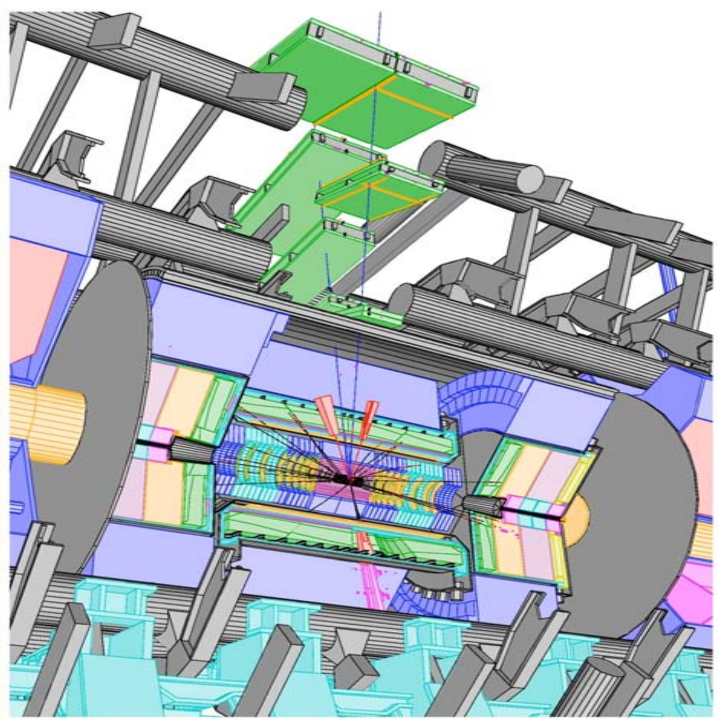
Rates for L = 10^{34} cm^{-2} s^{-1}: (LHC)

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

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

The only problem: you have to detect them !

Detector requirements from physics



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

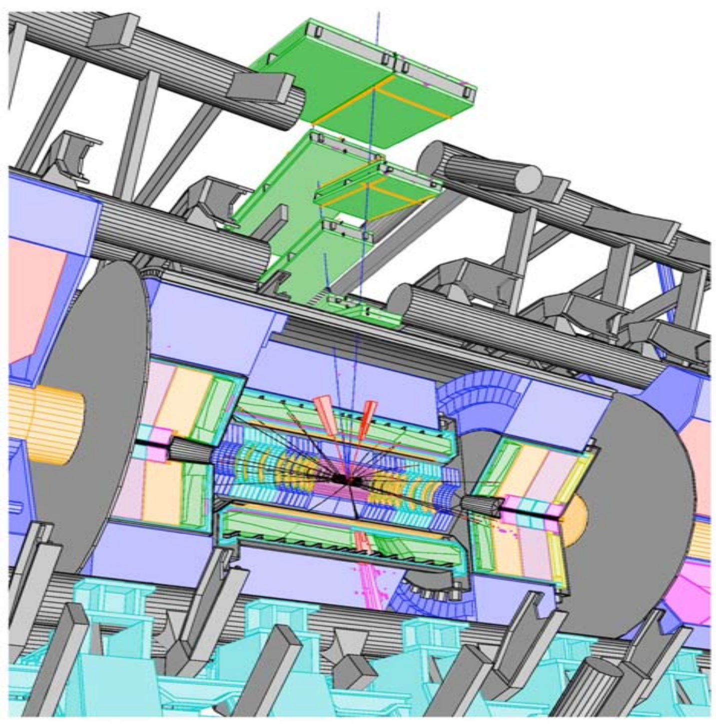
- Good measurement of missing transverse energy (E_T^{miss})

  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)



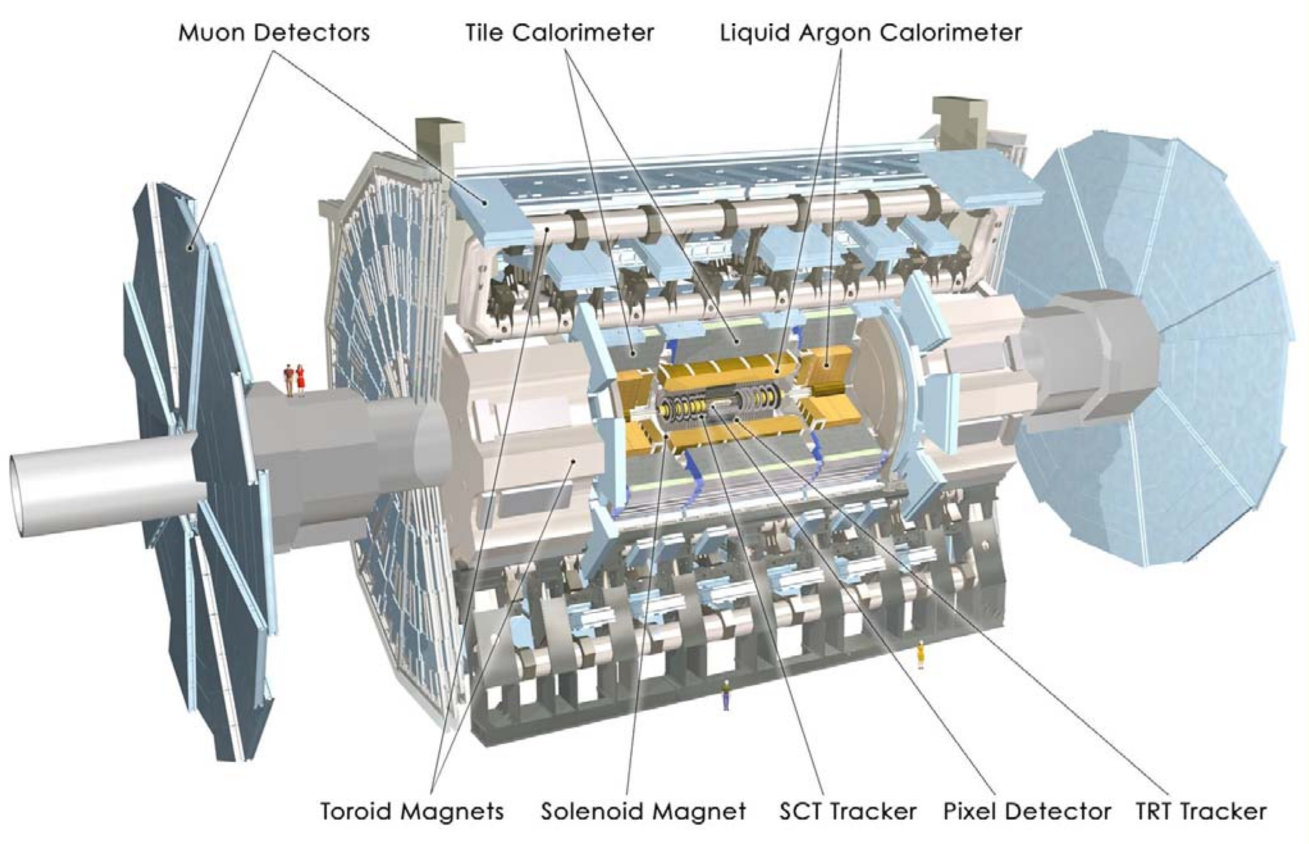
- LHC detectors must have **fast response**, otherwise integrate over many bunch crossings → too large pile-up

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

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

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

The ATLAS experiment



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

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

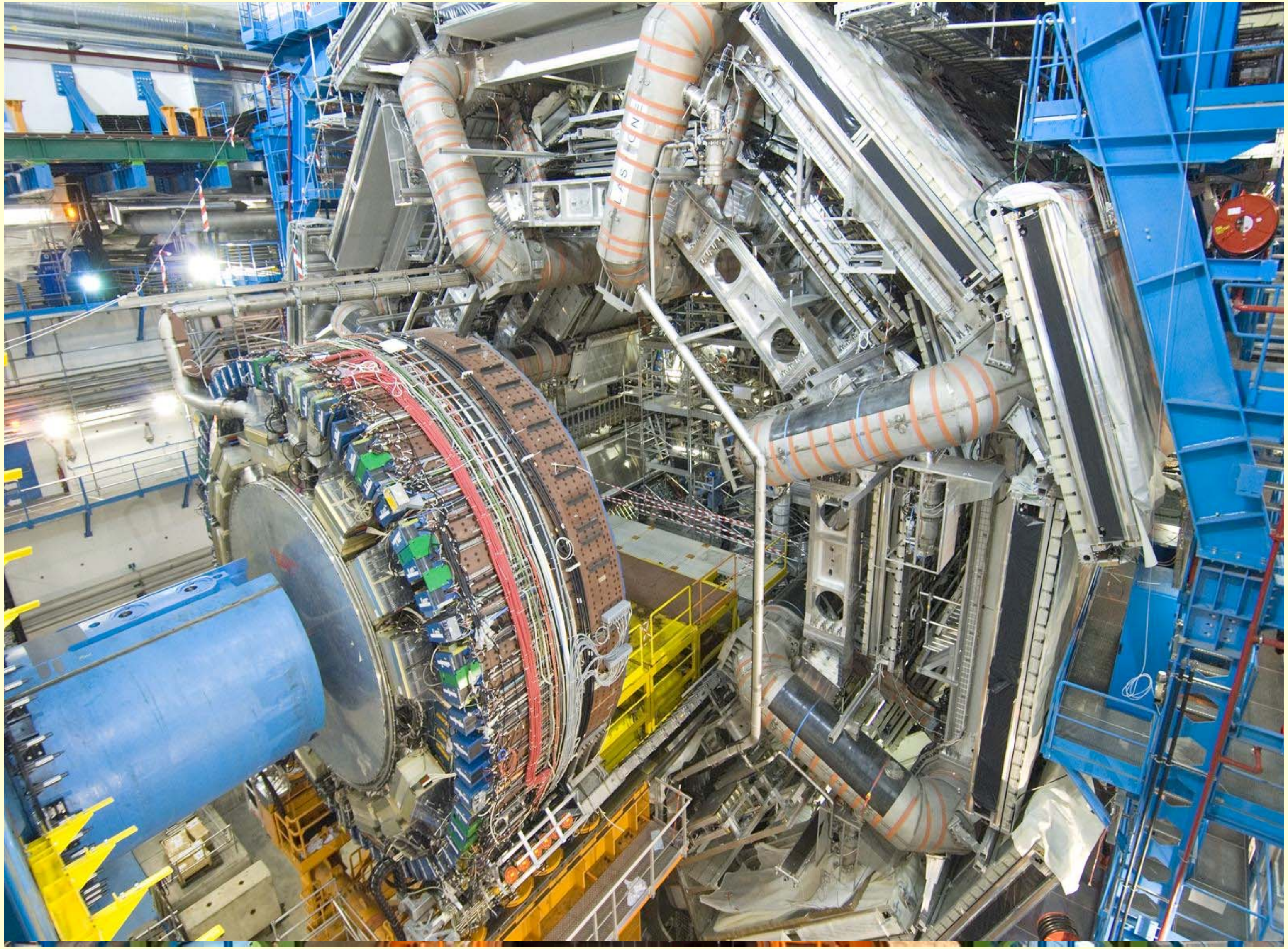
  space resolution: ~ 15 μm

- Energy measurement down to 1° to the beam line

- Independent muon spectrometer (supercond. toroid system)

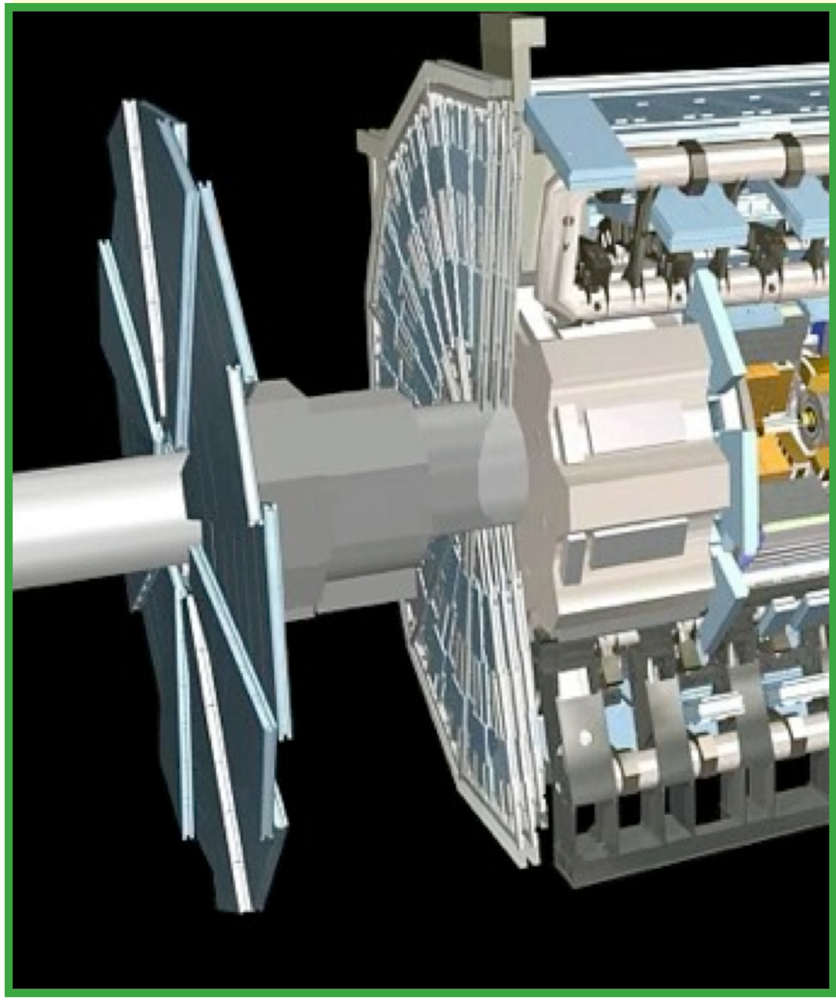
Diameter	25 m
Barrel toroid length	26 m
End-cap end-wall chamber span	46 m
Overall weight	7000 Tons

ATLAS Installation

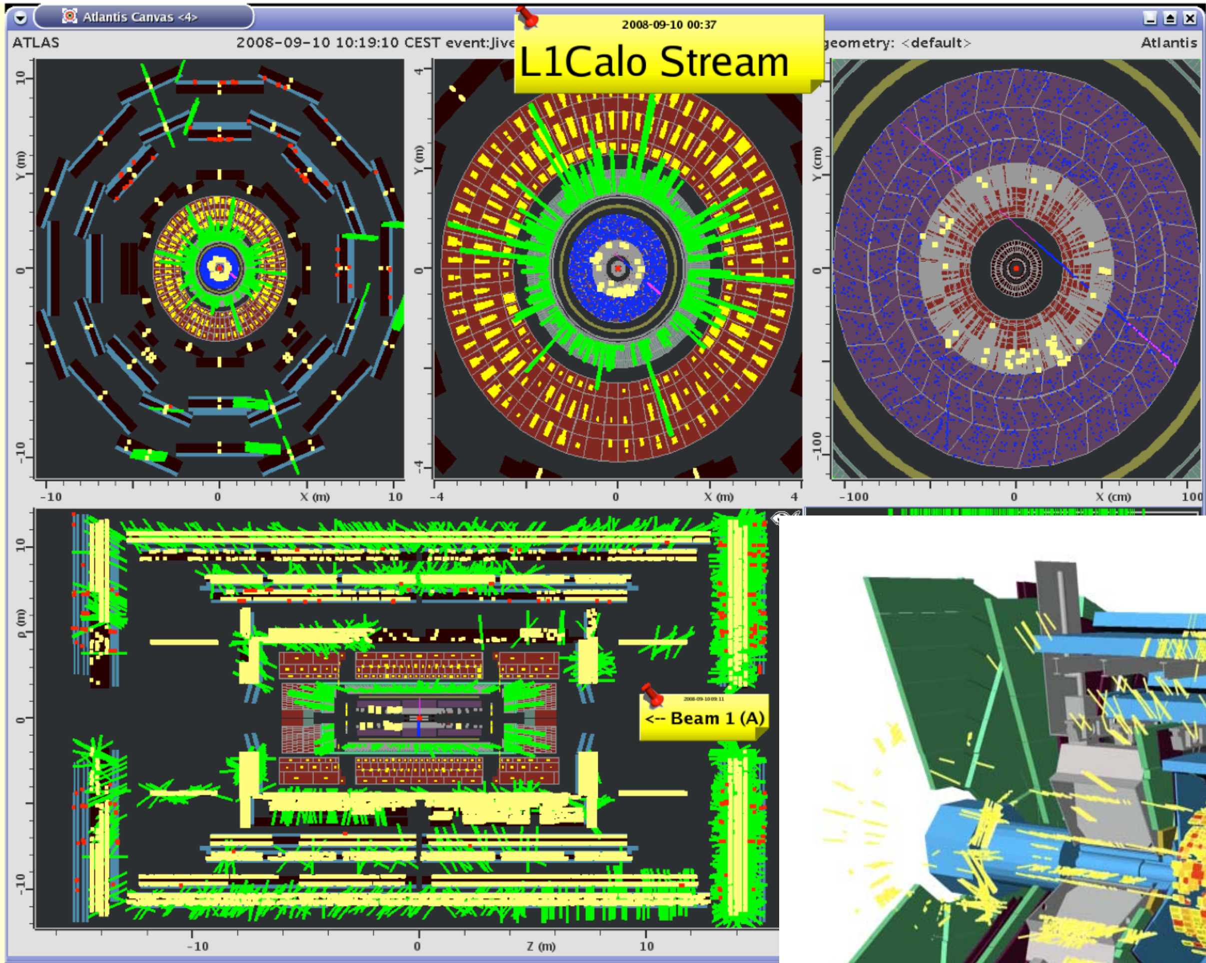


October 2006

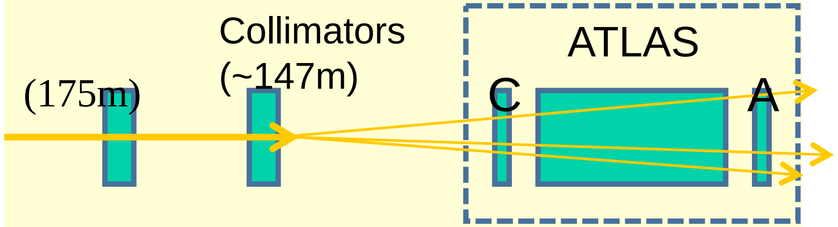
Muon detector system
In the forward region

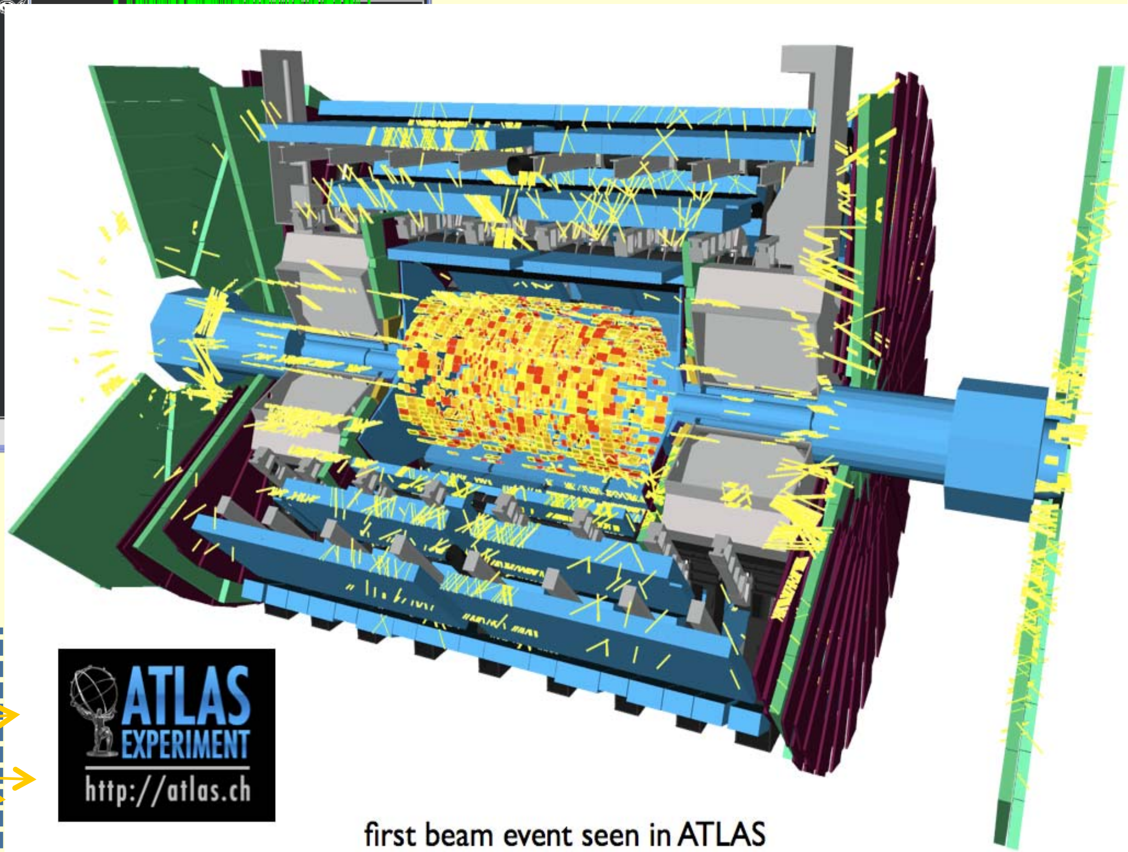


A historical moment:
Closure of the LHC beam pipe ring on 16th June 2008
ATLAS was ready for data taking in August 2008



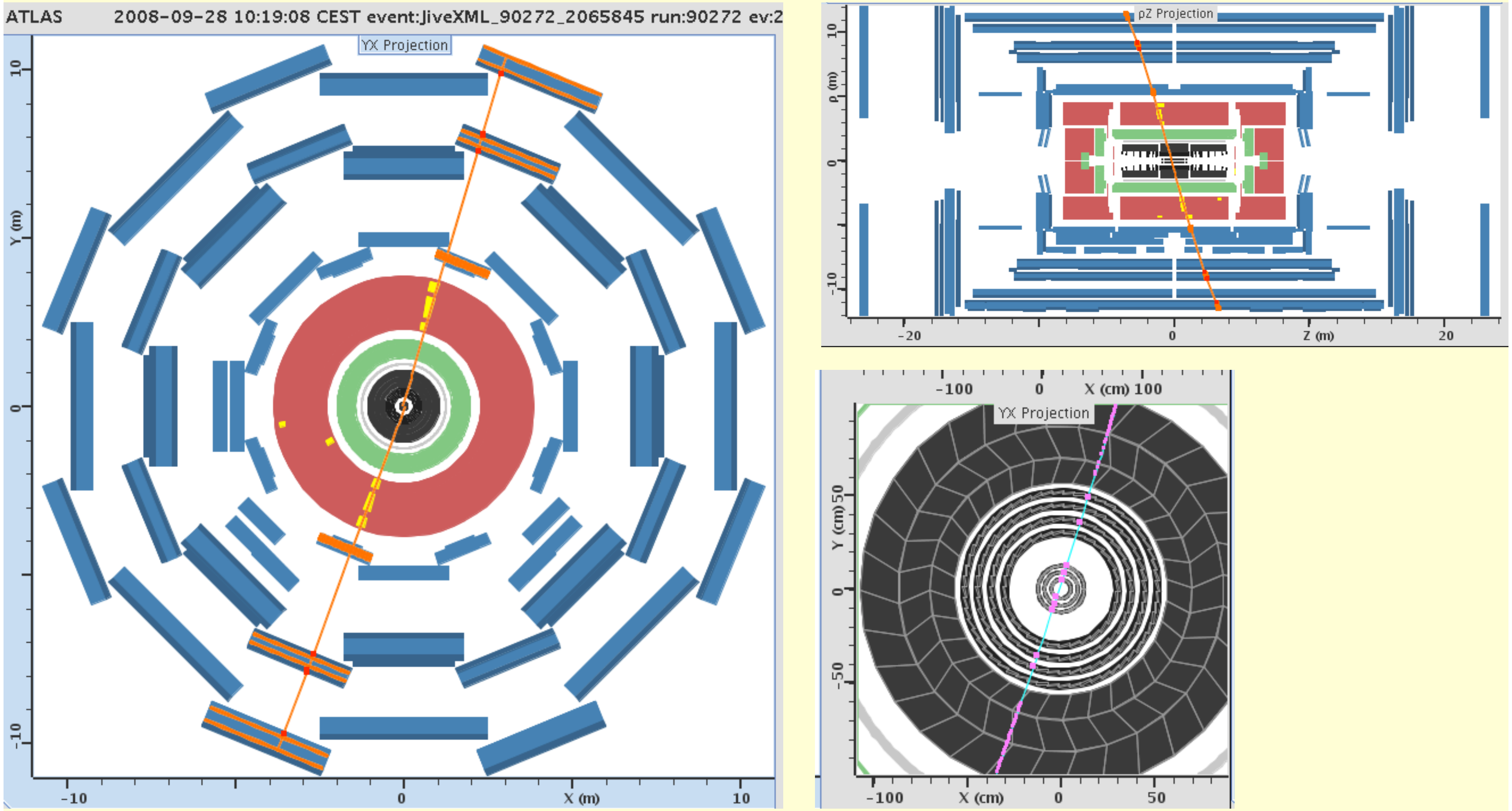
The very first
beam-splash event
from the LHC in ATLAS
on 10th September 2008,
10:19





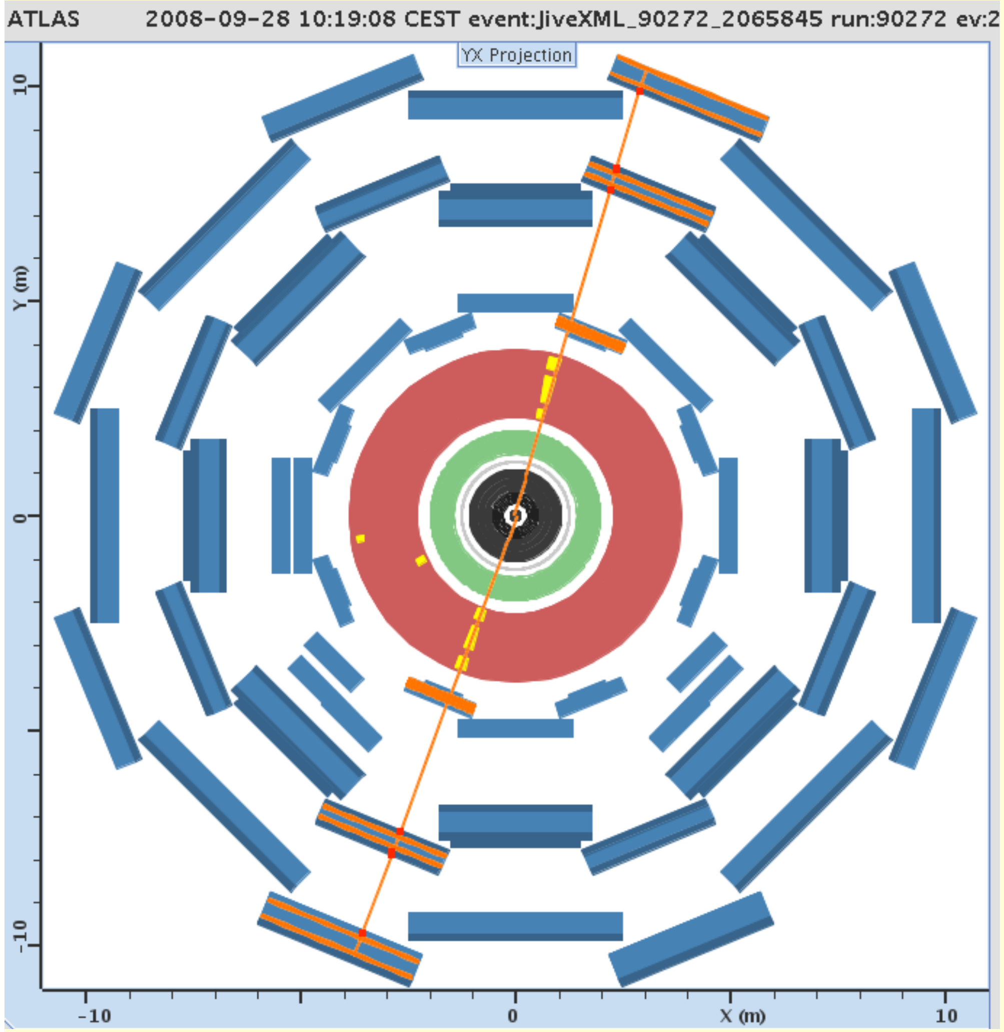
first beam event seen in ATLAS

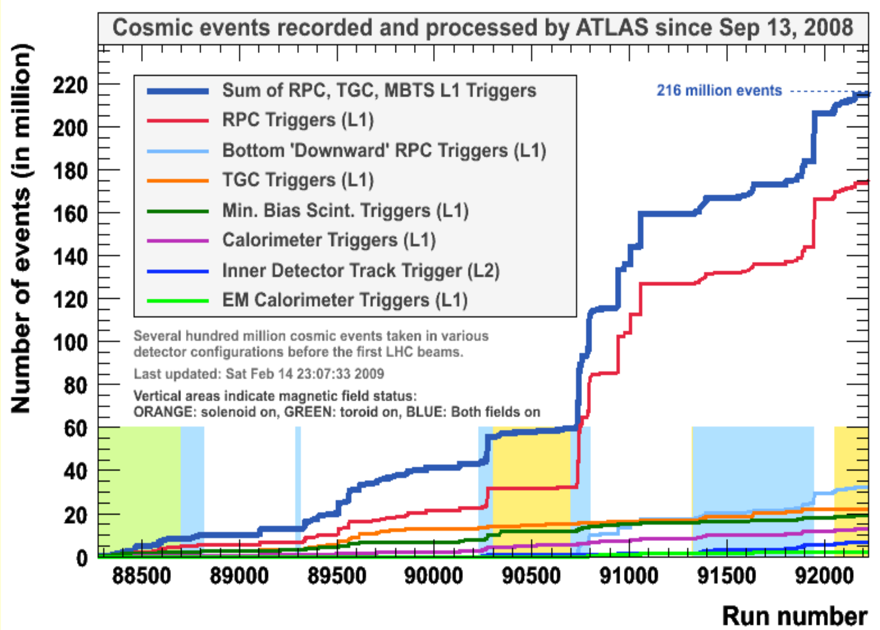
ATLAS Commissioning



with cosmic rays.....

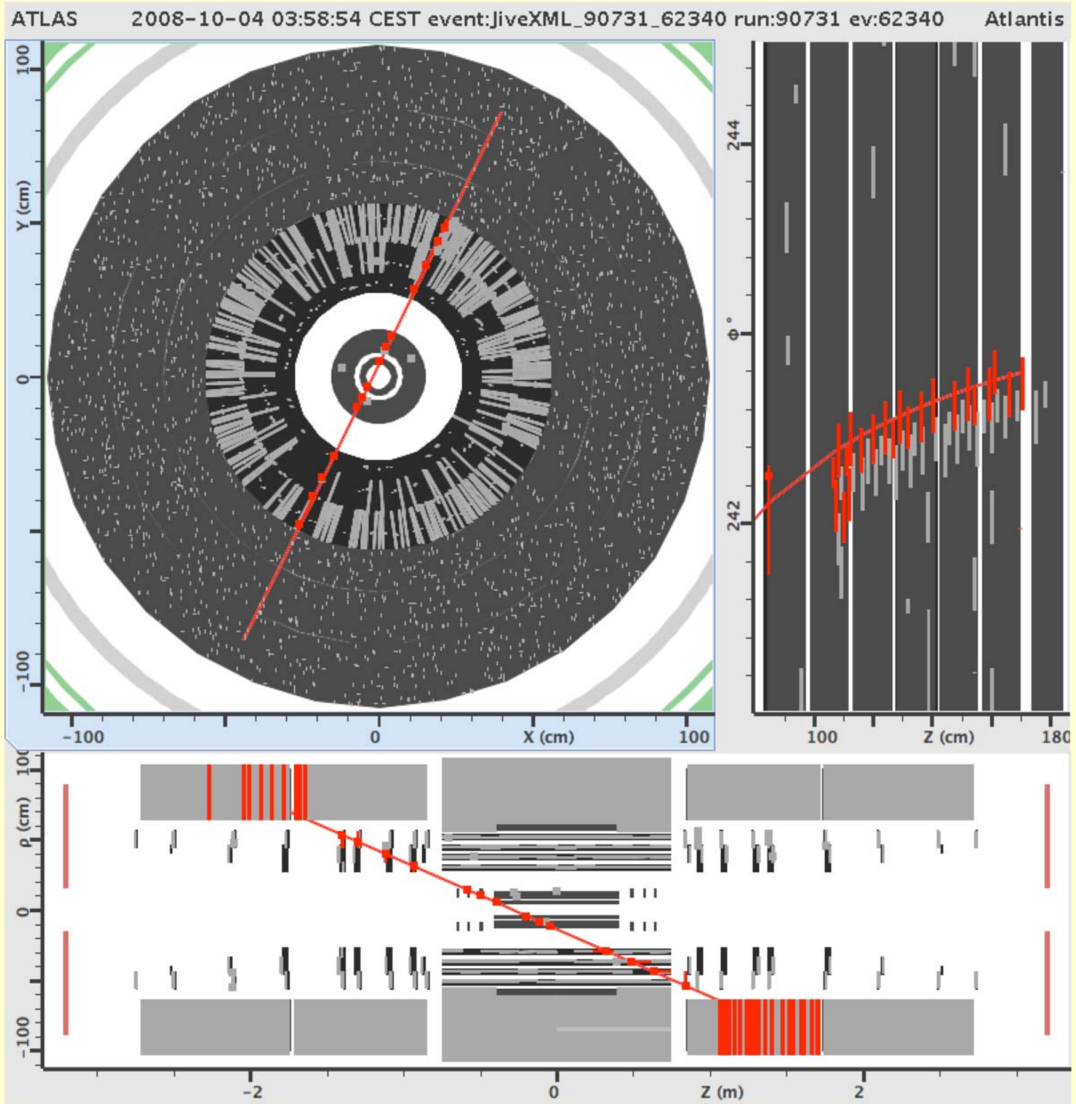
Commissioning with cosmics





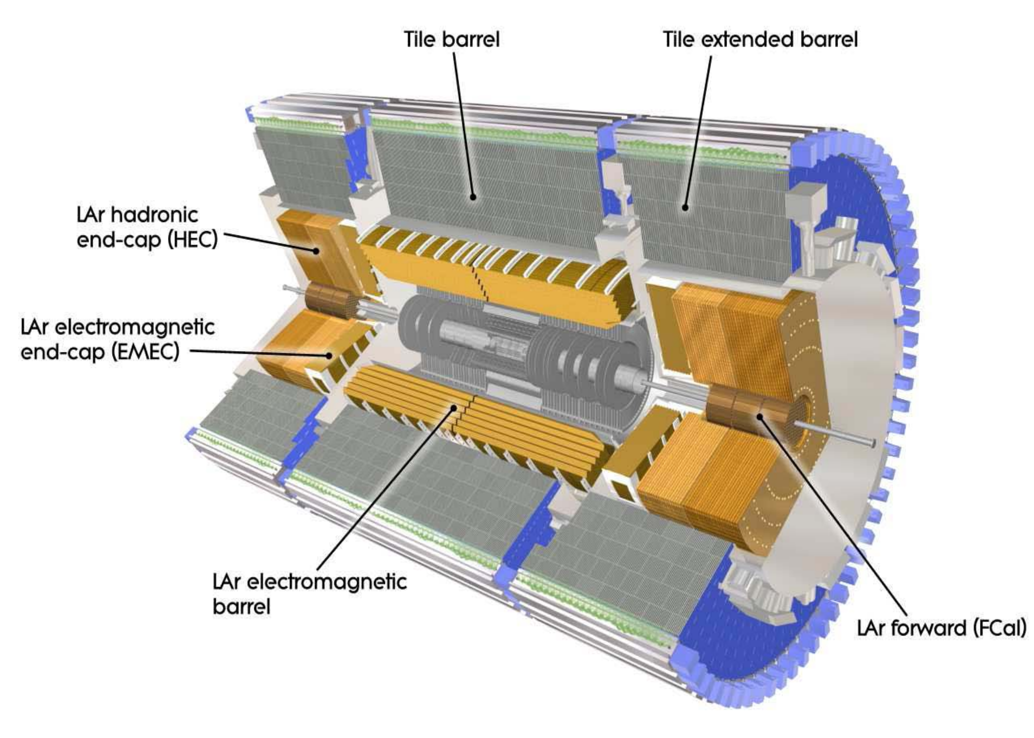
more than 200 M events recorded since Oct. 08

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":

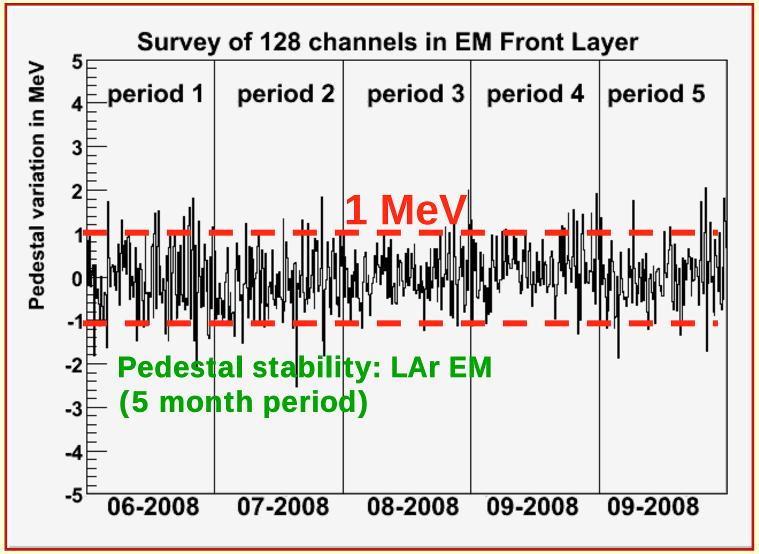
  - EM: ~0.01%
  - HEC: ~0.1%
    (+ Low voltage power supply problems, impacting ¼ of an endcap)
  - FCal: none
  - Tile Calorimeter: ~1.5%

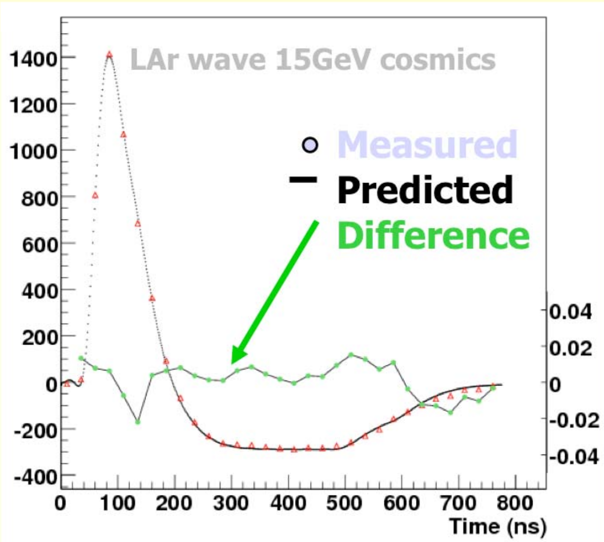
  Most of them recovered during the shutdown

- Effort is now more focussed on:

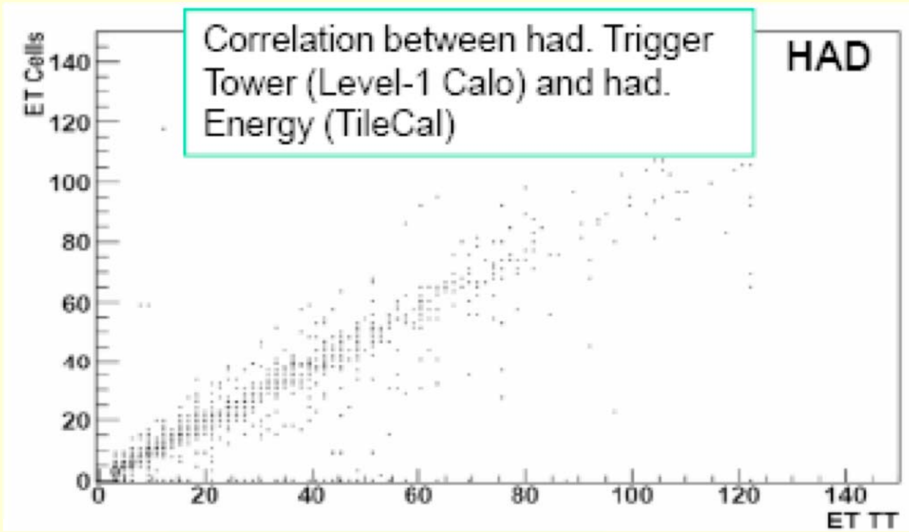
  * Long term stability
  * Prediction of the signal
  * Extraction of calibration constants

Some calorimeter commissioning results

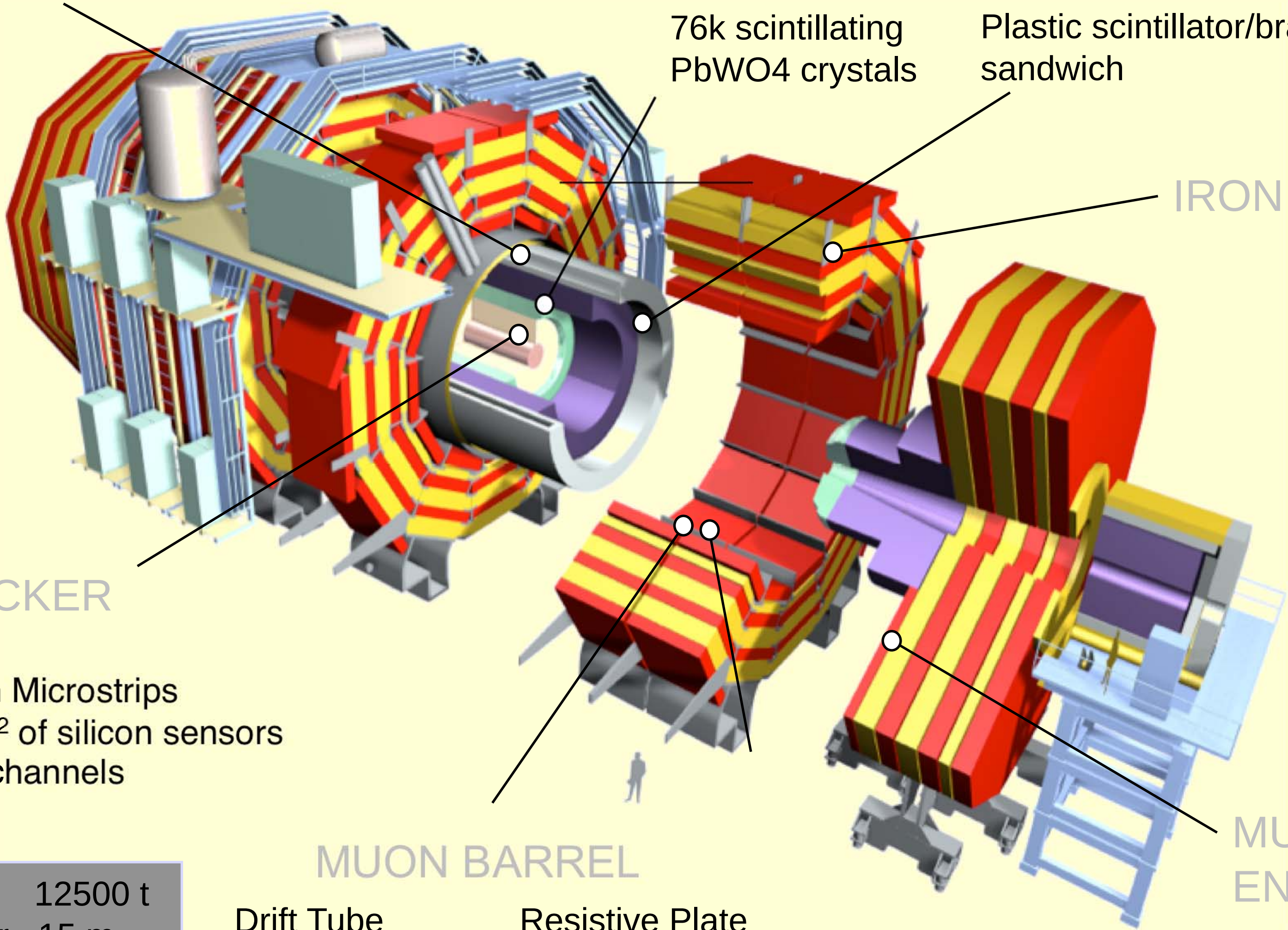




Precise knowledge is very important
for an accurate calibration

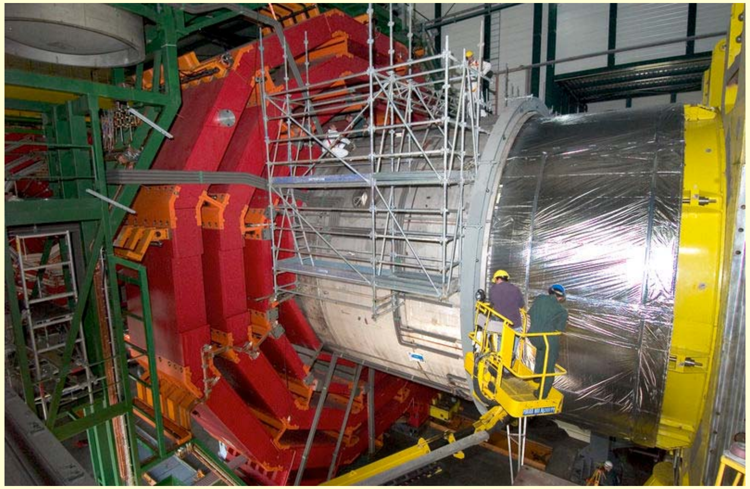


CMS



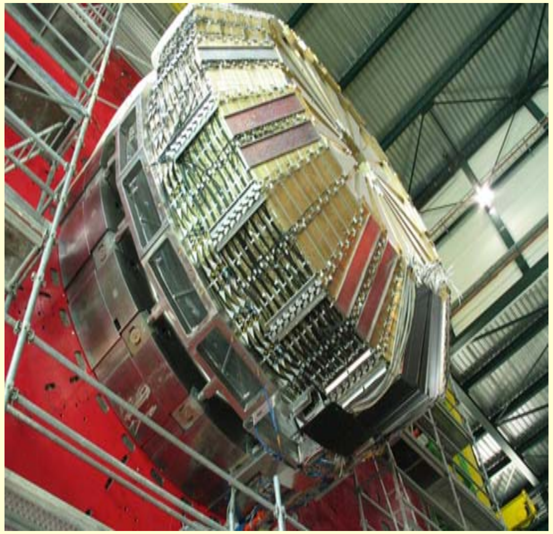
Total weight	12500 t
Overall diameter	15 m
Overall length	21.6 m

CMS Installation

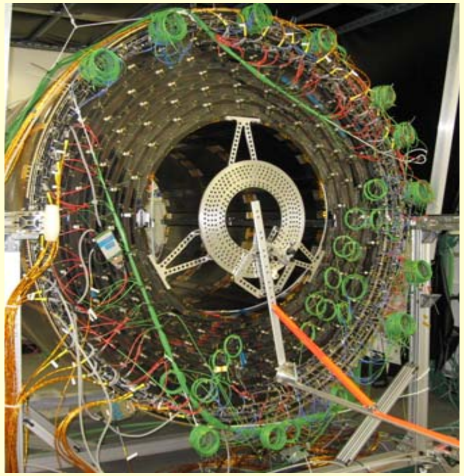


Coil inserted, 14. September 2005

Cathode Strip chambers and yoke endcaps

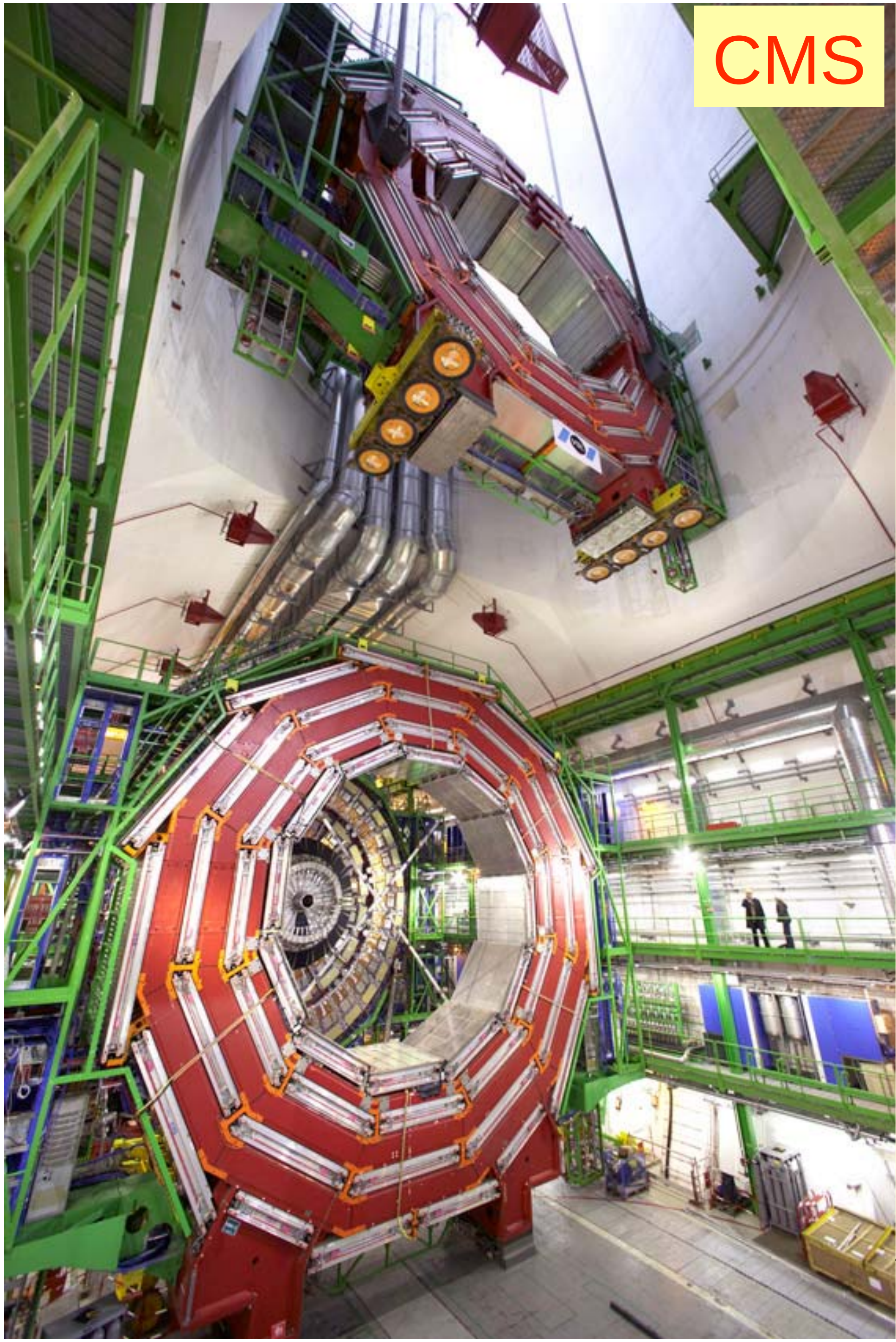


Hadronic calorimeter, endcap

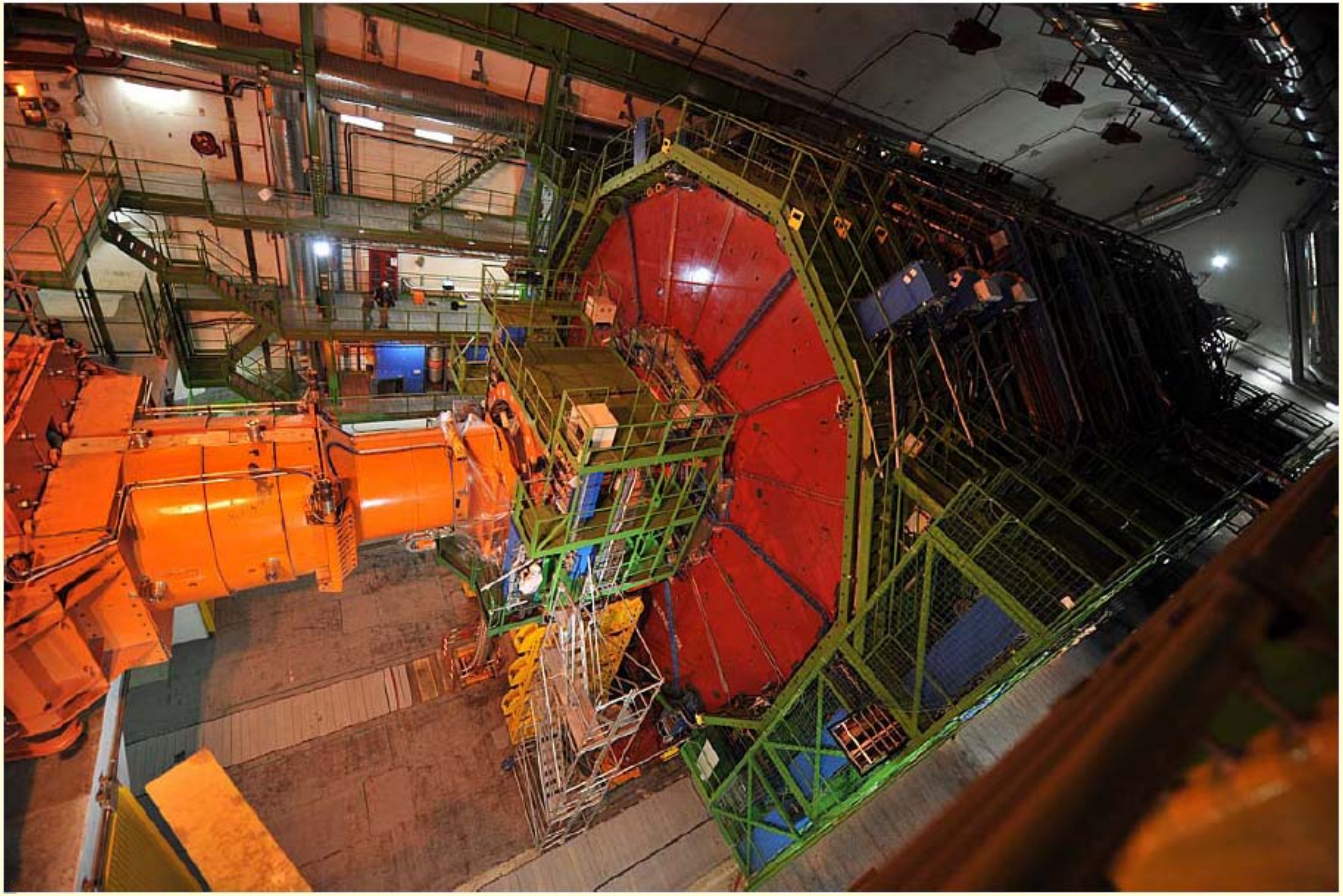


Tracker, outer barrel

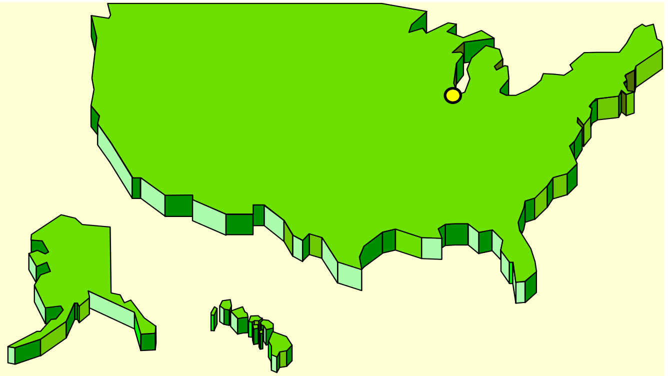
CMS



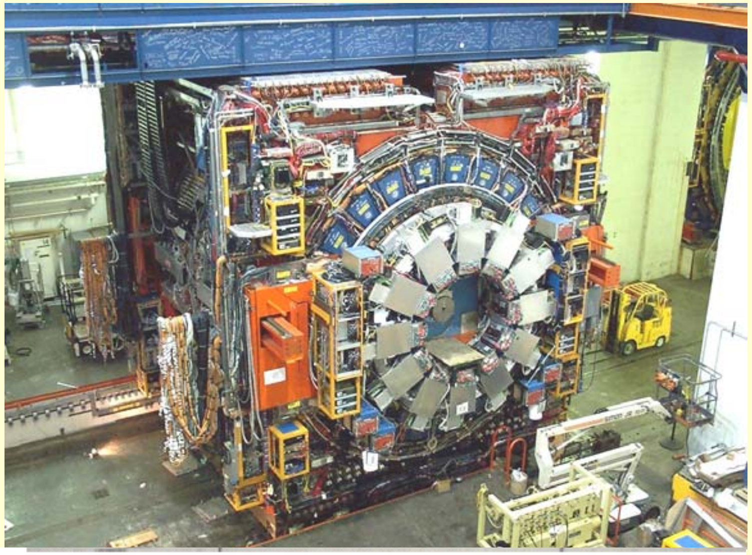
CMS Detector closed for 10th Sep.



Back to the Tevatron



The CDF experiment



12 countries, 59 institutions
706 physicists

The DØ collaboration

19 countries, 83 institutions
664 physicists

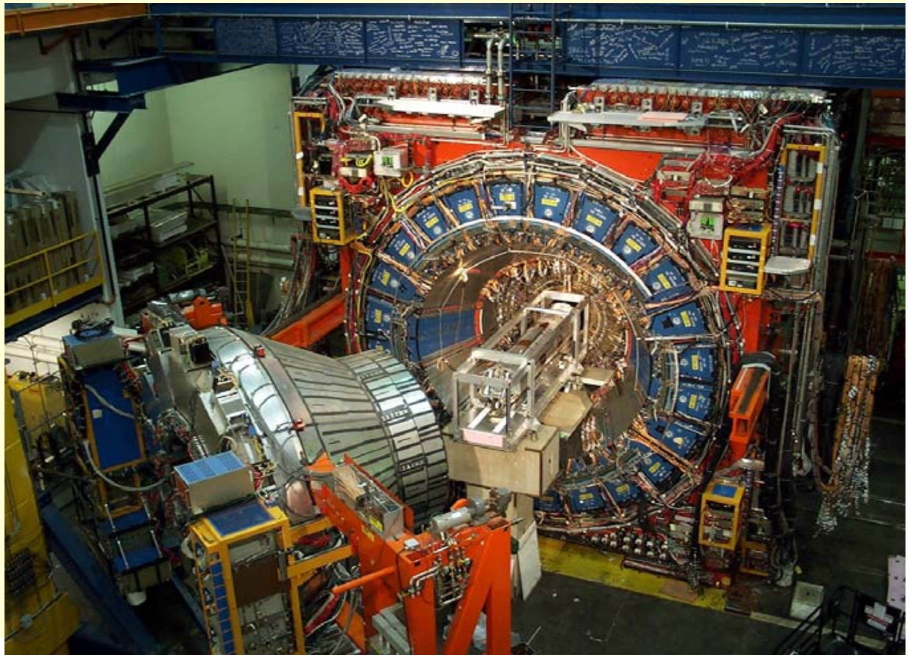
The CDF detector in Run II

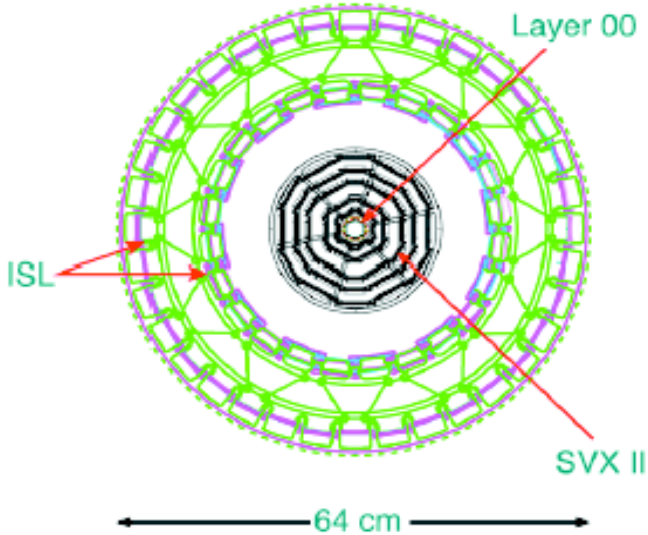
- Core detector operates since 1985:
  - Central Calorimeters
  - Central muon chambers

- 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

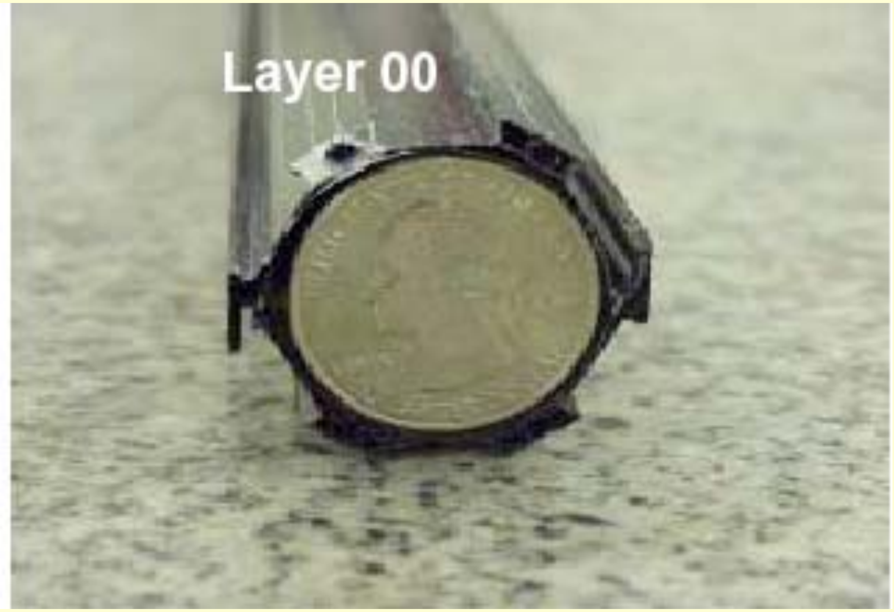
  - Forward calorimeters
  - Forward muon system
  - Time-of-flight system

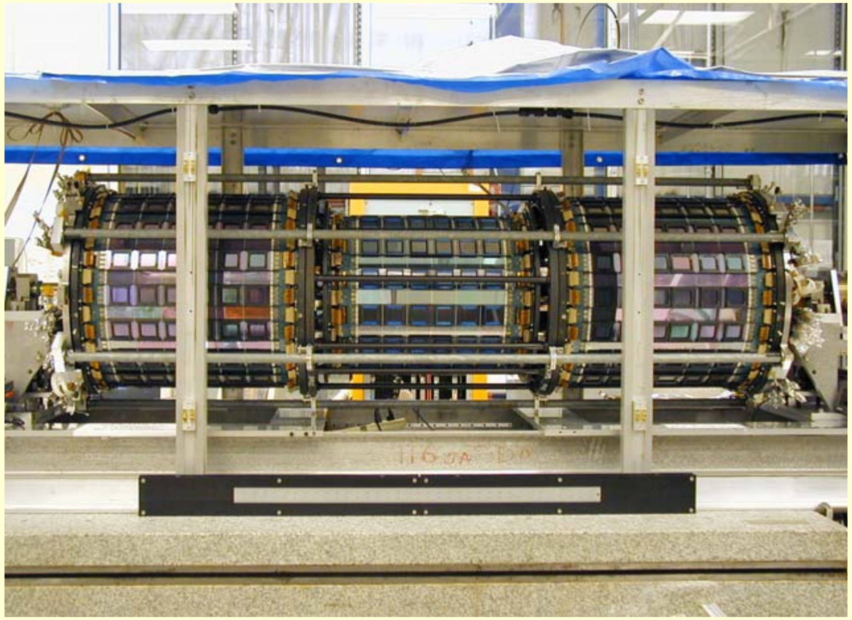
  - Trigger and DAQ
  - Front-end electronics

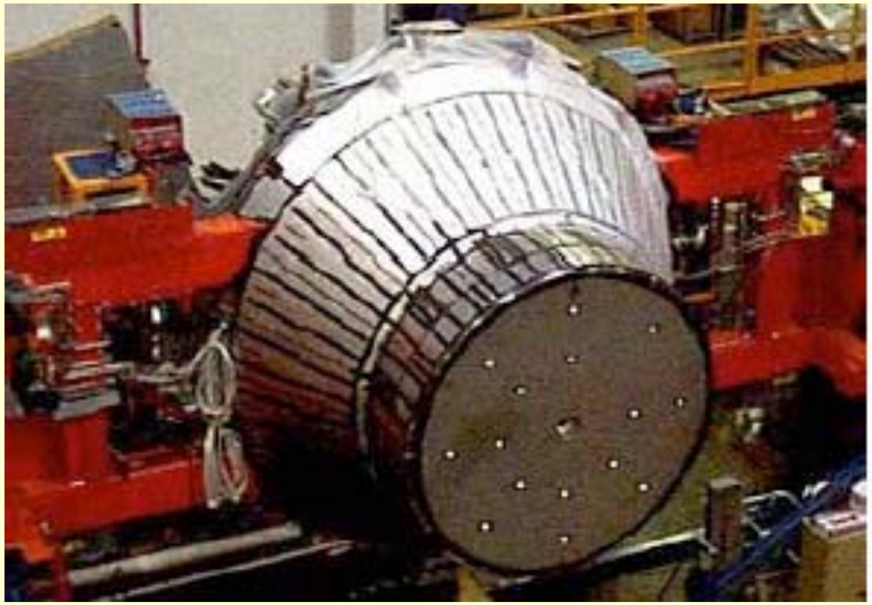




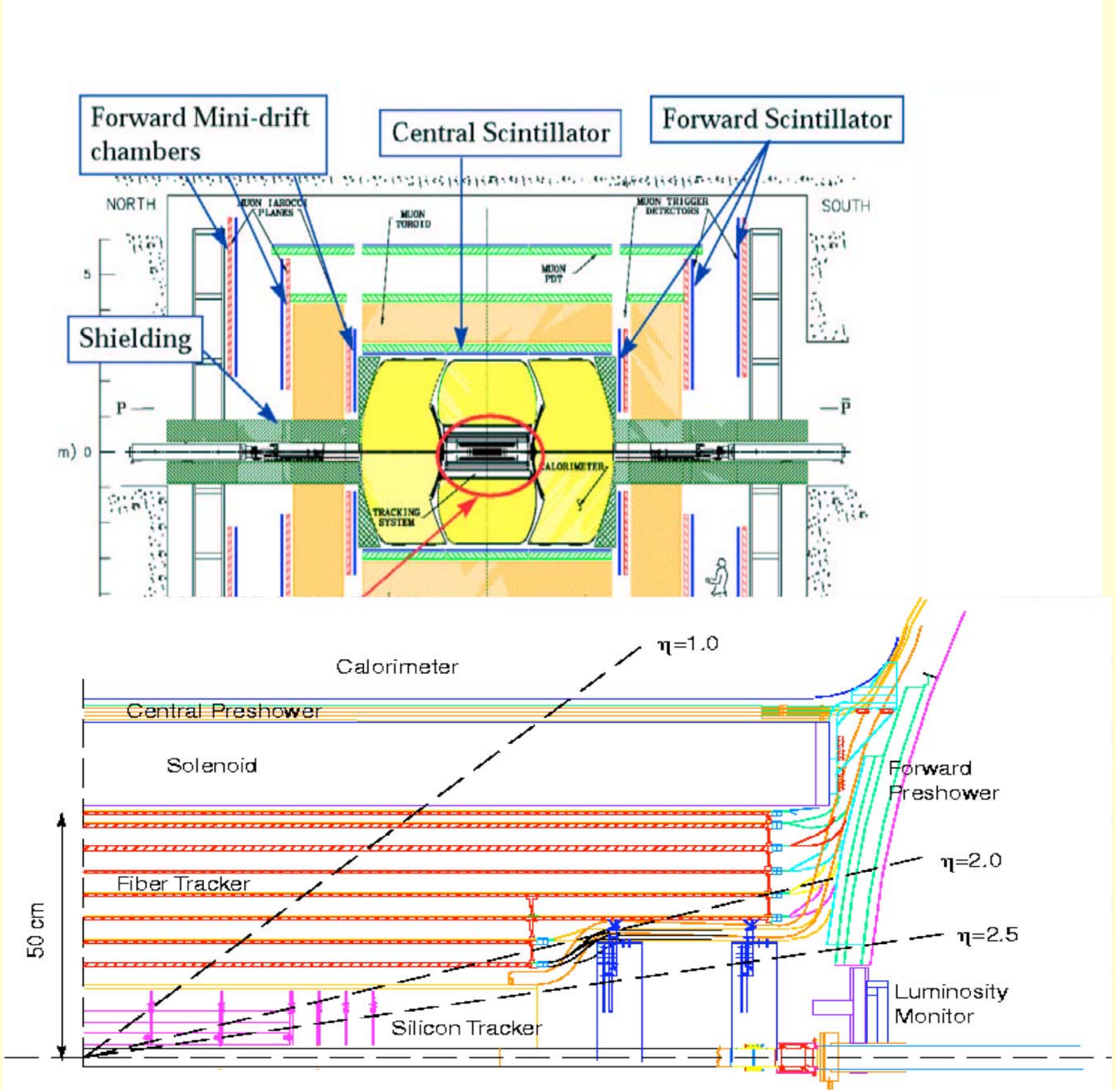
Some new CDF subdetectors







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

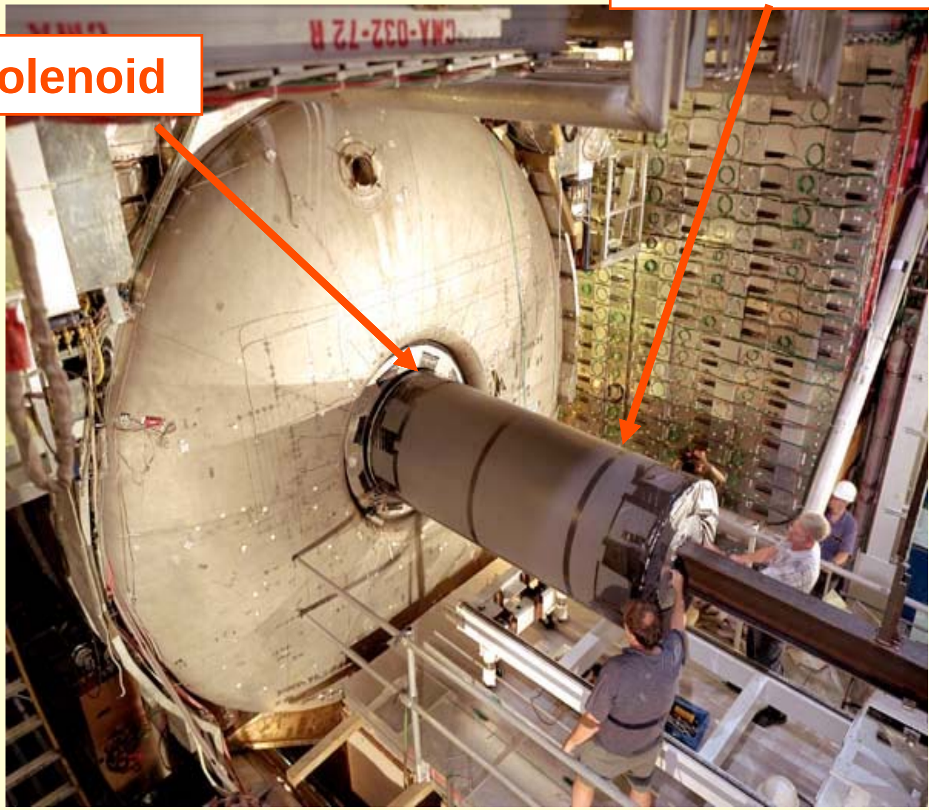
Forward muon detector

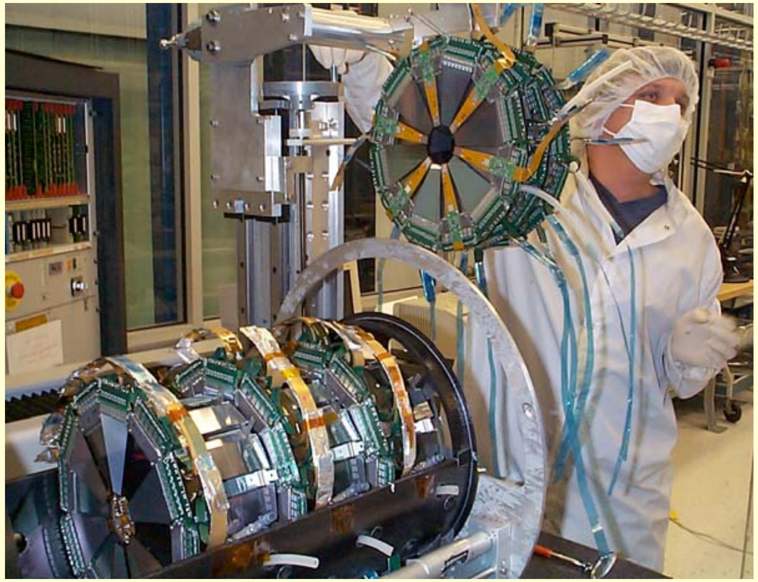
Front-end electronics

Trigger and DAQ

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

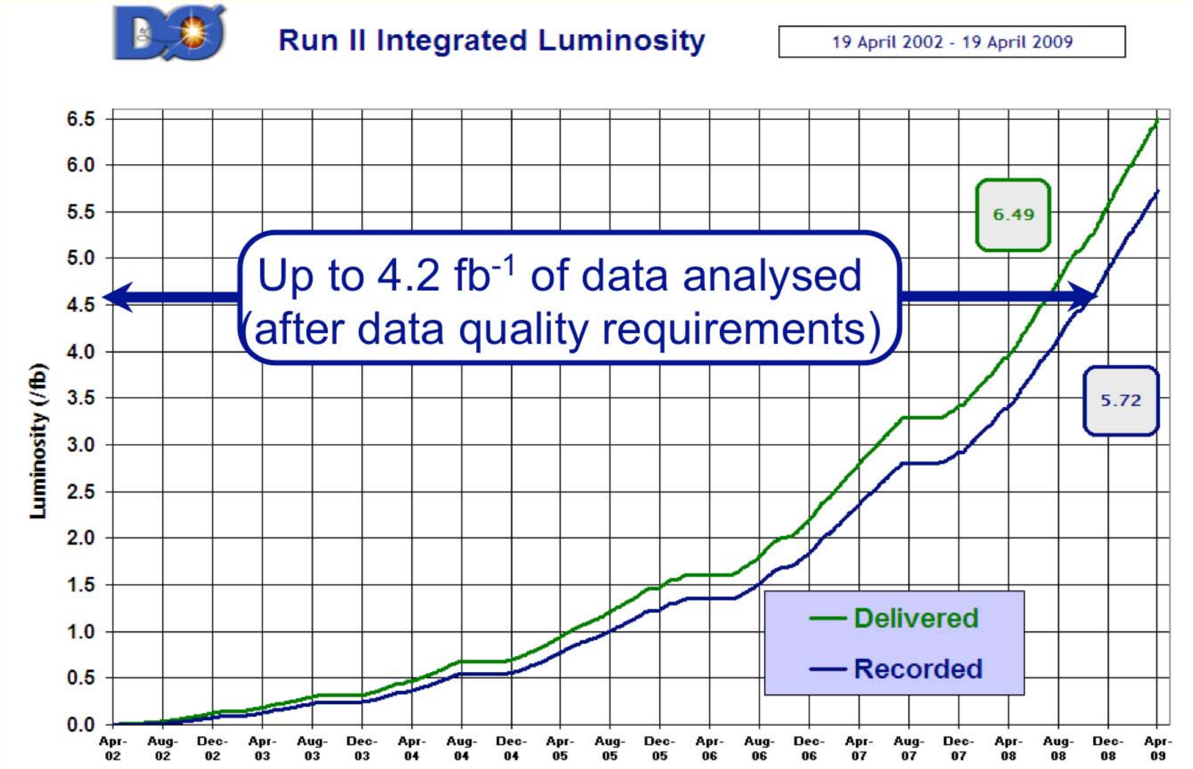
DØ Detector





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

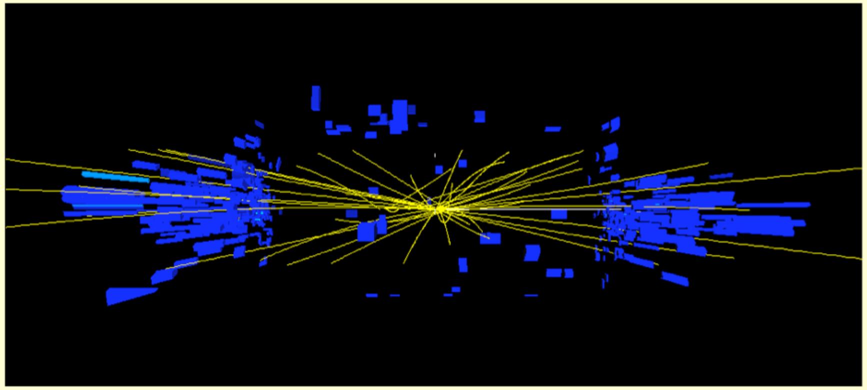
$$N_{event}\ [1/s] = \sigma \cdot L \cdot \varepsilon\ (\text{efficiency} \cdot \text{acceptance})$$

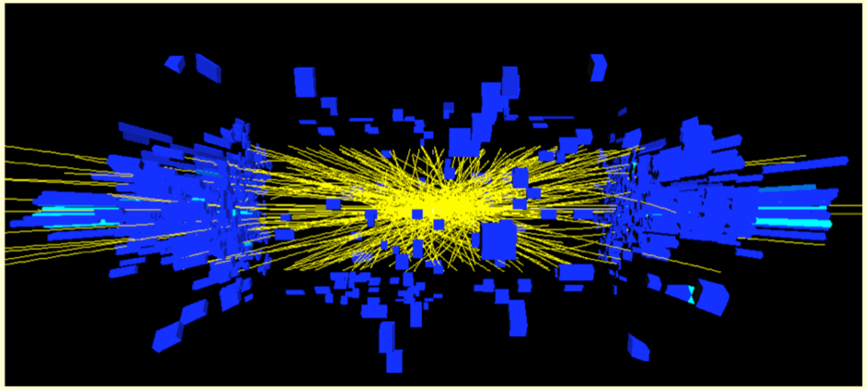
Physics ***accelerator*** ***experiment***

(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}

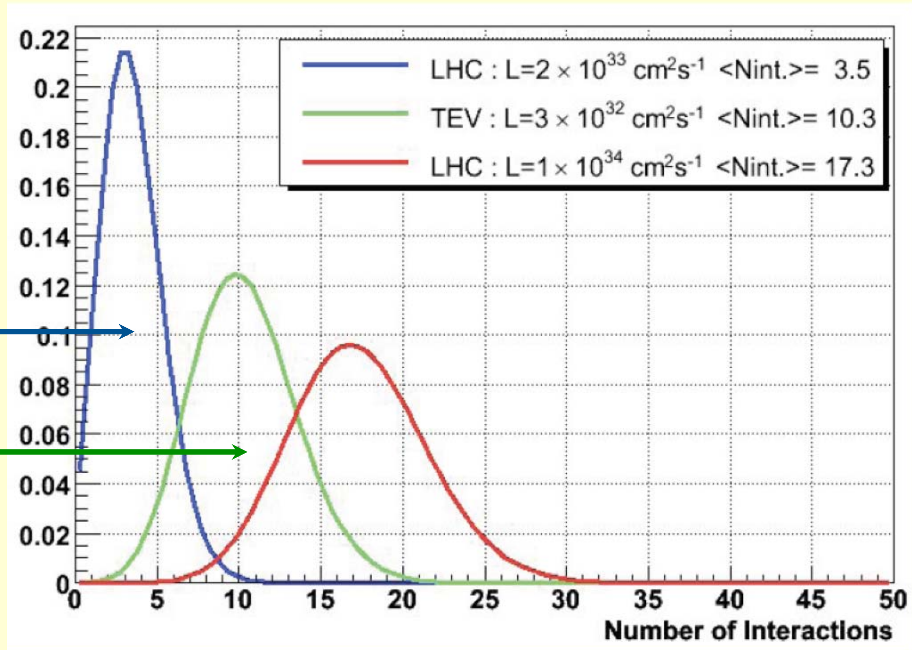




Average number of interactions:

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 ?

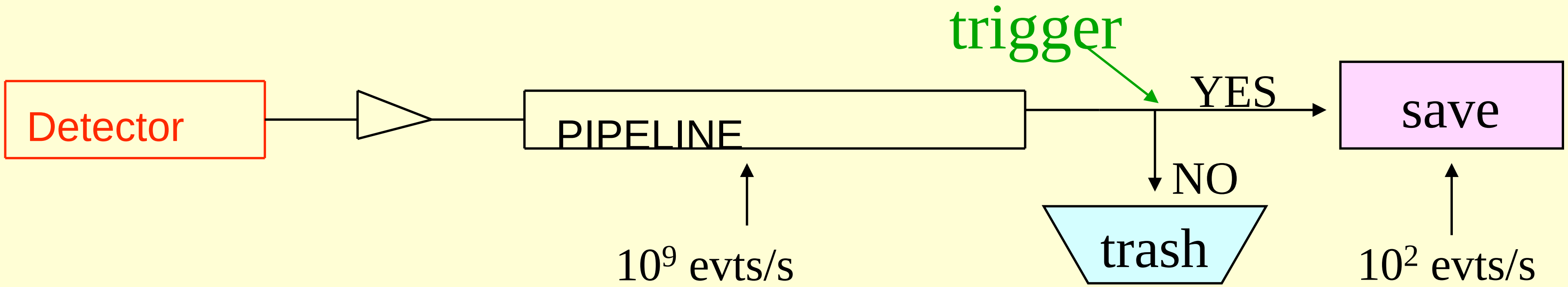
TRIGGER: much more difficult than at e^+e^- machines

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

⇒ **trigger rejection ~ 10^7**

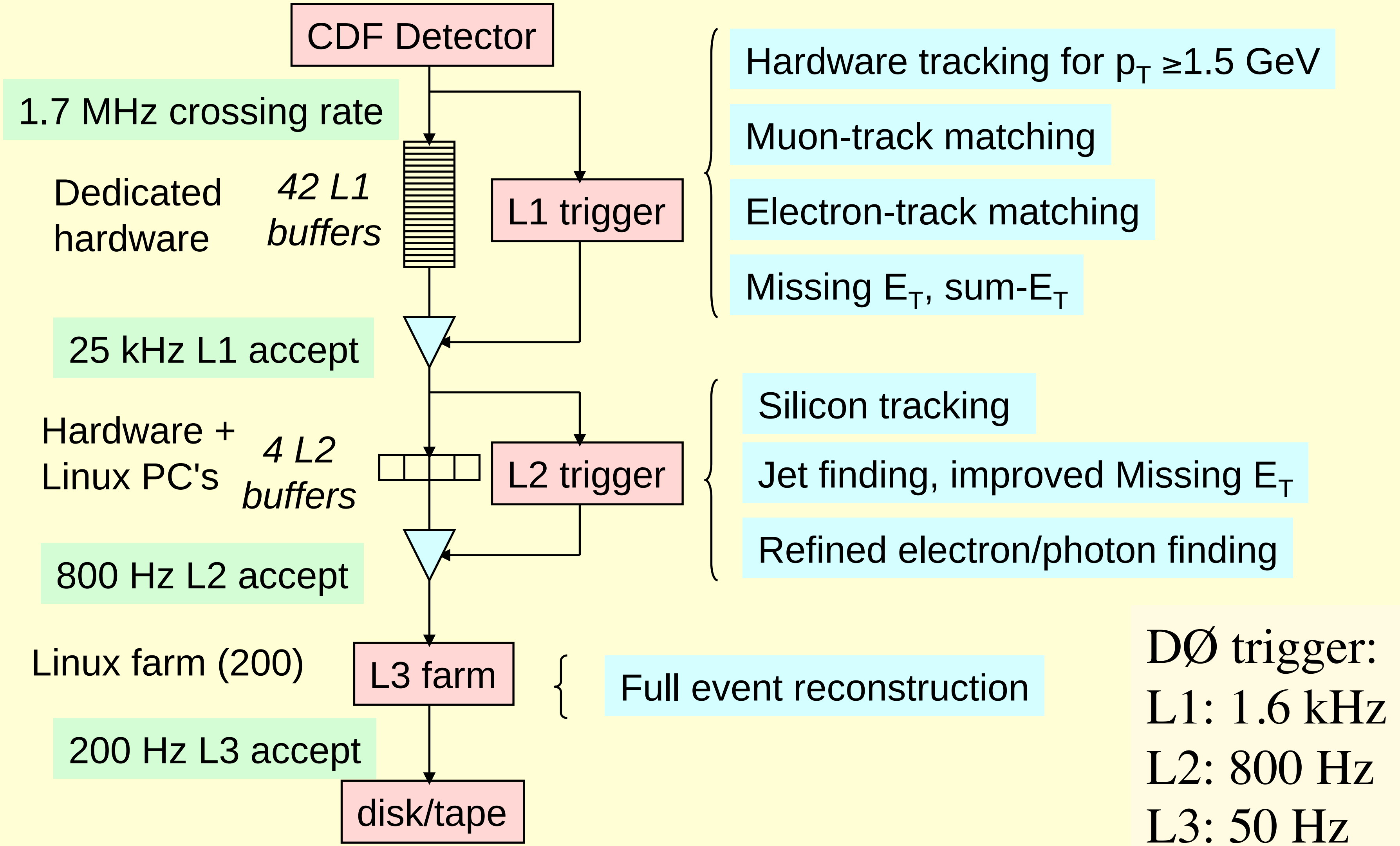
Trigger decision ≈ μs → larger than interaction rate of 25 ns

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

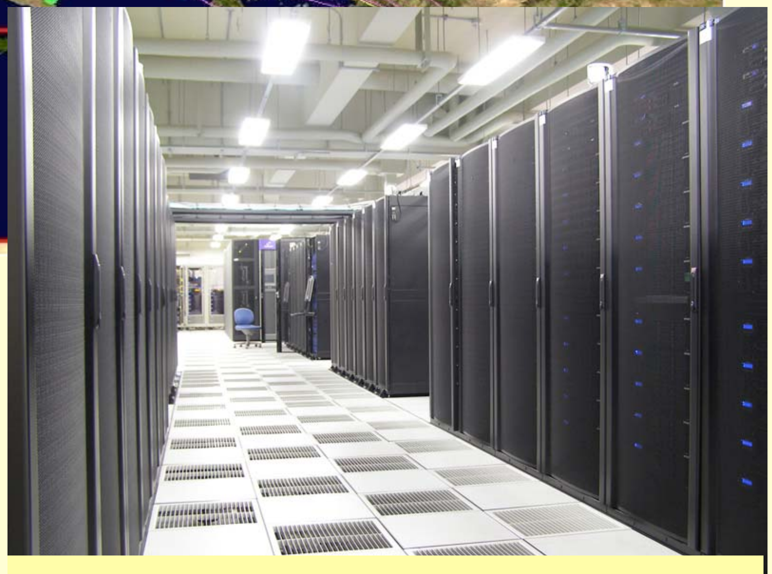


Triggering at hadron colliders

The trigger is the key at hadron colliders



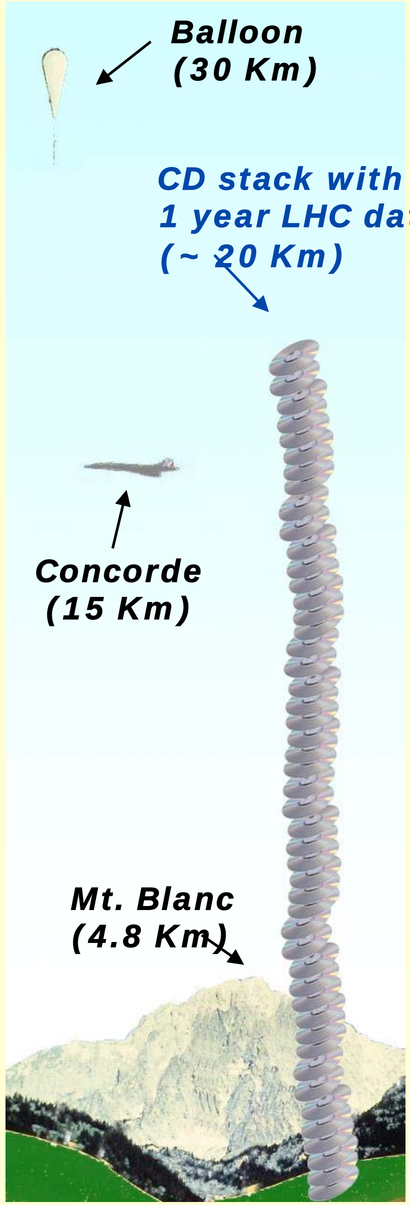
LHC data handling, GRID computing



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

Trigger system selects ~200 "collisions" per sec.

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



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

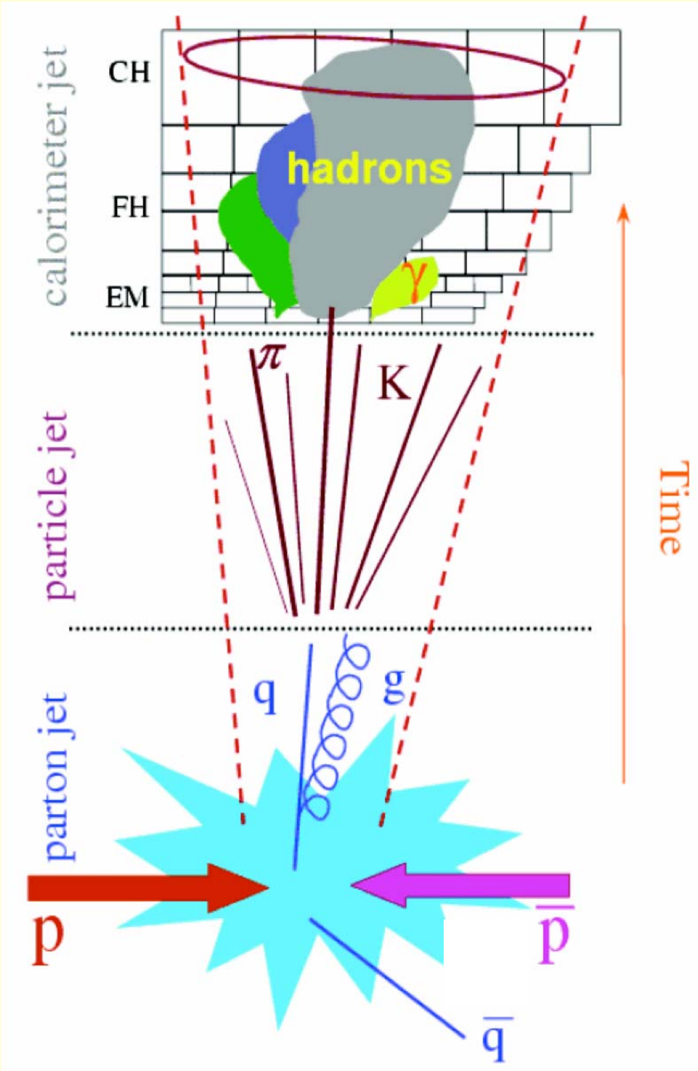
Jet reconstruction and energy measurement

- 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
  $\rightarrow$ for comparisons with theory, one needs to correct back the calorimeter energies to the „particle level" (particle jet)
  Common ground between theory and experiment

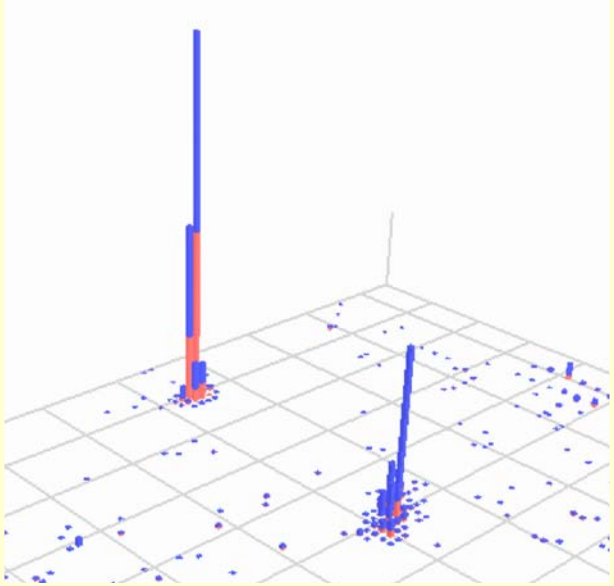
- One needs an algorithm to define a jet and to measure its energy
  conflicting requirements between experiment and theory (exp. simple, e.g. cone algorithm, vs. theoretically sound (no infrared divergencies))

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

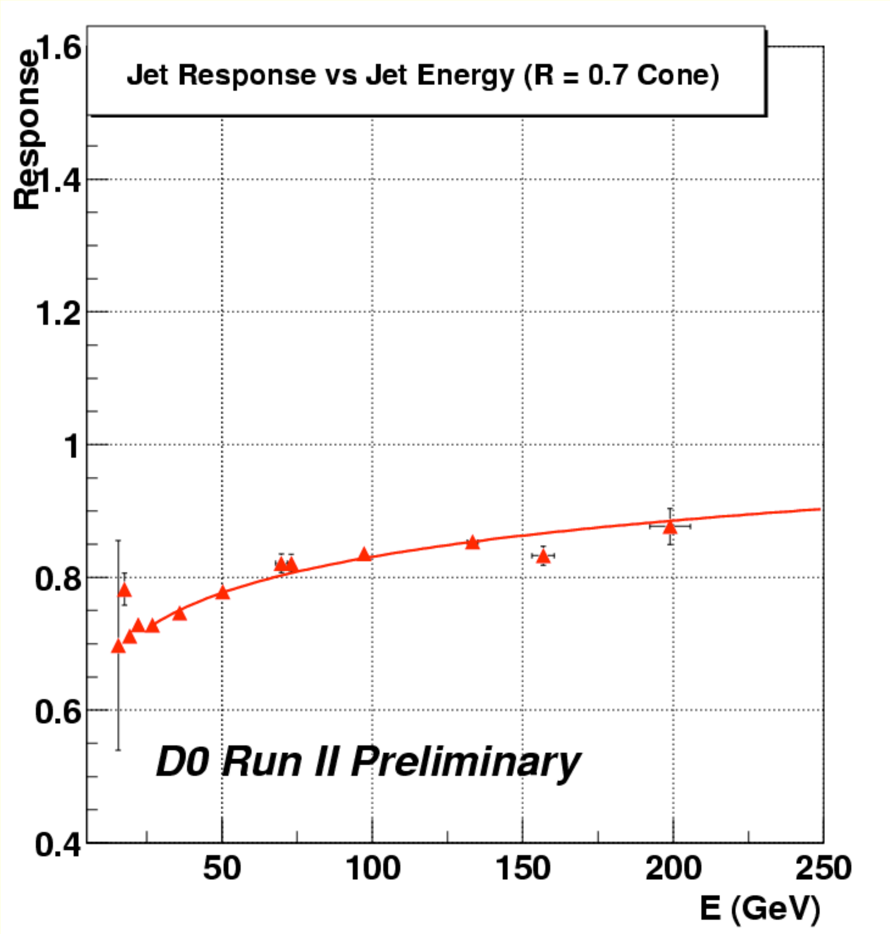


Main corrections:

- 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)

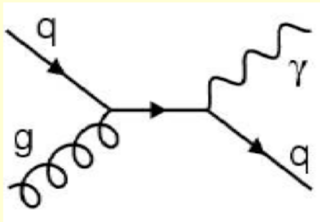


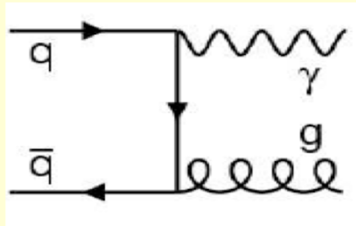
Jet Energy Scale



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

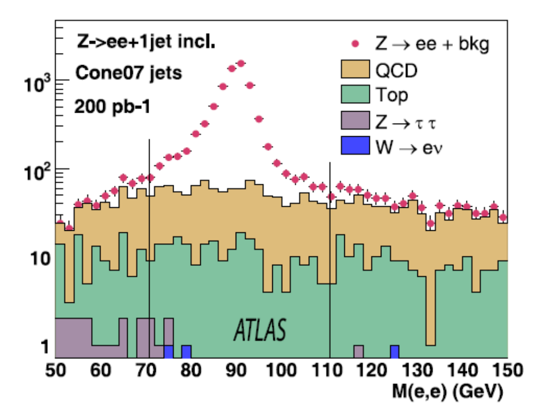
- A good jet-energy scale determination is essential for many QCD measurements
  (arguments similar to Tevatron, but kinematic range (jet p_T) is larger, ~20 GeV – ~3 TeV)

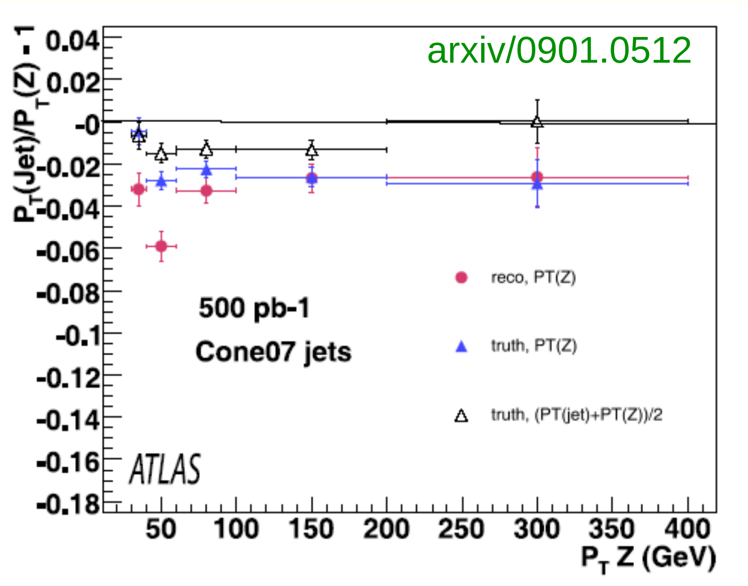
- Propagate knowledge of the em scale to the hadronic scale, but several processes are needed to cover the large p_T range

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