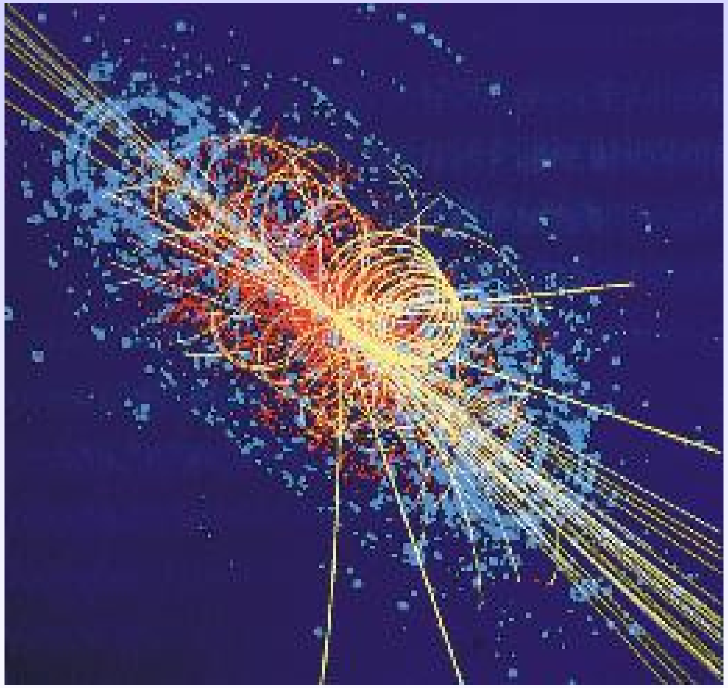
Physics at Hadron Colliders



Karl Jakobs
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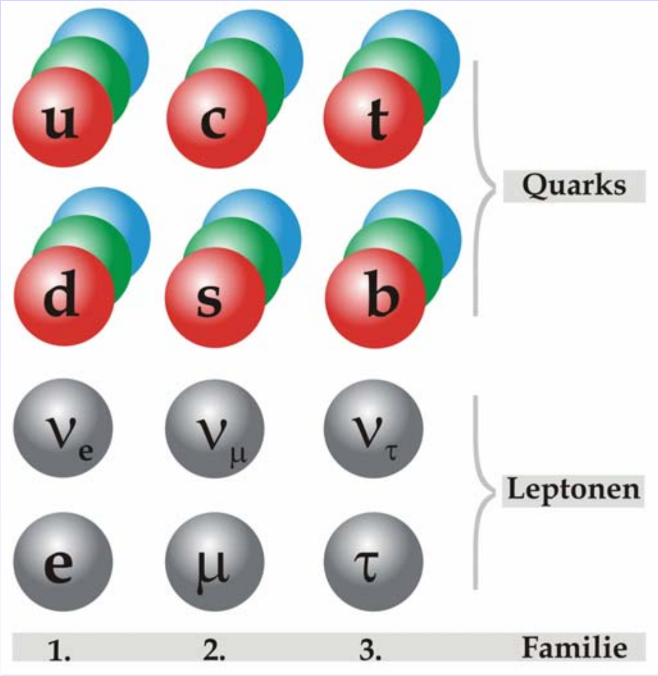
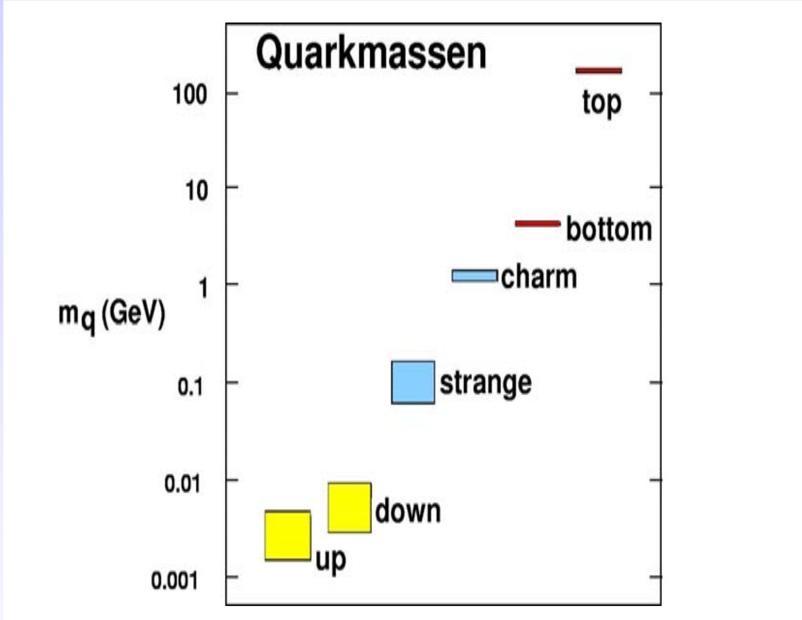
Universität Freiburg / Germany

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

The Standard Model of Particle Physics

(i) The building blocks of matter: Quarks and Leptons (Fermions)





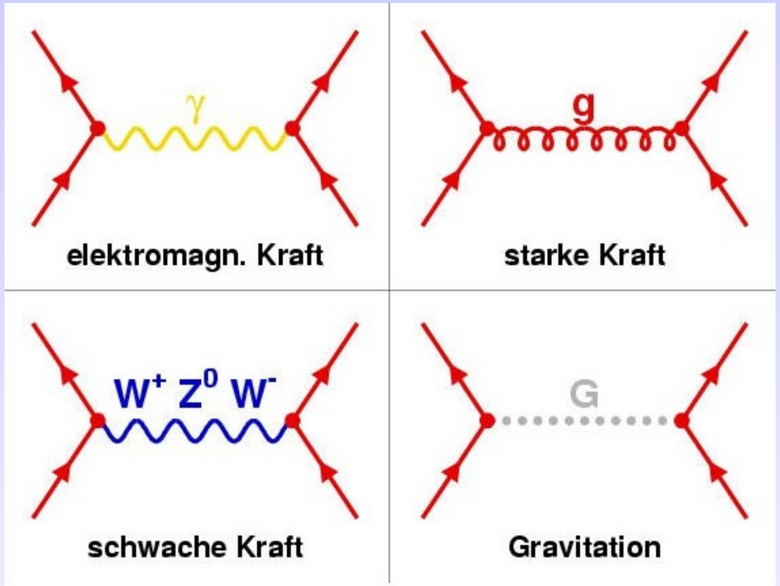
m (e) = 0,000511 GeV/c^2
m (τ) = ~1,8 GeV/c^2

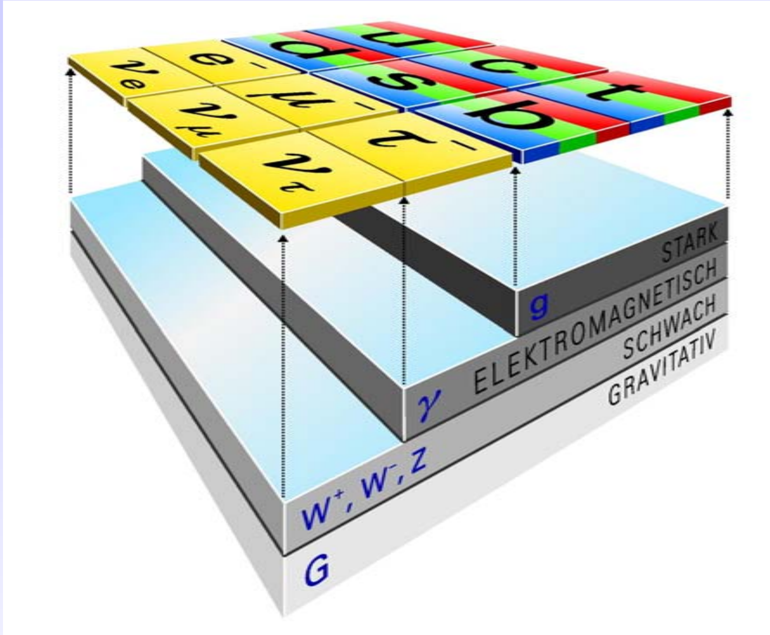
m (u) = 0,005 GeV/c^2
m (t) = ~ 174 GeV/c^2

In comparison: m (p) = 0,938 GeV/c^2

(ii) Force carriers / Interactions:

exchange of bosons





Electroweak Interaction: γ, $W^{\pm}$, Z

Quantum Chromodynamics (QCD): Gluons

$m_\gamma = 0$, $m_g = 0$

$M_W = 80.426 \pm 0.034$ GeV / c^2

$M_Z = 91.1875 \pm 0.0021$ GeV / c^2

Important open questions of particle physics

1. What is the origin of mass ?

e t γ, **g**, W

Does the Higgs particle exist **?**

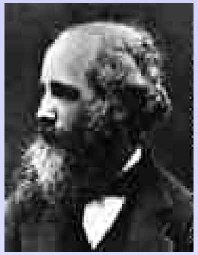
as proposed by P. Higgs (1964)

All properties of the Higgs particle are known, once its mass is fixed.
The mass is a free parameter in the Standard Model

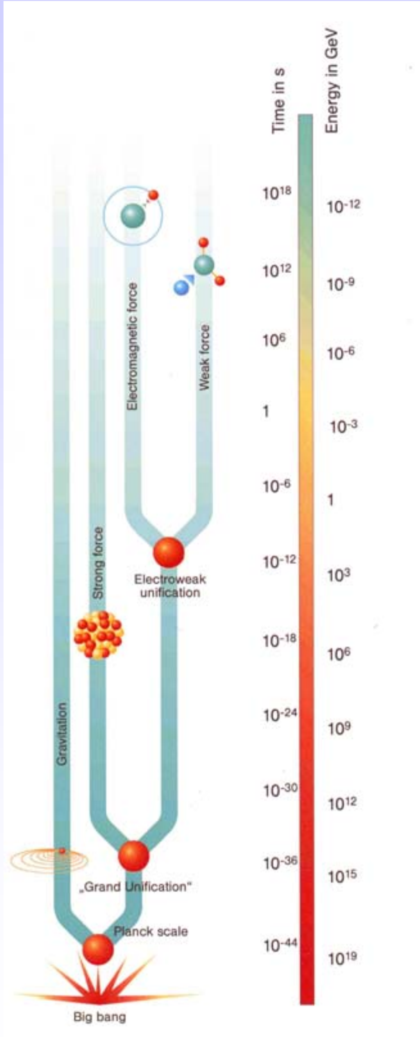
Constraints (from theory and experiment):

114.4 GeV/c² (exp.) < m_H < ~ 1000 GeV/c² (theo.)

2. The question of unification:
Is there a universal force, a common origin of the different interactions ?



Famous example: J.C.Maxwell (1864)
Unification of electricity and magnetism

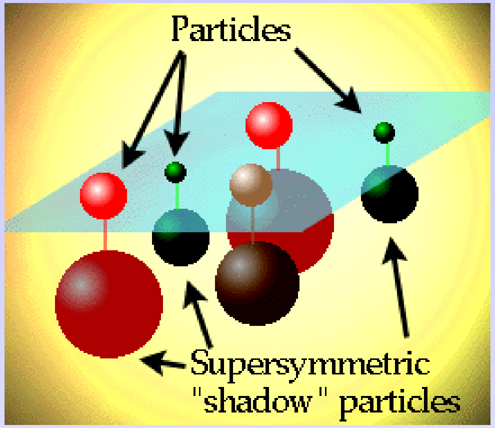


1962-1973: Glashow, Salam and Weinberg

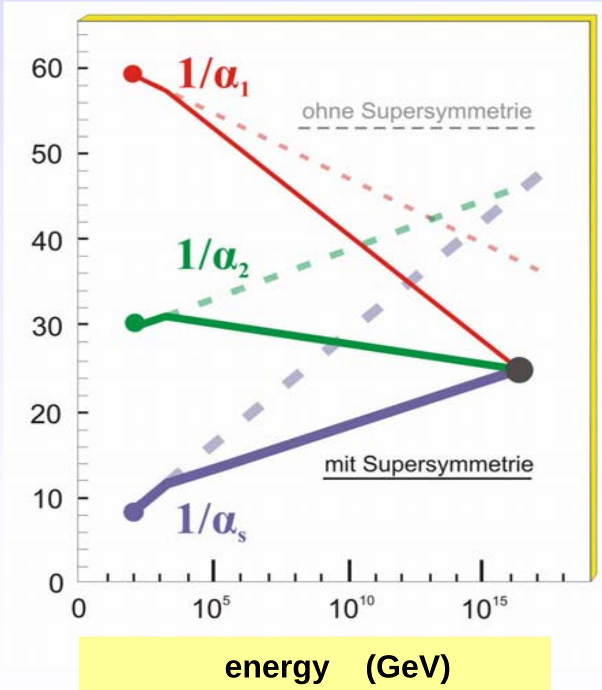
Unification of the electromagnetic and weak interactions
⇒ electroweak interaction
(prediction of W- und Z-bosons)

Higgs mechanism is a cornerstone of the model

Are there new, yet unknown types of matter ?
Will we meet supersymmetry (SUSY) on the way towards unification ?



Quark	**Squark**
Top	**Stop**
Electron	**Selectron**
Wino	**W**
Higgsino	**H**



Motivation for SUSY:

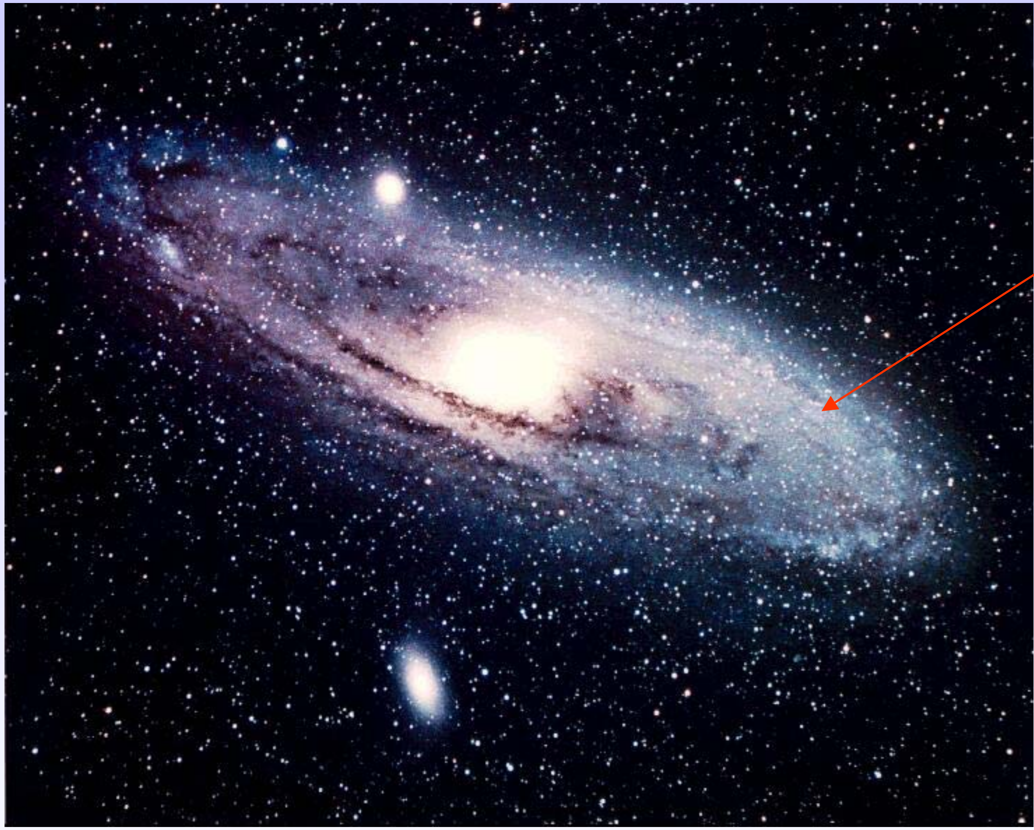
(i) Unification of forces seems possible

(ii) Supersymmetry provides a candidate for dark matter in the universe

SUSY

?

Where are we in the Universe ?

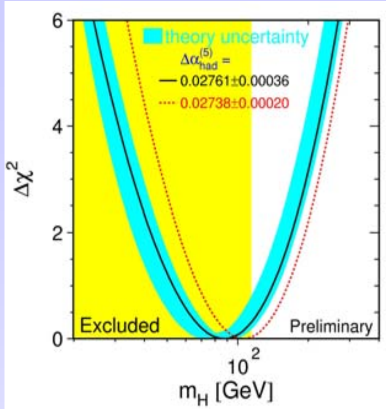


We are here

Surrounded by

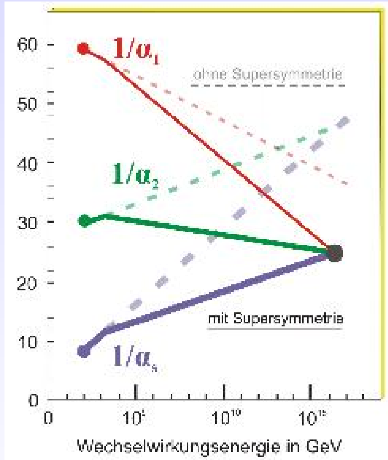
- Mass
  (planets, stars, ….,hydrogen gas)
- **Dark Matter**
- **Dark Energy**

Key Questions of Particle Physics



1. Mass: What is the origin of mass?

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



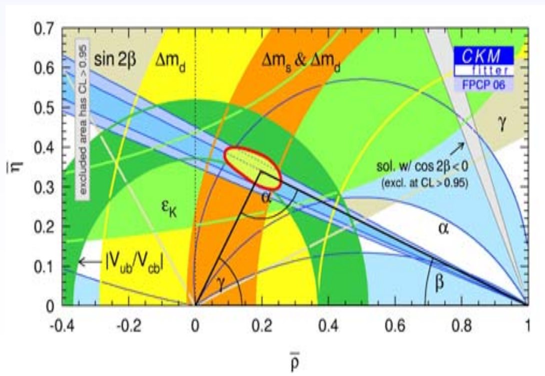
2. Unification: What is the underlying fundamental theory ?

Motivation: Gravity not yet included;
Standard Model as a low energy approximation

- Is our world supersymmetric ?
- Are there extra space time dimensions ?
- Other extensions ?

3. Flavour: or the generation problem

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



The role of Hadron Colliders

1. Mass

- Search for the Higgs boson

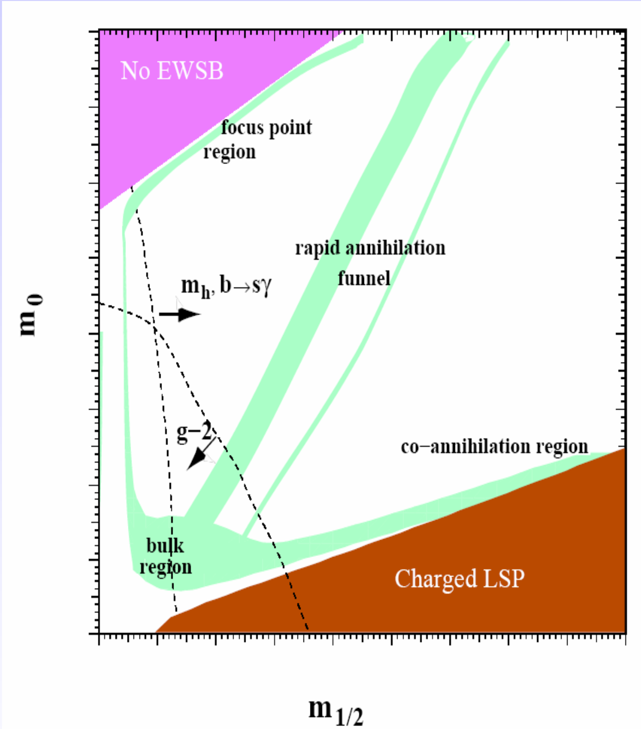
2. Unification

- Test of the Standard Model
- Search for Supersymmetry
- Search for other Physics Beyond the SM

3. Flavour

- B hadron masses and lifetimes
- Mixing of neutral B mesons
- CP violation

The link between SUSY and Dark Matter ?



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

Energy → Explore the TeV energy domain

Experiments must also be prepared for "the unexpected"

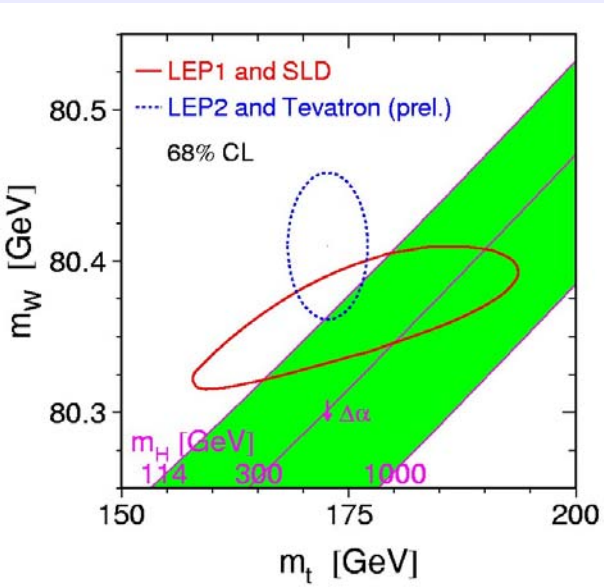
Precision → Further tests of the Standard Model

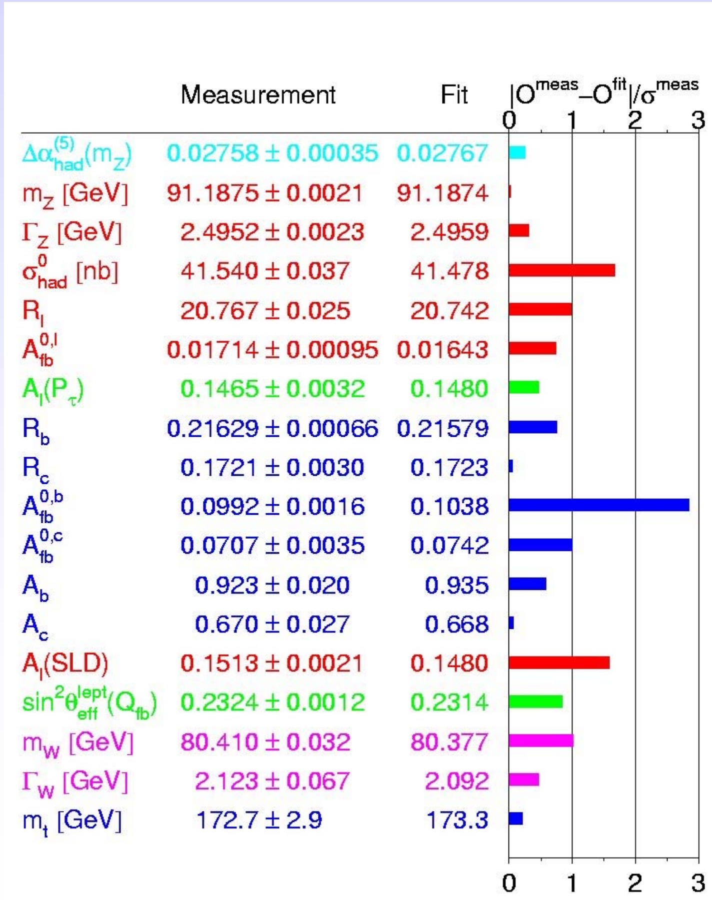
Where do we stand today ?

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

<u>However:</u>
The Standard Model is consistent
with all experimental data !

Light Higgs boson favoured
No evidence for phenomena beyond the SM

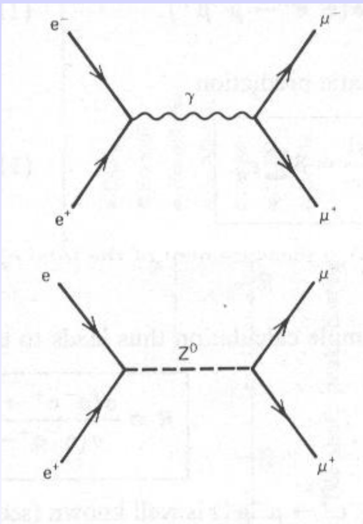


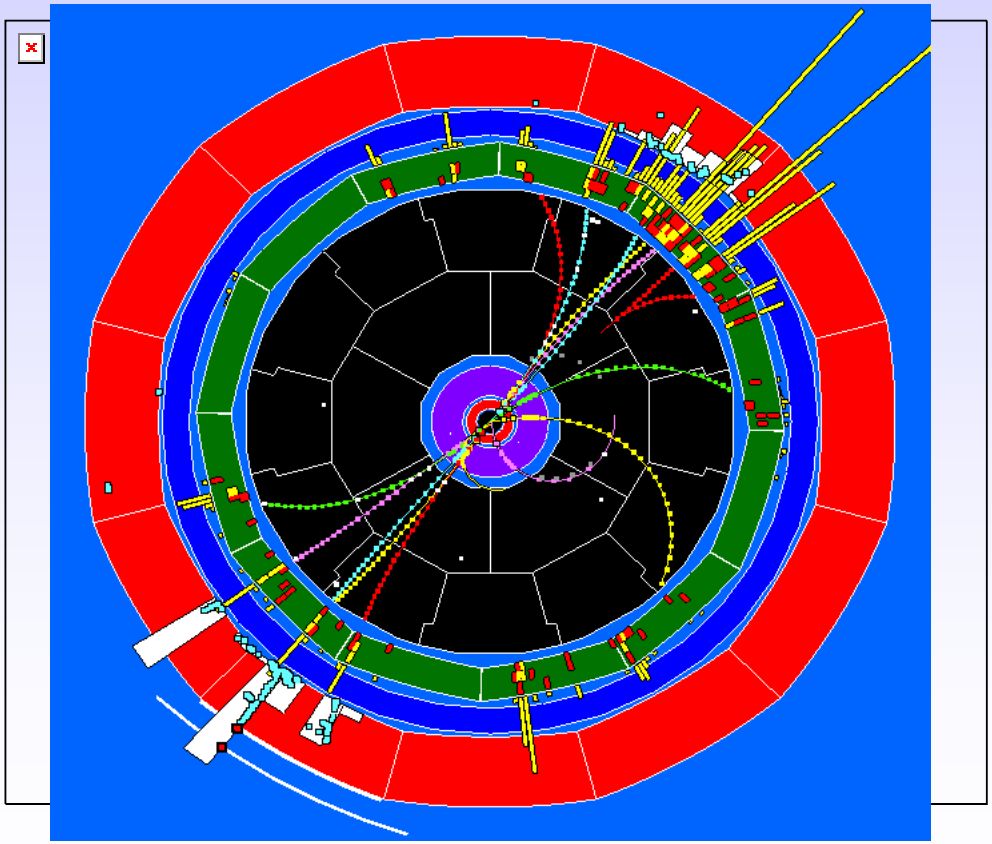


Why a hadron collider ?

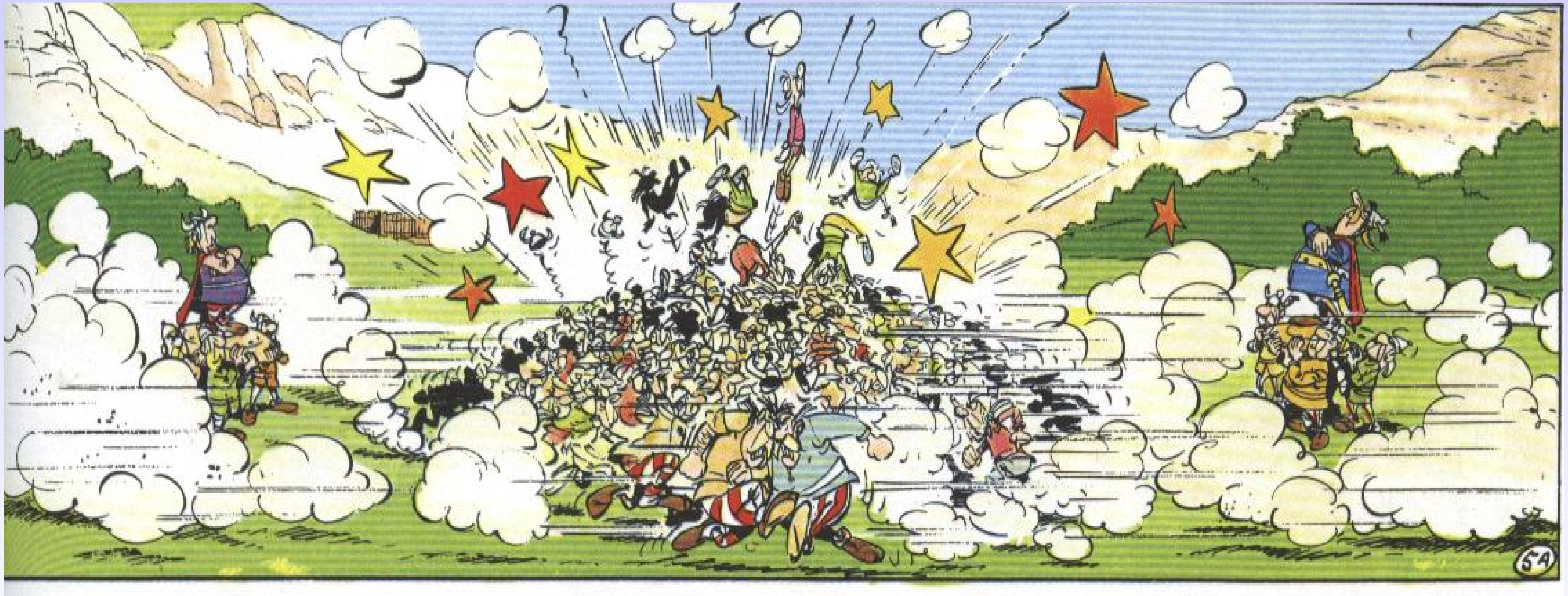
e^+e^- colliders are excellent machines for precision physics !!

- 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:

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

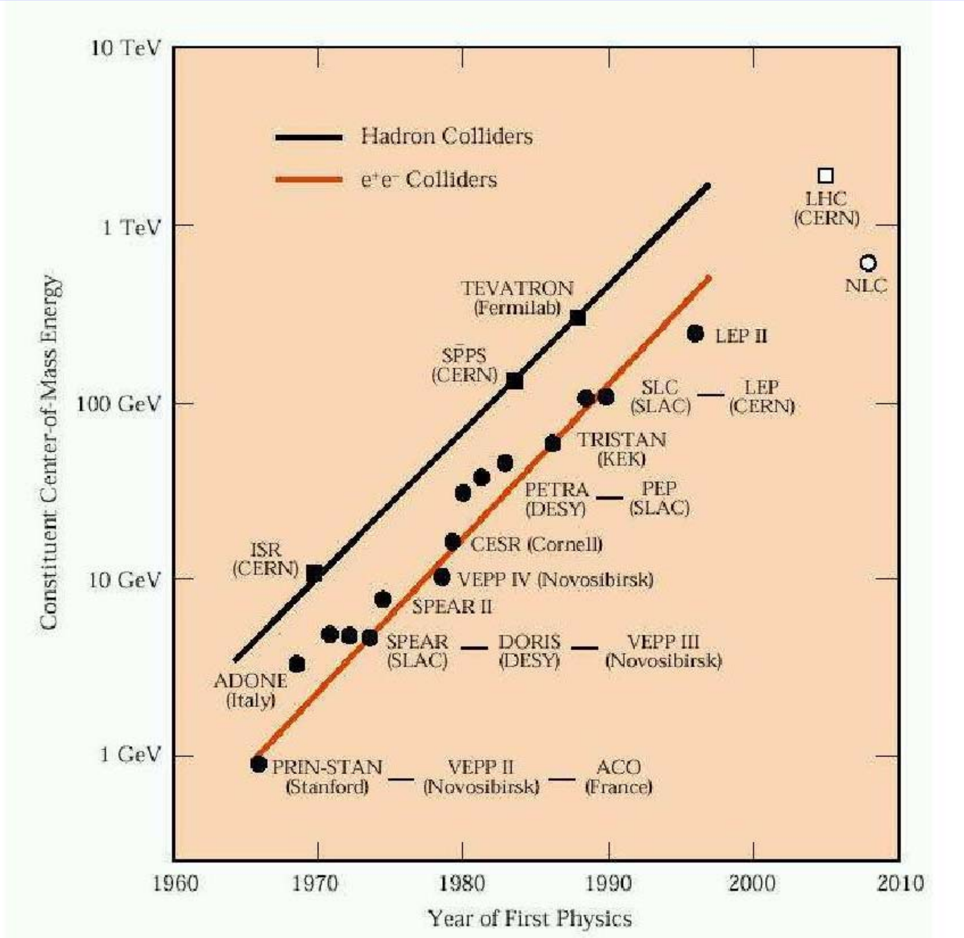
   - Ratio of the energy loss between protons and electrons:

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

Future accelerators:

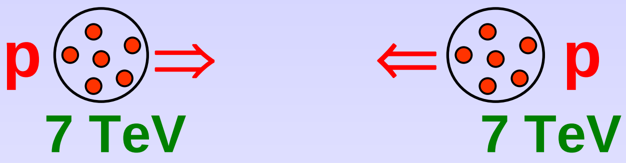
- pp ring accelerators (LHC, using existing LEP tunnel)
- or e^+e^- linear accelerators, International Linear Collider ILC (under study / planning)

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



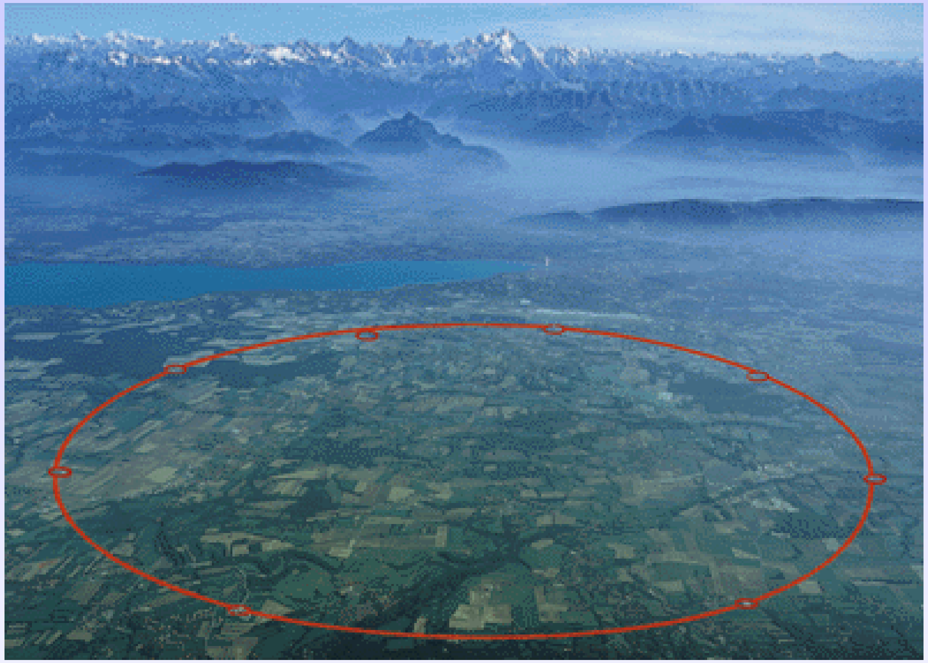
The Large Hadron Collider (LHC)

- Proton-proton accelerator in the LEP-tunnel at CERN



- Highest energies per collision

- Conditions as at times of 10^{-13} - 10^{-14} s after the big bang



- Four planned experiments:

ATLAS, CMS	(pp physics)
LHC-B	(physics of b-quarks)
ALICE	(Pb-Pb collisions)

- Constructed in an international collaboration

- Startup planned for late 2007

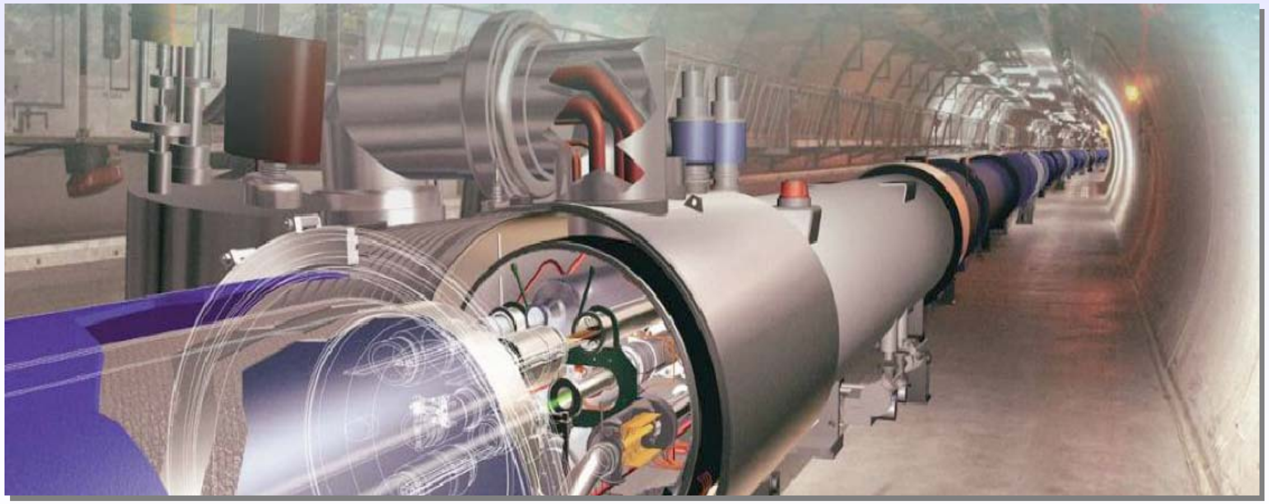
Important components of the accelerator

- superconducting dipole magnets

  - challenge: magnetic field of 8.33 Tesla
  - in total 1232 magnets, each 15 m long
  - operation temperature of 1.9 K

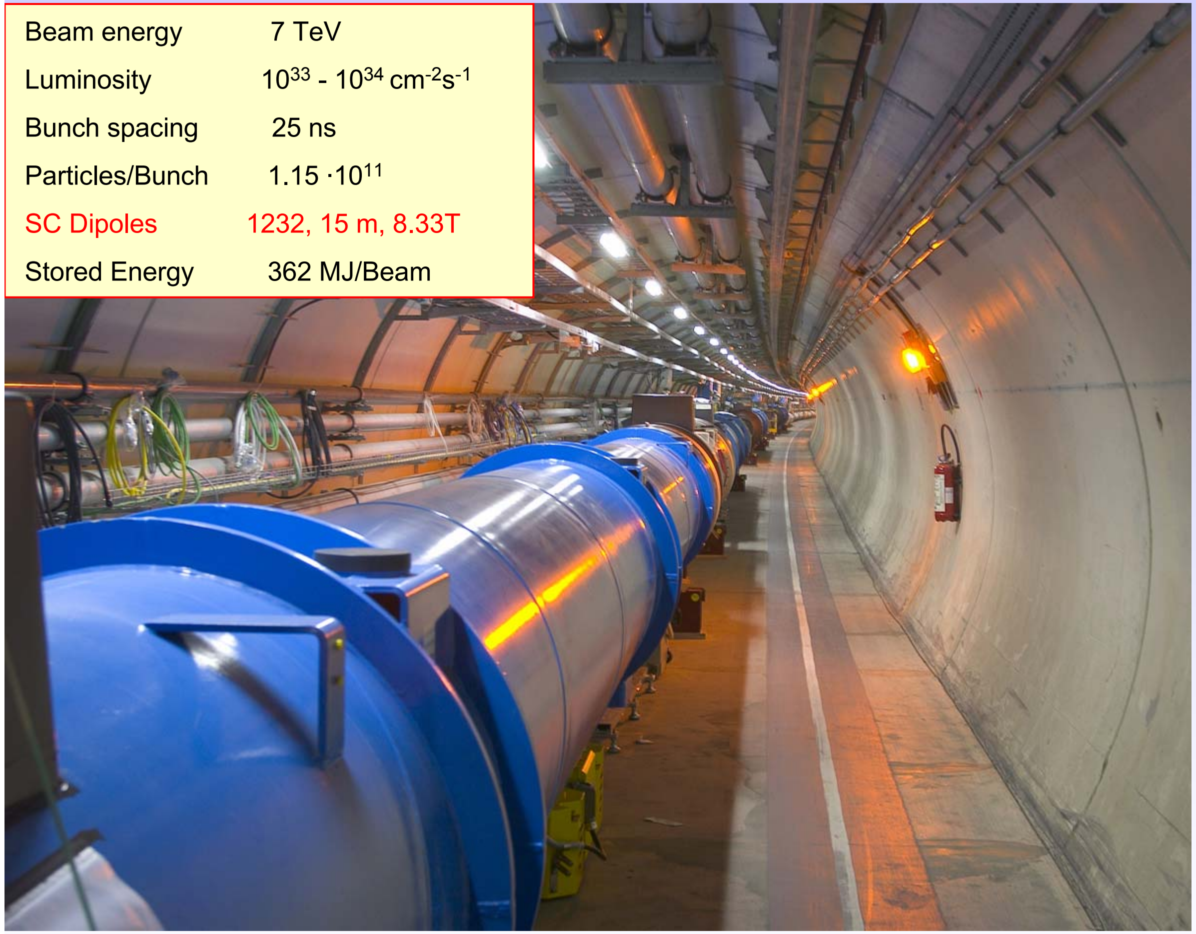
  LHC is the largest cryogenic system in the world

- Eight superconducting accelerator structures, acceleration gradient of 5 MV/m



Status of the LHC machine

Beam energy	7 TeV
Luminosity	10^{33} - 10^{34} $cm^{-2}s^{-1}$
Bunch spacing	25 ns
Particles/Bunch	$1.15 \cdot 10^{11}$
SC Dipoles	1232, 15 m, 8.33T
Stored Energy	362 MJ/Beam



- Key components available
- Installation progressing in parallel and at high speed; aim to finish by end March 2007
- "Every effort is being made to have first collisions by end of 2007"

<u>A "likely" startup scenario</u>:

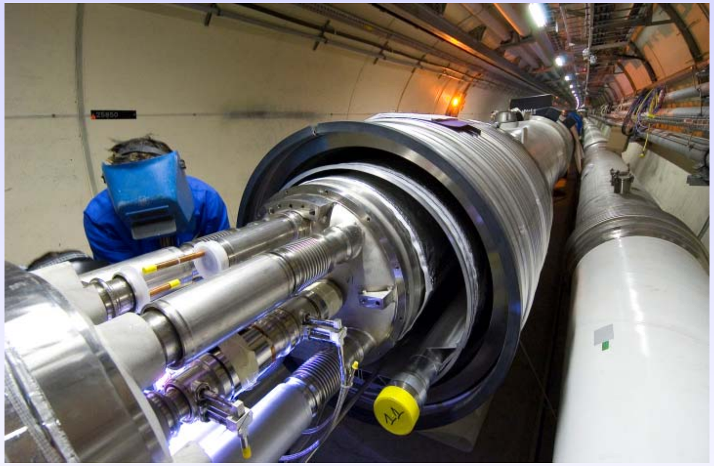
Late 2007: Pilot run, first collisions (at injection energy)

→ detector and trigger commissioning, calibration, early physics

2008: First Physics run at nominal energy

Installation work, underground

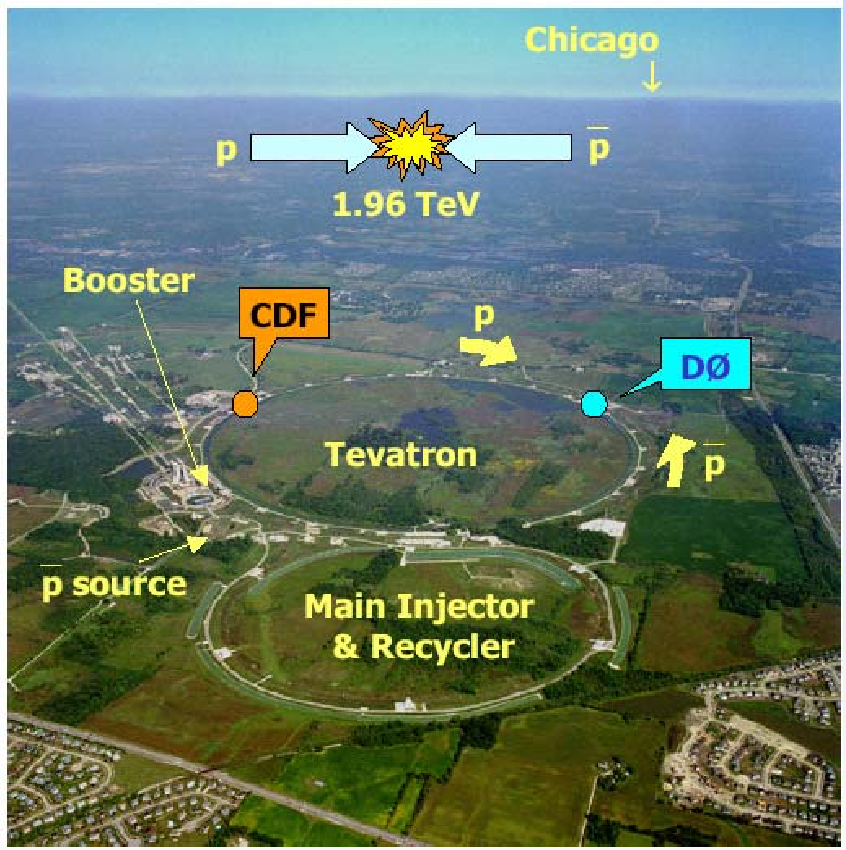
Preparation for installation, Hall SMI2



The Tevatron Collider at Fermilab

Proton antiproton collider

2 Experiments: CDF and DØ



- **1992 - 1996: Run I, $\sqrt{s}$ = 1.8 TeV**
  6 x 6 bunches, 3 μs spacing
  $\int L\,dt = 125\ pb^{-1}$

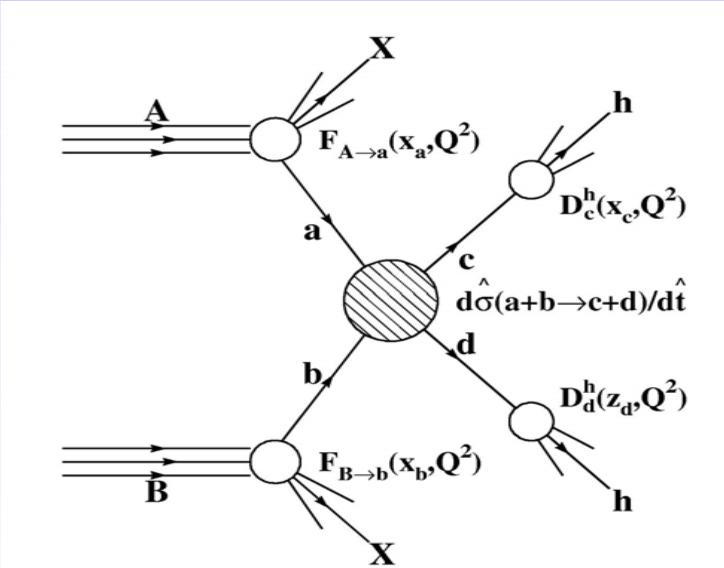
- **1996 - 2001: upgrade programme**
  Accelerator: new injector (x5)
  antiproton recycler (x2)
  36x36 bunches, 396 ns spacing

  + Detectors

- **March 2001 – Feb 2006: Run II a, $\sqrt{s}$ = 1.96 TeV, 1.2 fb^{-1}**
- **July 2006 - 2009: Run II b, $\sqrt{s}$ = 1.96 TeV, 5 - 8 fb^{-1}**

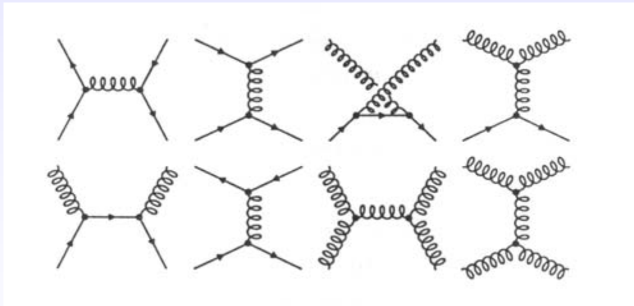
Real Data

Physics at Hadron Colliders



- Protons are complex objects:
  Partonic substructure:
  Quarks and Gluons
- Hard scattering processes:
  (large momentum transfer)

  quark-quark
  quark-gluon   scattering or annihilation
  gluon-gluon

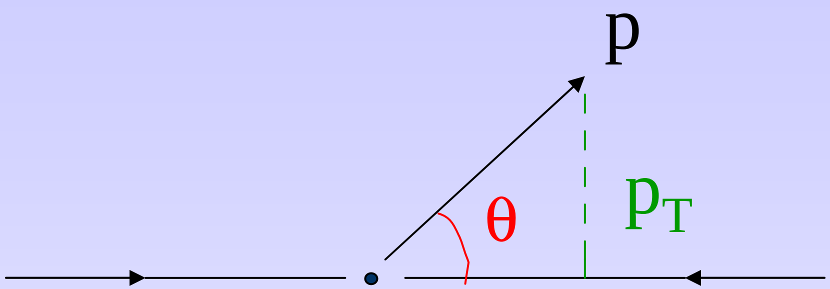


However: hard scattering (high P_T processes) represent only a tiny fraction
of the total inelastic pp cross section

Total inelastic pp cross section ~ 70 mb (huge)

Dominated by events with small momentum transfer

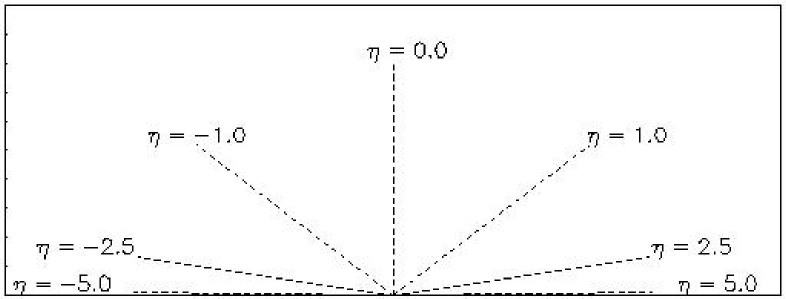
Variables used in the analysis of pp collisions



Transverse momentum
(in the plane perpendicular to the beam)

$$p_T = p \sin\theta$$

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



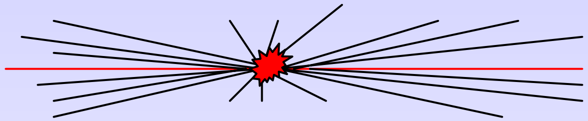
$\theta = 90^o \rightarrow \eta = 0$

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

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

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

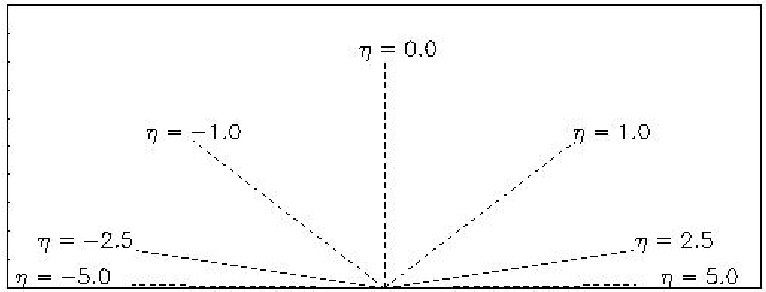


$< p_T > \approx 500$ MeV (of charged particles in the final state)

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

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

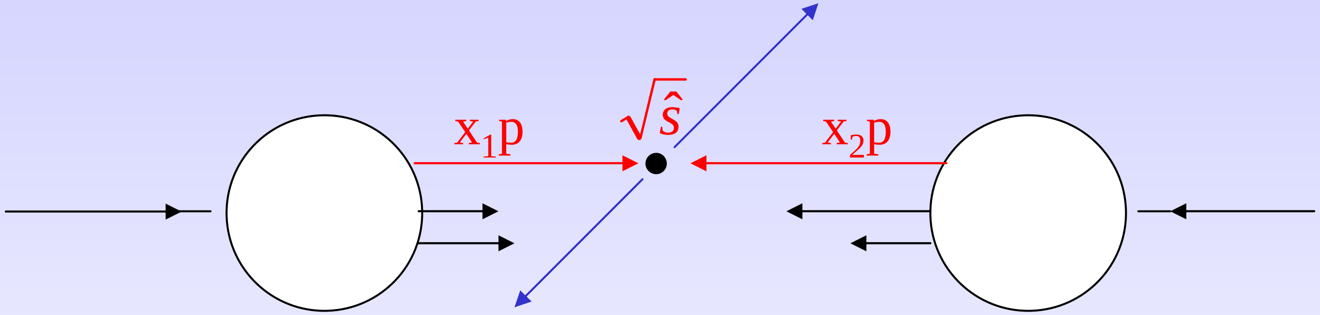
These events are called
"Minimum-bias events"



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:

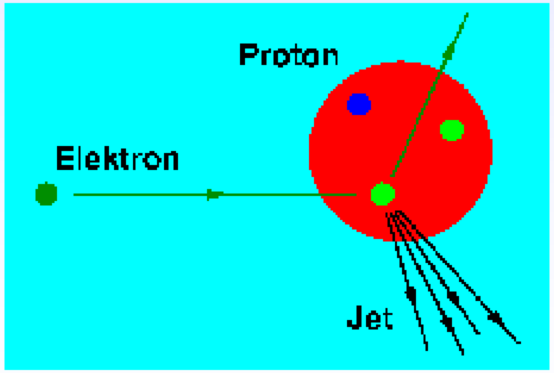
	LHC	Tevatron
100 GeV:	x ~ 0.007	0.05
5 TeV:	x ~ 0.36	--

From where do we know the x-values?

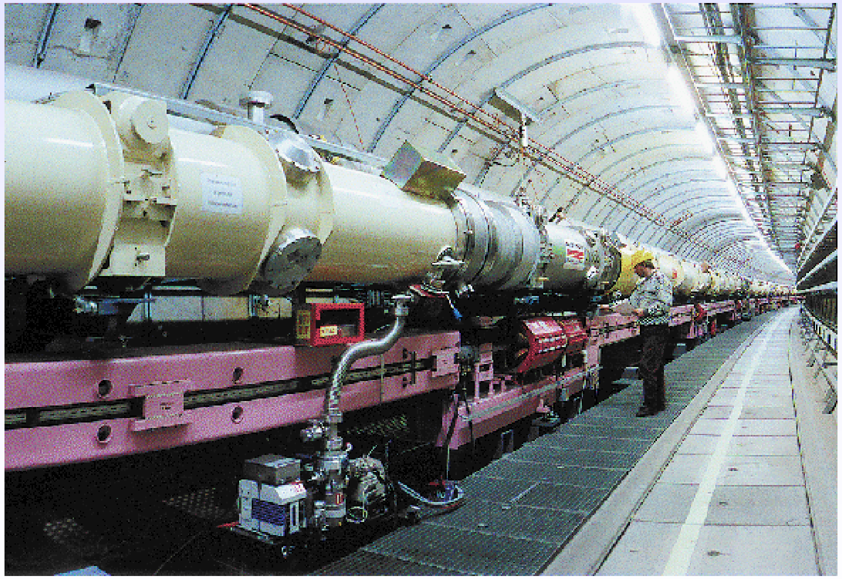
The structure of the proton is investigated in *Deep Inelastic Scattering* experiments:

Today's highest energy machine: the HERA ep collider at DESY/Hamburg

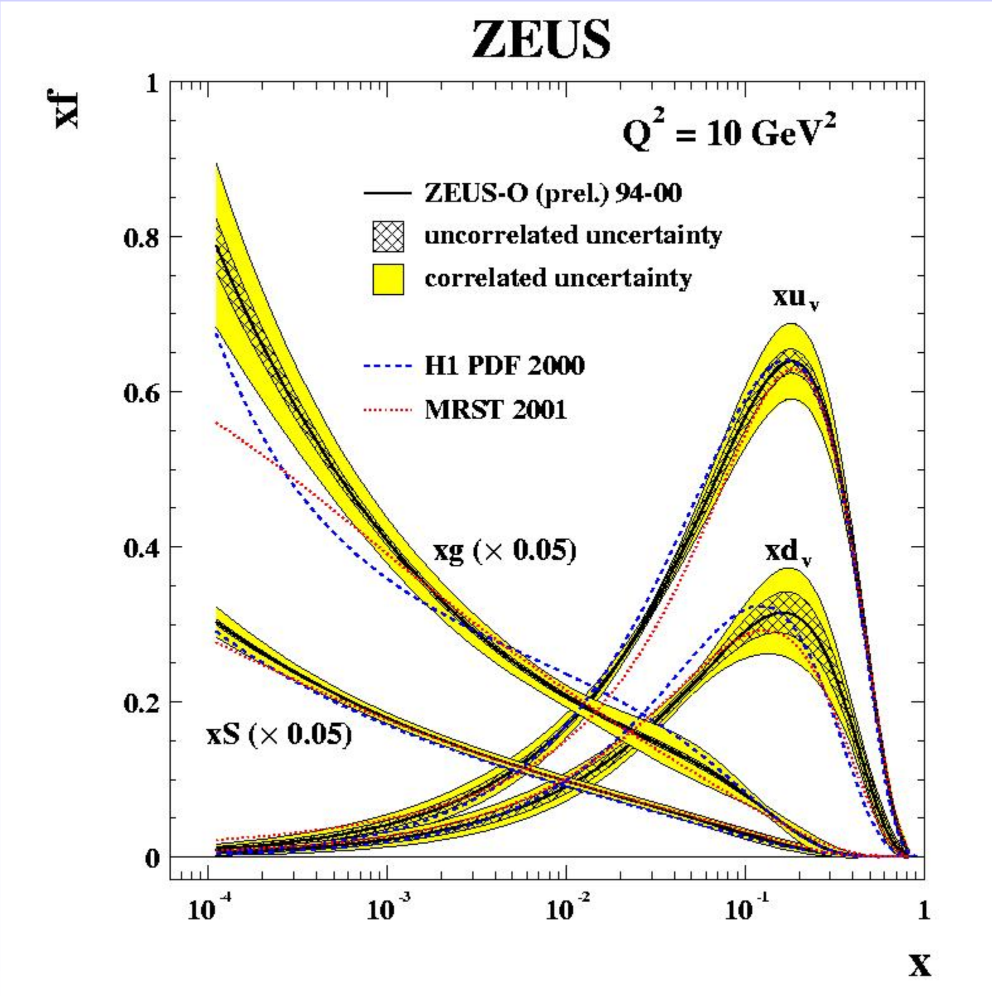
Scattering of 30 GeV electrons on 900 GeV protons:
→ Test of proton structure down to 10^{-18} m

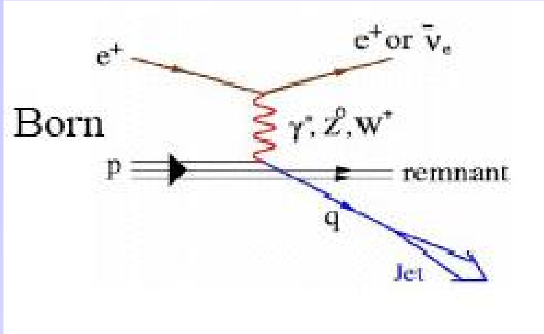


HERA ep accelerator, 6.3 km circumference



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





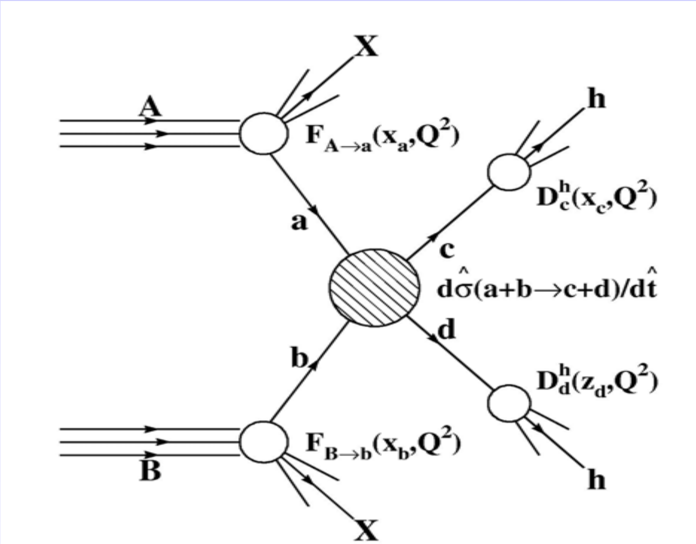
Parton density functions (pdf):

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

Calculation of cross sections



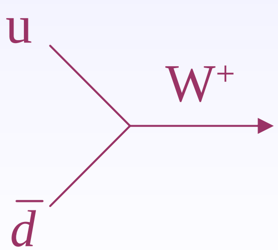
$$\sigma = \sum_{a,b} \int dx_a \, dx_b \, f_a(x_a, Q^2) \, f_b(x_b, Q^2) \, \hat{\sigma}_{ab}(x_a, x_b)$$

Sum over initial partonic states a,b

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

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

Example: W-production: (leading order diagram)



$\sigma(pp \to W) \sim 150$ nb $\sim 2 \cdot 10^{-6} \, \sigma_{tot}(pp)$

… + higher order QCD corrections (perturbation theory)

Luminosity

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

$$N = L \sigma$$

L = Luminosity
σ = cross section

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

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

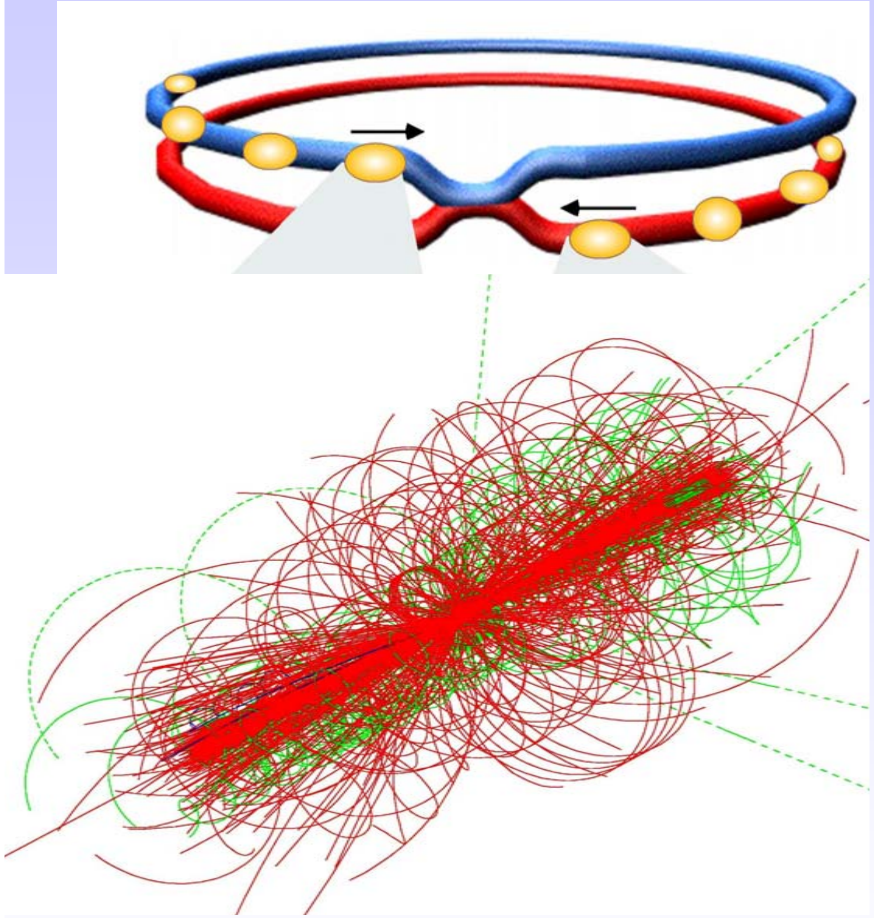
In order to achieve acceptable production rates for the interesting physics processes, the luminosity must be high !

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

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

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

Proton proton collisions at the LHC



Proton – proton:

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

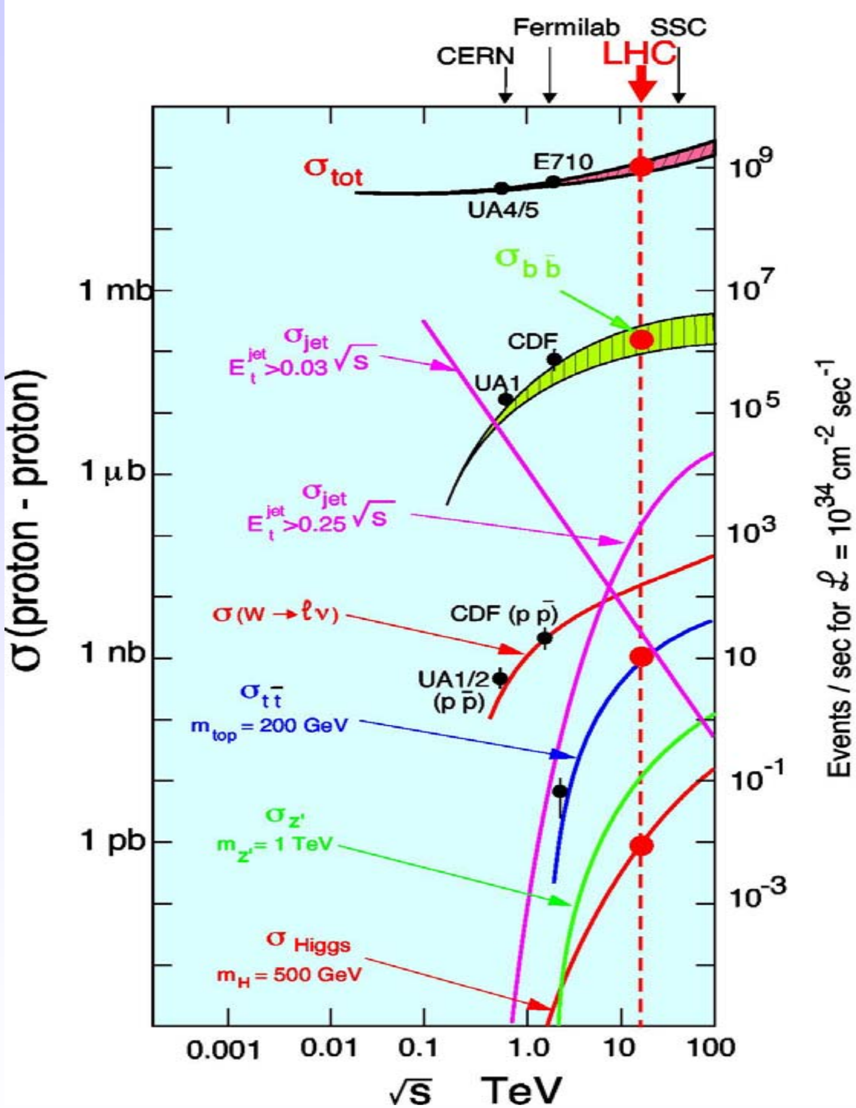
10^{11} protons / bunch
Crossing rate of p-bunches: 40 Mio. / s
Luminosity: $L = 10^{34}$ cm^{-2} s^{-1}

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

~1600 charges particles in the detector

⇒ high particle densities
high requirements for the detectors

Cross Sections and Production Rates



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

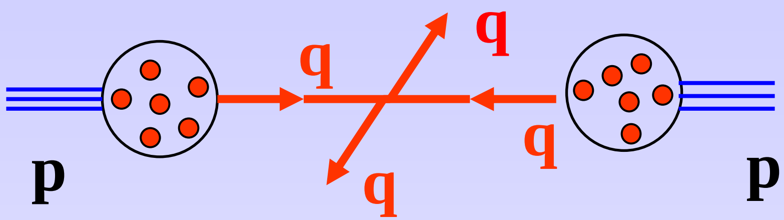
• Inelastic proton-proton reactions:	10^9 / s
• bb pairs • tt pairs	5 10^6 / s 8 / s
• W → e ν • Z → e e	150 / s 15 / s
• **Higgs (150 GeV)** • **Gluino, Squarks (1 TeV)**	**0.2 / s** **0.03 / s**

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

The only problem: you have to detect them !

What experimental signatures can be used ?

Quark-quark scattering:

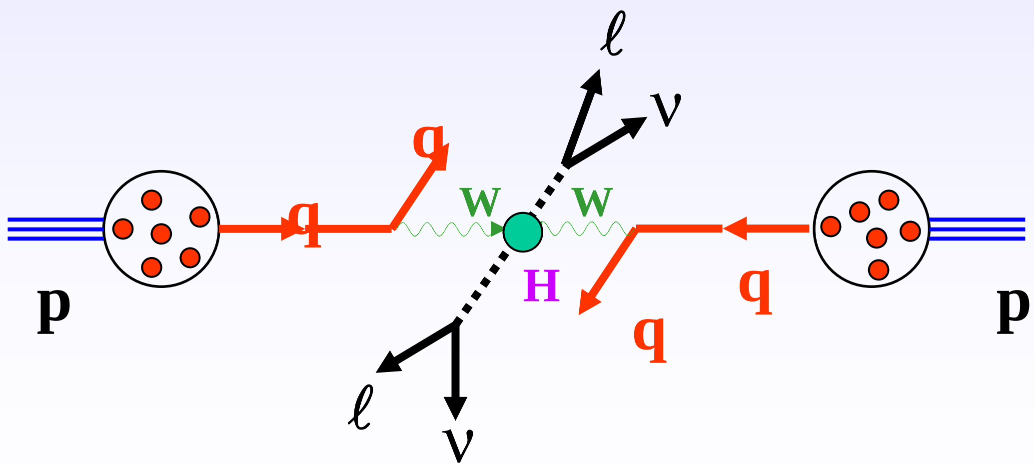


No leptons / photons in the initial and final state

If leptons with large transverse momentum are observed:

⇒ **interesting physics !**

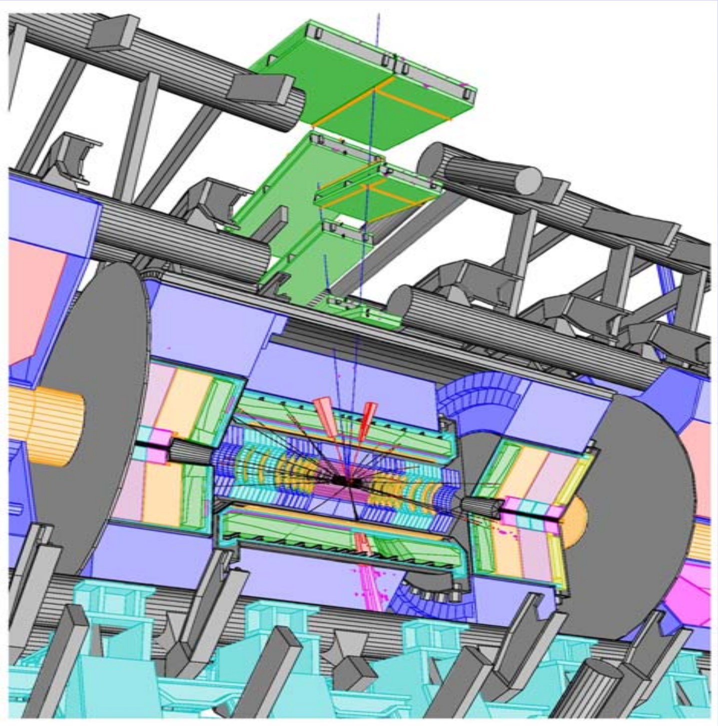
Example: Higgs boson production and decay



Important signatures:

- **Leptons und photons**
- **Missing transverse energy**

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

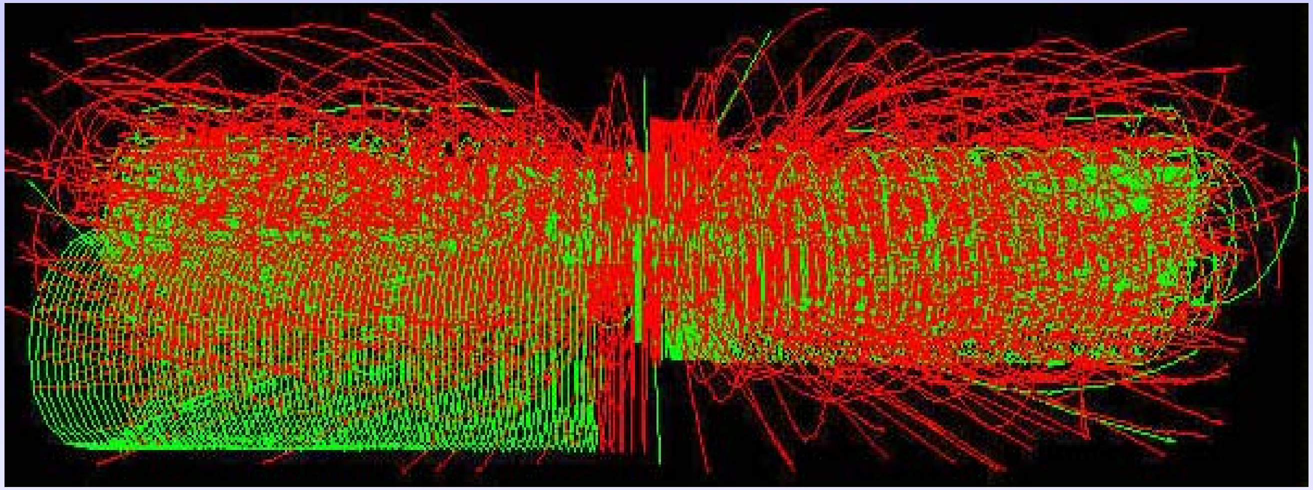
  energy measurements in the forward regions

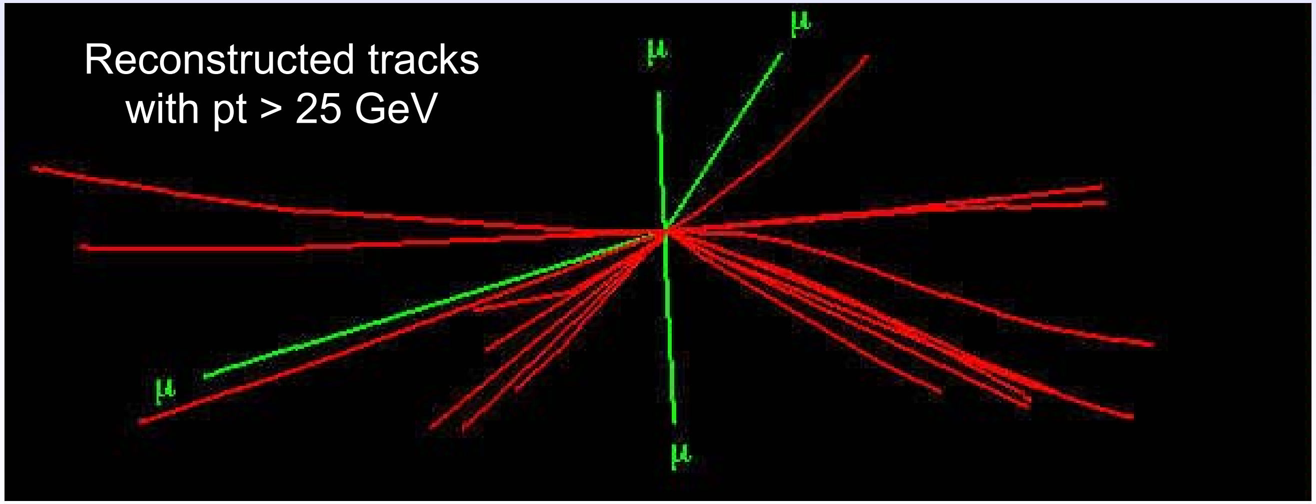
  $\Rightarrow$ calorimeter coverage down to $\eta \sim 5$

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

for more details: see lecture by D. Froidevaux

Suppression of background: Reconstruction of objects with large transverse momentum

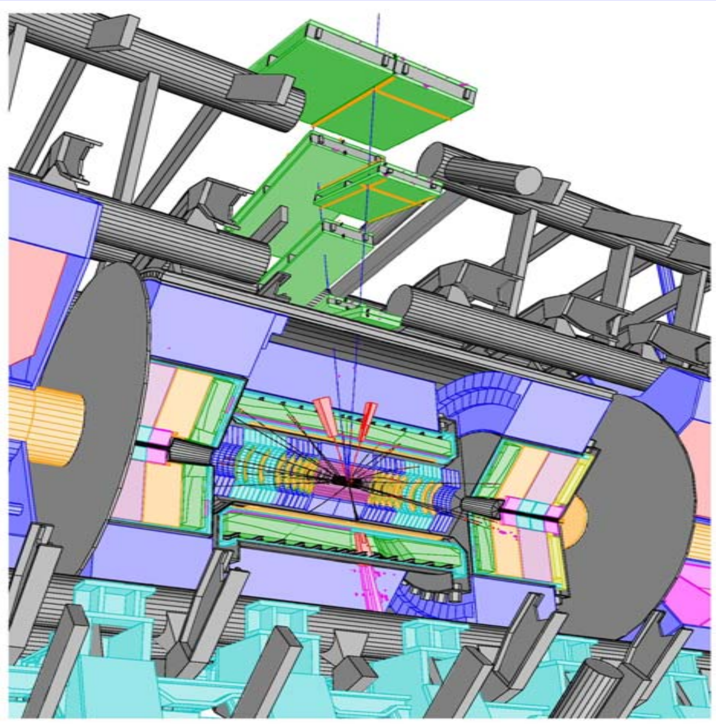




Detector requirements from the experimental environment (pile-up)

• 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

How are the interesting events selected ?

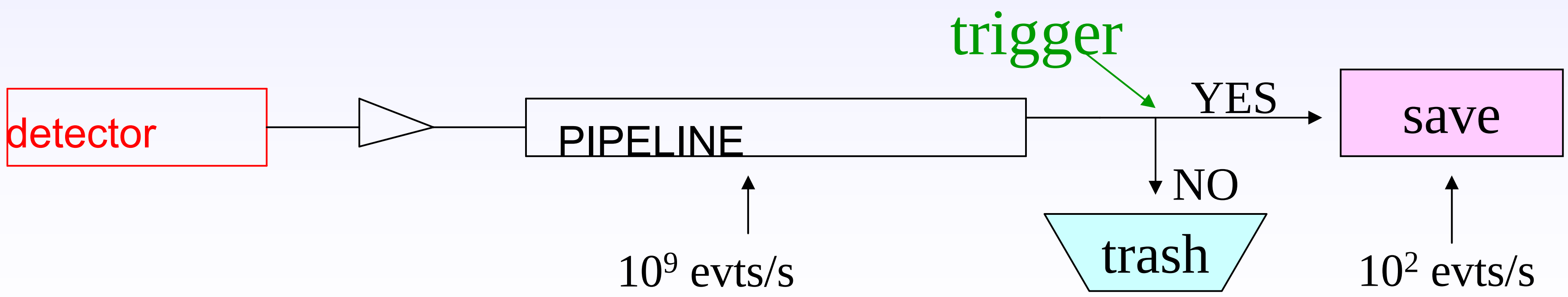
TRIGGER: much more difficult than at e^+e^- machines

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

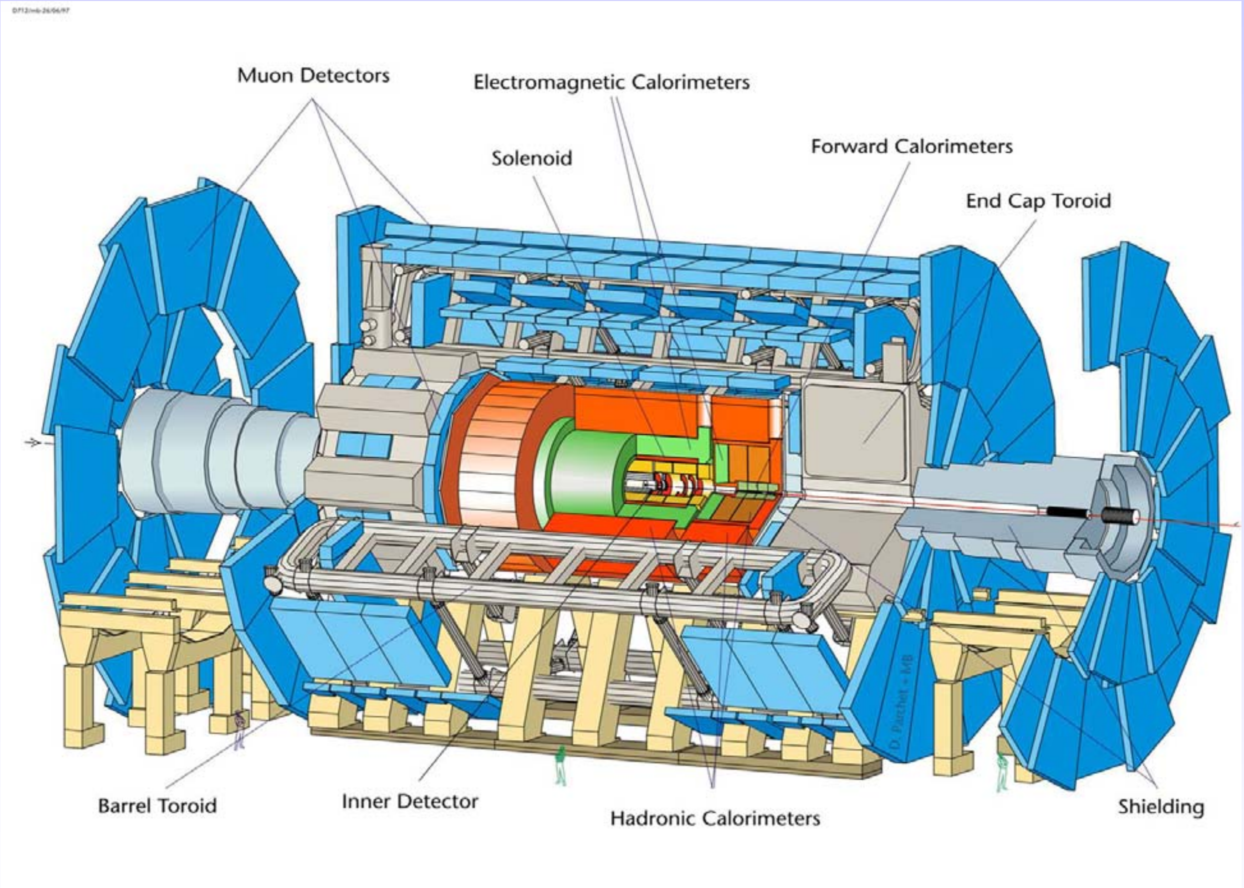
$\Rightarrow$ **trigger rejection ~ 10^7**

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



The ATLAS experiment



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

- 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)

Der ATLAS Detektor im Vergleich ....

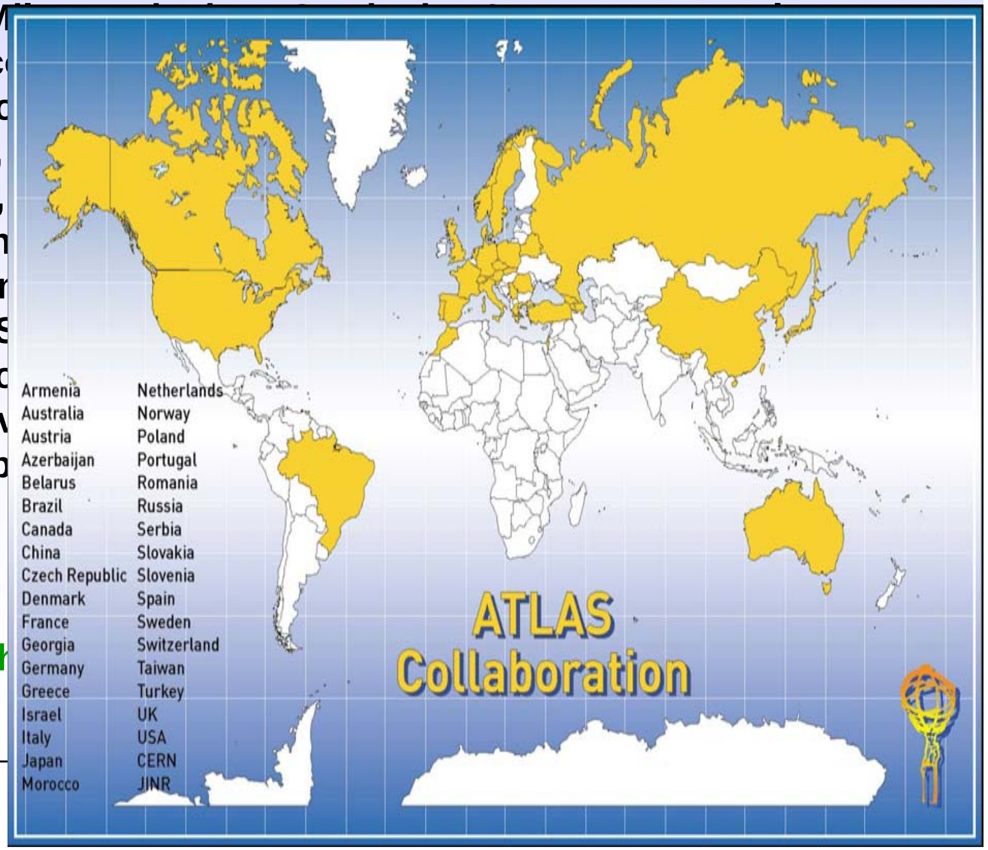
ATLAS Collaboration

(Status Oct. 2003)

Albany, Alberta, NIKHEF Amsterdam, Ankara, LAPP Annecy, Argonne NL, Arizona, UT Arlington, Athens, NTU Athens, Baku, IFAE Barcelona, Belgrade, Bergen, Berkeley LBL and UC, Bern, Birmingham, Bonn, Boston, Brandeis, Bratislava/SAS Kosice, Brookhaven NL, Bucharest, Cambridge, Carleton/CRPP, Casablanca/Rabat, CERN, Chinese Cluster, Chicago, Clermont-Ferrand, Columbia, NBI Copenhagen, Cosenza, INP Cracow, FPNT Cracow, Dortmund, JINR Dubna, Duke, Frascati, Freiburg, Geneva, Genoa, Glasgow, LPSC Grenoble, Technion Haifa, Hampton, Harvard, Heidelberg, Hiroshima, Hiroshima IT, Indiana, Innsbruck, Iowa SU, Irvine UC, Istanbul Bogazici, KEK, Kobe, Kyoto, Kyoto UE, Lancaster, Lecce, Lisbon LIP, Liverpool, Ljubljana, QMW London, RHBNC London, UC London, Lund, UA Madrid, Mainz, Manchester, Mannheim, CPPM Marseille,
MIT, Melbourne, Michigan, Michigan SU, M
FIAN Moscow, ITEP Moscow, MEPhI Mosc
Nagasaki IAS, Naples, Naruto UE, New Mexic
Ohio SU, Okayama, Oklahoma, LAL Orsay, Oslo,
Pittsburgh, CAS Prague, CU Prague, TU Prague,
Rochester, Rome I, Rome II, Rome III, Ruth
Santa Cruz UC, Sheffield, Shinshu, Siegen, Si
NPI Petersburg, Stockholm, KTH Stockholm, S
Thessaloniki, Tokyo ICEPP, Tokyo MU, Tokyo
Uppsala, Urbana UI, Valencia, UBC Vancouv
Wisconsin, Wupp

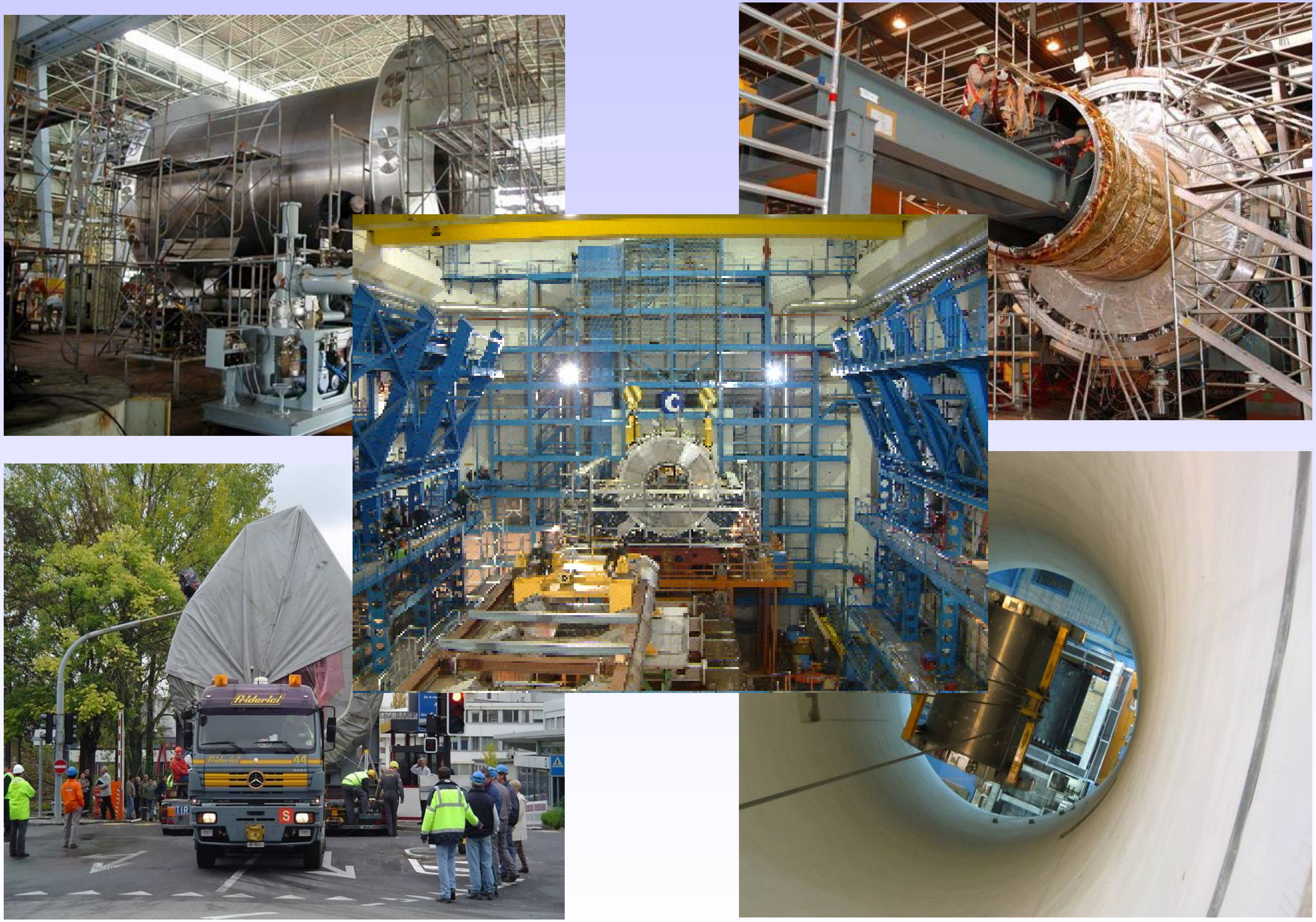
(151 Institutions

Total Scientific Authors
Scientific Authors holding a Ph

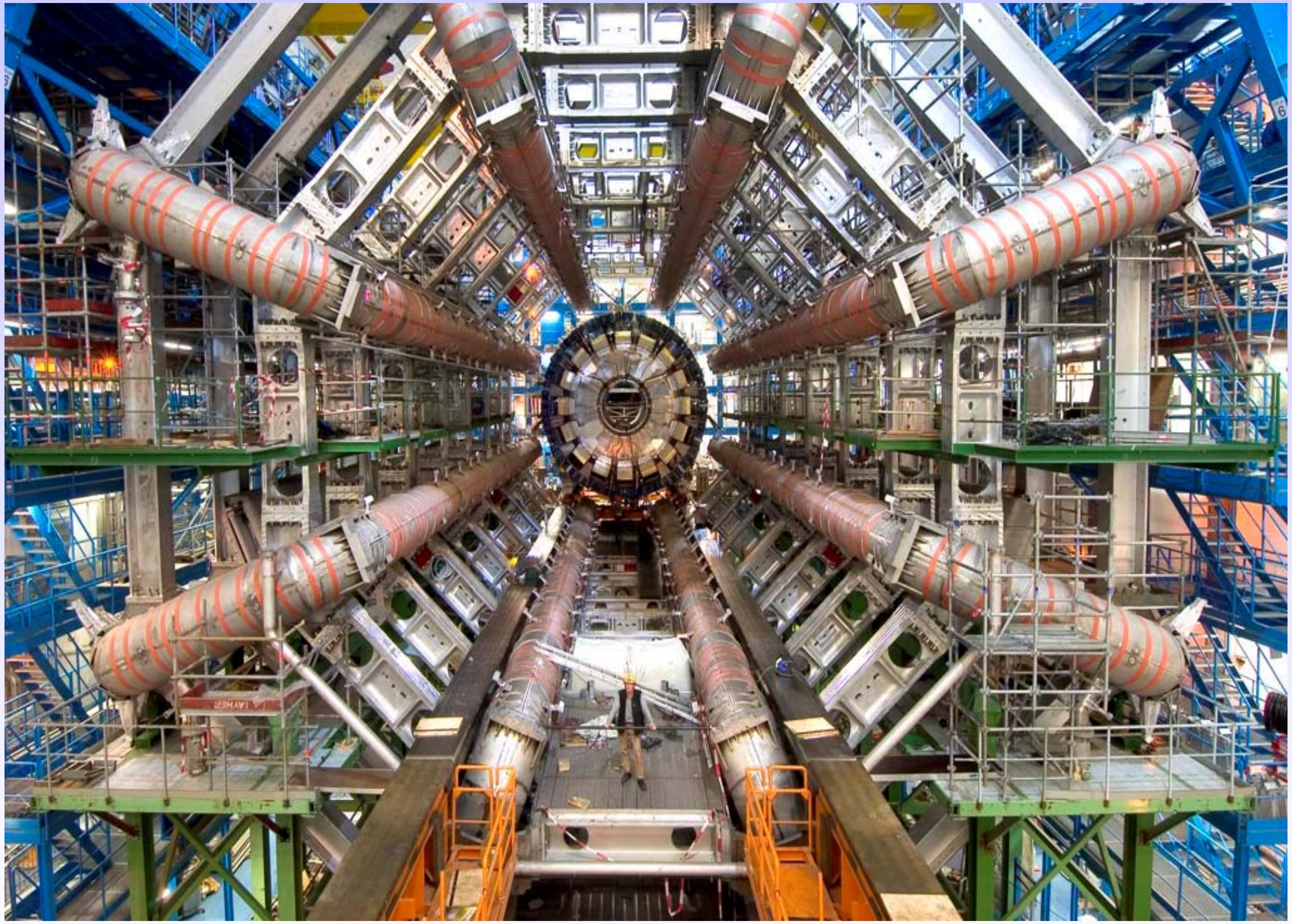


ATLAS detector construction and installation

ATLAS detector construction: Calorimeters



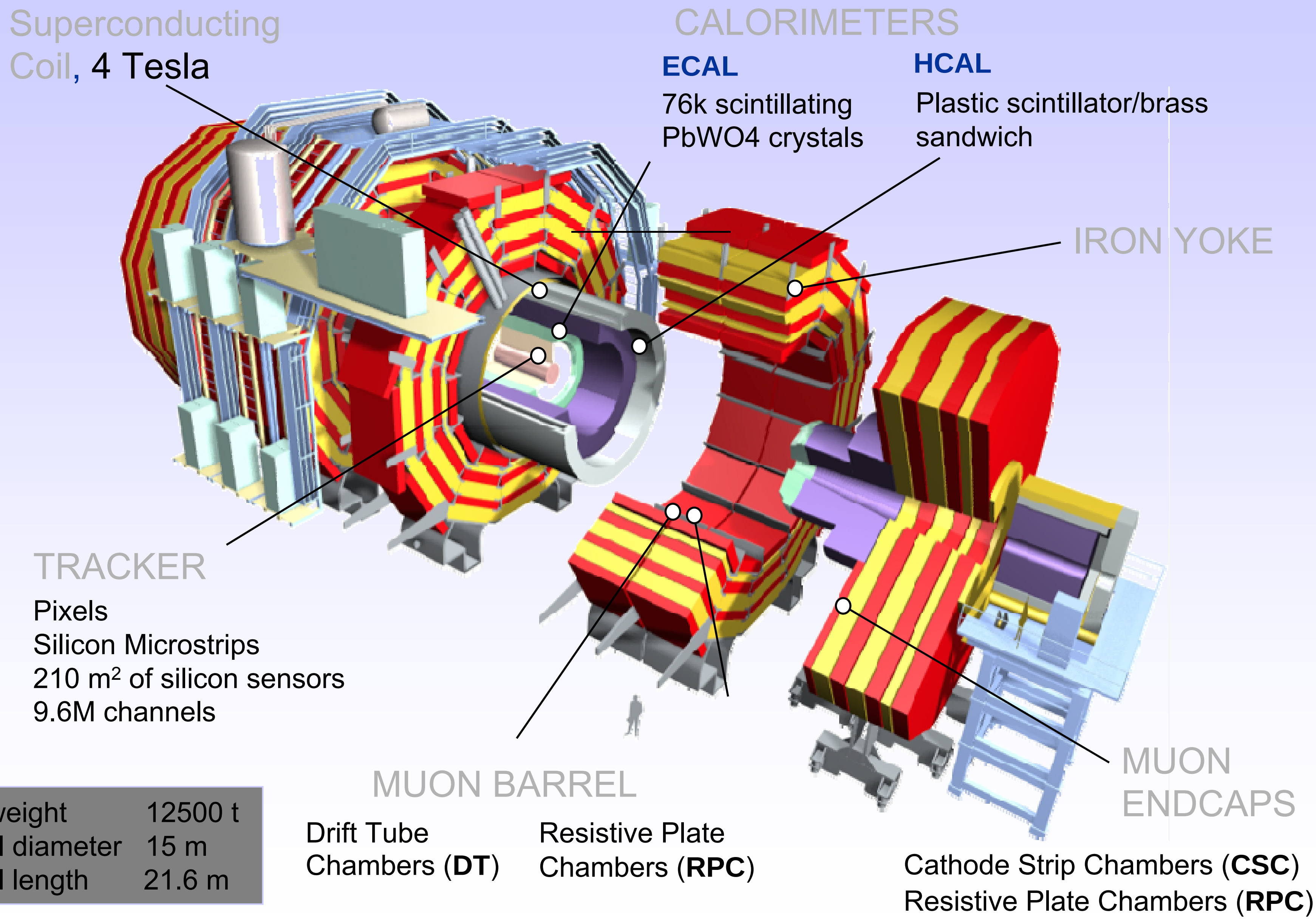
ATLAS Installation



November 2005

- Impressive progress! Nearly all detector components at CERN;
- Installation in the pit proceeding well, although time delays, work in parallel to catch up;
- On critical path: Installation of Inner detector services and forward muon wheels (time);
- ATLAS expected to be ready in August 2007   … one more tough year ...

CMS

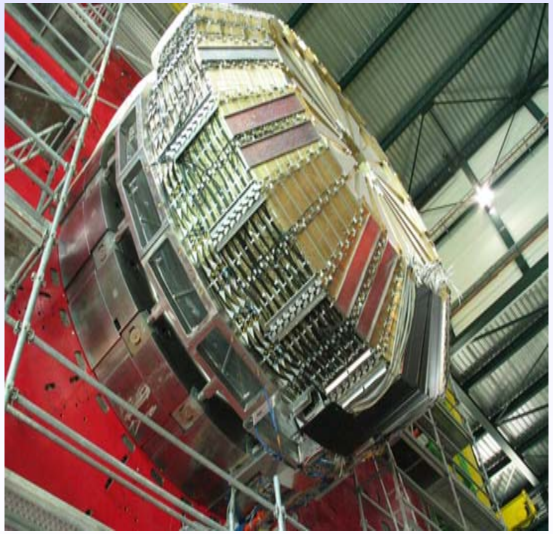


Total weight	12500 t
Overall diameter	15 m
Overall length	21.6 m

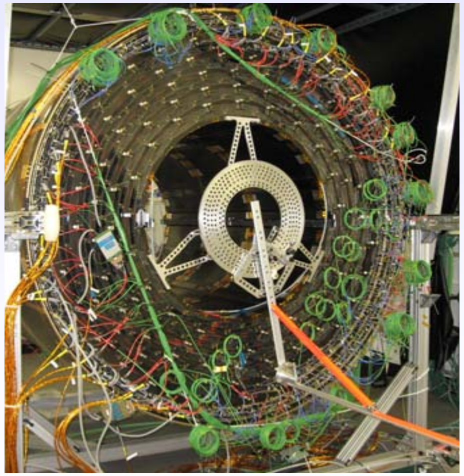
CMS Installation

Coil inserted, 14. September 2005

Cathode Strip chambers and yoke endcaps



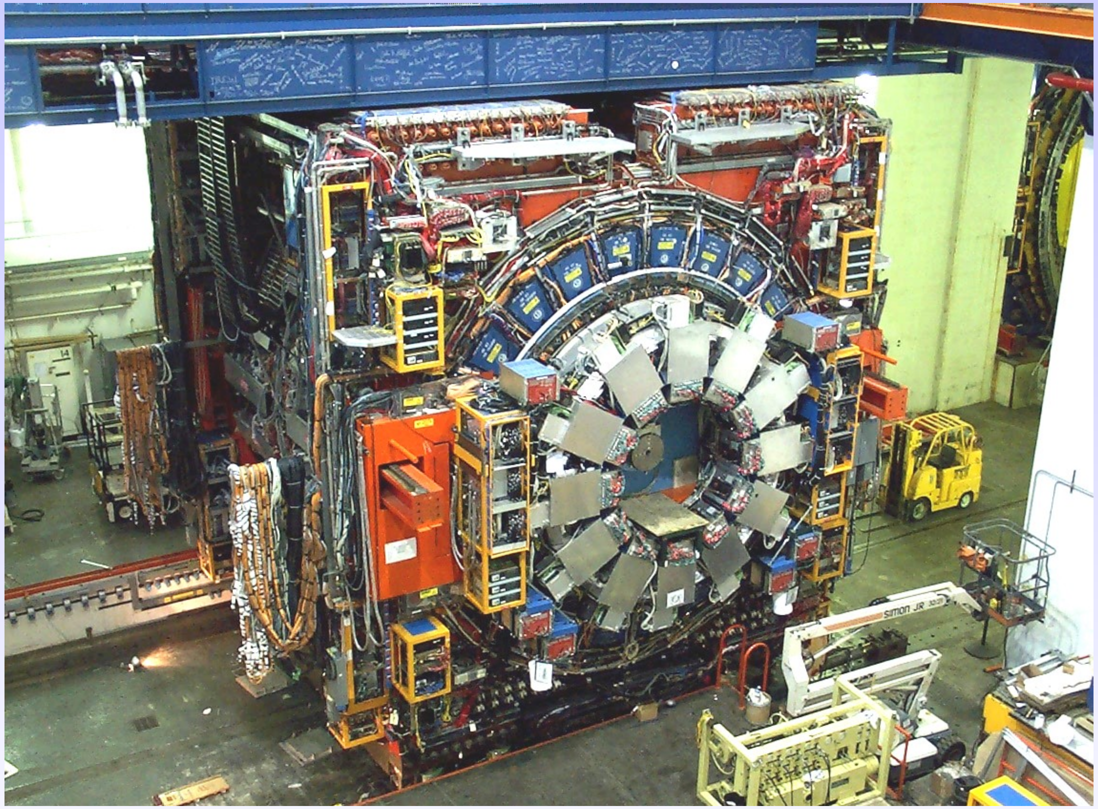
Hadronic calorimeter, endcap



Tracker, outer barrel

On critical path: ECAL crystal delivery (Barrel: Feb. 07, Endcaps: Jan. 08)
Pixel installation for 2008 physics run.

The CDF-Experiment



12 countries, 59 institutions
706 physicists

New in Run II :

Tracking system
- Silicon vertex detector (SVXII)
- Intermediate silicon layers
- Central outer tracker (COT)

End plug calorimeter
Time of flight system

Front-end electronics
Trigger and DAQ systems

The DØ Experiment

19 countries, 83 institutions

664 physicists

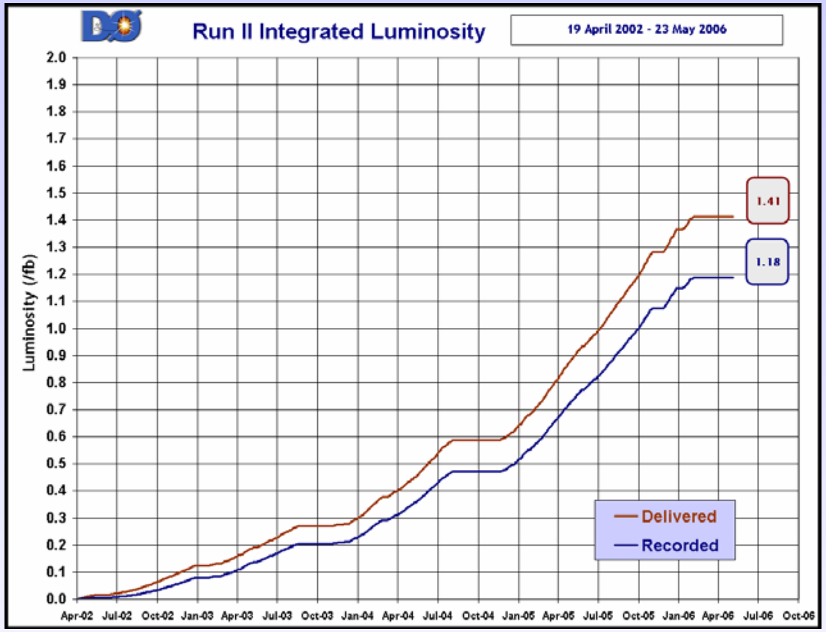
New for Run II

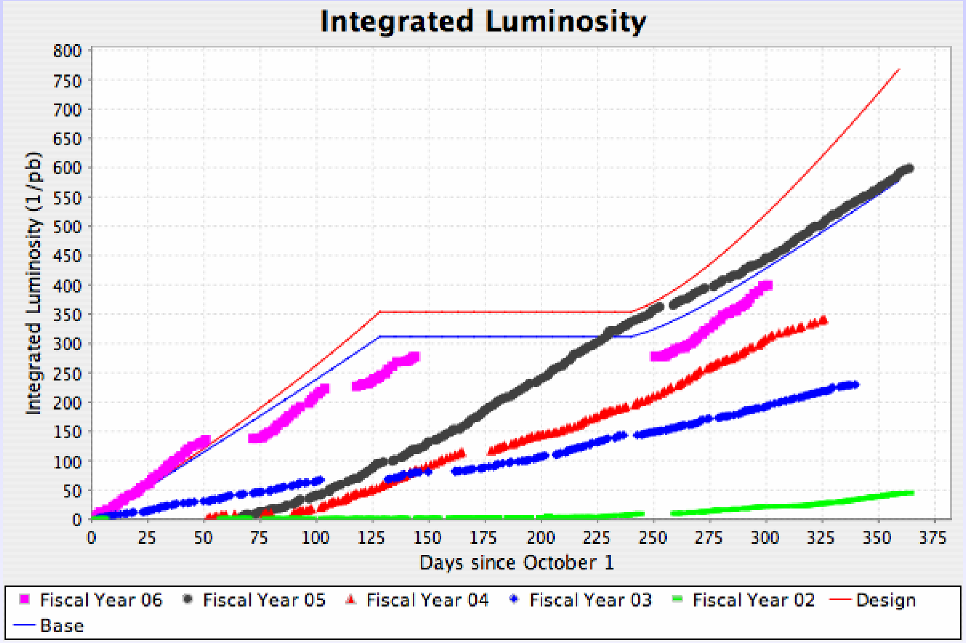
Inner detector
magnetic field added

Preshower detectors
Forward muon detector

Front-end electronics
Trigger and DAQ

Integrated and peak luminosities





integrated luminosity recorded by the D0 experiments until Feb.06: 1.18 fb^{-1}

Results shown during the next days are based On this data sample

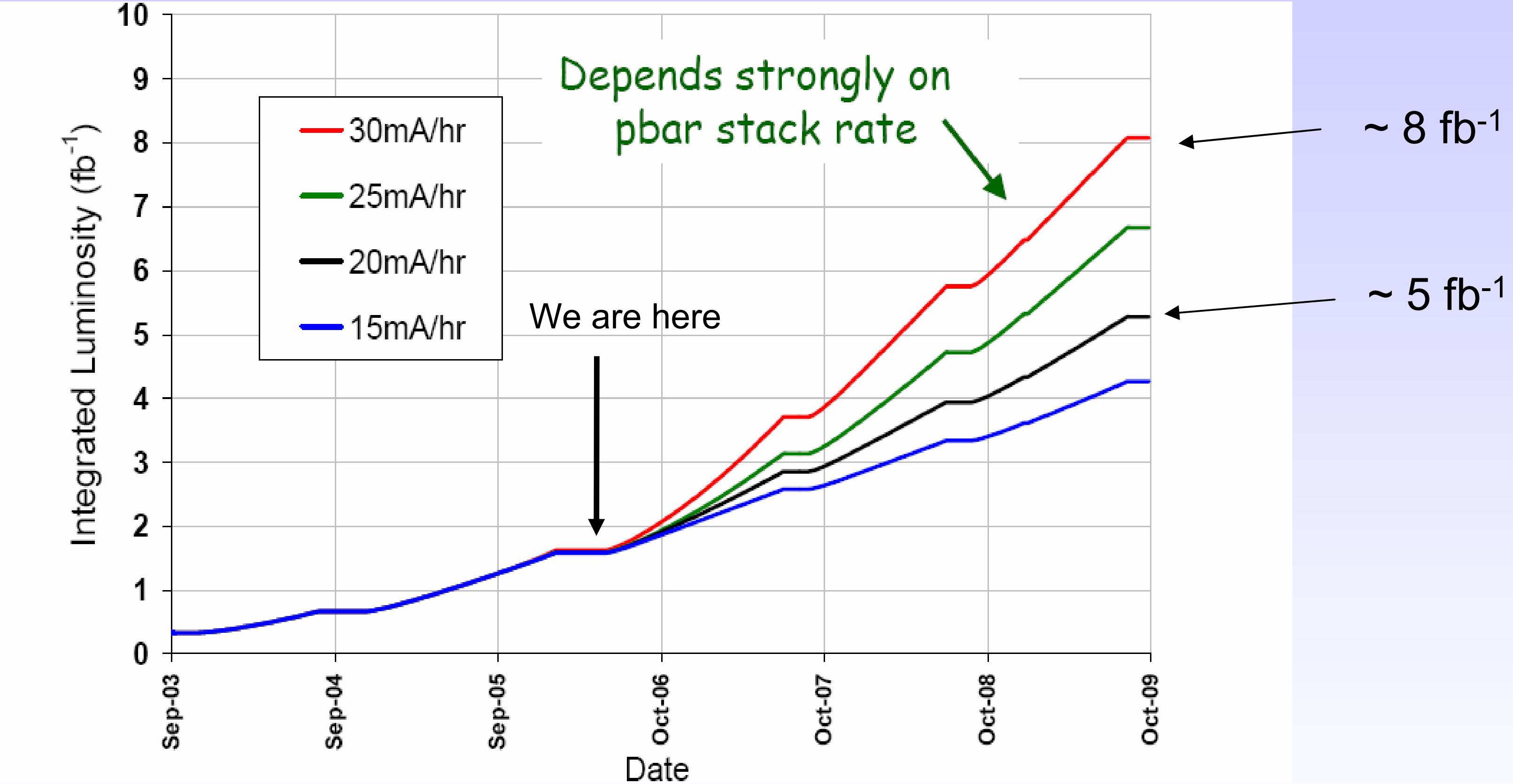
Peak luminosity

Run II goal: **3×10^{32} cm^{-2} s^{-1}**

Run II maximum: (to date) **1.7×10^{32} cm^{-2} s^{-1}**

Run I maximum: **2.4×10^{31} cm^{-2} s^{-1}**

Tevatron Luminosity Goals



- Additional improvements in shutdown 2006 (electron cooling in the recycler)
- Final performance depends on antiproton stacking rate in the accumulator (at present 20 mA/h = 0.2 · 10^{12} pbar /h)

Summary of the 1. Lecture

- Hadron Colliders play an important role in particle physics (today and over the next decade !)

- LHC machine has enough energy to explore the TeV energy range
  - Mass reach 3-5 TeV/c^2
  - Low energy region (above LEP energies) can already be addressed at the Tevatron today

  (Examples will be discussed during the week)

- Experiments at Hadron Colliders are challenging
  Huge interaction rate → complex trigger architecture,
  Large background from QCD jet production, pile-up at the LHC

  → requires highly performing (fast, high granularity, radiation hard) detectors and electronics

Tevatron experiment CDF and DØ are in the middle of data taking and physics analysis;

LHC pp experiments ATLAS and CMS in the final round of their construction phase, startup in 2007.