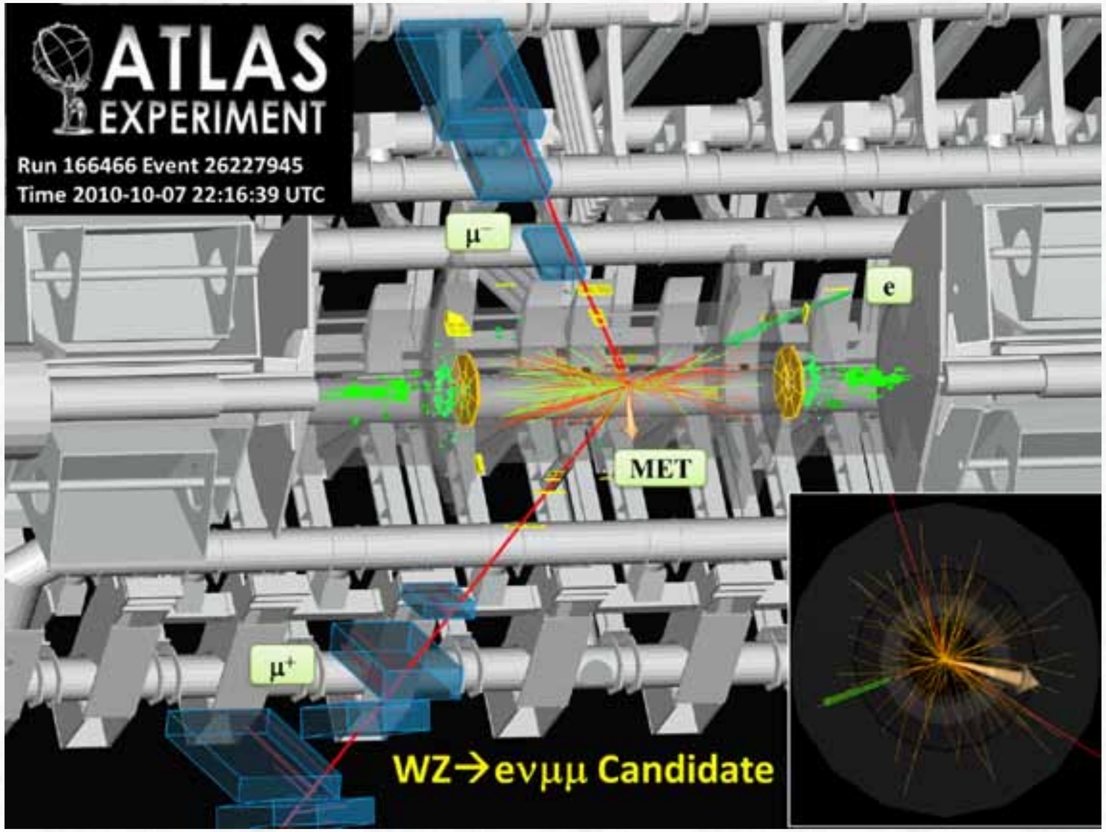
Particle Detection and
First Physics Results from the LHC



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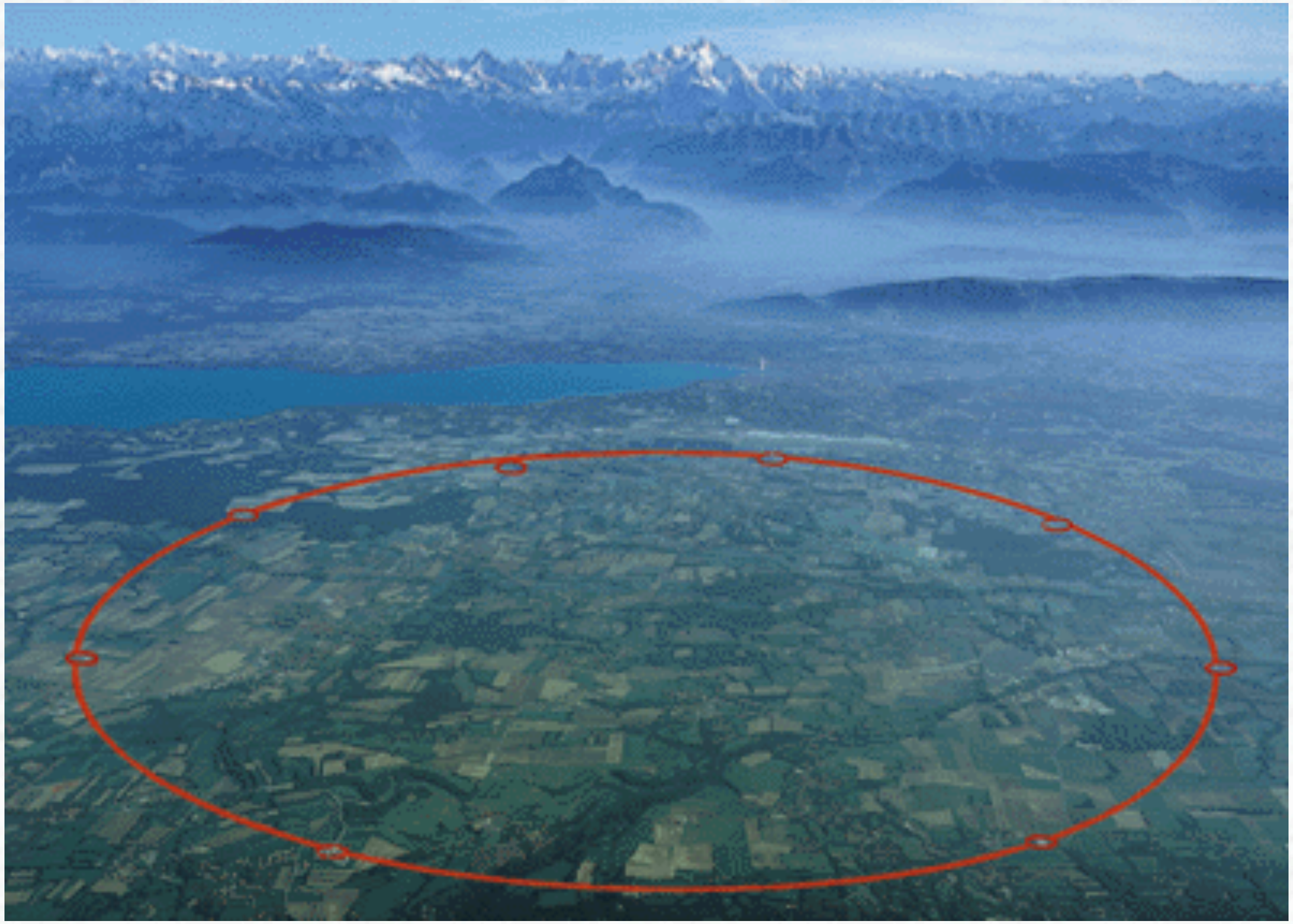
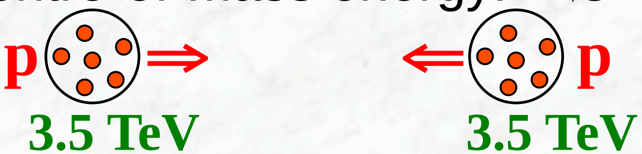
The Large Hadron Collider (LHC)



- Proton-proton accelerator in the LEP tunnel at CERN
- Centre-of-mass energy: $\sqrt{s}$ = 7 TeV (today), = 14 TeV (> 2015)



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

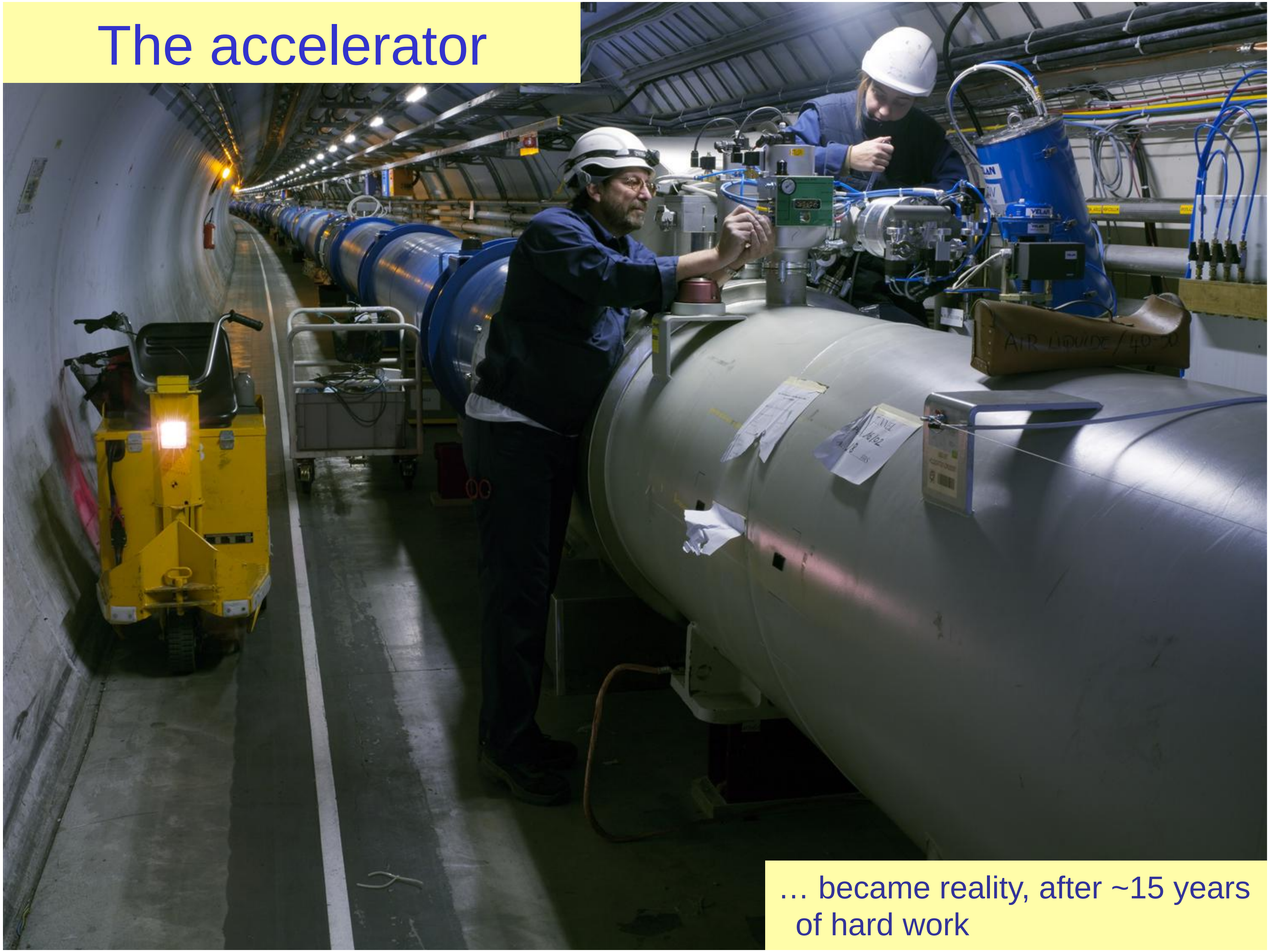
Assembling the machine

Lowering of the first dipole into the tunnel (March 2005).

Installation of the LHC in the tunnel

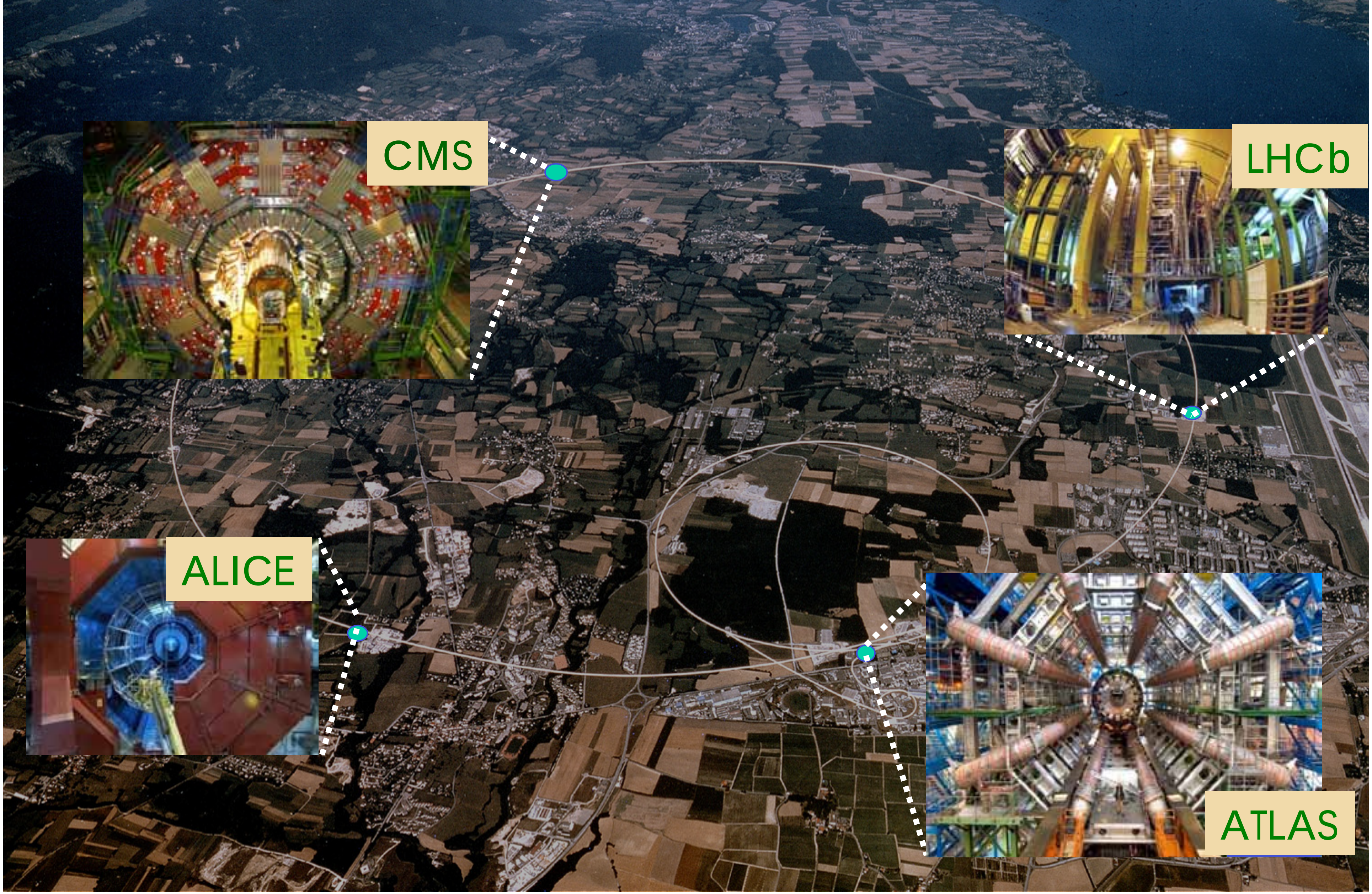
Cryogenic services line

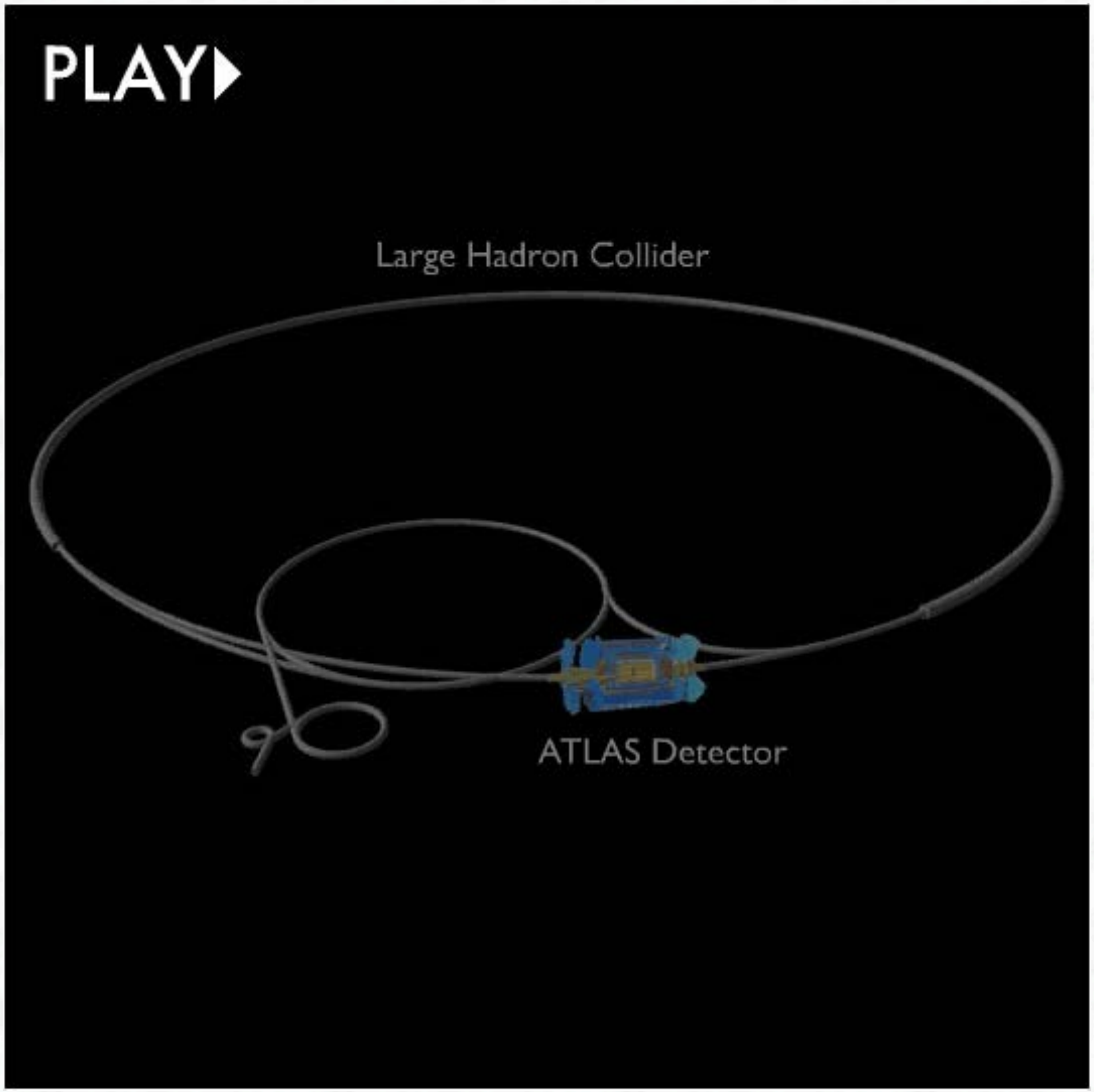
The accelerator



… became reality, after ~15 years of hard work

Begin of a new era in particle physics





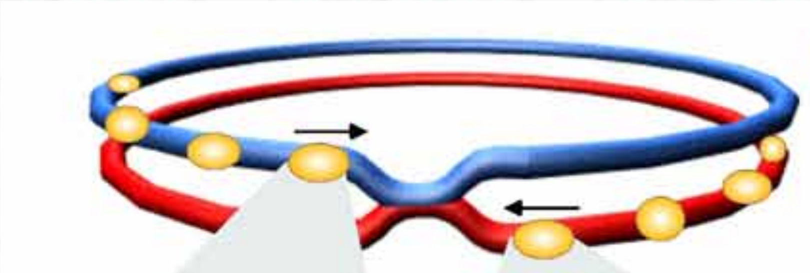
2835 x 2835 Pakete

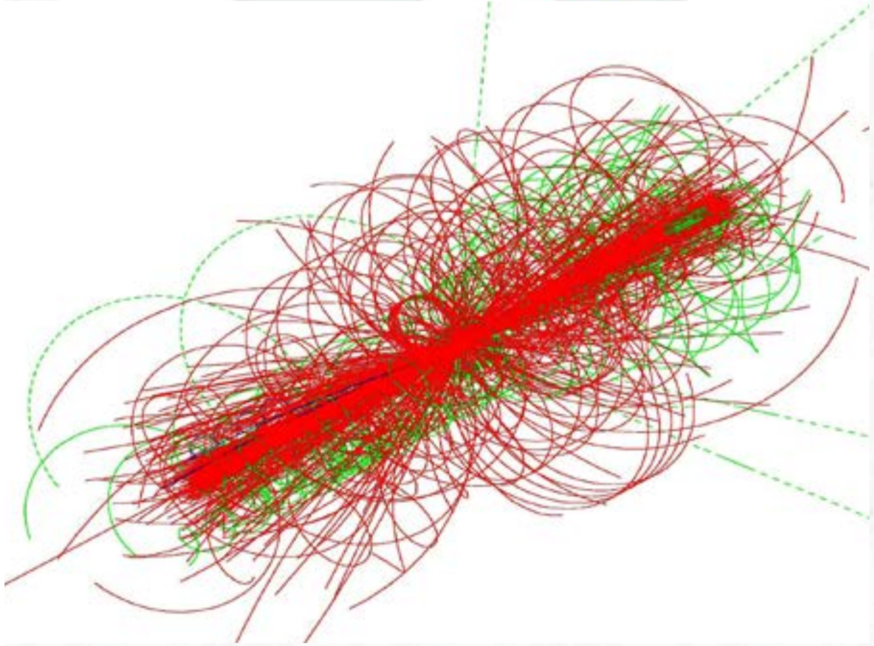
100 Milliarden Protonen
pro Paket

Abstand: 7.5 m (25 ns)

Kreuzungsrate der p-Pakete:
40 Mio. mal / sec.

Proton proton collisions at the LHC





Proton – proton:

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

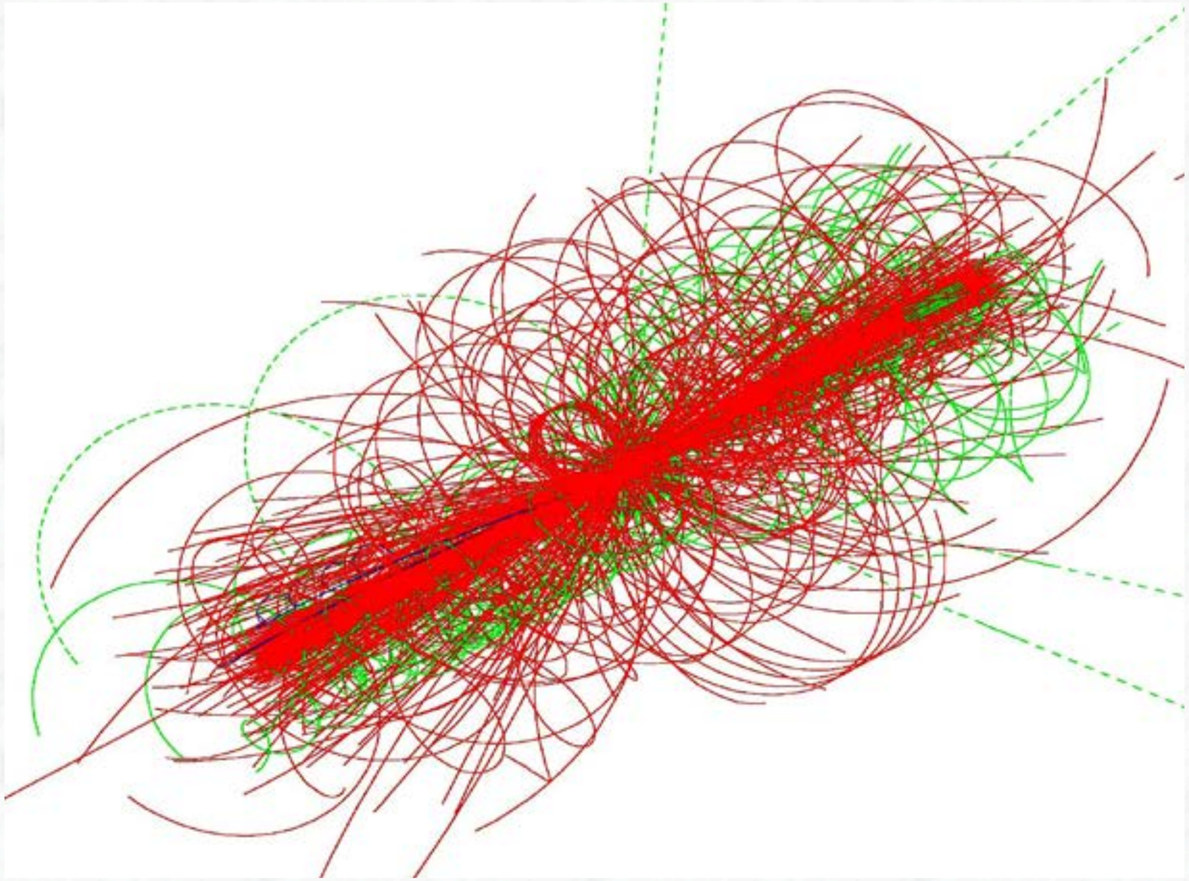
10^{11} protons / bunch
Crossing rate of p-bunches: 40 Mio. / s
Luminosity: $L = 10^{34}\ cm^{-2}\ s^{-1}$

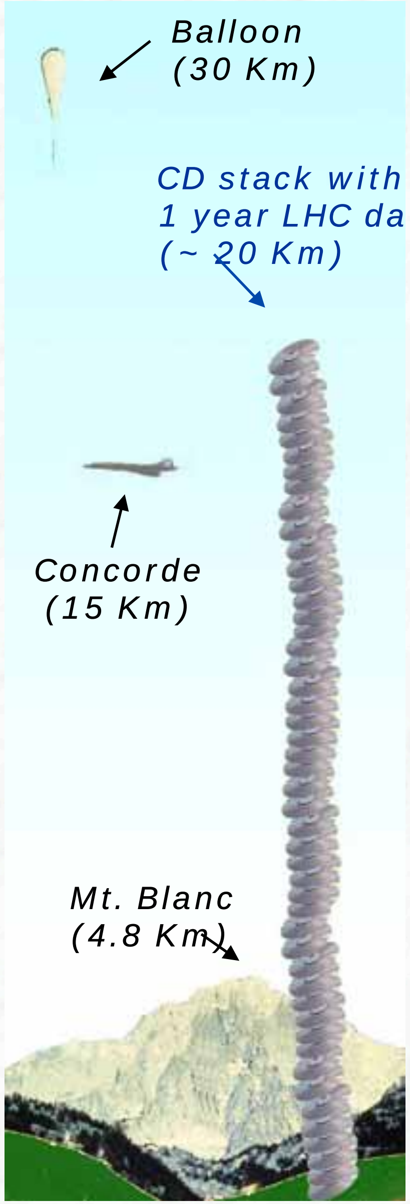
~10^9 pp collisions / s
(superposition of 23 pp-interactions per bunch crossing: **pile-up**)

~1600 charges particles in the detector

⇒ high particle densities
high requirements for the detectors

A huge data volume





Selection of 200 "collisions" per second

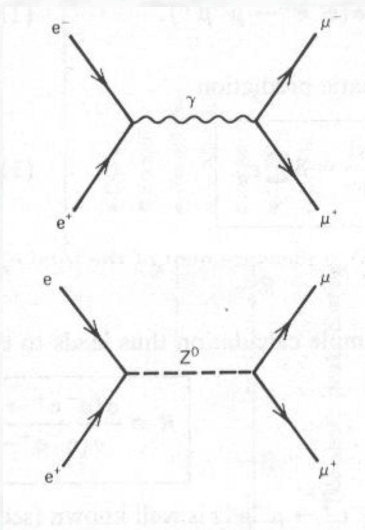
LHC data volume per year:
10-15 Peta bytes

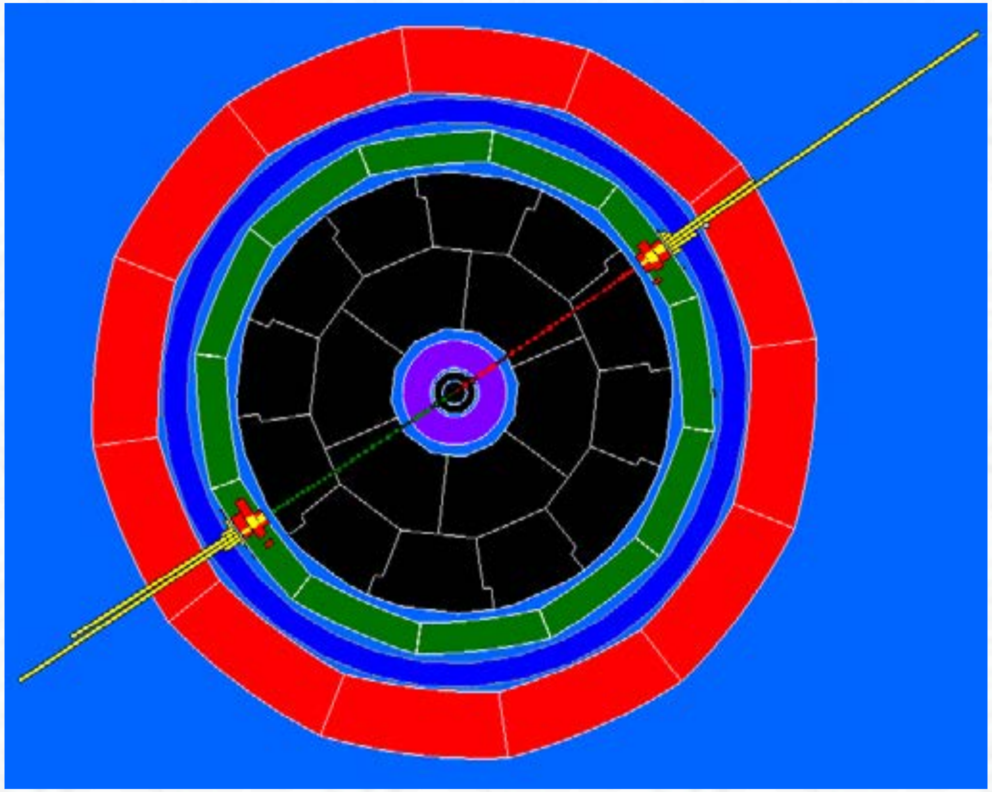
One CD has ~ 600 Mega bytes
1 Peta byte = 10^9 MB = 10^{15} Byte

Why a hadron collider ?

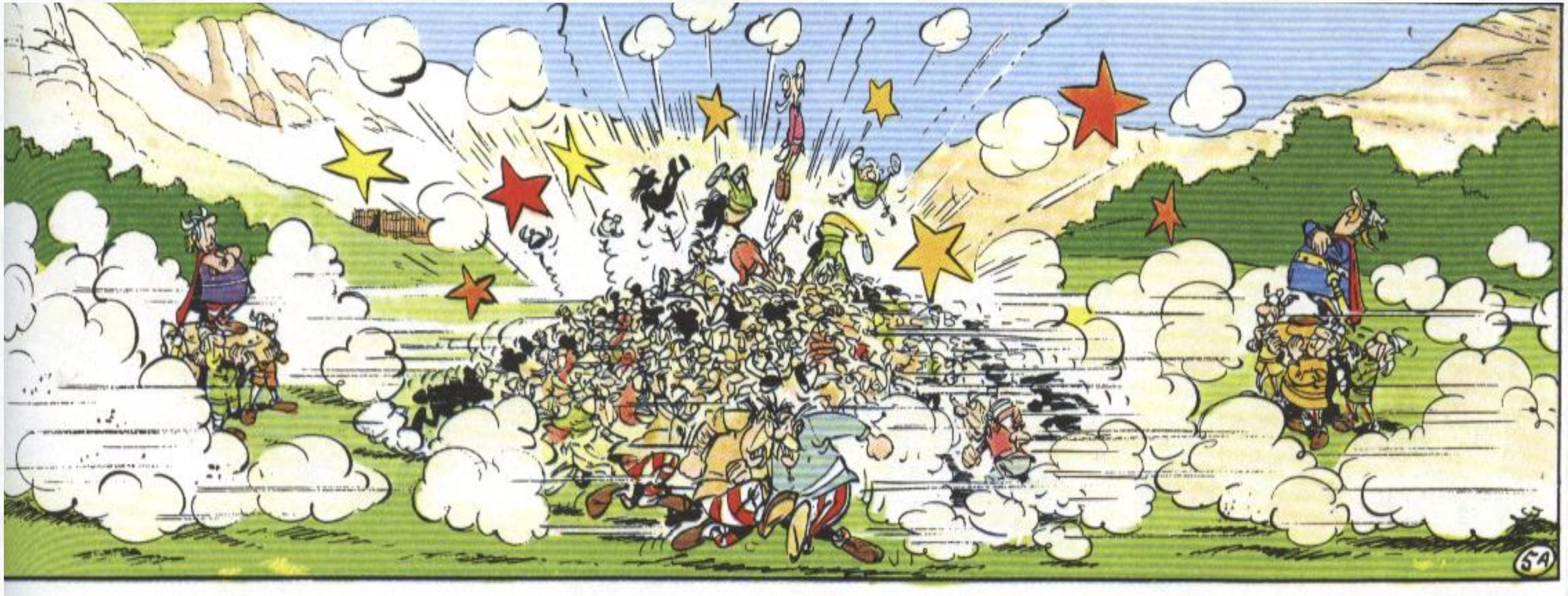
e^+e^- colliders are excellent machines for precision physics !!

- 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:

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

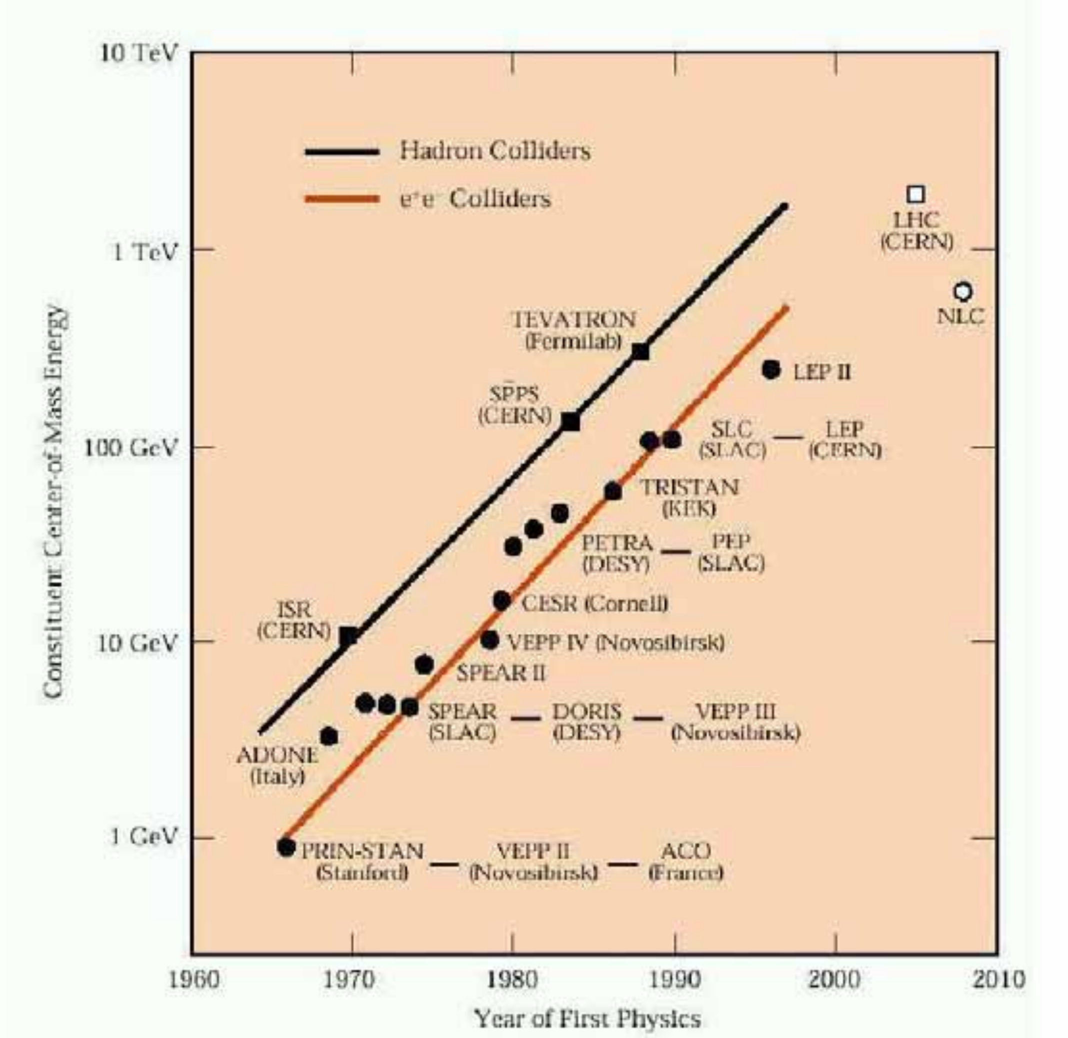
   - Ratio of the energy loss between protons and electrons:

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

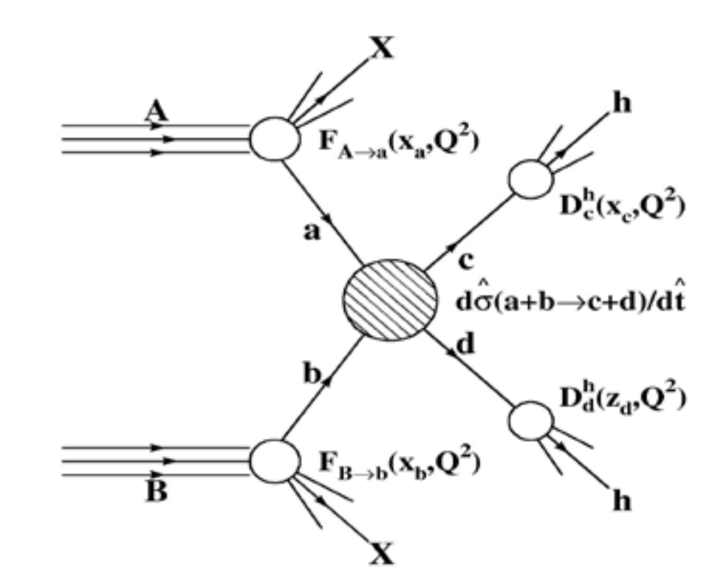
Future accelerators:

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

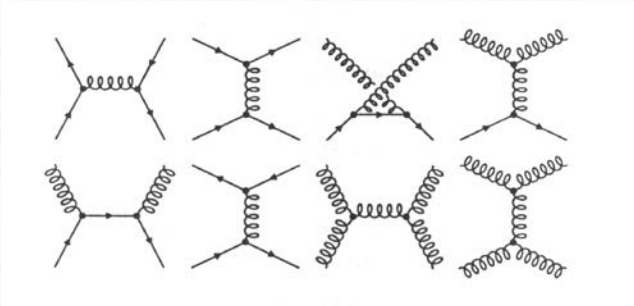


Physics at Hadron Colliders



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

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

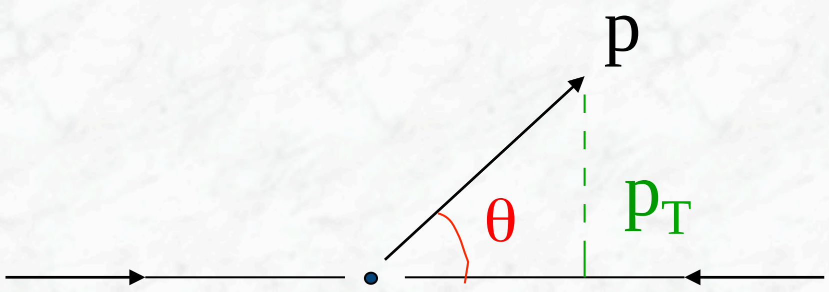


However: hard scattering (high p_T processes) represent only a tiny fraction of the total inelastic pp cross section

Total inelastic pp cross section ~ 70 mb (huge)

Dominated by events with small momentum transfer

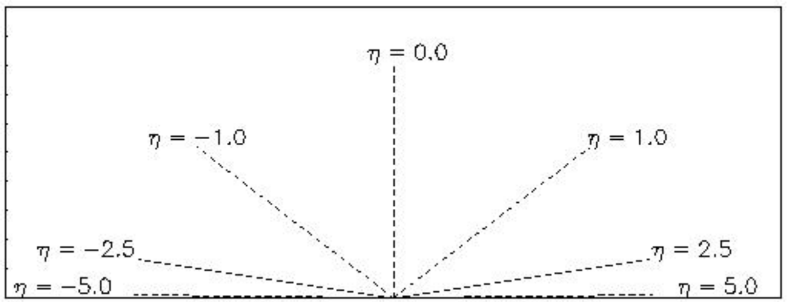
Variables used in the analysis of pp collisions



Transverse momentum
(in the plane perpendicular to the beam)

$p_T = p \sin\theta$

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



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

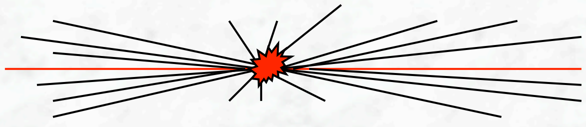
$\theta = 10^o \rightarrow \eta \cong 2.4$
$\theta = 170^o \rightarrow \eta \cong -2.4$

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

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

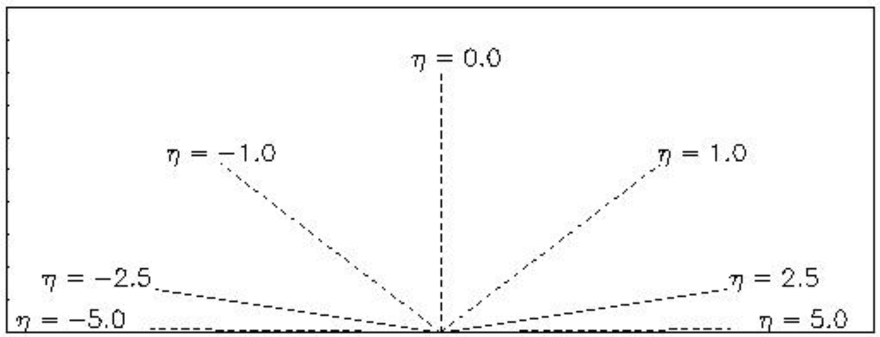


$< p_T > \approx 500$ MeV (of charged particles in the final state)

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

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

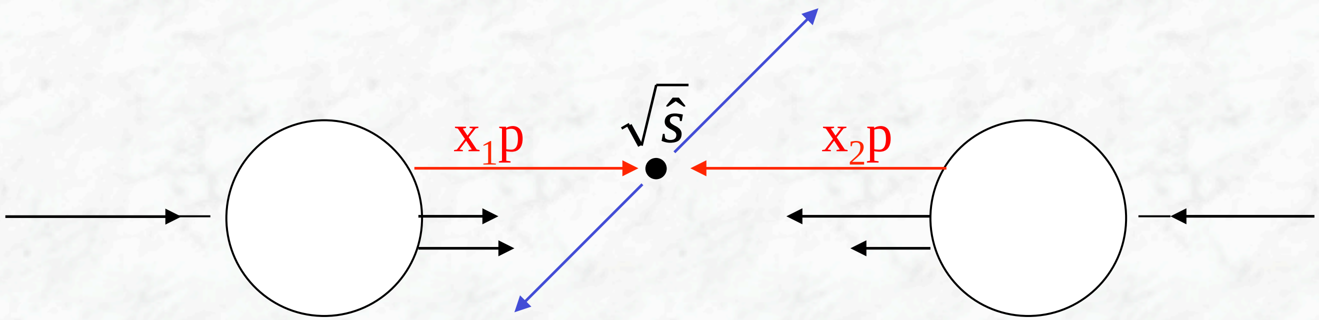
These events are called "Minimum-bias events"



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 $\sqrt{s}$ of the incoming protons

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

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

To produce a mass of:

	LHC
100 GeV:	x ~ 0.007
5 TeV:	x ~ 0.36

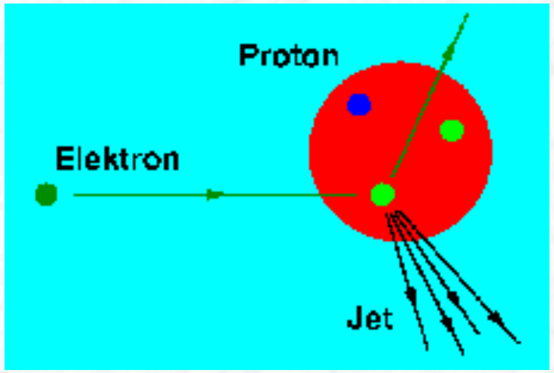
From where do we know the x-values?

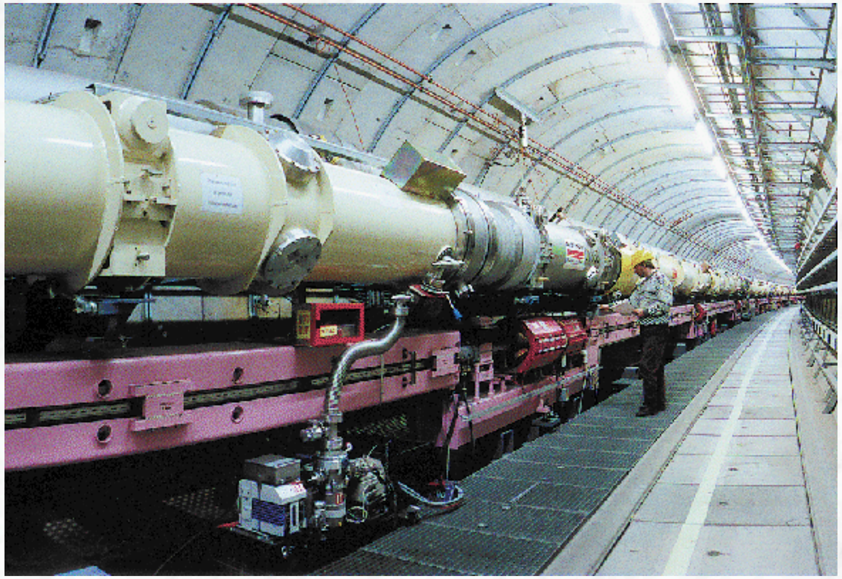
The structure of the proton is investigated in *Deep Inelastic Scattering* experiments:

Highest energy machine was the HERA ep collider at DESY/Hamburg

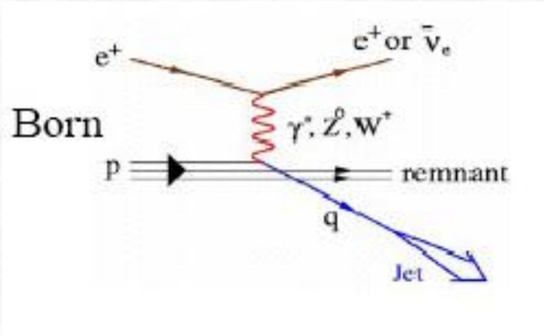
Scattering of 30 GeV electrons on 900 GeV protons:
→ Test of proton structure down to 10^{-18} m

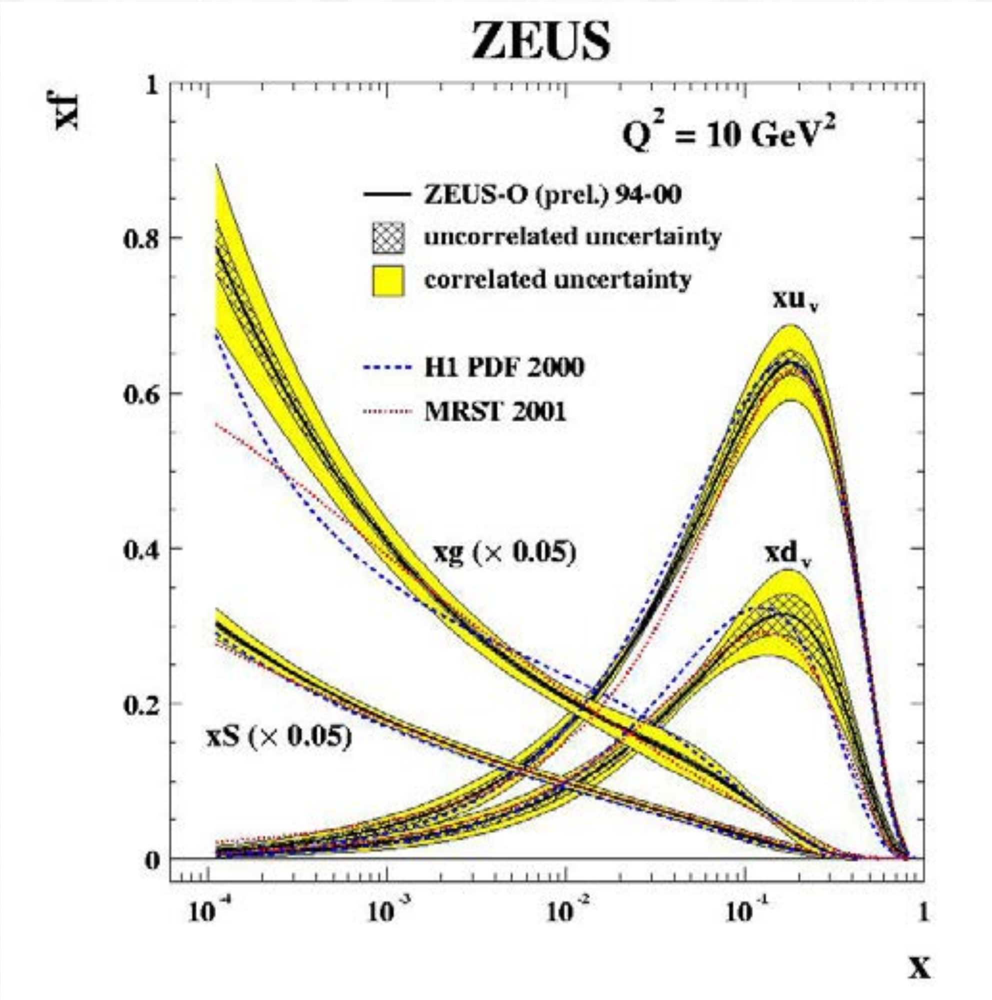
HERA ep accelerator, 6.3 km circumference





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





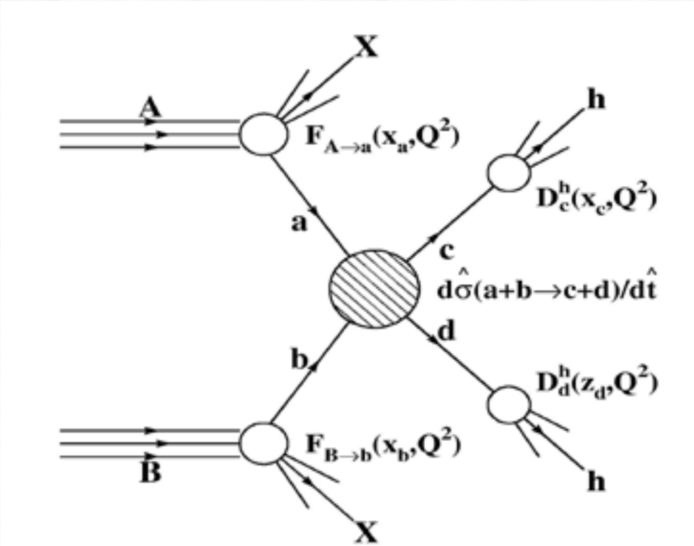
Parton density functions (pdf):

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



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

Sum over initial partonic states a,b

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

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

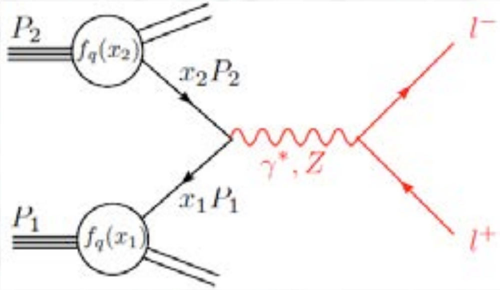
… + higher order QCD corrections (perturbation theory)
meanwhile available for many signal and background processes !

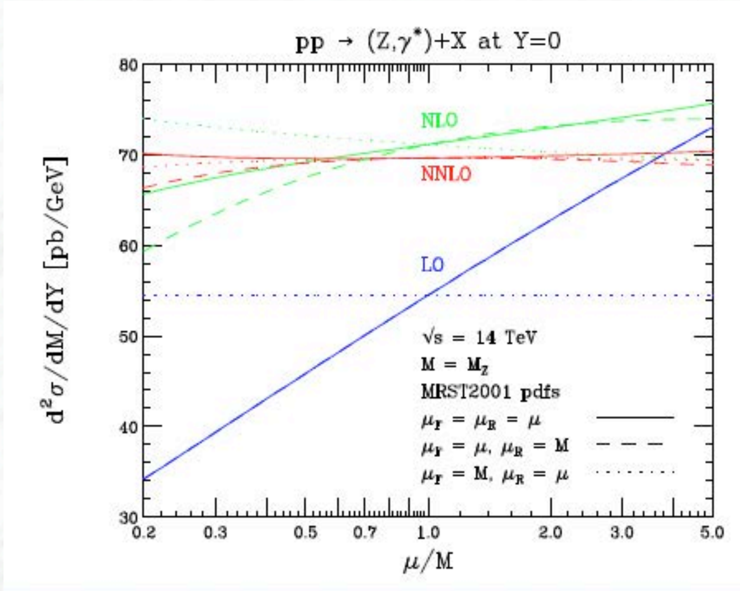
which for some processes turn out to be large
(e.g. Higgs production via gg fusion)

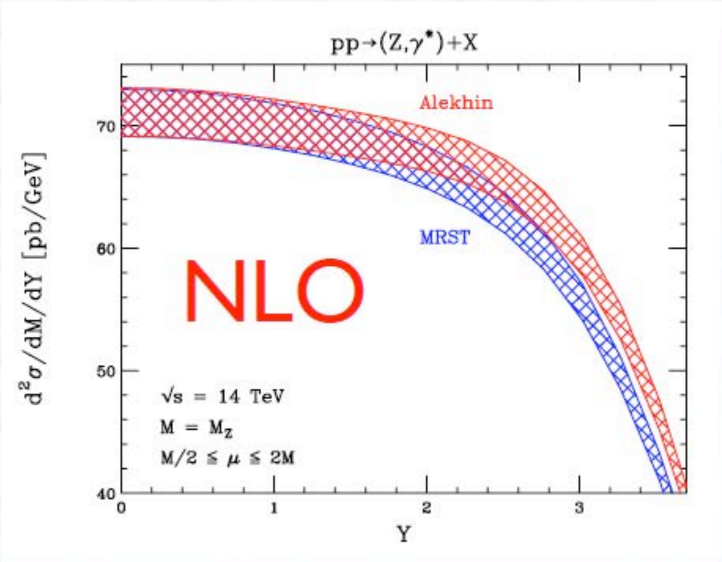
usually introduced as K-factors: $K_{[n]} = \sigma_{[n]} / \sigma_{[LO]}$

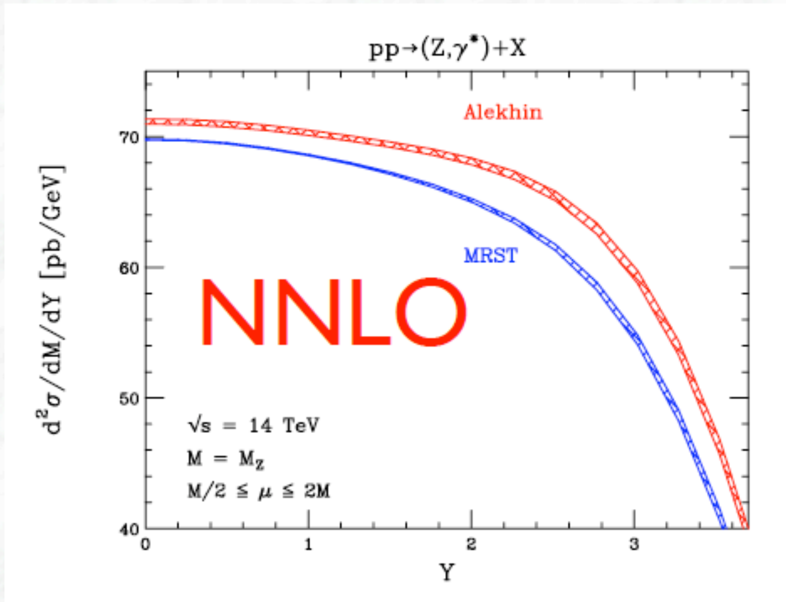
a few examples: Drell-Yan production of W/Z: $K_{NLO} \sim 1.2$
Higgs production via gg fusion: $K_{NLO} \sim 1.8$

Example: Drell-Yan production of W/Z bosons



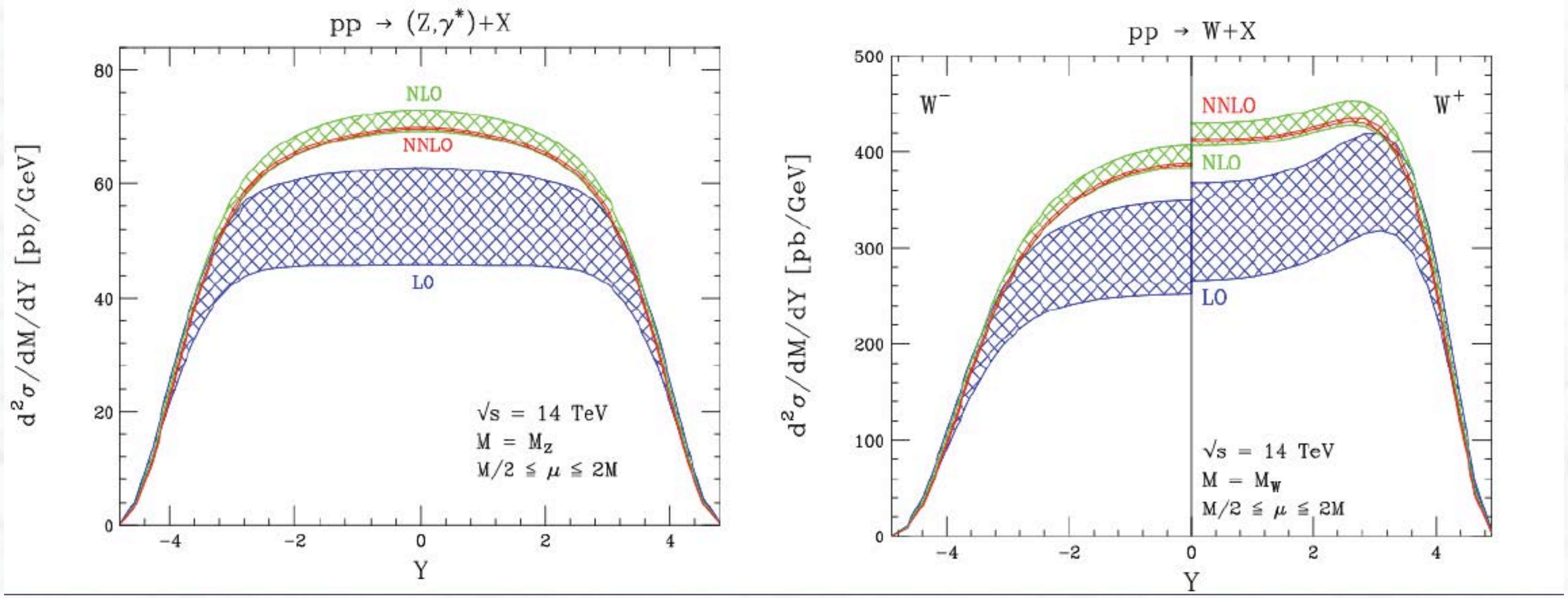






Example: Drell-Yan production of W/Z bosons (cont.)

Rapidity distributions for Z and $W^{\pm}$ production at LO, NLO, and NNLO



Note: LHC data will be used in the future to further constrain the parton densities

Luminosity

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

$$N = L \cdot \sigma$$

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,….

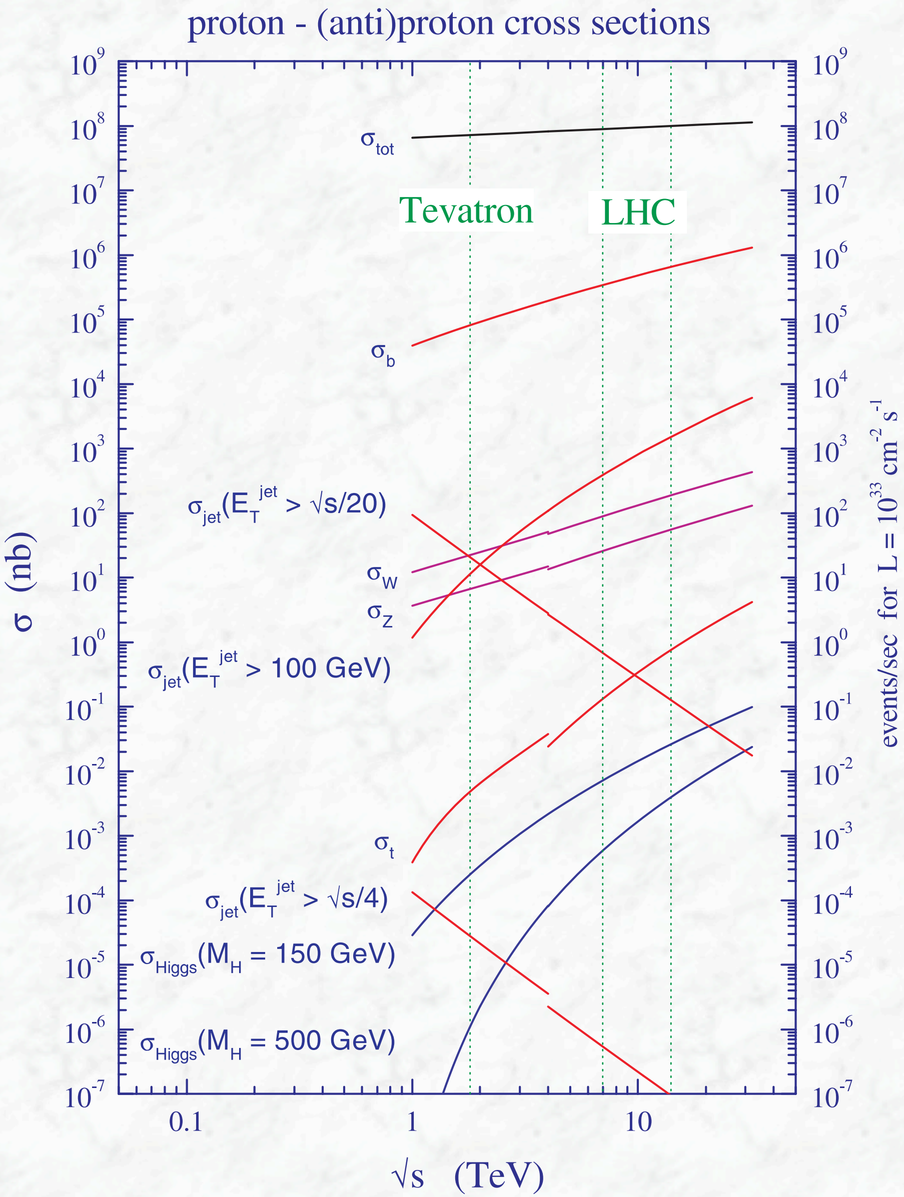
In order to achieve acceptable production rates for the interesting physics processes, the luminosity must be high !

$L = 2\cdot10^{32}\ cm^{-2}\,s^{-1}$ design value for first year
$L = 10^{33}\ cm^{-2}\,s^{-1}$ planned for the initial phase of the LHC (now)
$L = 10^{34}\ cm^{-2}\,s^{-1}$ 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, with $10^{33}\ cm^{-2}\,s^{-1}$
100 fb^{-1} per year, with $10^{34}\ cm^{-2}\,s^{-1}$

Cross Sections and Production Rates



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

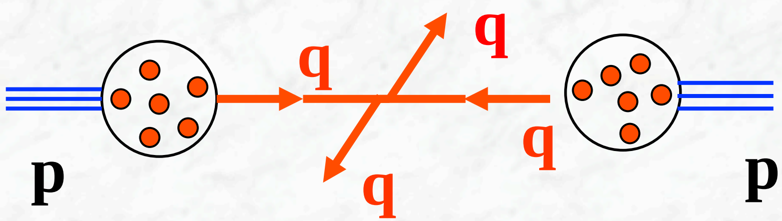
• Inelastic proton-proton reactions:	10^9 / s
• bb pairs • tt pairs	$5\ 10^6$ / s 8 / s
• $W \rightarrow e\ \nu$ • $Z \rightarrow e\ e$	150 / s 15 / s
• **Higgs (150 GeV)** • **Gluino, Squarks (1 TeV)**	**0.2 / s** **0.03 / s**

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

The only problem:
you have to detect them !

What experimental signatures can be used ?

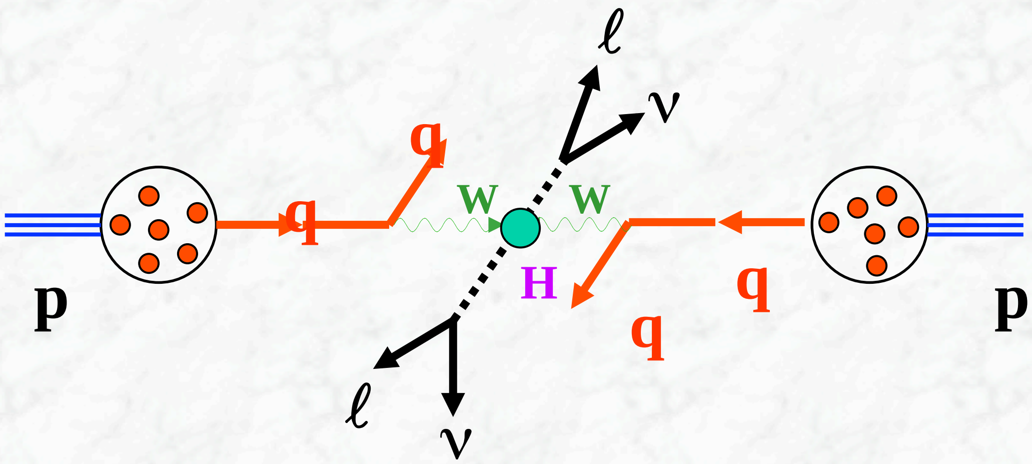
Quark-quark scattering:



No leptons / photons in the initial and final state

If leptons with large transverse momentum are observed:
⇒ interesting physics !

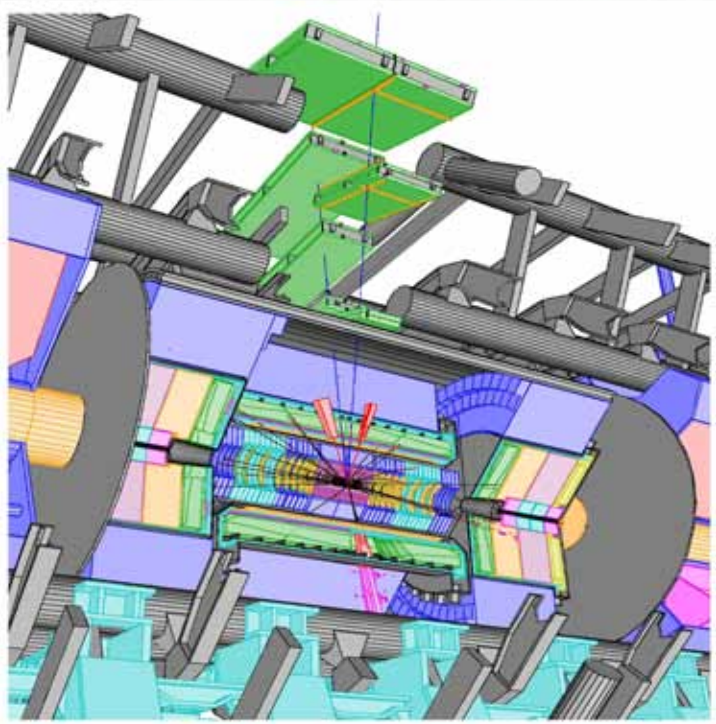
Example: Higgs boson production and decay



Important signatures:

- Leptons und photons
- Missing transverse energy

Detector requirements from physics



- Good measurement of leptons (e,μ) and photons with large transverse momentum p_T

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

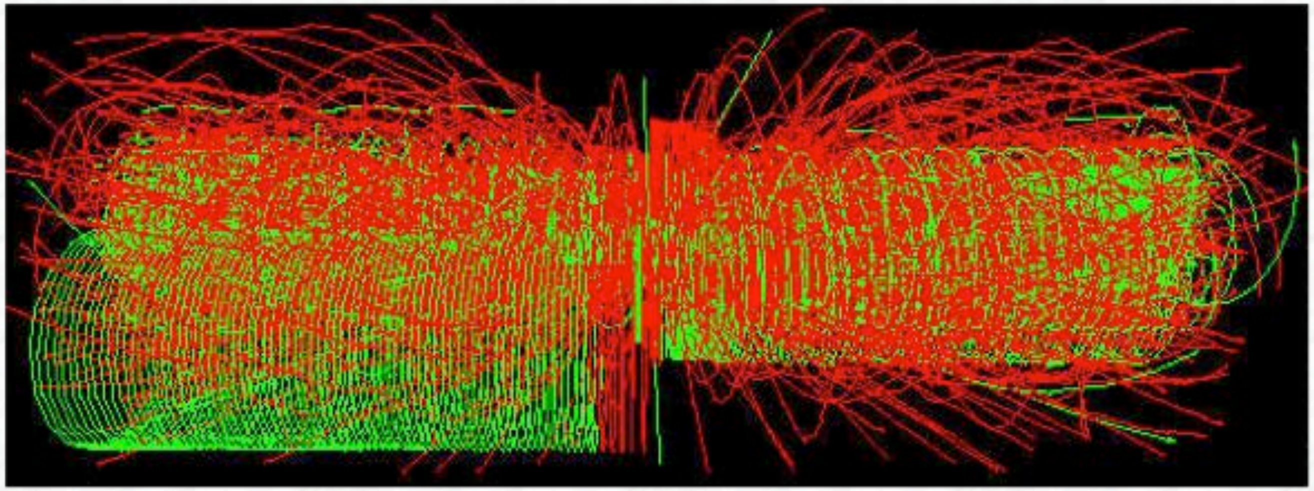
  and

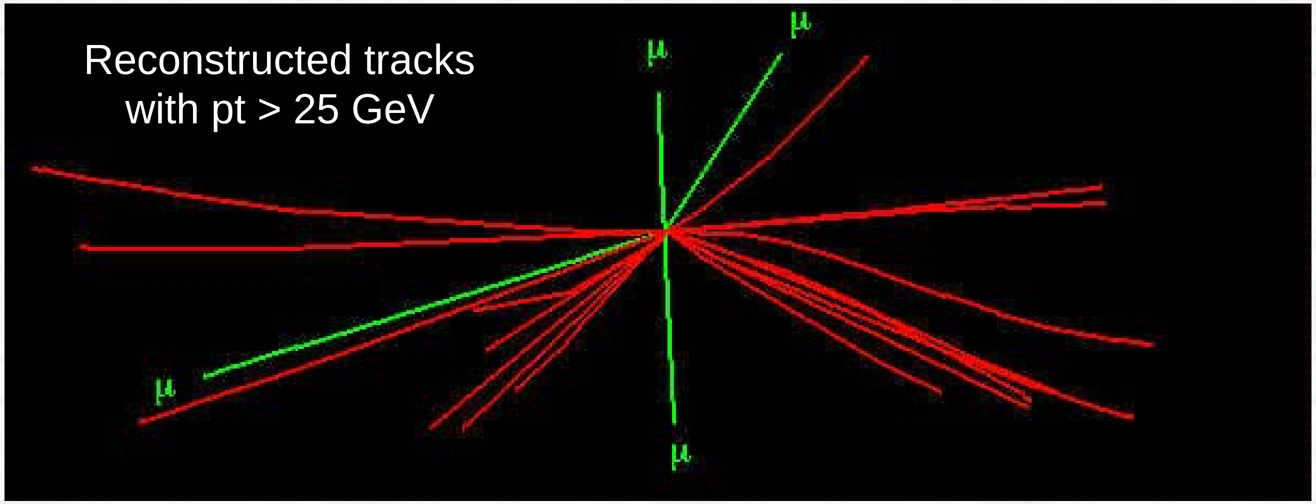
  energy measurements in the forward regions

  ⇒ calorimeter coverage down to $|\eta| < 5$

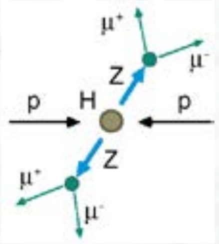
- Efficient identification of τ leptons and jets from b-quarks

Suppression of background:
Reconstruction of objects with large transverse momentum





$H \to ZZ^{(*)} \to \ell\ell\ell\ell$



Signal: σ BR = 5.7 fb (m_H = 100 GeV)

$P_T(1,2) > 20$ GeV
$P_T(3,4) > 7$ GeV
$|\eta| < 2.5$
Isolated leptons

Background: Top production

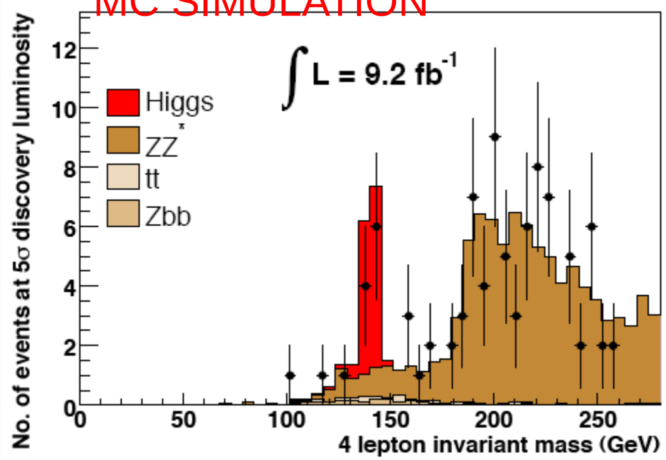
$tt \to Wb\,Wb \to \ell\nu\ c\ell\nu\ \ell\nu\ c\ell\nu$
σ BR ≈ 1300 fb

$M(\ell\ell) \sim M_Z$
$M(\ell'\ell') \sim < M_Z$

Associated production Z bb

$Z\,bb \to \ell\ell\ c\ell\nu\ c\ell\nu$

MC SIMULATION



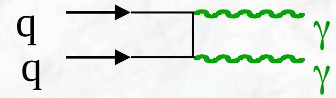
Background rejection:
Leptons from b-quark decays
→ non isolated
→ do not originate from primary vertex
(B-meson lifetime: ~ 1.5 ps)

Dominant background after isolation cuts: ZZ continuum
Discovery potential in mass range from ~130 to ~600 GeV/c^2

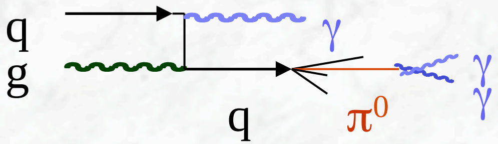
Decay modes at low mass: $H \rightarrow \gamma\gamma$

<u>Main backgrounds:</u>

$\gamma\gamma$ irreducible background



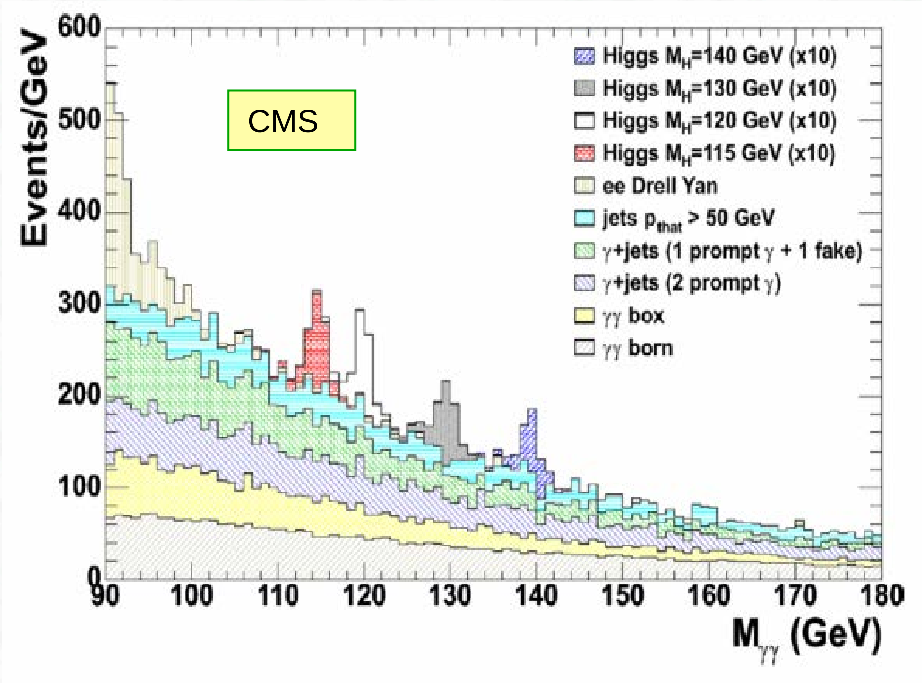
γ-jet and jet-jet (reducible)



$\sigma_{\gamma j+jj} \sim 10^6\ \sigma_{\gamma\gamma}$ with large uncertainties

$\rightarrow$ need $R_j > 10^3$ for $\varepsilon_\gamma \approx$ 80% to get $\sigma_{\gamma j+jj} \ll \sigma_{\gamma\gamma}$

MC SIMULATION

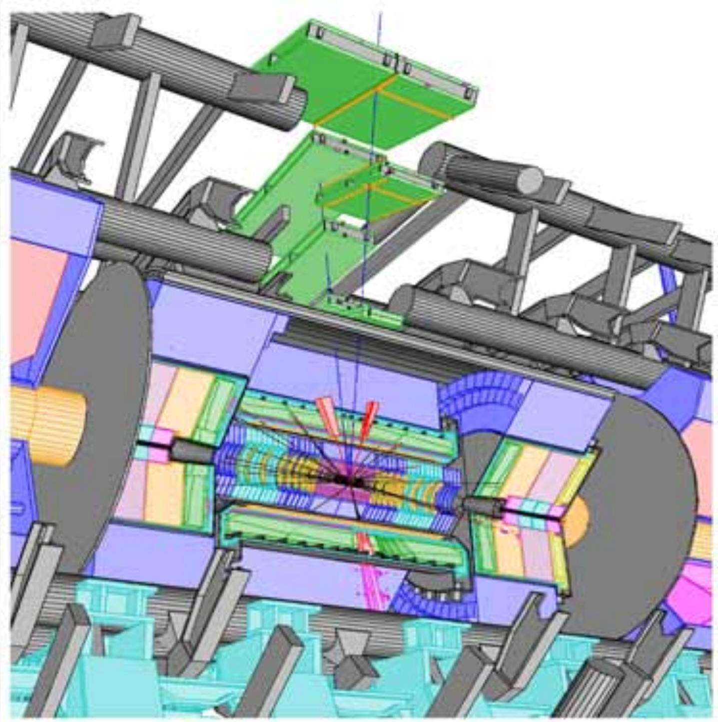


Signal expectation x 10, for 1 fb^{-1}

- <u>Main exp. tools for background suppression</u>:
  - photon identification
  - γ / jet separation (calorimeter + tracker)

Sensitivity in the low mass region, however, higher integrated luminosities required

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

How are the interesting events selected ?

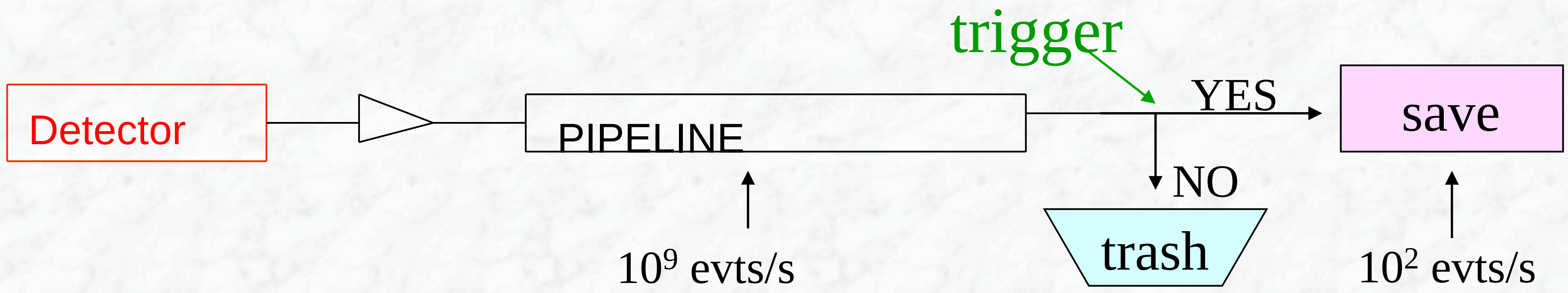
TRIGGER: much more difficult than at e^+e^- machines

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



The ATLAS experiment

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

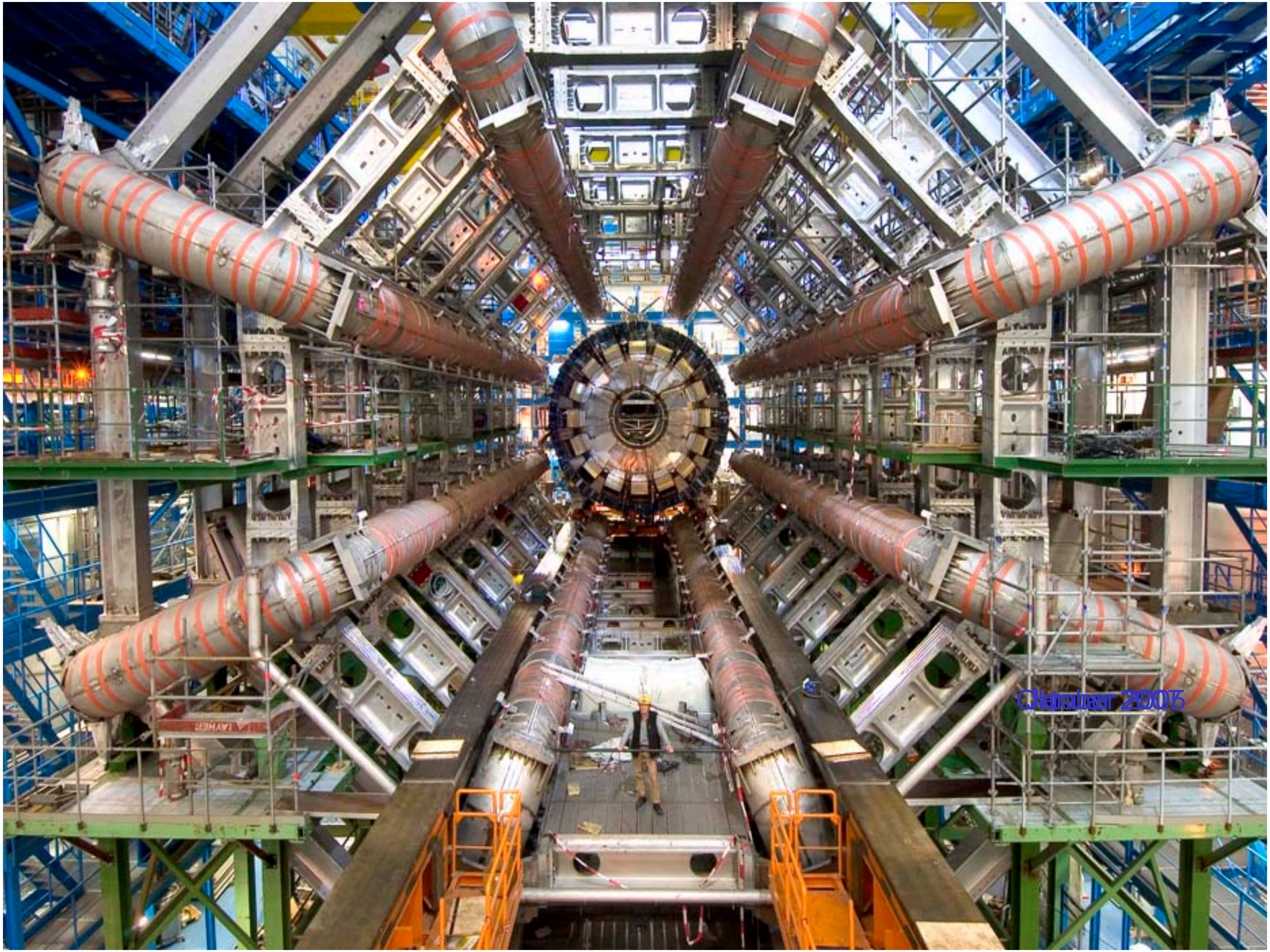
  High resolution silicon detectors:
  - 6 Mio. channels (80 µm x 12 cm)
  - 100 Mio. channels (50 µm x 400 µm)

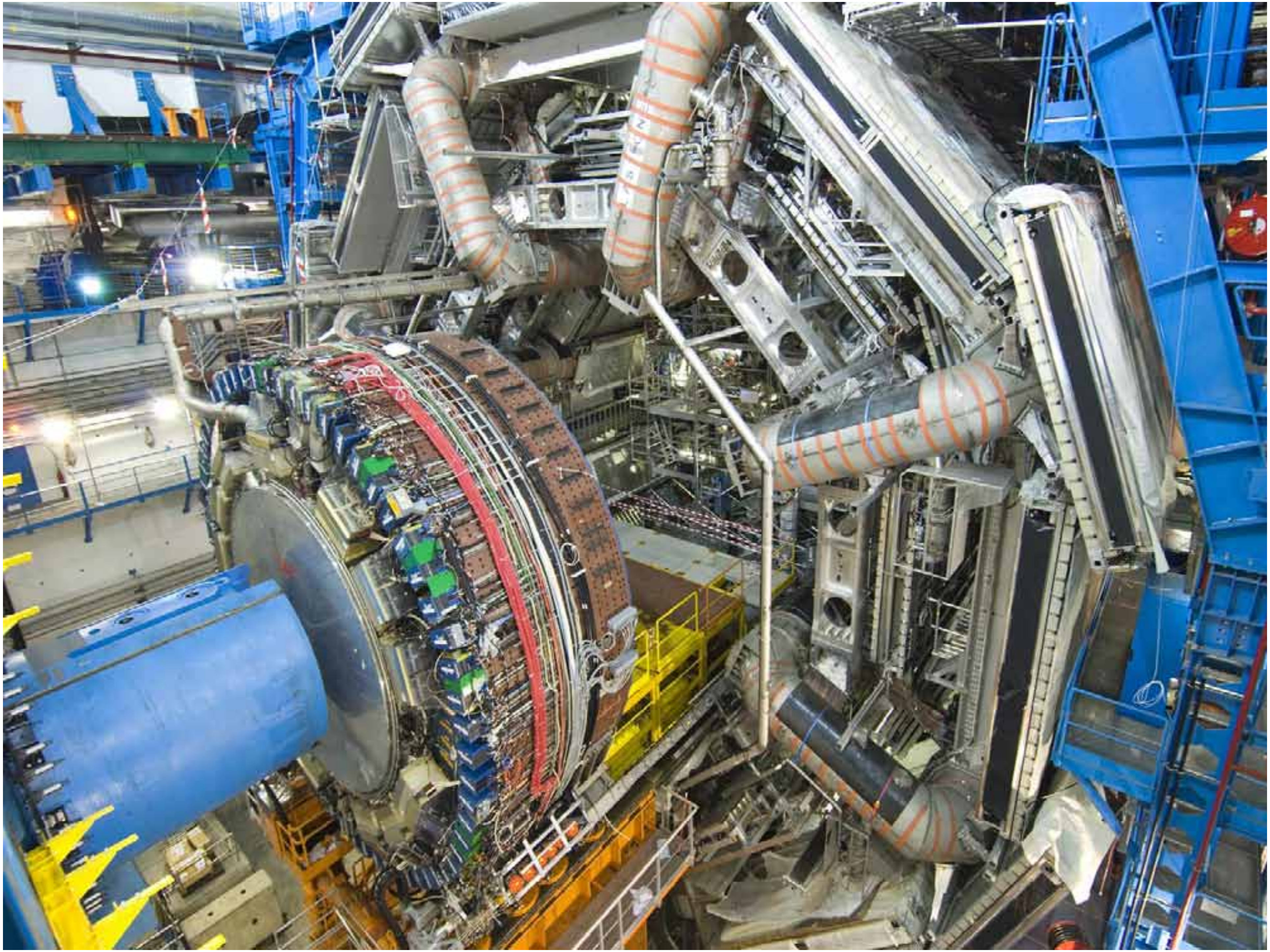
  space resolution: ~ 15 µm

- Energy measurement down to 1º to the beam line

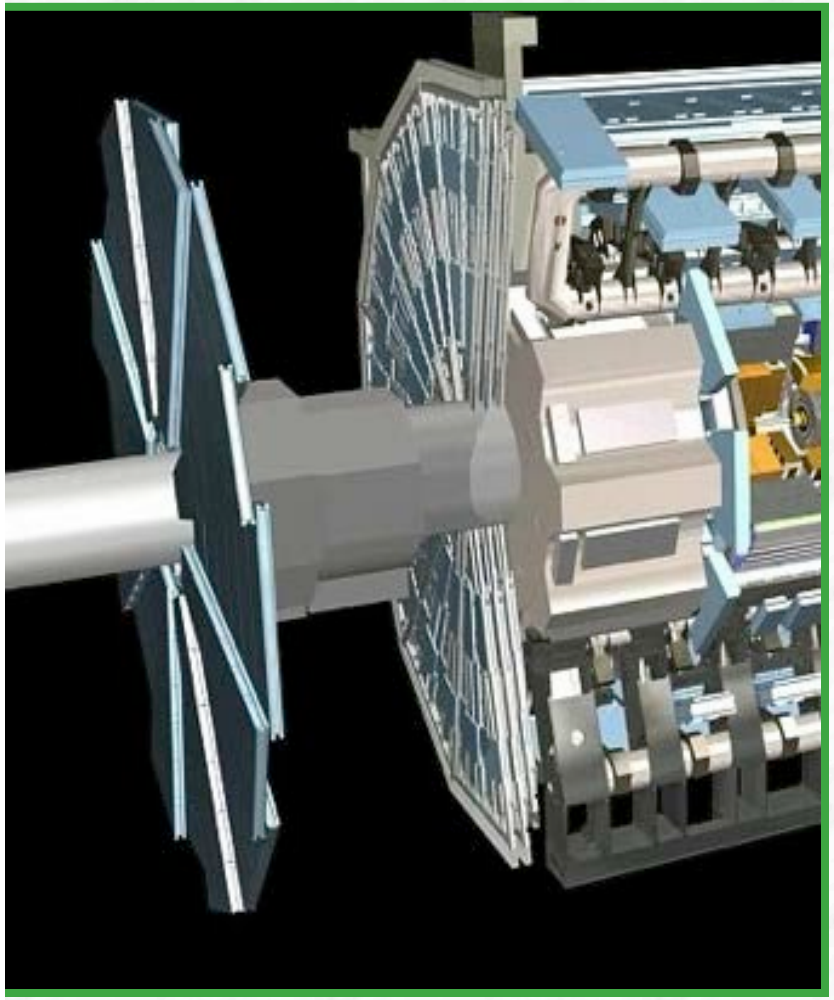
- Independent muon spectrometer (supercond. toroid system)

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


Oktober 2005
Januar 2007

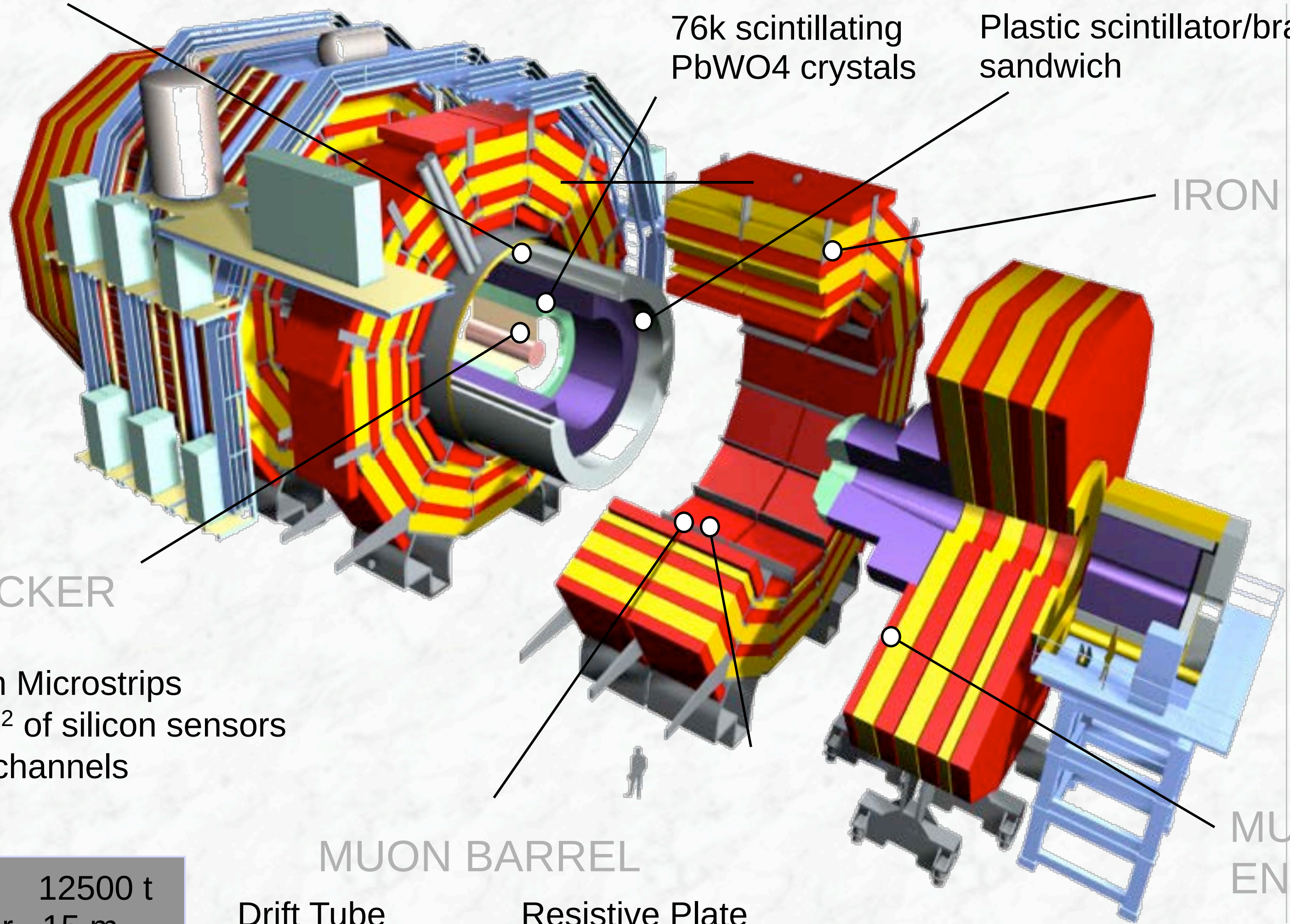


Muon detection system
in the forward region



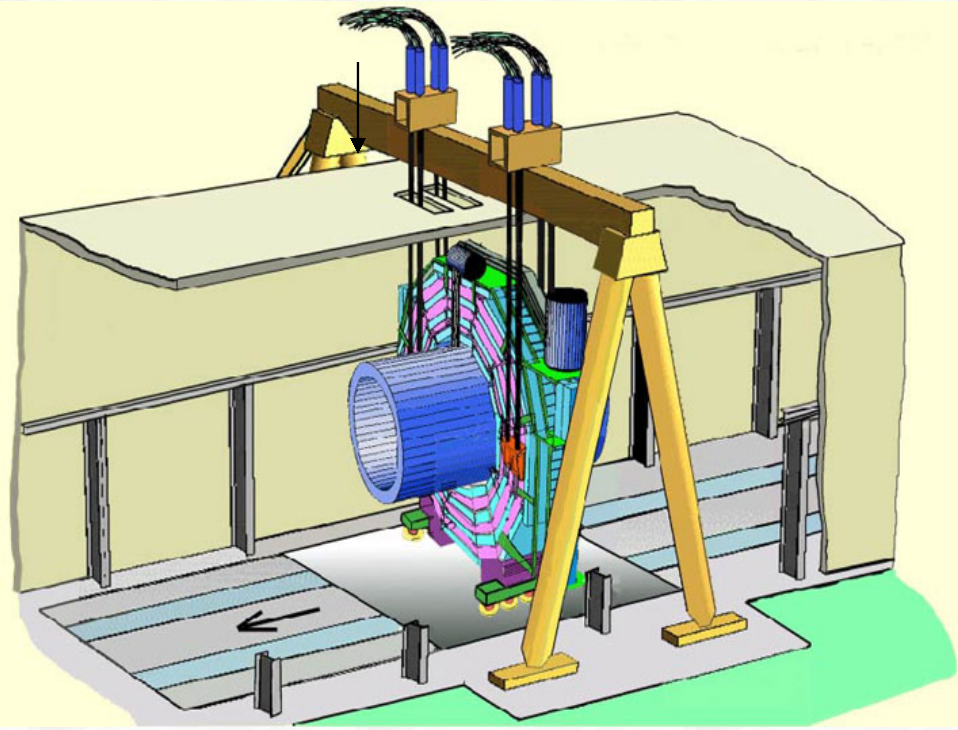
A historical moment:
Closure of the LHC beam pipe ring on 16th June 2008
ATLAS was ready for data taking in August 2008

CMS

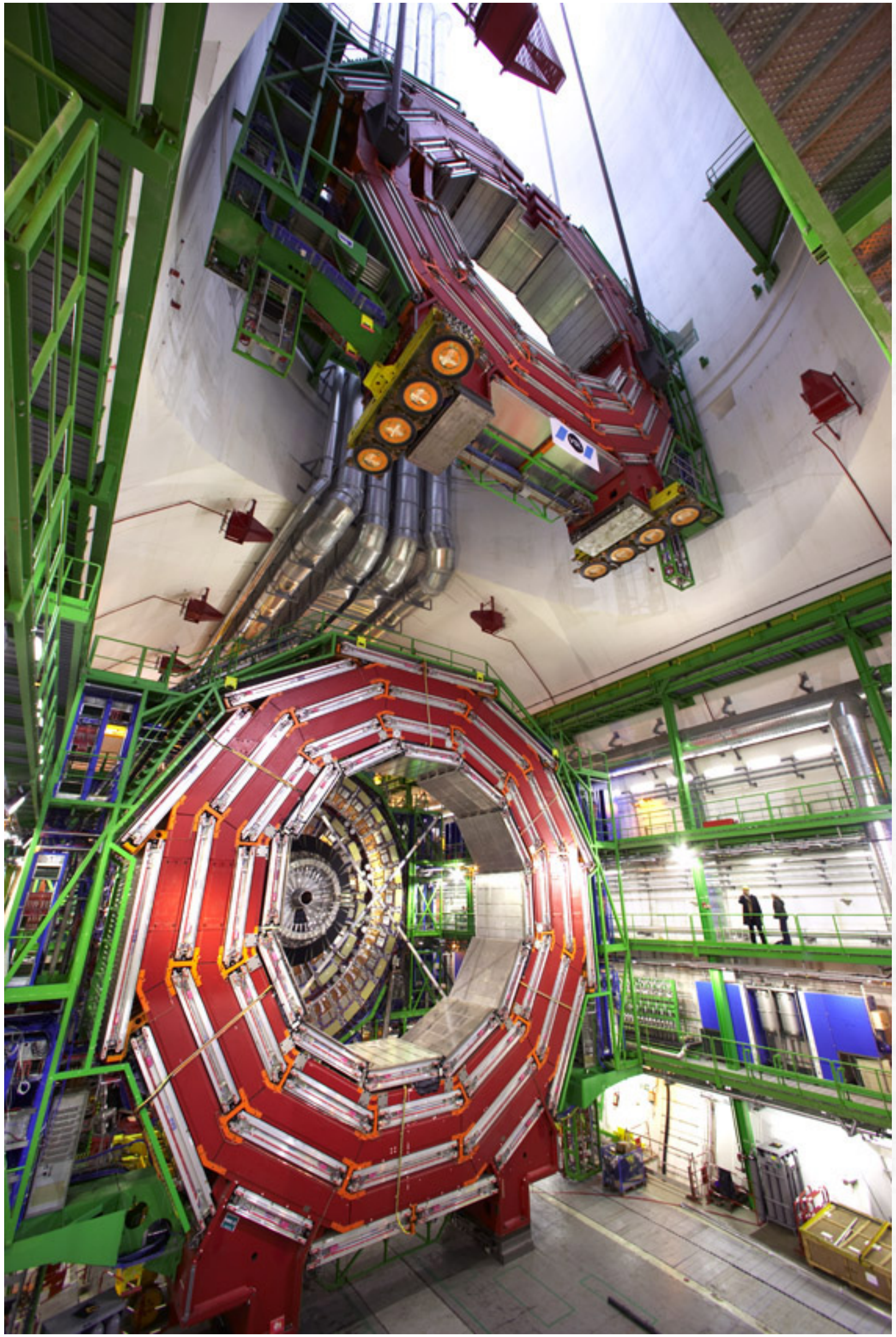


Total weight	12500 t
Overall diameter	15 m
Overall length	21.6 m

The CMS experiment



The central, heaviest slice (2000 tons) including the solenoid magnet lowered in the underground cavern in Feb. 2007



CMS Detector closed for 10th Sep. 2008