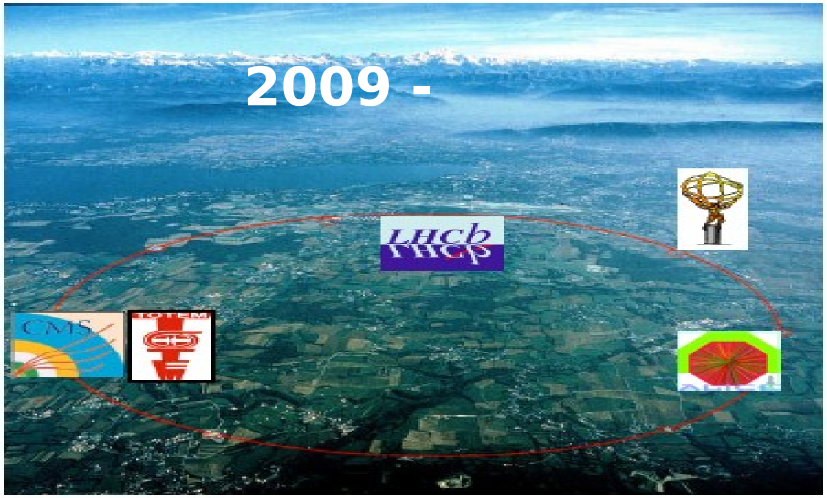
Lectures on LHC Physics

E. Richter -Was,

Inst. Physics, Jagiellonian University, Cracow

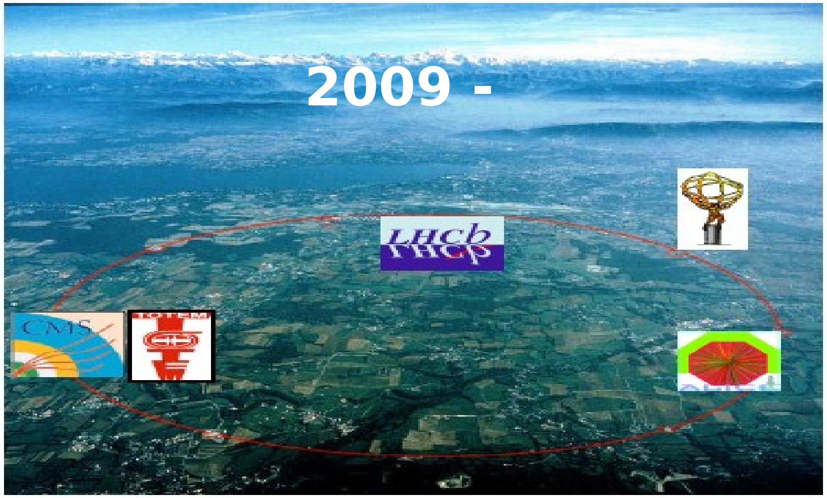
ATLAS experiment at LHC



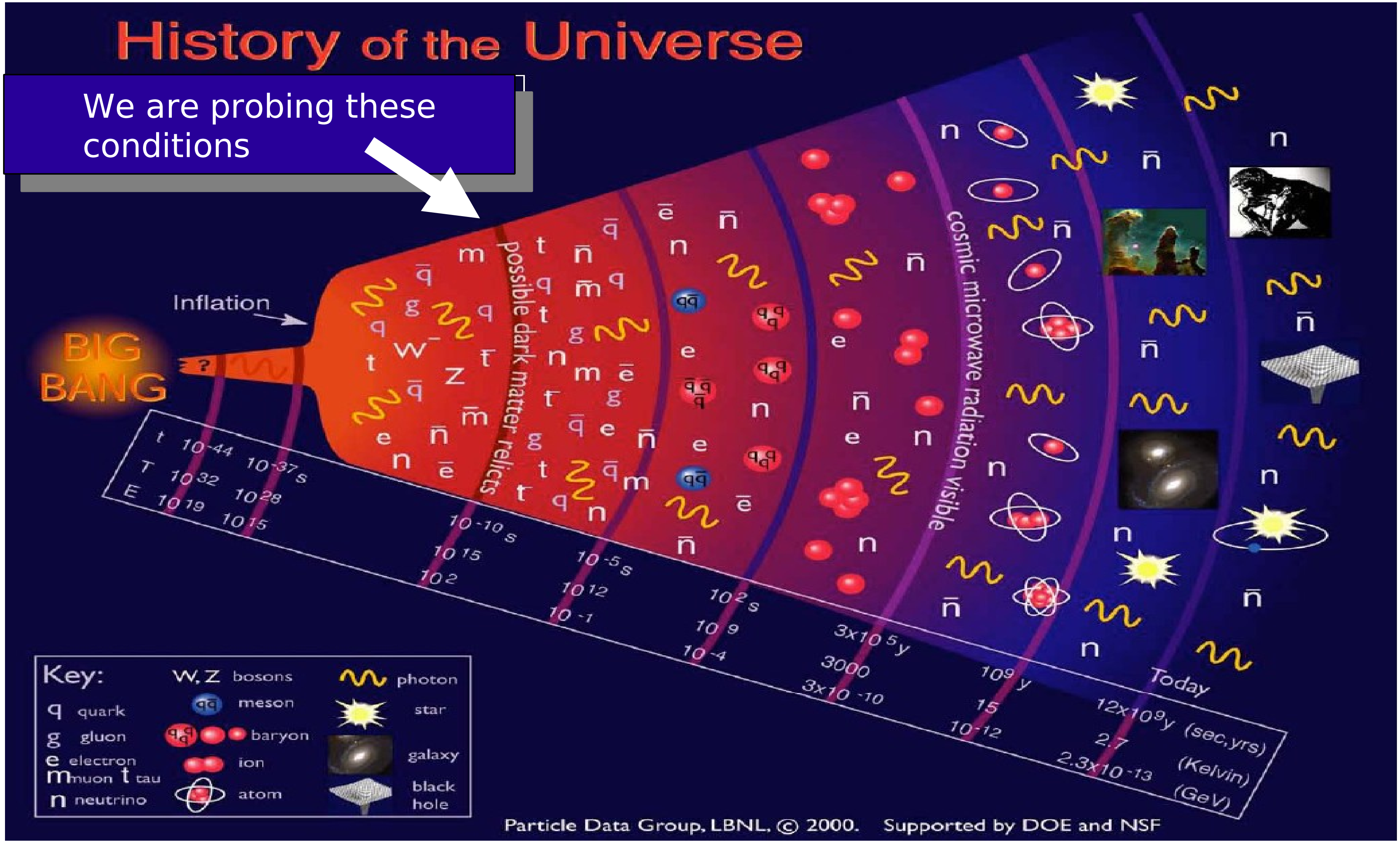
Hadron Collider Physics

Lecture 0

- Physics goals
- A bit of history, physics
- Accelerator
- Detectors
- Kinematics
- Experimental challenges
- LHC: first 3 years of operation



A big bang in the labolatory?



We are probing these conditions

Particle Data Group, LBNL, © 2000. Supported by DOE and NSF

Several open questions and mysteries ….

What is the origin of the particle masses ?

What is the nature of the Universe dark matter ?

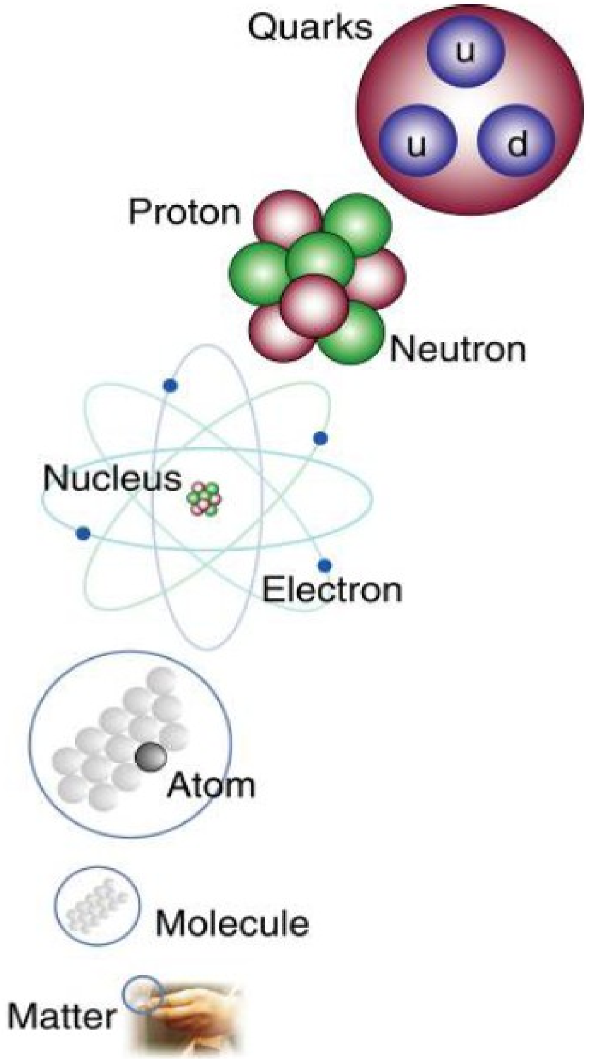
What is the origin of the Universe
matter-antimatter asymmetry ?

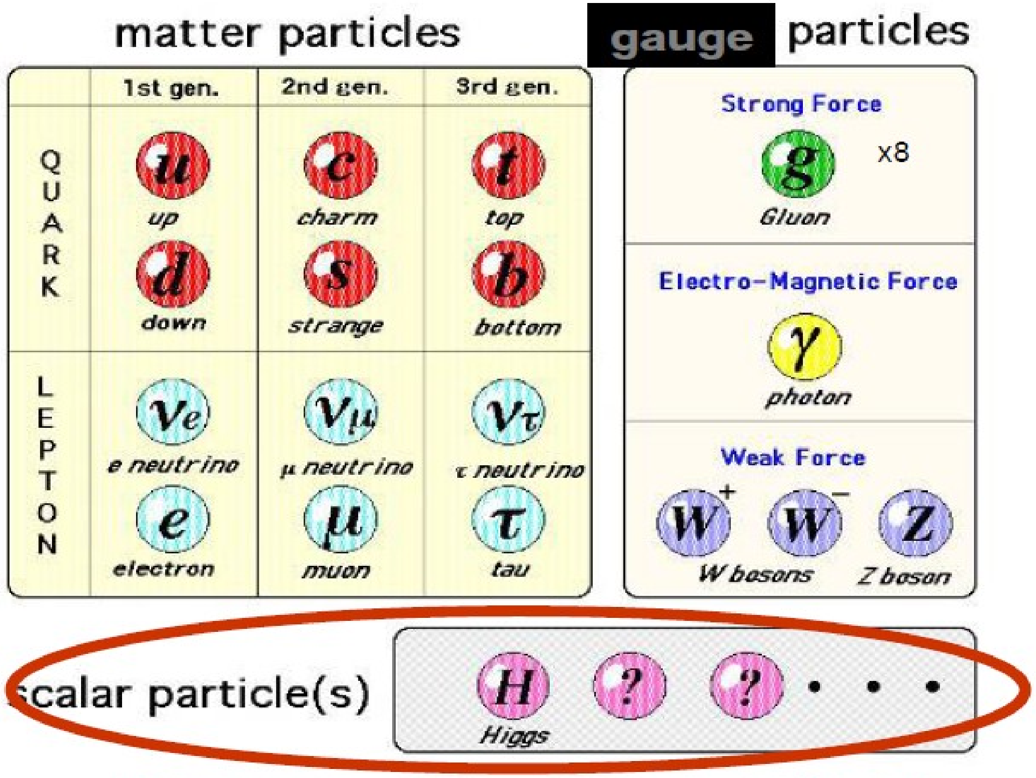
What are the constituents of the Universe
primordial plasma ~10 μs after the Big Bang ?

What happened in the first instants of the Universe
life (10^{-10} s after the Big Bang) ?

Etc. etc.

The study of elementary particles and fields and their interactions

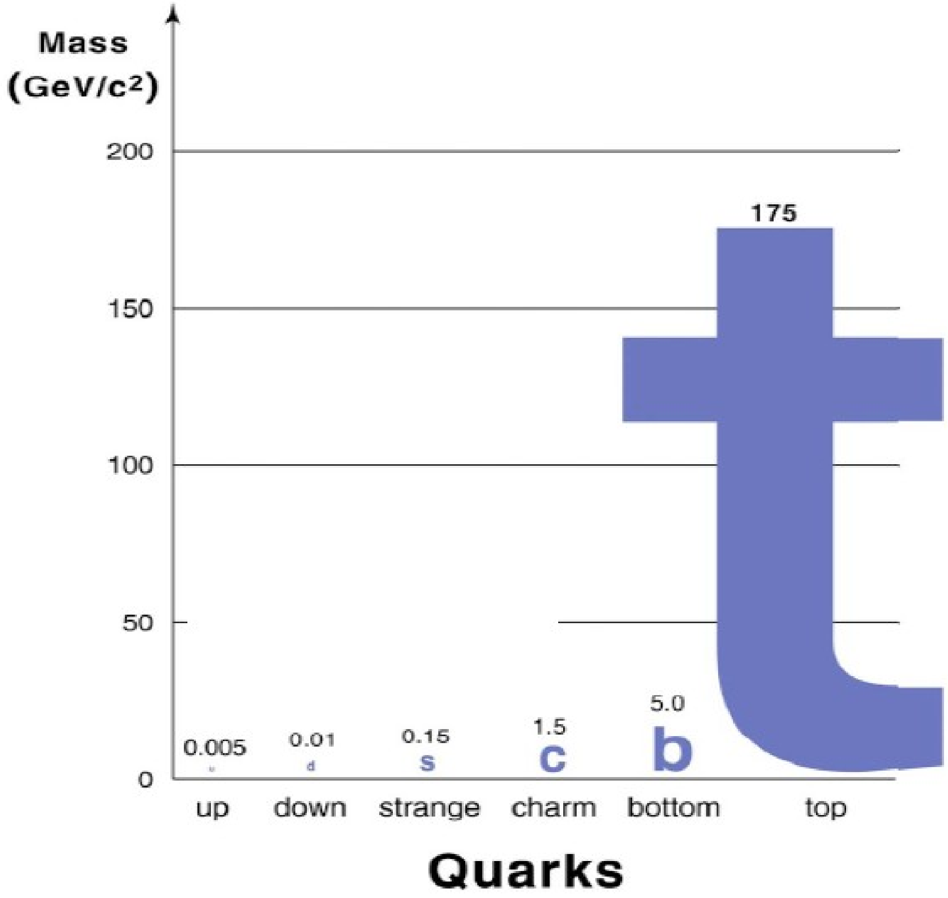




Elements of the Standard Model

A most basic question is why particles (and matter) have masses (and so different masses)

The mass mystery could be solved with the 'Higgs mechanism' which predicts the existence of a new elementary particle, the 'Higgs' particle (theory 1964, P. Higgs, R. Brout and F. Englert)



Peter Higgs

The Higgs (H) particle has been searched for since decades at accelerators

4.07.2012: observation of excess announced at CERN

→ see lecture M. Kado

Francois Englert

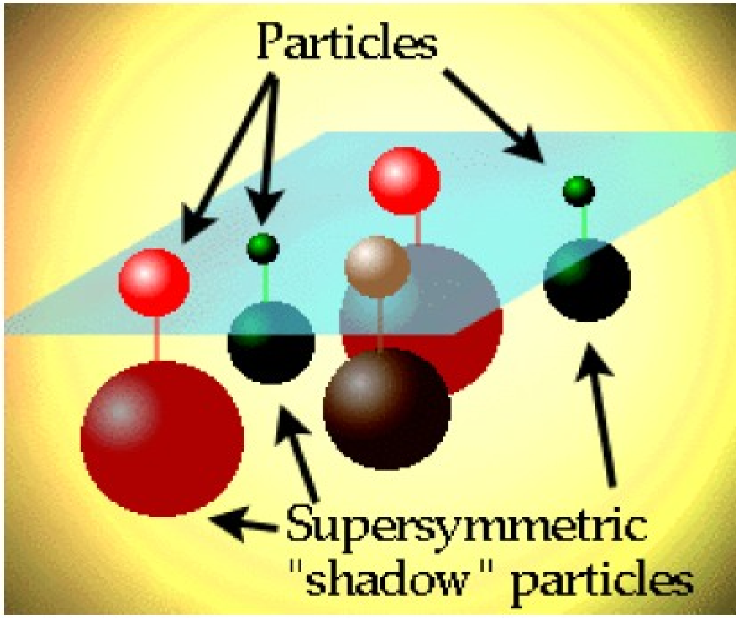
Supersymmetry (SUSY)

Establishes a symmetry between fermions (matter) and bosons (forces):

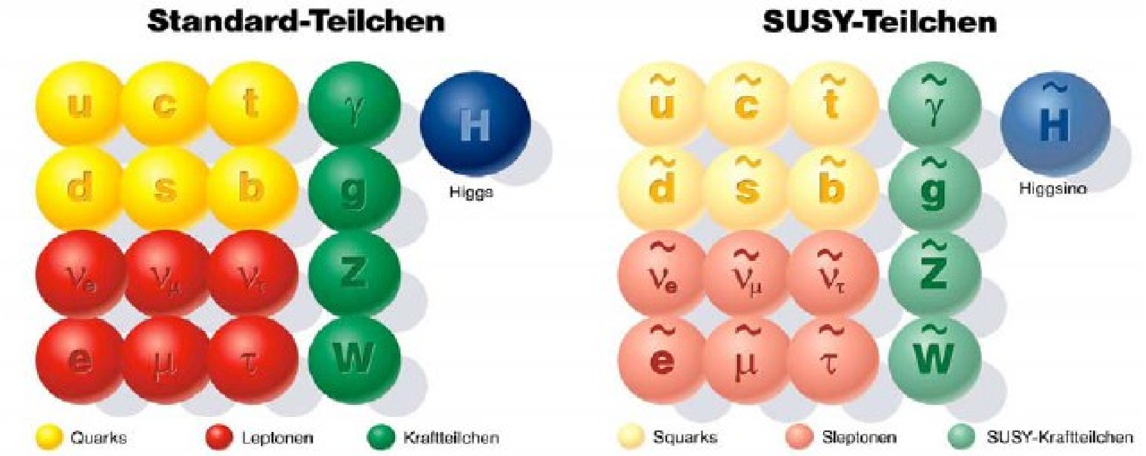
- Each particle p with spin s has a SUSY partner $\tilde{p}$ with spin s -1/2

- Examples q (s=1/2) → $\tilde{q}$ (s=0) squark

  g (s=1) → $\tilde{g}$ (s=1/2) gluino



Our known world **Maybe a new world?**



Motivation:

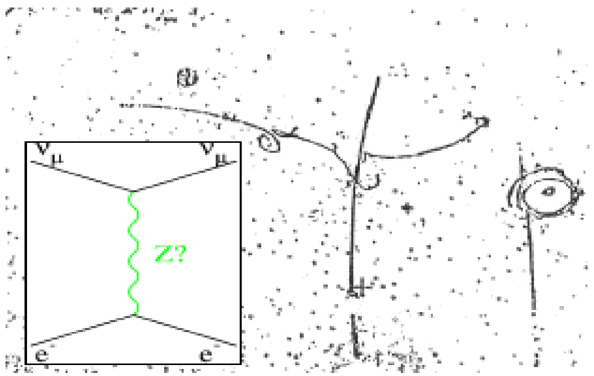
- Unification (fermions-bosons, matter-forces)
- Solves some deep problems of the Standard Model

A brief historical overview: (toward LHC)

1964: First formulation of Higgs mechanism (P.W.Higgs)

1967: Electroweak unification, with W, Z and H (Glashow, Weinberg, Salam)

1973: Discovery of neutral currents in ν_μ e scattering (Gargamelle, CERN)

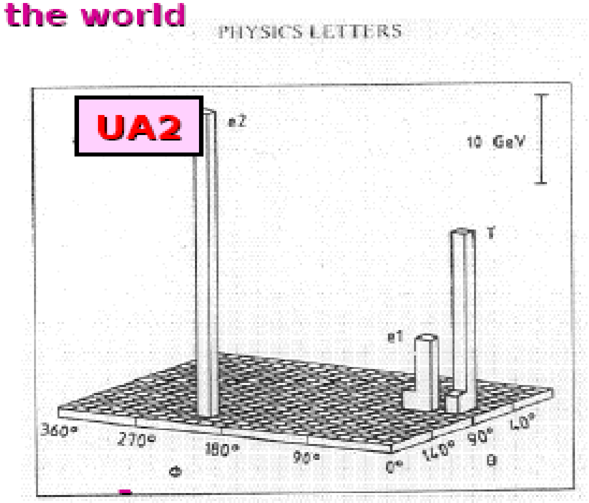


1974: Complete formulation of the standard model with $SU(2)_W \times U(1)_Y$ (Iliopoulos)

1981: The CERN SpS becomes a proton-antiproton collider LEP and SLC are approved before W/Z boson discovery

1983: LEP and SLC construction starts W and Z discovery (UA1, UA2)

One of the first Z-bosons detected in the world



$q\bar{q} \to Z \to e^+ e^- \gamma$

A brief historical overview: (toward LHC)

1984: Glimmerings of LHC and SSC

1987: First comparative studies of physics potential of hadron colliders (LHC/SSC) and e^+e^- linear colliders (CLIC)

1989: First collisions in LEP and SLC
Precision tests of the SM and search for the Higgs boson begin in earnest
R&D for LHC detectors begins

1993: Demise of the SSC

1994: LHC machine is approved (start in 2005)

1995: Discovery of the top quark at Fermilab by CDF (and D0)
Precision tests of the SM and search for the Higgs boson continue at LEP2

Approval of ATLAS and CMS

2000: End of LEP running

2001: LHC schedule delayed by two more years
2008: LHC started but after few days of operating with single beam very serious accident
2009: Restarted back just before Xmass with 900 GeV collision
2010: Since March collecting data at 7 TeV pp collision.
Time shared between machine commissioning and physics runs.

2011: LHC: collected about $5fb^{-1}$/exp.

2012: LHC: sqrt(s) = 8 TeV, collected till today about $7fb^{-1}$/exp.

Hadron colliders (last decade)

Hera, Desy

- 319 GeV proton – electron collider

Tevatron, Fermilab

- 1.96 TeV p-anti p collider

LHC, Cern

- ≤ 14 TeV p-p collisions

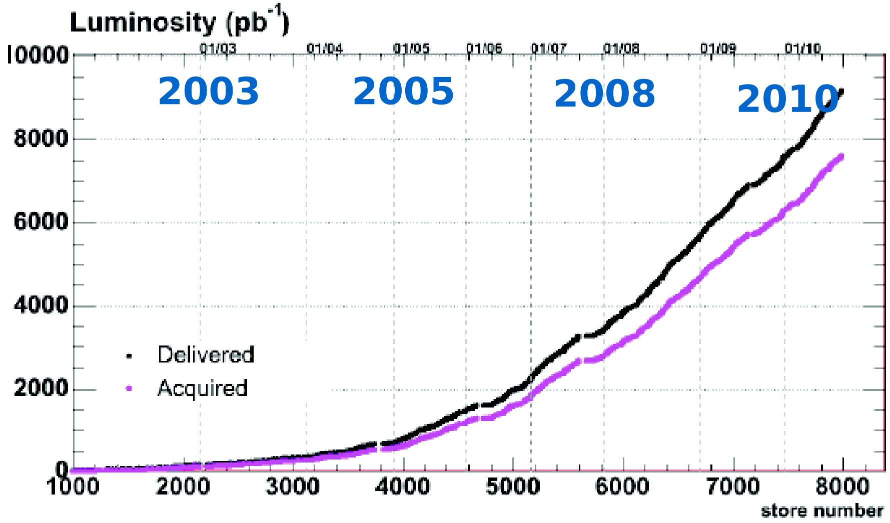
- Run 1992-2007
- Accumulated:
  - ~ 200pb-1 in e^-p
  - ~ 300pb-1 in e^+p

- RunII 2002-2011
- Delivered ~12fb^{-1}/ exp.

- Run phase I at sqrt(s)= 7 TeV started in 2010
- In 2012 with sqrt(s)=8 TeV

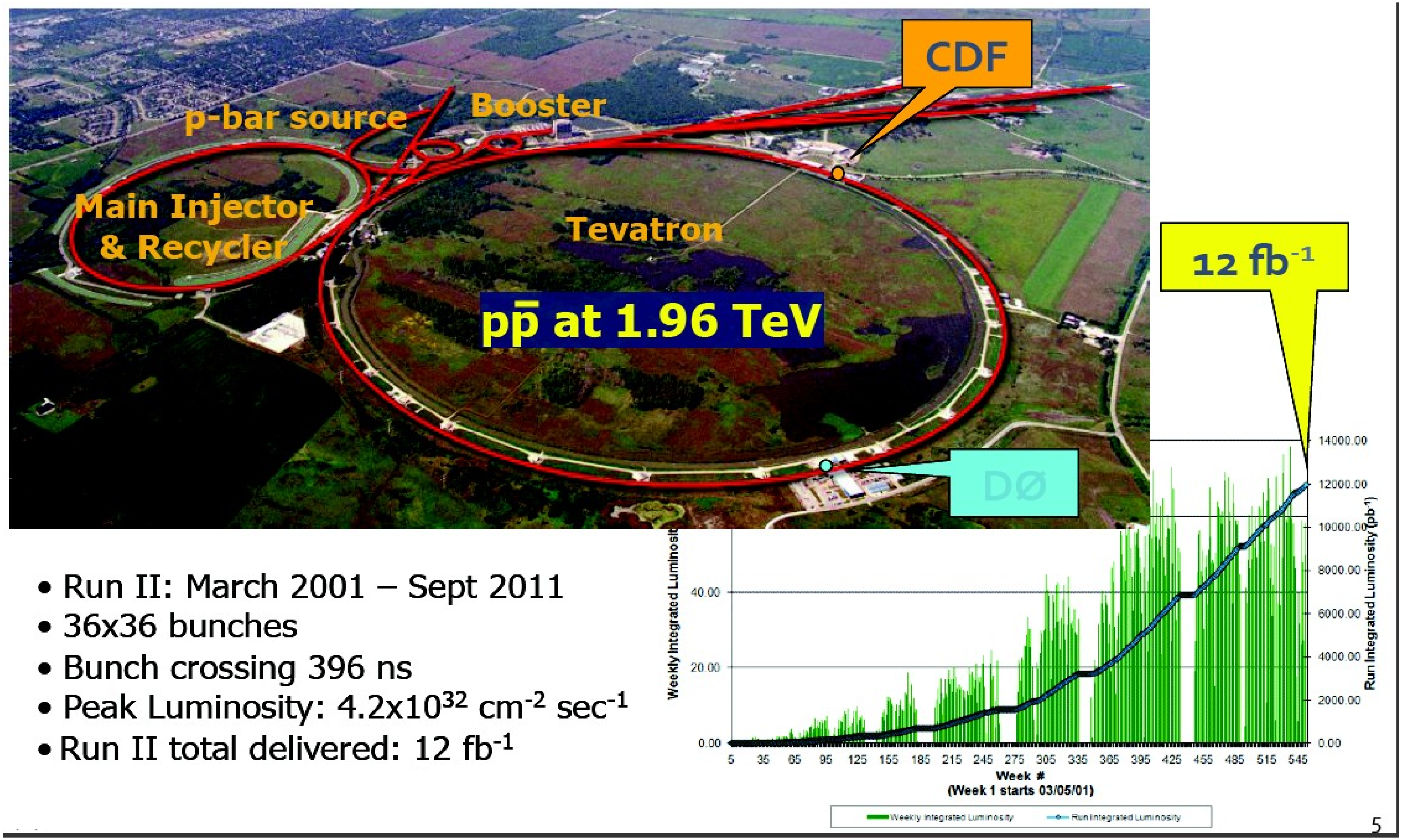
RHIC (BNL) is also joining with polarised pp program

The Tevatron



- 1.96 TeV p-anti p collider
- Run II, 2002 - 2011
- Had delivered ~ 12 fb^{-1} per experiment
- Last 2 years is a special moment with large dataset both from LHC and Tevatron being analysed and published

The Fermilab Tevatron: RUN II



- Run II: March 2001 – Sept 2011
- 36x36 bunches
- Bunch crossing 396 ns
- Peak Luminosity: 4.2×10^{32} cm^{-2} sec^{-1}
- Run II total delivered: 12 fb^{-1}

LHC at CERN laboratory

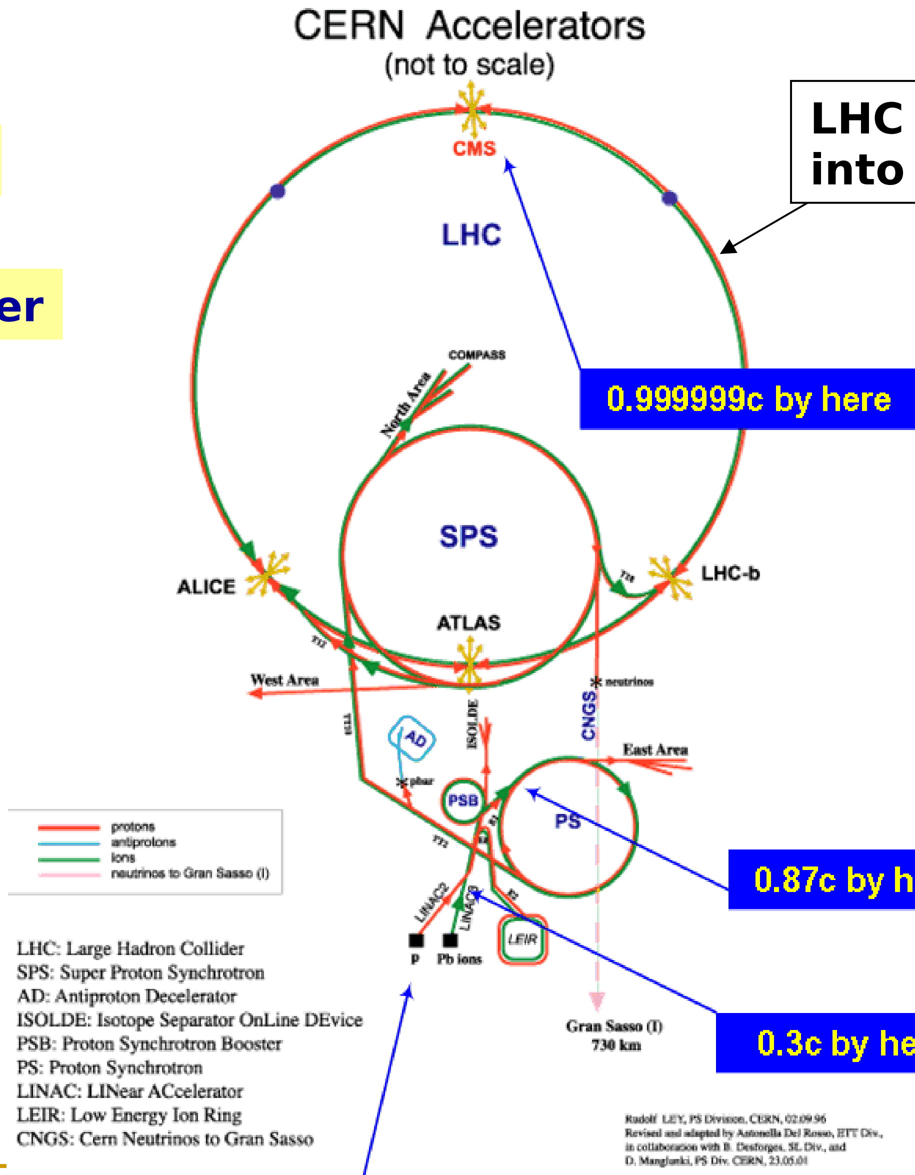
- CERN: the world’s largest particle physics laboratory
  - International organisation created in 1953/1954, initial membership: 12 countries
  - About 10000 active physicists, computing scientists, engineers

Situated between
Jura mountains
and Geneva
(France/Swiss)

http://public.web.cern.ch

The full LHC accelerator complex

Linac
↓
Booster
↓
PS
↓
SPS
↓
LHC



LHC: Large Hadron Collider
SPS: Super Proton Synchrotron
AD: Antiproton Decelerator
ISOLDE: Isotope Separator OnLine DEvice
PSB: Proton Synchrotron Booster
PS: Proton Synchrotron
LINAC: LINear ACcelerator
LEIR: Low Energy Ion Ring
CNGS: Cern Neutrinos to Gran Sasso

Rudolf LEY, PS Division, CERN, 02.09.96
Revised and adapted by Antonella Del Rosso, ETT Div.,
in collaboration with B. Desforges, SL Div., and
D. Manglunki, PS Div. CERN, 23.05.01

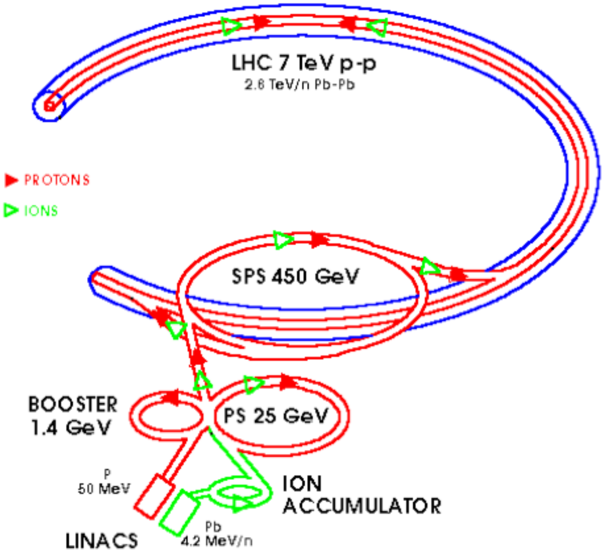
LHC ring is divided into 8 sectors

0.999999c by here

0.87c by here

0.3c by here

Start the protons out here



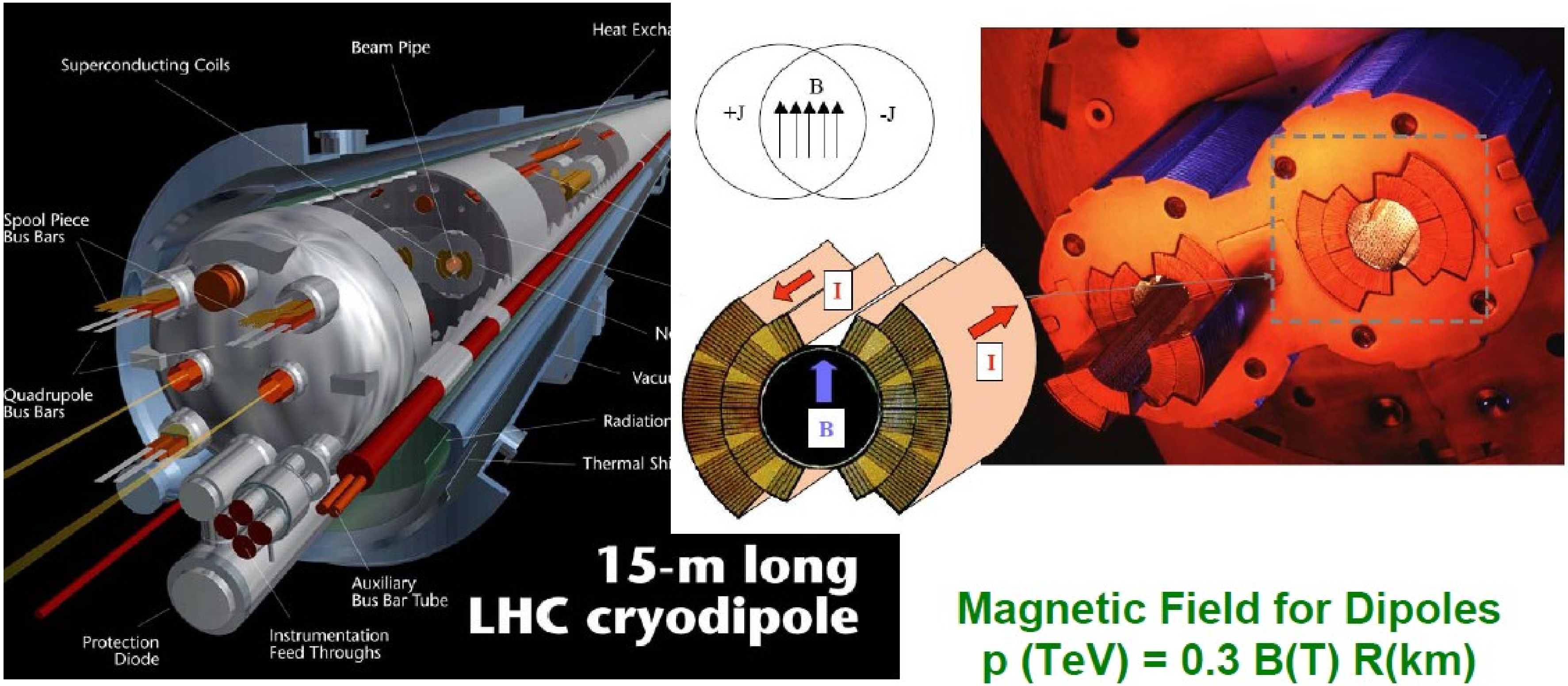
> 50 years of CERN history still alive and operational

The Large Hadron Collider is a 27 km long collider ring housed in a tunnel about 100 m underground near Geneva

Descent of the last dipole magnet, 26 April 2007

30’000 km underground transports at a speed of 2 km/h!

LHC Accelerator Challenge: Dipole Magnets



Magnetic Field for Dipoles
p (TeV) = 0.3 B(T) R(km)

For p = 7 TeV and R = 4.3 km
⇨ B = 8.4 T
⇨ Current 12 kA

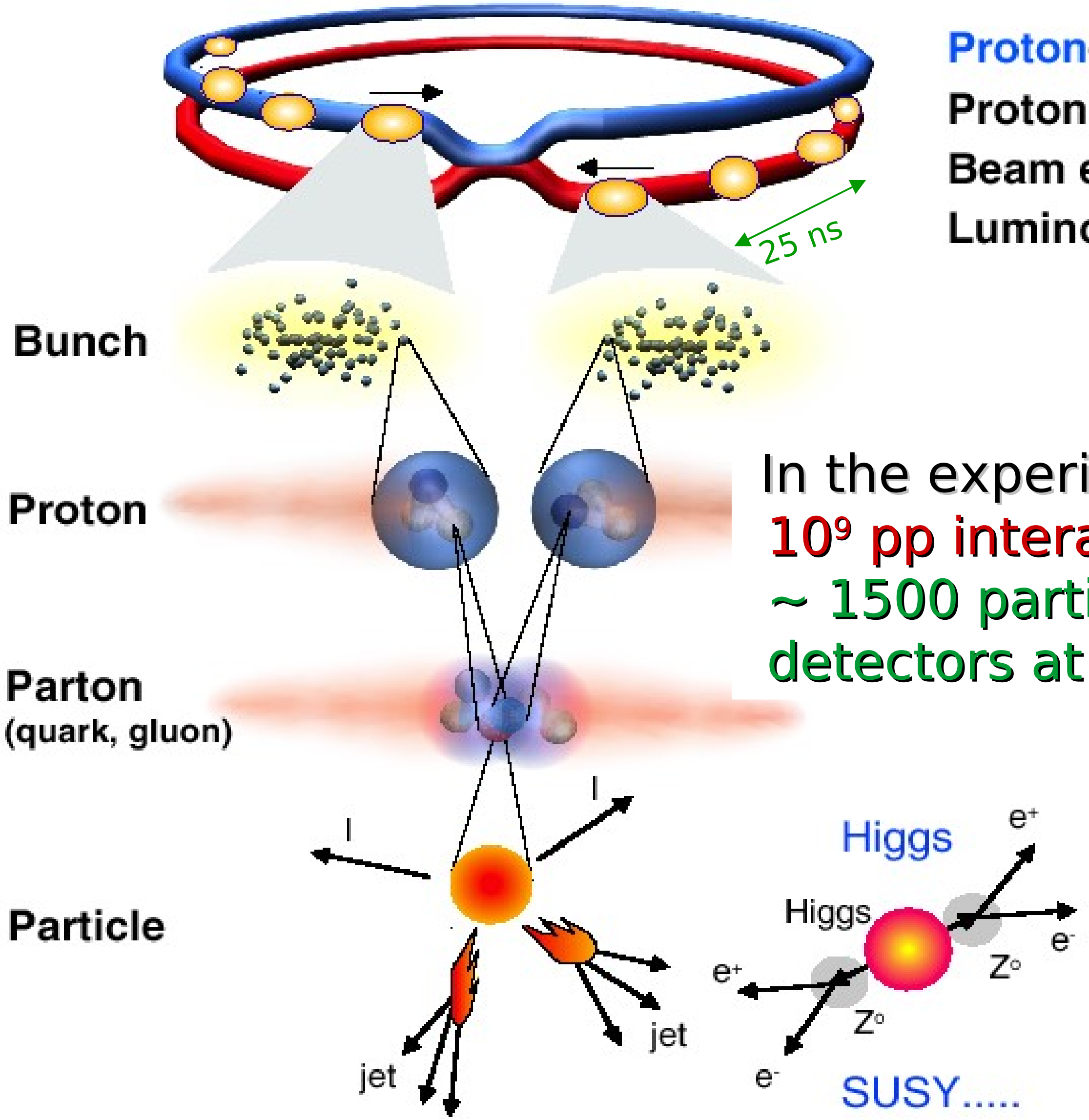
Coldest Ring in the Universe ?
1.9 K (CMBR is about 2.7 K)

LHC magnets are cooled with pressurized superfluid helium

Collisions at LHC

NOMINAL PARMETERS

Proton-Proton	**2835 bunch/beam**
Protons/bunch	**10^{11}**
Beam energy	**7 TeV ($7\text{x}10^{12}$ eV)**
Luminosity	**10^{34} cm^{-2} s^{-1}**



In the experiments:

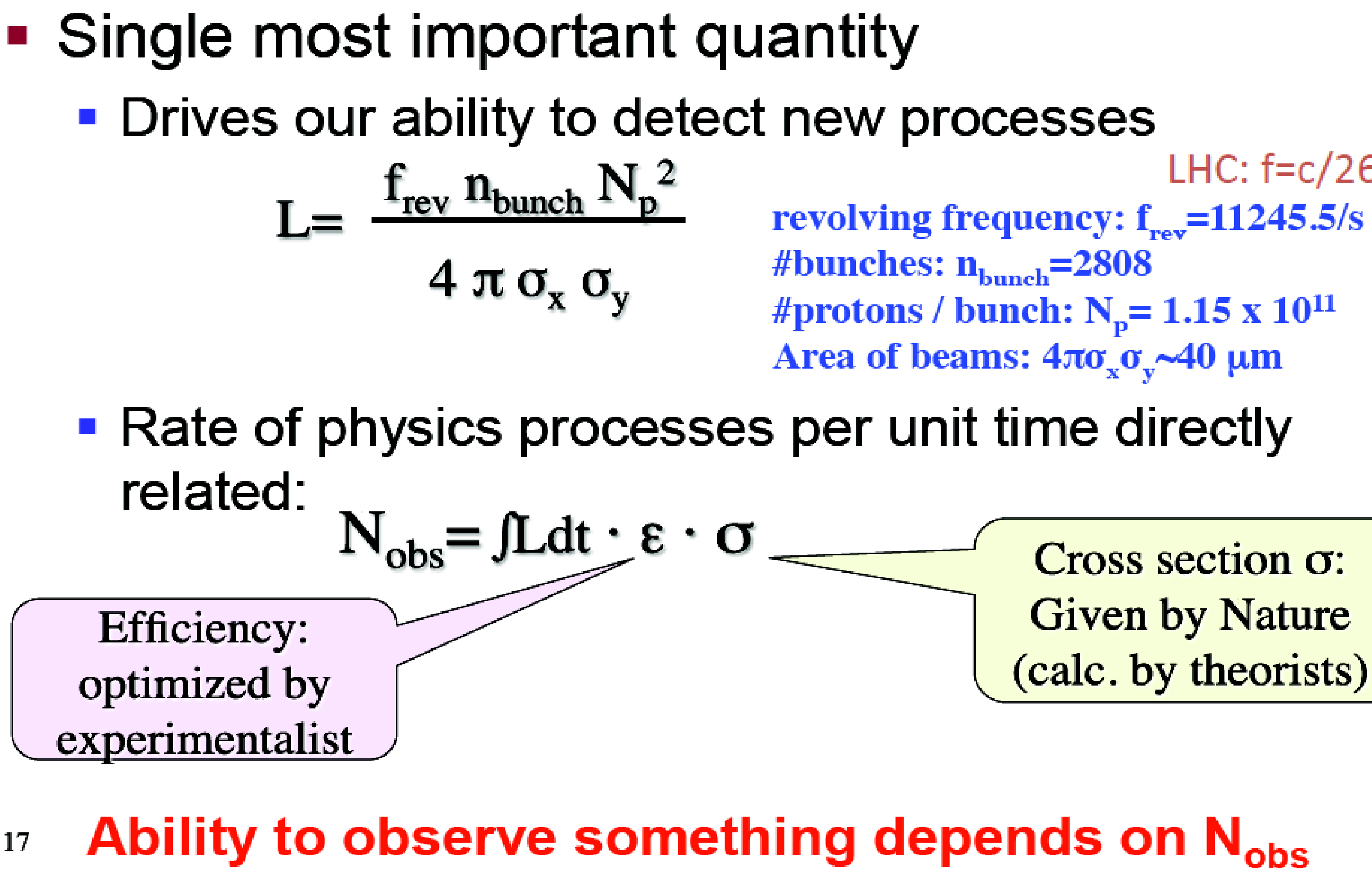
10^9 pp interactions per second

~ 1500 particles (p,n, π) produced in the detectors at each bunch-crossing

Selection of 1 in

10,000,000,000,000

Luminosity



- Single most important quantity
  - Drives our ability to detect new processes

$$L = \frac{f_{rev}\ n_{bunch}\ N_p^2}{4\ \pi\ \sigma_x\ \sigma_y}$$

LHC: f=c/26.7 km

revolving frequency: f_{rev}=11245.5/s
#bunches: n_{bunch}=2808
#protons / bunch: N_p= 1.15 x 10^{11}
Area of beams: $4\pi\sigma_x\sigma_y$~40 μm

  - Rate of physics processes per unit time directly related:

$$N_{obs} = \int L dt \cdot \varepsilon \cdot \sigma$$

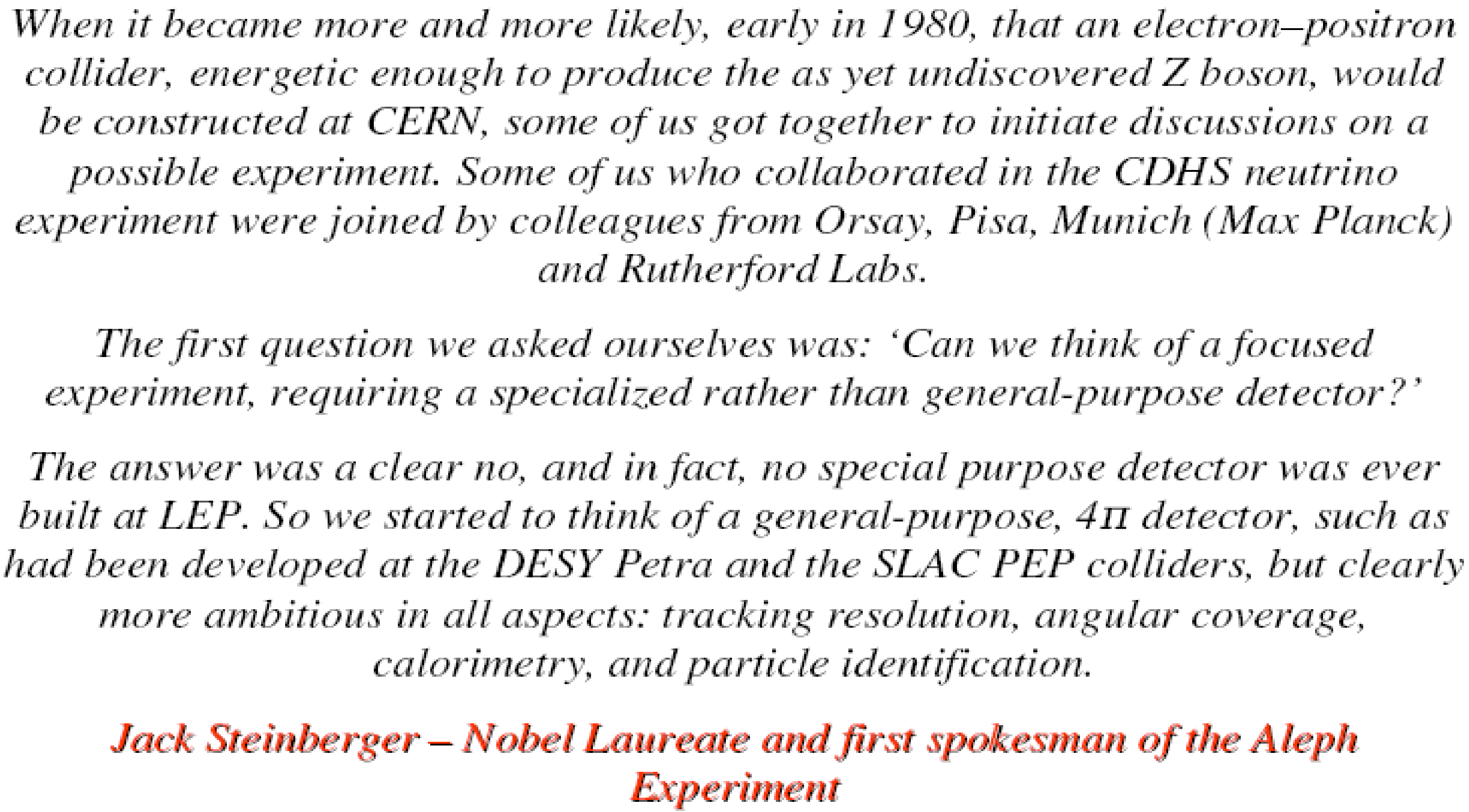
Efficiency:
optimized by
experimentalist

Cross section σ:
Given by Nature
(calc. by theorists)

17

Ability to observe something depends on N_{obs}

General Purpose Detectors



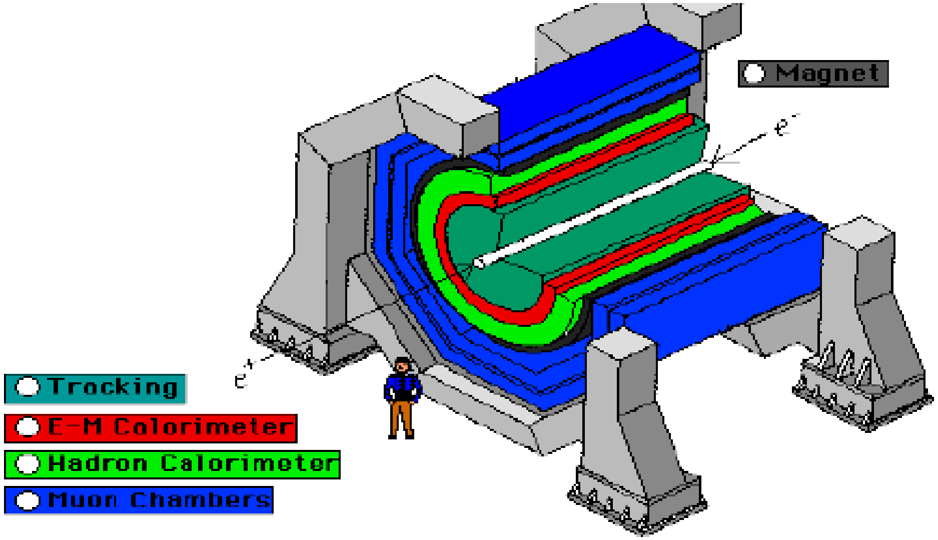
When it became more and more likely, early in 1980, that an electron–positron collider, energetic enough to produce the as yet undiscovered Z boson, would be constructed at CERN, some of us got together to initiate discussions on a possible experiment. Some of us who collaborated in the CDHS neutrino experiment were joined by colleagues from Orsay, Pisa, Munich (Max Planck) and Rutherford Labs.

The first question we asked ourselves was: 'Can we think of a focused experiment, requiring a specialized rather than general-purpose detector?'

The answer was a clear no, and in fact, no special purpose detector was ever built at LEP. So we started to think of a general-purpose, 4π detector, such as had been developed at the DESY Petra and the SLAC PEP colliders, but clearly more ambitious in all aspects: tracking resolution, angular coverage, calorimetry, and particle identification.

Jack Steinberger – Nobel Laureate and first spokesman of the Aleph Experiment

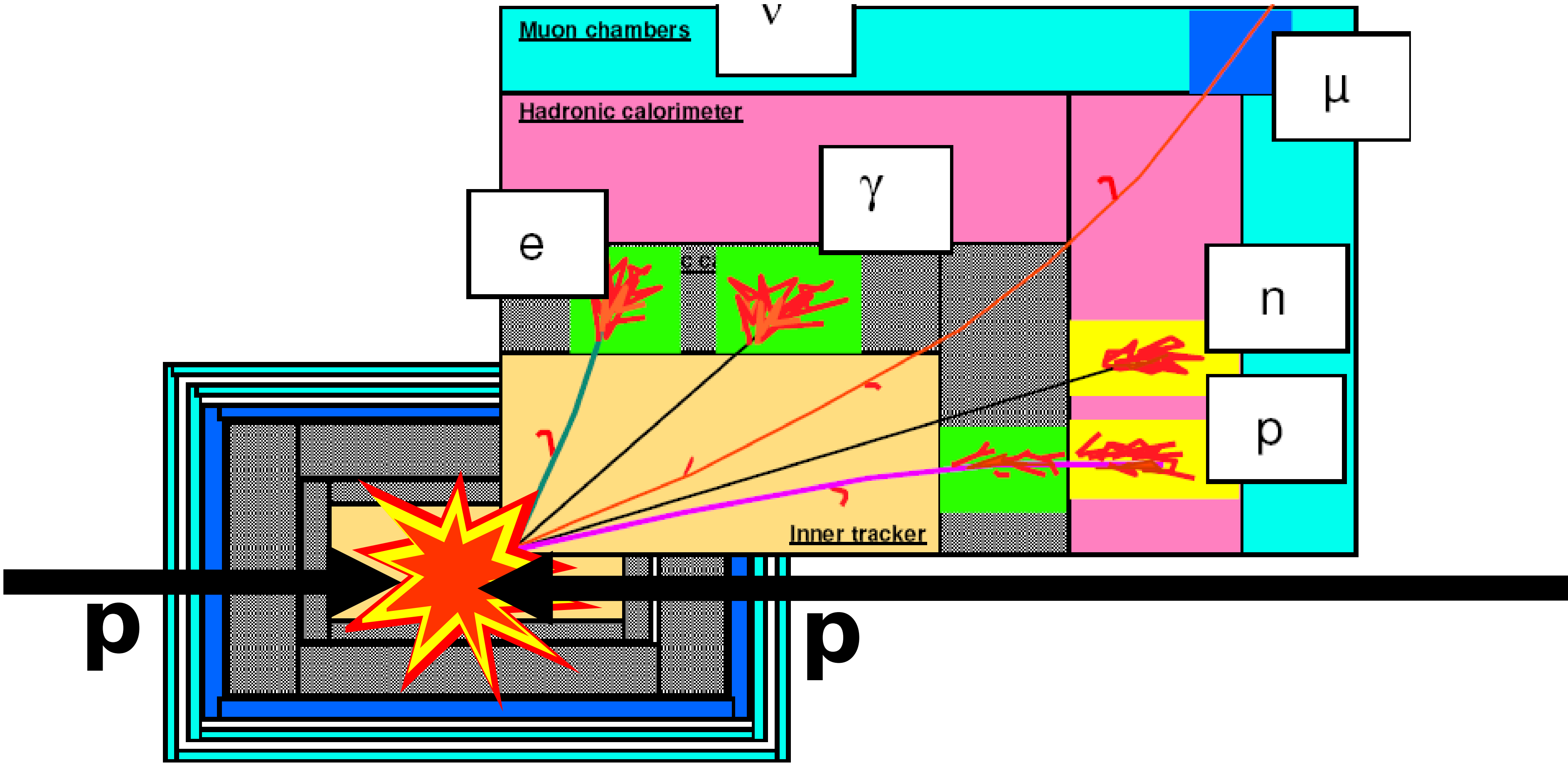
General Principle



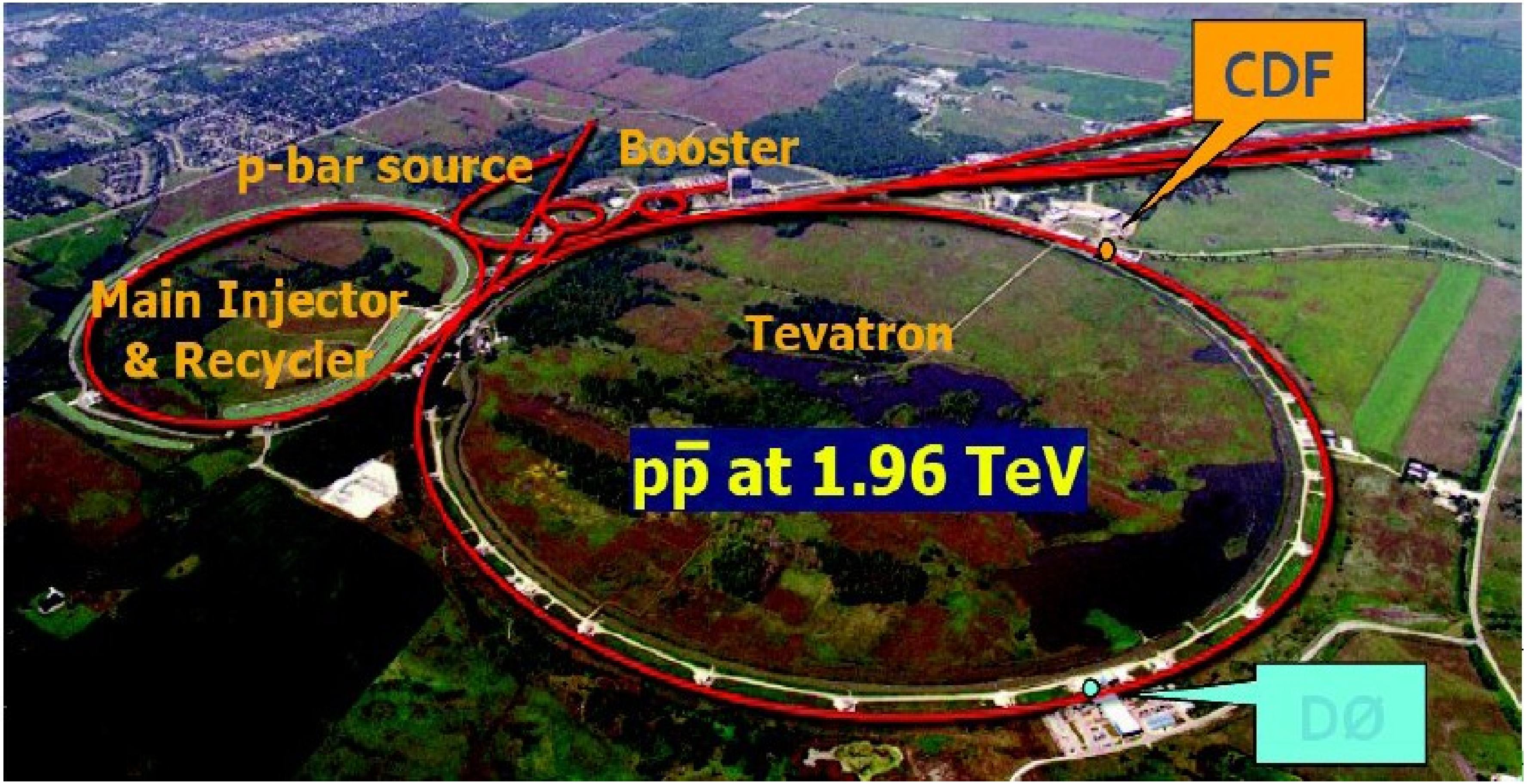
Collider detectors look all similar since they must perform in sequence the same basic measurements.

The dimension of the detector are driven by the required resolution . The calorimeter thickness change only with the logarithm of the energy: for this reason the dimension of the detectors change only slightly with the energy.

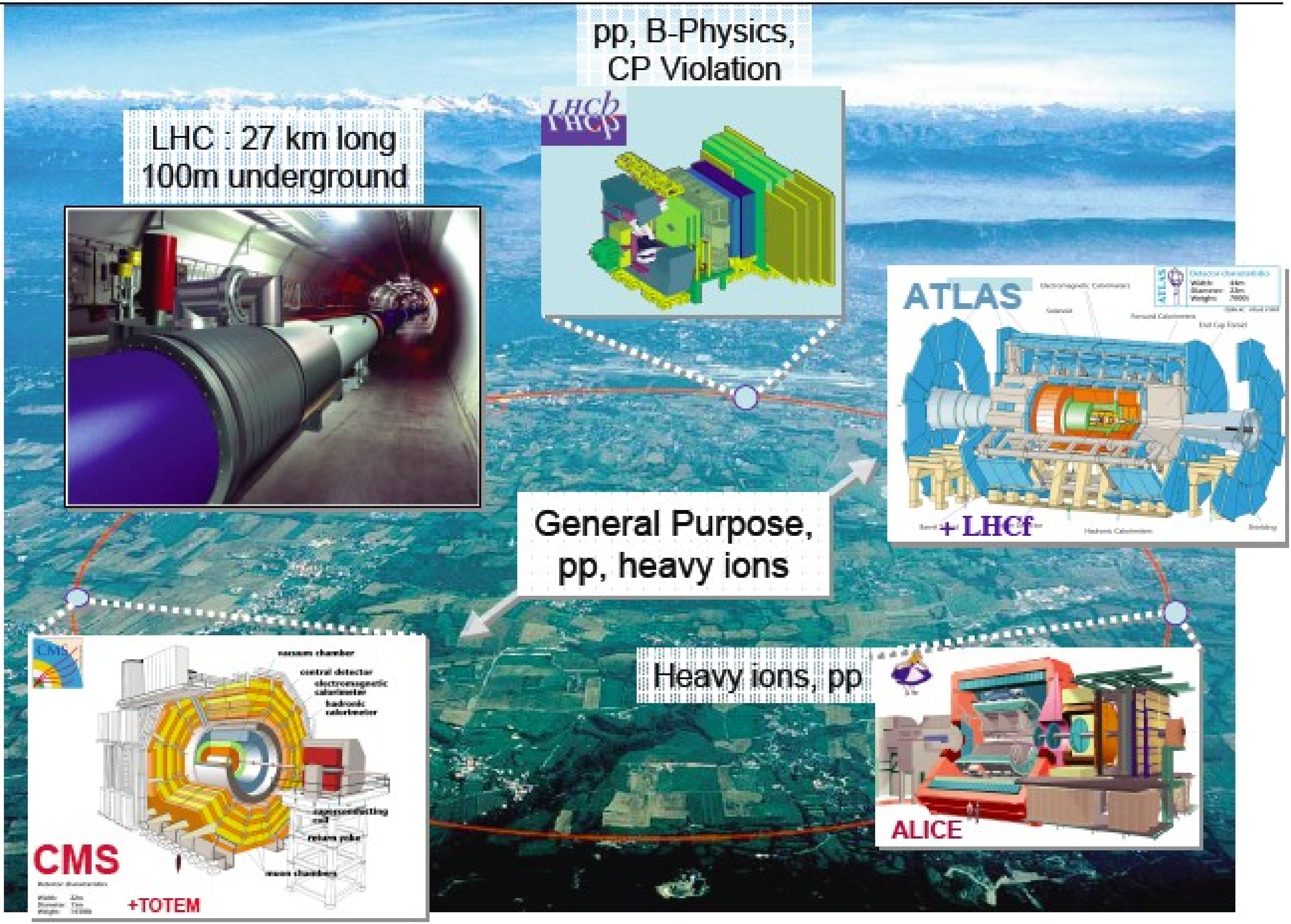
Particle identification



The Tevatron at FERMILAB



Large Hadron Collider@CERN

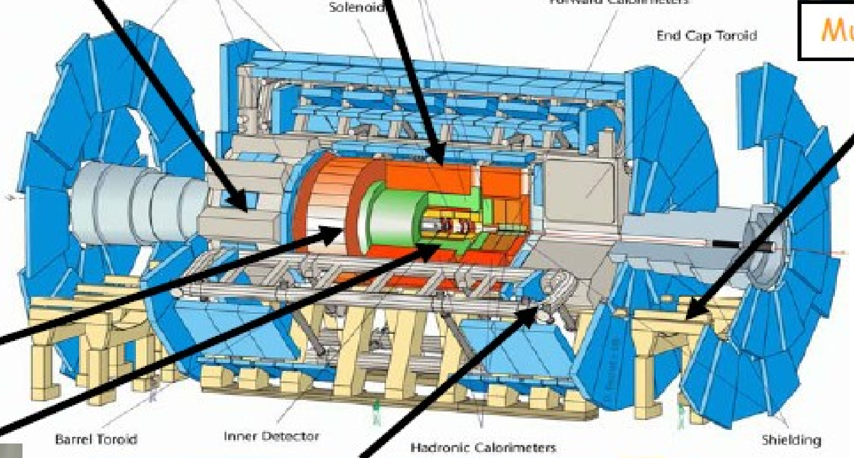

LHC : 27 km long
100m underground

pp, B-Physics,
CP Violation

General Purpose,
pp, heavy ions

Heavy ions, pp

A
T
L
A
S



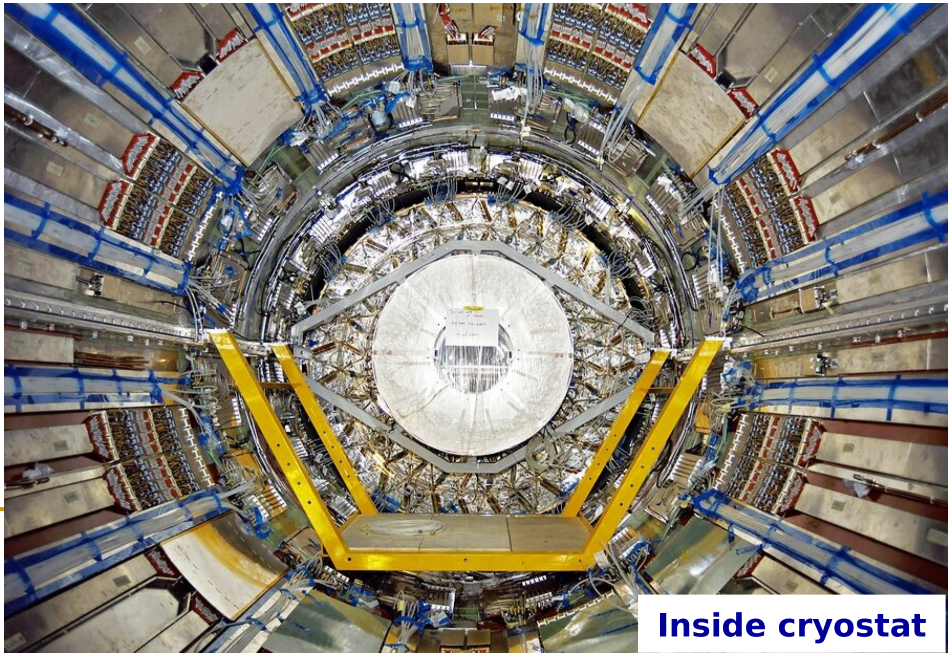
Construction phase
Year 2003

TRT+SCT barrel travelled to the pit, 24th Aug 2006

Through the parking area

A tight fit between BT and EC Calorimeter

From the trolley to the support rails

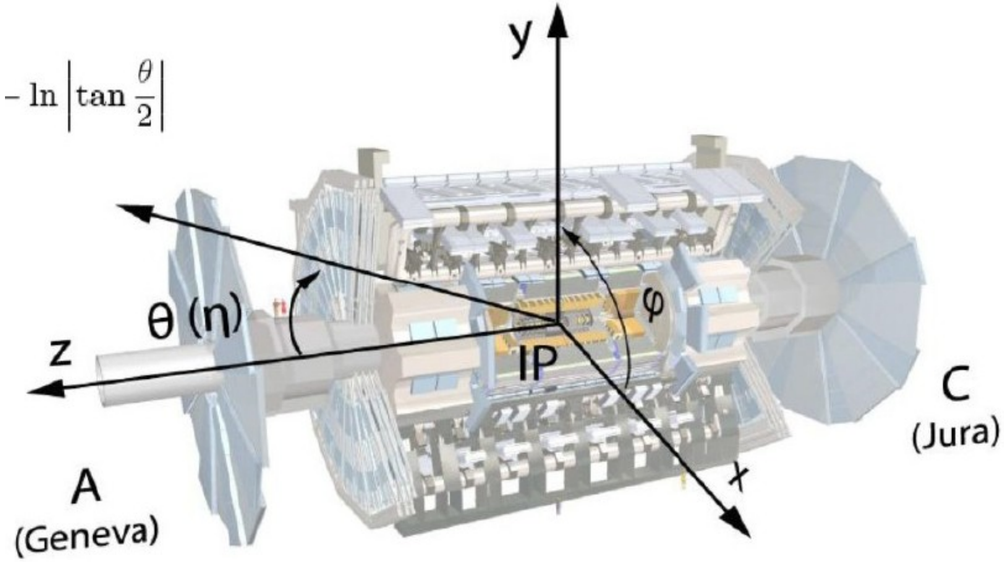


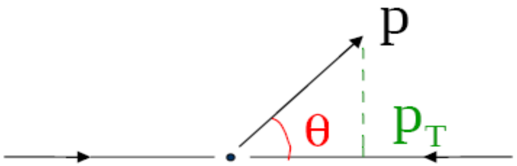
Inside cryostat

ATLAS Detector

THE ATLAS DETECTOR IS REALLY BIG!

- Length : ~ 46 m
- Radius : ~ 12 m
- Weight : ~ 7000 tons
- $\sim 10^8$ electronic channels
- 3000 km of cables





Transverse momentum

(in the plane perpendicular to the beam)

$$p_T = p \sin\theta$$

Rapidity: $\eta = -\log(\mathrm{tg}\,\frac{\theta}{2})$

$\theta = 90^\circ \rightarrow \eta = 0$
$\theta = 10^\circ \rightarrow \eta \cong 2.4$
$\theta = 170^\circ \rightarrow \eta \cong -2.4$

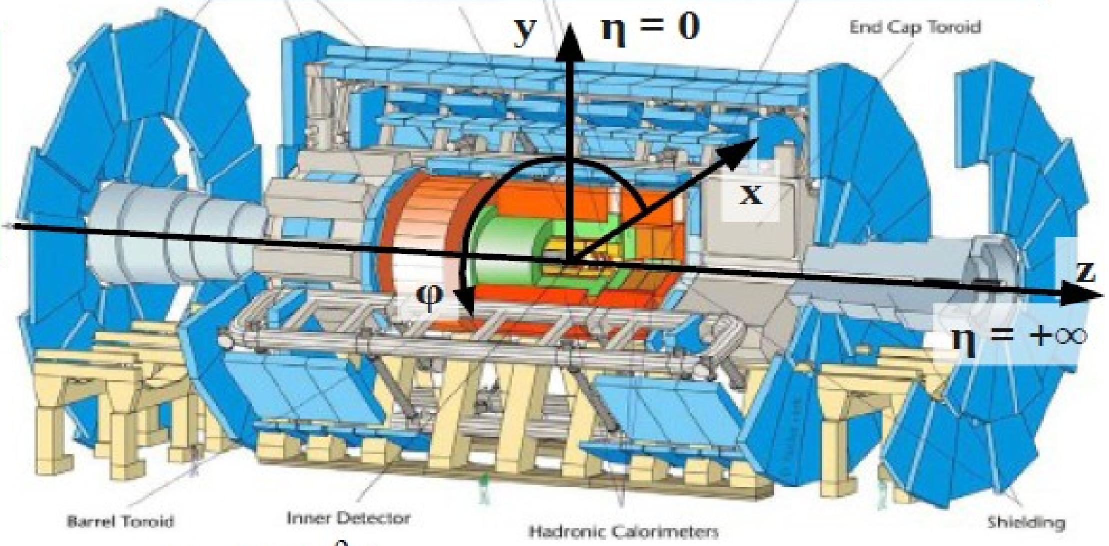
The ATLAS Detector

Inner detector (2 T)
$|\eta| < 2.5$
Si Pixel et SCT, TRT
tracks, vertex
$\sigma/p_T \sim 0.05\%\ p_T\ (\text{GeV}) \oplus 1\%$

Electromagnetic calorimeter
$|\eta| < 3.2$
Pb + LAr
electrons, photons, trigger
$\sigma/E \sim 10\%/\sqrt{E}\ (\text{GeV}) \oplus 0.7\%$

Hadronic calorimeter
$|\eta| < 4.9$
Fe/Tile (central)
Cu/W + LAr (forward)
jets, E_T^{miss}, trigger
$\sigma/E \sim 50\%/\sqrt{E}\ (\text{GeV}) \oplus 3\%$

Muon spectrometer (0.5 T)
$|\eta| < 2.7$
gas chamber in toroidal magnetic field
tracks, trigger
$\sigma/p_T < 10\%$ up to 1 TeV



$$\eta = -\ln\left(\tan\left(\frac{\theta}{2}\right)\right)$$

- ◆ > 96% operating channels
- ◆ > 90% of data used for physics

➔ Very good behaviour of all sub-detector

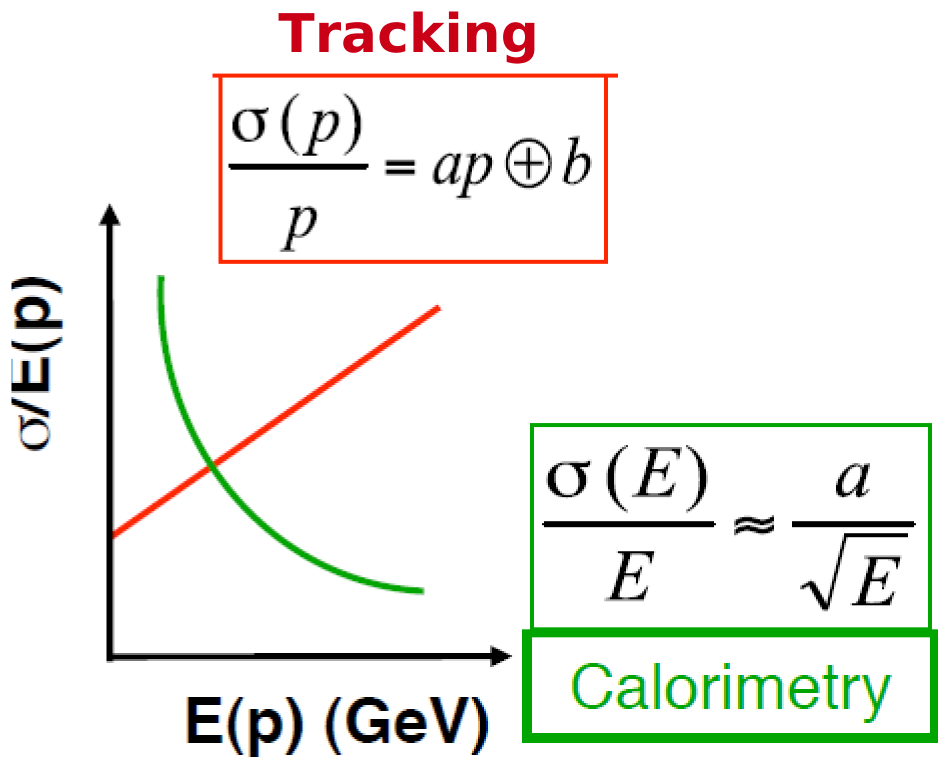
38 countries
~ 3000 members

Energy and momentum resolution

Calorimetry:

$$\frac{\sigma}{E} = \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus c$$

- a the stochastic term accounts for Poisson-like fluctuations
  - naturally small for homogeneous calorimeters
  - takes into account sampling fluctuations for sampling calorimeters
- b the noise term (hits at low energy)
  - mainly the energy equivalent of the electronics noise
  - at LHC in particular: includes fluctuation from non primary interaction (pile-up noise)
- c the constant term (hits at high energy)
  - Essentially detector non homogeneities like intrinsic geometry, calibration but also energy leakage



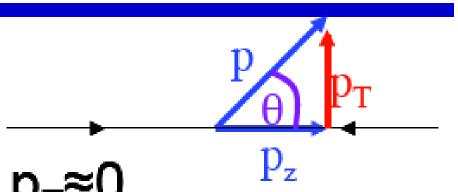
Tracking

$$\frac{\sigma(p)}{p} = ap \oplus b$$

$$\frac{\sigma(E)}{E} \approx \frac{a}{\sqrt{E}}$$

Calorimetry

Kinematical constraints



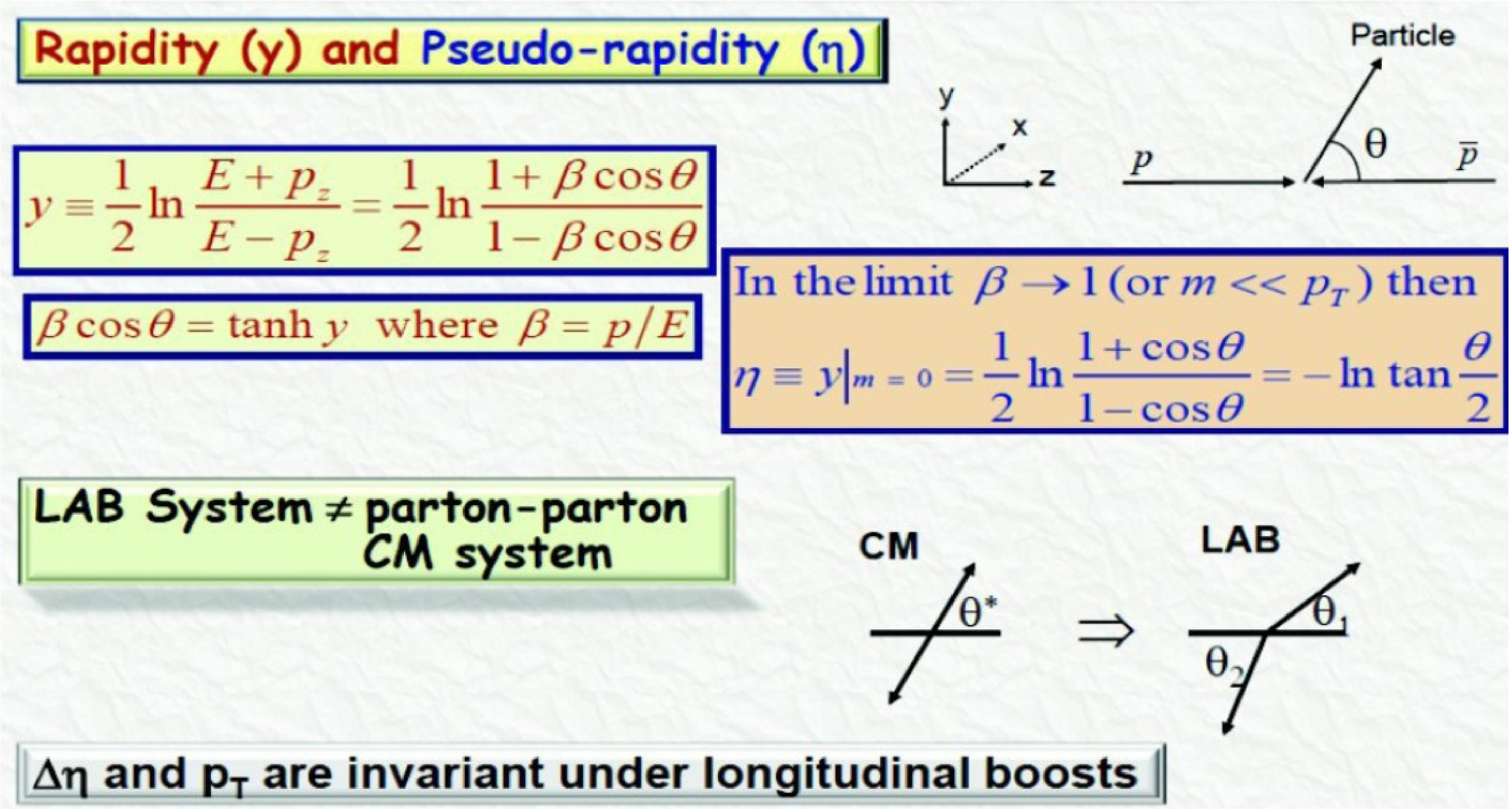
- **Transverse momentum, p_T**
  - Particles that escape detection (θ<3°) have $p_T \approx 0$
  - Visible transverse momentum conserved $\sum_i p_T^i \approx 0$
    - **Very useful variable!**
- **Longitudinal momentum and energy, p_z and E**
  - Particles that escape detection have large p_z
  - Visible p_z is not conserved
    - **Not a useful variable**
- **Polar angle θ**
  - Polar angle θ is not Lorentz invariant
  - Rapidity: y
  - Pseudorapidity: η

$$y = \frac{1}{2}\ln\frac{E+p_z}{E-p_z}$$

For M=0

$$y = \eta = -\ln(\tan\frac{\theta}{2})$$

Some kinematical variables



Rapidity (y) and Pseudo-rapidity (η)

$$y \equiv \frac{1}{2}\ln\frac{E+p_z}{E-p_z} = \frac{1}{2}\ln\frac{1+\beta\cos\theta}{1-\beta\cos\theta}$$

$$\beta\cos\theta = \tanh y \quad \text{where } \beta = p/E$$

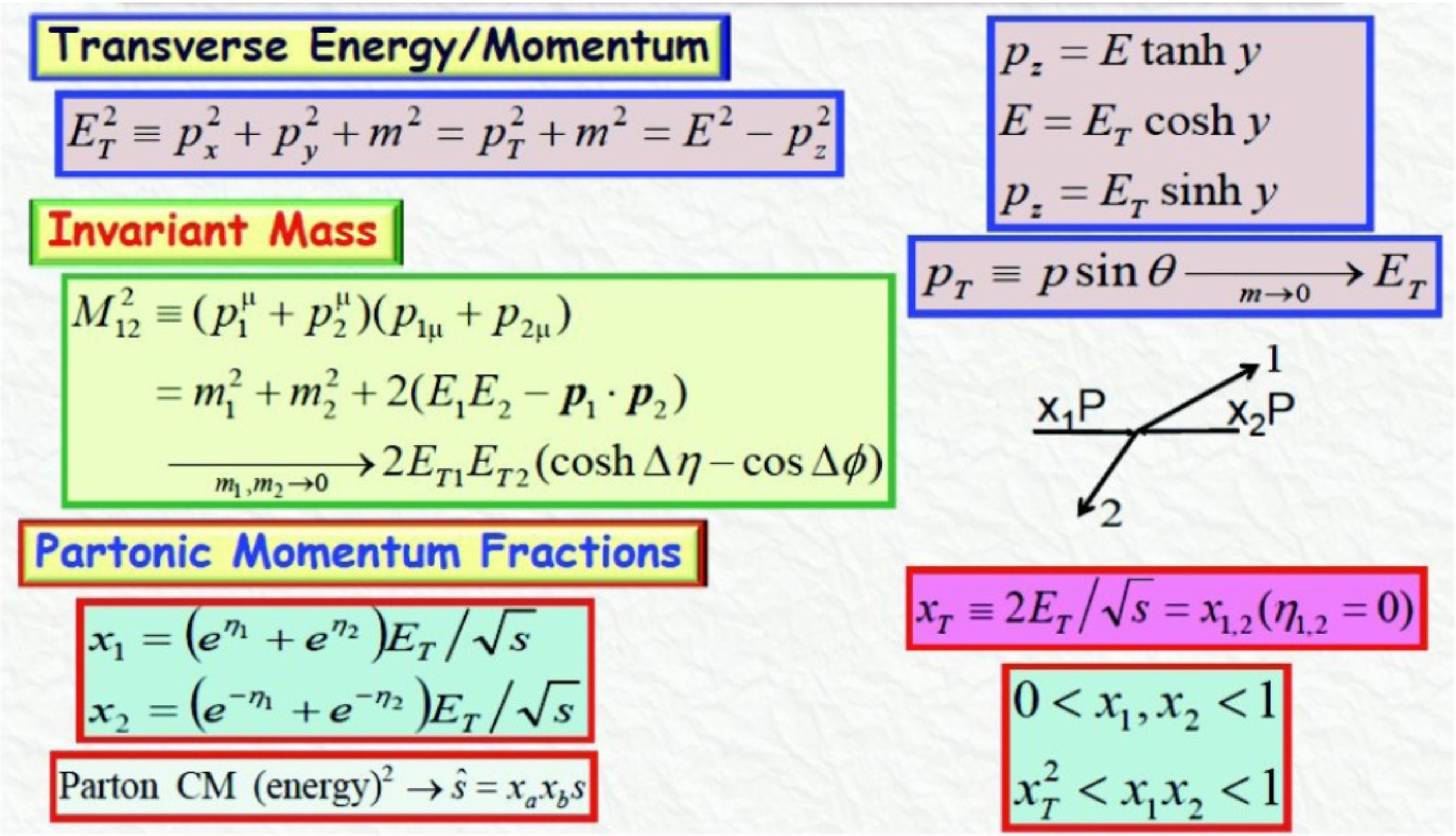
In the limit $\beta \to 1$ (or $m \ll p_T$) then

$$\eta \equiv y|_{m=0} = \frac{1}{2}\ln\frac{1+\cos\theta}{1-\cos\theta} = -\ln\tan\frac{\theta}{2}$$

LAB System ≠ parton-parton CM system

Δη and p_T are invariant under longitudinal boosts

Some kinematical variables



Transverse Energy/Momentum

$$E_T^2 \equiv p_x^2 + p_y^2 + m^2 = p_T^2 + m^2 = E^2 - p_z^2$$

Invariant Mass

$$M_{12}^2 \equiv (p_1^\mu + p_2^\mu)(p_{1\mu} + p_{2\mu})$$

$$= m_1^2 + m_2^2 + 2(E_1 E_2 - \mathbf{p}_1 \cdot \mathbf{p}_2)$$

$$\xrightarrow[m_1, m_2 \to 0]{} 2E_{T1}E_{T2}(\cosh\Delta\eta - \cos\Delta\phi)$$

Partonic Momentum Fractions

$$x_1 = (e^{\eta_1} + e^{\eta_2})E_T/\sqrt{s}$$

$$x_2 = (e^{-\eta_1} + e^{-\eta_2})E_T/\sqrt{s}$$

Parton CM (energy)$^2 \to \hat{s} = x_a x_b s$

$$p_z = E\tanh y$$

$$E = E_T\cosh y$$

$$p_z = E_T\sinh y$$

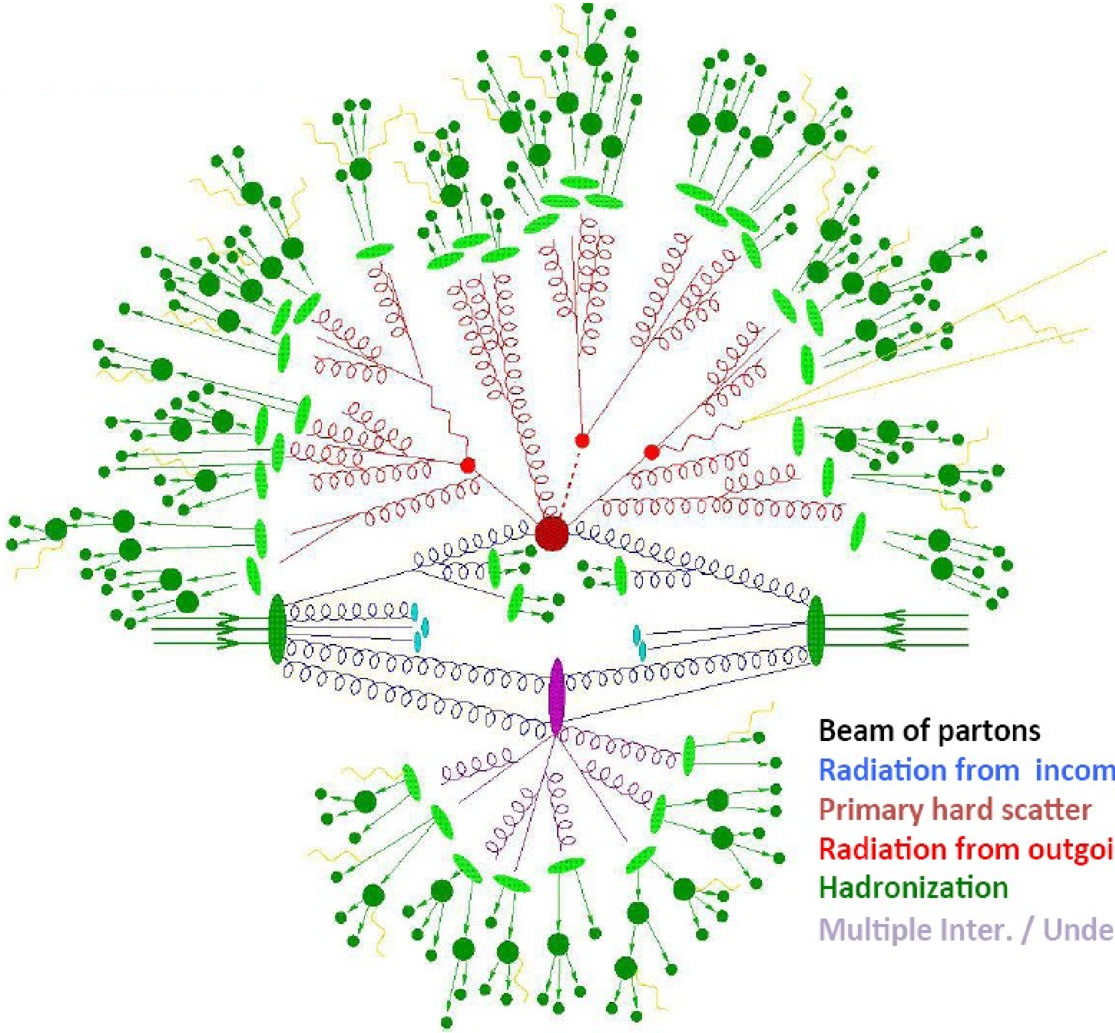
$$p_T \equiv p\sin\theta \xrightarrow[m \to 0]{} E_T$$

$$x_T \equiv 2E_T/\sqrt{s} = x_{1,2}(\eta_{1,2} = 0)$$

$$0 < x_1, x_2 < 1$$

$$x_T^2 < x_1 x_2 < 1$$

Typical pp collision



Beam of partons

Radiation from incoming partons

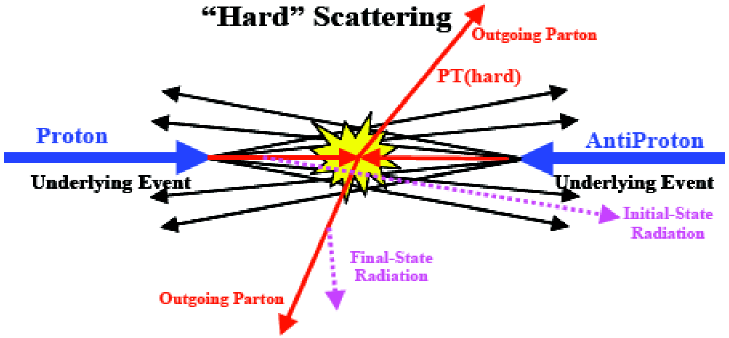
Primary hard scatter

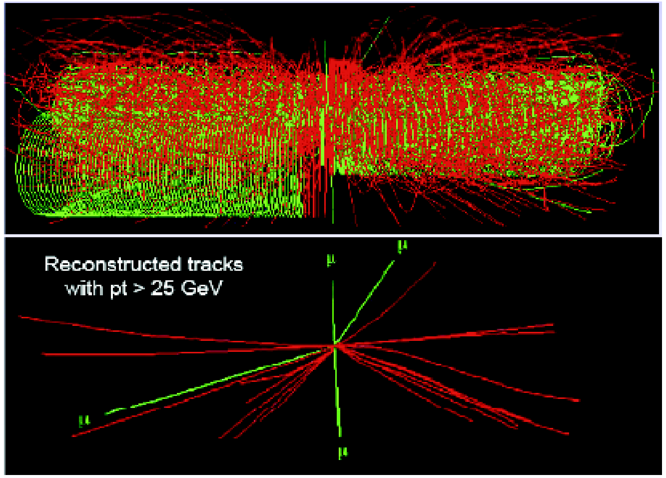
Radiation from outgoing partons

Hadronization

Multiple Inter. / Underlying event

Every event is complicated



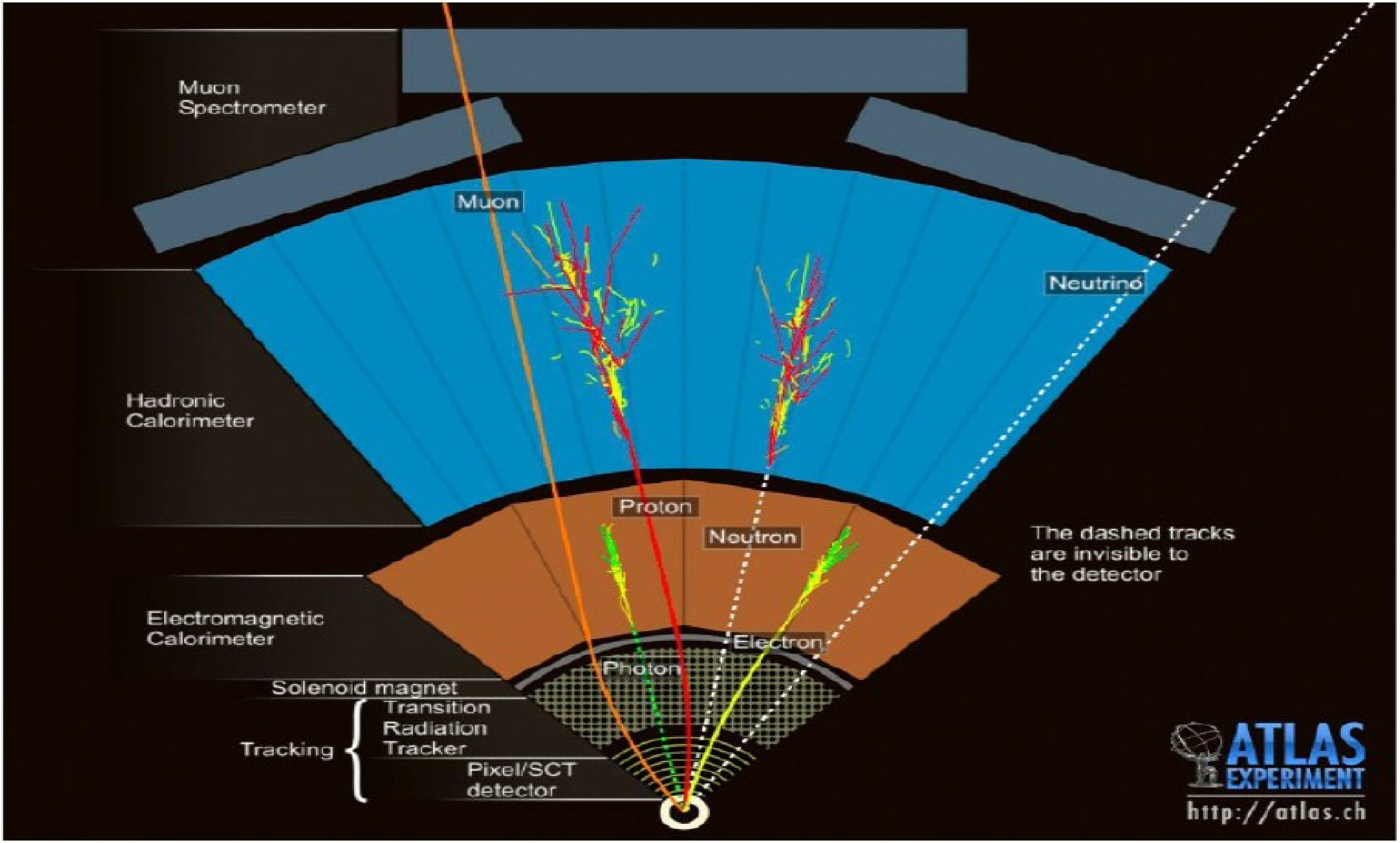

$H \rightarrow ZZ \rightarrow \mu^+\mu^-\mu^+\mu^-)$

- "Underlying event":
  - Initial state radiation
  - Interactions of other partons in proton
- Additional pp interactions
  - LHC: ~1.5 (~23 at design values) →
  - Tevatron: ~10

Even >30 with present operation conditions

- Many forward particles escape detection
  - Transverse momentum ~0
  - Longitudinal momentum >>0

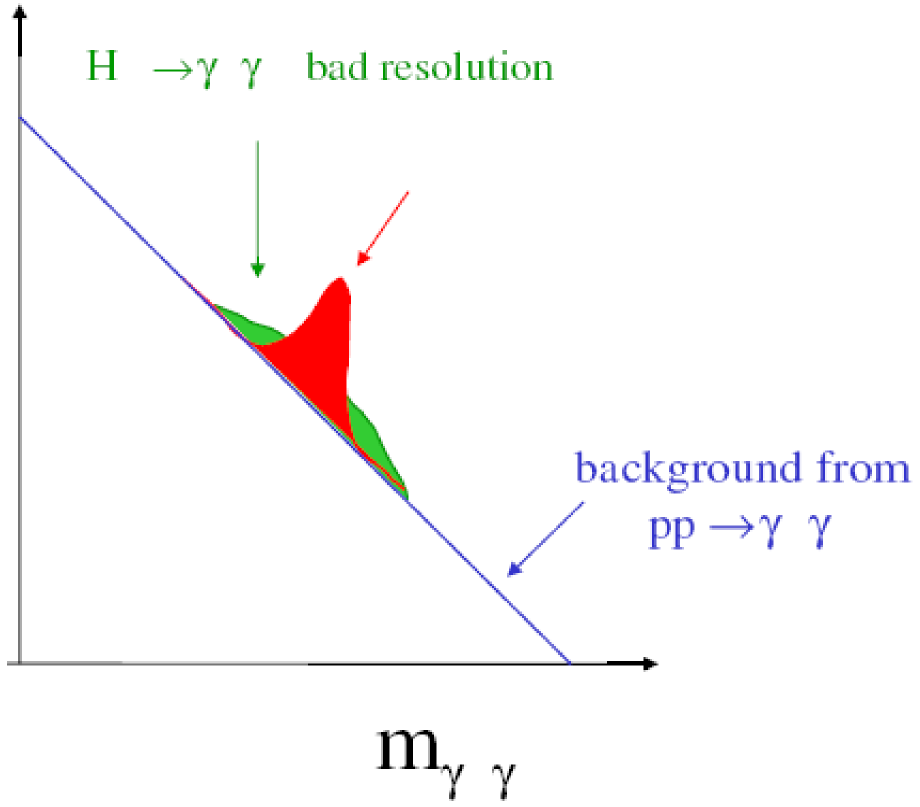
Particle identication



Example of performance requirements

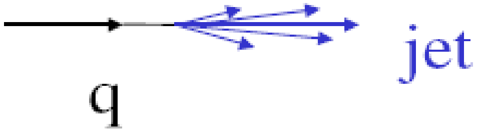
Excellent energy resolution of EM calorimeters for e/γ and of the tracking devices for μ in order to extract a signal over the backgrounds.

Example : $H \rightarrow \gamma\gamma$

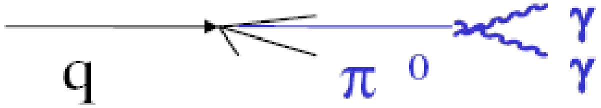


Example of performance requirements

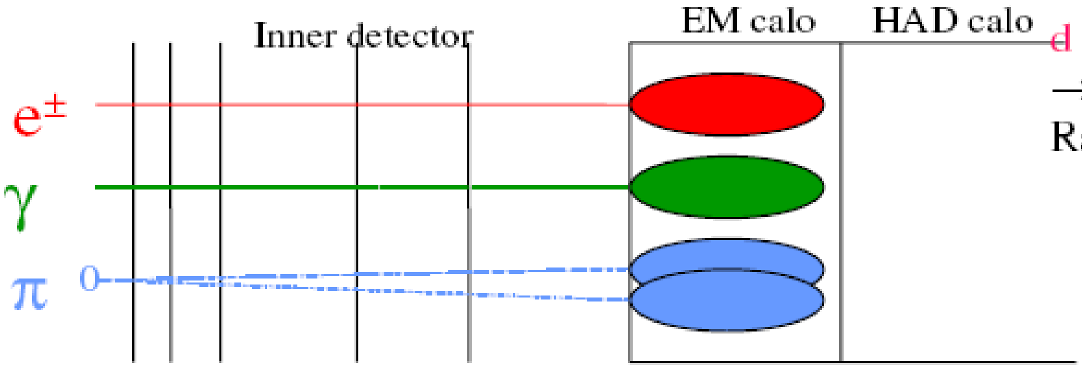
Excellent particle identification capability e.g. e/jet , γ /jet separation



number and p_T of hadron in a jet have large fluctuations



in some cases: one high-p_T π^0; all other particles too soft to be detected



d (γ γ) < 10 mm in calorimeter

→QCD jets can mimic photons.

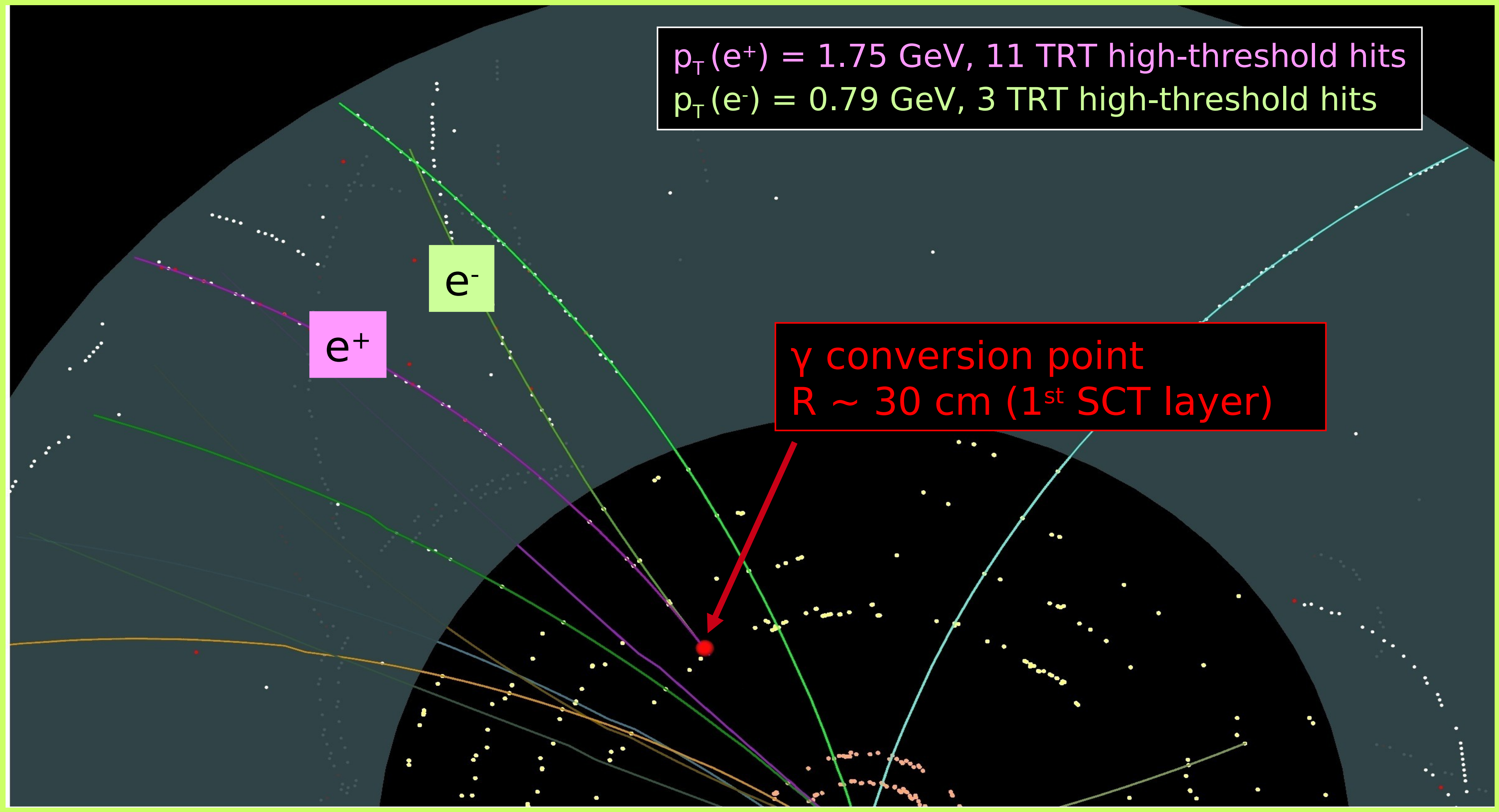
Rare cases, however:

$$\frac{\sigma_{jj}}{\sigma(H\rightarrow\gamma\gamma)} \sim 10^8$$

$m_{\gamma\gamma}$ ~ 100 GeV

need detector (calorimeter) with fine granularity to separate overlapping photons from single photons

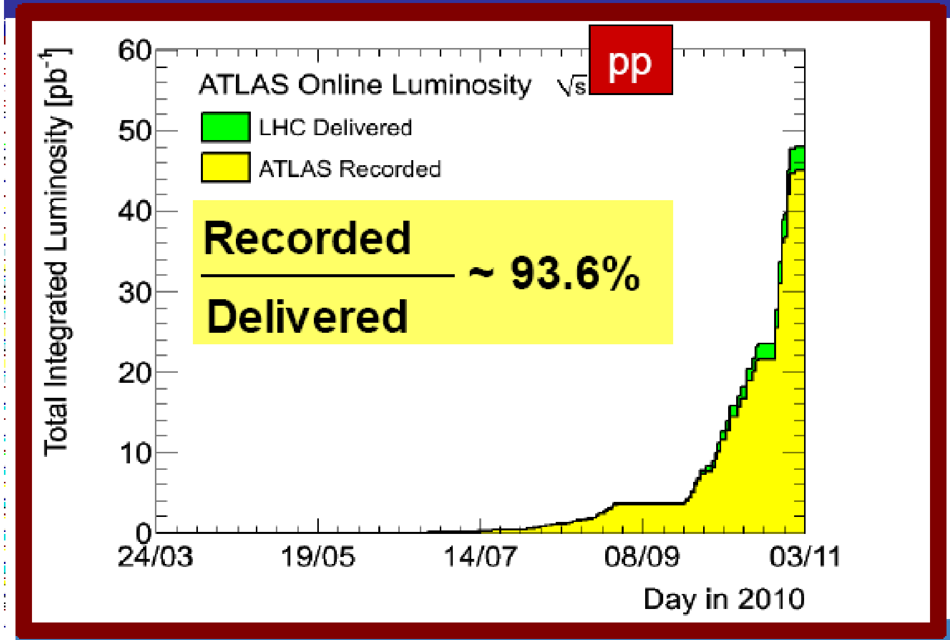
$\gamma \rightarrow e^+e^-$ conversions



$p_T(e^+)$ = 1.75 GeV, 11 TRT high-threshold hits
$p_T(e^-)$ = 0.79 GeV, 3 TRT high-threshold hits

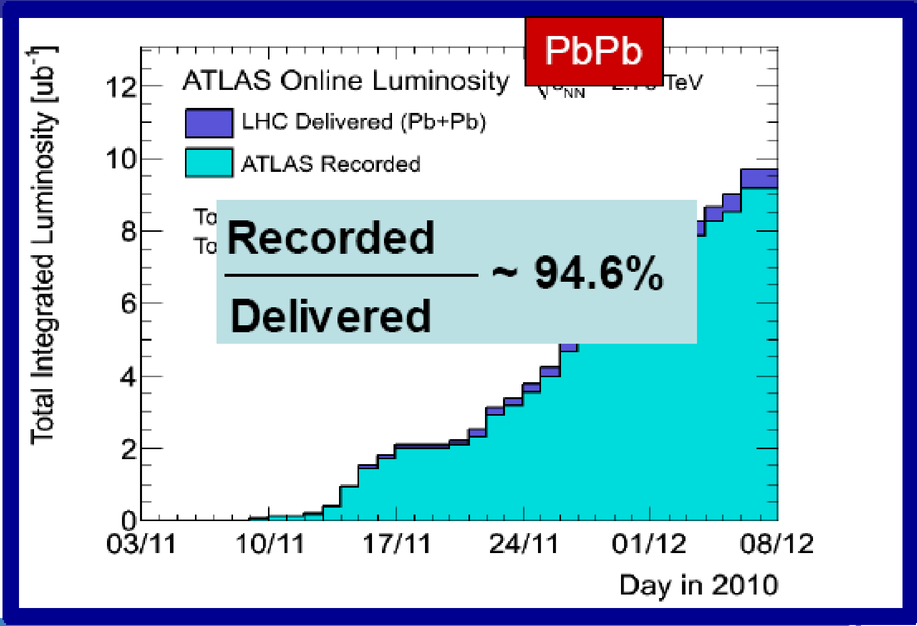
γ conversion point
R ~ 30 cm (1st SCT layer)

2010 Recorded Data



pp

$$\frac{\textbf{Recorded}}{\textbf{Delivered}} \sim \mathbf{93.6\%}$$



PbPb

$$\frac{\textbf{Recorded}}{\textbf{Delivered}} \sim \mathbf{94.6\%}$$

2010 pp run

Inner Tracking Detectors			Calorimeters				Muon Detectors			
Pixel	SCT	TRT	LAr EM	LAr HAD	LAr FWD	Tile	MDT	RPC	CSC	TGC
99.1	99.9	100	90.7	96.6	97.8	100	99.9	99.8	96.2	99.8

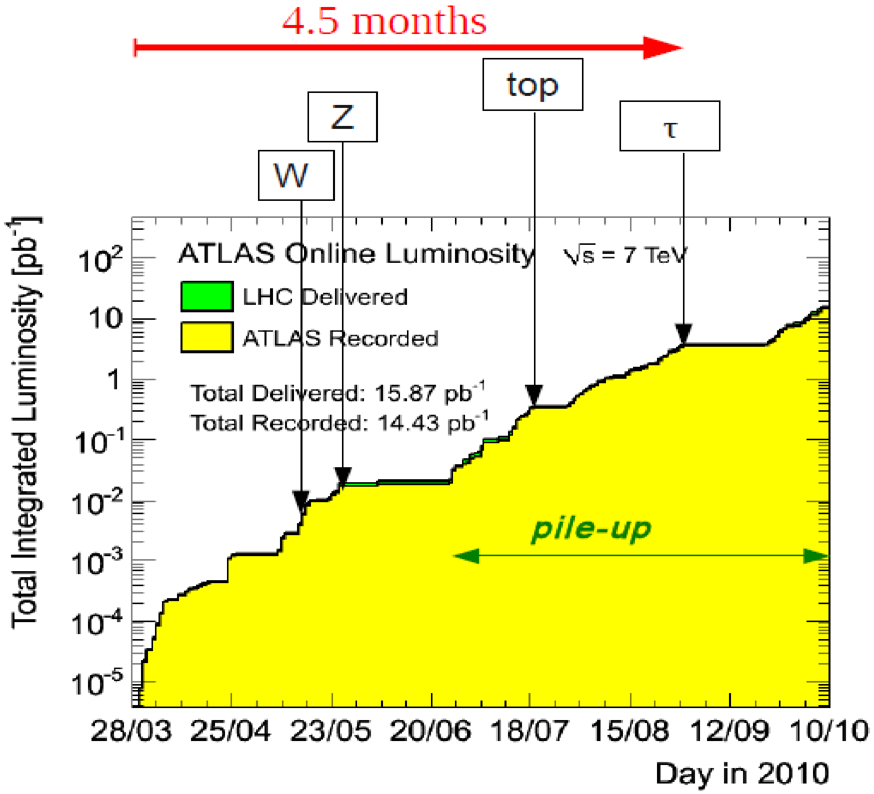
Luminosity weighted relative detector uptime and good quality data delivery during 2010 stable beams in pp collisions at √s=7 TeV between March 30th and October 31st (in %). The inefficiencies in the LAr calorimeter will partially be recovered in the future.

Retracing history of particle physics

- SM discovery:

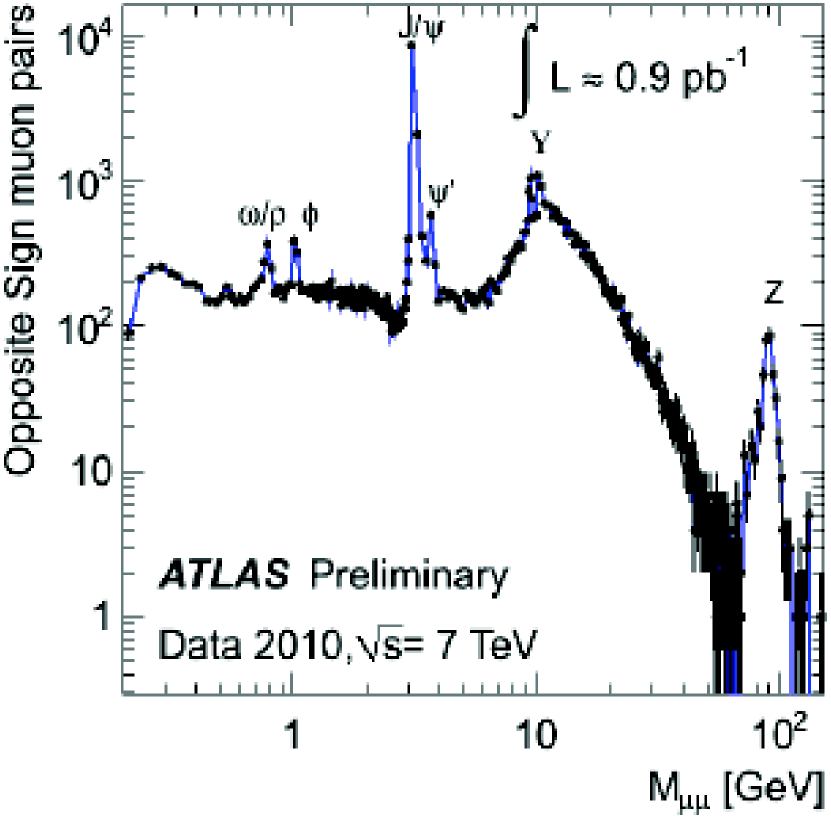
~100 years

  - electron: 1897
  - muon: 1936
  - ν_μ: ~1950
  - ν_e: 1956
  - quarks: 1968-1995
  - tau: 1975
  - W,Z : 1983-1984
  - ν_τ: 2000
  - Higgs: 2012 (?)



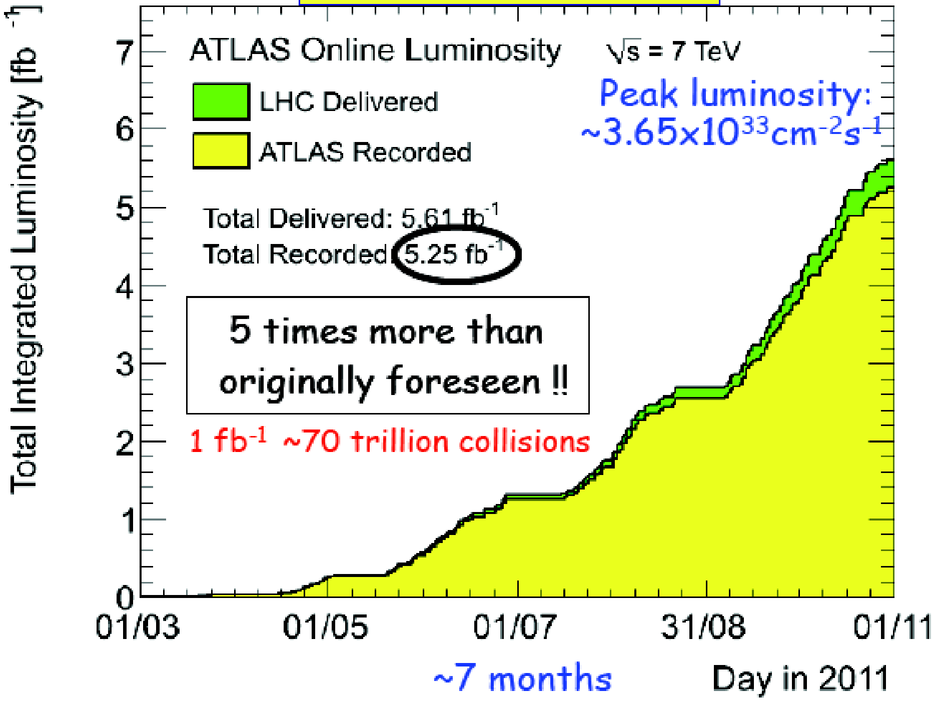
Retracing history of particle physics

- With up to 1pb^{-1} (public results) we made it up to 80's
- Results at sumer conferences 2010
- Onia(J/Psi, Ψ, Y,...) + first hundreds of W,Z in the leptonic channels



ATLAS data collected in 2011

Proton-proton running



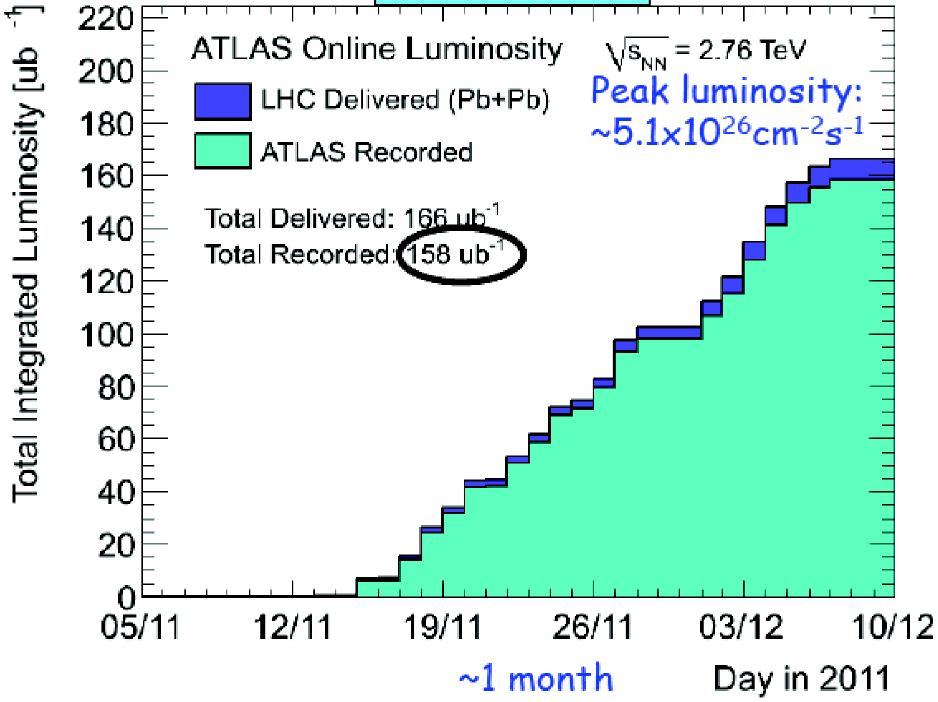
Peak luminosity: ~3.65×10^{33}cm^{-2}s^{-1}

5 times more than originally foreseen !!

1 fb^{-1} ~70 trillion collisions

~7 months

Pb-Pb running



Peak luminosity: ~5.1×10^{26}cm^{-2}s^{-1}

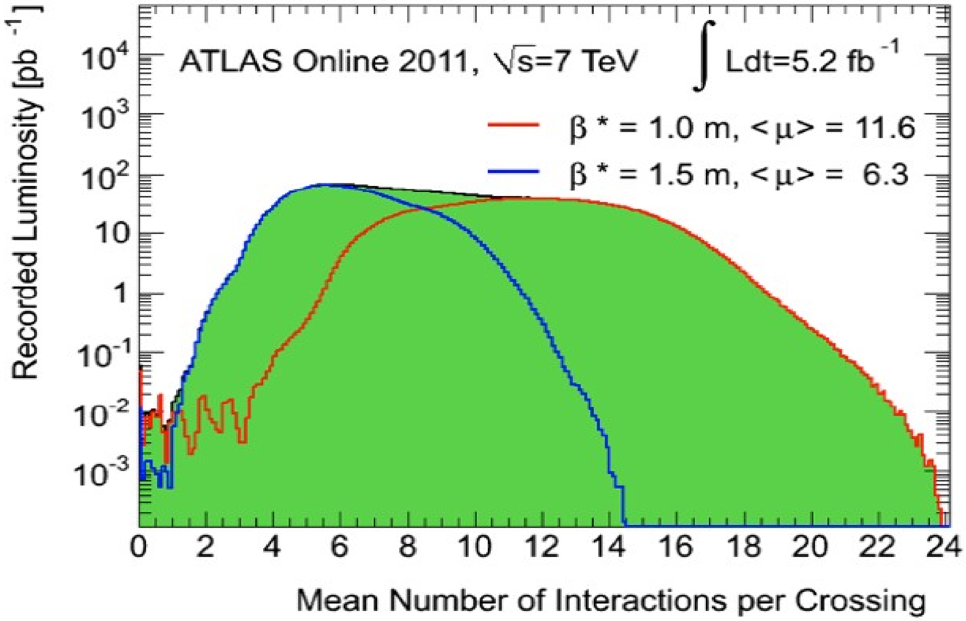
~1 month

- >100 times more proton-proton collisions:
  - 45 pb^{-1} in 2010
  - 5250 pb^{-1} in 2011
- Excellent recording efficiency: ~94%

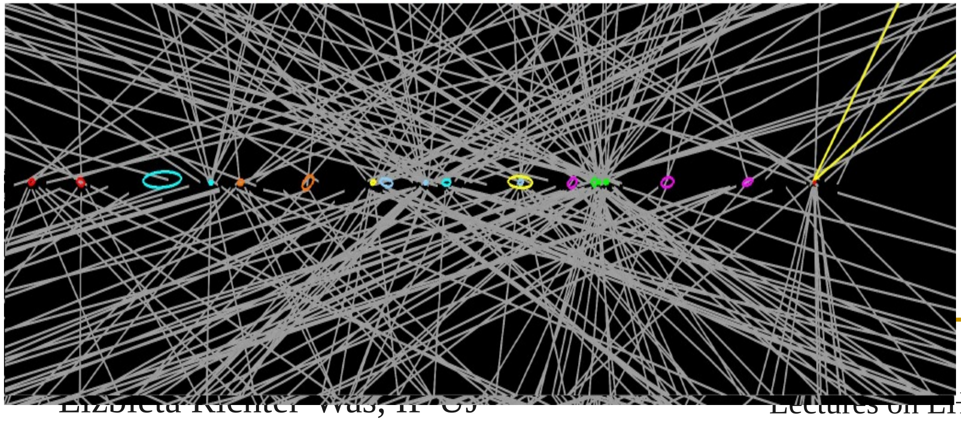
- 17 times more Pb-Pb collisions:
  - 9 μb^{-1} in 2010
  - 158 μb^{-1} in 2011
- Excellent recording efficiency: 95%

ATLAS reconstruction: impact of pileup

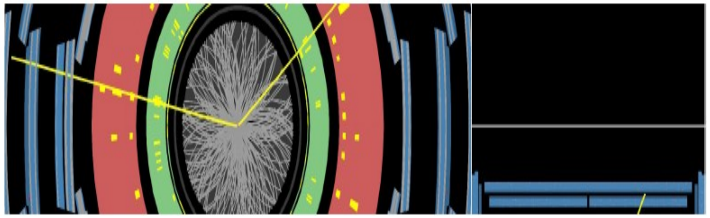
- Do not expect a significant impact on tracking, nor muons, nor even electrons and photons
- But sizable impact on jets (+E_T^{miss}) and τ's



Example of Z → μμ decay with 20 reconstructed vertices
Total scale along z is ~ ± 15 cm, p_T threshold for track reco is 0.4 GeV
(ellipses have size of 20σ for visibility)

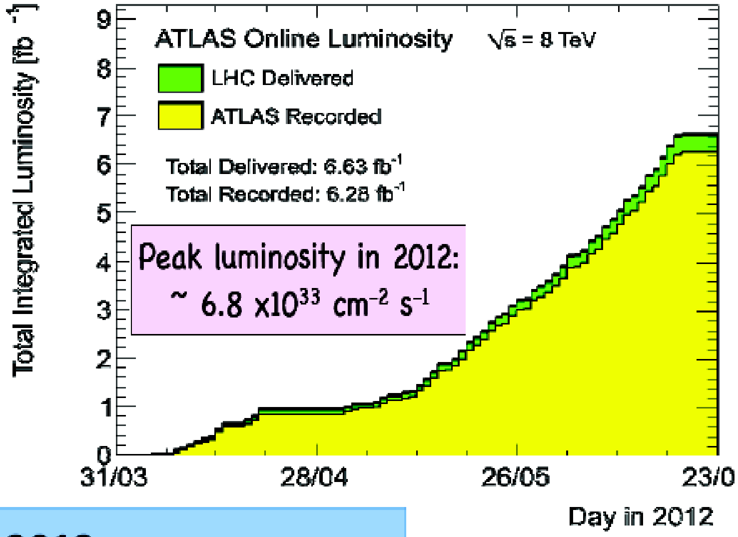


Now have <pile-up> ~ 14 per bunch crossing,
a challenge for tracking and for low-p_T jets!

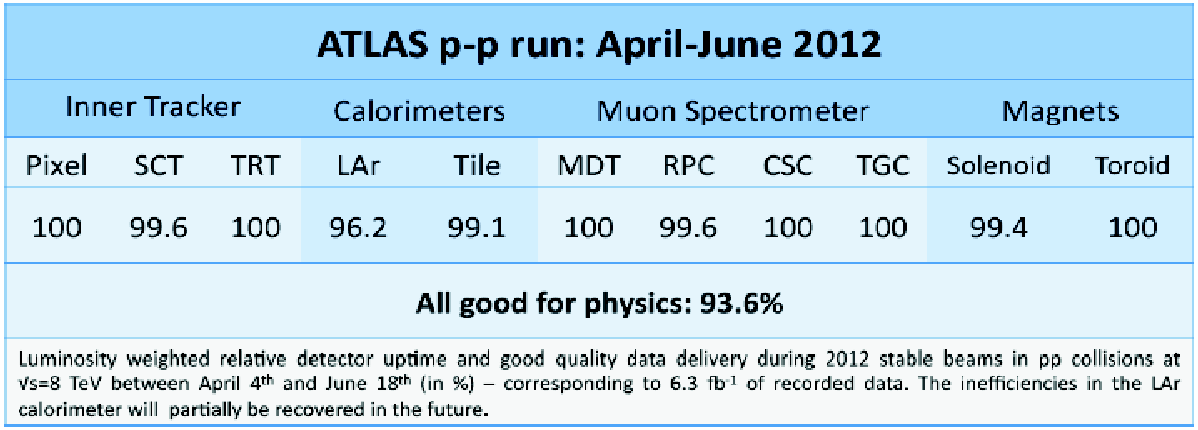


ATLAS data collected in 2012

- Very good start to 2012 data-taking at 8 TeV
  - 6.3 fb^{-1} recorded with ~95% data-taking efficiency
  - 5.8 fb^{-1} available for typical analysis selections
    - 93.6% data-quality efficiency, will improve after reprocessing this year's data



Peak luminosity in 2012: ~ 6.8 x10^{33} cm^{-2} s^{-1}



ATLAS p-p run: April-June 2012

Inner Tracker			Calorimeters		Muon Spectrometer				Magnets	
Pixel	SCT	TRT	LAr	Tile	MDT	RPC	CSC	TGC	Solenoid	Toroid
100	99.6	100	96.2	99.1	100	99.6	100	100	99.4	100

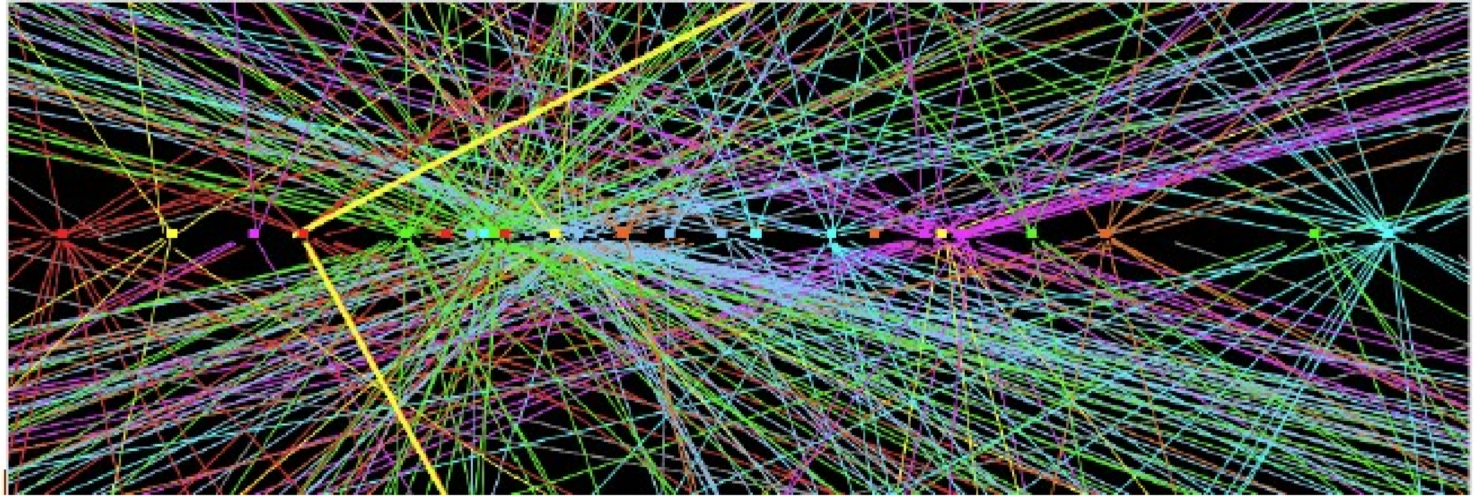
All good for physics: 93.6%

Luminosity weighted relative detector uptime and good quality data delivery during 2012 stable beams in pp collisions at √s=8 TeV between April 4th and June 18th (in %) – corresponding to 6.3 fb^{-1} of recorded data. The inefficiencies in the LAr calorimeter will partially be recovered in the future.

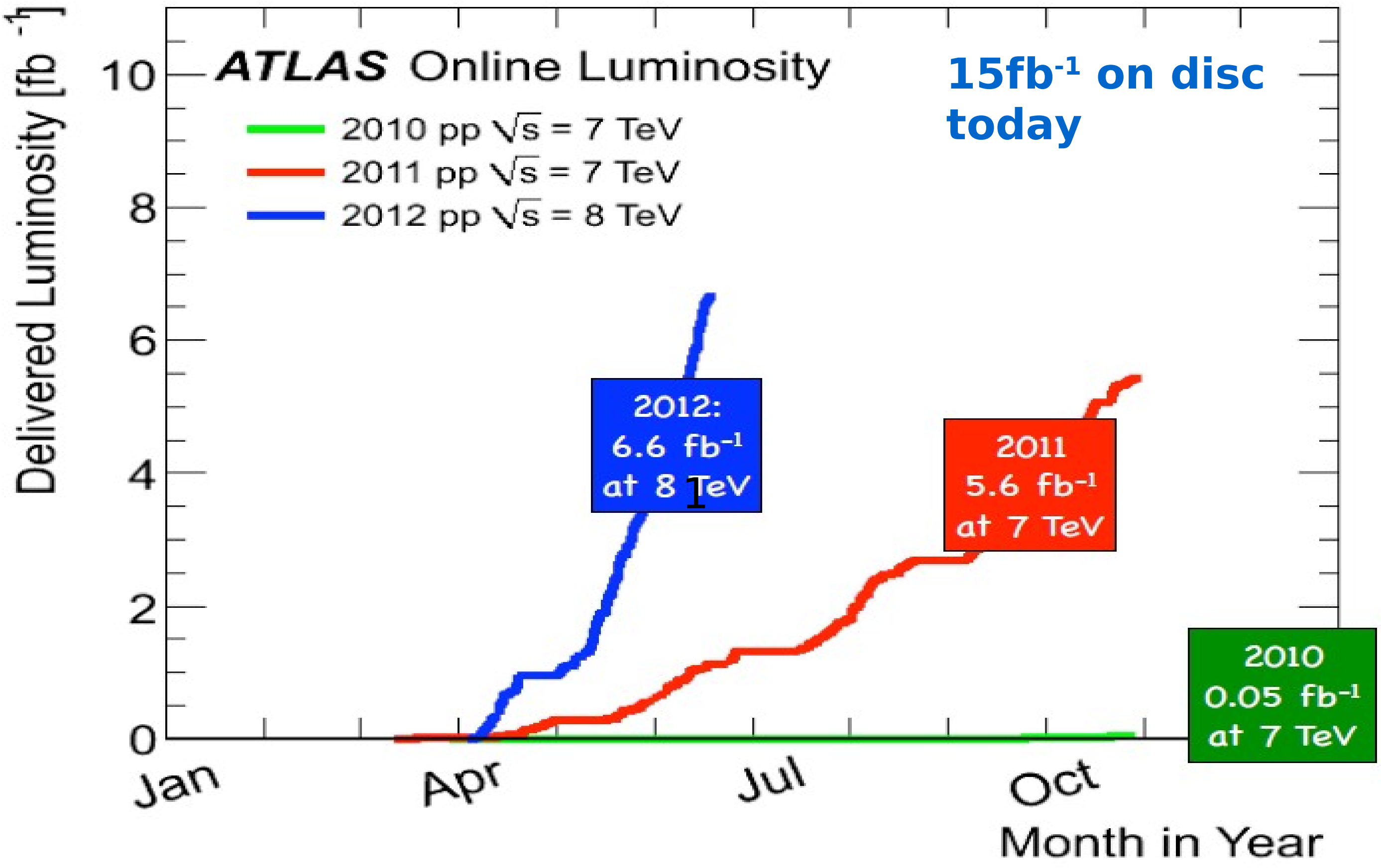
A big challenge of 2012

- The price to pay for the high luminosity is high pile-up

Z→μμ event from 2012 data with 25 vertices



Luminosity delivered to ATLAS since the beginning



$15 fb^{-1}$ on disc today