Hadron Accelerators: Tevatron and LHC

- Basics of particle acceleration

- Tevatron:
  - Antiprotons
  - stochastic cooling

- the Large Hadron Collider:
  - Visions
  - superconducting magnets
  - status and plans

early history of accelerator physics (in short)

- 1928: R. Wideroe reports about first operation of a linear accelerator (potassium (Ka) and sodium (Na) ions)
- 1931: Van de Graaff constructs first high voltage generator
- 1932: Lawrence und Livingston present first proton beam at the 1.2 MeV Cyclotron
- 1939: Hansen, Varian and Varian invent Clystron
- 1941: Kerst and Serber introduce first functioning Betatron; Touschek and Wideroe develop principle of circular accelerators
- 1947 Alvarez develops first proton linear accelerator
- 1950 Christofilos introduces concept of Strong Focussing

E.O. Lawrence

Basics of particle acceleration

Differentialform	Integralform
$\mathrm{div}\,\vec{D} = \rho_{frei}$	$\oint \vec{D}\cdot d\vec{A} = Q$
$\mathrm{div}\,\vec{B} = 0$	$\oint \vec{B}\cdot d\vec{A} = 0$
$\mathrm{rot}\,\vec{E} = -\frac{\partial \vec{B}}{\partial t}$	$\oint \vec{E}\cdot d\vec{s} = -\frac{d}{dt}\int \vec{B}\cdot d\vec{A}$
$\mathrm{rot}\,\vec{H} = \vec{j} + \frac{\partial \vec{D}}{\partial t}$	$\oint \vec{H}\cdot d\vec{s} = I + \frac{d}{dt}\int \vec{D}\cdot d\vec{A}$

Maxwell-Equations

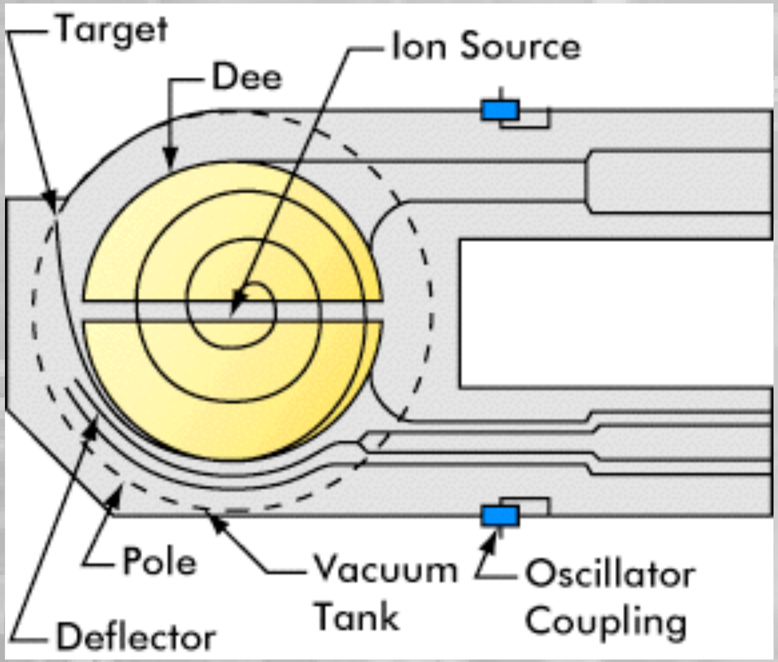
$$\vec{F} = q\left(\vec{E} + \vec{v} \times \vec{B}\right)$$

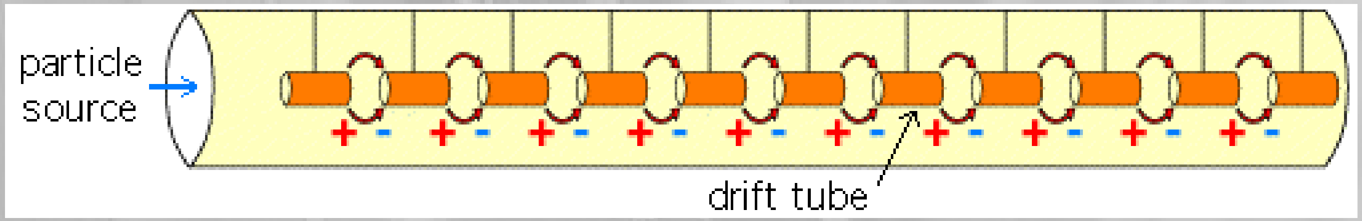
Lorentz Force

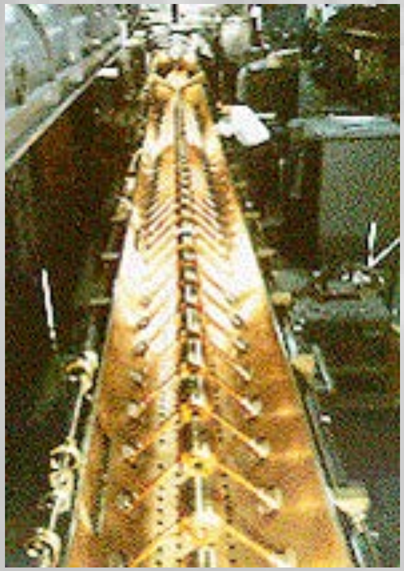
n.b.: Lorentz force from time dependent fields is no "conservative force", i.e. $\oint \vec{F}\, d\vec{s} \neq 0$

Basics of particle acceleration

Cyclotron



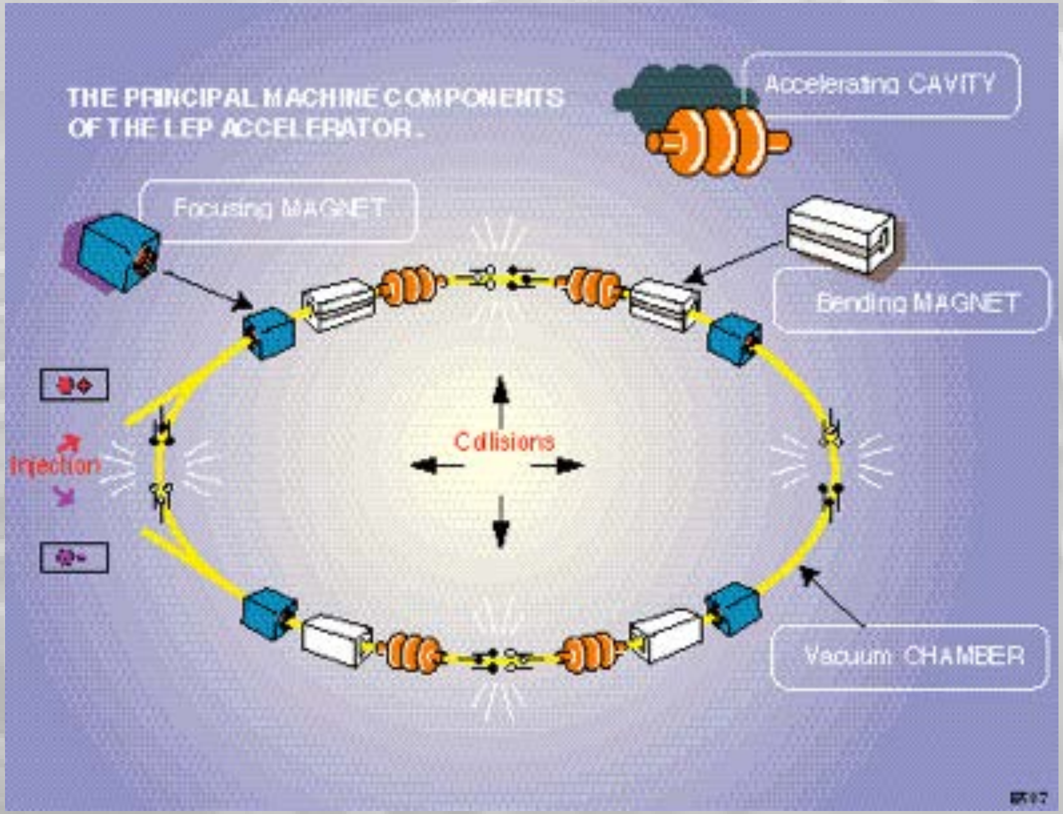




Linear accelerator

Basics of particle acceleration

circular accelerators (Synchrotron)



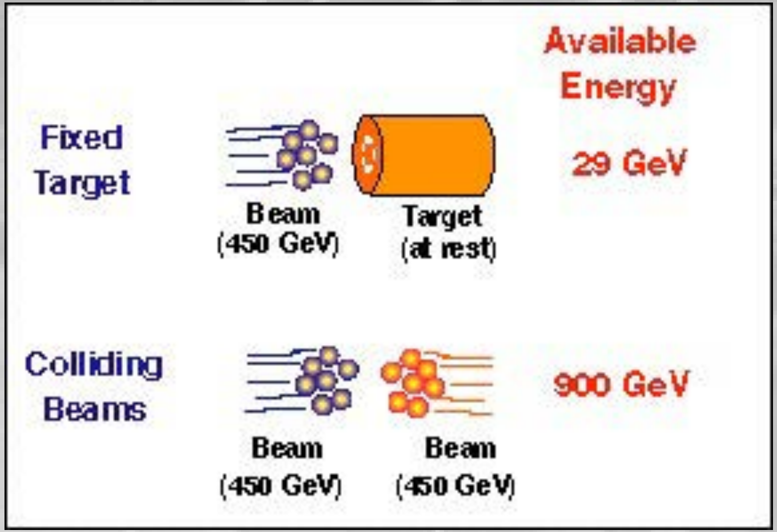
advantages:
- only local magnetic fields around beams (more economic)
- multiple use of accelerating structures
- higher effective centre-of-mass energy in "Collider"-Mode
- more effective use of particles (storage ring)

disadvantage:
- energy loss through Bremsstrahlung (Synchrotron radiation)

Basics of particle acceleration

Fixed Target versus Colliding Beams

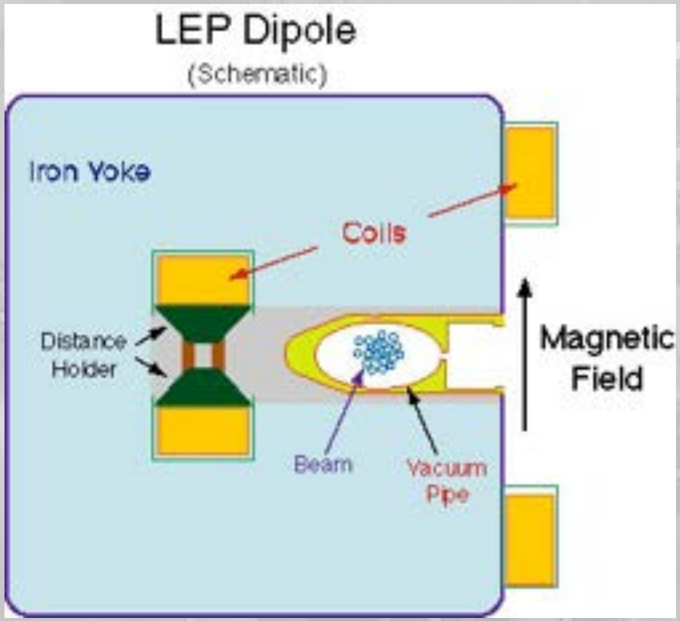
for Protons ($m_p c^2 \sim 1$ GeV):



$$E_{cm} = \sqrt{2(\gamma + 1)} m_p c^2$$

$$E_{cm} = 2E = 2\gamma m_p c^2$$

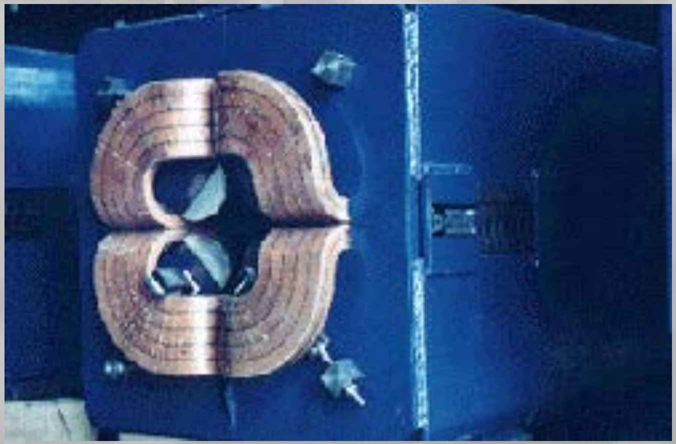
functional parts of circular accelerators:



Dipol
(circular path)

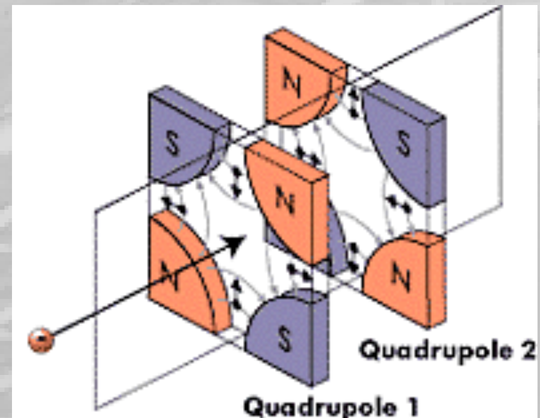
cavity
(acceleration)

Quadrupole
(focussing)



Tunnel, beam pipe,
vacuum pumps, Sextupole,
…

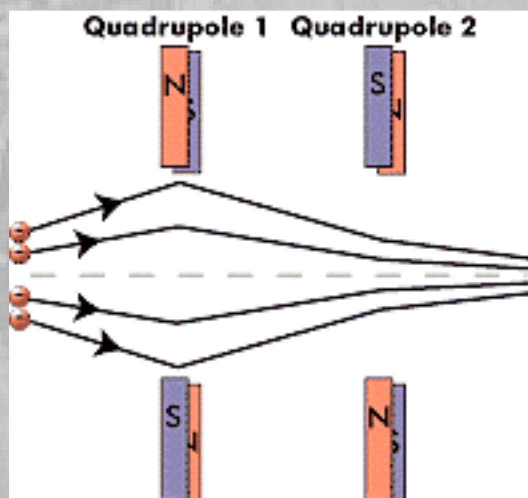
Strong Focussing

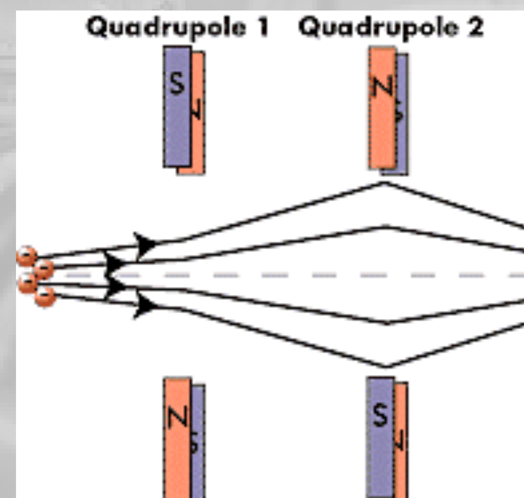


$$\frac{1}{f} = \frac{1}{f_1} + \frac{1}{f_2} - \frac{d}{f_1 f_2}$$

$$= \frac{f_1 + f_2 - d}{f_1 f_2}$$

side view





top view

two crossed quadrupoles at distance *d* smaller than double the focal length are focussing (in both planes)

Collider Parameters

event rate R: $R = L \cdot \sigma$ — σ: physical cross section

Luminosity L: $$L = f \frac{n_1 n_2}{4\pi \sigma_x \sigma_y}$$

f: collision frequency
n_i: # of particles per bunch i
σ_x: horizontal beam size
σ_y: vertical beam size

beam size:

- transversal emittance ε (beam quality)
- amplitude function β (beam optics)

$\varepsilon = \pi \sigma \sigma'$ — σ: transversal displacement
$\beta = \sigma / \sigma'$ — σ′: angle w.r.t. beam axis

β^* : value of β-function at interaction point.

Luminosity L: $$\Rightarrow \quad L = f \frac{n_1 n_2}{4\sqrt{\varepsilon_x \beta_x^* \varepsilon_y \beta_y^*}}$$

Basics of particle acceleration

Synchrotron radiation:

emission power of a relativistic particle at centripetal acceleration:

$$P = \frac{1}{6\pi\varepsilon_0}\frac{e^2 a^2}{c^3}\gamma^4$$

$a = v^2/\rho$

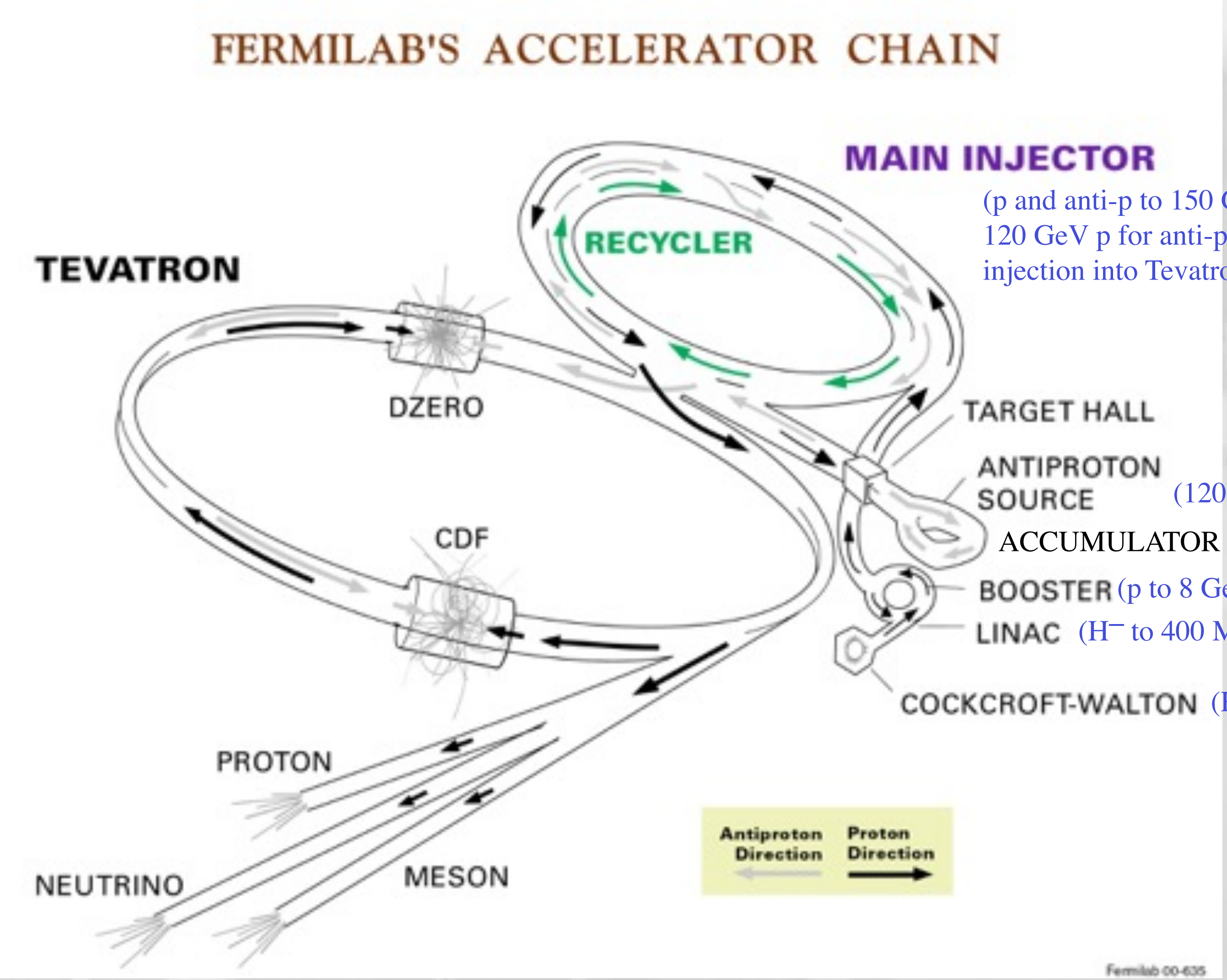
v: particle velocity

ρ: bending radius

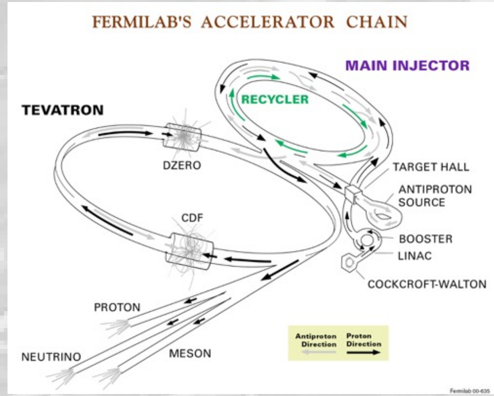
energy emitted per turn:

- Electron with v ≈ c $\quad W = 8.85 \times 10^{-5}\,\frac{E^4}{\rho}\frac{[MeV^4]}{[km]}\,\mathrm{MeV}$
- Proton with v ≈ c $\quad W = 7.8 \times 10^{-6}\,\frac{E^4}{\rho}\frac{[TeV^4]}{[km]}\,\mathrm{MeV}$

Fermilab: Tevatron Accelerator (1983 - 2011)



Fermilab's Accelerator Chain



Cockcroft-Walton DC accelerator

LINAC

Booster

Main Injector

Antiproton Source

Tevatron

why antiprotons?

- can fly in opposite directions using same magnetic fields in one beam pipe —> one ring instead of two.
- up to 3 TeV collision energy, the production cross sections of some reactions in proton-antiproton collisions are higher than in proton-proton

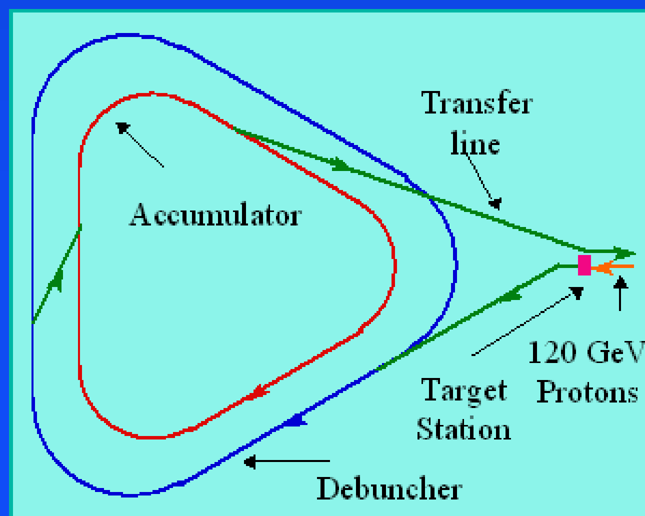
disadvantage of antiprotons:

- must be produced ...

Fermilab
Beams
Division

Anti-Proton Production

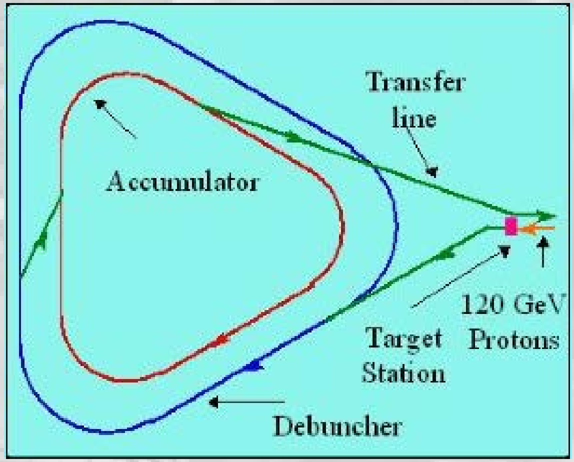
- The Anti-Proton Source consists of three major components:
  - The Target Station
  - The Debuncher
  - The Accumulator
- For every 1 million 120 GeV protons smashed on the pbar target, only about twenty 8 GeV pbars survive to make it into the Accumulator.

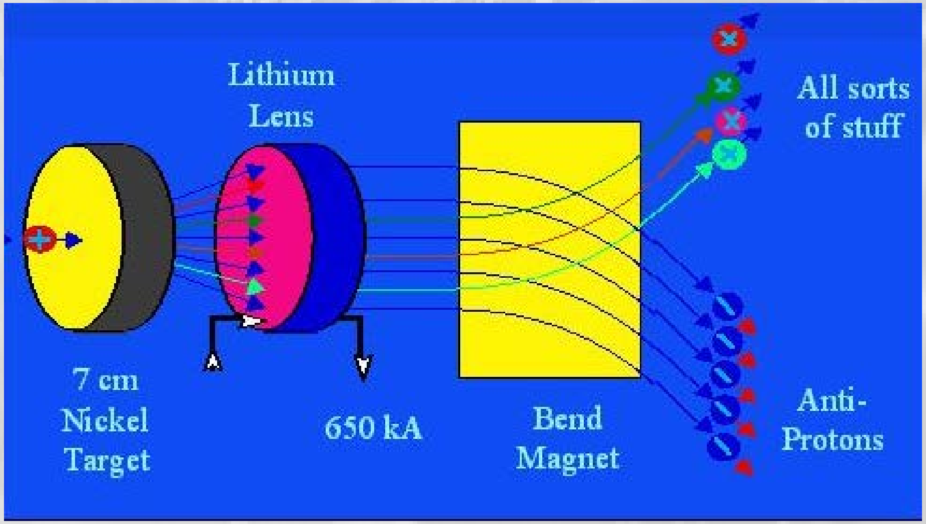


The price of pbars

$$\frac{15\,\mathrm{MW} \times \$45\ /\ \mathrm{MW{-}hr}}{5 \times 10^{10}\ \frac{\mathrm{pbars}}{\mathrm{hr}} \times 9.5 \times 1.67 \times 10^{-27}\ \frac{\mathrm{kg}}{\mathrm{pbar}} \times 2.2\ \frac{\mathrm{lbs}}{\mathrm{kg}} \times 16\ \frac{\mathrm{oz}}{\mathrm{lbs}}} = \$24{,}000 \times 10^{12}\ /\ \mathrm{oz}$$

The Antiproton Source

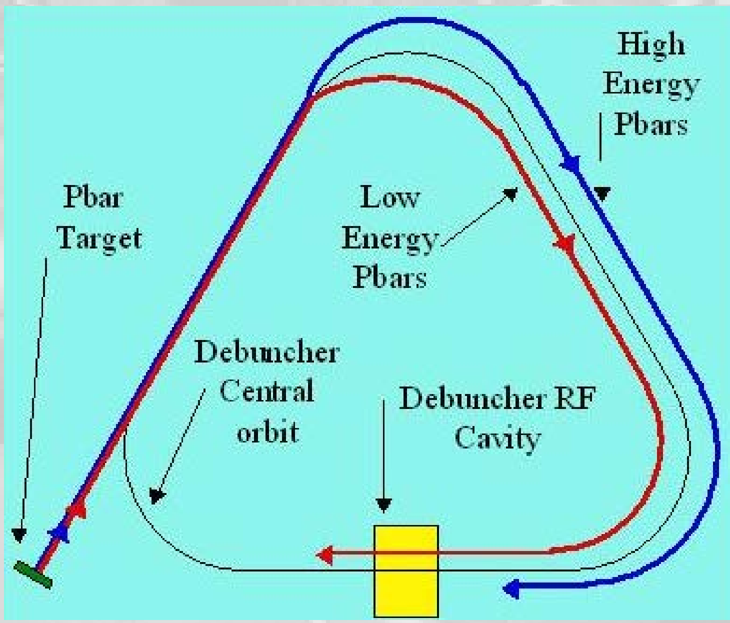


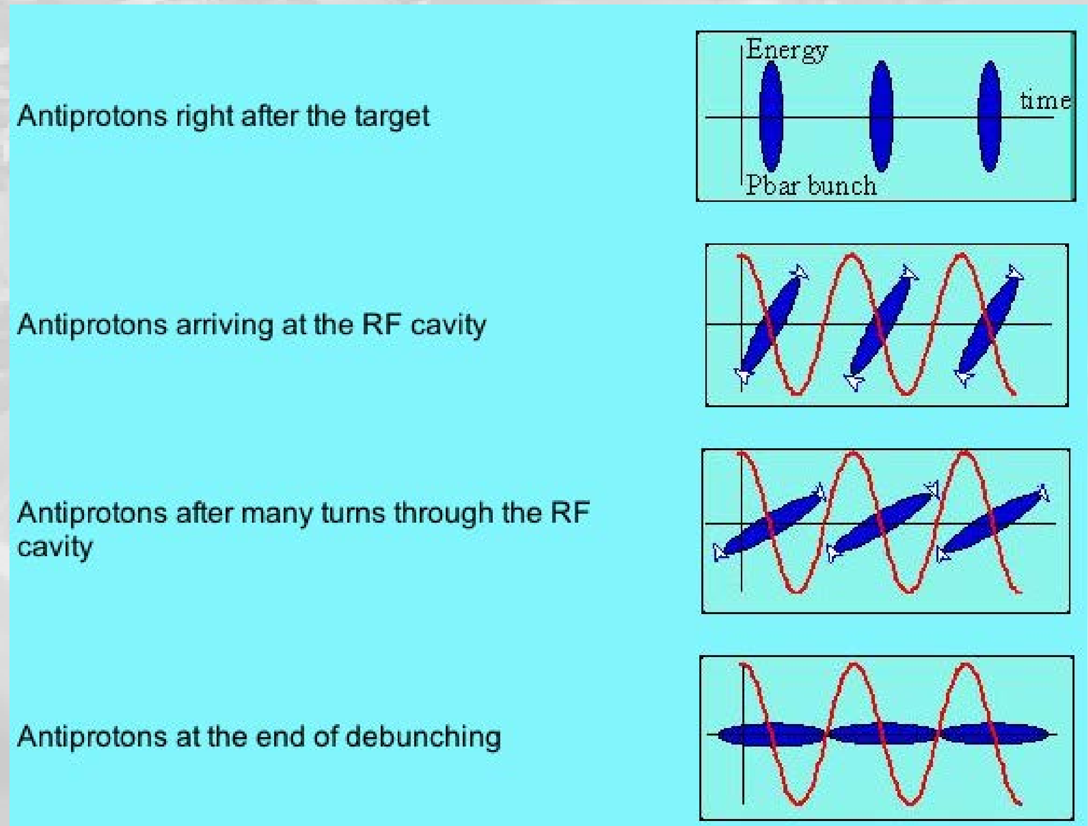


Debuncher & Accumulator

Debuncher

transfer of large energy- and small time spread zu small energy spread with long time structure.

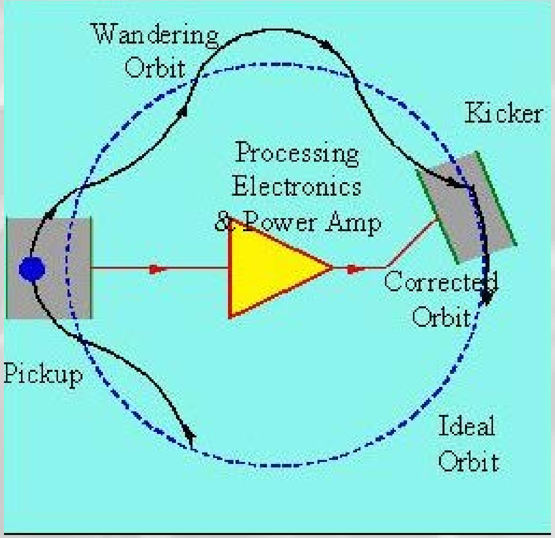




Stochastic Cooling

(Nobel price to Simon van der Meer 1984)

Reduction of transversal phase space of antiprotons, carried out in debuncher (retention time 1.5 sec) and in accumulator (several hours).



amplification of pick-up signal by 150 dB (10^{15}).

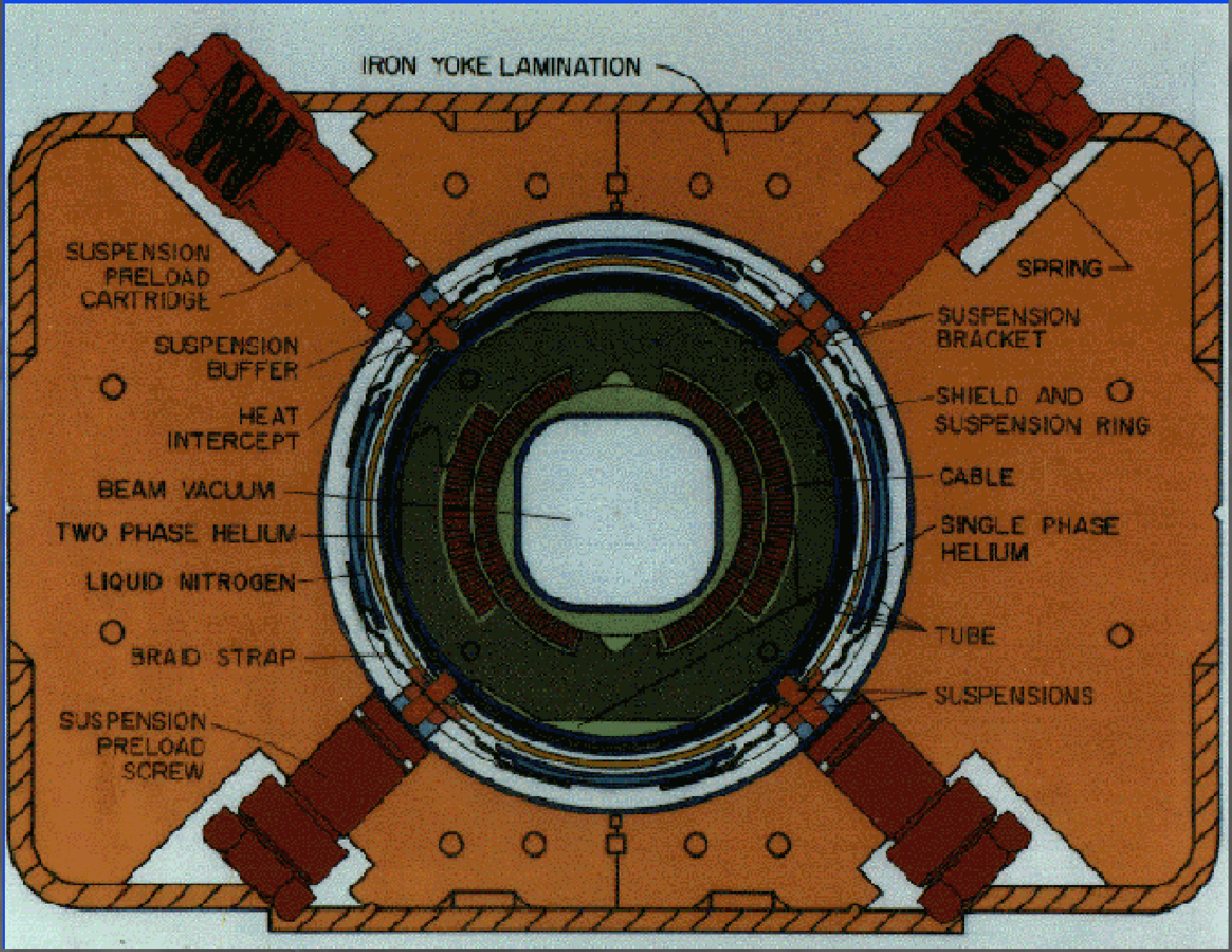
Tevatron

Fermilab
Beams
Division

Superconducting Magnets

- Magnets in the TEVATRON are superconducting.
- There are about 1000 magnets in the TEV
- The coils are made of niobuim-titanium alloy wire.
  - The size of the wire is 0.0003 inches (8 um)
  - There are 11 million wire-turns in a coil.
  - The dipole magnet is 21 feet long
  - There are 42,500 miles of wire in a magnet
- For 900 GeV operation, the magnets are kept at 4.6° Kelvin.
- For 1000 GeV operation, the cryogenic system has been upgraded to obtain a temperature of 3.6° Kelvin (-453°F)

TEVATRON Magnet Cross-Section

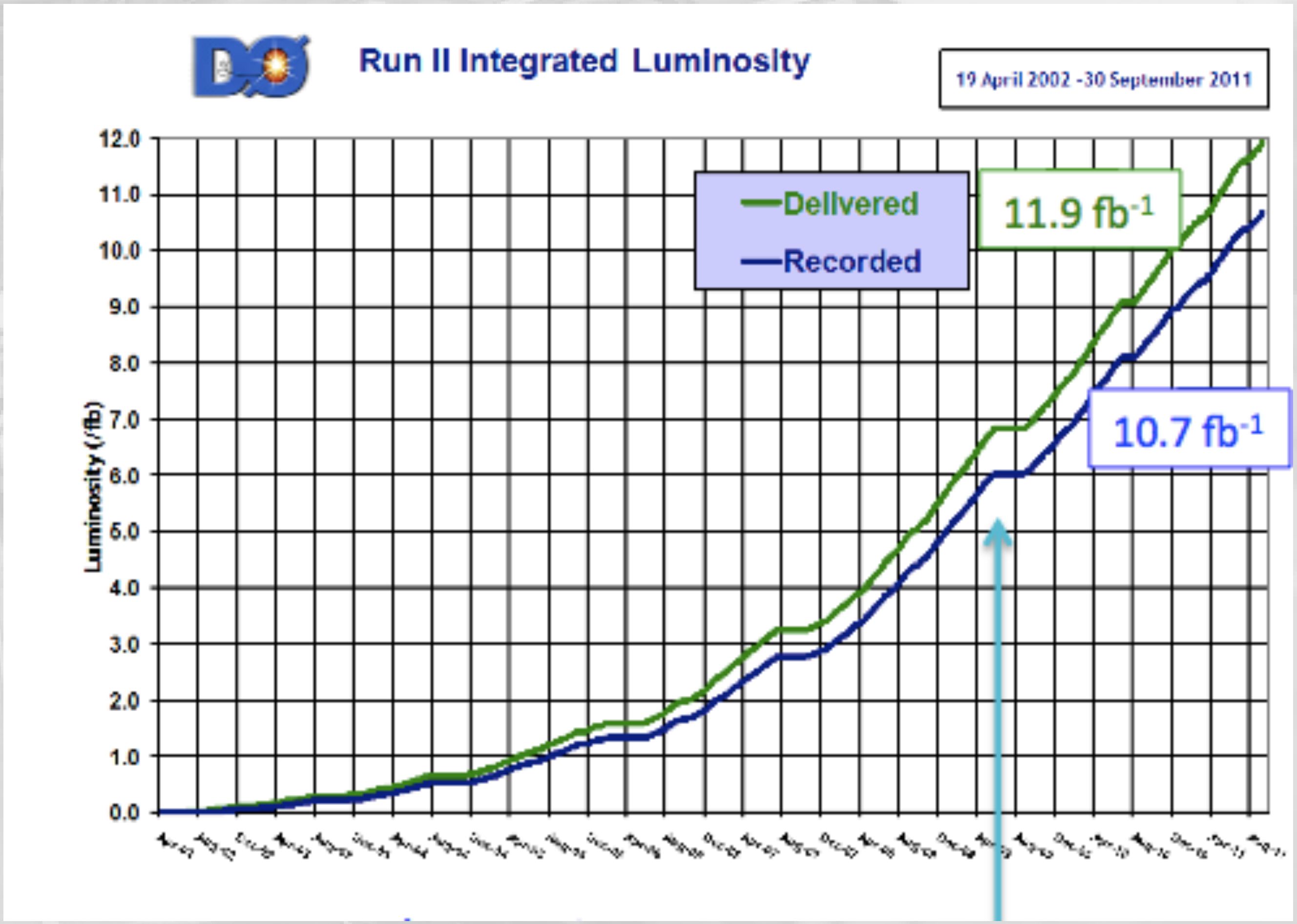


Fermilab
Beams
Division

Superconducting Magnets

- The field in the magnets at 900 GeV is 4 Tesla (The Earth's magnetic field is 0.0003 Tesla, 13,000 times weaker then a TEV magnet)
  - An LHC magnet (Large Hadron Collider in Geneva, Switzerland) will have a magnetic field between 8-10 Tesla.
  - The theoretical limit for mechanically constraining a superconducting magnet is about 15 Tesla.
- The current flowing through a magnet at 900 GeV is 4000 Amperes.
  - The total inductance of the TEVATRON is 36 H.
  - The total magnetic stored energy in the TEVATRON at 900 GeV is 288 MegaJoules.
  - The time constant of the current dump system is 12 seconds.
  - If all the current in the TEV needed to be dumped, the dump resistors would have to dissipate energy at 24 megawatts

Tevatron integrated Luminosity
(after project termination on 30 Sept 2011)



peak L: ~ 10^{32} cm^{-2} s^{-1}

the Large Hadron Collider

Visions (1980's)

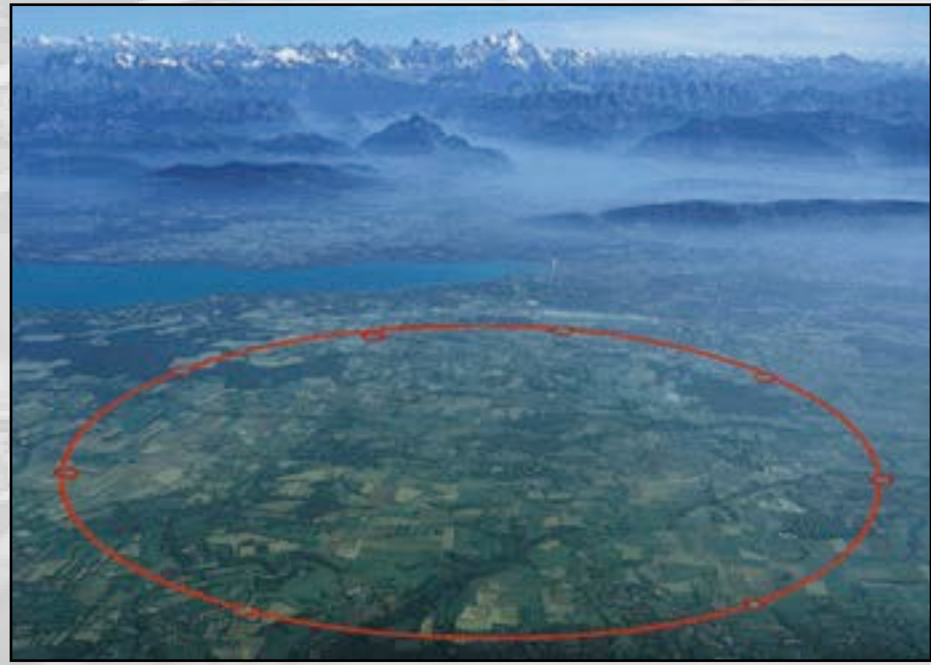
- particle accelerator with highest collisions energies, aiming at:
  - test of the Standard Model beyond energies of 1 TeV
  - finding the missing pieces of the SM: the top-quark ...
  - investigate the mechanism of elektroweak symmetry-breaking (i.e., find the Higgs Boson)
  - search for new physics beyond the Standard Model (SUperSYmmetriy; large extra dimensions; ...)
  - find the unexpected....

Challenges:

- “fast“ and „cheap“ –> use existing LEP tunnel and pre-accelerators of CERN
- highest energies at given radius of tunnel –> accelerate protons (instead of electrons at LEP)
- collision energies of constituents of ~TeV –> Proton energies of at least 5 TeV
- Proton energies of at least 5 TeV –> superconducting magnets at ~ 8 Tesla
- generate objects of very high masses –> need high luminosity ($L \sim 10^{34}\ cm^{-2}\ s^{-1}$)
- $L \sim 10^{34}\ cm^{-2}\ s^{-1}$ –> high data rates; radiation damage

The Large Hadron Collider (LHC)

- Proton-Proton accelerator in 27 km LEP-Tunnel at CERN



- Highest collision energies
- Highest luminosities

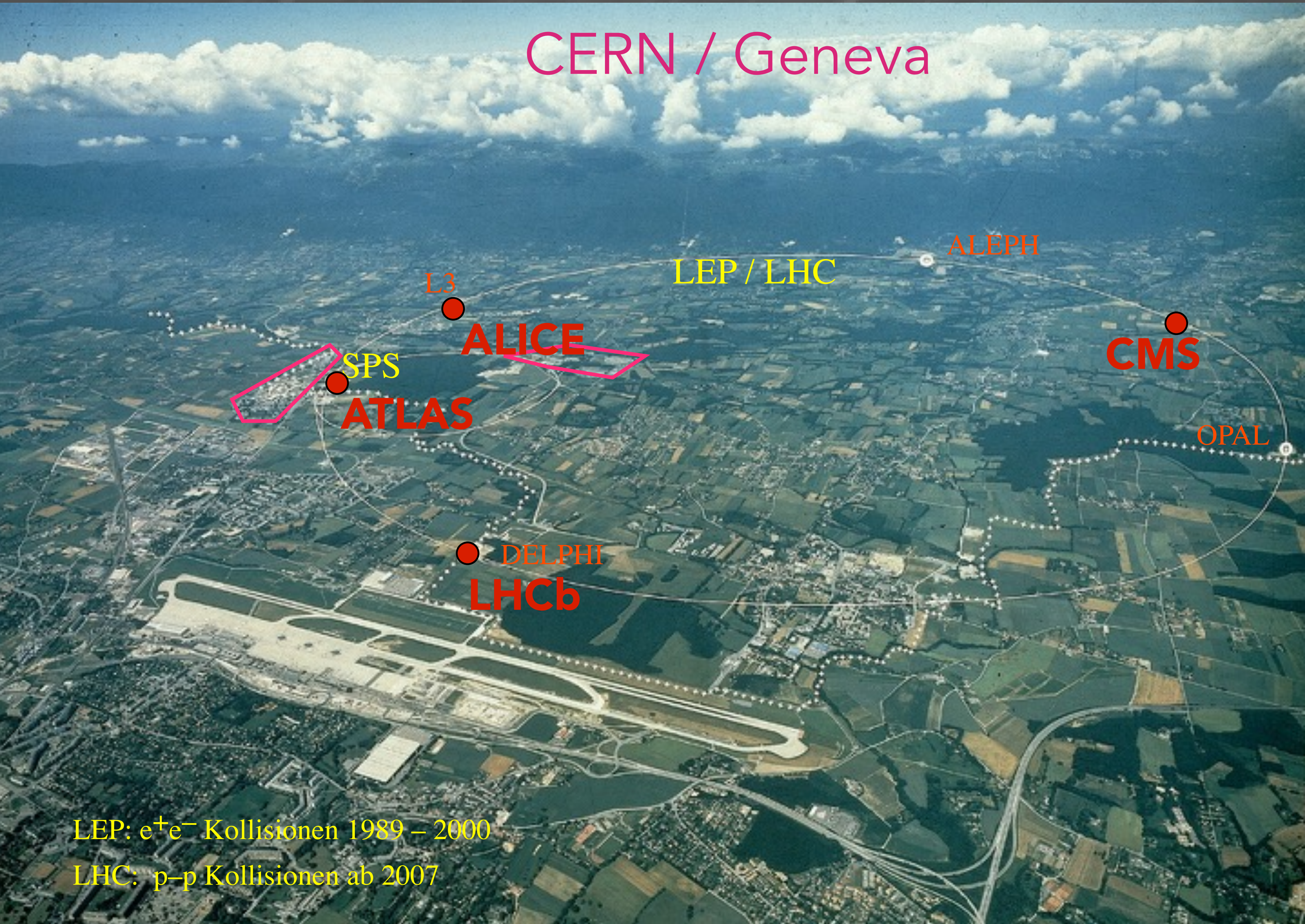
- 4 large experiments:

ATLAS, CMS	(p-p physics)
LHC-B	(physics of heavy quarks)
ALICE	(Pb-Pb collisions)

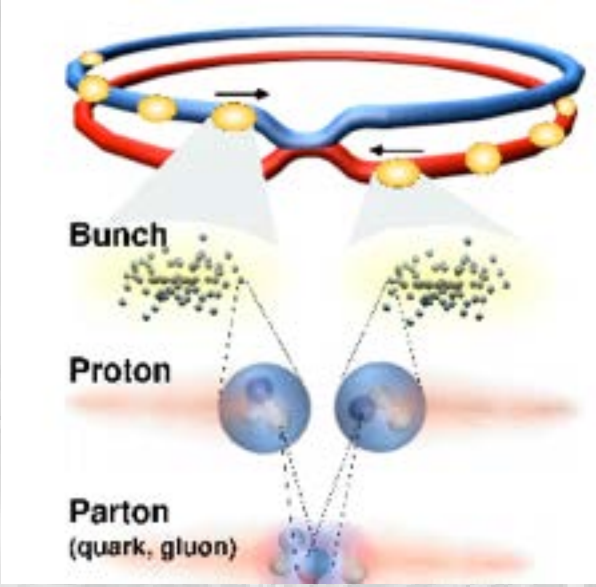
- constructed and operated in collaboration with ~40 nations

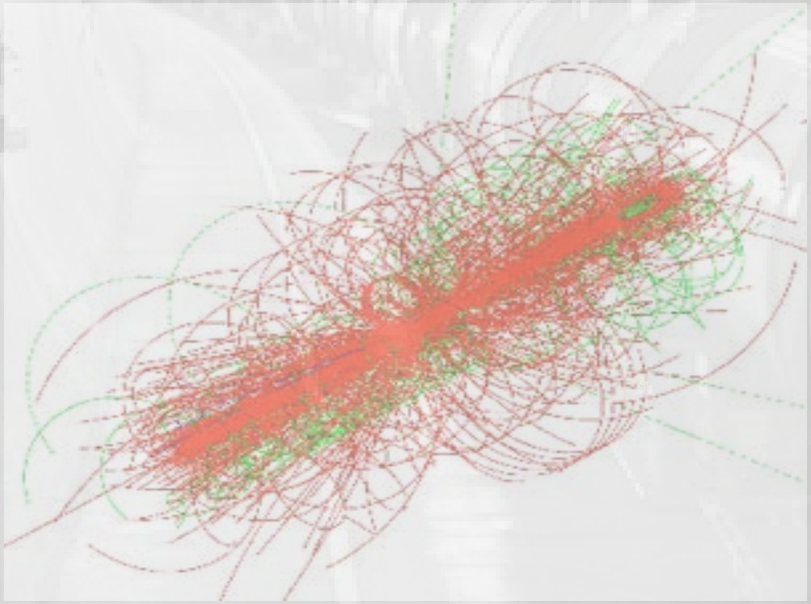
- start of operation: 2005 -> 2007 -> 2008 -> 2009 end: ~2035

CERN / Geneva


LEP / LHC
ALEPH
L3
ALICE
SPS
ATLAS
CMS
OPAL
DELPHI
LHCb
LEP: e^+e^- Kollisionen 1989 – 2000
LHC: p–p Kollisionen ab 2007

The Large Hadron Collider (LHC)





Proton – Proton collisions:

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

10^{11} Protonen / bunch
collision rate: 40 million / second
Luminosity: $L = 10^{34}\ cm^{-2}\ s^{-1}$

Proton-Proton collisions: ~10^{9} / s
(pile-up of 20-30 pp-interactions
for each beam crossing)

~1600 charged particles in detector

⇒ highest demands on detectors

Production cross sections and event rates at LHC

$N_{events} / s = \sigma \cdot L$

$N_{events} = \sigma \cdot \int L \cdot dt$

$1\ nb = 10^{-33}\ cm^2$

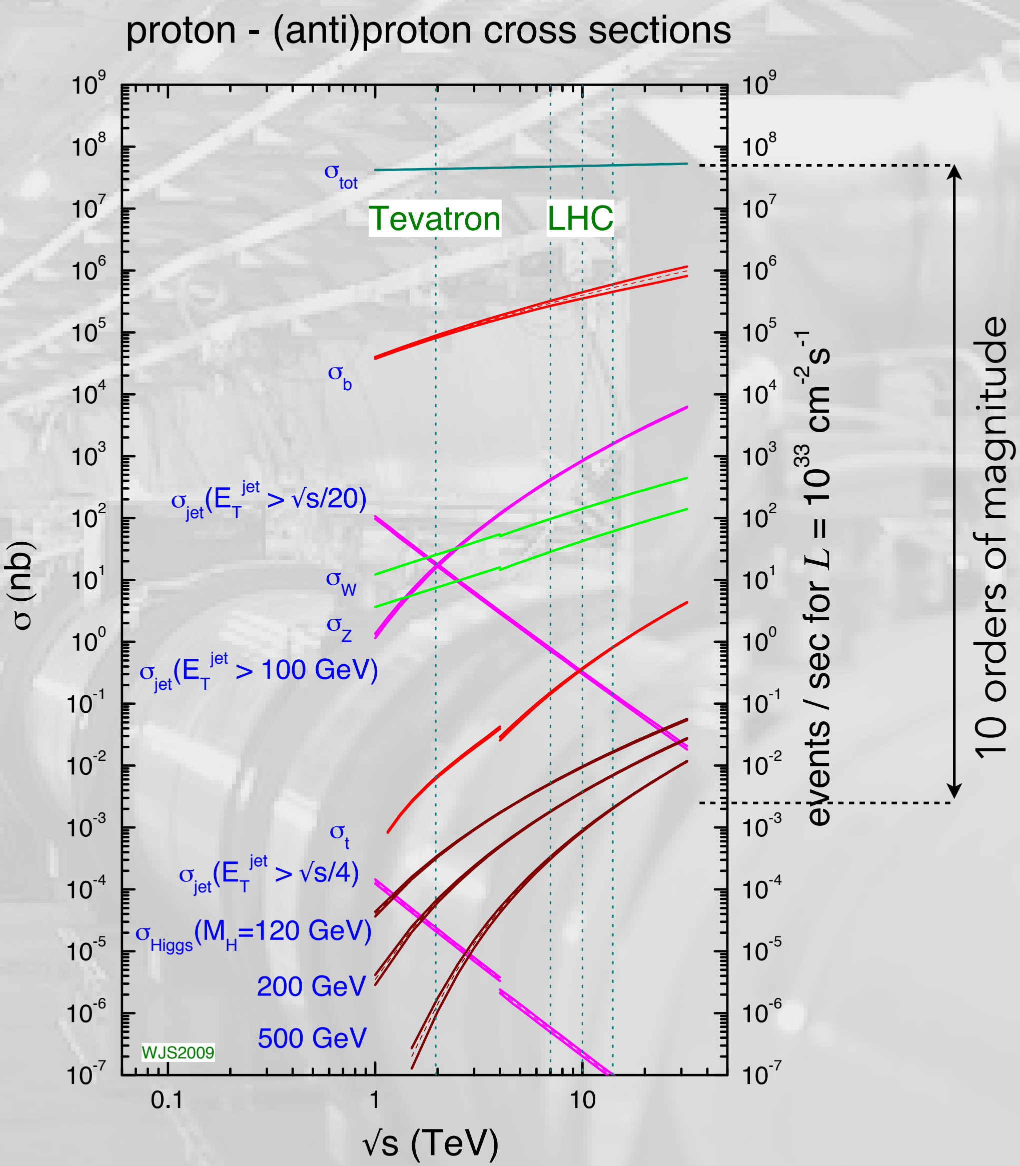
calculus (example):

End of 2010:
$\int Ldt = 40\ pb^{-1} = 40 \cdot 10^3\ nb^{-1}$

corresp. to ~ $4 \cdot 10^3$ top-quark- events (σ_t ~ 10^{-1} nb at 7 TeV)

corresp. to ~200 Higgs-evts. with M_H =120 GeV at 7 TeV

data sample 2011: ~ 5 fb^{-1}
data sample 2012: ~20 fb^{-1}



Production rates at LHC

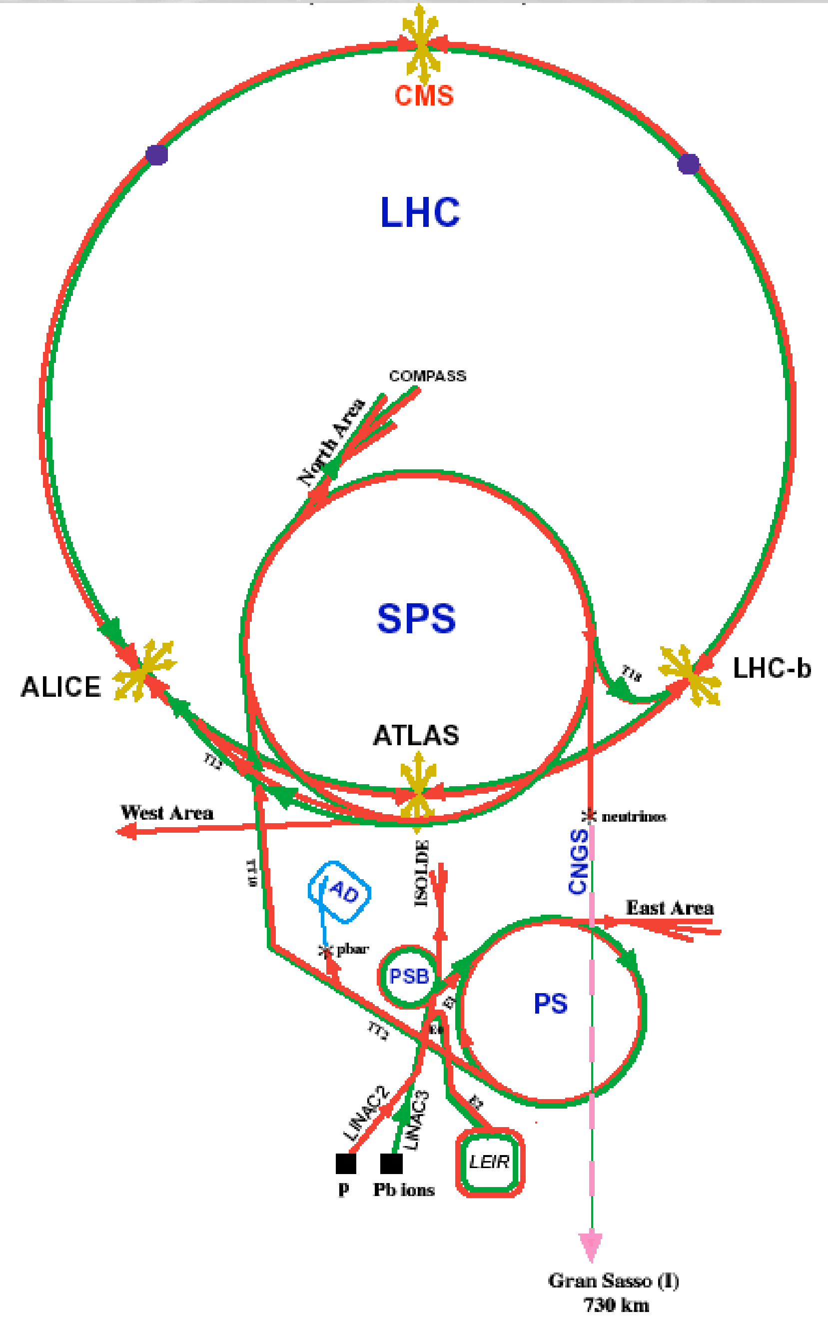
• Inelastic Proton-Proton collisions:	1 Billion / second
• Quark -Quark/Gluon scatterings with large transverse momenta (> 20 GeV)	~100 Millions/ sec
• b-Quark pairs	5 Millions / sec
• top-Quark pairs	8 / sec
• W $\rightarrow e\,\nu$	150 / sec
• Z $\rightarrow e\,e$	15 / sec
• Higgs (Mass = 150 GeV)	0.2 / sec
• Gluino, Squarks (Mass = 1 TeV)	0.03 / sec

- Interesting physics processes are extremely rare:
  $\Rightarrow$ high luminosities !,

extremely powerful detectors (to suppress background)

accelerator system of CERN

(not to scale)

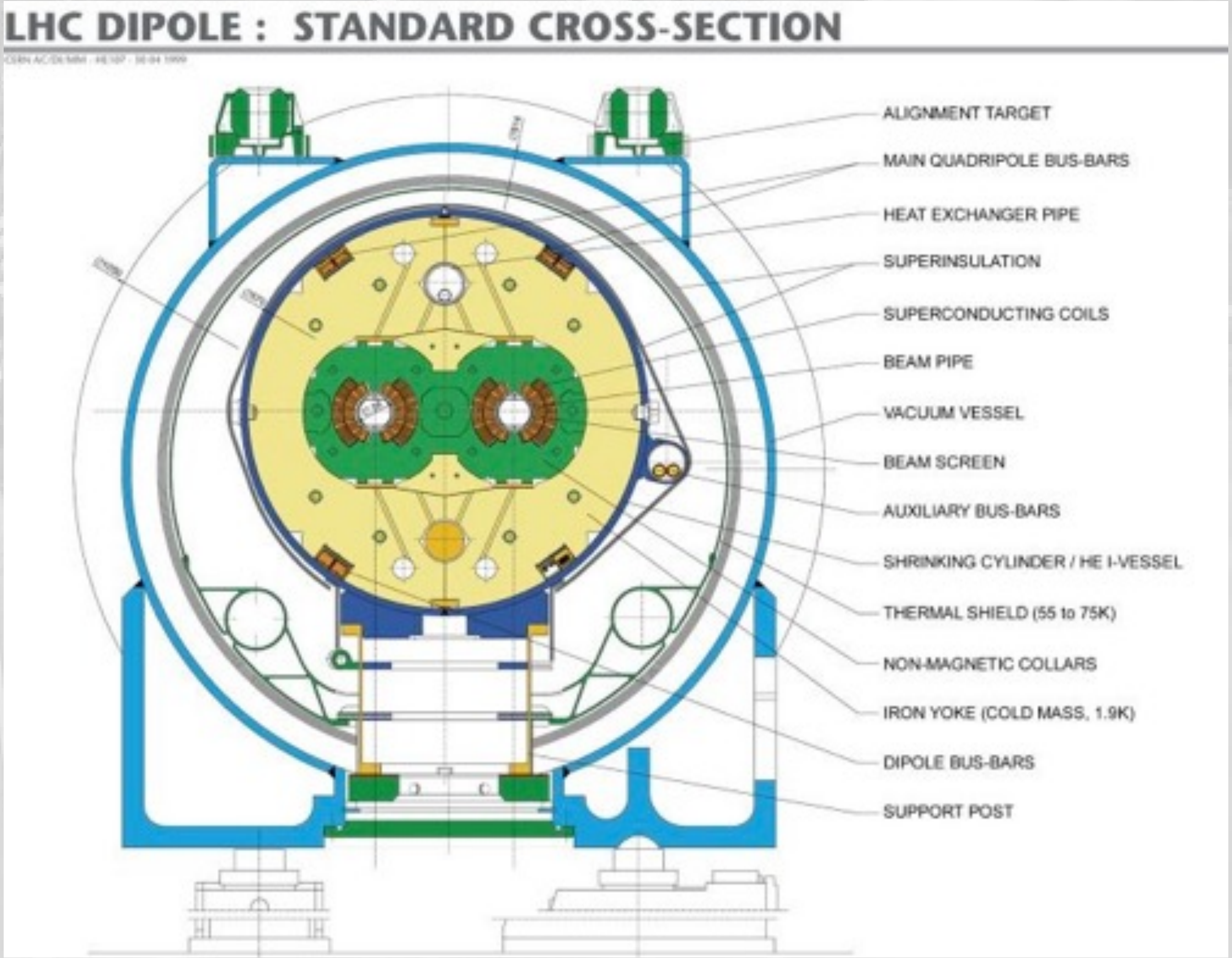


LHC: Large Hadron Collider
SPS: Super Proton Synchrotron
AD: Antiproton Decelerator
ISOLDE: Isotope Separator OnLine DEvice
PSB: Proton Synchrotron Booster
PS: Proton Synchrotron
LINAC: LINear ACcelerator
LEIR: Low Energy Ion Ring
CNGS: Cern Neutrinos to Gran Sasso

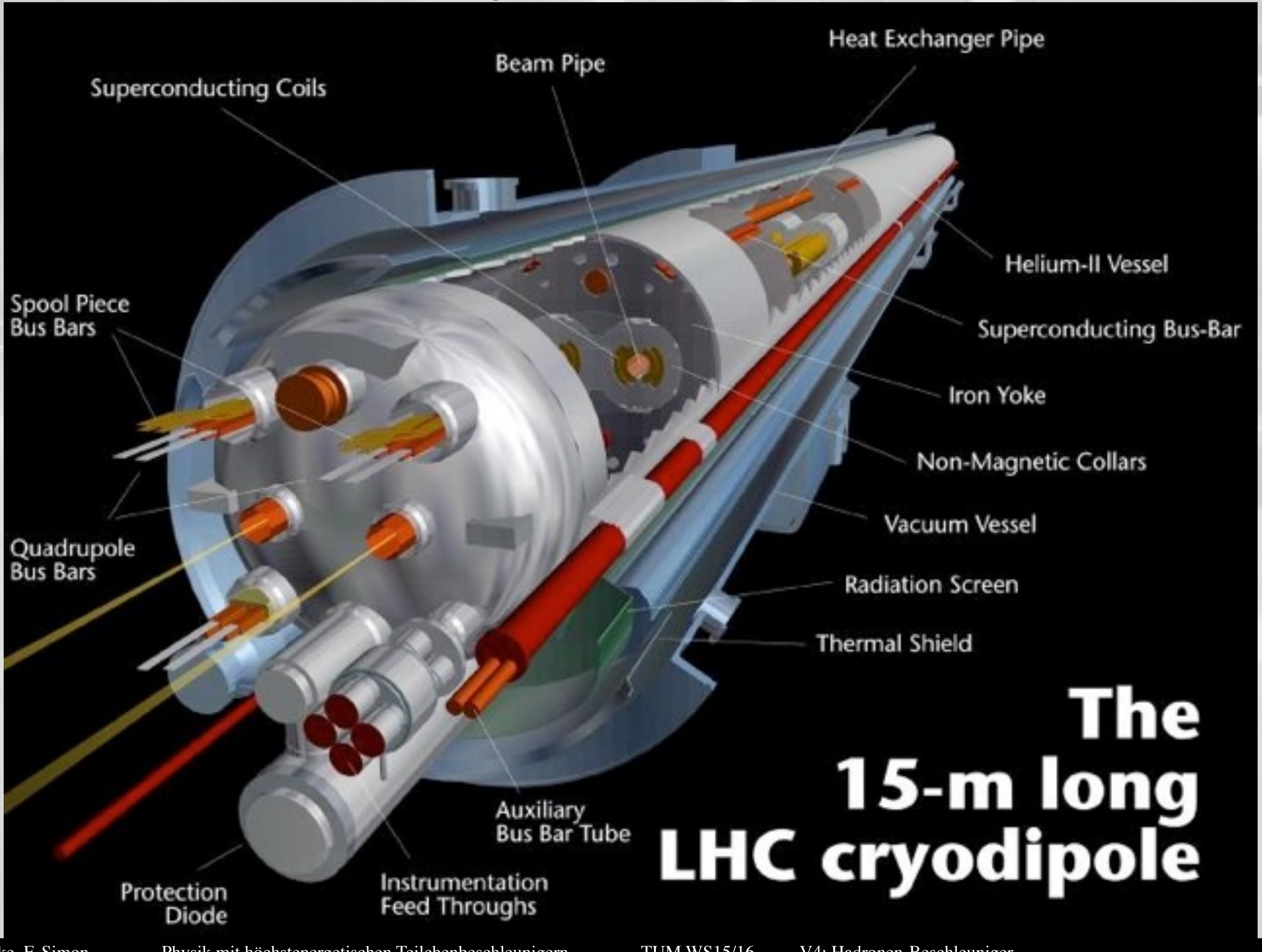
General LHC Parameters Version 4.0 (These parameters correspond to optics version 6.4 and the RF parameter update from the 14. LTC meeting (15. October 2003)) (the Version 3 parameters can be found here)		
Momentum at collision	7	TeV / c
Momentum at injection	450	GeV / c
Machine Circumference	26658.883	m
Revolution frequency	11.2455 (*)	kHz
Super-periodicity	1	
Lattice Type	FODO, 2-in-1	
Number of lattice cells per arc	23	
Number of insertions	8	
Number of experimental insertions	4	
Utility insertions	2 collimation 1 RF and 1 extraction	
Dipole field at 450 GeV	0.535	T
Dipole field at 7 TeV	8.33	T
Bending radius	2803.95	m
Main dipole coil inner diameter	56	mm
Distance between aperture axes (1.9 K)	194	mm
Main Dipole Length	14.3	m
Main Dipole Ends	236.5	mm
Half Cell Length	53.45	m
Phase advance per cell	90	degree
Horizontal tune at injection	64.28	
Vertical tune at injection	59.31	
Horizontal tune at collision	64.31	
Vertical tune at collision	59.32	
Maximum beta-function (cell)	177 / 180 (**)	m
Minimum beta-function (cell)	30 / 30 (**)	m

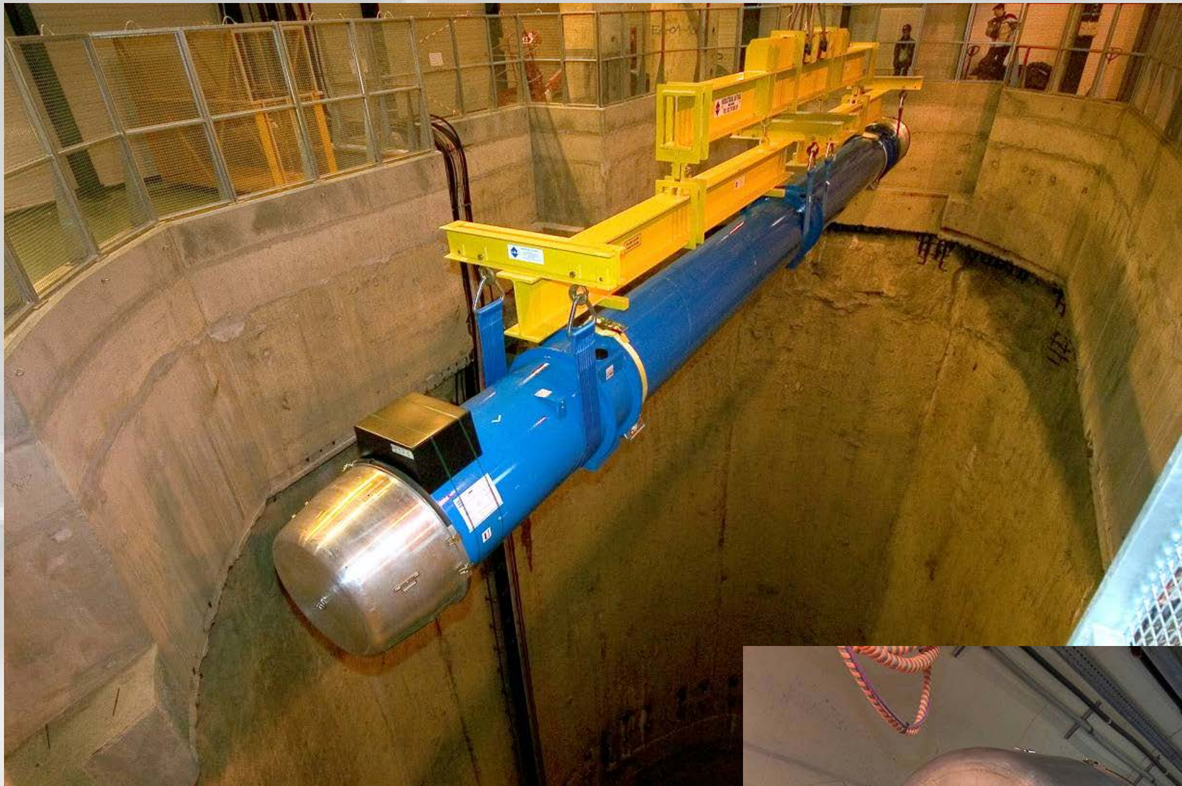
Maximum dispersion (cell)	2.018 / 0.0 (**)	m
Maximum beta-function (service insertions)	594.5 / 609.3 (**)	m
Free space for detectors	+/-23	m
Gamma Transition	55.678	
Momentum Compaction	0.0003225 (**)	
Main RF System	400.8	MHz
Harmonic number	35640	
Voltage of 400 MHz RF system at 7 TeV	16	MV
Synchrotron frequency at 7 TeV	23.0	Hz
Bucket area at 7 TeV	7.91	eV.s
Bucket half-height at 7 TeV	3.56	10^{-4}
Voltage of 400 MHz RF system at 450 GeV	8	MV
Synchrotron frequency at 450 GeV (without 200 MHz RF)	63.7	Hz
Bucket area at 450 GeV	1.43	eV.s
Bucket half-height at 450 GeV	10	10^{-4}
Capture RF system	200.4	MHz

- Superconducting dipole magnets
- biggest challenge: magnetic field of 9 Tesla
  - overall 1300 dipoles, each 15 m long
  - operation temperature of 1.9 K (super-fluidity)



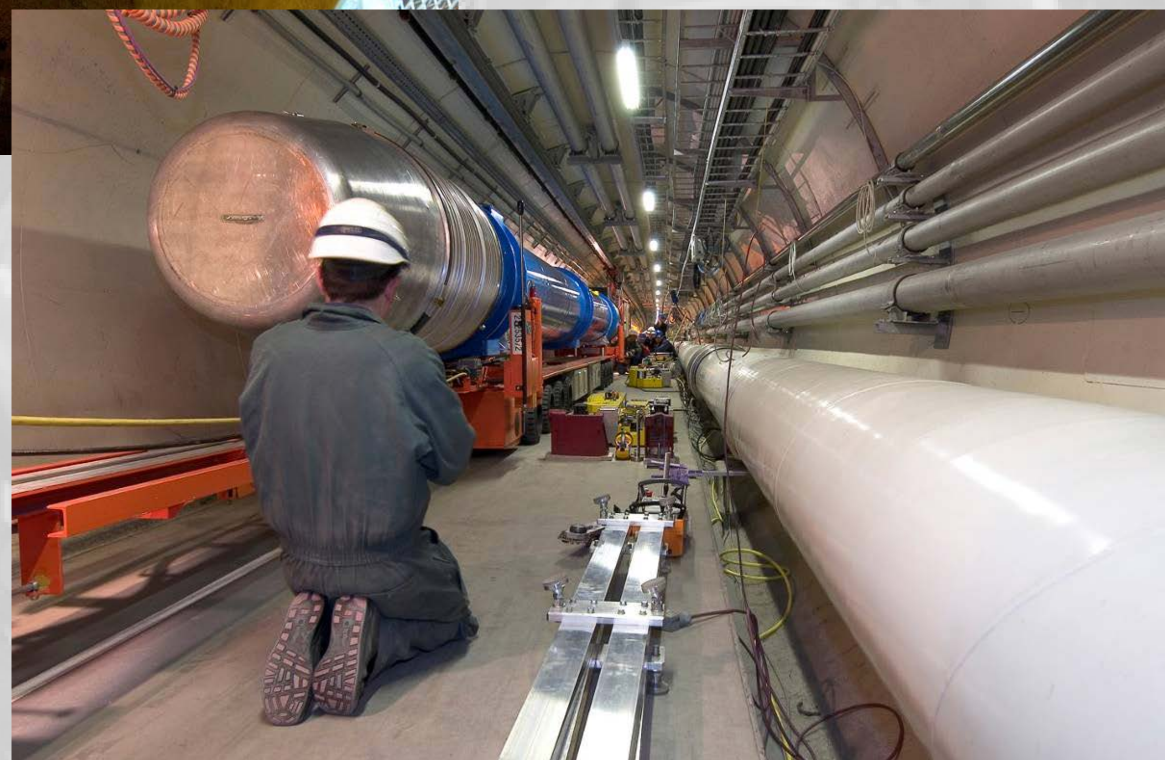
LHC Dipole Magnets

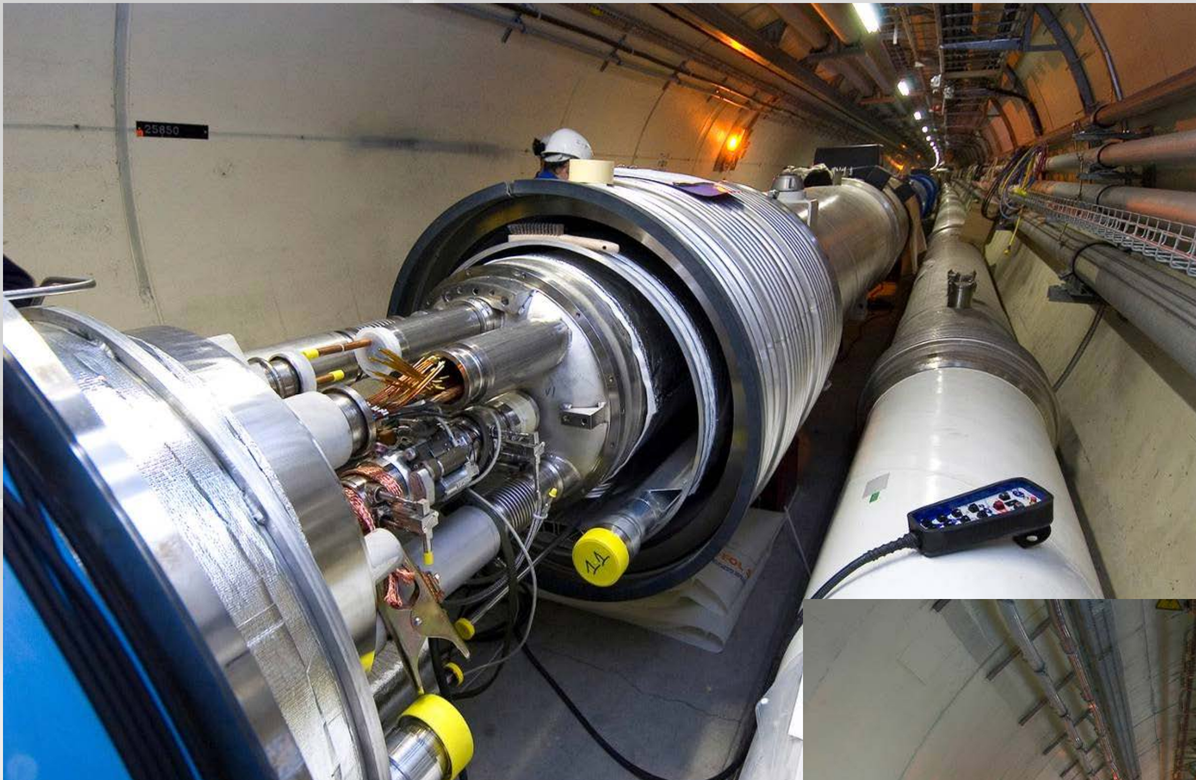




Lowering of the first dipole into the tunnel (March 2005)

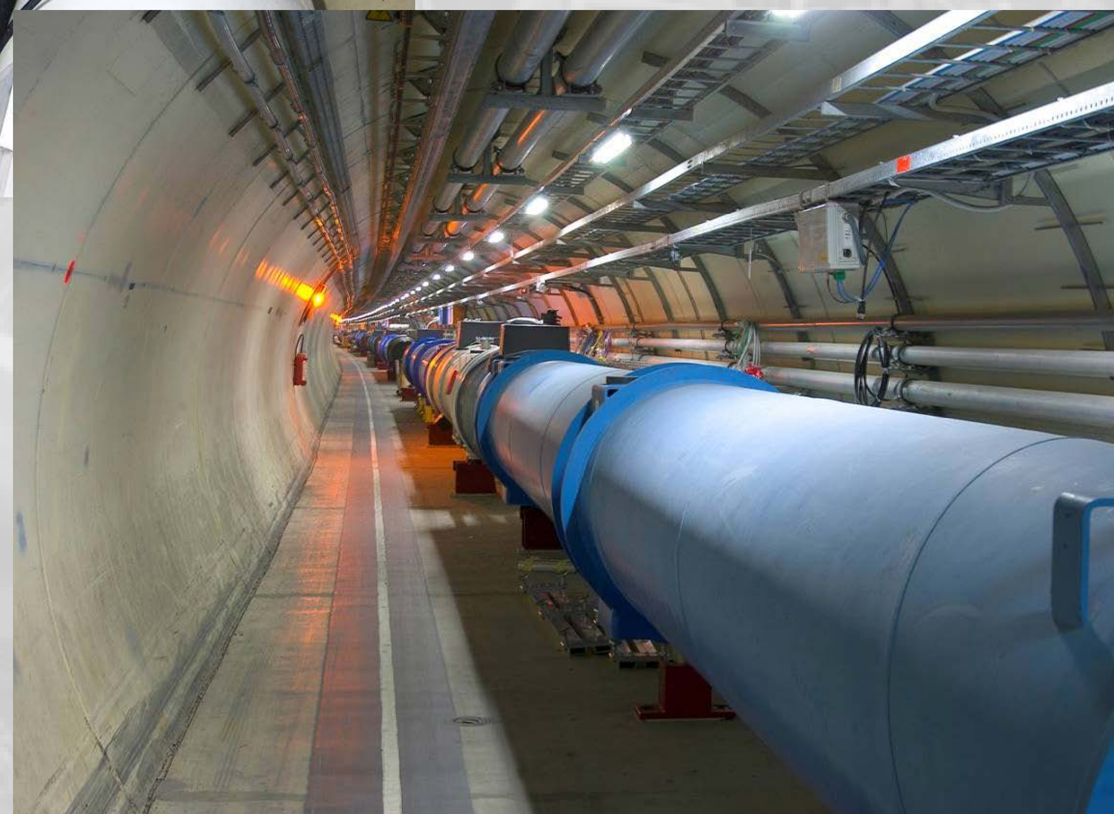
Installation of dipoles in the LHC ring





Interconnection of the dipoles
and connection to the cryoline

A view of the tunnel....



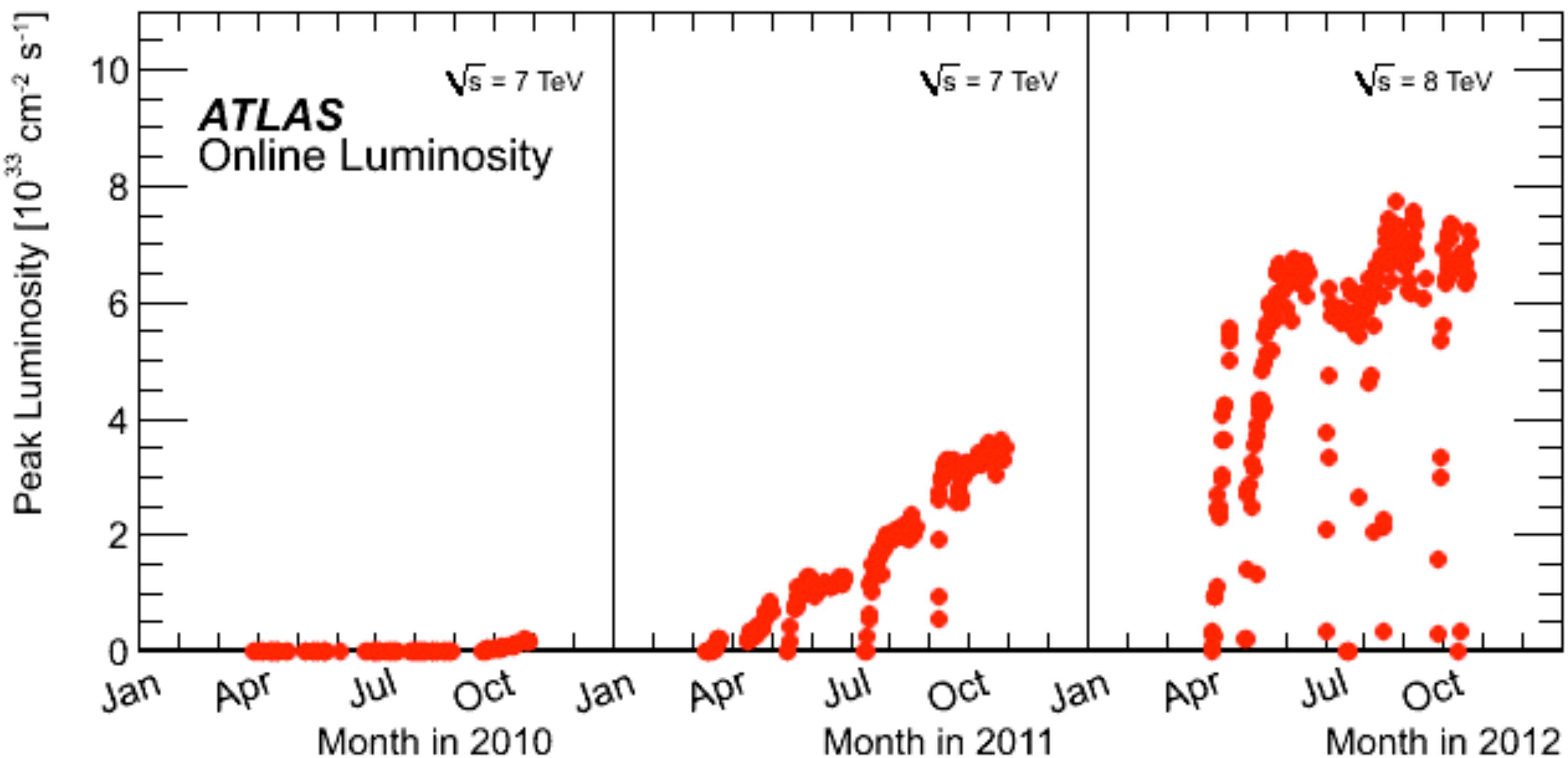
LHC Tunnel (12/2005)

LHC - Status:

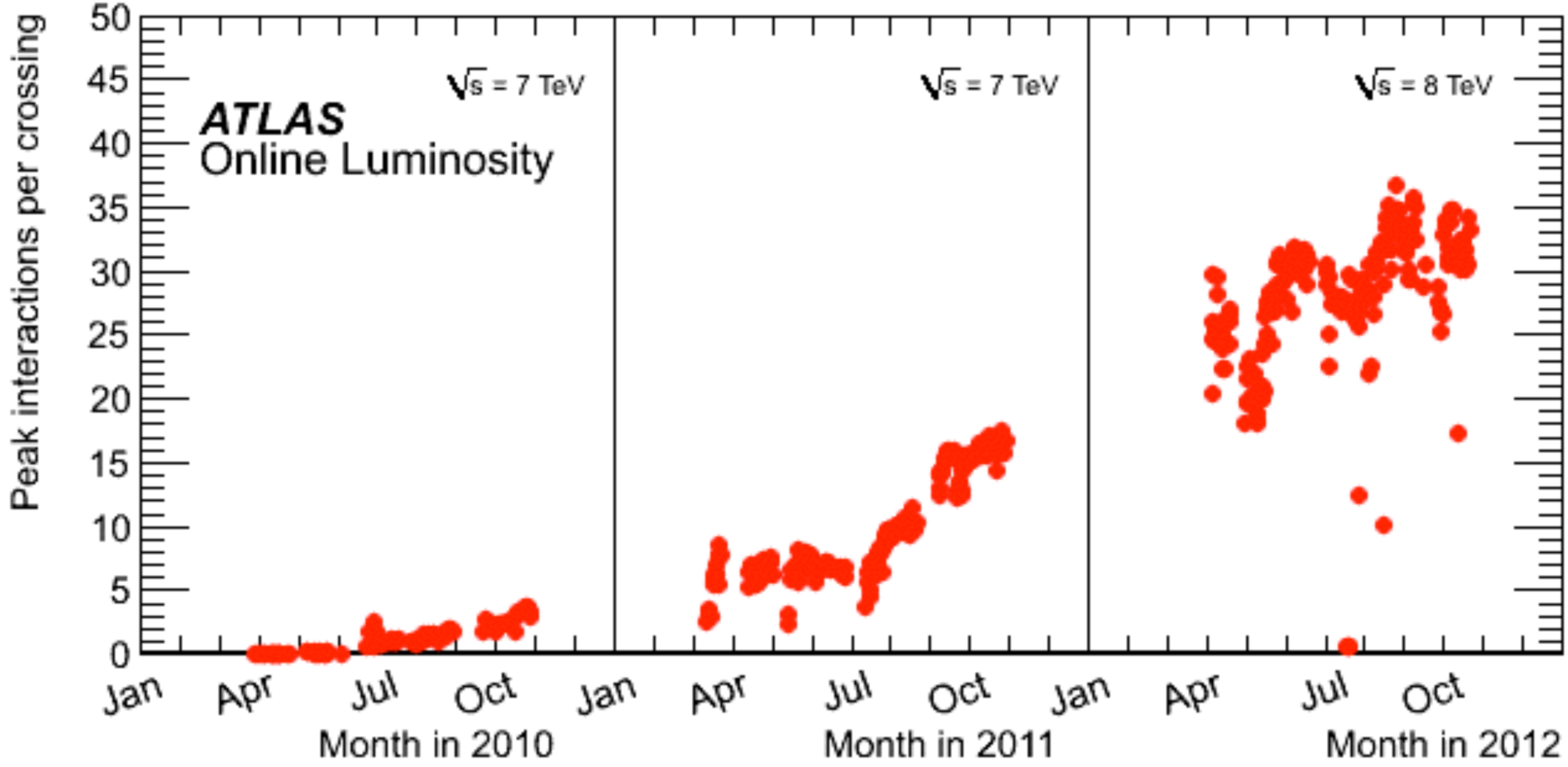
- 09.09.2008: first stable „beam“ in LHC
- 19.09.2008: technical problems with large impact: destruction of parts of LHC ring; repair of ~1 Jahr.
- 20.11.2009: restart after repair; first collisions!
- 11.12.2009: world record: collisions at 2.36 TeV! (2·1.18 TeV)
- 30.03.2010: collisions at7 TeV (2 · 3.5 TeV)
- Nov. 2011: 5 fb^{-1} at 7 TeV per experiment
- 2012:
  - collisions at 8 TeV
  - until Dec: ~20 fb^{-1}
  - 4. Juli 2012: a new Boson ...

- 2013/14: long shut-down (LS1);
- 2015: operation at 13 TeV; 25 ns bunch spacing

LHC Peak Luminosity ~ 8E33 (October 2012)



LHC: interactions per bunch x-ing

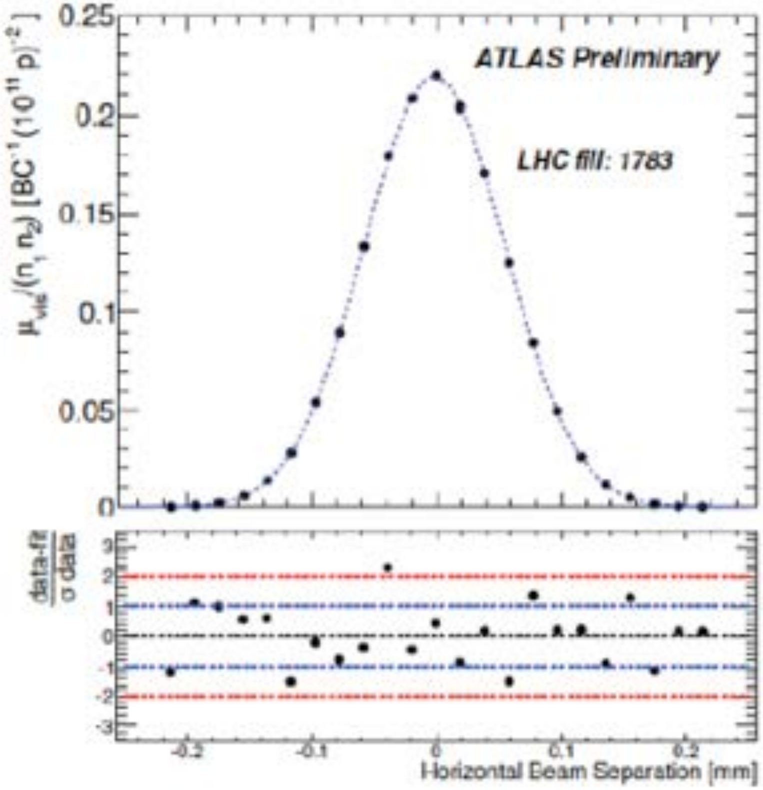


LHC luminosity determination

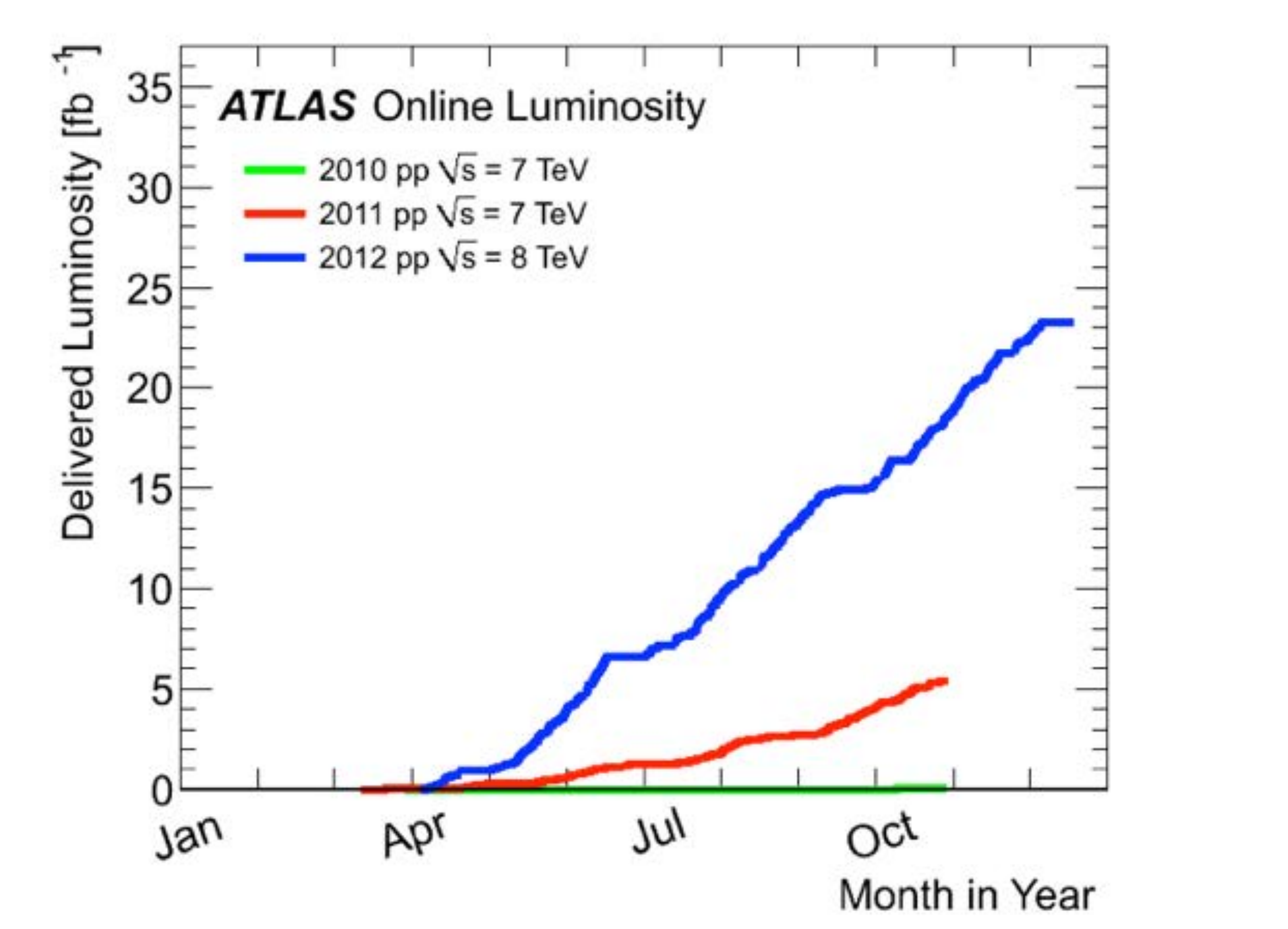
$$\mathcal{L} = \frac{n_b f_r n_1 n_2}{2\pi \Sigma_x \Sigma_y}$$

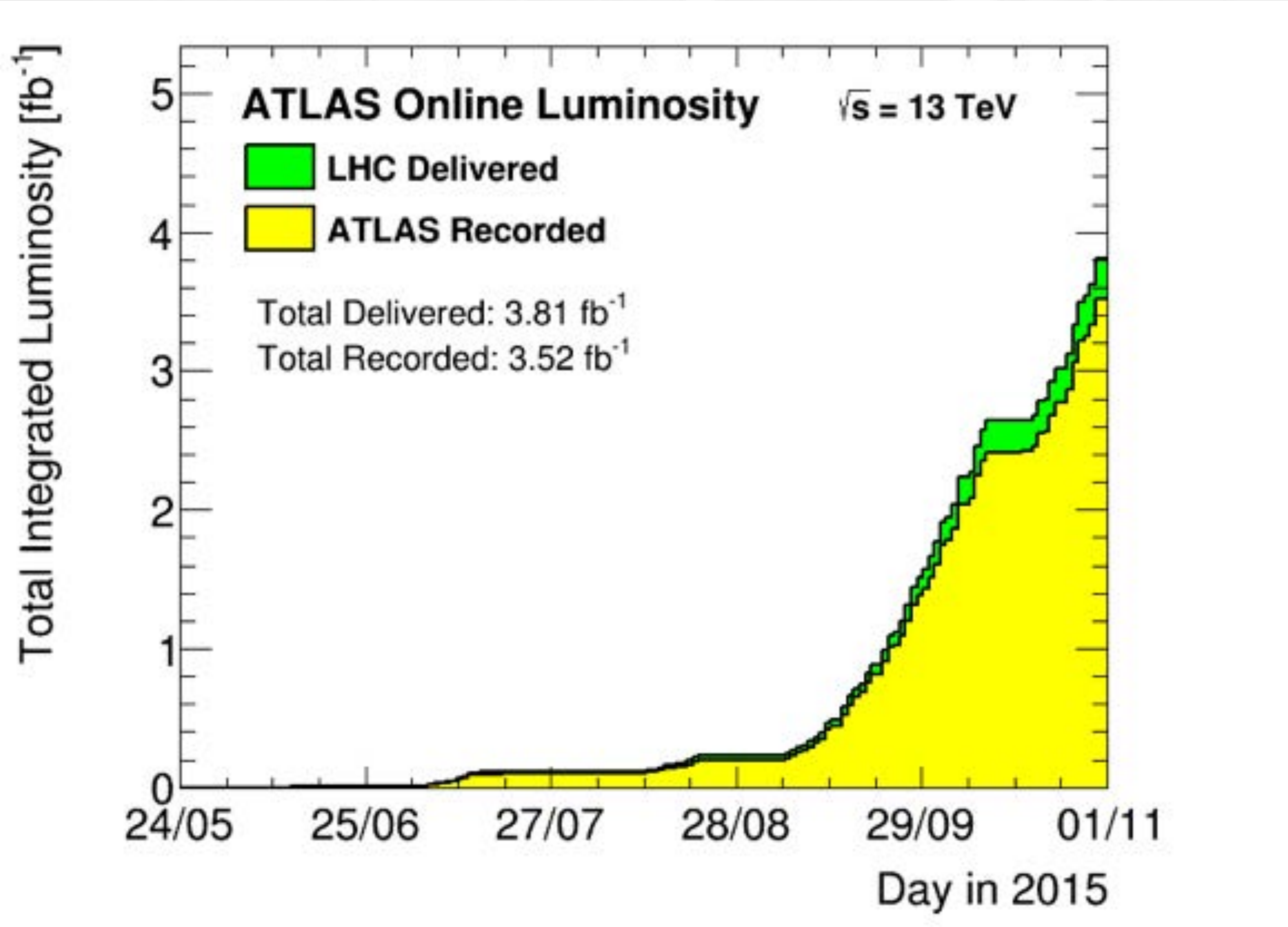
- Calibrated using van der Meer scans
- Present uncertainty ±3.7%
  - dominated by beam current measurements ±3%
    - already impressive
    - could come down by around a factor of two?

–> ± 1.8% achieved (2013)

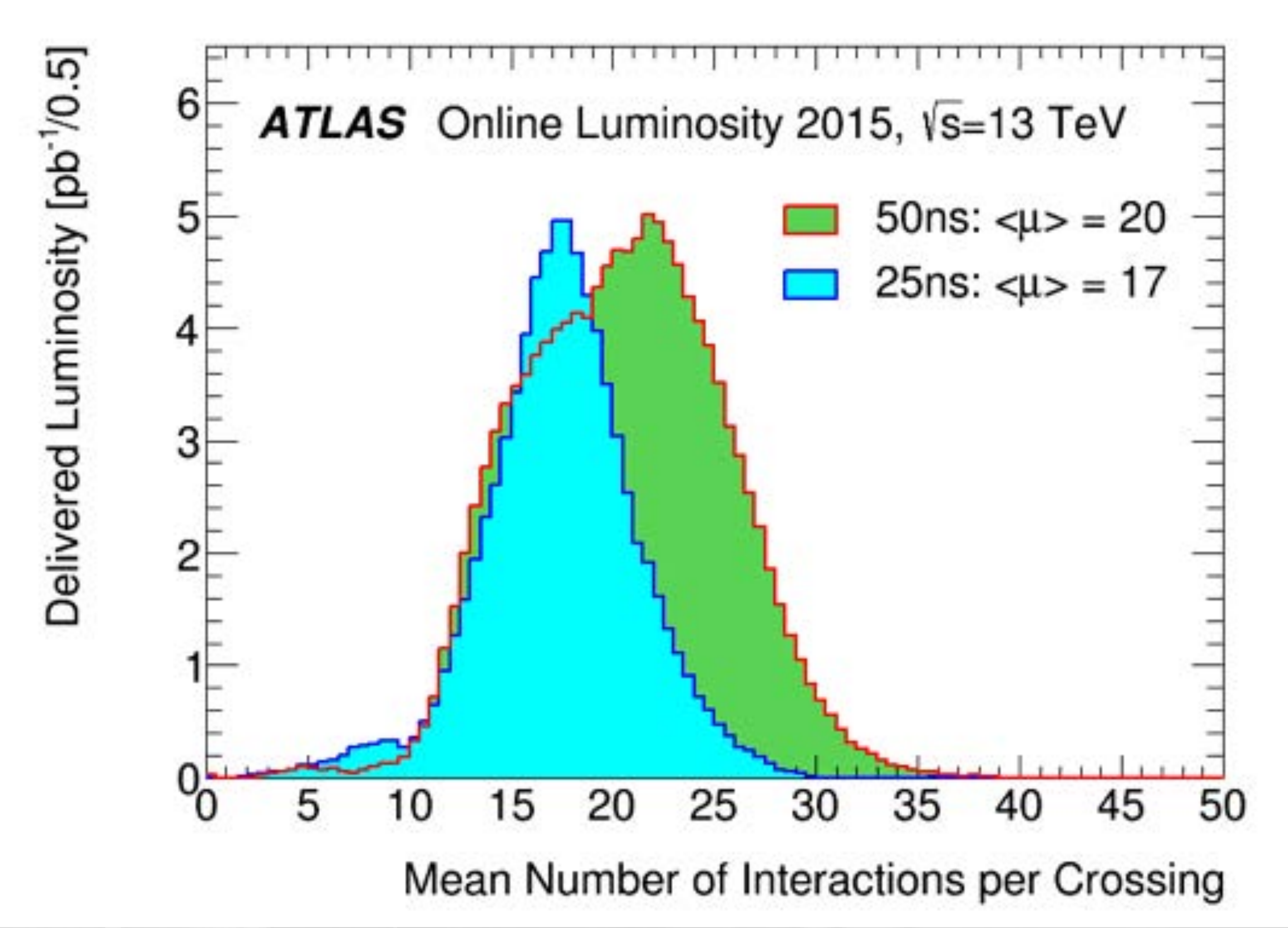


ATLAS online integ. Luminosity



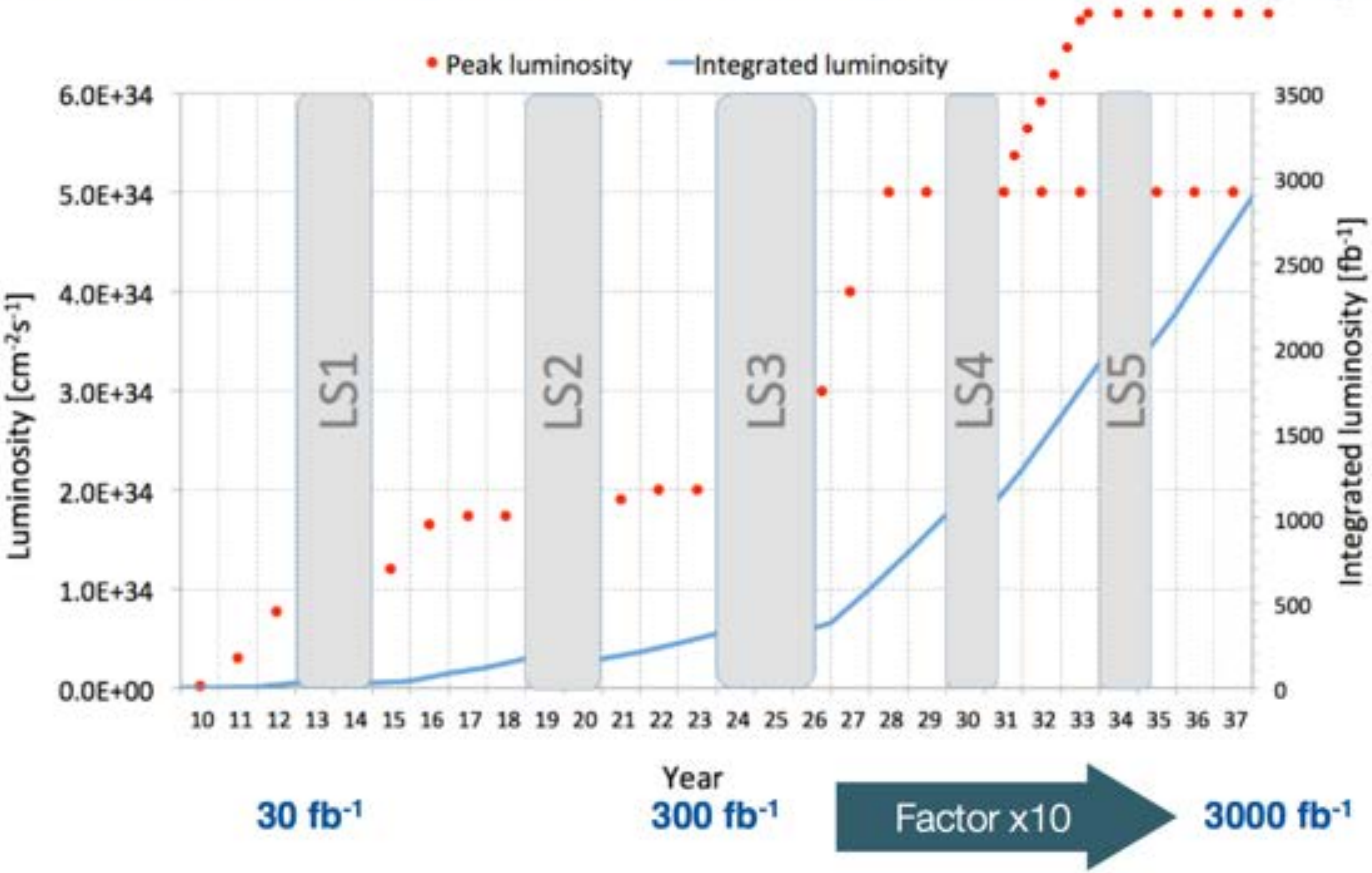


ATLAS Online Luminosity
√s = 13 TeV
LHC Delivered
ATLAS Recorded
Total Delivered: 3.81 fb⁻¹
Total Recorded: 3.52 fb⁻¹
Total Integrated Luminosity [fb⁻¹]
0
1
2
3
4
5
24/05
25/06
27/07
28/08
29/09
01/11
Day in 2015


ATLAS Online Luminosity 2015, √s=13 TeV
50ns: <μ> = 20
25ns: <μ> = 17
Delivered Luminosity [pb⁻¹/0.5]
Mean Number of Interactions per Crossing
0
1
2
3
4
5
6
0
5
10
15
20
25
30
35
40
45
50

HL-LHC Goals and Running Conditions

- 3000 fb^{-1} is the target integrated luminosity
- $5x10^{34}$ —> 140 Pile-up is the nominal peak luminosity
- $7x10^{34}$ —> 200 Pile-up is the ultimate peak luminosity (>LS4)



Literature:

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- H. Wiedemann, “Particle Accelerator Physics” I & II Springer 1993/1995
- K. Wille, Physik der Teilchenbeschleuniger, Teubner 2002
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- Fermilab, http://www.fnal.gov/
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next lecture: 9.11. Trigger, Data Acquisition, Computing