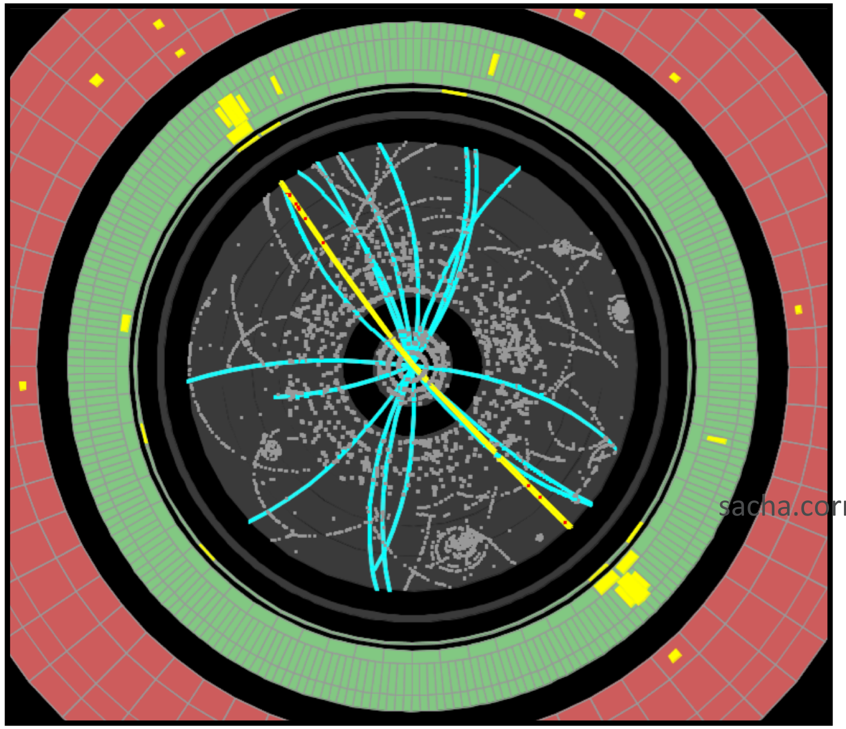
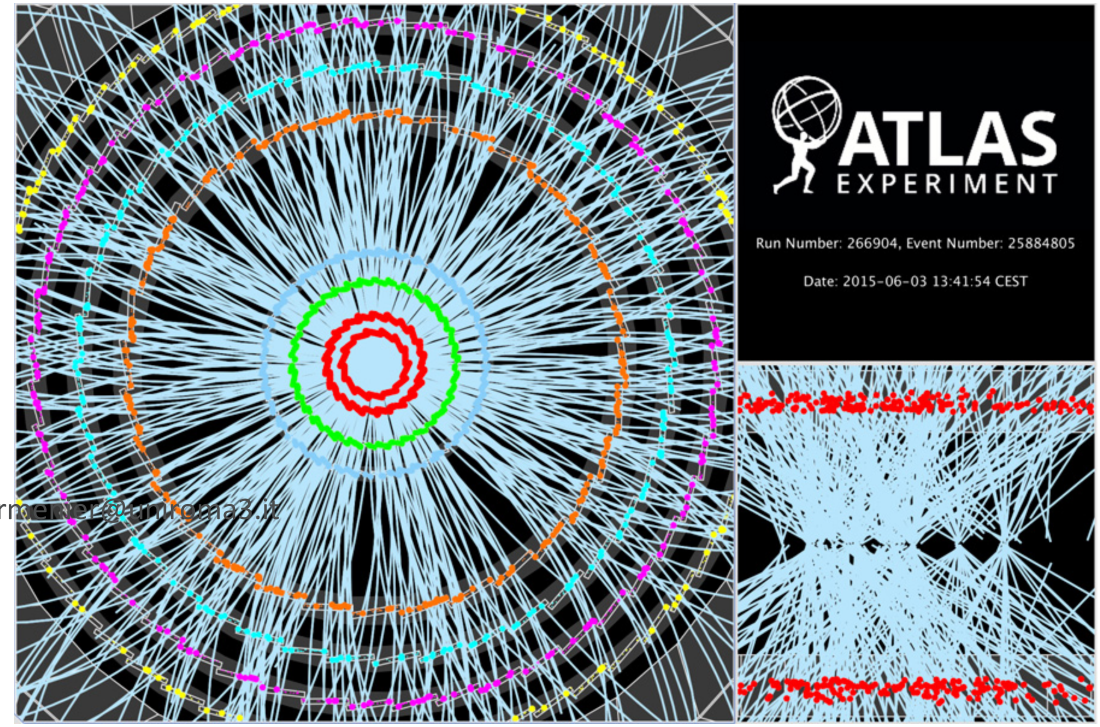
Lecture 1: Experiments & Accelerators





Z ➛ ee Candidate
[September 2010]

Display of a proton-proton collision event recorded by ATLAS on 3 June 2015, with the first LHC stable beams at a collision energy of 13 TeV. Tracks reconstructed by the tracking detector are shown as light blue lines, and hits in the layers of the silicon tracking detector are shown as colored filled circles. The four inner layers are part of the silicon pixel detector and the four outer layers are part of the silicon strip detector. The layer closest to the beam, called IBL, is new for Run 2. In the view in the bottom right it is seen that this event has multiple pp collisions. The total number of reconstructed collision vertices is 17 but they are not all resolvable on the scale of this picture.

Toni Baroncelli
INFN RomaTRE

Originally inspired by Hans-Christian Schultz-Coulon
Kirchhoff-Institut für Physik

but also Material from many different sources

Introduction & Motivation

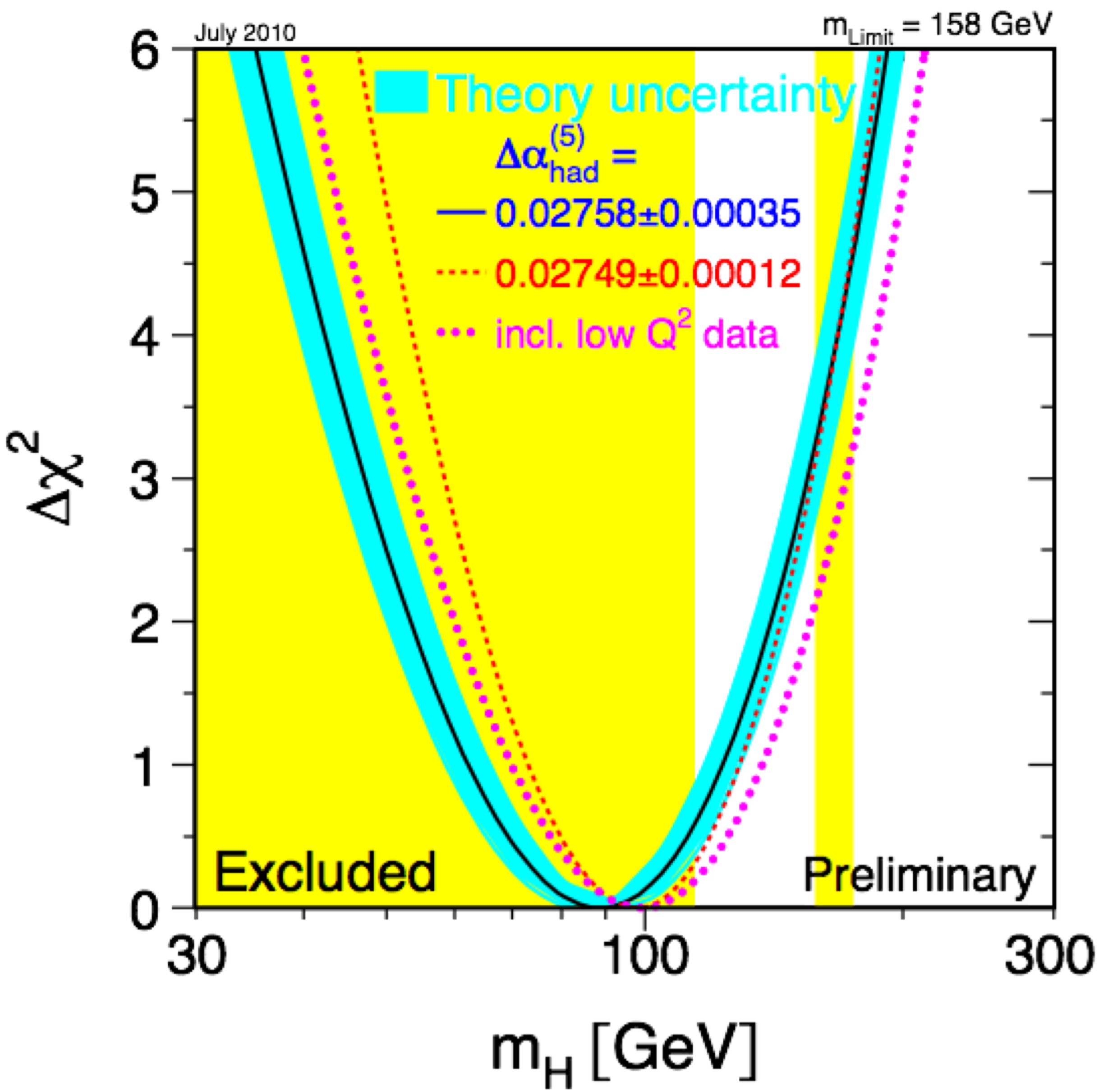
The LHC and its Experiments

LHC: motivations

• Is the mass of elementary particles being generated by the Higgs mechanism via **EW symmetry breaking**? The ATLAS and CMS experiments discovered the Higgs boson, which is strong evidence that the Standard Model has the correct mechanism of giving mass to elementary particles. **Check couplings!**
• Is **supersymmetry**, extension of the SM, realised in nature, implying that all known particles have supersymmetric partners?
• Are there **extra dimensions**, as predicted by various models based on string theory, and can we detect them?
•What is the nature of the **dark matter** that appears to account for 27% of the mass-energy of the universe?
•What about **dark energy**?

Other open questions that may be explored using high-energy particle collisions:
• Why is the **gravity** force so many orders of magnitude weaker than the other three fundamental forces?
• Why are there apparent violations of the symmetry between **matter and antimatter**?
• What are the nature and properties of **quark-gluon plasma**, thought to have existed in the early universe and in certain compact and strange and strange astronomical objects today? This will be investigated by *heavy ion collisions*, mainly in ALICE, but also in CMS, ATLAS and LHCb. First observed in 2010, findings published in 2012 confirmed the phenomenon of jet quenching in heavy-ion collisions.

Our Knowledge about the Higgs before its discovery



EW-Fits:

M_H = 89 GeV

M_H < 158 GeV @ 95% CL

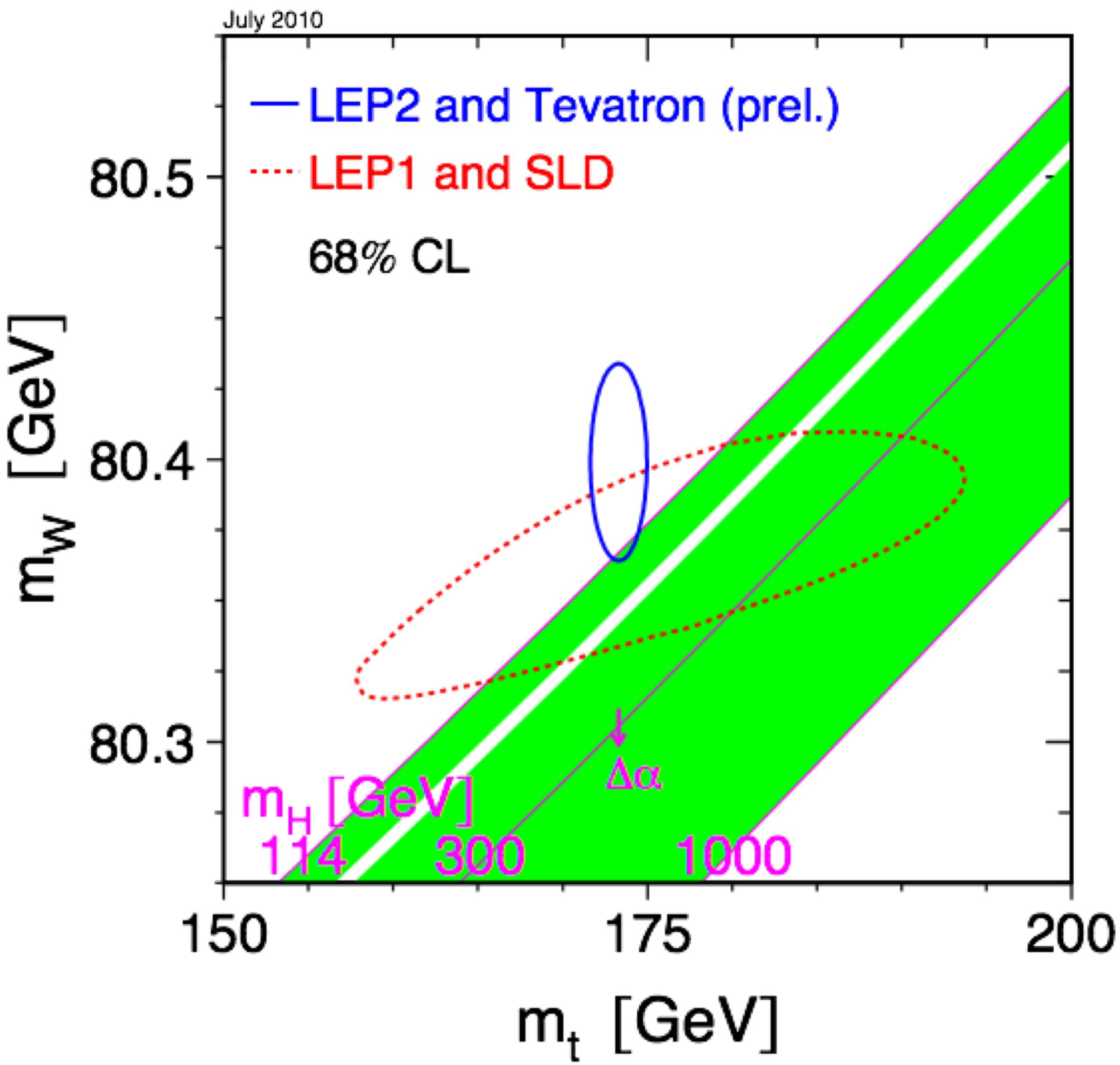
From direct search at LEP:

M_H > 114 GeV @ 95% CL

From direct search at Tevatron:

158 < M_H < 175 GeV @ 95% CL

Our Knowledge about the Higgs before its discovery



EW-Fits:

$M_H = 89^{+35}_{-26}$ GeV

$M_H < 158$ GeV @ 95% CL

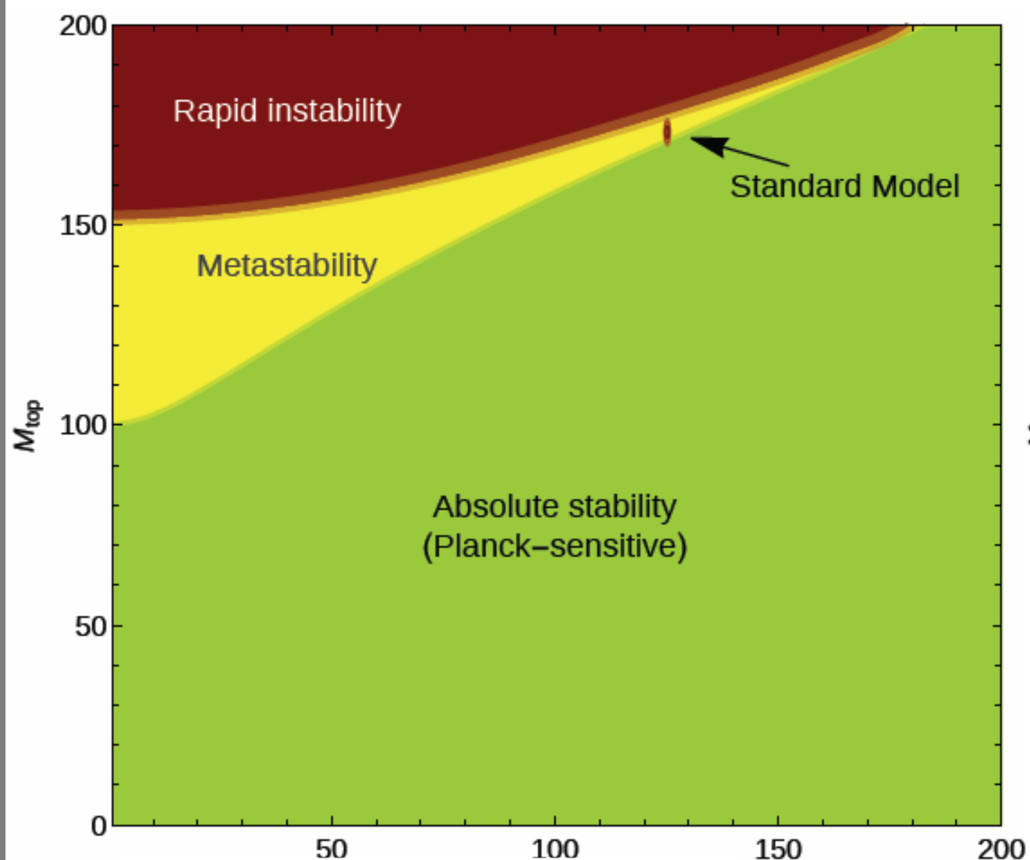
From direct search at LEP:

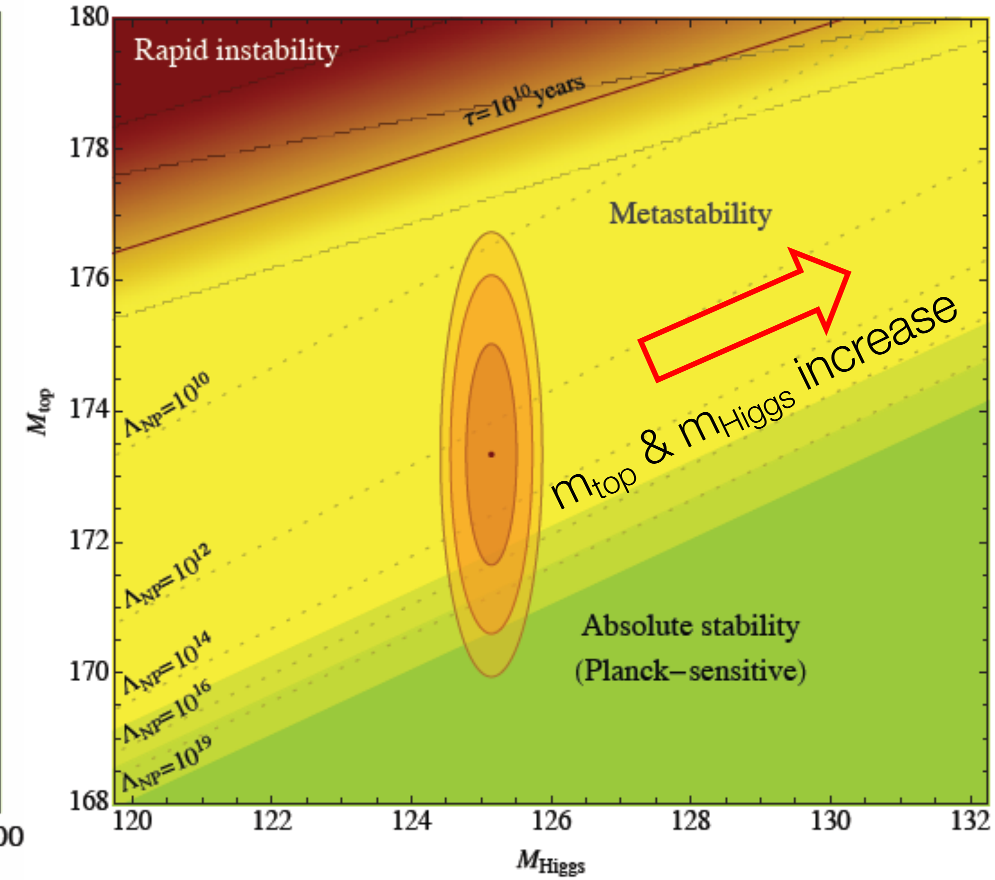
$M_H > 114$ GeV @ 95% CL

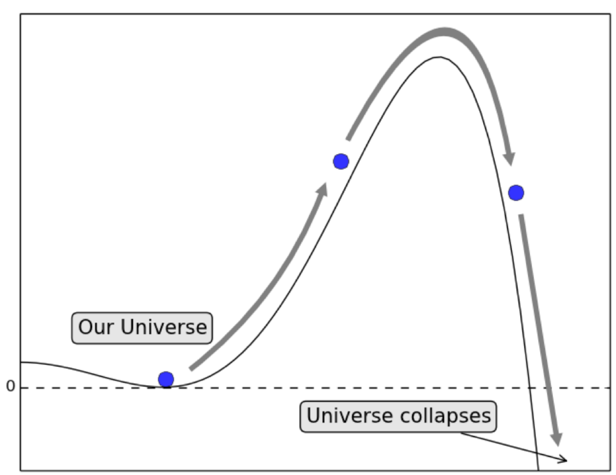
From direct search at Tevatron:

$158 < M_H < 175$ GeV @ 95% CL

After the Higgs discovery: m_{top} vs m_{Higgs} and stability of the Universe





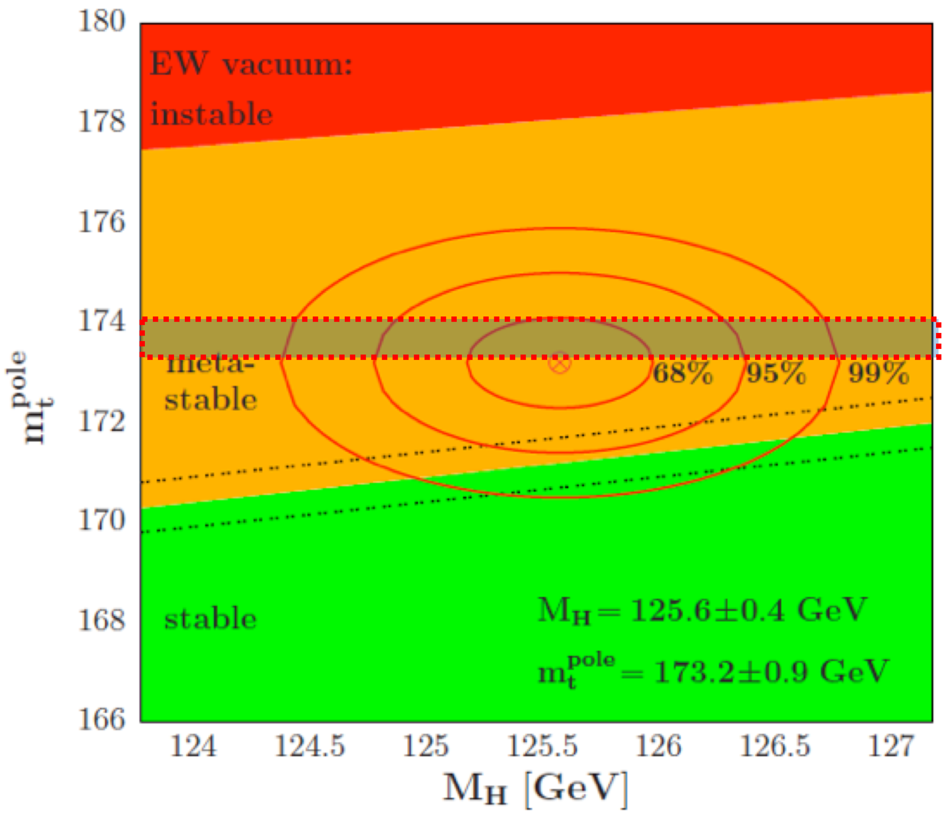


$$m_h^{pole} = (125.14 \pm 0.23)\ \text{GeV}$$

$$m_t^{pole} = (173.34 \pm 1.12)\ \text{GeV}$$

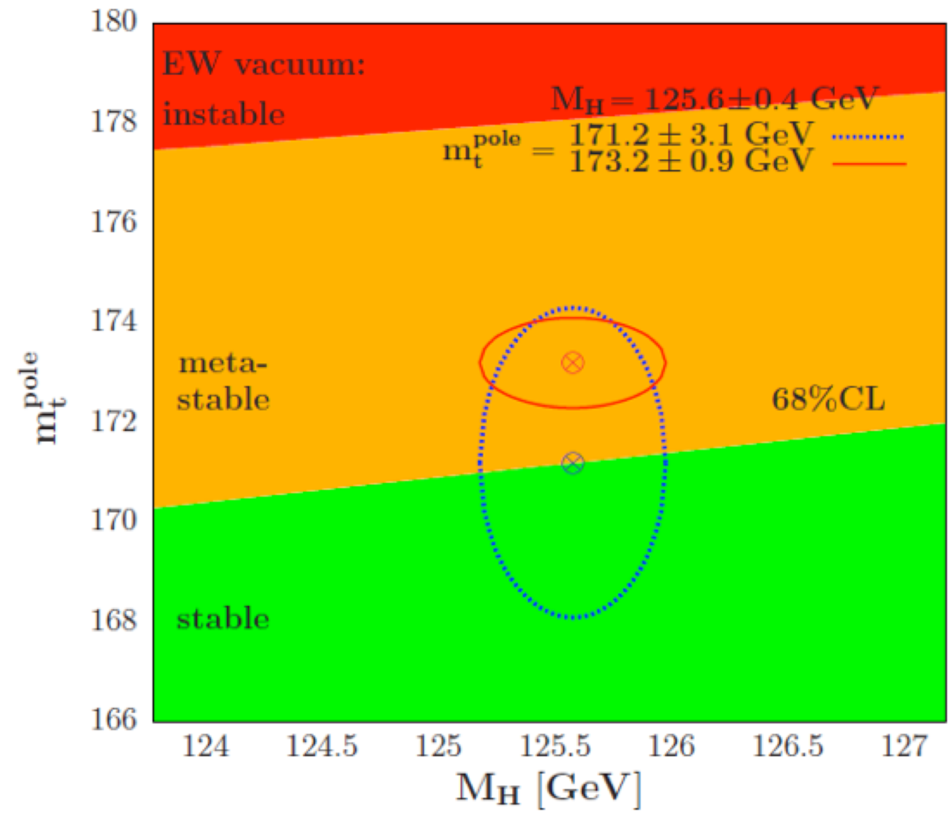
After the Higgs discovery: m_{top} vs m_{Higgs} and stability of the Universe

m_{top} = 173.2 ± 0.9 GeV



m_{top} = 173.2 ± 0.9 GeV

m_{top} = 171.2 ± 3.1 GeV

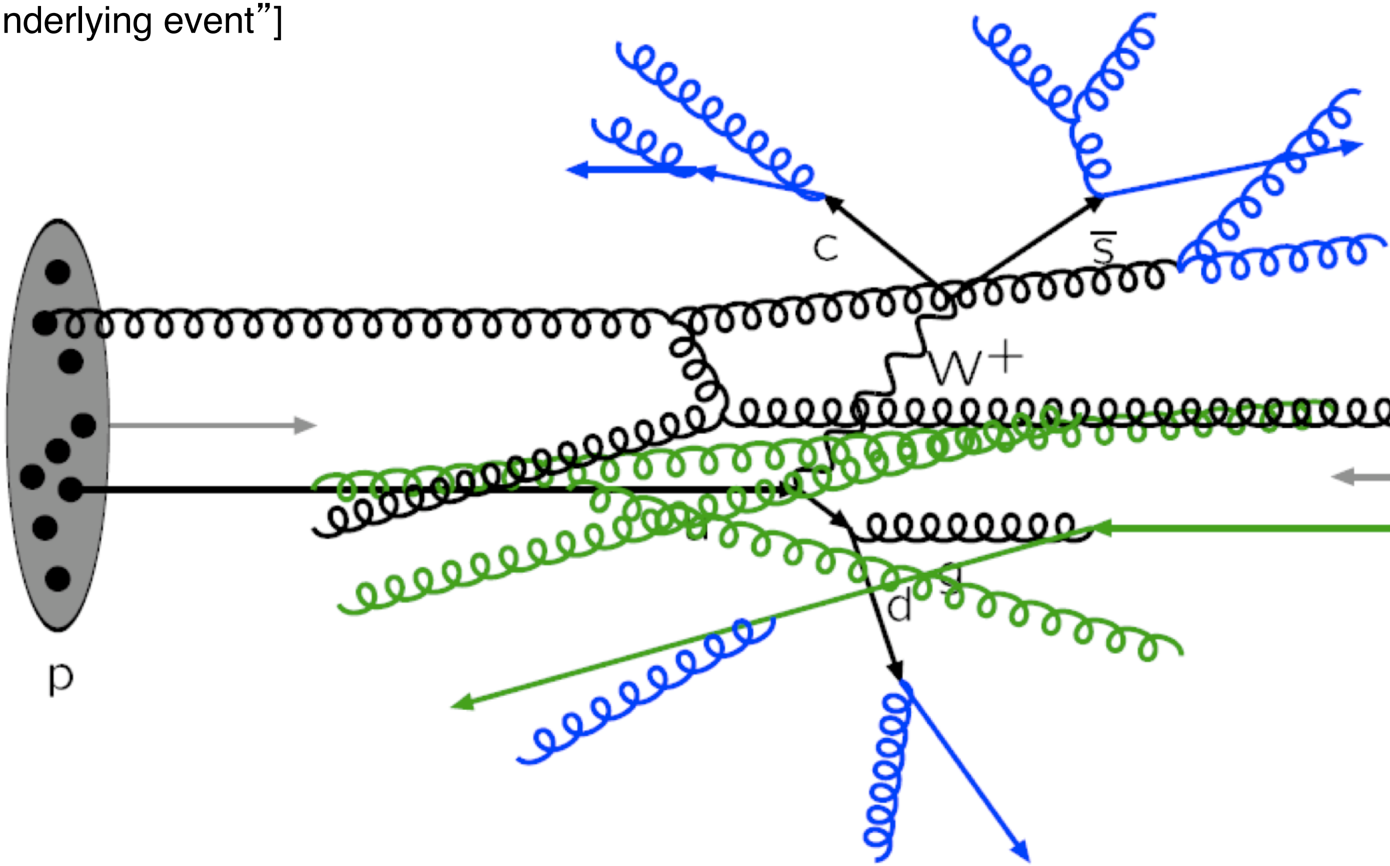


The ellipses in the [M_H,m_{tpole}] plane with the inputs M_H=125 +/-0.4 GeV and α_s=0.1187 are confronted with the areas in which the SM vacuum is absolutely stable, metastable and unstable up to the Planck scale. Left plot m_{tpole} is identified with the Tevatron measured top mass m_t=173.2+/-0.9 GeV, Right: m_{tpole} is taken as the as the one measured at the Tevatron m_t=171.2+/-3.1GeV extracted for the ttbar production cross section

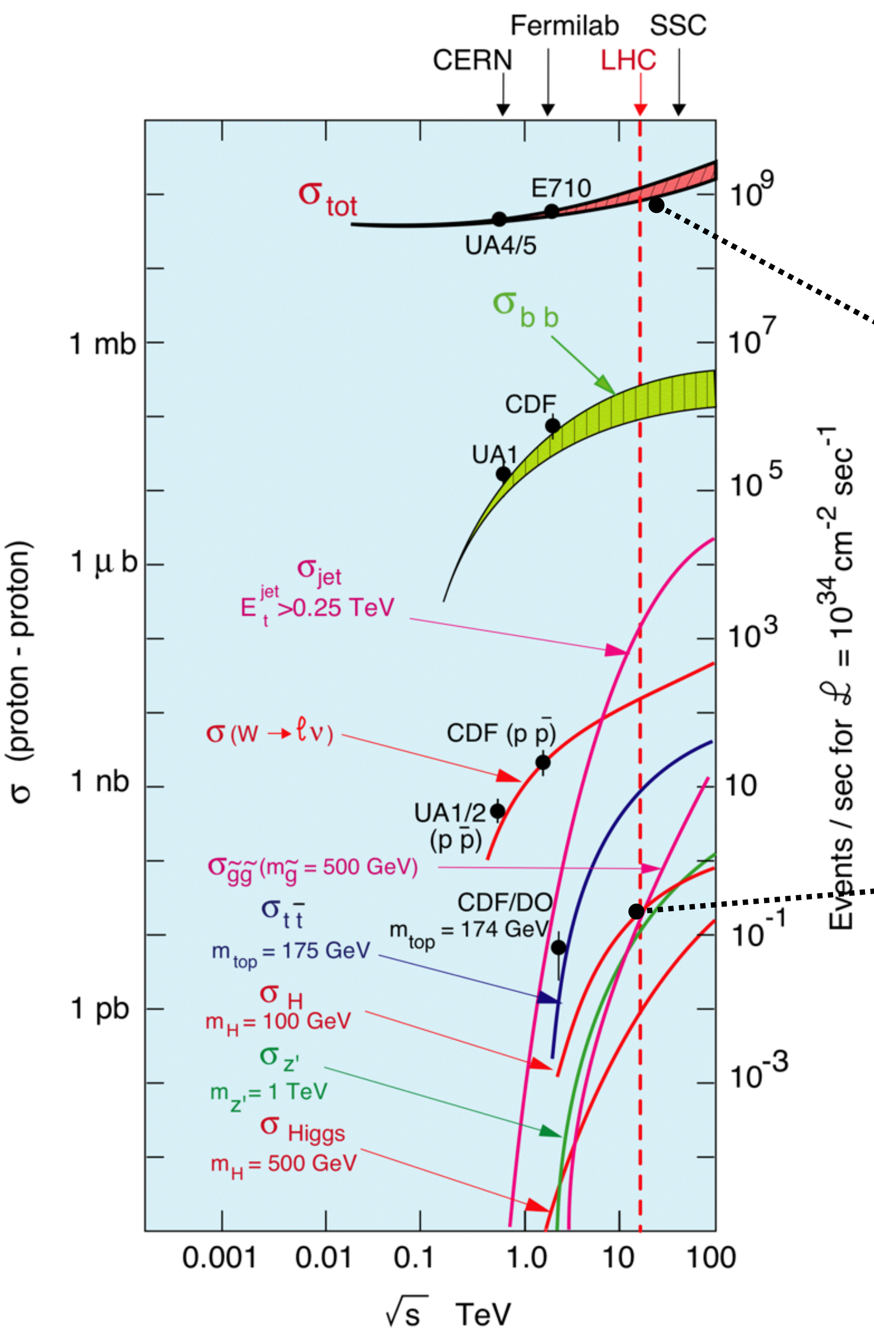
Proton-Proton Scattering @ LHC

Very complex topologies!
(very different from e^+e^- collisions)

- Hard interaction: qq, gg, qg fusion
- Initial and final state radiation (ISR,FSR)
- Secondary interaction
  ["underlying event"]



Needle in a Haystack



10^9 Events/sec
[1 Mbyte/Event]

~ 10^{10} reduction needed

Efficient
rate reduction needed

[Storage rate: 100 Hz]

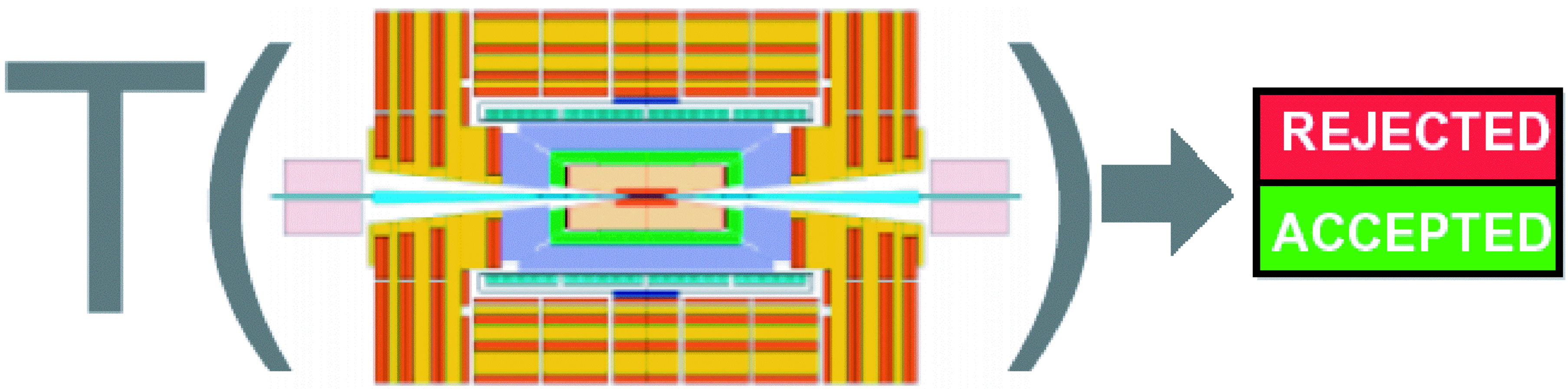
10 Events/min
[$m_H \approx$ 100 GeV]

with 0.2% $H \rightarrow \gamma\gamma$
1.5% $H \rightarrow ZZ$

Trigger !

Challenge 1: Fast Trigger System

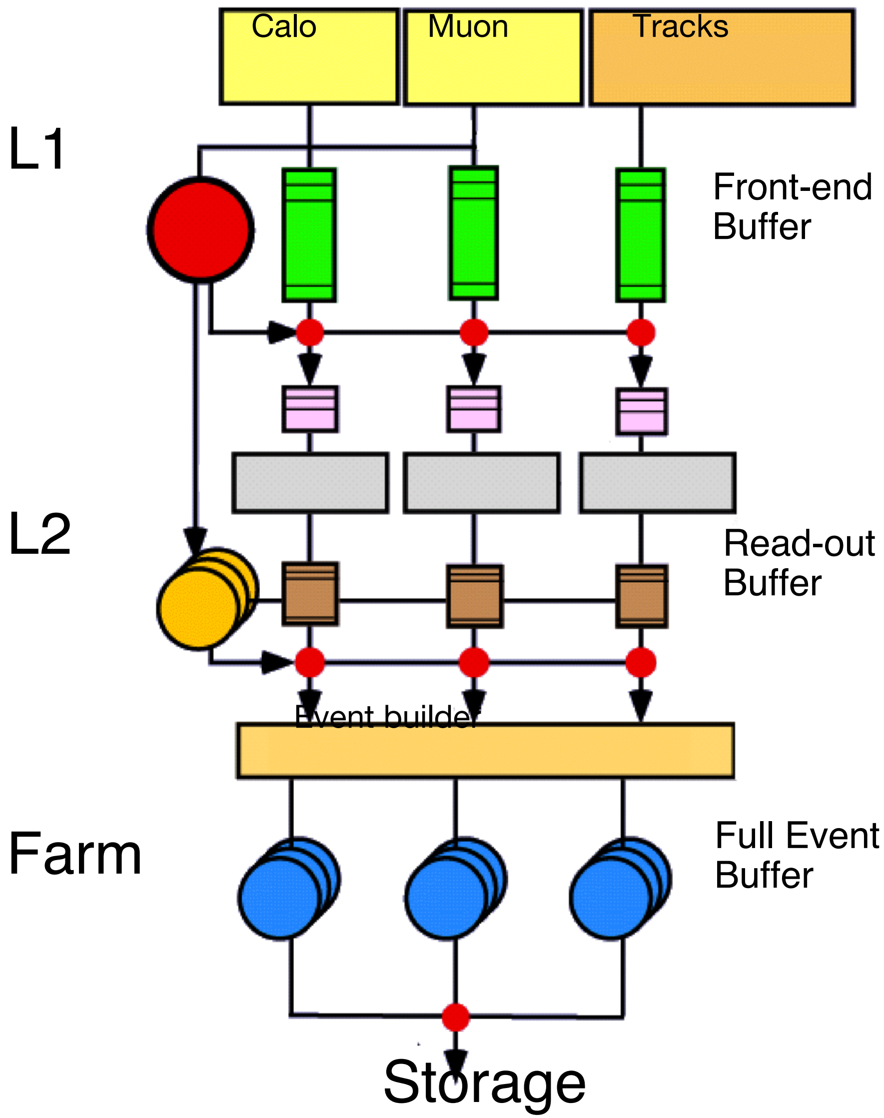
Fast selection of interesting Events
Number of necessary decisions: 40 million/sec



Function T(…) is highly complex
Detector data not directly available ➥ Stepwise decision

→ Trigger Levels

Challenge 1: Fast Trigger System



Out-dated schema! Now two levels only

40 MHz

LEVEL-1 TRIGGER

- Hardware-Trigger [FPGAs & ASICs]
- Information from calorimeters & muon systems; low granularity
- 2 µs latency [2.5 µs pipelines]

~75 kHz

LEVEL-2 TRIGGER

- Regions-of-Interest
- In principle full information of all subdetectors; high granularity
- Decision time: O(10 ms)

~2 kHz

EVENT FILTER

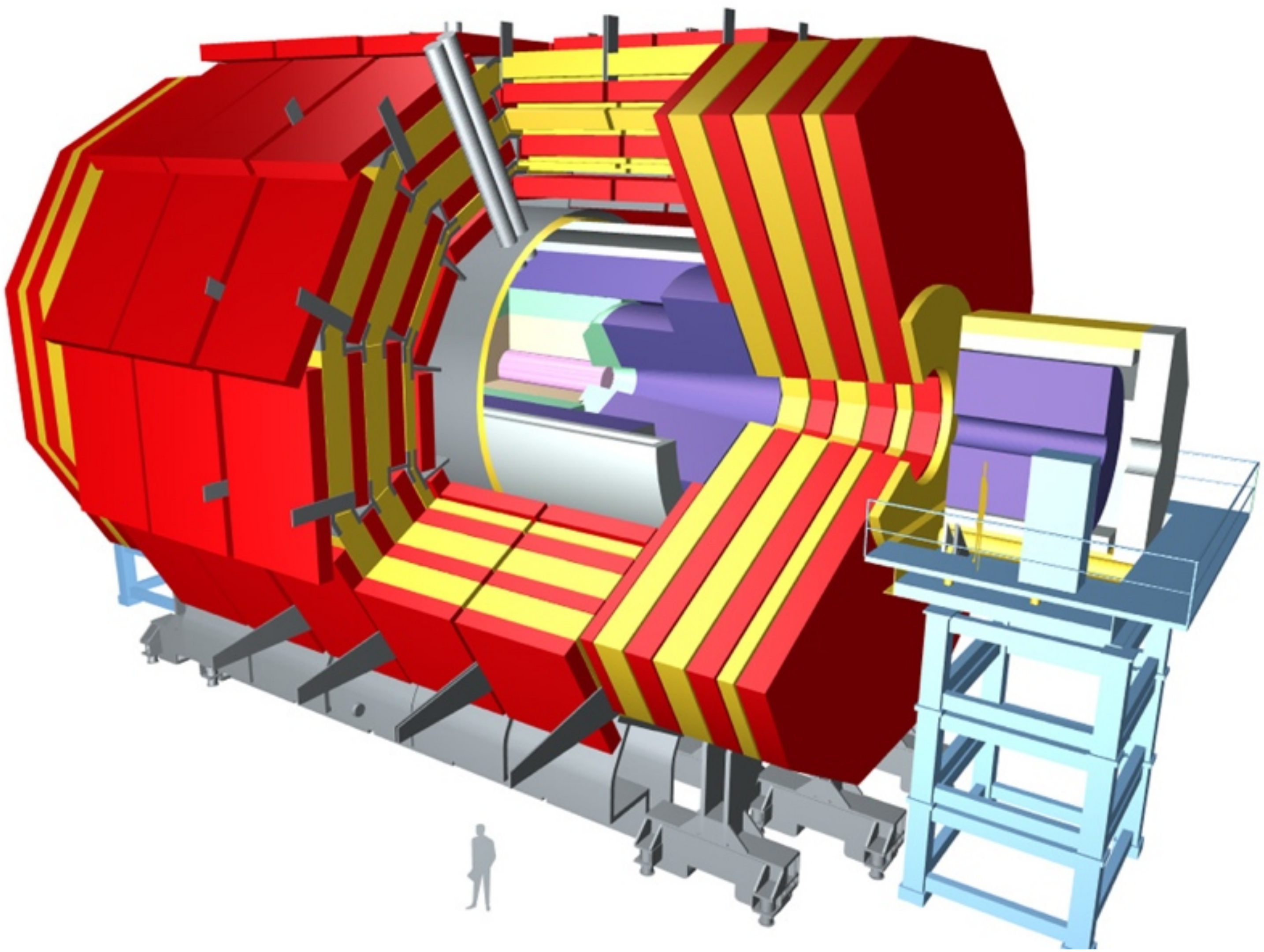
- Complete detector information
- Full event reconstruction
- Decision time: O(1 s)

~ 200 Hz

Experiments

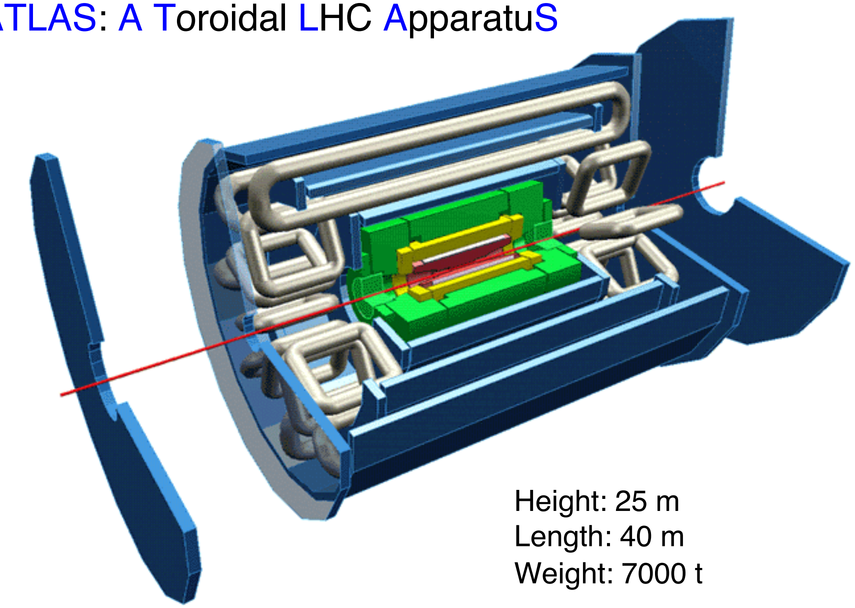
The LHC and its Experiments

LHC Detectors, mostly ATLAS & CMS



Basic Design Concepts

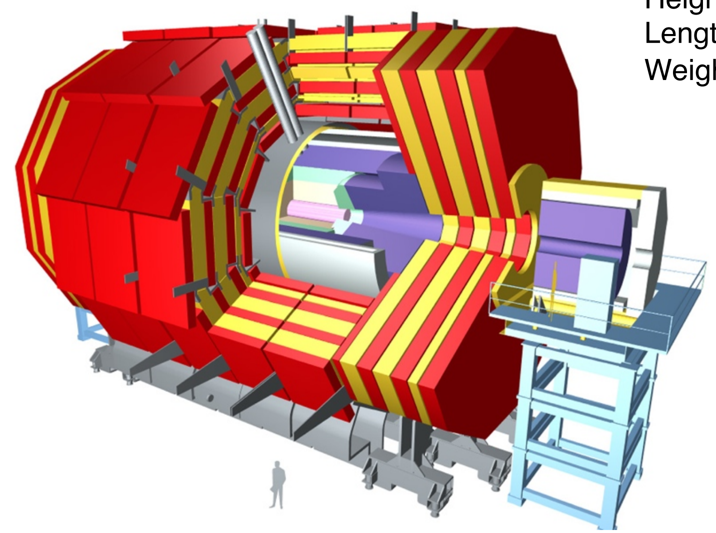
ATLAS: A Toroidal LHC ApparatuS

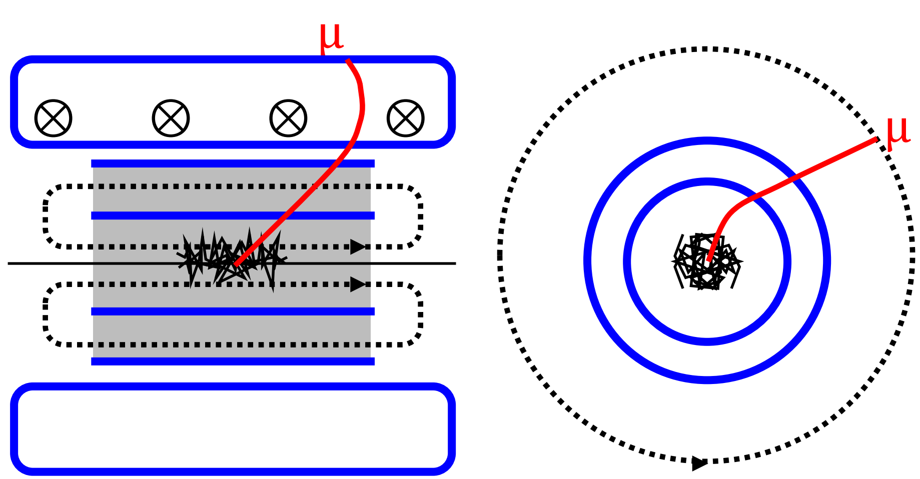


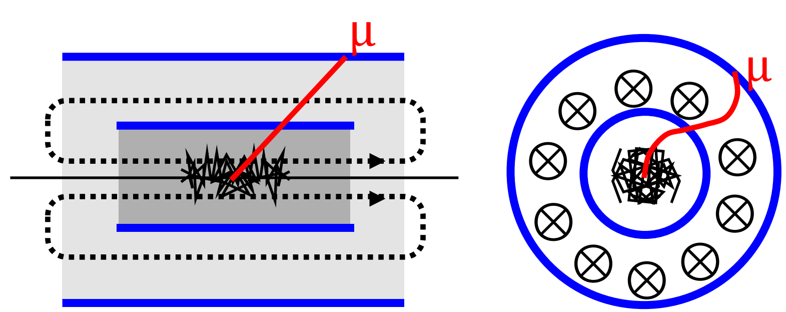
Height: 25 m
Length: 40 m
Weight: 7000 t

CMS: Compact Muon Solenoid

Height: 15 m
Length: 22 m
Weight: 12500 t







The ATLAS (and ~ CMS) Detector

The basic design criteria of the detector included the following points:

1. Excellent electromagnetic calorimetry for **electron and photon identification** and measurements, complemented by full-coverage hadronic calorimetry for accurate jet and ETmiss measurements;
2. High-precision **muon momentum measurements**, with the capability of accurate measurements at the highest collision rates using the external muon spectrometer alone;
3. Efficient **charged particle tracking at high luminosity** for high transverse momentum (p_T) lepton-momentum measurements, electron and photon identification, τ-lepton and heavy-flavour identification, and full event reconstruction capability at lower luminosity;
4. **Large acceptance in pseudorapidity (η)** with almost full azimuthal angle (ϕ) coverage everywhere. The azimuthal angle is measured around the beam axis z, whereas pseudorapidity relates to the polar angle (θ) where θ is the angle from the z direction, $\eta = -\ln(\tan\theta^2)$.
5. **Triggering and measurements of particles at low-p_T thresholds**, providing high efficiencies for most physics processes of interest at the LHC.

Leptons

Tracking + Calorimeters → MET

The main active detector components of the ATLAS detector, from the beam line towards the outside. The total readout channels for each component is given, as well as its pseudorapidity coverage.

ATLAS Detector

Detector component	Position	Channels (total)	η - coverage [Collapse]
Tracking			
Pixel B-layer (IBL, added for Run 2)	1 cylindrical barrel layer	6 million	±2.5
	Average radius 33 mm		
Pixel	3 cylindrical barrel layers	80.4 million	±2.5
	3 end-cap disks on each side		
	Radial envelope 45.5 - 242 mm		
SCT strips	4 cylindrical barrel layers	6.3 million	±2.5
	9 end-cap disks on each side		
	Radial envelope 251 - 610 mm		
TRT	73 barrel straw planes	351,000	±2.0
	80 end-cap straw planes		
	Radial envelope 554 - 1106 mm		
Calorimetry			
EM presampler	Barrel	7,808	±1.52
	End-caps	1,536	1.5 < |η| < 1.8
EM calorimeter	3 depth samples barrel	101,760	±1.48
	3 depth layers end-caps	62,208	1.375 < |η| < 3.2
Hadronic tile calorimeter	3 depth samples barrel	5,760	±1.0
	3 depth samples extended barrel	4,092	0.8 < |η| < 1.7
LAr hadronic end-caps	4 depth layers	5,632	1.5 < |η| < 3.2
LAr forward hadronic calorimeter	3 depth layers	3,524	3.1 < |η| < 4.9
Muon spectrometer			
MDT precision tracking	3 multi-layer stations	354,000	±2.7
CSC precision tracking	1 innermost station end-caps	31,000	2.0 < |η| < 2.7
RPC trigger chambers	2 multi-layer stations barrel	373,000	±1.05
TGC trigger chambers	2 multi-layer stations end-cap	318,000	1.05 < |η| < 2.4

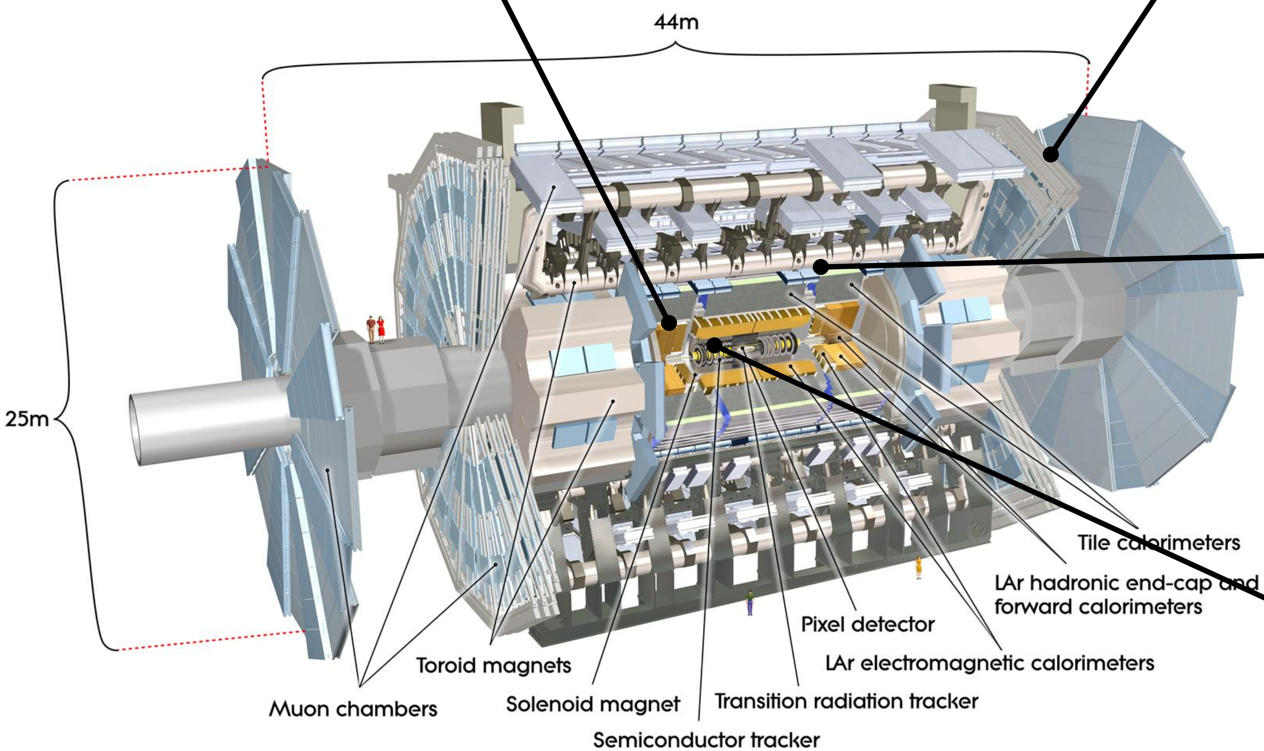
The ATLAS Detector

(http://www.scholarpedia.org/article/The_ATLAS_experiment)

Upgrades! → Detector evolves with time

EM Calorimeters: $\sigma/E \approx 10\%/\sqrt{E} \oplus 0.7\%$
excellent e/γ identification
good energy resolution (e.g. for $H \to \gamma\gamma$)

Precision Muon Spectrometer: $\sigma/p_t \approx 10\%$ @ 1 TeV
fast trigger response
good momentum resolution
(e.g. $A/Z' \to \mu\mu$, $H \to 4\mu$)



Hadron Calorimeter:
$\sigma/E \approx 50\%/\sqrt{E} \oplus 3\%$
good jet resolution
good missing E_T resolution
(e.g. $H \to \tau\tau$)

Inner Detector:
Si Pixel & strips; TRT
$\sigma/p_t \approx 5 \cdot 10^{-4}\, p_t \oplus 0.001$
good impact parameter res., i.e.
$\sigma(d_0) \approx 15\ \mu m$ @ 20 GeV
(e.g. $H \to bb$)

Magnets:

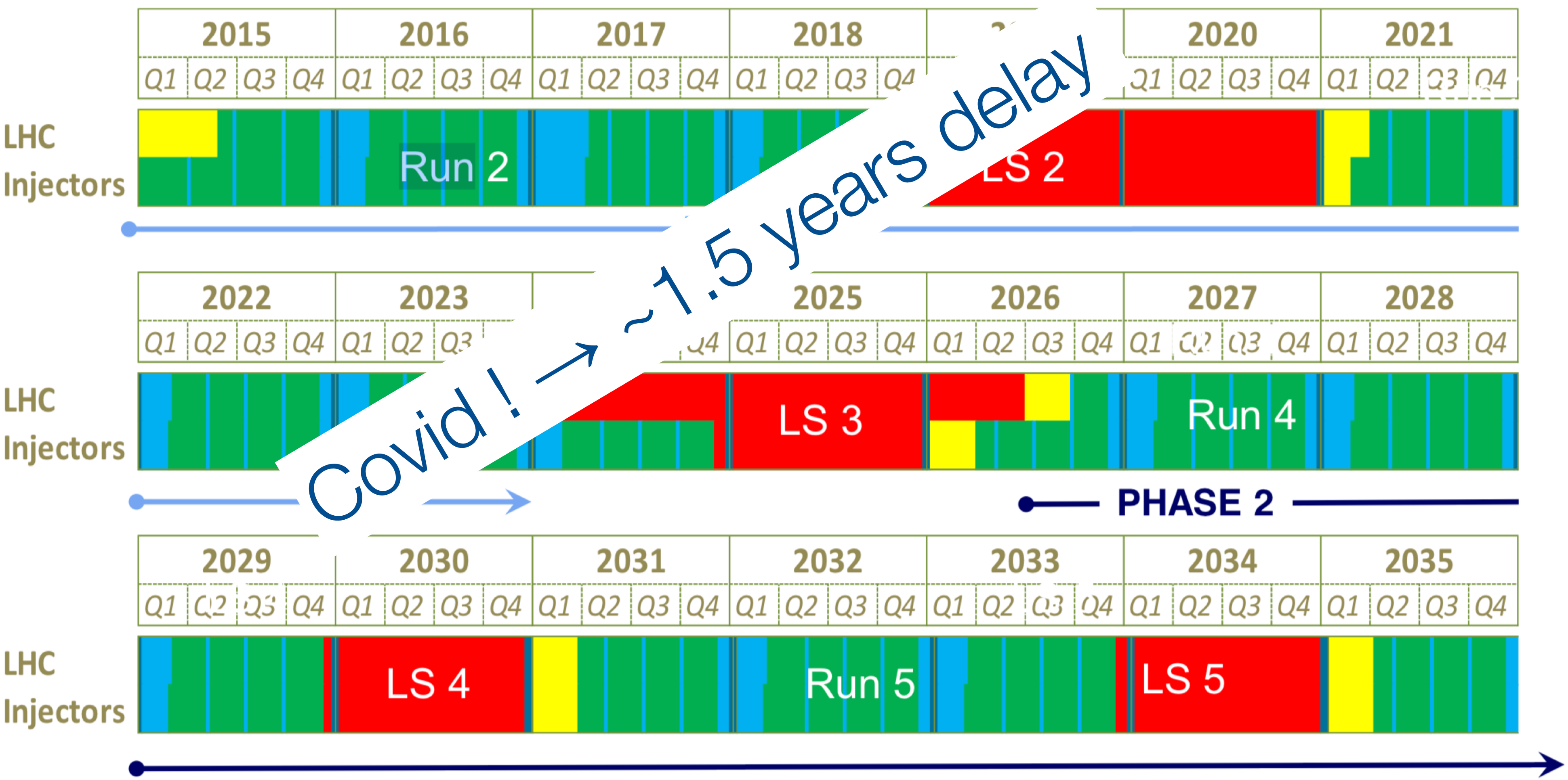
Solenoid (inner detector): 2 T
Toroid (muon spectrometer): 0.5 T

LHC Schedule as of Jan 2019

LHC roadmap: according to MTP 2016-2020 V1

LS2 starting in 2019 => 24 months + 3 months BC
LS3 LHC: starting in 2024 => 30 months + 3 months BC
Injectors: in 2025 => 13 months + 3 months BC

- Physics
- Shutdown
- Beam commissioning
- Technical stop



The ATLAS Detector

Reminder: the E_{CM} of scattering objects (two partons carrying an unknown fraction x_1 and x_2 of proton momentum) is not known.
→ the CM moves in the longitudinal plane.
However the CM has ~p_T=0

Indicative resolutions of the ATLAS detector components. The units for energy E and transverse momentum p_T are in GeV. The symbol $\oplus$ means adding both parts in quadrature.

Detector component	Resolution
Tracking	$\sigma_{p_T}/p_T = 0.05\% \, p_T \oplus 1\%$
EM calorimetry	$\sigma_E/E = 10\%/\sqrt{E} \oplus 0.7\%$
Hadronic calorimetry (jets)	
barrel and end-caps	$\sigma_E/E = 50\%/\sqrt{E} \oplus 3\%$
forward	$\sigma_E/E = 100\%/\sqrt{E} \oplus 10\%$
Muon spectrometer	$\sigma_{p_T}/p_T = 10\%$ at $p_T = 1$ TeV

$p_T \uparrow \sigma_{PT} \uparrow$

$E \uparrow \sigma_E \downarrow$

$E \uparrow \sigma_E \downarrow$

$p_T \uparrow \sigma_{PT} \uparrow$

The CMS Detector

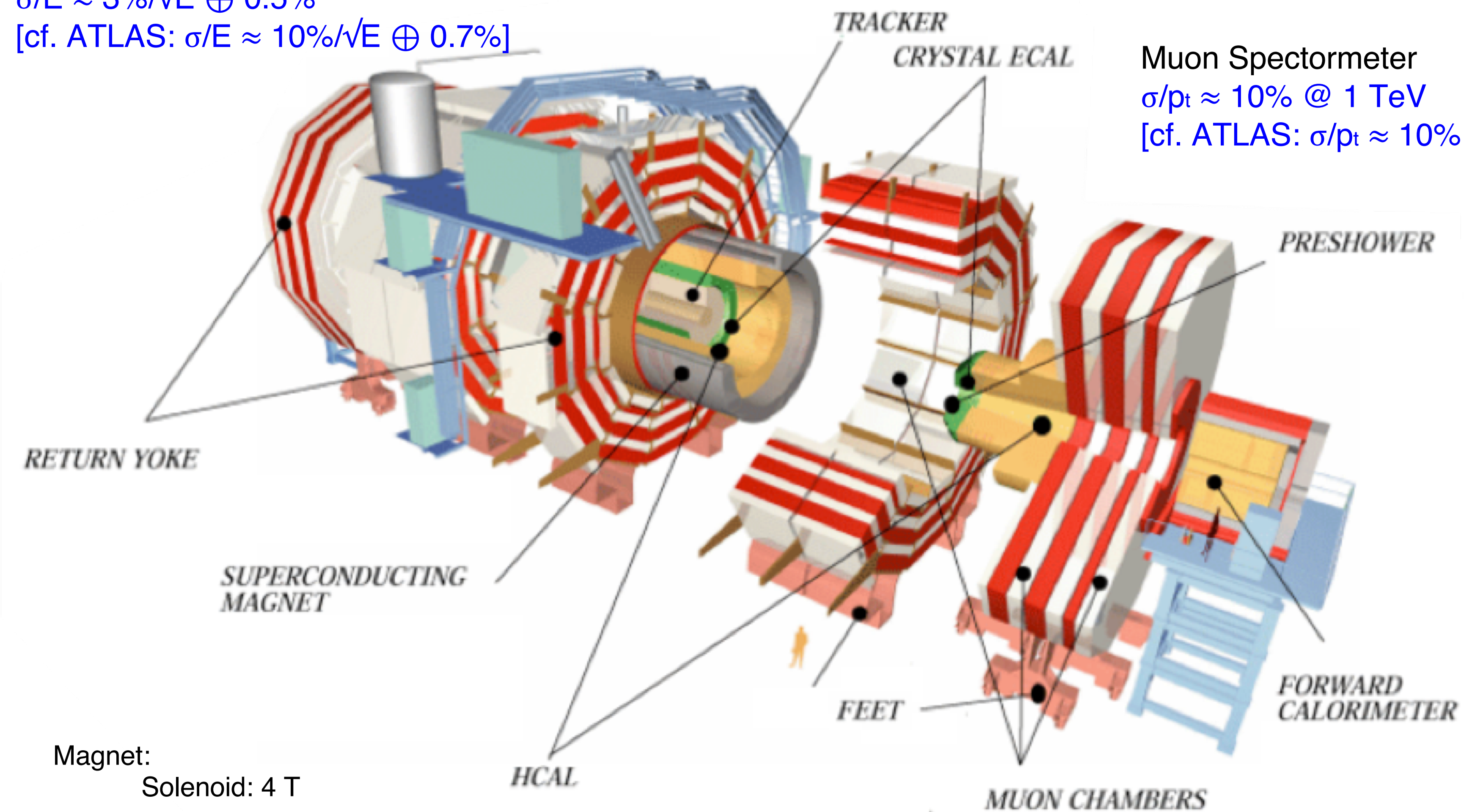
(https://en.wikipedia.org/wiki/Compact_Muon_Solenoid)

Inner Detector:
$\sigma/p_t \approx 5 \cdot 10^{-4}\, p_t \oplus 0.001$
[cf. ATLAS $\sigma/p_t \approx 5 \cdot 10^{-4}\, p_t \oplus 0.001$]

Hadron Calorimeter:
$\sigma/E \approx 100\%/\sqrt{E} \oplus 5\%$
[cf. ATLAS: $\sigma/E \approx 50\%/\sqrt{E} \oplus 3\%$]

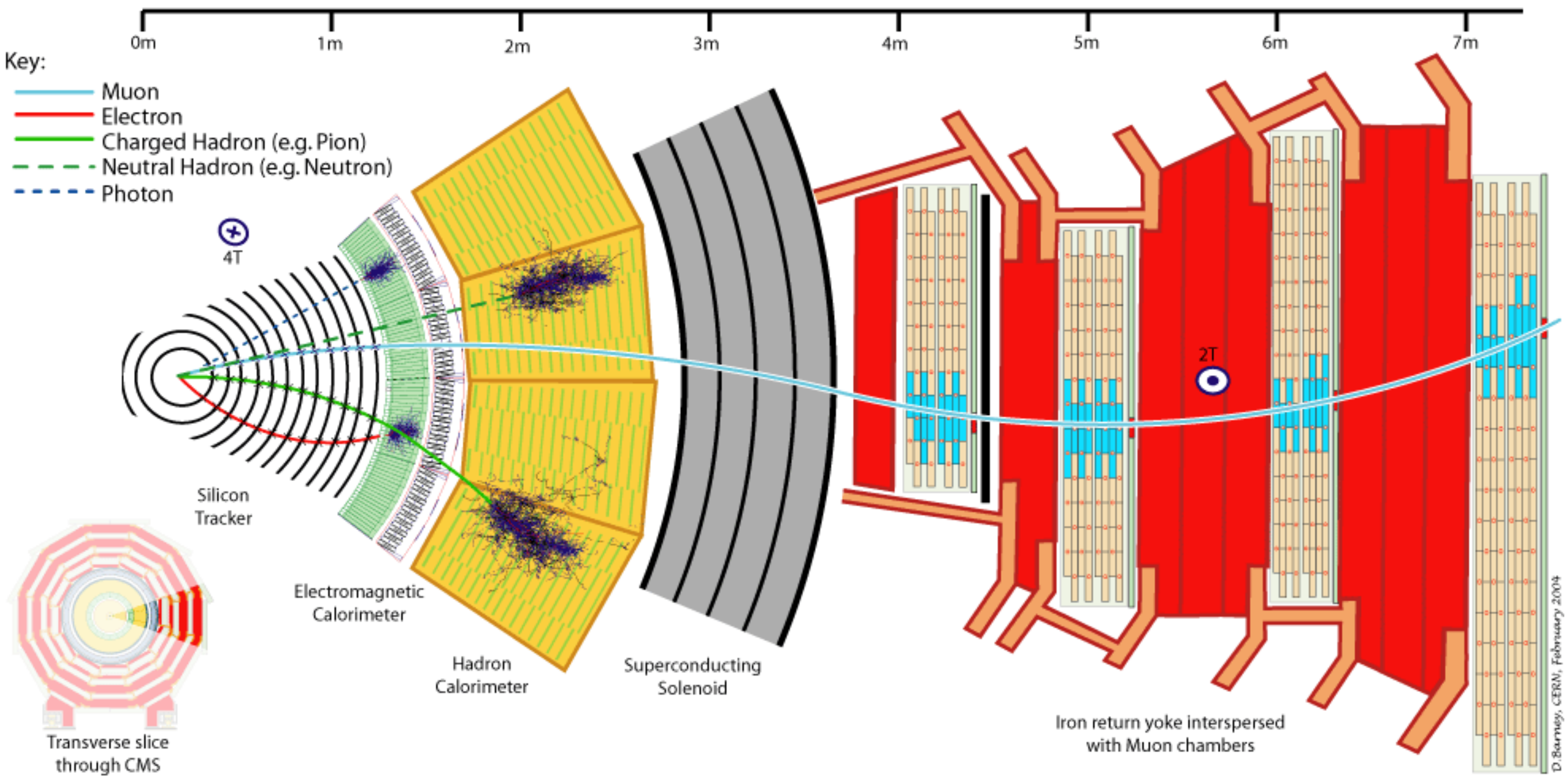
EM Calorimeters:
$\sigma/E \approx 3\%/\sqrt{E} \oplus 0.5\%$
[cf. ATLAS: $\sigma/E \approx 10\%/\sqrt{E} \oplus 0.7\%$]

Muon Spectormeter
$\sigma/p_t \approx 10\%$ @ 1 TeV
[cf. ATLAS: $\sigma/p_t \approx 10\%$ @ 1 TeV]



Magnet:
Solenoid: 4 T

The CMS Detector - 2



ATLAS vs CMS

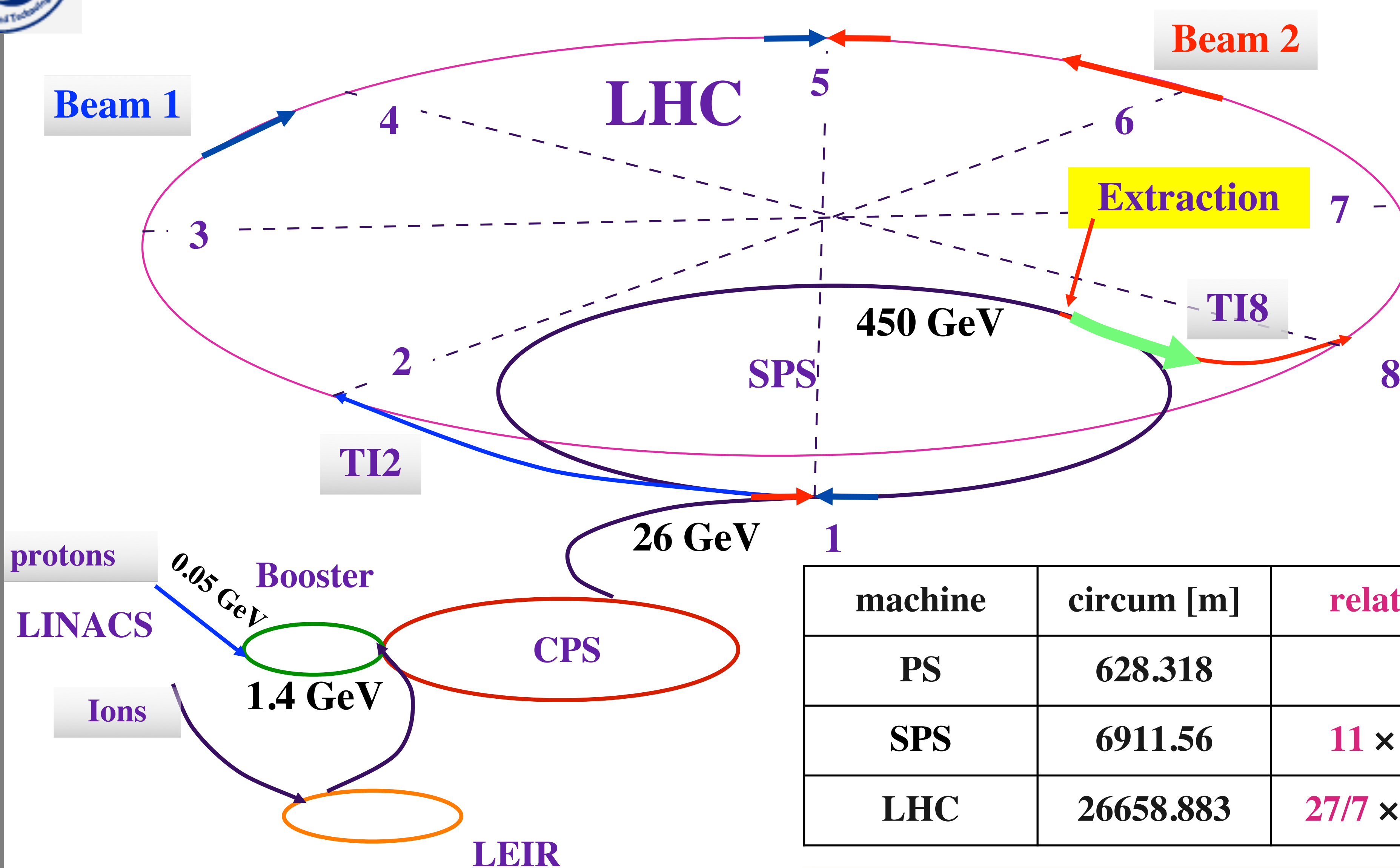
ATLAS		CMS
Silicon pixels; Silicon strips; Transition Radiation Tracker; 2 T magnetic field	Inner Detector	Silicon pixels, Silicon strips, 4 T magnetic field
Lead plates as absorbers; active medium: liquid argon; outside solenoid	Electrom. Calorimeter	Lead tungsten ($PbWO_4$) crystals; both absorber and scintillator; inside solenoid
Central region: Iron absorber with plastic scintillating tiles; Endcaps: copper and tungsten absorber with liquid argon	Hadronic Calorimeter	Stainless steel and copper with plastic scintillating tiles
Large air-core toroid magnet; muon chambers: drift tubes and resistive plate chambers;0.5 T magnetic field	Muon Chambers	Magnetic field from return yoke (solenoid field: 4 T); muon chambers: drift tubes and resistive plate chambers

Accelerators

The LHC and its Experiments

The Large Hadron Collider

The CERN accelerator complex : injectors and transfer

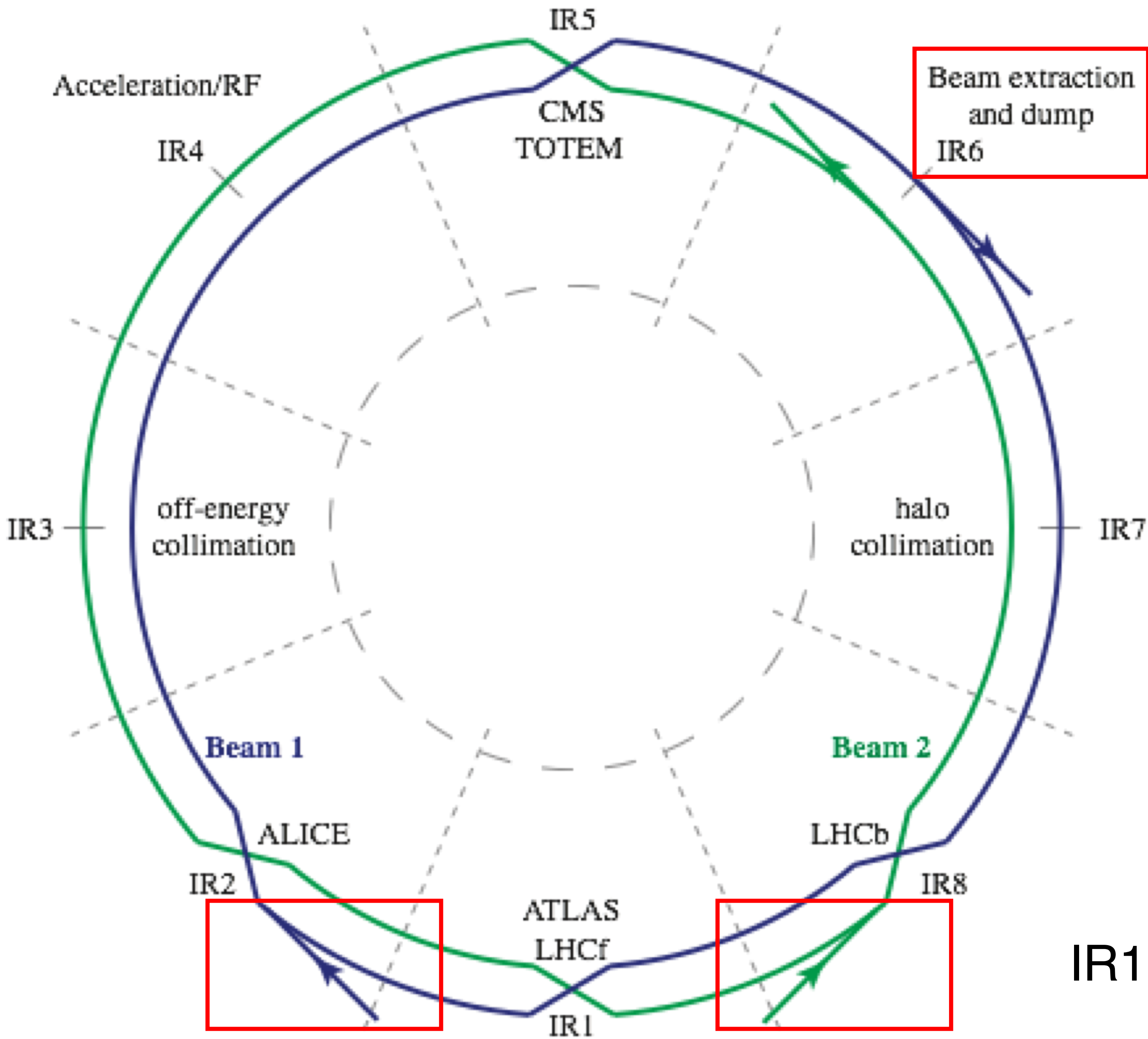


machine	circum [m]	relative
PS	628.318	
SPS	6911.56	11 × PS
LHC	26658.883	27/7 × SPS

simple rational fractions for synchronization based on a single frequency generator at injection

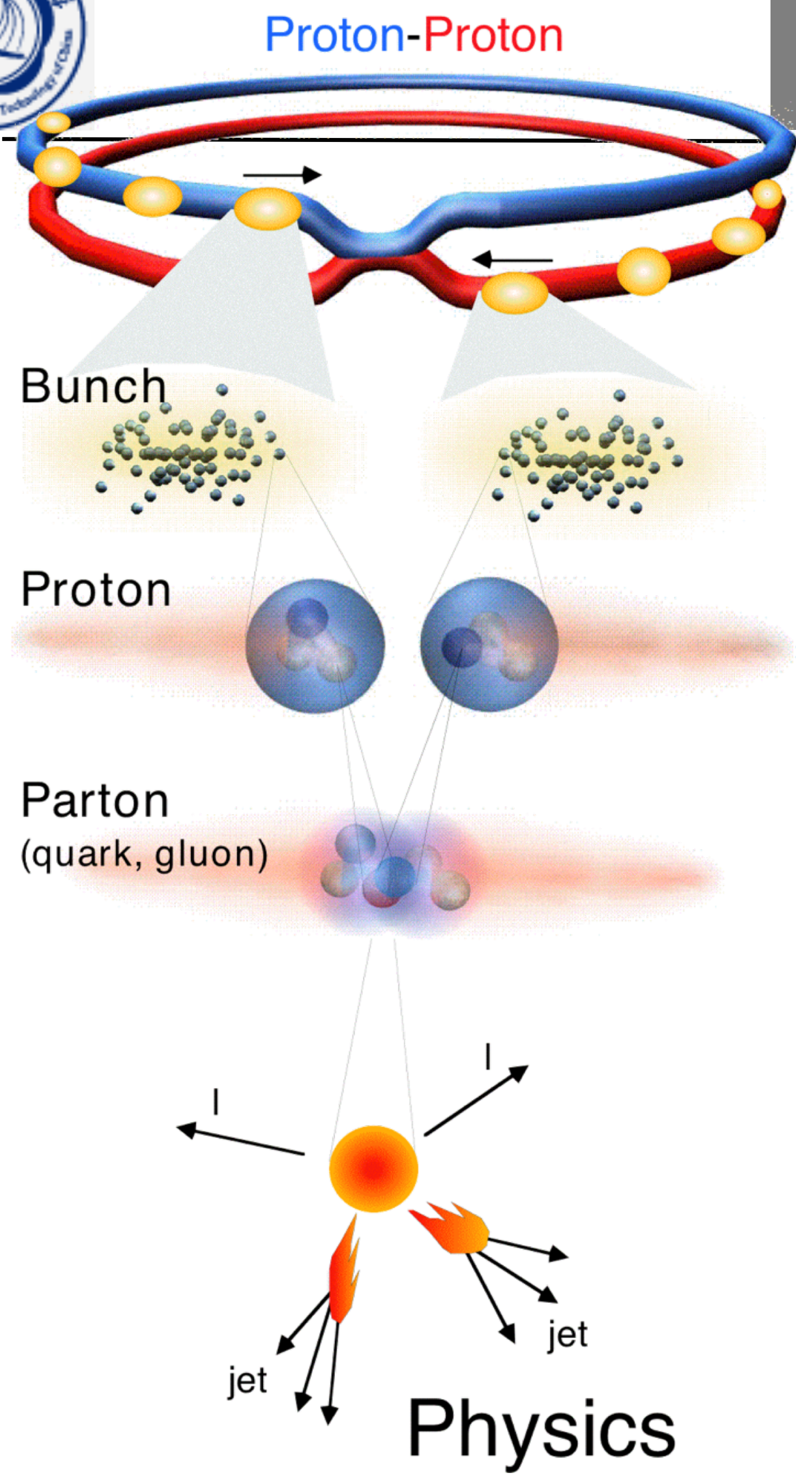
Beam size of protons decreases with energy : area $\sigma^2 \propto 1 / E$
Beam size largest at injection, using the full aperture

Layout of the LHC: Experiments



IR1=P1=IP1

Some numbers (relevant for ATLAS & CMS)



total number of bunches (some empty) 3564x3564

2835 x 2835 proton bunches
distance: 7.5 m [25 ns]

(1.7*) 10^{11} protons/bunch
bunch crossing rate: 40 MHz

10^9 pp-collisions/sec
[i.e.: 23 pp-interactions/bunch crossing.]

Dominant Interactions:
gluon-gluon, quark-quark and
quark-gluon scattering

2016,2017,2018 LHC performance

Fundamental relation

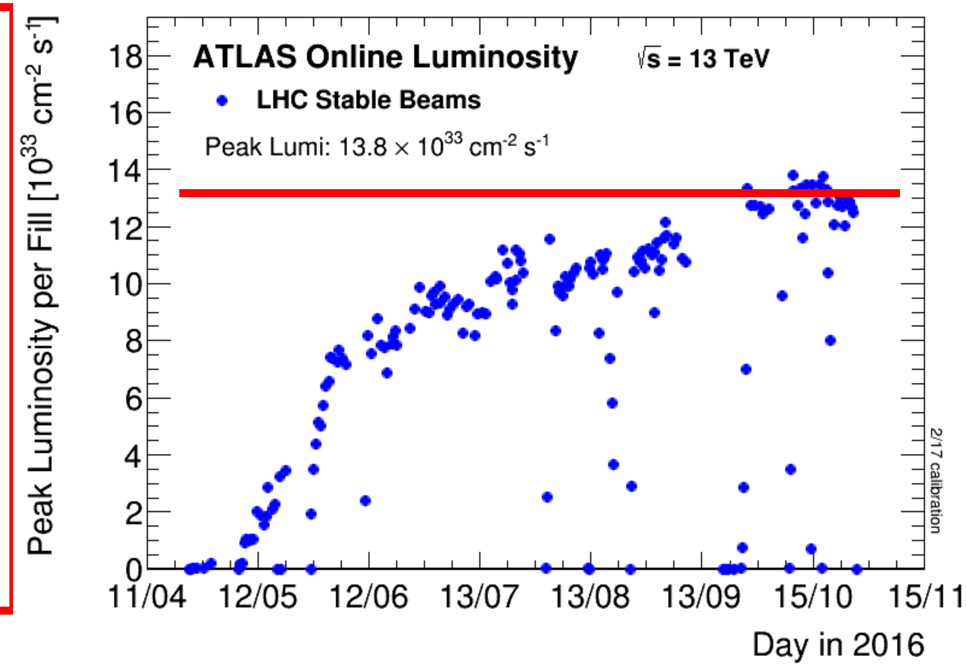
$$N = L \cdot \sigma$$

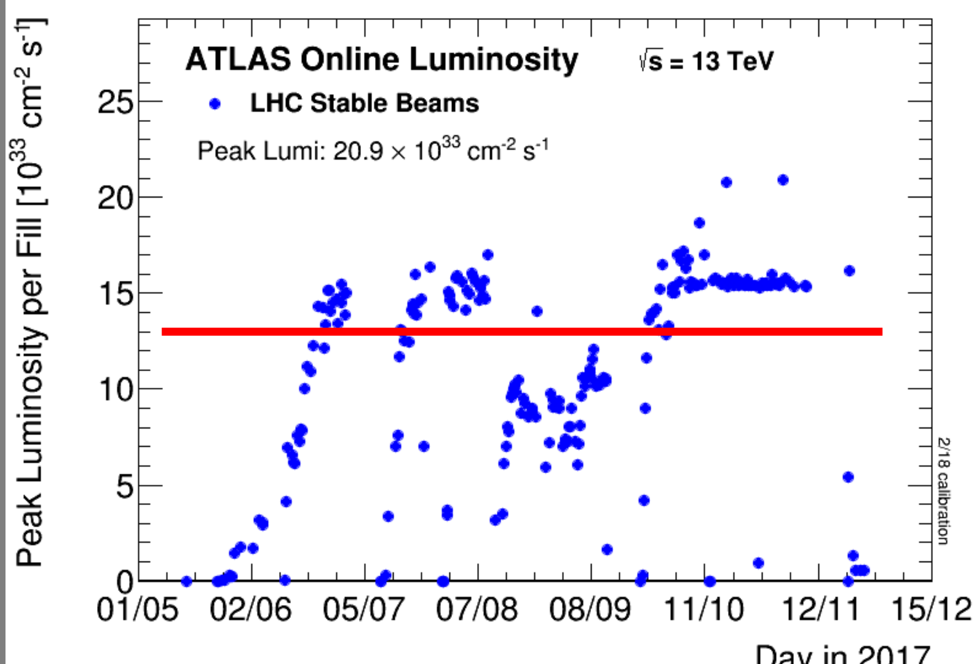
X-Sec →Physics.

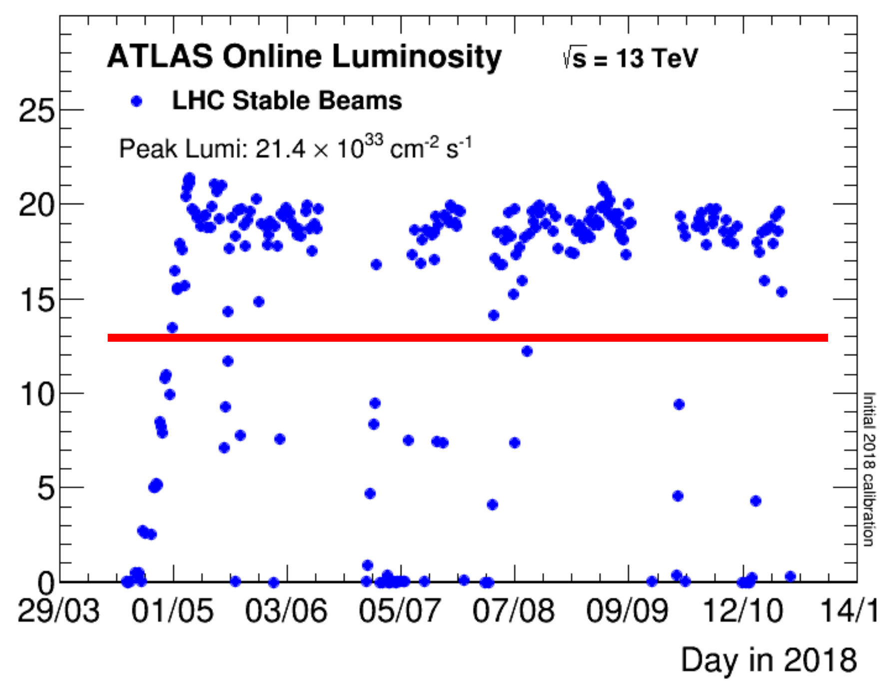
Number of Events → Experiment

Integrated Luminosity (function of Machine)

$\rightarrow \sigma = N/L$







LHC status, a bit of story!

β^* indicates longitudinal size of the bunch

LHC :

2009 first collisions, mostly at injection energy 2x450 GeV

2010 2x3.5 TeV, β^*= 3.5 m, **$L_{peak} = 0.2\times10^{33}$ cm^{-2}s^{-1} $\int L\,dt = 0.044$ fb^{-1}** 368 bunches

2011 2×3.5 TeV, β^*= 1.0 m, **$L_{peak} = 3.5\times10^{33}$ cm^{-2}s^{-1} $\int L\,dt = 6.1$ fb^{-1}** 1380 bunches

2012 2×4.0 TeV, β^*= 0.6 m, **$L_{peak} = 7.7\times10^{33}$ cm^{-2}s^{-1} $\int L\,dt = 23.3$ fb^{-1}** 1380 bunches

2013 2014 shutdown, magnet interconnections

2015 2×6.5 TeV, β^*= 0.6 m, **$L_{peak} = 0.5\times10^{34}$ cm^{-2}s^{-1} $\int L\,dt = 4.2$ fb^{-1}** 2232 bunches

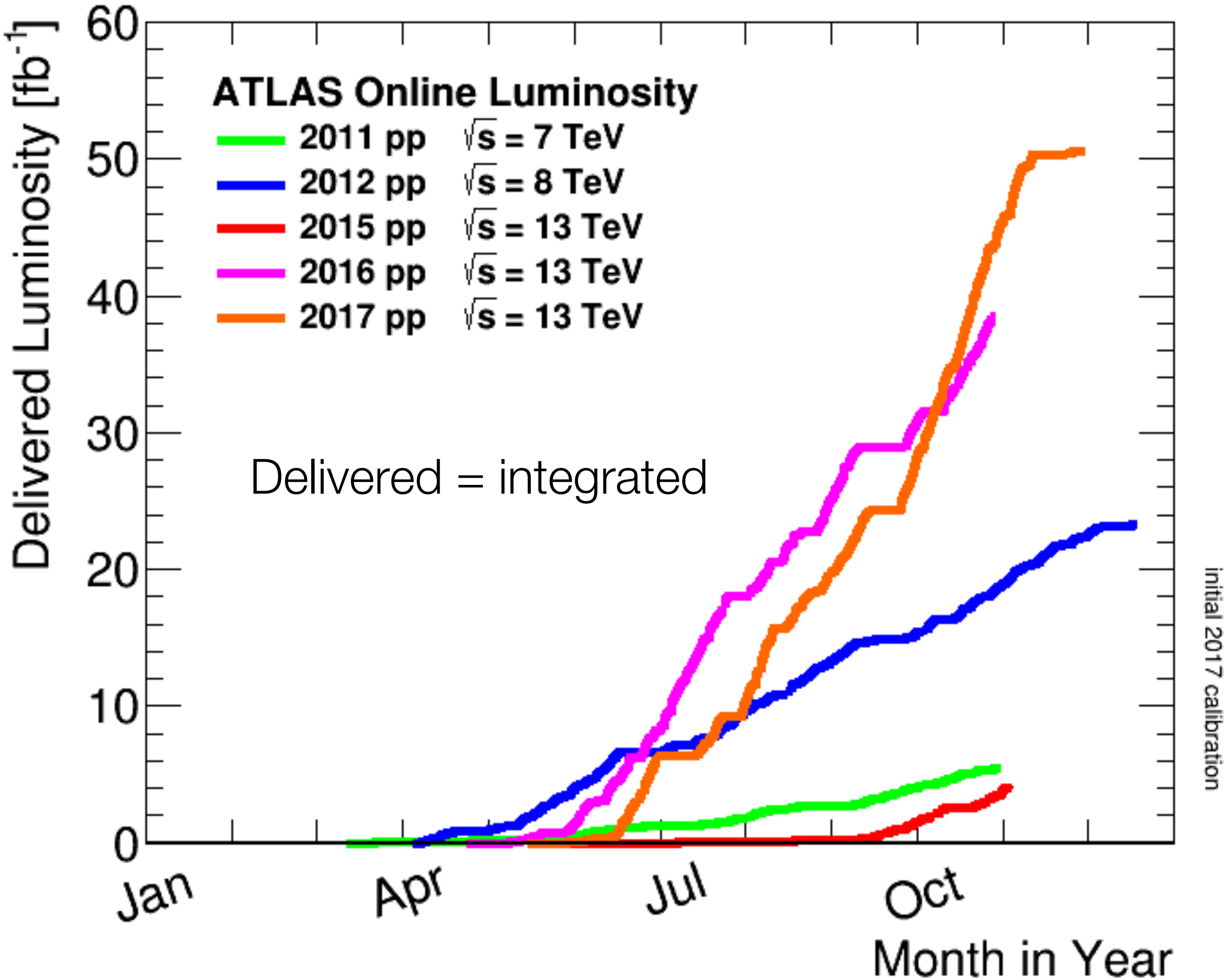
2016 2×6.5 TeV, β^*= 0.4 m, **$L_{peak} = 1.4\times10^{34}$ cm^{-2}s^{-1} $\int L\,dt = 35.6$ fb^{-1}** 2208 bunches

2017 2×6.5 TeV, β^*= 0.3 m, **$L_{peak} = 2.1\times10^{34}$ cm^{-2}s^{-1} $\int L\,dt = 50.4$ fb^{-1}** 2544 bunches

2018 $\int Ldt = 60\,fb^{-1}$ 2556 bunches

	LHC design	achieved
Momentum at collision, TeV/c	7	6.5
Luminosity, cm^{-2}s^{-1}	1.0E+34	2.1E+34
Dipole field at top energy, T	8.33	8.33
Number of bunches, each beam	3564	2544
Particles / bunch	1.15E+11	1.7E+11
Typical beam size in ring, µm	200 – 300	~300
Beam size at IP, µm	17	16

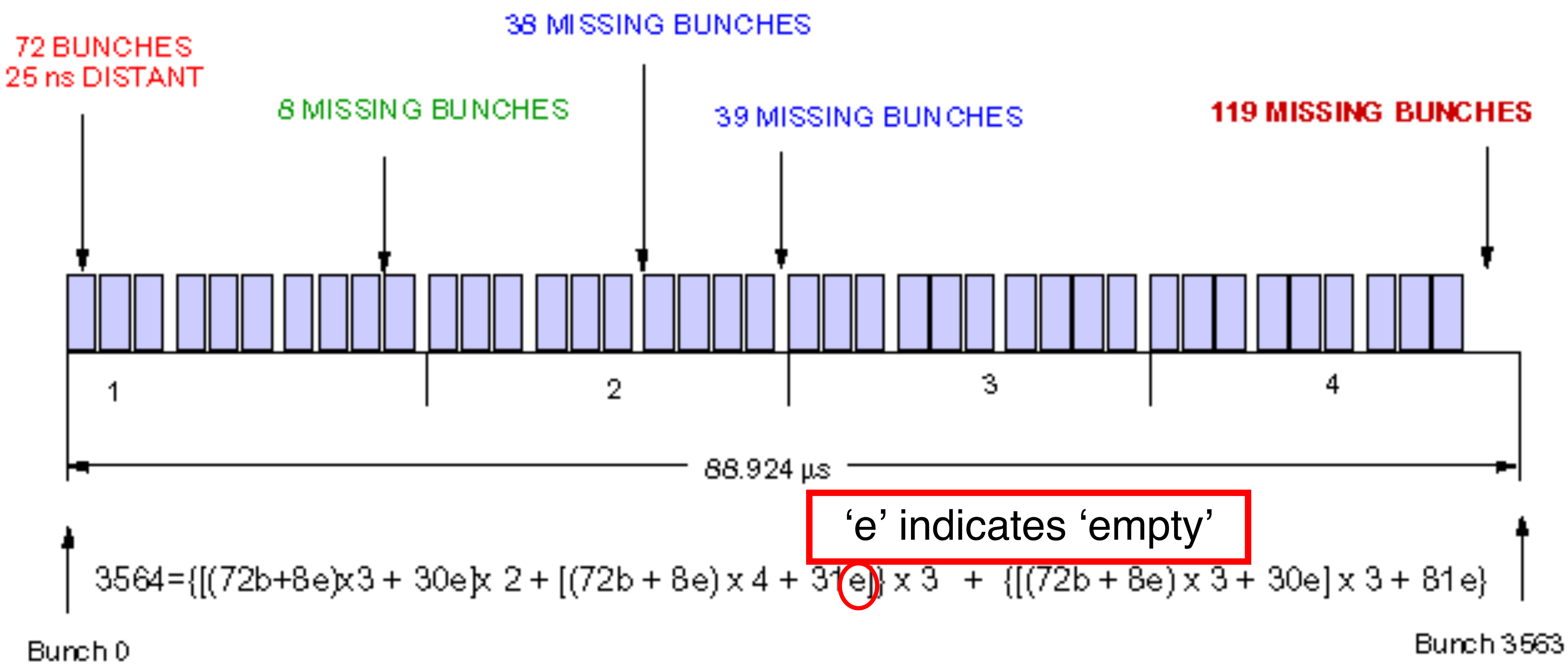
Luminosity delivered by LHC



Delivered = integrated

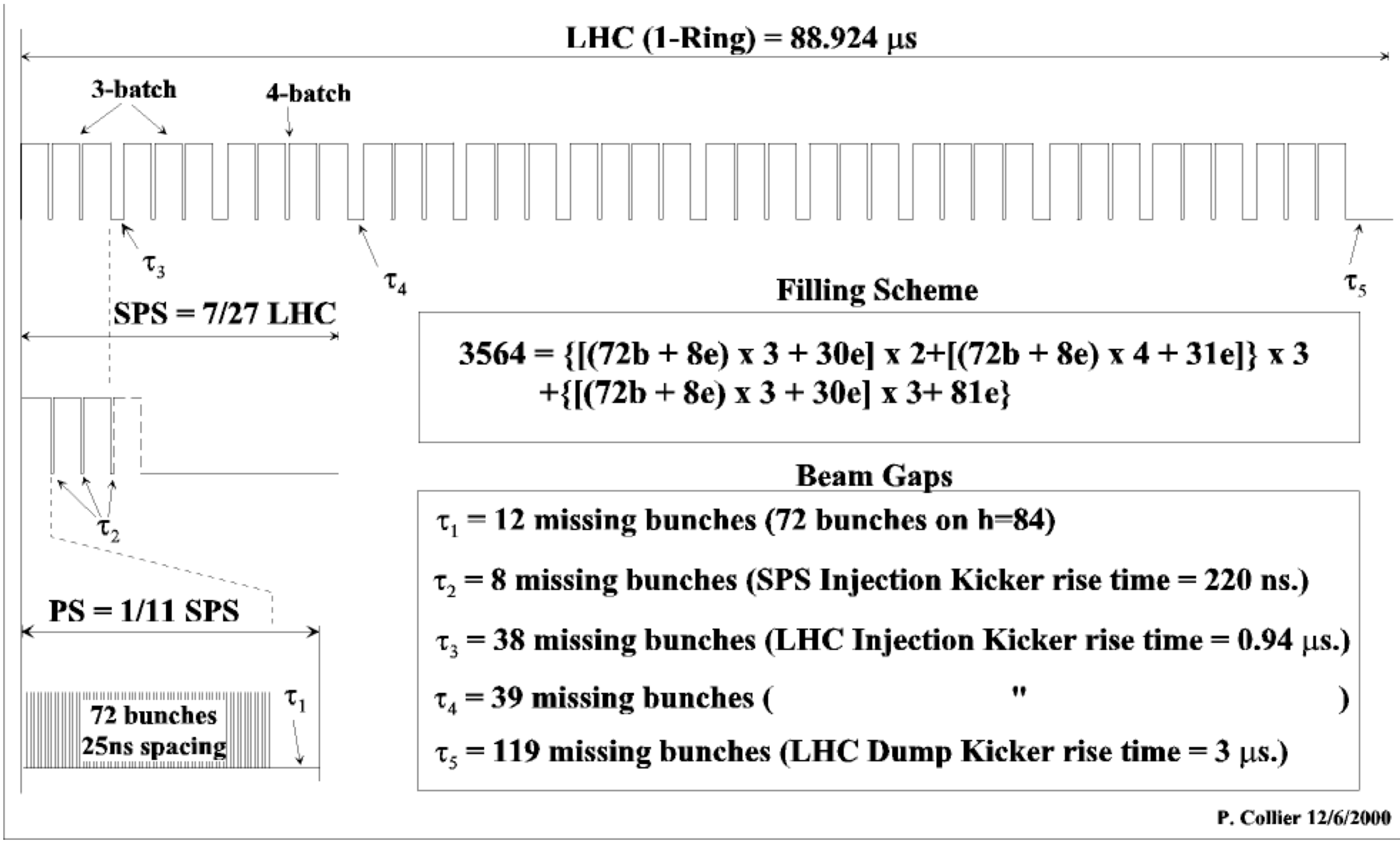
LHC Nominal Bunch Structure

Not all bunches collide!



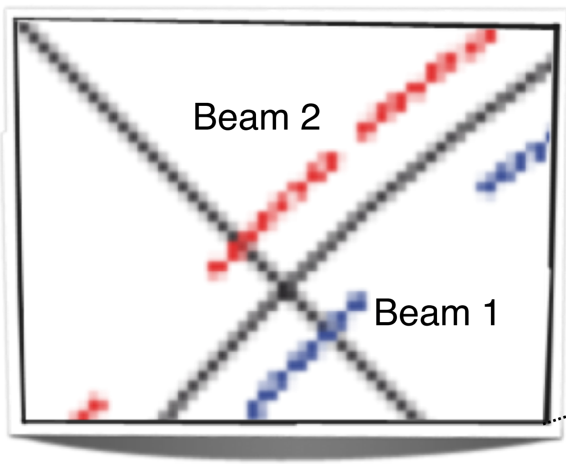
Filled bunches = 2808 = { [(72b)x3]x2 + [(72b)x4] }x3+{ [(72b)x3]x3 }

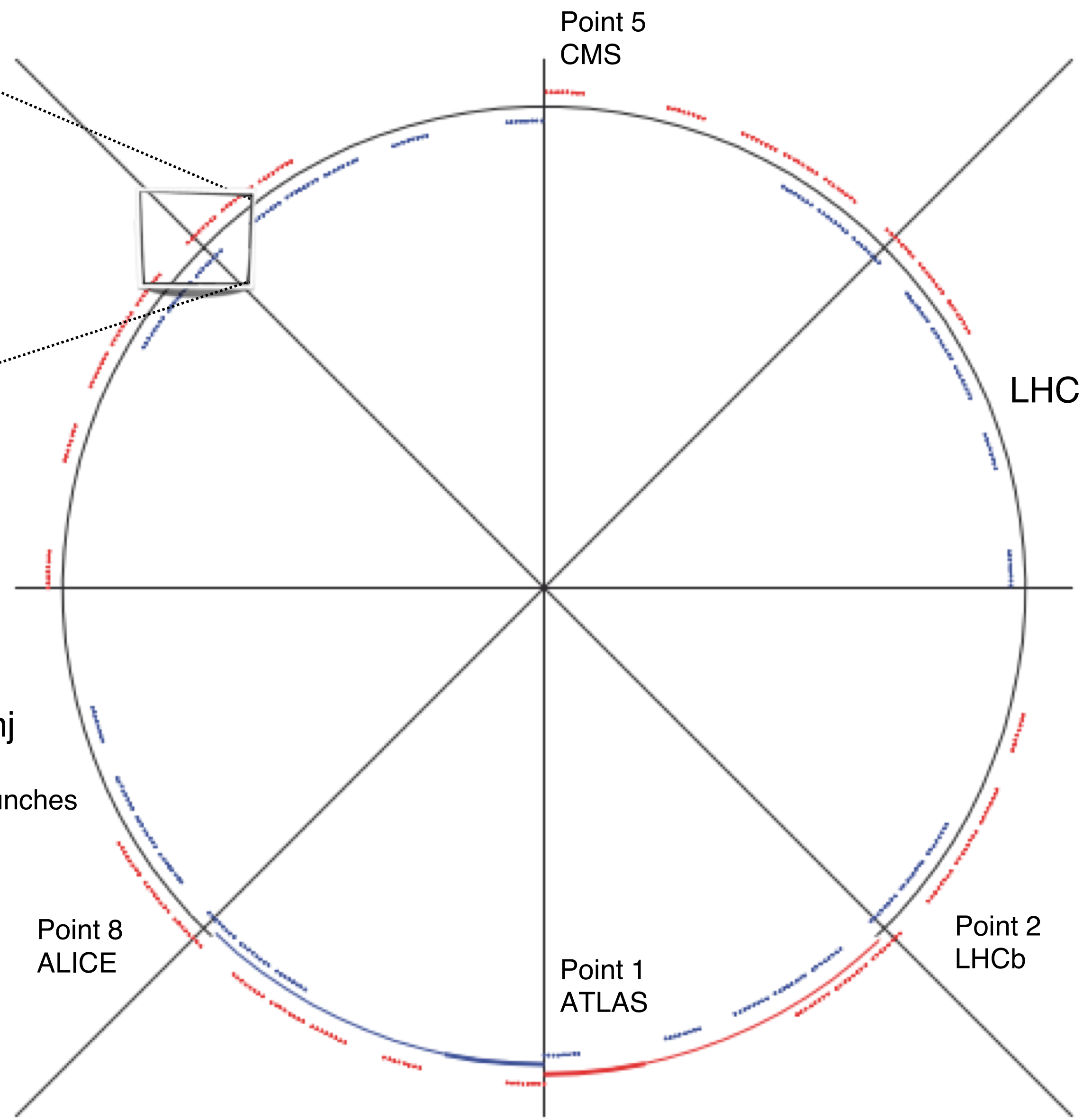
Bunch structures in LHC, SPS and PS



Present LHC Status

Luminosity (LHCb) << Luminosity(ATLAS, CMS, ALICE)





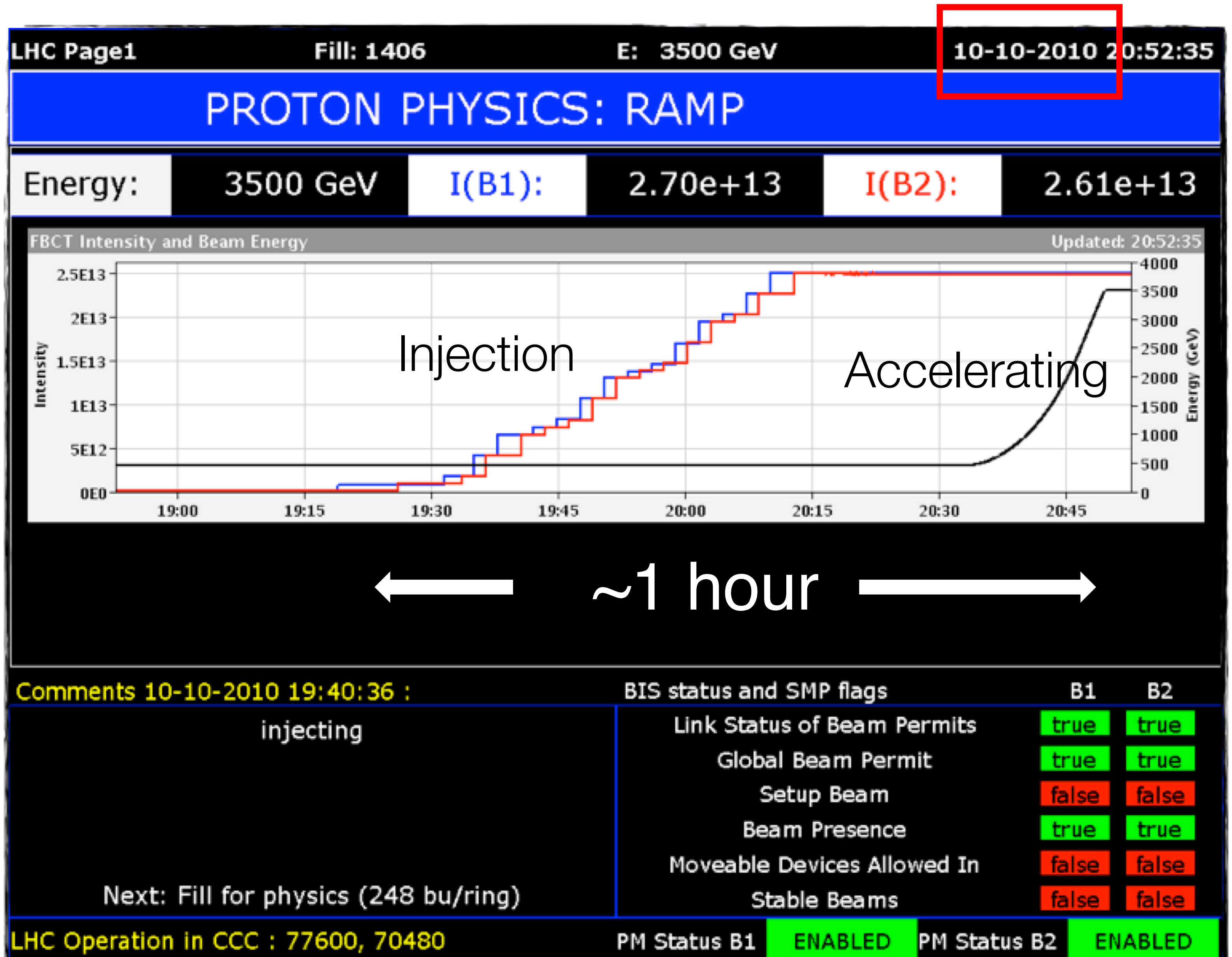
Present Bunch Structure:

150ns_248b_233_16_233_3x8bpi15inj

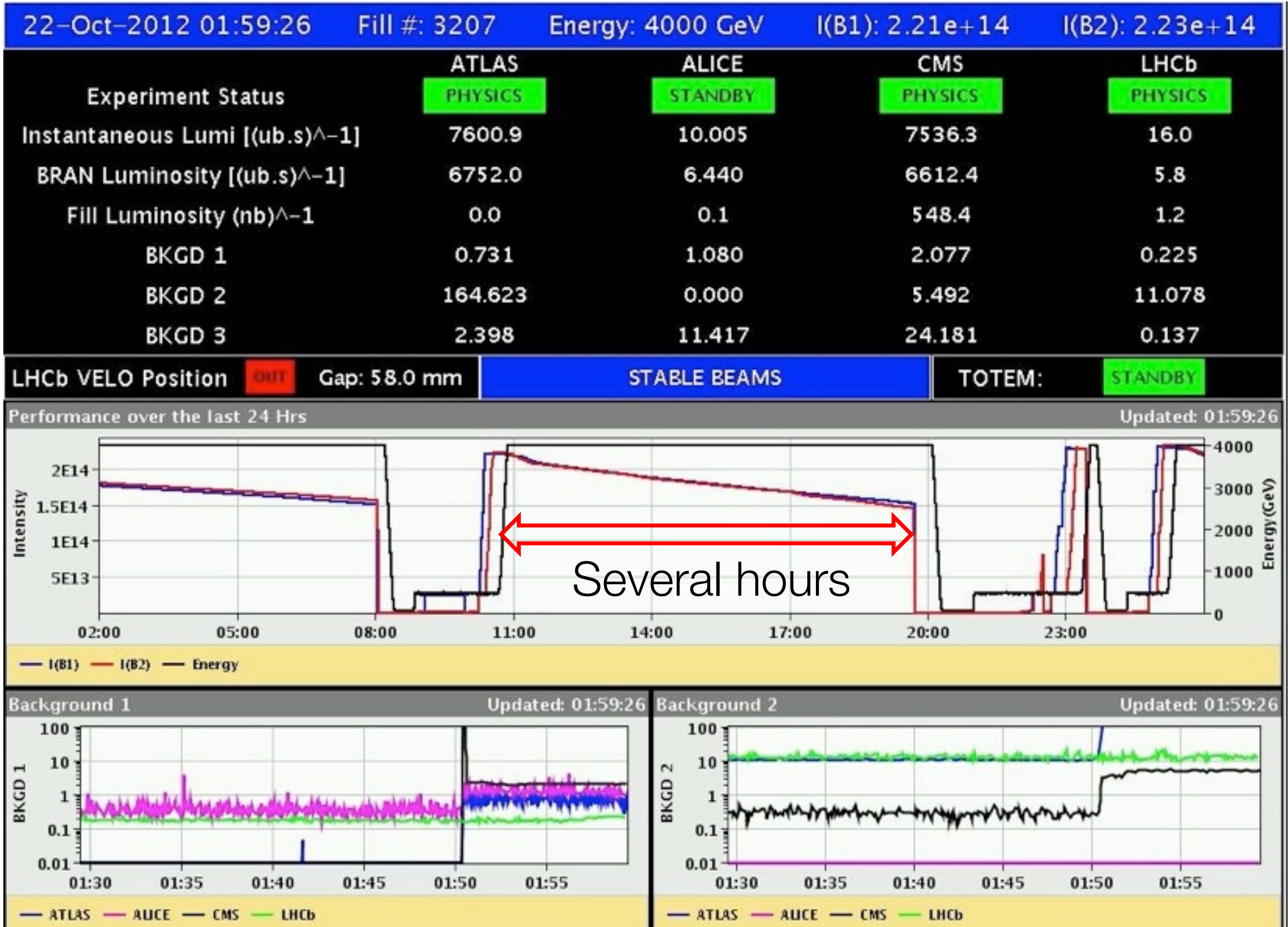
- 150ns: bunch distance
- 248b: number of bunches
- 233: colliding bunches in points 1/5
- 16: colliding bunches in point 2
- 233: colliding bunches in point 8

LHC in Operation: what you see in Control Room

- Injection probe beam
- Injection
- Ramp
- Squeeze
- Adjust
- Stable Beams

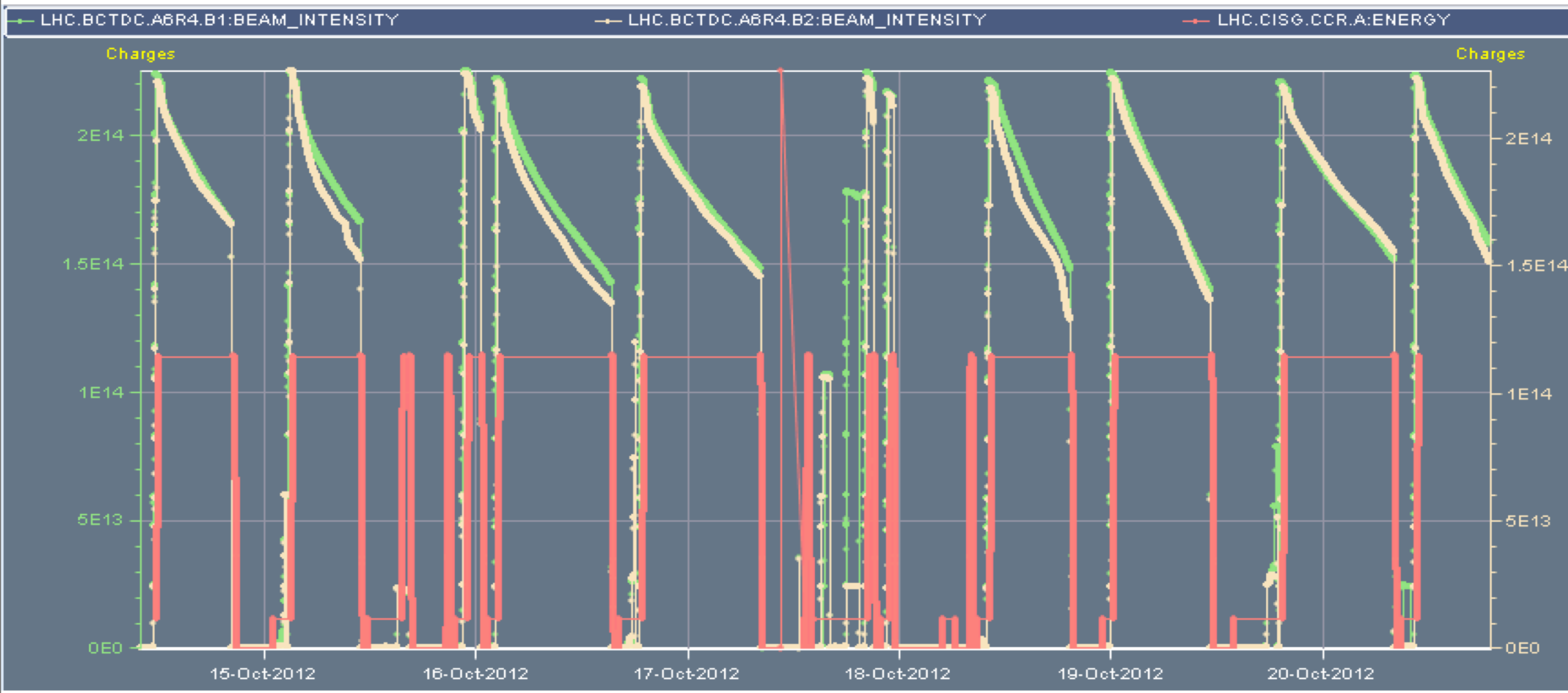


LHC in Operation: what you see in Control Room-2

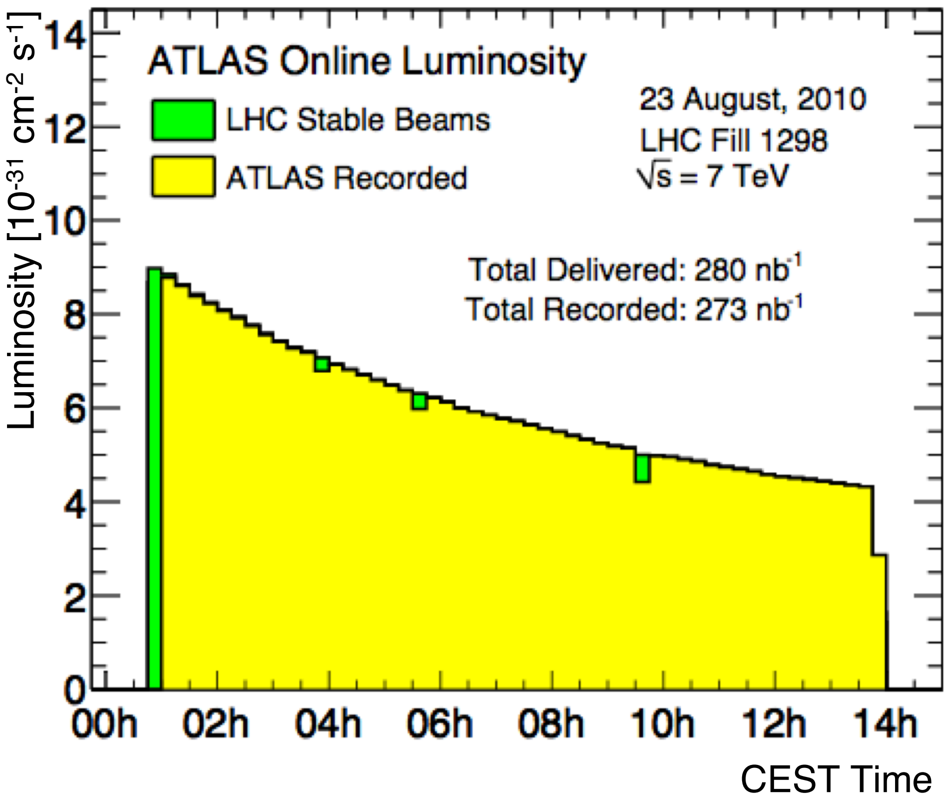


peak Luminosity 7.8 $\times 10^{33} cm^{-2} s^{-1}$

LHC typical week, Oct. '12, 1.2 pb-1

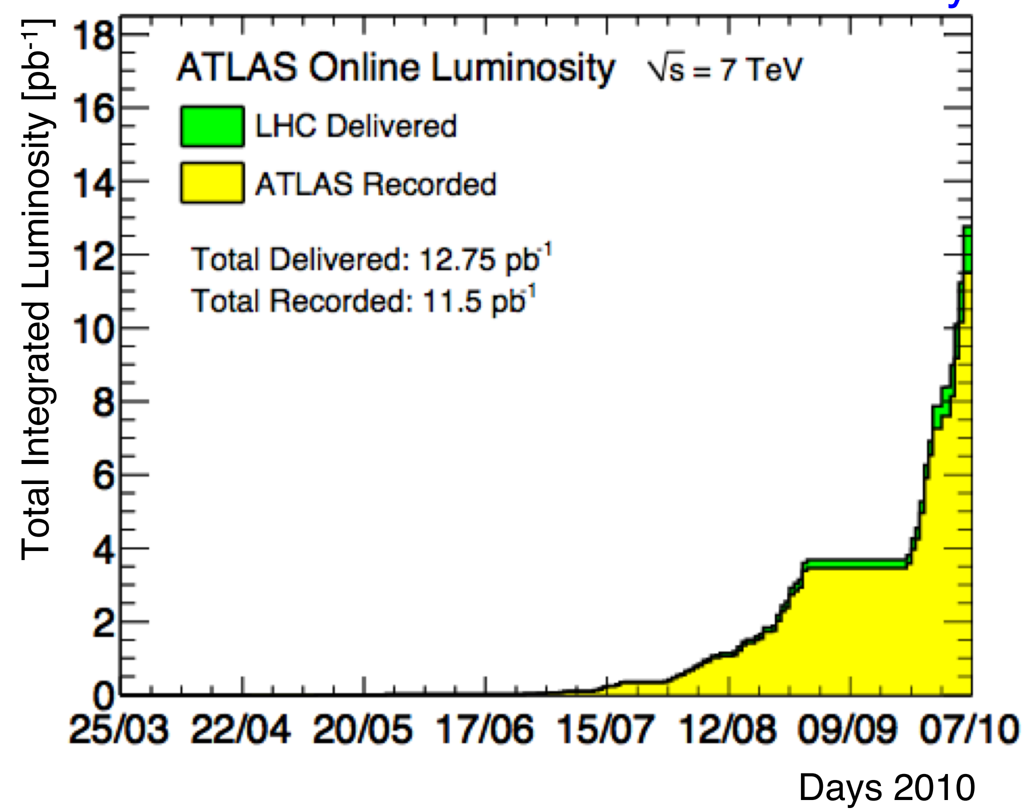


Present LHC Status



LHC Fill
[August 2010]

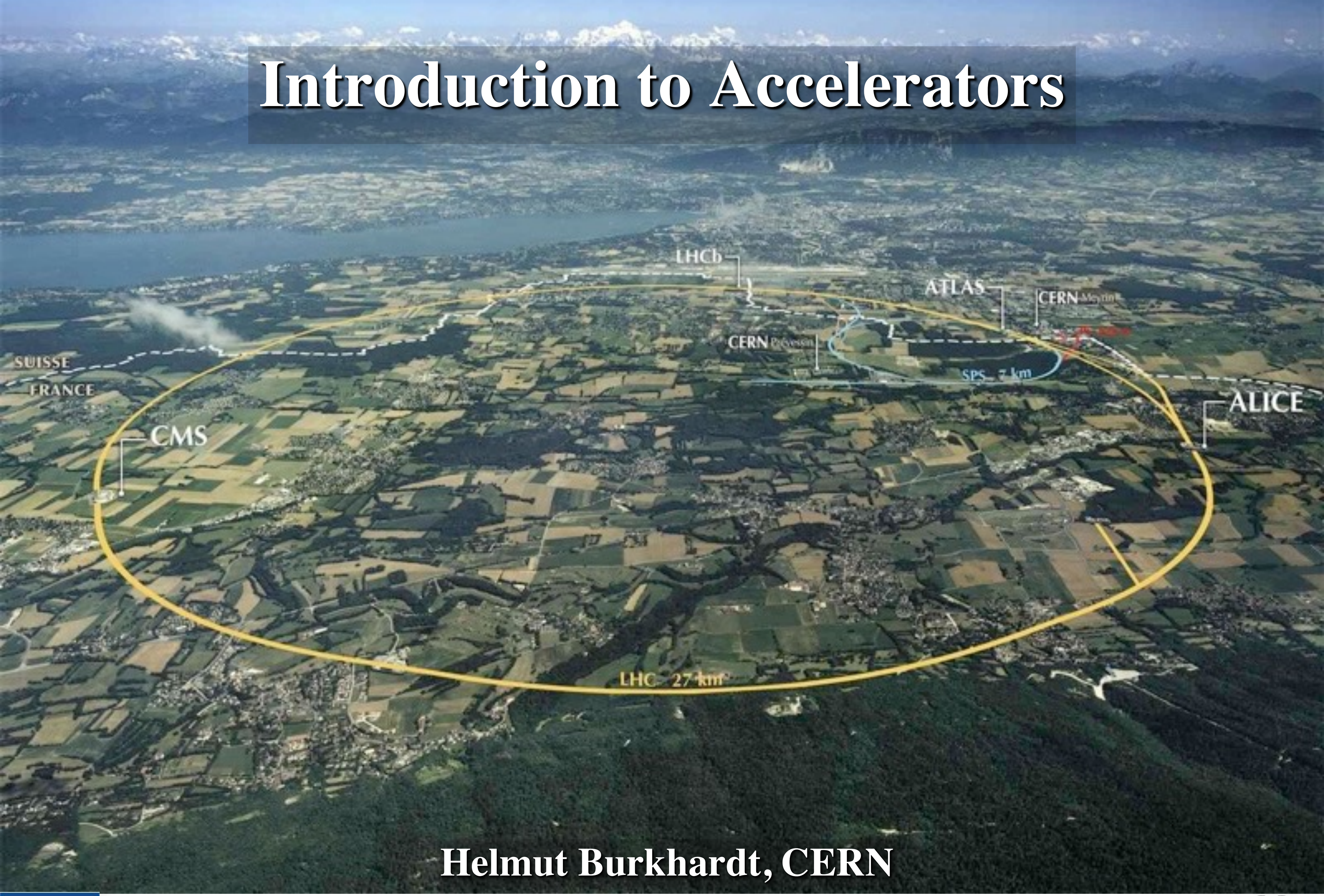
Delivered and Recorded
Luminosity



$$N = L \cdot \sigma$$

Number of Events — Integrated Luminosity — X-Sec.

Introduction to Accelerators



Helmut Burkhardt, CERN

ISEF 2013 24 June 2013

Contents

- **Concepts: Energy Gain, E / B field. Units**
- **Types of accelerators : Ring, Collider, Linac, e+e−, pp ; Cosmic**
- **Components: Source, Magnets, resonant Cavities**
- **Basic machine optics**
- **Energy and Luminosity**
- **Synchrotron Radiation**
- **Limitations, current and future challenges**

- **Mixed with examples - mostly from CERN machines and in particular the LHC**

General, introductory refs. and books on Accelerators :
E. D. Courant and H. S. Snyder, *Theory of the Alternating-Gradient Synchrotron,* pdf
M. Sands, *Physics of Electron Storage Rings*, SLAC Report No. 121; Wiedemann, *Particle Accelerator Physics* Bd. I,II
S.Y. Lee, *Accelerator Physics,* World Scientific; M. Conte, W. MacKay, *Physics of Particle Accelerators,* World Scientific
CERN CAS yellow reports ; K. Wille, *The physics of particle accelerators,* Oxford University Press, 1996

Accelerators for Particle Physics, H. Burkhardt, in Handbook of Particle Detection and Imaging, Ed. C. Grupen, Oct. 2011
The **L**arge **H**adron **C**ollider : O. Brüning, H. Burkhardt, S. Myers, 10.1016/j.ppnp.2012.03.001, CERN-ATS-2012-064
Accelerators and Colliders, Landolt-Börnstein New Series I/21C, Springer 2013

Accelerators at the Energy Frontier

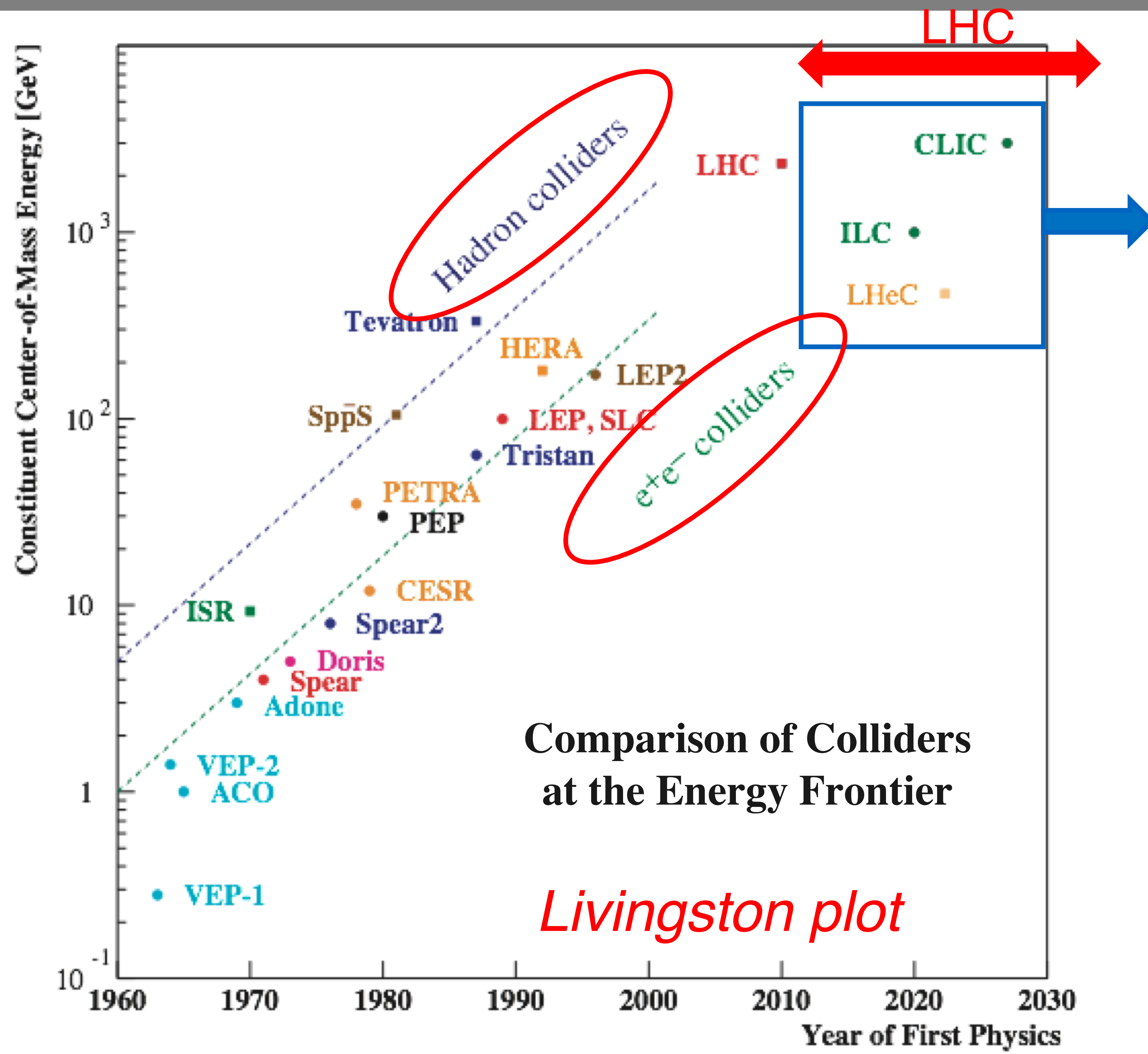
Livingston plot

Exponential growth of E_{cm} in time

Starting in 60's with e^+e^- at about 1GeV

Factor 4 every 10 y

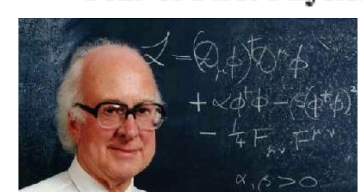
pp, $p\bar{p}$: E_{cm} / 6 still 5 × above e^+e^- at same time



pp, $p\bar{p}$: discovery
e^+e^- : precision
both required machines

+ ep : hadron structure, QCD
HERA, LHeC

The LHC is a major step forward
Discovery machine : Higgs ...



Livingstop plot

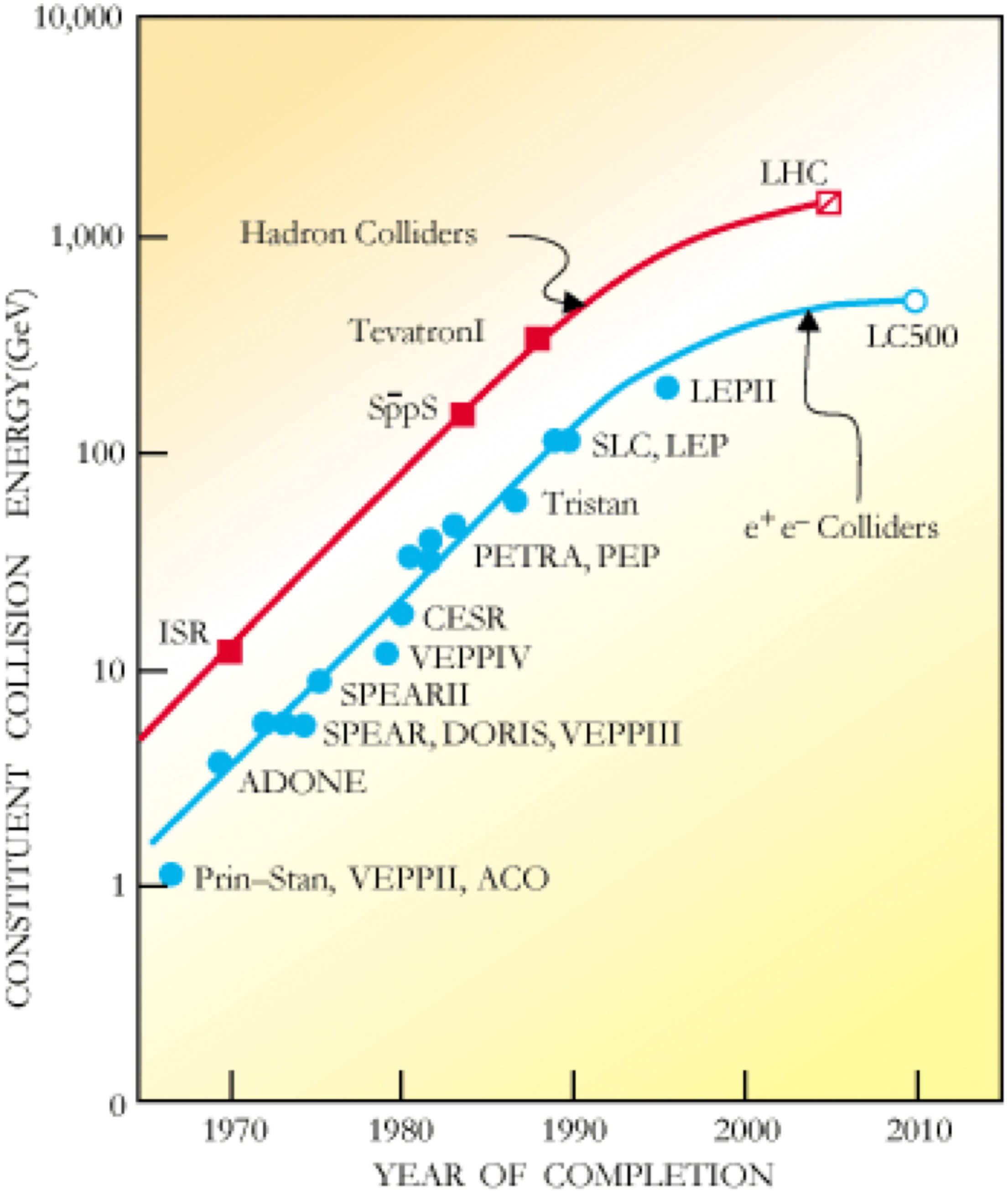
Livingston Plot:

Accelerator energy:

Energy reach has increased exponentially over the last 40 years

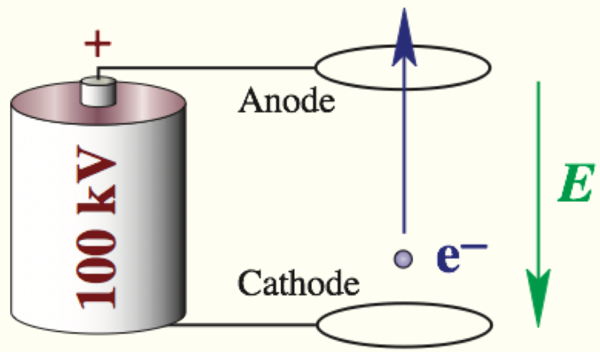
➔ Slow-down after 2000 (LHC and ILC)

➔ Indication for limit of existing technologies!!



Basic concepts and units

Electric field :
Acceleration
or rather
Energy gain
100 keV



Electric charge **e** and electric field **E**

Special relativity, Lorentz transformation

$$E=\gamma mc^2 \qquad p=\beta\gamma mc \qquad \beta=\frac{v}{c} \qquad \gamma=\frac{1}{\sqrt{1-\beta^2}}$$

$m_e \approx 0.511$ MeV/c^2 $m_p \approx 938$ MeV/c^2 e $\approx 1.602\times10^{-19}$ C

For $E = 10$ GeV :

Electron β = 0.999 999 9987 γ = 19569.5

Proton β = 0.995 588 4973 γ = 10.6579

Unit conversion

$$\frac{e^2}{4\pi\epsilon_0} = \alpha\hbar c = r_{part}\, m_{part}\, c^2$$
$$= 1.43996 \times 10^{-18}\ \text{GeV m}$$

$$\hbar c = 197.327 \times 10^{-18}\ \text{GeV m}$$

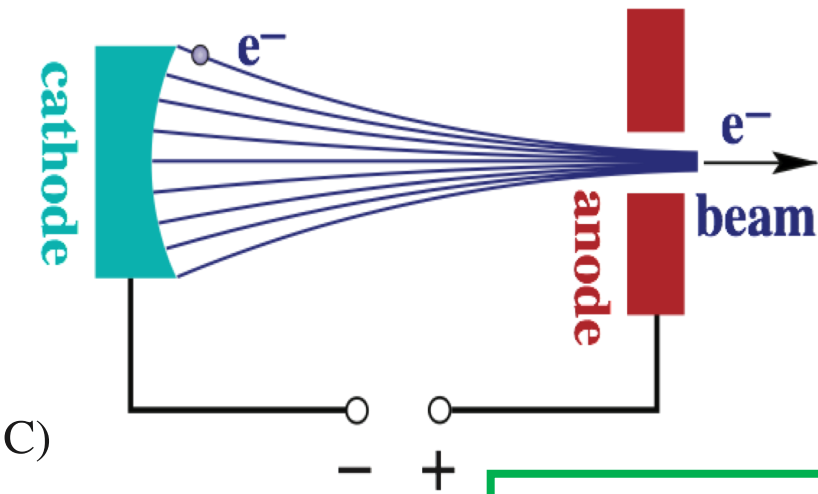
$$(\hbar c)^2 = 3.8938 \times 10^{-32}\ \text{GeV}^2\,\text{m}^2$$
$$= 3.8938 \times 10^{5}\ \text{GeV}^2\,\text{nb}$$

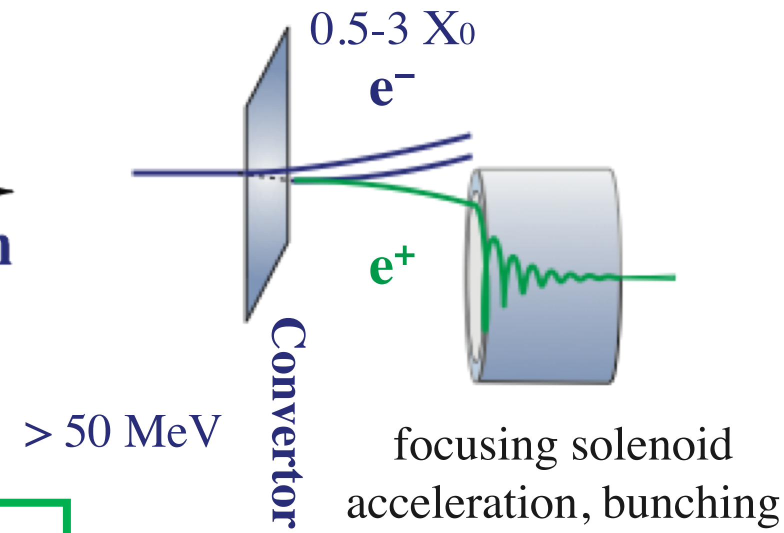
for precise numbers see PDG

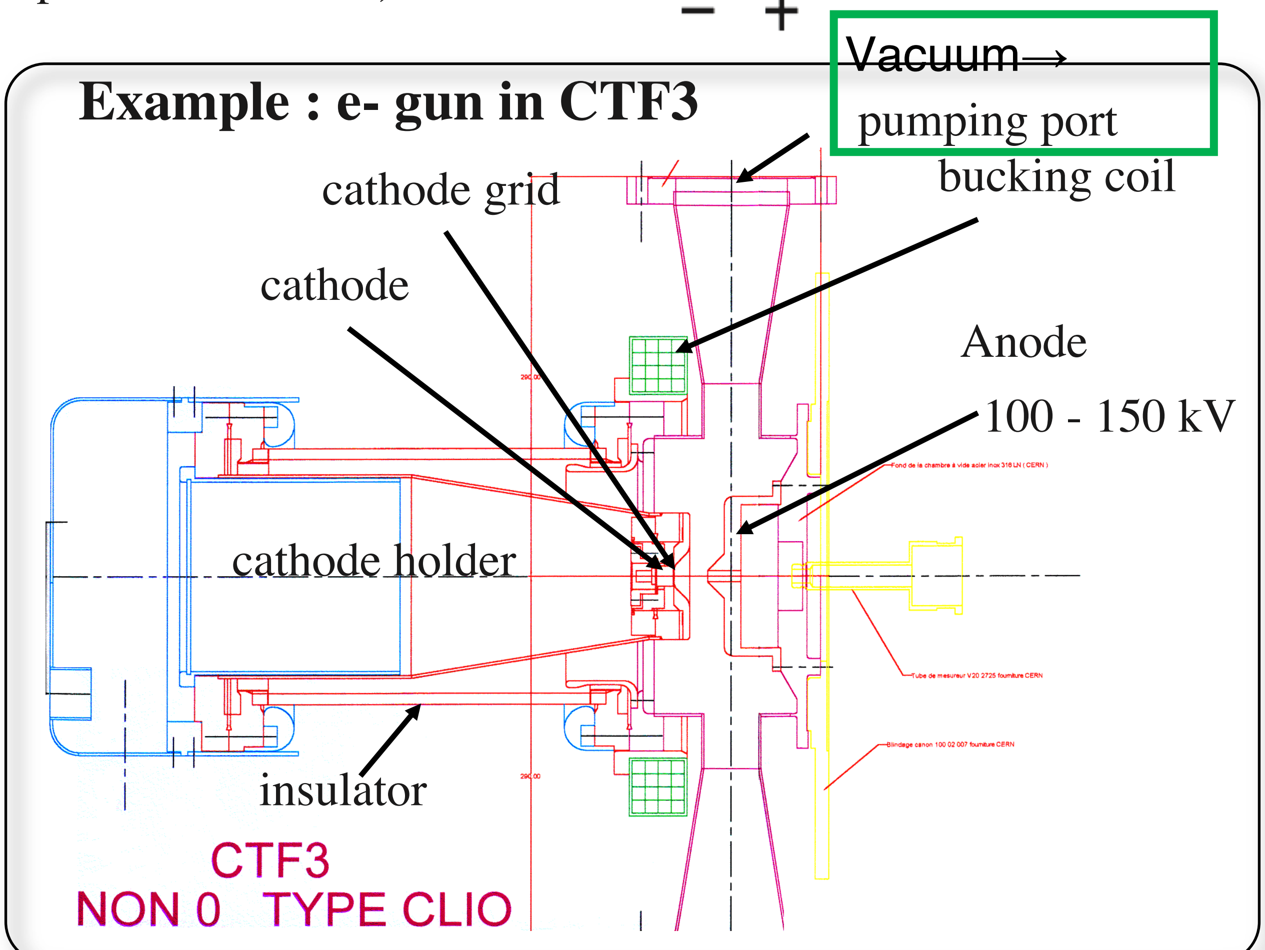
giga G = 10^9 tera T = 10^{12} peta P = 10^{15} exa E = 10^{18} zetta Z = 10^{21} yotta Y = 10^{24}

Particle sources

Thermionic **electron source** **principle** same as cathode ray tube (significant for temperatures ~ 700 C)







challenges :

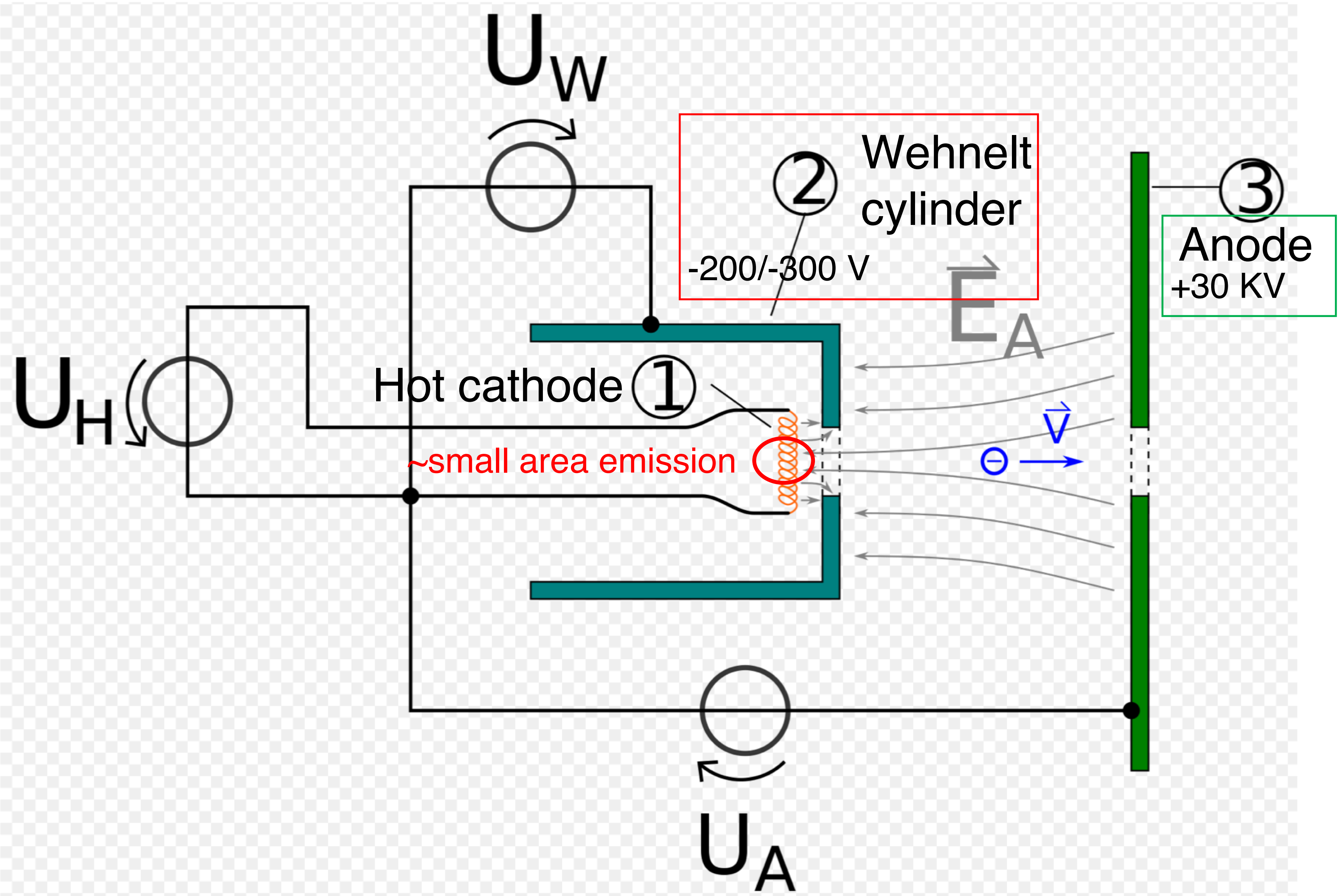
high intensity

polarized e^- **sources**

damping rings for minimum emittance

undulator polarized e^+ **sources**

Electron source



Electron sources, details

A Wehnelt cap has the shape of a topless, hollow cylinder. The bottom side of the cylinder has an aperture (through hole) located at its center, with a diameter that typically ranges from 200 to 1200 μm. The bottom face of the cylinder is often made from platinum or tantalum foil.

Operation

A Wehnelt acts as a control grid and it also serves as a convergent electrostatic lens. An electron emitter is positioned directly above the Wehnelt aperture, and an anode is located below the Wehnelt. The anode is biased to a high positive voltage (typically +1 to +30 kV) relative to the emitter so as to accelerate electrons from the emitter towards the anode, thus creating an electron beam that passes through the Wehnelt aperture. The Wehnelt is biased to a negative voltage (typically −200V to −300V) relative to the emitter, which is usually a tungsten filament or Lanthanum hexaboride (LaB_6) hot cathode with a "V" shaped (or otherwise pointed) tip. This bias voltage creates a repulsive electrostatic field that suppresses emission of electrons from most areas of the cathode.

The emitter tip is positioned near the Wehnelt aperture so that, when appropriate bias voltage is applied to the Wehnelt, a small region of the tip has a net electric field (due to both anode attraction and Wehnelt repulsion) that allows emission from only that area of the tip. The Wehnelt bias voltage determines the tip's emission area, which in turn determines both the beam current and effective size of the beam's electron source.

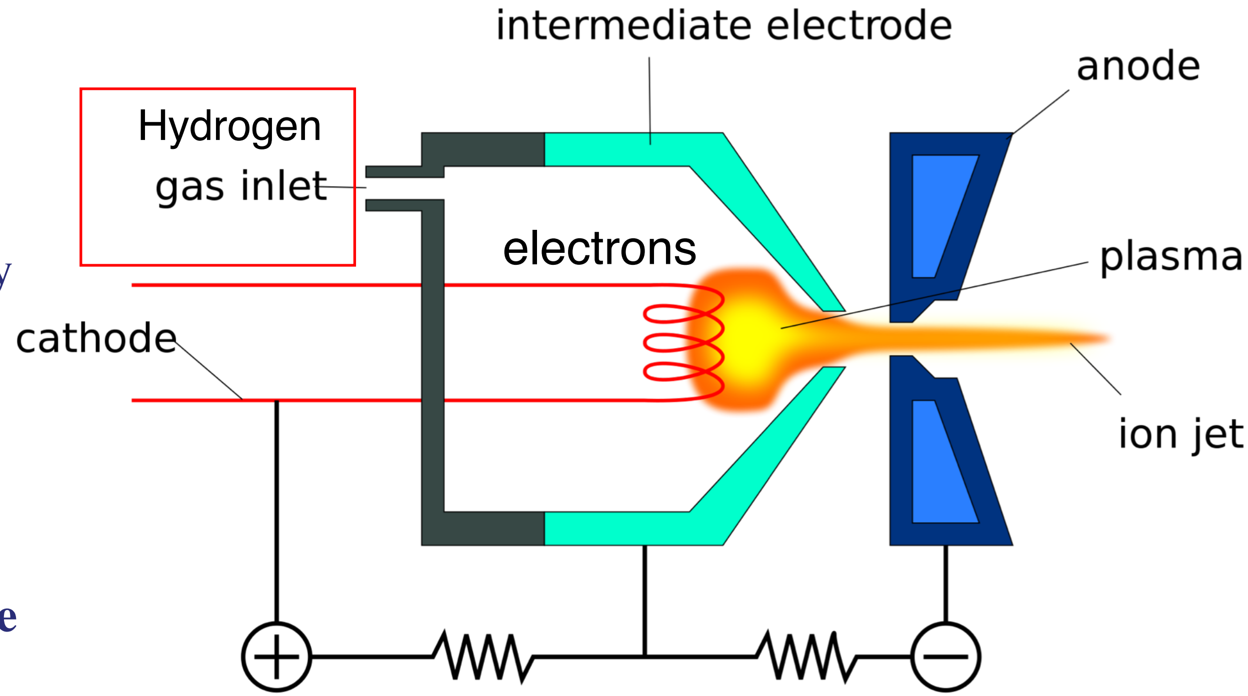
As the Wehnelt bias voltage increases, the tip's emitting area (and along with it, the beam diameter and beam current) will decrease until it becomes so small that the beam is "pinched" off. In normal operation, the bias is typically set slightly more positive than the pinch bias, and determined by a balance between desired beam quality and beam current.

The Wehnelt bias controls beam focusing as well as the effective size of the electron source, which is essential for creating an electron beam that is to be focussed into a very small spot (for scanning electron microscopy) or a very parallel beam (for diffraction). Although a smaller source can be imaged to a smaller spot, or a more parallel beam, one obvious trade off is a smaller total beam current.

Proton and ion sources

Various methods exist to produce
p (H^+), H^- (p with 2 e^-) and heavy ions - heavier atoms, most electrons removed

Typically involves : **low pressure heated gas** ionized gas / plasma, inject H_2 to get protons, **or surface sputtering and electric and magnetic fields** to keep the electrons

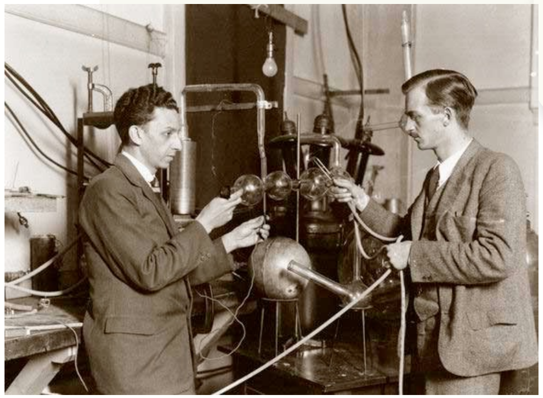


CERN p-source and 50 MeV Linac

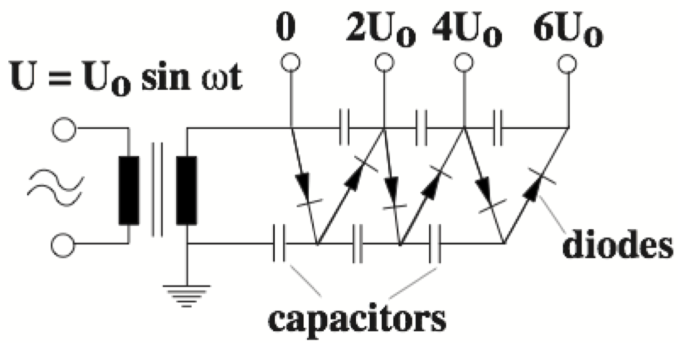
Linear Acceleration with Electrostatic Field

allows for DC, 100 % duty factor

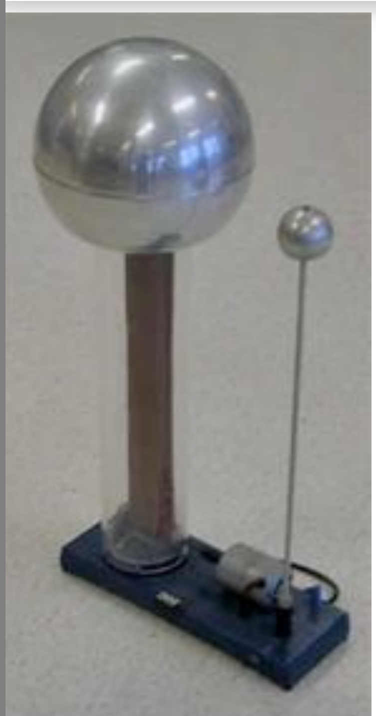
limited by HV-breakdown ~ 1 MV / m



Cockcroft Walton
voltage multiplier

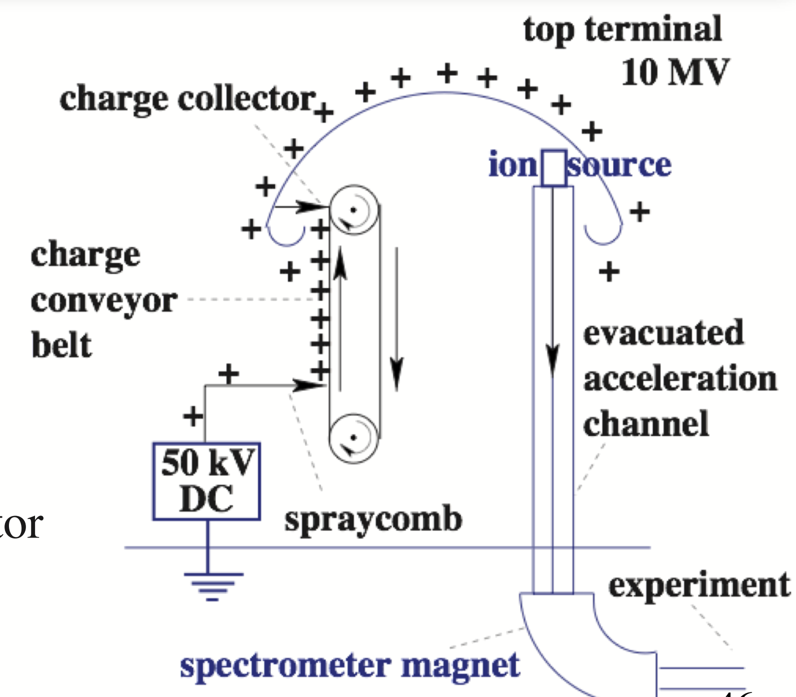


800 kV proton pre-injector used at CERN until 1993



Van de Graaff generator
static electricity from belts

Oak Ridge Tandem Van de Graaff generator reached 25.5 MV using pressurised SF_6

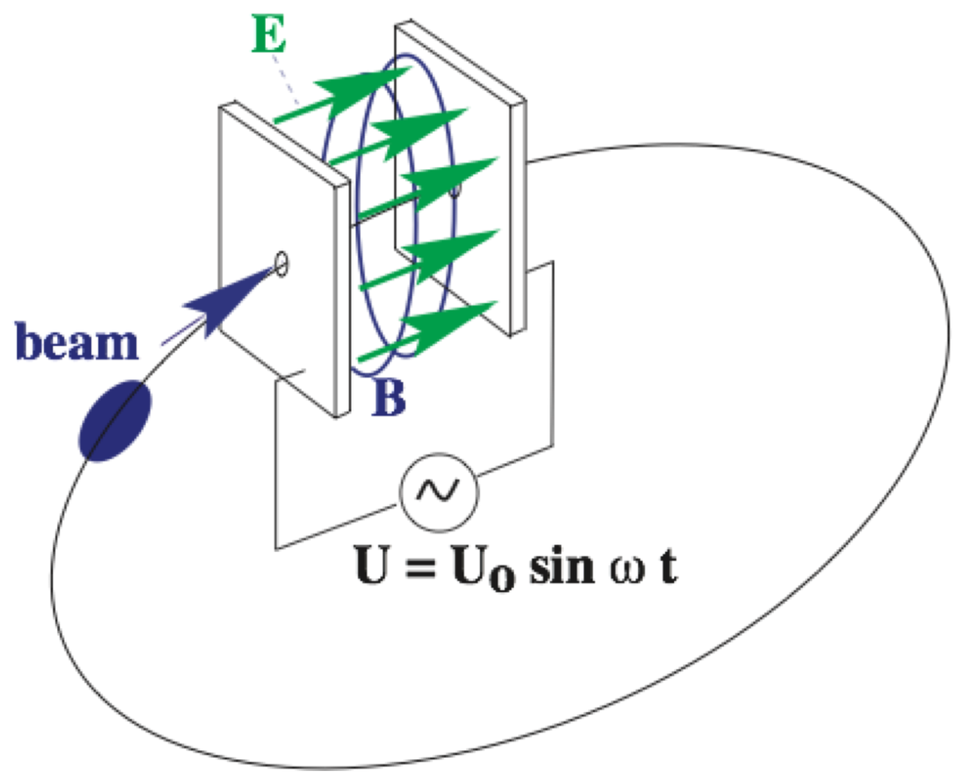


Time Varying Fields

Radio-Frequency or short RF acceleration

- **allows for multiple passages**
- **bunched beams, reduced duty cycle**
- **higher RF frequencies allow for higher acceleration gradients**

no time for breakdown / flashover



LEP , SC	**8 MV / m**	**at 352 MHz**
Tesla / ILC, SC	**31.5 MV / m**	**at 1.3 GHz**
CLIC	**100 MV / m**	**at 12 GHz**

little gain above 12 GHz
SC limit ~ 50 MV/m, reached for single cell
surface gradients higher then acceleration gradients, smooth structures

high f : shorter bunches - collective effects (peak current) and alignment more difficult
less energy stored in structure


9 cell 1.3 GHz SC niobium TESLA / ILC cavity

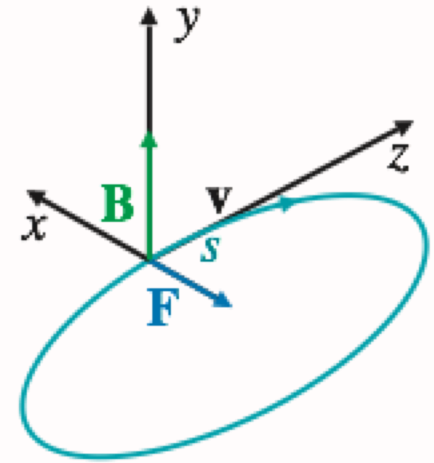
Basic parameters, Lorentz Force

$$\mathbf{F} = q\,(\mathbf{E} + \mathbf{v} \times \mathbf{B})$$

charge q, normally $q = e$; $q = Z e$ for ions

- Electric field **E** provides the acceleration or rather energy gain
- The magnetic field **B** keeps the particles on their path

Circular motion for
$\mathbf{E} = 0$
$\mathbf{v} \perp \mathbf{B}$



ρ is the radius of curvature for motion perpendicular to the static magnetic field. Often called
- gyromagnetic or Larmor radius in astroparticle physics
- bending radius for accelerators

Bρ known as magnetic rigidity, units Tm

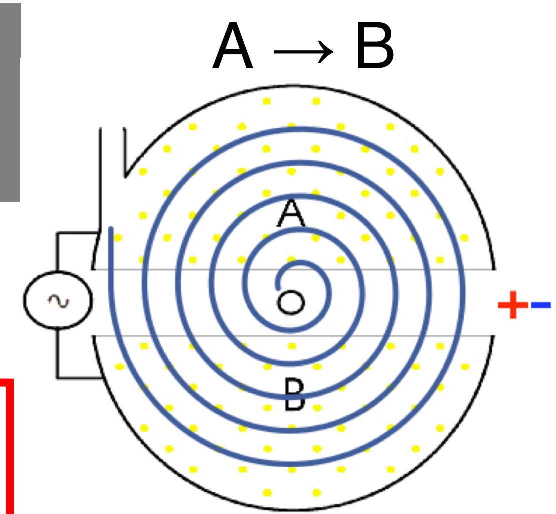
$$B = \frac{p}{q\,\rho}$$

for q = e numerically
$B\,[\mathrm{T}] = p\,[\mathrm{GeV/c}]\ \ 3.336\ \mathrm{m}/\rho$
high energy, v = c "p = E"
$E < E_H = q\,B\,\rho$ Hillas criterion

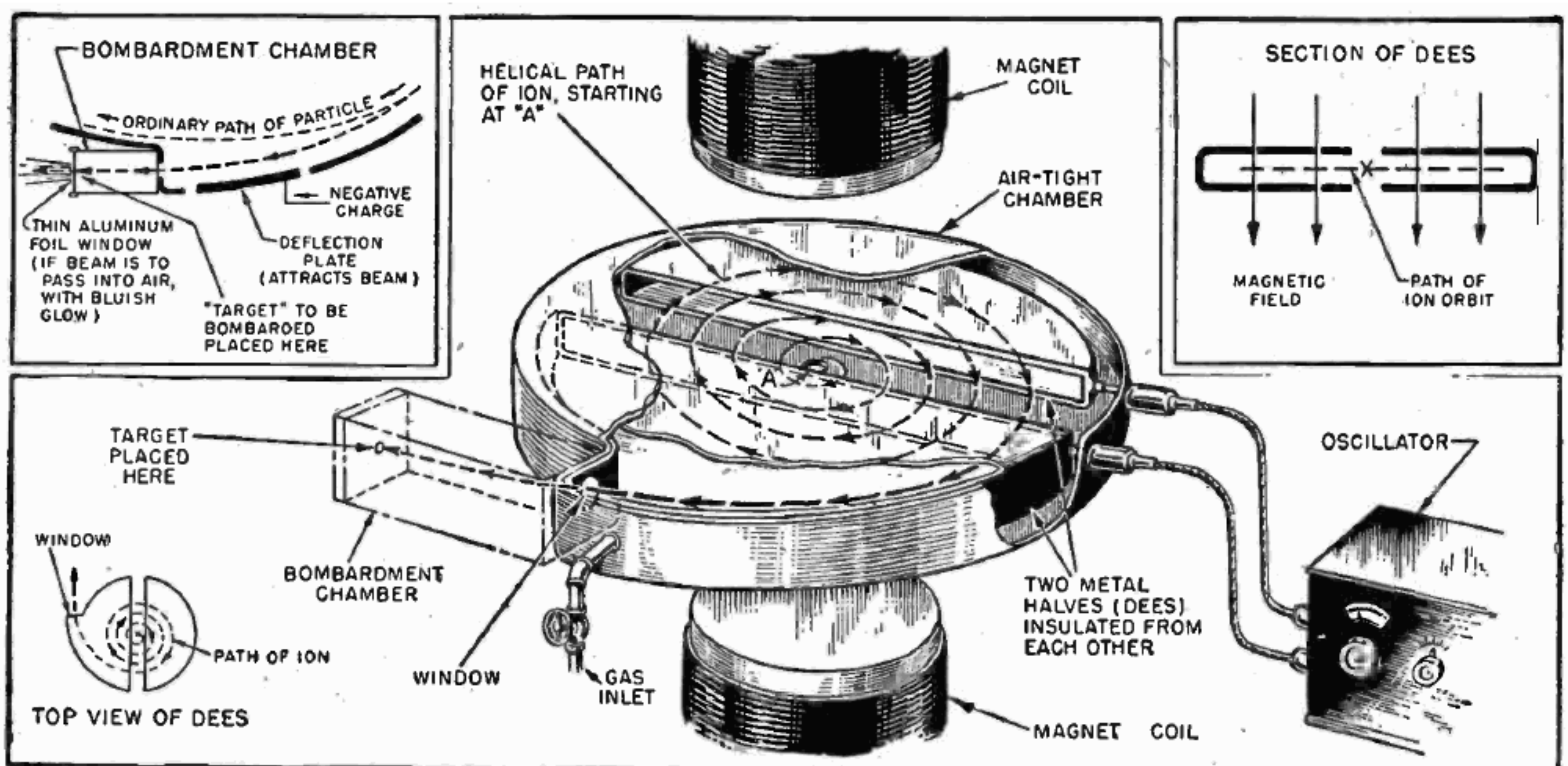
LHC
- **Momentum p = 7 TeV/c**
- **LHC bending radius ρ = 2804 m**
- **Bending field B = 8.33 Tesla**
- **magnets at 1.9 K, super-fluid He**

Astroparticle
units 10^{-4}T = 1Gauss ; a.u. = 1.5×10^{11}m
Solar system B = 10μG E = 5 TeV ρ = 11 a.u.
Intergalactic B = 1nG E = 5 PeV (knee)
$\rho = 1.7\times10^{19}$m (4 % of galaxy-radius)

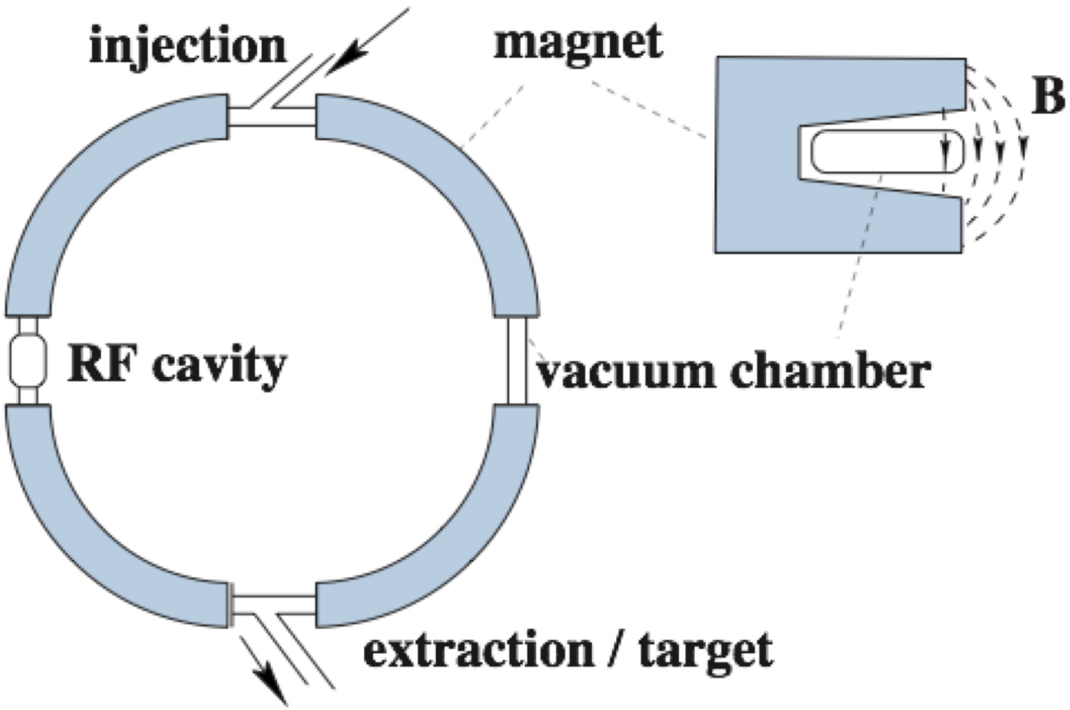
A sketch of an historical Cyclotron



- **Cyclotron : constant rf-frequency. Magnetic field radius ρ increases with energy. Used for smaller machines**



Circular Accelerator



$$B[T] = p\left[\frac{GeV}{c}\right] \cdot 3.336\frac{m}{\rho}$$

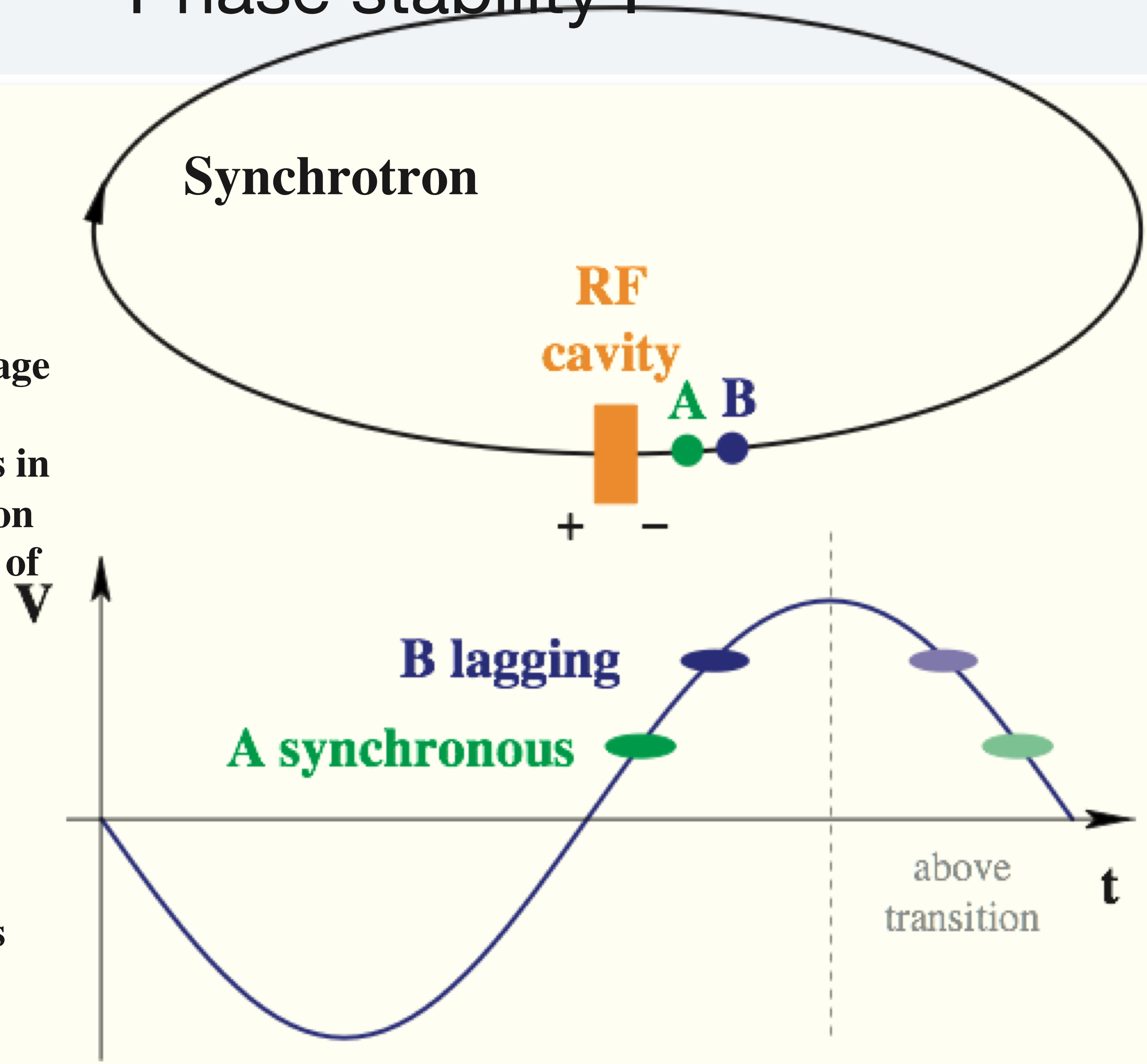
$$\rho \propto p$$

- **Synchrotron : ϱ = const. B increased with energy. RF-frequency adjusted slightly (β = 0.999 .. 1.0).** Most HEP and all CERN ring accelerators PS, SPS, LEP, LHC of this type. Principle same for e, p, heavy-ion – PS, SPS – accelerate(d) all of these, in some cases switching within seconds

Phase stability I

acceleration,
ramping up in energy :

- allow for enough RF-voltage
- ramp up magnets
- particle adjust themselves in radius and phase to gain on average the right amount of energy



LHC nominal RF parameters
Voltage at injection   8 MV
top energy 16 MV
Revolution frequency $f_{rf} = h\, f_{rev}$ $h = 35\,640$ $f_{rf} = 400.7896$ MHz $L = 26658.864$ m
Circumference $L = v / f_{rev} = \beta\, c / f_{rev}$ $f_{rev} = 11.2455$ kHz   1 turn in 88.92446 μs

Magnets and Power Consumption

Why super conducting magnets ?

$$P = R\, I^2$$

Lep = e^+e^- machine

LEP

B = 0.1 T LEP2 ~ 100 GeV

(half) **cells with each three 11.55 m long dipole magnets**

I = 4.5 kA together R = 1 mΩ P = 20 kW / cell

488 cells P = 10 MW

if we would have kept the same magnets for the LHC

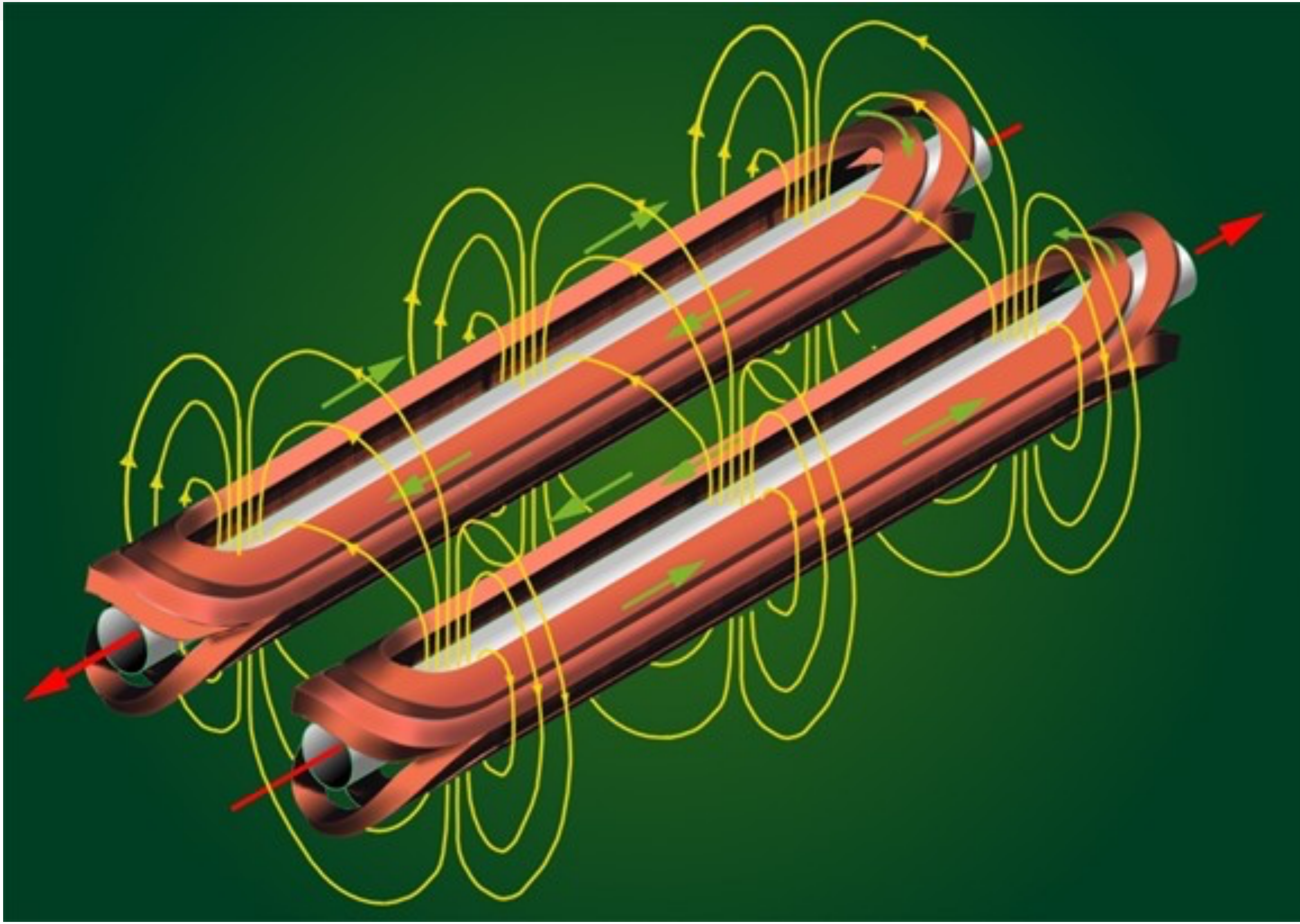
LHC = pp machine

LHC B ∝ I B = 8.38 T

would need now I = 280 kA with LEP magnets R = 1 mΩ

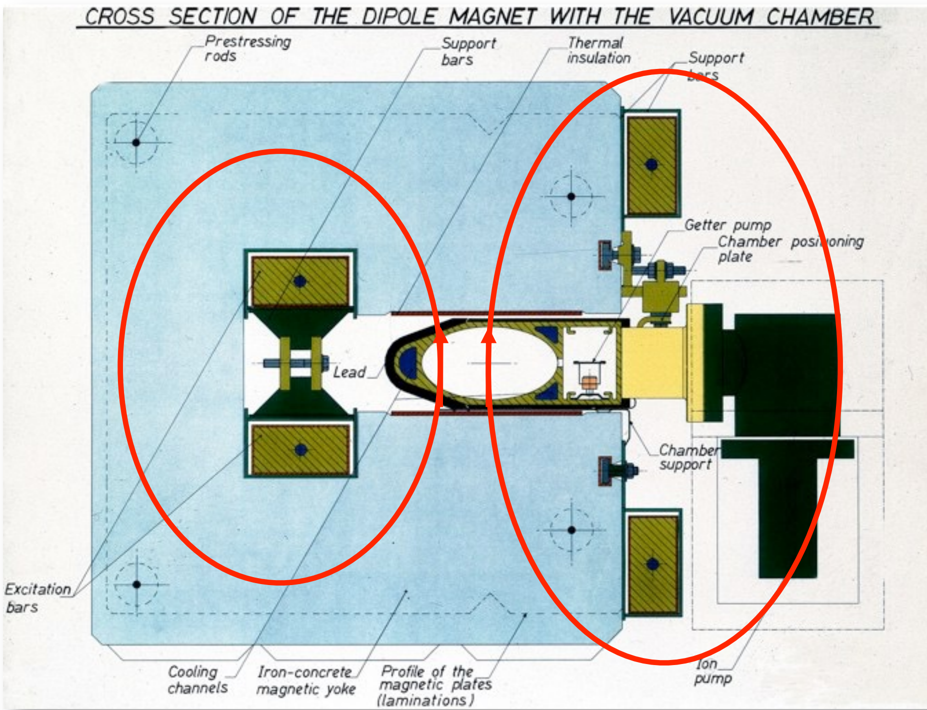
P = 78 MW / cell × 488 cells total power P = 38 GW

LHC dipoles



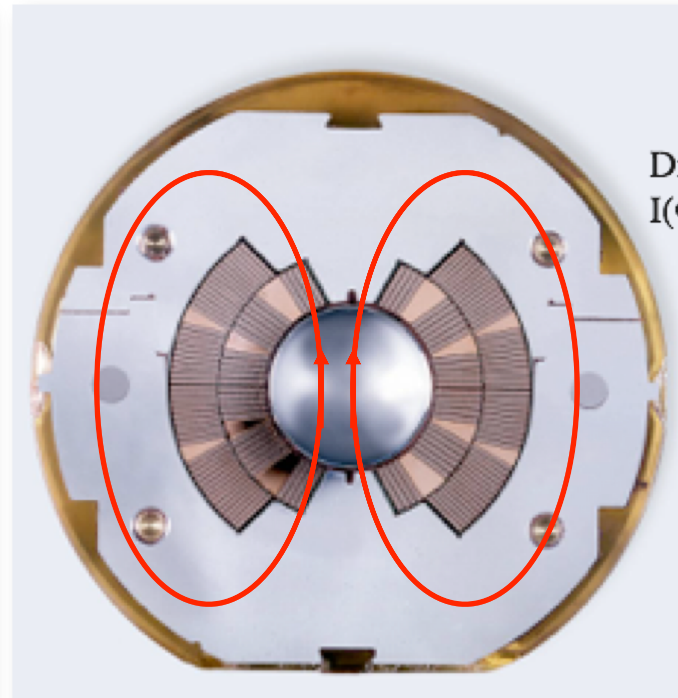
Magnet technology

warm

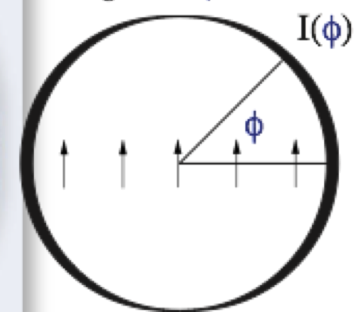


- field quality given by pole face geometry
- field amplified by Ferromagnetic material
- hysteresis and saturation ~ 2 T
- Ohmic losses for high magnet currents

cold



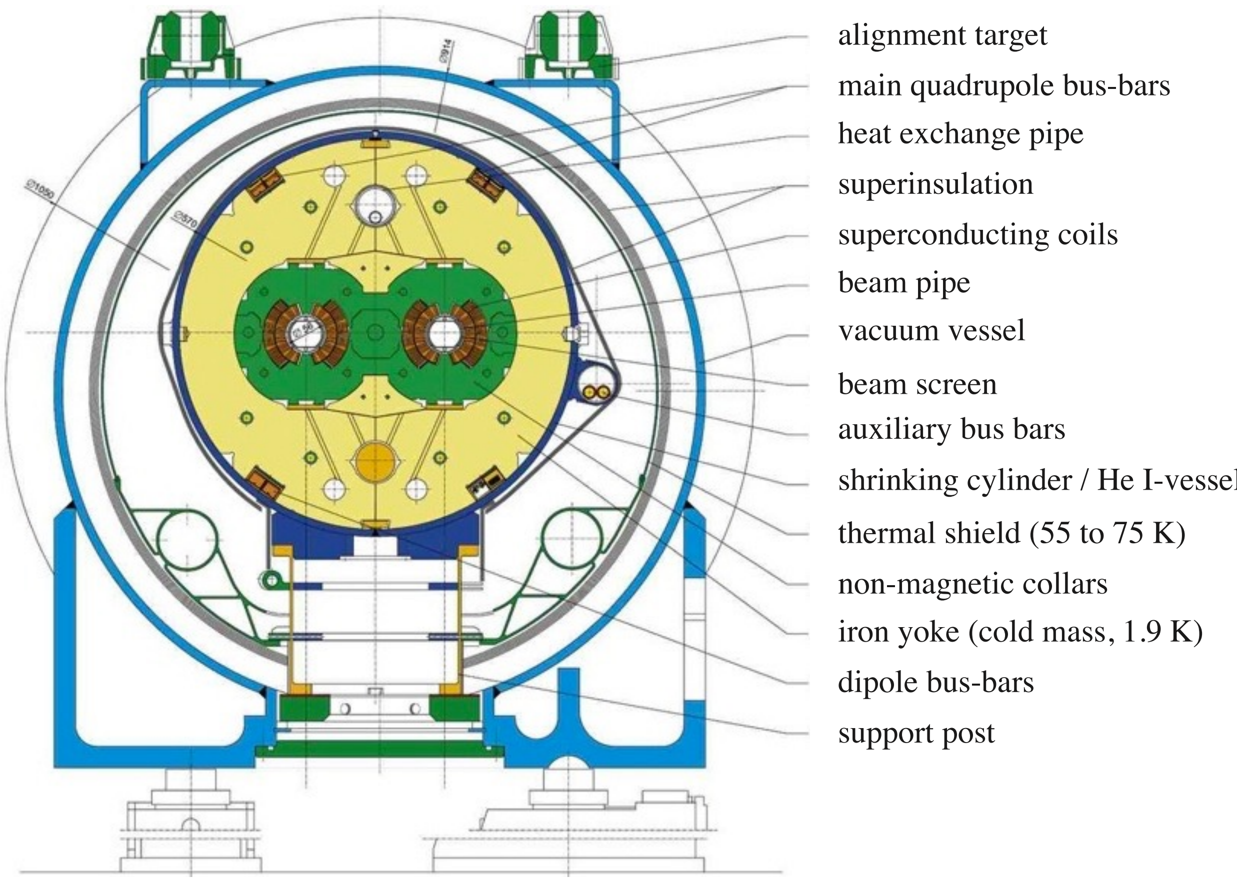
Dipole current distribution
$I(\Phi) = I_0 \cos(\phi)$



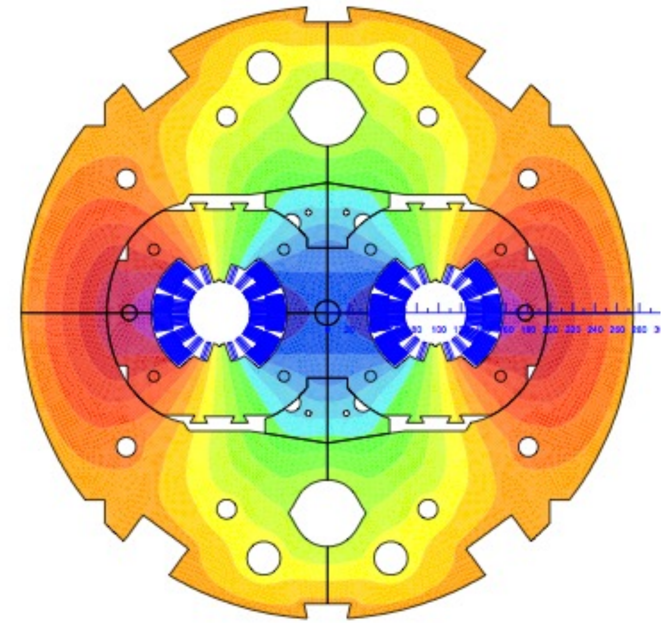
- field quality given by coil geometry
- requires cooling to cryogenic temperatures
- persistent currents and snap back
- risk of magnet quenches

LHC dipole magnet

2-in-1 dipole magnet, 8.33 T field, 15 m long, mass 30 ton

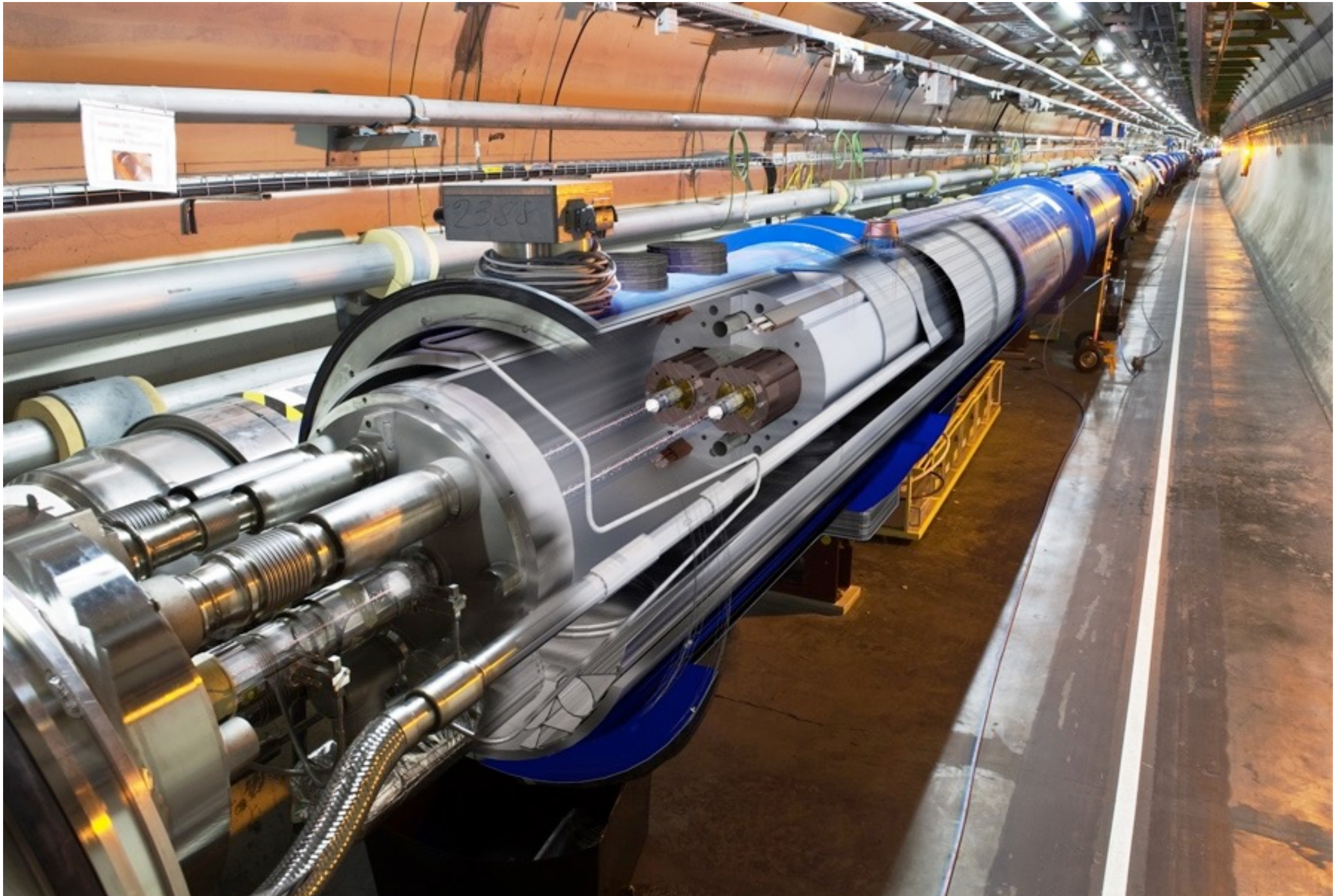


LHC dipole magnet cross-section

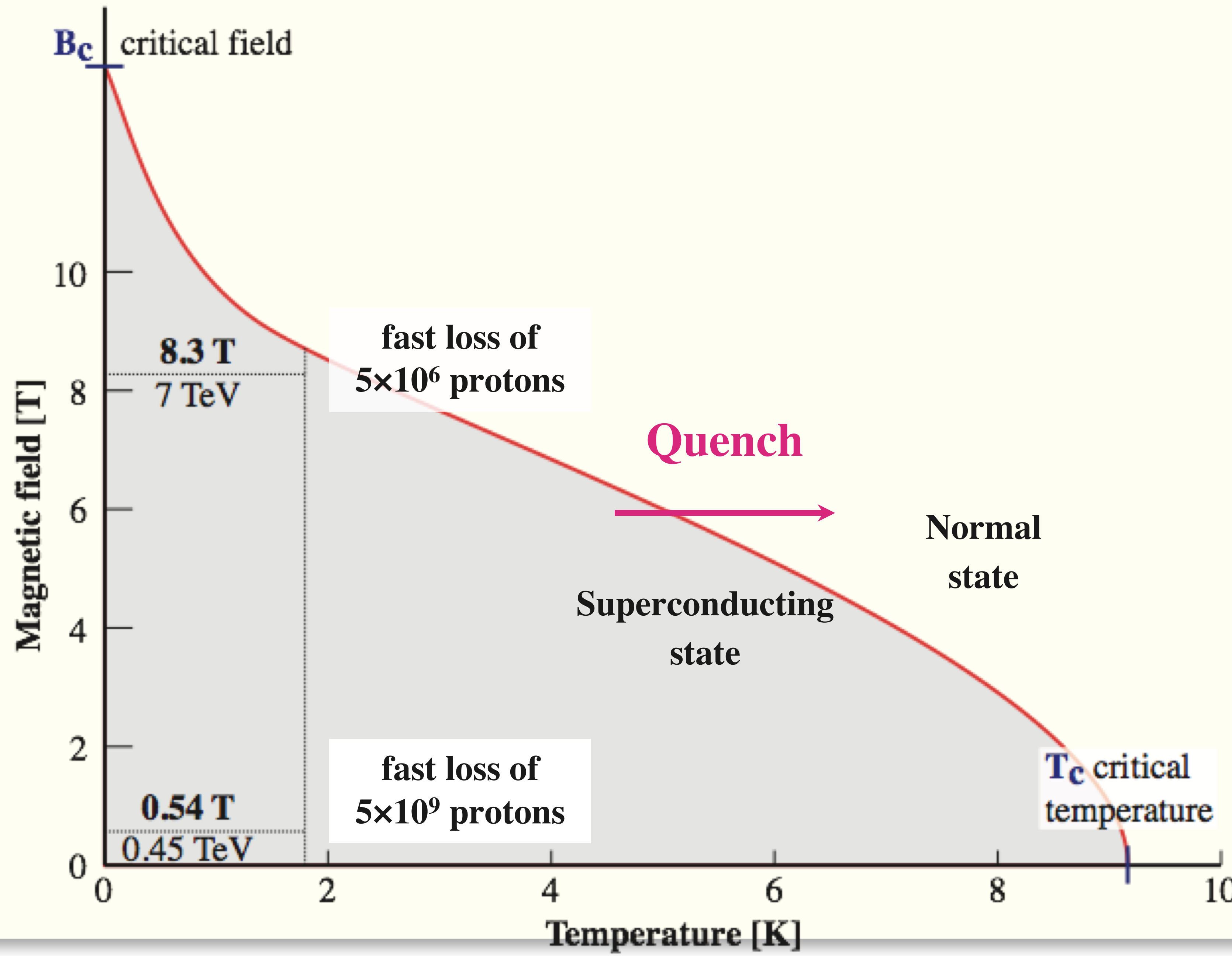


current distribution

LHC magnets installed in the tunnel



Operational margin of a superconducting LHC dipole



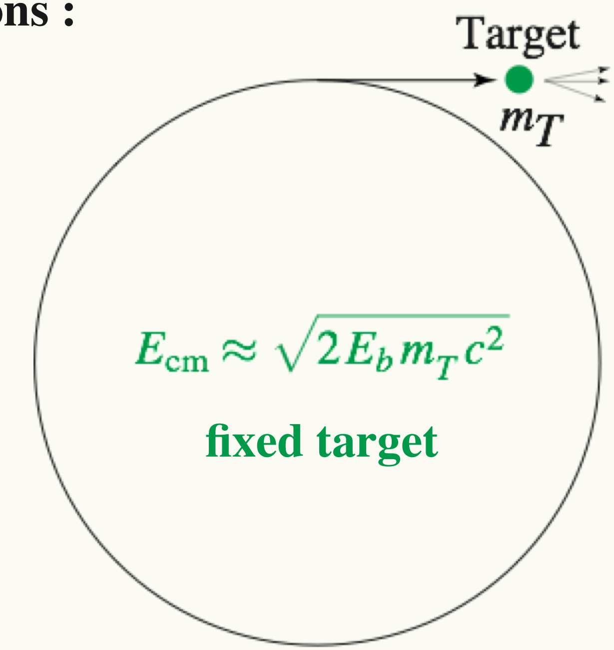
Fixed Target vs Collider

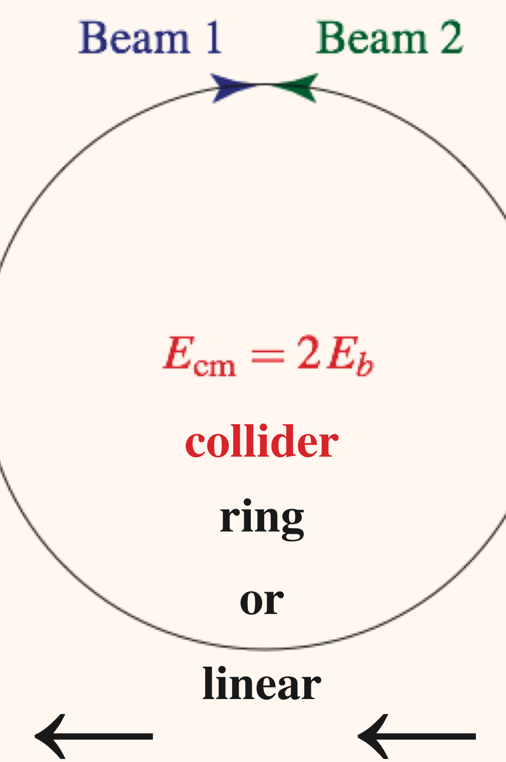
Fixed target, high energy collisions :

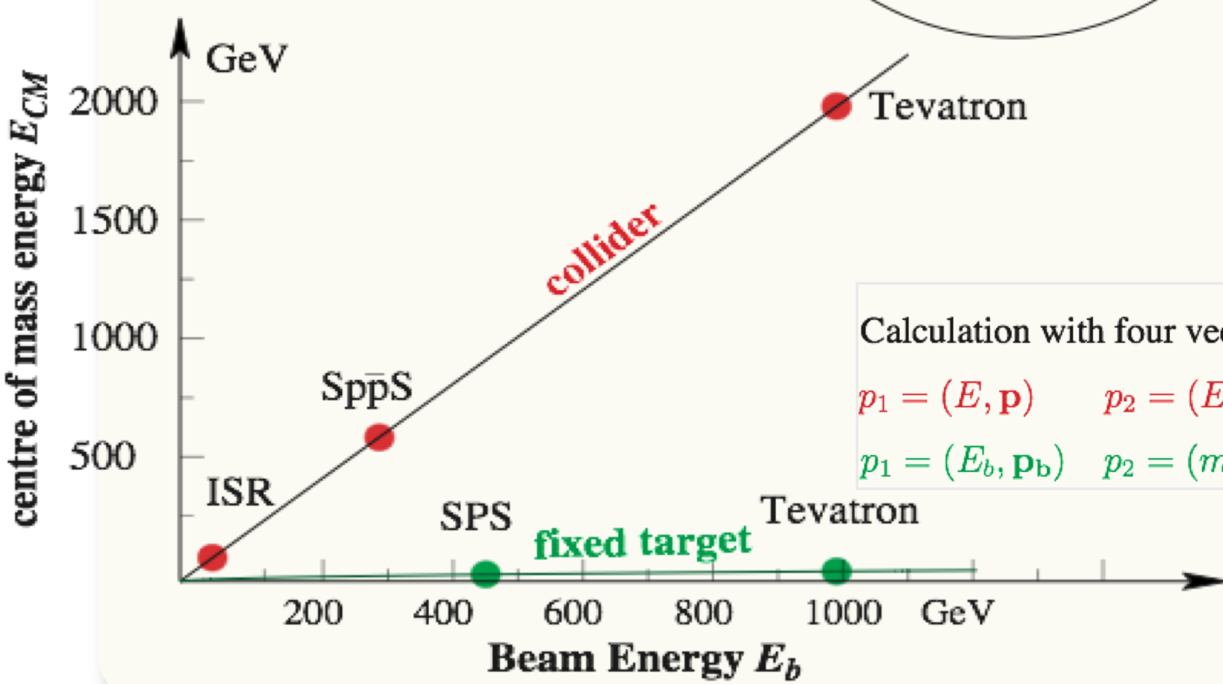
Energy "lost" as kinetic energy

High Energy e⁺e⁻ and very high energy pp gain a lot from colliders

Gain for LHC is by ×122
(14 TeV / 114.6 GeV)







Calculation with four vectors for c = 1 $\quad E_{CM} = \sqrt{s} \quad s = (p_1 + p_2)^2$

$p_1 = (E, \mathbf{p}) \quad p_2 = (E, -\mathbf{p}) \quad s = 2m^2 + 2E^2 + 2p^2 = 4E^2$ collider

$p_1 = (E_b, \mathbf{p}_b) \quad p_2 = (m_T, 0) \quad s = m_b^2 + m_T^2 + 2m_T E_b$ fixed target

Primary cosmic ray spectrum

E spectrum falls as $E^{-2.7}$
to knee at $E \approx 5e^{15}$ eV
$= 5\times10^{6}$ GeV
~1 particle/(m^2 year)

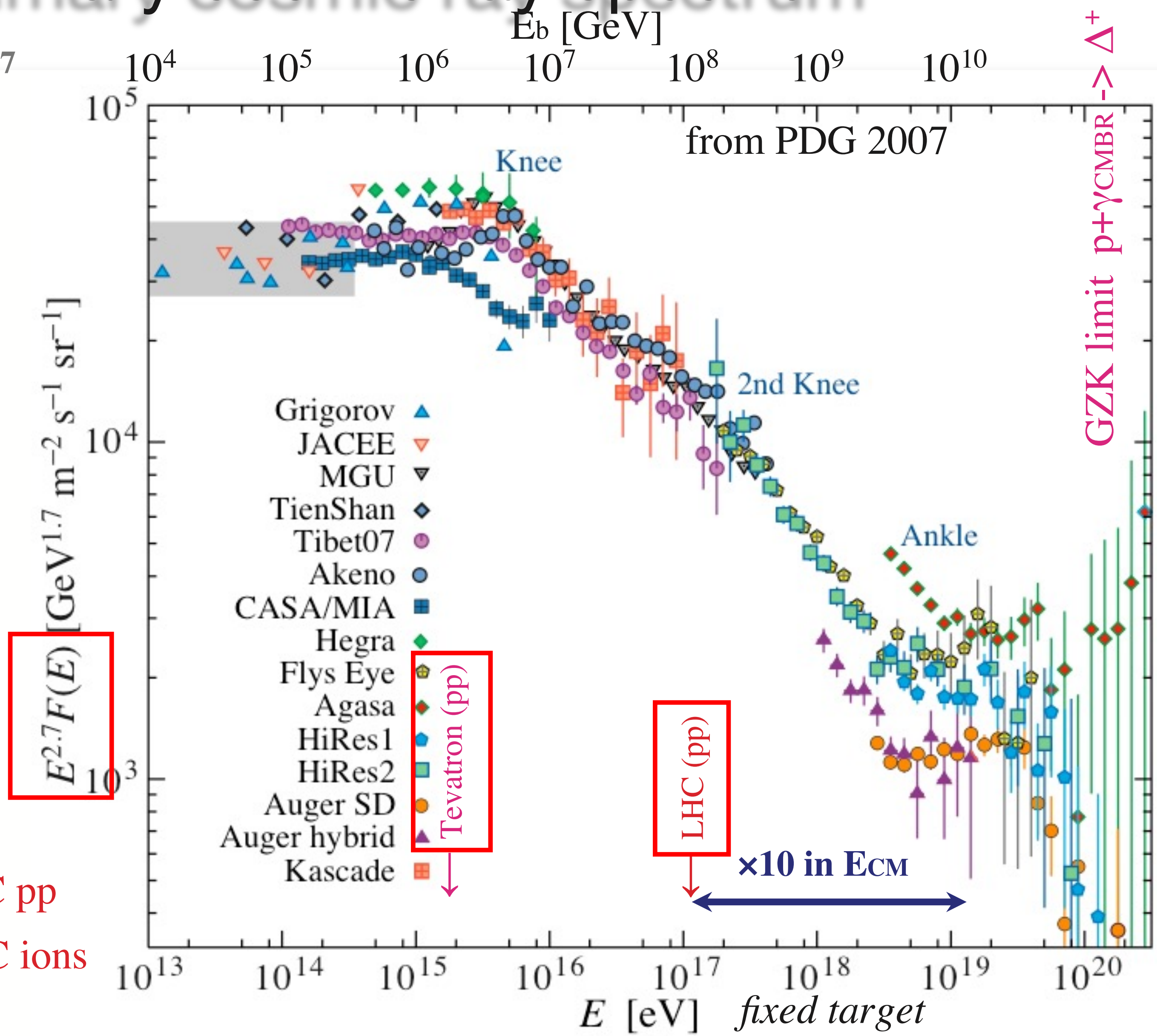
origin galactic

above ~ E^{-3}

back to $E^{-2.7}$ at very highest energies

conversion to E_{cm}

E_b [eV]	E_{cm} [TeV]	
10^{13}	0.137	
10^{15}	1.370	
10^{17}	13.70	≈ LHC pp
10^{19}	137.0	← LHC ions
10^{21}	1370.	



Nature has much larger and more powerful **cosmic accelerators** then we can ever built.
With colliders we can get to these collision energies in clean laboratory conditions.
The LHC already gets us to within 1-2 orders of magnitude of the very highest cosmic rays.

Luminosity and collision rates

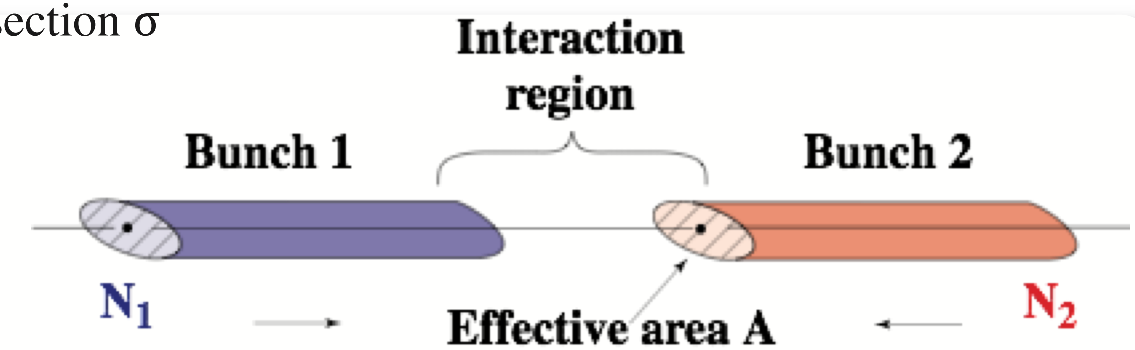
Event rate for process with cross section σ

$$\dot{n} = \mathcal{L}\sigma$$

Luminosity from bunch

crossings at frequency $f = f_{rev}\, n_b$

$$\mathcal{L} = \frac{N_1 N_2 f}{A}$$

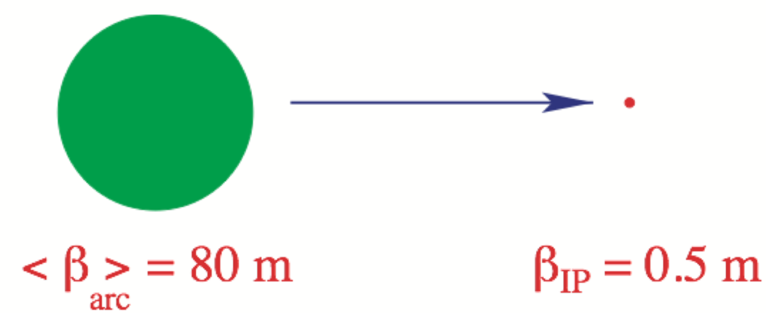


for Gaussian bunches with rms sizes $\sigma_x\ \sigma_y$ $\mathbf{A} = 4\pi\sigma_x\sigma_y$

High **Luminosity** : N↑ collide many particles, A↓ squeezed in small bunches

LHC 1.15×10^{11} protons, $n_b = 2808$ (f↑ crossings at 25 ns intervals)

Beams squeezed using strong large aperture quadrupoles around the interaction points from ~ 0.2 mm to $\sigma_x = \sigma_y = 17\ \mu m$



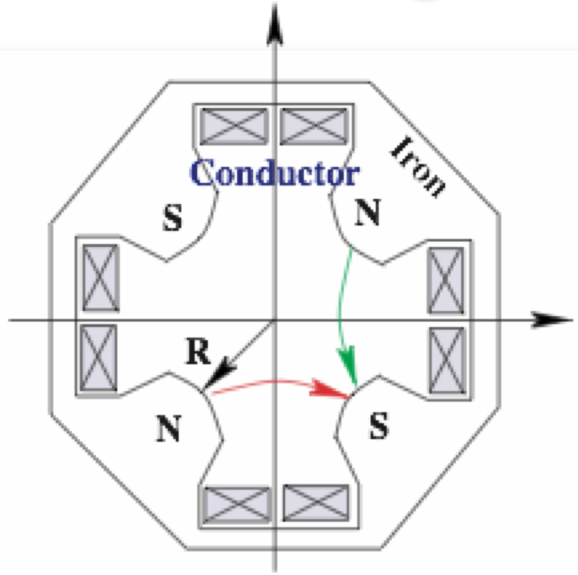
Rare new processes, like Higgs production can have very small cross section, like $1fb = 10^{-39} cm^2$. LHC designed for very high Luminosity $\mathbf{L = 10^{34}\ cm^{-2}s^{-1}}$

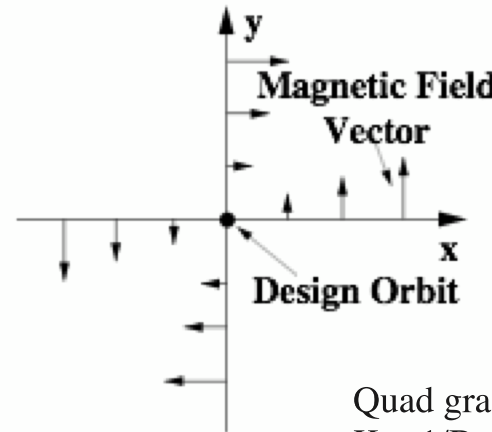
Event rate for such rare processes : ~ 1 new particle every 28h.

Instead pp $\sigma_{tot} \approx 0.1$ barn 30 / crossing

Alternate gradient focusing

Quadrupole lens focusing in x, defocusing in y or vice versa





$B_x = k\,y$
$B_y = k\,x$
$B_z = 0$

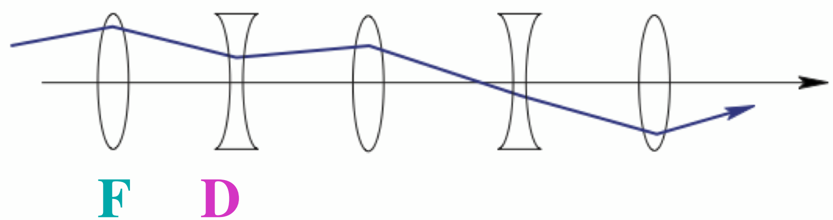
$\nabla \times \boldsymbol{B} = \boldsymbol{0}$

$\mathbf{F} = e\,(\mathbf{v} \times \mathbf{B})$
here
$\mathbf{F} = e\,(0, 0, v) \times (B_x, B_y, 0)$
$= e\,(-v\,B_y,\ +v\,B_x,\ 0)$

Quad gradients in the LHC
$K = 1/B\varrho\ \ \partial B_y/\partial x \approx 200$ T/m

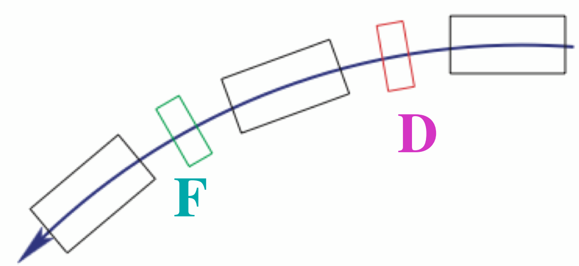
Combine F D
Defocusing when at small amplitude
Overall focusing

alternate gradient focusing



Normal (light) optics :
Focal length of two lenses at distance D
$1/f = 1/f_1 + 1/f_2 - D/f_1 f_2$
is overall focusing
with $1/f = D/f^2$
for $f = f_1 = -f_2$

together with bending magnets FODO lattice



N. C. Christofilos, unpublished manuscript in 1950 and patent
Courant, Snyder in 1952, Phys. Rev. 88, pp 1190 - 1196 + longer review in [Annals of Physics 3 (1958)]

Betatron motion

Equation of motion of particles in a ring (with bending fields) **and quadrupoles** (field gradients $\propto \partial B/\partial r$)

In both transverse planes, here written with x for x, y : known as Mathieu-Hill equation

$x''(s) + k(s)\, x(s) = 0,$ derived in 1801 to describe planetary motion

Generalised oscillator equation with position dependent, periodic restoring force $k(L+s) = k(s)$ given by the quadrupole gradients (+ the small weakly focusing bending term in the ring plane)

Solution : $x(s) = \sqrt{\epsilon\,\beta(s)}\cos(\mu(s) + \phi)$

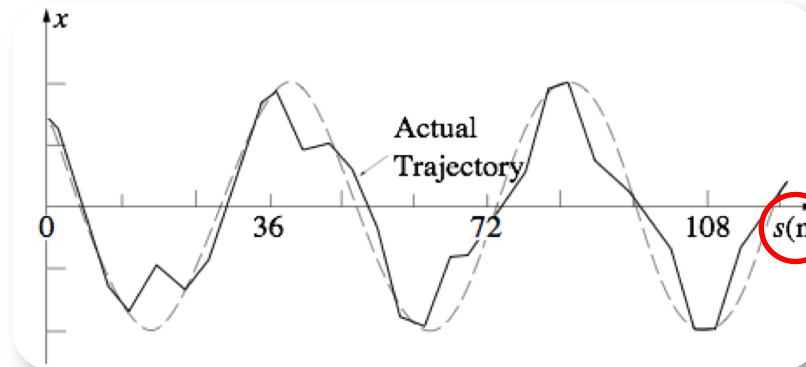
Phase advance

Lyapunov-Floquet Transformation

$$\mu(s) = \int_0^s \frac{ds}{\beta(s)}$$

Tune # of betatron oscillations

$$Q = \mu / 2\pi$$



motion $x/\sqrt{\beta}$ *plotted with phase advance normalised coordinates - becomes simple cos*

$\beta(s)$ **beta function**, describes the focusing properties of the magnetic lattice

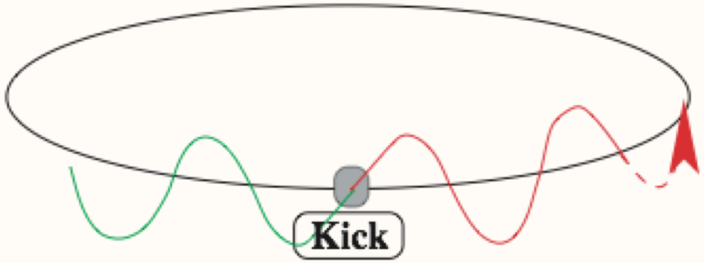
ε invariant, together with $\beta(s)$ amplitude. "single particle emittance"

Motion conveniently described in phase space (x, x') where $x' = p_x / p$
and linear optics elements as matrices ; with simple case for M, applies for IP to IP

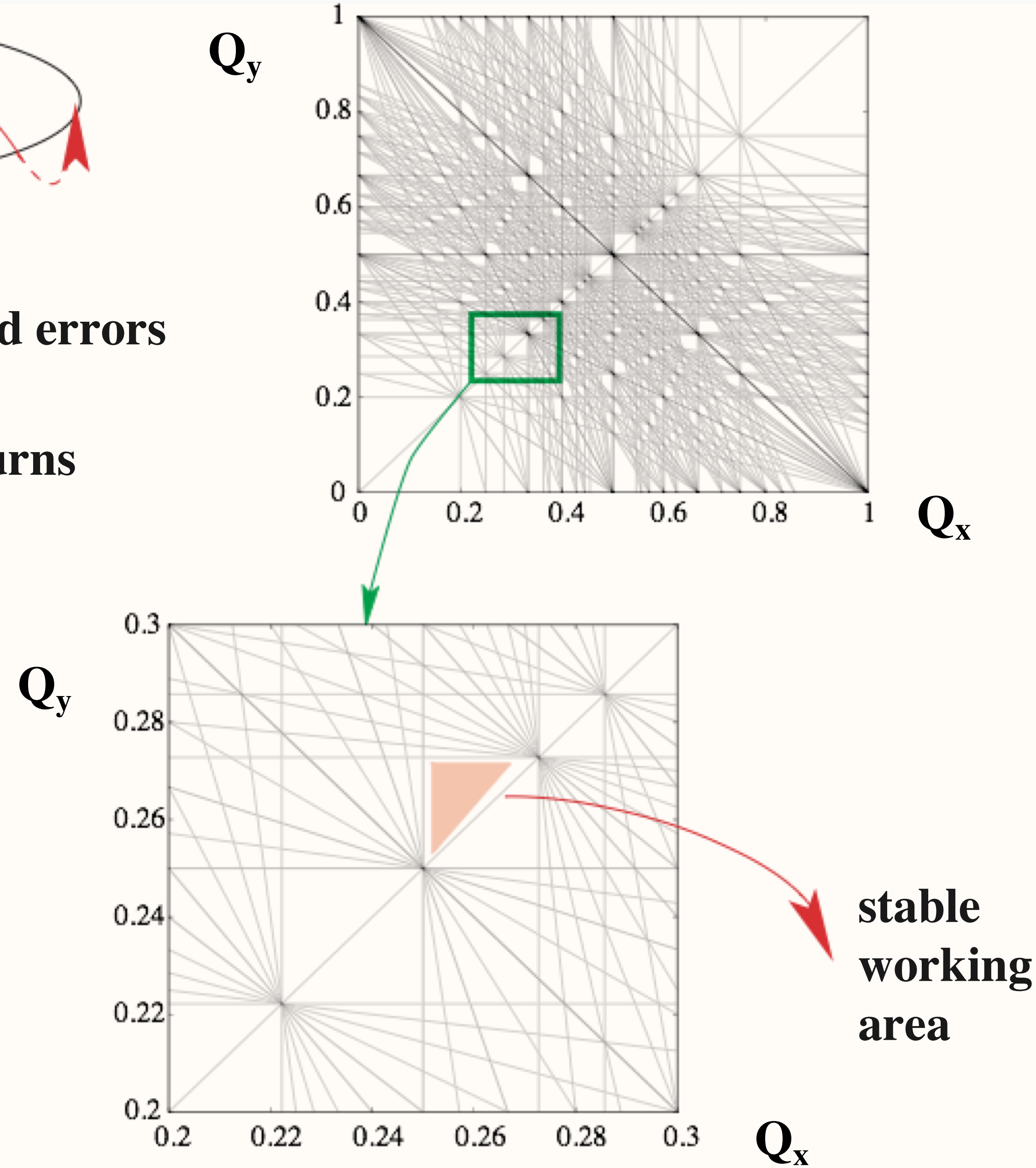
$$\begin{pmatrix} x(s) \\ x'(s) \end{pmatrix} = \mathbf{M} \begin{pmatrix} x(s_0) \\ x'(s_0) \end{pmatrix} \qquad \mathbf{M} = \begin{pmatrix} \cos 2\pi Q & \beta \sin 2\pi Q \\ -\frac{1}{\beta}\sin 2\pi Q & \cos 2\pi Q \end{pmatrix}$$

Accelerator design : starts with magnet lattice based on linear beam optics ; MAD program

Orbit stability and tune



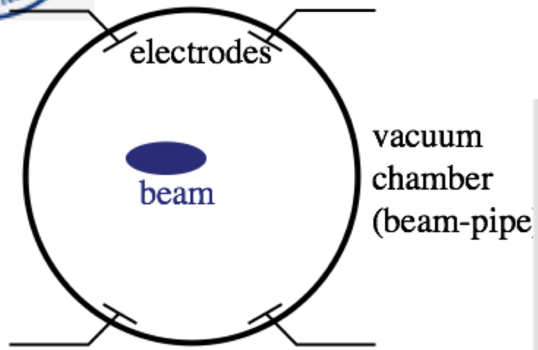
Misalignments and dipole field errors
→ orbit perturbations
would add up on successive turns
for integer tune Q = N



Higher order field errors,
Quad., Sext. perturbations.
Avoid simple fractional tunes
$nQ_x + m\ Q_y + m\ Q_s = \text{int}$.

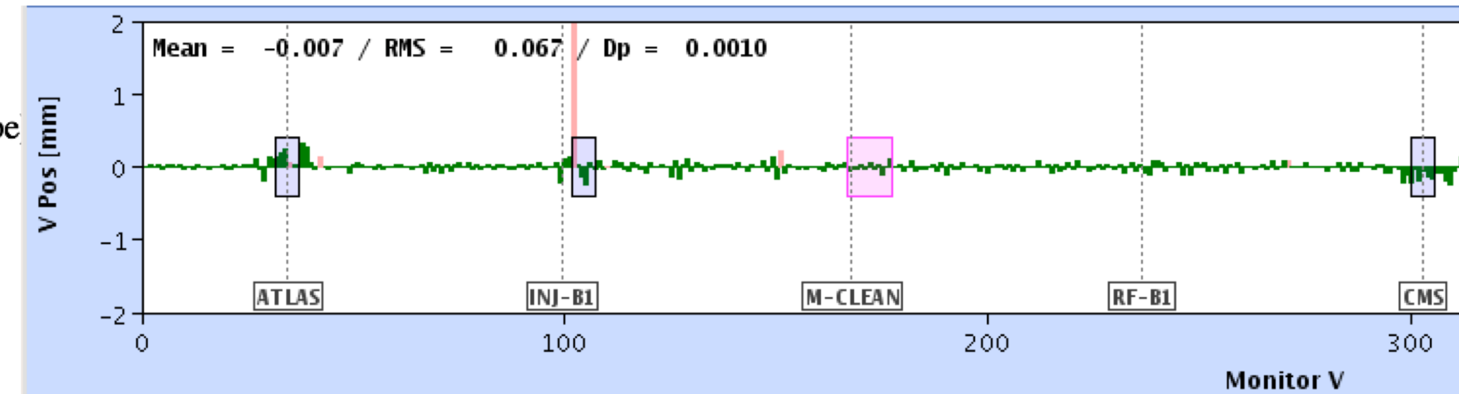
Minimise field and alignment errors

Orbit, tune measurement and peak beam current



Beam **P**ickup **M**onitor

vertical **orbit, June 2011, 1st half of LHC shown**



$\langle I_b \rangle$ average ring and

$\hat{I}$ local peak current

$$\hat{I} = \frac{\langle I_b \rangle L}{\sqrt{2\pi}\,\sigma_z}$$

Typical numbers, for a single bunch $\langle I_b \rangle = n\, e\, f_{rev}$

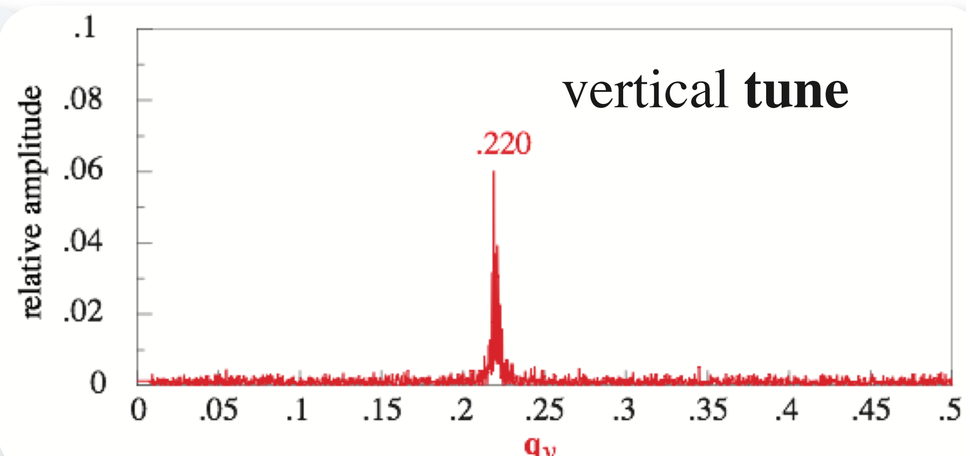
LEP $n = 4\times10^{11}$ $\langle I_b \rangle = 0.72$ mA $\sigma_z = 2$ cm $\hat{I} = 960$ A

LHC $n = 1.15\times10^{11}$ $\langle I_b \rangle = 0.21$ mA $\sigma_z = 7.55$ cm $\hat{I} = 73.2$ A

$f_{rev} = 11245$ kHz, $L = 26658.9$ m

Bunch peak currents are many Amperes !
Strong signals, used to monitor beam position and oscillations

Also source of undesirable effects :
wake fields, heating, instabilities



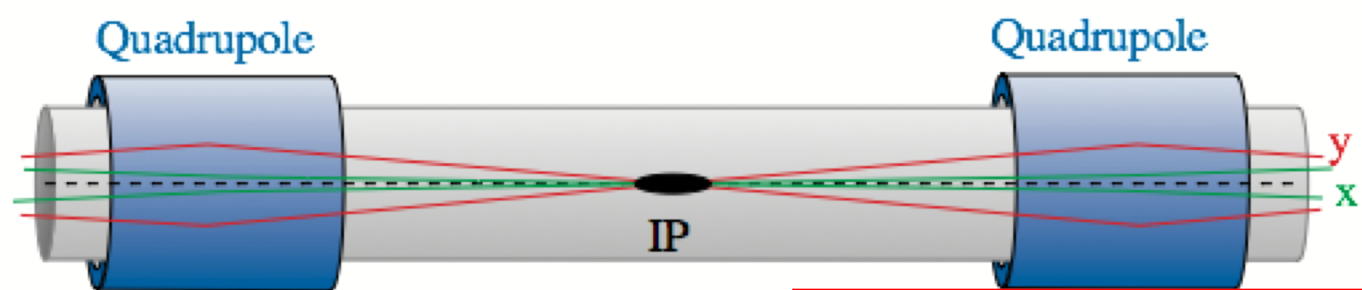
Transverse beam size and emittance

consider : beam of many particles on stable orbit and
simple case : dispersion and slope $\beta' = 0$ by default at IP - relevant for experiments

beam size, r.m.s.	$\sigma(s) = \sqrt{\varepsilon\beta(s)}$
beam divergence, r.m.s.	$\theta(s) = \sqrt{\varepsilon/\beta(s)}$
product	$\varepsilon = \sigma(s)\theta(s)$

β - function : local machine quantity - focusing of lattice
Emittance ε : beam quantity - the average action
related to phase space density or kind of beam temperature
given by initial conditions (injected beam)
or equilibrium of quantum excitation and damping - 2nd lecture
in ideal machine : x, y, z motion uncoupled, 3 emittances ε_x, ε_y, ε_z

IP: squeeze β to a minimum, called β* ⇒ maximum of divergence, needs aperture



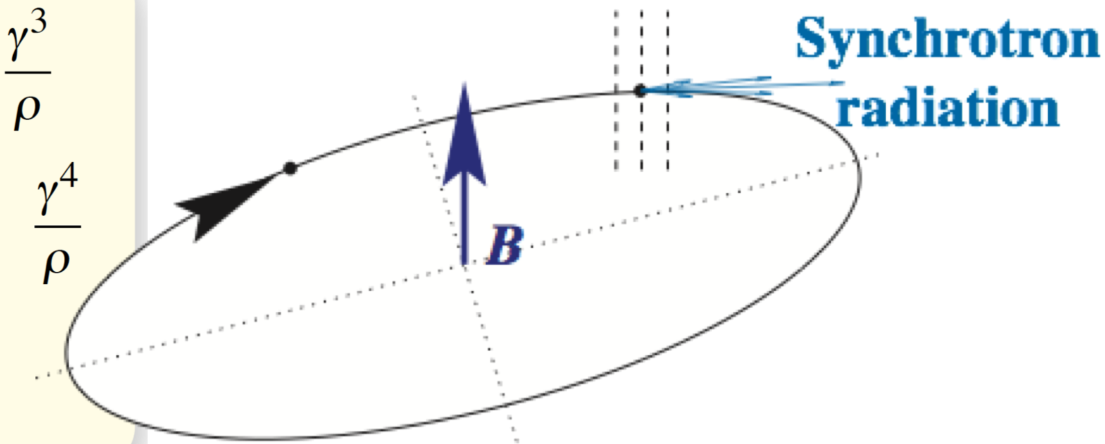
LHC $\varepsilon_N = \varepsilon\,\beta\gamma = 3.75\ \mu m$, at top $E_b = 7$ TeV: $\varepsilon = 0.503$ nm, $\beta^* = 0.55$ m, $\sigma^* = 16.63\ \mu m$, $\theta^* = 30\ \mu rad$

Standard Synchrotron Radiation

$$E_c = \frac{3}{2}\frac{\hbar c \gamma^3}{\rho} = 2.96 \times 10^{-7}\,\mathrm{eV\,m}\,\frac{\gamma^3}{\rho}$$

$$U_0 = \frac{e^2}{3\varepsilon_0}\frac{\gamma^4}{\rho} \approx 6.0317 \cdot 10^{-9}\,\mathrm{eV\ m}\ \frac{\gamma^4}{\rho}$$

$$P_b = \frac{U_0 I_b}{e}$$



		E GeV	γ	ϱ m	U_0 MeV	E_c keV	τ_d s	N 10^{12}	I mA	P_b MW	B T
RHIC	**Au**	**A×100**	**107.4**	**242.8**	**21×10⁻⁶**	**1.5×10⁻⁶**	**4.9×10⁶**	**0.06**	**60**	**1.3×10⁻¹²**	**3.42**
LHC	**p**	**7000**	**7460.5**	**2804**	**0.0067**	**0.044**	**61729**	**646**	**1163**	**0.0072**	**8.33**
LEP1	**e**	**45.6**	**89237**	**3026**	**126**	**69.5**	**23×10⁻³**	**2.22**	**4**	**0.5**	**0.05**
LEP2	**e**	**104.5**	**204501**	**3026**	**3490**	**836**	**1.9×10⁻³**	**2.8**	**5**	**18**	**0.115**

Same beam energy E and radius ϱ : electron instead of proton $U_0 \sim \gamma^4$: $(m_p/m_e)^4 = 1.13 \times 10^{13}$

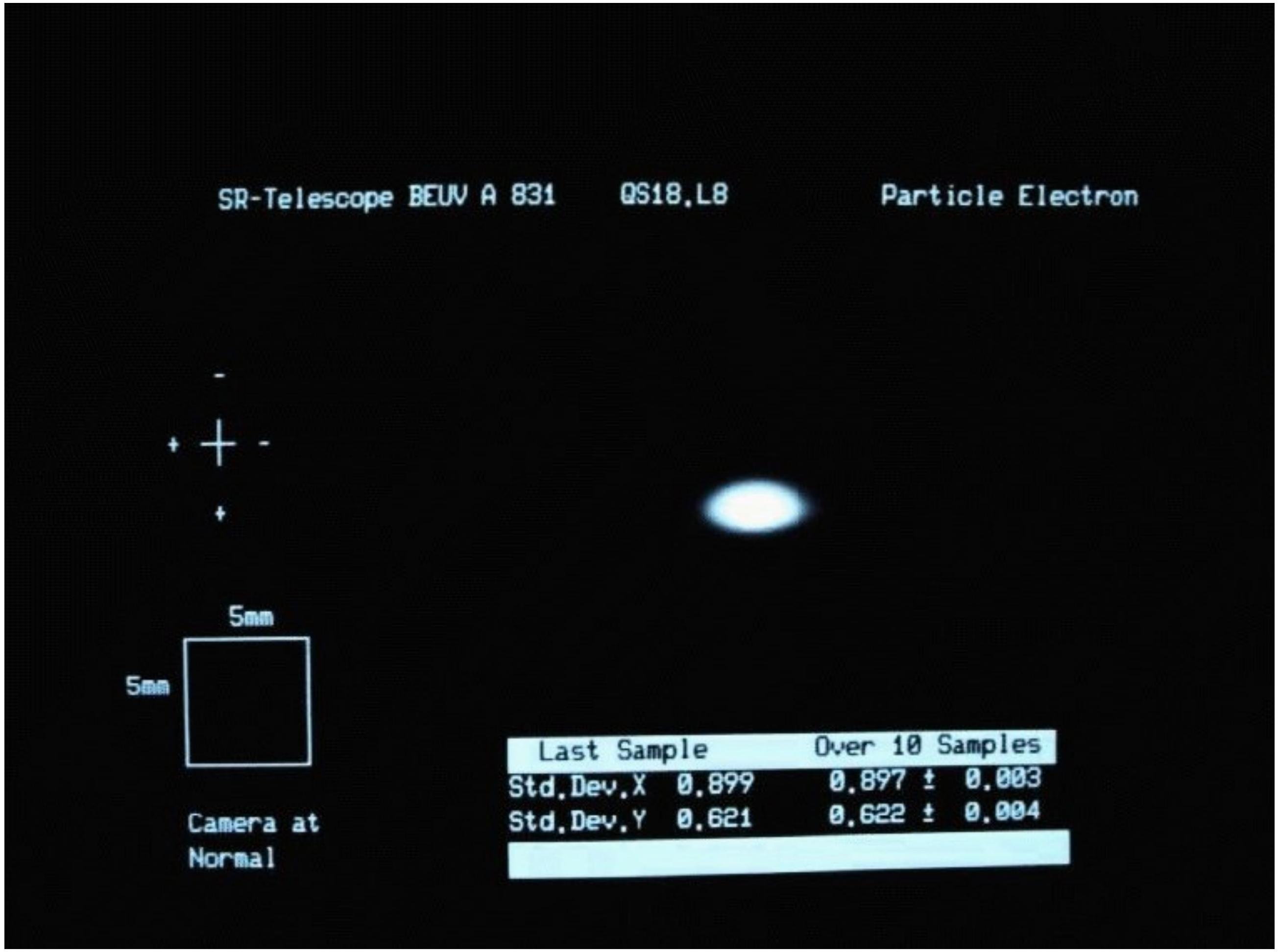
Electrons, E >> 100 GeV needs linear collider (ILC / CLIC)

Damping time E / U_0 turns or $\tau_d = t_{rev}\ E / U_0$ revolution time LEP/LHC t_{rev} = 88.9 μs

Gold ions Au^{79+} A=197 $\langle E_\gamma \rangle = 8/(15\sqrt{3})\ E_c$ $8/(15\sqrt{3}) \approx 0.308$

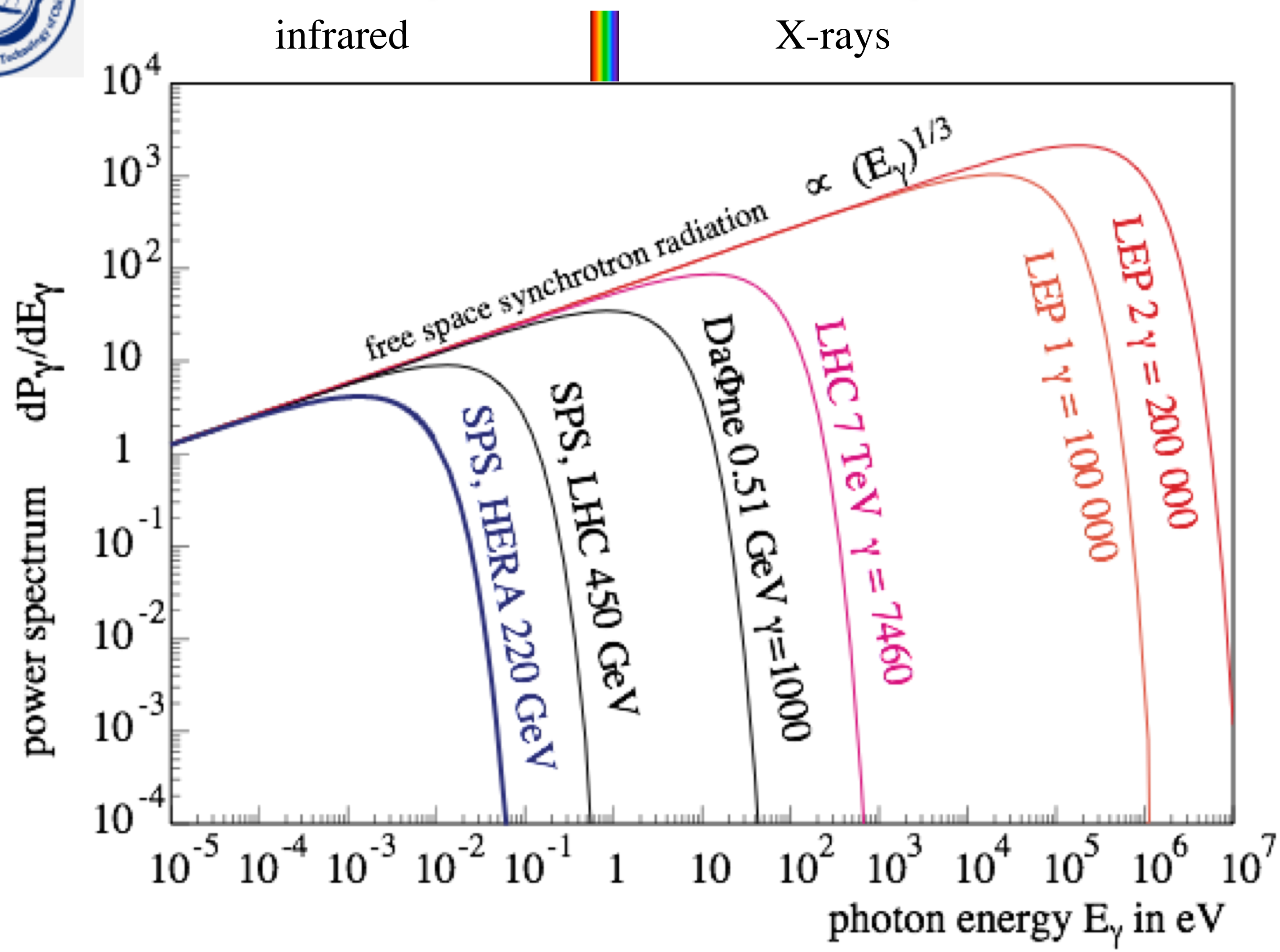
Synchrotron light monitor

Picture from LEP. Typical transverse rms beam size 0.15 mm vertical 1.5 mm horiz.



Mirror, small slit, telescope and camera : beams continuously visible.
Now also used for protons in the LHC.

Power Spectrum, Free space, Cutoff and CSR



$$\frac{f_{cutoff}}{f_{rev}} = \sqrt{\frac{2}{3}}\left(\frac{\pi\rho}{h}\right)^{3/2}$$

ϱ bending radius

h chamber height

cutoff relevant

for $\gamma \approx 100$

12 orders of magnitude in E_γ and λ

10^{-5} eV $\lambda = 0.124$ m

10^{+7} eV $\lambda = 124$ fm

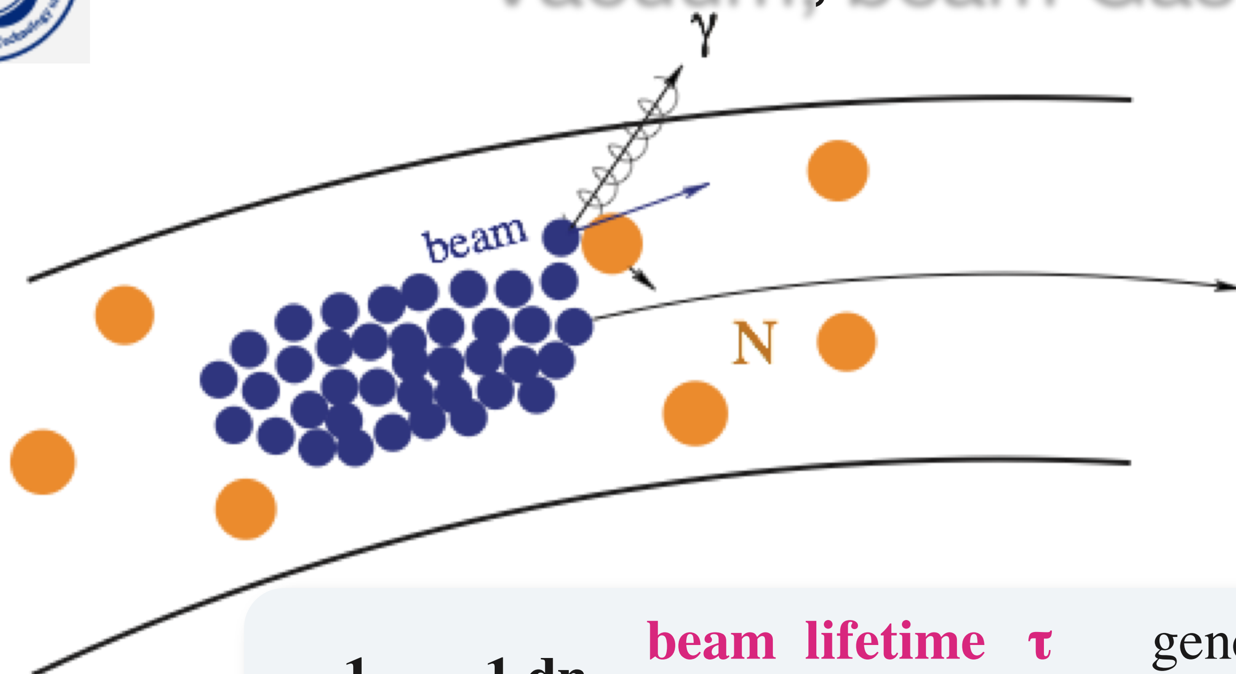
Effects which can modify the low energy, long wavelength spectrum :

i) Coherent Synchrotron Radiation CSR **increases radiation and loss**

ii) Boundary conditions - cutoff by conducting chamber **decreases radiation and loss**

Energy Loss of Gold Ions in RHIC, EPAC 2008

Vacuum, beam Gas - lifetime



Beam blow up, core + halo
Background to experiments
loss, radiation, beam and Luminosity lifetime

Minimize effect :
Good vacuum
O(nTorr or 10^{-9} mb)
Collimation

$$\frac{1}{\tau} = -\frac{1\,dn}{n\,dt}$$

beam lifetime τ general expression
average time between collisions leading to beam loss
inverse normalised loss rate

$$p = 1\,\text{ntorr} = 1.33 \times 10^{-7}\,\text{Pa}$$

$$\rho_m = \frac{p}{kT} = 3.26 \times 10^{13}\text{molecules / m}^3$$

$$\text{typical cross section } \sigma = 6\,\text{barn} = 6 \times 10^{-28}\text{m}^2$$

$$\text{collision probability } P_{\text{coll}} = \sigma\,\rho_m = 1.96 \times 10^{-14}/\,\text{m}$$

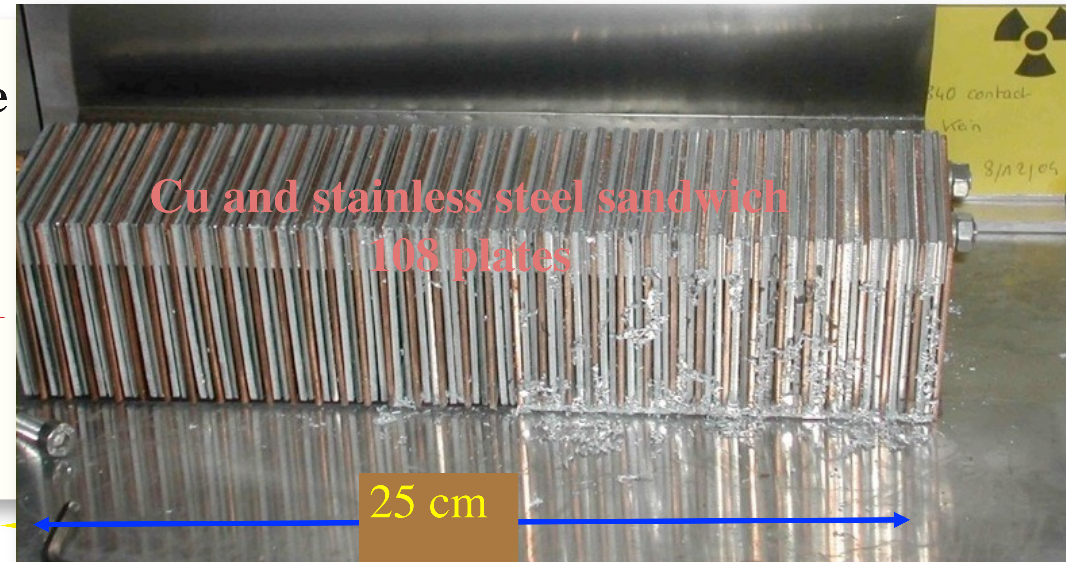
$$\tau = \frac{1}{P_{\text{coll}}\,c} = 1.7 \times 10^5\,\text{s} = 47\,\text{hours} \qquad \text{for } v \approx c$$

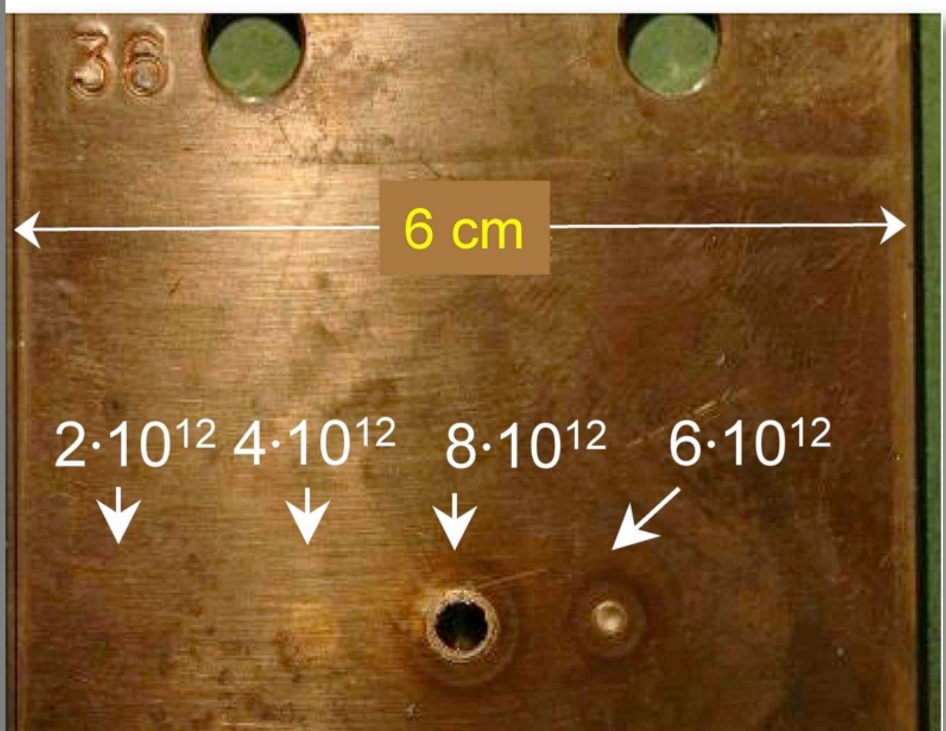
Damage potential : confirmed in controlled SPS experiment

controlled experiment with beam extracted from SPS at 450 GeV in a single turn, with perpendicular impact on Cu + stainless steel target

450 GeV protons →

r.m.s. beam sizes $\sigma_{x/y} \approx 1$ mm





SPS results confirmed :

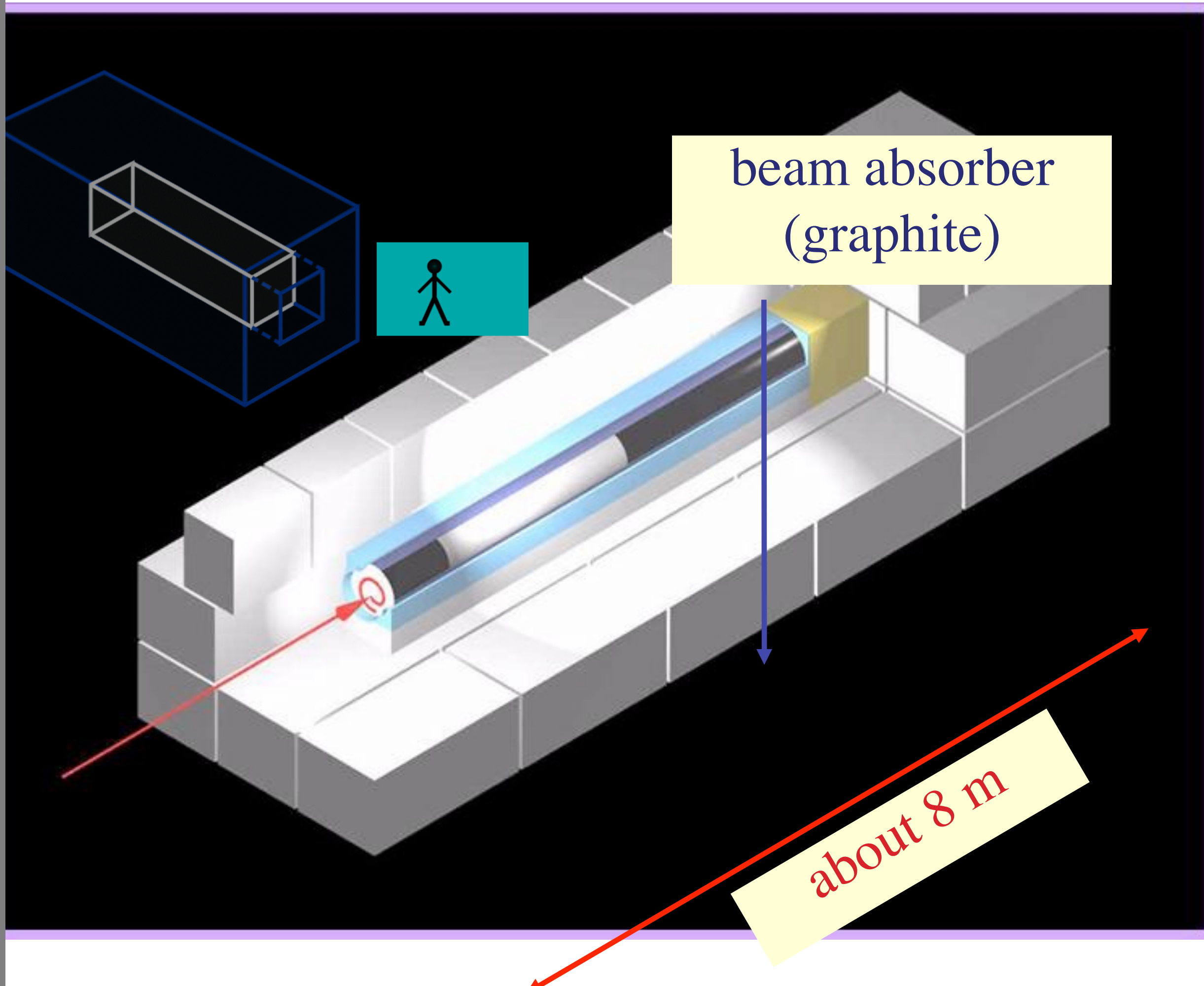
8×10^{12} clear damage

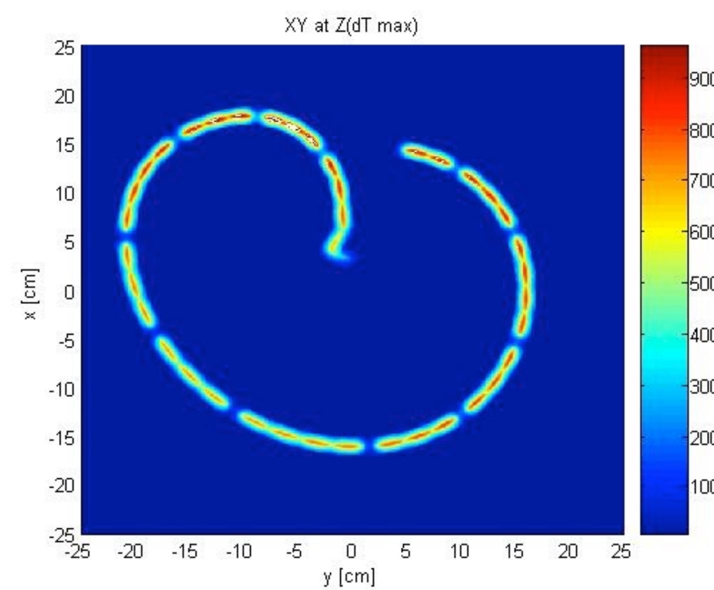
2×10^{12} below damage limit

for details see V. Kain et al., PAC 2005 RPPE018

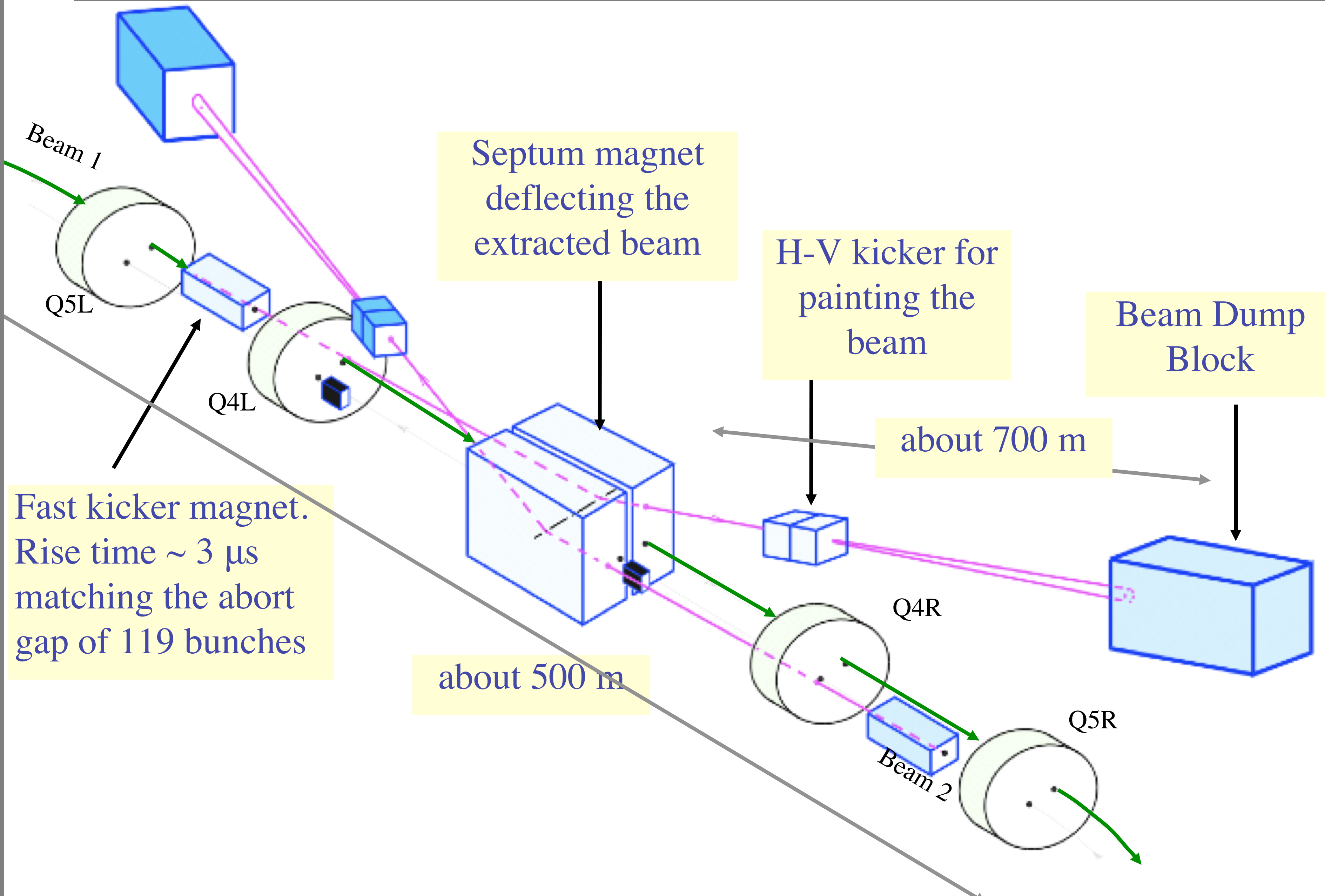
For comparison, the LHC nominal at 7 TeV :
$2808 \times 1.15\times10^{11} = 3.2\times10^{14}$ p/beam
at $< \sigma_{x/y} > \approx 0.2$ mm
over 3 orders of magnitude above damage level for perpendicular impact

Dumping the LHC beam





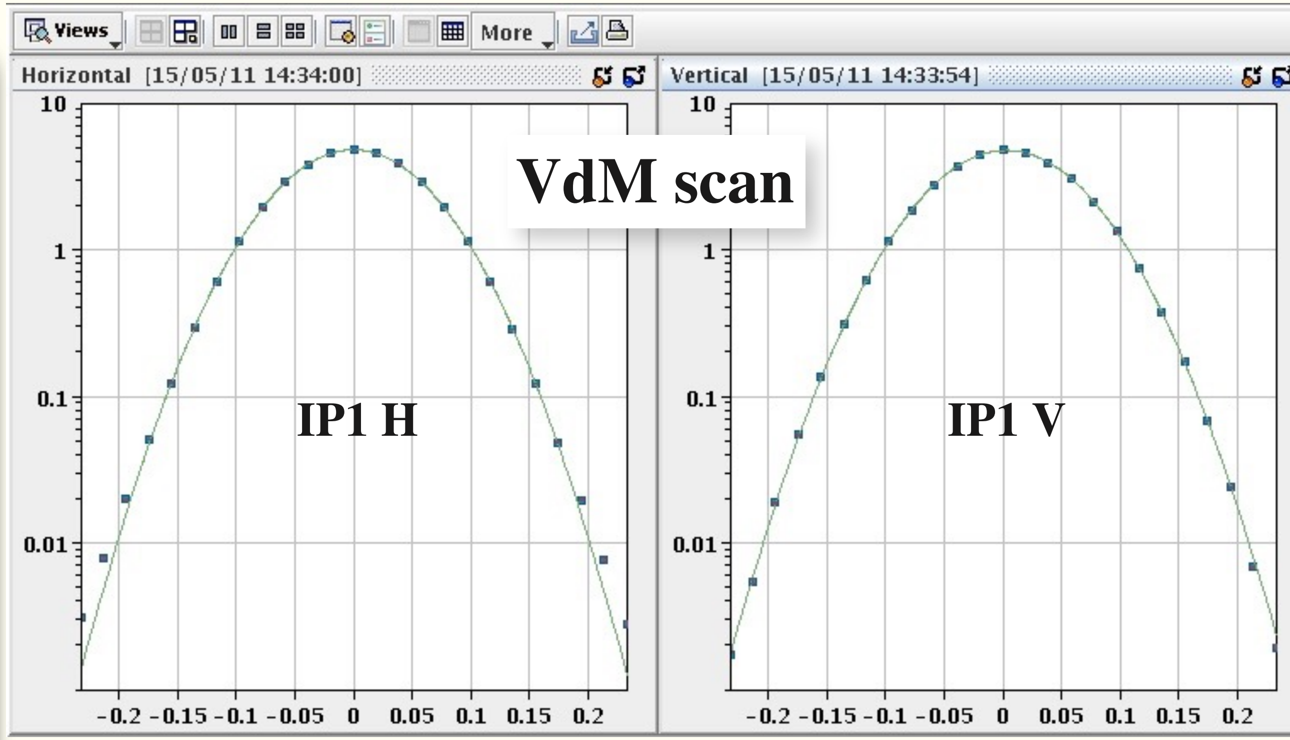
Schematic layout of beam dump system in IR6



Precision front - high quality of LHC beams

- **absolute luminosity normalization**
- **low, well understood backgrounds**
- **precision optics for ATLAS-ALFA and TOTEM**

β^* = 1000 m, Oct.'12

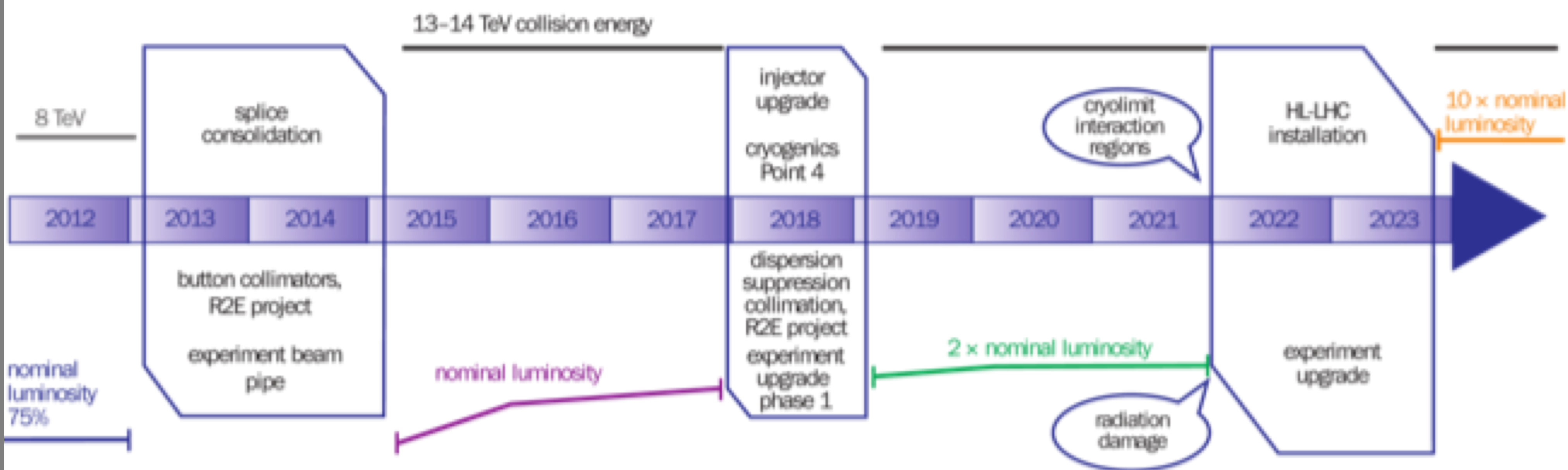


precise measurement of the luminous region + beam intensity --> absolute luminosity and cross section calibration

currently ~ 3 % level (Tevatron had ~ 15 %)

HL-LHC Timeline

The LHC is still a rather young machine
Operation planning + upgrade studies (HL-LHC) extend to ~ 2030



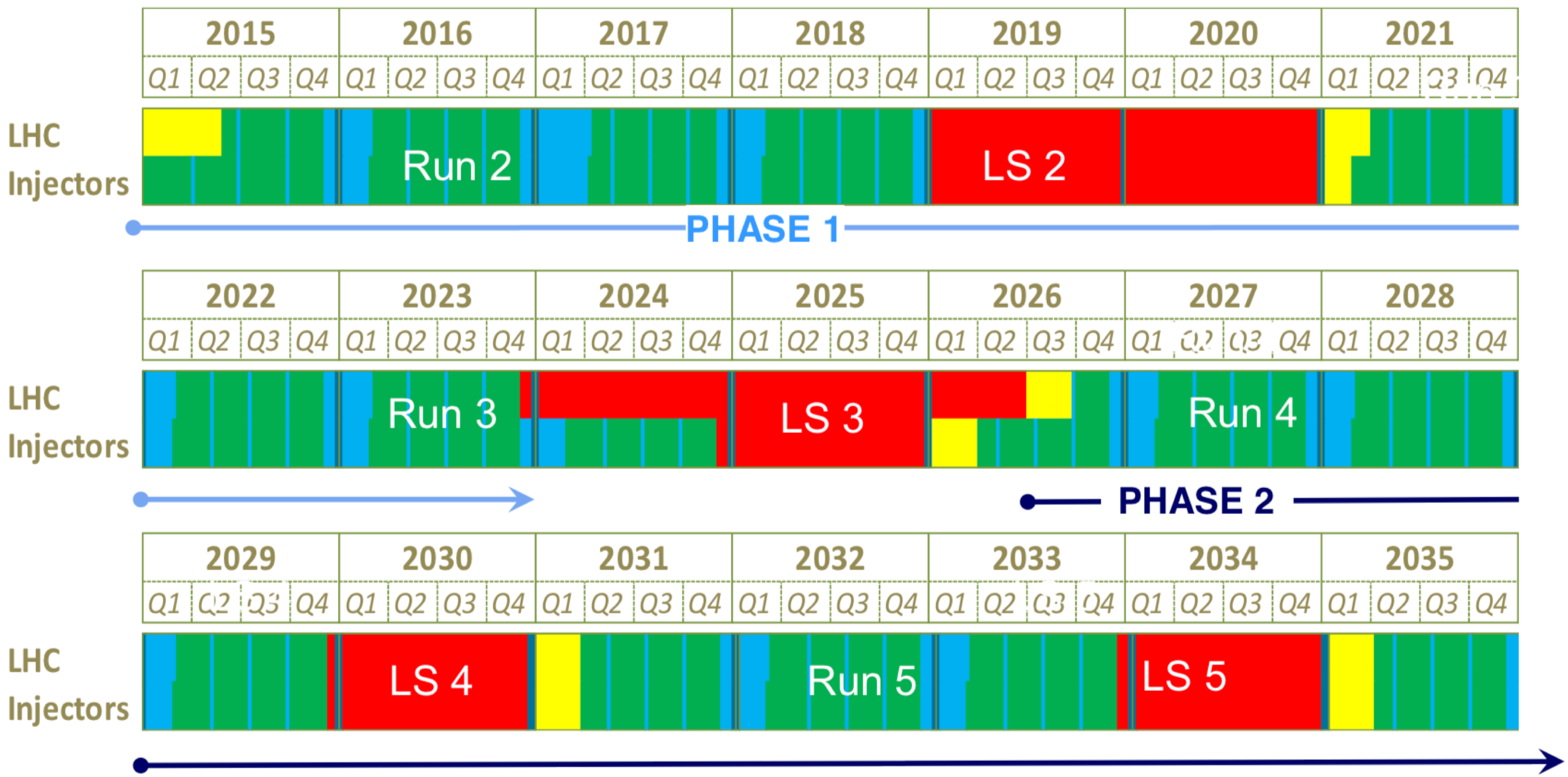
Further ideas already exist (HE-LHC, LHeC, TLEP)
We also study other machines, and in particular CLIC ➜

Up-to-date LHC schedule

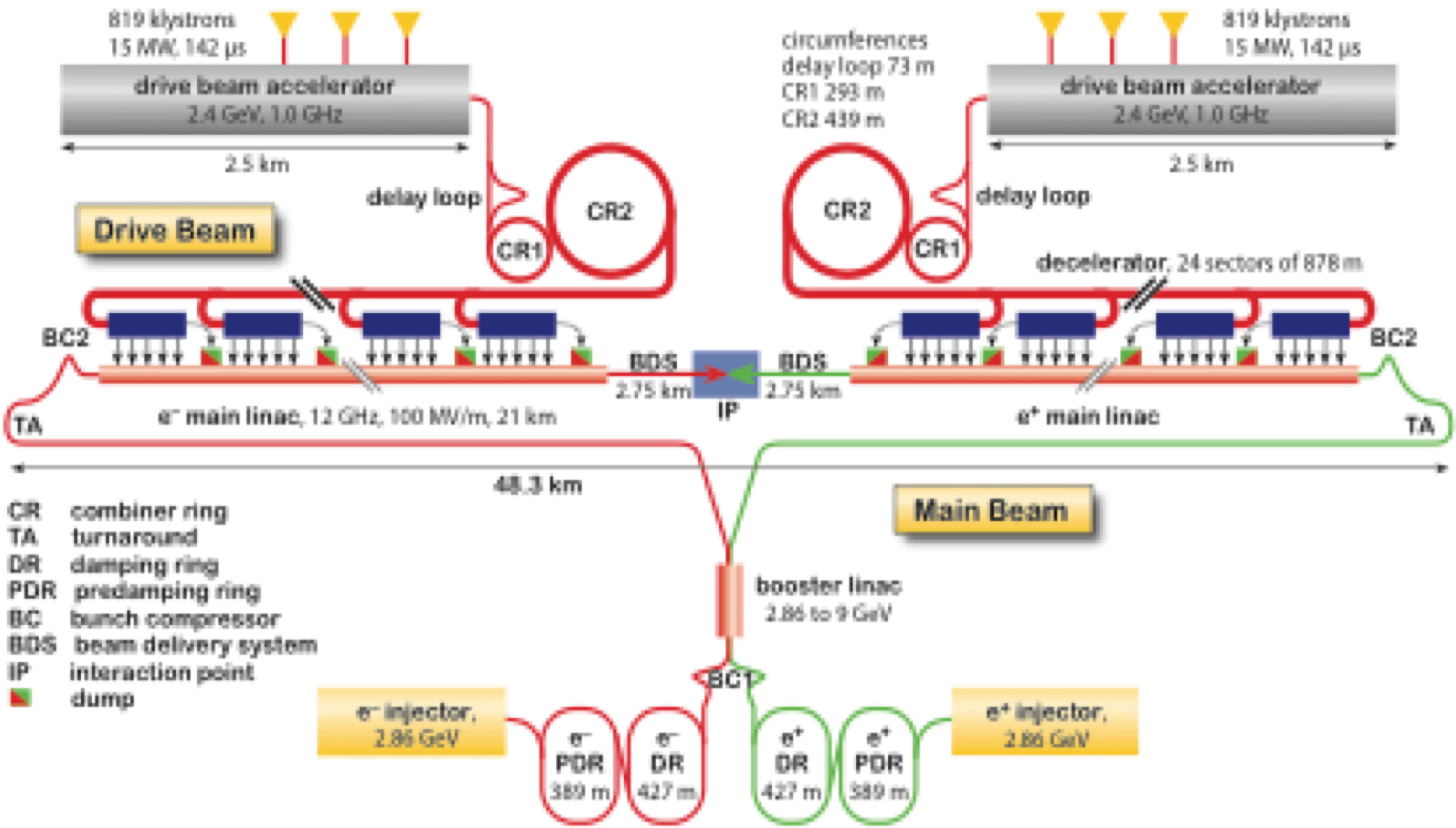
LHC roadmap: according to MTP 2016-2020 V1

LS2 starting in 2019 => 24 months + 3 months BC
LS3 LHC: starting in 2024 => 30 months + 3 months BC
Injectors: in 2025 => 13 months + 3 months BC

- Physics
- Shutdown
- Beam commissioning
- Technical stop



CLIC



Overview of the CLIC layout at $\sqrt{s} = 3$ TeV

The machine requires only one drive beam complex for stages 1 and 2.

Accelerator applications and R&D

- **The largest flag-ship accelerator is the LHC here at CERN**
- **By now many more accelerators outside particle physics**

#Accelerators in the world : O (30 000) mostly smaller for medical and industrial applications

- **Broad range of particle accelerator types and applications**

Large research facilities for :
Synchrotron light, UV, X-Ray (electron accelerators)
High intensity proton accelerators + neutron spallation sources
condensed matter, material science and biology research,
accelerator driven subcritical fission (energy production & radioactive waste incineration)

Yearly international accelerator conferences IPAC, last one in May'13 in Shanghai

Some of the hot-subjects and keywords :

- **Free electrons lasers FEL, X-FEL, Laser induced coherent SR**
- **Advanced LINACS -- including recirculation and energy recovery ERL**
- **New acceleration techniques :**
  - **Dieletric, LASER, Plasma driven**

Reserve

Radiation of an accelerated charge

General concept - power radiated by an accelerated charge. Relativistic version of Lamor's formula, derived by Lienard in 1898, before relativity was known.

Photon spectrum : J. Schwinger Phys. Rev. 75 (1949) pp. 1912-1925

Here written with formulas in SI units. More info + references in my paper on MC generation of SynRad CERN-OPEN-2007-018

power radiated by an accelerated charge

$$P = \frac{e^2\gamma^2}{6\pi\epsilon_0 m^2 c^3}\left[\left(\frac{dp}{dt}\right)^2 - \beta^2\left(\frac{dp}{dt}\right)^2\right]$$

relativistic Lamor formula

results in a major energy loss for a ring at high γ

$\mathrm{v} \perp \dot{\mathrm{v}}$

$$\left(\frac{d\mathrm{p}}{dt}\right)^2 - \beta^2\underbrace{\left(\frac{dp}{dt}\right)^2}_{0} = \dot{\mathrm{p}}^2 \qquad P = \frac{e^2}{6\pi\epsilon_0 m^2 c^3}\gamma^2\,\dot{\mathrm{p}}^2$$

Perpendicular acceleration, B-field (or E⊥ field). Motion in circular machine.

$\mathrm{v} \parallel \dot{\mathrm{v}}$

$$\left(\frac{d\mathrm{p}}{dt}\right)^2 = \left(\frac{dp}{dt}\right)^2 \qquad \left(\frac{dp}{dt}\right)^2 - \beta^2\left(\frac{dp}{dt}\right)^2 = \dot{p}^2(1-\beta^2) = \frac{\dot{p}^2}{\gamma^2}$$

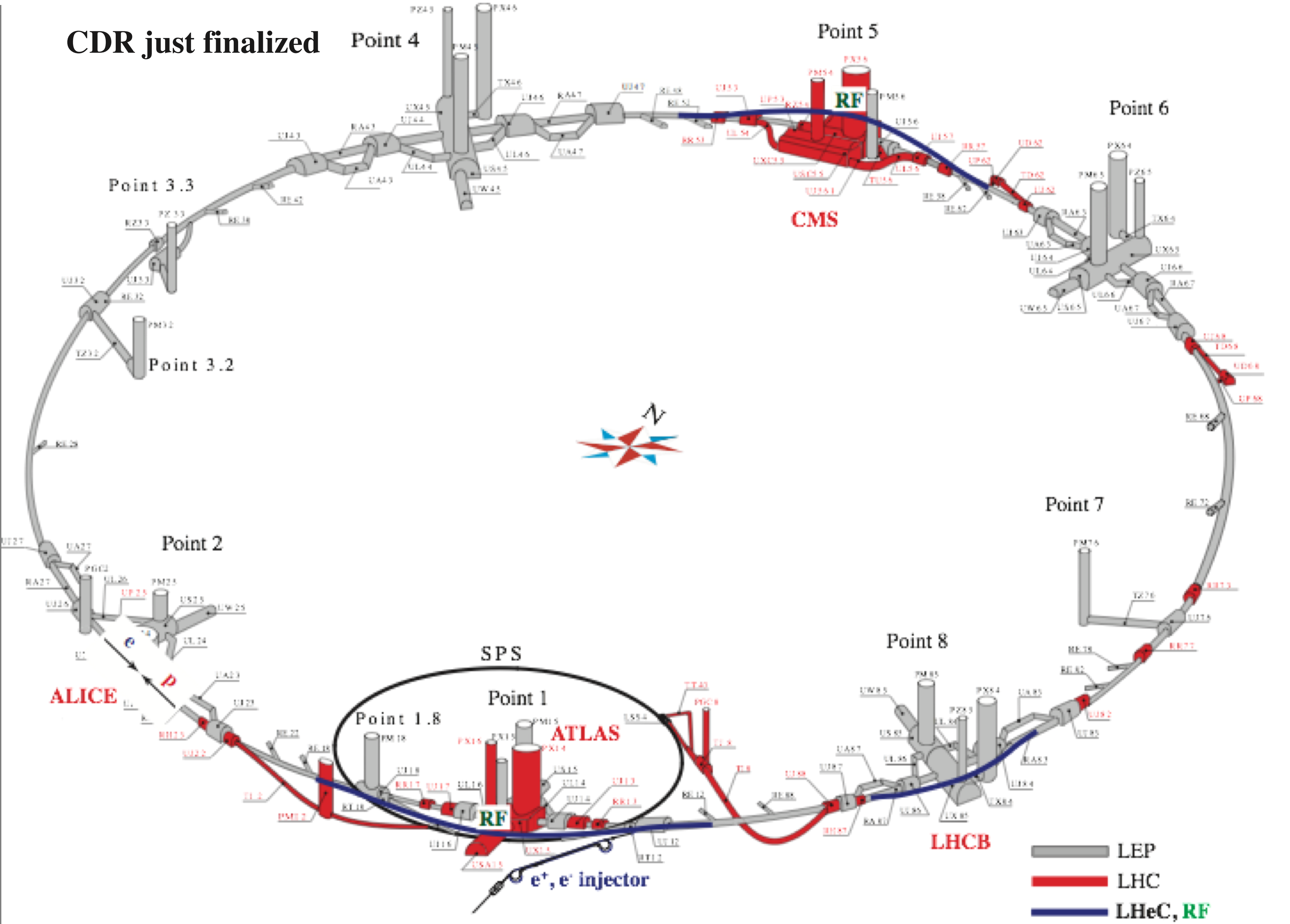
$$P = \frac{e^2}{6\pi\epsilon_0 m^2 c^3}\,\dot{p}^2$$

Parallel acceleration, E-field, Linac case cancellation, $1/\gamma^2$

The energy loss for linear acceleration is very small.

Example: CLIC gradient 100 MV/m. Loss is 11 keV/s or only 0.4 eV for a 1 TeV 10 km Linac

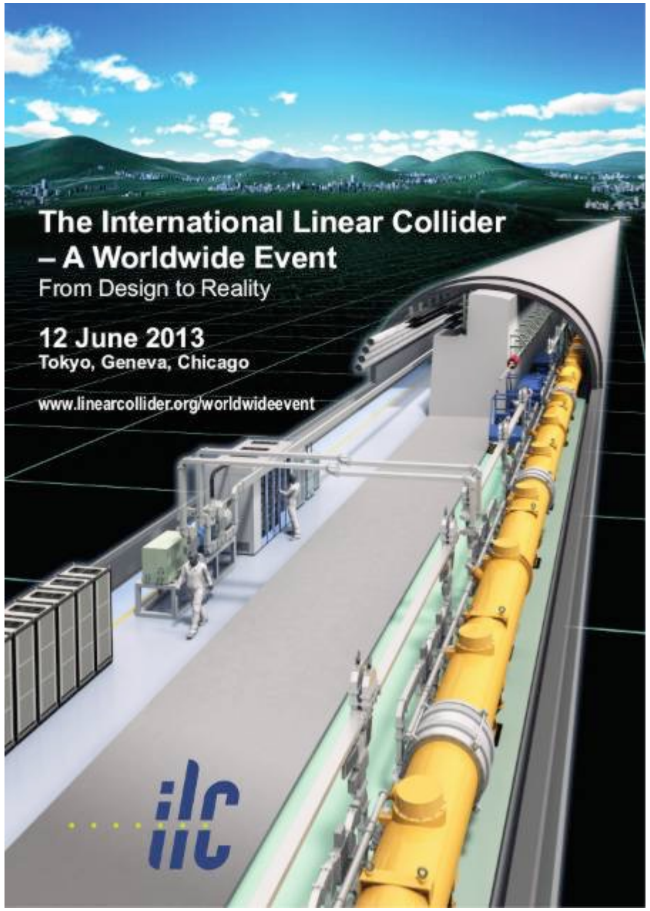
LHeC

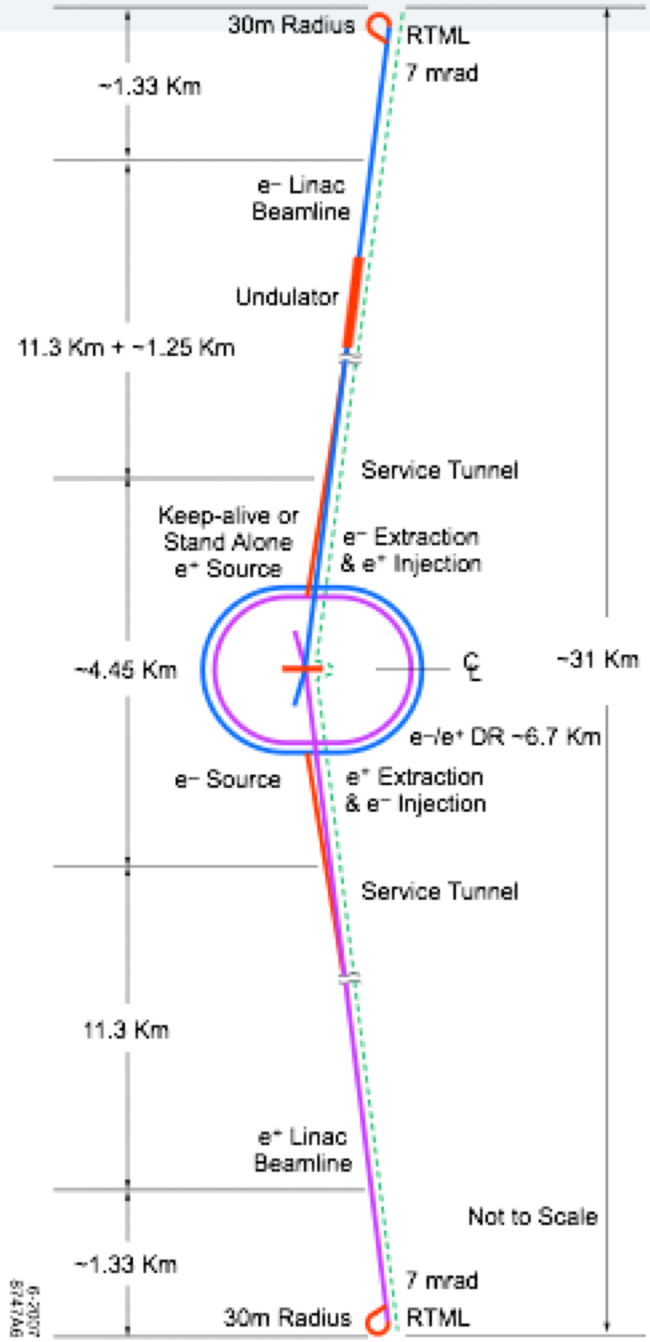

CDR just finalized
Point 4
Point 5
Point 6
Point 3.3
Point 3.2
Point 2
Point 7
Point 8
Point 1
Point 1.8
SPS
RF
CMS
ATLAS
ALICE
LHCB
RF
e
p
N
e⁺, e⁻ injector
LEP
LHC
LHeC, RF

ILC

ILC TDR Handover, 12 June 2013

- **200-500 GeV centre-of-mass, 31 km long**
- **Luminosity: 2×10^{34} $cm^{-2}s^{-1}$**
- **Based on accelerating gradient of 31.5 MV/m 1.3 GHz superconducting RF**





CLIC

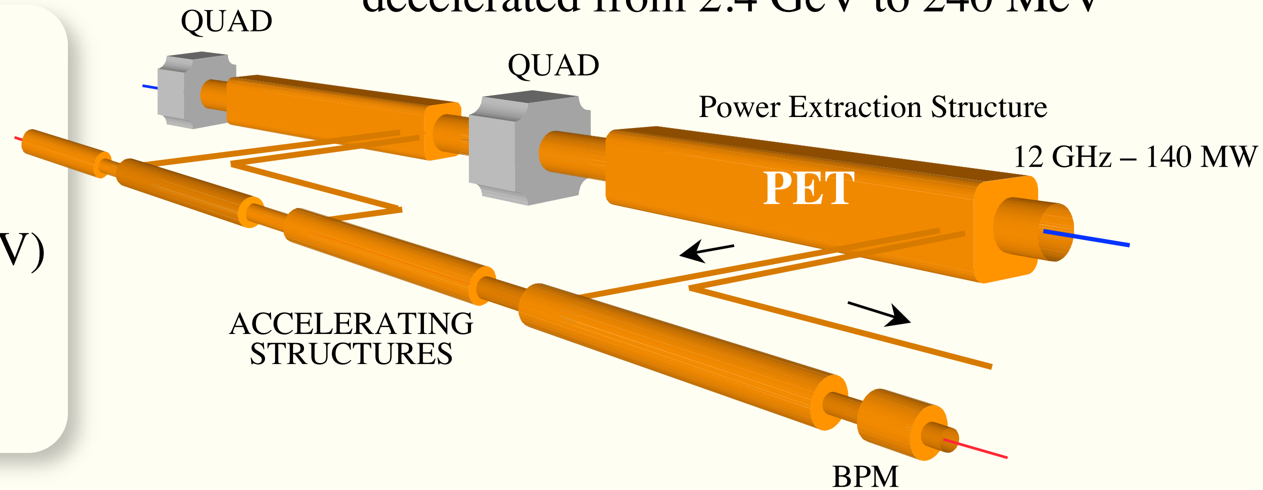
Compact **Li**near **C**ollider

Two Beam Scheme

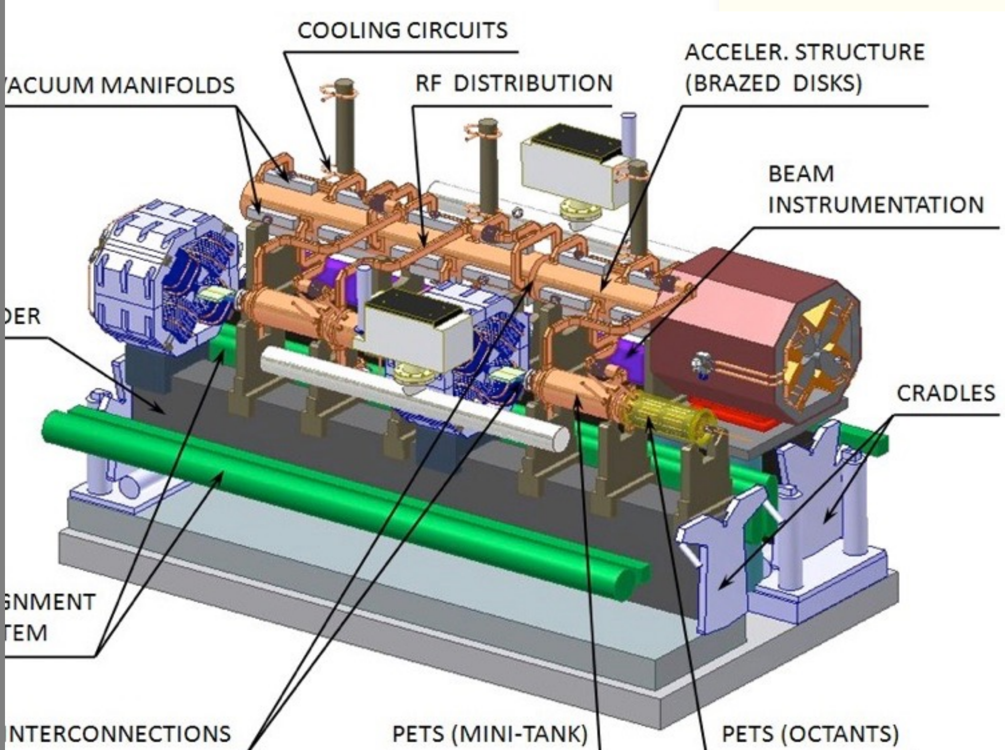
Drive Beam supplies RF power
- 12 GHz bunch structure
- low energy (2.4 GeV - 240 MeV)
- high current (100A)

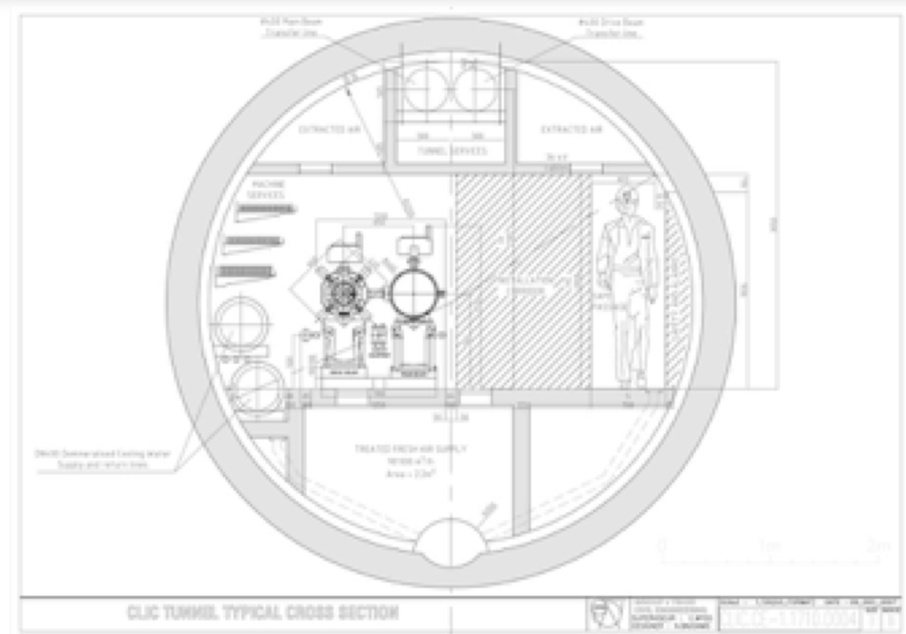
warm (not superconducting) RF

Drive beam - 100 A, 240 ns
decelerated from 2.4 GeV to 240 MeV



Main beam - 1.2 A, 156 ns bunch trains
accelerated from 9 GeV to 1.5 TeV





ILC and CLIC parameters

	ILC: Superconducting RF	CLIC: normal conducting copper RF
	500 GeV	**3 TeV**
accelerating gradient:	**31.5 MV/m** 35 MV/m target	**100 MV/m**
RF Peak power:	**0.37 MW/m , 1.6 ms, 5 Hz**	**275 MW/m, 240 ns, 50 Hz**
RF average power:	2.9 kW/m	3.7 kW/m
total length:	31 km	48.4 km
site power :	230 MW	392 MW

Beam structure:

	ILC	CLIC
particles per bunch:	**20×10^9**	**3.7×10^9**
bunches / pulse	2625 bunches / pulse of 0.96 ms	312 bunches / pulse of 156 ns
bunch spacing	**369 ns**	**0.5 ns**

EPS 2009 G.Geschonke, CERN

The main 2013-14 LHC consolidations