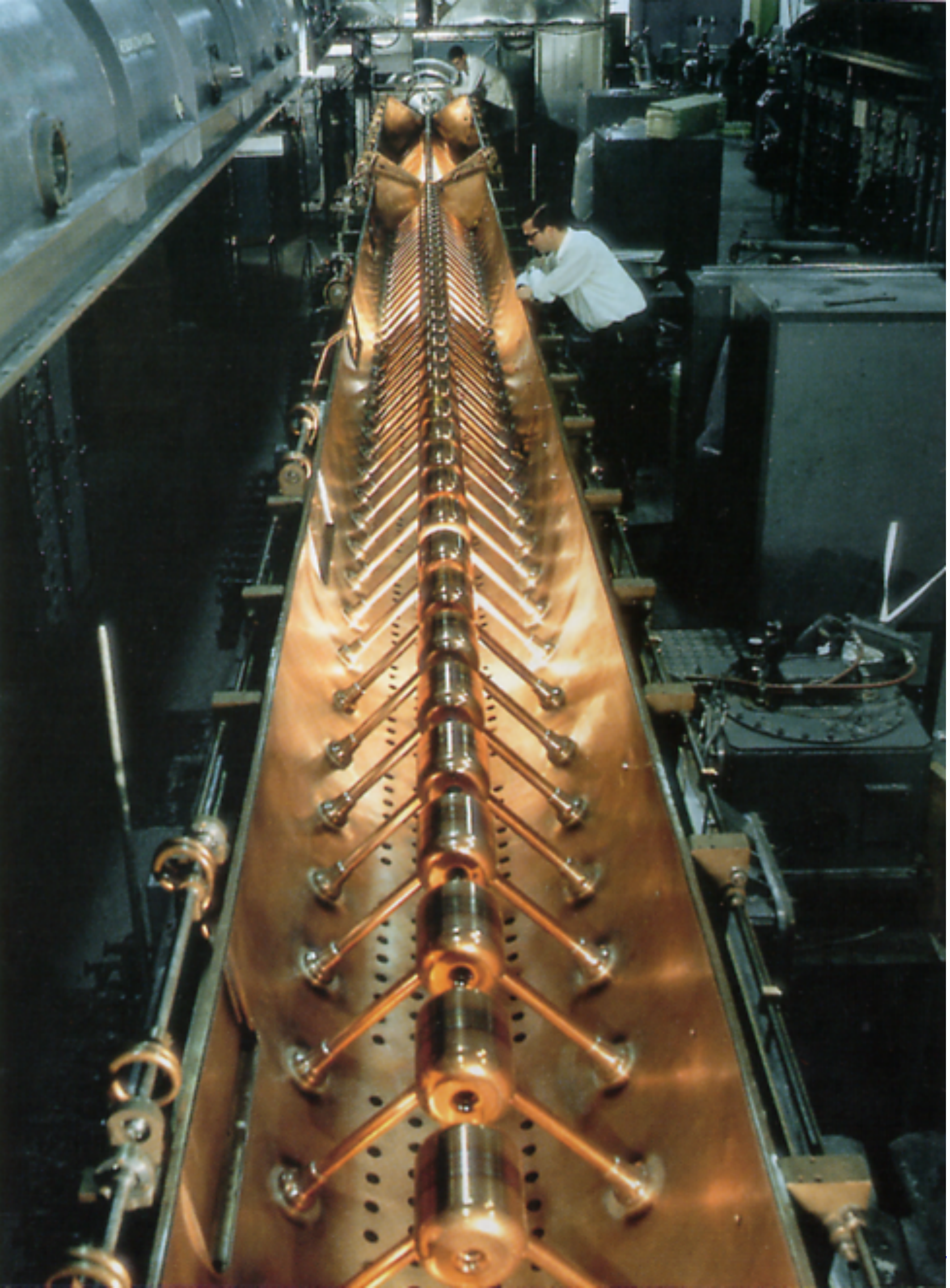
Manfred Jeitler

LHC results and future collider projects

Lecture 2:
Accelerators and Detectors

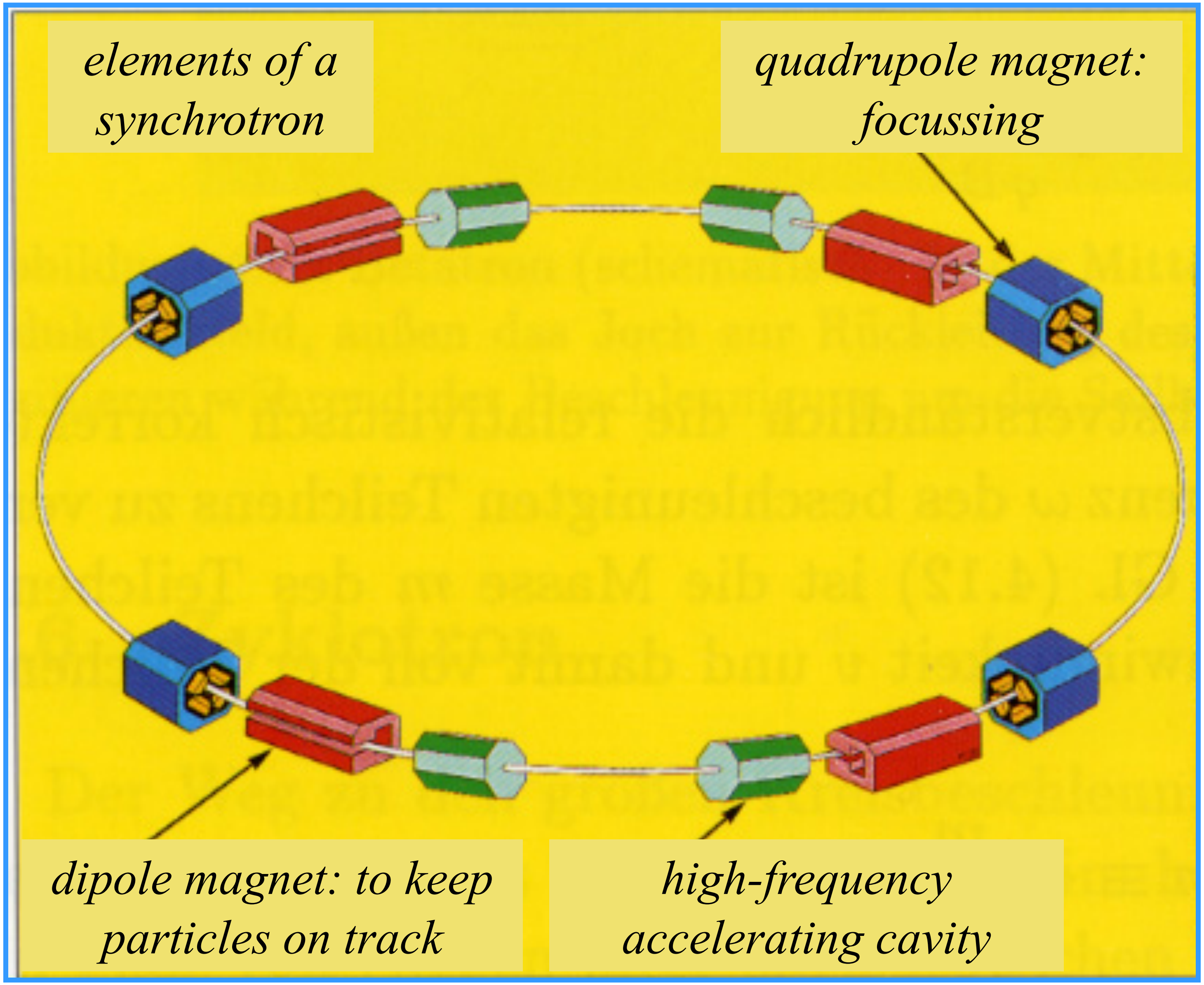
ACCELERATORS

Cockroft-Walton accelerator at CERN



inside of an Alvarez-type accelerating structure

Synchrotron



elements of a synchrotron

quadrupole magnet: focussing

dipole magnet: to keep particles on track

high-frequency accelerating cavity

Super-Proton-Synchrotron (Geneva)

SPS Tunnel

For a collider with beams of identical energy, the invariant mass of the collision products is twice the beam energy:

$$\begin{pmatrix} E \\ \vec{p} \end{pmatrix} + \begin{pmatrix} E \\ -\vec{p} \end{pmatrix} = \begin{pmatrix} 2\,E \\ \vec{0} \end{pmatrix} \tag{1.1}$$

For a fixed-target experiment consisting of the same particles of mass m as the beam, we get

$$\begin{pmatrix} E \\ \vec{p} \end{pmatrix} + \begin{pmatrix} m \\ \vec{0} \end{pmatrix} = \begin{pmatrix} E+m \\ \vec{p} \end{pmatrix} \tag{1.2}$$

and the invariant mass M of the collision products is

$$\begin{aligned} M^2 &= (E+m)^2 - \vec{p}^{\,2} \\ &= E^2 + 2Em + m^2 - (E^2 - m^2) \\ &= 2Em + 2m^2 \end{aligned} \tag{1.3}$$

If the beam and target consist of protons and we measure the energy in units of GeV, we can set $m = 1$. If the beam energy is high compared to the particle mass ($E \gg m$), we obtain

$$M = \sqrt{2E} \tag{1.4}$$

What is more?

Astroparticles
with
10^{19} eV

Collisions at
13 TeV

What is more?

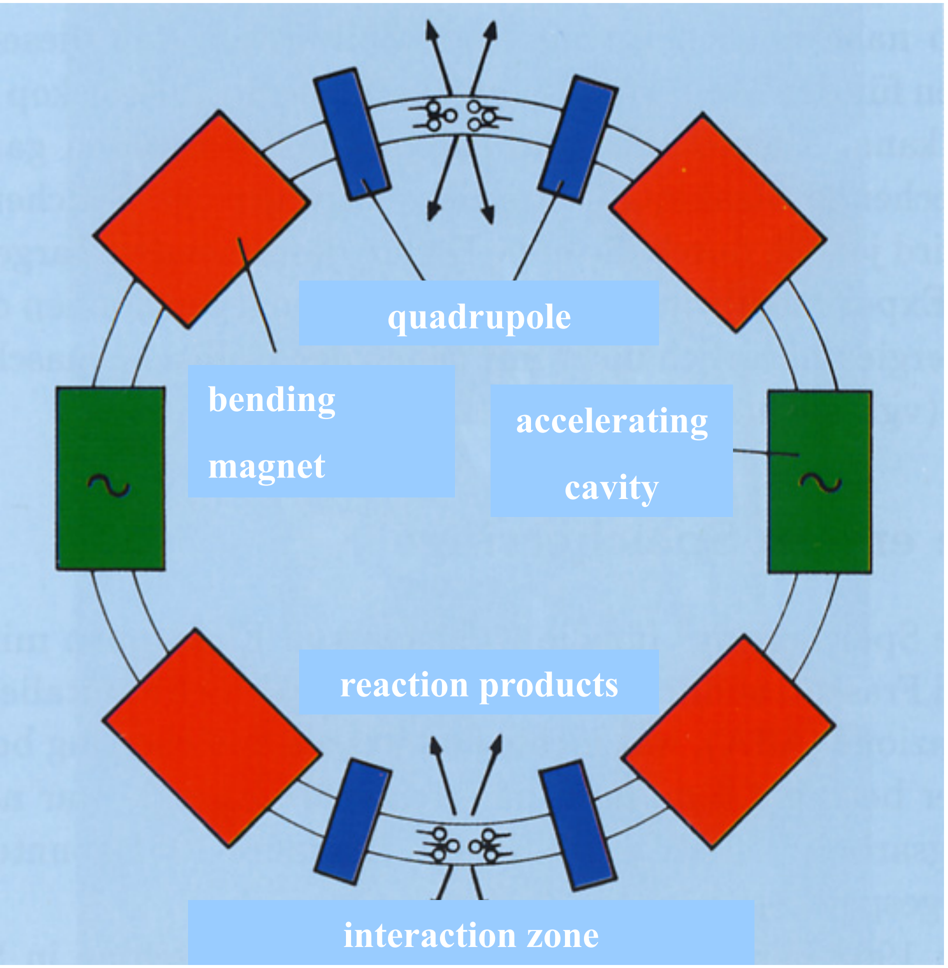
Astroparticles with 10^{19} eV

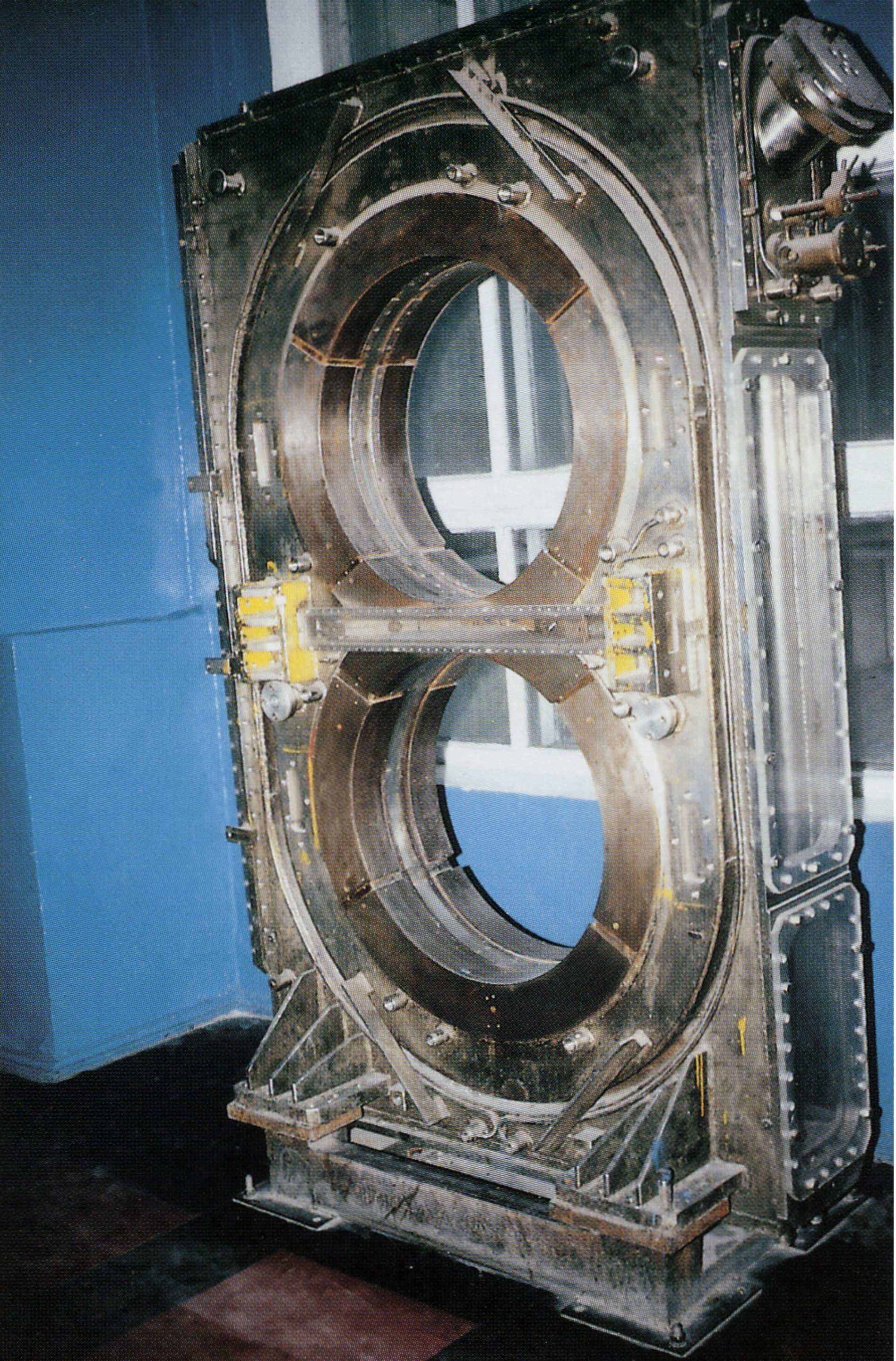
Collisions at 13 TeV

$\mathrm{sqrt}\ (10^{10})$ GeV = 10^{5} GeV

$13 * 10^{3}$ GeV

layout of a circular collider





first electron-electron collider: Novosibirsk / Russia

VEP-1

130+130 MeV

БАК

(Большой Адронный Коллайдер)

WHY ARE THOSE ACCELERATORS SO BIG?

superconducting RF cavity from LEP

synchrotron radiation

- scales with 4th power of Lorentz factor

$$\gamma = \frac{1}{\sqrt{1-\beta^2}} = \frac{E}{m_0 c^2}$$

- energy loss per turn: $\Delta E = \frac{(Ze)^2 \cdot \beta^3 \cdot \gamma^4}{\epsilon_0 \cdot 3R}$

- or $\Delta E = \frac{(Ze)^2 \cdot E^4}{\epsilon_0 \cdot 3R \cdot (m_0 c^2)^4}$

- electron synchrotron with same losses as LHC :
  - LHC circumference: 27 km
- 27 * 2000^4 ~ 4 * 10^{14} km ~ 40 lightyears

velocity

$$E = \frac{mc^2}{\sqrt{1-\frac{v^2}{c^2}}} \gg mc^2$$

$$\Rightarrow \quad 1-\frac{v^2}{c^2} \ll 1 \quad \Rightarrow \quad \Delta v := c - v \ll 1$$

Lorentz factor:

$$\frac{E}{mc^2} \quad = \quad \gamma = \frac{1}{\sqrt{1-\frac{v^2}{c^2}}} = \frac{1}{\sqrt{1-\frac{(c-\Delta v)^2}{c^2}}} = \frac{1}{\sqrt{1-[1-\frac{2\Delta v}{c}+\frac{\Delta v^2}{c^2}]}}$$

$$\approx \quad \frac{1}{\sqrt{\frac{2\Delta v}{c}}}$$

$$\Rightarrow \quad \frac{\Delta v}{c} \approx \frac{1}{2}\left(\frac{mc^2}{E}\right)^2$$

Measuring energies in GeV:

- proton: $mc^2 \sim 1$
- electron: $mc^2 \sim 0.0005 = 5 \times 10^{-4} \sim \frac{m_{\text{proton}}c^2}{2000}$

GeV	Δv	
	p	e
1	5×10^{-1}	1.25×10^{-7}
10	5×10^{-3}	1.25×10^{-9}
100	5×10^{-5}	1.25×10^{-11}
1000	5×10^{-7}	1.25×10^{-13}
10000	5×10^{-9}	1.25×10^{-15}

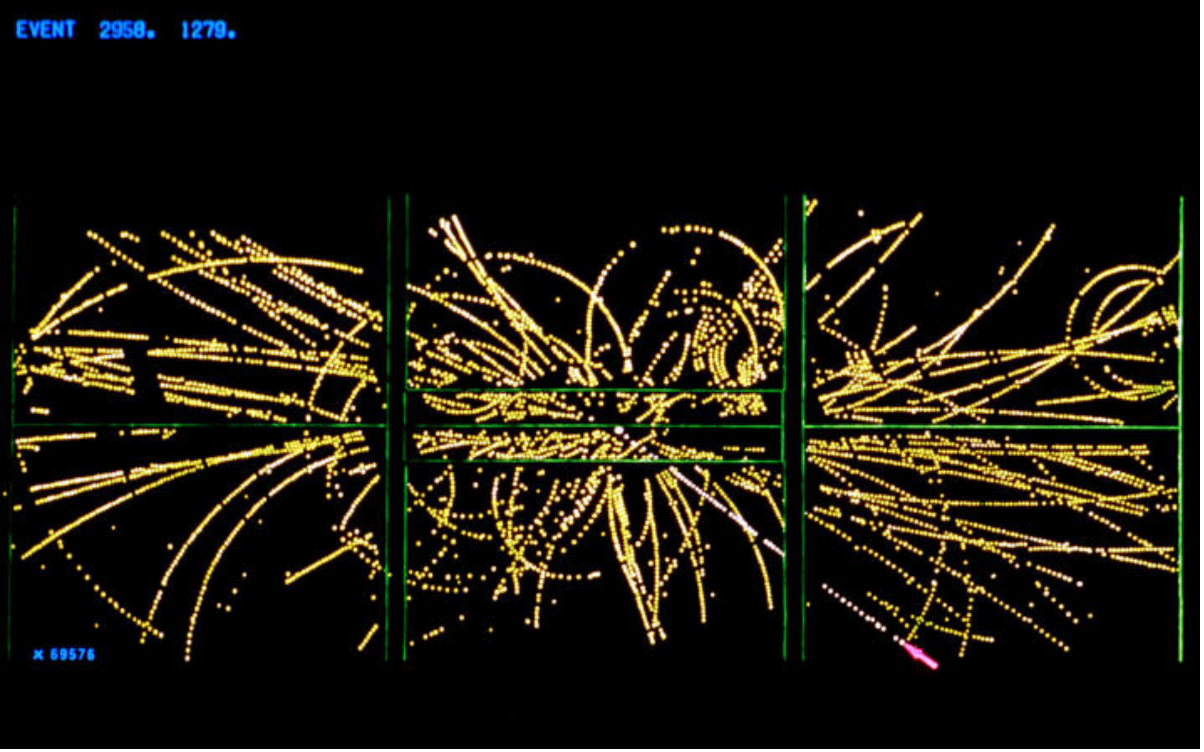
Δv: factor $2000^2 = 4 * 10^6$

so … better use protons?

- they are 2000 times heavier than electrons → much "slower" → much less synchrotron radiation
  - just put a couple of cavities somewhere and let the protons pass through them millions of times!

but

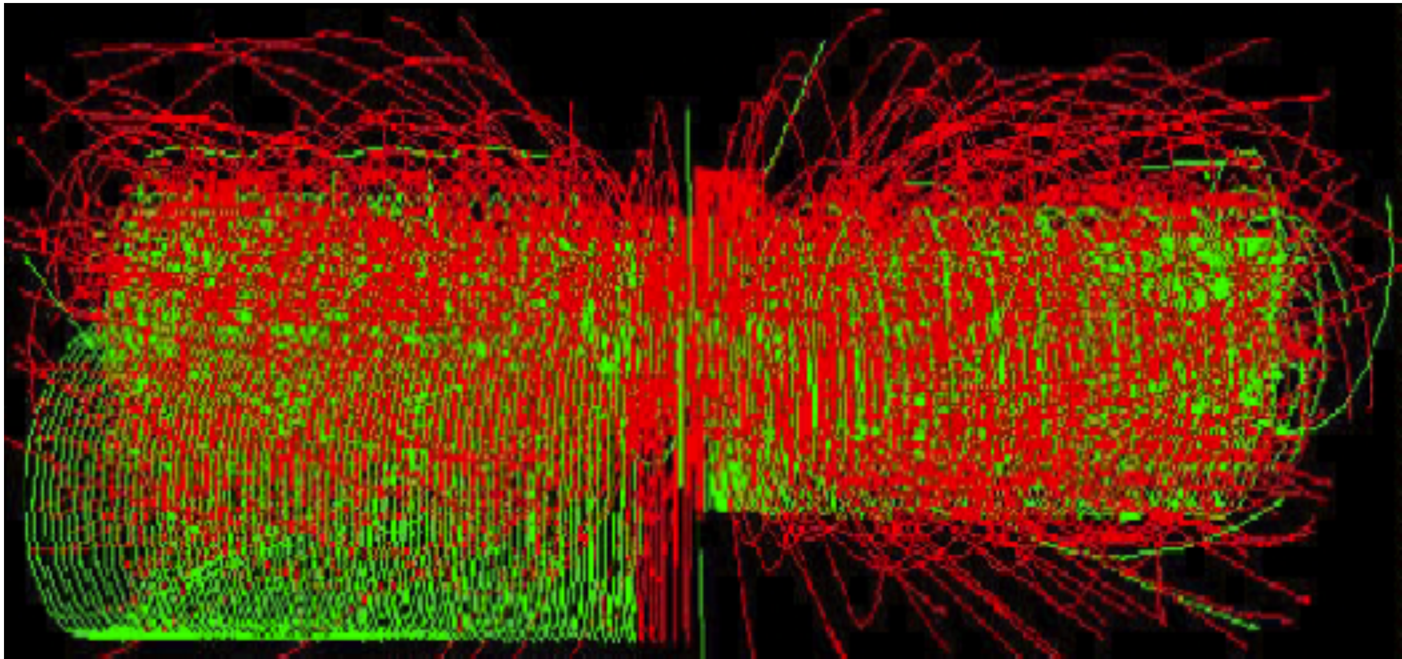
- we need stronger bending magnets
  - ~10 Tesla in LHC now : ~the maximum we can achieve at the moment for magnets of this shape and size
- and more importantly ….



electrons

vs.

protons

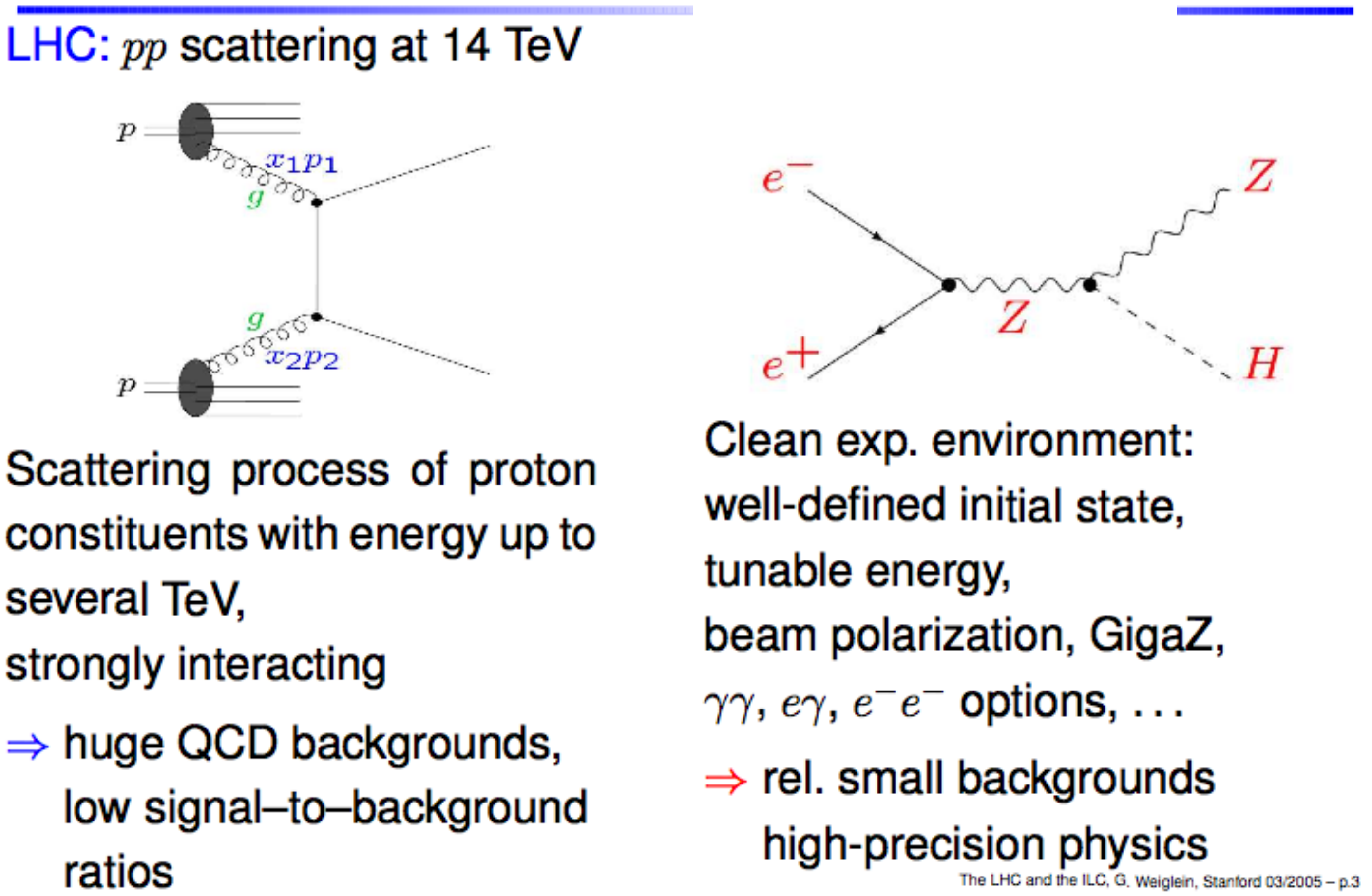


elementary particle or not?

- electrons (or other leptons): elementary
  - no substructure
  - few tracks
  - sharp energy
    - as long as beam-beam interaction can be neglected

- protons (hadrons): compounds made up of quarks
  - what collides is one quark or gluon with another quark or gluon
  - lots of other "spectators"
    - mess up the picture
  - never know collision energy of interacting constituents
    - only maximum

Collisions at the TeV scale



LHC: pp scattering at 14 TeV

Scattering process of proton constituents with energy up to several TeV, strongly interacting

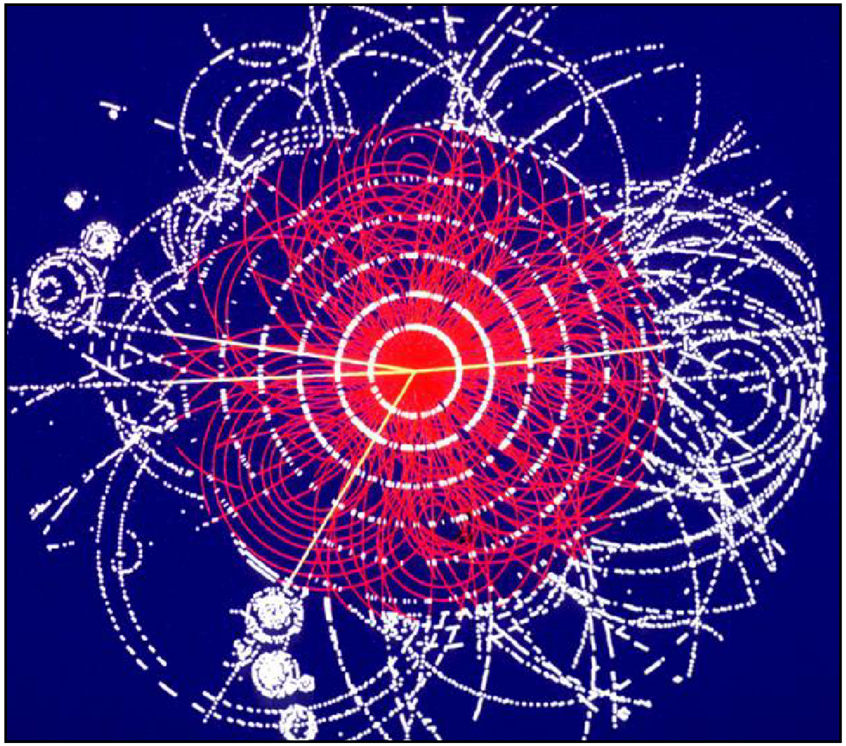
$\Rightarrow$ huge QCD backgrounds, low signal–to–background ratios

Clean exp. environment: well-defined initial state, tunable energy, beam polarization, GigaZ, $\gamma\gamma$, $e\gamma$, e^-e^- options, . . .

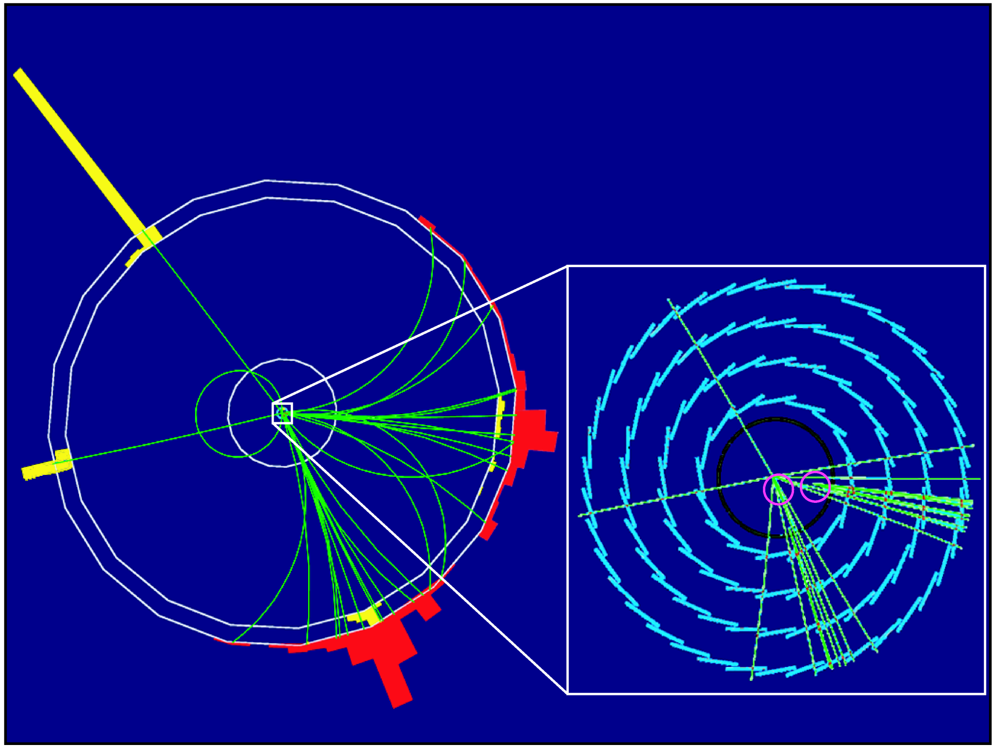
$\Rightarrow$ rel. small backgrounds high-precision physics

The LHC and the ILC, G. Weiglein, Stanford 03/2005 – p.3

Example: simulated Higgs event



LHC



$e^- e^+$ collider

what do you spend your money on (electricity bill)?

- electron colliders: accelerating RF-cavities to make up for synchrotron losses
- proton colliders: dipole magnets to keep protons on a circular track
  - conventional (“warm”) magnets: ohmic losses
  - superconducting magnets: cryogenics
    - LHC cryogenics: ~30 MW out of total of 180 MW for all of CERN

- *“there is no such thing as a free lunch”*

The solution: linear $e^- e^+$ collider !?

- no bending of beams → no synchrotron losses

but:

- must be long (or have very high acceleration gradient)
- only one shot – no recycling of particles

“discovery” vs. “precision” machines

- proton colliders are sometimes called “discovery” machines
  - proton-antiproton or proton-proton
  - SPS: W, Z bosons
    - Super Proton Synchrotron, CERN
  - Tevatron: top quark
    - Fermilab, Chicago
  - LHC: Higgs
    - Large Hadron Collider, CERN

- electron-positron colliders allow for precision measurements
  - LEP: precision measurements of Z mass
    - Large Electron-Positron Collider, CERN
  - KEKB/BELLE: b-physics precision measurements

how big is a proton?

- roughly 1 fm (10^{-15} m)
  - "femtometer" or "fermi"

- 1 barn is the area of a 10 fm × 10 fm square
  - big unit
  - derived from uranium nucleus
  - physicists joked: "that cross section is as big as a barn"

- proton-proton inelastic cross section at LHC energies: 70 mbarn
  - $= 7\ \mathrm{fm}^2$
  - $r \sim 1.5$ fm

luminosity

- (instant) luminosity is **rate per cross section**
- usual units: cm^{-2} s^{-1}
  - e.g., 10^{30} cm^{-2} s^{-1} corresponds, for a reaction cross section of 10^{-30} cm^{-2} (= 1 μbarn), to a rate of 1 event per second
- for a collider, the luminosity can be calculated as follows:

$$L = fn\frac{N_1 N_2}{A}$$

where

f is the revolution frequency

n is the number of bunches in one beam in the storage ring.

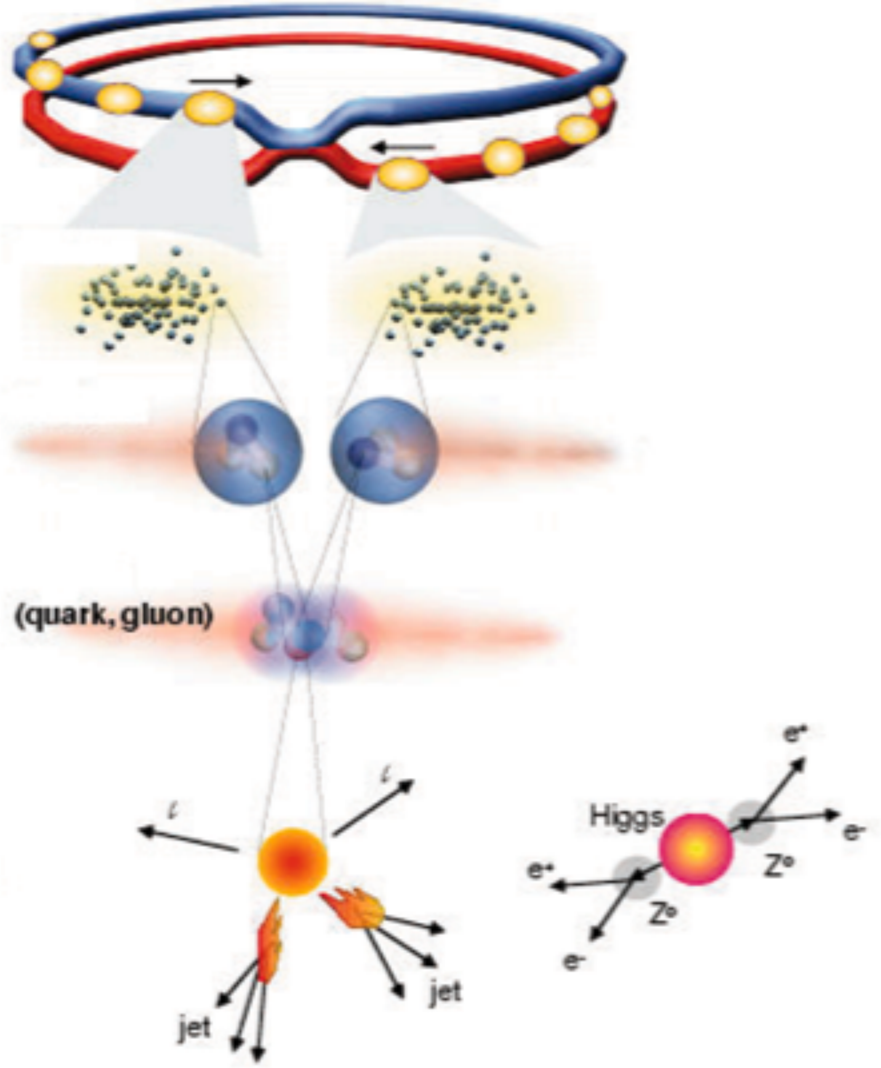
N_i is the number of particles in each bunch

A is the cross section of the beam.

integrated luminosity

- number of events collected divided by the cross section
- usual units: nb^{-1} (“inverse nanobarn”),
  pb^{-1} (“inverse picobarn”) etc.
- an integrated luminosity of 1 fb^{-1} means that for a process with a cross section of 1 fb, 1 event (on average) should have been collected
  - or 1000 events for a cross section of 1 nb, etc.
  - so, 1 inverse femtobarn = 1000 inverse picobarns :
    - $1\ fb^{-1} = 1000\ pb^{-1}$
- physicists are now looking for very rare events, so it is vital to reach not only high energies (so that heavy particles can be produced) but also high luminosities
  - handling the resulting data rates is a challenge also for the detectors, trigger systems, and readout electronics

LHC



proton-proton

circumference: 27 km

buckets: 3564 + 3564

protons / bunch: 10^{11}

beam energy: 2 x 6.5 (13) TeV

luminosity: ~ $2*10^{34}$ $cm^{-2}s^{-1}$

bunch spacing: 25 ns

collision rate: ~10^9 Hz

dipole field: 8.3 T

number of dipoles: ~ 1200

heavy ions (Pb-Pb)

beam energy:

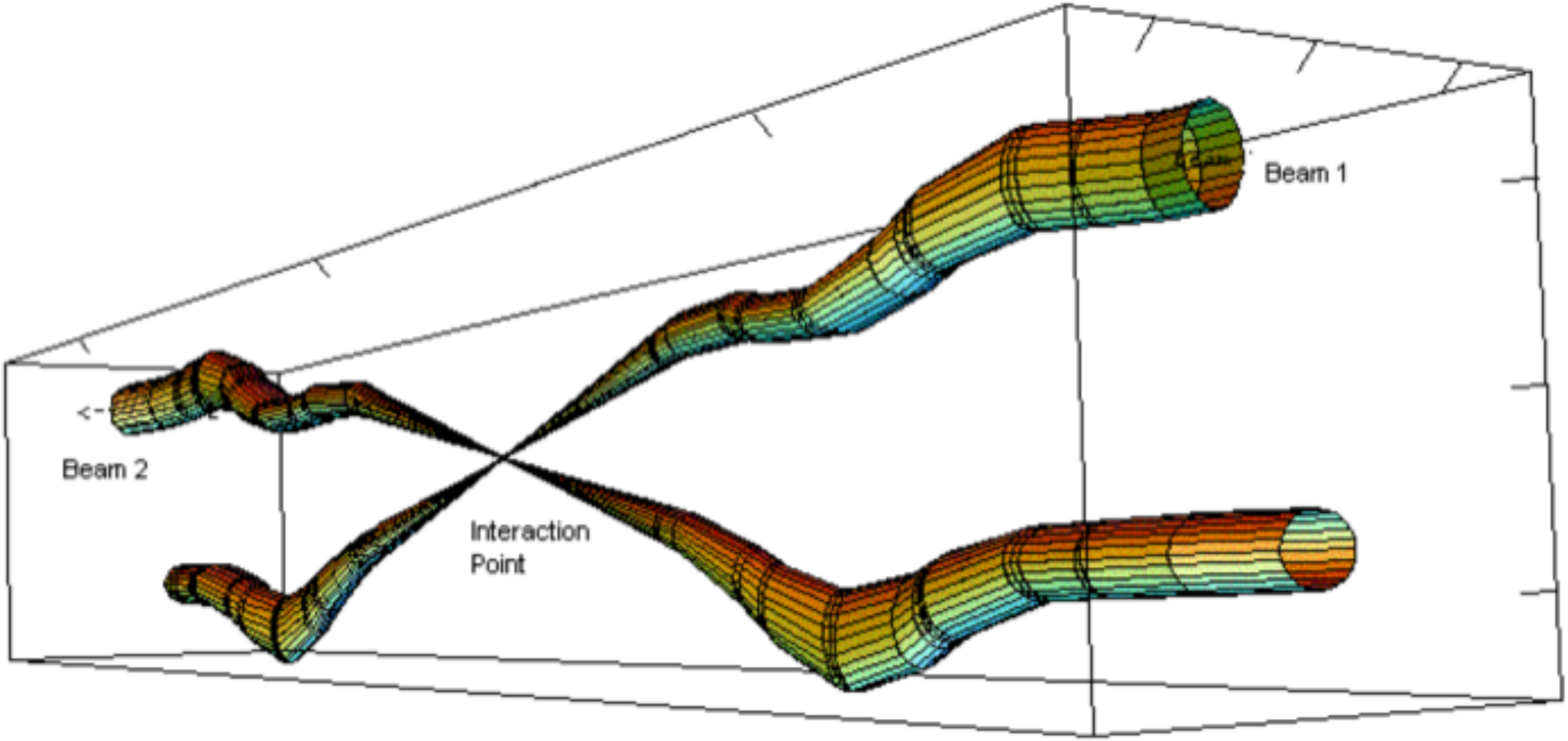
2.8 (5.5) TeV / nucleon pair

luminosity: 10^{27} $cm^{-2}s^{-1}$

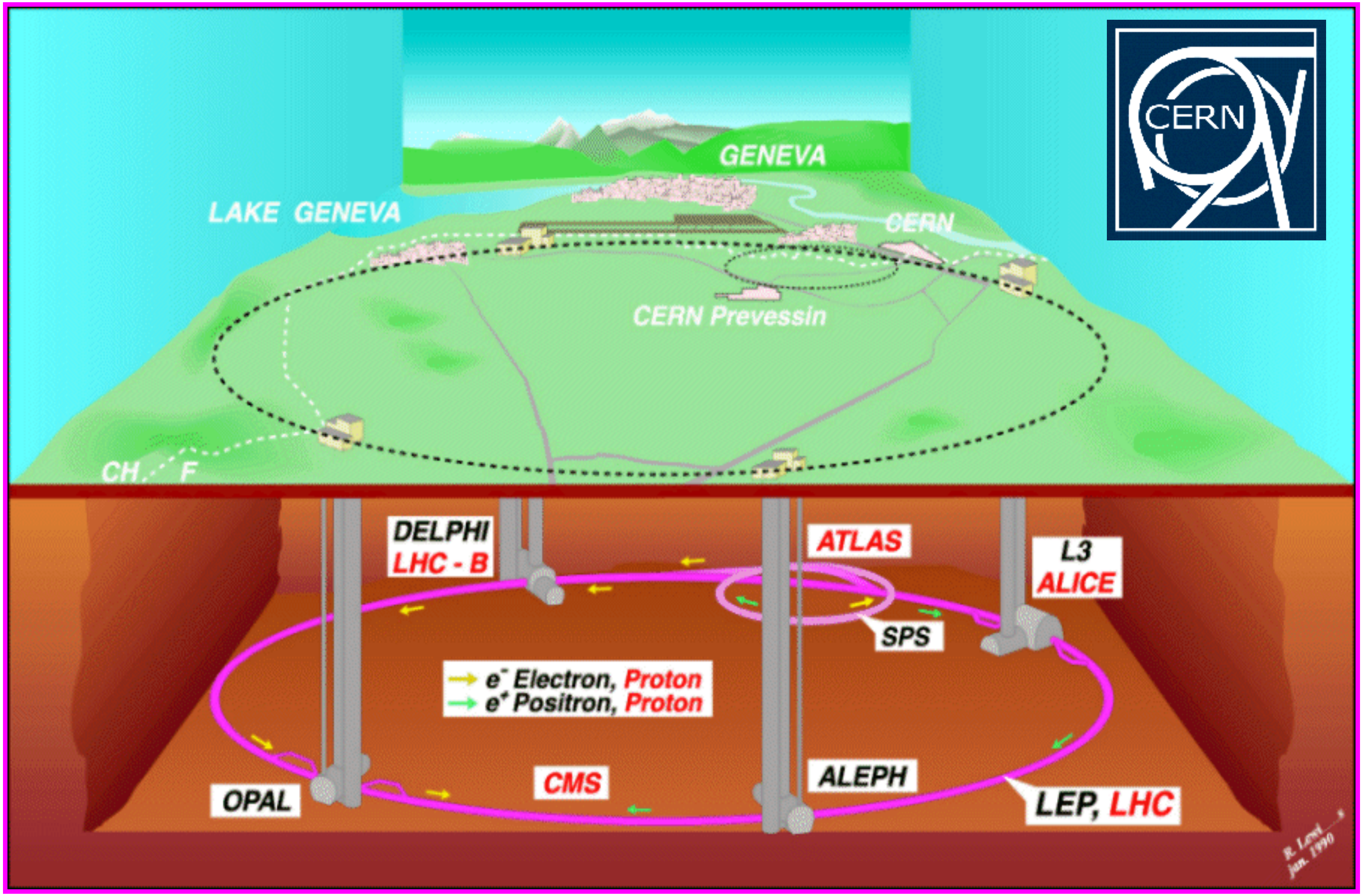
how to hit a proton

- p radius ~ 1 fm
- beam diameter ~ 10 μm = 10^{10} fm
- ratio of area: 10^{20}
  - 10^{-20} chance to hit one proton
- 10^{11} protons per bunch
  - typical distance between protons: ~ 10^{-10} m = 100' 000 fm
- rate: $10^{11} \times 10^{11} \times 10^{-20} = 10^{2}$
  - "pileup": order of magnitude ~ 100 proton-proton reactions in one collision of two bunches

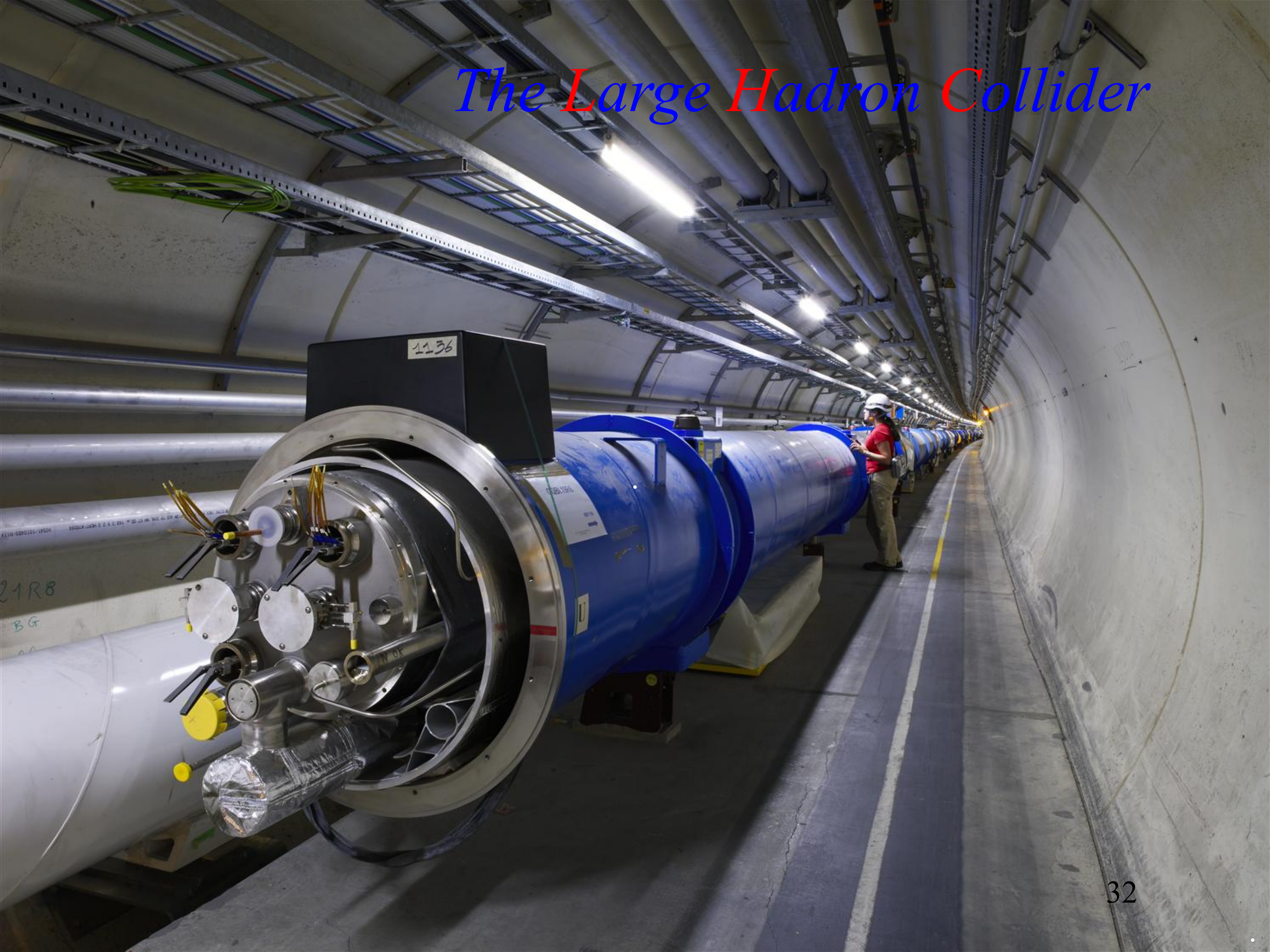
beam sizes around an LHC experiment



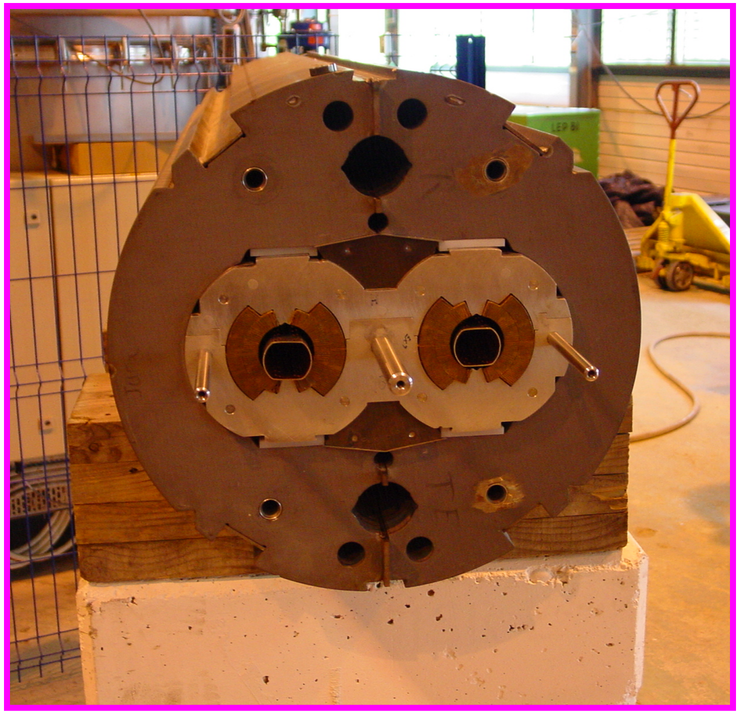
layout of the LHC storage ring (built into the former LEP tunnel)

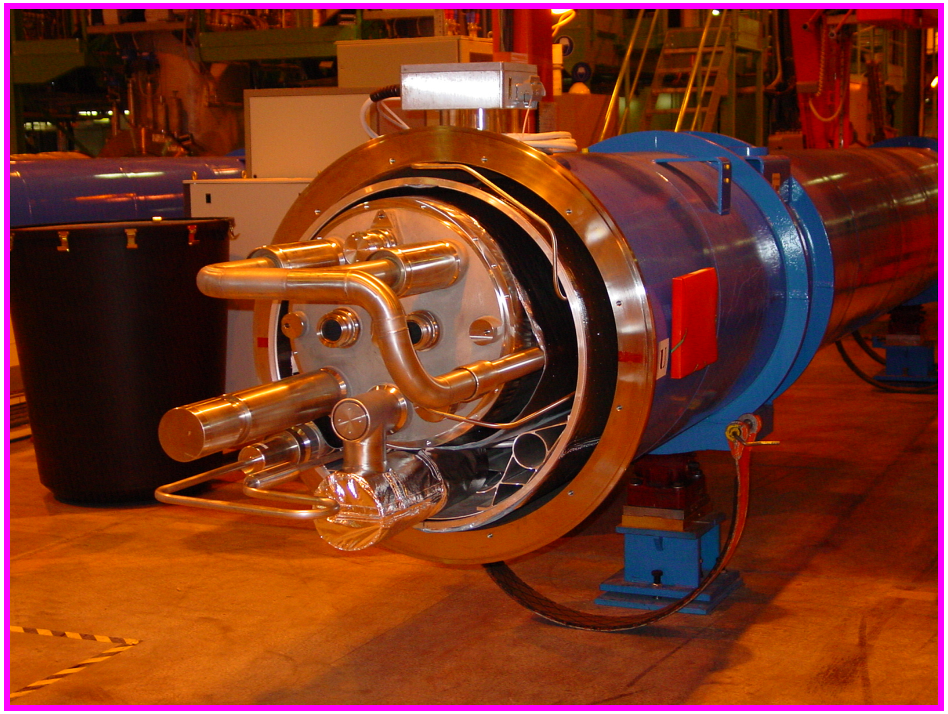


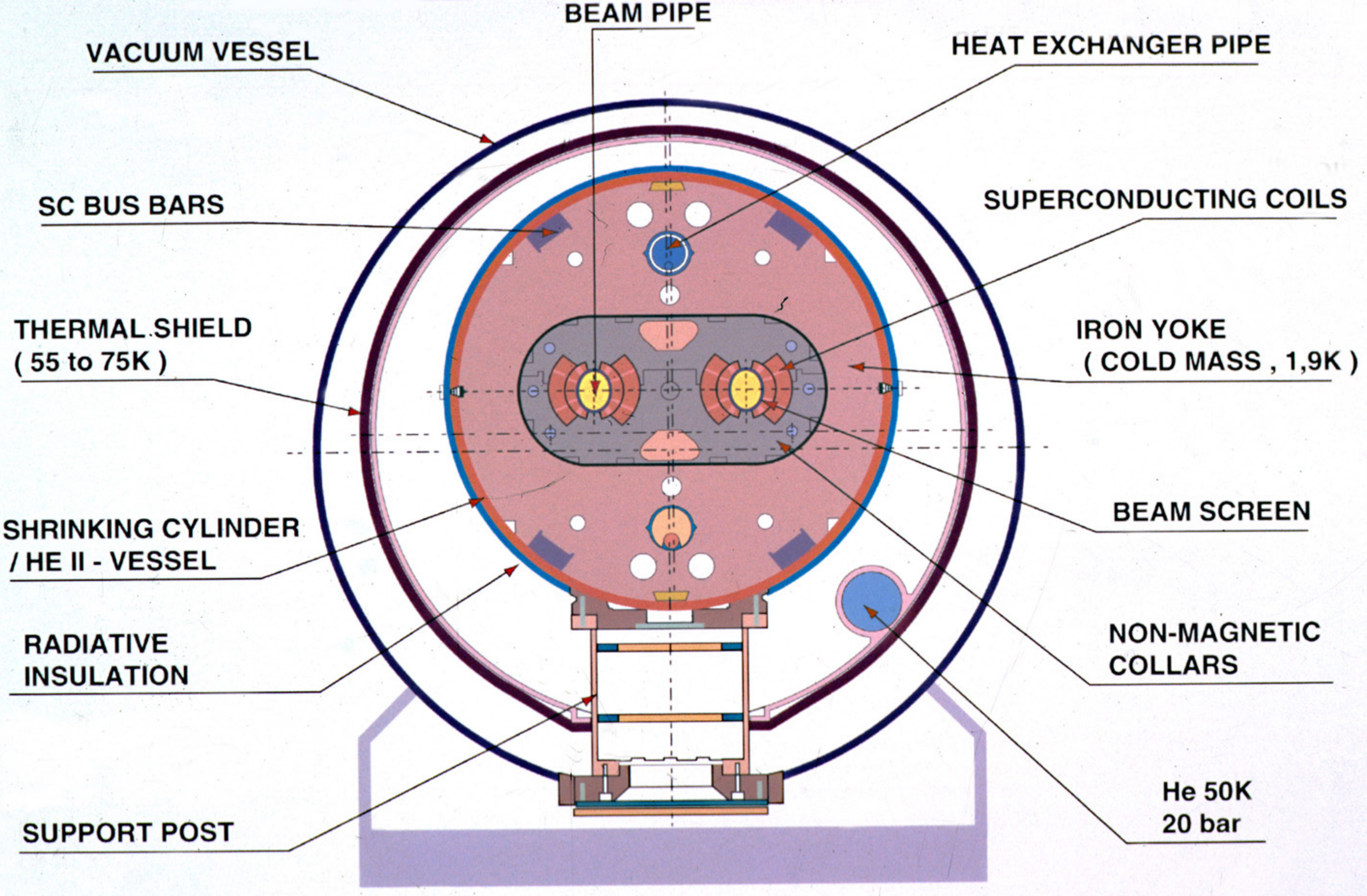
The Large Hadron Collider



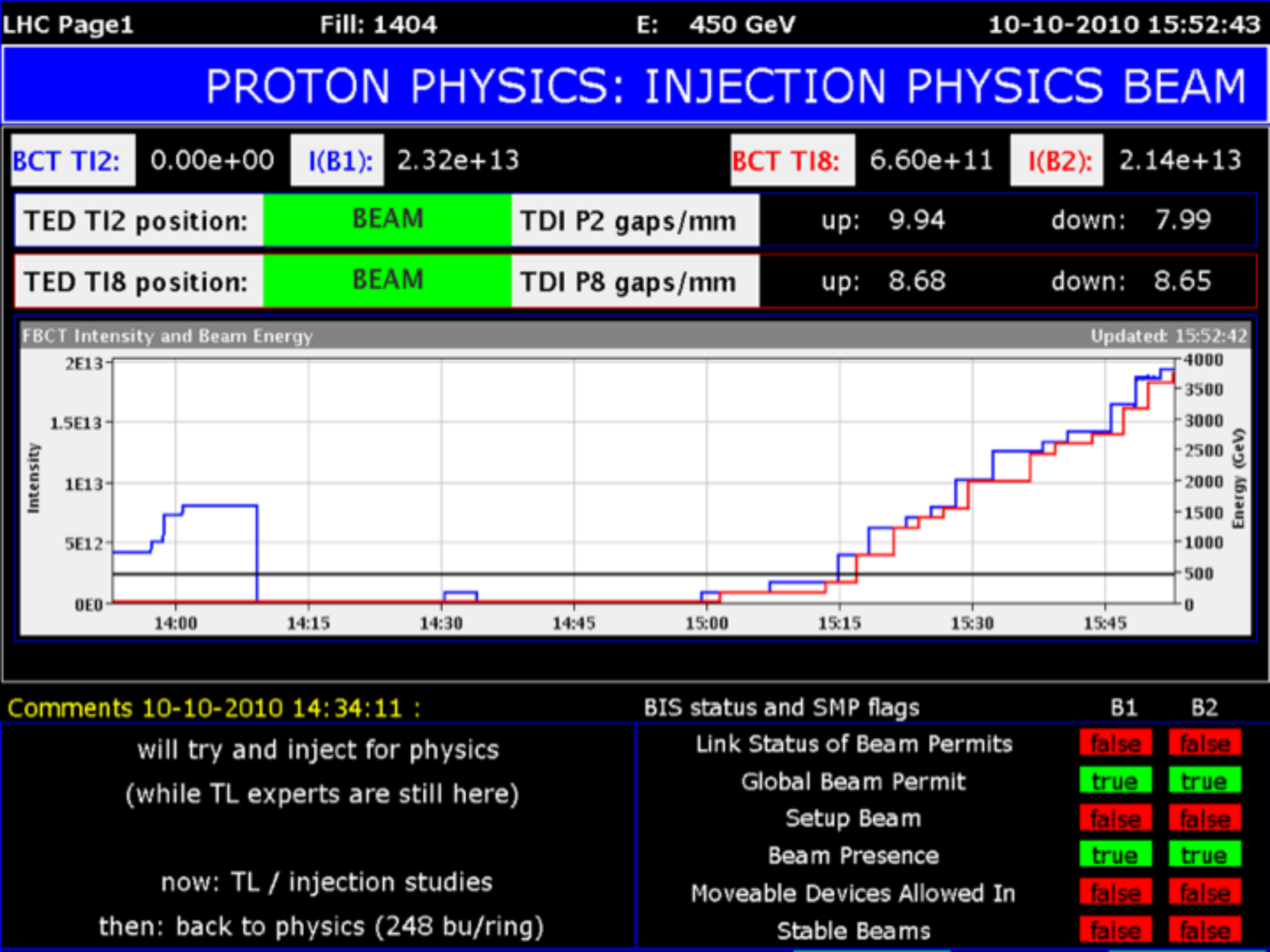
LHC dipole







Cross Section of LHC Dipole



LHC Page1 Fill: 1404 E: 450 GeV 10-10-2010 15:52:43

PROTON PHYSICS: INJECTION PHYSICS BEAM

BCT TI2:	0.00e+00	I(B1):	2.32e+13	BCT TI8:	6.60e+11	I(B2):	2.14e+13

TED TI2 position:	BEAM	TDI P2 gaps/mm	up: 9.94	down: 7.99
TED TI8 position:	BEAM	TDI P8 gaps/mm	up: 8.68	down: 8.65

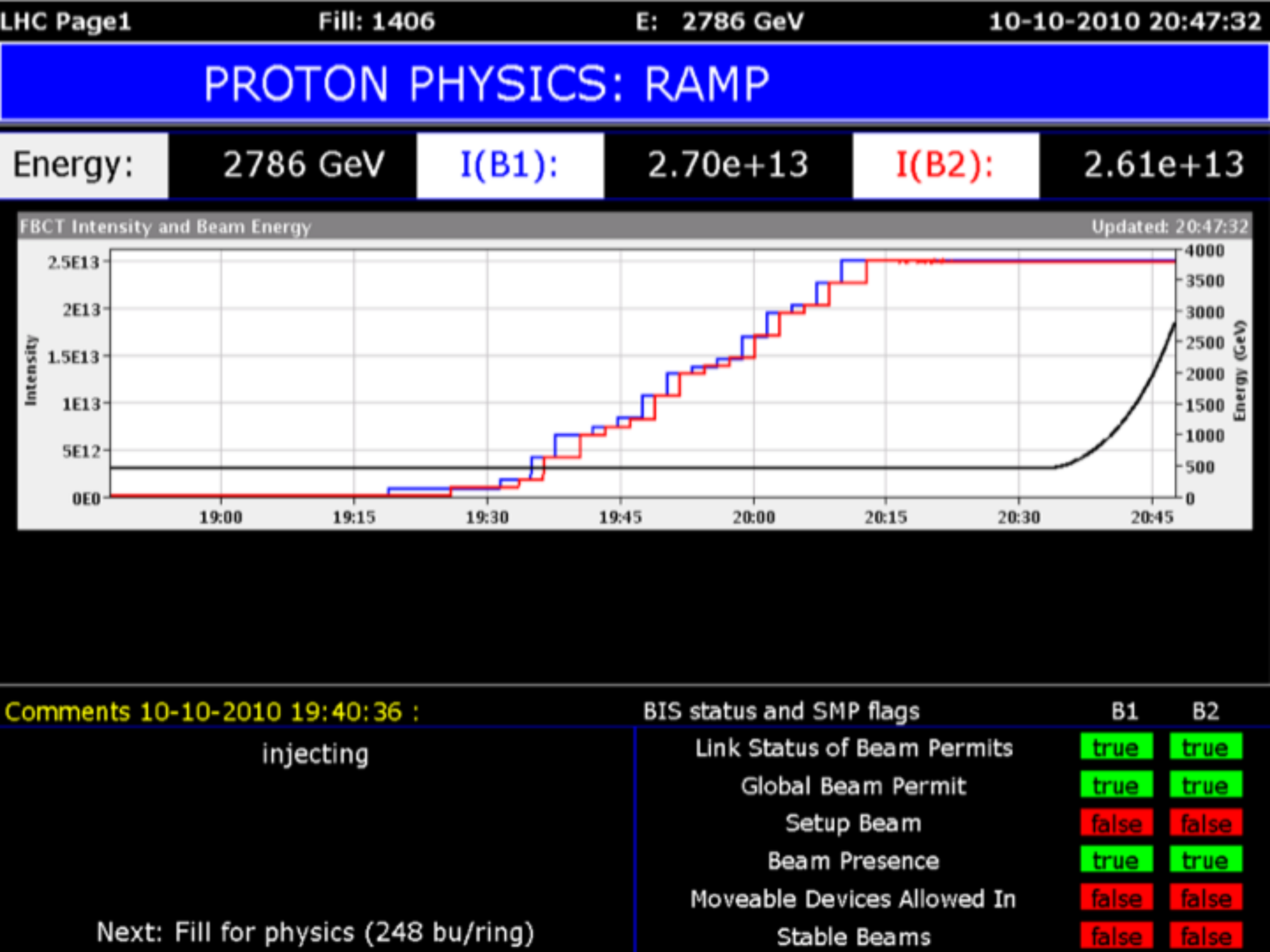
FBCT Intensity and Beam Energy Updated: 15:52:42

Comments 10-10-2010 14:34:11 :

will try and inject for physics
(while TL experts are still here)

now: TL / injection studies
then: back to physics (248 bu/ring)

BIS status and SMP flags	B1	B2
Link Status of Beam Permits	false	false
Global Beam Permit	true	true
Setup Beam	false	false
Beam Presence	true	true
Moveable Devices Allowed In	false	false
Stable Beams	false	false



LHC Page1 Fill: 1406 E: 2786 GeV 10-10-2010 20:47:32

PROTON PHYSICS: RAMP

Energy:	2786 GeV	I(B1):	2.70e+13	I(B2):	2.61e+13

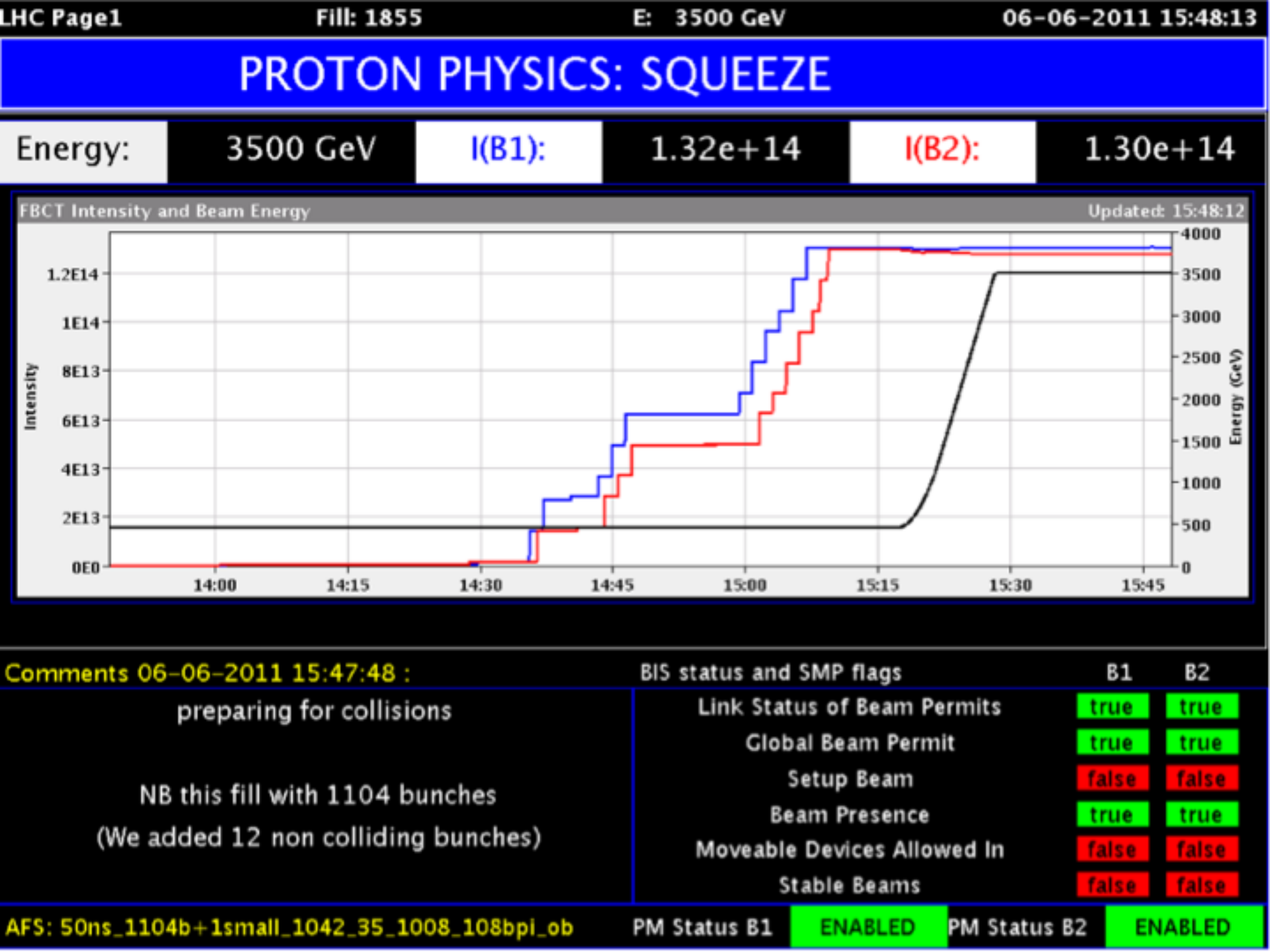
FBCT Intensity and Beam Energy Updated: 20:47:32

Comments 10-10-2010 19:40:36 :

injecting

Next: Fill for physics (248 bu/ring)

BIS status and SMP flags	B1	B2
Link Status of Beam Permits	true	true
Global Beam Permit	true	true
Setup Beam	false	false
Beam Presence	true	true
Moveable Devices Allowed In	false	false
Stable Beams	false	false



LHC Page1 Fill: 1855 E: 3500 GeV 06-06-2011 15:48:13

PROTON PHYSICS: SQUEEZE

Energy:	3500 GeV	I(B1):	1.32e+14	I(B2):	1.30e+14

FBCT Intensity and Beam Energy Updated: 15:48:12

Comments 06-06-2011 15:47:48 :

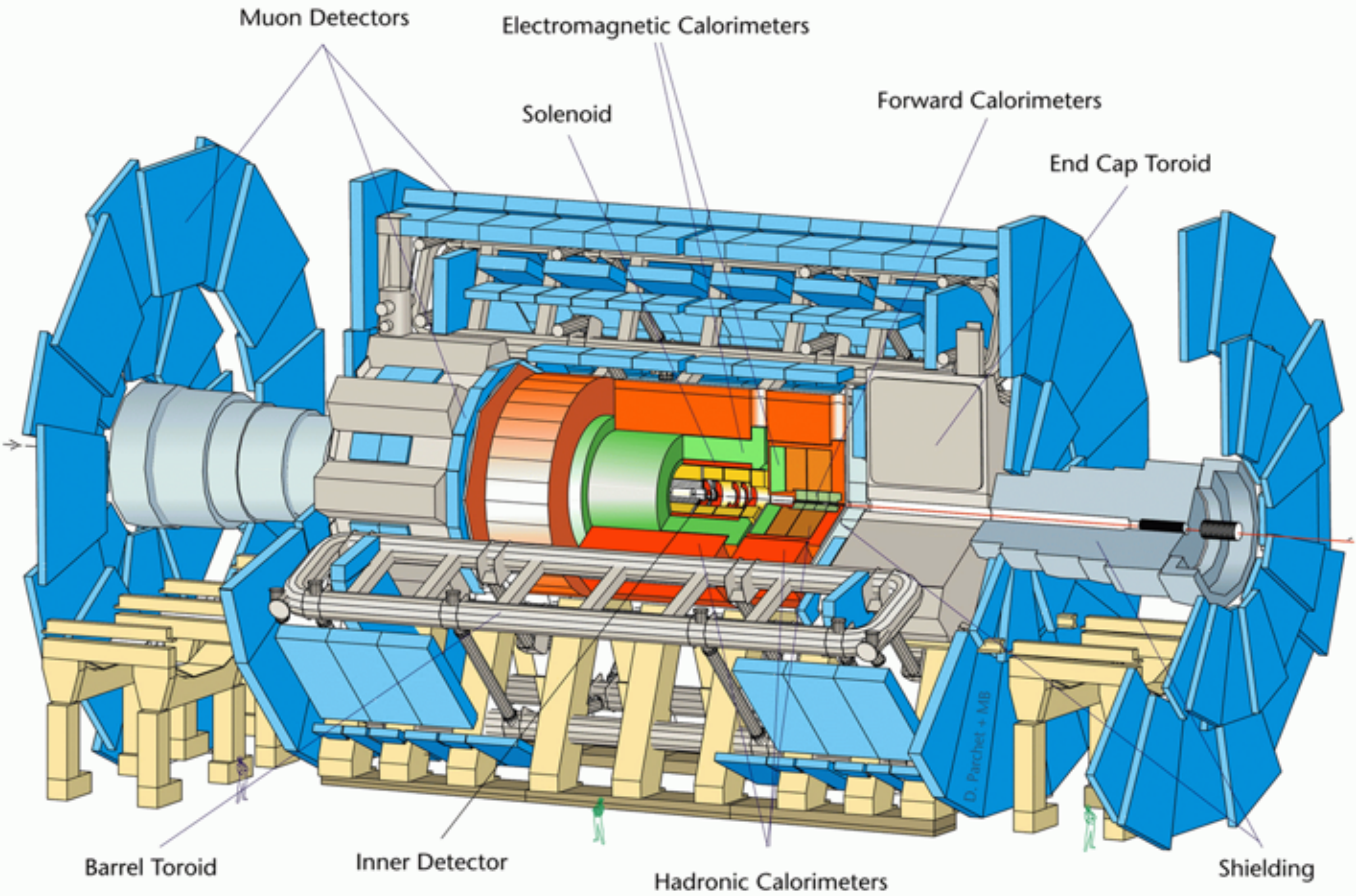
preparing for collisions

NB this fill with 1104 bunches
(We added 12 non colliding bunches)

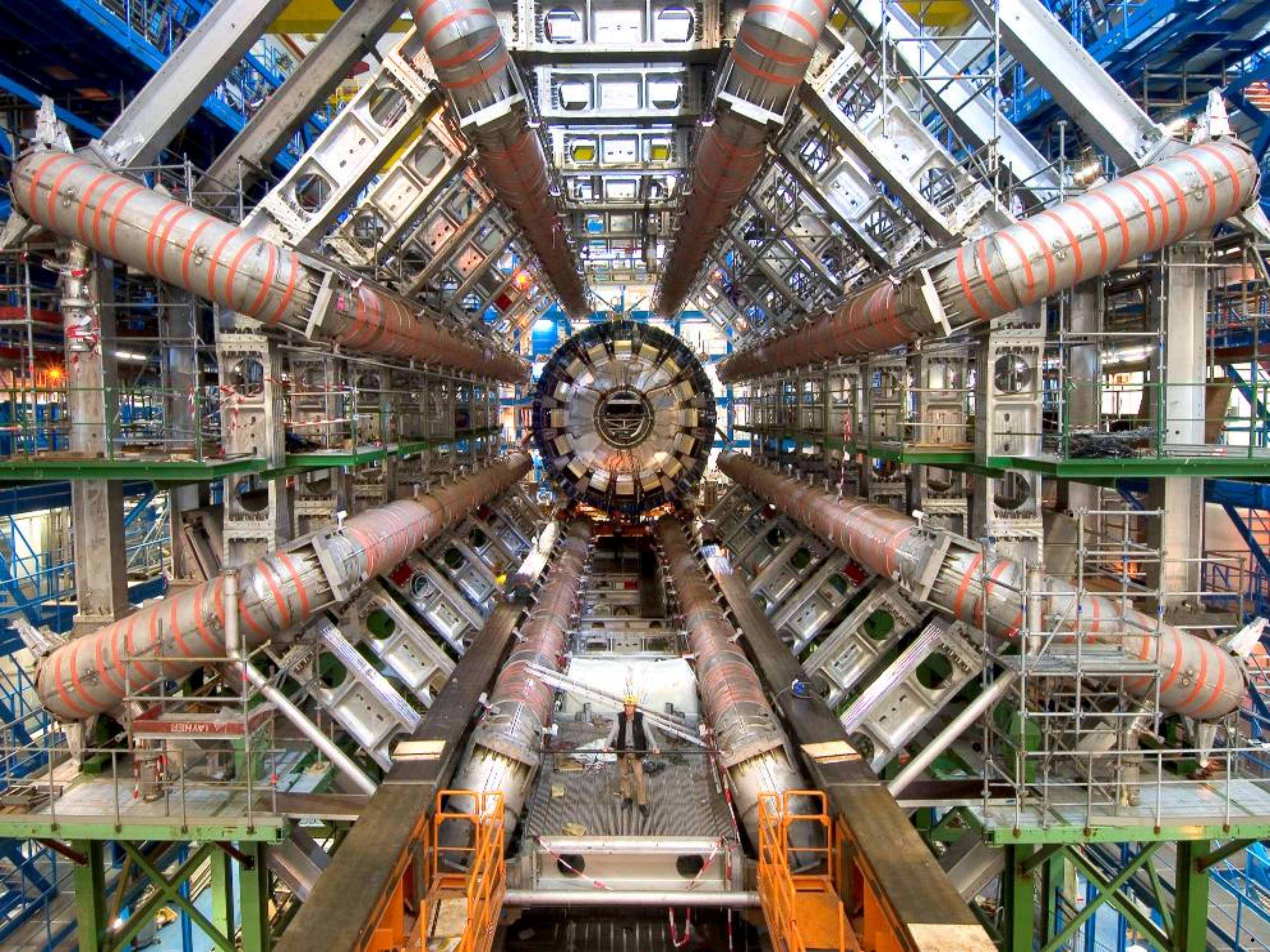
BIS status and SMP flags	B1	B2
Link Status of Beam Permits	true	true
Global Beam Permit	true	true
Setup Beam	false	false
Beam Presence	true	true
Moveable Devices Allowed In	false	false
Stable Beams	false	false

AFS: 50ns_1104b+1small_1042_35_1008_108bpi_ob PM Status B1 ENABLED PM Status B2 ENABLED

DETECTORS


D712/mb-26/06/97
Muon Detectors
Electromagnetic Calorimeters
Solenoid
Forward Calorimeters
End Cap Toroid
Barrel Toroid
Inner Detector
Hadronic Calorimeters
Shielding
D. Parchet + MB


LAS ONE

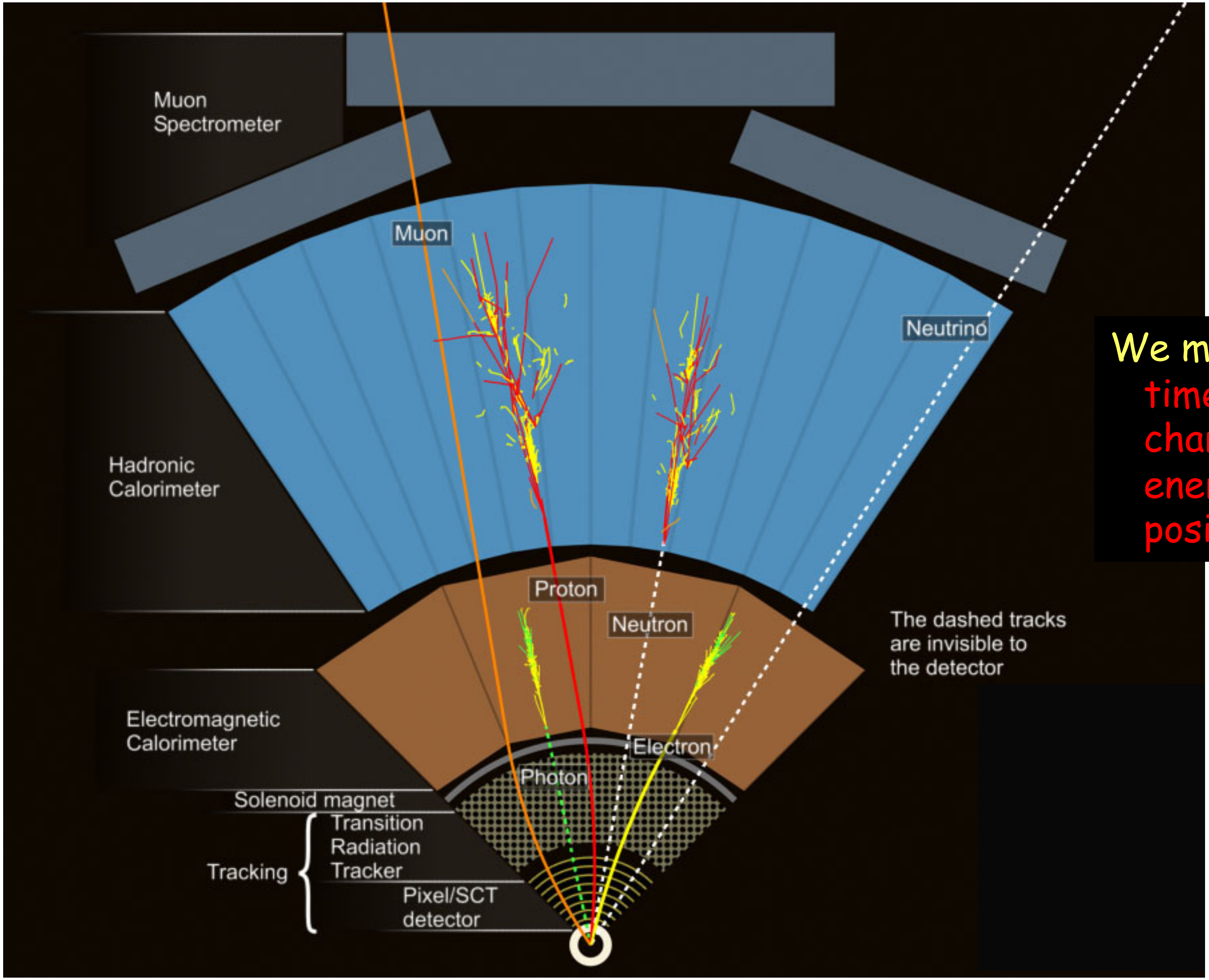


WHY ARE THOSE DETECTORS SO BIG?

need high-resolution measurements

- in momentum
  - good resolution in invariant mass
- in space
  - correctly assign tracks of secondary particles to interaction vertices
- achieve by large size and high magnetic field

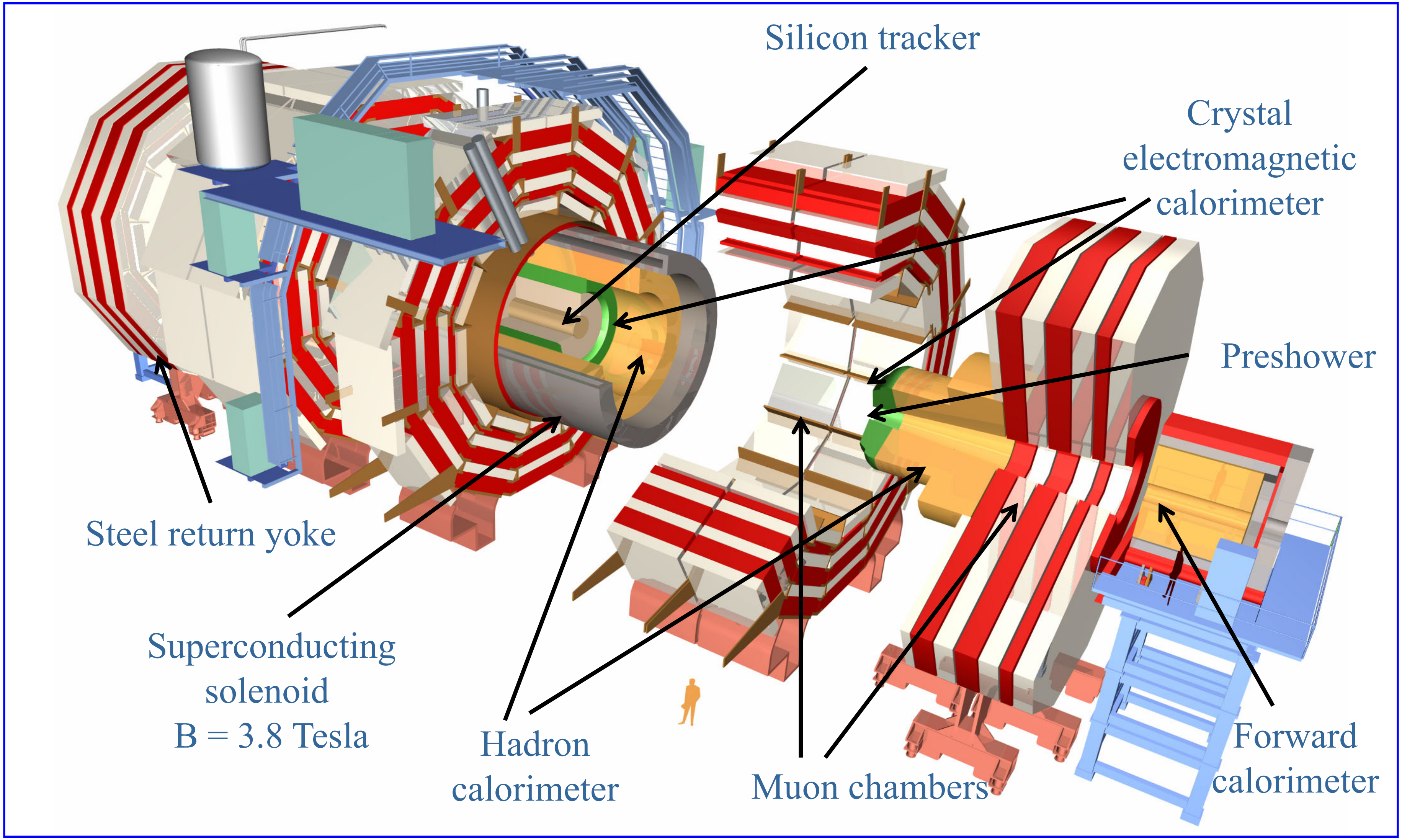
Particle detection in ATLAS

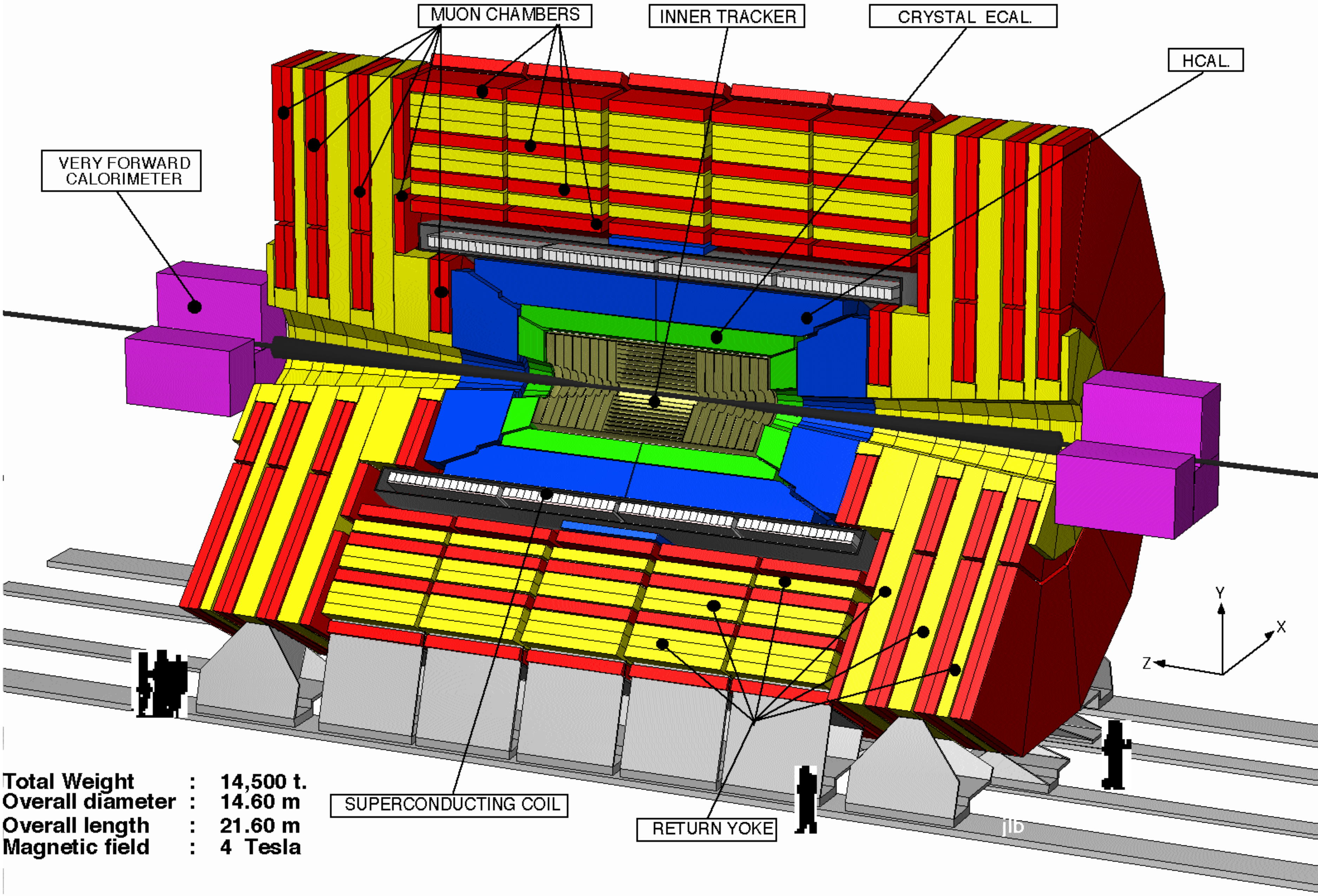


The dashed tracks are invisible to the detector

We measure:
- time
- charge
- energy
- position

CMS: Compact Muon Solenoid

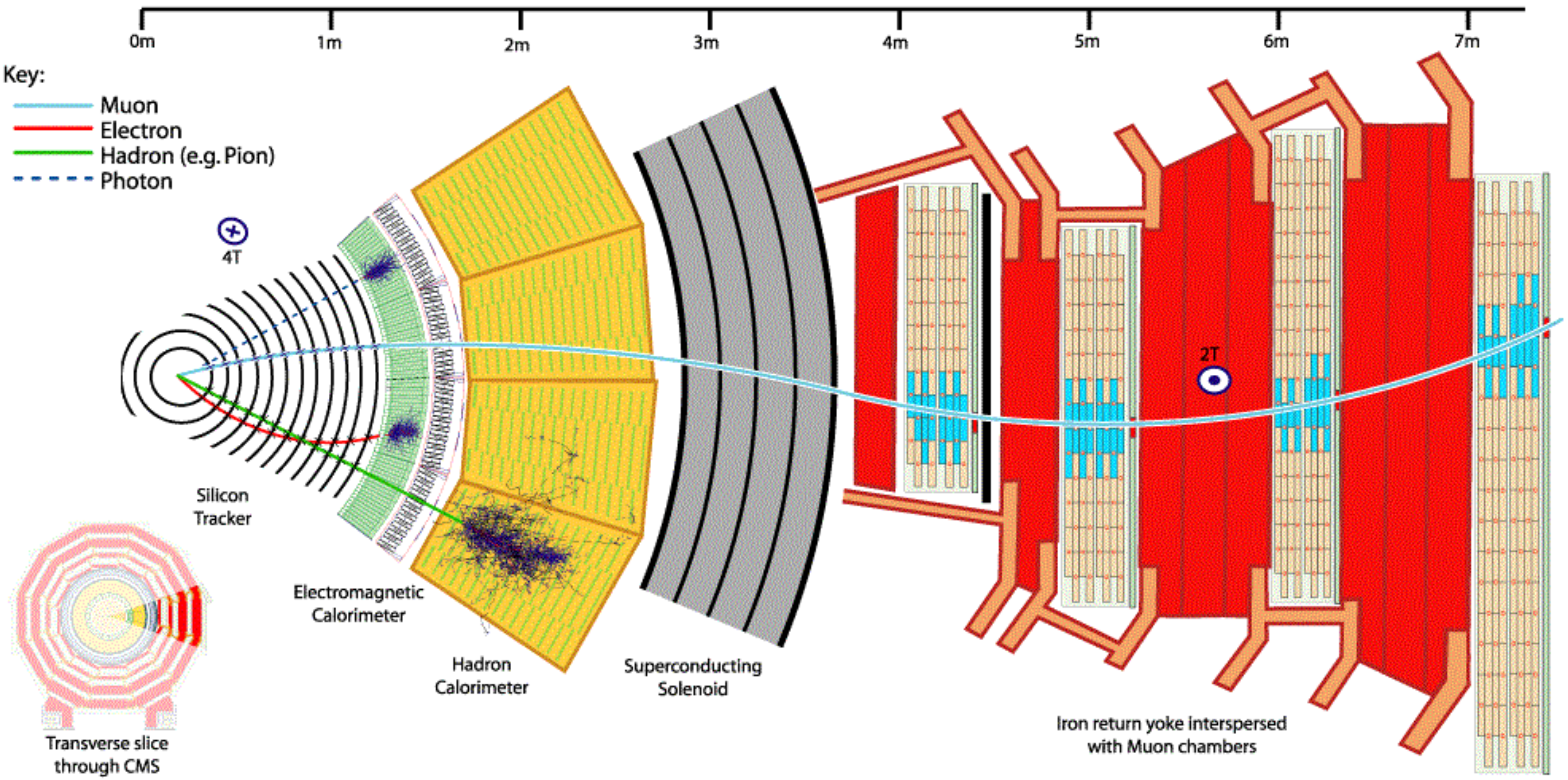




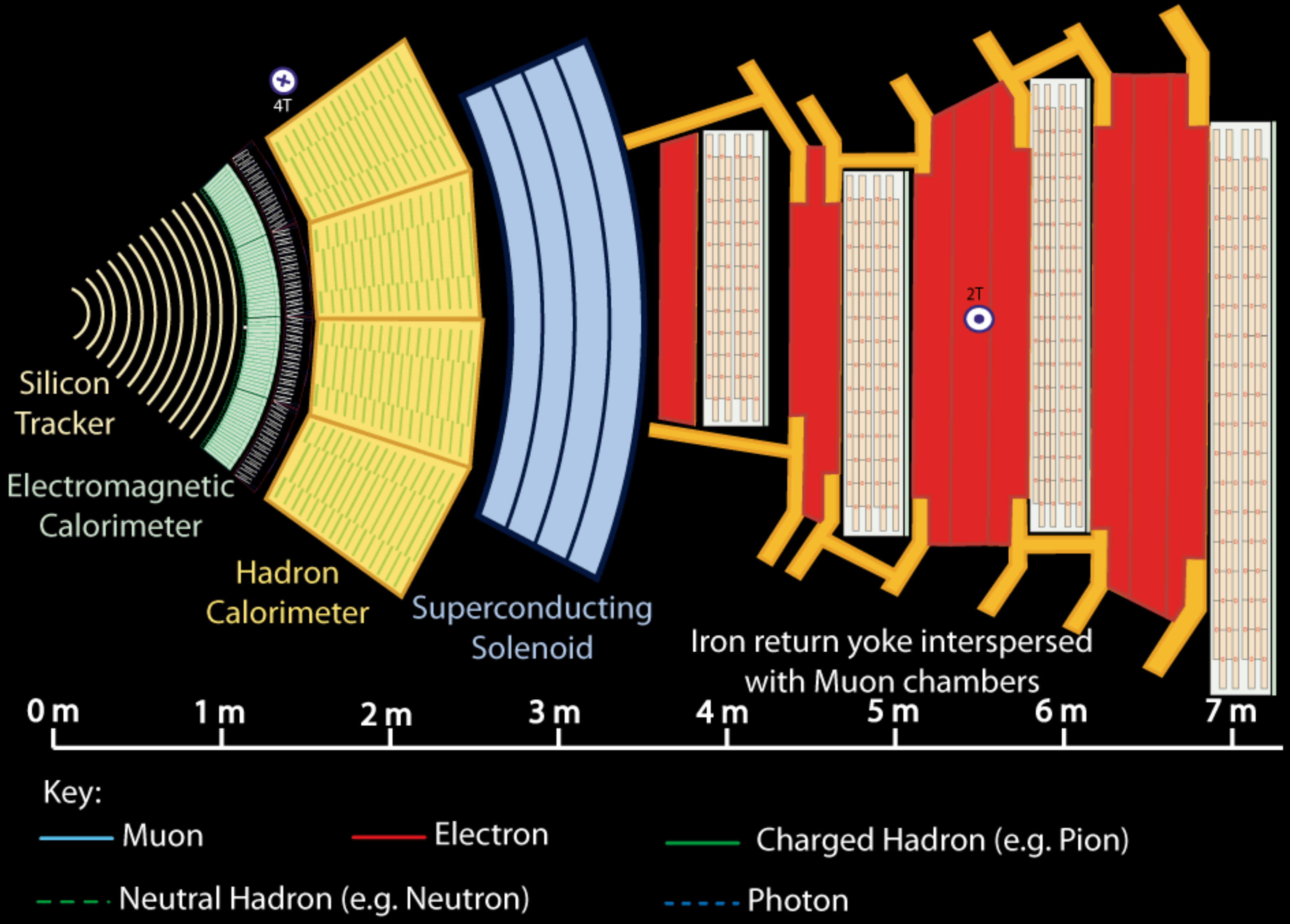
Total Weight : 14,500 t.
Overall diameter : 14.60 m
Overall length : 21.60 m
Magnetic field : 4 Tesla

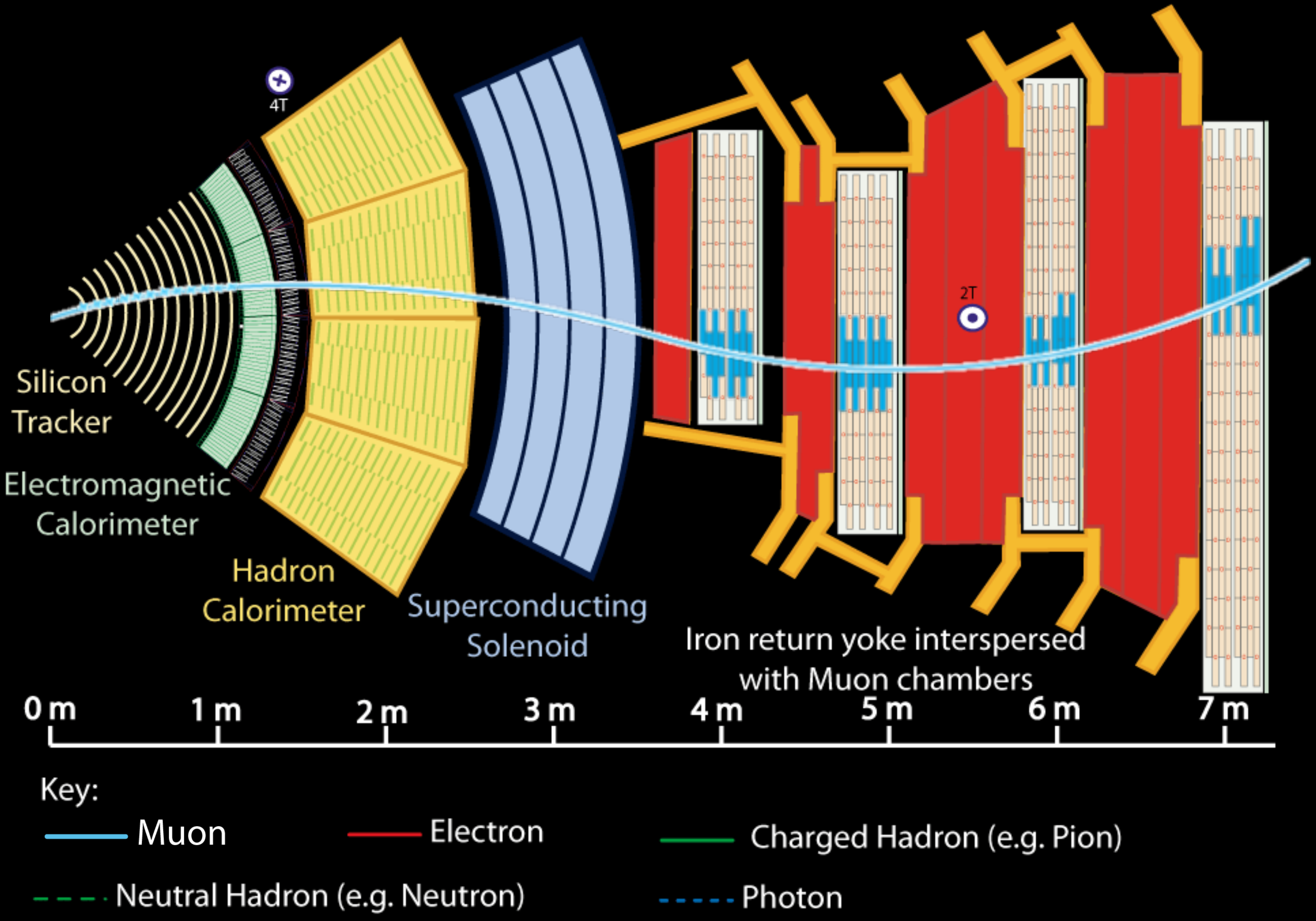
CMS

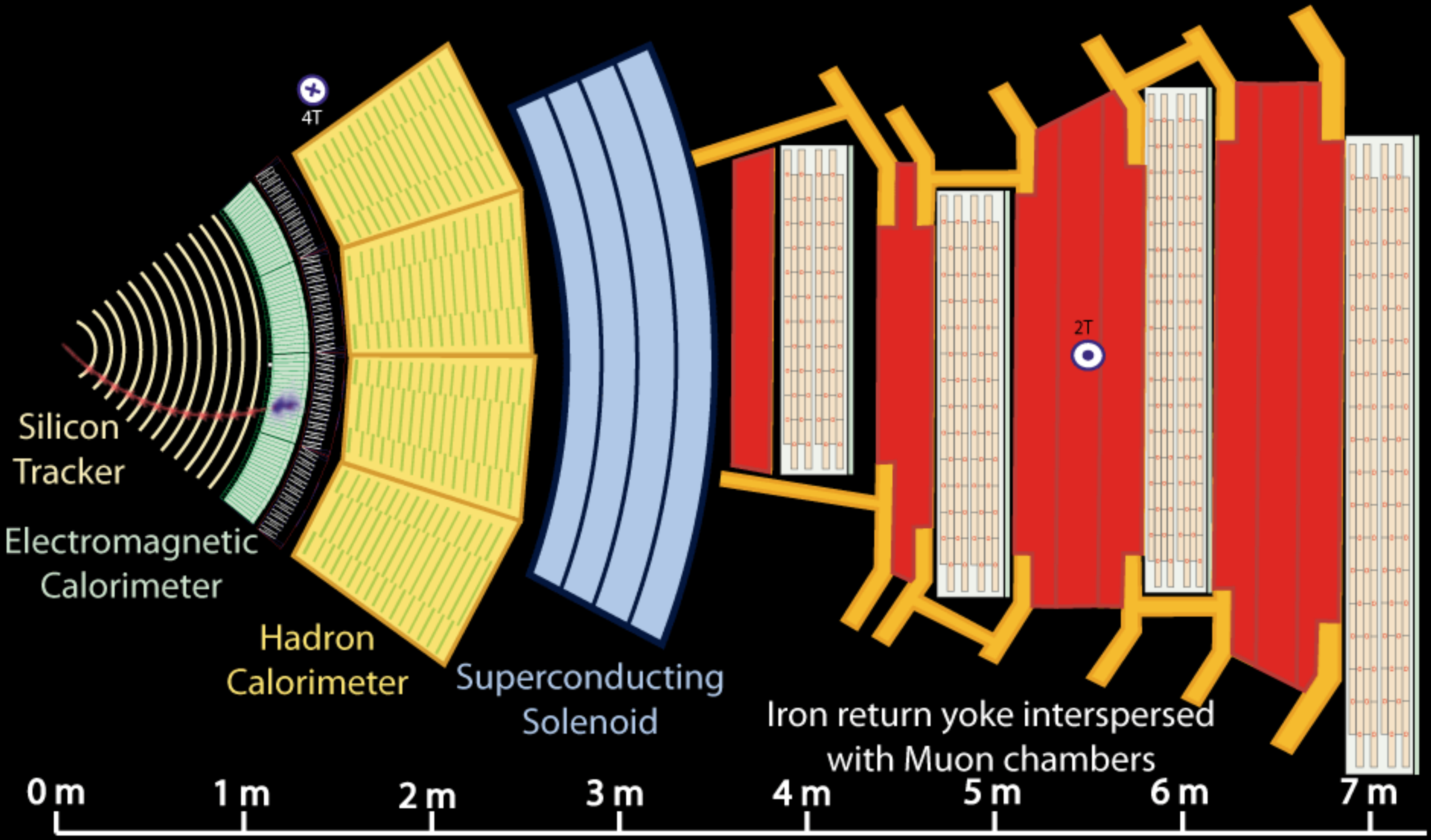
reconstruct particle tracks in the detector



tracks of particles in the CMS experiment

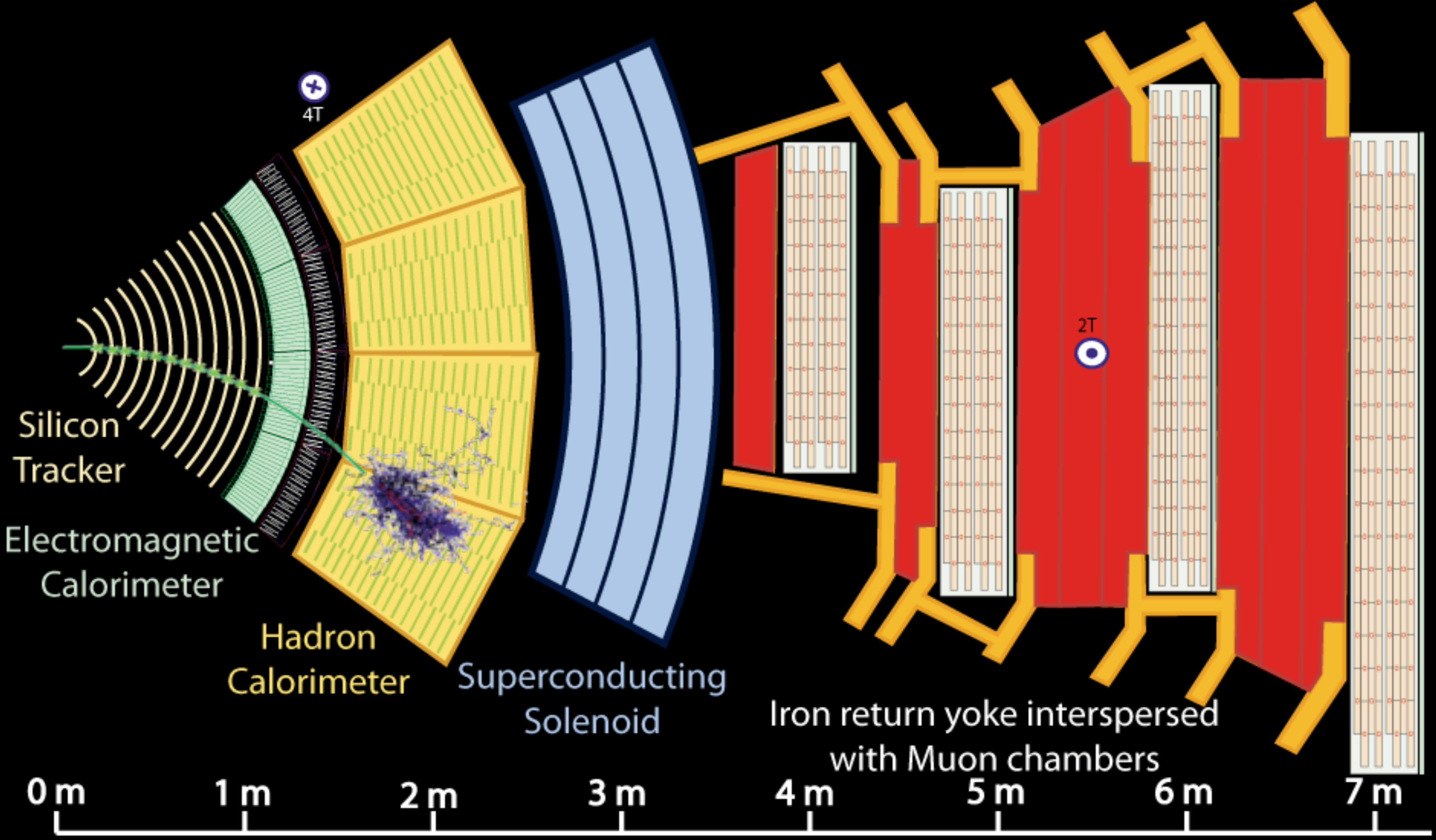

4T
Silicon Tracker
Electromagnetic Calorimeter
Hadron Calorimeter
Superconducting Solenoid
2T
Iron return yoke interspersed with Muon chambers
0 m
1 m
2 m
3 m
4 m
5 m
6 m
7 m
Key:
— Muon
— Electron
— Charged Hadron (e.g. Pion)
- - - Neutral Hadron (e.g. Neutron)
- - - Photon


4T
Silicon Tracker
Electromagnetic Calorimeter
Hadron Calorimeter
Superconducting Solenoid
2T
Iron return yoke interspersed with Muon chambers
0 m
1 m
2 m
3 m
4 m
5 m
6 m
7 m
Key:
Muon
Electron
Charged Hadron (e.g. Pion)
Neutral Hadron (e.g. Neutron)
Photon



Key:

- Muon
- Electron
- Charged Hadron (e.g. Pion)
- Neutral Hadron (e.g. Neutron)
- Photon



Key:

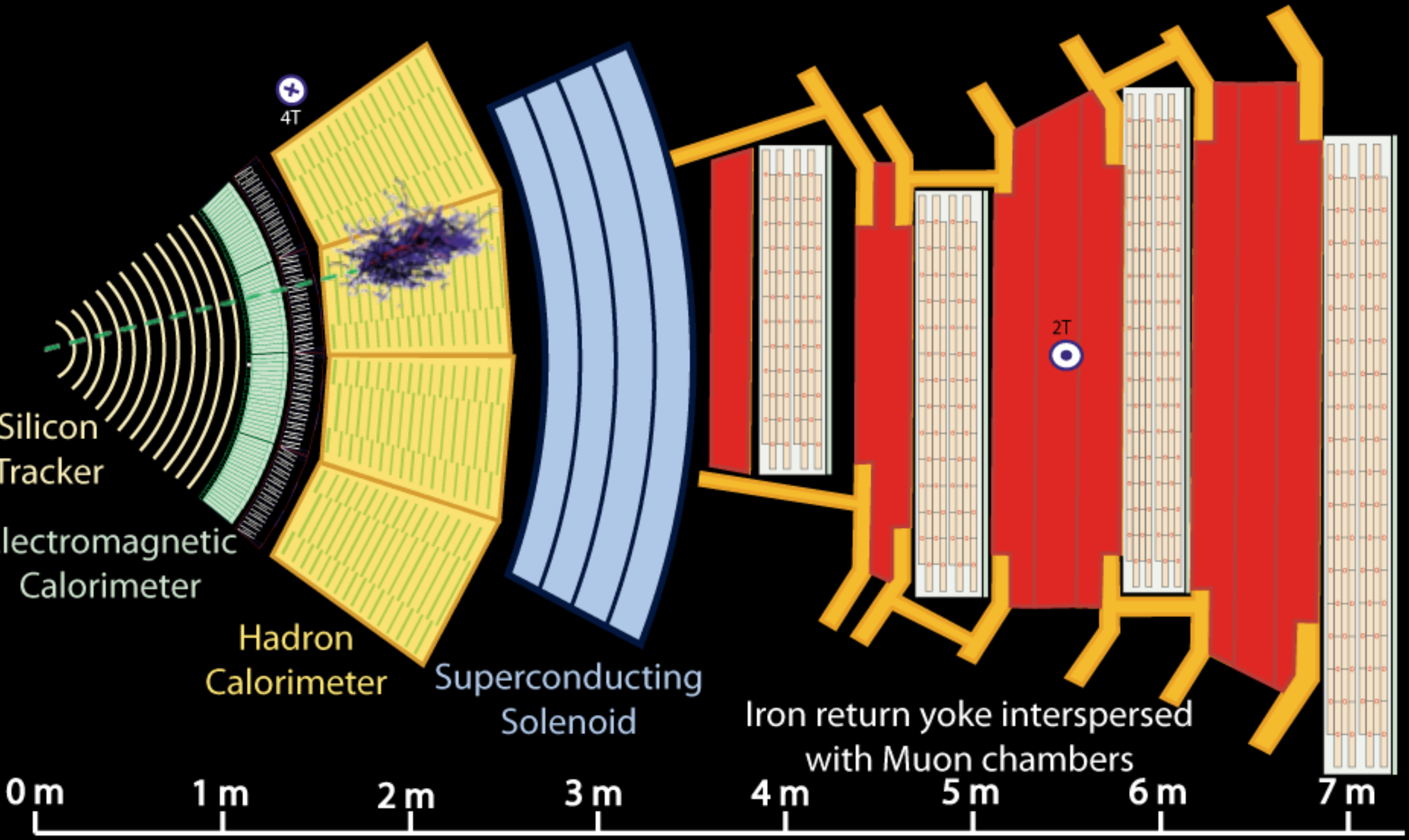
— Muon

— Electron

— Charged Hadron (e.g. Pion)

- - - Neutral Hadron (e.g. Neutron)

- - - Photon



Silicon Tracker

Electromagnetic Calorimeter

Hadron Calorimeter

Superconducting Solenoid

Iron return yoke interspersed with Muon chambers

Key:

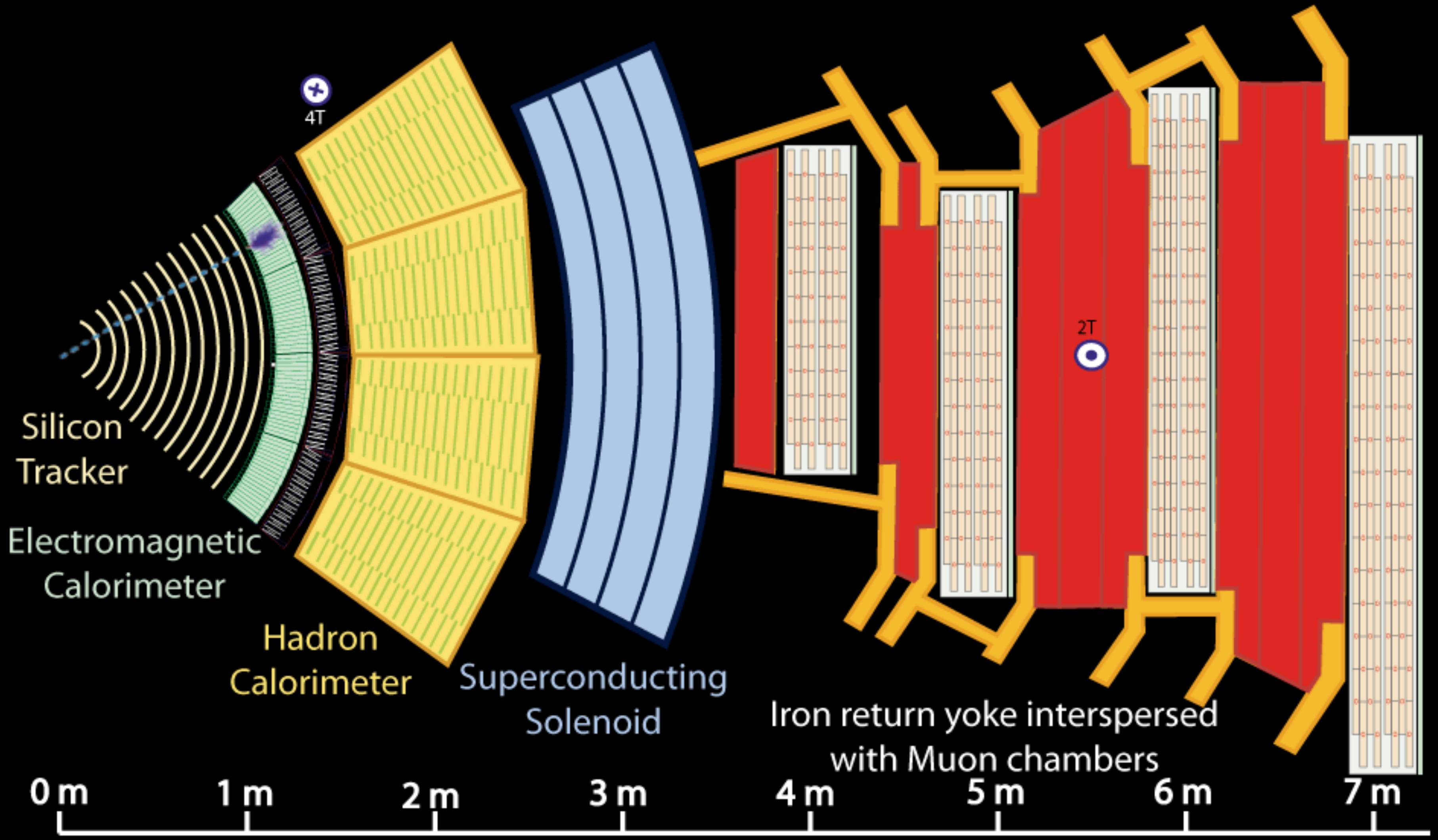
— Muon

— Electron

— Charged Hadron (e.g. Pion)

- - - Neutral Hadron (e.g. Neutron)

- - - Photon



Key:

Muon

Electron

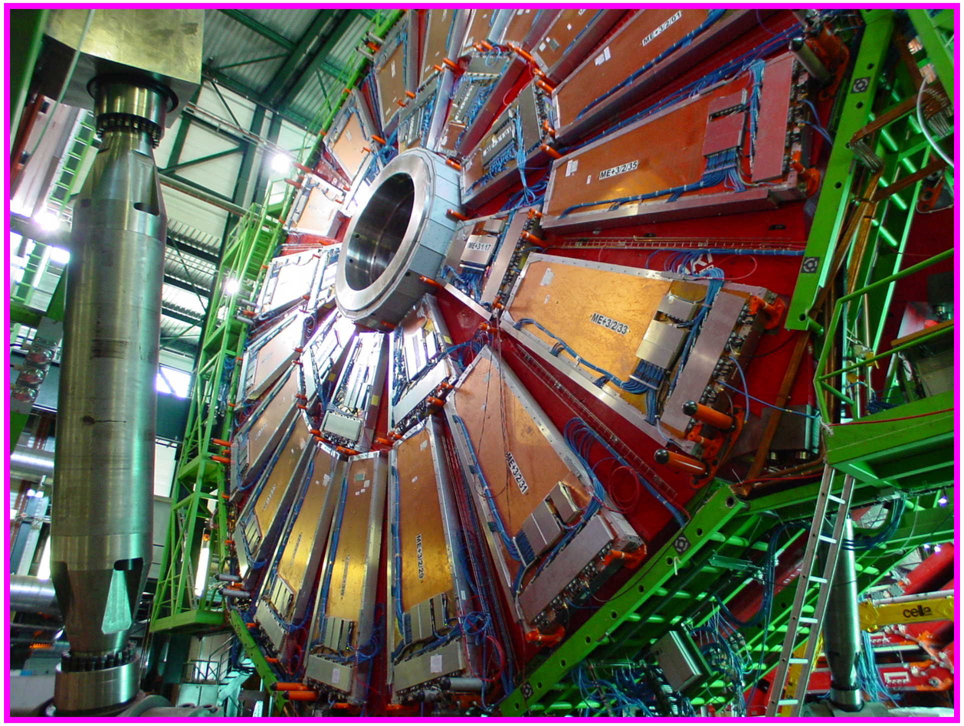
Charged Hadron (e.g. Pion)

Neutral Hadron (e.g. Neutron)

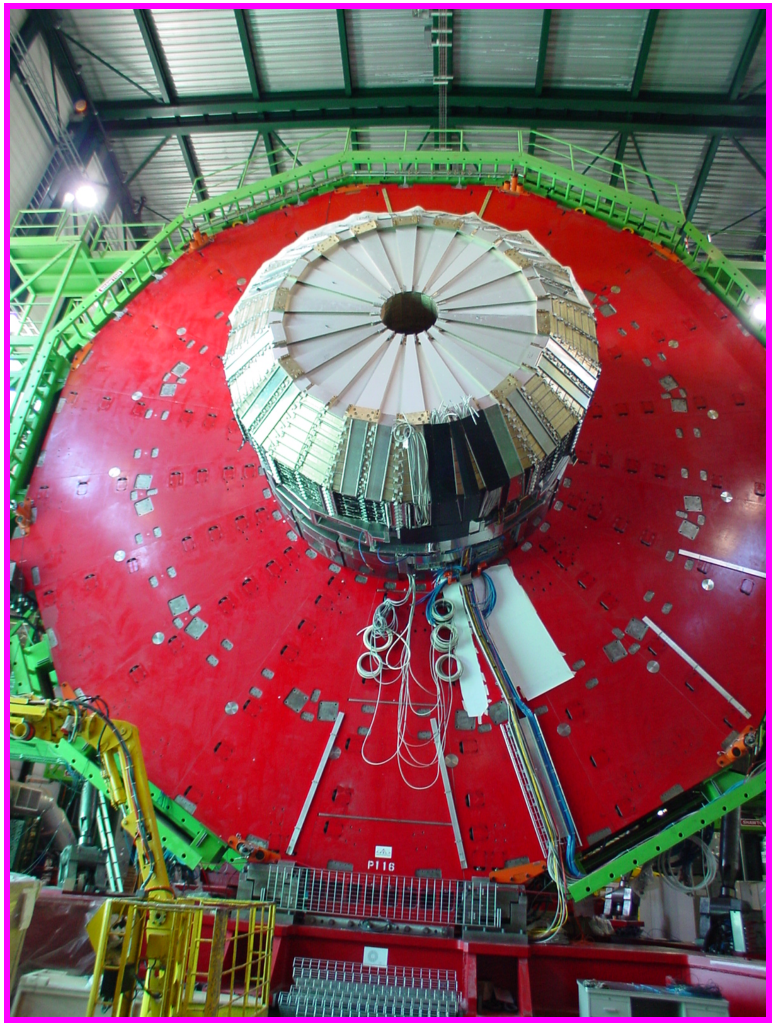
Photon

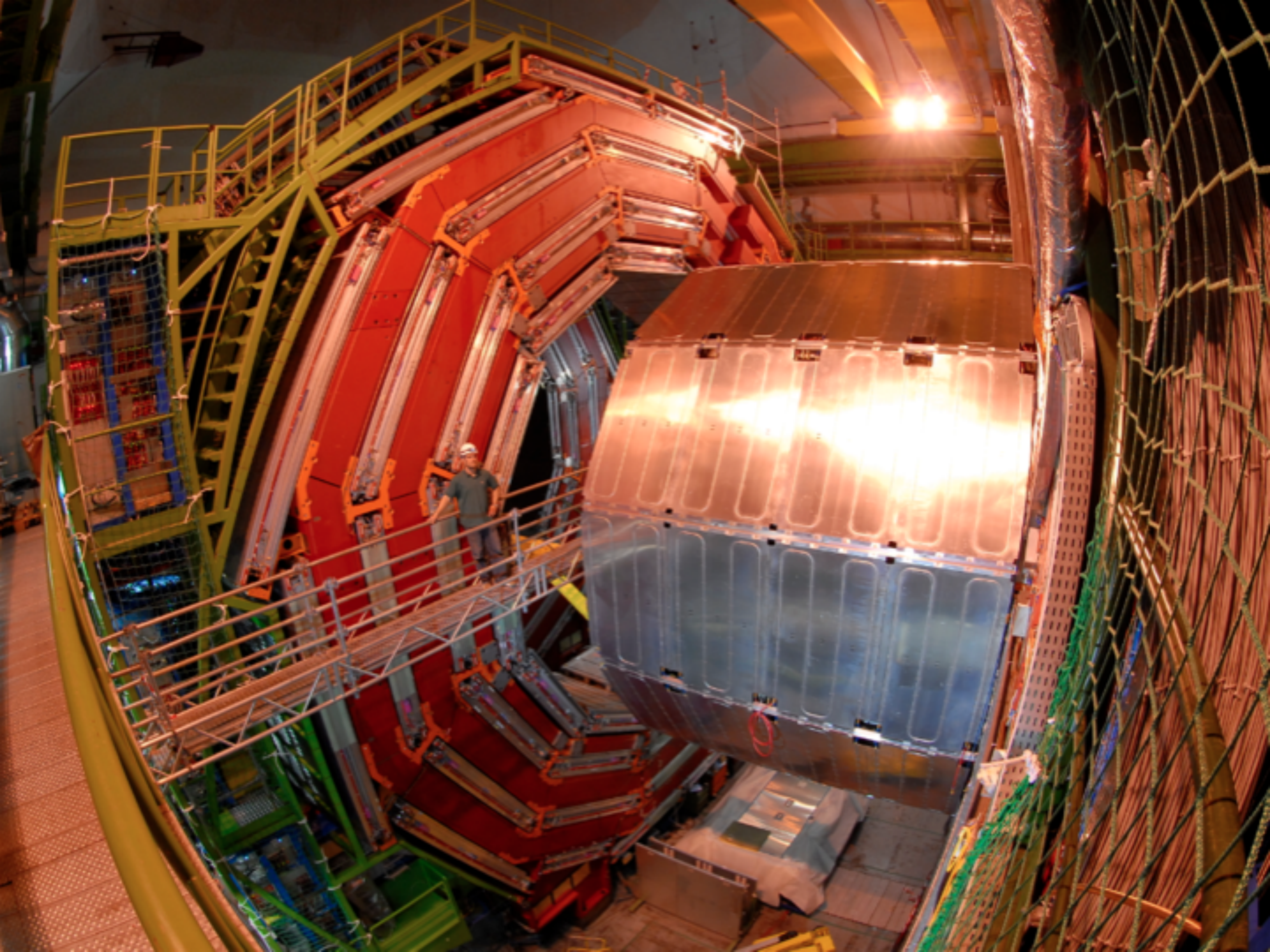
CMS

muon detector endcap

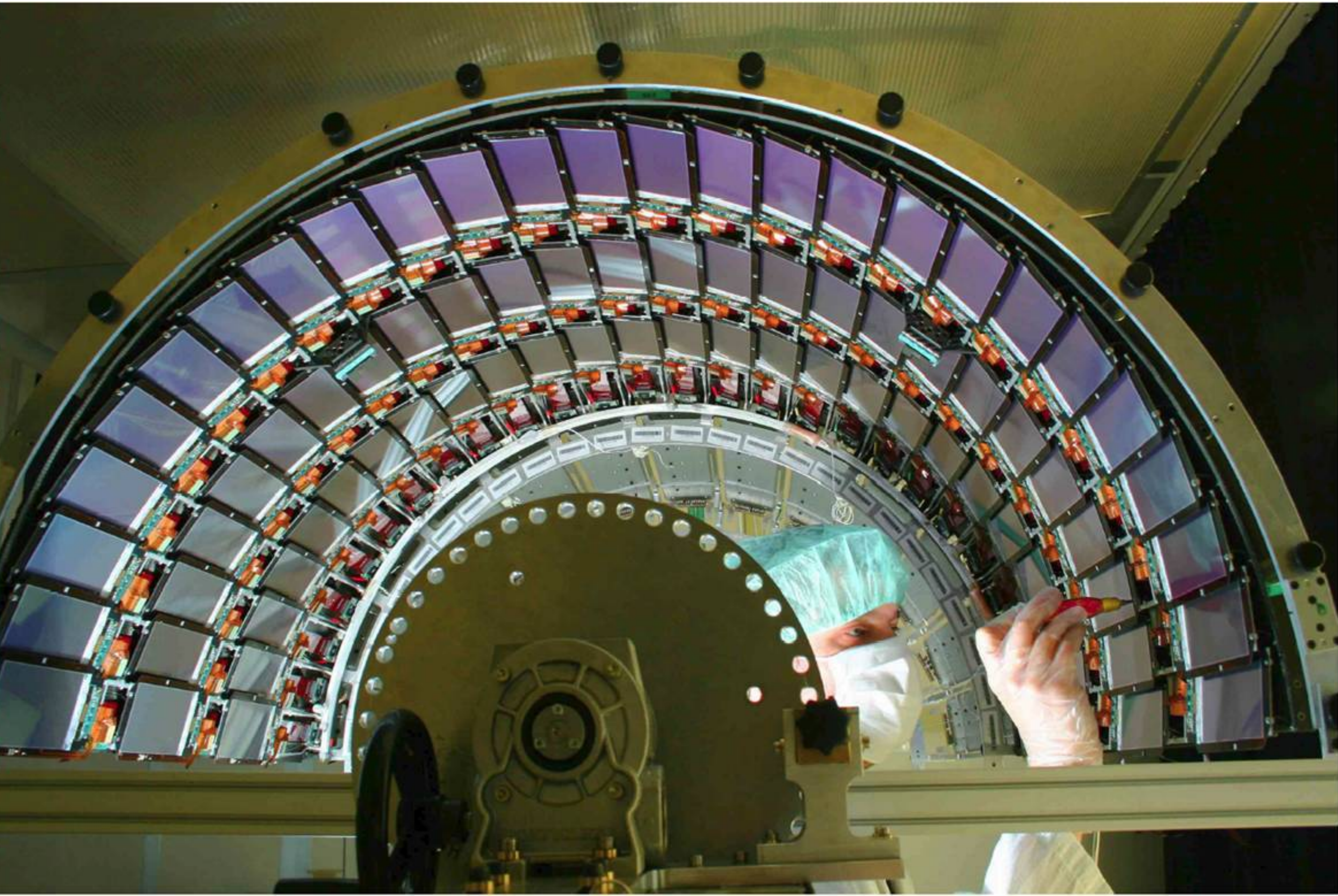


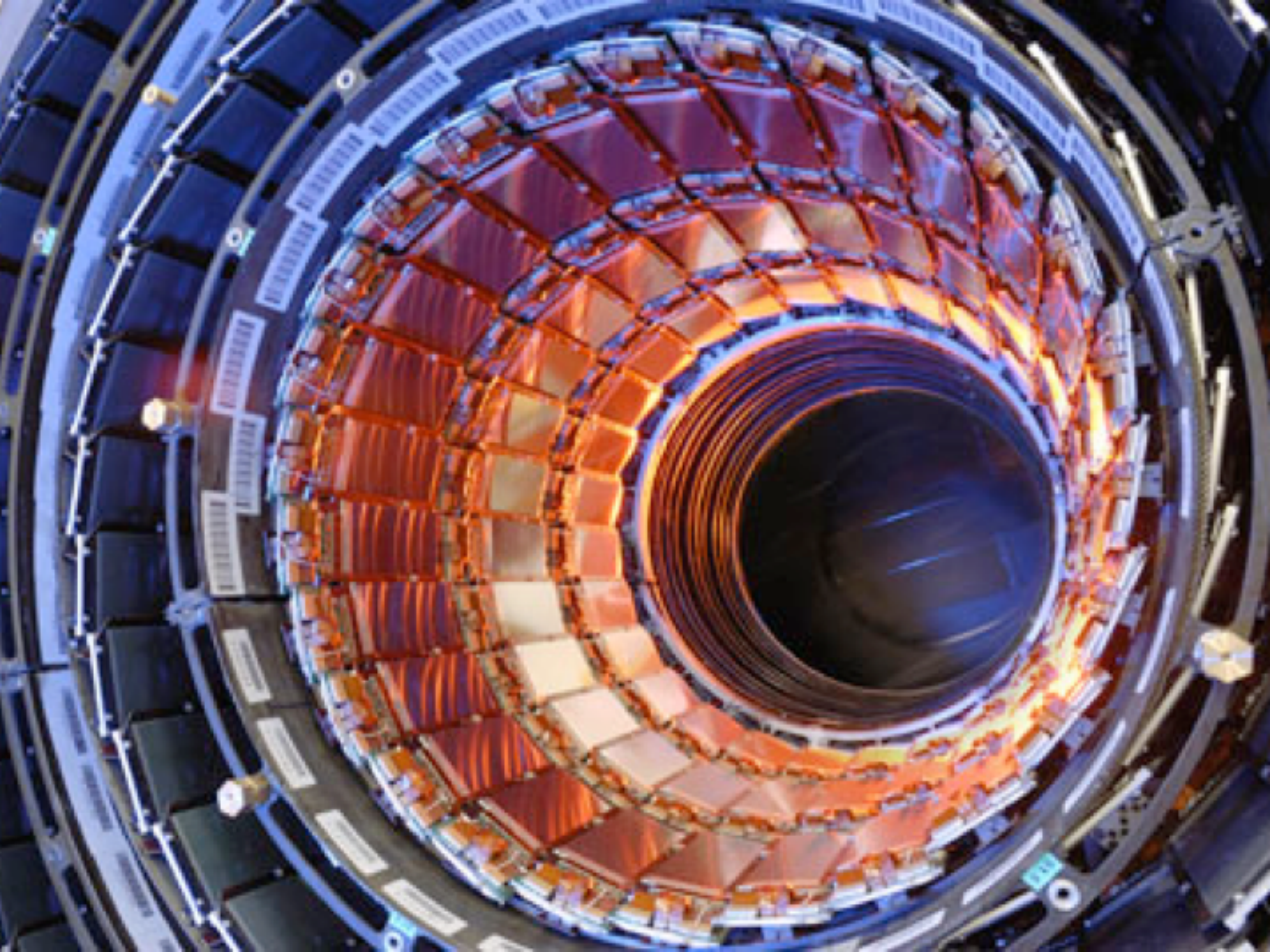
calorimeter endcap





“barrel” of the CMS silicon tracker





detectors see "messenger" particles only

- our detectors see only a few different types of particles
  - electrons, photons, muons, some mesons and baryons
  - if they are long-lived enough
    - must survive long enough to enter the detector
- can deduce "invisible" particles (such as neutrinos) from missing transverse momentum
  - use momentum conservation
  - "missing ET"
- most other particles too short-lived
  - we see only their decay products
- in normal life, we only detect photons !
  - with our eyes
  - plus sound waves, smells etc.

“prompt” versus “displaced” decays

- so far, mostly expected new particles to decay “instantaneously” to well-known Standard Model particles
  - or to be “invisible” in the detector

- now: also look for relatively long-lived particles
  - flight paths of centimeters or meters
  - because we have not seen “New Physics” with “prompt” decays

- requires different reconstruction and triggering techniques

BACKUP

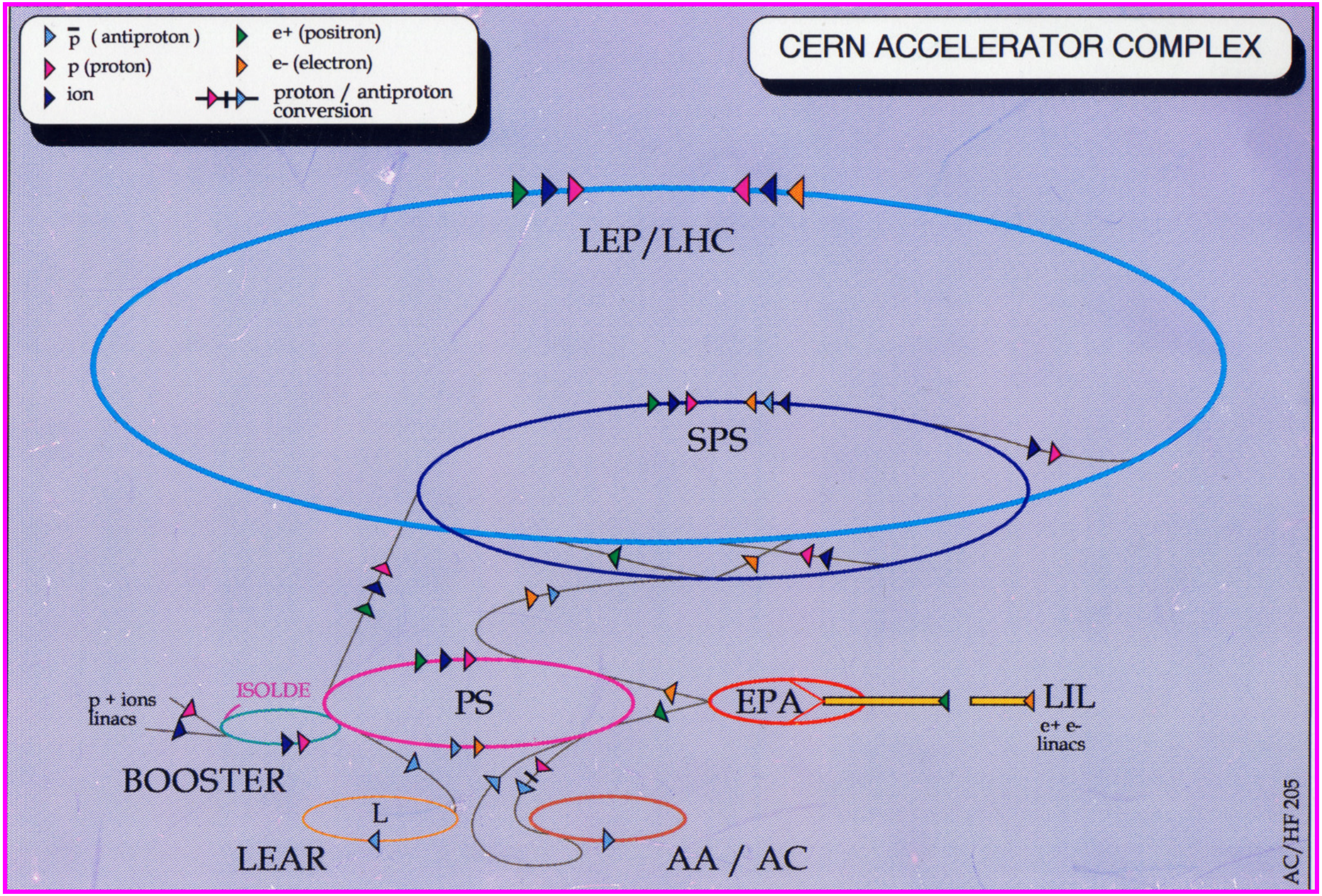
Instantaneous luminosity

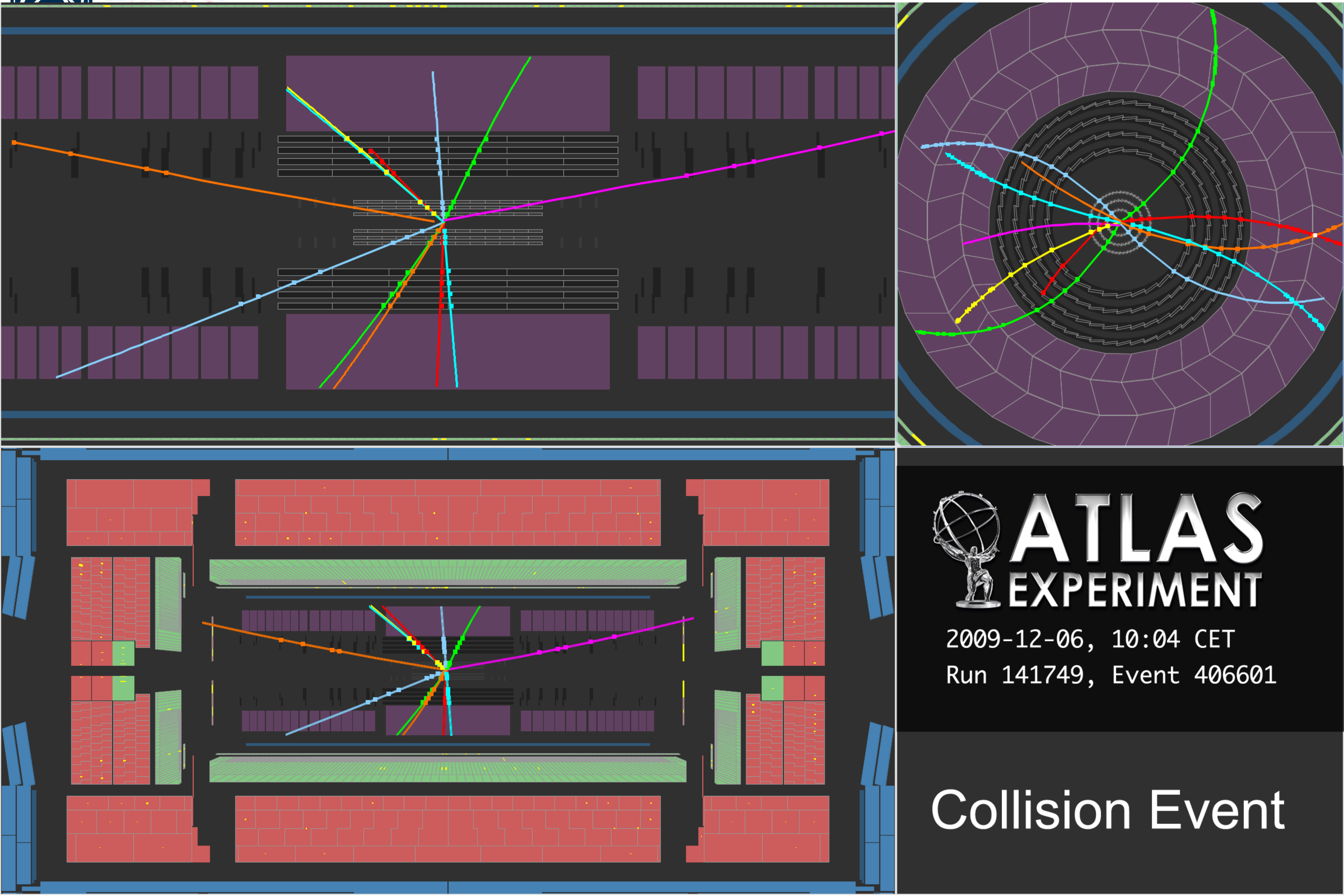
$$\boxed{L = \frac{N^2 k_b f}{4\pi\sigma_x\sigma_y} F = \frac{N^2 k_b f \gamma}{4\pi\varepsilon_n\beta^*} F}$$

- Nearly all the parameters are variable (and not independent)

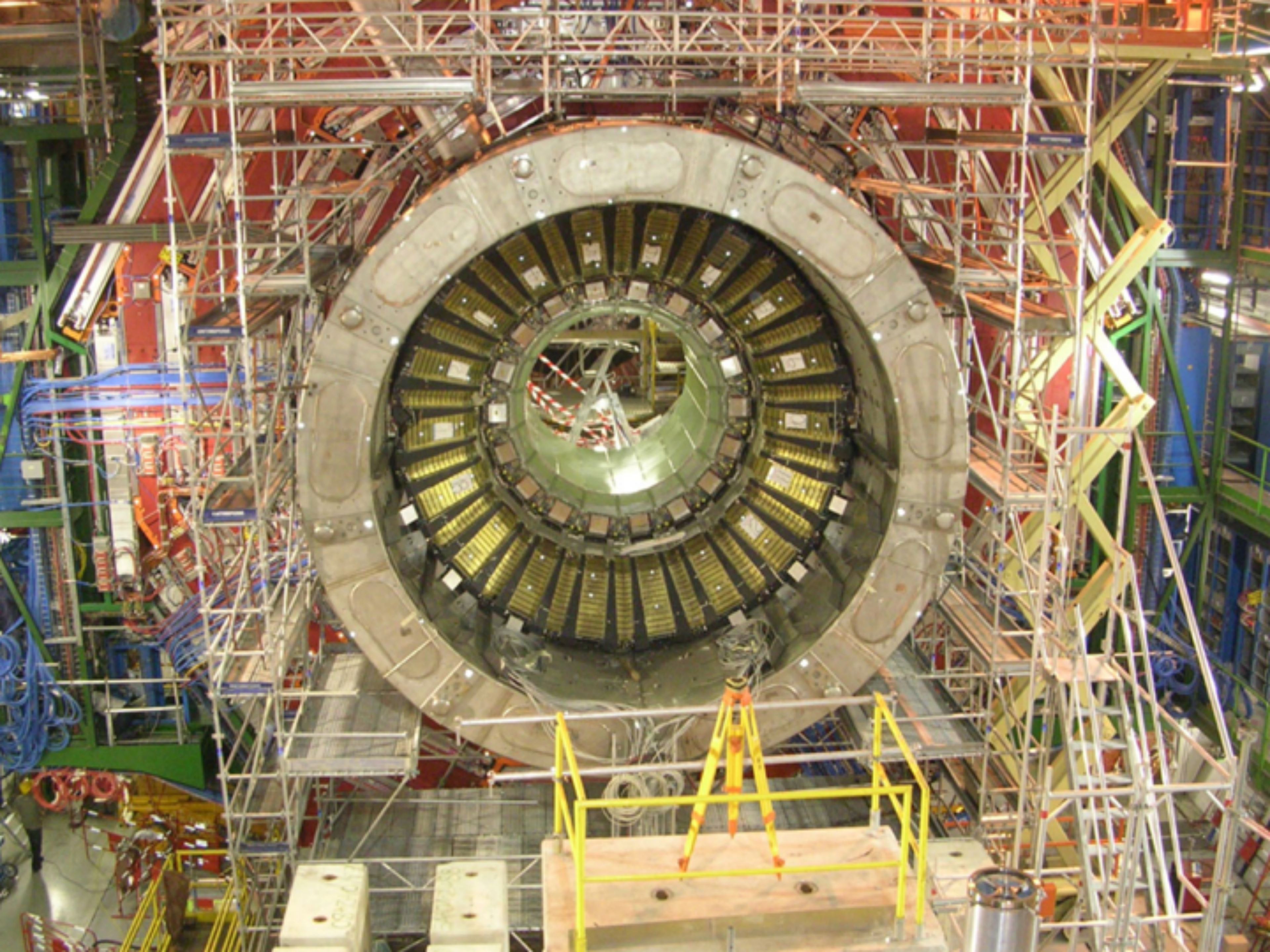
– Number of bunches per beam	k_b	Total Intensity
– Number of particles per bunch	N	Beam Brightness
– Normalized emittance	ε_n	
– Relativistic factor (E/m_0)	γ	Energy
– Beta function at the IP	β^*	Interaction Region
– Crossing angle factor	F	
• Full crossing angle	θ_c	
• Bunch length	σ_z	
• Transverse beam size at the IP	σ^*	

$$\boxed{F = 1 \Big/ \sqrt{1 + \left(\frac{\theta_c \sigma_z}{2\sigma^*}\right)^2}}$$


p̄ (antiproton)
p (proton)
ion
e+ (positron)
e- (electron)
proton / antiproton conversion
CERN ACCELERATOR COMPLEX
LEP/LHC
SPS
PS
ISOLDE
p + ions linacs
BOOSTER
EPA
LIL
e+ e- linacs
L
LEAR
AA / AC
AC/HF 205



http://atlas.web.cern.ch/Atlas/public/EVTDISPLAY/events.html



brass from Russian artillery shells

transformed into plates for the CMS hadron calorimeter