PHYSICS AT COLLIDERS

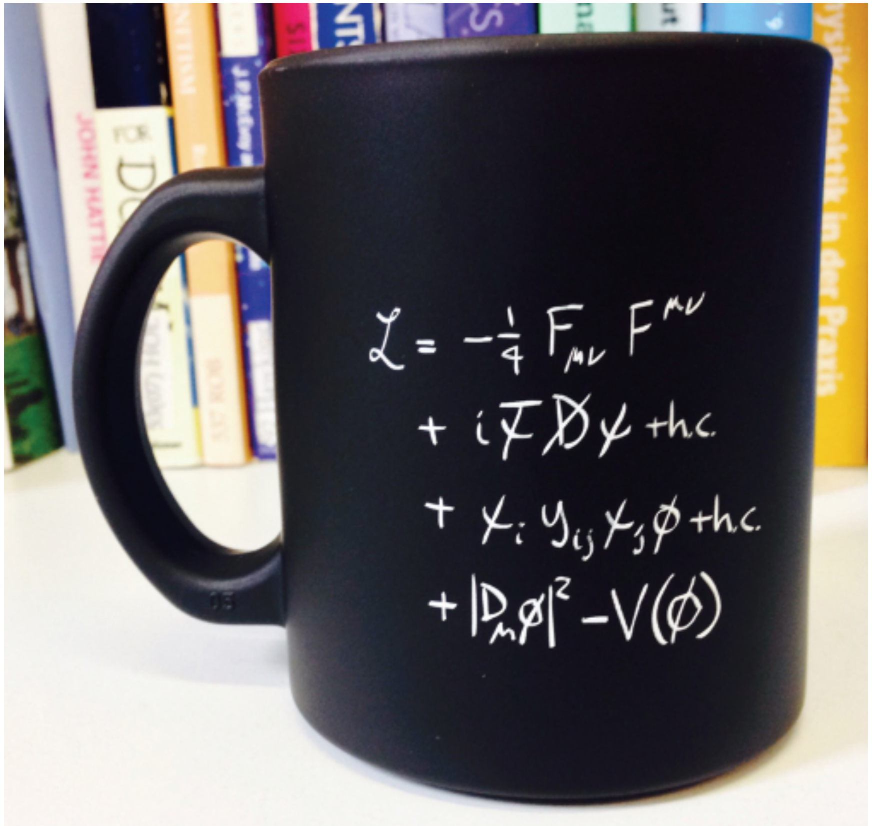
KAI SCHWEDA

OUTLINE

- The Large Electron Positron Collider (1989 - 2000)
- The Tevatron (1983 - 2011)
- The Large Hadron Collider (2009 - 2041)

  pp, p-Pb, Xe-Xe, and Pb-Pb collisions
- possible future colliders: ILC, FCC, CppC, CEPC (> 2045)

THE TRIUMPH OF THE STANDARD MODEL



source: CERN

masses and **couplings** are **free parameters** and must be **determined experimentally**, everything else follows from it

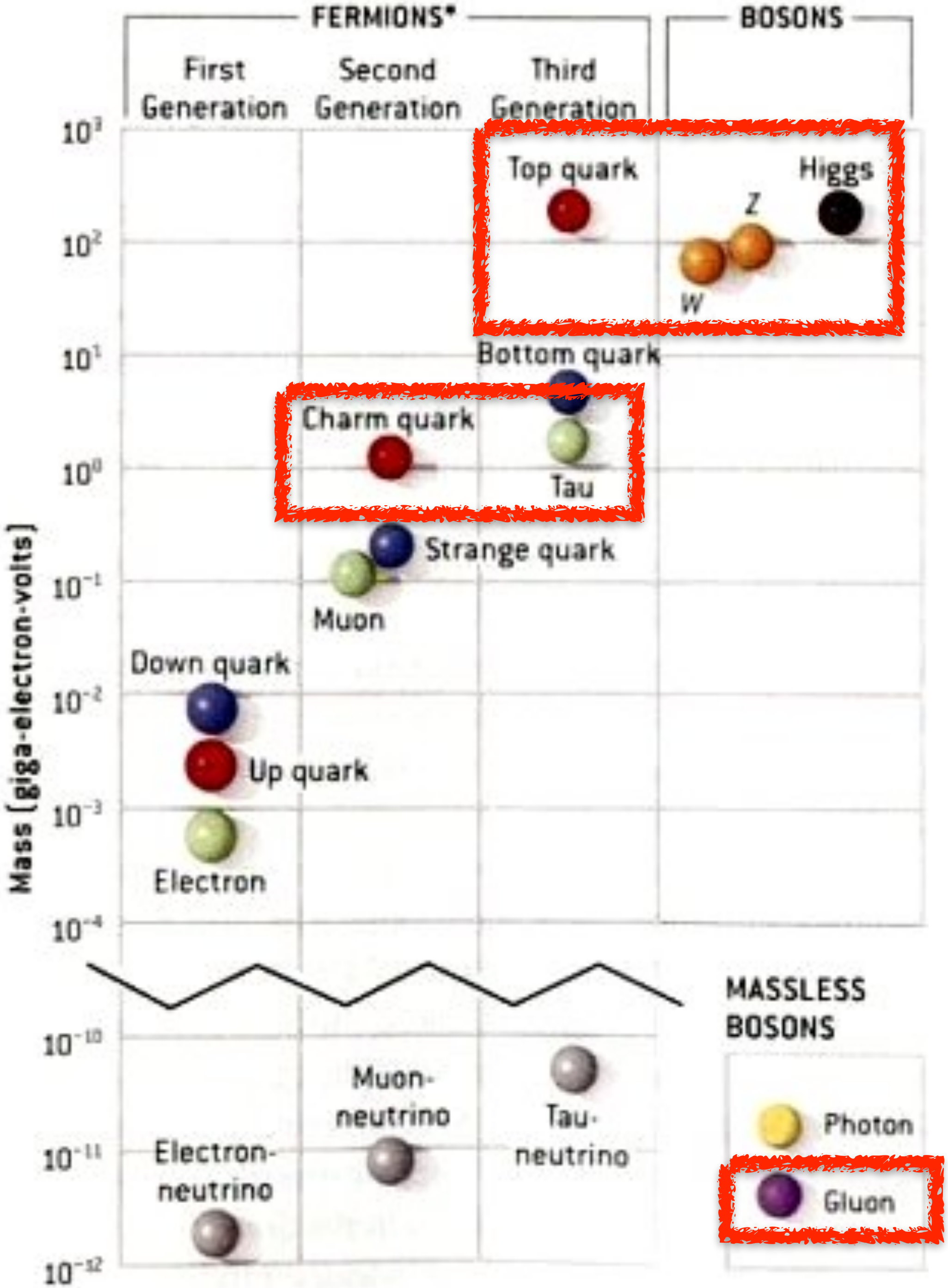
gauge sector ✅

flavor sector ✅

EWSB sector ✅

anything new?
- supersymmetry (many variants)
- extra spacetime dimensions
- compositeness

strong electroweak symmetry breaking
4th generation fermions
W’, Z’
… the unexpected



particles discovered at colliders

$\bar{p}p, pp$

e^+e^-

e^+e^-

universe-review.ca

TO COLLIDE OR NOT TO COLLIDE ?

collider*

$$
\begin{aligned}
s &= (P_1 + P_2)^2 = P_1^2 + P_2^2 + 2P_1 \cdot P_2 \\
&= m_1^2 + m_2^2 + 2(E_1 E_2 - 2p_1 \cdot p_2) \\
&= 2(E_1 E_2 + E_1 E_2) \\
&= 4E^2
\end{aligned}
$$

$$\sqrt{s} = 2E$$

fixed-target

$$
\begin{aligned}
s &= (P_1 + P_2)^2 = P_1^2 + P_2^2 + 2P_1 \cdot P_2 \\
&= m_1^2 + m_2^2 + 2(E_1 E_2 - 2p_1 \cdot p_2) \\
&= 2(E_1 m_2 - 2p_1 \cdot 0) \\
&= 2E_1 m_2
\end{aligned}
$$

$$\sqrt{s} \propto \sqrt{E}$$

At a **collider**, **all** beam **energy** is **available** in the cms system,

while at fixed target, the cms energy grows only with $\sqrt{E}$

*neglect particle masses, assume symmetric beams

ADA - THE FIRST COLLIDER EVER BUILT

Anello Di Accumulazione, Frascati National Laboratory, 250 MeV + 250 MeV, 1963 first collisions

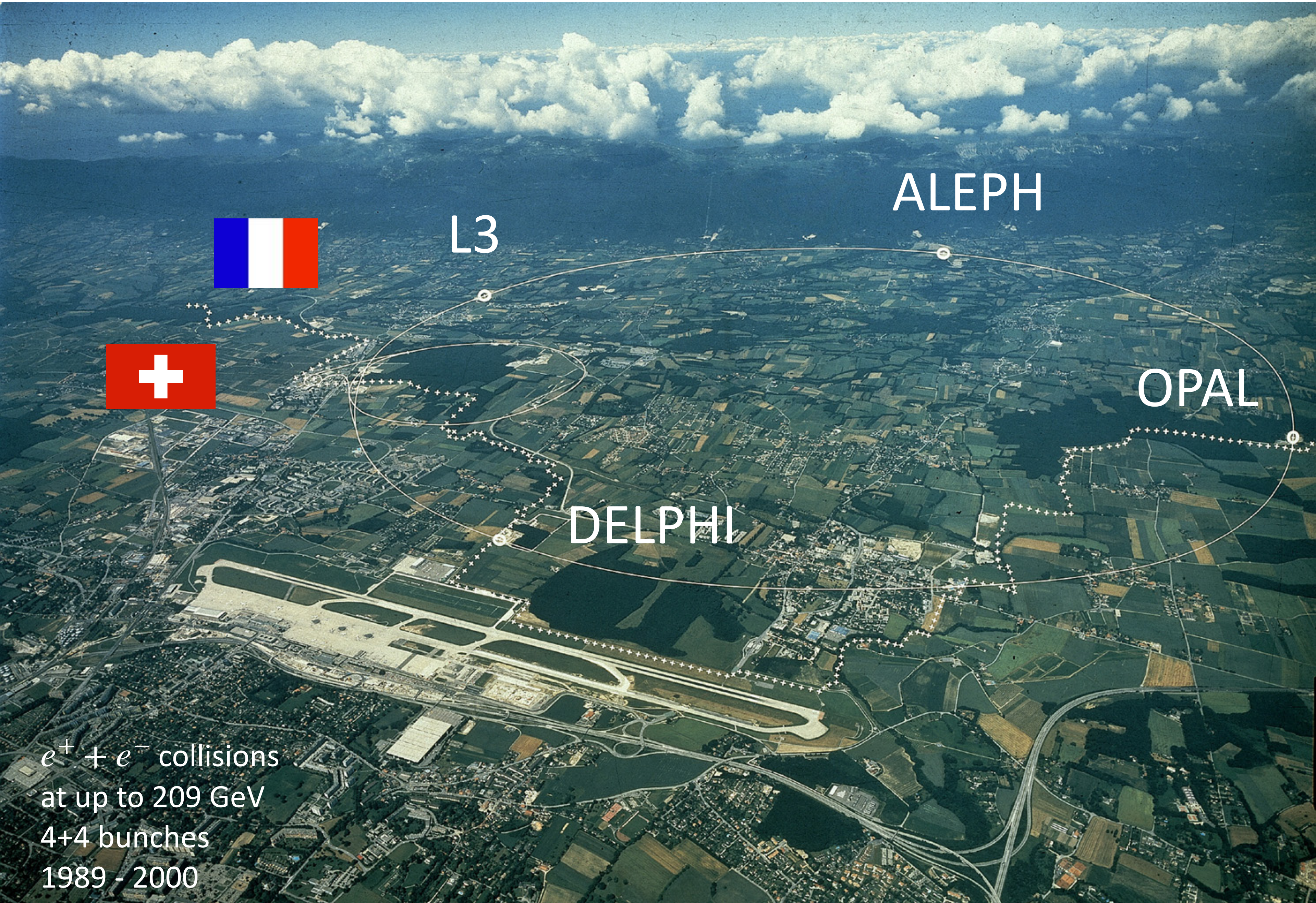
Keep **particle** and **antiparticle** in the **same machine**

discovered **Touschek effect** (intra beam scattering)

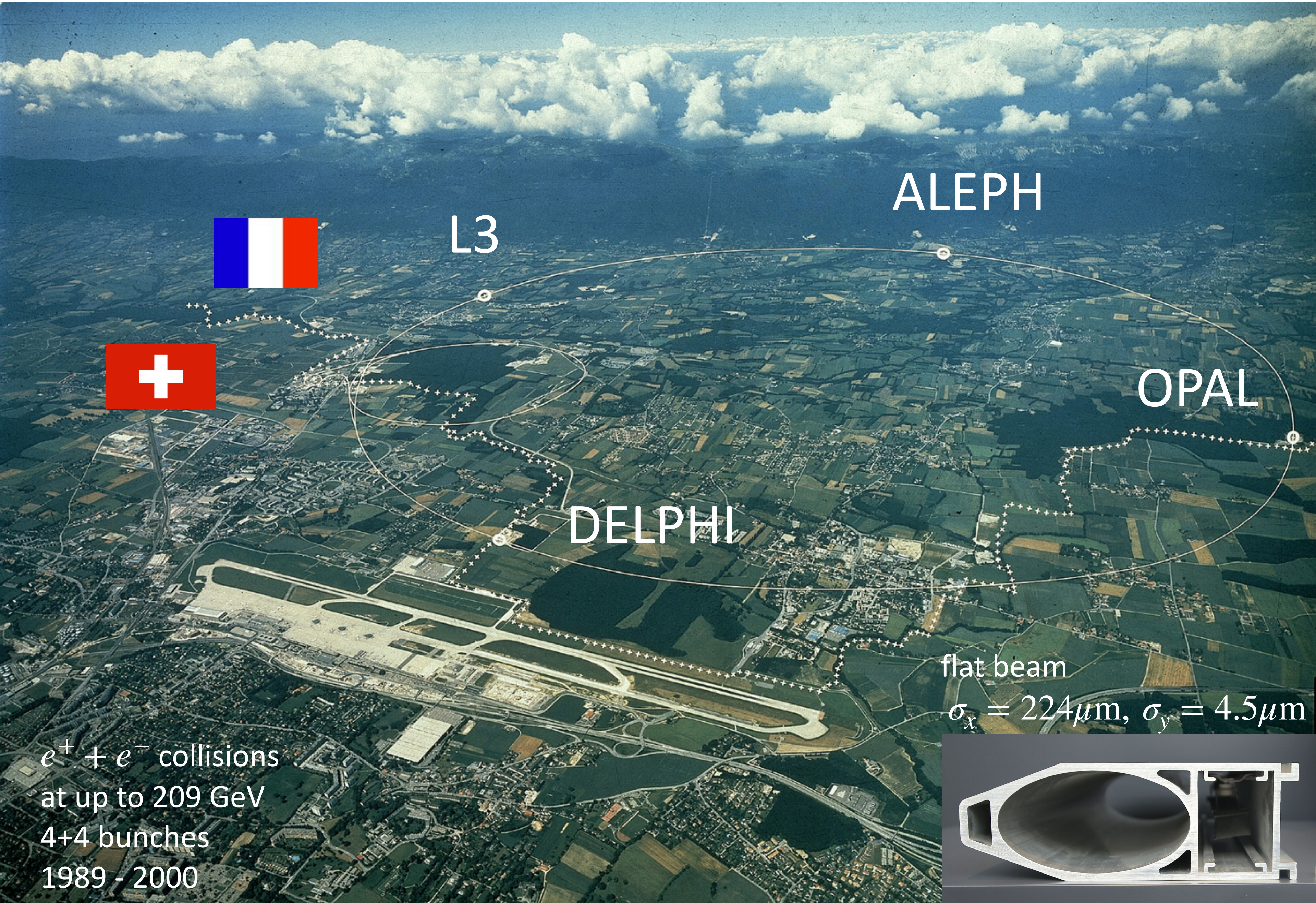
successor: ADONE (1969), 3.0 GeV collision energy, $m(J/\psi) \approx 3.097\,\mathrm{GeV}$

also: PRIN-STAN (USA), VEP-1 (Russia)

THE LARGE ELECTRON POSITRON COLLIDER AT CERN



THE LARGE ELECTRON POSITRON COLLIDER AT CERN



CIVIL ENGINEERING

Even with the reduced circumference, there was still a 3km part of the tunnel in the foothills of the Jura, which had to be blasted. After blasting 2km into the Jura, water burst into the tunnel, forming an underground river that took six months to eliminate. S. Myers.

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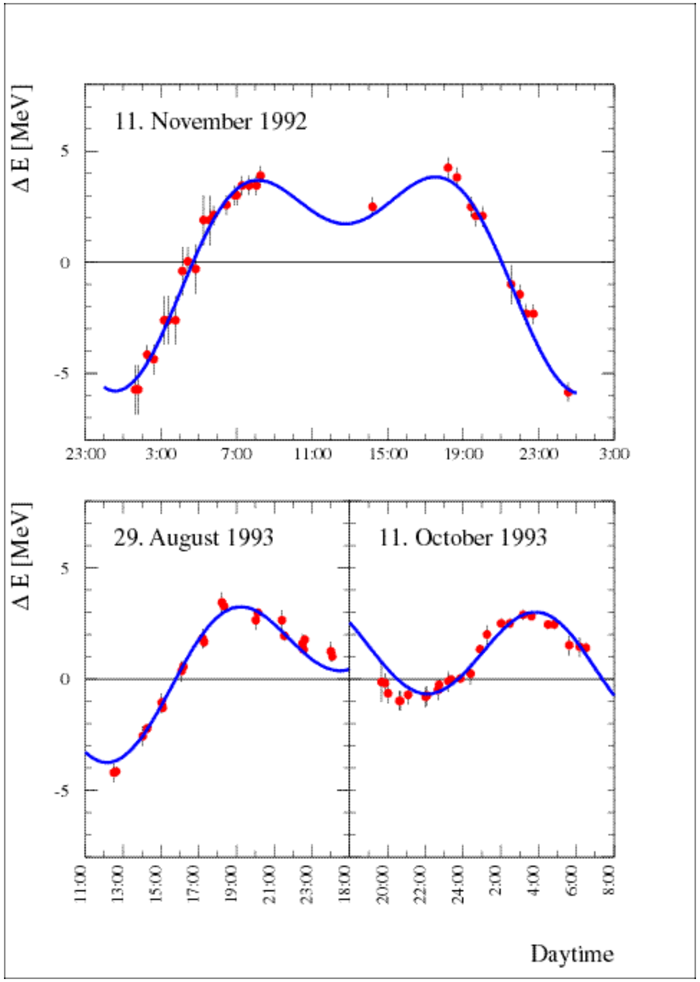
ENERGY CALIBRATION

Precise determination of the LEP beam energy **(10^{-5} relative accuracy, ~ 1 MeV)**
Precise measurement of the Z mass and width



S. Myers

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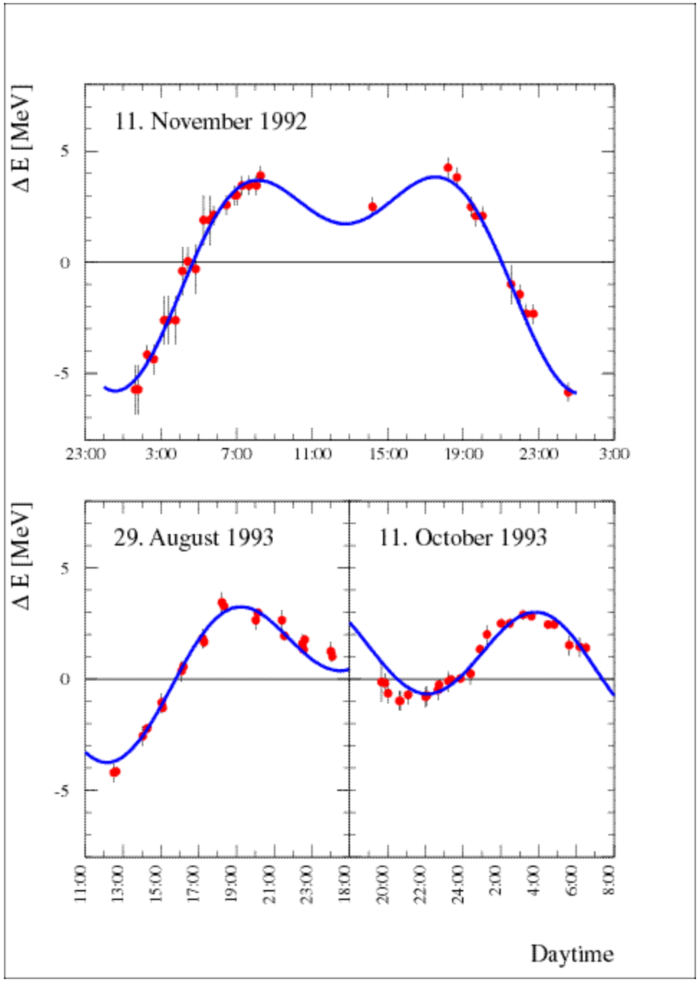
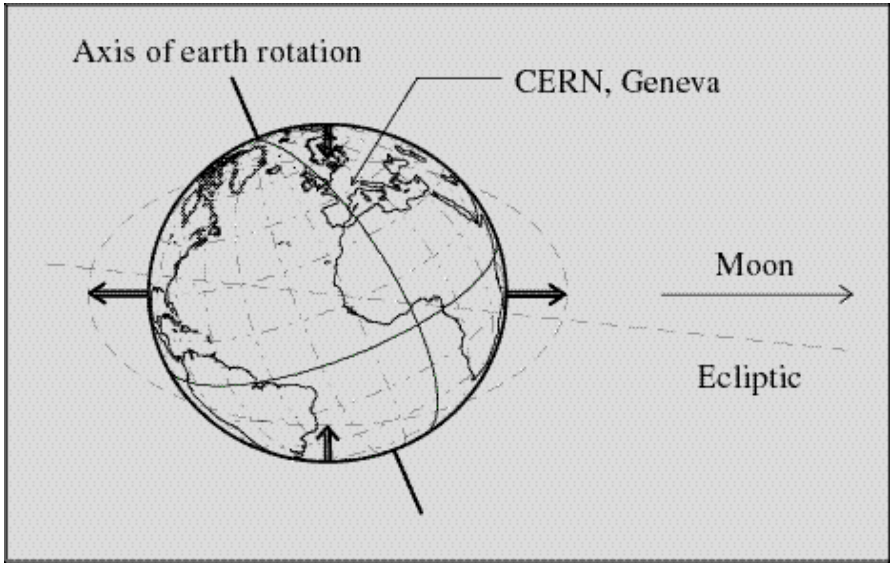
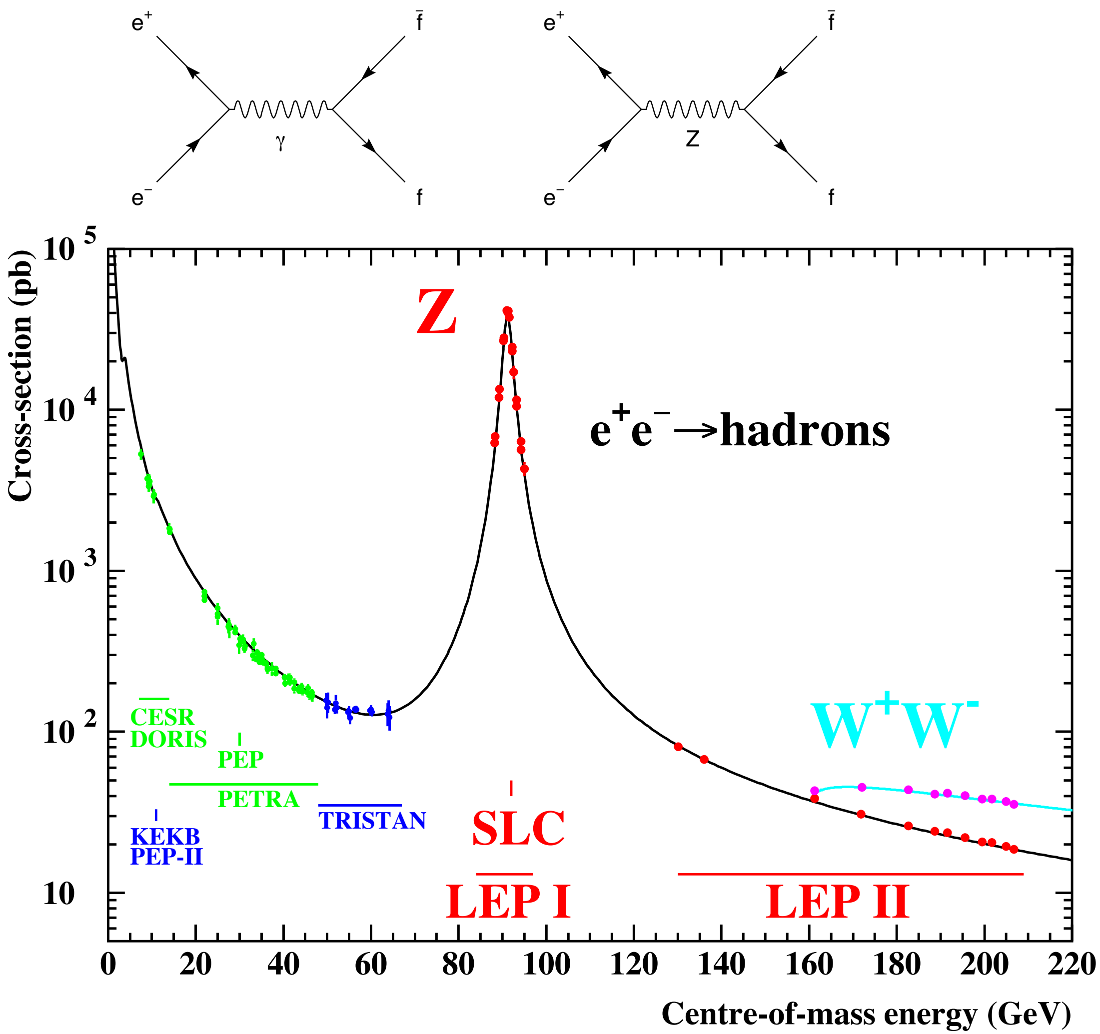




Small changes of energy accurately measured
(energy change from 1mm circumference change)

S. Myers

ELECTRON POSITRON - TOTAL CROSS SECTION



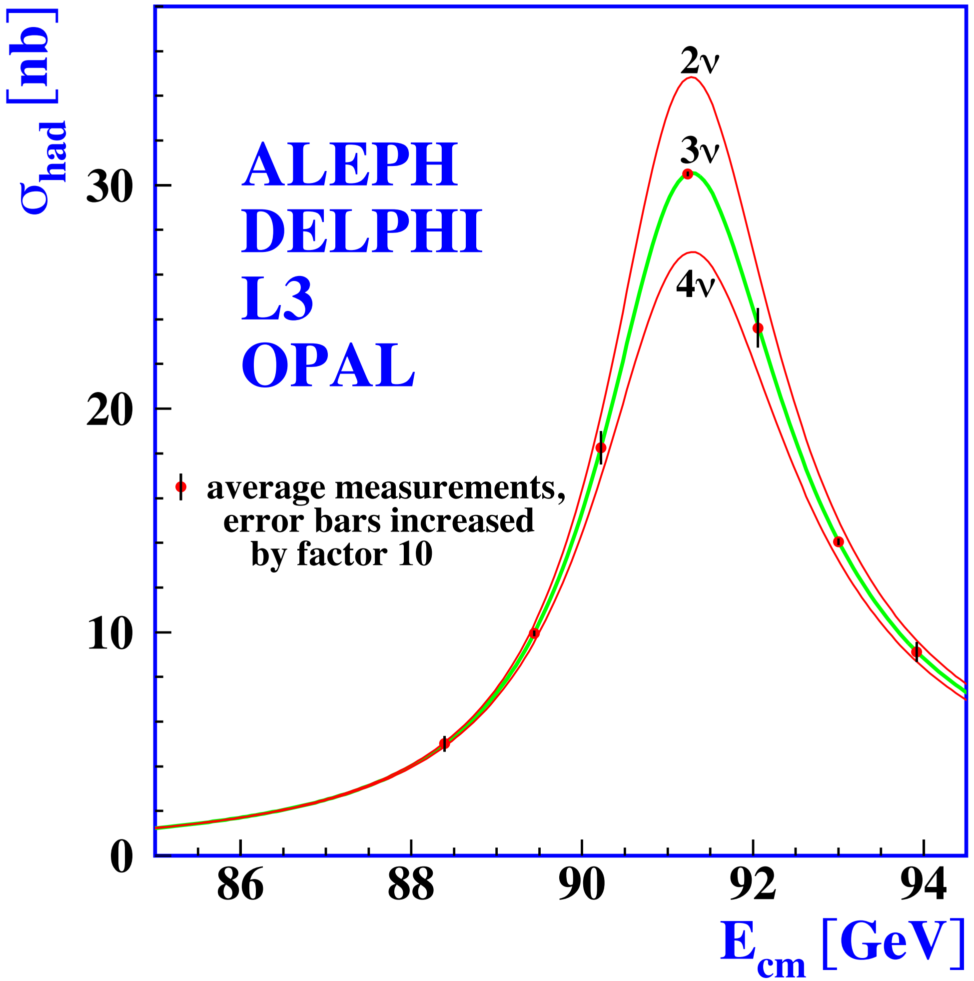
+ **higher orders & interference**

- poles at particle mass
- Z^0 boson is a dramatic resonance
- **high precision** cross section
- extremely **well described** by **theory**
- **fundamental** test of **electroweak interaction** at the **quantum level** ✅

$$M_Z = 91.1875 \pm 0.0021\,\mathrm{GeV}$$
$$\Gamma_Z = 2.4952 \pm 0.0023\,\mathrm{GeV}$$
$$\rho_l = 1.0050 \pm 0.0010$$
$$\sin^2\theta_{\mathrm{eff}}^{\mathrm{lept}} = 0.23153 \pm 0.00016$$

Phys. Repts. 427 (2006) 257.

NUMBER OF NEUTRINO FAMILIES



$$\Gamma_{tot} = \Gamma_{ee} + \Gamma_{\mu\mu} + \Gamma_{\tau\tau} + \Gamma_{qq} + N_{\nu}\Gamma_{\nu\nu}$$

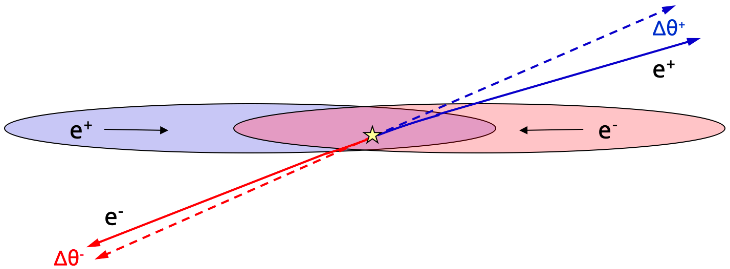
2006: $N_{\nu} = 2.9840 \pm 0.0082$

within 2-sigma equal to 3

2020: new insight in beam-beam interaction, luminosity corrected

$N_{\nu} = 2.9919 \pm 0.0081$ 1-sigma

Phys. Lett. B 800 (2020) 135068



PROTON (ANTI-)PROTON COLLIDERS

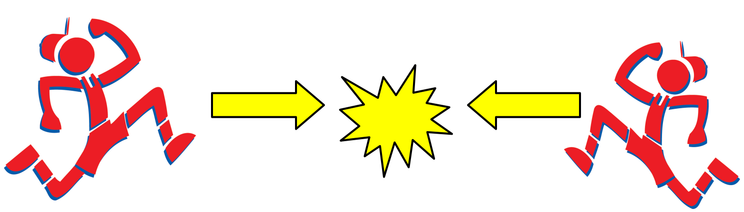
Disadvantages:

- Hadrons are complex objects
  - High multiplicity of other stuff
  - Energy and type of colliding parton (quark, gluon) unknown
    - Kinematics of events not fully constrained

Advantage:

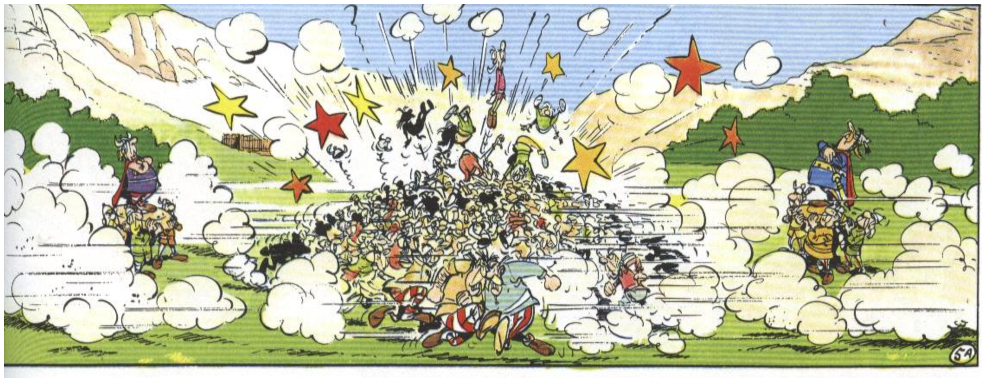
- Can access higher energies
- Do not need to precisely know new particle mass

Lepton Collider
(collision of two point-like particles)



K. Jakobs

Hadron collider
(collision of ~50 point-like particles)



It’s complicated:

Valence quarks, Gluons, Sea quarks

Exact mixture depends on:

Q^2: $\sim(M^2+p_T^2)$

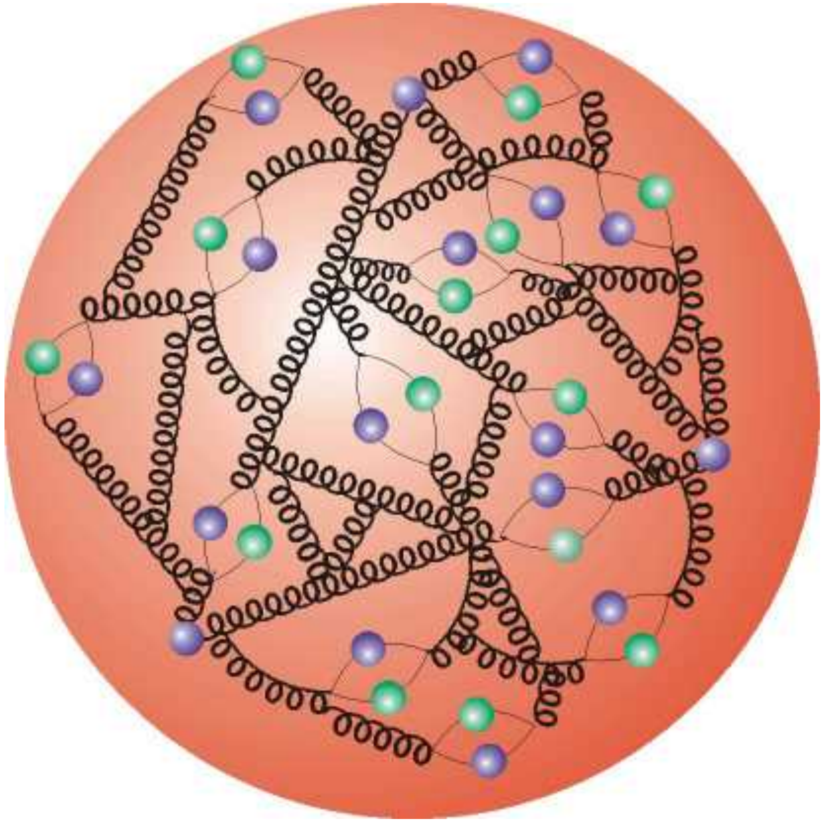
Björken-x:

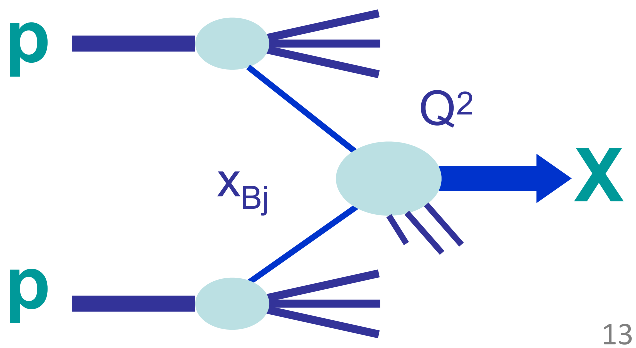
fraction or proton momentum carried by parton

Energy of parton collision:

$$\hat{s} = x_p \cdot x_{\bar{p}} \cdot s$$

$M_X = \sqrt{s}$





WHY ANTIPROTONS TO DISCOVER THE TOP QUARK?

Examples:

Higgs: M~100 GeV/c²

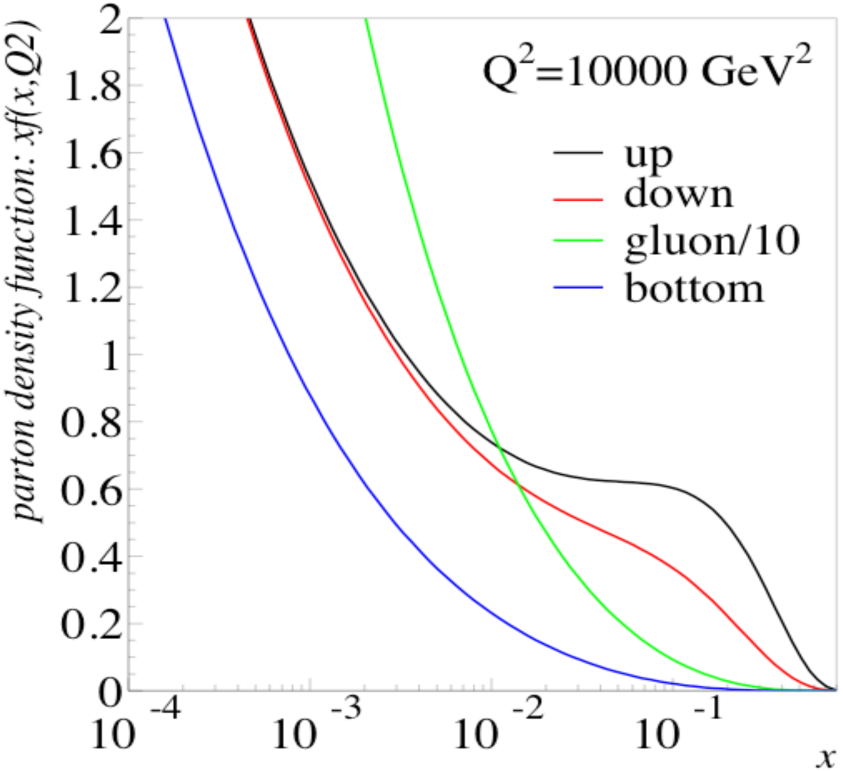
LHC: $<x_p>=100/14000\approx0.007$

TeV: $<x_p>=100/2000\approx0.05$

Gluino: M~1000 GeV/c²

LHC: $<x_p>=1000/14000\approx0.07$

TeV: $<x_p>=1000/2000\approx0.5$



Parton densities rise dramatically towards low x

Results in larger cross sections for LHC

LHC
proton-proton
Collider
7 TeV/c in the
LEP tunnel

LHC also collides nuclei, e.g. Pb + Pb at up to 2.6 TeV/c per nucleon

LHC 7 TeV:

$\beta_{\text{beam}} = c$ -10 km/h

Geiger and Marsden
1 MeV/nucleon

$\beta_{\text{beam}} = 0.05\ c$

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RF CAVITIES

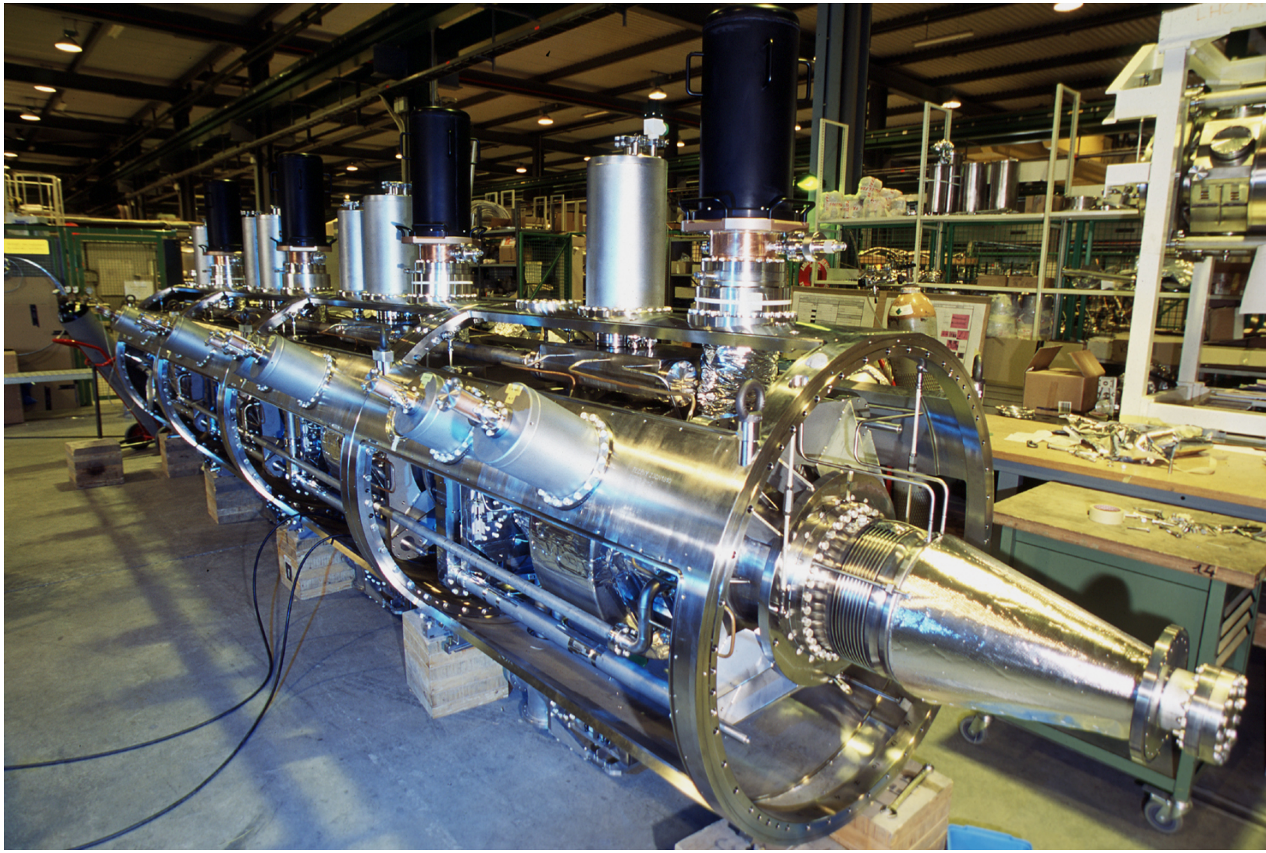
400 MHz system:

16 sc cavities (copper sputtered with niobium) for 16 MV/beam were built and assembled in four modules

Revolution frequency:

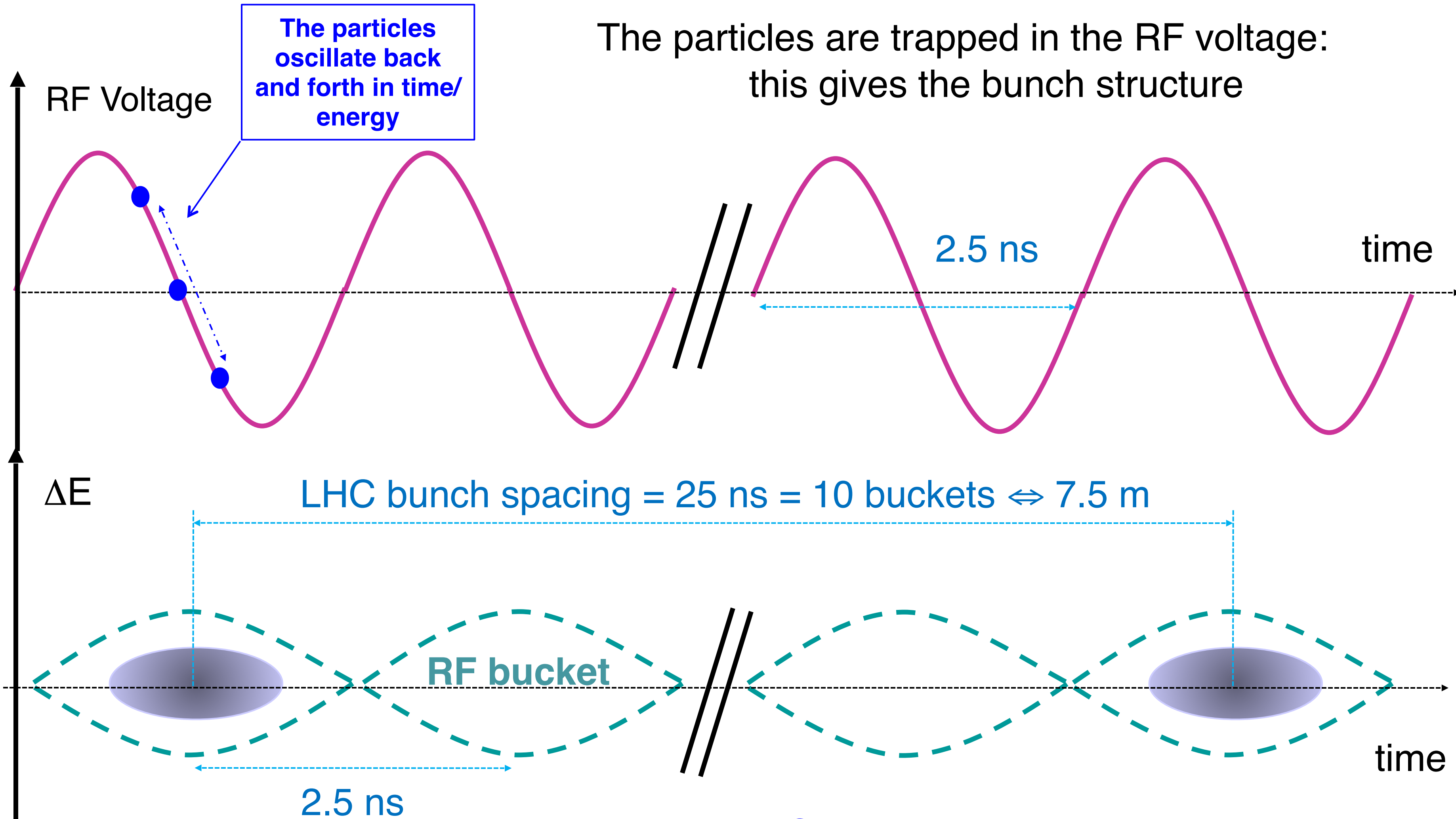
c / 26.8 km = 11246 Hz

Time varying field, up to 20 MV/m



RF BUCKETS AND BUNCHES

The particles are trapped in the RF voltage: this gives the bunch structure



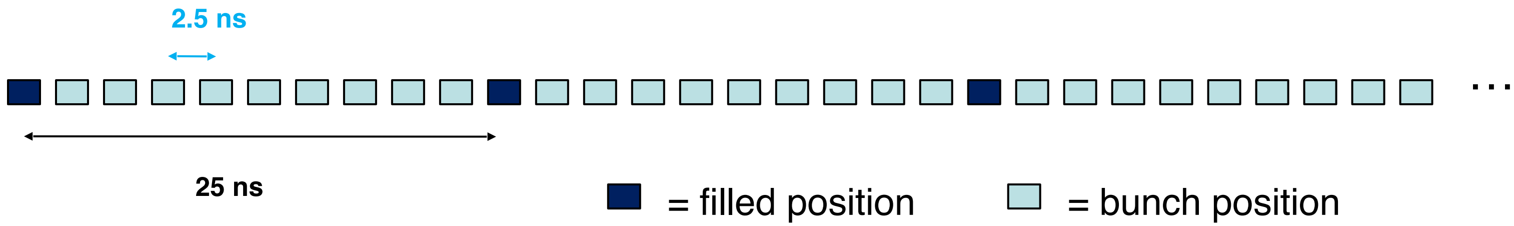
	450 GeV	3.5 TeV
RMS bunch length	12.8 cm	5.8 cm
RMS energy spread	0.031%	0.02%

COLLISION SCHEMES

The 400 MHz RF system provides **35'640 possible bunch positions** (buckets) at a distance of 2.5 ns along the LHC circumference.

A priori any of those positions could be filled with a bunch…

The smallest bunch-to-bunch distance is fixed to 25 ns, which is also the nominal distance: ***max. number of bunches is 3564***.



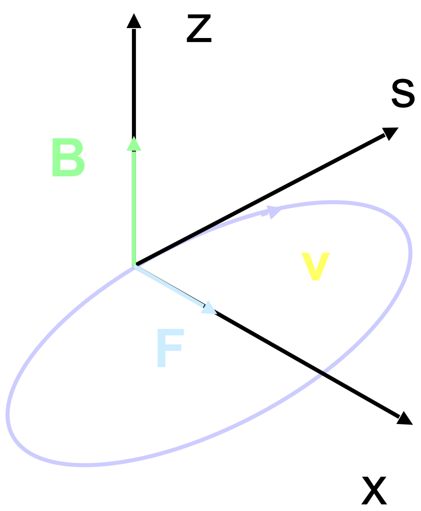
In practice there are fewer bunches because holes must be provided for the fast pulsed magnets (kickers) used for injection and dump.

But the LHC and its injectors are very flexible and can operate with many bunch patterns: ***from isolated bunches to trains***.

PARTICLE DEFLECTION: LORENTZ FORCE

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

$$B = \frac{p}{e_0 \cdot R}$$



Maximum momentum 7000 GeV/c

Bending radius 2805 m fixed by LEP tunnel

Magnetic field B = 8.33 Tesla

Iron magnets limited to 2 Tesla, therefore superconducting magnets are required

Deflecting magnetic fields for two beams in opposite directions

SYNCHROTRON RADIATION

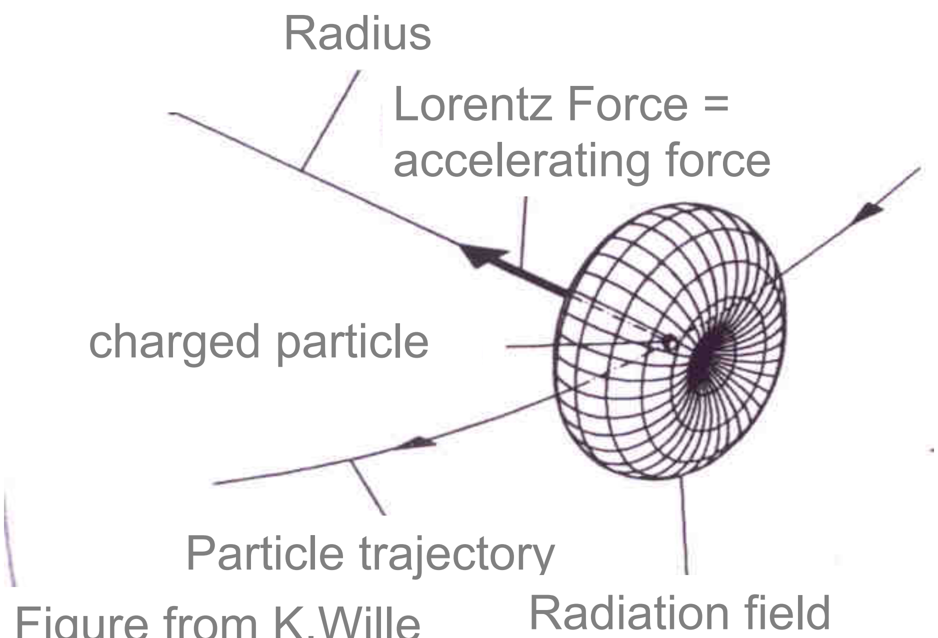


Figure from K.Wille

Power emitted for one particle: $P_s = \frac{e_0^2 \cdot c}{6 \cdot \pi \cdot \varepsilon_0 \cdot \left(m_0 \cdot c^2\right)^4} \cdot \frac{E^4}{\rho^2}$

with E = energy, m_0 = rest mass, e_0 = charge, and ρ = radius

ENERGY LOSS DUE TO SYNCHROTRON RADIATION

$E_{lep} := 100GeV$

$E_{lhc} := 7000GeV$

Energy loss for one particle per turn:

$U_{lep} = 3.844 \times 10^{9}\ eV$

$U_{lhc} = 8.121 \times 10^{3}\ eV$

Total power of synchrotronradiation:

Number of electrons in LEP: $N_{lep} := 10^{12}$

Number of protons in LHC $N_{lhc} := 10^{14}$

$P_{total\_lep} := N_{lep} \cdot P_{lep}$

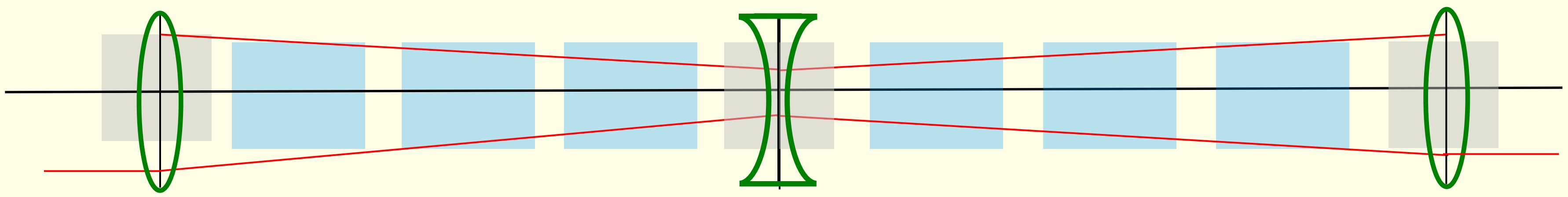
$P_{total\_lhc} := N_{lhc} \cdot P_{lhc}$

$P_{total\_lep} = 1.278 \times 10^{7}\ W$

$P_{total\_lhc} = 2.699 \times 10^{3}\ W$

The power of the synchrotronradiation emitted at the LHC is very small, but the radiation goes into the supraconducting magnets at 1.9 K ... 20 K

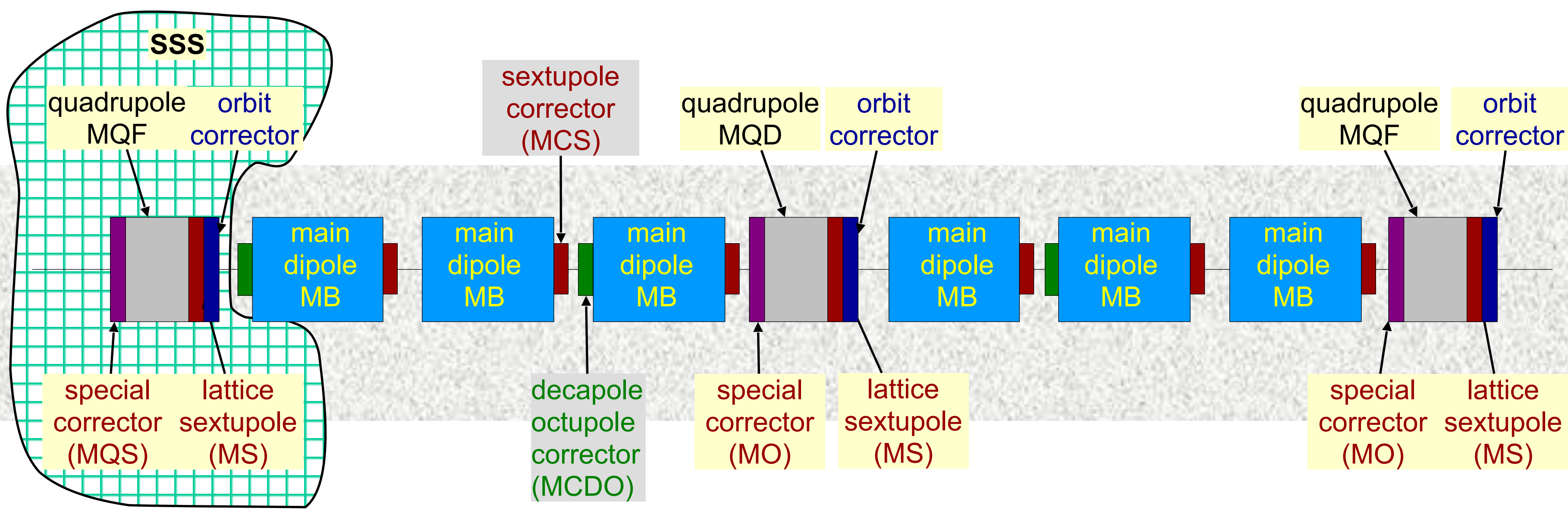
A CELL IN THE LHC ARCS

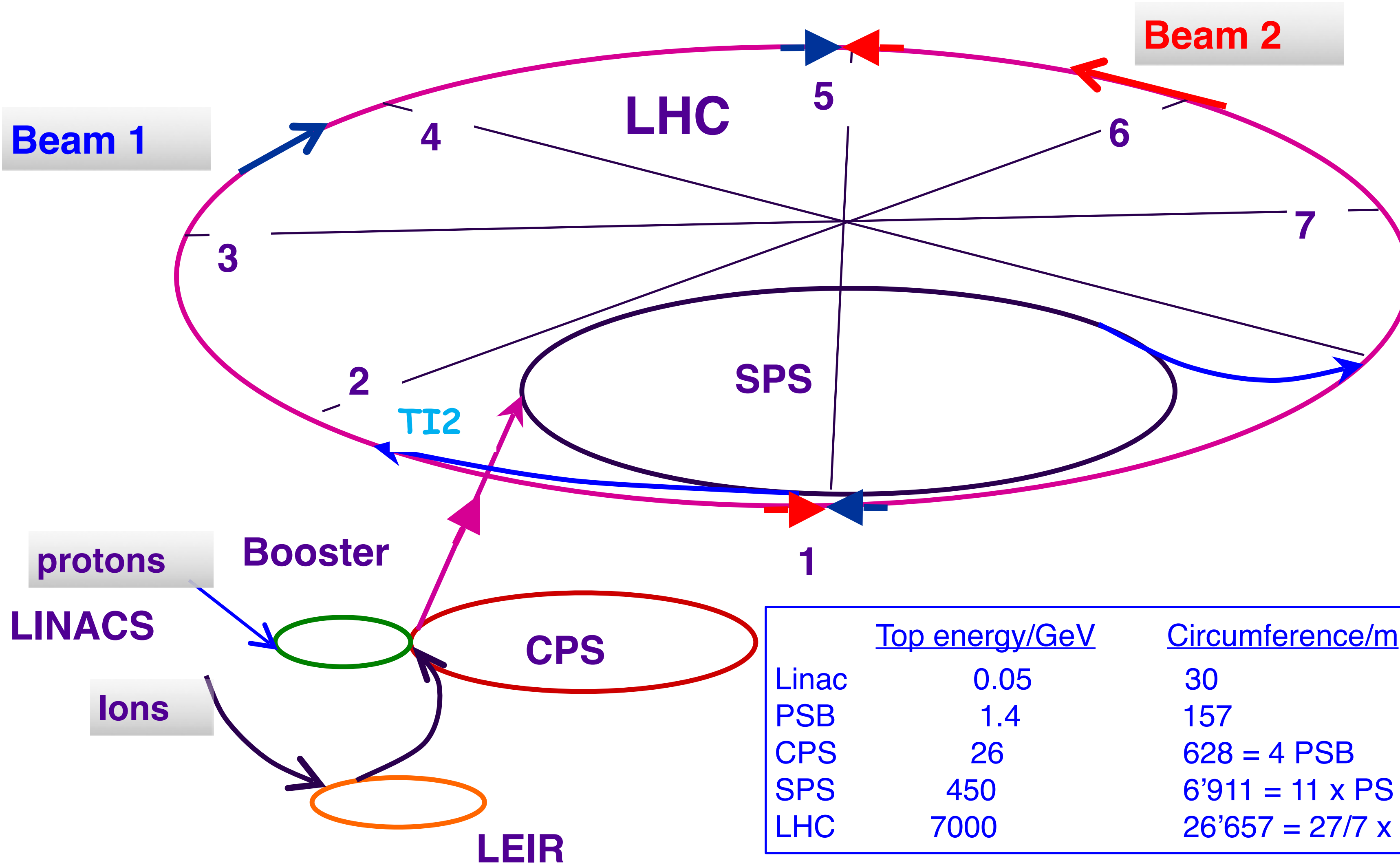


Vertical / Horizontal plane
(QF / QD)

Quadrupole magnets controlling the beam size „to keep protons together“ (similar to optical lenses)

LHC Cell - Length about 110 m (schematic layout)





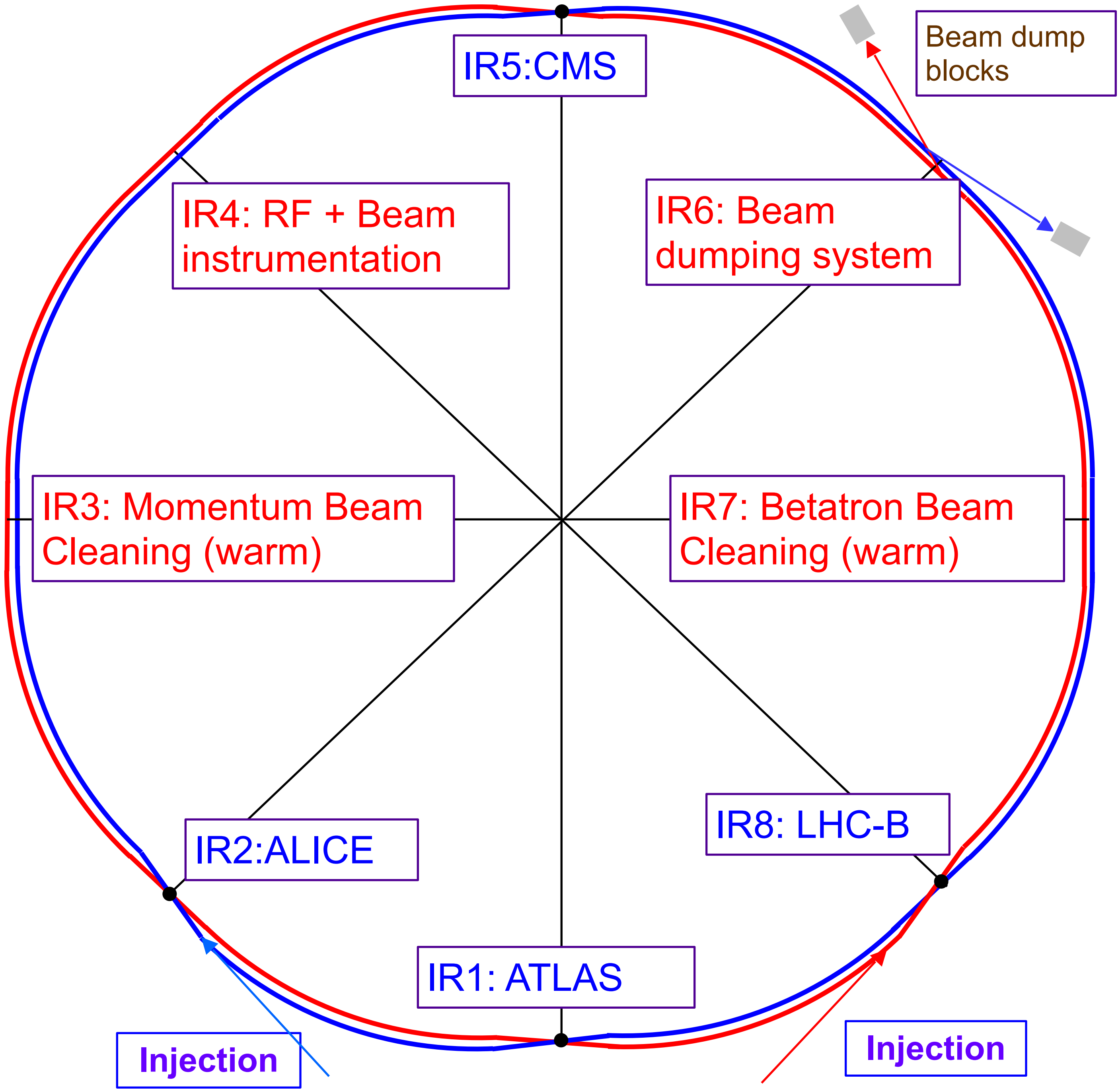
	Top energy/GeV	Circumference/m
Linac	0.05	30
PSB	1.4	157
CPS	26	628 = 4 PSB
SPS	450	6’911 = 11 x PS
LHC	7000	26’657 = 27/7 x SPS

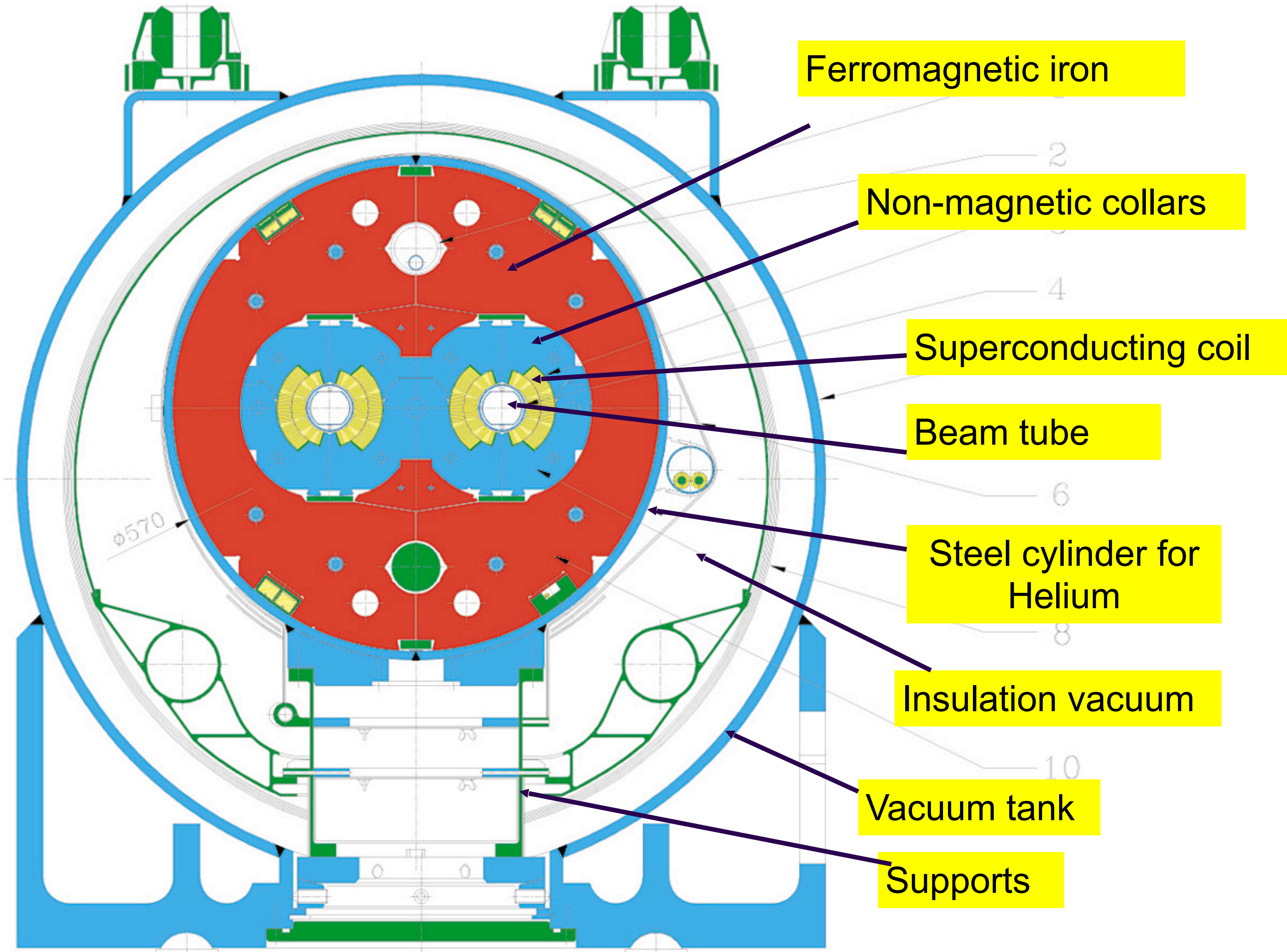
Note the energy gain/machine of 10 to 20.
The gain is typical for the useful range of magnets.

- **LHC Layout**

- eight sectors
- eight arcs

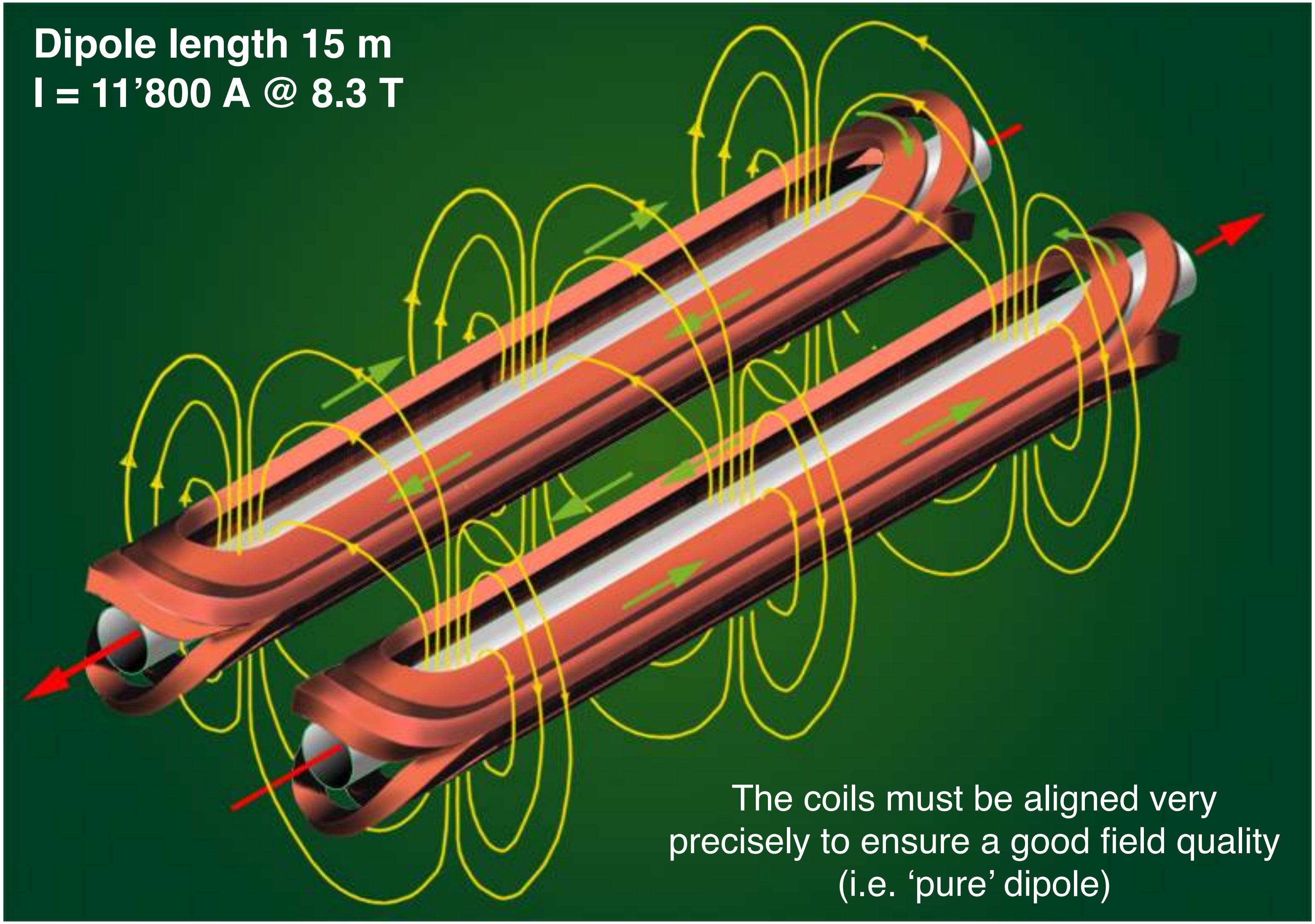
- eight long straight sections (insertions) about 700 m long
- The beams exchange their positions (inside/ outside) in 4 points to ensure that both
  - Main dipole magnets: making the circle





Weight (magnet + cryostat) ~ 30 tons, length 15 m

COILS FOR DIPOLMAGNETS



FIRST CRYODIPOLE LOWERED ON 7 MARCH 2005

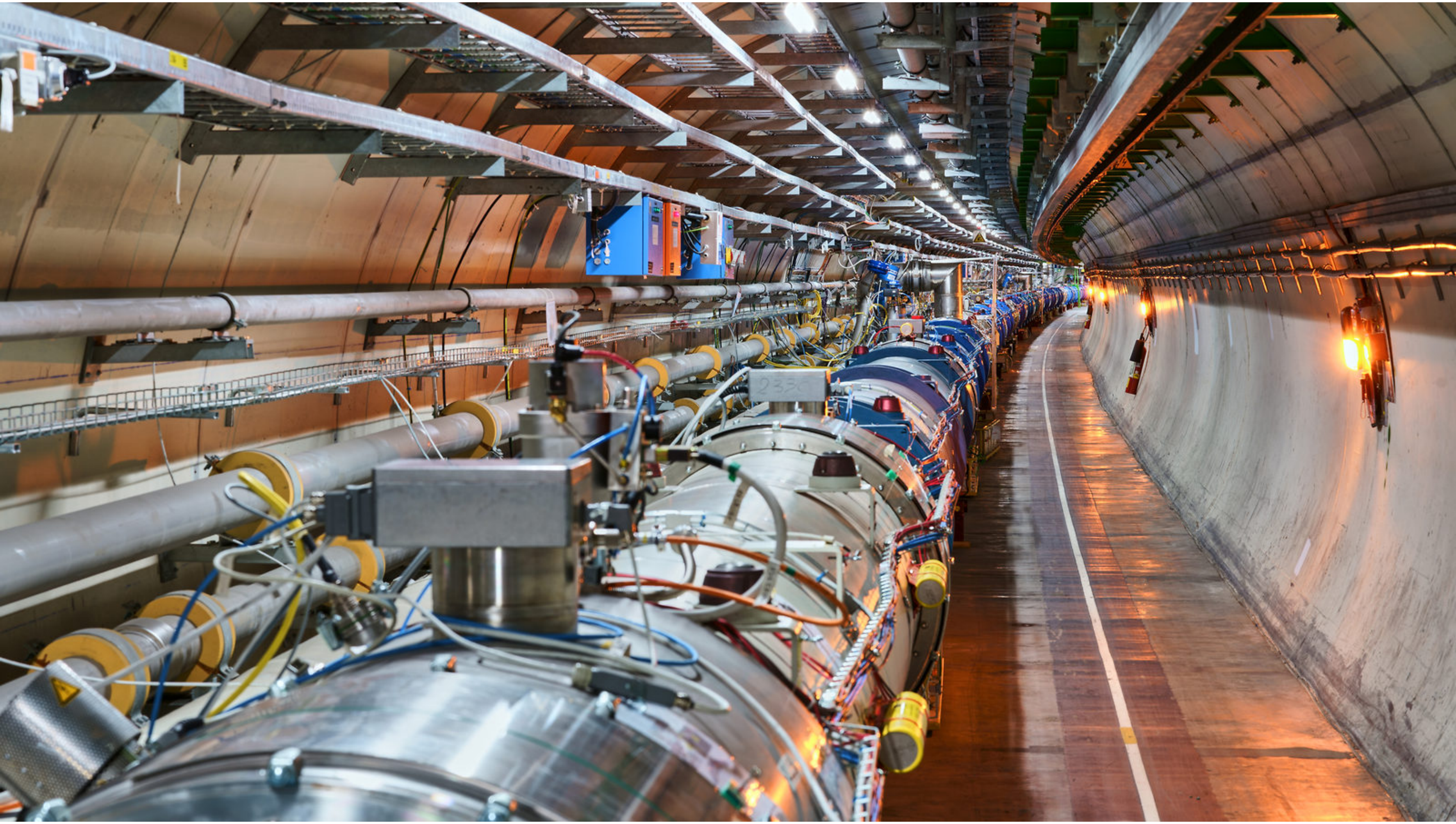
Only one access point for 15 m long dipoles, 35 tons each

Transport in the tunnel with an optical guided vehicle

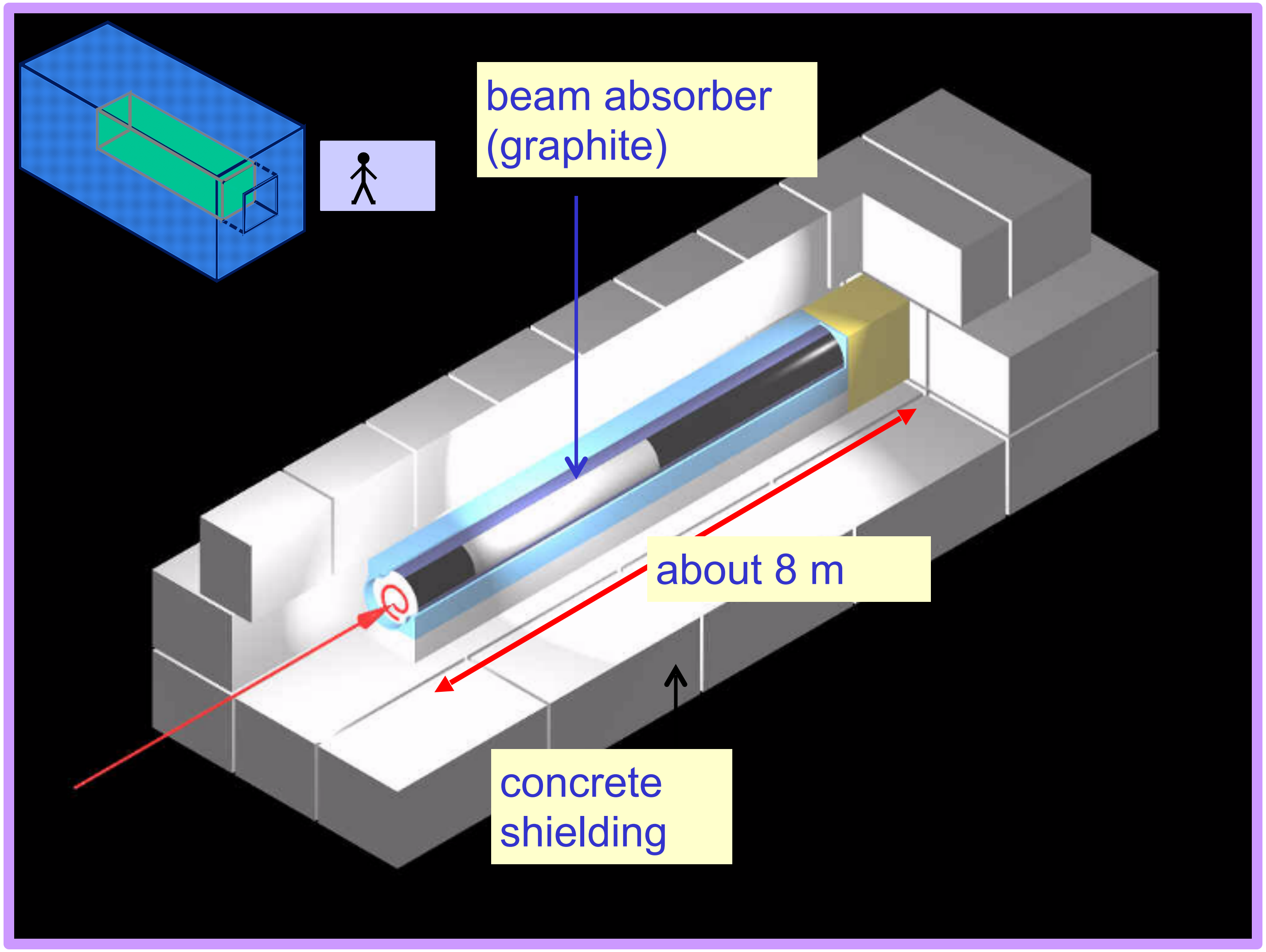
about 1600 magnets to be transported for 15 km

at 3 km/hour

INSIDE THE LHC

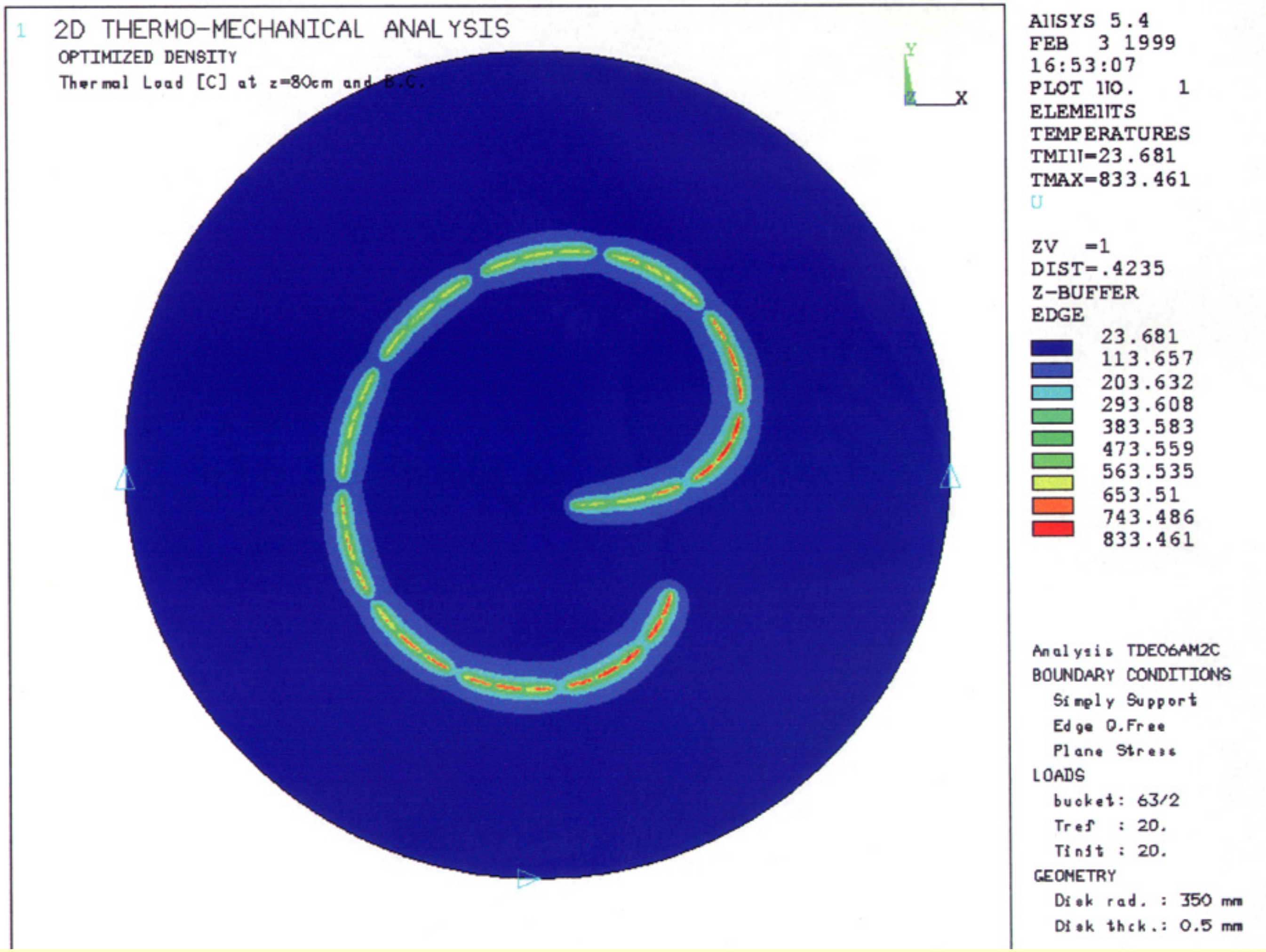


BEAM DUMP BLOCK - LAYOUT



L.Bruno

TEMPERATURE OF BEAM DUMP BLOCK AT 80 CM INSIDE



L.Bruno: Thermo-Mechanical Analysis with ANSYS

LUMINOSITY

Particle physicists wish collider with energies substantially E >> 1 TeV

Observation of rare events requires luminosity of L ≈ 10^{34} [$cm^{-2}s^{-1}$] (challenge for the LHC accelerator)

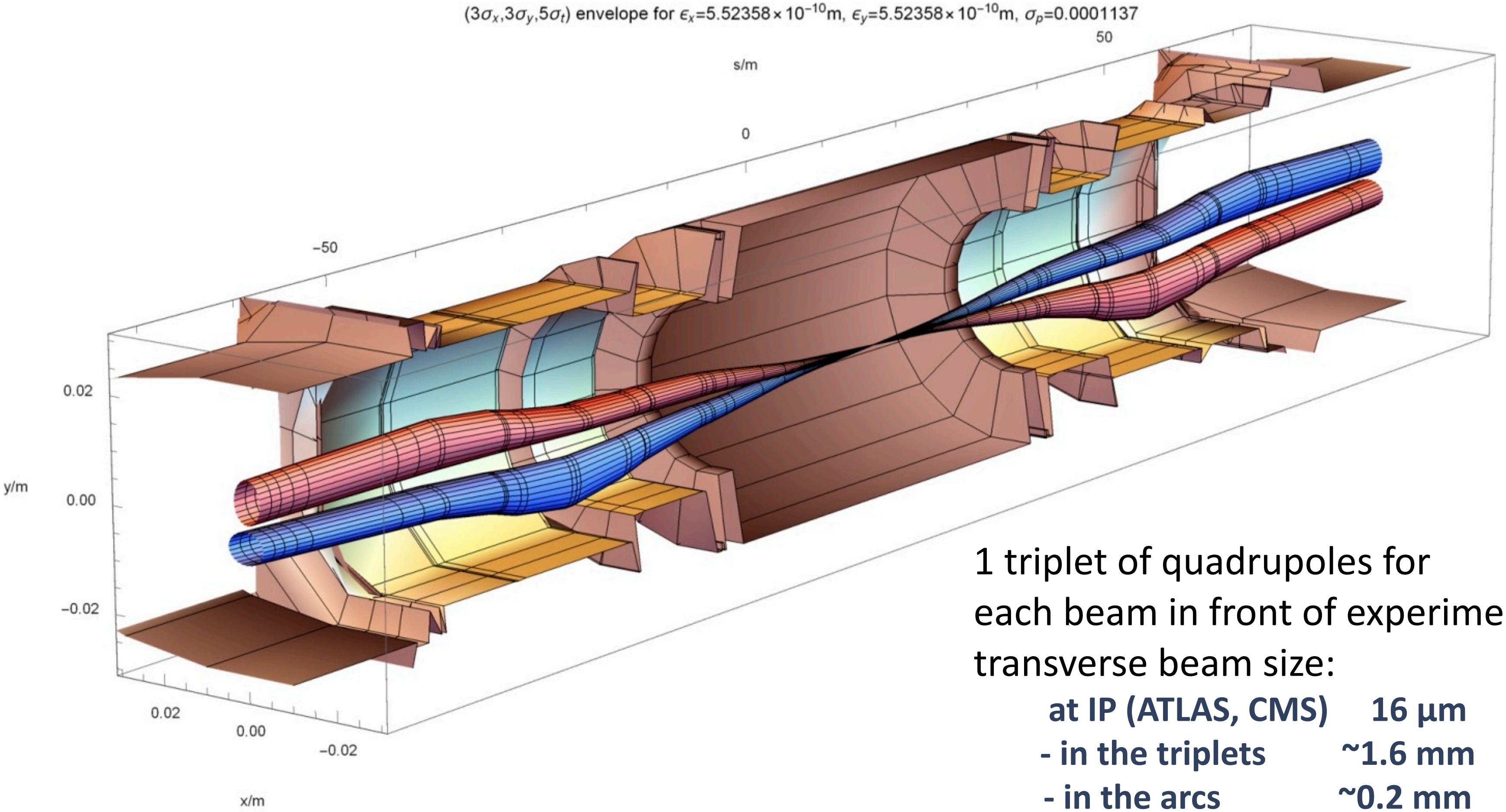
Event rate:

$$\frac{N}{\Delta t} = L[cm^{-2} \cdot s^{-1}] \cdot \sigma [cm^{2}]$$

Cross section for p+p collisionsis σ ≈ 100 mb , thus event rate for this luminosity is about 10^{9} events/second
(challenge for the LHC experiments)

Nuclear and particle physics require high-energy collisions of heavy nuclei in the LHC to create and study quark-gluon plasma

COLLISION REGION



1 triplet of quadrupoles for each beam in front of experiment

transverse beam size:

at IP (ATLAS, CMS) 16 µm

- in the triplets ~1.6 mm

- in the arcs ~0.2 mm

LUMINOSITY PARAMETERS

$$L = \frac{N^2 \cdot f \cdot n_b}{4\pi \cdot \sigma_x \cdot \sigma_y}$$

with :

N = Number of protons per bunch

f = revolution frequency

n_b = number of bunches per beam

$\sigma_x \cdot \sigma_y$ = beam dimensions at interaction point

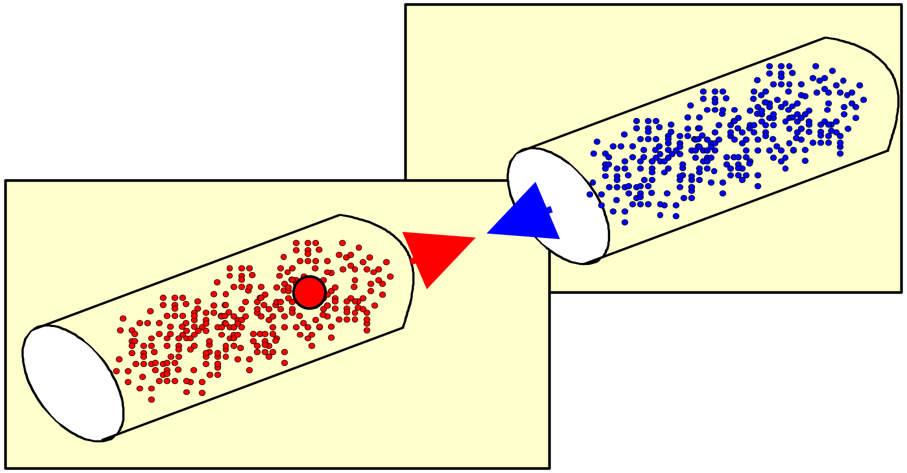
Every proton experiences the em-fields of 10^{11} protons in the other beam

Beam-beam interaction limits $N < 10^{11}$

$f = 11246$ Hz

$n_b = 2808$ bunches

$\sigma_x, \sigma_y = 16\ \mu m$



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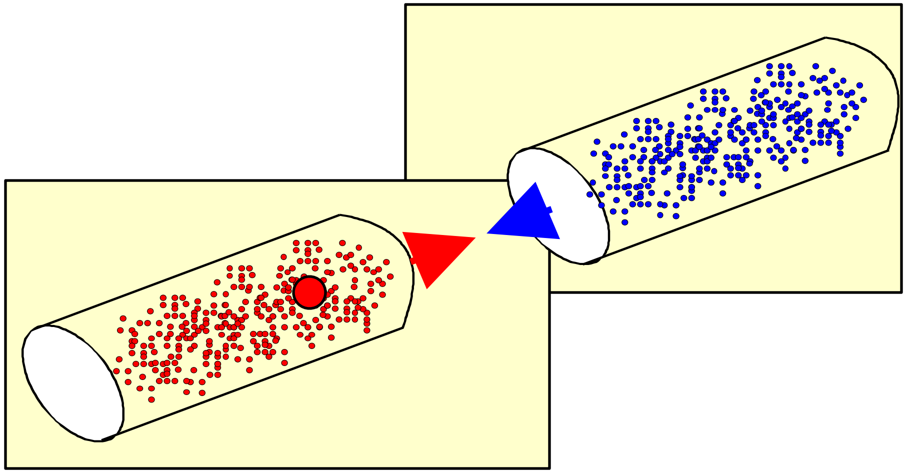

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$L = 10^{34}\ [cm^{-2}s^{-1}]$

ULTRA-RELATIVISTIC NUCLEAR COLLISIONS

The Beginning

“It would be **intriguing** to explore **new phenomena** by **distributing high energy** or **high nuclear matter** over a relatively **large volume**.”

“In this way one could temporarily **restore** broken **symmetries** of the physical vacuum and possibly **create** abnormal **states** of **nuclear matter**.”

T.D. Lee, Bear Mountain, NY, 1974.

“Nevertheless, such speculations reminds us that the **possibility** of totally **unexpected phenomena** may be the **most compelling** reason to consider **relativistic nucleus-nucleus collisions**. It is regrettable that It is so **hard** to **estimate** the **odds** for this to happen.”

J.D. Bjorken, FNAL, PRD 27 (1983) 140.

TASTING THE QUARK GLUON PLASMA

Source: Michael Turner, *National Geographic (1996)*

A SINGLE LEAD-LEAD COLLISION

collision happens here

4k charged particles

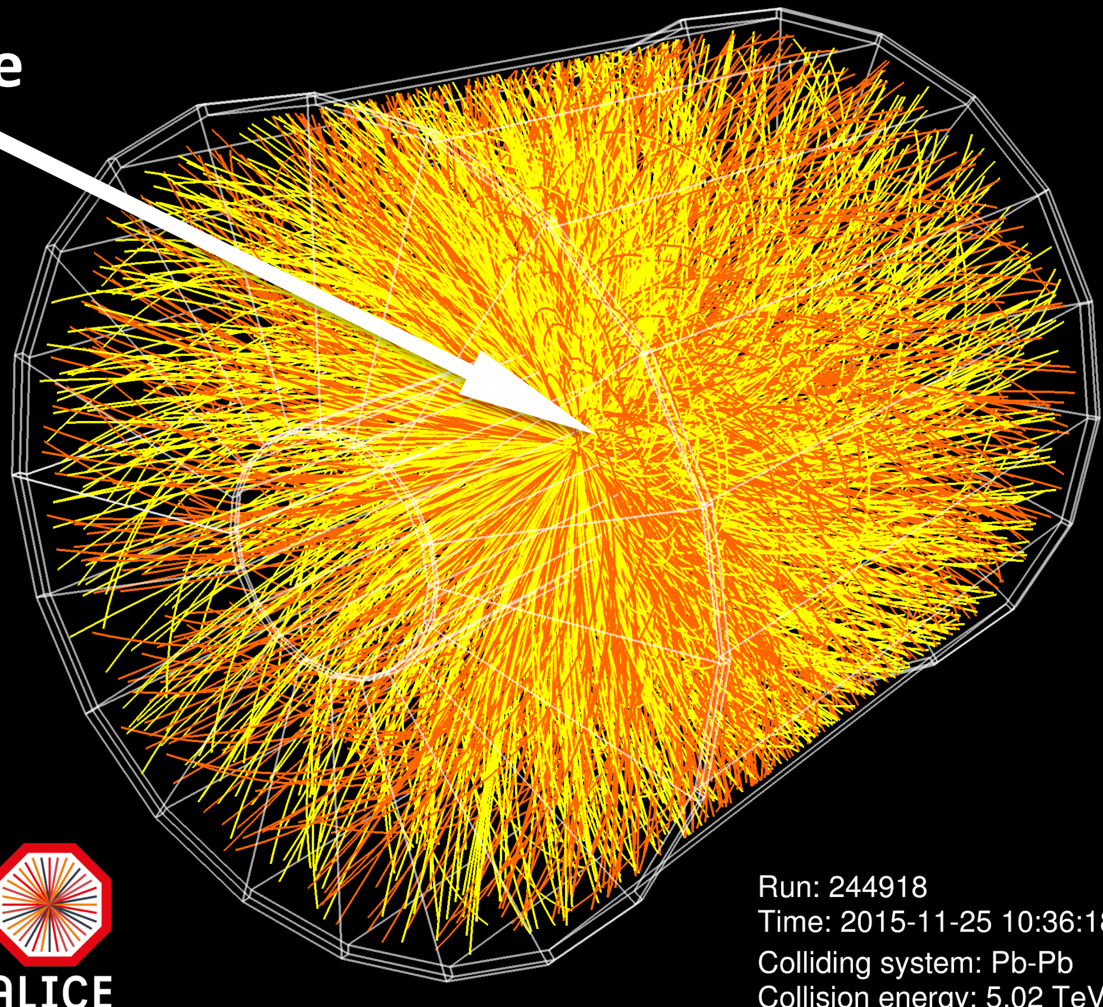
over two units of

rapidity

ALICE **tracks** and

identifies almost

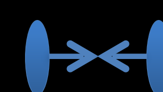
all particles



ALICE

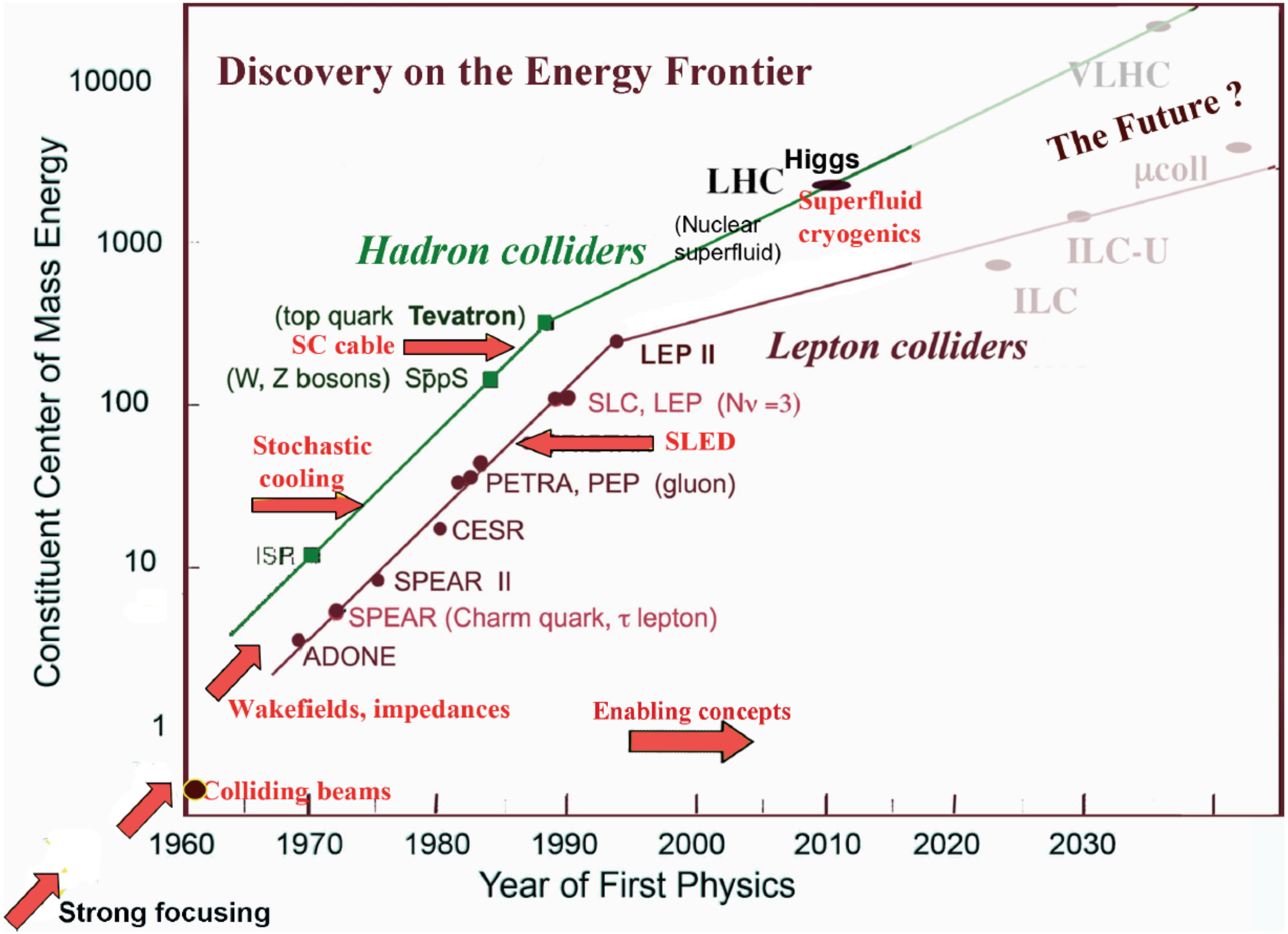
Multiplicity is a measure

of the **medium s size**



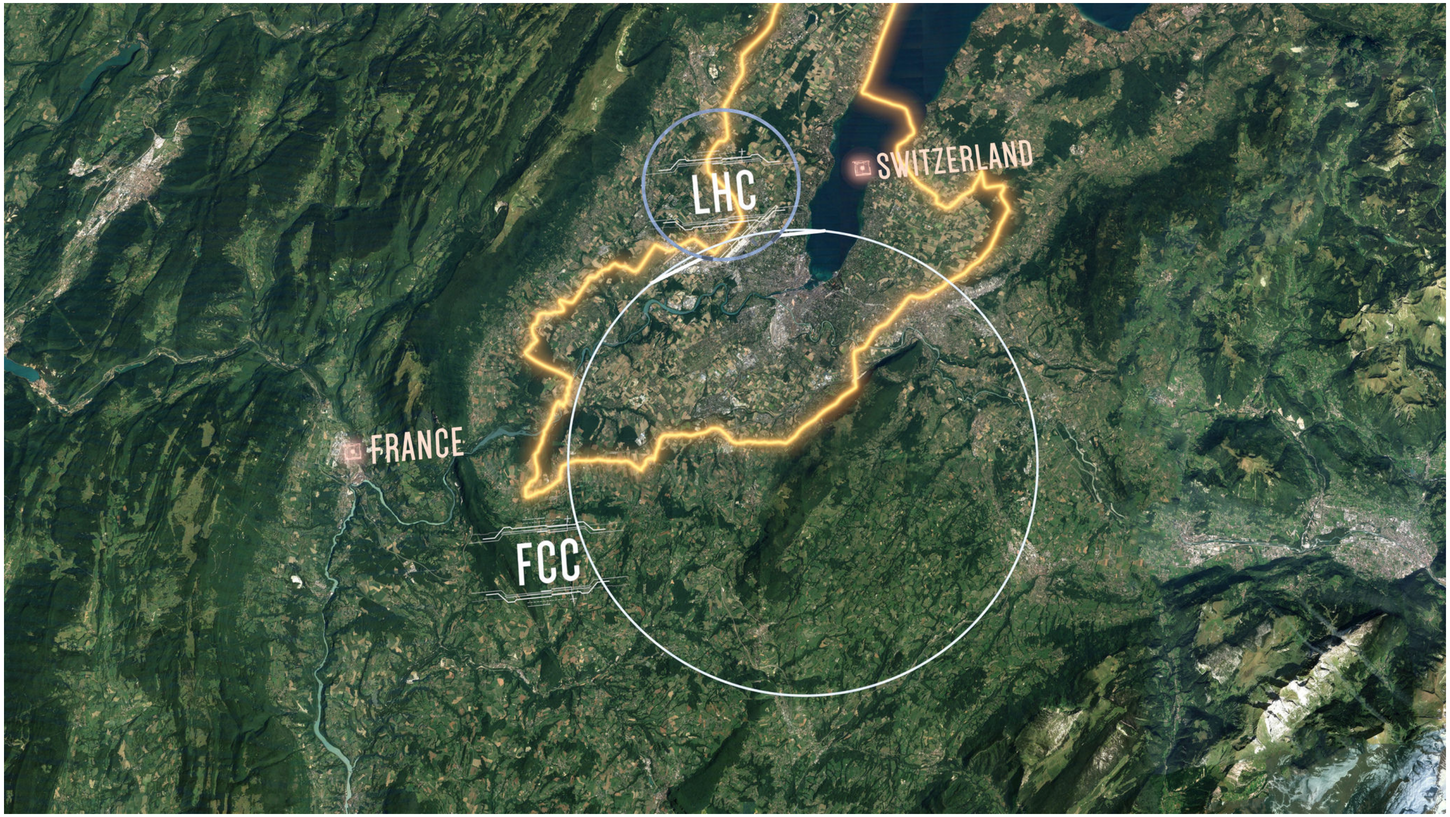
Central collision

LIVINGSTON PLOT



[Planning the Future of U.S. Particle Physics (Snowmass 2013): Chapter 6: Accelerator Capabilities]

THE NEXT ENERGY FRONTIER



https://fcc-cdr.web.cern.ch, and Annu. Rev. Nucl. Part. Sci. 2019. 69:389.

Future Circular Collider (FCC): 100km circumference, first e+e-, then pp and heavy nuclei
100 TeV collision energy, precision EW physics, Higgs self-coupling, dark matter particles, …
radius x 4 and magnet strength x 2 (8.3 T —> 16 T) —> ~order of magnitude in energy
Similar project in China, Circular proton-proton Collider (CppC)