Universität Zürich UZH

Physik-Institut

PAUL SCHERRER INSTITUT

PHY213 Kern- und Teilchenphysik II
(FS 2020)

Energy Frontier: Collider experiments

Lea Caminada

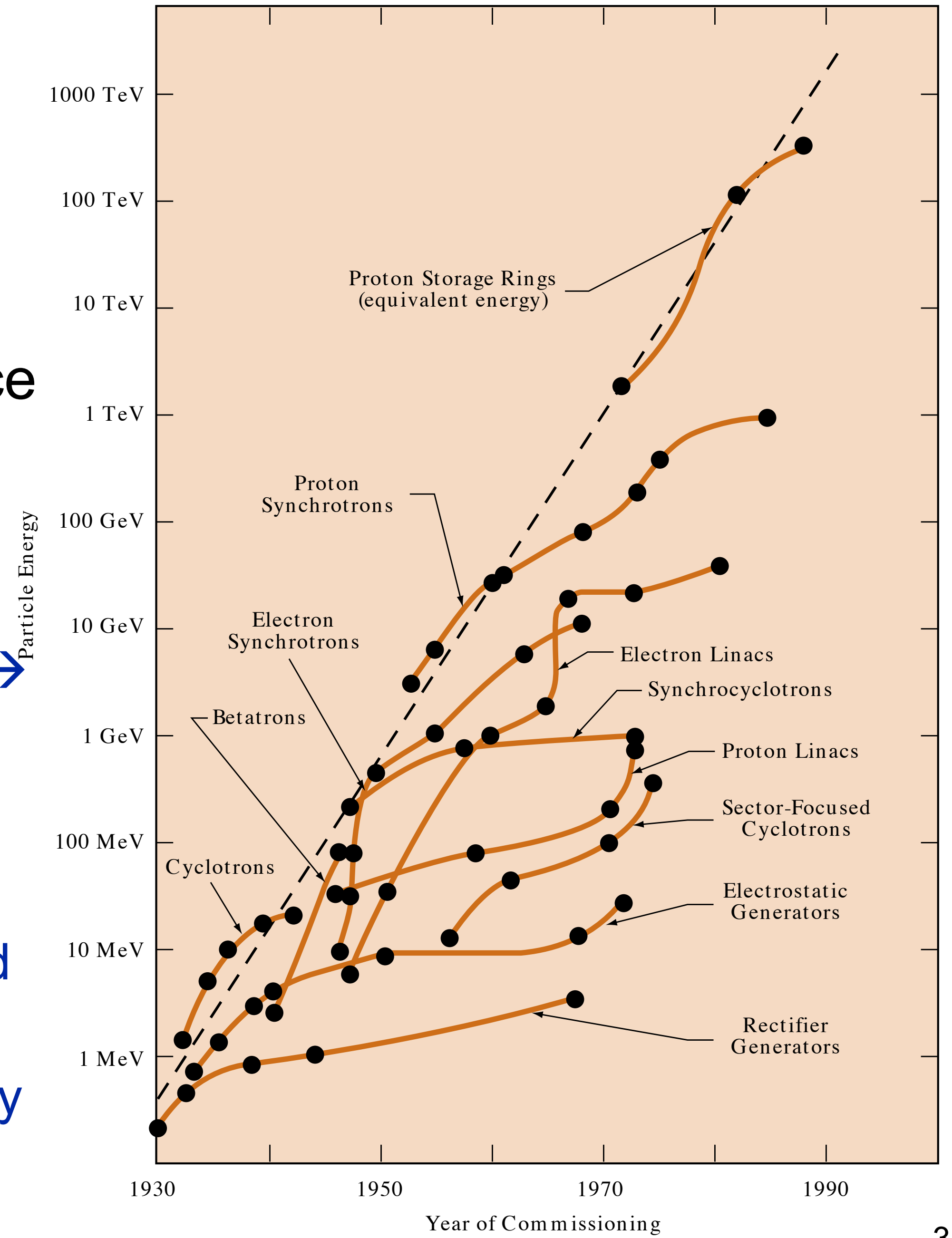
lea.caminada@physik.uzh.ch

Overview

- History of particle accelerators and colliders
- Complementarity of hadron and lepton colliders
- Probing the Standard Model at colliders
  - SLC
  - LEP
  - HERA
  - Tevatron
  - LHC

History

- 1924/28: First linear accelerator by Gustav Ising and Rolf Wideröe
- 1930: Cyclotron invented and built by Ernest Lawrence
- From 1950: Accelerators used in particle physics
  - Discovery of neutral pion, vector mesons, anti-proton → appearance of particle zoo
- 1970: First colliders
  - More particles discovered
  - Organization in the Standard Model
  - Towards modern high-energy physics



Electromagnetic acceleration

	Static acceleration	Resonant acceleration	Inductive acceleration
Configu-ration	• static E-field • accelerate particles in this field	• **oscillating E-fields** in cavities • particles pass ➔ one cavity several times or ➔ a sequence of cavities once for acceleration	• **oscillating B field** accelerates particles via the **induced E-field**
Linear	DC gun Cockcroft Walton Van de Graaf	RF linac • standing wave (= drift tube linac, DTL) • travelling wave	Induction linac
Circular		Cyclotron Microtron Iso-Cyclotron Synchro-Cyclotron Synchrotron	Betatron

→ Thomas Schietinger PHY461 - EMPP

Acceleration and beams

- Two key themes in particle physics for accelerator physics and technology
- High center-of-mass energy
  - Stimulated the transition from fixed target devices to devices with colliding beams
  - Stimulates the invention of new methods of acceleration and new technologies
- High event rate: high luminosity
  - Stimulates the physics of particle beams

$$\frac{dR}{dt} = \mathcal{L} \cdot \sigma$$

Event rate proportional to instantaneous luminosity and cross section

$$\mathcal{L} = \frac{N_1 N_2 f N_b}{4\pi\sigma_x\sigma_y}$$

$\mathcal{L}$: instantaneous luminosity [$cm^{-2}s^{-1}$]

N_1, N_2: number of particles per bunch

N_b: number of bunches

f: revolution frequency

σ_x, σ_y: transverse beam dimension

$$\mathcal{L}_{\text{int}} = \int_0^T \mathcal{L}(t')dt'$$

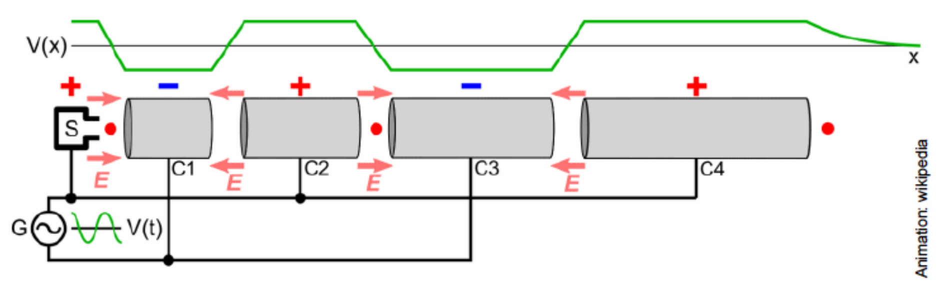
$\mathcal{L}_{\text{int}}$: integrated luminosity [pb^{-1}, fb^{-1}, ab^{-1}]

High center-of-mass energy

- Linear acceleration (Linac)
  - High acceleration gradient G (MV/m)
  - One-pass acceleration of particles
  - Dimension given by desired energy and gradient
    - $L \sim E_{cm}/G$
- Circular acceleration
  - Accelerate particles in one or few locations and bend particles back to those locations
  - Dimension given by momentum and magnetic field
    - $R \sim P_{cm}/B$
- E_{cm} is given by particle physics goal
- L is given by money, politics, available space
- G,B are given by technology (and money)

High center-of-mass energy

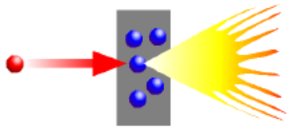
- Linear acceleration: High gradient
  - Cylindrical electrodes with alternating field, length matched to particle velocity



$$\frac{dp}{dt} = eE$$

- Circular acceleration: High magnetic field
  - Achieved with superconducting magnets

- Fixed target vs collider
  - Fixed target: $E_{cm} = \sqrt{2E_b m_t c^2}$
  - Collider: $E_{cm} = 2E_b$
  - Getting over $\sqrt{E_b}$ dependence has significant consequences for the required beam quality

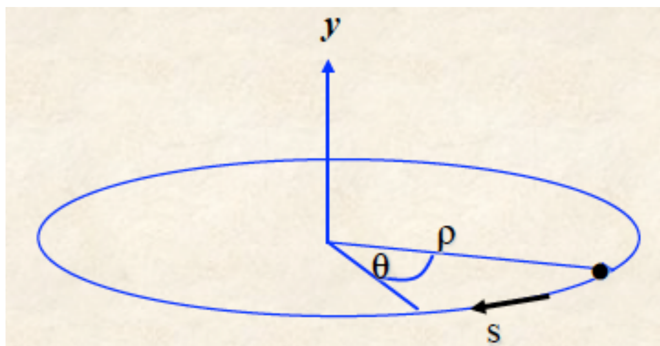


High luminosity

- Formation of beams of particles is needed for acceleration within accelerator
  - In the past, motivated by keeping the particles inside the accelerator
  - For fixed target experiments, the event rate does not depend on the beam size, just that it hits the target in roughly the right location
  - For colliders, the beam structure and size has a large influence on the luminosity
- Accelerator design begins with the concept of a design orbit (circular accelerator) or trajectory (Linac)
- The beam needs to be near this orbit or trajectory all the time and throughout the length of the device
  - Beam size should be small
  - Angular and transverse momentum divergence should be small
  - Timing matters → bunch structure
  - Energy spread should be small

Transverse motion

- A set of particles can be formed into a beam in the neighborhood of some design orbit or trajectory by having external fields confining all particles to that neighborhood
- For relativistic particles magnetic fields are used to do the bending



Lorentz force $F_L = e\,v\,B$

centrifugal force $F_{centr} = \dfrac{\gamma\, m_0\, v^2}{\rho}$

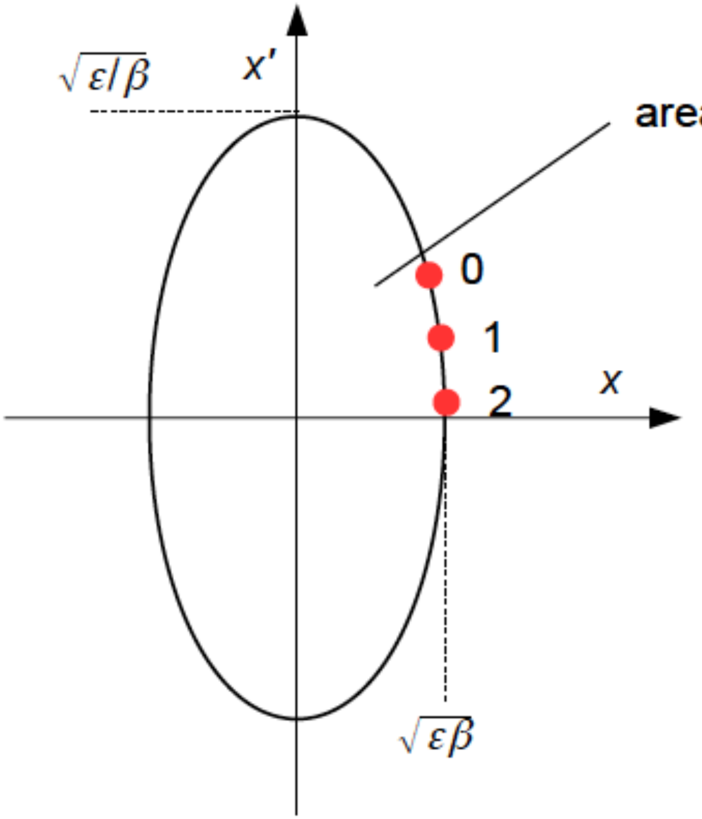
$$\frac{p}{e} = B\,\rho$$

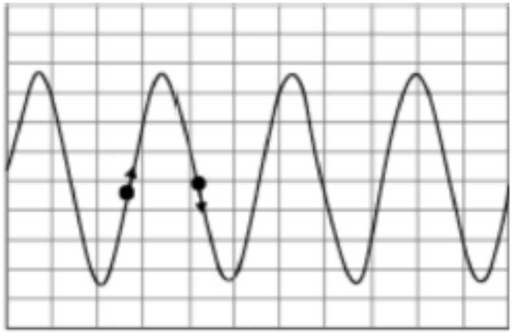
: magentic rigitdity describes the resistance of a particle for being reflected

- Example: LHC
  - B=8.3T, p=7000 GeV/c

  → ρ = 2.83 km, $2\pi\rho$ = 18 km ~66% of machine circumference

Phase space ellipse



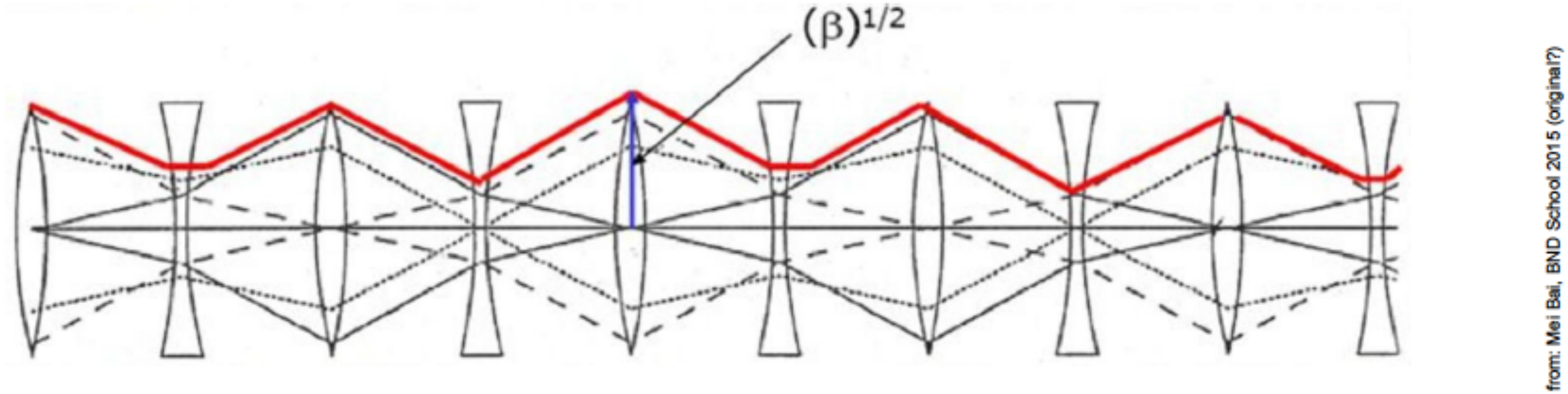


- A single particle undergoing betatron oscillations describes an ellipse in phase space, when measured turn after turn at the same position in the ring
  - periodically going from maximum position x to maximum divergence angle $x' = dx/ds$ and back
- The area $A = \pi\varepsilon$ of the ellipse is a measure of how much the particle departs from the reference trajectory.

- The quantity ε is called the **emittance.** (Single-particle emittance in case of one particle)
- The area in phase space occupied by all particles of a beam (modulo π) is called the **beam emittance.**

- Emittance is a property of the beam

β-function



- Depending on the initial conditions, different particles may follow very different trajectories along the accelerator
- The envelop of all trajectories is described by a periodic function, the β-function
- The β-function is a property of the accelerator!
- The beam size is defined by both, the emittance and the β-function

$$\sigma(s) = \sqrt{\epsilon \cdot \beta(s)}$$

- β* is the value of the β-function at the interaction point

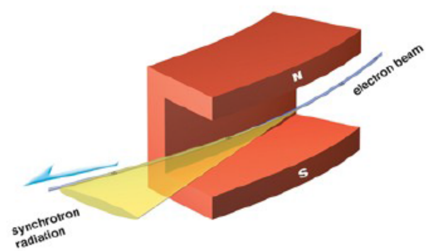
Synchrotron radiation

- The choice of accelerator type is strongly influenced by the particle type
- The power radiated off in circular motion is:

$$P_\gamma = \frac{e^2 c}{6\pi\varepsilon_0}\left(\frac{E}{mc^2}\right)^4 \frac{\beta^4}{\rho^2} \longrightarrow \text{Energy loss per turn:} \quad U_0 = P_\gamma \cdot t_{\text{turn}} = P_\gamma \frac{2\pi\rho}{c}$$

In practical units ($\beta \approx 1$):

$$U_0(\text{keV}) = \underbrace{10^{33} \frac{e}{3\,\varepsilon_0}\left(\frac{e}{mc^2}\right)^4}_{\substack{\approx 88.5 \text{ (electrons)} \\ \approx 4.84 \times 10^{-8} \text{ (muons)} \\ \approx 7.79 \times 10^{-12} \text{ (protons)}}} \frac{[E(GeV)]^4}{\rho(m)}$$

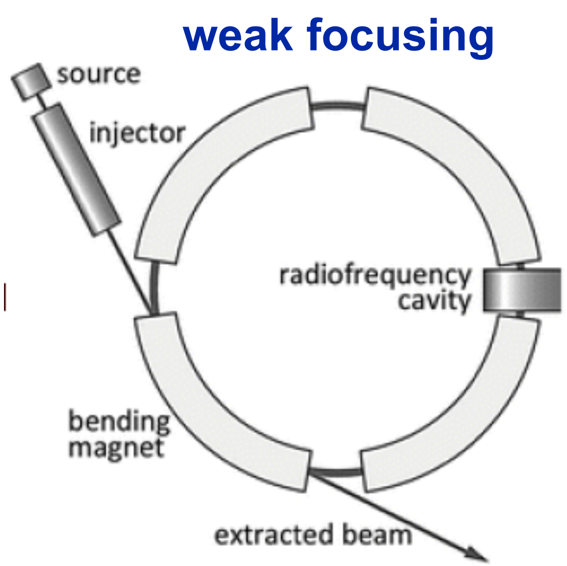


www.ritsumei.ac.jp/acd/re/src/aurora.html

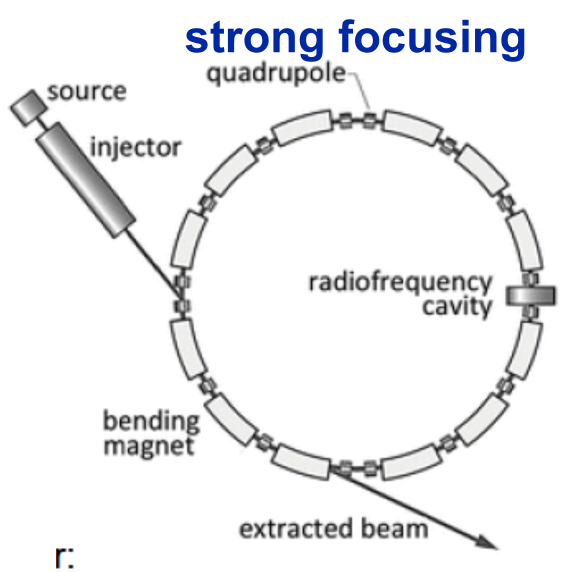
- In practice, using size (ρ) to compensate the increase in synchrotron radiation for electrons works only up to a certain point
- If the energy loss per turn gets too large, might as well use a Linac to reach higher energies
- Note: on the positive side, synchrotron radiation today is the reason why most electron accelerators are built

Synchrotron

- **Cyclotron:** constant magnetic field, constant-frequency electric field, varying orbit
- **Synchrotron:** Constant orbit with varying magnetic and electric fields → synchronization between particle revolution frequency, accelerating and bending field
- Dipole magnets need large aperture to accommodate particle oscillations
- Invention of strong focusing as breakthrough



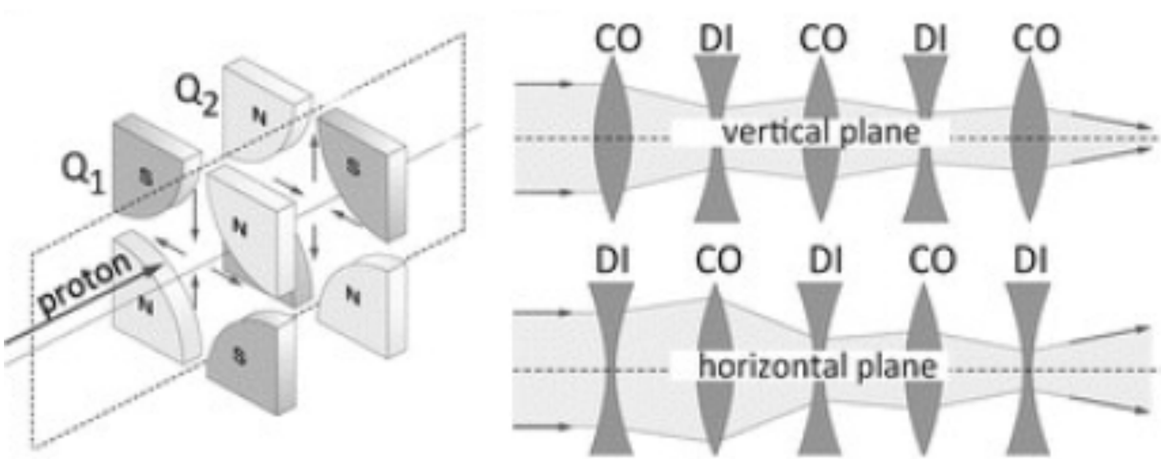
U. Amaldi, "Particle Accelerators: from Big Bang Physics to Hadron Therapy", Springer 2014



U. Amaldi, "Small Accelerators Grow", Springer 2014

Strong focusing

- Combination of focusing and defocusing magnets has an overall focusing effect (as with optical lenses)
- Fist time empirically tried by E.D Courant, S. Livingston and H.S. Snyder in 1952 at the Cosmotron (BNL)

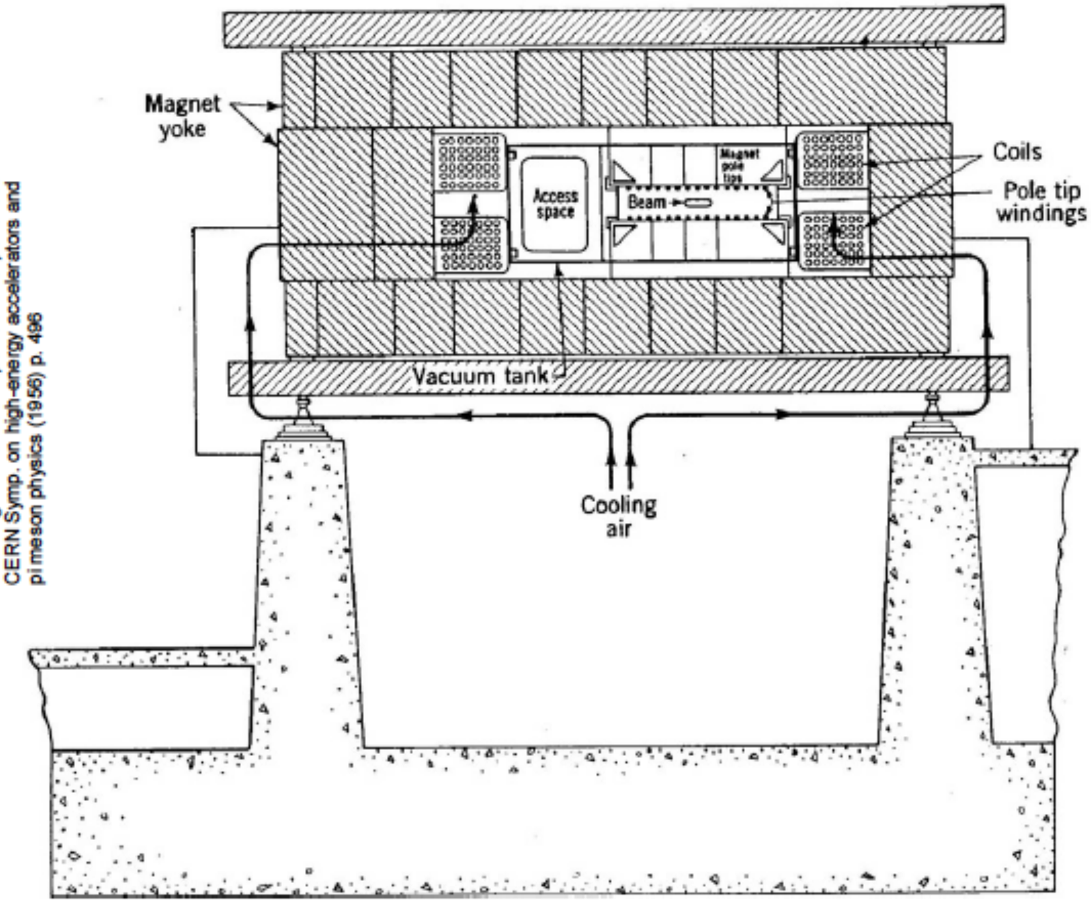


Sequences of converging (CO) and diverging (DI) focusing magnets have a net focusing effect!

U. Amaldi, "Particle Accelerators: from Big Bang Physics to Hadron Therapy", Springer 2014

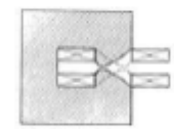
Strong focusing revolution

E.J. Lofgren: *Bevatron operational experiences* CERN Symp. on high-energy accelerators and pi meson physics (1956) p. 496



6-GeV Bevatron (Berkeley)

to scale!



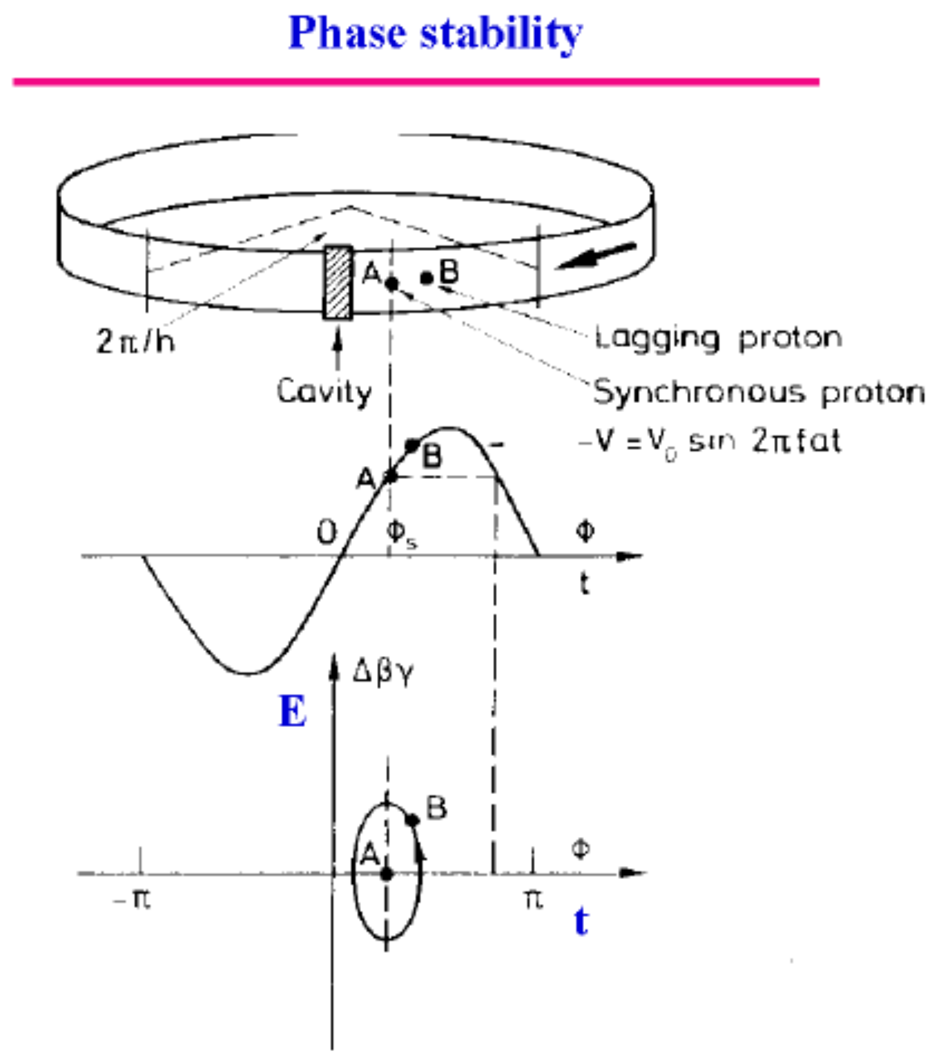
33-GeV AGS
(Brookhaven)

after M.K. Craddock, TRIUMF student seminar

Phase stability

- Second key prerequisite for modern synchrotrons is concept of phase stability
- Particles are only accelerated if they have the correct phase w.r.t. RF field
- Particles with too much energy arrive at a phase to get less
- Particles with too little energy arrive at the phase to get more

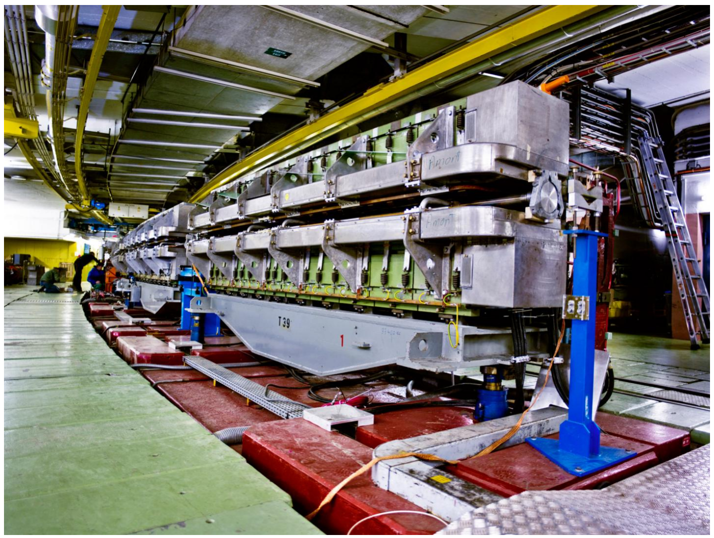
→ Formation of particle bunches



First modern synchrotrons

- Built in 1959, both still in use today

PS at CERN 28 GeV



- 628m circumference
- 245 dipole magnets (B^{dipole}=1.2T)
- First used for fixed-target experiments
- Later for pre-acceleration for ISR, SPS, LEP, LHC

AGS at BNL 33 GeV

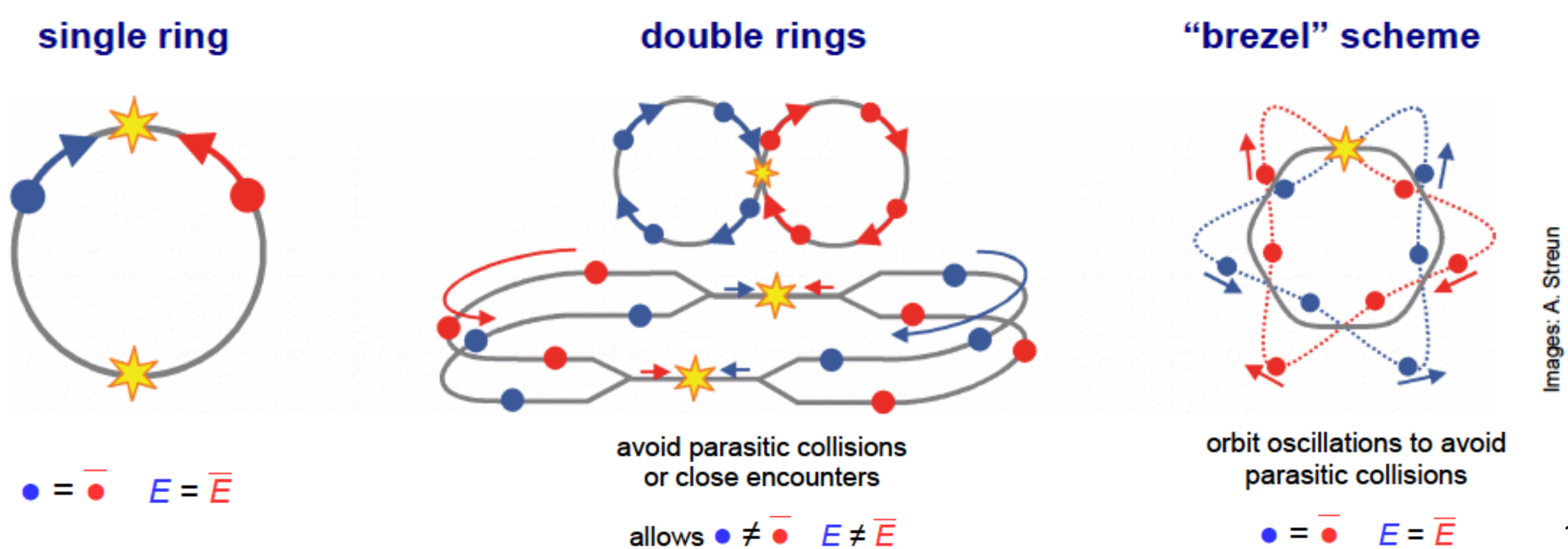
- 807m circumference
- 240 dipole magnets (B^{dipole}=1.2T)
- First used for fixed-target experiments
  - 1962: Discovery of ν_μ
  - 1976: Discovery of J/ψ
  - 1980: CP violation in the kaon system

- Later for pre-acceleration for RHIC

Storage ring collider

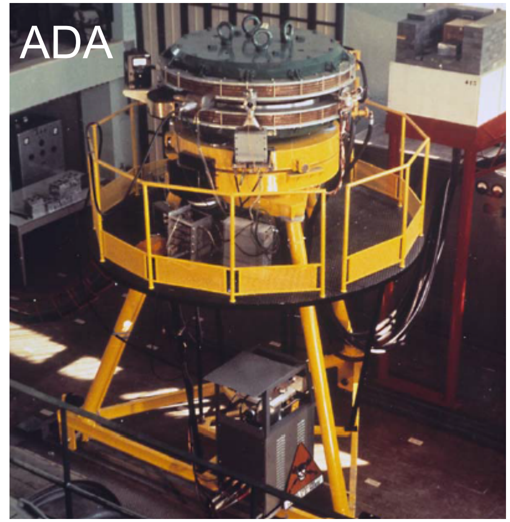
- Next step from synchrotron is the storage ring collider
  - Circular collider: one or two storage rings with opposite beams
  - Energy frontier: acceleration mode (synchrotron) followed by storage mode (in the same ring)
- Single ring can be used for particle-antiparticle collider → need to make sure that no unwanted collisions happen → use different orbits
- Decrease beam size at interaction point to increase density and hence luminosity

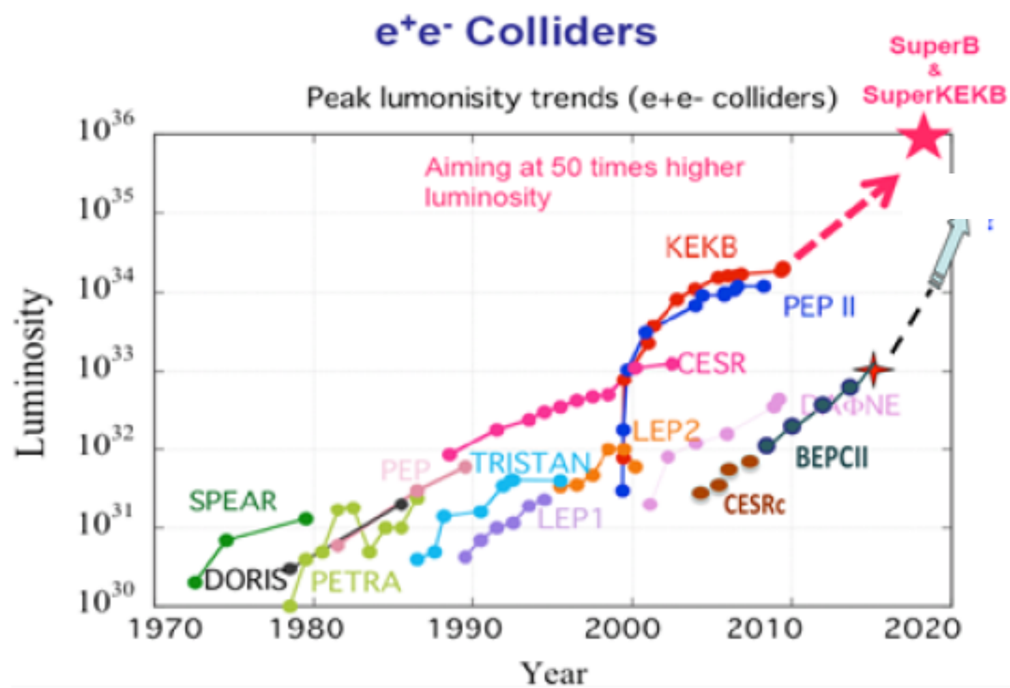
Collider schemes:



e^+e^- Colliders

- 1961: ADA, first electron-positron collider at Frascati, Italy
  - Proved technology
  - 4m circumference
  - E_{cm} = 500 MeV
- 1969-1993: ADONE
  - Used for particle physics
  - Circumference of 105m
  - E_{cm} = 3.1 GeV (initially 3.0 GeV → just missed J/ψ in 1974)
- Followed by many others all around the world
- Electron beams can be focused on very small spot → reach highest luminosities

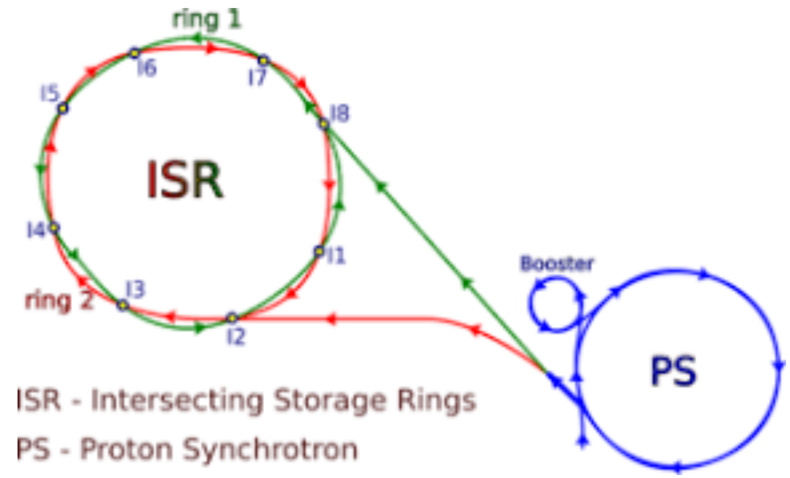




Proceedings of eeFACT2016, Daresbury, UK

Proton colliders

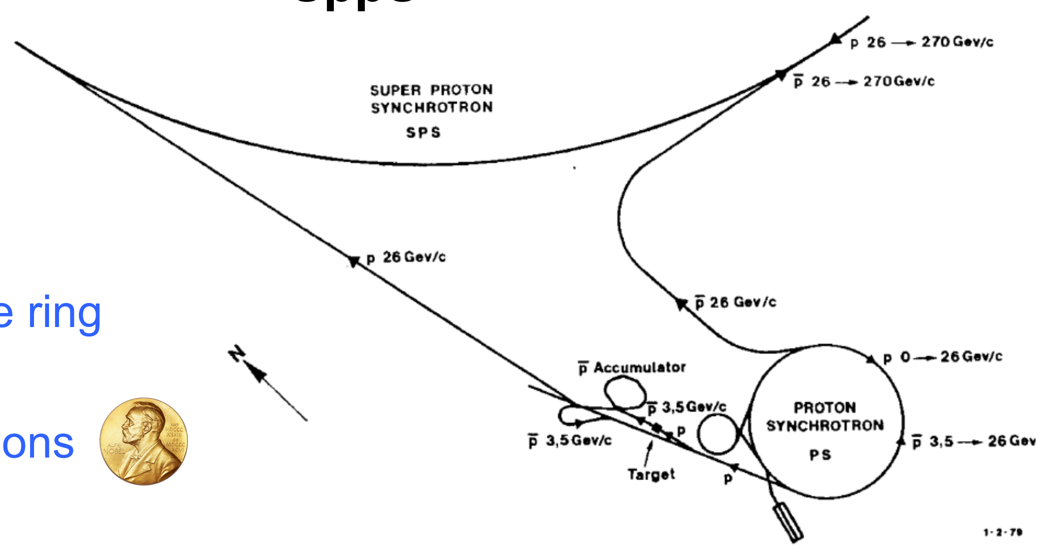
- 1971: Added storage ring to CERN PS → first proton-proton collider – intersecting storage rings (**ISR**)
  - Two rings with 300m circumference
  - E_{cm} = 62 GeV



- 1976: **SPS**
  - Circumference of 6.9km
  - 1425 magnets (B^{dipole}=2.0T)
  - E_{beam} = 450 GeV

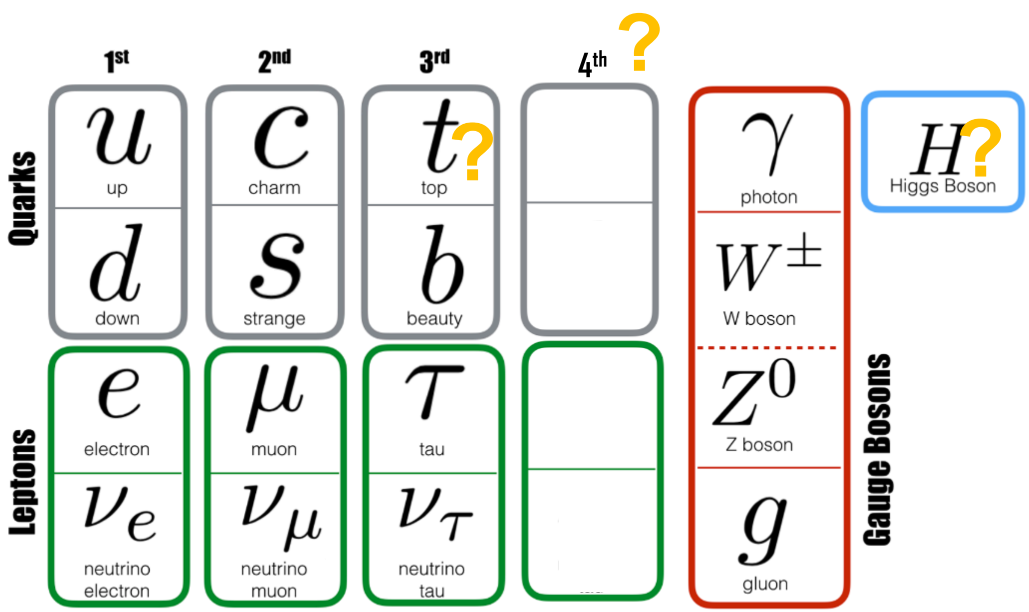
- 1981-1990: **Sp$\bar{p}$S**
  - Operation as p$\bar{p}$ collider in single ring
  - E_{cm}=546 GeV
  - 1984: Discovery of W and Z bosons
  - L_{inst}^{max} = $3\times10^{30}cm^{-2}s^{-1}$

SPS
Sp$\bar{p}$S

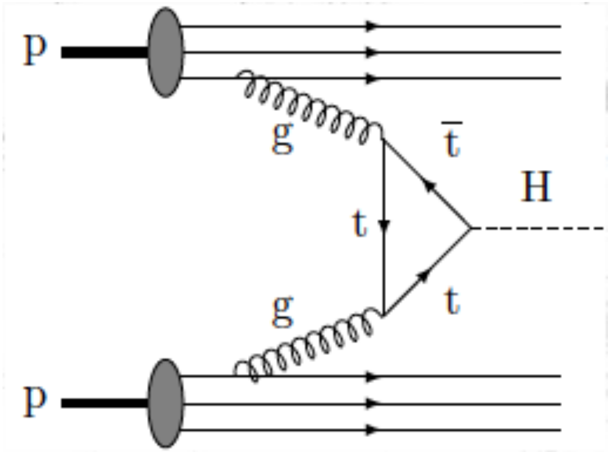


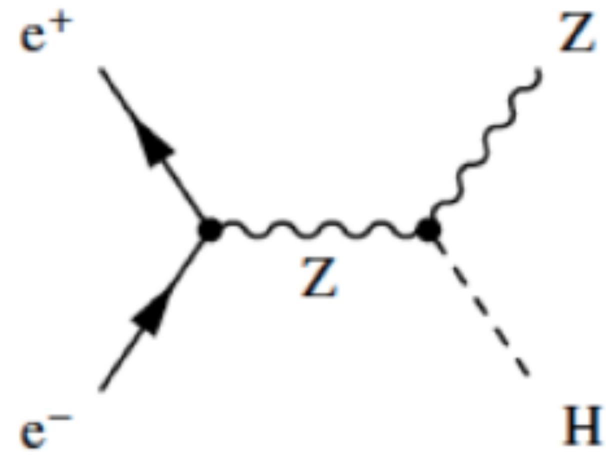
The Standard Model mid-1980

- Discovery of W and Z boson with predicted masses was spectacular confirmation of theory of electroweak unification by Glashow, Salam and Weinberg
- Still missing particles in the Standard Model: top quark, Higgs boson, additional families?
- In need of experiments reaching higher energies to explore new phase space and strive for discoveries



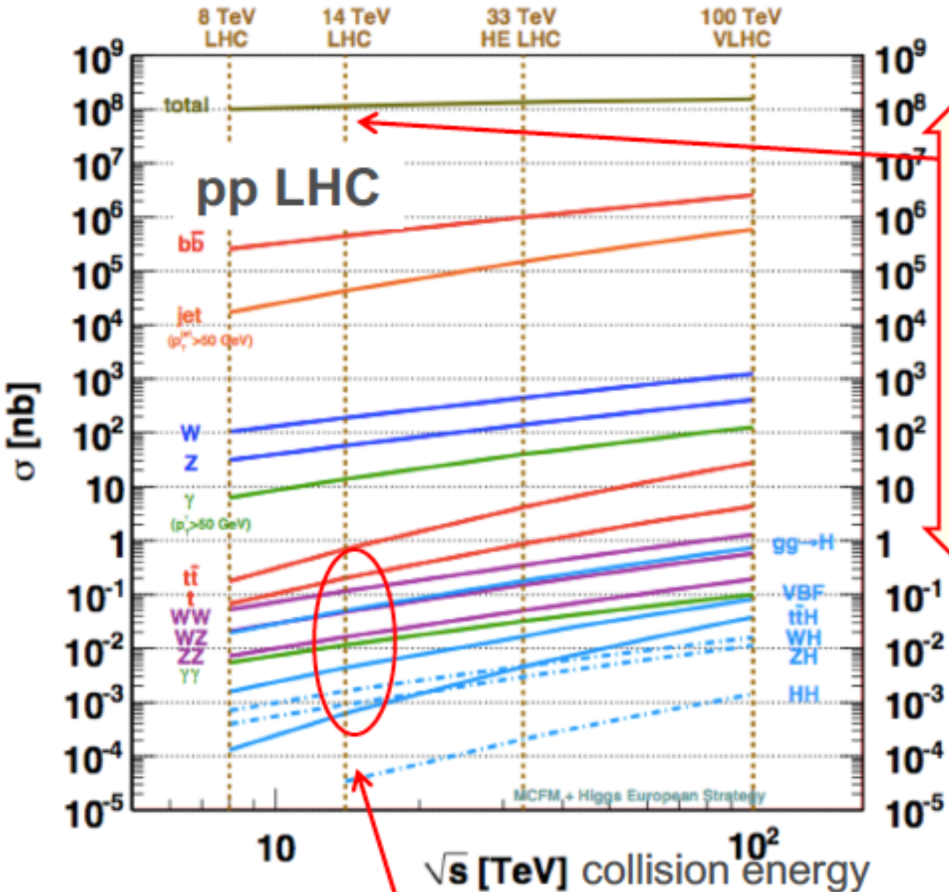
pp collisions vs e^+e^- collisions





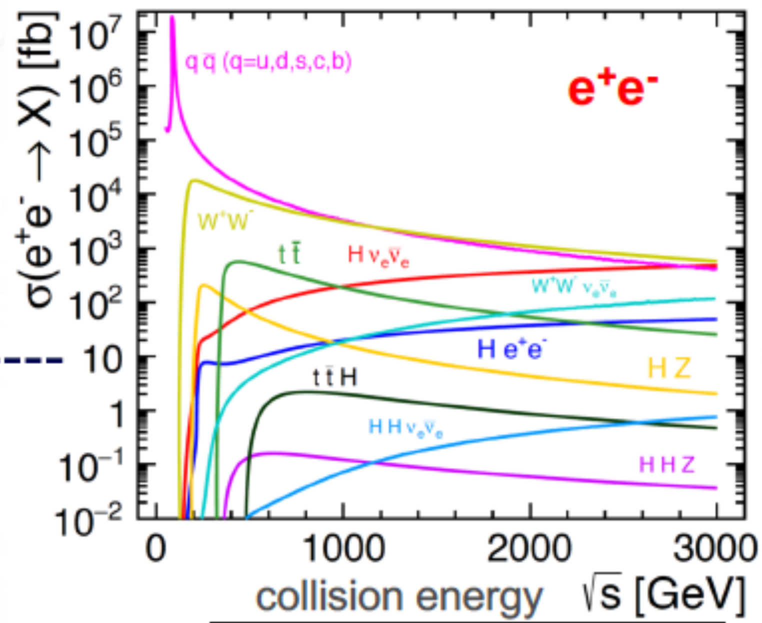
p-p collisions	e^+e^- collisions
Proton is compound object → Initial state not known event-by-event → Limits achievable precision	**e^+/e^- are point-like** → Initial state well defined (E, $\boldsymbol{p}$) → High-precision measurements
High rates of QCD backgrounds → Complex triggering schemes → High levels of radiation	**Clean experimental environment** → Trigger-less readout → Low radiation levels
High cross-sections for **colored-states**	Superior sensitivity for **electro-weak states**
High-energy **circular** pp colliders feasible	- At lower energies ($\lesssim$ 350 GeV) , **circular** e^+e^- colliders can deliver **very large luminosities.** - Higher energy e^+e^- requires **linear** collider.

pp collisions vs e⁺e⁻ collisions



LHC total cross section factor > 100 million !!

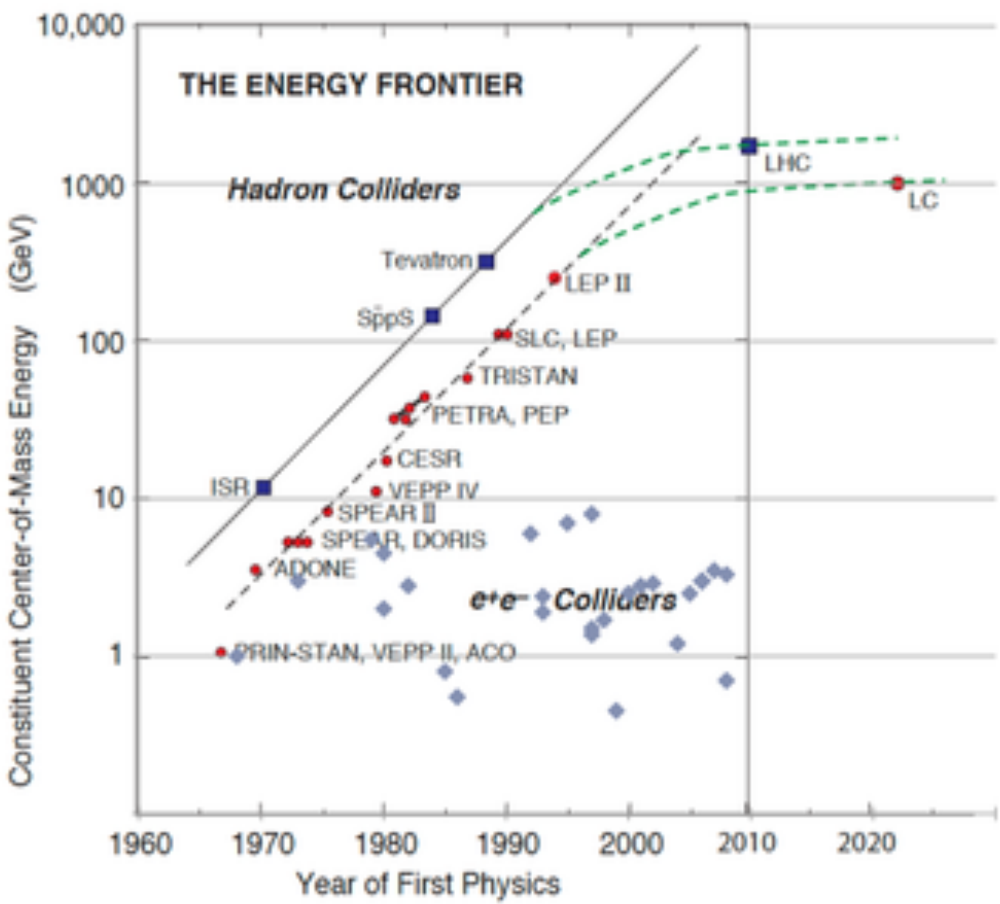
At LHC, much of the interesting physics needs to be found among a huge number of collisions



e⁺e⁻ events are "clean"

Followed both paths….

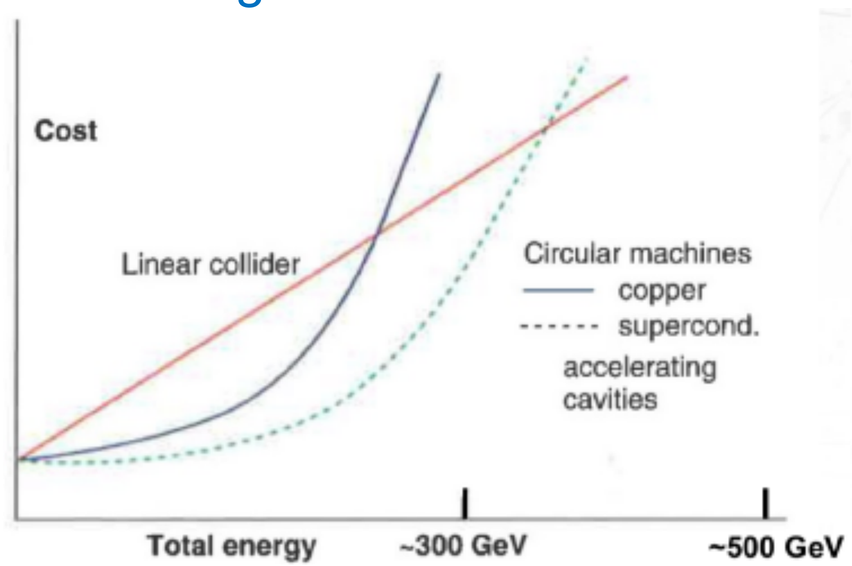
- Precision tests of the Standard Model at lepton colliders with $\sqrt{s}$ ~ 100 GeV → LEP and SLC
- Pushing toward highest energies with hadron colliders with $\sqrt{s}$ ~ 1-10 TeV → Tevatron and LHC

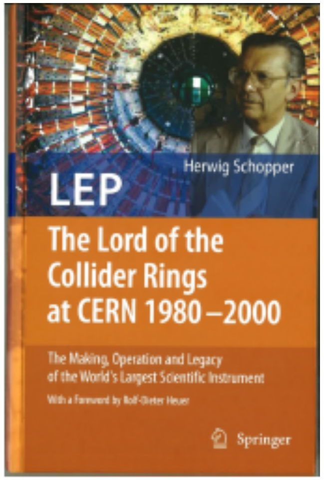


Lepton colliders

Linear or circular?

- Acceleration of electrons in circular machines limited by Synchrotron radiation
  - Energy loss per turn grows like $\Delta E \propto \frac{1}{R}\left(\frac{E}{m}\right)^4$
  - Must compensate with R and accelerating cavities
    → cost also grows like E^4



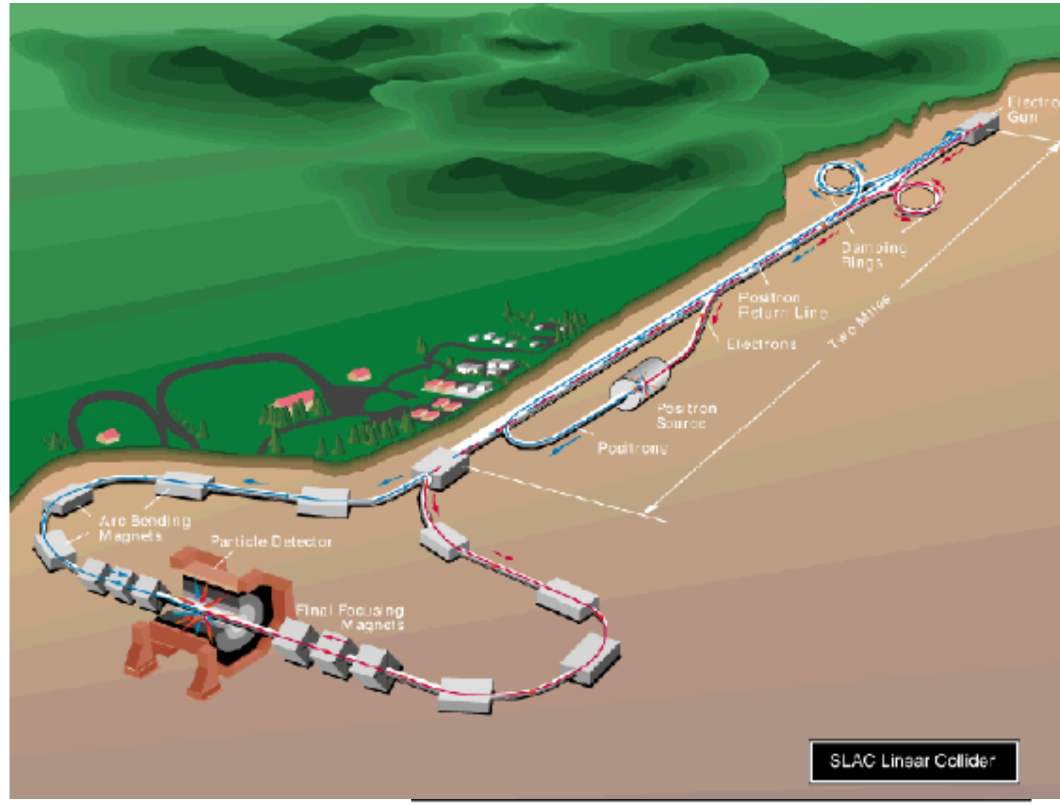


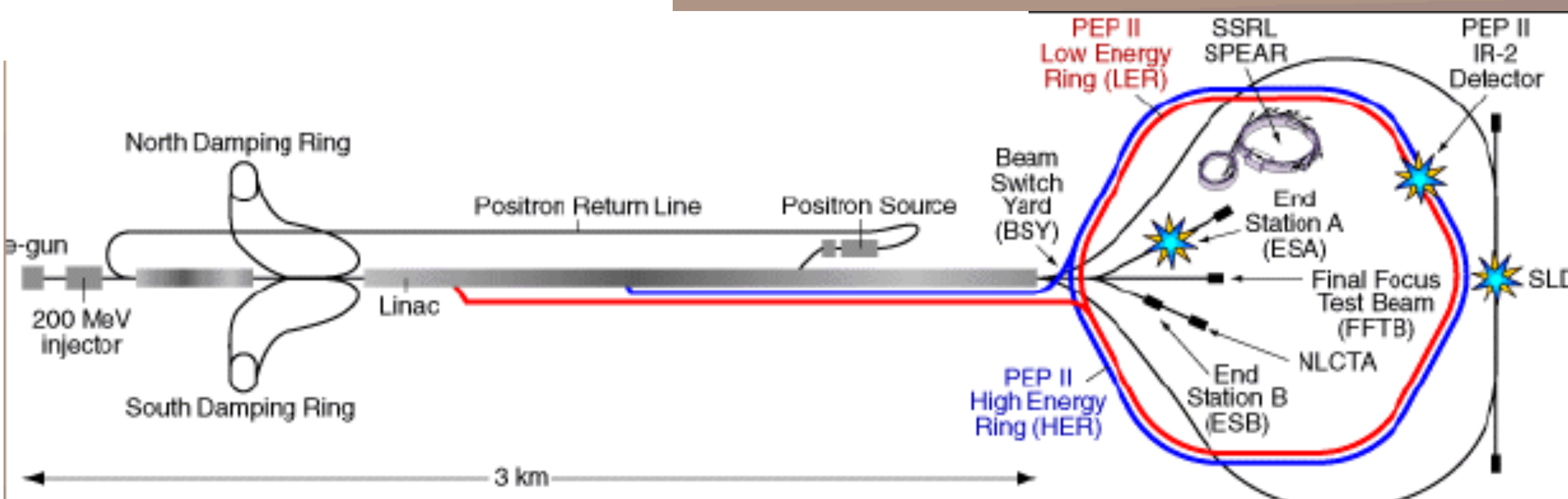
→ "Up to a center-of-mass energy of 350 GeV at least, a circular collider with superconducting magnets is the cheapest option"

→ "At and above 500 GeV, a e^+e^- collider can only be linear"

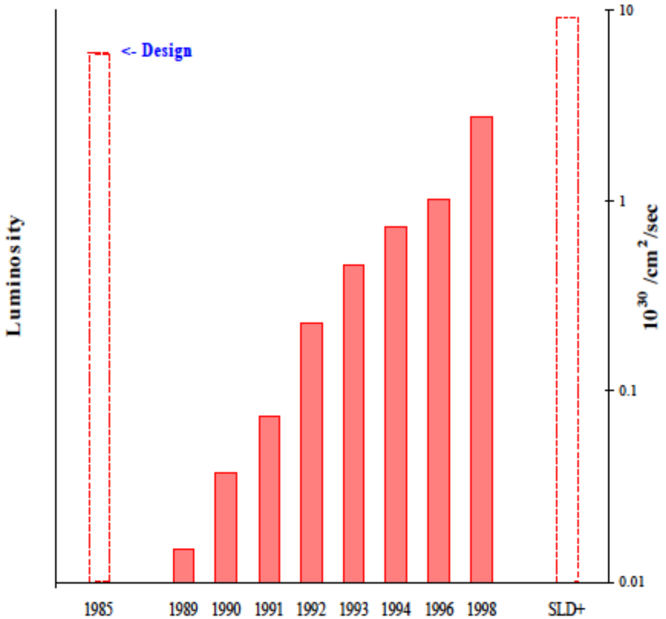
SLC at SLAC

- First linear e^+e^- collider
  - Construction started in 1983, experiments in 1989
- E_{cm}~90 GeV → Z peak
- Unique measurements thanks to highly polarized beam



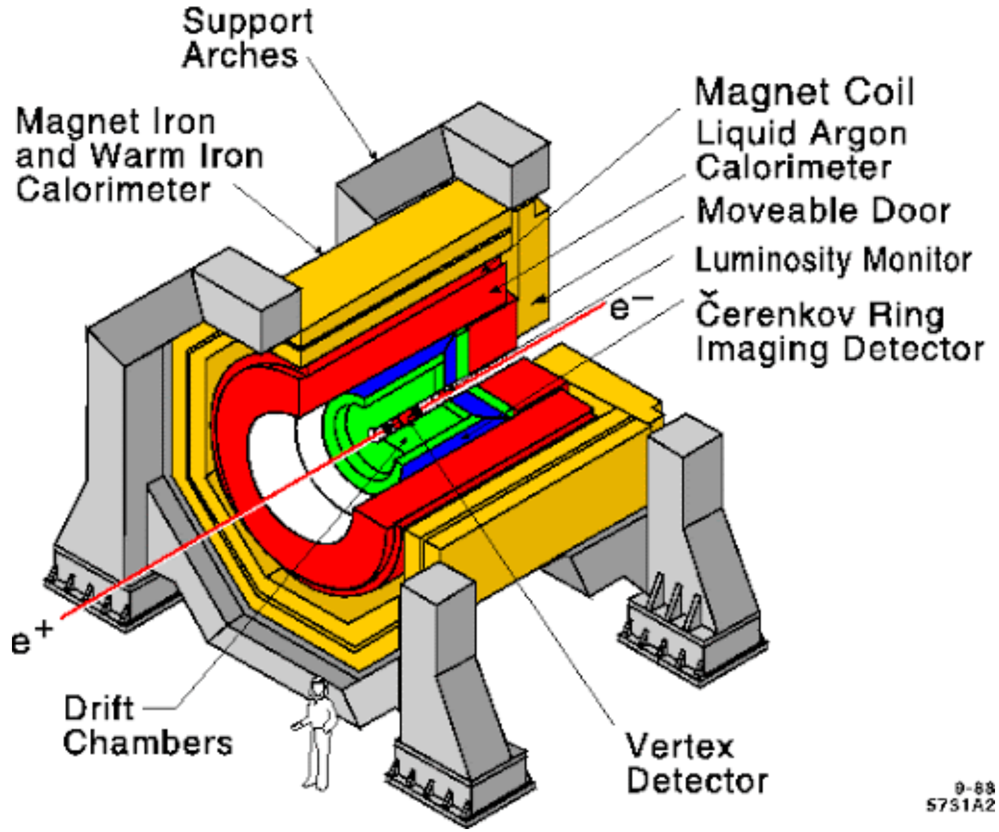


SLC luminosity



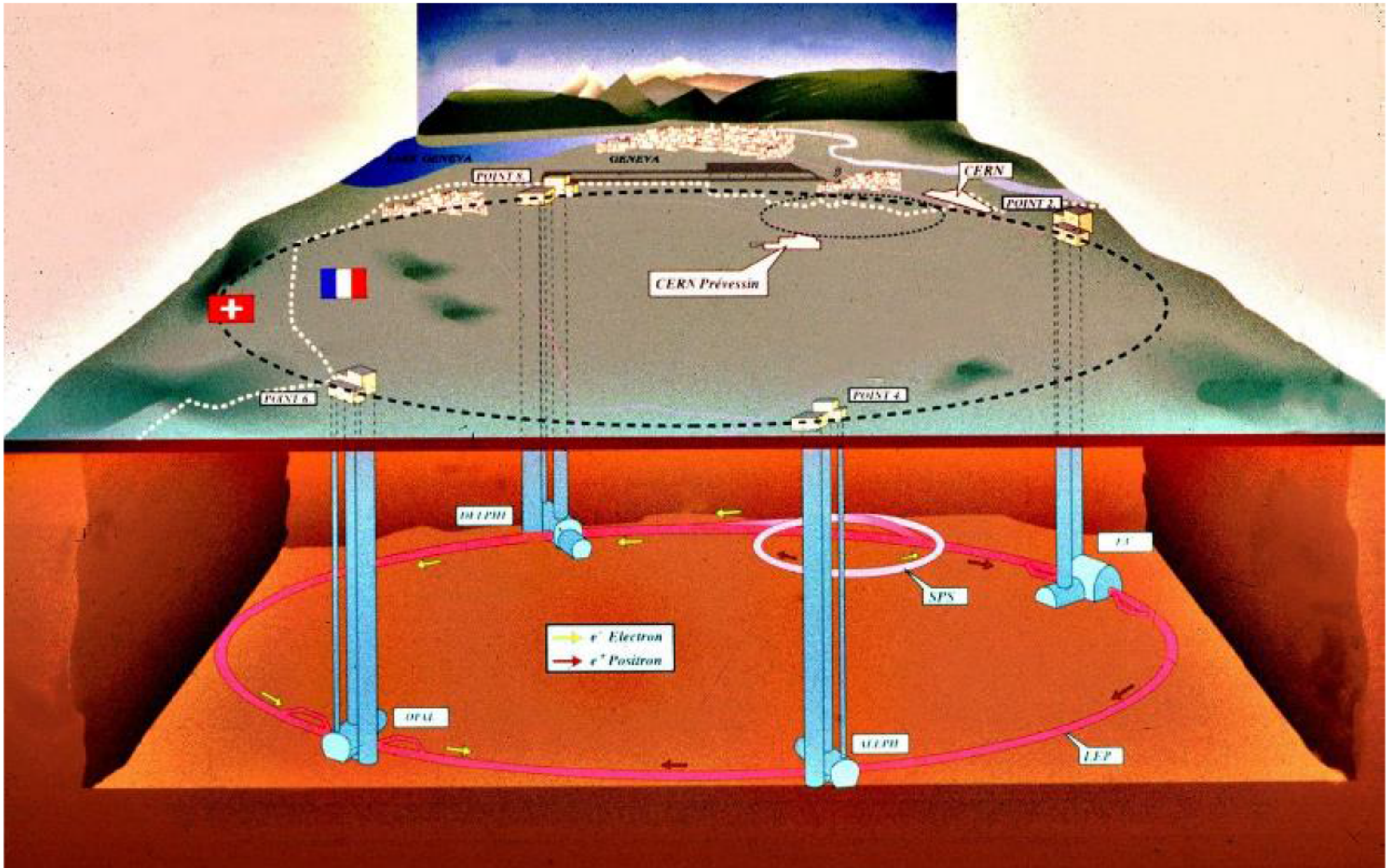
350‘000 Z events

SLD (1992-1998)



- Optimized for reconstruction of Z boson decays
- Silicon pixel detector for vertex reconstruction
  - Use of CCDs possible because of low collision rate (120 Hz)

LEP
Experiments: ALEPH, DELPHI, L3, OPAL

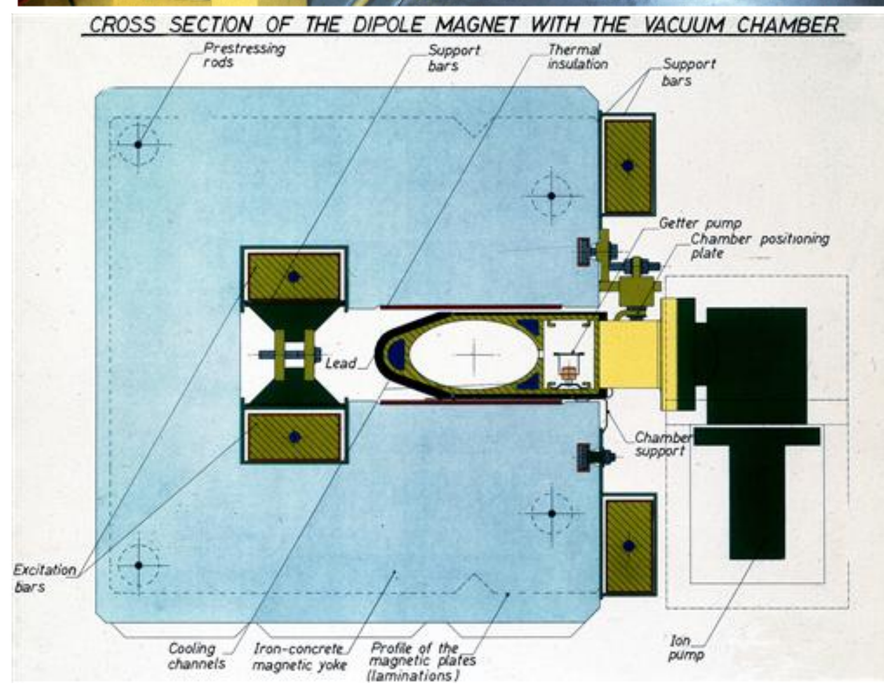


Tunnel (27km) built in 1983-1988: Largest civil engineering project in Europe

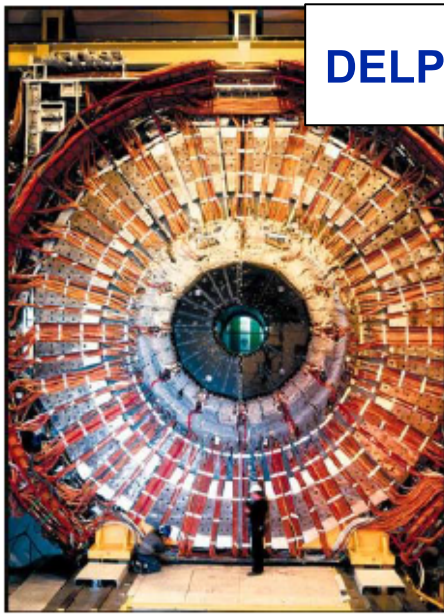
LEP

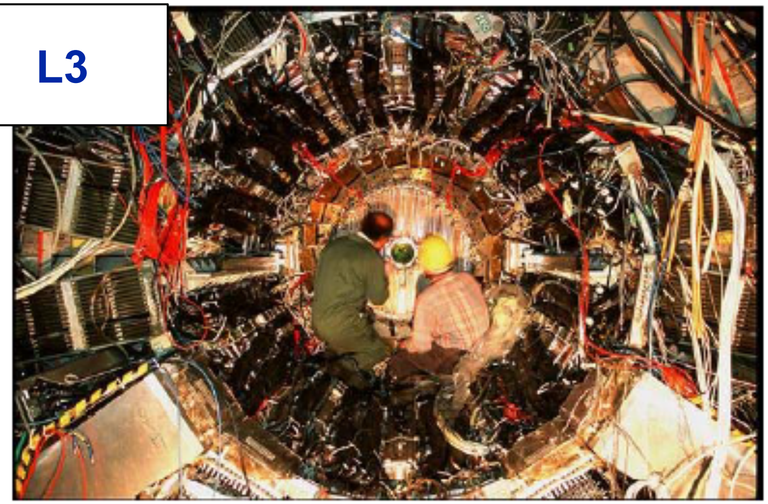
- e^+e^- collider
- Same magnets used for acceleration and storage of both beams
- B_{max} = 0.135T
- E = 104.5 GeV
- E_{inj} = 20 GeV
- 4x4, 8x8, 12x12 bunches
- 1.7×10^{11} e^+/e^- per bunch
- Bunch crossing rate of 450 kHz
- $L_{inst}^{max} = 1\times10^{32}cm^{-2}s^{-1}$

- LEP-I (1989-1995): Operated as Z factory with $\sqrt{s}$ ~ 91 GeV
- LEP-II (1996-2000): Operated at/above WW threshold up to $\sqrt{s}$ = 209 GeV

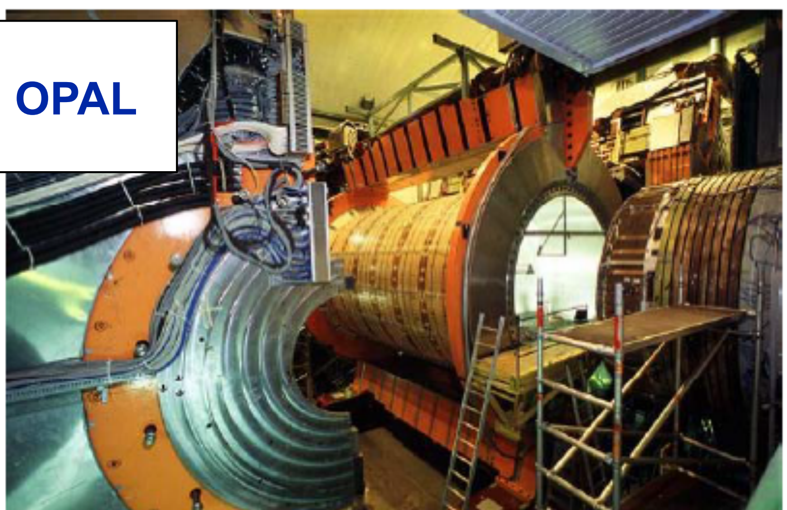


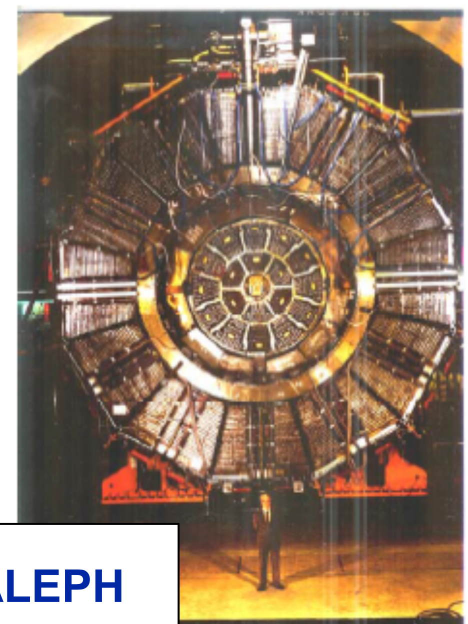
LEP experiments built by international collaborations





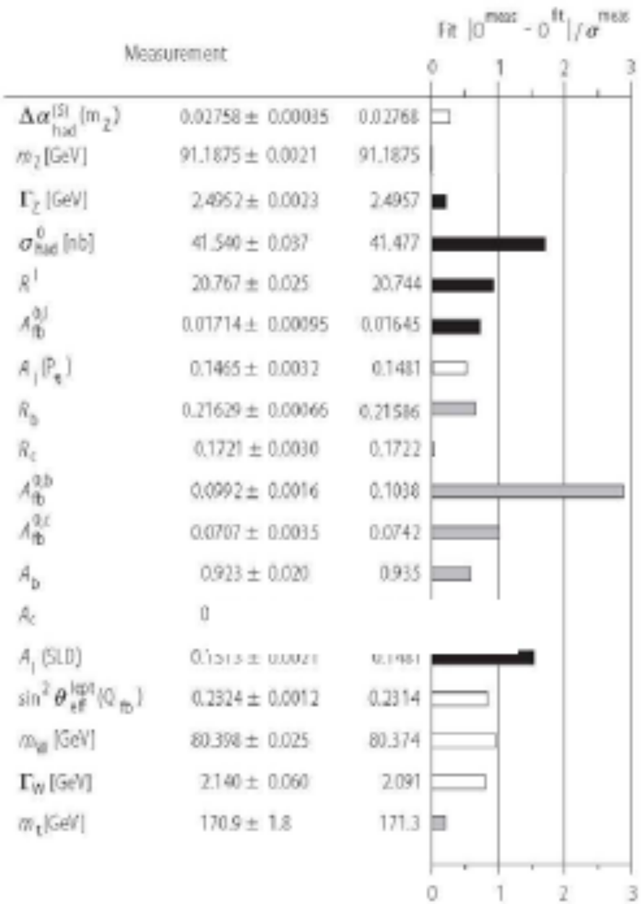
LEP Experiments



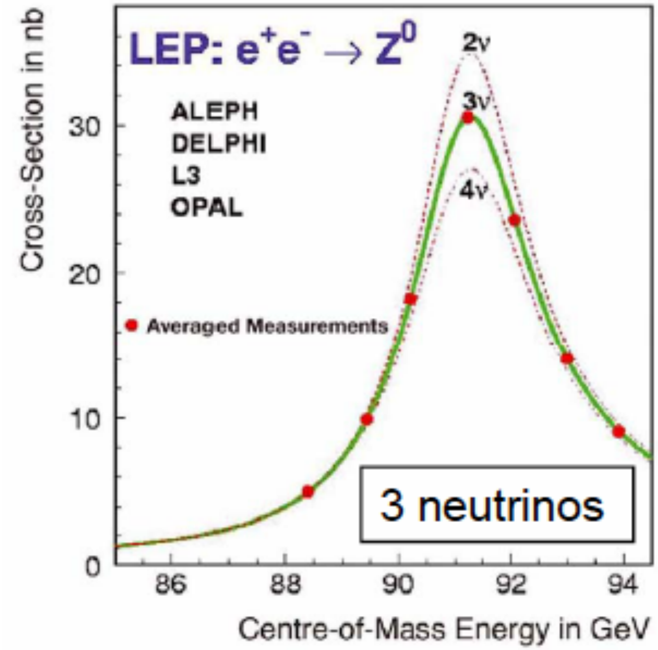


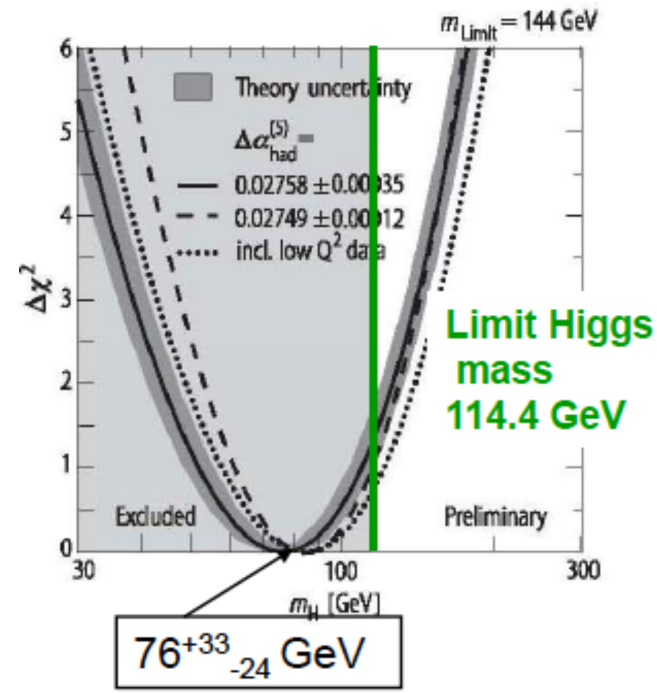
LEP results

- No sensations (top, Higgs, SUSY), but precision measurement
- LEP turned HEP into precision physics

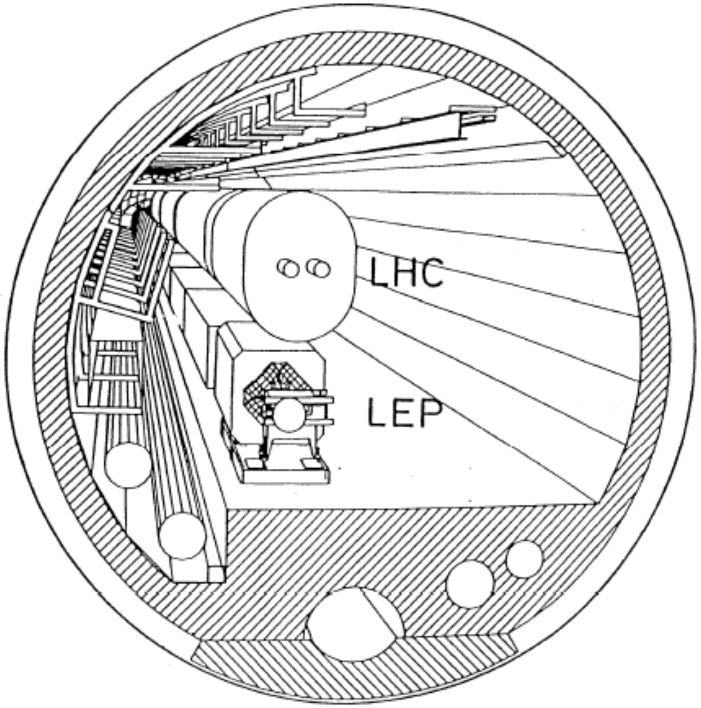


SM confirmed with <1%

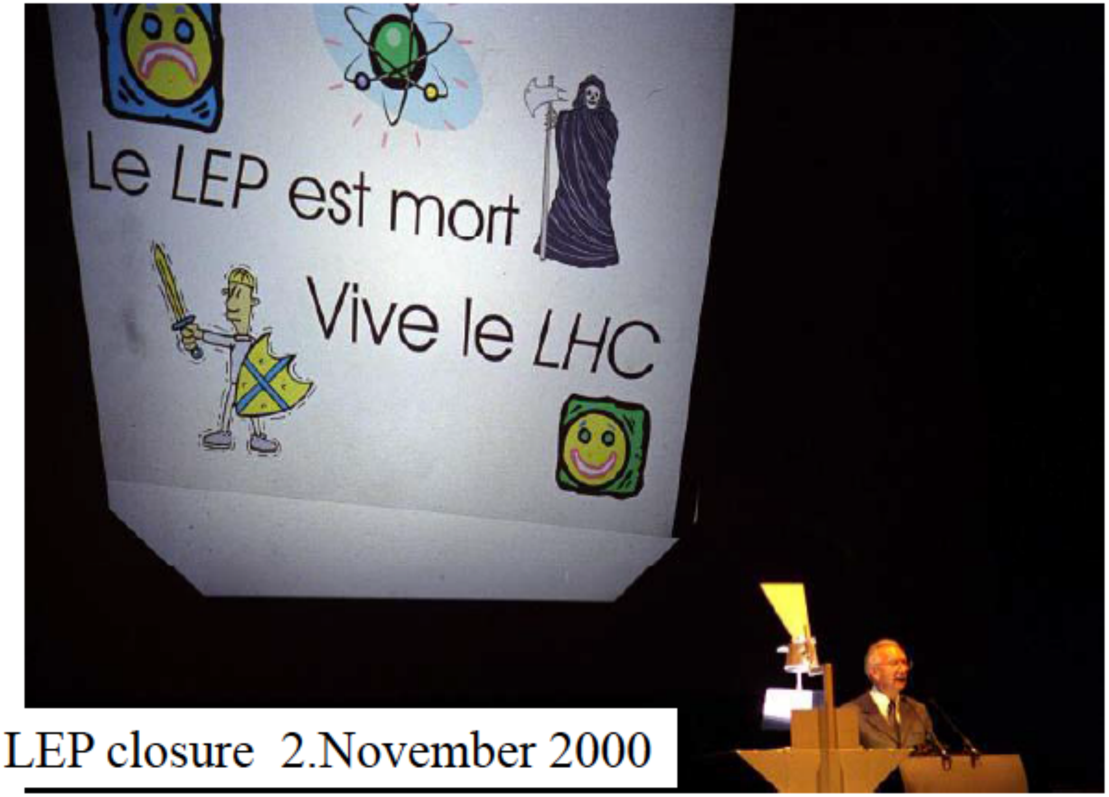




LEP stopped in 2000…



LARGE HADRON COLLIDER
IN THE LEP TUNNEL

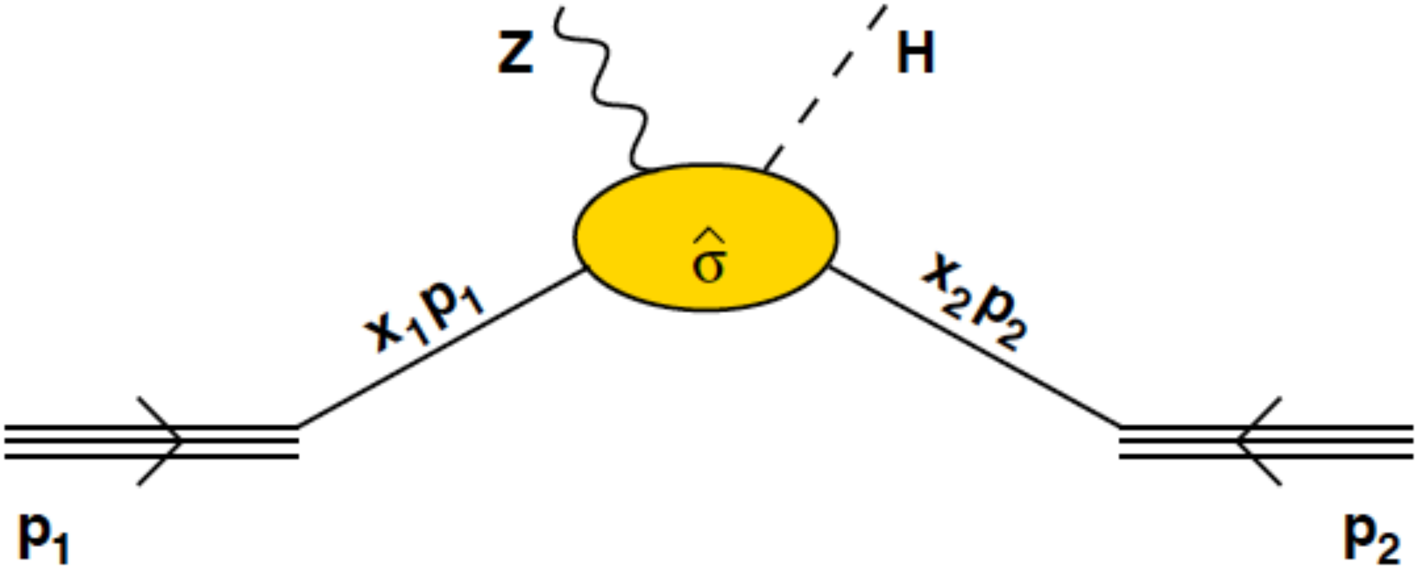


LEP closure 2.November 2000

→ Idea discarded…

Hadron colliders

Collisions at hadron colliders



- Calculation of cross section of an interaction process at a hadron collider can be factorized into:

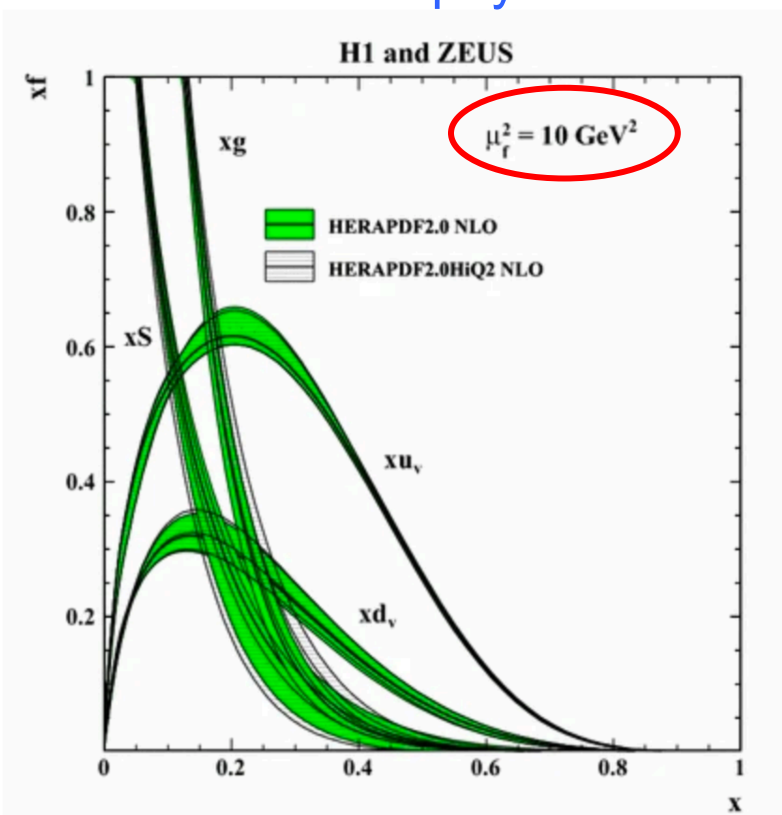
$$\sigma = \int dx_1 f_{q/p}(x_1, \mu^2) \int dx_2 f_{\bar{q}/\bar{p}}(x_2, \mu^2)\, \hat{\sigma}(x_1 p_1, x_2 p_2, \mu^2)\,, \quad \hat{s} = x_1 x_2 s$$

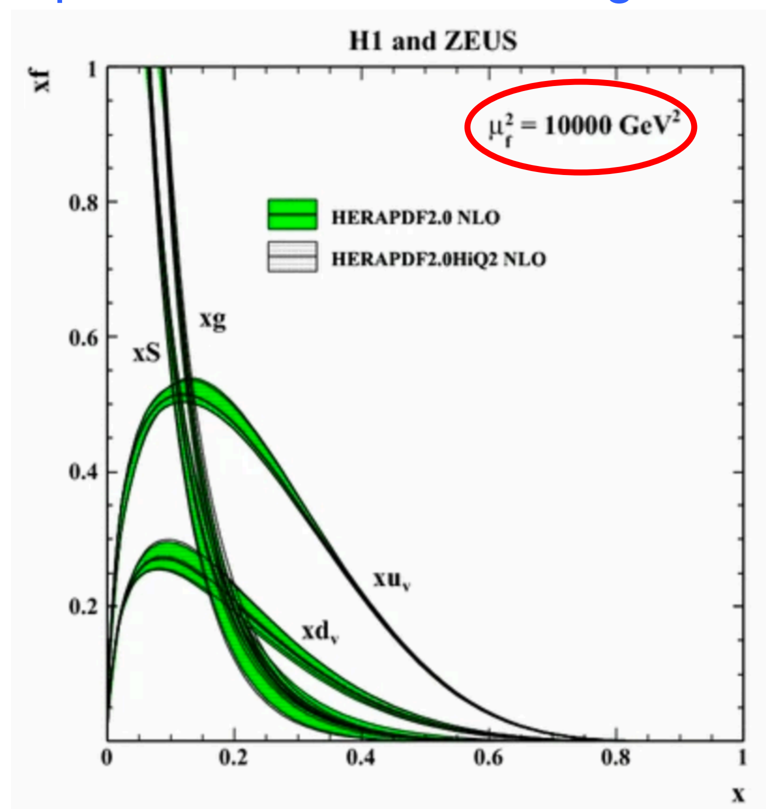
- Probability for extracting partons with momentum fraction x_1, x_2 (PDFs)
- Hard scattering cross section $\hat{\sigma}$ at $\hat{s}$ → calculable in pQCD

- Evaluated at factorization scale μ^2

Parton Distribution Functions (PDFs)

- PDFs: Probability for a parton to carry the fraction x of proton momentum
- Intrinsic property of the nucleon, process independent
- Dependence on Q^2
- Precise knowledge of PDFs crucial for physics at hadron colliders
  - Limits accuracy of SM predictions (e.g. Higgs boson production)
  - Reach of new physics searches depends on PDF knowledge at high x





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Properties of PDFs

***x*-dependence** of PDFs is not calculable in perturbative QCD

→ parametrise PDFs at the starting scale Q^2_0

***Q*^{2} dependence** is calculable in perturbative QCD:

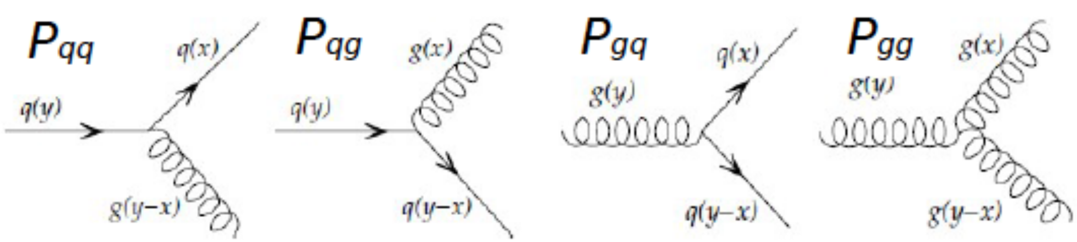
evolve PDFs using DGLAP equations to $Q^2 > Q^2_0$

DGLAP (Dokshitzer–Gribov–Lipatov–Altarelli–Parisi) evolution equations:

$$\frac{\partial q(x,Q^2)}{\partial lnQ^2} \propto \int_x^1 \frac{dz}{z}\left[q(z,Q^2)P_{qq}\left(\frac{x}{z}\right) + g(z,Q^2)P_{qg}\left(\frac{x}{z}\right)\right]$$

$$\frac{\partial g(x,Q^2)}{\partial lnQ^2} \propto \int_x^1 \frac{dz}{z}\left[q(z,Q^2)P_{gq}\left(\frac{x}{z}\right) + g(z,Q^2)P_{gg}\left(\frac{x}{z}\right)\right]$$

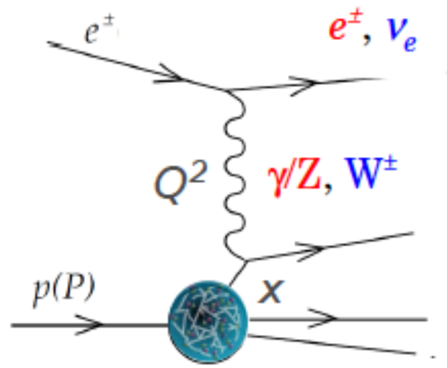
Probability via splitting functions:



Experimental data for PDFs

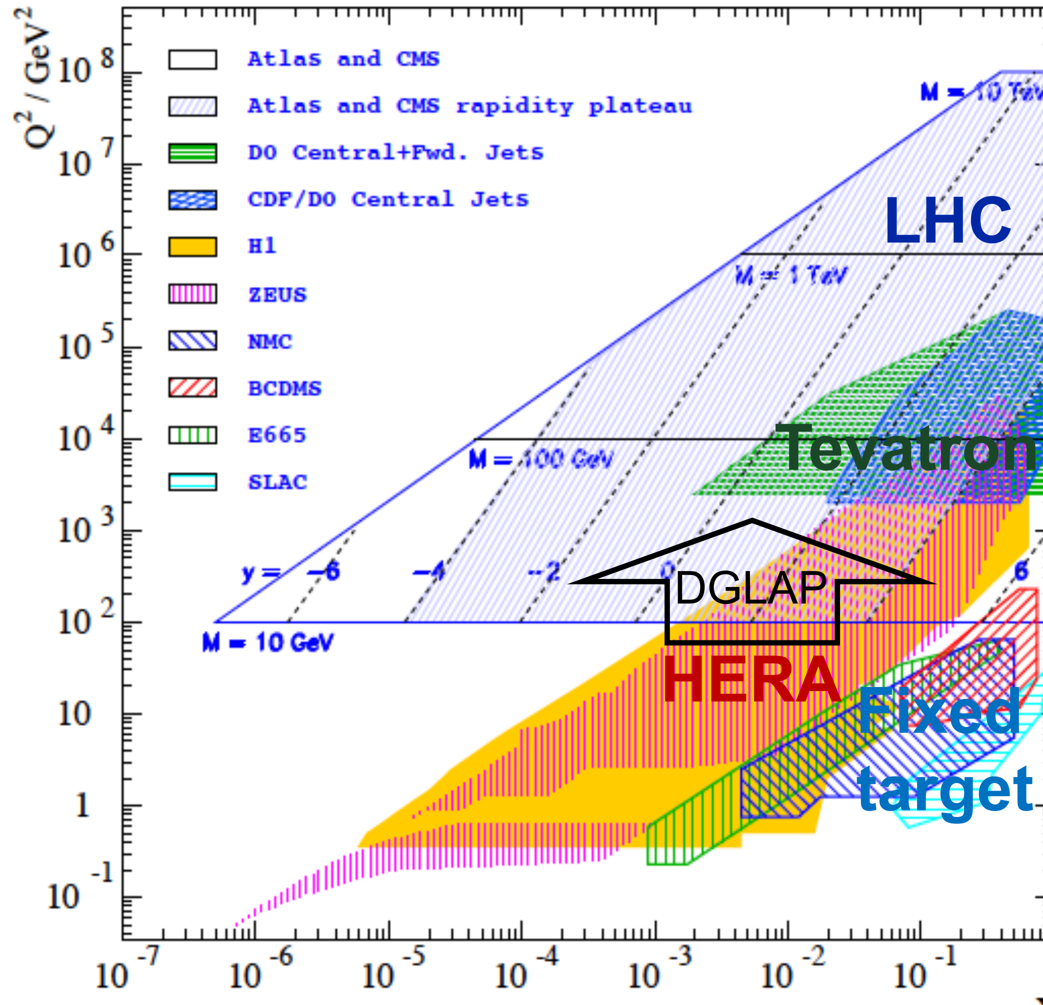
Deep Inelastic Scattering (**DIS**):

unique opportunity to study the structure of the proton (nucleon)



Neutral Current (NC): $ep \rightarrow eX$

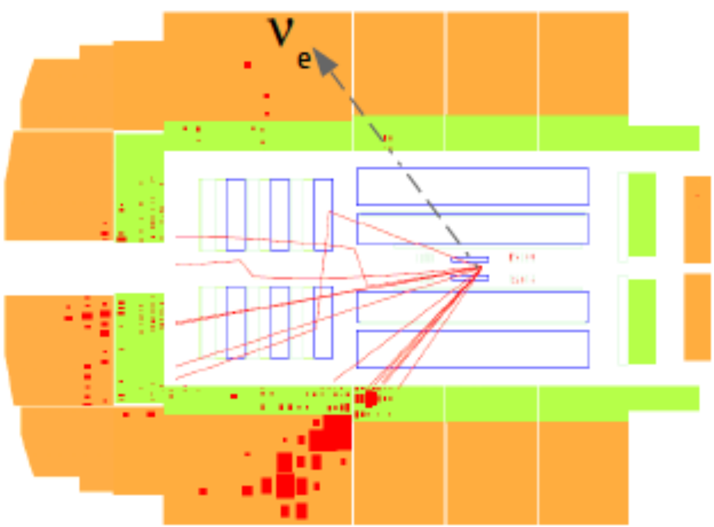
Charged Current (CC): $ep \rightarrow \nu X$



Braz. J. Phys. vol.37 no.2c São Paulo June 2007

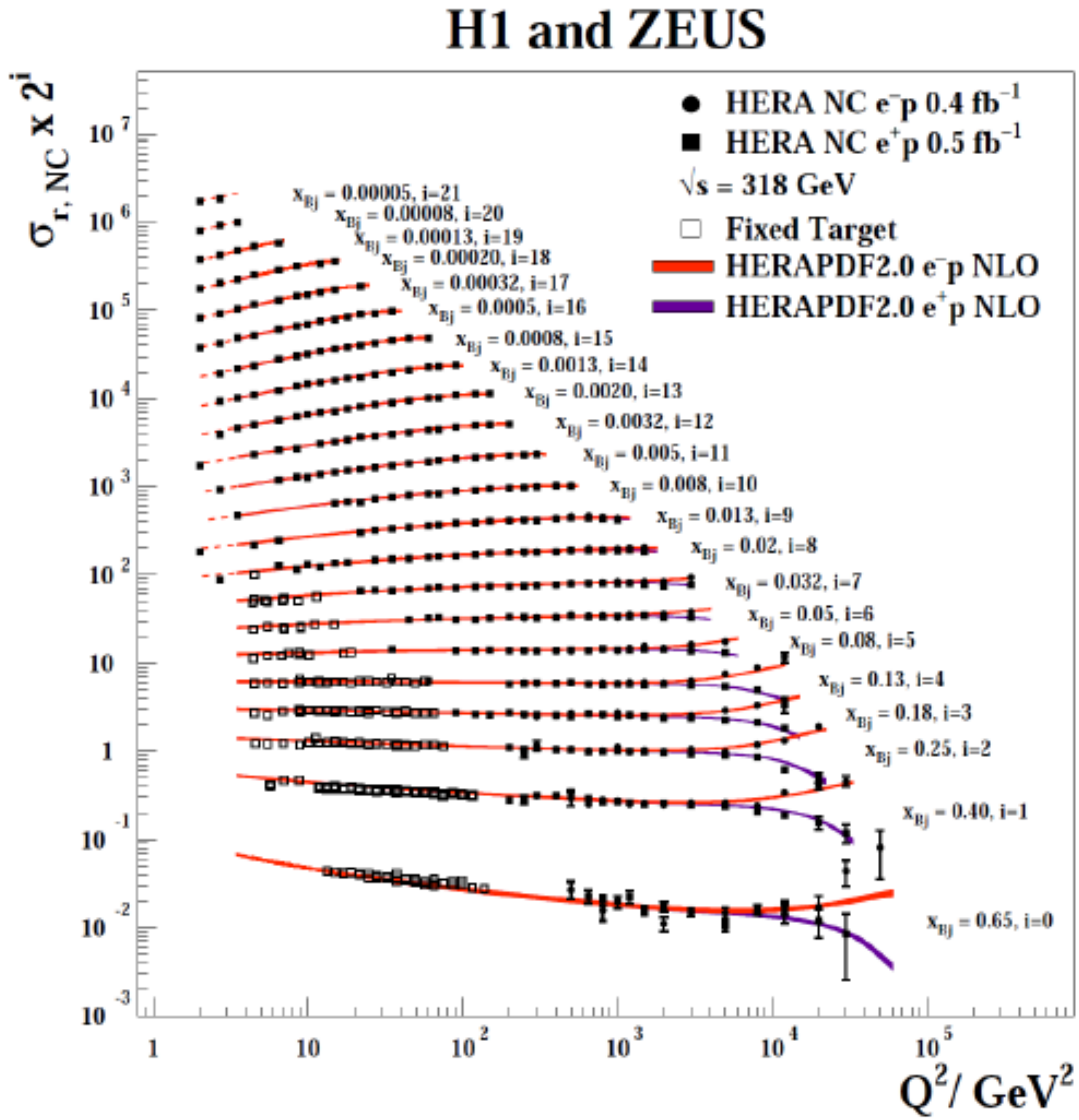
HERA (1992-2007)

- ep collider at DESY, Hamburg
- Up to now only collider in which two different types of particles were accelerated separately and then brought to collision
- Circumference of 6.3 km
- 4 experiments (H1, ZEUS, Hermes and HERA-B)



CC event in H1 detector

Legacy of HERA experiments



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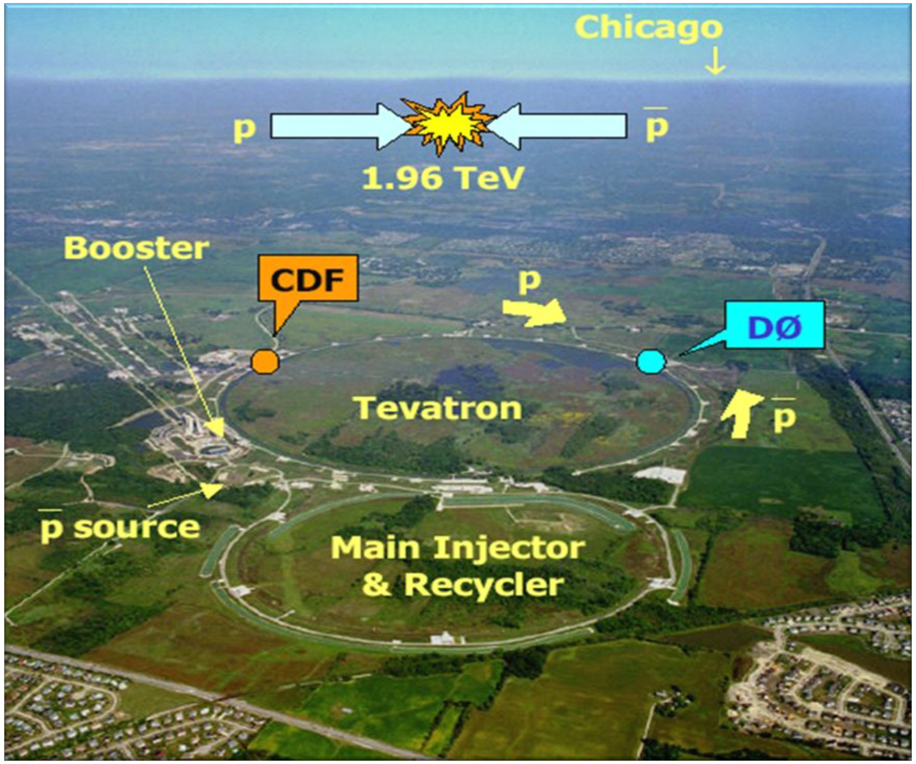
Tevatron

- 1972: Main ring (circumference of 6.3km) first operated with conventional magnets → 500 GeV proton beam
- 1981-1986 installation of superconducting magnets → 900 GeV proton beam → first machine to reach collisions at $\sqrt{s}$>1 TeV (hence the name)

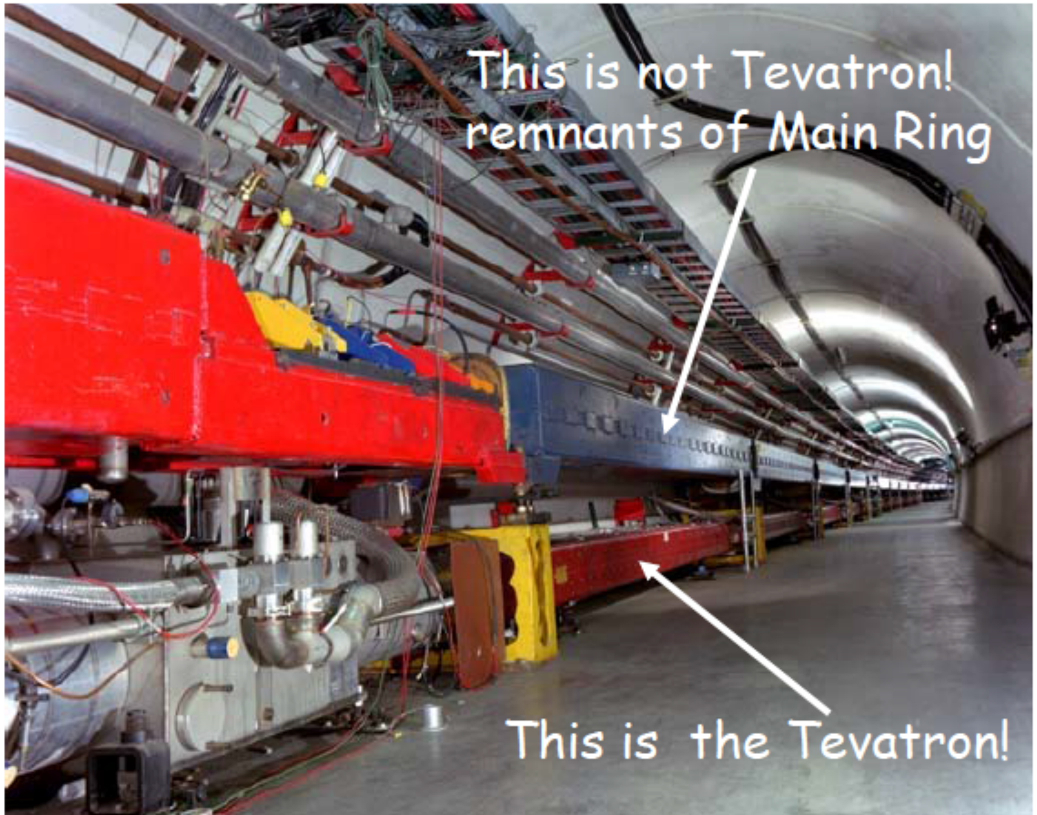
Run I 1992 - 1996
$\sqrt{s}$= 1.8 TeV
Integrated luminosity 110 pb^{-1}

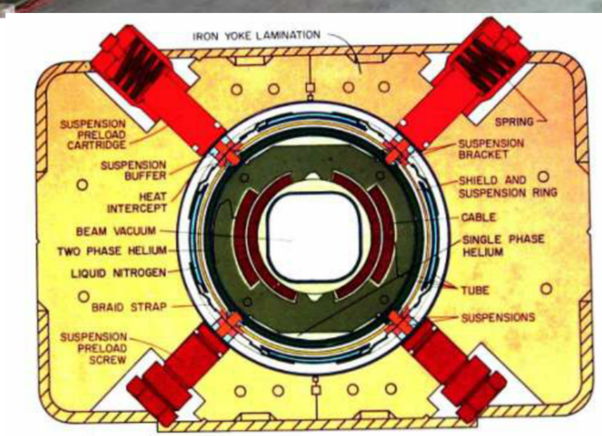
- 1993-1999 addition of main injector → 980 GeV proton beam, higher inst. luminosity

Run II 2001 - 2011
$\sqrt{s}$= 1.96 TeV
Integrated luminosity 1 fb^{-1}



Tevatron



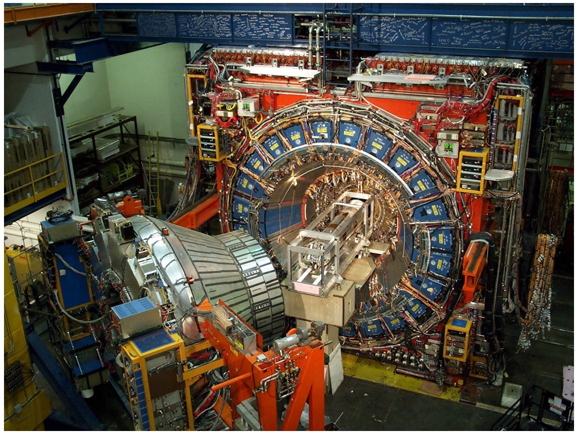


- $p\bar{p}$ collider
- Same magnets used for acceleration and storage of both beams
- Single beam pipe → $p/\bar{p}$ placed on different orbits
- $B_{max} = 4.5T$
- $E = 980$ GeV
- $E_{inj} = 150$ GeV
- 36 + 36 bunches
- $2.9(1.0)\times10^{11}$ $p(\bar{p})$ per bunch
- $L_{inst}^{max} = 4\times10^{32}cm^{-2}s^{-1}$

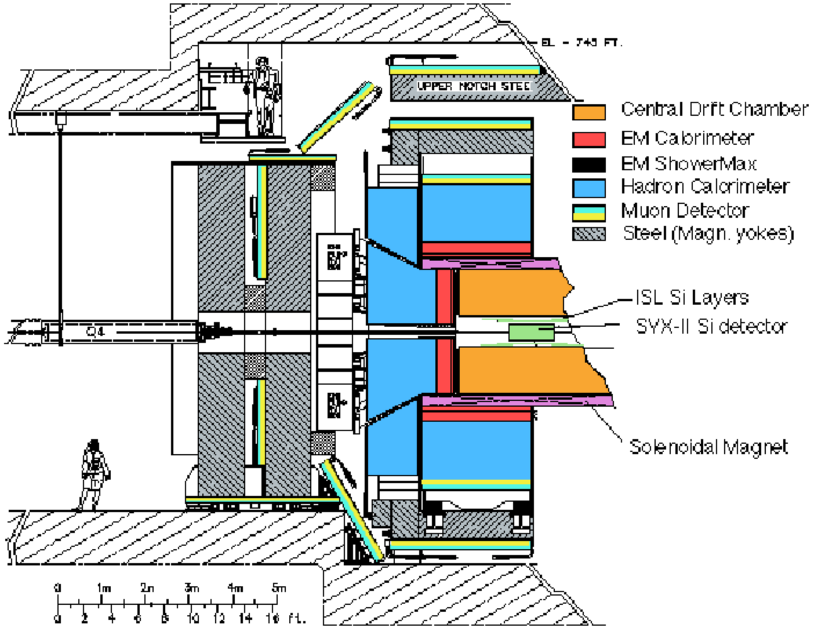
Tevatron experiments

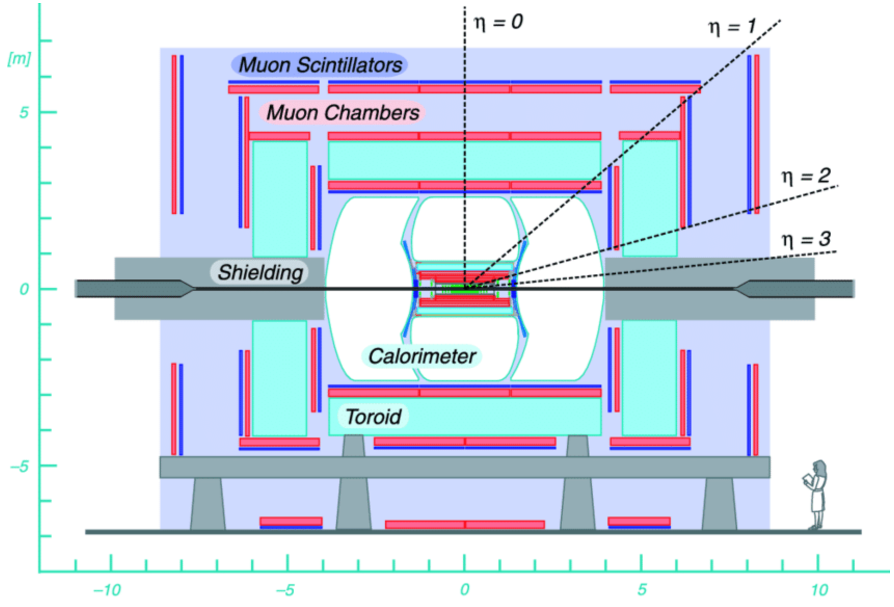
- Two multipurpose experiments CDF and D0
- Tracking and silicon vertex detector added for Run 2

CDF



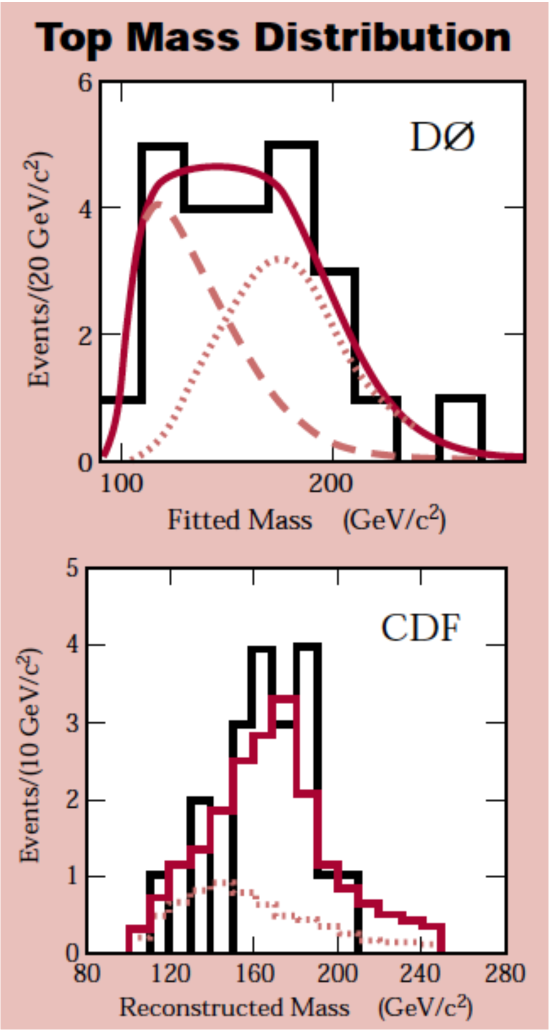
D0



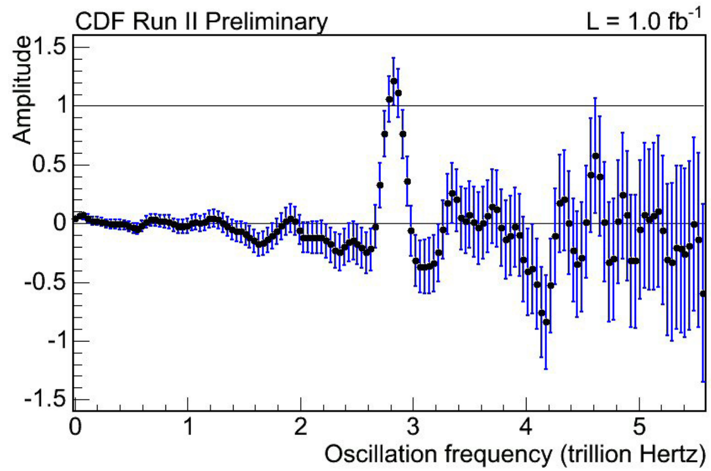


Legacy of Tevatron experiments

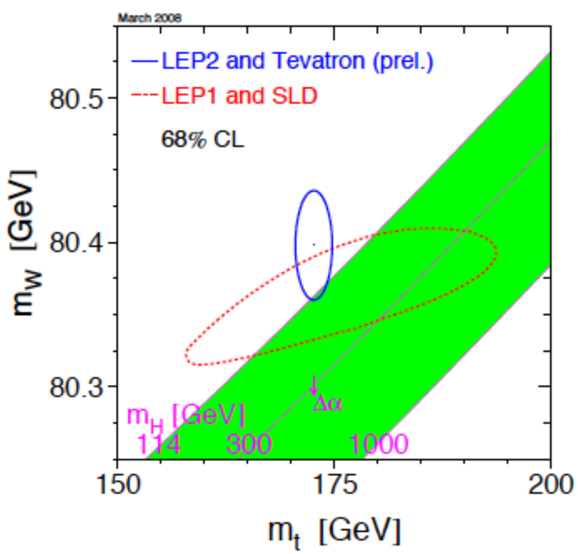
Top quark discovery 1995

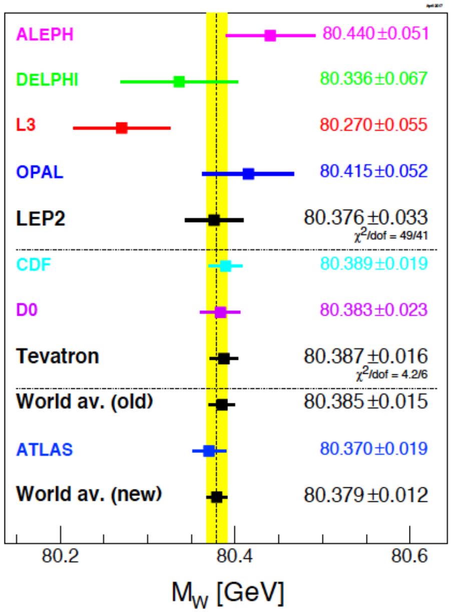


Discovery of B_s oscillations 2006



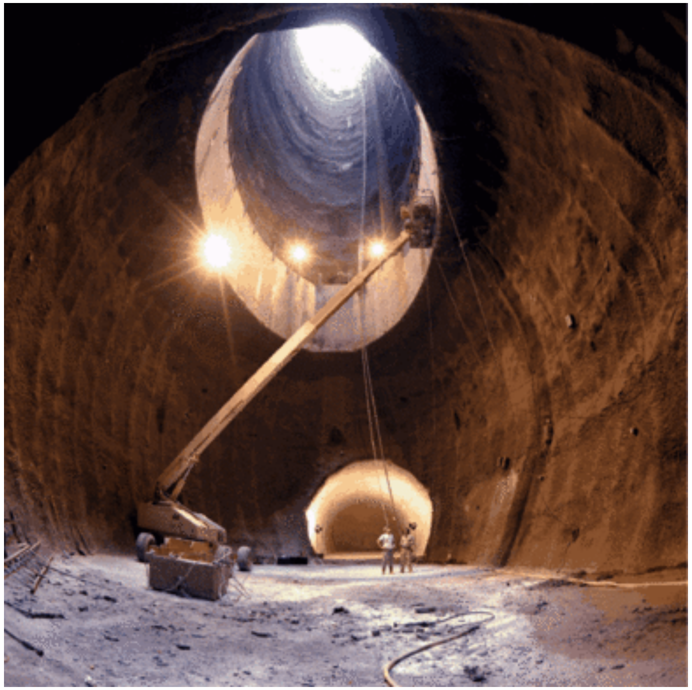
W mass measurement 2008





Superconducting Super Collider (SSC)

- SSC proposed by US HEP community and approved by President Reagan in 1987
  – 20+20 TeV pp collider in 87 km long tunnel in Texas
- Asked for international participation because of high cost
  – Denied as no participation in the design was possible
- 22.5 km of tunnel bored by 1993 when project got cancelled by US Congress
  – Many reasons…
- “Great tragedy of science”



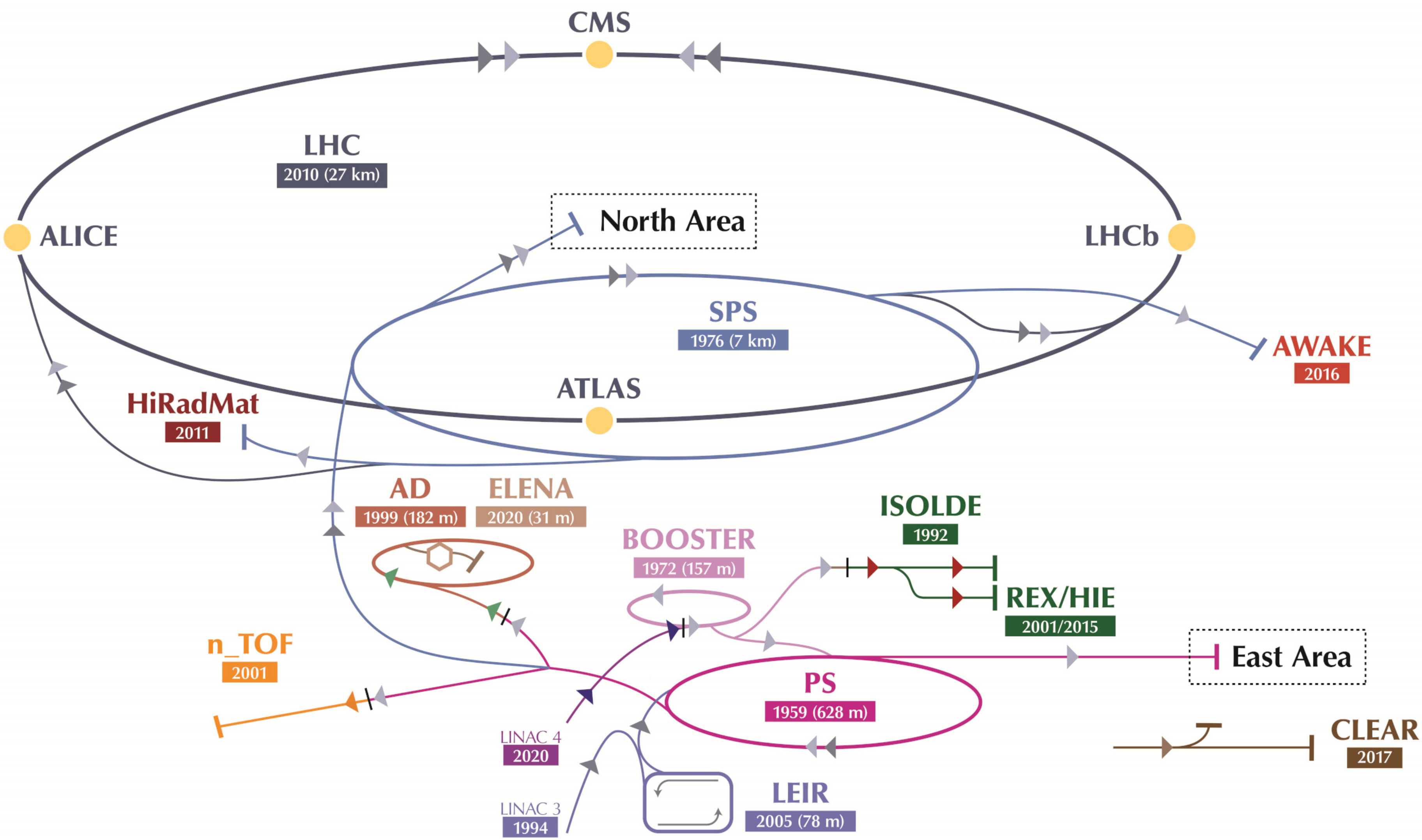
The Large Hadron Collider (LHC)

27 km circumference proton-proton collider at CERN

Largest and highest energy accelerator ever built

Started operation in 2010

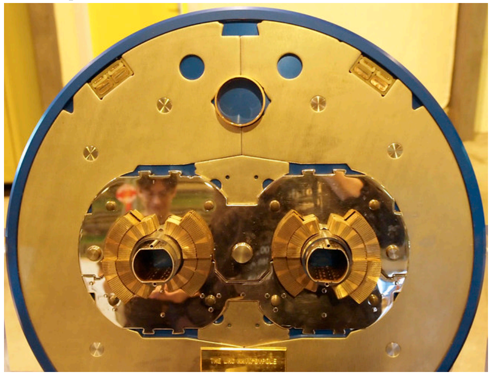
CERN accelerator complex



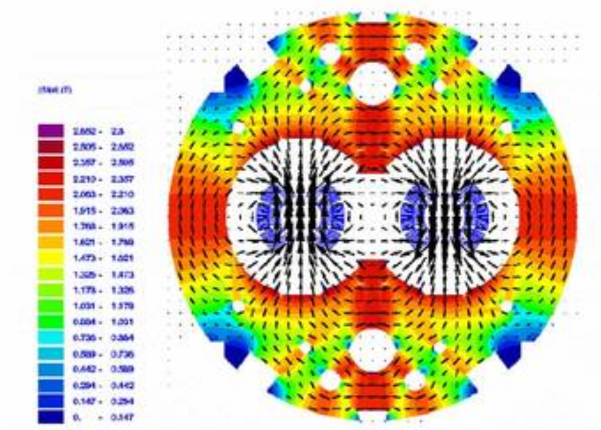
LHC

- 9300 magnets
- 1232 dipole magnets
- B_{max} = 8.3T
- "2 in 1" concept: both beams share same mechanical structure and cryostat (1.9K)
- E = 7 TeV
- E_{inj} = 450 GeV

Dipole cross section

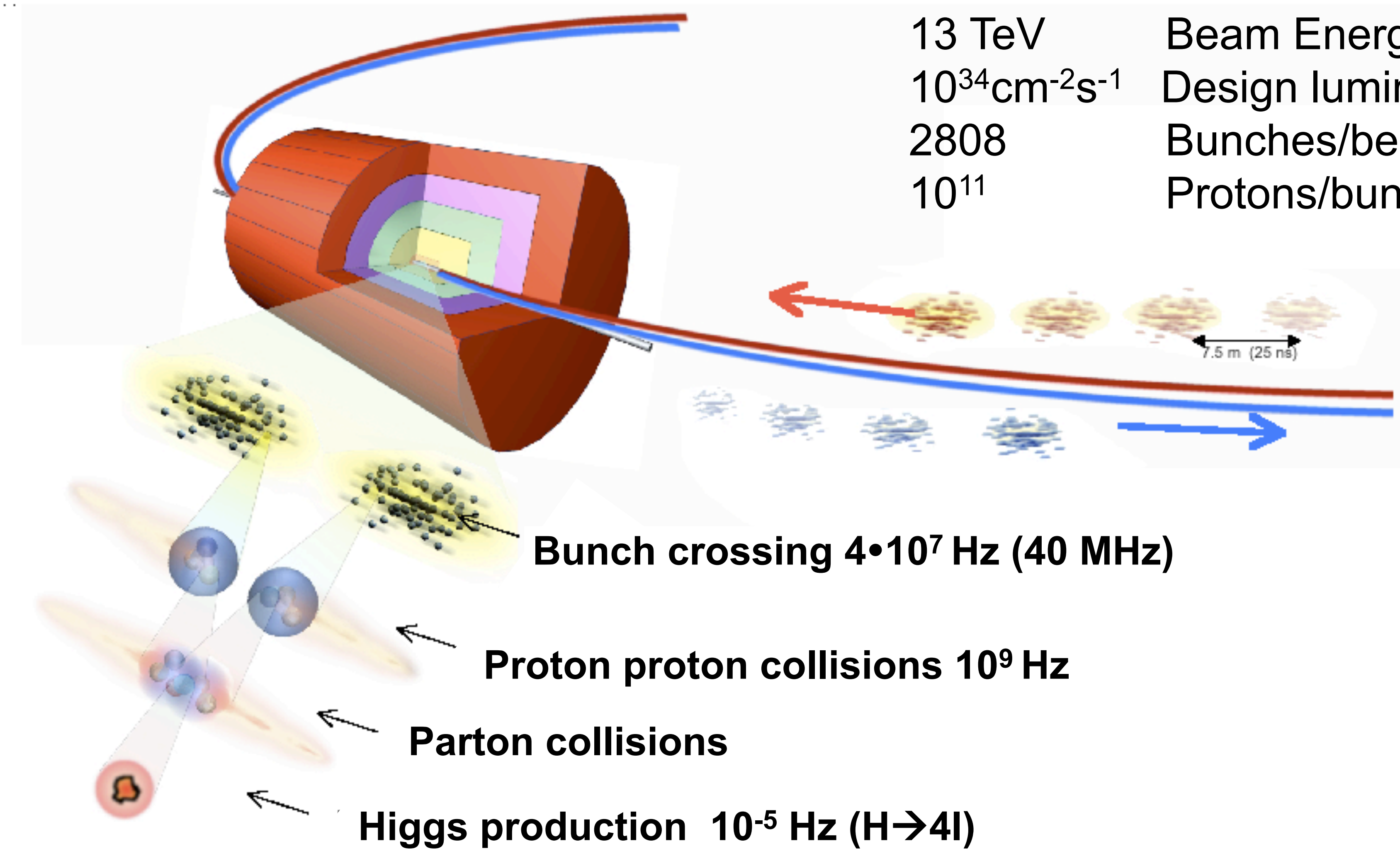


magnetic field configuration

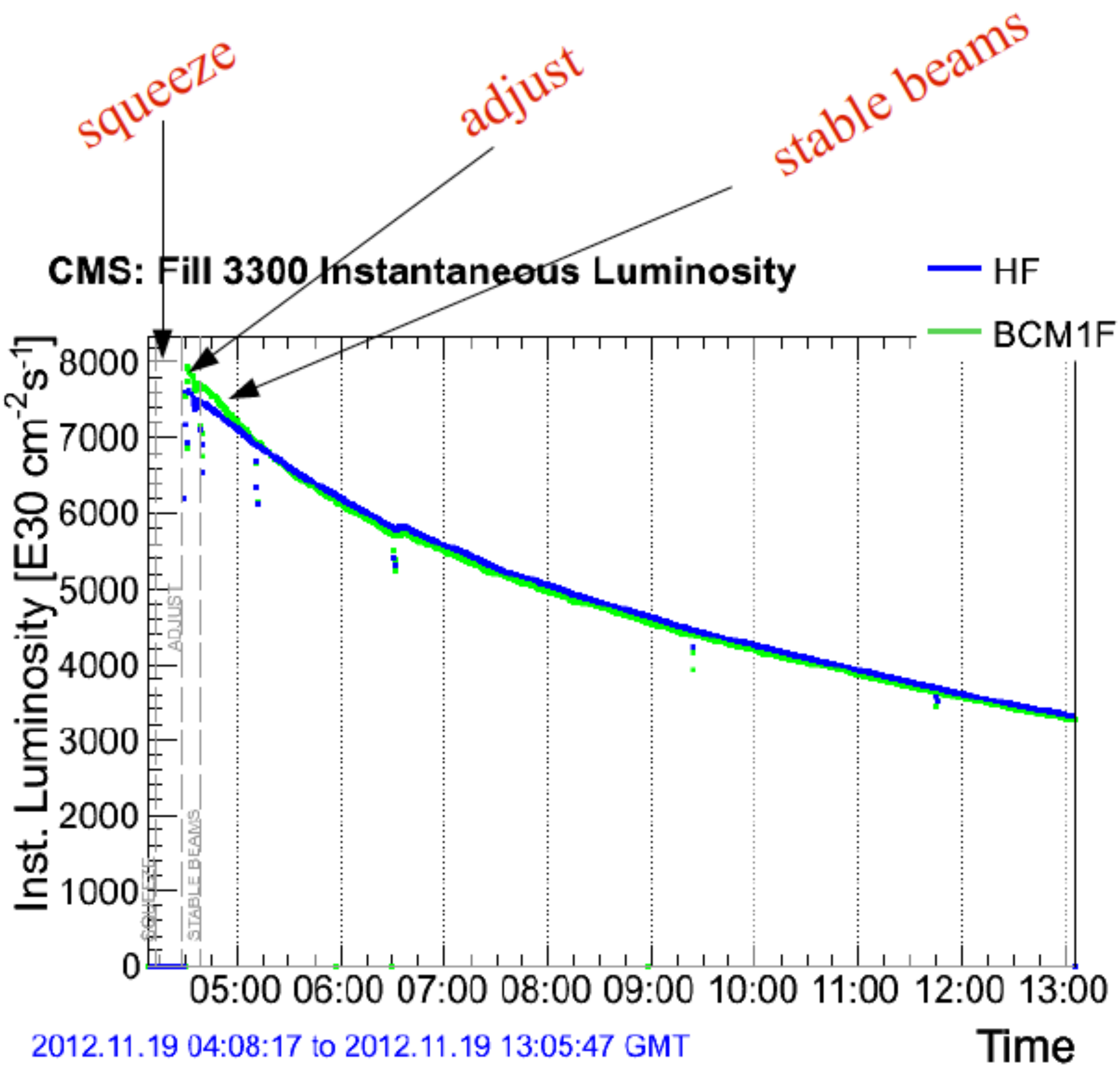


LHC parameters

13 TeV	Beam Energy
$10^{34} cm^{-2}s^{-1}$	Design luminosity
2808	Bunches/beam
10^{11}	Protons/bunch

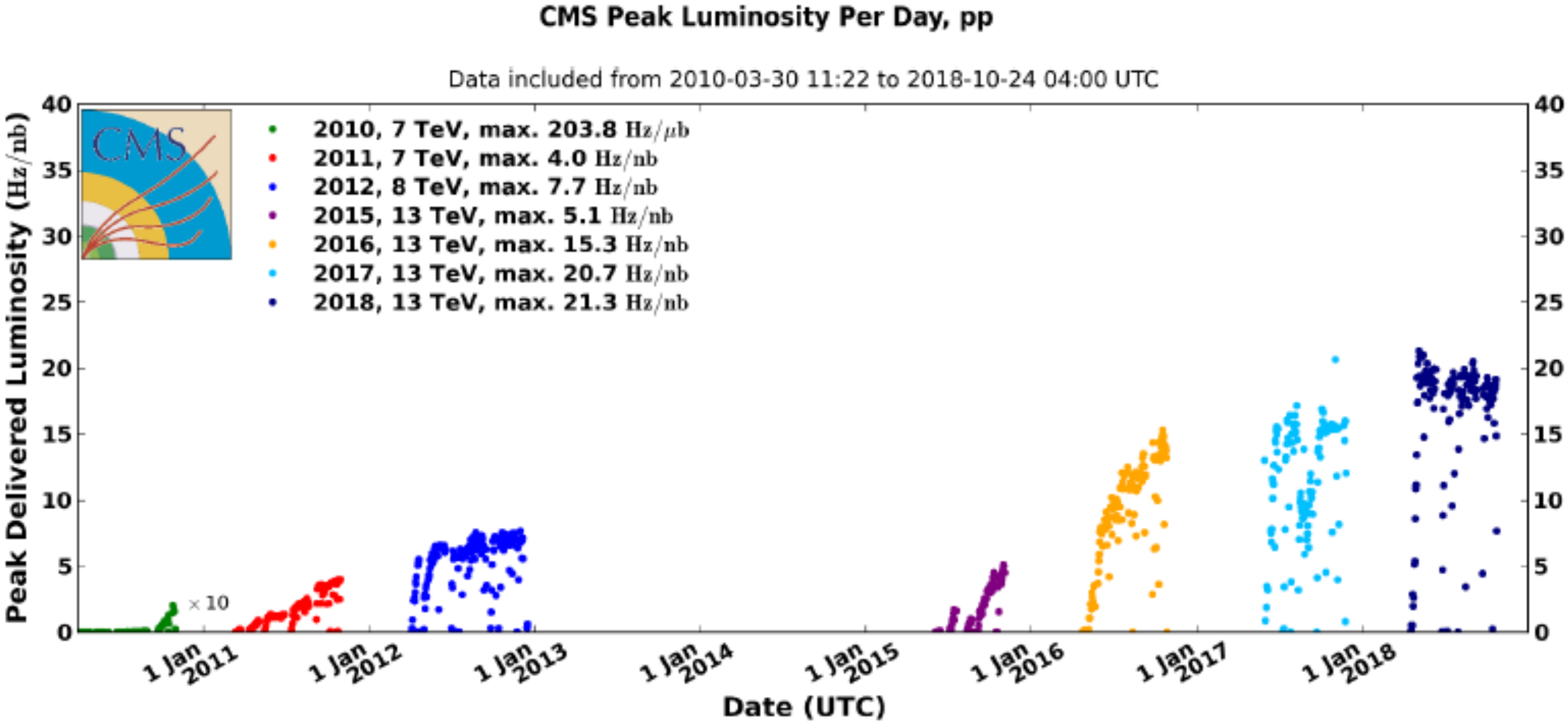


LHC Fill



- An LHC fill usually lasts a few hours
- After injection and acceleration, the beams are
  - first, focused
  - then, brought into collision
- LHC then "declares stable beams" → experiments start data-taking
- Luminosity decreases over the course of the run
- Divide run into "luminosity sections" (also called "luminosity blocks")

LHC luminosity



1 Hz/nb = $10^{33} cm^{-2} s^{-1}$

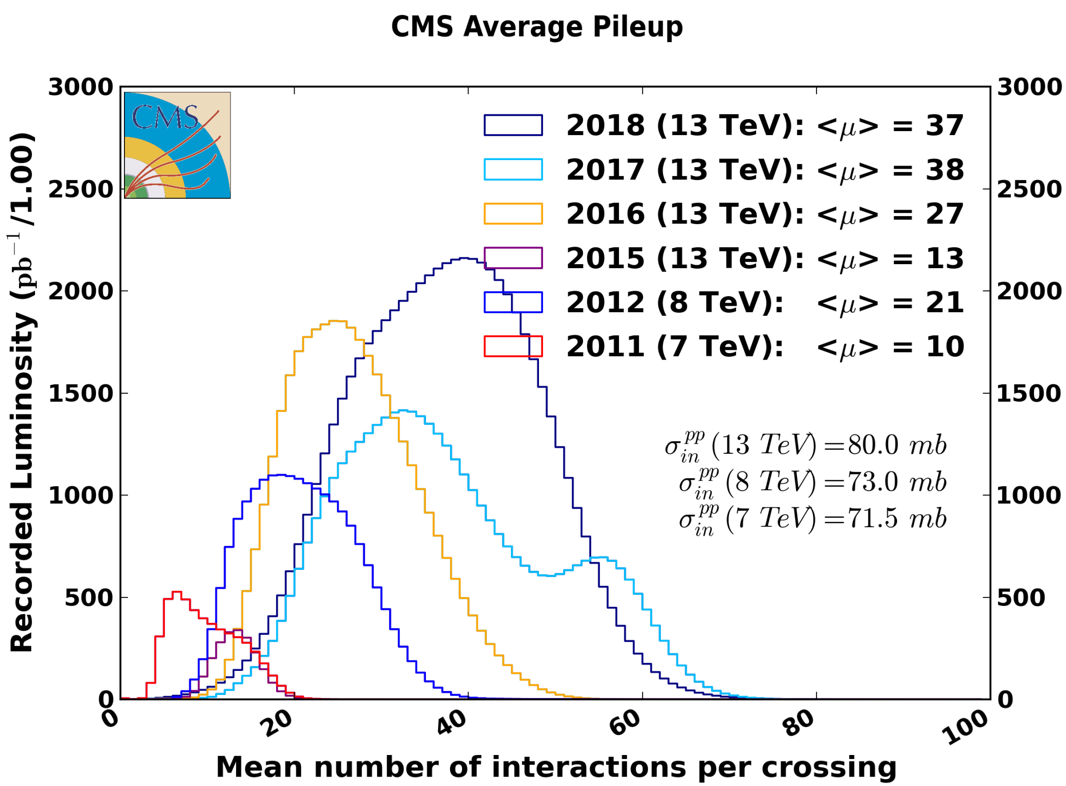
Pileup

- Average number of proton-proton collisions per bunch crossing

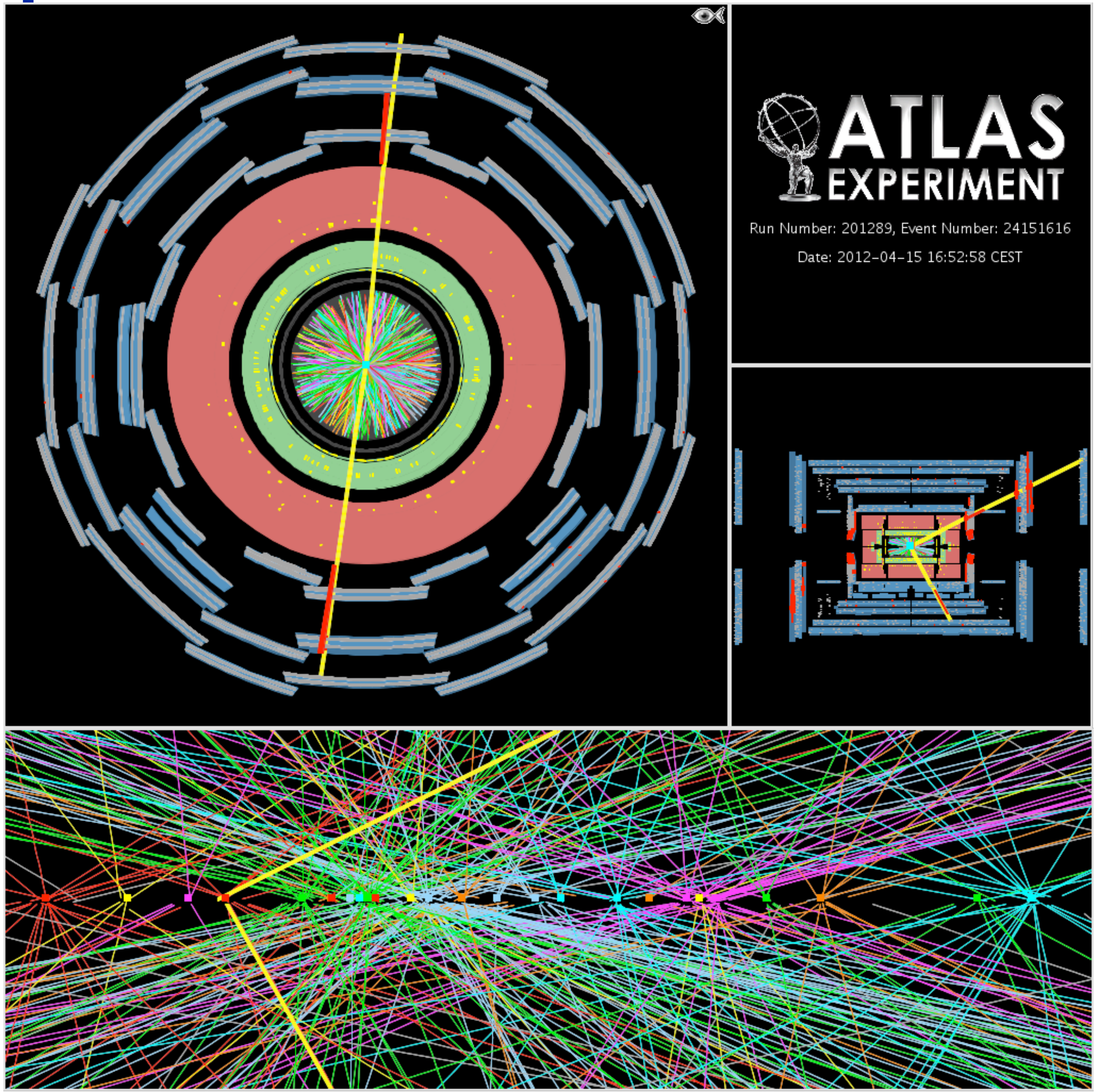
$$\mu(t) = \frac{\sigma \mathcal{L}(t)}{f n_b}$$

- s: inelastic proton-proton cross section
- L: instantaneous luminosity
- f: revolution frequency
- n_b: number of bunches

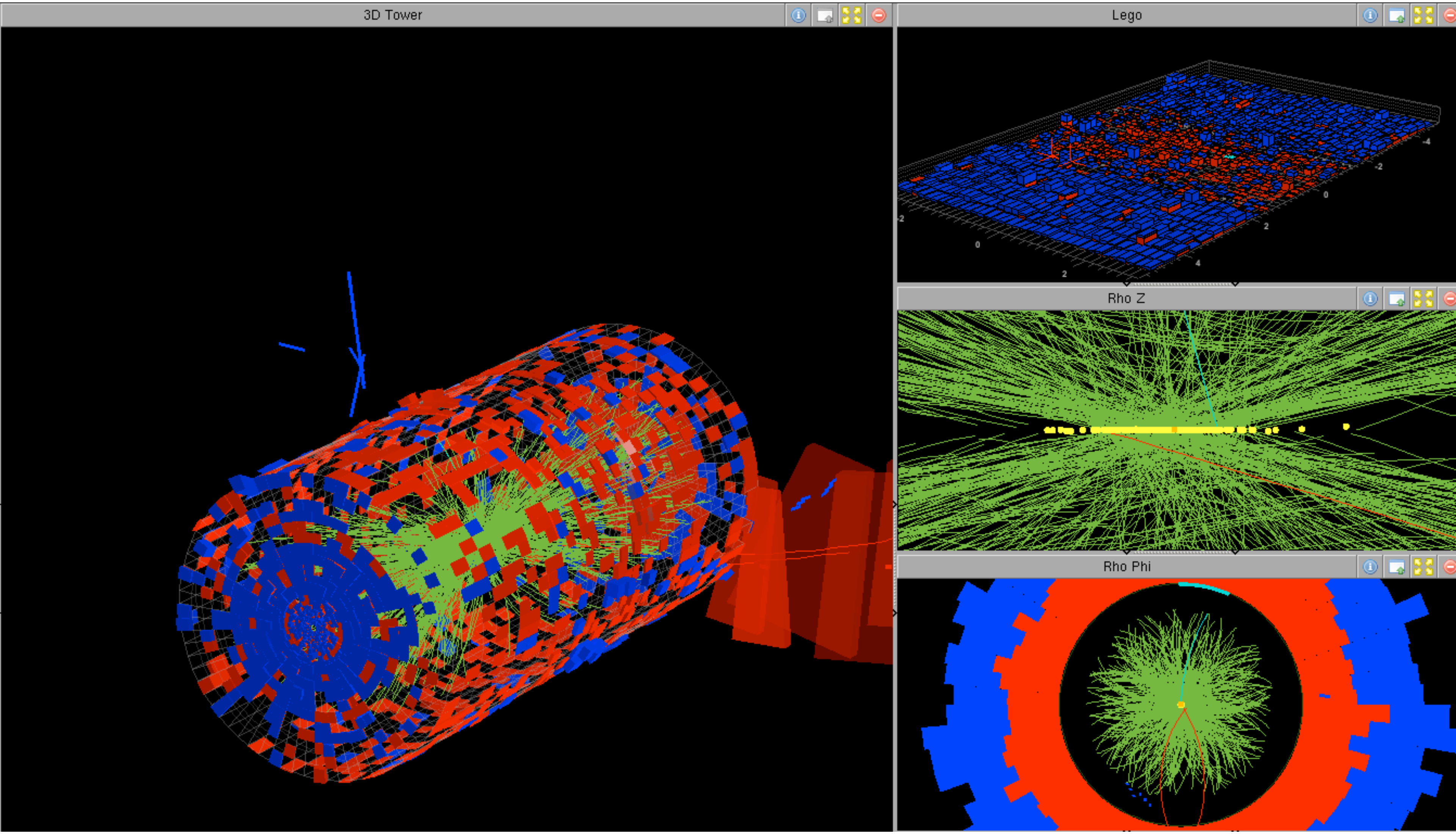
→ Major challenge for physics at the LHC experiments



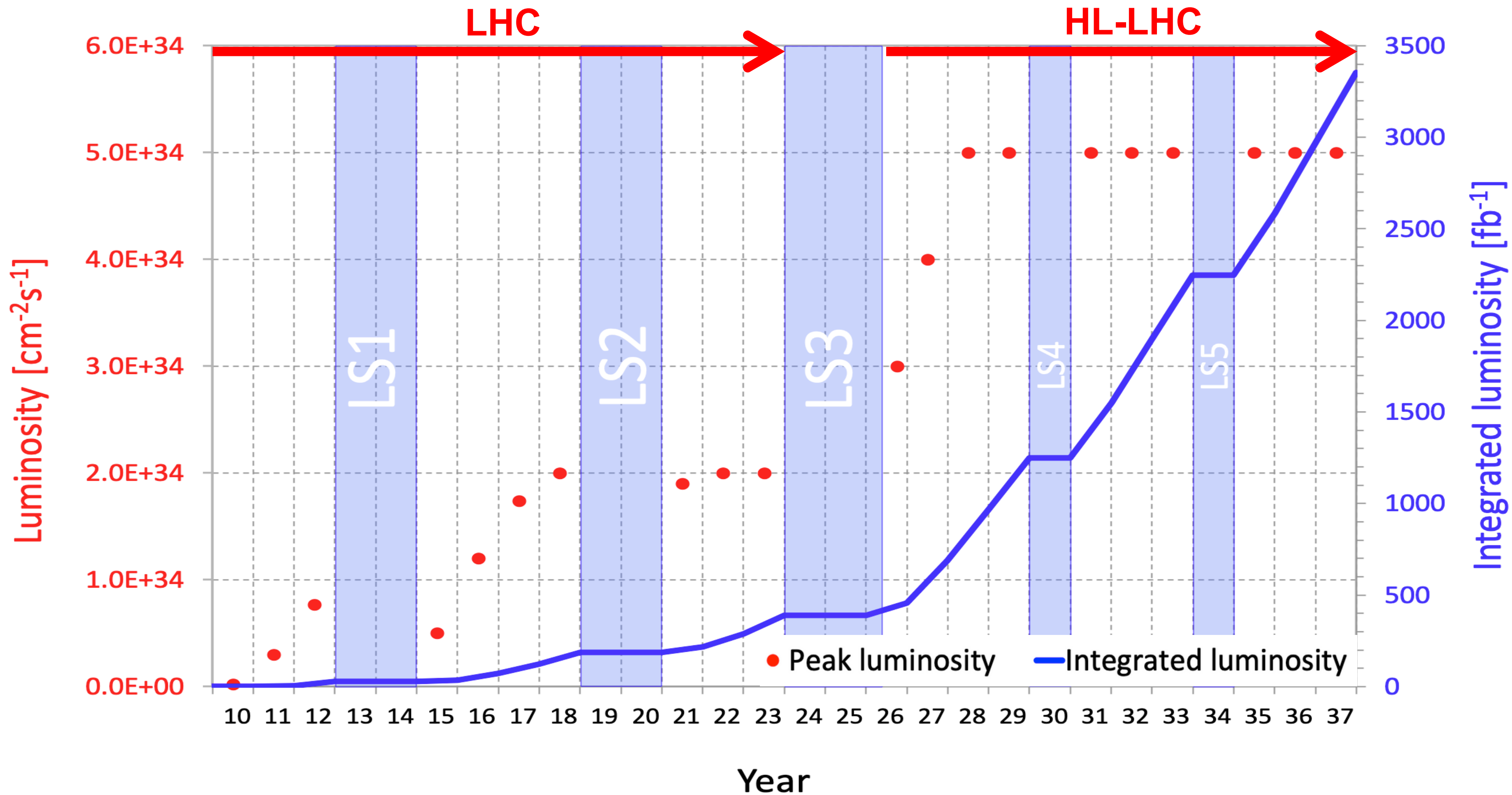
Pileup in ATLAS



Pileup in CMS



From LHC to HL-LHC



- High-luminosity LHC upgrade enables experiments to increase data set by one order of magnitude!

→ Need improved detectors to make best use of it in physics analysis

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