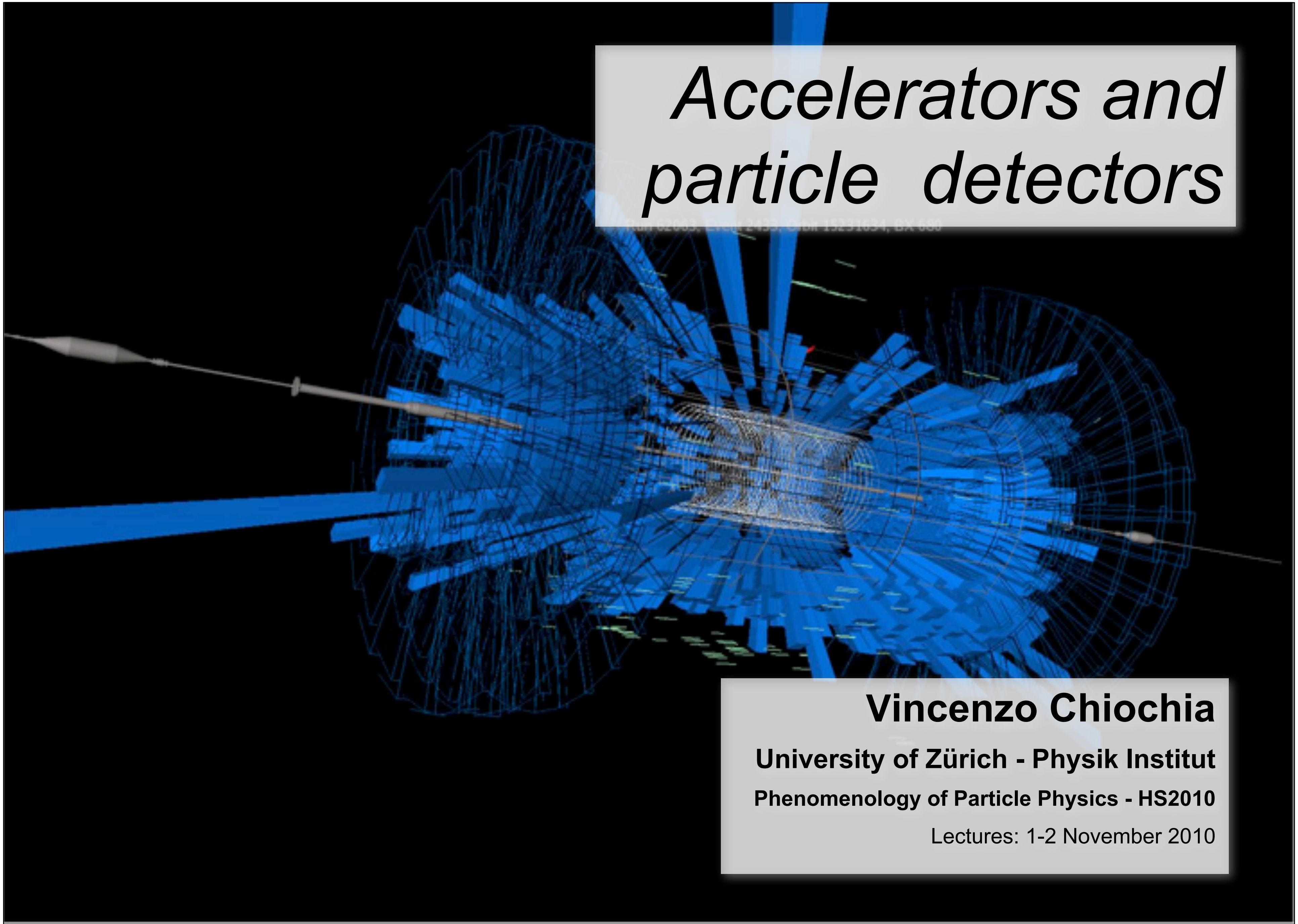

Accelerators and particle detectors

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Phenomenology of Particle Physics - HS2010

Lectures: 1-2 November 2010

Lectures outlook

- Introduction to particle accelerators and detectors
  - Basic principles of particle accelerators
  - Fixed target and collider experiments
  - Center of mass energy
  - Luminosity, Cross section, Event rates
  - Basic building blocks of a particle physics experiment
  - Momentum measurement
- Data analysis tools and kinematics:
  - Rapidity
  - Momentum conservation:
    - Transverse momentum, missing momentum
  - Invariant mass

Introduction

- Modern techniques in experimental particle physics can be divided into:
  - **Non accelerator-based** experiments
    - Examples: Cosmic rays, solar and atmospheric neutrinos, searches for dark matter
  - **Accelerator-based** experiments
    - Example: fixed target experiments, particle colliders

Particle accelerators: motivations

- Fundamental tool for research in physics
- Main parameter is the **beam energy**:
  - More energy → **Shorter wavelength**
    - Can investigate structures with size $\lambda = h/p$.
  - More energy → **Can produce new particles**
- Accelerate beam of stable particles (e.g. protons, anti-protons, e^+, e^-)
- Applications of a particle accelerator:
  - Collide with other beams and study resulting interactions
  - Collide against a fixed target
    - Study resulting interactions
    - Produce a secondary beam of particles (stable, unstable, charged, neutral) for a subsequent collision

Particle accelerators: motivations

- Search for new sub-structures:
  - **De-Broglie equation: $\lambda=h/p$. Increases resolving power at higher energies.**
  - $p=1$ GeV/c → $\lambda=1.24\cdot10^{-15}$ m
  - $p=10^3$ GeV/c → $\lambda=1.24\cdot10^{-18}$ m
- Search for new particles with high mass:
  - Example: collision in the laboratory frame between two particles: $(m_1,\mathbf{p_1})$ and $(m_2,\mathbf{p_2})$

$$E_L = \sqrt{p_1^2+m_1^2} + \sqrt{p_2^2+m_2^2} \qquad p_L = |\vec{p}_1 + \vec{p}_2|$$

$$\boxed{E_L^2 - p_L^2 = E_{CM}^2 - p_{CM}^2} \Rightarrow E_{CM} = \sqrt{E_L^2 - p_L^2}$$

$$\hookrightarrow = 0$$

Production energy threshold is: $E_{cm}=\Sigma_i m_i c^2$, $E_{kin}=0$

E_{cm} grows with E_L → can produce higher masses

Summary: can produce **particles not contained in ordinary matter**

Example: Inelastic proton collisions

- We want to produce 3 protons and 1 antiproton colliding a proton beam agains a proton target ($pp \rightarrow \bar{p}ppp$)
- What is the minimum momentum of the proton beam?
- Solution:
  - $m_1 = m_2 = 0.9383$ Gev/c^2
  - m(anti-proton) = m(proton)
  - $p_L = p_1$, $p_2 = 0$
  - At threshold: $E_{CM} = 4m = 3.7532$ GeV
  - **Solving in p_1: $p_1 = 6.5$ GeV/c**

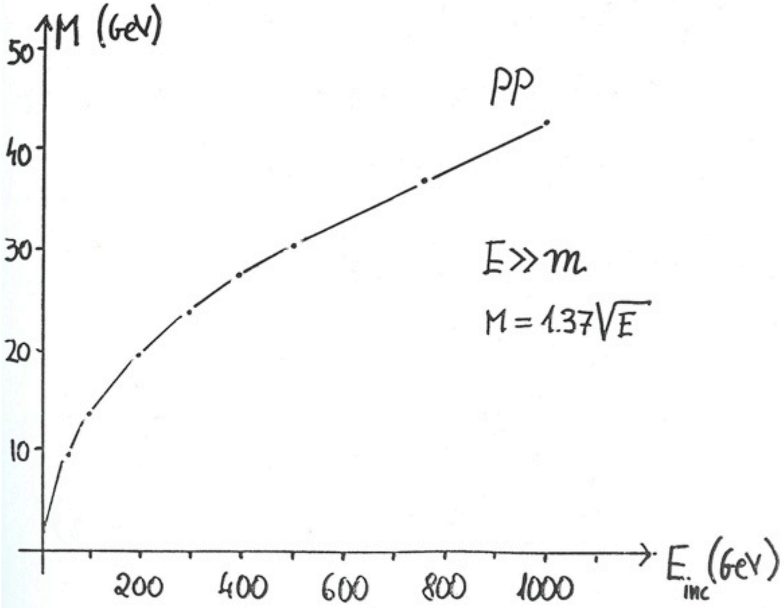
Center of mass energy

- As we have seen, E_{CM} is the energy available to generate mass
- In a beam-target collision E_{CM} grows slowly with the beam energy

$$E_\perp = \sqrt{p_\perp^2 + m^2} + m$$

$$M^2 = E_\perp^2 - p_\perp^2 = 2m^2 + 2m\sqrt{p_\perp^2 + m^2} \qquad p_\perp = p_{inc}$$

p_{inc} large $\quad M \to \sqrt{2m\,p_{inc}} = 1.37\sqrt{p_{inc}} = 1.37\sqrt{E_{inc}}$



Center of mass energy

- In beam-beam collisions: $E_{CM}=2xE_{beam}$
- Examples:
  - 22 GeV + 22 GeV has the same E_{CM} as 1 TeV+m_{target}
  - 1 TeV + 1 TeV has the same E_{CM} as 10^6 TeV+m_{target}
- Much more efficient to use two beams in opposite directions
- The concept naturally leads to the large circular accelerators
- Problem:
  - **Particle density** in a beam is much lower than **solid or liquid target**
- Solutions:
  - Cross beam many times
  - Maximize beam intensity (number of particle bunches per beam)
- Constraints:
  - Works only with stable (anti)particles (protons,electrons)
  - High vacuum needed to avoid beam-gas interactions: ~10^{-9} Pa
  - particle-particle → circulate in two separate beam lines
  - particle-antiparticle → circulate in the same beam line, opposite directions

Acceleration methods

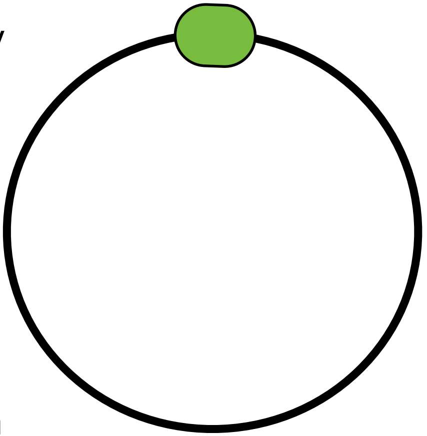
- Can we use an electrostatic field?
  - **F**=q**E** → Energy transfer to a charged particle → Acceleration
  - Electrostatic field generated by potential difference (in Volts)
  - Maximal difference ~10 MV → Maximal energy ~ 10 MeV
  - But: Electrostatic field is conservative (i.e. line integral is zero)!
  - Cannot be used more than one time. Total energy transferred to the beam is null!
- How about a variable electric field?
  - Main idea: utilize several times a **small** but **variable** potential difference
  - Two possibilities: **circular machines** and **linear machines (LINACs)**

CIRCULAR ACCELERATOR:
At least one accelerating cavity

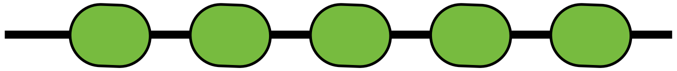
Particles **receive a ΔEnergy** at every turn.

Particles must be **in phase** with accelerating potential

Need **magnetic field** to keep the beam on circular path



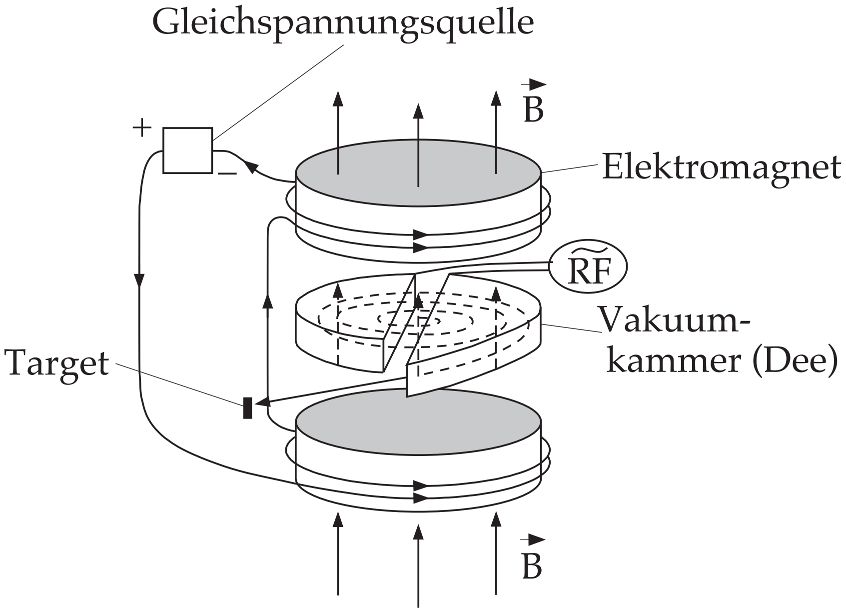
LINAC: multiple cavities



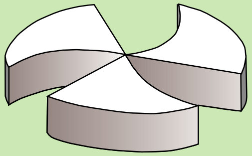
Particle accelerators: some history

- 1921: “Kaskadengenerator” (Greinacher)
- 1924-1928: Concept and first prototype of linear accelerator (Ising, Wideröe)
- 1932: First nuclear reaction induced by cascade particle accelerator, $p^7Li \rightarrow 2\alpha$ with 400 keV protons (Cockroft/Walton)
- 1930: First Van de Graaff accelerator with 1.5 MV
- 1930-1932: First 1.5 MeV cyclotron (concept: Lawrence)
- Upgraded cyclotrons (Synchrocyclotron): 300-700 MeV
- 1953: First synchrotron at Brookhaven lab - *Cosmotron* (concept: Oliphant/Veksler/McMillan): 3 GeV
- 1958: Proton Syncrotron (CERN): 28 GeV
- 1983: Tevatron (Fermilab): 1000 GeV
- 1990: HERA (DESY): first and only electron-proton collider
- 2008: Large Hadron Collider (CERN): up to 7000 GeV

Accelerators: Cyclotron



Maximal energy ~ 20 MeV
Synchro-cyclotron up to 600 MeV



Isochronous cyclotrons compensate the varying frequency by increasing the magnetic field with radius

- Centripetal force and Lorentz force are balanced:

$$m\frac{v^2}{\rho} = qvB.$$

- Cyclotron frequency:

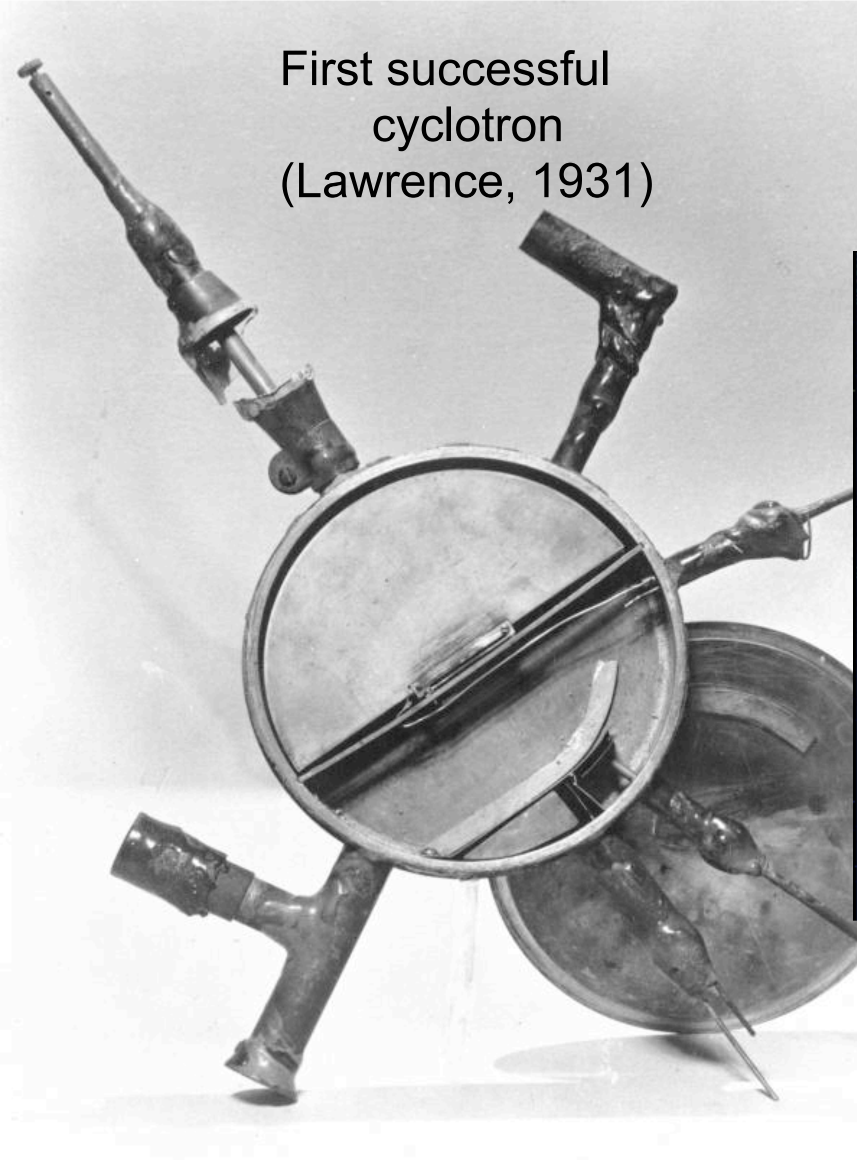
$$v = \omega\rho \qquad \omega = \frac{qB}{m}$$

- Alternating high voltage matches the cyclotron frequency
- The radius grows linearly with the impulse of the particle
- Cyclotron frequency for relativistic particles:

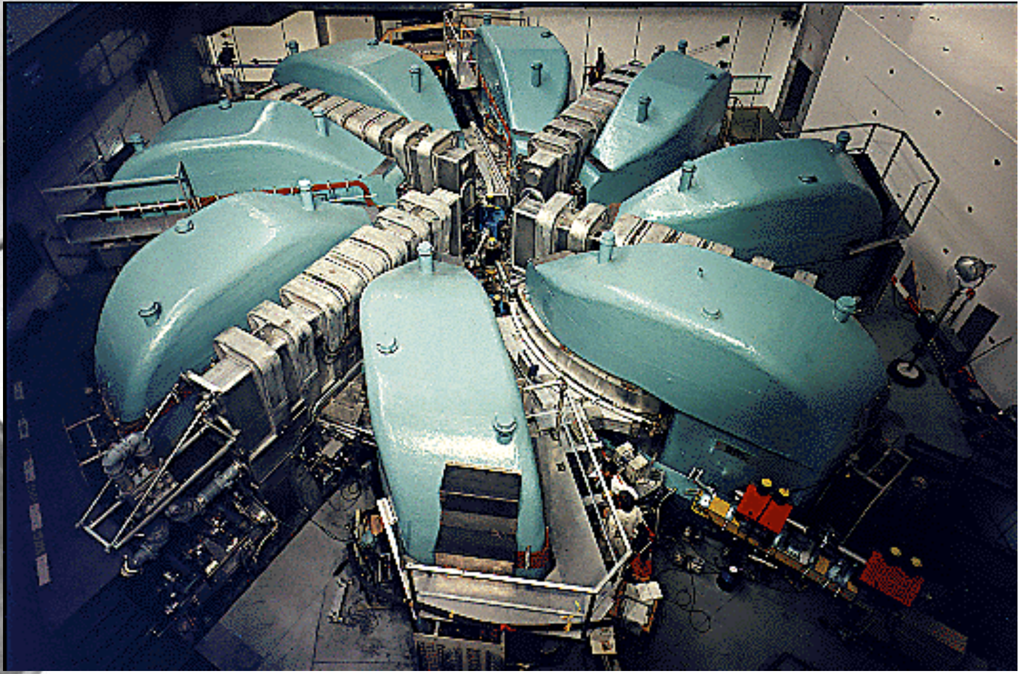
$$\omega = \frac{qB}{\gamma m}$$

v/c=50%, γ=1.155, $\omega'=0.86\cdot\omega$
v/c=99%, γ=7.1, $\omega'=0.14\cdot\omega$

Cyclotrons

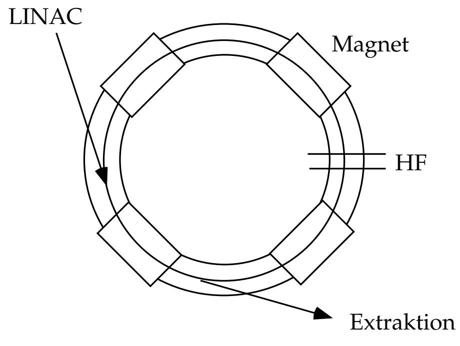


First successful cyclotron (Lawrence, 1931)

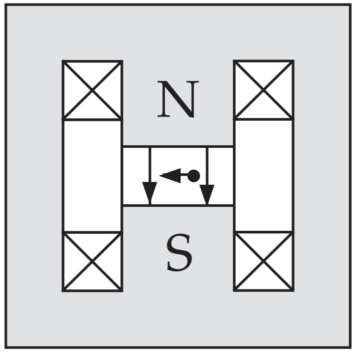


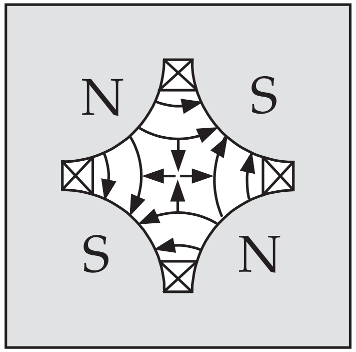
590 MeV cyclotron at the Paul Scherrer Institut

Accelerators: Synchrotron



Dipole = Bending





Quadrupole =Focusing

- Momentum, B field and radius are related by:

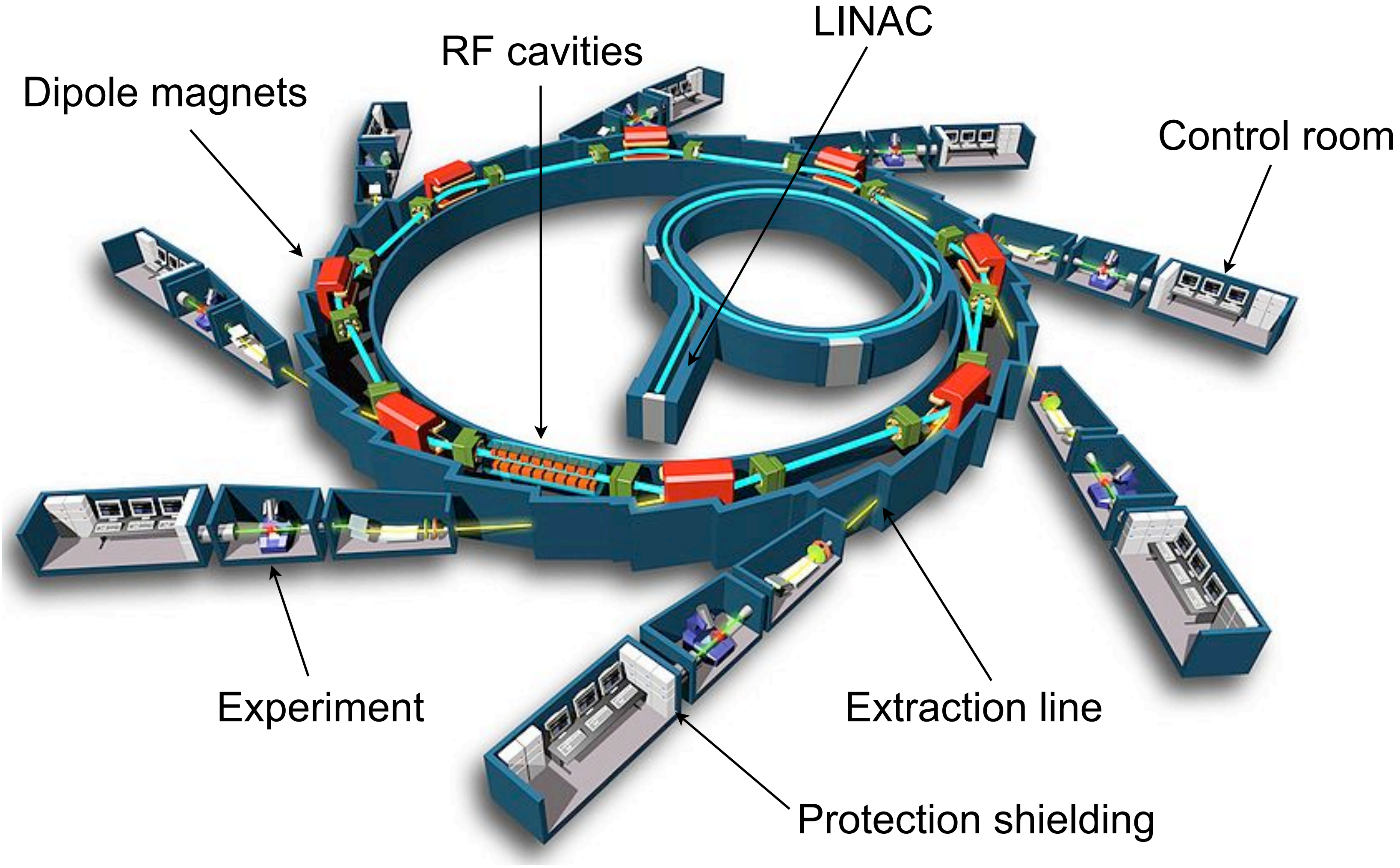
$$\rho = \frac{p}{qB}, \longrightarrow \begin{array}{l} cp\,[\mathrm{eV}] = czB\rho = 3 \times 10^{8}\ \mathrm{m \cdot s^{-1}} zB\,[\mathrm{T}]\rho\,[\mathrm{m}], \\ p\,[\mathrm{GeV/c}] = 0.3\ z\ B\ [\mathrm{T}]\ \rho[\mathrm{m}] \end{array}$$

- Example: Large Hadron Collider:
  - Circumference: 27 Km → Radius = 4.3 Km
  - Average magnetic field = 5.4 Tesla
  - Momentum = 7 TeV/c for protons

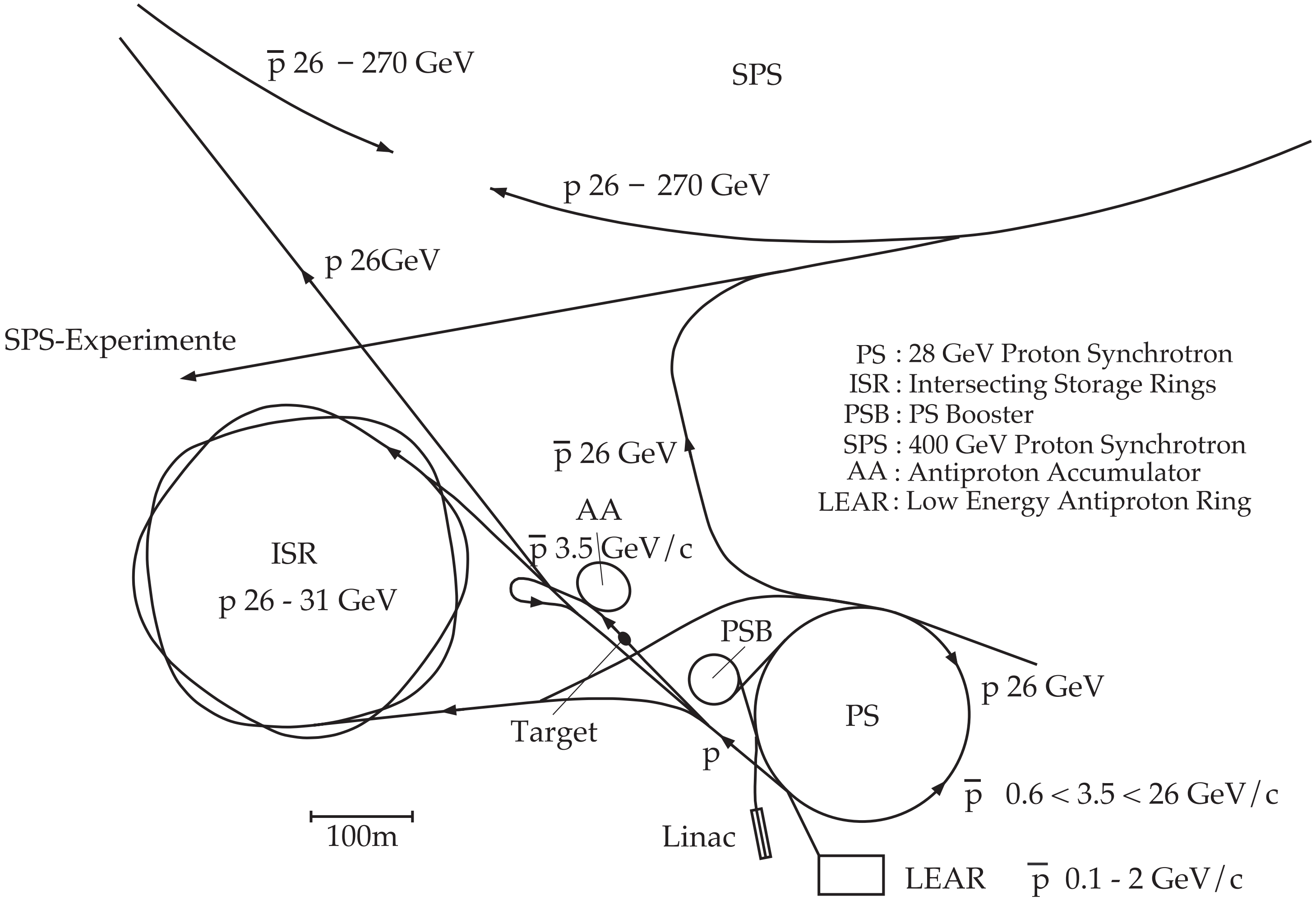
Synchrotron: main concepts

- Beams are injected at low energy with **B field** at its minimal value and particles move in a vacuum pipe
- At every turn the momentum grows:
  - To keep the beam on the same radius the B field has to grow accordingly
  - The revolution period also changes if the velocity grows
  - The potential difference (radio-frequency) must be kept in phase with the particles
- When the maximum momentum is reached the radio-frequency is switched off, then:
  - The beam can be extracted for experimental areas or to be injected in larger synchrotrons
  - The beams can be steered to meet in the collision points

Synchrotron: a sketch



Accelerator complexes at CERN



PS : 28 GeV Proton Synchrotron
ISR : Intersecting Storage Rings
PSB : PS Booster
SPS : 400 GeV Proton Synchrotron
AA : Antiproton Accumulator
LEAR : Low Energy Antiproton Ring

The 450 GeV SPS beam is injected in the Large Hadron Collider

Swiss light source

- Location: Paul Scherrer Institut
- 2.8 GeV electron synchrotron
- 288 m circumference
- 36 dipoles, 1.4 T field
- 177 quadrupoles
- 100 MeV linear injector

Reminder: cross section

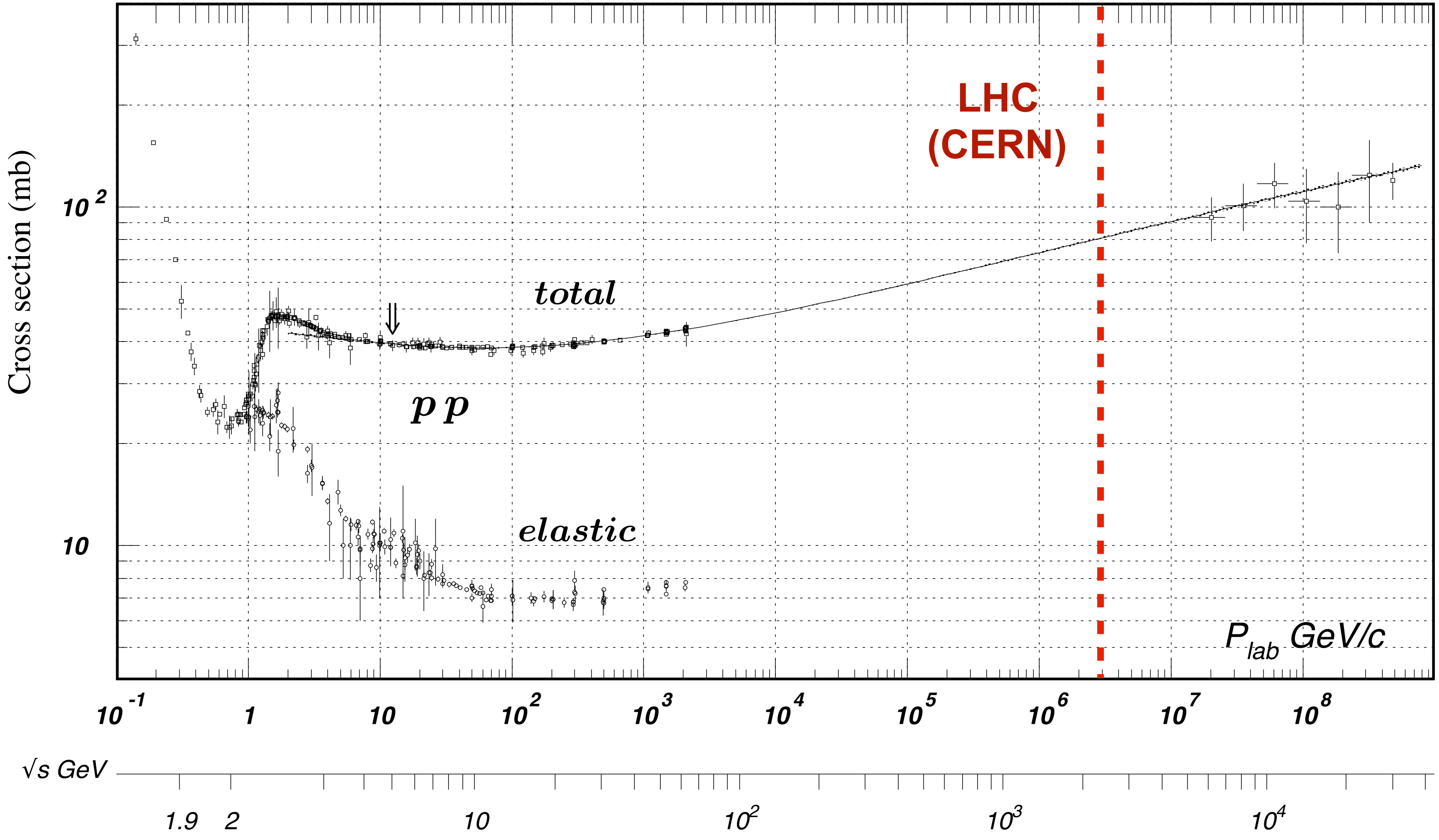
- Measured in cm^2. The common unit is:

$$\text{barn} = 10^{-24}\ \text{cm}^2 \qquad [\text{b}]$$

- In the formulas used until now, we have used the total cross section (s)
- The total cross section is the sum of many final states

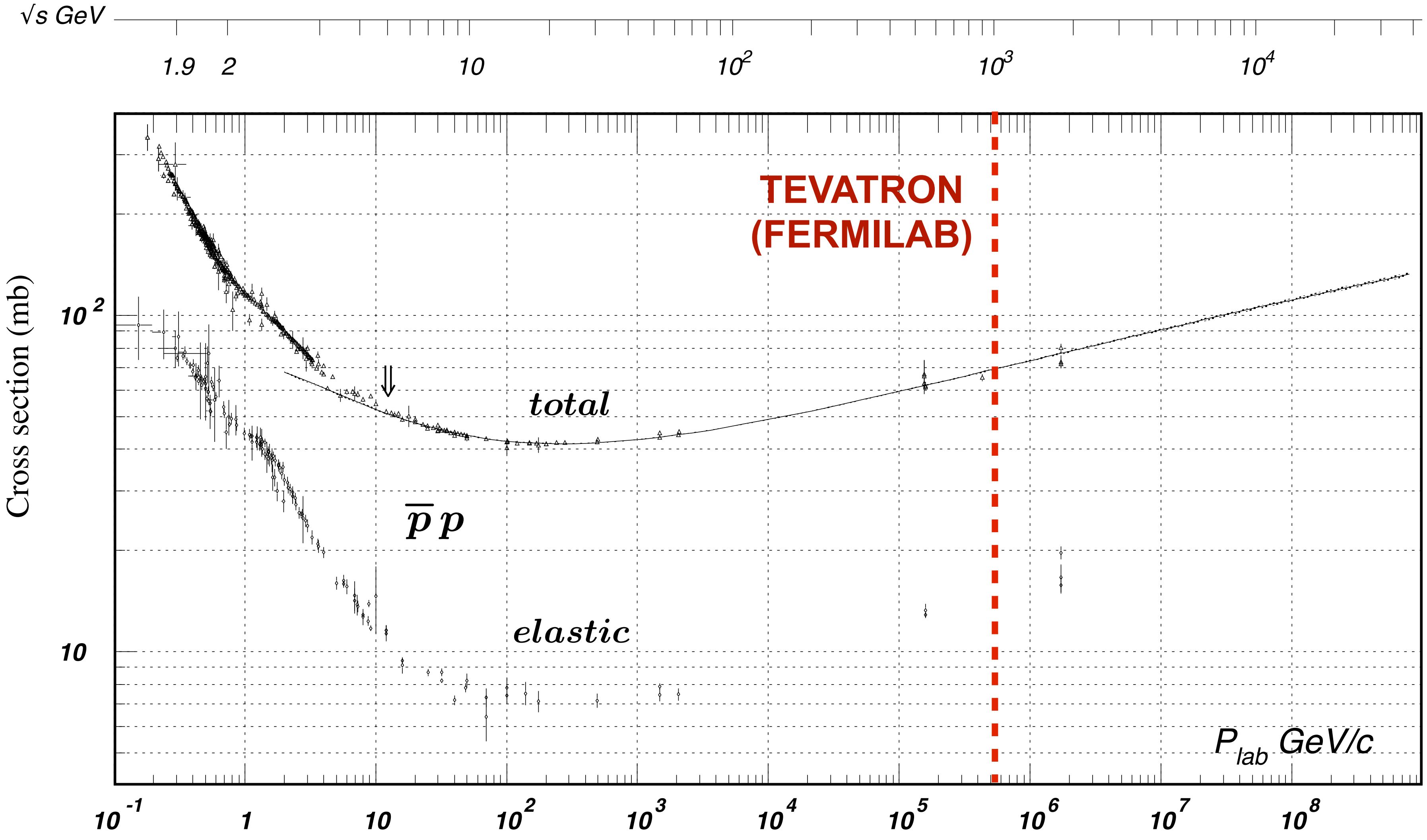
$$\sigma_{TOT} = \Sigma_i\ \sigma_i$$

Cross-sections: p-p



Source: http://pdg.lbl.gov/2006/hadronic-xsections/hadron.html

Cross sections: p-antip



Source: http://pdg.lbl.gov/2006/hadronic-xsections/hadron.html

Luminosity

- Cross section = σ
- Number of events per second = rate = R

$$\boxed{R = L\,\sigma}$$

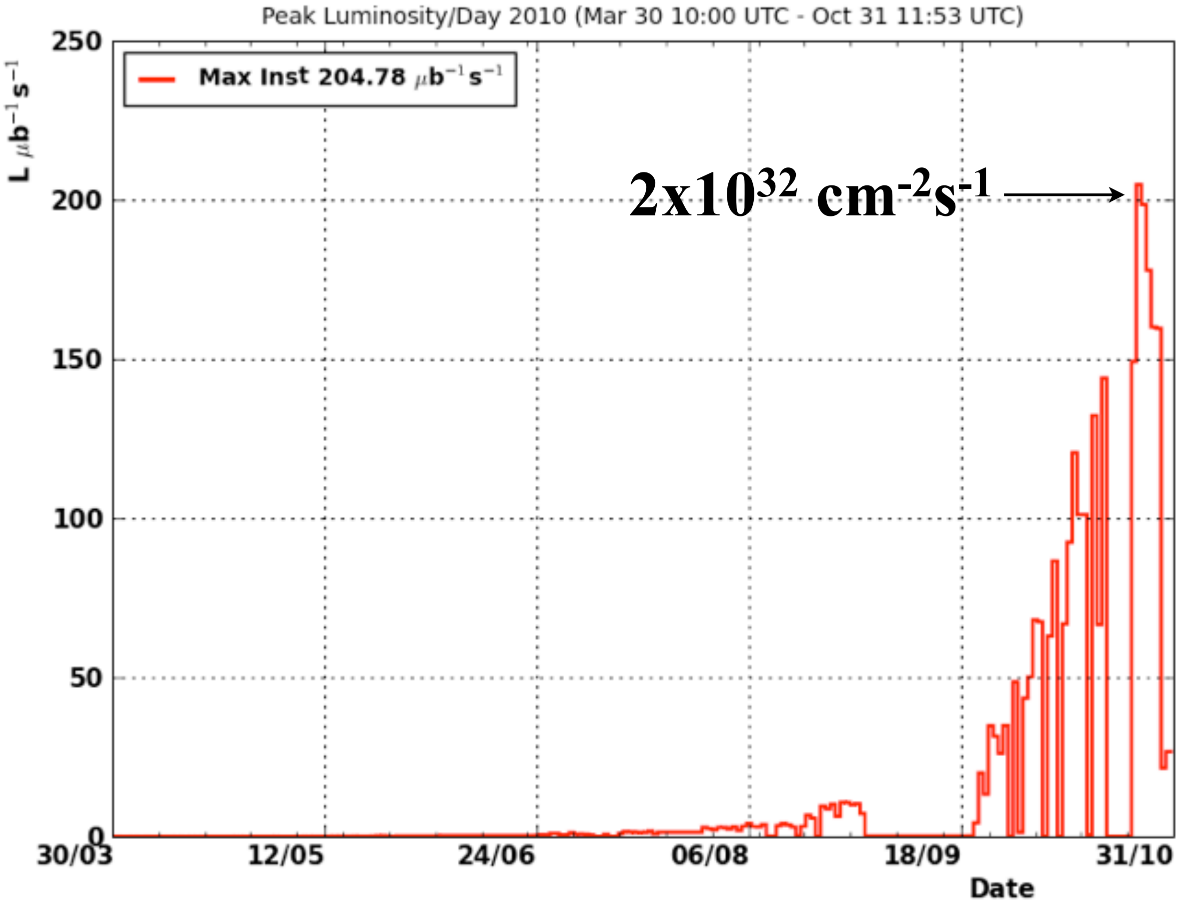
- L=Luminosity. Characterizes accelerator performances in [$\mathrm{cm^{-2}s^{-1}}$]
- Example:
  - Consider a e+e- accelerator with ***N*** particles per beam turning ***f*** times per sec.
  - Gaussian shaped beam with dimensions σ_x and σ_y → transverse size = $4\pi\sigma_x\sigma_y$
  - One electron in one turn crosses $N/(4\pi\sigma_x\sigma_z)$ positrons
  - Number of **collisions** per second

$$\frac{fN^2}{4\pi\sigma_x\sigma_y}$$

  - Number of **events** per second

$$R=\frac{\sigma f N^2}{4\pi\sigma_x\sigma_y}$$

Instantaneous luminosity: LHC

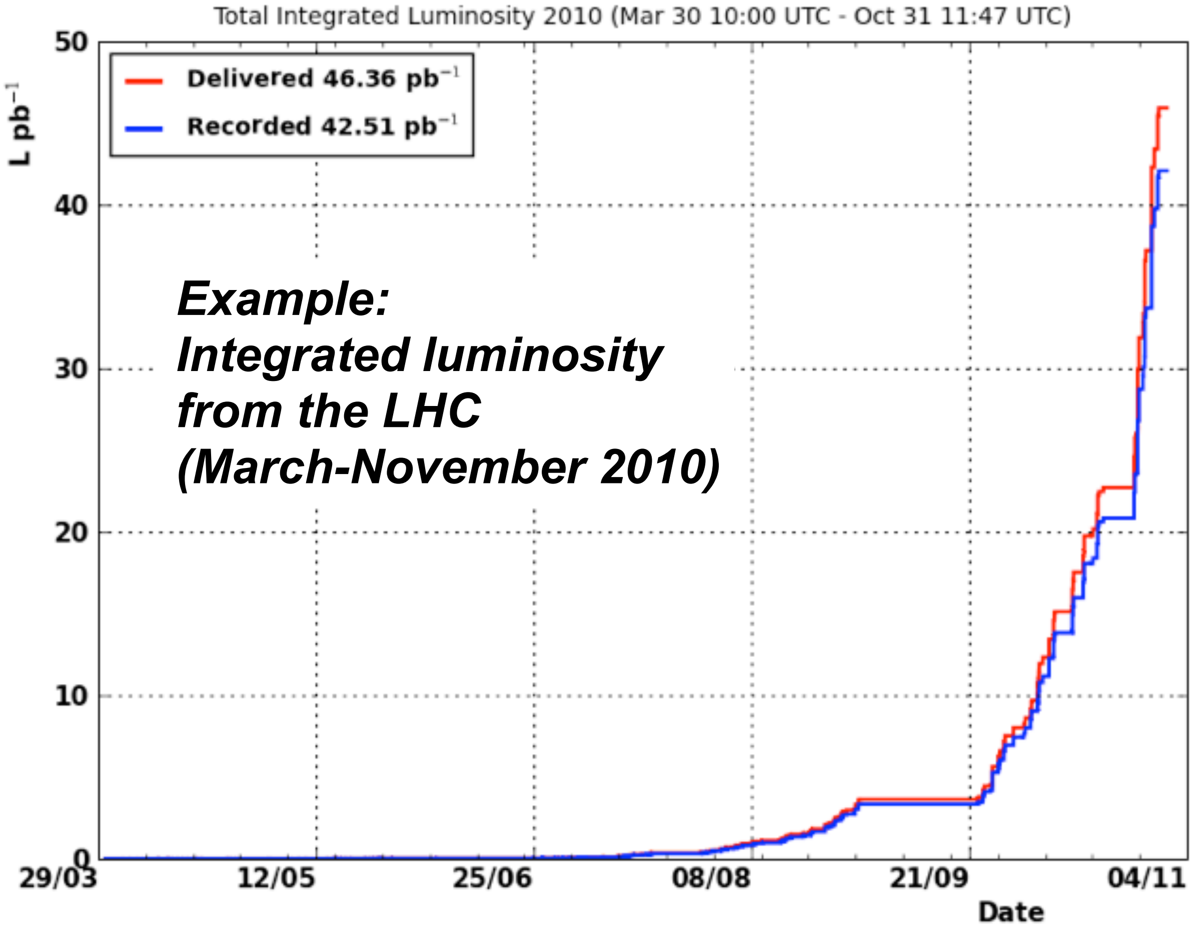


2×10^{32} cm^{-2}s^{-1} →

- Accelerator luminosity is gradually increased by increasing the number of particles in the beam and squeezing the beam size at the intersection point
- Note: final target instantaneous luminosity for LHC is 10^{34} cm^{-2}s^{-1}

Integrated luminosity

- The integral of the delivered luminosity over time is called integrated luminosity
- The integrated luminosity is a measurement of the collected data size



Example:
Integrated luminosity from the LHC (March-November 2010)

Luminosity: example

- Electron-Positron Accelerator ring:
  - Ring is 100m long and revolution frequency is $f=3\cdot 10^6$ Hz
  - $N=10^{10}$ particles, $\sigma_x=0.1$ cm, $\sigma_y=0.01$ cm
  - $L = 0.2\mathrm{x}10^{29}$ $\mathrm{cm}^{-2}\mathrm{s}^{-1}$
- We are interested in a rare process:
  - Example $e^+e^-\rightarrow\bar{p}p$ and $E_{CM}\sim 2\text{-}3$ GeV
  - Cross section: $\sigma = 1\mathrm{nb} = 10^{-33}\ \mathrm{cm}^2$
  - $R=10^{-4}$ events per second
  - ~0.35 events/hour
  - ~8.5 events/day

Particle physics experiments

- Particle detectors are disposed around the interaction region and detect (directly or indirectly) the reaction products
- Typical measurements performed:
    - Spatial coordinates and timing of final state particle
    - Momentum: P_x, P_y, P_z
    - Energy
    - Type of particle (particle ID): pion, Kaon, proton, muon, etc.

Momentum measurement

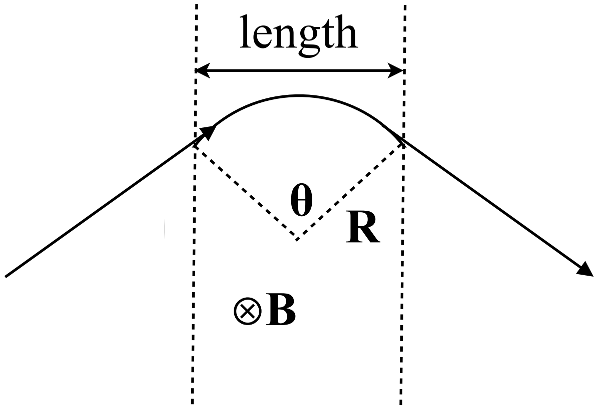
- In high energy experiments the momentum measurement is based on the deflection of charged particles in a magnetic field
- Simple case:
  - Dipole magnet
  - Measure track direction before and after magnet
- In collider experiment:
  - B field parallel to beams
  - Curvature only in the transverse plane
  - Momentum resolution:

$$\frac{\sigma(p_T)}{p_T} = \frac{\sigma_{r\phi}\, p_T}{0.3\, B\, l_R^2}\,[720/(n+4)]^{-1/2}$$

$\sigma_{r\phi}$ = error on each measurement point

l_R = radial length of the track

n = number of equidistant points

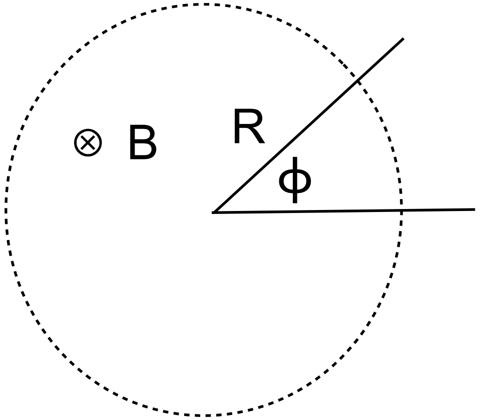


$$|p| = 0.3\,|B|\,R$$

$$\text{length} = l = 2\,R\,\sin(\theta/2) \sim R\,\theta$$

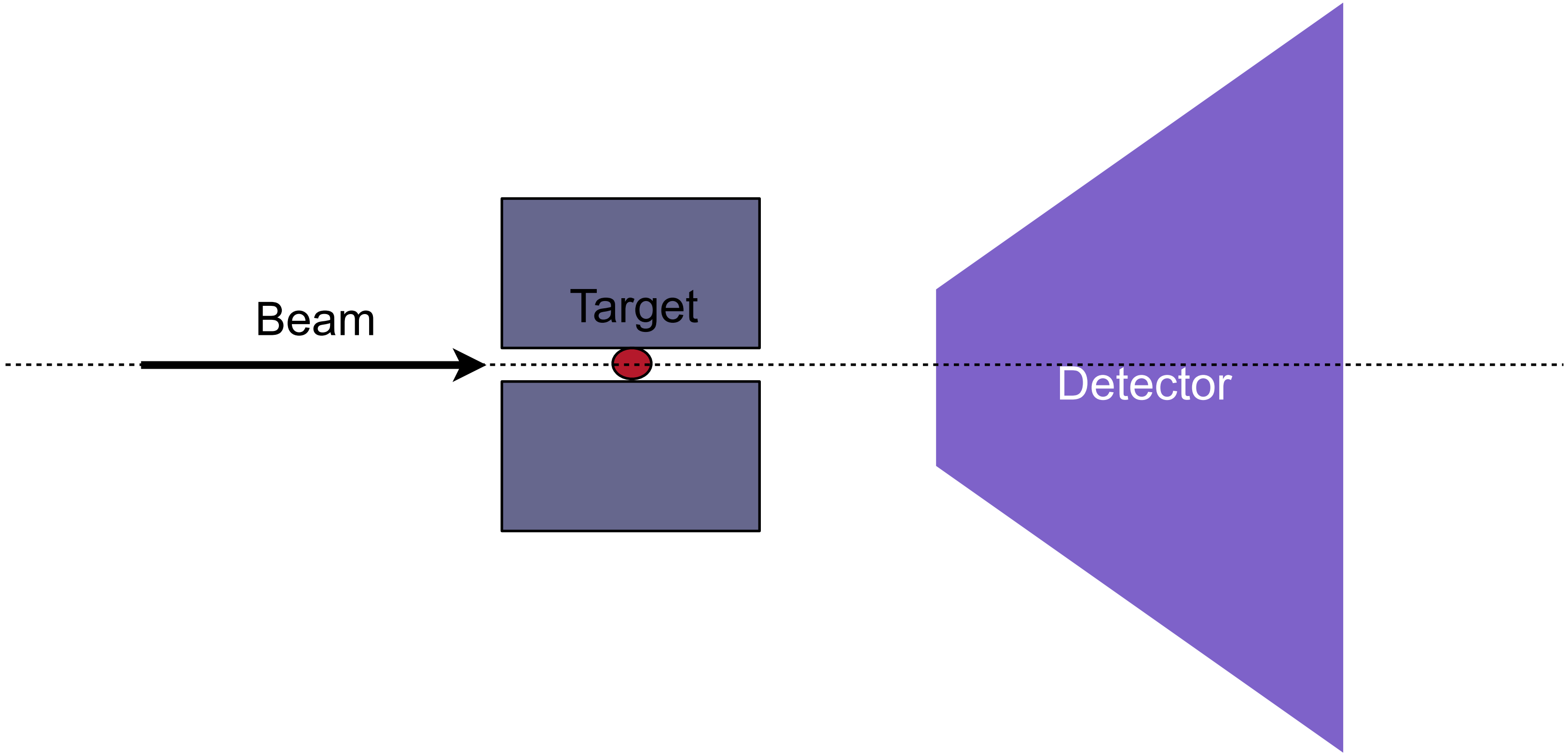
$$\theta = \text{length}/R = 0.3\,B\,l\,/\,p$$

$$p = 0.3\,B\,l\,/\,\theta$$

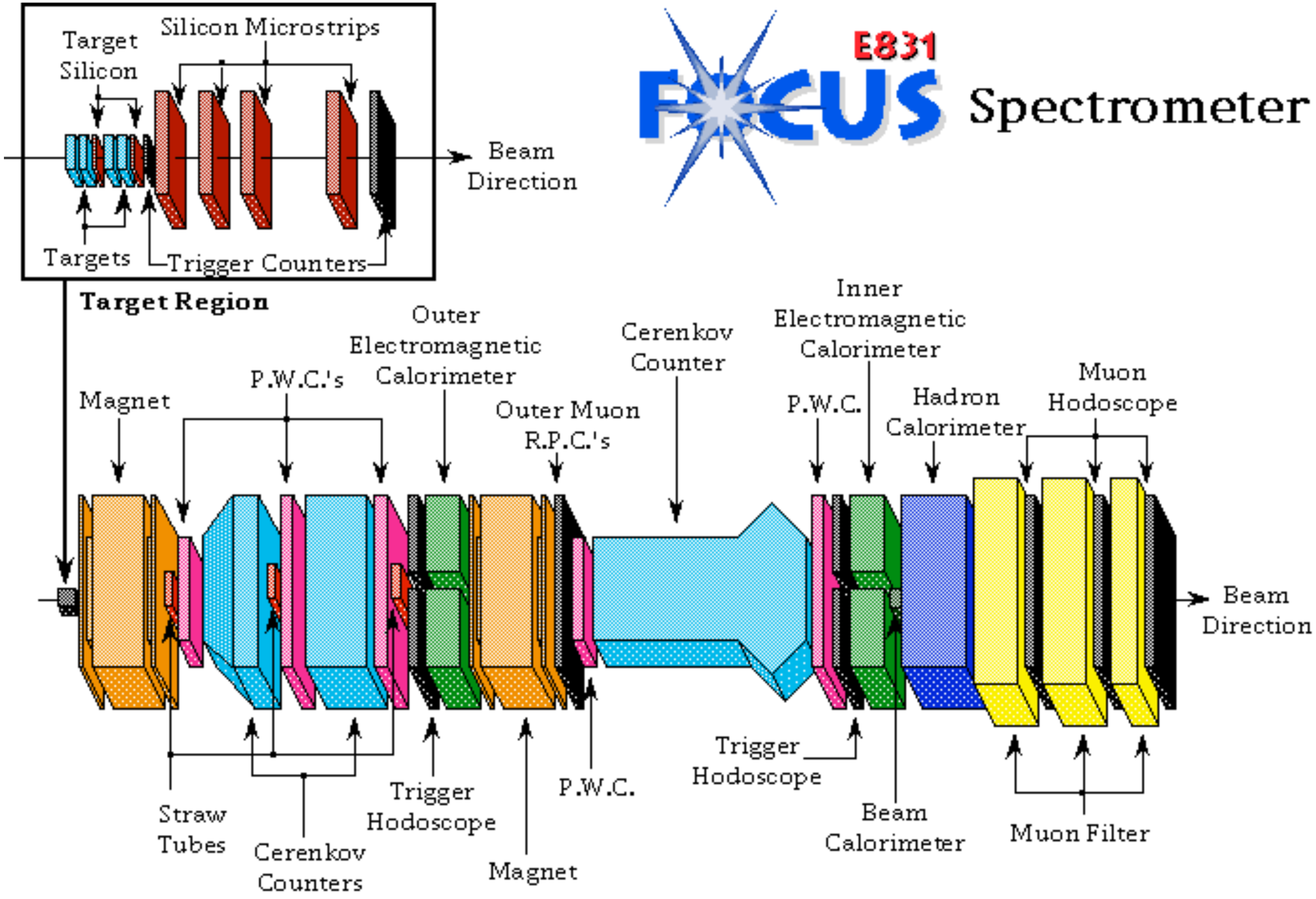


Fixed target experiments

- For fixed target experiments the production is essentially in the forward direction

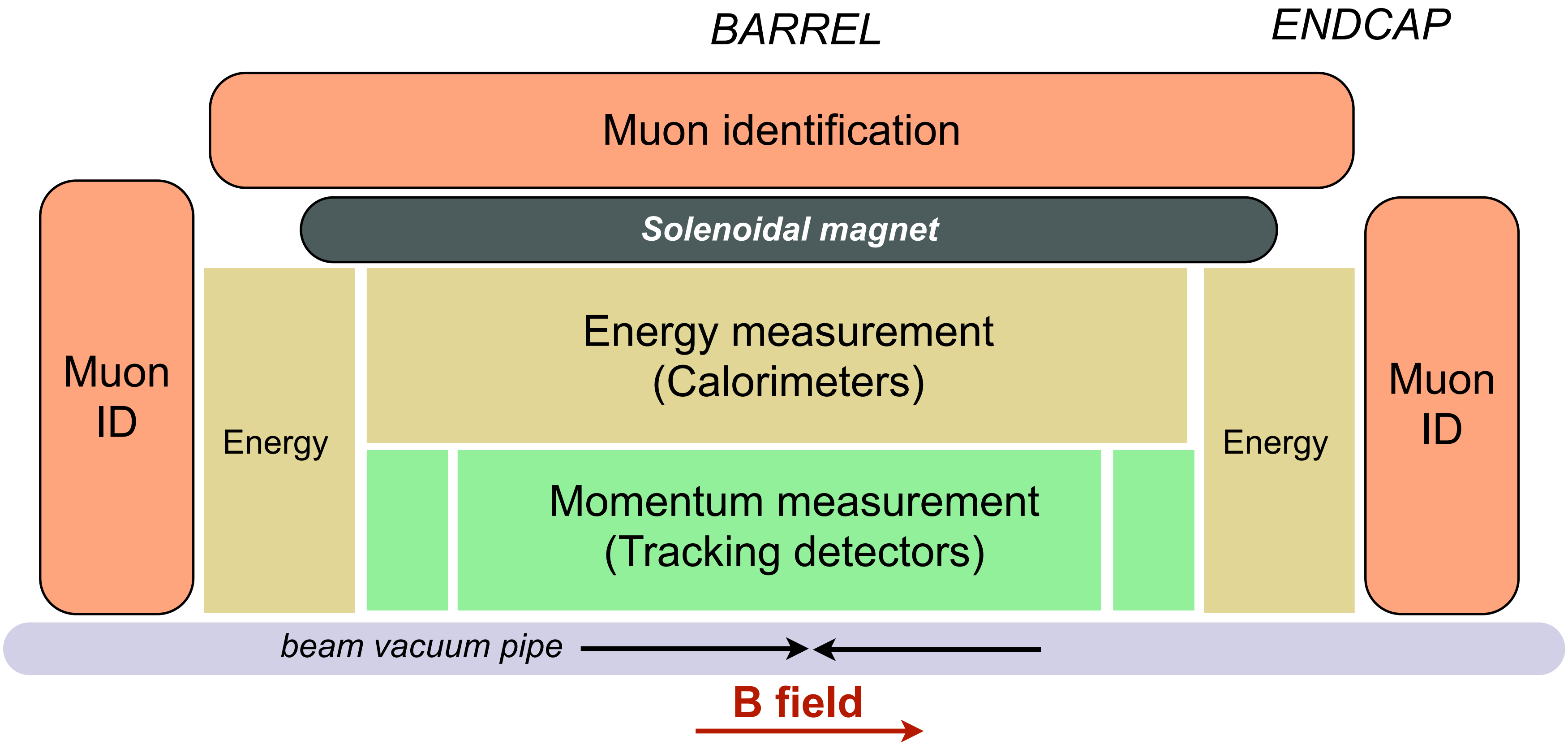


Example: FOCUS experiment



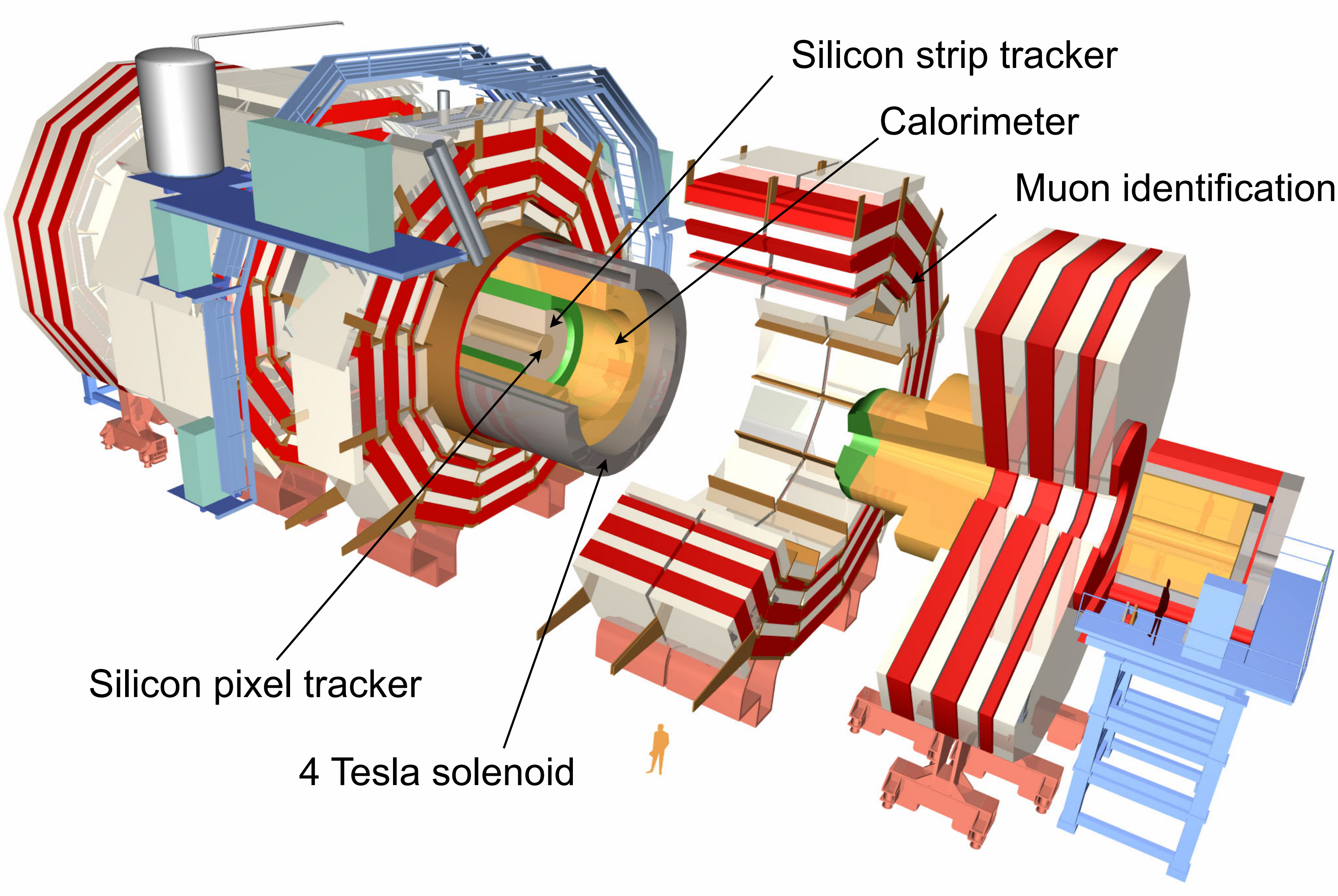
Collider experiments

- Cylindrical symmetry
- Ermeticity: measure as many of the final state particles as possible
- Magnetic field (solenoidal, **B** parallel to the colliding beams)



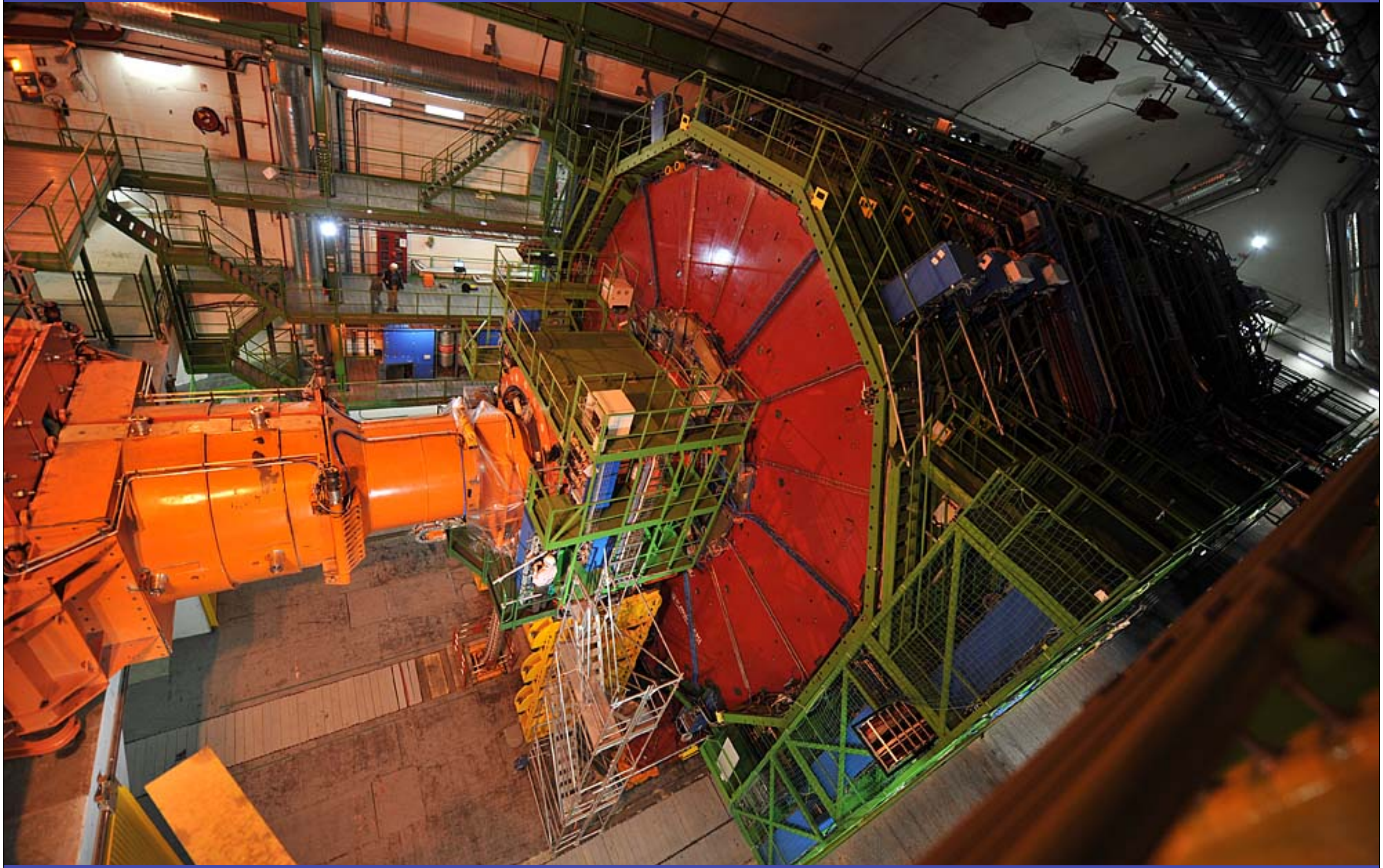
Basic building blocks of a particle collider experiment

Example: CMS Experiment



CMS: open configuration

CMS: closed configuration



References

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