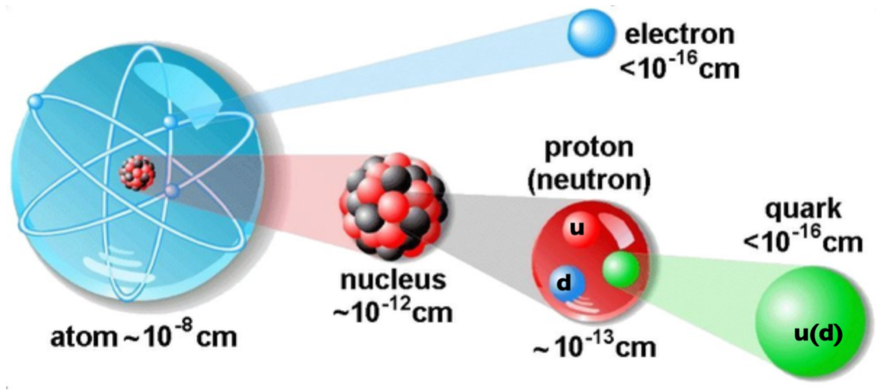
Experimental LHC physics - I

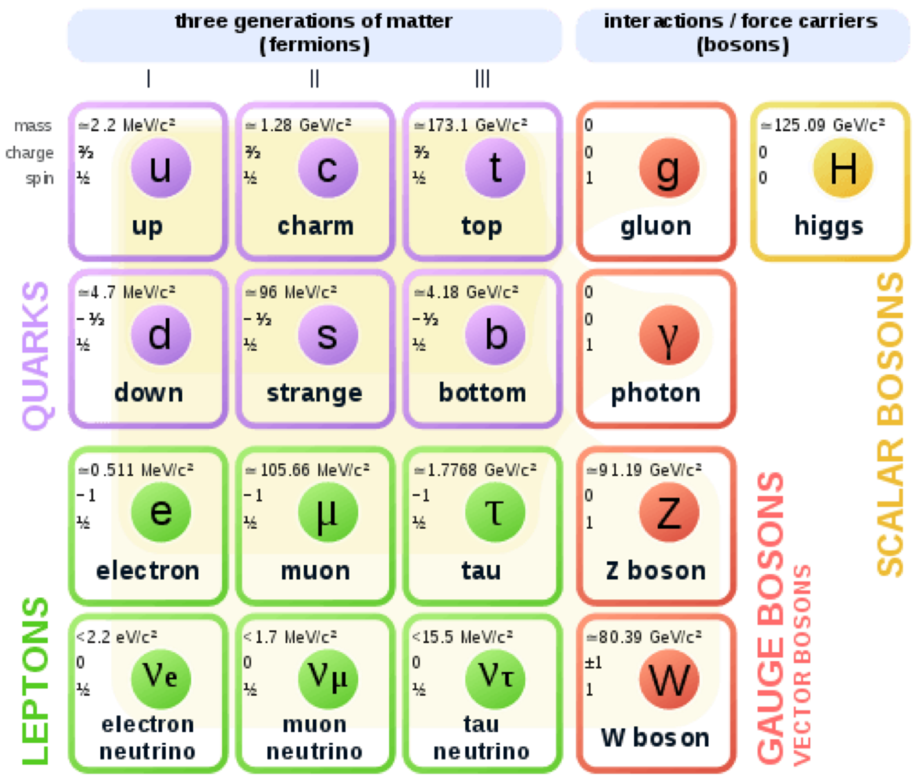
Experiment = probing and building theories with data!

In our case:
Theory is the Standard Model of Particle Physics
Data are obtained from collisions at
LHC or previous colliders

Let's see what all this means…

The Standard Model of particle physics…





Built from 1954 to ~1970

Gauge bosons

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + i\bar{\Psi}\not{D}\psi + D_\mu\Phi^\dagger D^\mu\Phi - V(\Phi) + \bar{\Psi}_L\hat{Y}\Phi\Psi_R + h.c.$$

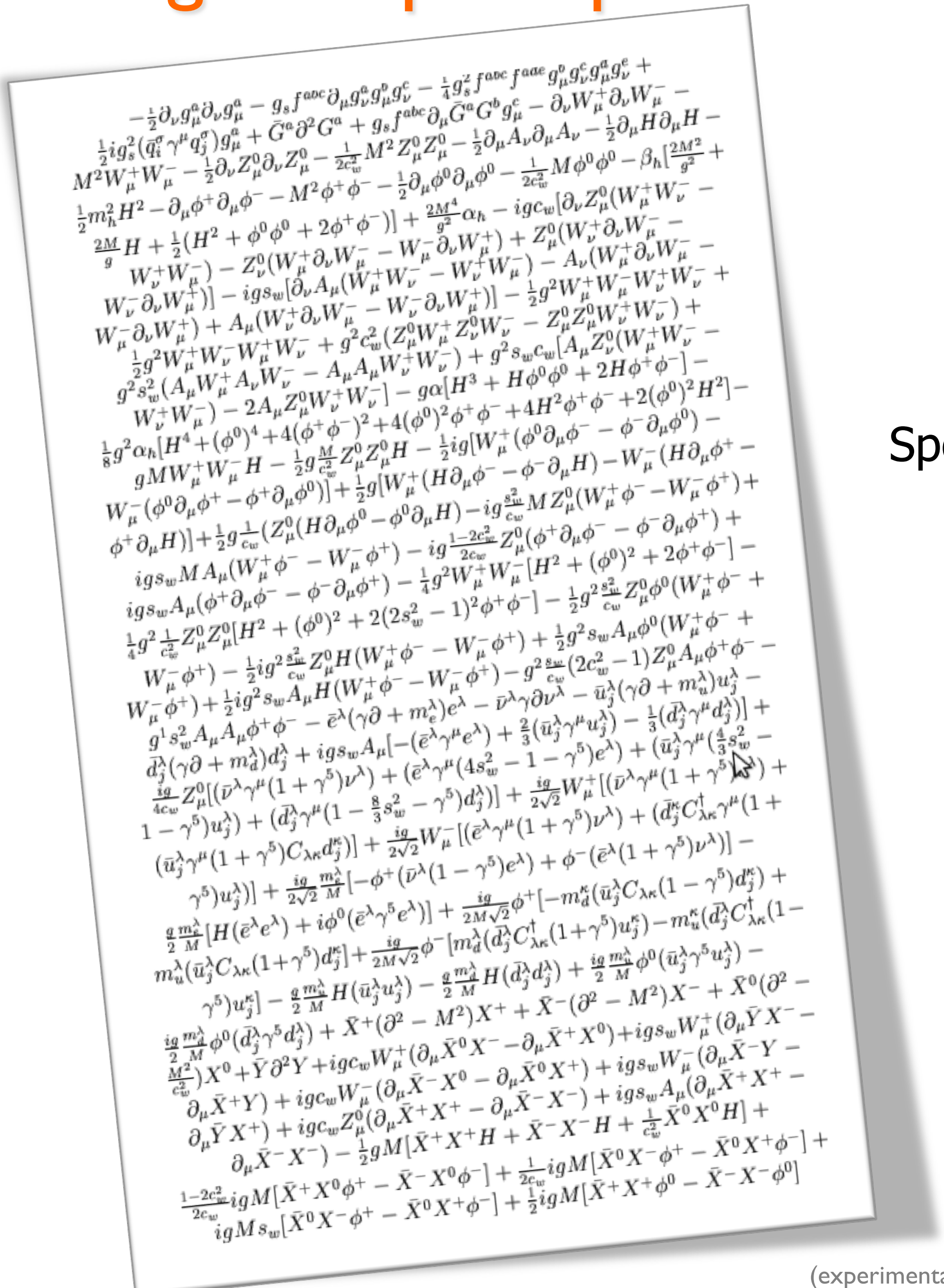
Gauge boson coupling to fermions (EW, QCD)

Higgs coupling to fermions (fermion masses)

Higgs coupling to bosons (boson masses)

Higgs self-coupling (Higgs potential)

A single simple equation to describe the wide world

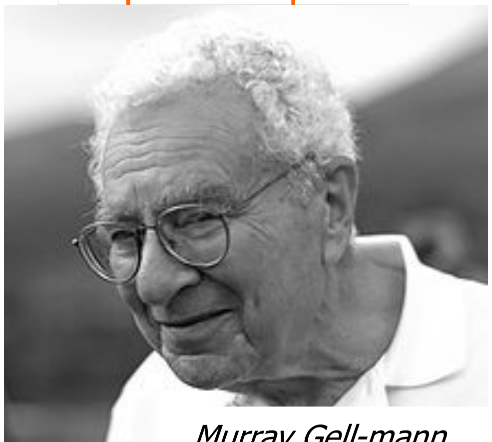


Not so simple when developed !

Spoiler: we will see in this lecture that it is in fact not describing everything …

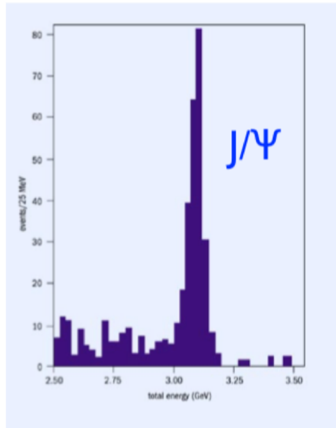
A theory built (and probed) over time…

1967 - SLAC
Up/Down quarks

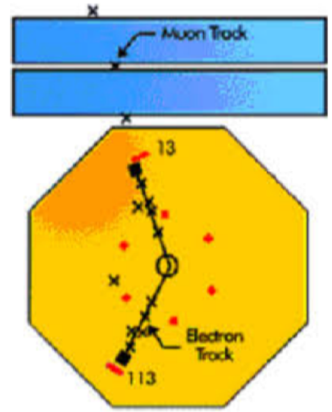


Murray Gell-mann, "inventor" of quarks

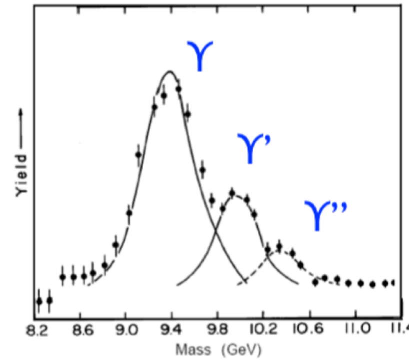
1974 – BNL, SLAC
Charm



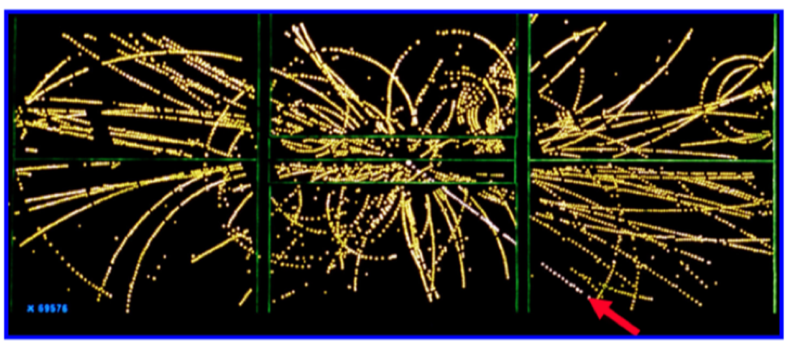
1976 – SLAC
Tau lepton



1979 – Fermilab
Beauty

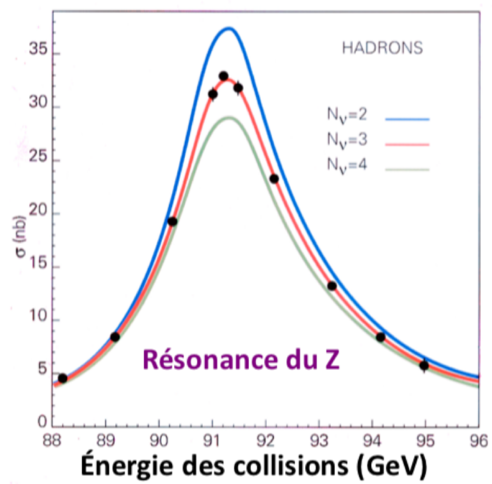


1983 – CERN/SppS
W and Z bosons



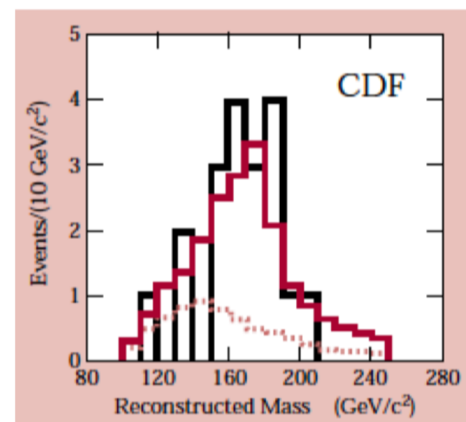
UA1, UA2

1990 – CERN/LEP
Three families of neutrinos



ALEPH, DEPHI, L3, OPAL

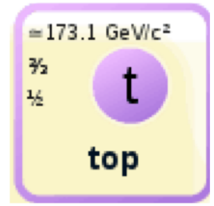
1994 – Fermilab/TeVatron
Top quark

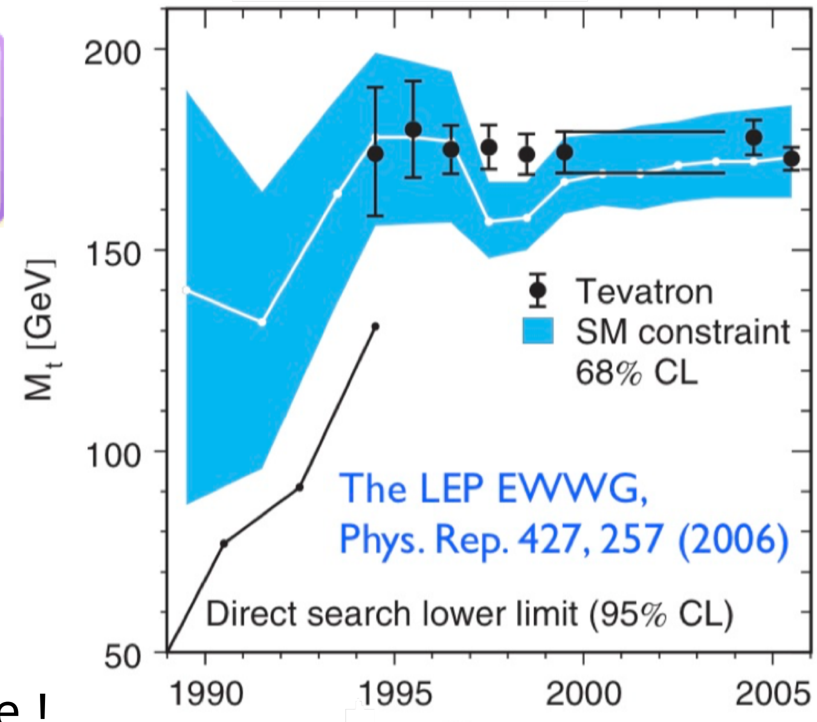


CDF, D0

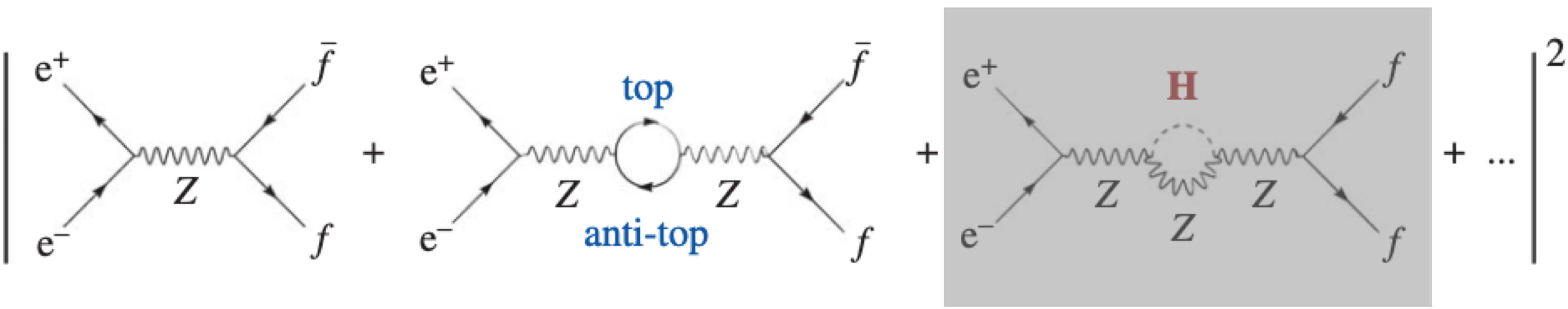
Before the LHC startup – indirect constraints

LEP1: 1989-1995 (91 GeV)
LEP2: 1995-2000 (130-206 GeV)
Tevatron 1: 1983-2000
Tevatron 2: 2001-2011 (1.96 TeV)





Per-mil precision on mW, and cross-sections
Correction at per-cent level -> constraints possible !



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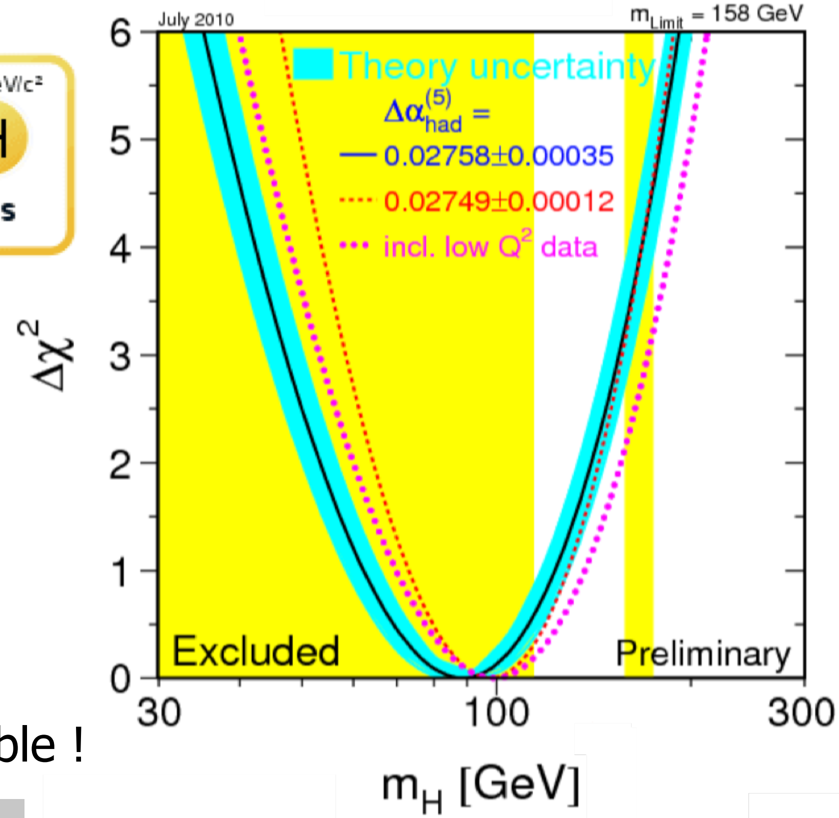

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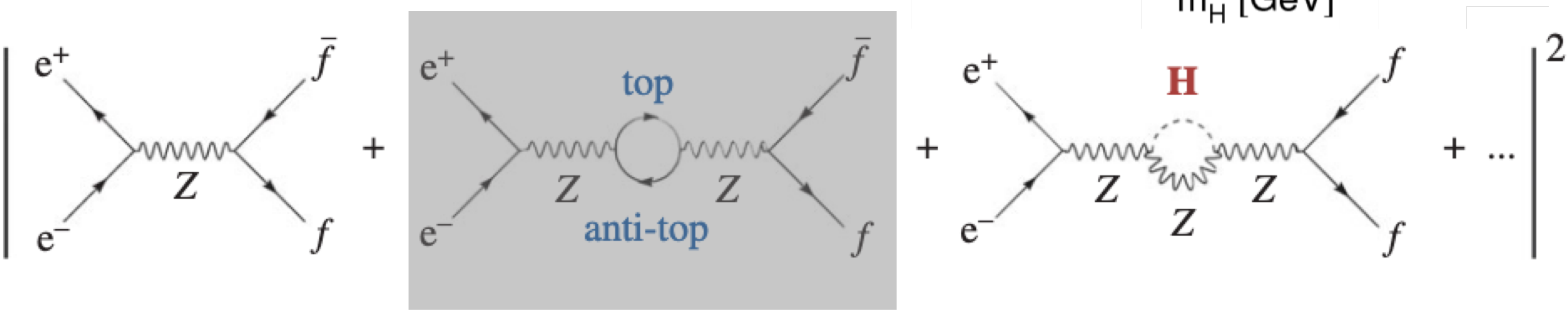
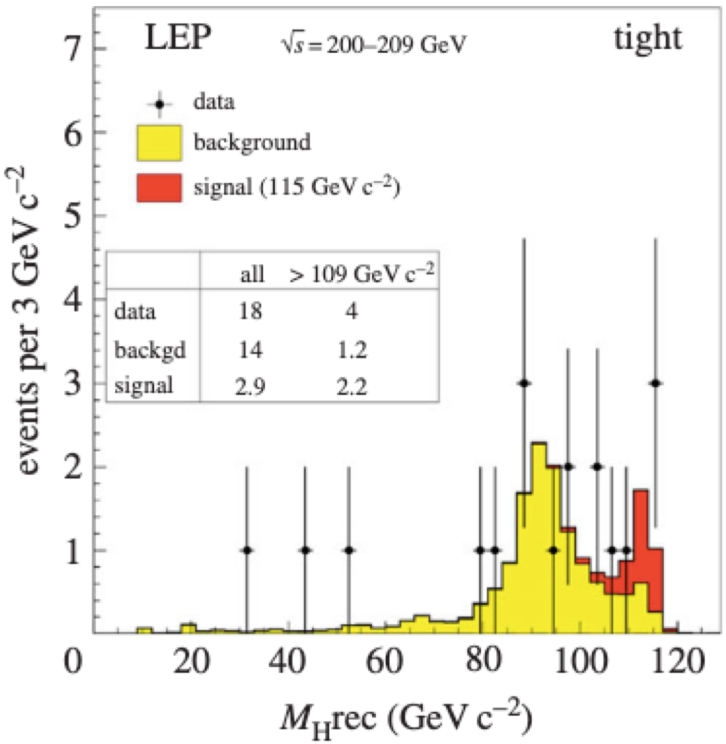
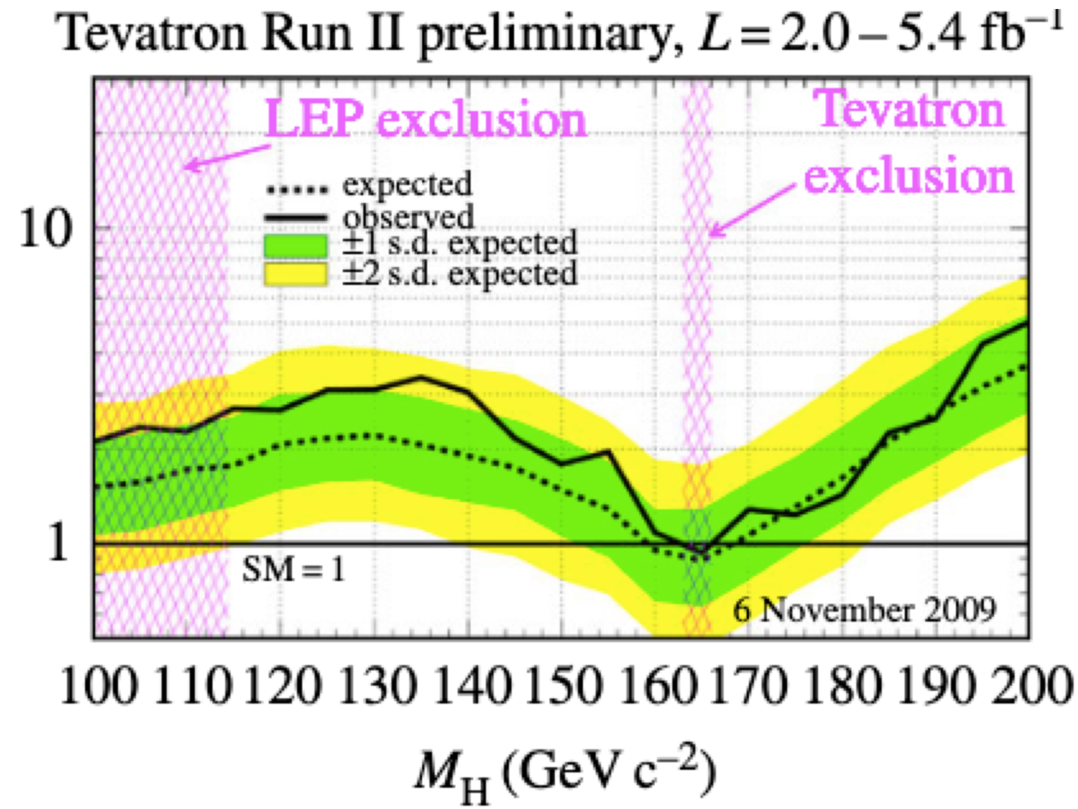


Before the LHC startup – direct searches





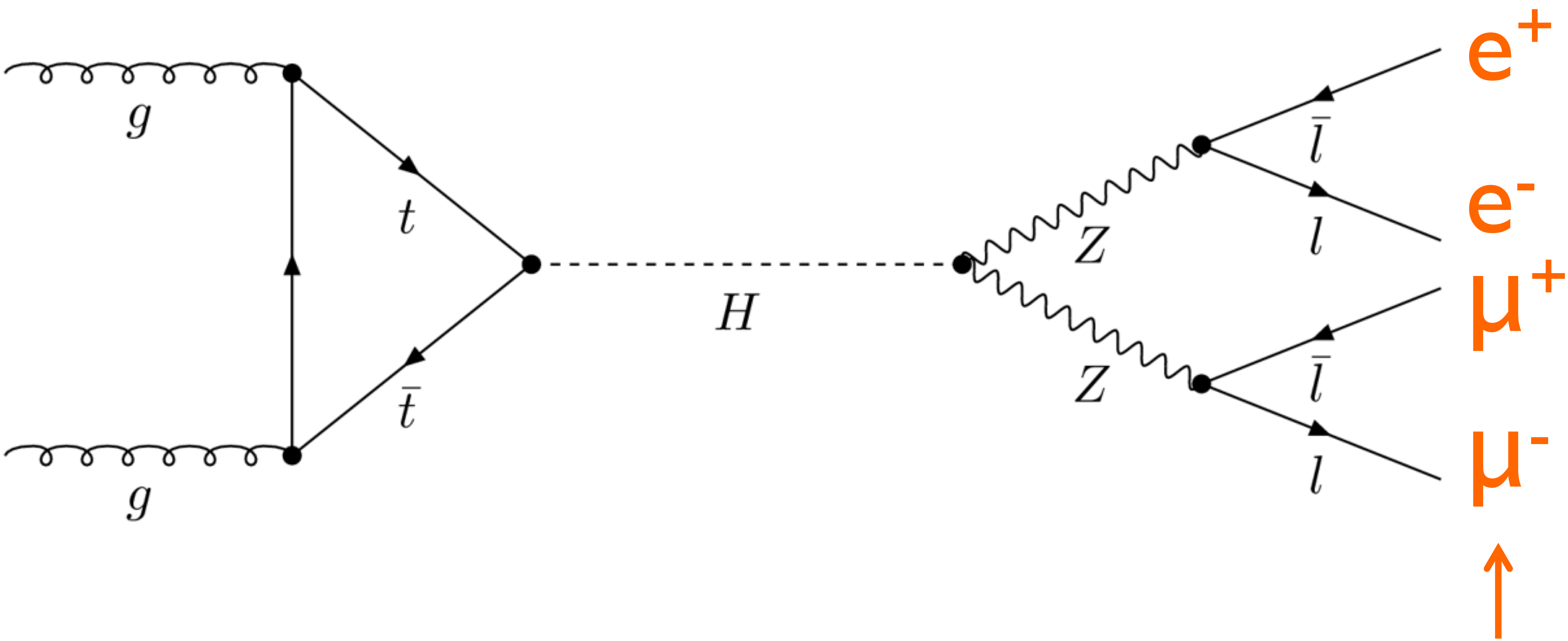
Direct limits on Higgs production from LEP-2 and Tevatron

LHC "no loose theorem"

Either the Higgs boson is discovered, or New Physics should manifest to avoid unitarity violation in WW scattering at TeV scale

What do we want to measure?

We look for "stable" particles from an unstable particle decays



this is what we are looking for…

What do we want to measure?

… "stable" particles from unstable particle decays!

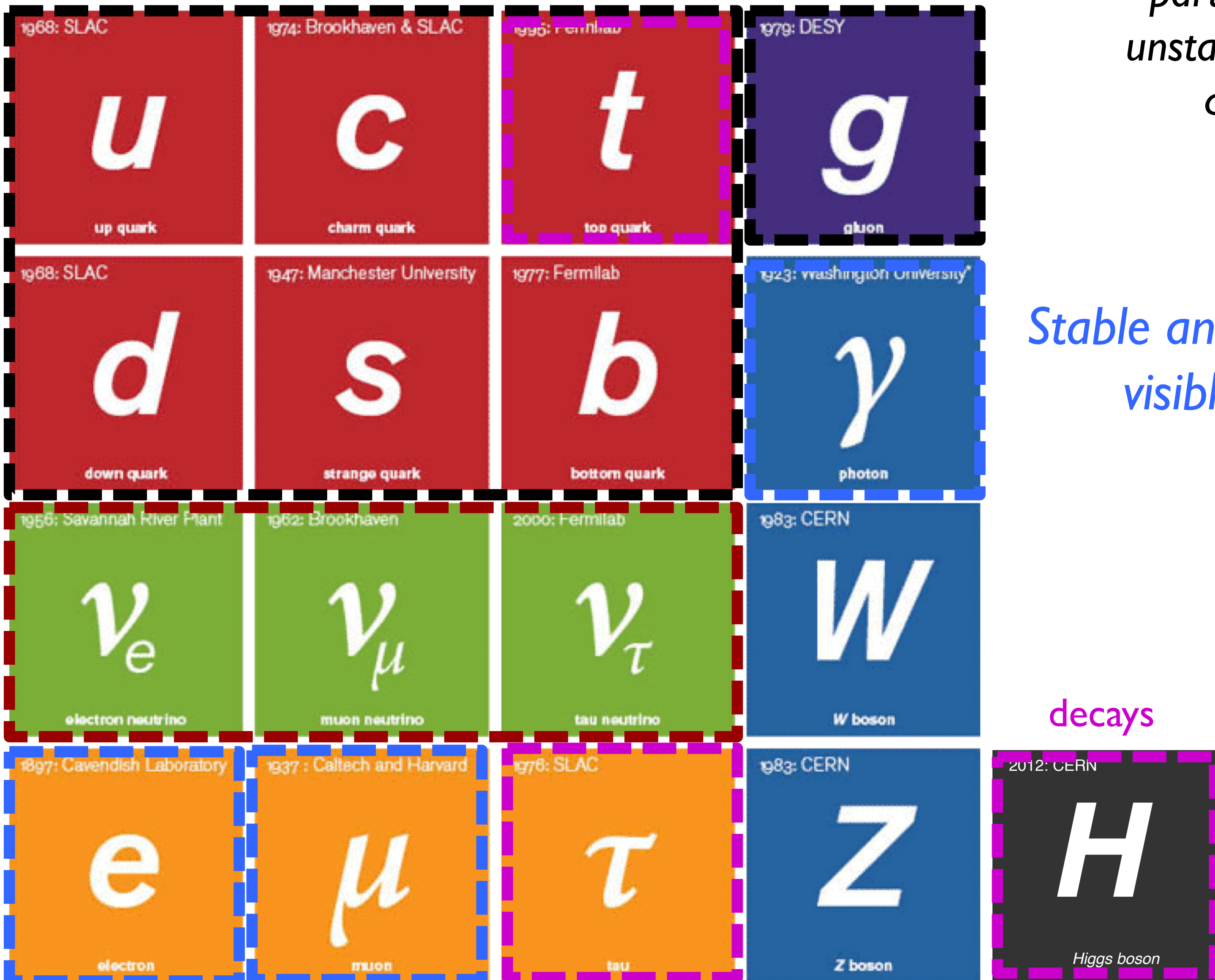
hadron jets

invisible

in particle detectors at accelerators

Stable and visible

decays



Stable and visible

decays

decays

Identifying and measuring "stable" particles

- Particles are characterized by
  - ✓ Mass (m) [Unit: eV/c^2 or eV]
  - ✓ Charge (Q) [Unit: e]
  - ✓ Energy (E) [Unit: eV]
  - ✓ Momentum (p) [Unit: eV/c or eV]
  - ✓ (+ spin, lifetime, …)

Particle identification via measurement of:

e.g. (E, p, Q) or (p, β, Q)
(p, m, Q) ...

- … and move at relativistic speed (here in "natural" unit: ħ = c = 1)

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

$$\ell = \frac{\ell_0}{\gamma}$$ length contraption

$$t = t_0\gamma$$ time dilatation

$$E^2 = \vec{p}^2 + m^2$$

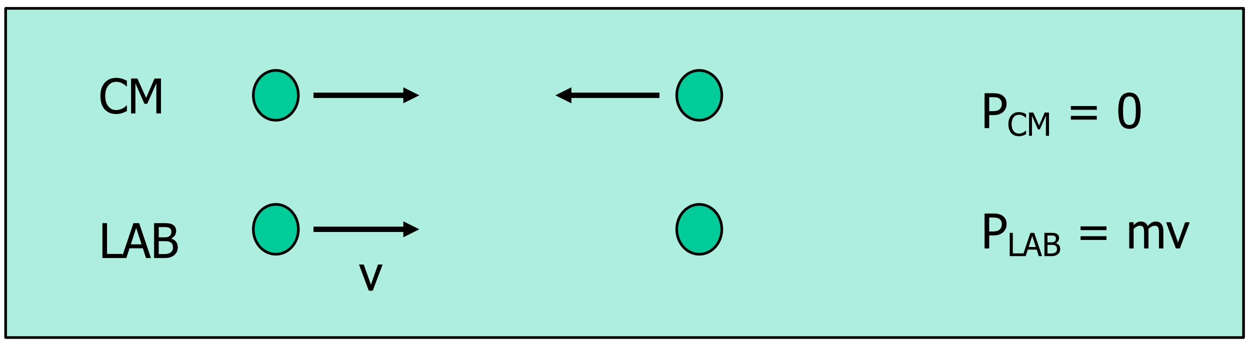
$$E = m\gamma \qquad \vec{p} = m\gamma\vec{\beta}$$

$$\vec{\beta} = \frac{\vec{p}}{E}$$

Center of mass energy

- In the center of mass frame the total momentum is 0
- In laboratory frame center of mass energy can be computed as:

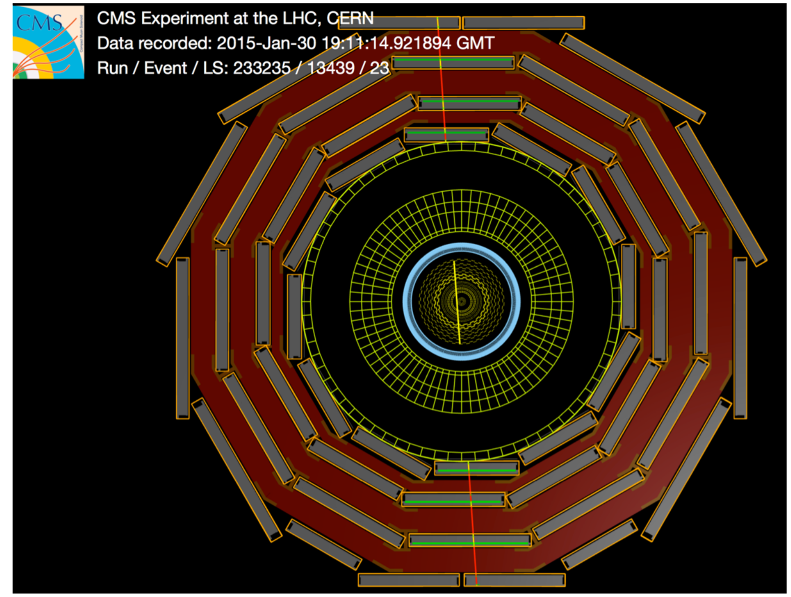
$$E_{\mathrm{cm}} = \sqrt{s} = \sqrt{\left(\sum E_i\right)^2 - \left(\sum \vec{p}_i\right)^2}$$



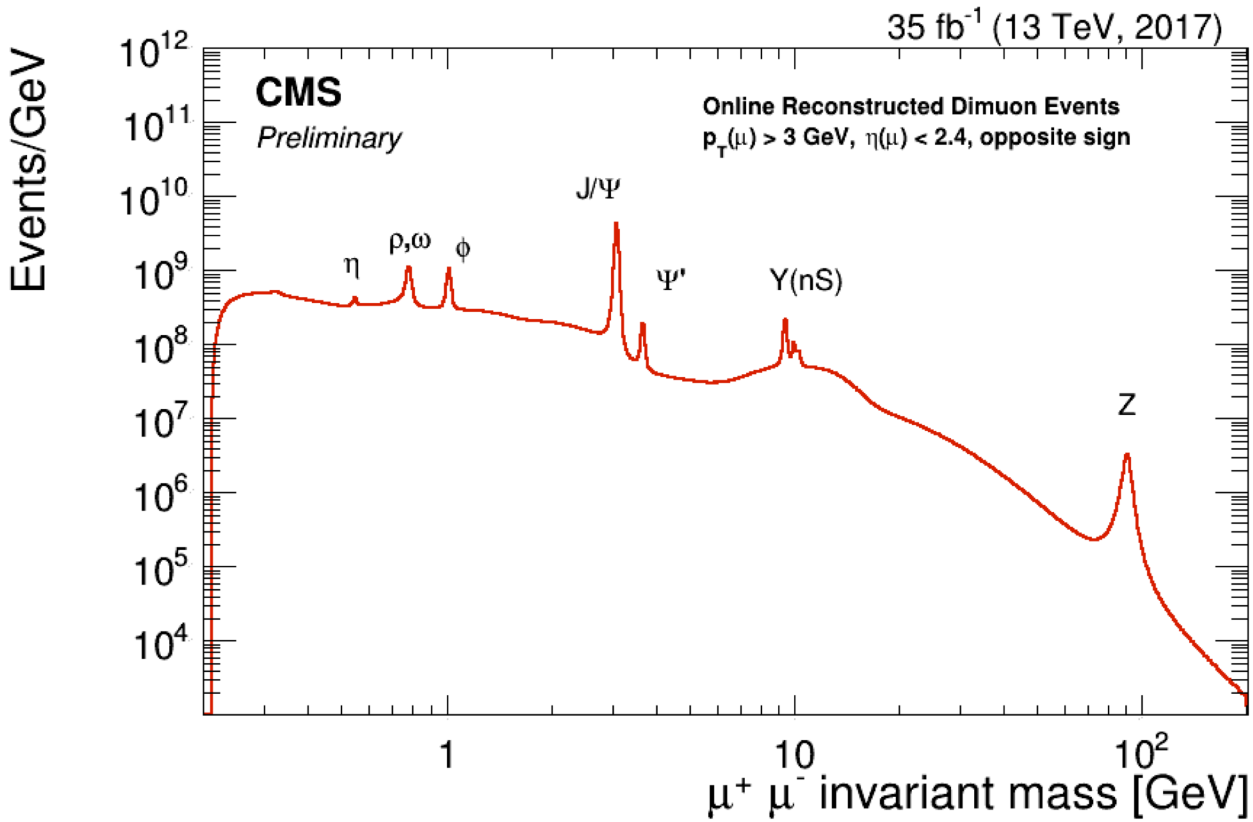
Hint: this corresponds to the "length" of the total four-momentum, that is a relativistic invariant:

$$p = (E, \vec{p}) \qquad \sqrt{p \cdot p}$$

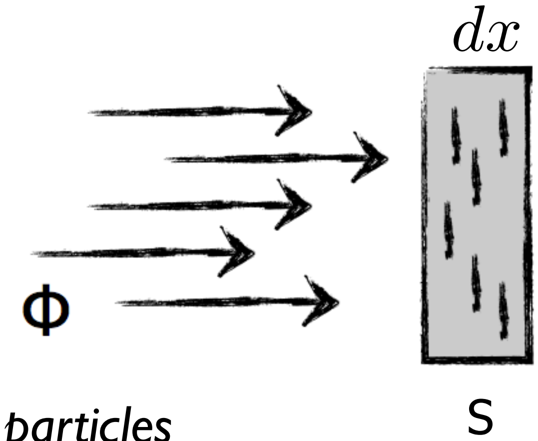
Invariant mass



$$M = \sqrt{\left(\sum E_i\right)^2 - \left(\sum \vec{p}_i\right)^2}$$



Interaction cross section



Flux $\Phi = \frac{1}{S}\frac{dN_i}{dt}$ [$L^{-2}\,t^{-1}$]

area occupied by target particles

Reactions per unit of time

$$\frac{dN_{\mathrm{reac}}}{dt} = \Phi\,\sigma\,N_{\mathrm{target}}\,dx$$

[t^{-1}] [$L^{-2}\,t^{-1}$] [?] [L^{-1}] [L]

Reaction rate per target particle $W_{if} = \Phi\sigma$ [t^{-1}]

Cross section per target particle

$$\sigma = \frac{W_{if}}{\Phi}$$

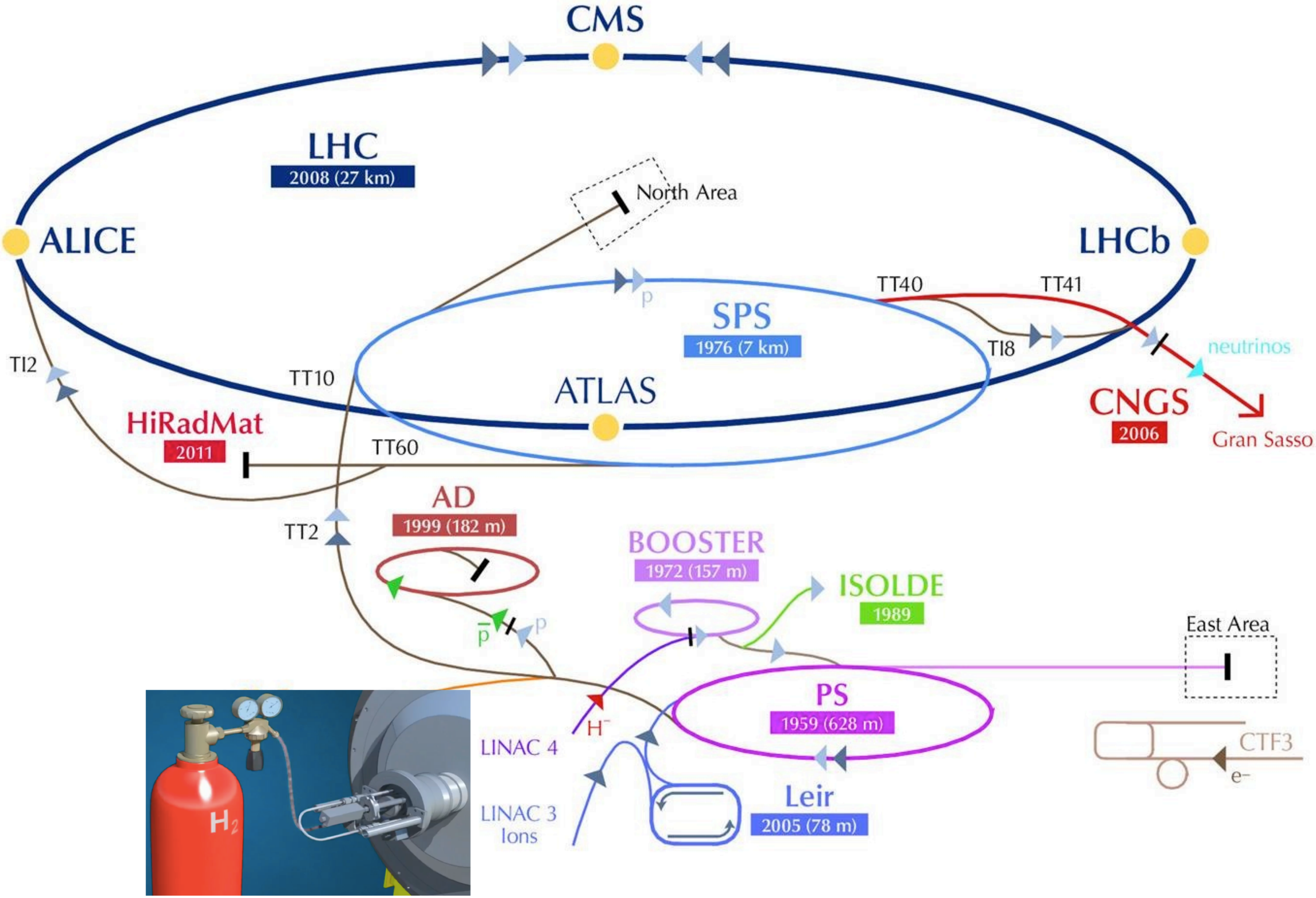
[L^2] = reaction rate per unit of flux

Unit: 1barn = 10^{-28} m² (roughly the area of a nucleus with A = 100)

LHC (Large Hadron Collider)

pp collider (2008-present)
$\sqrt{s}$ = 7-8-13 TeV

CERN accelerator complex or how to build high energy beams



Luminosity

Number of events
in unit of time

$$N = \mathcal{L} \cdot \sigma$$

$[t^{-1}]$ $[L^{-2}\, t^{-1}]$ $[L^{2}]$

$= 1 \times 10^{34}\ cm^{-2}s^{-1}$ (LHC)

In a collider ring…

$$\mathcal{L} = \frac{1}{4\pi} \frac{f k N_1 N_2}{\sigma_x \sigma_y}$$

Proton revolution frequency (40e9/s)

Number of bunches (~3000)

Number of protons in bunches (~1e11)

Beam sizes (RMS)

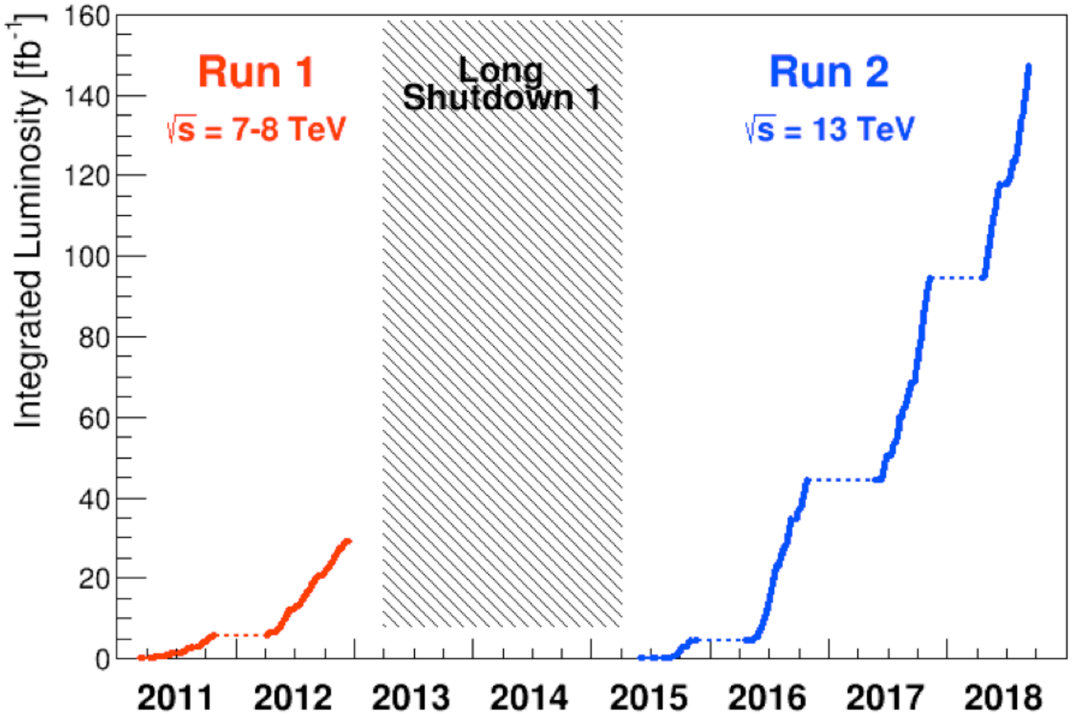
Integrated luminosity

Luminosity integrated over a given period

$$L = \mathcal{L} \cdot t$$

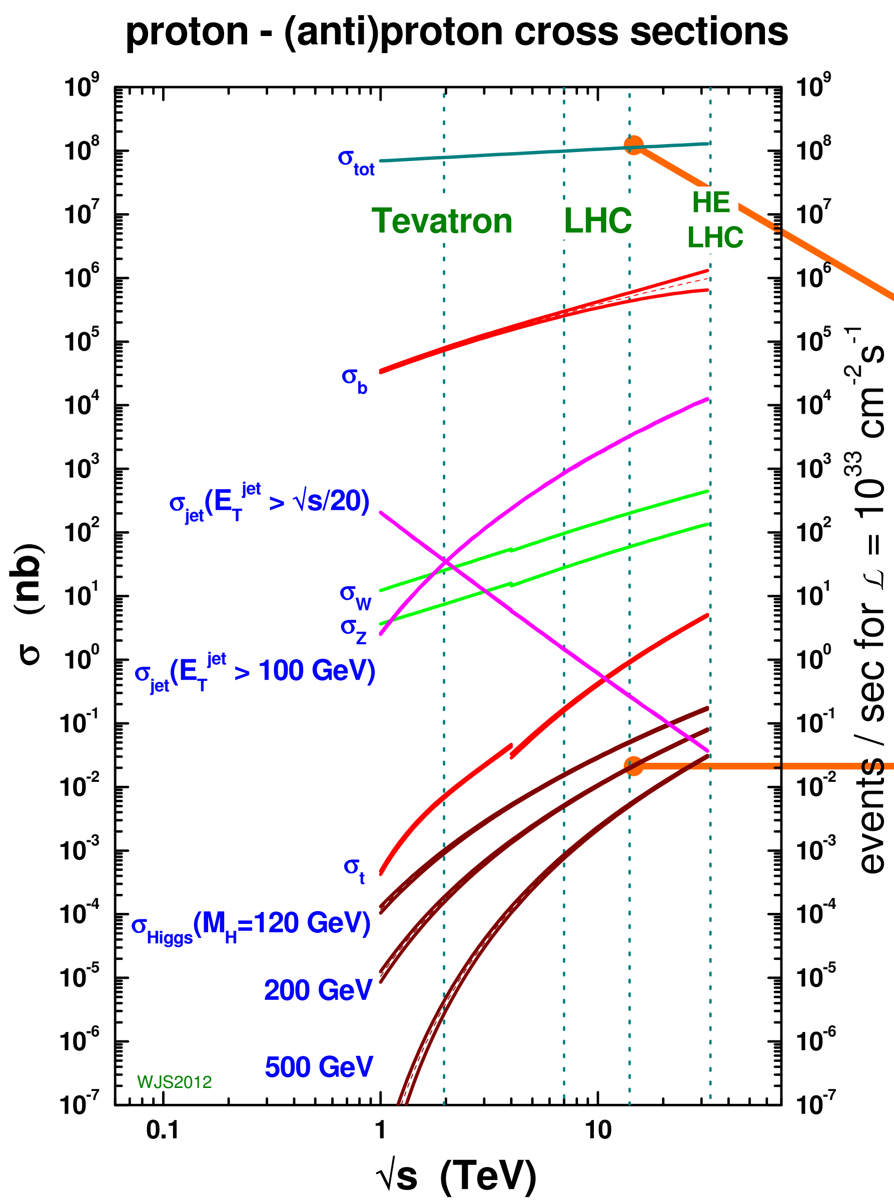
$[L^{-2}]$ $[L^{-2}\, t^{-1}]$ $[t]$

Unit: barn^{-1}



~ 150 fb^{-1} in Run2 for ATLAS and CMS
~ 2.5 fb^{-1} for LHCb (levelled luminosity)
~ 20 pb^{-1} for ALICE (only ~1 month per year)

Cross-sections at LHC



1 nb = 10^{-33} cm^2

σ_{tot} (13 TeV) = 10^8 nb

σ_H (13 TeV) = 0.05 nb

LHC instantaneous luminosity L = 1×10^{34} cm^{-2}s^{-1}

inelastic *pp* collisions

10^9 events/s

$\sim10^{10}$

10^{-1} events/s

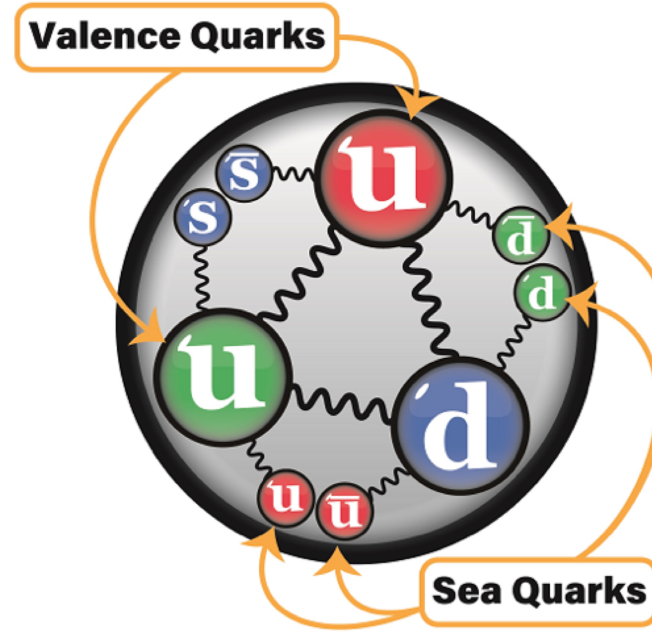
~ 1 Higgs boson produced every 2 seconds

[m_H ~ 125 GeV]

0.2% H → γγ

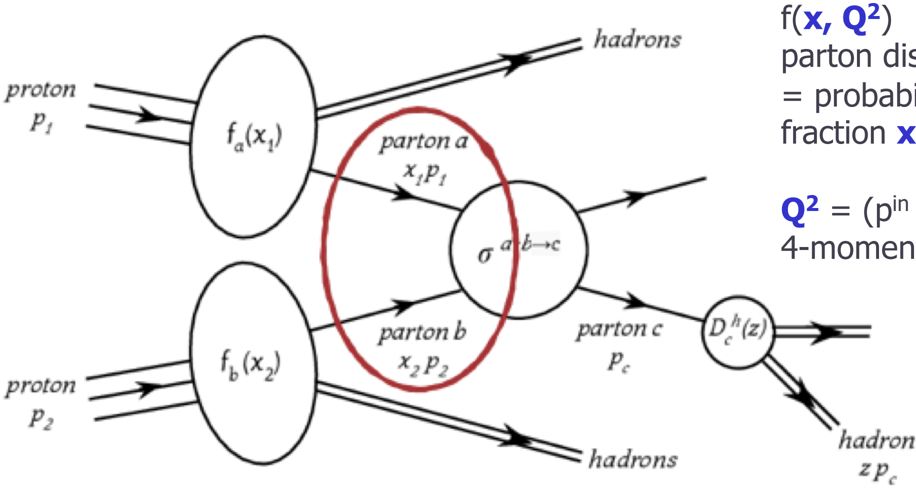
1.5% H → ZZ

About the inner life of a proton



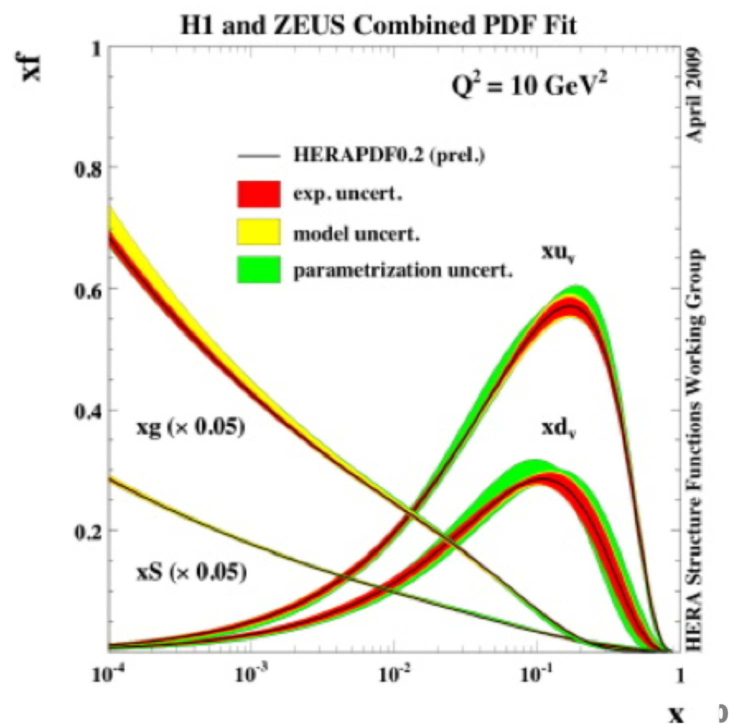
- ***p*rotons have substructures**
  - ✓ partons = quarks & gluons
  - ✓ 3 valence (coloured) quarks bound by gluons
  - ✓ Gluons (coloured) have self-interactions
  - ✓ Virtual quark pairs can pop-up (sea-quark)
  - ✓ *p* momentum shared among constituents
    - described by *p* structure functions

- **Initial state of LHC collisions unknown**
  - ✓ Any of the parton can interact with an unknown fraction of total momentum



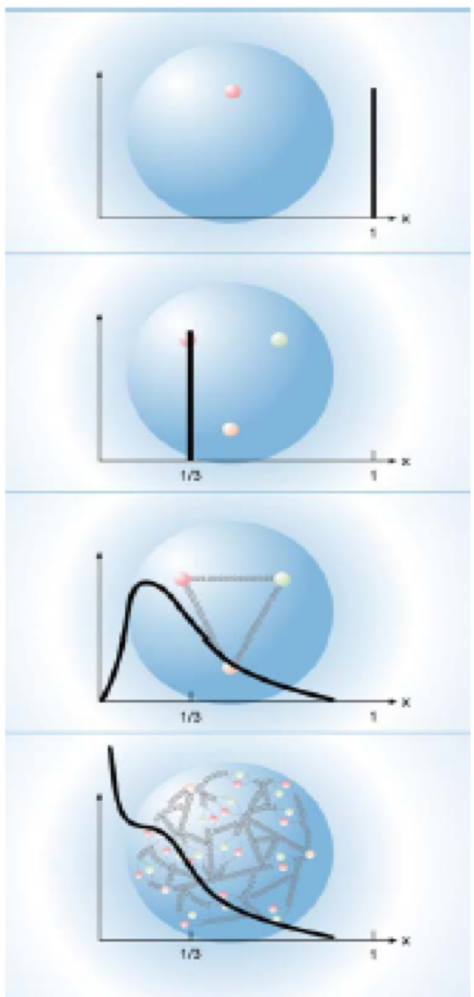
f(**x**, **Q²**)
parton distribution function (PDF)
= probability for a parton to carry a fraction **x** of proton momentum

Q^2 = $(p^{in} - p^{fin})^2$
4-momentum transfer



Q^2 evolution

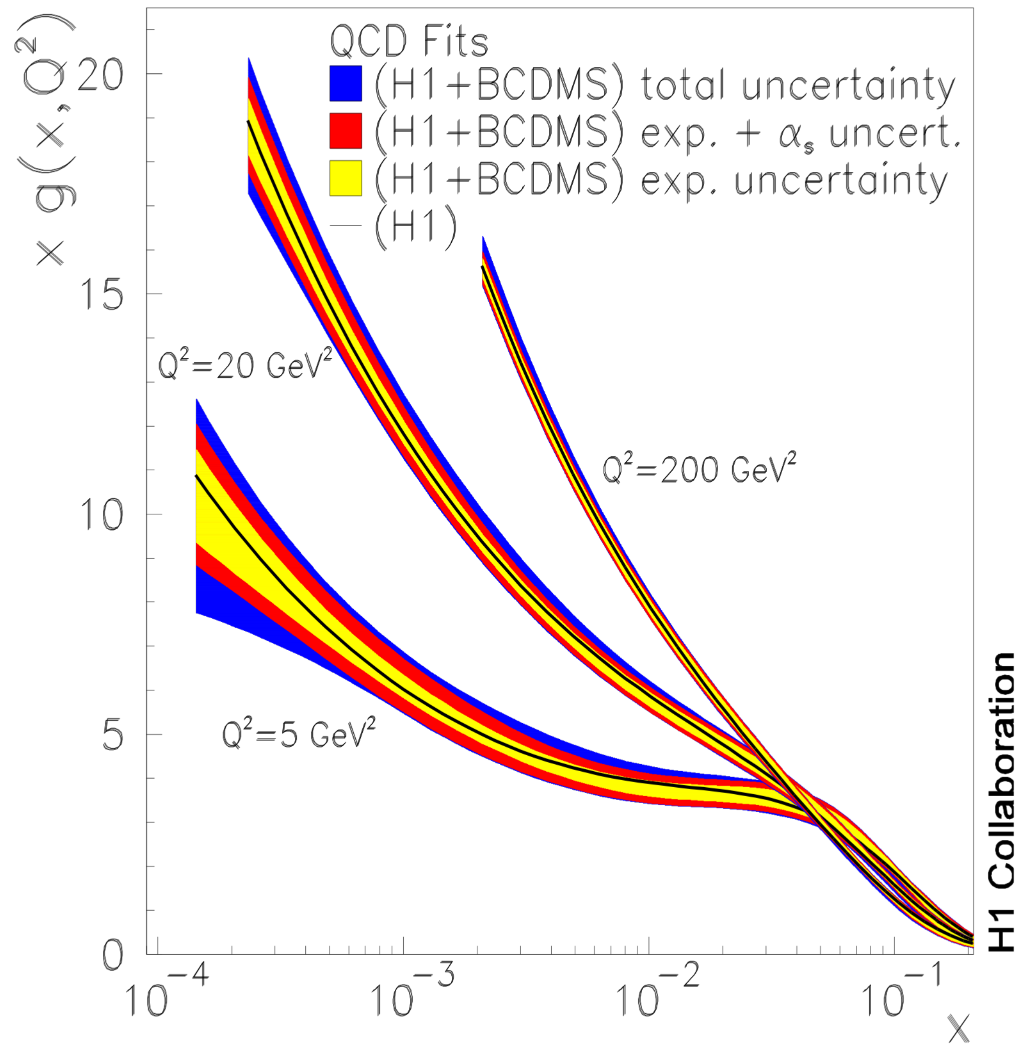
Q^2 evolution



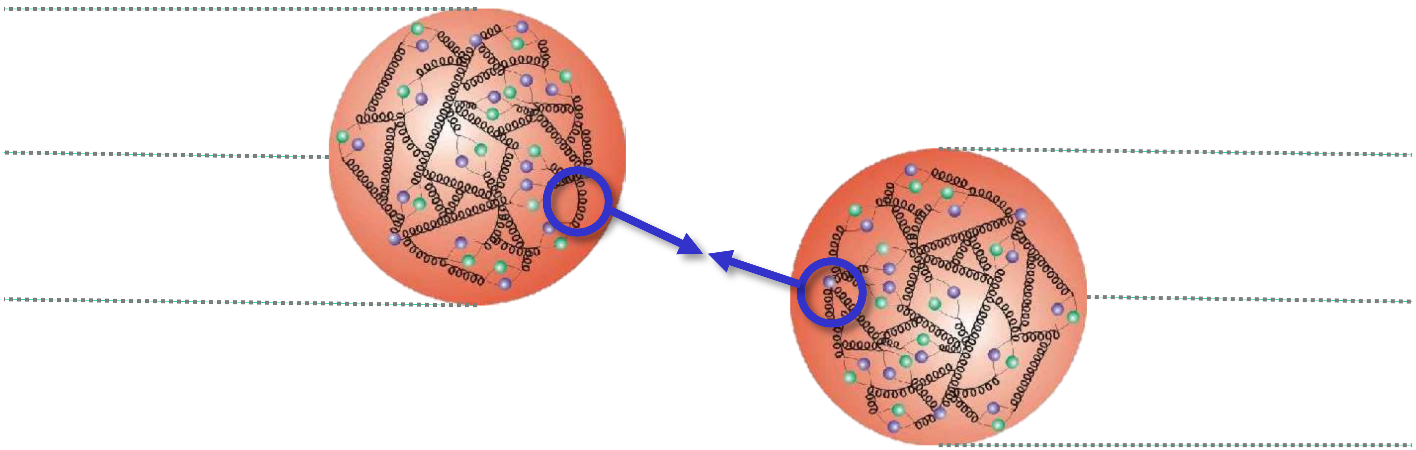
small Q^2

↓

large Q^2

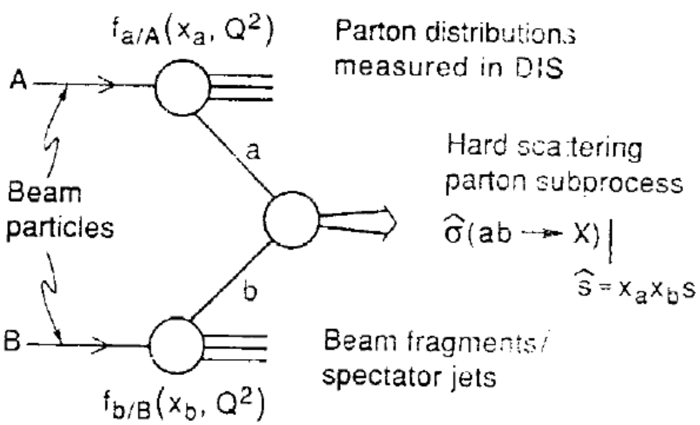


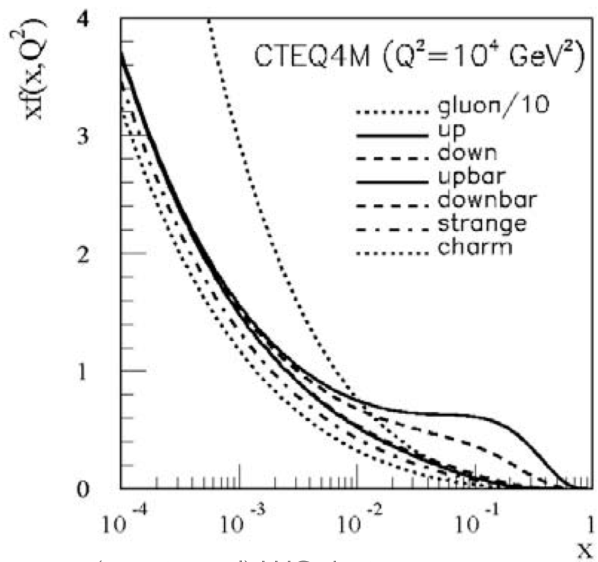
Cross sections at a proton-proton collider



$$\sqrt{\hat{s}} = \sqrt{x_a x_b s}$$

$$\sigma = \sum_{a,b} \int dx_a dx_b f_a(x, Q^2) f_b(x, Q^2) \hat{\sigma}_{ab}(x_a, x_b)$$



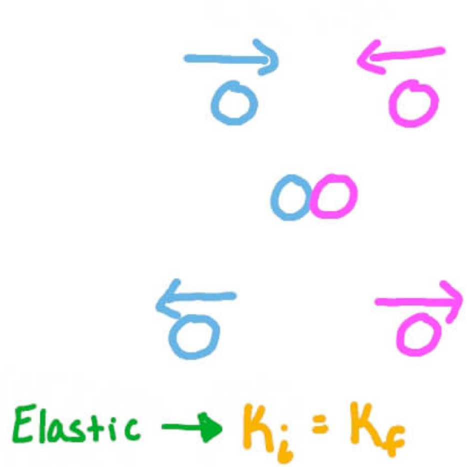


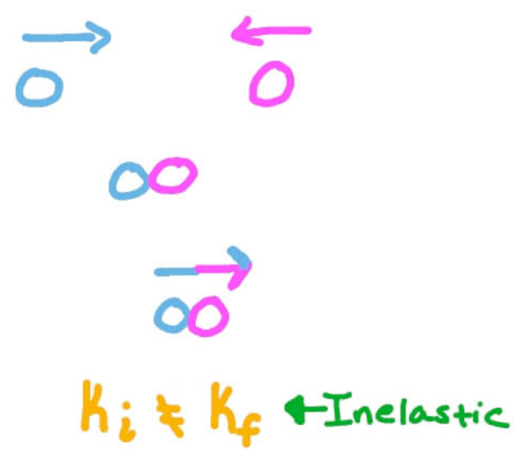
Example: to produce a particle with mass m = 100 GeV

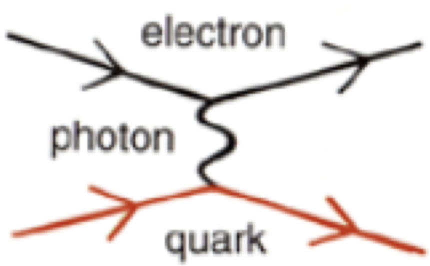
$\sqrt{\hat{s}}$ = 100 GeV

$\sqrt{s}$ = 14 TeV → $\sqrt{x_a x_b}$ = 0.007

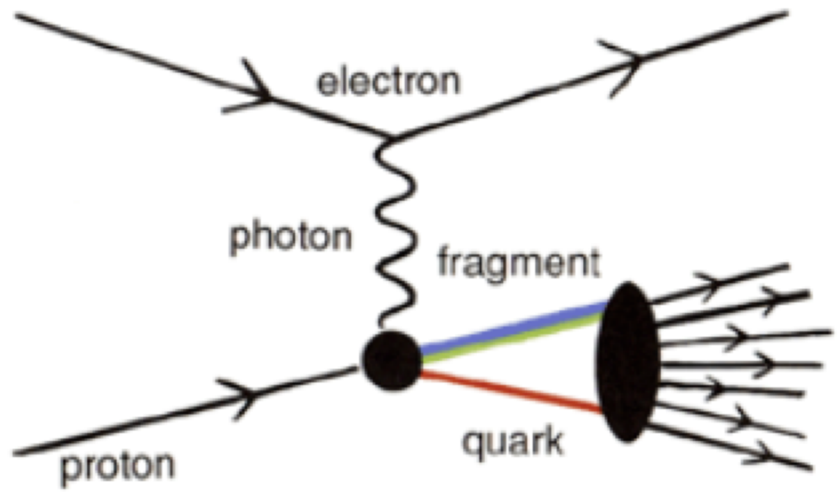
Elastic vs (deep) inelastic collisions





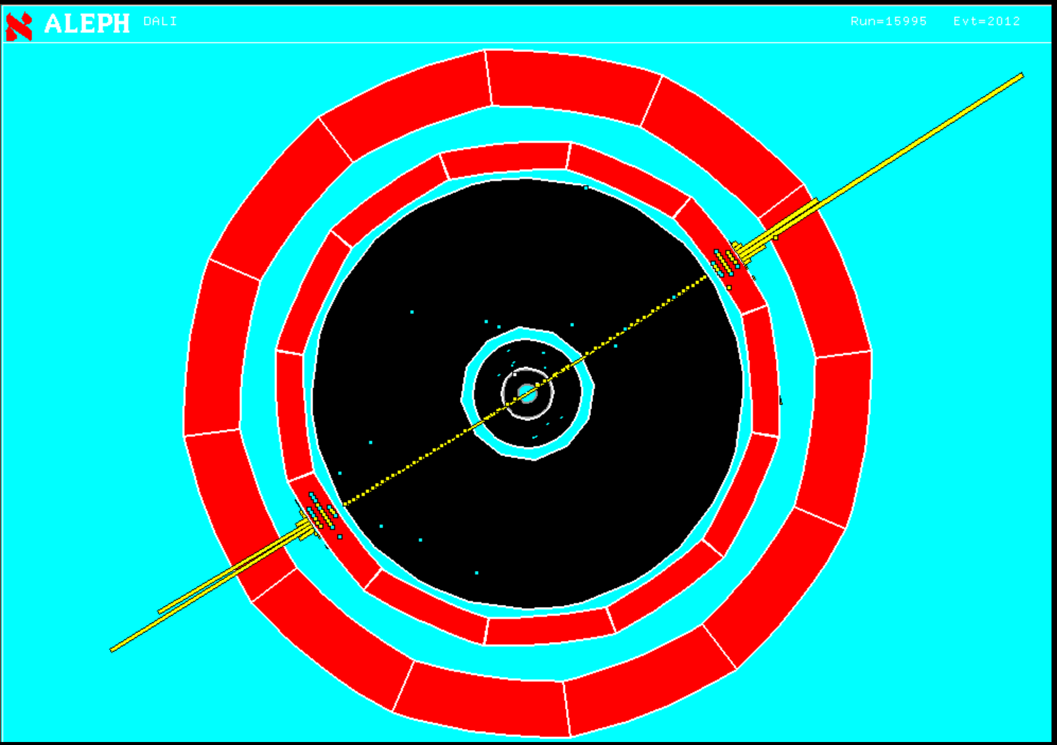


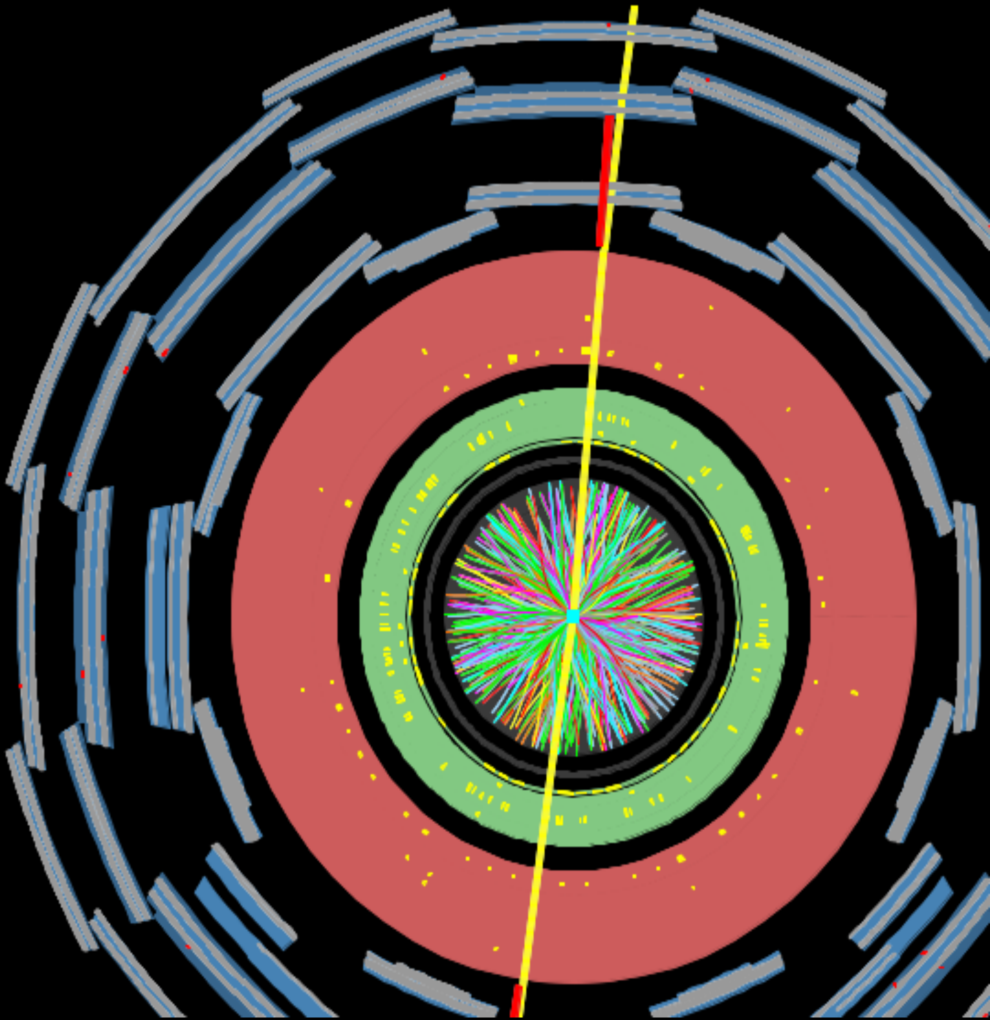
Elastic



Deep inelastic

A Z→e^+e^- event at LEP and ad LHC





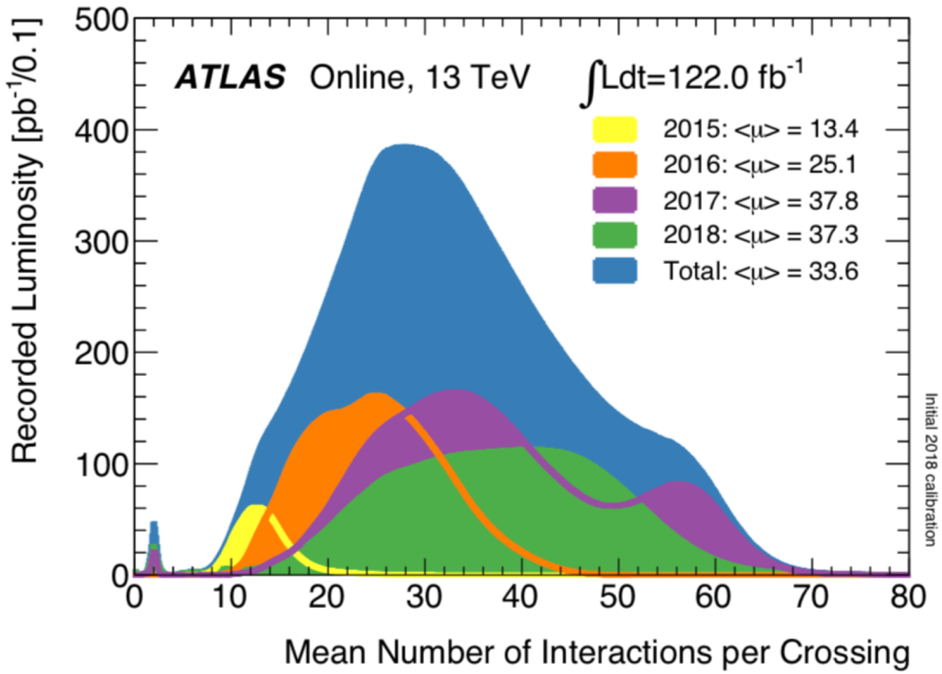
ALEPH @ LEP

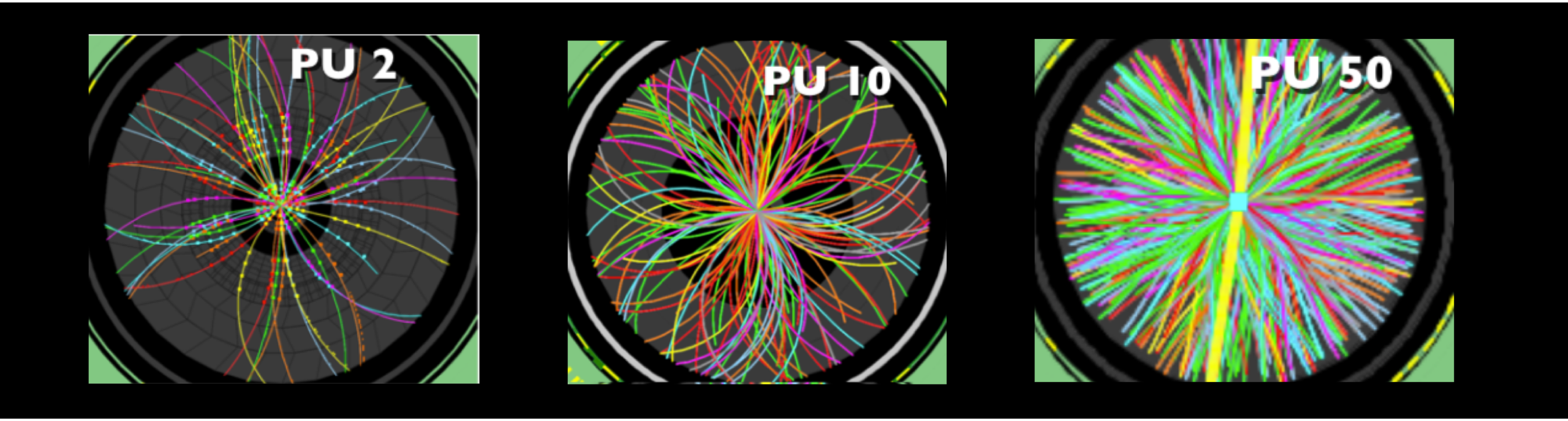
ATLAS @ LHC

Pile-Up

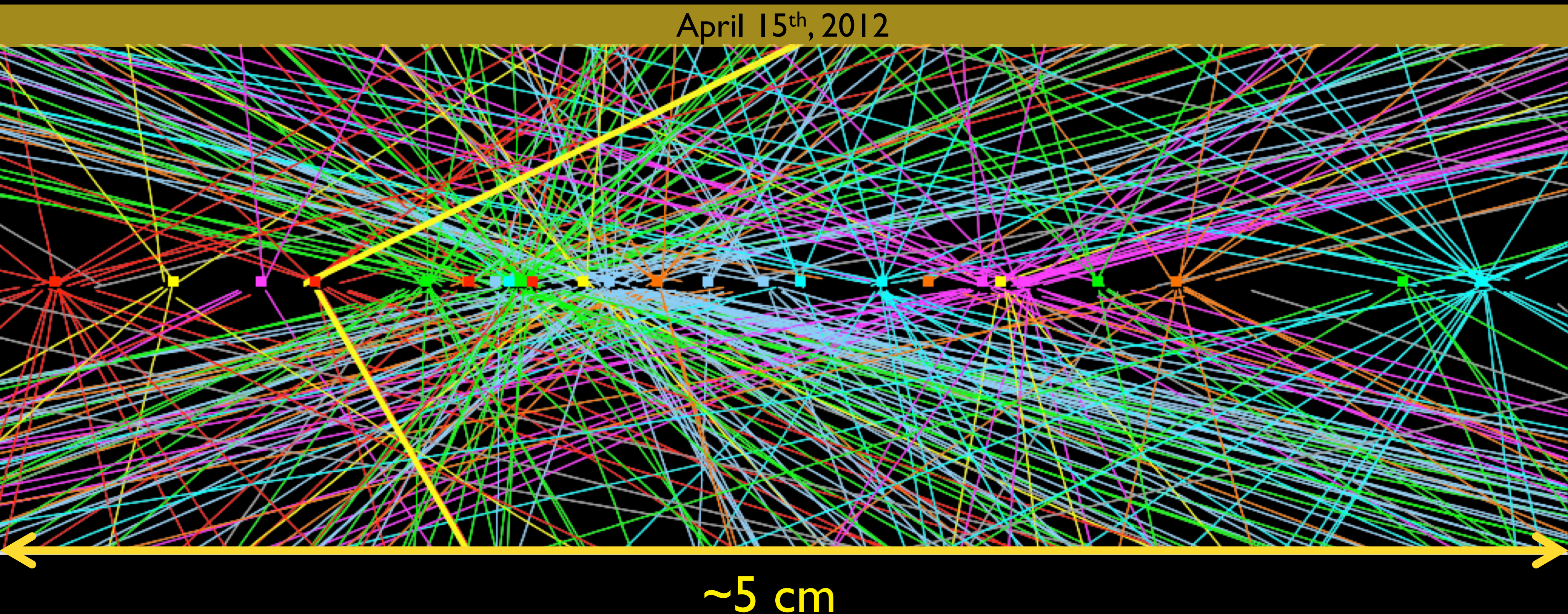
$$\mathcal{L} = \frac{1}{4\pi} \frac{f k N_1 N_2}{\sigma_x \sigma_y}$$

PU = number of inelastic interactions per beam bunch crossing

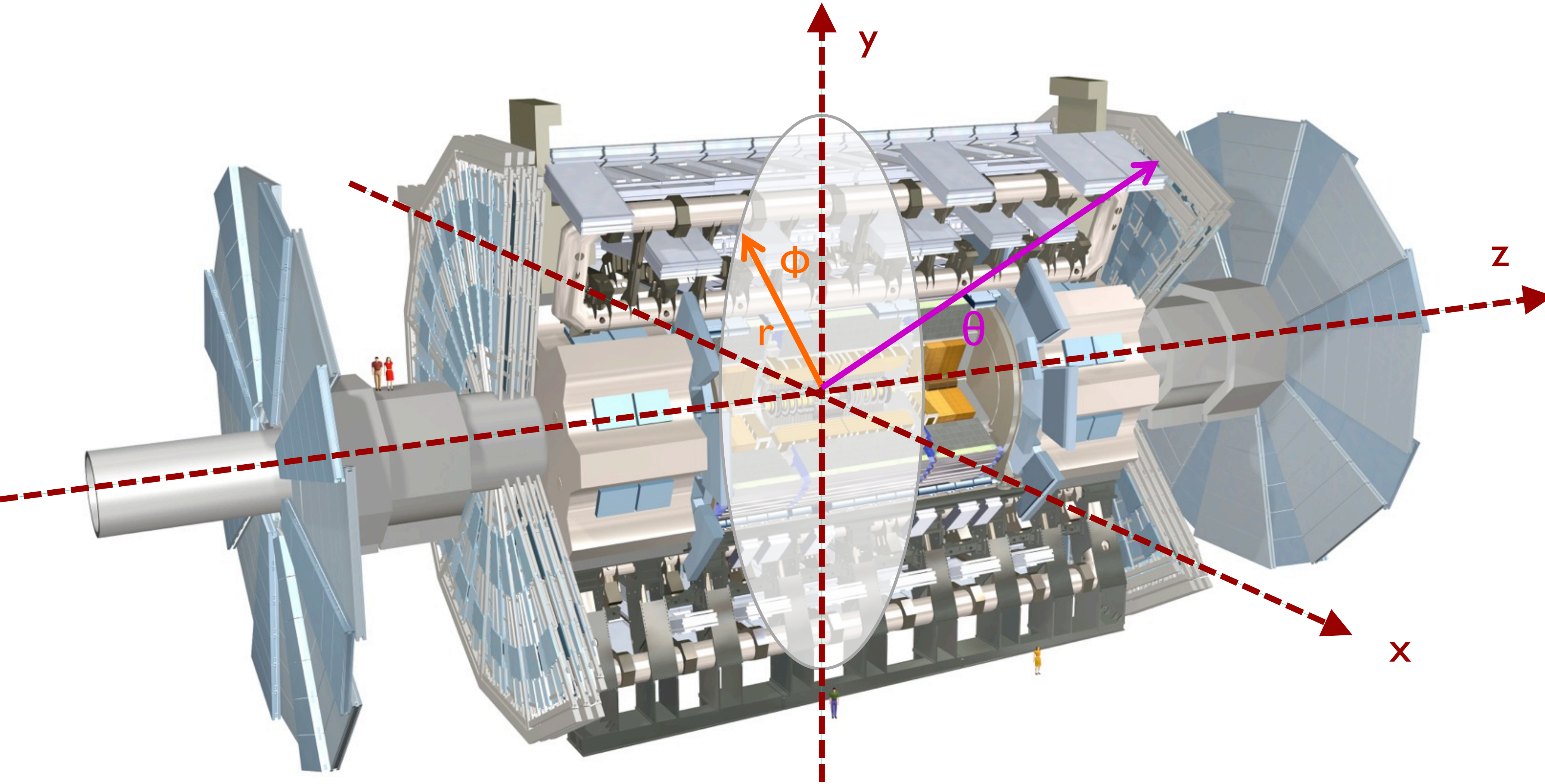




Z→μμ event with 25 reconstructed vertices

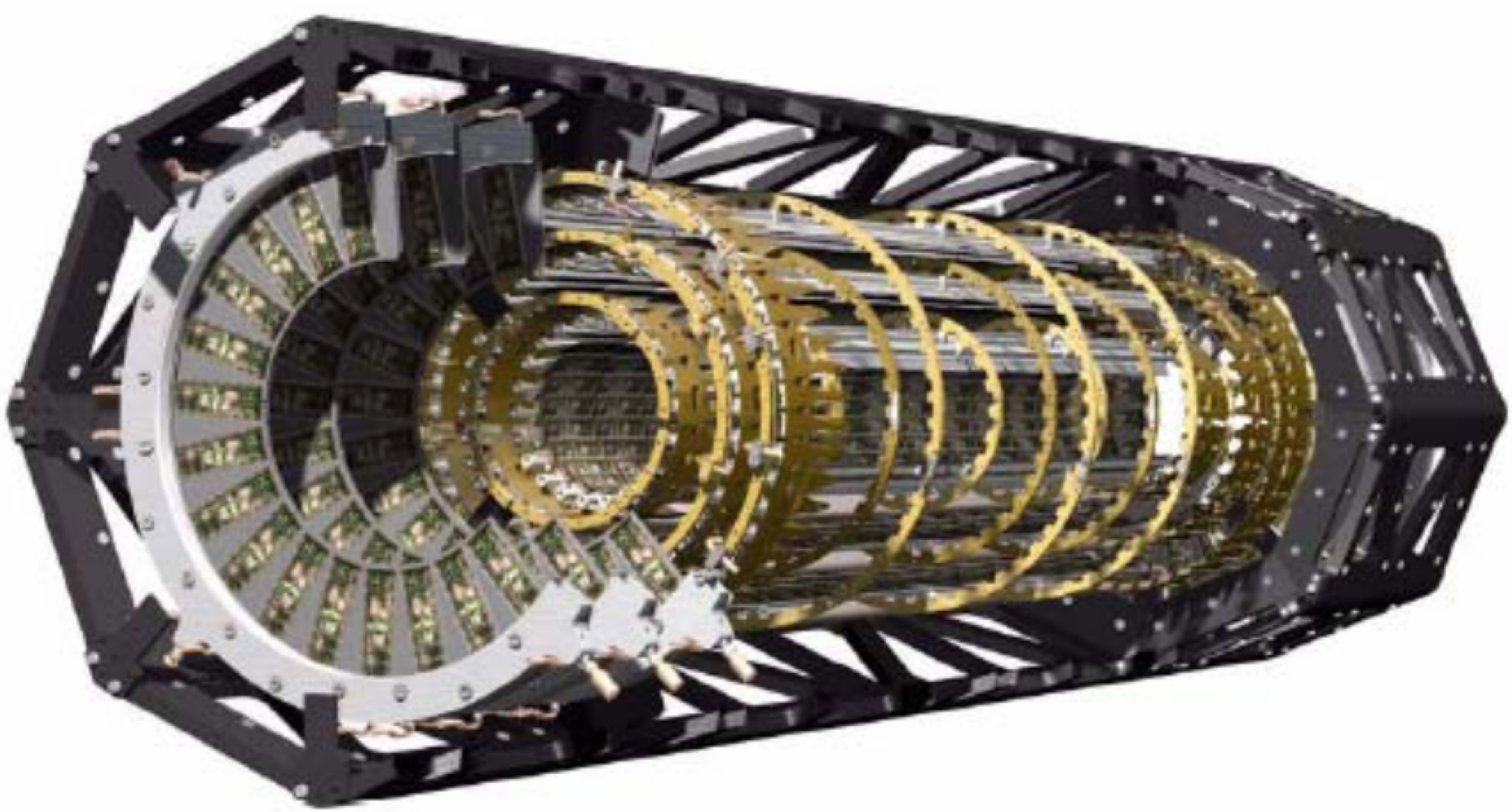


Collider experiment coordinates



Tracking system

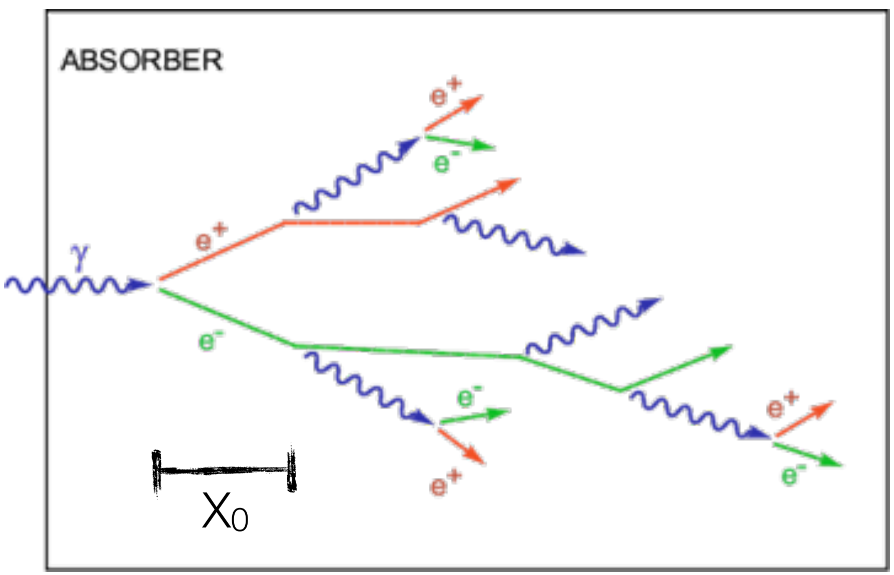
- A fast, radiation hard, and high resolution system to measure charged particle momentum
- Tracking device + magnetic field



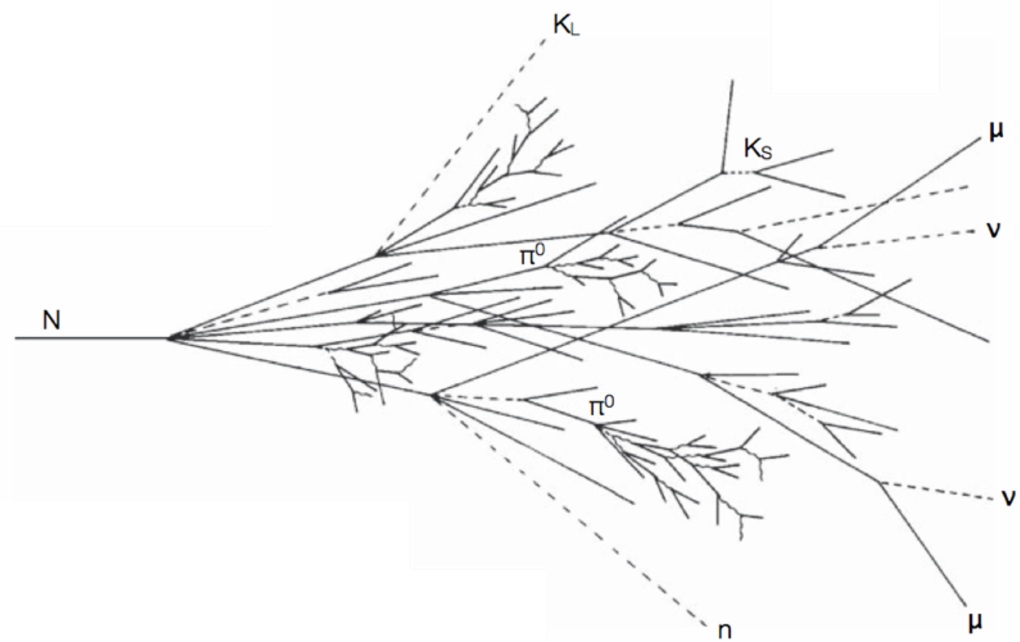
Calorimeters for showering particles

- Electromagnetic shower
  - ✓ Photons: pair production
    - Until below e^+e^- threshold
  - ✓ Electrons: bremsstrahlung
    - Until brem cross-section smaller than ionization

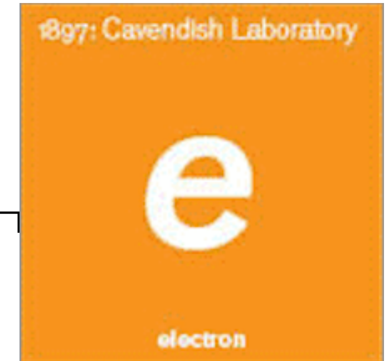
$$\frac{dE}{dx}(E_c)\Big|_{\text{Brems}} = \frac{dE}{dx}(E_c)\Big|_{\text{Ion}}$$

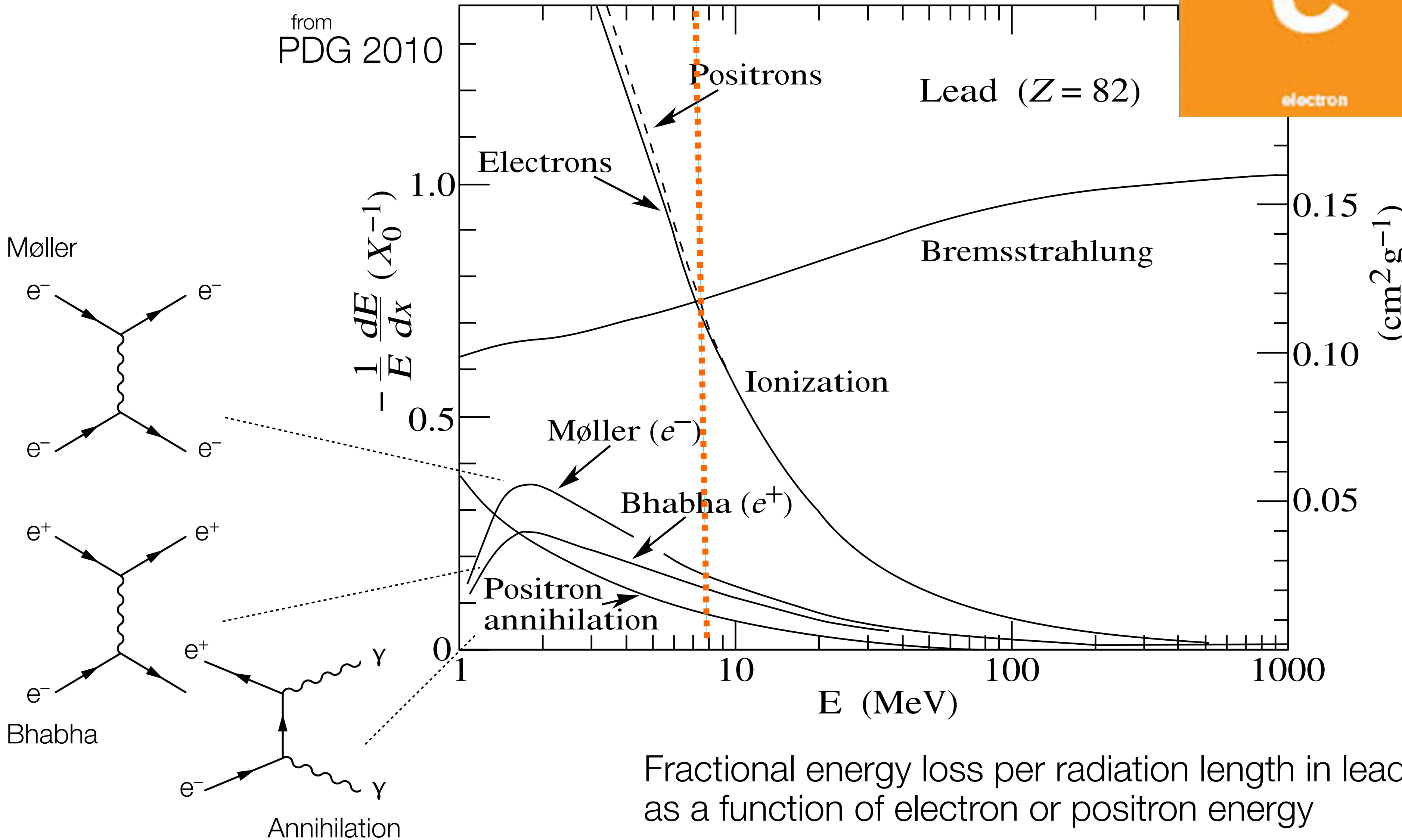


- Hadronic showers
  - ✓ Inelastic scattering w/ nuclei
    - Further inelastic scattering until below pion production threshold
  - ✓ Sequential decays
    - $\pi^0 \rightarrow \gamma\gamma$
    - Fission fragment: β-decay, γ-decay
    - Neutron capture, spallation, …



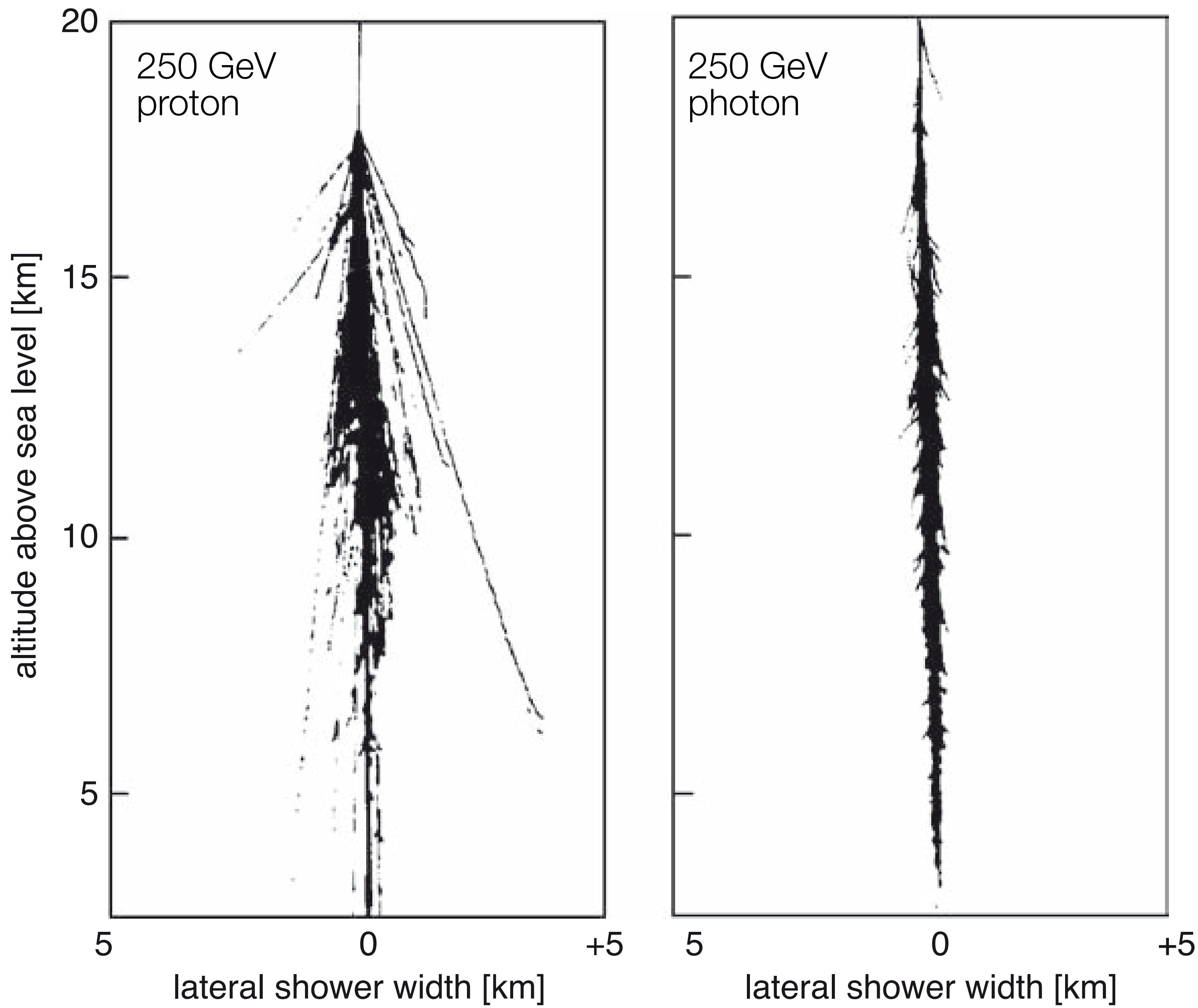
Electron energy loss





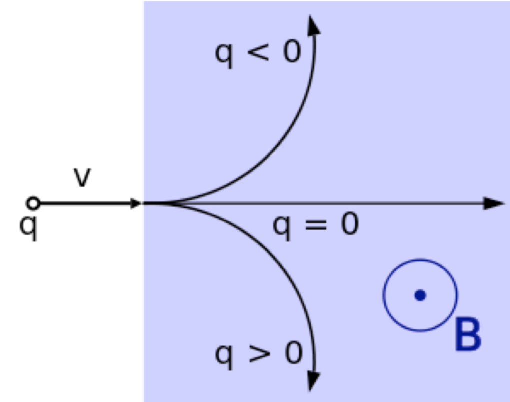
Fractional energy loss per radiation length in lead as a function of electron or positron energy

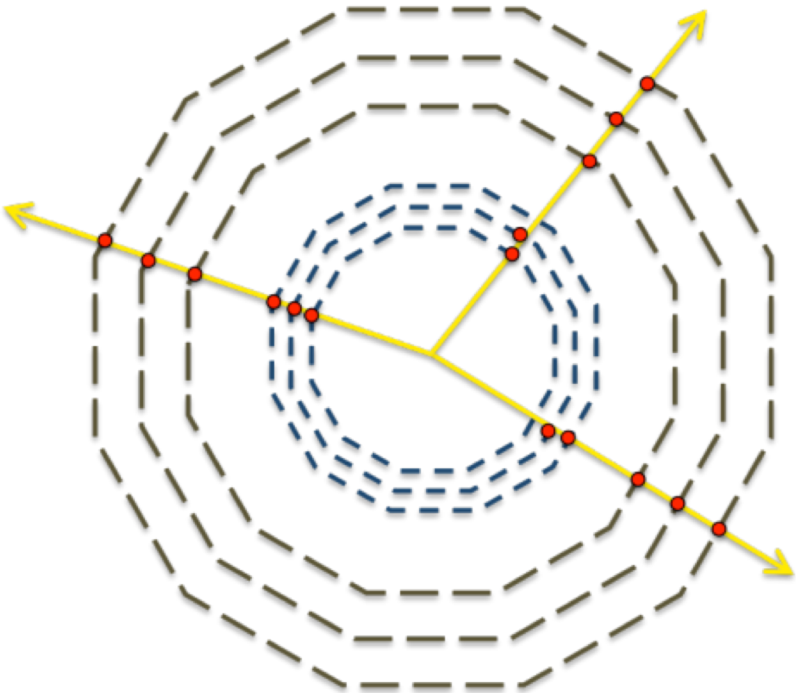
Hadronic vs. EM showers

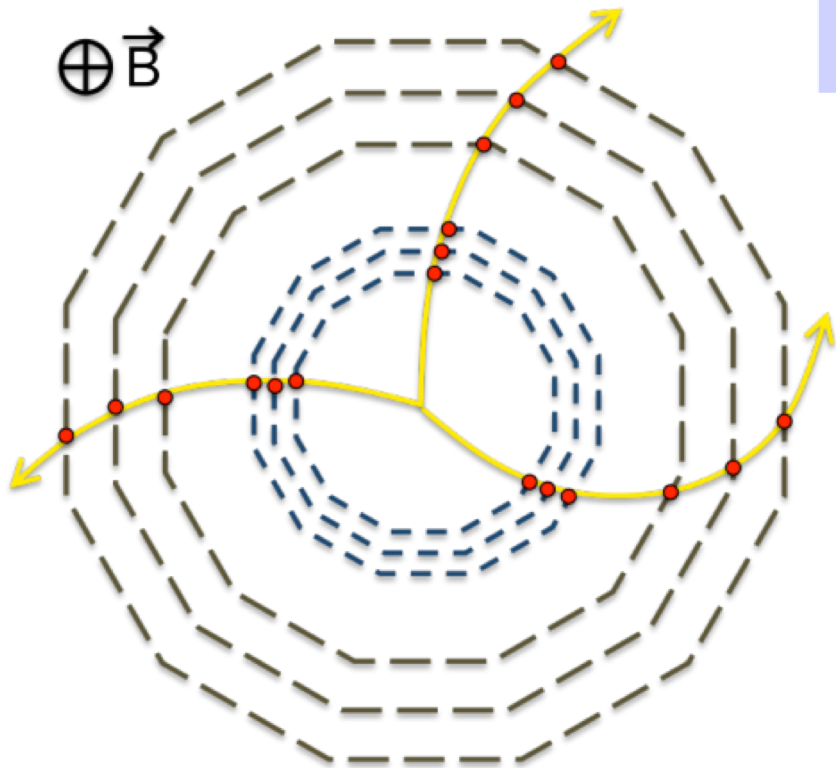


Magnetic spectrometer for ionizing particles

- A system to measure (charged) particle momentum
- Tracking device + magnetic field

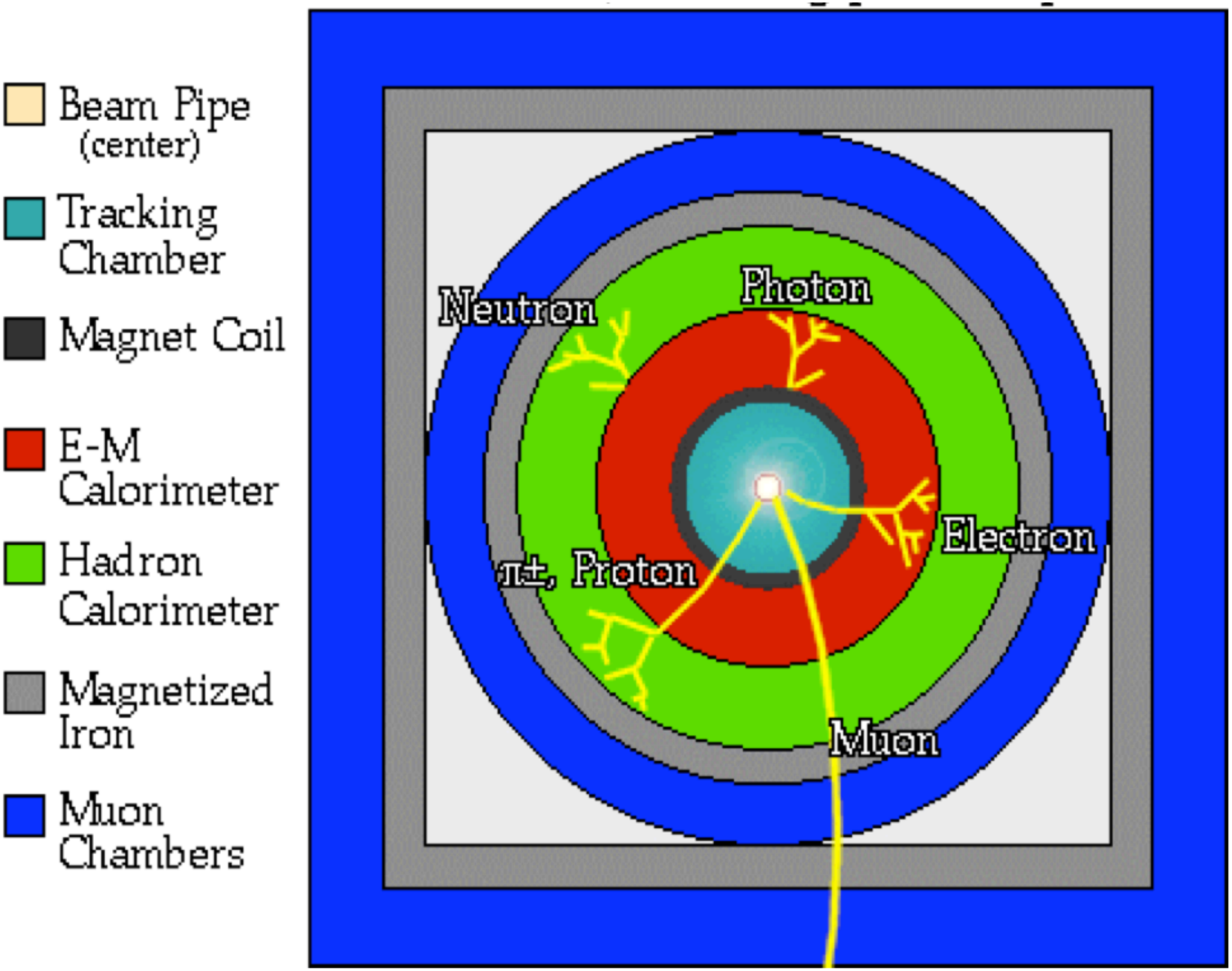




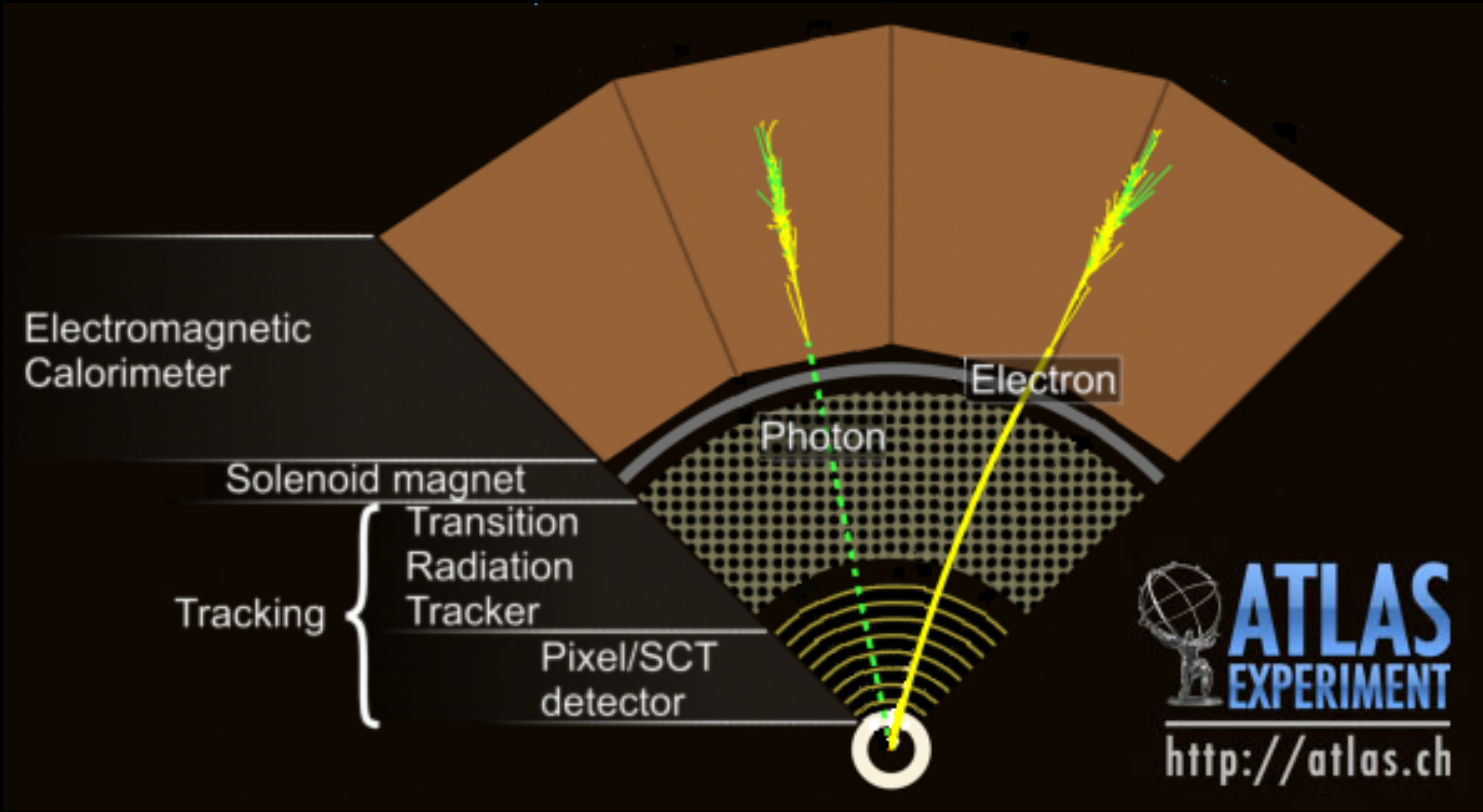


$$p[\mathrm{GeV}] = 0.3 B[\mathrm{T}] \rho[\mathrm{m}]$$

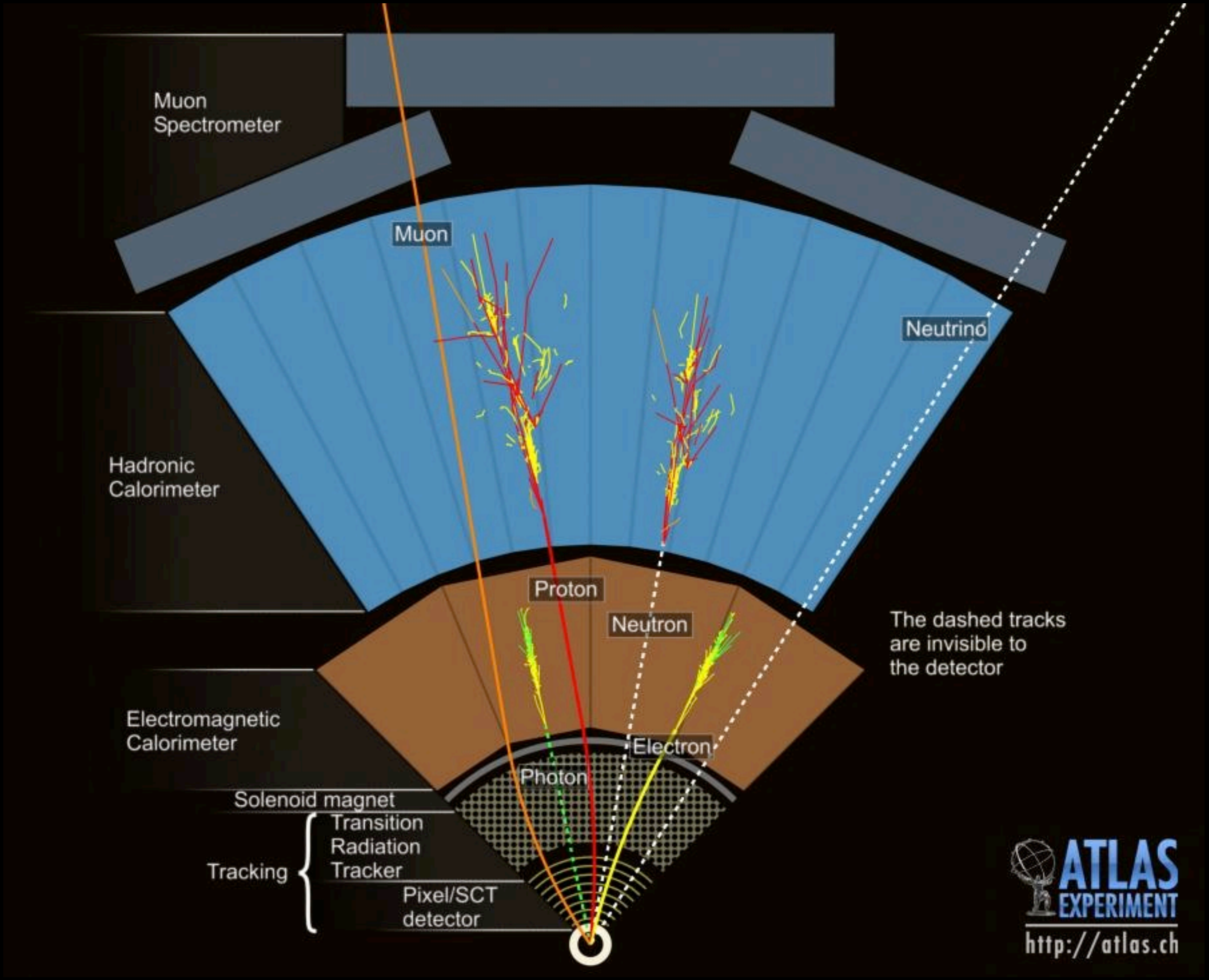
How do we “see” particles?



Particle identification with tracker and EM calo

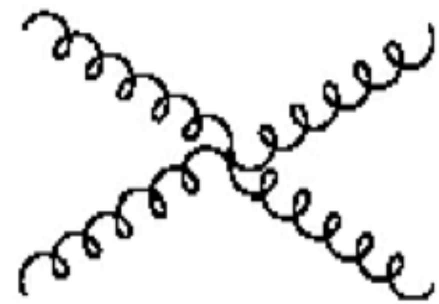


Particle identification with EM and HAD calos



A few words about hadronic particles

- **QCD (strong) interactions are carried out by gluons**
  - ✓ Gluons are massless
  - ✓ Gluons couple to color charges
  - ✓ Gluons have color themselves
    - They can couple to other gluons

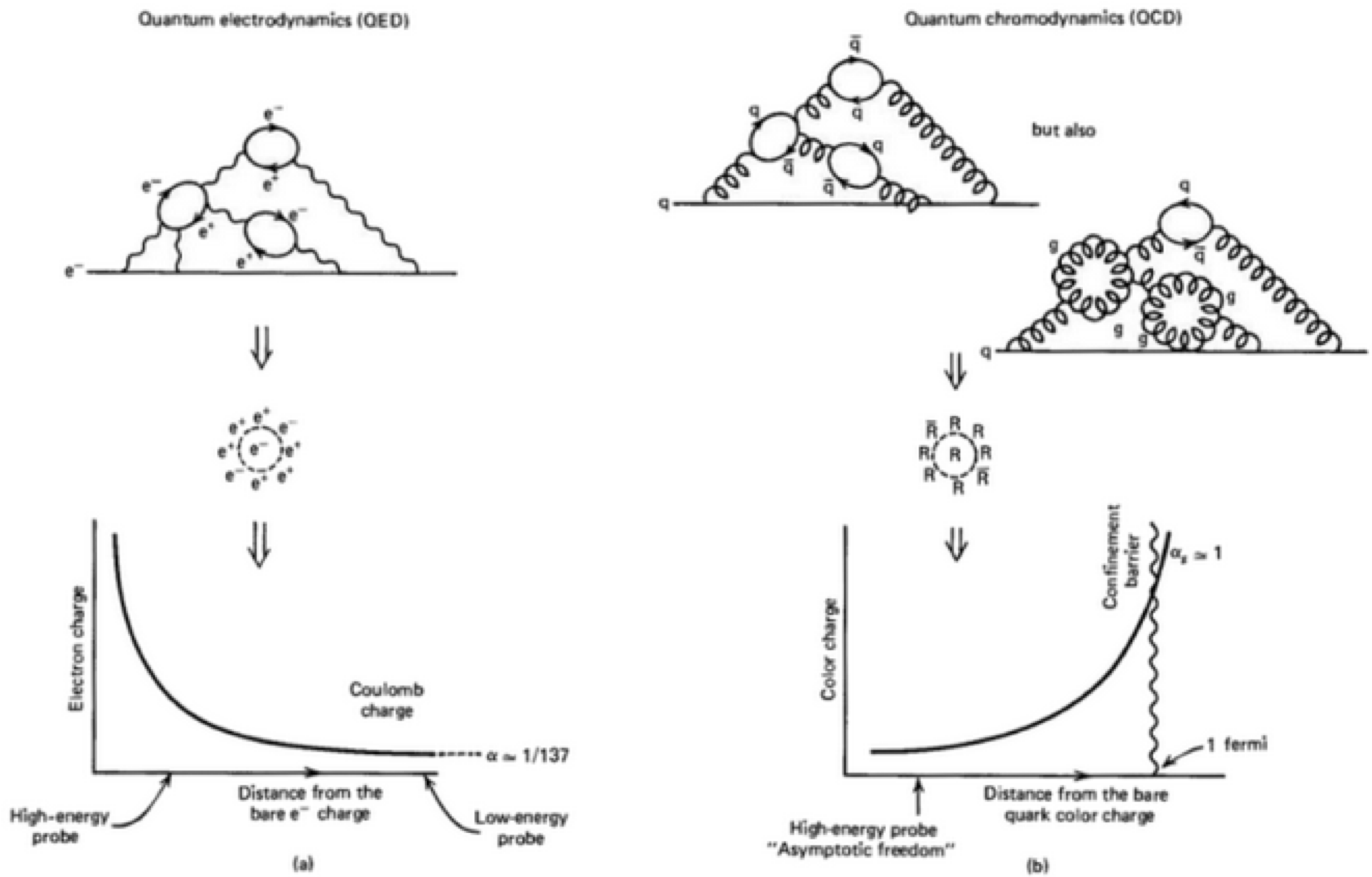


- **Principle of asymptotic freedom**
  - ✓ At short distances strong interactions are weak
    - Quarks and gluons are essentially free particles
    - Perturbative regime (can calculate!)
  - ✓ At large distances, higher-order diagrams dominate
    - Interaction is very strong
    - Perturbative regime fails, have to resort to effective models

quark-quark effective potential

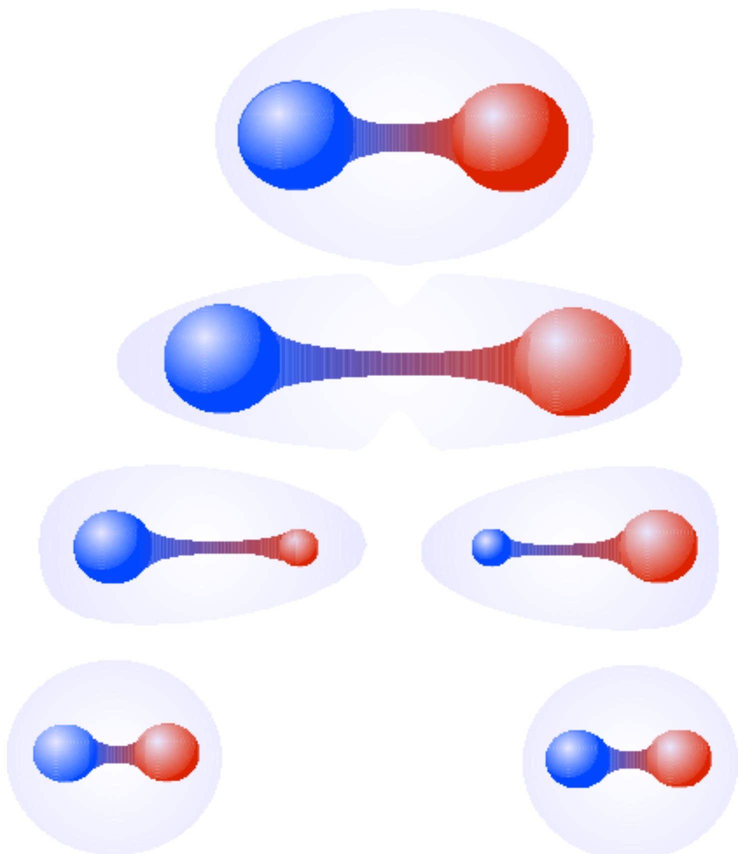
$$V_s = \underbrace{-\frac{4}{3}\frac{\alpha_s}{r}}_{\text{single gluon exchange}} + \underbrace{kr}_{\text{confinement}}$$

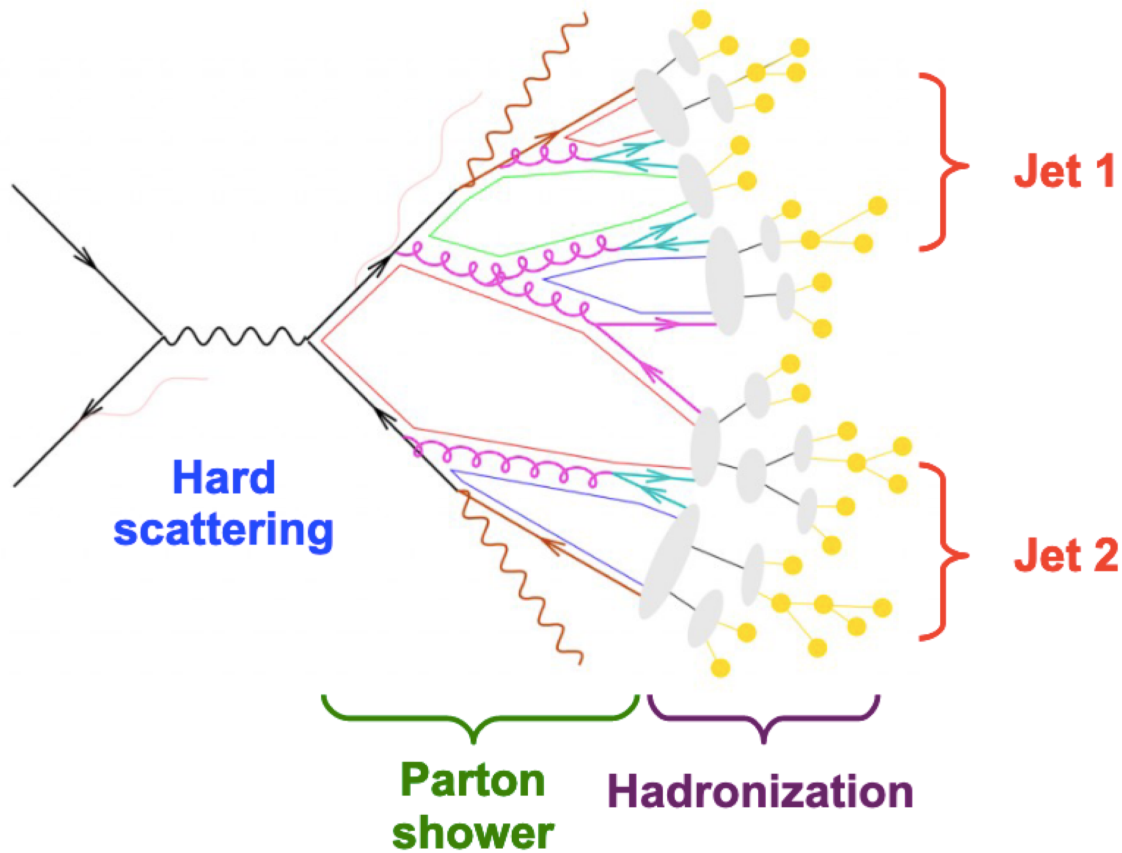
Asymptotic freedom



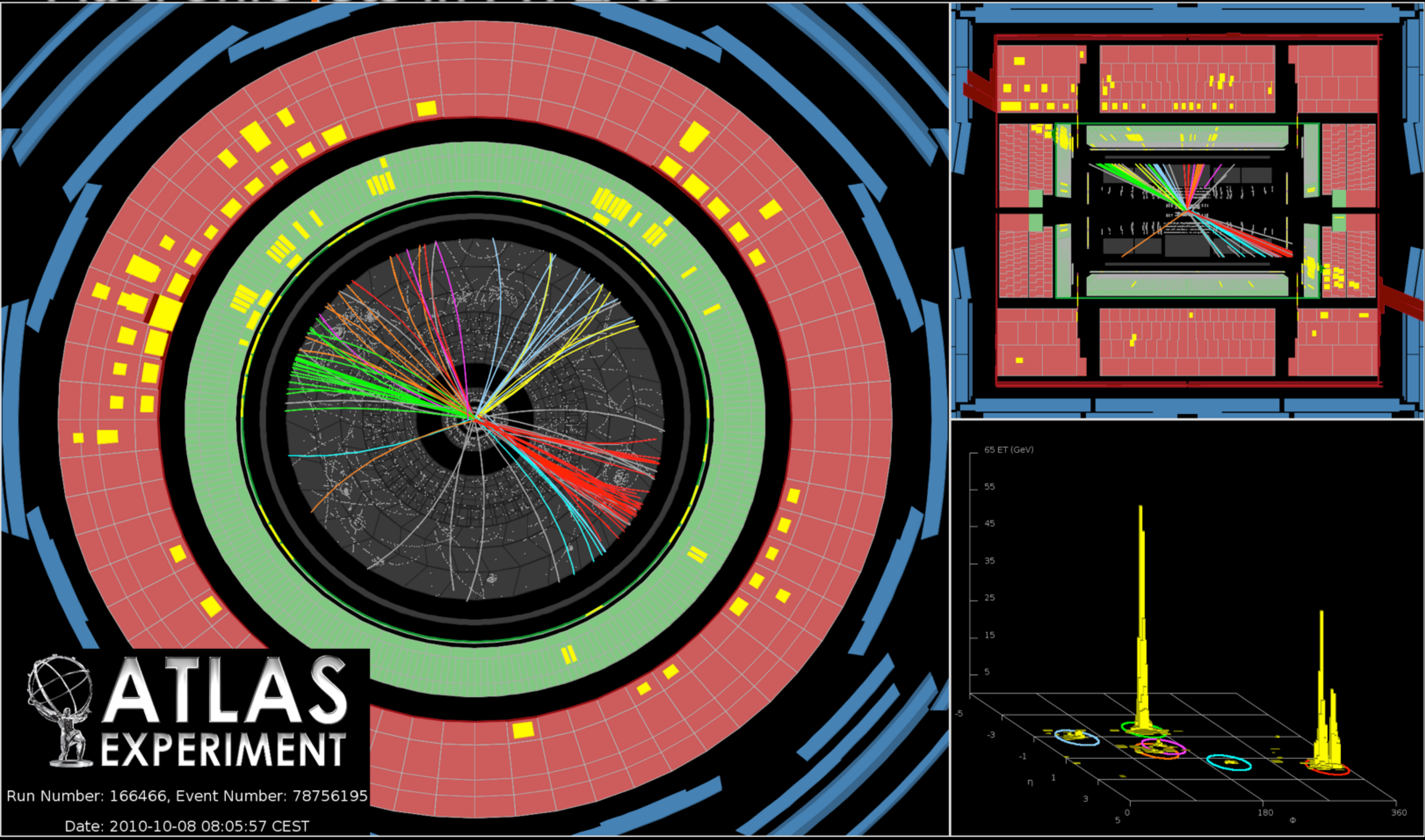
Screening of the electric (a) and colour (b) charges in quantum field theory. Feynman's diagrams for the creation of virtual particles for the two processes are also showed. [Picture from F. Halzen and D.H. Martin – see references

Confinement, hadronization, jets



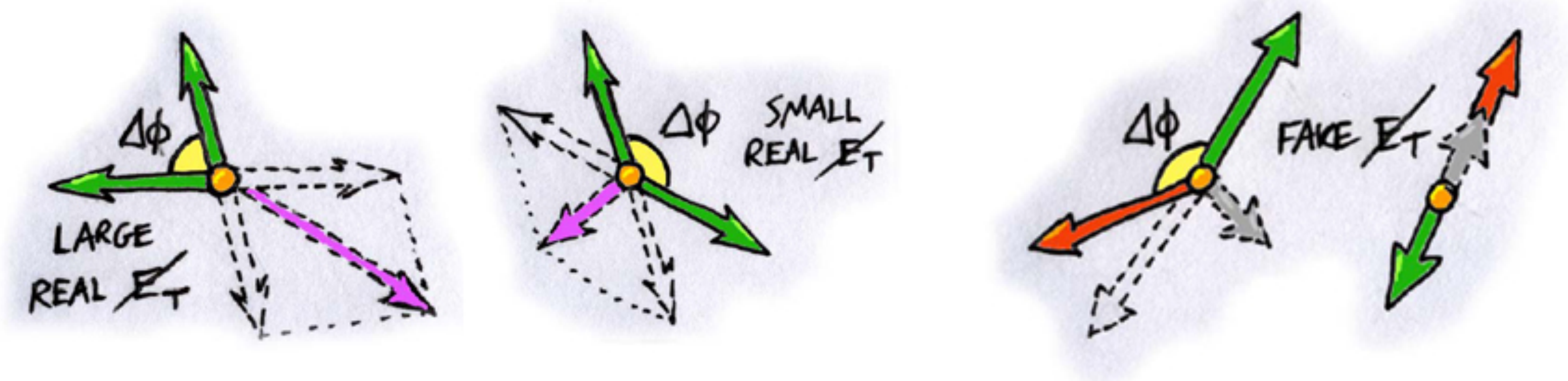


Hadronic jets in ATLAS



Neutrino (and other invisible particles) at colliders

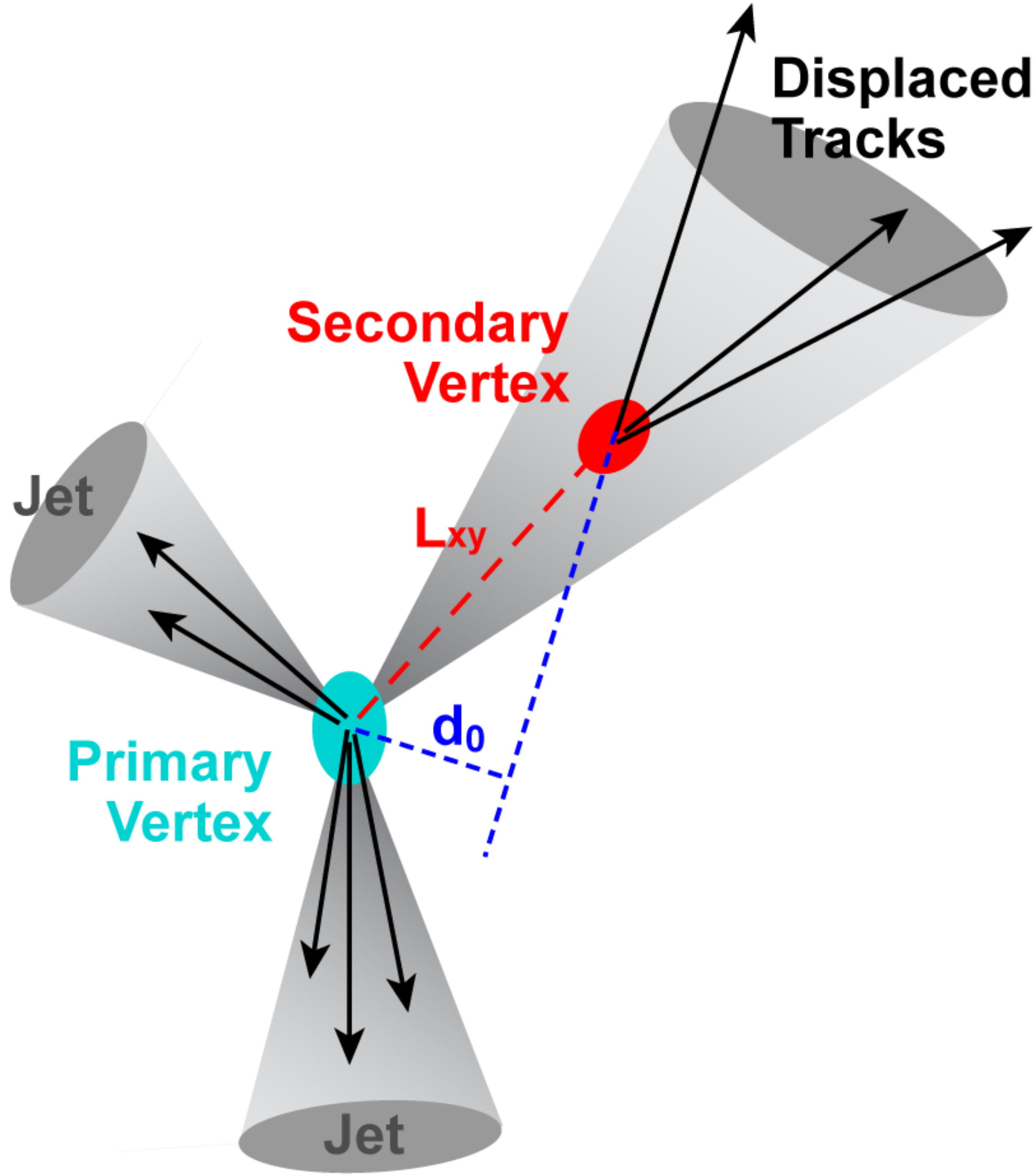
- Interaction length $\lambda_{int} = A/(\rho\ \sigma\ N_A)$
- Cross section $\sigma \sim 10^{-38}\ \text{cm}^2 \times E$ [GeV]
  - ✓ This means 10 GeV neutrino can pass through more than a million km of rock
- Neutrinos are usually detected in HEP experiments through *missing (transverse) energy (conservation of transverse momentum)*



- Missing energy resolution depends on
  - ✓ Detector acceptance
  - ✓ Detector noise and resolution (e.g. calorimeters)

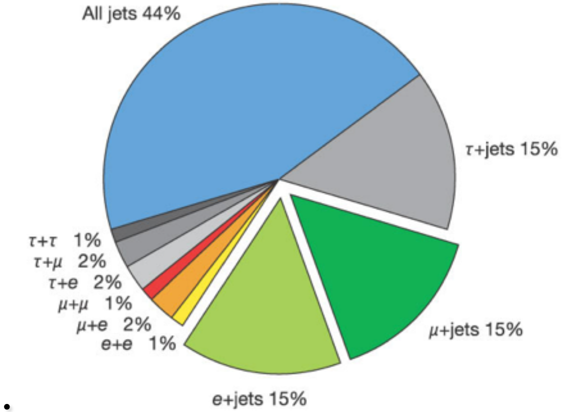
B-tagging

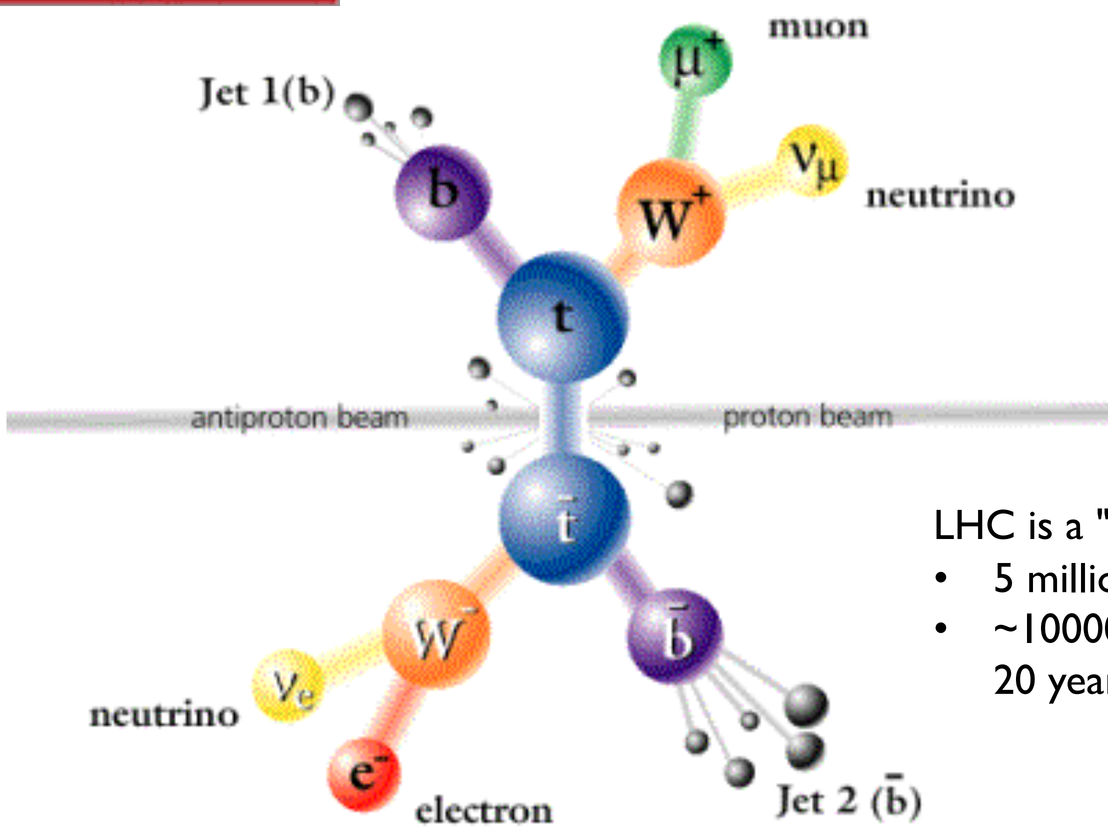
- When a b quark is produced, the associated jet will very likely contain at least one B meson or hadron
- B mesons/hadrons have relatively long lifetime
  - ✓ ~ 1.6 ps
  - ✓ They will travel away from collision point before decaying
- Identifying a secondary decay vertex in a jet allow to tag its quark content
- Similar procedure for c quark…

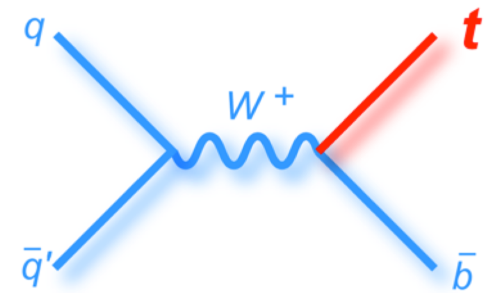


top quark

- Mean lifetime ~ 5×10^{-13} ps
  - ✓ Shorter than time scale at which QCD acts: no time to hadronize!
  - ✓ It decays as $t \to Wb$
- Events with top quarks are very rich in (b) jets…

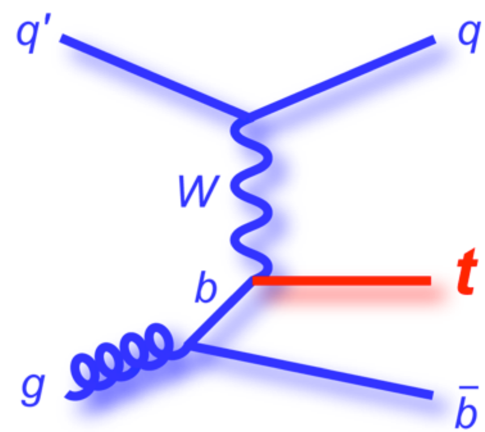






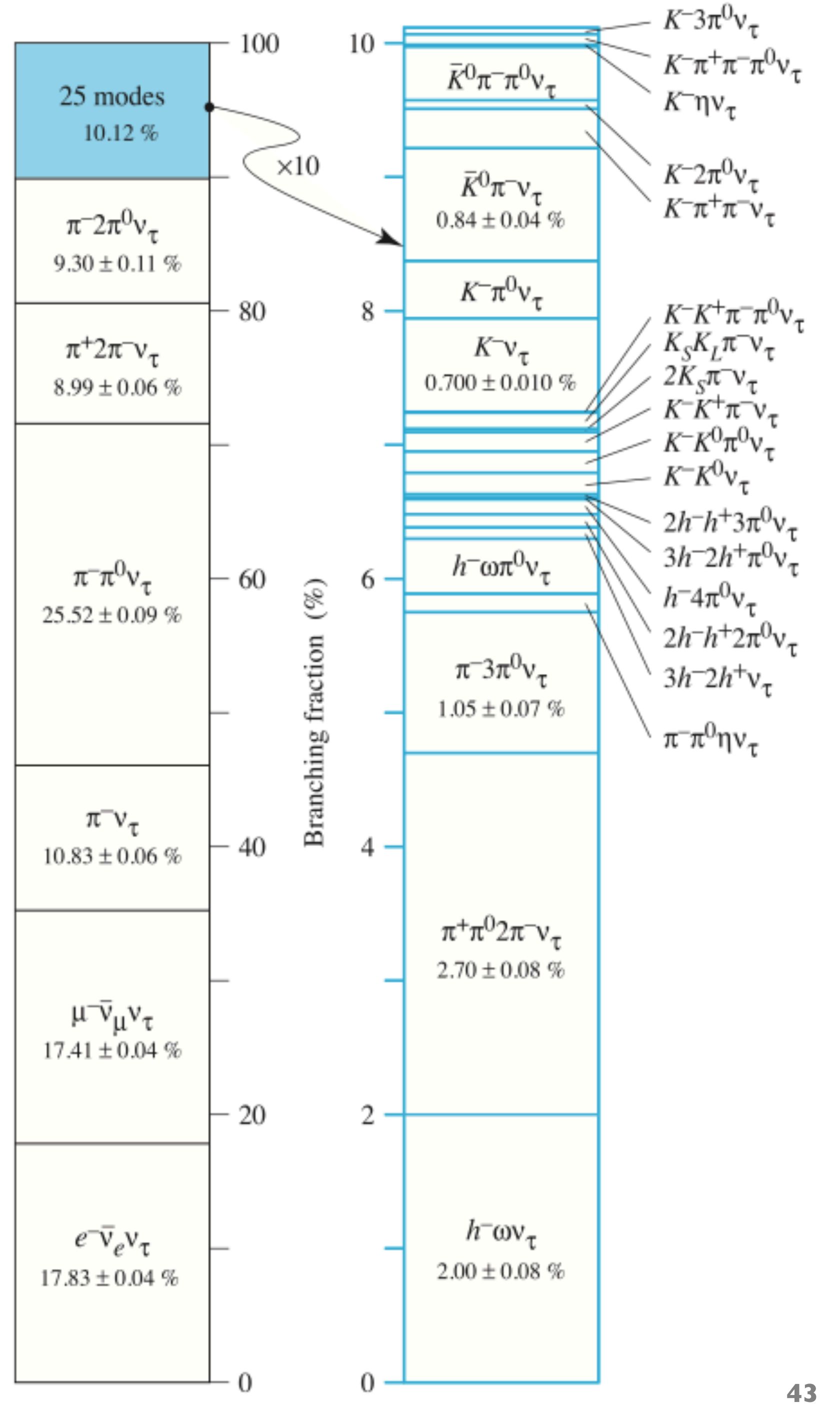
LHC is a "top factory"!

- 5 millions of tt pairs
- ~100000 in Tevatron in 20 years

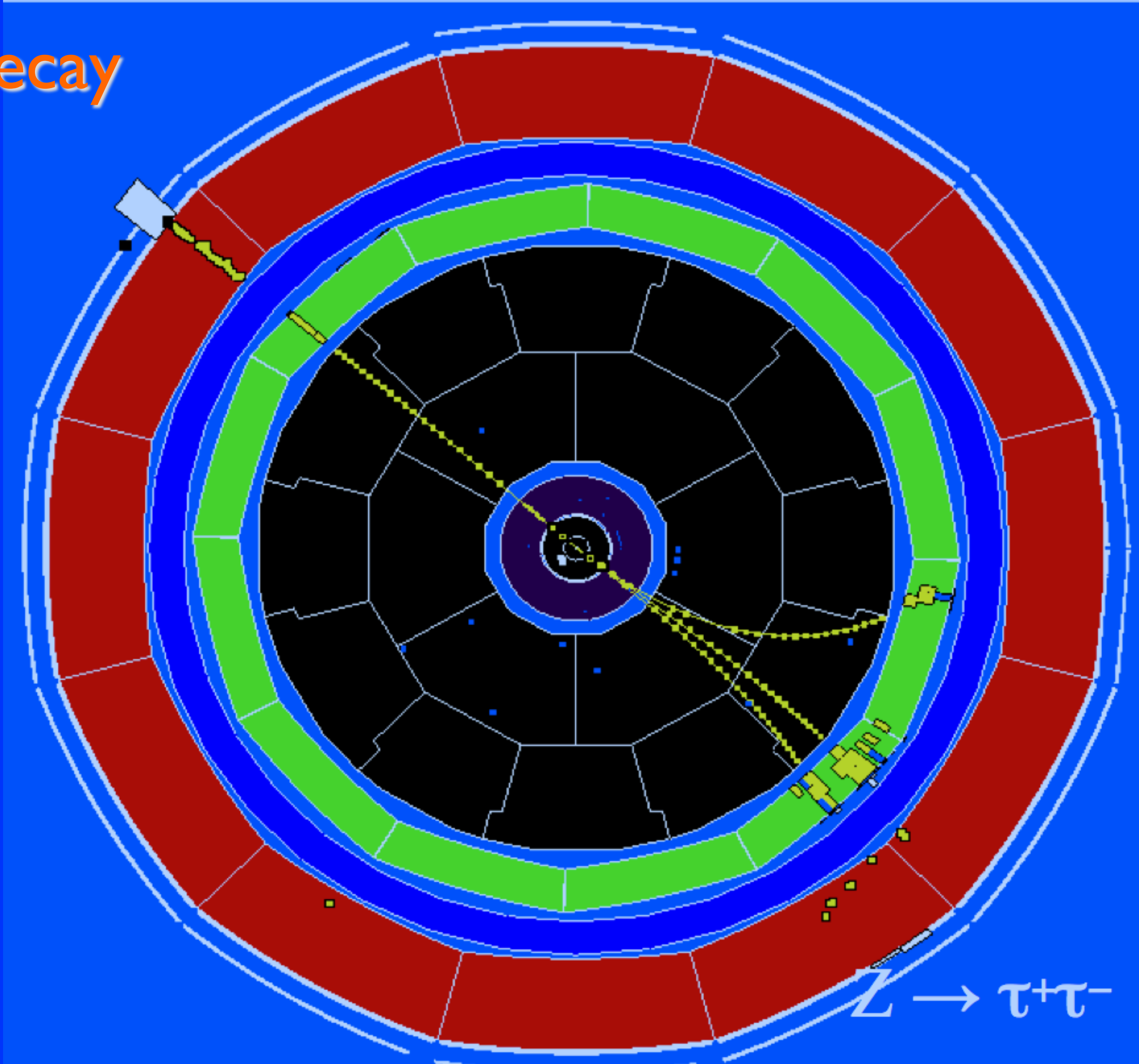


Tau

- Tau are heavy enough that they can decay in several final states
  - ✓ Several of them with hadrons
  - ✓ Sometimes neutral hadrons
- Mean lifetime ~ 0.29 ps
  - ✓ 10 GeV tau flies ~ 0.5 mm
  - ✓ Too short to be directly seen in the detectors
- Tau needs to be identified by their decay products
- Accurate vertex detectors can detect that they do not come exactly from the interaction point

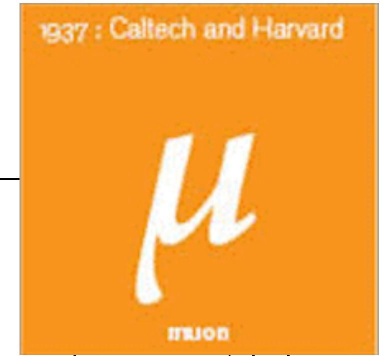


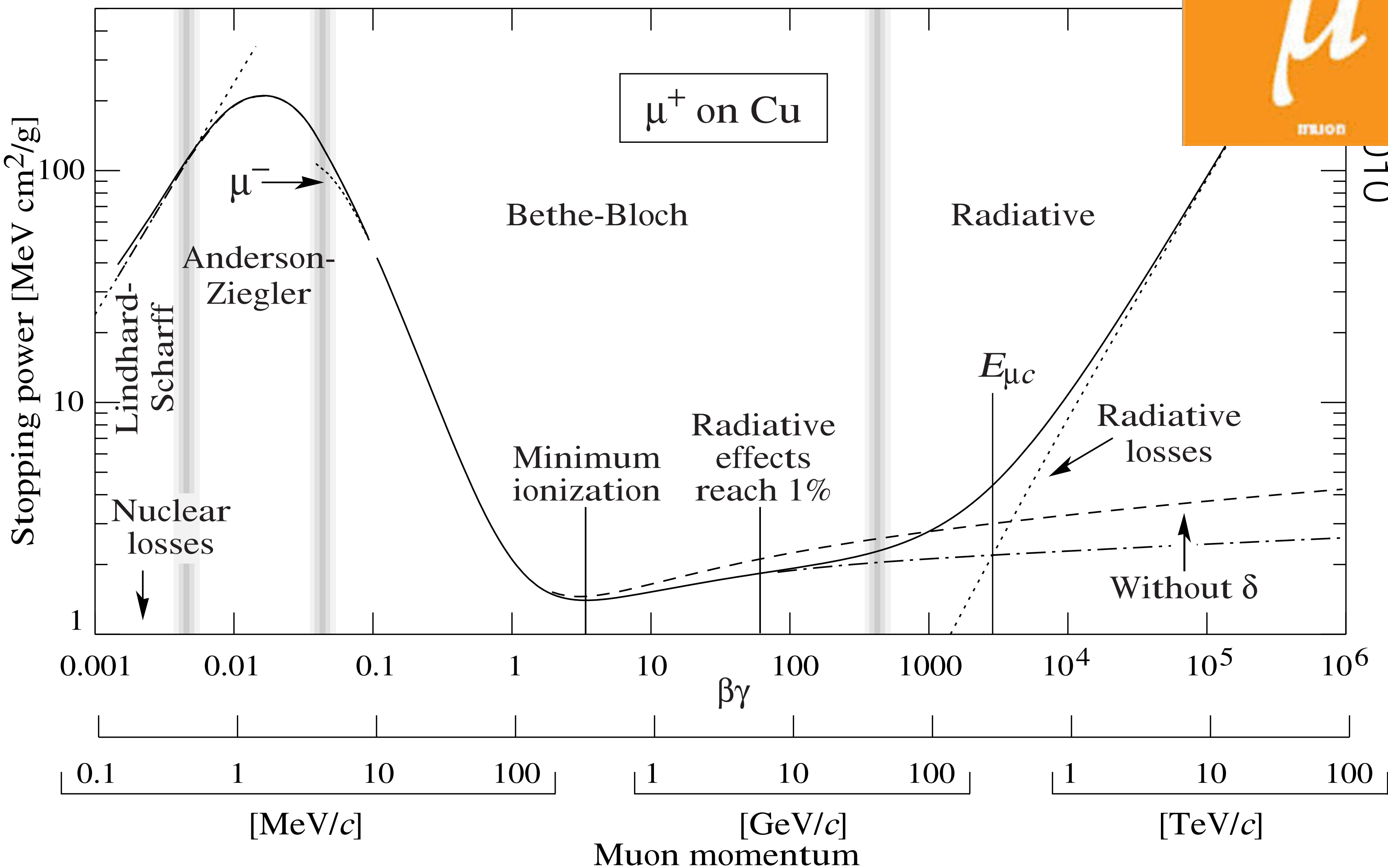
Tau decay



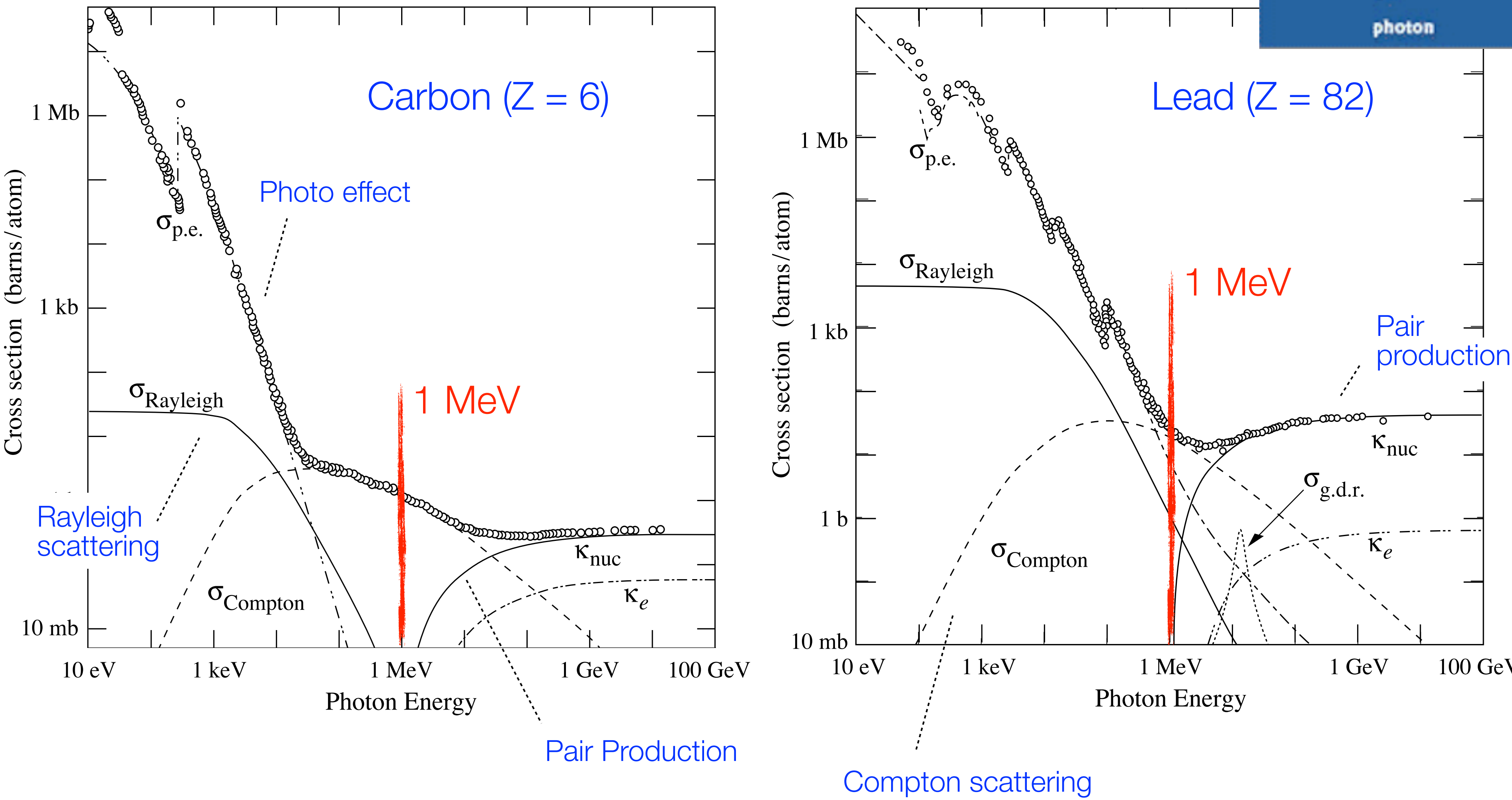
Additional information

Muon energy loss





Interaction of photons with matter



HEP, SI and "natural" units

Quantity	HEP units	SI units
length	1 fm	10^{-15} m
charge	e	$1.602 \cdot 10^{-19}$ C
energy	1 GeV	1.602×10^{-10} J
mass	1 GeV/c^2	1.78×10^{-27} kg
$\hbar = h/2$	6.588×10^{-25} GeV s	1.055×10^{-34} Js
c	2.988×10^{23} fm/s	2.988×10^{8} m/s
$\hbar c$	197 MeV fm	…

	"natural" units ($\hbar$ = c = 1)
mass	1 GeV
length	1 GeV^{-1} = 0.1973 fm
time	1 GeV^{-1} = 6.59×10^{-25} s

Relativistic kinematics in a nutshell

$$E^2 = \vec{p}^2 + m^2$$

$$\ell = \frac{\ell_0}{\gamma}$$

$$E = m\gamma$$

$$t = t_0\gamma$$

$$\vec{p} = m\gamma\vec{\beta}$$

$$\vec{\beta} = \frac{\vec{p}}{E}$$

Cross section: magnitude and units

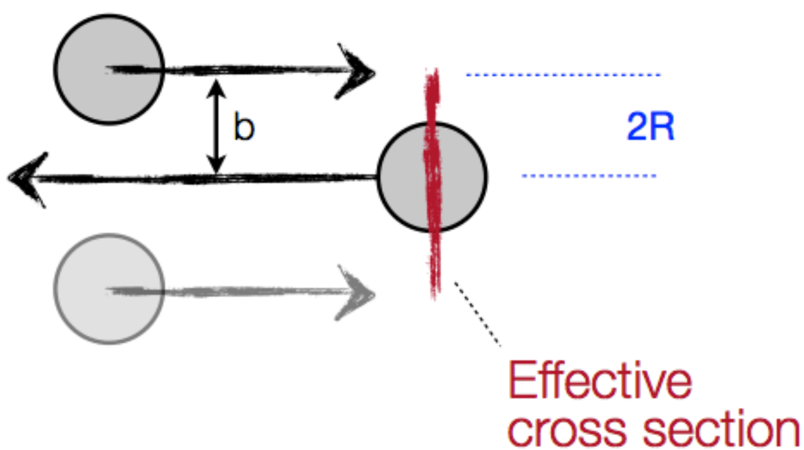
Standard
cross section unit: $[\sigma]$ = mb with 1 mb = 10^{-27} cm^2

or in
natural units: $[\sigma]$ = GeV^{-2} with 1 GeV^{-2} = 0.389 mb
1 mb = 2.57 GeV^{-2}

---

using: $\hbar c$ = 0.1973 GeV fm
$(\hbar c)^2$ = 0.389 GeV^2 mb

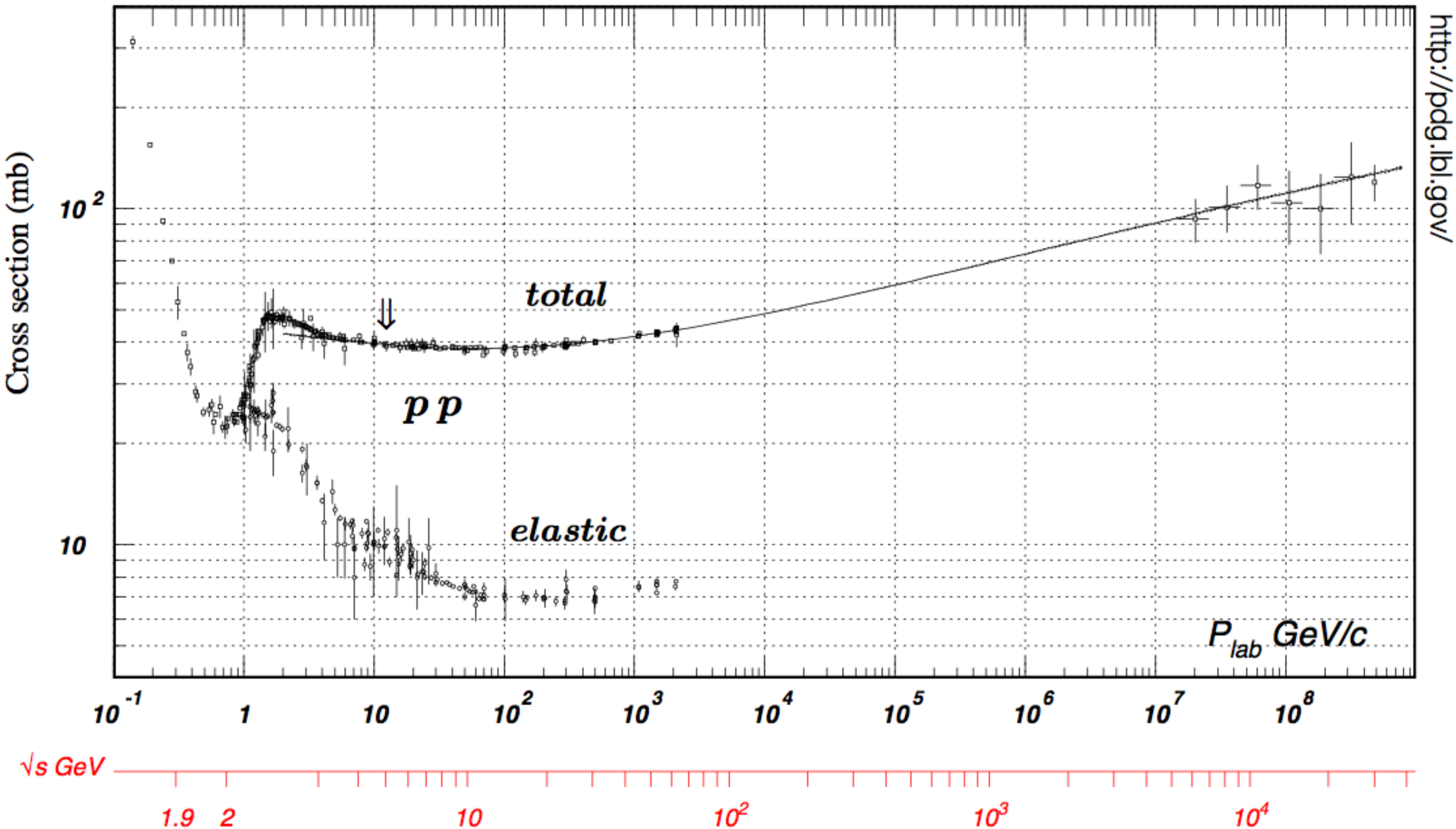
Estimating the
proton-proton cross section:



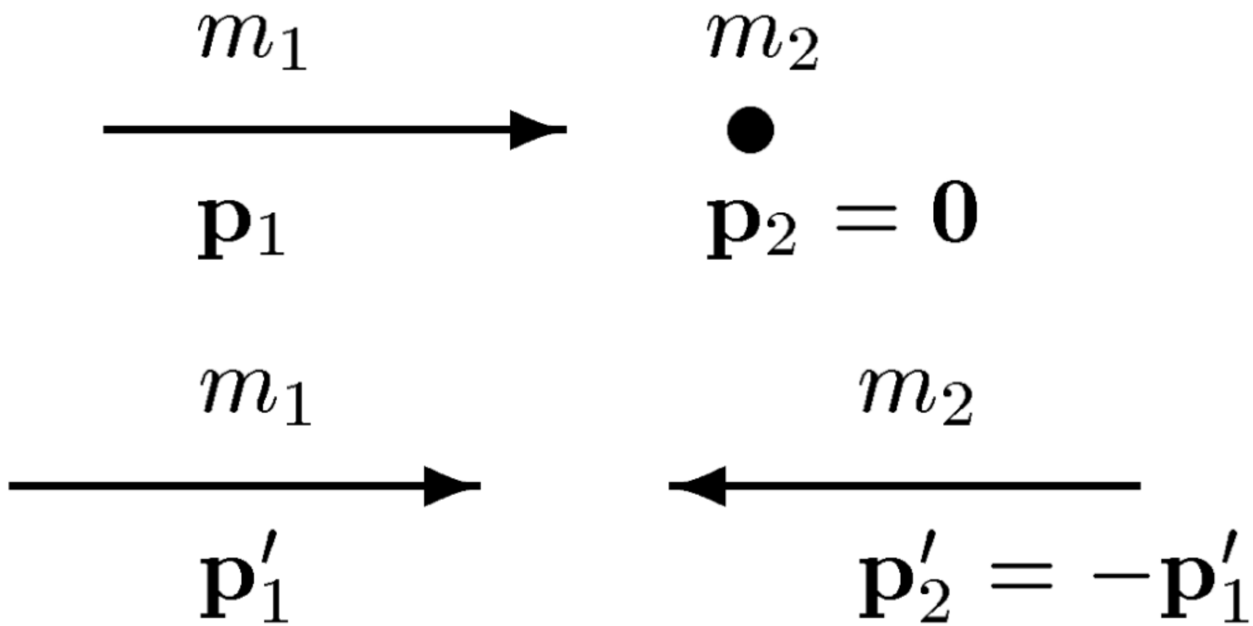
Proton radius: R = 0.8 fm
Strong interactions happens up to b = 2R

$$\sigma = \pi(2R)^2 = \pi \cdot 1.6^2 \text{ fm}^2$$
$$= \pi \cdot 1.6^2\ 10^{-26} \text{ cm}^2$$
$$= \pi \cdot 1.6^2\ 10 \text{ mb}$$
$$= 80 \text{ mb}$$

Proton-proton scattering cross-section



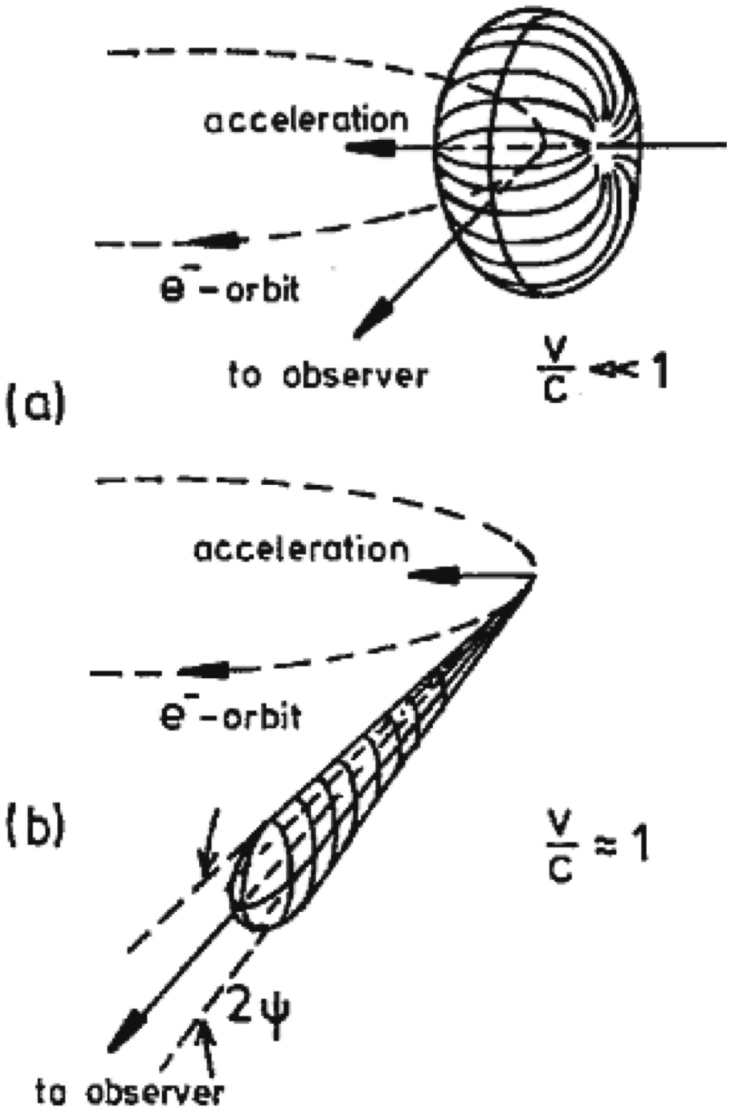
Fixed target vs. collider



How much energy should a fixed target experiment have to equal the center of mass energy of two colliding beam?

$$E_{\text{fix}} = 2\frac{E_{\text{col}}^2}{m} - m$$

Syncrotron radiation



energy lost per revolution

$$\Delta E = \frac{4\pi}{3} \frac{1}{4\pi\epsilon_0} \left(\frac{e^3 \beta^3 \gamma^4}{R} \right)$$

electrons vs. protons

$$\frac{\Delta E_e}{\Delta E_p} \simeq \left(\frac{m_p}{m_e} \right)^4$$

It's easier to accelerate protons to higher energies, but protons are fundamentals…

Magnetic spectrometer

Charged particle in magnetic field

$$\frac{d\vec{p}}{dt} = q\vec{\beta} \times \vec{B}$$

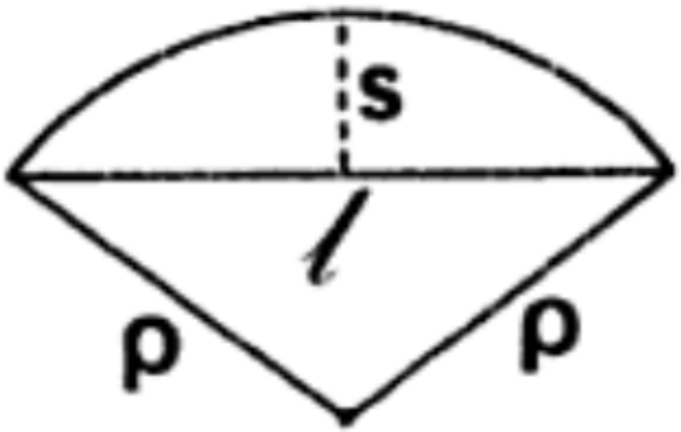
If the field is constant and we neglect presence of matter, momentum magnitude is constant with time, trajectory is helical

$$p[\mathrm{GeV}] = 0.3B[\mathrm{T}]\rho[\mathrm{m}]$$

Actual trajectory differ from exact helix because of:

- magnetic field inhomogeneity
- particle energy loss (ionization, multiple scattering)

Momentum measurement



s = sagitta

l = chord

ρ = radius

$$\rho \simeq \frac{l^2}{8s} \qquad p = 0.3\frac{Bl^2}{8s}$$

$$\left|\frac{\delta p}{p}\right| = \left|\frac{\delta s}{s}\right|$$

smaller for larger number of points — *measurement error (RMS)*

Momentum resolution due to measurement error

$$\left|\frac{\delta p}{p}\right| = \overbrace{A_N}\,\frac{\overbrace{\epsilon}}{\underbrace{L^2}}\,\frac{p}{0.3B}$$

projected track length in magnetic field

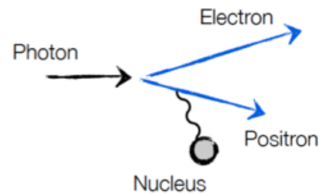
Momentum resolution gets worse for larger momenta

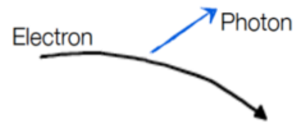
resolution is improved faster by increasing L then B

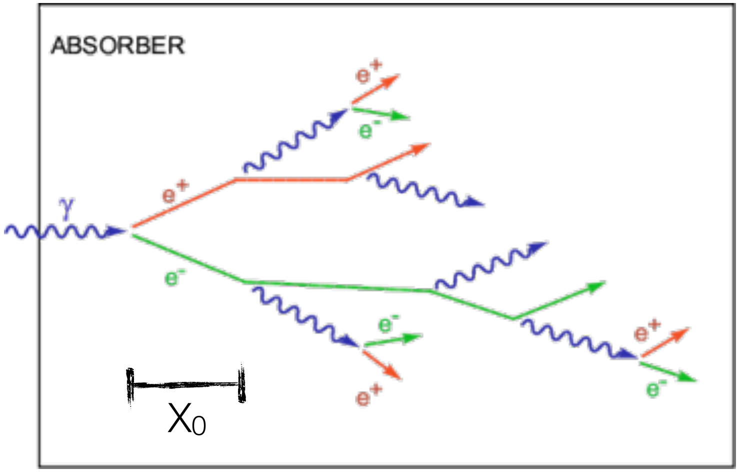
Electromagnetic showers

Dominant processes
at high energies ...

Photons : Pair production
Electrons : Bremsstrahlung







Pair production:

$$\sigma_{\text{pair}} \approx \frac{7}{9}\left(4\,\alpha r_e^2 Z^2 \ln\frac{183}{Z^{\frac{1}{3}}}\right)$$

$$= \frac{7}{9}\frac{A}{N_A X_0}$$

[X_0: radiation length]
[in cm or g/cm^2]

Absorption coefficient:

$$\mu = n\sigma = \rho\frac{N_A}{A}\cdot\sigma_{\text{pair}} = \frac{7}{9}\frac{\rho}{X_0}$$

Bremsstrahlung:

$$\frac{dE}{dx} = 4\alpha N_A\,\frac{Z^2}{A} r_e^2 \cdot E\,\ln\frac{183}{Z^{\frac{1}{3}}} = \frac{E}{X_0}$$

$$\rightarrow\; E = E_0 e^{-x/X_0}$$

After passage of one X_0 electron has only (1/e)th of its primary energy ...
[i.e. 37%]

Critical energy:

$$\left.\frac{dE}{dx}(E_c)\right|_{\text{Brems}} = \left.\frac{dE}{dx}(E_c)\right|_{\text{Ion}}$$

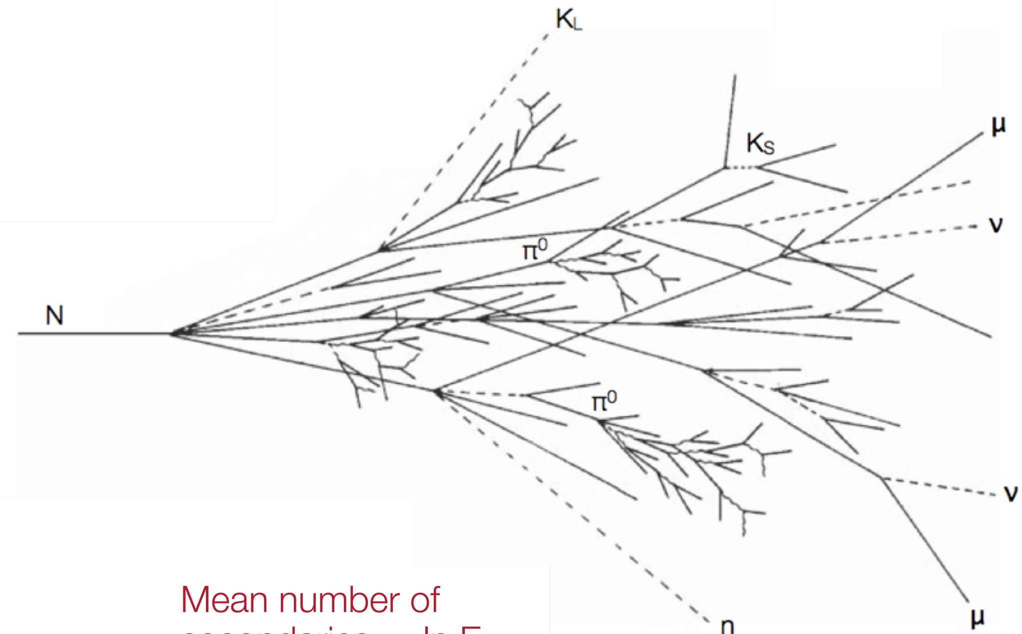
Hadronic showers

Shower development:

1. p + Nucleus ➛ Pions + N* + ...
2. Secondary particles ...

   undergo further inelastic collisions until they fall below pion production threshold
3. Sequential decays ...

   π_0 ➛ $\gamma\gamma$: yields electromagnetic shower
   Fission fragments ➛ β-decay, γ-decay
   Neutron capture ➛ fission
   Spallation ...



Mean number of secondaries: ~ ln E

Typical transverse momentum: p_t ~ 350 MeV/c

Substantial electromagnetic fraction

f_{em} ~ ln E
[variations significant]

Cascade energy distribution:
[Example: 5 GeV proton in lead-scintillator calorimeter]

Ionization energy of charged particles (p,π,μ)	1980 MeV [40%]
Electromagnetic shower (π^0,η^0,e)	760 MeV [15%]
Neutrons	520 MeV [10%]
Photons from nuclear de-excitation	310 MeV [6%]
Non-detectable energy (nuclear binding, neutrinos)	1430 MeV [29%]
	5000 MeV [29%]

Homogeneous calorimeters

★ In a homogeneous calorimeter the whole detector volume is filled by a high-density material which simultaneously serves as absorber as well as as active medium ...

Signal	Material
Scintillation light	BGO, BaF_2, CeF_3, ...
Cherenkov light	Lead Glass
Ionization signal	Liquid nobel gases (Ar, Kr, Xe)

★ Advantage: homogenous calorimeters provide optimal energy resolution

★ Disadvantage: very expensive

★ Homogenous calorimeters are exclusively used for electromagnetic calorimeter, i.e. energy measurement of electrons and photons

Sampling calorimeters

Principle:

Alternating layers of absorber and active material [sandwich calorimeter]

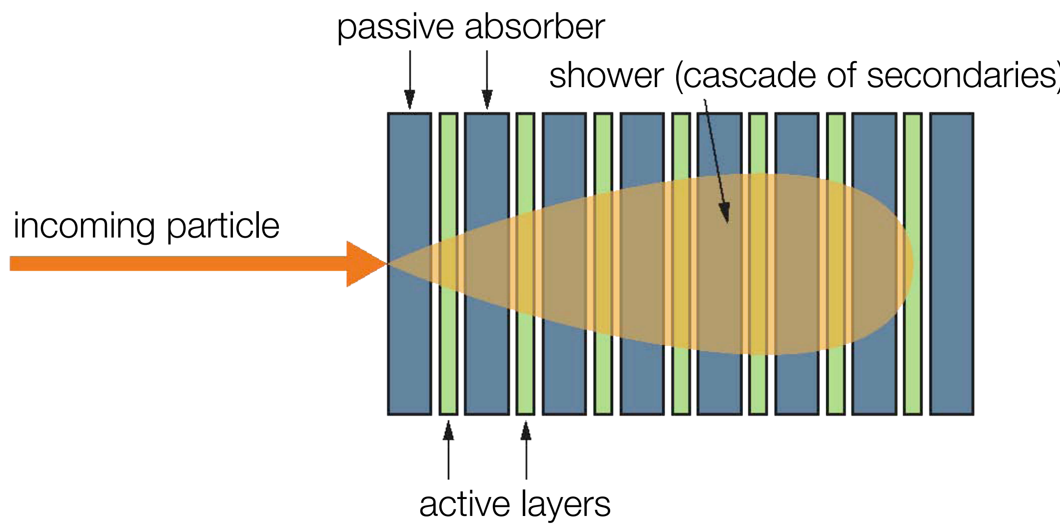
Absorber materials:
[high density]

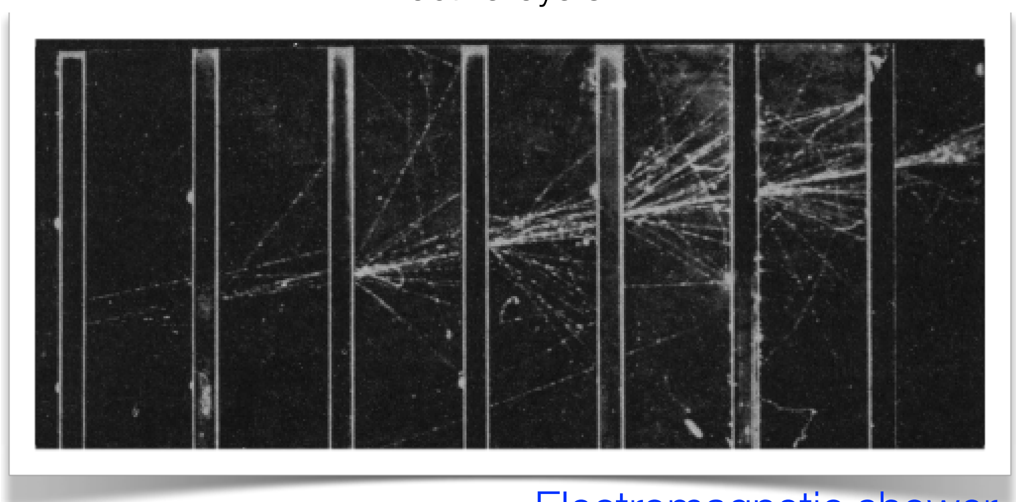
- Iron (Fe)
- Lead (Pb)
- Uranium (U)
  [For compensation ...]

Active materials:

- Plastic scintillator
- Silicon detectors
- Liquid ionization chamber
- Gas detectors

Scheme of a sandwich calorimeter





Electromagnetic shower

A typical HEP calorimetry system

Typical Calorimeter: two components ...

Electromagnetic (EM) +
Hadronic section (Had) ...

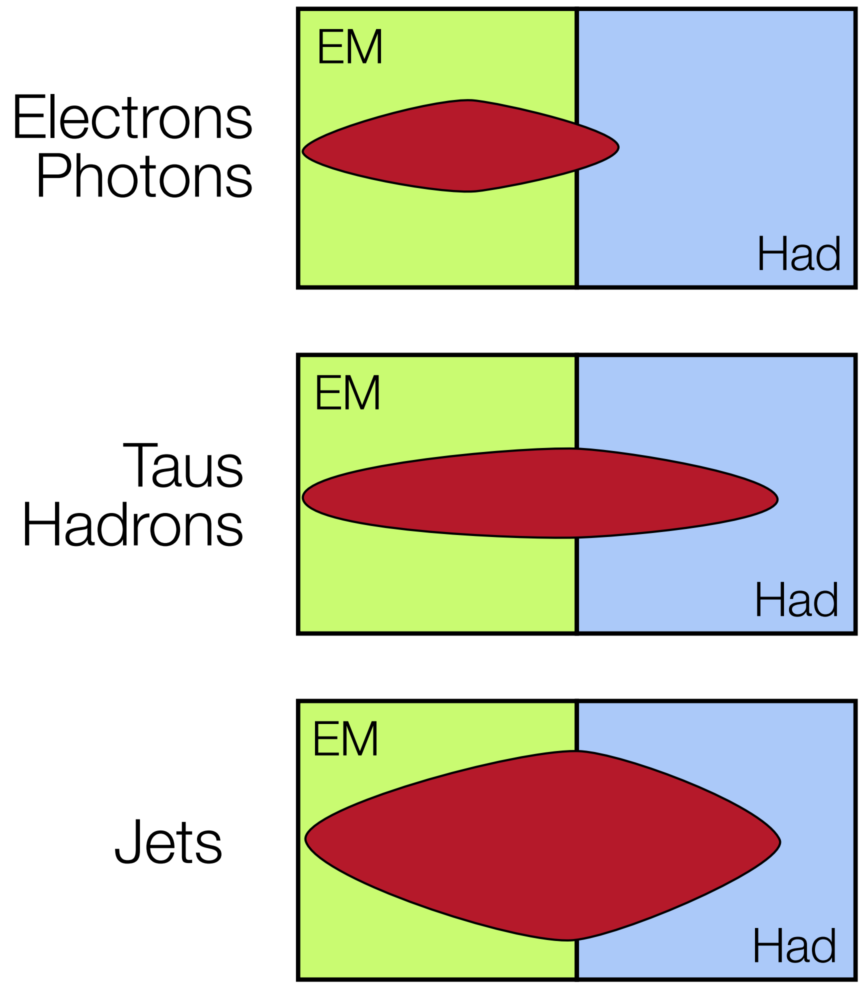
Different setups chosen for
optimal energy resolution ...

But:

Hadronic energy measured in
both parts of calorimeter ...

Needs careful consideration of
different response ...

Schematic of a
typical HEP calorimeter



Energy resolution in calorimeters

Energy resolution:

e.g. inhomogeneities
shower leakage

e.g. electronic noise
sampling fraction variations

$$\frac{\sigma_E}{E} = \frac{A}{\sqrt{E}} \oplus B \oplus \frac{C}{E}$$

Fluctuations:

- Sampling fluctuations
- Leakage fluctuations
- Fluctuations of electromagnetic fraction
- Nuclear excitations, fission, binding energy fluctuations ...
- Heavily ionizing particles

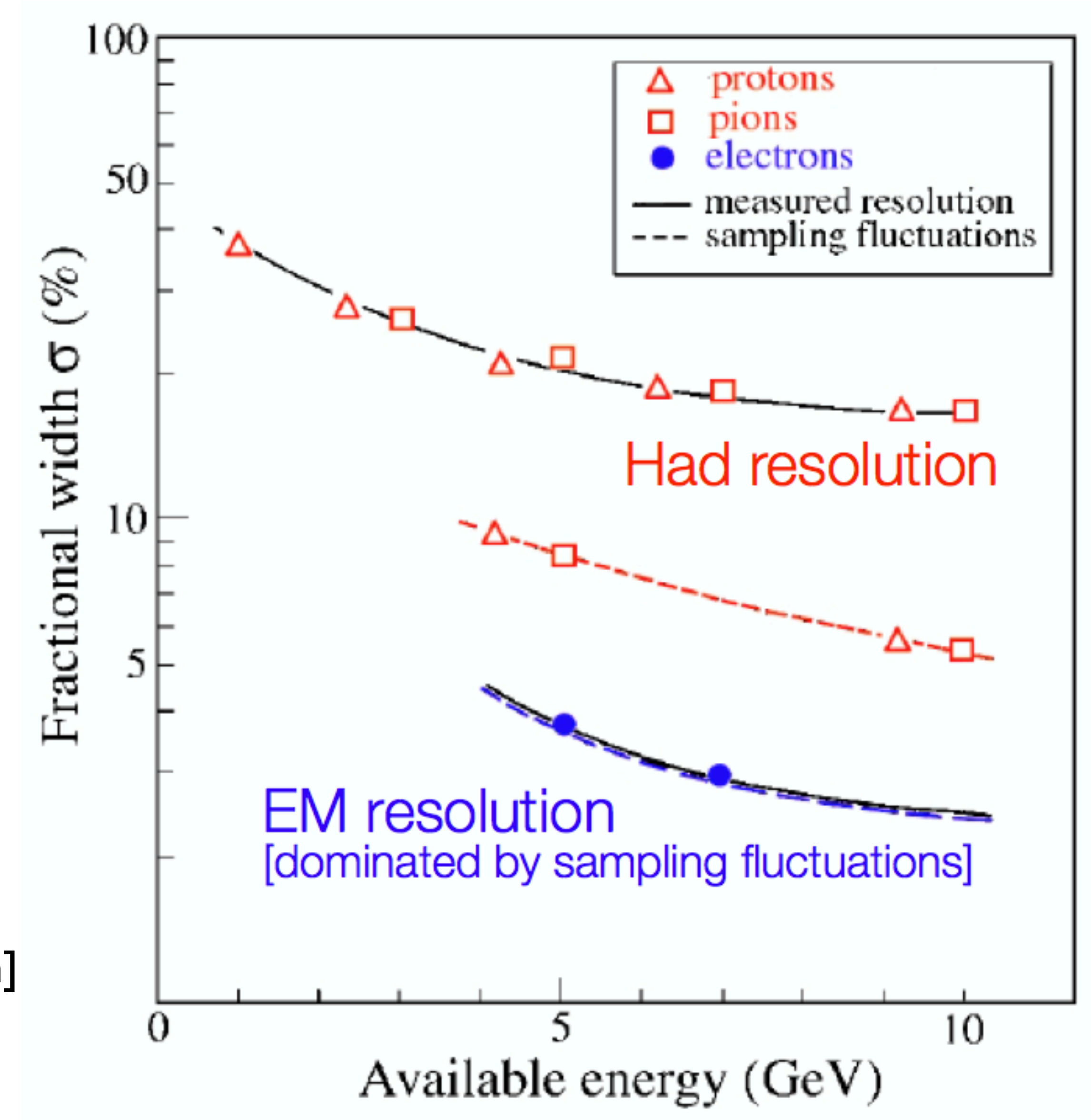
Typical:

A: 0.5 – 1.0 [Record:0.35]

B: 0.03 – 0.05

C: few %

Resolution: EM vs. HAD



[AFM Collaboration]

Sampling fluctuations only minor contribution to hadronic energy resolution

Radiation length

$$X_0 = \frac{716{,}4 \cdot A}{Z(Z+1)\ln\frac{287}{\sqrt{Z}}}$$

Où Z est le numéro atomique et A est le nombre de masse.

Interaction mode cheat sheet ("light" particles)

- electrically charged
- ionization (dE/dx)
- *electromagnetic shower…*

- electrically charged
- ionization (dE/dx)
- can emit photons
  - ✓ electromagnetic shower induced by emitted photon…
    - but it's rare…

- electrically neutral
- pair production
  - ✓ E > 1 MeV
- *electromagnetic shower…*

- produce *hadron(s)* jets via QCD hadronization process
- For now, let's just think about hadrons…
  - ✓ ionization
  - ✓ hadronic shower…

How do we "see" particles?