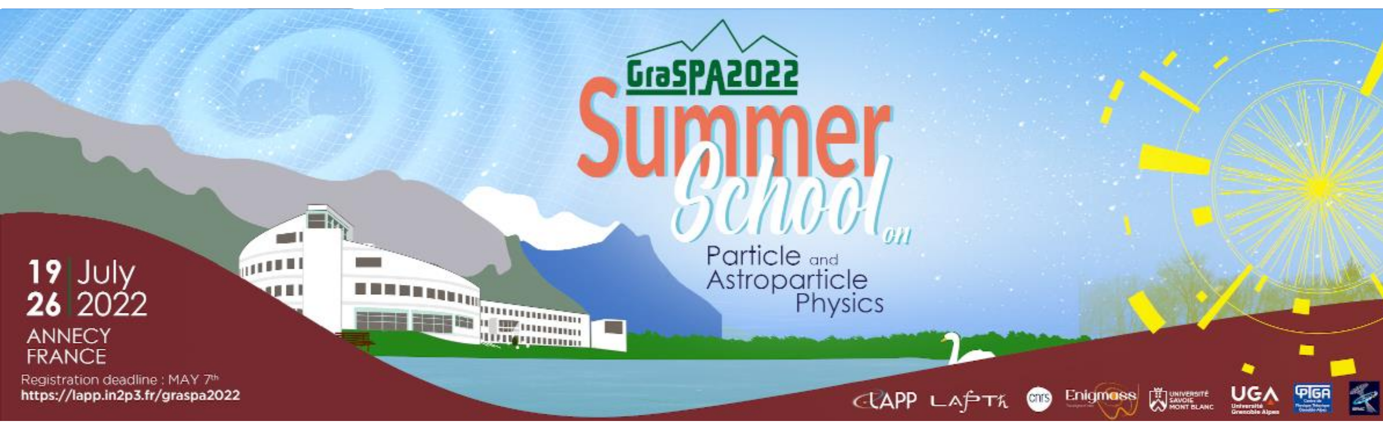
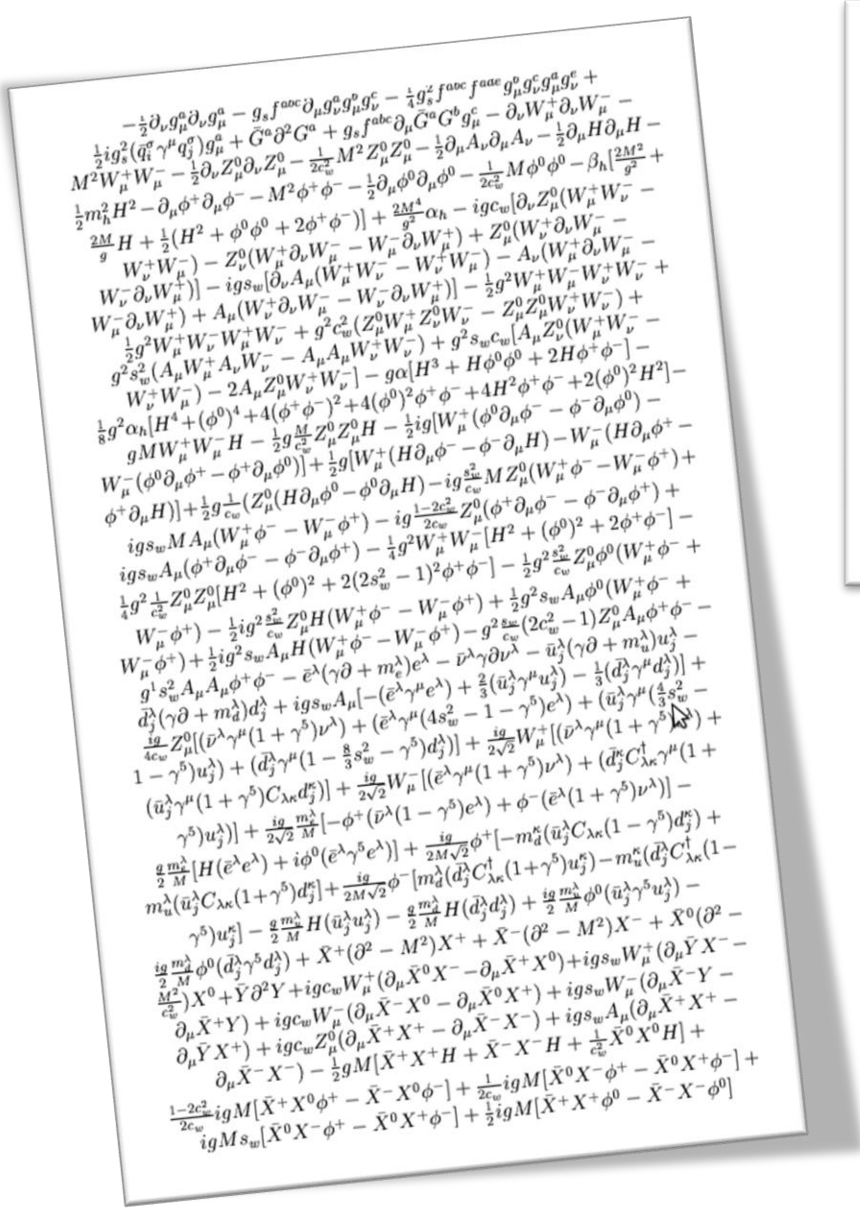
(experimental) LHC physics

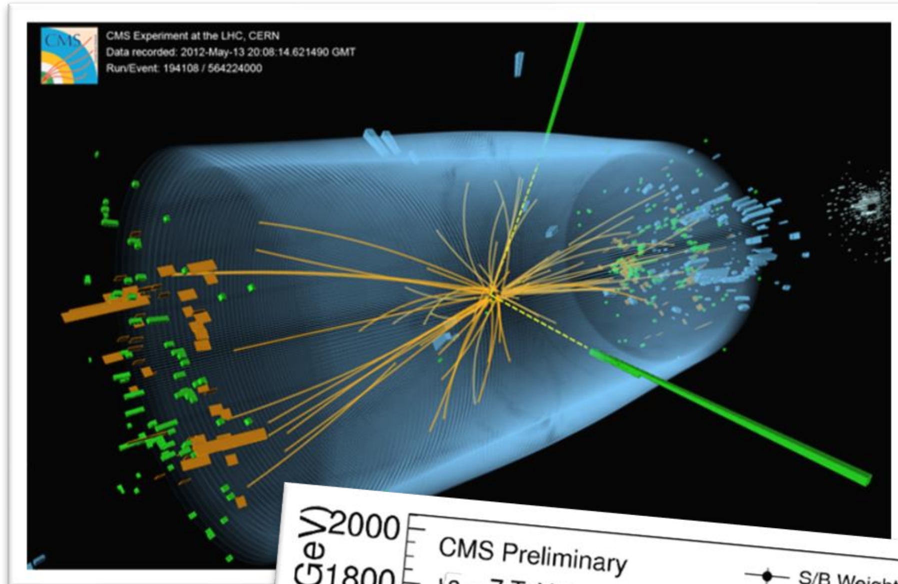


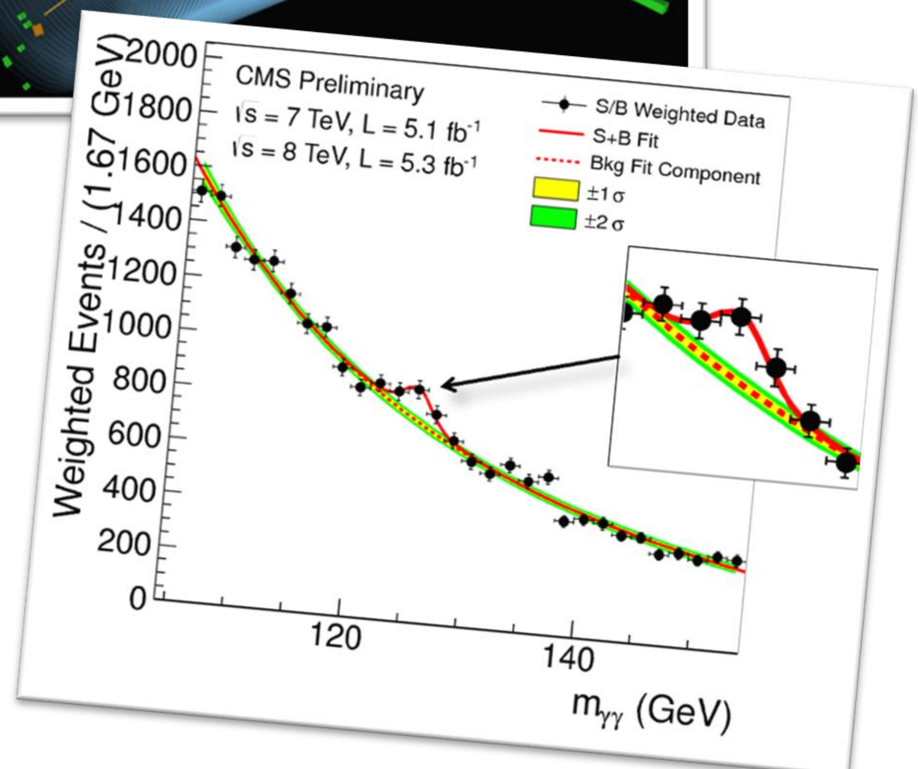
1. { how (which) particles are produced and measured? }

Roberto Covarelli

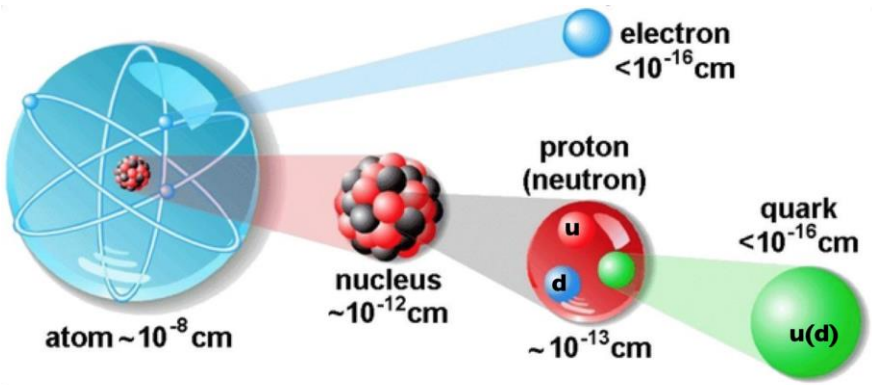
Experiment = probing/building theories with data!

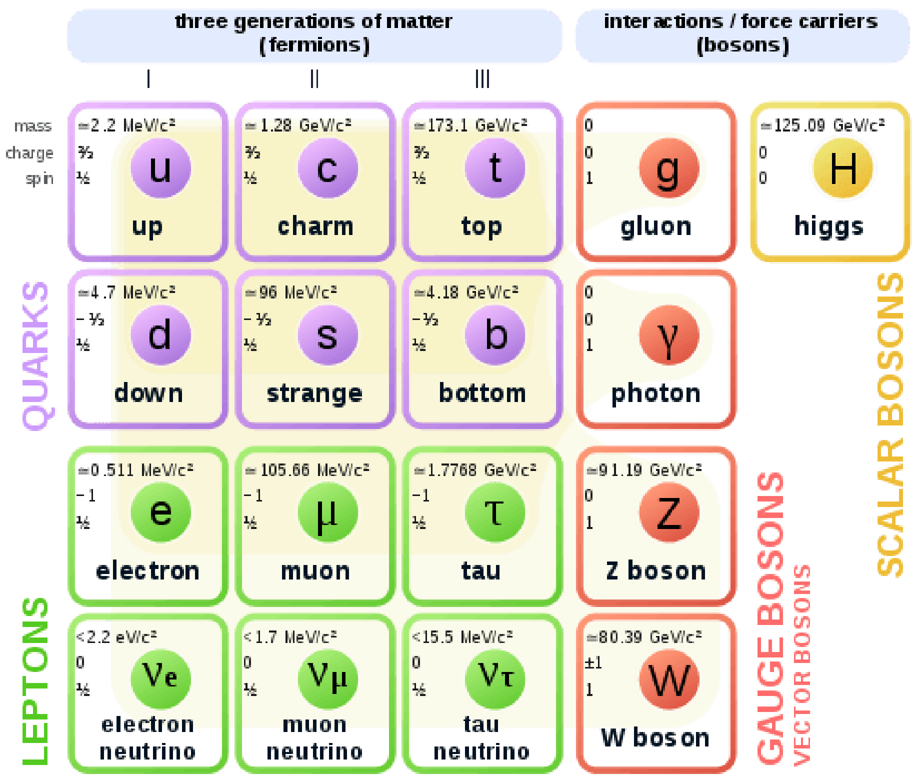






The Standard Model of particle physics…





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)

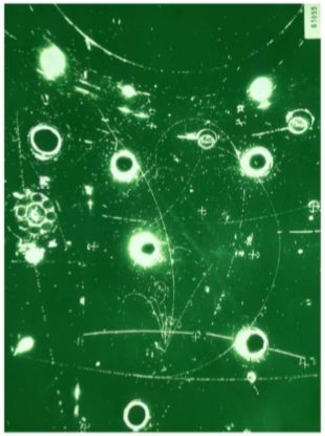
Higgs coupling to fermions (fermion masses)

Higgs coupling to bosons (boson masses)

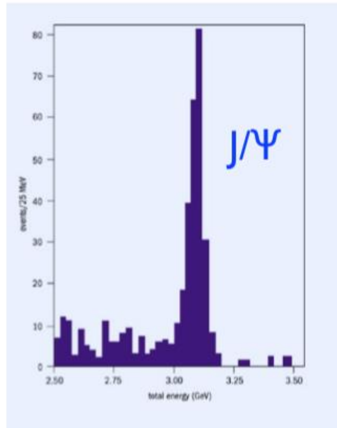
Higgs self-coupling (Higgs potential)

A theory built (and probed) over time…

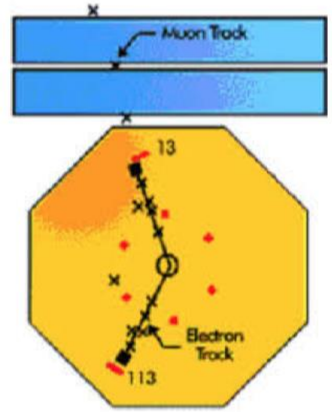
1972 – CERN
Neutral currents



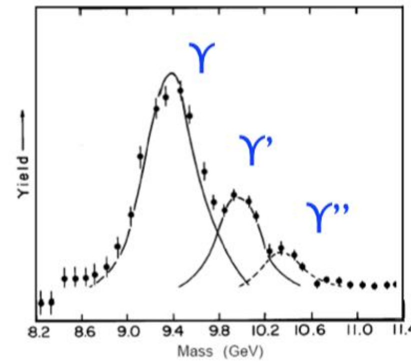
1974 – BNL, SLAC
Charm



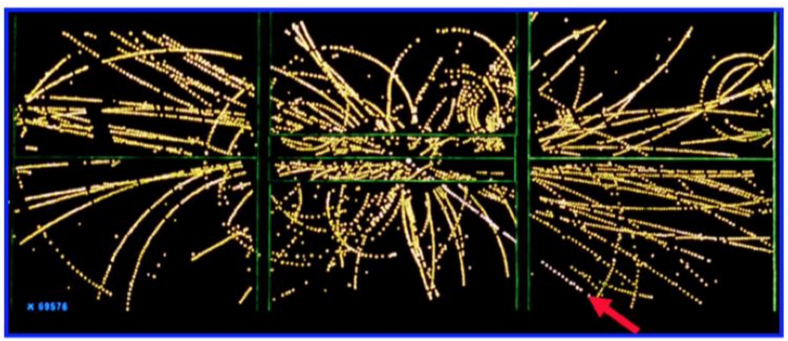
1976 – SLAC
Tau lepton



1979 – Fermilab
Beauty

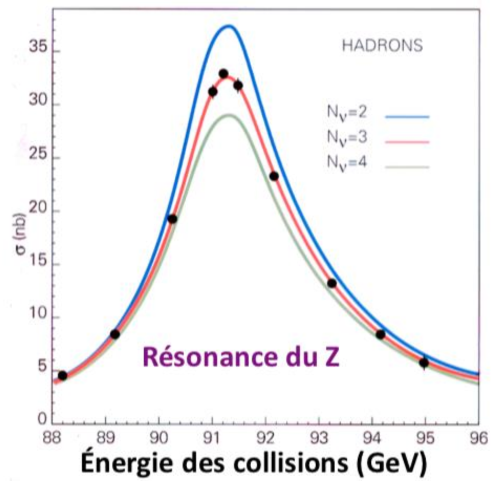


1983 – CERN/SppS
W and Z bosons



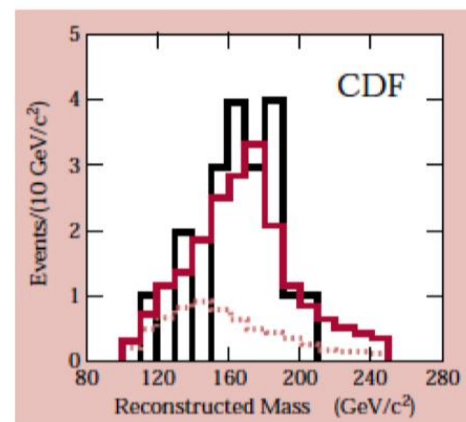
UA1, UA2

1990 – CERN/LEP
Three families of neutrinos



ALEPH, DEPHI, L3, OPAL

1994 – Fermilab/TeVatron
Top quark

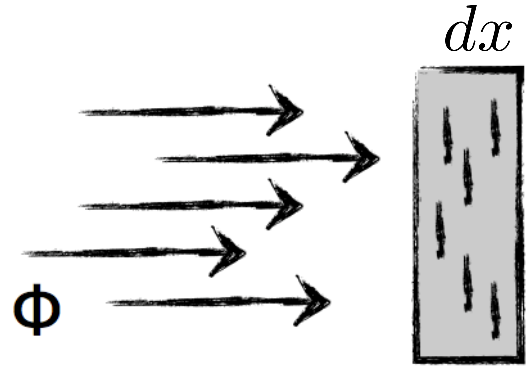


CDF, D0

How do we compare experiment and predictions in a **quantum** field theory?

- Through two fundamental quantities:
- **σ** (cross section): **probability** of a particle of being produced in collisions at a given energy (es. 13 TeV at LHC)
  - ✓ May be *differential*, that is, as a function of the energy of the particle, the angles of its trajectory, etc.
- Γ (decay rate): probability of a particle of decaying into certain specific final particles
  - ✓ The sum of all Γ's is the total decay rate, and because of resonance theory it is the inverse of its decay time: $\boxed{\tau = 1/\Gamma}$

Interaction cross section



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

Reactions per unit of time $$d\dot{N}_{\text{reac}} = \Phi \overbrace{\sigma N_{\text{target}} dx}^{\textit{area obscured by target particle}}$$ $[t^{-1}]$

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

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

1 b = 10^{-28} m^2 (roughly the area of a nucleus with A = 100)

LHC

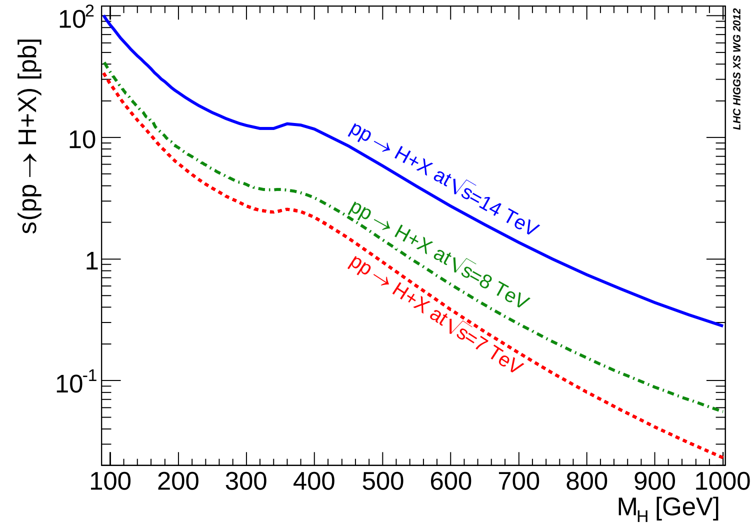
pp collider (2008-present)
$\sqrt{s}$ = 7-8-13 TeV

Luminosity

Number of events
in unit of time

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

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



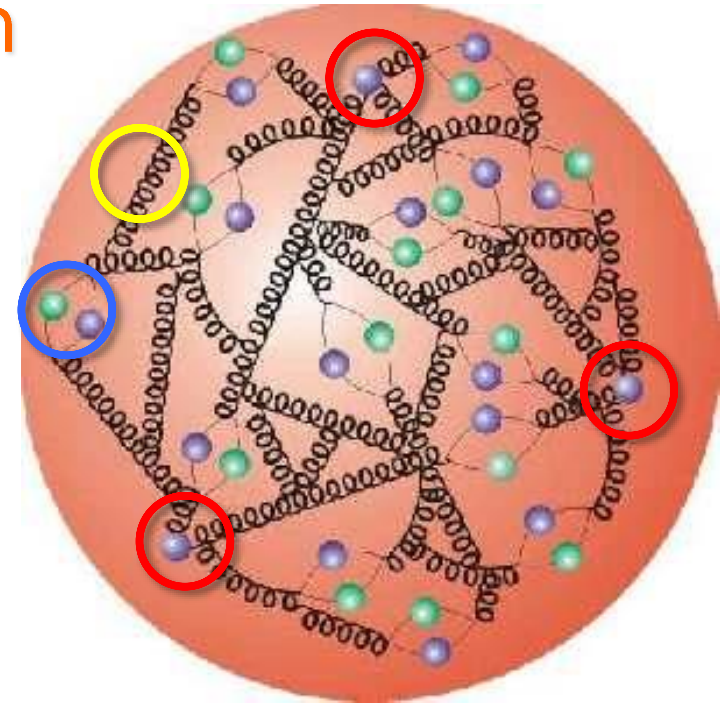
In a collider ring…

$$\mathcal{L} = \frac{1}{4\pi}\frac{fkN_1N_2}{\sigma_x\sigma_y}$$

Current

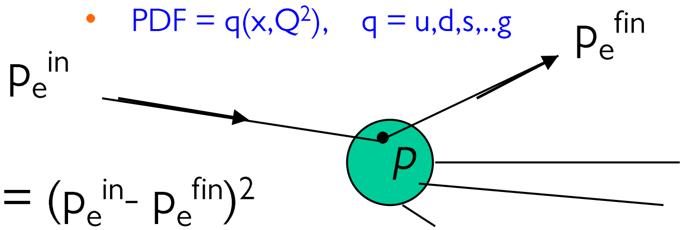
Beam sizes (RMS)

About the inner life of a proton



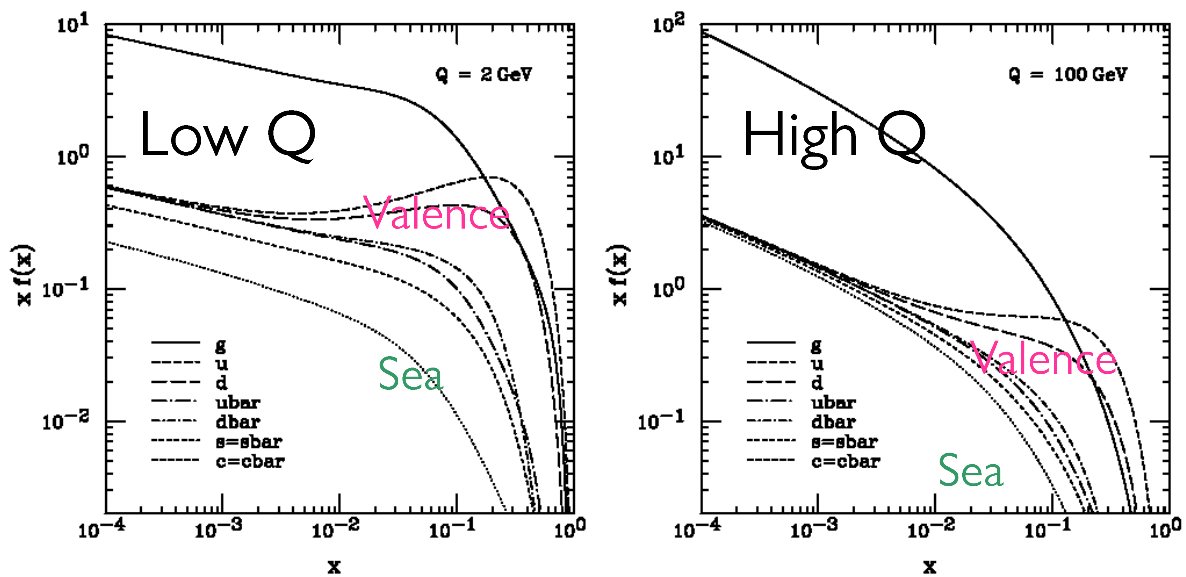
- ***p*** **rotons have substructure!**
  - ✓ partons = quarks & gluons
  - ✓ 3 valence (colored) quarks bound by gluons
  - ✓ Gluons (colored) have self-interactions
  - ✓ Virtual quark pairs can pop-up (sea-quark)
  - ✓ *p* momentum shared among constituents
    - described by *p* structure functions

- **Parton energy not 'monochromatic'**
  - ✓ Parton Distribution Function
    - PDF = $q(x,Q^2)$, $q = u,d,s,..g$

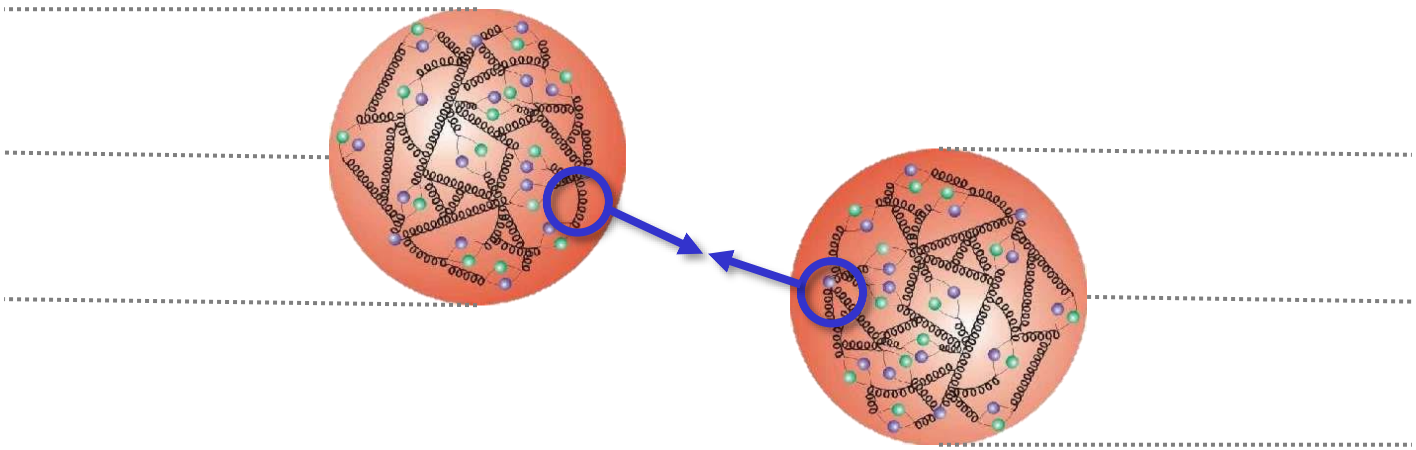


$Q^2 = (P_e^{in} - P_e^{fin})^2$

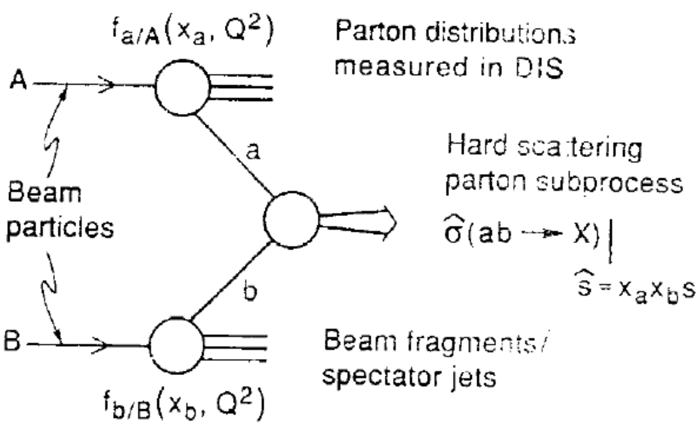
- **Kinematic variables**
  - ✓ Bjorken-x: fraction of the proton momentum carried by struck parton
    - $x = P_{parton}/P_{proton}$
  - ✓ Q^2 : 4-momentum^2 transfer

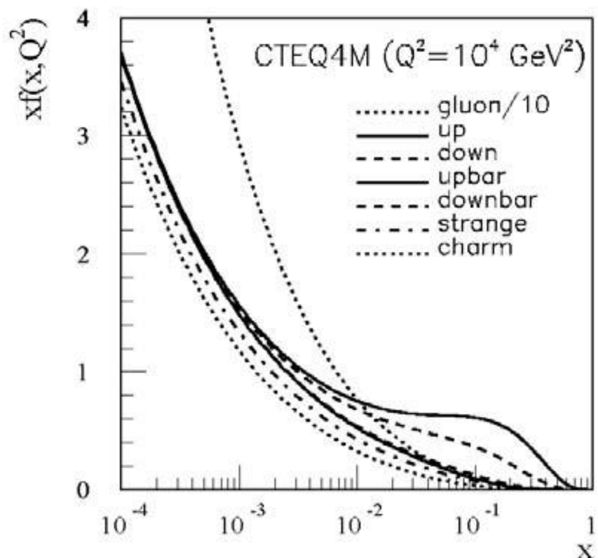


Cross sections at a proton-proton collider



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



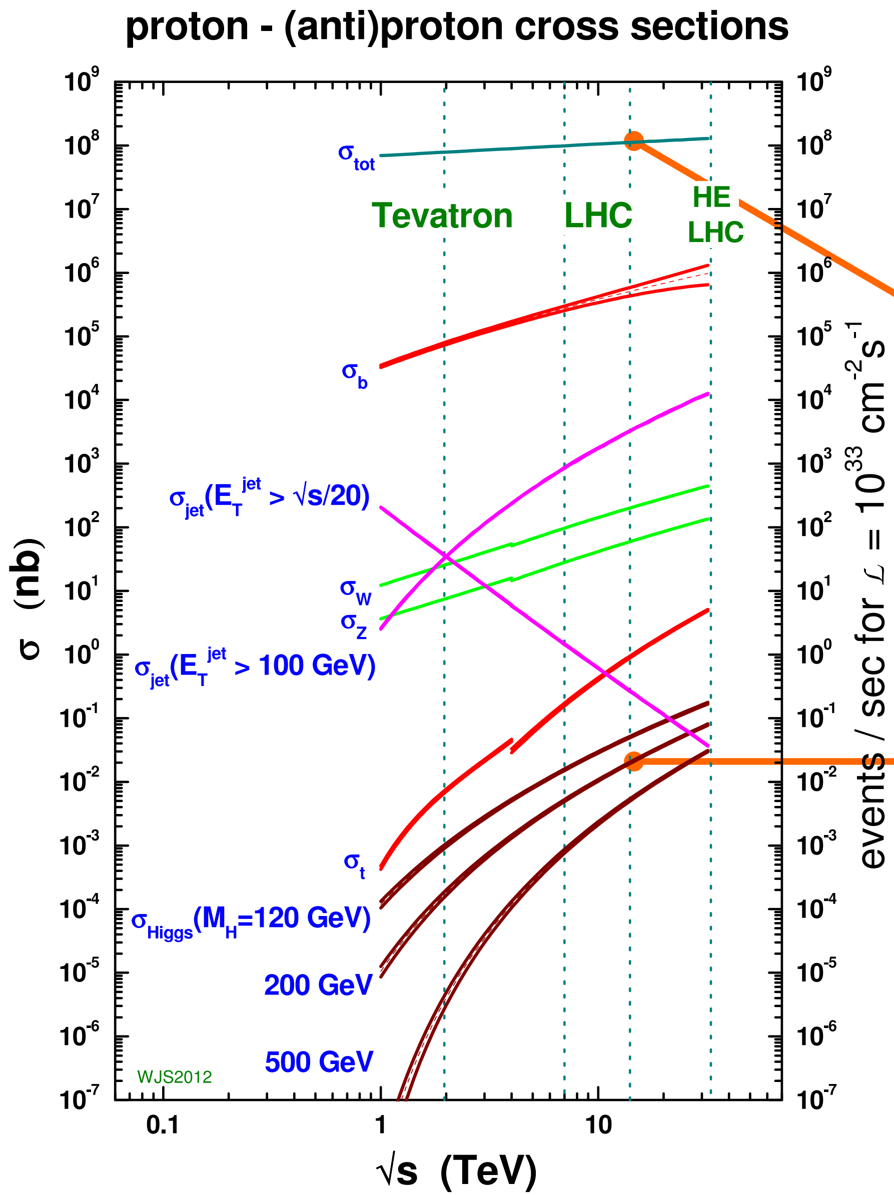


Example: to produce a particle with mass m = 100 GeV

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

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

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

$\sim 10^{10}$

10^{-1} events/s

~ 1 Higgs boson every 2 seconds

[m_H ~ 125 GeV]

How do we compare experiment and prediction in a **quantum** field theory?

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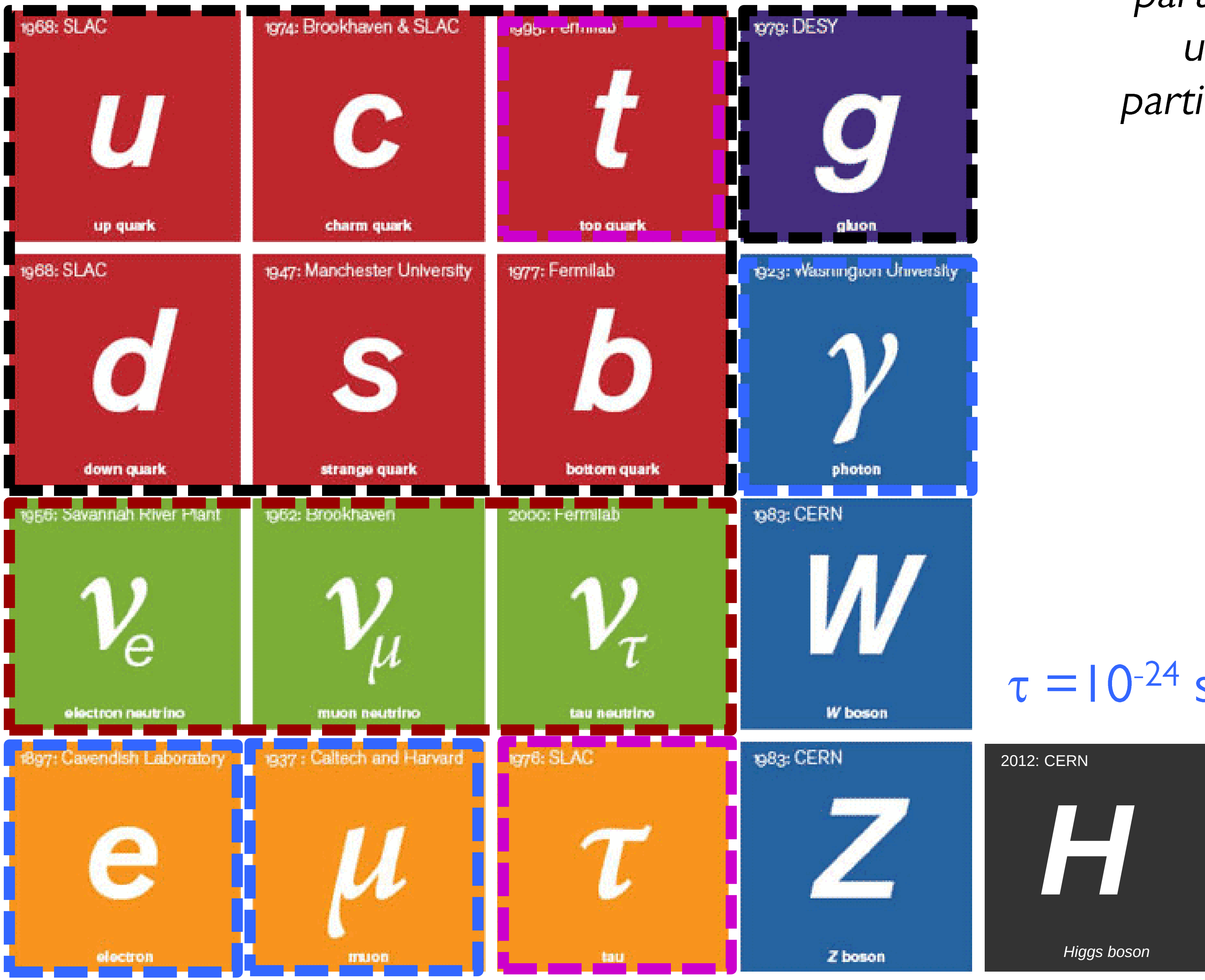
What do we want to measure?

… "stable" particles from unstable particle decays!



$\tau = 10^{-24}$ s

$\tau = \infty$

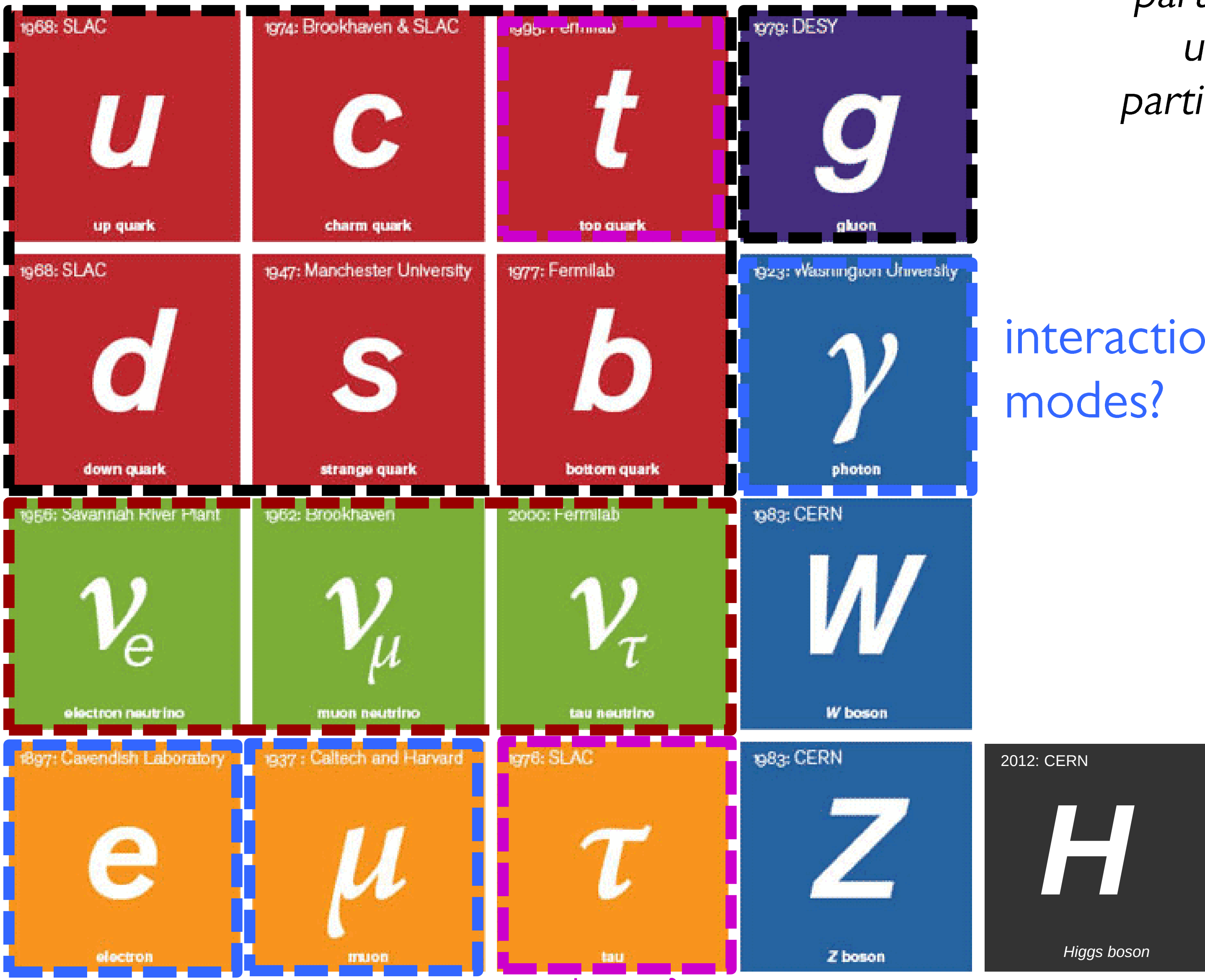
$\tau = 2.2\ \mu s$

What do we want to measure?

… "stable" particles from unstable particle decays!

decays?

hadron jets



interaction modes?

invisible

in particle detectors at accelerators

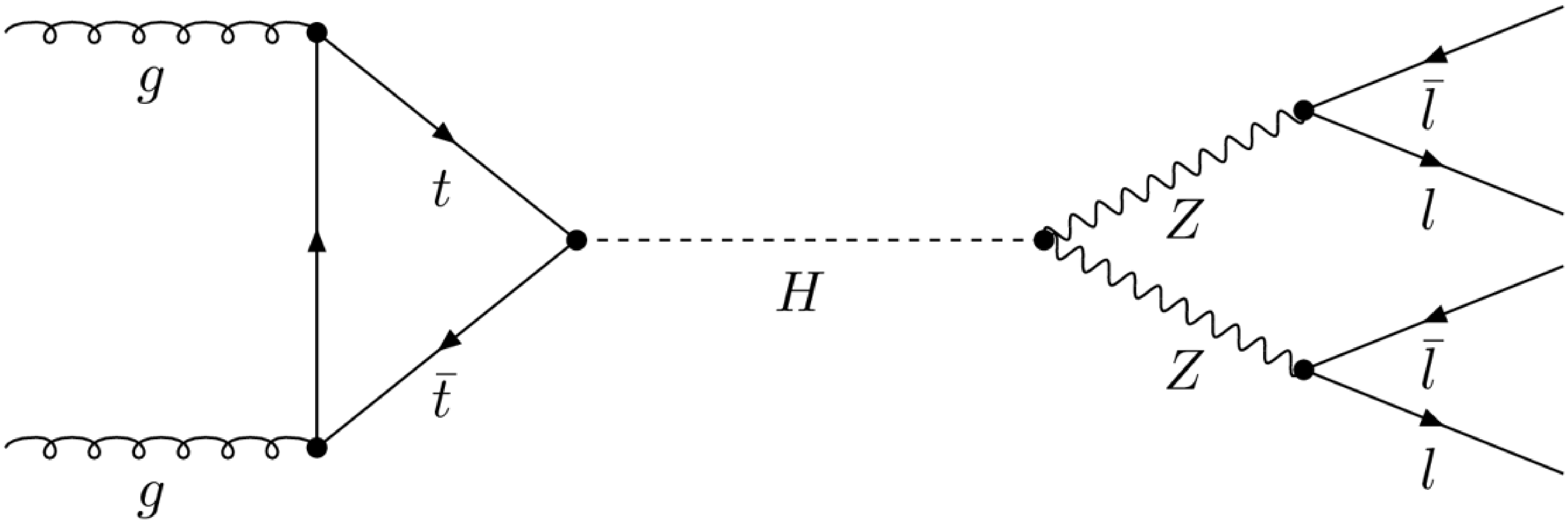
interaction modes?

decays?

What do we want to measure?

Example: let's assume a Higgs boson is produced at the LHC …
*It is a **SM particle**, we **can predict** how and how frequently*

… we look for "stable" particles from an unstable particle decays



e^+
e^-
μ^+
μ^-

this is what we are looking for…

Identifying and measuring "stable" particles

- Particles are characterized by
  - ✓ Mass [Unit: eV/c^2 or eV]
  - ✓ Charge [Unit: e]
  - ✓ Energy [Unit: eV]
  - ✓ Momentum [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 contraction

$$t = t_0\gamma$$ time dilation

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

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

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

Center of mass energy

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

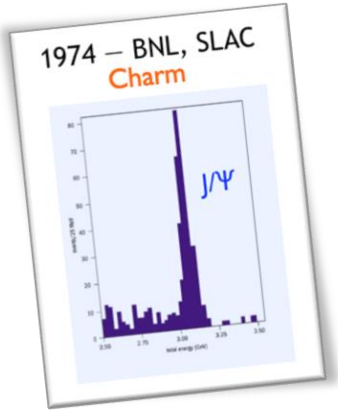
$$E_{\mathrm{cm}} = \sqrt{s} = \sqrt{\left(\sum E_i\right)^2 - \left(\sum \vec{p}_i\right)^2}$$

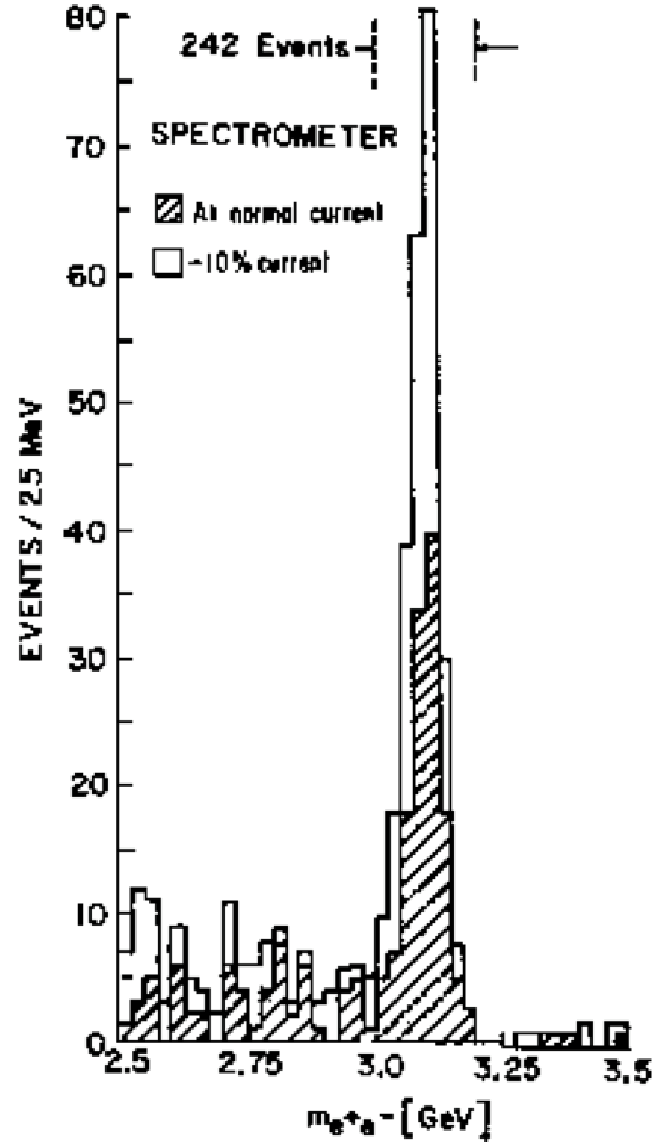
Hint: it can be computed as the "length" of the total four-momentum, that is invariant:

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

What is the "length" of a the four-momentum of a particle?

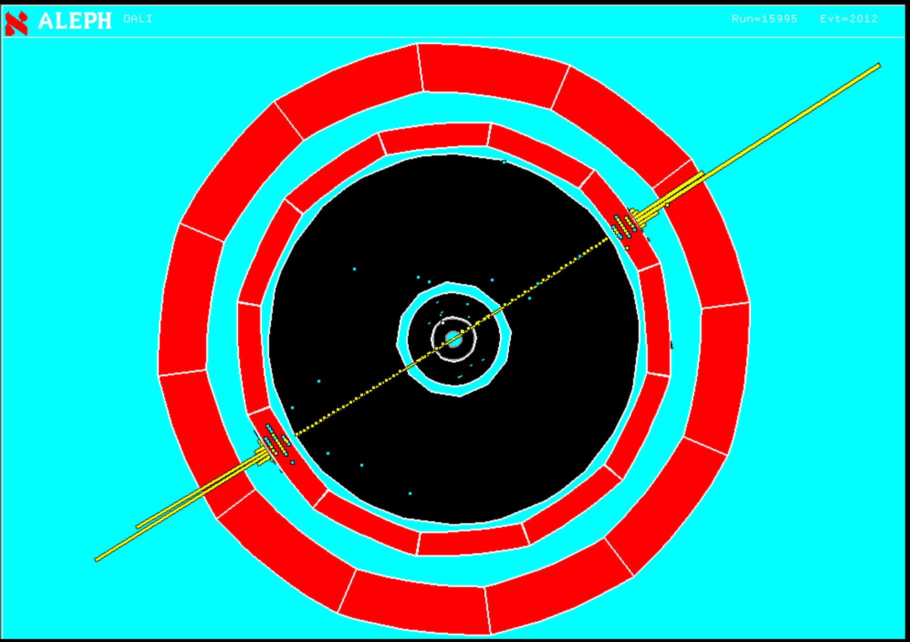
Invariant mass

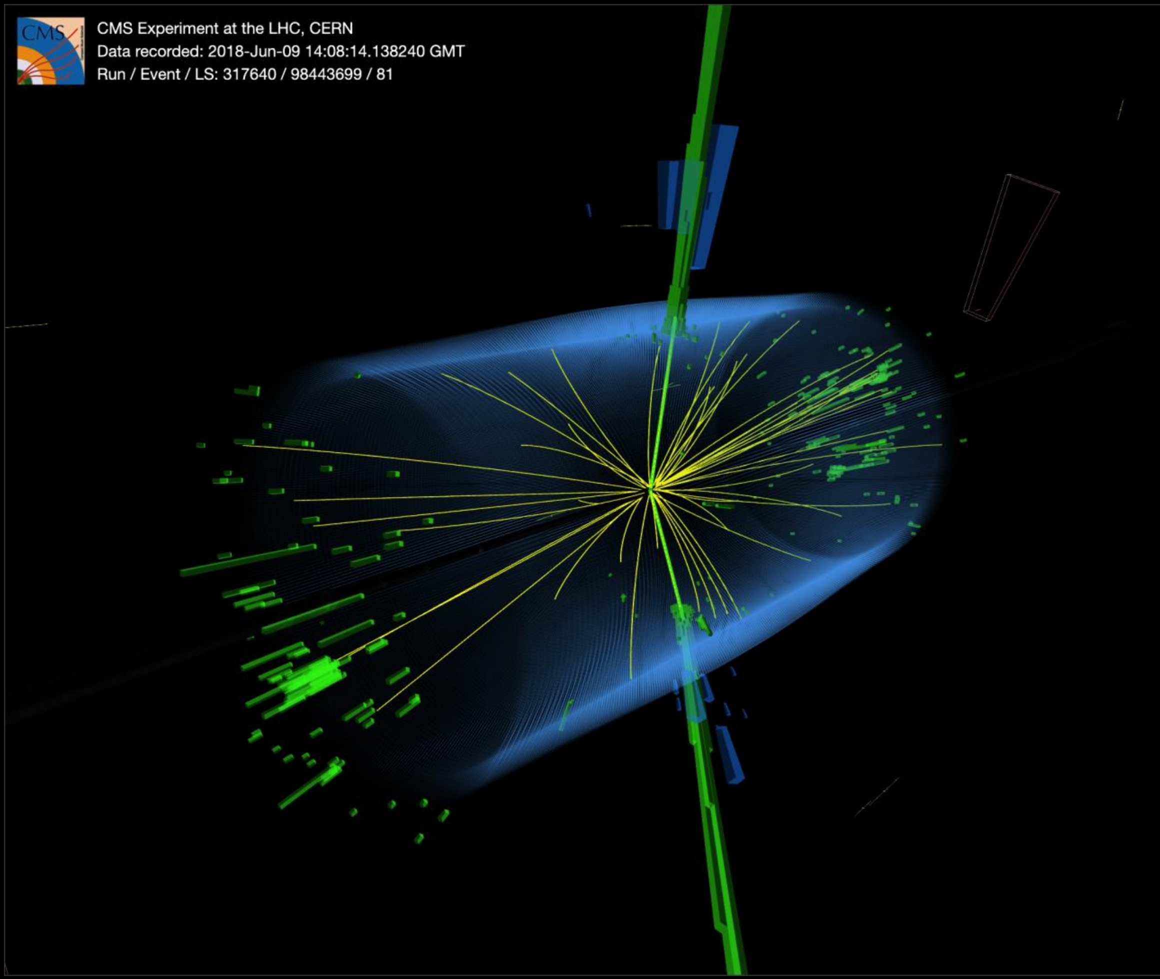




$$M = \sqrt{\left(\sum E_i\right)^2 - \left(\sum \vec{p}_i\right)^2}$$

A Z→e$^+$e$^-$ event at LEP and ad LHC





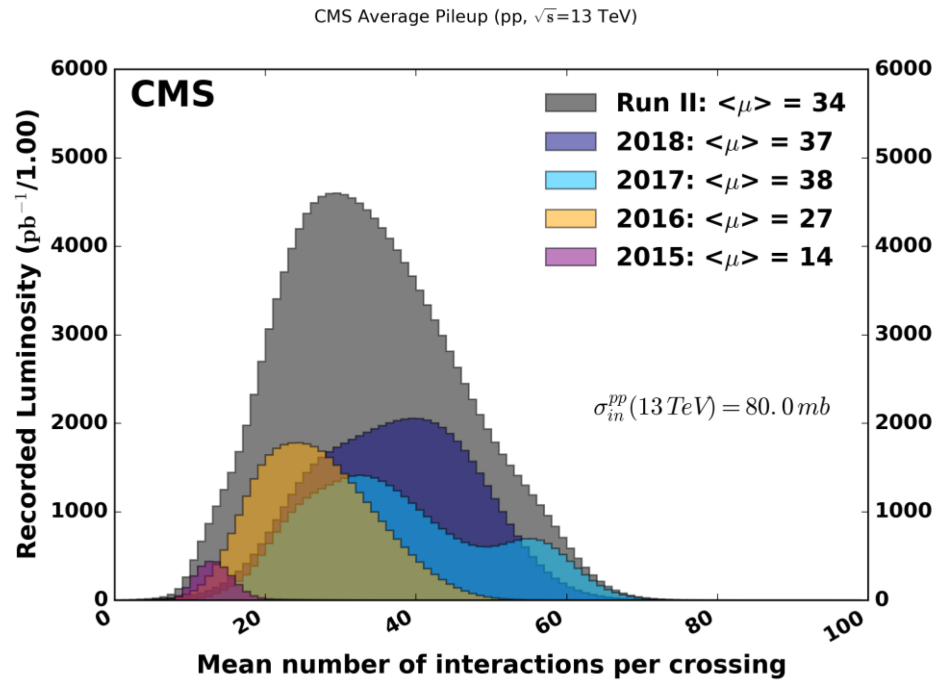
ALEPH @ LEP

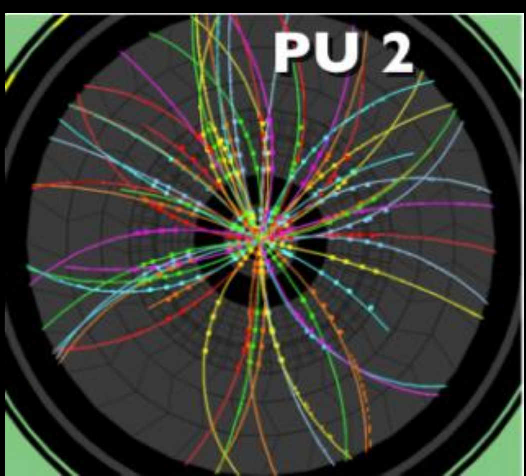
CMS @ LHC

Pile-Up

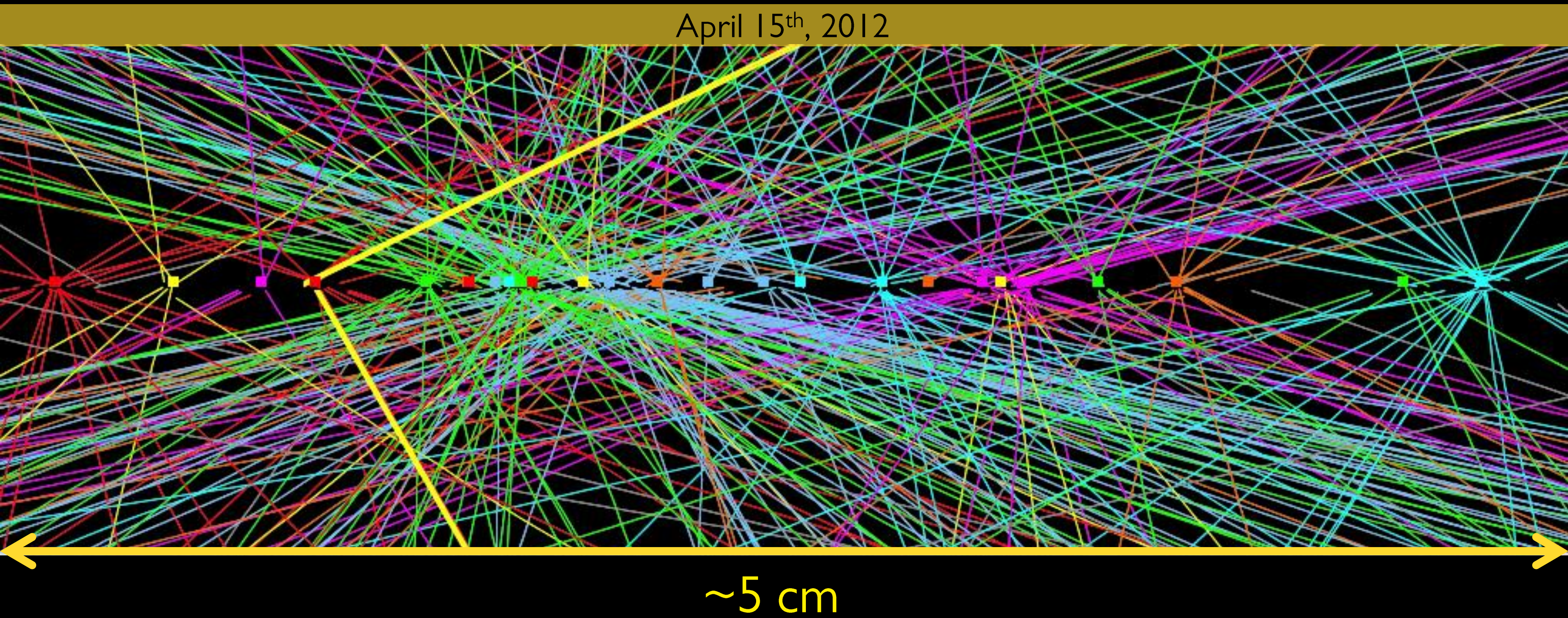
$$\mathcal{L} = \frac{1}{4\pi}\frac{f k N_1 N_2}{\sigma_x \sigma_y}$$

PU = number of inelastic interactions per beam bunch crossing

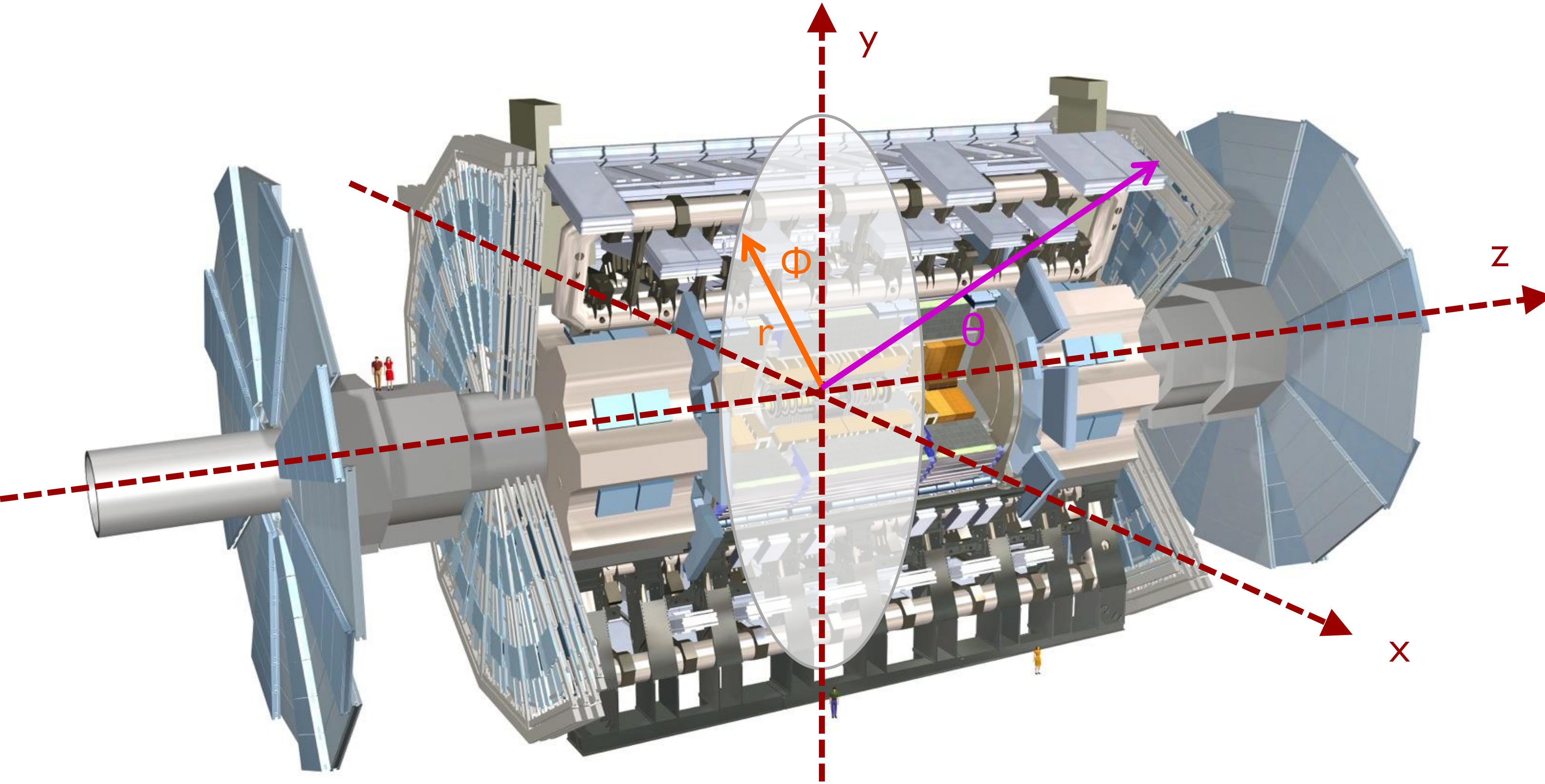




Z→μμ event with 25 reconstructed vertices



Collider experiment coordinates



Interaction mode cheat sheet ("light" particles)

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

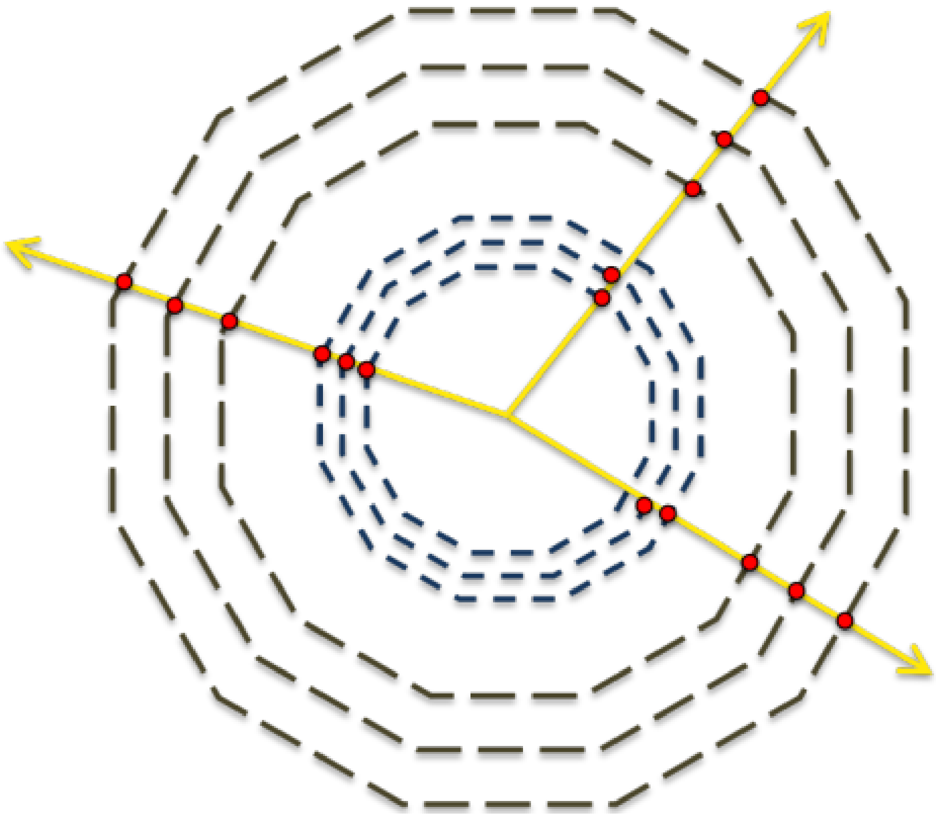
- electrically charged
- ionization (dE/dx)
- can emit photons
  - ✓ electromagnetic shower induced by emitted photon…
    - but it's rare…

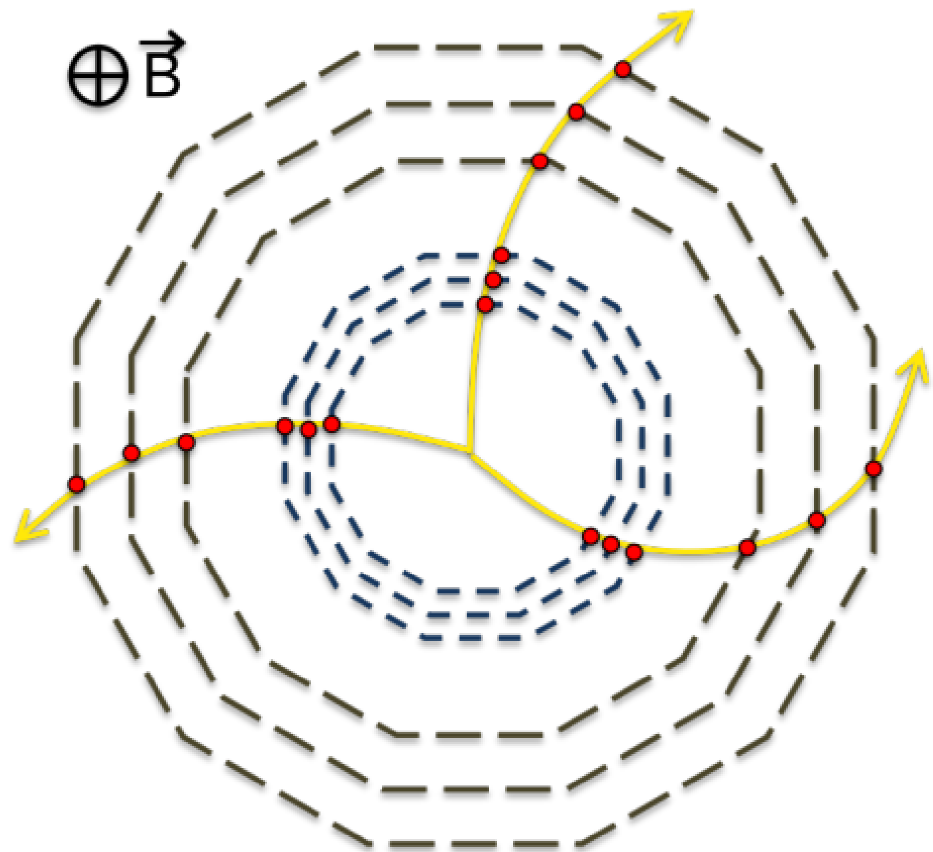
- electrically neutral
- pair production
  - ✓ E > 1 MeV
- *electromagnetic shower…*

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

Magnetic spectrometer for ionizing particles

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



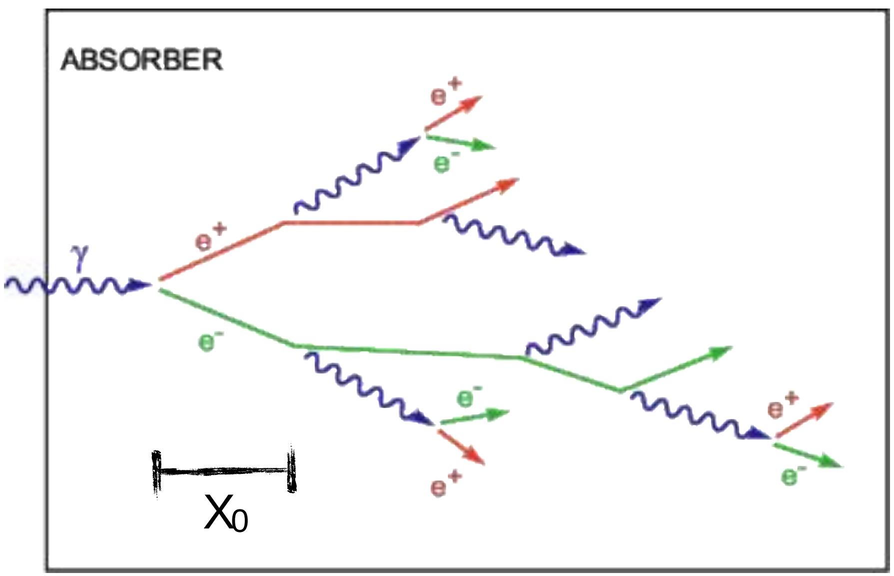


$$p[\mathrm{GeV}] = 0.3 B[\mathrm{T}] \rho[\mathrm{m}]$$

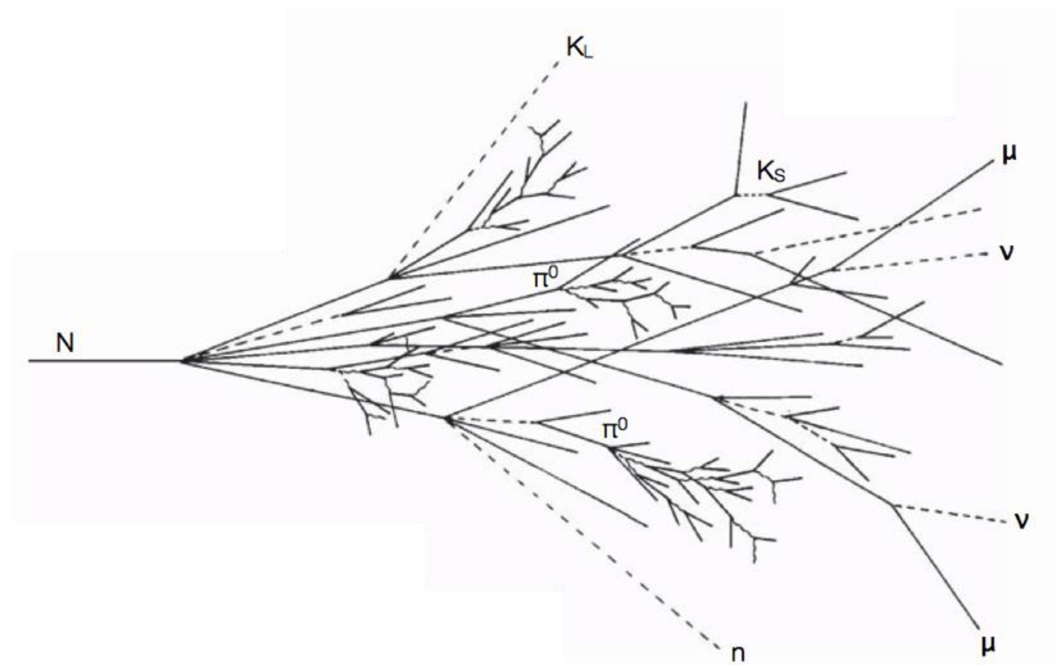
Calorimeters for showering particles

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

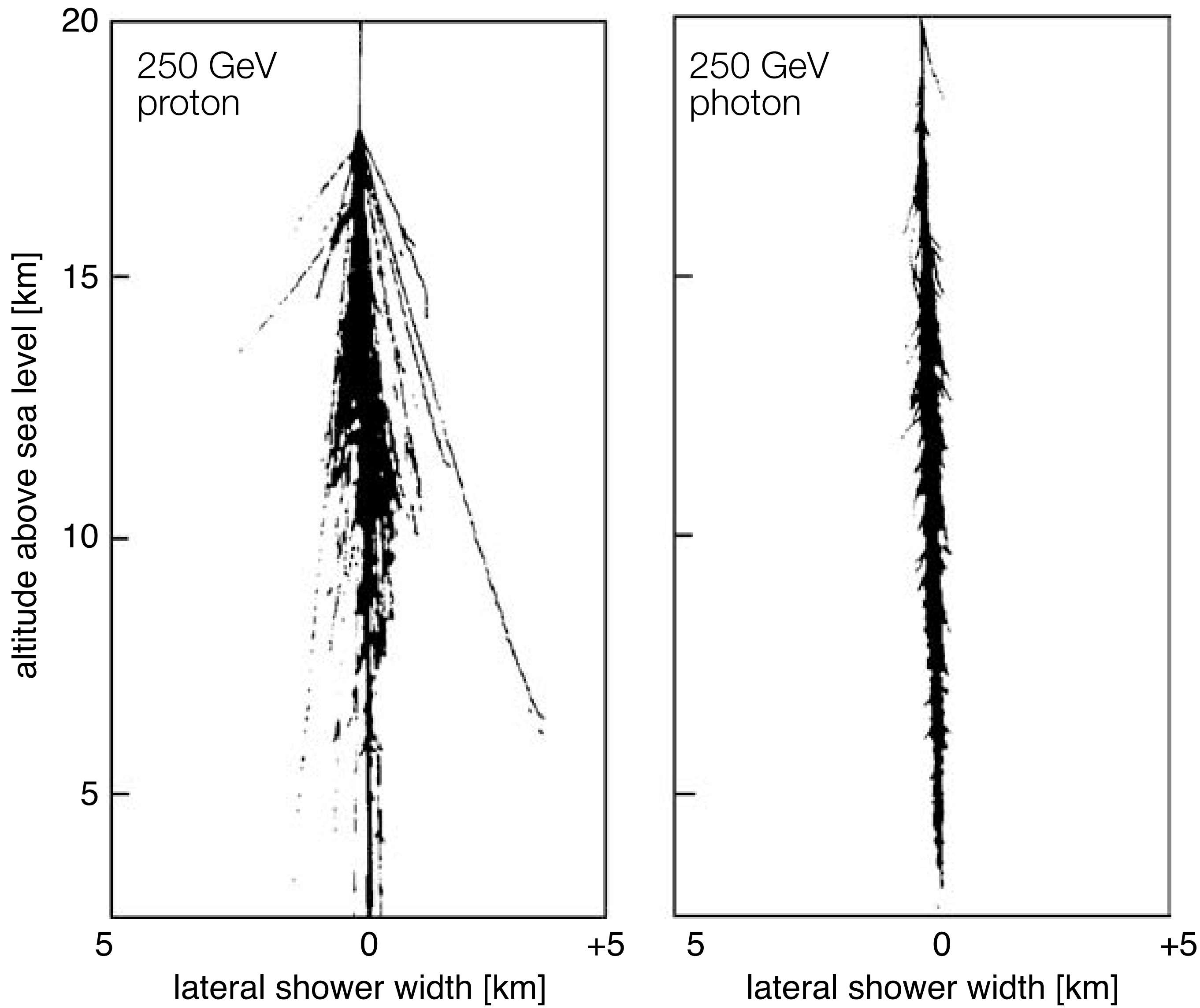
$$\frac{dE}{dx}(E_c)\bigg|_{\mathrm{Brems}} = \frac{dE}{dx}(E_c)\bigg|_{\mathrm{Ion}}$$



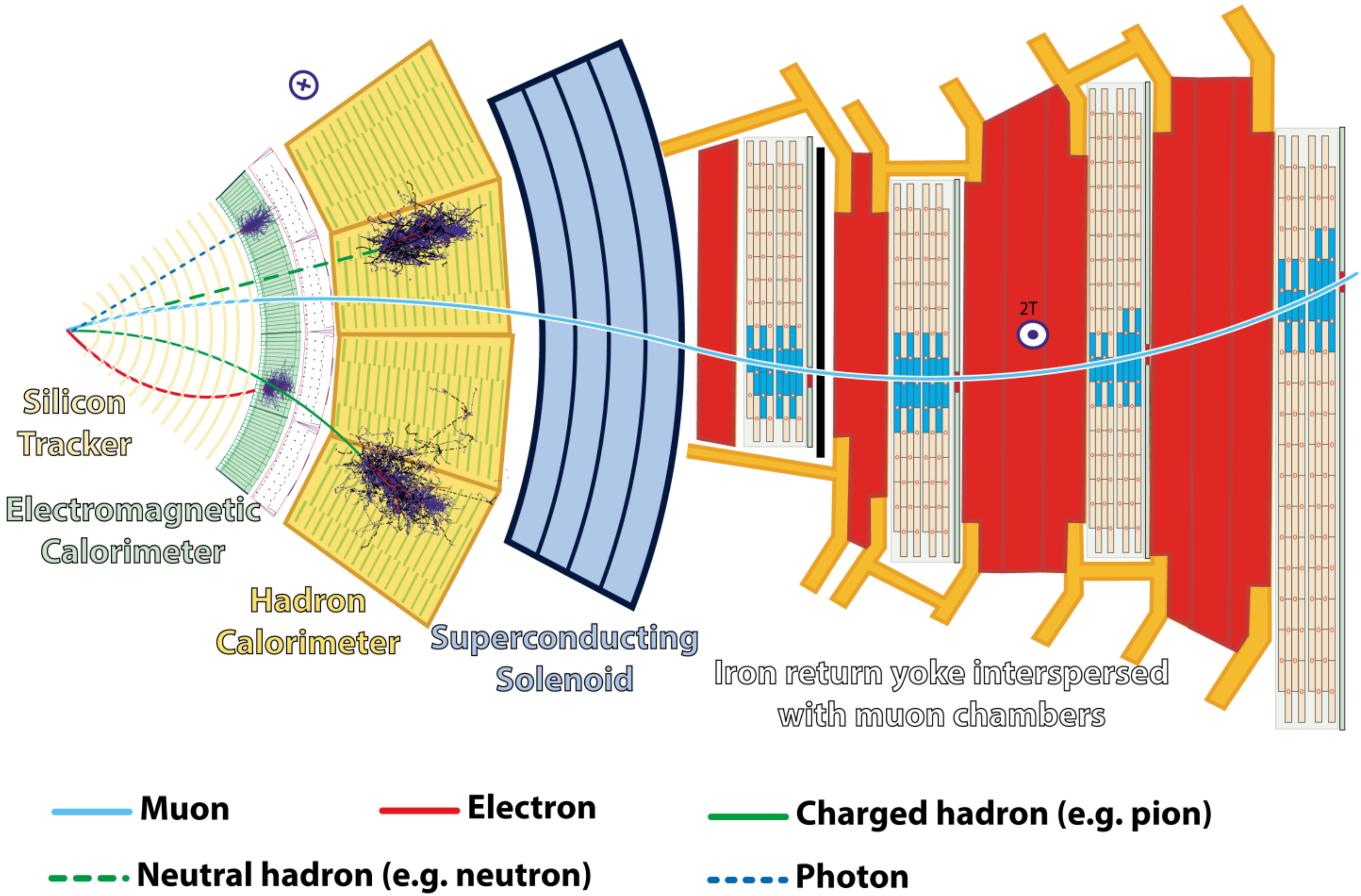
- Hadronic showers
  - ✓ Inelastic scattering w/ nuclei
    - Further inelastic scattering until below pion production threshold
  - ✓ Sequential decays
    - $\pi^0 \rightarrow \gamma\gamma$
    - Fission fragment: β-decay, γ-decay
    - Neutron capture, spallation, …



Hadronic vs. EM showers

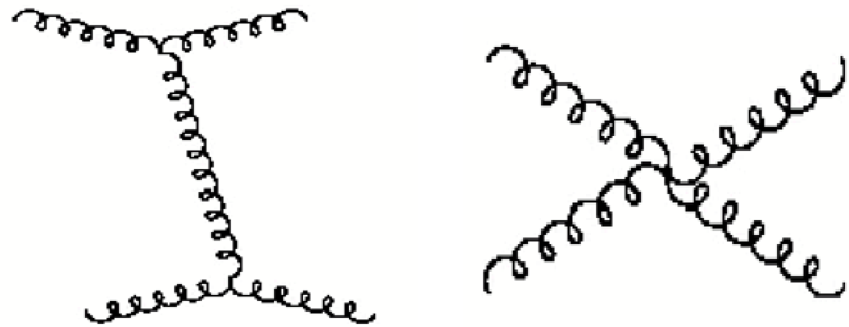


Particle identification with CMS@LHC



A few more words on QCD

- QCD (strong) interactions are carried out by massless spin-1 particles called gluons
  - ✓ Gluons are massless
    - Long range interaction
  - ✓ Gluons couple to color charges
  - ✓ Gluons have color themselves
    - They can couple to other gluons

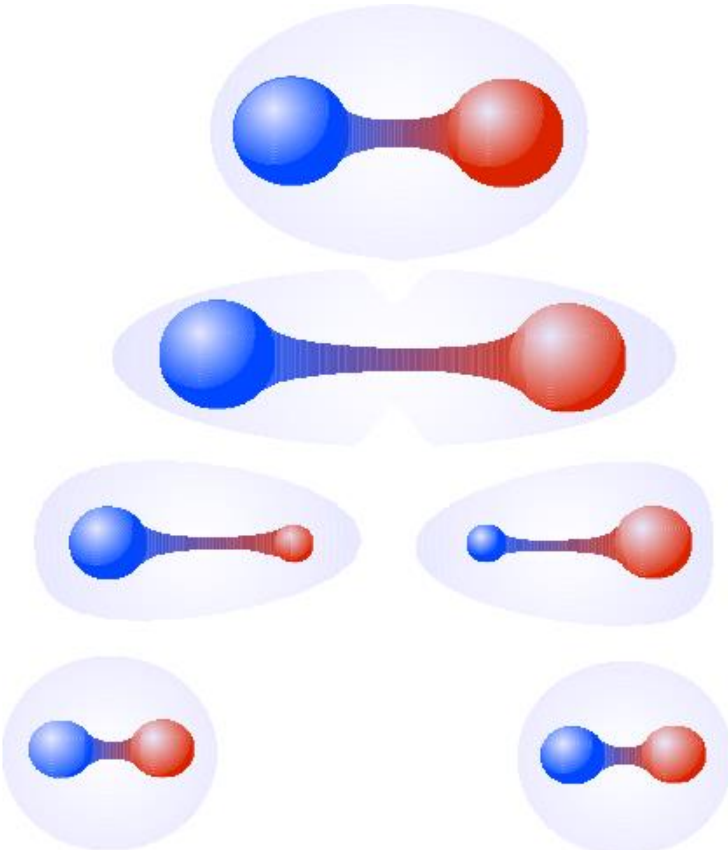


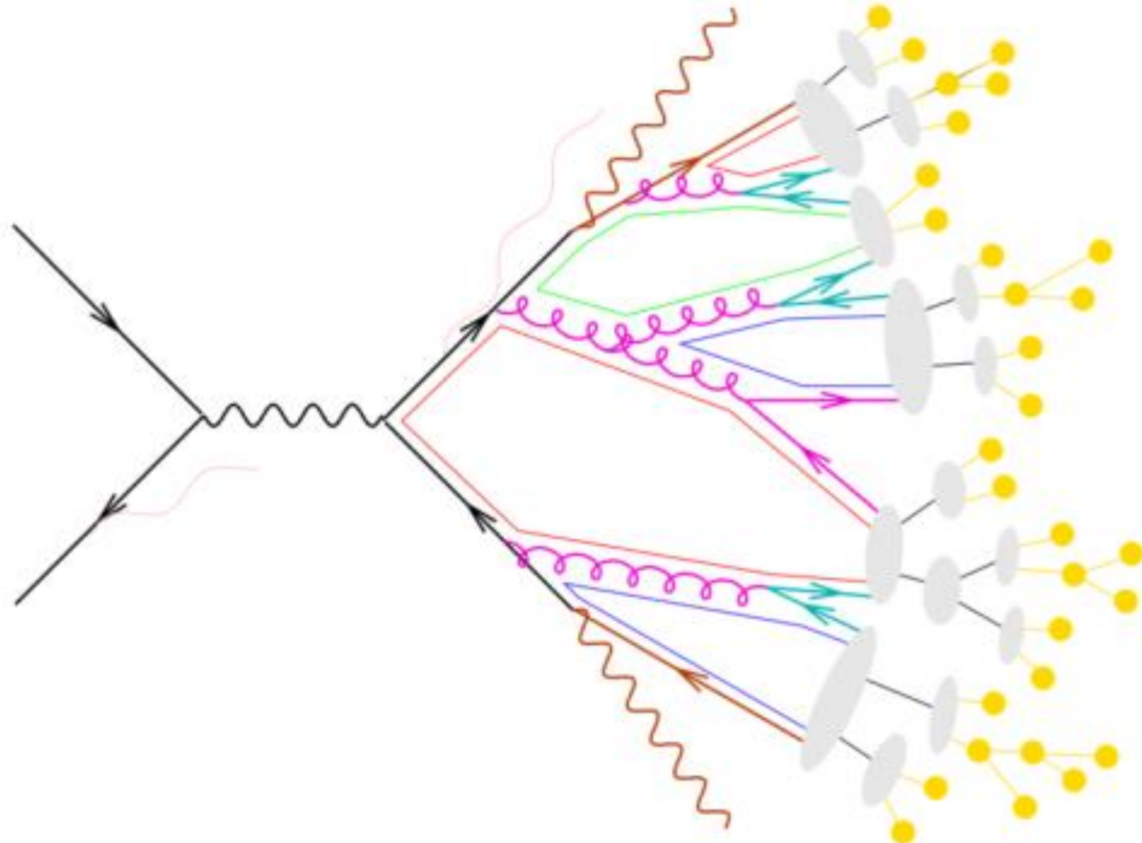
- **Principle of asymptotic freedom**
  - ✓ At short distances strong interactions are weak
    - Quarks and gluons are essentially free particles
    - Perturbative regime (can calculate!)
  - ✓ At large distances, higher-order diagrams dominate
    - Interaction is very strong
    - Perturbative regime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

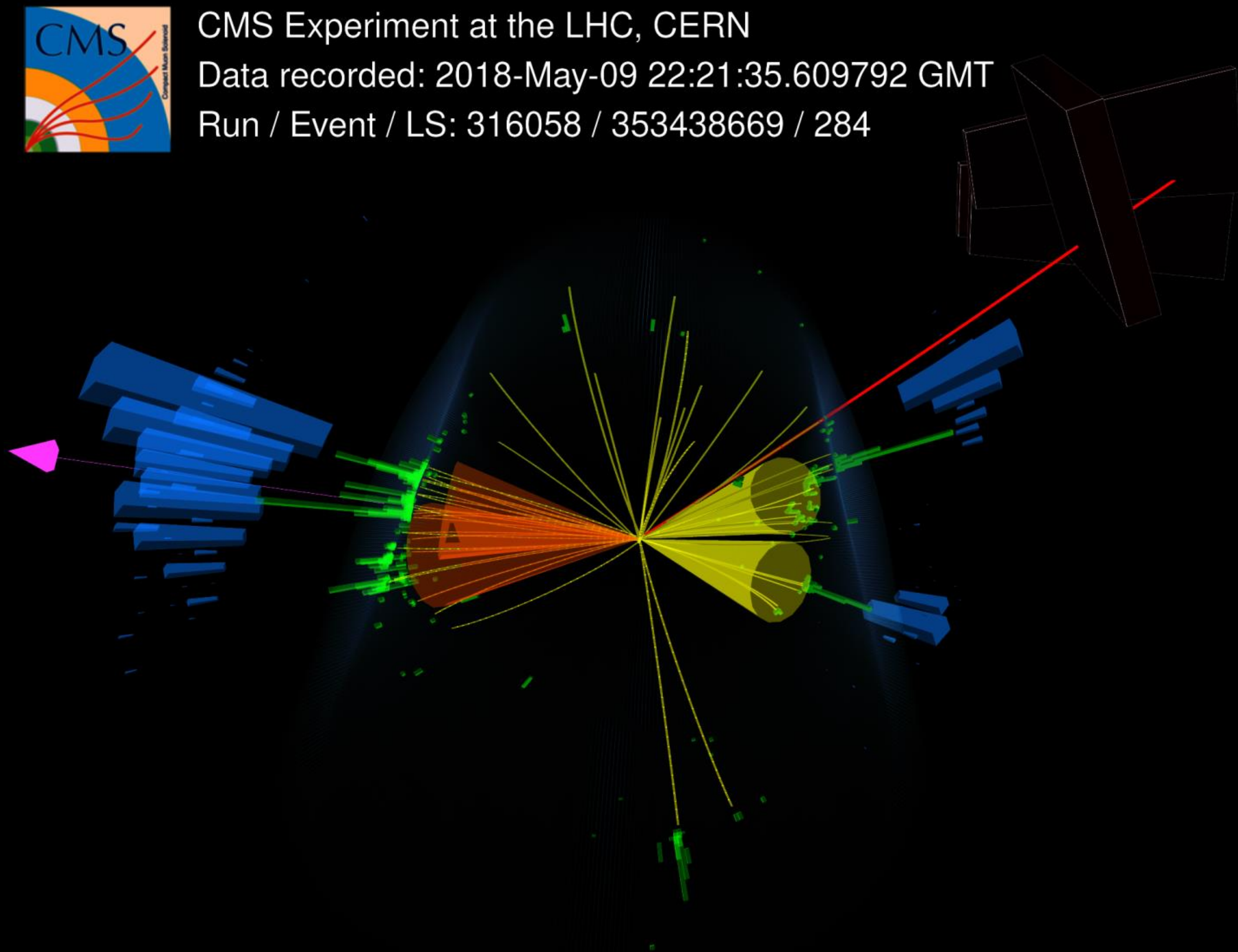
quark-quark effective potential

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

Confinement, hadronization, jets

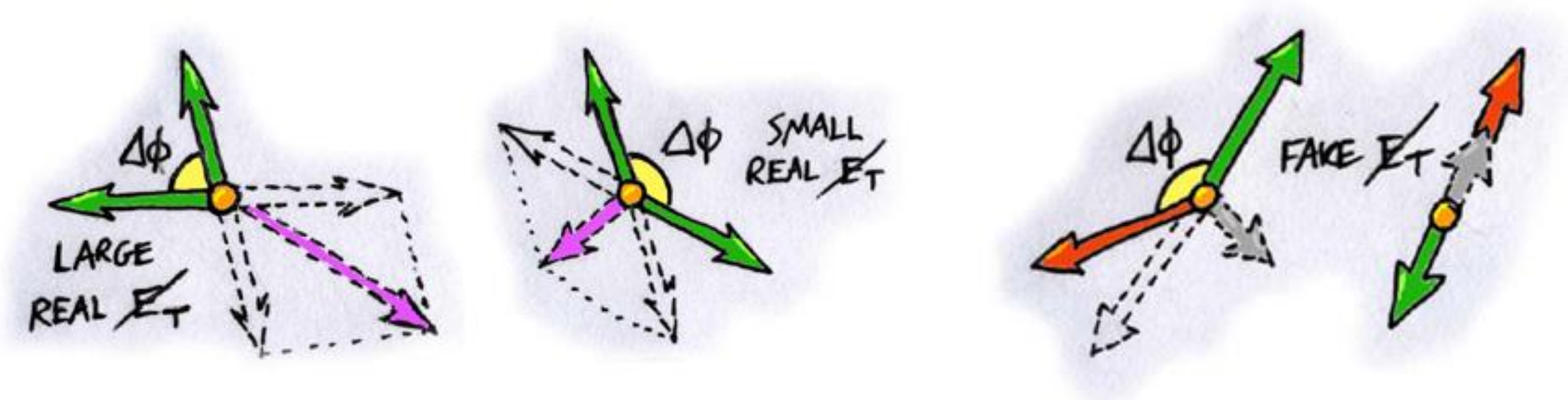





CMS Experiment at the LHC, CERN
Data recorded: 2018-May-09 22:21:35.609792 GMT
Run / Event / LS: 316058 / 353438669 / 284

Neutrino (and other invisible particles) at colliders

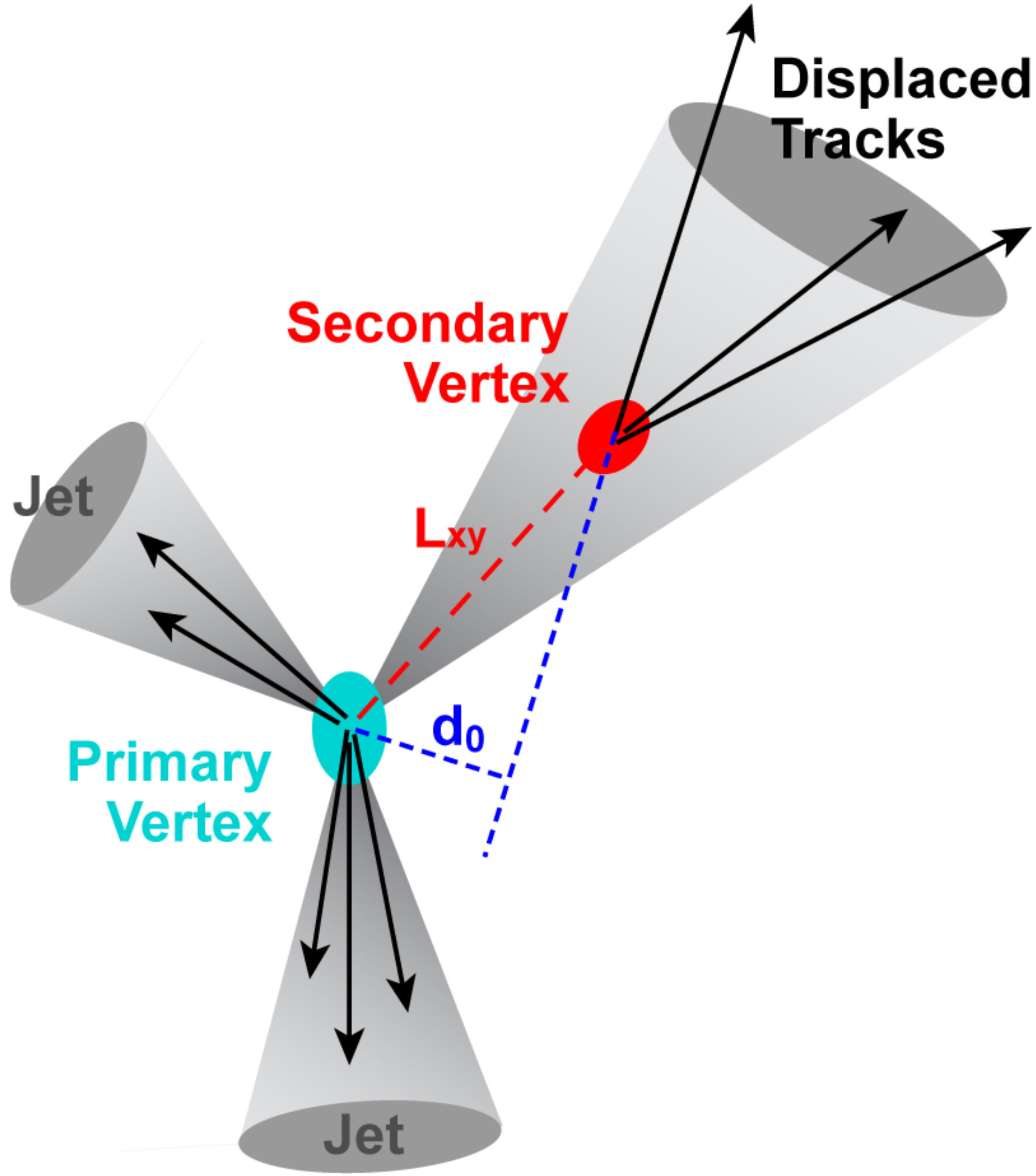
- Interaction length $\lambda_{int} = A\,/(\rho\ \sigma\ N_A)$
- Cross section $\sigma \sim 10^{-38}\ \mathrm{cm}^2 \times E\,[\mathrm{GeV}]$
  - ✓ This means 10 GeV neutrinos can pass through more then a million km of rock
- Neutrinos are usually detected in HEP experiments through *missing (transverse)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



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

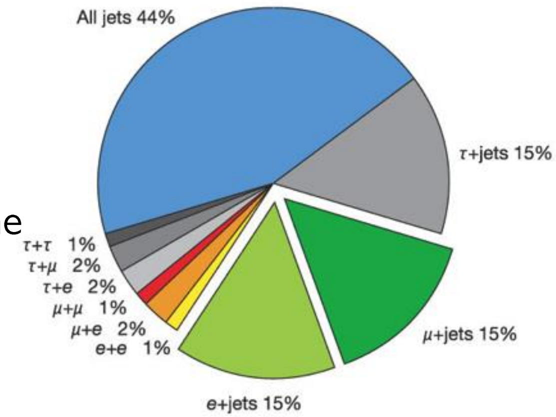
B-tagging

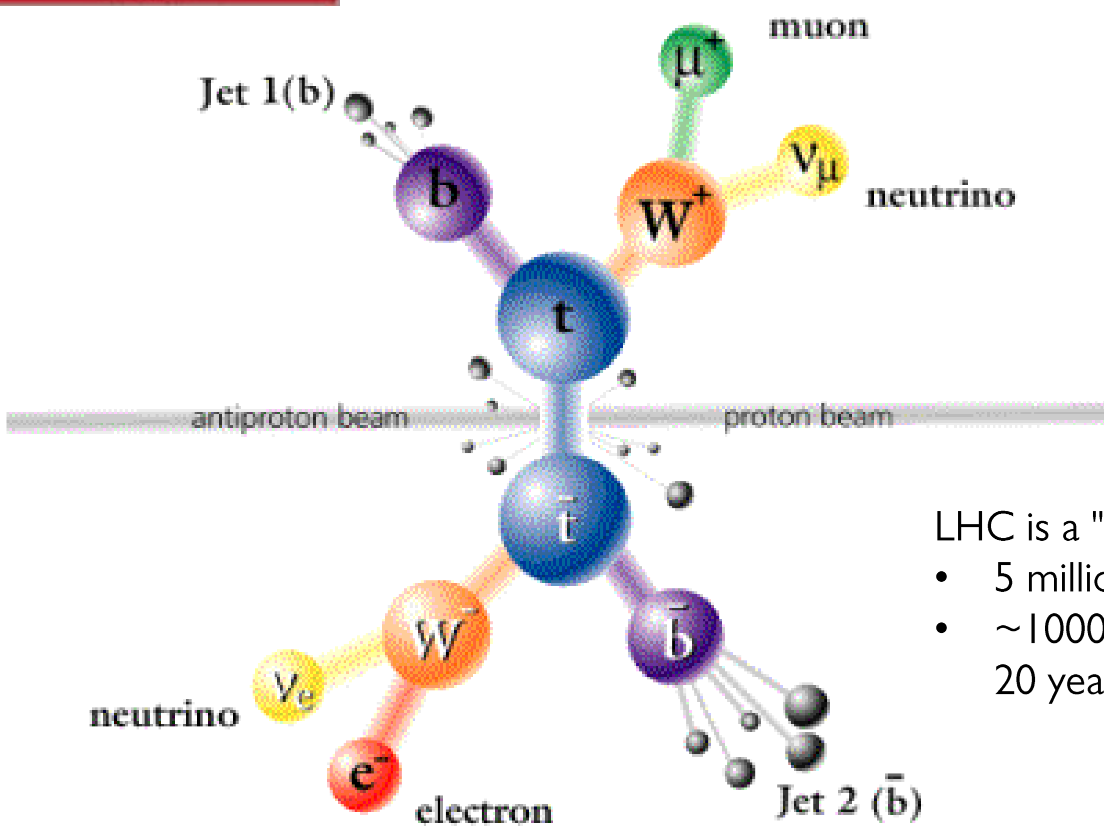
- When a b quark is produced, the associated jet will very likely contain at least one B meson or hadron
- B mesons/hadrons have relatively long lifetime
  - ✓ ~ 1.6 ps
  - ✓ They will travel away form collision point before decaying
- Identifying a secondary decay vertex in a jet allow to tag its quark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

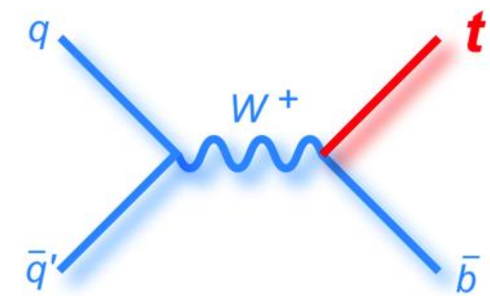


top quark

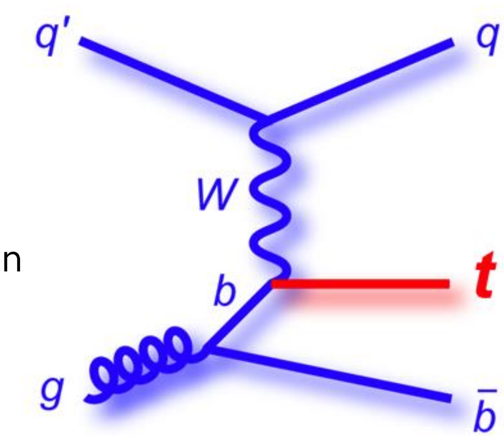
- Mean lifetime ~ 5×10^{-13} ps
  - ✓ Shorter than time scale at which QCD acts: no time to hadronize!
  - ✓ It decays as $t \rightarrow Wb$
- Events with top quarks are very rich in (b) jets…





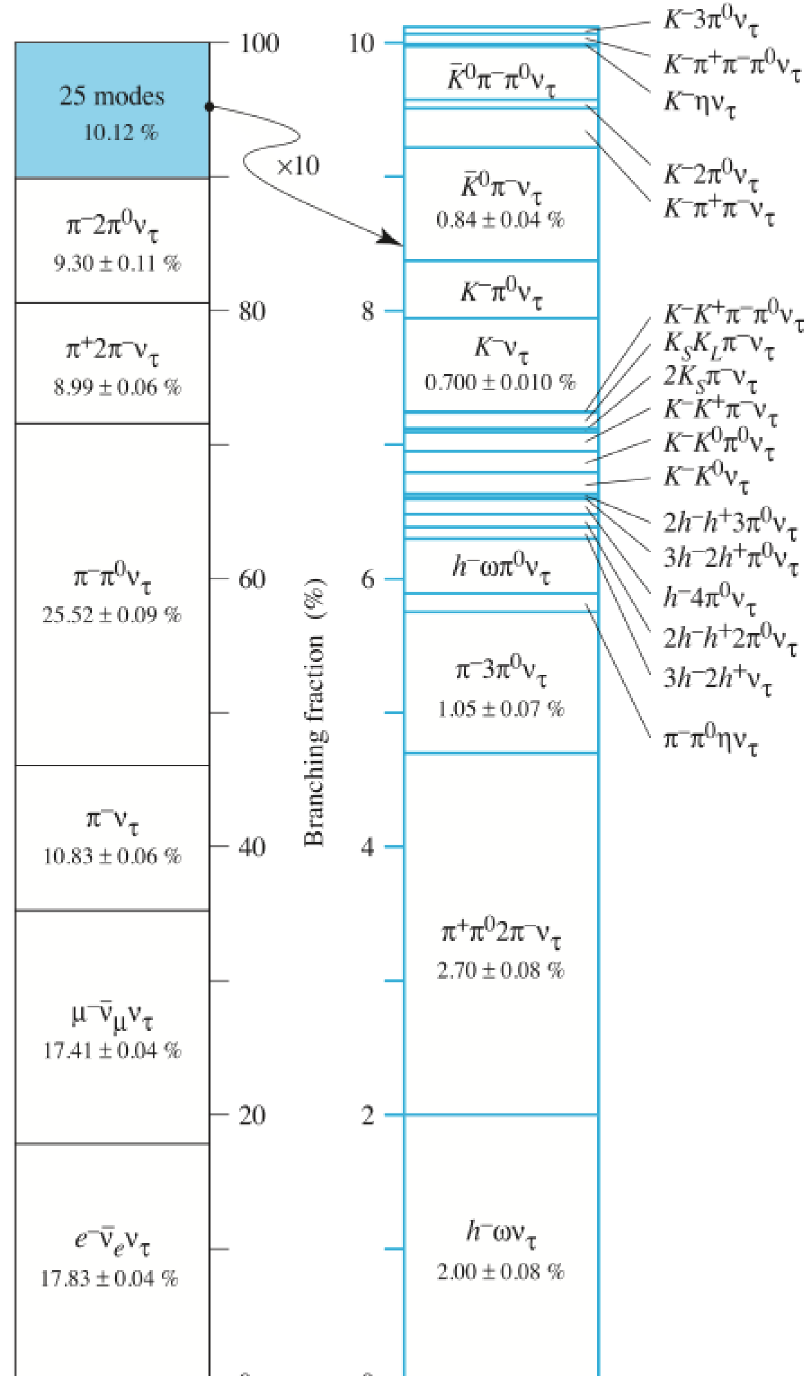


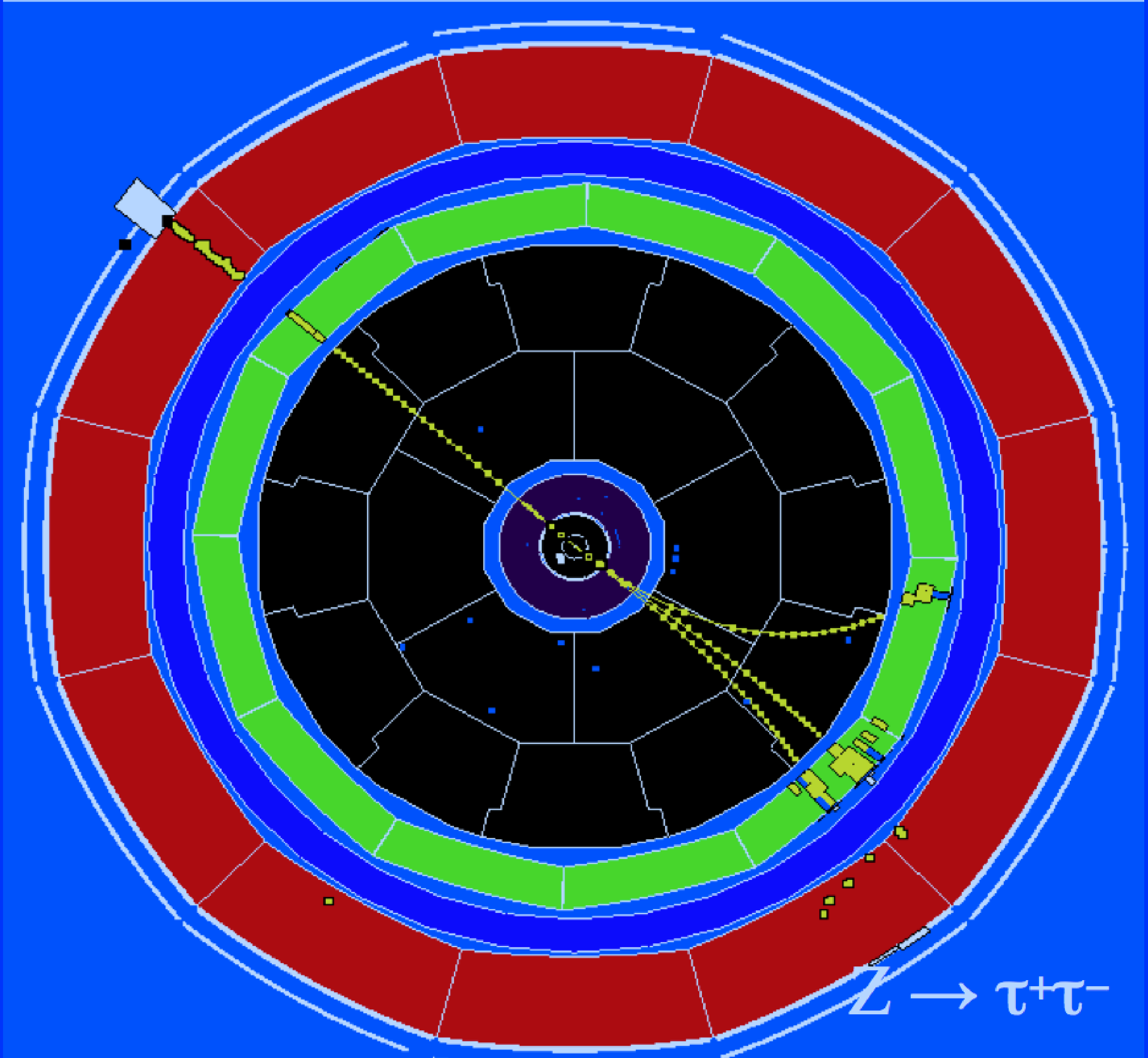
LHC is a "top factory"!
- 5 millions of tt pairs
- ~100000 in Tevatron in 20 years



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

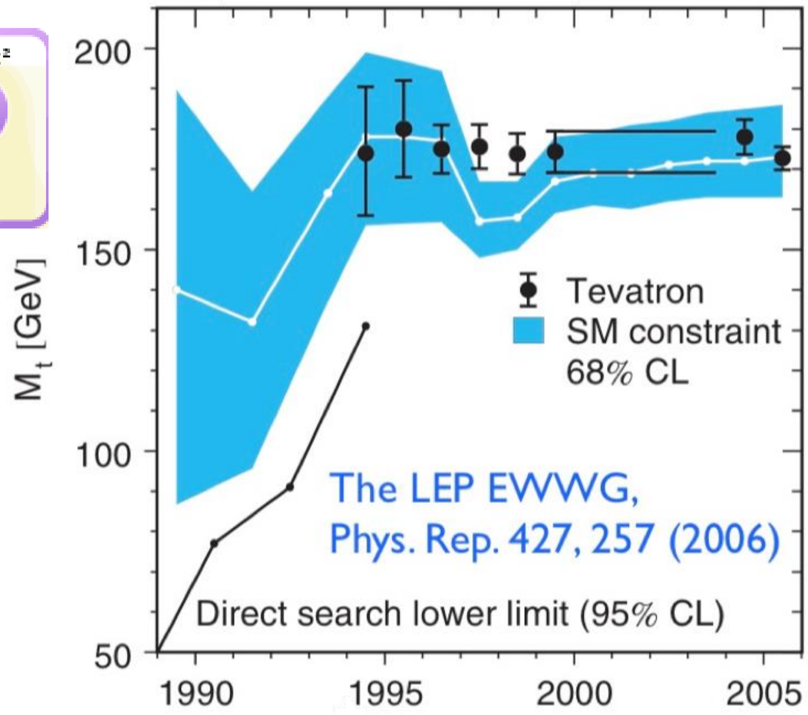


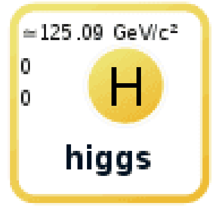

$Z \to \tau^+\tau^-$

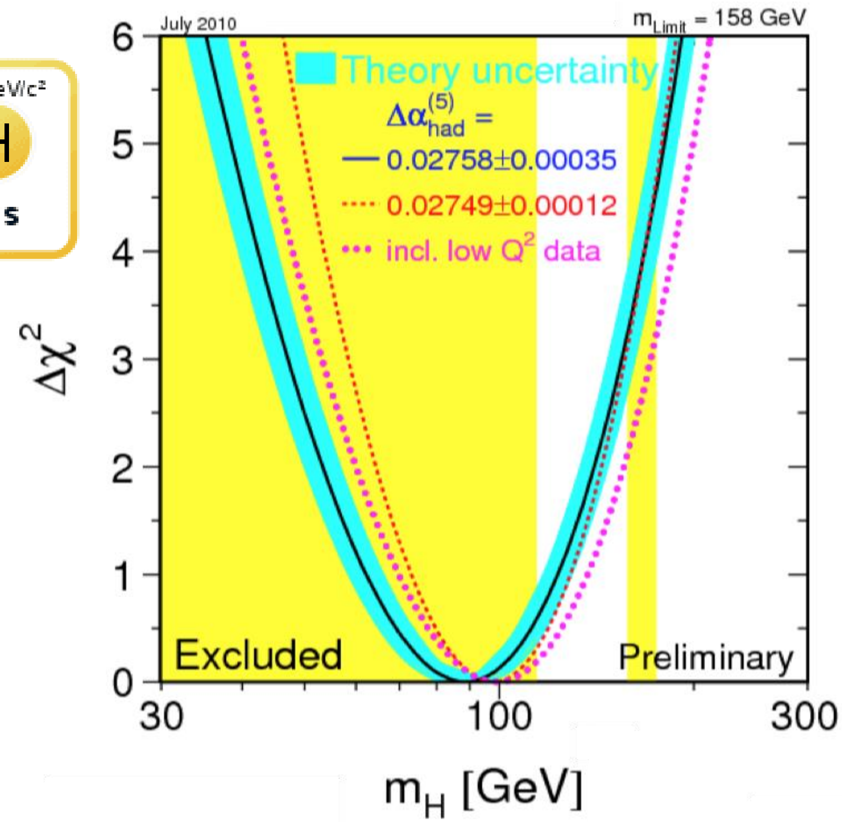
Additional information

(I find you lack of faith disturbing)

Before the LHC startup







m_W measurement at SppS and LEP-1 precision measurements

top quark discovery (1994)

m_W measurement at LEP-2

electroweak fit and indirect limit on m_H

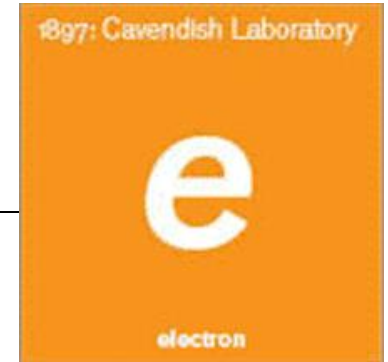
Direct limits on Higgs production from LEP-2 and Tevatron

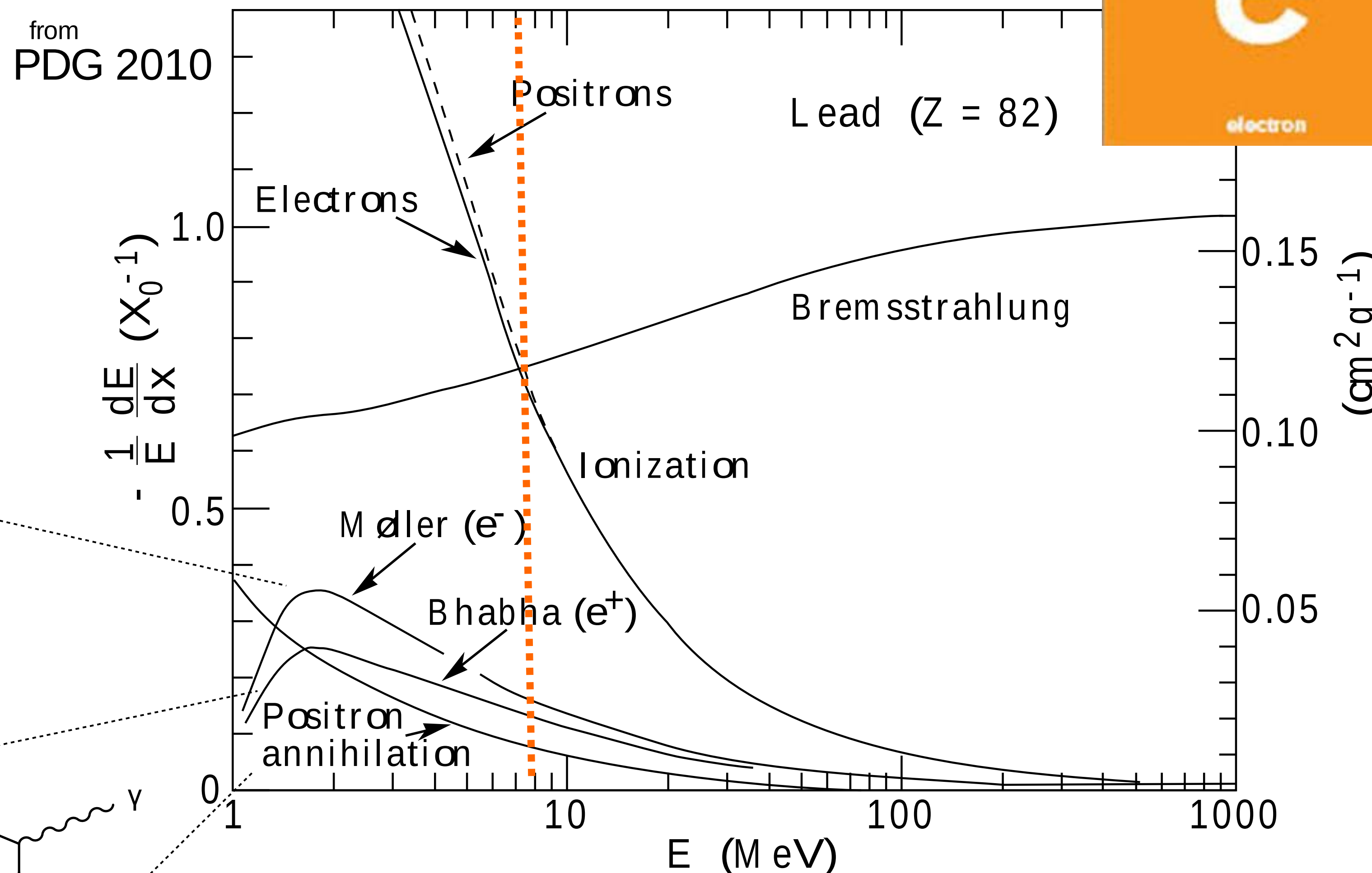
LHC "no lose theorem"

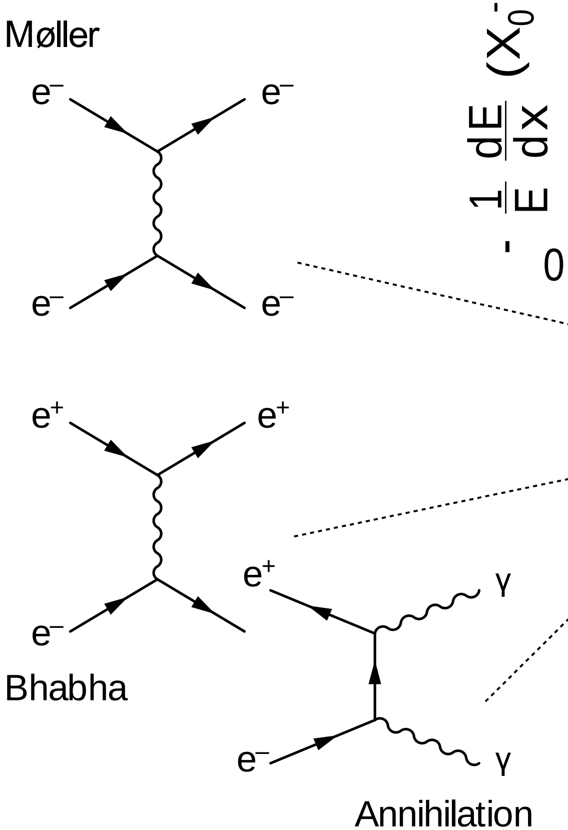
Either the Higgs boson is discovered,

or New Physics should manifest to avoid unitarity violation in WW scattering at TeV scale

Electron energy loss

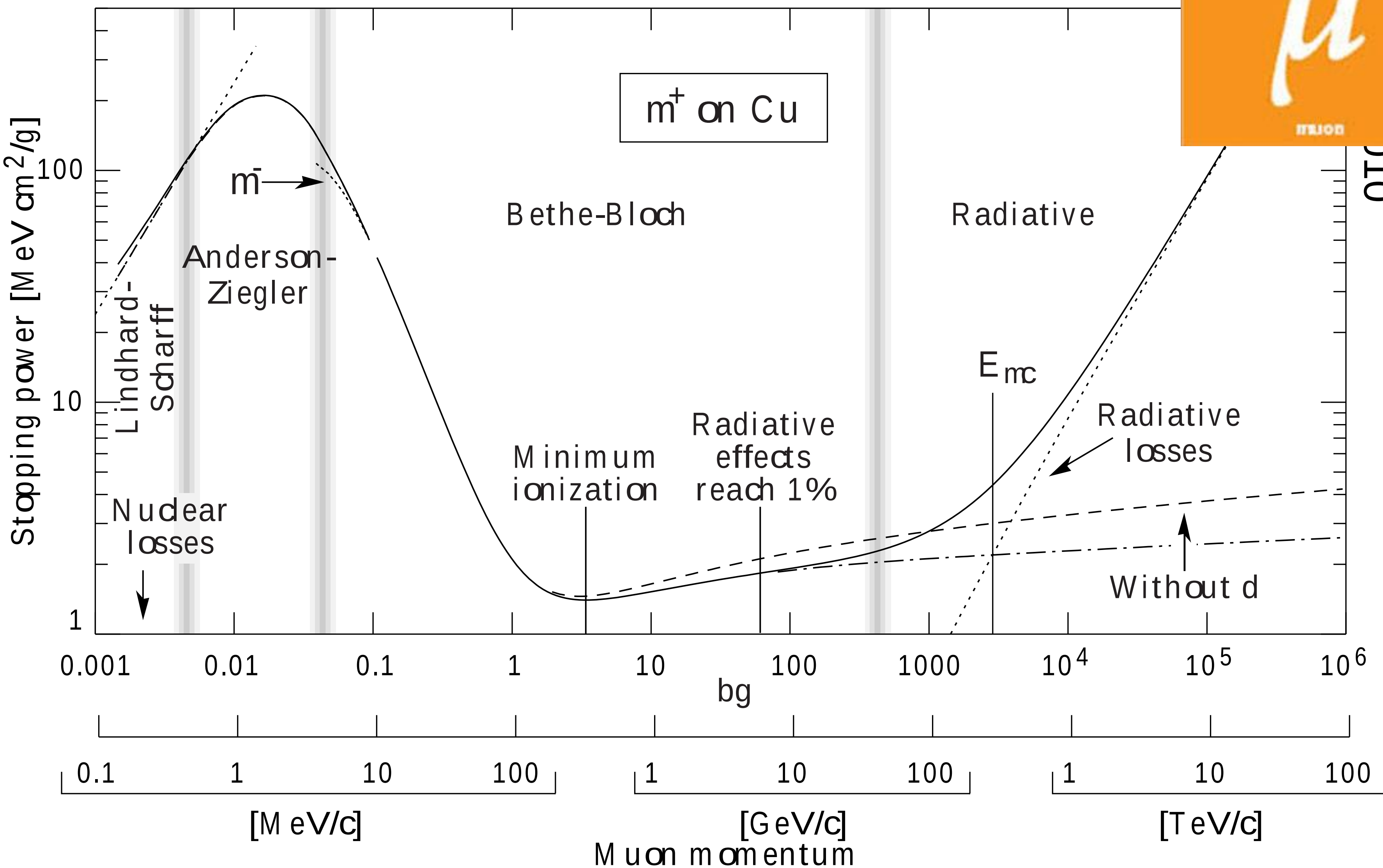




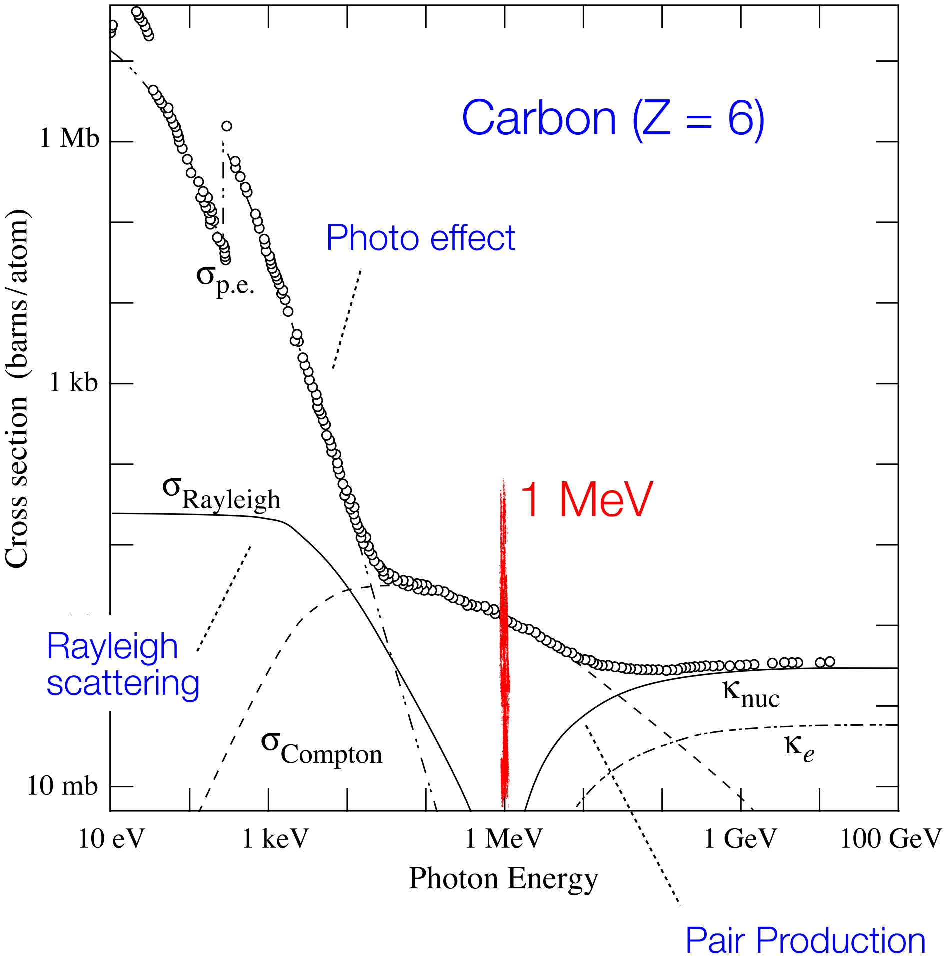


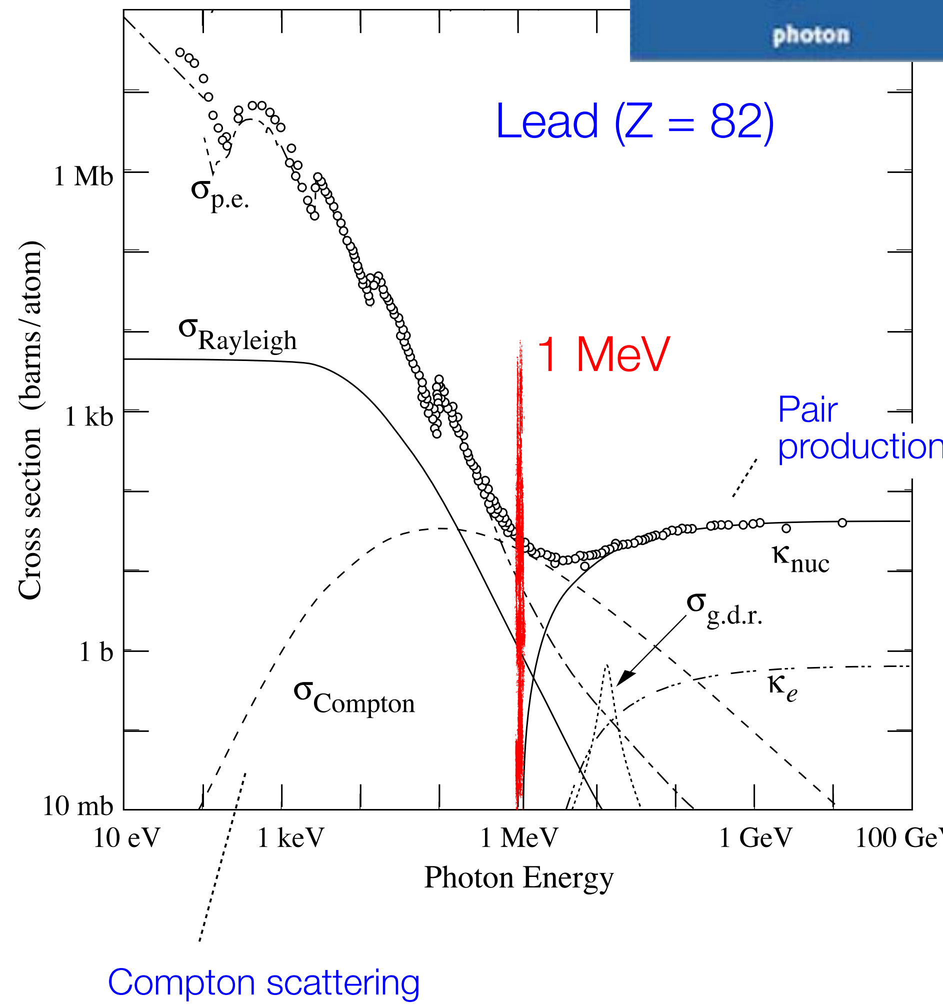
Fractional energy loss per radiation length in lead as a function of electron or positron energy

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
$\hbar = h/2pi$	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	$1\ \text{GeV}^{-1} = 0.1973$ fm	
time	$1\ \text{GeV}^{-1} = 6.59 \times 10^{-25}$ s	

Relativistic kinematics in a nutshell

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

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

$$E = m\gamma$$

$$t = t_0\gamma$$

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

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

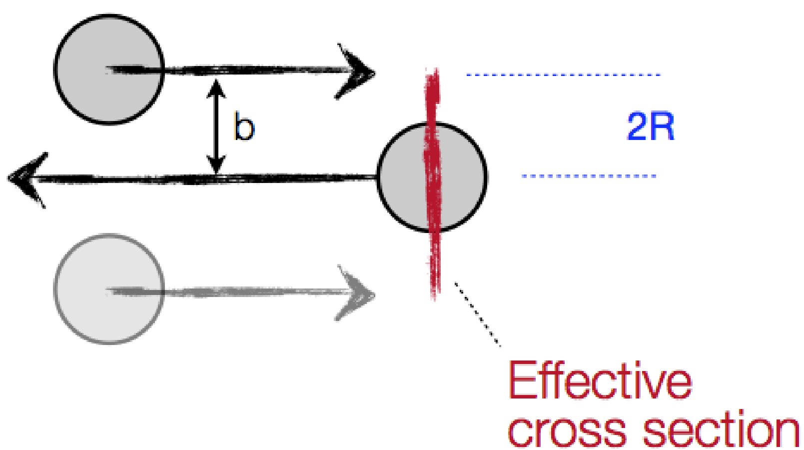
Cross section: magnitude and units

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

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

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

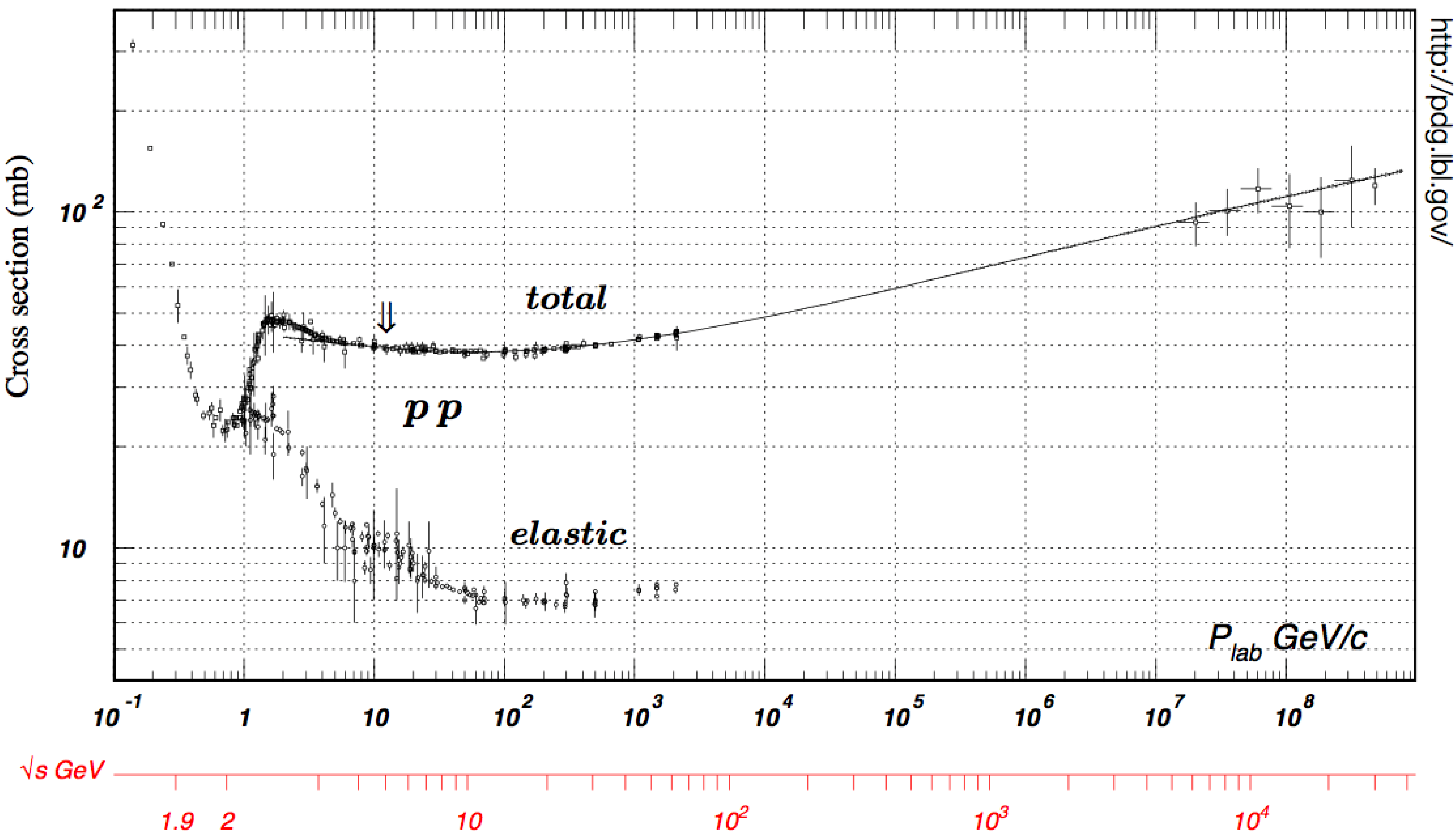
Estimating the
proton-proton cross section:



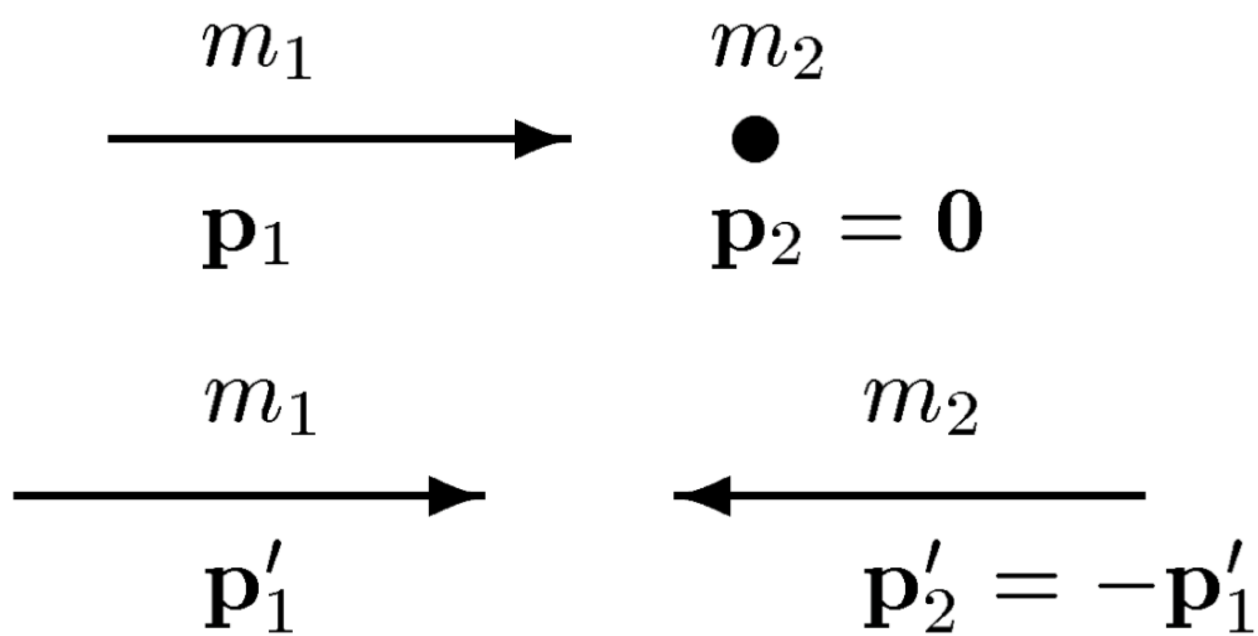
Proton radius: R = 0.8 fm
Strong interactions happens up to b = 2R

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

Proton-proton scattering cross-section



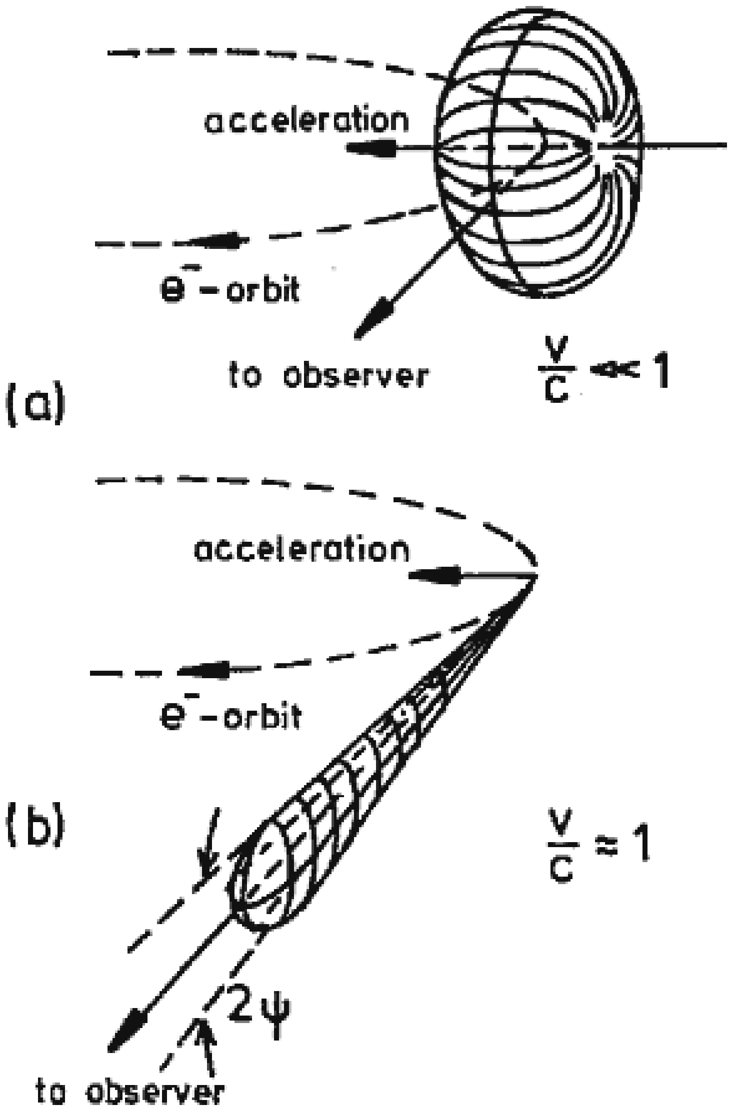
Fixed target vs. collider



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

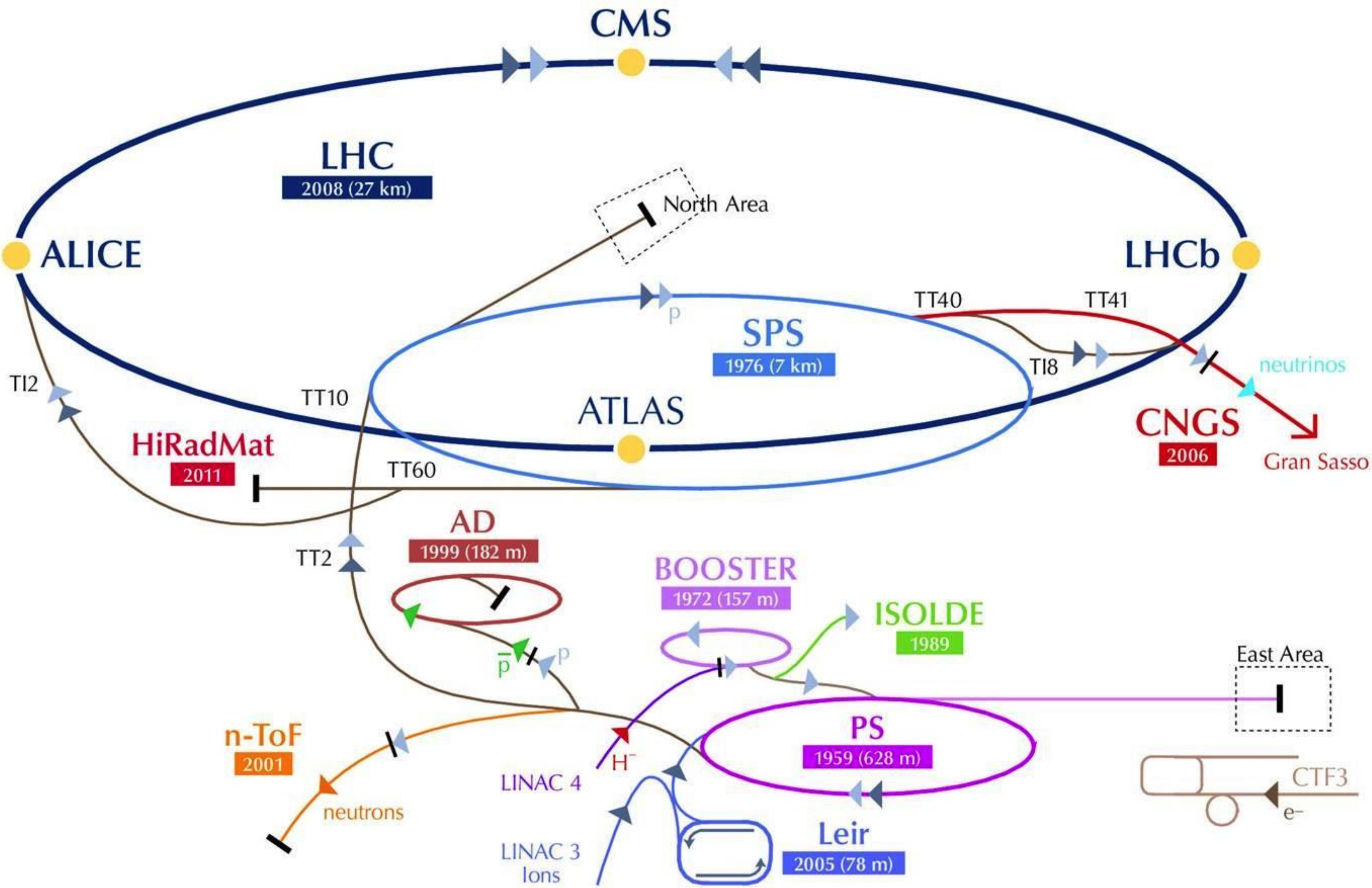
$$\Delta E = \frac{4\pi}{3}\frac{1}{4\pi\epsilon_0}\left(\frac{e^3\beta^3\gamma^4}{R}\right)$$

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…

CERN accelerator complex



Magnetic spectrometer

Charged particle in magnetic field

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

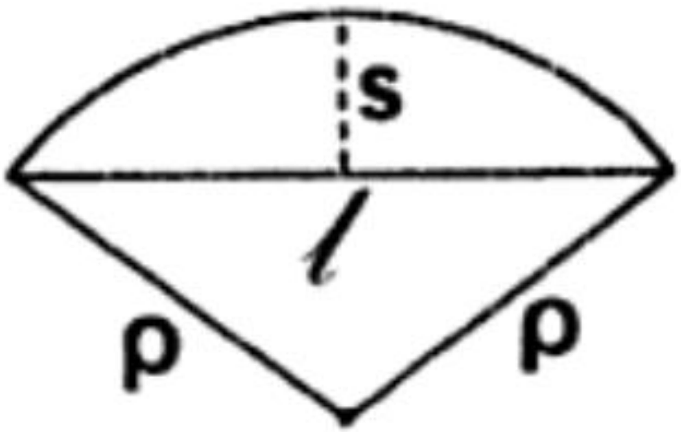
If the field is constant and we neglect presence of matter, momentum magnitude is constant with time, trajectory is helical

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

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

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

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

Momentum resolution due to measurement error

$$\left|\frac{\delta p}{p}\right| = \overbrace{A_N}^{\textit{smaller for larger number of points}} \frac{\overbrace{\epsilon}^{\textit{measurement error (RMS)}}}{\underbrace{L^2}_{\textit{projected track length in magnetic field}}} \frac{p}{0.3B}$$

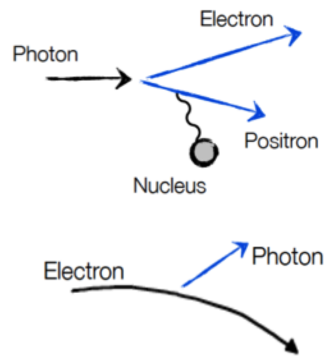
Momentum resolution gets worse for larger momenta

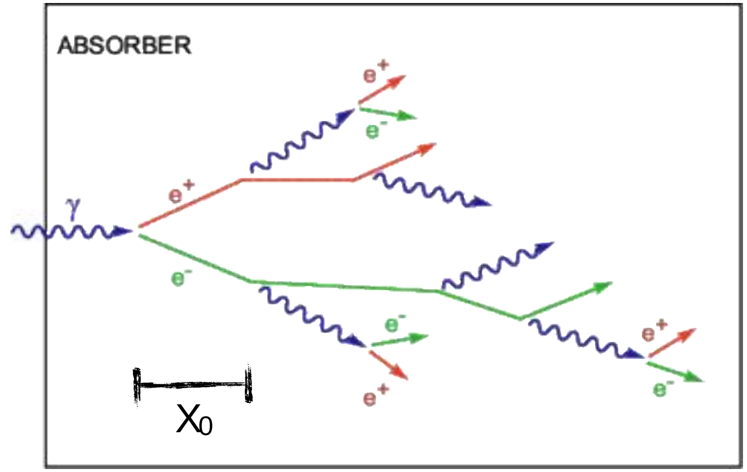
resolution is improved faster by increasing L then B

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:

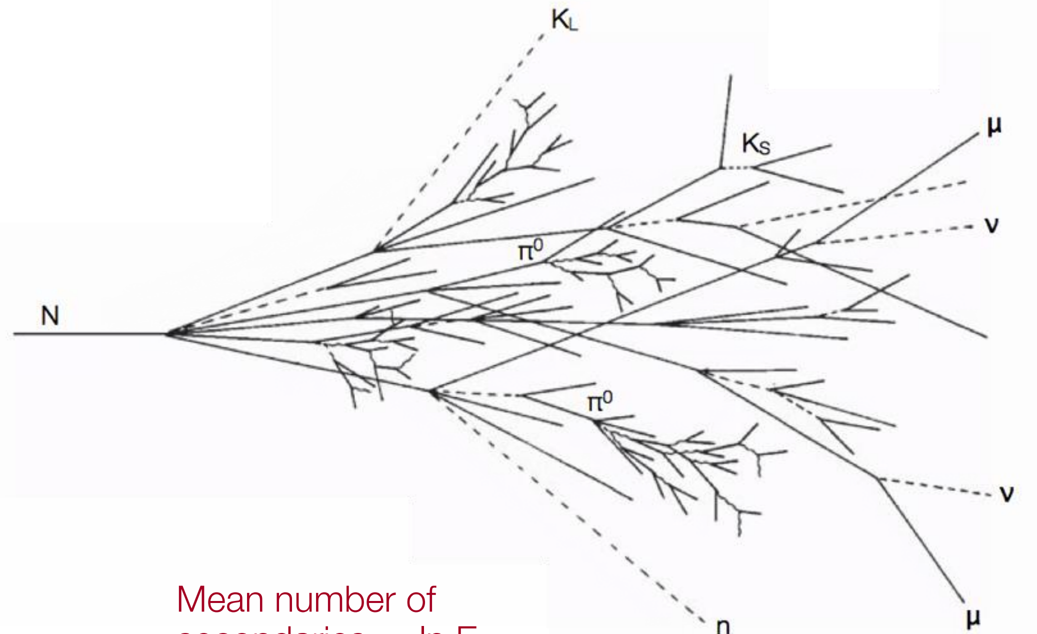
$$\frac{dE}{dx} = 4\alpha N_A \frac{Z^2}{A} r_e^2 \cdot E \ln\frac{183}{Z^{\frac{1}{3}}} = \frac{E}{X_0}$$

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

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



Mean number of secondaries: ~ ln E

Typical transverse momentum: p_t ~ 350 MeV/c

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 ➛ γγ: yields electromagnetic shower
   Fission fragments ➛ β-decay, γ-decay
   Neutron capture ➛ fission
   Spallation ...

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]

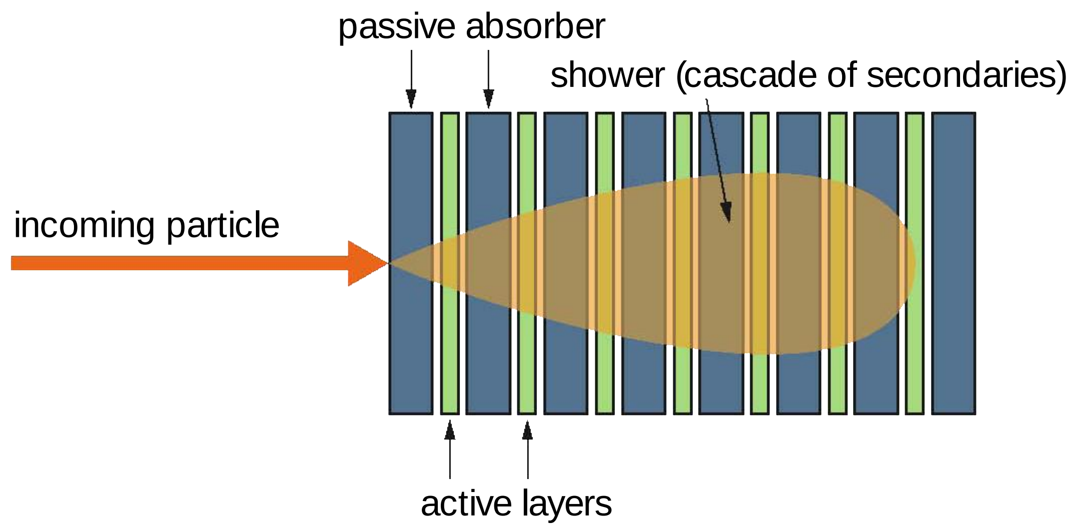
Absorber materials:
[high density]

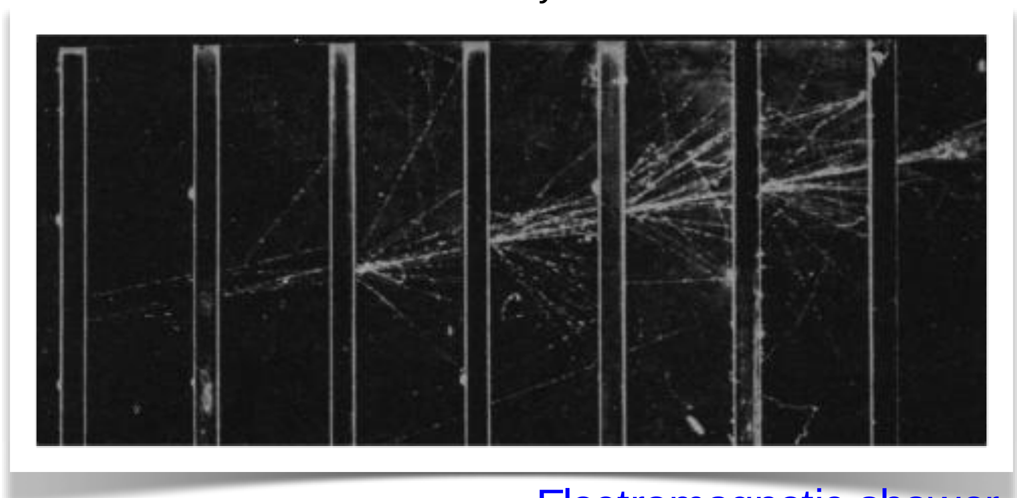
- Iron (Fe)
- Lead (Pb)
- Uranium (U)
  [For compensation ...]

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) ...

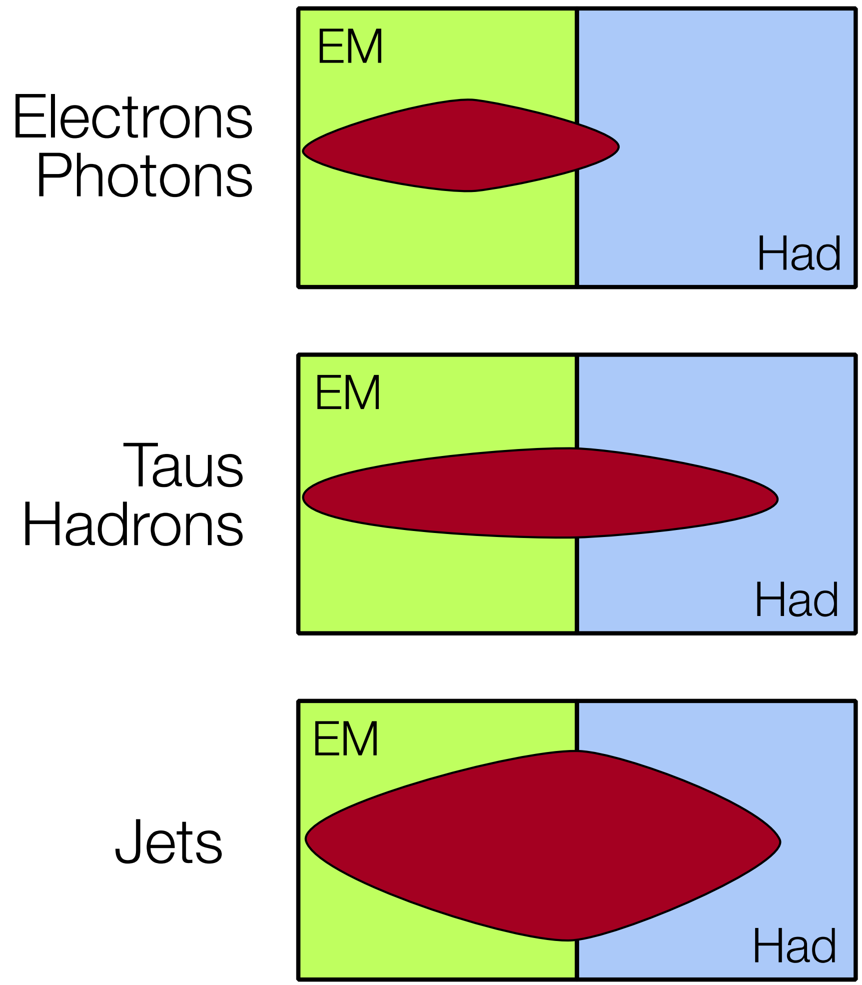
Different setups chosen for
optimal energy resolution ...

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

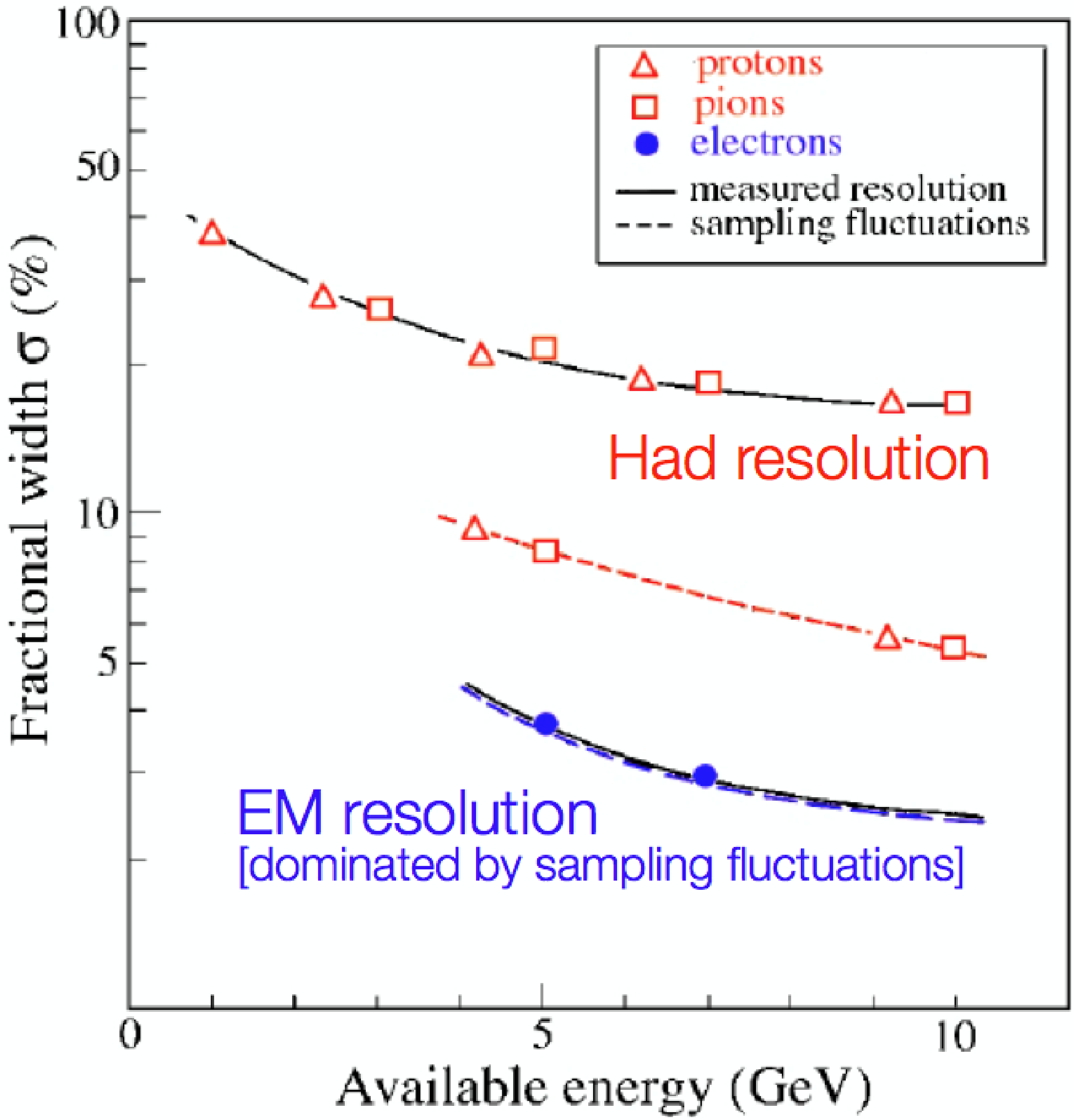
Typical:

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