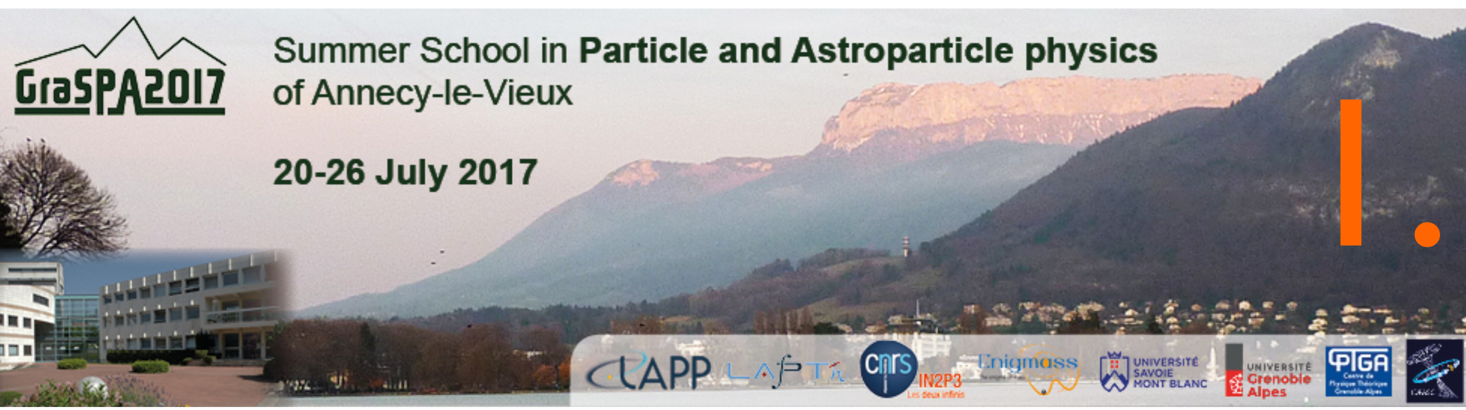
(experimental) LHC physics

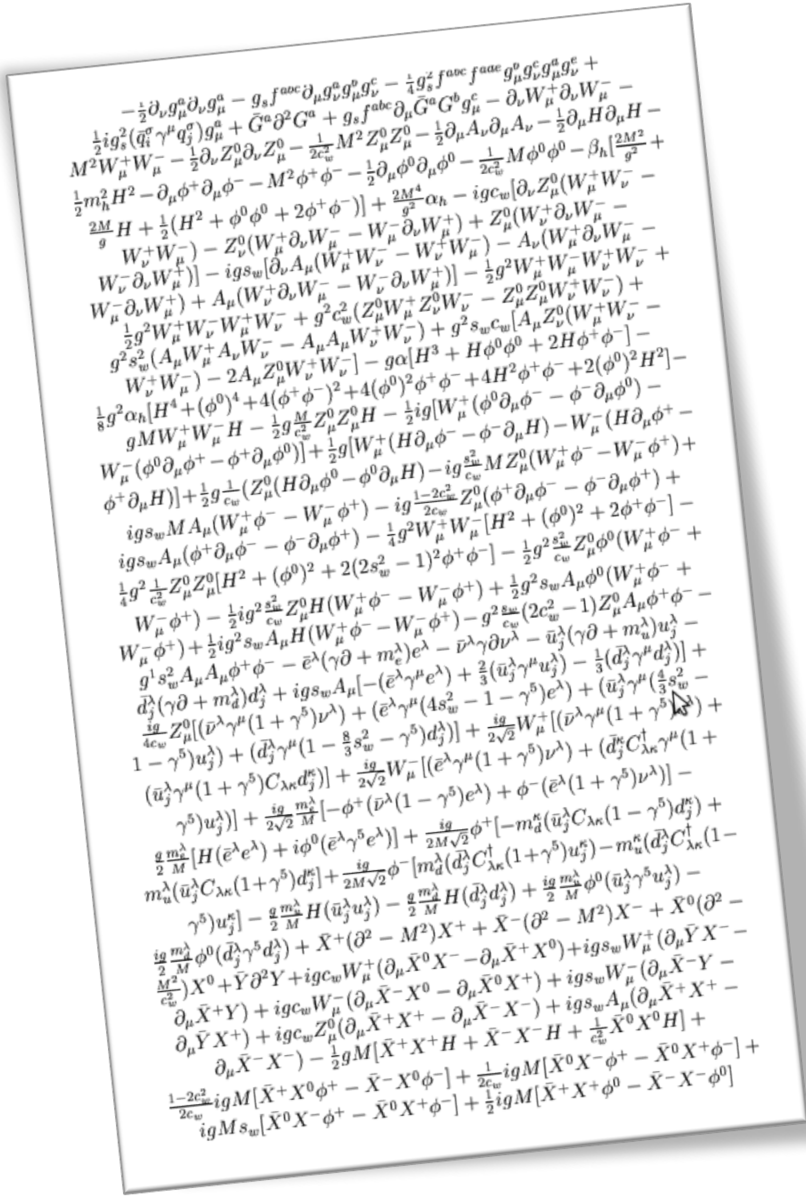


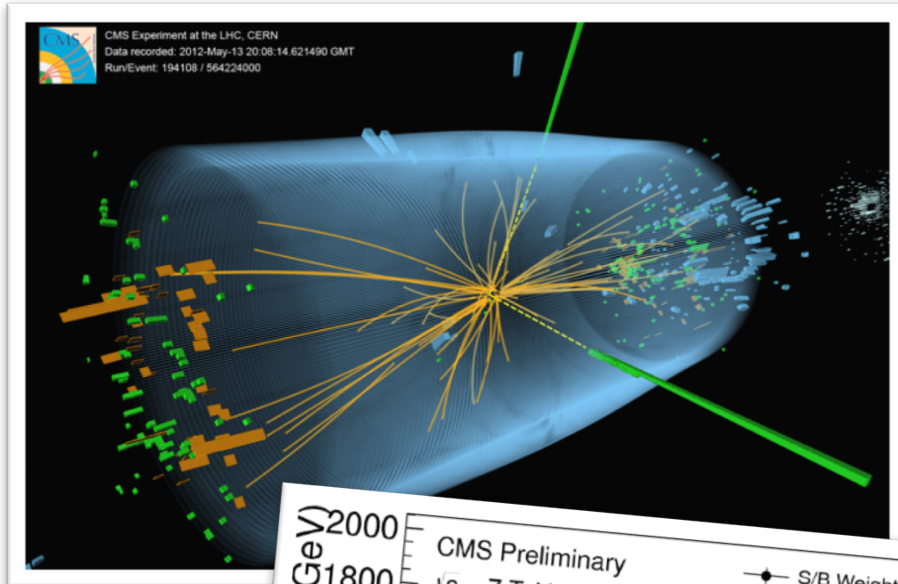
I.

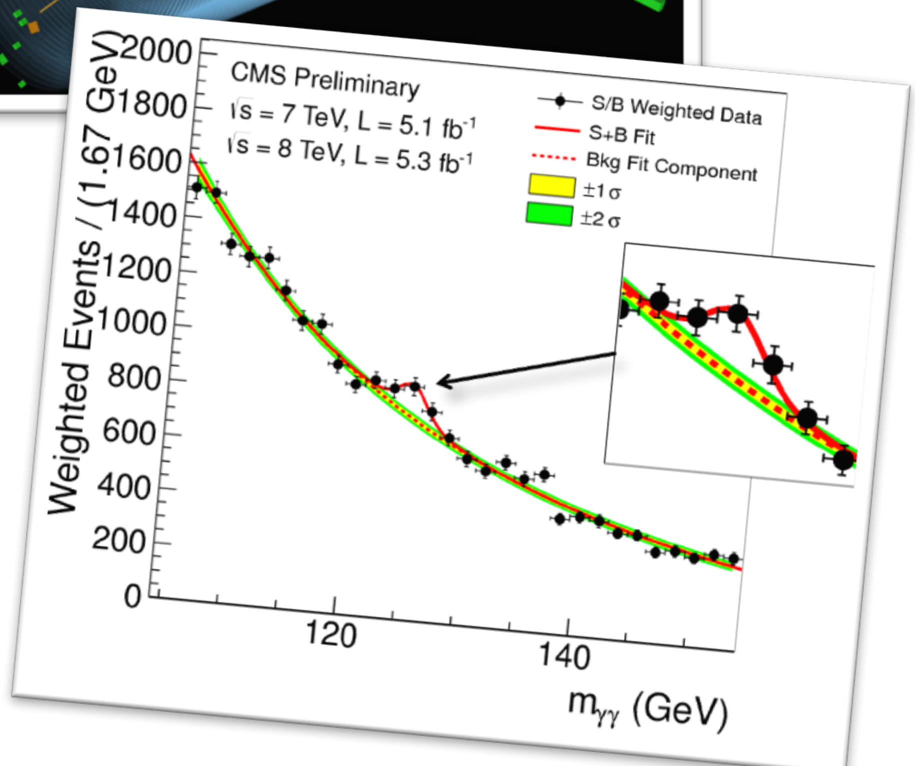
{ how particles are produced and measured }

Marco Delmastro

Experiment = probing theories with data!





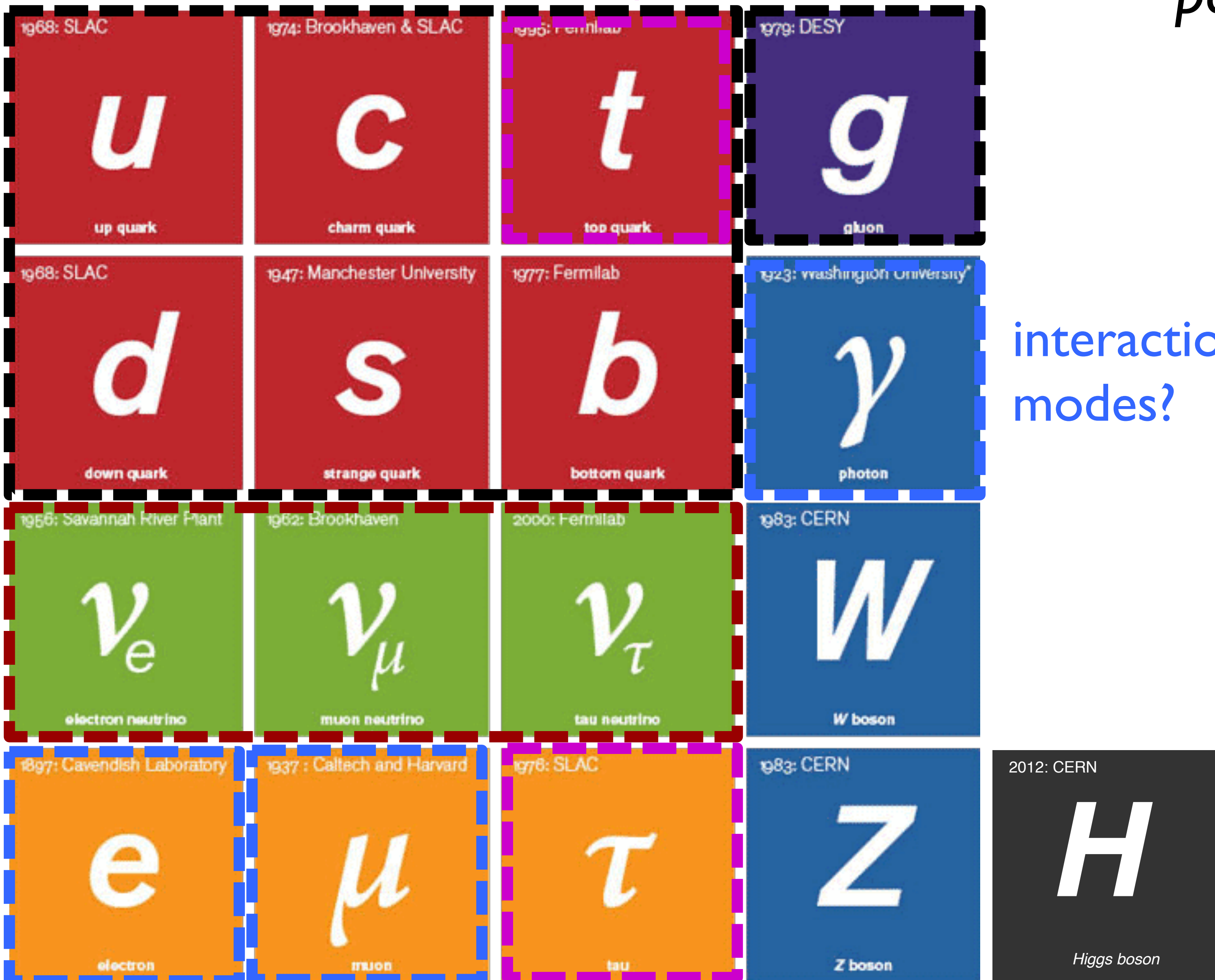


What do we want to measure?

… "stable" *particles!*

decays?

hadron jets



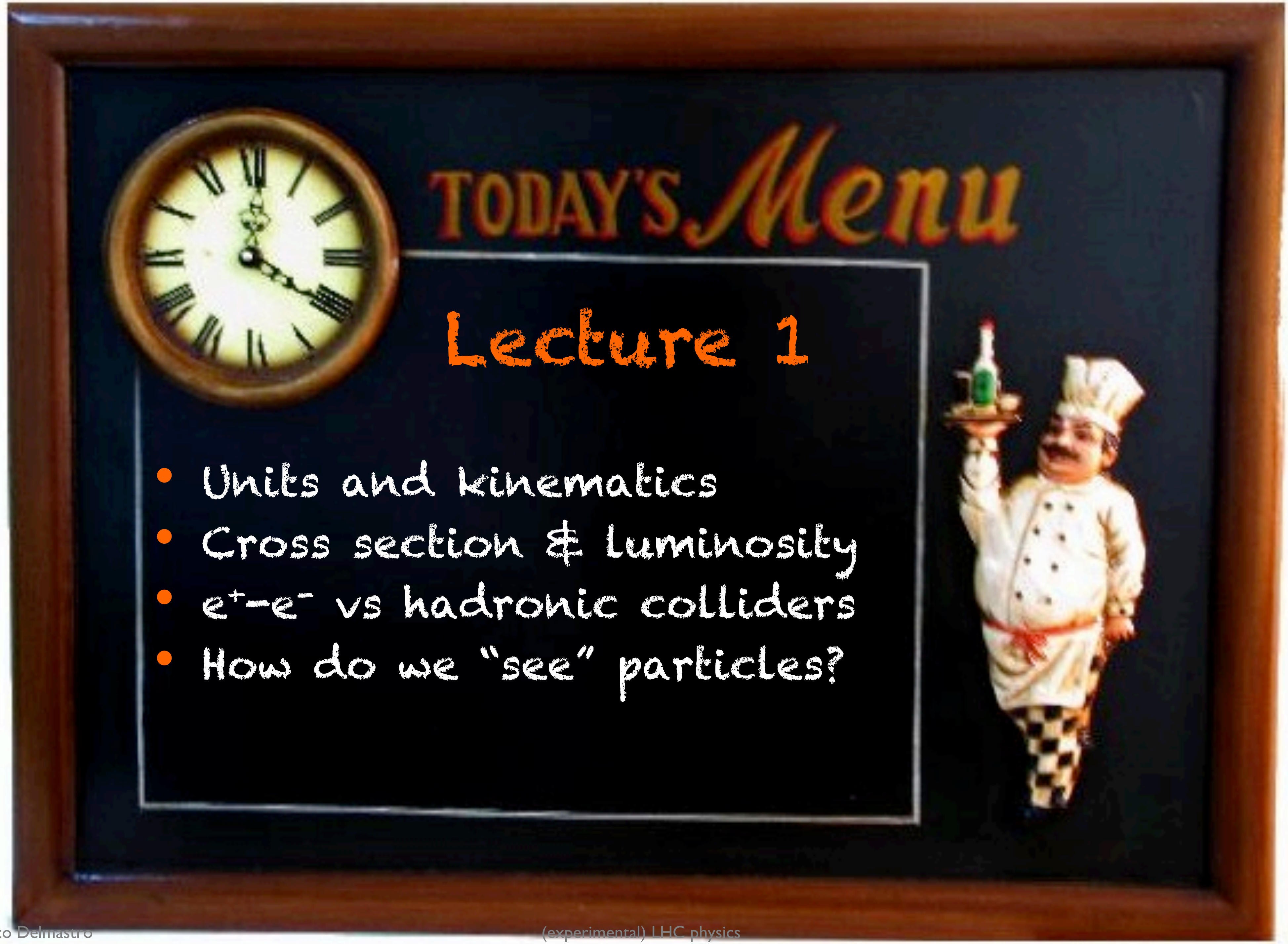
interaction modes?

invisible

in particle detectors at accelerators

interaction modes?

decays?



Lecture 1

- Units and kinematics
- Cross section & luminosity
- e^+-e^- vs hadronic colliders
- How do we "see" particles?

Measuring 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 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:

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

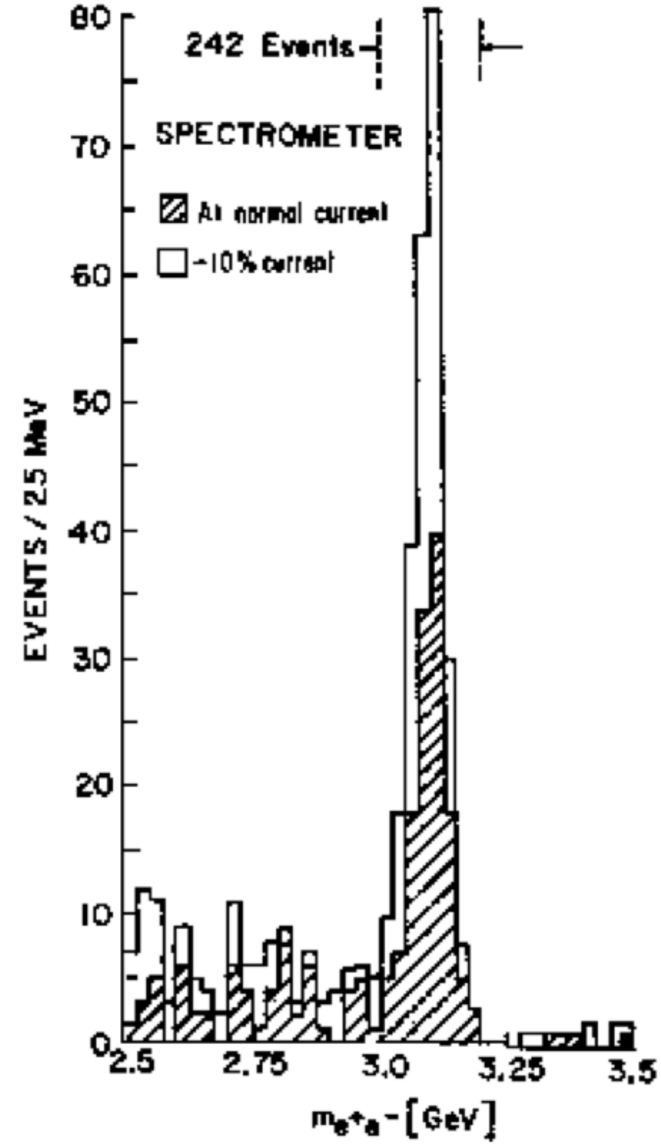
Hint: it can be computed as the "length" of the total four-momentum, that is invariant:

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

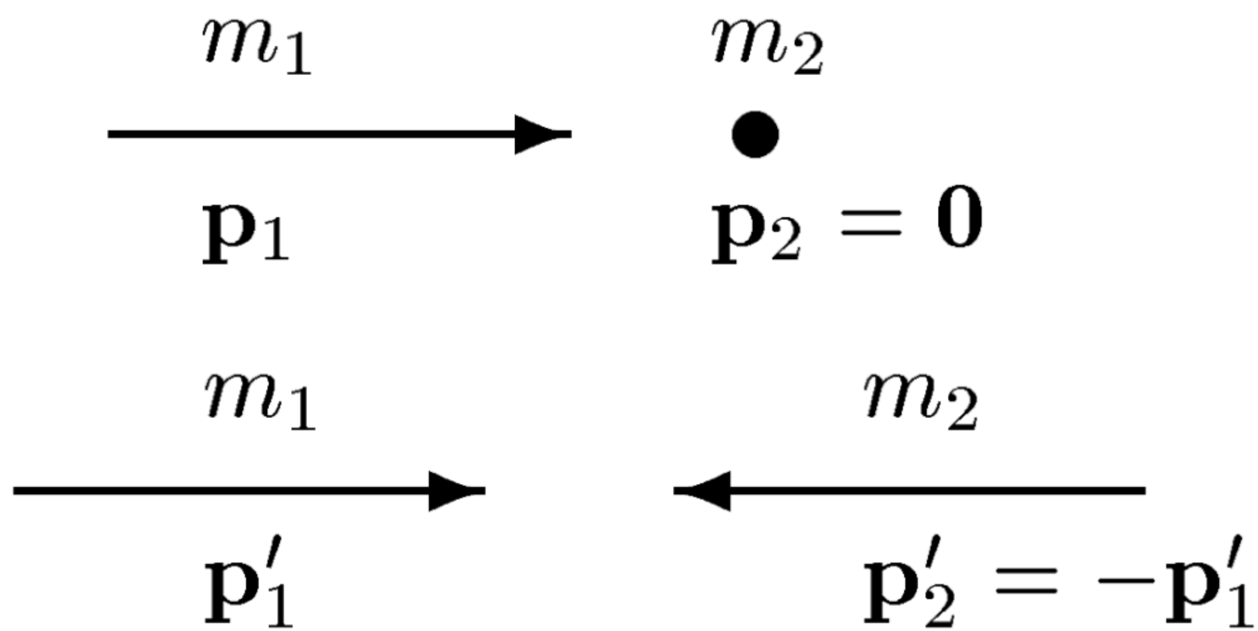
What is the "length" of a the four-momentum of a particle?

Invariant mass

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



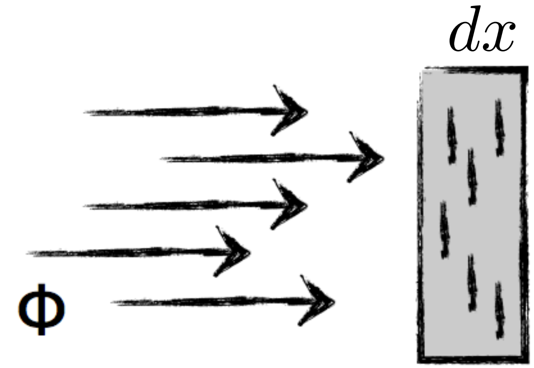
Fixed target vs. collider



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

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

Interaction cross section



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

Reactions per unit of time

$$\frac{dN_{\text{reac}}}{dt} = \Phi\,\overbrace{\sigma\, N_{\text{target}}\, dx}^{\textit{area obscured by target particle}}$$ $[t^{-1}]$

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

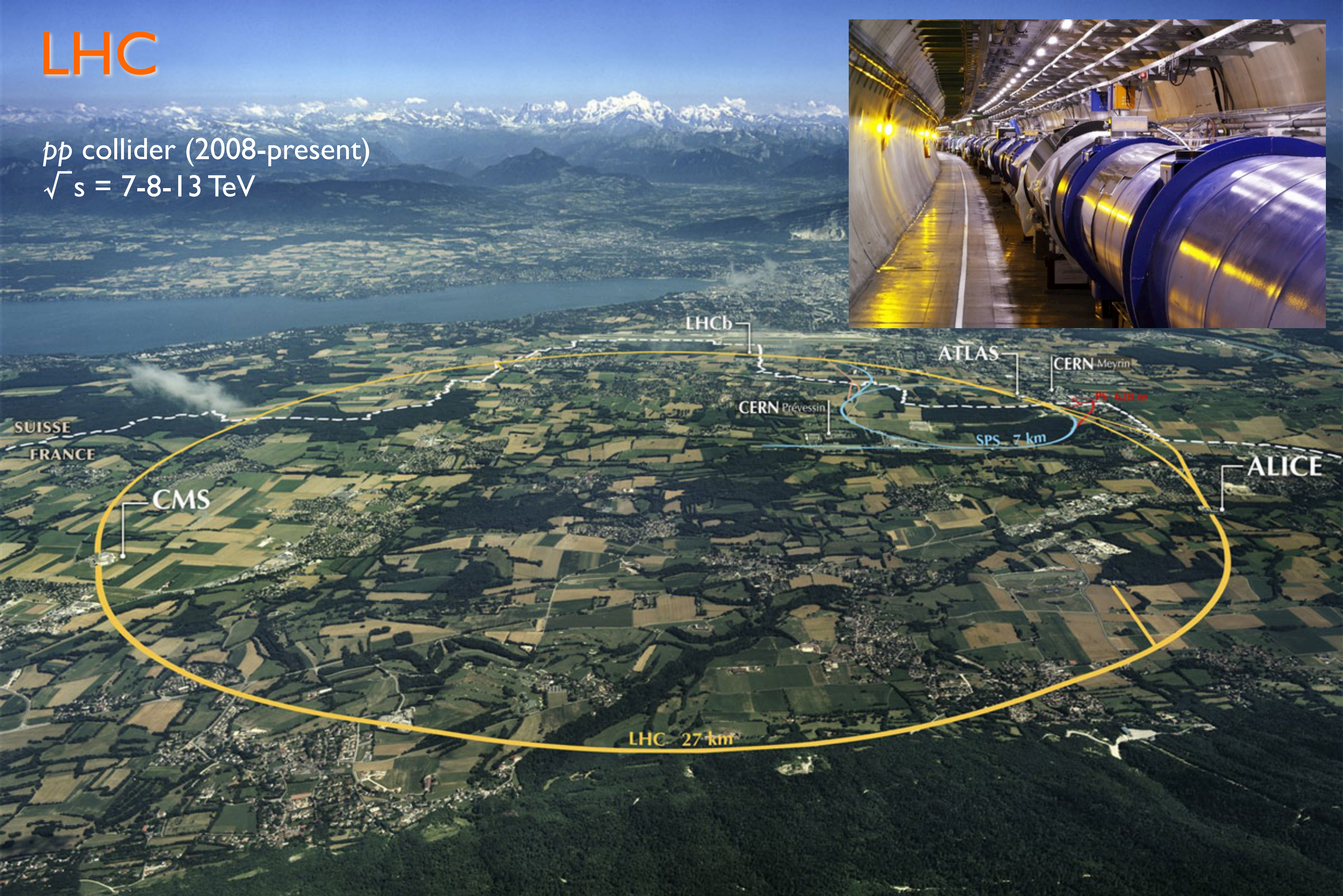
Reaction rate per target particle $$W_{if} = \Phi\sigma$$ $[t^{-1}]$

Cross section per target particle $$\sigma = \frac{W_{if}}{\Phi}$$ $[L^2]$ = reaction rate per unit of flux

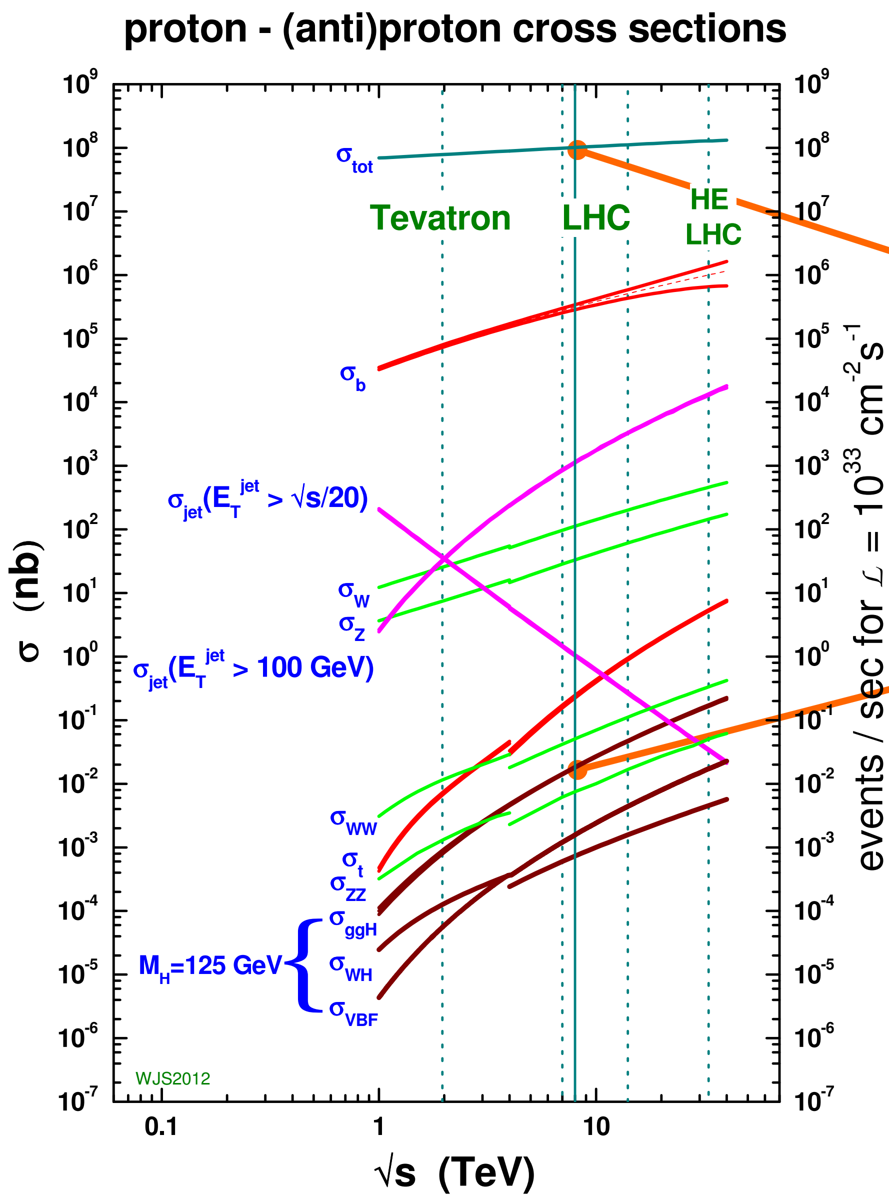
1b = 10^{-28} m^2 (roughly the area of a nucleus with A = 100)

LHC

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



Cross-sections at LHC



10^8 events/s

$\sim 10^{10}$

10^{-2} events/s ~

10 events/min

[m_H ~ 125 GeV]

0.2% H → γγ

1.5% H → ZZ

Why accelerating and colliding particles?

Aren't natural radioactive processes enough? What about cosmic rays?

High energy

$$E = mc^2$$

- Probe smaller scale
- Produce heavier particles

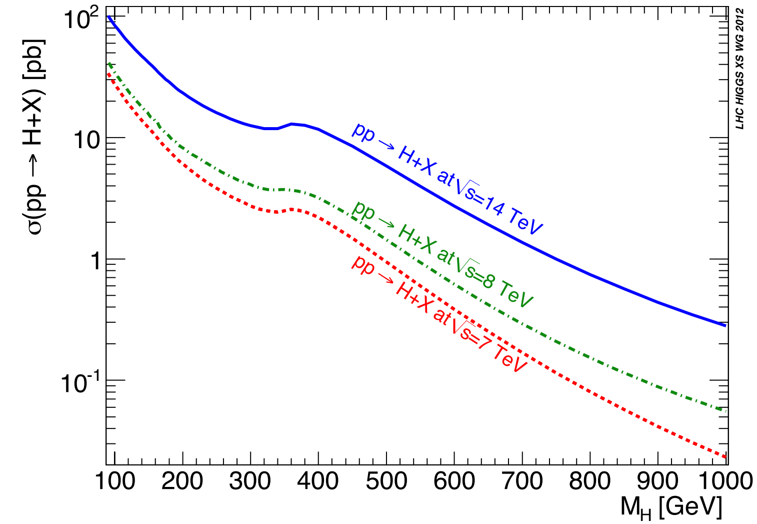
Large number of collisions

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

- Detect rare processes
- Precision measurements

Luminosity

Number of events
in unit of time



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

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

? 10^{34} cm^{-2} s^{-1} σ(pp → H+X) ~ 20 pb

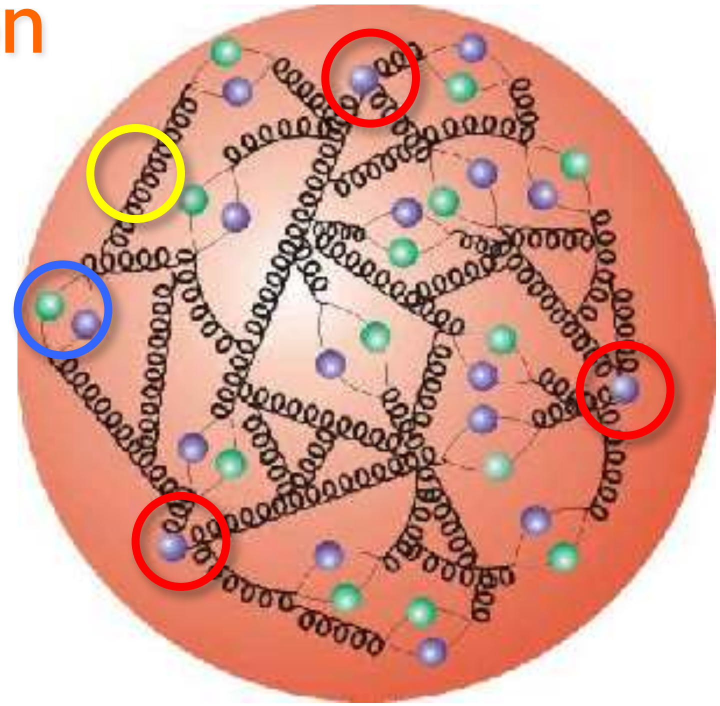
In a collider ring…

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

Current

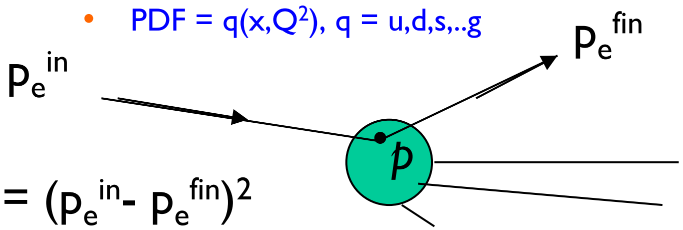
Beam sizes (RMS)

About the inner life of a proton



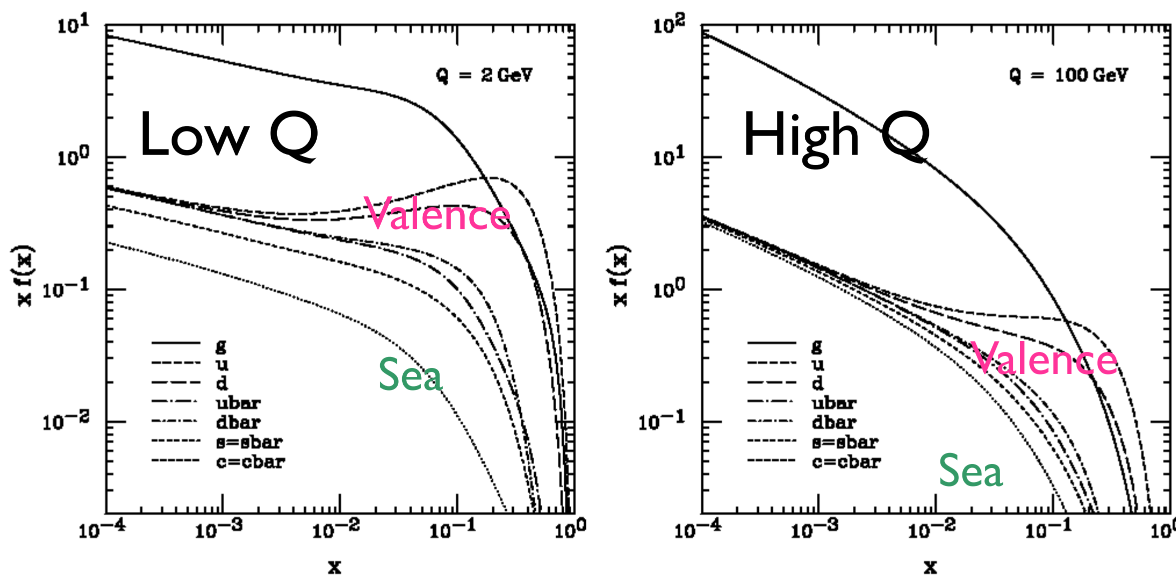
- ***p*rotons have substructures**
  - ✓ partons = quarks & gluons
  - ✓ 3 valence (colored) quarks bound by gluons
  - ✓ Gluons (colored) have self-interactions
  - ✓ Virtual quark pairs can pop-up (sea-quark)
  - ✓ *p* momentum shared among constituents
    - described by *p* structure functions

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

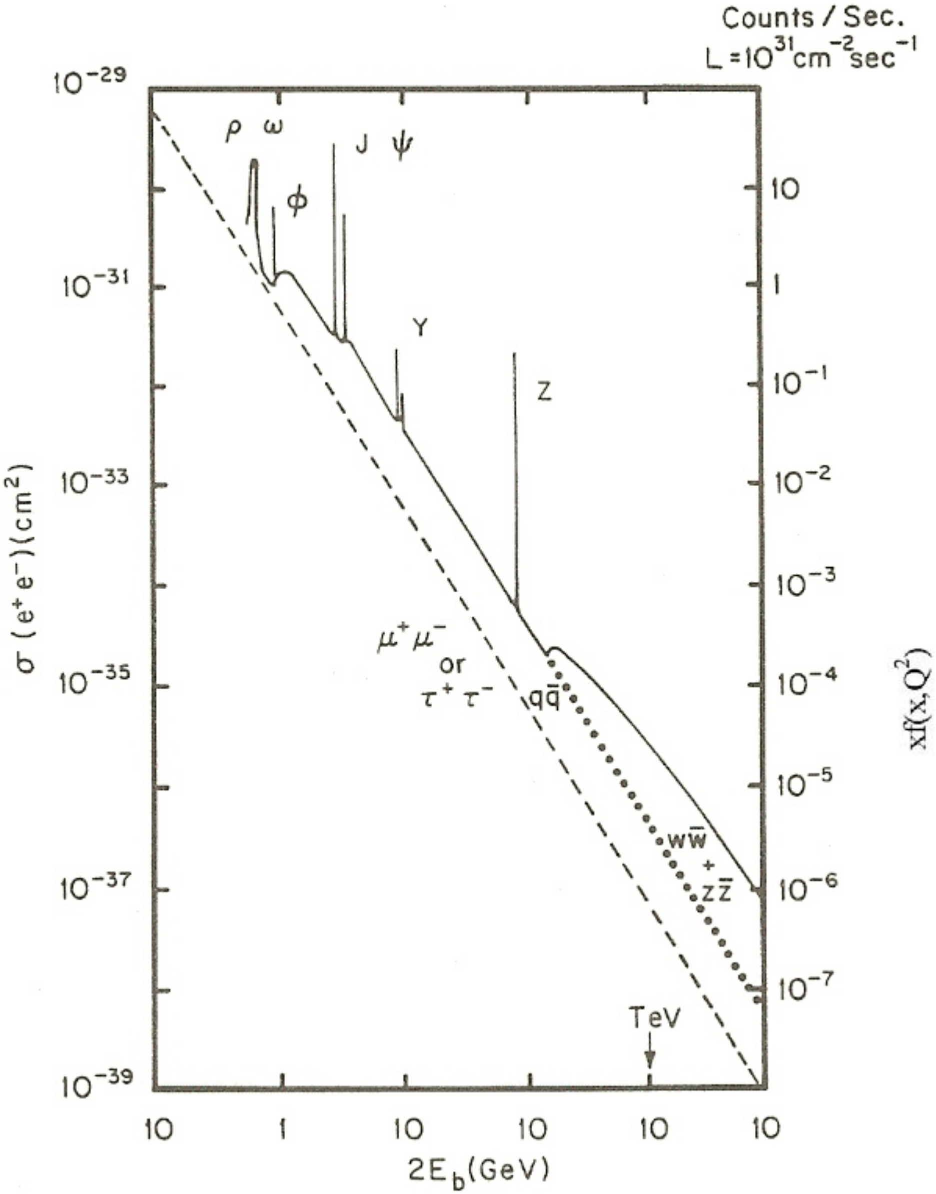


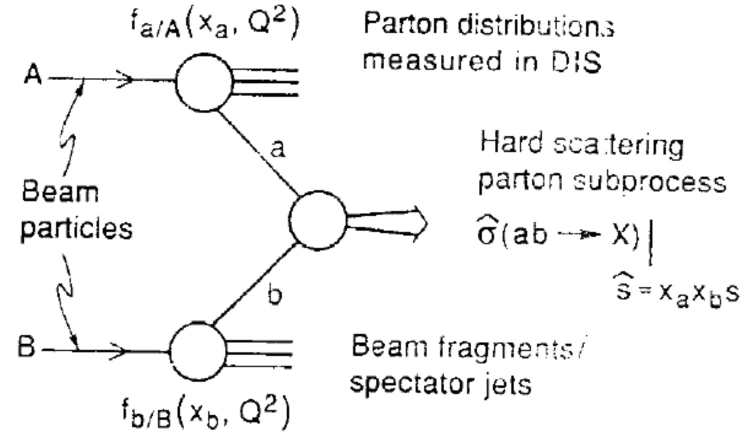
$Q^2 = (P_e^{in} - P_e^{fin})^2$

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



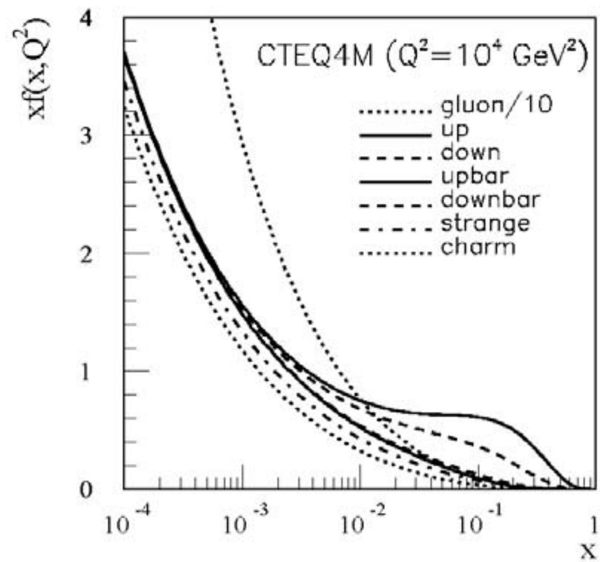
e^+-e^- vs. hadron collider





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

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



to produce a particle with mass M = 100 GeV

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

$\sqrt{s}$ = 14 TeV → x = 0.007

$\sqrt{s}$ = 5 TeV → x = 0.36

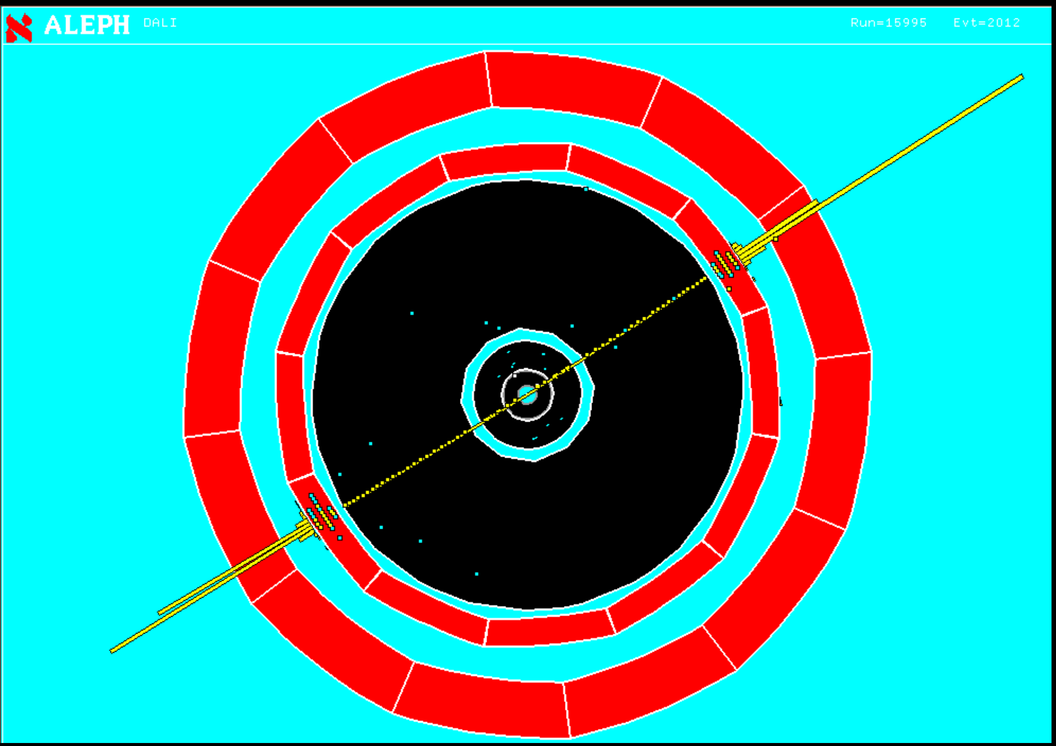
e^+-e^- vs. hadron collider

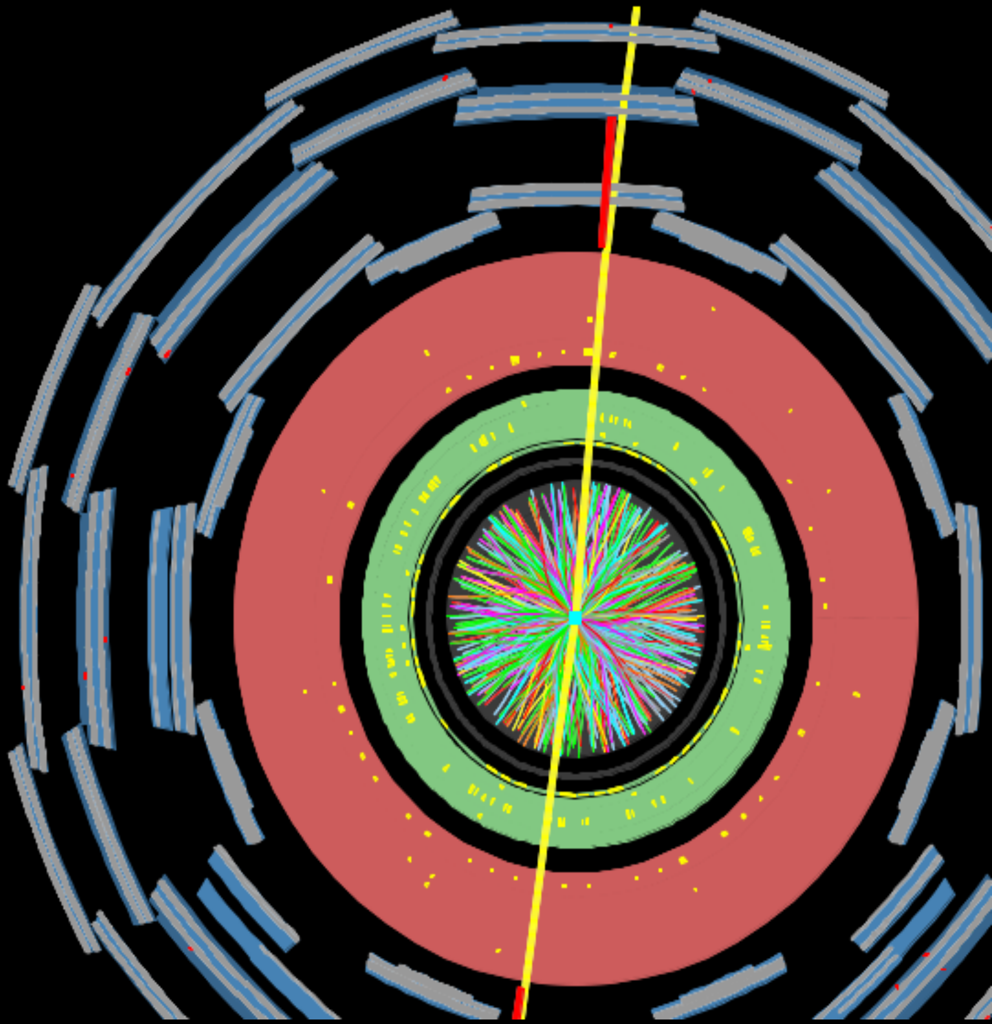
- **e^+-e^- collider**
  - ✓ no internal structure
  - ✓ $E_{collision} = 2\ E_{beam}$
  - ✓ Pros
    - Probe precise mass
      - Precision measurements
    - Clean!
  - ✓ Cons
    - Only one $E_{collision}$ at a time
    - limited by synchrotron radiation

- **Hadronic collider**
  - ✓ quarks + gluons (PDF)
  - ✓ $E_{collision} < 2\ E_{beam}$
  - ✓ Pros
    - Scan different masses
      - Discovery machine
  - ✓ Cons
    - $E_{collision}$ not known
    - Dirty! several collisions on top of interesting one (pileup)

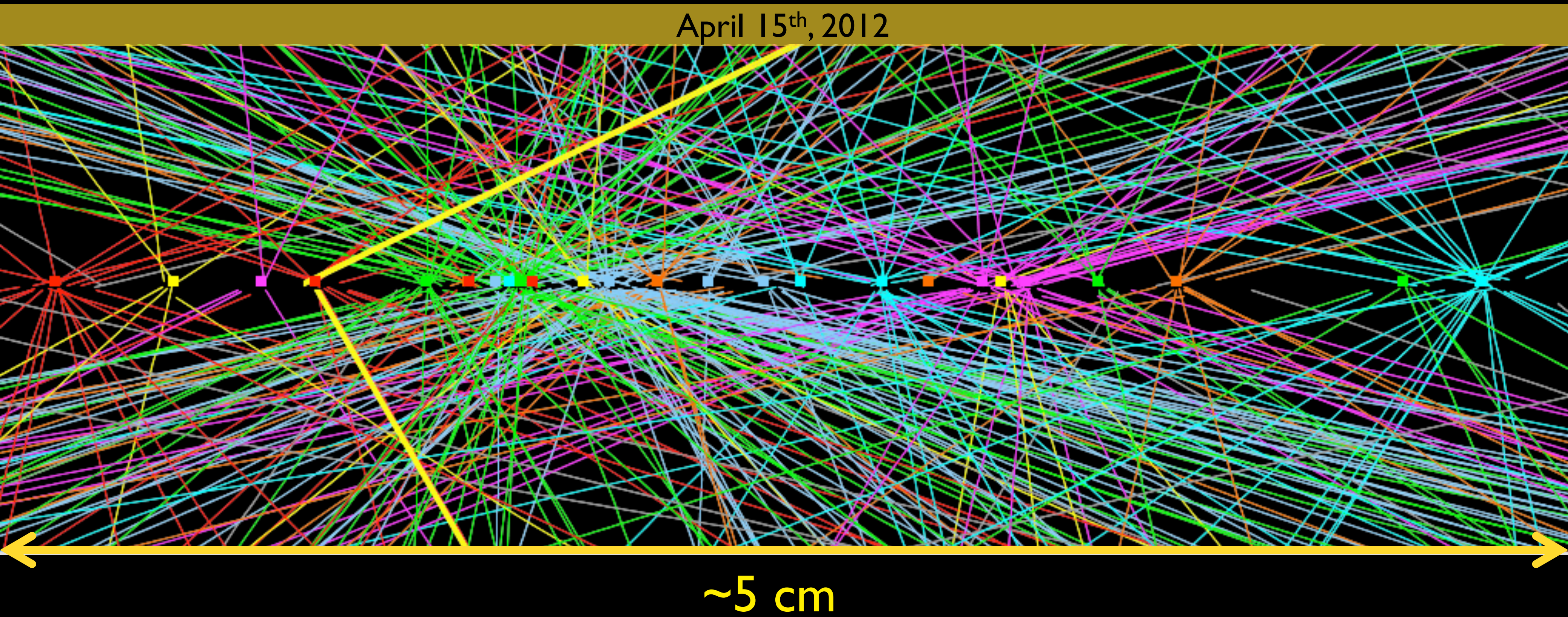
ALEPH @ LEP

ATLAS @ LHC

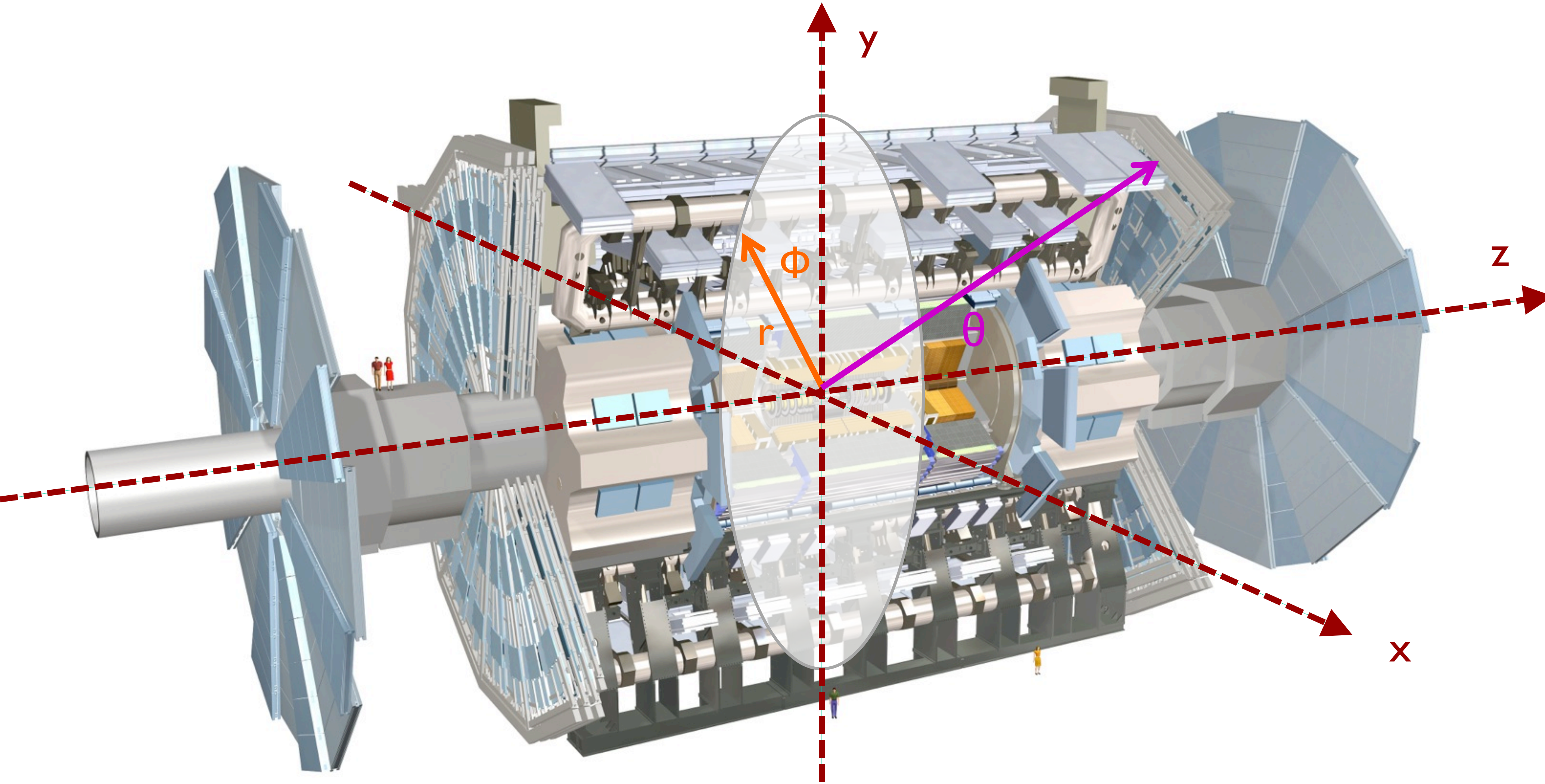




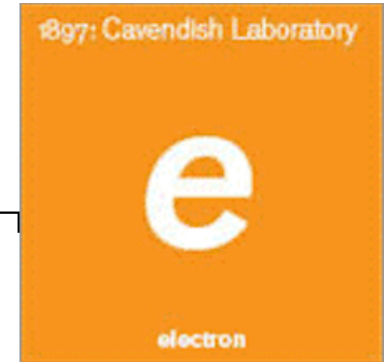
Z→μμ event with 25 reconstructed vertices



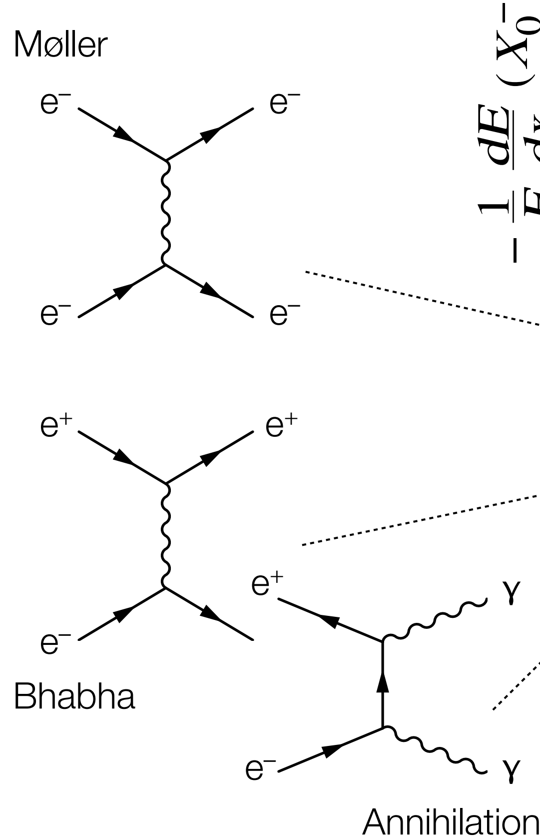
Collider experiment coordinates

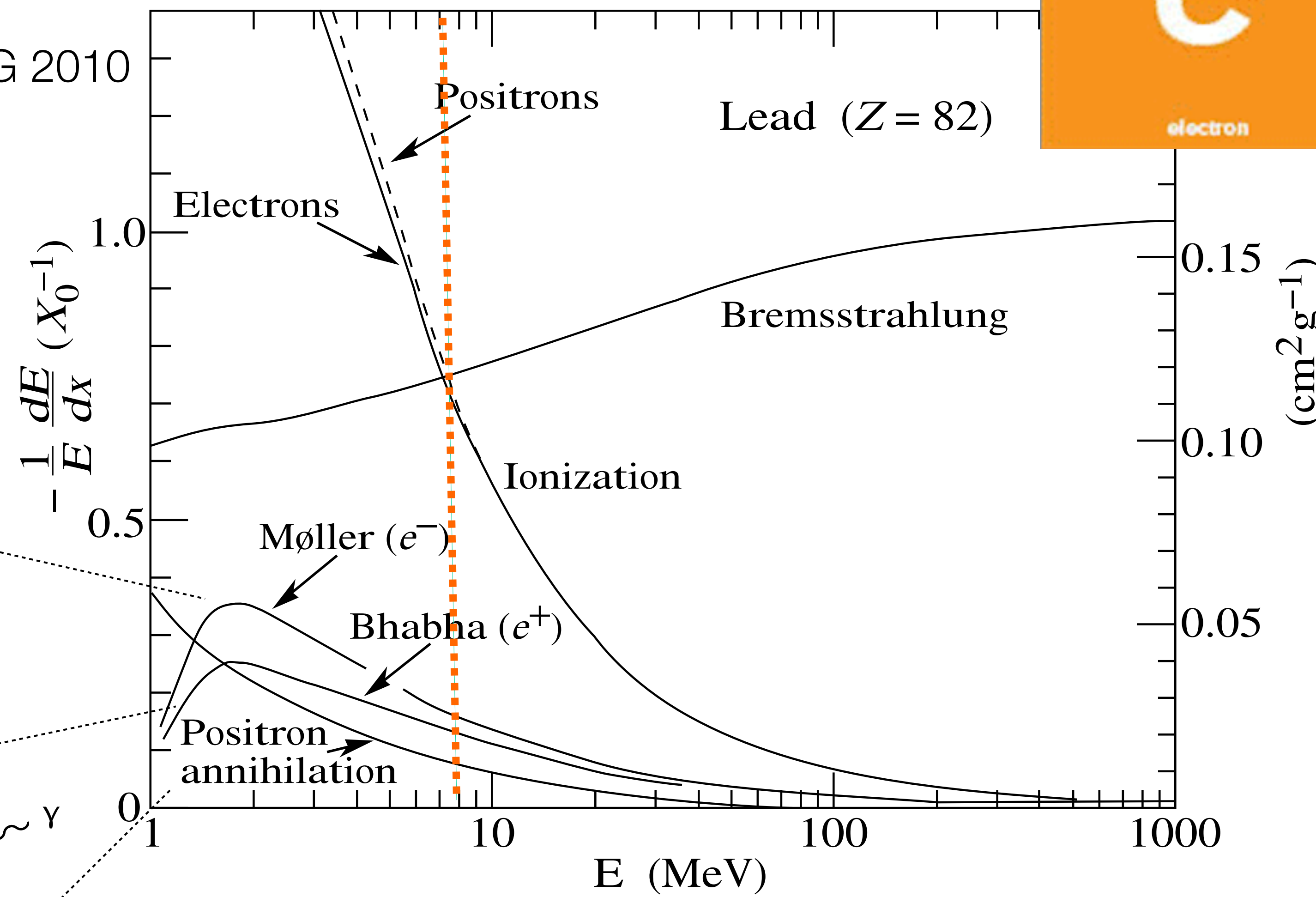


Electron energy loss



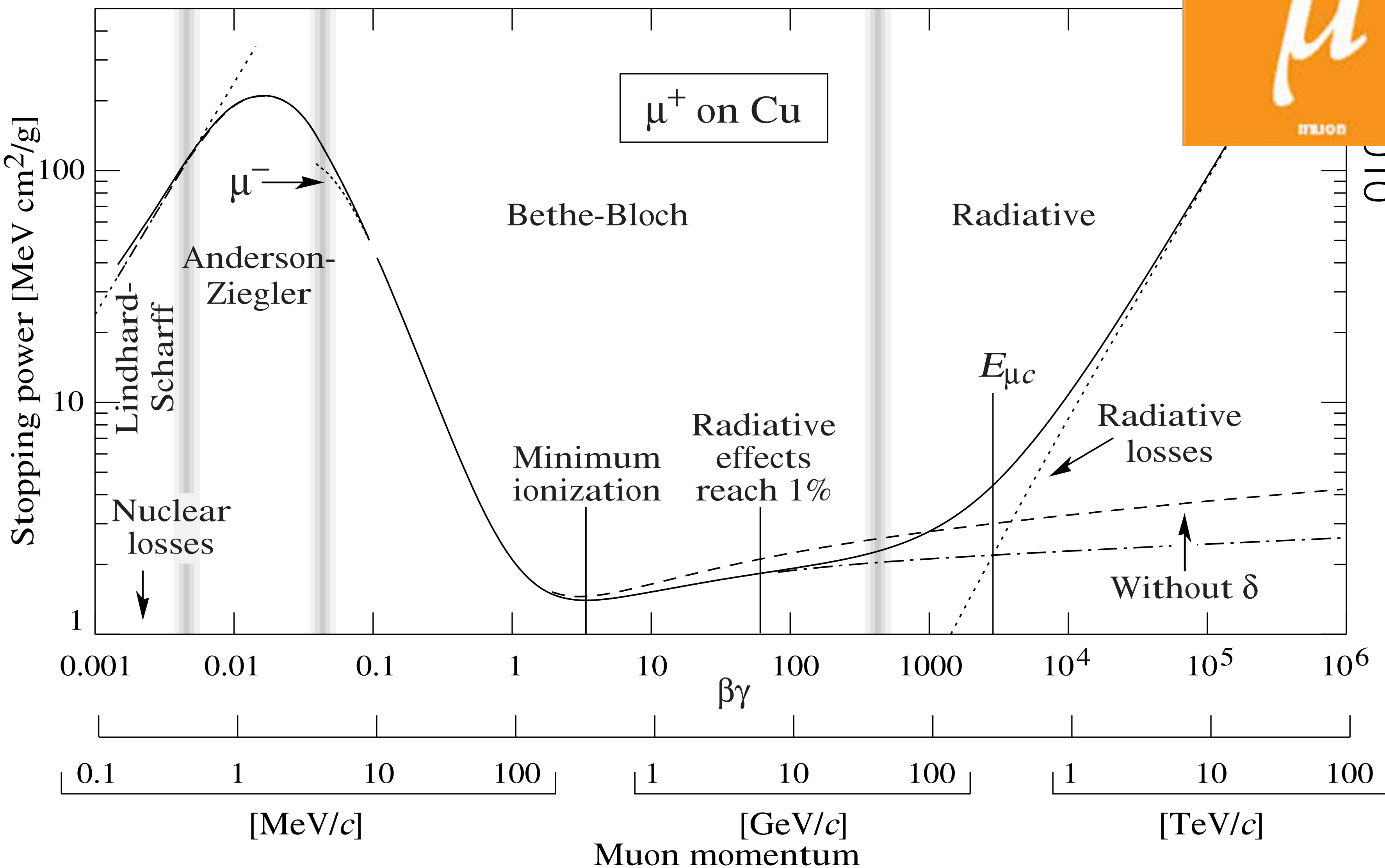
from
PDG 2010



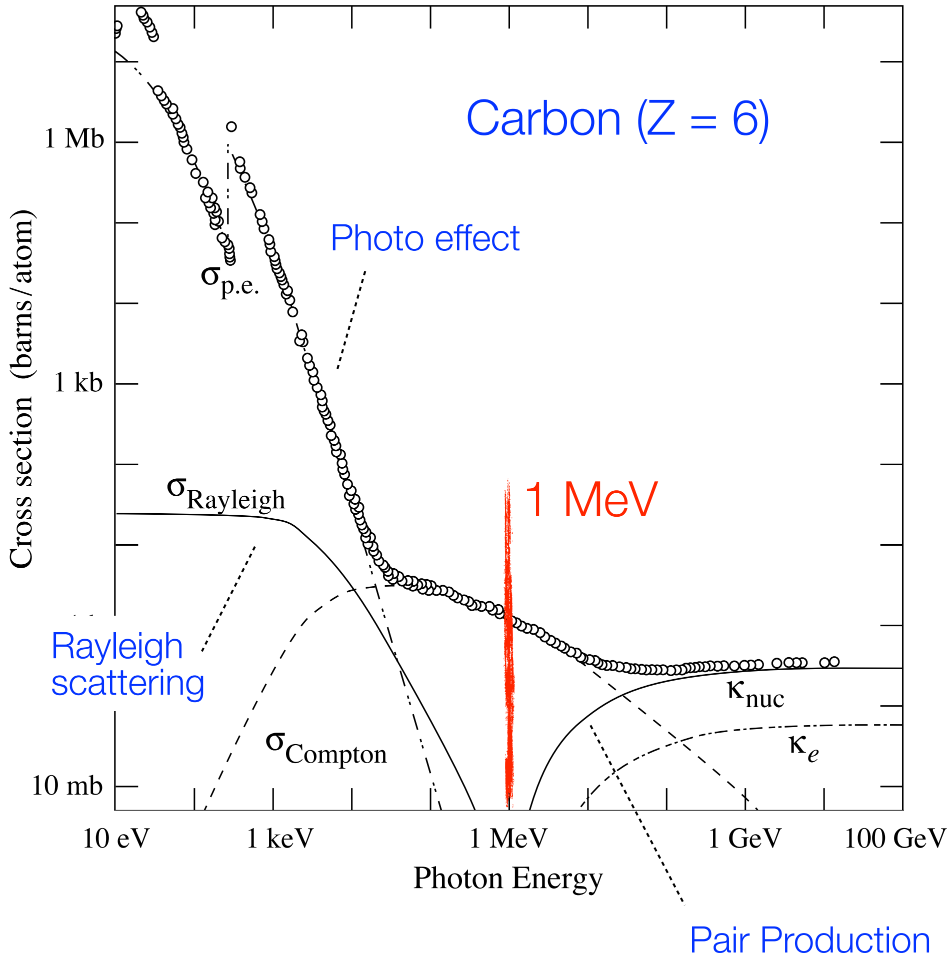


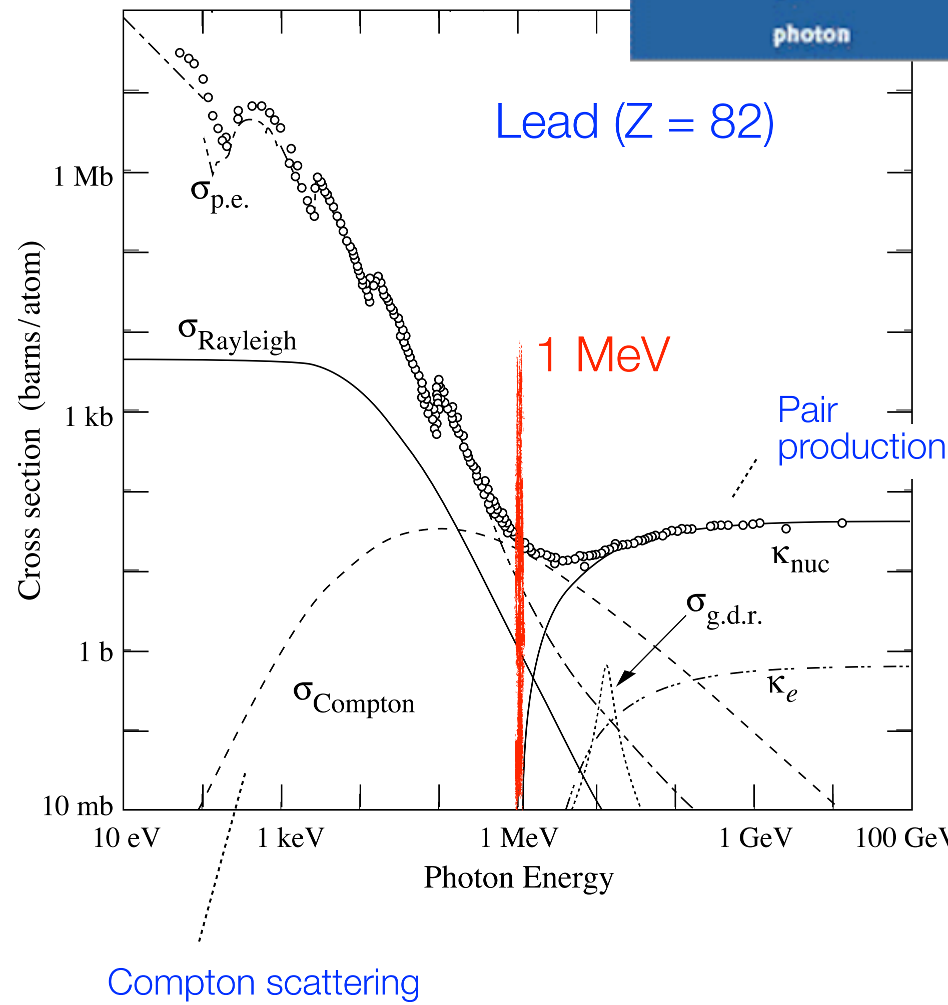
Fractional energy loss per radiation length in lead as a function of electron or positron energy

Muon energy loss



Interaction of photons with matter





Interaction mode recap

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

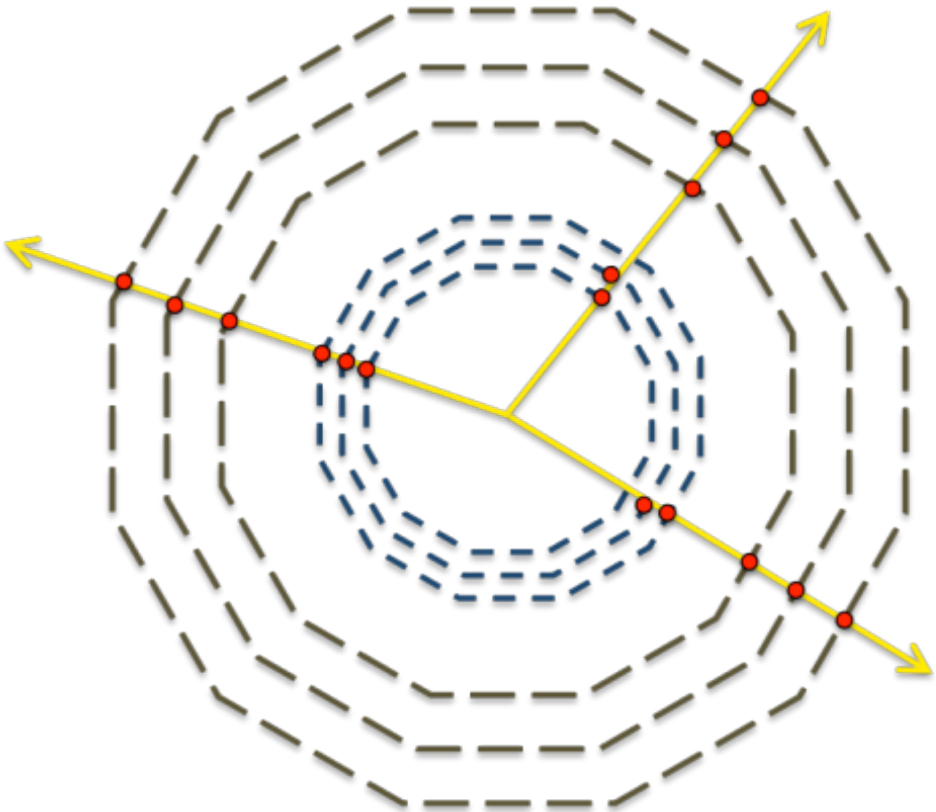
- electrically charged
- ionization (dE/dx)
- can emit photons
  - ✓ electromagnetic shower induced by emitted photon…
    - but it's rare…

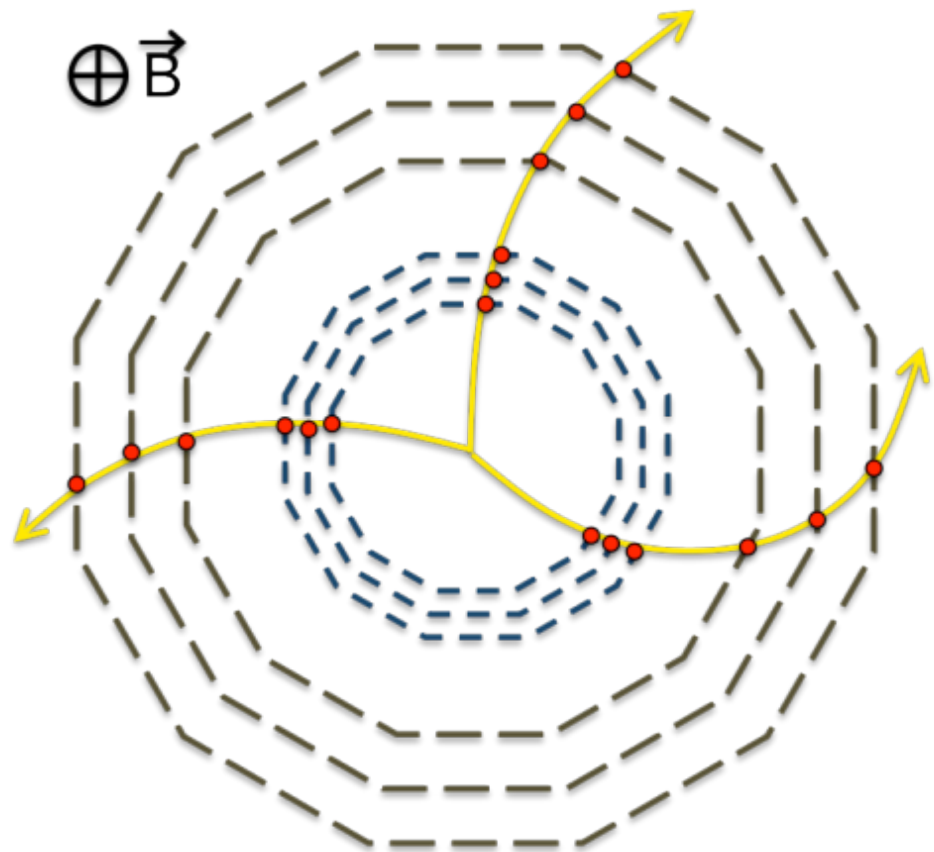
- electrically neutral
- pair production
  - ✓ E > 1 MeV
- *electromagnetic shower…*

- 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



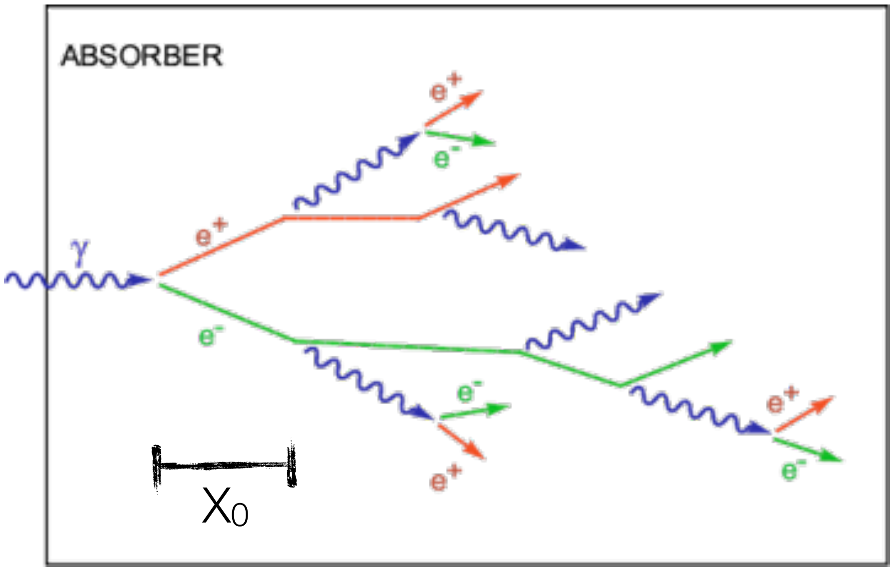


$$p[\mathrm{GeV}] = 0.3B[\mathrm{T}]\rho[\mathrm{m}]$$

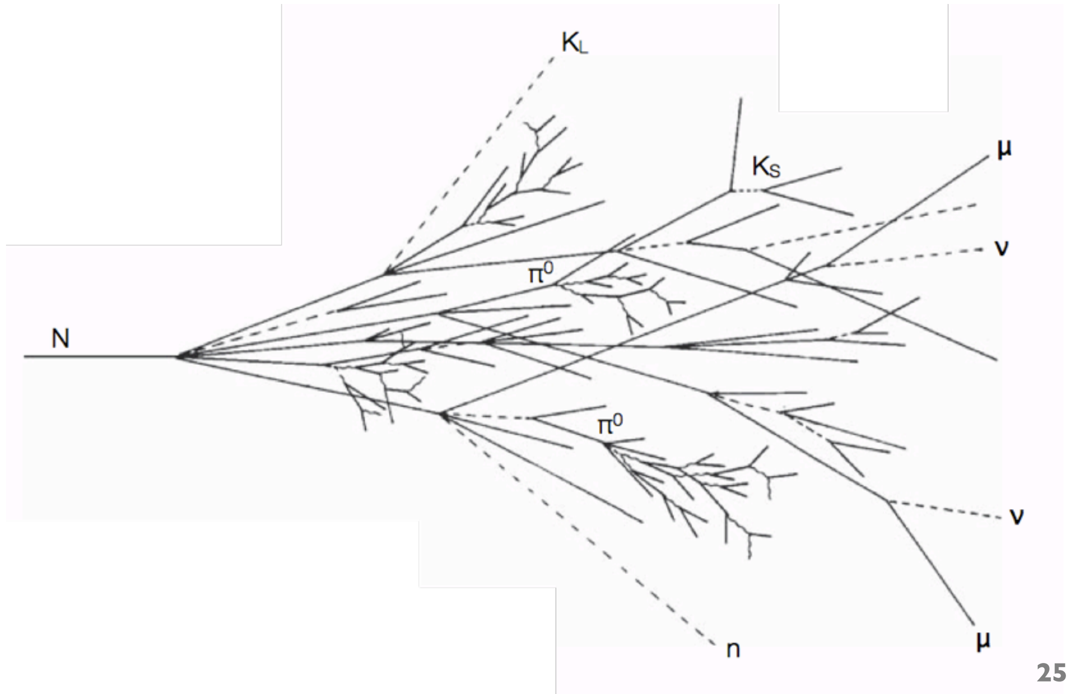
Calorimeters for showering particles

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

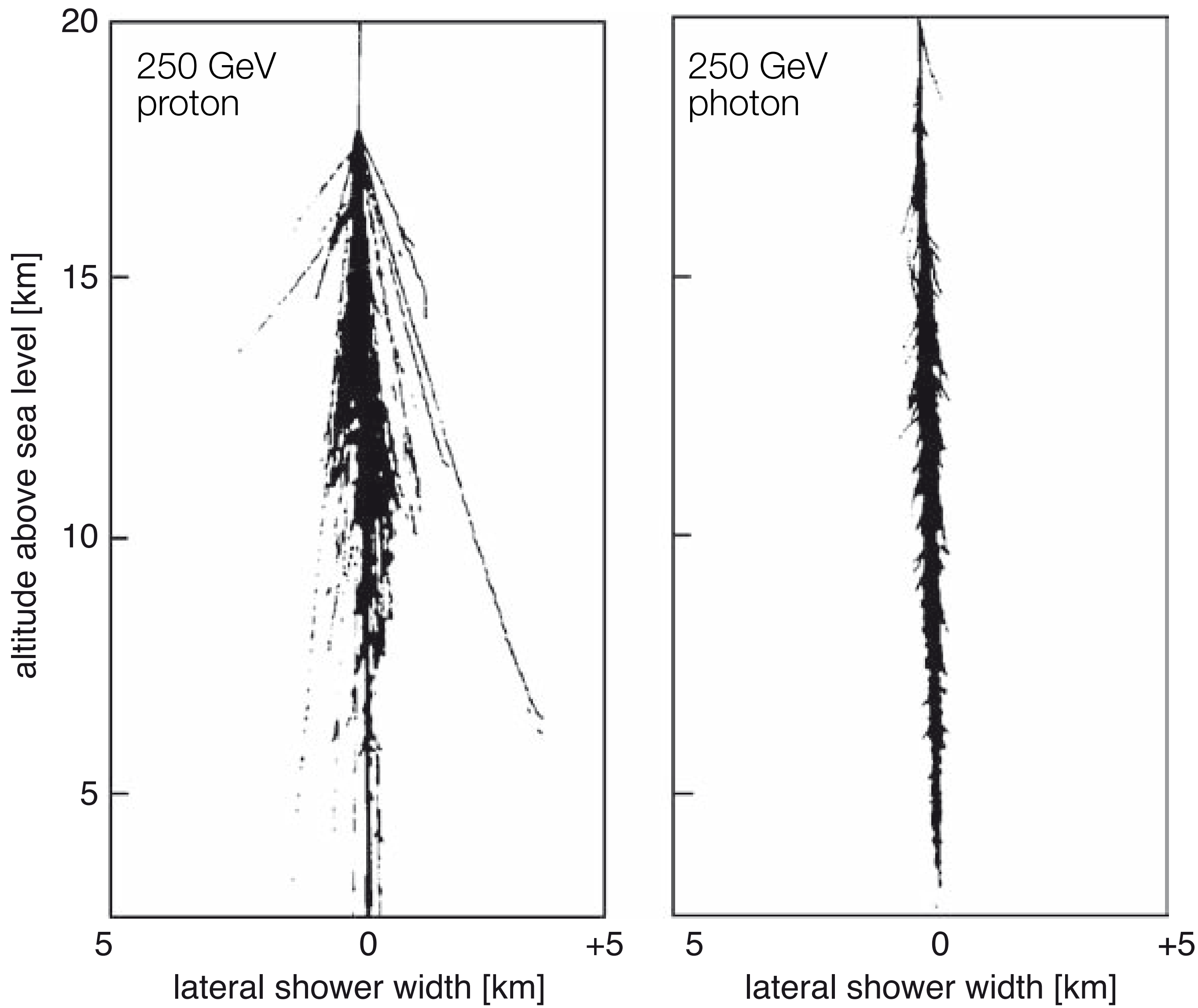
$$\frac{dE}{dx}(E_c)\bigg|_{\text{Brems}} = \frac{dE}{dx}(E_c)\bigg|_{\text{Ion}}$$



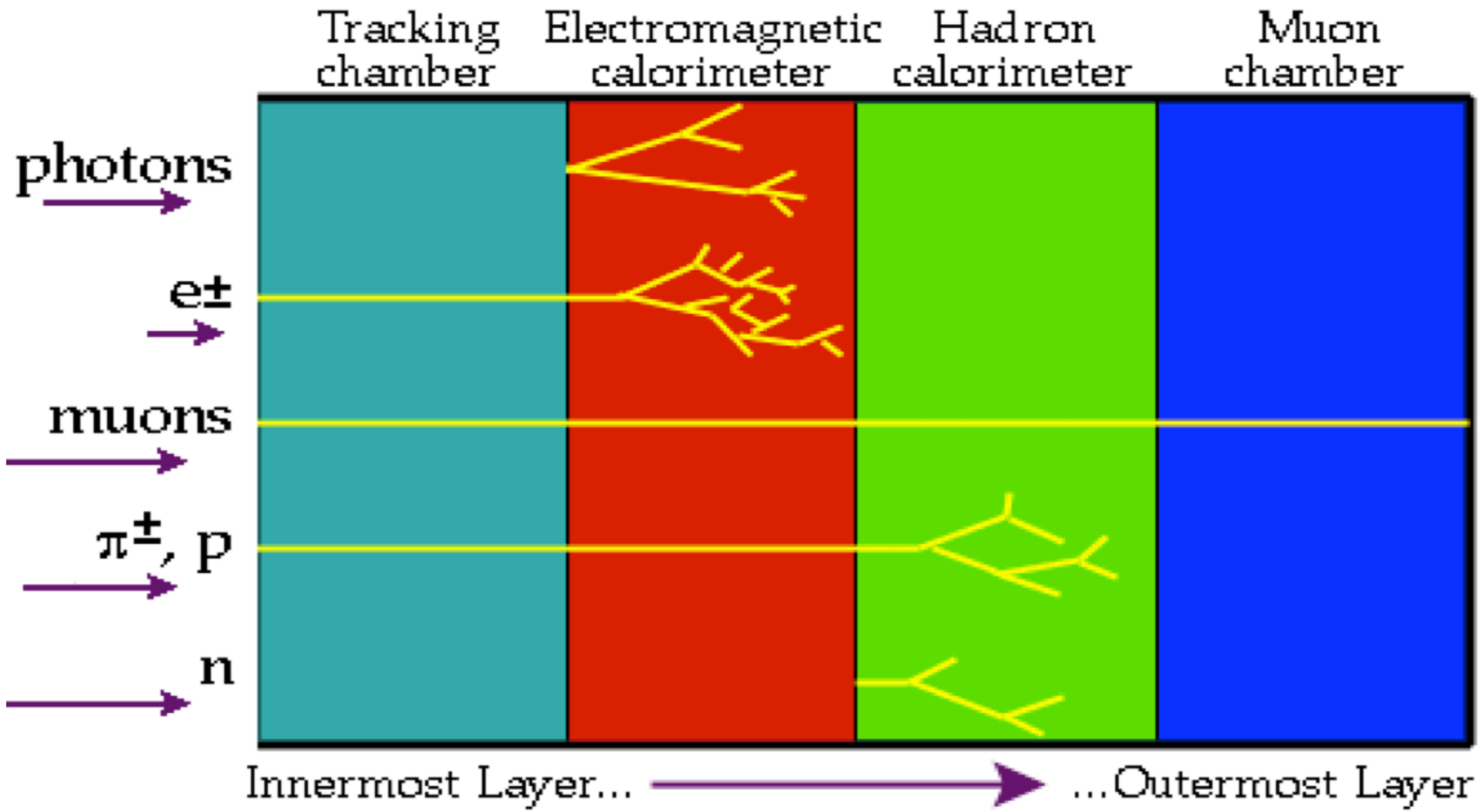
- Hadronic showers
  - ✓ Inelastic scattering w/ nucleai
    - Further inelastic scattering until below pion production threshold
  - ✓ Sequential decays
    - $\pi^0 \rightarrow \gamma\gamma$
    - Fission fragment: β-decay, γ-decay
    - Neutron capture, spallation, …



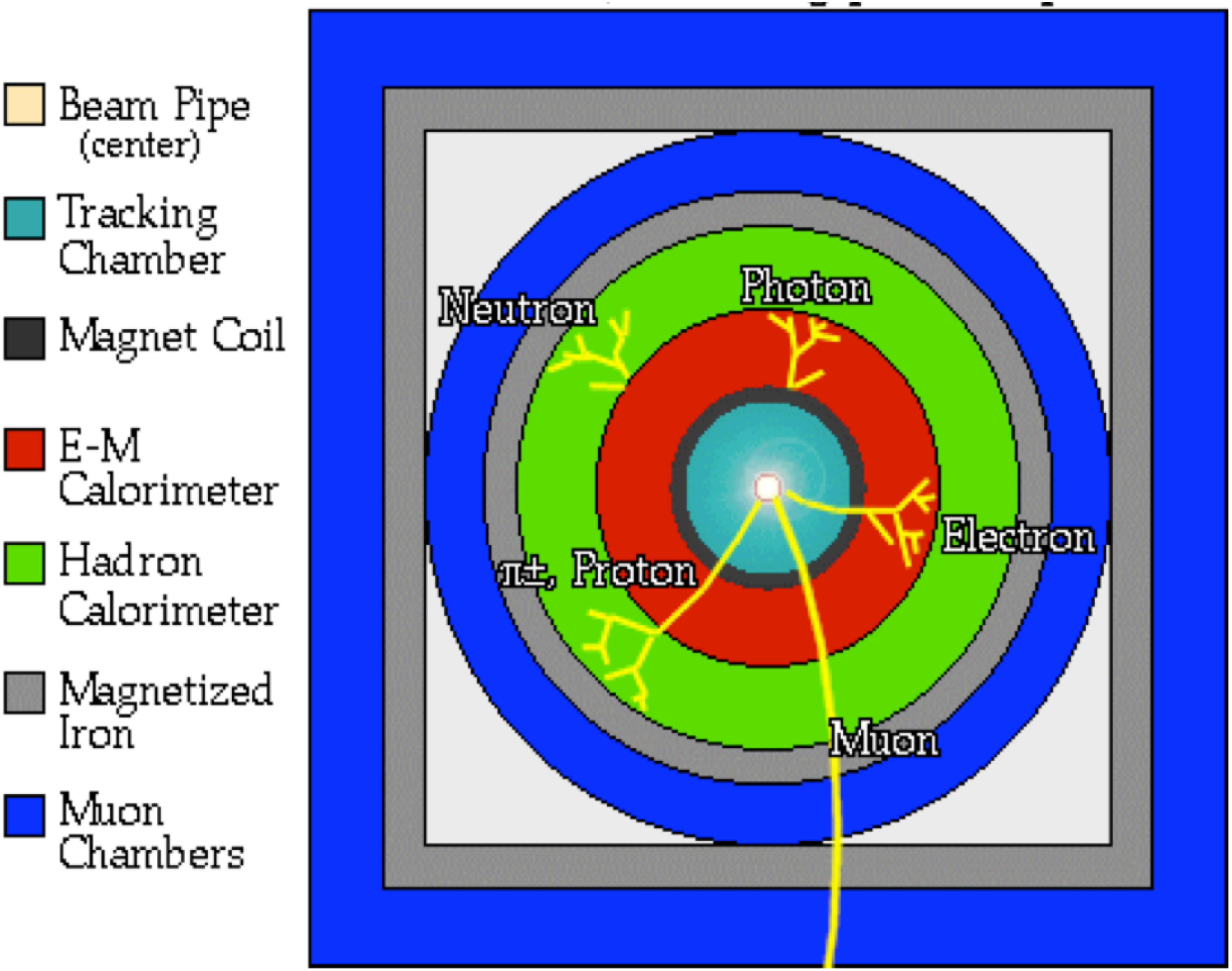
Hadronic vs. EM showers



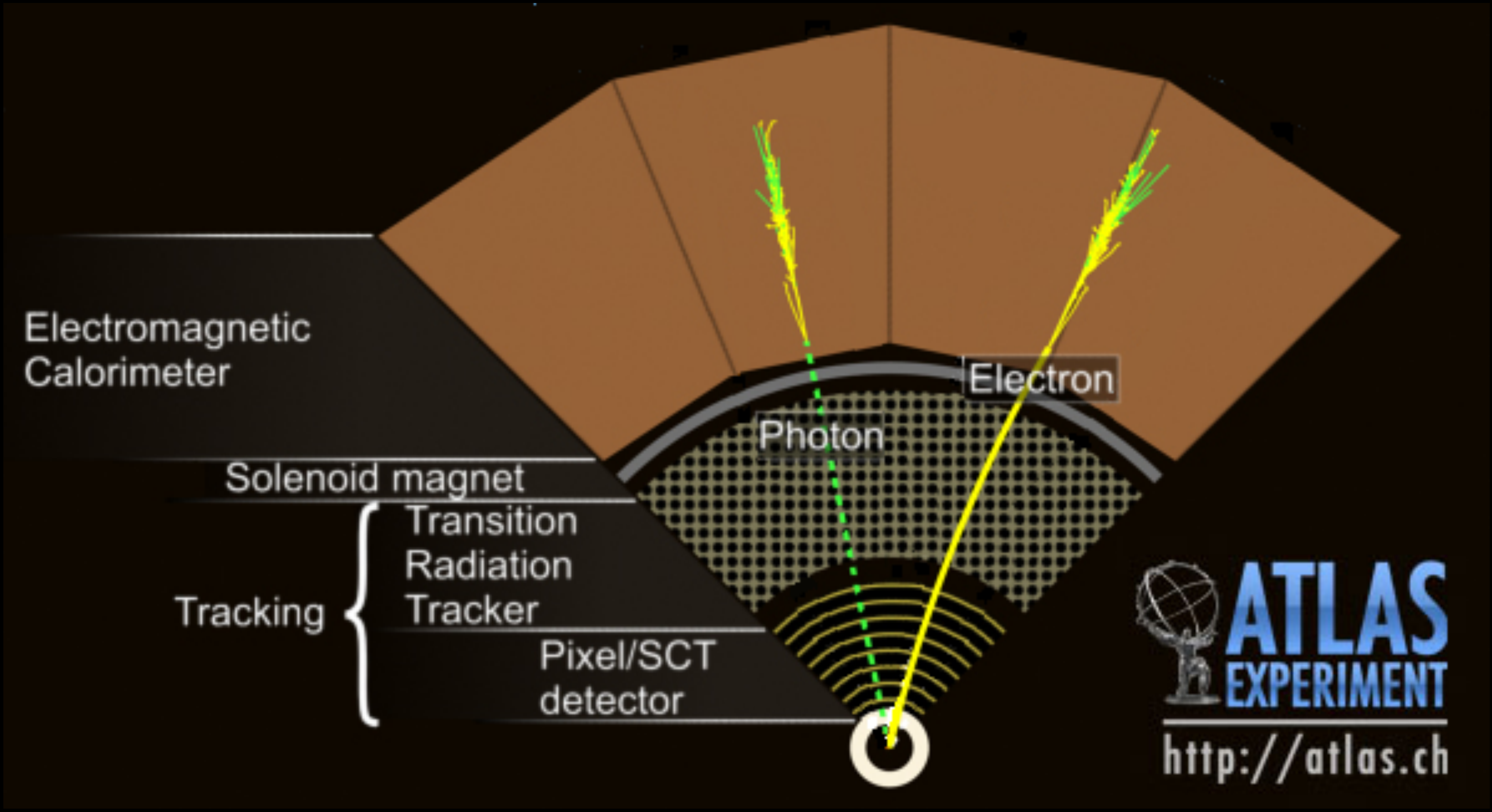
How do we "see" particles?



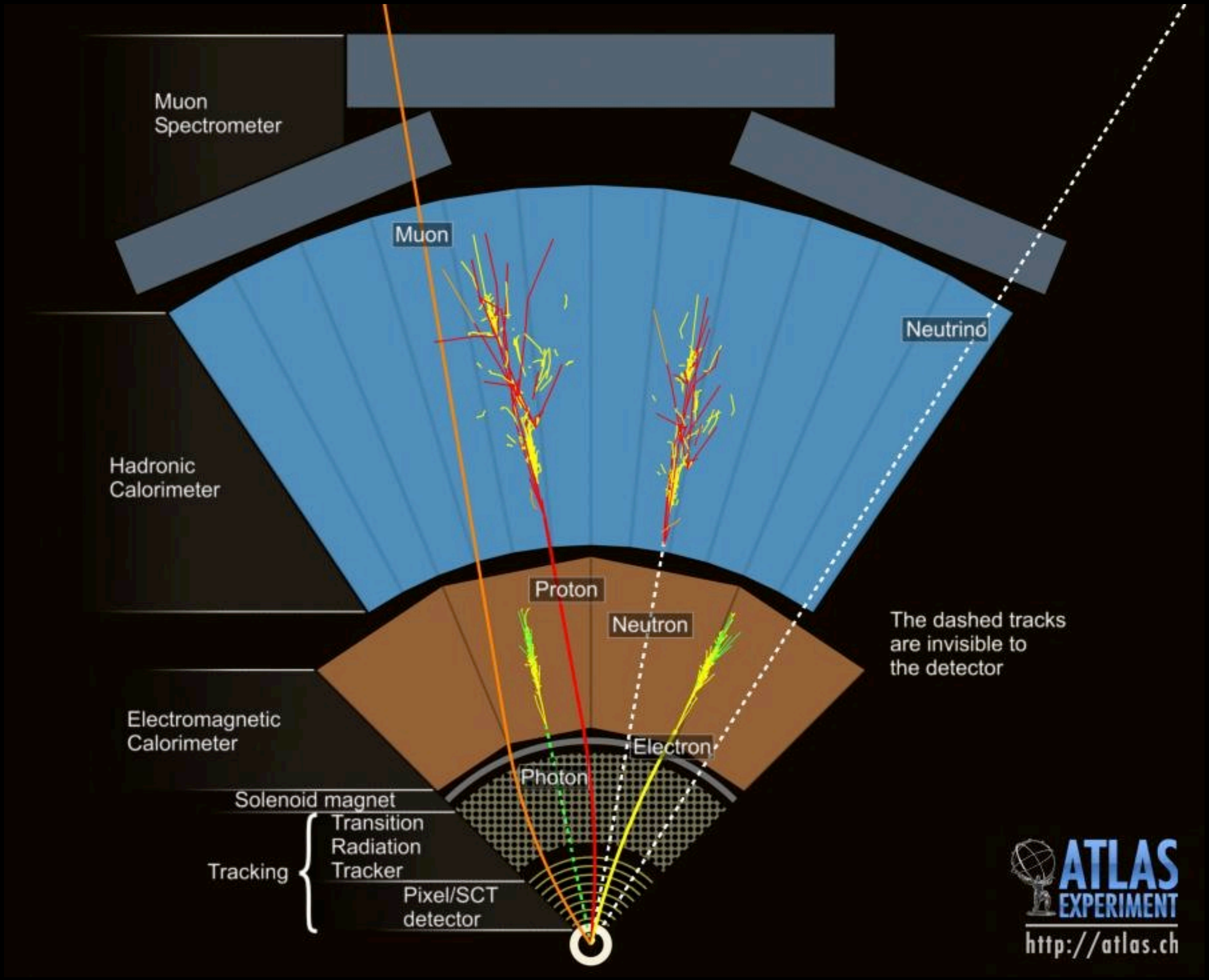
How do we “see” particles?



Particle identification with tracker and EM calo

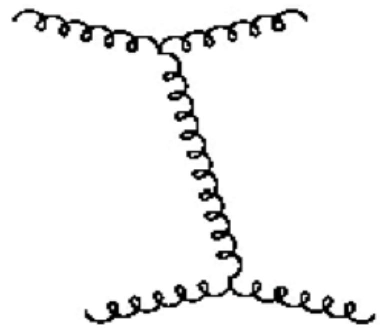


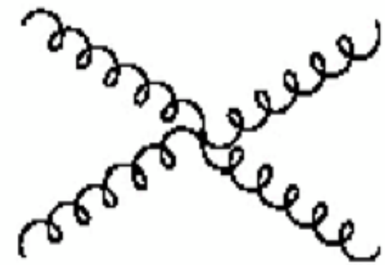
Particle identification with EM and HAD calos



A few 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



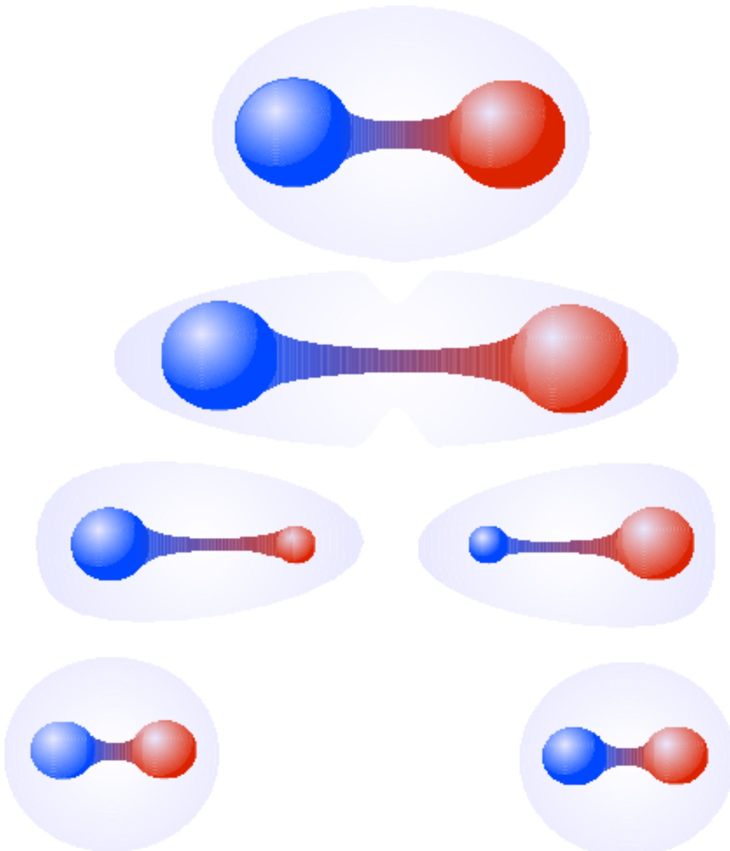


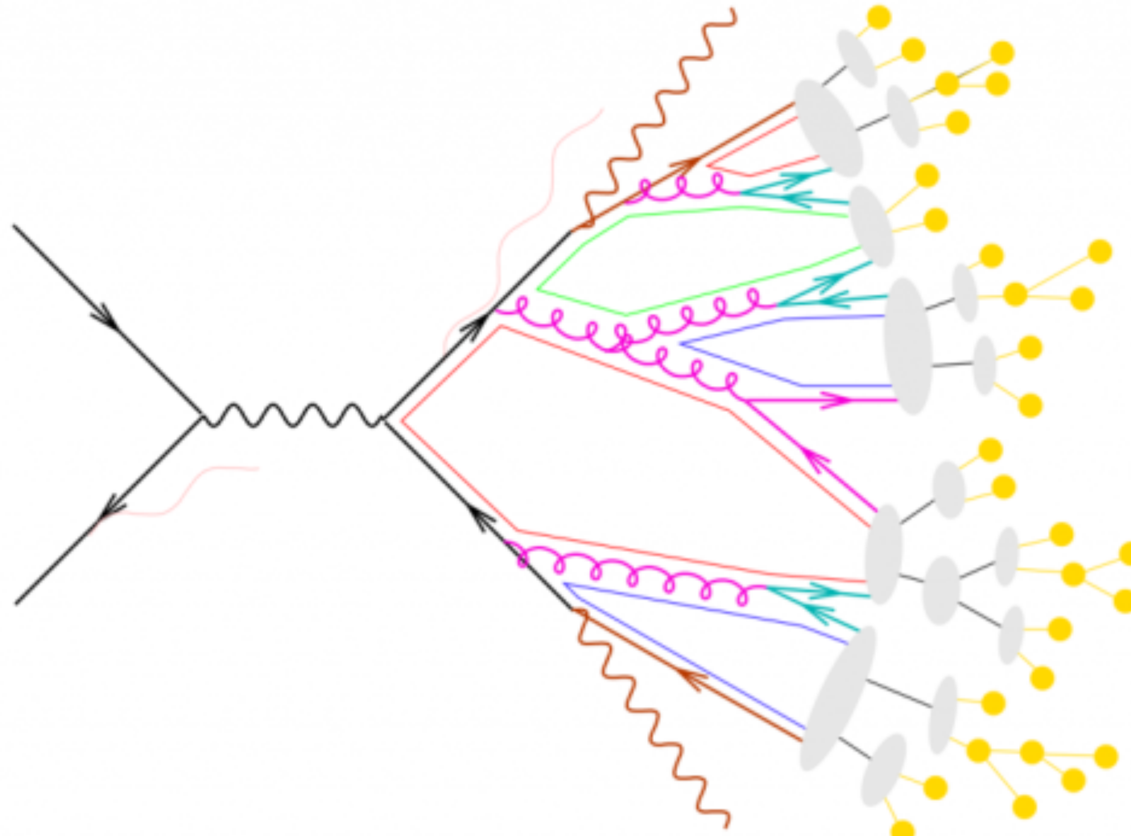
- **Principle of asymptotic freedom**
  - ✓ At short distances strong interactions are weak
    - Quarks and gluons are essentially free particles
    - Perturbative regime (can calculate!)
  - ✓ At large distances, higher-order diagrams dominate
    - Interaction is very strong
    - Perturbative regime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

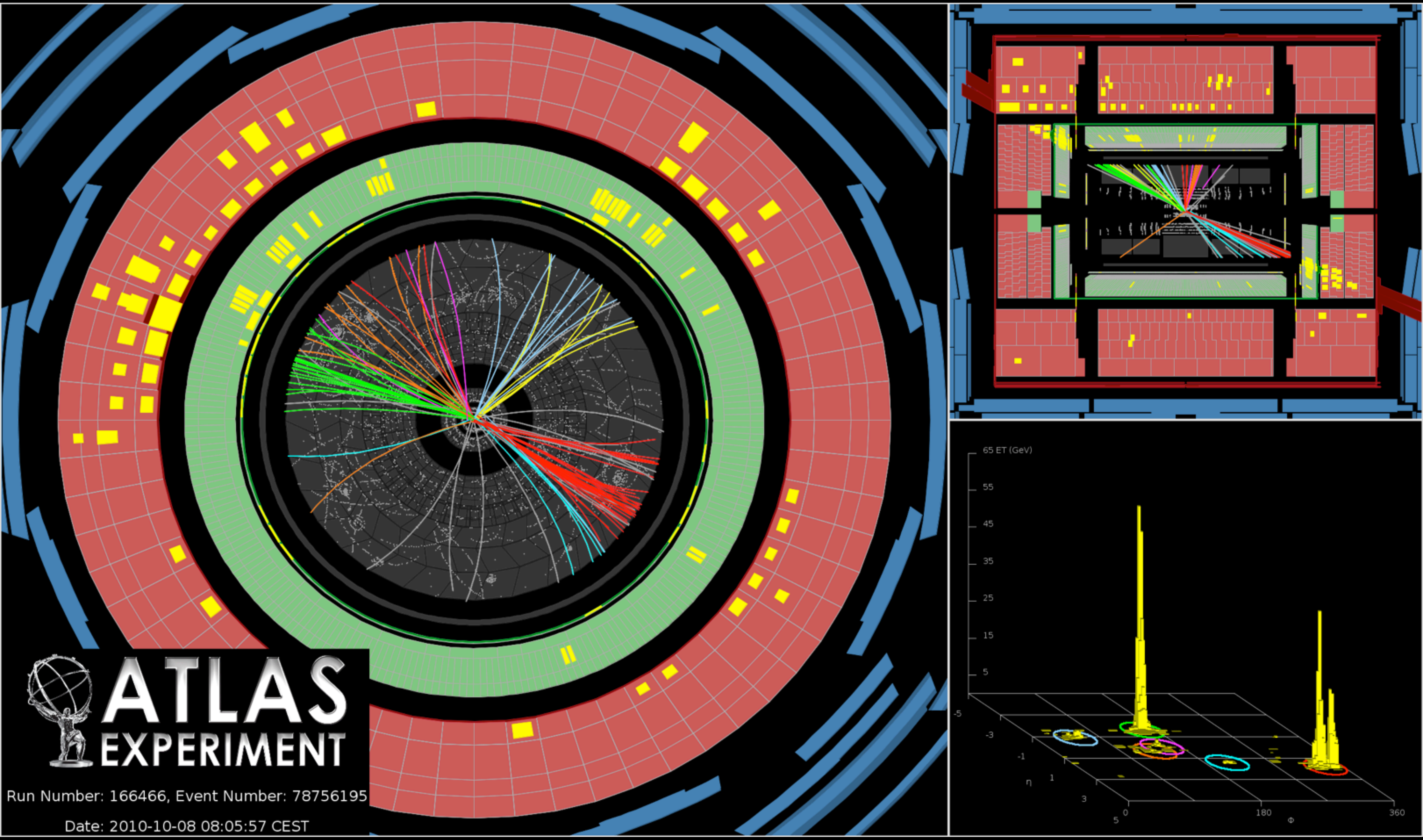
quark-quark effective potential

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

Confinement, hadronization, jets

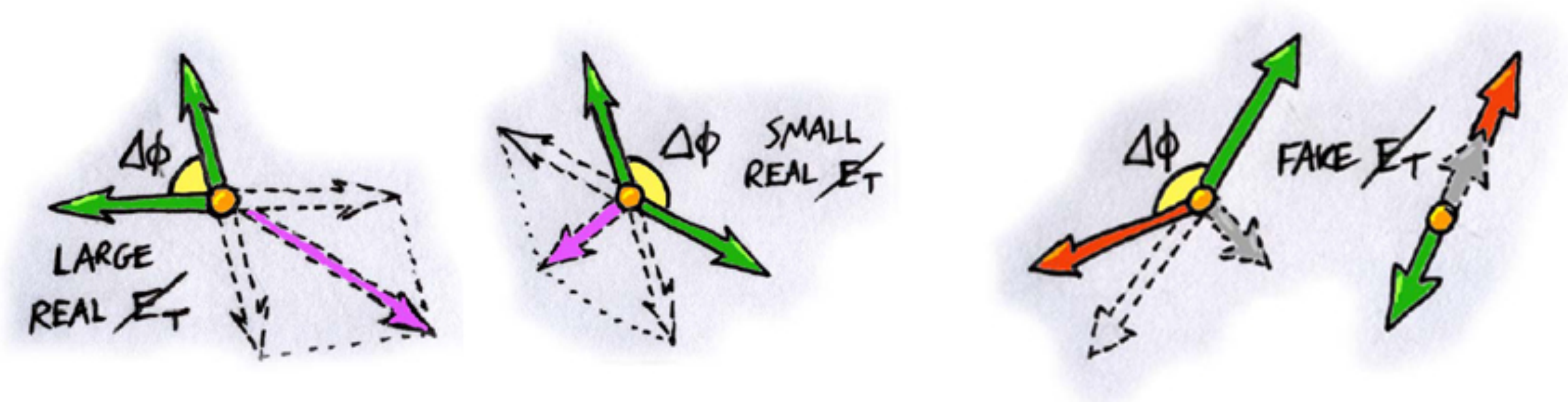





ATLAS
EXPERIMENT
Run Number: 166466, Event Number: 78756195
Date: 2010-10-08 08:05:57 CEST
65 ET (GeV)
55
45
35
25
15
5
-5
-3
-1
η
1
3
5
0
180
Φ
360

Neutrino (and other invisible particles) at colliders

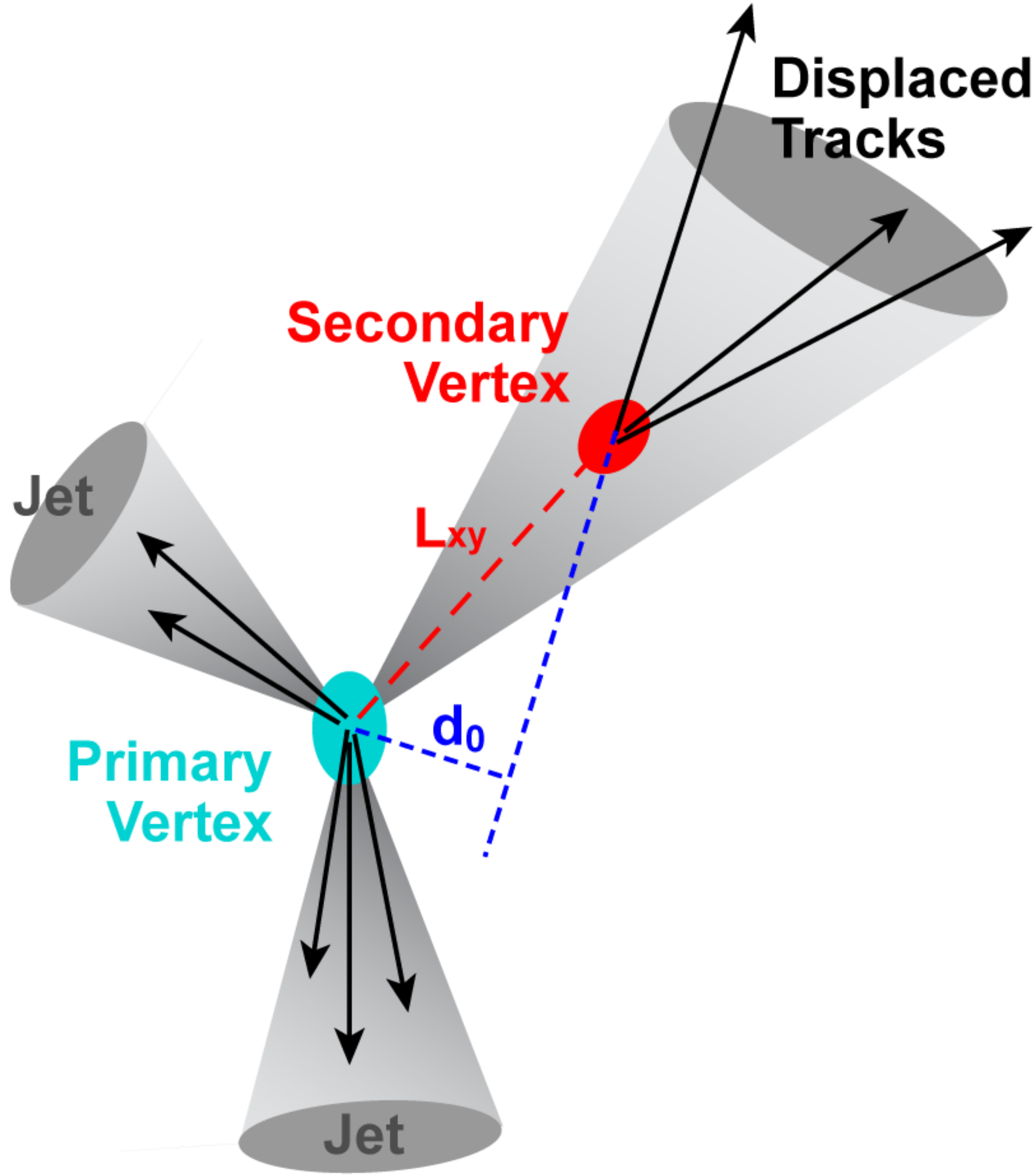
- Interaction length $\lambda_{int} = A/(\rho\ \sigma\ N_A)$
- Cross section $\sigma \sim 10^{-38}$ cm^2 × E [GeV]
  - ✓ This means 10 GeV neutrino can pass through more then a million km of rock
- Neutrinos are usually detected in HEP experiments through *missing (transverse) energy*



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

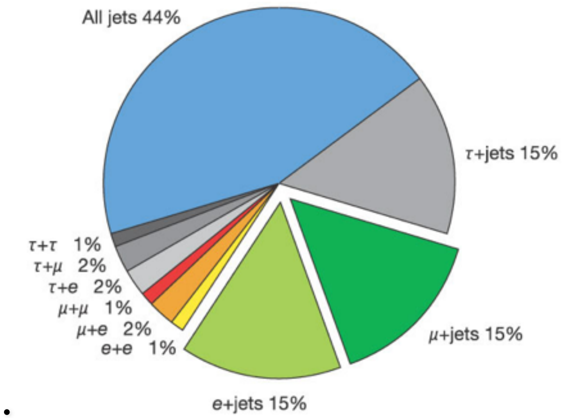
B-tagging

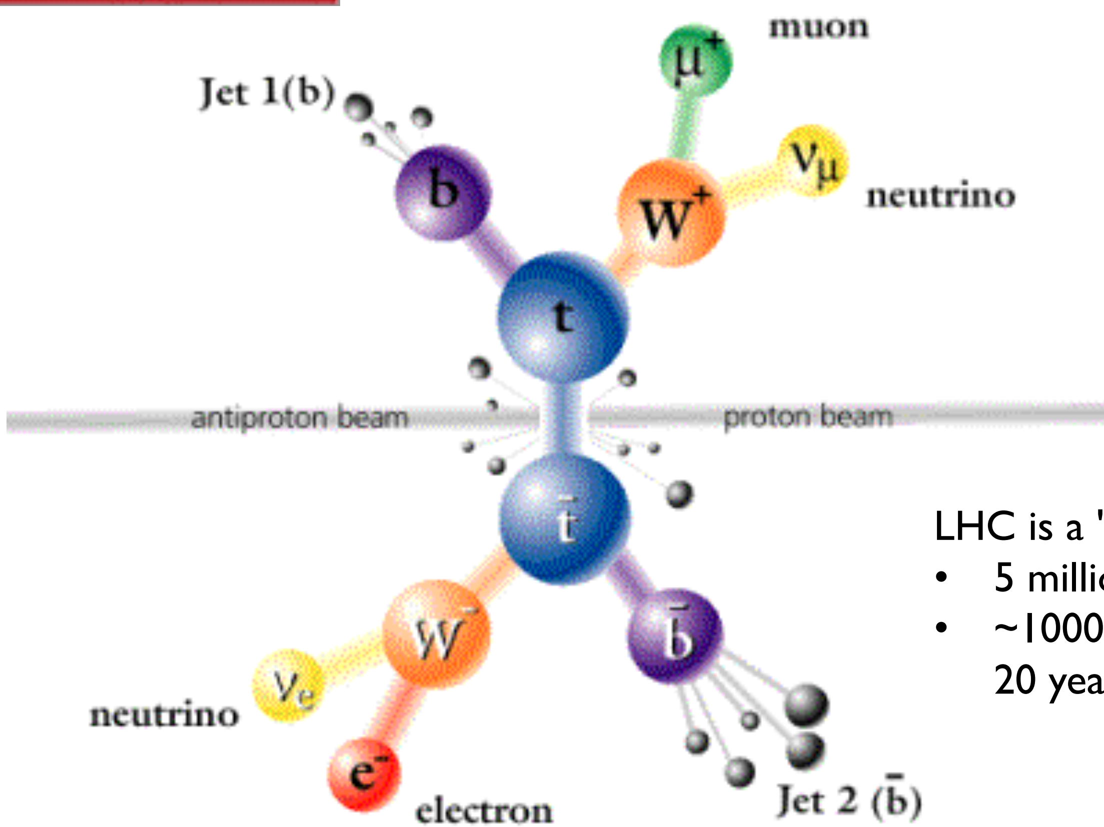
- When a b quark is produced, the associated jet will very likely contain at least one B meson or hadron
- B mesons/hadrons have relatively long lifetime
  - ✓ ~ 1.6 ps
  - ✓ They will travel away form collision point before decaying
- Identifying a secondary decay vertex in a jet allow to tag its quark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

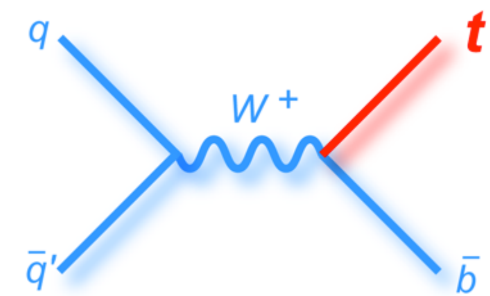


top quark

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

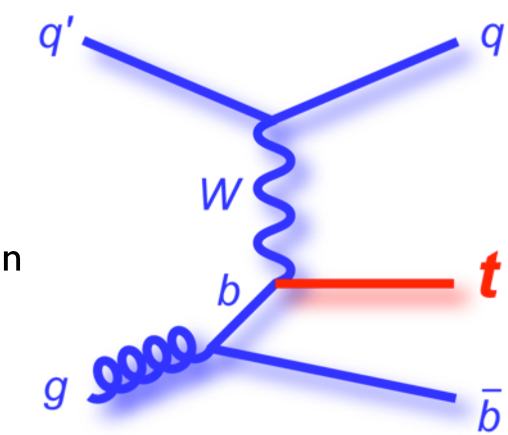






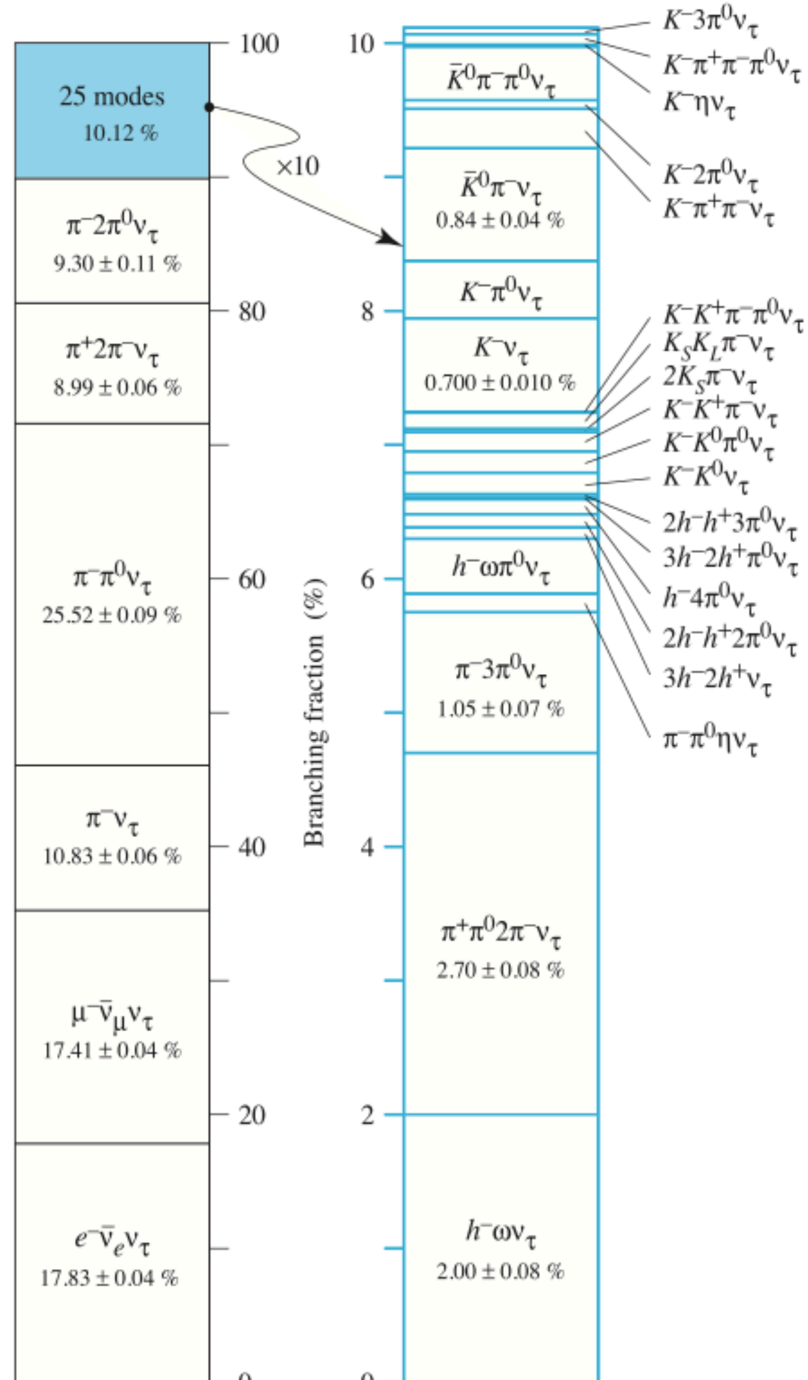
LHC is a "top factory"!

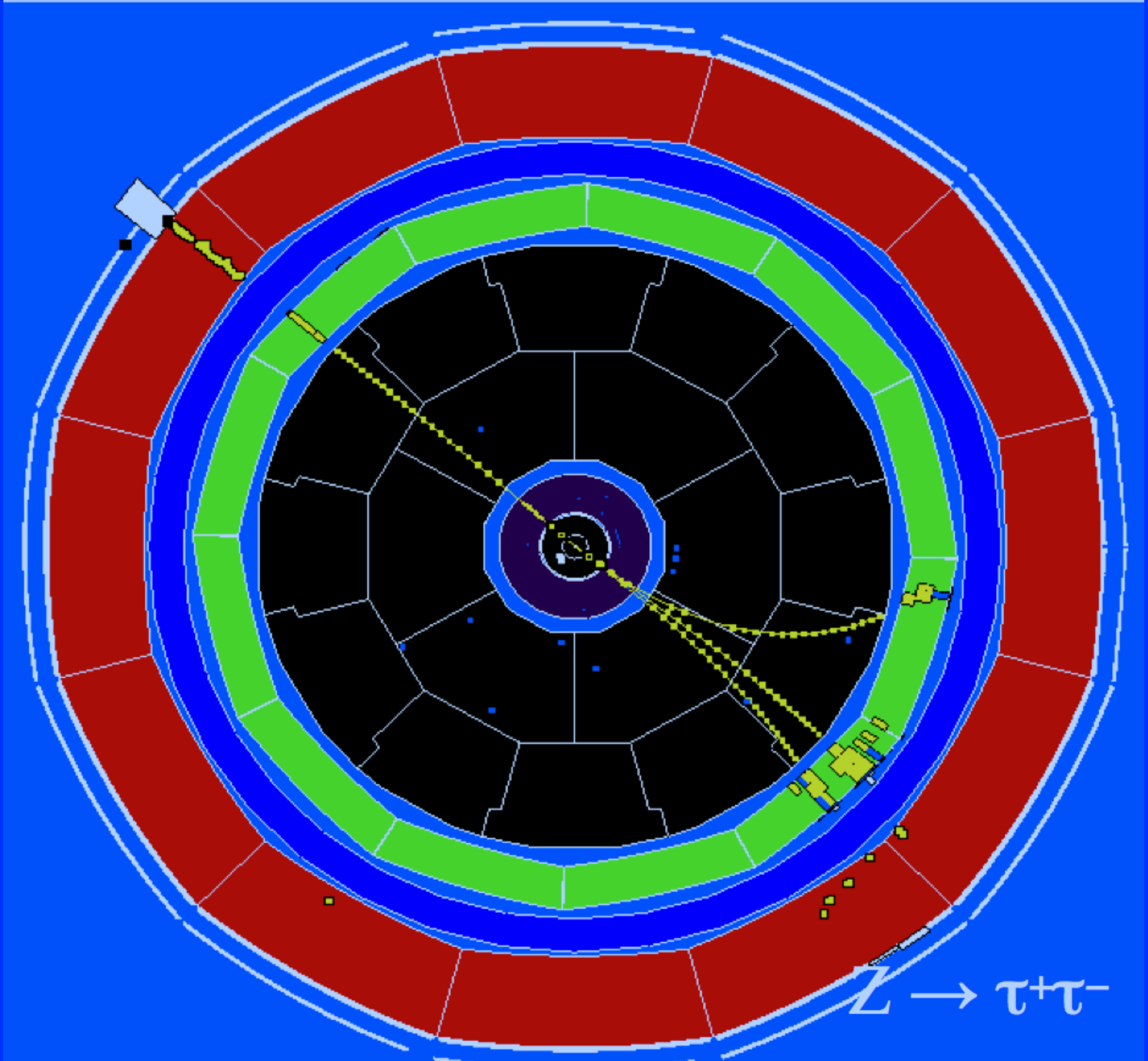
- 5 millions of tt pairs
- ~100000 in Tevatron in 20 years



Tau

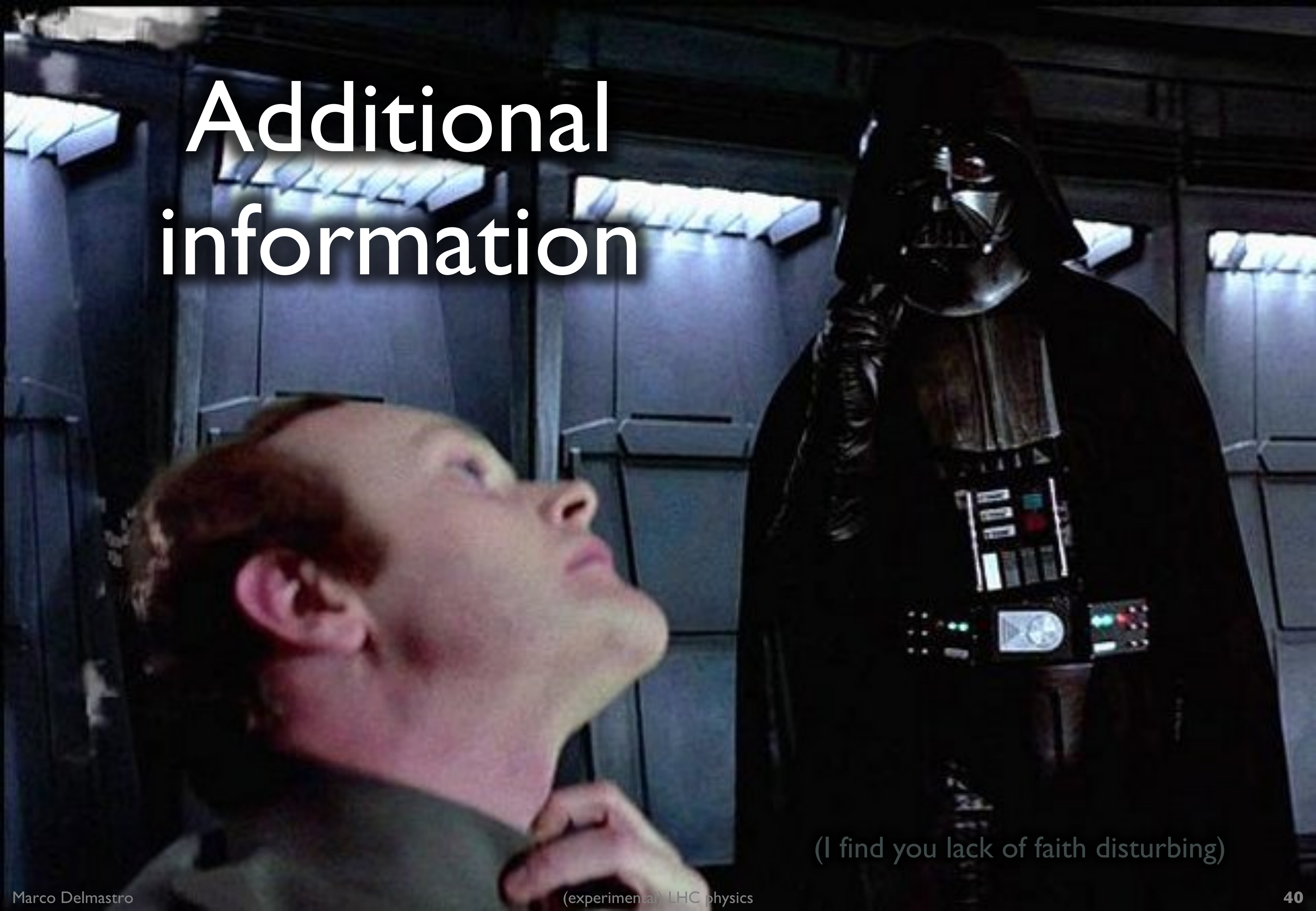
- Tau are heavy enough that they can decay in several final states
  - ✓ Several of them with hadrons
  - ✓ Sometimes neutral hadrons
- Mean lifetime ~ 0.29 ps
  - ✓ 10 GeV tau flies ~ 0.5 mm
  - ✓ Too short to be directly seen in the detectors
- Tau needs to be identifies by their decay products
- Accurate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




$Z \rightarrow \tau^+\tau^-$


"That's all Folks!"

Additional information



(I find you lack of faith disturbing)

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

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

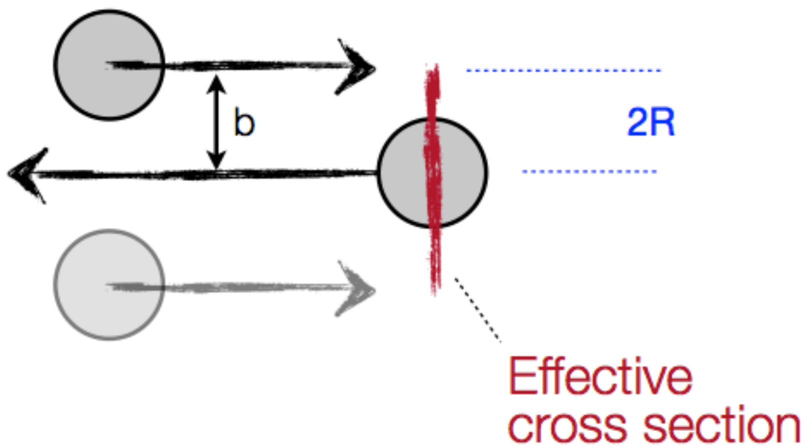
$1\ \text{mb} = 2.57\ \text{GeV}^{-2}$

---

using: $\hbar c = 0.1973\ \text{GeV fm}$

$(\hbar c)^2 = 0.389\ \text{GeV}^2\ \text{mb}$

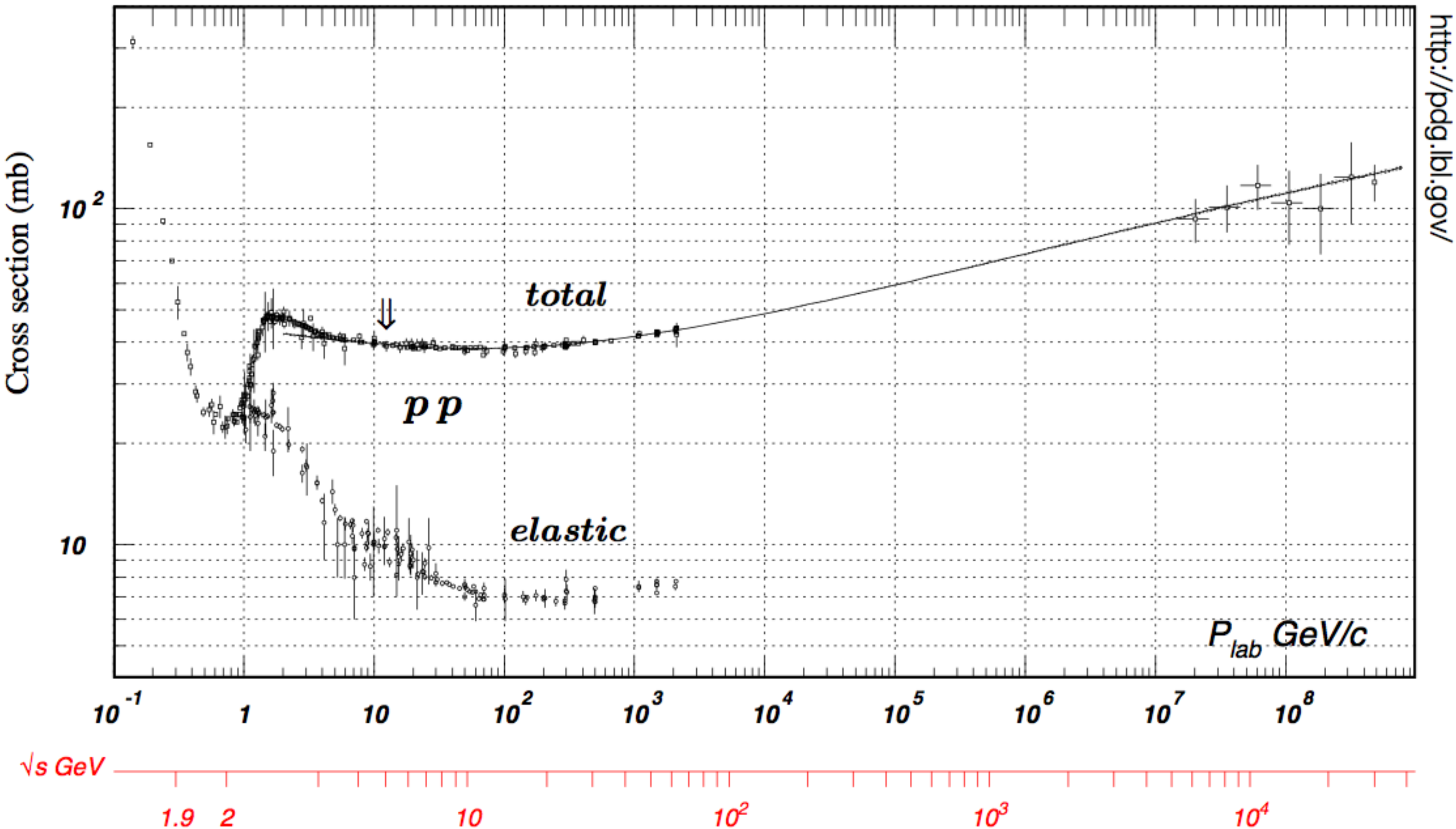
Estimating the
proton-proton cross section:



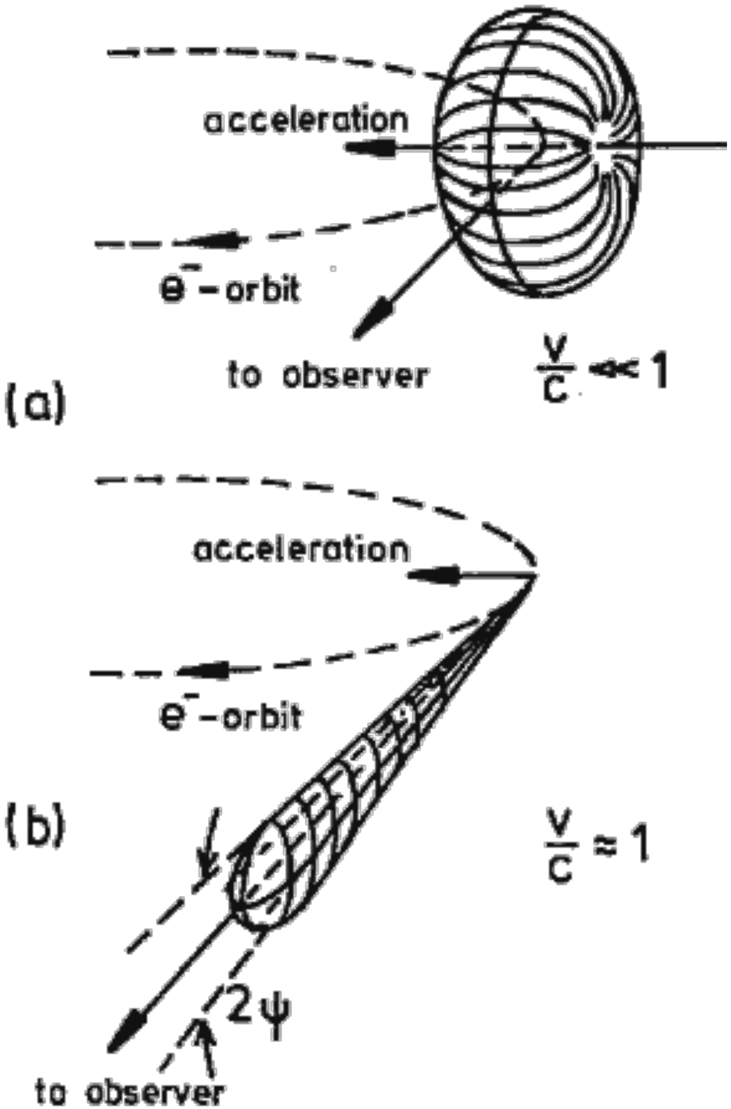
Proton radius: R = 0.8 fm
Strong interactions happens up to b = 2R

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

Proton-proton scattering cross-section



Syncrotron radiation



energy lost per revolution

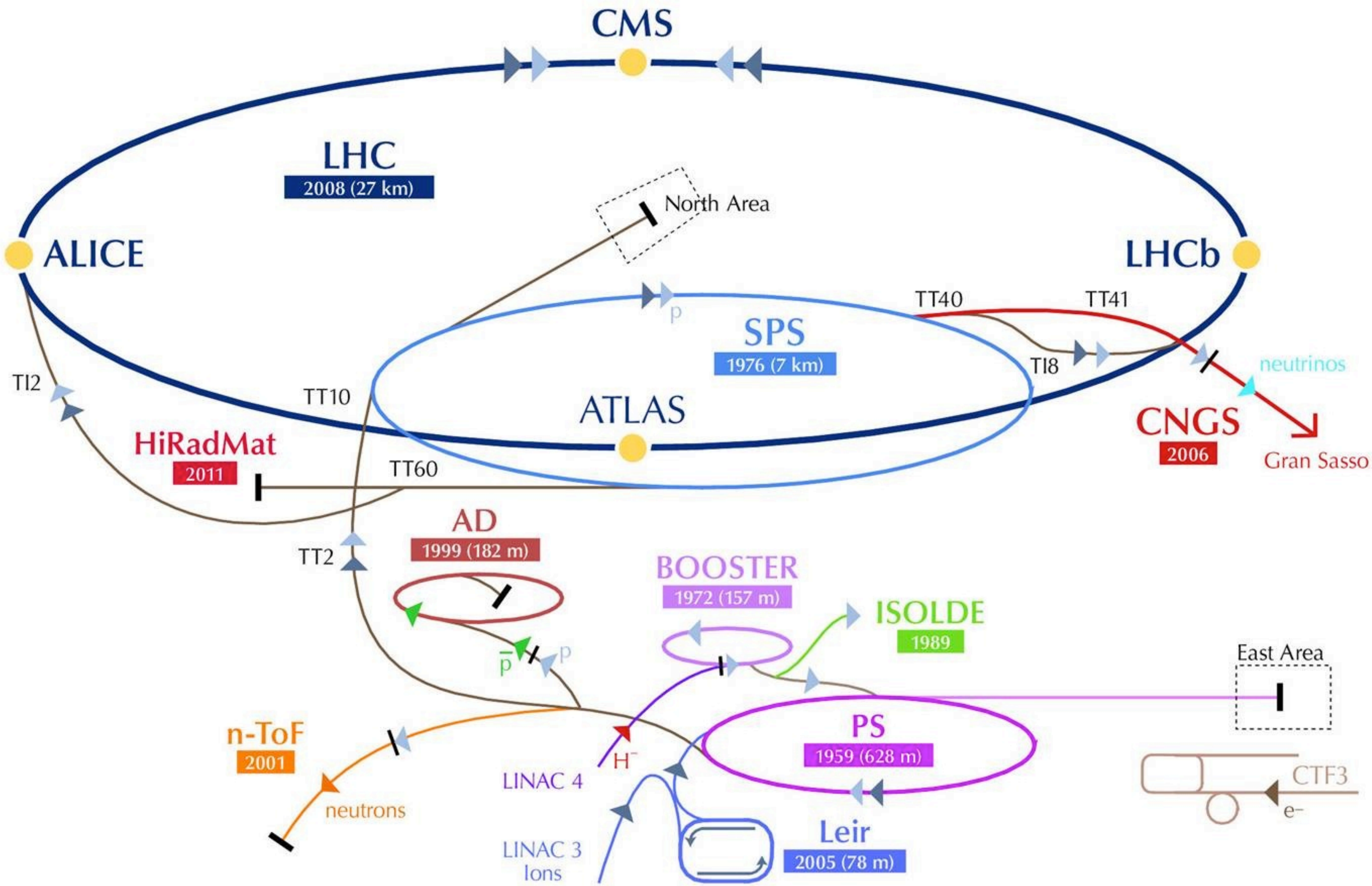
$$\Delta E = \frac{4\pi}{3} \frac{1}{4\pi\epsilon_0} \left(\frac{e^3 \beta^3 \gamma^4}{R} \right)$$

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

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

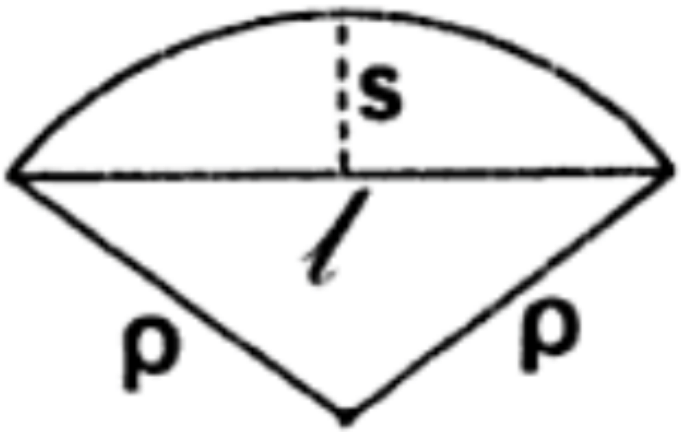
If the field is constant and we neglect presence of matter, momentum magnitude is constant with time, trajectory is helical

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

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

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

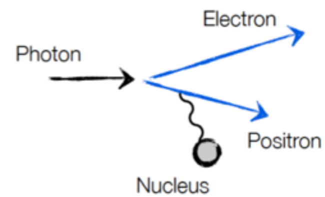
Momentum resolution gets worse for larger momenta

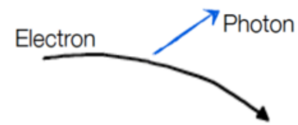
resolution is improved faster by increasing L then B

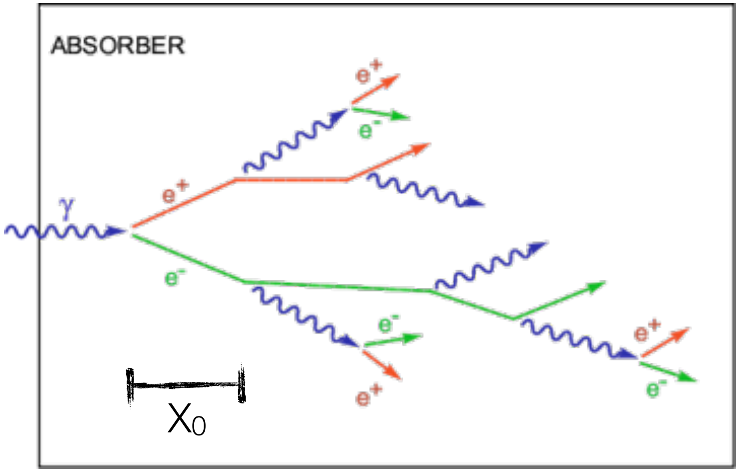
Electromagnetic showers

Dominant processes
at high energies ...

Photons : Pair production
Electrons : Bremsstrahlung







Pair production:

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

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

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

Absorption coefficient:

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

Bremsstrahlung:

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

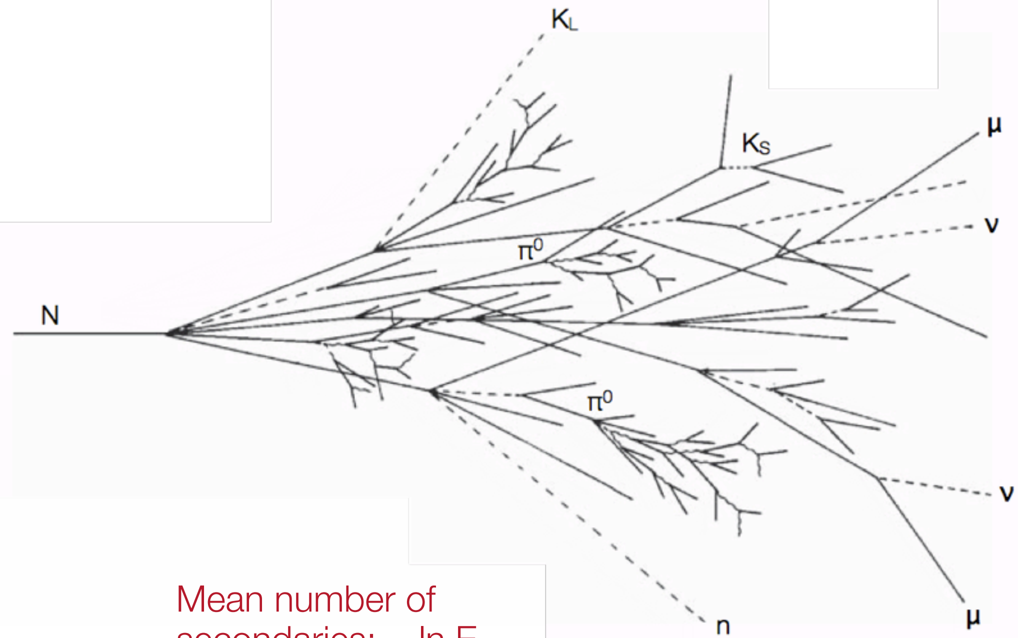
$$\rightarrow\; E = E_0 e^{-x/X_0}$$

After passage of one X_0 electron has only (1/e)$^{\mathrm{th}}$ of its primary energy ...
[i.e. 37%]

Critical energy:

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

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]

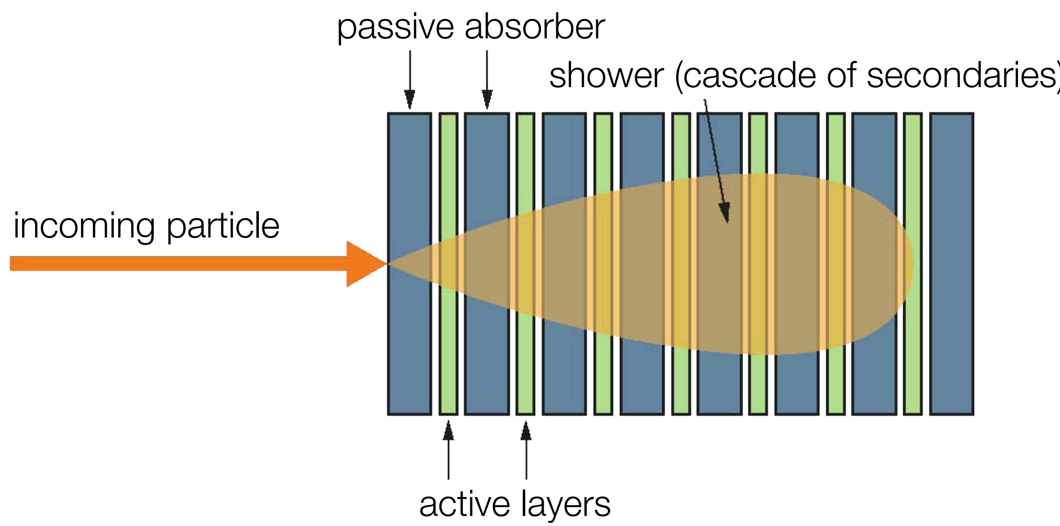
Absorber materials:
[high density]

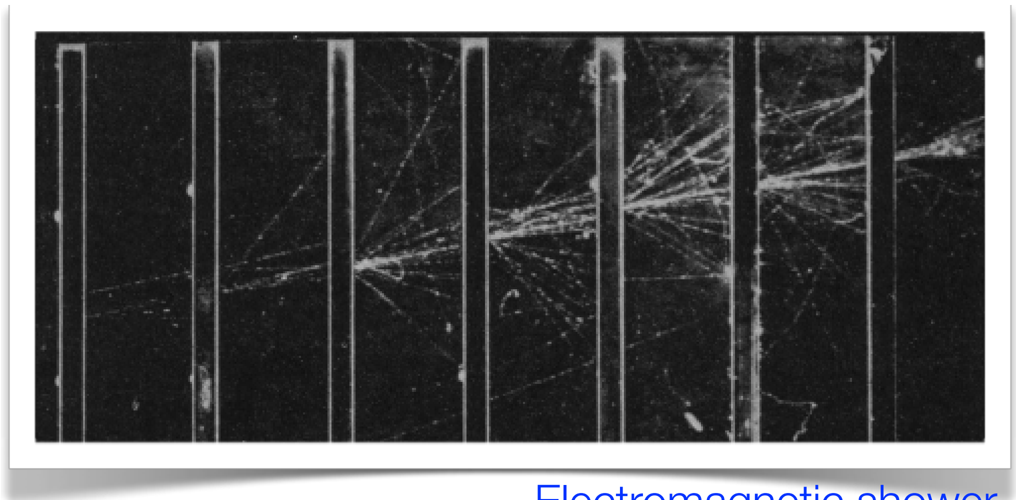
Iron (Fe)
Lead (Pb)
Uranium (U)
[For compensation ...]

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) ...

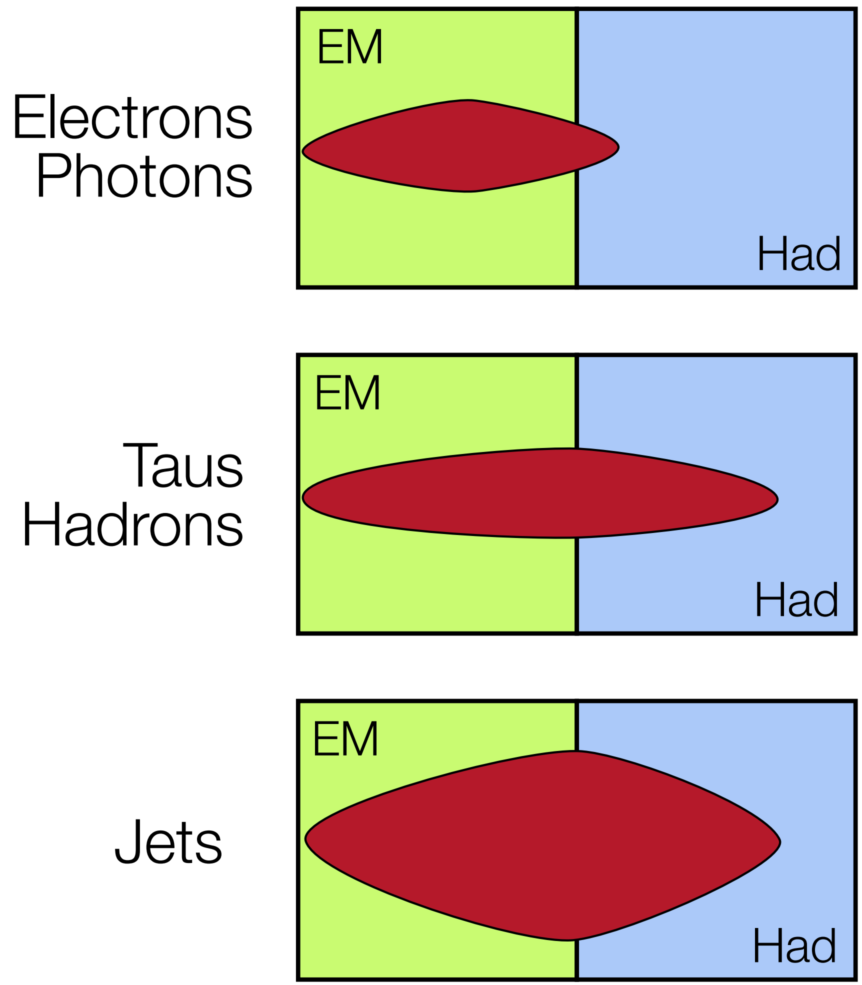
Different setups chosen for
optimal energy resolution ...

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

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

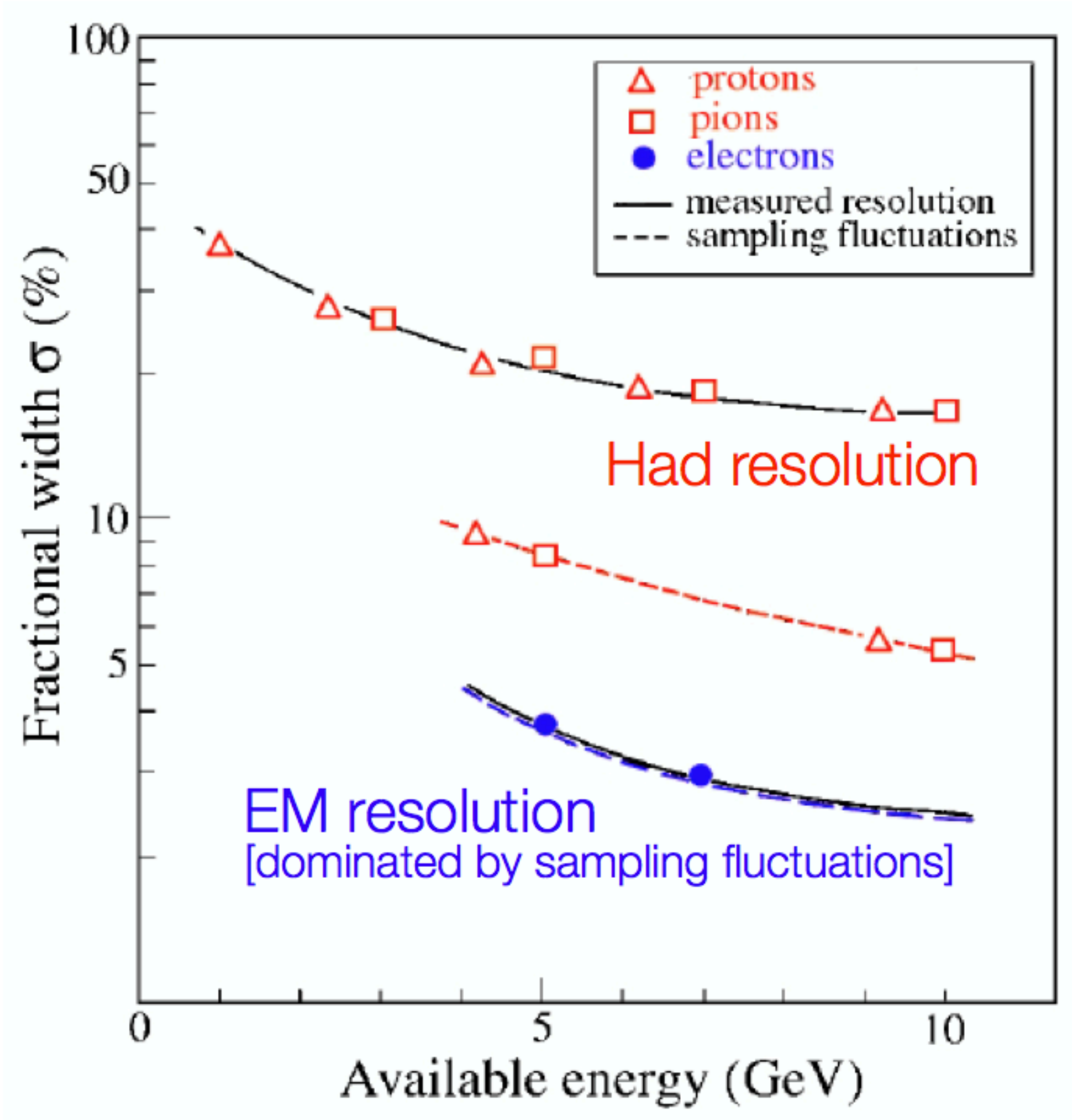
Fluctuations:

- 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