

(experimental) LHC physics

GrASPA2016

Summer School in Particle and
Astroparticle physics
of Annecy-le-Vieux

Special lecture on
the observation
of gravitational waves



21-27 July 2016

{on how particles are
produced and measured}

LAPP

LAFTA



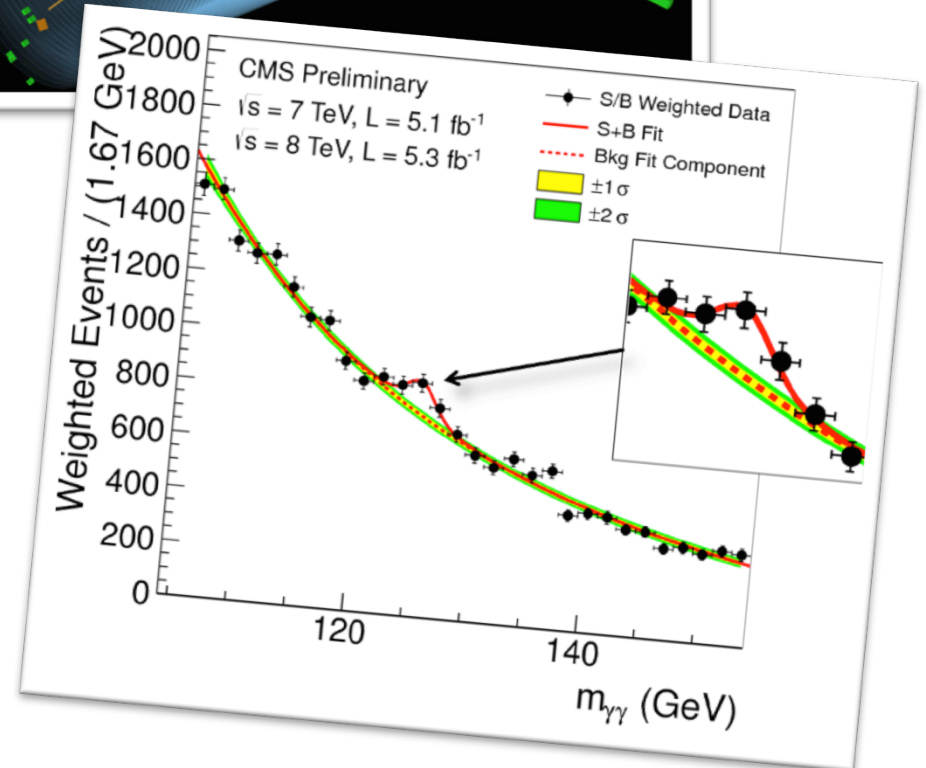
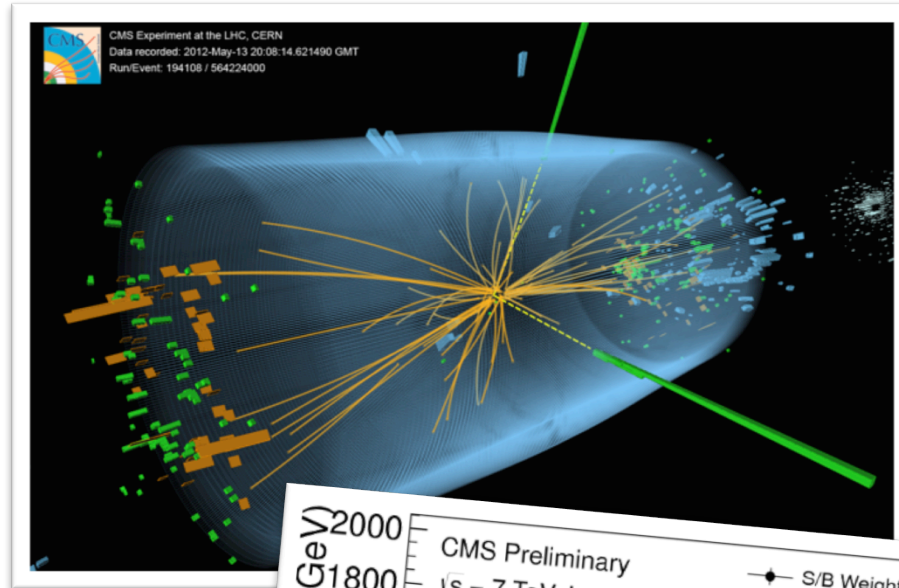
IN2P3
Les deux infinis



Marco Delmastro

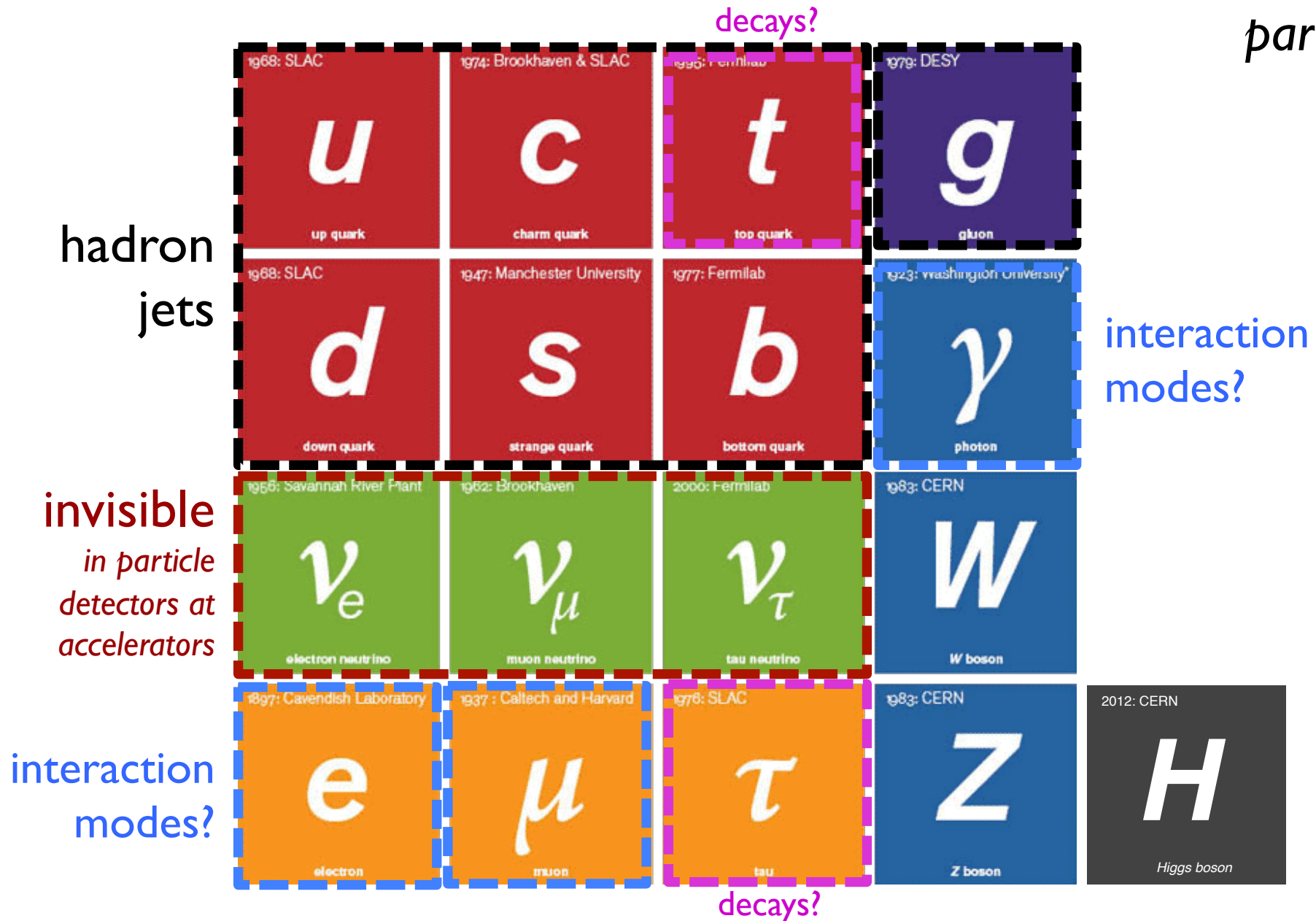
Experiment = probing theories with data!

$$\begin{aligned}
 & -\frac{1}{2}\partial_\nu g_\mu^a \partial_\nu g_\mu^a - g_s f^{abc} \partial_\mu g_\nu^a g_\nu^b g_\nu^c - \frac{1}{4}g_s^2 f^{abc} f^{ade} g_\mu^a g_\nu^b g_\nu^c g_\nu^d g_\nu^e + \\
 & \frac{1}{2}i g_s^2 (\bar{q}_i^\alpha \gamma^\mu q_j^\alpha) g_\mu^a + \bar{G}^a \partial^2 G^a + g_s f^{abc} \partial_\mu \bar{G}^a G^b g_\mu^c - \partial_\nu W_\mu^+ \partial_\nu W_\mu^- - \\
 & M^2 W_\mu^+ W_\mu^- - \frac{1}{2}\partial_\nu Z_\mu^0 \partial_\nu Z_\mu^0 - \frac{1}{2c_w^2} M^2 Z_\mu^0 Z_\mu^0 - \frac{1}{2}\partial_\mu A_\nu \partial_\mu A_\nu - \frac{1}{2}\partial_\mu H \partial_\mu H - \\
 & \frac{1}{2}m_h^2 H^2 - \partial_\mu \phi^+ \partial_\mu \phi^- - M^2 \phi^+ \phi^- - \frac{1}{2}\partial_\mu \phi^0 \partial_\mu \phi^0 - \frac{1}{2c_w^2} M \phi^0 \phi^0 - \beta_h \left[\frac{2M^2}{g^2} + \right. \\
 & \left. \frac{2M}{g} H + \frac{1}{2}(H^2 + \phi^0 \phi^0 + 2\phi^+ \phi^-) \right] + \frac{2M^4}{g^2} \alpha_h - ig_{cw} [\partial_\nu Z_\mu^0 (W_\mu^+ W_\nu^- - \\
 & W_\nu^+ W_\mu^-) - Z_\mu^0 (W_\mu^+ \partial_\nu W_\nu^- - W_\nu^+ \partial_\mu W_\mu^-) + Z_\mu^0 (W_\nu^+ \partial_\nu W_\mu^- - \\
 & W_\nu^- \partial_\nu W_\mu^+) - ig_{sw} [\partial_\nu A_\mu (W_\mu^+ W_\nu^- - W_\nu^+ W_\mu^-) - A_\nu (W_\mu^+ \partial_\nu W_\mu^- - \\
 & W_\nu^- \partial_\nu W_\mu^+) + A_\mu (W_\nu^+ \partial_\nu W_\mu^- - W_\nu^- \partial_\nu W_\mu^+) - \frac{1}{2}g^2 W_\mu^+ W_\nu^- W_\nu^+ W_\mu^- + \\
 & \frac{1}{2}g^2 W_\mu^+ W_\nu^- W_\mu^+ W_\nu^- + g^2 c_w^2 (Z_\mu^0 W_\mu^+ Z_\nu^0 W_\nu^- - Z_\mu^0 Z_\nu^0 W_\mu^+ W_\nu^-) + \\
 & g^2 s_w^2 (A_\mu W_\mu^+ A_\nu W_\nu^- - A_\mu A_\nu W_\mu^+ W_\nu^-) + g^2 s_w c_w [A_\mu Z_\nu^0 (W_\mu^+ W_\nu^- - \\
 & W_\nu^+ W_\mu^-) - 2A_\mu Z_\mu^0 W_\nu^+ W_\nu^-] - g\alpha [H^3 + H\phi^0 \phi^0 + 2H\phi^+ \phi^-] - \\
 & \frac{1}{8}g^2 \alpha_h [H^4 + (\phi^0)^4 + 4(\phi^+ \phi^-)^2 + 4(\phi^0)^2 \phi^+ \phi^- + 4H^2 \phi^+ \phi^- + 2(\phi^0)^2 H^2] - \\
 & gM W_\mu^+ W_\mu^- H - \frac{1}{2}g \frac{M}{c_w} Z_\mu^0 Z_\mu^0 H - \frac{1}{2}ig [W_\mu^+ (\phi^0 \partial_\mu \phi^- - \phi^- \partial_\mu \phi^0) - \\
 & W_\mu^- (\phi^0 \partial_\mu \phi^+ - \phi^+ \partial_\mu \phi^0)] + \frac{1}{2}g [W_\mu^+ (H \partial_\mu \phi^- - \phi^- \partial_\mu H) - W_\mu^- (H \partial_\mu \phi^+ - \\
 & \phi^+ \partial_\mu H)] + \frac{1}{2}g \frac{1}{c_w} (Z_\mu^0 (H \partial_\mu \phi^0 - \phi^0 \partial_\mu H) - ig_{cw} M Z_\mu^0 (W_\mu^+ \phi^- - W_\mu^- \phi^+) + \\
 & ig_{sw} M A_\mu (W_\mu^+ \phi^- - W_\mu^- \phi^+) - ig \frac{1-2c_w^2}{2c_w} Z_\mu^0 (\phi^+ \partial_\mu \phi^- - \phi^- \partial_\mu \phi^+) + \\
 & ig_{sw} A_\mu (\phi^+ \partial_\mu \phi^- - \phi^- \partial_\mu \phi^+) - \frac{1}{4}g^2 W_\mu^+ W_\mu^- [H^2 + (\phi^0)^2 + 2\phi^+ \phi^-] - \\
 & \frac{1}{4}g^2 \frac{1}{c_w^2} Z_\mu^0 Z_\mu^0 [H^2 + (\phi^0)^2 + 2(2s_w^2 - 1)^2 \phi^+ \phi^-] - \frac{1}{2}g^2 \frac{s_w^2}{c_w} Z_\mu^0 \phi^0 (W_\mu^+ \phi^- + \\
 & W_\mu^- \phi^+) - \frac{1}{2}ig^2 \frac{s_w^2}{c_w} Z_\mu^0 H (W_\mu^+ \phi^- - W_\mu^- \phi^+) + \frac{1}{2}g^2 s_w A_\mu \phi^0 (W_\mu^+ \phi^- + \\
 & W_\mu^- \phi^+) + \frac{1}{2}ig^2 s_w A_\mu H (W_\mu^+ \phi^- - W_\mu^- \phi^+) - \bar{\nu}^\lambda \gamma \partial_\nu \nu^\lambda - \bar{u}_j^\lambda (\gamma \partial + m_u^\lambda) u_j^\lambda + \\
 & g^1 s_w^2 A_\mu A_\mu \phi^+ \phi^- - e^\lambda (\gamma \partial + m_e^\lambda) e^\lambda + \frac{2}{3}(\bar{u}_j^\lambda \gamma^\mu u_j^\lambda) - \frac{1}{3}(\bar{d}_j^\lambda \gamma^\mu d_j^\lambda) + \\
 & \bar{d}_j^\lambda (\gamma \partial + m_d^\lambda) d_j^\lambda + ig_{sw} A_\mu [-(\bar{e}^\lambda \gamma^\mu e^\lambda) + \frac{2}{3}(\bar{u}_j^\lambda \gamma^\mu u_j^\lambda) - \frac{1}{3}(\bar{d}_j^\lambda \gamma^\mu d_j^\lambda)] + \\
 & \frac{ig}{4c_w} Z_\mu^0 [(\bar{\nu}^\lambda \gamma^\mu (1 + \gamma^5) \nu^\lambda) + (\bar{e}^\lambda \gamma^\mu (4s_w^2 - 1 - \gamma^5) e^\lambda) + (\bar{u}_j^\lambda \gamma^\mu (\frac{4}{3}s_w^2 - \\
 & 1 - \gamma^5) u_j^\lambda) + (\bar{d}_j^\lambda \gamma^\mu (1 - \frac{8}{3}s_w^2 - \gamma^5) d_j^\lambda)] + \frac{ig}{2\sqrt{2}} W_\mu^+ [(\bar{\nu}^\lambda \gamma^\mu (1 + \gamma^5) \nu^\lambda) + \\
 & (\bar{d}_j^\lambda \gamma^\mu (1 + \gamma^5) C_{\lambda\kappa} d_j^\kappa)] + \frac{ig}{2\sqrt{2}} W_\mu^- [(\bar{e}^\lambda \gamma^\mu (1 + \gamma^5) e^\lambda) + (\bar{u}_j^\lambda \gamma^\mu (1 + \gamma^5) C_{\lambda\kappa} u_j^\kappa)] - \\
 & \gamma^5 u_j^\lambda) + \frac{ig}{2\sqrt{2}} M [-\phi^+ (\bar{\nu}^\lambda (1 - \gamma^5) e^\lambda) + \phi^- (\bar{e}^\lambda (1 + \gamma^5) \nu^\lambda)] - \\
 & \frac{g}{2} \frac{m_h^2}{M} [H (\bar{e}^\lambda e^\lambda) + i\phi^0 (\bar{e}^\lambda \gamma^5 e^\lambda)] + \frac{ig}{2M\sqrt{2}} \phi^+ [-m_d^\lambda (\bar{u}_j^\lambda C_{\lambda\kappa} (1 - \gamma^5) d_j^\kappa) + \\
 & m_u^\lambda (\bar{u}_j^\lambda C_{\lambda\kappa} (1 + \gamma^5) d_j^\kappa) + \frac{ig}{2M\sqrt{2}} \phi^- [m_d^\lambda (\bar{d}_j^\lambda C_{\lambda\kappa}^\dagger (1 + \gamma^5) u_j^\kappa) - m_u^\lambda (\bar{d}_j^\lambda C_{\lambda\kappa}^\dagger (1 - \\
 & \gamma^5) u_j^\kappa) - \frac{g}{2} \frac{m_h^2}{M} H (\bar{u}_j^\lambda u_j^\lambda) - \frac{g}{2} \frac{m_h^2}{M} H (\bar{d}_j^\lambda d_j^\lambda) + \frac{ig}{2} \frac{m_h^2}{M} \phi^0 (\bar{u}_j^\lambda \gamma^5 u_j^\lambda) - \\
 & \gamma^5 u_j^\lambda) + \bar{X}^+ (\partial^2 - M^2) X^+ + \bar{X}^- (\partial^2 - M^2) X^- + \bar{X}^0 (\partial^2 - \\
 & \frac{ig}{2} \frac{m_h^2}{M} \phi^0 (\bar{d}_j^\lambda \gamma^5 d_j^\lambda) + \bar{X}^+ (\partial^2 - M^2) X^+ - \partial_\mu \bar{X}^+ X^0 + ig_{sw} W_\mu^+ (\partial_\mu \bar{X}^- X^- - \\
 & \frac{M^2}{2} X^0 + \bar{Y} \partial^2 Y + ig_{cw} W_\mu^+ (\partial_\mu \bar{X}^- X^0 - \partial_\mu \bar{X}^+ X^+) + ig_{sw} W_\mu^- (\partial_\mu \bar{X}^- X^- - \\
 & \partial_\mu \bar{X}^+ X^+) + ig_{cw} Z_\mu^0 (\partial_\mu \bar{X}^- X^+ - \partial_\mu \bar{X}^+ X^-) + ig_{sw} A_\mu (\partial_\mu \bar{X}^- X^+ - \\
 & \partial_\mu \bar{X}^+ X^-) - \frac{1}{2}gM [\bar{X}^+ X^+ H + \bar{X}^- X^- H + \frac{1}{c_w} \bar{X}^0 X^0 H] + \\
 & \frac{1-2c_w^2}{2c_w} igM [\bar{X}^+ X^0 \phi^+ - \bar{X}^- X^0 \phi^-] + \frac{1}{2c_w} igM [\bar{X}^+ X^+ \phi^0 - \bar{X}^- X^- \phi^0] \\
 & igM s_w [\bar{X}^0 X^- \phi^+ - \bar{X}^0 X^+ \phi^-] + \frac{1}{2}igM [\bar{X}^+ X^+ \phi^0 - \bar{X}^- X^- \phi^0]
 \end{aligned}$$



What do we want to measure?

... “stable”
particles!





TODAY'S Menu

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/c² 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: $\hbar = c = 1$)

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

$$\ell = \frac{\ell_0}{\gamma} \quad \text{length contraction}$$

$$t = t_0 \gamma \quad \text{time dilatation}$$

$$E^2 = \vec{p}^2 + m^2$$
$$E = m\gamma \quad \vec{p} = m\gamma\vec{\beta}$$
$$\vec{\beta} = \frac{\vec{p}}{E}$$

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:

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

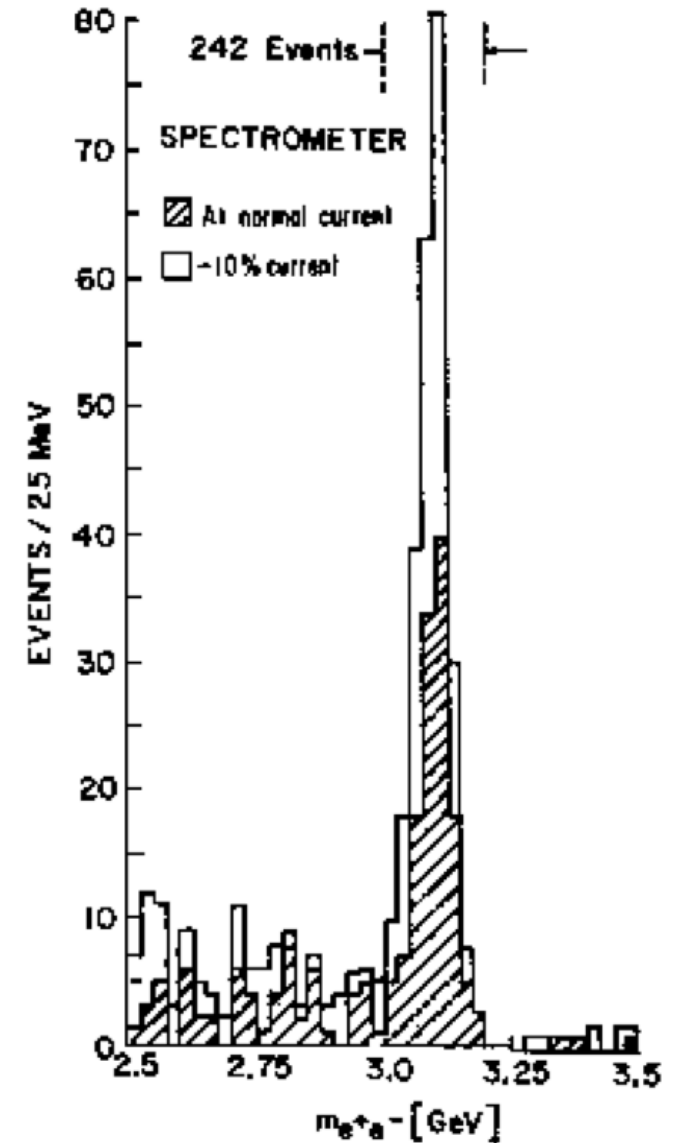
Hint: it can be computed as the “length” of the total four-momentum, that is invariant:

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

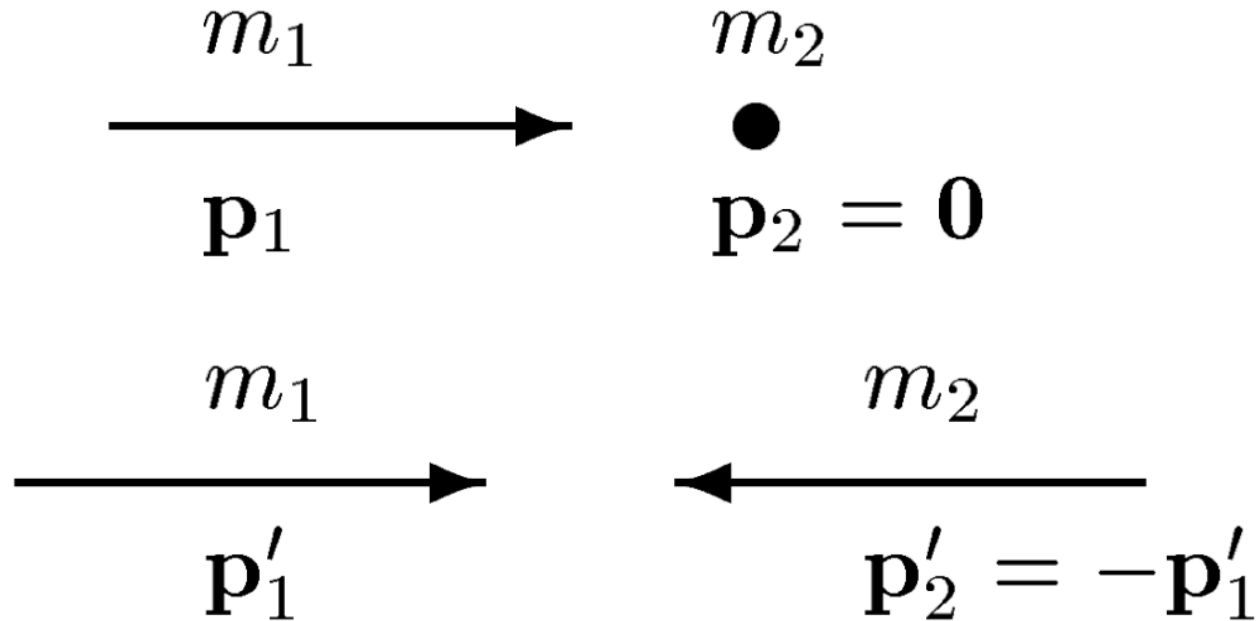
What is the “length” of a the four-momentum of a particle?

Invariant mass

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



Fixed target vs. collider

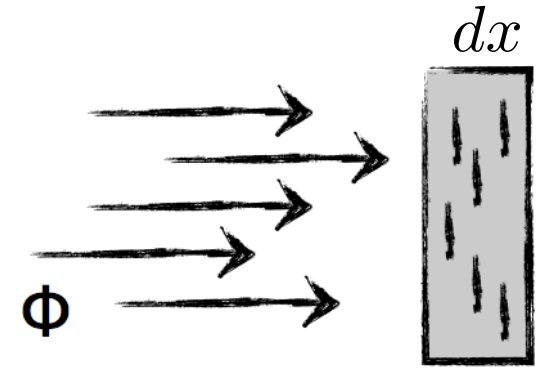


How much energy should a fixed target experiment have to equal the center of mass energy of two colliding beam?

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

Interaction cross section

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



Reactions per unit of time $\frac{dN_{\text{reac}}}{dt} = \Phi \overbrace{\sigma N_{\text{target}} dx}^{\text{area obscured by target particle}}$ $[t^{-1}]$

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

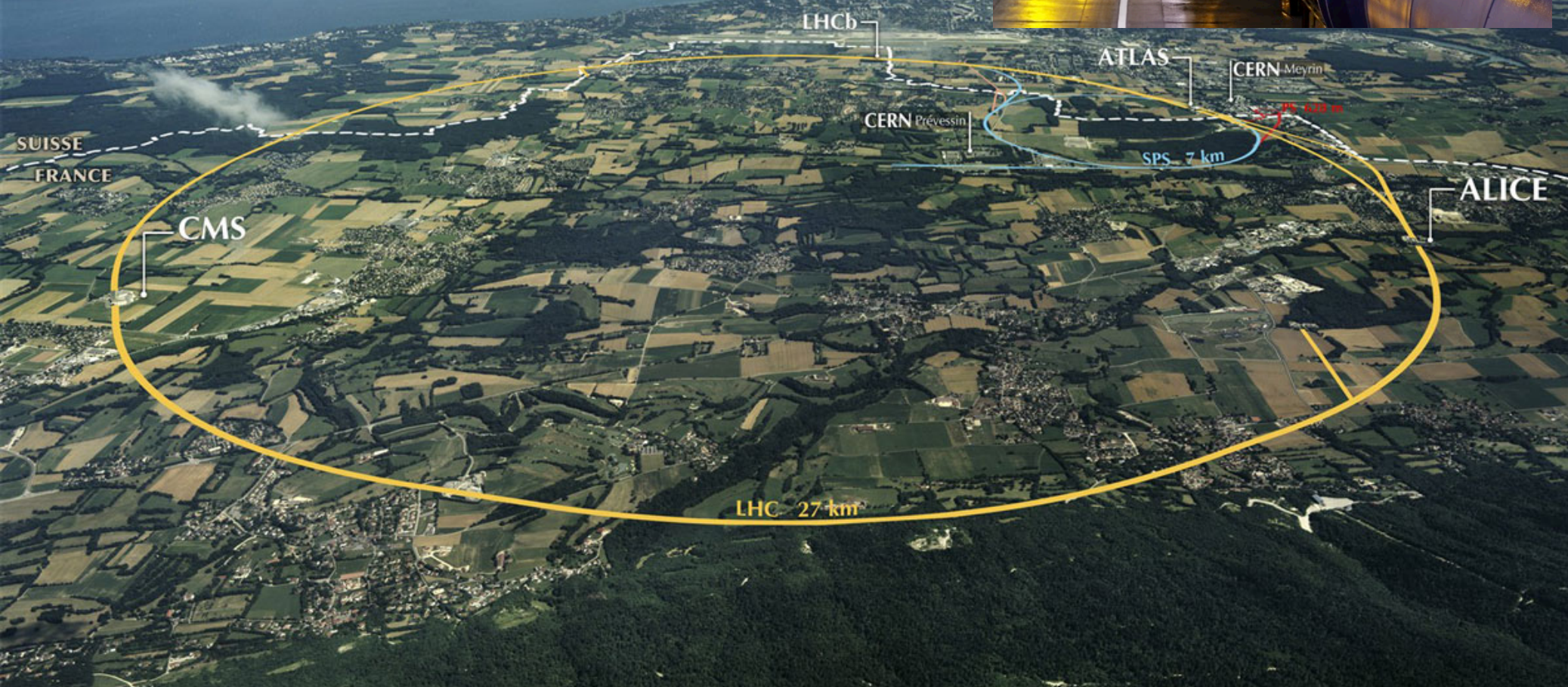
Reaction rate per target particle $W_{if} = \Phi \sigma$ $[t^{-1}]$

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

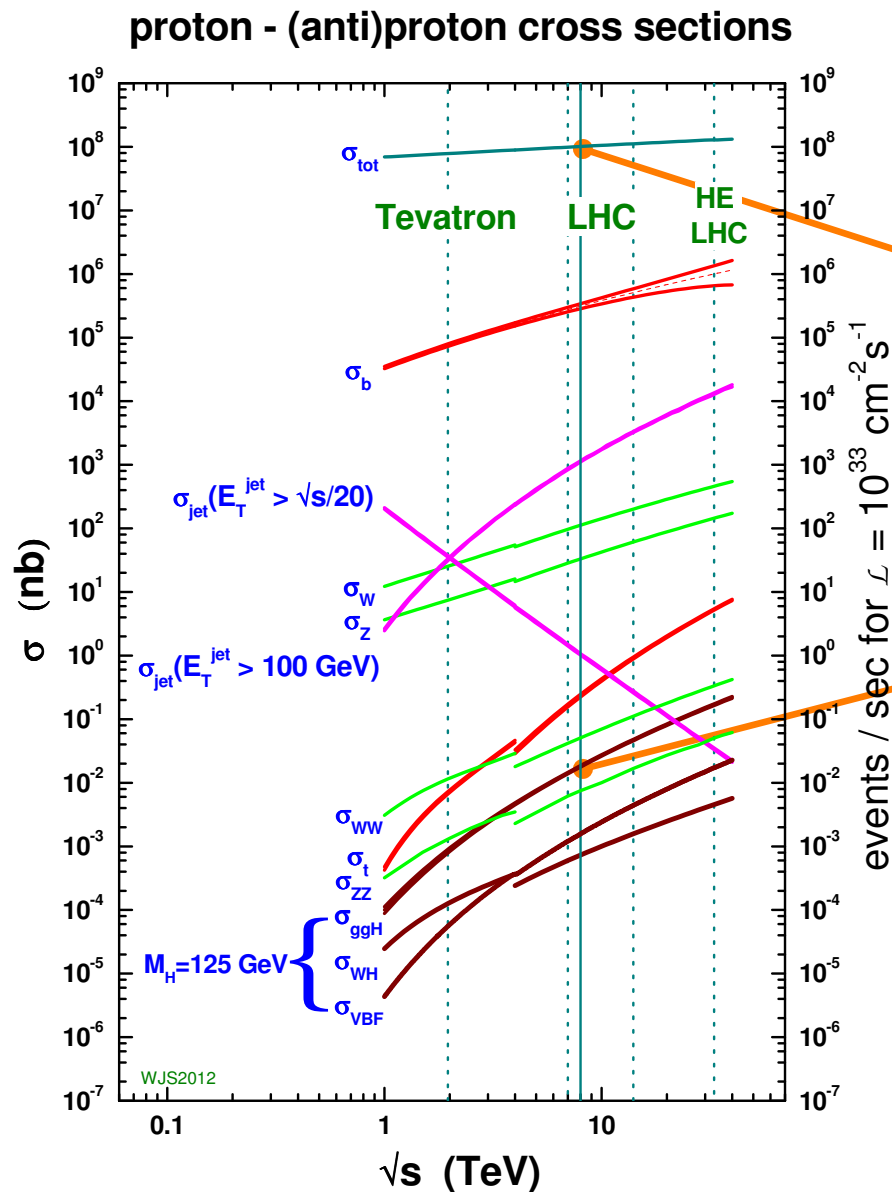
$1b = 10^{-28} \text{ m}^2$ (roughly the area of a nucleus with $A = 100$)

LHC

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



Cross-sections at LHC



10^8 events/s

$\sim 10^{10}$

10^{-2} events/s $\sim$

10 events/min

$[m_H \sim 125 \text{ GeV}]$

0.2% $H \rightarrow \gamma\gamma$

1.5% $H \rightarrow ZZ$

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

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

$[\text{t}^{-1}]$

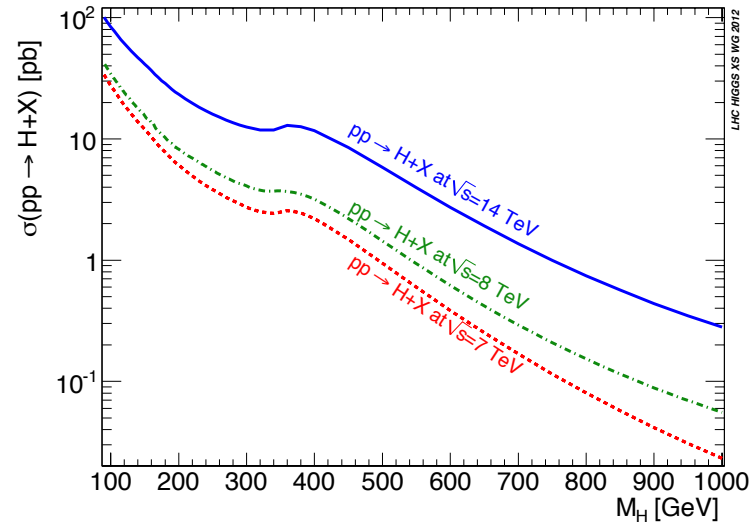
?

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

$10^{34} \text{ cm}^{-2} \text{ s}^{-1}$

$[\text{L}^2]$

$\sigma(\text{pp} \rightarrow \text{H}+\text{X}) \sim 20 \text{ pb}$



In a collider ring...

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

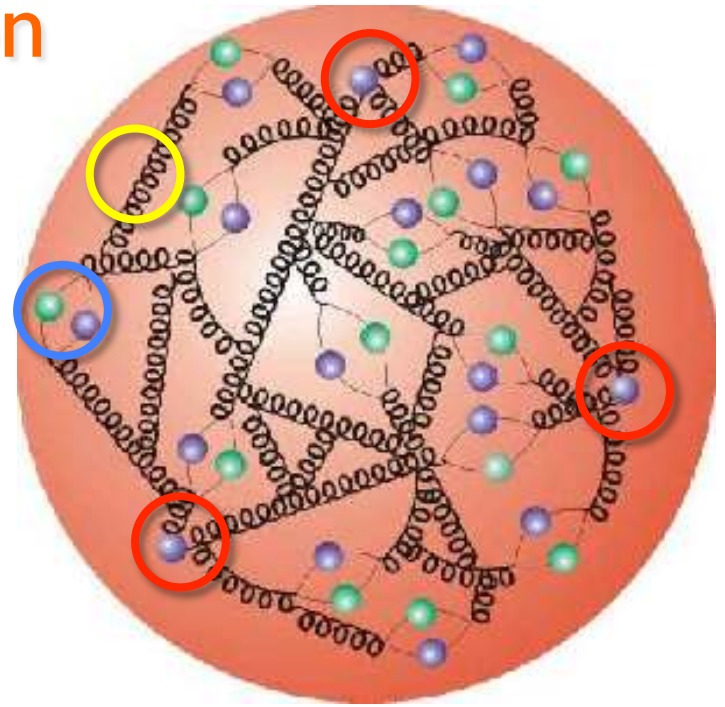
Current

Beam sizes (RMS)

About the inner life of a proton

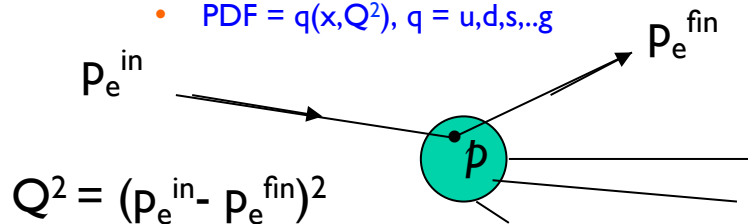
- **protons have substructures**

- ✓ 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



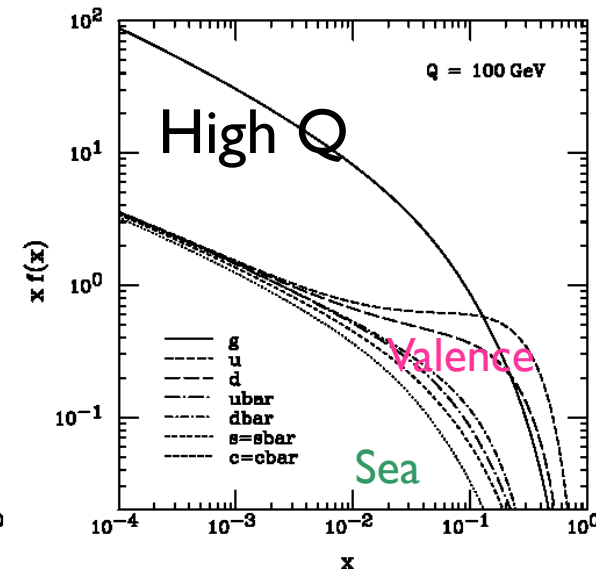
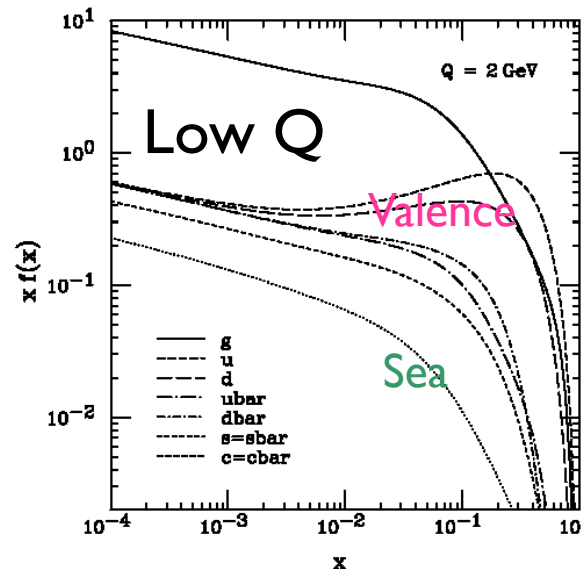
- **Parton energy not 'monochromatic'**

- ✓ Parton Distribution Function
 - $PDF = q(x, Q^2)$, $q = u, d, s, \dots g$



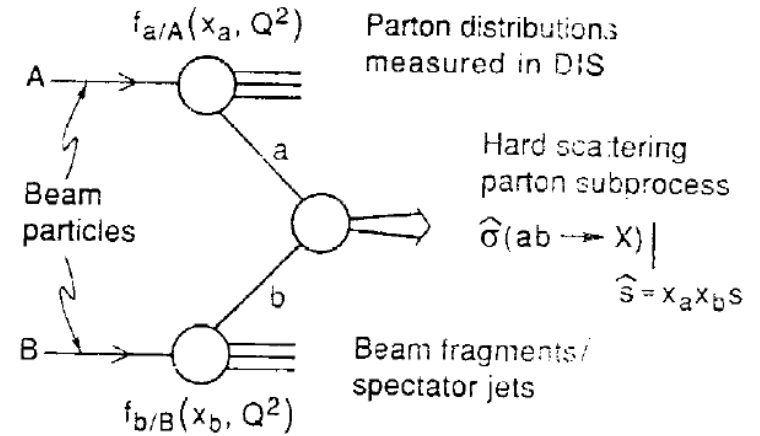
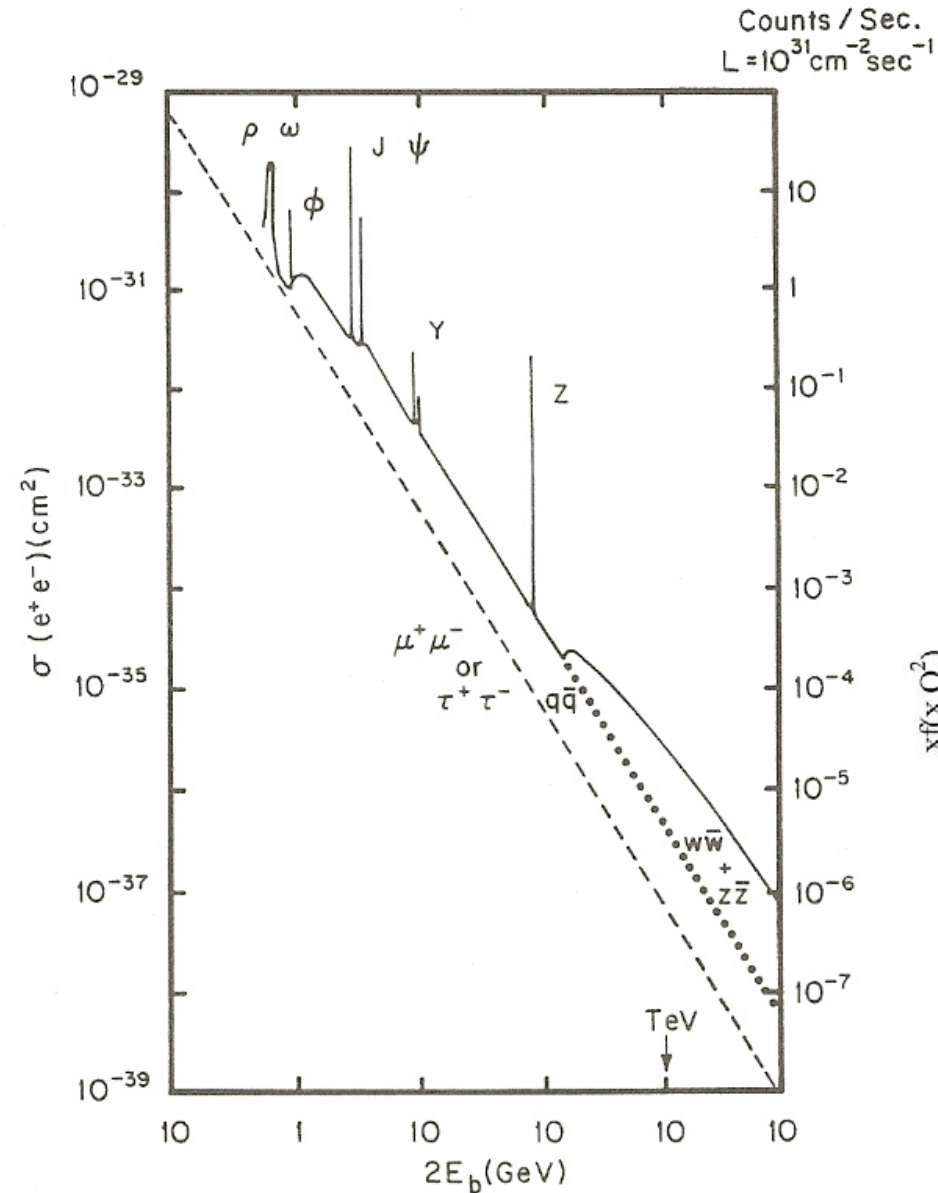
- **Kinematic variables**

- ✓ Bjorken- x : fraction of the proton momentum carried by struck parton
 - $x = p_{\text{parton}}/p_{\text{proton}}$
- ✓ Q^2 : 4-momentum² transfer



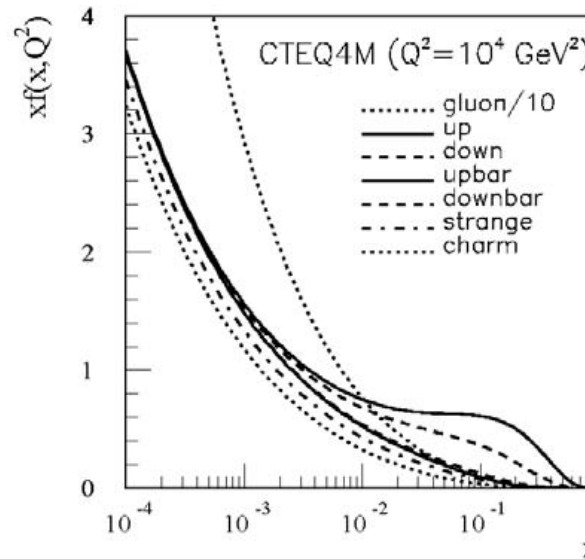
(experimental) LHC physics

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 $M = 100 \text{ GeV}$

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

$$\sqrt{s} = 14 \text{ TeV} \rightarrow x = 0.007$$

$$\sqrt{s} = 5 \text{ TeV} \rightarrow x = 0.36$$

e^+e^- vs. hadron collider

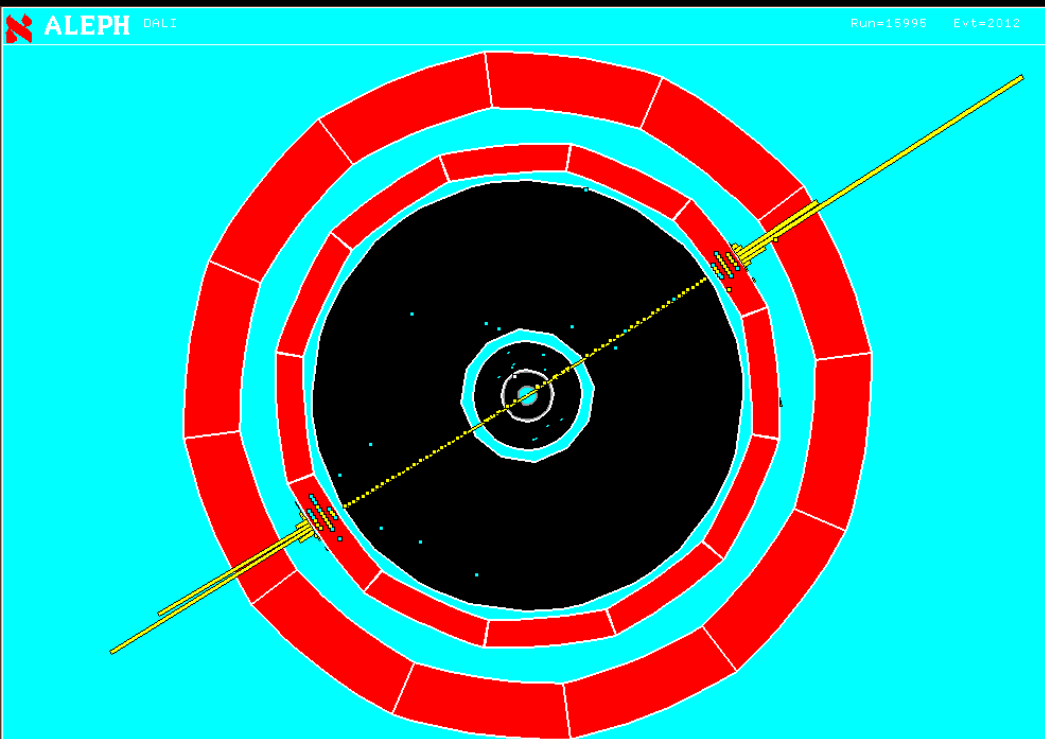
• e^+e^- collider

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

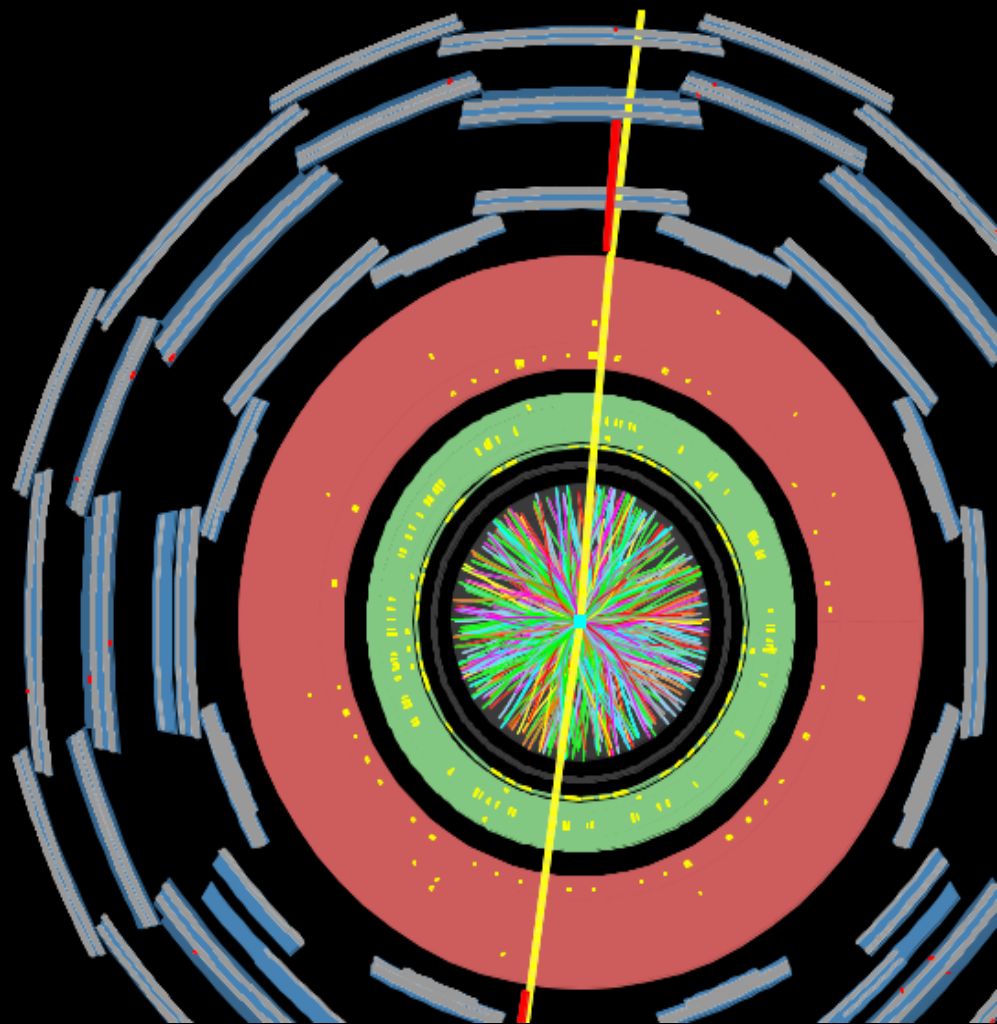
• Hadronic collider

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

ALEPH @ LEP

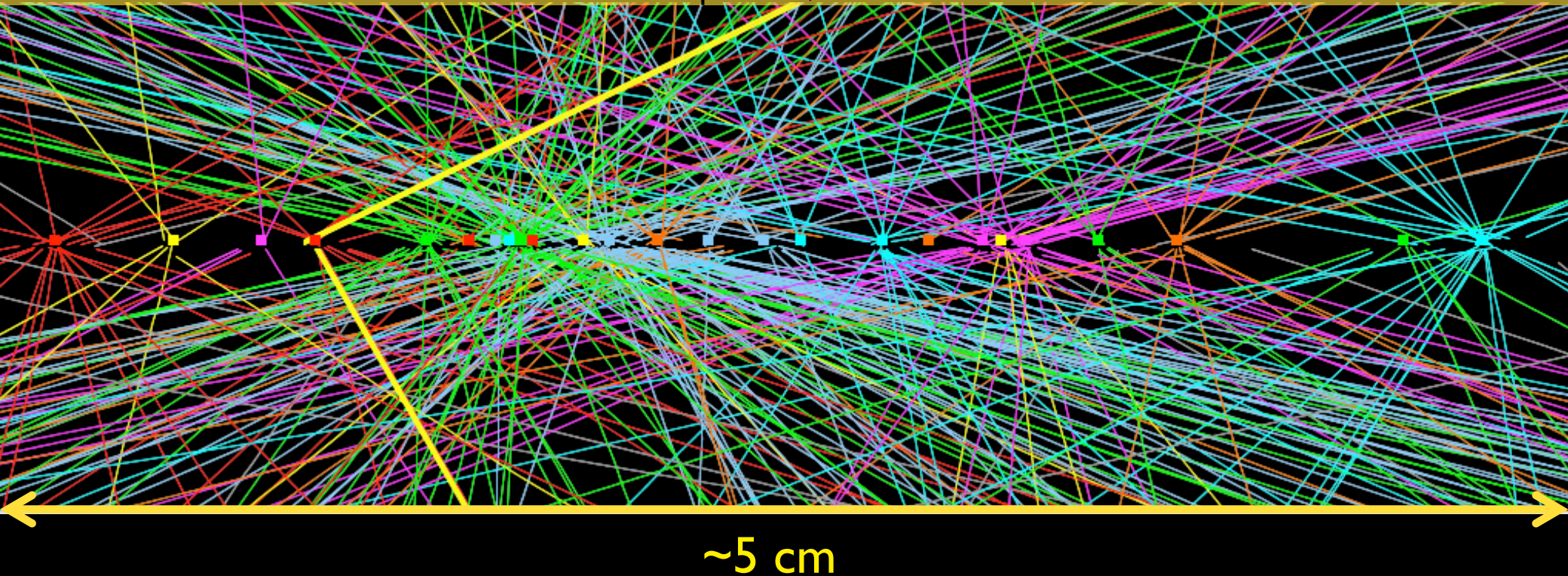


ATLAS @ LHC



$Z \rightarrow \mu\mu$ event with 25 reconstructed vertices

April 15th, 2012



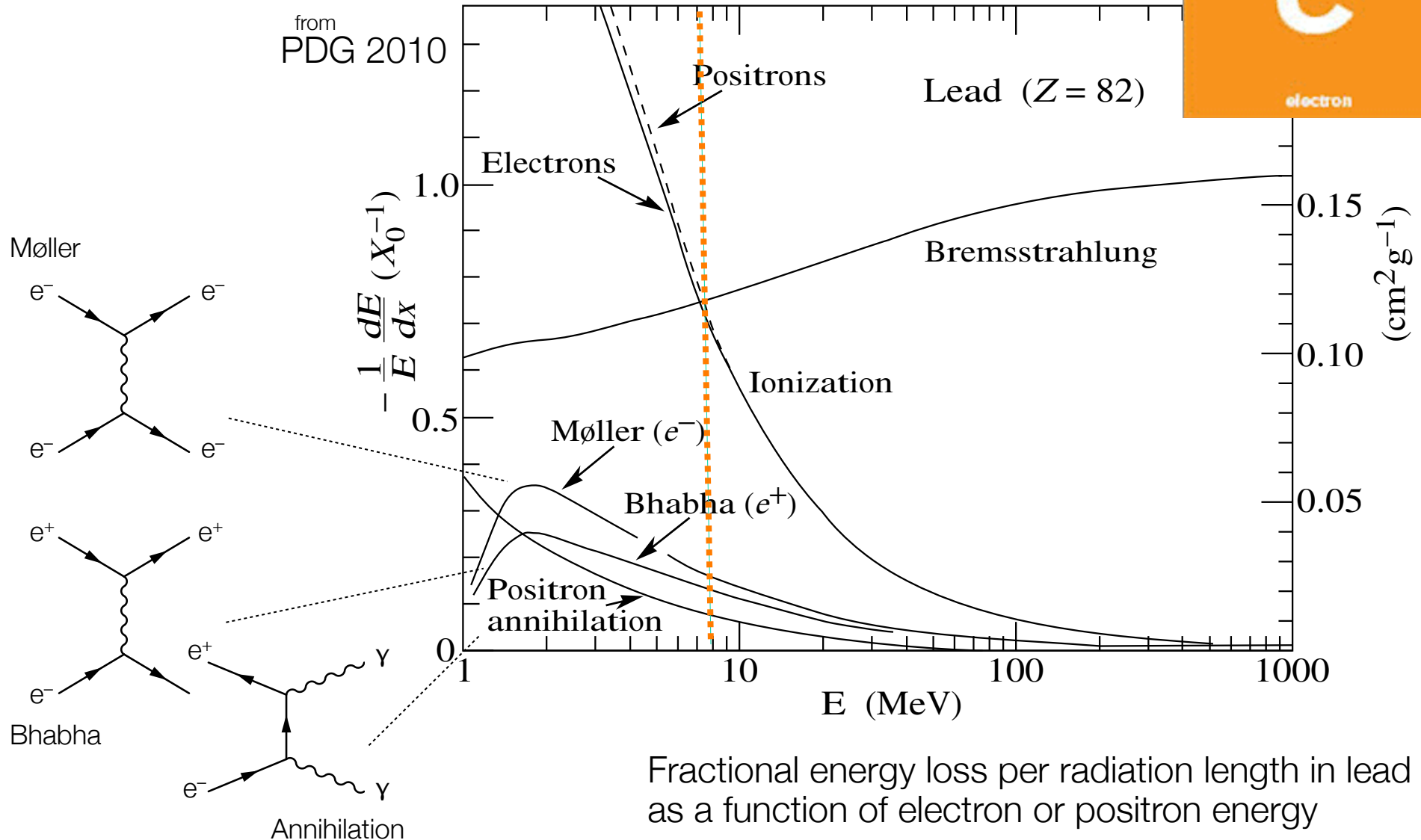
Electron energy loss

1897: Cavendish Laboratory

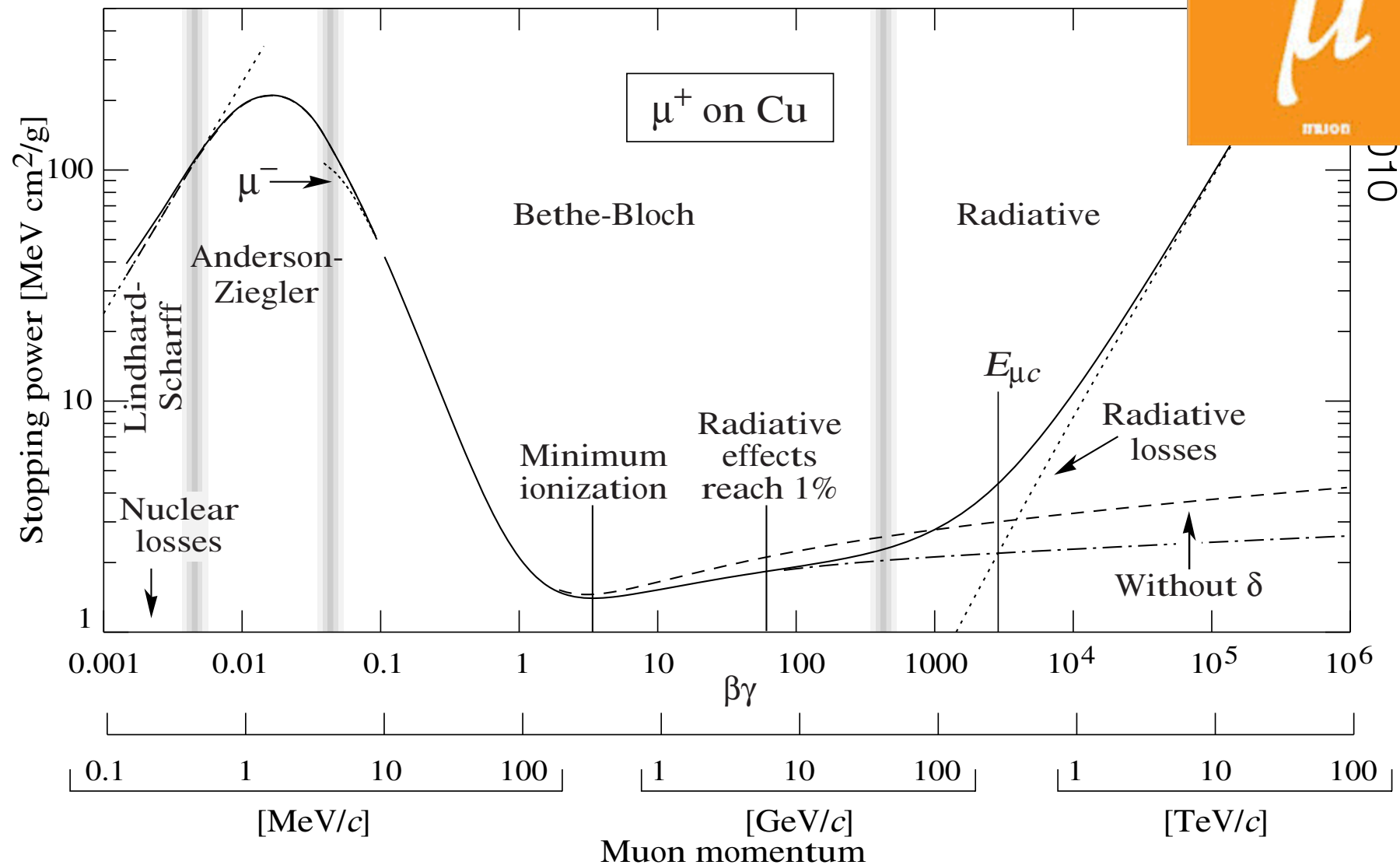
e

electron

from
PDG 2010

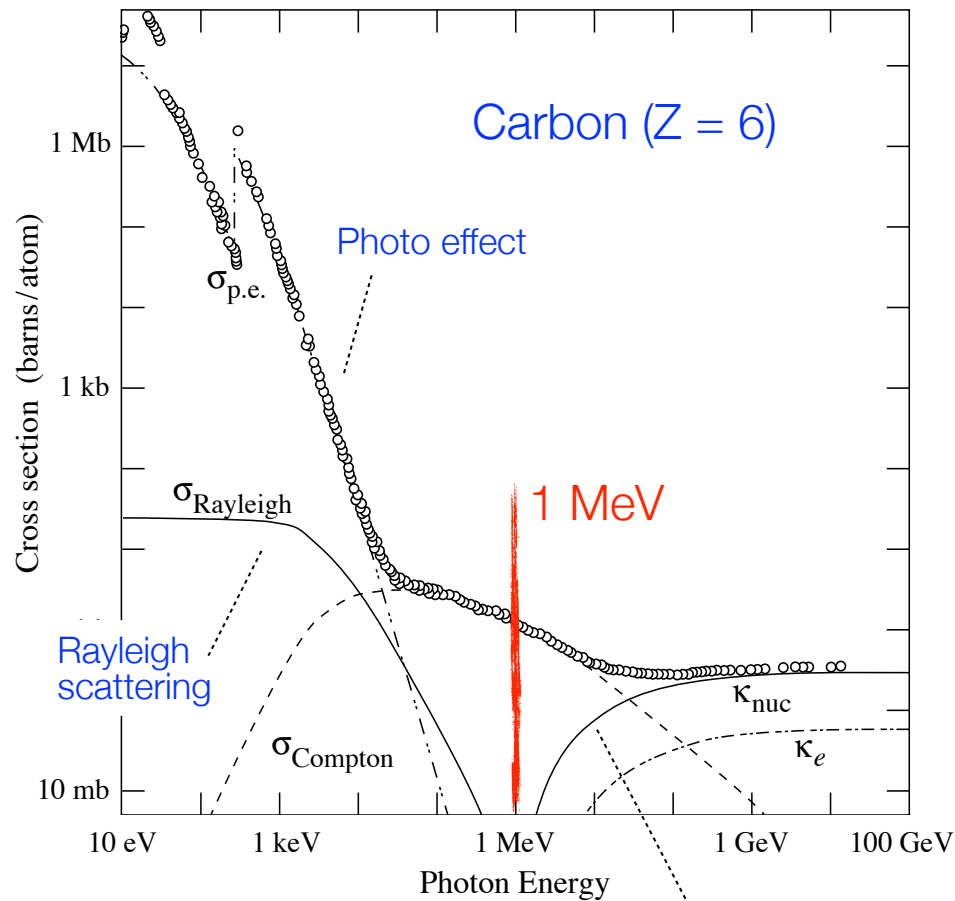


Muon energy loss

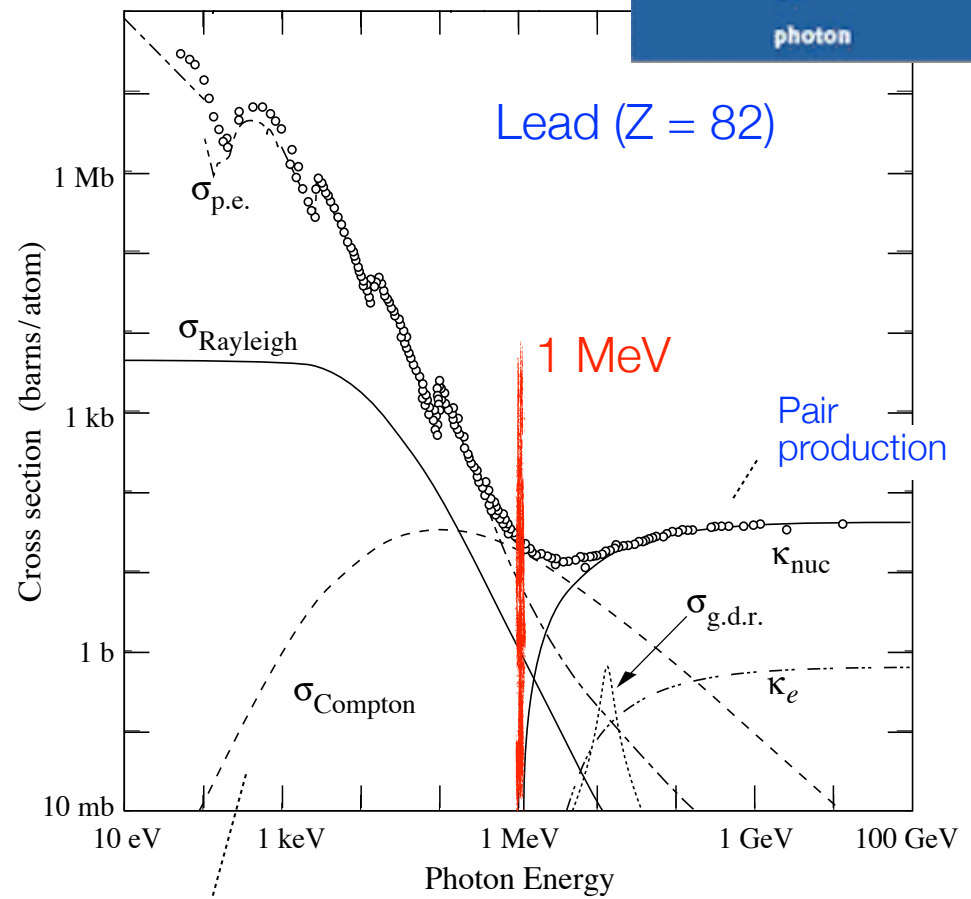


010

Interaction of photons with matter



Pair Production



Compton scattering

Pair production

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...



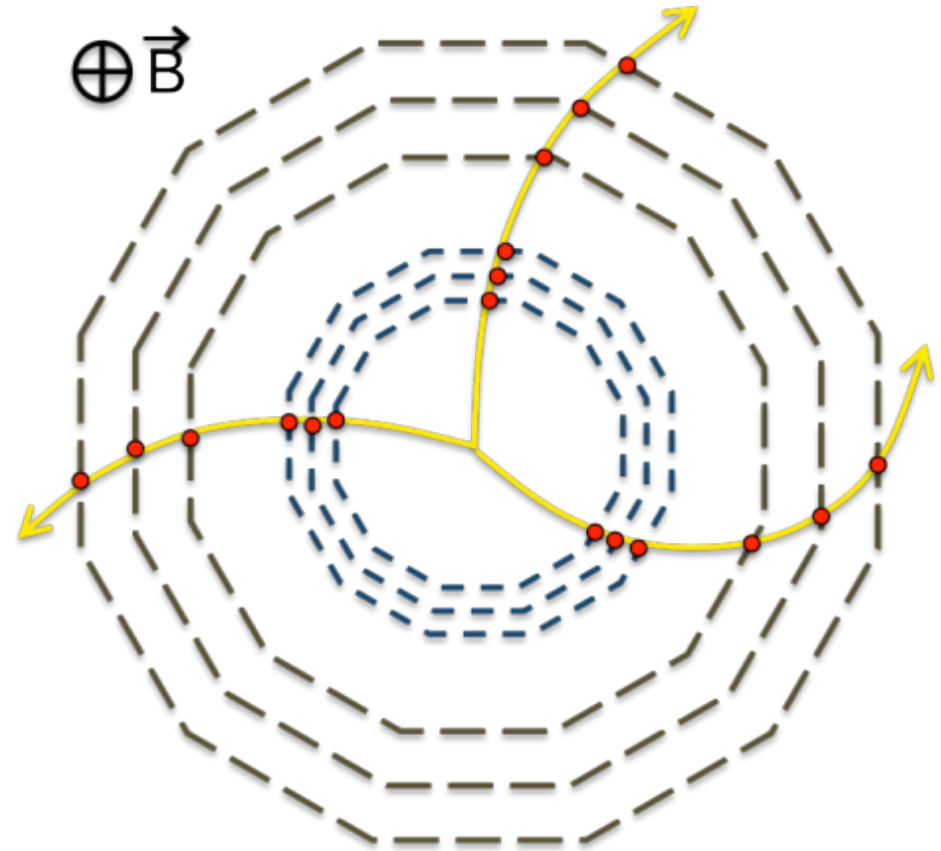
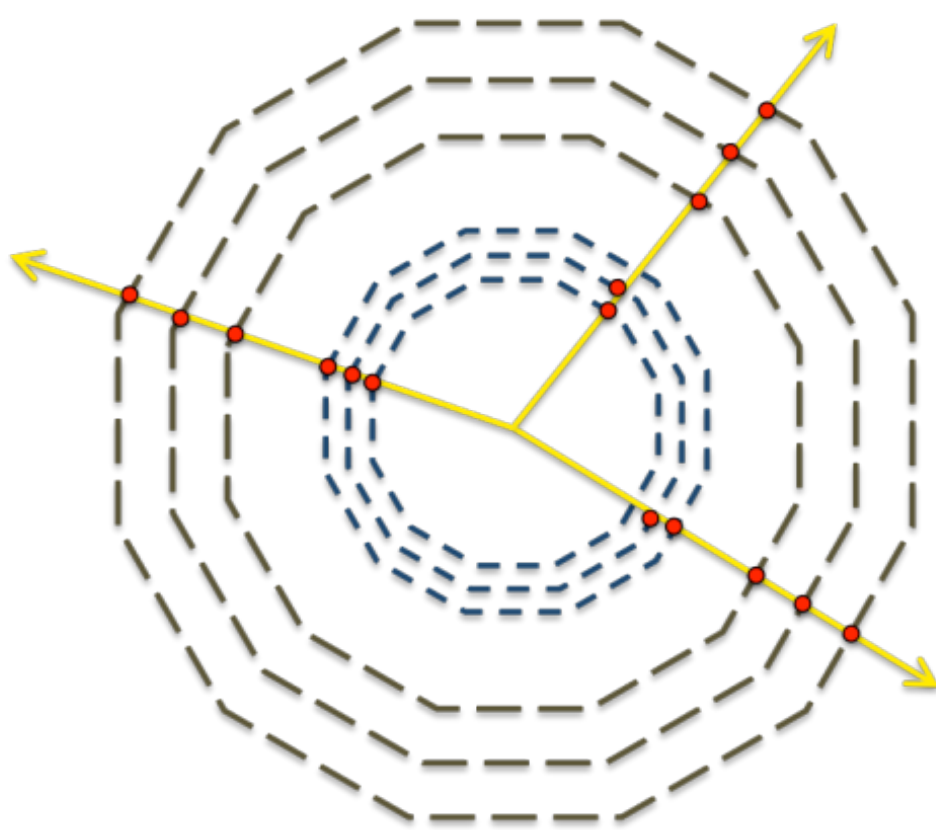
- electrically neutral
- pair production
 - ✓ $E > 1 \text{ MeV}$
- *electromagnetic shower...*



- 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



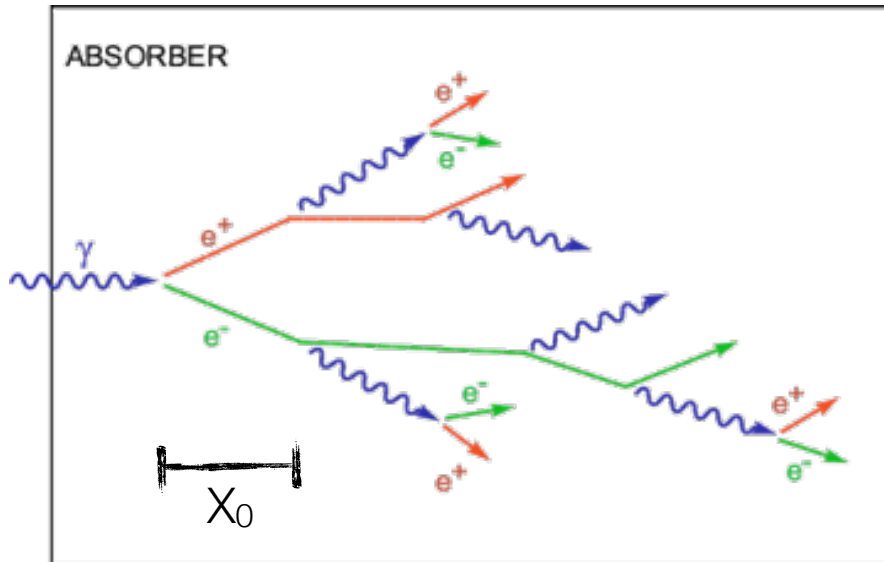
$$p[\text{GeV}] = 0.3B[\text{T}]\rho[\text{m}]$$

Calorimeters for showering particles

- Electromagnetic shower

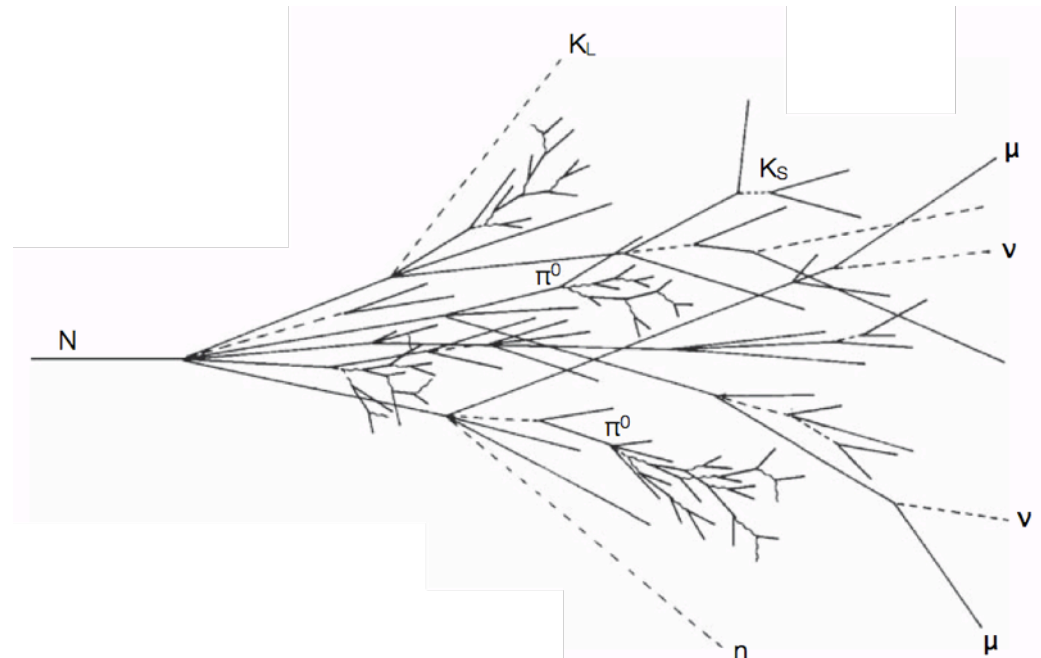
- ✓ Photons: pair production
 - Until below e^+e^- threshold
- ✓ Electrons: bremsstrahlung
 - Until brem cross-section smaller than ionization

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

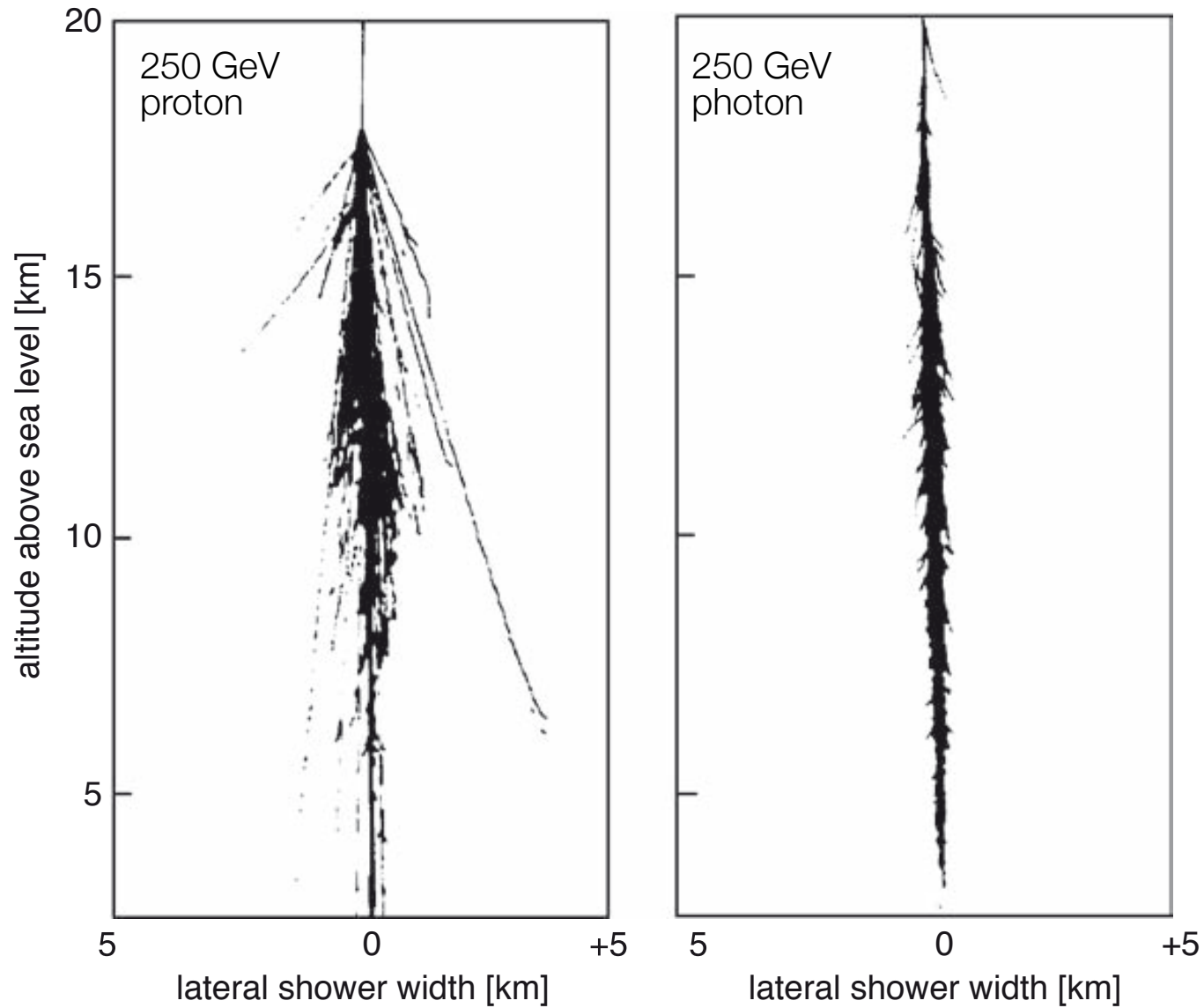


- Hadronic showers

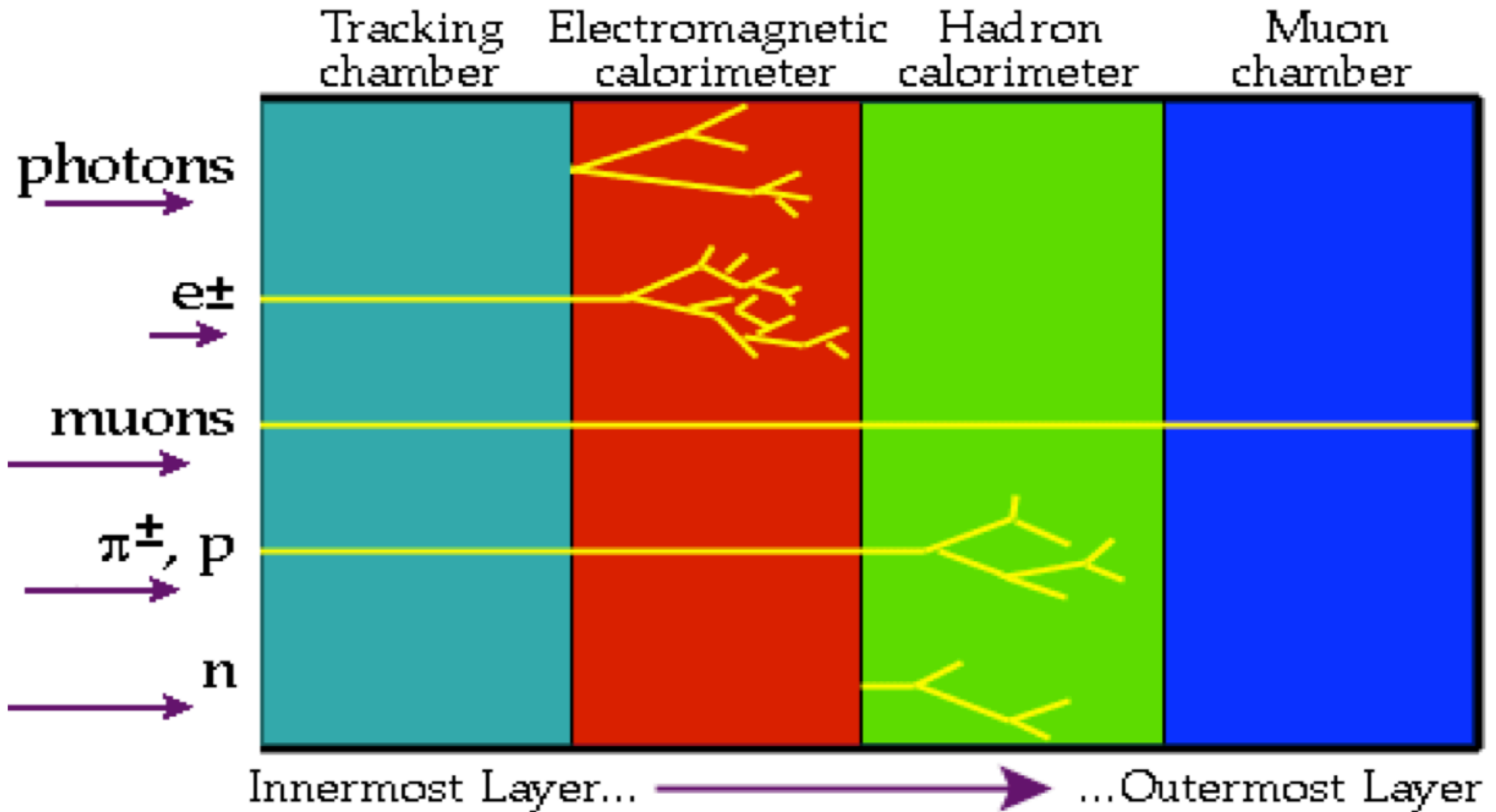
- ✓ Inelastic scattering w/ nuclei
 - Further inelastic scattering until below pion production threshold
- ✓ Sequential decays
 - $\pi^0 \rightarrow \gamma\gamma$
 - Fission fragment: β -decay, γ -decay
 - Neutron capture, spallation, ...



Hadronic vs. EM showers

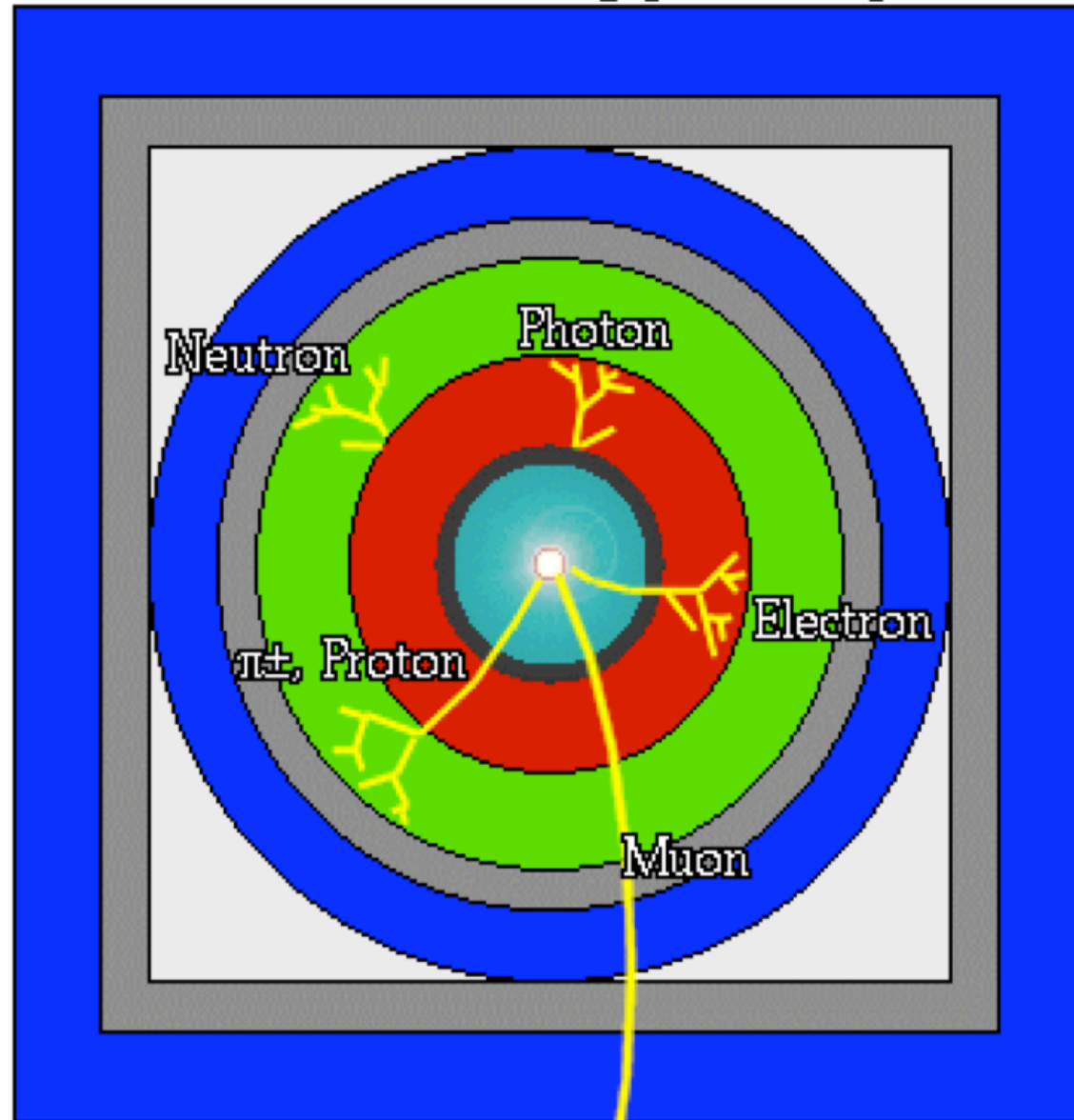


How do we “see” particles?

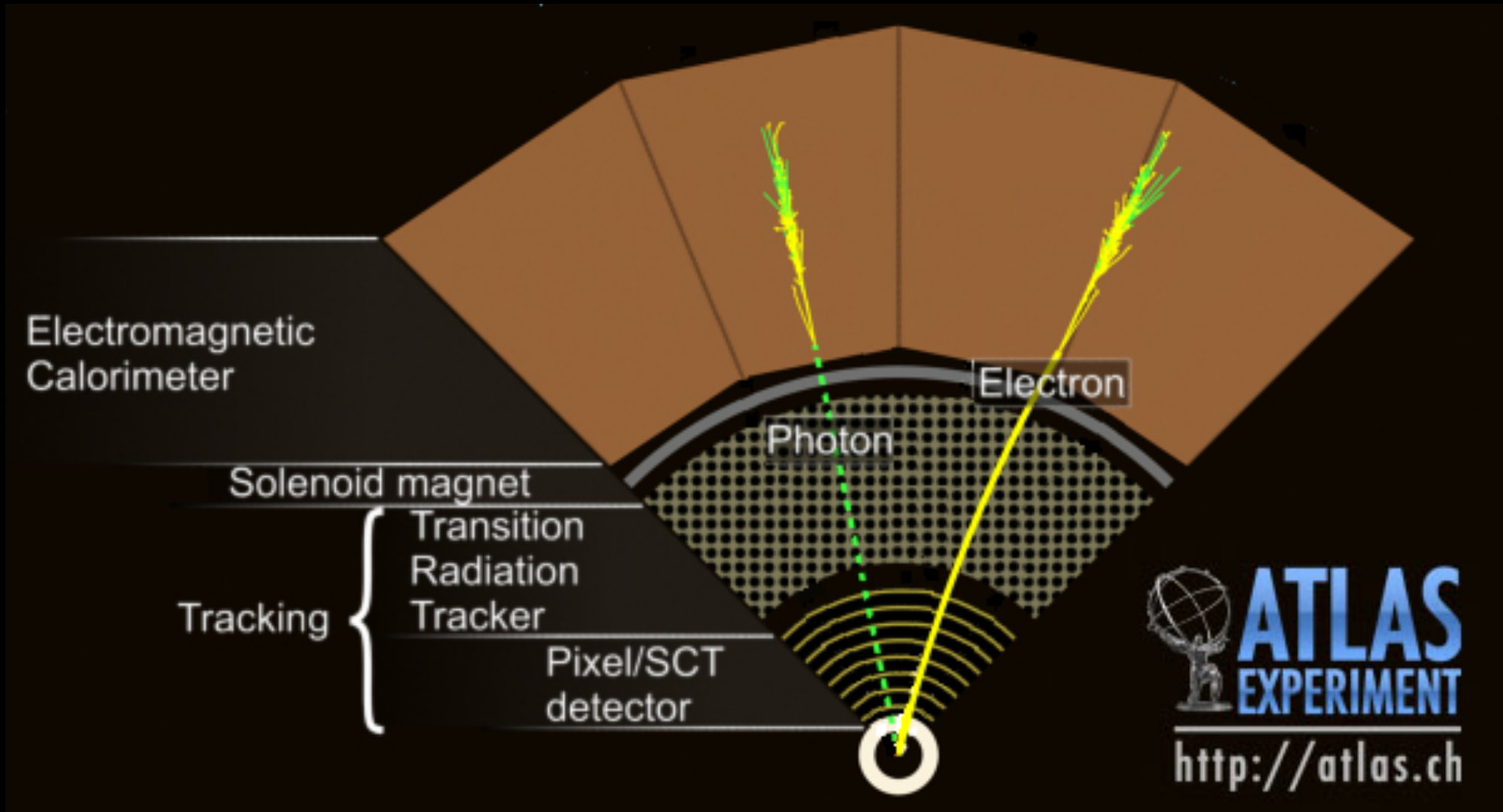


How do we “see” particles?

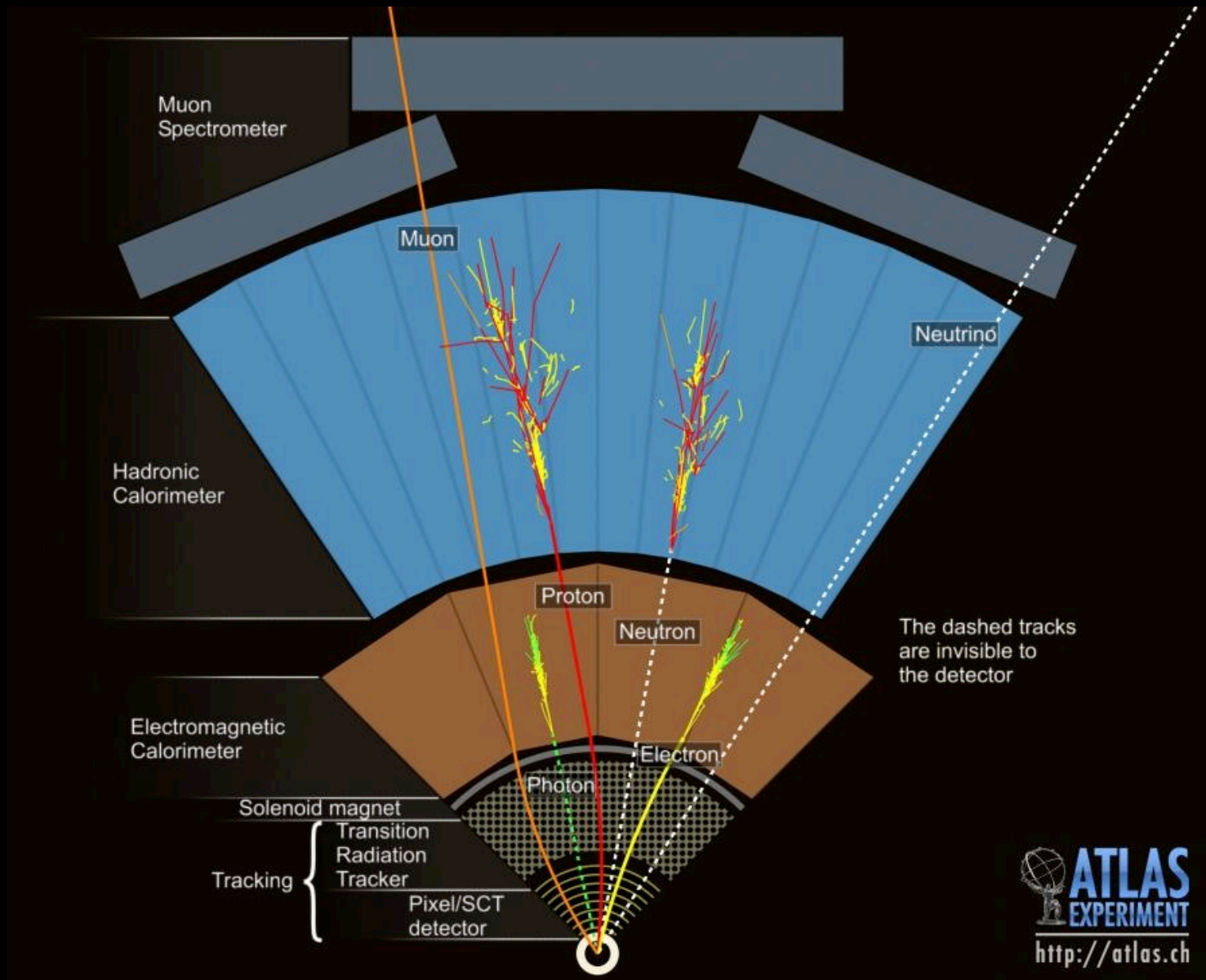
- Beam Pipe (center)
- Tracking Chamber
- Magnet Coil
- E-M Calorimeter
- Hadron Calorimeter
- Magnetized Iron
- Muon Chambers



Particle identification with tracker and EM calo



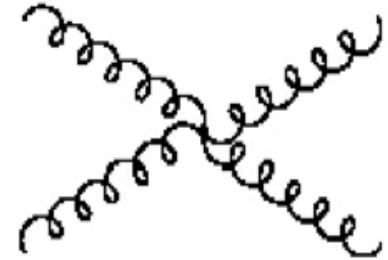
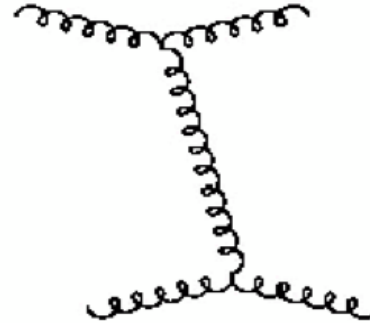
Particle identification with EM and HAD calos



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**

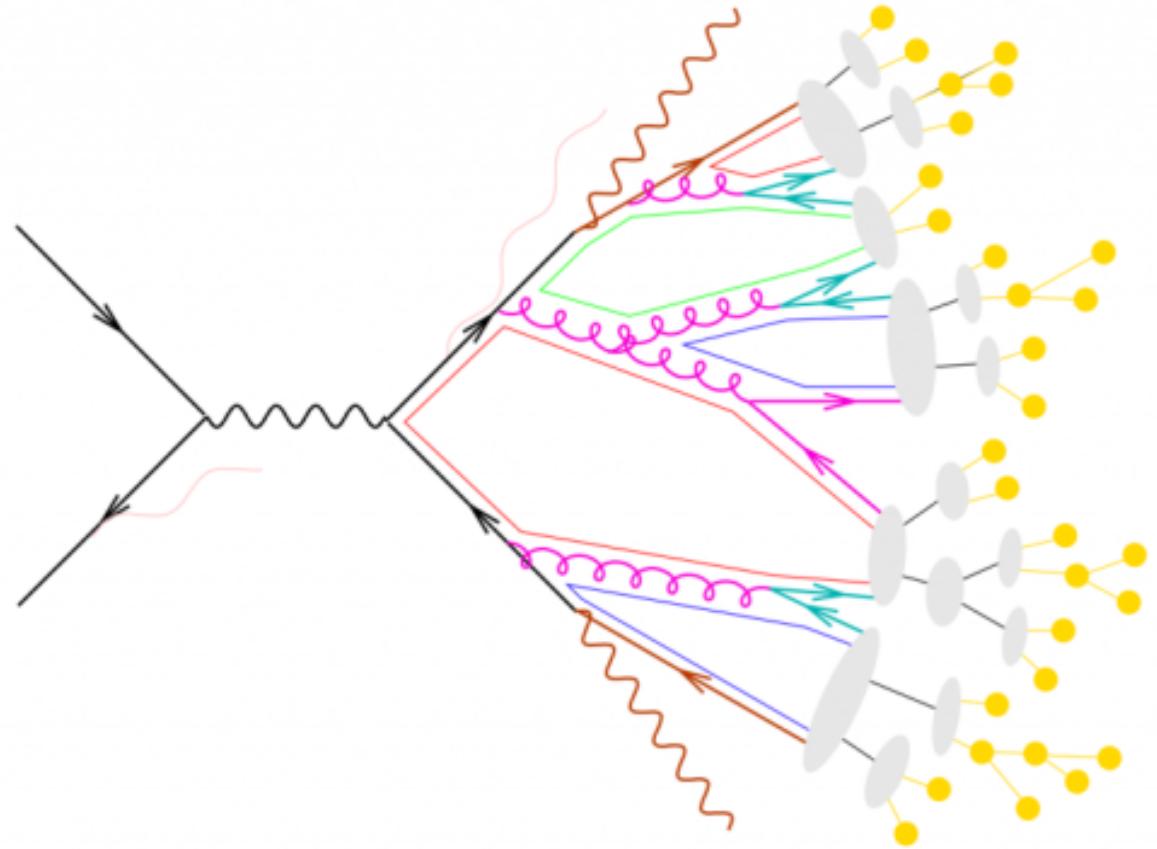
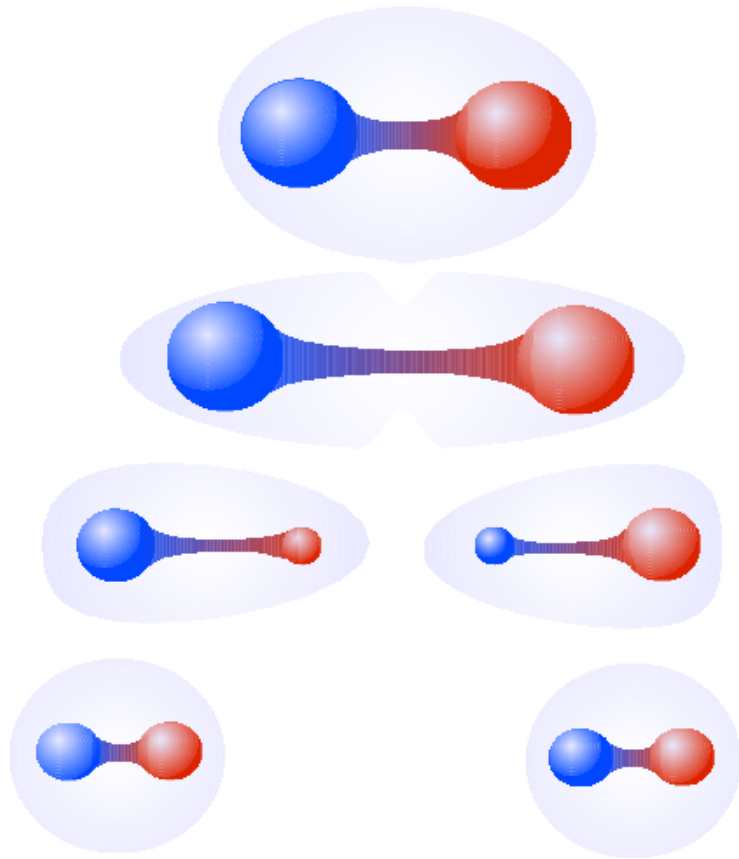
- ✓ At short distances strong interactions are weak
 - Quarks and gluons are essentially free particles
 - Perturbative regime (can calculate!)
- ✓ At large distances, higher-order diagrams dominate
 - Interaction is very strong
 - Perturbative regime fails, have to resort to effective models

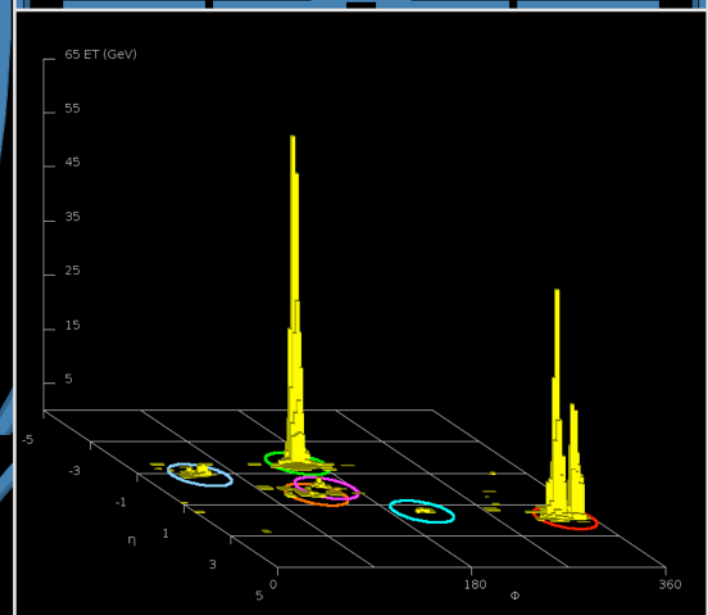
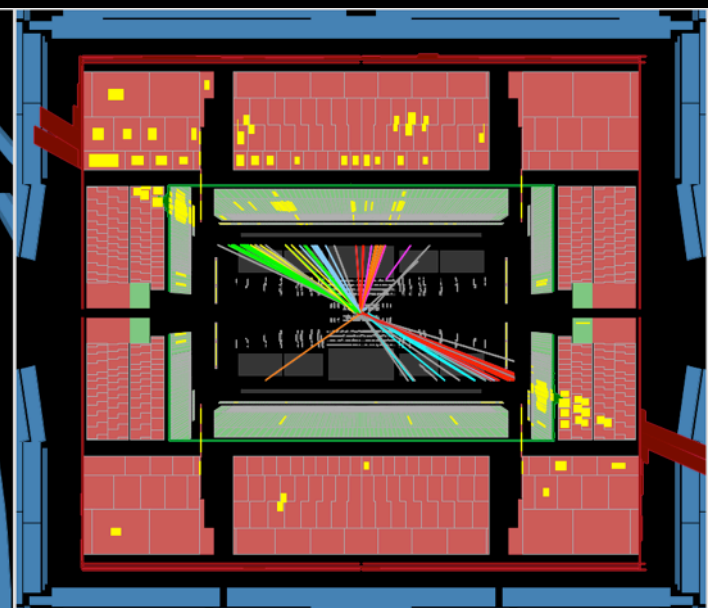
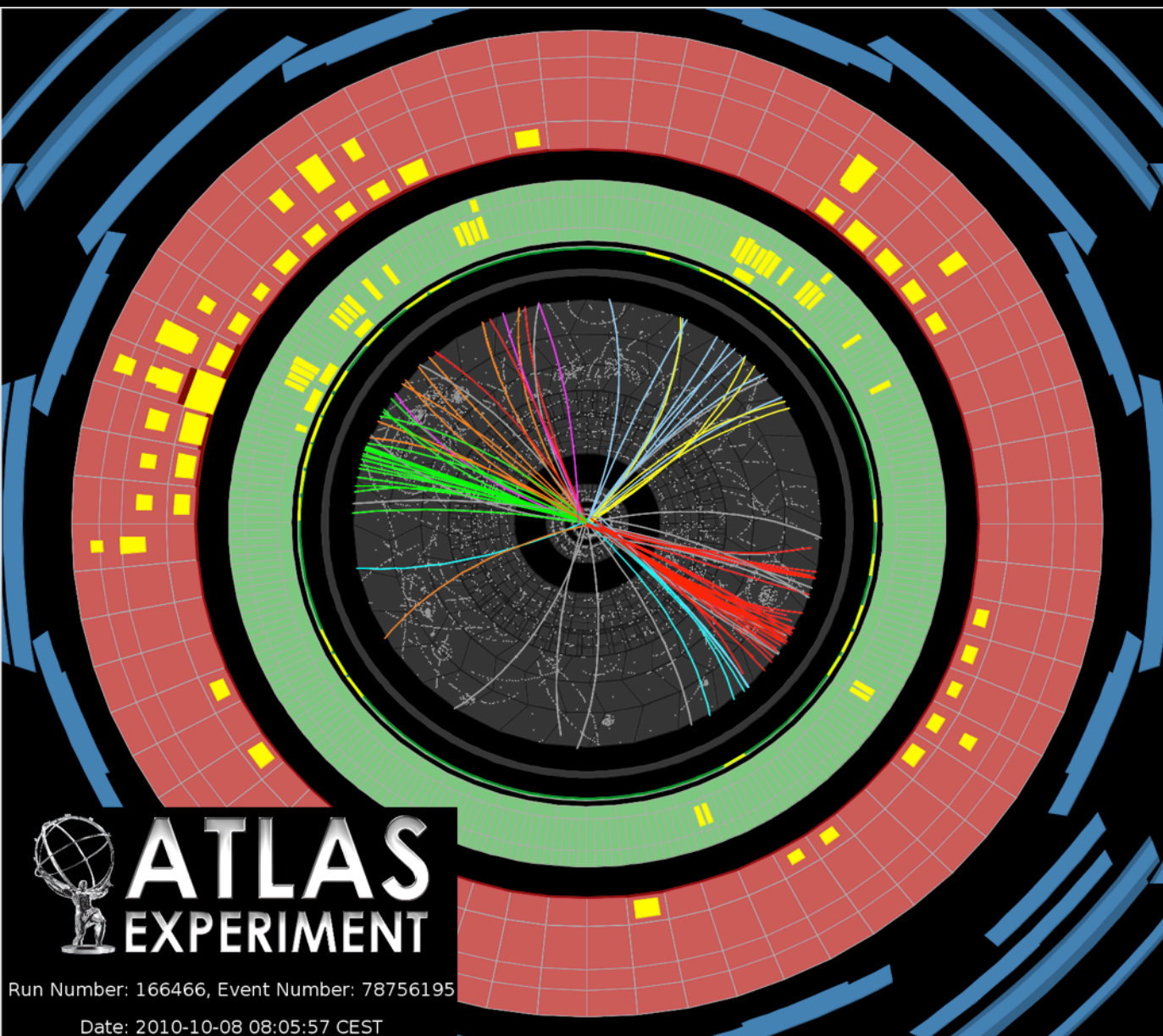
quark-quark effective potential

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

single gluon exchange confinement

Confinement, hadronization, jets

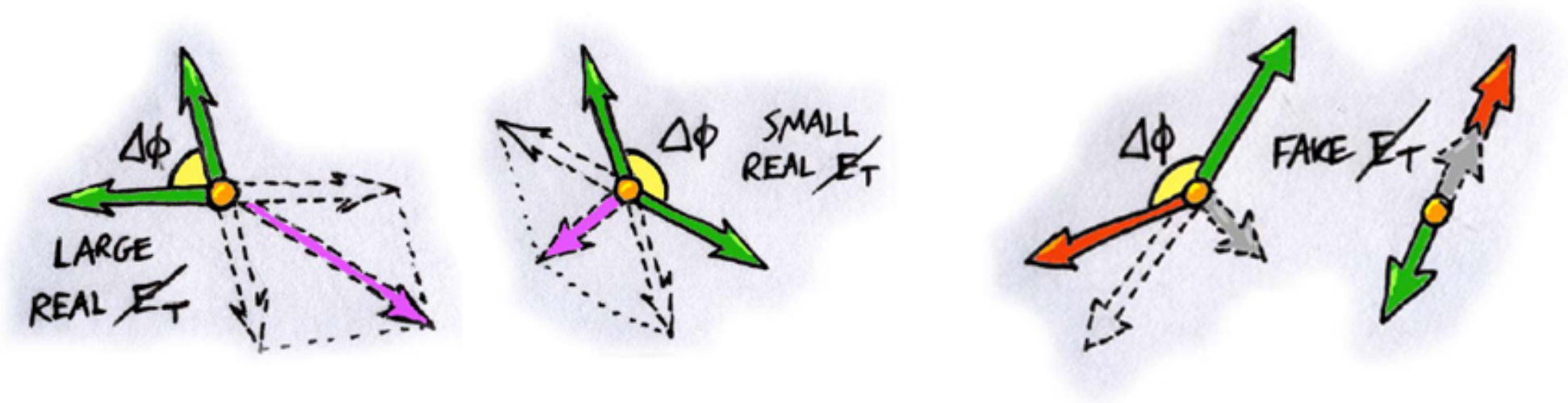




Neutrino (and other invisible particles) at colliders



- Interaction length $\lambda_{\text{int}} = A / (\rho \sigma N_A)$
- Cross section $\sigma \sim 10^{-38} \text{ cm}^2 \times E [\text{GeV}]$
 - ✓ 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*

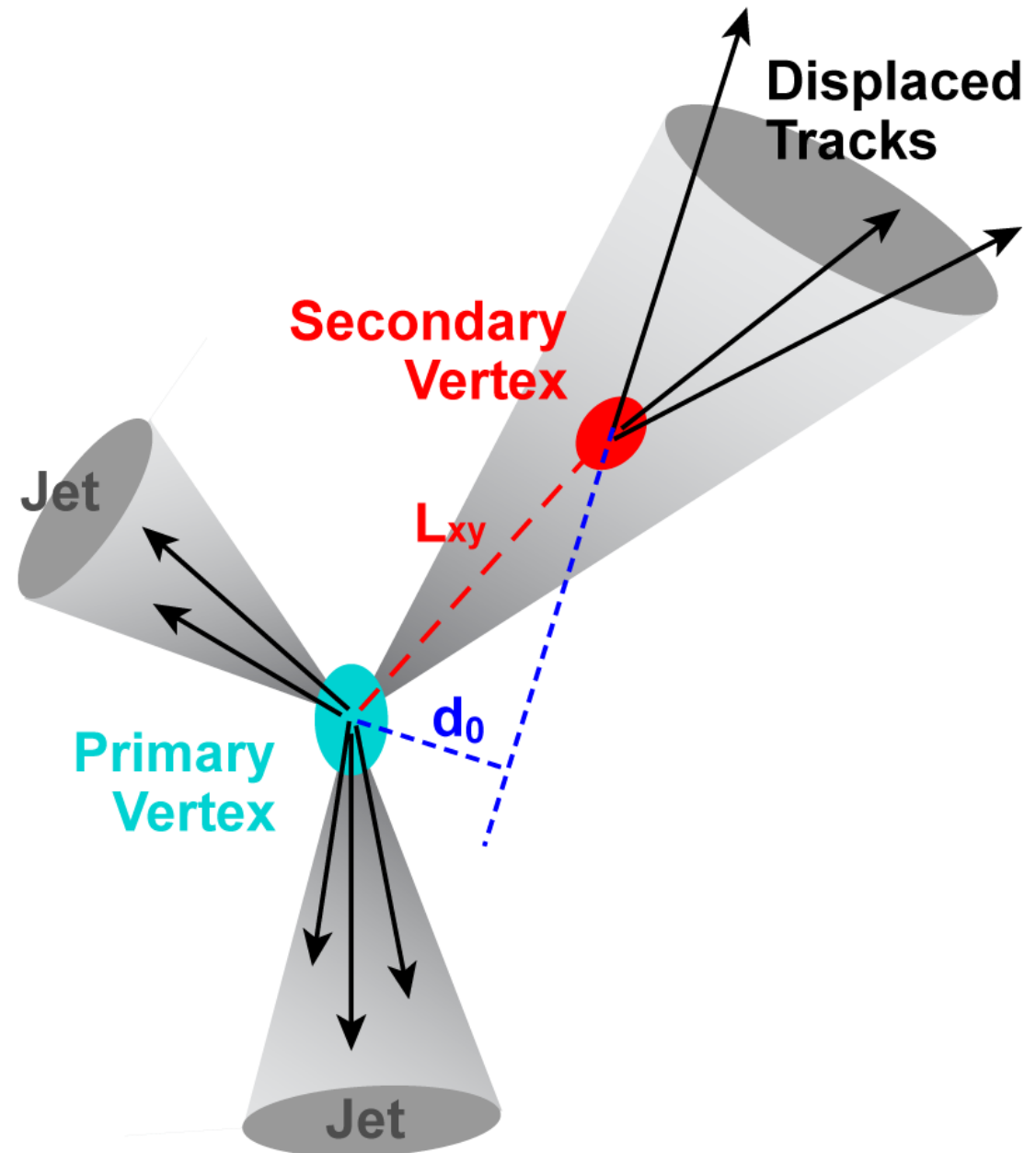


- Missing energy resolution depends on
 - ✓ Detector acceptance
 - ✓ Detector noise and resolution (e.g. calorimeters)

B-tagging



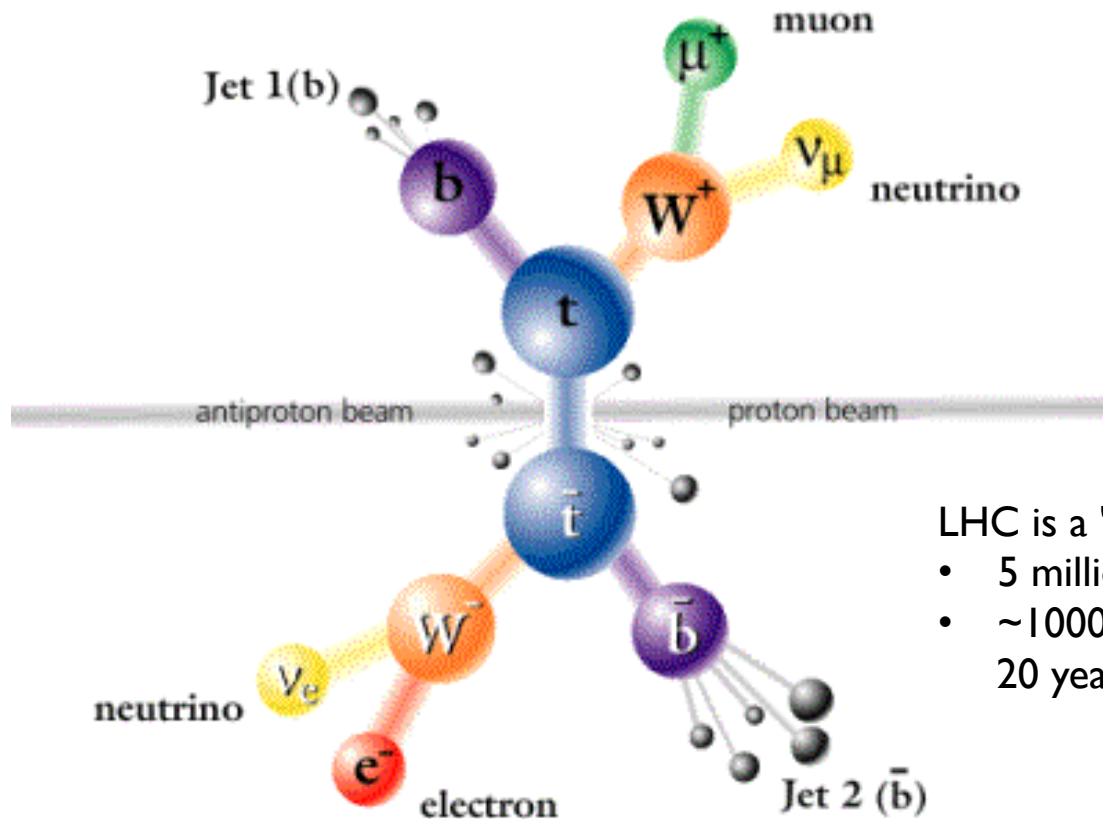
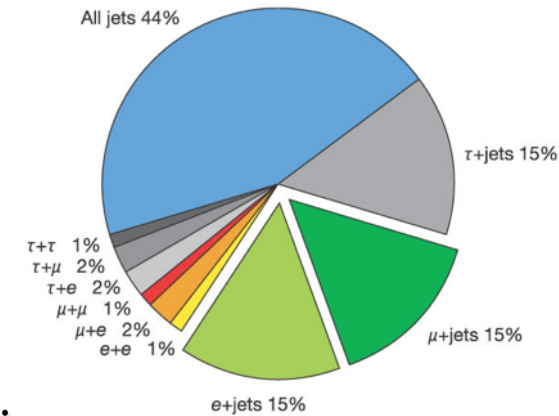
- When a b quark is produced, the associated jet will very likely contain at least one B meson or hadron
- B mesons/hadrons have relatively long lifetime
 - ✓ ~ 1.6 ps
 - ✓ They will travel away from collision point before decaying
- Identifying a secondary decay vertex in a jet allow to tag its quark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



top quark

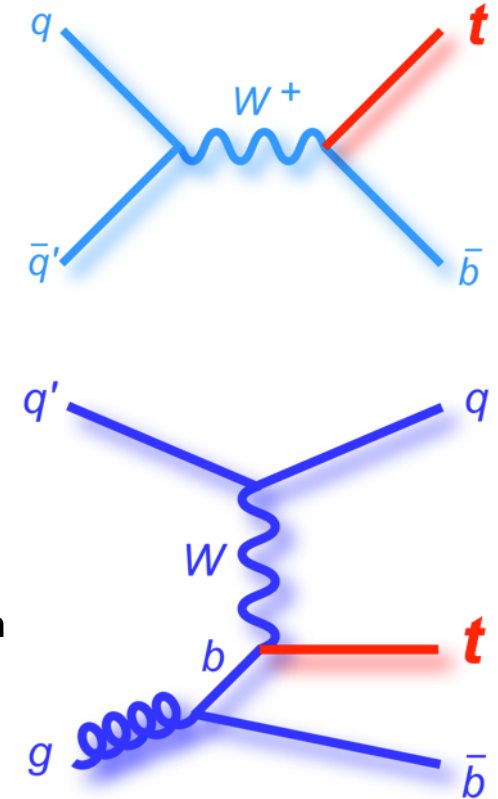


- Mean lifetime $\sim 5 \times 10^{-13}$ ps
 - ✓ Shorter than time scale at which QCD acts: no time to hadronize!
 - ✓ It decays as $t \rightarrow Wb$
- Events with top quarks are very rich in (b) jets...



LHC is a "top factory"!

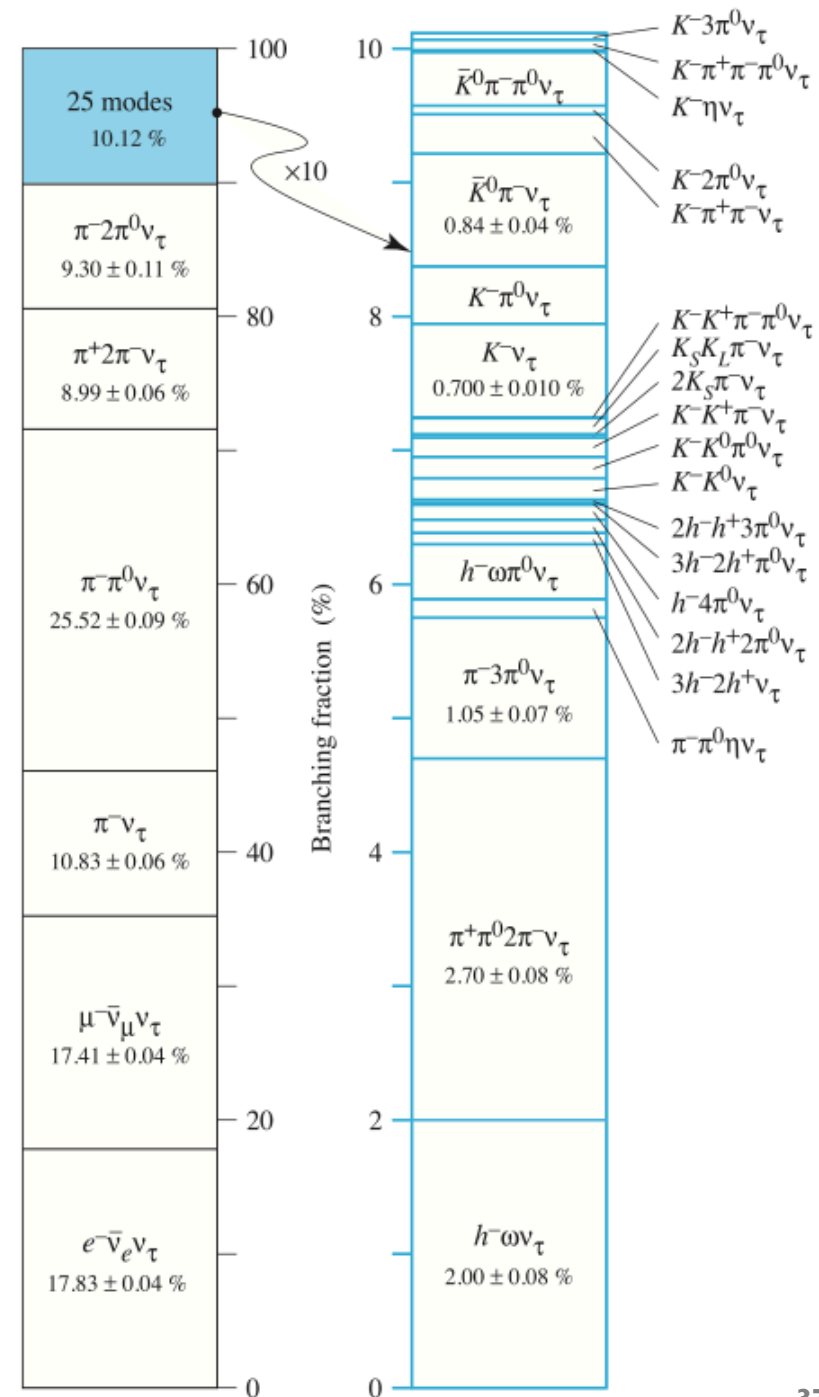
- 5 millions of $t\bar{t}$ pairs
- ~ 100000 in Tevatron in 20 years

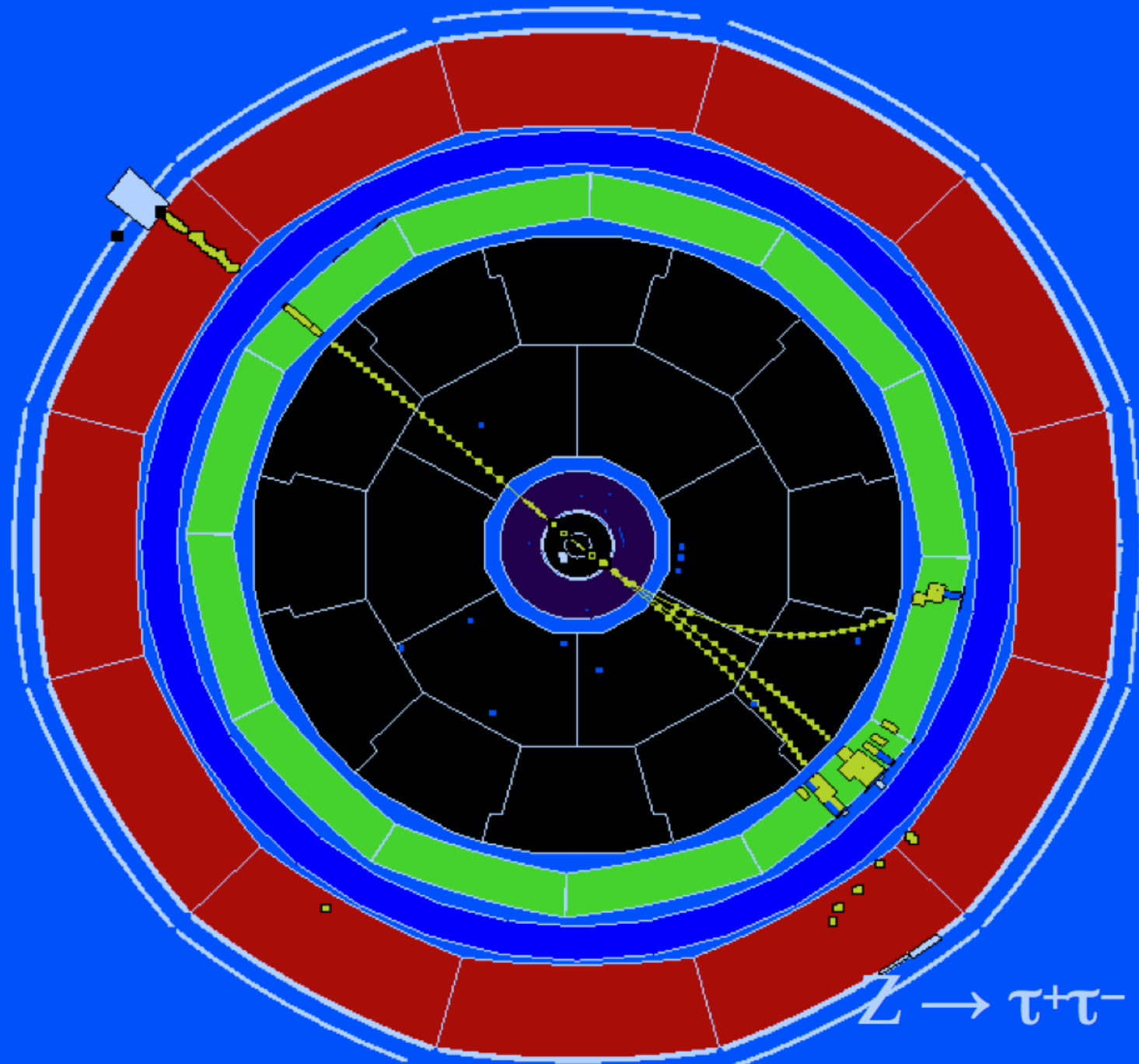


Tau



- 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







“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:

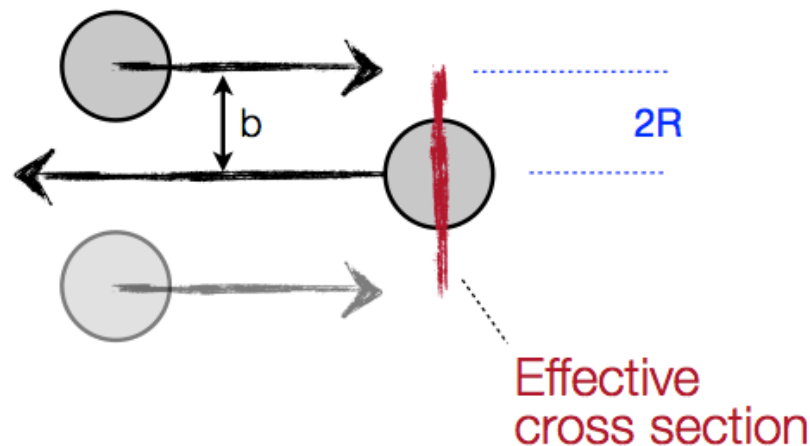
$$[\sigma] = \text{GeV}^{-2}$$

with $1 \text{ GeV}^{-2} = 0.389 \text{ mb}$

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

Estimating the
proton-proton cross section:

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

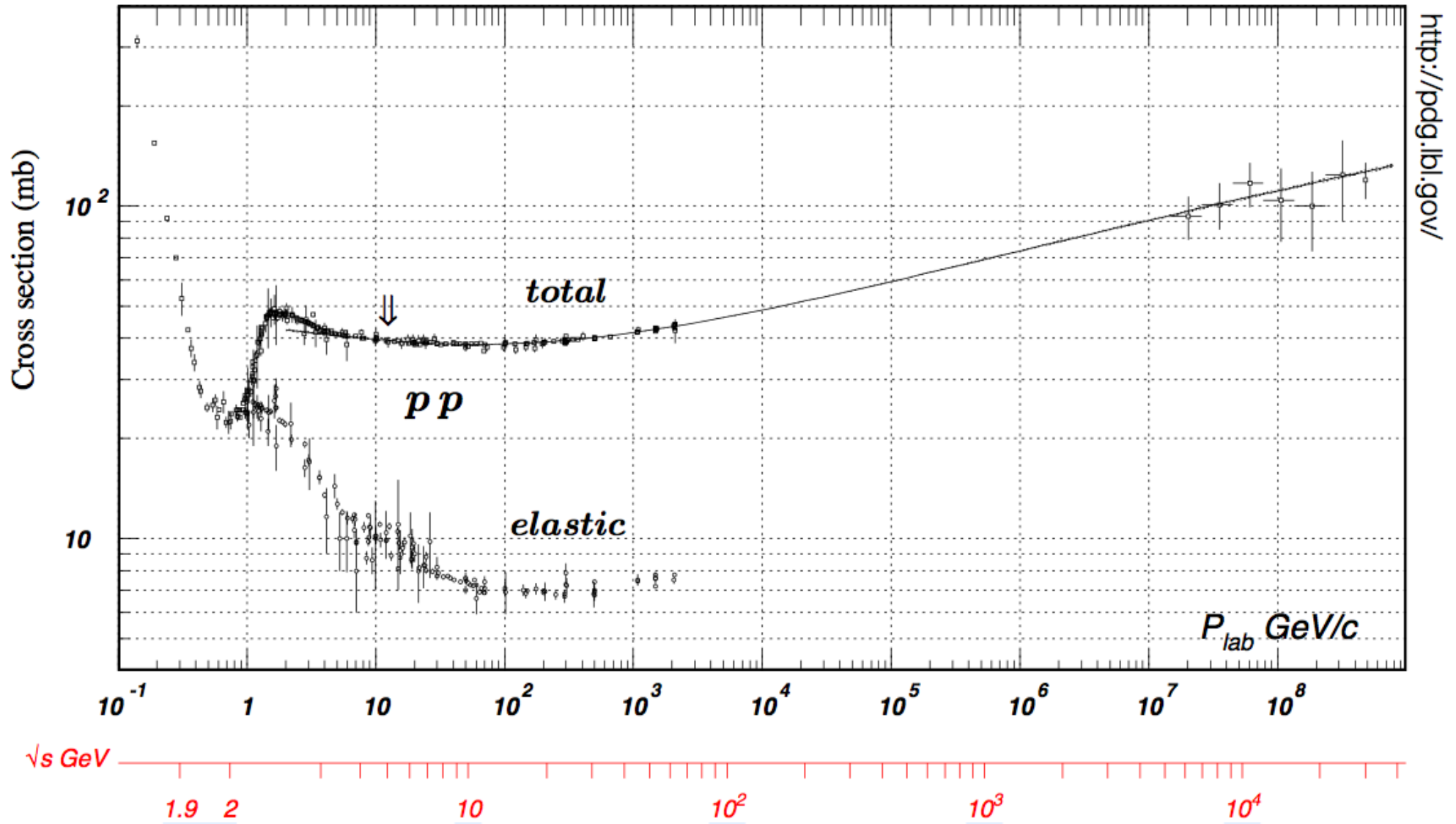


Proton radius: $R = 0.8 \text{ fm}$

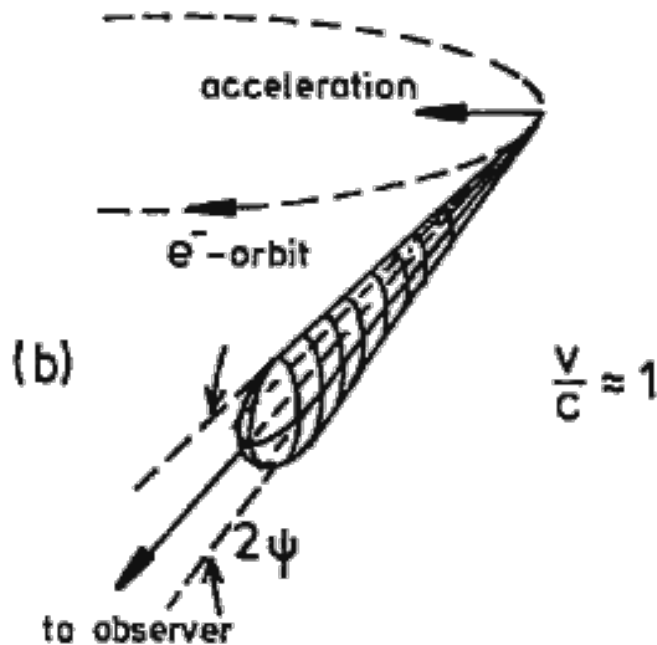
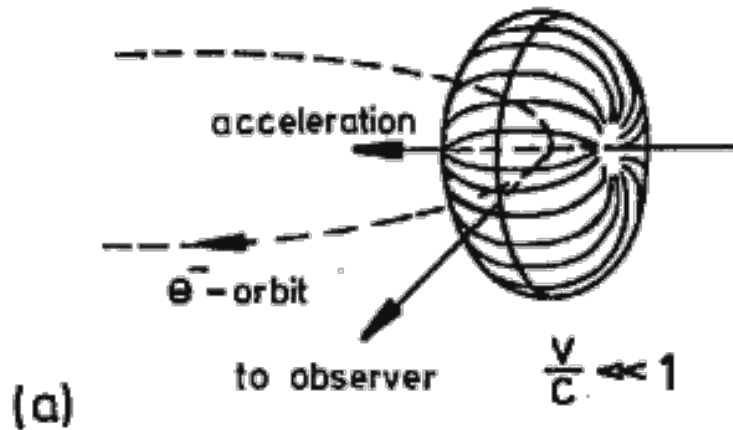
Strong interactions happens up to $b = 2R$

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

Proton-proton scattering cross-section



Synchrotron radiation



energy lost per revolution

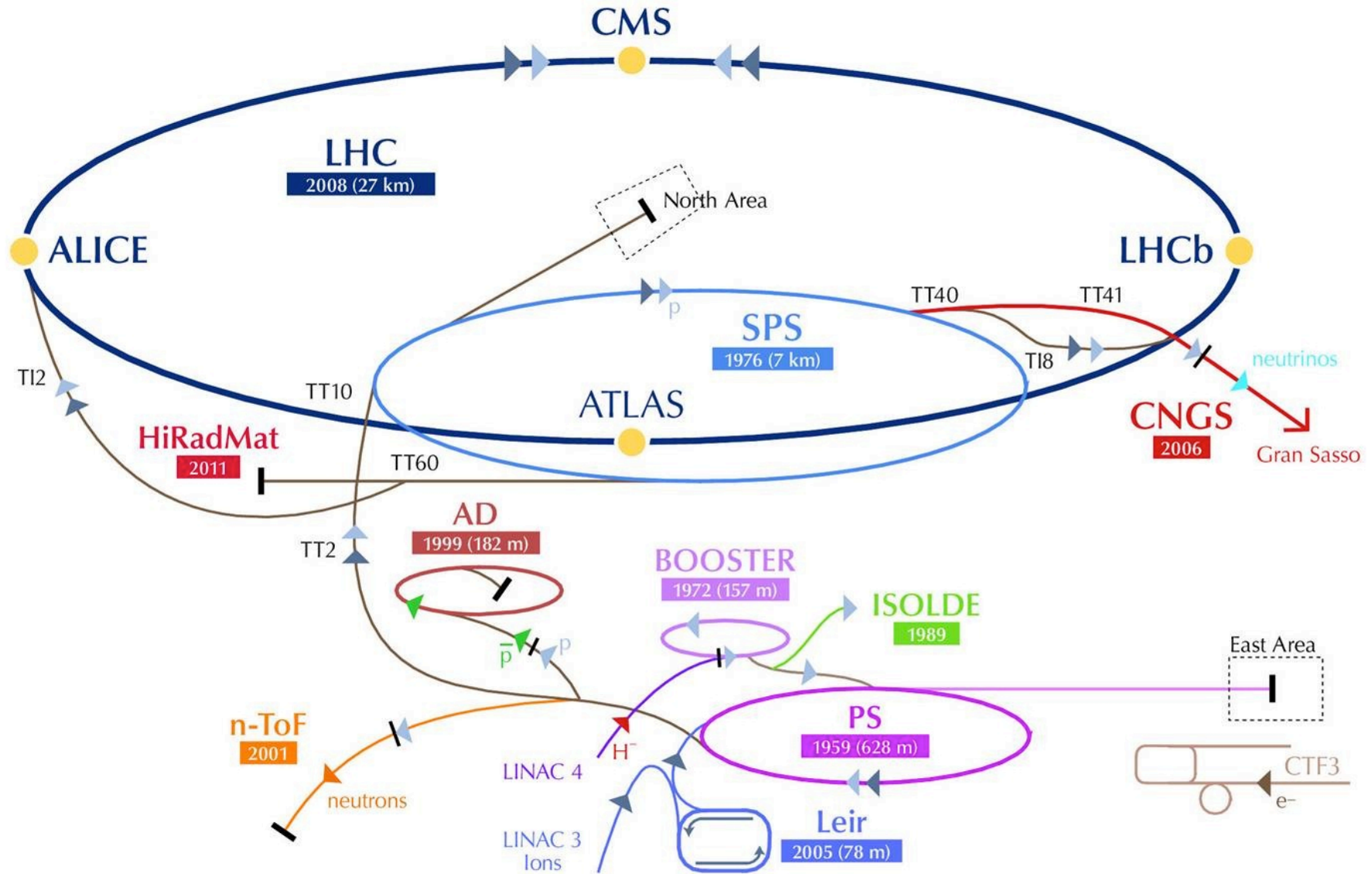
$$\Delta E = \frac{4\pi}{3} \frac{1}{4\pi\epsilon_0} \left(\frac{e^3 \beta^3 \gamma^4}{R} \right)$$

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

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

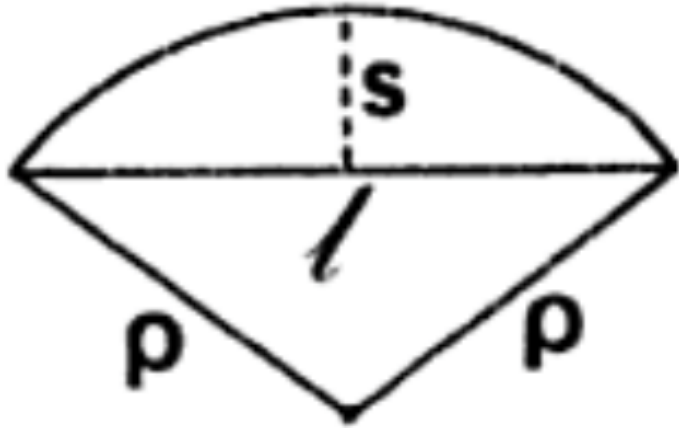
If the field is constant and we neglect presence of matter, **momentum magnitude is constant** with time, **trajectory is helical**

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

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

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

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

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

Momentum resolution due to measurement error

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

Momentum resolution gets worse for larger momenta

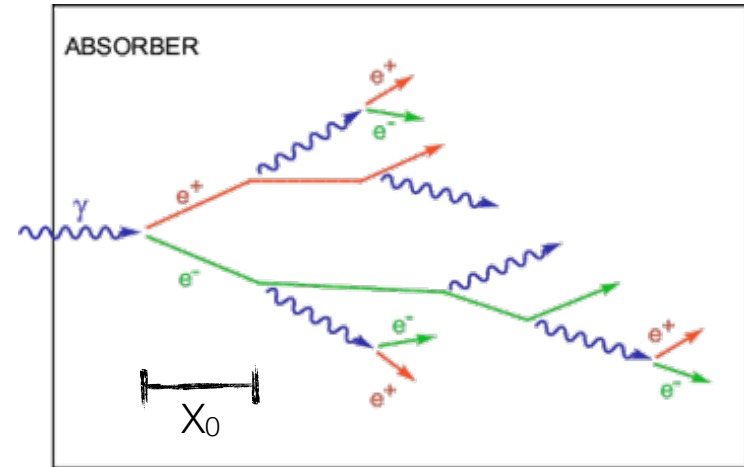
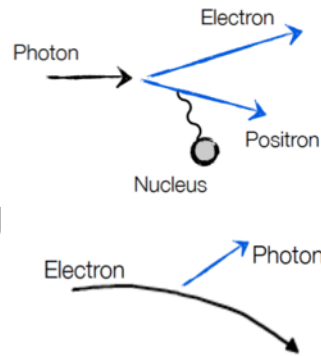
projected track length in magnetic field *resolution is improved faster by increasing L then B*

Electromagnetic showers

Dominant processes
at high energies ...

Photons : Pair production

Electrons : Bremsstrahlung



Pair production:

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

$$= \frac{7}{9} \frac{A}{N_A X_0} \quad [X_0: \text{radiation length}]$$

[in cm or g/cm²]

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 $(1/e)^{\text{th}}$ of its primary energy ...
[i.e. 37%]

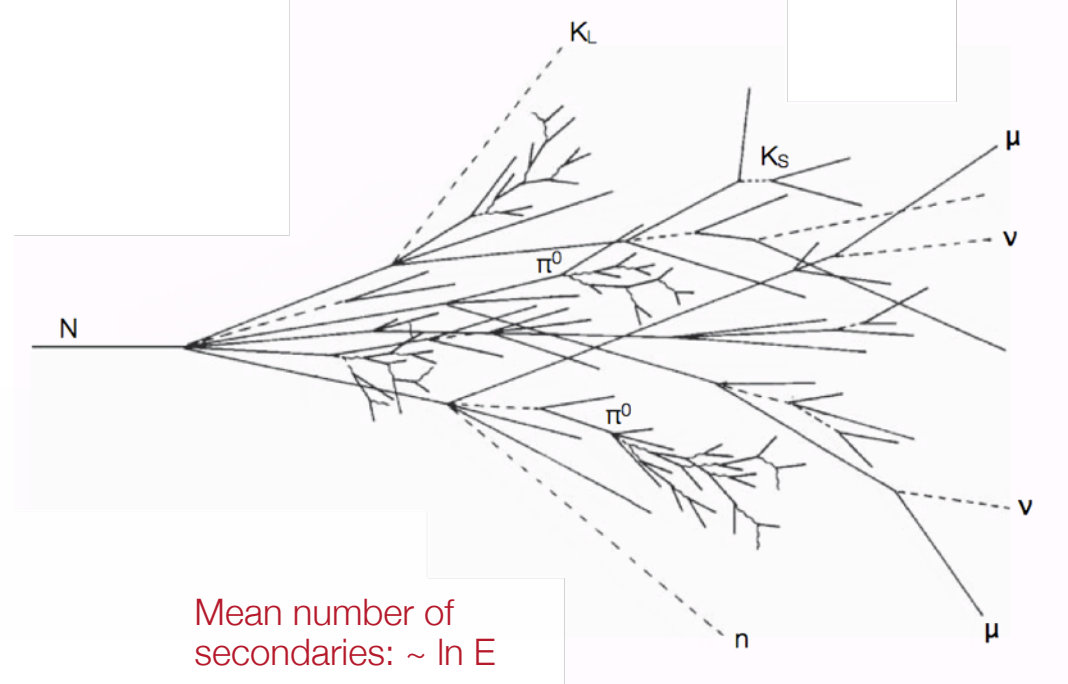
Critical energy:

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

Hadronic showers

Shower development:

1. $p + \text{Nucleus} \rightarrow \text{Pions} + N^* + \dots$
2. Secondary particles ...
undergo further inelastic collisions until they
fall below pion production threshold
3. Sequential decays ...
 $\pi^0 \rightarrow \gamma\gamma$: yields electromagnetic shower
 Fission fragments $\rightarrow \beta$ -decay, γ -decay
 Neutron capture $\rightarrow$ fission
 Spallation ...



Mean number of
secondaries: $\sim \ln E$

Typical transverse
momentum: $p_t \sim 350 \text{ MeV}/c$

Substantial
electromagnetic fraction

$f_{em} \sim \ln E$
[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 noble gases (Ar, Kr, Xe)

- ★ Advantage: homogeneous calorimeters provide optimal energy resolution
- ★ Disadvantage: very expensive
- ★ Homogeneous 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:

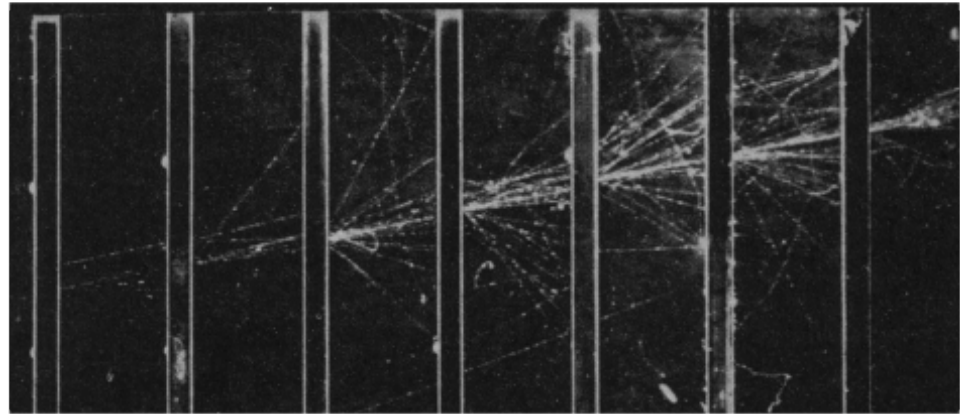
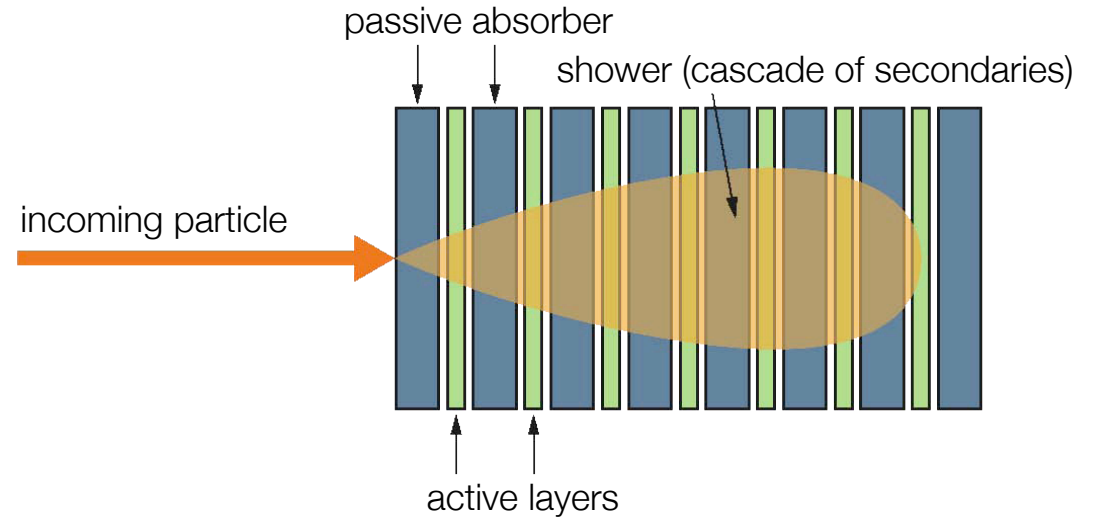
Plastic scintillator

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 ...

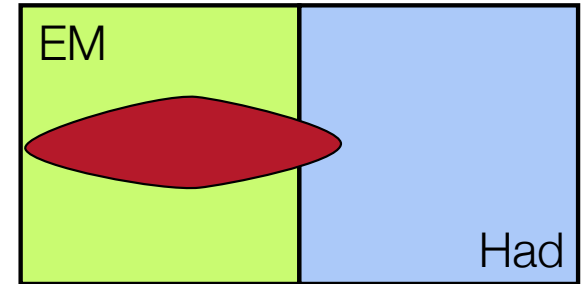
But:

Hadronic energy measured in
both parts of calorimeter ...

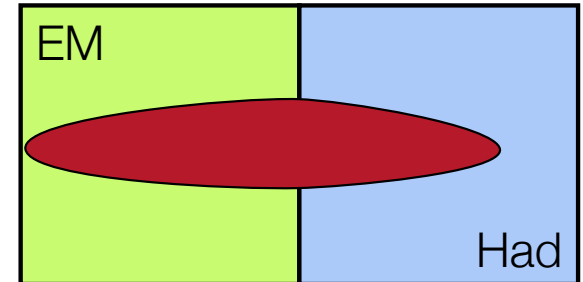
Needs careful consideration of
different response ...

Schematic of a
typical HEP calorimeter

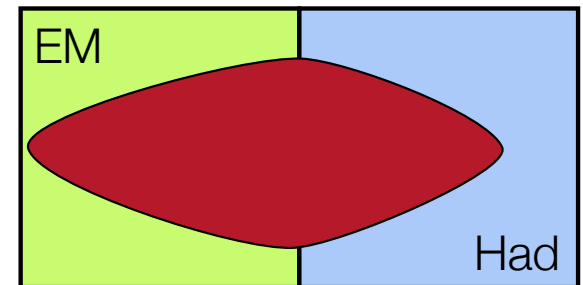
Electrons
Photons



Taus
Hadrons



Jets



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

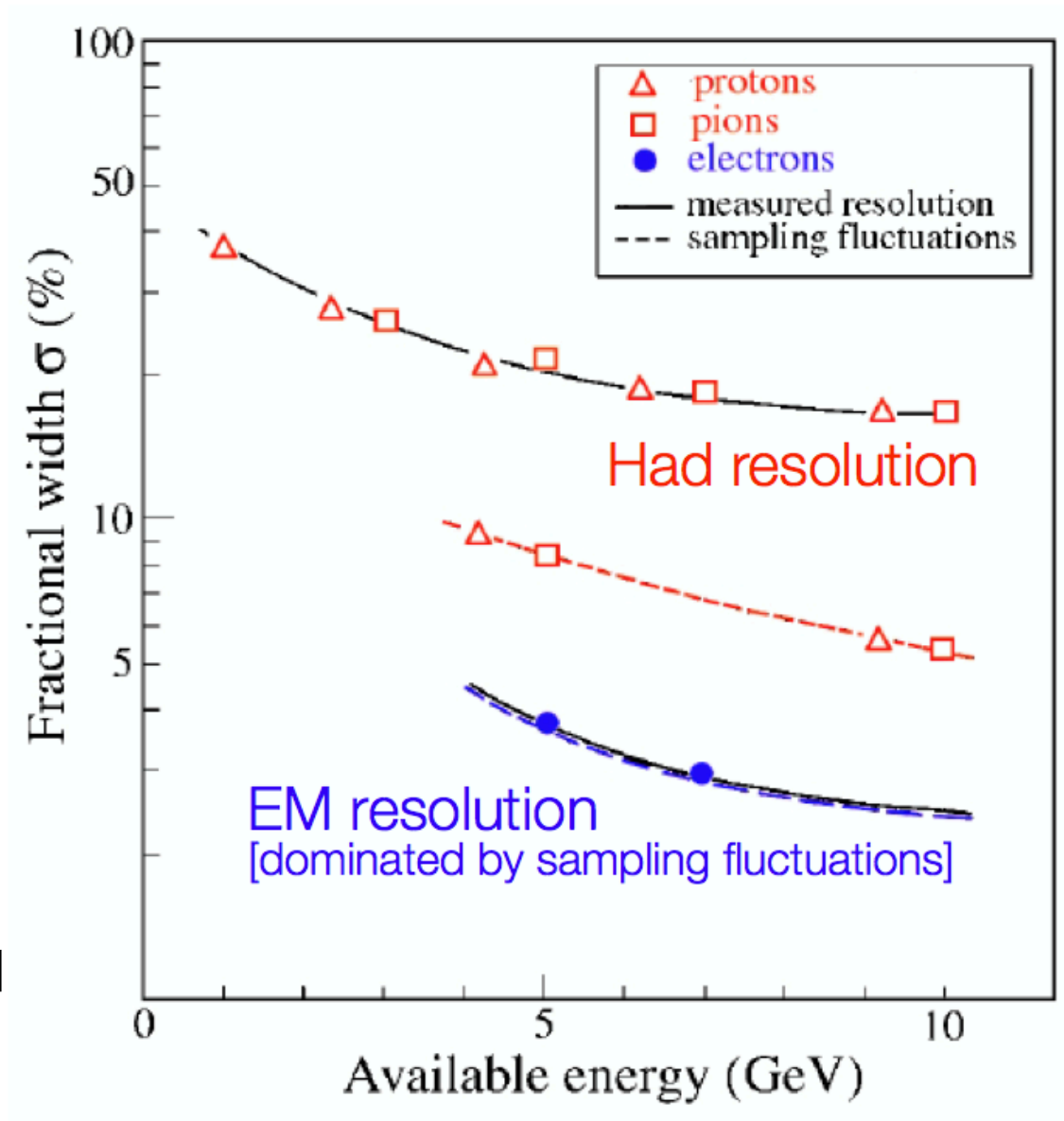
Typical:

A: 0.5 – 1.0 [Record:0.35]

B: 0.03 – 0.05

C: few %

Resolution: EM vs. HAD



Sampling fluctuations only minor contribution to hadronic energy resolution

[AFM Collaboration]