

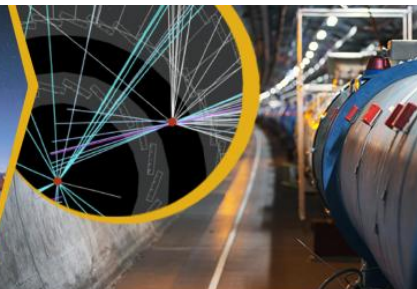
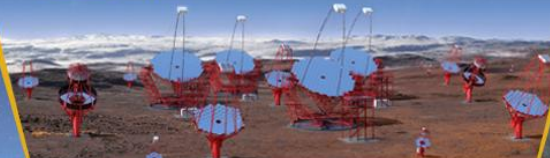
(experimental) LHC physics

GraSPA2026

16 July
23 2026

Summer School

Particle and Astroparticle Physics



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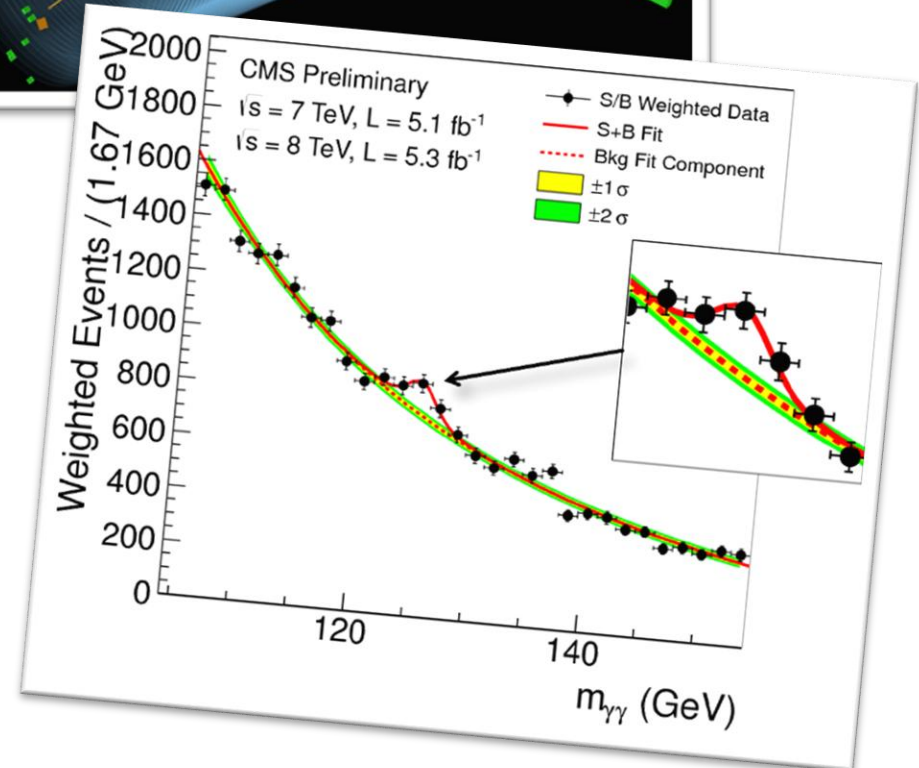
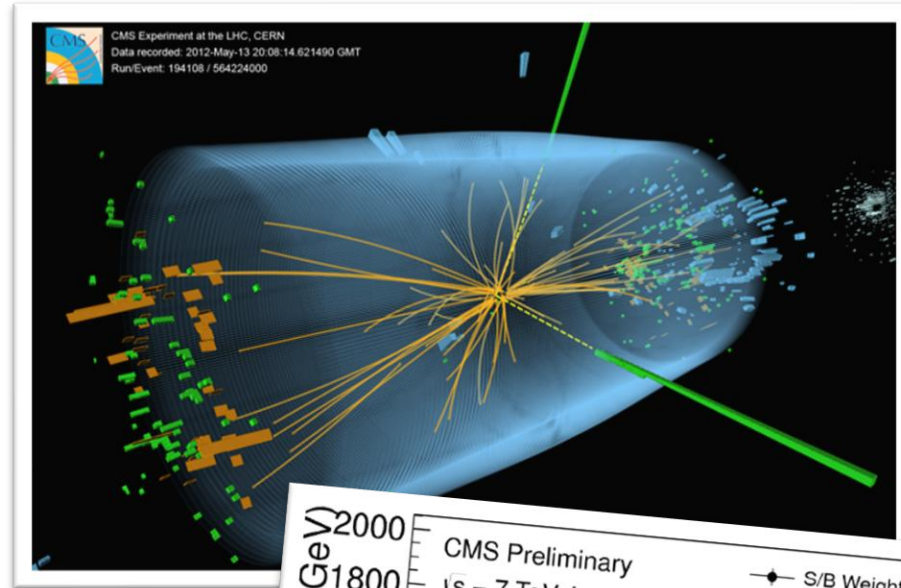
PIGA

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

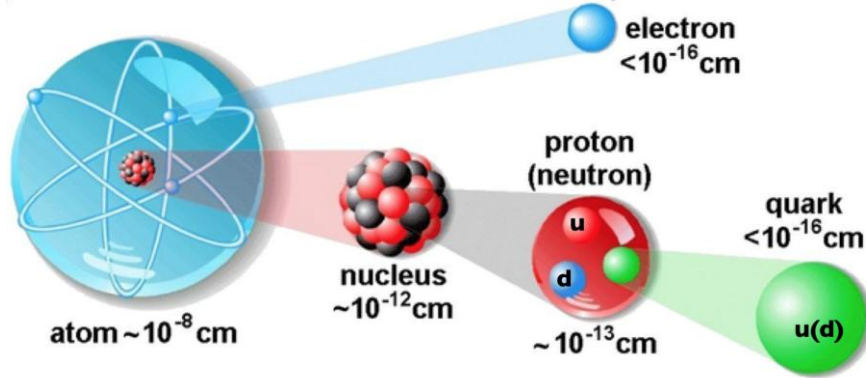
Roberto Covarelli

Experiment = probing/building 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 + \\
 & \frac{1}{2}ig_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{M^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_\mu^+ \partial_\nu W_\nu^- - \\
 & W_\nu^- \partial_\mu W_\mu^+)] - ig_{sw} [\partial_\mu A_\nu (W_\mu^+ W_\nu^- - W_\nu^+ W_\mu^-) - A_\nu (W_\mu^+ \partial_\mu W_\nu^- - \\
 & W_\nu^- \partial_\mu W_\mu^+) + A_\mu (W_\nu^+ \partial_\nu W_\mu^- - W_\mu^- \partial_\nu W_\nu^+) - \frac{1}{2}g^2 W_\mu^+ W_\mu^- W_\nu^+ W_\nu^- + \\
 & \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^+ \partial_\mu \phi^- - \phi^- \partial_\mu W_\mu^+) - W_\mu^- (H \partial_\mu \phi^+ - \\
 & \phi^+ \partial_\mu W_\mu^-) - (W_\mu^+ \partial_\mu \phi^+ - \phi^+ \partial_\mu W_\mu^+) + \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^- - \bar{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)] - \\
 & \gamma^5 u_j^\lambda) + \frac{ig}{2\sqrt{2}} \frac{m_h^2}{M} [-\phi^+ (\bar{\nu}^\lambda (1 - \gamma^5) e^\lambda) + \frac{ig}{2M\sqrt{2}} \phi^+ [-m_d^2 (\bar{u}_j^\lambda C_{\lambda\kappa} (1 - \gamma^5) d_j^\kappa) + \\
 & \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^2 (\bar{u}_j^\lambda C_{\lambda\kappa} (1 + \gamma^5) u_j^\kappa) - m_e^2 (\bar{d}_j^\lambda C_{\lambda\kappa}^1 (1 - \\
 & m_u^2 (\bar{u}_j^\lambda C_{\lambda\kappa} (1 + \gamma^5) d_j^\kappa) + \frac{ig}{2M\sqrt{2}} \phi^- [m_d^2 (\bar{d}_j^\lambda C_{\lambda\kappa}^1 (1 + \gamma^5) u_j^\kappa) - m_e^2 (\bar{d}_j^\lambda C_{\lambda\kappa}^1 (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) - \frac{g}{2} \frac{m_h^2}{M} H (\bar{u}_j^\lambda 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}^0 X^- - \partial_\mu \bar{X}^+ X^0) + ig_{sw} W_\mu^- (\partial_\mu \bar{X}^- X^0 - \\
 & \partial_\mu \bar{X}^- X^+) + ig_{cw} W_\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^-) + ig_{cw} Z_\mu^0 (\partial_\mu \bar{X}^+ X^+ - \partial_\mu \bar{X}^- X^-) + \frac{1}{c_w} \bar{X}^0 X^0 H] + \\
 & \partial_\mu \bar{X}^- X^+ - \frac{1}{2}gM [\bar{X}^+ X^+ H + \bar{X}^- X^- H + \bar{X}^0 X^0 H] + \\
 & \frac{1-2c_w^2}{2c_w} igM s_w [\bar{X}^0 X^+ \phi^- - \bar{X}^- X^0 \phi^-] + \frac{1}{2c_w} igM [\bar{X}^0 X^+ \phi^- - \bar{X}^- X^0 \phi^-] + \\
 & igM s_w [\bar{X}^0 X^+ \phi^- - \bar{X}^- X^0 \phi^-] + \frac{1}{2}igM [\bar{X}^0 X^+ \phi^- - \bar{X}^- X^0 \phi^-]
 \end{aligned}$$



The Standard Model of particle physics...



$$\mathcal{L} = \begin{aligned} & \text{Gauge bosons} \\ & -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} \\ & + i\bar{\Psi}\not{D}\psi \\ & + D_{\mu}\Phi^{\dagger}D^{\mu}\Phi - V(\Phi) \\ & + \bar{\Psi}_L\hat{Y}\Phi\Psi_R + h.c. \end{aligned} \quad \begin{aligned} & \text{Gauge boson} \\ & \text{coupling to} \\ & \text{fermions (EW,} \\ & \text{QCD)} \end{aligned}$$

three generations of matter (fermions)			interactions / force carriers (bosons)	
I	II	III		
mass charge spin				
$\approx 2.2 \text{ MeV}/c^2$ $\frac{2}{3}$ $\frac{1}{2}$ u up	$\approx 1.28 \text{ GeV}/c^2$ $\frac{2}{3}$ $\frac{1}{2}$ c charm	$\approx 173.1 \text{ GeV}/c^2$ $\frac{2}{3}$ $\frac{1}{2}$ t top	0 0 1 g gluon	$\approx 125.09 \text{ GeV}/c^2$ 0 0 0 H higgs
QUARKS				SCALAR BOSONS
$\approx 4.7 \text{ MeV}/c^2$ $-\frac{1}{3}$ $\frac{1}{2}$ d down	$\approx 96 \text{ MeV}/c^2$ $-\frac{1}{3}$ $\frac{1}{2}$ s strange	$\approx 4.18 \text{ GeV}/c^2$ $-\frac{1}{3}$ $\frac{1}{2}$ b bottom	0 0 1 γ photon	
$\approx 0.511 \text{ MeV}/c^2$ -1 $\frac{1}{2}$ e electron	$\approx 105.66 \text{ MeV}/c^2$ -1 $\frac{1}{2}$ μ muon	$\approx 1.7768 \text{ GeV}/c^2$ -1 $\frac{1}{2}$ τ tau	$\approx 91.19 \text{ GeV}/c^2$ 0 1 Z Z boson	
LEPTONS			GAUGE BOSONS VECTOR BOSONS	
$< 2.2 \text{ eV}/c^2$ 0 $\frac{1}{2}$ ν_e electron neutrino	$< 1.7 \text{ MeV}/c^2$ 0 $\frac{1}{2}$ ν_μ muon neutrino	$< 15.5 \text{ MeV}/c^2$ 0 $\frac{1}{2}$ ν_τ tau neutrino	$\approx 80.39 \text{ GeV}/c^2$ ± 1 1 W W boson	

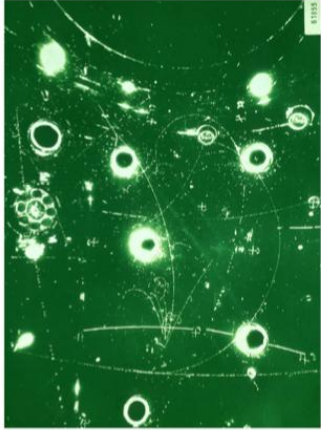
Higgs coupling to fermions (fermion masses)

Higgs coupling to bosons (boson masses)

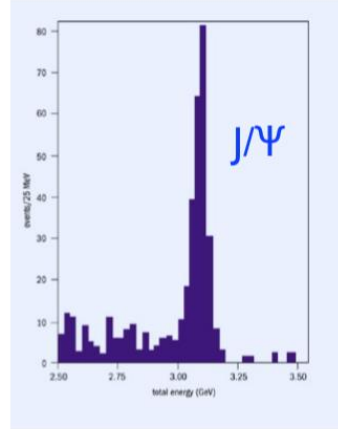
Higgs self-coupling (Higgs potential)

A theory built (and probed) over time...

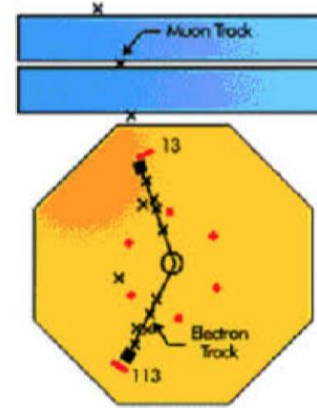
1972 — CERN
Neutral currents



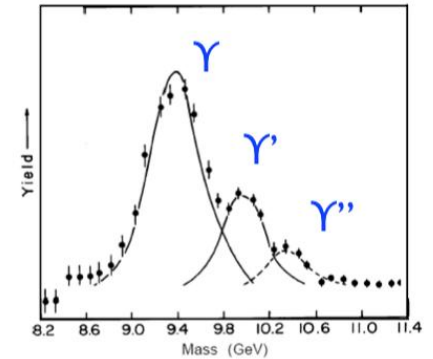
1974 — BNL, SLAC
Charm



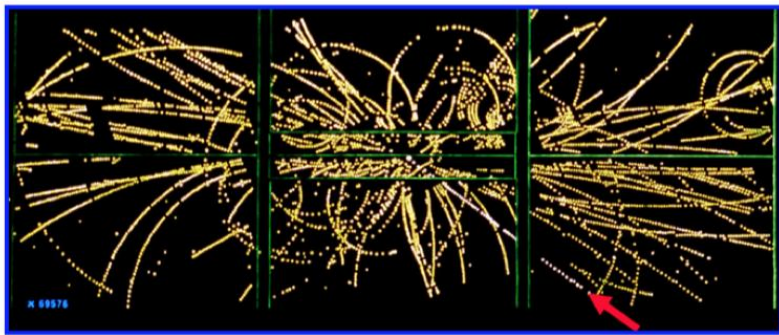
1976 — SLAC
Tau lepton



1979 — Fermilab
Beauty

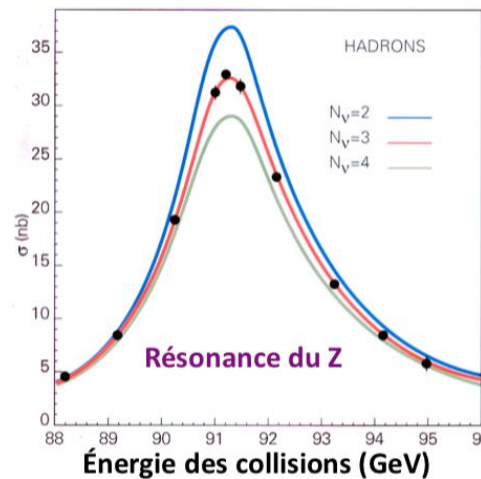


1983 — CERN/SppS
W and Z bosons



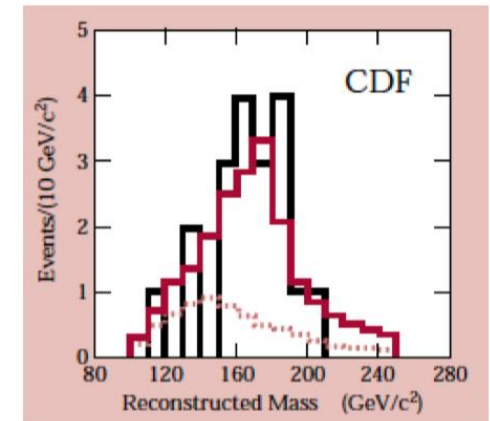
UA1, UA2

1990 — CERN/LEP
Three families of neutrinos



ALEPH, DEPHI, L3, OPAL
(experimental) LHC physics

1994 — Fermilab/TeVatron
Top quark



CDF, D0

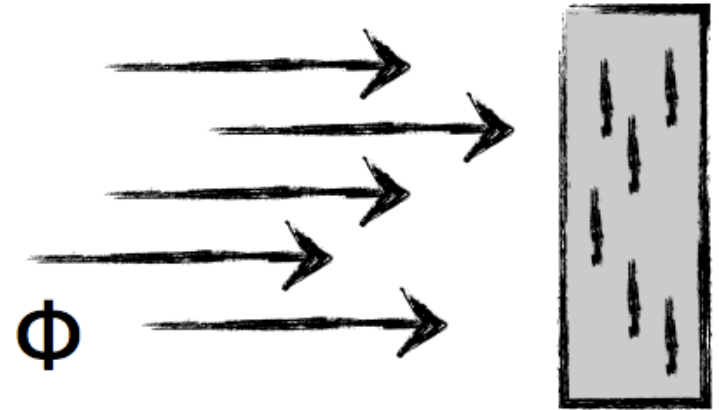
How do we compare experiment and predictions in a **quantum** field theory?

- Through two fundamental quantities:
- σ (**cross section**): **probability** of a particle of **being produced** in collisions **at a given energy** (es. 13.6 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: $\tau = 1/\Gamma$

(Classical) interaction cross section

dx

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



Flux
decrease
per unit of
distance

$$\frac{d\Phi}{dx} = \Phi \underbrace{\sigma N_{\text{target}}}_{[L^{-2} t^{-1}] [?] [L^{-3}]}$$

$[L^{-3} t^{-1}]$

Effective THICKNESS of material
(interaction centres per unit length)

Cross section
per target
particle

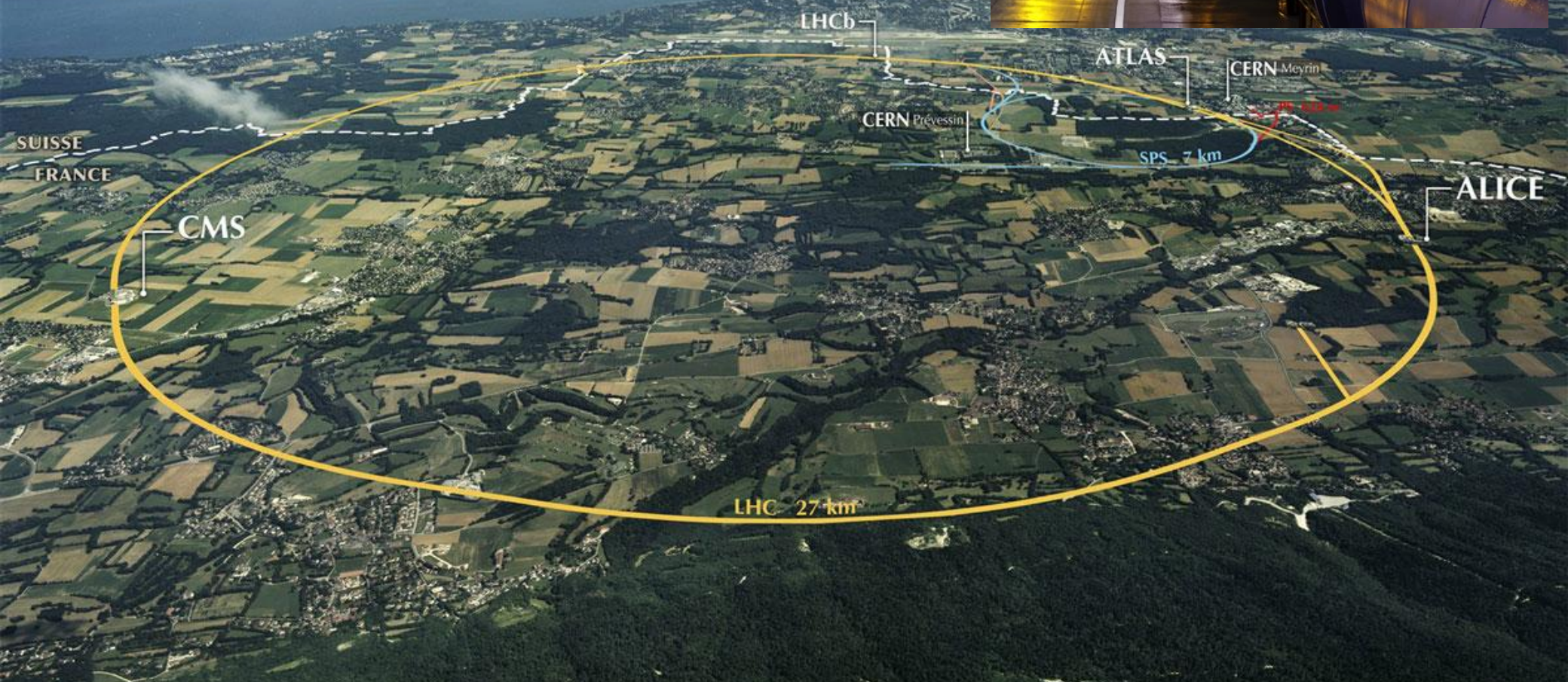
$[L^2]$ = reaction rate per unit of flux

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

LHC

pp collider (2008-present)

$\sqrt{s} = 7\text{-}8\text{-}13\text{ TeV}$

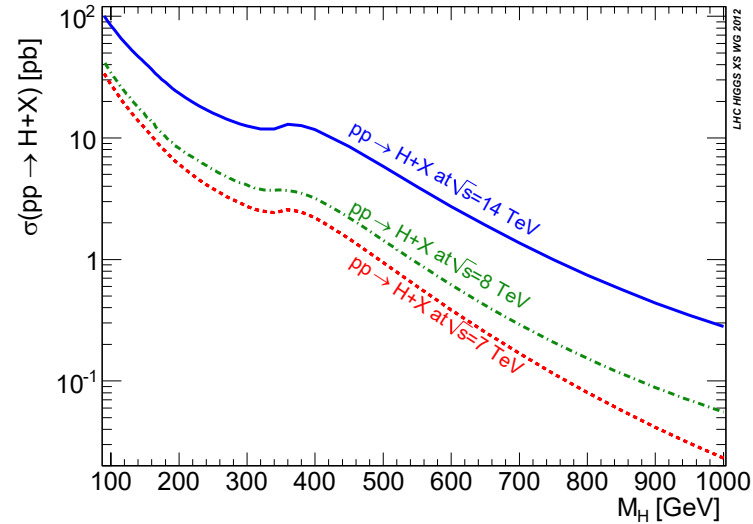


Collider cross-section / Luminosity

Number of events
in unit of time

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

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



In a collider ring...

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

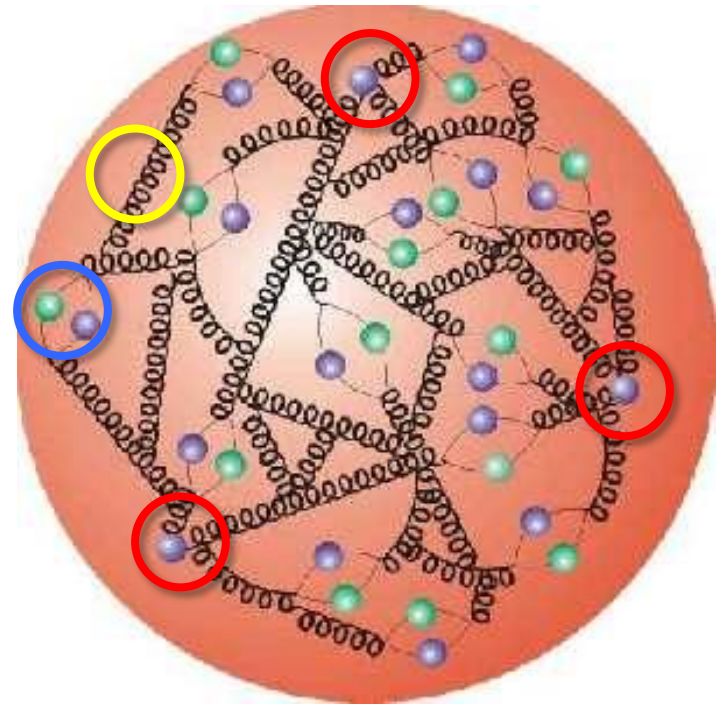
Current

Beam sizes (RMS)

Proton colliders

- **Protons have substructure!**

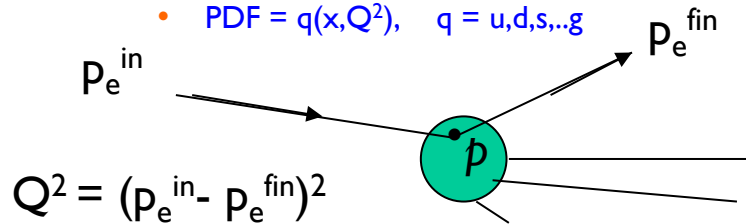
- ✓ partons = quarks & gluons
- ✓ 3 valence (colored) quarks bound by gluons
- ✓ Gluons (colored) have self-interactions
- ✓ Virtual quark pairs can pop-up (sea-quark)
- ✓ p momentum shared among constituents
 - described by p structure functions



- **Parton energy not 'monochromatic'**

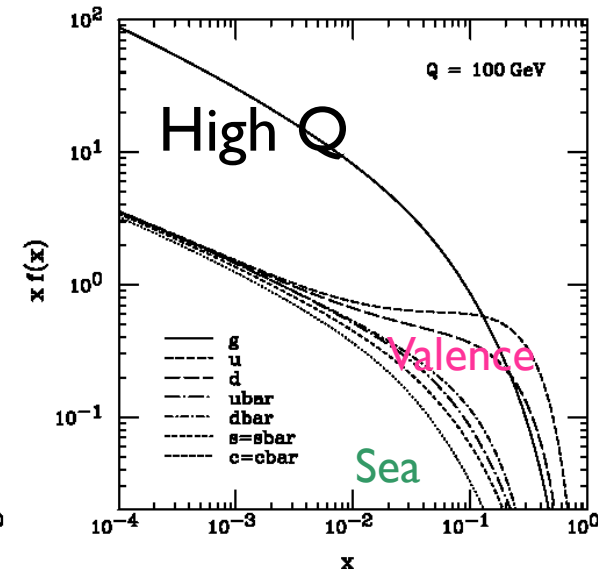
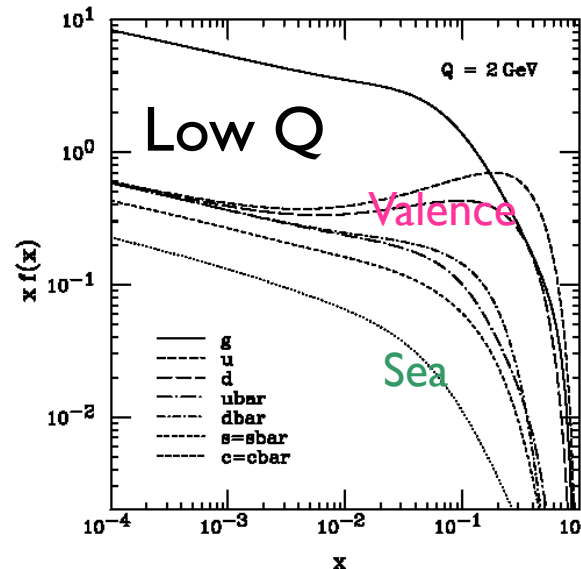
- ✓ Parton Distribution Function

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

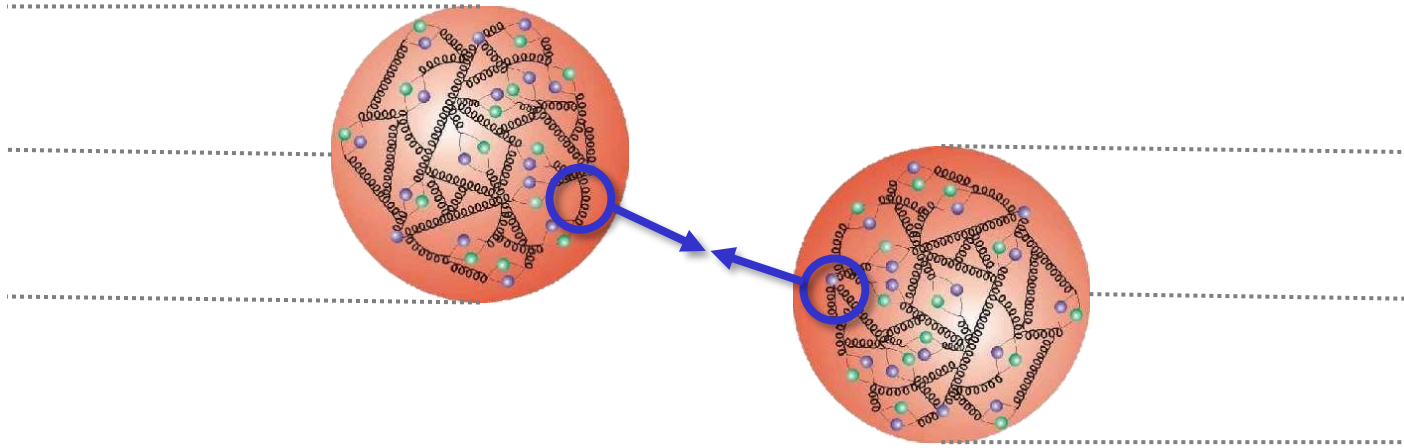


- **Kinematic variables**

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

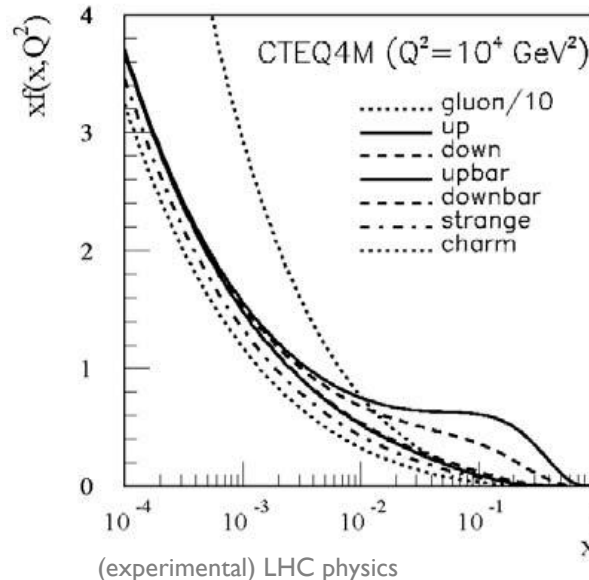
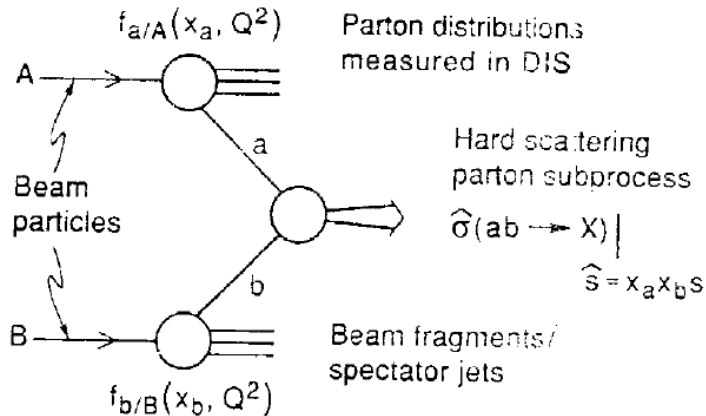


Cross sections at a proton-proton collider



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

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

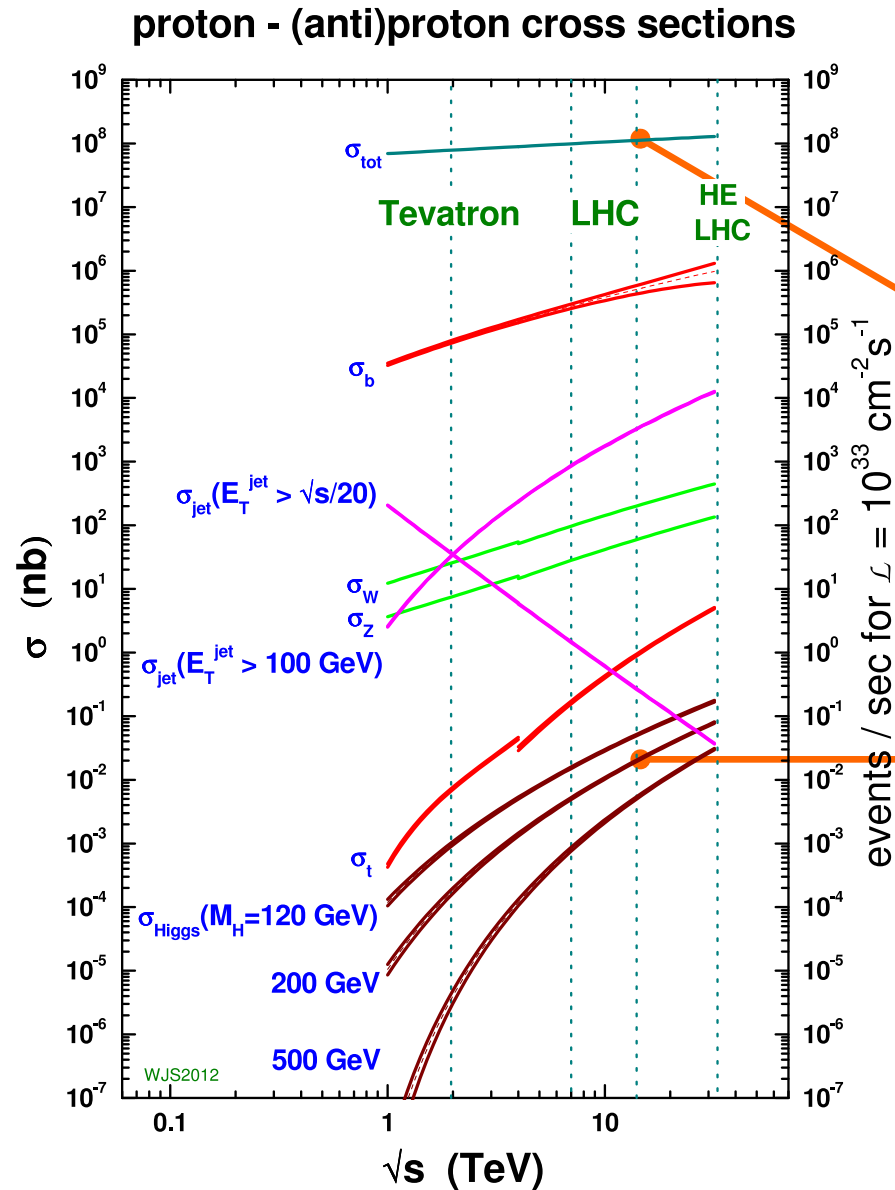


Example: to produce a particle with mass $m = 100 \text{ GeV}$

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

$$\sqrt{s} = 13.6 \text{ TeV} \rightarrow x_a x_b = 0.007$$

Cross-sections at LHC



$$1 \text{ nb} = 10^{-33} \text{ cm}^2$$

$$\sigma_{\text{tot}} (13.6 \text{ TeV}) \sim 10^8 \text{ nb}$$

$$\sigma_H (13.6 \text{ TeV}) \sim 0.05 \text{ nb}$$

$$\text{LHC instantaneous luminosity } L \sim 1 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$$

inelastic pp collisions

10^9 events/s

$\sim 10^{10}$

10^{-1} events/s

~ 1 Higgs boson
every 2 seconds

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

How do we compare experiment and prediction 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**: $\tau = 1/\Gamma$

What do we want to measure?

... “stable”
particles from
unstable particle
decays!

$$\tau = \infty$$

1968: SLAC <i>u</i> up quark	1974: Brookhaven & SLAC <i>c</i> charm quark	1995: Fermilab <i>t</i> top quark	1979: DESY <i>g</i> gluon
1968: SLAC <i>d</i> down quark	1947: Manchester University <i>s</i> strange quark	1977: Fermilab <i>b</i> bottom quark	1923: Washington University γ photon
1956: Savannah River Plant ν_e electron neutrino	1962: Brookhaven ν_μ muon neutrino	2000: Fermilab ν_τ tau neutrino	1983: CERN <i>W</i> W boson
1897: Cavendish Laboratory <i>e</i> electron	1937: Caltech and Harvard μ muon	1976: SLAC τ tau	1983: CERN <i>Z</i> Z boson
			2012: CERN <i>H</i> Higgs boson

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

$$\tau = 2.2 \text{ } \mu\text{s}$$

(experimental) LHC physics

What do we want to measure?

decays?

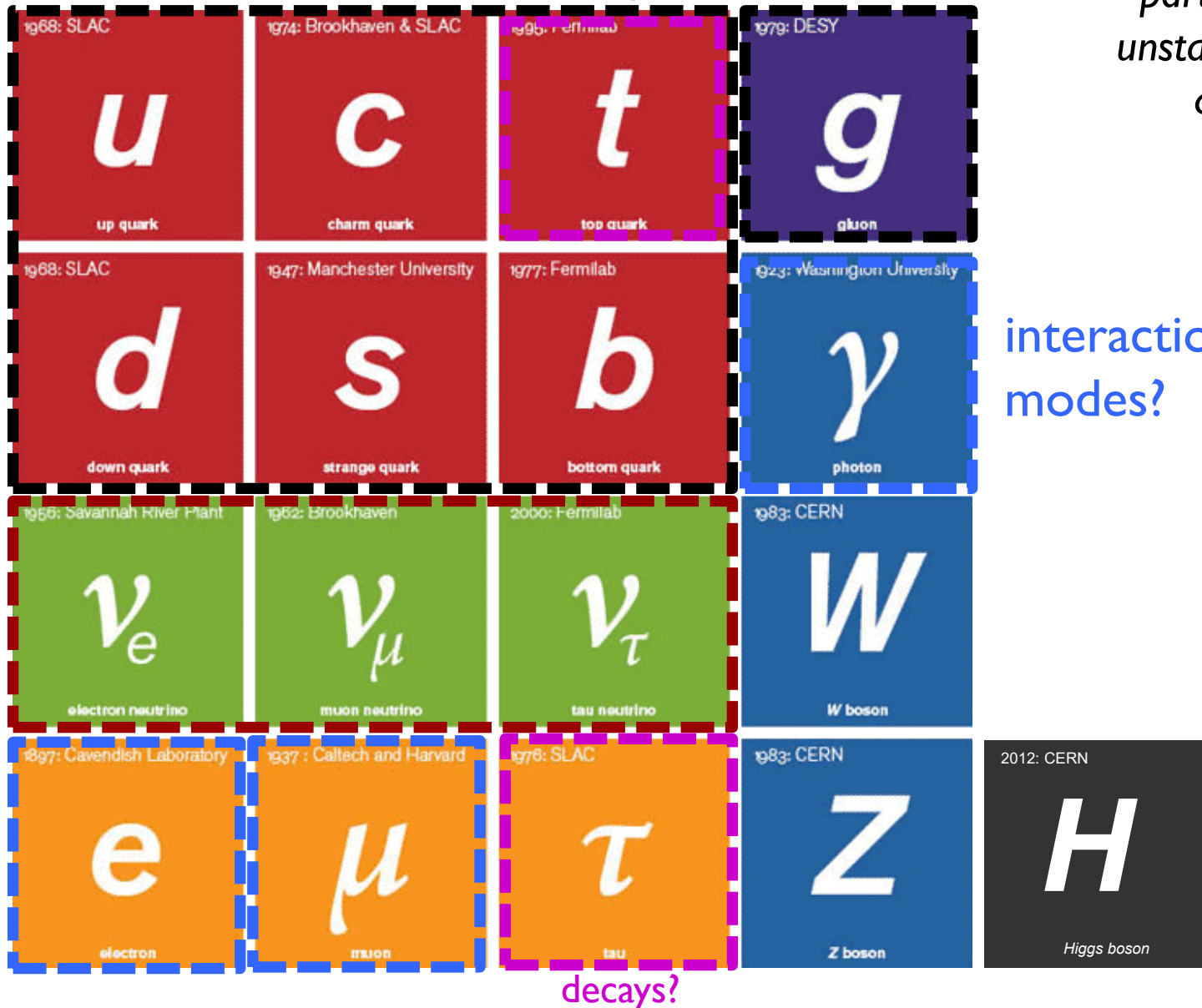
... “stable”
particles from
unstable particle
decays!

hadron
jets

interaction
modes?

invisible
*in particle
detectors at
accelerators*

interaction
modes?



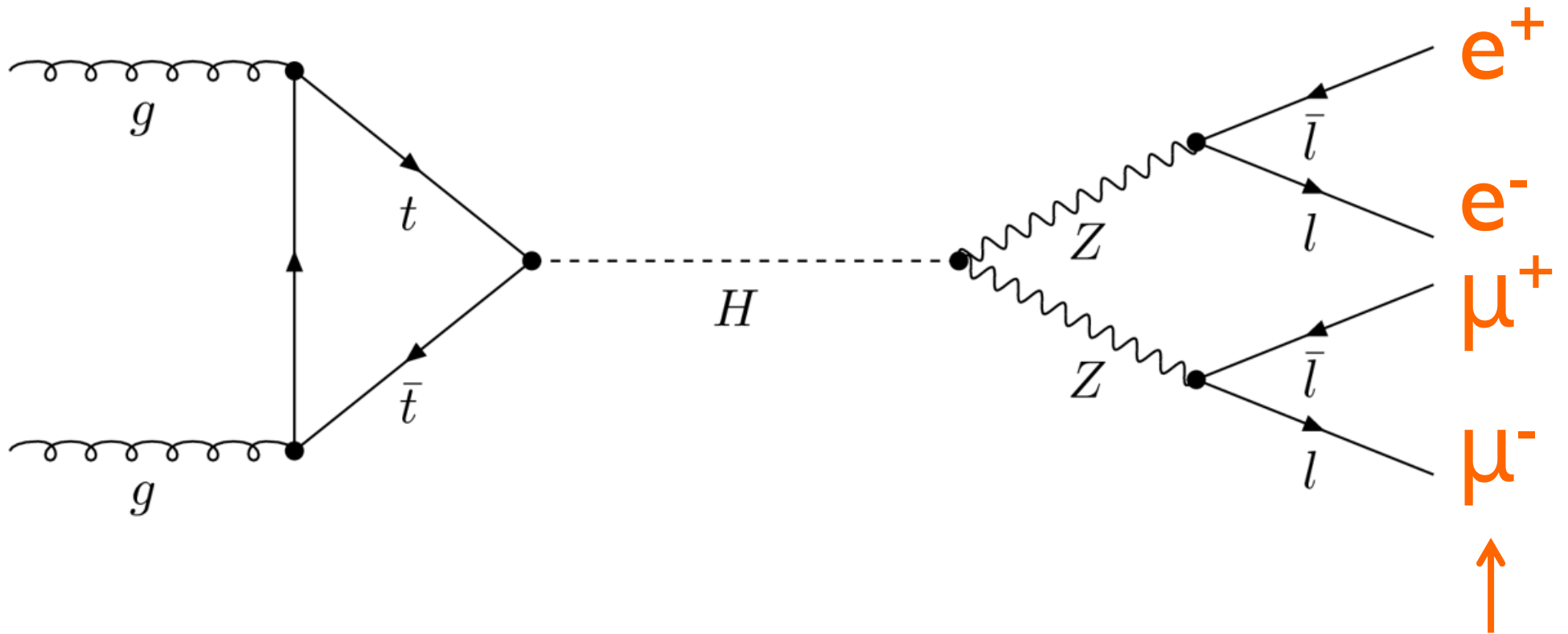
decays?

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



this is what we are looking for...

Identifying and measuring “stable” 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” units: $\hbar = c = 1$)

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

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

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

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

Center of mass energy

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

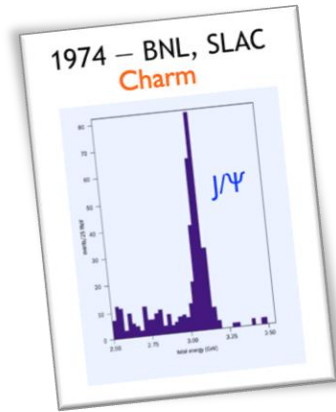
$$E_{\text{cm}} = \sqrt{s} = \sqrt{\left(\sum E_i\right)^2 - \left(\sum \vec{p}_i\right)^2}$$

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

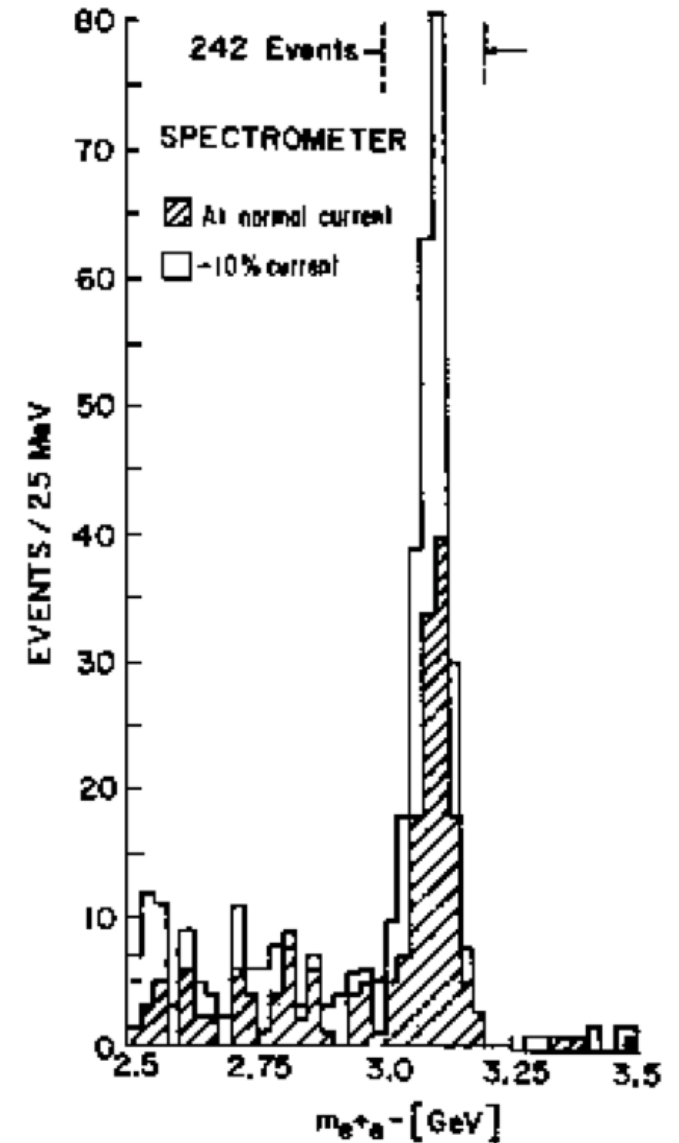
$$p = (E, \vec{p}) \quad \sqrt{p \cdot p}$$

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

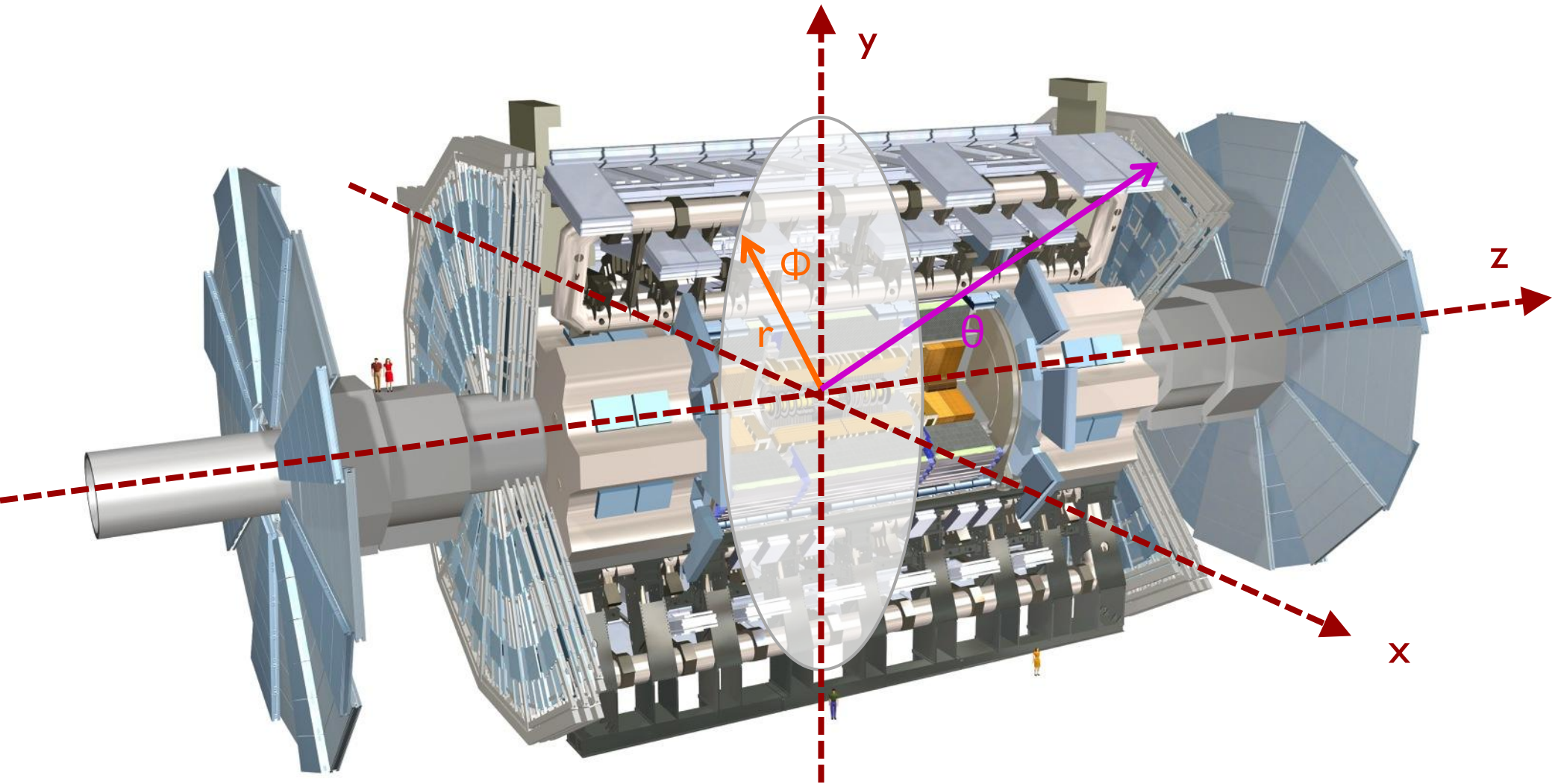
Invariant mass



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



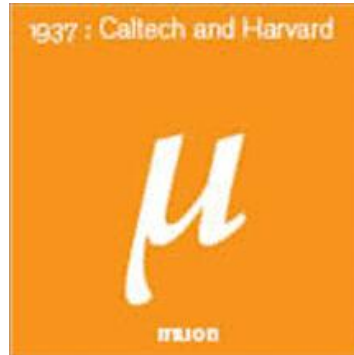
A collider experiment



Interaction mode cheat sheet (“light” particles)



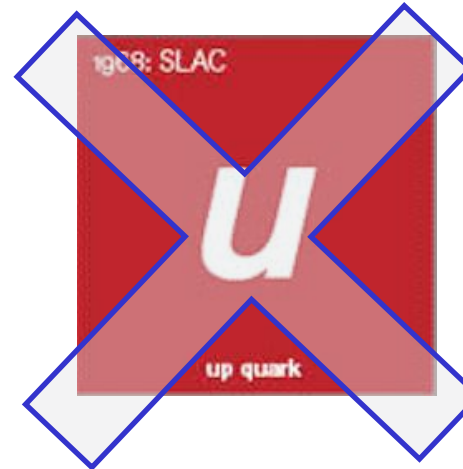
- electrically charged
- ionization (dE/dx)
- *electromagnetic shower...*



- electrically charged
- ionization (dE/dx)



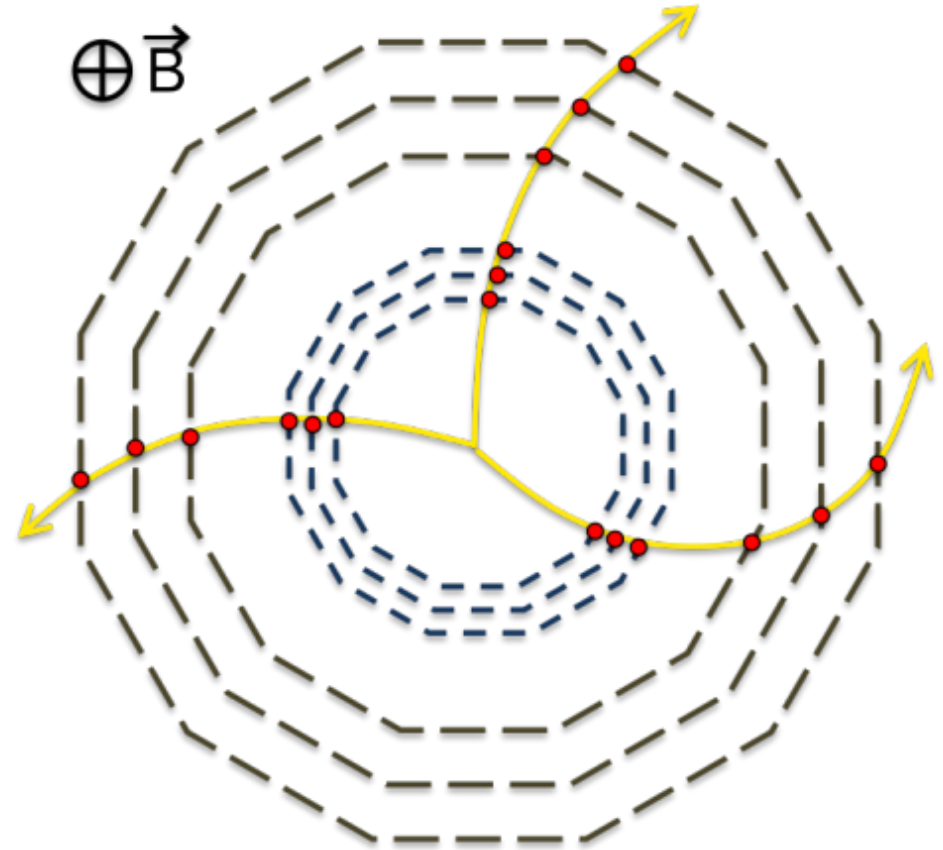
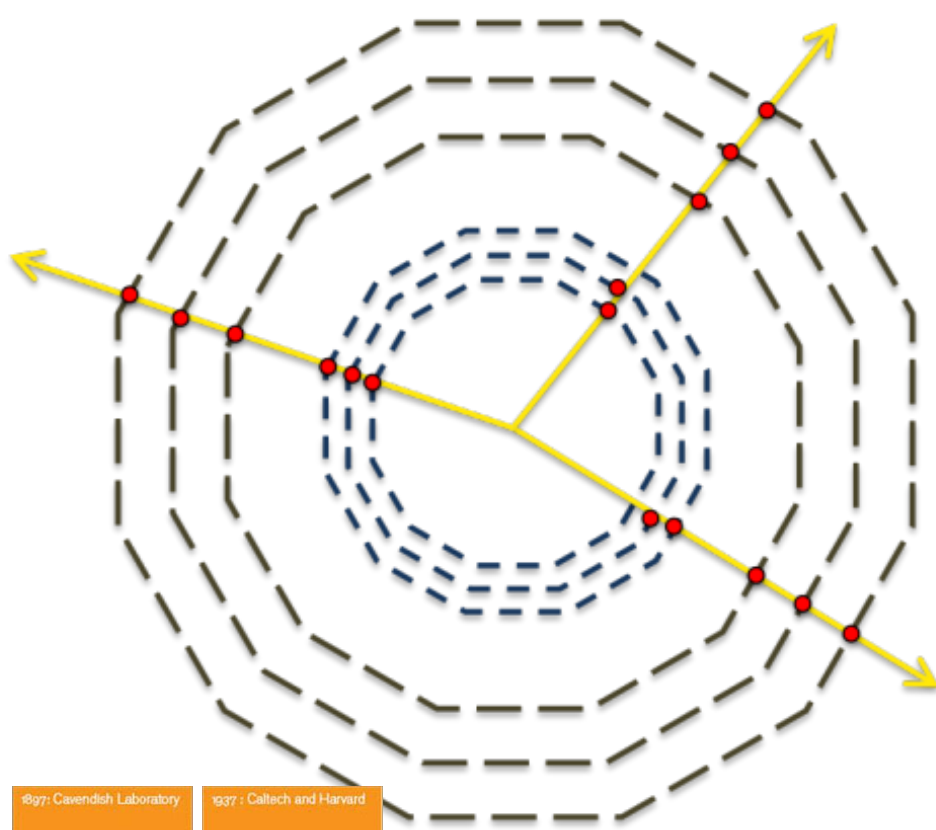
- electrically neutral
- pair production
 - ✓ $E > 1 \text{ MeV}$
- *electromagnetic shower...*



- produce *hadron(s)* jets via QCD hadronization process

Magnetic spectrometer for ionizing particles

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



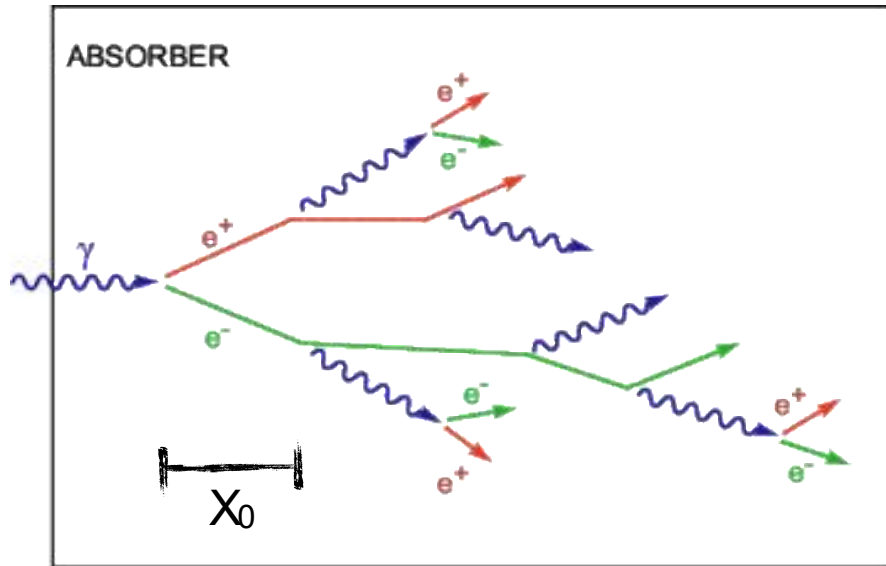
$$p[\text{GeV}] = 0.3B[\text{T}]\rho[\text{m}]$$

Calorimeters for showering particles

- Electromagnetic shower

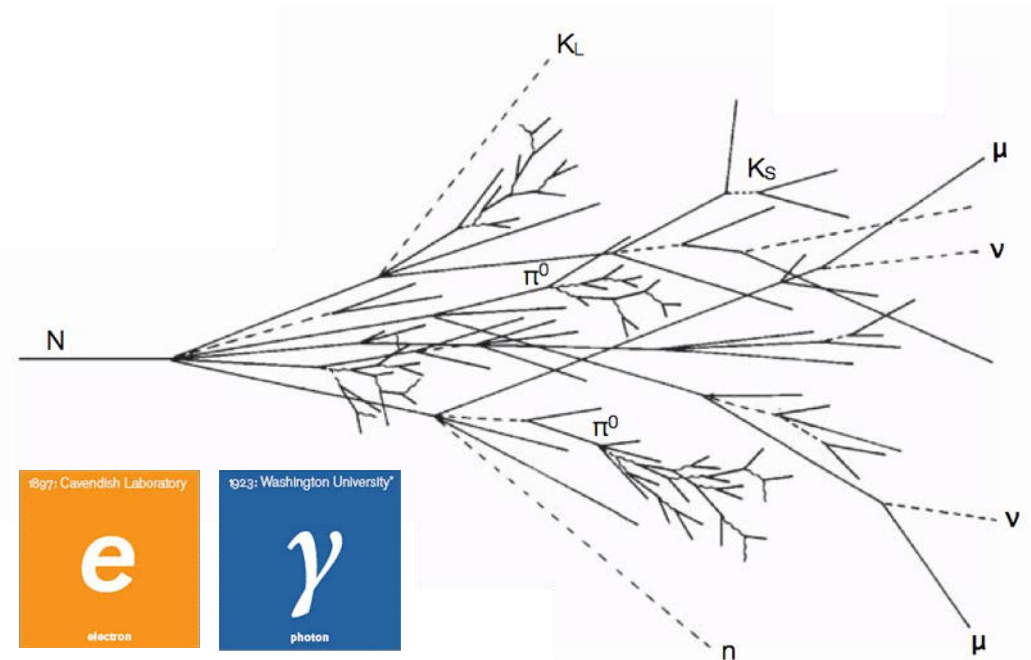
- ✓ Photons: pair production
 - Until below e^+e^- threshold
- ✓ Electrons: bremsstrahlung
 - Until brem cross-section smaller than ionization

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

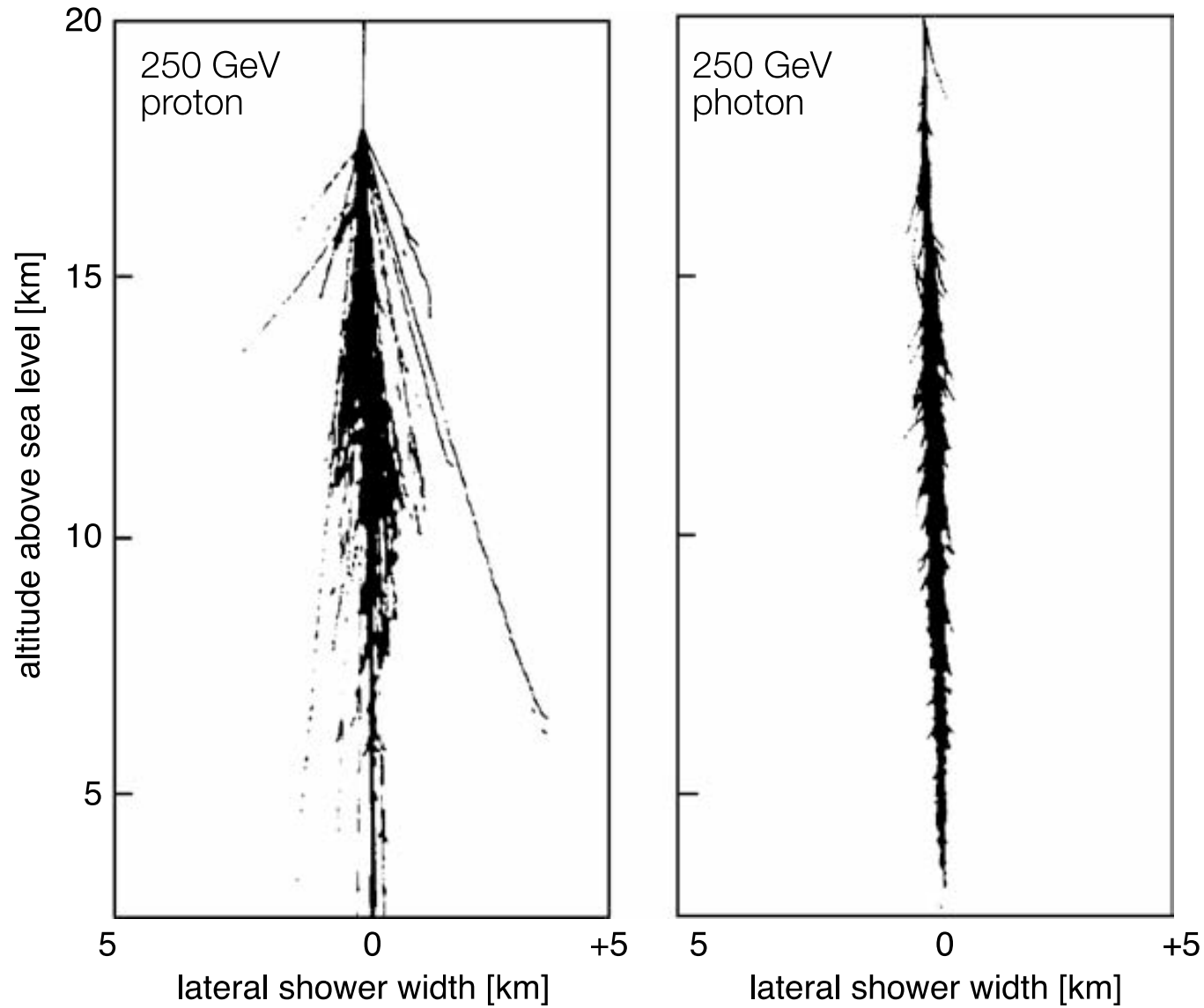


- Hadronic showers

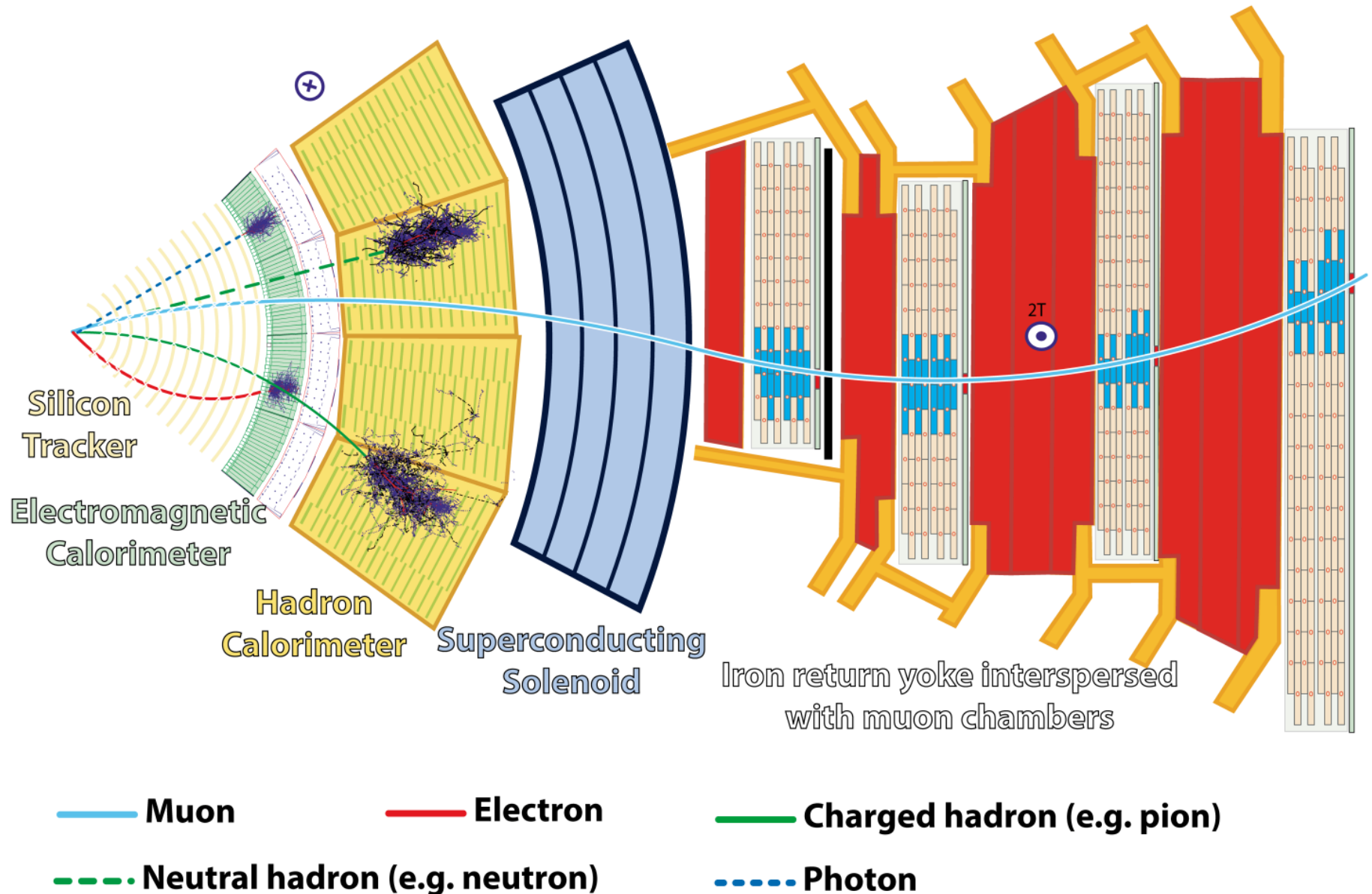
- ✓ Inelastic scattering w/ nuclei
 - Further inelastic scattering until below pion production threshold
- ✓ Sequential decays
 - $\pi^0 \rightarrow \gamma\gamma$
 - Fission fragment: β -decay, γ -decay
 - Neutron capture, spallation, ...



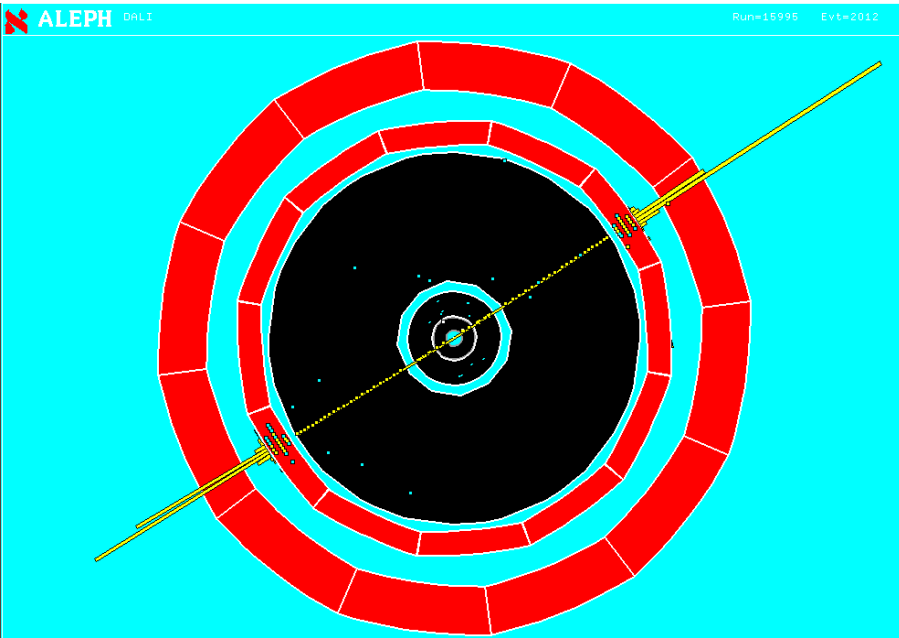
Hadronic vs. EM showers



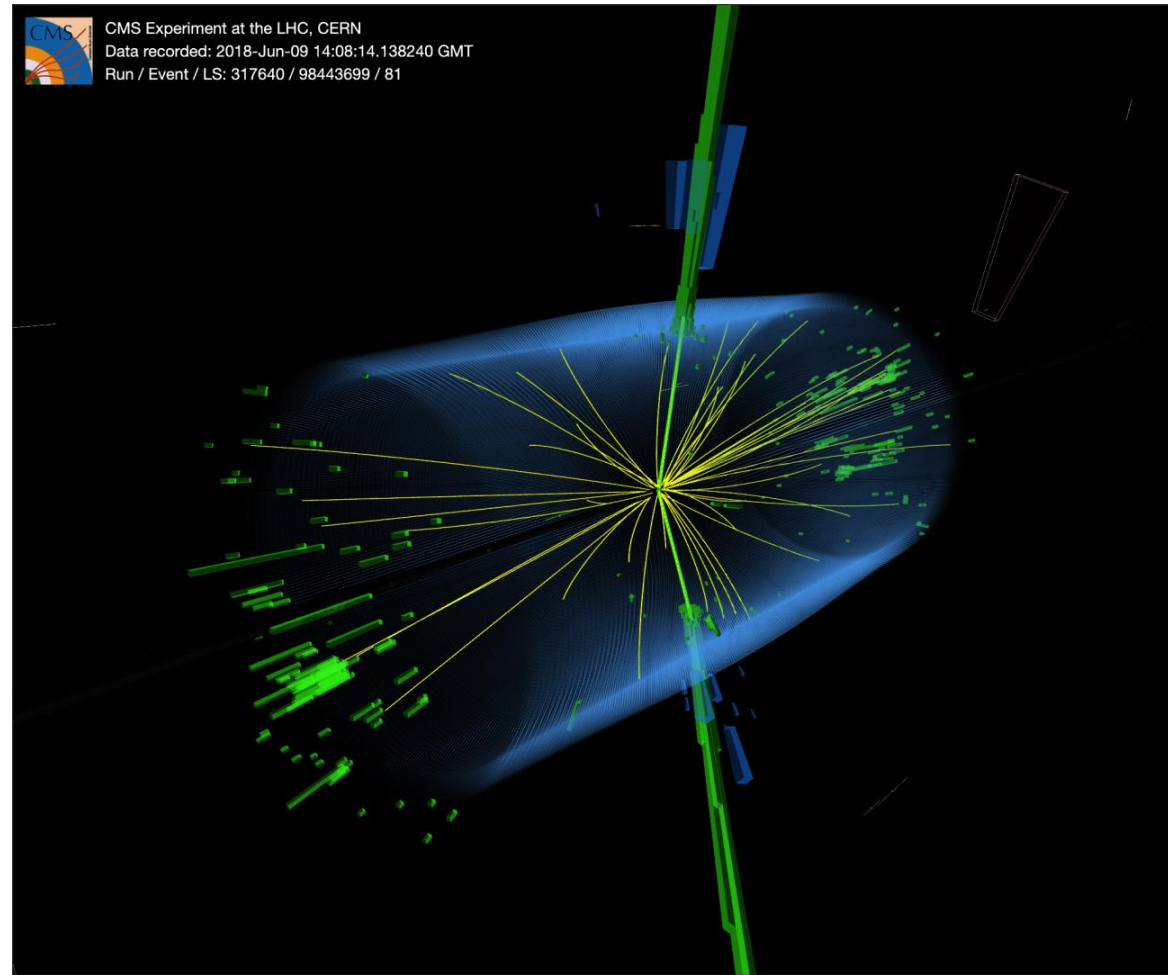
Particle identification with CMS@LHC



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



ALEPH @ LEP

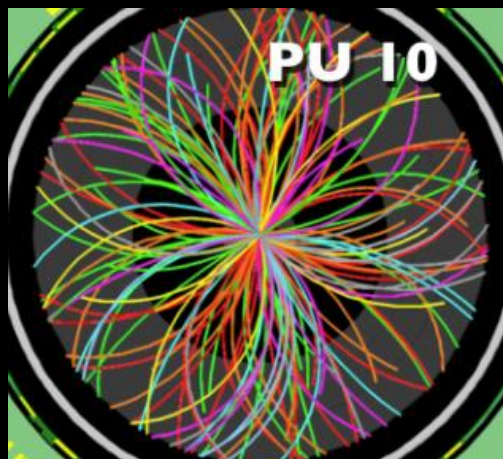
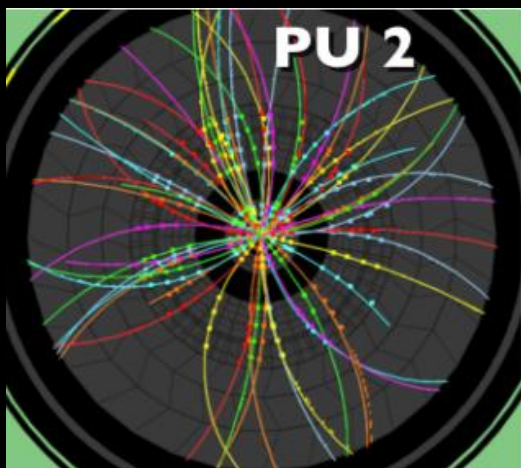
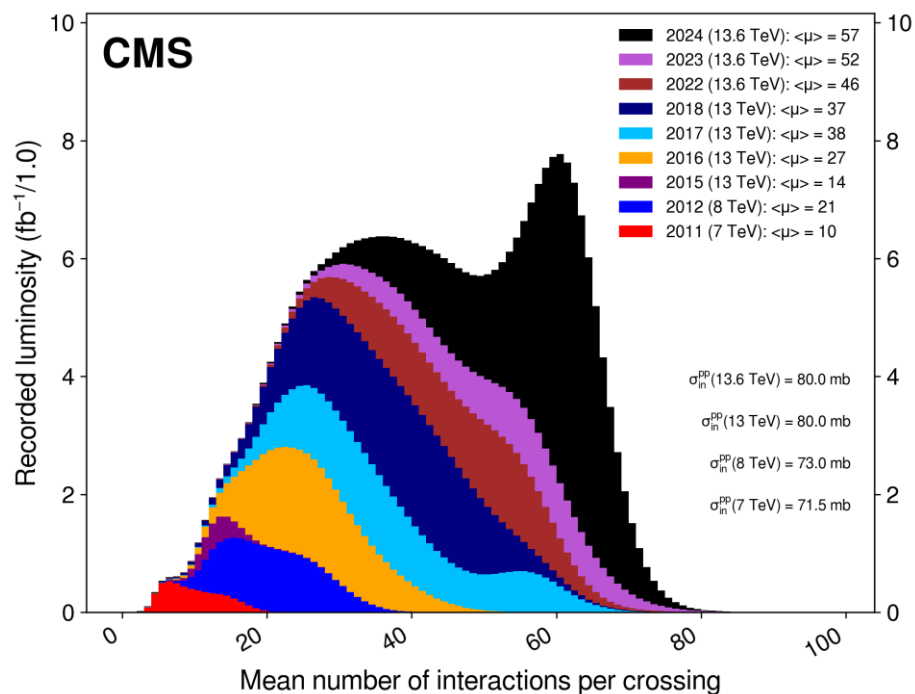


CMS @ LHC

Pile-Up

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

PU = number of inelastic interactions per beam bunch crossing



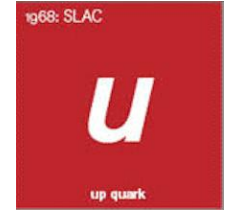
$Z \rightarrow \mu\mu$ event with 25 reconstructed vertices

April 15th, 2012



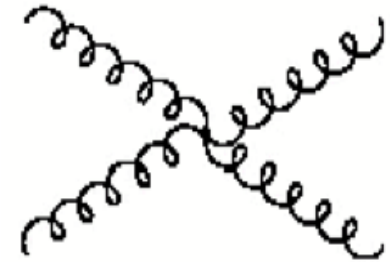
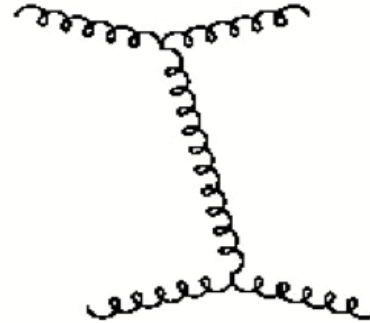
~5 cm

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

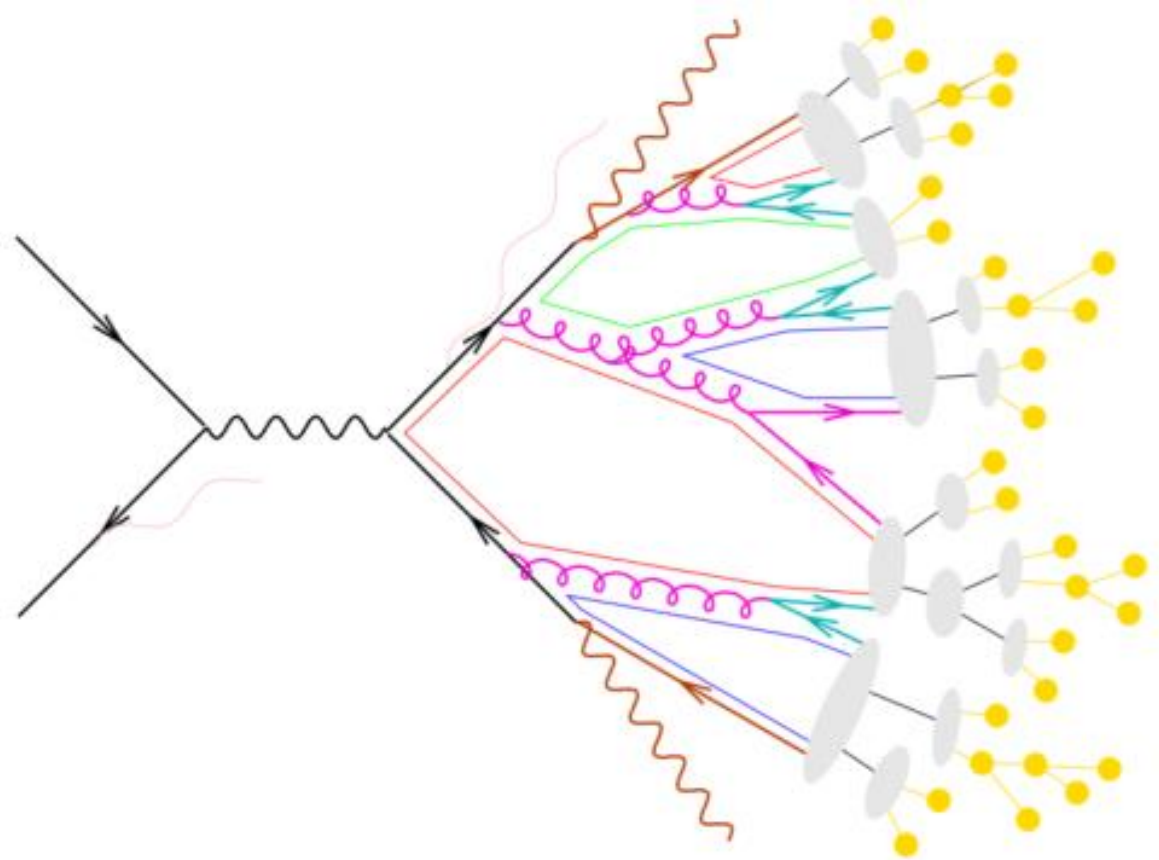
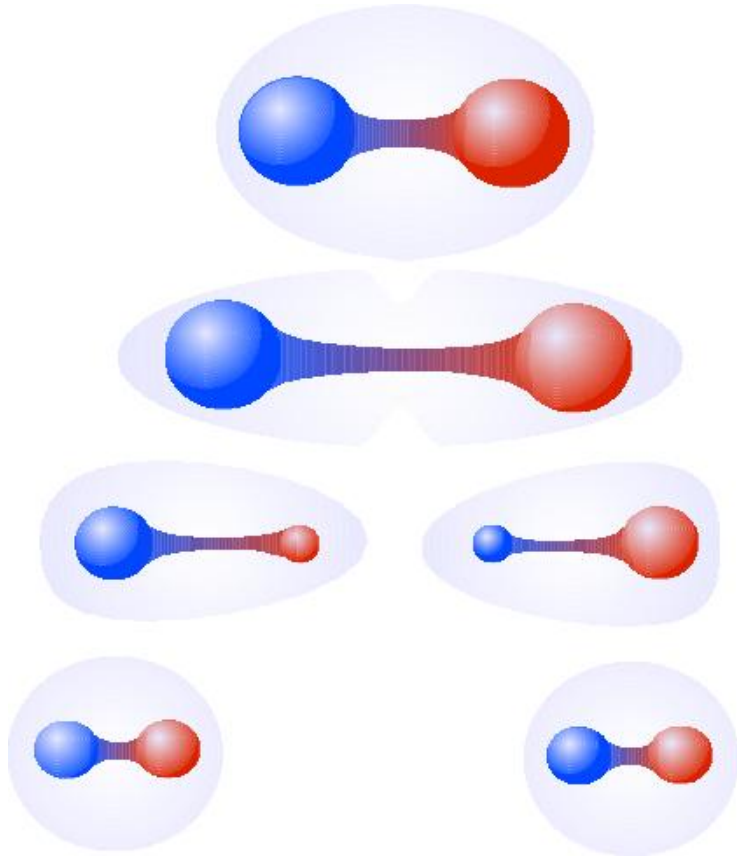
quark-quark effective potential

$$V_s = -\frac{4}{3} \frac{\alpha_s}{r} + kr$$

$\underbrace{\hspace{1.5cm}}$ $\underbrace{\hspace{1.5cm}}$

single gluon exchange confinement

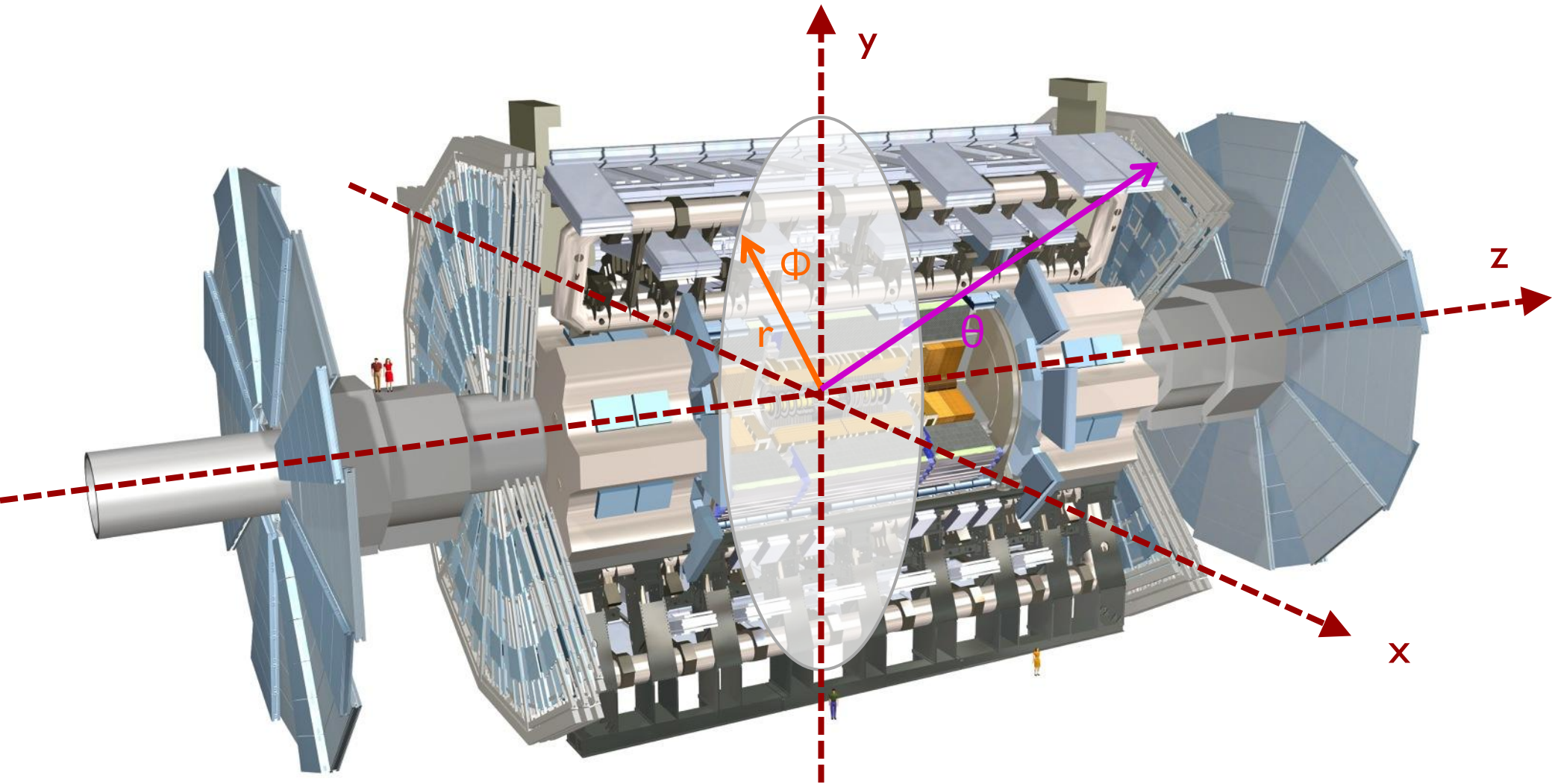
Confinement, hadronization, jets



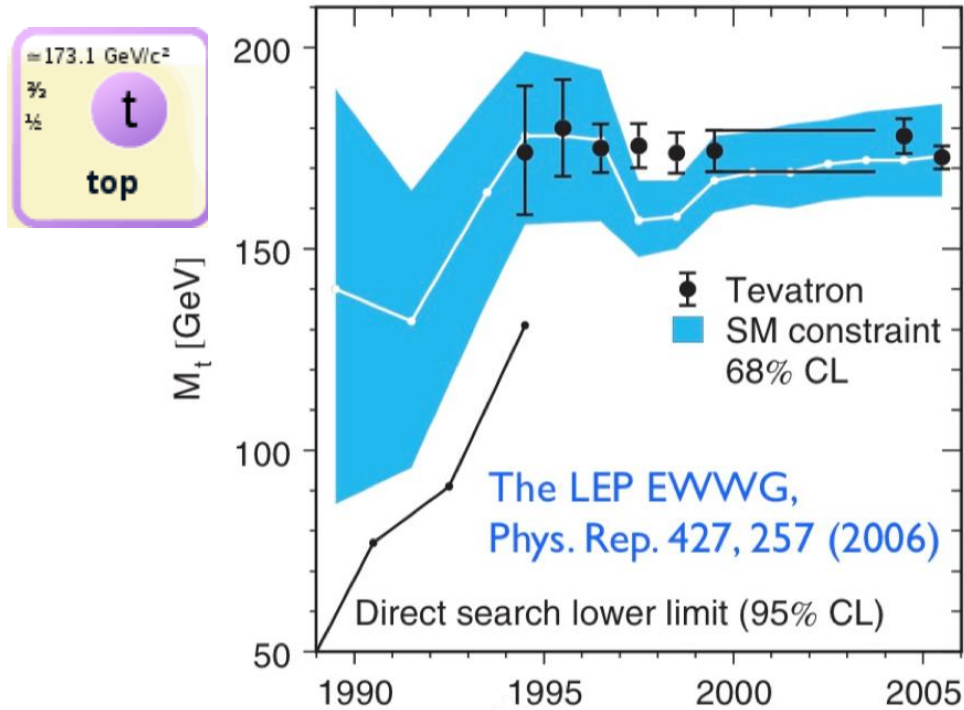
Additional information

(I find you lack of faith disturbing)

Collider experiment coordinates



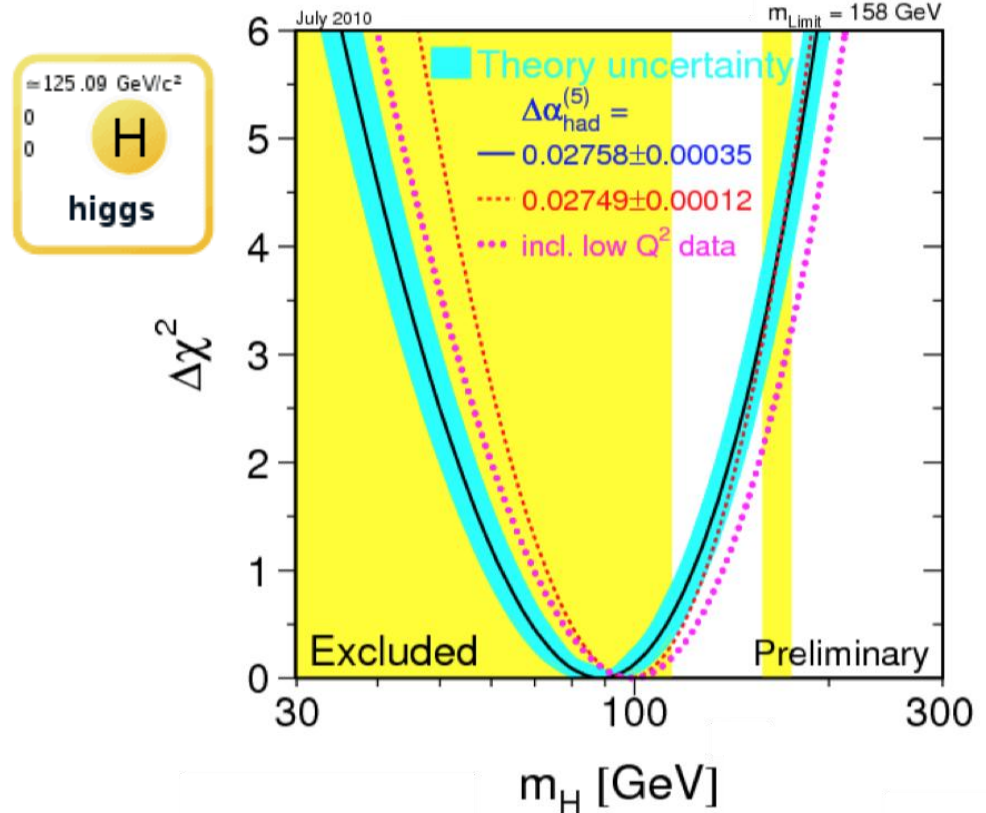
Before the LHC startup



m_W measurement
at SppS and LEP-I
precision
measurements

top quark
discovery
(1994)

m_W measurement
at LEP-2



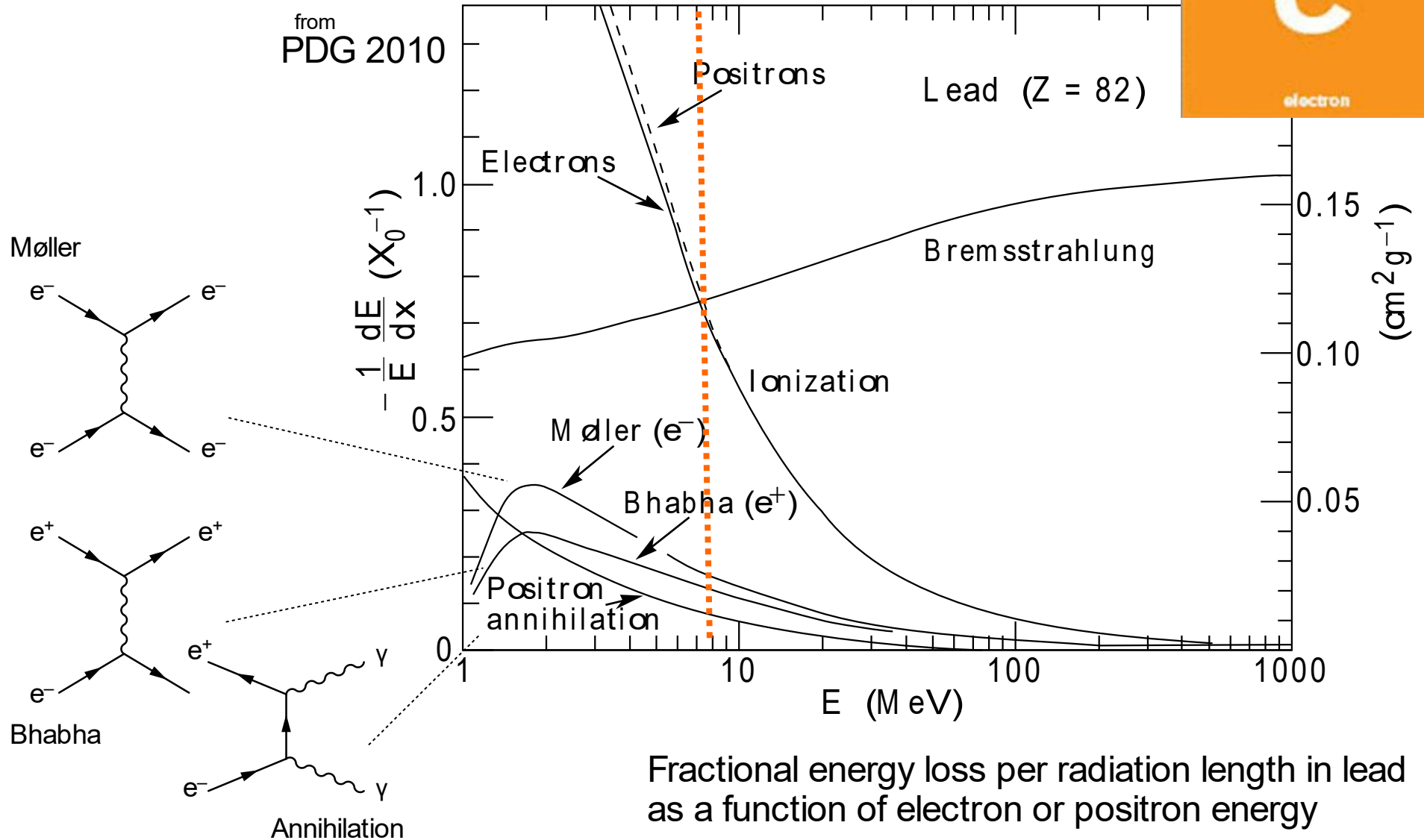
electroweak fit
and indirect limit on m_H

Direct limits on Higgs
production from LEP-2
and Tevatron

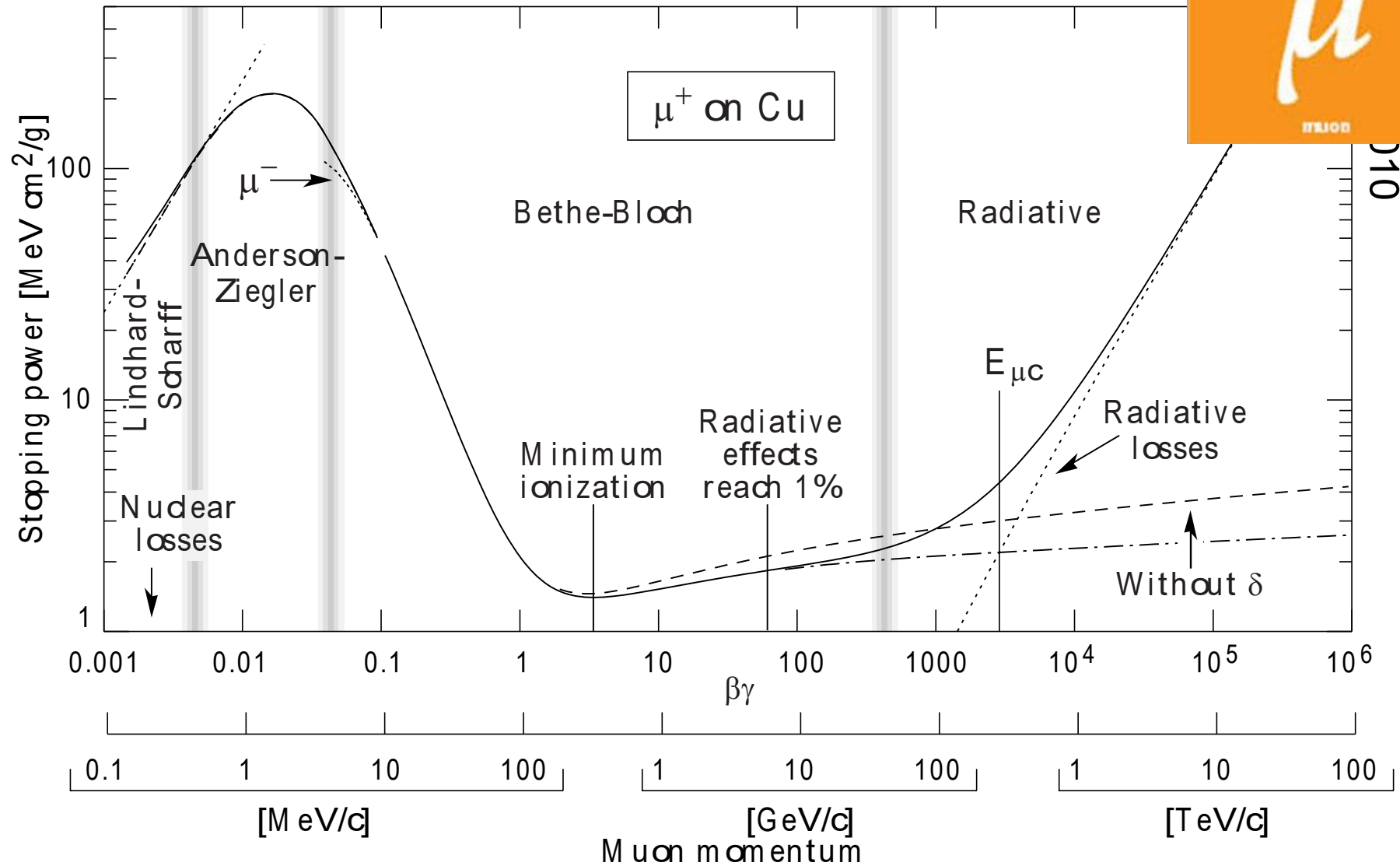
LHC “no lose theorem”

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

Electron energy loss

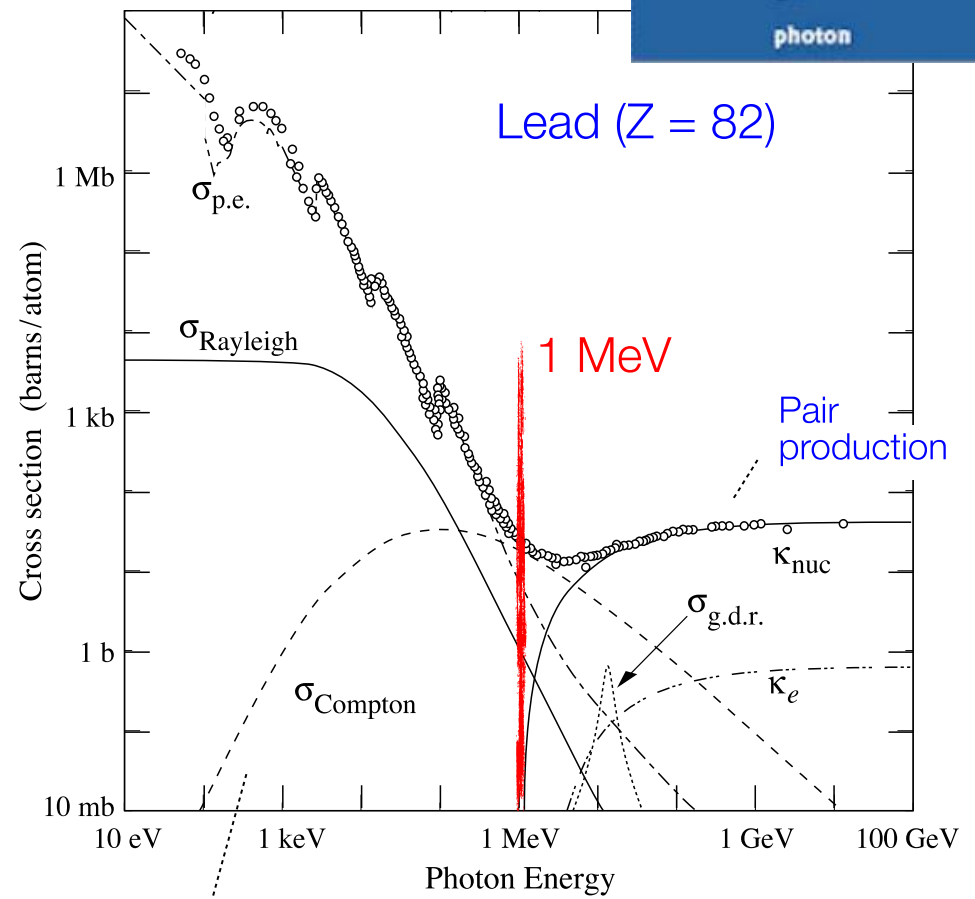
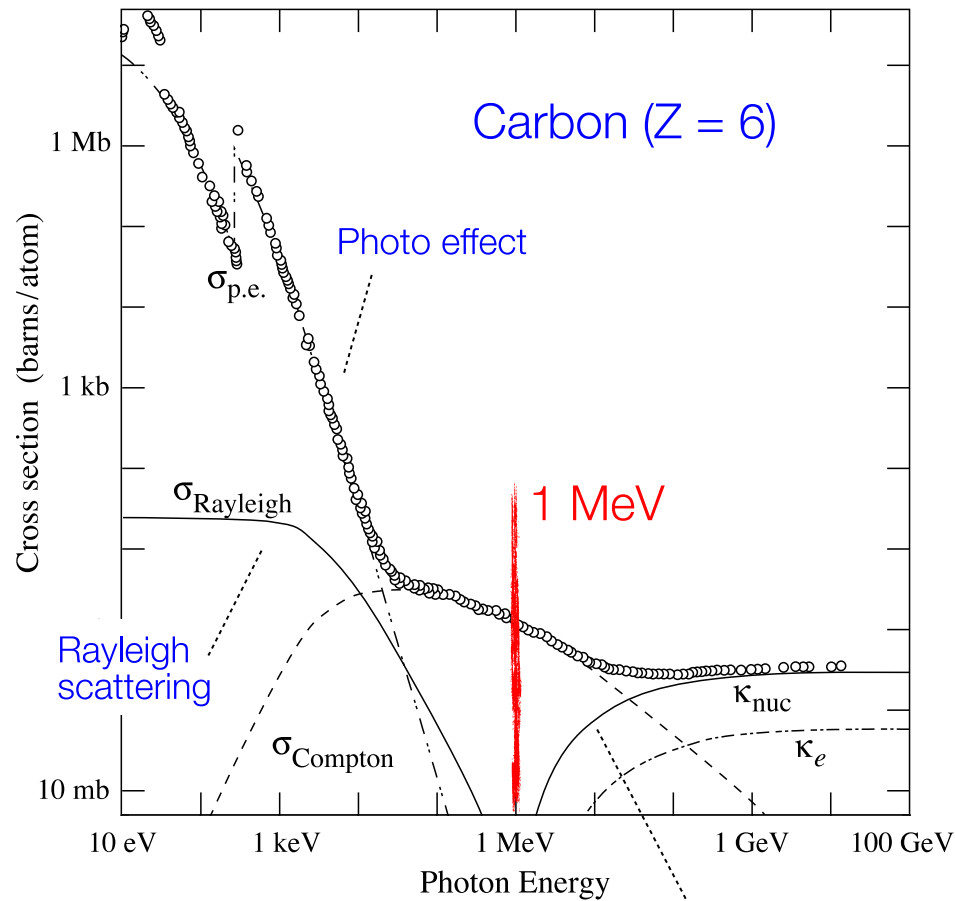


Muon energy loss



010

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
$\hbar = h/2\pi$	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:

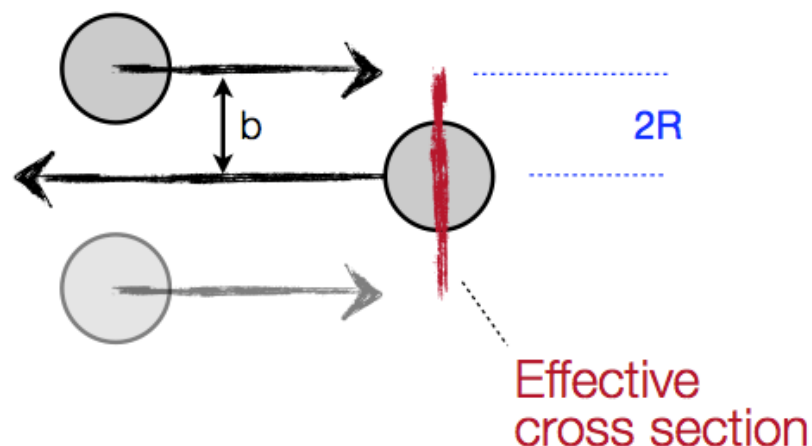
$$[\sigma] = \text{GeV}^{-2}$$

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

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

Estimating the
proton-proton cross section:

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

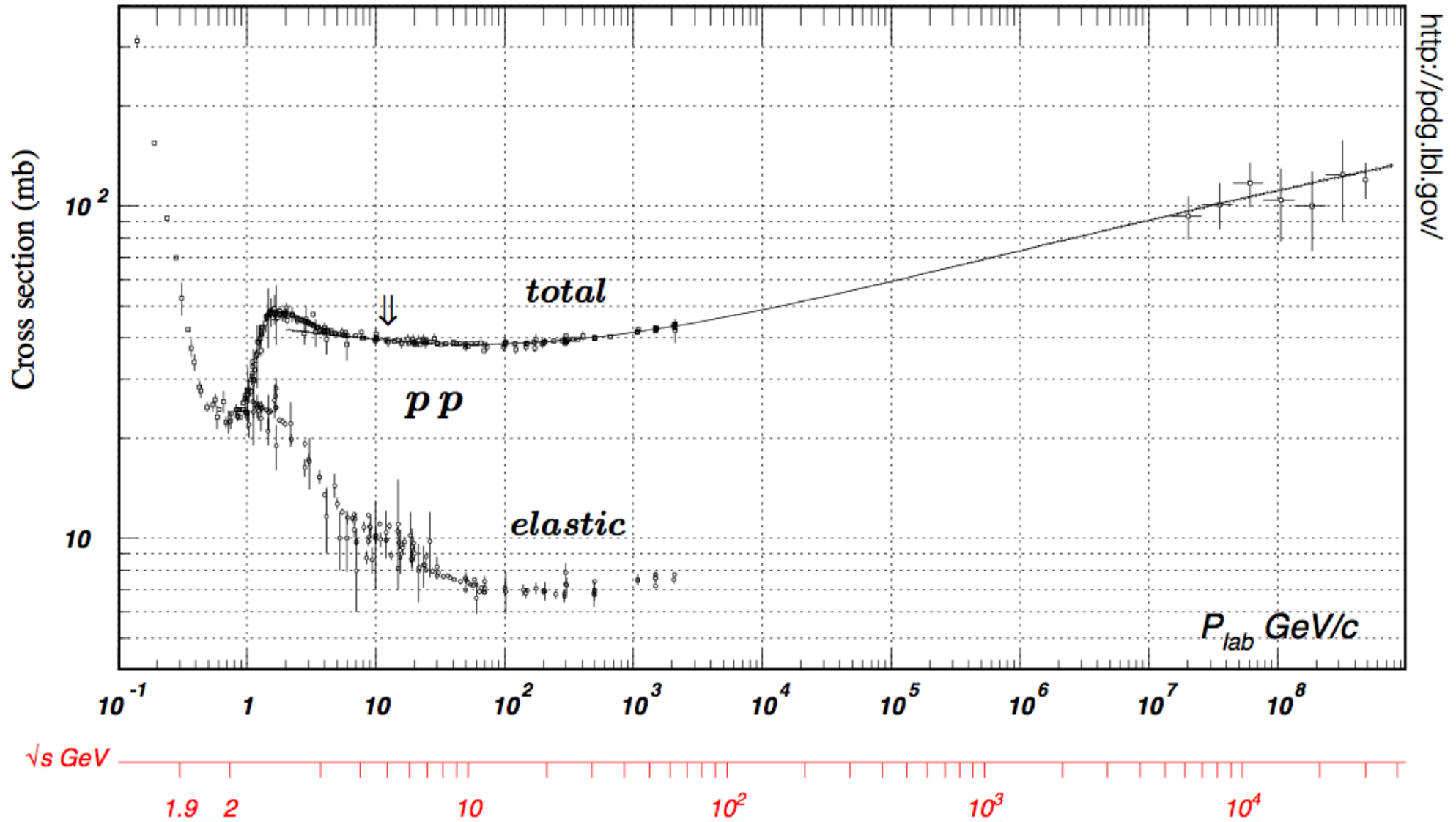


Proton radius: $R = 0.8 \text{ fm}$

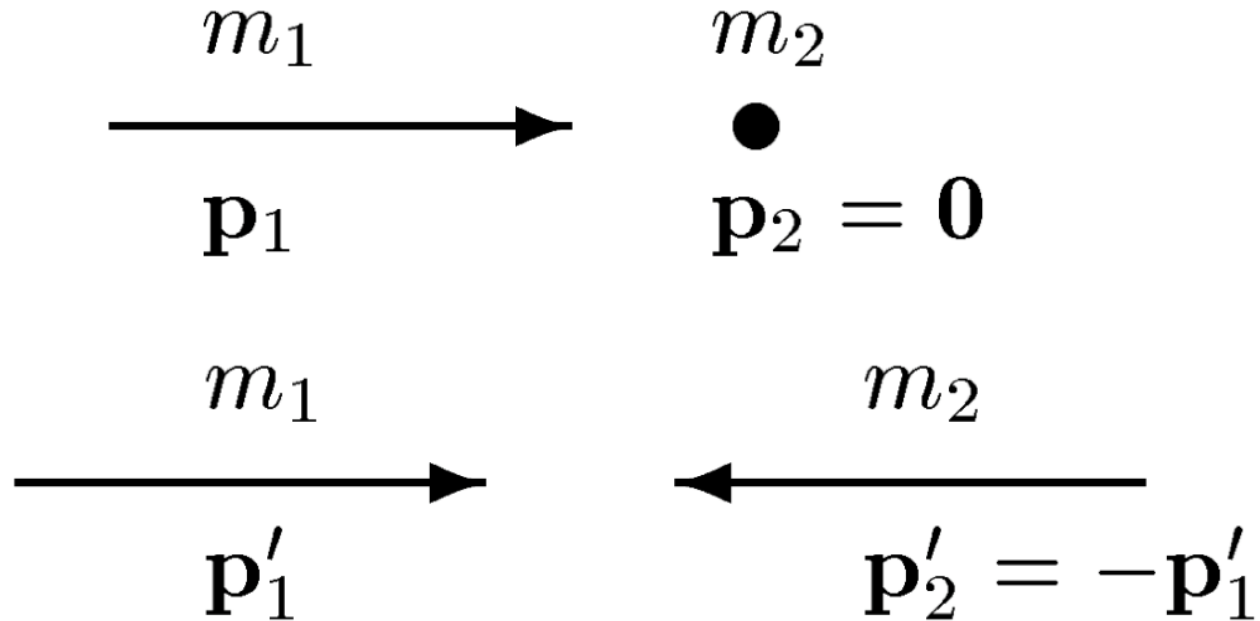
Strong interactions happens up to $b = 2R$

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

Proton-proton scattering cross-section



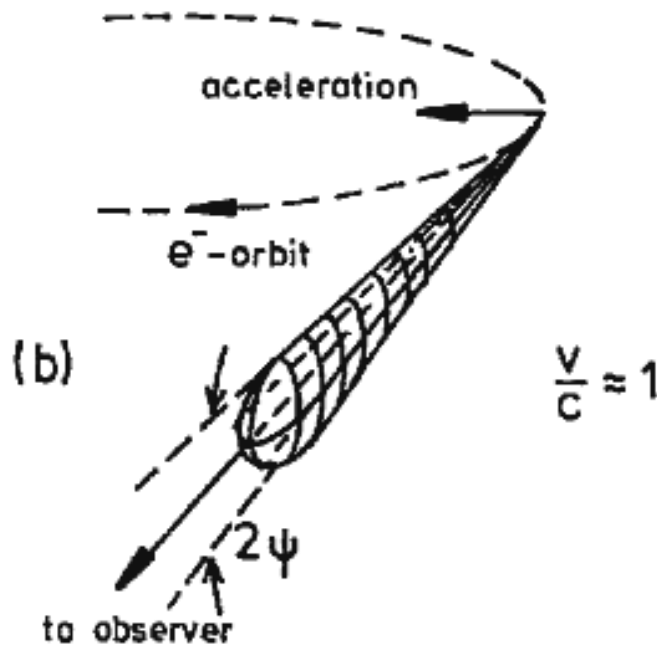
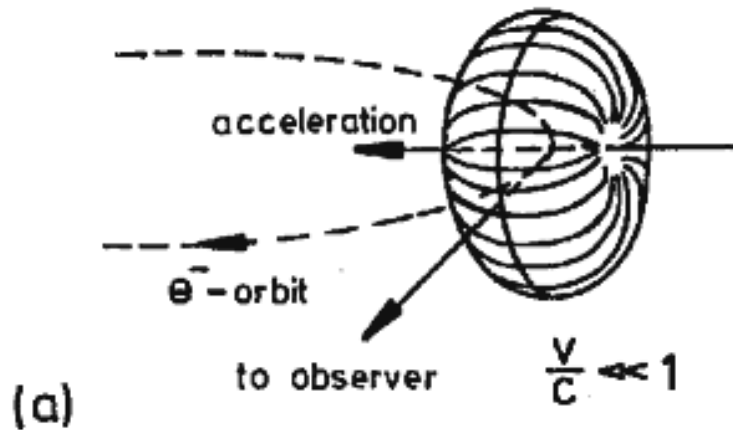
Fixed target vs. collider



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

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

Synchrotron radiation



energy lost per revolution

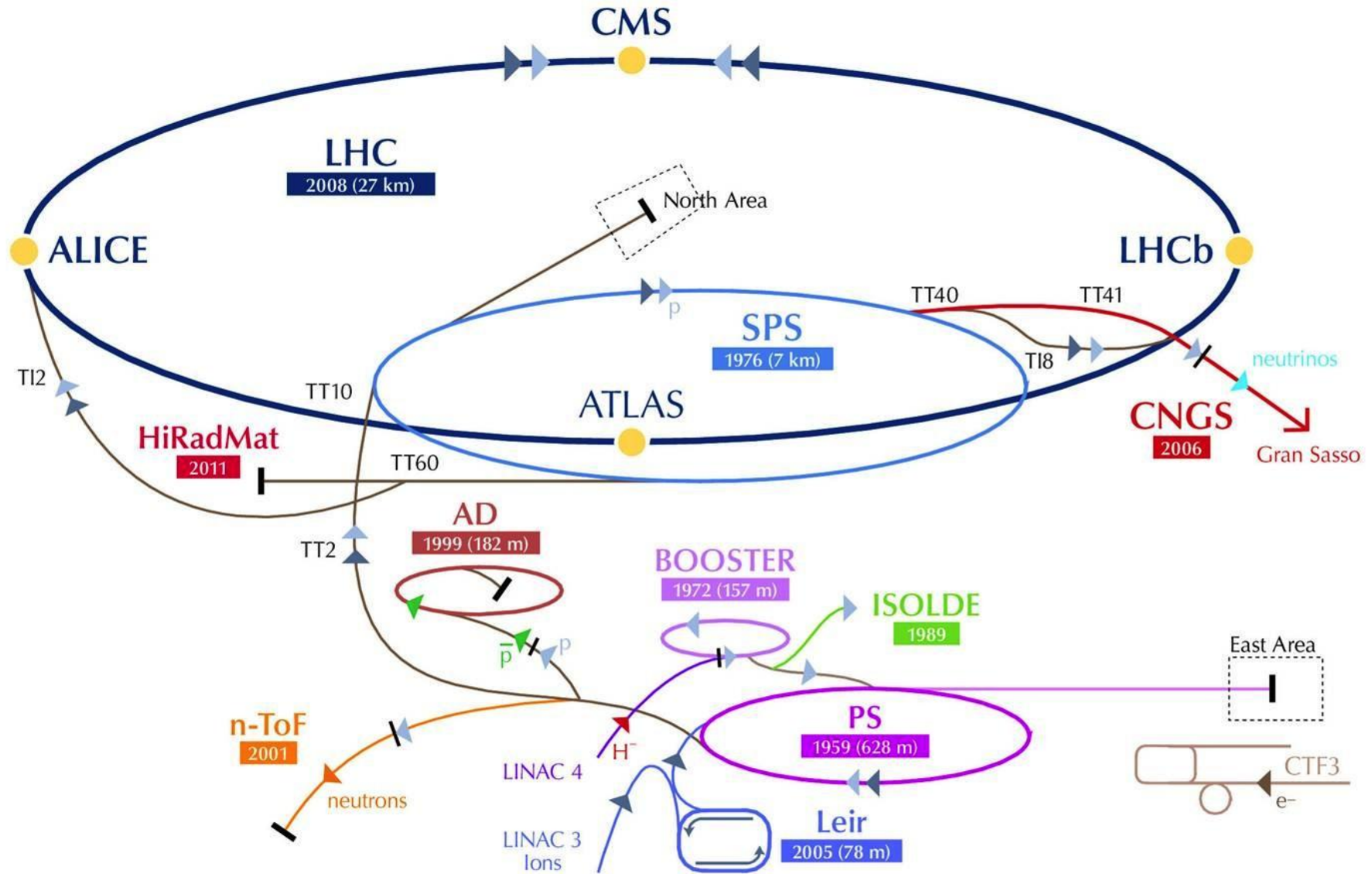
$$\Delta E = \frac{4\pi}{3} \frac{1}{4\pi\epsilon_0} \left(\frac{e^3 \beta^3 \gamma^4}{R} \right)$$

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

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

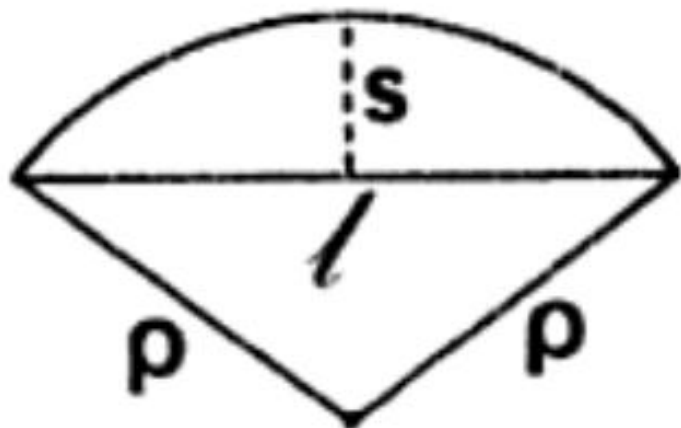
If the field is constant and we neglect presence of matter, **momentum magnitude is constant** with time, **trajectory is helical**

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

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

$$\left| \frac{\delta p}{p} \right| = \underbrace{A_N}_{\text{projected track length in magnetic field}} \underbrace{\frac{\epsilon}{L^2}}_{\text{resolution is improved faster by increasing } L \text{ then } B} \frac{p}{0.3B}$$

Momentum resolution gets worse for larger momenta

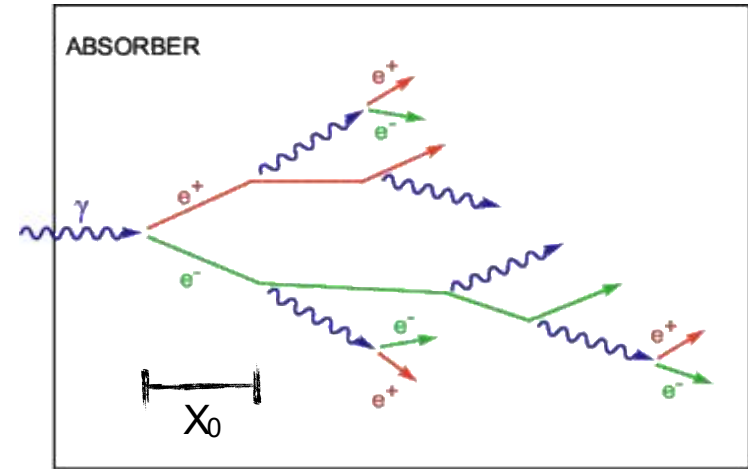
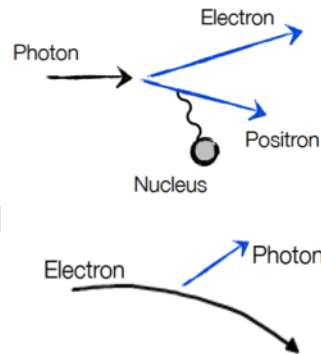
resolution is improved faster by increasing L then B

Electromagnetic showers

Dominant processes
at high energies ...

Photons $\square$: Pair production

Electrons $\blacksquare$: Bremsstrahlung



Pair production:

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

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

[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:

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

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

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

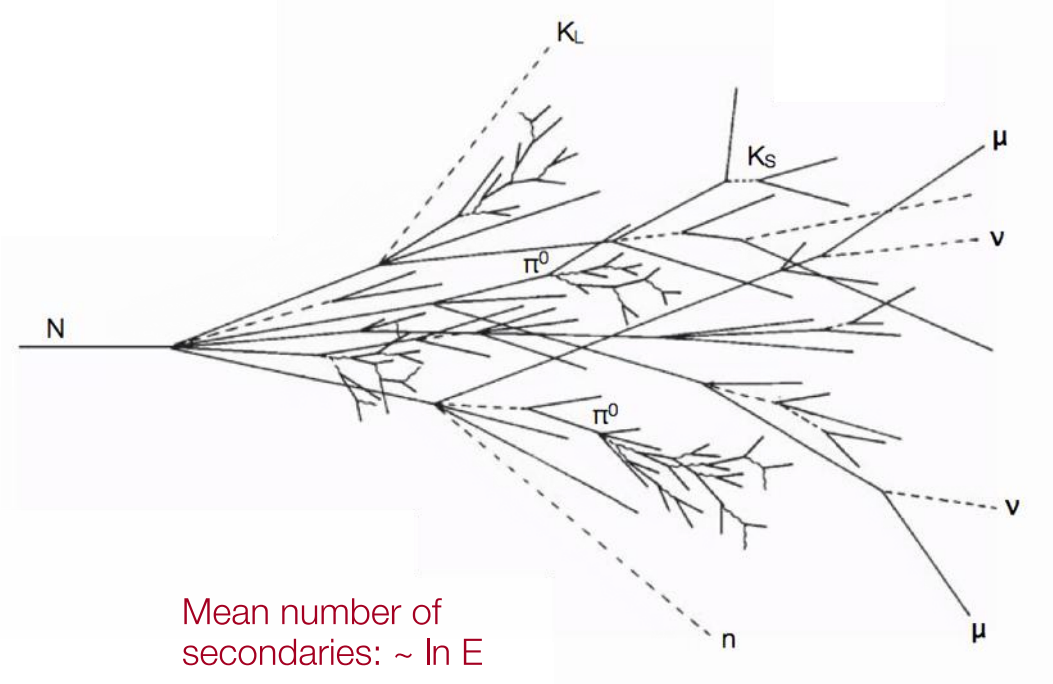
Critical energy:

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

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:

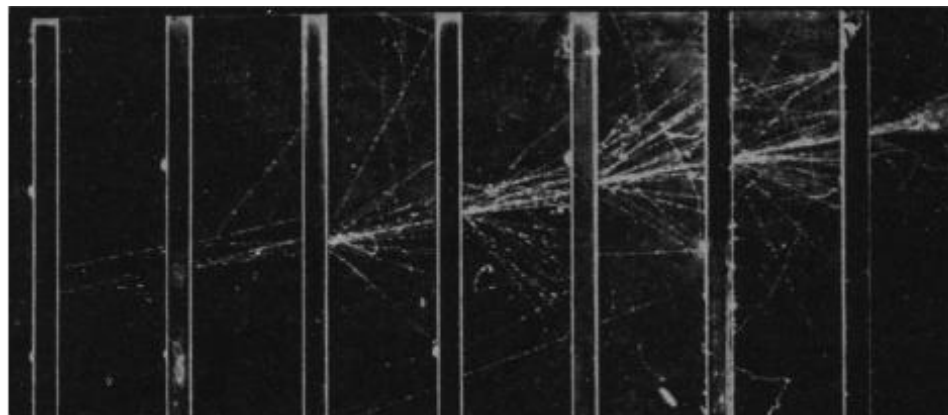
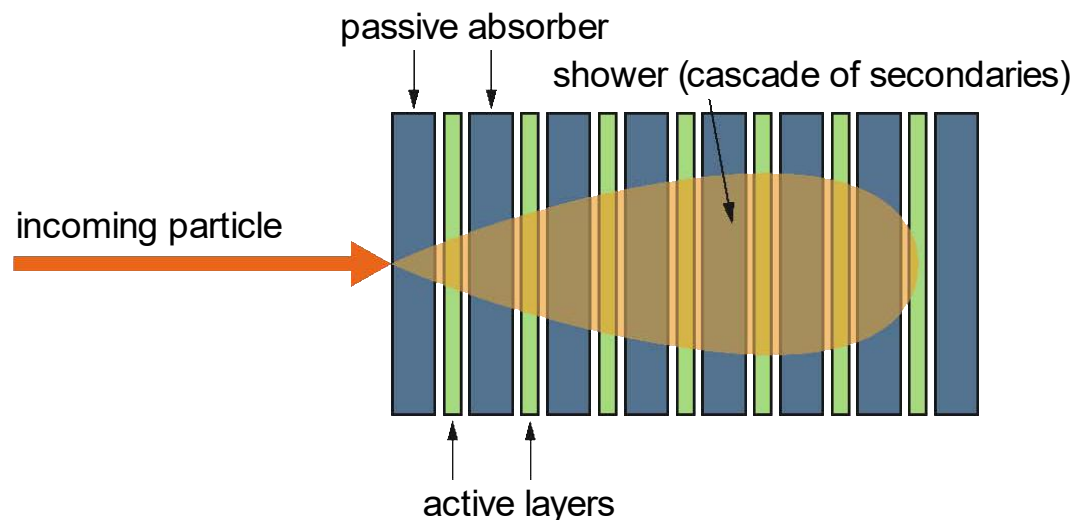
Plastic scintillator

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 ...

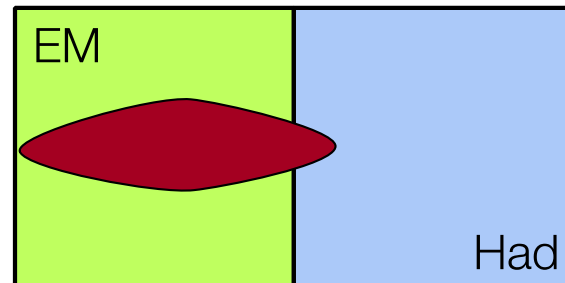
But:

Hadronic energy measured in
both parts of calorimeter ...

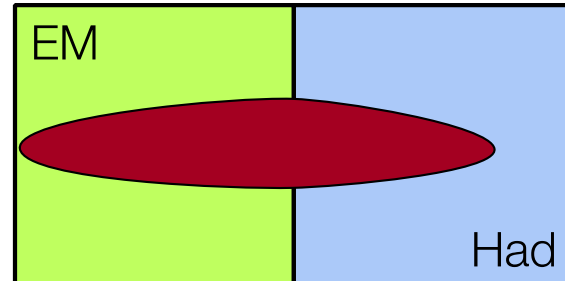
Needs careful consideration of
different response ...

Schematic of a
typical HEP calorimeter

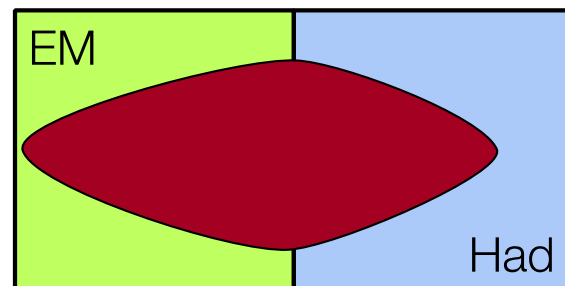
Electrons
Photons



Taus
Hadrons



Jets



Energy resolution in calorimeters

Energy resolution:

e.g. inhomogeneities

□□ shower leakage

e.g. electronic noise

□□ sampling fraction variations

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

Fluctuations:

□ Sampling fluctuations

□ Leakage fluctuations

Fluctuations of electromagnetic fraction

Nuclear excitations, fission, binding energy fluctuations ...

□ Heavily ionizing particles

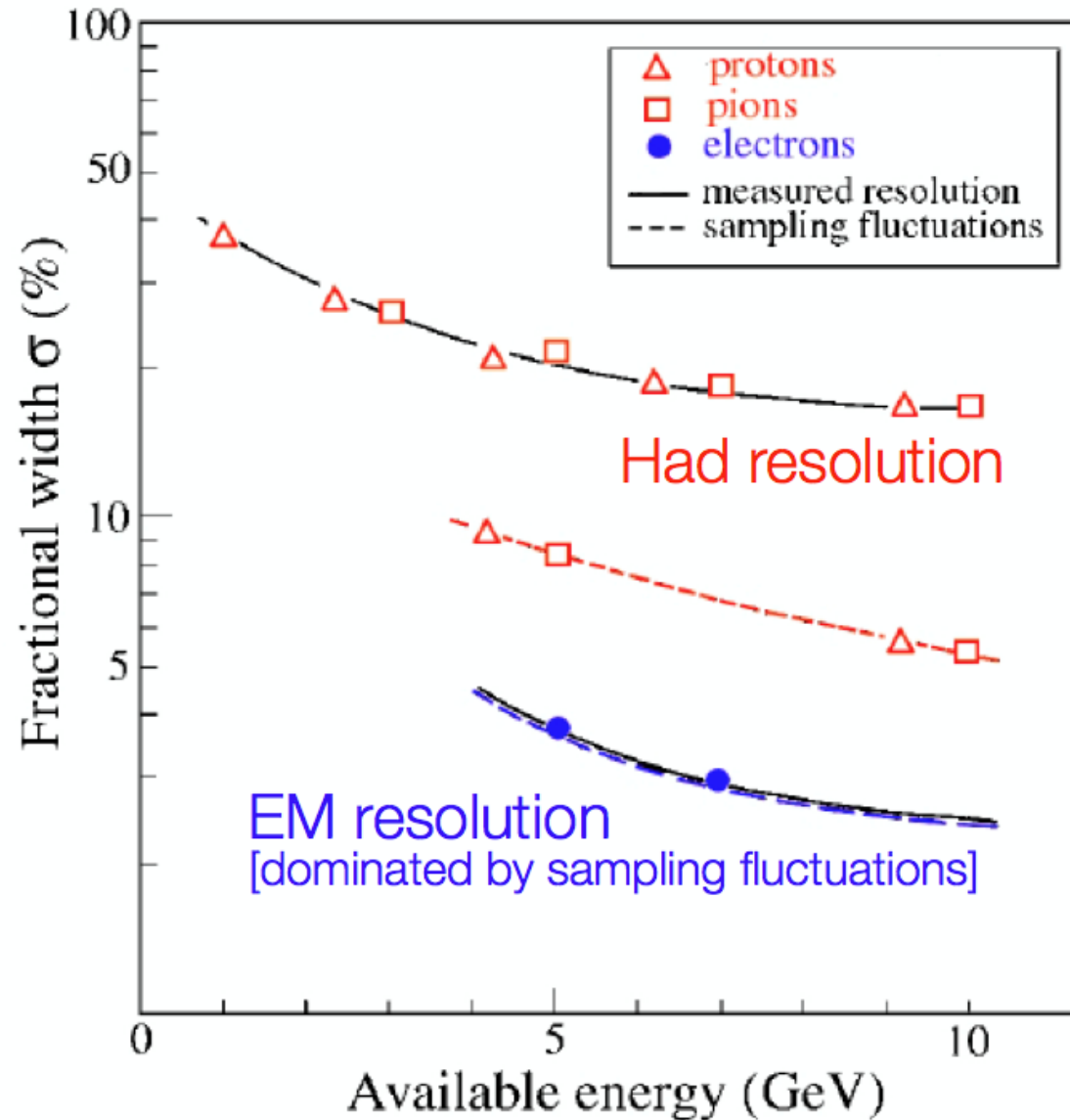
Typical:

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]