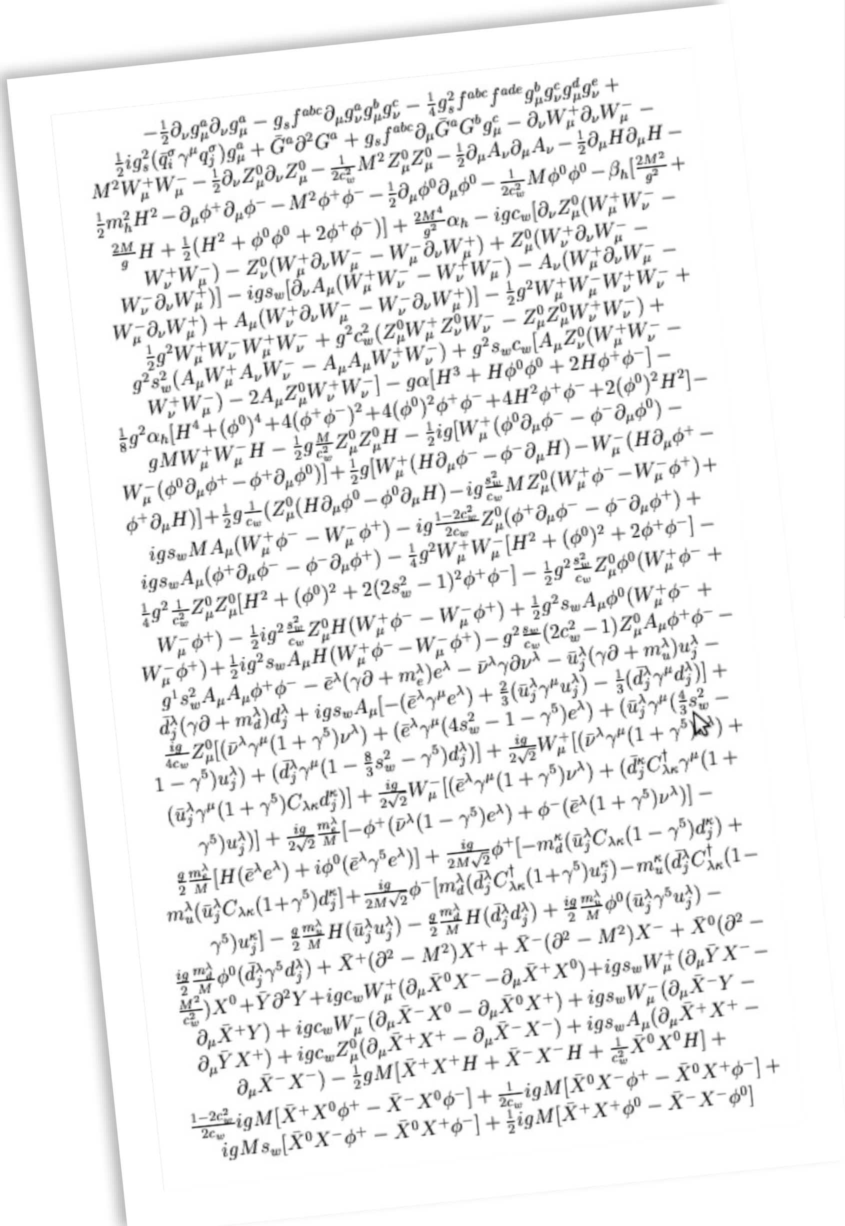
(experimental)

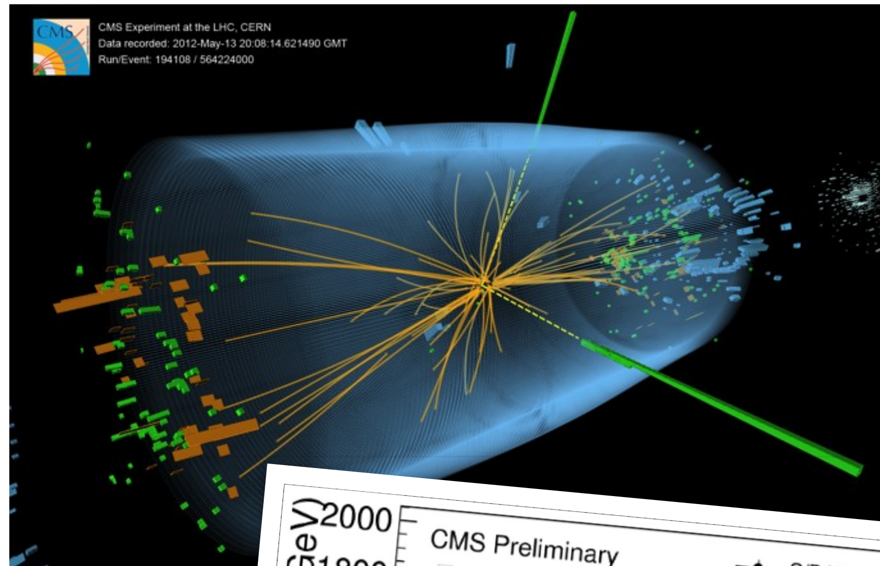
LHC physics

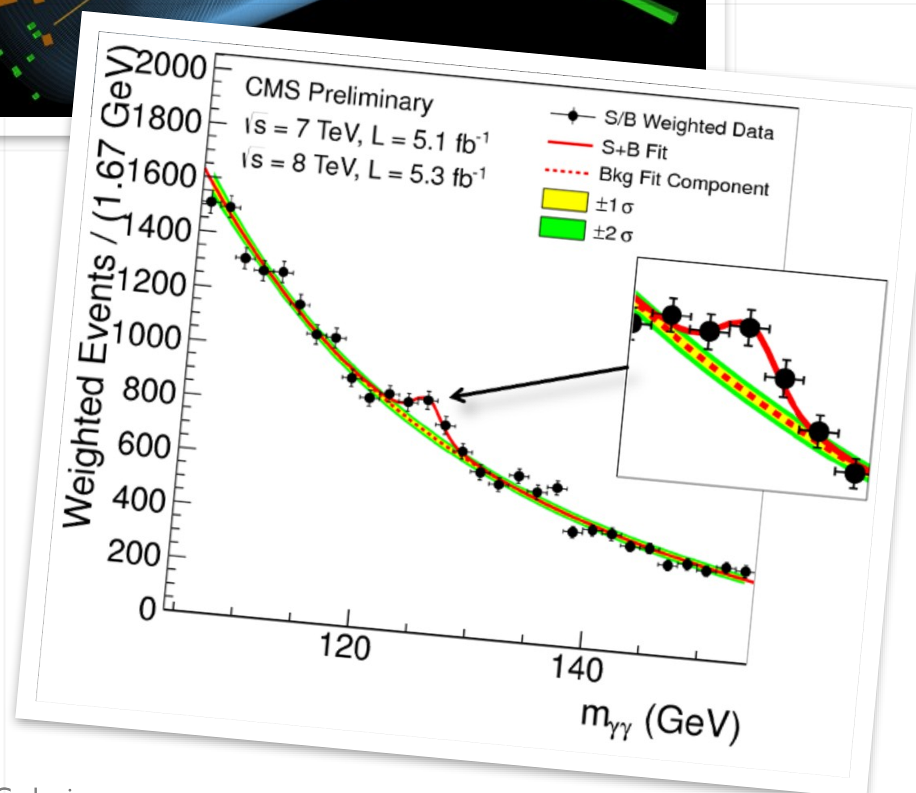
I. { how (which) particles are produced and measured? }

Riccardo Bellan

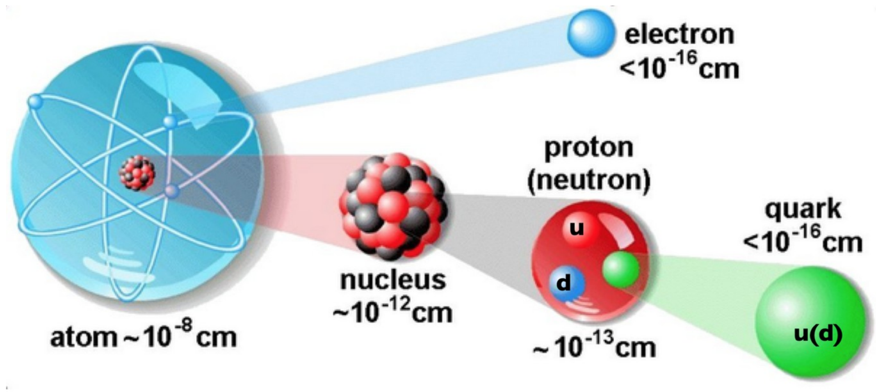
Experiment = probing/building theories with data!

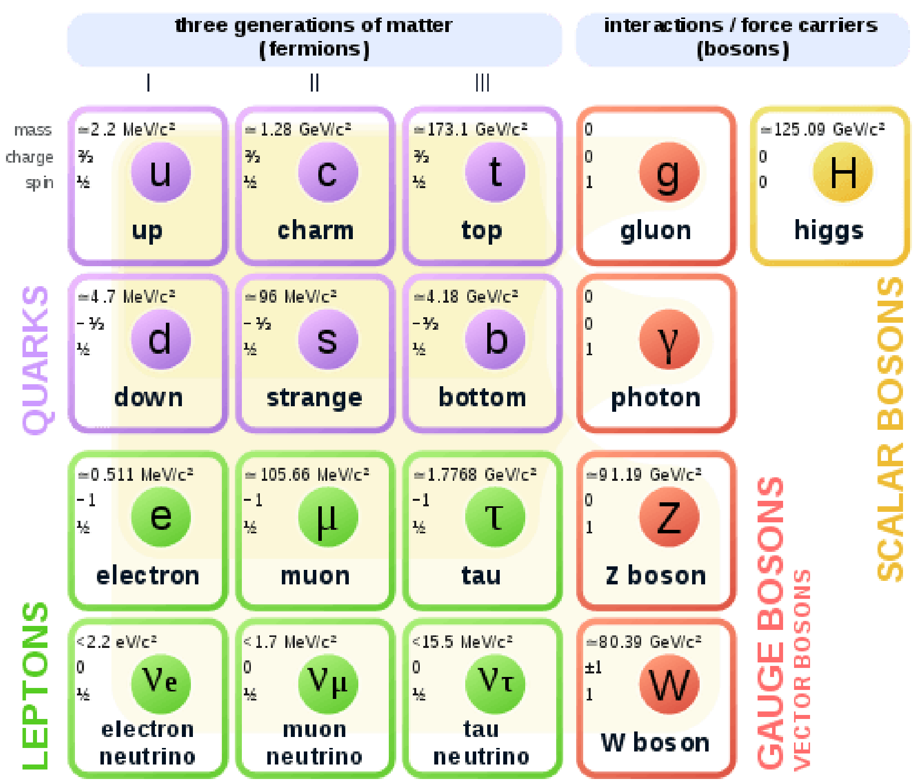






The Standard Model of particle physics in a nutshell





Gauge bosons

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

Gauge boson coupling to fermions (EW, QCD)

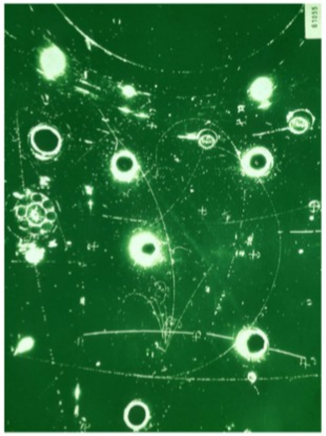
Higgs coupling to fermions (fermion masses)

Higgs coupling to bosons (boson masses)

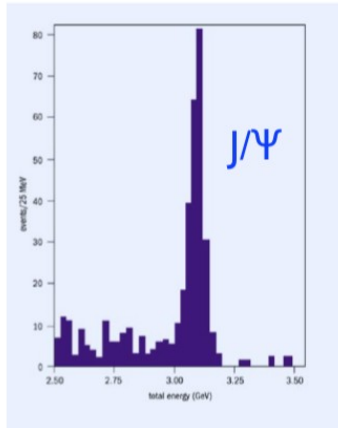
Higgs self-coupling (Higgs potential)

A theory built (and probed) over time…

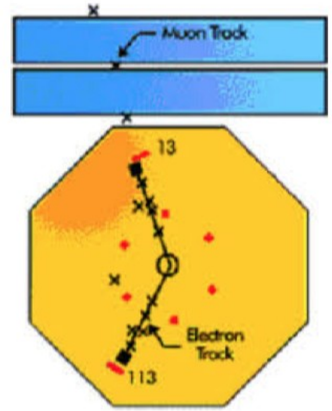
1972 – CERN
Neutral currents



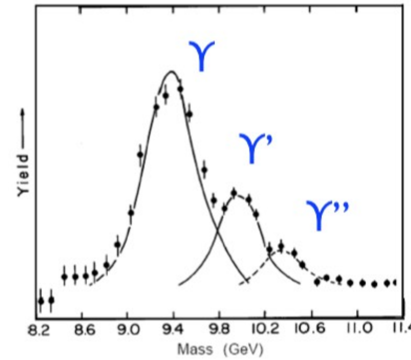
1974 – BNL, SLAC
Charm



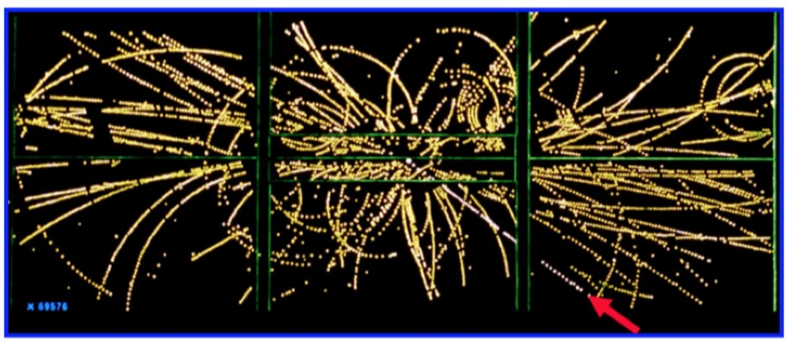
1976 – SLAC
Tau lepton



1979 – Fermilab
Beauty

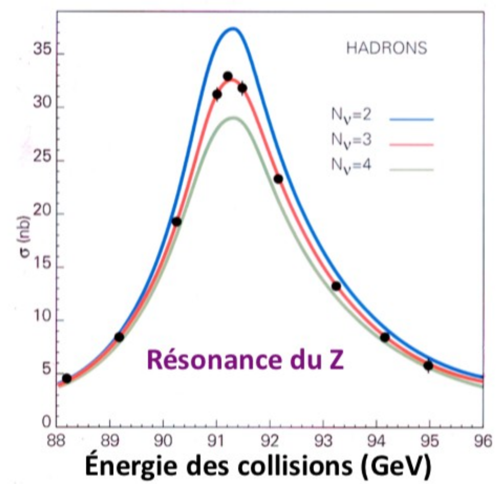


1983 – CERN/SppS
W and Z bosons



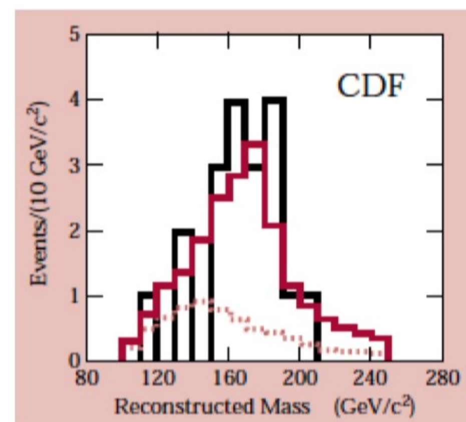
UA1, UA2

1990 – CERN/LEP
Three families of neutrinos



ALEPH, DEPHI, L3, OPAL

1994 – Fermilab/TeVatron
Top quark



CDF, D0

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

Through two fundamental quantities:

- **σ** (cross section): **probability** of a particle of being produced in collisions at a given energy (es. 13 TeV at LHC)
  - ✓ May be *differential*, that is, as a function of the energy of the particle, the angles of its trajectory, or both of them, etc.
- **Γ** (decay rate): **probability** (over time) of a particle of decaying into other particles
  - ✓ The sum of all possible decay rates Γ_i, gives the total decay rate, and because of resonance theory, it is the inverse of decay time: $\tau = 1/\Gamma$

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

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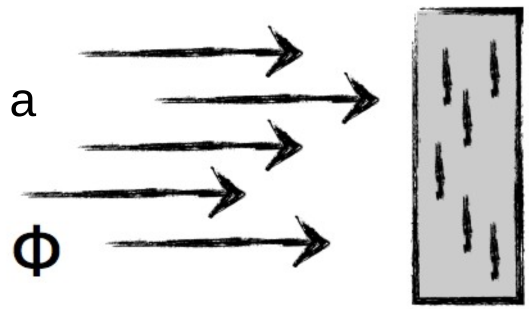
Interaction cross section



The flux $\Phi = \frac{1}{S}\dot{N}_a$ represent the number of particles, per unit of time, sent over a surface S (the illuminated area) of the target. $[\Phi]=[L^{-2}t^{-1}]$

The number of reactions per unit of time is proportional to the number of targets and the flux of the incoming particles

$$\dot{N}_r = \sigma \Phi N_{targets} \qquad [\sigma] = [L^2]$$

σ is the interaction cross section and the quantity $\mathscr{L} = \Phi N_{targets}$ is the so called instantaneous luminosity. The **integrated luminosity** is defined as $L = \int \mathscr{L} dt$.

The reaction rate per single target and single incoming particle is

$$W_r = \frac{\dot{N}_r}{N_a N_{targets}} = \sigma \frac{v_a}{V} = \frac{2\pi}{\hbar} |M_{fi}|^2 \rho(E')$$

Interaction cross section

We can go to differentials

$$dW_r = \frac{2\pi}{\hbar} |M_{fi}|^2 \rho(E')$$

(the differential in the right part is hidden in the density state term)

With some math, see for example [], we can obtain, e.g., the cross section as a function of the solid angle

$$\frac{d\sigma_r}{d\Omega} = \frac{1}{4\pi^2\hbar^4} \frac{p_f^2}{v_f v_i} |M(q^2)|^2 = \frac{1}{\mathscr{L}} \frac{\Delta \dot{N}_r}{\Delta\Omega}$$

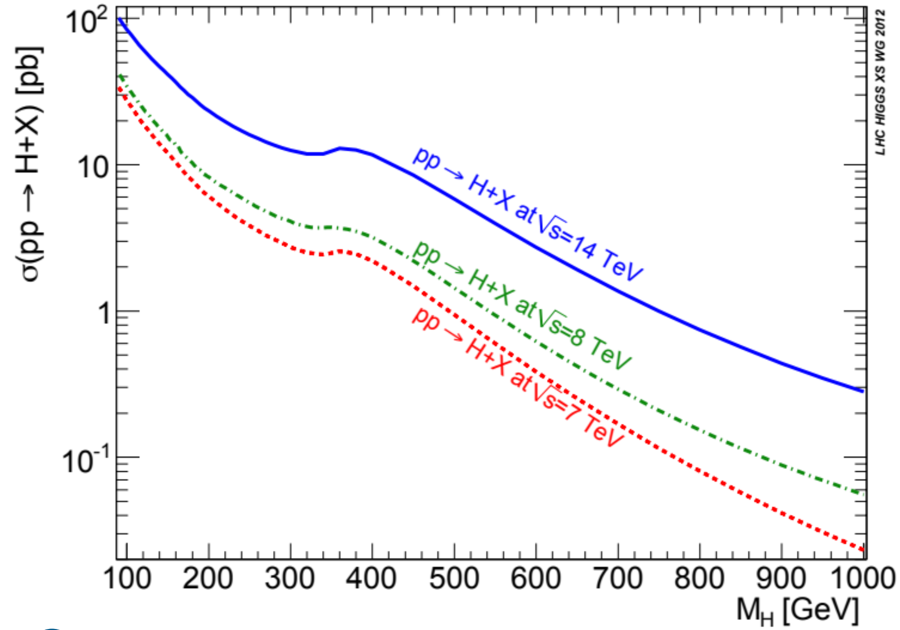
We can compare experiments and theory!

The typical units in which the cross section is expressed is the *barn*

$$1\,b = 100\,fm^2 = 10^{-24}\,cm^2 \simeq \pi r^2_{uranium}$$

Luminosity in a collider

Number of events in unit of time $\dot{N}_r = \sigma \mathscr{L}$



We want to **explore very rare processes**, i.e., with very low cross sections (or very rare decays).

→ go higher with instantaneous luminosity!

In a collider ring: $$\mathscr{L} = \frac{1}{4\pi} \frac{f N_1 N_2}{\sigma_x \sigma_y}$$

Current

Beam sizes (RMS)

At LHC

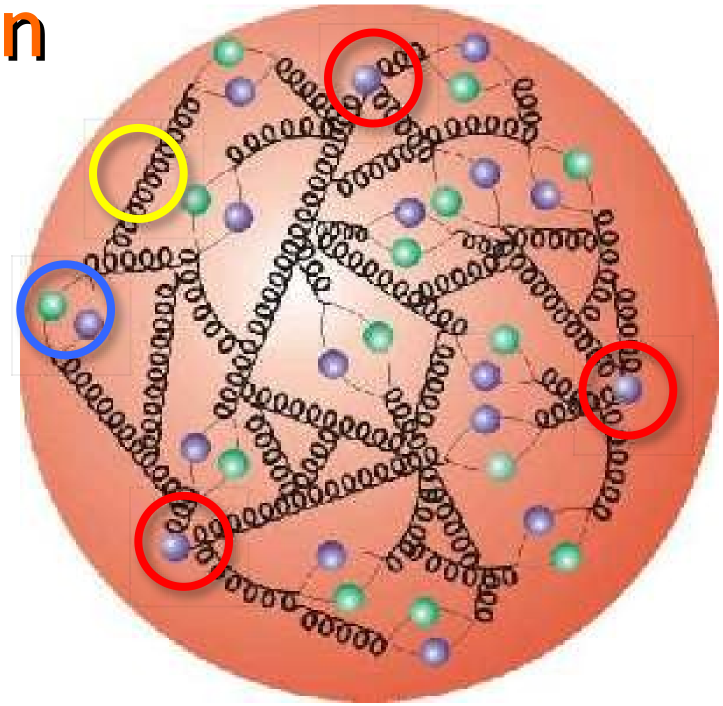
- $\mathbf{N_1 = N_2}$ = 1.15 · 10^{11} # of protons
- **f** = bunch crossing frequency = j v/ℓ, v = c and ℓ = 2πr with r = 26659 m
  - j = 2808 effective bunches, one crossing every 25 ns (f = 40 MHz), each bunch spaced 7.5 m. The effective number of bunches is 2808 (f = 31,6 MHz)
- $\sigma_x \sim \sigma_y$ = 16 μm
- **$\mathscr{L}$ ~ 1.3 · 10^{34} cm^{-2}s^{-1}**

LHC

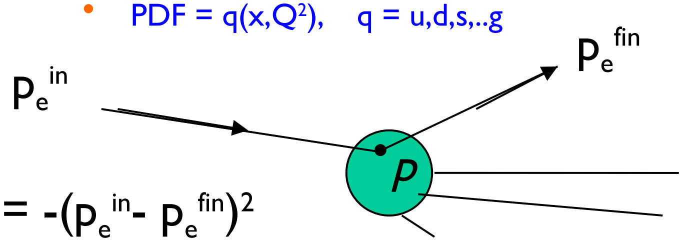
pp collider (2008-present)

$\sqrt{s}$ = 7-8-13-13.6 TeV

About the inner life of a proton

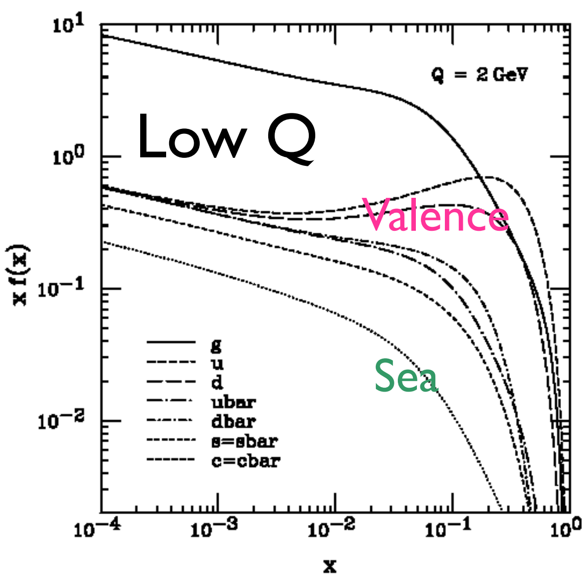


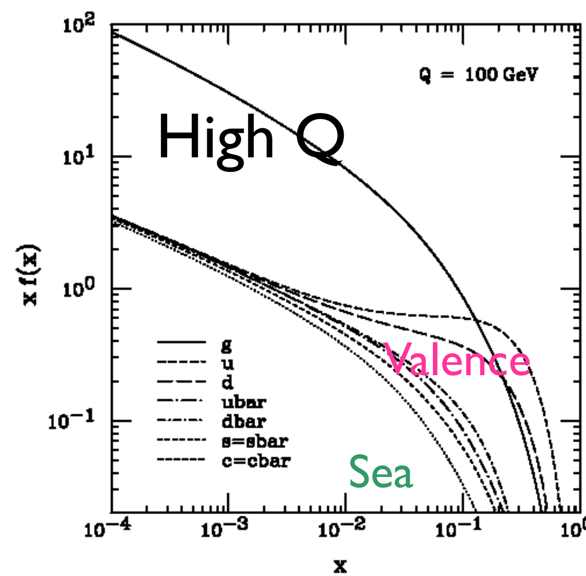
- ***p*** **rotons have substructure!**
  - ✓ partons = quarks & gluons
  - ✓ 3 valence (colored) quarks bound by gluons
  - ✓ Gluons (colored) have self-interactions
  - ✓ Virtual quark pairs can pop-up (sea-quark)
  - ✓ *p* momentum shared among constituents
    - described by *p* structure functions
- **Parton energy not 'monochromatic'**
  - ✓ Parton Distribution Function
    - PDF = $q(x,Q^2)$, $q = u,d,s,..g$



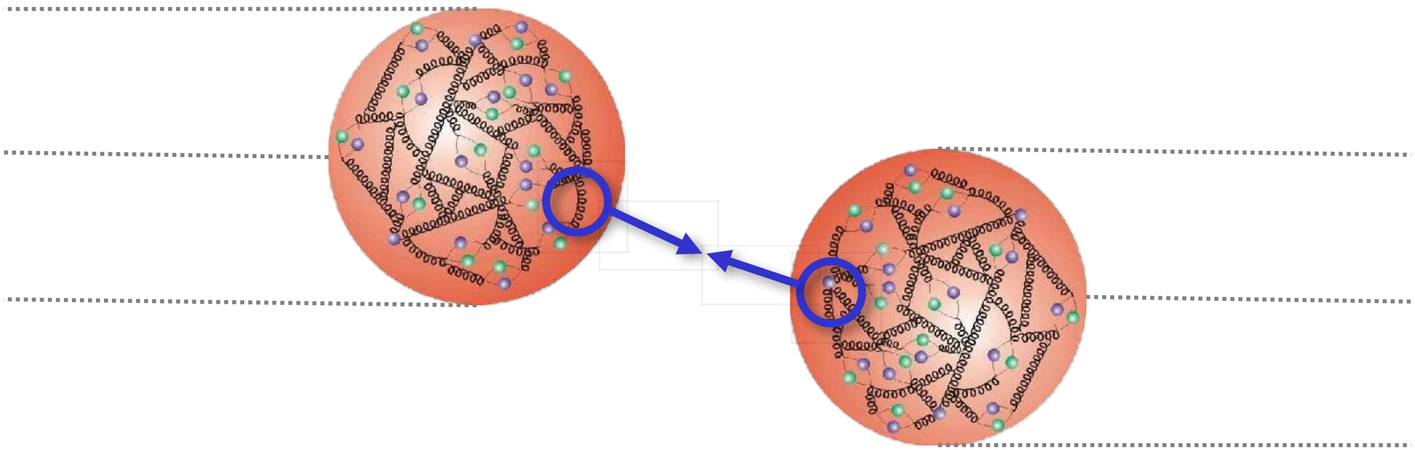
$Q^2 = -(p_e^{in} - p_e^{fin})^2$

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



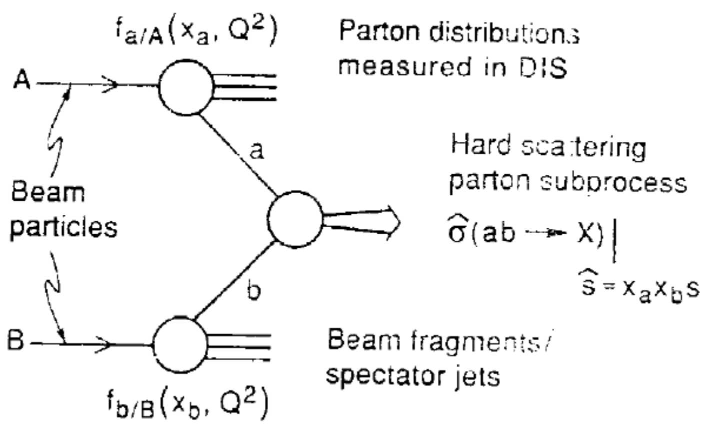


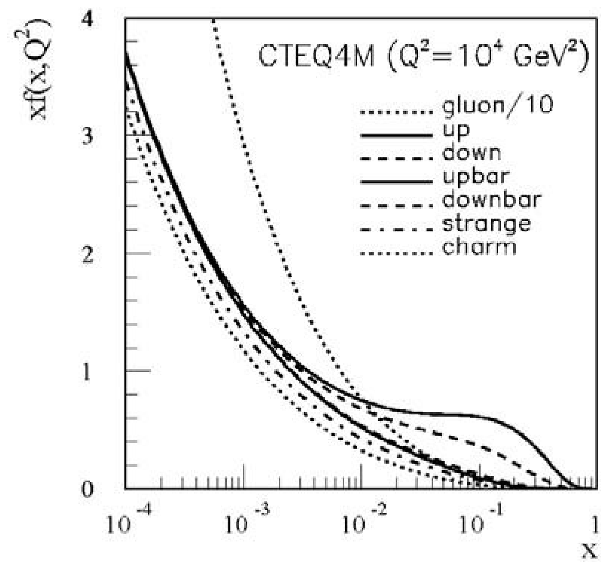
Cross sections at a proton-proton collider



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

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



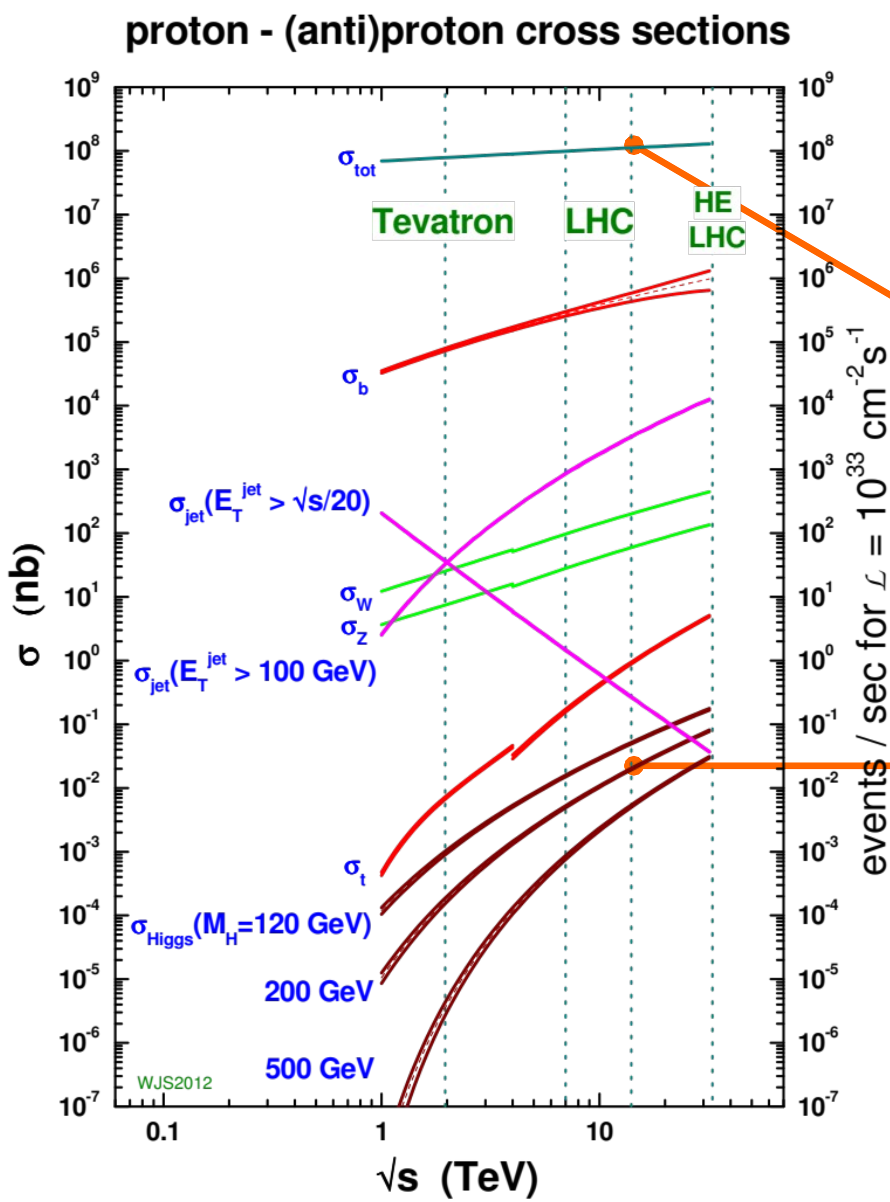


Example: to produce a particle with mass m = 100 GeV

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

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

Cross-sections at LHC



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

σ_{tot} (13 TeV) = 10^8 nb = 10^{-25} cm^2

σ_H (13 TeV) = 0.05 nb = $5 \cdot 10^{-35}$ cm^2

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

total *pp* collisions

10^9 events/s

$\sim10^{10}$

10^{-1} events/s

~ 1 Higgs boson every 2 seconds

[m_H ~ 125 GeV]

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

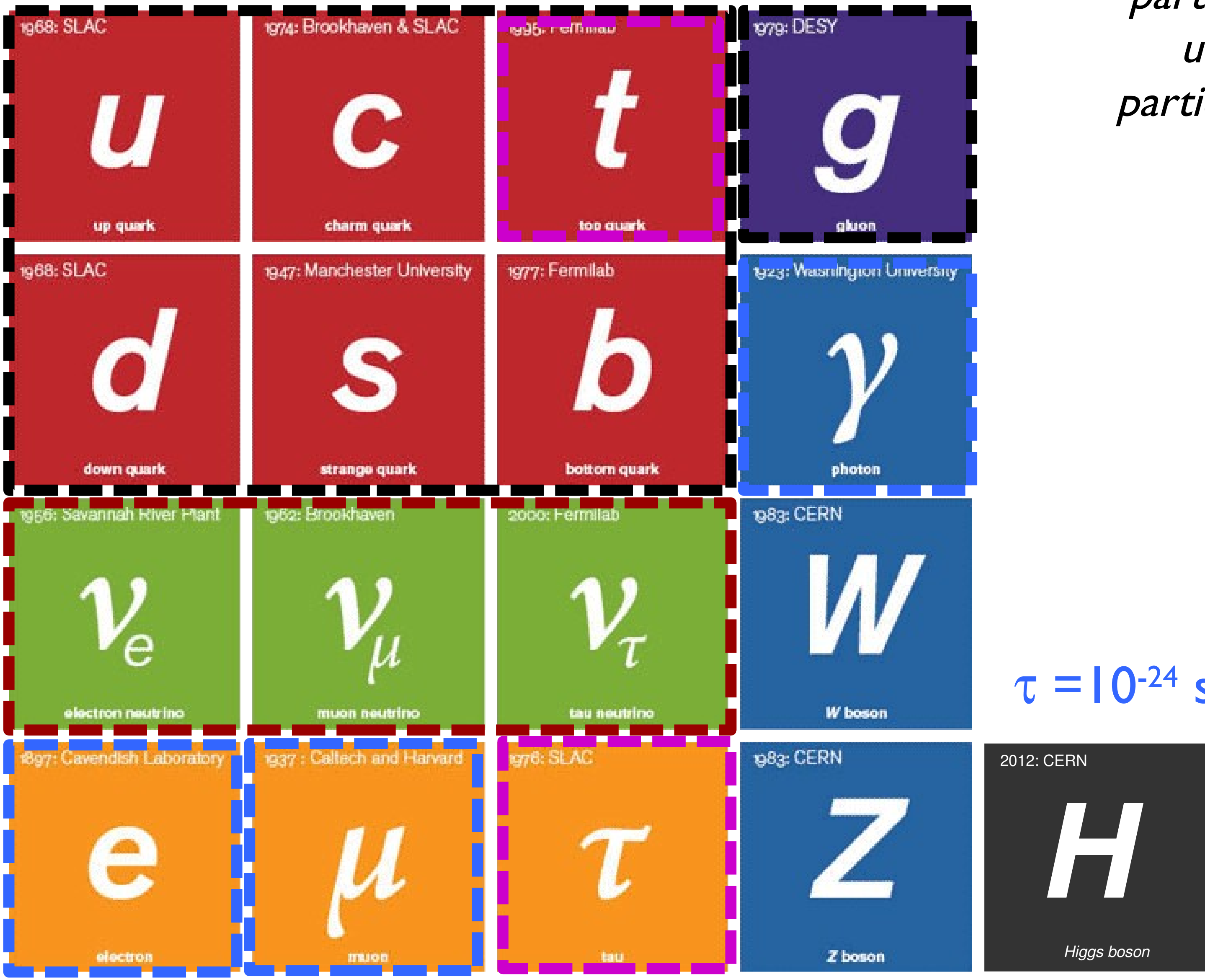
Through two fundamental quantities:

- 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: $\tau = \hbar/\Gamma$

$$W_r = \frac{\Gamma}{\hbar}$$

What do we want to measure?

… "stable" particles from unstable particle decays!



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

$\tau = \infty$

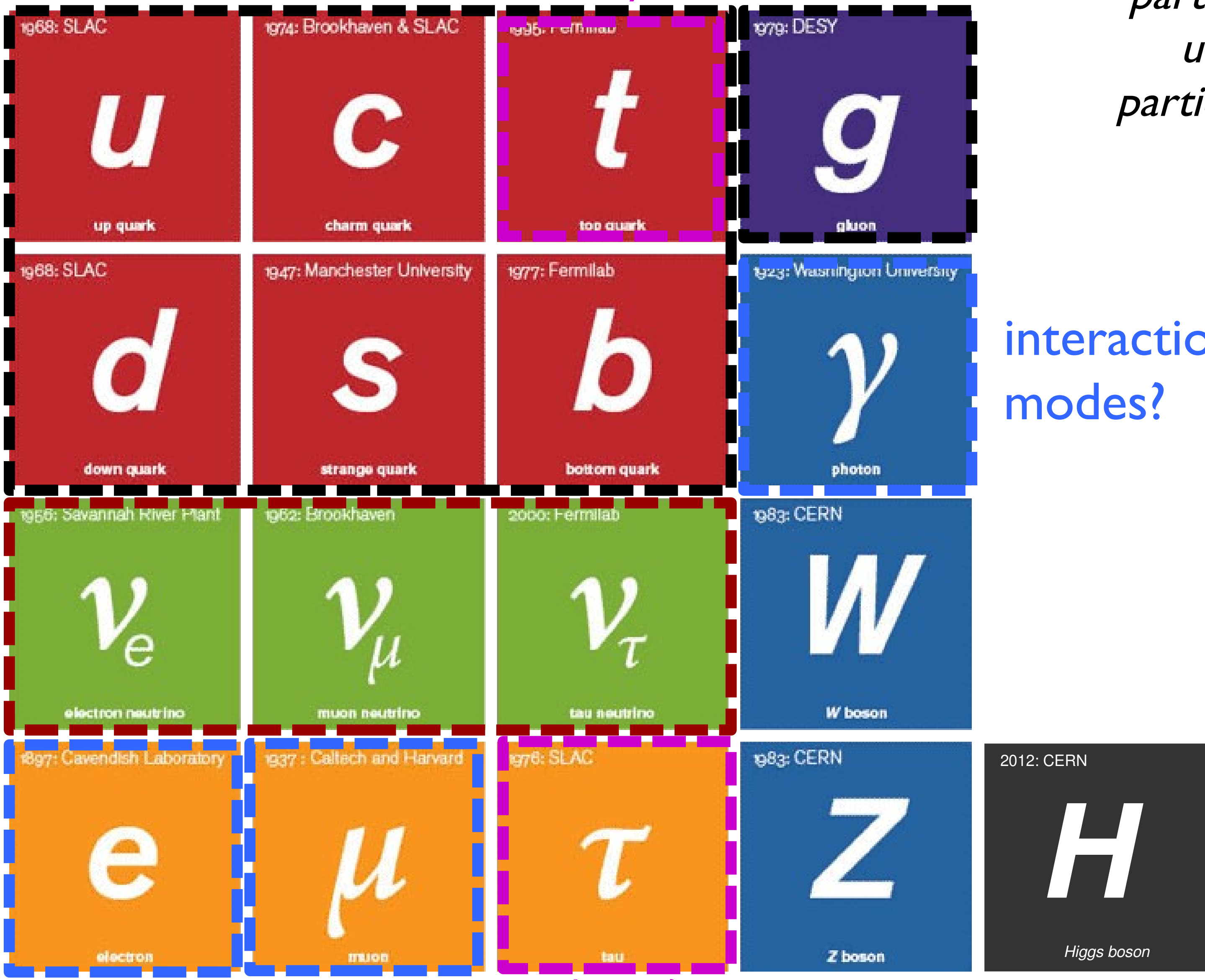
$\tau = 2.2\ \mu s$

What do we want to measure?

… "stable" particles from unstable particle decays!

decays?

hadron jets



interaction modes?

invisible

in particle detectors at accelerators

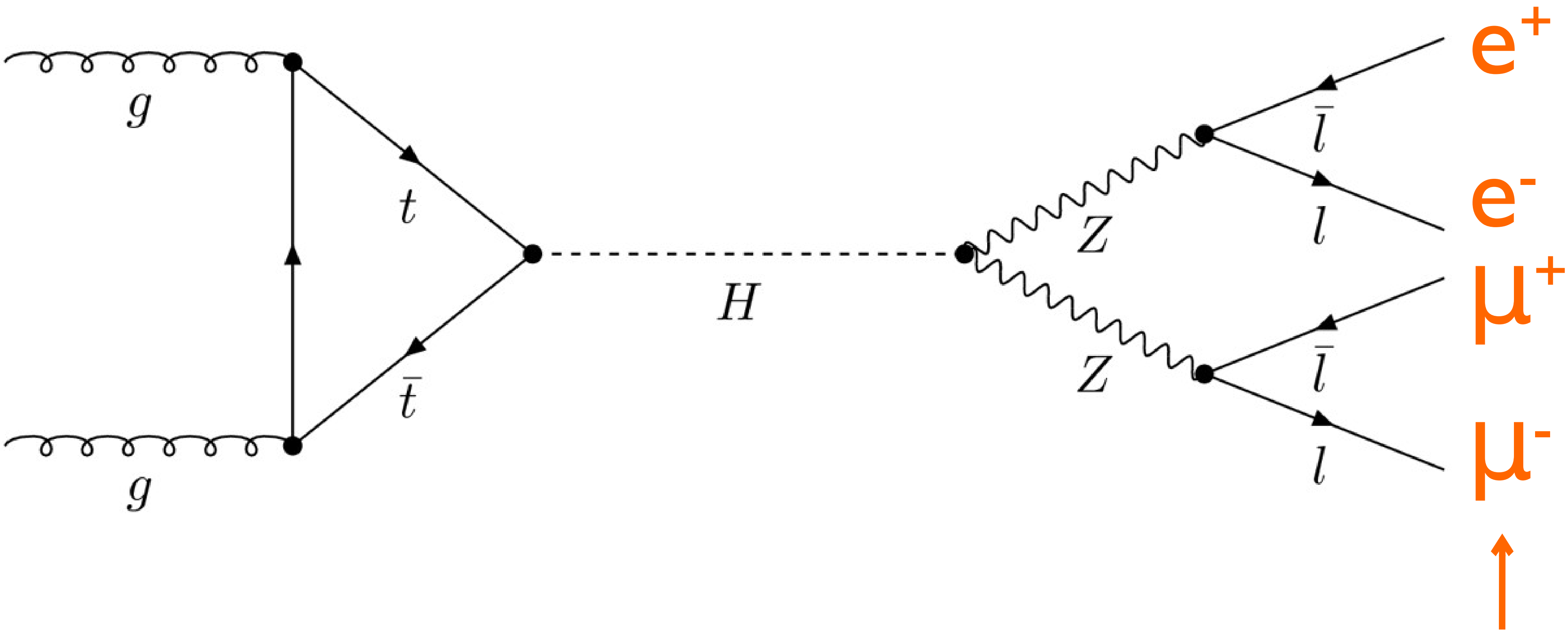
interaction modes?

decays?

What do we want to measure?

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

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



this is what we are looking for…

Identifying and measuring "stable" particles

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

Particle identification via measurement of:

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

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

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

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

$$t = t_0\gamma$$ time dilation

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

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

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

Center of mass energy

- In the center-of-mass frame the total 3-momentum is 0
- In laboratory frame, the center of mass energy can be computed as:

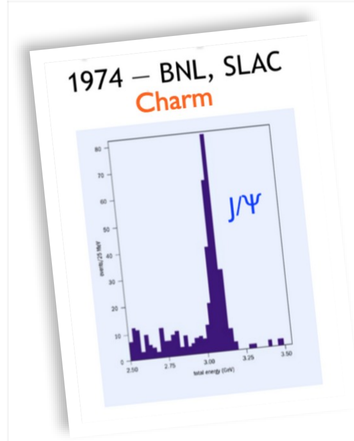
$$E_{\mathrm{cm}} = \sqrt{s} = \sqrt{\left(\sum E_i\right)^2 - \left(\sum \vec{p}_i\right)^2}$$

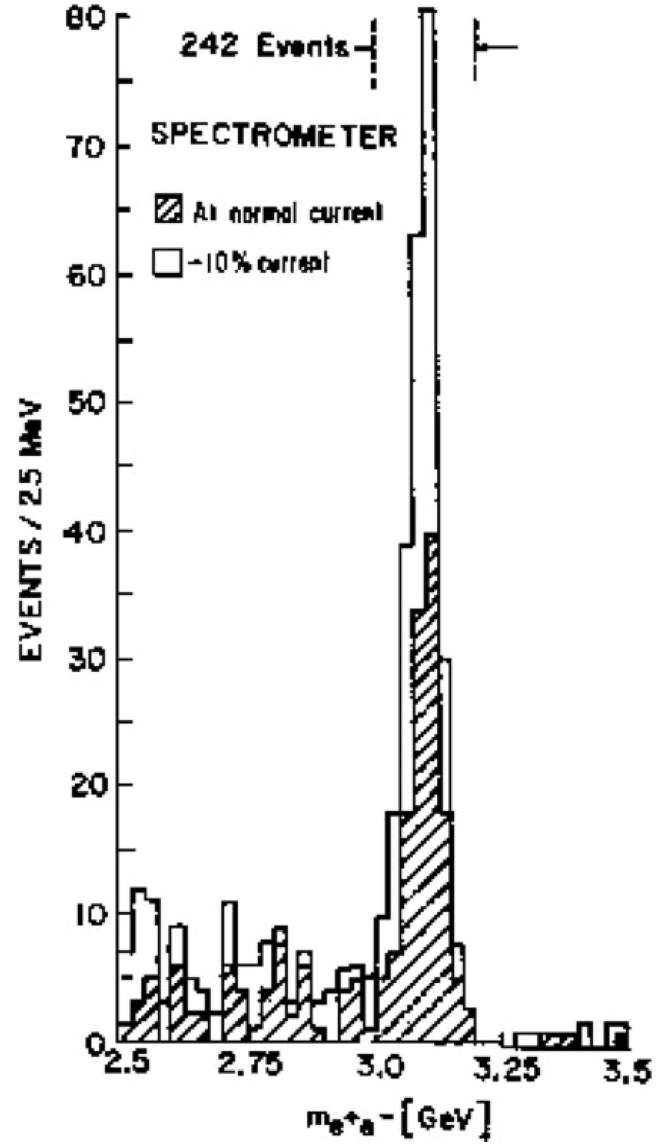
Hint: it can be computed as the "length" of the total four-momentum, that is invariant:

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

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

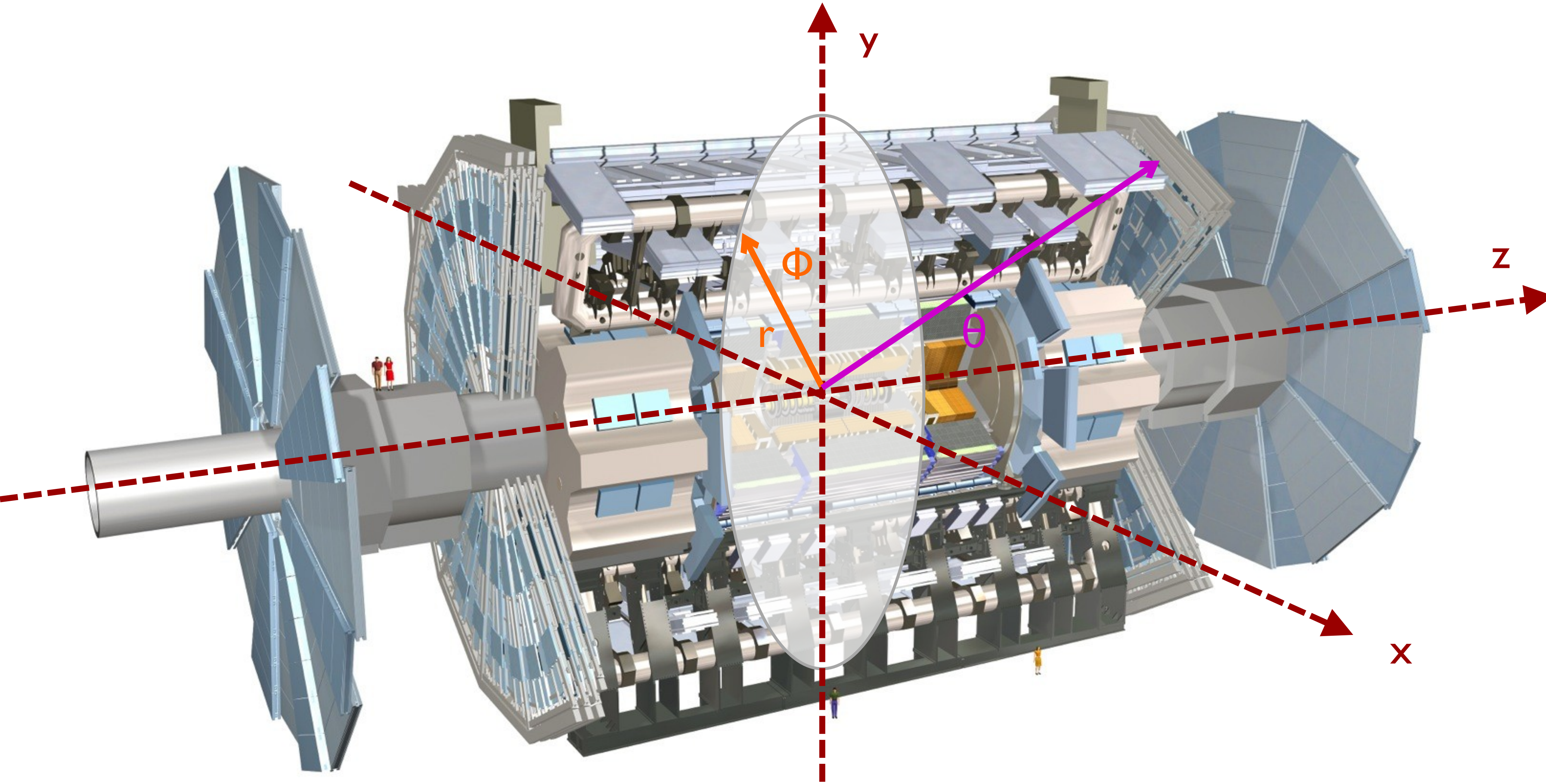
Invariant mass





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

A collider experiment



Presudorapidity $\eta = -\ln\left[\tan\left(\frac{\theta}{2}\right)\right]$

Interaction mode cheat sheet ("light" particles)

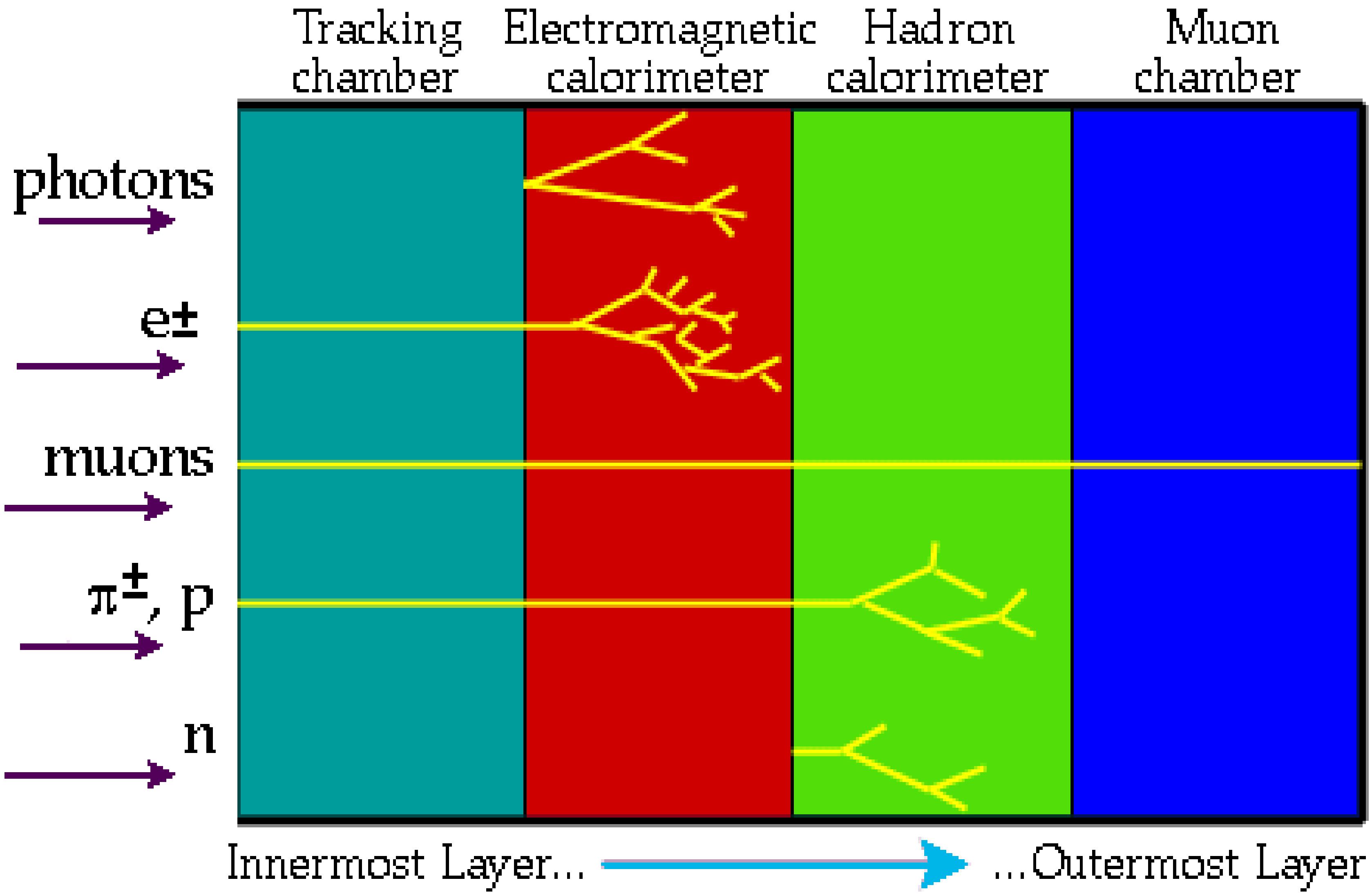
- electrically charged
- ionization (dE/dx)
- *electromagnetic shower…*

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

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

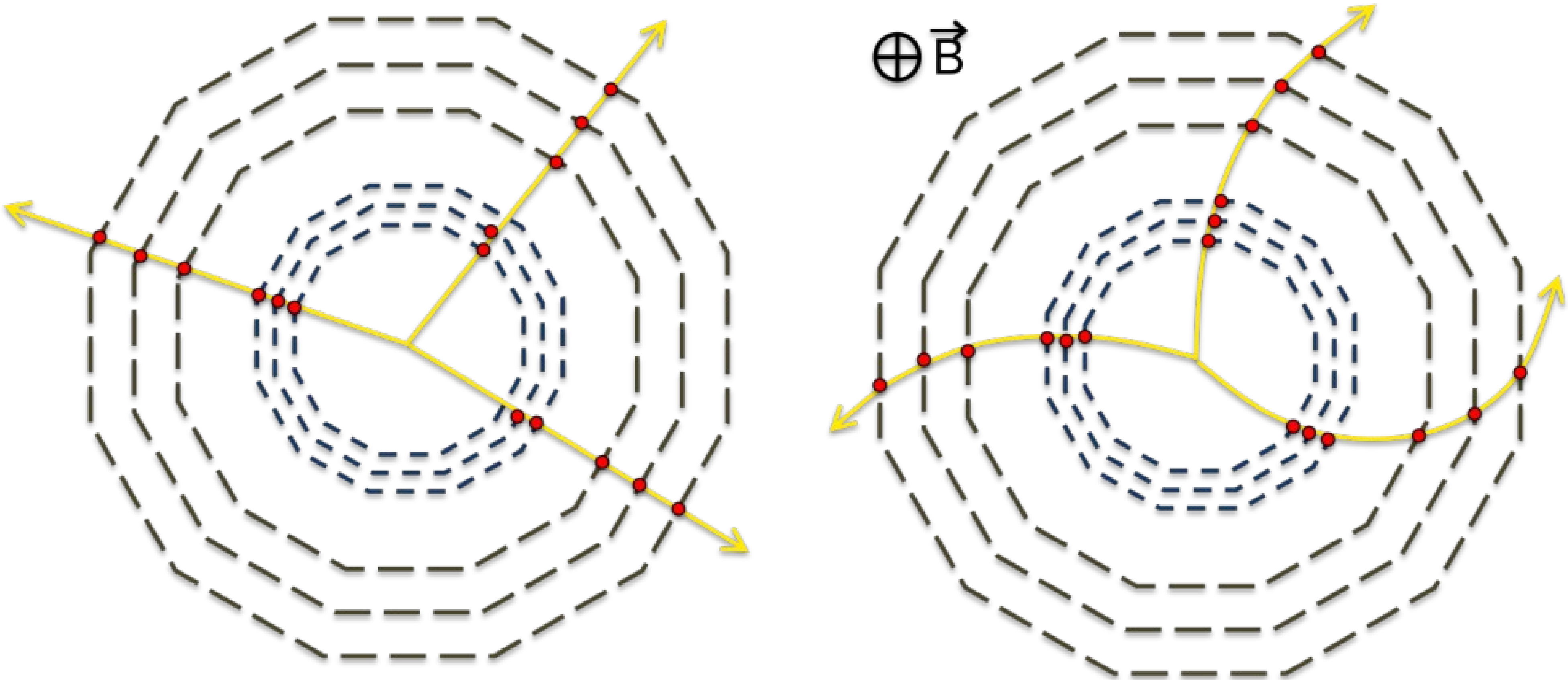
- produce *hadron(s)* jets via QCD hadronization process

Interaction mode cheat sheet ("light" particles)



Magnetic spectrometer for ionizing particles

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

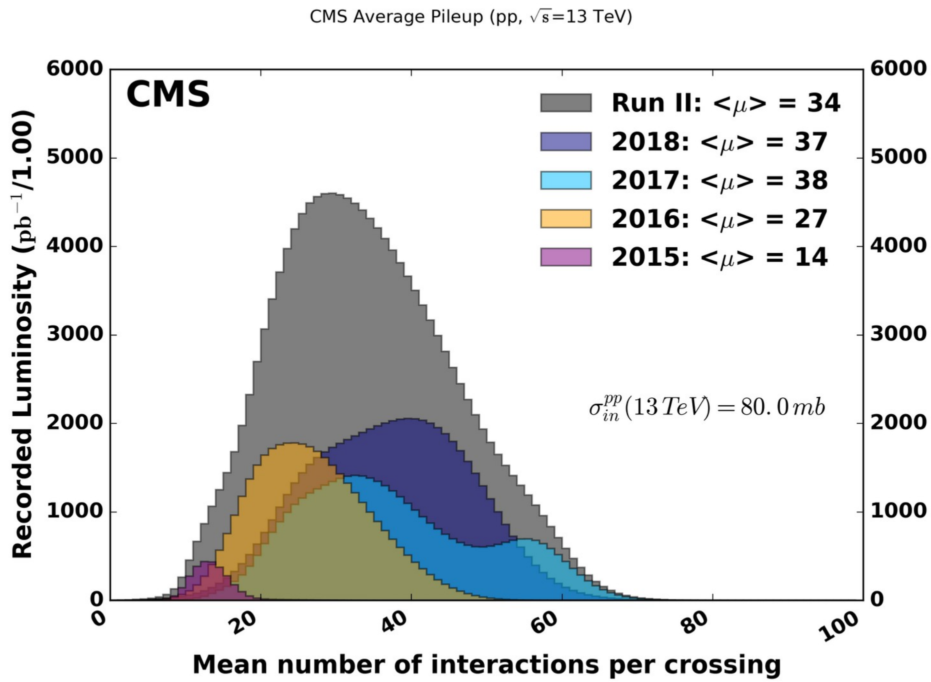


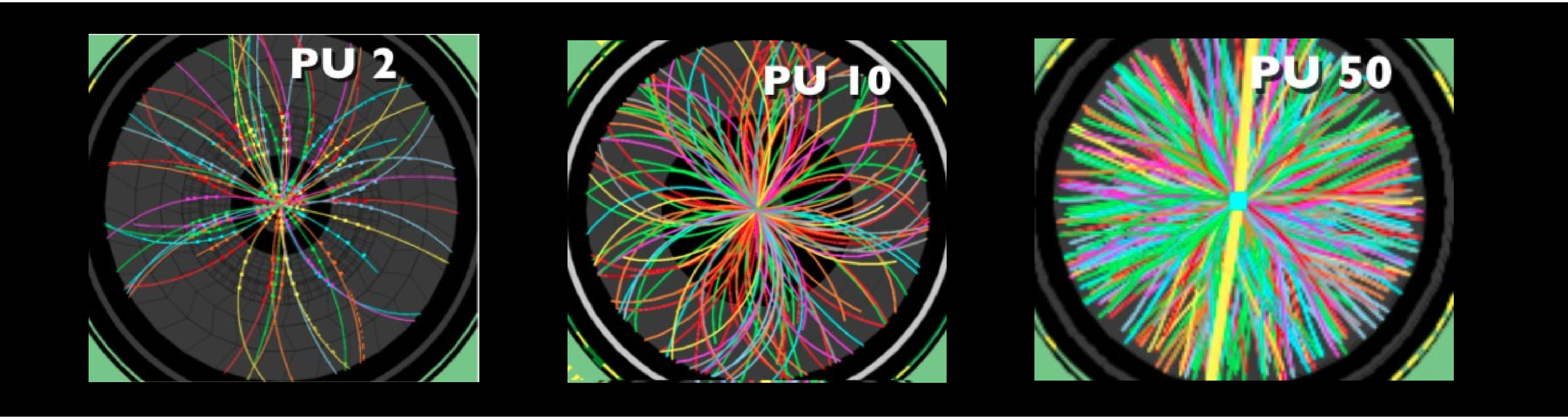
$$p[\mathrm{GeV}] = 0.3B[\mathrm{T}]\rho[\mathrm{m}]$$

Pile-Up

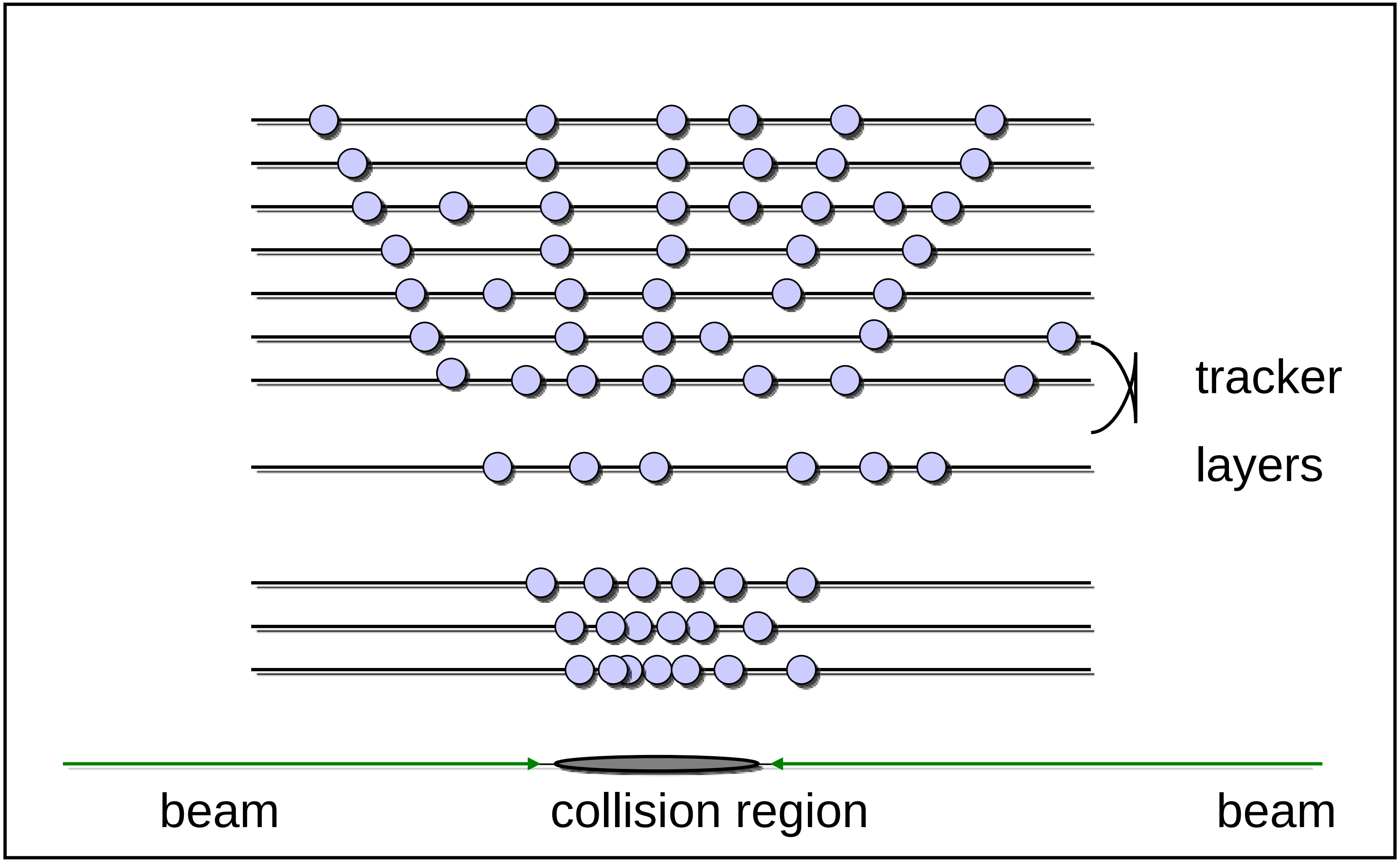
$$\mathcal{L} = \frac{1}{4\pi} \frac{f N_1 N_2}{\sigma_x \sigma_y}$$

PU = number of inelastic interactions per beam bunch crossing





Tracking



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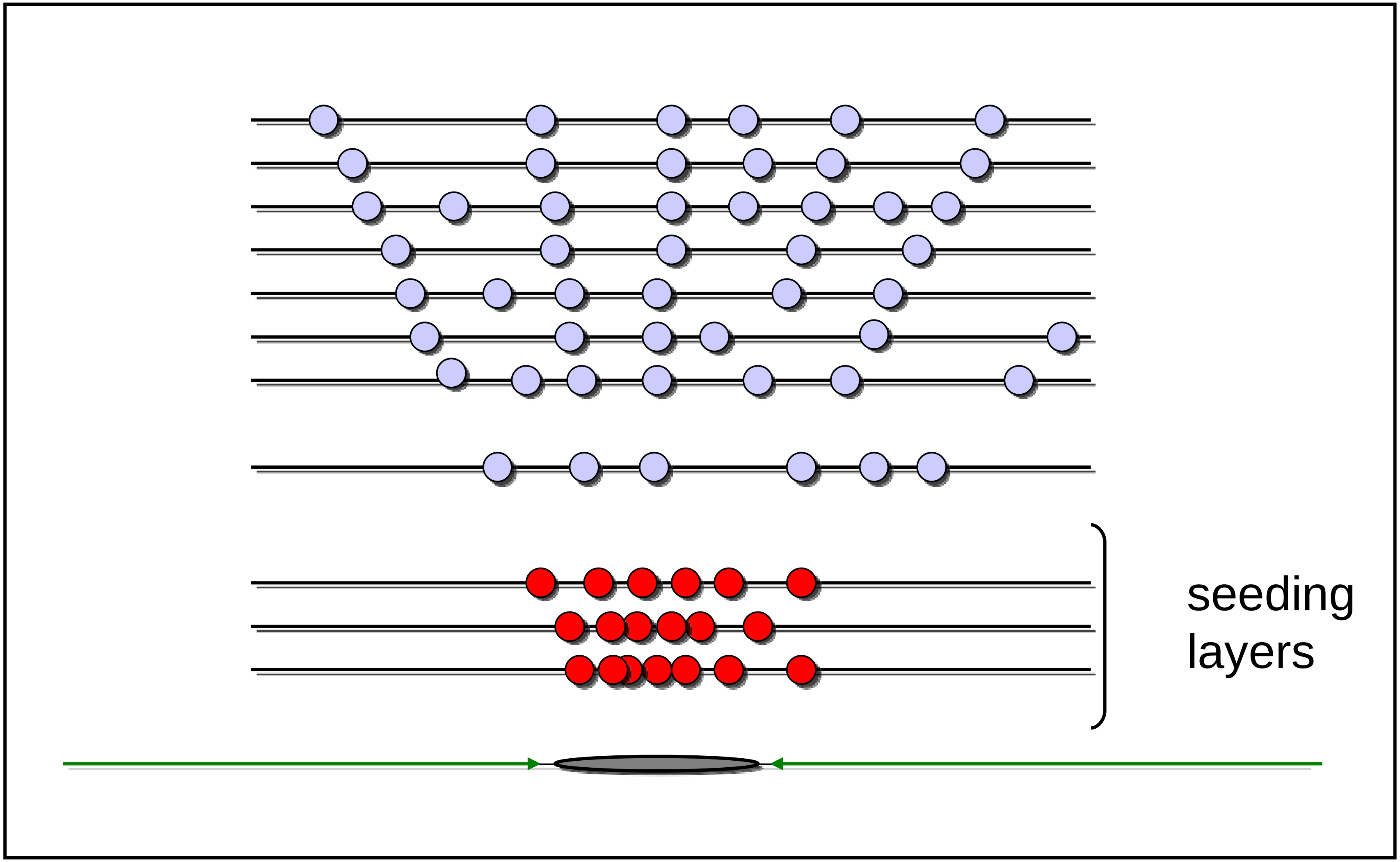
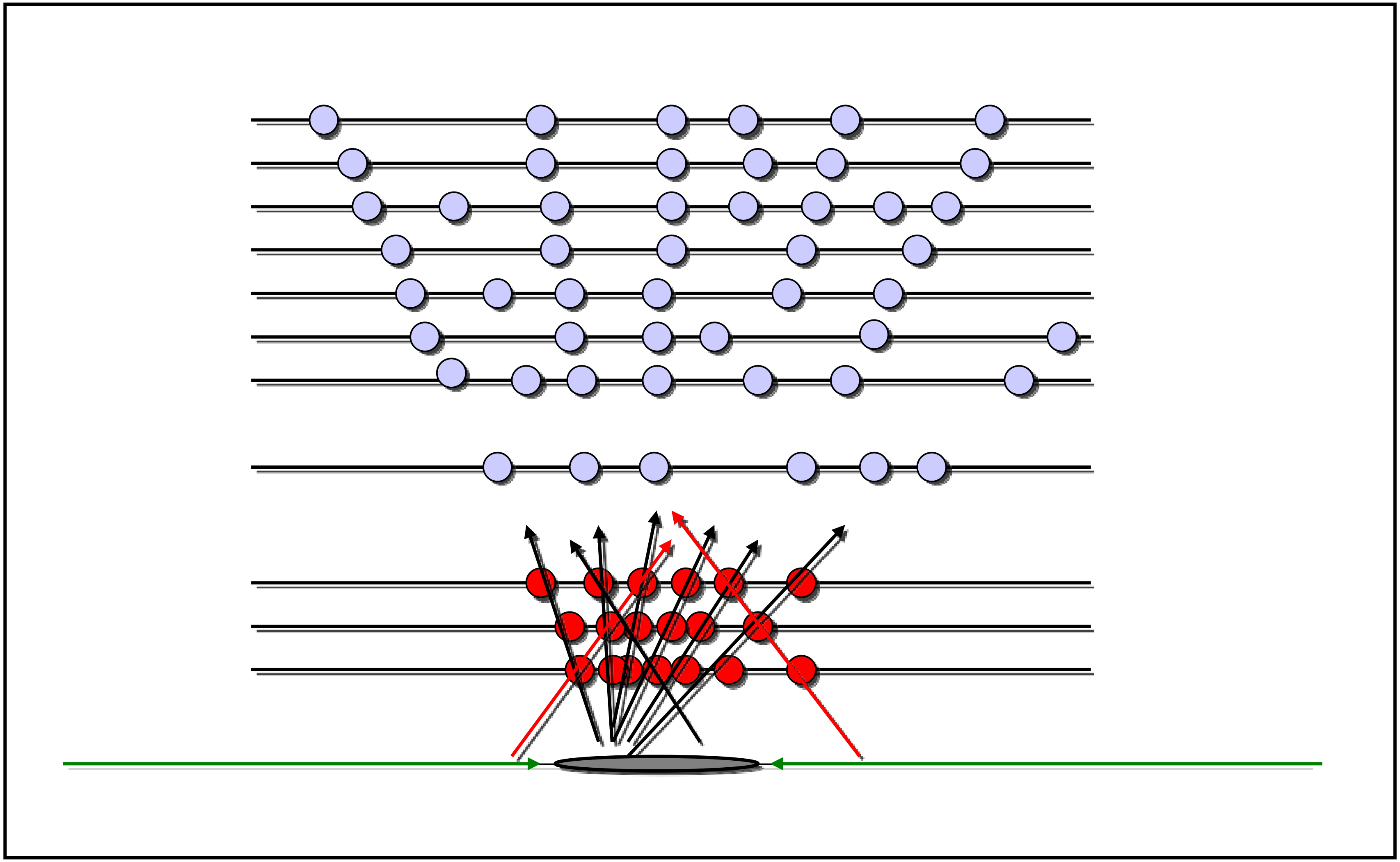


Only a subset of layers is used for the construction of **trajectory seeds**

Tracking



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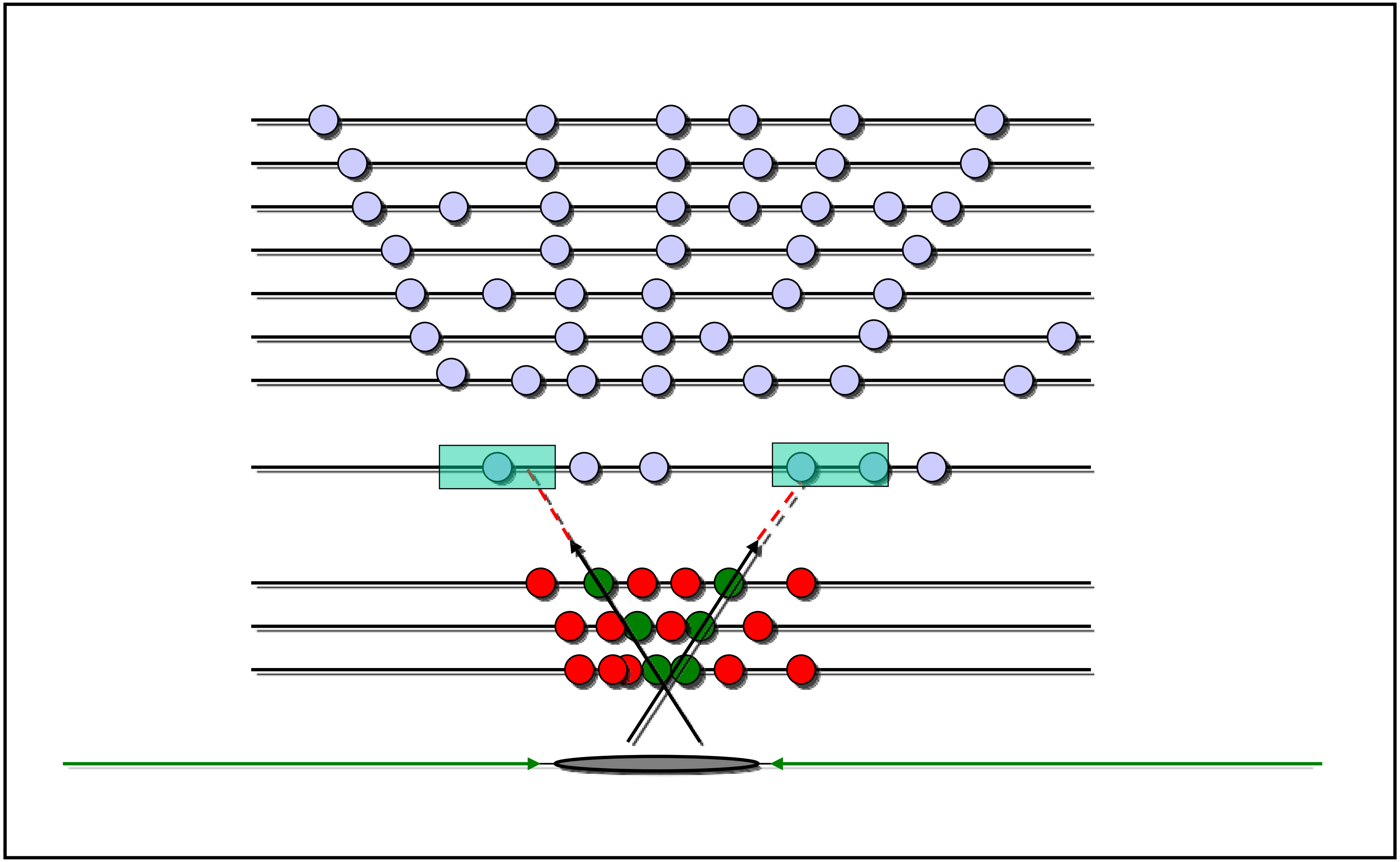

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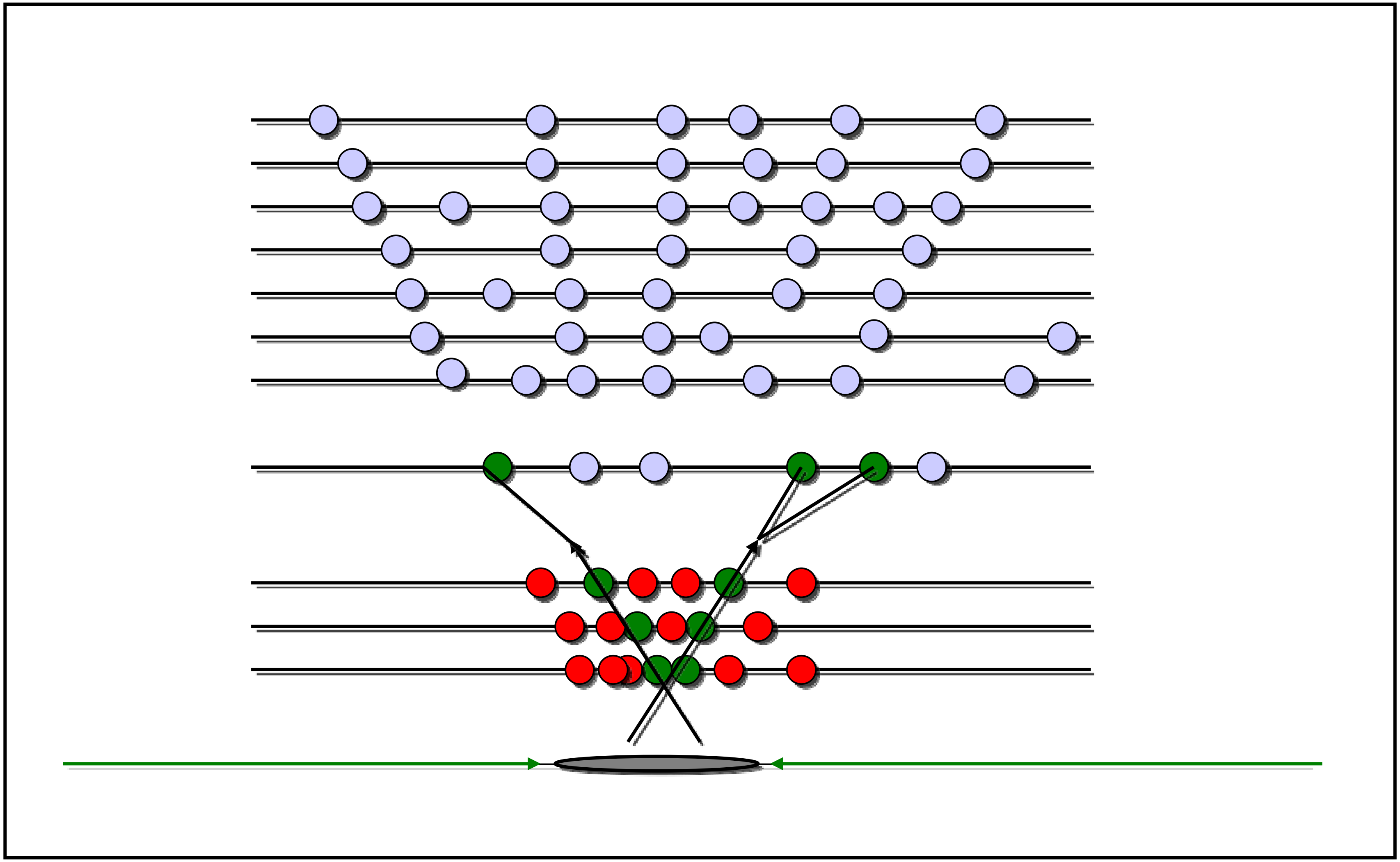

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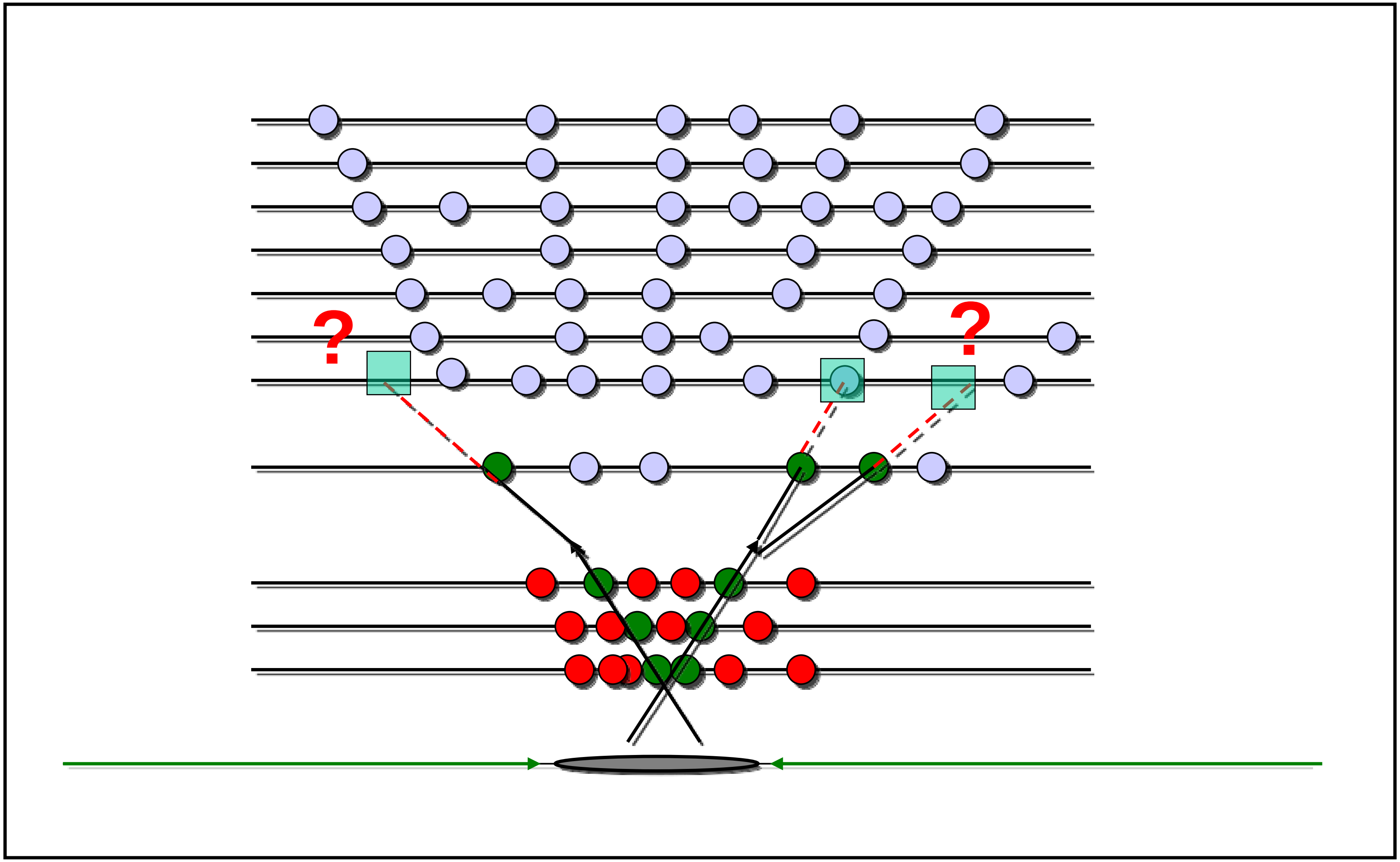

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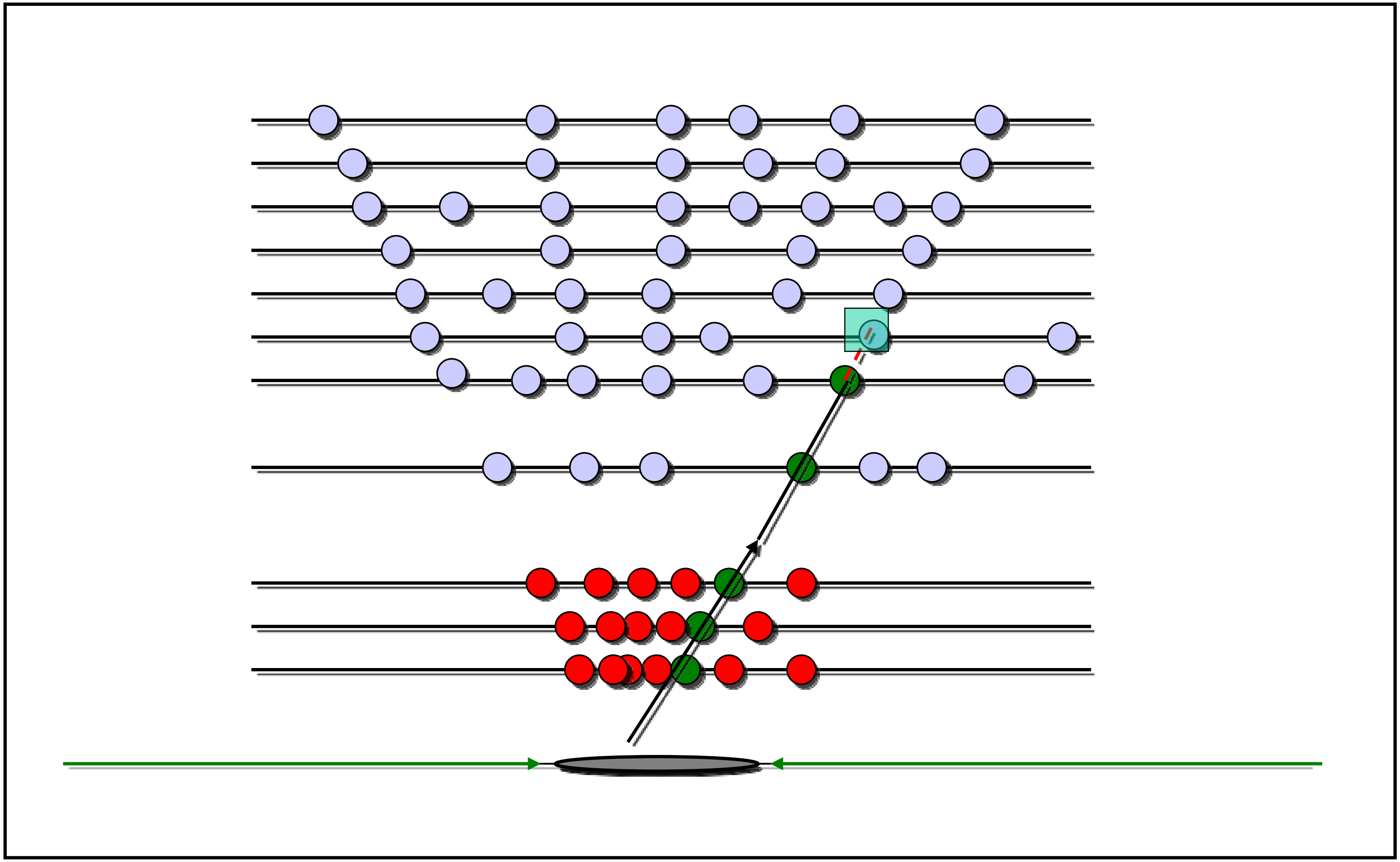

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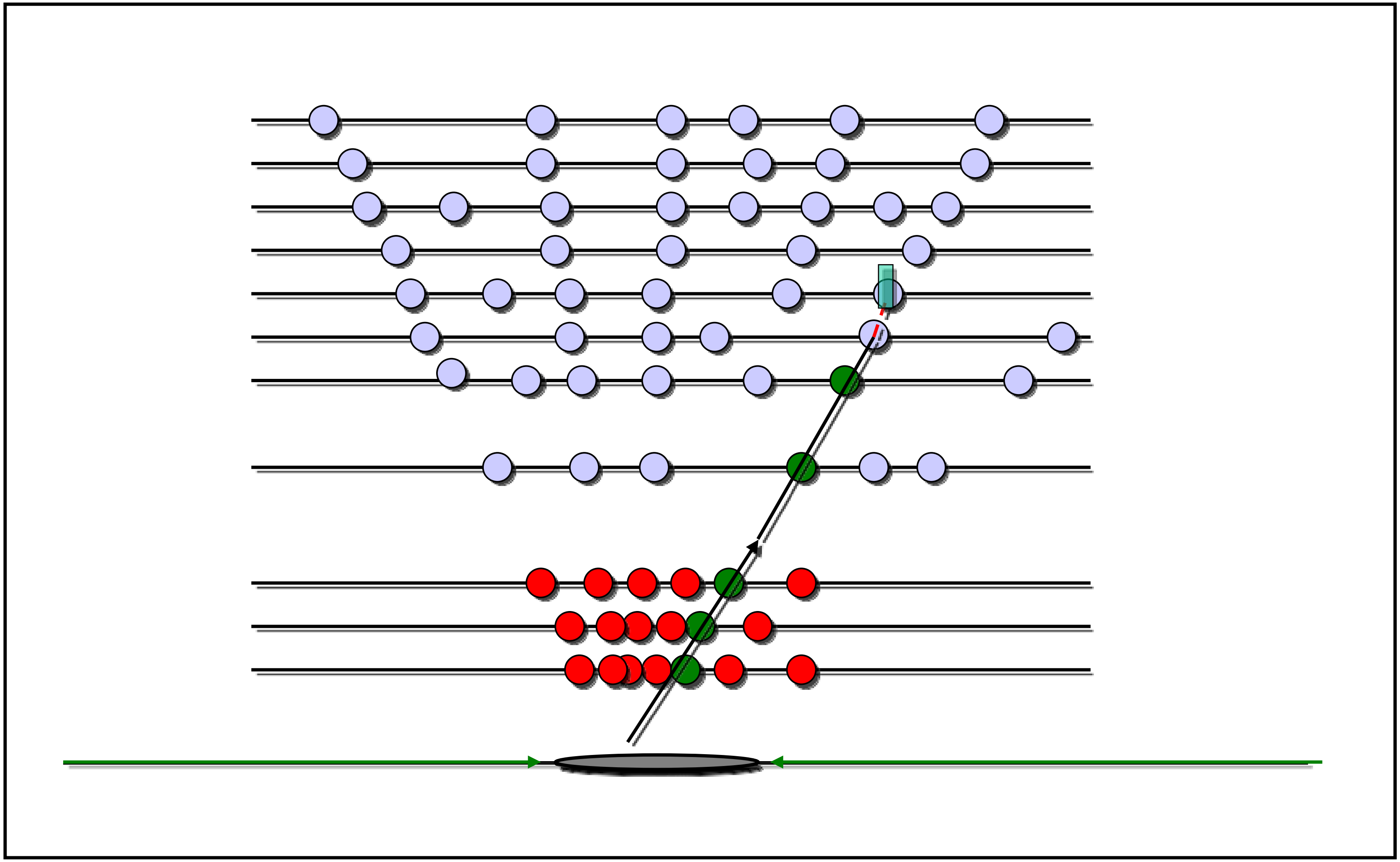

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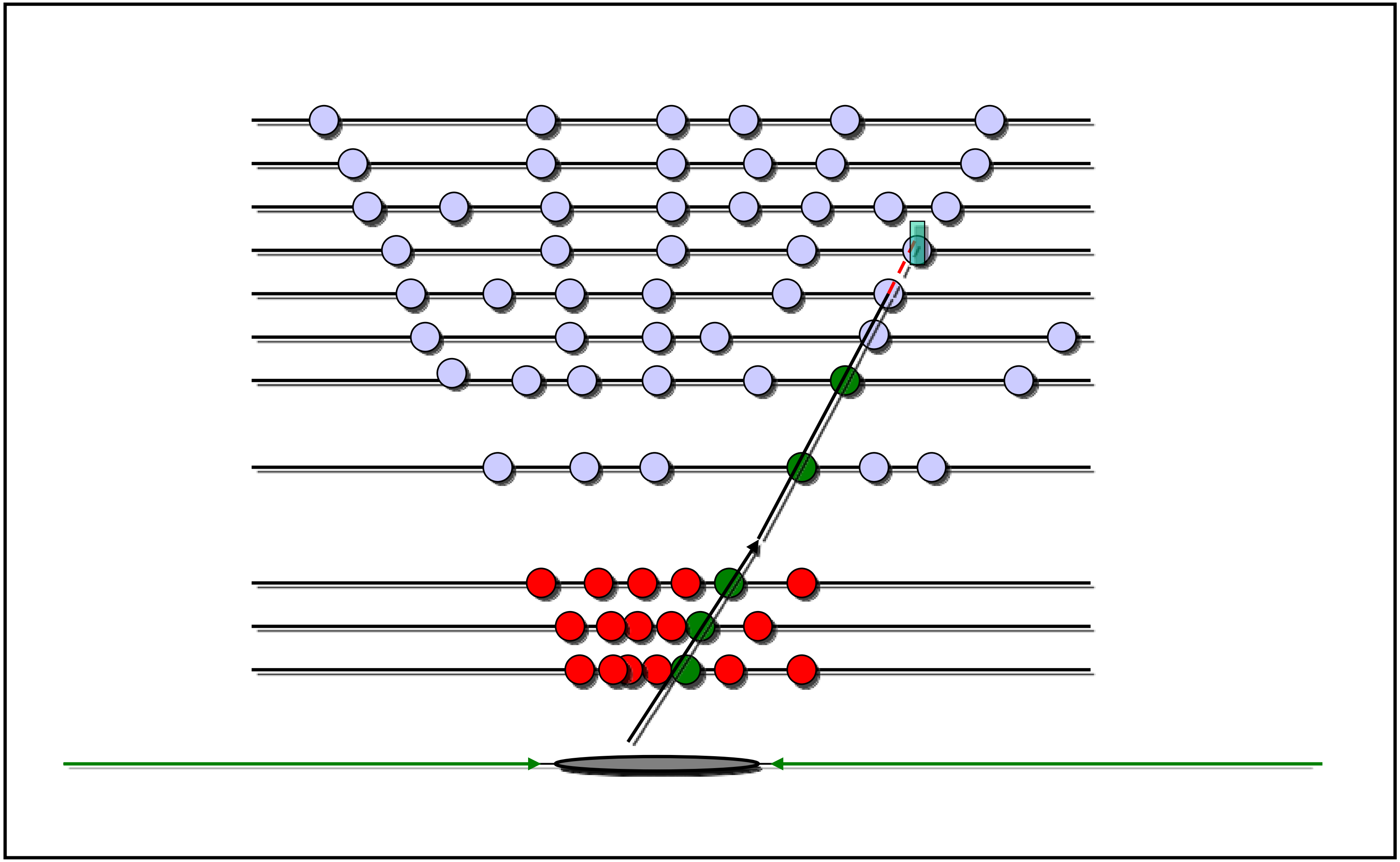

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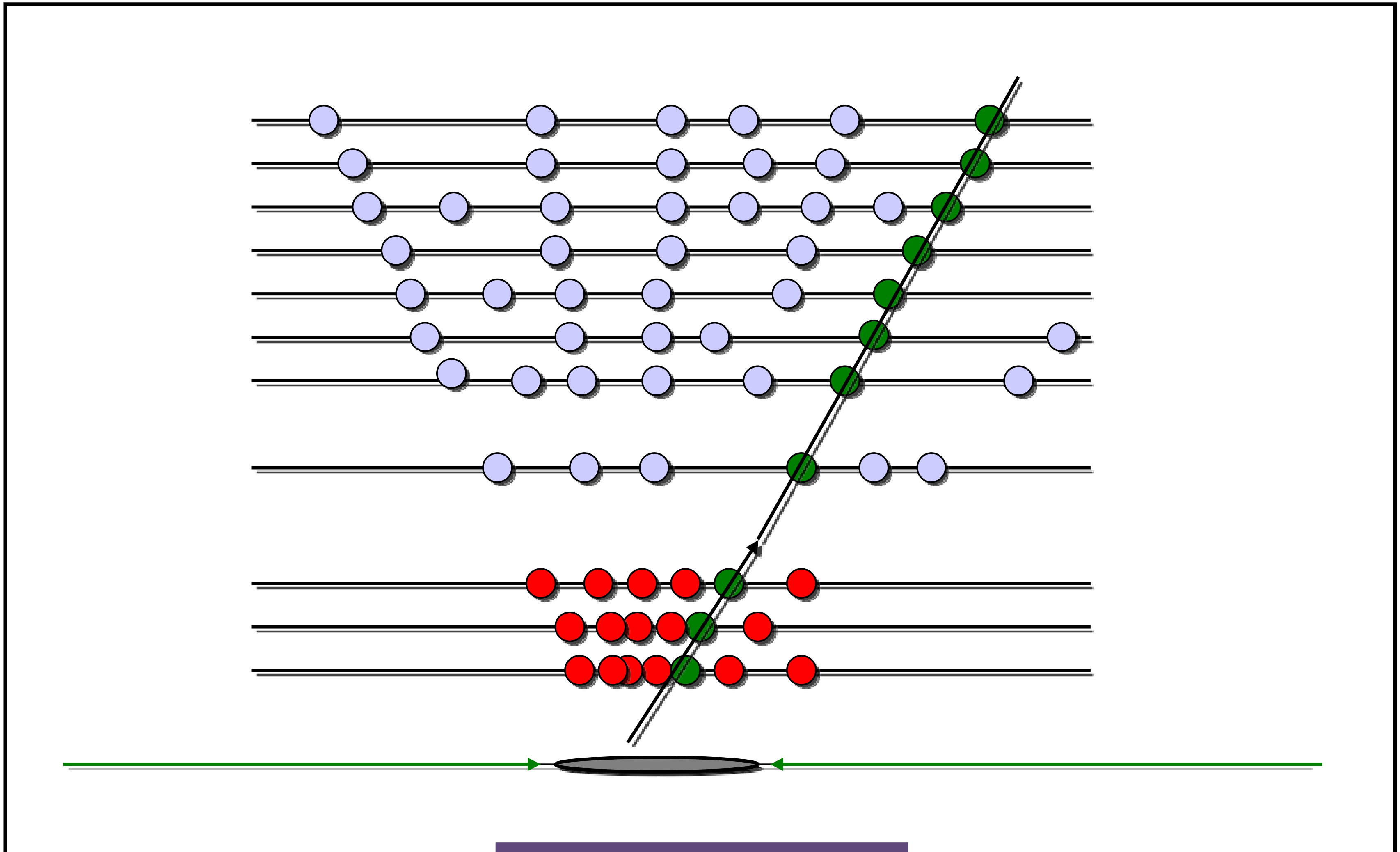
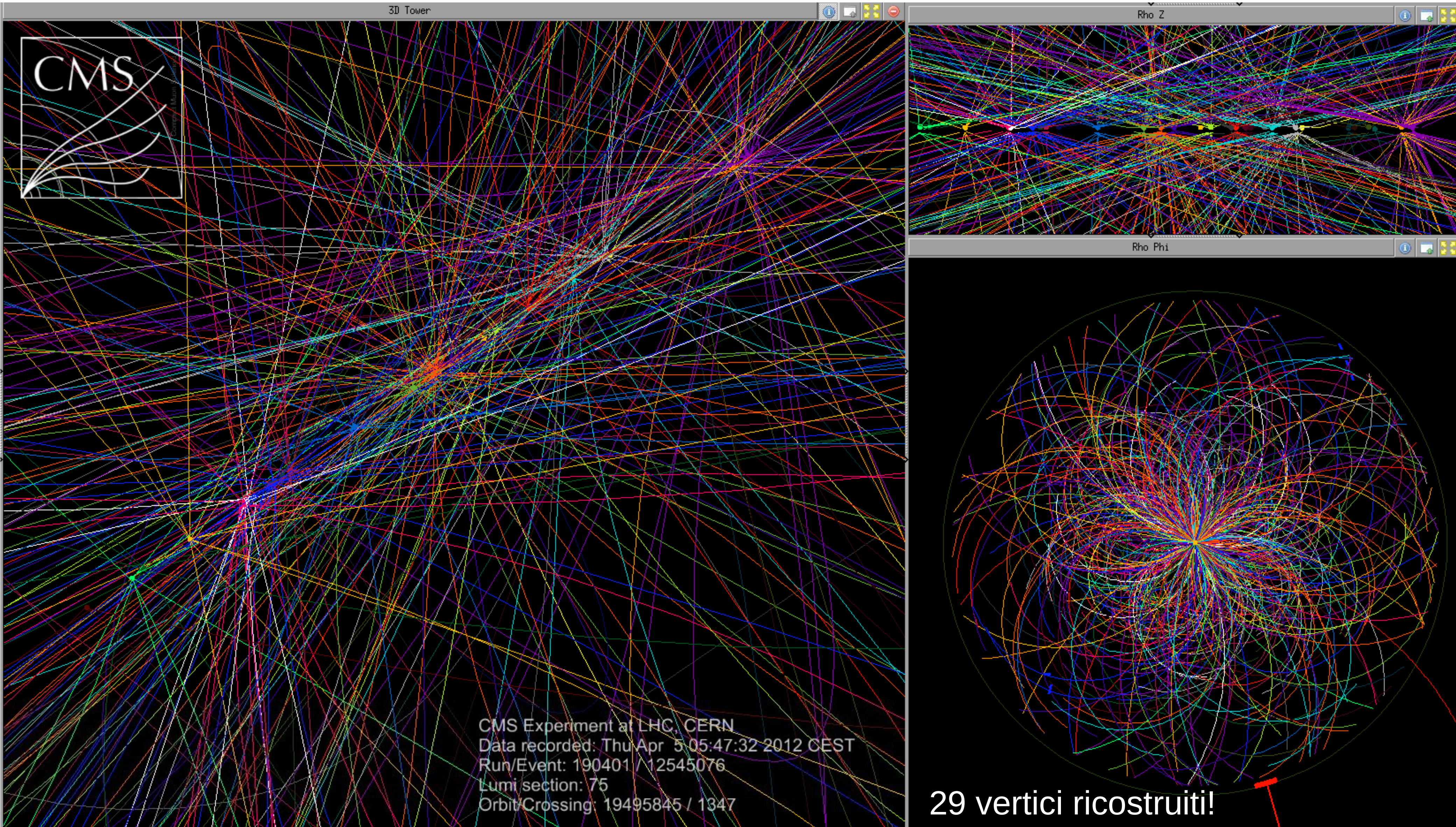


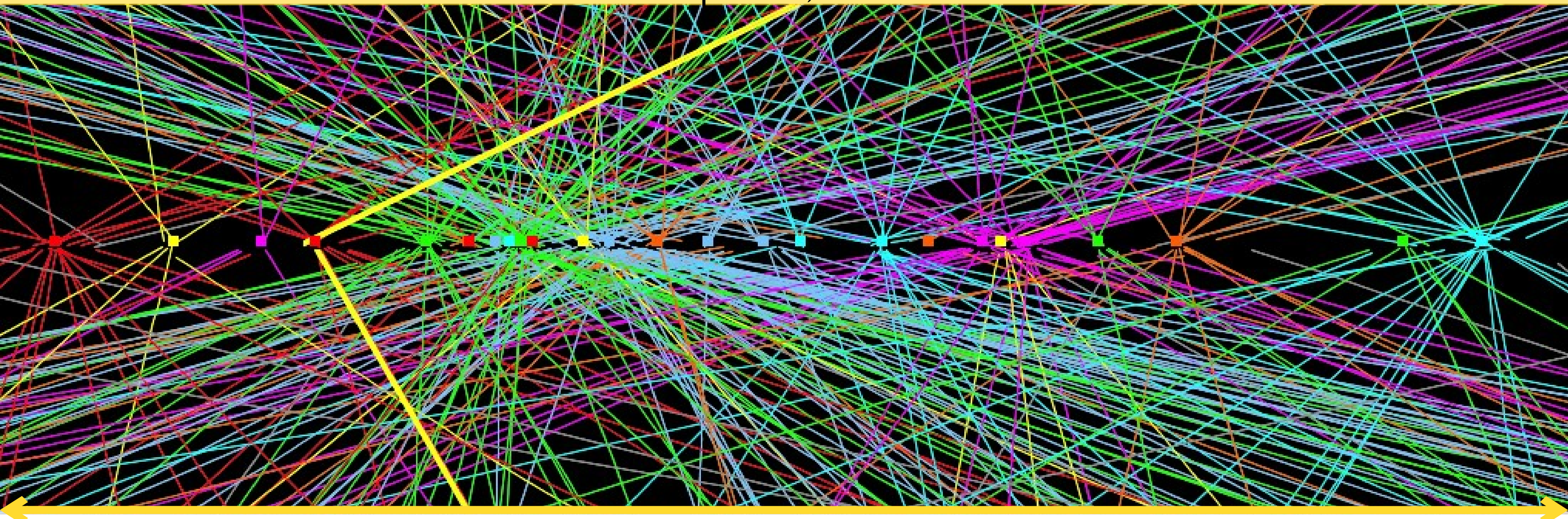
Pattern
recognition

Tracking in dense environment



Z→ μμ event with 25 reconstructed vertices

April 15th, 2012

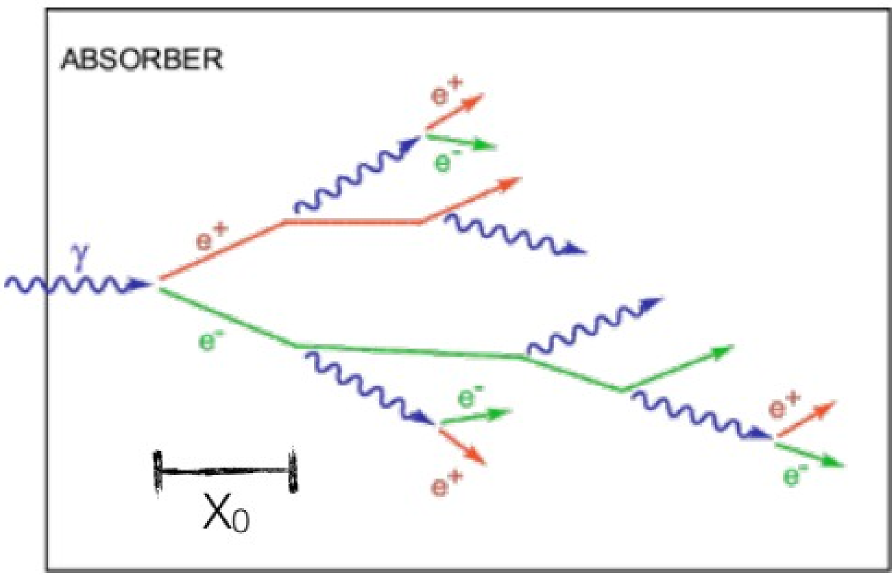


~5 cm

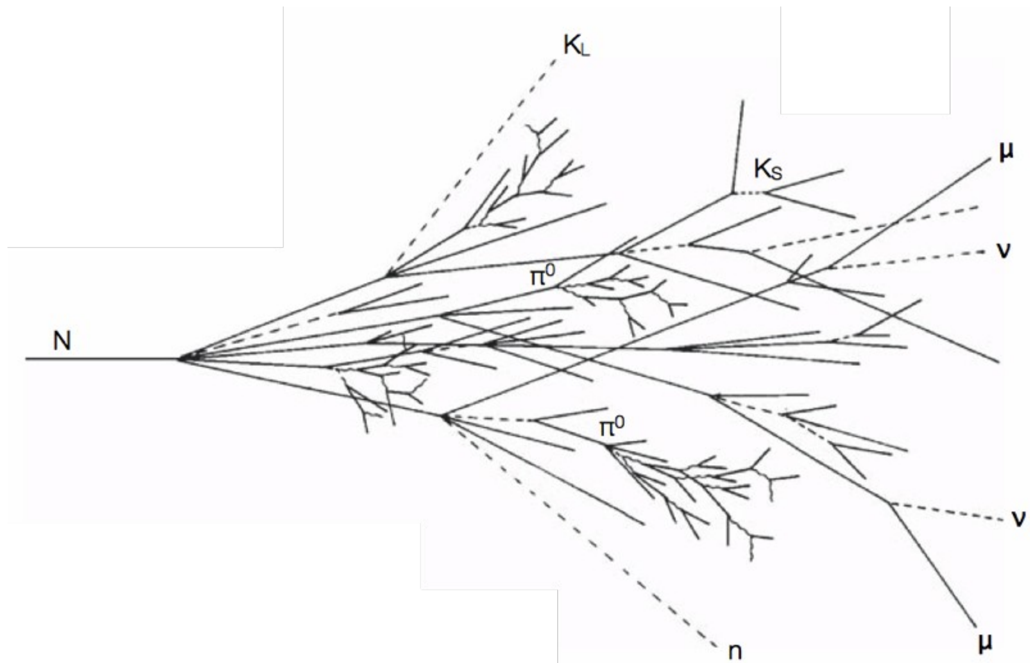
Calorimeters for showering particles

- Electromagnetic shower
  - ✓ Photons: pair production
    - stops below e^+e^- threshold
  - ✓ Electrons: bremsstrahlung
    - Dominates, till brem cross section become smaller than ionization

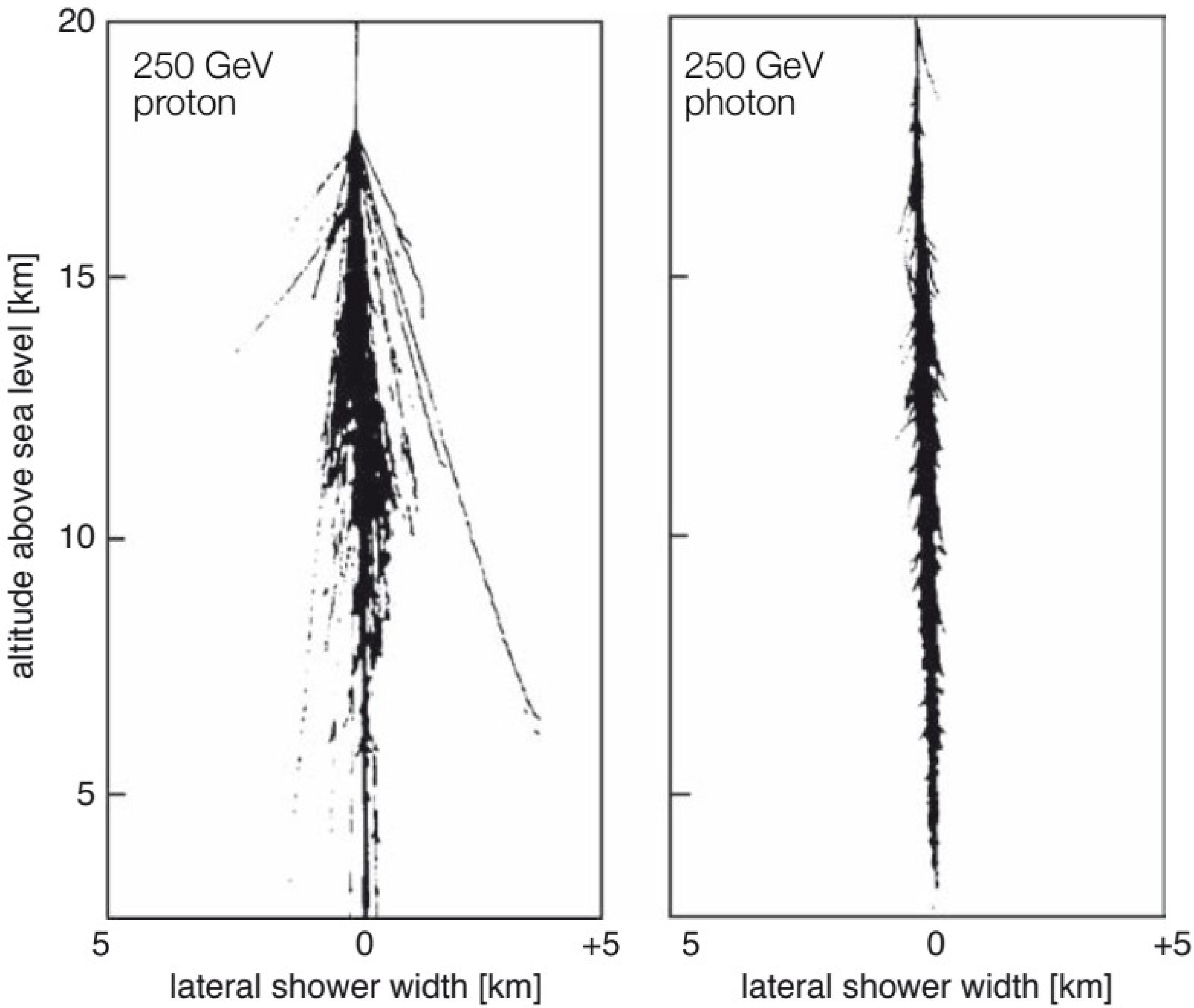
$$\left.\frac{dE}{dx}(E_c)\right|_{\text{Brems}} = \left.\frac{dE}{dx}(E_c)\right|_{\text{Ion}}$$



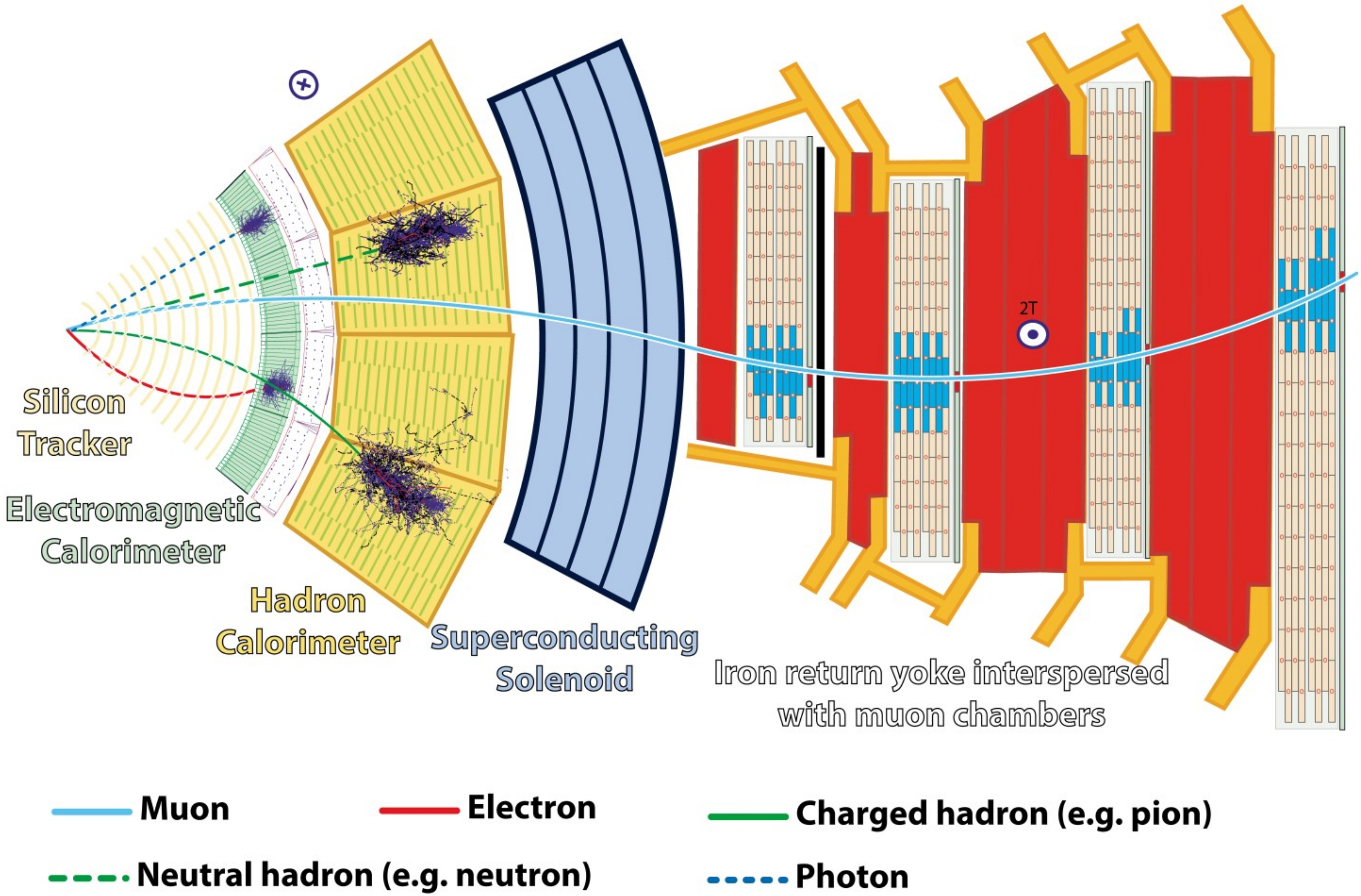
- Hadronic showers
  - ✓ Inelastic scattering w/ nuclei
    - Further inelastic scattering until below pion production threshold
  - ✓ Sequential decays
    - $\pi^0 \to \gamma\gamma$
    - Fission fragment: β-decay, γ-decay
    - Neutron capture, spallation, …



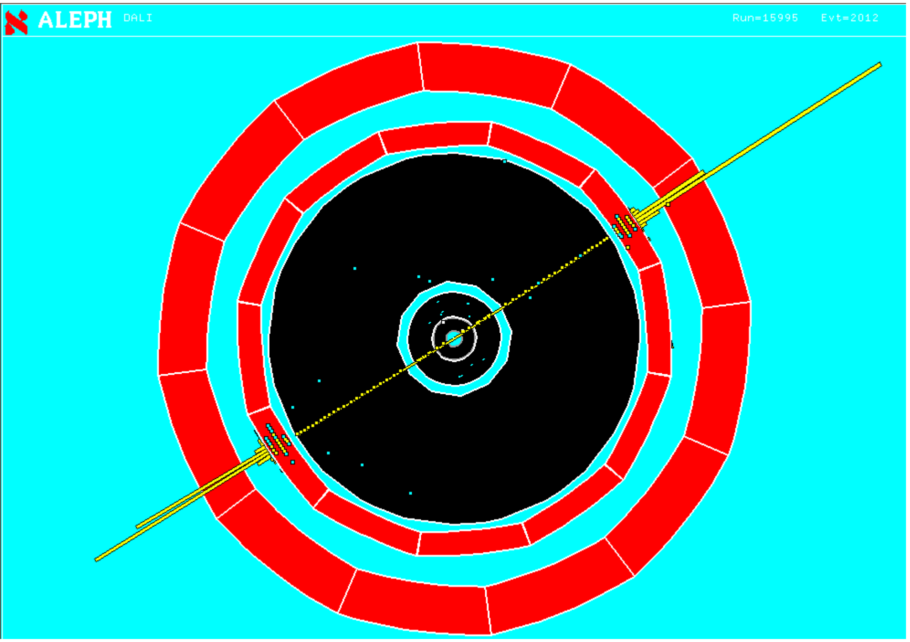
Hadronic vs. EM showers

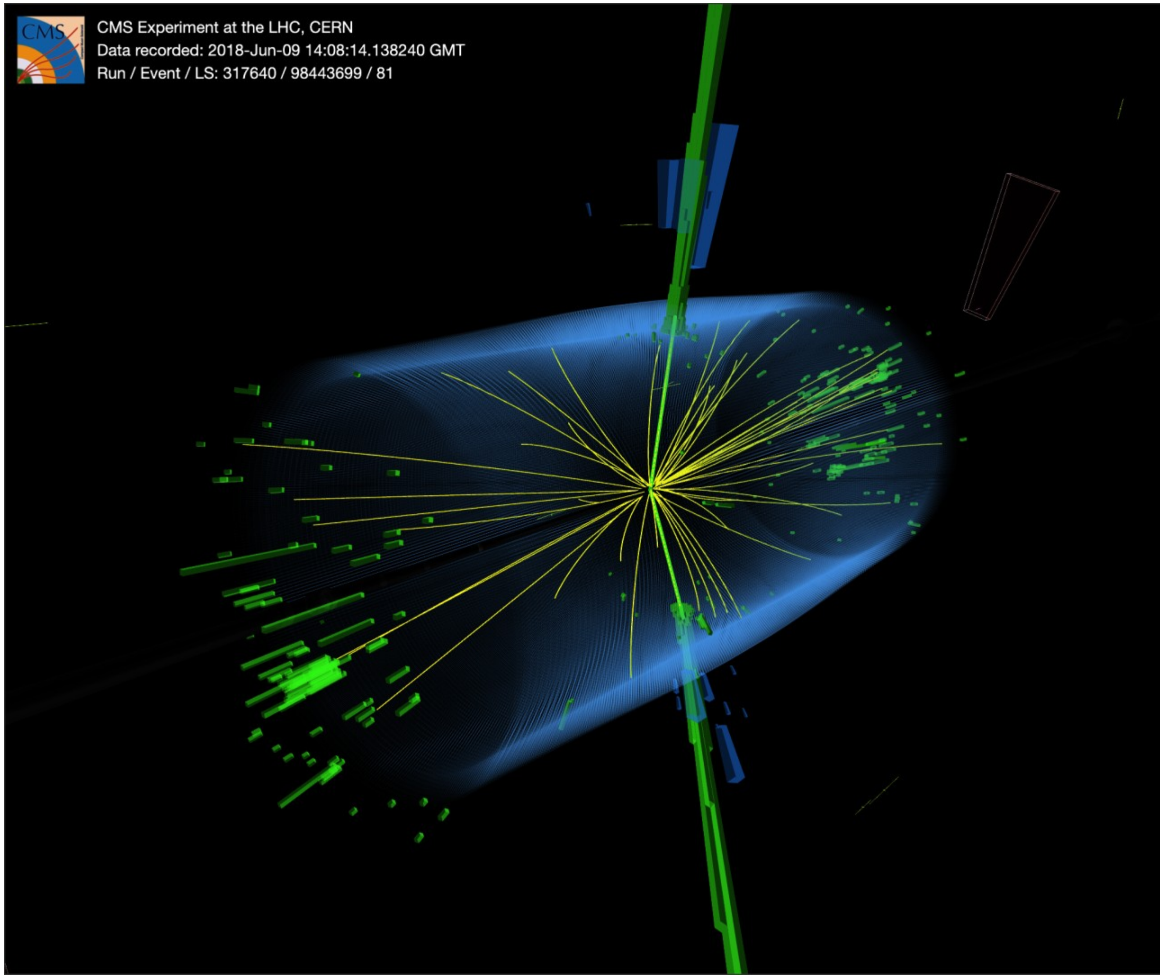


Particle identification with CMS@LHC



A Z→ e^+e^- event at LEP and ad LHC





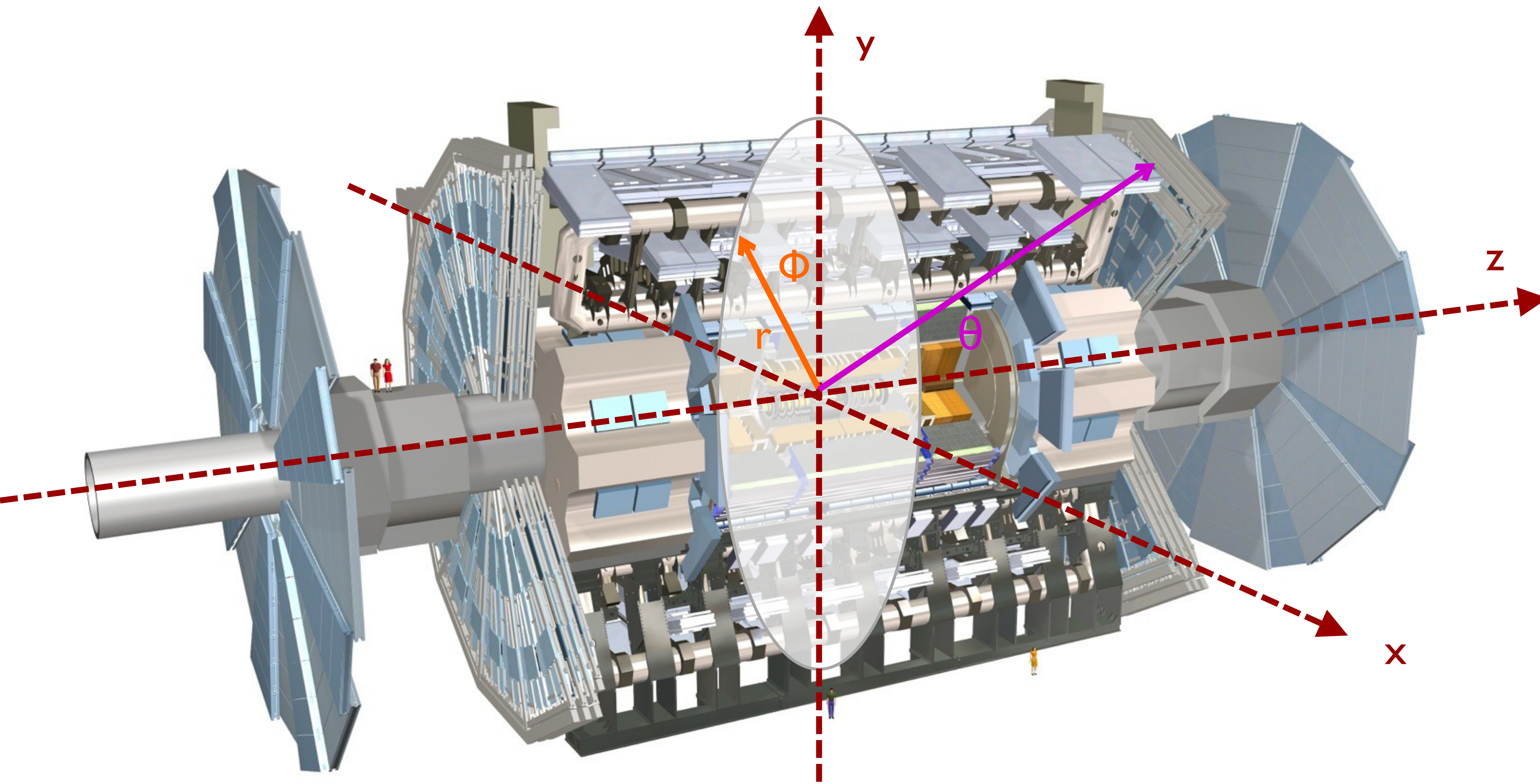
ALEPH @ LEP

CMS @ LHC

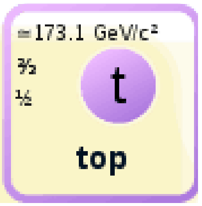
Additional information

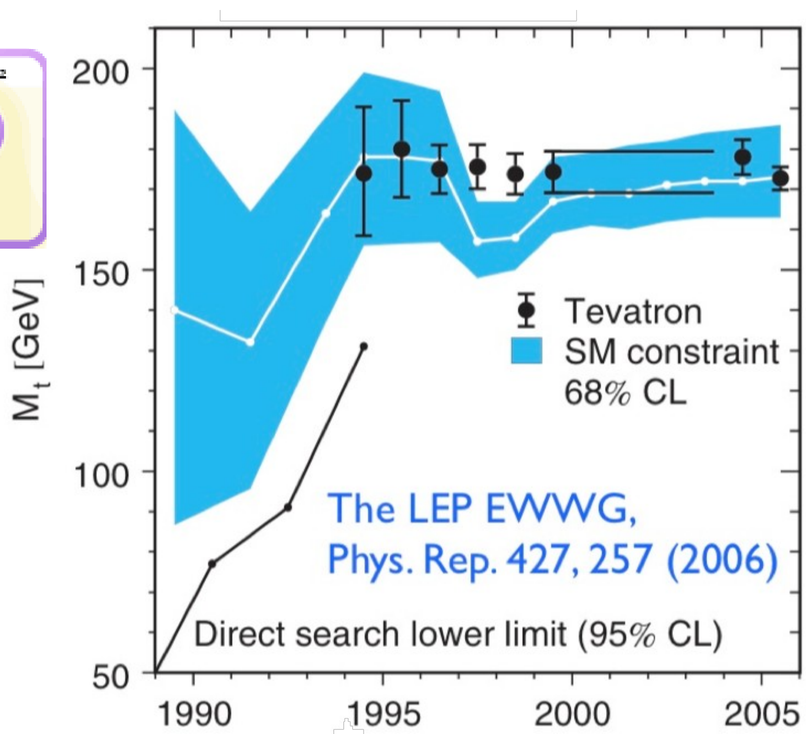
(I find you lack of faith disturbing)

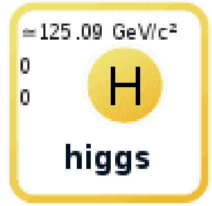
Collider experiment coordinates

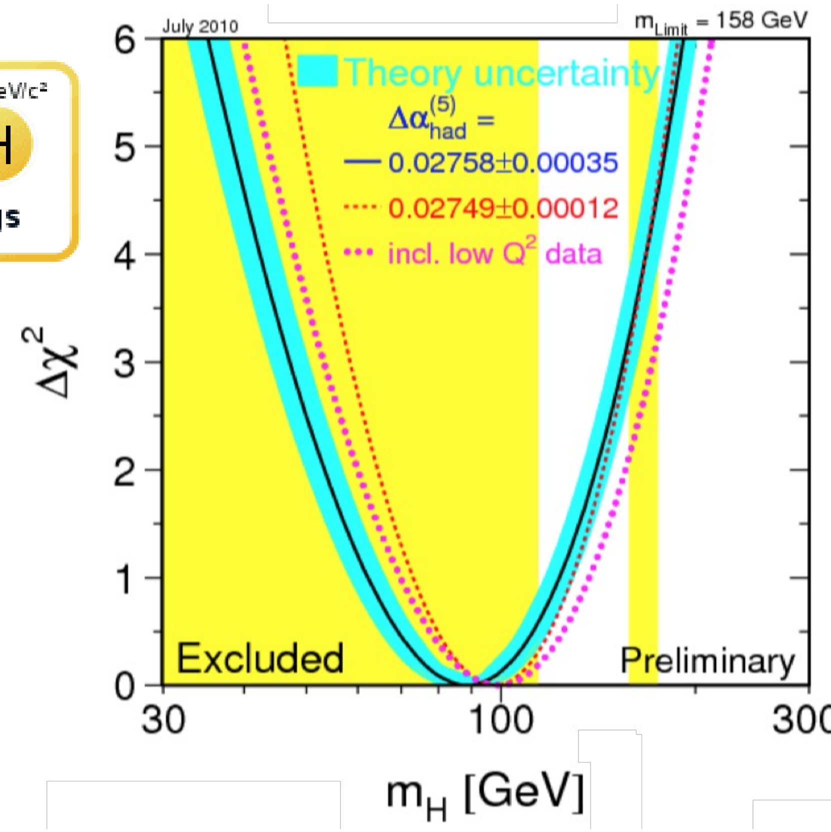


Before the LHC startup









m_W measurement at SppS and LEP-1 precision measurements

top quark discovery (1994)

m_W measurement at LEP-2

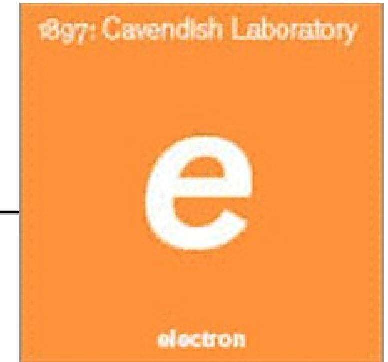
electroweak fit and indirect limit on m_H

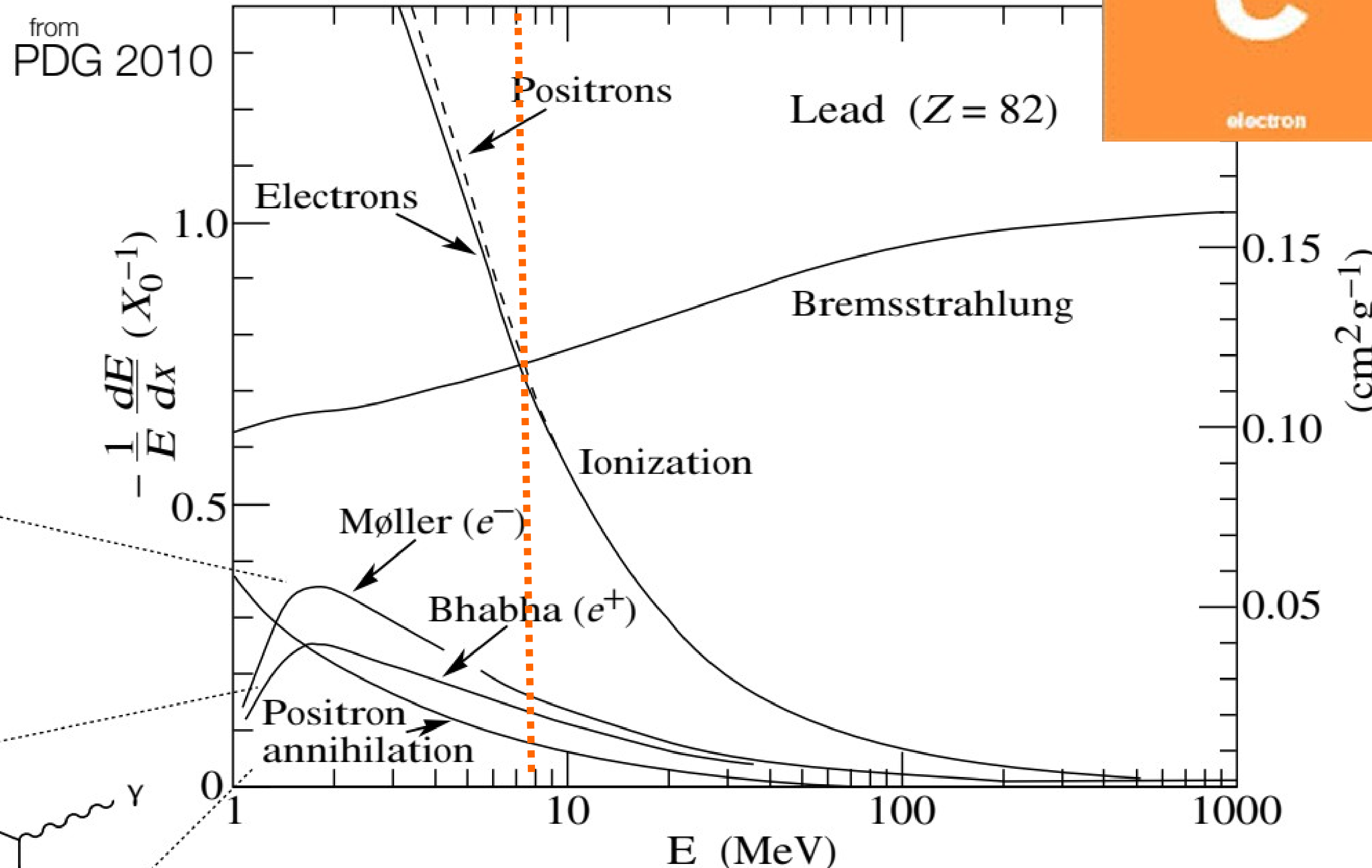
Direct limits on Higgs production from LEP-2 and Tevatron

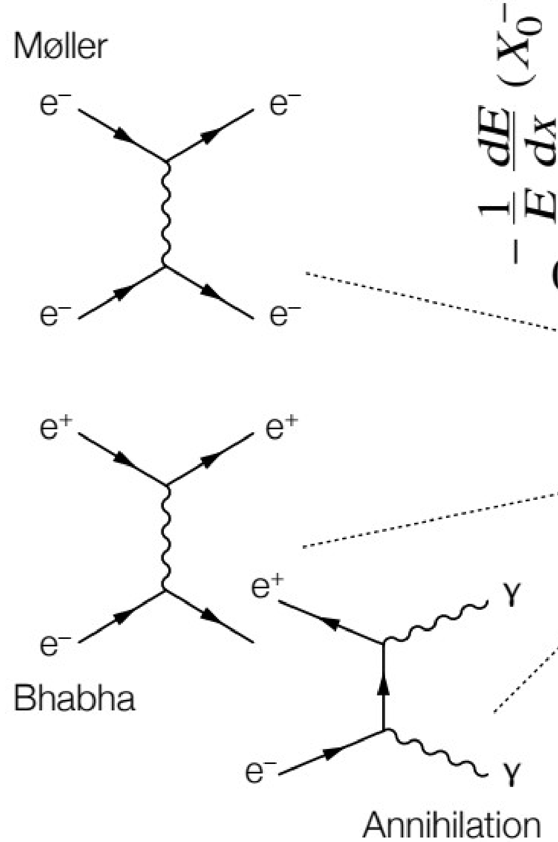
LHC "no lose theorem"

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

Electron energy loss

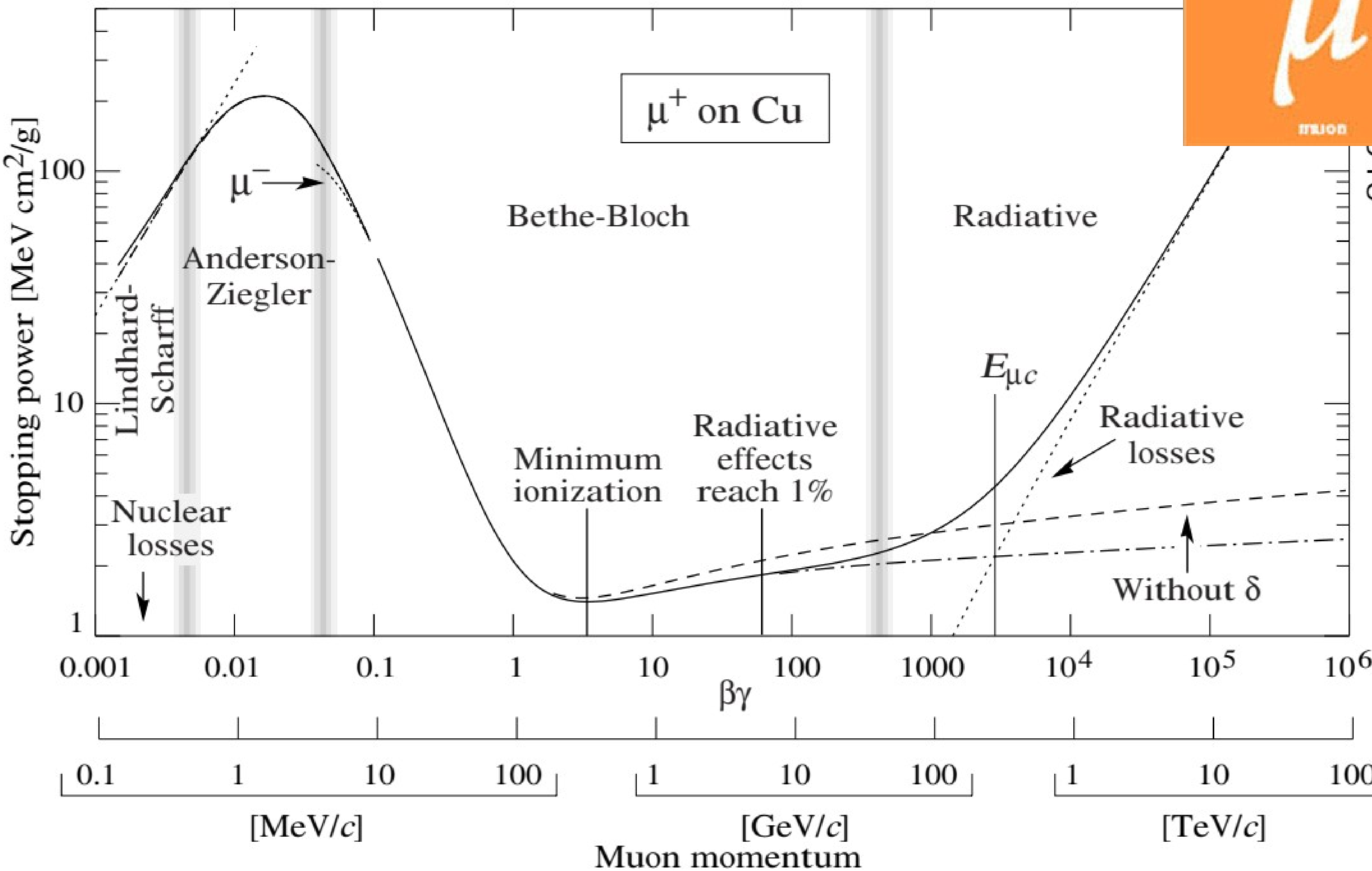




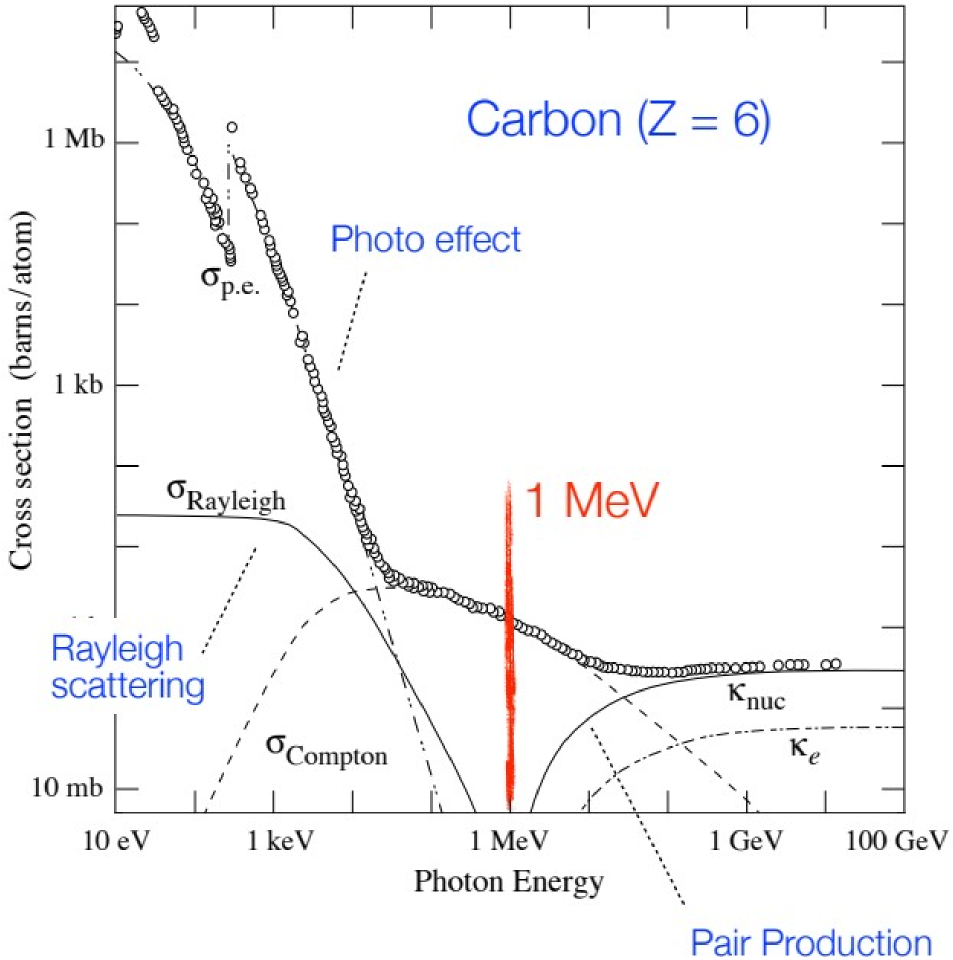


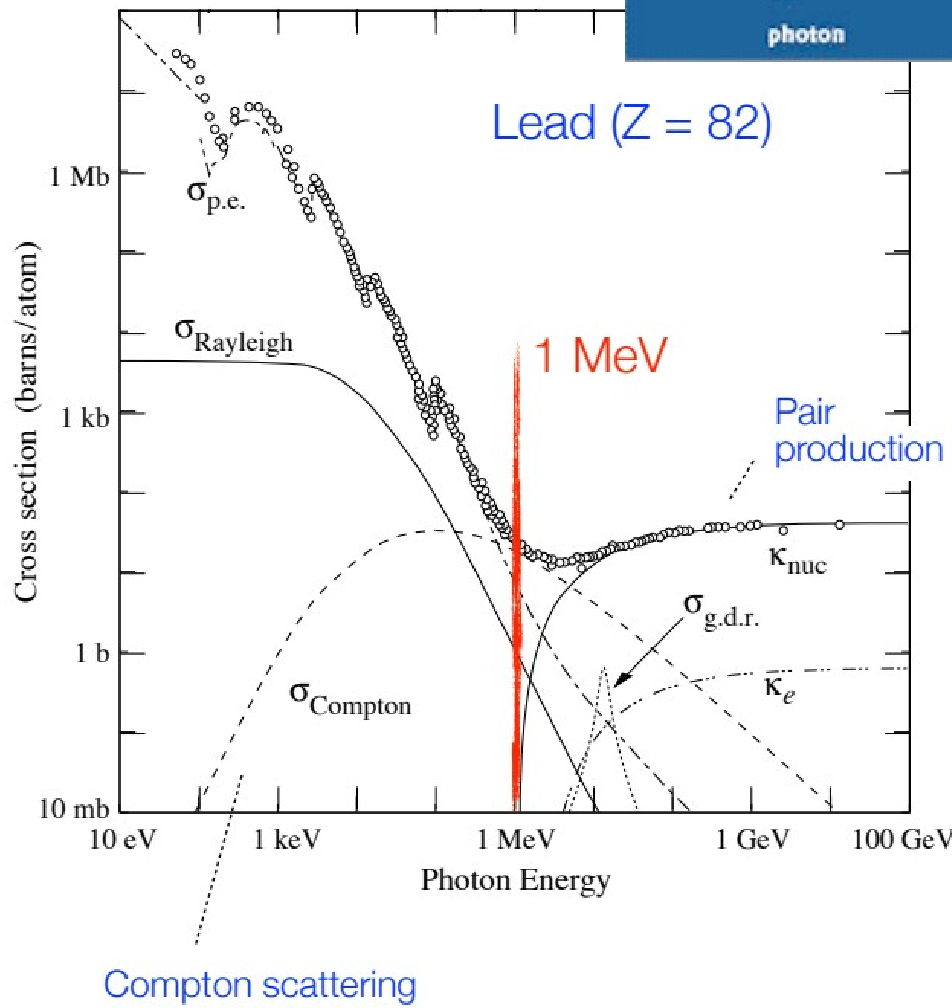
Fractional energy loss per radiation length in lead as a function of electron or positron energy

Muon energy loss



Interaction of photons with matter





HEP, SI and "natural" units

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

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

Relativistic kinematics in a nutshell

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

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

$$E = m\gamma$$

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

$$t = t_0\gamma$$

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

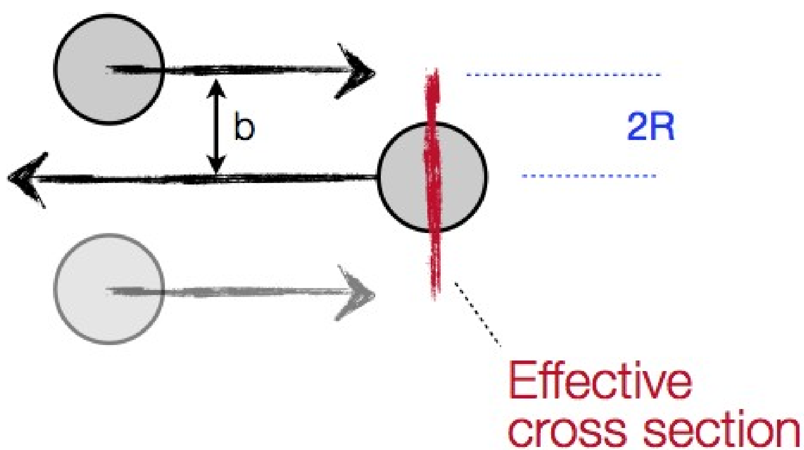
Cross section: magnitude and units

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

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

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

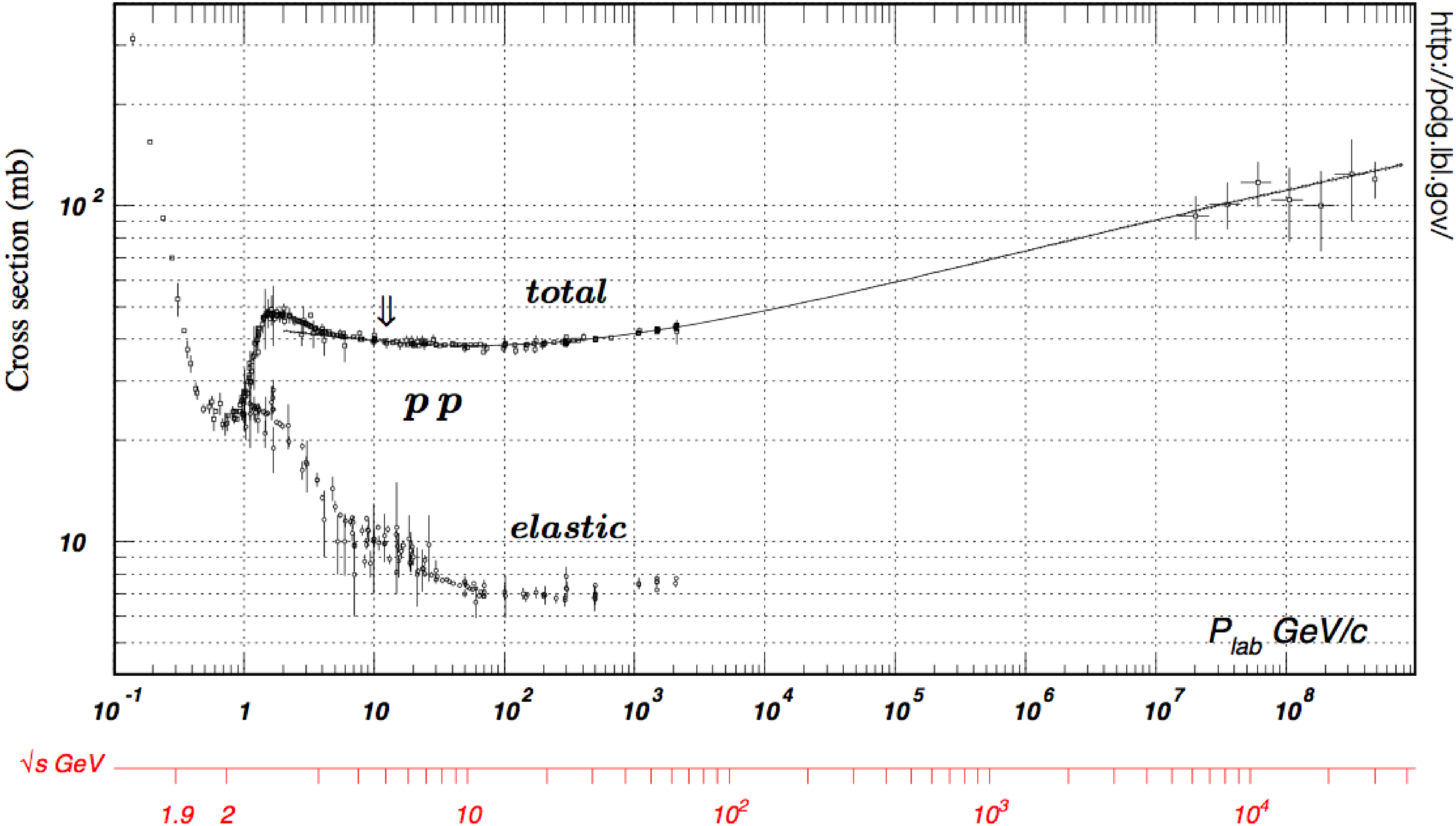
Estimating the
proton-proton cross section:



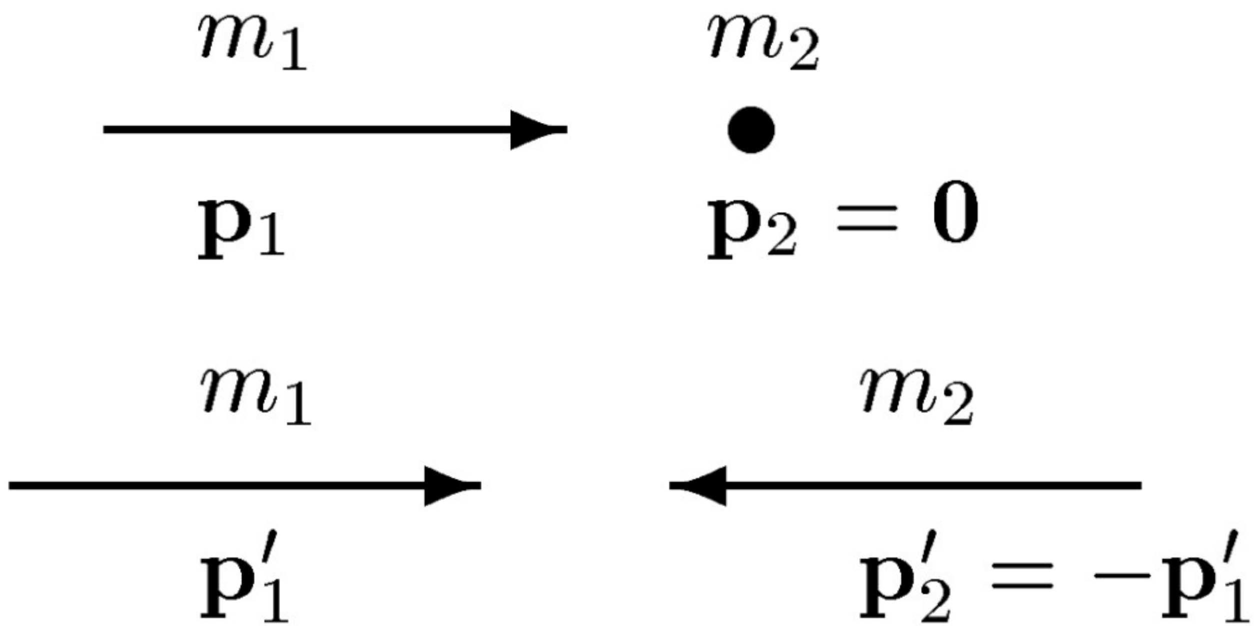
Proton radius: R = 0.8 fm
Strong interactions happens up to b = 2R

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

Proton-proton scattering cross-section



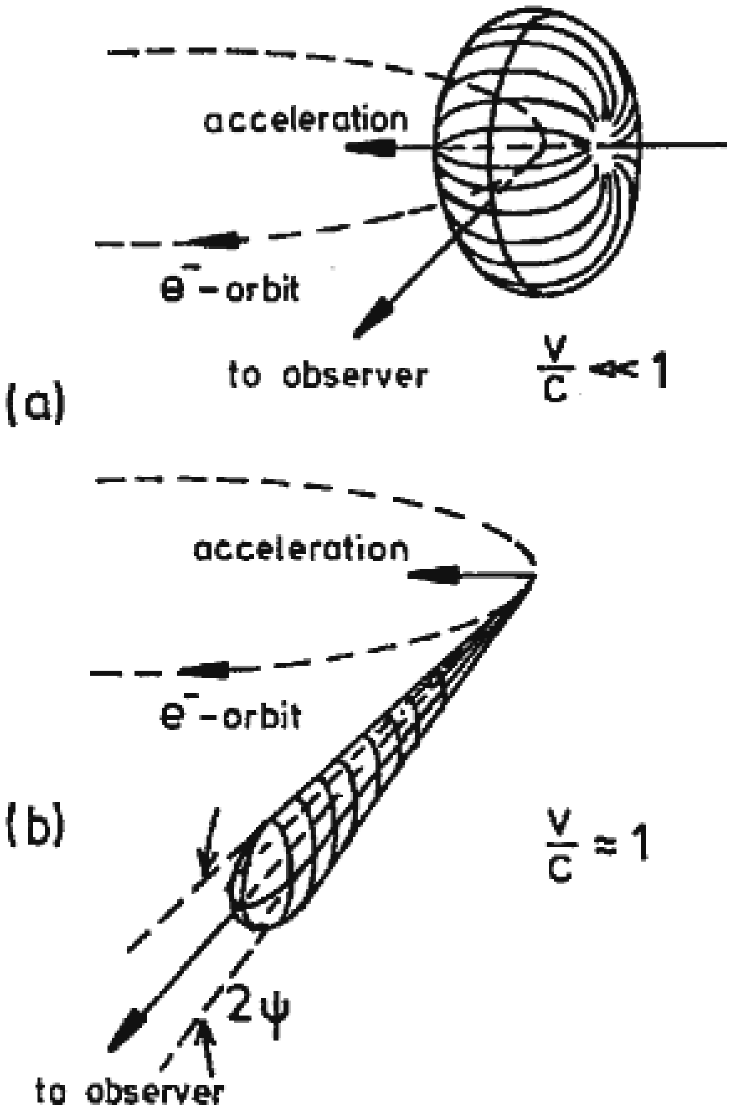
Fixed target vs. collider



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

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

Syncrotron radiation



energy lost per revolution

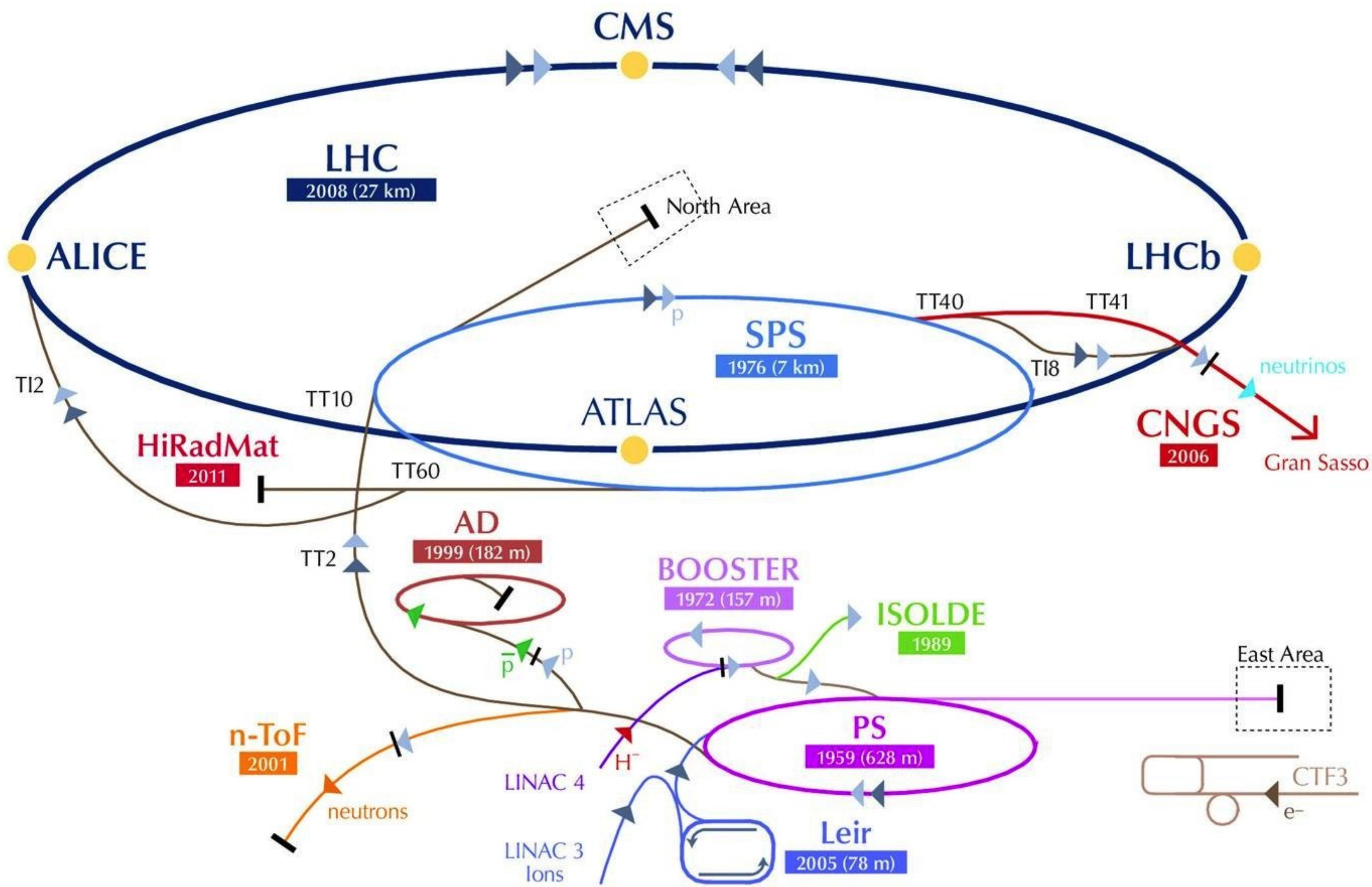
$$\Delta E = \frac{4\pi}{3}\frac{1}{4\pi\epsilon_0}\left(\frac{e^3\beta^3\gamma^4}{R}\right)$$

electrons vs. protons

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

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

CERN accelerator complex



Magnetic spectrometer

Charged particle in magnetic field

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

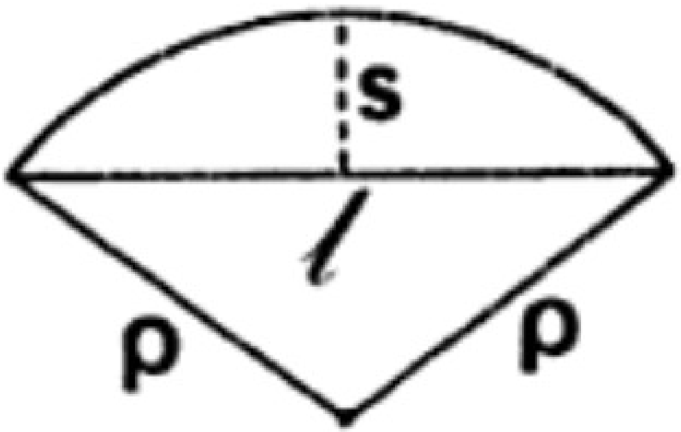
If the field is constant and we neglect presence of matter, momentum magnitude is constant with time, trajectory is helical

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

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

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

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

smaller for larger number of points

measurement error (RMS)

Momentum resolution due to measurement error

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

projected track length in magnetic field

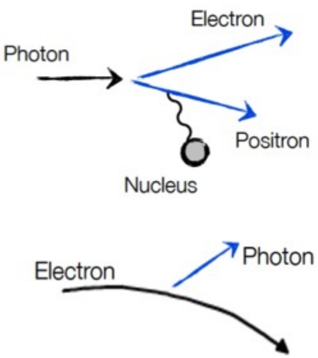
Momentum resolution gets worse for larger momenta

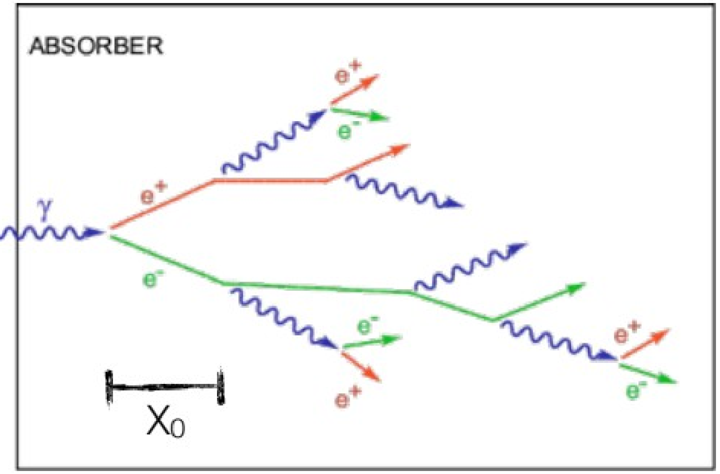
resolution is improved faster by increasing L then B

Electromagnetic showers

Dominant processes
at high energies ...

Photons : Pair production
Electrons : Bremsstrahlung





Pair production:

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

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

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

Absorption coefficient:

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

Bremsstrahlung:

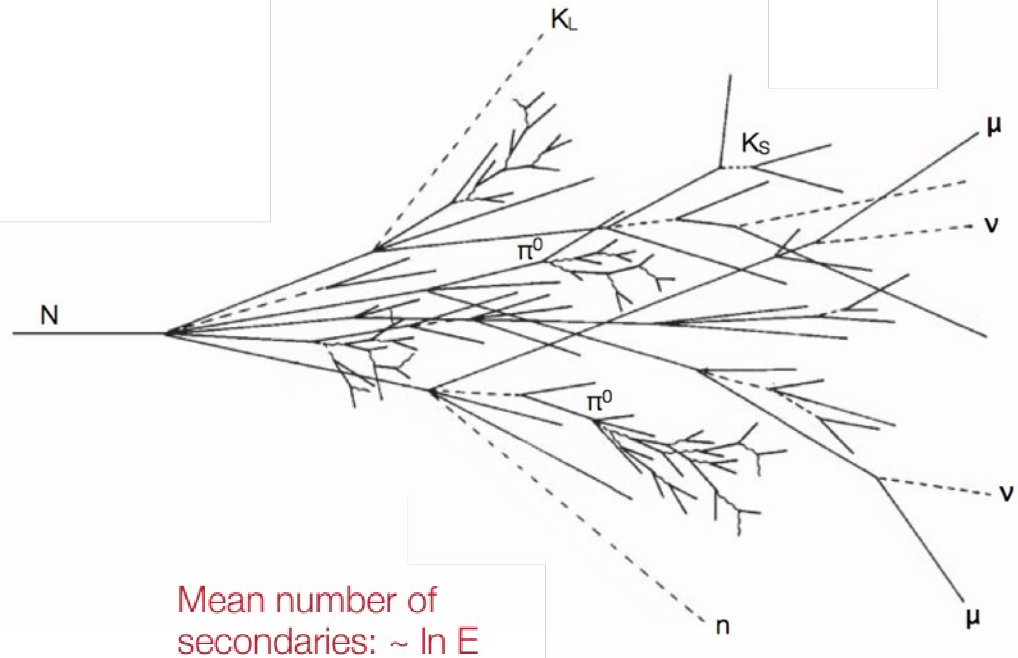
$$\frac{dE}{dx} = 4\alpha N_A \frac{Z^2}{A} r_e^2 \cdot E \,\ln \frac{183}{Z^{\frac{1}{3}}} = \frac{E}{X_0}$$

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

After passage of one X_0 electron has only $(1/e)^{\text{th}}$ 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 + Nucleus ➛ Pions + N* + ...
2. Secondary particles ...

   undergo further inelastic collisions until they fall below pion production threshold

3. Sequential decays ...

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

Mean number of secondaries: ~ ln E

Typical transverse momentum: p_t ~ 350 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 nobel gases (Ar, Kr, Xe)

- ★ Advantage: homogenous calorimeters provide optimal energy resolution
- ★ Disadvantage: very expensive
- ★ Homogenous calorimeters are exclusively used for electromagnetic calorimeter, i.e. energy measurement of electrons and photons

Sampling calorimeters

Principle:

Alternating layers of absorber and active material [sandwich calorimeter]

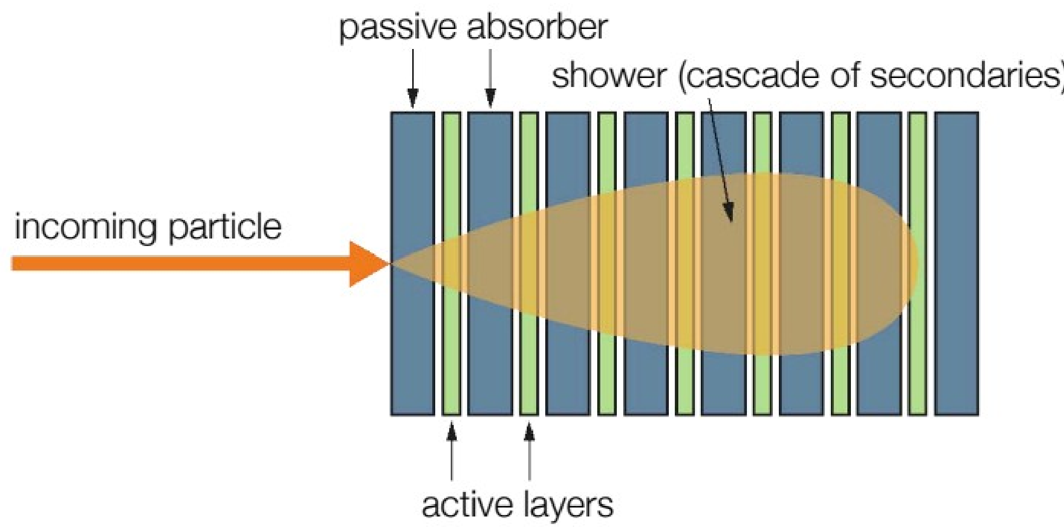
Absorber materials:
[high density]

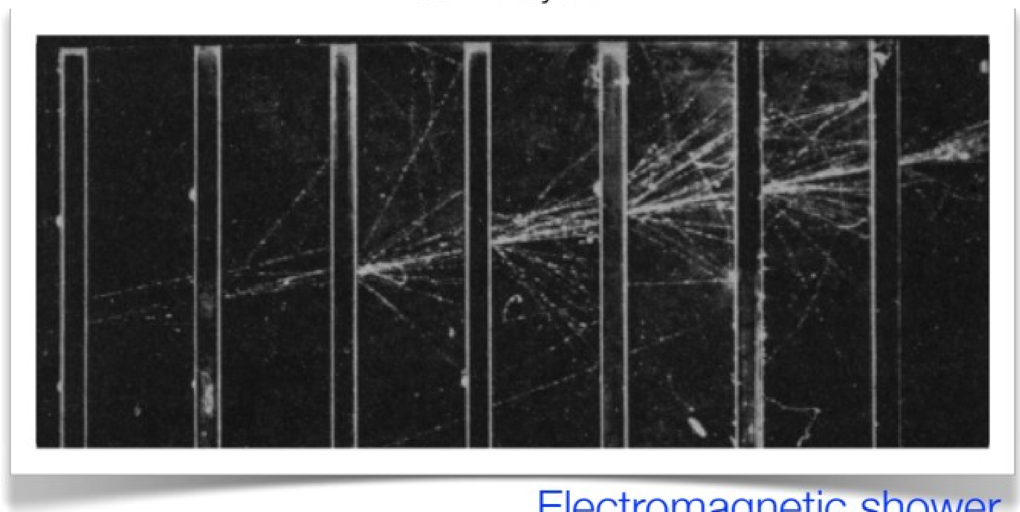
- Iron (Fe)
- Lead (Pb)
- Uranium (U)
[For compensation ...]

Active materials:

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

Scheme of a sandwich calorimeter





Electromagnetic shower

A typical HEP calorimetry system

Typical Calorimeter: two components ...

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

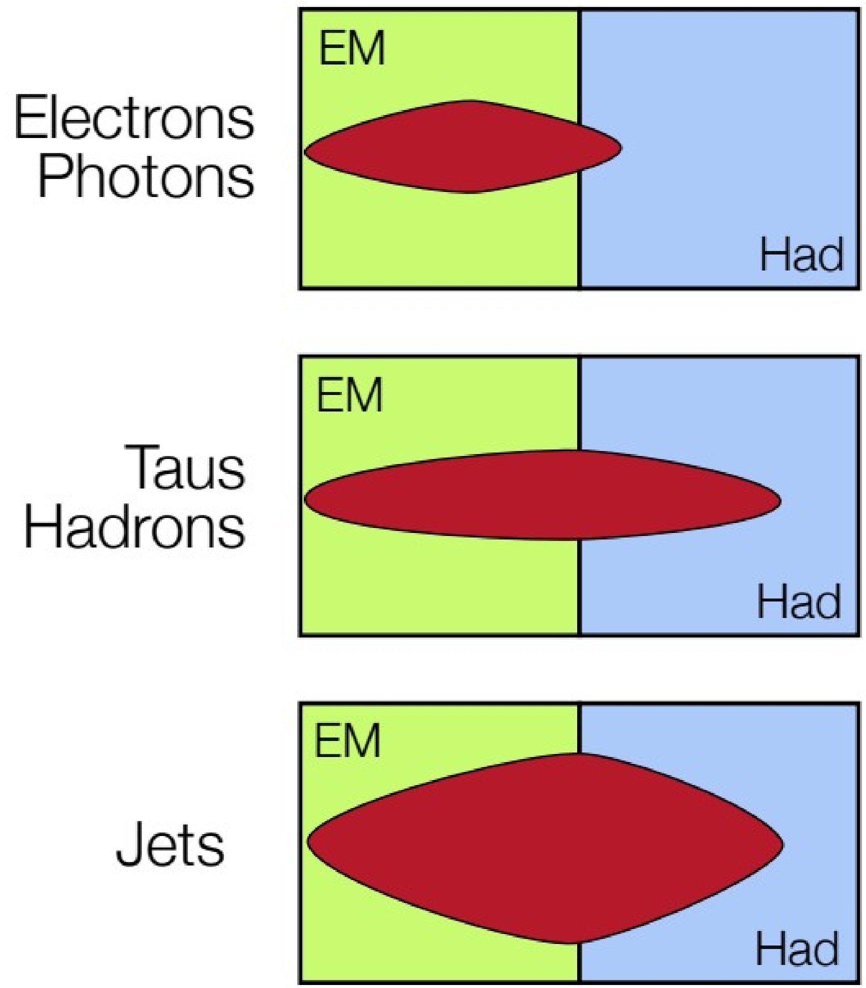
Different setups chosen for
optimal energy resolution ...

But:

Hadronic energy measured in
both parts of calorimeter ...

Needs careful consideration of
different response ...

Schematic of a
typical HEP calorimeter



Energy resolution in calorimeters

Energy resolution:

e.g. inhomogeneities
shower leakage

e.g. electronic noise
sampling fraction variations

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

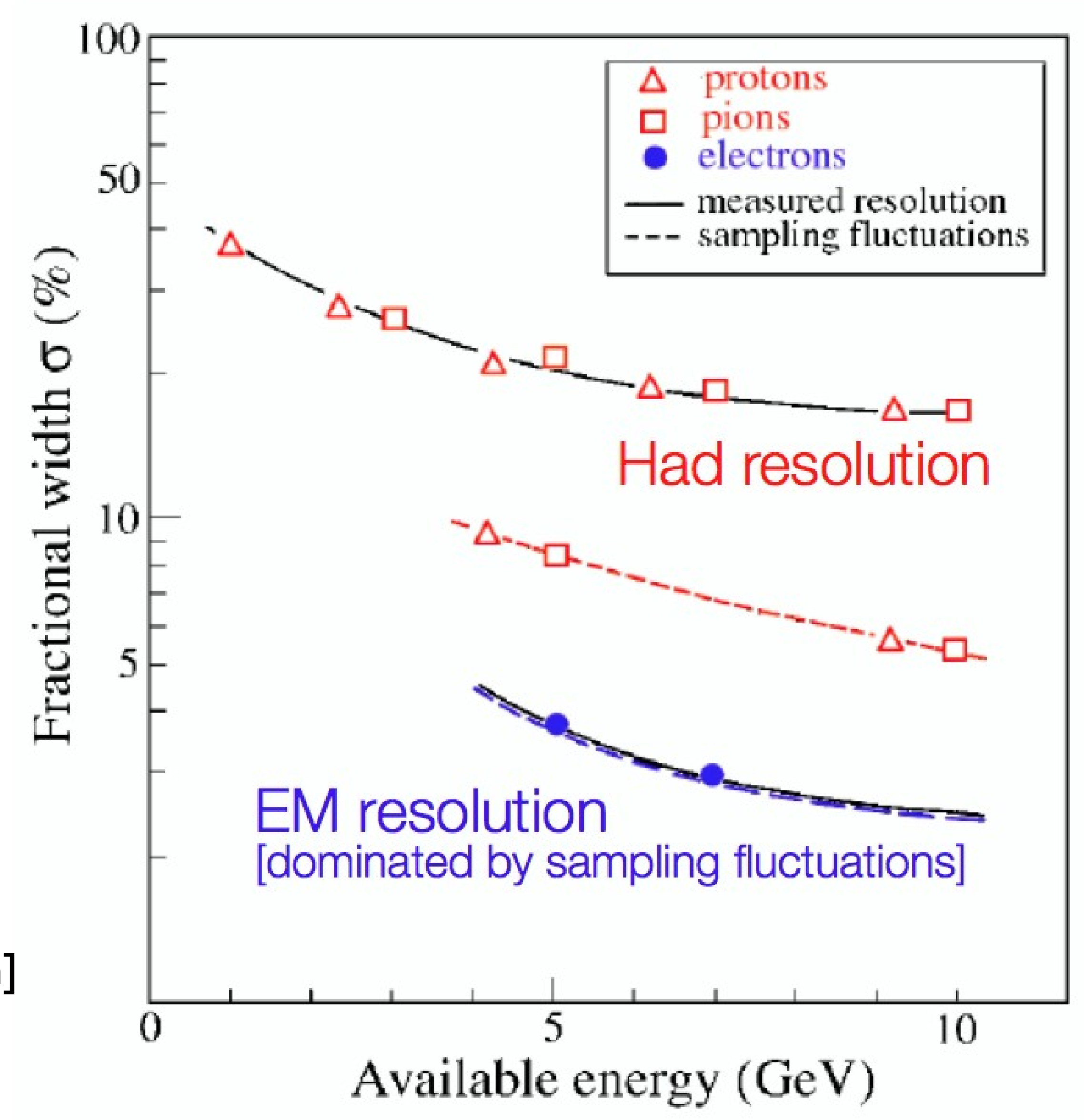
Fluctuations:

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

Typical:

A: 0.5 – 1.0 [Record:0.35]
B: 0.03 – 0.05
C: few %

Resolution: EM vs. HAD



[AFM Collaboration]

Sampling fluctuations only minor contribution to hadronic energy resolution