(experimental) LHC physics

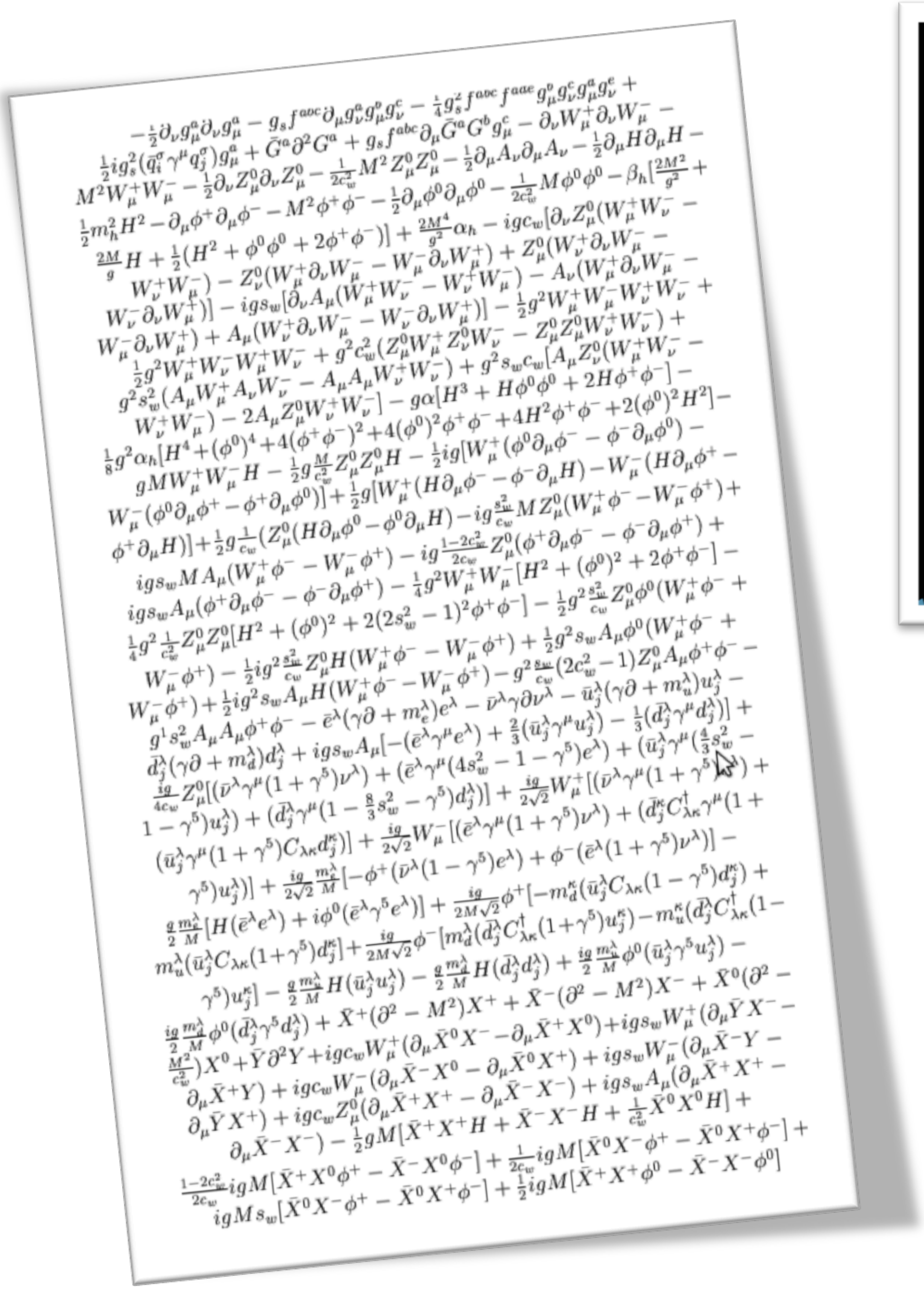

Summer School in **Particle and Astroparticle physics** of Annecy-le-Vieux

21-25 July 2014

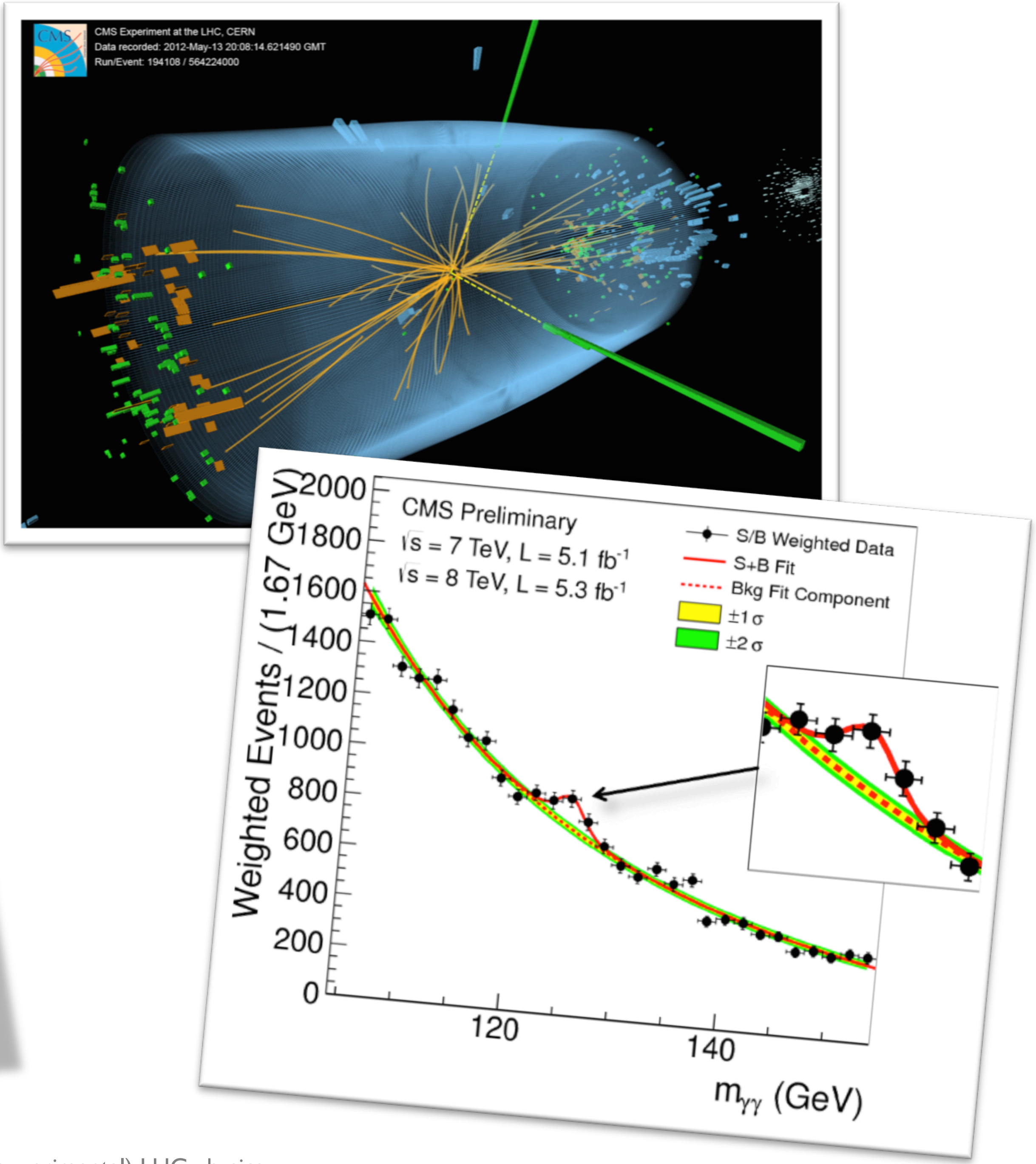
I.

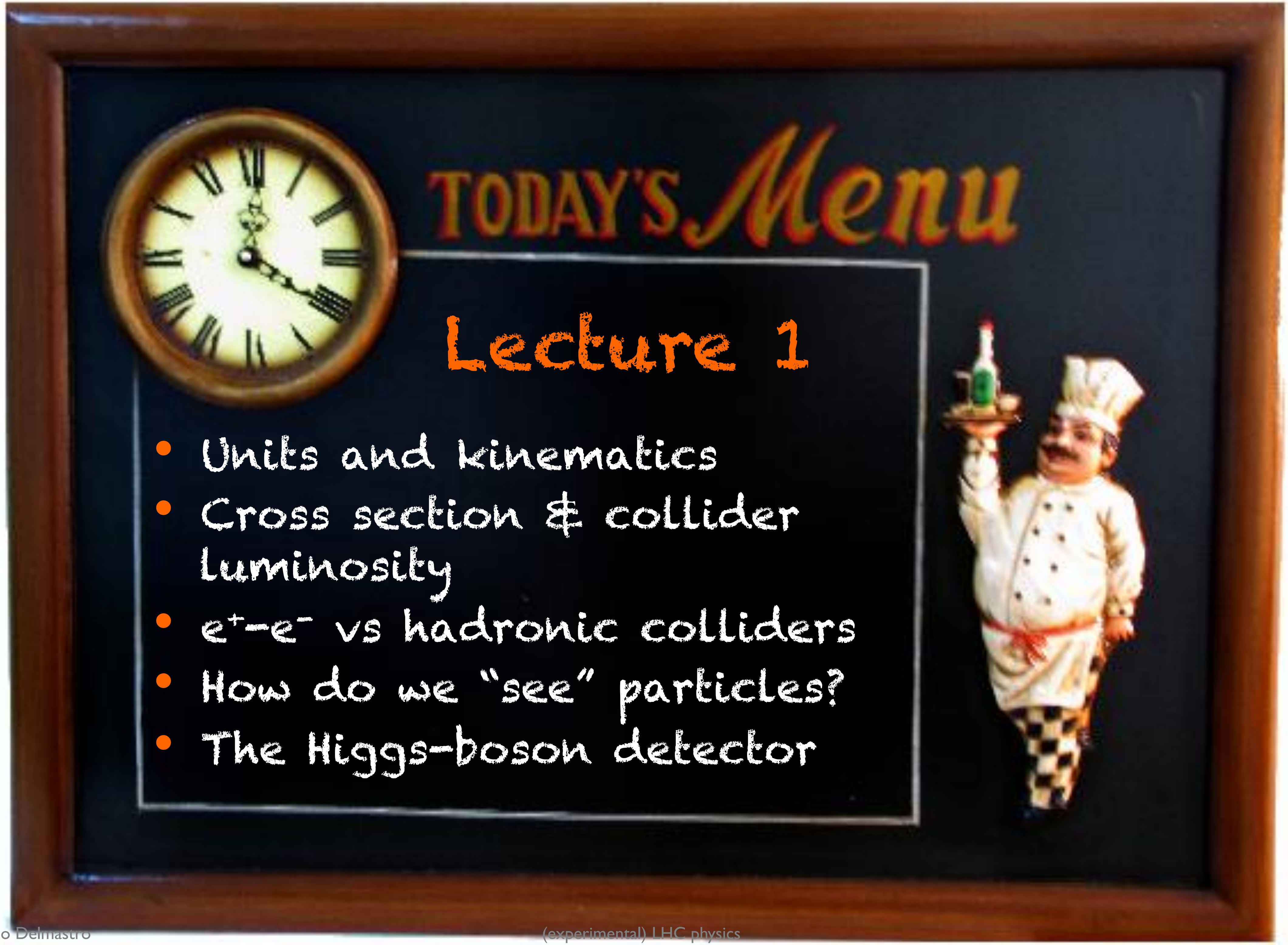
The tools:
Collider + Detectors
+ Data analysis

Experiment = probing theories with data!



$$
\begin{gathered}
-\tfrac{1}{2}\partial_\nu g^a_\mu \partial_\nu g^a_\mu - g_s f^{abc}\partial_\mu g^a_\nu g^b_\mu g^c_\nu - \tfrac{1}{4}g_s^2 f^{abc} f^{ade} g^b_\mu g^c_\nu g^d_\mu g^e_\nu + \\
\tfrac{1}{2}ig_s^2(\bar{q}^\sigma_i \gamma^\mu q^\sigma_j)g^a_\mu + \bar{G}^a\partial^2 G^a + g_s f^{abc}\partial_\mu \bar{G}^a G^b g^c_\mu - \partial_\nu W^+_\mu \partial_\nu W^-_\mu - \\
M^2 W^+_\mu W^-_\mu - \tfrac{1}{2}\partial_\nu Z^0_\mu \partial_\nu Z^0_\mu - \tfrac{1}{2c_w^2}M^2 Z^0_\mu Z^0_\mu - \tfrac{1}{2}\partial_\mu A_\nu \partial_\mu A_\nu - \tfrac{1}{2}\partial_\mu H \partial_\mu H - \\
\tfrac{1}{2}m_h^2 H^2 - \partial_\mu\phi^+\partial_\mu\phi^- - M^2\phi^+\phi^- - \tfrac{1}{2}\partial_\mu\phi^0\partial_\mu\phi^0 - \tfrac{1}{2c_w^2}M\phi^0\phi^0 - \beta_h[\tfrac{2M^2}{g^2} + \\
\tfrac{2M}{g}H + \tfrac{1}{2}(H^2 + \phi^0\phi^0 + 2\phi^+\phi^-)] + \tfrac{2M^4}{g^2}\alpha_h - igc_w[\partial_\nu Z^0_\mu(W^+_\mu W^-_\nu - \\
W^+_\nu W^-_\mu) - Z^0_\nu(W^+_\mu\partial_\nu W^-_\mu - W^-_\mu\partial_\nu W^+_\mu) + Z^0_\mu(W^+_\nu\partial_\nu W^-_\mu - \\
W^-_\nu\partial_\nu W^+_\mu)] - igs_w[\partial_\nu A_\mu(W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - A_\nu(W^+_\mu\partial_\nu W^-_\mu - \\
W^-_\mu\partial_\nu W^+_\mu) + A_\mu(W^+_\nu\partial_\nu W^-_\mu - W^-_\nu\partial_\nu W^+_\mu)] - \tfrac{1}{2}g^2 W^+_\mu W^-_\mu W^+_\nu W^-_\nu + \\
\tfrac{1}{2}g^2 W^+_\mu W^-_\nu W^+_\mu W^-_\nu + g^2c_w^2(Z^0_\mu W^+_\mu Z^0_\nu W^-_\nu - Z^0_\mu Z^0_\mu W^+_\nu W^-_\nu) + \\
g^2 s_w^2(A_\mu W^+_\mu A_\nu W^-_\nu - A_\mu A_\mu W^+_\nu W^-_\nu) + g^2 s_w c_w[A_\mu Z^0_\nu(W^+_\mu W^-_\nu - \\
W^+_\nu W^-_\mu) - 2A_\mu Z^0_\mu W^+_\nu W^-_\nu] - g\alpha[H^3 + H\phi^0\phi^0 + 2H\phi^+\phi^-] - \\
\tfrac{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)^2H^2] - \\
gMW^+_\mu W^-_\mu H - \tfrac{1}{2}g\tfrac{M}{c_w^2}Z^0_\mu Z^0_\mu H - \tfrac{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)] + \tfrac{1}{2}g[W^+_\mu(H\partial_\mu\phi^- - \phi^-\partial_\mu H) - W^-_\mu(H\partial_\mu\phi^+ - \\
\phi^+\partial_\mu H)] + \tfrac{1}{2}g\tfrac{1}{c_w}(Z^0_\mu(H\partial_\mu\phi^0 - \phi^0\partial_\mu H) - ig\tfrac{s_w^2}{c_w}MZ^0_\mu(W^+_\mu\phi^- - W^-_\mu\phi^+) + \\
igs_wMA_\mu(W^+_\mu\phi^- - W^-_\mu\phi^+) - ig\tfrac{1-2c_w^2}{2c_w}Z^0_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) + \\
igs_wA_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) - \tfrac{1}{4}g^2W^+_\mu W^-_\mu[H^2 + (\phi^0)^2 + 2\phi^+\phi^-] - \\
\tfrac{1}{4}g^2\tfrac{1}{c_w^2}Z^0_\mu Z^0_\mu[H^2 + (\phi^0)^2 + 2(2s_w^2 - 1)^2\phi^+\phi^-] - \tfrac{1}{2}g^2\tfrac{s_w^2}{c_w}Z^0_\mu\phi^0(W^+_\mu\phi^- + \\
W^-_\mu\phi^+) - \tfrac{1}{2}ig^2\tfrac{s_w^2}{c_w}Z^0_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) + \tfrac{1}{2}g^2 s_w A_\mu\phi^0(W^+_\mu\phi^- + \\
W^-_\mu\phi^+) + \tfrac{1}{2}ig^2 s_w A_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) - g^2\tfrac{s_w}{c_w}(2c_w^2 - 1)Z^0_\mu A_\mu\phi^+\phi^- - \\
g^1 s_w^2 A_\mu A_\mu\phi^+\phi^- - \bar{e}^\lambda(\gamma\partial + m_e^\lambda)e^\lambda - \bar{\nu}^\lambda\gamma\partial\nu^\lambda - \bar{u}^\lambda_j(\gamma\partial + m_u^\lambda)u^\lambda_j - \\
\bar{d}^\lambda_j(\gamma\partial + m_d^\lambda)d^\lambda_j + igs_wA_\mu[-(\bar{e}^\lambda\gamma^\mu e^\lambda) + \tfrac{2}{3}(\bar{u}^\lambda_j\gamma^\mu u^\lambda_j) - \tfrac{1}{3}(\bar{d}^\lambda_j\gamma^\mu d^\lambda_j)] + \\
\tfrac{ig}{4c_w}Z^0_\mu[(\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}^\lambda_j\gamma^\mu(\tfrac{4}{3}s_w^2 - \\
1 - \gamma^5)u^\lambda_j) + (\bar{d}^\lambda_j\gamma^\mu(1 - \tfrac{8}{3}s_w^2 - \gamma^5)d^\lambda_j)] + \tfrac{ig}{2\sqrt{2}}W^+_\mu[(\bar{\nu}^\lambda\gamma^\mu(1 + \gamma^5)e^\lambda) + \\
(\bar{u}^\lambda_j\gamma^\mu(1 + \gamma^5)C_{\lambda\kappa}d^\kappa_j)] + \tfrac{ig}{2\sqrt{2}}W^-_\mu[(\bar{e}^\lambda\gamma^\mu(1 + \gamma^5)\nu^\lambda) + (\bar{d}^\kappa_j C^\dagger_{\lambda\kappa}\gamma^\mu(1 + \\
\gamma^5)u^\lambda_j)] + \tfrac{ig}{2\sqrt{2}}\tfrac{m_e^\lambda}{M}[-\phi^+(\bar{\nu}^\lambda(1 - \gamma^5)e^\lambda) + \phi^-(\bar{e}^\lambda(1 + \gamma^5)\nu^\lambda)] - \\
\tfrac{g}{2}\tfrac{m_e^\lambda}{M}[H(\bar{e}^\lambda e^\lambda) + i\phi^0(\bar{e}^\lambda\gamma^5 e^\lambda)] + \tfrac{ig}{2M\sqrt{2}}\phi^+[-m_d^\kappa(\bar{u}^\lambda_j C_{\lambda\kappa}(1 - \gamma^5)d^\kappa_j) + \\
m_u^\lambda(\bar{u}^\lambda_j C_{\lambda\kappa}(1 + \gamma^5)d^\kappa_j] + \tfrac{ig}{2M\sqrt{2}}\phi^-[m_d^\lambda(\bar{d}^\lambda_j C^\dagger_{\lambda\kappa}(1 + \gamma^5)u^\kappa_j) - m_u^\kappa(\bar{d}^\lambda_j C^\dagger_{\lambda\kappa}(1 - \\
\gamma^5)u^\kappa_j] - \tfrac{g}{2}\tfrac{m_u^\lambda}{M}H(\bar{u}^\lambda_j u^\lambda_j) - \tfrac{g}{2}\tfrac{m_d^\lambda}{M}H(\bar{d}^\lambda_j d^\lambda_j) + \tfrac{ig}{2}\tfrac{m_u^\lambda}{M}\phi^0(\bar{u}^\lambda_j\gamma^5 u^\lambda_j) - \\
\tfrac{ig}{2}\tfrac{m_d^\lambda}{M}\phi^0(\bar{d}^\lambda_j\gamma^5 d^\lambda_j) + \bar{X}^+(\partial^2 - M^2)X^+ + \bar{X}^-(\partial^2 - M^2)X^- + \bar{X}^0(\partial^2 - \\
\tfrac{M^2}{c_w^2})X^0 + \bar{Y}\partial^2 Y + igc_wW^+_\mu(\partial_\mu\bar{X}^0X^- - \partial_\mu\bar{X}^+X^0) + igs_wW^+_\mu(\partial_\mu\bar{Y}X^- - \\
\partial_\mu\bar{X}^+Y) + igc_wW^-_\mu(\partial_\mu\bar{X}^-X^0 - \partial_\mu\bar{X}^0X^+) + igs_wW^-_\mu(\partial_\mu\bar{X}^-Y - \\
\partial_\mu\bar{Y}X^+) + igc_wZ^0_\mu(\partial_\mu\bar{X}^+X^+ - \partial_\mu\bar{X}^-X^-) + igs_wA_\mu(\partial_\mu\bar{X}^+X^+ - \\
\partial_\mu\bar{X}^-X^-) - \tfrac{1}{2}gM[\bar{X}^+X^+H + \bar{X}^-X^-H + \tfrac{1}{c_w^2}\bar{X}^0X^0H] + \\
\tfrac{1-2c_w^2}{2c_w}igM[\bar{X}^+X^0\phi^+ - \bar{X}^-X^0\phi^-] + \tfrac{1}{2c_w}igM[\bar{X}^0X^-\phi^+ - \bar{X}^0X^+\phi^-] + \\
igMs_w[\bar{X}^0X^-\phi^+ - \bar{X}^0X^+\phi^-] + \tfrac{1}{2}igM[\bar{X}^+X^+\phi^0 - \bar{X}^-X^-\phi^0]
\end{gathered}
$$





Lecture 1

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

Measuring particles

- Particles are characterized by

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

Particle identification via measurement of:

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

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

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

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

$$t = t_0\gamma$$ time dilatation

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

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

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

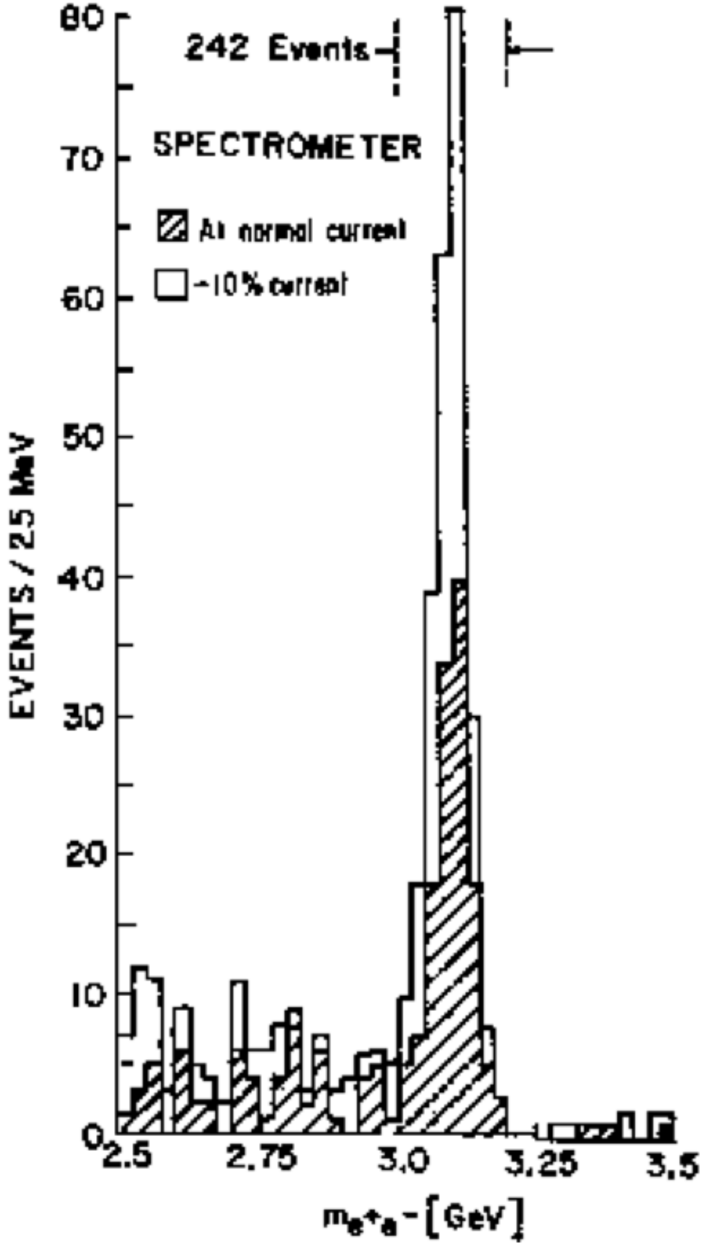
Center of mass energy

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

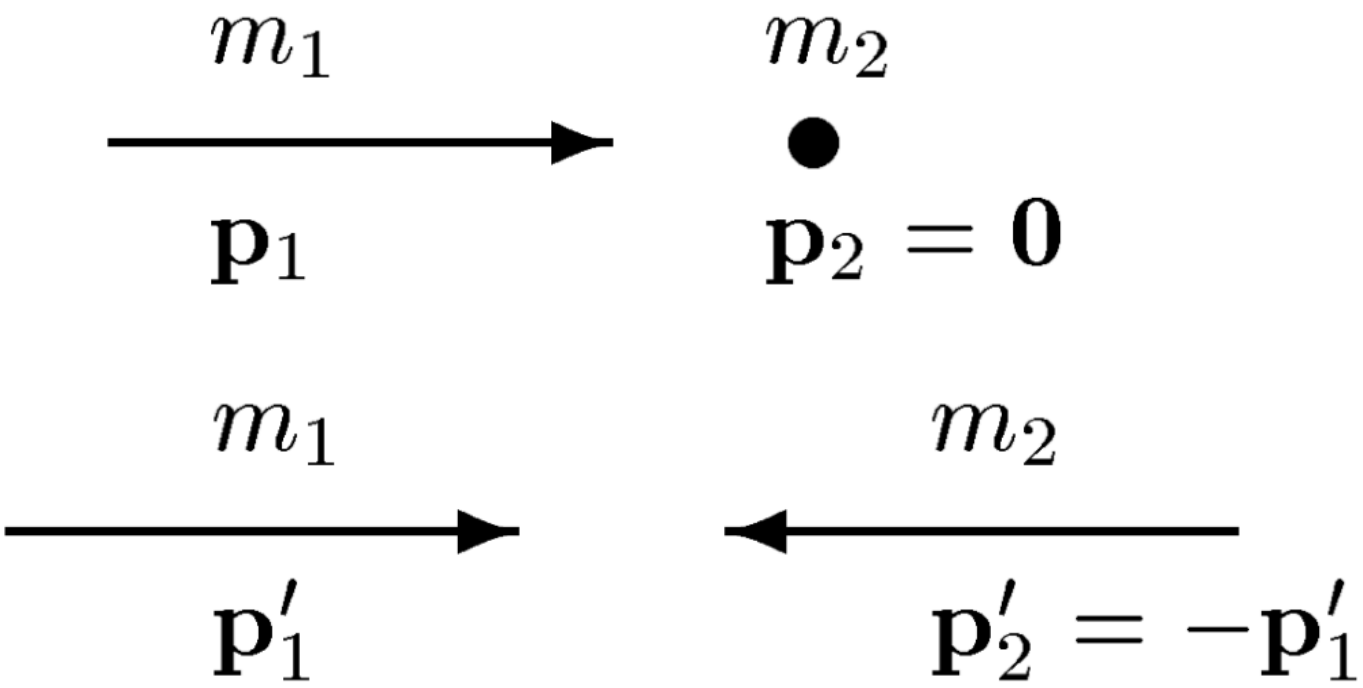
$$E_{\rm cm} = \sqrt{s} = \sqrt{\left(\sum E_i\right)^2 - \left(\sum \vec{p}_i\right)^2}$$

Invariant mass

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



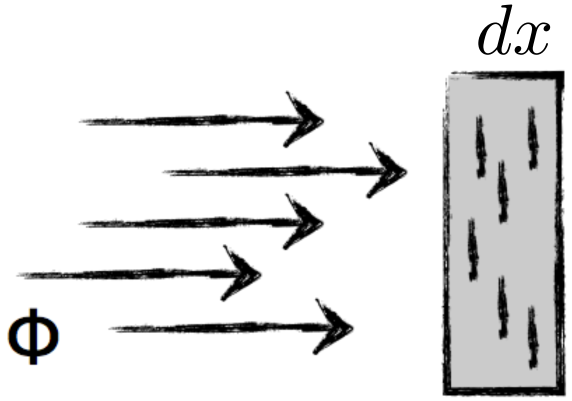
Fixed target vs. collider



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

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

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

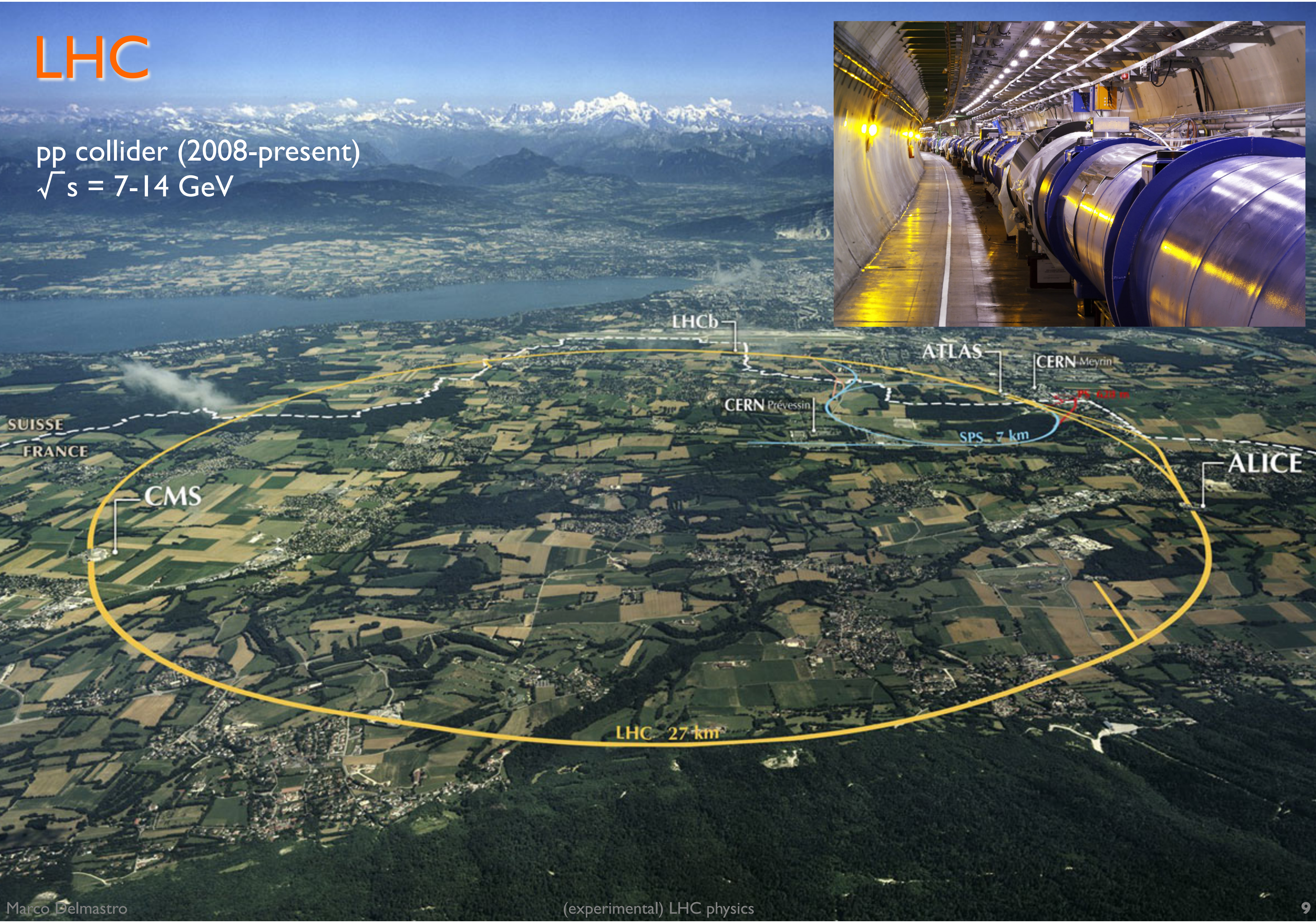
Reaction rate per target particle $$W_{if} = \Phi\sigma \qquad [t^{-1}]$$

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

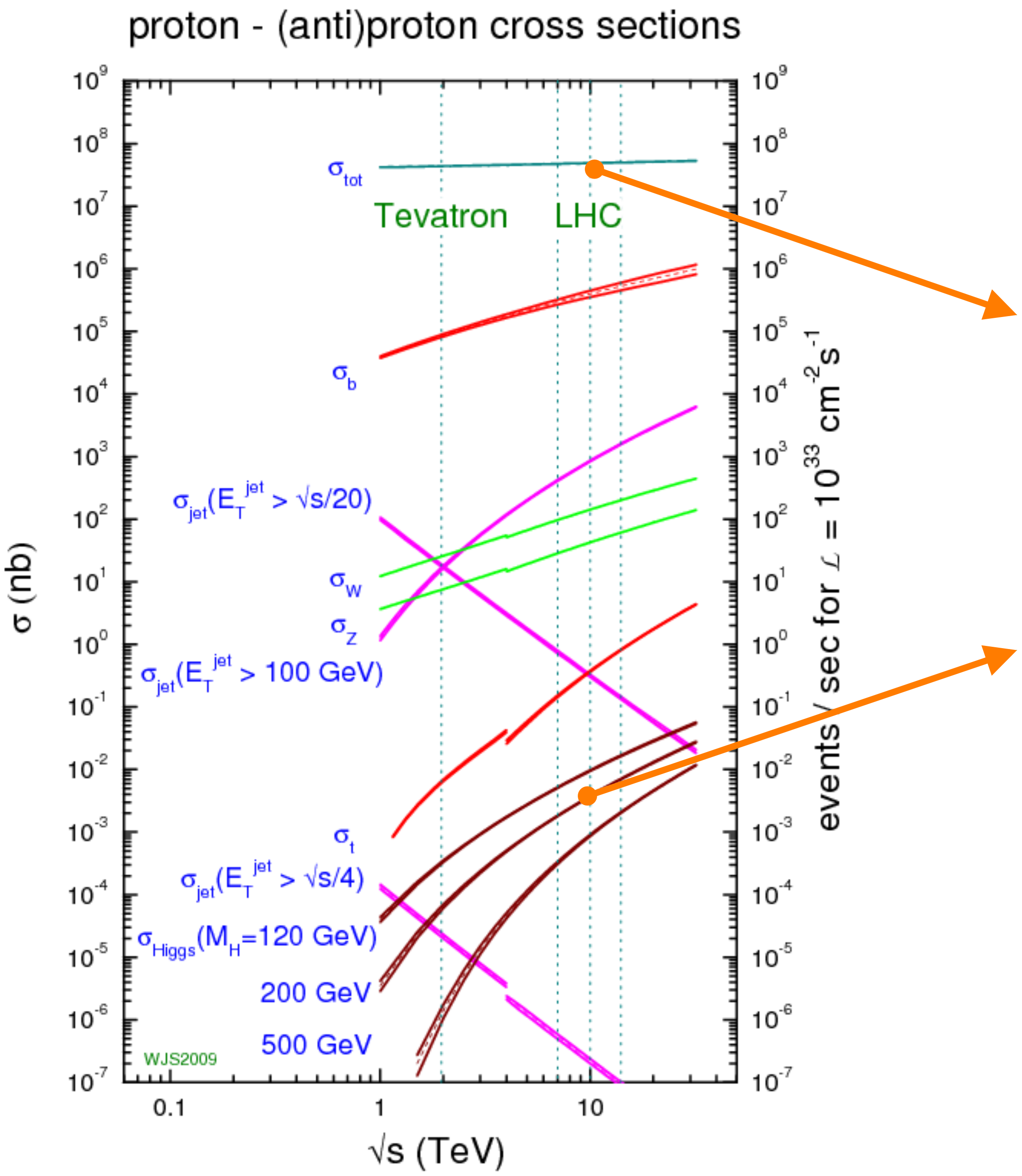
1b = 10^{-28} m^{2} (roughly the area of a nucleus with A = 100)

LHC

pp collider (2008-present)
$\sqrt{s}$ = 7-14 GeV



Cross-sections at LHC



10^8 events/s

~10^{10}

10^{-2} events/s ~
10 events/min

[m_H ~ 120 GeV]

0.2% H → γγ
1.5% H → ZZ

Why accelerating and colliding particles?

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

High energy

$$E = mc^2$$

- Probe smaller scale
- Produce heavier particles

Large number of collisions

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

- Detect rare processes
- Precision measurements

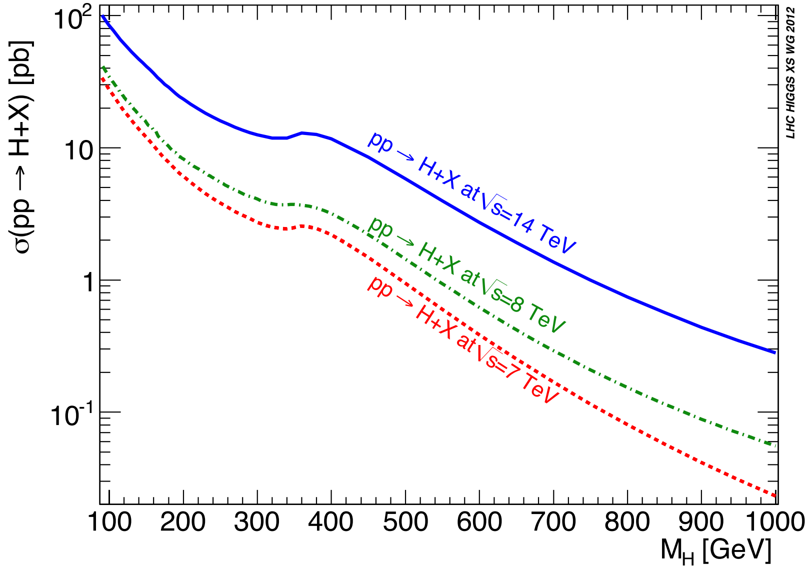
Luminosity

Number of events
in unit of time

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

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

? $10^{34}\ \mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ $\sigma(pp \rightarrow H+X) \sim 20$ pb



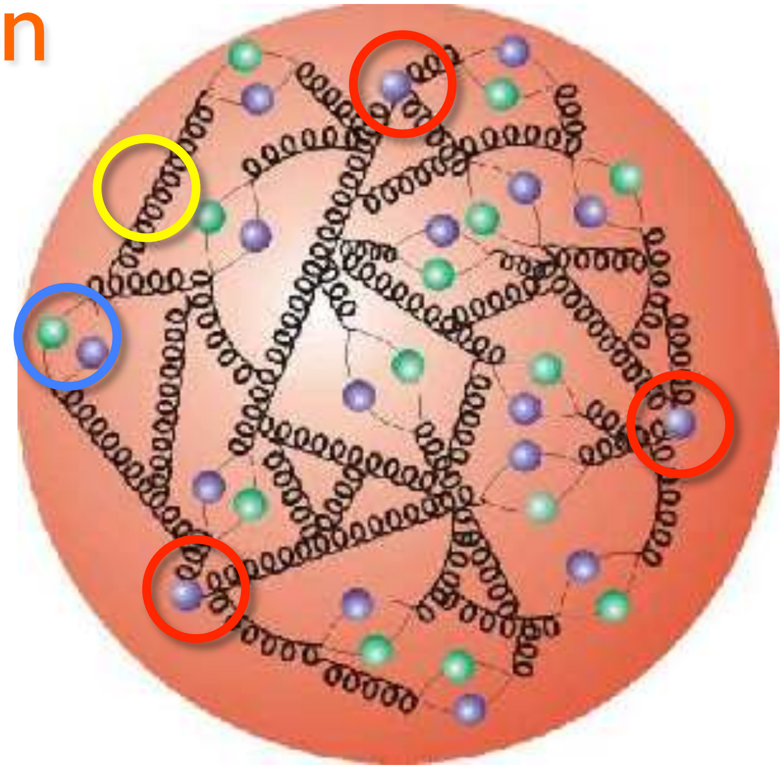
In a collider ring…

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

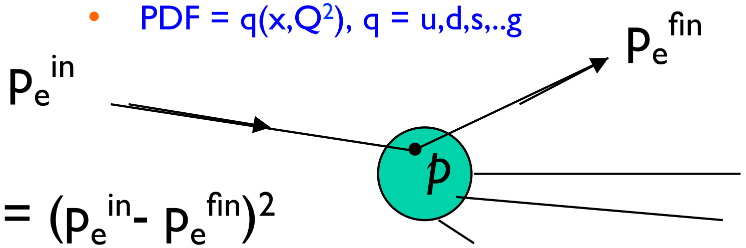
Current

Beam sizes (RMS)

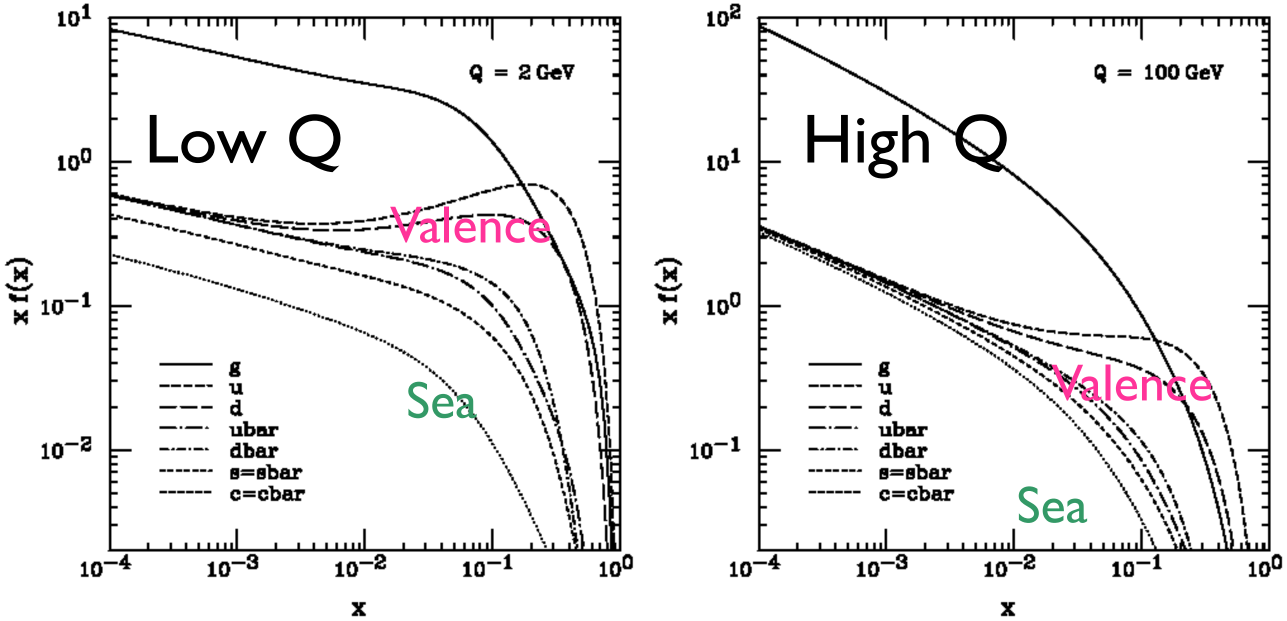
About the inner life of a proton



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

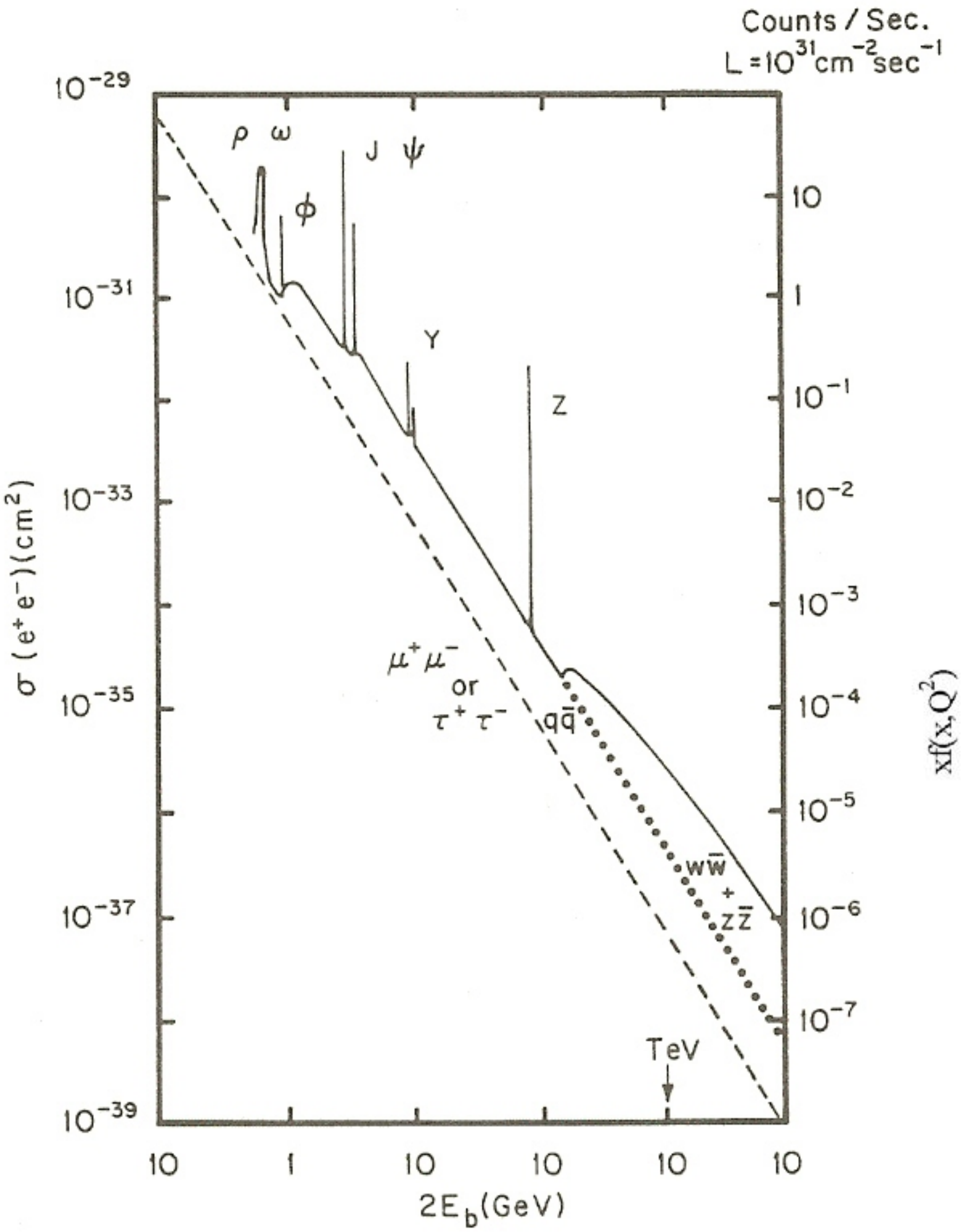


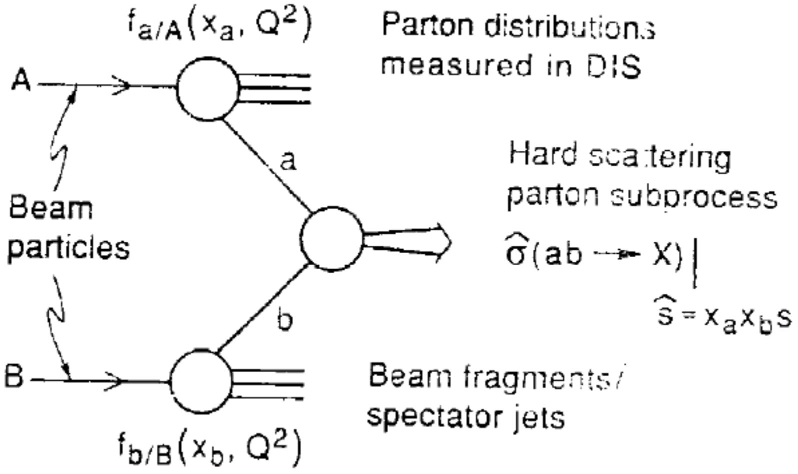
$Q^2 = (p_e^{in} - p_e^{fin})^2$



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

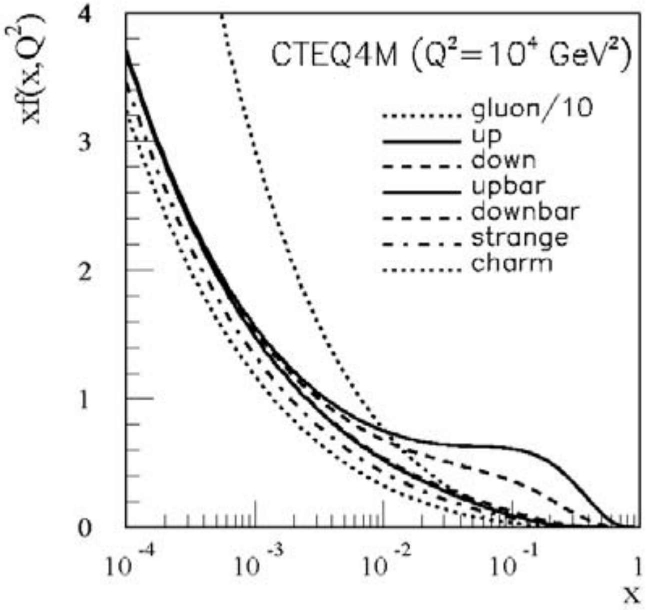
e$^+$-e$^-$ vs. hadron collider





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

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



to produce a particle with mass M = 100 GeV

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

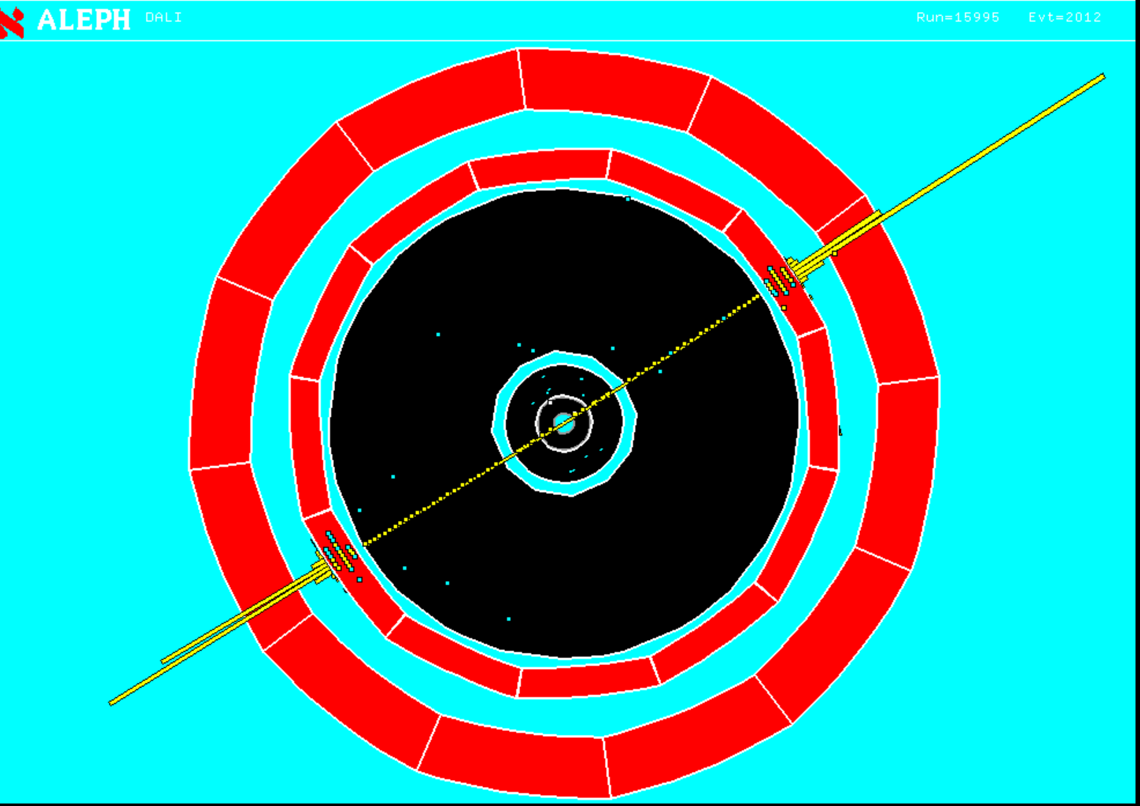
$\sqrt{s}$ = 14 TeV → x = 0.007
$\sqrt{s}$ = 5 TeV → x = 0.36

e^+-e^- vs. hadron collider

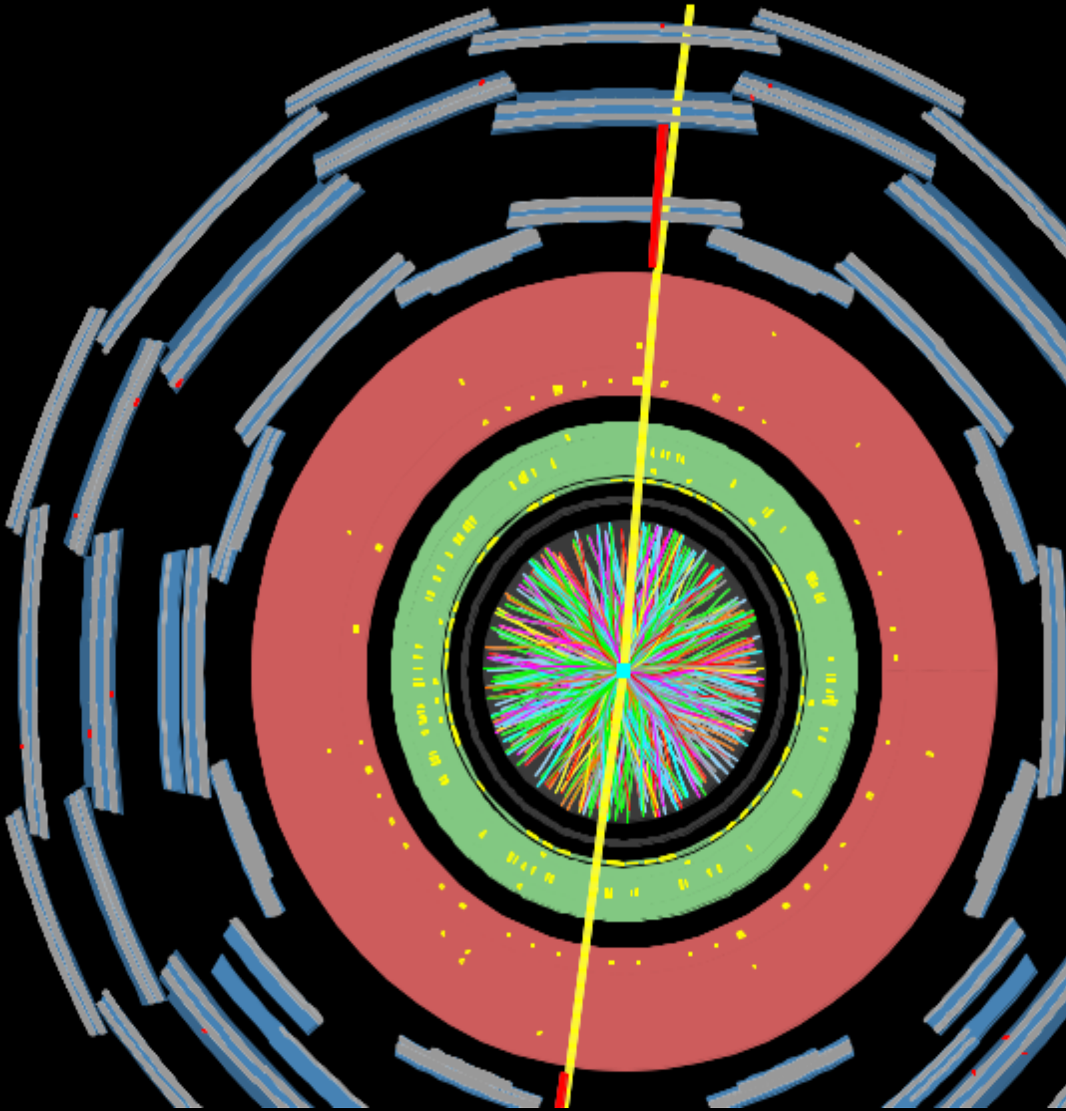
- **e^+-e^- collider**
  - ✓ no internal structure
  - ✓ $E_{collision} = 2\ E_{beam}$
  - ✓ Pros
    - Probe precise mass
      - Precision measurements
    - Clean!
  - ✓ Cons
    - Only one $E_{collision}$ at a time
    - limited by synchrotron radiation

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

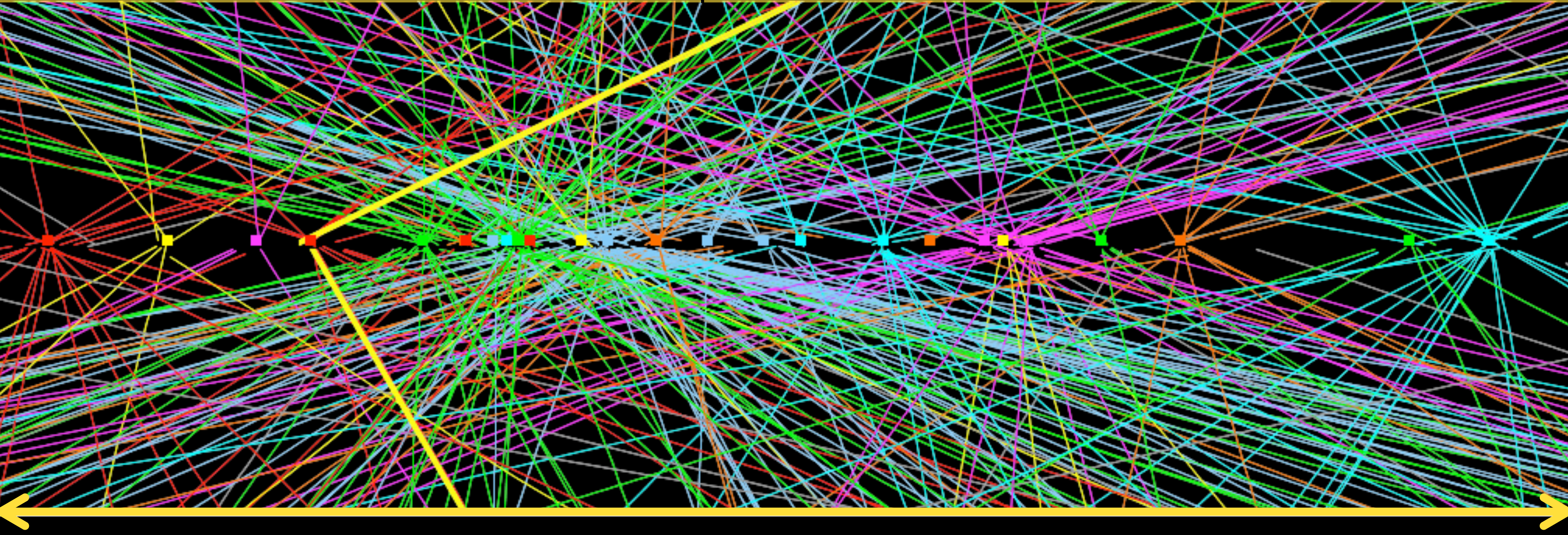
ALEPH @ LEP



ATLAS @ LHC



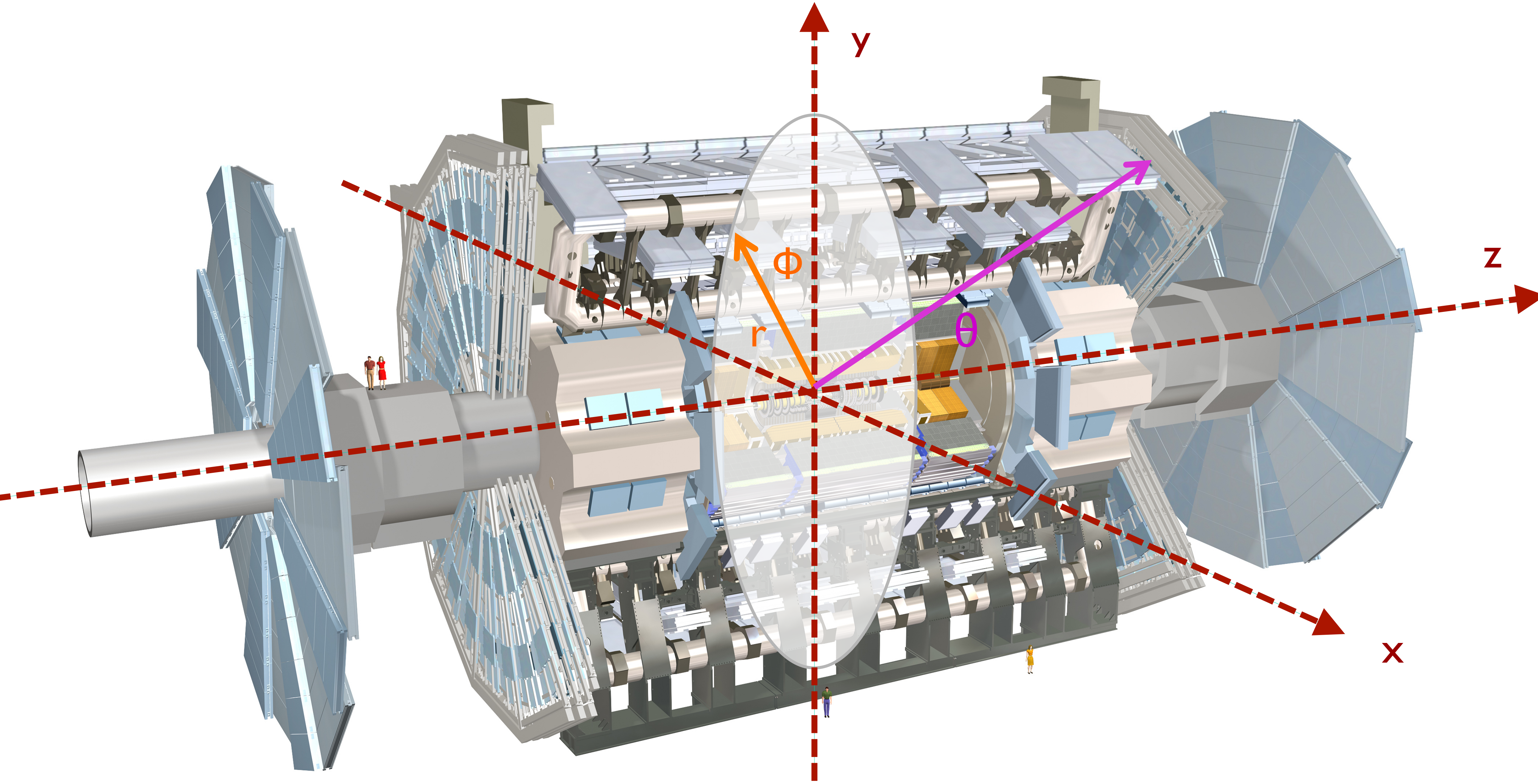
Z→μμ event with 25 reconstructed vertices



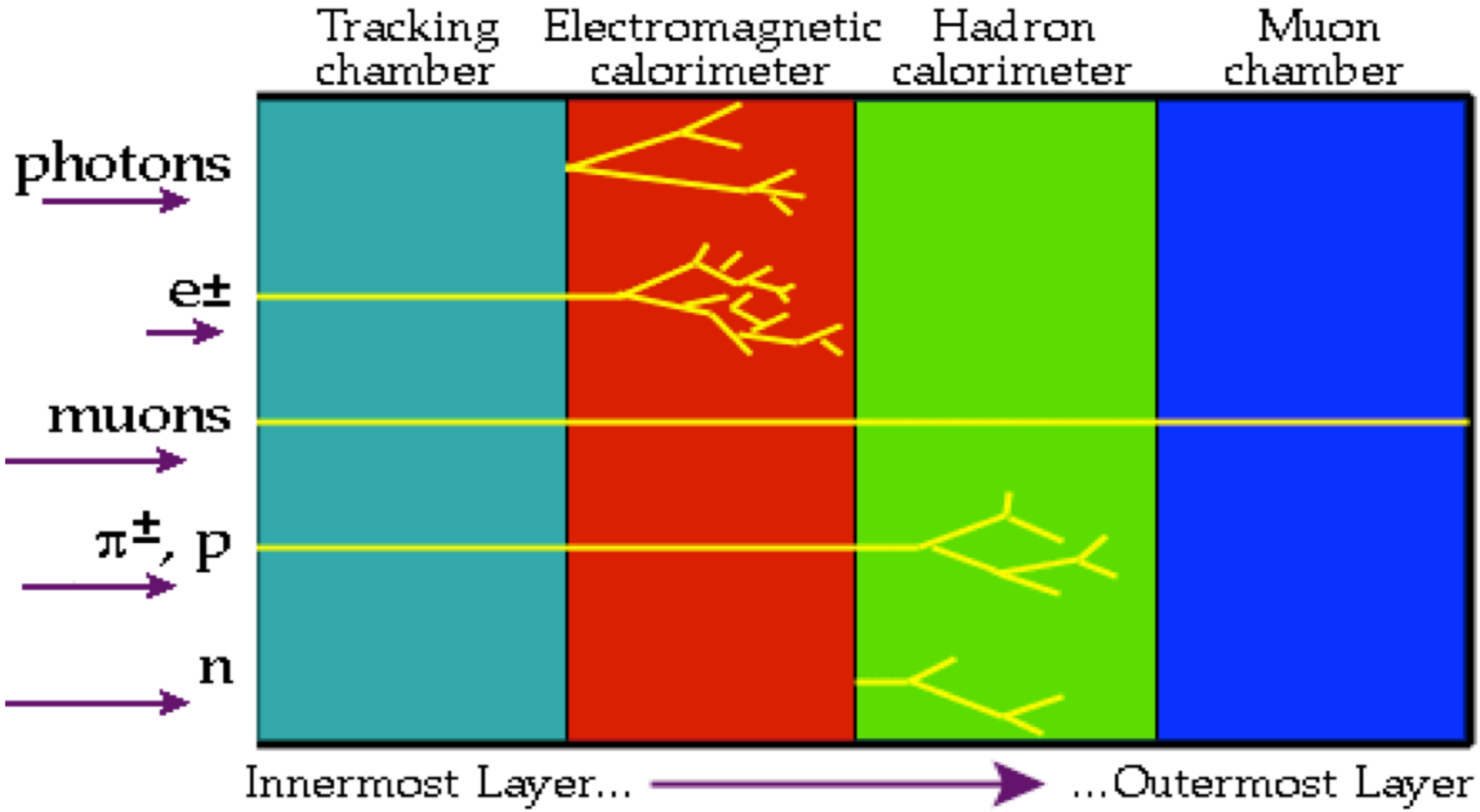
April 15th, 2012

~5 cm

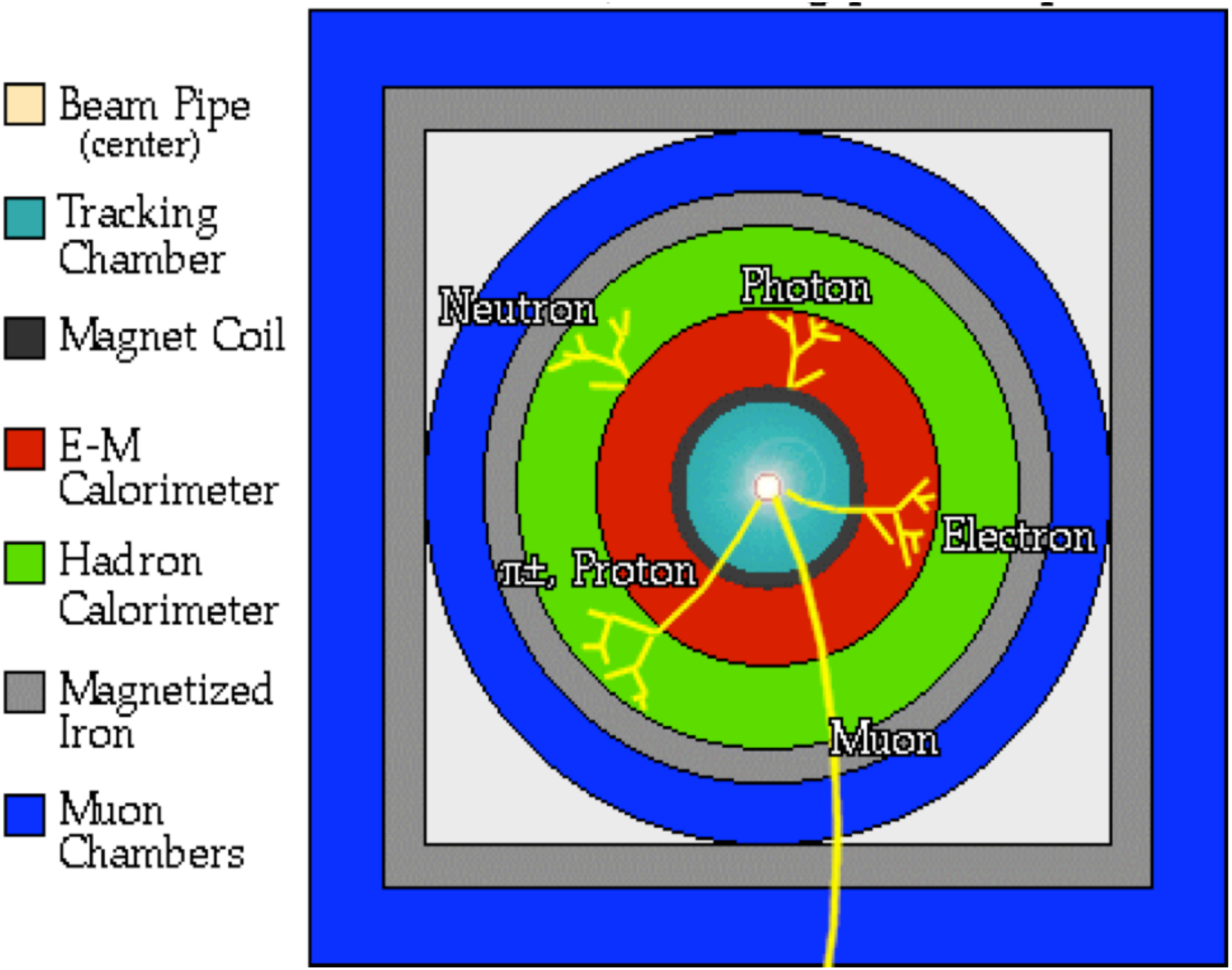
Collider experiment coordinates



How do we “see” particles?

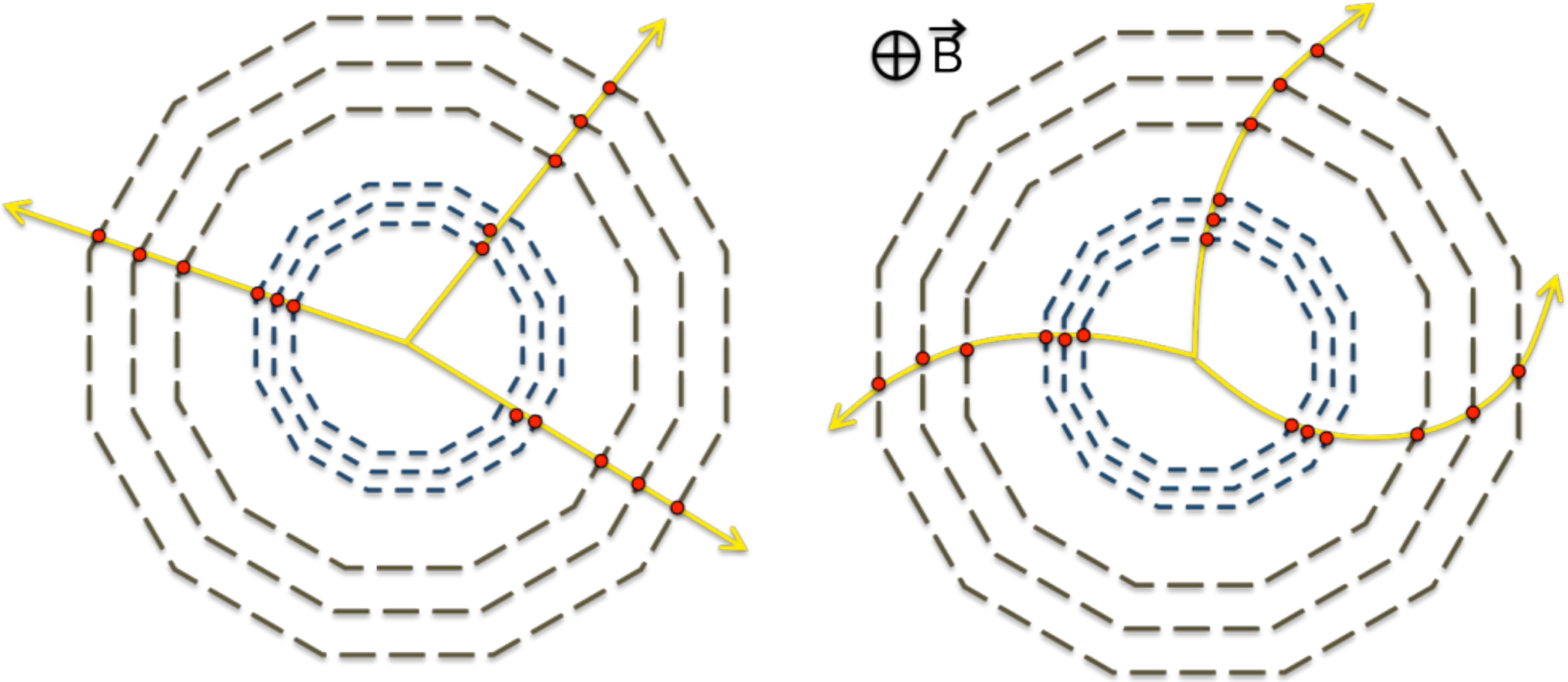


How do we “see” particles?



Magnetic spectrometer

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



Magnetic spectrometer

Charged particle in
magnetic field

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

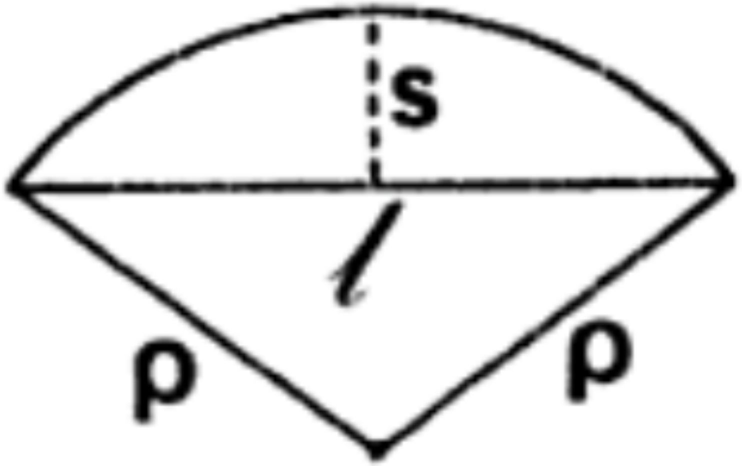
If the field is constant and we neglect presence of matter, momentum magnitude is constant with time, trajectory is helical

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

Actual trajectory differ from exact helix because of:

- magnetic field inhomogeneity
- particle energy loss (ionization, multiple scattering)

Momentum measurement



s = sagitta

l = chord

ρ = radius

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

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

Momentum resolution due to measurement error

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

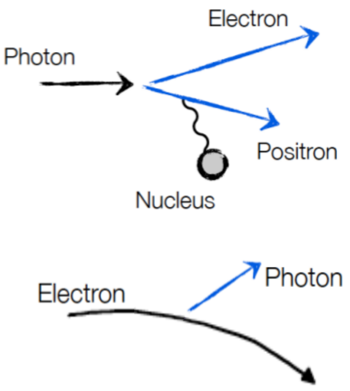
Momentum resolution gets worse for larger momenta

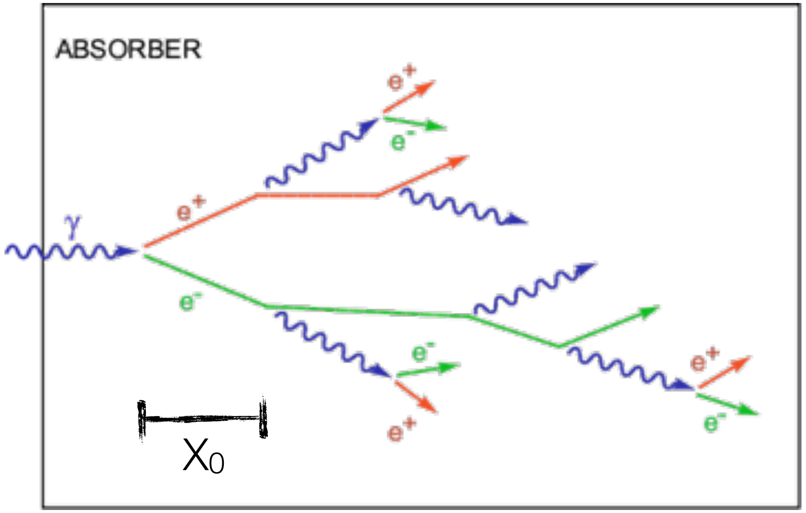
resolution is improved faster by increasing L then B

Electromagnetic showers

Dominant processes
at high energies ...

Photons : Pair production
Electrons : Bremsstrahlung





Pair production:

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

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

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

Absorption coefficient:

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

Bremsstrahlung:

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

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

After passage of one X_0 electron has only (1/e)th of its primary energy ...
[i.e. 37%]

Critical energy:

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

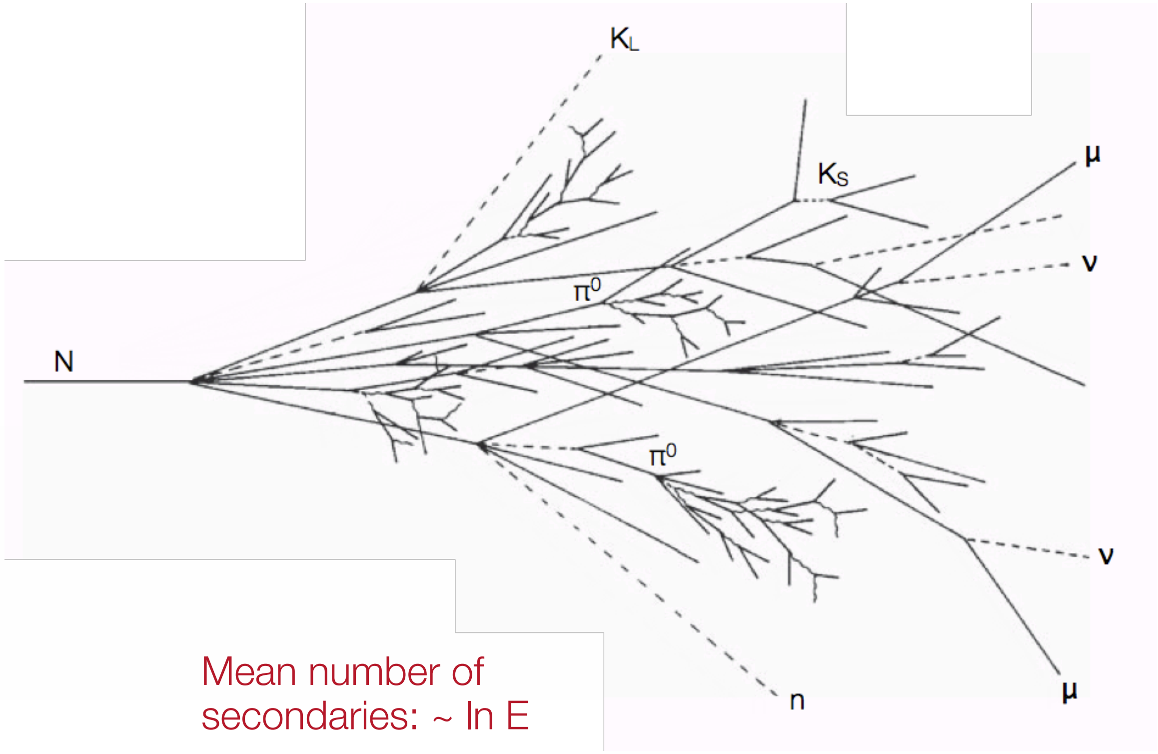
Hadronic showers

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



Mean number of secondaries: ~ ln E

Typical transverse momentum: p_t ~ 350 MeV/c

Substantial electromagnetic fraction

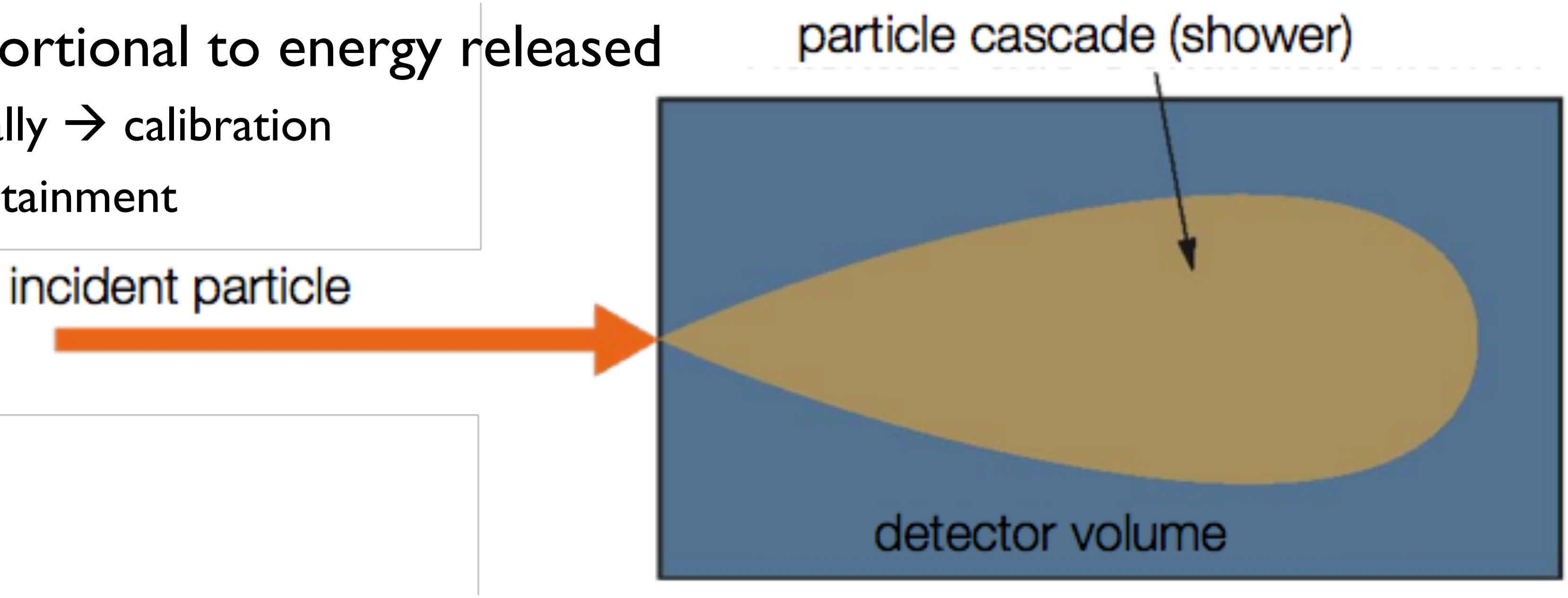
$f_{em} \sim \ln E$
[variations significant]

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%]

Calorimetry

- **Energy measurement via total absorption of particles**
- **Principles of operation**
  - ✓ Incoming particle initiates particle shower
    - Electromagnetic, hadronic
    - Shower properties depend on particle type and detector material
  - ✓ Energy is deposited in active regions
    - Heat, ionization, atom excitation (scintillation), Cherenkov light
    - Different calorimeters use different kind of signals
  - ✓ Signal is proportional to energy released
    - Proportionally → calibration
    - Shower containment



Energy resolution

Energy resolution:

e.g. inhomogeneities
shower leakage

e.g. electronic noise
sampling fraction variations

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

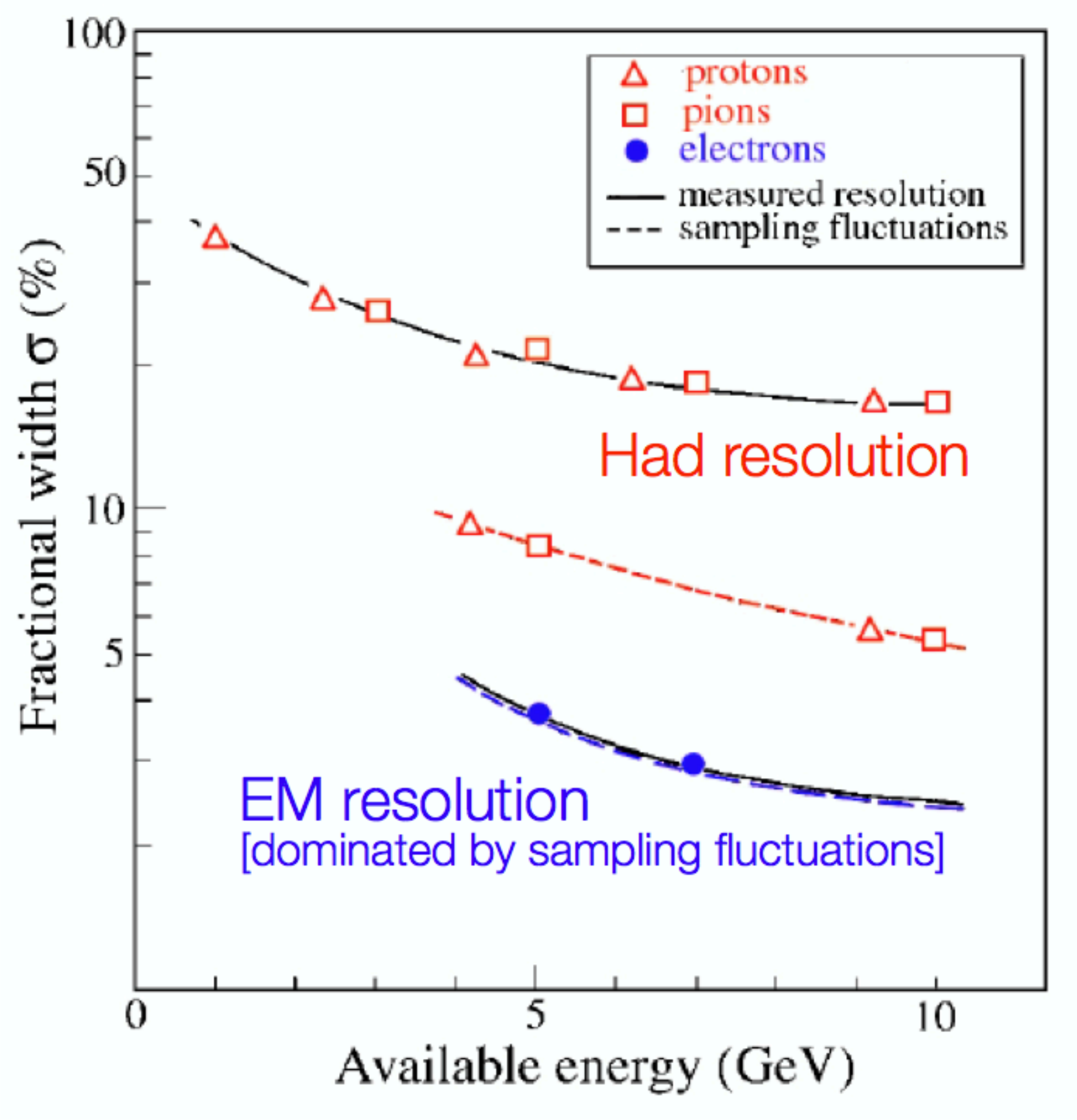
Fluctuations:

- 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 %

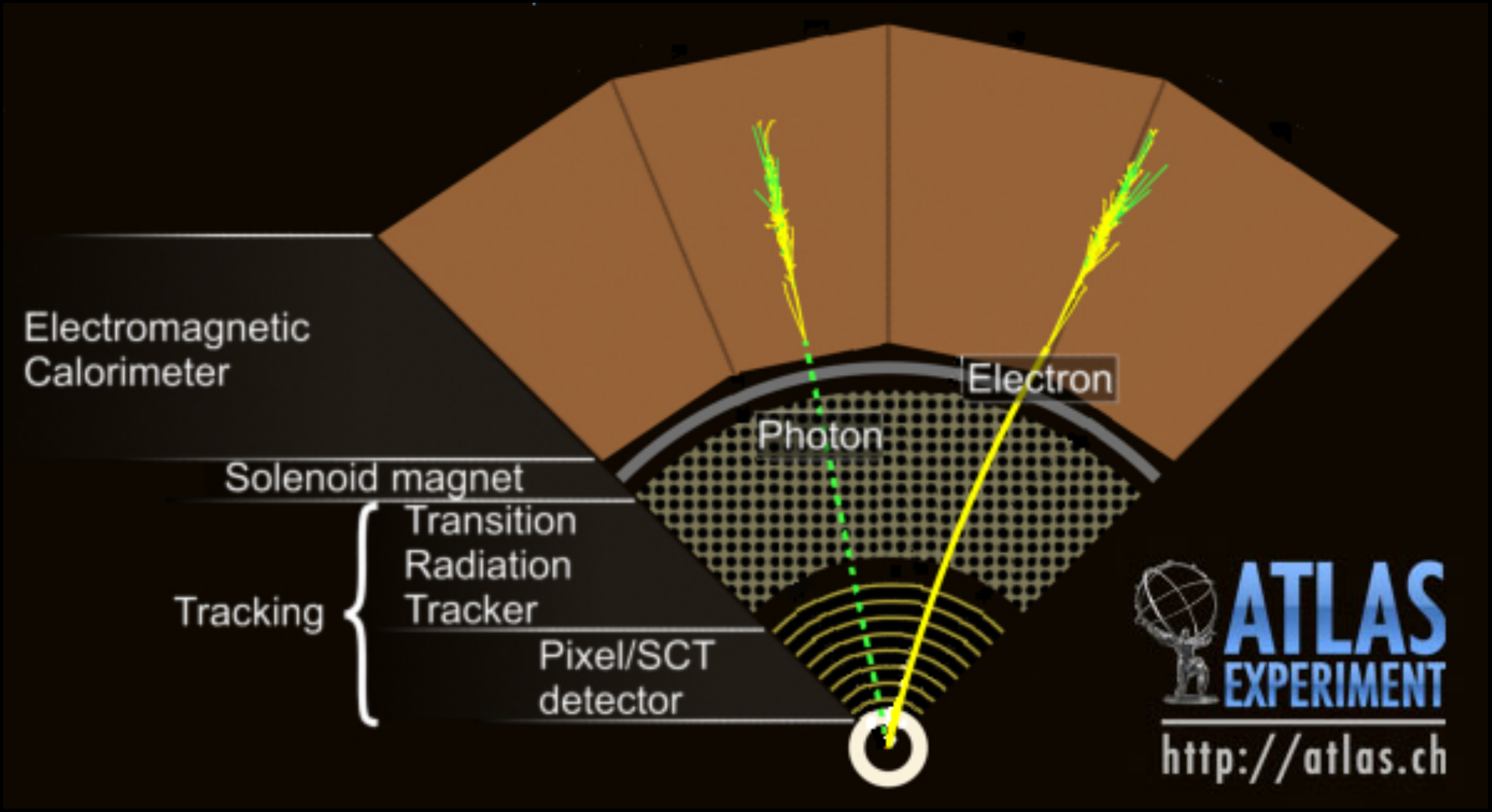
Resolution: EM vs. HAD



[AFM Collaboration]

Sampling fluctuations only minor contribution to hadronic energy resolution

Particle identification with tracker and calo



A typical HEP calorimetry system

Typical Calorimeter: two components ...

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

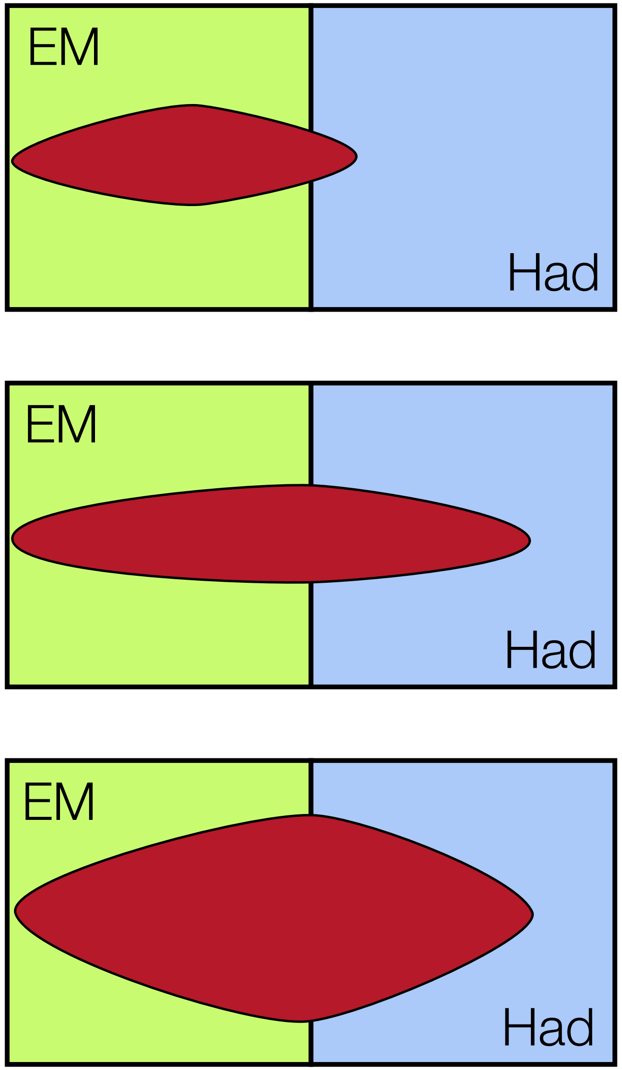
Different setups chosen for
optimal energy resolution ...

But:

Hadronic energy measured in
both parts of calorimeter ...

Needs careful consideration of
different response ...

Schematic of a
typical HEP calorimeter

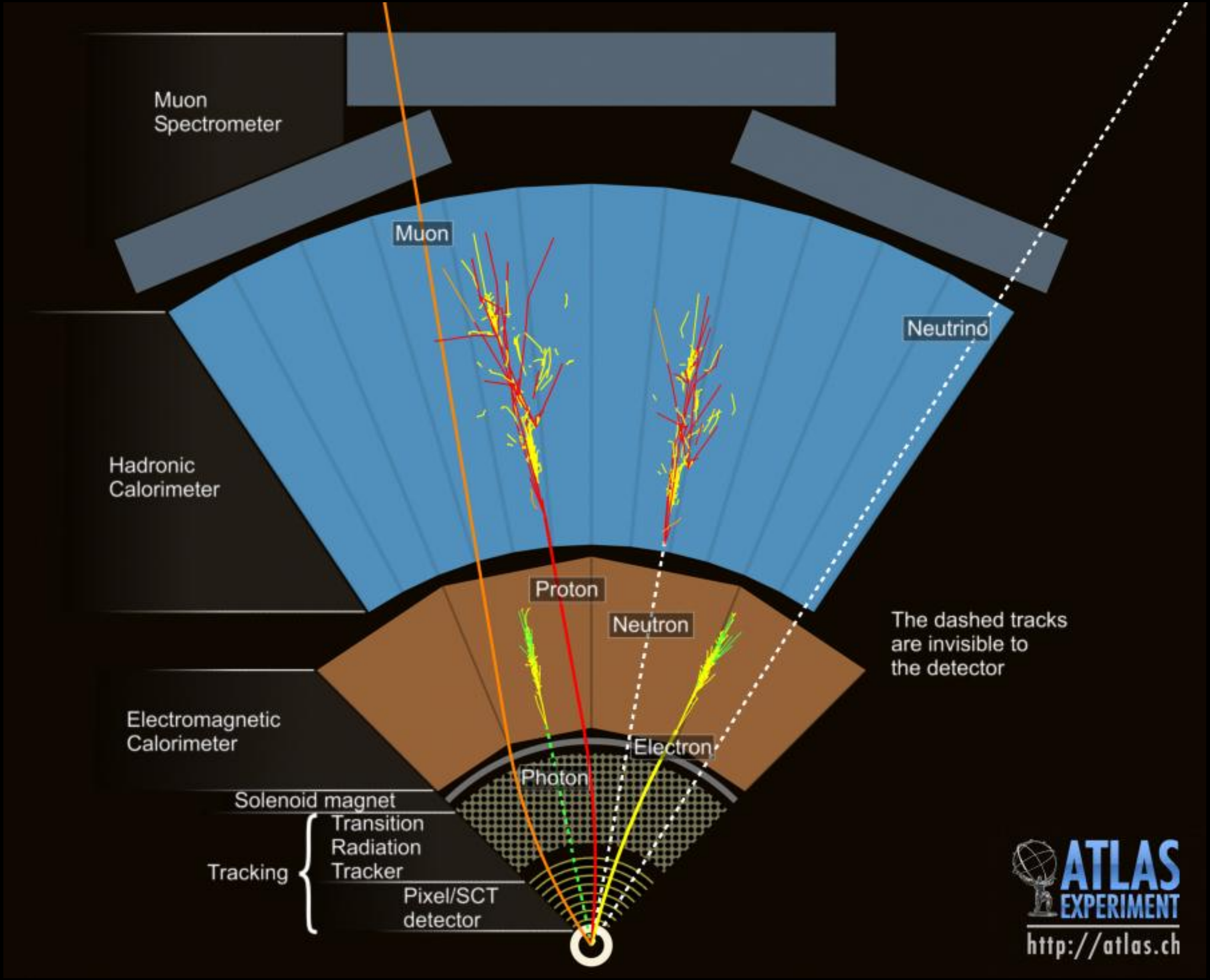


Electrons
Photons

Taus
Hadrons

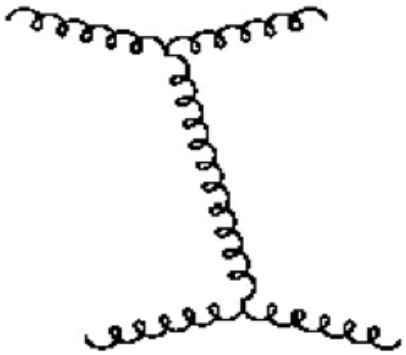
Jets

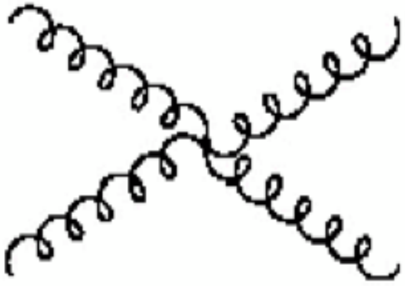
How do we "see" particles?



A few words on QCD

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



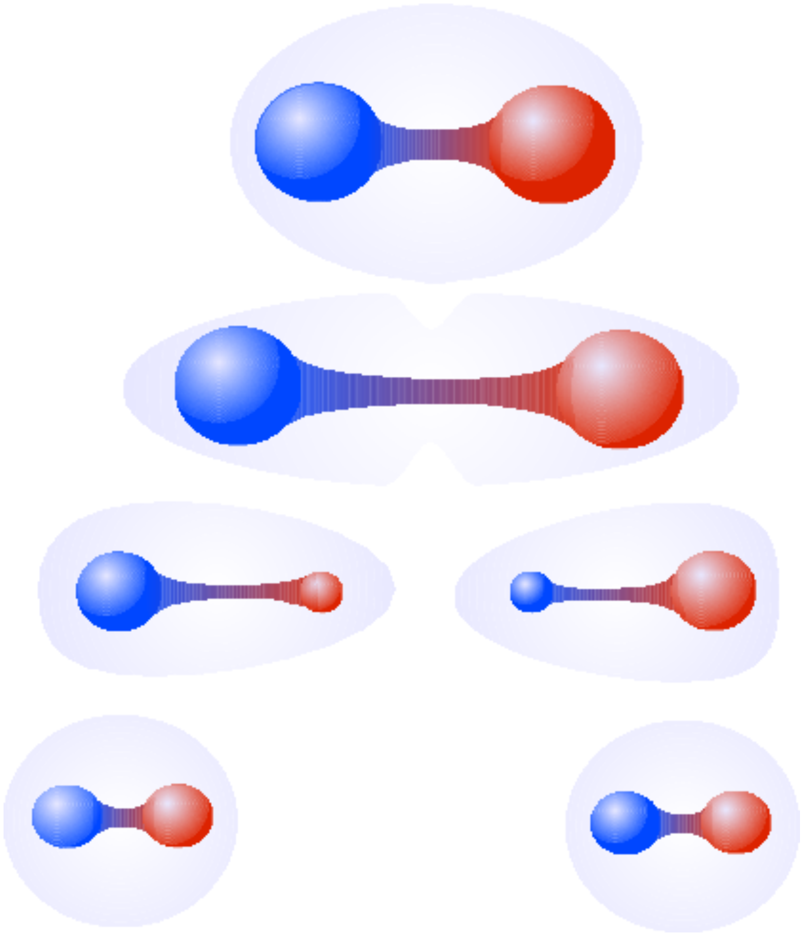


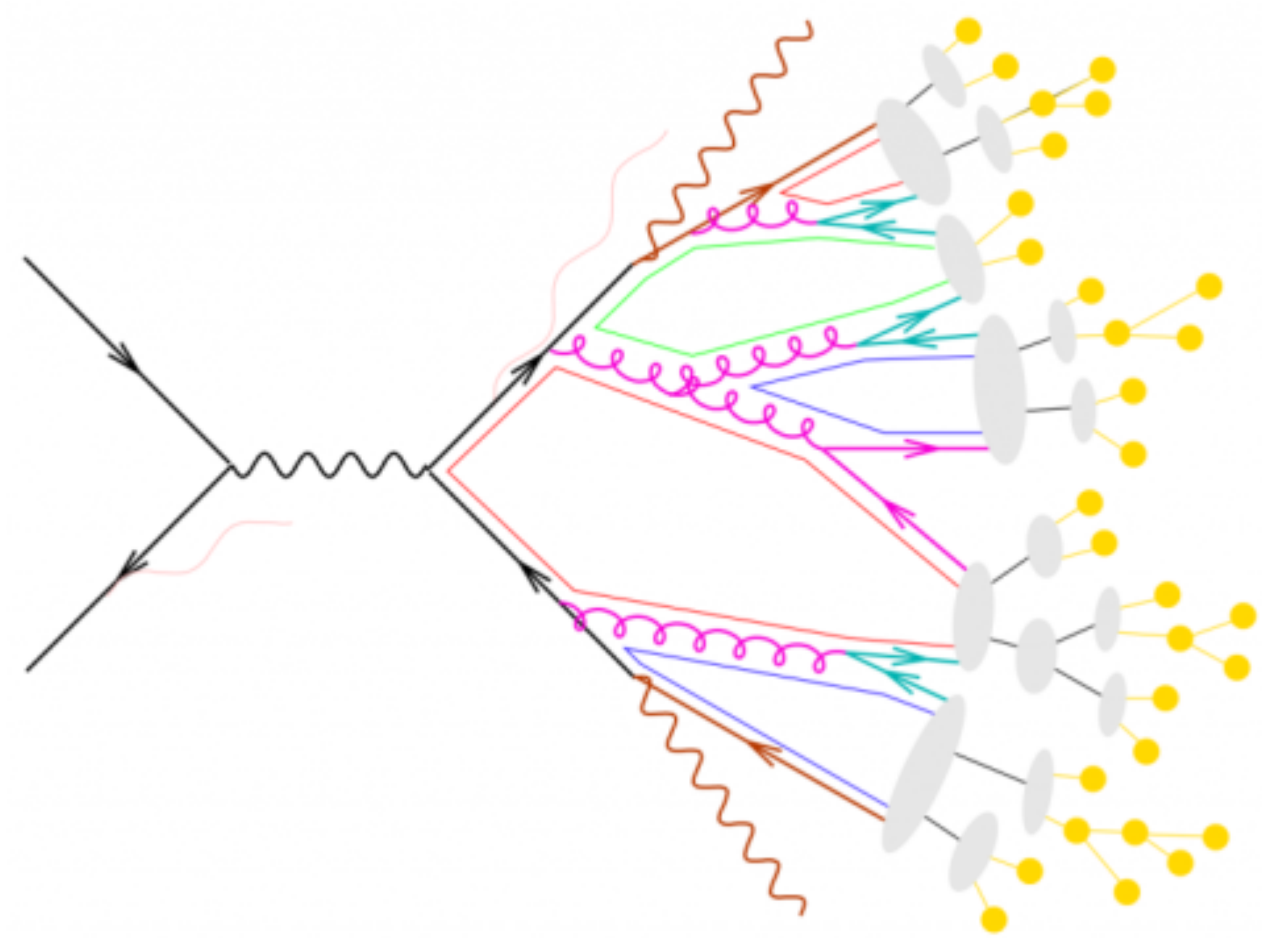
- **Principle of asymptotic freedom**
  - ✓ At short distances strong interactions are weak
    - Quarks and gluons are essentially free particles
    - Perturbative regime (can calculate!)
  - ✓ At large distances, higher-order diagrams dominate
    - Interaction is very strong
    - Perturbative regime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

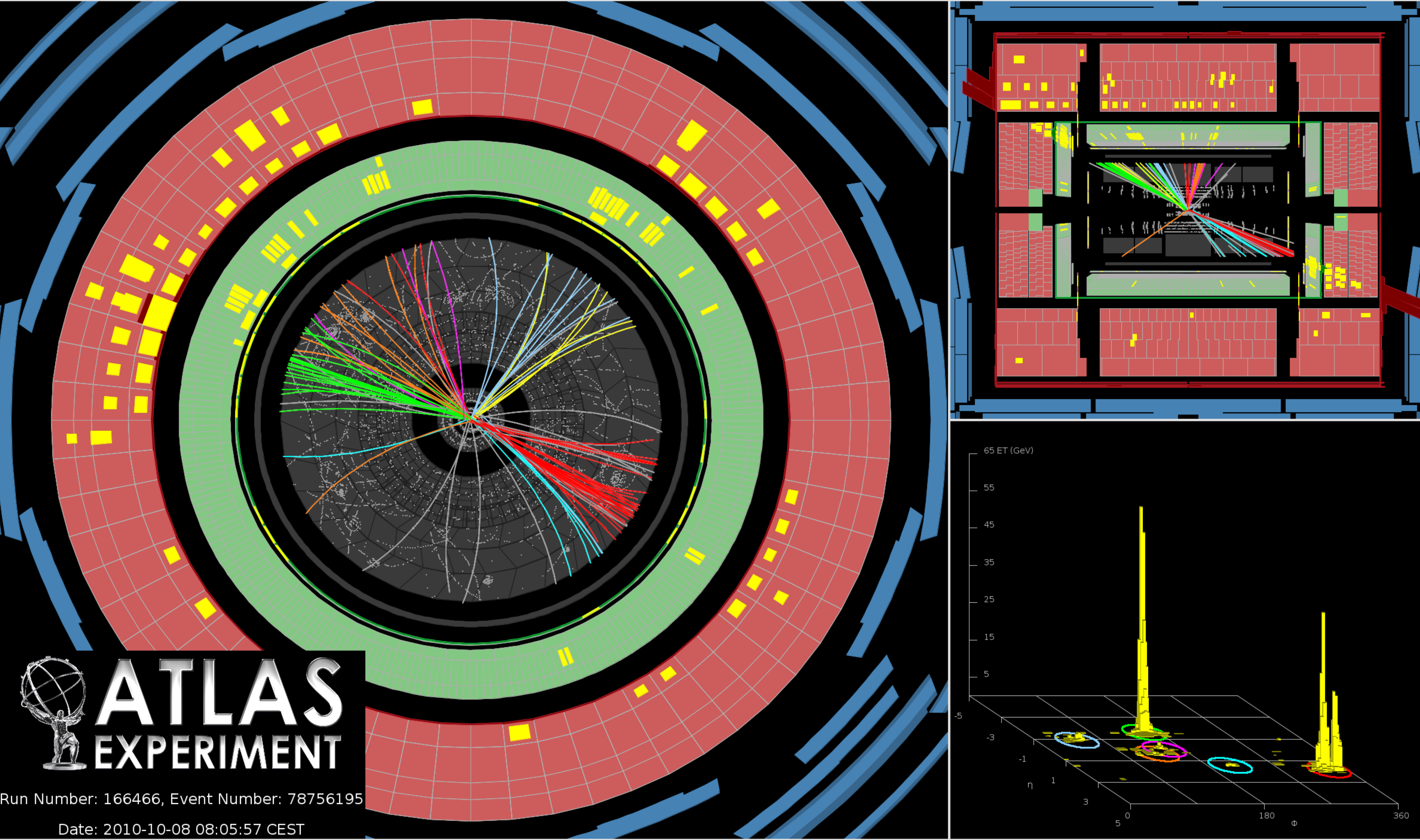
quark-quark effective potential

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

Confinement, hadronization, jets







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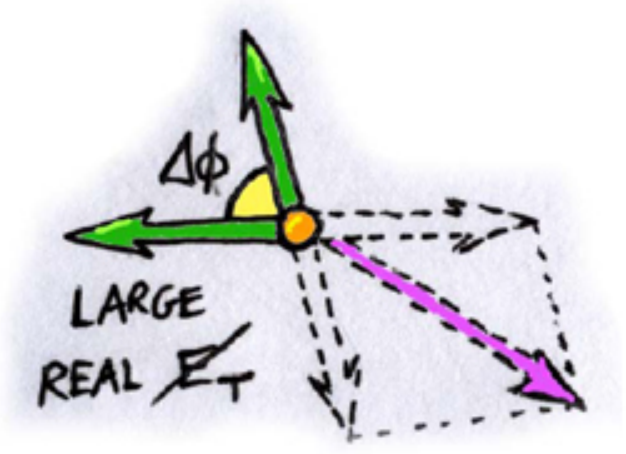
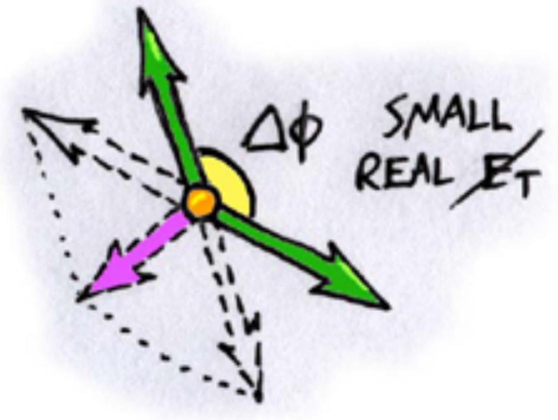
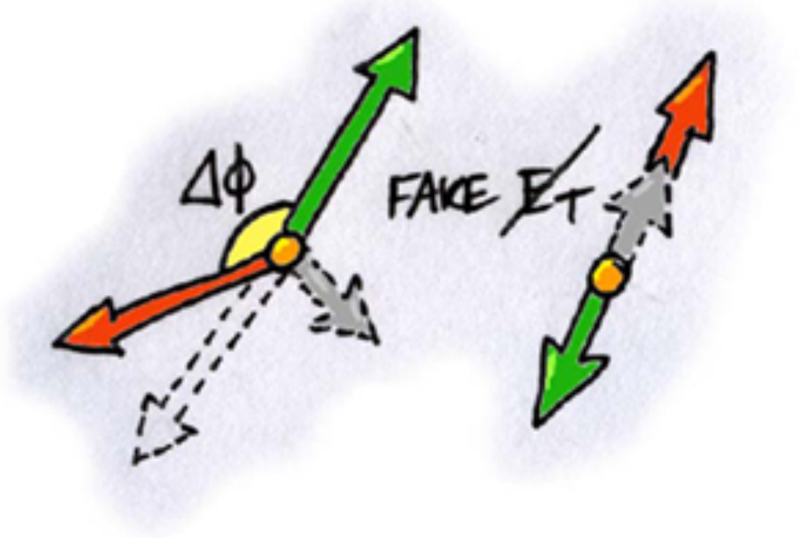
Date: 2010-10-08 08:05:57 CEST

Neutrino (and other invisible particles) at colliders

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

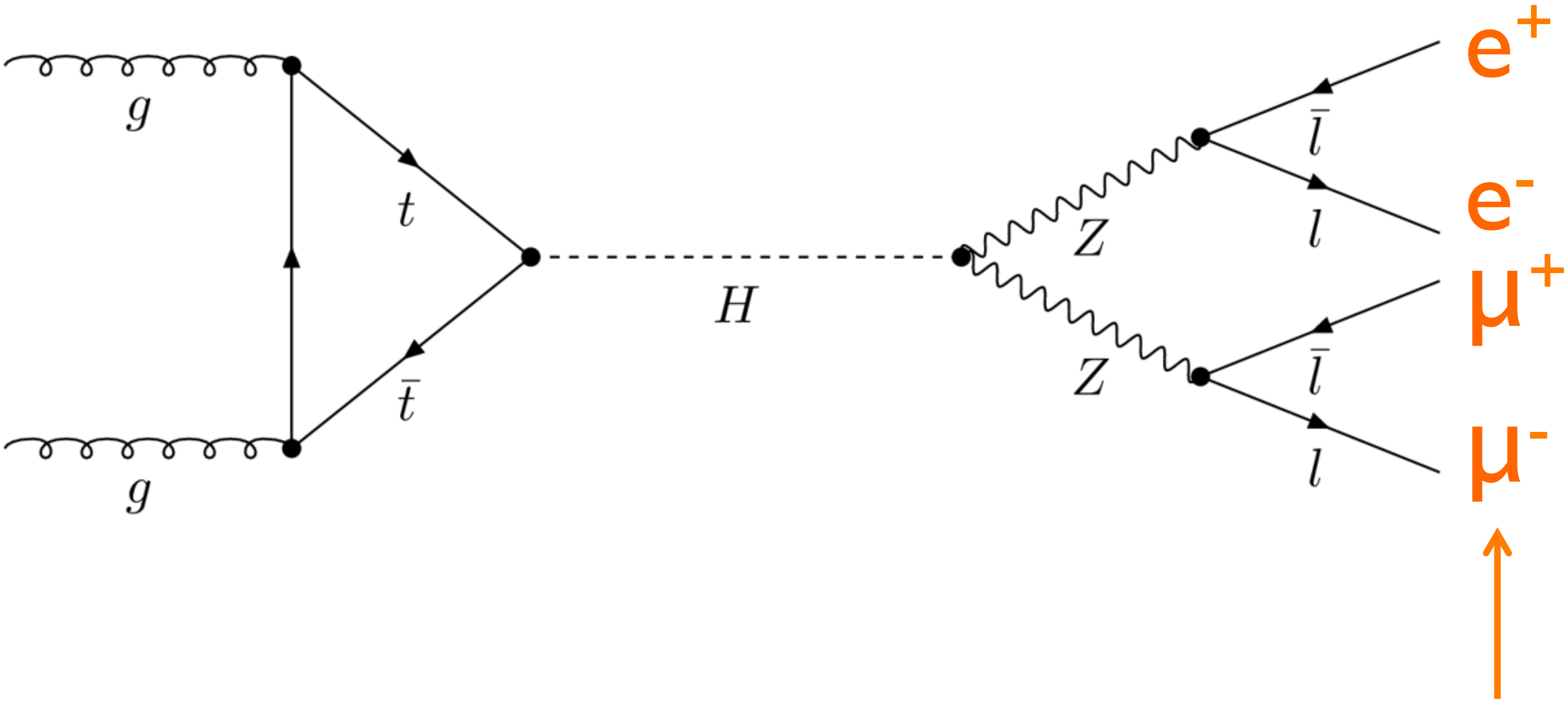






- Missing energy resolution depends on
  - ✓ Detector acceptance
  - ✓ Detector noise and resolution (e.g. calorimeters)

There is no Higgs-boson detector!

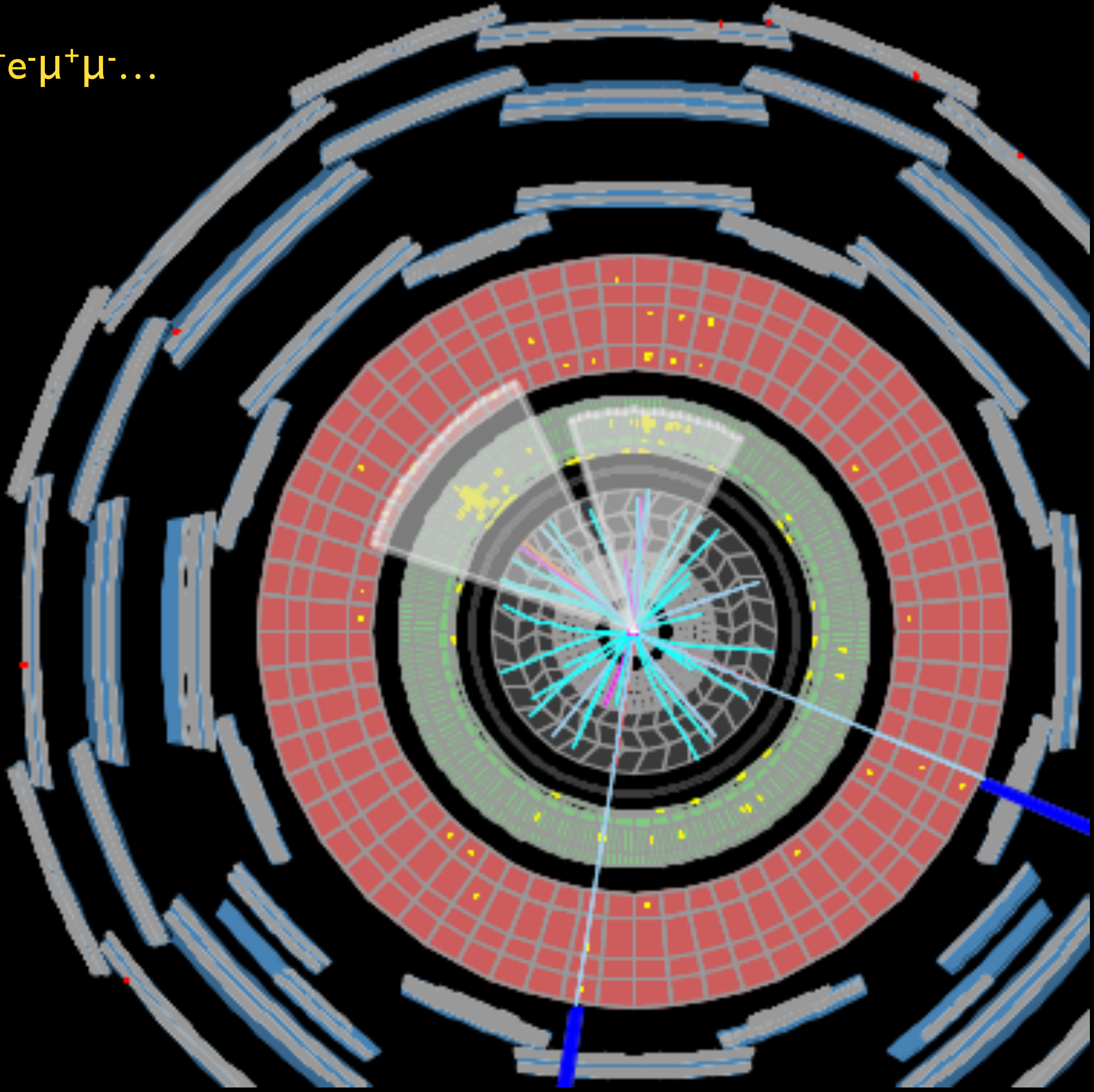


this is what we are looking for…

Step 1: find events with the right ingredients

We are looking for $e^+e^-\mu^+\mu^-$…

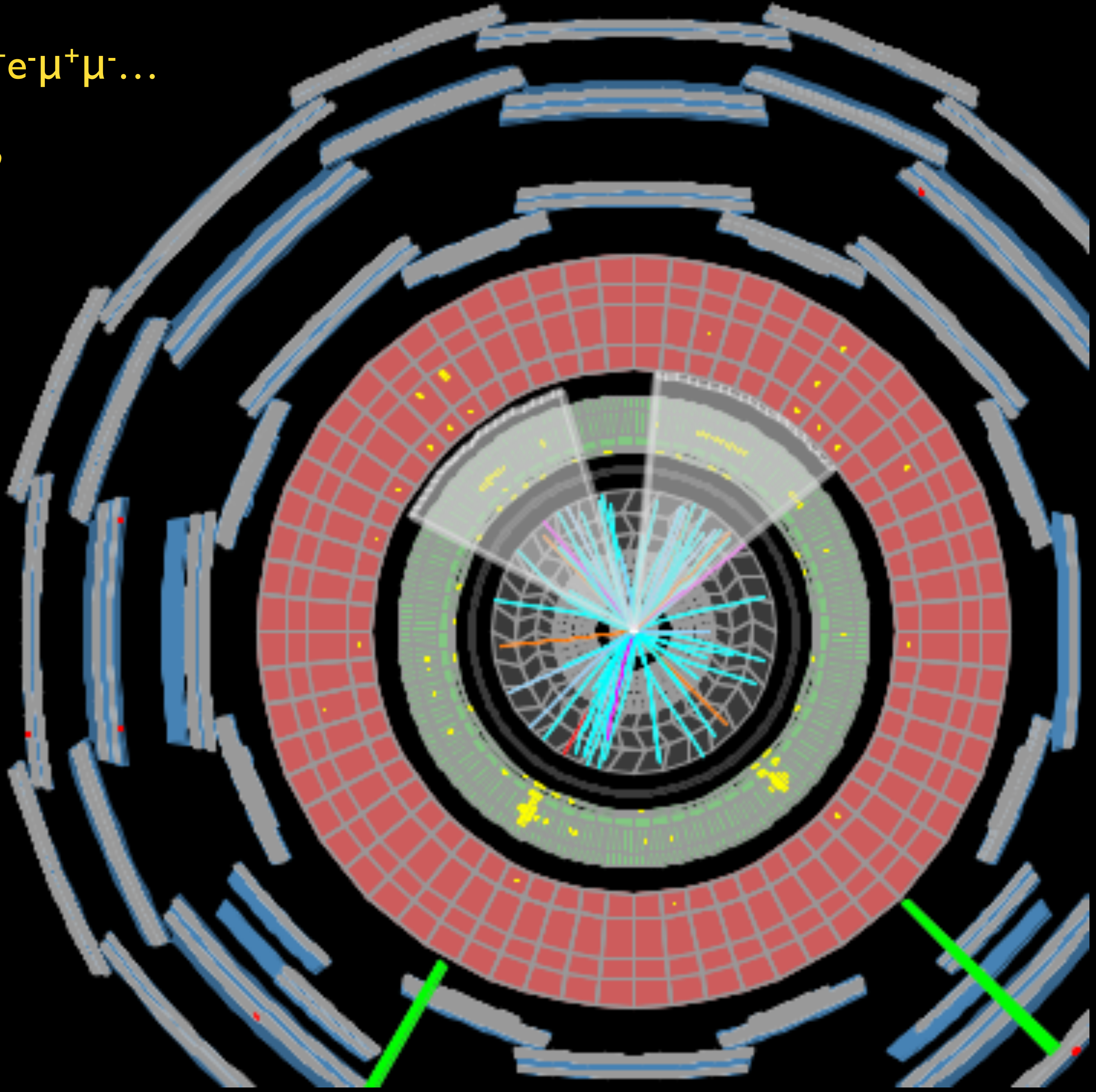
Is this event ok?



Step 1: find events with the right ingredients

We are looking for $e^+e^-\mu^+\mu^-$…

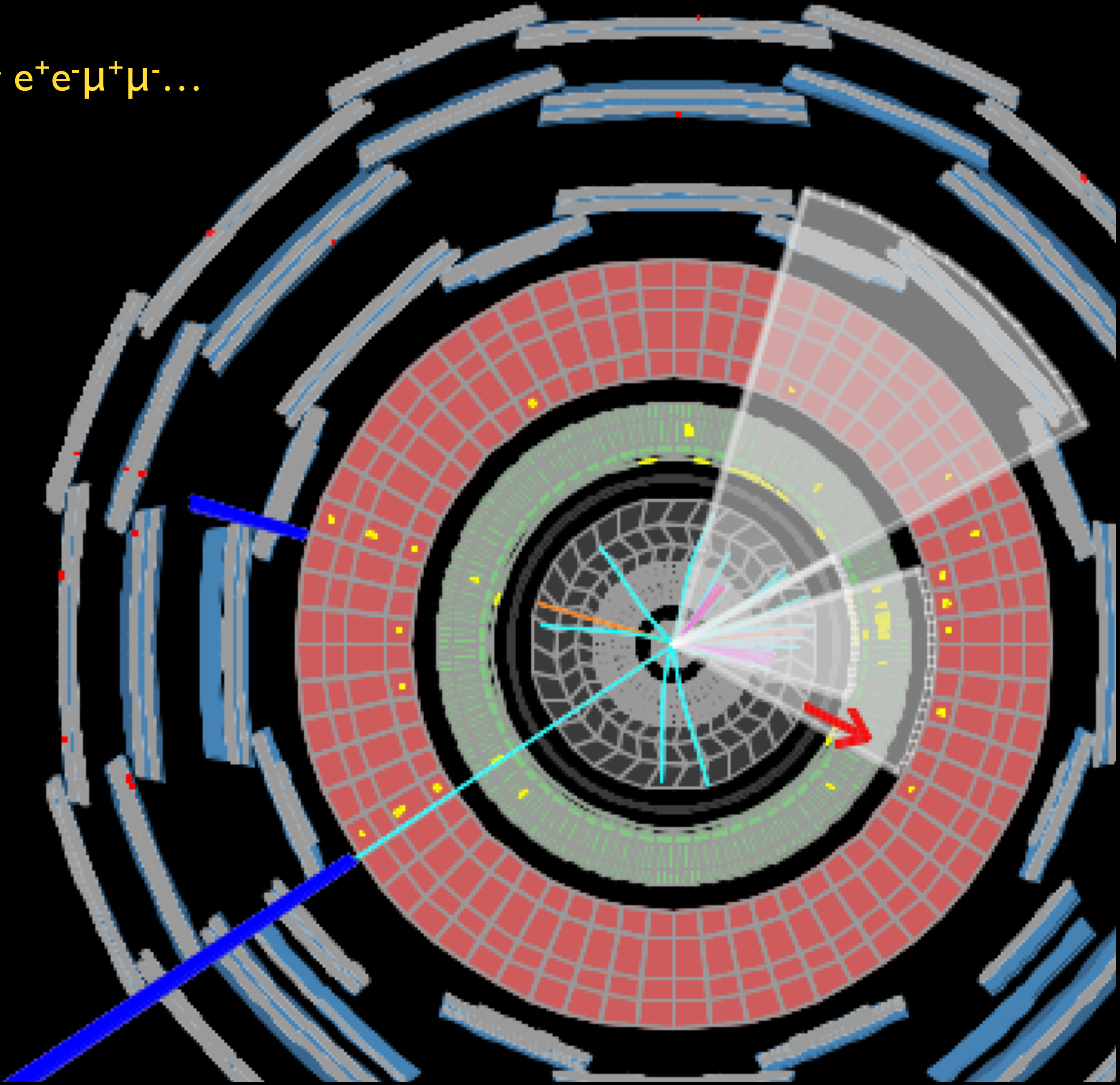
What about this one?



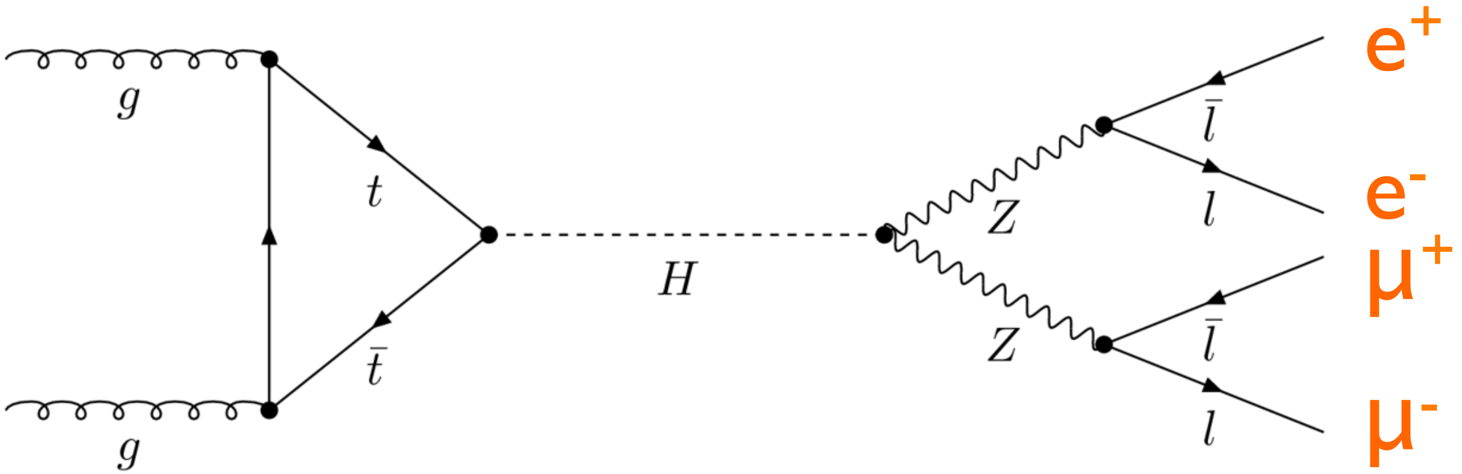
Step 1: find events with the right ingredients

We are looking for $e^+e^-\mu^+\mu^-$…

And this one?

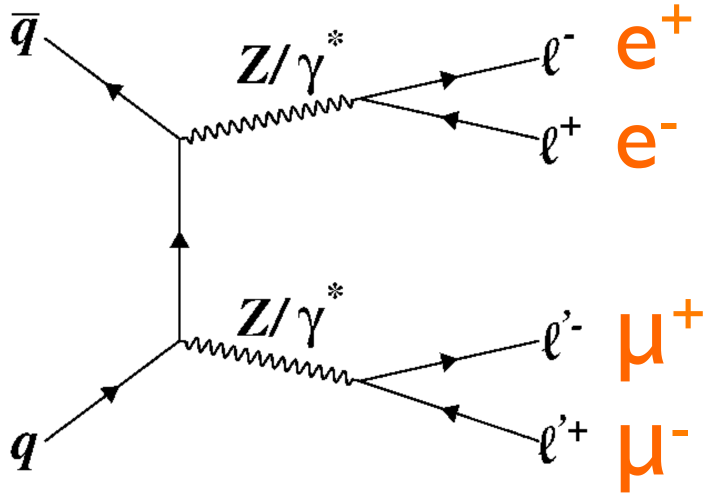


Signal and background



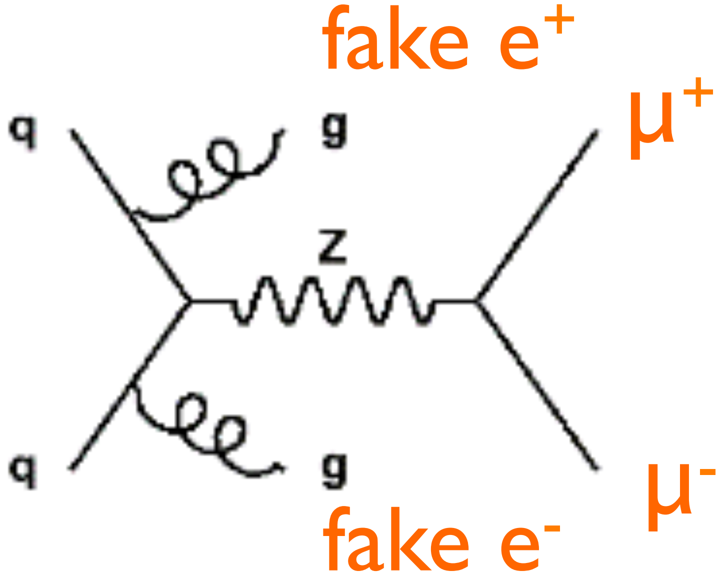
Irreducible background

The final state is exactly the same, but it does not come from the particle you are looking for



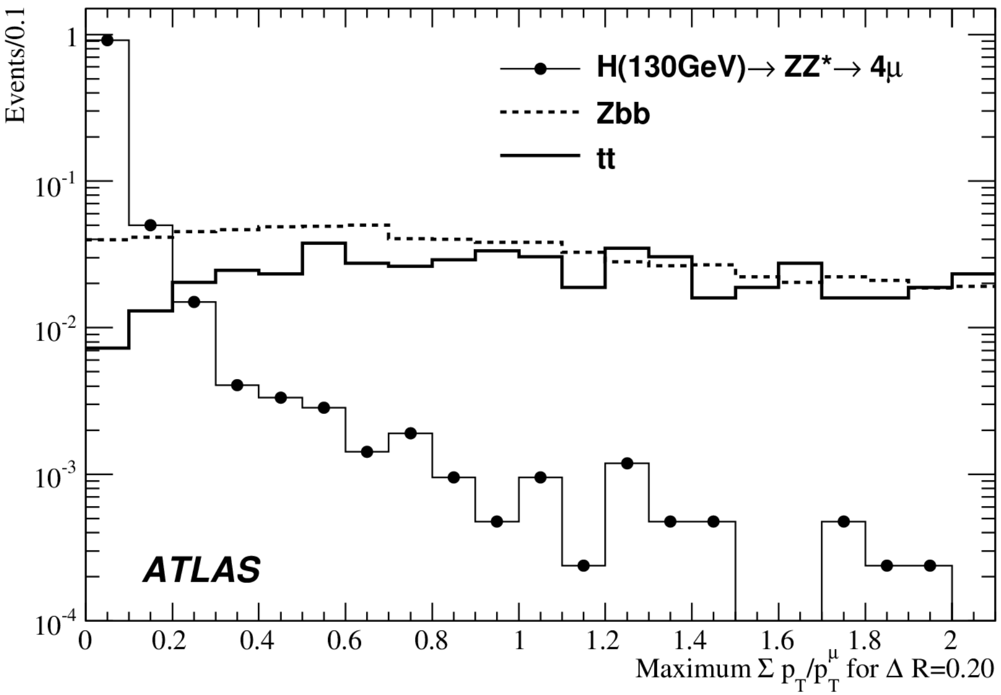
Reducible background

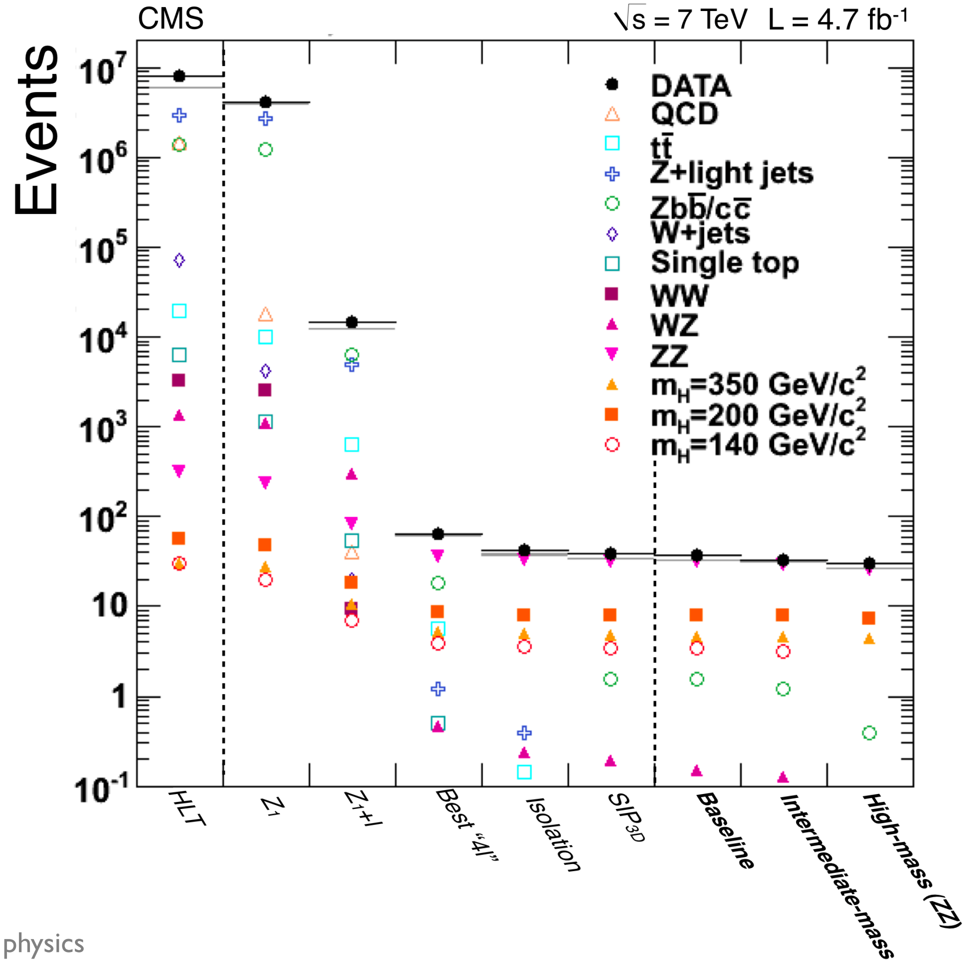
The final state looks like the same, but some f the particle fakes what you are looking for



Selections

- Cut on particle properties to reduce reducible background
  - ✓ Shower shapes, track properties, …
- Cut on event properties to distinguish signal from background
  - ✓ Particle kinematics, decay kinematics event shape, …
- Try to keep signal while reducing background!
  - ✓ Increase S/B

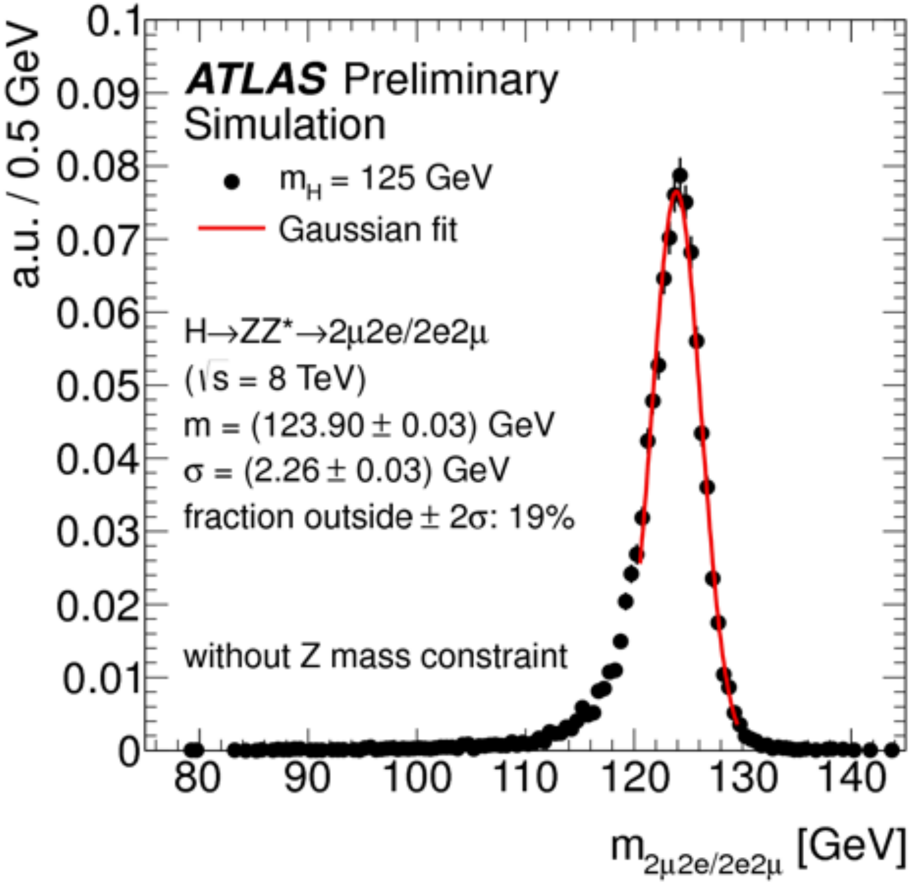


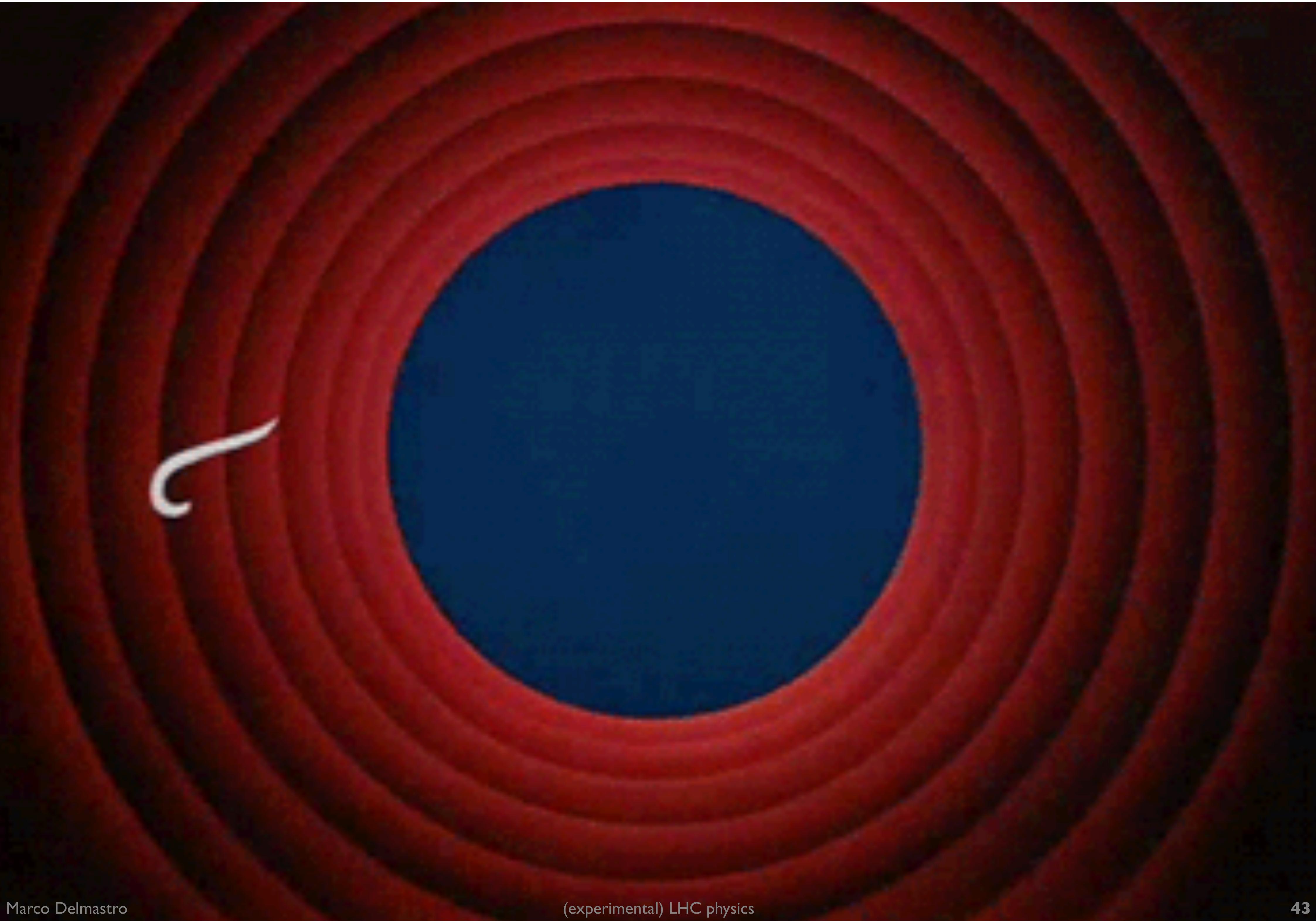


Step 2: reconstruct properties of initial particle

- We have 4 particles…
  - ✓ … with their energy (calorimeters), charge and momentum (tracker)
- Use pairs of opposite sign e^+e^- and $\mu^{+}\mu^{-}$
- Reconstruct invariant mass from the 4 particles

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





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 $\text{GeV}^{-1} = 0.1973$ fm
time	1 $\text{GeV}^{-1} = 6.59 \times 10^{-25}$ s

Relativistic kinematics in a nutshell

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

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

$$E = m\gamma$$

$$t = t_0\gamma$$

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

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

Cross section: magnitude and units

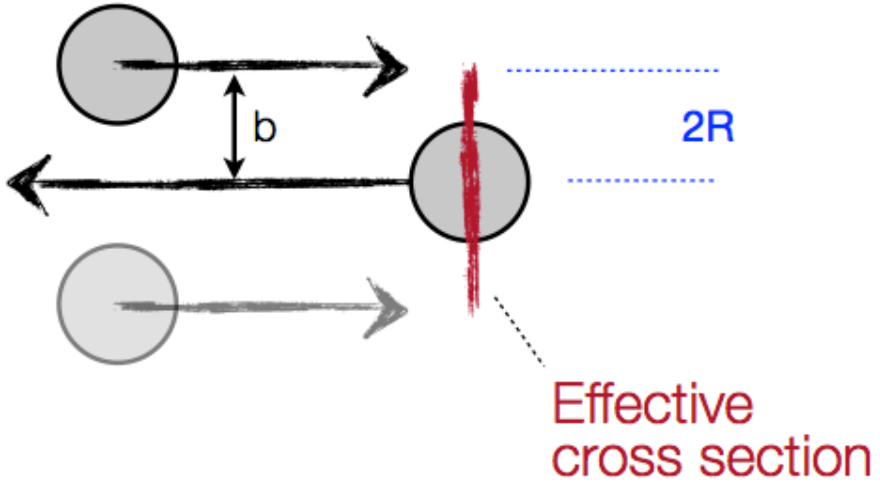
Standard
cross section unit: $[\sigma]$ = mb with 1 mb = 10^{-27} cm^2

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

---

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

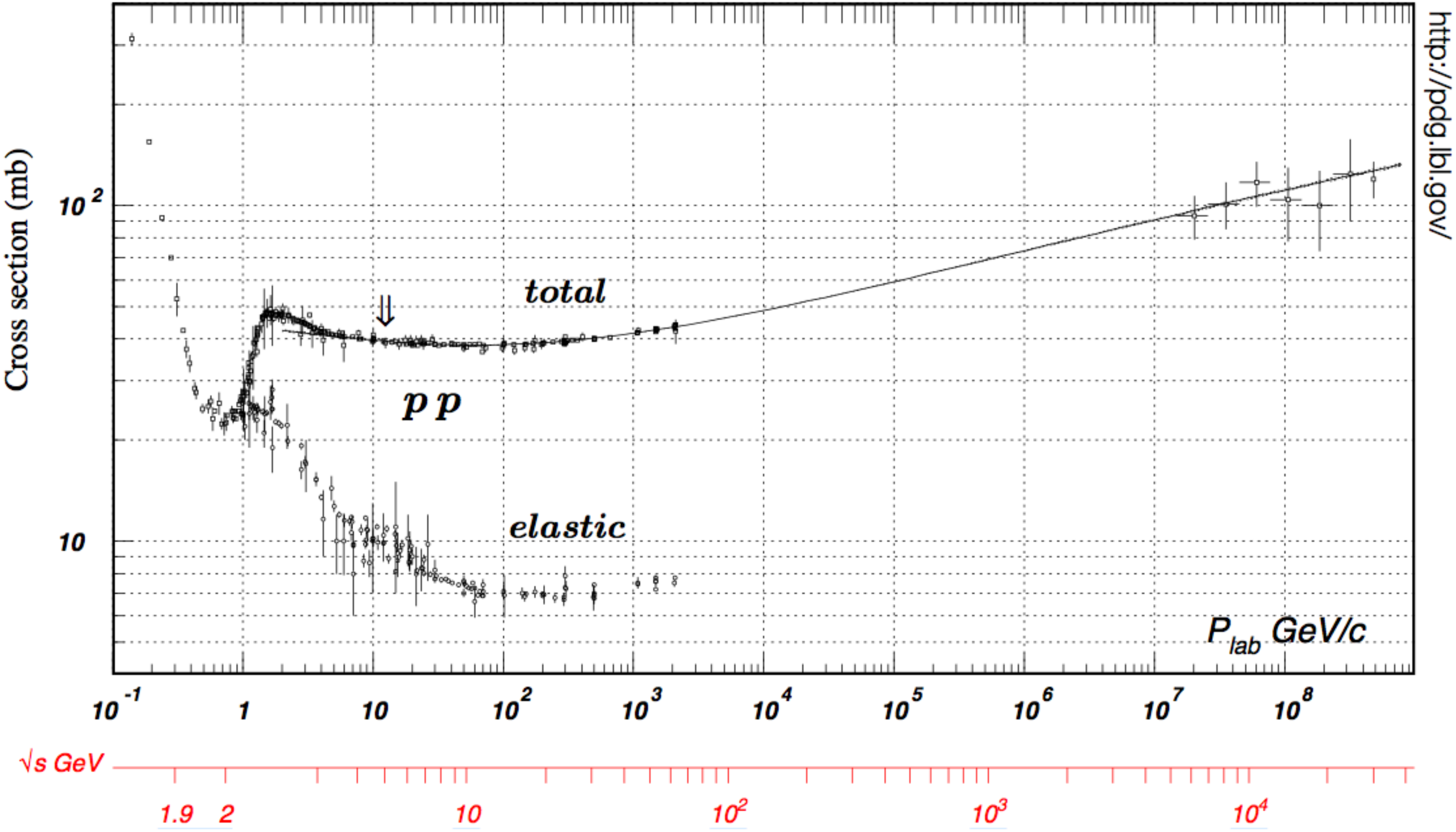
Estimating the
proton-proton cross section:



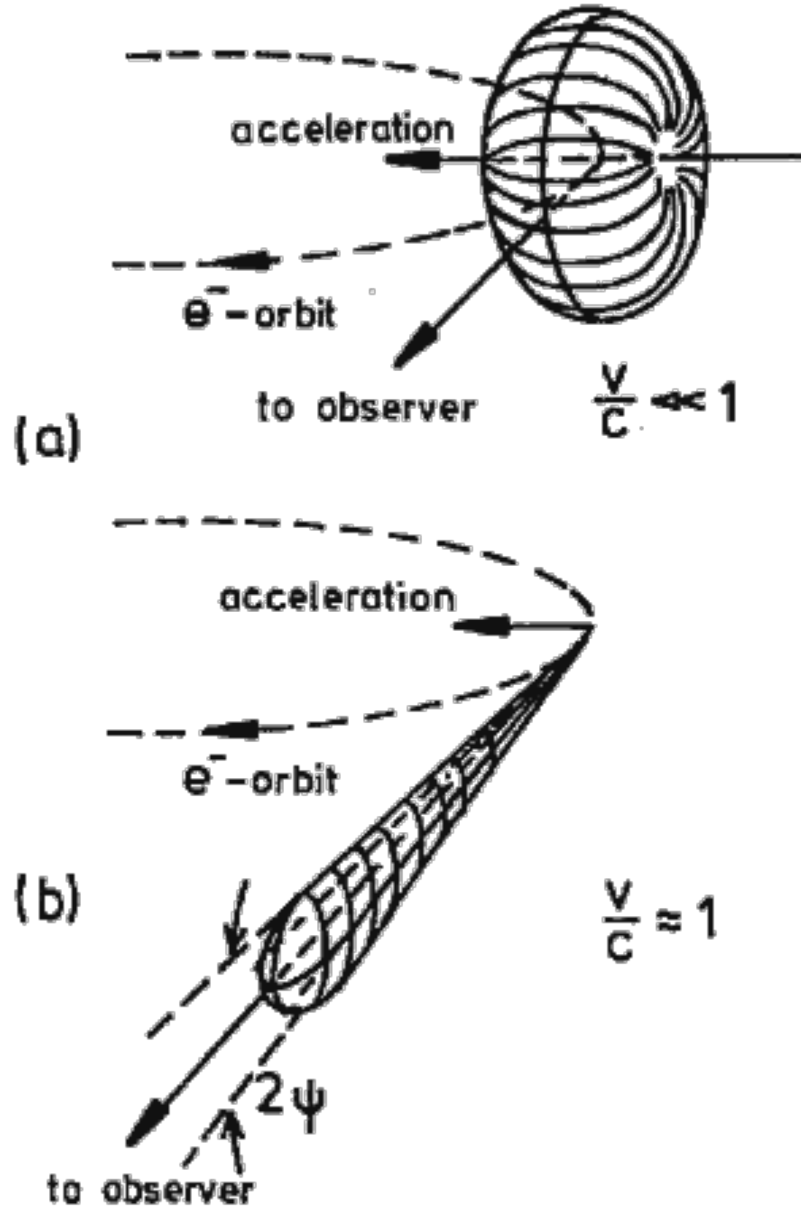
Proton radius: R = 0.8 fm
Strong interactions happens up to b = 2R

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

Proton-proton scattering cross-section



Syncrotron radiation



energy lost per revolution

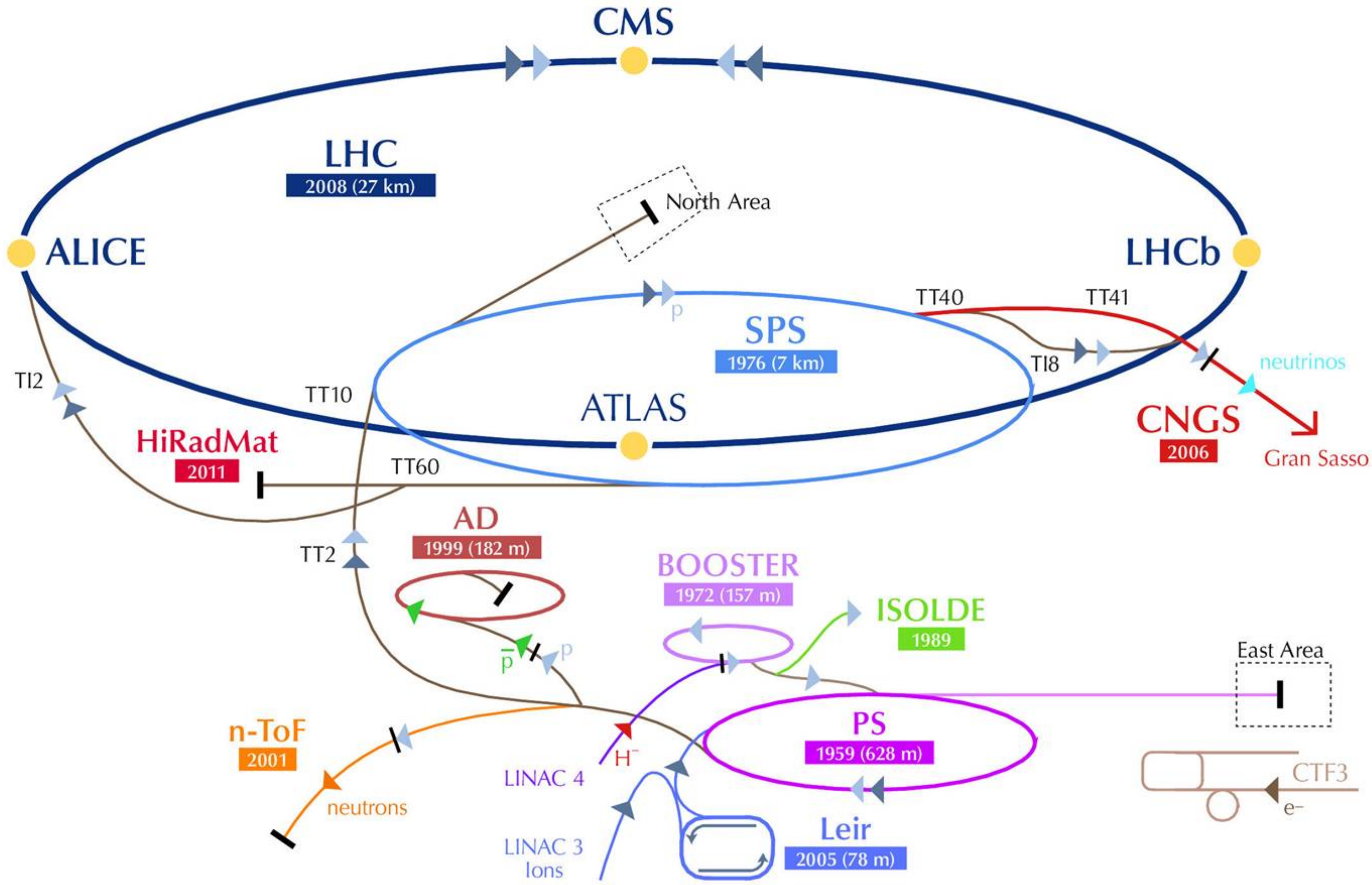
$$\Delta E = \frac{4\pi}{3}\frac{1}{4\pi\epsilon_0}\left(\frac{e^3\beta^3\gamma^4}{R}\right)$$

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



What do we want to measure?

… "stable" particles!

decays?

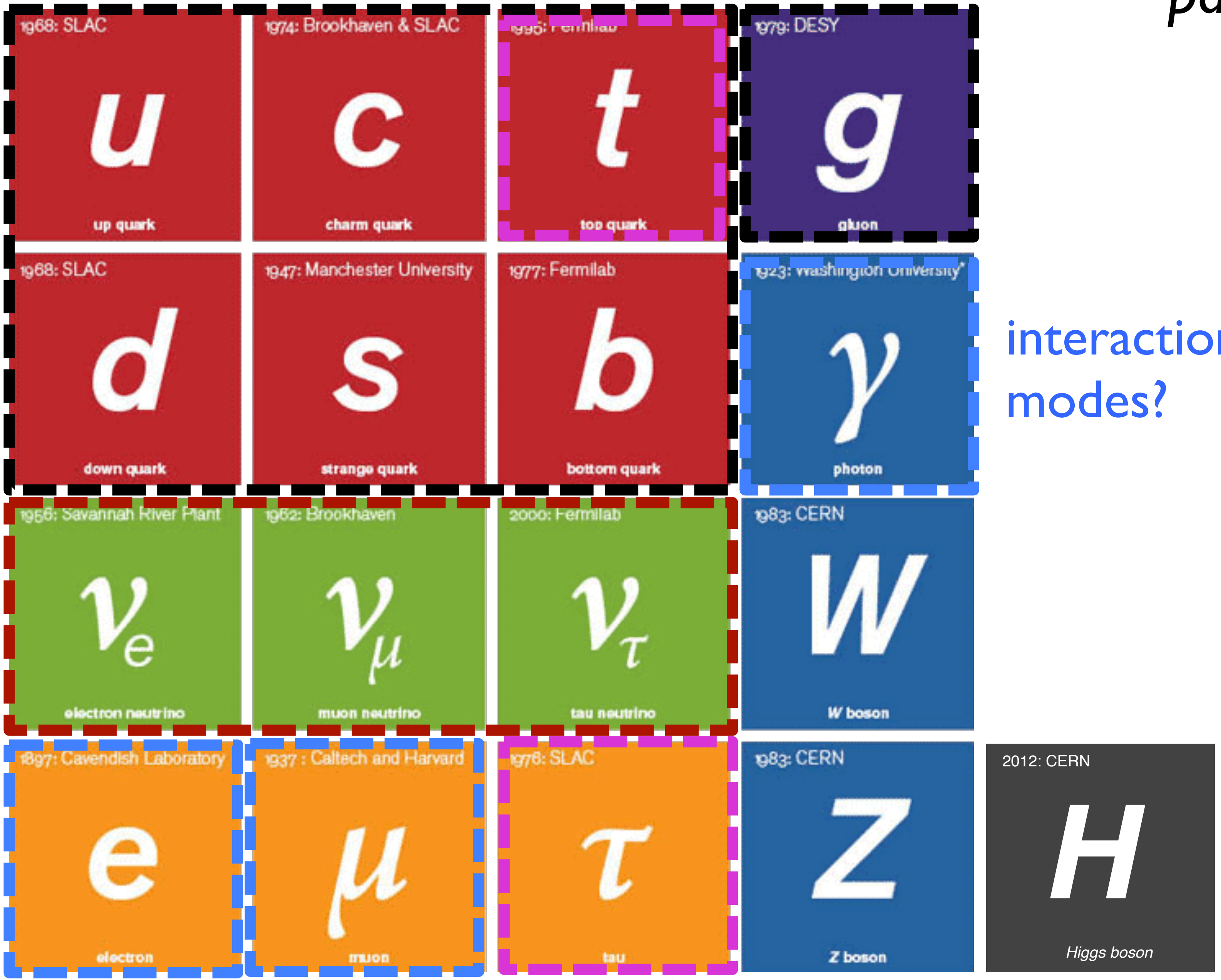
jets

invisible

in particle detectors at accelerators

interaction modes?

interaction modes?



decays?

Interaction mode recap…

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

- electrically charged
- ionization (dE/dx)
- can emit photons
  - ✓ electromagnetic shower induced by emitted photon

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

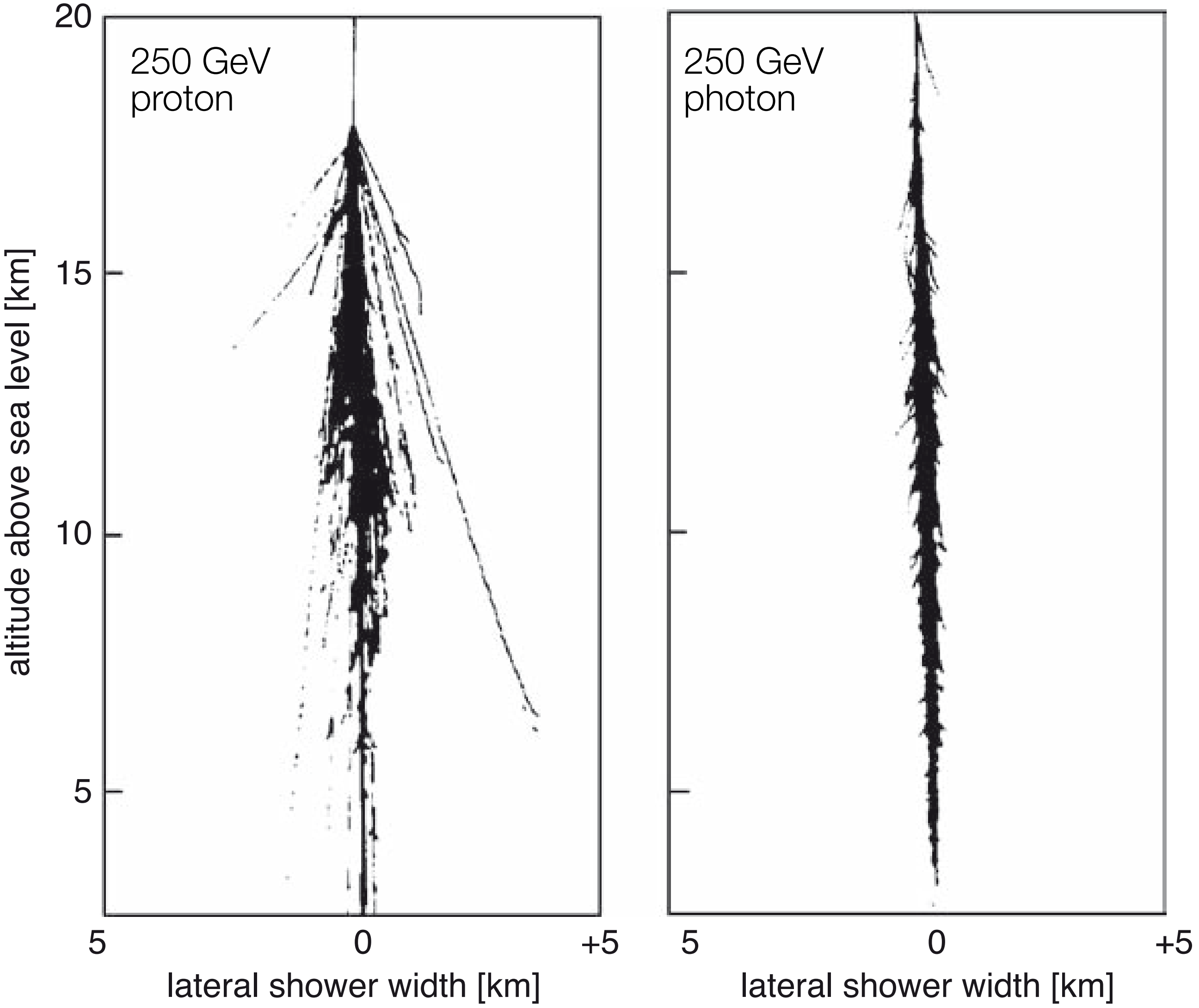
- produce hadron(s) jets via QCD hadronization process

Hadronic vs. EM showers

Comparison

hadronic vs. electromagnetic shower ...

[Simulated air showers]



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]

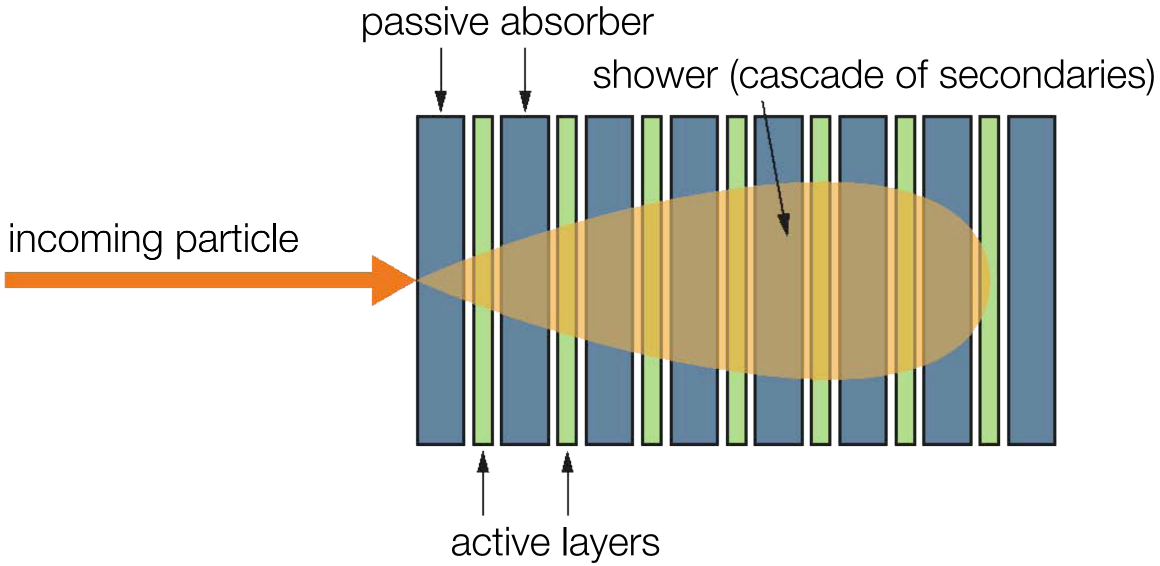
Absorber materials:
[high density]

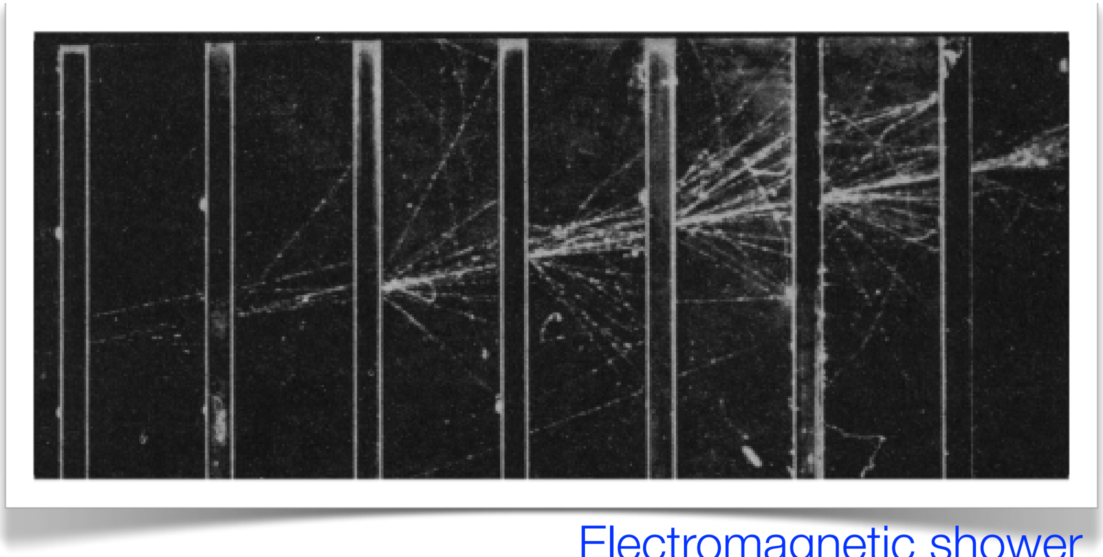
Iron (Fe)
Lead (Pb)
Uranium (U)
[For compensation ...]

Active materials:

Plastic scintillator
Silicon detectors
Liquid ionization chamber
Gas detectors

Scheme of a sandwich calorimeter

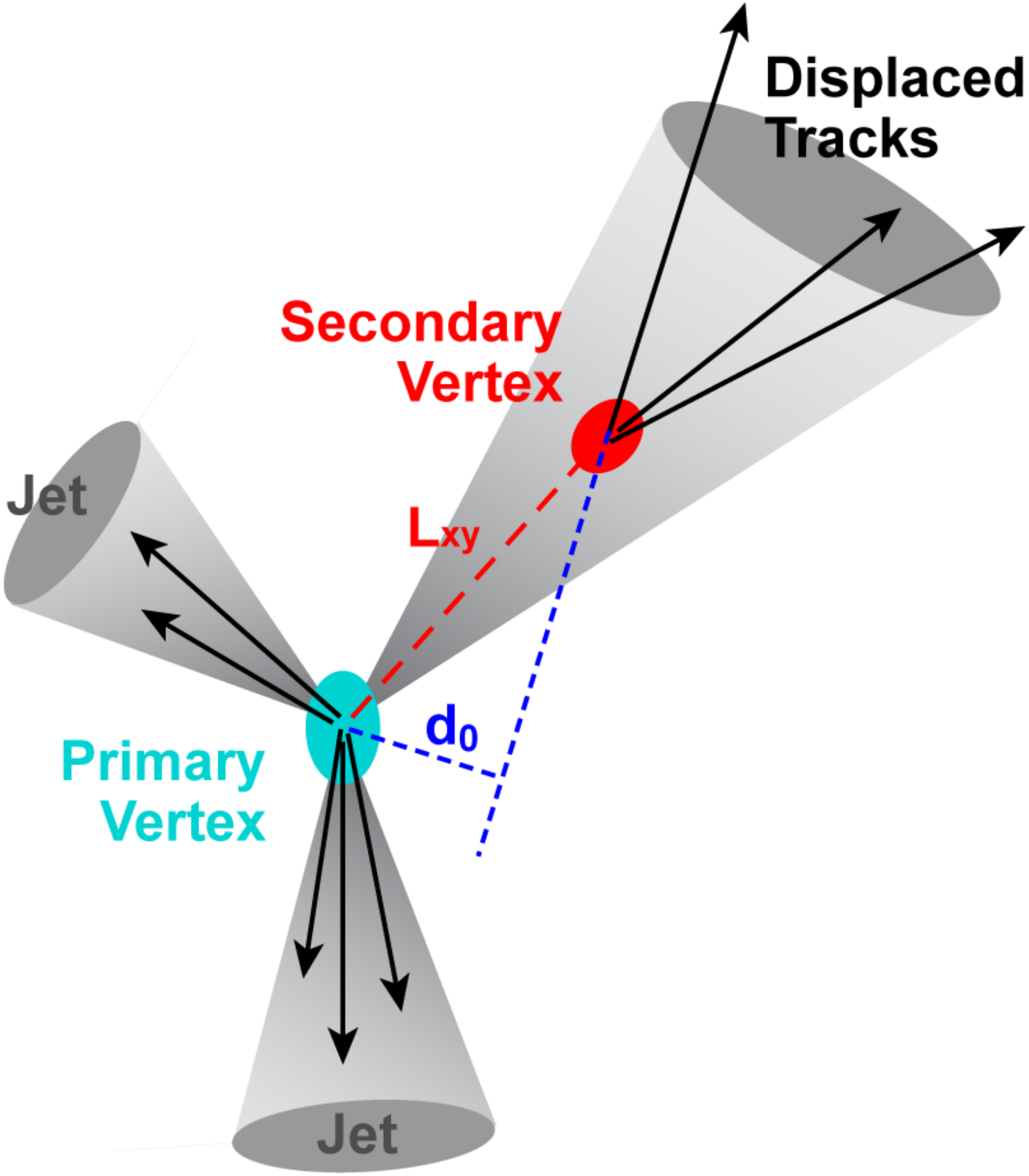




Electromagnetic shower

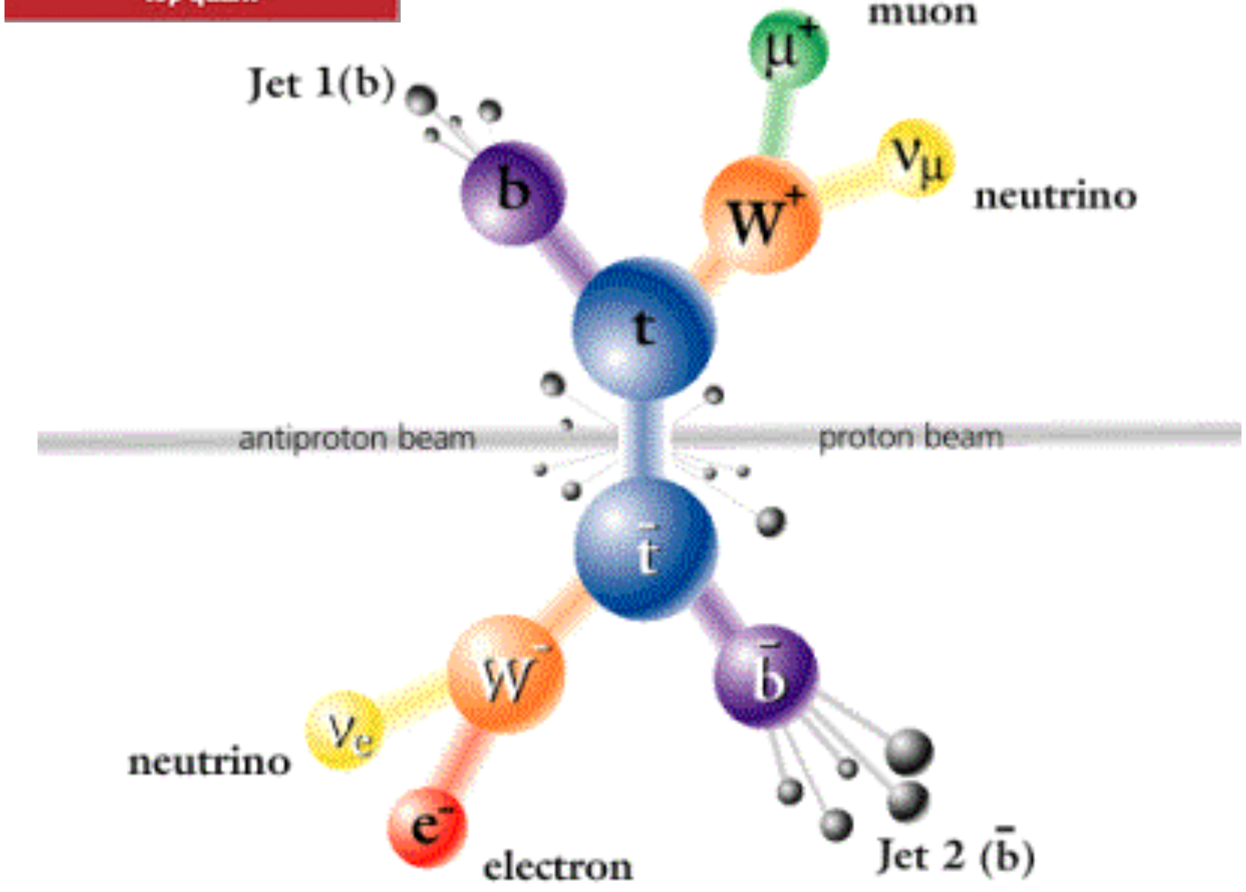
B-tagging

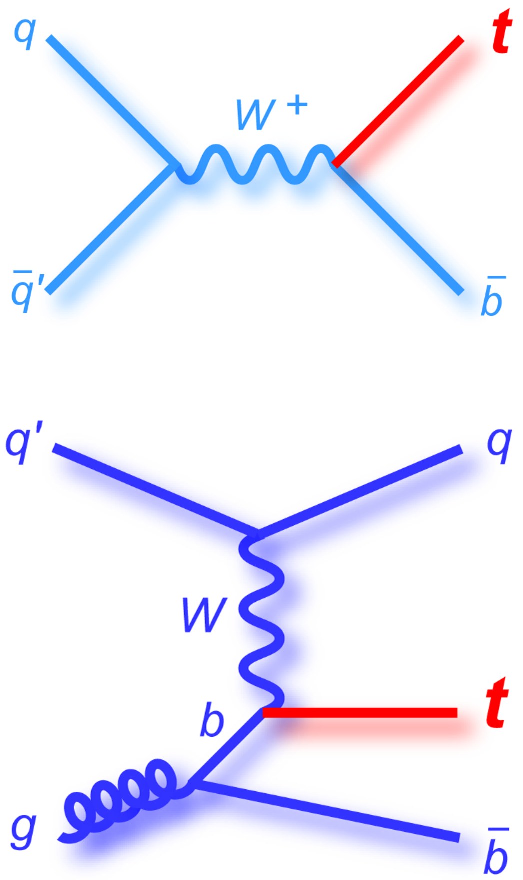
- When a b quark is produced, the associated jet will very likely contain at least one B meson or hadron
- B mesons/hadrons have relatively long lifetime
  - ✓ They will travel away form collision point before decaying
- Identifying a secondary decay vertex in a jet allow to tag its quark content
- Similar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



top quark

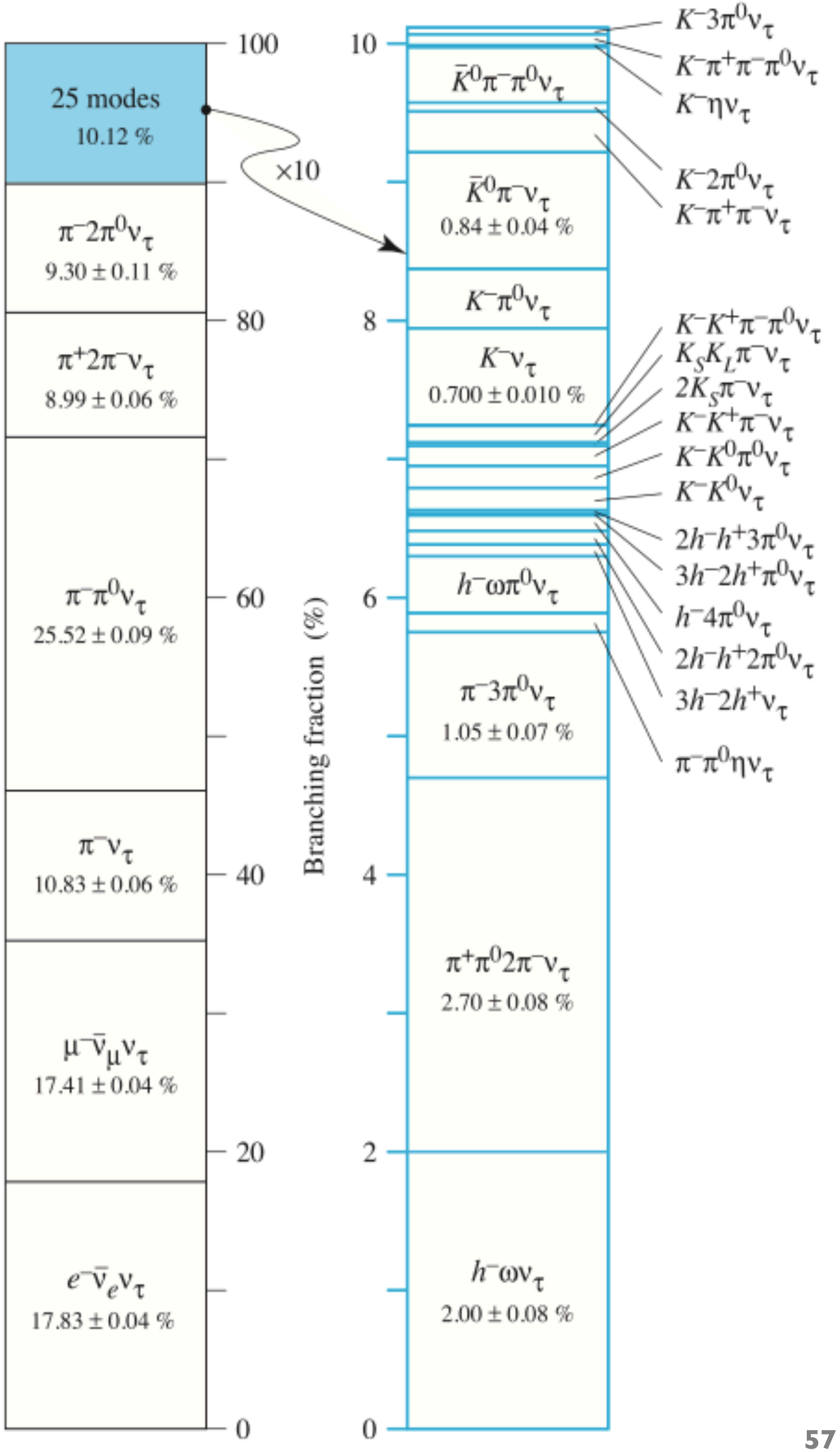
- Top quark has a mean lifetime of 5×10^{-25} s, shorter than time scale at which QCD acts: not time to hadronize!
  - ✓ It decays as $t \to Wb$
- Events with top quarks are very rich in (b) jets…

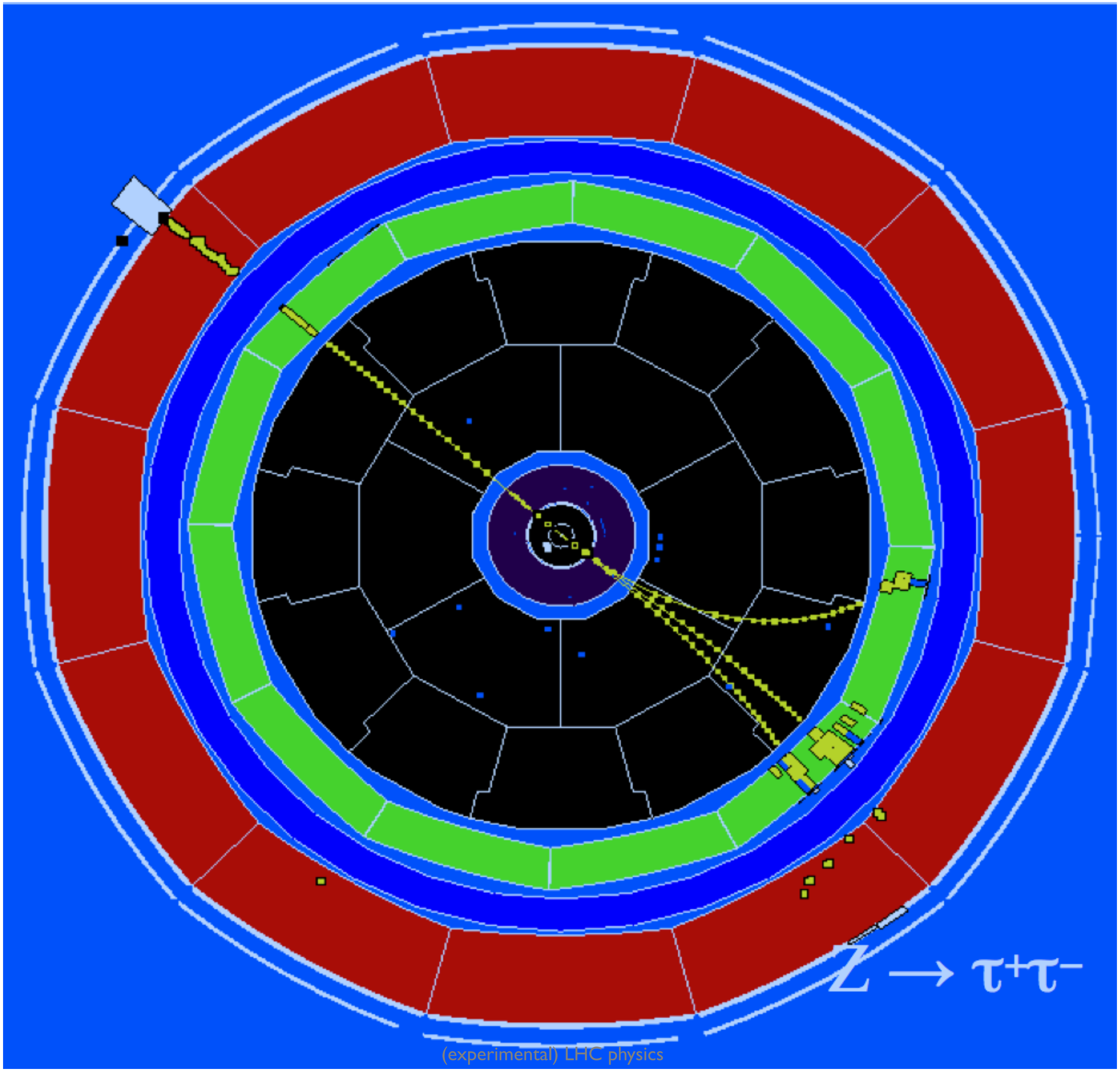




Tau

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





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