Karlsruher Institut für Technologie

QCD and Collider Physics

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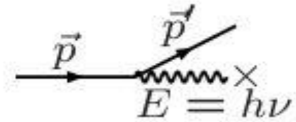
Lecture supporting slides summer 2018

KIT Center Elementary Particle and Astroparticle Physics - KCETA

Hadron collider basics

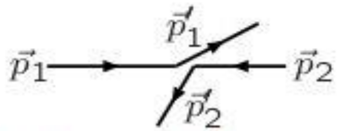
To study the deepest layers of matter,
we need the probes with highest energies.



$p = h/\lambda$

Two parameters of importance:

1. The energy:

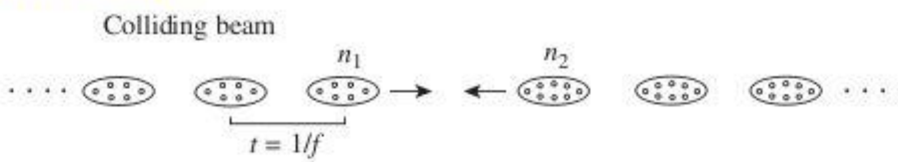


$$s \equiv (p_1 + p_2)^2 = \begin{cases} (E_1 + E_2)^2 & \text{in the c.m. frame } \vec{p}_1 + \vec{p}_2 = 0, \\ m_1^2 + m_2^2 + 2(E_1 E_2 - \vec{p}_1 \cdot \vec{p}_2). & \end{cases}$$

$$E_{cm} \equiv \sqrt{s} \approx \begin{cases} 2E_1 \approx 2E_2 & \text{in the c.m. frame } \vec{p}_1 + \vec{p}_2 = 0, \\ \sqrt{2E_1 m_2} & \text{in the fixed target frame } \vec{p}_2 = 0. \end{cases}$$

Hadron collider at 14 TeV = cosmic rays at 100.000 TeV $=10^8$ GeV $= 10^{17}$ eV

2. The luminosity:



$$\mathcal{L} \propto f n_1 n_2 / a,$$

(a some beam transverse profile) in units of #particles/cm^2/s
$\Rightarrow 10^{33}$ cm^{-2}s $^{-1} = 1$ nb^{-1} s$^{-1} \approx 10$ fb^{-1}/year.

Tevatron and LHC

LHC precursor: Tevatron, $p\bar{p}$ collisions at
$\sqrt{s} = 1.96$ TeV $\quad \mathcal{L} \approx 2 - 3 \times 10^{32}\ \mathrm{cm}^{-2}\mathrm{sec}^{-1} \leftrightarrow 2 - 3\mathrm{fb}^{-1}/\mathrm{year}$

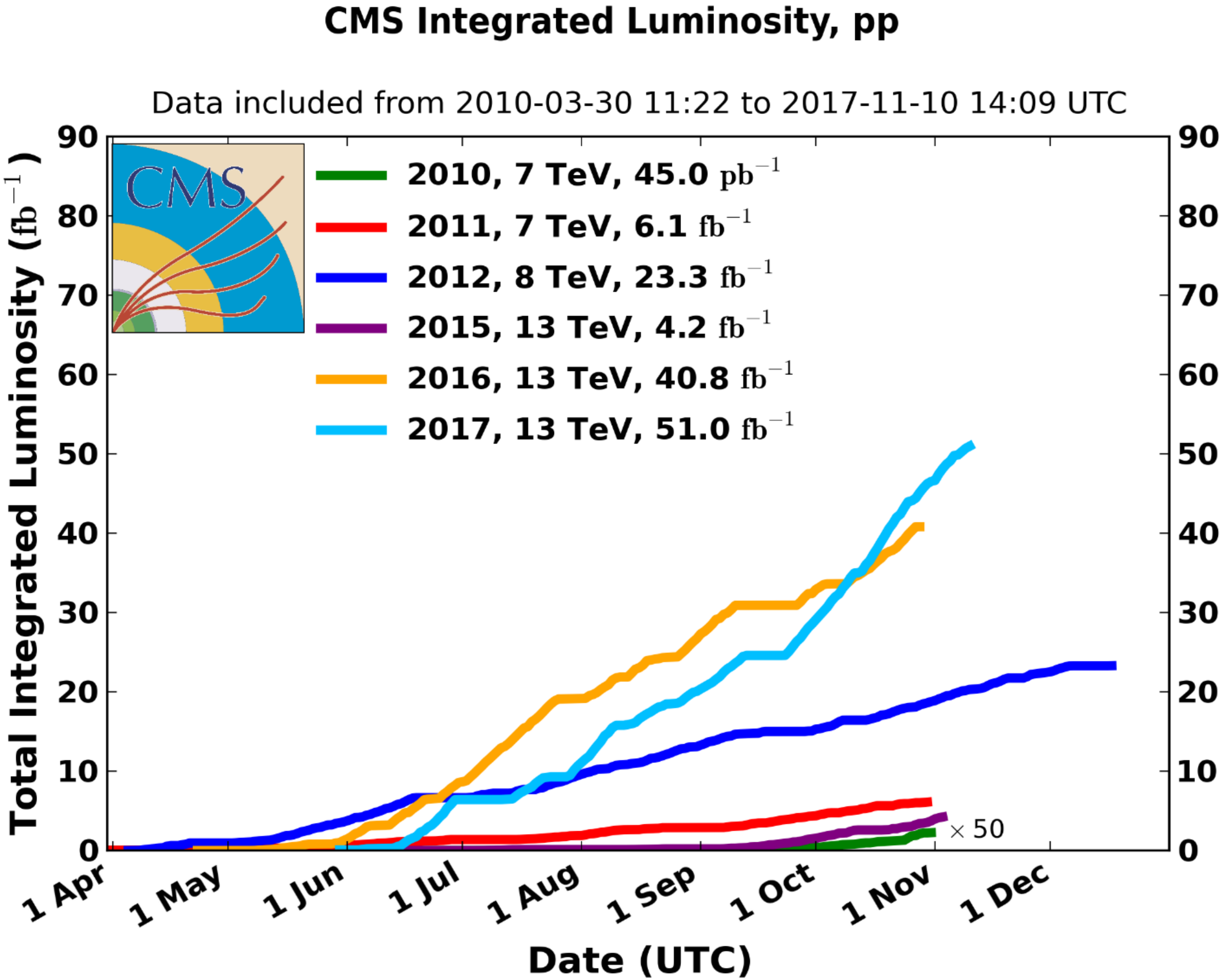
LHC, designed for pp collisions at
$\sqrt{s} = 14$ TeV $\quad \mathcal{L} \approx 10^{33}$–$10^{34}\ \mathrm{cm}^{-2}\mathrm{sec}^{-1} \leftrightarrow$ 10–100$\mathrm{fb}^{-1}/\mathrm{year}$
lower energy and luminosity at beginning:
$\sqrt{s} = 7 + 8$ TeV and $\quad \int \mathcal{L}dt \approx 5 + 20\ \mathrm{fb}^{-1}$ in 2011/12 $\quad$ Run I
$\sqrt{s} = 13$ TeV and $\quad \int \mathcal{L}dt \approx 3 + > 20\ \mathrm{fb}^{-1}$ in 2015/16 $\quad$ Beginning of Run II

Advantage: available energy is much larger than at e^+e^- colliders

- $t\bar{t}$ pairs could not be produced at LEP...

Disadvantage: protons are composite $\Longrightarrow$

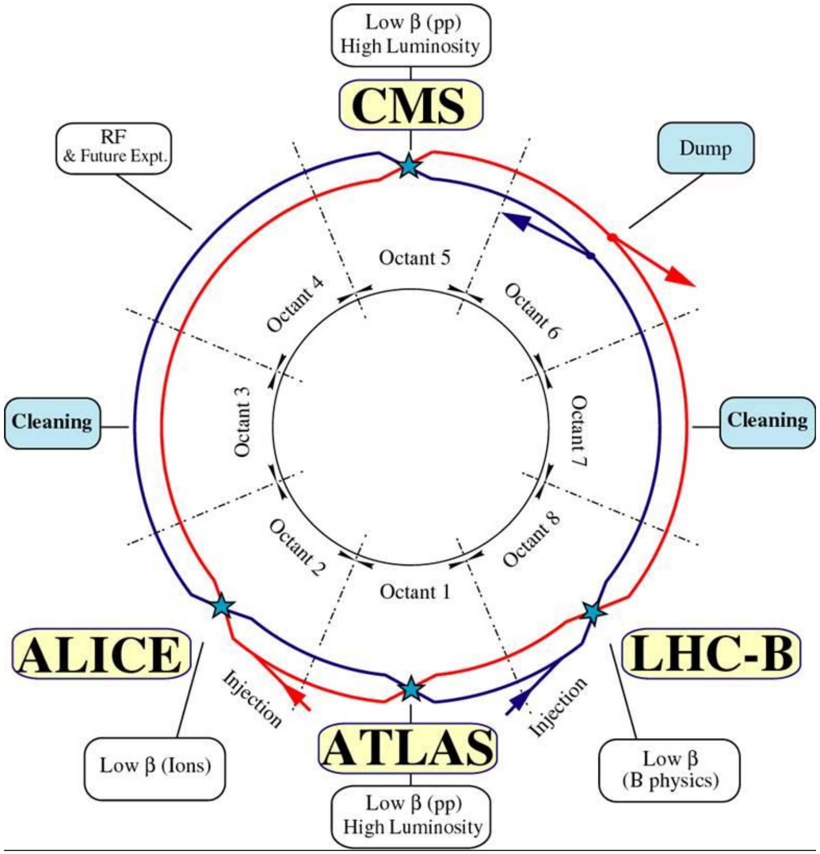
- hard scattering is between
  partons = quarks, anti-quarks, gluons
- useful energy = $\sqrt{\hat{s}}$ of partons $<< \sqrt{s}$
- proton-(anti)proton cross section is large
  $\sigma_{tot}(p\bar{p}) \approx 100$ mb $\geq 10^{11}$ times new physics cross sections
  $\Longrightarrow$ Must understand patterns of SM and new physics processes to identify something new



CMS Integrated Luminosity, pp
Data included from 2010-03-30 11:22 to 2017-11-10 14:09 UTC
CMS
2010, 7 TeV, 45.0 pb^{-1}
2011, 7 TeV, 6.1 fb^{-1}
2012, 8 TeV, 23.3 fb^{-1}
2015, 13 TeV, 4.2 fb^{-1}
2016, 13 TeV, 40.8 fb^{-1}
2017, 13 TeV, 51.0 fb^{-1}
× 50
Total Integrated Luminosity (fb^{-1})
0
10
20
30
40
50
60
70
80
90
1 Apr
1 May
1 Jun
1 Jul
1 Aug
1 Sep
1 Oct
1 Nov
1 Dec
Date (UTC)

The LHC is housed about 100 m underground in a 27 km circumference tunnel straddling the French-Swiss border

Experiments at the LHC



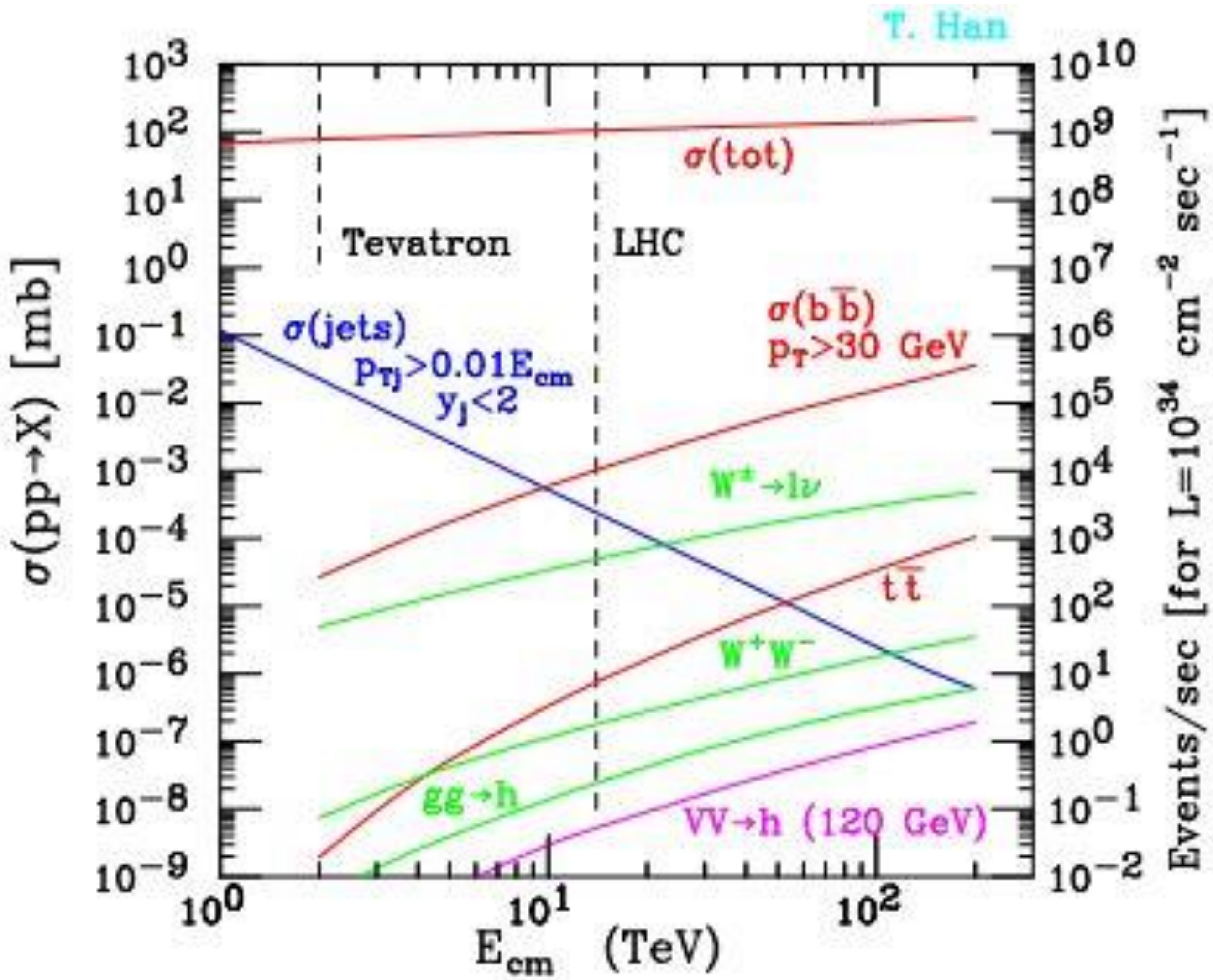
Collisions take place in four experiments

- ATLAS and CMS are general purpose detectors aiming at study of all hard interactions
- LHCb looks for B-mesons and baryons produced in the forward direction
- ALICE is a detector designed for the extremely high particle numbers produced in heavy ion collisions

What to look for at the LHC?

- Jet production = elastic parton-parton scattering
- Top Quarks
- Electroweak gauge bosons: W and Z
- Higgs production and decay
- Combinations of the above
- Evidence for beyond the SM physics
  - Supersymmetry
  - non-standard electroweak interactions
  - extra gauge bosons ….. and more

Expected cross sections in pp collisions



Signatures for processes

- W production

  decay to leptons and neutrinos: $W^{\pm} \rightarrow l^{\pm}\nu$

- Higgs production

  decay to pair of photons: $H \rightarrow \gamma\gamma$

  decay to Z boson pair: $H \rightarrow ZZ \rightarrow e^{+}e^{-}\,\mu^{+}\mu^{-}$

- Top quark

  decay to Wb

- Quarks and gluons

  very energetic partons manifest as jets of hadrons (pions, nucleons, kaons etc.)

➔ Distinguish electron, muon, photon, pion etc. and measure their four-momenta

Detecting hadrons, leptons and photons

What we "see" as particles in the detector: (a few meters)

For a relativistic particle, the travel distance:

$$d = (\beta c\tau)\gamma \approx (300\ \mu m)\left(\frac{\tau}{10^{-12}\ s}\right)\ \gamma$$

- stable particles directly "seen":

  $$p,\ \bar{p},\ e^{\pm},\ \gamma$$

- quasi-stable particles of a life-time $\tau \geq 10^{-10}$ s also directly "seen":

  $$n, \Lambda, K_L^0, ...,\ \mu^{\pm},\ \pi^{\pm}, K^{\pm}...$$

- a life-time $\tau \sim 10^{-12}$ s may display a secondary decay vertex, "vertex-tagged particles":

  $$B^{0,\pm},\ D^{0,\pm},\ \tau^{\pm}...$$

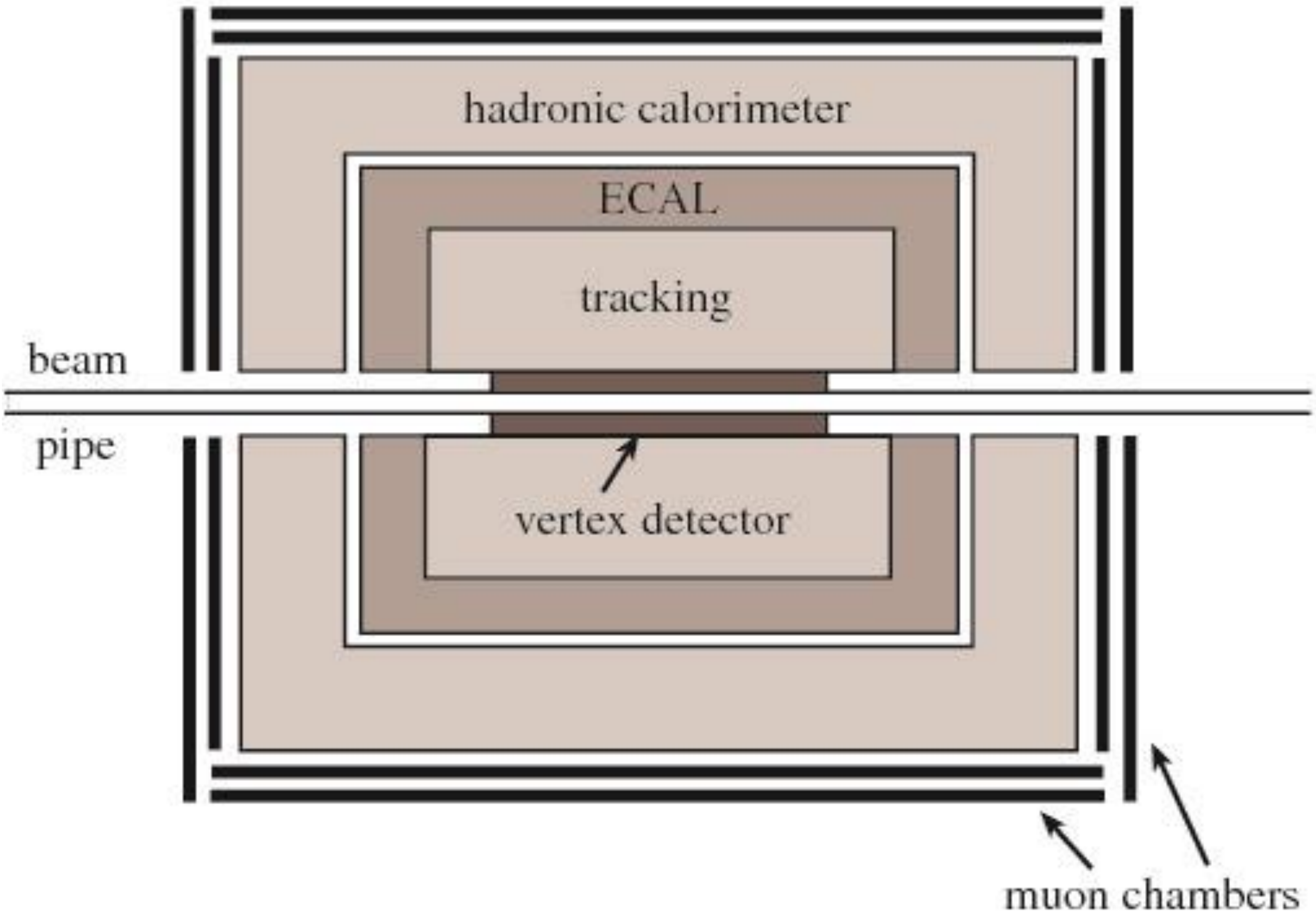
- short-lived not "directly seen", but "reconstructable":

  $$\pi^0,\ \rho^{0,\pm}...\ ,\quad Z, W^{\pm}, t, H...$$

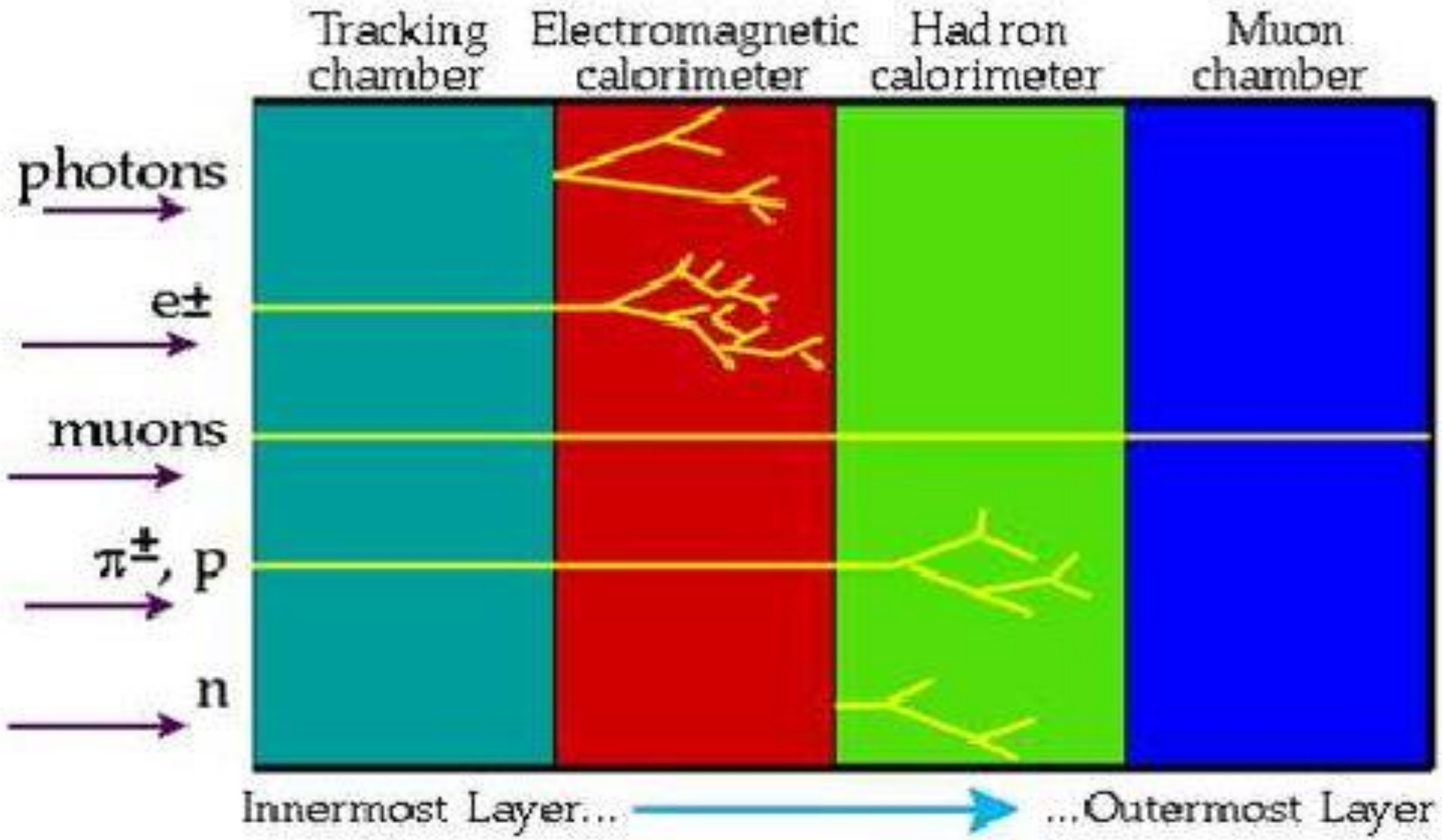
- missing particles are weakly-interacting and neutral:

  $$\nu,\ \tilde{\chi}^0, G_{KK}...$$

Basic concept of a general purpose detector

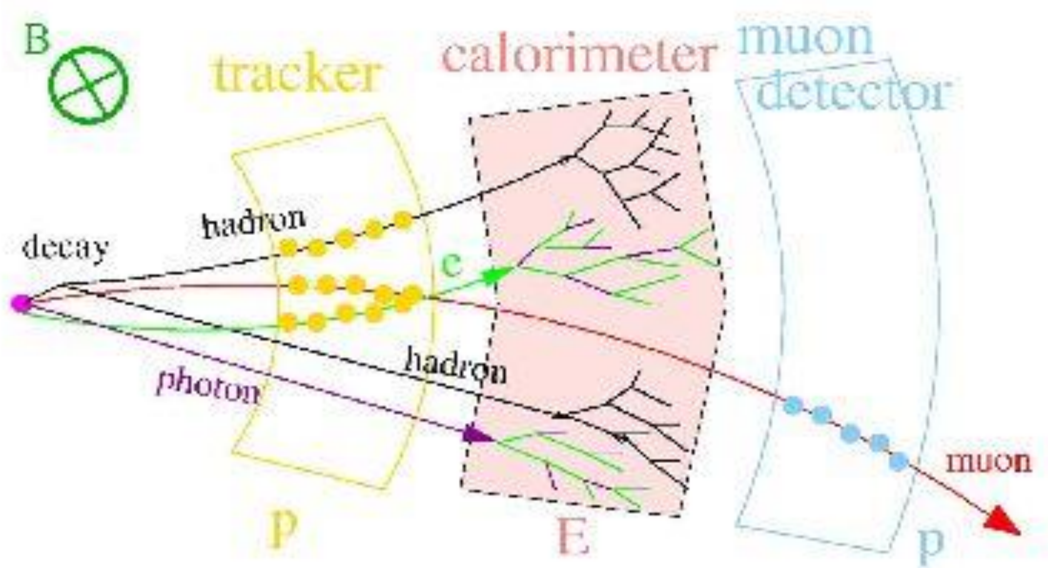


† For stable and quasi-stable particles of a life-time $\tau \geq 10^{-10} - 10^{-12}$ s, they show up as



Charge identification and momentum resolution

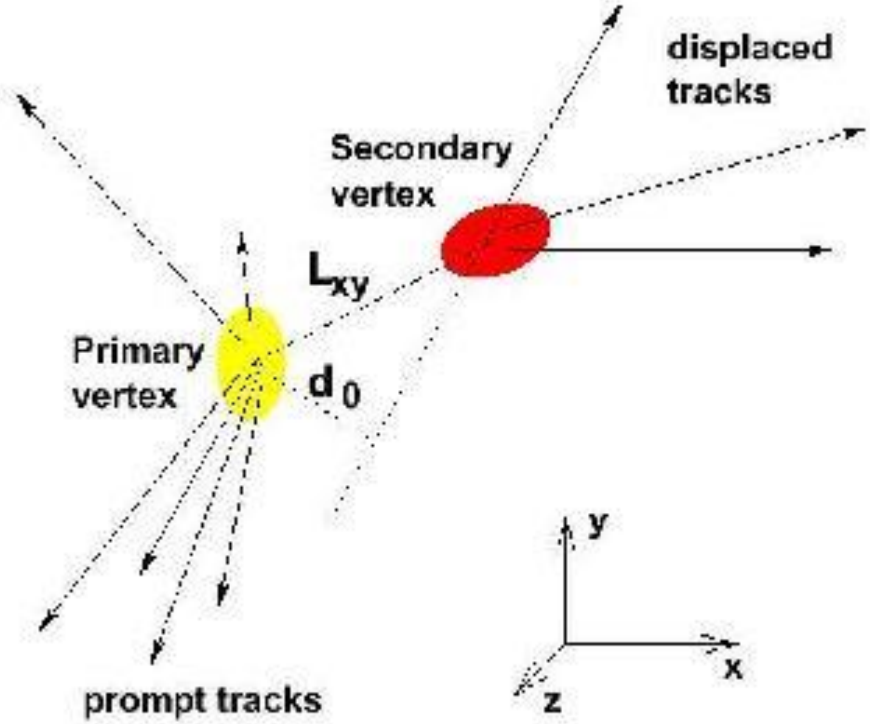
A closer look:



Theorists should know:

$$\text{For charged tracks}: \quad \Delta p/p \;\propto\; p,$$
$$\text{typical resolution}: \quad \sim\; p/(10^4\ GeV).$$
$$\text{For calorimetry}: \quad \Delta E/E \;\propto\; \frac{1}{\sqrt{E}},$$
$$\text{typical resolution}: \quad \sim\; (5-80\%)/\sqrt{E}.$$

† For vertex-tagged particles $\tau \approx 10^{-12}$ s,
heavy flavor tagging: the secondary vertex:



Typical resolution: $d_0 \sim 30 - 50\ \mu$m or so

$\Rightarrow$ need at least two charged tracks, that are not colinear.

For theorists: just multiply a "tagging efficiency" $\epsilon_b \sim 40 - 60\%$ or so.

Short lived and „invisible“ particles:

† For short-lived particles: $\tau < 10^{-12}$ s or so,
make use of kinematics to reconstruct the resonance.

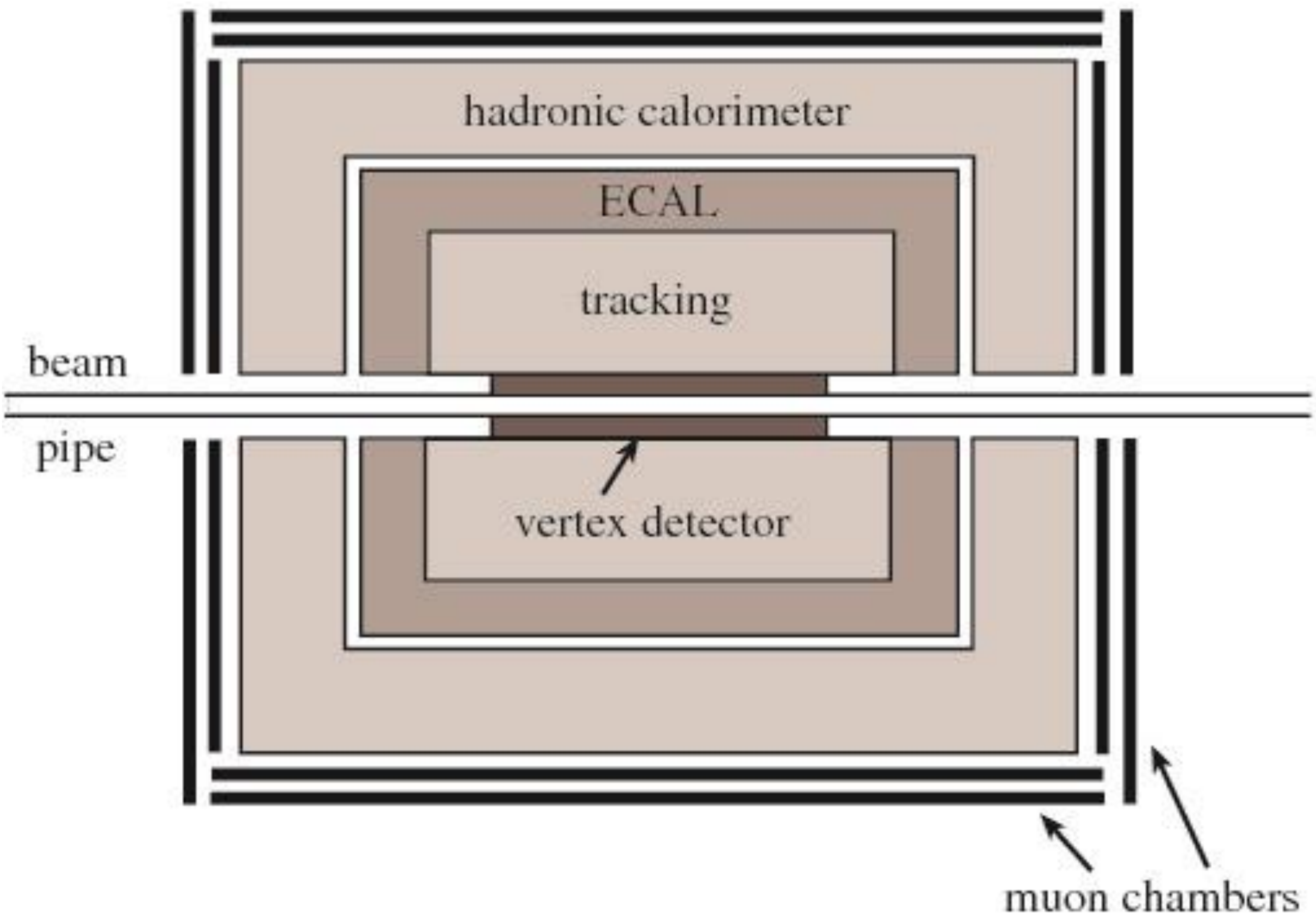
† For missing particles:
make use of energy-momentum conservation to deduce their existence.
(or transverse direction only for hadron colliders.)

$$p_1^i + p_2^i = \sum_f^{obs.} p_f + p_{miss}.$$

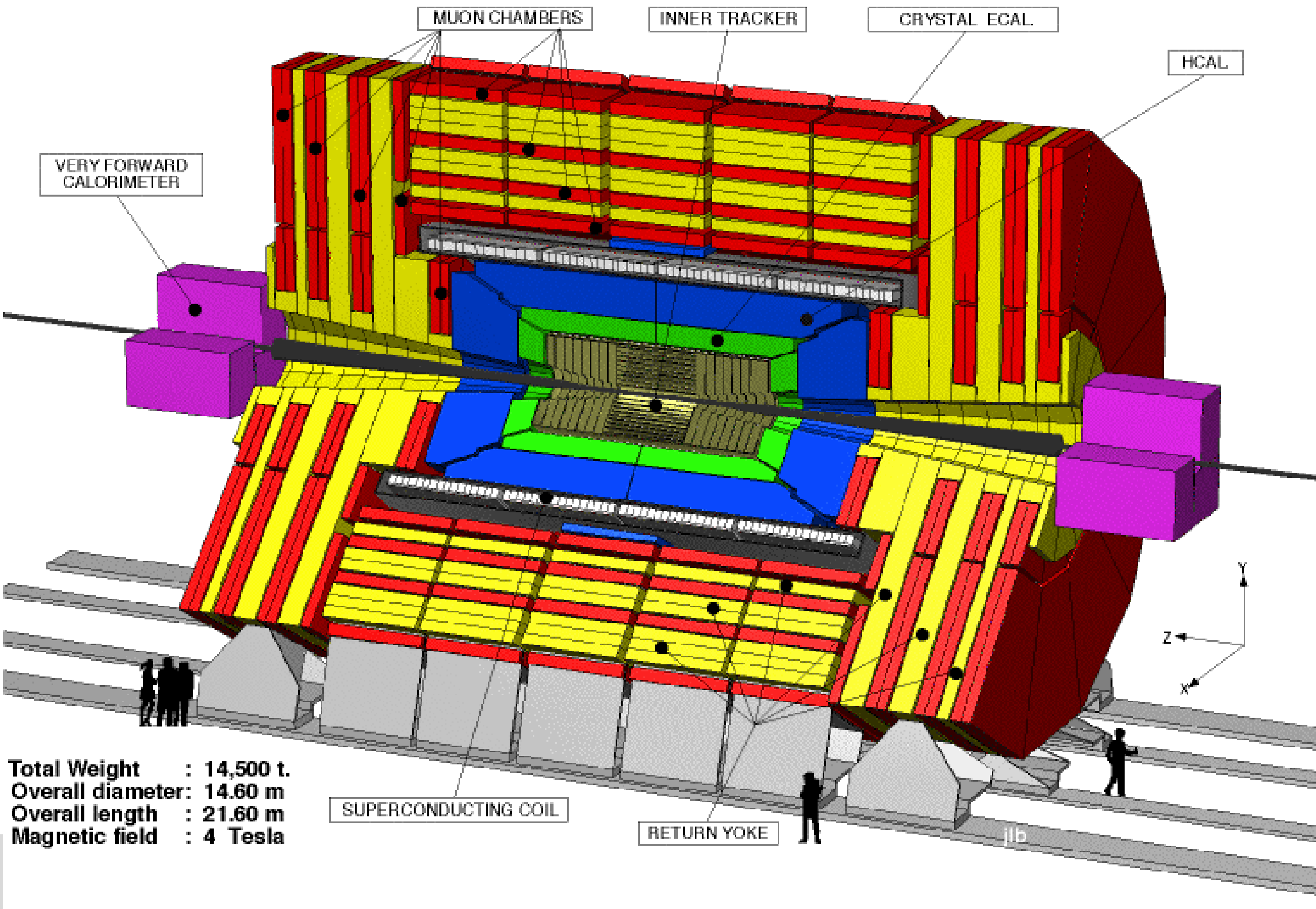
But in hadron collisions, the longitudinal momenta unkown:

$$0 = \sum_f^{obs.} \vec{p}_{f\ T} + \vec{p}_{miss\ T}.$$

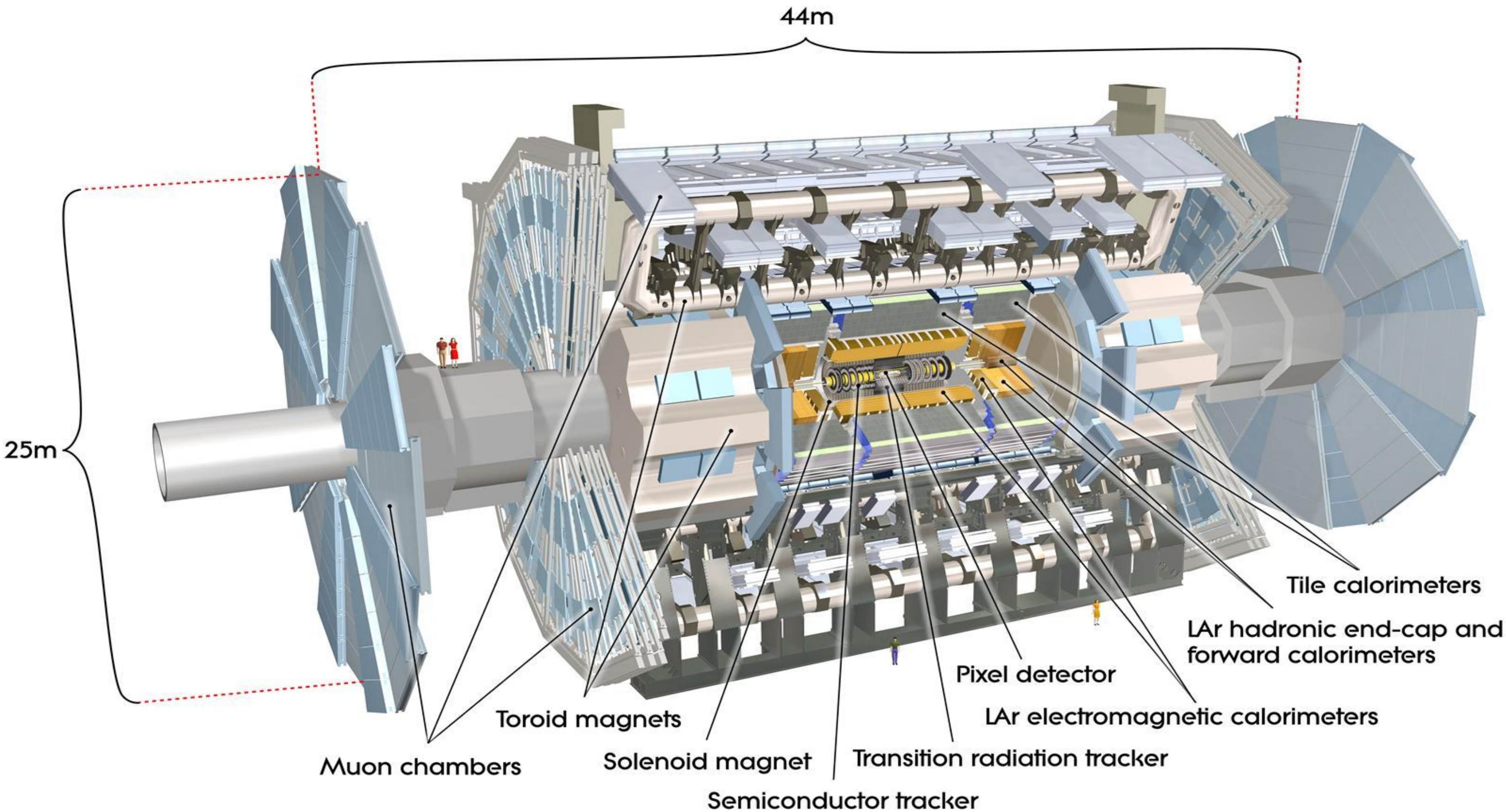
Cartoon of a general purpose detector



Layout of the CMS detector



Components of the ATLAS detector



Differential cross sections for hadronic collisions

…. and QCD as a quantum field theory