QCD Physics for Colliders

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ICTP Summer School 2021

Lecture 1

Colliders

Outline "cloud"

Colliders

IRC safety

QCD

Jets

Higher orders

PDFs

Monte Carlos

Parton shower

DIS

"Ingredients for predictions"

Prerequisites: QED and QFT

We won't likely cover everything

Bibliography

Many lectures on YouTube

ICTP: Michelangelo Mangano 2015
Ian Stewart 2017
Matt Schwartz 2019

GGI (Galileo Galilei Institute):
Stefano Catani 2014
Michael Peskin 2015 ← book
Fabio Maltoni 2017 ← notes
Gregory Soyez 2019 ← notes
Jesse Thaler 2020 ← notes

Gavin Salam 1011.5131
Peter Skands 1207.2389

And many others

Introduction

In "QCD and Collider Physics", let us start with "Colliders"

Why colliders?
Breaking things and look inside at small distance scales (= high energy) is still the best way to explore fundamental physics

Why QCD.
Especially at hadron colliders, one needs to control strong interactions to make sense of observations and measurements

Today, colliders largely means hadron colliders. In fact, largely the LHC. In the future, perhaps, the e^+e^- linear collider (ILC) and FCC-ee and FCC-hh

We shall see how to use QCD to answer, quantitatively, <u>some</u> of the questions that we need to answer in order to model and understand events at hadron colliders.

Eventually, we want to be able to predict the quantum-mechanical scattering process

(initial state) $\longrightarrow$ (final state)

e.g.

$pp \longrightarrow \text{Higgs}$

$pp \longrightarrow \text{jets}$

$pp \longrightarrow H \to Z^* Z^* \to 4 \text{ leptons}$

Of course, (final state) will be some process that is measurable experimentally and physically useful and relevant for exploring fundamental physics.

Note that, even if QCD may be the correct theory for strong interactions (more on this later), today we cannot use it to answer <u>all</u> questions we may want to throw at it. We will have to be <u>selective</u>, and/or <u>make approximations</u>

Colliders

We collide things, we observe what comes out.

How often do we collide things?
How often do we observe a given final state?

The link between these two quantities is given by the dynamics, i.e. the prediction of the theory that we use to make the calculation

We shall call this link the cross section, and write

$$\begin{pmatrix}\text{Number of} \\ \text{events}\end{pmatrix} = \begin{pmatrix}\text{Integrated} \\ \text{Luminosity}\end{pmatrix} \times \begin{pmatrix}\text{Cross} \\ \text{section}\end{pmatrix}$$

How many events we observe

How many photons we collide

How often the photon collisions give a certain final state

Eventually, we shall want to calculate cross sections, so as to make predictions:

$$d\sigma_{AB \to \text{final state}} = \underbrace{\frac{1}{\text{flux}}}_{\text{normalisation}} \underbrace{\sum_{\text{final state}} \overline{|M|^2}}_{\text{Dynamics. This is where things happen}} \underbrace{d\text{Lips}}_{\text{Lorentz invariant phase space}}$$

cross section

normalisation

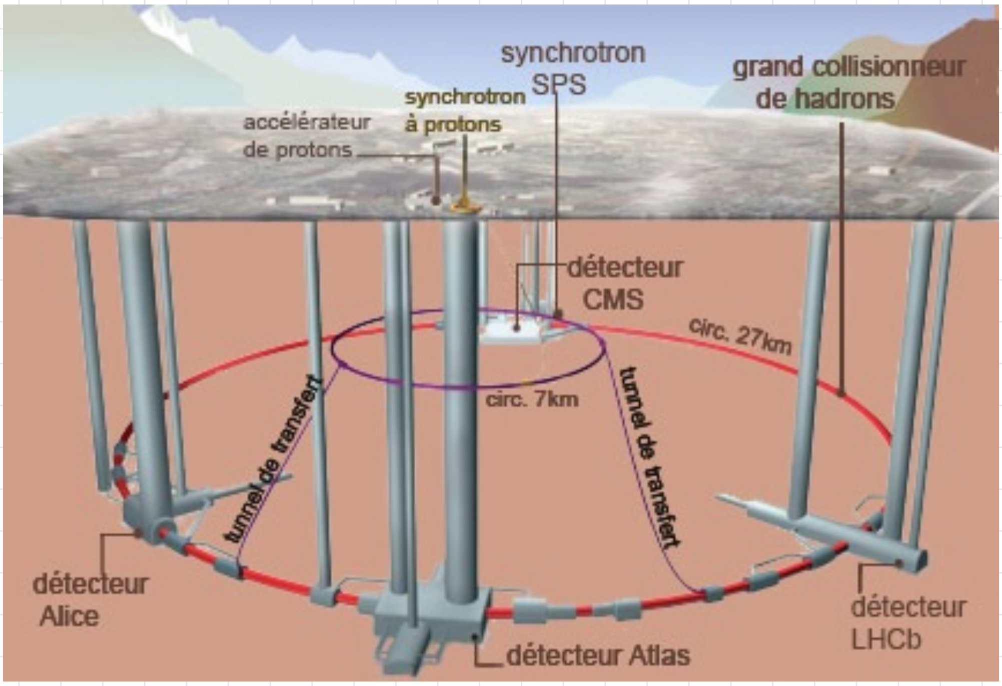
Dynamics.
This is where
things happen

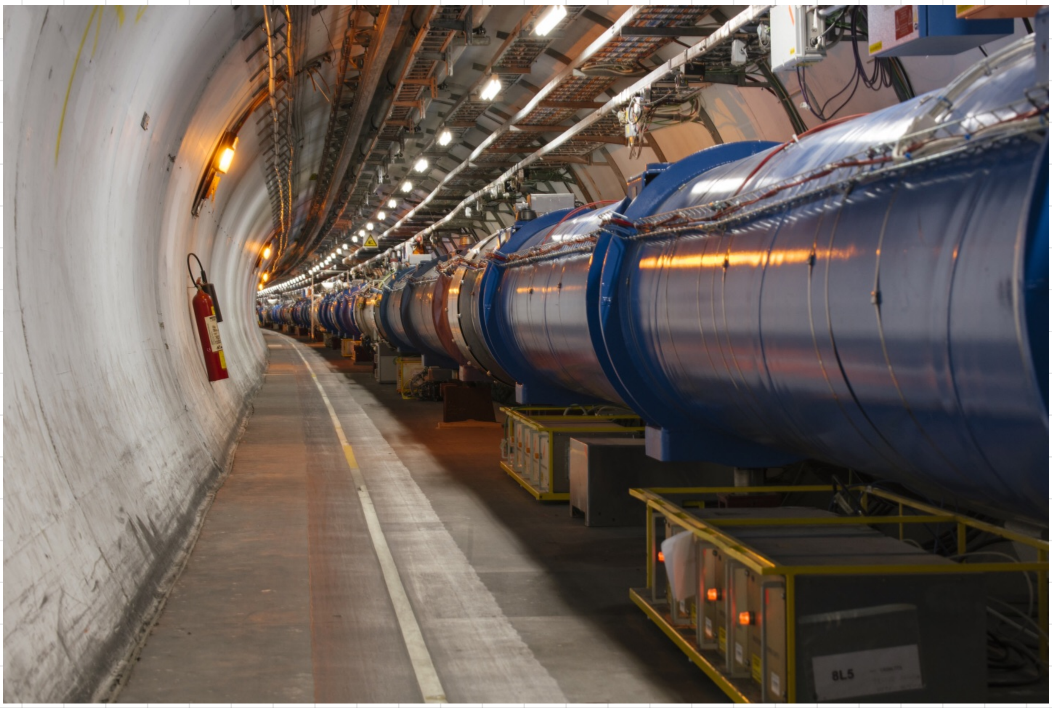
Lorentz
invariant
phase
space

Inevitably, we'll have to make approxs.
in order to calculate things

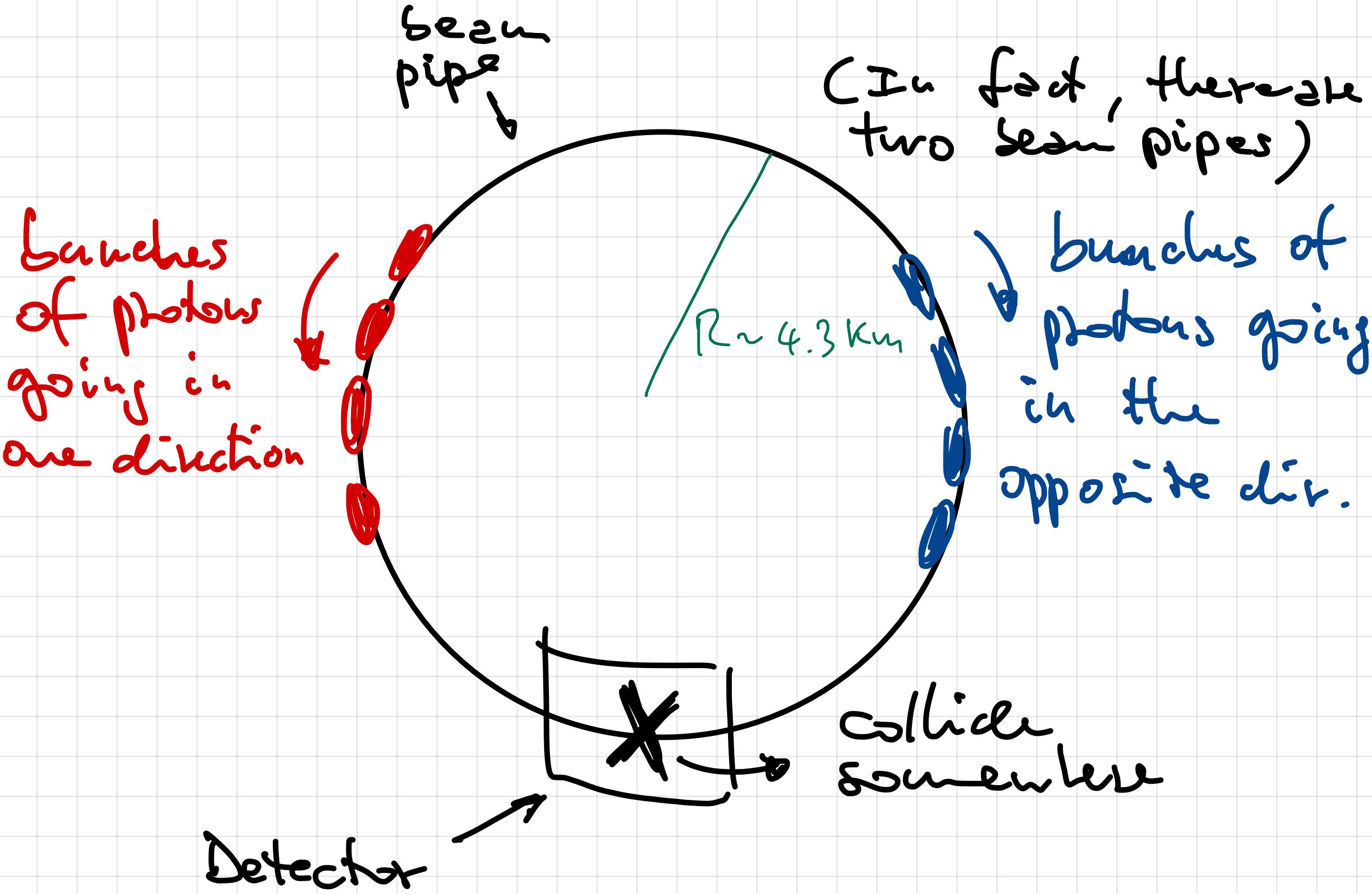
Some facts and numbers about the LHC

In the LHC, we collide protons, at a centre of mass energy of a few TeV $\rightarrow$ eventually, 14 TeV



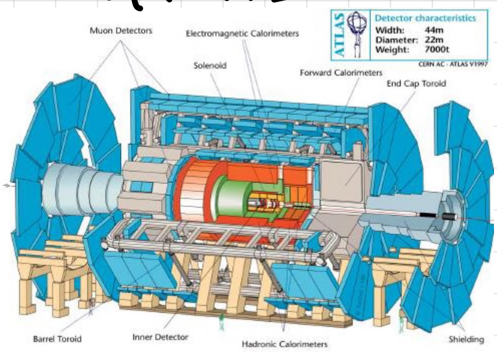


Beams are actually organized in bunches. They travel inside beam pipes

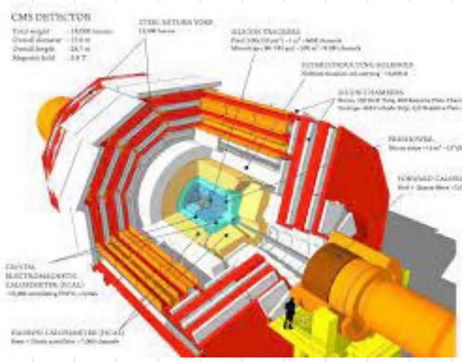


Four big detectors (ATLAS, CMS, LHCb ALICE) observe and analyse the results of the collisions

ATLAS



CMS



How many bunches we have in the in the LHC? Presently, about 2800 per beam, crossing one another every 25 nanoseconds (40 MHz), and there are $\sim 10^{11}$ protons per bunch → in a second, a lot of protons "see" each other

(But protons rarely collide:

volume of a bunch:

$$(1\ \mathrm{mm})^2 \times 30\ \mathrm{cm} = 3 \times 10^{-7}\ \mathrm{m}^3$$

squeezed at interaction point

$$(16 \times 10^{-6}\ \mathrm{m})^2 \times 30\ \mathrm{cm} = 7 \times 10^{-11}\ \mathrm{m}^3$$

Small!

But volume of 10^{11} protons

$$\simeq (10^{-15}\ \mathrm{m})^3 \times 10^{11} = 10^{-34}\ \mathrm{m}^3$$

Smaller!

⇒ still a lot of empty space!)

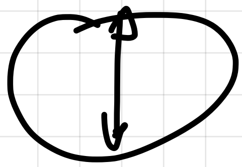
The rate of proton collisions can be written (<u>geometrically!</u>) as a function of

$$\text{Luminosity} \times \text{cross-section}$$

$$\text{Instantaneous Luminosity} \quad \mathcal{L} = \frac{\overset{10^{11}}{N_1}\, \overset{10^{11}}{N_2}\, \overset{40\,\text{MHz}}{f}}{\text{beam cross size}} \simeq 10^{34}\,cm^{-2}\,s^{-1}$$

$\to (17\,\mu m)^2$

cross section of a proton



10^{-15} m

$\Rightarrow$ x-sect $\simeq 10^{-30}\,m^2$

Consider also

Integrated luminosity over 1 year

$$L = \int dt\, \mathcal{L} \simeq \underbrace{10^7 \text{ seconds}}_{\text{a third of a year run time}} \times 10^{34}\,cm^{-2}\,s^{-1}$$

$$\Rightarrow L \simeq 10^{41}\,cm^{-2}$$

$$\Rightarrow L \times \text{x-sect} \simeq 10^{45}\,m^{-2} \times 10^{-30}\,m^2$$

$$\simeq 10^{15} \text{ events/year}$$

Rewrite this using <u>barns</u>

$$\boxed{1 \text{ barn} = 10^{-28}\,m^2 = 10^{-24}\,cm^2}$$

$\Rightarrow$ pp cross section $\simeq 10^{-30}\,m^2$

$\simeq 10^{-2}$ barn (In fact, more like 0.1 b in practice)

and integrated luminosity

$$L \simeq 10^{45}\,m^{-2}/\text{year} = 100\,fb^{-1}/\text{year}$$

"inverse femtobarn"

So that (using barns, simpler numbers):

Number of pp collision events in one year at the LHC

$$\simeq L\,\sigma_{pp} \simeq 100\,fb^{-1}/\text{year}\;\; 0.1\,b$$

$$= 100\,fb^{-1}/\text{year}\;\; 0.1\; 10^{15}\,fb$$

$$\simeq 10^{16} \text{ collisions}/\text{year}$$

$$\simeq 10^{9} \text{ collisions}/\text{second}$$

Even with pp collision being "rare", this is a lot of collisions.

It's about

$$\frac{10^{16}}{10^7} \text{ collisions/second} = 10^9 \text{ collisions/s}$$

and writing to disk all the details of a collision is $\simeq$ 1 MB

$$\Rightarrow \quad 10^9 \frac{\text{collisions}}{\text{second}} \; 1 \frac{\text{MB}}{\text{collisions}} = 1 \frac{\text{TB}}{\text{second}}$$

to write to disk.

→ impossible with present technology.
Need a reduction by a factor $\mathcal{O}(10^3) \to 1$ GB/s

The problem is, we are not interested in <u>all</u> pp collisions, but only in very rare ones.

To estimate cross section sizes for interactions, let us use a different unit:
not cm^2 or barns, but rather inverse energy

Using $\hbar c = 197$ MeV fm, in natural units ($\hbar = c = 1$) we can turn a length into inverse energy.

Proton radius $\simeq 10^{-15}$ m $= 1$ fm $= \dfrac{\hbar c}{197 \text{ MeV}}$

$$\simeq \frac{1}{200 \text{ MeV}}$$

and the σ_{pp} cross section will be

$$\sigma_{pp} \simeq \left(\frac{1}{200 \text{ MeV}} \right)^2$$

and this can be converted to barns using

$$(\hbar c)^2 = 0.389\ldots \text{ GeV}^2 \text{ mbarn}$$

so that

$$\sigma_{pp} \simeq \left(\frac{1}{200\,\text{MeV}}\right)^2 0.389\ \text{GeV}^2\,\text{mbarn}$$

$$\simeq 10\ \text{mb} = 10^{-2}\,\text{barn}$$

[Same approx estimate as earlier. It's actually rather 10^{-1} barn]

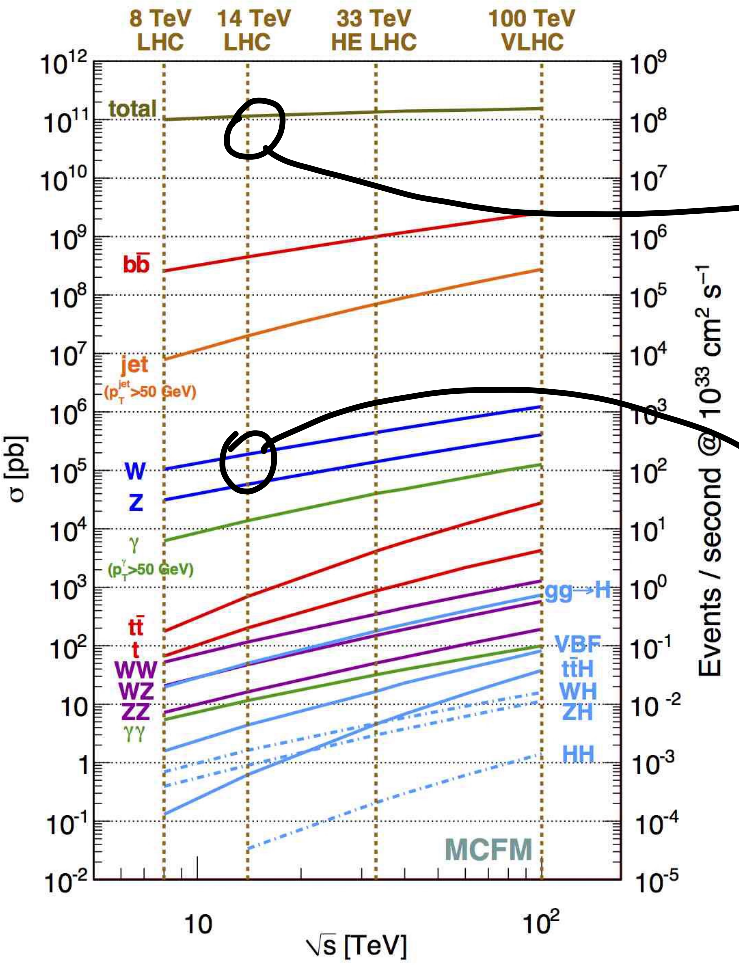
Now, compare this to the x-sect for a weak interaction. This is proportional to the Fermi constant:

$$\sigma_{weak} \simeq G_F \simeq 1.16 \times 10^{-5}\ \text{GeV}^{-2}$$

(conveniently, units of energy^{-2})

$$\Rightarrow \quad \frac{\sigma_{weak}}{\sigma_{pp}} \simeq \left(\frac{10^{-5}}{\text{GeV}^2}\right)\left(200\ \text{MeV}\right)^2$$

$$= \frac{10^{-5}}{\text{GeV}^2}(0.2)^2\,\text{GeV}^2 \simeq 10^{-7}$$



σ_{pp}

at least 6 orders of magnitude

σ_{weak}

This means that from 10^{16} pp collisions / year we get down to $10^8 - 10^{10}$ weak events per year.

A Higgs boson is even rarer:

$$\sigma(pp \to gg \to H) \simeq 10^2 \, pb = 10^5 \, fb$$

$$\Rightarrow N_{pp\to H}/_{year} = 100 \, fb^{-1}/_{year} \; 10^5 \, fb$$

$$= 10^7 \text{ events}/_{year}$$

If we scale these down by a factor of 1000 or more, there's not much left (all the more so that we can't necessarily detect them all.

For instance,

$$BR(H \to \gamma\gamma) = 2.27 \times 10^{-3}$$

and this is the easiest way to see a Higgs at the LHC

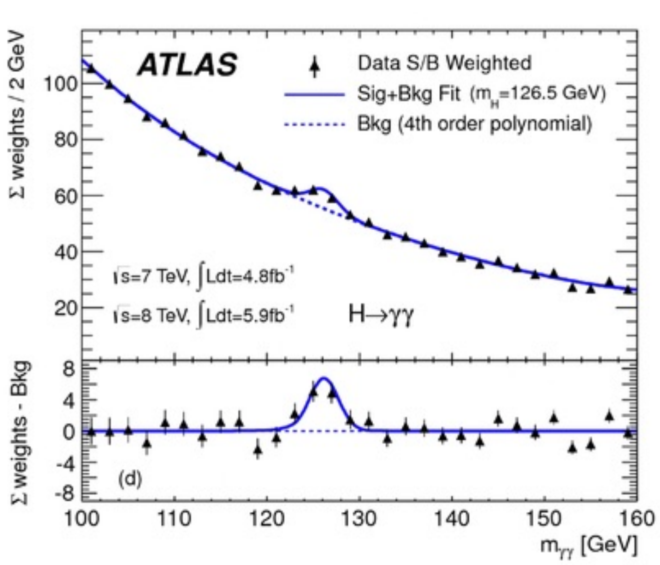
$\Rightarrow$ only about 10^4 events, assuming perfect detection

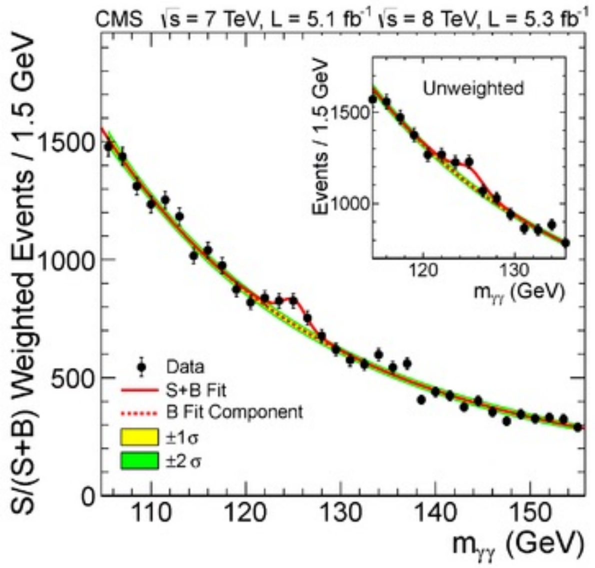
(Also note that, especially at Higgs discovery time in 2011-2012, the LHC did <u>NOT</u> deliver $100\,fb^{-1}$/year. The discovery was made with $\sim 5\,fb^{-1}$)

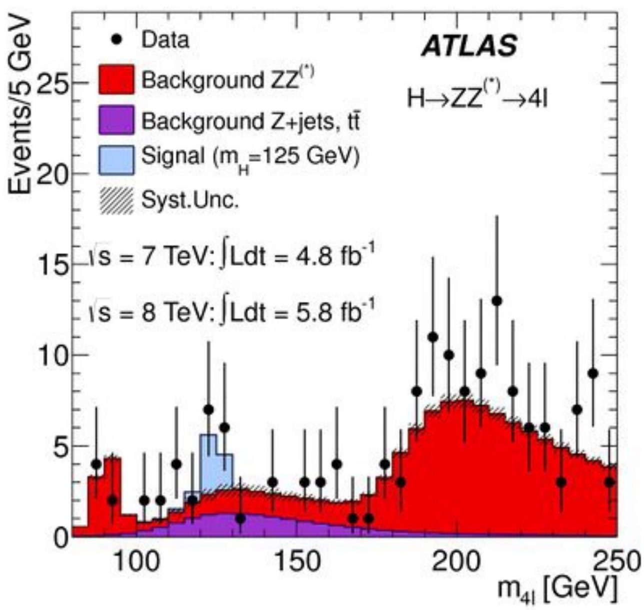
An even rarer (but with less background) channel is

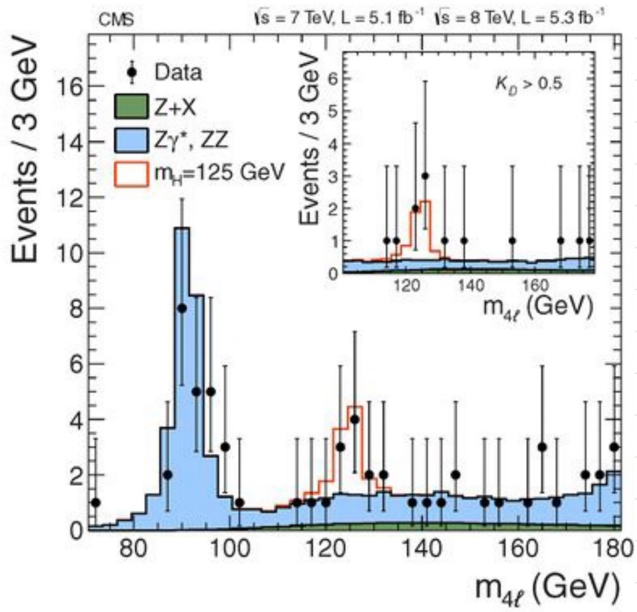
$$H \to ZZ \to 4 \text{ leptons}$$

Eventually, the Higgs was discovered with about 10 events per experiment in this channel









plots from http://www.scholarpedia.org/articleThe_Higgs_Boson_discovery

⇒ need selective triggering

→ only record interesting collisions

What do we actually observe in a detector?

Not much. Only the particles that make it as far, i.e. don't decay earlier.

The critical number is $c\tau$, the distance travelled before decay.

Some particles are absolutely stable (at least, as far as we know):

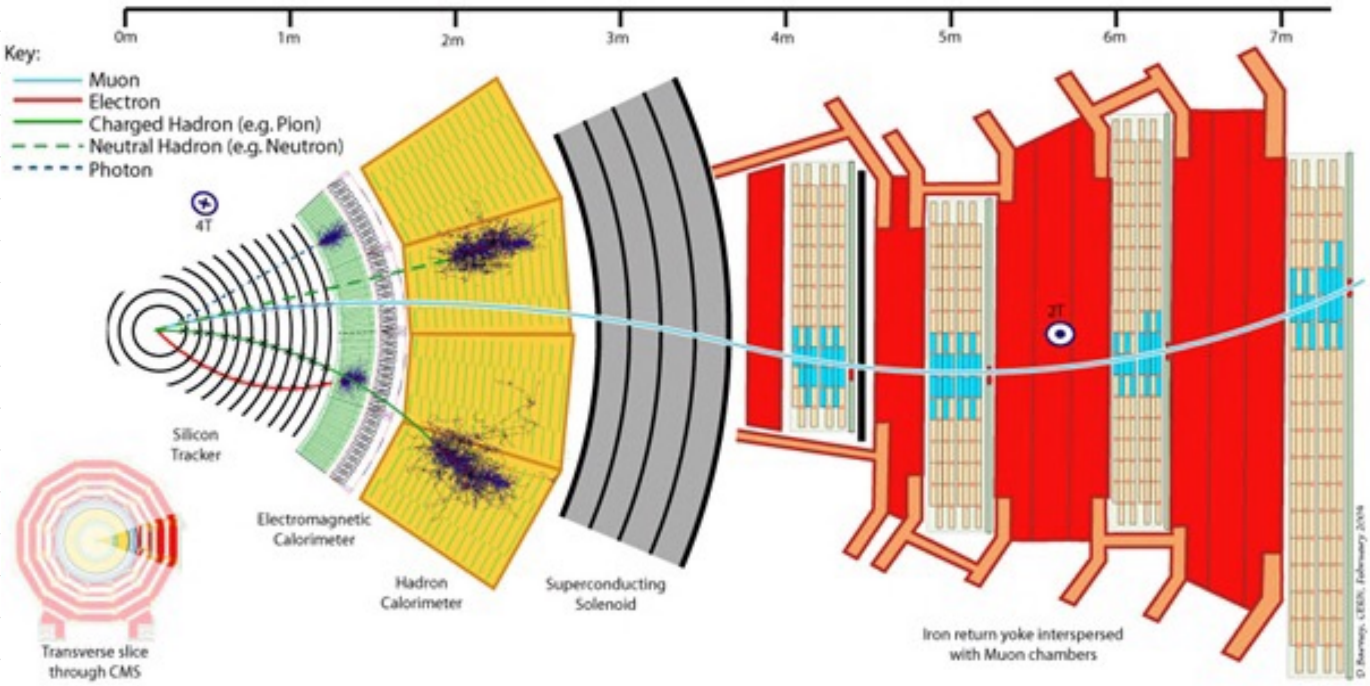
$\underbrace{p, e^{\pm}, \gamma}$, neutrinos

$\hookrightarrow$ not only they always reach a detector, but we also make beams out of these

Some particles easily reach a detector ($c\tau > 1$ m):

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

This is what we can actually see:



Other particles decay very quickly ($c\tau \sim 0.01\,\text{mm} - 1\,\text{m}$)

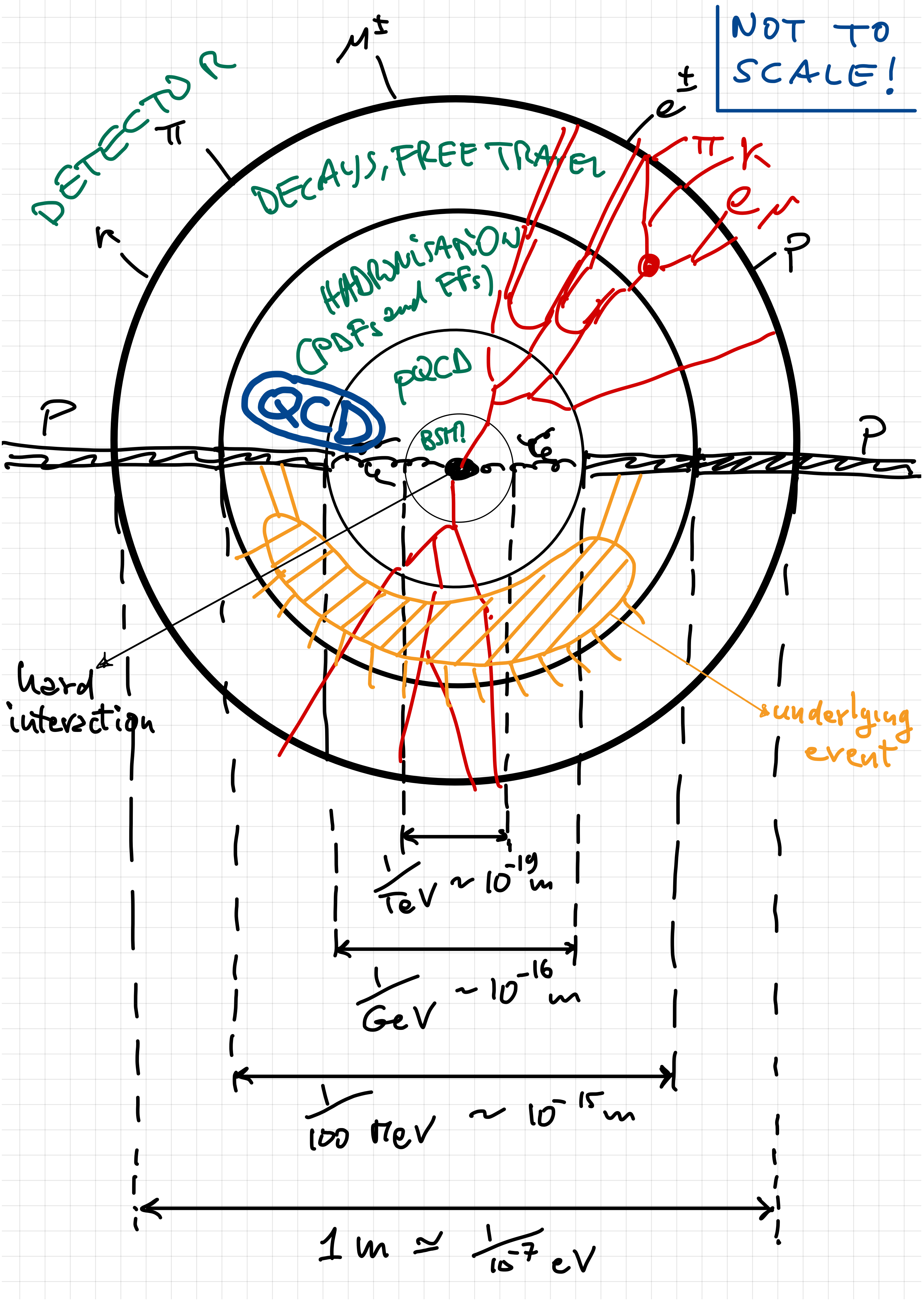
strange, charm, beauty hadrons

We can still "observe" them via reconstructed invariant mass of their decays, displaced vertices, or other characteristics of decay products

This is about it. Everything else (W, Z, Higgs, BSM physics) must be deduced from measurements of

- electron/positron candidate
- muon/antimuon candidate
- charged hadron
- neutral hadron (no tracks, cal only)
- photon
- missing transverse momentum

The challenge is to calculate predictions at the "fundamental physics" scale (<< proton size), and connect it to what we observe at macroscopic scales (detector size)


NOT TO SCALE!
DETECTOR
DECAYS, FREE TRAVEL
HADRONISATION
(PDFs and FFs)
pQCD
QCD
BSM!
P
P
P
π
μ±
e±
r
e
μ
hard interaction
underlying event
1/TeV ~ 10^-19 m
1/GeV ~ 10^-16 m
1/100 MeV ~ 10^-15 m
1 m ≃ 1/10^-7 eV

In these lectures we will concentrate on the "pQCD" shell, i.e. what we can calculate from first principle in QCD

> The "hadronisation" shell implies non-perturbative physics. While some "exact" methods exist (e.g. lattice QCD) one usually resorts to models respecting broad QCD symmetries and aspects. We won't talk about this much

We shall assume that the "BSM" circle is contracted to a point. I.e., we'll neglect it and only consider Standard Model physics.

New physics could of course be suspected by observing discrepancies between SM calculations and measurements (though, more often than not it will actually be wrong or not sufficiently accurate calculations)