QCD & Collider Physics

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Four Lectures

1. Overview & Inspiration
2. From Diagrams to Cross Sections
3. An Introduction to Jets
4. A Case Study in Jet Substructure.

(Though these lectures are being recorded, I hope you can avoid thinking about the camera and ask questions. I assure you that I will make many more silly mistakes on the blackboard that will make your questions seem very insightful by comparison!)

Lecture 1: Overview & Inspiration

Why colliders?

Smash particles together at ever increasing energies to learn about fundamental physics?

Yes! It is our best (known) strategy to study:

- heavy objects
- short lifetimes
- rarely produced

[If you come up with a better method, you will revolutionize particle physics.]

E.g. Higgs boson

$m_h \approx 125$ GeV

$c\tau_h \approx 5 \times 10^{-11}$ mm ← Have to simultaneously produce <u>and</u> study

$\sigma_h^{LHC} \approx 50$ pb

Why QCD?

Our most powerful direct probe of short distance physics is the Large Hadron Collider, which collides protons.

Protons are bound states of quarks and gluons.

Therefore QCD dynamics is an inevitable challenge for any LHC analysis.

At its most basic, collider physics is just an application of quantum mechanical scattering theory.

Start at time $-T$, evolve to $+T$, and take $T \to \infty$ limit.

$$\lim_{T \to \infty} \sum\!\!\!\!\!\!\int_{out} \left| \langle out | e^{-iH(2T)} | in \rangle \right|^2 w_{out}$$

$|in\rangle$ = incoming plane waves for colliding beams. In LHC case, this is proton from $+\hat{z}$ direction and proton from $-\hat{z}$ direction.

$|out\rangle$ = some outgoing configuration of interest.

$\sum\!\!\!\!\!\!\int_{out}$ = Key! Have to include <u>all</u> states that contribute to your measurement. Even states that don't interfere! If your detector can't distinguish X from X + low energy pion, you have to include "+ pion" in your sum/integral.

w_{out} = a possible weight factor for different final states.

The key to collider physics is choosing $\sum\!\!\!\!\!\!\int_{out} w_{out}$ in such a way that:

- the answer is physically interesting/relevant
- you can compute it theoretically
- you can measure it experimentally

QCD dynamics feature prominently in the choice of collider measurements. While you could ask about the cross section for

$$pp \to 37\pi^0 + 31\pi^+ + 29\pi^- + 10K^+ + 10K^- + 2n$$

(Hopefully this conserves charge and baryon number...) this is a very non-perturbative question from the QCD perspective.

You want to choose observables (i.e. choices of $\oint_{out} w_{out}$) such that:

$$\sum_{\text{hadrons}} pp \to \text{hadrons} \simeq \sum_{\text{partons}} pp \to \text{partons}$$

More formally, you want "factorizable" observables where there is a clean separation between perturbative and non-perturbative QCD dynamics.

As we will see later in these lectures, jets are one example of an analysis strategy where what you measure on hadrons is closely related to what you can calculate perturbatively on partons.

Though there have been ~40 years of jet physics, there are still creative new ways to analyze hadronic final states, and you have the potential to make a contribution in this area!

Let's start with some numbers to give a sense of scale.

Parameters of the LHC: p ⟶ ⟵ p

proton-proton $E_{cm} = 7, 8, 13$, eventually 14 TeV

collision rate: $40\ \text{MHz} = \frac{1}{25\ \text{nanoseconds}}$

protons per bunch: $\approx 10^{11}$ (similar to number of stars in the Milky Way)

Instantaneous Luminosity: $\frac{N_1 N_2 f}{A_{eff}} \approx \frac{2 \times 10^{34}}{\text{cm}^2\ \text{sec}}$

(A_{eff} ← $\approx (.1\text{mm})^2$)

Integrated Luminosity: $\int dt\, \mathcal{L} \approx 100\ \text{fb}^{-1}/\text{yr}$ ← ok, but what does this mean?

(dt ↑ actual uptime (2 months/yr))

proton radius $\text{fm} = 10^{-15}\ \text{m} \approx \frac{1}{200\ \text{MeV}}$

barn $100\ \text{fm}^2 = 10^{-28}\ \text{m}^2$

σ_{pp} $\approx 0.1\ \text{b}$ (total cross section)

$\Rightarrow 100\ \text{fb}^{-1} \cdot 0.1\ \text{b} = 10^{16}$ proton-proton collisions

↑ in principle, huge dataset

But there is no way to record all of those collisions!

Proton-proton collisions per beam crossing?

$$\mathcal{L} \cdot T \cdot \sigma \approx 50 \quad (!)$$

- $\mathcal{L}$: $\frac{2\times10^{34}}{cm^2\, sec}$
- T: 25 ns
- σ: 0.1 b
- 50: most of these are uninteresting "pileup"

Collisions to tape?

1 collision ≈ 1 cute picture of my kid ≈ 1 MB (with compression)

Total data rate: $40\,MHz \cdot 1\,MB = 40000 \frac{GB}{sec}$

- 40000: Rough factor by which you have to reduce data volume
- $\frac{GB}{sec}$: Write speed for array of fast hard drives

"Triggering": real time decision about whether to keep a collision or lose information forever.

How many Higgs bosons have been produced in diphoton channel?

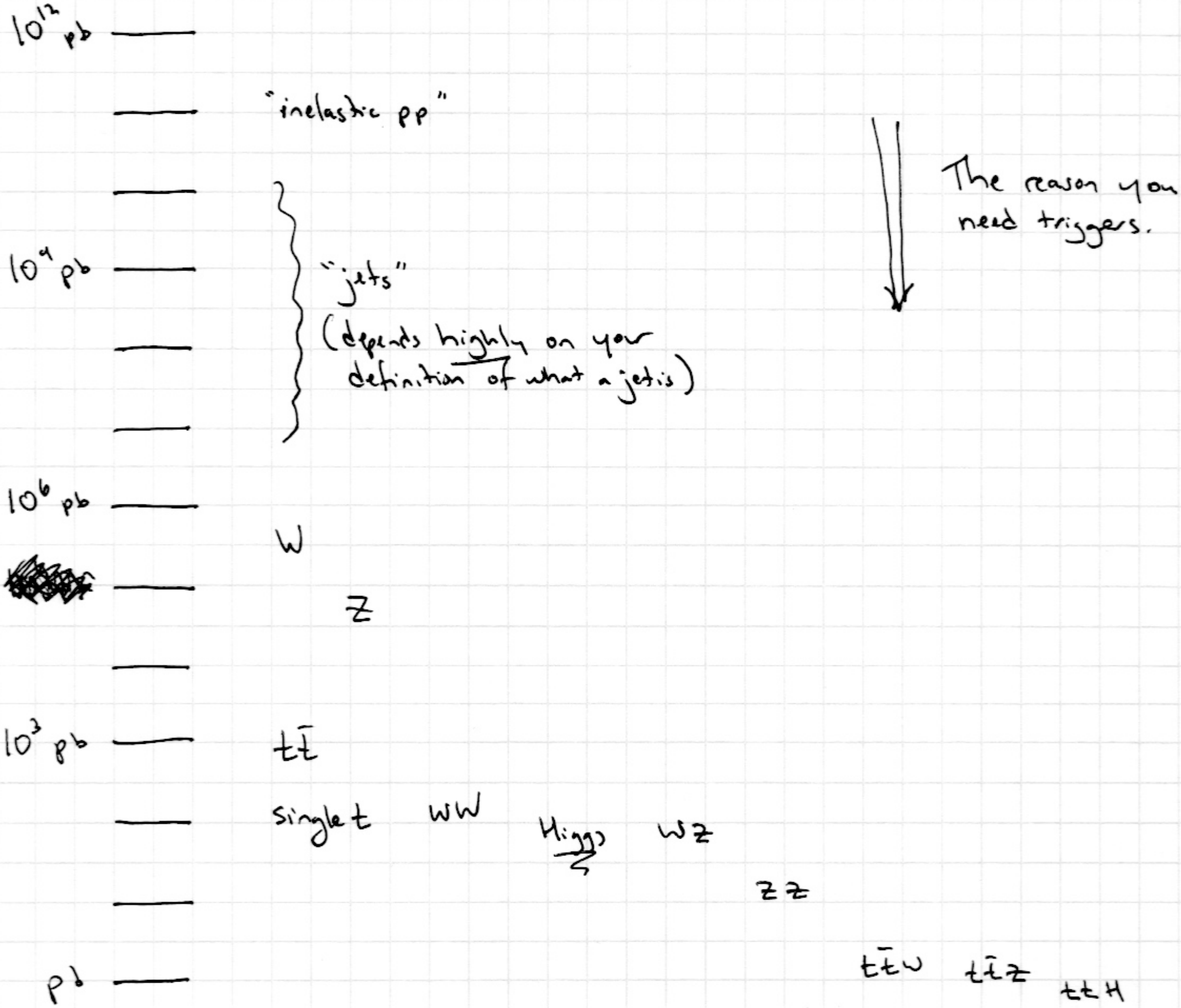
$$N_{H\to\gamma\gamma} = \underbrace{\mathcal{L}\cdot T}_{100\,fb^{-1}} \cdot \underbrace{\sigma^{LHC}_{Higgs}}_{50\,pb} \cdot \underbrace{Br(H\to\gamma\gamma)}_{2\times10^{-3}}$$

(100 fb^{-1}: actually a bit more by end of Run 2.)

≈ 10,000

A big number! But you have to wrestle with non-Higgs $pp\to\gamma\gamma$ background.

To give you a sense of scale, here are processes in the standard model, arranged by cross section.



A huge range (and range of scales) of processes!

These are backgrounds to each other and backgrounds to new physics.

The Master Formula for Collider Physics

All of our analyses will, in one way or another, stem from this:

$$AB \to 1 \; 2 \; 3 \; \ldots \; n$$

$$\sigma_{obs} = \frac{1}{2E_{cm}^2} \sum_{n=2}^{\infty} \int d\Phi_n \left|\mathcal{M}_{AB\to 12\ldots n}\right|^2 f_{obs}(\Phi_n)$$

- σ_{obs} ↑ cross section for an observable ("measurement")
- $\frac{1}{2E_{cm}^2}$ ↑ geometric factor (assuming massless beams)
- $\sum_{n=2}^{\infty}$ ↑ all possible final states
- $d\Phi_n$ ↑ n-body Lorentz invariant phase space
- $\mathcal{M}$ ↑ Scattering amplitude
- $f_{obs}(\Phi_n)$ ↑ a measurement function.

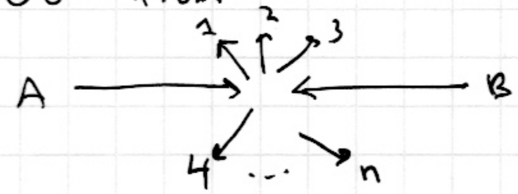
Key: The cross section you measure depends on what you measure.

Need to think carefully about observables and the choice of f_{obs} to use for a given physical process.

Have to sum/integrate over all final states that contribute to f_{obs}. This will be very important when we talk about jets.

Note: Cross sections have units of area, saturated by $1/2E_{cm}^2$ factor.

Goal: Go from



to σ_{obs}.

Challenge: What you measure are hadrons (e.g. pions, kaons, ...) but the scattering amplitudes you know how to calculate involve partons (quarks & gluons)

Bridging this divide is a major open issue, but clever choices of observables can mimimize the gap.

In many ways, we are lucky because QCD dynamics are "simple" compared to other strongly-coupled theories, since QCD yields jets, and jets are reasonable proxies for quarks/gluons.

Let's remind ourselves about QCD (turning off electroweak processes for simplicity)

$$\mathcal{L}_{QCD} = -\frac{1}{4g_s^2} G^a_{\mu\nu} G^{\mu\nu a} \qquad (a = 1,2,3,4,5,6,7,8)$$

$$+ \sum_{q \in \{d,u,s,c,b,t\}} \Big[\bar{\psi}_q i \bar{\sigma}^\mu D_\mu \psi_q + \bar{\psi}^c_q i \bar{\sigma}^\mu D_\mu \psi^c_q$$

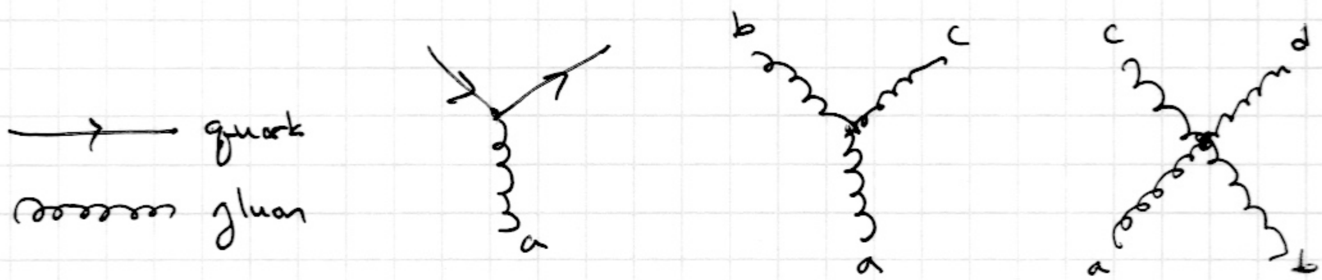
↑ covariant derivative $\equiv \partial_\mu - i A^a_\mu t^a$

(in two component spinor notation)

$$- m_q \left(\psi_q \psi^c_q + \bar{\psi}_q \bar{\psi}^c_q \right) \Big]$$

↑ quark masses

And that's it!

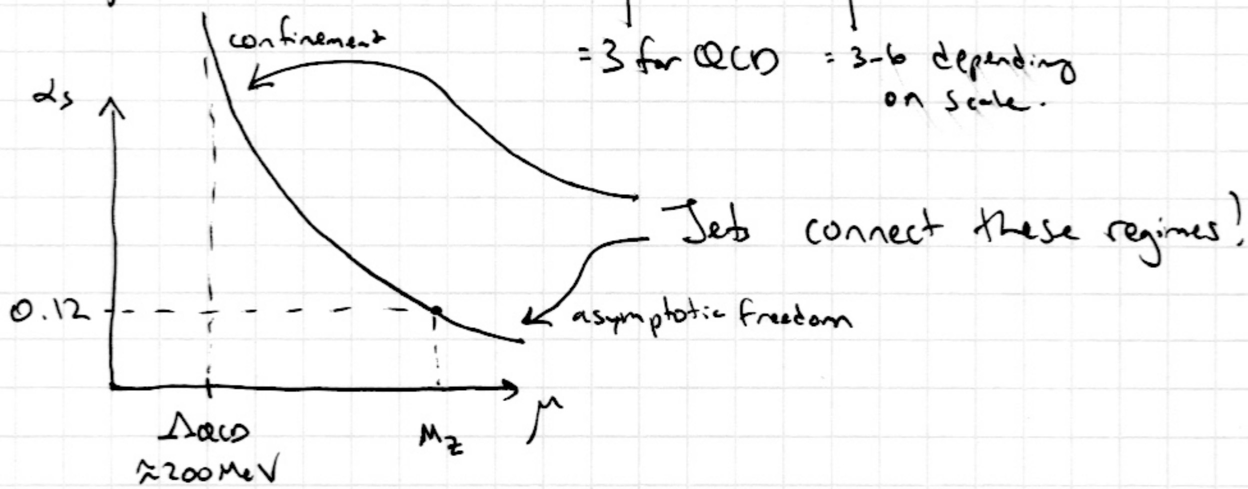


$\propto g_s t^a$ $\qquad$ $\propto g_s f_{abc}$ $\qquad$ $\propto g_s^2 f^2$

Fact: strong coupling constant runs! $\alpha_s \equiv \frac{g_s^2}{4\pi}$

$$\mu \frac{\partial}{\partial \mu}\left(\frac{1}{\alpha_s}\right) = \frac{1}{4\pi}\left(\frac{11}{3}N_c - \frac{2}{3}N_f\right)$$

N_c = 3 for QCD; N_f = 3-6 depending on scale.



At short distances: gluons & quarks (down, up, strange, charm, bottom, top)

At long distances ⟹ Confinement!

Mesons ($q\bar{q}$)

spin-0: $\pi^+ \pi^- \pi^0 \eta K^+ K^- K^0 \eta' \ldots$

spin-1: $\rho^+ \rho^- \rho^0 \omega K^{*+} K^{*-} K^{*0} \phi \ldots$

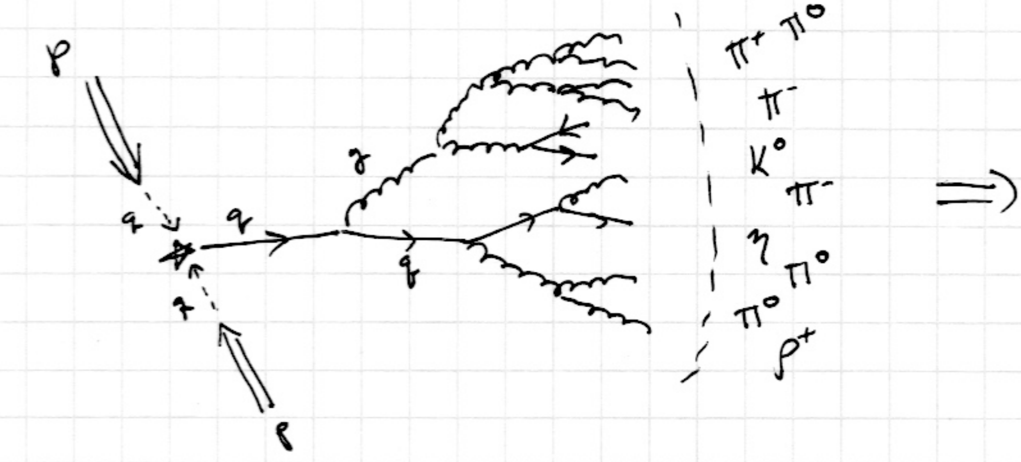
Baryons (qqq)

spin-1/2: $p\ n\ \Lambda^0\ \Sigma^+ \Sigma^0 \Sigma^- \Xi^0 \Xi^- \ldots$

spin-3/2: $\Delta^{++} \Delta^+ \Delta^0 \Delta^- \Sigma^{*+} \Sigma^{*0} \Sigma^{*-} \Xi^{*0} \Xi^{*-} \Omega^- \ldots$

Recently: tetraquarks ($qq\bar{q}\bar{q}$) & pentaquarks ($qqqq\bar{q}$)

A Cartoon of Jet Formation



LHC Detector
(not part of these lectures)

Hard collision of partons | Perturbative parton showering | Nonperturbative hadronization

We will return to this picture in later lectures, but key is that

energy flow of partons $\approx$ energy flow of hadrons $\approx$ energy deposits measured experimentally

This fact is somewhat special to QCD, and the fact that it is true is why jet clustering is a sensible observable strategy.

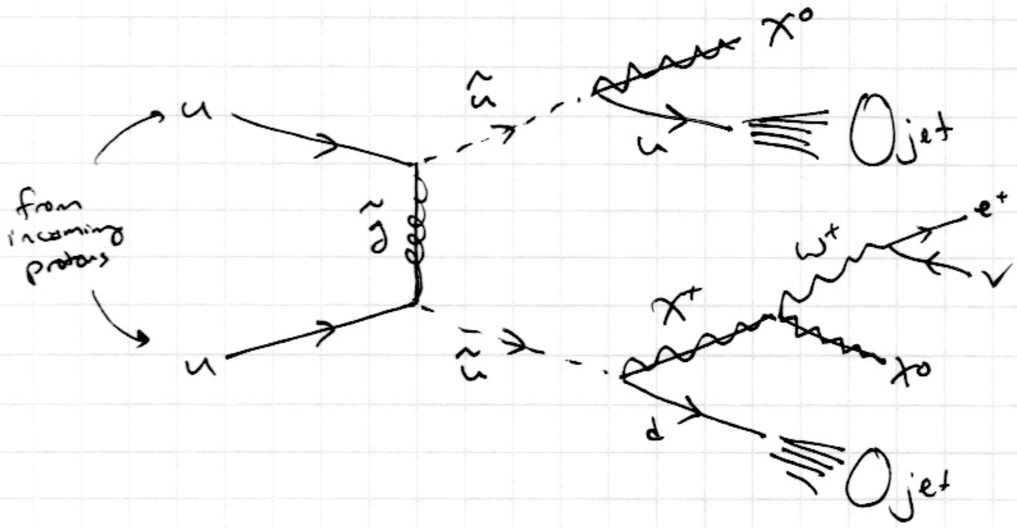
More generally, we need to learn how different fundamental particles manifest observationally:

Not Jets (at least at LHC energies)	:	e μ τ ($\uparrow$ microjet) ν_1 ν_2 ν_3 γ
Jets	:	d u s c b (heavy flavor tagged) g
Fat Jets (~70% of the time, when Lorentz boosted)	:	$W \to q\bar{q}'$ $Z \to q\bar{q}$ $H \to b\bar{b}$ $t \to bW$ ($\hookrightarrow q\bar{q}'$)

Can't ignore hadronic final states! Can't ignore QCD!

Searching for physics beyond the Standard model is essentially the same as measuring a cross section and looking for deviations from Standard Model predictions.

E.g. Search for supersymmetry using jets plus leptons plus missing momentum.



+ ISR/FSR/UE

+ pileup.

Intuitively, this is a "2 jet + positron + missing momentum" final state, but depending on precise kinematics & jet definition could be any number of jets.

How do you distinguish from

$$pp \to Z + W^+ + \text{jets}\,?$$
$$Z \hookrightarrow \nu\nu \qquad W^+ \hookrightarrow e^+\nu$$

What about

$$pp \to t + \bar{t}\,?$$
$$t \hookrightarrow b W^+, \quad W^+ \hookrightarrow e^+\nu \qquad \bar{t} \hookrightarrow \bar{b} W^-, \quad W^- \hookrightarrow \text{jets}$$

Measurements unavoidably mix these processes to some degree (at minimum by detector effects). Goal is to separate as much as possible (limited of course by quantum mechanics).

Formally, in scattering theory, we take the $T \to \infty$ limit, but experimentally, there are always finite time limitations.

To orient the discussion, it is instructive to take a tour of the PDG (Particle Data Group) to get a sense of the time scales involved for practical scattering experiments.

Absolutely Stable (to the best of our knowledge)

p	proton	$m_p = 938$ MeV	We know how to make beams of these
e^-	electron	$m_e = 511$ keV	
γ	photon	$m_\gamma = 0$	
$\nu_1\ \nu_2\ \nu_3$	neutrinos	$m_\nu \approx 0$	No idea how to make beams of these
G	graviton	$m_G = 0$	

Workhorse colliders: e^+e^-, pp, $p\bar{p}$, e^-p

(For nuclear physics, also heavy-ion colliders.)

Collider Stable ($c\tau > 1\,m$)

n neutron $m_n = 940$ MeV $c\tau = 2.7 \times 10^{14}$ mm

(Can make beams of these, but hard to control)

μ^- muon $m_\mu = 106$ MeV $c\tau = 6.6 \times 10^5$ mm

(Might eventually make beams of these.
Definitely design detectors around measuring them.)

K_L kaon-long $m_{K_L} = 498$ MeV $c\tau = 1.5 \times 10^4$ mm

(Need hadronic calorimeters to catch these)

$\pi^\pm$ charged pion $m_{\pi^\pm} = 140$ MeV $c\tau = 7.8 \times 10^3$ mm

$K^\pm$ charged kaon $m_{K^\pm} = 494$ MeV $c\tau = 3.7 \times 10^3$ mm

(Mostly stable, detectable as charged tracks, though their decays can give you "punchthrough")

At a basic level, all* scattering amplitudes relevant for collider physics just involve the above particles in the final state

* Not really true, since you can infer shorter-lived particles through displaced signatures. More in a moment...

Sort of Stable ($c\tau > 10$ mm)

Ξ^0 Λ^0
Ξ^- Σ^-
Ω^- Σ^+

} Strangeness carrying baryons: $m \approx 1.2 - 1.7$ GeV, $c\tau \approx 24 - 87$ mm

K_s kaon-short $m_{K_s} = 498$ MeV $c\tau = 27$ mm

(This decays to $\pi^0 \pi^0$ or $\pi^+ \pi^-$, and the intermediate lifetime makes it kind of a pain.)

Remember, by time dilation, lifetime in the lab frame scaled by a Lorentz γ factor. So some of these do actually hit the detector sometimes.

Displaced Vertex ($c\tau > .01$ mm)

B^+ B^0 B_s^0	bottom mesons	$m_B = 5.3$ GeV	$c\tau = .44 - .49$ mm
Λ_b^0 Ξ_b^- etc.	bottom baryons		
Ξ_{bc}^+ etc.	bottom-charm baryons	$m = 5.6 - 15.1$ GeV	$c\tau = .36$ mm
Ω_{bb}^- etc.	bottom-bottom (-b) baryons		
D^+ D_s^+	charm mesons	$m_D = 1.9$ GeV	$c\tau = .12 - .15$ mm
D_0 (B_c^+)		(6.2 GeV)	
Ξ_c^+ (Λ_c^+)	charm baryon		
Ξ_{cc}^+ etc.	charm-charm baryon	$m = 2.5 - 4.9$ GeV	$c\tau = .10 - .13$ mm (.02 - .06 mm)
Ω_{ccc}^{++}	charm-charm-charm baryon		
τ^-	tau lepton	$m_\tau = 1.78$ GeV	$c\tau = .087$ mm

(Has diverse decays that must be reconstructed)

Everything else cannot be resolved directly at (current) colliders! (And these displaced vertex decays are hard!)

These are only ingredients you need for $AB \to 1 2 3 \cdots n$

Wait! You mentioned $\pi^\pm$. Where is neutral pion?

π^0 neutral pion $m_{\pi^0} = 135$ MeV $c\tau = 2.6 \times 10^{-5}$ mm

(Unstable on collider time scales, seen as $\pi^0 \to \gamma\gamma$ and sometimes difficult to distinguish from single photon.)

At ATLAS & CMS, not all of these particles are distinguishable. Generic particle categories are:

"$e^\pm$"	electron/positron candidate
"$\mu^\pm$"	muon/anti-muon candidate
"$\pi^\pm$"	charged hadron (includes $K^\pm$, $p/\bar{p}$, etc.)
"K^0_L"	neutral hadron (includes n, etc.)
"γ"	photon (may or may not include $\pi^0 \to \gamma\gamma$)
$\not{E}_T$	missing transverse momentum (includes neutrinos)

All of the rest of the standard model has been <u>inferred</u> by these detectable ingredients.

This is a triumph of theoretical reasoning and experimental ingenuity.

If we are really lucky, new physics will show up as a long-lived particle we can "see" directly, but most likely, we'll have do infer it from these same ingredients.