Particle Physics Phenomenology

Peter Skands, Monash University

October 1-2, 2015, Sydney
Spring School on Particle Physics & Cosmology

THEORY

PHENOMENOLOGY

EXPERIMENT

QCD

INTERPRETATION

"Jets"

Figure by T. Sjöstrand
Come up with theory idea (e.g., SM, SUSY, QGP, CP, ...)  
... should be testable in experiments

Formulate phenomenological model (based on theoretical ideas)  
... working-hypothesis physics model capturing essence of idea

Propose new sensitive observables (based on models)  
... which can be measured in experiments

Make (detailed and precise) calculations  
... which can be compared (statistically) against experiments

Provide theoretical interpretations  
... of the experimental results
The main particle-physics units of energy is MeV, GeV, TeV

1 electron-Volt = kinetic energy obtained by an electron accelerated by potential difference of 1 Volt

\[ 1 \text{eV} = Q_e \cdot 1 \text{V} = 1.602176565(35) \times 10^{-19} \text{C} \cdot 1 \text{J/C} = 1.6 \times 10^{-19} \text{J} \]

(So for accelerators, the beam energy in eV is a measure of the equivalent electrostatic potential difference, for unit charge)

Planned **linear** accelerators (ILC, CLIC) could reach \( E_{\text{CM}} \sim 1000 \text{ GeV}. \)

The highest-energy (**circular**) accelerator LHC \( \sim 6500 \text{ GeV/beam}. \)

Using \( E=mc^2 \) we typically express mass in units of eV/c^2

\[
\begin{align*}
  m_e &= 9.11 \times 10^{-31} \text{kg} = 0.511 \text{ MeV/c}^2 \\
  m_\mu &= 106 \text{ MeV/c}^2 \\
  m_\tau &= 1780 \text{ MeV/c}^2 \\
  m_{\text{proton}} &= 938 \text{ MeV/c}^2 \sim 1 \text{ GeV/c}^2
\end{align*}
\]

(sometimes we don’t even say the 1/c^2; it is implied by the quantity being mass)
In fact, we use MeV and GeV for **everything**!

**Define** a set of units in which $\hbar = c = 1$

- **Action** [Energy*Time] : dimensionless ($\hbar = 1$)
  
  All actions are measured in units of $\hbar$

- **Velocity** [Length/Time] : dimensionless ($c = 1$)
  
  All velocities are measured in units of $c$ (i.e., $\beta = v/c$)

**Energy** : dimension 1

**Mass** : dimension 1 ($E=m$)

  E.g., $m_p = 0.94$ GeV; masses ~ measured in units of $m_p$

**Time** : dimension -1 ($\Delta E \Delta t \geq 1$; $E = 2\pi \nu$)

**Length** : dimension -1 (velocity is dimensionless)

**Momentum** : dimension 1 ($\Delta p \Delta x \geq 1$)

---

<table>
<thead>
<tr>
<th>$\lambda$</th>
<th>$E$</th>
</tr>
</thead>
<tbody>
<tr>
<td>HEP</td>
<td>$&lt; 1$ fm</td>
</tr>
<tr>
<td>gamma</td>
<td>1 pm</td>
</tr>
<tr>
<td>X-rays</td>
<td>0.1 nm</td>
</tr>
<tr>
<td>UV</td>
<td>100 nm</td>
</tr>
</tbody>
</table>

Example: lengths $\rightarrow$ energies
Predicted number of counts
= integral over solid angle

\[ N_{\text{count}}(\Delta \Omega) \propto \int_{\Delta \Omega} d\Omega \frac{d\sigma}{d\Omega} \]

In particle physics:
Integrate over all quantum histories
(+ interferences)
Consider Electromagnetism = electron-photon interactions
All based on the same vertex

1) $e \rightarrow e + \gamma$
2) $e^- + e^+ \rightarrow \gamma$
3) $\gamma \rightarrow e^- + e^-$

What about 4-momentum conservation?

1) Electron at rest decaying to a recoiling electron + a photon?
2) Two massive particles reacting to produce a massless photon?
3) Massless photon decaying to two massive electrons?

This all sounds very strange (even for relativity)
Let us consider first the pure electromagnetic interactions

All based on the same vertex

What about 4-momentum conservation?

At least one of the involved particles must have $E^2 - p^2 \neq m^2$

(Can exist for a brief time due to Heisenberg)

We call such particles virtual; and say they are off mass shell
Virtual Particles: Examples

Stitch vertices together to form Feynman diagrams

\[
E_{e^*}^2 - |\vec{p}_{e^*}|^2 > m_e^2
\]

\[
\gamma + e \rightarrow e^*
\]

A) \[ E_{\gamma^*}^2 - |\vec{p}_{\gamma^*}|^2 > 0 \] ?

B) \[ E_{\gamma^*}^2 - |\vec{p}_{\gamma^*}|^2 < 0 \] ?

\[
\gamma^* \rightarrow e^- + e^-
\]

\[
E_{\gamma^*}^2 - |\vec{p}_{\gamma^*}|^2 > 0
\]

\[
e^+ + e^- \rightarrow \gamma^*
\]

\[ (\text{for } m_e = 0) \]

\[
p_{\gamma}^2 = (p_1 - p_3)^2
\]
Quantum Field Theory (QFT)

We use Feynman diagrams to draw the possible histories. These are symbolic (correspond to state changes in the underlying QFT).

Diagram representing QM amplitude for:
“an electron and a positron annihilated to produce a (virtual) photon, which then split back up into an \( e^+ e^- \) pair again.”

\[
e^{-}(p_1) + e^{+}(p_2) \rightarrow e^{-}(p_3) + e^{+}(p_4)
\]

E.g., in Bhabha scattering, the force is attractive (an electron and a positron attract) but we still draw them as heading away from each other.

Example (units in GeV):
\[
p_1 = (5, 0, 0, 5) \\
p_2 = (5, 0, 0, -5) \\
p_3 = (5, 0, 3, 4) \\
p_4 = (5, 0, -3, -4)
\]
Actually, two Quantum “histories” contribute to Bhabha

Must sum both amplitudes; then square to get probability
(two “paths”; analogously to double-slit experiment)

$$|A|^2 = |A_1 + A_2|^2 = |A_1|^2 + |A_2|^2 + 2\text{Re}[A_1 A_2^*]$$

Q.M. interference
Scattering: cross sections

Want to express scattering probability independently of the intensity (flux) of incident particles (beams)

\[ N_{\text{events}} = \text{Probability-per-particle} \times \text{Number-of-particles} \]

\[ \Rightarrow N_{\text{events}} = \text{Probability [area/particle]} \times N_{\text{particles/area}} \]

\[ \Rightarrow N_{\text{events/time}} = \text{Probability [area/particle]} \times N_{\text{particles/area/time}} \]

Event Rate = Cross Section \times Luminosity

“\( \sigma \)”

Measure in Experiment

Compare with Prediction

Calculate from fundamental theory

Determined by accelerator parameters. In principle measurable (e.g., Van der Meer scans)
Disintegration : decay rates

Murphy’s law for particles: anything that can decay, will decay

What we actually measure is typically a cross section times a branching fraction

E.g., the event rate for $h^0 \rightarrow \gamma\gamma$ observed at LHC is compared to a theoretical calculation of

$$N(h^0 \rightarrow \gamma\gamma)_{LHC} = \sigma(pp \rightarrow h^0) \times BR(h^0 \rightarrow \gamma\gamma) \times L_{pp} \times <\text{efficiency}>$$

How does a particle decay?

It sits in its rest frame and gets time evolved, by $e^{iHt}$

Unstable $\rightarrow$ H contains operators that want to kill it ... They compete about which one goes first (can only decay once)
Particles are **elementary**, indistinguishable.

Any “history” information is encoded in their quantum numbers

An “old” particle doesn’t have a higher probability of decaying in the next second than a “young” one

What matters is the instantaneous decay rate per unit time

\[ dN = -\Gamma N dt \quad \Rightarrow \quad N(t) = N(0) e^{-\Gamma t} \quad \Rightarrow \quad \tau = \frac{1}{\Gamma} \]

Generalise to multiple different decay modes

\[ \Gamma = \sum_i \Gamma_i \]

\( \Gamma_i \) : “Partial Width”

Branching Ratio : \( \text{BR}(i) = \frac{\Gamma_i}{\sum_j \Gamma_j} \)

or “branching fraction”

\[ \begin{array}{|c|c|c|}
\hline
\text{Mode} & \Gamma_j / \Gamma & \text{Confidence level} \\
\hline
\gamma^+ & \mu^+ \nu_\mu & \text{[a]} \quad (99.98770 \pm 0.00004) \% \\
\gamma^+ & \mu^+ \nu_\mu \gamma & \text{[b]} \quad (2.00 \pm 0.25) \times 10^{-4} \\
\gamma^+ & e^+ \nu_e & \text{[a]} \quad (1.230 \pm 0.004) \times 10^{-4} \\
\gamma^+ & e^+ \nu_e \gamma & \text{[b]} \quad (7.39 \pm 0.05) \times 10^{-7} \\
\gamma^+ & e^+ \nu_e \pi^0 & \text{[c]} \quad (1.036 \pm 0.006) \times 10^{-8} \\
\gamma^+ & e^+ \nu_e e^+ e^- & \text{[d]} \quad (3.2 \pm 0.5) \times 10^{-9} \\
\gamma^+ & e^+ \nu_e \nu \pi & < 5 \times 10^{-6} \quad 90\% \\
\hline
\end{array} \]

example from the “PDG book” pdg.lbl.gov
Thresholds

An object cannot be produced unless the colliding particles have enough CM energy to create its rest mass.

An object cannot decay to any (combination of) particles heavier than itself.

Unless …

*Heisenberg*: the energy is uncertain…

If a particle is unstable (has a non-zero decay rate), then we at most have the duration of its life to measure its energy.

Analogous to line-broadening of lines in spectra of excited atoms.

→ *Shapes like this: “Breit-Wigner” “resonances”*
Quantity of interest:

Effective cross-sectional area presented by a “target particle” to a stream of “incident particles”

- Relativity must get the same if we swap the roles of incident and target particles, or in any other frame
- So more precisely it’s really the cross-sectional area two streams of particles present to each other

Complications

This isn’t classical physics: each particle has a probability to go through the target unaffected, + all possible scatterings

- A plane wave comes in
- An interaction Hamiltonian (of which the incoming plane wave is not an eigenstate) evolves it for a while
- ➜ the evolved state is a superposition of all possible outgoing states

+ not only elastic scattering. Creation + annihilation : inelastic.
Scattering off a Hard Spherical Cow

What’s the total cross section?
(Scattering off a hard sphere)

Generalise to quantum scattering of relativistic particles: Quantum Field Theory
Fermi’s Golden Rule

Two basic ingredients to calculate decay rates and cross sections

1) The **amplitude** for the process: $\mathcal{M}$
   - Contains all the *dynamical* information; couplings, propagators, ...
   - Calculated by evaluating the relevant Feynman Diagrams, using the "Feynman Rules" for the interaction(s) in question

2) The **phase space** available for the process
   - Contains only *kinematical* information;
   - Depends only on external masses, momenta, energies;
   - "Counts" the number/density of available final states

The Golden Rule is*:

$$\text{transition rate} = \frac{2\pi}{\hbar} |\mathcal{M}|^2 \times (\text{phase space})$$

*For a derivation, see QM (nonrelativistic) or QFT (relativistic)
Many from One (well … from Two, really)
Quantum processes convert the kinetic energy of the beam particles into rest energy (mass) + momentum of outgoing particles

\[ E = mc^2 \sqrt{1 + \frac{p^2}{(mc^2)^2}} \]

What are we really colliding?
Take a look at the quantum level

Hadrons are composite, with time-dependent structure

\[ u \quad d \quad g \]

\[ p \quad u \quad u \]
Many from One (well … from Two, really)

Quantum processes convert the kinetic energy of the beam particles into rest energy (mass) + momentum of outgoing particles

\[ E = mc^2 \sqrt{1 + \frac{p^2}{(m^2c^2)}} \]

What are we really colliding?

Take a look at the quantum level
Lifetime of typical fluctuation $\sim \frac{r_p}{c}$ (=time it takes light to cross a proton)

$\sim 10^{-23}$ s; Corresponds to a frequency of $\sim 500$ billion THz

To the LHC, that’s slow! (reaches “shutter speeds” thousands of times faster)

Planck-Einstein: $E=nh \nu \Rightarrow \nu_{LHC} = 13$ TeV/$h = 3.14$ million billion THz

$\Rightarrow$ Protons look “frozen” at moment of collision

But they have a lot more than just two “u” quarks and a “d” inside

Hard to calculate, so use statistics to parametrise the structure: parton distribution functions (PDFs)

Every so often I will pick a gluon, every so often a quark (antiquark)

Measured at previous colliders, as function of energy fraction

Then compute the probability for all possible quark and gluon reactions and compare with experiments …
Rates and Triggers

Not all reactions are created equally

- The most likely collision type is $gg \rightarrow gg$
- The top quark is the heaviest elementary particle
  - Discovered in 1995 by Fermilab’s “Tevatron” accelerator.
  - The LHC can make $\sim 1$ top quark / second.
- The reaction $gg \rightarrow$ Higgs will happen $\sim 1$ / minute
  - We don’t want to lose too many of them …

We get $\sim 40$ million collisions / sec.
We can save $\sim 100$ / sec to disk.

**WHICH ONES?**

Automated “trigger” systems decide which collisions may be interesting
Easy to collect millions of events of “high-cross-section-physics”

→ Test models of “known physics” to high precision

Triggers target the **needles in the haystack**

Trigger on signatures of decays of heavy particles, violent reactions

“Photons”  “Leptons”  “Missing Energy”  “Jets”
**Precision & Discovery** go hand in hand

E.g., after the Higgs discovery, now comes *precision study*

**Recognise** the unknown: understand the known

Calibrate your methods, test your strategies, …

& occasionally discover that you didn’t understand “the known” …

My own work focuses on the modelling of “jets”

Sprays of nuclear matter, produced by energetic quarks and gluons

Such as when they scatter off each other

Or when a heavy particle decays to quarks / gluons

\[ h^0 \rightarrow \overline{b} b \]
**Example: Decays of the Z boson**

**Leptons**
- electron-positron pair creation
- muon-antimuon pair creation

(from the ALEPH experiment at the Large Electron Positron Collider)

**Jets**
- quark-antiquark pair creation ➔ 2 Jets
- quark-antiquark + gluon ➔ 3 Jets
Collider Calculations

Calculate Everything $\approx$ solve QFT* $\rightarrow$ requires compromise!

Start from lowest-order perturbation theory,
Include the ‘most significant’ corrections
$\rightarrow$ **Monte Carlo event generators**

*QFT = Quantum Field Theory
**Organising the Calculation**

**Divide and Conquer** → Split the problem into many (nested) pieces

+ Quantum mechanics → Probabilities → Random Numbers

\[ P_{\text{event}} = P_{\text{hard}} \otimes P_{\text{dec}} \otimes P_{\text{ISR}} \otimes P_{\text{FSR}} \otimes P_{\text{MPI}} \otimes P_{\text{Had}} \otimes \ldots \]

**Hard Process & Decays:**
- The basic hard process. E.g., \( gg \rightarrow H^0 \rightarrow \gamma\gamma \)
- Sets highest resolvable scale: \( Q_{\text{MAX}} \)

**Initial- & Final-State Radiation (ISR & FSR):**
- Bremsstrahlung, driven by differential evolution equations, \( dP/dQ^2 \), as function of resolution scale; run from \( Q_{\text{MAX}} \) to ~ 1 GeV

**MPI (Multi-Parton Interactions)**
- Protons contain lots of partons → can have additional (soft) parton-parton interactions → Additional (soft) “Underlying-Event” activity

**Hadronization**
- Non-perturbative modeling of parton → hadron transition
Bremsstrahlung

a.k.a. Initial- and Final-state radiation

Radiation

Accelerated Charges

Radiation

The harder they get kicked, the harder the fluctuations that continue to become strahlung

cf. equivalent-photon approximation
Weiszäcker, Williams ~ 1934
The Structure of Jets

**Partons** ab → "collinear":
\[ |M_{F+1}(\ldots, a, b, \ldots)|^2 \xrightarrow{a\|b} g_s^2 C \frac{P(z)}{2(p_a \cdot p_b)} |M_F(\ldots, a + b, \ldots)|^2 \]

**Gluon** j → "soft":
\[ |M_{F+1}(\ldots, i, j, k, \ldots)|^2 \xrightarrow{j \to 0} g_s^2 C \frac{(p_i \cdot p_k)}{(p_i \cdot p_j)(p_j \cdot p_k)} |M_F(\ldots, i, k, \ldots)|^2 \]

+ scaling **violation**: \[ g_s^2 \to 4\pi\alpha_s(Q^2) \]


Can apply this many times → nested factorizations

Most bremsstrahlung is driven by divergent propagators → simple structure

Amplitudes **factorize** in singular limits (→ universal "scale-invariant" or "conformal" structure)
What we actually see when we look at a “jet”, or inside a proton

An ever-repeating self-similar pattern of quantum fluctuations

At increasingly smaller energies or distances: *scaling* (modulo $\alpha(Q)$ scaling violation)

To our best knowledge, this is what a fundamental (‘elementary’) particle really looks like
The Structure of Quantum Fields

What we actually see when we look at a “jet”, or inside a proton

An ever-repeating self-similar pattern of quantum fluctuations
At increasingly smaller energies or distances: scaling (modulo $\alpha(Q)$ scaling violation)
To our best knowledge, this is what a fundamental (‘elementary’) particle really looks like

Nature makes copious use of such structures
Called Fractals

Note: this is not an elementary particle, but a different fractal, illustrating the principle
When highly energetic quarks fly apart, a very strong potential builds up between them.

Increase in potential energy

\[ \sim 1 \text{ GeV} / \text{femtometer} \]

(\sim \text{energy density of pure nuclear matter})

This is the force that normally keeps quarks locked inside hadrons.

But when the kick is hard enough, \( E=mc^2 \) gets a second chance to act.

As the quarks separate, this happens multiple times → Jets
Vortices Through the Vacuum

The force is approximately **constant** with distance

Suggestive of **strings** (aka vortex lines)

Similar to those in superfluids and superconductors

Inspired the “**string model**” of jet fragmentation

Breakup process modelled by **quantum tunnelling**

Used for 30 years

Generally good agreement with collider experiments

Until we started looking closely at the LHC Run-1 data …

**More high-mass hadrons appear to be produced** (than predicted)

**And they appear to be moving faster** (than predicted)
What’s Going On?

Remember that this is what we are colliding

This is one of the main problems that are currently causing me to scratch my head

Heat? Hydrodynamics?  Fat Strings?
String-String Forces?  Black Strings?
String Reconnections?  Hadron-Gas Rescattering?
Thank You
What is a Fundamental Particle?

Abstractly, we think of an idealised “pointlike” particle
But could we ever really see “a point”?

How do we see, in the quantum world?

To see something small, we scatter waves off it

→ Heisenberg’s uncertainty principle.

To resolve “a point”, we would need infinitely short wavelengths

Heisenberg would then give it an infinitely hard kick
(Classical) particle bouncing off a (classical) hard sphere

What is the relation between $b$ and $\theta$?

$$\theta = 2 \cos^{-1}(b/R)$$

If the particle comes in with an impact parameter between $b$ and $b+db$ it will emerge with a scattering angle between $\theta$ and $\theta+d\theta$.

If the particle passes through an infinitesimal area $d\sigma$, it will scatter into a corresponding solid angle $d\Omega$.

![Figure 6.2: Hard-sphere scattering.](image)

Thus

$$b = R \sin \alpha, \quad 2\alpha + \theta = \pi$$

and hence

$$b = R \cos(\theta/2) \quad \text{or} \quad \theta = 2 \cos^{-1}(b/R)$$
A differential quantity of interest for $2 \rightarrow 2$ is thus

The differential scattering cross section per unit solid angle

$$\frac{d\sigma}{d\Omega}$$
We found the relation

\[ b = R \cos(\theta/2) \]

Hence:

\[ \frac{db}{d\theta} = -\frac{R}{2} \sin(\theta/2) \]

Note:

\[ d\sigma = |b \, d\phi \, db| \]
\[ d\Omega = |d\phi \, d\cos \theta| \]

So the differential cross section is:

\[ \frac{d\sigma}{d\Omega} = \frac{|b \, d\phi \, db|}{|\sin \theta \, d\phi \, d\theta|} = \frac{R \, b \, \sin(\theta/2)}{2 \sin \theta} \]

\[ = \frac{R^2 \, \cos(\theta/2) \sin(\theta/2)}{2 \sin \theta} = \frac{R^2}{4} \]

Integration yields:

\[ \sigma = \int \frac{R^2}{4} \, d\Omega = \pi R^2 \]