QCD and Collider Physics

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Hadron collider basics

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

Two parameters of importance:

1. The energy:
   
   \[
   s \equiv (p_1 + p_2)^2 = \begin{cases} 
   (E_1 + E_2)^2 & \text{in the c.m. frame } \vec{p}_1 + \vec{p}_2 = 0, \\
   m_1^2 + m_2^2 + 2(E_1E_2 - \vec{p}_1 \cdot \vec{p}_2) & \text{in the fixed target frame } \vec{p}_2 = 0.
   \end{cases}
   \]

   \[
   E_{cm} \equiv \sqrt{s} \approx \begin{cases} 
   2E_1 \approx 2E_2 & \text{in the c.m. frame } \vec{p}_1 + \vec{p}_2 = 0, \\
   \sqrt{2E_1m_2} & \text{in the fixed target frame } \vec{p}_2 = 0.
   \end{cases}
   \]

2. The luminosity:

   Colliding beam

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

   \( (a \text{ some beam transverse profile}) \) in units of \#particles/cm\(^2\)/s

   \( \Rightarrow 10^{33} \text{ cm}^{-2}\text{s}^{-1} = 1 \text{ nb}^{-1}\text{ s}^{-1} \approx 10 \text{ fb}^{-1}/\text{year}. \)

   \[ p = h/\lambda \]

Hadron collider at 14 TeV =

cosmic rays at 100,000 TeV

=10\(^8\) GeV = 10\(^{17}\) eV
Tevatron and LHC

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

LHC, designed for $pp$ collisions at
$$\sqrt{s} = 14 \text{ TeV} \quad \mathcal{L} \approx 10^{33} - 10^{34} \text{ cm}^{-2}\text{sec}^{-1} \leftrightarrow 10 - 100 \text{ fb}^{-1}/\text{year}$$

lower energy and luminosity at beginning:
$$\sqrt{s} = 7 + 8 \text{ TeV and } \int \mathcal{L} dt \approx 5 + 20 \text{ fb}^{-1} \text{ in 2011/12} \quad \text{Run I}$$
$$\sqrt{s} = 13 \text{ TeV and } \int \mathcal{L} dt \approx 3 + > 20 \text{ fb}^{-1} \text{ in 2015/16} \quad \text{Beginning of Run II}$$

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

- 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
  $$\sigma_{tot}(p\bar{p}) \approx 100 \text{ mb} \geq 10^{11} \text{ times new physics cross sections}$$
  $$\implies$$ 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

- 2010, 7 TeV, 45.0 fb\(^{-1}\)
- 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\(^{-1}\)
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:

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

- **stable particles** directly “seen”:
  \[ p, \ \bar{p}, \ e^\pm, \ \gamma \]
- **quasi-stable particles** of a life-time \( \tau \geq 10^{-10} \text{s} \) also directly “seen”:
  \[ n, \Lambda, K_L^0, ..., \mu^\pm, \pi^\pm, K^\pm, ... \]
- a life-time \( \tau \sim 10^{-12} \text{s} \) may display a secondary decay vertex, “vertex-tagged particles”:
  \[ B^{0,\pm}, \ D^{0,\pm}, \ \tau^{\pm}, ... \]
- **short-lived** not “directly seen”, but “reconstructable”:
  \[ \pi^0, \ \rho^{0,\pm}, \ Z, W^\pm, t, H, ... \]
- **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

![Diagram showing different particle detection regions in a particle detector](image-url)
Charge identification and momentum resolution

A closer look:

Theorists should know:

For charged tracks: \( \Delta p/p \propto p \),

\[ \text{typical resolution: } \sim \frac{p}{(10^4 \text{ GeV})}. \]

For calorimetry: \( \Delta E/E \propto \frac{1}{\sqrt{E}} \),

\[ \text{typical resolution: } \sim \frac{(5-80\%)}{\sqrt{E}}. \]
† 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.)

\[ p_1^i + p_2^i = \sum_f p_f + p_{\text{miss}}. \]

But in hadron collisions, the longitudinal momenta unkown:

\[ 0 = \sum_f \vec{p}_f T + \vec{p}_{\text{miss}} T. \]
Cartoon of a general purpose detector
Layout of the CMS detector

Total Weight: 14,500 t.
Overall diameter: 14.60 m
Overall length: 21.60 m
Magnetic field: 4 Tesla
Components of the ATLAS detector
Differential cross sections for hadronic collisions
.... and QCD as a quantum field theory