Collider Mechanics

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Abstract:

"In this talk, we'll dive into the basics of high energy colliders. We'll begin by understanding how coordinates work and the electronics behind the machinery. This all comes under the pre-collision portion, as in what happens before we observe an event. Then we'll examine how the machinery effectively "observes" the events followed by the mathematics that we employ to understand uncertainties and discoveries."

Motivation

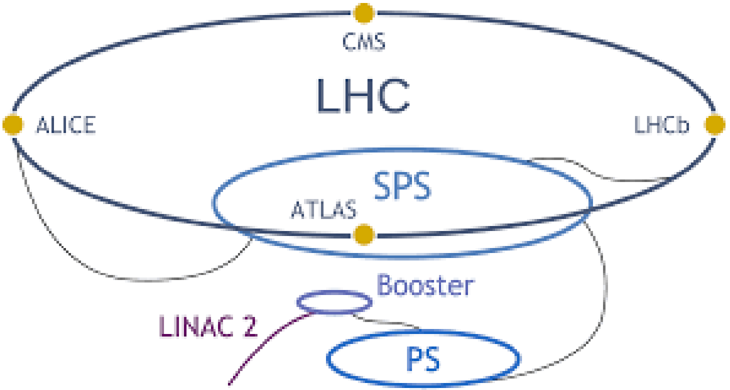
Before Collision: Particle Acceleration

- After photons and electrons, protons are probably the easiest particles to isolate and create a beam of. Protons are just atomic hydrogen nuclei, so to get a proton you just need to ionize hydrogen
- It is done by taking hydrogen gas and putting it in a strong electric field. In this electric field, the electron and proton are pulled apart. Once hydrogen is broken up, we can use electric and magnetic fields to do whatever you want to the protons
- After isolating protons, the LHC manipulates them with a radio-frequency (RF) electromagnetic field. The protons are organized into collections of about 100 billion protons called bunches that sit in the troughs of the field

Before Collision: Particle Acceleration

- These bunches have a size fixed by the wavelength of the RF field and are separated in space from one another. The RF field at the LHC has a frequency of 400 MHz, corresponding to a wavelength of about 3/4 of a meter. No proton exists in isolation at the LHC; it is always within its bunch.

Before Collision: Particle Acceleration



LHC Pre-Collision Layout

Before Collision: Particle Acceleration

As a circular accelerator, the proton bunches can be sent around the circle many times to reach the desired energy. This is an advantage with respect to a linear collider, which only gets one chance to accelerate the protons. However, this advantage comes at a cost.

Even with a constant speed, protons traveling in a circle are accelerating and therefore emit electromagnetic radiation, called synchrotron radiation

A circular accelerator must input enough energy to both speed up the protons and maintain their energy, as they lose energy continuously through synchrotron radiation. This is one of the main limitations on the energy to which circular accelerators can reach

Before Collision: Particle Acceleration

The value of synchrotron radiation for LHC is

$$P_{\mathrm{LHC}} \simeq 40\mathrm{MeV} \cdot \mathrm{s}^{-1} \quad (1)$$

Accounting for all protons accelerated at the LHC, the power emitted from synchrotron radiation is about a kilowatt

In addition to synchrotron losses from the protons traveling in a circle, we have to keep the protons in the LHC ring. This is accomplished with thousands of superconducting electromagnets that bend the path of the protons, without affecting their kinetic energy.

The strength of the magnetic field that is required is

$$|\vec{B}| = \frac{|\vec{p}|}{qR} \quad (2)$$

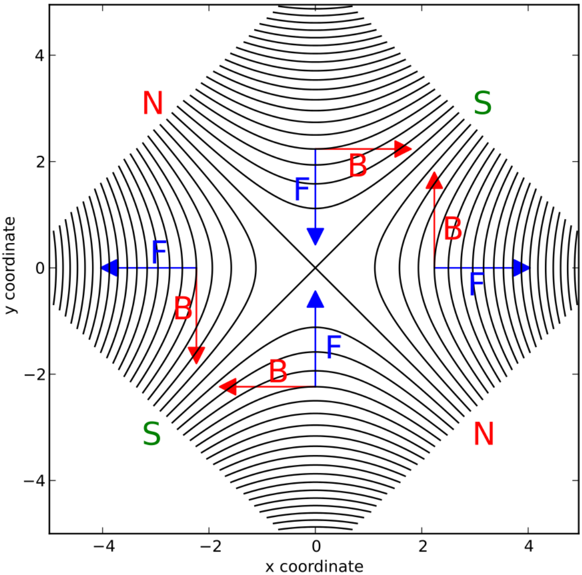
Before Collision: Particle Acceleration

- Now that protons are traveling in the LHC ring at their maximum energy, we need to collide them. The two counterrotating beams consisting of thousands of proton bunches are set to collide at specific locations around the LHC ring.
- However, even though bunches consist of billions of protons, protons are very small and the vast majority of the volume of a bunch is empty space.
- The volume of a proton bunch is $\mathrm{Vol}_{\text{bunch}} \simeq 10^{-4}\mathrm{m}^3$ while the total volume of the bunch occupied by 100 billion protons is only about $\mathrm{Vol}_{\text{protons}} \simeq 10^{-37}\mathrm{m}^3$
- The volume of empty space is more than 30 orders of magnitude larger than the volume of the protons .This makes it extremely challenging for any of the protons to interact in an interesting way

Before Collision: Particle Acceleration

- To improve the likelihood that protons actually collide, we need to make the beam volume much smaller. This is accomplished at the LHC by quadrupole focusing magnets located around the collision points
- The bunch can be focused in both top–bottom and left–right regions by stacking a series of quadrupole magnets that are rotated $90\circ$ degrees from one another.
- At the LHC, these quadrupole magnets can focus the beam width down to a radius of less than 10 micrometers! Therefore, at the collision point, the volume of the bunch is reduced to Vol $_{\text{bunch},\mathrm{col}} \simeq 10^{-8}\mathrm{m}^3$

Before Collision: Particle Acceleration



At Collision

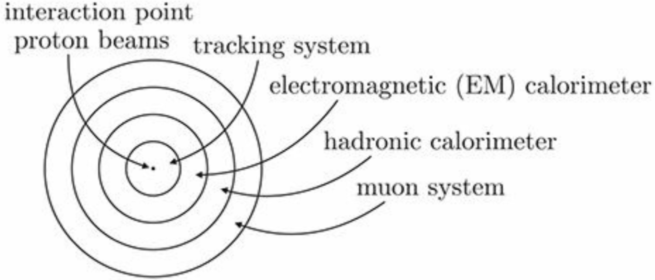
- Once the proton beams have been accelerated to their maximum energy and focused at a collision point, they are collided, which just means that two opposite-traveling bunches are passed through one another.
- When two protons collide and exchange a significantly large amount of momentum, they explode into a shower of particles emanating from the collision point.
- The dynamics of what happened at the moment of the proton collision is imprinted on these final- state particles, through energy and momentum conservation, through angular momentum conservation, or through charge conservation.

At Collision

- At a particle physics detector, we are able to measure many particle properties, but many others we don't even try to measure
- For example, measuring energy and momentum are relatively easy, Electric charge is also relatively easy to measure
- Angular momentum or spin, on the other hand, is not easy or convenient to measure, and so we don't design our detectors to be sensitive to spin.
- But spin leaves its mark through energy and momentum conservation, so we will be able to infer spin from other measurements.

Detector Components

- Let's move on to how to measure particle properties from the various components of the detector. We will work with a much simplified picture which ATLAS and CMS are to both equivalent.
- Like an onion, the experiments consist of many layers, each of which measures particular properties or is sensitive to particular particles.



Detector components

- Detectors like ATLAS or CMS are often referred to as 4π hermetic detectors because they capture all particles produced from proton collision throughout 4π steradians of a sphere as best as possible.
- This task is impossible because, at least, the proton beams must come in somewhere and cables have to go somewhere.
- However, the coverage is otherwise exceptional.

Detector Components; Tracking Systems

- Immediately outside the region of the collision point and proton beams is the tracking system. The tracking system consists of millions of individual channels that respond when a charged particle hits them.
- These channels consist of silicon or gas that ionizes when a high-energy particle with charge passes through. This ionization is recorded at numerous points along the trajectory of the charged particle and traces out a track of the charged particle.
- Observing these tracks provides information about the direction of charged particles, but by itself doesn't provide information about the energy of the particles.

Detector Components; Tracking Systems

- What makes the tracker especially useful is that it is embedded in a solenoidal magnetic field. The solenoidal field points parallel to the proton beam and so charged particles' trajectories are affected by the magnitude of their charge and momentum p
- Only the component of momentum perpendicular to the magnetic field is affected by the magnetic field. Because of this solenoidal magnetic field, the tracking system is sensitive to both the charge and the transvers momentum of particles.

Detector Components; Tracking Systems

- The tracking system consists of many layers of material away from the interaction point.Curvature can be determined by a minimum of three hits, though the tracking system typically has about 30 layers for redundancy.
  Importantly, it is the curvature, not the radius of curvature, that is more easily measured.
- The curvature is just the inverse of the radius of curvature, which is inversely proportional to transverse momentum

$$\Delta \frac{1}{R} \propto \Delta \frac{1}{p_\perp} = \frac{\Delta p_\perp}{p_\perp^2} \tag{3}$$

- The uncertainty on the measurement of momentum in this way increases with increasing momentum

Detector components; Calorimetry

- The next layer of the particle detector onion is the calorimetry. The electromagnetic and hadronic calorimeters have the same basic function, but are designed to be sensitive to different types of particles.
- The calorimeters are designed to stop particles and have them explode all of their energy into individual cells of the calorimeters
- The electromagnetic and hadronic calorimeters are sensitive to electromagnetic and hadronic radiation, respectively. In particular, the electromagnetic calorimeter stops electrons and photons, low mass particles that interact via electromagnetism

Detector Components; Calorimetry

- The most important way that the electromagnetic calorimeter stops high-energy electrons and photons is through bremsstrahlung
- Bremsstrahlung is the process by which an electron emits a photon which decreases its energy. In a similar way, a photon can split into an electron– positron pair, and each resulting particle has less energy than the initial photon

Detector Components; Calorimetry

- At ATLAS, for example, the electromagnetic calorimeter consists of lead plates immersed in liquid argon. The liquid argon ionizes, and the energies of low-energy particles can be measured efficiently.
- The lead plates have strong stopping power for more energetic particles, Together with Ar they form the electromagnetic calorimeter and stop nearly all electrons and photons created in collision

Detector Components; Calorimetry

- The hadronic calorimeter acts in much the same way as the electromagnetic calorimeter; however, it must stop particles with a much higher mass than electrons. Hadrons, like pions, interact most strongly with atomic nuclei, and not atomic electrons.
- As such, their interactions are more complicated to understand, but the same basic principles are at work. Hadrons pass through a material and lose energy by inelastic collisions with atomic nuclei

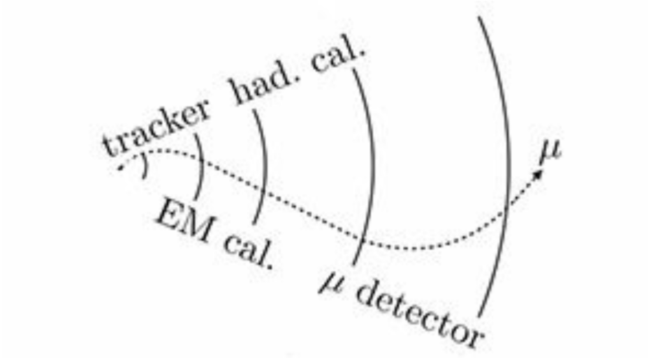
Detector Components; Calorimetry

- The hadronic calorimeter consists mostly of iron for stopping and plastic scintillators are used to measure energies of hadrons
- Electromagnetic calorimeters measure the energy of electrons and photons as they interact with matter.
- Hadronic calorimeters sample the energy of hadrons (particles that contain quarks, such as protons and neutrons) as they interact with atomic nuclei.
- Calorimeters can stop most known particles except muons and neutrinos

Detector Components; Muon System

- At both ATLAS and CMS, outside of the hadronic calorimeter there is a muon detection system.
- At ATLAS, it consists of detectors for tracking in a high-tesla, toroidal magnetic field. CMS, by contrast, uses a high-tesla solenoidal magnet to bend muons
- CMS is extremely dense, which ensures that the calorimetry can stop particles and the muon system significantly bends the trajectory of muons. Though much smaller than ATLAS, the weight of CMS is more than twice that of ATLAS

Detector Components; Muon System



Because the calorimetry at ATLAS and CMS is so good at stopping high-energy hadrons, essentially every charged particle that makes it to the muon system is considered to be a muon

Detector components; Unobservable Neutrino

- The tracker, calorimetry, and muon system detects and measures the momentum of almost all detector-stable particles
- But there is one class of particle that is detector-stable but cannot be measured: neutrinos
- Like photons, neutrinos are electrically neutral and have very small mass. Unfortunately, neutrinos interact incredibly weakly with matter, and so the vast majority of the time pass right through all detector components

Detector Components; Unobservable Neutrino

- But we can indirectly calculate neutrinos, While taking account all the transverse energy happening inside, there will be a small gap in the measurements which are mostly neutrino

Post-Collision

LHC $\Leftarrow$ 40m bunches s^{-1}

↳ store
↳ Process
↳ Available

} 40 TB s^{-1}

Cloud Computing
↳ MongoDB

'High frequency'

Statistical Analyses

"Interesting" $\longrightarrow$ Triggers 'Filter'

$p_\perp \simeq 1$ GeV

Systemic Uncertainties

↳ Measurement device/technique

↳ Inherent

L.C !

Statistical Uncertainties

'Finite'

Normalized Distributions

$$\int_{-\infty}^{\infty} dx\ p(x) = 1 \tag{4}$$

Normalized Distributions over a Finite Region

$$0 < \int_{a}^{b} dx\ p(x) < 1 \quad \neq [a,b] \tag{5}$$

$> \mu \geq 0$

$e^{+} + e^{-} + x$

Distribution

Bin Approximation

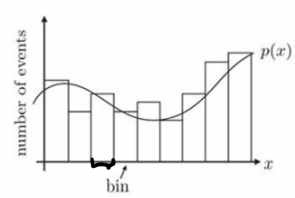


Figure: An example of Bin approximation

No. of events

$$\frac{1}{N_{ev}\Delta x} \tag{6}$$

Bin width

$$1 = \sum_{i\ \in \text{bins}} \frac{N_i}{N_{ev}\Delta x}\Delta x \tag{7}$$

Bin Approximation

$$p(x_i) \approx \frac{N_i}{N_{ev}\Delta x} \tag{8}$$

- However, if we take the limit

$$\lim_{N_{ev}\to\infty, \Delta x\to 0} \frac{N_i}{N_{ev}\Delta x} = p(x_i) \tag{9}$$

Binomial Expansion

Assumption: Each event is indp.

$$P = p(x)dx \tag{10}$$

$$p_k = P^k(1-P)^{N_{ev}-k}\binom{N_{ev}}{k} \tag{11}$$

Where,

$$\text{Choosing} \binom{N_{ev}}{k} = \frac{N_{ev}!}{k!(N_{ev}-k)!} \qquad k \in N_{ev}$$

This is called a Binomial Probability distribution since it represents an expansion of the Binomial expression:

$$(x+y)^N = \sum_{i=0}^{N} x^i y^{N-i}\binom{N}{i} \tag{12}$$

$N_{ev} \to \infty$
k finite
$p \ll 1$

Poisson Distribution

$$\lim_{\cancel{min}} \binom{N_{ev}}{k} = \lim_{N_{ev}\to\infty} \frac{(N_{ev})^k}{k!(N_{ev}-k)!} = \frac{{N_{ev}}^k}{k!} \tag{13}$$

$N_{ev} \to \infty$

$$\lim_{N_{ev}\to\infty} p_k = \lim_{N_{ev}\to\infty} \frac{(N_{ev}P)^k}{k!} \left(1 - \frac{N_{ev}P}{N_{ev}}\right)^{N_{ev}} \tag{14}$$

$$\lim_{N_{ev}\to\infty} p_k = \frac{(N_{ev}P)^k}{k!} e^{-N_{ev}P} \tag{15}$$

= Poisson

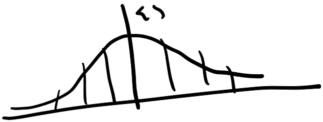
Mean and Expectation Values

$$\langle k \rangle = \sum_{k=0}^{\infty} k \frac{(N_{ev}P)^k}{k!} e^{-N_{ev}P} = \underline{N_{ev}P} \tag{16}$$

$$\sigma^2 = \langle k^2 \rangle - \langle k \rangle^2 \tag{17}$$

$$\sigma = \sqrt{N_{ev}P} \tag{18}$$

$$\frac{\sigma}{\langle k \rangle} = \frac{1}{\sqrt{\langle k \rangle}} = \frac{1}{\sqrt{N_{ev}P}} \tag{19}$$



Diphoton Excess

$\dot{x} \cdot 5\sigma$

2015: 3.4σ
2016: ×

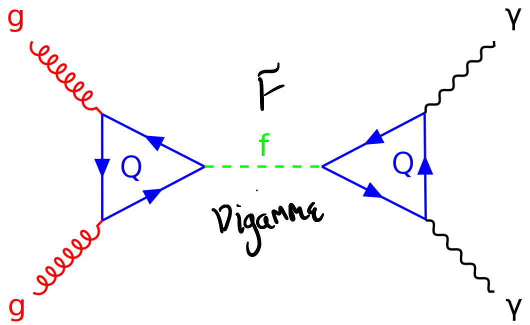


Figure: The 750 GeV diphoton excess in particle physics was an anomaly in data collected at the Large Hadron Collider (LHC) in 2015, which could have been an indication of a new particle or resonance

Significance and Discovery

Central Limit Theorem

$$p_k = \cancel{\frac{num}{den}} \to p(x) \tag{20}$$

$N_{cr} \to \infty$
k continuos var.
w.r.t Poisson

- Where,

$$p(x) = \int_{-\infty}^{\infty} dx \, \frac{1}{\sqrt{2\pi N_{ev} P}} \exp\left(-\frac{(x - N_{ev} P)^2}{2(N_{ev} P)}\right) \tag{21}$$

Normalization

$$1 = \int_{-\infty}^{\infty} dx \, \frac{1}{\sqrt{2\pi N_{ev} P}} \exp\left(-\frac{(x - N_{ev} P)^2}{2(N_{ev} P)}\right) \tag{22}$$

Significance and Discovery

p-value

- Let's calculate the probability that there was a deviation that was at least $X\sigma$ above the mean. This is called the pvalue of the deviation and requires integrating from $N + X\sigma = N + X\sqrt{N}$ to ∞:

$$p_X = \int_{N+X\sqrt{N}}^{\infty} dx \frac{1}{\sqrt{2\pi N}} \exp\left(-\frac{(x-N)^2}{2N}\right) \tag{23}$$

Simplifying it,

$$p_X = \int_X^{\infty} dx \frac{1}{\sqrt{2\pi}} \exp\left(-\frac{x^2}{2}\right)$$

- This integral can be evaluated in terms of the error function erf:

$$p_x = \frac{1}{2} - \frac{\mathrm{erf}(\frac{X}{\sqrt{2}})}{2} \tag{24}$$

The Higgs

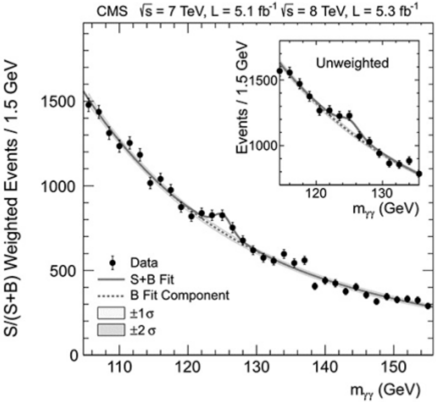


Figure: Invariant mass distribution of photon pairs $m_{\gamma\gamma}$ collected in proton collisions at the CMS experiment up through the end of June, 2012. The bump near a mass of 125 GeV is now known to be the Higgs boson.