From Quark to Jet: A Beautiful Journey
Lecture 1

Beauty Physics, Tracking, and Distributed Computing

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Explaining the Title: An outline

- Theoretical

Quarks
Mathematical Objects:
Matrices, operators, etc.
Explaining the Title: An outline

- **Theoretical**
  - **Quarks**
    - Mathematical Objects: Matrices, operators, etc.

- **Hadronization**
  - **Particles**
    - intermediate and quasi-final state objects
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- **Reconstruction**
  - Jets
    - Energy deposits in detector used to recreate particles

- model uncertainties
- hadronization schemes
- experimental uncertainties
  - Reconstructed

parton

\[ \sigma (\alpha \rightarrow \beta) \]

\[ \alpha_s \]

\[ \gamma \]

\[ \bar{t} \]

\[ t \]
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Explaining the Title: An outline

• Theoretical
  Quarks
  Mathematical Objects: Matrices, operators, etc.
  Huge numbers of complex equations

• Hadronization
  Particles
  intermediate and quasi-final state objects
  Entirely Simulated, particles are subjected to decay conditions

• Reconstruction
  Jets
  Energy deposits in detector used to recreate particles
  Detector simulation, Algorithmic reconstruction
Explaining the Title: An outline

- **Theoretical**
  - Quarks
    - Mathematical Objects: matrices, operators, etc.
  - Hadronization
    - Particles: intermediate and quasi-final state objects
  - Reconstruction
    - Jets: energy deposits in detector

- **Hadronization**
  - Particles: intermediate and quasi-final state objects
  - hadronization schemes
  - model uncertainties

- **Reconstruction**
  - Jets: energy deposits in detector
  - Hadronization schemes
  - Experimental uncertainties

Different computing solutions used to tackle the unique challenges at each step:

- Complex equations
- Particles are subjected to decay conditions
- Algorithmic reconstruction
Explaining the Title: An outline

- **Theoretical**
  - Quarks: Mathematical Objects

- **Hadronization**
  - Particles: intermediate and quasi-final state objects

- **Reconstruction**
  - Jets: Energy deposits in detector

Different computing solutions used to tackle the unique challenges at each step

The first lecture will explore a bit more theory, tracking and how to cope with the increased demands of new physics environments.
Ask Questions here

- Use theory to make predictions for observables of particles
- Design detectors to detect these observables
- Algorithms to remake the objects
Beauty Physics - Theory

- Beauty quark discovered in 1977 at Fermilab
- Lighter than top quark and W/Z/H bosons
  - Significant decay channel
- Beauty (and charm) quarks have a lifetime that allows for decay lengths of a few millimeters
  - Top is too short, up/down/charm is too long
Beauty Physics - Theory

- **b-jets are extremely powerful background reducers**
  - Many important signals have b-quarks

- **Huge order of magnitude reduction from identifying b-quarks**

- **Very important tool**

### Graphical Content

- **Temperature (T)**
  - Various temperatures are shown, ranging from 0.1 to 10 TeV.
  - The graph includes logarithmic scales for both the horizontal (E, [10^0, 10^10]) and vertical (σ, [10^-10, 10^0]) axes.
  - Major temperature points indicated:
    - **Tevatron**
      - Temperature close to 100 GeV.
    - **M_{H} = 125 GeV**
      - Indicates a specific energy level.

- **Proton-antiproton cross-section**
  - The graph includes data points for **pp -> anything** and **pp -> beauties**.
  - The cross-section is shown in units of nb (nanobarns).
  - Significant reduction noted for **pp -> beauties**.

- **Events per second**
  - Events per second are shown for different cross-sections.
  - Example: 10^3 cm^2 s^-1.

- **Additional**
  - The graph illustrates the impact of various processes on the cross-section, highlighting the effectiveness of b-quark identification.
Hadronization

- Most calculations are confined to simple elements
- What we actually measure is much more complicated
Hardonization

- We know that as quarks get further away from each other they make pairs with other quarks
  - These are called hadrons

- Hadronization depends on many experimentally adjusted factors

- Most importantly we can begin to look at event topology
Beauty Physics – Particle Level

- If a b-quark is paired with an s-quark the resulting meson, B_s, has a long lifetime, and some very interesting decay signatures.

- We use these particular decay signatures to determine what experimental signature we want to see.
Experimental signature

- Now we have a distinct signature to search for:
  - A secondary vertex
  - Jet
  - Displaced track
  - Lepton

- Rare, but not unique:
  - We will use different techniques to classify
  - Essentially a probability the jet came from a b-quark
Beauty Physics – Detector Level

Secondary vertex

Jet

Displaced tracks

Lepton

Key:
- Blue: Muon
- Red: Electron
- Green: Charged Hadron (e.g., Pion)
- Dashed: Neutral Hadron (e.g., Neutron)
- Blue dashed: Photon

Transverse slice through CMS
Theory Questions

- Use theory to make predictions for observables of particles
- Design detectors to detect these observables
- Reconstruction algorithms to remake the objects
Tracking - an Introduction

\[ r = \frac{p}{BQ} \]

Interaction region (80-100cm)
Fitting

- An nth degree polynomial will exactly fit (n+1) points
- Therefore, any three points can be fit with a circle
- Fits generally classified by distances of points to fitted curve (chi-squared)
- For nth degree polynomial, n+2 ... n+m points are degrees of freedom

Polynomial fits to a sine curve
Track Seeding and Reconstruction

- Inside of the collision region we will have many hits we can associate with a primary vertex
Track Seeding and Reconstruction

- Choose an initial set of layers that we name the “seeding layers” that provide an initial estimate of track parameter
Track Seeding and Reconstruction

- Choose an initial set of layers that we name the “seeding layers” that provide an initial estimate of track parameter

- Then collect all possible hits associated with different seeds
Track Seeding and Reconstruction

- Choose an initial set of layers that we name the “seeding layers” that provide an initial estimate of track parameter
- Then collect all possible hits associated with different seeds
- Using techniques to estimate the goodness of the fit we can then estimate the final track parameters

Particle’s parameters (q/p, eta, phi, dz, d0)
Fake Removal

- Choose an initial set of layers that we name the “seeding layers” that provide an initial estimate of track parameter.

- Then collect all possible hits associated with different seeds.

- Using techniques to estimate the goodness of the fit we can then estimate the final track parameters.

- And remove hits not associated with good tracks.
Iterative Tracking

- With iterative tracking certain quality tracks can be chosen and then removed from further inspection
Iterative Tracking

- With iterative tracking certain quality tracks can be chosen and then removed from further inspection
- Then use the remaining hits to create the remaining tracks
- After many iterations we end with the final set of tracks
Real data examples
Tracking as a primary time user

Time Spent on which part of reconstruction
Top-quark pair production events

CMS CR-2011-002

- Tracking
- EGamma
- Muon
- PartFlow
- LocalCalo
- LocalMuon
- Jets
- BTag
- LocalTracker
- Tau
- HCAL
- ECAL
Looking Towards 2015

Current algorithms were developed considering the run conditions for 2011-2012 where there was an average of 20 interactions per bunch crossing.

For 2015, there could be over 40 interactions on average.

With no changes, the computing power needed could be 6 times what is currently used.
Tracking

- Charged particles make curves in magnetic fields
- Basic algorithms can be used to find tracks
- Tracking one of the largest time consumers and sensitive to pileup
Problems with pile up

- Higher and higher luminosity means we have longer event reconstruction times

- New event architecture might be able to help
CMS Computing Network

- **7 Tier-1 sites** (CPU, disk & tape)
  - Tier-1 USA
  - Tier-1 UK
  - Tier-1 Italy
  - Tier-1 Germany
  - Tier-1 Spain
  - Tier-1 Taiwan
  - Tier-1 Russia

- **52 Tier-2 sites** (CPU, disk)

  - General purpose Scientific Networks (GPN)

  - Every Tier-1 is connected to the Tier-0 and other Tier-1 sites
  - Every Tier-2 is connected to every Tier-1 site
  - Every Tier-2 is connected to every Tier-2 site

Full-Mesh Network Topology
 CMS Current Event Model

- Global configurations are loaded into memory
  - Then configurations specific to the specific time of running

- Events then processed serially

- The most time intensive part of event reprocessing is tracking
Amdahl’s Law

- Amdahl’s Law is the upper limit on the speedup gained by a number of processors

\[ S(N) = \frac{1}{(1 - P)} + \frac{P}{N} \]
CMS Threaded Design

- Events are not seen globally
- Multiple events are run concurrently
  - Less backup from very complicated events
- Streams still process serially
Concurrent Processing Inside an Event

- Current event Processing
Concurrent Processing Inside an Event

- Threading inside of a module
Performance Results

- Single threaded runs out of memory at 3000 simultaneous events
- Definite improvement through multithreading

Throughput

Scaled Rate
Conclusions

- Beauty physics is a very diverse and large part of high energy physics

- B-Hadrons have distinguishing traits we can use to make b-jets very powerful tools for background reduction

- To make use of this, we must use information from many parts of the detector which all require their own reconstruction algorithms and different levels of computing resources

- By restructuring the event processing structure to accommodate threaded applications we can meet the demands required for tracking in the future
Speedup from