Hadron Collisions
and the LHC

TASI 2006 - Lecture 1
John Conway
If you ask me anything I don't know, I'm not going to answer.

- Yogi Berra

Actually, this is probably not true...Male Answer Syndrome...but there is a lot I do not know about this topic! :)
Outline

A. Overview of the LHC Program
B. Anatomy of a Hadron Collision
C. PDFs and $Q^2$ Evolution
D. Hard Collision Processes
E. LHC Machine Design and Operation
The LHC Program

- In 1976, Burt Richter, visiting CERN, designed a large 200 GeV electron position collider: LEP

- He envisioned that come day the concrete/steel LEP magnets could be replaced with SC ones

- Collide protons: more energy!
  - huge cost
  - “dirty” collisions
  - enormous rates

- The lesson: once you have the tunnel...
Age of the Great Colliders


- New dimensions??
- Higgs, SUSY, ??
- Top quark, W mass
- Z mass/width/couplings
- Definitive proton structure
- W, Z discovery
- b hadrons
- Gluons/jets

Colliders:
- Tevatron (FNAL)
- LEP (CERN)
- SLC (SLAC)
- HERA (DESY)
- SppS (CERN)
- Tristan (KEK)
- PEP (SLAC)
- PEP 2 (SLAC)
- PETRA (DESY)
- KEK-B
- CESR (Cornell)
- LHC (CERN)

ILC?
Livingston plot of accelerator history: it’s getting harder!
Site of the LHC near Geneva, Switzerland
LHC Physics: Questions

- Why are there three generations?
- Are the quark generations related to the lepton ones?
- Why is there a huge range of particle masses?
- What is the nature of electroweak symmetry breaking?
- Is there a Higgs boson at ~120 GeV?
- Are there supersymmetric partners to be found?
- What is the particle nature of dark matter?
- What is the Lagrangian of the world?
The Billion-Dollar Plot
Is this the theory of everything? Probably not...
Anatomy of a Hadron Collision

- hard collision - governed by PDFs
- initial state/final state radiation (ISR/FSR)
- proton remnants (very forward)
- "underlying event" (color strings breaking)
PDFs and $Q^2$ Evolution

- PDF - parton distribution function
- measured in many experiments
- evolve with $Q^2$ - described by DGLAP equations
- functional fits: MRS and CTEQ groups
- uncertainties mean we cannot predict well-understood processes perfectly!
- extrapolation to LHC cross section calculations can vary a lot!
PDFs and $Q^2$ Evolution

- ad hoc functional form used in fit:

$$f_q(x, Q_0) = Ax^\alpha (1 - x)^\beta e^{\gamma x} (1 + Bx)^\delta$$

- $Q_0 = 1.3$ GeV (evolve from that)
- light quarks are treated as massless
- use input from neutrino DIS experiments, HERA ep scattering, Tevatron
- $Q^2$ evolution softens the distributions
Hard Collision Processes

- QCD diagrams dominate
- "Drell-Yan" production of $Z/\gamma^*$:

$$m^3 \frac{d^2\sigma}{dmdx_F} = \left(\frac{8\pi\alpha^2}{9}\right) \left(\frac{x_1 x_2}{x_1 + x_2}\right) \sum_i e_i^2[q_i^A(x_1)q_i^B(x_2) + \bar{q}_i^A(x_1)q_i^B(x_2)]$$

- falling continuum distribution as a function of mass, plus $Z$ resonance
- analogous expression for $W$ production
- antiquarks are non-valence ("sea") quarks!
The Underlying Event

- color strings breaking lead to a sort of cloud of soft mesons in the events
- we often think in terms of the underlying event actually being a min-bias event accompanying the hard collision (or vice versa)
- rule of thumb: number of particles per unit of pseudorapidity is roughly constant...but at what?
We tend, at hadron colliders, to use $\Delta R$ as a measure of “distance” or separation in direction between particles.

$$\Delta R \equiv \sqrt{(\Delta \eta)^2 + (\Delta \phi)^2}$$

Here $\phi$ is the azimuthal angle around the beam direction, and the pseudorapidity $\eta$ is related to the polar angle by

$$\eta \equiv -\log \left( \tan \frac{\theta}{2} \right)$$
Pseudorapidity

- near $\eta=0$ (or $\theta=90^\circ$), $\Delta\eta \approx \Delta\theta$
- for large $\eta$, the nonlinearity is such that a given $\Delta\theta$ corresponds to a much larger $\Delta\eta$:
ΔR cones

- we use "cones" in ΔR to associate particles with each other

- we tend to think of these cones as circular and uniform, but they are not
$\Delta R$ cones
Is $\Delta R$ the right thing?

- Typical applications of $\Delta R$ cones include
  - lepton isolation (e.g. $e$ isolation in $W \rightarrow e\nu$)
  - jet reconstruction
  - tau reconstruction ($\tau \rightarrow h\nu$)
- Is it desirable to use $\Delta R$ in any or all of these cases?
- Let’s look at some actual (well, simulated) 14 TeV pp collisions...
The LHC Machine

- 27 km circumference
- 100-150 m underground
- dipole bend radius $\sim 2.8$ km
- SC dipole field $\sim 8.4$ Tesla
- 1232 dipoles (14.3 m length)
- 2-in-1 "cos\theta" design
- plane of machine tilted at 1.4° (Jura)
- eightfold symmetry
- four experiments: ATLAS, CMS, ALICE, LHC-B
Overall view of the LHC experiments.
LHC 2-in-1 design - note cosθ current density
LHC: Synchrotron

- LHC is actually two accelerators - synchrotrons
- Particle bunches arrive at a certain moment at an RF station which has a longitudinal E field; phasing?
- 400 MHz (2.5 nsec) SC at Point 4 (42 cm separation)
LHC bunch structure

- machine frequency = \( \frac{c}{26659} \) m = 11.25 kHz
- 88.9 \( \mu \)s per turn
- design: 24.95 ns bunch spacing
- 2808 bunches maximum due to abort/injection gaps
- initially: 75 ns bunch spacing (936x936 bunches)
- later: 25 ns bunch spacing
- bunch length?
Strong Focusing

- want beam bunches as small (dense!) as possible in all three dimensions
- quadrupole magnets interspersed among dipoles
Beta and Tune

- betatron oscillations: departure of particle from nominal orbit path $\beta_x$ and $\beta_y$
- betatron oscillations decrease with beam energy
- betatron oscillations excited by machine imperfections
- want minimal x-y coupling in betatron oscillations
- want number of betatron oscillations per turn (the "tune") in machine to be non-integer
- interaction region: “low-beta insertion” in straight section
- trade angular spread for IP size!
Luminosity

- “fundamental equation of high energy physics”

\[ N = L \sigma \epsilon \]

- 1 fb = 10^{-39} \text{ cm}^{-2}
- 1 year \sim 10^7 \text{ s}
- 10^{33} \text{ cm}^{-2} \text{ s}^{-1} \sim 10 \text{ fb}^{-1} \text{ per year}
Luminosity

- luminosity depends on beam parameters:

\[ L = \frac{f \sum_{i=1}^{n_b} N_{1i} N_{2i}}{4\pi \sigma_x \sigma_y} \approx \frac{f n_b N^2}{4\pi \sigma_x \sigma_y} \]

- assume \( f = 11.25 \text{ kHz} \), \( n_b = 2800 \), \( N=10^{11} \ \text{p/bunch} \)
- for \( 10^{34} \) we need 15 \( \mu \text{m} \) rms spot size
- (Tevatron beam size \( \sim 35 \ \mu \text{m} \))
Dipole storage before installation

Dipole installation in tunnel
Birth of The LHC

- date of “first beam” has long been July 1, 2007
- this could mean
  - vacuum in beam pipe
  - one bunch circulating at low energy
  - no collisions
- recent change: moved to November, 2007
- initial energy: 0.9 TeV (435 GeV beam energy)
- first real physics running in 2008
Prediction is very difficult, especially about the future.

- Niels Bohr
Staged commissioning plan for protons

My guess:

I. Pilot physics run
   - First collisions
   - 43 bunches, no crossing angle, no squeeze, moderate intensities
   - Push performance (156 bunches, partial squeeze in 1 and 5, push intensity)
   - Performance limit $10^{22}$ cm$^{-2}$ s$^{-1}$ (event pileup)

II. 75ns operation
   - Establish multi-bunch operation, moderate intensities
   - Relaxed machine parameters (squeeze and crossing angle)
   - Push squeeze and crossing angle
   - Performance limit $10^{20}$ cm$^{-2}$ s$^{-1}$ (event pileup)

III. 25ns operation I
   - Nominal crossing angle
   - Push squeeze
   - Increase intensity to 50% nominal
   - Performance limit $2 \times 10^{13}$ cm$^{-2}$ s$^{-1}$

IV. 25ns operation II
   - Push towards nominal performance

from Lyn Evans, LHCC report, March 2006
Breakdown of a normal year

~ 140-160 days for physics per year

from Lyn Evans, LHCC report, March 2006
LHC Daily Operations

LHC operational cycle

- PHYSICS
- BEAM DUMP
- RAMP DOWN
- PREINJECTION PLATEAU
- INJECTION
- START RAMP
- SQUEEZE
- PREPARE PHYSICS
- PHYSICS

**Table:**

<table>
<thead>
<tr>
<th>Stage</th>
<th>Time [s]</th>
</tr>
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<tbody>
<tr>
<td>Ramp down</td>
<td>≈ 18 Mins</td>
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<tr>
<td>Pre-Injection Plateau</td>
<td>15 Mins</td>
</tr>
<tr>
<td>Injection</td>
<td>≈ 15 Mins</td>
</tr>
<tr>
<td>Ramp</td>
<td>≈ 28 Mins</td>
</tr>
<tr>
<td>Squeeze</td>
<td>&lt; 5 Mins</td>
</tr>
<tr>
<td>Prepare Physics</td>
<td>≈ 10 Mins</td>
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<tr>
<td>Physics</td>
<td>10 - 20 Hrs</td>
</tr>
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</table>

from Lyn Evans, LHCC report, March 2006
Other random LHC facts

- bunch length: 8 cm
- crossing angle: 285 μrad
- stored energy, per beam: 300 MJ (150 sticks dynamite)
- interactions per crossing at \(10^{33}\): 2.1
- operating temperature: 1.9 K
- power consumption: 120 MW
SuperLHC

- after ~500 fb\(^{-1}\) (roughly 2012-13?) the experiments will require major upgrades
  - radiation damage to inner detectors
  - improved readout
  - improved triggering
- major upgrade for accelerator too!
- goal for SuperLHC: \(10^{35} \text{ cm}^{-2} \text{ s}^{-1}\)
(1) LHC IR quads life expectancy estimated <10 years from radiation dose
(2) the statistical error halving time will exceed 5 years by 2011-2012
(3) therefore, it is reasonable to plan a machine luminosity upgrade based on new low-\(\beta\) IR magnets before \(~2014\)
<table>
<thead>
<tr>
<th>parameter</th>
<th>symbol</th>
<th>nominal LHC</th>
<th>ultimate LHC</th>
<th>shorter bunches</th>
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<tbody>
<tr>
<td># bunches</td>
<td>( n_b )</td>
<td>2808</td>
<td>2808</td>
<td>5616</td>
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<tr>
<td>protons/bunch</td>
<td>( N_b \times 10^{11} )</td>
<td>1.15</td>
<td>1.7</td>
<td>1.7</td>
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<tr>
<td>bunch spacing</td>
<td>( \Delta t_{\text{sep}} ) [ns]</td>
<td>25</td>
<td>25</td>
<td>12.5</td>
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<tr>
<td>average current</td>
<td>( I ) [A]</td>
<td>0.58</td>
<td>0.86</td>
<td>1.72</td>
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<tr>
<td>norm. transv. emittance</td>
<td>( \varepsilon_n ) [\mu m]</td>
<td>3.75</td>
<td>3.75</td>
<td>3.75</td>
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<tr>
<td>longit. profile</td>
<td></td>
<td>Gaussian</td>
<td>Gaussian</td>
<td>Gaussian</td>
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<tr>
<td>rms b. length</td>
<td>( \sigma_z ) [cm]</td>
<td>7.55</td>
<td>7.55</td>
<td>3.78</td>
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<tr>
<td>beta at IP1&amp;IP5</td>
<td>( \beta^* ) [m]</td>
<td>0.55</td>
<td>0.5</td>
<td>0.25</td>
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<tr>
<td>crossing angle</td>
<td>( \theta_c ) [\mu rad]</td>
<td>285</td>
<td>31.5</td>
<td>445</td>
</tr>
<tr>
<td>Piwinski parameter luminosity</td>
<td>( \theta_c \sigma_z / (\sigma^*_z)^{2} )</td>
<td>0.64</td>
<td>0.75</td>
<td>0.75</td>
</tr>
<tr>
<td>events/crossing</td>
<td>( \mathcal{L} \times 10^{34} ) ( \text{cm}^{-2} \cdot \text{s}^{-1} )</td>
<td>1.0</td>
<td>2.3</td>
<td>9.2</td>
</tr>
<tr>
<td>length luminous region (rms)</td>
<td>( \sigma_{\text{lumi}} ) [mm]</td>
<td>44.9</td>
<td>42.8</td>
<td>21.8</td>
</tr>
</tbody>
</table>

very difficult!
$H \rightarrow ZZ \rightarrow \mu\mu ee, \ M_H = 300 \text{ GeV}$ for different luminosities in CMS

$10^{32} \text{ cm}^{-2}\text{s}^{-1}$

$10^{33} \text{ cm}^{-2}\text{s}^{-1}$

$10^{34} \text{ cm}^{-2}\text{s}^{-1}$

$10^{35} \text{ cm}^{-2}\text{s}^{-1}$

Holy crap!