CERN and the LHC

- Birthplace of the World Wide Web
The Large Hadron Collider
- Largest machine in the world
- Cost over $4 billion
- Proton - Proton collisions at 14 TeV
- 4 main experiments and several smaller ones

Source: CERN
LHC by the numbers

- 150 million sensors in the detectors
- 300 million collisions per second
- 50,000 TB a year (50 PB) produced
- Power: 230 MW (130 MW for LHC alone)
- Operating costs: $21M per year
- Protons travel at 0.999999991c (7 TeV)
- 6,000+ superconducting magnets

If you unravel all the filaments in the magnets, it would stretch to the sun and back 6 times, plus 150 trips to the moon

One day at the LHC would fill 137 1TB hard drives!

Most of the LHC power goes to the supercooled magnets!

The energy stored in the magnets is 30x larger than the energy stored in the beam!

Protons travel the 27km ring 11,000 times per second!

There is more iron in the CMS magnet system than in the Eiffel tower!
The Beam

Beam crossing

Produced particles
(measured by the detectors)

Protons

Interaction points

Protons
Why was the LHC built?

- Higgs Boson discovery (2012) (ATLAS, CMS)
- Look for evidence for supersymmetry or other unifying theories
- Look for dark matter
- Study matter / antimatter asymmetry
- Quark Gluon plasma (ALICE)
The detectors at the LHC

ATLAS/CMS surround the collision

LHCb is a forward spectrometer

B mesons stay close to the beam pipe
(and other light particles, too)
The LHCb Detector

- 21 meters in length
- 10 meters high
- 13 meters wide
- 100 m underground
- Weighs 6,000+ tons
- Construction cost over $75M
- 850 collaborators in 18 countries
The Standard Model

Particles made of quarks: Hadrons
• Two quarks: meson
  • Pions, Kaons, and many more
• Three quarks: baryon
  • Protons, neutrons, and many more

Quarks

<table>
<thead>
<tr>
<th>Quark</th>
<th>Mass (GeV/c²)</th>
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<tbody>
<tr>
<td>u</td>
<td>.002</td>
</tr>
<tr>
<td>c</td>
<td>1.3</td>
</tr>
<tr>
<td>t</td>
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</tr>
<tr>
<td>d</td>
<td>.005</td>
</tr>
<tr>
<td>s</td>
<td>.098</td>
</tr>
<tr>
<td>b</td>
<td>4.2</td>
</tr>
</tbody>
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Masses in GeV/c²

Note: Neutrinos and bosons not shown
New Physics

Direct search (ATLAS, CMS)
• Looking for new particles

Indirect Search (LHCb)
• Looking for enhancements of rare processes

Precision measurements enable:
• CP violation in beauty and charm decays
• Rare decays
• New exotic states

Matter/Antimatter asymmetry:
CP violation
Experimental detection

- Long lived particles are tracked in the detector
- Electronic calorimeters measure energy of charged particles
- Hadronic calorimeters measure energy of hadrons
- Magnetic fields allow momentum and sign of charge measurement
The LHCb Detector specs

- Mass resolution: 24 MeV/c² (2-body B)
- Momentum resolution ~ 1%
- Magnetic field measured to 0.03% precision
- About 24 tracks per event

b mass: 4,200 MeV
Pentaquark

- $\Lambda_b^0 \rightarrow J/\psi p K^-$
- 2015: Observed
  - Now looks like 2 structures
- 2019: Second pentaquark observed

\[ \Lambda_b^0 \{ \begin{array}{ccc}
    b & c \\
    u & \bar{c} \\
    d & s \\
    u & c \\
    d & u \\
\end{array} \] $J/\psi$

\[ \Lambda_b^0 \{ \begin{array}{ccc}
    b & u \\
    u & d \\
    s & u \\
    u & c \\
    d & u \\
\end{array} \] $\Lambda^*$

\[ \Lambda_b^0 \{ \begin{array}{ccc}
    b & d \\
    u & d \\
    s & u \\
    u & c \\
    d & u \\
\end{array} \] $P_c^+$

\[ \Lambda_b \rightarrow J/\psi p K^- \]

\[ \Lambda_b^0 \rightarrow J/\psi p K^- \]

LHCb

Data

- $P_c(4450)$
- $P_c(4380)$
- $\Lambda(1405)$
- $\Lambda(1520)$
- $\Lambda(1600)$
- $\Lambda(1670)$
- $\Lambda(1690)$
- $\Lambda(1800)$
- $\Lambda(1810)$
- $\Lambda(1820)$
- $\Lambda(1830)$
- $\Lambda(1890)$
- $\Lambda(2000)$
- $\Lambda(2100)$
- $\Lambda(2110)$
Loosely bound molecular state?
Tightly bound state?
Charm CP violation

- 53 million $D^0 \rightarrow K^-K^+$ decays
- 17 million $D^0 \rightarrow \pi^-\pi^+$ decays

CP violation observed in charm decays at LHCb!
The Upgrade

- We are now in the upgrade era (run 3, CMS/ATLAS change in run 4)
- We are looking for new physics and trying to take high precision measurements
- Software L0 trigger
- More PP collisions per event
- Opportunity for charm physics and dark matter candidate searches!
Challenges

• 1MHz to 40 MHz readout
• Factor of five luminosity increase
  • More interactions per crossing
• Computers have been getting more transistors but not faster
• Storage will also be a huge issue

Looking into GPUs, FPGAs, machine learning algorithms, and more
Conclusions

• The LHC is an exciting place to do physics
• LHCb is uniquely positioned to capture interesting physics
• Ground breaking results are have been and will be achieved!
• LHCb in the lead facing challenges for the LHC upgrade
References

Resources