Searches for New Physics at Hadron Colliders

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Mass Shapes the Universe

- Gravitation is the only force that is important over astronomical distances

- Despite the successes of general relativity, we still do not understand gravity in a quantum framework

- But we believe we are getting closer to understanding the origin of mass
Mass in the Cosmos

- **Masses of Atoms**
  - rest masses of the fermions
  - plus binding energies of quarks in nucleons, nucleons in nucleus, electrons in electromagnetic field.

- **Dark Matter**
  - mass implied by dynamics (rotational velocities) is much greater than visible luminous material
  - primordial nucleosynthesis predicts D/He abundance as a function of nucleon density
  - all this mass cannot be “baryonic” (protons and neutrons) and suggests the presence of unobserved or “new” particles?
Mass of Hadrons

- Mass of a proton = 938 MeV but mass of two u quarks and a d quark ~ 10 MeV
  - 99% of the mass of a proton (and therefore of the mass of a hydrogen atom) is due to the binding energy
- Which is described with Quantum Chromodynamics (QCD)
  - the strong force that acts on quarks
  - a gauge theory (like electromagnetism)
  - unlike electromagnetism, the vector bosons of the theory (gluons) themselves carry the charge ("color")
    - gluons are self-interacting
    - coupling constant runs rapidly — force becomes strong for small momentum transfers
    - confinement
Understanding QCD

- As we saw in Lecture 3, precisely testable QCD calculations are available for high momentum transfer processes at particle accelerators.
  - In particular, the production of jets of high momentum hadrons through quark-antiquark scattering in pp collisions.
- Soft QCD is calculable only numerically — lattice gauge theory.
  - Initially somewhat disappointing.
  - Recent advances in computing, and in the techniques used, lead to very credible results.
  - Predicted and measured hadron masses.
Does this mean we understand mass?

- There is not much doubt that QCD is the theory of the strong interaction, and we are making progress in understanding how to calculate reliably in this framework.
- But:
  - We still need to understand fermion masses
    - Second and third generations of quarks and leptons are much more massive
    - The masses exhibit patterns
  - We still need to understand vector boson masses
    - Masses of the W and Z bosons are what makes the weak force weak.
The Higgs Mechanism

- In the Standard Model (Glashow, Weinberg, Salam, ‘t Hooft, Veltmann)
  - Higgs field, $\phi$, permeates space with a finite vacuum expectation value - cosmological implications!
  - “Electroweak symmetry breaking” through introduction of a scalar field $\phi \rightarrow$ masses of W and Z
  - If $\phi$ also couples to fermions $\rightarrow$ generates fermion masses

- An appealing picture: is it correct?
  - One clear and testable prediction: there exists a neutral scalar particle which is an excitation of the Higgs field.
  - All its properties (production and decay rates, couplings) are fixed except its mass.

- A very high priority of worldwide high energy physics program: find it!

- Since it’s massive and unknown the hadron collider may be the best opportunity
Searching for the Higgs

- Over the last decade, the focus has been on experiments at the LEP $e^+e^-$ collider at CERN (European Laboratory for Particle Physics)
  - Precision measurements of parameters of the W and Z bosons, combined with Fermilab’s top quark mass measurements, set an upper limit of $m_H$ of 251 GeV
  - direct searches for Higgs production exclude $m_H < 114.4$ GeV

- Summer and Autumn 2000: Hints of a Higgs
  - the LEP data may have indicated a Higgs with mass 115 GeV (right at the limit of sensitivity)
  - LEP ceased operation in order to start construction on a future machine (the Large Hadron Collider or LHC)

- Eyes are on Fermilab until the LHC data are available in about 2008
Direct computation reveals that the individual WW scattering diagrams diverge as $\frac{s^2}{M_W^4}$, the divergence of the sum is more gentle: $\frac{s}{M_W^2}$.

The only solution is to introduce a scalar particle which cancels these residual divergences:

A detailed investigation would reveal that the Higgs couplings are proportional to masses.

As the Higgs mass increases, the amplitude for WW scattering via Higgs exchange becomes large, and lowest-order diagrams exceeds the unitarity limit unless the mass of the Higgs is less than 1 TeV.

Again hadron colliders are good tools for this energy regime now bounded between 114 and 1000 GeV.
Hadron Collider Advantage

- Huge statistics for precision physics at low mass scales
- Formerly rare processes become high statistics processes
- Increased reach for discovery physics at highest masses
- Extend the third orthogonal axis: the breadth of our capabilities
- Energy in the subprocess center-of-mass

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Higgs Hunting at the Tevatron

- If you know the Higgs mass, then the production cross section and decays are all calculable within the Standard Model
- inclusive Higgs cross section is quite high:
  \( \sim 1 \text{pb} \rightarrow 500 \text{ events/ year} \)
- but the dominant decay \( H \rightarrow bb \) is swamped by background
- Best bet
  - appears to be associated production of \( H \) plus a \( W \) or \( Z \)
  - Leptonic decays of \( W/Z \) help give the needed background rejection
  - \( \sim 0.2 \text{ pb} \rightarrow 100 \text{ events/ year} \)
Higgs Discovery Channels

\( m_H < 140 \text{ GeV} \)

- WH → qq bb is the dominant decay mode but is overwhelmed by QCD background
- WH → l\nu bb backgrounds Wbb, WZ, tt, single top
- ZH → l l bb backgrounds Zbb, ZZ, tt
- ZH → \nu\nu bb backgrounds QCD, Zbb, ZZ, tt
- Powerful mode but requires relatively soft missing \( E_T \) trigger (35 GeV?)

\( m_H > 140 \text{ GeV} \)

- gg → H → WW* backgrounds Drell-Yan, WW, WZ, ZZ, tt, tW, \( \tau\tau \)
  initial signal:background ratio \( \sim 0.007! \)
- Angular cuts to separate signal from “irreducible” WW background
Displaced Vertex Tagging

- The ability to identify b-quarks is very important in Higgs searches (also top, supersymmetry)
- b quark forms a B-meson, travels ~ 1-2mm before decaying
- To reconstruct this decay, need to measure tracks with a precision at the 10\(\mu\)m level, silicon vertex trackers!
**bb Mass Resolution**

- Directly influences ability to pull signal from background (See Homework 9, Slide 21, Lecture 3) and associated signal significance
- Requires corrections for missing $E_T$ and muon
- $Z \rightarrow \overline{b}b$ will be a calibration signal: silicon trigger

**CDF observation in Run I**

**DØ simulation for 2fb^{-1}**

**Higgs simulation for 30fb^{-1}**

$m_H = 120$ GeV
Higgs Mass Reach

The limits have been somewhat improved with recent working group studies.

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What about $m_H = 115$ GeV?

- If the LEP hints are false, we can exclude at 95% with $\sim 2\text{fb}^{-1}$ of data if no evidence is seen.
- Evidence at 3 standard deviation level with $\sim 5\text{ fb}^{-1}$.
- If we do see something, we will want to test whether it is really a Higgs by measuring:
  - mass
  - production cross section
  - Can we see $H \rightarrow WW$? (Branching Ratio $\sim 9\%$)
  - Can we see $H \rightarrow \tau\tau$? (Branching Ratio $\sim 8\%$)
  - Most likely this is the realm of the LHC at CERN
Searches at the Tevatron

- In Lecture 1 we introduced and discussed a low mass $H \rightarrow bb$ search. Searches for high mass $H \rightarrow WW^*$ underway as well.
- An interesting channel since di-leptons from the decay of $W$ and virtual $W$ are easily distinguished from backgrounds.
  - $H \rightarrow WW^* \rightarrow e^+e^-, \mu^+\mu^-, \nu^+\nu^-, e^+\nu^-, \mu^+\nu^-$
- Procedure:
  - Select high pt electrons and muons, $> 10-20$ GeV
  - Calculate backgrounds: $Z$, $WW$, $tt$, $WZ$, $W$ all decaying into leptons
  - Calculate efficiency ($\sim 5-15\%$) for observing $H \rightarrow WW^*$ as a function of $H$ mass.
  - Calculate cross section in the usual way:
    \[
    \frac{[N(\text{candidates}) - N(\text{background})]}{[\text{Efficiency} \times \text{Luminosity}]}
    \]
  - If no events seen set an upper limit on possible cross-section.
This is an exciting story which awaits more data!

Homework 11: For 2, 4 and 8 fb⁻¹ what are the ranges and likely search channels in each range for evidence of the Higgs at the Tevatron?
Beyond the Higgs...SUSY & Exotica

- The standard model works at the $10^{-3}$ level and would be completed by the discovery of the Higgs. But there are good reasons to believe that the Higgs is in fact the first window on to a new domain of physics at the electroweak scale.

- Strong suggestions that there is something beyond the Higgs:
  - There are no other elementary scalars particles
  - The patterns of the fundamental particles suggest a deeper structure
  - A fundamental Higgs would have a mass unstable to radiative corrections (quantum effects: $m_H \sim 10^{15}$ GeV, unless parameters fine tuned at the level of 1 part in $10^{26}$)

- Perhaps the SM is a low energy approximation to something larger. Theoretically the most attractive option is supersymmetry
Theoretical Problems of the Standard Model

As much as we love the Standard Model, it is unlikely to be a complete theory

Higgs boson mass receives radiative corrections which are quadratically divergent

Standard Model does not incorporate gravity

Strong, electromagnetic and weak interactions do not unify at high energies without new physics
Supersymmetry Solution

Provides a solution to Higgs mass problem

Offers a path to the incorporation of gravity

Unifies strong, electromagnetic and weak forces at high energies

It is a theory popular theoretically but unobserved experimentally

Predicts the radiative breaking of EW symmetry
Supersymmetry Particles

The simplest supersymmetric model is the minimal supersymmetric standard model (MSSM)

1. An extra Higgs doublet of opposite hypercharge
2. Supersymmetrizing the gauge field

For every spin degree of freedom in SM, there is a supersymmetric spin degree of freedom

Lots of new particles and lots of free parameters ⇒ lots of opportunity
Supersymmetry must be broken

The symmetry is assumed to be broken in a hidden sector, a messenger sector mediates the breaking to the visible sector.

Different mediation leads to different classes of models:

Gravity inspired models
The messenger interaction is of gravitational strength

Gauge mediated models
SM gauge interactions play the role of messenger force

Anomaly mediations, Gaugino mass dominance
MSSM Higgs Production at Tevatron

**Note:** \(\tan \beta\) is a reflection of the strength of the supersymmetric Higgses and is related to the coupling with other particles.
Supersymmetry Searches at Hadron Colliders

- **Supersymmetry predicts**
  - Partners to the quarks and gluons: strongly interacting squarks and gluinos
  - Partners to the leptons, W, Z: electroweakly interacting sleptons, charginos, and neutralinos
  - Multiple partners to the Higgs bosons: Higgsinos
  - Masses depend on unknown parameters, but expected to be 100 GeV - 1 TeV

- **Direct searches all negative so far. From LEP**
  - squarks (stop, sbottom) > 80-90 GeV
  - sleptons (selectron, smuon, stau) > 70-90 GeV
  - charginos > 70-90 GeV
  - lightest neutralino > 36 GeV

- **Many searches are possible at a hadron collider with high mass reach and varied initial states.**
Supersymmetric Signatures

- Squarks and gluinos most copiously produced SUSY particles
- If R-parity (a new quantum number associated with many SUSY theories) is conserved, cannot decay to normal particles
- Missing transverse energy from escaping neutralinos (lightest supersymmetric particle or LSP)

Possible decay chains always end in the LSP:

Search region typically > 75 GeV
Squarks & Gluinos

- Produced in pairs
- Each would decay to normal particle and LSP
- Event would have two jets + missing transverse energy
- Four events with expected
- Background of three.

![Graphs showing cross-sections and event distributions for squarks and gluinos.](image)

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Squarks & Gluinos: Limits & Expectations

Reach with 2 fb⁻¹:
gluino mass ~ 400 GeV

\[ m_g > 333 \text{ GeV} \] for \( M_0 = 25 \text{ GeV} \)

Run I reach

- gluino \( \sim 200 \text{ GeV} \)
- squark \( \sim 250 \text{ GeV} \)

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Charginos & Neutralinos: Tri-leptons

“Golden” channel with low backgrounds
Coupling strength, undetermined, denoted $\tan \beta$
Experimental Challenge

- Leptons are “soft” or have low momentum:
  - at $\tan\beta > 8$ most of the leptons are $\tau$’s
  - $e$ and $\mu$ from cascade decays are even softer

- Many Backgrounds to soft leptons
  - electrons - asymmetric photon conversions from pion in flight decays (remember problem 3?)
  - Muons - from $b$ and $c$ quark jets
  - Hadronic taus - QCD jets

- Preparatory work and calibration:
  - Study $Y \rightarrow ee, \mu\mu$ production
  - Study $Z \rightarrow \tau\tau$ production
Soft Leptons

- **Selecting soft electrons**
  - Two electrons $p_T > 10$ GeV
  - At least one electron $p_T < 20$ GeV
- Good agreement with MC
- Implies mis-identification is small

A specific channel: $e^+e^+l$

<table>
<thead>
<tr>
<th>“Cuts”</th>
<th>Backgrounds</th>
<th>Observed</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. $p_T^{e1} &gt; 8$ GeV, $p_T^{e2} &gt; 12$ GeV</td>
<td>21540 ± 520</td>
<td>23035</td>
</tr>
<tr>
<td>2. $15 &lt; m(ee) &lt; 60$ GeV</td>
<td>2149 ± 60</td>
<td>2182</td>
</tr>
<tr>
<td>3. Remove Jet, Drell-Yan</td>
<td>21 ± 7</td>
<td>33</td>
</tr>
<tr>
<td>4. Track $p_T &gt; 3$ GeV</td>
<td>2.5 ± 1.6</td>
<td>7</td>
</tr>
<tr>
<td>5. Tr x missing $E_T &gt; 250$ GeV</td>
<td>0.7 ± 0.5</td>
<td>1</td>
</tr>
</tbody>
</table>

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• **Adding four channels**
  - \(e^+e^+l\), \(e^+\mu^+l\), \(\mu^+\mu^+l\), **two like-sign** \(\mu^+\mu\)
  - 3 events observed and 3 expected.

• **Can calculate cross sections and set limits**

The Future:
SUSY is an exciting topic experimentally and theoretically, it may well dominate particle physics in the coming decades!
One Example of Exotica: Leptoquarks

- Lepton and quarks appear in three very similar generations.
- Theories suggest a symmetry between the leptons and quarks give rise to a particle that couples to both: leptoquarks.
- Couples to strong and weak forces.
- Produced in pairs: scalar or vector.
- Three generations: LQ1, LQ2, LQ3.
  - Each one decays to the same generation of quarks and leptons.
  - Prevents flavor changing neutral currents such as e → μ and u → c.
1st Generation Leptoquarks

- $LQ_1 \rightarrow e^+e^-qq$
  - 2 high Et electrons
  - 2 jets
  - Sum of Et > 450 GeV
- Background, 1.1 expected:
  - Z/ DY
  - Multijet
  - top antitop
- One Event Observed

- $LQ_1 \rightarrow e^-qq$
  - 1 high Et electron
  - 2 high Et jets
  - Sum of Et > 330 GeV
- Background, 3.6 expected:
  - W + jet
  - Multijet
  - top antitop
- One Event Observed
Setting Leptoquark Limits

![Graphs showing leptoquark mass limits](image)

- **Left Graph:**
  - Title: $\sigma_{eejj}^{95}$
  - Legend: $\sigma_{eejj}$, NLO Theory
  - x-axis: Scalar Leptoquark Mass (GeV/c$^2$)
  - y-axis: Cross Section $\times \beta^2$ (pb)
  - DØ 252pb$^{-1}$

- **Right Graph:**
  - Title: $\sigma_{evjj}^{95}$
  - Legend: $\sigma_{evjj}$, NLO Theory
  - x-axis: Scalar Leptoquark Mass (GeV/c$^2$)
  - y-axis: Cross Section $\times 2(1-\beta)$ (pb)
  - DØ 252pb$^{-1}$

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A Second Example: Quark Compositeness

- An excess of very high mass dielectron pairs (which are preferentially produced at 90 degrees relative to the proton-antiproton beams) would signal scattering between sub-constituents of the quarks.
- This is completely analogous to Rutherford scattering (Lecture 2).
- Look for two electrons with $p_T > 25$ GeV
- Calculate efficiency for high mass pair detection, $\sim 55\%$.
- Estimate background, dominated by jets faking electrons.
Coupling of constituents

Mass scale Eliminated

270 pb⁻¹
The Future

• Until the end of the decade the Tevatron proton-antiproton collider offers a real opportunity to discover new physics.
• The Large Hadron Collider with a 2007 start, will almost certainly discover the Higgs and/or new phenomena.

2007: The next “discovery machine” pp collisions @ 14 TeV!
5σ Higgs Signals (statistical errors only)

Discovery Luminosity [fb⁻¹]

MHiggs [GeV]

LHC 14 TeV (SM NLO Cross Sections)

- - - H → γγ
- - - H → ZZ
- - - H → WW

1 year ~ 10 fb⁻¹
The CMS $\tilde{q}_1\tilde{g}$ mass reach in $E_T^{\text{miss}} + \text{jets}$ inclusive channel for various integrated luminosities.
In Conclusion

✓ We’ve explored particle from one hadron collider experimentalists (biased) view.
✓ Most notable omissions would be a quantitative description of kinematics, the Standard Model, and Standard Model extensions; and heavy flavor physics.
✓ Lectures by P. Darriulat are an excellent companion!
✓ Two good links to start broader reading:
  • The Particle Adventure: http://particleadventure.org/particleadventure/
  • The Particle Data Group: http://pdg.lbl.gov/
✓ Thank You & Happy New Year!