Physics at the Tevatron II

Meenakshi Narain
The standard model

leptons

\( e^- \) \( \nu_e \)
\( \mu^- \) \( \nu_\mu \)
\( \tau^- \) \( \nu_\tau \)

quarks

\( u \) \( d \)
\( c \) \( s \)
\( t \) \( b \)

electromagnetism \( \gamma \)
weak force \( W^+ \) \( Z^0 \) \( W^- \)
strong force \( g \)

Higgs \( H \)
# The standard model

## Particle masses

<table>
<thead>
<tr>
<th>Quarks</th>
<th>Leptons</th>
</tr>
</thead>
<tbody>
<tr>
<td>u (\approx 3 \text{ MeV})</td>
<td>e (511.0 \text{ keV})</td>
</tr>
<tr>
<td>d (\approx 7 \text{ MeV})</td>
<td>\mu (105.7 \text{ MeV})</td>
</tr>
<tr>
<td>c (\approx 1.3 \text{ GeV})</td>
<td>\tau (1.777 \text{ GeV})</td>
</tr>
<tr>
<td>t (175 \text{ GeV})</td>
<td>W (80.42 \text{ GeV})</td>
</tr>
<tr>
<td>s (\approx 110 \text{ MeV})</td>
<td>Z (91.188 \text{ GeV})</td>
</tr>
</tbody>
</table>
The standard model

- The Tevatron allows us to study the heaviest particles in the standard model
  - W and Z bosons
    - Precise measurements of properties
  - Top quark
    - Discovered in 1995
  - Higgs boson
    - Sensitive up to $m_H \approx 130$ GeV (?)
  - New heavy particles (⇒ Andy Foland)

- These are the states that are most relevant for understanding the mechanism of electroweak symmetry breaking
The accelerator

CDF

DØ

2 km
Proton  Anti-proton  36x36 bunches

Protons/bunch  \( 10^{11} \)
Anti-protons/bunch  \( 10^{10} \)

Beam Energy  0.98 TeV/beam
Luminosity  \( 5 \times 10^{31} \text{ cm}^{-2} \text{ s}^{-1} \)
bunch crossing time  396 ns
Collision Rate  7 MHz
Event Rates

• Protons & anti-proton bunches collide at the rate of 7 MHz starting April 1, 2001.
• We expect ~2-3 pp collisions per crossing
• We record 50 events/sec (write 0.5-1 PByte/yr)
• During 1991-1996:
  – rate was 3.5 micro-seconds
  – 6x6 bunches, 286,000 bunch crossings/sec
  – 1-2 pp collisions per crossing
  – max rate data written to tape - 5 Hz
  – recorded about 65 million events (preferentially chosen for interesting physics analyses)
  – out of these events - identified 50 top pair production events!
Recording the signals from the detector

- Use sophisticated **electronics** to convert detector information into digital signals and use powerful computers to process this information. With over several million interactions per second, we need all the help we can get!

- We can store only one in 100,000 collisions at the Tevatron for later analysis so we rely on specialized hardware and software called "triggers" to select the most interesting events.

- Even with this enormous reduction, the CDF and DØ experiments record about 20 megabytes per second which must be shipped over computer networks for storage.
Data Recorded

• In the 1992-1996 Run:
  – In the experimental run that discovered the top quark, each experiment recorded 40 terabytes of data on 8000 tapes, a stack of tapes 500 feet tall, over twice the height of Wilson Hall!

• Since start of RunII in April 2001:
  – Both experiments have recorded large quantities of data
  – About 550 Million events recorded by each experiment
    • DØ and CDF each have close to 900 TB of data stored
      – includes reconstructed data
      – Both waiting to cross the 1PB mark soon!!
    • Use 60GB - 200GB tapes, robotic tape drives
    • Data is in about 5,500 tapes for each experiment!
Proton-antiproton collisions

• protons/antiprotons are not elementary
  – de Broglie wavelength of 980 GeV protons
    \[ \lambda = \frac{hc}{E} = 10^{-18} \text{ m} \ll \text{size of the proton} \approx 10^{-15} \text{ m} \]
  – quark-antiquark and quark-gluon scattering
Proton-antiproton collisions

- Proton structure functions give the probability that a single quark (or gluon) carries a fraction $x$ of the proton momentum (which is 980 GeV/c at the Tevatron)
History of Top Quark Searches

- direct and indirect mass measurements
- lower limits from searches

C. Quigg, Top-ology, Physics Today, May 1997
The top quark

- **top-antitop pair production**

\[ \sigma(t\bar{t}) = 6.7...7.5 \text{ pb} \]

\[ \text{expect 1 event every } 10^{10} \text{ crossings!} \]
Top Quarks: Rate of production

- Cross Section prediction
  - Pair production:
    \[ \sigma(pp \rightarrow tt + X) \approx 4.7 - 6.2 \text{ pb (} \sqrt{s} = 1.8 \text{ TeV)} \]
    \[ \approx 6 - 9 \text{ pb (} \sqrt{s} = 1.96 \text{ TeV)} \]

- Variations in resummation procedure
- QCD renormalization scale
  - BC = Berger and Contopoulos, 
  - BCMN = Bonciani et al, 
  - LSN = Laenen et al, 
  - NLO = Nason et al.
Top Production: a rare process

• Rate of dominant processes at the Tevatron:

$$N = \sigma \int L \, dt$$

$\sigma$ is $\propto$ to the probability that a given process will occur.

$L$ is a measure of the beam intensity ( $L \approx 5 \times 10^{31}/\text{cm}^2\text{s}$ )

$\int L \, dt$ is a measure of the amount of data collected (~100 pb$^{-1}$)

<table>
<thead>
<tr>
<th>Process</th>
<th>$\sigma$(pb)</th>
<th>events</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 jets</td>
<td>$3 \times 10^6$</td>
<td>300 million</td>
</tr>
<tr>
<td>4 jets</td>
<td>125,000</td>
<td>12,500,000</td>
</tr>
<tr>
<td>6 jets</td>
<td>5,000</td>
<td>500,000</td>
</tr>
<tr>
<td>$W$</td>
<td>25,000</td>
<td>$\times 100 \text{ pb}^{-1}$</td>
</tr>
<tr>
<td>$Z$</td>
<td>11,000</td>
<td>1,100,000</td>
</tr>
<tr>
<td>$WW$</td>
<td>10</td>
<td>1000</td>
</tr>
<tr>
<td>$tt$</td>
<td>5</td>
<td>500</td>
</tr>
</tbody>
</table>

And one in every 3 billion collisions will produce a $tt$
Top Quark Decay

- Top quark decays predominantly to W boson and a b quark ($t \rightarrow W^+b$, $\bar{t} \rightarrow W^-b$)

- Width of the top quark: $\Gamma(t \rightarrow bW) \approx 1.55$ GeV
  - Corresponds to a lifetime
  - $\tau(t) \approx 0.4 \times 10^{-24}$ s
  - Time scale for confinement
    - $1/\Lambda_{QCD} \approx \text{few} \times 10^{-24}$ s
  - Top quark decays before it can be hadronized

\[ \Gamma(Q \rightarrow qW^+) = \frac{G_F m_Q^5}{8\pi} |V_{tb}|^2 \left(1 - \frac{M_W^2}{m_Q^2}\right)^2 \left(1 + \frac{2M_W^2}{m_Q^2}\right) \]

$V_{tb}$ is an element of the quark mixing matrix, bounded by the requirement of Unitarity and weak interaction phenomenology.

\[
\begin{pmatrix}
V_{td} & V_{ts} & V_{tb} \\
V_{ud} & V_{us} & V_{ub} \\
V_{cd} & V_{cs} & V_{cb}
\end{pmatrix} = \begin{pmatrix}
0.9745 & -0.217 & 0.0018 \\
0.217 & 0.9737 & 0.036 \\
0.004 & 0.035 & 0.9991
\end{pmatrix}
\]
The top quark

- top decay
  - \( t \rightarrow W + b \) (11\%)
  - dilepton channel
    - \( tt \rightarrow (e,e,\mu,\mu,\mu) v v b b \)
    - 5\% of all \( tt \) decays
  - lepton+jets channel
    - \( tt \rightarrow (e,\mu) v q q b b \)
    - 30\% of all \( tt \) decays

- characteristics of top
  - leptons \( (e,\mu) \) with high \( p_T \)
  - neutrinos \( \rightarrow \) missing \( p_T \)
  - lots of jets with high \( p_T \)
  - \( b \) quarks
Searching for the needle in haystack…

- For example, the l+jets final state is swamped by backgrounds from W+n-jets ⇒ select events with an electron + missing $p_T$

- To select a $tt$ enriched samples exploit differences between $tt$ and background events:
  
  A) Kinematic Distributions
  B) Final State Particle Content
Kinematic Distributions

- Some distributions for $tt \rightarrow e\mu + \text{jets}$ events and major backgrounds

$t\bar{t} \rightarrow e\mu$ (170 GeV), $Z \rightarrow \tau\tau \rightarrow e\mu$, WW $\rightarrow e\mu$

High $p_T$ leptons

Large $p_T$

Many jets

...various other variable e.g. $H_T$, #b-jets etc
Identifying top quark events…

• Look for events with kinematics different from those of the backgrounds
  – Large Lepton $p_T$
  – Large Missing $p_T$
  – multiple jets with high $p_T$
  – sum of $p_T$ of all jets in the event
  – etc…

• Use the fact that there are two b-jets in the event
  – Jets in $W$+jets background events arise mostly from fragmentation of gluons and light quarks ($W \rightarrow cs$)
Look for our friend the b-quark

- Exploit the existence of b-quarks in top events
- W+jets events have only little heavy flavor, mainly from $g \rightarrow bb/cc$

- Top decays are rich in heavy flavor
  $$tt \rightarrow Wb \rightarrow c \rightarrow s \rightarrow Wb \rightarrow c \rightarrow s$$
  $$\Rightarrow 2b \text{ quarks and } 2.5c \text{ quarks per top decay}$$

- Soft lepton tag
  $$B(b \rightarrow lvc) \approx B(c \rightarrow lvs) \approx 11\%$$
  $$\Rightarrow \text{tag b-quark jet with secondary } \mu \text{ (DØ)}$$
The top quark
Top Event with b-jet (D0)

Max ET = 53.3 GeV
CAEH ET SUM = 257.8 GeV
VTX in Z = 42.6 (cm)
Identifying b-quarks

• b-jet tagging
  – b lifetime ≈ 1.6 ps
    • travels a few mm before decaying

secondary vertex

large impact parameter

primary vertex
B-tagging using displaced vertex

• Compute distance in the transverse plane between the secondary and primary vertex
• (idealized sketch of vertex tagging in transverse plane)

• positive tags: decay of a long lived particle at the primary vertex.
• Negative tags: indication of algorithm performance
μ+jets Candidate Event

Jet 1

Jet 2

IP

SV

8/22/200:
Double b-tagged dilepton event - CDF

- Jet2 63.2 GeV
  - $L_{xy} = 13$ mm
- Jet1 69.7 GeV
  - $L_{xy} = 16$ mm
- $\mu$ (tl) 25.9 GeV
- $\mu$ TCL 34.8 GeV
- $E_T$ 97 GeV
- $E_T = 38.66$ GeV

Run 162820 Event 7050764 Sun May 11 16:53:57 2003
And….

- Clear excess in the jet multiplicity spectrum
- Signal region: \( \geq 3 \) jets

- Dependence of background on numbers of jets is logarithmic

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What we can measure...

- Top mass
- Top spin
- Top charge
- Top width

Production Cross Section
Production Kinematics
Resonance Production
Spin Correlations/Polarization

- W helicity

Decay modes
Branching ratios
CKM matrix element $|V_{tb}|$
Rare decays
Non-SM decays
Anomalous couplings
CP violation
Measure Cross Section

- Rate of production
  - Compare to theory
  - Deviations indicate non-SM modes of production.

  e.g. Maybe production via high mass intermediate state?

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Run I Summary

Top Cross Sections

- CDF preliminary
  - $7.6^{+2.5}_{-2.0}$ pb
  - $5.1^{+1.4}_{-1.2}$ pb
  - $9.2^{+3.8}_{-3.5}$ pb
  - $8.4^{+1.5}_{-1.5}$ pb
  - $6.5^{+1.7}_{-1.6}$ pb

- Theory (4.7 - 5.5)
  - $6.4^{+1.4}_{-1.1}$ pb
  - $4.1^{+1.1}_{-0.7}$ pb
  - $8.3^{+2.8}_{-2.6}$ pb
  - $7.1^{+1.2}_{-1.3}$ pb
  - $5.9^{+1.7}_{-1.6}$ pb

- Combined
  - HAD
  - SVX
  - SLT
  - DIL

CDF and DØ Run II Preliminary

- Kidonakis NNLO-NNNLLA (hep-ph/0303186)
- Cacciari et al. (hep-ph/0303085)

CDF Run I
- CDF Run II (ll)
- DØ Run II (ll jets)
- DØ Run II (4 jets)
- DØ Run I

$\sqrt{s}$ (GeV)
Top quark mass

- Lepton+4jets events: Kinematic fit to the lepton+4 jets hypothesis

- 6 particles in the final state - 18 observables
- cannot measure $p_z(\nu)$ - 1 unknown
- 3 constraints:
  - $m(\nu) = m_W$
  - $m(jj) = m_W$
  - $m(jjj) = m(t) = m(top)$

$\Rightarrow$ twice overconstrained problem (2C fit)

There are, however, a few complications...
Complications

- Combinatorics:
  - 4 possible $j\nu$ pairings
  - there are 12 possible assignments of the 4 jets to the 4 quarks ($bbqq$)
  - only 6 if one of the jets is b-tagged
  - only 2 for events with double b-tagged jets
- Gluon radiation can add extra jets:

Complications (cont’d)

- Monte Carlo tests:
  - shaded plots show correct combinations
    (Herwig MC, $m_t = 175$ GeV)

Ideal case
Correct combinations

Add detector resolutions by smearing the partons
Correct combinations

Process through “Geant”
  an extensive detector modeling Package
Object reconstruction
Correct combinations

Process through “Geant”
“Real analysis”
The Basic procedure

- Select a sample of $t\bar{t}$ candidate events
- For each candidate make a measurement of $X = f(m_t)$
- $X$ is a suitably selected estimator for the top mass,
  – e.g. result of the kinematic fit
- This distribution contains signal and background.

- From MC determine shape of $X$ as a function of $m_t$.
- Determine shape of $X$ for background (MC & data).
- Add these together and compare with data
  – likelihood fit for $m_t$.

8/22/2003
Top quark mass

- the systematic error is dominated by uncertainties in jet energy scale and gluon radiation.

\[ m_t = 173.3 \pm 5.6 \pm 5.5 \text{ GeV} \]

CDF RunII preliminary, 108 pb\(^{-1}\)

\[ 177.5^{+12.7}_{-9.4} \text{ (stat)} \pm 7.1 \text{(syst)} \text{ GeV} \]
Issues to address....

• A precise measurement of the top mass combined cutting edge theoretical knowledge with the state of the art detector calibration

• Jet energy scale
  – gamma-jet balancing: basic in situ calibration tool
  – Z+jet balancing: interesting with large statistics
  – Hadronic W mass: calibration tool in tt double tagged events
  – Z→bb mass: calibration line for b-jets, dedicated trigger

Reconstruct W mass in top decays

Reconstruct Z→ bb events

• Theory/MC Generators: understand ISR/FSR, PDF’s
• Simulation: accurate detector modeling

8/22/2003
Measure Mass

• Why is top so massive?
• Why does any fundamental particle have mass?
  – Is the answer to these questions connected with the interactions that govern the behavior of particles?

• Fundamental parameter of SM

• Affects predictions of SM via radiative corrections
  – BB mixing
  – W and Z mass
  – measurements of $M_W$, $m_t$ constrain $M_H$
The top quark

• single top production

weak interaction ($\propto |V_{tb}|^2$)

$\sigma(t) = 2.9 \text{ pb}^*$

see with $< 0.5 \text{ fb}$

measure $|V_{tb}|$ to 11% with 2 fb$^{-1}$

Top Quark Charge

- The top quark charge, one of the most fundamental quantities characterizing a particle, has not been directly measured yet.
- A priori there is no guarantee that we are observing pair production of resonances with charge $\pm \frac{2}{3}$.

- A possible scenario (Phys Rev D59, 09153 (1999)):
  - Introduce exotic 4th family of quarks and leptons + heavy Higgs triplet. In particular:
    
    \[(Q_1, Q_4), q_{Q_1} = -1/3, q_{Q_4} = -4/3 \text{ and } m_{Q_4} = 175 \text{ GeV}.
    \]

- This model accounts for all data, in particular $R_b$ and $A_{FB}^b$ ($Z-b_R-b_R$ modified through mixing between $b$ and $Q_1$).
- The SM top quark is heavier ($m_t \sim 230$ GeV) and has not been observed yet.
- The actual “discovered top-quark” is really $Q_4$:
  
  \[pp \rightarrow Q_4 Q_4 \rightarrow (W^- b) (W^+ b)\]

- Top quark charge measurement
  - Require $b$-jet charge measurement and correlation with the lepton mass
  - This method doesn’t allow for a “direct measurement”, but mainly to rule out $q_t \neq 2/3$ at some CL.
Spin Correlation

• Significant asymmetry exists in same-spin vs. opposite-spin top quark pairs
  – expect 70% $tt$ opposite helicity
• Non-zero measurement
  – Confirms top quark spin = 1/2
Top Couplings to Gauge Bosons: $\gamma$ and $Z$

- **EW-mediated top pair production:**
  \[
  \frac{\sigma(p\bar{p} \rightarrow (\gamma/Z)^* \rightarrow t\bar{t})}{\sigma(p\bar{p} \rightarrow t\bar{t})} \sim O\left(\frac{1}{100}\right)
  \]

  Looks challenging in terms of rate.
  Can we discriminate EW vs QCD? (color coherence, modification in angular distributions from axial $Z$-$t$-$t$ coupling, slightly different $M_{tt}$,...).

- **Higher order process**
  - Low total rate
  - (~10 double b-tagged events in 2fb$^{-1}$).
  Decay-decay interference can lead to modifications in differential distributions.

Use $p\bar{p} \rightarrow \gamma lvjjb\bar{b}$ to measure ($q_t \times$ coupling strength) (Phys Rev D64, 094019, 2001)

- Use "Zstrahlung": $p\bar{p} \rightarrow t\bar{t}Z$
  - Challenging, rate
  - (~few fb).
  Search for anomalous couplings.
  - Establish $T_3(t_L) = +1/2$, $T_3(t_R) = 0.$
Top Couplings to Gauge Bosons: FCNC

• Tiny within the SM:
  • $\text{BR}(t \rightarrow cg) \approx 10^{-10}$, $\text{BR}(t \rightarrow cg) \approx 10^{-12}$
  • $\text{BR}(t \rightarrow cZ) \approx 10^{-12}$, $\text{BR}(t \rightarrow ch) \approx 10^{-7}$

• Can be significantly enhanced in models beyond the SM ($\sim 10^3$-$10^4$):
  • 2HDM, SUSY, dynamical EWSB.
  • In some models, large Yukawa coupling makes $\text{BR}(t \rightarrow ch) \approx 1\%$.

• Implement effective lagrangian with FCNC interactions and set limits on coupling strengths, e.g.:

$$L_{\text{eff}} = \frac{1}{2\Lambda} \left[ \kappa_g g_s \bar{t} \sigma_{\mu\nu} \frac{2}{\Lambda} q G^{\mu\nu} \right] + H \cdot c.$$ 

• Search strategy:
  1) rare top decays (in $tt$ or single top)
  2) anomalous single top production

Assuming $\kappa = 0.1$:
- $\sigma(ug \rightarrow t) \sim 230$ pb
- $\sigma(cg \rightarrow t) \sim 9$ pb
- $\sigma(gg \rightarrow tc) \sim 5$ pb

Observation is a signal of New Physics!
New Resonance?

• A general purpose tool for search for heavy objects decaying to top pairs
• Dynamical models of EWSB
  
  color octet resonances $\rightarrow$ tt (mass $\approx$ several hundred GeV.)
  
  • Technicolor $gg \rightarrow \eta_T \rightarrow (tt, gg)$
  • Topcolor $qq \rightarrow V_8 \rightarrow (tt, bb)$
  • $\Rightarrow$ peak in tt invariant mass
  
<table>
<thead>
<tr>
<th>m_{tt} (GeV/c^2)</th>
<th>Events/25 GeV/c^2</th>
</tr>
</thead>
<tbody>
<tr>
<td>200</td>
<td>3</td>
</tr>
<tr>
<td>300</td>
<td>4</td>
</tr>
<tr>
<td>400</td>
<td>5</td>
</tr>
<tr>
<td>500</td>
<td>2</td>
</tr>
<tr>
<td>600</td>
<td>1</td>
</tr>
<tr>
<td>700</td>
<td>0</td>
</tr>
</tbody>
</table>

Run1 Data

Expected in Run2

8/22/2003
The standard model

- Electroweak unification
  - Photons and W/Z bosons couple to fermions with the same strength
- We experience electromagnetism every day but who has felt the weak force lately?
  - The photon is massless but W and Z are massive particles
- The symmetry is “broken”

- What is the origin of the masses of the elementary particles?
Theoretical limits on Higgs mass

- If SM is valid up to $\Lambda \approx \text{Planck Scale}$
  - $130 \lesssim M_H \lesssim 180 \text{ GeV}$

$M_H$ too large:
- Higgs self coupling blows up at some scale $\Lambda$

$M_H$ too small:
- for scalar field values $O(\Lambda)$ the Higgs potential becomes unstable

- EW vacuum is absolute minimum
- updated EW precision
- updated direct limit

$M_{\text{Planck gravity}}$
The standard model

• 18 parameters
  – gauge couplings:
    • photon: $\alpha$
    • $W$ and $Z$ bosons: $g$
    • gluon: $\alpha_s$
  – Higgs-boson coupling:
    • $m_Z$ or $m_W$
  – Higgs-fermion coupling:
    • $m_e$ $m_\mu$ $m_\tau$
    • $m_u$ $m_d$ $m_s$ $m_c$ $m_b$ $m_t$
  – Higgs mass:
    • $m_H$
  – quark mixing parameters:
    • $\theta_1$ $\theta_2$ $\theta_3$ $\delta$

• many observables
  – $\alpha = 1/127.934(27)$
  – $G = 1.16637(1) \times 10^{-5}$ GeV$^{-2}$
  – $m_Z = 91.1876(21)$ GeV
  – $\sin^2 \theta_{\text{eff}} = 0.23148(17)$
    • couplings of $Z$ to fermions
    • $\nu$ scattering cross sections
  – $m_W = 80.426(34)$ GeV
  – $\Gamma_W = 2.139(69)$ GeV
  – $m_t = 174.3(5.1)$ GeV

• unknown
  – $m_H$
The standard model

- global electroweak fit
  - are all measurements consistent with one set of parameters?
    - $m_t = 174.0 \pm 4.5$ GeV
    - $m_H = 91^{+58}_{-37}$ GeV
    - $\sin^2 \theta_{\text{eff}} = 0.23142 \pm 0.00015$
    - $m_W = 80.386 \pm 0.019$ GeV
    - $\chi^2/\text{dof} = 25.5/15 (4.4\%)$
  - Higher order corrections link SM parameters

\[ \begin{align*}
  e.g. \quad M_W &= M_{\text{tree}} + \\
  &\left[ M_Z, \alpha_{EM}, G_F, m_t^2/M_W^2 \right] \\
  \ln \frac{M_H}{M_W} &\propto \text{Higgs}
\end{align*} \]

- Measure $M_W, m_t$ (or others) $\Rightarrow$ constrain $M_H$
Indirect constraints on Higgs mass

• Top mass

<table>
<thead>
<tr>
<th></th>
<th>now</th>
<th>2 fb⁻¹</th>
<th>15 fb⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>l+jets</td>
<td>5.1</td>
<td>2.7</td>
<td>1.3</td>
</tr>
<tr>
<td>dilepton</td>
<td>2.8</td>
<td>1.3</td>
<td>GeV</td>
</tr>
</tbody>
</table>

- systematics → MC model, jet scale

• W mass

<table>
<thead>
<tr>
<th></th>
<th>now</th>
<th>2 fb⁻¹</th>
<th>15 fb⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>W→lν</td>
<td>34</td>
<td>27</td>
<td>17</td>
</tr>
<tr>
<td></td>
<td></td>
<td>MeV</td>
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</table>

- systematics → production and decay model

<table>
<thead>
<tr>
<th>m_H [GeV]</th>
<th>m_t [GeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>114</td>
<td>130</td>
</tr>
<tr>
<td>300</td>
<td>150</td>
</tr>
<tr>
<td>1000</td>
<td>170</td>
</tr>
</tbody>
</table>

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Is there anything beyond the SM?

• Problems of the SM
  – Many free parameters
  – Hierarchy: Planck scale vs ewk scale
    • $\Rightarrow$ large corrections to scalar masses ($M_H$)
    • $\Rightarrow$ fine tuning required to keep $M_H$ light
  – Triviality:
    • $\Rightarrow$ self couplings of scalars blow up at high energies
  – Gravity not included

• $\Rightarrow$ SM can only be the low energy limit of a more comprehensive theory
Supersymmetry

- Symmetry between fermions and bosons
  - Natural solution to hierarchy problem
    - Additional corrections to $M_H$ precisely cancel divergences
- More complicated Higgs sector
  - $\geq 2$ Higgs doublets $\rightarrow$ 5 physical scalar particles:
    - CP-even: $h^0$, $H^0$, CP-odd: $A^0$, charged: $H^\pm$

- MSSM:
  - $M_h \lesssim 135$ GeV
- SUSY with gauge coupling unification:
  - $M_h \lesssim 205$ GeV (Quiros&Espinosa hep-ph/9809269)
Supersymmetric Higgs sector

- Expanded Higgs sector: $h, H, A, H^\pm$
- Properties depend on
  - At tree level, two free parameters (usually taken to be $m_A, \tan \beta$)
  - Plus radiative corrections depending on sparticle masses and $m_t$
Can the Higgs be heavy?

- Global fit to electroweak data $\Rightarrow M_H < 211$ GeV
  - Assumes no physics beyond SM
  - If Higgs heavier, there must be new physics at some scale $\Lambda$
    - Peskin, Wells PRD 64, 093003 (2001)
    - e.g. topcolor-seesaw model
      - positive contributions to $\Delta T$
      - allows $M_H \lesssim 450$ GeV
      - Chivukula, Hölbling, hep/ph-0110214
A Tantalizing Hint of Higgs Boson Signal from Direct Searches by the LEP experiments
Higgs production at LEP

- Dominant Production Process:
  - Bjorken Process
  - "Higgsstrahlung"

\[ \sqrt{s} = m_Z \]

\[ \sqrt{s} \geq m_H + m_Z \]

Higgs Production Cross Section

Center of mass energy (GeV)

<table>
<thead>
<tr>
<th>m_H (GeV/c^2)</th>
<th>50</th>
<th>60</th>
<th>70</th>
<th>85</th>
<th>100</th>
<th>115</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sensitivity</td>
<td></td>
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</tr>
</tbody>
</table>

Sensitivity for 200 pb^{-1}

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most significant Hvv candidate

measured ll mass = 114.4 GeV
ll mass resolution ~ 3 GeV
SM Higgs combined results

Data 4
Bkg  1.2
Sig  2.2

\( \sqrt{s} = 200-210 \) GeV

LEP tight
background

hZ Signal
(m\( _h \)=115 GeV)

Events / 3 GeV/c^2

Reconstructed Mass m\( _H \) [GeV/c^2]

L3: Few candidate events compatible with the Higgs hypothesis
ALEPH: Excess of events compared to what is expected from SM background, suggesting a Higgs boson with mass m\( _H \sim 114 \) GeV/c^2
DELPHI: No evidence for any Higgs signal, limit set to m\( _H > 114.1 \) GeV/c^2
OPAL: No evidence for any Higgs signal, limit set to m\( _H > 112.7 \) GeV/c^2

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What NOW?

Search for the Higgs Boson at the Tevatron
The Higgs boson

- $m_H > 140$ GeV
  - $\sigma(H) \approx 0.45$ pb

- $m_H < 140$ GeV
  - $\sigma(W,Z+H) \approx 0.15$ pb

Gluon fusion

Associated Production

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The Higgs boson

- **Higgs decay**
  - $H \rightarrow ff, \ W^+W^-, \ ZZ$
  - couples to mass
  - heaviest final state dominates
  - $m_H < 140 \text{ GeV}$
    - $H \rightarrow bb$
  - $m_H > 140 \text{ GeV}$
    - $H \rightarrow WW$
Low Mass Higgs Search

- Higgs couples most strongly to massive particles:
  \[ H \rightarrow b\bar{b}, \tau^+ \tau^- \]

- Focus on associated production (WH/ZH)
  - Best Prospects: leptonic W/Z decays
  - QCD background large hadronic channels

- SM Background processes:
  - Sensitivity will depend on
    - b-jet tagging
    - dijet mass resolution

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SM Higgs: Event Signatures

$H^0 W \rightarrow l\nu b\bar{b}$  \hspace{1cm} $H^0 Z^0 \rightarrow \nu\nu b\bar{b}$  \hspace{1cm} $H^0 Z^0 \rightarrow llb\bar{b}$

$p\bar{p} \rightarrow HX \rightarrow WW(*)X \rightarrow ll\ell'\ell'$

$W/ZH \rightarrow WWW^*/ZWW^*$, $\rightarrow \ell^\pm\ell'^\pm jj$

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Low Mass Higgs Search

• It’s going to be challenging…

A 115 GeV Higgs signal

This is a statistically ‘unlucky’ case…

This is a statistically ‘typical’ case…
The Higgs boson

- Run 2A (2 fb\(^{-1}\))
  - exclude \(m_H \lesssim 115\) GeV

- Run 2B (10 fb\(^{-1}\))
  - exclude \(m_H < 140\) GeV
  - 3\(\sigma\) for \(115 < m_H < 130\) GeV
Indirect constraints on the Higgs mass

• global electroweak fit

\[ \Delta \alpha_{\text{had}}^{(5)} = 0.02761 \pm 0.00036 \]

Without NuTeV

theory uncertainty

Grünewald, Heintz, Narain, Schmitt, hep-ph/0111217

\[ \Delta \chi^2 \approx 2010 \]
Neutral Higgs

- Translate SM results into SUSY (tan$\beta$, $M_A$) parameter space according to SUSY couplings
- $V_h$, $V_H$ can be Standard Model-like

\[
\begin{align*}
\sigma(q\bar{q} \to V_h) &= \sin^2(\beta - \alpha) \sigma(q\bar{q} \to V_{h_{SM}}) \\
\sigma(q\bar{q} \to V_H) &= \cos^2(\beta - \alpha)\sigma(q\bar{q} \to V_{H_{SM}})
\end{align*}
\]

- In addition: $b\bar{b}A$, $b\bar{b}h$, $b\bar{b}H$ enhanced at large $\tan\beta$

\[
\sigma(p\bar{p} \to b\bar{b}\Phi) = (g_b^{h,A,H})^2\sigma(p\bar{p} \to b\bar{b}H_{SM})
\]

where, $g_b^h \sim 1/\cos\beta$, $g_b^H \sim 1/\cos\beta$, $g_b^A \sim \tan\beta$

\[\tan\beta = \frac{v_2}{v_1}, \quad \alpha = \text{mixing angle between CP even } h \text{ and } H\]
$h \rightarrow W^+ W^-$

...important in high mass region $140 < m_h < 190$ GeV.

- two energetic, isolated leptons + large $E_T$
- large SM rates eliminated by topological cuts
- note similarity with continuum $p\bar{p} \rightarrow W^+ W^-$
- limit $\sigma \times Br < 8$ pb about $100 \times \sigma(h)$
Tevatron Physics

- Exciting possibilities for Top quark physics:
  - Measure production rates, spin correlations
  - Isolate Single Top quark events
  - Measure Top Quark Mass with greater precision
  - Clues to origin of mass?

- Lots of searches for physics beyond SM

- The next 5-10 years will hopefully lead to findings which may change the course of particle physics.... 😊
References

• For this talk I have drawn heavily from the Fermilab web site and CDF/D0 experiments:
  – FNAL: http://www.fnal.gov
  – D0:     http://www-d0.fnal.gov

• A nice description of HEP maybe found at
  http://www-ed.fnal.gov/projects/exhibits/searching/

• The Tevatron studies described were performed by the RunII SUSY/Higgs working group at the Tevatron. The details of the study can be found in hep-ph/0010338.
  – A comprehensive note – with multitude of theoretical and experimental references.

• Latest LEP results:
  – For Higgs from LHWG Note/2002-01
  – For Electroweak Global Fits: LEP EWWG/2001-02

• LHC:
  – ATLAS and CMS TDR