Non-SM Electroweak Symmetry Breaking
Searches at the Tevatron

19th International Workshop on
Weak Interactions & Neutrinos
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for the CDF Collaboration

Outline:
• CDF, Run-I and Run-II
• Review results on CDF searches for
  Non-SM Electroweak Symmetry
  Breaking
• Summary
CDF in Run-I and Run-II

• In Run-I (1992-1996) CDF used ~100pb⁻¹ data to investigate electroweak symmetry breaking in SM/Non-SM approach
  • Applied several important tools for these studies
    • e/μ/τ identification
    • Good calorimetry for jet/MET measurements
    • Tagging b,c jets
• Run-II upgrades:
  • New data acquisition electronics to cope with higher luminosity
  • Extend lepton acceptance
  • Larger geometrical acceptance for silicon tracker
• Have collected ~200pb⁻¹ data
Understanding the Run-II Detector

- Have made baseline measurements to demonstrate the level of understanding of our new detector and the new operating environment.

  - \[ \int L \, dt = 72.0 \, \text{pb}^{-1} \]
  
  \[ \sigma(p p \rightarrow W \rightarrow \tau \nu) \]

  \[ \sigma(p p \rightarrow W \rightarrow \mu \nu) \]

  \[ \sigma(p p \rightarrow W \rightarrow e \nu) \]

  \[ \sigma_{W}(e + \mu) \]

- t\(\bar{t}\) candidate, di-lepton channel (two displaced vertices)

- Good understanding of lepton Id

- MET+jets (good understanding of MET)
Non-SM Electroweak Symmetry Breaking

Several models created to solve the hierarchy problem, and to explain the origin of EW symmetry breaking

- Extra Dimensions
- Technicolor
- SUSY/MSSM
- Little Higgs

Review CDF results on searches for the predicted phenomena based on these models
Searches for Extra Dimensions

Extra Dimensions (ED)

• The large gap between EW and Planck scales is assumed to be due to the geometry of the extra dimensions

• The gap is narrowed by reducing the effective fundamental scale to ~ 1 TeV

• Only Graviton propagates in the ED, other SM particles are trapped in our 3-D brane

• In the compactified ED, the gravity expands into a series of Kaluza-Klein (KK) states
Large Extra Dimensions (ADD) Model

(“ADD” => Arkani-Hamed, Dimopoulos, and Dvali)

• Hierarchy between EW and Planck scales is generated by large volume of extra dimensions

(for \( M_D \approx 1 \text{ TeV} \), \( n=2 \) => \( R_c \approx \text{mm} \))

• Gravity propagates freely in ED
  • \( M_{Pl}^2 \sim R^n c^n M_{D}^{2+n} \)
  • \( M_{Pl} \): Planck scale
  • \( R_c \): radius of ED
  • \( M_D \): new effective fundamental scale
  • \( n \): # extra dimensions

Search for ADD ED at Tevatron

• Direct G emission:
  \[
  q \bar{q} \rightarrow \gamma G
  
  q \bar{q} \rightarrow Gg
  
  qg \rightarrow Gq
  
  gg \rightarrow Gg
  
\]

• Virtual G exchange:
  • \( q\bar{q} \rightarrow l^+l^-, q\bar{q}, \gamma\gamma \)
  • contribute to normal SM scattering amplitude
  • Enhancement tail in ee/\( \mu\mu/jj \) spectra
  • No resonance in spectra because KK spectrum uniformly spaced => continuous spectrum
Searches for Extra Dimensions (ADD)

Direct $G$ Emission (MET+jet)

- Search events with large MET and 1 or 2 jets
  - MET $> 80$ GeV
  - $E_t(\text{jet}_1) > 80$ GeV, $E_t(\text{jet}_2) > 30$ GeV (if 2$^{nd}$ jet present)

- Reduce QCD multi-jets:
  - $\Delta\phi(\text{MET},\text{jets}) > 0.3$ rad (MET due to jet energy mis-measurement)

- Reduce $W(\rightarrow l\nu)$, $Z(\rightarrow l^+l^-)$:
  - Two highest energy jets not purely electromagnetic
  - No isolated track

- Remaining background from:
  - $Z(\rightarrow \nu\nu)+$jets, $W(\rightarrow l\nu)+$jets ($l: e, \mu, \tau$)
  - QCD
  - $tt$, single $t$, diboson

#Observe=284, #Expected=274.1 $\pm$ 15.9
No excess in observed events, thus excluded effective Planck scale ($M_D$)

<table>
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<tr>
<th>n</th>
<th>CDF (K=1.0)</th>
<th>D0 (K=1.0)</th>
<th>D0 (K=1.34)</th>
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<tr>
<td>6</td>
<td>0.71</td>
<td>0.63</td>
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</tbody>
</table>

**Best limit from the Tevatron on search for direct graviton emission**
**Randall-Sundrum (RS) Model**

- Hierarchy between EW and Planck scales is generated by a large curvature of the extra dimensions

  - Planck brane
  - Our world (3+1dim)
  - TeV brane

- $G$ is localized in the Planck brane

- The scale of physical phenomena on the TeV brane is $\Lambda_\pi = M_{Pl} e^{-kR_\pi}$

  - $k$: parameter governs the degree of curvature

**Search for RS ED at Tevatron**

- Virtual $G$ exchange:
  - Virtual contribution to scattering processes
  - Spectrum of KK states are discrete, and unevenly spaced

- Look for bumps in $M_{ee}$, $M_{\mu\mu}$, $M_{jj}$

**Graph:**

- $d\sigma/dM$ vs. $M_{ll}$ (GeV)
- $k / M_{Pl}$
- Points for $k/\Lambda_{Pl}$:
  - 1, 0.3, 0.1
- $d\sigma/dM$ (Pb/GeV)

**Reference:**

- hep-ph/0006041

Oct 7th 2003

Song Ming Wang, WIN’03, Lake Geneva, Wisconsin
Searches for Extra Dimensions (RS)
(Di-lepton)

- Using Inclusive high Pt $e(\mu)$ data sample, select events w/ 2 energetic lepton candidates, $E_t > 25$ GeV ($Pt > 20$ GeV)
- Reconstruct invariant mass ($M_{l+ l-}$) to search for resonance at high mass
- Observe no excess at high mass in $e^+e^-$ and $\mu^+\mu^-$
- Combine $e$ and $\mu$ results to set limits for Randall-Sundrum model

- Sensitive to low $k/M_{Pl}$ and low $M_G$
Searches for Extra Dimensions (RS)

(\text{Di-jet})

- Look for SM deviation in the inclusive jet sample (75 pb\(^{-1}\))
- Select two highest Et jets in event with |\eta_{\text{jet}}|<2
- Observe no resonance in the di-jet mass spectrum
- Set 95\% CL excluded regions
  - Randall-Sundrum G: 220<M<840 \text{ GeV} (k / M_{Pl} = 0.3)

\begin{align*}
\text{CDF Run II Preliminary (75 pb}^{-1}) \\
\text{Randall–Sundrum Graviton} \\
95\% \text{ CL Excluded Region in di-jet decay mode}
\end{align*}

\begin{align*}
\text{Semi-sensitive to high} \\
k/M_{Pl} \text{ and high } M_G
\end{align*}
**Searches for Technicolor**

- Technicolor is a dynamic version of the Higgs mechanism, does not contain elementary scalar boson
- Introduce a new strong gauge force (technicolor) and new fermions (technifermions)
- Technicolor acts between technifermions to form bond states
- “Higgs” boson replaced by states of two techniquarks (technipion)

**Previous CDF searches:**

- $\omega_T \rightarrow \gamma \pi_T^0 \rightarrow \gamma b\bar{b}$
- $\rho_T \rightarrow \pi_{LQ} \pi_{LQ} \rightarrow \tau^+ \tau^- b\bar{b}$
  - $\rightarrow c\bar{c}\nu\nu$
  - $\rightarrow b\bar{b}\nu\nu$

- $\rho_T^\pm \rightarrow W^\pm \pi_T^0 \rightarrow l\nu b\bar{b}$
- $\rho_T^0 \rightarrow W^\pm \pi_T^{\pm} \rightarrow l\nu b\bar{c}$

\(\pi_T\) expect to have Higgs boson like coupling to ordinary fermion, \(\Rightarrow\) perfer couple to 3\textsuperscript{rd} gen. fermions

Describe this analysis next
Searches for Technicolor
(Lepton+MET+jets)

• Search for color singlet $\rho_T$ and $\pi_T$ in lepton ($e$ or $\mu$) + MET + jets
• Select isolate $e$ (Et>20 GeV) or isolate $\mu$ (Pt>20 GeV) in central region ($|\eta|<1$)
• MET>20 GeV
• Only 2 jets, Et>15 GeV, $|\eta|<2$, at least one jet tagged as b-jet candidate
• Major background from:
  • $Wbb$, $Wcc$, $Wc$
• Set 95% CL exclusion region in $M(\pi_T)$ vs $M(\rho_T)$ plane

CDF 109 pb⁻¹

PRL, 84, 1110
Run-II Technicolor Sensitivity
(Lepton+MET+jets)

- Predicted reach for $L \sim 2 \text{fb}^{-1}$
- Assume the same selections and systematic uncertainty as in Run-I search, but double signal efficiency (due to larger coverage in lepton id, and b-jet tagging)

hep-ph/0007304
Searches for Technicolor

(Di-jet)

Di-jet

• Use results from the search for resonance at high di-jet mass to set limits for the mass of Color Octet Technirho

Exclude the mass range:
260<M<640 GeV (Run-II)

CDF Run-I exclusion:
260<M<480 GeV
Searches for Non-SM Higgs

Results on CDF searches for:

• Higgs from SUSY/MSSM
• Double Charged Higgs
Searches for Charged Higgs (MSSM)

• If \( m_{H^+} < m_t - m_b \), then \( t \to H^+b \)

• \( \text{BR}(t \to H^+b) \) depends on \( \tan(\beta) \)

**Direct Search:**

\[
\begin{align*}
q & \to W^+ \to \tau^+ + \text{jets} + \text{MET} \\
\bar{q} & \to W^- \to \text{leptons} + \text{jets} + \text{MET}
\end{align*}
\]

• Select events of these signatures:
  - \( e/\mu + \tau + \text{jets} + \text{MET} \)
  - \( \tau\tau + \text{jets} + \text{MET} \)

\( \tau \) identified in hadronic decay mode

**Indirect (Disappearance) Search:**

• Observe if the di-lepton and lepton+jets top events (lepton : \( e, \mu \)) are suppressed

• For given \( \sigma(t \bar{t}) \) and \( \{M(H^+), \tan(\beta)\} \), how likely is it to observe \( N \) events

• Set exclusion regions in \( \{M(H^+), \tan(\beta)\} \)
Searches for Charged Higgs (MSSM)

CDF Preliminary
Excluded 95% C.L.

\[ \int L \, dt = 0.1 \, \text{fb}^{-1} \]
\[ M_t = 175 \, \text{GeV} \]

- \( t \rightarrow H^+ b \) searches

- \( \alpha(tbH^+) \) large

- CDF \( \sigma = 5.0 \, \text{pb} \)
- D0 \( \sigma = 5.5 \, \text{pb} \)

Direct search

- CDF \( \sigma = 5.0 \, \text{pb} \)

Indirect search

\[ \Gamma_t > 15 \, \text{GeV} \]
No limit

\[ \tan \beta \]

80
60
40
20
60
100
120
140
160
180
200
60
100
120
140
160
180
200

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Searches for Neutral Higgs (MSSM)

$gg \rightarrow \phi \; \; (\phi = h, H, A)$

- Look at the channel $\phi \rightarrow \tau \tau$ with Run-I data (BR~10%)
- Use high Et electron dataset (Pt>18 GeV), no Tau trigger
- Select events with one hadronic $\tau$ and one isolated electron candidate
- Observe no excess of events
- Cannot set limit, since search is not sensitive enough due to low acceptance by the trigger

Implementation Tau Triggers in Run-II

- Lepton(Pt>8) + track(Pt>5) • MET+tau
- Di-tau (2 narrow jets)

![CDF Run 2 Preliminary (72 pb$^{-1}$)](chart)
Searches for Neutral Higgs (MSSM)

$$gg, qq \rightarrow \phi + b\bar{b} \rightarrow b\bar{b}b\bar{b}$$  \hspace{1cm} (\phi=h,H,A)

BR($\phi \rightarrow b\bar{b}$) $\sim$ 90%

Event Selection:
- $\geq 4$ jets, $|\eta_{\text{jet}}|<1.5$
- $\geq 3$ jets tagged as b-quark candidate
- $\Delta \phi(bb) > 1.9$ (bb well separated), to reduce $gg \rightarrow b\bar{b}b\bar{b}$
- Signal acceptance:
  - $\sim 0.2\% - 0.6\%$

Background:
QCD, ttbar, W/Zbb, W/Zcc

PRL, 86, 4472
**Searches for Neutral Higgs (MSSM) (Run-II Sensitivity)**

$gg, qq \rightarrow \phi + bb \rightarrow b\overline{b}b\overline{b}$

- $\phi + b\overline{b}$: best discovery channel for new Fermilab Run-II luminosity baseline
Searches for Doubly Charged Higgs

- Doubly charged Higgs are predicted in models that contain Higgs triplets
  - Models w/ extension to Higgs sector of SM
  - Left-Right symmetric models
  - Supersymmetric Left-Right models
- In the Left-Right symmetric models, the Higgs triplets are one of the Higgs multiplets that breaks the symmetry between L and R handed weak interactions at low energy

Event Selection:

- Select $H^{++/--}$ pair or singly produced
- Search for 1 pair of same sign $ee$, or $\mu\mu$, or $e\mu$
  - same sign leptons decay contains low SM backgrounds, provide clean environment for new physics search
- Datasets: inclusive high Pt electron/muon samples (~90 pb$^{-1}$ for both)
Searches for Doubly Charged Higgs

- No excess in observed events
- Example in the same sign $e\mu$ for $M_{e\mu} > 80$ GeV
  - $\#\text{Obs}=1, \#\text{Bgd}=3.2^{+1.6}_{-0.9}$

**Exclusion mass region:**
- $ee$: no exclusion
- $\mu\mu$: $M_{H^{++/--}} < 110$ GeV
- $e\mu$: $M_{H^{++/--}} < 110$ GeV
Summar

• Non-SM Electroweak Symmetry breaking searches have been performed in several channels at CDF
• No evidence of deviation from SM expectation observed so far
• Limits are set for various Non-SM parameters
• CDF Run-II has started successfully. The upgrades will improve the sensitivities to these searches
• Integrated luminosity of data collected at sqrt(s)=1.96 TeV is ~2X that of Run-I

=>STAY TUNED for more NEW results in the next winter conferences!!!