Selected Topics from the Tevatron

A CDF Perspective

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Ettore Majorana, Erice, September 2, 2006
Topics To Be Covered

- “Primer” Tevatron--CDF--D0
- Jet Production
- Top
  - cross section
  - precision mass
- $B_s$ oscillation frequency
- Searches
  - Susy (tri-leptons)
  - Signature based
  - Extra dimensions
  - Higgs (low mass SM)
“Primer”
Accelerator Complex and Delivered Luminosity

Peak Luminosity $1.8 \times 10^{32}$ cm$^{-2}$ sec$^{-1}$

Goal $\sim 4 \times 10^{32}$

Electron Cooling in Recycler a success
Pbars Needed!

- Recorded 1.3 fb\(^{-1}\)
- Slightly above base now
  - 20 mA/hr at zero current

CDF and D0 have similar amounts of data

- Recorded 1.3 fb\(^{-1}\)
CDF

MUONS

1 inch diameter

ELECTRONS
The trigger is critical at hadron colliders

Very Different Approaches by CDF and D0

CDF Detector

Hardware tracking for $p_T \geq 1.5$ GeV
Muon-track matching
Electron-track matching
Missing $E_T$, sum-$E_T$

CDF triggers on B mesons at L1

Hardware + Linux PC's

Silicon tracking
Jet finding
Refined electron/photon finding

L1 trigger

L2 trigger

L3 farm

Full event reconstruction

L1: 1.6 kHz
L2: 800 Hz
L3: 100 Hz

40-80 MB/s

Both experiments write about 100 Hz to tape- offline cost driven
Typical CDF Triggers and their Usage

- **Unprescaled triggers** for primary physics goals (>150 trigger paths)
- **Examples:**
  - Inclusive electrons, muons $p_T>18$ GeV:
    - W, Z, top, WH, single top, SUSY, Z'
  - Dileptons, $p_T>4$ GeV:
    - SUSY
  - Lepton+$\tau$, $p_T>8$ GeV:
    - MSSM Higgs, SUSY, Z
    - Also have $\tau$+MET: $W\rightarrow\tau\nu$
  - Jets, $E_T>100$ GeV
    - Jet cross section, Mono-jet search
    - Lepton and b-jet fake rates
  - Photons, $E_T>25$ GeV:
    - Photon cross sections, Jet energy scale
    - Searches (GMSB SUSY)
  - Missing $E_T>45$ GeV
    - SUSY
    - $ZH\rightarrow\nu\nu b\bar{b}$

- **Dynamic Prescale triggers** because:
  - Not possible to keep at highest luminosity
  - Needed for monitoring
  - Prescales depend often on Lumi
- **Examples:**
  - Jets at $E_T>20$, 50, 70 GeV
  - Inclusive leptons >8 GeV
  - B-physics triggers
  - Backup triggers for any threshold, e.g. Met, jet ET, etc.

An Unfortunate reality: CS vs lum

![Graph showing cross section vs. instantaneous luminosity]

Complex trigger strategies necessary: Table $n$ is from $n-1$ etc. Incremental
Complex Collisions to Untangle—LHC worse

Multiple collisions (Tevatron several—LHC 20+)
Lose forward going particles down beamline

\[ \hat{S} = x_p \cdot x_\bar{p} \cdot S \]

X: fractional momentum carried by parton

Valence quarks:
- Gluons
- Sea quarks

Exact mixture depends on:
\[ Q^2: \sim (M^2 + pT^2) \]
W Charge Asymmetry

Effect of quark PDF’s easy to see

CDF

\[ A_\ell(\eta) = \frac{d\sigma(e^+) / d\eta - d\sigma(e^-) / d\eta}{d\sigma(e^+) / d\eta + d\sigma(e^-) / d\eta} \approx \frac{d(x)}{u(x)} \]

most sensitive

Lepton and Charge ID up to high |\eta|
Strong Interaction
Central Jets Probe Quark Sub-Structure

0.1 < |\eta_j| < 0.7

Tevatron parton kinematics

\[ x_{1,2} = \left( \frac{M}{1.96 \text{ TeV}} \right) \exp(y) \]
\[ Q = M \]

Probes \( Q^2 \sim O(10^6) \text{ GeV}^2 \)

No evidence of structure
$B_s$ Mixing

Mission Accomplished
The Measurement Principle

- reconstruct $B_s$ decays—decay flavor from decay products
- infer $B_s$ production flavor (production flavor tagging)
- measure proper time of the $b$-quark decay (very precisely)
CDF-II Upgraded for $B_s$ Mixing

- multi-purpose detector
- excellent momentum resolution $\sigma(p)/p < 0.1\%$
- Yield:
  - SVT based trigger
- Tagging power (SSKT)
  - TOF, $dE/dX$ in COT
- Proper time resolution:
  - SVXII, L00 (not in trigger)
  - SVX-III deadtimeless
Triggering On Displaced Tracks Critical

- trigger $B_s \rightarrow D_s^{-}\pi$, $B_s \rightarrow D_s^{-} l^+$

```
trigger extracts 20 TB/sec

“unusual” trigger requirement:

two displaced tracks:
($p_T > 2$ GeV/c, $120 \mu m < |d_0| < 1$ mm)
```
**B_s Mixing Basics**

- **Neutral B Meson system**
  \[ |B \rangle \equiv (\bar{b}s); \quad |\bar{B} \rangle \equiv (b\bar{s}) \]

- Mixture of two states (No CP violation case):
  \[
  |B_H \rangle = \frac{1}{\sqrt{2}} \left( |B\rangle + |\bar{B}\rangle \right), \\
  |B_L \rangle = \frac{1}{\sqrt{2}} \left( |B\rangle - |\bar{B}\rangle \right)
  \]

- \( B_H \) and \( B_L \) may have different mass and decay width
  - \( \Delta m = M_H - M_L \) 
    (>0 by definition)
  - \( \Delta \Gamma = \Gamma_H - \Gamma_L \)

- The case of \( \Delta \Gamma = 0 \)
  \[
  p(B \rightarrow B) = \frac{e^{-t/\tau}}{2\tau} \left( 1 + \cos \Delta m t \right) \\
  p(B \rightarrow \bar{B}) = \frac{e^{-t/\tau}}{2\tau} \left( 1 - \cos \Delta m t \right)
  \]
Measurement .. In a Perfect World

what about detector effects?

\[ A(t) = \frac{N_{RS} - N_{WS}}{N_{RS} + N_{WS}} \]

Production Flavor = Decay Flavor

\[ p(t) = \frac{1}{2\tau} e^{-\frac{t}{\tau}} [1 + \cos(\Delta m_s t)] \]

Production Flavor ≠ Decay Flavor

\[ p(t) = \frac{1}{2\tau} e^{-\frac{t}{\tau}} [1 - \cos(\Delta m_s t)] \]
Realistic Effects

- **Flavor tagging power, background**
  - Mis-tag rate 40%

- **Displacement resolution**
  - $\sigma(L) \sim 50 \, \mu m$

- **Momentum resolution**
  - $\sigma(p)/p = 5\%$

Mathematical expression:

$$\frac{1}{\sigma} = \sqrt{\frac{S \epsilon D^2}{2}} e^{-\frac{(\Delta m_s \sigma_t)^2}{2}} \sqrt{\frac{S}{S + B}}$$
Amplitude

\[ \mathcal{L}_t \propto \left(1 + A \cdot D \cos(\Delta m t) \right) \]

- Oscillatory factor in pdf
  \(+/-\) is flavor at production versus decay
- \(A\) is amplitude of oscillation and \(A=1\) for signal and \(A=0\) background
- \(D\) is event dilution (\(\text{epsilon } D^2\) is about 5%)
- \(A=1\) for real signal
- Width will be proportional to \(B\) lifetime

Amplitude Scanning

fixed value of \(\Delta m_s\), fit for Amplitude
repeat for different values of \(\Delta m\)

if a signal is found, fit for mixing frequency!
**Signal Yield Summary: Hadronic**

<table>
<thead>
<tr>
<th>Process</th>
<th>Yield</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B_s \rightarrow D_s \pi (\phi \pi)$</td>
<td>1600</td>
</tr>
<tr>
<td>$B_s \rightarrow D_s \pi (K^* K)$</td>
<td>800</td>
</tr>
<tr>
<td>$B_s \rightarrow D_s \pi (3\pi)$</td>
<td>600</td>
</tr>
<tr>
<td>$B_s \rightarrow D_s 3\pi (\phi \pi)$</td>
<td>500</td>
</tr>
<tr>
<td>$B_s \rightarrow D_s 3\pi (K^*K)$</td>
<td>200</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>3700</strong></td>
</tr>
</tbody>
</table>

- high statistics light B meson samples:
  - $B^+ (D^0 \pi^-)$: 26k events
  - $B^0 (D^- \pi)$: 22k events
Same Side Kaon Tags

- exploit b quark fragmentation signatures in event
- $B^0/B^+$ likely to have a $\pi^-/\pi$ nearby
- $B^0_s$ likely to have a $K^+$
- use TOF and COT dE/dX info. to separate pions from kaons
- problem: calibration using only $B^0$ mixing will not work
- tune Monte Carlo simulation to reproduce $B^0$, $B^-$ distributions, then apply directly to $B^0_s$
$B_s$ – Sufficient Proper Time Resolution

- Period $= 0.33 \text{ ps} \sim 100 \mu m$
- Resolution $\sim 26 \mu m$

CDF Run II Preliminary $L = 1.00 \text{ fb}^{-1}$

$B_s \to D_s^- (3) \pi^+$

$\langle \sigma_{ct} \rangle = 25.9 \mu m$

osc. period at $\Delta m_s = 18 \text{ ps}^{-1}$
D0 Amplitude Scan

DØ Run II

Amplitude

Δm_s [ps^{-1}]

0 5 10 15 20 25

P-value=5%

95% CL limit: 14.8 ps^{-1}

Expected limit: 14.1 ps^{-1}

data ± 1σ

data ± 1.645 σ (stat.)

data ± 1.645 σ (stat. + syst.)

1 fb^{-1}
CDF Amplitude Scan

Prob. of stat. fluctuation: 0.2%

$\Delta m_s = 17.31 \pm 0.33 \pm 0.07 \text{ ps}^{-1}$

$|V_{td}/V_{ts}| = 0.208 + 0.001 \text{ (exp)} + 0.008 \text{ (th.)}$
The experimental precision on unitarity triangle greatly improved => the triangle still closes!
Top Physics
Why Is the Top Quark Interesting?

- Heaviest known fundamental particle
- Is this large mass telling us something about electroweak symmetry breaking?

- Related to $m_W$ and $m_H$:
  - $m_W \sim M_{\text{top}}^2$
  - $m_W \sim \ln(m_H)$

- If there are new particles the relation might change:
  - Precision measurement of top quark and W boson mass can reveal new physics

- Precision measurements of mass, couplings, charge, spin, helicity of W…?

\[
M_W = 80.404 \pm 0.030 \text{ GeV/c}^2 \\
M_{\text{top}} = 172.5 \pm 2.3 \text{ GeV/c}^2
\]
Top Production and Decay

Top production by strong interaction
85% quark annihilation
15% gluon fusion

Final state complex
Weak decay of W-boson

$$\text{Br}(t \rightarrow bW) = 100\% , \ \text{Br}(W \rightarrow l\nu) = 1/9 = 11\%$$

- dilepton (4/81) 2 leptons + 2 jets + missing ET
- lepton+jets (24/81) 1 lepton + 4 jets + missing ET
- fully hadronic (36/81) 6 jets

Gluon radiation ISR and FSR adds more jets
Tagging (not mis-tagging) b-jets is Critical

- Exploit large lifetime of the b-hadron
- reconstruct primary vertex: μm resolution ~ 30
- Form $L_{xy}$: transverse decay distance projected onto jet axis:
  - $L_{xy}>0$: b-tag along the jet direction $\Rightarrow$ real b-tag or mistag
  - $L_{xy}<0$: b-tag opposite to jet direction $\Rightarrow$ mistag!
- Significance: $L_{xy} > 7 \delta(L_{xy})$ i.e. 7 sigma

Want this high

Want this low
Top hadronic cross section

- NN discriminates between top and multi-jet backgrounds
- Control in pretag sample and 4- and 5-jet bins
- Dominant syst. Uncertainty: JES

$\sigma_{tt} = 8.3 \pm 1.0^{+0.5}_{-0.5} (\text{stat})^{+2.0}_{-1.5} (\text{lum})^{+2.3}_{-1.9} (\text{syst}) = 8.3^{+2.3}_{-1.9} \text{ pb}$
Top Quark Cross section: Lepton + Jets

- Select:
  - 1 electron or muon
  - Large missing $E_T$
  - 1 or 2 b-tagged jets

Top Signal $(t\bar{t}) = 8.2 \pm 0.6 \text{ (stat)} \pm 1.1 \text{ (syst)} \text{ pb}$

45 double-tagged Events, nearly no background

$\sigma(t\bar{t}) = 8.2 \pm 0.6 \text{ (stat)} \pm 1.1 \text{ (syst)} \text{ pb}$

Single tag result (OK with SM)
**Summary of top cross sections**

- **CDF Preliminary**
  - Dilepton (L = 750 pb⁻¹)
    - 8.3 ± 1.5 ± 1.0 ± 0.5
  - Lepton+Jets: Kinematic (L = 760 pb⁻¹)
    - 6.0 ± 0.6 ± 0.9 ± 0.3
  - Lepton+Jets: Vertex Tag (L = 685 pb⁻¹)
    - 8.2 ± 0.6 ± 0.9 ± 0.5
  - Lepton+Jets: Soft Muon Tag (L = 193 pb⁻¹)
    - 5.3 ± 3.3 ± 1.3 ± 0.3
  - MET+Jets: Vertex Tag (L = 311 pb⁻¹)
    - 6.1 ± 1.2 ± 1.4 ± 0.9 ± 0.4
  - All-hadronic: Vertex Tag (L = 311 pb⁻¹)
    - 8.0 ± 1.7 ± 3.3 ± 2.2 ± 0.5
  - Combined (L = 760 pb⁻¹)
    - 7.3 ± 0.5 ± 0.6 ± 0.4 (stat) ± (syst) ± (lumi)

**DØ Run II Preliminary**

- **dilepton (topological)**
  - L = 230 pb⁻¹
    - 8.6 ± 3.2 ± 1.1 ± 1.1 ± 0.5 pb
  - L = 370 pb⁻¹
    - 8.6 ± 2.3 ± 1.2 ± 1.0 ± 0.5 pb

- **l+jets (topological)**
  - L = 230 pb⁻¹
    - 6.7 ± 1.4 ± 1.6 ± 1.3 ± 1.1 pb
  - L = 370 pb⁻¹
    - 7.1 ± 1.2 ± 1.4 ± 1.2 ± 1.1 pb

- **combined (topological)**
  - L = 230 pb⁻¹
    - 7.1 ± 1.2 ± 1.4 ± 1.2 ± 1.1 pb
  - L = 370 pb⁻¹
    - 8.6 ± 2.3 ± 1.2 ± 1.0 ± 0.5 pb

- **ltrack/emu combined**
  - L = 370 pb⁻¹
    - 8.5 ± 1.9 ± 1.1 ± 1.7 ± 1.1 pb

- **l+jets (Vertex tag)**
  - L = 363 pb⁻¹
    - 8.2 ± 0.9 ± 0.9 ± 0.9 ± 0.8 pb

- **all hadronic**
  - L = 350 pb⁻¹
    - 5.2 ± 2.6 ± 1.5 ± 2.5 ± 1.0 pb

- **all hadronic NEW**
  - L = 360 pb⁻¹
    - 12.1 ± 4.9 ± 4.8 ± 4.9 ± 4.6 pb

Cross sections consistent across decay modes—agree with SM
Top Mass: All-jets Final State

- Background control critical:
  - Signal/Background=1/2
  - Background checked in background rich regions
- Templates used for the signal and

\[ m_{\text{top}} = 174.0 \pm 2.2 \text{ (stat.)} \pm 4.8 \text{ (syst.)} \text{ GeV}/c^2 \]
Top Mass--Matrix Element Method

Use knowledge of top event kinematics to weight “top-like”

For each event \( x \), form probability as function of top mass \( m_t \) by integrating over all unmeasured quantities:

\[
P(m_t; x) = \int d\Phi \ |M_{tt}(x, m_t)|^2 \ W(x)_{\text{res.}}
\]

\( X \): measured quantities (angles, momenta..)
Integrate over phase space (pdfs)

**LO Matrix Element for \( tt \) production**

Parametrization of jet energy resolution from MC
Top mass: Lepton + Jets(4)

- Matrix-Element method
  - ≥1 b-tag => Signal/Background=4/1
  - Add jet energy scale as 2nd unknown and fit for it:
    - $\Delta\text{JES}=0.99\pm0.02$
      - Constrain 2 untagged jets to $W$ mass (apply to b-jets also)

$$m_{\text{top}}=170.9\pm2.2 \text{ (stat.+JES)}\pm1.4 \text{ (syst.)} \text{ GeV/c}^2$$

$$m_{\text{top}}=170.9\pm2.6 \text{ GeV/c}^2$$
Top Mass: Dilepton Final State

- Improved matrix-element method:
  - \( \geq 0 \) b-tag: Signal/Background=3/2
  - \( \geq 1 \) b-tag: Signal/Background=30/1
  - New: Measure recoil (\( p_T \) of ttbar system) and include this information
    - A priori uncertainty improved by 10%

\[
m_{\text{top}} = 164.5 \pm 3.9 \text{ (stat.)} \pm 3.9 \text{ (syst.) GeV/c}^2
\]

with b-tagging: \( m_{\text{top}} = 167.3 \pm 4.6 \text{ (stat.)} \pm 3.8 \text{ (syst.)} \)

CDF II Preliminary
\[ \int L dt = 1.0 \text{ fb}^{-1} \] (78 events)
CDF $m_{\text{top}} = 170.9 \pm 2.4 \text{ GeV/c}^2$

(CDF and D0 best (last updated 07/26/2006)
**Top Mass: Future**

CDF Run 2 preliminary - $L=333 \text{ pb}^{-1}$
- Selected events
- Background
- $Z$ signal: $3394 \pm 515$ events
- Fit result

**Goal: Understand b-jets**

Z$\to$ b bar Enriched Sample from Trigger
Searches

- SUSY
- Signature searches
- Extra Dimensions
- Low Mass Higgs
Most SUSY models predict the sparticle spectrum accessible at TEV scale. Tevatron would be able to discover SUSY.
SUSY is (by observation) a broken symmetry

mSUGRA (Minimal SuperGravity)

- Gravity breaks SUSY
- Model with 5 parameters
  - Masses $m_{1/2}$, $m_0$
  - Coupling $A_0$
  - Higgs sector: $\text{sgn}(\mu)$, $\tan\beta$
- New parity $R_p$ is conserved
  - $R_p = +1$ for SM particle
  - $R_p = -1$ for SUSY particle
Chargino Neutralino--Golden Mode at TeV

Signature: Three leptons and Missing Energy in the Transverse plane

\( \tilde{W}, \tilde{H}, \tilde{B} \) mix into charginos and neutralinos (\( \chi \)) \( \Leftrightarrow \chi_1^0 \) is the LSP
R-parity conserved \( \Rightarrow \) LSP stable dark matter candidate
Chargino Neutralino Search

- Acceptance (three leptons difficult)
- achieved using different trigger paths

<table>
<thead>
<tr>
<th>CHANNEL</th>
<th>p/E_T’s (GeV/c)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\mu\mu)</td>
<td>20, 5, 5</td>
</tr>
<tr>
<td>(\mu e)</td>
<td>20, 5, 5</td>
</tr>
<tr>
<td>ee</td>
<td>20, 5, 5</td>
</tr>
<tr>
<td>(\mu\mu)</td>
<td>5, 5, 5</td>
</tr>
<tr>
<td>ee</td>
<td>15, 5, 4</td>
</tr>
<tr>
<td>LS (\mu^\pm\mu^\pm, e^\pm e^\pm), (\mu^\pm e^\pm)</td>
<td>20, 10</td>
</tr>
</tbody>
</table>

Wide p_T range
Soft leptons more difficult

Need good mSUGRA parameter space coverage use third lepton
# CDF Results !!!

<table>
<thead>
<tr>
<th>Channel</th>
<th>SM</th>
<th>Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mu\mu + l$</td>
<td>$0.6 \pm 0.1 \pm 0.1$</td>
<td>1</td>
</tr>
<tr>
<td>$\mu e + l$</td>
<td>$0.8 \pm 0.1 \pm 0.2$</td>
<td>0</td>
</tr>
<tr>
<td>$ee + l$</td>
<td>$0.17 \pm 0.03 \pm 0.04$</td>
<td>0</td>
</tr>
<tr>
<td>$\mu\mu + l$</td>
<td>$0.13 \pm 0.03 \pm 0.03$</td>
<td>0</td>
</tr>
<tr>
<td>$ee + \text{track}$</td>
<td>$0.72 \pm 0.04 \pm 0.05$</td>
<td>1</td>
</tr>
<tr>
<td>LS</td>
<td>$6.8 \pm 0.5 \pm 1.0$</td>
<td>9</td>
</tr>
</tbody>
</table>

![Graph showing CDF results](image-url)
Systematic uncertainties have negligible impact---Need more statistics!

With ~ 8 fb\(^{-1}\), sensitive up to Chargino mass ~ 240 GeV/c\(^2\) Covers ILC Mass Range
Sneutrino Decay with R-parity violation

- Sneutrino: neutral, scalar, superpartner of SM tau neutrino
- R-parity violating production & decay
- Lepton flavor violating decay
- Final State:
  - High $P_T$ muon & electron
  - No MET requirement (can extend for leptonic tau decays)
- this analysis is also sensitive to the Lepton Flavor Violating decays of new gauge boson $Z'$ into $e\mu$ predicted by the Models with $U(1)'$ gauge symmetry.

Increasing Interest In Flavor Violating Decays

Excellent experimental signature—very clean
\[ R_P = (-1)^{3(B-L)+2S} \]

**R-parity Violating Couplings**

- \( R_P \) is assumed in most SUSY models
  - Not a fundamental symmetry
  - Motivated by CDM, proton lifetime

- With RPV, most SUSY models do not provide dark matter candidate
  - Other source required?

\( \lambda, \lambda', \lambda'' \) control strength of RPV
\( \lambda, \lambda' \): lepton \# violating
\( \lambda'' \): baryon \# violating
\( \lambda\lambda' \) or \( \lambda'' = 0 \) (proton decay)
Backgrounds

<table>
<thead>
<tr>
<th>Channel</th>
<th>Control Region</th>
<th>Signal Region</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Z \rightarrow \tau\tau$</td>
<td>$38.77 \pm 0.63 \pm 2.33$</td>
<td>$0.57 \pm 0.01 \pm 0.03$</td>
</tr>
<tr>
<td>diboson</td>
<td>$6.63 \pm 0.18 \pm 0.37$</td>
<td>$3.48 \pm 0.10 \pm 0.19$</td>
</tr>
<tr>
<td>$t\bar{t}$</td>
<td>$3.57 \pm 0.05 \pm 0.21$</td>
<td>$3.16 \pm 0.05 \pm 0.19$</td>
</tr>
<tr>
<td>fake lepton</td>
<td>$2.90 \pm 1.10 \pm 1.33$</td>
<td>$0.44 \pm 0.40 \pm 0.40$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Prediction</th>
<th>Control Region</th>
<th>Signal Region</th>
</tr>
</thead>
<tbody>
<tr>
<td>Observation</td>
<td>$51.87 \pm 1.11 \pm 2.72$</td>
<td>$7.66 \pm 0.41 \pm 0.48$</td>
</tr>
</tbody>
</table>

Standard Procedure to define a control region and predict the number of events in that region from data and Monte Carlo

In this case, good understanding of event yields versus pair mass
Results

FIG. 1 (color online). Observed and predicted $M_{e\mu}$ Distributions. The observed $e\mu$ invariant mass spectrum agrees well with that of the combined SM and fake lepton backgrounds. No events are observed in data beyond 159 GeV/$c^2$.

FIG. 2 (color online). Observed 95% C.L. upper limit on $\sigma \times$ BR for $d\bar{d} \rightarrow \tilde{\nu}_e(\tilde{\nu}_\tau) \rightarrow e\mu$ (solid line) and the NLO prediction (dashed line) as a function of $e\mu$ invariant mass. Their intersection gives a 530 GeV/$c^2$ $\tilde{\nu}_e$ mass limit for the values of $\Lambda'_{311}$ and $\Lambda_{132}$ indicated. Because of small differences in the signal acceptances, the 95% C.L. upper limit on the $Z' \sigma \times$ BR (not shown) is larger than that of the sneutrino, $\sim 0.02$ pb greater at 200 GeV/$c^2$ and $\sim 0.003$ pb greater at 600 GeV/$c^2$, for example.

Limit on sneutrino cross section $\times$ BR = 530 GeV/$c^2$ at 95% CL
Extra Spatial Dimensions could solve the hierarchy problem:
- Effective Planck scale is lowered

Good signature:
- Monojet = 1 jet + missing $E_T$
- Main background $Z$+jet→$\nu\nu$ +jet measured from data

No evidence for Extra Dimensions

CDF has world’s best sensitivity for $>3$ dimensions
Search for High Mass Diphotons

- Resonance in diphoton mass spectrum?
  - E.g. predicted in Randall-Sundrum model:
    - alternative ED model to solve the hierarchy problem
    - predicts $\gamma\gamma$ and $ee$ resonances

M > 875 GeV for $k/M_{Pl}=0.1$
Model-Independent Searches

- New searches for anomalous production of:
  - W’s and Z’ at high $H_T$
  - Anomalous ZZ
  - Diphotons+X ($X=\gamma$ ...more to come)
- A spectacular event at $H_T \sim 900$ GeV
Higgs Boson Searches at Tevatron

CDF & D0 mounting increasingly large efforts

Focus here on low mass Higgs
  - Preferred by electroweak precision measurements
  - Main analysis modes:
    - WH → lνbb
    - ZH → νν(II)bb
    - H → WW*

b-jets

Precision EWK fit assuming SM:

\[ M_H = 89^{+42}_{-30} \text{ GeV}/c^2 \]

\[ M_H < 175 \text{ GeV}/c^2 \text{ 95\%CL} \]

including LEP-2 \( M_H > 114.4 \text{ GeV}/c^2 \) @95C.L.

\[ M_H < 207 \text{ GeV}/c^2 \text{ 95\% CL} \]
SM Higgs Production and Decay

Search strategy:

$M_H < 135$ GeV: associated production WH and ZH with $H \rightarrow bb$ decay  
Backgrounds: Wbb (CDF just measured), Zbb, top, WZ (must see), QCD

$M_H > 135$ GeV: $gg \rightarrow H$ production with decay to $WW^*$  
Backgrounds: WW, DY, W/ZZ, tt, tW, $\tau\tau$
Higgs: $ZH \rightarrow \nu\nu bb$

- **Signature:**
  - 2 b-jets + missing ET
- **Many improvements lead to effective luminosity gain of** $(S/\sqrt{B})^2 = 6.3$
  - Improved lepton veto
  - Separate single and double b-tags
  - Include WH as signal
  - Use fit to dijet mass spectrum
- **Plus inclusion of full data luminosity:**
  - No evidence for deviation from background

Exp. Limit / SM rate = 14.2 (at $m_H = 115$ GeV)
Higgs: WH → ℓνbb

- Lepton, missing $E_T$ and 2 jets:
  - One or two b-tags
- New since last year:
  - NN b-tagger
  - Include double-tag
  - Include full 1 fb$^{-1}$ dataset
  - Luminosity equivalent gain
    - $(S/\sqrt{B})^2=1.25^2=1.6$

Exp. Limit / SM rate=23.0 (at $m_H=115$ GeV)
Search for \( H \to WW^* \to l\bar{l}l\bar{l} \)

**Search strategy:**
- \( \to 2 \) high \( P_t \) leptons and missing \( E_t \)
- \( \to WW \) comes from spin \( 0 \) Higgs: leptons prefer to point in the same direction

95% C.L. limits

4th Generation Model starts to be excluded

10x 160 GeV Higgs
All CDF and DØ results now combined for the first time

Combined CDF & D0 Ratio wrt SM
### Luminosity equivalent

\[ \text{Luminosity equivalent} = \left( \frac{S}{\sqrt{B}} \right)^2 \]

<table>
<thead>
<tr>
<th>Improvement</th>
<th>WH- &gt;lvbb</th>
<th>ZH- &gt;vvbb</th>
<th>ZH- &gt;llbb</th>
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<tbody>
<tr>
<td>mass resolution</td>
<td>1.7</td>
<td>1.7</td>
<td>1.7</td>
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<tr>
<td>Continuous b-tag (NN)</td>
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<td>Forward b-tag</td>
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<td>Forward leptons</td>
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<td>Track-only leptons</td>
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<td>NN selection</td>
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<td>WH signal in ZH</td>
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<tr>
<td>Product of above</td>
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<td>7.2</td>
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<td>CDF+DØ combination</td>
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<tr>
<td>All combined</td>
<td>17.8</td>
<td>26.6</td>
<td>14.4</td>
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</tbody>
</table>

---

### Prospects Compelling

**D0 Neural Net b-jet Tagger**

- Increase efficiency by 30% or purity by 30%
- Expect to exceed LEP limit with about 2 fb-1

---

**Diagram:**

- Plot showing b-jet efficiency and fake rate for various neural net (NN) and JLIP tags.
- Graph showing integrated luminosity vs. mass resolution.
- Lines indicating SUSY/Higgs Workshop (98-99) and Higgs Sensitivity Study (03) with 5σ discovery, 3σ evidence, and 95% CL exclusion.

---

**Table:**

<table>
<thead>
<tr>
<th>m_H (GeV)</th>
<th>Lumi Sens Study ('98-'99)</th>
<th>Higgs Sens Study ('03)</th>
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</tbody>
</table>

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**Text:**

- Statistical power only (no systematics)
- Integrated luminosity (fb⁻¹/exp.) PRELIMINARY

---

**Other:**

- SUSY/Higgs Workshop ('98-'99)
- Higgs Sensitivity Study ('03)
- Discovery: 5σ, Evidence: 3σ, 95% CL exclusion
Summary Conclusion

• Both CDF and D0 running well
• D0 upgraded to improve b-tagging (Higgs)
• Significant prospects for major discovery at Tevatron in next 2-3 years
• Luminosity and high efficiency detectors
• Areas to watch: SUSY, low mass Higgs