Physics with Tau Leptons at CDF

Anton Anastassov (Rutgers University)
On behalf of the CDF Collaboration

Wine and Cheese Seminar - July 23, 2004

Outline:
• Physics topics
• CDF Detector
• Taus at CDF
• Results, analyses in progress
• Summary and Outlook

Contact: aa@fnal.gov
The Tau Lepton

Third generation; charged: $Q^\tau = \pm 1$

Heavy: $m_\tau = 1.777$ GeV

Decays:
- Leptonic: $\tau \rightarrow e\bar{\nu}_e \nu_\tau$, $\tau \rightarrow \mu\bar{\nu}_\mu \nu_\tau$ ($\sim 36\%$)
- Hadronic: $\tau \rightarrow \pi \nu_\tau$, $\tau \rightarrow \pi \pi^0 \nu_\tau$, $\tau \rightarrow \pi \pi \pi^0 \nu_\tau$, $\tau \rightarrow \pi \pi^0 \pi^0 \nu_\tau$ ... ($\sim 64\%$)

→ rich decay spectrum!

Why use taus?
- Many SUSY models predict enhanced couplings to third-generation particles ($b$, $\tau$)
- Important for MSSM Higgs search, other SUSY particles at the Tevatron and beyond

Valuable tool for new physics searches!

Throughout this talk we use $\tau_e$, $\tau_\mu$, $\tau_h$ as shorthand notations for $\tau \rightarrow e\bar{\nu}_e \nu_\tau$, $\tau \rightarrow \mu\bar{\nu}_\mu \nu_\tau$, and $\tau \rightarrow$ hadrons $\nu_\tau$, respectively.
Physics Topics at a Glance

Measurements:
\[ \sigma(p\bar{p}\rightarrow W)\cdot\text{BR}(W\rightarrow\tau\nu), \quad \text{BR}(W\rightarrow\tau\nu)/\text{BR}(W\rightarrow e\nu) \]
\[ \sigma(p\bar{p}\rightarrow Z)\cdot\text{BR}(Z\rightarrow\tau\tau) \]

Searches:
- MSSM Higgs
- Other “high-mass” particles decaying to \(\tau\tau\)
- Anomalous production of \(t\rightarrow q\tau\nu\)
- Prospects for SUSY searches with \(\tau\)’s:
  - R-parity Violating (RPV) stop
  - Minimal Super-Gravity (mSUGRA) with tri-lepton final states
  - Trileptons in Gauge Mediated SUSY Breaking (GMSB) models
The CDF Detector at the Tevatron

- Multipurpose detector for studying products of \( pp \) collisions
- Tracking: SVX and Wire Chambers
- Calorimetry: EM, Hadronic
- Shower Maximum for EM
- Pre-shower Radiators
- Muon Detectors
- TOF System
Taus at CDF in Run 2

Build on the experience from Run 1

Dedicated tau triggers in Run 2:

- Require a “narrow isolated jet” object ($\tau_h$)
  - Must be *tau-like*: Cluster-Matched track with $p_T > 4.5$ GeV, no tracks with $p_T > 1.5$ GeV in isolation annulus 10-30°

- **Electron + $\tau_h$ (~30 nb at L3)**
  - Central electron ($E_T > 8$ GeV) + narrow isolated jet

- **Muon + $\tau_h$ (~30 nb at L3)**
  - Central muon ($p_T > 8$ GeV) + narrow isolated jet

- **Missing Transverse Energy + $\tau_h$ (~5 nb at L3)**
  - $\not{E}_T > 20$ GeV + narrow isolated jet

- **Di-tau: $\tau_h + \tau_h$ (~13 nb at L3)**
  - Two narrow, isolated jets

A committed Tau Working Group serves as a driving force for analyses using tau leptons.
Taus at CDF: Reconstruction

Refers to reconstruction of the visible products of semi-hadronic tau decays

- Taus in the detector: narrow isolated jets
- Tau “objects” formed using calorimeter and tracking information
  - Seed tower with $E_T > 6$ GeV
  - Adjacent towers added to form a calorimeter cluster with $N^{\text{twr}} \leq 6$
  - Matched (seed) track with $p_T > 4.5$ GeV
  - Tracks and $\pi^0$’s around seed track added to be used in tau reconstruction isolation
Successfully reconstructed taus have:

- Characteristic 1,3 track enhancement in signal cone
- Net charge 1
- Low $\pi^0$ multiplicity
- $m < 1.8$ GeV
- No energetic tracks, $\pi^0$’s in isolation annulus
- Applied electron removal
Taus: efficiency and jet→τ fake rate

Depend on tau isolation applied (analysis specific)

Example efficiency and fake rate:

(Examples from the high-mass ττ search)
Clean tau sample from $W \rightarrow \tau \nu$

$W$'s are the largest source of isolated taus at CDF
Select clean $\tau$ sample: large $E_T$, veto extra jets
Natural choice for understanding tau reconstruction

Good agreement between data and MC simulation
Study of $W \rightarrow \tau \nu$

Measurement of:
- $\sigma(pp \rightarrow W) \cdot \text{BR}(W \rightarrow \tau \nu)$
- $\text{BR}(W \rightarrow \tau \nu)/\text{BR}(W \rightarrow e\nu)$
- Test lepton universality via $g_\tau/g_e$

Uses the “tau + MET” trigger
Selection criteria:
- Isolated tau candidate with $E_T > 25$ GeV
- No other jet with $E_T^{\text{jet}} > 5$ GeV
- Missing transverse energy: $E_T > 25$ GeV
- Electron removal

Major backgrounds: jet$\rightarrow\tau$ misidentification, $Z \rightarrow \tau \tau$
$W \rightarrow \mu \nu, e\nu$
Study of $W \rightarrow \tau \nu$ (cont.)

- $N_{\text{obs}} = 2345$
- $N_{\text{bg}}^{\text{tot}} = 612 \pm 61$
- $A \cdot e_{\tau}^{\text{ID}} = (1.06 \pm 0.047(\text{stat}) \pm 0.043(\text{syst}) \%)$

**Trigger efficiencies:**
- $\varepsilon(L1) = 0.881 \pm 0.005$
- $\varepsilon(L3) = 0.982 \pm 0.004$

**Cross section (nb):**

$$\sigma(p\bar{p} \rightarrow W) \cdot \text{BR}(W \rightarrow \tau \nu) = 2.62 \pm 0.07(\text{stat}) \pm 0.21(\text{syst}) \pm 0.16(\text{lum})$$

Systematics limited!
Study of $W \rightarrow \tau \nu$ (cont.)

$\frac{BR(W \rightarrow \tau \nu)}{BR(W \rightarrow e \nu)}$ measurement

- Large $W \rightarrow e \nu$ sample
- Common systematics are cancelled
- Can use same trigger as the tau channel

$$BR(W \rightarrow \tau \nu)/BR(W \rightarrow e \nu) = 0.99 \pm 0.04\text{(stat)} \pm 0.07\text{(syst)}$$

$$g_\tau/g_e = \sqrt{BR(W \rightarrow \tau \nu)/BR(W \rightarrow e \nu)}$$

$$g_\tau/g_e = 0.99 \pm 0.02\text{(stat)} \pm 0.04\text{(syst)}$$
Study of $W \rightarrow \tau \nu$ (cont.)

- Very competitive result
- Consistent with SM
- Still dominated by systematics:
  - Tau ID
  - Background estimation

Work on reducing the systematics is converging. Updated result coming soon!
Measurement of $\sigma(p\bar{p}\rightarrow Z) \cdot BR(Z\rightarrow\tau\tau)$

- Z’s are the second-largest source of isolated taus
- No (published) Z cross-section measurement in tau channel from hadron collider
- Major background in new physics searches
- Many techniques for background suppression and estimation apply to SUSY searches

The presented result is based on 72 pb$^{-1}$ of data
- Look at $\tau_e\tau_h$ channel
- Events selected with the “electron+track” trigger
**Z→ττ Study: Selection Criteria**

- Isolated τ, electron
- $P_T^{τ} > 15$ GeV
- $E_T^{e} > 10$ GeV
- $p_T(e, E^{'}) > 25$ GeV
- $m_T(e, E^{'}) < 25$ GeV
- $Q^e Q^{τ} = -1$; $N_{trk}=1, 3$
**Z → ττ Study: Observed Events**

- **Clear tau signature**
- **Backgrounds under control even before** $Q^eQ^\tau = -1$
- **Charge and track multiplicity clean the sample significantly**

![Graph](image)

Track multiplicity of tau candidates before opposite charge requirement.
**Z\rightarrow\tau\tau** Study: Observed Events

Electron $E_T$ and tau $p_T$ distributions after all cuts

**CDF Run II Preliminary**

Relatively low $E_T^e$ and $p_T^\tau \rightarrow Z$ will cause trouble in SUSY searches and need to be well understood.
**Z→ττ Study: Results and Prospects**

- Observe total of 50 events, 39 signal
- Measured cross-section (pb):
  \[
  \sigma(p\bar{p} \rightarrow Z) \cdot \text{BR}(Z \rightarrow \tau\tau) = 242 \pm 48\text{(stat)} \pm 26\text{(syst)} \pm 15\text{(lum)}
  \]
- Consistent with measurements in Z→ee, μμ channels
- Statistics limited

**Next steps:**
- Add available data
- Include channel with one tau decaying to muon and neutrinos
Searches for New Particles
Decaying to Tau(s)

We can do EW measurements with taus

What about seeing new particles?
The Higgs Boson(s)

One of the priorities of Run 2
However, need large luminosity (>3-5 fb$^{-1}$ for 3$\sigma$ observation CDF+D0)
The last SM particle…

… or is it going to be “the first” SUSY particle?

MSSM:
Five physical states: H, h, A; H$^{\pm}$
Enhanced production for large $tan\beta$
$BR(A \rightarrow \tau^{+}\tau^{-}) \sim 8\%, \; BR(A \rightarrow bb) > 90\%$

We could use some help from Nature!
Case for MSSM Higgs $\rightarrow \tau \tau$ Search

$BR(A \rightarrow b\bar{b})$ is larger, however, it is difficult to control backgrounds for $gg, b\bar{b} \rightarrow A$

$A \rightarrow \tau \tau$ is important for MSSM Higgs searches
Higgs → ττ Signatures

Determined by the decay modes of the taus

<table>
<thead>
<tr>
<th>Mode</th>
<th>Fraction (%)</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>τₑτₑ</td>
<td>3</td>
<td>large Z/γ*→ee bg</td>
</tr>
<tr>
<td>τµτµ</td>
<td>3</td>
<td>large Z/γ*→μμ bg</td>
</tr>
<tr>
<td>τₑτµ</td>
<td>6</td>
<td>low jet backgrounds</td>
</tr>
<tr>
<td>τₑτₙ</td>
<td>23</td>
<td>golden</td>
</tr>
<tr>
<td>τµτₙ</td>
<td>23</td>
<td>golden</td>
</tr>
<tr>
<td>τₙτₙ</td>
<td>41</td>
<td>challenging (jet bg)</td>
</tr>
</tbody>
</table>

Reminder: τₑ, τµ, τₙ are shorthand notations for τ→eνν, τ→μνν, and τ→hadrons ν, respectively.
MSSM Higgs Search: Event Selection

- Identify unique $e, \mu, \tau$ in the event
- Exactly one $\tau_e\tau_h$ or $\tau_\mu\tau_h$ candidate
- Suppress multi-jet bg:
  $$|p_T^e| + |p_T^\tau| + |E_T| > 50 \text{ GeV}$$
- Relation between of $E_T, e(\mu)$, and $\tau$
  used to suppress $W \rightarrow l\nu + \text{jet(s)}$
  (contributes to jet $\rightarrow \tau$ fakes)

Transverse Plane

$$\vec{p}_T^{\text{vis}}(\tau_1)$$

$$\vec{E}_T$$

$$\vec{p}_T^{\text{vis}}(\tau_2)$$

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Can we Separate Z and Higgs?

Not enough information for full mass reconstruction

- Methods using $\slashed{E}_T$ projection onto directions of visible decay products significantly reduce statistics
- Compromise: construct mass-like quantity $m_{\text{vis}}(\ell, \tau, \slashed{E}_T)$

\begin{itemize}
  \item Weaker discriminator than full mass
  \item Non-linear relation with mass
  \item Still, there is substantial non-overlapping region
  \item Can be calculated for all events
\end{itemize}
Higgs Search: Observed Events

\( \tau_e\tau_h \) and \( \tau_\mu\tau_h \) channels combined:

Track multiplicity of tau candidates before applying
\( N_{\text{trk}} = 1,3 \) and \( Q^f Q^\tau = -1 \)

Mass distribution for tau candidates after applying
\( N_{\text{trk}} = 1,3 \) and \( Q^f Q^\tau = -1 \)

(all subsequent plots and have these cuts)

Observed events: 236
Estimated non \( \tau_{e(\mu)}\tau_h \): 27
The 95% CL upper limits are extracted using a binned likelihood fit of the $m_{\text{vis}}(\ell, \tau, E_T)$ distributions.

The observed limits are compared with pseudo-experiment predictions.
Higgs Search: 95% CL Upper Limit

- MC generated with $\tan\beta=30$ used in acceptance estimation
- Observed limits fall in the realm of theory predictions for large $\tan\beta$, where Higgs width becomes a factor for acceptance
Higgs $\rightarrow \tau\tau$ Search: What is Next

- More data is available
- Add $\tau_e\tau_\mu$ and $\tau_h\tau_h$ channels (clear signatures observed, di-tau trigger efficiency study in progress)
- Some tau reconstruction and event selection optimization
- Include exclusive search for Ab(b) (following Willenbrock et al.)
Other “High-mass” ττ

- Search for Z' with SM couplings, or
- Other exotic particles decaying to tau pairs

“History”

Run 1 event with two very energetic tau candidates, and $E_T$. 

E = 160 GeV

E > 135 GeV
Z$^\prime \rightarrow \tau \tau$ Search: Event Selection

Require $\tau_e \tau_h$, $\tau_\mu \tau_h$, or $\tau_h \tau_h$

$E_T > 15$ GeV

$|\Delta \phi (\tau_l, E_T)| < 30^\circ$

Suppress $Z \rightarrow \tau \tau$:

$M(\tau, \tau, E_T) > 120$ GeV

Blind analysis

- control region:
  $M(\tau, \tau, E_T) < 120$ GeV

- Signal region:
  $M(\tau, \tau, E_T) > 120$ GeV

“Counting experiment”

Here $\tau_l$ is either $\tau_e$, $\tau_\mu$, or the lower-$p_T \tau_h$ (in $\tau_h \tau_h$ case)
Z' → ττ Search: Observed Events

Predicted backgrounds and observed events
CDF Run 2 Preliminary (195 pb⁻¹)

<table>
<thead>
<tr>
<th>source</th>
<th>τₑτₕ</th>
<th>τµτₕ</th>
<th>τₕτₕ</th>
<th>combined</th>
</tr>
</thead>
<tbody>
<tr>
<td>Z/γ* → ττ</td>
<td>0.56 ± 0.11</td>
<td>0.50 ± 0.09</td>
<td>0.36 ± 0.08</td>
<td>1.42 ± 0.19</td>
</tr>
<tr>
<td>Z/γ* → ee</td>
<td>0.16 ± 0.14</td>
<td>0</td>
<td>0</td>
<td>0.16 ± 0.14</td>
</tr>
<tr>
<td>Z/γ* → µµ</td>
<td>0</td>
<td>0.50 ± 0.25</td>
<td>0</td>
<td>0.50 ± 0.25</td>
</tr>
<tr>
<td>jet → τ fakes</td>
<td>0.29 ± 0.14</td>
<td>0.18 ± 0.09</td>
<td>0.28 ± 0.10</td>
<td>0.75 ± 0.19</td>
</tr>
<tr>
<td>Total predicted BG</td>
<td>1.01 ± 0.23</td>
<td>1.18 ± 0.28</td>
<td>0.64 ± 0.13</td>
<td>2.83 ± 0.39</td>
</tr>
</tbody>
</table>

| Observed | 4   | 0    | 0    | 4    |

No significant excess of events observed
The 95% CL upper limits are extracted as a function of Z' mass
**Z' → ττ Search: 95% CL Upper Limit**

- Z' with SM couplings used in estimating acceptance
- Sequential Z' boson with mass below 394 GeV is excluded at 95% CL

**Further development:** Examine the impact on production of particles other than sequential Z'
Search for Anomalous Rate in $t \rightarrow \tau \nu q$

Look at di-lepton channel - 5% of $\sigma(t\bar{t})$

Select events with $l\tau_h + 2$ jets ($l = e, \mu$)

Compare $t\bar{t} \rightarrow l\tau_h \nu \nu + 2$ jets prediction to observation

Model independent

Modified coupling or particle other than $W$ (like $H^{\pm}$) may lead to anomalous $t \rightarrow \tau \nu q$ rate
Search for Anomalous $t \rightarrow \tau \nu q$ (cont.)

- **Backgrounds:**
  - $W+$jet(s)
  - Multi-jet
  - $Z \rightarrow \tau \tau + \text{jets}$; $Z \rightarrow \ell \ell + \text{jets}$, with $e, \mu \rightarrow \tau$ misidentification
  - $WW, WZ$

- **Event cuts**
  - Identified $\tau$, $e(\mu)$, $\geq 2$ jets
  - $E_{T}^{\text{jet1}} > 30$ GeV, $E_{T}^{\text{jet2}} > 15$ GeV, $p_{T}(\tau_{h}) > 15$ GeV, $E_{T}^{e(\mu)} > 20$ GeV;
    $E_{T} > 20$ GeV; $H_{T} > 205$ GeV
  - Opposite charge of $e(\mu)$ and $\tau_{h}$
  - $Z \rightarrow \tau \tau$ removal in region $65 < m_{\tau \tau} < 115$ GeV

**Total acceptance for $t \bar{t}$:** $(0.080 \pm 0.005 \pm 0.014)$ %

$H_{T}$: scalar sum of $E_{T}$ of the selected leptons, jets, and $E_{T}$
Result for Anomalous $t \rightarrow \tau \nu q$ Search

<table>
<thead>
<tr>
<th>Source</th>
<th>Events (num ± stat ± sys)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Z/\gamma^* \rightarrow \tau \tau + \text{jets}$</td>
<td>$0.26 \pm 0.06 \pm 0.05$</td>
</tr>
<tr>
<td>jet→τ fakes</td>
<td>$0.75 \pm 0.12 \pm 0.20$</td>
</tr>
<tr>
<td>e→τ fakes</td>
<td>$0.08 \pm 0.03 \pm 0.02$</td>
</tr>
<tr>
<td>$Z \rightarrow \mu \mu$</td>
<td>$0.05 \pm 0.03$</td>
</tr>
<tr>
<td>WW</td>
<td>$0.14 \pm 0.02 \pm 0.03$</td>
</tr>
<tr>
<td>WZ</td>
<td>$0.02 \pm 0.02$</td>
</tr>
<tr>
<td><strong>Total bg</strong></td>
<td><strong>$1.30 \pm 0.14 \pm 0.21$</strong></td>
</tr>
<tr>
<td><strong>Expected $t\bar{t}$</strong></td>
<td><strong>$1.03 \pm 0.06 \pm 0.17$</strong></td>
</tr>
<tr>
<td><strong>Observed</strong></td>
<td><strong>2</strong></td>
</tr>
</tbody>
</table>

$r_\tau < 5.0$ at 95% CL

Expected improvement with larger data sample
Search for Anomalous $t\bar{t} \rightarrow \tau \nu \nu + 2$ jets candidate event
Prospects for SUSY Searches with Taus
Prospects for RPV Stop Search

**Light stop (t₁):**
- Potentially smaller mass than other squarks (may be even smaller than $m_{top}$)
- Expected large Yukawa couplings
- Parameter space where stop decays to $b\tau$ is favored
- Pair-produced

**Result from Run 1:**
- Pre-scaled $e$ trigger
- Limited muon coverage
- Lower cross-section (due to $\sqrt{s}$)
Stop Search: Event Selection

Final state: $\tau \tau bb \rightarrow \ell \tau_h + 2\text{jets} \ (\ell = e, \mu)$

Dominant backgrounds:
- $Z \rightarrow \tau \tau + \text{jets}$, $W + \text{jets}$
- Di-boson, $t\bar{t}$
- Multi-jet

“Lepton+track” trigger used

Event selection:
- Isolated $\tau_h$, $\ell$, 2jets ($E_T > 15$ GeV)
- $p_T^{\tau} > 15$ GeV, $E_T^\ell (p_T^\mu) > 10$ GeV
- $H_T(\ell, \tau_h, E_T) > 100$ GeV
- $m_T(\ell, E_T) < 35$ GeV

Expected total bg $\sim 2$ events

$H_T$ distributions:
- Signal (open histogram)
- $Z \rightarrow \tau \tau + \text{jets}$ (yellow)
Stop Search: Projected Limit

Results using 200 pb\(^{-1}\) of data coming soon!
mSUGRA Tri-lepton Search

- Taus in final state dominant at large $\tan\beta$
- Soft taus, still accessible
- Expect up to 2.4 events/fb$^{-1}$ (~8 if only two like-sign leptons are required)
- Important, but needs >1 fb$^{-1}$ data
- Backgrounds are being studied

![Diagram showing mSUGRA model](image)

**Branching fraction vs. $\tan\beta$**

**Event distributions**

- Lepton+Track Trig Pt Cut
- Tau+MET Trig Pt Cut

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Anton Anastassov  Physics with Tau Leptons at CDF  Wine and Cheese Seminar (July 23, 2004)
Prospects for Tri-leptons in GMSB

Consider case where gravitino is LSP, stau is NLSP

Similar signature to mSUGRA scenario

Harder tau spectrum due to small gravitino mass

Expect ~4-5 events/fb⁻¹

Work on W+jets suppression needed
Summary and Outlook

Use of taus expands the physics program at hadronic colliders
Dedicated set of tau triggers in place
EW measurements with taus - already a fact
The search for neutral MSSM Higgs \( \rightarrow \tau\tau \) shows real promise
Prospects for SUSY searches
Finalize most of the preliminary results using data up to the shutdown
Other analyses in early (or planning) stages:
  - Charged Higgs, double-charged Higgs
  - Lepto-quarks decaying to \( b\tau \)

Physics with tau leptons at CDF is strong and results are coming out!