Search for MSSM Higgs Boson Production in di-tau Final States at DØ

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Outline

- Overview: DØ at Fermilab Tevatron
- Higgs Bosons in MSSM
- DØ τ reconstruction & identification
- Search for Neutral $\phi \rightarrow \tau \tau$
- Search for Neutral $\phi b \rightarrow \tau \tau b$
- Interpretation of Results in MSSM
- Prospects & Summary
• silicon detector and scintillating fiber tracker in 2.0 T solenoidal field
• liquid argon/uranium calorimeters: central (CC) and two forward, end (EC) calorimters
• muons: scintillators and mini-drift tubes ⇒ coverage up to $\eta = 2.0$
• upgraded trigger & electronics for Run IIb
Tevatron Collider and DØ operating successfully in Run II

- Tevatron delivered $\int L \, dt \rightarrow 5.4 \text{ fb}^{-1}$
  - DØ recorded $> 4.7 \text{ fb}^{-1}$
  - reached peak luminosities $> 3.40 \times 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$
  - weekly integrated luminosity $\sim 50 \text{ pb}^{-1}$/week

- Projections through end-FY09 (FY10): $\sim 7 \text{ fb}^{-1}$ ($\sim 9 \text{ fb}^{-1}$)

- In this talk, report on up to $2.2 \text{ fb}^{-1}$ dataset (Run IIa and Run IIb)
Higgs boson decay to taus in SM

- Largest coupling of SM Higgs to leptons is via $\tau$'s

- SM Higgs exclusion $M_H > 114.4$ GeV limits search in di-tau final states
  - $\text{BR}(H \rightarrow \tau\tau) < 10\%$ compared to $b\bar{b}$ or WW decay
  - interesting (low mass) region further suffers from large irreducible $Z/\gamma \rightarrow \tau\tau$ background

- But several $D\emptyset$ analyses exist for SM Higgs search considering taus
  - rely on associated production of Higgs with $W, Z$
    - $WH \rightarrow \tau\nu b\bar{b}$ (2008 preliminary result, $1.0 \text{ fb}^{-1}$)
    - $ZH \rightarrow \tau\tau b\bar{b}$ (in progress)
Higgs bosons in the MSSM

- MSSM Higgs requires 2 doublets
  - $H_u$ ($H_d$) couple to up- (down-) type fermions
  - ratio of their vacuum expectation values: $\tan\beta = \langle H_u \rangle / \langle H_d \rangle$

$\Rightarrow$ 5 physical Higgs bosons after EWSB
- two neutral CP-even: $h^0$, $H^0$
- one neutral CP-odd: $A^0$
- charged pair: $H^+$ and $H^-$ (not in this talk)

- at tree-level, MSSM Higgs fully specified by two free parameters
  - $M_A$ and $\tan\beta$

- $\sigma(p\overline{p} \rightarrow h/H/A) \propto \tan^2 \beta$
  - at large $\tan\beta$, (low $M_A$) $\Rightarrow$ enhanced coupling of $A$, $h/H$ to down-type fermions $\Rightarrow$ enhanced production cross-section
  - provides a golden search mode

- at large $\tan\beta$, $\phi$ ($= h/H$ & $A$) ~ degenerate in mass
  - further increase in cross-section

$\Rightarrow$ Low $M_A$, high $\tan\beta$: Tevatron extend Higgs search region
Signatures: MSSM Neutral Higgs to di-tau

- $h/H/A$ decays, in most parameter space:
  - $h/H/A \rightarrow b\overline{b}$ (~90%)
  - $h/H/A \rightarrow \tau\tau$ (~10%)
    * smaller BR but cleaner signature (vs. large QCD background in $b$ mode)

- Signatures
  a) inclusive production mode: Higgs decay to 2 opposite sign $\tau$'s
    * subsequent leptonic or hadronic decay of $\tau$'s define final states
  b) production in association with at least one $b$-quark
    * same as (a) + additional jet from $b$-quark

$\phi \rightarrow \tau^+\tau^-$ (Gluon fusion)
$\phi b \rightarrow \tau^+\tau^- b$ (in association with $b$)
Why these channels?

- Current experimental 68% C.L. region for $m_t$ and $M_W$
  - slight preference of MSSM over SM

- Real discovery potential before we reach SM sensitivity

- The experimental challenge:
  - identifying a $\tau$ signal from far more copious jets produced by strong interaction processes
  - efficient $b$-tagging for $\phi b \rightarrow \tau\tau b$ search

Ref: Heinemeyer, Hollick, Stockinger, Weber, Weiglein '08
### τ properties

- **Mass** = 1.78 GeV; Short lifetime, \( c\tau = 87.11 \mu m \)
  - \( \tau (10^{-13} \text{ s}) \)
  - taus decay prior to reaching any detector active element

- **Main decay channels:**

<table>
<thead>
<tr>
<th>τ Decay Final State</th>
<th>BR (%)</th>
<th>Decay Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>( e + \nu_e + \nu_\tau )</td>
<td>17.8</td>
<td>Leptonic (35.2%)</td>
</tr>
<tr>
<td>( \mu + \nu_\mu + \nu_\tau )</td>
<td>17.4</td>
<td>( \tau_\mu )</td>
</tr>
<tr>
<td>( \pi(\text{/K}) + \nu_\tau )</td>
<td>11.8</td>
<td>1-prong (48.7%)</td>
</tr>
<tr>
<td>( \pi(\text{/K}) + \nu_\tau + \geq 1\pi^0 )</td>
<td>36.9</td>
<td>( \tau_h )</td>
</tr>
<tr>
<td>( \pi\pi\pi + \geq 0\pi^0 + \nu_\tau )</td>
<td>13.9</td>
<td>3-prong</td>
</tr>
</tbody>
</table>

Detect using standard electron / muon ID algorithms

Need dedicated tau ID to measure “narrow”, low multiplicity jet objects

- Taus decay \(~17\%\) to \( e, \mu; \) \(~65\%\) to hadrons
- For Higgs to di-tau final state, three channels studied
  - \( \tau \rightarrow \mu \nu
  + \tau \rightarrow \text{hadrons} \nu : \quad \tau_\mu \tau_h \)
  - \( \tau \rightarrow e \nu
  + \tau \rightarrow \text{hadrons} \nu : \quad \tau_e \tau_h \)
  - \( \tau \rightarrow e \nu
  + \tau \rightarrow \mu \nu : \quad \tau_e \tau_\mu \)
DØ: τ reconstructed candidate

- **Begin with Calorimeter Cluster**
  - Tau calorimeter clusters found using Simple Cone Algorithm
    - core cone size $R = 0.3$, isolation cone size $R_{\text{iso}} = 0.5$
    - require CAL cluster rms < 0.25
      - rms = energy weighted width of cluster = \[
      \sqrt{\sum_{i=1}^{n} \left( \Delta\phi_{i}^{2} E_{T_{i}} / E_{T} + \Delta\eta_{i}^{2} E_{T_{i}} / E_{T} \right)}
      \]

- **Associate EM Sub-clusters**
  - Nearest Neighbor Algorithm in 3rd EM layer (= shower max); EM$_3$ cluster energy > 800 MeV
  - attach EM cells in other layers and preshower hits to the found EM$_3$ cluster

- **Associate up to 3 tracks with $p_{\tau} > 1.5$ GeV to the τ candidate**
  - track within 0.3 cone around CAL cluster
  - if more than one track, associate highest $p_{\tau}$ track with τ candidate
  - add 2nd (3rd) track if invariant mass calculated from tracks < 1.1 (1.7) GeV and $Q_{\text{tot}} \neq \pm 3$
Categorize hadronic $\tau$ candidates into 3 types, based on their detector signature

$\tau$-type 1 ($\pi\nu$-like): one track + calorimeter cluster, no EM sub-clusters

$\tau$-type 2 ($\rho\nu$-like): one track + calorimeter cluster and > 0 EM sub-clusters

$\tau$-type 3 (3-prong): > one track + calorimeter cluster and $\geq$ 0 EM sub-clusters

Reduce backgrounds from $\tau$’s with Neural Network (NN) techniques

Type 1

$\tau^\pm \rightarrow \pi^\pm \rightarrow \nu_\tau$

Type 2

$\tau^\pm \rightarrow \rho^\pm \rightarrow \pi^0 \rightarrow \gamma$

Type 3

$\tau^\pm \rightarrow \pi^\pm \rightarrow \pi^\pm \rightarrow \gamma$

Jet-Background

$q \rightarrow \pi^0 \rightarrow \pi^\pm \rightarrow \pi^\pm$
\( \tau \) candidates: Reconstruction Efficiencies

**Taus (MC)**
- \( \tau \)-type 1
- \( \tau \)-type 2

**Jets faking taus (data)**
- (a) \( \tau \)-type 1
- (b) \( \tau \)-type 2

- \( \tau \)-type 3
- all \( \tau \)-types

- Overall \( \tau \) reconstruction efficiency \( > 90\% \) can be achieved for \( E_T > 15 \text{ GeV} \), but rejection of jets is low \( \Rightarrow \) further discrimination needed
  - depends on \( \tau \)-type and \( E_T \)
**τ-ID Neural Network**

- three separate anti-jet Neural Networks ⇒ one for each τ-type
- one additional NN to reject electrons, $NN_e$
  - effective in separating τ-type 2 and electrons
- training samples for NN’s:
  - signal: τ’s from $Z\rightarrow\tau\tau$ MC
  - background: recoiling jets in events with a non-isolated μ from data
    * for $NN_e$: electrons from $Z\rightarrow ee$ MC
- NN input variables based on isolation & shower shape parameters, and correlations built from calorimeter clusters and tracks

**Signal (MC τ) and Background (jets from data)**

**CAL isolation =**
\[
\frac{E_T^{\Delta R<0.5} - E_T^{\Delta R<0.3}}{E_T^{\Delta R<0.3}}
\]

**CAL profile =**
\[
\frac{E_T^{Tower 1} + E_T^{Tower 2}}{E_T^{\tau}}
\]

**Ett1 =**
\[
\frac{p_T^{lead-tau}}{E_T^{\tau}}
\]
**NN’s for τ-ID (cont.)**

- **apply NN to separate QCD jets from τ’s**

  **Efficiencies (%)**
  \[20 < E_T^\tau < 40 \text{ GeV}, \ |\eta^\tau| < 2.5\]

<table>
<thead>
<tr>
<th>τ-type</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>all</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jets</td>
<td>2</td>
<td>12</td>
<td>38</td>
<td>52</td>
</tr>
<tr>
<td>τ</td>
<td>11</td>
<td>60</td>
<td>24</td>
<td>95</td>
</tr>
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</table>

<table>
<thead>
<tr>
<th></th>
<th>NN &gt; 0.9</th>
</tr>
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<tbody>
<tr>
<td>Jets</td>
<td>0.06</td>
</tr>
<tr>
<td></td>
<td>0.24</td>
</tr>
<tr>
<td></td>
<td>0.80</td>
</tr>
<tr>
<td></td>
<td>1.1</td>
</tr>
<tr>
<td>τ</td>
<td>7</td>
</tr>
<tr>
<td></td>
<td>44</td>
</tr>
<tr>
<td></td>
<td>16</td>
</tr>
<tr>
<td></td>
<td>67</td>
</tr>
</tbody>
</table>

- **NN > 0.9 reduces jet background by \(\times \sim 50\) while keeping total \(\tau\) efficiency near 70%**

- **if exclude τ-type 3 \(\Rightarrow \times \sim 3\) increase in S/B, with only 16% loss in efficiency**
Summary of DØ Analyses


- Search for $\phi \rightarrow \tau\tau$
  - Result using 1.0 fb$^{-1}$ Run IIa dataset for $\tau_\mu \tau_h$, $\tau_e \tau_h$, and $\tau_e \tau_\mu$
    * PRL 101, 071804 (2008)
  - Preliminary Result using 1.2 fb$^{-1}$ Run IIb dataset for $\tau_\mu \tau_h$
    * DØ CONF-Note 5728 (2008) ← recent
  - For limits, combined results for Run IIa and Run IIb $\Rightarrow$ 2.2 fb$^{-1}$
    * DØ CONF-Note 5740 (2008) ← recent
    - Run IIb results for $\tau_e \tau_h$ and $\tau_e \tau_\mu$ ... in progress

- Search for $\phi b \rightarrow \tau\tau b$
  - Result using 328 pb$^{-1}$ Run IIa dataset for $\tau_\mu \tau_h b$
    * Submitted to PRL (2008); FERMILAB-PUB-08/451-E
  - Run IIa results using 1.0 fb$^{-1}$ dataset for $\tau_\mu \tau_h b$ ... in progress
  - Preliminary Result using 1.2 fb$^{-1}$ Run IIb dataset for $\tau_\mu \tau_h b$
    * DØ CONF-Note 5727 (2008) ← recent
    - Run IIa and Run IIb results for $\tau_e \tau_h b$ ... in progress

Ref: www-d0.fnal.gov/Run2Physics/WWW/results.htm
Precursor to $\phi$: $\tau$-NN and $Z \rightarrow \tau^+\tau^-$

- Published $Z \rightarrow \tau\tau$ cross section: $\tau_\mu \tau_h$
  - PRD 71, 072004 (2005): 226 pb$^{-1}$
  - benchmark study for testing and certifying $\tau$-ID algorithm
  - accepted by PLB (2008): 1.0 fb$^{-1}$
  - extend developed method to other $\tau$ physics channels

- Basic selections
  - $p_\tau^\mu > 15$ GeV
  - $p_\tau^\tau > 10, 10, 5$ GeV for $\tau$-types 1, 2, 3
  - opposite sign (OS) and back-to-back ($|\phi_\mu - \phi_\tau| > 2.5$) $\mu\tau$ pairs

- $\sigma(p\bar{p} \rightarrow Z + X) \cdot Br(Z \rightarrow \tau^+\tau^-)$
  - PRD: $237 \pm 15$ (stat) $\pm 18$ (sys) $\pm 15$ (lum) pb
  - PLB: $240 \pm 8$ (stat) $\pm 12$ (sys) $\pm 15$ (lum) pb
  - SM theory (NNLO): $241.6^{+3.6}_{-3.2}$ pb
Dominant Backgrounds

- $\phi \rightarrow \tau^+\tau^-$ search
  - $Z/\gamma^* \rightarrow \tau^+\tau^-$
    * irreducible; similar final state
  - $Z/\gamma^* \rightarrow l\ell$, where $l = e, \mu$ with
    mis-identified 2$^{nd}$ lepton
  - $W + $ jets, where a jet is
    mis-identified as $\tau$, $\mu$ or $e$
  - QCD multi-jets with mis-identified
    leptons/jets from heavy flavors
    (jets fake $\tau$’s)
  - Diboson, top decays to real taus
    * small cross section

- $\phi b \rightarrow \tau^+\tau^- b$ search
  - similar to inclusive $\tau\tau$ channel
    * but after b-tag, dominated by
      top events and QCD multi-jets
Strategy In Presenting Results

• Search for $\phi \rightarrow \tau \tau$ using selections for $e$, $\mu$, and $\tau_h$
  – per each tau pair decay channel and $\tau$-type
    * require $b$-tag for associated $\phi b$ mode
  – help suppress dominant backgrounds

• Look for excess of Higgs signal in data over background; if no significant excess, first calculate:
  – 95% C.L. limit for production cross section times branching ratio, $\sigma \times BR$

• Translate & interpret results in MSSM
  – calculate exclusion in $(m_A, \tan\beta)$ plane for two MSSM benchmark scenarios
**φ → τ⁺τ⁻ Search Channel**

- **h/H/A → ττ** search considers final states: τ_μτ_μ, τ_eτ_μ, and τ_μτ_e
  - di-τ decays to ee, μμ not considered
  - large Z/γ* → μμ or Z/γ* → ee background ⇒ small S/B

- **τ_μτ_μ** event selections
  - recent, updated 1.2 fb⁻¹ Run IIb result
  - one isolated μ: p_T > 15 GeV, |η_μ| < 1.6
    - veto events with more than one μ
      ⇒ suppress Z → μμ
  - one τ, opposite sign (OS) from μ
    - E_T > 15, 15, 20 GeV (types 1, 2, 3)
    - p_T^{τ-trk} > 15, 5, 5 GeV (types 1, 2, 3)
    - Σ p_T^{τ-trk} > 15 GeV (type 3)
    - separated from muon: ΔR(μ, τ) > 0.5
    - NN > 0.9, 0.9, 0.95 (types 1, 2, 3)
  - correct MC tau energy such that E_T/p_T^{trk} matches data in Z → ττ events
  - veto events: electron p_T^e > 12 GeV for orthogonality with eμ channel
  - M_T < 40 GeV ⇒ reject W+jets
Background Modeling

- Backgrounds estimated by a combination of MC and controlled data samples
  - $Z/\gamma^*$, diboson, and $t\bar{t}$ taken from PYTHIA MC
  - QCD multi-jet + $W$ determined from data
  - divide data in opposite-sign (OS) & same-sign (SS) events (any signal ↔ OS events)
    * medium NN (mNN, QCD-enriched region): 0.25 < $\tau$-NN < 0.75
    * high NN (hNN, signal region): $NN > 0.9$ (0.95) for $\tau$-types 1, 2 (3)

- After MC bkg subtraction, OS & mNN region determines QCD + $W$ shape
  - relatively flat region of $\tau$-NN space
    - $N_{hNN}^{OS:QCD+W} = \rho \times (N_{mNN}^{OS:MC} - N_{mNN}^{OS:MC})$

- Normalize using ratio of hNN to mNN in SS sample:
  \[ \rho = \frac{N_{hNN}^{SS:MC}}{N_{mNN}^{SS:MC}} - \frac{N_{hNN}^{SS:MC}}{N_{mNN}^{SS:MC}} \]

<table>
<thead>
<tr>
<th>QCD Multi-jet + $W$ + jets Control Regions</th>
</tr>
</thead>
<tbody>
<tr>
<td>mNN (data, MC)</td>
</tr>
<tr>
<td>OS (data, MC) [Shape]</td>
</tr>
<tr>
<td>SS (data, MC) Normalize Distributions [(\rho), via ratio]</td>
</tr>
</tbody>
</table>
\( \phi \rightarrow \tau_\mu \tau_h \) 1.2 fb\(^{-1}\) Result: \( p_T^{\tau} \)

- Predicted backgrounds consistent with events in data

<table>
<thead>
<tr>
<th>Process</th>
<th>Events (all ( \tau )-types)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( Z/\gamma^* \rightarrow \tau \tau, \mu \mu )</td>
<td>1078 ± 33</td>
</tr>
<tr>
<td>QCD Multi-jet + W</td>
<td>96 ± 9</td>
</tr>
<tr>
<td>Diboson</td>
<td>6 ± 2</td>
</tr>
<tr>
<td>Top</td>
<td>2.7 ± 1.6</td>
</tr>
<tr>
<td>Total Expected</td>
<td>1189 ± 34</td>
</tr>
<tr>
<td>Data</td>
<td>1109</td>
</tr>
</tbody>
</table>
Consider $\tau_e \tau_h$ final state

- suppress electrons from $Z/\gamma^* \rightarrow ee$
decays that reconstructed as $\tau$-type 2
  - $e \nu_e \tau$-ID discriminant: $NN_e > 0.8$
- remove larger multi-jet background
  with $\Delta \phi(e, \tau) > 1.6$
- reject $W +$ jet events
  - $M_T < 50$ GeV
  - cut in $2D \Delta \phi(e, E_T) - \Delta \phi(\tau, E_T)$ plane

$\phi \rightarrow \tau\tau$, 200 GeV

$\phi / Z \rightarrow \tau\tau$ accepted

$W +$ jets rejected
\( \phi \rightarrow \tau^+ \tau^- \) Selections

- Consider \( \tau^+ \tau^- \) final state
  - isolated e (\( p_T^e > 12 \text{ GeV} \)) and \( \mu \) (\( p_T^\mu > 8 \text{ GeV} \)) with \( m_{\ell\ell} > 15 \text{ GeV} \)
  - impose kinematic selections based on leptons and \( E_T \) to remove QCD multi-jet and W backgrounds
    * \( p_T^e + p_T^\mu + E_T > 65 \text{ GeV} \)
    * \( M_T^{\text{min}}(\ell, E_T) = \min (M_T(e, E_T), M_T(\mu, E_T)) < 10 \text{ GeV} \)
  - cut on scalar sum of jet \( p_T \) to remove top events
    * \( H_T < 70 \text{ GeV} \)

- Final efficiency for a signal
  - summing channels: 1 – 4.5% across Higgs boson masses analyzed
  - comparable efficiencies but \( \tau^+ \tau^- \) suffers from larger multi-jet backgrounds
    \( (x \sim 3.5 \text{ higher than } \tau^+ \tau^- \text{ mode}) \)
Visible Mass

- After final event selections, dominant background is Z
  - small contribution from EW and QCD multi-jet
- Distinguish Higgs boson by its mass
  - presence of neutrinos in final states ⇒ not possible to reconstruct $\tau\tau$ mass
  - use visible mass: the invariant mass of the sum of the $\tau$ decay plus missing transverse energies
    * exploit fact that signal appears as an enhancement above $Z \rightarrow \tau\tau$

\[ M_{VIS} = \sqrt{(P^{\tau_1} + P^{\tau_2} + P_T')^2} \]

- Use 4-vectors of:
  - $P^{\tau_1}, P^{\tau_2}$ of visible tau decay products
  - $P_T' = (E_T', E_x', E_y', 0)$, where $E_x'$ and $E_y'$ indicate components of $E_T'$
$M_{\text{vis}}$: 1–2.2 fb$^{-1}$ Results

- $M_{\text{vis}}$: Run IIA 1.0 fb$^{-1}$ per decay channel
- Run IIB 1.2 fb$^{-1}$ $\tau_\mu \tau_h$
- Combined Run IIA + IIB

**Figure:**

- **DØ, 1.0 fb$^{-1}$**
  - Data
  - $Z \to \tau \tau$
  - Multijet
  - $W + $ jets
  - Other EW + $t\bar{t}$

- **DØ, 1.0 fb$^{-1}$**
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- **DØ, 1.0 fb$^{-1}$**
  - Data
  - $Z \to \tau \tau$
  - Multijet
  - $W + $ jets
  - Other EW + $t\bar{t}$

- **DØ Preliminary (1.2 fb$^{-1}$)**

- **DØ Preliminary (1-2.2 fb$^{-1}$)** Combined Run IIA + IIB

**Legend:**

- Multijet & $W$+jets
- $t\bar{t}$
- WW/WZ/ZZ
- $Z \to \mu\mu$
- $Z \to \tau\tau$
- data
- $M_W=160$ GeV ($\sigma = 50$ pb)
**Φ → ττ: σ × BR Limit**

- Study $M_{\text{vis}}$ for Higgs boson masses from 90 to 300 GeV
  - no significant evidence for Higgs production observed
  - modified frequentist method used to extract upper limits on $\sigma \times \text{BR}$
  - $M_{\text{vis}}$ used as input to limit calculation

**DØ Preliminary (1-2.2 fb⁻¹) Combined Run IIa + IIb Result**

![Graph showing $\sigma \times \text{BR} (\Phi \rightarrow \tau \tau)$ versus $M_\Phi$ (GeV).](image)

- Combined Exp. (Run IIa + Run IIb)
- Combined Obs. (Run IIa + Run IIb)
- Run IIa Exp.
- Run IIa Obs.

2.2 fb⁻¹ DØ Combination in Run II:
10 – 20% improvement in $\sigma \times \text{BR}$ from PRL result

**Major Systematic Uncertainties**

- Luminosity (6.1%)
- τ-ID (4-8%, τ-type dependent)
- τ energy scale (2-4%, type dependent)
- Z cross section (5%)
- Trigger efficiency (shape)
\( \phi b \to \tau^+ \tau^- b \) Search ...Few Words on Triggers

- \( \phi \to \tau_\mu \tau_\tau \) channel triggered on logical “OR” of single muon triggers
  - mainly adapted from Run IIa triggers
    * focused on muon trigger terms at all three levels of D\( \Phi \) Trigger (L1\( \to \)L3)
    * essentially no tau trigger terms at L1 and L2 (L3 used basic \( \tau \) NN algorithm)
  - increasing Run IIb luminosity (\( > 2 \times 10^{32} \) cm\(^{-2} \) s\(^{-1} \)) required tightening conditions to avoid trigger pre-scales
    * offline selection cuts restricted to \( p_T^\mu > 15 \) GeV and \( |\eta^\mu| < 1.6 \)

- Run IIb: implement L1Cal2b trigger upgrade
  - introduced suite of \( \tau \) triggers
    - L1: \( \tau \)'s are “narrow jets”
      * pass \( E_T \) thresholds and CAL isolation (\( = E_{2 \times 2} / E_{4 \times 4} \))
      * efficiency \( \sim 90\% \); background rejection \( > 75\% \)
  - \( \mu-\tau \) triggers un-prescaled up to \( L \sim 2.8 \times 10^{32} \) cm\(^{-2} \) s\(^{-1} \)
    * built on combination of muon and tau terms
  - allows using full D\( \Phi \) muon system coverage: \( \eta^\mu \to 2.0 \)

- \( \phi b \to \tau_\mu \tau_h b \) search
  - trigger on logical “OR” of single muon triggers (9 total, \( \varepsilon_{\text{tot}} \sim 50-60\% \))
  - trigger on logical “OR” of new \( \mu-\tau \) triggers (24 total, \( \varepsilon_{\text{tot}} \sim 60-70\% \))
**φb → τ_μ τ_h b Search Channel**

- Use similar search techniques as those in τ_μ τ_h mode
  - advantages: inclusion of μ-τ triggers plus a b-jet allows for looser cuts
  - but limited statistics available in channel after imposing final b-tag

- **Event Selections**
  - one isolated μ: \( p_T > 12 \text{ GeV}, |\eta^\mu| < 2.0 \)
    * suppress \( Z \rightarrow \mu\mu \) by veto events with more than one \( \mu \)
  - one \( \tau \), opposite sign (OS) from \( \mu \)
    * \( E_T > 10, 10, 15 \text{ GeV} \) (types 1, 2, 3)
    * \( p_T^{\tau-trk} > 7, 5, 5 \text{ GeV} \) (types 1, 2, 3)
    * \( \Sigma p_T^{\tau-trk} > 10 \text{ GeV} \) (type 3)
    * separated from muon: \( \Delta R(\mu, \tau) > 0.5 \)
    * NN > 0.9, 0.9, 0.95 (types 1, 2, 3)
  - at least one jet, \( p_T > 15 \text{ GeV} \)
    * separated from muon and tau: \( \Delta R(\mu, j) > 0.5 \text{ and } \Delta R(\tau, j) > 0.5 \)
  - final selections
    * \( M_W < 60 \text{ GeV} \) ⇒ suppress W+jets bkg
    * one b-tagged jet
b-jet identification & tagging

- **B-hadrons are long lived**
  - search for displaced vertices & tracks with large impact parameters
- **Tag via neural network (NN) tagger**
  - combines several dca & vertex based tagging algorithms

**Neural Network Input Variables**
- vertex mass
- number of tracks for vertex
- vertex decay length significance
- \( \chi^2 / \text{d.o.f.} \) of vertex
- number of vertices
- combined impact parameter significances from two methods

| Loose tag: \(~70\%\) eff; \(~4.5\%\) mis-tag |
| Tight tag: \(~48\%\) eff; \(~0.3\%\) mis-tag |
Background Estimation

- Similar to $\phi \rightarrow \tau\tau$ search, backgrounds estimated from combination of simulated events and control data samples
  - top and diboson processes take from PYTHIA
  - ($W, Z$) + jets; ($W, Z$) + heavy flavor + jets events generated with ALPGEN
  - multi-jet “QCD” events difficult to simulate and hence, estimated from data

- QCD-enriched sample: pre-tag
  - use a strategy similar to the $\phi \rightarrow \tau\tau$ search
    * invert muon isolation and select mNN events: $0.3 < \tau$-NN < $0.8$
  - QCD in signal region extrapolated via ratio of OS to SS events in QCD-enriched sample

- Multi-jets: post b-tag
  - poor stats from b-tag require two methods
  - Tag-rate Function (TRF) method
    * measure probability for jet to be b-tagged in QCD-enriched sample in terms of jet $p_T$ and apply to pre-tag sample
  - Fake Rate Method
    * determine muon isolation fake rate in events with $E_T < 20$ GeV
    * further measure jet-to-tau fake rate from independent $W \rightarrow \mu\nu +$ jets sample
    * apply both on control b-tag + mNN sample

<table>
<thead>
<tr>
<th>$\tau$-type</th>
<th>TRF Method (QCD shape)</th>
<th>Fake Rate Method</th>
<th>Avg.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>4.94</td>
<td>1.73</td>
<td>3.34</td>
</tr>
<tr>
<td>2</td>
<td>9.27</td>
<td>6.10</td>
<td>7.69</td>
</tr>
<tr>
<td>3</td>
<td>7.17</td>
<td>4.22</td>
<td>5.69</td>
</tr>
<tr>
<td>Total</td>
<td>21.38</td>
<td>12.05</td>
<td>16.72</td>
</tr>
</tbody>
</table>

TRF method $\Rightarrow$ QCD shape
Avg. of two methods $\Rightarrow$ Normalization
Half the difference $\Rightarrow$ Systematic Error
**φb \rightarrow ττb: Pre b-tagging**

- Invariant mass of $μ$, $τ$, $E_T$ system $\Rightarrow$ data in agreement with pred. backgrounds
  - dominant backgrounds: $Z + $ jet & QCD multi-jet events

<table>
<thead>
<tr>
<th>PRE b-tag</th>
<th>$Z(\mu\mu,\tau\tau)$</th>
<th>Top</th>
<th>Multi-jet</th>
<th>Other EW</th>
<th>Total Pred.</th>
<th>DATA</th>
</tr>
</thead>
<tbody>
<tr>
<td>all $τ$-types</td>
<td>$532.3 \pm 5.6$</td>
<td>$26.5 \pm 1.0$</td>
<td>$252.7 \pm 17.0$</td>
<td>$56.0 \pm 2.1$</td>
<td>$867.4 \pm 24.8$</td>
<td>$906 \pm 30$</td>
</tr>
</tbody>
</table>
**φb → ττb: Post b-tagging**

- After (NN tight) b-tag, dominant backgrounds: top & QCD multi-jet events
  - motivates constructing techniques to further discriminate against each

<table>
<thead>
<tr>
<th>POST b-tag</th>
<th>Z (μμ,ττ)</th>
<th>Top</th>
<th>Multi-jet</th>
<th>Other EW</th>
<th>Total Pred.</th>
<th>DATA</th>
</tr>
</thead>
<tbody>
<tr>
<td>all τ-types</td>
<td>7.8 ± 0.1</td>
<td>16.0 ± 0.6</td>
<td>16.8 ± 1.4</td>
<td>1.0 ± 0.1</td>
<td>41.7 ± 1.5</td>
<td>54 ± 7.4</td>
</tr>
</tbody>
</table>
Multivariate Methods

- Post b-tag: two techniques used to suppress tt and QCD multi-jet events
  - Kinematic NN (KNN) ⇒ rejects top
  - Log-Likelihood Ratio (LHood) ⇒ rejects QCD

- KNN input variables
  - Jet multiplicity, $H_T$=scalar sum of jet $p_T$’s, energy sum of ($\mu$, $\tau$, jets), and $\Delta \phi(\tau, \mu)$
  - KNN > 0.3 offers ~75% rejection of top events with only ~4% signal loss

- LHood trained separately for each signal mass point
  - $p_T^\mu$, $p_T^\tau$, $\Delta R(\mu, \tau)$, $\mu-\tau$ invariant mass, and $M_{\text{vis}}$
  - compute likelihood of event to be signal-like or QCD-like & take ratio
    * higher LHood value ⇒ signal-like; lower LHood value ⇒ QCD-like
• **KNN vs. LHood 2D distributions**
  
  – apply cuts in (LHood, KNN) plane
  
  $\Rightarrow$ chosen at values that optimize the expected significance

  * dependent on $M_\phi$ and $\tau$-type

• no significant excess in data over predicted backgrounds
  
  – 2D signal and background distributions used to set limit on $\sigma \times BR$
• Limits on $\sigma \times \text{BR}$ calculated using modified frequentist approach
• Study within Higgs boson mass range from 90 to 160 GeV in 10 GeV intervals
• Presently limited by large systematics on: $Z \rightarrow \tau\tau + b(c)$ scale factor (NNLO heavy-quark enhancements), $t\bar{t}$ cross section, and QCD estimate

**Summary of Systematic Uncertainties**

- Luminosity (6.1%)
- $\tau$-ID (4-8%, type dependent)
- $\tau$ energy scale (2-4%, type dependent)
- QCD (40%, 21%, 26%, type dependent)

**MC cross sections**
- Single top (12%)
- $t\bar{t}$ (11%)
- Diboson (6%)
- $W + l\bar{p}$ (10%)
- $W + H + l\bar{p}$ (50%, from K-factor)
- $Z \rightarrow \mu \mu, \tau\tau + l\bar{p}$ (+2/-5%, NNLO theory)
- $Z \rightarrow \mu \mu, \tau\tau + H$ (50%, from K-factor)

Jet Energy Scale (shape)
- b-tag (shape)
- Trigger efficiency (shape)
MSSM Benchmark Scenarios

- $\sigma \times \text{BR Limits} \Rightarrow \text{interpreted in MSSM}$
- Tree-level: Higgs sector of MSSM described by $M_A$ & $\tan\beta$
  - radiative corrections introduce dependence on additional SUSY parameters
- Five additional, relevant parameters
  - $M_{\text{SUSY}}$: Common Scalar mass: parameterizes squark, gaugino masses
  - $X_t$: Mixing Parameter: related to the trilinear coupling $A_t \to$ stop mixing
  - $M_2$: SU(2) gaugino mass term
  - $\mu$: Higgs mass parameter
  - $m_{\tilde{g}}$: gluino mass: comes in via loops

- Two common benchmarks
  - $m_h^\text{max}$ (max-mixing): Higgs boson mass, $m_h$, close to maximum possible value for a given $\tan\beta$
  - no-mixing: vanishing mixing in stop sector $\Rightarrow$ small Higgs boson mass, $m_h$

<table>
<thead>
<tr>
<th>Constrained Model: Unification of SU(2) and U(1) gaugino masses</th>
<th>$m_h^\text{max}$</th>
<th>no-mixing</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M_{\text{SUSY}}$</td>
<td>1 TeV</td>
<td>2 TeV</td>
</tr>
<tr>
<td>$X_t$</td>
<td>2 TeV</td>
<td>0</td>
</tr>
<tr>
<td>$M_2$</td>
<td>200 GeV</td>
<td>200 GeV</td>
</tr>
<tr>
<td>$\mu$</td>
<td>$\pm 200$ GeV</td>
<td>$\pm 200$ GeV</td>
</tr>
<tr>
<td>$m_{\tilde{g}}$</td>
<td>800 GeV</td>
<td>1600 GeV</td>
</tr>
</tbody>
</table>
**φ → ττ: Interpretation within MSSM**

- From cross section limits, (M_A, tanβ) parameter space scanned & regions excluded in MSSM benchmark scenarios
  - cross sections taken from FeynHiggs v.2.6.4
  - h/H degenerate with A ⇒ production cross section for gg→φ and b̅b→φ added at each (M_A, tanβ) point
- Reach sensitivity for M_A < 180 GeV: tanβ ~ 40 – 50

### MSSM: 95% CL Exclusion Limits (μ > 0)

**No-mixing, μ = +200 GeV**

![Graph showing no-mixing exclusion limits](image)

**m_h^{max}, μ = +200 GeV**

![Graph showing maximum exclusion limits](image)
\( \phi b \rightarrow \tau \tau b: \) Interpretation within MSSM (I)

- Similarly, limits interpreted for \( \phi b \) in MSSM parameter space using FeynHiggs
  - expect sensitivity to continually improve with increased datasets
  - and gain from better understanding of systematics

**MSSM: 95% CL Exclusion Limits (\( \mu > 0 \))**

- **No-mixing** \( \mu = +200 \text{ GeV} \)
  - DØ Preliminary, 1.2 fb
  - Observed limit
  - Expected limit
  - LEP 2

- **\( m_h^{\text{max}} \)** \( \mu = +200 \text{ GeV} \)
  - DØ Preliminary, 1.2 fb
  - Observed limit
  - Expected limit
  - LEP 2
\[ \phi b \rightarrow \tau\tau b: \text{ Interpretation within MSSM (II)} \]

- Similarly, constraints for \( \mu < 0 \)
- General, complementary to inclusive \( \phi \rightarrow \tau\tau \) channel: helps contribute to overall Tevatron sensitivity, at low \( M_A \Rightarrow \) does not suffer from \( Z \rightarrow \tau\tau \) background
- Excluded regions largely insensitive to MSSM scenario and \( \mu \)
  - different from \( b\phi \rightarrow b\bar{b}b \) final state (i.e., “3b” Channel)

MSSM: 95% CL Exclusion Limits (\( \mu < 0 \))

![Graphs showing exclusion limits in the MSSM model](image-url)
Comparisons with $\Phi b \rightarrow b b\bar{b}$

- **3b channel gives strong limits for $m_{h}^{\text{max}}$ scenario with $\mu < 0$**
  - radiative corrections give large sensitivity to $\mu$ and its sign
    - negative $\mu$ gives enhanced production
  - positive $\mu$: tau mode competitive especially at low masses despite 1:9 BR

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PRL 101, 221802 (2008)
Higgs Width

- Limit on $\sigma \times \text{BR}$ calculated assuming SM Higgs boson width
  - negligible compared to experimental resolution on $M_{\text{vis}}$

- In MSSM models, Higgs width can be larger than value in SM
  - increases with $\tan\beta$
  - also large dependence on other parameters... for e.g., $\mu$

- e.g., factor $\sim 2$ or more difference for fixed $\tan\beta$ in models with $\mu > 0$ vs. $\mu < 0$
**φ → ττ Result & Width**

- **1.0 fb⁻¹ PRL result** ⇒ provide a ‘model-independent’ correction for effect of a large Higgs boson width
  - simulate effect by adding together neighbouring Higgs boson signal samples with correct weights
- **Build wide signal templates of M_{vis} distribution for Higgs mass M_φ and width Γ_φ**
  - re-calculate cross section limits corresponding to various values of Γ_φ
  - take ratio of limits for wide Higgs boson with SM Higgs boson width (=Γ_φ / Γ_{SM})
  - study ratio as function of width and 4 different Higgs masses

- **Can be used to obtain cross section limits for non-SM relative to limit for a Higgs with SM width**
  - must specify M_φ and Γ_φ
  - for e.g., model with (Γ_φ , M_φ) = (16 GeV, 160 GeV) ⇒ correct limits by 8%

(PRL 101, 071804 (2008))
Projections

• MSSM projections for full 2010 dataset
  – both experiments
  – if no Higgs boson observed, exclusions reach \( \tan \beta \sim 20 \) for \( M_A \sim 120-160 \text{ GeV} \)

[Graph showing \( m_{h_{\text{max}}, \mu < 0} \) and \( \tan \beta \) vs. \( M_A \) for DØ \( \phi \to \pi \) projection and No-mixing, \( \mu < 0 \).

• LHC experiments
  – exclude the entire \( M_A - \tan \beta \) plane
    * eliminate MSSM Higgs sector as a viable model
  – or achieve 5\( \sigma \) discovery of at least one MSSM Higgs boson
Closing Summary

• **DØ** searches for neutral MSSM Higgs boson at high $\tan \beta$ in two major di-tau decay channels
  – 3b channel and charged Higgs bosons in top decays also studied
  – analyses well-developed; results with up to 2.2 fb$^{-1}$ of Run II data

• No signal observed in data over expected backgrounds

• **Upper limits set for** $\sigma \times \text{BR}$ and subsequently translated into 95% CL exclusions in MSSM parameter space
  – reached sensitivity $\tan \beta \sim 40 - 50$ for $M_A < 180$ GeV
  – combination of different channels studied at DØ is in progress and with CDF (Tevatron result)

• **Tevatron delivered** > 5.4 fb$^{-1}$ of Run II data ...and more coming
  – updated results from other channels decaying to tau pairs expected soon...
  – expect sensitivity to continually improve
Reference Slides
Neural Networks and $\tau$-ID

- multivariate analysis method $\Rightarrow$ Neural Networks (NN)
  - parallel operation with neurons (nodes) arranged in series per layer connected via links

$$
N_{\text{var}} \xrightarrow{\text{discriminating}} \text{input variables}
$$

$1$ input layer $\xrightarrow{k}$ hidden layers $\xrightarrow{} 1$ output layer

$$
X_{i=1-N_{\text{var}}}^{(0)} \xrightarrow{W_{ij}} \sum_{j=1}^{M_k} W_{ij} \cdot X_{j}^{(k-1)} \xrightarrow{} \text{NN output (signal and background) $\in [0,1]$}
$$

(input nodes, one for each measured variable ($x_i$))

$\rightarrow$ hidden nodes ($h_j$) $\leftrightarrow$ neuron performs a linear combination of input signals $\sim \sum_{i=1}^{N_{\text{var}}} \omega_{ij} x_i$

$- \quad$ weights ($\omega_{ij}$) for links between node $i$ to node $j$

signal and background control samples

$\Rightarrow$ adjust weights and biases using iterative back-propagation technique (training)

$\Rightarrow$ optimize signal at $\text{NN}_{\text{out}} \rightarrow 1.0$ and produce weight file (kernel)

$\Rightarrow$ apply kernels to $\tau$-physics analysis
SM Higgs Production at Tevatron

- Gluon fusion: $gg \rightarrow H$

  \[ \sigma = 0.70 \text{ pb} \]
  for $M(H) = 120 \text{ Gev}/c^2$
  with QCD NLO correction

- Higgsstrahlung: $q\bar{q} \rightarrow VH$
  $(V=W, Z)$

  \[ \text{WH: } \sigma = 0.16 \text{ pb} \]
  \[ \text{ZH: } \sigma = 0.10 \text{ pb} \]

- Vector Boson Fusion: $q\bar{q} \rightarrow q\bar{q}H$

  \[ \sigma = 0.10 \text{ pb} \]

- Radiation off heavy quark: $q\bar{q} \rightarrow t\bar{t}H, b\bar{b}H$

  \[ \sigma = 0.004 \text{ pb} \]
MSSM $\phi \rightarrow \tau^+\tau^-$: Yields

- Observed & expected number of events for backgrounds
  - given efficiencies for a signal relative to $M_\phi = 160$ GeV

<table>
<thead>
<tr>
<th>Channel</th>
<th>$e\tau_h$ (Run IIa, 1 fb$^{-1}$)</th>
<th>$\mu\tau_h$ (Run IIa, 1 fb$^{-1}$)</th>
<th>$e\mu$ (Run IIa, 1 fb$^{-1}$)</th>
<th>$\mu\tau_h$ (Run IIb, 1.2 fb$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Z/\gamma^* \rightarrow \tau\tau$</td>
<td>$581 \pm 5$</td>
<td>$1130 \pm 7$</td>
<td>$212 \pm 3$</td>
<td>$1030 \pm 32$</td>
</tr>
<tr>
<td>$Z/\gamma^* \rightarrow \mu\mu$, ee</td>
<td>$31 \pm 2$</td>
<td>$19 \pm 1$</td>
<td>$12 \pm 1$</td>
<td>$48 \pm 6$</td>
</tr>
<tr>
<td>QCD Multi-jet + W</td>
<td>$374 \pm 21$</td>
<td>$118 \pm 6$</td>
<td>$38 \pm 2$</td>
<td>$96 \pm 9$</td>
</tr>
<tr>
<td>Diboson + Top</td>
<td>$3.0 \pm 0.1$</td>
<td>$7.0 \pm 0.4$</td>
<td>$6.1 \pm 0.1$</td>
<td>$8.7 \pm 2.6$</td>
</tr>
<tr>
<td>Total Prediction</td>
<td>$989 \pm 23$</td>
<td>$1274 \pm 9$</td>
<td>$269 \pm 3$</td>
<td>$1189 \pm 34$</td>
</tr>
<tr>
<td>Data</td>
<td>$1034$</td>
<td>$1231$</td>
<td>$274$</td>
<td>$1109$</td>
</tr>
<tr>
<td>Efficiency (%)</td>
<td>$1.04 \pm 0.03$</td>
<td>$1.46 \pm 0.04$</td>
<td>$0.57 \pm 0.03$</td>
<td>$1.40 \pm 0.05$</td>
</tr>
</tbody>
</table>

- Data consistent with expected backgrounds
  - $M_{\text{vis}}$ spectrum used in limit calculation
  - Modified frequentist approach using likelihood-fitter
    - confidence level $\text{CL}_s = \text{CL}_{s+b}/\text{CL}_b$; where $\text{CL}_{s+b}$ = signal-plus-background & $\text{CL}_b$ = background-only hypothesis
    - calculate expected & observed limits by scaling signal until $1-\text{CL}_s = 0.95$
Tevatron Projections & SM Higgs

- Recent Tevatron luminosity projections
  - plan on ~7 fb$^{-1}$ (up to ~9 fb$^{-1}$) delivered for end-FY09 (end-FY10) running

- Tevatron expected SM Higgs reach
  - up to 6.8 fb$^{-1}$ analyzed: 2σ exclusion for $M_H > 125$ GeV or 3σ evidence for $M_H = 154$-175 GeV
  - low mass region more difficult
CDF: MSSM Higgs Decay to di-tau

- CDF 1.8 fb\(^{-1}\) result: observe no significant excess in data above backgrounds
  - exclusion limits set for \(M_A = 90 - 250 \text{ GeV}\)

(CDF CONF-Note 9071)