(Some) Recent Results from DØ

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(DØ Collaboration)

XI Mexican Workshop on Particles and Fields
Tuxtla Gutierrez, Mexico
7–12 Nov. 2007
Outline

DØ and CDF cover enormous breadth of physics:

- QCD
- \( B \) Physics
- Top Quark
- Electroweak
- New Particle Searches
- Higgs Boson Searches

Impossible to cover it all (>35 papers this year, >100 new results)

More available at:
http://www-d0.fnal.gov/Run2Physics/WWW/results.htm
QCD

* **B Physics** (CINVESTAV group, talks this workshop, therefore stressing more)

* Top Quark
* Electroweak
* New Particle Searches
* Higgs Boson Searches
Highest energy collider in the world:

~1 TeV proton beam colliding with
~1 TeV anti-proton beam

~4 miles in circumference
Tevatron running with peak luminosities of $300 \times 10^{30}$ cm$^{-2}$ s$^{-1}$

DØ has recorded $\sim 2.8$ fb$^{-1}$ of data and have results on up to 2.4 fb$^{-1}$

Up to 10 interactions per x-ing!
DØ Data Set

Run II Integrated Luminosity

Run 2b upgrades installed:
Layer 0 Silicon Microvertex
(Calorimeter) Trigger upgrades

New Results

- Tevatron running with peak luminosities of $300 \times 10^{30} \, \text{cm}^{-2} \, \text{s}^{-1}$
  - Up to 10 interactions per x-ing!

- DØ has recorded $\sim2.8 \, \text{fb}^{-1}$ of data and have results on up to $2.4 \, \text{fb}^{-1}$
- "Local" momentum measurement in toroidal field
- Swap polarity of toroid or solenoid biweekly, unique for cancellation of systematics for charge asymmetries
- Muon trigger scintillators
- Excellent muon coverage $|\theta| < 2$
- Excellent, hermetic uranium liquid-Argon calorimeter
- Tracking out to $|\theta| \sim 3$ (\(\theta \sim 6\) deg.)
- Single hit resolution of 10 \(\mu\)m, S/N > 10
**DØ Detector: Run 2b Upgrades**

- New calorimeter trigger (replaced last piece of electronics from the late 80's)
- New tracker electronics and trigger (less noise and better granularity)
- Deal with increased luminosity!
- Can now match calorimeter objects and tracks at Level 1 trigger!

**Graphs:**
- Efficiency vs. Reconstructed Jet $E_T$ (GeV)
- Efficiency vs. Reconstructed EM $E_T$ (GeV)
- Rate (kHz) vs. Luminosity ($10^{30}$ cm$^{-2}$ s$^{-1}$)

- **Doublets (run IIa):**
  - One track
  - Two tracks

- **Singlets (run IIb):**
  - One track
  - Two tracks

- $p_T > 10$ GeV
DØ Detector: Run 2b Upgrades

- New Layer 0 for Silicon Microvertex Tracker, installed inside existing tracker - improved vertex resolution, improved $b$ jet id.

Radiation damage; improved tracking

First oscillation if $\Delta m_s = 18 \text{ ps}^{-1}$
Program concentrates on states not produced at the $\Upsilon(4S)$
e.g.,

$B_s^0, B^{**}, \Lambda_b, \Xi_b$
One heavy quark, plus all else, light degrees of freedom
(light quark(s), gluons, "brown muck")

Heavy quark limit: each energy level has pair of degenerate states
given by \( j_q, J = \vec{s}_Q + \vec{j}_q \)

\[
\begin{align*}
L &= 0 & L &= 1 \\
\vec{j}_q &= 1/2 & \vec{j}_q &= 1/2 \\
J &= 0 & J &= 0, 1 \\
J &= 1 & J &= 1, 2 \\
\end{align*}
\]

Collectively referred to as:
Two will be narrow, 
two will be wide
**$B^{**}$ States**

\[ B_1 \rightarrow B^{**+} \pi^-; \quad B^{**+} \rightarrow B^+ \gamma \]
\[ B_2^* \rightarrow B^{**+} \pi^-; \quad B^{**+} \rightarrow B^+ \gamma \]
\[ B_2^* \rightarrow B^+ \pi^- \]

- Reconstruct $B^+ \rightarrow J/\psi K^+$ then add a pion
- First time these states have been separated

\[ M(B_1) = 5720.6 \pm 2.4 \pm 1.4 \text{ MeV} \]
\[ M(B_2^*) = 5746.8 \pm 2.4 \pm 1.7 \text{ MeV} \]
$B_{s1} \rightarrow B^{*+}K^{-}$; $B^{*+} \rightarrow B^{+}\gamma$

$B_{s2}^{*} \rightarrow B^{*+}K^{-}$; $B^{*+} \rightarrow B^{+}\gamma$

$B_{s2}^{*} \rightarrow B^{+}K^{-}$

- **Reconstruct**
  
  $B^{+} \rightarrow J/\psi K^{+}$

  then add a kaon

- Only indirectly observed at LEP

\[
M(B_{s2}^{*}) = 5839.6 \pm 1.1 \pm 0.7 \text{ MeV}
\]
What about??

**Change in likelihood equivalent to less than 3σ; current data neither confirms or excludes second $B_{s1}$ state.**

- CDF has observed a second narrow state.
New Baryon Discovered: $\square_b$

$J = 1/2$ $b$ Baryons

2 $b$

1 $b$

0 $b$

$\begin{array}{c}
\text{udb} \\
\text{sbb} \\
\text{ubb} \\
\text{dbb} \\
\text{uub} \\
\text{dsb} \\
\text{ddb} \\
\text{n} \\
\text{uus} \\
\text{uss} \\
\text{dss} \\
\text{dds} \\
\text{p} \\
\end{array}$
New Baryon Discovered: $\Xi_b$

$J = \frac{1}{2}$ $b$ Baryons

"Strangely Beautiful Baryon"
"Triple-Scoop Baryon"
New Baryon Discovered: $\Xi_b$

$\Xi_b^{-}$ discovery in DØ, 1.3 fb$^{-1}$

- Data
- Fit

$M(\Xi_b^{-}) = 5774 \pm 11 \pm 15$ MeV

- 5.5$\Xi_b^{-}$ observation
- Has lifetime behavior

Consistent with later CDF result and theory prediction:

$M(\Xi_b) = 5795 \pm 5$ MeV

hep-ph/0706.2163
New Baryon Discovered: $\Xi_b$

Run 179200, Event 55278820, $M(\Xi_b) = 5.788$ GeV
Lifetimes

- Interested in differences in lifetimes between the $B$ hadrons beyond the naive weak decay spectator model:

\[ \Gamma = \Gamma_0 \]
Lifetimes

- Interested in differences in lifetimes between the $B$ hadrons beyond the naive weak decay spectator model:

- Test Operator Product Expansion (OPE), Heavy Quark Effective Theory (HQET) and lattice gauge predictions

\[ \Gamma = \Gamma_0 + \frac{\Lambda^2}{m_b^2} (\Gamma_2^{(0)} + \Gamma_2^{(1)}) + \frac{\Lambda^3}{m_b^3} (\Gamma_3^{(0)} + \Gamma_3^{(1)}) + \ldots \]

See A. Lenz's talk for state-of-the-art

First corrections due to kinetic and chromomagnetic operator

Weak annihilation and Pauli interference
\( B_s \) Semileptonic Lifetime

\[
B_s^0 \rightarrow D_s \mu^\pm \nu
\]

\( D_s \rightarrow \phi \pi \)

- Reconstruct
  \( D_s \rightarrow \phi \pi \)
in association with an identified muon

\[
\tau(B_s^0) = 1.398 \pm 0.044^{+0.028}_{-0.025} \text{ ps}
\]
$B_s$ Semileptonic Lifetime

$\bar{B}_s^0 \rightarrow D_s \mu^\pm \nu$

$D_s \rightarrow \phi \pi$

Most precise in world

![Graph showing $B_s$ flavor-specific lifetime measurements from various experiments. The graph includes data points from ALEPH 91-95, CDF 92-96, DELPHI 91-95, OPAL 90-95, CDF 02-04, and D0 02-04 experiments. The HFAG average is highlighted with a red circle and a value of $1.440 \pm 0.036$ picoseconds.]}
**$b\bar{b}$ Lifetime**

One of the un-solved mysteries of HF lifetime measurements

- long-standing discrepancy between theory and measurement

Recent HQE calculation refinements
  - inclusion of sub-leading spectator ($1/m_b^4$) terms
  - inclusion of NLO and $1/m_b$ spectator effects

lowered expected value of $\tau(L_b)/\tau(B_d)$

**But be careful! (See A. Lenz's talk)**

**Exclusive Lifetime, $\Lambda_b^0 \rightarrow J/\psi \Lambda^0$**

$\Lambda_b^0 \rightarrow J/\psi \Lambda^0$

Former CINVESTAV
Eduard de la Cruz Burelo

PRL 99, 142001 (2007)

$\tau(L_b) = 1.218^{+0.130}_{-0.115} \pm 0.042$ ps
$\Lambda_b$ Lifetime

Semileptonic Lifetime, $\Lambda_b^0 \rightarrow \Lambda_c \mu \nu \rightarrow p K_S^0$

- S/N not great, fit signal yield in bins of proper decay time, then $\chi^2$ fit

$\tau(\Lambda_b^0) = 1.290^{+0.119+0.087}_{-0.110-0.091}$ ps
**\( \Psi_b \) Lifetime**

**\( \Psi_b \) Lifetime Measurements**

**ALEPH** \( \Psi_c \) I
(91-95)  
1.18 ± 0.13 ± 0.03

**ALEPH** \( \Psi_c^0 \) I+I
(91-95)  
1.30 ± 0.26 ± 0.04

**OPAL** \( \Psi_c \) I
(90-95)  
1.29 ± 0.24 ± 0.06

**DELPHI** \( \Psi_c \) I
(91-95)  
1.11 ± 0.19 ± 0.05

**CDF** \( \Psi_c \) I
(92-95)  
1.32 ± 0.15 ± 0.06

**D0 J/\( \Psi_c^0 \)
250 pb\(^{-1}\) (02-04)  
1.22 ± 0.22 ± 0.04

**CDF** J/\( \Psi_c^0 \)
1 fb\(^{-1}\) (02-06)  
1.59 ± 0.08 ± 0.03

**D0** \( \Psi_c \) I
1.3 fb\(^{-1}\) (02-06)  
1.29 ± 0.12 ± 0.09

**D0** J/\( \Psi_c^0 \)
1.2 fb\(^{-1}\) (02-06)  
1.22 ± 0.13 ± 0.04

**D0 Combined** (02-06)  
1.25 ± 0.10

1.230 ± 0.074 PDG 2006

**\( \Psi_b \) lifetime [ps]**
**$b$** _Lifetime_  

**Lifetime Measurements**  

<table>
<thead>
<tr>
<th>Experiment</th>
<th>$b$ Lifetime [ps]</th>
<th>Error [ps]</th>
</tr>
</thead>
<tbody>
<tr>
<td>ALEPH $b^0 I^+$ (91-95)</td>
<td>1.30 $^{+0.26}_{-0.21}$</td>
<td>± 0.04</td>
</tr>
<tr>
<td>OPAL $b$ (90-95)</td>
<td>1.29 $^{+0.24}_{-0.22}$</td>
<td>± 0.06</td>
</tr>
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**PDG 2007**  
1.409 $^{±0.055}_{-0.055}$  
(no scaling of errors)
Lifetime of $B_c$ Meson

- Unique in that it carries two different heavy quarks
- In a "race" to decay
- Predictions that lifetime is $\sim 1/3$ that of other $b$ hadrons

Use tri-muon invariant mass distribution to distinguish signal from background, simultaneous mass & lifetime fits

Increasing cut on proper decay length

![Graphs showing mass distributions for different cuts on proper decay length]
Lifetime of $B_c$ Meson

- Simultaneous fit to mass templates and lifetime models
- Most precise by factor of $\sim 2$

$$\tau(B_c) = 0.444^{+0.039+0.039}_{-0.036-0.034} \text{ ps}$$

- c.f. theory prediction

$$\tau(B_c) = 0.48 \pm 0.05 \text{ ps}$$

hep-ph/0308214
**$B_s^0$ Decays**

Want to probe all the parts of:

\[
\frac{d}{dt} \begin{pmatrix} B_s^0 \\ \bar{B}_s^0 \end{pmatrix} = \begin{pmatrix} M - \frac{i\Box}{2} & M_{12} - \frac{i\Box_{12}}{2} \\ M_{12}^* - \frac{i\Box_{12}^*}{2} & M - \frac{i\Box}{2} \end{pmatrix} \begin{pmatrix} B_s^0 \\ \bar{B}_s^0 \end{pmatrix}
\]

| $B_H$\rangle = p| $B_s^0$\rangle + q| $\bar{B}_s^0$\rangle  
Heavier mass eigenstate

| $B_L$\rangle = p| $B_s^0$\rangle − q| $\bar{B}_s^0$\rangle  
Lighter mass eigenstate

If CP conserved, in mixing

| $B_L$\rangle = | $B^{CP-even}$\rangle

| $B_H$\rangle = | $B^{CP-odd}$\rangle

\[
\Box m_s = M_H \Box M_L \sim 2 |M_{12}| \quad \text{Sensitive to new physics}
\]

\[
\Box_{CP} = \Box_{even} - \Box_{odd} \sim 2 |\Box_{12}| \quad \text{Not sensitive to new physics}
\]

\[
\Box s = \Box_L + \Box_H \sim 2 |\Box_{12}| \cos \Box_s \quad \Box \sim 0.3^\circ \text{ in SM}
\]

\[
\Box s = \text{arg}(\Box_{12}/M_{12}) \quad \text{Sensitive to new physics}
\]

\[
\Box s = \frac{\Box_L + \Box_H}{2}; \quad \Box = \frac{1}{\Box_s}
\]
**CKM Triangle**

Area of the triangle indicates CP violation in the SM due to the CKM matrix.

\[ V_{td} = |V_{td}| e^{-i\phi} \]

Want precision

\[ V_{ub} = V_{ud}^* \]
\[ V_{cb} = V_{cd}^* \]
\( B_d^0 \) mixing and oscillations:

- **\( B_d^0 \) oscillation frequency:**
  \[
  \Delta m_d = \frac{G_F^2}{6} m_b m_t^2 F \left( \frac{m_t^2}{m_W^2} \right) QCD B_{B_d} f_{B_d}^2 |V_{tb}V_{td}|^2
  \]

  - Measured well
  - Large uncertainties!

- If measure \( \Delta m_d \) and \( \Delta m_s \):
  \[
  \frac{\Delta m_s}{\Delta m_d} = \frac{Q_{Bs}}{Q_{Bd}} \frac{m_{Bs}}{m_{Bd}} \frac{f_{Bs}^2}{f_{Bd}^2} \frac{B_{Bs}}{B_{Bd}} \left| \frac{V_{ts}}{V_{td}} \right|^2
  \]

  - Smaller uncertainty
  - 1.21 ± 0.04 ± 0.05

- If initially start with a \( B_s^0 \)
  \[
  \text{Prob}[B_s^0](t) = \frac{1}{4} [ \exp(-\frac{1}{2} t) + \exp(-\frac{3}{2} t) + 2\exp(-t) \cos(\Delta m_s t) ]
  \]

  - Better Precision (only ~5% theory systematic)
**B_0^s Oscillations**

- **Reconstructed or signal-side**
- **Opposite side**
- **Event Charge**
- **Jet Charge**

**New?**
- track-by-track error rescaling
- More data (2.4 fb^{-1})
- Layer 0 SMT
- Same-side flavor tag (from charge of fragmentation K^\pm)

**Hadronic signal decay modes:**

**DØ Run II Preliminary**

![Graph showing m_{KK} (GeV) vs entries / 0.1 GeV]
**$B_s^0$ Oscillations**

**History**

- DØ sets first two-sided limit

$$17 < \Delta m_s < 21 \text{ ps}^{-1} \text{ at 90\% CL}$$

*PRL 97, 021802 (2006)*
B$_s^0$ Oscillations

History

- DØ sets first two-sided limit

\[ 17 < \Delta m_s < 21 \text{ ps}^{-1} @ 90\% \text{ CL} \]

PRL 97, 021802 (2006)

Already rules out large new physics
$B^0_s$ Oscillations

History

- DØ sets first two-sided limit
  
  $17 < \Delta m_s < 21 \text{ ps}^{-1} @ 90\% \text{ CL}$

  PRL 97, 021802 (2006)

  Already rules out large new physics

- CDF makes precision SM measurement
  
  $\Delta m_s = 17.77 \pm 0.10 \pm 0.07 \text{ ps}^{-1}$

  PRL 97, 062003 (2006)

  PRL 97, 243003 (2006)
\( B_s^0 \) Oscillations

**History**

- DØ sets first two-sided limit
  \[ 17 < \Delta m_s < 21 \text{ ps}^{-1} @ 90\% \text{ CL} \]
  PRL 97, 021802 (2006)

  Already rules out large new physics

- CDF makes precision SM measurement
  \[ \Delta m_s = 17.77 \pm 0.10 \pm 0.07 \text{ ps}^{-1} \]
  \[ |V_{td}/V_{ts}| \]
  PRL 97, 062003 (2006)
  ~0.5% exp. error
  ~3.4% theo. error

- DØ sees evidence at > 3\( \sigma \), makes measurement
  \[ \Delta m_s = 18.56 \pm 0.87 \text{ ps}^{-1} \]
First study of CP violation in $B_s$ mixing

- Again, define Heavy ($H$, CP-odd) and Light ($L$, CP-even) $B_s$ states

$$B_s^0 = L \times H; \quad B_s^0 = (L + H)/2$$

- Not "flavor-specific", predicted to be more CP-even

$$\phi_s \neq 0$$

New Physics!
(since tiny in SM)

- Decays into vector mesons that are either CP-odd ($L=1$) or CP-even ($L=0,2$)

- Time-dependent angular distributions allow separation of components

- Simultaneous fit to lifetime and angles

- Use Monte Carlo to correct for acceptances
First study of \( CP \) violation in \( B_s \) mixing

- Again, define Heavy (\( H, CP\)-odd) and Light (\( L, CP\)-even) \( B_s \) states
  \[
  0_s = 0_L 0_H; \quad 0_s = (0_L + 0_H)/2
  \]

- Not "flavor-specific", predicted to be more \( CP\)-even

- Decays into vector mesons that are either \( CP\)-odd (\( L=1 \)) or \( CP\)-even (\( L=0,2 \))

- Time-dependent angular distributions allow separation of components

- Simultaneous fit to lifetime and angles

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---

CINVESTAV group working on same analysis for both \( B_d^0 \rightarrow J/\psi K^{*0} \) and \( B_s^0 \rightarrow J/\psi \phi \) (in preparation)
First study of CP violation in $B_s$ mixing

$\Delta \Gamma_s = 0.17 \pm 0.09 \pm 0.02 \text{ ps}^{-1}$

$\phi_s = -0.79 \pm 0.56^{+0.14}_{-0.01}$
First study of CP violation in $B_s$ mixing

- Combine with DØ measured asymmetries
  
  \[ a_{SL}^s = \frac{\Gamma(B_s^0 \to f) - \Gamma(B_s^0 \to \bar{f})}{\Gamma(\bar{B}_s^0 \to f) + \Gamma(B_s^0 \to \bar{f})} = \frac{\Delta \Gamma_s}{\Delta m_s} \tan \phi_s \]

- PRD 74, 092001 (2006)
  
  \[ N(b\bar{b} \to \mu^+ \mu^+ X) \quad \text{vs.} \quad N(b\bar{b} \to \mu^- \mu^- X) \]

- PRL 98, 151801
  
  \[ N(B_s^0 \to D_s^- \mu^+ \nu) \quad \text{vs.} \quad N(\bar{B}_s^0 \to D_s^+ \mu^- \bar{\nu}) \]

- Semileptonic $B_s$ lifetime
  
  (50% CP-even, 50% CP-odd)

\[
a_{SL}^s = 0.0001 \pm 0.0090
\]
\[
\Delta \Gamma_s \tan \phi_s = 0.02 \pm 0.16 \text{ ps}^{-1}
\]

\[
\Delta \Gamma_s = 0.13 \pm 0.09 \text{ ps}^{-1}
\]
\[
\phi_s = -0.70^{+0.47}_{-0.39}
\]
**$s$ and $f_s$**

- Combine with DØ measured asymmetries

\[
a_{SL}^s = \frac{\Gamma(\bar{B}_s^0 \to f) - \Gamma(\bar{B}_s^0 \to \bar{f})}{\Gamma(\bar{B}_s^0 \to f) + \Gamma(\bar{B}_s^0 \to \bar{f})}
= \frac{\Delta \Gamma_s}{\Delta m_s} \tan \phi_s
\]

- PRD 74, 092001 (2006)

\[
N(b \bar{b} \to \mu^+ \mu^+ X) \quad \text{vs.} \quad N(b \bar{b} \to \mu^- \mu^- X)
\]

- PRL 98, 151801

\[
N(B_s^0 \to D_s^- \mu^+ \nu) \quad \text{vs.} \quad N(\bar{B}_s^0 \to D_s^+ \mu^- \bar{\nu})
\]

- Semileptonic $B_s$ lifetime (50% CP-even, 50% CP-odd)

CINVESTAV

For the DØ T-shirt (see A. Lenz's talk):

\[
|\Delta_s| = \frac{\Delta m_s}{\Delta M_{s}^{SM}}
\]

**Constrained**

\[
\Delta \Gamma_s = 0.13 \pm 0.09 \text{ ps}^{-1}
\]

\[
\phi_s = -0.70^{+0.47}_{-0.39}
\]
Top Quark Physics

Precision measurements systematics limited
Large enough samples for other properties

Decay mode and Branching fractions
Rare decays
Anomalous decays
CKM matrix element $|V_{tb}|$

Top spin polarization
Spin correlations

Top mass

Production cross-section
Production kinematics
New Resonance production

W helicity

$W^+$
Top Physics: Bread & Butter

Top Quark Mass [GeV]

<table>
<thead>
<tr>
<th>Source</th>
<th>Mass (GeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Run I Dileptons</td>
<td>168.4 ±12.3 ±3.6</td>
</tr>
<tr>
<td>Run I Lepton+jets</td>
<td>180.1 ±3.6 ±3.9</td>
</tr>
<tr>
<td>Run I Alljets</td>
<td>178.5 ±13.7 ±7.7</td>
</tr>
<tr>
<td>Run II Dileptons</td>
<td>173.7 ±5.4 ±3.4</td>
</tr>
<tr>
<td>Run II Lepton+jets</td>
<td>170.5 ±1.8 ±2.0</td>
</tr>
<tr>
<td>DØ combination (August 2007)</td>
<td>172.1 ±1.5 ±1.9 GeV (1.4% precision)</td>
</tr>
<tr>
<td>World average (March 2007)</td>
<td>170.9 ±1.1 ±1.5 GeV</td>
</tr>
</tbody>
</table>

- With 2 fb⁻¹ samples, many working hard driving systematics down, legacy measurements (along with cross section)

See G. Gomez's talk for implications with W mass
Observation of Single Top

$\bar{t}t$ pairs only produced strongly

Single top only produced via electroweak interaction (with direct access to $V_{tb}$)

- Requires sophisticated multivariate techniques to extract small signal
- Requires solid understanding of $W+$jets background
- "Stepping stone" to Higgs, milestone for the Tevatron
Observation of Single Top

\[ |V_{tb}| = 1.3 \pm 0.2 \]

\[ 0.68 < |V_{tb}| < 1 @ 95\% \text{ CL} \]

- First direct measurement
- Does not assume 3 generations or unitarity
**W Helicity in Top Decays**

left-handed \( f_- = 0.3 \)

longitudinal \( f_0 = 0.7 \)

right-handed \( f_+ \approx 10^{-4} \)

Submitted to PRL, hep-ex/0711.0032
**t̅t̅ Resonance**

- Have enough top pairs to look for resonances!

\[ M(Z') > 740 \text{ GeV} \]

**Other Properties, results on**

- Top electric charge
- Forward-backward production charge asymmetry
- Ratio of leptonic decays to hadronic decays (such as via charged Higgs)
- Search for admixture of scalar top quarks (stop) in final states

**DØ Run II Preliminary**

<table>
<thead>
<tr>
<th>Process</th>
<th>Events</th>
</tr>
</thead>
<tbody>
<tr>
<td>197.0 data</td>
<td>35</td>
</tr>
<tr>
<td>10.84 Zprime750</td>
<td>30</td>
</tr>
<tr>
<td>148.56 t̅t̅jet</td>
<td>25</td>
</tr>
<tr>
<td>5.89 t̅t̅l̅l̅</td>
<td>20</td>
</tr>
<tr>
<td>0.12 ZZ</td>
<td>15</td>
</tr>
<tr>
<td>0.31 WZ</td>
<td>10</td>
</tr>
<tr>
<td>1.00 WW</td>
<td>5</td>
</tr>
<tr>
<td>2.35 t̅b̅q</td>
<td>2</td>
</tr>
<tr>
<td>1.09 t̅b̅</td>
<td>1</td>
</tr>
<tr>
<td>3.58 Z+jet</td>
<td>1</td>
</tr>
<tr>
<td>9.20 Wbb</td>
<td>1</td>
</tr>
<tr>
<td>5.01 Wcc</td>
<td>1</td>
</tr>
<tr>
<td>3.90 Wl̅p</td>
<td>1</td>
</tr>
<tr>
<td>6.27 Multijet</td>
<td>1</td>
</tr>
</tbody>
</table>

Excess less than 2σ
Electroweak Physics

W and Z Production and Decay Precision Measurements
Focusing on Dibosons
Precision Mass of W
(work continues)
Z Production and Decay

- Huge samples
- Drell-Yan $p_T$: ideal testing ground for QCD and MC generators
- $W$ and $Z$ $p_T$ determined by QCD radiation
- Essential part of $W$ mass measurement, and understanding PDF's

$Z \rightarrow \tau^+\tau^-$; $\tau \rightarrow \mu$; $\tau \rightarrow$ hadrons

- Illustrates success of tau-identification
- Measured
  \[ \sigma(p\bar{p} \rightarrow Z + X) \cdot Br(Z \rightarrow \tau^+\tau^-) \]
  consistent with SM prediction
- Confidence in use of tau-id in SUSY Higgs & other searches

DØ Run II preliminary, 0.98 fb$^{-1}$

Prediction signal

Visible Mass [GeV]
Dibosons

- Backgrounds to SUSY, top, Higgs

- Trilinear gauge couplings (TGC's) (like $WW\gamma$, $WWZ$) are a feature of the SM (required!)

- Instances where they are forbidden ($ZZZ$, $ZZ\gamma$, $Z\gamma g$); deviations can be new physics!

- Limits now competitive with LEP2!

$qq' \rightarrow WZ$ tests TGC $WWZ$ clean

$qq' \rightarrow WW$ tests $WWZ, WW\gamma$ tangled

$e^+ e^- \rightarrow WW$ (LEP2)
**Dibosons**

**DØ Electroweak Run II pp at $\sqrt{s} = 1.96$ TeV**

Cross-Section [pb]

- $W$
- $Z$
- $WZ$
- $ZZ$
- $WW$
- $H \rightarrow WW$

**Theory**

M$_H = 160$
Dibosons

**DØ Electroweak Run II $p\bar{p}$ at $\sqrt{s} = 1.96$ TeV**

*Cross-Section [pb]*

- $W$ and $Z$
- $WW$
- $WZ$
- $ZZ$
- Single top

**Candidate**

$qq' \rightarrow (Z, \gamma) (Z, \gamma) \rightarrow e^+e^-\mu^+\mu^-$

**Event**

Run 208854 Evt 35162371

Triggers:
- EM
- ICD
- MG
- HAD
- CH

Bins: 367
- Mean: 0.413
- Rms: 2.28
- Min: 0.00916
- Max: 28.6

**Statistics**
- Mu particle et: 19.02
- Em particle et: 66.7
- Mu particle et: 25.86
- Em particle et: 32.16

**Electromagnetic (EM) and Hadronic (HAD) Components**

- Bins: 367
- Mean: 0.413
- Rms: 2.28
- Min: 0.00916
- Max: 28.6

**ET (GeV)**

- 0 to 40

**ET (GeV) Distribution**

- Mu particle et: 19.02
- Em particle et: 66.7
- Mu particle et: 25.86
- Em particle et: 32.16
Higgs Physics

We have a shot!
Analysis strategy depends on mass:

$M_H < 135 \text{ GeV}$
- $gg \rightarrow H \rightarrow b\bar{b}$ overwhelmed by QCD multijet background
- Stick to associated production: $WH, ZH$ followed by $H \rightarrow b\bar{b}$ (and leptonic decays of VB's)
- Complement it with $H \rightarrow WW^*$
- Backgrounds: $Wbb, Zbb, W/Zjj$ top, QCD, diboson...

$M_H > 135 \text{ GeV}$
- Use $gg \rightarrow H \rightarrow WW$ production and distinctive multilepton final states
- Backgrounds: $WW, DY, WZ, ZZ$, $tt, tW, \tau\tau...$
**SM Higgs**

$WH \rightarrow \ell v b \bar{b}$

- Pre-selection, then multivariate techniques, e.g., neural net

$gg \rightarrow H \rightarrow WW^{(*)} \rightarrow e\mu$

- Two isolated leptons, missing $E_T$

![Graph](image)
SM Higgs

**Combine:**

**Low Mass**

\[ WH \rightarrow e\nu\bar{b}b \]
\[ \rightarrow \mu\nu\bar{b}b \]
\[ ZH \rightarrow e\bar{e}b\bar{b} \]
\[ \rightarrow \mu\mu\bar{b}b \]
\[ \rightarrow \nu\nu\bar{b}b \]

**Intermediate, High Mass**

\[ WH \rightarrow WW^* \rightarrow \ell^\pm\ell^\pm X \]
\[ H \rightarrow WW \rightarrow e\nu e\nu \]
\[ \rightarrow \mu\nu\mu\nu \]
\[ \rightarrow e\nu\mu\nu \]
\[ \rightarrow \mu\nu\tau_h\nu \]

Results added since combination done (improves low-mass)

- For \( m_H = 115 \text{ GeV} \), expected (observed) 95% CL relative to \( \Delta_{SM} = 6.0 \) (8.3)
- For \( m_H = 160 \text{ GeV} \), expected (observed) 95% CL relative to \( \Delta_{SM} = 2.8 \) (2.5)

DØ Higgs Combination
DØ Preliminary, \( L=0.9-1.7 \text{ fb}^{-1} \)

Limit / Limit (WH/ZH/H\|BR(H\|b\bar{b}\|W/W'))
SM Higgs

Tevatron Run II Preliminary

- For $m_H=115$ GeV, expected (observed) 95% CL relative to $\Delta\chi^2_{SM} = 4.3 (7.8)$
- For $m_H=160$ GeV, expected (observed) 95% CL relative to $\Delta\chi^2_{SM} = 2.5 (1.4)$

Does not include DØ September updates
SM Higgs Projections

For background dominated searches, one generally expects the cross section limit to improve with integrated luminosity in proportion to $\sqrt{Ldt}$.

So far in Run II, limits have improved approximately in proportion to $Ldt$ itself:
- able to use more lepton acceptance
- improvements in b-tagging
- more/better multivariate techniques (neural nets)
- better statistical treatment of separate channels with different signal/background
- Increasing trigger efficiency

Further improvements expected
- Layer 0 enhancement in b-tagging
- jet resolution optimization
- Include additional channels: tau, $WH\ell\ell$, $WW\ell\ell$, $H\ell\ell$, etc.
- even more/better multivariate techniques (matrix element)
- Upgraded trigger efficiency
SM Higgs Projections

Median Projected
SM Higgs Sensitivity

DØ x 2 Luminosity Projection

95% CL Limit

3-σ Evidence

Assumes 2 Experiments
Assumes 2 Experiments
SM Higgs Projections

Being considered by FNAL PAC and P5 (8 fb⁻¹ delivered)

Assumes 2 Experiments

Median Projected SM Higgs Sensitivity

SM Higgs Mass [GeV]

DØ x 2 Luminosity Projection

95% CL Limit

3-σ Evidence

5.5 fb⁻¹

6.8 fb⁻¹

2010

2009
SM Higgs Projections

Assumes 2 Experiments
SM Higgs Projections

- Work is underway to achieve and exceed these levels of sensitivity

- With data accumulated by the end of 2010, we will be able to explore much of the SM Higgs mass region allowed by the constraints from precision measurements and LEP direct exclusion.
Summary

Lots more physics to do with ~3–4 times more data!

- QCD
- $B$ Physics
- Top Quark
- Electroweak
- New particle searches
- Higgs boson searches/discovery

Highly dependent on LHC schedule
Backup
A_{SL} in \( B_s \) Decays

**DØ Analyses:** Use Inclusive muons or \( B_s \) \( D_s \Xi \) \( X, D_s \)

Experimentally,

\[
A_{\mu\mu} = \frac{N(b\bar{b} \rightarrow \mu^+\mu^+X) - N(b\bar{b} \rightarrow \mu^-\mu^-X)}{N(b\bar{b} \rightarrow \mu^+\mu^+X) + N(b\bar{b} \rightarrow \mu^-\mu^-X)}
\]

\[
A_{SL}^{s,unt} = \frac{N(\mu^+D_s^-) - N(\mu^-D_s^+)}{N(\mu^+D_s^-) + N(\mu^-D_s^+)}
\]

Detector systematics controlled by flipping muon toroid & solenoid polarity

Both results must be corrected for flavor composition of sample:

\[
A = -0.0092 \pm 0.0044 \text{ (stat)} \pm 0.0032 \text{ (syst)}
\]

\[
= \frac{f_s Z_s}{f_d Z_d} A_{SL}^d + \frac{f_s Z_s}{f_d Z_d} A_{SL}^s
\]

Combining factors yields:

\[
A_{SL}^s = -0.0064 \pm 0.0101
\]

**\( B_s \) \( D_s \Xi \) \( X \):**

\[
A = 0.0102 \pm 0.0081 \text{ (stat)}
\]

Correcting for flavor non-specific \( B_s \) decays in the sample yields:

\[
A_{SL}^s = 0.0001 \pm 0.0090
\]

(Constraints on \( s \) will be discussed later)
The graph shows the Flavour Specific WA Lifetime for $B_s$ mesons. The data comes from the DØ experiment with 1.1 fb$^{-1}$ of data. The green area represents the constraint on the lifetime, while the blue and red lines indicate the results from specific experiments. The SM (Standard Model) prediction is shown by the yellow band. The star (*) indicates the constrained region.
SUSY Higgs

MSSM Higgs Sector

- Five physical states: $h^0, H^0, A^0, H^\pm$
- Two important parameters: $M_A, \tan \beta = \nu_{up}/\nu_{down}$
- LEP limits: $M_A > 93$ GeV (higher for small $\tan \beta$)
- Enhanced production ($\propto \tan^2 \beta$)
- $Br(h, H, A \rightarrow b\bar{b}) \approx 90\%, Br(h, H, A \rightarrow \tau^+\tau^-) \approx 10\%$

$$bg \rightarrow \phi b \rightarrow bbb$$  
$$gg \rightarrow \phi bb \rightarrow bbbb$$  
$$gg, bb \rightarrow \phi \rightarrow \tau^+\tau^-$$

Need associated production to cope with QCD backgrounds  
More distinctive, use fusion production

Comparable sensitivities!
SUSY Higgs

\[ b(b)φ \rightarrow bbb(b) \]

Associated Production

MSSM Higgs bosons

\[ b\bar{b}\Box(\Box \bar{b}\bar{b}), \Box = h, H, A \]

\[
\begin{array}{c|c|c|c}
\text{Max. mixing} & \text{No mixing} & 1\text{ fb}^{-1} & 2\text{ fb}^{-1} & 4\text{ fb}^{-1} & 8\text{ fb}^{-1} \\
\hline
\text{CDF} & \text{DØ} & \text{DØ} & \text{(DØ 2 fb}^{-1}) & \text{(DØ 4 fb}^{-1}) & \text{(DØ 8 fb}^{-1}) \\
\text{Excluded at LEP} & & & & & \\
\hline
\end{array}
\]

\[ m_A (\text{GeV}) \]

\[ \tan\beta \]

260 pb\(^{-1}\)
SUSY Higgs

\[ b(b)\phi \rightarrow bbb(b) \]

Associated Production

MSSM Higgs bosons

\[ b\bar{b}\phi(\bar{b}b), \phi = h, H, A \]

\( \tan \beta = 40 \sim m_{\text{top}} / m_\phi \)

Excluded at LEP

<table>
<thead>
<tr>
<th>260 pb(^{-1} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>No mixing</td>
</tr>
<tr>
<td>Max. mixing</td>
</tr>
</tbody>
</table>

CDF & DØ

1 fb\(^{-1} \) (DØ 2 fb\(^{-1} \))

2 fb\(^{-1} \) (DØ 4 fb\(^{-1} \))

4 fb\(^{-1} \) (DØ 8 fb\(^{-1} \))

8 fb\(^{-1} \)

Alone

Each, Combined
SUSY Higgs

MSSM Higgs Sector

- Five physical states: $h^0, H^0, A^0, H^\pm$
- Two important parameters: $M_A, \tan \beta = \frac{\nu_{up}}{\nu_{down}}$
- LEP limits: $M_A > 93 \text{ GeV}$ (higher for small $\tan \beta$)
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- $Br(h, H, A \rightarrow b\bar{b}) \approx 90\%$, $Br(h, H, A \rightarrow \tau^+\tau^-) \approx 10\%$

\[ bg \rightarrow \phi b \rightarrow bbb \]
\[ gg \rightarrow \phi bb \rightarrow bbbb \]
\[ gg, bb \rightarrow \phi \rightarrow \tau^+\tau^- \]

Need associated production to cope with QCD backgrounds
More distinctive, use fusion production

Comparable sensitivities!
SUSY Higgs

\[ \phi (h, H, A) \rightarrow \tau^+ \tau^- \rightarrow \mu, e, \text{hadronic} \]

- After cutting on scalar mom. sum and MET:

- Best fit corresponds to \( M_\phi \simeq 160 \text{ GeV} \) and \( \sigma \cdot Br(\phi \rightarrow \tau\tau) \simeq 2 \text{ pb} \)

i.e., \( \tan \beta \simeq 50 \)
While the significance at the best-fit mass exceeds 2\sigma, careful analysis of all channels and all search windows shows that the overall significance of the excess is less than 2\sigma (simply need more data!).

Check with an independent sample?
**SUSY Higgs**

\[ \phi (h, H, A) \rightarrow \tau^+ \tau^- \]

- Expected limit at 160 GeV is 1.7 pb, CDF's most likely value is 2 pb
- Observed limit is 1.2 pb which is within 1 sigma uncertainty band from 1.0 to 2.8 pb
SUSY Higgs

\[ \phi (h, H, A) \rightarrow \tau^+ \tau^- \]

$\mu$

Higgs signal normalized to CDF's most likely value of 2 pb cross section
SUSY Higgs

$\phi (h, H, A) \rightarrow \tau^+ \tau^-$
SUSY Higgs

\[ \phi (h, H, A) \rightarrow \tau^+ \tau^- \]

- \[ \square = +200 \text{ GeV}, M_2 = 200 \text{ GeV}, m_\tilde{g} = 0.8 \, M_{\text{SUSY}} \]
- \[ M_{\text{SUSY}} = 1 \text{ TeV}, X_t = \bar{\tilde{t}} \, M_{\text{SUSY}} \, (m_h^\text{max}); \]
- \[ M_{\text{SUSY}} = 2 \text{ TeV}, X_t = 0 \text{ (no-mixing)} \]

CDF

- \[ m_h^\text{max} \]
- \[ m_h^\text{max} \text{ no mixing} \]

CDF Run II 1 fb\(^{-1}\)

MSSM \[ \square \square \text{ Search} \]

Preliminary
\[ \phi (h, H, A) \rightarrow \tau^+ \tau^- \]

\[ \square = +200 \text{ GeV}, M_2 = 200 \text{ GeV}, m_\tilde{g} = 0.8 M_{\text{SUSY}} \]
\[ M_{\text{SUSY}} = 1 \text{ TeV}, X_t = \sqrt{6} M_{\text{SUSY}} (m_{h_{\text{max}}}); \quad M_{\text{SUSY}} = 2 \text{ TeV}, X_t = 0 \quad \text{(no-mixing)} \]

CDF Observed Exclusion
CDF Expected Exclusion
DØ Observed Exclusion
DØ Expected Exclusion

\[ m_h \]
\[ m_{h_{\text{max}}} \]

Similar sensitivity

CDF Run II 1 fb\(^{-1}\)
MSSM \[ \Box \quad \Box \quad \text{Search Preliminary} \]
SUSY Higgs

\[ \phi (h, H, A) \rightarrow \tau^+ \tau^- \]

Old projections:

- D0 Alone, \( \sim 1 \text{ fb}^{-1} \)
- CDF Alone, \( \sim 1 \text{ fb}^{-1} \)

95% exclusion sensitivity

\[ \tan \beta = 40 \sim \frac{m_{\text{top}}}{m_b} \]
SUSY Higgs

\[ b(b)\phi \rightarrow bbb(b) \]

- \( H/A \rightarrow bb \) swamped by QCD bckg
- Look for \( \geq 3 \) high-pT \( b \) jets
- Signal: invariant mass of two leading jets should peak at \( M_A \)
- Backgrounds (from data):
  - Shape is from the double-b-tagged data sample (taking into account kinematic bias from the 3rd b-tag)
  - Normalized outside the “signal region”

Both experiments working on updates with larger data sets

Understanding multi-\( b \) backgrounds \textit{tough}