Top and $b$-physics at the Tevatron

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for the CDF and DØ collaborations

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The Tevatron at Fermilab

Run I 1992-1995
\[ E_{CM} = 1.8 \text{ TeV} \]
125 pb\(^{-1}\)

Run II
\[ E_{CM} = 1.96 \text{ TeV} \]
> 500 pb\(^{-1}\)

April 2002 - July 2002

Tevatron
CDF
DO
protons
anti-protons
Recycler
Chicago
The CDF and DØ detectors

CDF
- excellent tracking resolution
- particle ID (TOF and dE/dx)
- displaced vertex trigger
- new plug calorimeter $1.6 < |\eta| < 3.6$

DØ
- excellent muon coverage $|\eta| < 2.0$
- new tracking system (Silicon and Fiber Tracker)
- 2 T magnetic field
- impact parameter trigger
Top physics at the Tevatron

- The top quark is the only known fermion with a mass on the electroweak scale:
  - decays as a ‘free quark’
  - may include non-SM contributions in decay
  - $m_W$ and $m_{\text{top}}$ together constrain the Higgs mass

- Discovered in Run I: mass and cross-section, $W$-helicity $\rightarrow$ missing: spin, charge, width

- Run II programme
  - improve previous measurements: mass, cross-section, $W$-helicity and spin-correlations
  - single top
  - branching ratios (non-SM, Higgs)
  - anomalous kinematics (non-SM)
  - resonance production
  - anomalous couplings
Top quark production

In pp-collisions at $\sqrt{s} = 1.96$ TeV, top quarks are mostly produced in pairs:

- 90% single top-production
  - no single top observed (so far)
  - current Run II CDF limits:
    - $\sigma(s+t) < 13.7$ pb @ 95 % CL
    - $\sigma(t$ only) < 8.5 pb @ 95 % CL
Top quark decay

\[ Br(t \rightarrow Wb) \cong 100\% \text{ in the SM} \]

- **dilepton**: Both \( W \) decay via \( W \rightarrow l \nu \) (\( l=\text{e} \) or \( \mu \), \( \sim 5\% \))
- **lepton+jets**: One \( W \) decays via \( W \rightarrow l \nu \) (\( l=\text{e} \) or \( \mu \), \( \sim 30\% \)), the other via \( W \rightarrow q\bar{q} \)

- **all jets**: Both \( W \) decay via \( W \rightarrow q\bar{q} \)

![Pie chart showing the decay modes](chart.png)

- e-e (1/81)
- mu-mu (1/81)
- tau-tau (1/81)
- e-mu (2/81)
- e-tau (2/81)
- mu-tau (2/81)
- e+jets (12/81)
- mu+jets (12/81)
- tau+jets (12/81)
- all jets (36/81)
Top cross section: dilepton channels

very clean, low yield

2 high $p_T$ isolated leptons
($e, \mu$, not $\tau$)
neutrinos: large missing $E_T$
2 high $p_T$ jets (from $b$-quarks)

3 channels:
$ee, \mu\mu, e\mu$

Backgrounds:
$Z \rightarrow l^+ l^-$ (incl. $\tau\tau$)
$WW \rightarrow ee, \mu\mu, e\mu +$ jets (small, but has very toplike signature)
QCD leptons (esp. $\mu$)
Event selection:
- trigger
- missing $E_T > 25$ GeV ($e\mu$) /35 GeV ($ee$, $\mu\mu$)
- isolated leptons, $p_T$ lepton > 15 (20 for $ee$)
- $H_T > 120 /140$ GeV
- 2 or more jets with $p_T > 20$ GeV
- $105$ (110) GeV < $M(ee)$, $(M(\mu\mu)) < 75$ (70)GeV

Combined: $\sigma_{ttbar} = 14.3^{+5.1}_{-4.3} \, (\text{stat}) \,^{+2.6}_{-1.9} \, (\text{syst}) \pm 0.9 \, (\text{lumi}) \, \text{pb}$
Top cross-section: Lepton + jets

“Golden” mode for top studies: ~30% yield and relatively clean

One (and only one) high $p_T$ isolated lepton.

Neutrino: large missing $E_T$

large jet multiplicity ($\geq 3,4$)

**Background:** QCD+multijet
W+multijet

- topological: event shape, $H_T = \Sigma p_T^{jet} + p_T^{W}$
- $b$-tagged: secondary vertex tag
  soft lepton tag
lepton + jets

Event selection:
• lepton trigger
• missing $E_T > 20$ GeV
• $E_T$, $p_t(\mu) > 20$ GeV
• at least 3 jets with $p_t > 15$ GeV and $|\eta| < 2.0$
• at least one $b$-tagged jet
• $H_T = \Sigma E_T + \text{missing } E_T + E_T (p_t(\mu))$
• $H_T > 200$ GeV

$\sigma(t\bar{t}) = 5.6^{+1.2}_{-1.1} \text{ (stat)}^{+1.0}_{-0.7} \text{ (syst)} \text{ pb}$
Top to all jets

\(~45\%\) of all decays, but what a mess!

50\% of all \(tt\rightarrow\)jets have \(\leq 5\) reconstructed jets

but: swamped by background
(QCD hard scatter 2 \(\rightarrow\) 2 parton processes)

6 or more jets (one jet per parton)
no isolated leptons
\(b\)-tagging
event shape

\(\sigma(t\bar{t}) = 7.7^{+3.4}_{-3.3}\) (stat) \(^{+4.7}_{-3.5}\) (syst) \(\pm 0.5\) (lumi)

\(\sigma(t\bar{t}) = 7.8 \pm 2.5\) (stat) \(^{+4.7}_{-2.3}\) (syst) pb
Production Cross-Section Summary

All observed cross sections consistent with each other…

Theory predicts $\sigma(t\bar{t}) = 6.7^{+0.7}_{-0.9} \text{ pb at } m_{\text{top}} = 175 \text{ GeV}$. 
DØ Run I Top Quark Mass Measurement

\[ m_t = 180.1 \pm 3.6 \text{ (stat)} \pm 3.9 \text{ (syst) GeV/c}^2 \]

- Statistical uncertainty reduced from 5.6 to 3.6 GeV/c^2
  \( \rightarrow \) equivalent to a 2.4x larger dataset

The probability for a top (or background) event to give rise to observed jets, leptons andMET is computed.

\( M_{\text{top}} \) is measured by maximizing Poisson likelihood for entire event sample.

**Advantages:**
- all jet permutations contribute
- event-by-event resolutions considered
- non-Gaussian detector response accounted for

**Problems:**
- only leading-order \( \text{tt} \) cross section is used
  \( \rightarrow \) only events with exactly four jets can be used
- gluon fusion diagrams neglected
- only background process computed is \( W + \text{jets} \)

This measurement increases the world-average top mass from 174 ± 5.1 GeV to 178 ± 4.3 GeV

Nature (429, pp. 638-642)
Lepton+ jets:
- template (Run I)
- multivariate
- dynamical likelihood

→ best Run II CDF result so far

\[ M_{\text{top}} = 177.8 \pm 4.5 \text{ (stat.)} \pm 6.2 \text{ (syst.) GeV/c}^2 \]

Systematic error is dominated by modeling of the calorimeter response

improved result for Winter 2005

First Run II DØ mass measurement soon.
**W-helicity in top decays**

- In the SM only left-handed ($W_-$) and longitudinally polarized ($W_0$) are produced.

$$F_0 \equiv \frac{\Gamma(t\rightarrow W_0 b)}{\Gamma(t\rightarrow W_0 b) + \Gamma(t\rightarrow W_+ b)} = \frac{\frac{1}{2}(m_t/m_W)^2}{1 + \frac{1}{2}(m_t/m_W)^2}$$

With $m_t = 175$ GeV

$$F_0 = 0.703$$

**Run I results:**

CDF (2000): $F_0 = 0.91 \pm 0.37$ (stat) $\pm 0.13$ (syst)

DØ (2004): $F_0 = 0.56 \pm 0.32$ (stat + $m_t$) $\pm 0.07$ (syst)
lepton + jets:
$F_0 = 0.88^{+0.12}_{-0.47} \text{ (stat+syst)}$
$F_0 > 0.24 \text{ @ 95 % CL}$

di-lepton:
$F_0 < 0.52 \text{ @ 95 % CL}$
$F_0 < 0.94 \text{ @ 99 % CL}$

combined:
$F_0 = 0.27^{+0.35}_{-0.21} \text{ (stat + syst)}$
$F_0 < 0.88 \text{ @ 95 % CL}$

Updated DØ measurement soon
$b$-physics at the Tevatron

The Tevatron is a $b$-factory:

$$\sigma(pp \rightarrow bb) = 150 \mu b \text{ (at 1.96 TeV)}$$

All types of $B$-hadrons are being produced ($B_d$, $B_s$, $B^{**}$, $\Lambda_b$ etc)

CDF and DØ have a large and varied $b$-physics programme → can only present a limited selection today

- Mixing
- Lifetimes
- Lifetime difference in $B_s \rightarrow J/\Psi \Phi$
- $X$
- $B_s \rightarrow \Phi \Phi$
- $B_{s/d} \rightarrow \mu \mu$
- Pentaquarks

not covered:
- $b$ and quarkonia production
- CP violation
- hadronic moments
- $B_c$
- $B^{**}$
- $B \rightarrow D^{**} X$
- Helicity amplitudes in $B \rightarrow J/\Psi K^*/\Phi$
- etc.
To measure B-mixing:
- proper decay time $c\tau$
- identify $b$-flavour at production
- identify $b$-flavour at decay

Flavour tagging:
- same side tagging: charge of ‘nearby’ track correlated with $b$-quark flavour ($b \leftrightarrow \pi^+$, $b\bar{b} \leftrightarrow \pi^-$)
- opposite side jet charge tagging: sign of $b$-quark $\sim$ sign of momentum weighted sum of particles charges in jet
- opposite side lepton (here: $\mu$) tagging: from semileptonic $b$-decays ($b \leftrightarrow l^-$, $b\bar{b} \leftrightarrow l^+$)

Tagging efficiency $\varepsilon = \frac{N_{\text{tag}}}{N_{\text{tot}}}$
Dilution $D = \frac{N_R - N_W}{N_R + N_W}$
Tag power $= \varepsilon D^2$
Mixing Results from CDF

- exclusive decays
  \( B^0 \rightarrow J/\Psi K^*0 \)
  \( B^0 \rightarrow D^- \pi^+ \)

  \[ \Delta m_d = 0.55 \pm 0.10 \pm 0.01 \text{ ps}^{-1} \]

  world average: \( \Delta m_d = 0.502 \pm 0.007 \)

- semileptonic \( b \)-decays using same side tagging

  \[ \Delta m_d = 0.443 \pm 0.052 \text{ (stat.)} \pm 0.030 \text{ (s.c.)} \pm 0.012 \text{ (syst.)} \text{ ps}^{-1} \]

  \( D_0 = 12.8 \pm 1.6 \text{ (stat.)} \pm 1.0 \text{ (s.c.)} \pm 0.6 \text{ (syst.)} \% \)

  \( D_+ = 28.3 \pm 1.3 \text{ (stat.)} \pm 1.1 \text{ (s.c.)} \pm 1.0 \text{ (syst.)} \% \)

  \( \varepsilon D^2(B^0) = 1.1 \pm 0.3 \text{ (stat.)} \pm 0.2 \text{ (s.c.)} \pm 0.1 \text{ (syst.)} \% \)
Mixing Results from DØ

Semileptonic B-decays:

\[ B \rightarrow D^* \rightarrow D^0 \pi^- \]

\[ D^0 \rightarrow K^+\pi^- \]

opposite-side muon tagging

world average: \( \Delta m_d = 0.502 \pm 0.007 \)

\[ \Delta m_d = 0.506 \pm 0.055 \text{ (stat.)} \pm 0.049 \text{ (syst.)} \text{ ps}^{-1} \]

- Tagging efficiency: 4.8 ± 0.2 %
- Tagging purity, \( \frac{N_R}{N_R+N_W} = 73.0 \pm 2.1 \% \)
- \( \rightarrow D = 46 \% \), \( \varepsilon D^2 = 1.0 \% \)
Run II lifetime measurements

HQET/OPE predict lifetime ratios: \( \tau(B^+)/\tau(B^0_d) = 1.053 \pm 0.016 \pm 0.017 \)

<table>
<thead>
<tr>
<th>( B ) meson</th>
<th>( N(B) )</th>
<th>( \tau(B) ) in ps</th>
<th>PDG 03 in ps</th>
</tr>
</thead>
<tbody>
<tr>
<td>( B^+ \to J/\Psi K^+ )</td>
<td>( \sim 3390 )</td>
<td>( 1.662 \pm 0.033 \pm 0.008 )</td>
<td>( 1.671 \pm 0.018 )</td>
</tr>
<tr>
<td>( B^0 \to J/\Psi K^{*0} )</td>
<td>( \sim 1160 )</td>
<td>( 1.539 \pm 0.051 \pm 0.008 )</td>
<td>( 1.537 \pm 0.015 )</td>
</tr>
<tr>
<td>( B_s \to J/\Psi \Phi )</td>
<td>( \sim 260 )</td>
<td>( 1.369 \pm 0.100^{+0.008}_{-0.010} )</td>
<td>( 1.461 \pm 0.057 )</td>
</tr>
</tbody>
</table>

\( \tau (B^+) / \tau (B^0) = 1.080 \pm 0.042 \) (tot.)

\( \tau (B_s) / \tau (B^0) = 0.890 \pm 0.072 \) (tot.)

Correlated errors

CDF

semileptonic decays

\( \tau(B^+)/\tau(B^0) = 1.093 \pm 0.021 \) (stat) \( \pm 0.022 \) (syst)

DØ

preliminary

updated DØ measurements in exclusive modes \((B_d, B_s, \Lambda_b)\) at ICHEP
Lifetime difference and in $B_s \rightarrow J/\Psi \Phi$ (Method)

$B_s^H = \frac{1}{\sqrt{2}} (|B_s\rangle + |\overline{B_s}\rangle) = CP - odd$

$B_s^L = \frac{1}{\sqrt{2}} (|B_s\rangle - |\overline{B_s}\rangle) = CP - even$

scalar $\rightarrow$ VV decay

$\Rightarrow$ 3 amplitudes

$L = 0$ (even), 1 (odd), 2 (even)
described in \textit{transversity} basis

In $J/\Psi$ restframe:

$K^+K^-$ plane defines $(x,y)$ plane

$K^+$ defines $+y$ direction

$\Theta$, $\Psi$ polar and azimuthal angles of $\mu^+$

$\phi$ in $\Phi$ restframe: angle($K^+$, -$J/\Psi$)
Lifetime difference and in $B_s \rightarrow J/\Psi \Phi$ (Results)

\[ \Gamma = \frac{1}{2} (\Gamma_L + \Gamma_H) \equiv \frac{1}{\tau} \]
\[ \Delta \Gamma = \Gamma_L - \Gamma_H \]

theory:
\[ \frac{\Delta \Gamma}{\Gamma_s} = 0.12 \pm 0.06 \]

CDF Run II Preliminary

\[ \Gamma_s = \frac{1}{2} (\Gamma_L + \Gamma_H) \]

constrained fit
\[ \Gamma_s = \Gamma_d \]

\[ \tau_L = 1.13^{+0.13}_{-0.09} \pm 0.02 \text{ ps} \]
\[ \tau_H = 2.38^{+0.56}_{-0.43} \pm 0.03 \text{ ps} \]

unconstrained fit: \[ \frac{\Delta \Gamma}{\Gamma_s} = 0.65^{+0.25}_{-0.33} \pm 0.01 \]
Belle: \(M_X = 3872.0 \pm 0.6 \text{ (stat)} \pm 0.5 \text{ (sys)} \text{ MeV/c}^2\)

\[
X(3872) \rightarrow J/\Psi \, \pi^+ \pi^- 
\]

| Exp | Lumi [pb\(^{-1}\)] | \(|y| < 1\) | \(|y| < 2\) |
|-----|----------------|------|------|
| CDF | 220            | 3871.3 ± 0.7 ± 0.3 | 730 ± 90 | \(\approx 12\sigma\) |
| DØ  | 230            | 3871.8 ± 3.1 ± 3.0 | 522 ± 100 | \(\approx 5\sigma\) |
X(3872) – Ψ(2S) comparison

Is the X(3872) charmonium, molecule, … ?

θ_π, θ_µ helicity: angle between π(µ) and X in di-π(µ) restframe

|y(J/ψππ)| < 1

Decay Length < 0.01 cm

Similar in decay length and isolation → similar prompt production fraction as Ψ(2S)

No significant differences between ψ(2S) and X have been observed yet.
Charmless $B$-decays: $B_s \rightarrow \Phi \Phi$

First ‘observation’ ($\sigma = 4.7$) at CDF

$$BR(B_s \rightarrow \Phi \Phi) = (1.4 \pm 0.6 \text{ (stat)} \pm 0.2 \text{ (syst)} \pm 0.5 \text{ (BRs)}) \times 10^{-5}$$

You won’t see this at the $b$-factories…..
Rare decays: $B_{s/d} \rightarrow \mu^+\mu^-$

SM prediction: $BR(B_s \rightarrow \mu\mu) = (3.4 \pm 0.5) \cdot 10^{-9}$

$B_d \rightarrow \mu\mu$ suppressed by $|V_{td}/V_{ts}| \approx 4 \cdot 10^{-2}$

CDF Run II limits:

$BR(B_s \rightarrow \mu\mu) < 5.8 \cdot 10^{-7}$ @ 90 % CL

$BR(B_d \rightarrow \mu\mu) < 1.5 \cdot 10^{-7}$ @ 90 % CL

**DØ**

**Sensitivity** @ 95 % CL:

$BR(B_s \rightarrow \mu^+\mu^-) < 9.1 \cdot 10^{-7}$ (stat only)

$BR(B_s \rightarrow \mu^+\mu^-) < 1.0 \cdot 10^{-6}$ (stat+syst)

Box will be opened for ICHEP

~180 pb⁻¹
CDF has performed a search in the following channels:

- $\Theta^+ (uudd\bar{s}) \rightarrow p \, K_s \rightarrow p \, \pi^+ \pi^-$
- $\Theta_c (uudd\bar{c}) \rightarrow D^* \, p \rightarrow D^0 \, \pi^- \, p$
- $\Xi^{0}_{3/2} (ssdu\bar{d}) \rightarrow \Xi^- \, \pi^+ \rightarrow \Lambda \, \pi^+ \, \pi^-$
- $\Xi^{--}_{3/2} (ssdu\bar{u}) \rightarrow \Xi^- \, \pi^- \rightarrow \Lambda \, \pi^- \, \pi^-$

So far CDF has not observed any pentaquark states.
Summary

• The Tevatron integrated luminosity > 500 pb\(^{-1}\)/experiment

• Top
  ▪ Run II luminosity in measurements now exceeds Run I
  ▪ Sophisticated analysis techniques in place
  ▪ Measurement of top properties in progress

• \(b\)-physics
  ▪ Rich programme, not all covered in this talk
  ▪ Competitive and complementary to \(b\)-factories

*** Many more results coming soon ***
Backup Slides
Tagging Tools: Vertexing and Soft Muons

B hadrons in top signal events

Vertex of displaced tracks

Identify low-pt muon from decay

- $b \rightarrow \ell \nu_c$ (BR $\sim 20\%$)
- $b \rightarrow c \rightarrow \ell \nu_s$ (BR $\sim 20\%$)
Lepton+jets: topological

\[ H_T = \Sigma p_T^{jet} + p_T^W \] Highly correlated with the top mass!

Aplanarity \( A = \frac{3}{2} \times \) smallest eigenvalue of the normalized momentum tensor \( M_{ij} \)

\[ M_{ij} = \frac{\sum p_i^o p_j^o}{\sum |\vec{p}^o|^2} \]

Large values of \( A \) indicate spherical (top) events.
DØ: New analysis of Run I Data  

- Rather than a kinematic fit, the probability for a top (or background) event to give rise to observed jets, leptons and MET is computed.

- Also define background probability for each event.

- $M_t$ measured by maximizing Poisson likelihood for entire event sample.

Advantages:

- All jet permutations contribute.
- Additional kinematic information used.
- Event-by-event resolutions considered.
- Non-Gaussian detector response accounted for.

Compromises:

- Only leading-order tt cross section is used.
- Only events with exactly four jets can be used.
- Gluon fusion diagrams neglected.
- Only background process computed is $W +$ jets.

22 events including 10 background

$M_t = 180.1 \pm 3.6 \text{ (stat)} \pm 4.0 \text{ (syst)} \text{ GeV}$
Lepton + jets CDF Run II mass measurements -- methods

**Template Method** (Run I method):
- Kinematic fitter to reconstruct top mass
- Kinematic constraints \( m_t = m_{t\bar{t}} \) etc
- Use best (smallest \( \chi^2 \)) of 12 (4 if double btag) solutions
- One dimensional templates parametrized for top and background as function of top mass

**Multivariate Template Method**:
- Refined kinematic fitter with jet energy scale optimization
- Kinematic constraints
- Best combination, weight according to correct permutation probability
- Multidimensional non-parametric templates

**Dynamical Likelihood Method**:
- Matrix Element Method
- Use all 12 (4) combinations
- Calorimeter transfer functions
Top mass constraint on the Higgs mass
b - Lifetimes

spectator model

Heavy Quark Effective Theory \((m_Q >> \Lambda_{QCD})\) but not top!
Mixing

$B_s (\sim \bar{b}s), \bar{B}_s (\sim b\bar{s})$ are produced in one of the two possible flavour states. This initial state evolves into a time-dependent superposition of the two states according to:

$$i \frac{\partial}{\partial t} \begin{pmatrix} B_q^0(t) \\ \tilde{B}_q^0(t) \end{pmatrix} = \left( M - i \frac{\Gamma}{2} \right) \begin{pmatrix} B_q^0(t) \\ \tilde{B}_q^0(t) \end{pmatrix}$$

$M = \text{mass matrix}$
$\Gamma = \text{decay matrix}$

$\Delta \Gamma_s / \Gamma < 0.52$ at 95% c.l.
$\Delta \Gamma_s / \Gamma_{\text{light}} = 0.26 \ (^{+0.30})$ ALEPH theory: $0.12 \pm 0.06$

$\frac{\Delta m_{B_s}}{\Gamma} > 19.0$ at 95% c.l.

$x_s = \frac{\Delta m_{B_s}}{\Gamma} = 0.755 \pm 0.015$
Rare decays: $B_{s/d} \rightarrow \mu \mu$ – theoretical predictions

**Main contributing Standard Model diagrams**

**Theoretical predictions**

<table>
<thead>
<tr>
<th>l</th>
<th>$BR(B_d \rightarrow l^+ l^-)$</th>
<th>$BR(B_s \rightarrow l^+ l^-)$</th>
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<tbody>
<tr>
<td>$l = e$</td>
<td>$(3.4 \pm 2.3) \cdot 10^{-15}$</td>
<td>$(8.0 \pm 3.5) \cdot 10^{-14}$</td>
</tr>
<tr>
<td>$l = \mu$</td>
<td>$(1.5 \pm 0.9) \cdot 10^{-10}$</td>
<td>$(3.4 \pm 0.5) \cdot 10^{-9}$</td>
</tr>
<tr>
<td>$l = \tau$</td>
<td>$(3.1 \pm 1.9) \cdot 10^{-8}$</td>
<td>$(7.4 \pm 1.9) \cdot 10^{-7}$</td>
</tr>
</tbody>
</table>

**Experimental upper limits (at 90% (95%) confidence level)**

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</tr>
</thead>
<tbody>
<tr>
<td>$l = e$</td>
<td>$&lt; 5.9 \cdot 10^{-8}$</td>
<td>$&lt; 5.4 \cdot 10^{-5}$</td>
</tr>
<tr>
<td>$l = \mu$</td>
<td>$&lt; 1.5(1.9) \cdot 10^{-7}$</td>
<td>$&lt; 5.8(7.5) \cdot 10^{-7}$</td>
</tr>
<tr>
<td>$l = \tau$</td>
<td>$&lt; 2.5%$</td>
<td>$&lt; 5.0%$</td>
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