Recent results from TEVATRON

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for CDF and D0 collaborations

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Particle Physics Phenomenology
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Contents
• Latest Results of Heavy Flavor Physics at \( \sim 0.7 \text{fb}^{-1} \)
  • \( \Delta M_s \) (Search for Bs Oscillations)
  • Bc
  • Top Xs, mass, ttbar resonance
• Search for SM higgs (\( h^0 \rightarrow WW(*) \) at \( \sim 360 \text{pb}^{-1} \))
TEVTRON

- Operating at world’s highest particle energy collisions
  - $\sqrt{s} = 1.8$ TeV
  - Integrated Lum $\sim 110$ pb$^{-1}$
- Run II (2001-present)
  - $\sqrt{s} = 1.96$ TeV
  - Two multi-purpose detectors

![Diagram of the Tevatron with CDF and DØ detectors]
CDF:
- Excellent silicon vertex detector
- Good particle identification (K,π)
- Good momentum and mass resolutions

D0:
- Extended muon coverage
- Good electron identification
- New silicon detector will be installed in March
Integrated luminosity

Record initial luminosity at CDF = $1.8 \times 10^{32} \text{ cm}^{-2}\text{s}^{-1}$

1.5 fb$^{-1}$
RunII Projected Integrated Luminosity

Integrated Luminosity (fb⁻¹)

Start of Fiscal Year

9/29/03 9/29/04 9/30/05 10/1/06 10/2/07 10/2/08 10/3/09

Oct. ’09 8.5fb⁻¹

Jan. ’07 3fb⁻¹

Now

Design

Base

Integrated Luminosity (fb⁻¹)

10fb⁻¹

9

8

7

6

5fb⁻¹

5

4

3

2fb⁻¹

2

1

0

Now
Bs Oscillation
- Unitarity of CKM matrix:

\[ V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0 \]

- Knowledge of both \( B_d \) and \( B_s \) mixing frequencies would provide better constraints on one side of unitarity triangle:

\[ \frac{\Delta m_s}{\Delta m_d} = \frac{m_{B_s}}{m_{B_d}} \frac{f_{B_s}^2 B_{B_s}}{f_{B_d}^2 B_{B_d}} \frac{|V_{ts}|^2}{|V_{td}|^2} = \frac{m_{B_s}}{m_{B_d}} \xi^2 \frac{|V_{ts}|^2}{|V_{td}|^2} \]

New lattice result

\[ \xi = 1.21^{+0.041}_{-0.026} \text{ (} \sim 3\% \text{ uncertainty)} \]
Current $B_s$ Status

- $B_s$ mixing not observed yet
- $B_s$ oscillates more than 30 times faster than $B_d$
- $\Delta m_s > 14.4 \text{ ps}^{-1}(95\%\text{CL})$ with sensitivity of 17.8 ps$^{-1}$
B Mixing Phenomenology

- Neutral B system: $|B_q> = |\bar{b}q>, |\overline{B}_q> = |\bar{b}q>, \quad q = d, s$

- Mass eigenstates:
  \[ |B_H> = \frac{1}{\sqrt{2}}(|B> + |\overline{B}>), \quad |B_L> = \frac{1}{\sqrt{2}}(|B> - |\overline{B}>) \]

- Oscillation frequency of $B_q$ mesons given by $\Delta m_q = M_H - M_L$

- Lifetime difference $\Delta \Gamma = \Gamma_H - \Gamma_L$

- Neglecting $\Delta \Gamma$, mixing probability after time $t$ is given by:
  \[
P_{B \rightarrow \overline{B}} = P_{mix} = \frac{e^{-t/\tau}}{2\tau} (1 - \text{Cos}(\Delta mt))
  \]
  \[
P_{B \rightarrow B} = P_{unmix} = \frac{e^{-t/\tau}}{2\tau} (1 + \text{Cos}(\Delta mt))
  \]
  \[
  A = \frac{P_{unmix} - P_{mix}}{P_{unmix} + P_{mix}} = \text{Cos}(\Delta mt)
  \]
**B_s Candidates**

CDFII Preliminary, 355 pb^{-1}, B_s \rightarrow D_s \pi, D_s \rightarrow \phi \pi

- $\mu^+(\phi \pi^-)$
- $N(D_s)=15636\pm193$
- $N(D_s^0)=4349\pm152$

DØ Run II Preliminary

- $B_s \rightarrow D_s \mu \nu$ (where $D_s \rightarrow \phi \pi$, $K^* K$)
- ~34K semileptonic $B_s$

- $B_s \rightarrow D_s \pi$ (where $D_s \rightarrow \phi \pi$, $K^* K$, $3\pi$)
- $B_s \rightarrow D_s 3\pi$ (where $D_s \rightarrow \phi \pi$, $K^* K$)

- ~1100 fully reconstructed $B_s$
Amplitude Fit Results

D0 Result:
Sensitivity = 9.5 ps$^{-1}$
Exclusion: $\Delta m_s < 7.3$ ps$^{-1}$ @95%CL

CDF Result:
Sensitivity = 13.0 ps$^{-1}$
Exclusion: $\Delta m_s < 8.6$ ps$^{-1}$ @95%CL
New Tevatron results improved the world $\Delta m_s$ limit from 14.5 to 16.6 ps$^{-1}$ @ 95%CL
This plots assume:

- **flavor tagging:**
  - add same-side kaon tagging
  \[ \epsilon D^2 = 1.6 + 3.0\% \]
- **Vertex resolution:**
  - improved by 20%
- **Trigger bandwidth:**
  - utilize 50% of CDF data

**5 \sigma observation:**

- \( L=2 \, fb^{-1} : \Delta m_S < 15 \, ps^{-1} \)
- \( L=8 \, fb^{-1} : \Delta m_S < 22 \, ps^{-1} \)
Bc
**B_c Mass Measurement**

Mass(B_c) = 6275.2 +/- 4.3 +/- 2.3 MeV/c^2

Best in world!

Num(events)_{FIT} = 38.9 sig
26.1 bkg between 6.24-6.3
Significance > 6s
Lattice calculations that show good agreement with experiment were used to predict the mass of the $B_c$

$$M(B_c)_{CDF} = 6275.2 \pm 4.3 \pm 2.3 \text{ MeV}/c^2$$

$$M(B_c)_{LAT} = 6304 \pm 12^{+18}_{-0} \text{ MeV}/c^2$$
$\sigma_{t\bar{t}}$
Why is the top quark so interesting ...

- Top mass is a fundamental parameter
- Unexpectedly huge mass: $y_t = \sqrt{2} \frac{M_t}{v} \sim 1$
  - Special role in the dynamics of EWSB?
- Due to its huge mass, Decays before hadronizing
  - Passes momentum and spin info to its decay products
Top Quark Production & Decay

✓ Produce in pairs via strong interaction

At $\sqrt{s}=1.96 \text{ TeV}$:
- 85% $qq$
- 15% $gg$

✓ Decay singly via electroweak interaction $t\rightarrow W^+b$

Final state characterized by number and type of charged leptons

$t\bar{t} \rightarrow W^+bW^-\bar{b}$ final states
Lepton+jets cross section

- Neural Network
- Topological/kinematical analyses

CDF Preliminary (760 pb$^{-1}$)

$\sigma = 6.0 \pm 0.6 \text{ (stat)} \pm 0.9 \text{(syst)} \text{ pb}$

CDF RUN II Preliminary (695 pb$^{-1}$)

$\sigma = 8.2 \pm 0.6 \text{ (stat)} \pm 1.0 \text{(syst)} \text{ pb}$

with $\geq1$ b-tag with HT $>200$ GeV
Cross Section in Dilepton channel

\[ \sigma = 8.3 \pm 1.5 \text{ (stat)} \pm 1.0 \text{ (syst)} \pm 0.5 \text{ (lumi)} \text{ pb} \]
Top Quark Pair Production: Summary

- **Dilepton**
  - \( L = 750 \text{ pb}^{-1} \)
  - \( 8.3 \pm 1.5 \pm 1.0 \pm 0.5 \)

- **Lepton+Jets: Kinematic ANN**
  - \( L = 760 \text{ pb}^{-1} \)
  - \( 6.0 \pm 0.6 \pm 0.9 \pm 0.3 \)

- **Lepton+Jets: Vertex Tag**
  - \( L = 695 \text{ pb}^{-1} \)
  - \( 8.2 \pm 0.6 \pm 0.9 \pm 0.5 \)

- **Lepton+Jets: Soft Muon Tag**
  - \( L = 193 \text{ pb}^{-1} \)
  - \( 5.3 \pm 3.3 \pm 1.3 \pm 0.3 \)

- **MET+Jets: Vertex Tag**
  - \( L = 311 \text{ pb}^{-1} \)
  - \( 6.1 \pm 1.2 \pm 1.4 \pm 0.4 \)

- **All-hadronic: Vertex Tag**
  - \( L = 311 \text{ pb}^{-1} \)
  - \( 8.0 \pm 1.7 \pm 3.3 \pm 0.5 \)

- **Combined**
  - \( L = 760 \text{ pb}^{-1} \)
  - \( 7.3 \pm 0.5 \pm 0.6 \pm 0.4 \)
Top Mass
Top mass relation to Higgs

- Top quark mass is a fundamental parameter of SM
- Radiative corrections to SM predictions dominated by top mass
- Together with W mass places a constraint on Higgs mass

\[ \Delta M_W \propto M_t^2 \quad \Delta M_W \propto \ln M_H \]
Template Method

- Constrain $m(jj) = m_W$ and $m(\ell \nu b) = m(jjb)$
  - 24 possibilities for 0 b-tags
  - 12 possibilities for 1 b-tag
  - 4 possibilities for 2 b-tags
- Select configuration with best $\chi^2$ fit -> obtain $M_{\text{reco}}$

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2005 Novelty: Jet Energy Calibration in situ
Simultaneous fit to to invariant mass of $W \to jj$
Global JES factor used to correct energies of jet
Reduces systematic uncertainty
CDF $M_{\text{top}}$ Measurement in Lepton+Jets

$m_{\text{top}} = 173.4 \pm 2.5_{\text{(stat)}} \pm 1.3_{\text{(syst)}} \text{GeV} / c^2$

Up to date the best single measurement in the world!
Expect significant reduction in JES uncertainty with more data
Will be able to achieve 1.5 GeV uncertainty on top mass!
Mtt resonance
Previous Measurements

- Lepton + jets:
  - Observed quite intriguing excess around 500 GeV
  - Had a similar although smaller excess in Run 1

D0 searches

Lepton + jets:

No similar anomaly seen in D0 data


Excluded with 95%CL

\[ M_{Z'} < 680 \text{ GeV} \]

\[ (\Gamma_{Z'} = 0.012M_{Z'}) \]
Latest CDF measurement (682pb⁻¹)

An excess has washed out!
SM Higgs in $h^0 \rightarrow WW^{(*)}$
SM Higgs in $h^0 \rightarrow WW(*)$

- At Tevatron, single neutral $h^0$ is dominant Higgs production
- $h^0 \rightarrow WW$ is dominant decay for $M_{Higgs} > 135$ GeV/$c^2$

Use $W \rightarrow ev$ and $W \rightarrow \mu v$ decay modes

Use azimuthal angle between 2 leptons to separate $h^0 \rightarrow WW$ from dominant SM background of WW production

New result with 360 pb$^{-1}$
SM Higgs in $h^0 \rightarrow WW(*)$

**Tevatron Run II Preliminary**

Cross-Section $\times$ BR (pb)

- $WH \rightarrow e\nu bb$
  - D0 382 pb$^{-1}$
- $ZH \rightarrow \nu\nu bb$
  - CDF 289 pb$^{-1}$
- $H \rightarrow WW \rightarrow l\nu l\nu$
  - D0 261 pb$^{-1}$
  - D0 299-325 pb$^{-1}$
- $WH \rightarrow WWW$
  - D0 363-384 pb$^{-1}$
  - CDF 319 pb$^{-1}$
  - CDF 360 pb$^{-1}$
- $ZH \rightarrow v\nu bb$
- $WH \rightarrow l\nu bb$
  - CDF 319 pb$^{-1}$

$95\%$ CL limits on Cross-section $\times$ BR

Standard Model Cross-section $\times$ BR

$m_H$ (GeV)
Conclusion

- CDF experiment is operating well. Better than ever!
- Results with $L \sim 0.7\text{fb}^{-1}$ are now arriving at TEVATRON.
- **Watch out for interesting results with $\geq 1\text{fb}^{-1}$ in 2006!**
Backup
Mixing Analysis Overview

- Mixing analysis ingredients:
  - Event selection
  - Signal reconstruction
  - Decay time
  - B flavor at decay
  - B flavor at production inferred through flavor tagging:
    - lepton tags
    - jet charge tags

- Statistical significance of $\Delta m_s$ measurement:

$$\frac{\sqrt{\varepsilon D^2}}{2} \frac{S}{\sqrt{S+B}} e^{-\left(\Delta m_s \sigma_{\ell}\right)^2/2}$$
Amplitude Scan Method

- Introduce Fourier coefficient $A$ (amplitude)
- Fix $\Delta m$ at different test values and fit for $A$:
  
  $A \approx 1$ for true value of $\Delta m$
  $A \approx 0$ away from true value

(Moser et.al., NIMA 384 491)

\[
\frac{e^{-t/\tau}}{\tau} (1 \pm A \times \cos(\Delta m_s t))
\]

- Test amplitude method on $B^0$ oscillations by scanning for $\Delta m_d$ in hadronic modes
   - points: $A \pm 1\sigma$
   - yellow band: $A \pm 1.645\sigma$
   - dotted line: $1.645\sigma$
- Yellow band bellow 1 $\rightarrow$ exclusion at 95% CL
Extract DG from B_s → K+ K- Lifetime

- Measurement of B_s → K^+K^- lifetime (\(=\tau_L\)) in 360pb\(^{-1}\)
- Mass fit as in BR and CP measurements
- Lifetime fit:
  - Extraction of \(\Delta \Gamma/\Gamma\) (CP)
  - This measurement gives \(c\tau_L = 458 \pm 24 \pm 6 \mu\text{m}\)
  - HFAG average gives weighted average: \((\tau_L^2 + \tau_H^2) / (\tau_L + \tau_H)\)
  - Extract \(\tau_H\)
  - Thus derive \(\Delta \Gamma/\Gamma = -0.080 \pm 0.23 \text{ (stat)} \pm 0.03 \text{ (syst)}\)
Semileptonic $B_s$ Signals

- Missing neutrino → cannot see $B_s$ mass peak
- Use $D_s$ mass peak and (lepton, $D_s$) charge correlation:
  \[ l^+D^- \ - \ \text{right sign combination} \]
  \[ l^-D^- \ - \ \text{wrong sign combination} \]

- Decay modes:
  \[ D_s \to \phi \pi \ (4355 \pm 94) \]
  \[ D_s \to K^*K \ (1750 \pm 83) \]
  \[ D_s \to 3\pi \ (1573 \pm 88) \]

- Total of 7000 $B_s$ candidates but ~20% come from “Physics backgrounds”:
  \[ B^0/+ \to D_s D \]
  \[ B_s \to D_s \tau \quad (D / \tau / D(s) \to \text{lepton } X) \]
  \[ B_s \to D_s D(s) \]
Semileptonic $B_s$ Signals (cont)

$D_s \rightarrow K^*K \ (1750 \pm 83)$

$D_s \rightarrow 3\pi \ (1573 \pm 88)$
• CDF projections were made ~ 1 year ago: “current” = Spring 2005
• Goal is to reach “stretched” by Summer 2006
• At “stretched”, CDF will be probing SM region at 3-sigma level
**B_c Lifetime**

- B_c lifetime extracted from B_c → J/ψ e ν sample

![CDF Run 2 Preliminary: ~360 pb^{-1}]

- More stat than hadronic mode
- But also more background too

- B_c lifetime measured with J/ψ + e channel
  
  \[ 0.474 \pm 0.074/-0.066 \pm 0.033 \text{ ps (Best in the world)} \]

- Theoretical prediction: \( 0.55 \pm 0.15 \text{ ps} \)
Top Mass: Summary (up to ~360 pb$^{-1}$)
Top Charge

Is it the Standard Model top?

W.-F. Chang et al., Phys. Rev. D 59, 091503 (1999), (hep-ph/9810531) proposes an exotic doublet of quarks \((Q_1, Q_4)_R\) with charges \((-1/3, -4/3)\) and \(M \sim 175\) GeV

- Right-handed b quark mixes with the isospin +1/2 component
- \(M_{\text{top}} \sim 274\) GeV escaped detection
- \(q = -4/3\) is consistent with EW data, new b-couplings improve the EW fit (E. Ma et al., hep-ph/9909537)
Top Quark Charge Measurement

Lepton+jets, double b-tag events

Determine:

- charge of W (lepton)
- pairing between W and b ($\chi^2$ fit)
- flavor of b-jet

Jet Charge:

$$Q_{\text{jet}} = \frac{\sum q_i p_{T_i}^{0.6}}{\sum p_{T_i}^{0.6}}$$
(sum over tracks within a jet)

$$Q_{\text{top}, 1} = | q_l + q_{b(l)} |$$
$$Q_{\text{top}, 2} = | - q_l + q_{b(j)} |$$

Perform likelihood ratio test:

Excluded $Q=4/3$ with 94%CL
Top Lifetime

- Within the SM $\tau_{\text{top}} \sim 10^{-24}$ s
- Long-lived top?
- Use $d_{0}$-lepton impact parameter with respect to beamline
- Determine detector resolution from

$$ \gamma^0 / \gamma \rightarrow e^+e^- / \mu^+\mu^- $$

![Graph showing $d_{0}$-lepton impact parameter distribution]

- Fit combination of signal/BG templates to the data: lepton+jets with $\geq 1$ b-tag

$c\tau < 52.5 \, \mu m$ with 95% CL