QCD and B and charm Physics at the Tevatron

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On behalf of the CDF and DØ Collaborations
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Overview

- Introduction
- Recent QCD results
  - Inclusive jets (DØ)
  - γ+b, γ+c jets (DØ, CDF)
- Heavy quark (b and c) physics
  - Fragmentation (CDF)
  - CP asymmetries in B and D physics (CDF)
  - Rare decays and new states (DØ, CDF)
  - Lifetimes (DØ)
- Summary
Tevatron Collider

- The Tevatron Collider ran from 1985 to 2011 (with intervals of fixed-target running and upgrades)
- Run 2 covers the years from 2001 to 2011
- In Run 2 proton-antiproton collisions occurred at center of mass energy 1.96 TeV
- \( \approx 10 \text{ fb}^{-1} \) luminosity was recorded for each experiment
- This is a large and well-understood dataset
CDF and DØ Experiments

- The focus today will be on recent CDF and DØ measurements that satisfy one or more of the following:
  - Use the entire \(~10 \text{ fb}^{-1}\) dataset
  - Update previous results
  - Are significant new results in the areas of QCD or B and charm physics

- Take advantage of:
  - The p-pbar initial state
  - Higher luminosity and statistics
  - Specialized triggers
  - New analysis techniques
  - Improved understanding of the detectors and errors
QCD PHYSICS
The QCD analyses are primarily concerned with:

- Parton Distribution Functions (pdfs)
- Tests of QCD calculations (LO, NLO, NNLO, etc.)
- Higher precision and new kinematic regions
- Rarer processes only accessible now with larger datasets
- Processes where p-pbar allow for interesting and potentially unique measurements
- Many of the QCD analysis involve heavy quarks, and some of the heavy quark analyses have natural connections to QCD and fragmentation.
QCD Inclusive Jets

- Inclusive jets with:
  
  \[-2.4 < \eta < 2.4, 50 \text{ GeV} < p_T < 600 \text{ GeV}\]

- Probe of parton distributions and qq, qg and gg subprocesses in \(p\bar{p}\) collisions.
  
  - Contributions depend on the \(p_T\) of the jets (\(x_T\) of partons)
  
  - Measurements are sensitive to high \(x\) gluon distributions

- Agreement with CTEQ6.5M and MRST2004 pdf's is seen.

- PRD 85, 052006 (2012)

\[x_T = \frac{2p_T}{\sqrt{s}}\]
\( \gamma + b \) jets

- **DØ analysis uses 8.7 fb\(^{-1}\)**
- **Contributions from Qg\( \rightarrow \gamma Q \) (Compton) and qq\( \rightarrow \gamma qq \) (annihilation)**

  - **Probe of quark and gluon distributions in the proton**

  - **Select central (|y|<1.0) and forward (1.5<|y|<2.5) photons.**
  - **The differential cross section is measured as a function of photon p\(_T\).**
  - **NLO QCD predictions show good agreement with data up to p\(_T\) < 70 GeV. Higher order QCD corrections are required at higher p\(_T\).**
γ + b jets, γ + c jets

Luminosity 9.1 fb$^{-1}$

$30 < E_T^\gamma < 300, |y^\gamma| < 1.0$

$E_T^{jet} > 20, |y^{jet}| < 1.5$

Fits to b, c, light quark jet fractions are made using templates from MC simulation.

Cross sections for γ+b and γ+c events are measured, taking into account efficiencies, unfolding, and other effects.
The NLO calculations match the data at low $E_T$, but fall below the data at high $E_T$, showing the need for higher order terms.

- Similar conclusion to the DØ results in $\gamma+b$ jets.
- CDF Public Note 10818
Heavy Quark Physics

• Heavy Quark Physics
  - The study of heavy quark physics in p-pbar collisions provides valuable insight to HEP.
  - In particular, beyond standard model physics at higher energy scales can be accessed using low-energy, well-predicted flavor observables.
  - This talk will cover just a few results in the areas of:
    • Fragmentation
    • CP asymmetry
    • Decay modes
    • Lifetimes
Quark fragmentation using K in association with $D_s^+ / D^+$

- A study of fragmentation looking at the charged K of same and opposite sign associated with $D^+$ and $D_s^+$
  - Expect to see differences in rates of opposite-sign and same-sign K

- $\sim 260,000 D_s^+$ and $140,000 D^+$ decaying to $KK\pi$. The impact parameter distribution was used to separate prompt $D_s^+/D^+$ from $D_s^+/D^+$ from B decays.

- The results show expected qualitative behavior of opposite and like-sign K rates as a function of $K_{pT}$.
Quark fragmentation using $K$ in association with $D_s^+/D^+$

Big difference between $D_s$ (left) and $D$ (right) in opposite sign $K$ production.

Agrees with models

$D_s$ and $D$ similar in same sign $K$ production

Disagrees with fragmentation models

- Valuable input for further tuning of models.

CDF Public Note 10704
CP Asymmetry in Heavy Quark Decay:
$\Delta A_{cp}(D^0\rightarrow hh)$

- CDF measured $A_{cp}(D^0\rightarrow KK)$ and $A_{CP}(D^0\rightarrow \pi\pi)$, as well as the difference in the two quantities, $\Delta A_{cp}(D^0\rightarrow hh)$ in 5.9 fb$^{-1}$
  - $A_{cp}(D^0\rightarrow KK) = [-0.24 \pm 0.22(\text{stat}) \pm 0.10(\text{sys})] \%$
  - $A_{CP}(D^0\rightarrow \pi\pi) = [0.22 \pm 0.24(\text{stat}) \pm 0.11(\text{sys})] \%$
  - $\Delta A_{cp}(D^0\rightarrow hh) = [-0.46 \pm 0.31(\text{stat}) \pm 0.12(\text{sys})] \%$

(PRD 85, 012009 (2012))

- The analysis for $\Delta A_{cp}$ has been updated with the full Run 2 dataset
- The event selection is relaxed due to cancellation of systematics in the difference measurement, leading to more signal events
- $D^0$ flavor is determined by the $D^*\rightarrow D^0\pi_s$ decay
- Detector effects are canceled by using the difference of raw asymmetries of the KK and $\pi\pi$ decays:

$\Rightarrow \Delta A_{cp} = A(KK^*)-A(\pi\pi^*) = A_{cp}(K^+K^-)-A_{cp}(\pi^+\pi^-)$
Δ$A_{cp}(D^0\rightarrow hh)$

CDF Run II Preliminary

- ~550K $D^*$ tagged $D^0\rightarrow \pi^+\pi^-$
- ~1.21M $D^*$ tagged $D^0\rightarrow K^+K^-$
- Fits were used to extract the signal, BG, and multibody decays.
- $A(\pi\pi^*) = (-1.71\pm0.15)\%$
- $A(KK^*) = (-2.33\pm0.14)\%$
  - (Raw quantities)

$\Delta A_{cp} = [-0.62\pm0.21\pm0.10]\%$

2.7σ different from 0

CDF public note 10784

This result is a confirmation of LHCb measurement:

$\Delta A_{cp} = [-0.83\pm0.21\pm0.11]\%$
$A_{cp}$ in $D^0 \rightarrow K_s \pi \pi$

- $A_{cp}$ is also measured in CDF in $D^0$ decay to $K_s \pi \pi$
  - Standard Model expectations $\sim 10^{-6}$
- $D^*$ tag is used to determine $D^0$ flavor
- Two methods are used:
  - A full Dalitz fit using the isobar model
  - A model independent bin-by-bin comparison of $D^0$ and $D^0$-bar plots.
- From the fits $A_{cp}$ is extracted
$A_{cp}$ in $D^0\to K^0\pi\pi$

- Resonance substructure (amplitude and phases) are measured
  - No evidence for CP violation is found in any sub resonance, with resolutions better than previous experiments.
- A model-independent difference bin-by-bin subtraction is also measured
- Integrating over all modes:
  - $A_{cp} = -0.0005 \pm 0.0057 \pm 0.0054$
  - Assuming no direct CP asymmetry one can derive:
    - $A_{cp}^{ind} = -0.0002 \pm 0.0025 \pm 0.0024$
$B \rightarrow \mu^+\mu^-$

- Processes involving FCNC are an excellent way to search for new physics
- SM predictions: $\text{BR}(B_s \rightarrow \mu^+\mu^-) = (3.2 \pm 0.2) \times 10^{-9}$, $\text{BR}(B_d \rightarrow \mu^+\mu^-) = (1.0 \pm 0.1) \times 10^{-10}$
- CDF published results using 7 fb$^{-1}$ (PRL 107, 191801 (2011))
  - $\text{BR}(B_d \rightarrow \mu^+\mu^-) < 6.0 \times 10^{-9}$ at 95% C.L.
  - $\text{BR}(B_s \rightarrow \mu^+\mu^-) = 1.8^{+1.1}_{-0.9} \times 10^{-8}$
- The CDF analysis was extended to full Run 2 dataset (9.7 fb$^{-1}$)
  - No change to analysis methods
  - NN to discriminate signal from background
  - Normalize to $\text{BR}(B^+ \rightarrow J/\psi K^+)$:
B→μ+μ−

- The challenge is to reject a large background while keeping most of the signal.
- 14 discriminating variables were used to build an optimized neural net classifier to separate signal from background.
- Combinatorial background is estimated from mass sidebands.
- Fake muon background estimated from B→hh and D→Kπ.

CDF Preliminary 9.7 fb⁻¹
$B_s \rightarrow \mu^+\mu^-$

**Results:**

- $\text{BR}(B_d \rightarrow \mu^+\mu^-) < 4.6 \times 10^{-9}$ (95% CL)
- $\text{BR}(B_s \rightarrow \mu^+\mu^-) = (1.3^{+0.9}_{-0.7}) \times 10^{-8}$
- $0.8 \times 10^{-9} < \text{BR}(B_s \rightarrow \mu^+\mu^-) < 3.4 \times 10^{-8}$ (95% CL)
- $\text{BR}(B_s \rightarrow \mu^+\mu^-) < 3.1 \times 10^{-8}$ (2.7× 10^{-8})

95% (90%) CL

CDF publication is in preparation

Getting closer to a measurement of the $B_s \rightarrow \mu\mu$

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Using the full Run 2 dataset CDF measures the ratio:

\[ R = \frac{f_s \times BR(B_s \rightarrow J/\psi \phi)}{f_d \times BR(B^0 \rightarrow J/\psi K^*)} \]

Selection is optimized by maximizing \( S/\sqrt{S+B} \).

A binned log likelihood fit is made to signal shape templates and background functions:

\(~11,000 ~ J/\psi\phi\)
\(~57,000 ~ J/\psi K^*\)

Final result, corrected for acceptance:

\[ R = 0.239 \pm 0.003 \pm 0.019 \]

Using CDF \( f_s/f_d \) and PDG \( BR(B^0 \rightarrow J/\psi K^*) \) we can extract:

\[ BR(B_s \rightarrow J/\psi \phi) = (1.18 \pm 0.02 \pm 0.09 \pm 0.14 \pm 0.05) \times 10^{-3} \]

- World’s best measurement.
The fits to $B_s \rightarrow J/\psi \phi$ and $B_s \rightarrow J/\psi K^*$ are performed in 4 $p_T$ ranges

- $f_s/f_d(p_T)$ can be extracted using Belle's latest $BR(B_s \rightarrow J/\psi \phi)$
- This is the first measurement of $f_s/f_d$ as a function of $p_T$.
- Averaging over all $p_T$: $f_s/f_d = 0.254 \pm 0.003 \pm 0.020 \pm 0.044$
- More generally, the CDF measurement of $f_s/f_d$ is a function of $BR(B_s \rightarrow J/\psi \phi)$ and is shown below.

**CDF Run II Preliminary, 9.6 fb$^{-1}$**

- **Statistic Uncertainty**
- **Systematic Uncertainty**
- **Correlated Uncertainty**
- $f_s/f_d$, PDG value

**CDF II measurement**
- **Uncertainty**
- **Belle BR($B_s \rightarrow J/\psi \phi$)**
- **PDG $f_s/f_d$**

$$BR(B_s \rightarrow J/\psi \phi) = (3.17 \pm 0.30) \times 10^{-4}$$
CDF has measured the BR’s of $B_s$ decays:

- $(B_s \rightarrow D_s^+ D_s^-)$, $(B_s \rightarrow D_s^{*+} D_s^0)$, $(B_s \rightarrow D_s^{*+} D_s^{*-})$
  - where: $(D_s \rightarrow \phi \pi)$, $(D_s \rightarrow K^0 K)$

- These measurements may provide information on $\Delta \Gamma_s$
- A neural net is used to separate signal and background contributions.
- The final sample contains $\sim 750$ $B_s \rightarrow D_s^{(*)} D_s^{(*)}$ decays
- A simultaneous fit is made to $B_s$ and $B_d$ decays to separate the decay contributions. BR’s were normalized to well-measured $B_d \rightarrow D_s D$ BR’s.
  - The fitting procedure accounts for partially reconstructed $D_s^{*}$ decays in the fit using mass shapes.
$B_s \rightarrow D_s^{(*)+} + D_s^{(*)-}$

- World’s best measurements of the BR’s.
- Published in PRL 108, 201801 May 14, 2012
- $\text{Br}(B^0_s \rightarrow D^+_s D^-_s) = (0.49 \pm 0.06 \pm 0.05 \pm 0.08)\%$
  $\text{Br}(B^0_s \rightarrow D^{*-}_s D^{*+}_s) = (1.13 \pm 0.12 \pm 0.19 \pm 0.09)\%$
  $\text{Br}(B^0_s \rightarrow D^{(*)+}_s D^{(*)-}_s) = (1.75 \pm 0.19 \pm 0.17 \pm 0.29)\%$
  $\text{Br}(B^0_s \rightarrow D^{(*)+}_s D^{(*)-}_s) = (3.38 \pm 0.25 \pm 0.30 \pm 0.56)\%$

- Values are lower than but consistent with recent Belle result.
- These provide important constraints for indirect searches for new physics.
This measurement uses the full Run 2 dataset: 10.4 fb-1

- Require a 4 track vertex, where the $\mu^+\mu^-$ consistent with $J/\psi$, and $1.35 < M(K^+K^-) < 2.0$ GeV

- MC templates used to separate contributions from $(J/\psi f_2'(1525))$, $(J/\psi \phi)$, $(J/\psi K_2^*(1430))$, $(J/\psi K^0*(1430))$,

- Fitting is done as a function of $K^+K^-$ mass to extract the $f_2(1525)$ contribution. Contributions from $K^0*(1430)$ and $f_2'(1525)$ are seen.
$B_{s}^{0} \rightarrow J/\psi f_{2}^{'}(1525)$

- Spin of $K^{+}K^{-}$ is studied and is consistent with a combination of spin 0 and spin 2 and is inconsistent with spin 1.

- $R = \frac{BR(B_{s} \rightarrow J/\psi f_{2}^{'}(1525))}{BR(B_{s} \rightarrow J/\psi \varphi)} = 0.22 \pm 0.05 \pm 0.04$

- $R(LHCb) = 0.26 \pm 0.027 \pm 0.024$
$\chi_b \rightarrow \Upsilon(1S) + \gamma$

$\Upsilon$ candidates in the mass range $9.1 < M < 9.7$ are combined with photons identified by their conversions into $e^+e^-$ pairs.

3 peaks in the mass difference $M_{\mu\mu\gamma} - M_{\mu\mu}$ are seen corresponding to $\chi_b(1P)$, $\chi_b(2P)$ and a new state with significance $5.6\sigma$, consistent with a state seen by ATLAS.

$M_{\text{new state}} = 10.551 \pm 0.014 \pm 0.017$

arXiv:1203.6034 (Submitted to PRD RC)

ATLAS: $M = 10.530 \pm 0.005 \pm 0.009$

(PRL 108, 152001 (2012))
Λ_b Lifetime

- Λ_b lifetime is a puzzle, measurements don’t agree, deviations from predictions.
  - New measurements are needed to help resolve the mystery.
- New DØ analysis of the Λ_b lifetime
- Uses full Run 2 Dataset – 10.4 fb⁻¹
- This analysis measures lifetimes in two similar decay modes:
  - Λ_b→J/ψΛ, B⁰→J/ψK_s⁰
- Separate fits to both Λ_b and B⁰ lifetimes in topologically similar decays
**Final fit results:**
- $\tau(\Lambda_b) = 1.303 \pm 0.075 \pm 0.035$ ps
- $\tau(B^0) = 1.508 \pm 0.025 \pm 0.043$ ps
- $\tau(\Lambda_b)/\tau(B^0) = 0.864 \pm 0.052 \pm 0.033$

- arXiv:1204.2340, accepted by PRD
- Compare to other values (2011):
  - $\tau(\Lambda_b) = 1.425 \pm 0.032$ ps (PDG 2011)
  - $\tau(\Lambda_b) = 1.537 \pm 0.045 \pm 0.014$ ps (CDF, PRL 106, 121804 (2011))

- There remains disagreement among the measurements in the value of $\tau(\Lambda_b)$
  - Puzzle is not yet resolved
Summary and Prospects

• DØ and CDF have new and important results on many areas of QCD and heavy quark physics.
  – Many results are world’s best or the only measurements of these quantities.
• Both experiments continue analysis of the full Run 2 dataset.
• The emphasis will be on higher precision and use of the unique capabilities of the Tevatron datasets.
• You can expect to see important and interesting results for some time to come.
Z + b jets

- Full CDF Run 2 dataset is used (9.1 fb-1)
- Z\(\rightarrow\mu\mu\) and Z\(\rightarrow\)ee events are selected using an ANN
- Templates are used to fit b jet, c jet and light jet contributions
- Total Z+b jet cross section is normalized to Z+inclusive jets and Inclusive Z events
- The results for the differential cross section is calculated and agrees with MCFM NLO calculations

\[
R = \frac{\sigma(Z\rightarrow ll + b \text{ jets})}{\sigma(Z \rightarrow ll)} = \frac{A_Z^{MC}}{A_{Z+b\text{jet}}^{MC}} \cdot \frac{N_{Z+b\text{jet}}^{data}}{N_Z^{data}}
\]
$Z + b$ jets

CDF Run II Preliminary

\[ \frac{1}{\sigma_Z} \cdot \frac{d\sigma_{Z+b\text{-jet}}}{dp_T} \text{ [GeV/c]}^{-1} \]

\[ \frac{Z/\gamma^* \rightarrow l^+ l^- \pm 1 \text{ b-jet}}{p_T} \]

- $\sigma(Z+b\text{-jet})/\sigma(Z) = [0.261 \pm 0.023 \pm 0.29]\%$
- $\sigma(Z+b\text{-jet})/\sigma(Z) = 0.23\%$ (NLO + MCFM, $Q^2=m_Z^2+p_{T,Z}^2$)
- $0.29\%$ (NLO + MCFM, $Q^2<p_{T,jet}^2$)

CDF Data - 9.13 fb\(^{-1}\)

Systematic uncertainties

NLO MCFM $Q^2=m_Z^2+p_{T,Z}^2$
MSTW 2008 NLO PDF
Corrected to hadron level

CDF

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• Analysis uses full CDF dataset
• Neural-net used to separate signal and background
• ~11,000 $J/\psi\phi$ events are analyzed
• A Likelihood fit was used to extract parameters:
  - $\Delta \Gamma_s$ and $\beta_s^{J/\psi\phi}$
CDF update of $\beta_s^{J/\psi\phi}$ measurement

The confidence interval of $\varphi_s$ is measured to be $[-0.60, 0.12]$ rad at 68% CL, in agreement with the CKM value and recent LHCb and DØ values.
$Z/\gamma*$ + jets

- Full CDF Run 2 dataset (9.4 fb-1)
- Jets are reconstructed using midpoint algorithm with $R=0.7$ and $p_T\text{jet}>30\text{ GeV}$ and $|y_{\text{jet}}|<2.1$
- $Z/\gamma*\rightarrow\mu\mu$ or $ee$
- Backgrounds estimated using MC and data-driven techniques

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**Figure:**

CDF Run II Preliminary

$Z/\gamma*(\rightarrow e^+e^-) + \geq1\text{ jet}$

$Z/\gamma*(\rightarrow \mu^+\mu^-) + \geq1\text{ jet}$

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<th>$M_{Z\rightarrow ll} \text{[GeV/c}^2\text{]}$</th>
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Data - 9.43 fb$^{-1}$

Total Prediction

- $Z\gamma$
- QCD, W + jet
- $t\bar{t}$
- ZZ, ZW, WW
- $Z \rightarrow \tau\tau + \text{jet}$

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$Z/\gamma*(\rightarrow \mu^+\mu^-) + \geq1\text{ jet}$

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Data - 9.44 fb$^{-1}$

Total Prediction

- $Z\gamma$
- QCD, W + jet
- $t\bar{t}$
- ZZ, ZW, WW
- $Z \rightarrow \tau\tau + \text{jet}$

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• Results are unfolded to hadron level and compared to several theoretical predictions
• Comparisons are made with theory.
\[ \Delta A_{cp}(D^0 \rightarrow hh) \]

- Result:

\[ \Delta A_{cp} = [-0.62 \pm 0.21 \pm 0.10] \% \]

2.7\( \sigma \) different from 0

CDF public note 10784

Using the equation:

\[ A_{cp} = A_{cp}^{dir} + \langle \tau \rangle / \tau A_{cp}^{ind} \]

One can plot:

\[ \Delta A_{cp}^{dir} \text{ vs } A_{cp}^{ind} \]

This result is a confirmation of LHCb measurement:

\[ \Delta A_{cp} = [-0.83 \pm 0.21 \pm 0.11] \% \]

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