Searches for BSM physics using flavor transitions at the Tevatron

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on behalf of the CDF and D0 collaborations
A matter of Flavor

- Generic new couplings could introduce new sources of flavor/CP violation.
- If NP scale above LHC reach, flavor might be the only way to probe it.

in this talk: **NEW** Tevatron results for winter 2012

Bs mixing
- ✔ CPV in Bs mixing with whole CDF RunII dataset
- ✔ CDF Measurement of Bs→Ds(*)Ds(*)branching ratios

Rare B decays
- ✔ searches for B → μ⁺μ⁻ with whole CDF RunII dataset

CPV in Charm
- ✔ CPV in D⁰→h⁺h⁻ with whole CDF RunII dataset
- ✔ CDF Measurement of CP Violation in the D⁰→Ks π⁺π⁻ Decay
NP out of the box

CP violation in Bs mixing

CPV in Bs mixing with whole CDF RunII dataset
CDF Measurement of $B_s \rightarrow D_{s(*)} D_{s(*)}$ branching ratios
A broad class of BSM models can introduce significant CP violation in Bs mixing.

This would maximally affect the phase $\phi_s$ which is predicted tiny in the SM. And will also decrease the value of the decay-width difference $\Delta \Gamma_s$.

2011 DØ: 3.9$\sigma$ deviation from SM in B semileptonic asymmetry. Measuring CPV in $B_s \rightarrow J/\psi \phi$ provides a cleaner, independent probe.

NEW

CDF updated the time-dependent analysis of $B_s \rightarrow J/\psi \phi$ decays to the whole Run II dataset.
Mixing phase through tagged $B_s \rightarrow J/\psi\phi$ decays

Exploits interference between $B_s \rightarrow J/\psi\Phi$ decays w and w/o flavor oscillations.

- Dimuon trigger data. Off-line optimized NN selection @CDF; BDT/square cuts @DØ.
- Joint likelihood fit to: Mass, Angles, Decay time, production flavor, production flavor.

9.6 fb$^{-1}$ of data @CDF
8.0 fb$^{-1}$ of data @DØ

Flavor tagging to separate $B$ from $\bar{B}$

Mass to separate Signal for Bkg

Angles to separate CP even/odd

Decay time to know time evolution
The Analysis

✓ Signal yield

~11,000 signal events

✓ Angular analysis

\[ B_s(\text{spin} = 0) \rightarrow J/\psi(\text{spin} = 1)\phi(\text{spin} = 1) \]

Results in 3 final states with
\[ L = 0, 2 \text{ (CP even)} \]
\[ L = 1 \text{ (CP odd)} \]

Enhanced sensitivity to the phase if these are separated

Separate them using angular distributions of kaons and muons

✓ Flavor tagging

Greater sensitivity to phase if production flavor is known.

CDF flavor tagging performance ~ 5 %
Decay-width difference and lifetime

\[ \Delta \Gamma_s = 0.163^{+0.065}_{-0.064} \text{ps}^{-1} \]
\[ \tau_s = 1.443^{+0.038}_{-0.035} \text{ps} \]

PRD 85, 032006 (2012)

Assuming SM CP-violation

\[ \Delta \Gamma_s = 0.068 \pm 0.027(\text{stat}+\text{syst}) \text{ps}^{-1} \]
\[ \tau_s = 1.528 \pm 0.021(\text{stat}+\text{syst}) \text{ps} \]

\[ \frac{\Delta \Gamma_s}{\Gamma_s} = 0.1045 \pm 0.048(\text{stat.}) \pm 0.011(\text{syst.}) \]

\[ \frac{\tau_{B_s}}{\tau_{B_d}} = 1.006 \pm 0.015(\text{stat} + \text{syst}) \]

Theor: \[ \frac{\tau_{B_s}}{\tau_{B_d}}^{SM} = 0.996...1.000 \]

Moriond 2012 Talk A. Lenz

CDF Public Note 10778
CP-violating mixing phase bounds

CDF Run II Preliminary $L = 9.6 \text{ fb}^{-1}$

$\phi_s$ in $[-\pi, -2.52] \cup [-0.60, 0.12] \cup [3.02, \pi] \text{ rad} @ 68\% \text{ C.L.}$

consistent with SM and with other experimental results

Restricting fit range to select only one solution

$\phi_s = -0.55^{+0.38}_{-0.36}$


$\pm (0.087 \pm 0.021) \text{ ps}^{-1}$

PRD 85, 032006 (2012)
A different point of view

\[ Br(B_s \rightarrow D_s^{(*)} + D_s^{(*)}) \]

Predominantly CP-even. May give dominant contribution to Bs width difference in SM.

6.8 fb\(^{-1}\) collected by displaced track trigger

simultaneous fit to signal: \( B_s \rightarrow D_s^{(*)} + D_s^{(*)} \)
and normalization mode: \( B^0 \rightarrow D_s^+ D^- \)

Most precise BR measurements:

\[
\begin{align*}
BR(B_s \rightarrow D_s^{+} D_s^{-}) &= (0.49 \pm 0.06 \pm 0.05 \pm 0.08) \%, \\
BR(B_s \rightarrow D_s^{*\pm} D_s^{\mp}) &= (1.13 \pm 0.12 \pm 0.09 \pm 0.19) \%, \\
BR(B_s \rightarrow D_s^{*+} D_s^{*-}) &= (1.75 \pm 0.19 \pm 0.17 \pm 0.29) \%, \\
BR(B_s \rightarrow D_s^{(*)+} D_s^{(*)-}) &= (3.38 \pm 0.25 \pm 0.30 \pm 0.56) \%.
\end{align*}
\]

Under some theoretical assumptions, from BR possible to infer:

\[ \Delta \Gamma_s/\Gamma_s = (6.99 \pm 0.54 \pm 0.64 \pm 1.20)\% \]
Rare B decays

searches for $B \rightarrow \mu^+\mu^-$ with whole CDF RunII dataset
$B \rightarrow \mu^+ \mu^-$

- SM rates well understood
  
  \[ BR(B^0_s \rightarrow \mu^+ \mu^-) = (3.2 \pm 0.2) \times 10^{-9}, \quad BR(B^0 \rightarrow \mu^+ \mu^-) = (1.0 \pm 0.1) \times 10^{-10} \]

- Broad class of NP models can enhance it by up to x100

summer 2011 situation

Interesting \( \sim 2.5\sigma \) deviation from bkg in \( B_s \rightarrow \mu^+ \mu^- \) observed by CDF in 7 fb\(^{-1}\)

Compatible with other experiments and SM

CDF updates the analysis with whole Run II sample, \( \sim 10\text{fb}^{-1}(+30\% \text{ data}) \) while keeping the analysis unchanged
$B \rightarrow \mu^+ \mu^-$: The Analysis on 9.7 fb$^{-1}$ of data

- TRIGGER: on two muons with $p_t > 1.5 - 2$ GeV/c
- Use NN to reject $10^6$ larger backgrounds while keeping high the signal efficiency

- Bkg ($B \rightarrow h^+ h^-$ peaking, combinatorial) prediction checked on many control samples
- Search in bins of mass and NN and normalize observed signal rate to $B^+ \rightarrow J/\psi K^+$

![Diagrams](image.png)
\[ B^0 \rightarrow \mu^+ \mu^- : \text{final CDF II result} \]

\[ B^0 \rightarrow \mu^+ \mu^- \text{ analysis validates } B_s^0 \rightarrow \mu^+ \mu^- \text{ background estimations and limit setting} \]

Observed limit < 4.6 \times 10^{-9} (Expected 4.2 \times 10^{-9}). Consistent with SM. 

p-value for background-only hypothesis is 41%.
$B_s^0 \rightarrow \mu^+ \mu^-$ : final CDF II result

\[ 0.8 \times 10^{-9} < \text{BR}(B_s \rightarrow \mu \mu) < 3.4 \times 10^{-8} \quad @95\% \text{ C.L.} \]

Bkg+SM p-value 7.1%. Bkg-only p-value 0.94%

Summer deviation not reinforced by new data, but still $>2\sigma$ over background.

$$[BR = (1.3^{+0.9}_{-0.7}) \times 10^{-8}]$$
Getting closer...

March 2012

- **D0 6 fb**⁻¹
  - PLB 693 (2010) 539

- **CDF 7 fb**⁻¹
  - PRL 107 (2011) 191801

- **CDF 10 fb**⁻¹
  - www-cdf.fnal.gov/physics/new/bottom/120209.bmumu10fb/

- **ATLAS 2.4 fb**⁻¹
  - ATLAS-CONF-2012-010

- **CMS 4.9 fb**⁻¹
  - CMS PAS BPH-11-020

- **LHCb 1 fb**⁻¹
  - LHCb-PAPER-2012-007

**SM Prediction**

(68% CL region)

**BF(B_s \rightarrow \mu^+\mu^-) \times 10^9 @ 95\% CL**
when “Charm is more than just beauty.”

CP violation in charm

CPV in $D^0 \rightarrow h^+ h^-$ with whole CDF RunII dataset
CDF Measurement of CP Violation in the $D^0 \rightarrow K_s \pi^+ \pi^-$ Decay
CP violation in neutral charmed mesons

Probes CPV in up-quark sector.
Asymmetry > 1% (expected in SM) suggestive of NP

- 2011 CDF: using 5.9/σf of two-track trigger data, CDF produced with unprecedented sensitivity the CP asymmetries in 2-body D decays:

\[
A_{CP}(D^0 \to K^+ K^-) = (-0.24 \pm 0.22 \pm 0.10)\
A_{CP}(D^0 \to \pi^+ \pi^-) = (+0.22 \pm 0.24 \pm 0.11)\%
\]

PRD85, 012009 (2012)

- Difference of asymmetries: \( \Delta A_{CP} = A_{CP}(D^0 \to K^+ K^-) - A_{CP}(D^0 \to \pi^+ \pi^-) \)

maximally sensitive to \( A_{CP}^{dir} \)

- First Evidence of CPV in charm from LHCb measurement:

\( \Delta A_{CP} = (-0.82 \pm 0.21 \pm 0.11)\% \)

3.5σ from zero arXiv1112.0938

An independent confirmation is crucial to establish it.
The Analysis with full Run II dataset

- **New selection** to improve the resolution on $\Delta A_{CP}$:
  - ✔ doubled the signal yield

- Use $D^*-tag$ to identify the $D^0$ flavor

- $\Delta A_{CP}$ Experimentally convenient:
  - Detector effects cancel in the subtraction of the raw asymmetries
Result

\[ \Delta A_{CP} = [-0.62 \pm 0.21(\text{stat}) \pm 0.10(\text{syst})]\% \]

2.7\sigma from zero

Strongly supports CP violation in charm, by confirming the LHCb result with same sensitivity

When combining à la HFAG No CPV point is at \(~4\sigma\)

\[ \Delta A_{CP}^{\text{dir}} = (-0.67 \pm 0.16)\% \]
\[ A_{CP}^{\text{ind}} = (-0.02 \pm 0.22)\% \]
Is there CPV in other charm decays?

CP Violation in the $D^0 \rightarrow K_S \pi^+ \pi^-$ Decay

- In 6 fb$^{-1}$ of two-track trigger data we search for time-integrated CPV in the resonant substructures of the 3-body $D^0 \rightarrow K_S \pi^+ \pi^-$ decay

- First full Dalitz analysis at hadron collider

- Big improvement wrt previous results from CLEO (PRD 70, 091101 (2004))...

- ..but still no hints for any CP violating effect

- The measured value for the overall integrated CP asymmetry is:

\[ A_{CP} = ( -0.05 \pm 0.57 \text{(stat)} \pm 0.54 \text{(syst)}) \%

- CP asymmetries of the individual resonances:
Conclusions

• The Tevatron keeps producing new, important results on the benchmark channels of heavy flavor physics with full Run II dataset shown today:

  Bs mixing
  CDF Bs → J/Ψϕ update: Closer to SM expectations.

  Rare B decays
  CDF B → μ⁺μ⁻ extension to full sample confirms summer result.

  CPV in Charm sector
  CDF result confirms LHCb ΔACP with the same precision.

• Pioneered and established role of hadron collisions in HF. Keep improving flagship measurements.

  don't relax just yet ... a few aces still up our sleeve
Back up
### \( \Delta \Gamma_s \) and \( \tau_s \) systematics

| Source of systematic effect                     | \( c \tau \, [\mu \text{m}] \) | \( \Delta \Gamma \, [\text{ps}^{-1}] \) | \( |A_{||}(0)|^2 \)   | \( |A_0(0)|^2 \)   | \( \delta_{\perp} \) |
|------------------------------------------------|-------------------------------|-----------------------------------|-----------------|-----------------|-----------------|
| Signal Angular Efficiency                       | 0.29                          | 0.0014                            | 0.0134          | 0.0162          | 0.076           |
| Mass Signal Model                               | 0.17                          | 0.0007                            | 0.0006          | 0.0020          | 0.018           |
| Mass Bkg Model                                  | 0.14                          | 0.0006                            | 0.0003          | 0.0002          | 0.034           |
| ct Resolution                                  | 0.52                          | 0.0010                            | 0.0004          | 0.0002          | 0.066           |
| ct Bkg                                          | 1.31                          | 0.0057                            | 0.0006          | 0.0012          | 0.064           |
| Angular Bkg                                     | 0.46                          | 0.0037                            | 0.0011          | 0.0022          | 0.009           |
| Sigma mass                                      | 0.85                          | 0.0006                            | 0.0003          | 0.0002          | 0.036           |
| Sigma ct                                        | 0.63                          | 0.0006                            | 0.0003          | 0.0002          | 0.038           |
| \( B_d \rightarrow J/\psi K^* \) cross-feed   | 0.18                          | 0.0018                            | 0.0002          | 0.0015          | 0.034           |
| SVX alignment                                   | 2.0                           | 0.0004                            | 0.0002          | 0.0001          | 0.034           |
| Pull bias                                       | 0.2                           | 0.0012                            | 0.0021          | 0.0008          | 0.02            |
| **TOT**                                         | **2.7**                       | **0.007**                         | **0.014**       | **0.017**       | **0.15**        |
\[ B_s^0 \rightarrow \mu^+ \mu^- : \text{The analysis} \]

\[
\text{BR}(B_s \rightarrow \mu^+ \mu^-) = \frac{N_s}{N_+} \cdot \frac{\alpha_+}{\alpha_s} \cdot \frac{\epsilon_+}{\epsilon_s} \cdot \frac{1}{\epsilon_N} \cdot \frac{f_u}{f_s} \cdot \text{BR}(B^+) \]

- Signal decays at 95\% CL to be measured
- Trigger acceptance ratio from MC ~ 0.2-0.3
- Reconstruction efficiency ratio MC/DATA ~ 0.8
- B^+ \rightarrow J/\psi K^+ decays from data ~ 20K
- Efficiency of NN requirement from MC, approx 80-20\% (cut dependent)
\[ B_s^0 \rightarrow \mu^+ \mu^- \] : The third bin

- Unlikely to be peaking Bkg. The only one would be \( B \rightarrow hh \), but it's x10 larger in the \( B_d \) search window and there is no excess there.

- Unlikely to be a systematics problem with combinatorial: we use the same procedure in \( B_d \) and no excess is there.

- Unlikely to be an issue of the NN: all tests done show that is independent on mass and reproduces \( B^+ \) at better than 5%

- The only remaining possibility is a statistical fluctuation, supported by the fact that the 3rd bin excess did not strengthened with adding more data

- Results do not significantly change if the last two NN bins are used only:

\[
BR = \left( 1.0^{+0.8}_{-0.6} \right) \times 10^{-8}
\]

\[
0.8 \times 10^{-9} < BR(B_s \rightarrow \mu \mu) < 2.5 \times 10^{-8} \text{ @90% C.L.}
\]

\[
BR(B_s \rightarrow \mu \mu) < 2.9 \times 10^{-8} \text{ @95% C.L.}
\]
ΔACP systematics

<table>
<thead>
<tr>
<th>Source</th>
<th>ΔACP [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Approximations in the suppression of detector-induced effects</td>
<td>0.009</td>
</tr>
<tr>
<td>Shapes assumed in fits</td>
<td>0.020</td>
</tr>
<tr>
<td>Charge-dependent mass distributions</td>
<td>0.100</td>
</tr>
<tr>
<td>Asymmetries from residual backgrounds</td>
<td>0.013</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>0.103</strong></td>
</tr>
</tbody>
</table>
Single $A_{CP}$ and $\Delta A_{CP}$

- To measure each single $A_{CP}$ we need to compare raw asymmetries, $A$, of three event samples
  
  \begin{align*}
  \text{D*-tagged } \, &\, D^0 \to hh \\
  A(\text{hh}^*) &= A_{CP}(\text{hh}) + \delta(\pi_s) \\
  \text{D*-tagged } \, &\, D^0 \to K\pi \\
  A(\text{K}\pi^*) &= A_{CP}(\text{K}\pi) + \delta(\pi_s) + \delta(K\pi) \\
  \text{Untagged } \, &\, D^0 \to K\pi \\
  A(K\pi) &= A_{CP}(K\pi) + \delta(K\pi)
  \end{align*}

\[ A_{CP}(\text{hh}) = A(\text{hh}^*) - A(\text{K}\pi^*) + A(K\pi) \]

- For $\Delta A_{CP}$ we need just two samples

\[ \Delta A_{CP}(\text{hh}) = A(KK^*) - A(\pi\pi^*) \]

thus making the measurement easier and much more robust against second order effects which do not completely cancel in the linear combination of raw asymmetries.
Direct and indirect CPV in $D^0 \rightarrow h^+ h^-$

The time-integrated asymmetry receives contribution from both direct and indirect sources of CPV

\[
\text{Direct: } \left| D^0 \rightarrow f \right|^2 \neq \left| \bar{D}^0 \rightarrow f \right|^2
\]

\[
\text{Mixing: } \left| D^0 \rightarrow \bar{D}^0 \rightarrow f \right|^2 \neq \left| \bar{D}^0 \rightarrow D^0 \rightarrow f \right|^2
\]

Since flavour mixing parameters are small in the charm sector, at first order, the measured asymmetry is the linear combination of the two terms

\[
A_{CP}(h^+ h^-) \approx A_{CP}^{\text{dir}}(h^+ h^-) + \frac{\langle t \rangle}{\tau} A_{CP}^{\text{ind}}
\]

where $\langle t \rangle/\tau$ is the mean value of the $D^0$ meson proper decay-time in unit of lifetimes

Assuming no large weak phases in the decay, the indirect component is \textit{universal}, then

\[
\Delta A_{CP} = A_{CP}(K^+ K^-) - A_{CP}(\pi^+ \pi^-) = \Delta A_{CP}^{\text{dir}} + \frac{\Delta \langle t \rangle}{\tau} A_{CP}^{\text{ind}}.
\]