Searches for BSM physics through CP violation at CDF

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On behalf of CDF Collaboration
CP VIOLATION MEASUREMENTS AT CDF

- $10^{14}$ $p\bar{p}$ collisions at 2 TeV in 10 years
  - CP symmetric, same number of produced meson and anti meson.
  - 0.1-1% of collisions produce $b\bar{b}$ and $c\bar{c}$ pair, only 0.1-10% recorded

- Final states with charged particles only preferred:
  - Easier to reconstruct
  - Mass discriminates against background

- Good decay-time resolution:
  - 90 fs for $B_s \to J/\psi\phi$

- Need tagging to know flavor at production
  - very challenging, $\epsilon D^2$ of 5%

- Today: four 2012 results
  - $B_s \to J/\psi\phi$ (full CDF Run II dataset)
  - $BR(B_s^0 \to D_s^{(*)+}D_s^{(*)-})$
  - Update $\Delta A_{CP}$ in $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$ decays (full CDF Run II dataset)
  - CPV in $D^0 \to K_S\pi^+\pi^-$ decay
SEARCH FOR NP IN THE $B_s$ SYSTEM
B_s mixing and NP

- B_s meson flavor oscillations:
  - Powerful indirect probe for non-SM physics
  - Broad class of SM extension models
- Two physical states (B_{sH} - B_{sL}) with different mass and lifetime
- 3 main observables:
  - Strength (ΔM), very sensitive to NP but consistent with SM (CDF, Phys. Rev. Lett. 97, 242003 (2006))
  - Mixing phase \( β_s = arg \left( -\frac{V_{tb}^*V_{ts}}{V_{cb}^*V_{cs}} \right) \) very sensitive to NP
    - Any value significantly larger than a few 10^-2 indicates NP
    - Direct and theoretically solid access through time-evolution \( B_s \to J/\psi\phi \) decays
  - Width difference (ΔΓ), moderately sensitive to NP
    - Best probed with \( B_s \) in \( J/\psi\phi \) angular analysis
\( B_s \rightarrow J/\psi\phi \) AT A GLANCE

Very complex likelihood fit, 11 physical parameter 21 nuisance: use mass, angles, decay-time and production flavor distributions

- Dimuon trigger
- Offline selection
- Flavor tagging to separate \( B \) from \( \bar{B} \)
- Decay time to know time evolution
- Angles to separate CP-even/odd
- Mass to separate signal from bckg

June 12th 2012

HQL 2012, Prague
Full Run II Dataset (10 fb\(^{-1}\))

- ~11,000 signal events
- 95% of bkg is prompt J/\(\psi\) + random track pair

CDF Run II Preliminary \(L = 9.6\) fb\(^{-1}\)

10950 ± 111 Signal Events

\(\sigma \sim 9\) Mev/c\(^2\)

J/\(\psi\) \(K^+K^-\) Mass [GeV/c\(^2\)]
Angular analysis

$B_s^0$ (spin-0) $\rightarrow J/\psi$ (spin-1) $\phi$ (spin-1).

Angular distributions to disentangle different CP states

$B_s^0$ $J/\psi \phi$

$\mu^+ \mu K^+ K^-$

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

<table>
<thead>
<tr>
<th>Events per 0.01 rad</th>
<th>Events per 0.03 rad</th>
<th>Events per 0.01 rad</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\cos \psi$</td>
<td>$\cos \theta$</td>
<td>$\Phi$ [rad]</td>
</tr>
</tbody>
</table>

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FLAVOR TAGGING

Greater sensitivity to mixing phase if production flavor is known.

Opposite Side Tagging
- Total tagging power ($\varepsilon D^2$) is 1.4%
- Calibrated using 82k $B^+$ decays

Same Side Kaon Tagging
- $\varepsilon D^2$ is 3.5%

Same side tagger used only in first half of data. Calibration in latest data not yet completed.
- Modest degradation of the expected mixing phase resolution

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

$B^+ \to J/\Psi K^+$

$S_{D^+} = 1.09 \pm 0.05$ ~ 1

Good agreement with the prediction

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ΔΓ_S = 0.068 ± 0.026 ± 0.007 ps^{-1}
τ_S = 1.528 ± 0.019 ± 0.009 ps

CDF Note 10778

- ΔΓ_S slightly lower than DØ and LHCb determination, but still consistent with them and with SM.
- Important constraint to probe DØ measurement of a_{SL}
- Among the best world’s measurements.
Mixing phase compatible with SM prediction \( \Phi_s \) in \([-0.60, 0.12]\) rad @ 68% C.L.

Contours shrink to ~50% w.r.t. PRD 85, 072002 (2012)

CDF Note 10778


\(^2\) \(2|\Gamma_{12}| = (0.087 \pm 0.021) \) ps\(^{-1}\)
$B_S^0 \rightarrow D_S^{(*)+} D_S^{(*)-}$ BRANCHING RATIOS

Update of early Run II analysis (PRL 100, 021803 (2008))

- ~6.8 fb$^{-1}$ of Two Track Trigger data:
- Extract $B_S^0 \rightarrow D_S^{(*)+} D_S^{(*)-}$ rate relative to $B_d^0 \rightarrow D^- D_S^+$ rate using an unbinned ML fit:
- Simultaneous fit to $B_S^0$ signal and $B_d^0$ normalization mode exploits maximum of statistical information and allows using partially reconstructed $D_S^*$ decays as well

- $D_S^+ \rightarrow K^+ K^- \pi^+$ and $D^- \rightarrow K^+ \pi^- \pi^-$ reconstructed from combination of three tracks.
- First use of Dalitz structure in this analysis to identify better the $\phi$ and $K^*$ components

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SIMULTANEOUS FIT

\[ D_s^+ D^- \]

CDF II Preliminary  
6.8 fb^{-1}

\[ D_s^+(\psi\pi^+) D^-(K^+\pi^-\pi^-) \]

\[ N_B \sim 1901 \]

\[ D_s^+(\bar{K}^0 K^-) D^-(K^+\pi^-\pi^-) \]

\[ N_B \sim 1107 \]

Candidates per 10 MeV/c^2

Invariant Mass (GeV/c^2)

Normalization

\[ D_s^+(\psi\pi^+) D_s^-(\psi\pi^-) \]

\[ N_{B_S} \sim 469 \]

\[ D_s^+(\bar{K}^*0 K^+) D_s^*(\phi\pi^-) \]

\[ N_{B_S} \sim 276 \]

Candidates per 10 MeV/c^2

Invariant Mass (GeV/c^2)

Signal
RESULTS

- Using known values for $B_d$ branching ratios

$$\mathcal{B} \left( B_s^0 \rightarrow D_s^{(*)+} + D_s^{(*)-} \right) = (3.38 \pm 0.25 \pm 0.30 \pm 0.56)\%$$


World’s most precise measurement of this BR
CP VIOLATION IN CHARM
CP VIOLATION IN CHARM

- Probe the up-quark sector.
  Direct CPV >1% level suggestive of NP.

  
  \[
  A_{CP}^{D_0 \to K^+ K^-} = (-0.24 \pm 0.22 \pm 0.09)\%
  \]
  
  \[
  A_{CP}^{D_0 \to \pi^+ \pi^-} = (+0.22 \pm 0.24 \pm 0.11)\%
  \]

  \[
  \Delta A_{CP} = A_{CP}^{D_0 \to K^+ K^-} - A_{CP}^{D_0 \to \pi^+ \pi^-}
  \]

  Maximally sensitive to NP and experimentally convenient, instrumental asymmetries cancel.

- LHCb 2011: \(\Delta A_{CP} = (-0.82 \pm 0.21 \pm 0.11)\%\), 3.5σ from zero.
  First evidence of CPV in charm PRL 108, 111602 (2012)

  Independent confirmation crucial to establish it.
Measurement updated with full Run II data sample

Analysis strategy unchanged but new selection has been designed to specifically improve the resolution on $\Delta A_{CP}$

- About twice more signal events used in the new measurement
- Expected resolution is competitive with LHCb

Use $D^* \rightarrow D^0\pi_S$ tag to identify the charm flavor at production

The instrumental asymmetries induced by soft pion reconstructed in the charge-asymmetric CDF tracker gets canceled in the difference of asymmetries:

$$\Delta A_{CP} = (A(K^+K^-) + \delta(\pi_S)) - (A(\pi^+\pi^-) + \delta(\pi_S))$$

Reweight kinematic in $KK$ and $\pi\pi$ to be equal for a more accurate cancellation.
**FIT RESULTS**

**270K $D^0 \rightarrow \pi\pi$**

CDF Run II Preliminary

$N(D^{*-} \rightarrow D^0 (\rightarrow \pi^+ \pi^-) \pi^-) = 269871 \pm 590$

$\chi^2/ndf = 366/308$

**280K $\bar{D}^0 \rightarrow \pi\pi$**

CDF Run II Preliminary

$N(D^{*-} \rightarrow D^0 (\rightarrow \pi^+ \pi^-) \pi^-) = 279288 \pm 599$

$\chi^2/ndf = 366/308$

**591K $D^0 \rightarrow KK$**

CDF Run II Preliminary

$N(D^{*-} \rightarrow D^0 (\rightarrow K^+ K^-) \pi^-) = 590874 \pm 1265$

$\chi^2/ndf = 394/299$

**619K $\bar{D}^0 \rightarrow KK$**

CDF Run II Preliminary

$N(D^{*-} \rightarrow D^0 (\rightarrow K^+ K^-) \pi^-) = 619011 \pm 1311$

$\chi^2/ndf = 394/299$

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$Raw\ A(\pi^+ \pi^-) = (-1.71 \pm 0.15)\%$  \hspace{1cm}  $Raw\ A(K^+ K^-) = (-2.33 \pm 0.14)\%$
ΔA_{CP} = [-0.62 ± 0.21 (stat) ± 0.10 (syst)]%  

Strong indication of CPV in CDF charm decays

- Confirms LHCb result: same resolution, <1σ difference in central value
  \[ \Delta A_{CP} = (-0.82 ± 0.21 ± 0.11)\% \]

- When combining à la HFAG, no CPV point is at ~4σ from zero
  \[ \Delta A_{CP}^{dir} = (-0.67 ± 0.16)\% \]
  \[ A_{CP}^{ind} = (-0.02 ± 0.22)\% \]
CP VIOLATION IN $D^0 \rightarrow K_S\pi^+\pi^-$

- 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

- Model-independent bin-by-bin comparison of the $D^0$ and $\bar{D}^0$ Dalitz plots (Miranda method)
D^0 \rightarrow K_S \pi^+ \pi^- \textbf{RESULTS}

- Table lists asymmetries between sub-resonances fit fractions
  - Large improvement w.r.t. CLEO results ([PRD70, 091101 (2004)](https://journals.aps.org/prd/abstract/10.1103/PhysRevD.70.091101))
  - No hints for any CP violating effect

- Overall integrated asymmetry:

\[ A_{CP}(D^0 \rightarrow K_S \pi^+ \pi^-) = (-0.05 \pm 0.57 \pm 0.54)\% \]

CDF Run II preliminary

<table>
<thead>
<tr>
<th>Resonance</th>
<th>CPV amplitude</th>
<th>CPV Phase</th>
</tr>
</thead>
<tbody>
<tr>
<td>(K^*(892)^-)</td>
<td>0.004 ± 0.004 ± 0.011</td>
<td>-0.8 ± 1.4 ± 1.3</td>
</tr>
<tr>
<td>(K_0^*(1430)^-)</td>
<td>0.044 ± 0.028 ± 0.041</td>
<td>-1.8 ± 1.7 ± 2.2</td>
</tr>
<tr>
<td>(K_2^*(1430)^-)</td>
<td>0.018 ± 0.024 ± 0.023</td>
<td>-1.1 ± 1.8 ± 1.1</td>
</tr>
<tr>
<td>(K^*(1410)^-)</td>
<td>-0.010 ± 0.037 ± 0.021</td>
<td>-1.6 ± 1.9 ± 2.2</td>
</tr>
<tr>
<td>(\rho(770))</td>
<td>-0.003 ± 0.006 ± 0.008</td>
<td>-0.5 ± 1.5 ± 1.4</td>
</tr>
<tr>
<td>(\omega(782))</td>
<td>-0.003 ± 0.002 ± 0.000</td>
<td>-1.8 ± 2.2 ± 1.4</td>
</tr>
<tr>
<td>(f_0(980))</td>
<td>-0.001 ± 0.005 ± 0.004</td>
<td>-0.1 ± 1.3 ± 1.1</td>
</tr>
<tr>
<td>(f_2(1270))</td>
<td>-0.035 ± 0.037 ± 0.013</td>
<td>-2.0 ± 1.9 ± 2.1</td>
</tr>
<tr>
<td>(f_0(1370))</td>
<td>-0.002 ± 0.008 ± 0.021</td>
<td>-0.1 ± 1.7 ± 2.8</td>
</tr>
<tr>
<td>(\rho(1450))</td>
<td>-0.016 ± 0.022 ± 0.135</td>
<td>-1.7 ± 1.7 ± 3.9</td>
</tr>
<tr>
<td>(f_0(600))</td>
<td>-0.012 ± 0.017 ± 0.025</td>
<td>-0.3 ± 1.5 ± 1.4</td>
</tr>
<tr>
<td>(\sigma_2)</td>
<td>-0.011 ± 0.012 ± 0.004</td>
<td>-0.2 ± 2.9 ± 1.1</td>
</tr>
<tr>
<td>(K^*(892)^+)</td>
<td>0.001 ± 0.005 ± 0.002</td>
<td>-3.8 ± 2.3 ± 1.2</td>
</tr>
<tr>
<td>(K_0^*(1430)^+)</td>
<td>0.022 ± 0.024 ± 0.035</td>
<td>-3.3 ± 4.0 ± 3.9</td>
</tr>
<tr>
<td>(K_2^*(1430)^+)</td>
<td>-0.018 ± 0.029 ± 0.017</td>
<td>4.2 ± 5.3 ± 3.0</td>
</tr>
</tbody>
</table>

CDF Public Note 10654

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CONCLUSIONS

- Data taking ended in September 30th 2011
  - Big effort in getting the analyses finalized in full dataset:
    All shown results are less than 6 months old
- CDF keeps contributing to HF while passing baton to LHC experiments
  - Finalizing flagship analyses on full Run II dataset ...Still more to come!
  - Then refocus on measurements that are unique to Tevatron or systematics-limited
- B_s Mixing Phase
  - Got closer to SM
- CPV in Charm Sector
  - Confirmed LHCb’s evidence of CPV in charm with same precision
  - ...but No hints of CPV in $D^0 \rightarrow K_s \pi^+ \pi^-$ decay