Measurements of CP Violation at the Tevatron

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May 31, 2011
SM Success and Failure

- B meson mixing and decays probe 5 of the 9 elements of the CKM matrix
  - Measure angles and sides independently
  - CP Violation: $A \sim 3 \times 10^{-5}$
  - Fails to accommodate observed baryon asymmetry by about 10 orders of magnitude!
- Need Physics beyond SM!
- $B_s$ is the least explored system
- Charm
- Predicted CP phases are very small in SM – search for large deviations
CP Violation in $B_s$

- Assume no CPV in decays
- CPV is possible through mixing
  - 2 phases involved
  - $\beta_s$ access through $B_s \to J/\psi \phi$
  - $\phi_s$ access through semileptonic decays

\[ \beta_s^{SM} = \arg \left[ -V_{ts}V_{tb}^*/V_{cs}V_{cb}^* \right] = \lambda \eta^2 \approx 1^\circ \left( \beta = 22^\circ \right) \]

\[ \phi_s = \arg \left( -\frac{M_{12}}{\Gamma_{12}} \right) = (4.2 \pm 1.3) \times 10^{-3} \]

- Contribution of new particles in the box diagram can enhance both:
  - $2\beta_s = 2\beta_s^{SM} - \phi_s^{NP}$
  - $\phi_s = \phi_s^{SM} - \phi_s^{NP}$ with $\phi_s^{NP} >> \phi_s^{SM}$, $2\beta_s^{SM}$
  - $-2\beta_s \sim \phi_s \sim \phi_s^{NP}$
$A_{s_{l}}^{b}$ in neutral B mesons

- Measurement of the charge asymmetry induced by $B$ mixing

\[ A_{s_{l}}^{b} = \frac{\Gamma(B \rightarrow \mu^+ X) - \Gamma(B \rightarrow \mu^- X)}{\Gamma(B \rightarrow \mu^+ X) + \Gamma(B \rightarrow \mu^- X)} = \frac{1}{2 f} \left[ A_{s_{l}} + \frac{f_s \chi_{s_0}}{f_d \chi_{d_0}} A_{s_{l}}^s \right] \]

\[ A_{s_l}^{(s)} = \text{Im} \frac{\Gamma_{12}}{M_{12}} = \left| \frac{\Gamma_{12}}{M_{12}} \right| \sin \varphi_{(s)} = \frac{\Delta \Gamma_{(s)}}{\Delta m_{(s)}} \cdot \tan \varphi_{(s)} \]

- $A_{s_{l}}^{b}$ is equal to the charge asymmetry of "wrong sign" semileptonic B decays:

\[ A_{s_{l}}^{b} = (0.506 \pm 0.043) a_{s_{l}}^d + (0.494 \pm 0.043) a_{s_{l}}^s \]

- Since both $B_d$ and $B_s$ are produced at the Tevatron, $A_{s_{l}}^{b}$ is a linear combination of $a_{s_{l}}^d$ and $a_{s_{l}}^s$:

$B$ factories provide independent measurement of $a_{d_{s}}^d$
Analysis Strategy

1 Experimentally, we measure two quantities:
   - Like-sign dimuon charge asymmetry \((3.731 \times 10^6\) events): \[ A \equiv \frac{N^{++} - N^{- -}}{N^{++} + N^{- -}} = KA_{sl}^b + A_{bkg} = (+0.564 \pm 0.053)\% \]
   - Inclusive muon charge asymmetry \((1.495 \times 10^9\) muons): \[ a \equiv \frac{n^+ - n^-}{n^+ + n^-} = kA_{sl}^b + a_{bkg} = (+0.955 \pm 0.003)\% \]
   - \(N^{++}, N^{- -}\) – the number of events with two same charge dimuons
   - \(n^+, n^-\) – the number of muons with given charge
   - Both \(A\) and \(a\) linearly depend on the charge asymmetry \(A_{sl}^b\)

2 Determine the background contributions \(A_{bkg}\) and \(a_{bkg}\) from other processes plus detector-related backgrounds

3 Determine Fractions \(K\) and \(k\) from mixed B hadron decays

4 Exploit different signal and correlated background content to extract \(A_{sl}^b\)
Closure Test

- The value of $a$ is mainly determined by the background asymmetry $a_{bkg}$
  - $A_{sl}^b$ is suppressed by $k = 0.041 \pm 0.003$
- Construct $a_{bkg}$ from $f_K, f_n, f_p, a_K, a_n, a_p$ and $\bar{\delta}$, verify how well does it describe the observed asymmetry $a$
- $a$ and $a_{bkg}$ are compared as a function of muon $p_T$
- $\chi^2/dof = 2.4/5$ for the difference between these two distributions

Excellent agreement between the expected and observed values of $a$, including a $p_T$ dependence
Final Result

- From $A' = A - \alpha a$ we obtain a value of $A_{sl}^{b}$:

$$A_{sl}^{b} = (-0.957 \pm 0.251 \text{ (stat)} \pm 0.146 \text{ (syst)})\%$$

- To be compared with the SM prediction:

$$A_{sl}^{b} (SM) = (-0.023^{+0.005}_{-0.006})\%$$

This result differs from the SM prediction by $\sim 3.2 \sigma$

- Previous D0 measurement

$$A_{SL} = (-0.92 \pm 0.44 \pm 0.32)\%$$

Further Improvements

- Precision of current result is dominated by statistical uncertainties
  - $6 \text{ fb}^{-1} \rightarrow 9 \text{ fb}^{-1}$
  - Improve event selection - 12% increase in number of like sign muons

- New measurement technique takes advantage of correlated uncertainties in $f_K$ and $F_K$ measurement
  - *Reduce uncertainties by ~30%*

- Anticipate ~30% reduction in final uncertainty on $A_{sl}^b$
Time Integrated Mixing

- Use muon impact parameter distribution to separate bb contribution from other sources.
- Plot the IP distributions \((d1,d2)\) for opposite sign (OS) and same sign \((++, --)\) muons.
- Simultaneously fit the distributions for muons from b-pairs (BB), c-pairs (CC), sequential decays (BC), Drell-Yan (PP), and D.I.F.’s or misID’s with a muon or in pairs \((\text{BB}_{\text{FK}}, \text{CC}_{\text{FK}}, \text{and other})\).
Time Integrated Mixing

- Average mixing probability:
  \[ \overline{\chi}_b = \frac{\Gamma(B^0 \rightarrow \bar{B}^0 \rightarrow \ell^+X)}{\Gamma(B \rightarrow \ell^+X)} = f_d \chi_d + f_s \chi_s \]

- Measure through:
  \[ R = \frac{N^{++} + N^{--}}{N^{OS}} \]
  \[ R = \frac{f \left[ \overline{\chi}^2 + (1 - \overline{\chi})^2 \right] + 2\overline{\chi}(1 - \overline{\chi})(1 - f)}{(1 - f) \left[ \overline{\chi}^2 + (1 - \overline{\chi})^2 \right] + 2\overline{\chi}(1 - \overline{\chi})f} \]

- \( f = 0.176 \pm 0.011 \) accounts for sequential and other \( b \) -decays

- Extracted value: \( 0.126 \pm 0.008 \) (0.006 due to \( f \))
  Compare to LEP: \( 0.1259 \pm 0.0042 \)
  - Previous measurement \( \text{PRD 82.032001; PRL.105.081801} \)
  - \( A_b^{SL} \) measurement to follow with larger dataset
\( \varphi^{J/\psi\phi}_s \) in \( B_s \rightarrow J/\psi\phi \)

- Measure \( \varphi^{J/\psi\phi}_s(\beta_s) \) and \( \Delta \Gamma_s \) by studying time evolution of flavor tagged \( B_s \rightarrow J/\psi(\mu^+\mu^-)\phi(K^+K^-) \) decays
  - Pseudoscalar \( \rightarrow \) Vector Vector
  - 3 possible angular momentum states

- The mass eigenstates are expected to be almost pure CP-eigenstates
  - \( S,D \) (CP even): linear combination of \( A_0, A_1 \)
  - \( P \) (CP odd): \( A_\perp \)

- Decay parameterized by three angles
  \[
  \Gamma(t) \approx |A_{even}(\theta,\psi,\varphi,t)|^2 + |A_{odd}(\theta,\psi,\varphi,t)|^2 \\
  + A^*A(CPC) \quad \text{CP-conserving interference} \\
  + A^*A(CPV)(e^{-\Gamma_L t} - e^{-\Gamma_H t})\sin\phi_s^{J/\psi\phi} \quad \text{CP-violating interference}
  \]

- CP eigenstates - well separated in transversity (\( \cos\theta \))
\( \phi^{J/\psi \phi} \) in \( B_s \to J/\psi \phi \)

**Preliminary**

- \( \phi^{J/\psi \phi} = -0.76 \pm 0.37 \text{(stat)} \pm 0.02 \text{ (syst)} \)
- \( \Delta \Gamma_s = 0.15 \pm 0.06 \text{(stat)} \pm 0.01 \text{ (syst)} \text{ ps}^{-1} \)

\[ \begin{align*}
\delta_1 &\equiv -0.42 \pm 0.18 \\
\delta_2 &\equiv 3.01 \pm 0.14 \\
\Delta M_s &\equiv 17.77 \pm 0.12 \text{ ps}^{-1}
\end{align*} \]

- D0 Note 6098
  - 3400 \( B_s \) candidates

- CDF Note 10206
  - 6500 \( B_s \) candidates

- \( \beta_s \) within \([0.02,0.52]\) U \([1.08,1.55]\) at 68% C.L.
- p-value (SM) = 0.44 (~0.8 \( \sigma \))
- \( \Delta \Gamma_s = 0.075 \pm 0.035 \text{(stat)} \pm 0.01 \text{ (syst)} \text{ ps}^{-1} \)

- Fitted fraction of S-wave contamination is < 6.7% @ 95% C.L.
Additional channels for $\beta_s$

$\frac{\text{BF}(B_s \to J/\psi f_0(980))\text{BF}(f_0(980) \to \pi^+\pi^-)}{\text{BF}(B_s \to J/\psi \phi)\text{BF}(\phi \to K^+K^-)} = (1.85\pm0.13\text{(stat)}\pm0.11\text{(sys)}\pm0.57\text{(pdg)}) \times 10^{-4}$

Since $f_0(980)$ is scalar no angular analysis needed

CDF: 0.292 ± 0.020(stat) ± 0.017(sys)
D0 : 0.210 ± 0.032 (stat) ± 0.036(sys)

D0 Note 6152
CDF Note 10404
Search for CPV in $B_s \rightarrow \varphi\varphi$

- Decay and mixing phases cancel out
  - CPV is predicted to be 0
  - Large deviation points to New Physics
- Limited sample statistics (~300) does not allow time – dependent analysis
  - Use Triple Products asymmetries
  - Odd under time reversal (T)
  - Sensitive to CP if CPT is conserved
- Define:
  - $u = \cos \phi \sin \phi \sim \Im(A_{||}A^*_{\text{perp}})$
  - $v = \sin \phi$ for $\cos \theta_1 \cos \theta_2 > 0$
  - $\sin(-\phi)$ for $\cos \theta_1 \cos \theta_2 \leq 0$
  - $\sim \Im(A_0 A^*_{\text{perp}})$
Search for CPV in $B_s \to \phi \phi$

CDF Run II Preliminary $L=2.9 \text{ fb}^{-1}$

Construct asymmetries: $A_{u,v} = \frac{N^+ - N^-}{N^+ + N^-}$

- $A_u = -0.007 \pm 0.064 \text{ (stat)} \pm 0.018 \text{ (syst)}$
- $A_v = -0.120 \pm 0.064 \text{ (stat)} \pm 0.016 \text{ (syst)} \ 1.8\sigma \text{ effect}$
Time Integrated $A_{CP}$ in $D^0 \to h^+h^-$ Decays

- CP violation significantly larger than $\sim 1\%$ in singly-Cabibbo suppressed transitions $D^0 \to \pi^+\pi^-$ and $D^0 \to K^+K^-$ would point to presence of NP
- Extract asymmetries

$$A_{CP}(h^+h^-) = \frac{\Gamma(D^0 \to h^+h^-) - \Gamma(D^0 \to h^+h^-)}{\Gamma(D^0 \to h^+h^-) + \Gamma(D^0 \to h^+h^-)}.$$  

- From $A_{CP}(h^+h^-) = A_{CP}^{raw}(h\pi^*) - A_{CP}^{raw}(K\pi^*) + A_{CP}^{raw}(K\pi)$.
  - Using $D^*$-tagged $D^0 \to h^+h^-$ and $D^0 \to \pi^+K^-$ decays, and untagged $D^0 \to \pi^+K^-$
    - Soft pion determines flavor
    - Non-zero asymmetry is due to CP violation or detector/reconstruction
Time Integrated $A_{CP}$ in $D^0 \to h^+h^-$ Decays

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

$A_{CP}(D^0 \to \pi^+\pi^-) = [+0.22 \pm 0.24 \, (\text{stat}) \pm 0.11 \, (\text{syst})] \%$

$A_{CP}(D^0 \to K^+K^-) = [-0.24 \pm 0.22 \, (\text{stat}) \pm 0.10 \, (\text{syst})] \%$
Summary and Conclusions

- Mature Tevatron experiments producing exciting results
- The observed $A_{SL}^b$ asymmetry is inconsistent with the SM prediction at a 3.2$\sigma$ level
  - Observed number of produced particles of matter (negative muons) is almost 50 times larger than the number of produced particles of antimatter
  - Result is consistent with other Tevtron measurements of CP violation in mixing
  - Dominant uncertainty is statistical – precision can be improved with more luminosity!
- Most precise experimental results on the CPV phase $\phi_s$ and the mass eigenstates width difference $\Delta \Gamma_s$ from the Tevatron, using reconstructed $B_s \rightarrow J/\psi \phi$ decays
  - Doubling of data sets by the end of the Tevatron run
  - Addition of new channels allows better precision
- World’s most precise measurement of mixing-induced CP violation in charm sector