Measurement of CP Violation in $B_s \rightarrow J/\psi \phi$ at CDF

Michal Kreps for the CDF collaboration

CDF Run II Preliminary  
$L = 1.35 \text{ fb}^{-1}$  
95\% C.L. 68\% C.L. SM prediction

CDF Run II Preliminary  
$L = 2.8 \text{ fb}^{-1}$  
SM prediction  95\% C.L.  68\% C.L.  
New Physics

$\beta_s (\text{rad})$
Discovery of CP violation

- Neutral kaon puzzle in late 1950s
- Two particles ($K_1$, $K_2$) with same mass, but different lifetime and different decay mode
- $K_2$ is CP odd and if CP is conserved can decay only to $3\pi$
- Observation of $K_2 \rightarrow \pi^+\pi^-$ in 1964 by Cronin and Fitch $\Leftrightarrow$ CP is not conserved
Explaining CP violation

- Observation by Cronin and Fitch requires $\approx 10^{-3}$ admixture of wrong CP state in wave function
- In 1973 Kobayashi and Maskawa concludes that
  - No reasonable way to include CP violation in model with 4 quarks
  - Introduction of CP violation needs new particles
  - One of the suggested ways uses 6 quark model
- CP violation $\Leftrightarrow$ complex phase in quark mixing (CKM) matrix

$$
\begin{pmatrix}
V_{ud} & V_{us} & V_{ub} \\
V_{cd} & V_{cs} & V_{cb} \\
V_{td} & V_{ts} & V_{tb}
\end{pmatrix} =
\begin{pmatrix}
1 - \lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\
-\lambda & 1 - \lambda^2/2 & A\lambda^2 \\
A\lambda^3(1 - \rho - i\eta) & -A\lambda^2 & 1
\end{pmatrix}
$$

- Nobel prize in 2008
Implications

- When Kobayashi and Maskawa proposed their explanations, only 3 quarks were known.
- The six quark model had several implications:
  - Existence of another 3 quarks to be seen by experiment
  - In 1980/1981 several people predicted large CP violation in $B$ system
- Start of dedicated $B$ physics experiments
- In 2001 Belle and Babar experiments observe large CP violation in $B^0$ decay
- Since then many measurements performed to check idea
Global status

\[ V_{CKM} = \begin{pmatrix} 1 - \frac{\lambda^2}{2} & \lambda A \lambda^3 (\rho - i \eta) \\ -\lambda & 1 - \frac{\lambda^2}{2} A \lambda^2 \\ A \lambda^3 (1 - \rho - i \eta) & -A \lambda^2 \\ 1 \end{pmatrix} \]

\( \alpha = \phi_2 \)

\( \gamma = \phi_3 \)

\( \beta = \phi_1 \)

\( (0,0) \) - \( (1,0) \)

\( (\overline{\rho}, \overline{\eta}) \)

\( \frac{V_{ud}}{V_{ub}} \frac{V_{*ud}}{V_{*ub}} \)

\( \frac{V_{td}}{V_{tb}} \frac{V_{*td}}{V_{*tb}} \)

\( \text{excluded area has } CL > 0.95 \)

\( \text{ICHEP 10} \)
Are we done?

- Does not look to be case
- Many unanswered questions
  - SM has many free parameters
  - What is the meaning of generation, why we need more than one?
  - What is the origin of dark matter and dark energy?
  - How current matter-antimatter asymmetry is generated?
    - No baryon number violation in SM
    - CP violation in SM is many order of magnitude too small
    - In SM cannot generate needed phase transition
- SM is probably just low energy approximation of final big theory of everything
Role of flavor physics

- Several extensions of SM exists, each postulating new particles
- Some examples
  - Fourth generation introduces two additional quark, $V_{CKM}$ is changed to $4 \times 4$ matrix
  - Supersymmetry has partner for each SM particle
  - In supersymmetry squarks/sleptons mix through $3 \times 3$ matrix

$$
\begin{pmatrix}
m_{11}^2 & m_{12}^2 & m_{13}^2 \\
m_{21}^2 & m_{22}^2 & m_{23}^2 \\
m_{31}^2 & m_{32}^2 & m_{33}^2
\end{pmatrix}
$$

- Looking for indirect effects of new physics to discover it
- If new physics is discovered, understand which model is right one
CPV in $B_s \rightarrow J/\psi \phi$

\[
\begin{pmatrix}
V_{ud} & V_{us} & V_{ub} \\
V_{cd} & V_{cs} & V_{cb} \\
V_{td} & V_{ts} & V_{tb}
\end{pmatrix}
= \begin{pmatrix}
1 - \frac{\chi^2}{2} & \frac{\chi}{2} & A\chi^3(\rho - i\eta) \\
-\chi & 1 - \frac{\chi^2}{2} & A\chi^2 \\
A\chi^3(1 - \rho - i\eta) & -A\chi^2 & 1
\end{pmatrix}
\]

- $V_{ts}$ known from unitarity
- Need to check also by experiment
- Best testing ground is decay $B_s \rightarrow J/\psi \phi$
- New physics in mixing can have large effect on CP violation
- Search for large CP violation in $B_s \rightarrow J/\psi \phi$
Sidenote on phases

- $B_s$ system is described by equation

\[
i \frac{d}{dt} \left( \begin{vmatrix} \bar{B}_s^0(t) \\ B_s^0(t) \end{vmatrix} \right) = \left( M - \frac{i}{2} \Gamma \right) \left( \begin{vmatrix} \bar{B}_s^0(t) \\ B_s^0(t) \end{vmatrix} \right)
\]

- Box diagram of mixing give rise to $M_{12}$ and $\Gamma_{12}$

- Interesting quantities and relation to observables:
  - $\Delta M_s = 2 |M_{12,s}^{SM}| \cdot |\Delta_s|$
  - $\phi_s = \arg(-M_{12}/\Gamma_{12}) = \phi_{s}^{SM} + \phi_{s}^{\Delta}$, in SM $\phi_s = (4.2 \pm 1.4) \cdot 10^{-3}$
  - $\Delta \Gamma_s = 2 |\Gamma_{12,s}| \cdot \cos(\phi_{s}^{SM} + \phi_{s}^{\Delta})$

- CP Violation in $B_s \rightarrow J/\psi \phi$ measures
  - $\phi_{s}^{J/\psi \phi} = -2\beta_s + \phi_{s}^{\Delta} + \delta_{Peng}^{SM} + \delta_{Peng}^{NP}$

- With current CDF precision we really test presence of large $\phi_{s}^{\Delta}$
Analysis logic

- Principle is to measure time dependent asymmetry of CP eigenstate

\[ A = \frac{N(B, t) - N(\bar{B}, t)}{N(B, t) + N(\bar{B}, t)} \]

- We need to find in data
  - \( B_s \rightarrow J/\psi \phi \) decays
  - Measure decay time
  - Find out whether it was produced as \( B \) or \( \bar{B} \)
Likelihood anatomy

- Signal PDF for single tag

\[ P_s(t, \bar{\rho}, \xi | D, \sigma_t) = \frac{1 + \xi D}{2} P(t, \bar{\rho} | \sigma_t) \epsilon(\bar{\rho}) + \frac{1 - \xi D}{2} \bar{P}(t, \bar{\rho} | \sigma_t) \epsilon(\bar{\rho}) \]

- $\xi = -1, 0, 1$ is tagging decision
- $D$ is event-specific dilution
- $\epsilon(\bar{\rho})$ - acceptance function in angular space
- $P(t, \bar{\rho} | \sigma_t)$ ($\bar{P}(t, \bar{\rho} | \sigma_t)$) is PDF for $B_s$ ($\bar{B}_s$)
Likelihood anatomy

\[
\frac{d^4 P(t, \vec{\rho})}{dtd\vec{\rho}} \propto |A_0|^2 T_+ f_1(\vec{\rho}) + |A_\parallel|^2 T^+ f_2(\vec{\rho}) + |A_\perp|^2 T^- f_3(\vec{\rho}) \\
+ |A_\parallel||A_\perp| U \pm f_4(\vec{\rho}) + |A_0||A_\parallel| \cos(\delta_\parallel) T_+ f_5(\vec{\rho}) \\
+ |A_0||A_\perp| V \pm f_6(\vec{\rho})
\]

\[
T_\pm = e^{-\Gamma t} \times \left[ \cosh(\Delta \Gamma t/2) \mp \cos(2\beta_s) \sinh(\Delta \Gamma t/2) \mp \eta \sin(2\beta_s) \sin(\Delta m_s t) \right],
\]

\[
U_\pm = \pm e^{-\Gamma t} \times \left[ \sin(\delta_\perp - \delta_\parallel) \cos(\Delta m_s t) \right.
\mp \cos(\delta_\perp - \delta_\parallel) \cos(2\beta_s) \sin(\Delta m_s t) \\
\pm \cos(\delta_\perp - \delta_\parallel) \sin(2\beta_s) \sinh(\Delta \Gamma t/2) \left. \right],
\]

\[
V_\pm = \pm e^{-\Gamma t} \times \left[ \sin(\delta_\perp) \cos(\Delta m_s t) \right.
\mp \cos(\delta_\perp) \cos(2\beta_s) \sin(\Delta m_s t) \\
\pm \cos(\delta_\perp) \sin(2\beta_s) \sinh(\Delta \Gamma t/2) \left. \right].
\]
**Issue of s-wave**

- We reconstruct $B_s \to J/\psi \phi$ with $\phi \to K^+ K^-$
- But wide resonance $f_0(980)$ can also decay to $K^+ K^-$ and $B_s \to J/\psi K^+ K^-$ is also possible (called s-wave)
- There are arguments that s-wave can be large
    \[
    \frac{B(B_s \to J/\psi f_0(980)) B(f_0(980) \to \pi \pi)}{B(B_s \to J/\psi \phi) B(\phi \to KK)} \approx 0.2 - 0.3
    \]
- Best upper bound from Belle
  \[
  B(B_s \to J/\psi f_0(980)) B(f_0(980) \to \pi \pi) < 1.63 \cdot 10^{-4} \text{ at 90\% C.L.}
  \]
- S-wave can contribute to reconstructed signal
- It is CP-odd eigenstate with its own angular and time dependence
- Sizeable contribution which is not accounted for can bias result
  ⇒ Account for it in the likelihood
Treatment of s-wave

- Add amplitude for s-wave ⇔ four angular terms \((\text{amplitude}^2 + 3\) interference terms)
- S-wave amplitude is pure CP-odd eigenstate with its own angular dependence
- Strong phases vary over resonance
  ⇒ Need to start with \(K^+K^-\) mass included
    - Relativistic Breit-Wigner propagator for p-wave
    - Constant for s-wave
- Keep \(K^+K^-\) mass as unobserved ⇔ integrate over it
- Interference between p-wave and s-wave could break last symmetry
- Full math spelled out in arXiv:1008.4283
Previous results

CDF 1.35 fb$^{-1}$
p-value = 15%

CDF 2.8 fb$^{-1}$
p-value = 7%

CDF 2.8 fb$^{-1}$ + DØ 2.8 fb$^{-1}$
p-value = 3.4%

What next?
Tevatron and CDF experiment

- $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV
- Peak luminosity $\approx 3.5 - 3.8 \cdot 10^{32}$ cm$^{-2}$s$^{-1}$
- Collected about $\approx 7$ fb$^{-1}$
Selection

- Latest analysis uses 5.2 fb⁻¹
- Events selected using dimuon trigger
- Typical event has few dozens tracks ⇒ lot of background
- Neural network to select interesting events
- Select ≈ 6500 \( B_s \rightarrow J/\psi \phi \) decays
Flavor tagging

Determination of the flavor at production time

Difficult task due to large number of tracks

Benefits from PID

Calibrated with data
OST Calibration

- Flavor tagging algorithm is characterized by
  - Efficiency $\epsilon$
  - Dilution $D = 2 \cdot P - 1$
- Quantity $\epsilon D^2$ defines effective statistics
- Opposite side tagging is independent of studied hadron
- Effective power of OST is $\epsilon D^2 = 1.2\%$

CDF II Preliminary, 5.2 fb$^1$

CDF Run II Preliminary $L = 5.2$ fb$^1$

<table>
<thead>
<tr>
<th>Flavour</th>
<th>$B^+$</th>
<th>$B^-$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Event</td>
<td>$1.2%$</td>
<td>$1.12 \pm 0.10$</td>
</tr>
<tr>
<td>Dilution Predicted</td>
<td>$0.93 \pm 0.09$</td>
<td>$1.12 \pm 0.10$</td>
</tr>
<tr>
<td>Dilution Measured</td>
<td>$0.93 \pm 0.09$</td>
<td>$1.12 \pm 0.10$</td>
</tr>
</tbody>
</table>

Efficiency $\epsilon$ defines effective statistics

Effective power of OST is $\epsilon D^2 = 1.2\%$

Opposite side tagging is independent of studied hadron

B+ events
Slope = $0.93 \pm 0.09$

B+ events
Slope = $1.12 \pm 0.10$
SSKT Calibration

- SSKT depends on the meson we study
- Only way to calibrate is to use $B_s$ itself
- Fortunately $B_s$ oscillation is sensitive to quality of tagging

Principle

$$A = \frac{N_{mix} - N_{unmix}}{N_{mix} + N_{unmix}} = A \cdot D \cos(\Delta m t)$$

Use decays:

- $B_s \rightarrow D_s \pi$ with $D_s \rightarrow \phi \pi$, $D_s \rightarrow K^* K$ and $D_s \rightarrow \pi \pi \pi$
- $B_s \rightarrow D_s \pi \pi \pi$ with $D_s \rightarrow \phi \pi$

In total $\approx 12900$ signal events

Total tagging power $\epsilon D^2 = 3.2 \pm 1.4\%$

$\Delta m_s = 17.79 \pm 0.07($stat$)$
Angular efficiencies

- Derived from large statistics MC
- Parameterized in three dimensions
- CP Violation relatively insensitive to exact details
- Efficiency compares well with angular distributions of combinatorial background
Lifetime and width difference

Distribution for $B_{sL}$
Distribution for $B_{sH}$
Signal mass region

Under SM assumption ($\beta_s = 0$) we measure:

\[
c_T = \frac{2}{\Gamma_H + \Gamma_L} = 1.529 \pm 0.025\text{(stat)} \pm 0.012\text{(syst)} \text{ ps}^{-1}
\]

\[
\Delta \Gamma_s = 0.075 \pm 0.035\text{(stat)} \pm 0.01\text{(syst)} \text{ ps}^{-1}
\]
Polarization amplitudes

\[ |A_\parallel|^2 = 0.231 \pm 0.014 \text{(stat)} \pm 0.015 \text{(syst)} \]
\[ |A_0|^2 = 0.524 \pm 0.013 \text{(stat)} \pm 0.015 \text{(syst)} \]
\[ \phi_\perp = 2.95 \pm 0.64 \text{(stat)} \pm 0.07 \text{(syst)} \]
CP Violation

- SM p-value is 44%
- Corresponds to 0.8σ
- Significant improvement
- Strong phases free

- SM p-value is 31%
- Comparable to 2D case ⇔ ΔΓ consistent with SM
- \( \beta_s \in [0.02, 0.52] \cup [1.08, 1.55] \) @ 68% C.L.
Comparison to previous result

Concentrate on size of the allowed region

Significant improvement compared to our previous result
Size of the adjustment

CDF Run II Preliminary

L = 5.2 fb^{-1}

\begin{align*}
\Delta \Gamma \text{ (ps}^{-1}) & \quad 1-\text{CL} \\
\beta_s \text{ (rad)} & \\
\end{align*}

-1 0 1

\begin{align*}
\Delta \Gamma \text{ (ps}^{-1}) & \quad 1-\text{CL} \\
\beta_s \text{ (rad)} & \\
\end{align*}

-1 0 1

CDF Run II Preliminary

L = 5.2 fb^{-1}

\begin{align*}
\text{1-CL} & \\
2\Delta \ln(L_p) & \\
\end{align*}

0 5 10 15

-68\% CL

95\% CL

SM prediction

CDF Run II Preliminary

L = 5.2 fb^{-1}

\begin{align*}
\text{1-CL} & \\
2\Delta \ln(L_p) & \\
\end{align*}

0 5 10 15

-68\% CL

95\% CL

SM prediction

21 September 2010

Michal Kreps – Measurement of CP Violation in $B_s \rightarrow J/\psi \phi$ at CDF
**S-wave check**

- **Q:** Is change since last time due to previously omitted s-wave?
  - **A:** No, likelihood almost same with s-wave fixed to zero

- **Q:** Is the $K^+K^-$ mass consistent with our fit model?
  - **A:** Yes it is
Effect of flavor tagging

- With tagging of $\epsilon D^2 \approx 5\%$ we don’t gain lot in precision

- Main effect in reducing ambiguities

- Untagged case symmetric under each
  - $2\beta_s \to -2\beta_s$
  - $\delta_\perp \to \delta_\perp + \pi$
  - $\Delta\Gamma \to -\Delta\Gamma$
  - $2\beta_s \to 2\beta_s - \pi$

- Tagged symmetry
  - $2\beta_s \to \pi - 2\beta_s$
  - $\Delta\Gamma \to -\Delta\Gamma$
  - $\delta_\parallel \to 2\pi - \delta_\parallel$
  - $\delta_\perp \to \pi - \delta_\perp$
Different parts of data
Different parts of data

CDF Run II Preliminary  $L = 5.2 \text{ fb}^{-1}$

Data 0-1.35 fb$^{-1}$  S-wave not included

Data 1.35-2.8 fb$^{-1}$  S-wave not included

Data 2.8-5.2 fb$^{-1}$  S-wave not included

Michal Kreps – Measurement of CP Violation in $B_s \rightarrow J/\psi \phi$ at CDF
Conclusions

- Significantly improved measurement of the CPV in $B_s \rightarrow J/\psi \phi$
  $\beta_s \in [0.02, 0.52] \cup [1.08, 1.55]$ @ 68% C.L.
- CDF data now agree on the $\approx 1\sigma$ level with SM
- Best measurement of
  - Mean lifetime
  - Width difference between mass eigenstates
  - Polarization amplitudes

![Graph showing measurement of CPV in $B_s \rightarrow J/\psi \phi$.](image)
Prospects

- Couple of improvements possible beyond collecting data
  - Include other triggers gives $\approx 25\%$ more statistics
  - Add $B_s \rightarrow \psi(2S)\phi$
  - Look for $B_s \rightarrow J/\psi f_0(980)$ with $f_0(980) \rightarrow \pi^+\pi^-$
  - Add $K^+K^-$ mass as fit variable - helps in ambiguity resolution
- Still collecting data, expect to have $\approx 2$ times more by the end of 2011
- Extension of running by 3 years under discussion