B_s Physics at CDF

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on behalf of the CDF collaboration

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Introduction

- $B_s (s\bar{b}, \bar{s}b, J^P=0^-)$, like many other $B$ hadrons, produced copiously at Tevatron

- No NP-source of CPV in $B^+/B^0$ decays at leading order as found by Belle/BaBar

- In $B_s$, NP can affect both the strength and phase of mixing amplitude

- The strength $\Delta m$ measured at CDF precisely:
  $\Delta m = 17.77 \pm 0.12 \text{ps}^{-1}$

- Phase measurement is the main topic of this talk
Time evolution of $B_s$ flavor eigenstates governed by Schrodinger equation:

\[ i \frac{d}{dt} \left( \begin{array}{c} |B_s^0(t)\rangle \\ |\tilde{B}_s^0(t)\rangle \end{array} \right) = \left( M - \frac{i}{2} \Gamma \right) \left( \begin{array}{c} |B_s^0(t)\rangle \\ |\tilde{B}_s^0(t)\rangle \end{array} \right) \]

⇒ Obtain mass eigenstates

\[ |B_s^H\rangle = p |B_s^0\rangle - q |\tilde{B}_s^0\rangle \quad |B_s^L\rangle = p |B_s^0\rangle + q |\tilde{B}_s^0\rangle \]

⇒ $\Delta m = m_H - m_L = 2|M_{12}|$

$\Gamma = (\Gamma_L + \Gamma_H)/2$

$\Delta \Gamma = \Gamma_L - \Gamma_H = 2|\Gamma_{12}|\cos(\phi_{SM})$

where $\phi_{SM} = \text{arg}(-M_{12}/\Gamma_{12})$

In SM, $\phi_{SM} \sim 4.2 \times 10^{-3}$ very small!

Another interesting parameter

$\alpha_{fs} = \text{Im}(\Gamma_{12}/M_{12}) = |\Gamma_{12}/M_{12}|\sin(\phi_{SM}) = \Delta \Gamma/\Delta m \times \tan(\phi_{SM})$

$B_s$ Neutral System

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CP violation occurs through interference of decay with and without mixing, and predicted to be very small in SM:

\[ \beta_s^{\text{SM}} = \arg(-V_{ts}V_{tb}^*/V_{cs}V_{cb}^*) \approx 0.02 \]

New Physics will affect both the phase \( \phi_s^{\text{SM}} \) and \( \beta_s^{\text{SM}} \) by introducing new physics phase \( \phi_s^{\text{NP}} \):

\[
\phi_s = \phi_s^{\text{SM}} + \phi_s^{\text{NP}}
\]
\[
2\beta_s = 2\beta_s^{\text{SM}} - \phi_s^{\text{NP}}
\]

If NP phase dominates
\[
2\beta_s = -\phi_s = \phi_s^{\text{NP}}
\]
Event Reconstruction

- Data selected by dimuon trigger
- Neural Network trained to separate signal and combinatorial backgrounds
- Cut on NN output to maximize significance $S/\sqrt{S+B}$
Untagged Measurement

- No flavor identification at production time
- 1.7 fb⁻¹ data, ~2500 signal events
- Maximum likelihood fit using mass, time and transversity angles
- Assuming CP conservation, fix $\beta_s$ to 0 to get better sensitivity in average lifetime ($\tau$) and decay width difference ($\Delta\Gamma$)
Measurement without flavor tagging

(CP conservation assumption)

CDF II Preliminary \( L = 1.7 \text{ fb}^{-1} \)

\[ \tau = 1.52 \pm 0.04 \text{(stat)} \pm 0.02 \text{(syst)} \text{ ps} \]

\[ \Delta \Gamma = 0.08 \pm 0.06 \text{(stat)} \pm 0.01 \text{(syst)} \text{ ps}^{-1} \]

Improves the current best measurement by 30\%-50% arXiv:0712.2348
Bias observed in pseudo experiments
4-fold ambiguity causes irregular likelihood profile
→ Can’t quote a central value with uncertainty reliably
→ Using Feldman Cousins construction to obtain a confidence region in $\Delta \Gamma - \beta_s$ space
ΔΓ-β_s Confidence Region
(without flavor tagging)

Consistent with SM expectation

Sizeable values allowed within new physics models can’t be ruled out

ΔΓ=|Γ_{12}|x\cos(φ_s)

CDF Run II Preliminary L = 1.7 fb⁻¹

For SM prediction, the probability to get equal or bigger likelihood ration than the one observed in data is p=22%, corresponding to 1.2 Gaussian standard deviation

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arXiv:0712.2348
Measurement with Tagging
(with flavor identification at production time)

- Ambiguity: $4 \rightarrow 2$
- More sensitivity to $\beta_s$
- Calibrated up to $1.35 \text{ fb}^{-1} \sim 2000$ signal events
- Confidence region in $\Delta \Gamma - \beta_s$ plane with Feldman-Cousins Method for the same reason as in untagged case

Semileptonic Muon Tag
Semileptonic Electron Tag
Jet Charge Tag

Each tagged event has:
Correct tagging prob: $P = (1+D_i)/2$
OST: $\varepsilon \sim 96\%$, $\overline{D} \sim 11 \pm 2\%$
SST: $\varepsilon \sim 50\%$, $\overline{D} \sim 27 \pm 4\%$

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**β_s Final Result in Tagged B_s → J/ψ φ**

- **without flavor tagging**
  - Reduce the space of solutions by 50%!
  - Excluded large negative β_s values!
  - arXiv:0712.2397

- **with flavor tagging**
  - Assuming SM(β_s=0.02, ΔΓ=0.96), the probability is 15%, 1.5σ effect
  - 1D Feldman-Cousins with external constraints on strong phases, lifetime and |Γ12|, 2β_s in [0.40, 1.20] at 68% C.L.

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CP Asymmetry for Semileptonic $B_s$ Decays (1.6 fb$^{-1}$)

Using semileptonic decays of $b\bar{b}$ pairs, looking for same-sign muons states that indicates mixing, fitting the 2D distribution of impact parameter significance:

$$A_{SL} = 0.0080 \pm 0.0090 \text{ (stat)} \pm 0.0068 \text{ (syst)}$$

With knowledge of world average $f_s Z_s$, $f_d Z_d$, and $B^0$ semileptonic asymmetry from $B$ factories, we can get:

$$A^{s}_{SL} = 0.020 \pm 0.028$$

68% CL

Can be used to further constrain $\phi_s$ with the CP violation measurement from $B_s \rightarrow J/\psi \phi$

http://www-cdf.fnal.gov/physics/new/bottom/070816.blessed-acp-bsemil/
**B_s Lifetime in B_s → D_s(φπ)X**

using both the fully and partially reconstructed modes in 1.3 fb\(^{-1}\) of data reconstructed as B_s → D_s(φπ)π.

\[ \tau(B_s \rightarrow D_s(\phi\pi)) = 1.518 \pm 0.041 \text{(stat.)} \pm 0.025 \text{(syst.)} \text{ ps} \]
Conclusion

- Best $B_s$ lifetime and decay width difference measurement
- First CP violation result using tagged $B_s\rightarrow J/\psi \phi$ decays
- Large negative $\beta_s$ (positive $\phi^s$) values excluded
- Working hard on double statistics for the summer
DØ quotes only a point-estimate with strong phases constrained. This makes the result dependent on theoretical assumptions.

Can be compared to CDF constrained result \( 2\beta_s \in [0.40, 1.20] \) @ 68% CL
Collider and Detector

- pp collisions at 1.96 TeV
- 1.7 MHz collision rate (396 ns bunch spacing)
- ~2.9 fb⁻¹ data on tape
- Initial instantaneous luminosity 2.9 x 10³² cm⁻² s⁻¹
- Average 5-6 pp⁻¹ interactions per bunch crossing

- Central tracking includes silicon vertex detector surrounded by drift chamber
- Excellent vertex resolution ~23 μm
- p_T resolution δp_T/p_T = 0.15%p_T
- Particle identification: dE/dX and TOF
- Good electron and muon identification by calorimeters and muon chambers

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CP Violation in $B_s$ System

- Standard Model CP violation occurs through complex phases in the unitary CKM quark mixing matrix:

$$
\begin{pmatrix}
    d' \\
    s' \\
    b'
\end{pmatrix}
= 
\begin{pmatrix}
    V_{ud} & V_{us} & V_{ub} \\
    V_{cd} & V_{cs} & V_{cb} \\
    V_{td} & V_{ts} & V_{tb}
\end{pmatrix}
\begin{pmatrix}
    d \\
    s \\
    b
\end{pmatrix}
$$

- Expanded in $\lambda = \sin(\theta_{\text{Cabibbo}}) \approx 0.23$:

$$
\begin{pmatrix}
    1 - \frac{1}{2} \lambda^2 - \frac{1}{8} \lambda^4 \\
    -\lambda + \frac{1}{2} A^2 \lambda^5 [1 - 2(\rho + i\eta)] \\
    A\lambda^3 [1 - (1 - \frac{1}{2} \lambda^2)(\rho + i\eta)]
\end{pmatrix}
\begin{pmatrix}
    \lambda \\
    1 - \frac{1}{2} \lambda^2 - \frac{1}{8} \lambda^4 (1 + 4A^2) \\
    -A\lambda^2 + \frac{1}{2} A\lambda^4 [1 - 2(\rho + i\eta)]
\end{pmatrix}
\begin{pmatrix}
    A\lambda^3(\rho - i\eta) \\
    A\lambda^2 \\
    1 - \frac{1}{2} A^2 \lambda^4
\end{pmatrix}
$$

- Unitarity relations:

$$
V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0 \\
V_{us}V_{ub}^* + V_{cs}V_{cb}^* + V_{ts}V_{tb}^* = 0
$$

$B_d$ unitarity triangle  $B_s$ unitarity triangle

- Unitarity triangles

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Transversity Angles
\[ \frac{d^4 P(t, \vec{\rho})}{dt d\vec{\rho}} \propto |A_0|^2 T_+ f_1(\vec{\rho}) + |A_\parallel|^2 T_+ f_2(\vec{\rho}) \\
+ |A_\perp|^2 T_- f_3(\vec{\rho}) + |A_\parallel| A_\perp U_+ f_4(\vec{\rho}) \\
+ |A_0| |A_\parallel| \cos(\delta_\parallel) T_+ f_5(\vec{\rho}) \\
+ |A_0| |A_\perp| \nu f_6(\vec{\rho}), \]

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

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

\[ V_\pm = \pm e^{-\Gamma t} \times \left[ \sin(\delta_\perp) \cos(\Delta m_s t) \right] \\
\pm \cos(\delta_\perp) \cos(2\beta_s) \sin(\Delta m_s t) \]

\text{\textit{\textquoteleft\textquoteleft strong phases:}}
\delta_\parallel \equiv \text{arg}(A^*_\parallel A_0) \\
\delta_\perp \equiv \text{arg}(A^*_\perp A_0) \]
Neural Network details

- Signal pattern: Monte Carlo
- Background pattern: J/ψ background
- Input variables includes
  - $B_s$: $P_T$ and vertex prob
  - $J/ψ$: $P_T$ and vertex prob
  - $ϕ$: mass and vertex prob
  - $K^{±}$: $P_T$ and PID (dE/dX, TOF)
Further Results

- 1D Feldman-Cousins procedure, \( 2\beta_s \) in \([0.32, 2.82]\) at the 68% C.L.

- 1D Feldman-Cousins procedure, apply constraint \(|\Gamma_{12}| = 0.048 \pm 0.018\)
\( 2\beta_s \) in \([0.24, 1.36] \cup [1.78, 2.90]\) at the 68% C.L.

- 1D Feldman-Cousins with external constraints on strong phases, lifetime and \(|\Gamma_{12}|\), \( 2\beta_s \) in \([0.40, 1.20]\) at 68% C.L.

\( \beta_s \) Physics at CDF/chunlei Liu
Future sensitivity

Projected Confidence Regions in 6 fb$^{-1}$ assuming same yield per fb$^{-1}$ in future and same tagging efficiency and dilution

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Measure same sign muon charge asymmetry
at CDF with 1.6 fb⁻¹:

\[ A_{BB} = \frac{N^{++} - N^{--}}{N^{++} + N^{--}} \rightarrow A_{\mu\mu}^{\mu\mu} \]

\[ A_{SL}^{\mu} = \frac{(f_d Z_d) A_{SL}^d + (f_s Z_s) A_{SL}^s}{f_d Z_d + f_s Z_s} \]

With knowledge of world average \( f_s Z_s \), \( f_d Z_d \), and \( B^0 \) semileptonic asymmetry from B factories, we can get:

\[ A_{SL}^s = 0.020 \pm 0.021 \text{ (stat)} \pm 0.016 \text{ (syst)} \pm 0.009 \text{ (inputs)} \]

\[ A_{SL}^s = \frac{\Delta \Gamma_s}{\Delta M_s} \tan \phi_s \]

\( f_s, f_d \) are fractions of produced \( B_s \) and \( B_d \) mesons, \( Z_s \) and \( Z_d \) are mixing related weights

\( B_s \) Physics at CDF/chunlei Liu