First CP Violation Measurements in B_s Mesons System at CDF

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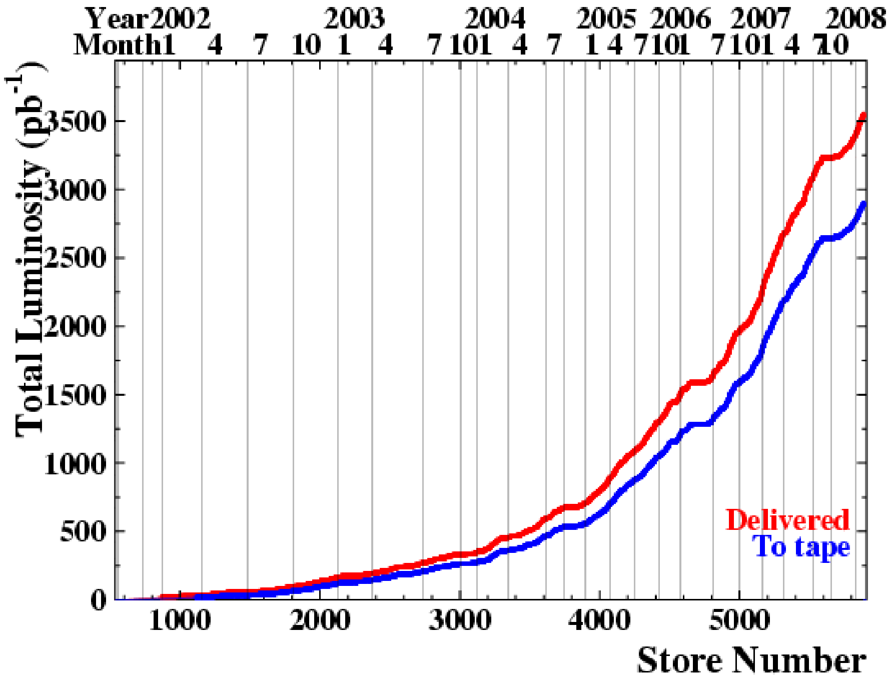
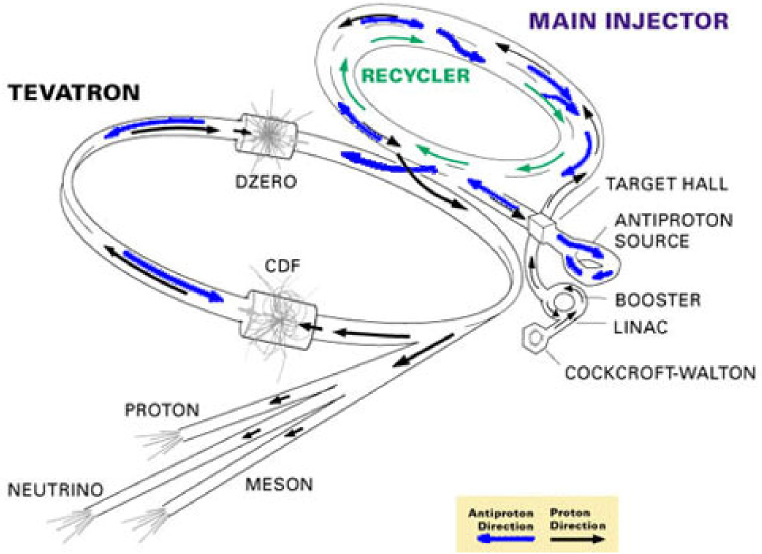
Synopsis

- Theory and Motivations
- CDF Detectors
- Analysis Review:
    - Polarization Measurements on $B_d \to J/\Psi\ K^{*0}$ decays
    - Sin(2β_s) measurement:
        - ✓ Untagged Analysis on $B_s \to J/\Psi\ \Phi$ decays
        - ✓ Flavor Tagged Analysis on $B_s \to J/\Psi\ \Phi$ decays
- Summary and Conclusions

The Tevatron

- $p\bar{p}$ collisions at 1.96 TeV
- Excellent Performance
- Peak Initial Luminosity: $\underline{3 \times 10^{32}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}}$
- Challenge for Detectors, Triggers and Reconstructions





- Tevatron detectors are the only one to have currently access to B_s mesons
- The analyses presented in this talk span from 1.35 to 1.7 fb^{-1}
- Currently on tape ~3 fb^{-1}

CP Violation in Standard Model

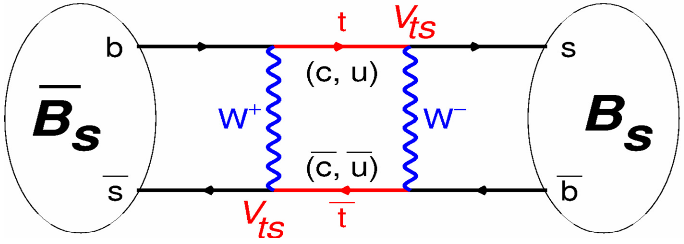
- CP Violation is the non-conservation of combined charge-parity quantum numbers

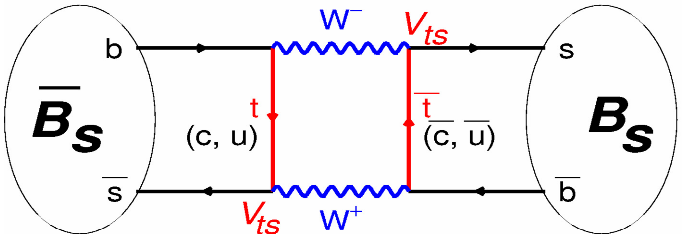
- CP Violation in SM is due to complex coupling of the W boson to quarks through the CKM mechanism:

$$\textbf{WEAK EIGENSTATES} \quad \begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = V \begin{pmatrix} d \\ s \\ b \end{pmatrix} \quad \textbf{STRONG EIGENSTATES}$$

$$V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

Neutral B_s System





Flavor eigenstates:

$$|B_s\rangle = (\bar{b}s)$$
$$|\overline{B}_s\rangle = (b\bar{s})$$

Mass eigeinstates are ($|p|^2+|q|^2=1$):

$$|B_H(t)\rangle = p|B_s(t)\rangle + q|\overline{B}_s(t)\rangle;$$
$$|B_L(t)\rangle = p|B_s(t)\rangle - q|\overline{B}_s(t)\rangle$$

⇒ Different Masses:

$\Delta m_s = M_H - M_L \approx 2|M_{12}|$ defines the Mixing Oscillation Frequency

⇒ Different Lifetimes:

$$\Delta\Gamma_s = \Gamma_L - \Gamma_H \approx 2|\Gamma_{12}|\cos\Phi_s,$$

CPV phase:

$$\Phi_s = \arg(-\frac{M_{12}}{\Gamma_{12}})$$

Sizeable $\Delta\Gamma_s$:

$$\Delta\Gamma_s > \Delta\Gamma_d$$

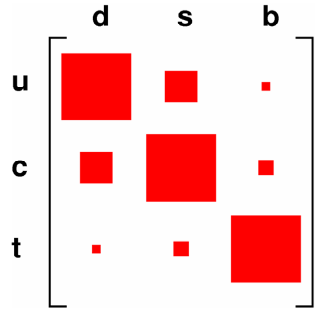
CKM Matrix

- Unitarity condition for CKM matrix $V^{\dagger}V=1$:
  - ✓ Three families ⇒ 4 independent parameters
- Wolfenstein Parameterization:

$$V_{CKM} = \begin{pmatrix} 1-\frac{1}{2}\lambda^2-\frac{1}{8}\lambda^4 & \lambda & A\lambda^3(\rho-i\eta) \\ -\lambda+\frac{1}{2}A^2\lambda^5[1-2(\rho+i\eta)] & 1-\frac{1}{2}\lambda^2-\frac{1}{8}\lambda^4(1+4A^2) & A\lambda^2 \\ \boxed{A\lambda^3[1-(1-\frac{1}{2}\lambda^2)(\rho-i\eta)]} & \boxed{-A\lambda^2+\frac{1}{2}A\lambda^4[1-2(\rho+i\eta)]} & 1-\frac{1}{2}A^2\lambda^4 \end{pmatrix} + 0(\lambda^6)$$

Large CPV

Suppressed CPV



- Expansion in terms of $\lambda=\sin(\theta_c)\sim 0.23$
- η responsible for CP Violation ⇒ $\eta \neq 0$ implies CPV

⇒ Standard Model does not predict values for CKM elements

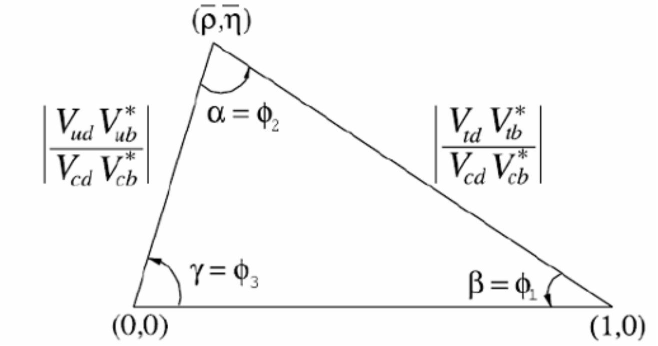
⇒ Experimental Input is crucial

Unitarity of CKM Matrix

- Unitarity condition for CKM matrix $V^{\dagger}V=1$:

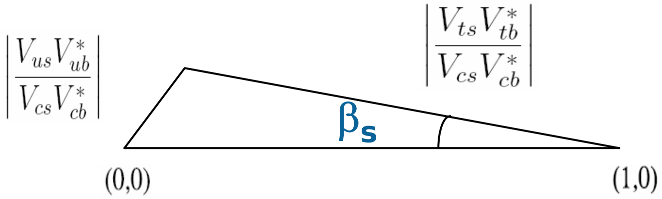
  ⇒ Can construct six unitarity relation between distinct columns or rows of CKM matrix

- Unitarity Triangle:



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

- Unitarity Triangle in B_s System:



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

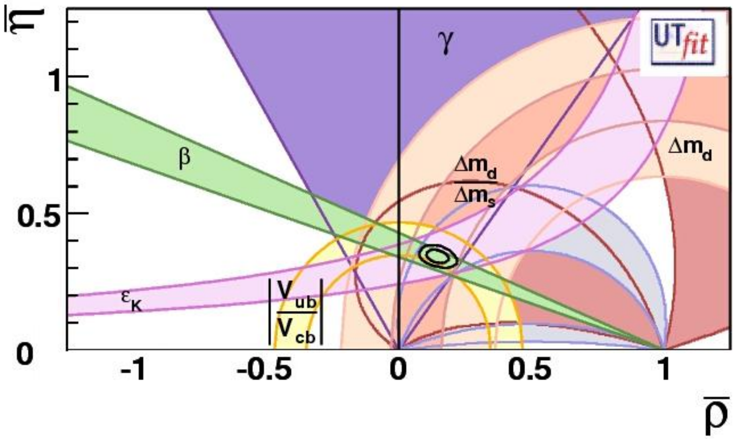
$$\beta_S^{SM} = \arg\left(-\frac{V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*}\right) \sim 0.02 \text{ rad}$$

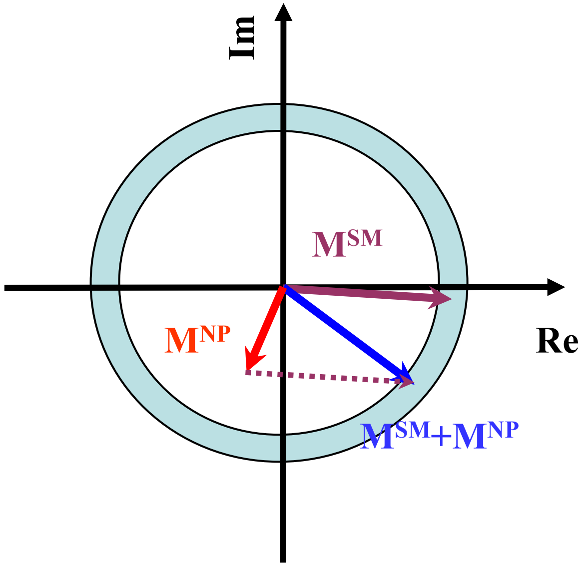
⇒ Evidence of non-unitarity would suggest presence of unknown physics contributions

CP Violation in B_s System

- B_s mixing oscillation observed by **CDF**:
  - ✓ $\Delta m_s = M_H - M_L \approx 2|M_{12}|$ is well measured
  - ✓ Precisely determines $|M_{12}|$ in good agreement with the Standard Model

$\Delta m_s = 17.77 \pm 0.10\ (\text{stat}) \pm 0.07\ \text{ps}^{-1}$





- Phase of the mixing amplitude is instead poorly determined
- Both are needed to constrain New Physics:

$$M_{12} = |M_{12}|e^{i\Phi M}$$

New Physics in $\cancel{CP}$ in B_s Decays

- If New Physics present in mixing amplitude:
  - $\boxed{\Phi_s = \Phi_s^{SM} + \Phi_s^{NP} \sim \Phi_s^{NP}}$ $[\Phi_s^{SM} \sim 0.004 \text{ rad}]$
  - Phase Φ_s can be measured directly using charge asymmetry in B_s semileptonic decays or through $\Delta\Gamma_s$ measurement
- CP violation phase β_s is also expected to be <u>small</u> in the Standard Model:
  - $\boxed{\beta_s = \arg\left(-\frac{V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*}\right) \sim 0.02 \text{ rad}}$
- <u>Same</u> New Physics phase Φ_s^{NP} would add to $\beta_s \Rightarrow$ $2\beta_s = 2\beta_s^{SM} - \Phi_s^{NP}$
- if NP dominates $2\beta_s = -\Phi_s$

$\Rightarrow$ Sensitive to NP effect in $M_{12} = |M_{12}|e^{i\Phi M} = |M_{12}|e^{-i2\beta s} = |M_{12}|e^{i\Phi s}$

$\Rightarrow$ Large CP violation phase in $B_s \rightarrow J/\Psi\ \Phi$ decay is unequivocal sign of physics beyond the Standard Model

CP Violation in Meson Decays

1. **Direct** CP Violation in decay:

$$\boxed{\Gamma(B \to f) \neq \Gamma(\bar{B} \to \bar{f})}$$

$$A(B \to f) = \sum A_k e^{i(\boxed{\delta_k} + \boxed{\Phi_k})} \longrightarrow A(\bar{B} \to \bar{f}) = \sum A_k e^{i(\delta_k - \Phi_k)} \quad \Rightarrow \quad |\bar{A}_f / A_f| \neq 1$$

from QCD

from CKM

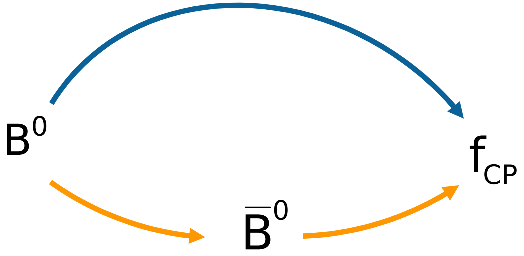
2. CP Violation in **Mixing**:

$$|B^0\rangle \ \ldots\ldots \ t \ \ldots\ldots \ (q/p) g_-(t) |\bar{B}^0\rangle$$

$$|\bar{B}^0\rangle \ \ldots\ldots \ t \ \ldots\ldots \ (p/q) g_-(t) |B^0\rangle$$

- If $|q/p|^2 \neq 1$ it is possible to measure CP violation in decays to final states accessible only to B^0 or $\bar{B}^0$

3. **Indirect** CP Violation in the interference of decays with and without mixing:



$$\Rightarrow \quad \lambda_f = \frac{q}{p}\frac{\bar{A}_f}{A_f} \neq 1$$

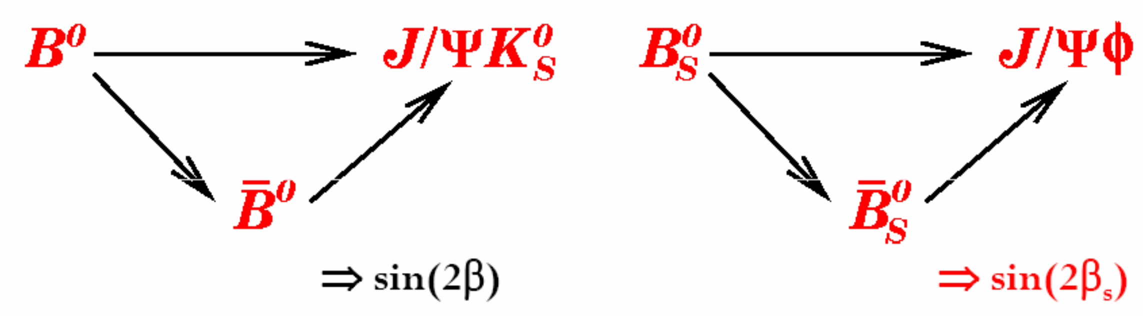
Today Physics Topic!

$\cancel{CP}$ in $B_s \to J/\Psi\Phi$ Decays

- CP Violation arises from the interference between decay ($B \to f_{CP}$) and mixing ($B \to \overline{B} \to f_{CP}$) amplitudes:
- $A_{f_{cp}}(t) = \dfrac{\Gamma(\overline{B} \to f) - \Gamma(B \to f)}{\Gamma(\overline{B} \to f) + \Gamma(B \to f)} = \dfrac{2\mathrm{Im}\lambda_f}{1+|\lambda_f|^2}\sin(\Delta m\, t) - \cancel{\dfrac{1-|\lambda_f|^2}{1+|\lambda_f|^2}}\cos(\Delta m\, t)$

In the limit of
$|\lambda_f| = 1$
(No direct CPV)

$$\boxed{\begin{array}{l} \lambda_f = \dfrac{q\overline{A}_f}{pA_f} = \eta_f\, e^{-i2\beta}, \\ \eta_f = \pm 1 \text{ for } CP(f) = \pm 1 \end{array}} \Rightarrow A_{f_{cp}}(t) = \eta_f \boxed{\sin(2\beta)} \sin(\Delta m\, t)$$



- $\sin(2\beta_s) \approx 0$, compared to $\sin(2\beta) \approx 0.70$

Analysis Strategy

General Analysis Strategy

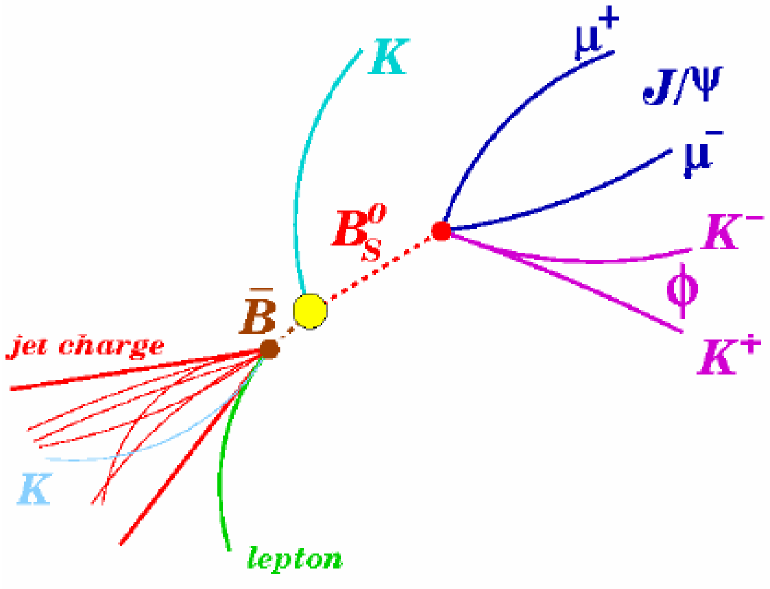
1. Reconstruct decays from stable products:
   - $B_s \rightarrow J/\Psi[\mu^+\mu^-]\ \Phi[K^+K^-]$
   - $B_d \rightarrow J/\Psi[\mu^+\mu^-]\ K^{*0}[K^+\pi^-]$
   - B_d is used a control sample

2. Measure lifetime $ct = m_B * L_{xy}/p_T$

3. Measure decay angles $\vec{w} = (\theta,\ \Phi,\ \psi)$

4. Identify B_s / $\overline{B}_s$ at production time:
   - Flavor Tagging (Tag decision ξ)

5. Perform maximum likelihood fit:
   - Likelihood in m, ct, $\vec{w}$, ξ



Overview of the decay:

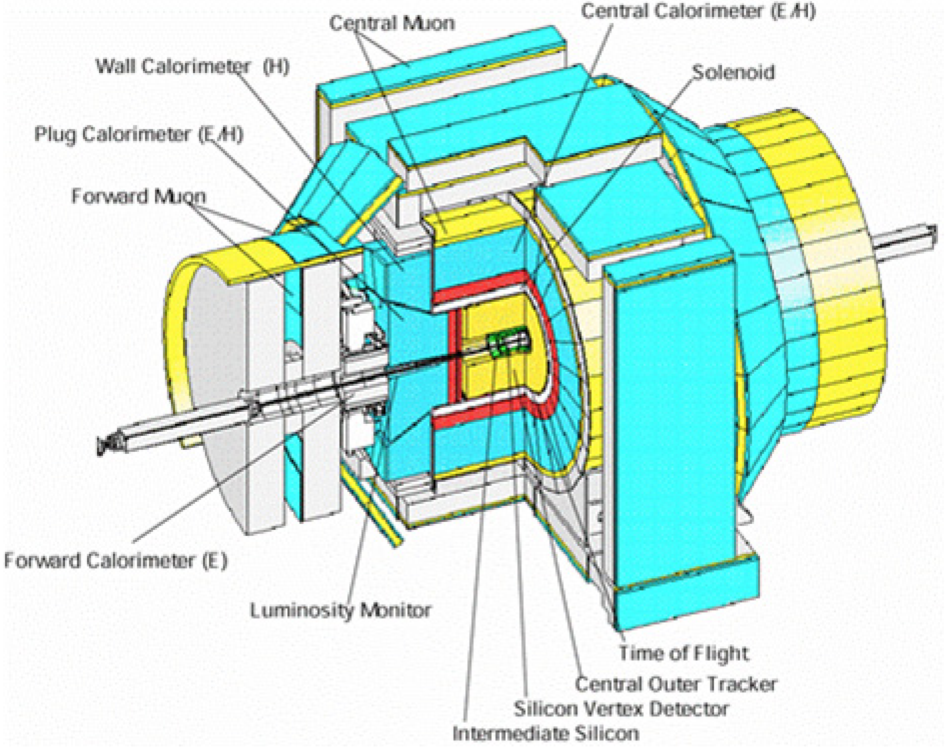
- B_s travels ~450 μm before decaying into J/Ψ and Φ

CDF Run II Detector

- Multi-purpose detector
- Classical layered structure
- Excellent momentum resolution $\sigma(p)/p < 0.1\%$
- Triggered Muon Coverage $|\eta| < 1.0$

- **Yield (S)**:
  - ✓ Displaced Track Trigger
  - ✓ Di-muon Trigger
- **Proper time resolution (σ_{ct})**:
  - ✓ ISL, SVXII, L00
    (Silicon Strip Vertex Detector)
- **Particle Identification**:
  - ✓ TOF (Time Of Flight)
  - ✓ dE/dx in COT (Drift Chambers)

    ⇒ Flavor Tagging Power (εD^2)



Data Sample and Selection

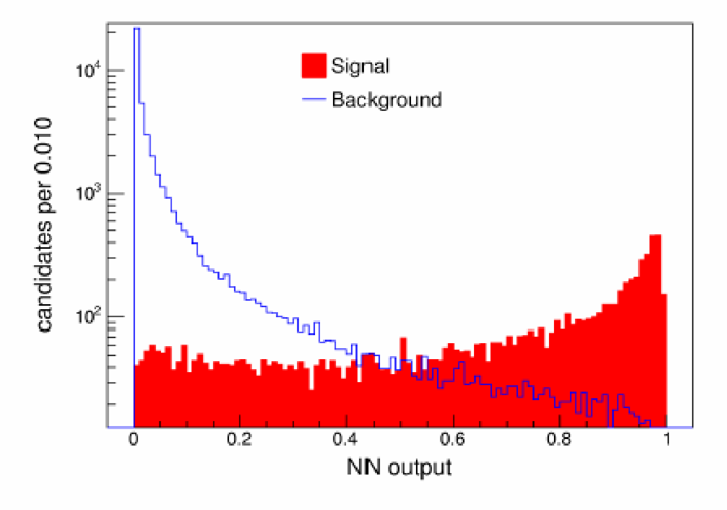
- Data with 1.35 fb^{-1} (1.7 fb^{-1})

- Di-muon trigger

- Soft preselection followed by neural network selection

- <u>NN trained on</u>:
  - ✓ Simulated events for signal
  - ✓ B_s mass sidebands for background

- Selection maximizes $\boxed{S/\sqrt{S+B}}$ under signal peak



<u>NN Variables</u>:

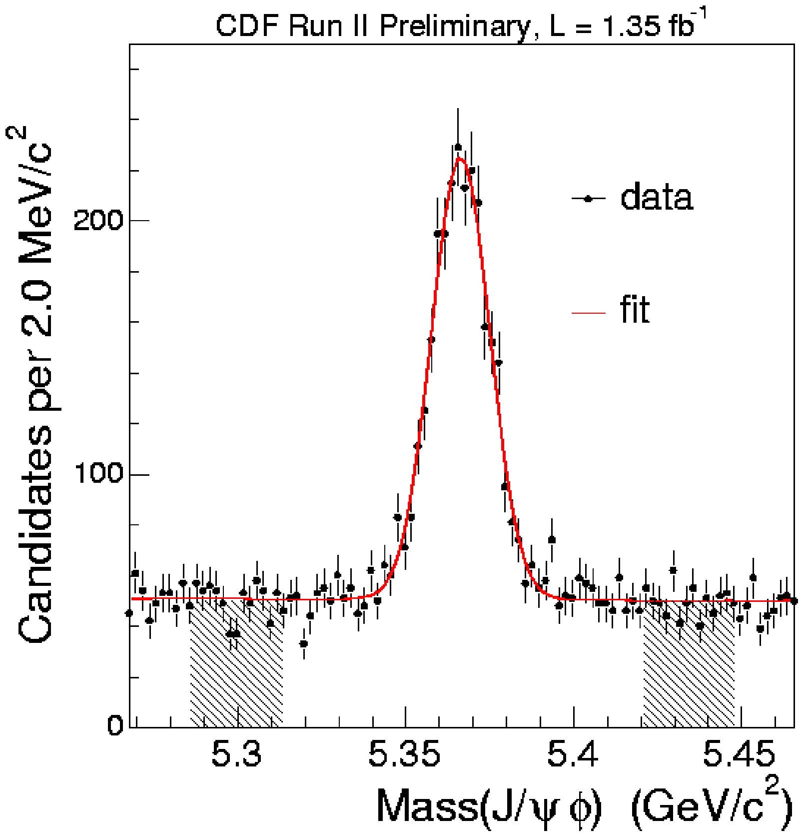
B_s: p_T and vertex quality

J/Ψ: p_T and vertex quality

Φ: mass and vertex quality

K^+/K^-: p_T and PID (TOF, dE/dx)

$B_s \rightarrow J/\Psi\ \Phi$ Signal

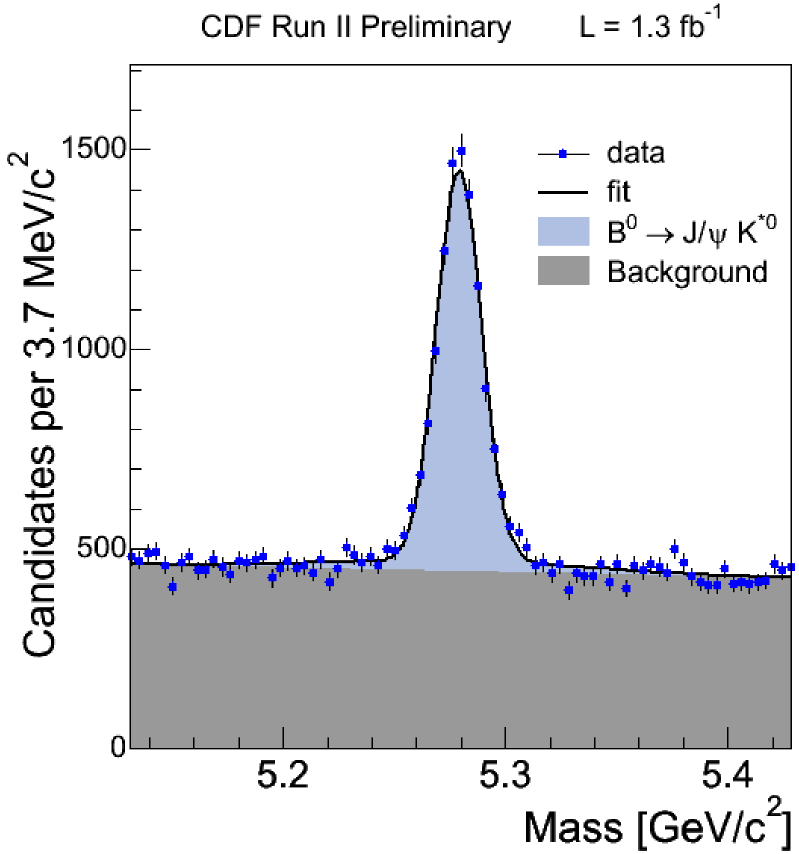


Signal Candidates:

- ~2000 in 1.35 fb^{-1} (Tagged analysis)
- ~2500 in 1.7 fb^{-1} (Untagged analysis)

S/B~2

$B_d \rightarrow J/\Psi\ K^{*0}$ Signal

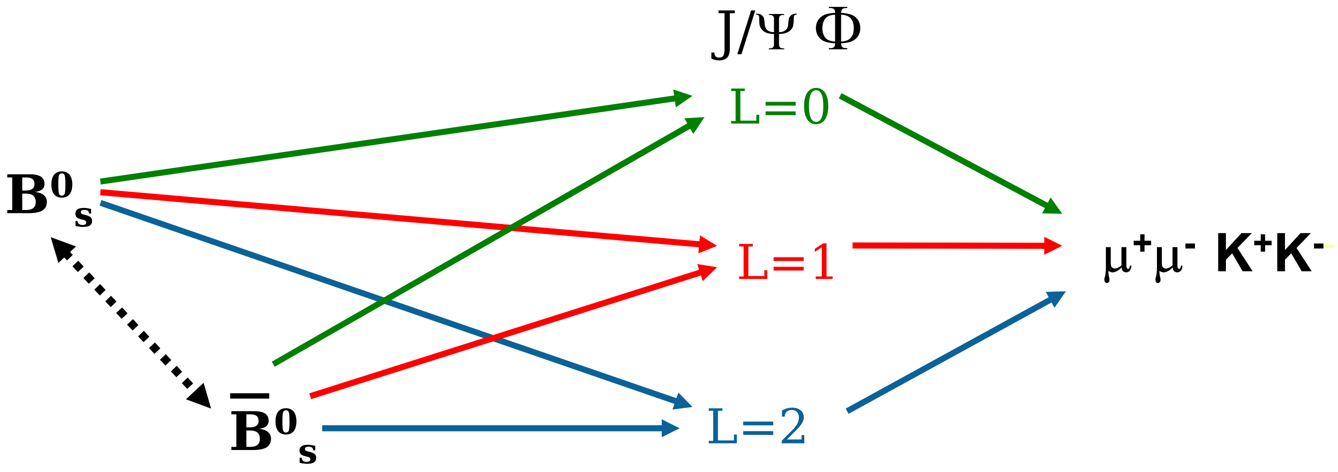


Signal Candidates:

- ~7800 in 1.35 fb^{-1}

CP Eigeinstates Separation

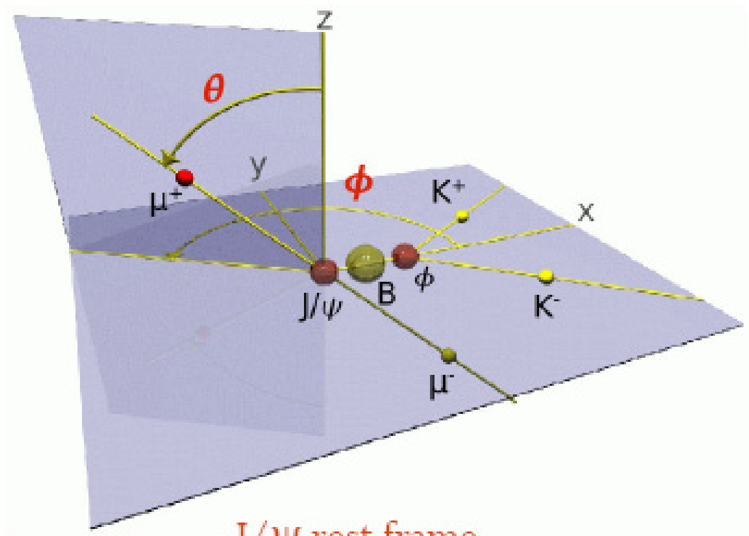
- $B_s \to J/\Psi\ \Phi$ ($B_d \to J/\Psi\ K^{*0}$) decays into <u>admixture</u> CP eigeinstates
- Spin-0 B_s decays to spin-1 J/Ψ and spin-1 Φ three different angular momentum final states:
  - ✓ L=0 (S-wave), L=2 (D-wave) ⇒ P-even
  - ✓ L=1 (P-wave) ⇒ P-odd



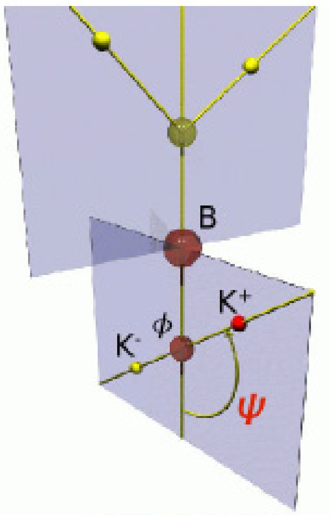
- C-even ⇒ <u>Different Parity</u> ⇒ Separate CP contributions
- Different parity contributions disentangled by their different decay angle distributions

$B_s \to J/\Psi\ \Phi$ Angular Analysis

TRANSVERSITY BASIS



J/ψ rest frame



φ rest frame

Angular momentum:

- $P \to VV$ decay:
  - ✓ L=0
  - ✓ L=1
  - ✓ L=2

Transversity Basis:

- 3 Angles $\vec{w} = (\theta,\ \Phi,\ \psi)$:
  - ✓ θ (J/Ψ rest frame)
  - ✓ Φ (J/Ψ rest frame)
  - ✓ Ψ (Φ rest frame)

- In the Transversity basis the vector mesons polarization w.r.t the direction of motion is:

✓ Longitudinal ⇒ A_0 [CP-even]
✓ Transverse and parallel to each other ⇒ $A_{||}$ [CP-even]
✓ Transverse and perpendicular to each other ⇒ $A_\perp$ [CP-odd]

$P \rightarrow VV$ Decay Rate Formula (I)

General decay rate formula:

$$\begin{aligned}\frac{d^4P(t,\vec{w})}{dt\,d\vec{w}} \propto\ & |A_0|^2\, T_+ f_1(\vec{w}) + |A_{||}|^2\, T_+ f_2(\vec{w}) \\ & + |A_\perp|^2\, T_- f_3(\vec{w}) + |A_{||}||A_\perp|\, U_+ f_4(\vec{w}) \\ & + |A_0||A_{||}|\cos(\delta_{||}) T_+ f_5(\vec{w}) \\ & + |A_0||A_\perp|\, V_+ f_6(\vec{w})\end{aligned}$$

- Strong phases:
  - ✓ $\delta_{||} \equiv \arg(A_{||}^* A_0)$
  - ✓ $\delta_\perp \equiv \arg(A_\perp^* A_0)$

- Decay rate is a function of time, decay angles $\vec{w}$, initial B_s flavor and parameters $\Delta\Gamma_s$, β_s

- B_s decays into admixture of CP eigeinstates $\Rightarrow$ interference terms in general decay rate formula

- f_i (i=1,…,6) encode the different angular distributions

$P \to VV$ Decay Rate Formula (II)

General decay rate formula:

$$\frac{d^4P(t,\vec{w})}{dtd\vec{w}} \propto |A_0|^2\, T_+ f_1(\vec{w}) + |A_{||}|^2\, T_+ f_2(\vec{w})$$
$$+ |A_\perp|^2\, T_- f_3(\vec{w}) + |A_{||}||A_\perp|\, U_+ f_4(\vec{w})$$
$$+ |A_0||A_{||}|\cos(\delta_{||}) T_+ f_5(\vec{w})$$
$$+ |A_0||A_\perp|\, V_+ f_6(\vec{w})$$

- Strong phases:

✓ $\delta_{||} \equiv \arg(A_{||}^* A_0)$
✓ $\delta_\perp \equiv \arg(A_\perp^* A_0)$

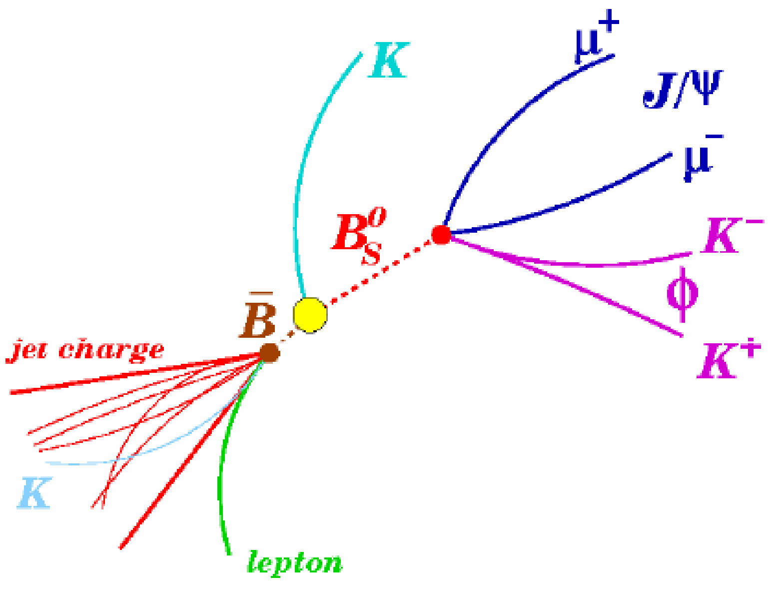
$$T_\pm = e^{-\Gamma t} \text{ x } [\cosh(\Delta\Gamma t/2) \mp \cos(2\beta_s)\sinh(\Delta\Gamma t/2)$$
$$\mp \eta \sin(2\beta_s)\sin(\Delta m_s t)\,],\quad \eta = +1(-1) \text{ for } P(\overline{P})$$

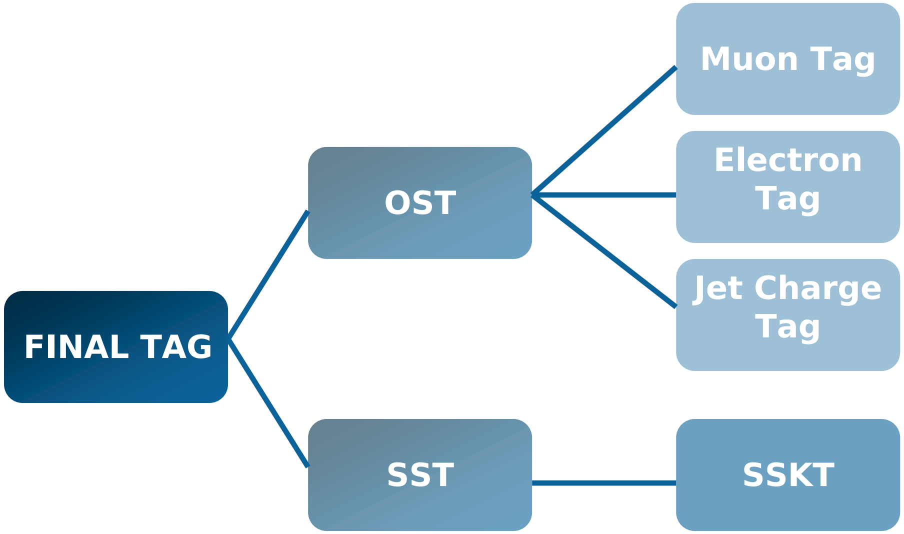
$$U_\pm = \pm e^{-\Gamma t} \text{ x } [\,\sin(\delta_\perp - \delta_{||})\cos(\Delta m_s t)$$
$$- \cos(\delta_\perp - \delta_{||})\cos(2\beta_s)\sin(\Delta m_s t)$$
$$\pm \cos(\delta_\perp - \delta_{||})\sin(2\beta_s)\sinh(\Delta\Gamma t/2)]$$

$$V_\pm = \pm e^{-\Gamma t} \text{ x } [\,\sin(\delta_\perp)\cos(\Delta m_s t)$$
$$- \cos(\delta_\perp)\cos(2\beta_s)\sin(\Delta m_s t)$$
$$\pm \cos(\delta_\perp)\sin(2\beta_s)\sinh(\Delta\Gamma t/2)]$$

Terms with Δm_s dependence flip sign for initial B_s flavor

Flavor Tagging





- Two independent methods of tagging: same and opposite side
- Opposite Side Tagger is calibrated using data (high stat B^+, B^0)
- Same Side Tagger is calibrated on Monte Carlo
- Efficiency ε=P(tag decision)
- Dilution D=1-2q, q is mistag probability

Flavor Tagging

Opposite Side Tagging

- Soft Lepton Taggers
- Jet Charge Tagger

OST’s perform identically in $B_{u,d,s}$:
Calibrated in high statistics B^+/B^0 data

- Combined Performance:

✓ Efficiency: $\varepsilon = 0.96 \pm 0.01$
✓ Average Dilution: $D = 0.11 \pm 0.02$

Same Side Kaon Tagging

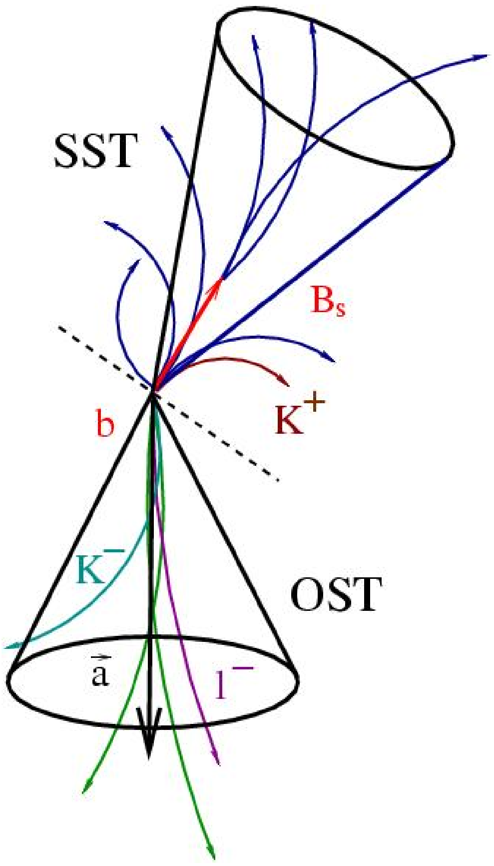
- Most powerful tagger available:

✓ 2-3 times more effective than combined OST

SSKT is different for B^0, B^+ and B_s:
SST needs to rely on MC simulation

- Performance:

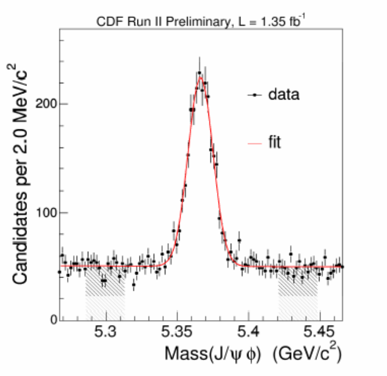
✓ Efficiency: $\varepsilon = 0.50 \pm 0.01$
✓ Average Dilution: $D = 0.27 \pm 0.04$



OST and SST combined independently

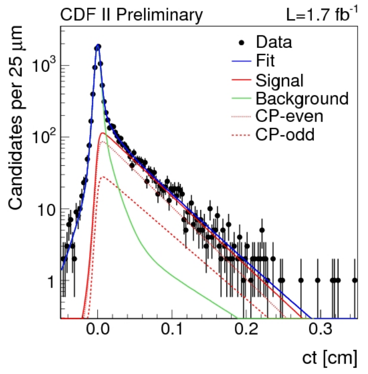
Signal PDF for $B_s \rightarrow J/\Psi\ \Phi$

$$P_s = P_M(\boxed{m \mid \sigma_m})\ P_L(\boxed{ct,}\ \boxed{\vec{w},}\ \boxed{\xi} \mid D,\ \boxed{\sigma_{ct}})\ P(\boxed{D})\ \varepsilon(\vec{w})$$



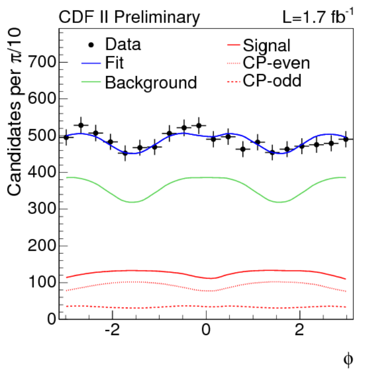
Mass:

discriminates signal against background



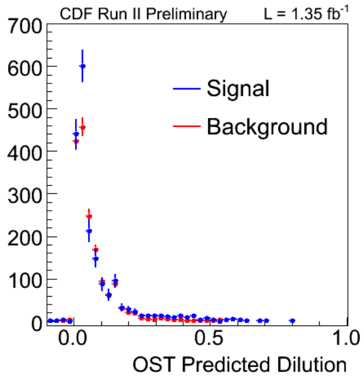
Decay-time:

determines lifetime of CP and flavor state



Angles:

separate CP-even from CP-odd final states



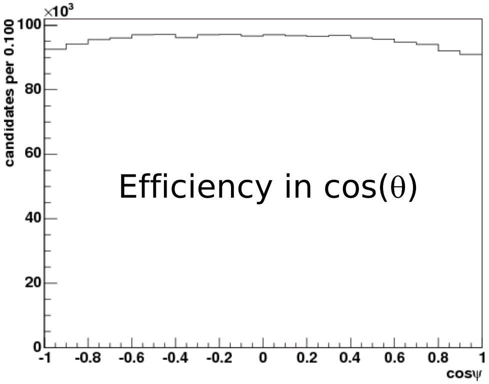
Tagging:

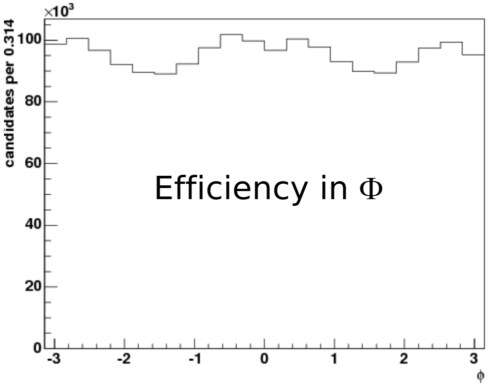
determine flavor of initial states

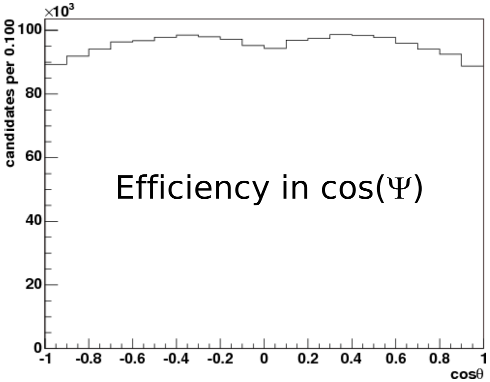
- $\varepsilon(\vec{w})$ is the sculpting of transversity angles due to detector acceptance

Detector Sculpting of Angles

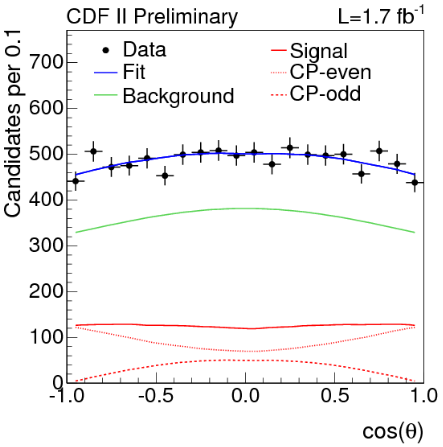
- Monte Carlo passed through detector simulation and to determine angular sculpting
- Deviation from flat distribution indicates detector effects

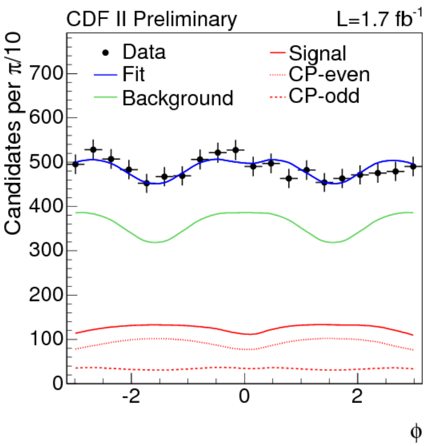


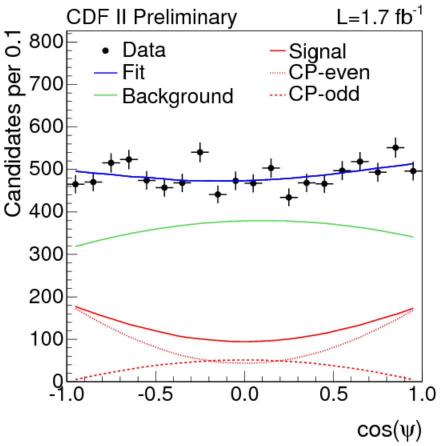




- Data projections uncorrected for detector sculpting

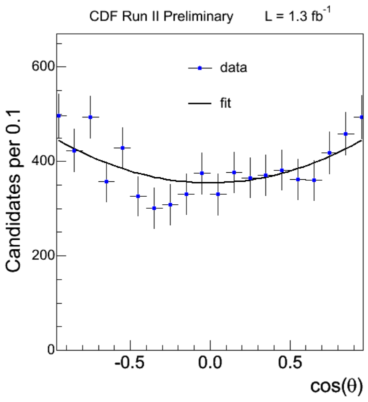


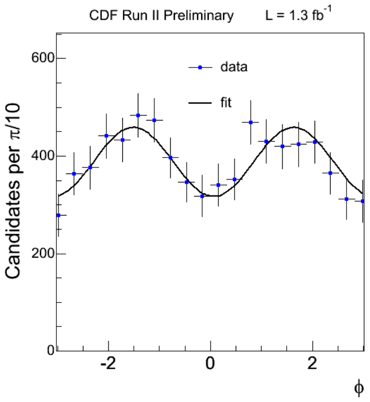


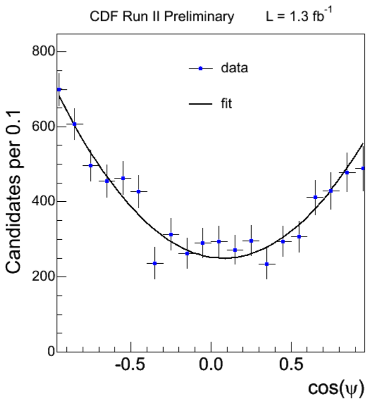


Cross-check with B^0 Decays

- Corrected distributions-fits agrees well: validates treatment of detector acceptance!







- Results for $B^0 \rightarrow J/\Psi\, K^{*0}$ in good agreement with BaBar and errors are competive!

Phys. Rev. D 76, 031102 (2007)

$c\tau = 456 \pm 6\ (\text{stat}) \pm 6\ (\text{syst})\ \mu\text{m}$

$|A_0(0)|^2 = 0.569 \pm 0.009\ (\text{stat}) \pm 0.009\ (\text{syst})$

$|A_{||}(0)|^2 = 0.211 \pm 0.012\ (\text{stat}) \pm 0.006\ (\text{syst})$

$\delta_{||} = -2.96 \pm 0.08\ (\text{stat}) \pm 0.03\ (\text{syst})$

$\delta_{\perp} = +2.97 \pm 0.06\ (\text{stat}) \pm 0.01\ (\text{syst})$

$|A_0(0)|^2 = 0.556 \pm 0.009\ (\text{stat}) \pm 0.010\ (\text{syst})$

$|A_{||}(0)|^2 = 0.211 \pm 0.010\ (\text{stat}) \pm 0.006\ (\text{syst})$

$\delta_{||} = -2.93 \pm 0.08\ (\text{stat}) \pm 0.04\ (\text{syst})$

$\delta_{\perp} = +2.96 \pm 0.05\ (\text{stat}) \pm 0.03\ (\text{syst})$

Untagged Analysis

Untagged Angular PDF

- Drop the information on flavor tagging $\Rightarrow$ several terms in the likelihood are canceled
- Simpler likelihood suited for precise measurements of $\Delta\Gamma$, width-difference and τ, average lifetime
- Reduced but still available sensitivity to phase β_s due to CP-even/CP-odd interference
- Sensitive to $|\cos(2\beta_s)|$ and $|\sin(2\beta_s)|$ (note absolute values)

4-fold ambiguity in the likelihood

General decay rate formula:

$$\frac{d^4P(t,\vec{w})}{dtd\vec{w}} \propto |A_0|^2\, T_+ f_1(\vec{w}) + |A_\parallel|^2\, T_+ f_2(\vec{w}) + |A_\perp|^2\, T_- f_3(\vec{w}) + |A_\parallel||A_\perp|\, U_+ f_4(\vec{w}) + |A_0||A_\parallel|\cos(\delta_\parallel) T_+ f_5(\vec{w}) + |A_0||A_\perp|\, V_+ f_6(\vec{w})$$

$$T_\pm = e^{-\Gamma t} \times [\cosh(\Delta\Gamma t/2) \mp \cos(2\beta_s)\sinh(\Delta\Gamma t/2) \cancel{\mp \eta \sin(2\beta_s)\sin(\Delta m_s t)}],\ \eta = +1(-1) \text{ for } P(\bar{P})$$

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

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

Untagged Results (within SM)

- Sizeable $\Delta\Gamma_s \Rightarrow$ CP-even and CP-odd contributions of the signal can be distinguished
- Results assuming no CP violation $\Rightarrow$ β_s**=0**
- **CDF:** ~2500 signal events (1.7 fb^{-1})

World Best Measurements (arXiv: 0712.2348)

Lifetime: $\tau_s = 1.52 \pm 0.04$ (stat) ± 0.02 (syst) ps

Decay Width: $\Delta\Gamma_s = 0.076^{+0.059}_{-0.063}$ (stat) ± 0.006 (syst) ps^{-1}

$|A_0(0)|^2 = 0.531 \pm 0.020$ (stat) ± 0.007 (syst)

$|A_{||}(0)|^2 = 0.230 \pm 0.026$ (stat) ± 0.009 (syst)

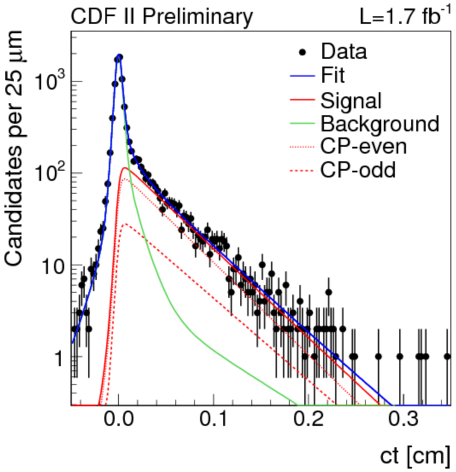
Theory:

$\tau(B_s)/\tau(B_d) = 1.00 \pm 0.01$

Using PDG:

$\tau(B_d) = 1.530 \pm 0.009$ ps

$\tau(B_s)/\tau(B_d) = 0.99 \pm 0.03$



Systematics Evaluation:

- B_d decays reco'd as B_s: O(3%) contamination
- Signal Mass model
- Lifetime Mass Model
- Detector Angular acceptance
- Silicon detector alignment

Untagged Analysis: Search for NP

- Allowing CP violation phase β_s to float in the fitter
- Biases: non-Gaussian estimates in pseudo-experiments
- Significant bias w.r.t statistical uncertainties and dependent on true values in the simulated experiment

$\Rightarrow$ Dependence on one parameter in the likelihood vanishes for some values of other parameters: Likelihood looses degrees of freedom

e.g., if $\Delta\Gamma=0$, $\delta_\perp$ is undetermined: $\cos(\delta_\perp)\sin(2\beta_s)\sinh(\Delta\Gamma_s t/2)$

$\Rightarrow$ Two exact symmetries are present in $B_s \rightarrow J/\Psi\,\Phi$ untagged analysis:

$$\left.\begin{array}{l} \bullet\ 2\beta_s \leftrightarrow -2\beta_s,\ \ \delta_\perp \leftrightarrow \delta_\perp+\pi \\ \bullet\ \ \Delta\Gamma \leftrightarrow -\Delta\Gamma\ ,\ 2\beta_s \leftrightarrow 2\beta_s+\pi \end{array}\right\}$$

4 equivalent minima

- Difficult to quote a central value with standard uncertainties!

$2\beta_s$-$\Delta\Gamma$ Confidence Region

- Quote instead Feldman-Cousins confidence region
- Use likelihood ratio to determine probability of result to fluctuate above a given value of input parameters (p-value)

Standard Model expectations:

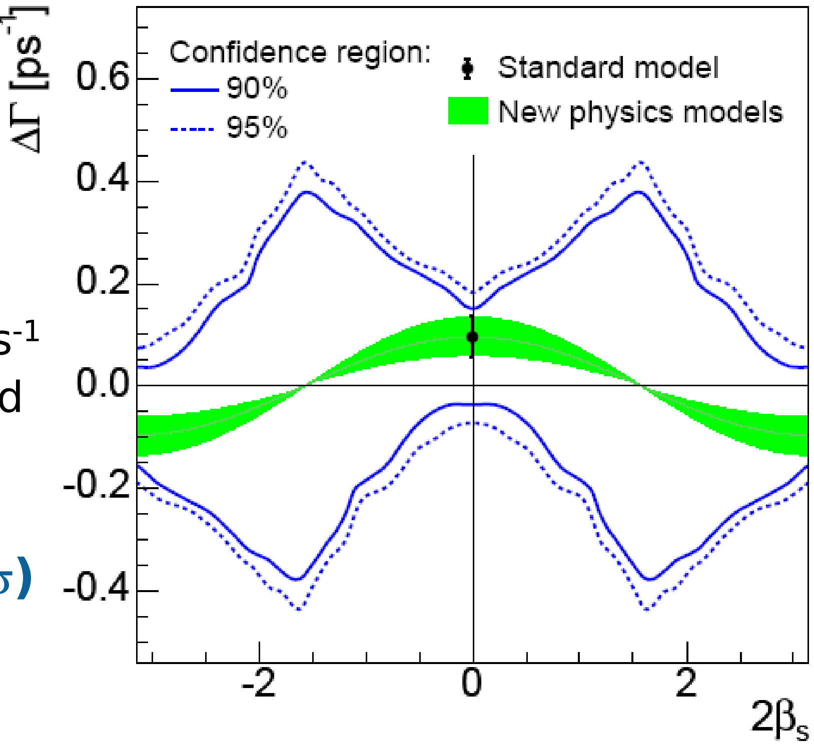
(arXiv:hep-ph/0612167)

$\Delta\Gamma_s$=0.096 ± 0.039 ps^{-1}

$2\beta_s$ = 0.04 ± 0.01 rad

Standard Model

p_{value} = 22% (1.2σ)



$\Delta\Gamma = 2|\Gamma_{12}|\cos(2\beta_s)$

Accepted by PRL arXiv:0712.2343 [hep-ex]

Tagged Analysis

Flavor Tagging Effect

- Tagging improves sensitivity to CP violation phase β_s
- Exact symmetry present in signal probability distribution
- Two minima in the likelihood

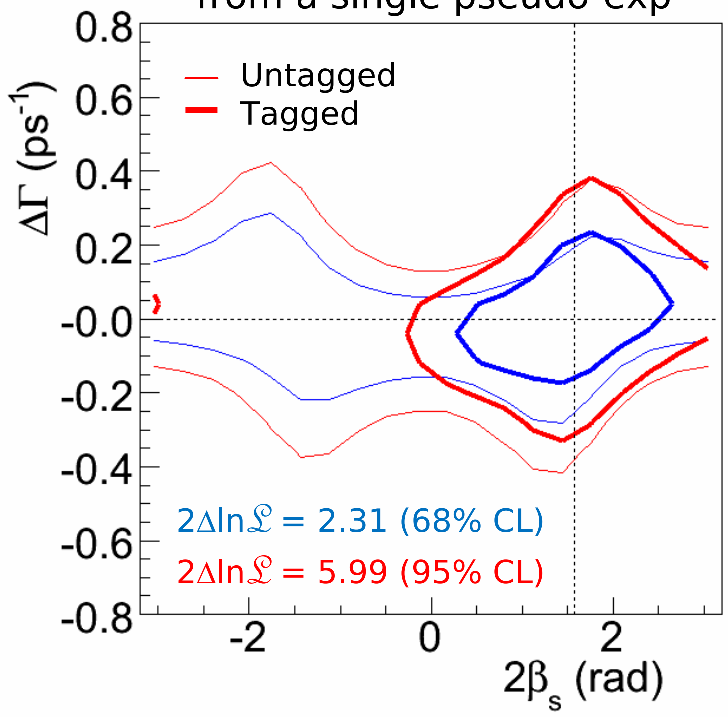
$2\beta_s \leftrightarrow \pi - 2\beta_s$
$\Delta\Gamma_s \leftrightarrow -\Delta\Gamma_s$
$\delta_{||} \leftrightarrow \pi - \delta_{||}$
$\delta_{\perp} \leftrightarrow \pi - \delta_{\perp}$

- Check β_s-$\Delta\Gamma_s$ likelihood profile with Toy MC to understand tagging effect

- Likelihood: with tagging, gain sensitivity to both $|\cos(2\beta_s)|$ and $\sin(2\beta_s)$, rather than only $|\cos(2\beta_s)|$ and $|\sin(2\beta_s)|$ (note absolute value)

- $\beta_s \leftrightarrow -\beta_s$ is no longer a likelihood symmetry:
  - $\Rightarrow$ 4-fold ambiguity reduced to <u>2-fold</u>
  - $\Rightarrow$ allowed region for β_s is reduced to half

$2\beta_s$-$\Delta\Gamma_s$ likelihood profile from a single pseudo-exp



Results on Tagged $B_s \rightarrow J/\Psi\ \Phi$ (I)

Likelihood contour does **not** have the correct coverage: the resulting confidence region do not contain the true value with desired CL independently of true value

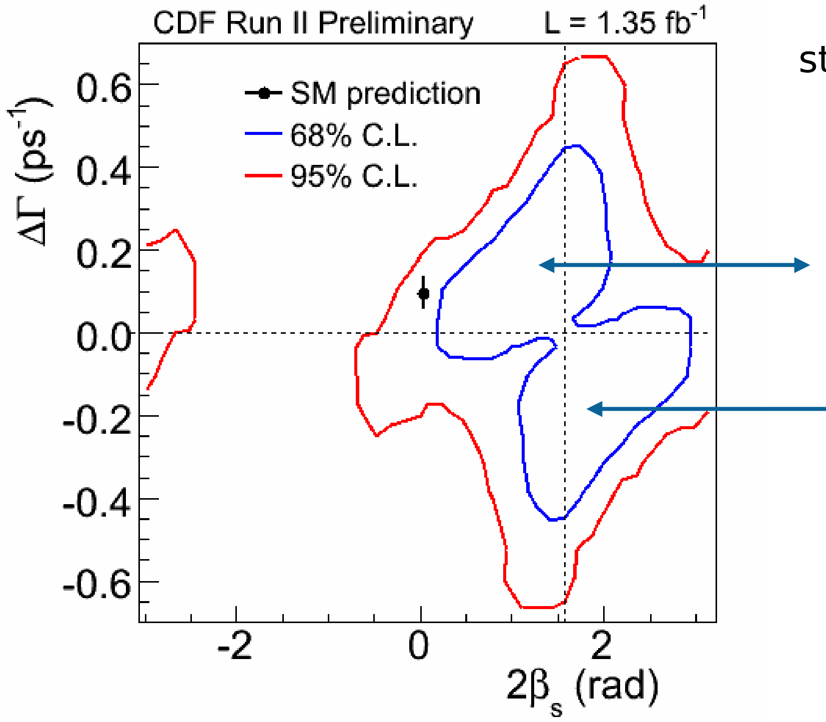
⇩

Feldman-Cousins likelihood ratio ordering

Standard Model expectations:

(arXiv:hep-ph/0612167)
$\Delta\Gamma_s$=0.096 ± 0.039 ps^{-1}
$2\beta_s$ = 0.04 ± 0.01 rad

Standard Model
p_{value} = 15% (1.5σ)



strong phases can separate the two minima

$\cos(\delta_\perp) < 0$
$\cos(\delta_\perp - \delta_{||}) > 0$

$\cos(\delta_\perp) > 0$
$\cos(\delta_\perp - \delta_{||}) < 0$

Under PRL review arXiv:0712.2397 [hep-ex]

Results on Tagged $B_s \to J/\Psi\ \Phi$ (II)

1-dim Feldman-Cousins procedure on CP violation phase β_s

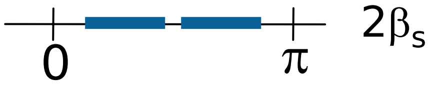
1. Without External Constraints:

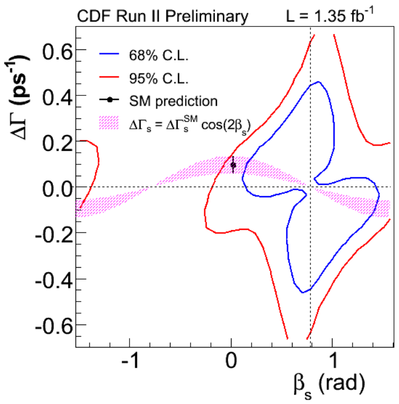
   $2\beta_s$ in [0.32, 2.82] at the 68% C.L.

2. $\Delta\Gamma_s$ is theoretically constrained:

   - Input $\Delta\Gamma_s = 2|\Gamma_{12}|\cos\Phi_s \approx 2|\Gamma_{12}|\cos(2\beta_s)$: ($\Gamma_{12}$=0.048±0.018):

   $2\beta_s$ in [0.24, 1.36] U [1.78, 2.90] at 68% C.L.





3. Strong phases from $B_d \to J/\Psi\ K^{*0}$ [PRD 71, 032005 (2005)], B_s lifetime from B_d [PDG] and $\Delta\Gamma_s \approx 2|\Gamma_{12}|\cos(2\beta_s)$:

   $2\beta_s$ in [0.40, 1.20] at 68% C.L.

$\cancel{CP}$ in Mixing (I)

- Inclusive dimuon charge asymmetry $A_{SL}^{\mu\mu} = \dfrac{N(b\bar{b} \to \mu^{+}\mu^{+}X) - N(b\bar{b} \to \mu^{-}\mu^{-}X)}{N(b\bar{b} \to \mu^{+}\mu^{+}X) + N(b\bar{b} \to \mu^{-}\mu^{-}X)}$

$$A_{SL}^{\mu\mu} = \frac{1}{4}\left(A_{SL}^{d} + \frac{f_s Z_s}{f_d Z_d} A_{SL}^{s}\right)$$

$$Z_q = \frac{1}{1 - [\Gamma_q/(2\Gamma_q)]^2} - \frac{1}{1 + (\Delta m_q/\Gamma_q)^2}$$

f_q is the production rate of B_q mesons in the hadronization of the *b* quark

Combine this result with the measurement from $B_s \to J/\Psi\Phi$ to constrain the phase β_s

- Using world averages for f_q, the semileptonic asymmetry for B_d from B factories and the measured parameters Δm_q and $\Delta\Gamma_q$ we can extract A_{SL}^{s}

- if $\Delta m_s / \bar{\Gamma}_s >> 1 \Rightarrow \boxed{A_{SL}^{s} = \dfrac{\Delta\Gamma_s}{\Delta m_s} \tan\Phi_s}$

~~CP~~ in Tagged $B_s \to J/\Psi\ \Phi$

- <u>Tagged analysis</u> of $B_s \to J/\Psi\Phi$ decay from **DØ**

arXiv: 0802.2255

- **<u>DØ</u>:** ~2000 B_s events with 2.8 fb^{-1}
- Combined Tagging Power $\Rightarrow \varepsilon D^2 = (4.68 \pm 0.54)\%$
- Quoting point estimate:

$$\tau_s = 1.52 \pm 0.06\ (\text{stat}) \pm 0.01\ (\text{syst})\ \text{ps}$$

$$\Delta\Gamma_s = 0.19 \pm 0.07\ (\text{stat})^{+0.02}_{-0.01}\ (\text{syst})\ \text{ps}^{-1}$$

$$\Phi_s = -2\beta_s = -0.57^{+0.24}_{-0.30}\ (\text{stat})^{+0.07}_{-0.02}\ (\text{syst})\ \text{rad}$$

FIT <u>inputs</u>:

Δm_s fixed to 17.77 ps^{-1} ← **CDF**

Gaussian constraint on Strong phases:

$\delta_\perp - \delta_{||} = -0.46 \pm (\pi/5)$

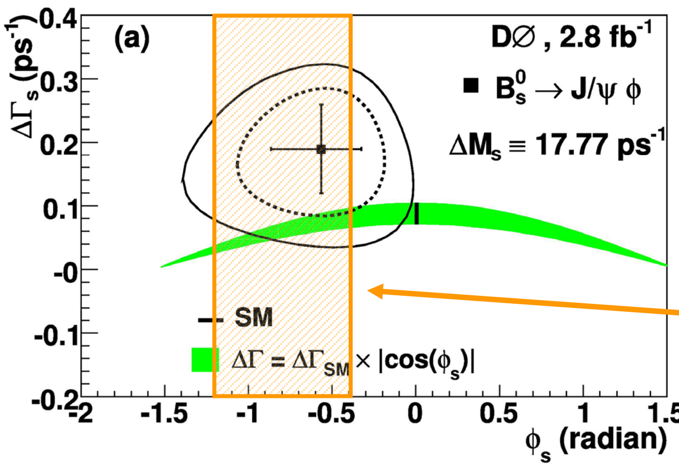
$\delta_\perp = +2.92 \pm (\pi/5)$ ← **B Factories**

Standard Model expectations:

(arXiv:hep-ph/0612167)

$2\beta_s = 0.04 \pm 0.01$ rad

Standard Model p_{value} = 6.6%



90% C.L. <u>contours:</u>

$-1.20 < 2\beta_s < 0.06$ rad

$0.06 < \Delta\Gamma_s < 0.30$ ps^{-1}

<u>CDF 68% CL:</u>

Constraining lifetime, strong phases and $\Delta\Gamma_s$

$\not{CP}$ in Mixing (II)

- **CDF:** 1.6 fb^{-1} of data collected (di-muon charge asymmetry):

$$\boxed{A^s_{SL} = 0.020 \pm 0.021\ (stat) \pm 0.016\ (syst) \pm 0.009\ (inputs)}$$

(http://www-cdf.fnal.gov/physics/new/bottom/070816.blessed-acp-bsemil/)

- **DØ:** 1.0 fb^{-1} of data collected (di-muon charge asymmetry):

$$\boxed{A^s_{SL} = -0.0064 \pm 0.0101\ (stat + syst)}$$

PRD 74, 092001 (2006)

- **DØ:** 1.3 fb^{-1} of data collected (B_s semileptonic decays):

$$\boxed{A^s_{SL} = [2.45 \pm 1.93\ (stat) \pm 0.35\ (syst)] \times 10^{-2}}$$

PRL 98, 151801 (2007)

- **Unofficial Tevatron Average (Rescaled to common inputs):**

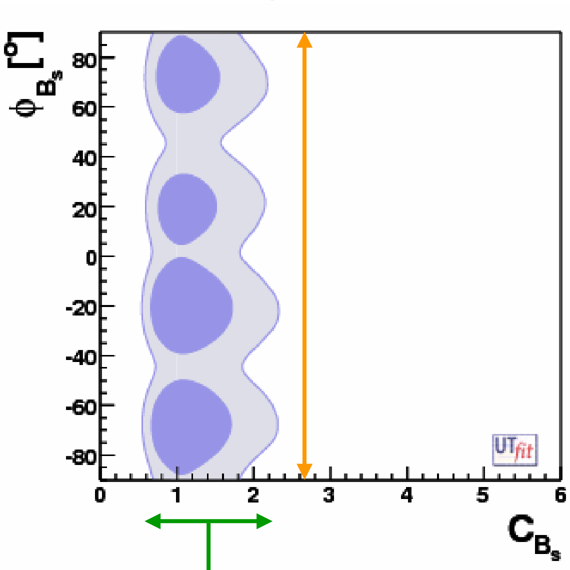
$$\boxed{A^s_{SL} = [-0.0054 \pm 0.0072\ (stat + syst)]}$$

Before CDF…

UT_{fit} inputs:

Δm_s measurement (CDF)
Lifetime τ_s (CDF and D∅)
$\Delta\Gamma_s$ (CDF on 200 pb^{-1})
$\Delta\Gamma_s$ and Φ_s (D∅ on 1.1 fb^{-1})
Semileptonic A_{SL} (D∅)

B_s System

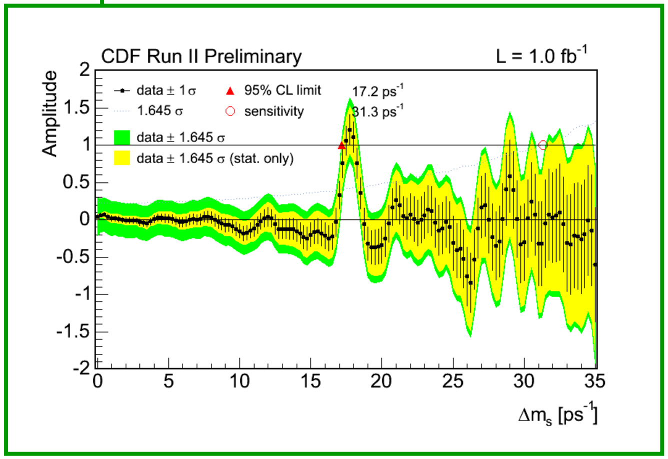


UTfit Group

$\Delta m_s = C_{Bs} * \Delta m_s^{SM}$: Lattice-QCD dominated uncertainty

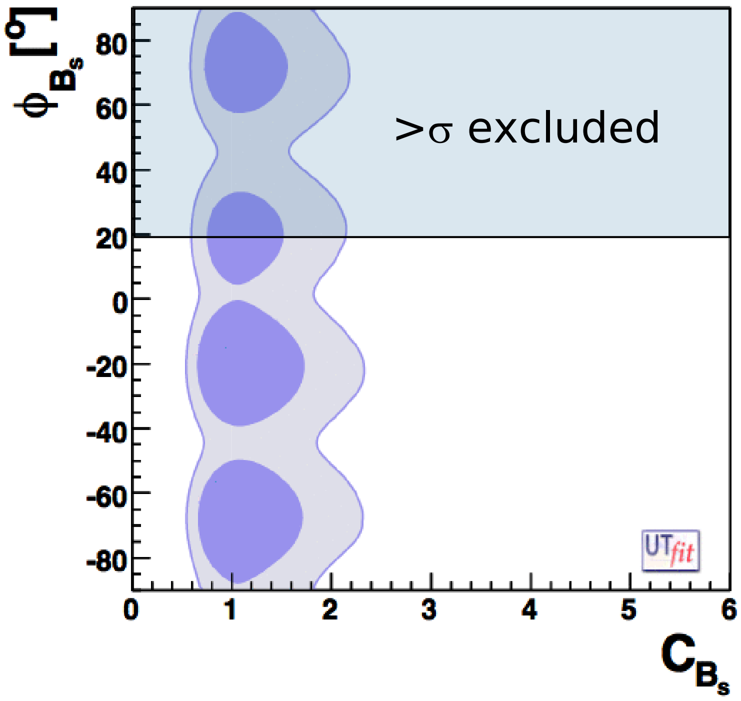
$$\frac{\langle B_s | H_{eff}^{full} | \bar{B}_s \rangle}{\langle B_s | H_{eff}^{SM} | \bar{B}_s \rangle} = \boxed{C_{Bs}}\, e^{2i\boxed{\Phi Bs}}$$

$\beta_s = \beta_s^{SM} - \Phi_{Bs}$: Experimentally dominated uncertainty
(today physics topic)



Conclusions (I)

New Physics in B_s mixing



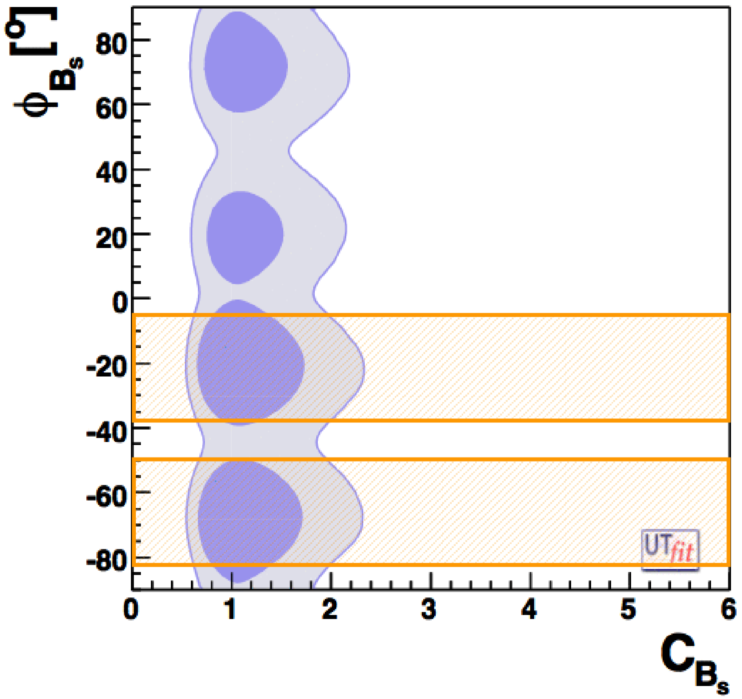
(http://www.utfit.org/)

$$C_{Bs} e^{2i\Phi_{Bs}} = \frac{\langle B_s | H_{eff}^{full} | \overline{B}_s \rangle}{\langle B_s | H_{eff}^{SM} | \overline{B}_s \rangle}$$

$$\Delta m_s = C_{Bs} \bullet \Delta m_s^{SM}$$

$$\beta_S^{exp} = \beta_S^{SM} - \Phi_{Bs}$$

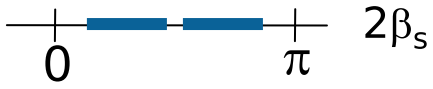
Conclusions (II)

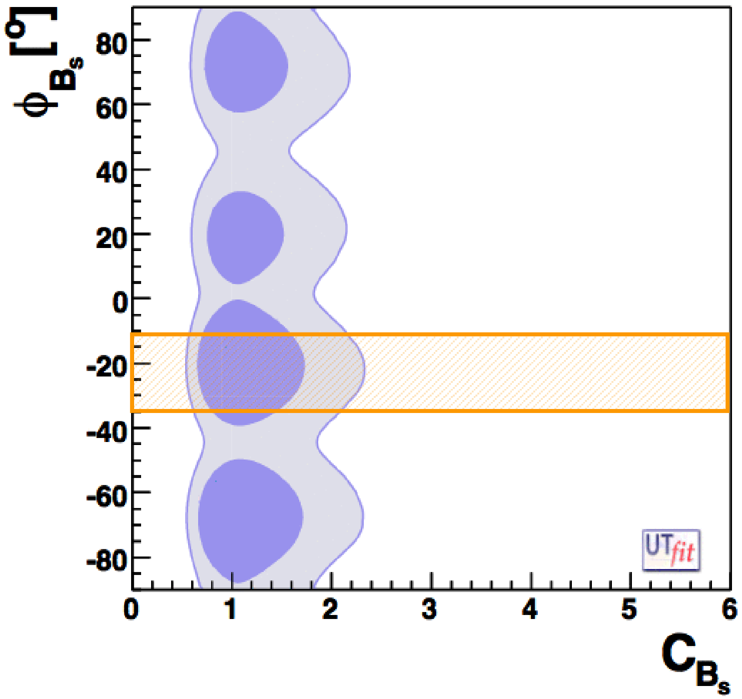


- <u>Constraint:</u>

✓ $\Delta\Gamma_s = 2|\Gamma_{12}|\cos\Phi_s \approx 2|\Gamma_{12}|\cos(2\beta_s)$ with (Γ_{12}=0.048±0.018):

$2\beta_s \in [0.24, 1.36] \cup [1.78, 2.90]$ at 68% C.L.

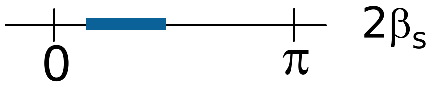




- <u>Constraints:</u>

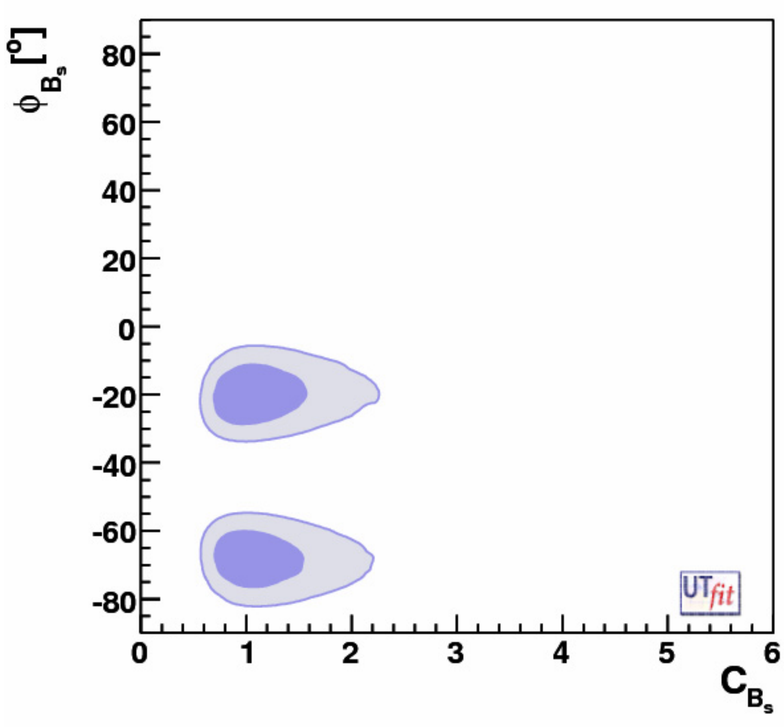
✓ Strong phases from J/Ψ K^{*0} [hep-ex/0411016], B_d lifetime [PDG] and $\Delta\Gamma_s \approx 2|\Gamma_{12}|\cos(2\beta_s)$:

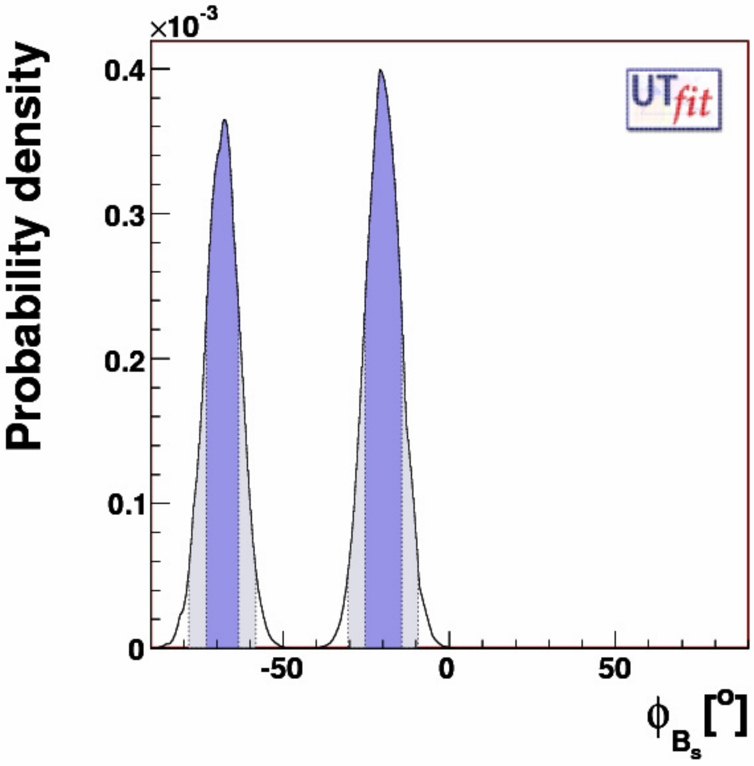
$2\beta_s \in [0.40, 1.20]$ at 68% C.L.



Last Minute Plots…

Thanks to Luca Silvestrini & Marco Ciuchini!

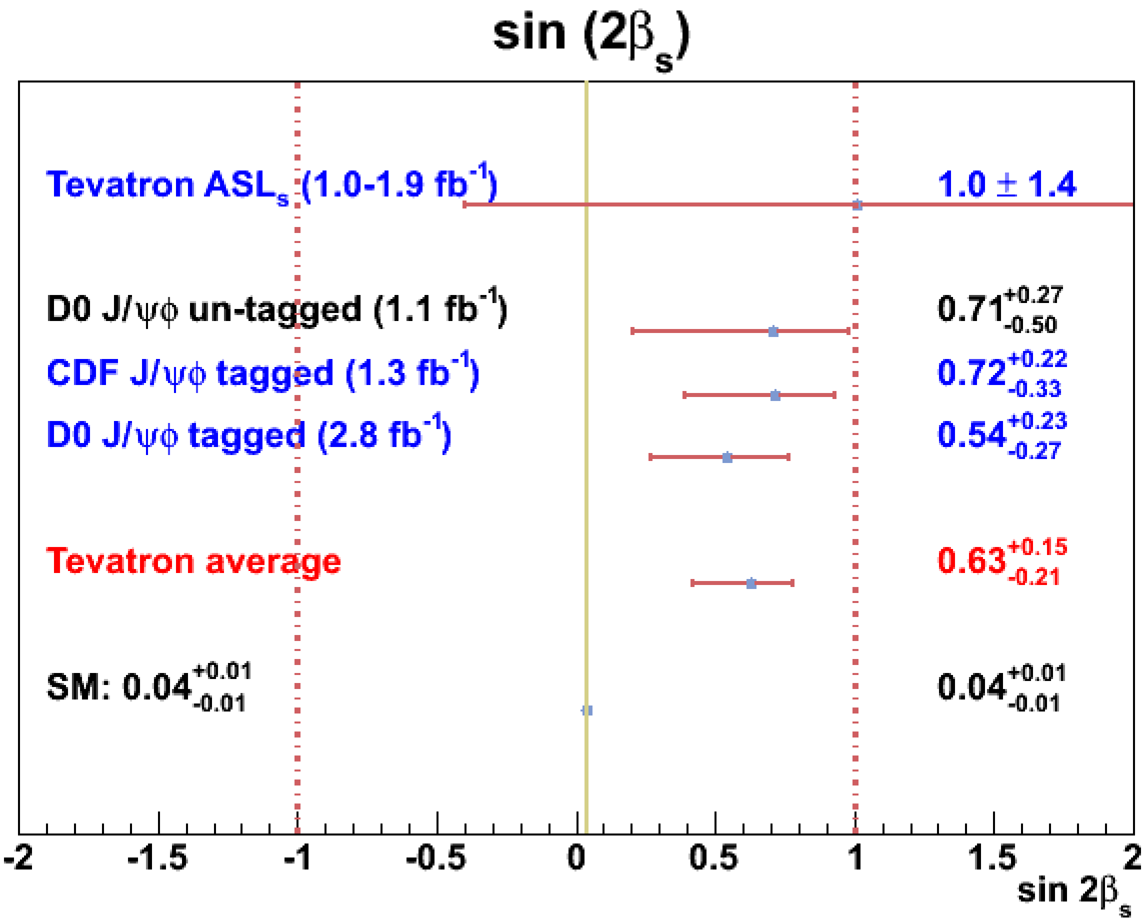




Conclusions

- CDF(D∅) searches for CP violation in B_s system:
  - ✓ Direct CP violation (e.g. $B_s \to K^- \pi^+$)
  - ✓ CP Violation in Mixing: precise A^S_{SL} measurement (to be compare in perspective with A^d_{SL})
  - ✓ CP Violation in the interference between mixing and decay: sin($2\beta_s$) measurement → today topic
- Interesting sin($2\beta_s$) fluctuation at Tevatron experiments:
  - ✓ Both experiments, CDF and D∅
  - ✓ In both measurements, untagged and tagged
  - ✓ In the same direction of A_{SL}

Current Experimental Picture



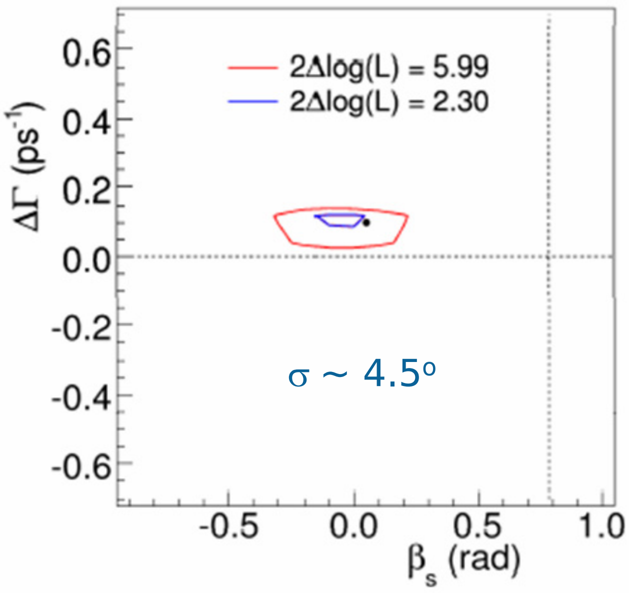
Future Sensitivity (I)

- Measurement of $\sin(2\beta_s)$ is a key part of the LHCb flavor program

Analysis improvements:

- Add more data: so far only 15% of available statistics at the end of next year
- Exploit additional 50% statistics from other triggers
- Better behaved likelihood at higher statistics
- Improve tagger performances

Generated with $\beta_s=0.02$

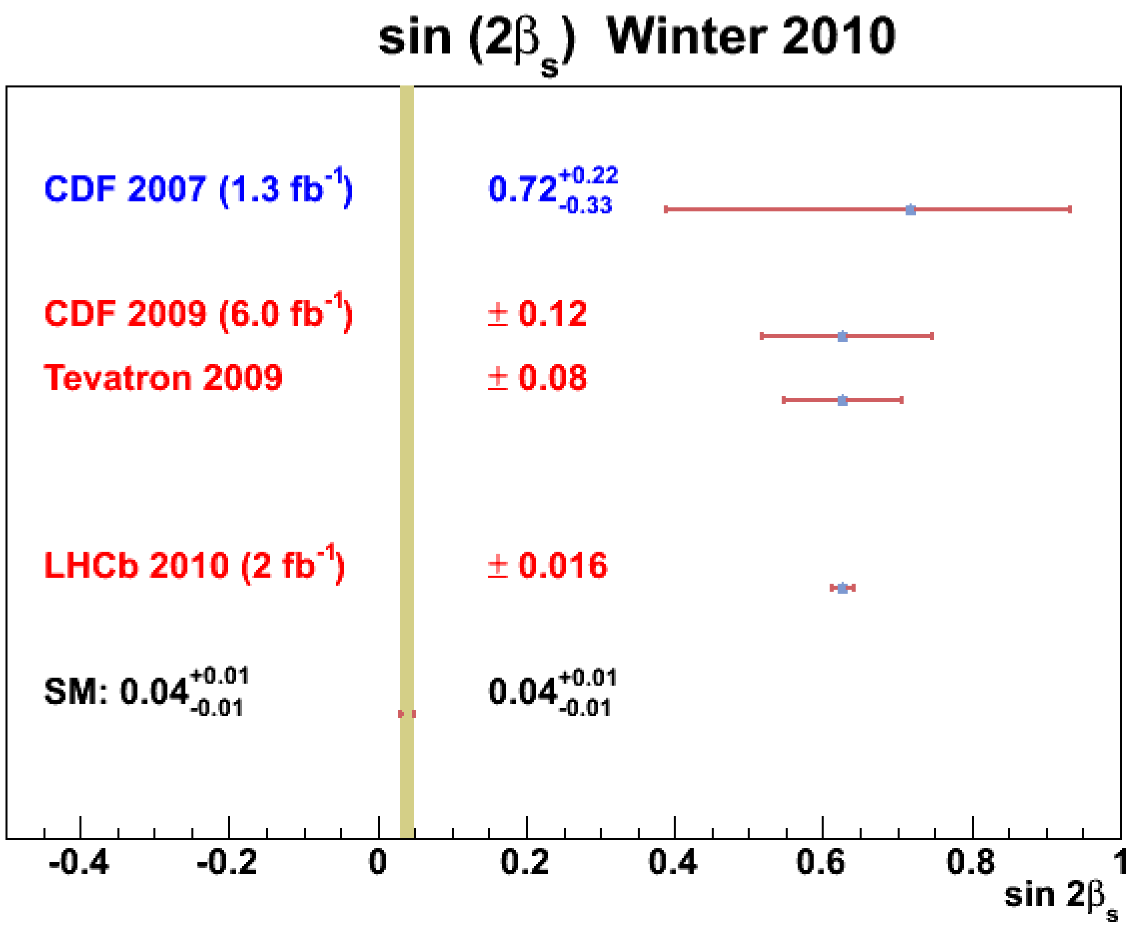


$\sigma \sim 4.5^{o}$

Baseline expectation w/ 6 fb^{-1}:

- Same yield per fb^{-1}
- Same tagging efficiency
- Same dilution

Future Sensitivity (II)



Backup Slides

Feldman-Cousins Procedure

Likelihood Ratio: $$R(\Delta\Gamma,\Phi) = \log\frac{L(\Delta\hat{\Gamma},\hat{\Phi},\hat{\theta})}{L(\Delta\Gamma,\Phi,\hat{\theta}')}$$

^ = parameters minimized by the likelihood L

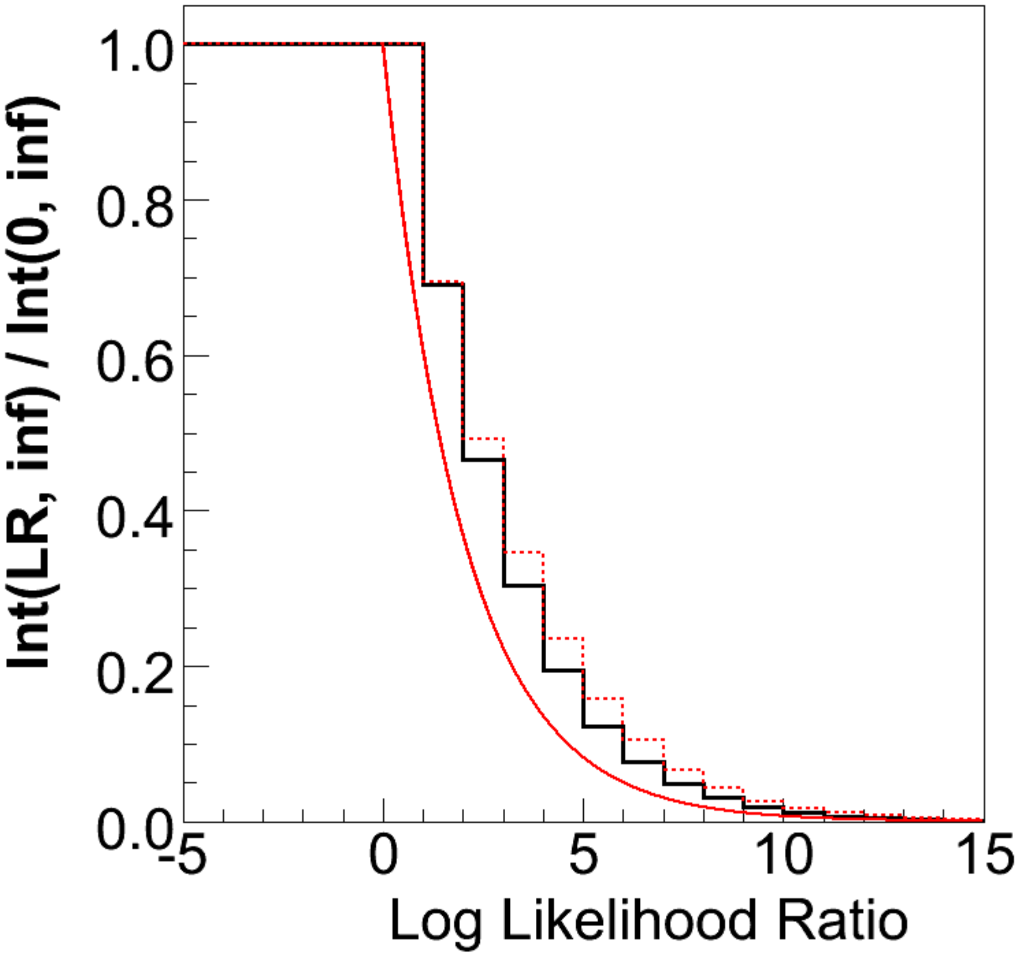
θ' = parameters which minimize L for a specific choice of $\Delta\Gamma,\Phi$

1. For a specific choice of $\Delta\Gamma,\Phi$ pseudo-exp are generated using θ'
2. $p_{value} = \int_{Rdata}^{\infty} f(R,\Delta\Gamma,\Phi)\,dR$

Plug-In
Method

Frequentist approach: probability to observe a result with $R \geq R_{data}$, if $\Delta\Gamma$ and Φ are the values predicted by some model

Feldman-Cousins Procedure



Likelihood for $B_s \to J/\Psi\ \Phi$ (I)

$B_s \to J/\Psi\ \Phi$ differential decay rate depends on 4 event variables:

- **ct:** Proper decay length
- **$\vec{w}$:** vector formed by the 3 angles that characterize the decay
- **ξ:** tag decision (+1 if B_s, -1 if $\overline{B}_s$, 0 if no tag)

… some other parameters describing the physics:

- ✓ **$|A_\alpha|$, α={0,||,⊥}:** amplitudes for decay to longitudinal (CP-even), transverse and parallel to each other (CP-even) or perpendicular to each other (CP-odd) polarizations of $J/\Psi\ \Phi$
- ✓ **δ_α:** Strong phases associated with those amplitudes
- ✓ **Γ, $\Delta\Gamma$:** Average lifetime and lifetime difference
- ✓ **β_s:** CP violation phase in $b \to c\bar{c}s$ transition

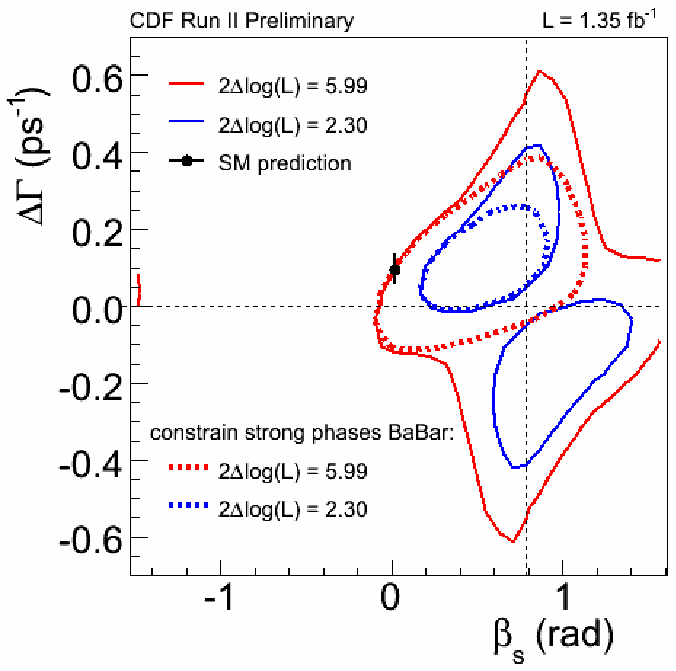
$$P(ct,\vec{w}\,|\,\xi) = \frac{1+\xi D}{1+|\xi|} P_B(ct,\vec{w})\ \varepsilon(\vec{w}) + \frac{1-\xi D}{1+|\xi|} P_{\overline{B}}(ct,\vec{w})\ \varepsilon(\vec{w})$$

- $\varepsilon(\vec{w})$ is the sculpting of transversity angles due to detector acceptance

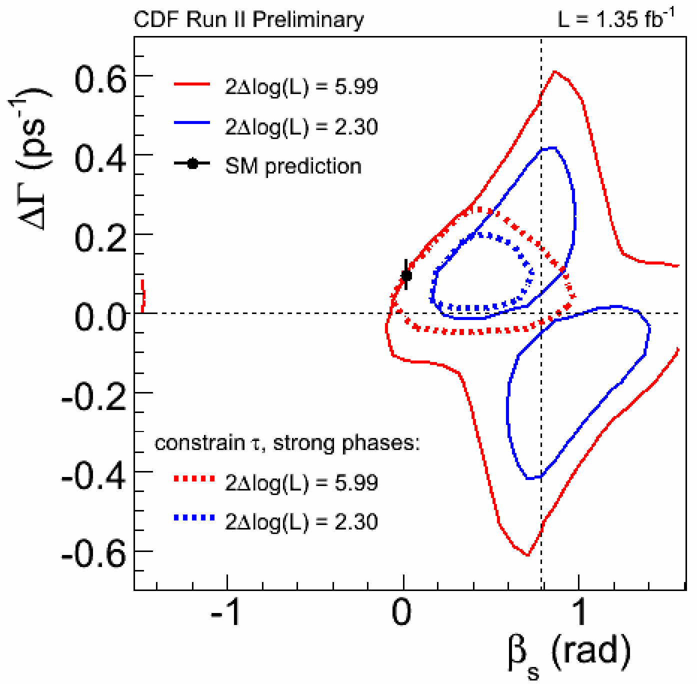
Constraints on Tagged $B_s \rightarrow J/\Psi\ \Phi$

- SU(3) flavor symmetry suggests that B_s and B^0 have similar lifetimes and strong phases
- Likelihood profiles with external constraints from B factories
- Underestimated confidence regions when using $2\Delta\ln\mathscr{L} = 2.31\ (5.99)$ to approximate 68% (95%) C.L. regions

constrain strong phases



constrain lifetime and strong phases



⇒ External constraints on strong phases remove residual 2-fold ambiguity

Same Side Flavor Tagging

Most powerful tagger available:

- ✓ 2-3 times more effective than combined OST

Exploit charge correlation between b and fragmentation tracks:

- ✓ B^+, B^0 likely to have a π^-, π^+ nearby
- ✓ B_s likely to have K^+

Neural Network separates kaons and pions:

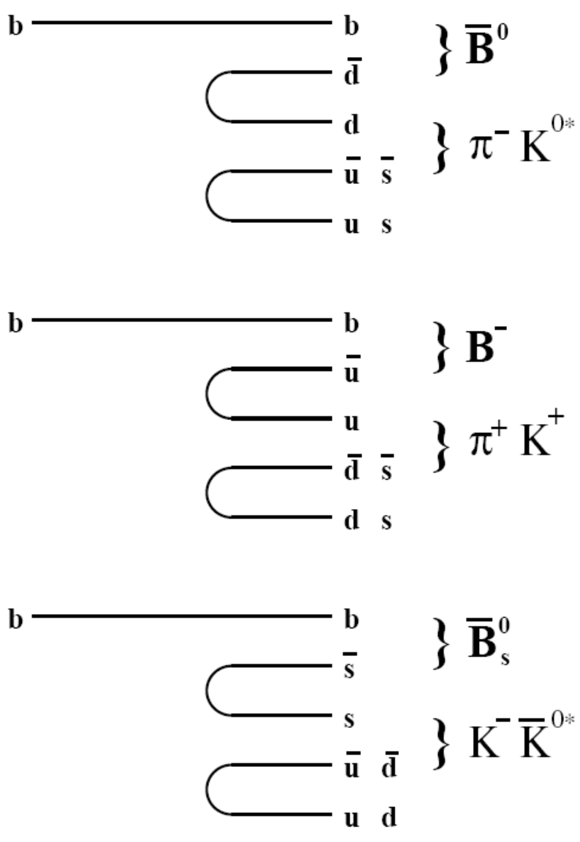
- ✓ TOF and COT dE/dx crucially important
- ✓ Kinematic of candidate provide additional separating power

Unlike OST, SSKT is different for B^0, B^+ and B_s:

- ✓ SST needs to rely on MC simulation
- ✓ Data and MC thoroughly compared

Performance:

- ✓ Efficiency: $\varepsilon = 0.50 \pm 0.01$
- ✓ Average Dilution: $D = 0.27 \pm 0.04$



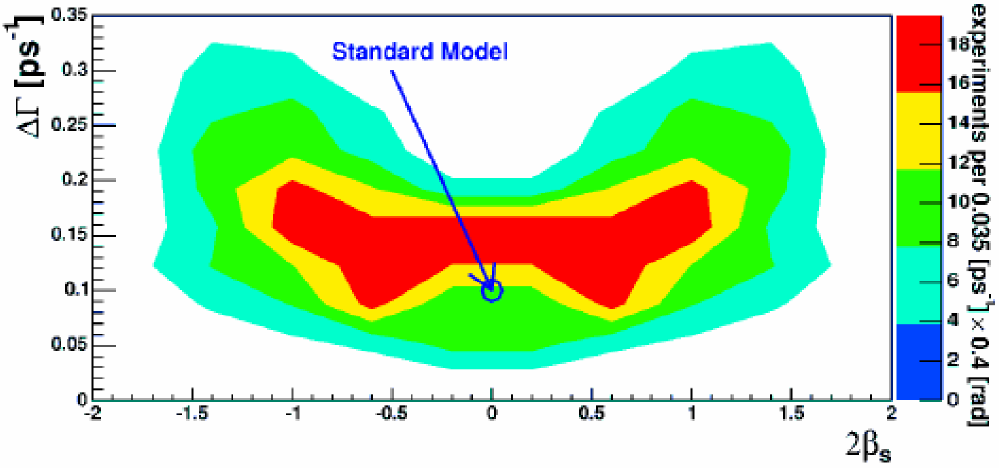
OST and SST combined independently

Untagged Analysis: Search for NP

- Biases
- Non-Gaussian estimates in pseudo-experiments
- Strong dependence on true values for biases on some fit parameters

Fits on simulated samples

generated with SM inputs for $\Delta\Gamma_s$ and β_s



$\Rightarrow$ Dependence on one parameter in the likelihood vanishes for some values of other parameters: Likelihood looses degrees of freedom

e.g., if $\Delta\Gamma=0$, $\delta_\perp$ is undetermined: $\cos(\delta_\perp)\sin(2\beta_s)\sinh(\Delta\Gamma_s t/2)$

$\Rightarrow$ Two exact symmetries are present in $B_s \rightarrow J/\Psi\ \Phi$ untagged analysis:

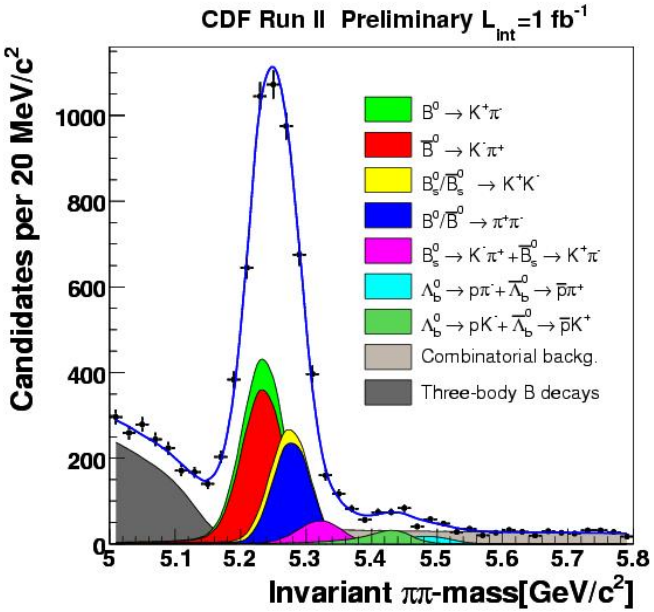
- $2\beta_s \leftrightarrow -2\beta_s,\ \ \delta_\perp \leftrightarrow \delta_\perp+\pi$
- $\Delta\Gamma \leftrightarrow -\Delta\Gamma\ ,\ 2\beta_s \leftrightarrow 2\beta_s+\pi$

} 4 equivalent minima

Direct CP Violation

- Direct CP asymmetry $A_{CP}(B_s \to K^-\pi^+)$ in a self tagging mode:

$$\boxed{A_{CP} = \frac{N(\overline{B}_s^0 \to K^+\pi^-) - N(B_s^0 \to K^-\pi^+)}{N(\overline{B}_s^0 \to K^+\pi^-) + N(B_s^0 \to K^-\pi^+)}}$$



- Observed for the first time three new rare charmless modes:

  $N(B_s^0 \to K^-\pi^+) = 230 \pm 34$ (stat) ± 16 (syst) [8σ signif]

- Direct CP violation due to interference between peguin and tree diagrams:

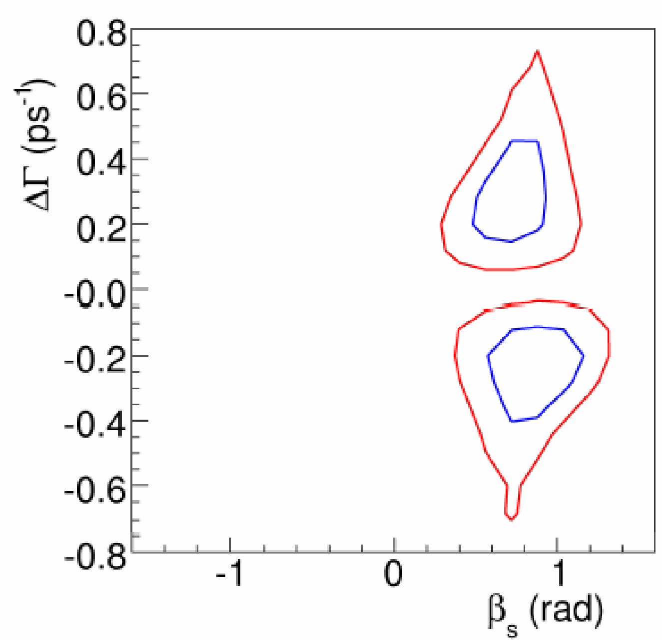
$$A_{CP}(B_s^0 \to K^-\pi^+) = 0.39 \pm 0.15 \text{ (stat)} \pm 0.08 \text{ (syst)}$$

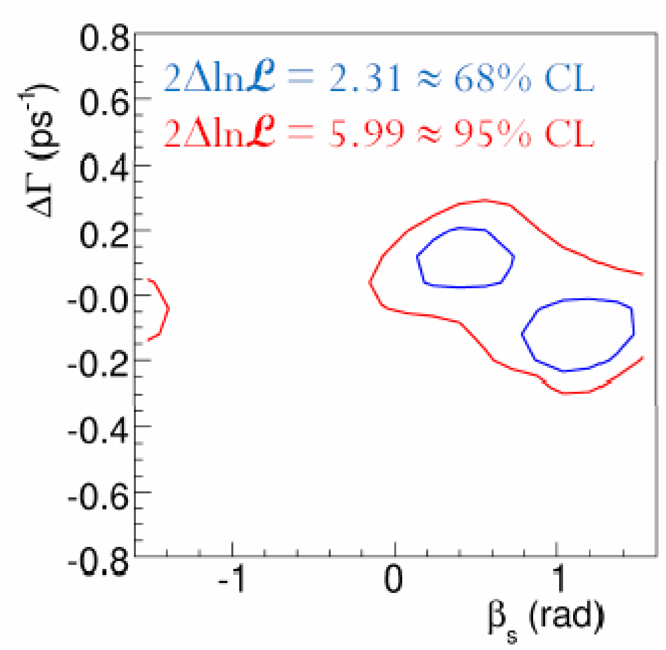
- A_{CP} is 2.5σ different from 0
- Compatible with SM expectation (~0.37) [H.J.Lipkin, Phys. Lett. B **621**, 126 (2005)]

Likelihood Shape

- Check β_s-$\Delta\Gamma$ likelihood profile on Toy MC
- Likelihood profile is NOT parabolic
- Shape strongly dependent on "true" values

} Cannot reliably quote central values and uncertainties

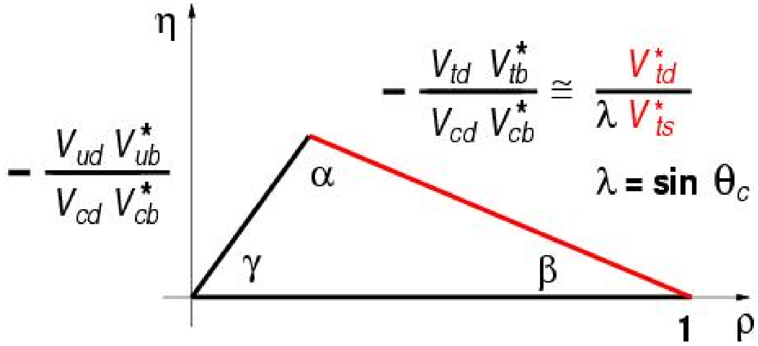




B_s Mixing Oscillation

CDF: World First Observation (5σ)

- Unitarity Triangle:



- Integrated Luminosity: 1 fb^{-1}

- $\Delta m_s = 17.77 \pm 0.10\ (\text{stat}) \pm 0.07\ \text{ps}^{-1}$
- $\frac{|V_{td}|}{|V_{ts}|} = 0.2060 \pm 0.0007\ (\text{exp})^{+0.0081}_{-0.0060}\ (\text{theor})$

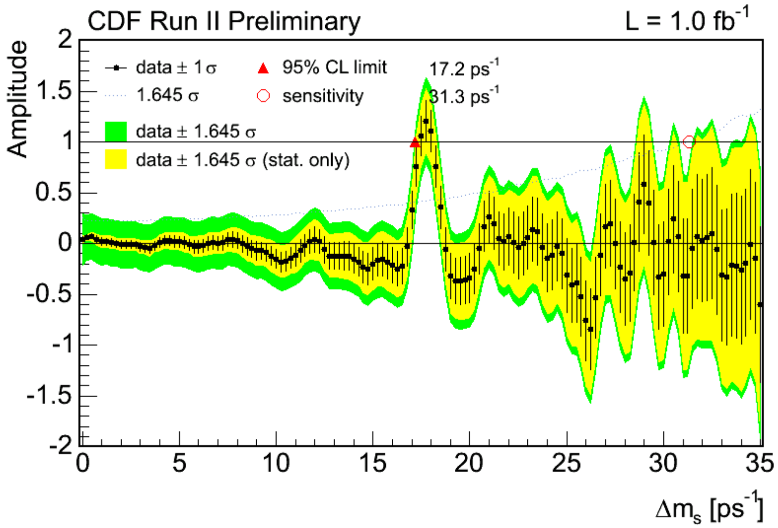
Ratio of frequencies for B^0 and B_s

$$\frac{\Delta m_s}{\Delta m_d} = \frac{m_{Bs}}{m_{Bd}} \frac{f_{Bs}B_{Bs}}{f_{Bd}B_{Bd}} \frac{|V_{ts}|^2}{|V_{td}|^2} = \frac{m_{Bs}}{m_{Bd}} \xi^2 \frac{|V_{ts}|^2}{|V_{td}|^2}$$

$\xi = 1.210^{+0.047}_{-0.035}$ from lattice QCD

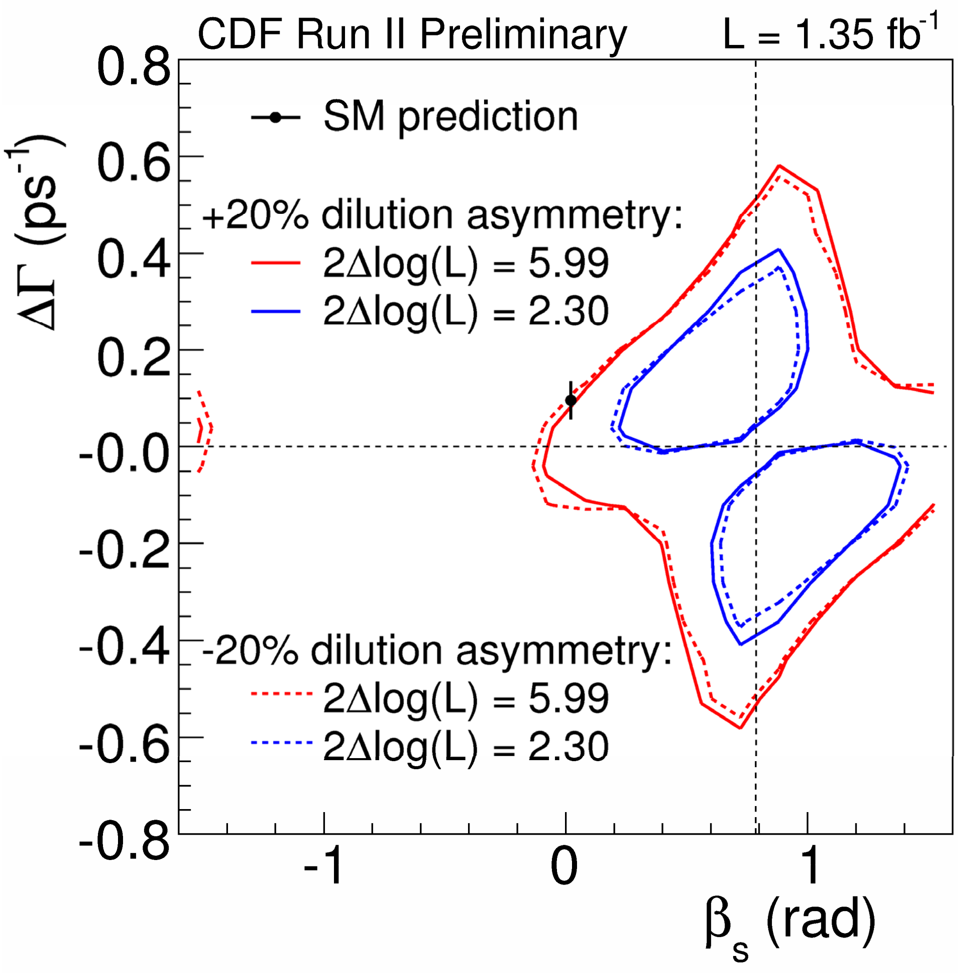
(hep/lat-0510113)

$V_{ts} \sim \lambda^2$, $V_{td} \sim \lambda^3$, $\lambda = 0.224 \pm 0.012$



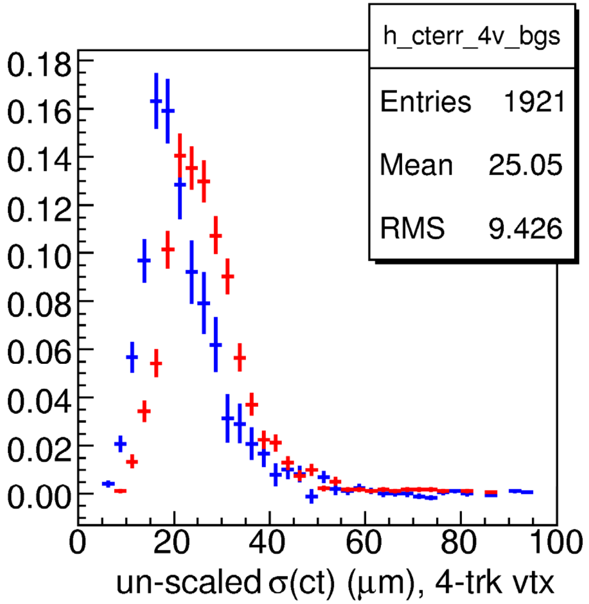
Dilution Asimmetry on β_s

Effect of 20% b-bbar dilution asymmetry is very small

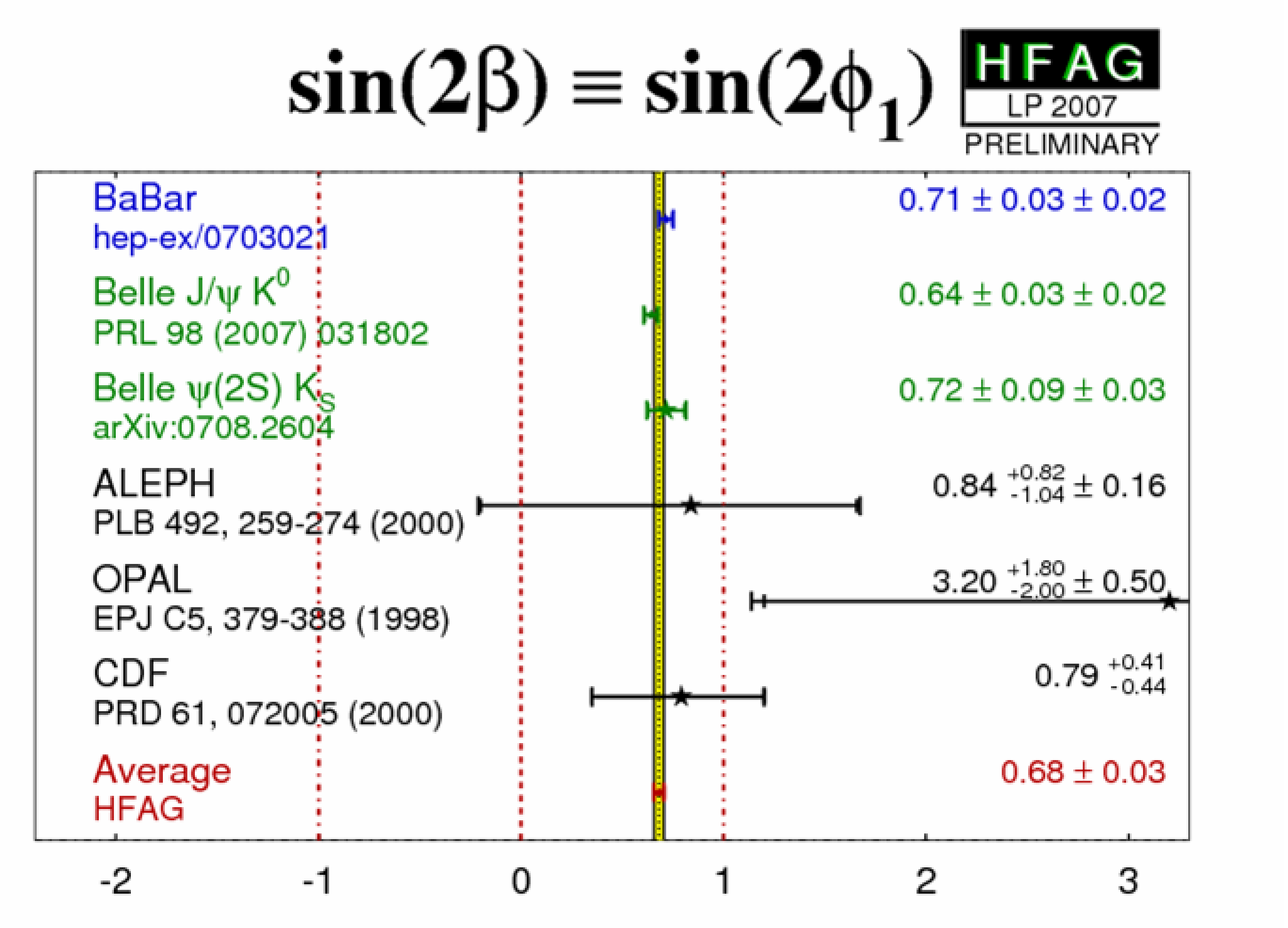


σ_{ct} distributions

- The mean is of the sideband subtracted σ_{ct} resolution for a 4-track vertex is 25.05 μm
- This has to be multiplied by the ct resolution scale factor determined from the prompt peak: s = 1.262 +/- 0.020
- The most probable value is at 18.5 μm. This means 23.3 μm after sigma ct scaling or 77.8 fs.



Sin(2β) History



History Review

2000:

- **CDF Run I** measurement on sin(2β) on 110 pb^{-1}
- $B^0 \rightarrow J/\Psi K_s$: ~400 signal candidates
- $\sin(2\beta) = 0.79^{+0.41}_{0.44}$ (stat + syst) PRD 61, 072005 (2000)

B Factories:

- **2005 Babar:** $\sin(2\beta) = 0.722 \pm 0.040$ (stat) ± 0.023 (syst) PRL 94, 161803 (2005)
- **2007 Belle:** $\sin(2\beta) = 0.642 \pm 0.031$ (stat) ± 0.017 (syst) PRL 98, 031802 (2007)
- **2007 PDG:** $\sin(2\beta) = 0.673 \pm 0.028$

2005:

- **CDF Run II** measurement on $\Delta\Gamma_s$ assuming $\beta_s=0$ on 260 pb^{-1}
- $B_s \rightarrow J/\Psi\ \Phi$: ~ 200 signal candidates PRL 94, 101803 (2005)

2007:

- **D∅** measurement on $\Delta\Gamma_s$ and β_s on 1.1 fb^{-1}
- $B_s \rightarrow J/\Psi\ \Phi$: ~ 1040 signal candidates
- $2\beta_s = -0.79 \pm 0.56$ (stat)$^{+0.14}_{-0.01}$ (syst) rad PRL 98, 121801 (2007)