Measurement of CP Violation in $B_s \rightarrow J/\Psi\Phi$ Decay at CDF

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Introduction

- *CP* violation means that the laws of nature are not invariant under the simultaneous transformation of Charge and Parity

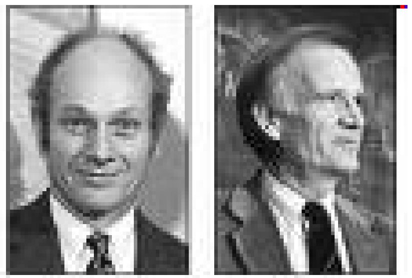
- Charge conjugation transforms particles into anti-particles

- Parity transformation is a mirror reflection (space inversion)

- Parity conservation was first questioned by T.D. Lee and C.N. Yang in 1956 when they argued that there was no experimental evidence for parity conservation in weak interactions

- Same year, C.S. Wu showed that Parity is violated in beta decays of Cobalt nuclei

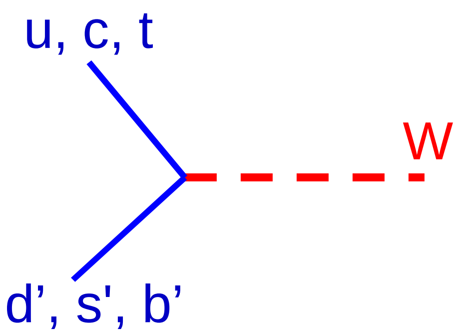
- The combined *CP* was soon adopted as the correct symmetry, just to be shown wrong by Cronin and Fitch in 1964 when they showed that *CP* is violated in neutral Kaon decays

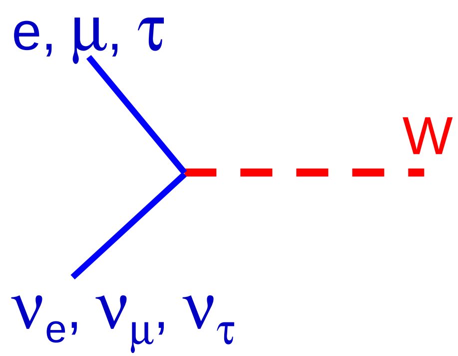


James Cronin Val Fitch

CP Violation in the Standard Model

- *CP* violation enters the Standard Model through complex phases in mixing matrices that connect up-type fermions with down-type fermions via W bosons:





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

- Cabibbo-Kobayashi-Maskawa (CKM) quark mixing matrix transforms quark mass eigenstates into weak eigenstates and induces *CP* violation in the hadronic sector

- Pontecorvo-Maki-Nakagawa-Sakata (PMNS) neutrino mixing matrix
→ induces neutrino oscillations and possibly *CP* violation in lepton sector

$$\begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix}$$

CKM Matrix

- Expand CKM matrix in $\lambda = V_{us} = \sin(\theta_{Cabibbo}) \approx 0.23$

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \approx \begin{pmatrix} 1-\frac{1}{2}\lambda^2-\frac{1}{8}\lambda^4 & \lambda & A\lambda^3(\rho-i\eta) \\ -\lambda+\frac{1}{2}A^2\lambda^5[1-2(\rho+i\eta)] & 1-\frac{1}{2}\lambda^2-\frac{1}{8}\lambda^4(1+4A^2) & A\lambda^2 \\ A\lambda^3[1-(1-\frac{1}{2}\lambda^2)(\rho+i\eta)] & -A\lambda^2+\frac{1}{2}A\lambda^4[1-2(\rho+i\eta)] & 1-\frac{1}{2}A^2\lambda^4 \end{pmatrix}$$

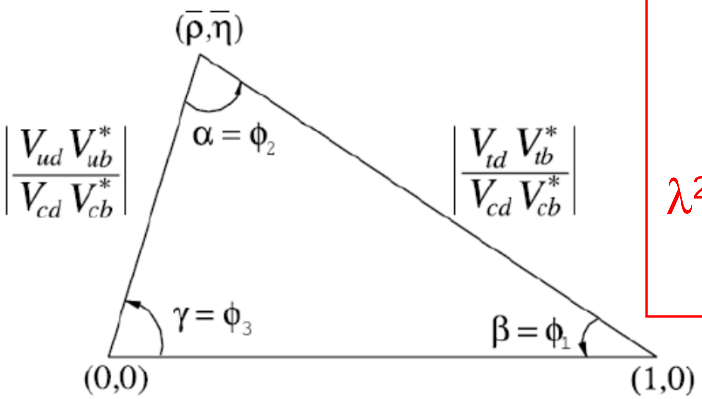
- To conserve probability CKM matrix must be unitary
  → Unitary relations can be represented as "unitarity triangles"

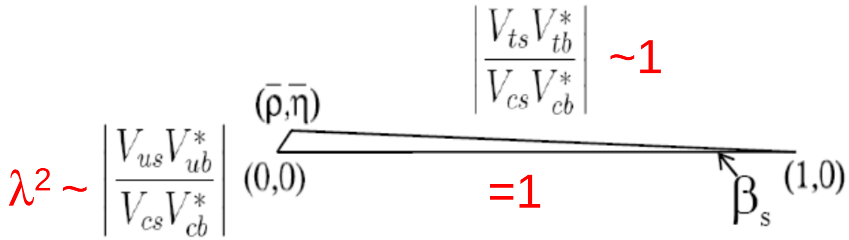
unitarity relations:

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

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

unitarity triangles:



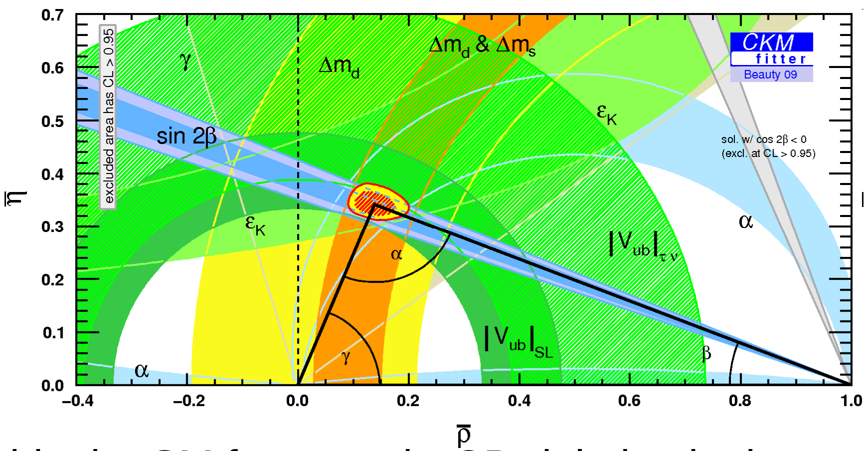


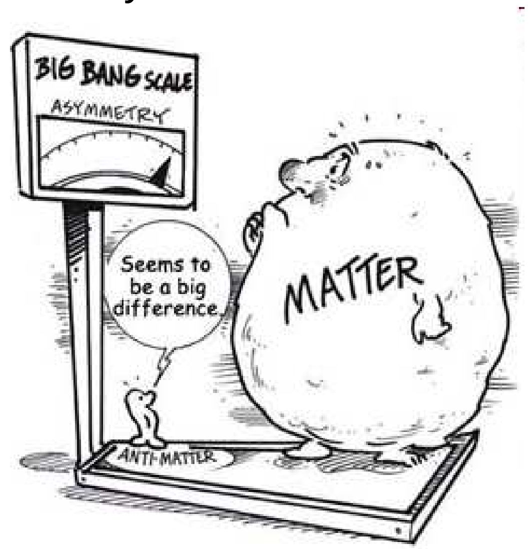
Small *CP* violation phase β_s accessible in $B_s \to J/\psi\Phi$ decays

Why Look for CPV in B_s System ?

- *CP* violation has been studied in various Kaon and *B*-meson decays

- CKM matrix is well constrained by experimental data





- Within the SM framework, *CP* violation in the quark sector is too small to explain the matter - antimatter asymmetry in the universe

- Could find additional *CP* violation within the SM in the lepton sector
  - initial asymmetry between leptons and anti-leptons may induce baryon asymmetry through baryon number violation processes (lepto-genesis)
  - long baseline neutrino experiments will investigate CP violation in neutrino sector

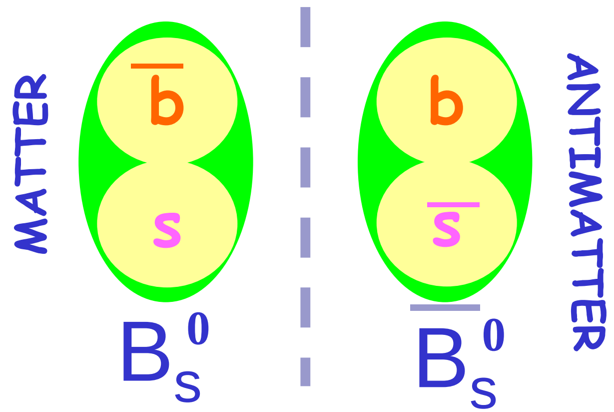
- Alternatively we look for sources of *CP* violation beyond the SM in the quark sector

- Promising place to look for non-SM *CP* violation is the neutral B_s meson system

Neutral B_s System

- Time evolution of B_s flavor eigenstates described by Schrodinger equation:

$$i\frac{d}{dt}\begin{pmatrix}|B_s^0(t)\rangle\\|\bar{B}_s^0(t)\rangle\end{pmatrix} = \left(\mathbf{M}-\frac{i}{2}\Gamma\right)\begin{pmatrix}|B_s^0(t)\rangle\\|\bar{B}_s^0(t)\rangle\end{pmatrix}$$



-Diagonalize mass (M) and decay (Γ) matrices
→ mass eigenstates :

$$|B_s^H\rangle = p\,|B_s^0\rangle - q\,|\bar{B}_s^0\rangle \qquad |B_s^L\rangle = p\,|B_s^0\rangle + q\,|\bar{B}_s^0\rangle$$

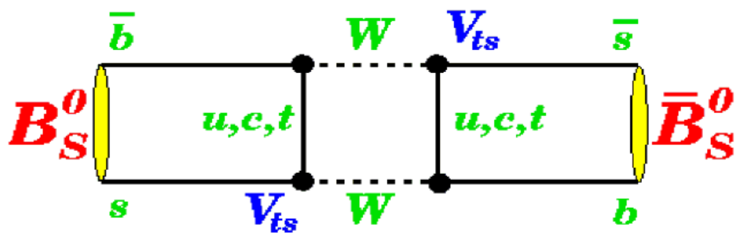
- Flavor eigenstates differ from mass eigenstates and mass eigenvalues are also different:

$\Delta m_s = m_H - m_L \approx 2|M_{12}|$

→ B_s oscillates with frequency Δm_s precisely measured by

CDF $\Delta m_s = 17.77$ +/- $0.12\ ps^{-1}$

DØ $\Delta m_s = 18.56$ +/- $0.87\ ps^{-1}$

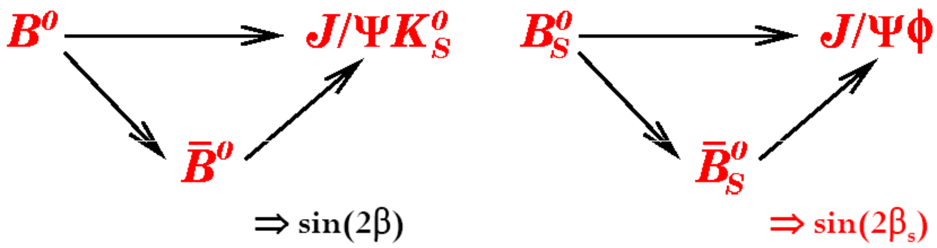


- Mass eigenstates have different decay widths

$\Delta\Gamma = \Gamma_L - \Gamma_H \approx 2|\Gamma_{12}|\cos(\Phi_s)$ where $\phi_s^{SM} = \arg\left(-\frac{M_{12}}{\Gamma_{12}}\right) \approx 4 \times 10^{-3}$

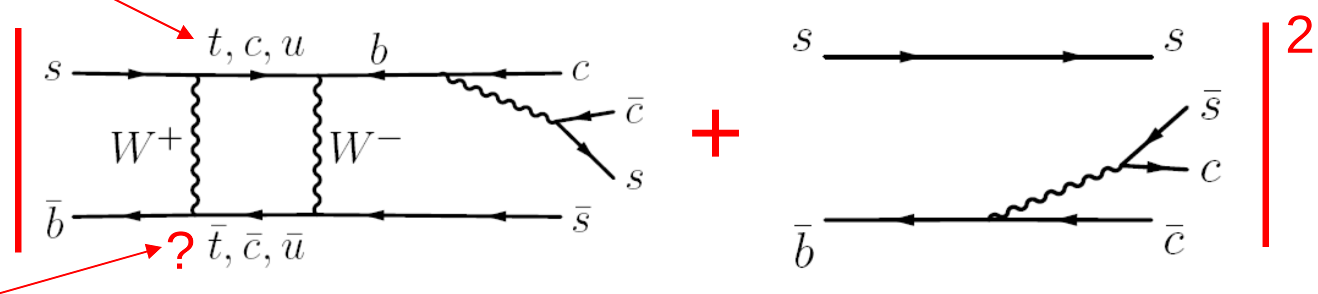
CP Violation in $B_s \rightarrow J/\Psi\Phi$ Decays

- Analogously to the neutral B^0 system, *CP* violation in B_s system is accessible through interference of decays with and without mixing:



dominant contribution from top quark

Decay rate ~



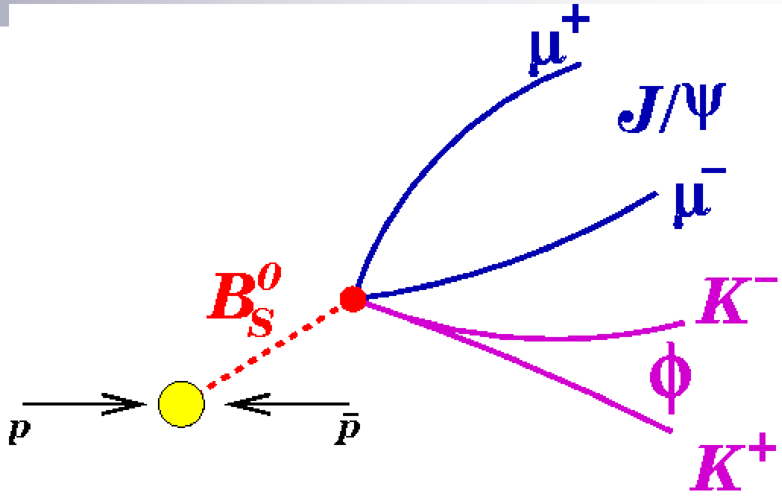
New Physics particles ?

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

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

- *CP* violation phase β_s in SM is predicted to be very small, *$O(\lambda^2)$*
- New physics particles running in the mixing diagram may enhance β_s
  - large β_s $\rightarrow$ clear indication of New Physics !

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

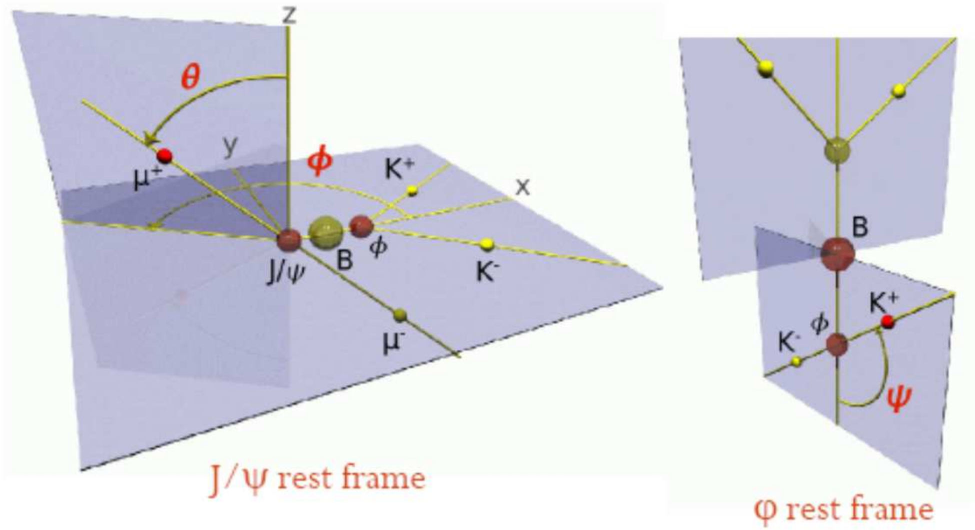


- Measure:
  - B_s lifetime τ_s
  - B_{sH}, B_{sL} decay width difference $\Delta\Gamma_s$
  - CP violating phase β_s

- Decay of B_s (spin 0) to J/Ψ (spin 1) and Φ (spin 1) leads to three different angular momentum final states:

  $L = 0$ (s-wave), 2 (d-wave) → *CP even* (= short lived or light B_s if no *CPV*)

  $L = 1$ (p-wave) → *CP odd* (= long lived or heavy B_s if no *CPV*)



- Three decay angles $\vec{\rho} = (\theta, \phi, \psi)$ describe directions of final decay products

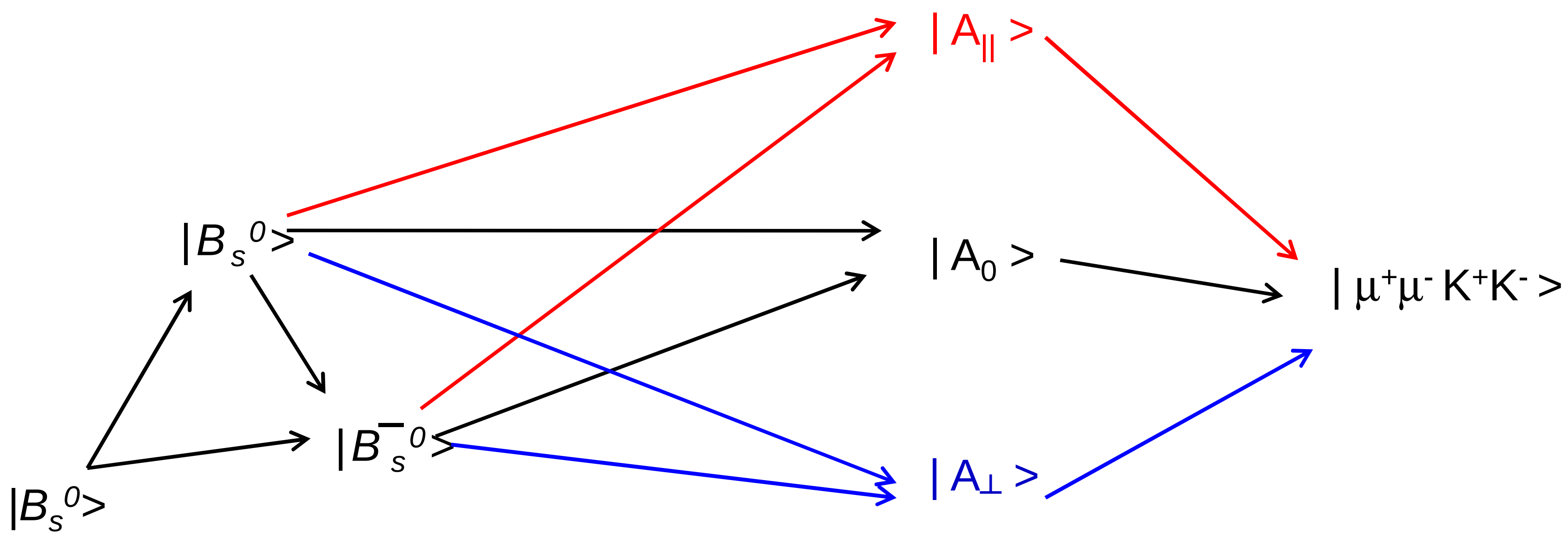
  $\mu^+ \mu^- K^+ K^-$

Transversity Basis

- Use "transversity basis" in which the vector meson polarizations w.r.t. direction of motion are either (Phys. Lett. B 369, 144 (1996), 184 hep-ph/9511363):

  - transverse ($\perp$ perpendicular to each other) → *CP odd*
  - transverse ($\|$ parallel to each other) → *CP even*
  - longitudinal (0) → *CP even*

- Corresponding decay amplitudes: A_0, $A_\|$, $A_\perp$



Decay Rate

- $B_s \rightarrow J/\Psi\Phi$ decay rate as function of time, decay angles and initial B_s flavor:

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

time dependence terms

angular dependence terms

terms with β_s dependence

$$\mathcal{T}_\pm = e^{-\Gamma t} \times [\cosh(\Delta\Gamma t/2) \mp \cos(2\beta_s)\sinh(\Delta\Gamma t/2) \mp \eta\sin(2\beta_s)\sin(\Delta m_s t)],$$

terms with Δm_s dependence present if initial state of B meson (B vs anti-B) is determined (flavor tagged)

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

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

'strong' phases:

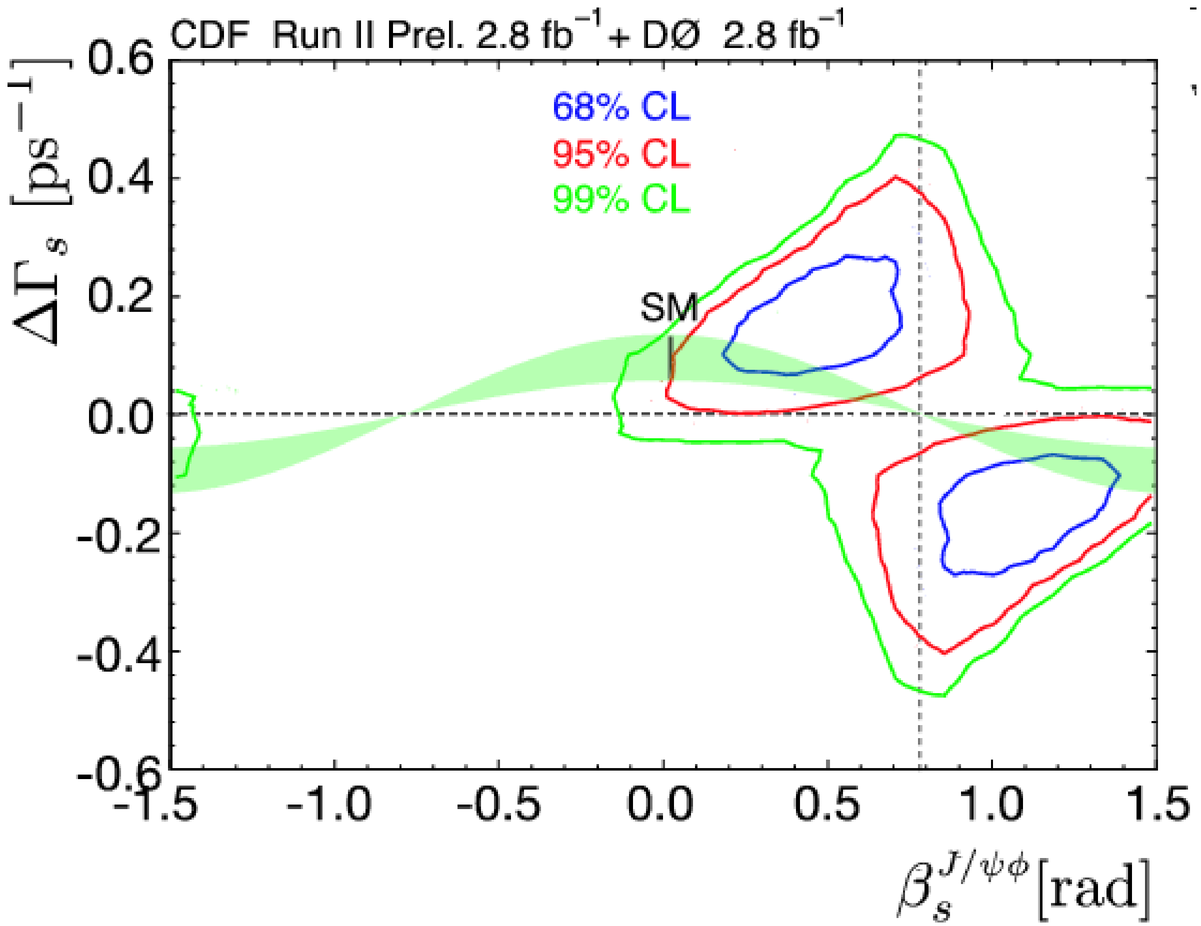
$$\delta_\parallel \equiv \mathrm{Arg}(A_\parallel(0)A_0^*(0))$$
$$\delta_\perp \equiv \mathrm{Arg}(A_\perp(0)A_0^*(0))$$

- Identification of *B* flavor at production (flavor tagging) → better sensitivity to β_s

Some History

- Tagged analysis first performed by CDF in 2007 and soon followed by D0

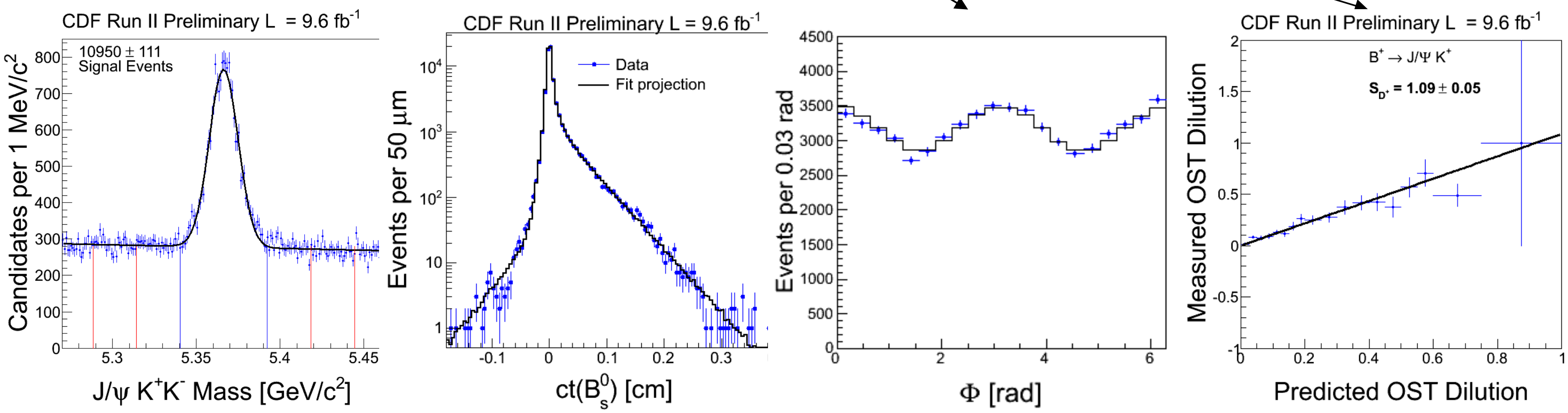
- In 2009, CDF + DØ combination with 2.8/fb done by the Tevatron B Working Group (http://tevbwg.fnal.gov/) showed intriguing 2.1σ deviation from SM expectation



Analysis Components

- Multi-dimensional likelihood fit

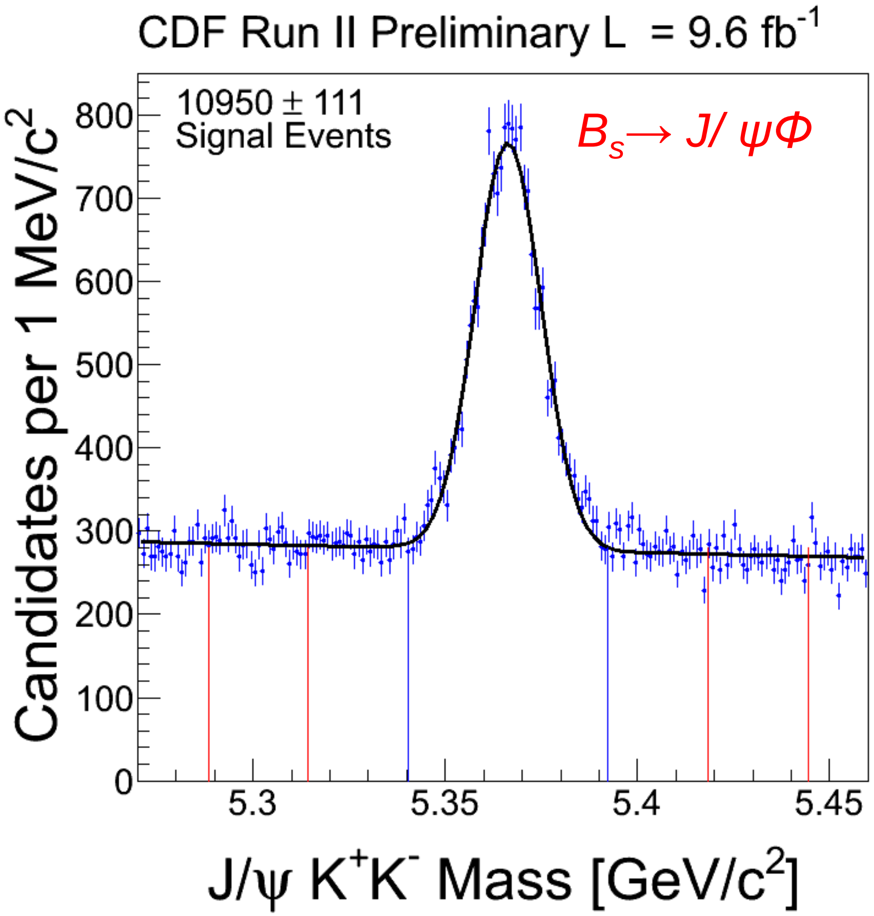
$$f_s P_s(m|\sigma_m) P_s(t, \vec{\rho}, \xi | \mathcal{D}, \sigma_t) P_s(\sigma_t) P_s(\mathcal{D})$$



Mass discriminate signal against background	Decay-time determines lifetime of each mass eigenstate	Angles separate CP-even from CP-odd final states	Tagging determines flavor of initial B_s state

Signal Reconstruction

- Reconstruct $B^0_s \rightarrow J/\psi\Phi$ in 9.6 fb^{-1} of data from sample selected by di-muon trigger
- Combine kinematic variables with particle ID information (dE/dx, TOF) in neural network to discriminate signal from background
- Yield of ~11000 B_s events with S/B ~ 1



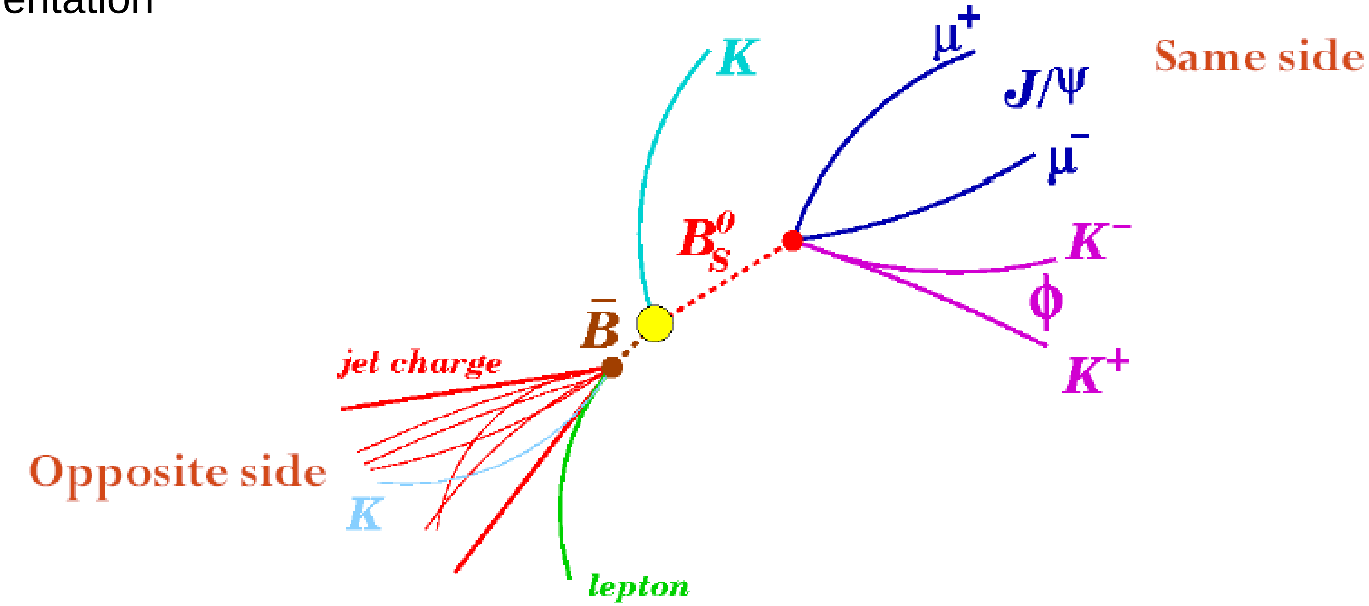
Flavor Tagging

- Tevatron: *b*-quarks mainly produced in pairs of *bottom anti-bottom*

→ flavor of the *B* meson at production inferred with:

- Opposite Side Tagger (OST): exploits decay products of other *b*-hadron in the event

- Same Side Kaon Tagger (SSKT): exploits correlations with particles produced in fragmentation



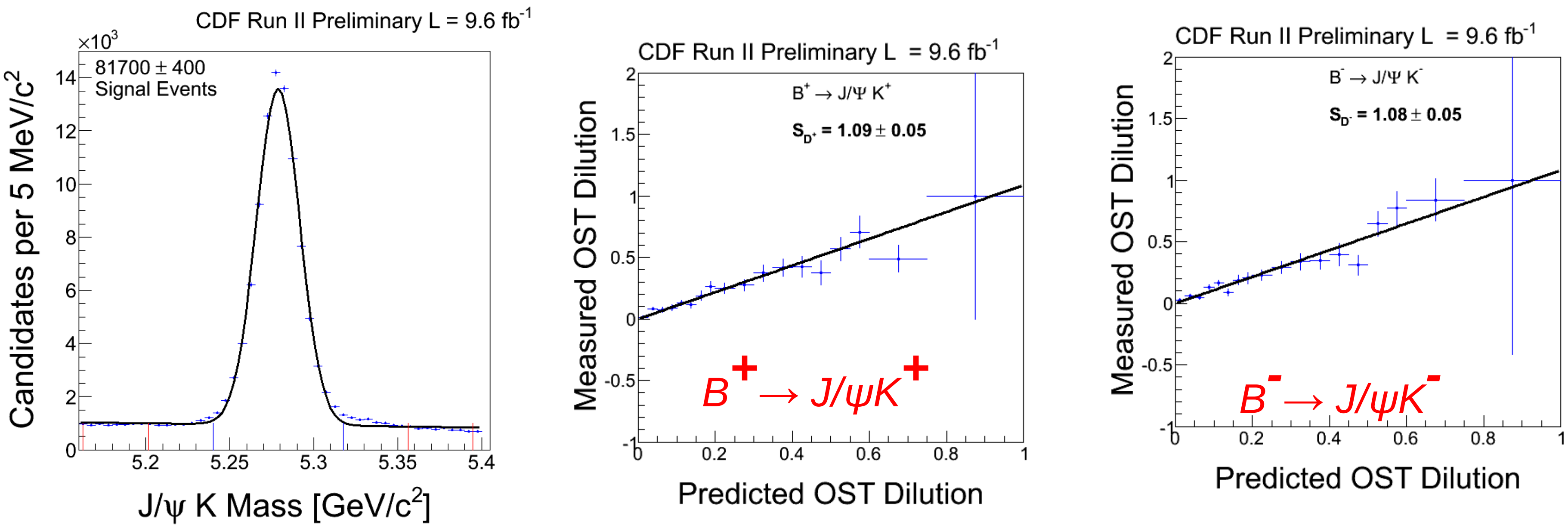
- Output of flavor tagger:

  - flavor decision (*b*-quark or anti-*b*-quark)

  - probability that the decision is correct: *P = (1 + Dilution) / 2*

Opposite Side Tagging Calibration and Performance

- OST combines in a NN opposite side lepton and jet charge information
- Initially calibrated using a sample of inclusive semileptonic *B* decays
    - predicts tagging probability on event-by-event basis
- Re-calibrated using ≈ 82,000 $B^{+/-} \rightarrow J/\Psi K^{+/-}$ decays



- OST efficiency = 93%, OST dilution = 11.5 +/- 0.2 % (correct tag probability ~56%)
- Total tagging power = 1.2%

Same Side Tagging Calibration

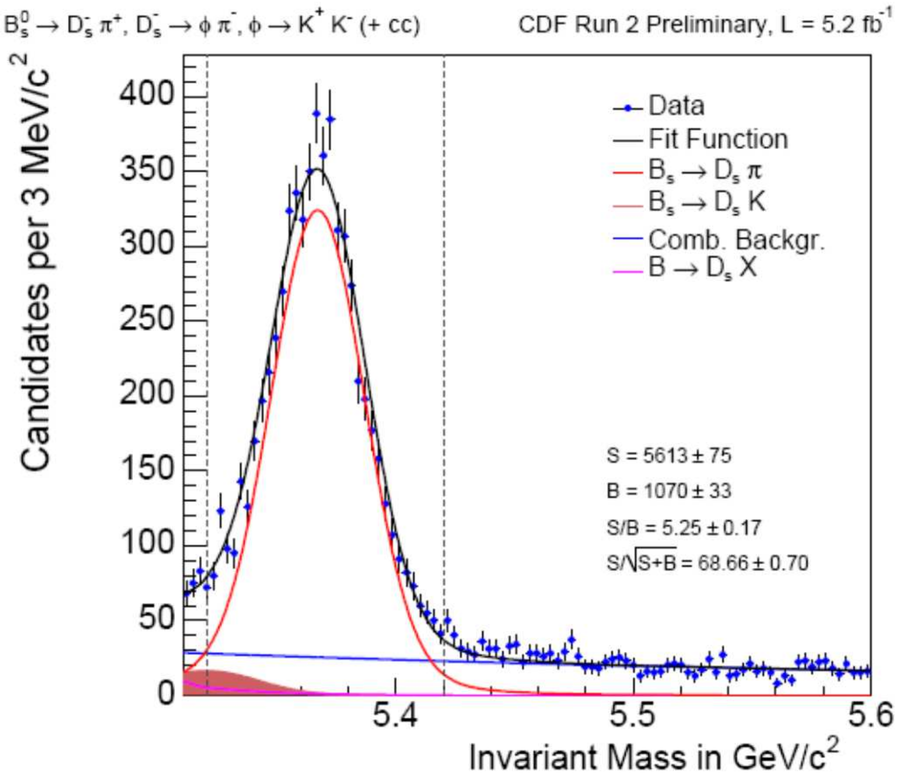
- Event-by-event predicted dilution based on simulation
- Calibrated with 5.2 fb^{-1} of data; only use SSKT for corresponding 5.2/fb
- Simultaneously measuring the B_s mixing frequency Δm_s and the dilution scale factor A

$$P_{Sig}(ct|\sigma_{ct},\xi=\xi_D\cdot\xi_P,D)=\frac{1}{N}\cdot\left[\frac{1}{\tau}e^{-\tilde{t}/\tau}\cdot(1+\xi\mathcal{A}D\cdot\cos(\Delta m_s\tilde{t}))\right]\otimes\mathcal{G}(c\tilde{t}|\sigma_{ct})\cdot\epsilon(ct|\sigma_{ct})$$

- D – event by event predicted dilution
- ξ – tagging decision = +1, -1, 0 for B_s, $\overline{B}_s$ and un-tagged events

- Fully reconstructed B_s decays selected by displaced track trigger

Decay Channel	S
$B_s^0\to D_s^-\pi^+,\ D_s^-\to\phi\pi^-$	5613 ± 75
$B_s^0\to D_s^-\pi^+,\ D_s^-\to K^*K^-$	2761 ± 53
$B_s^0\to D_s^-\pi^+,\ D_s^-\to(3\pi)^-$	2652 ± 52
$B_s^0\to D_s^-(3\pi)^+,\ D_s^-\to\phi\pi^-$	1852 ± 43
Sum	12877 ± 113



Same Side Tagging Performance

- B_s oscillation frequency measured $\Delta m_s = (17.79 \pm 0.07)\ \mathrm{ps}^{-1}$ (statistical error only)

- In good agreement with the published CDF measurement with 1 fb^{-1}
PRL 97, 242003 2006, PRL 97, 062003 2006

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

used as external constraint in β_s measurement

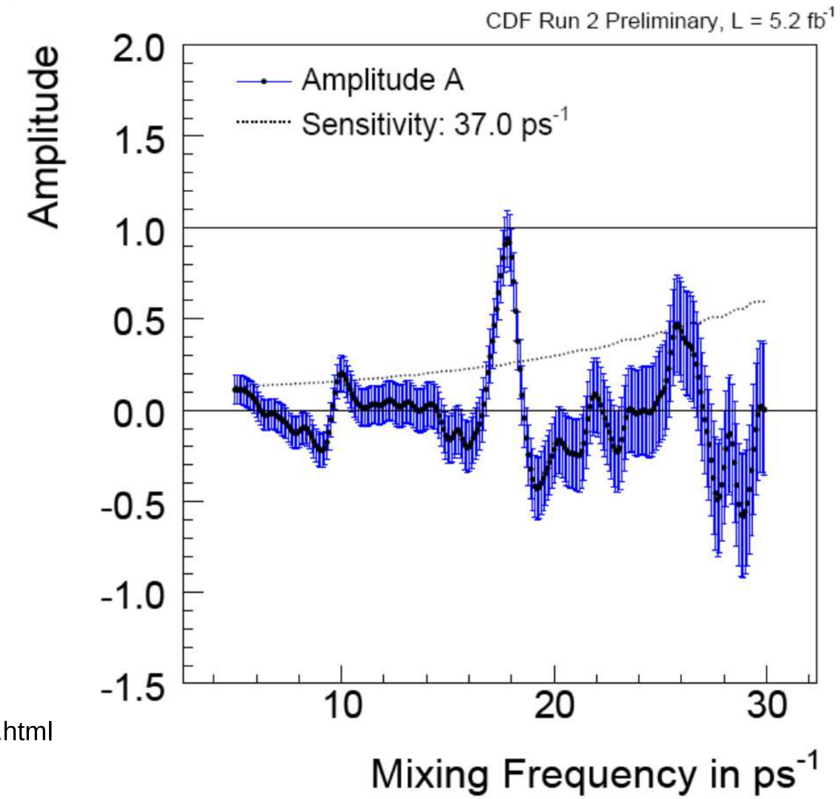
- Dilution scale factor (amplitude) in good agreement with 1:

$$\mathcal{A} = 0.94 \pm 0.15\ (stat.) \pm 0.13\ (syst.)$$

- Largest systematic uncertainty from decay time resolution modeling

- Total SSKT tagging power:

$$\varepsilon \mathcal{A}^2 D^2 = (3.2 \pm 1.4)\ \%.$$



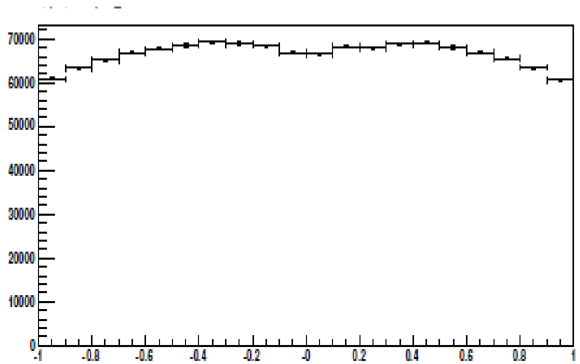
http://www-cdf.fnal.gov/physics/new/bottom/100204.blessed-sskt-calibration/index.html
CDF public note 10108

Detector Angular Efficiency

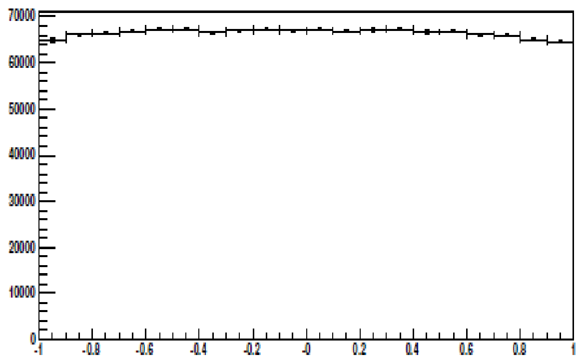
- *CP even* and *CP odd* final states have different angular distributions
  → use angles $\rho = (\theta, \phi, \psi)$ to statistically separate *CP even* and *CP odd* components

- Detector acceptance distorts the angular distributions
  → determine 3D angular efficiency function from simulation and account for this effect in the fit

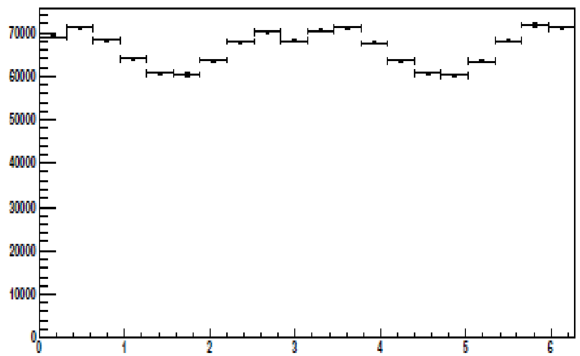
CDF Simulation of Detector Angular Sculpting



cos(θ)



cos(ψ)



Φ(rad)

B_s Lifetime and Decay Width Difference

- Assuming SM value of β_s obtain lifetime τ_s and decay width difference $\Delta\Gamma_s$:

$$\tau(B_s^0) = 1.528 \pm 0.019\ (\text{stat}) \pm 0.009\ (\text{syst})\ \text{ps},$$
$$\Delta\Gamma_s = 0.068 \pm 0.026\ (\text{stat}) \pm 0.007\ (\text{syst})\ \text{ps}^{-1}$$

- Compared to LHCb

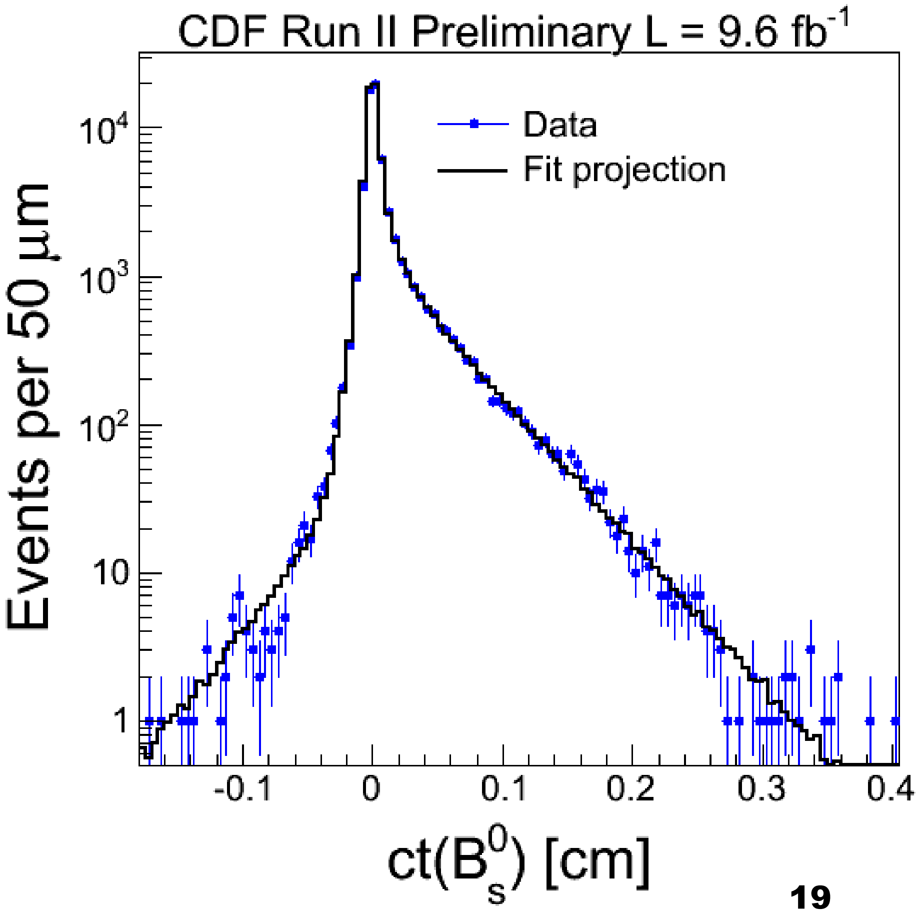
Phys. Rev. Lett. 108, 101803 (2012), arXiv:1112.3183v3

$$\Gamma_s = 0.657 \pm 0.009\ (\text{stat}) \pm 0.008\ (\text{syst})\ \ \text{ps}^{-1},$$
$$\Delta\Gamma_s = 0.123 \pm 0.029\ (\text{stat}) \pm 0.011\ (\text{syst})\ \ \text{ps}^{-1},$$

- Compared to D0

Phys. Rev. D **85**, 032006 (2012), arXiv:1109.3166

$$\overline{\tau}_s = 1.426^{+0.035}_{-0.032}\ \text{ps},$$
$$\Delta\Gamma_s = 0.129^{+0.076}_{-0.053}\ \text{ps}^{-1}$$

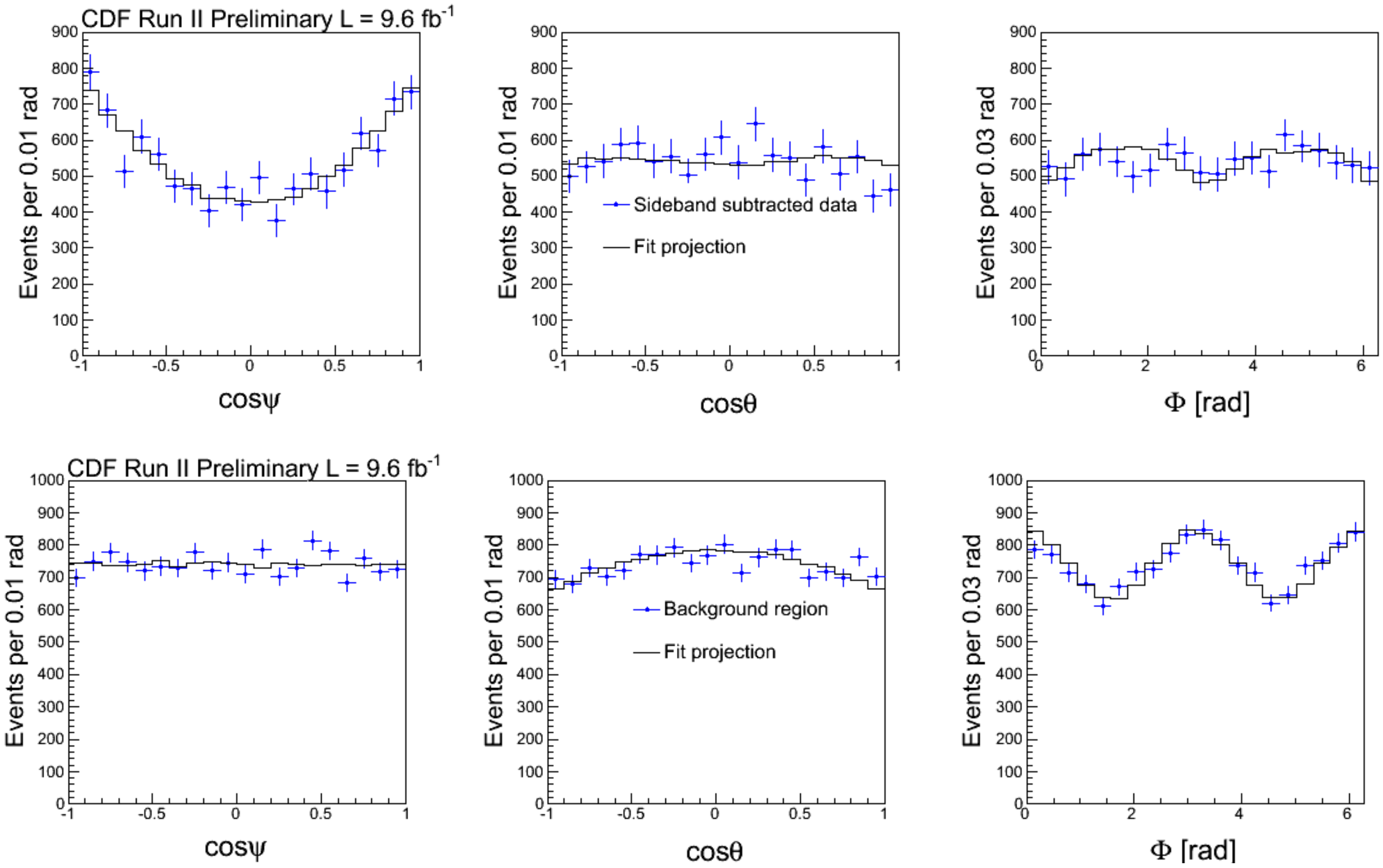


Polarization Amplitudes

$$|A_0(0)|^2 = 0.512 \pm 0.012\ (\text{stat}) \pm 0.017\ (\text{syst}),$$
$$|A_\parallel(0)|^2 = 0.229 \pm 0.010\ (\text{stat}) \pm 0.014\ (\text{syst}),$$
$$\delta_\perp = 2.79 \pm 0.53\ (\text{stat}) \pm 0.15\ (\text{syst})\ \text{rad}.$$

Signal fit projections

Background fit projections



S-Wave

- As noted in arxiv:0812.2832v3, the KK pair in $B_s \rightarrow J/\Psi\ KK$ decays can be in an s-wave state with ~6% contribution in a +/-10 MeV window around the Φ peak

- Systematic effects from neglecting such contribution were first investigated by Clarke *et al* in arxiv:0908.3627v1

- S-wave contribution can be either non-resonant KK or from the $f^0(980)$ resonance

- To account for potential s-wave contribution, enhance the likelihood function to account for the s-wave amplitude A_S and interference between s-wave and p-wave

- Time dependence of the s-wave amplitude A_S is *CP-odd*, same as $A_\perp$

- Mass and phase of s-wave component are assumed flat (good approximation in a narrow +/- 10 MeV around the Φ mass)

- The fitted s-wave fraction is found to be very small in the KK mass range used in this analysis: [1.009, 1.028] GeV

s-wave fraction < 6% at 95% C.L.

- Interesting to compare with latest D0 result: ~15 +/- 4% s-wave fraction

Phys. Rev. D **85**, 032006 (2012), arXiv:1109.3166

and LHCb result: ~ 4 +/- 2% - // - arXiv:1202.4717v2

CP Violation Phase β_s in Tagged $B_s \to J/\Psi\Phi$ Decays

- Without the s-wave the likelihood function is symmetric under the transformation

$$2\beta_s \to \pi - 2\beta_s \qquad \Delta\Gamma \to -\Delta\Gamma$$

$$\delta_{\parallel} \to 2\pi - \delta_{\parallel}, \qquad \delta_{\perp} \to \pi - \delta_{\perp}$$

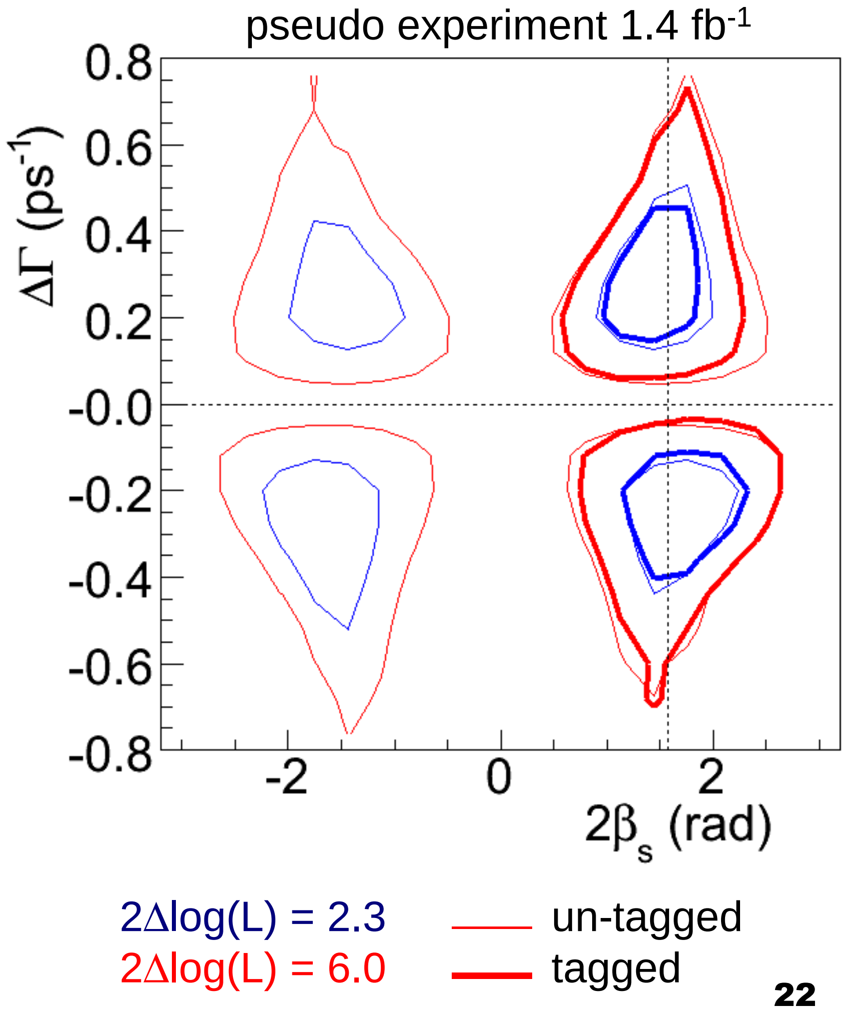
- Study expected effect of tagging using pseudo-experiments

- Improvement of parameter resolution is small due to limited tagging power ($\varepsilon D^2 \sim 4.5\%$ compared to B factories ~30%)

- However, $\beta_s \to -\beta_s$ no longer a symmetry
  $\to$ 4-fold ambiguity reduced to 2-fold ambiguity

- Adding the s-wave "slightly" breaks the symmetry due to asymmetric Φ mass shape

- Symmetry still valid with good approximation…



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- Without the s-wave the likelihood function is symmetric under the transformation

$$2\beta_s \rightarrow \pi - 2\beta_s \qquad \Delta\Gamma \rightarrow -\Delta\Gamma$$

$$\delta_{\|} \rightarrow 2\pi - \delta_{\|}, \qquad \delta_{\perp} \rightarrow \pi - \delta_{\perp}$$

- Study expected effect of tagging using pseudo-experiments

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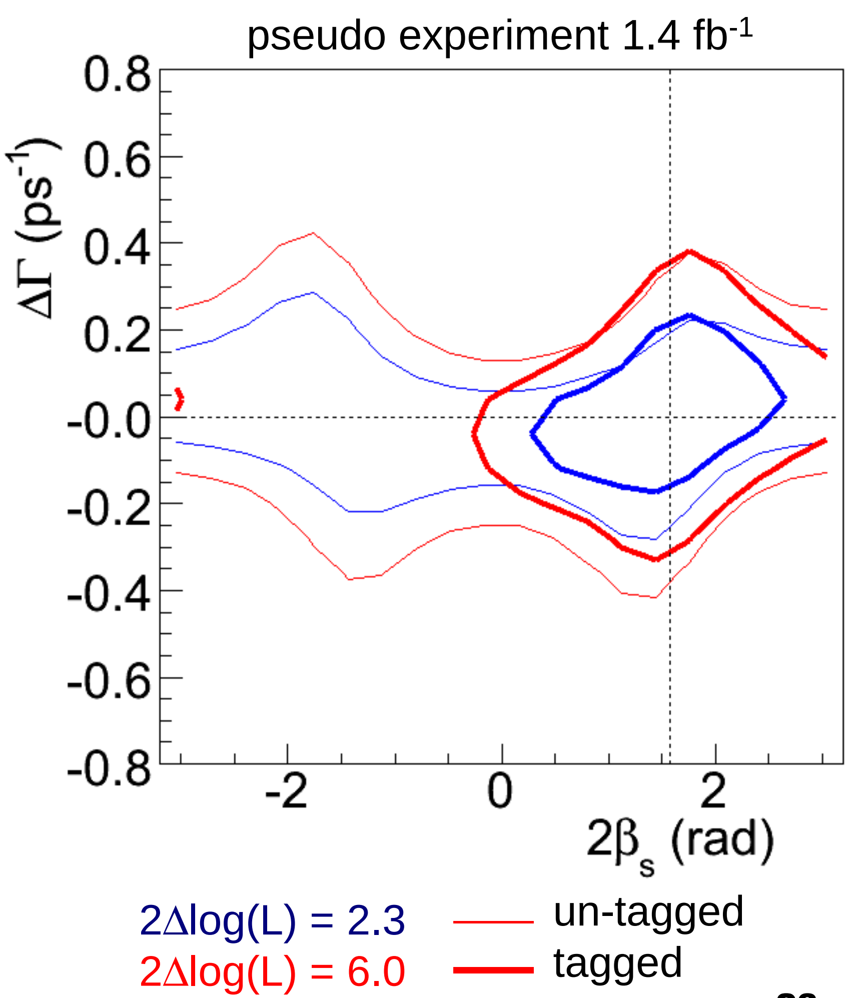
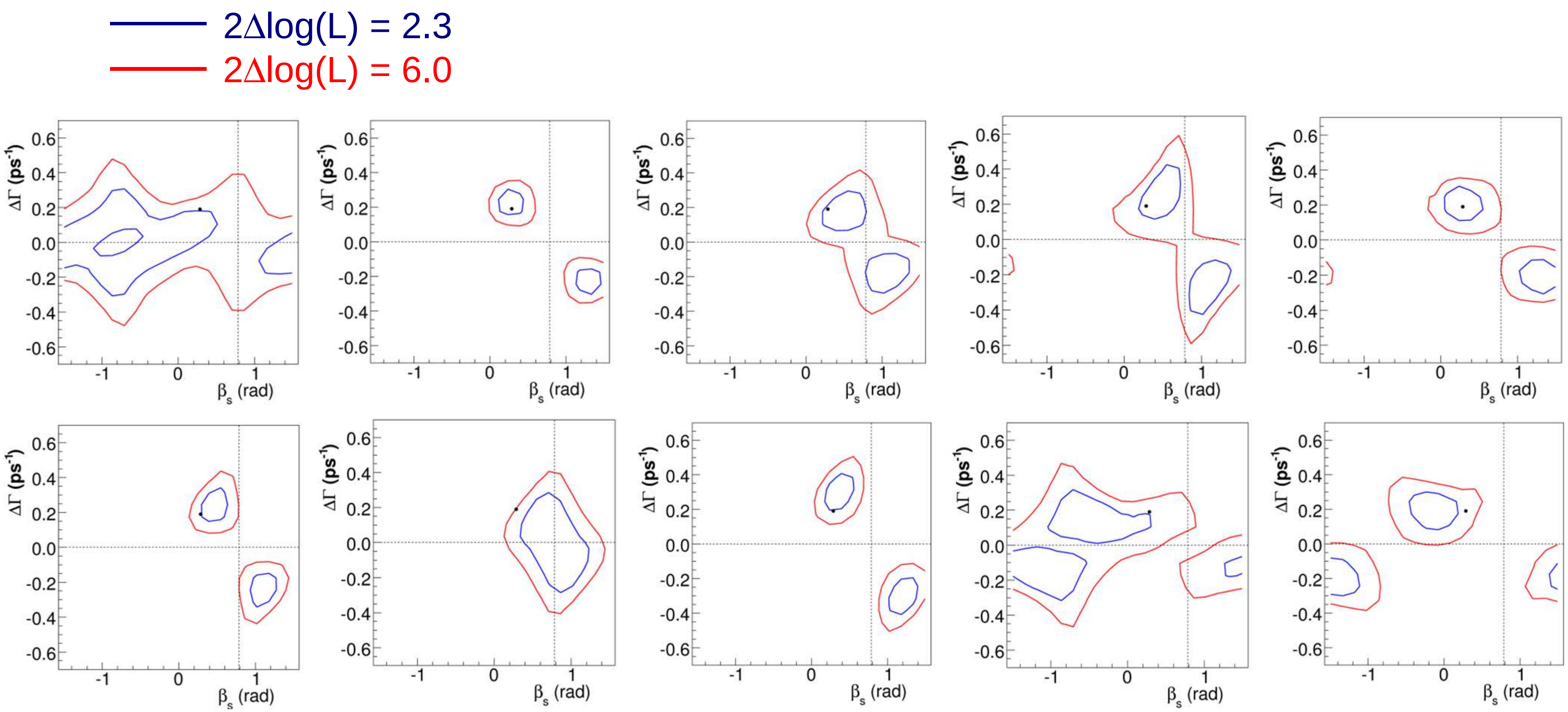


Cross Checks With Pseudo-Experiments

- Generate 10 pseudo-experiments with β_s = 0.3 and $\Delta\Gamma$ = 0.2 corresponding to 1.4 fb^{-1}
  - same parameters, just different random seeds

- Large fluctuations expected in shape and size of confidence regions



Comparison Between Different Data Periods

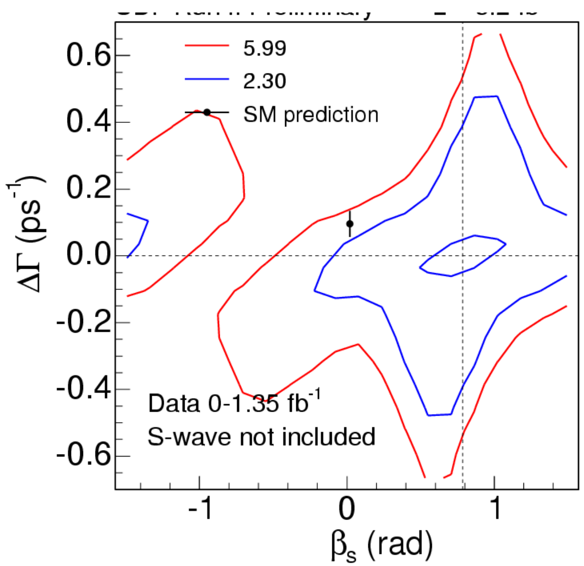
- Divide 9.6 fb^{-1} sample in four sub-samples corresponding to four public releases:

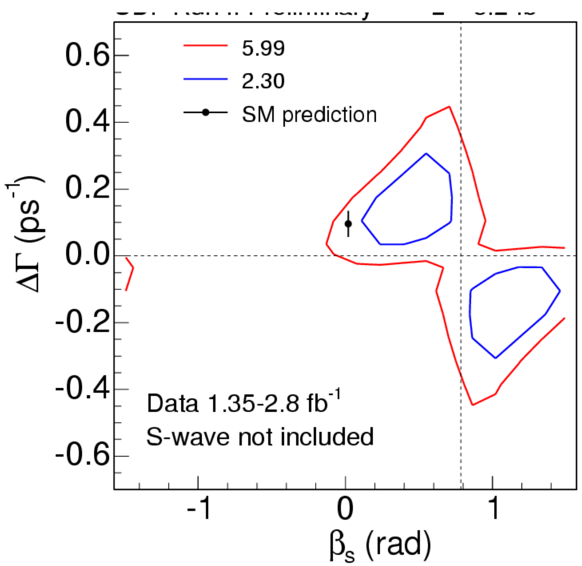
0 - 1.4 fb^{-1}

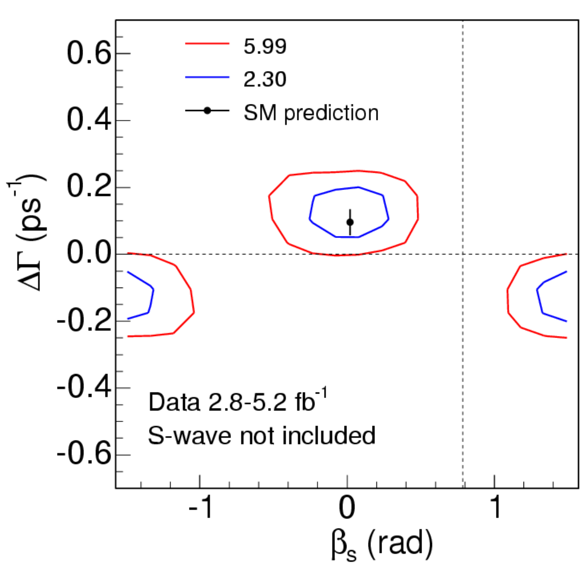
1.4 - 2.8 fb^{-1}

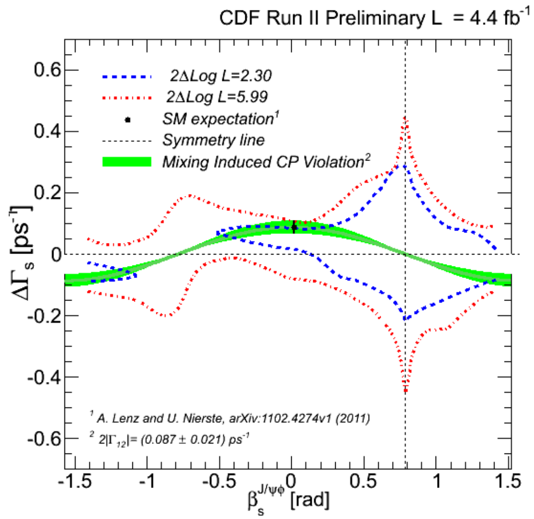
2.8 - 5.2 fb^{-1}

5.2 – 9.6 fb^{-1}









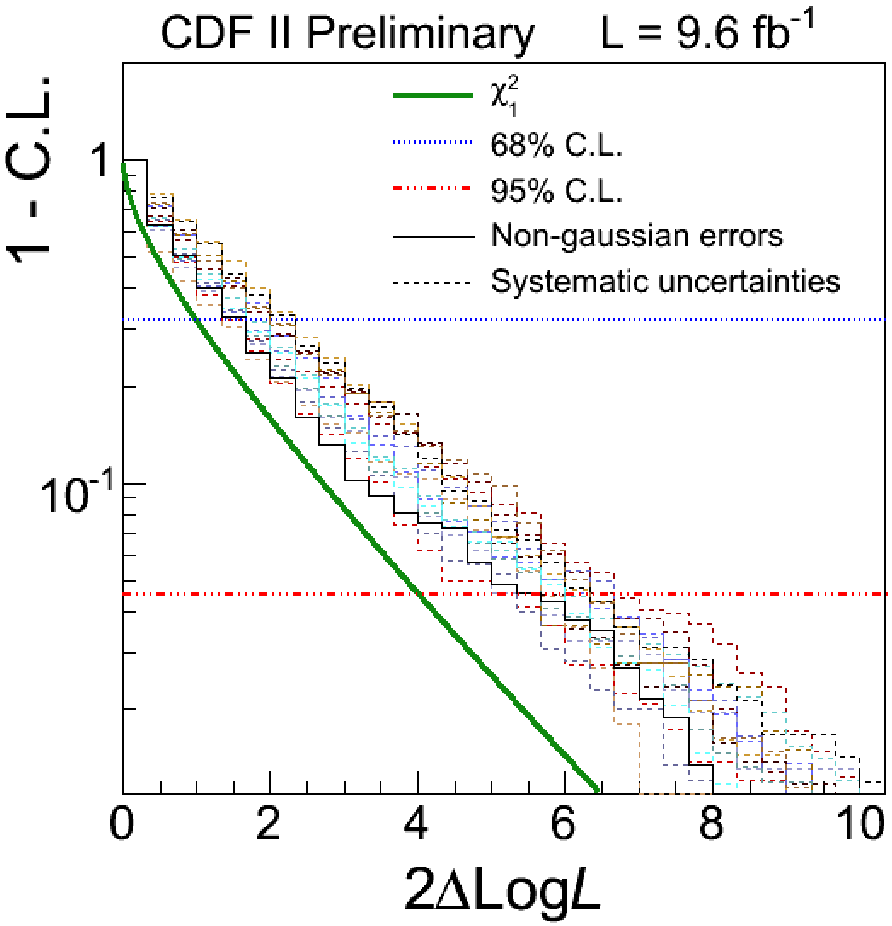
Non-Gaussian Regime

- Pseudo-experiments show that we are not in Gaussian regime
  → *quote confidence regions instead of point estimates*

- Using pseudo-experiments establish a “map” between Confidence Level and 2Δlog(L)

- All nuisance parameters are randomly varied within +/- 5σ from their best fit values and maps of CL vs 2Δlog(L) re-derived

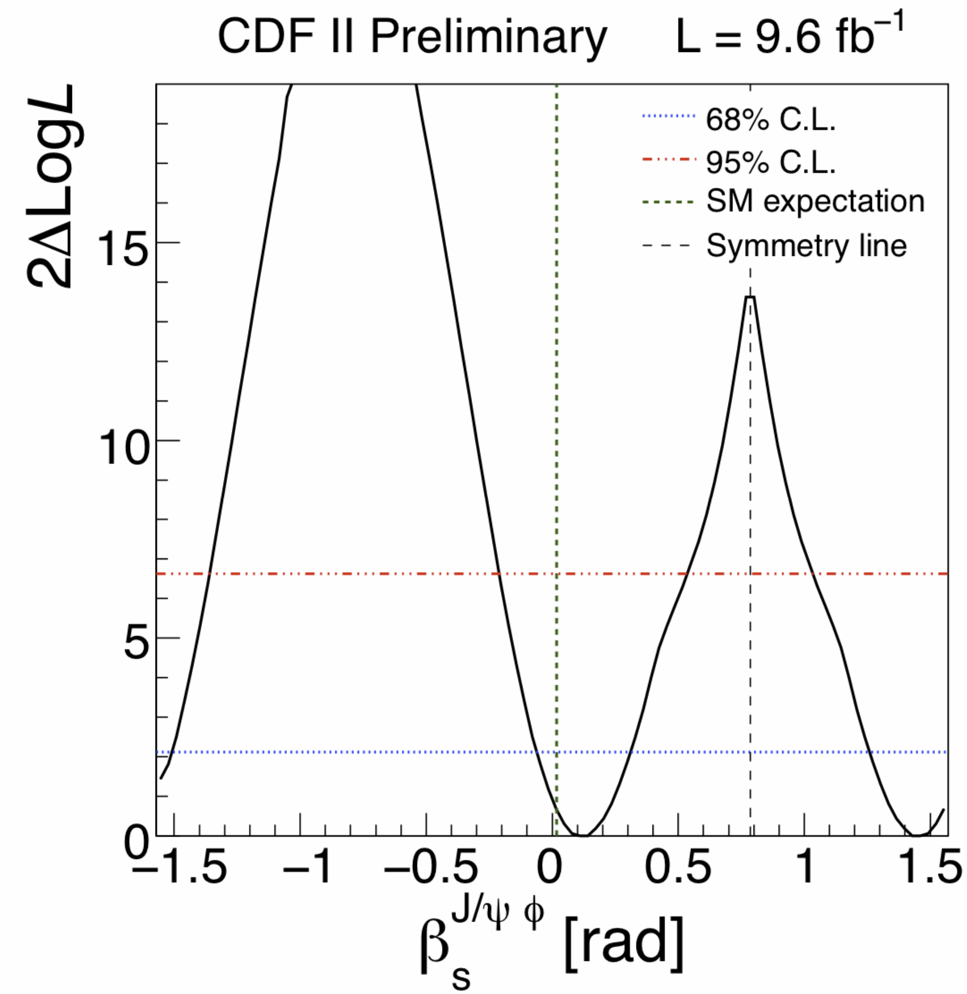
- To establish final confidence regions use most conservative case



CP Violation Phase β_s with 9.6 fb^{-1} at CDF

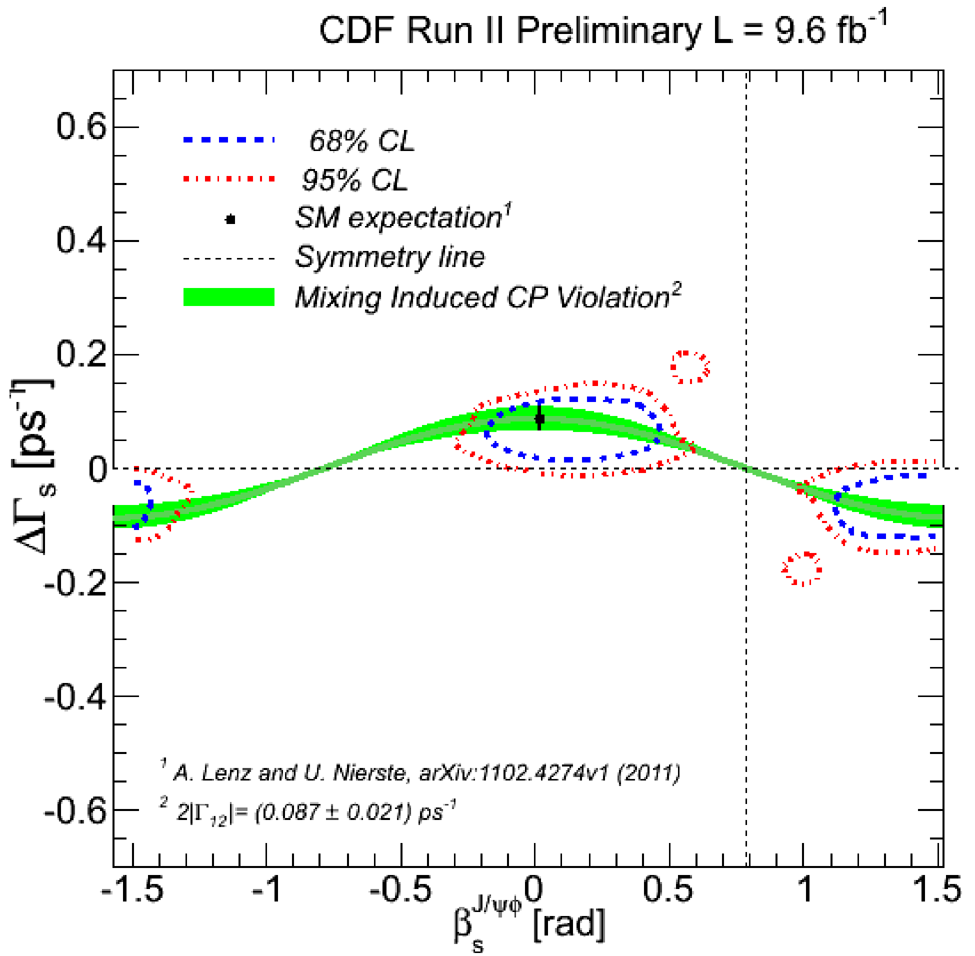
$$\beta_s^{J/\psi\phi} \in [-\pi/2, -1.51] \bigcup [-0.06, 0.30] \bigcup [1.26, \pi/2] \quad \text{at 68\% CL}$$

$$[-\pi/2, -1.36] \bigcup [-0.21, 0.53] \bigcup [1.04, \pi/2]) \quad \text{at 95\% CL}$$



CP Violation Phase β_s with 9.6 fb^{-1} at CDF

- Final confidence regions in β_s-$\Delta\Gamma_s$ space:



Summary of CDF results

- Measurement of CP violation in B_s system updated by CDF with full 10/fb sample

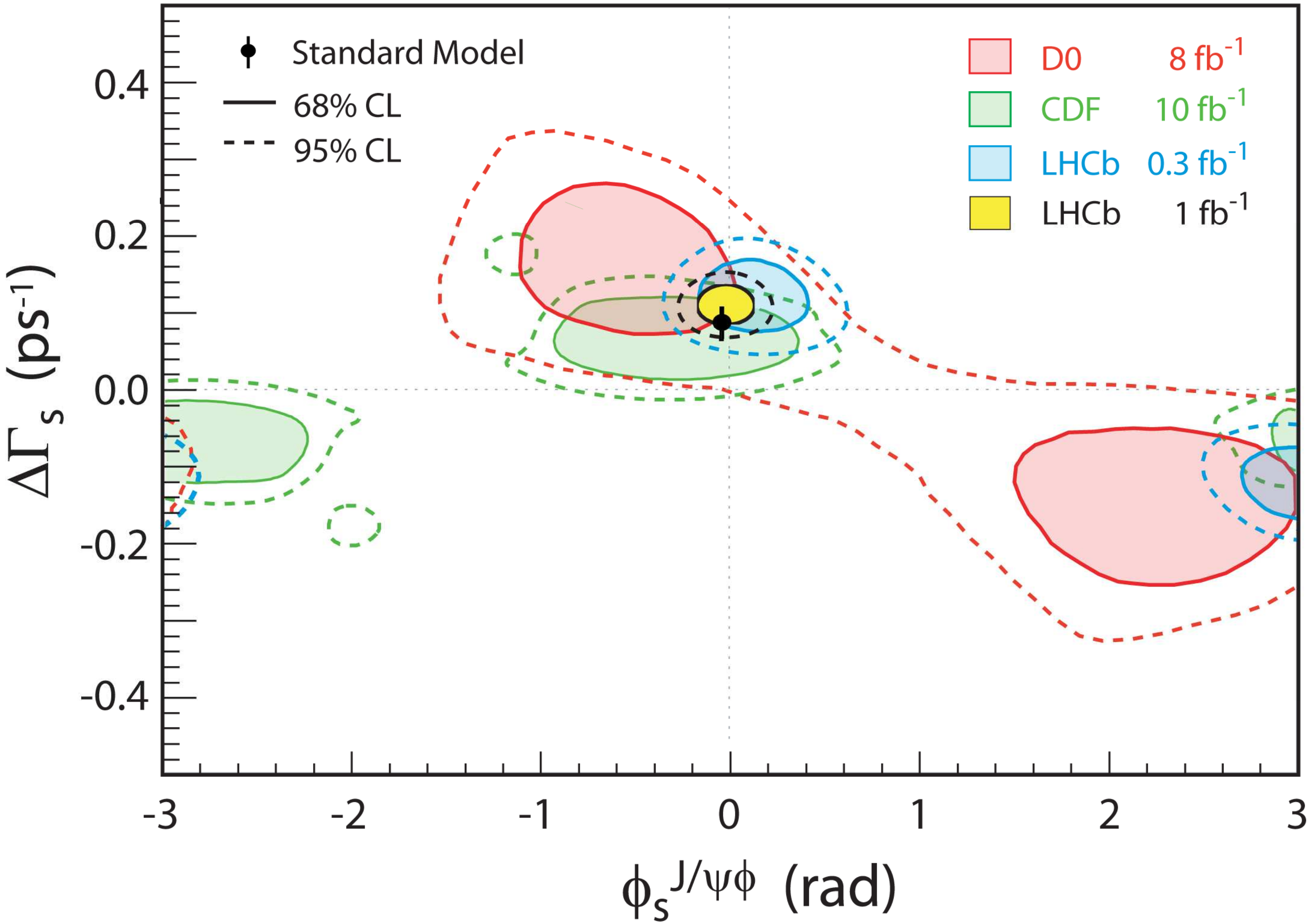
- Tightened constraints in β_s space:

$$\beta_s^{J/\psi\phi} \in [-\pi/2, -1.51] \bigcup [-0.06, 0.30] \bigcup [1.26, \pi/2] \quad \text{at 68\% CL}$$

- Measurements of B_s lifetime, decay width difference $\Delta\Gamma_s$ and polarization amplitudes

$$\begin{aligned}
\tau(B_s^0) &= 1.528 \pm 0.019 \text{ (stat)} \pm 0.009 \text{ (syst) ps},\\
\Delta\Gamma_s &= 0.068 \pm 0.026 \text{ (stat)} \pm 0.007 \text{ (syst) ps}^{-1},\\
|A_0(0)|^2 &= 0.512 \pm 0.012 \text{ (stat)} \pm 0.014 \text{ (syst)},\\
|A_{\|}(0)|^2 &= 0.229 \pm 0.010 \text{ (stat)} \pm 0.017 \text{ (syst)},\\
\delta_{\perp} &= 2.79 \pm 0.53 \text{ (stat)} \pm 0.15 \text{ (syst) rad.}
\end{aligned}$$

Comparison Between CDF, D0 and LHCb



Note on s-wave and sign of $\Delta\Gamma_S$ (from P. Clarke at Moriond 2012)

- There are two ambiguous solutions related by $\phi_s \Leftrightarrow \pi - \phi_s$ and $\Delta\Gamma \Leftrightarrow -\Delta\Gamma$
- We can disambiguate using the P-Wave ⇔ S-Wave interference

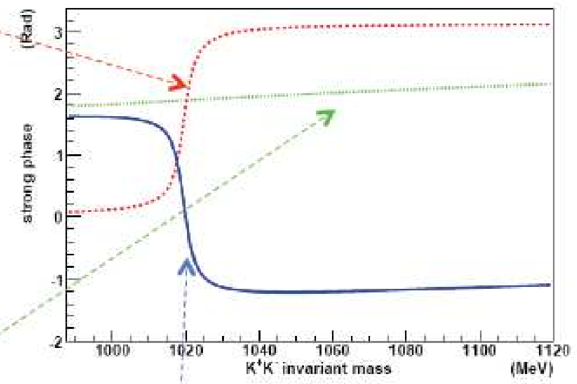
[Y. Xie et al., JHEP 0909:074, 2009]

Similar to Babar measurement of sign of cos(2β), PRD 71, 032005 (2007)

K^+K^- P-wave:

Phase of Breit-Wigner amplitude increases rapidly across ϕ(1020) mass region

$$BW(m_{KK}) = \frac{F_r F_D}{m_\phi^2 - m_{KK}^2 - i m_\phi \Gamma(m_{KK})}$$



K^+K^- S-wave:

Phase of Flatté amplitude for $f_0(980)$ relatively flat (similar for non-resonance)

Phase difference between S- and P-wave amplitudes

Decreases rapidly across ϕ(1020) mass region

Resolution method: choose the solution with decreasing trend of $\delta_S - \delta_P$ vs m_{KK} in the ϕ(1020) mass region

5

β_s ambiguity resolved by LHCb (from P. Clarke at Moriond 2012) **arxiv:1202.4717v2**

- Solution with $\Delta\Gamma>0$ has decreasing trend at 4.6 sigma significance

http://lhcb-public.web.cern.ch/lhcb-public/
"Recently LHCb physicists have succeeded to measure that the heavier strange-beauty B_s mesons live longer than the light one"

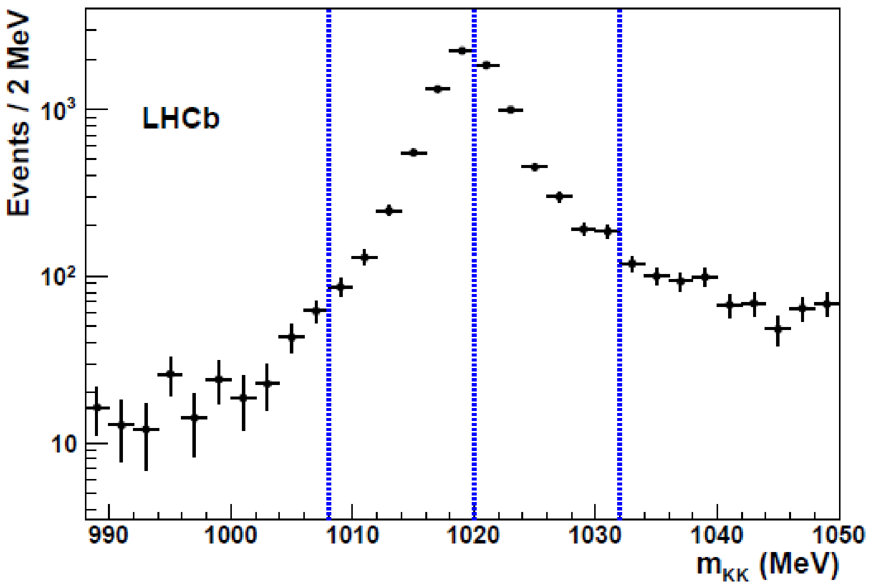


FIG. 2. Background subtracted K^+K^- invariant mass distribution for $B_s^0 \to J/\psi K^+K^-$ candidates. The vertical dotted lines separate the four intervals.

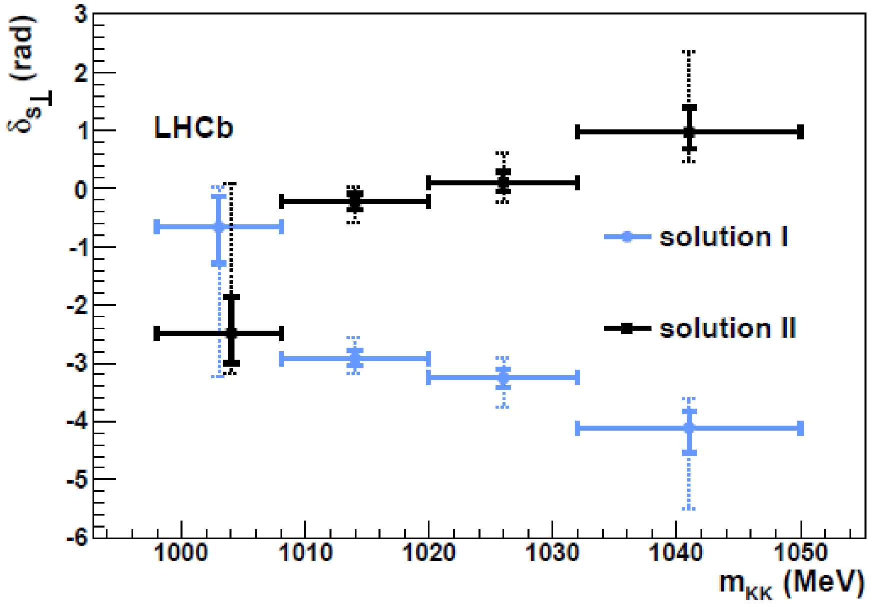
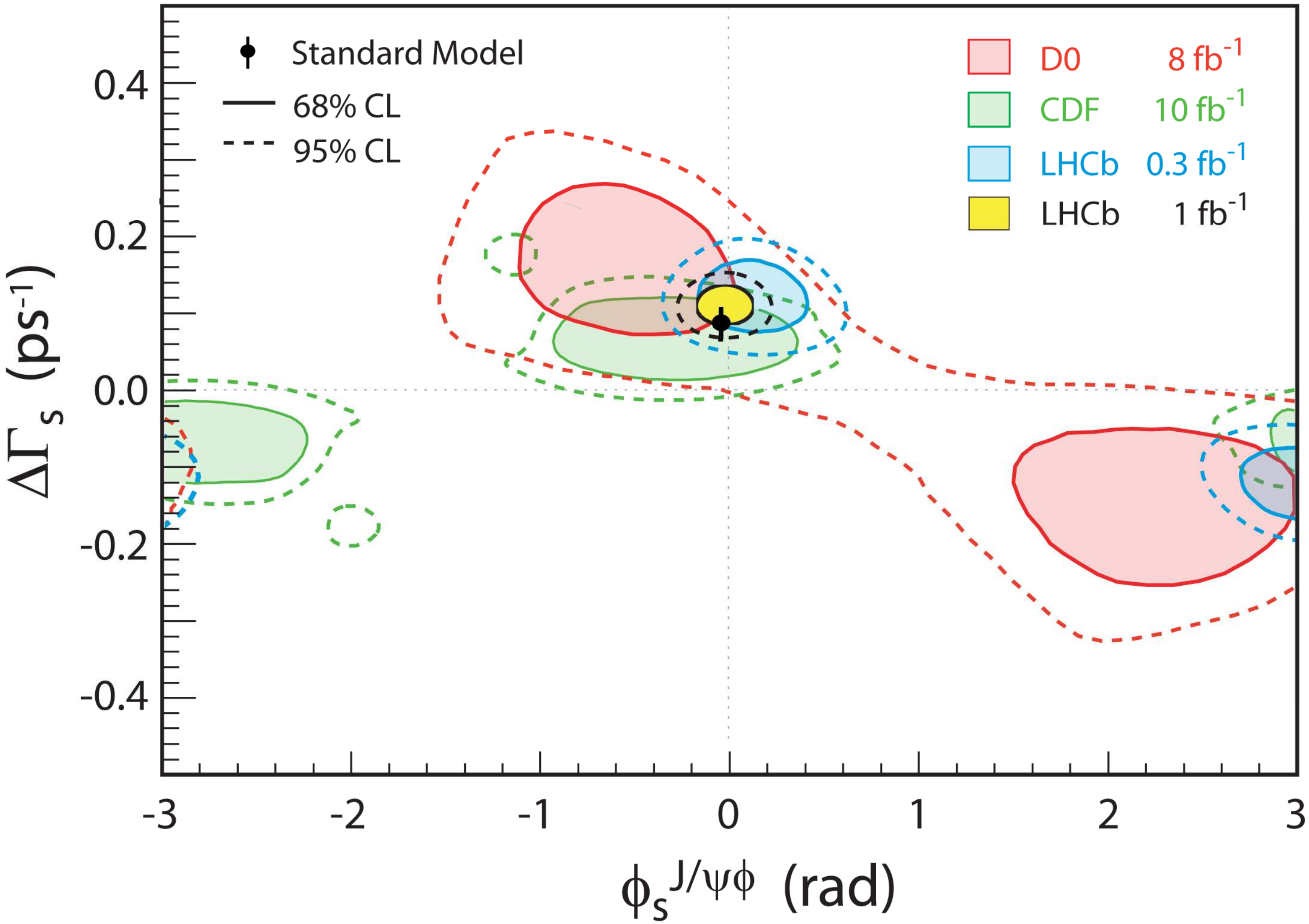


FIG. 4. Measured phase differences between S-wave and perpendicular P-wave amplitudes in four intervals of m_{KK} for solution I (blue full circles) and solution II (black full squares). The asymmetric error bars correspond to $\Delta \ln L = -0.5$ (solid) and $\Delta \ln L = -2$ (dotted).

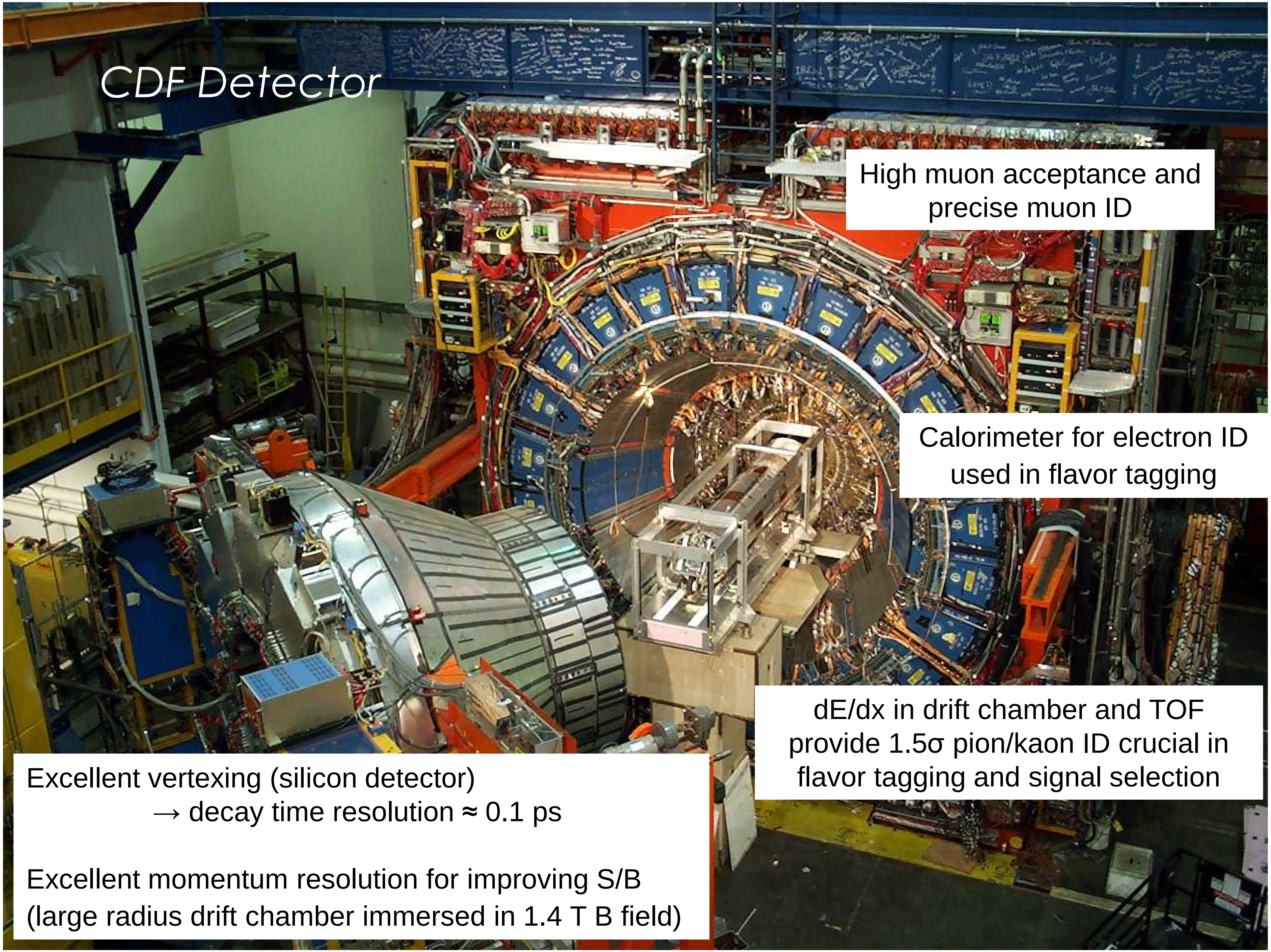
Summary

- CDF and D0 have performed first measurements of CP violation in B_s system
- New Physics may still show up in B_s decays, hopefully to be found by precision measurements at LHCb



More slides

CDF Detector



High muon acceptance and precise muon ID

Calorimeter for electron ID used in flavor tagging

dE/dx in drift chamber and TOF provide 1.5σ pion/kaon ID crucial in flavor tagging and signal selection

Excellent vertexing (silicon detector)
→ decay time resolution ≈ 0.1 ps

Excellent momentum resolution for improving S/B
(large radius drift chamber immersed in 1.4 T B field)

β_s vs ϕ_s

- Up to now, introduced two different phases:

$\phi_s^{SM} = \arg\left(-\frac{M_{12}}{\Gamma_{12}}\right) \approx 4x10^{-3}$ and $\beta_s^{\rm SM} = \arg(-V_{ts}V_{tb}^*/V_{cs}V_{cb}^*) \approx 0.02$

- New Physics affects both phases by same quantity $\phi_s^{\rm NP}$ (arxiv:0705.3802v2):

$$2\beta_s = 2\beta_s^{\rm SM} - \phi_s^{\rm NP}$$

$$\phi_s = \phi_s^{\rm SM} + \phi_s^{\rm NP}$$

- If the new physics phase $\phi_s^{\rm NP}$ dominates over the SM phases $2\beta_s^{\rm SM}$ and $\phi_s^{\rm SM}$
→ neglect SM phases and obtain:

$$2\beta_s = -\phi_s^{\rm NP} = -\phi_s$$

Decay Rate

- $B_s \rightarrow J/\Psi\Phi$ decay rate (A.S. Dighe *et al.,* Phys. Lett. B **36**9 144 (1996)) :

$$P_B(\theta,\phi,\psi,t) = \frac{9}{16\pi}|\mathbf{A}(t)\times\hat{n}|^2$$

where: $\mathbf{A}(t) = (\mathcal{A}_0(t)\cos\psi, -\frac{\mathcal{A}_{\parallel}(t)\sin\psi}{\sqrt{2}}, i\frac{\mathcal{A}_{\perp}(t)\sin\psi}{\sqrt{2}})$ and $\hat{n} = (\sin\theta\cos\phi, \sin\theta\sin\phi, \cos\theta)$

- Time evolution of transversity amplitudes A_0, $A_{||}$, $A_\perp$:

$$\mathcal{A}_i = \frac{e^{-\Gamma t/2}}{\sqrt{\tau_H + \tau_L \pm \cos 2\beta_s\,(\tau_L - \tau_H)}}\left[E_+(t) \pm e^{2i\beta_s}E_-(t)\right]a_i$$

where ± corresponds to CP-even and CP-odd final states, $\sum_i |a_i|^2 = 1$ and

$$E_\pm(t) \equiv \frac{1}{2}\left[e^{+\left(\frac{-\Delta\Gamma}{4}+i\frac{\Delta m}{2}\right)t} \pm e^{-\left(\frac{-\Delta\Gamma}{4}+i\frac{\Delta m}{2}\right)t}\right]$$

- Finally:

$$\begin{aligned} P_B(\theta,\psi,\phi,t) &= \frac{9}{16\pi}\{|\mathbf{A}_+(\mathbf{t})\times\hat{n}|^2 + |\mathbf{A}_-(\mathbf{t})\times\hat{n}|^2 + 2Re((\mathbf{A}_+(\mathbf{t})\times\hat{n})\cdot(\mathbf{A}^*_-(\mathbf{t})\times\hat{n}))\} \\ &= \frac{9}{16\pi}\{|\mathbf{A}_+\times\hat{n}|^2|f_+(t)|^2 + |\mathbf{A}_-\times\hat{n}|^2|f_-(t)|^2 + 2Re((\mathbf{A}_+\times\hat{n})\cdot(\mathbf{A}^*_-\times\hat{n})\cdot f_+(t)\cdot f^*_-(t))\} \end{aligned}$$

$$|f_\pm(t)|^2 = \frac{1}{2}\frac{(1\pm\cos 2\beta_s)e^{-\Gamma_L t} + (1\mp\cos 2\beta_s)e^{-\Gamma_H t} \mp 2\sin 2\beta_s e^{-\Gamma t}\sin\Delta mt}{\tau_L(1\pm\cos 2\beta_s) + \tau_H(1\mp\cos 2\beta_s)}$$

$$f_+(t)f^*_-(t) = \frac{e^{-\Gamma t}\cos\Delta mt + i\cos 2\beta_s e^{-\Gamma t}\sin\Delta mt + i\sin 2\beta_s(e^{-\Gamma_L t} - e^{-\Gamma_H t})/2}{\sqrt{[(\tau_L-\tau_H)\sin 2\beta_s]^2 + 4\tau_L\tau_H}}$$

Decay Rate with S-Wave Included

- Including the s-wave contribution the probability density function becomes:

CP-odd

$$\rho_B(\theta,\phi,\psi,t,\mu) = \frac{9}{16\pi}\left|\left[\sqrt{1-F_s}g(\mu)\mathbf{A}(t) + e^{i\delta_s}\sqrt{F_s}\frac{h(\mu)}{\sqrt{3}}\mathbf{B}(t)\right]\times\hat{n}\right|^2$$

where: $\mathbf{B}(t) = (\mathcal{B}(t),0,0)$ and $\mathcal{B}(t) = \frac{e^{-\Gamma t/2}}{\sqrt{\tau_H+\tau_L-\cos 2\beta_s(\tau_L-\tau_H)}}\left[E_+(t) - e^{2i\beta_s}E_-(t)\right]$

g(μ) is relativistic Breit-Wigner to describe asymmetric *Φ* mass shape and *h(μ)* is constant

- Integrating out the dependence on the KK mass:

$$\begin{aligned}\rho_B(\theta,\psi,\phi,t) &= (1-F_s)\cdot P_B(\theta,\psi,\phi,t) + F_s Q_B(\theta,\psi,\phi,t)\\ &+ 2\frac{\sqrt{27}}{16\pi}Re\left[\mathcal{I}_\mu\left((\mathbf{A}_-\times\hat{n})\cdot(\mathbf{B}\times\hat{n})\cdot|f_-(t)|^2 + (\mathbf{A}_+\times\hat{n})\cdot(\mathbf{B}\times\hat{n})\cdot f_+(t)\cdot f_-^*(t)\right)\right]\end{aligned}$$

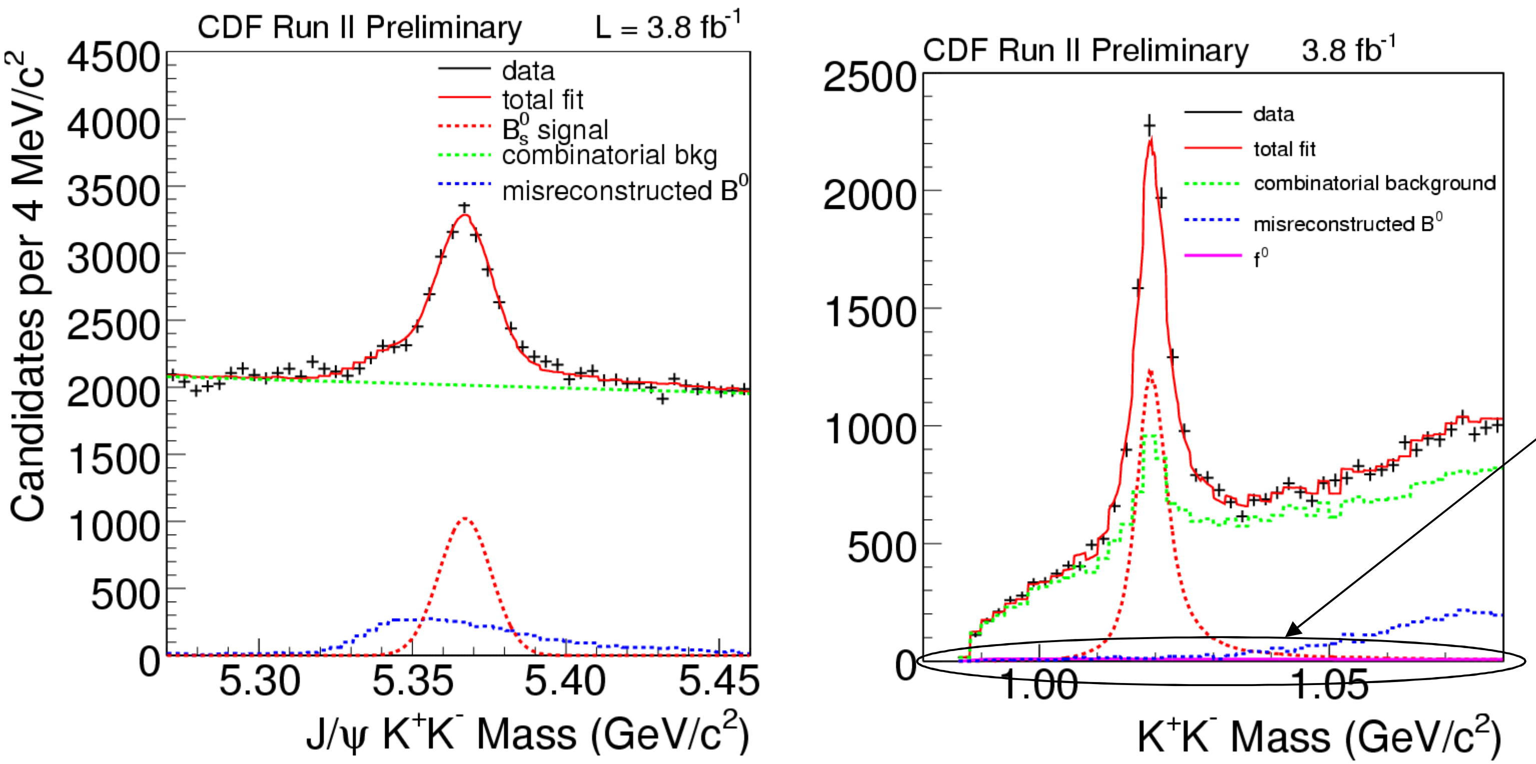
where: $I(\mu)$ is a function of the s-wave phase and $Q_B(\theta,\phi,\psi,t) = \frac{3}{16\pi}|\mathbf{B}(t)\times\hat{n}|^2$

S-Wave Cross Check Using KK Mass Spectrum

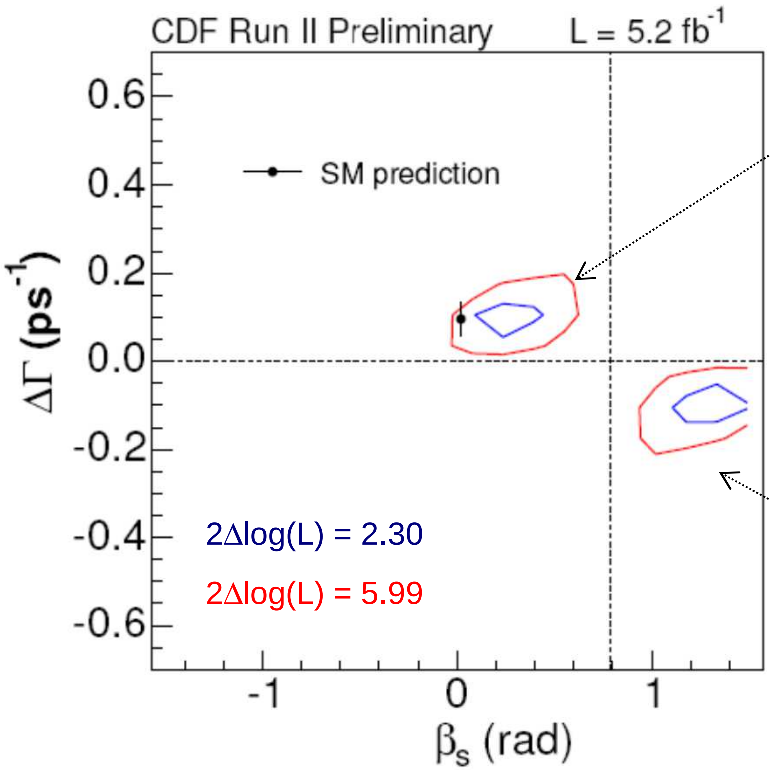
- Cross check the result from angular fit by fitting the KK invariant mass spectrum

- From a fit to the B_s mass distribution with wide KK mass range selection (0.980,1.080 GeV), determine contributions of combinatorial background, mis-reconstructed B^0, and B_s events

- Good fit of the KK mass spectrum with 2% f^0 contributions



Barely visible S-wave component



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

strong phases
could separate
the two minima

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

Fit parameters

β_s	β_s CP -violating phase
$\Delta\Gamma$	$\Gamma_L - \Gamma_H$
$\alpha_\perp$	CP odd fraction
$\alpha_\parallel$	fraction in CP even states
$\delta_\perp$	$\arg(A_\perp A_0)$
$\delta_\parallel$	$\arg(A_\parallel A_0)$
$c\tau$	$\frac{1}{\Gamma_s} = \frac{2}{\Gamma_L+\Gamma_H}$
A_{SW}	fraction of S-wave KK component in the signal
δ_{SW}	phase of S-wave component
Δm_s	B_s^0 mixing frequency
f_s	Signal fraction
s_m	Mass error scale factor
p_1	mass background slope
$s_{c\tau}1$	lifetime error scale factor 1
$s_{c\tau}2$	lifetime error scale factor 2
f_{sf_1}	fraction of first lifetime error scale factor
f_p	fraction of prompt background
f_-	fraction of bkg which decays with λ_-
f_{++}	fraction of bkg which decays with λ_{++}
λ_-	Effective bkg lifetime, neg. component
λ_+	Effective bkg lifetime, pos. component 1
λ_{++}	Effective bkg lifetime, pos. component 2
ϕ_1	parameter in bkg fit to Φ
$cos(\vartheta)_1$	parameter in bkg fit to $\cos(\Theta)$
$S_D(OST)$	OST dilution scale factor
$S_D(SST)$	SST dilution scale factor
$\varepsilon_b(OST)$	OST tagging efficiency for background
$\varepsilon_b(SST)$	SST tagging efficiency for background
$A^+(OST)$	OST background positive tag asymmetry
$A^+(SST)$	SST background positive tag asymmetry
$\varepsilon_s(OST)$	OST tagging efficiency for signal
$\varepsilon_s(SST)$	SST tagging efficiency for signal

LHCb results, 0.37/fb

Phys. Rev. Lett. 108, 101803 (2012), arXiv:1112.3183v3

TABLE I. Fit results for the solution with $\Delta\Gamma_s > 0$ with statistical and systematic uncertainties.

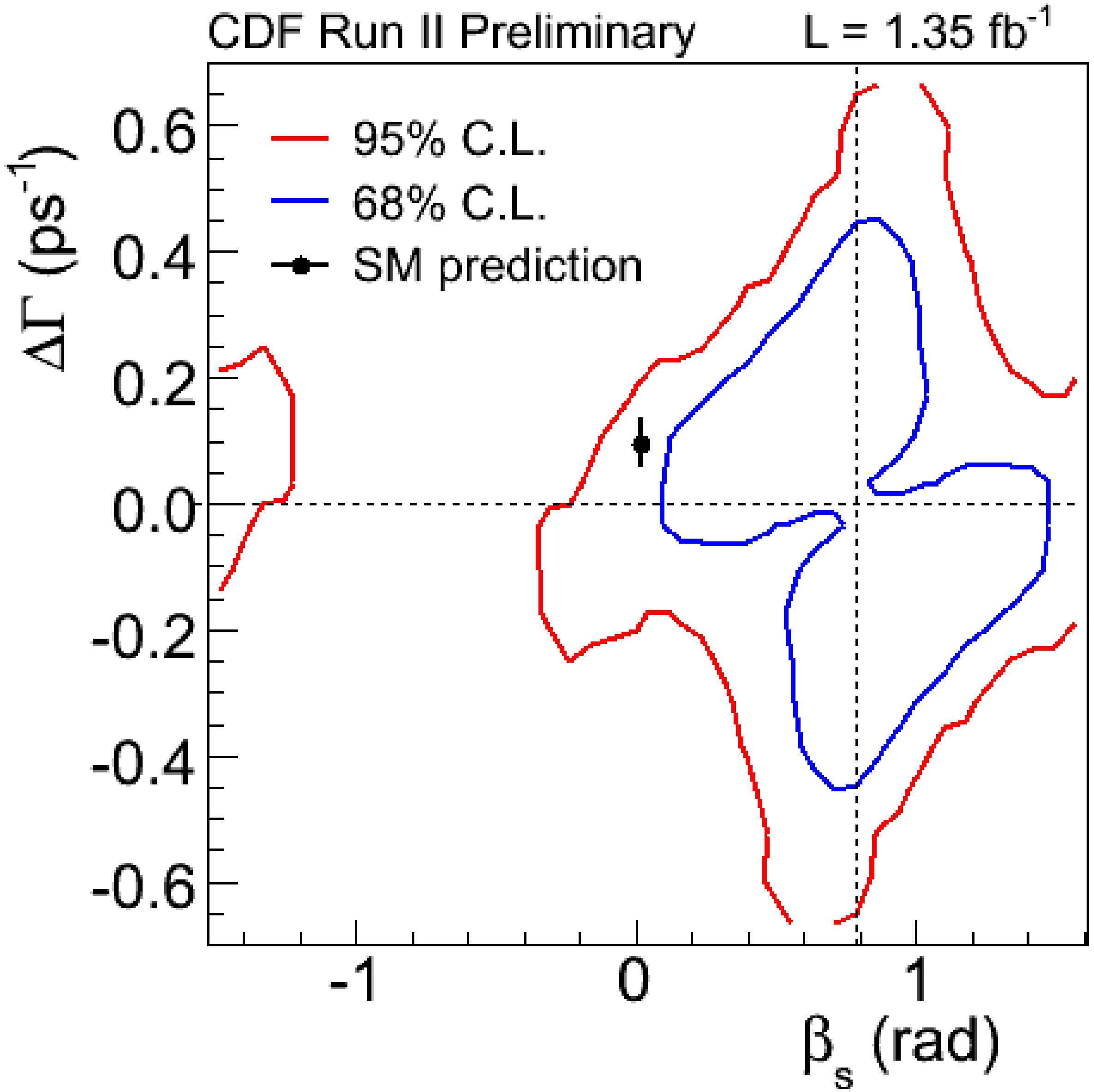
parameter	value	$\sigma_{\text{stat.}}$	$\sigma_{\text{syst.}}$
Γ_s [ps^{-1}]	0.657	0.009	0.008
$\Delta\Gamma_s$ [ps^{-1}]	0.123	0.029	0.011
$\lvert A_\perp(0)\rvert^2$	0.237	0.015	0.012
$\lvert A_0(0)\rvert^2$	0.497	0.013	0.030
$\lvert A_S(0)\rvert^2$	0.042	0.015	0.018
$\delta_\perp$ [rad]	2.95	0.37	0.12
δ_S [rad]	2.98	0.36	0.12
ϕ_s [rad]	0.15	0.18	0.06

D0 results, 8/fb

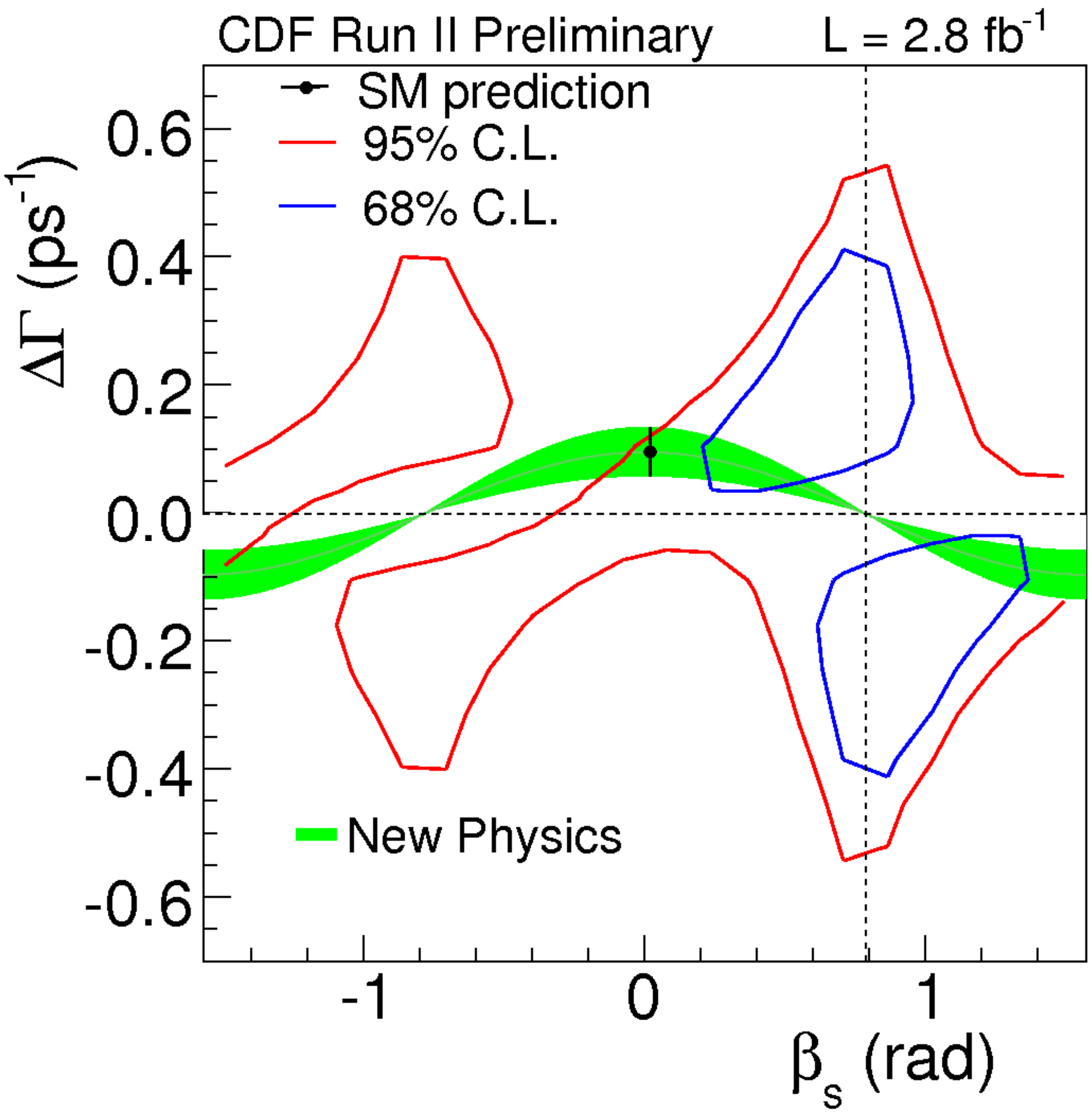
Phys. Rev. D **85**, 032006 (2012), arXiv:1109.3166

$$\begin{aligned}
\overline{\tau}_s &= 1.426^{+0.035}_{-0.032}\ \text{ps}, \\
\Delta\Gamma_s &= 0.129^{+0.076}_{-0.053}\ \text{ps}^{-1} \\
\phi_s^{J/\psi\phi} &= -0.49^{+0.48}_{-0.40}, \\
|A_0|^2 &= 0.552^{+0.016}_{-0.017}, \\
|A_{||}|^2 &= 0.219^{+0.020}_{-0.021}, \\
\delta_{||} &= 3.15 \pm 0.27, \\
\cos(\delta_\perp - \delta_s) &= -0.06 \pm 0.24, \\
F_S(\text{eff}) &= 0.146 \pm 0.035.
\end{aligned}$$

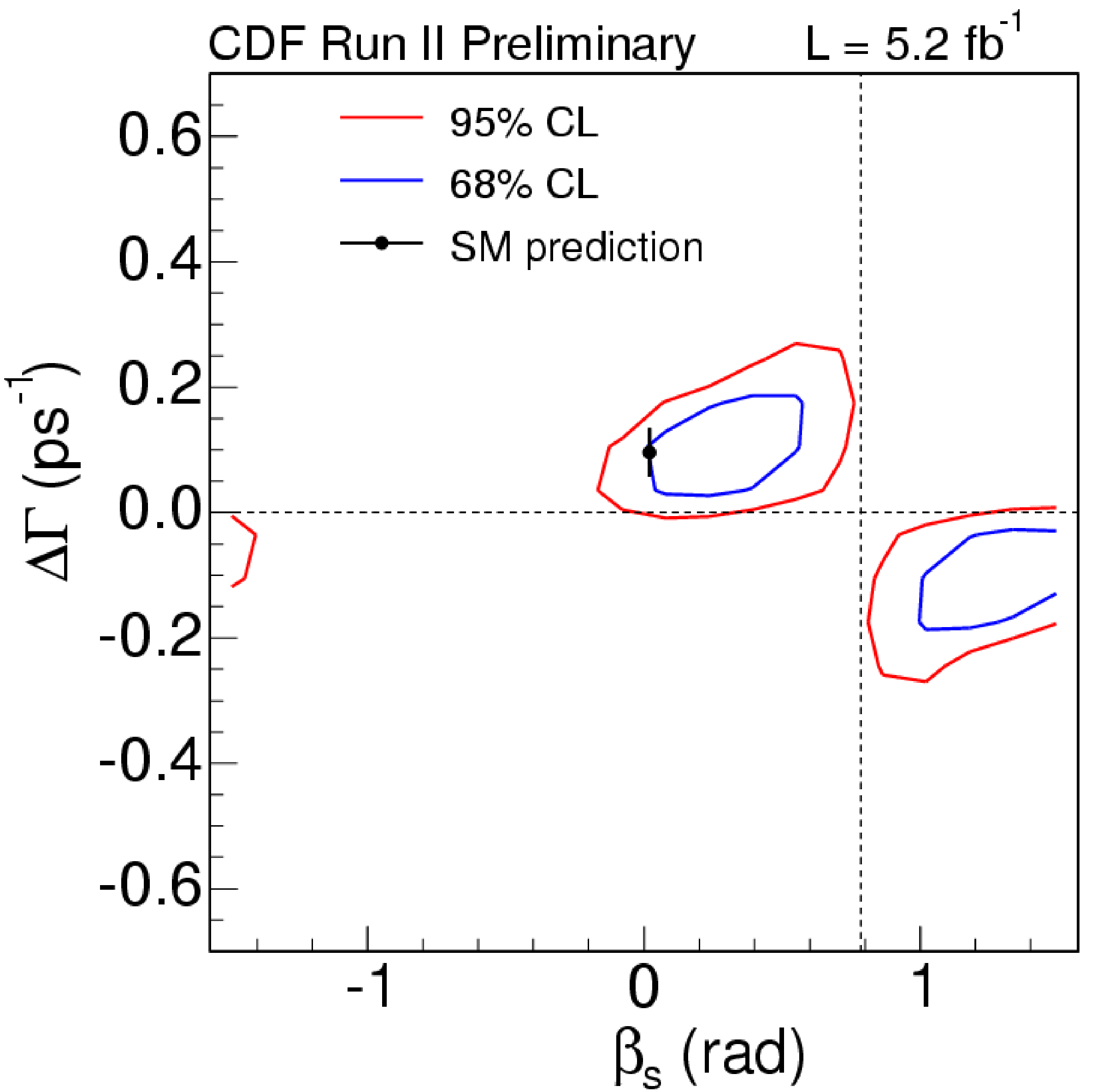
CDF 2007 initial result , arXiv:0712.2397, PRL 100,161802 (2008) , 1.4/fb, ~2000 signal events



CDF 2008 ICHEP update with, preliminary PID and tagging. 2.8/fb, ~3150 signal events



CDF 2010 update accepted by PRL, arXiv:1112.1726, 5.2/fb, ~6500 signal events



CDF 2012 update, 5.6/fb, ~11000 signal events