Measurement of Φ_s and $\Delta\Gamma_s$ at the Tevatron

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on behalf of the CDF and DØ collaborations

Flavor Physics and CP Violation 2009
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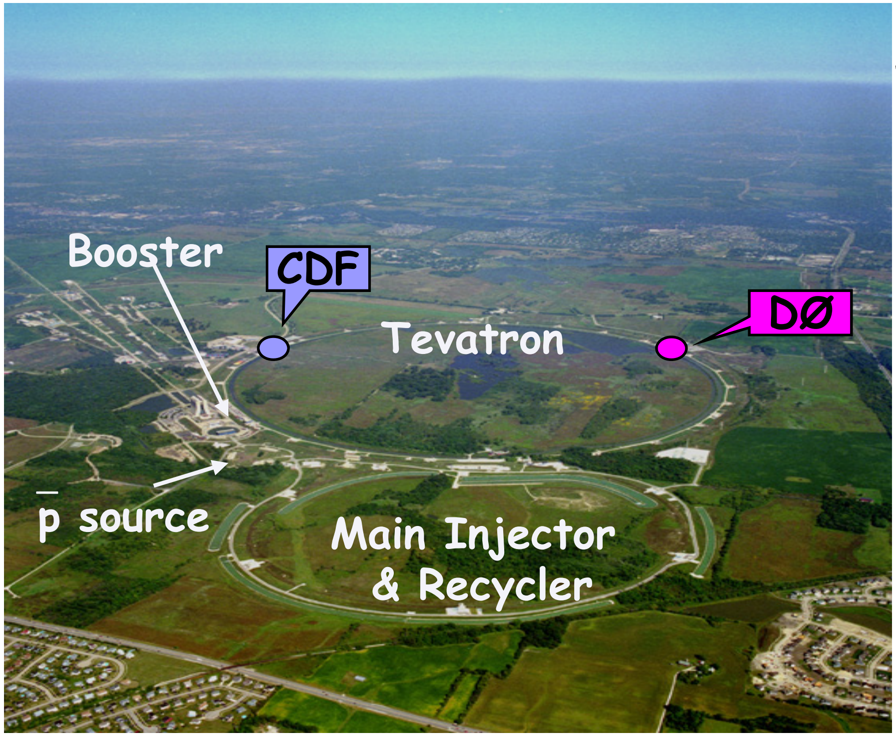
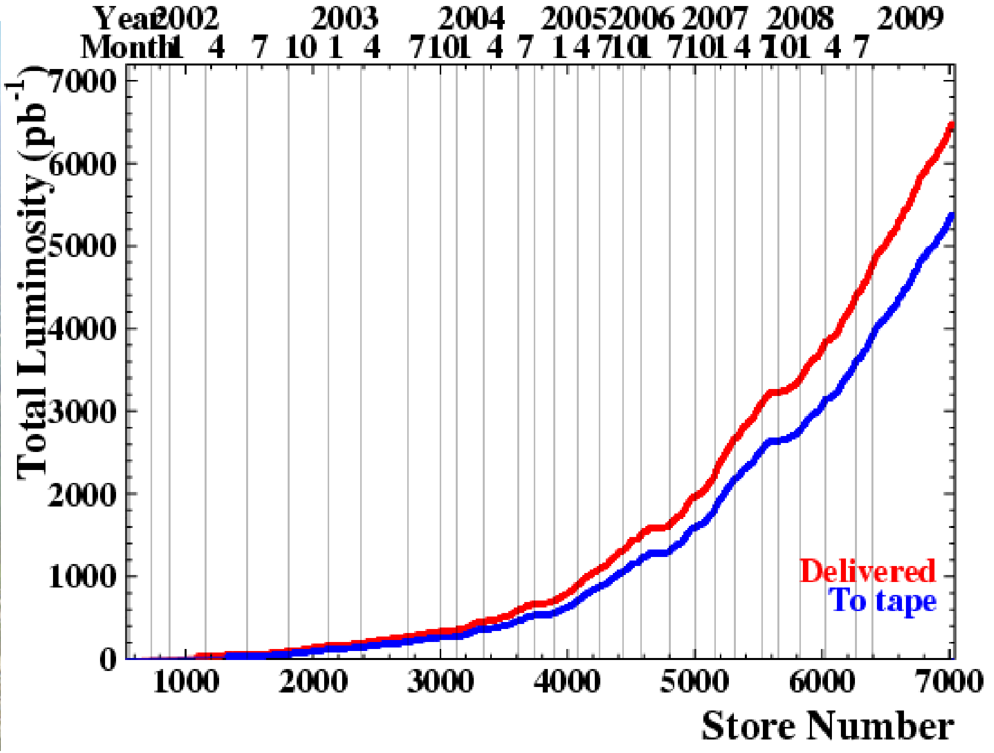
Tevatron

- $p\bar{p}$ collisions at 1.96 TeV

- 5 fb^{-1} data on tape for each experiment
- Show analyses with 2.8 fb^{-1}





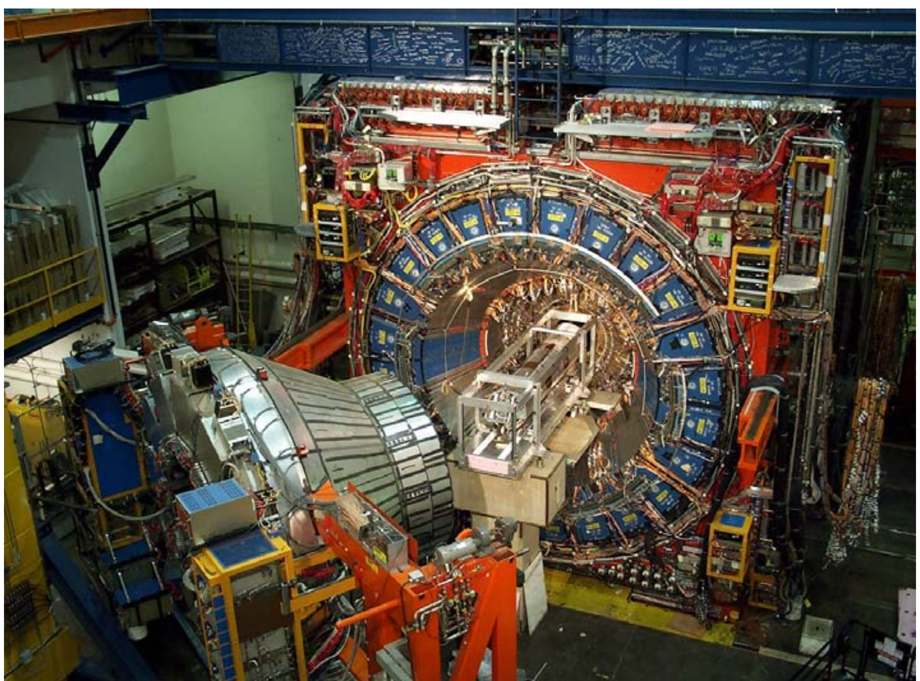
CDF II Detector

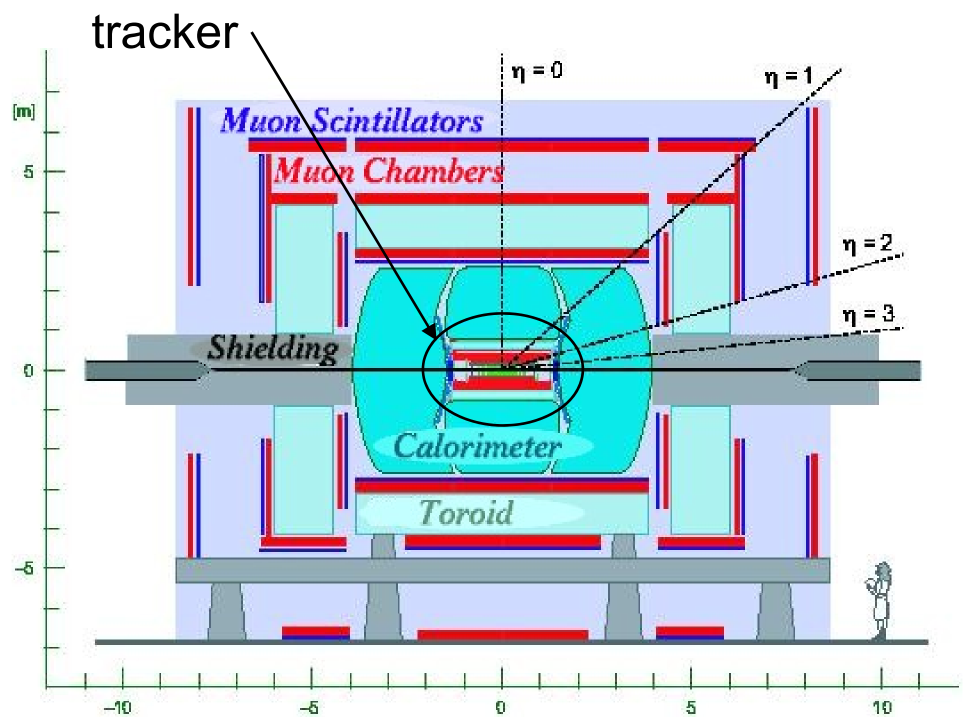
- Central tracking: - silicon vertex detector
  - drift chamber

  → excellent vertex, momentum and mass resolution
- Particle identification: dE/dX and TOF
- Electron and muon ID by calorimeters and muon chambers

DØ Detector

- Excellent tracking and muon coverage
- Excellent calorimetry and electron ID
- Silicon layer 0 installed in 2006 improves track parameter resolution





β_s Phase and the CKM Matrix

- CKM matrix connects mass and weak quark eigenstates
- Expand CKM matrix in $\lambda = \sin(\theta_{Cabibbo}) \approx 0.23$

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

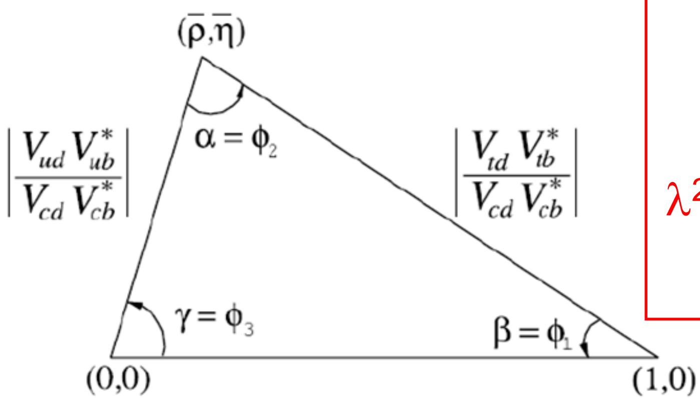
- To conserve probability CKM matrix must be unitary
  → Unitary relations can be represented as "unitarity triangles"

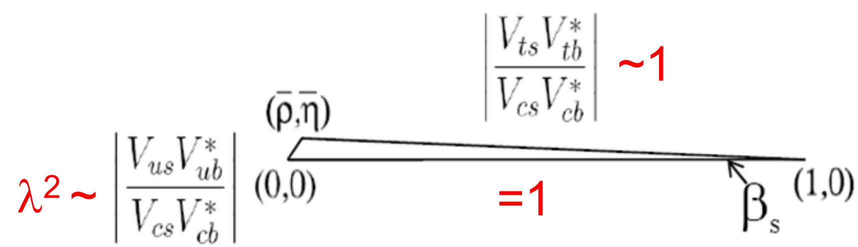
unitarity relations:

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

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

unitarity triangles:



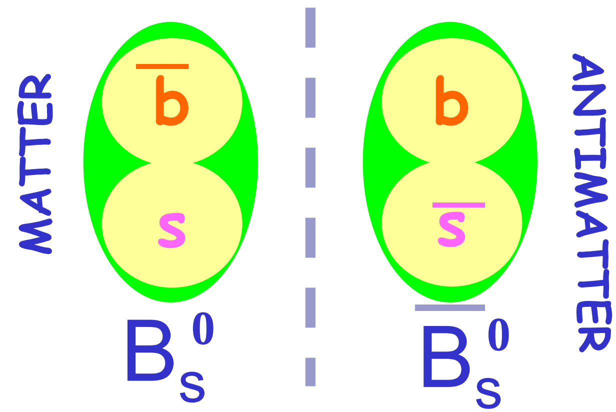


very small CPV phase β_s of order λ^2 accessible in B_s decays

Neutral B_s System

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

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



- Diagonalize mass (M) and decay (Γ) matrices

→ mass eigenstates :

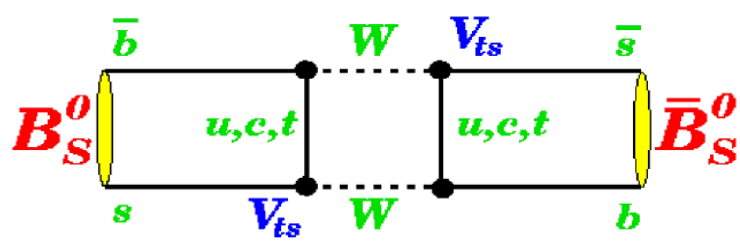
$$|B_s^H\rangle = p\,|B_s^0\rangle - q\,|\bar{B}_s^0\rangle \qquad |B_s^L\rangle = p\,|B_s^0\rangle + q\,|\bar{B}_s^0\rangle$$

- Flavor eigenstates differ from mass eigenstates and mass eigenvalues are different ($\Delta m_s = m_H - m_L \approx 2|M_{12}|$)

→ B_s oscillates with frequency Δm_s precisely measured by

CDF Δm_s = 17.77 +/- 0.12 ps^{-1}

DØ Δm_s = 18.56 +/- 0.87 ps^{-1}

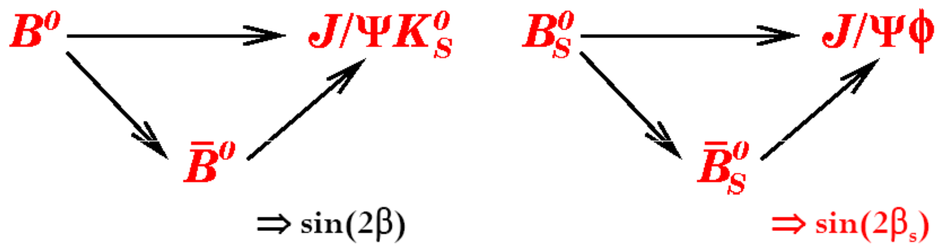


- Mass eigenstates have different decay widths

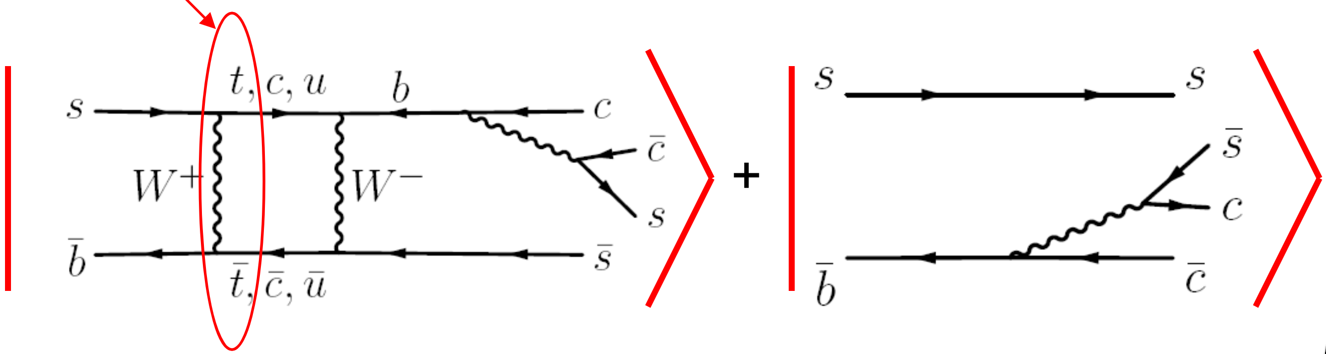
$\Delta\Gamma = \Gamma_L - \Gamma_H \approx 2|\Gamma_{12}|\cos(\Phi_s)$ where $\phi_s^{SM} = \arg\left(-\frac{M_{12}}{\Gamma_{12}}\right) \approx 4 \times 10^{-3}$

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

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



dominant contribution from top quark



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

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

- CP violation phase β_s in SM is predicted to be very small, $O(\lambda^2)$
  → New Physics CPV can compete or even dominate over small Standard Model CPV

- Ideal place to search for New Physics

β_s vs ϕ_s

- Up to now, introduced two different phases:

$$\phi_s^{SM} = \arg\left(-\frac{M_{12}}{\Gamma_{12}}\right) \approx 4\text{x}10^{-3} \quad \text{and} \quad \beta_s^{\rm SM} = \arg(-V_{ts}V_{tb}^*/V_{cs}V_{cb}^*) \approx 0.02$$

- New Physics can affect both phases by same quantity $\phi_s^{\rm NP}$ (A. Lenz, arxiv:0705.3802v2):

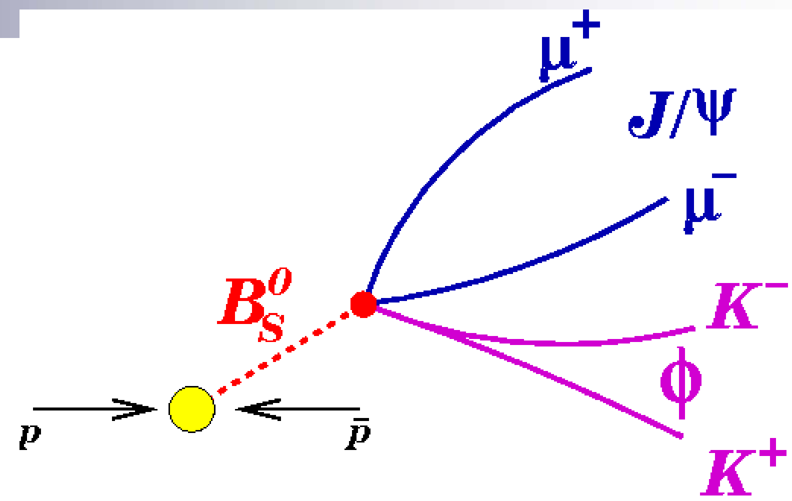
$$2\beta_s = 2\beta_s^{\rm SM} - \phi_s^{\rm NP}$$

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

- 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:

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

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



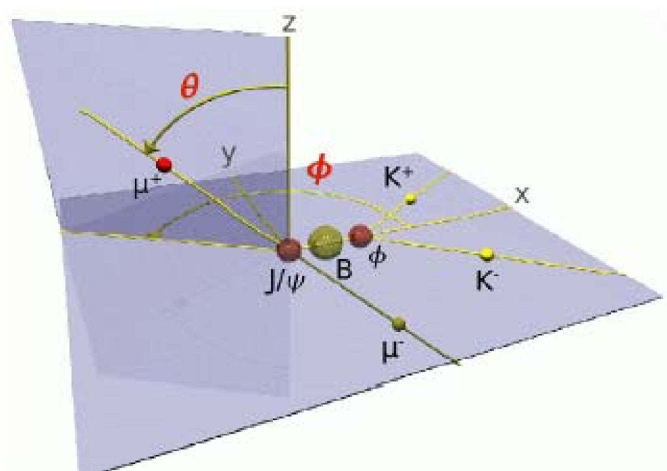
- Extremely physics rich decay mode

- Can measure lifetime, decay width difference $\Delta\Gamma$ and CP violating phase β_s

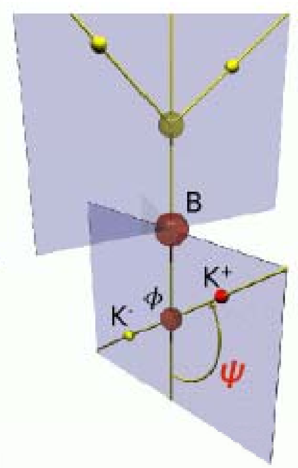
- Decay of B_s (spin 0) to J/Ψ(spin 1) Φ(spin 1) leads to three different angular momentum final states:

L = 0 (s-wave), 2 (d-wave) → CP even (≈ short lived or light B_s if $\Phi_s \approx 0$)

L = 1 (p-wave) → CP odd (≈ long lived or heavy B_s if $\Phi_s \approx 0$)



J/ψ rest frame



φ rest frame

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

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

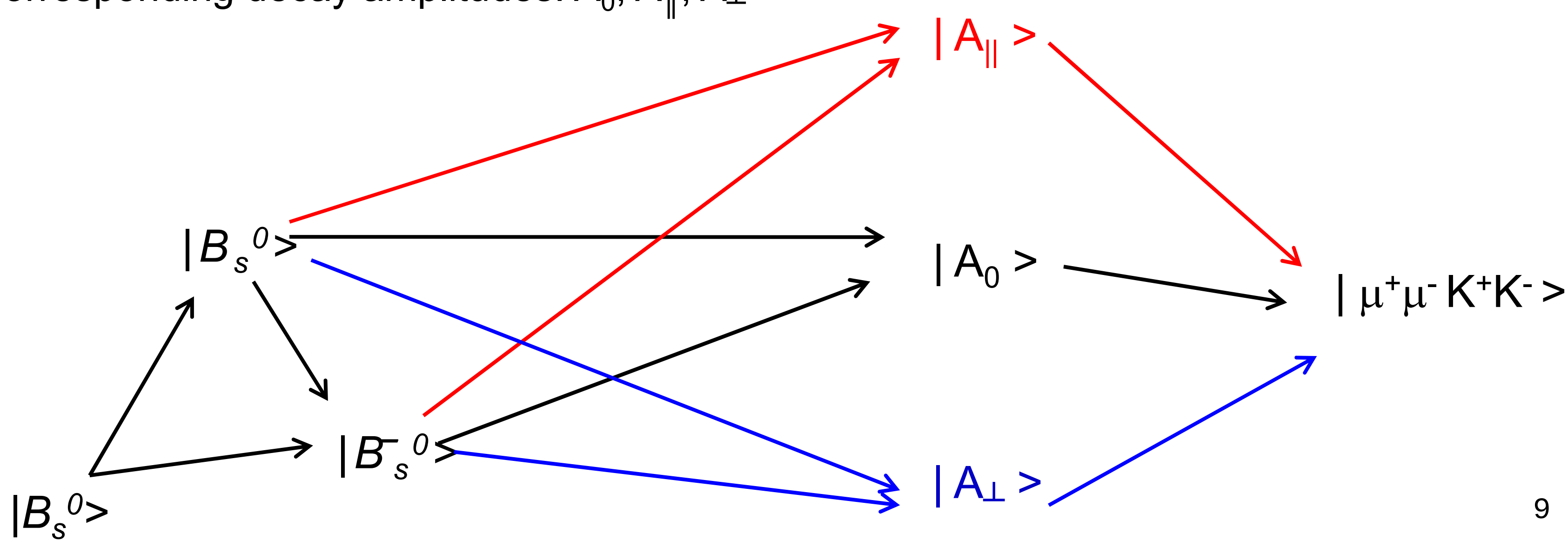
- Three angular momentum states form a basis for the final $J/\Psi\Phi$ state

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

  - transverse ($\perp$ perpendicular to each other) $\rightarrow$ CP odd

  - transverse ($\parallel$ parallel to each other) $\rightarrow$ CP even
  - longitudinal (0) $\rightarrow$ CP even

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



$B_s \to J/\Psi\Phi$ Decay Rate

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

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

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)

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

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

'strong' phases:

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

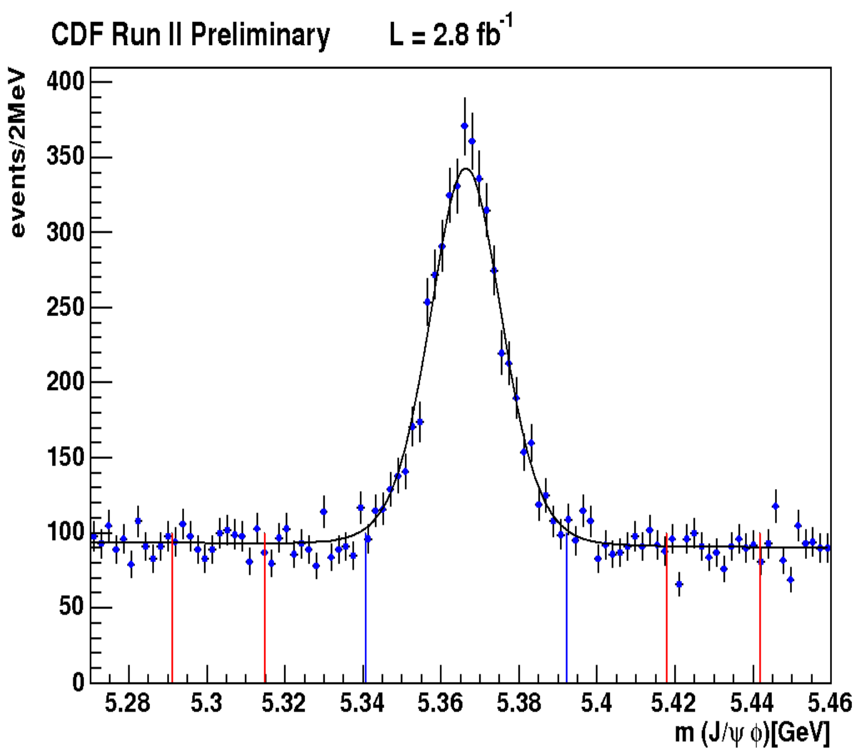
- Identification of B flavor at production (flavor tagging) → better sensitivity to β_s

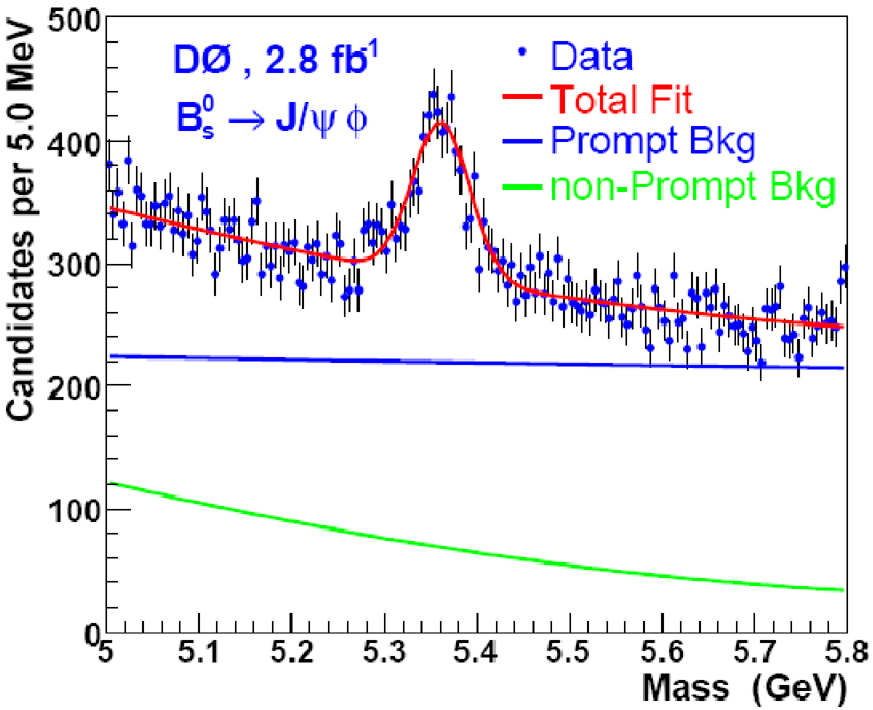
Signal Reconstruction

- Both CDF and DØ reconstruct $B^0_s \rightarrow J/\psi(\rightarrow \mu^+\mu^-)\Phi(\rightarrow K^+K^-)$ in 2.8 fb^{-1}

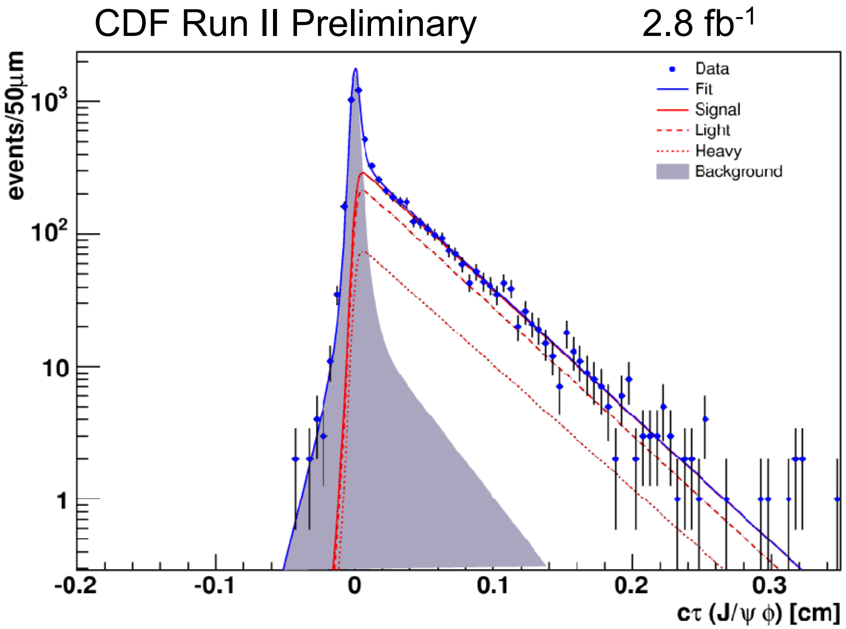
CDF ~3200 signal events (neural network selection)

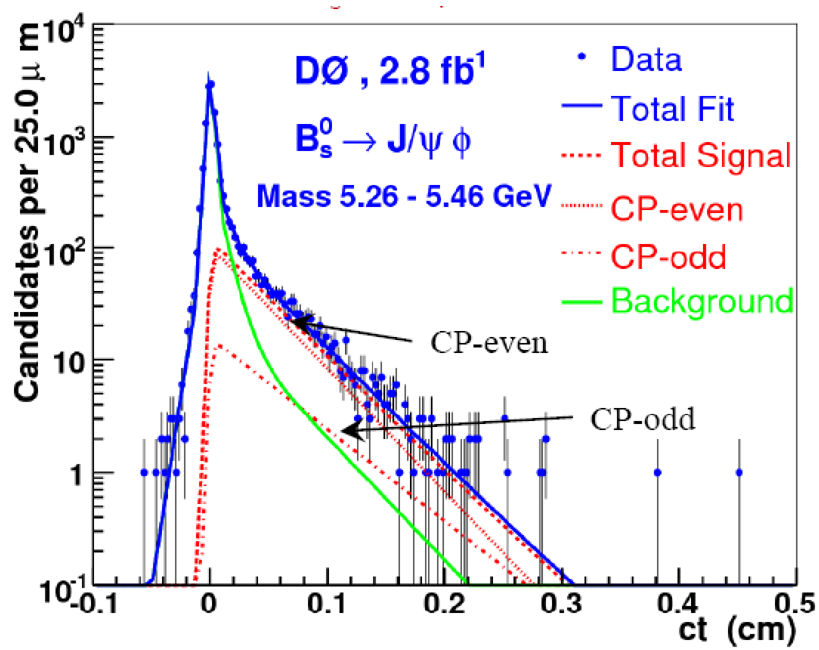
DØ ~2000 signal events (square cut selection)





Lifetime and Lifetime Difference





- Average B_s lifetime:

$\tau(B_s)$ = 1.53 ± 0.04 (stat) ± 0.01 (syst) ps

$\tau(B_s)$ = 1.52 ± 0.05 (stat) ± 0.01 (syst) ps

- Decay width difference $\Delta\Gamma$:

$\beta_s = 0$:

$$\Delta\Gamma = 0.02 \pm 0.05\ (\text{stat.}) \pm 0.01\ (\text{syst.})\ \text{ps}^{-1}$$

$$\Delta\Gamma_s = 0.14 \pm 0.07\ \text{ps}^{-1}$$

β_s free:

- - -

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

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

- Likelihood expression predicts better sensitivity to β_s but still double minima due to symmetry: $2\beta_s \to \pi - 2\beta_s$

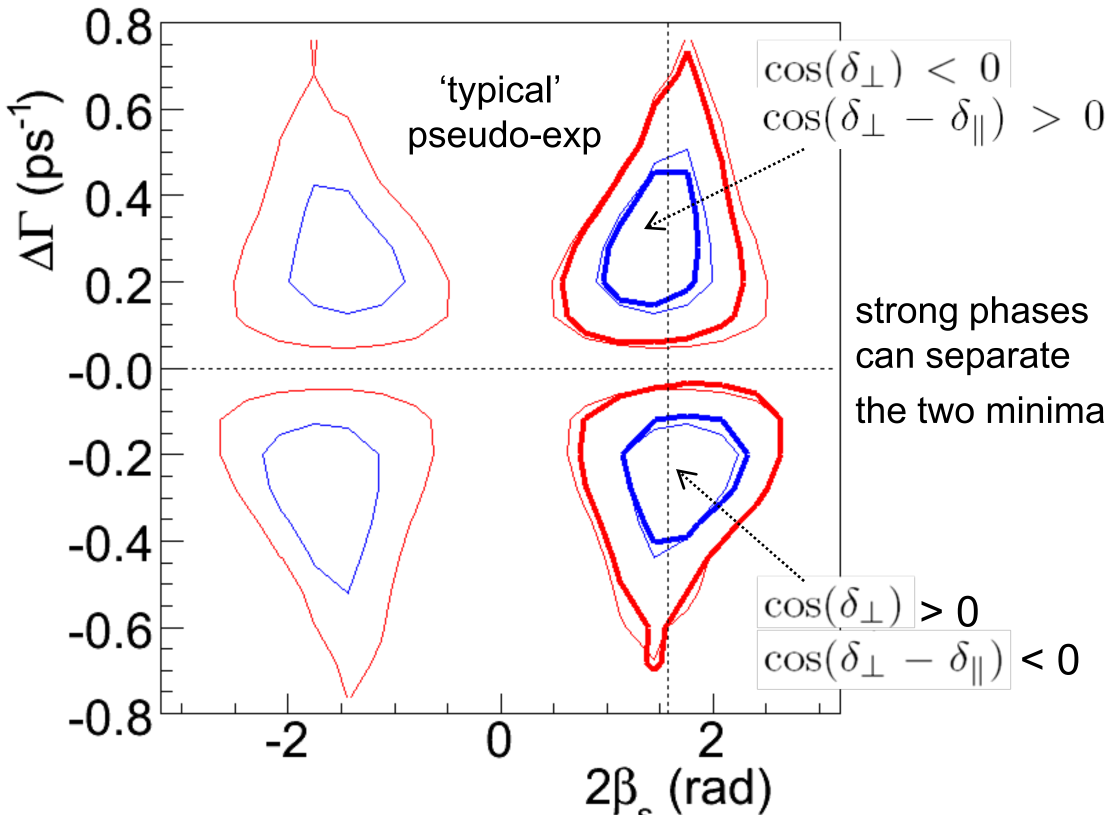
$$\Delta\Gamma \to -\Delta\Gamma$$
$$\delta_\parallel \to 2\pi - \delta_\parallel$$
$$\delta_\perp \to \pi - \delta_\perp$$

- 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
  - → 4-fold ambiguity reduced to 2-fold ambiguity
  - → allowed region for β_s is reduc to half

pseudo experiment $2\beta_s$-$\Delta\Gamma$ likelihood profile



$2\Delta\log(L) = 2.3 \approx 68\%$ CL — un-tagged

$2\Delta\log(L) = 6.0 \approx 95\%$ CL — tagged

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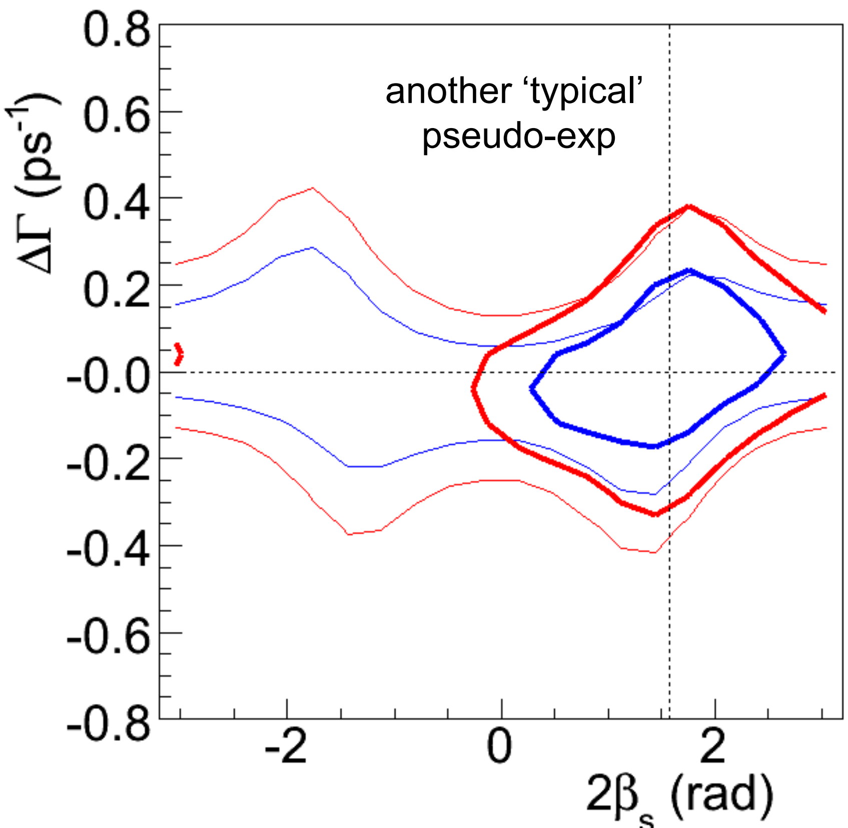

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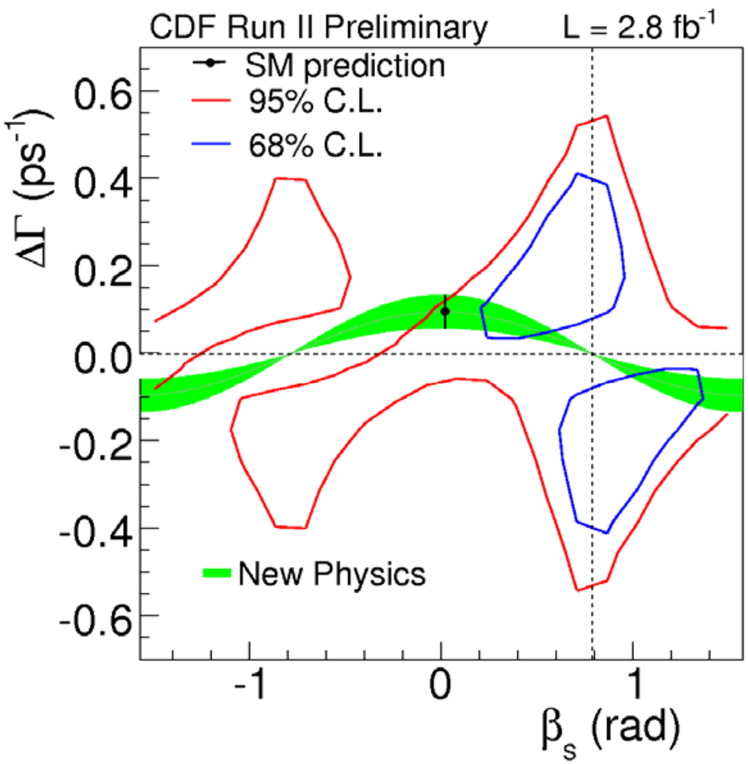
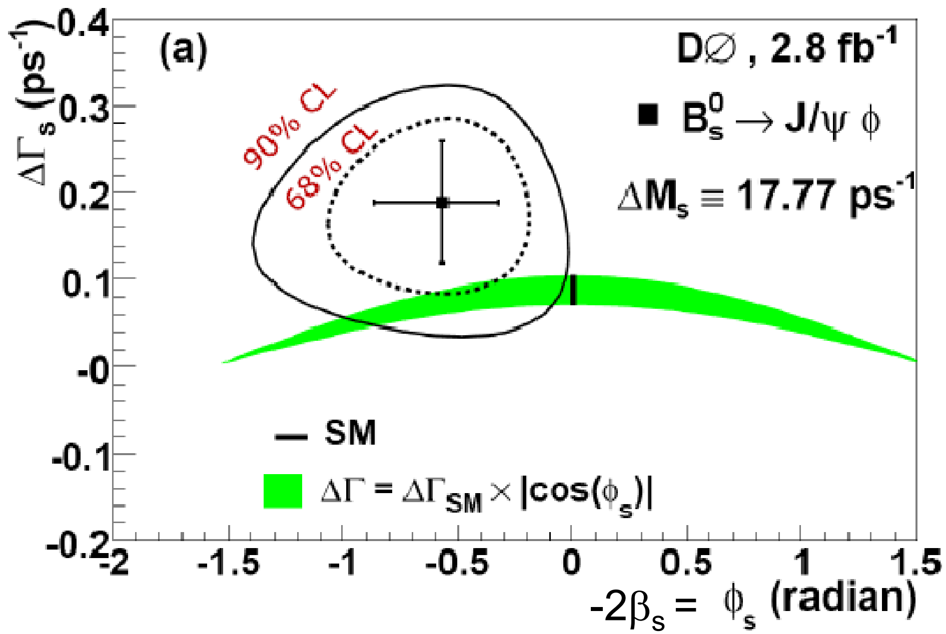
CP Violation Phase β_s in Tagged $B_s \rightarrow J/\Psi\Phi$ Decays

- Both DØ and CDF results fluctuate in the same direction 1-2σ from SM prediction

($\Phi_s = -2\beta_s$)

strong phases constrained to B factories measurements in $B^0 \rightarrow J/\Psi K^{*0} \rightarrow$ unique minimum





- Standard Model probability

CDF: 7%, ~1.8σ

DØ: 6.6%, ~1.8σ

http://www-cdf.fnal.gov/physics/new/bottom 080724.blessedtagged_BsJPsiPhi_update_prelim/

Phys. Rev. Lett. 101, 241801 (2008), arXiv:/0802.2255

- Recent DØ analysis shows consistency of strong phase and amplitudes in $B_s \rightarrow J/\Psi\ \Phi$ and $B^0 \rightarrow J/\Psi K^{*0}$ and supports the strong phase constraint (arXiv:0810.0037v1)

Non-Gaussian Regime

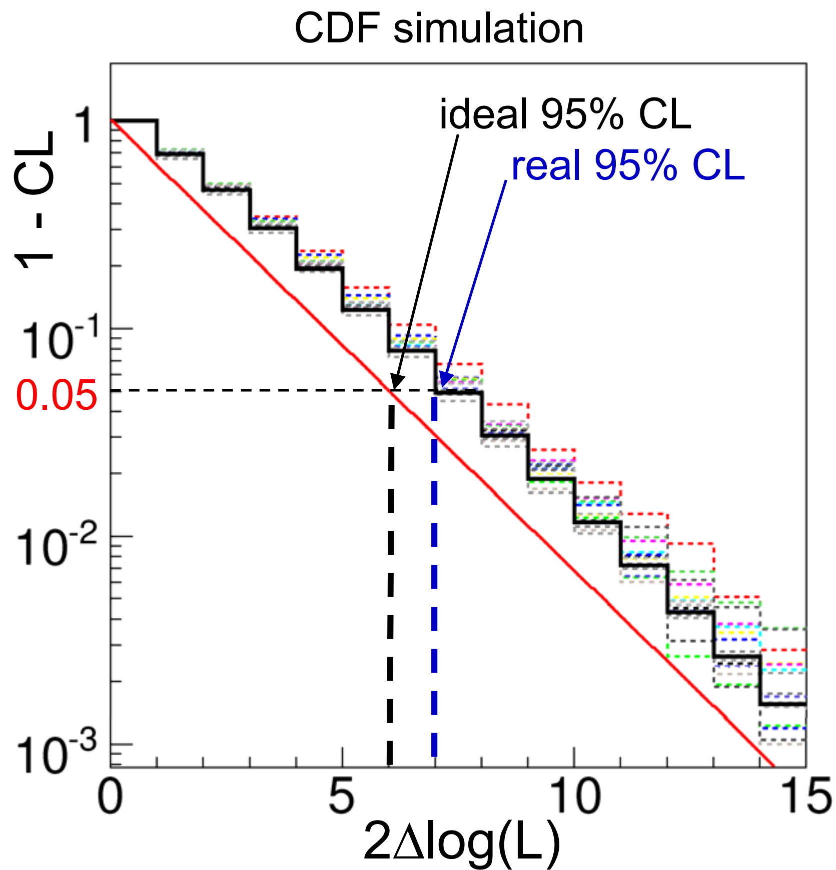
- In ideal case (high statistics, Gaussian likelihood), to get the 2D 68% (95%) C.L. regions, take a slice through profile likelihood at 2.3 (6.0) units up from minimum

- In this analysis integrated likelihood ratio distribution (black histogram) deviates from ideal χ^2 with 2dof distribution (red continuous curve)

- Use pseudo-experiments to determine a map between CL and 2ΔlogL (e.g. 95% CL need to go up ~7 instead of 6 units from minimum)

- Procedure used by both CDF and DØ

- From pseudo experiments find that Gaussian regime is indeed reached as sample size increases



Systematic Uncertainties

- At CDF, systematic uncertainties studied by varying all nuisance parameters +/- 5σ from observed values and repeating LR curves (dotted histograms)

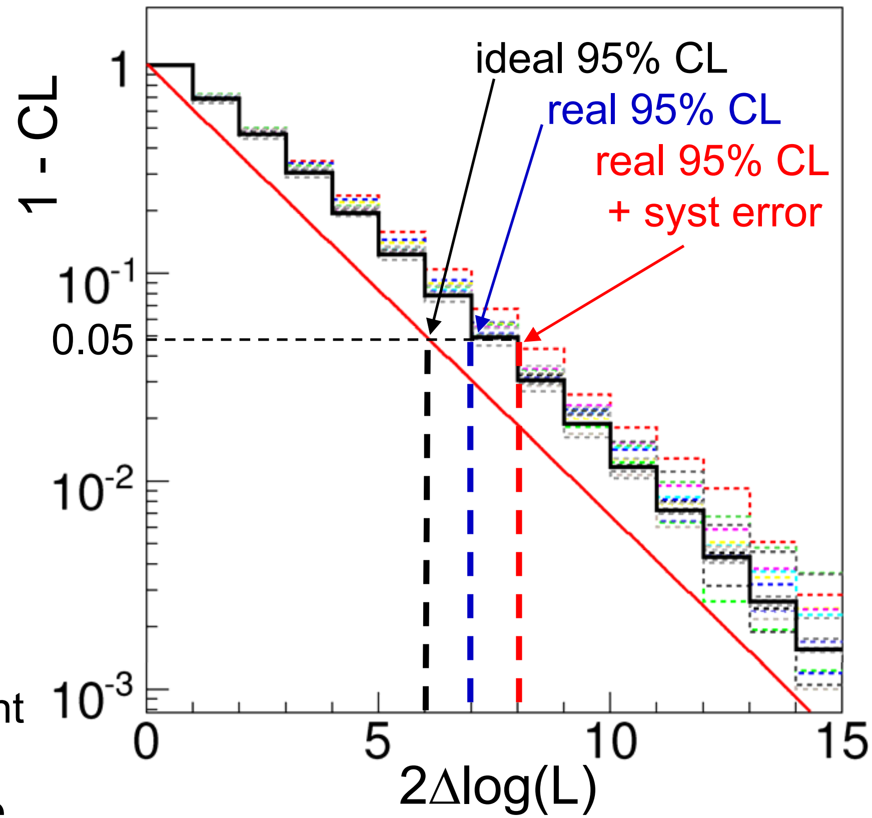
- Nuisance parameters:
  - lifetime, lifetime scale factor uncertainty,
  - strong phases,
  - transversity amplitudes,
  - background angular and decay time parameters,
  - dilution scale factors and tagging efficiency
  - mass signal and background parameters

- Take the most conservative curve (dotted red histogram) as final result

- DØ updated analysis includes similar treatment of dominant systematics:
  - dms, flavor dilution, detector acceptance parameter varied by +/- 1σ

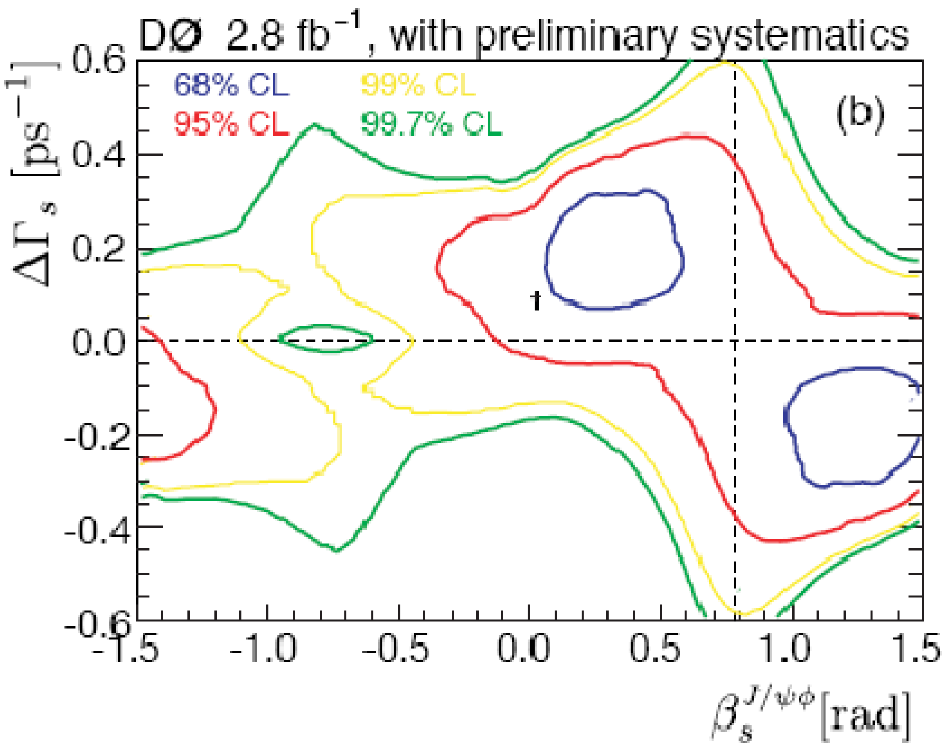
http://www-d0.fnal.gov/Run2Physics/WWW/results/prelim/B/B58/

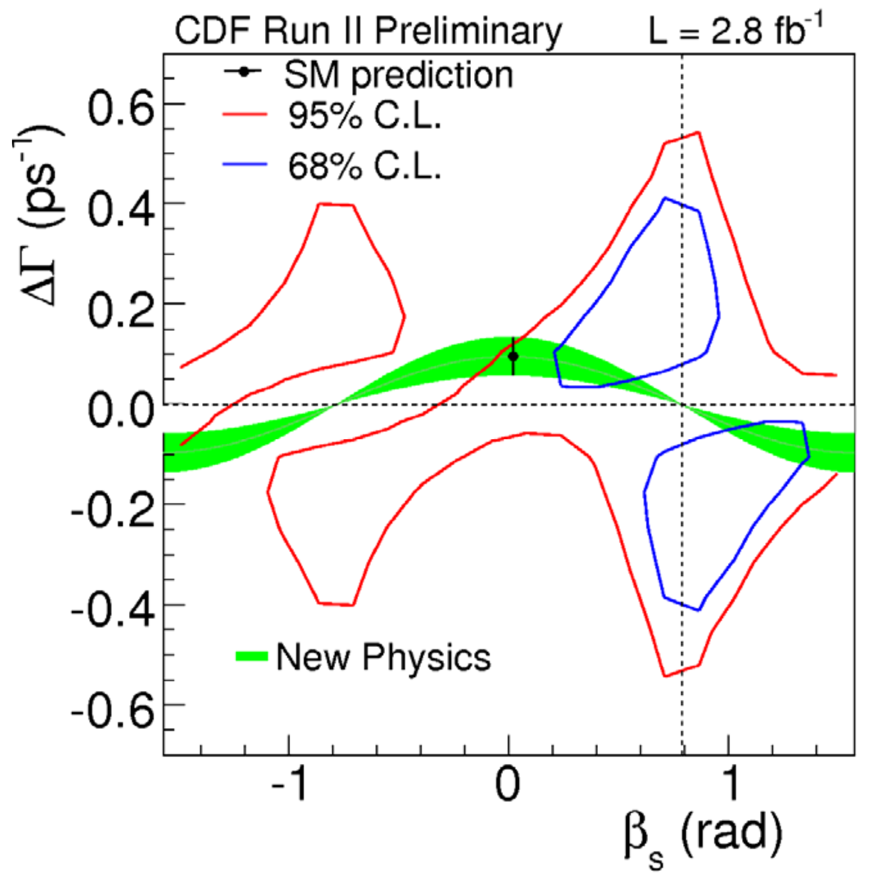
CDF simulation



Comparison Between CDF and DØ

- CDF and DØ are in good agreement and both favor negative values of $\Phi_s = -2\beta_s$ (positive values of β_s)



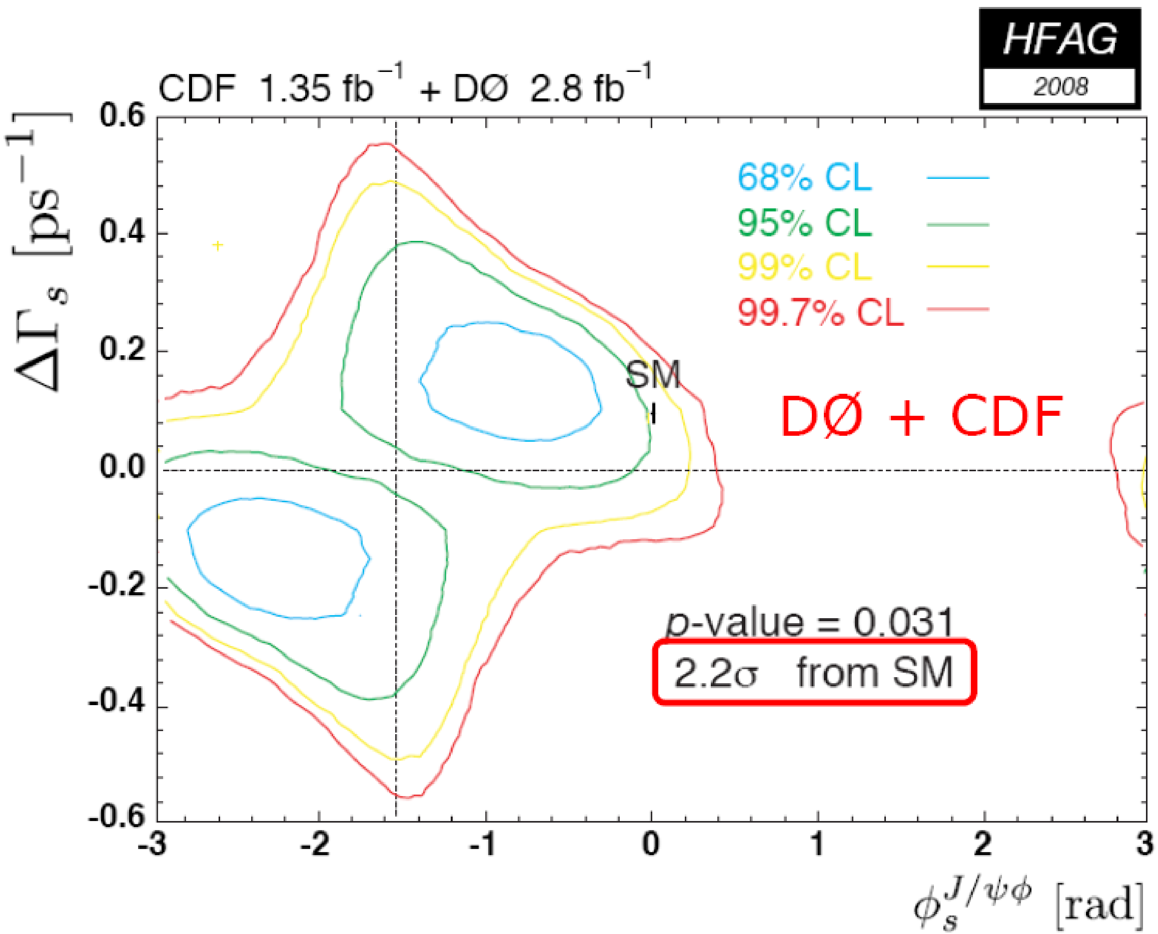


DØ SM p-value = 24%
compared to 8.5% without systematics
(see talk by S. Beale for DØ results with additional constraints)

CDF SM p-value = 7%

Combining CDF and DØ Results

- HFAG combination of old CDF (1.4 fb^{-1}, 1.5 σ from SM, PRL 100, 161802 (2008)) and old DØ (2.8 fb^{-1}, 1.7 σ from SM, no systematics) results yield a 2.2 σ deviation from SM (similar results found by UTFit and CKM collaborations)



Tevatron β_s Average Coming Soon

- Ongoing CDF and DØ work to produce Tevatron $\Delta\Gamma$ - β_s average using 2.8 fb^{-1}

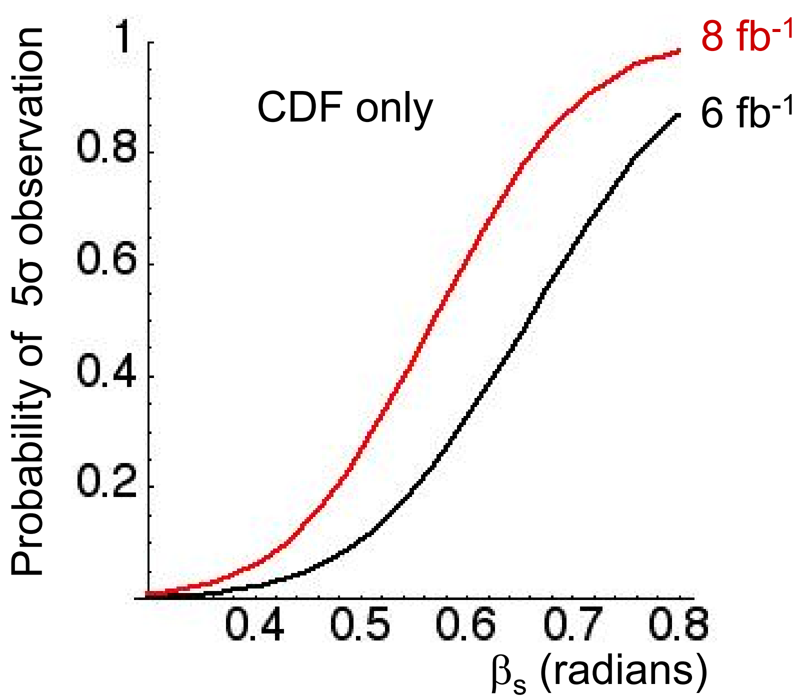
- Significant progress made to ensure coherence of CDF and DØ analyses
    - similar treatment of:
        - strong phase
        - non-gaussian effects
        - systematic uncertainities

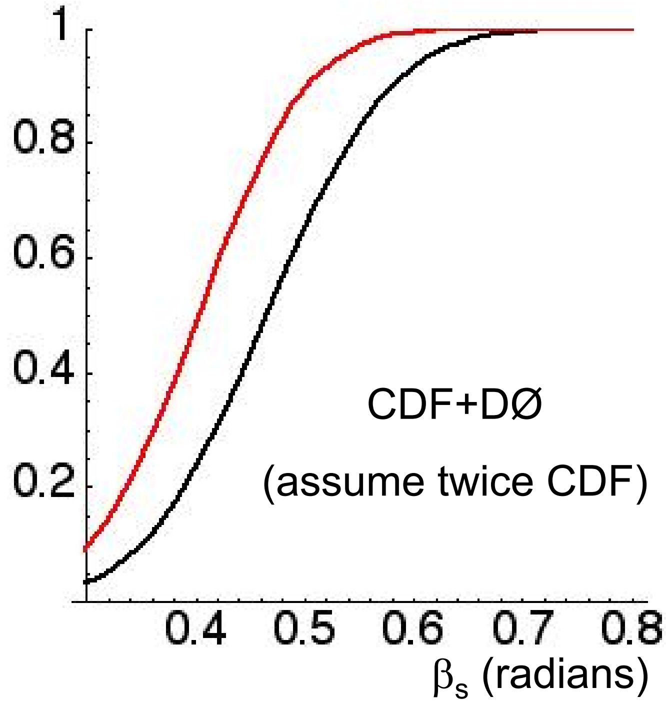
- Combined C.L. contours will be publicly available in numerical format

- Investigating two combination methods:
    - combine 2D profile likelihoods
        - will be ready very soon (still working on coherent treatment of systematics and inclusion of Tevatron constraints)
    - perform simultaneous fit of CDF and DØ data
        - expect to be more powerful, longer timescale

Future

- Shown results with 2.8 fb^{-1}, but 5 fb^{-1} already on tape to be analyzed
- Expect 8 fb^{-1} by end of Run 2 in 2010 (maybe 10 fb^{-1} by end of 2011 ?)





If β_s is indeed large combined CDF and DØ results have good chance to prove it

Conclusions

- Measurements of CPV in B_s system done by both CDF and DØ

- Significant regions in β_s space are ruled out

- Best measurements of B_s lifetime and decay width difference $\Delta\Gamma$

- Both CDF and DØ observe 1-2 sigma β_s deviations from SM predictions

- Combined HFAG result 2.2 σ w.r.t SM expectation
  - updated Tevatron average expected soon

- Interesting to see how these effects evolve with more data

- Updated analyses from both CDF and D0 expected soon

Backup Slides

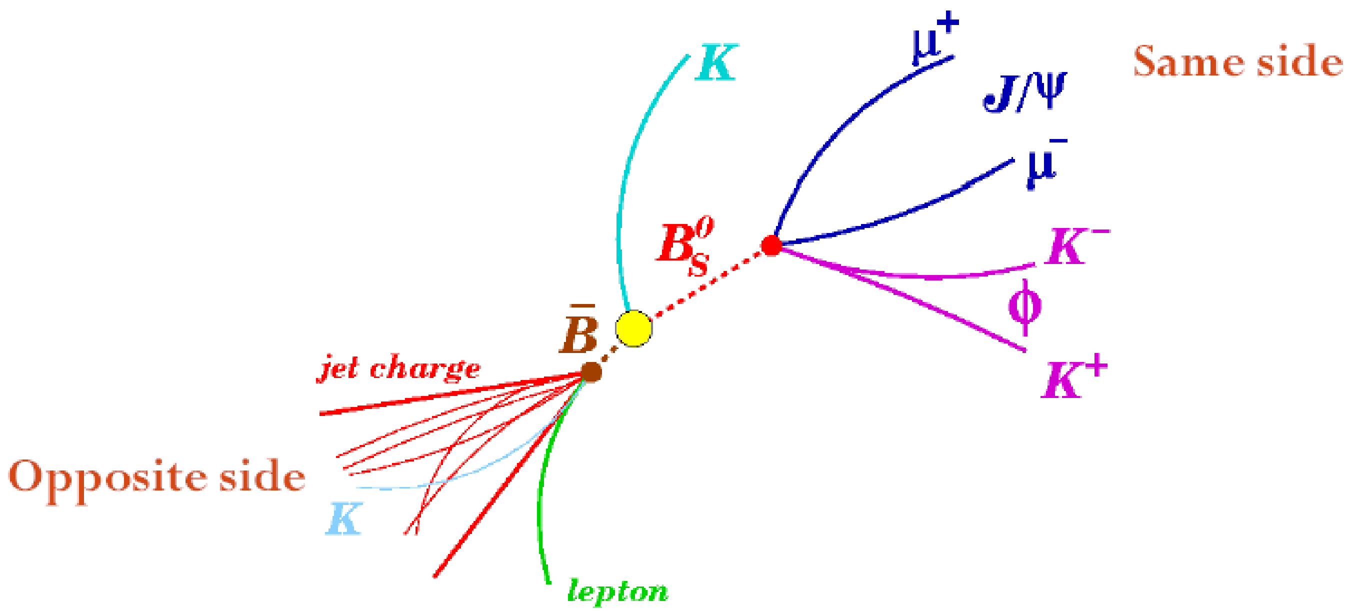
Flavor Tagging

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

→ flavor of the B meson at production inferred with

- OST: exploits decay products of other *b*-hadron in the event

- SST: exploits the correlations with particles produced in fragmentation

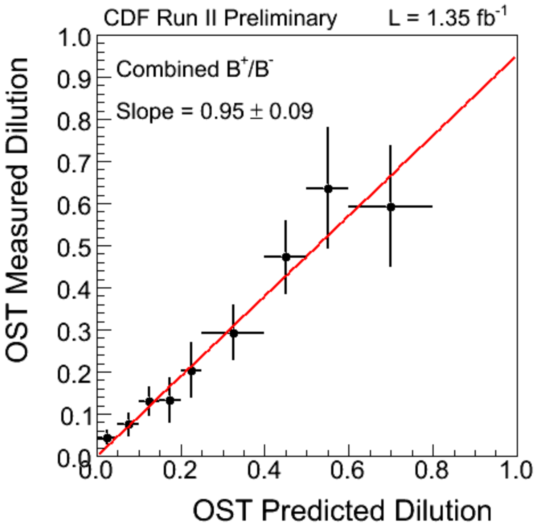


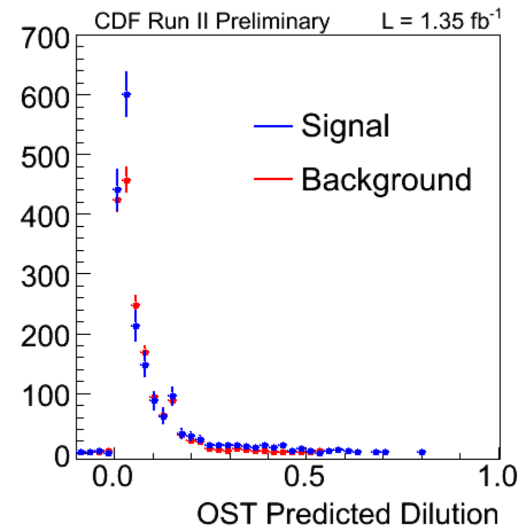
- Output: decision (*b*-quark or anti-*b*-quark) and probability the decision is correct

- Similar tagging power for both CDF and DØ ~4.5% (compared to ~30% at B factories)

CDF Tagging Calibration and Performance

- OST calibrated on $B^{+/-} \rightarrow J/\Psi\ K^{+/-}$
- SST calibrated on MC, but checked on B_s mixing measurement





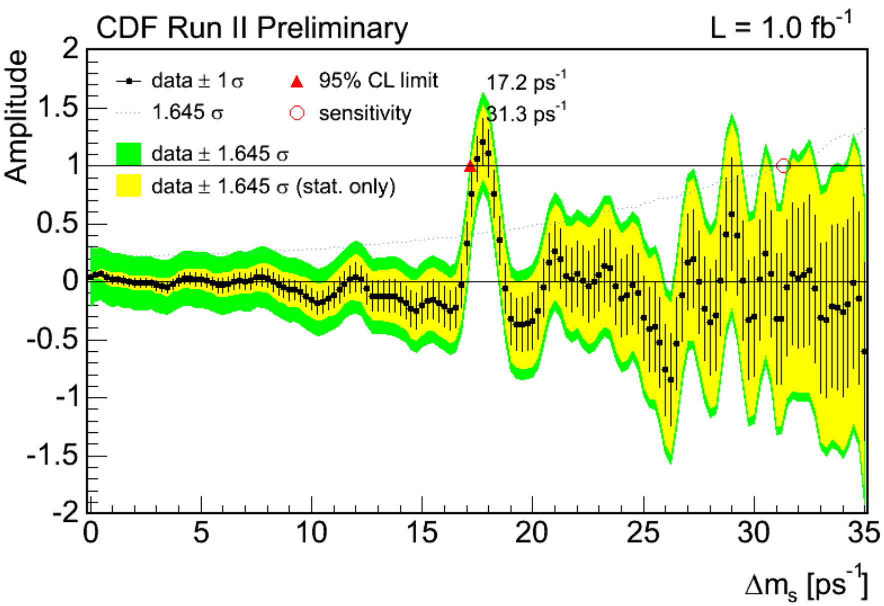
correct tag probability = (1 + dilution) / 2

OST efficiency = 96 +/- 1%

dilution = 11 +/- 2%

SST efficiency = 50 +/- 1%

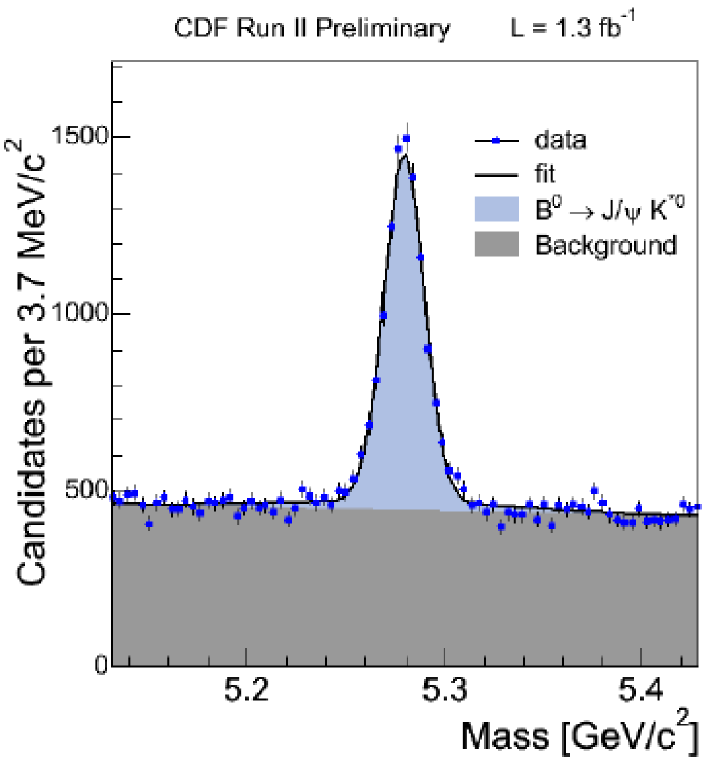
dilution = 27 +/- 4%



CDF Cross-check on $B^0 \to J/\Psi\ K^{*0}$

$B^0 \to J/\psi K^{*0}$: high-statistics test of angular efficiencies and fitter

$$c\tau = 456 \pm 6\ (\text{stat}) \pm 6\ (\text{syst})\ \mu\text{m}$$
$$|A_0(0)|^2 = 0.569 \pm 0.009\ (\text{stat}) \pm 0.009\ (\text{syst})$$
$$|A_\parallel(0)|^2 = 0.211 \pm 0.012\ (\text{stat}) \pm 0.006\ (\text{syst})$$
$$\delta_\parallel = -2.96 \pm 0.08\ (\text{stat}) \pm 0.03\ (\text{syst})$$
$$\delta_\perp = 2.97 \pm 0.06\ (\text{stat}) \pm 0.01\ (\text{syst})$$

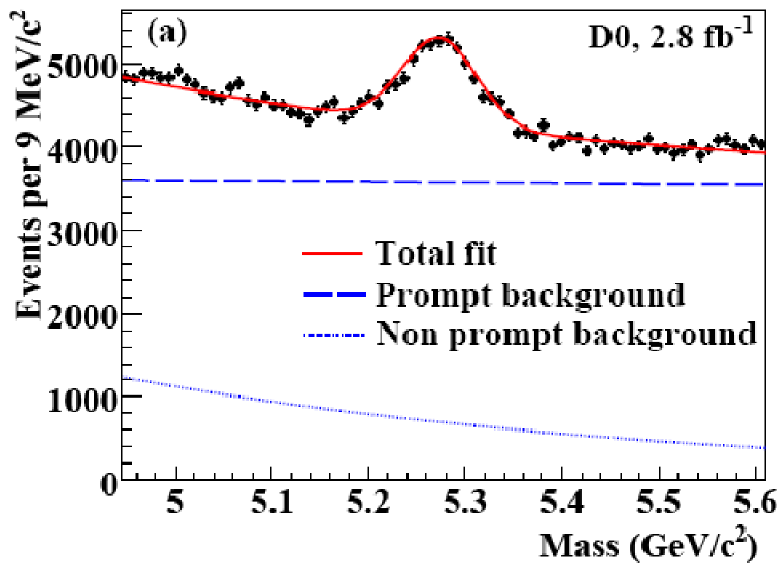


- Not only agree with latest BaBar results, (PRD 76,031102 (2007)) but also competitive

$$|A_0(0)|^2 = 0.556 \pm 0.009\ (\text{stat}) \pm 0.010\ (\text{syst})$$
$$|A_\parallel(0)|^2 = 0.211 \pm 0.010\ (\text{stat}) \pm 0.006\ (\text{syst})$$
$$\delta_\parallel = -2.93 \pm 0.08\ (\text{stat}) \pm 0.04\ (\text{syst})$$
$$\delta_\perp = 2.91 \pm 0.05\ (\text{stat}) \pm 0.03\ (\text{syst})$$

DØ Cross-check on $B^0 \rightarrow J/\Psi\ K^{*0}$

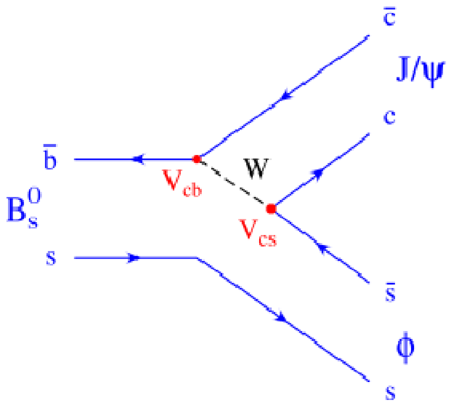
Parameter	B_d^0	B_s^0	Units
$\lvert A_0 \rvert^2$	0.587 ± 0.011	0.555 ± 0.027	–
$\lvert A_\parallel \rvert^2$	0.230 ± 0.013	0.244 ± 0.032	–
δ_1	-0.38 ± 0.06	–	rad
δ_2	3.21 ± 0.06	–	rad
$\delta_\parallel$	3.59 ± 0.08 ± 0.08	$2.72^{+1.12}_{-0.27}$	rad
τ	1.414 ± 0.018	1.487 ± 0.060	ps
$\Delta\Gamma_s$	–	$0.085^{+0.072}_{-0.078}$	ps^{-1}
N_{sig}	11195 ± 167	1926 ± 62	–



- Consistency of amplitudes and strong phase between B_s and B^0

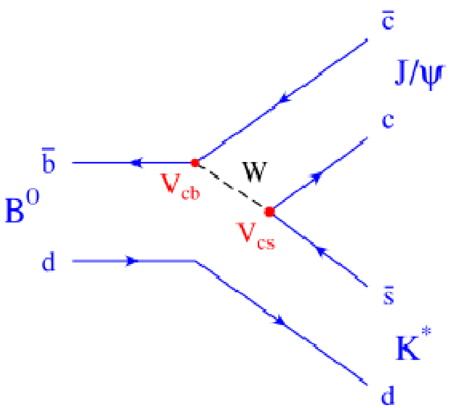
arXiv:0810.0037v1

- Same phases in



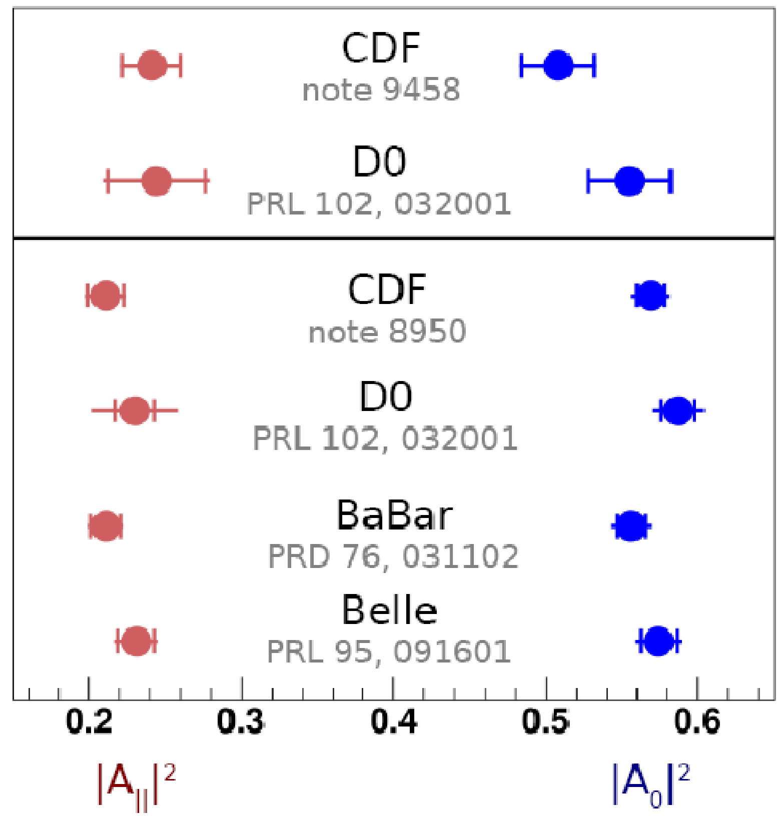
$B_s \rightarrow J/\psi\ \phi$

and



$B^0 \rightarrow J/\psi\ K^*$

?



M. Gronau, J.L. Rosner, Phys.Lett.B669:321-326,2008, arXiv:0808.3761

→ argue that strong phases $\delta_{||}$ and $\delta_{\perp}$ in $B_s \rightarrow J/\Psi\Phi$ and $B^0 \rightarrow J/\Psi\ K^{*0}$ should be within ~10 degrees from each other

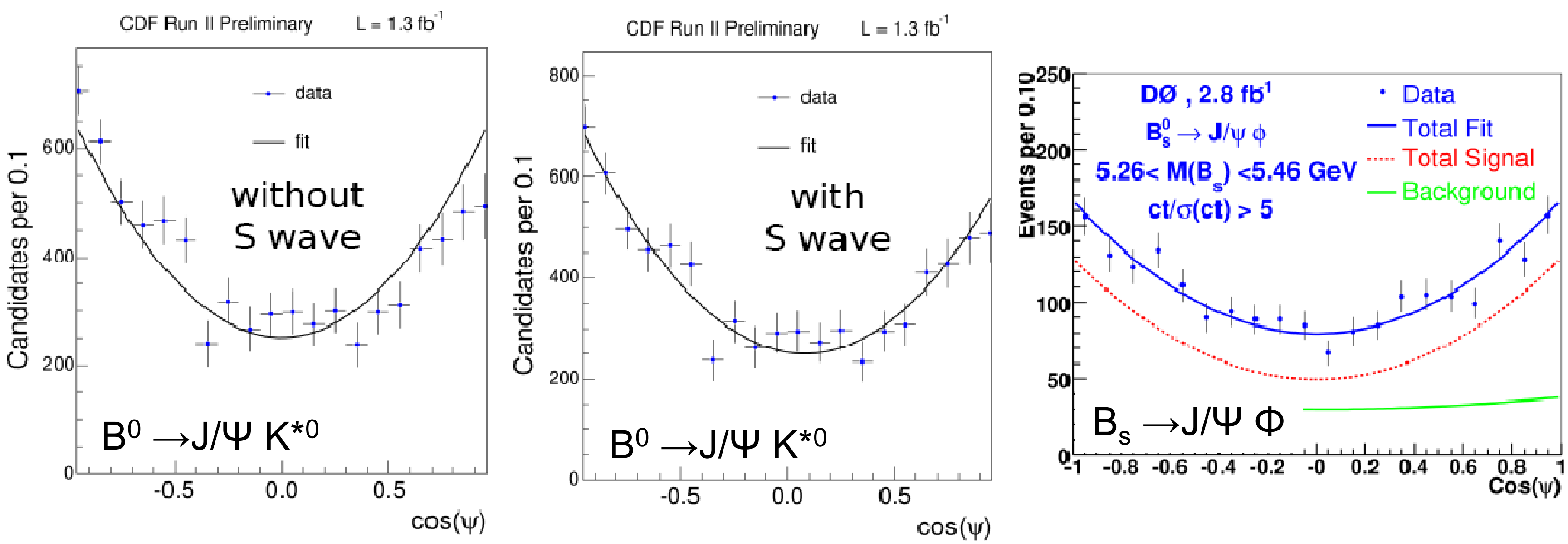
S-wave Effect on Measurement of CP Violating Phases ?

S.Stone, L.Zhang, arXiv:0812.2832

- What is effect of interference between S-wave $B_s \to J/\Psi\ f^0$ or $B_s \to J/\Psi\ K^+K^-$ (non-resonant) and $B_s \to J/\Psi\ \Phi$?

- Within statistics, no evidence for f^0 or non-resonant KK S-wave in Φ(KK) mass distribution

- cos(Ψ) distribution sensitive to S-wave interference:



Evidence for S-wave in $B^0 \to J/\Psi\ K^{*0}$

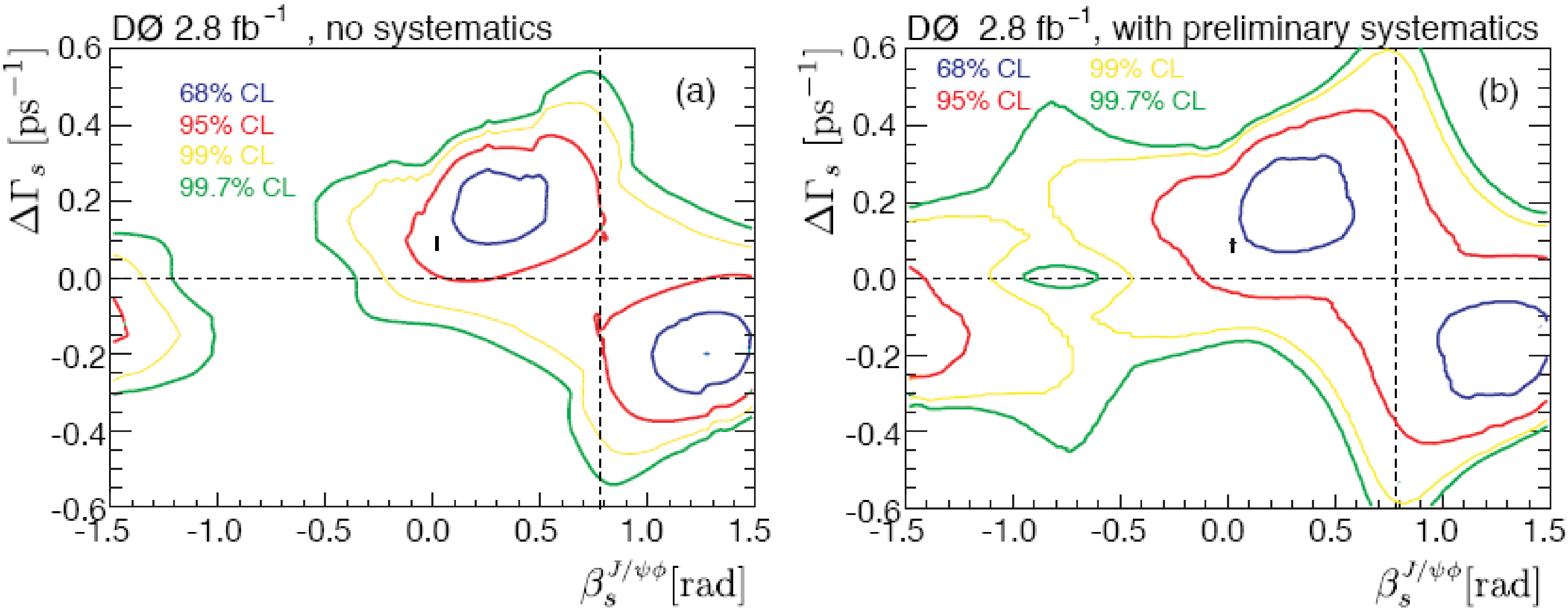
No evidence for S-wave in $B_s \to J/\Psi\ \Phi$

DØ Results Before and After Systematics

DØ dominant systematics included in CL contours:

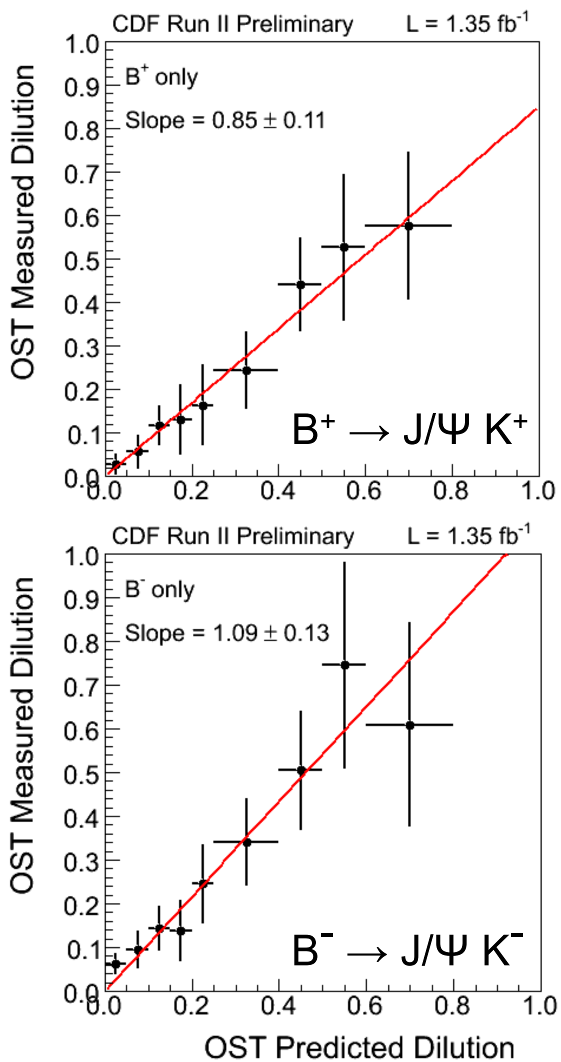
- dms, flavor dilution, detector acceptance (parameters varied by +/- 1σ)

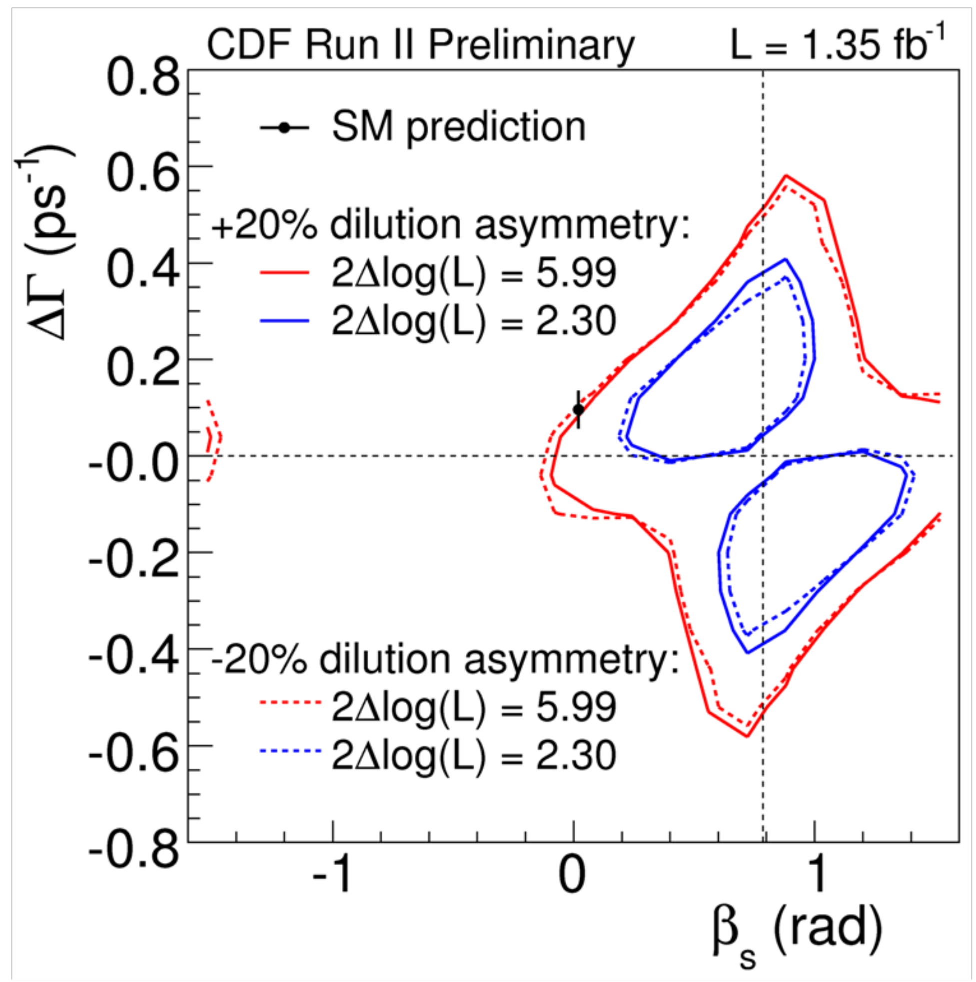
SM p-value increases from 8.5% to 24% after inclusion of systematic uncertainties



Effect of Dilution Asymmetry on β_s

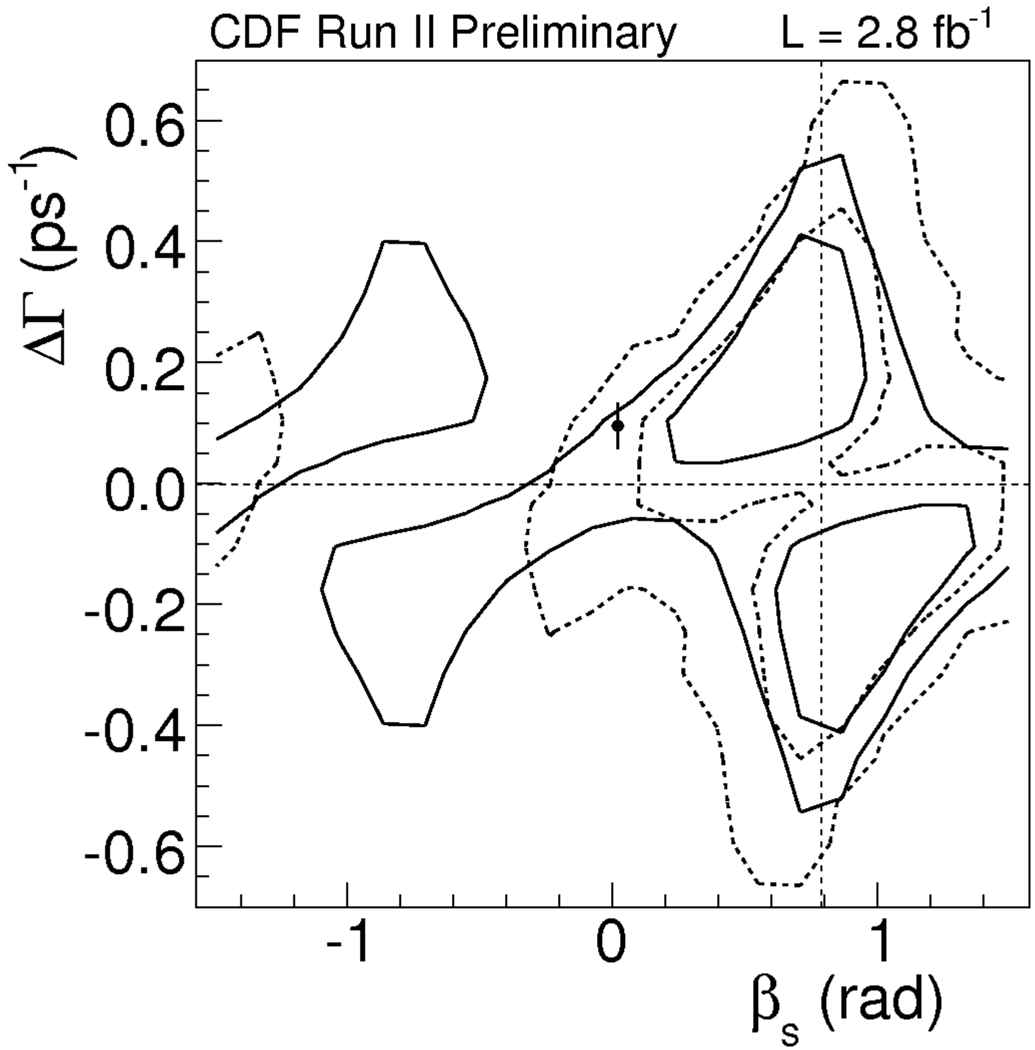
- Effect of 20% b-bbar dilution asymmetry is very small





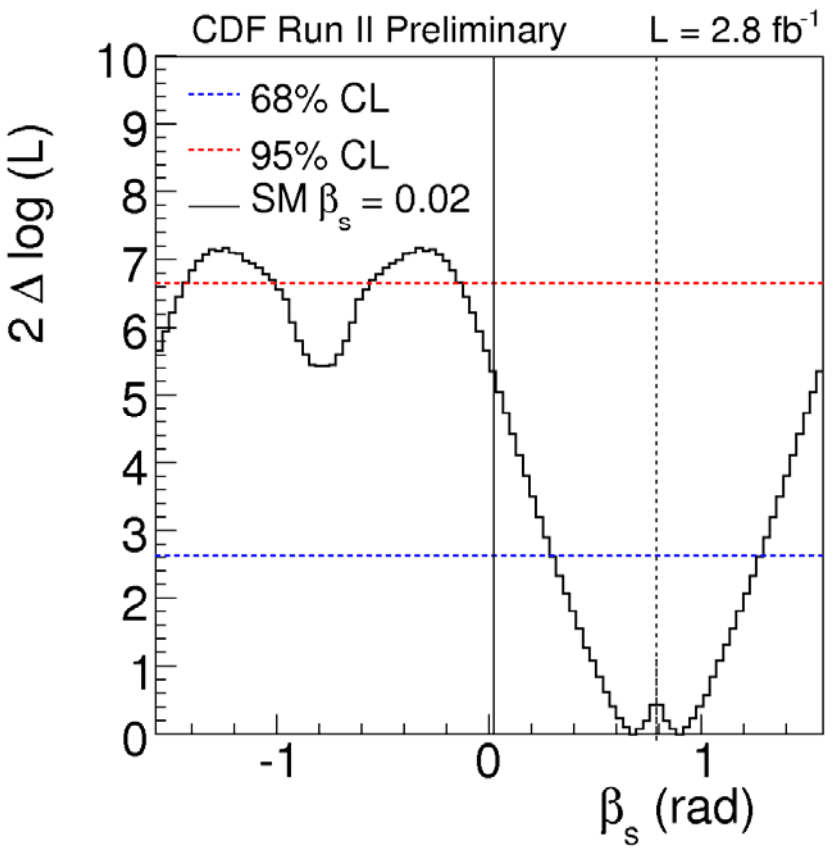
CDF Comparison Between 1.4 fb^{-1} and 2.8 fb^{-1}

- dotted line = 1.4 fb^{-1}
- solid line = 2.8 fb^{-1}

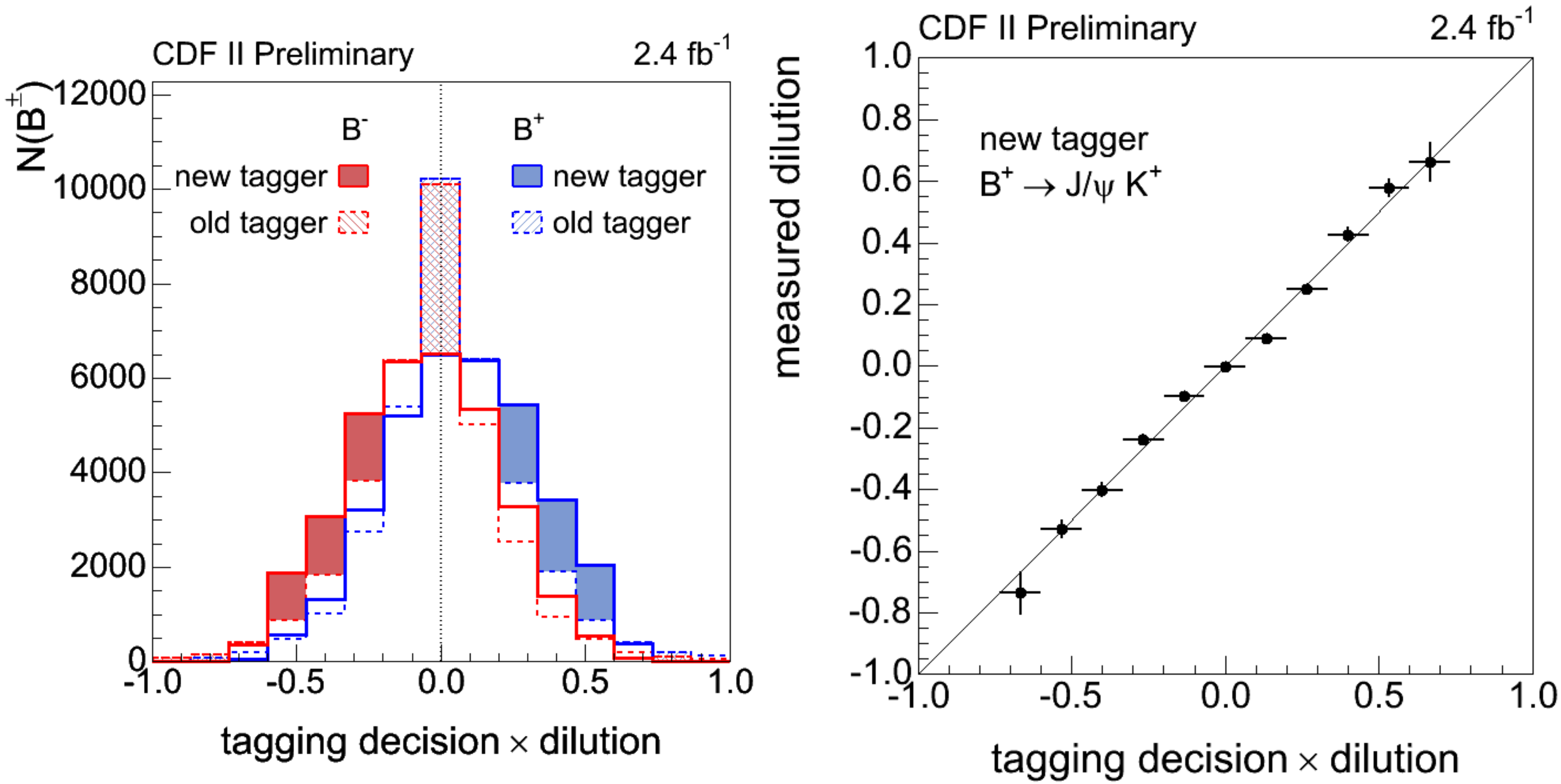


CDF 1D Profile Likelihood

β_s is within [0.28, 1.29] at the 68% CL



CDF Updated Tagger Coming Soon



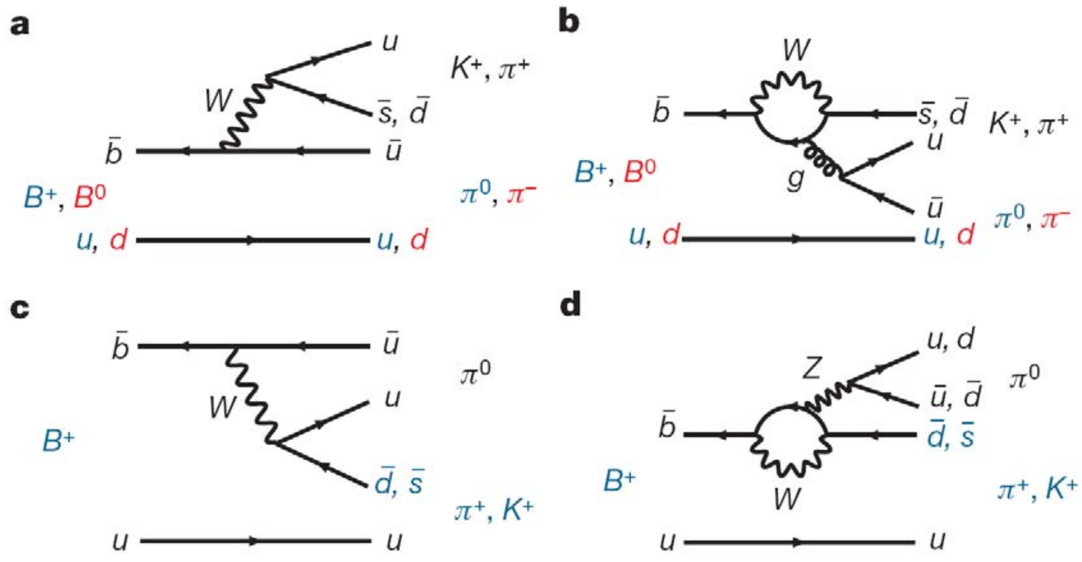
Another Related Puzzle ?

- Direct CP in $B^+ \to K^+ \pi^0$ *and* $B^0 \to K^+\pi^-$ should have the same magnitude.

- But Belle measures $\Delta\mathcal{A} \equiv \mathcal{A}_{K^\pm\pi^0} - \mathcal{A}_{K^\pm\pi^\mp} = +0.164 \pm 0.037,$ (4.4 σ)

Lin, S.-W. et al. (The Belle collaboration) Nature 452,332–335 (2008)

- Including BaBar measurements: > 5σ



- W.-S. Hou explains above effects by introducing the fourth fermion generation and predicts large β_s value (arXiv:0803.1234v1)

Asymmetry in the Mirror Lake !