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B_s Mixing Parameters and the Search for CP Violation at CDF/D0

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Fermilab

Outline

- Motivation
- B_s System – Decay Modes, etc.
- Mixing Parameter Measurements
- CP Violation : Meas. method/results
- Combination Issues/Methods
- Conclusion
- Outlook

B-physics: Where theory meets expt.

- EW symmetry breaking: determines flavor physics – CKM matrix, CPV, & FCNC structure.
- b-quark mass, etc. theoretical calculations well adapted to b-physics : HQET, lattice gauge, and other strong symmetries.

➢ B-state mass spectra: Much progress incl. lattice

➢ Lifetime comparisons: (theory) (exp.)

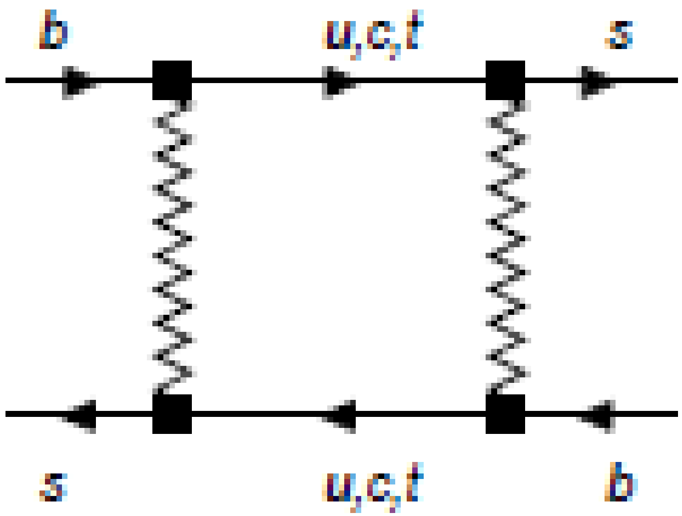
τ_{B+} / τ_{Bd} = 1.063 ± 0.027 1.071 ± 0.009 HFAG

τ_{Bs} / τ_{Bd} = 1.00 ± 0.01 0.939 ± 0.021 HFAG

τ_{Bc} = $0.52^{+0.18}_{-0.12}$ ps 0.463 ± 0.071 ps "

Neutral K, D & B mesons

Box diagrams give FCNC:



e.g.

$$\bar{B}_s \rightarrow B_s$$

$$B_s \rightarrow \bar{B}_s$$

$$K \leftrightarrow \bar{s}d \quad D \leftrightarrow c\bar{u} \quad B_d \leftrightarrow \bar{b}d \quad B_s \leftrightarrow \bar{b}s$$

$$\bar{K} \leftrightarrow s\bar{d} \quad \bar{D} \leftrightarrow \bar{c}u \quad \bar{B}_d \leftrightarrow b\bar{d} \quad \bar{B}_s \leftrightarrow b\bar{s}$$

Evolution of B_s

$$i\frac{d}{dt}\begin{pmatrix} B_s^0 \\ \overline{B}_s^0 \end{pmatrix} = \begin{pmatrix} M - \frac{i\Gamma}{2} & M_{12} - \frac{i\Gamma_{12}}{2} \\ M_{12}^* - \frac{i\Gamma_{12}^*}{2} & M - \frac{i\Gamma}{2} \end{pmatrix} \begin{pmatrix} B_s^0 \\ \overline{B}_s^0 \end{pmatrix}$$

Weak Eigenstates time evolution via the Schroginger equation.

Diagonalize

CP Eigenstates $\quad \left|B_s^{odd}\right\rangle = \left|B_s^0\right\rangle + \left|\overline{B}_s^0\right\rangle, \quad \left|B_s^{even}\right\rangle = \left|B_s^0\right\rangle - \left|\overline{B}_s^0\right\rangle$

Mass Eigenstates $\quad \left|B_s^H\right\rangle = p\left|B_s^0\right\rangle + q\left|\overline{B}_s^0\right\rangle, \quad \left|B_s^L\right\rangle = p\left|B_s^0\right\rangle - q\left|\overline{B}_s^0\right\rangle$

Heavy — Light

If CP is conserved in Mixing, $p = q \quad \left|B_s^H\right\rangle = \left|B_s^{odd}\right\rangle \quad \left|B_s^L\right\rangle = \left|B_s^{even}\right\rangle$

$$\Delta m_s = M_H - M_L \approx 2\left|M_{12}\right|$$ = 17.77 ± 0.12 ps^{-1} Precision better than theory!

$$\Delta\Gamma_s^{CP} = \Gamma_{even} - \Gamma_{odd} \approx 2\left|\Gamma_{12}\right|$$

$$\Delta\Gamma_s = \Gamma_L - \Gamma_H \approx 2\left|\Gamma_{12}\right|\cos\phi_s$$

small for B_d / ***but not for B_s*** } ***different osc. freqs.***

$$\Gamma_s = \frac{\Gamma_L + \Gamma_H}{2} \; ; \; \overline{\tau}_s = \frac{1}{\Gamma_s}$$

$$\phi_s^{SM} = arg\left[-\frac{M_{12}}{\Gamma_{12}}\right] \approx 0.004 \text{ in the SM}$$

Evolution of B_s

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$$\Delta m_s = M_H - M_L \approx 2\left|M_{12}\right|$$

Sensitive to new physics => New high-mass box diagram states.

$$\Delta\Gamma_s^{CP} = \Gamma_{even} - \Gamma_{odd} \approx 2\left|\Gamma_{12}\right|$$

Small for B_d (Cabibbo Sup) , B_s Mixing sens.

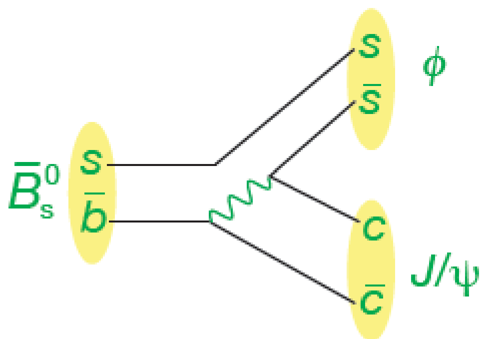
$$\Delta\Gamma_s = \Gamma_L - \Gamma_H \approx 2\left|\Gamma_{12}\right|\cos\phi_s$$

Very sensitive: $\phi_s \Rightarrow \phi_s + \phi_{\text{New Physics}}$

$$\Gamma_s = \frac{\Gamma_L + \Gamma_H}{2} \; ; \quad \bar{\tau} = \frac{1}{\Gamma_s} \qquad \phi_s^{SM}$$

For CPV look for an imaginary amplitude in a B_s final state.

B_s □ $\psi(\mu^+\mu^-) + \phi(K^+K^-)$ $\phi_s \sim 0$



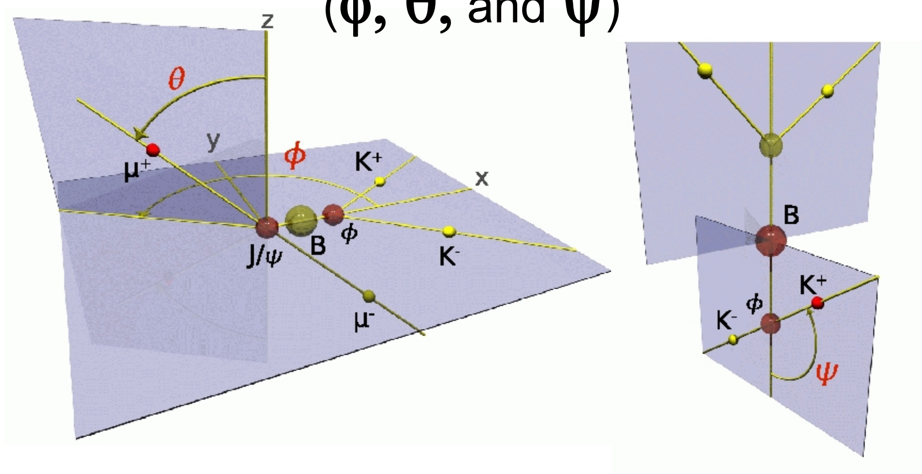
Since CP violation is expected to be small, assume no CPV, $\phi_s = 0$ and mass eigenstates are the CP eigenstates: Heavy (H, CP - odd) and Light (L, CP – even) for B_s.

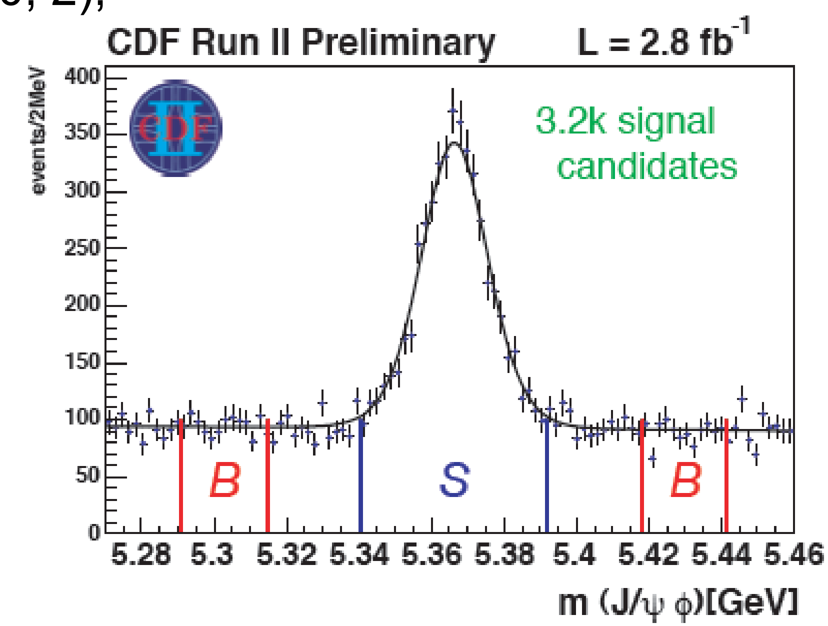
The weak decay states are not flavor specific.

But, since the decay products, ϕ and J/ψ, are vector particles the final states are CP - odd (L=1) or CP – even (L= 0, 2),

Analysis proceeds using Transversity basis:

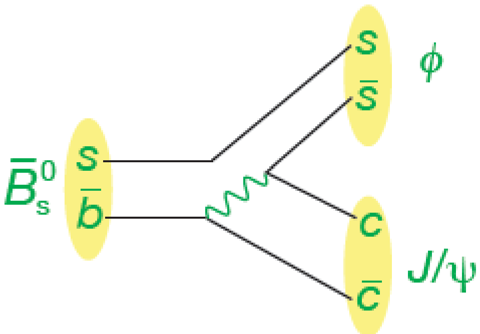
(ϕ, θ, and ψ)





DØ: ~2k signal candidates

B_s □ $\psi(\mu^+\mu^-) + \phi(K^+K^-)$ $\phi_s \sim 0$



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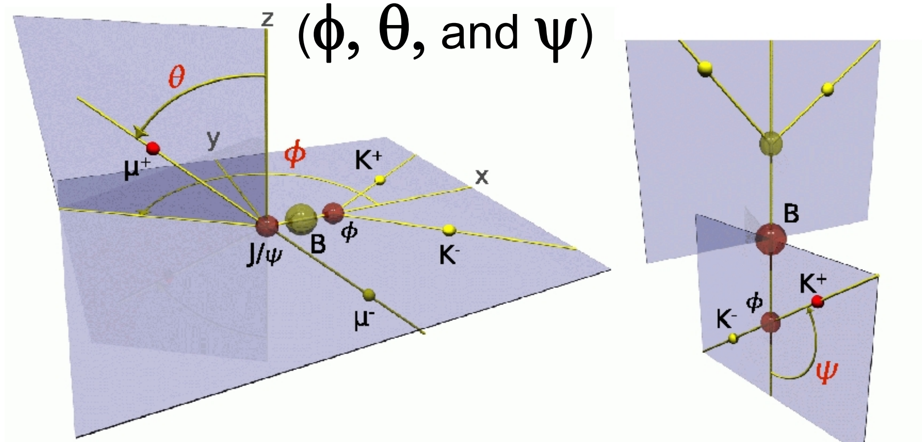
The weak decay states are not flavor specific.

But, since the decay products, ϕ and J/ψ, are vector particles the final states are CP - odd (L=1) or CP – even (L= 0, 2),

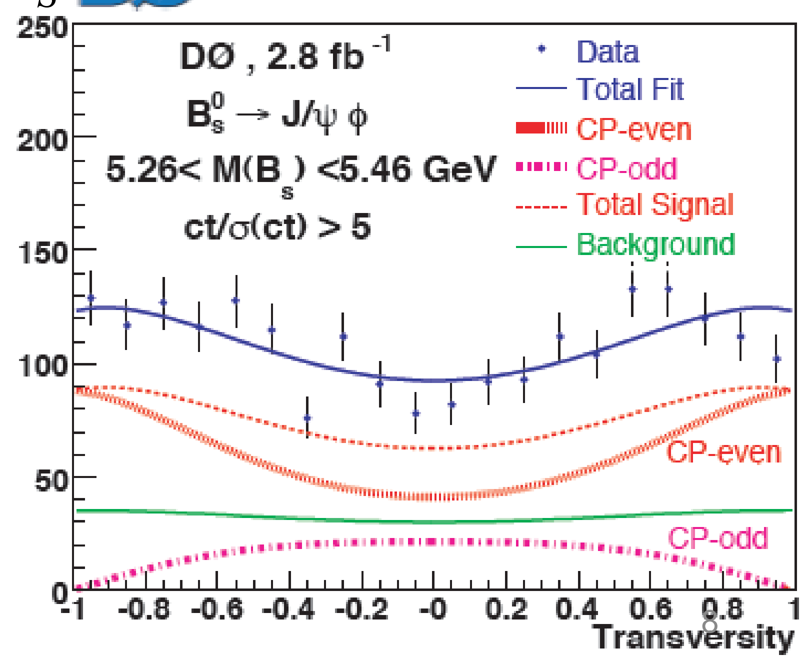
$$\Delta\Gamma_S = \Gamma_L - \Gamma_H ; \Gamma_S = (\Gamma_L + \Gamma_H)/2; \ \bar{\tau}_S = 1/\Gamma_S$$

Analysis proceeds using Transversity basis:

(ϕ, θ, and ψ)



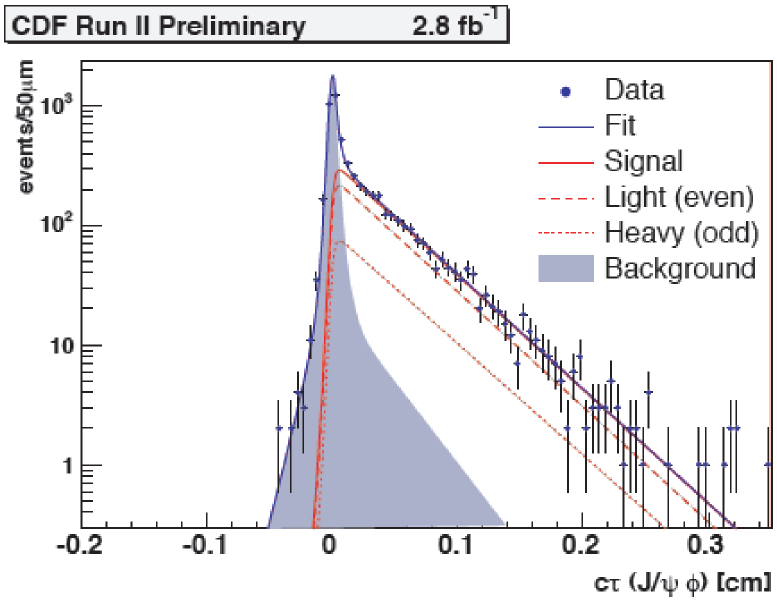
Simultaneous fit to lifetime, ϕ, θ, and ψ.

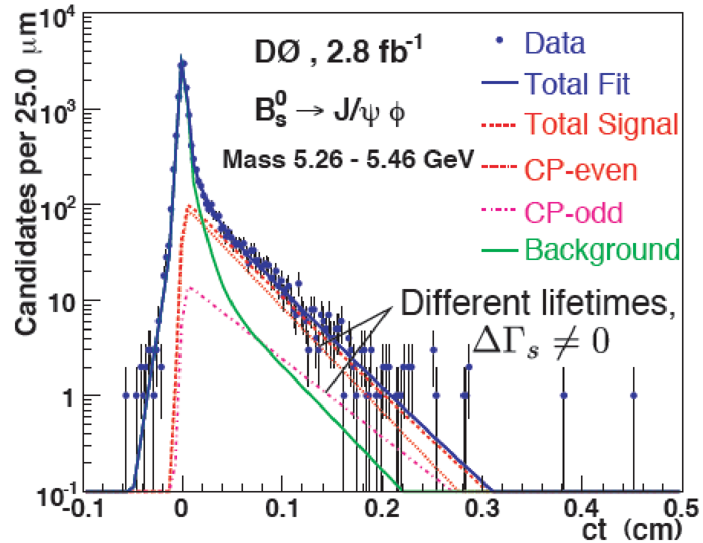


Γ_s & $\Delta\Gamma_s$ $B_s \to J/\psi(\mu\mu) + \phi(K^+K^-)$

no *CP* violation in B_s mixing, $\phi_s \sim 0$

Mass and CP eigenstates the same





CDF/ANAL/BOTTOM/PUBLIC/9458

$$\Delta\Gamma_s = 0.02 \pm 0.05 \pm 0.01\,\mathrm{ps}^{-1}$$
$$\bar{\tau}_s = 1.53 \pm 0.04 \pm 0.01\,\mathrm{ps}$$

No flavor tag

Phys. Rev. Lett. 101, 241801 (2008)

$$\Delta\Gamma_s = 0.14 \pm 0.07\,\mathrm{ps}^{-1}$$
$$\bar{\tau}_s = 1.53 \pm 0.05 \pm 0.01\,\mathrm{ps}$$

$$\bar{\tau}_s = \frac{1}{\Gamma_s} = \frac{2}{\Gamma_H + \Gamma_L}$$

c.f. $\Delta\Gamma_s^{SM,pred} = 0.088 \pm 0.017\,\mathrm{ps}^{-1}$ (hep-ph/0612167)

($0.096 \pm 0.039\,\mathrm{ps}^{-1}$ if don't use $\Delta m_s^{\mathrm{meas.}}$)

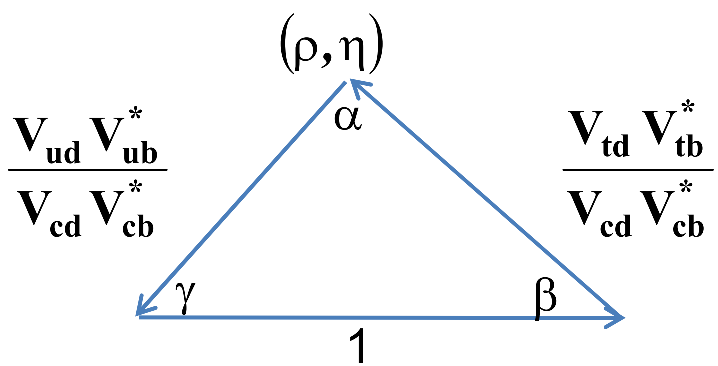
CKM and CP Violation: B_d

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

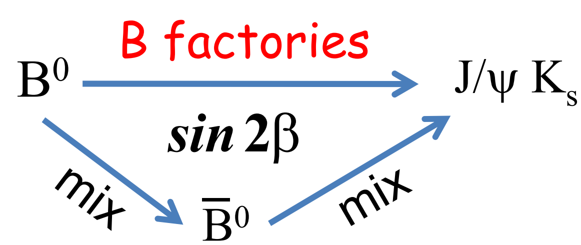
CP violation in the Standard Model appears in complex phases in the unitary CKM matrix. New physics => new phases?

B_d unitary condition: $$V_{ud} V_{ub}^* + V_{cd} V_{cb}^* + V_{td} V_{tb}^* = 0$$

$$\begin{pmatrix} C & & \\ & K & \\ & & M \end{pmatrix} \begin{pmatrix} C & & \\ & K & \\ & & M \end{pmatrix}^{T*} = \begin{pmatrix} & & \\ & I & \\ & & \end{pmatrix}$$



Area of triangle ~ |CPV|



CPV via interference with or w/o mixing.

CKM and CP Violation: B_s

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

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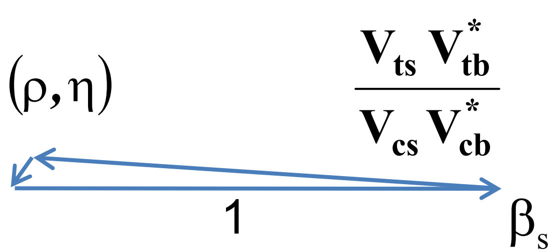

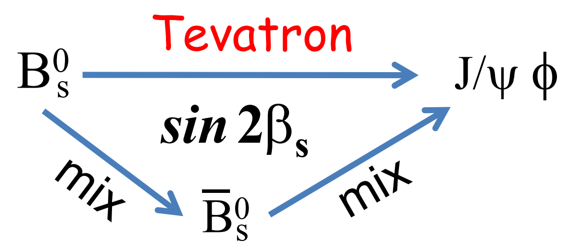

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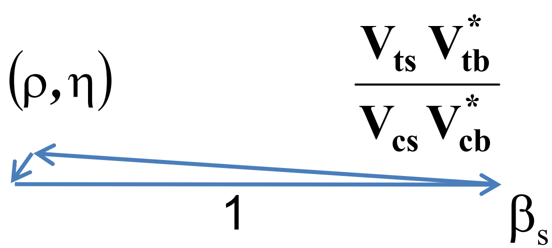


Squashed triangle

$$\beta_s^{SM} = arg\left[-\frac{V_{ts} V_{tb}^*}{V_{cs} V_{cb}^*} \right]$$

$$\approx 0.02$$

Tiny

Searching for new physics in B_s

- How might new physics affect CKM phases?

$$2\beta_s^{SM} = 2\arg\left[-V_{ts}V_{tb}^{*}/V_{cs}V_{cb}^{*}\right] \rightarrow 2\beta_s^{SM} - \phi_s^{NP}$$

~ 0.04

$$\phi_s^{SM} = \arg\left[-M_{12}/\Gamma_{12}\right] \rightarrow \phi_s^{SM} + \phi_s^{NP}$$

~ 0.004

- DØ and CDF measure the phase for CPV in $B_s^0 \rightarrow J/\psi\,\phi$ decays.

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

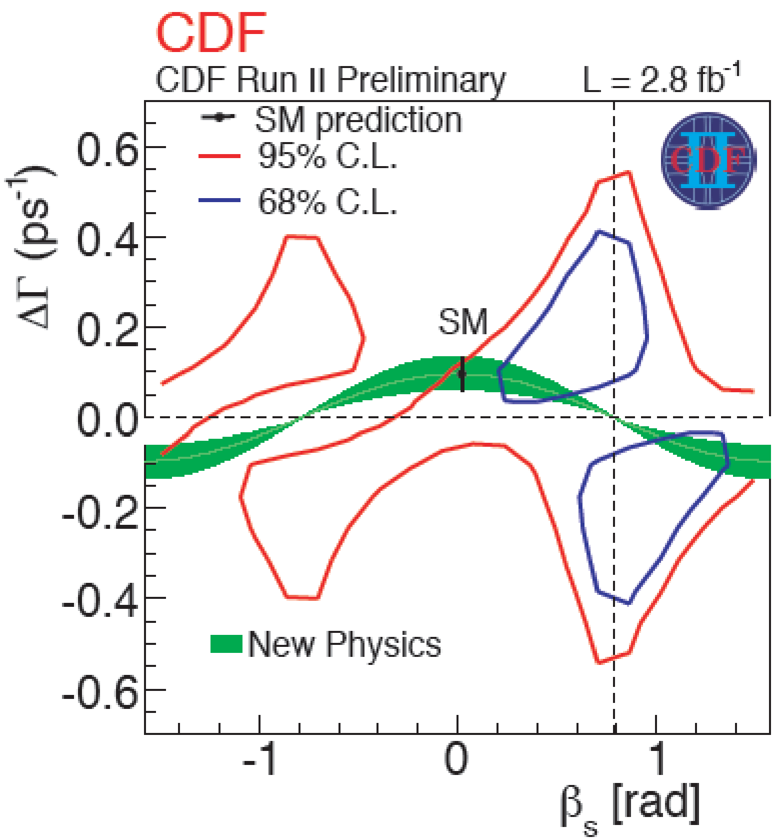
DØ CDF If large

- Use opposite-side flavor tagging to identify the initial flavor: B_s or $\overline{B}_s$ $\longrightarrow$ $J/\psi\,\phi$; tagging efficency and dilution

- Use the known value of Δm_s .

CP Violation in $B_s \to J/\Psi\ \phi$

- Using initial state flavor tagging and no constraints on strong phases:



Standard Model Probability = 7% ; ~1.8σ

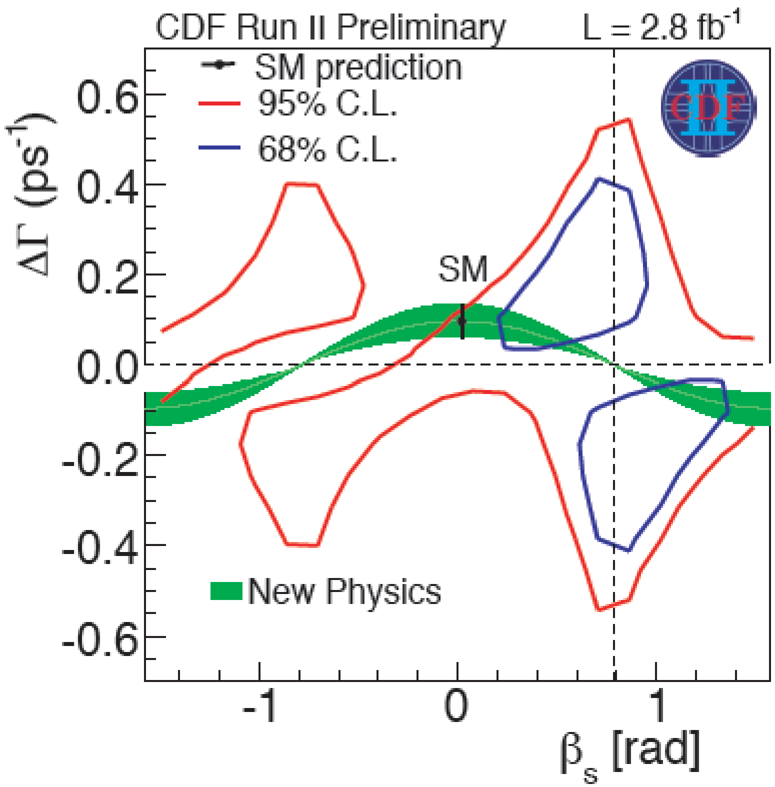
- Ambiguities:

$$2\beta_s^{J/\psi\,\phi} \to \pi - 2\beta_s^{J/\psi\,\phi};\ \Delta\Gamma_s \to -\Delta\Gamma_s;\ \delta_{\parallel} \to 2\pi - \delta_{\parallel};\ \delta_{\perp} \to \pi - \delta_{\perp}$$

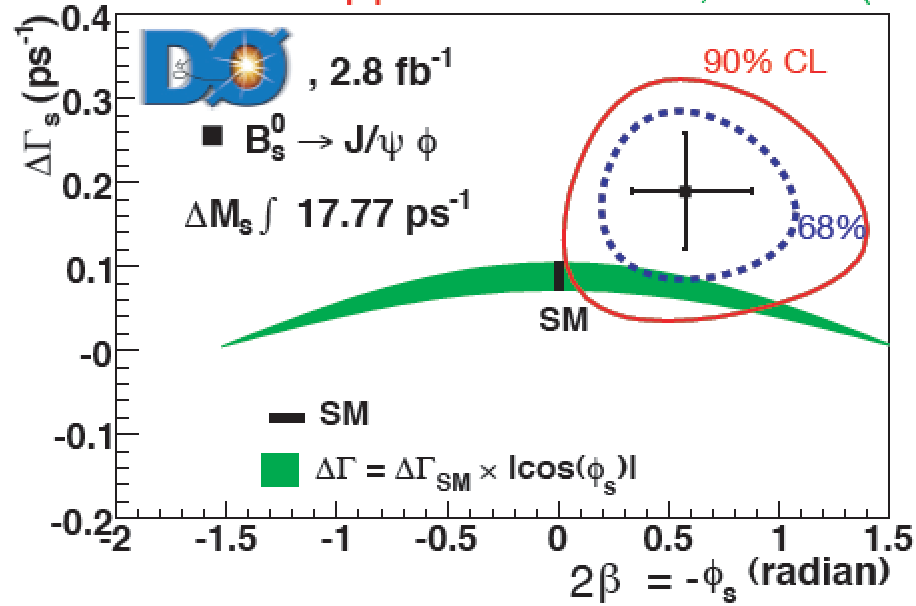
CP Violation in $B_s \to J/\Psi\ \phi$

- Using initial state flavor tagging and no constraints on CDF strong phases:

CDF



DØ "Flipped" PRL 101, 241801 (2008)



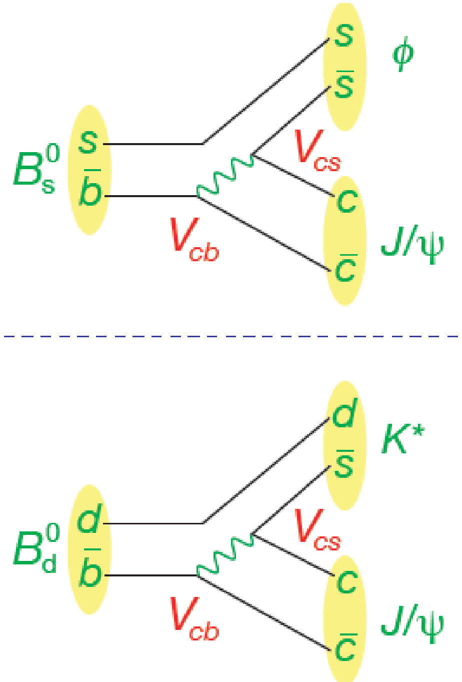
… use weak constraints on strong phases δ_i (between polarization decay amplitudes in B_s => $J/\psi\phi$ and B_d => $J/\psi K^*$)

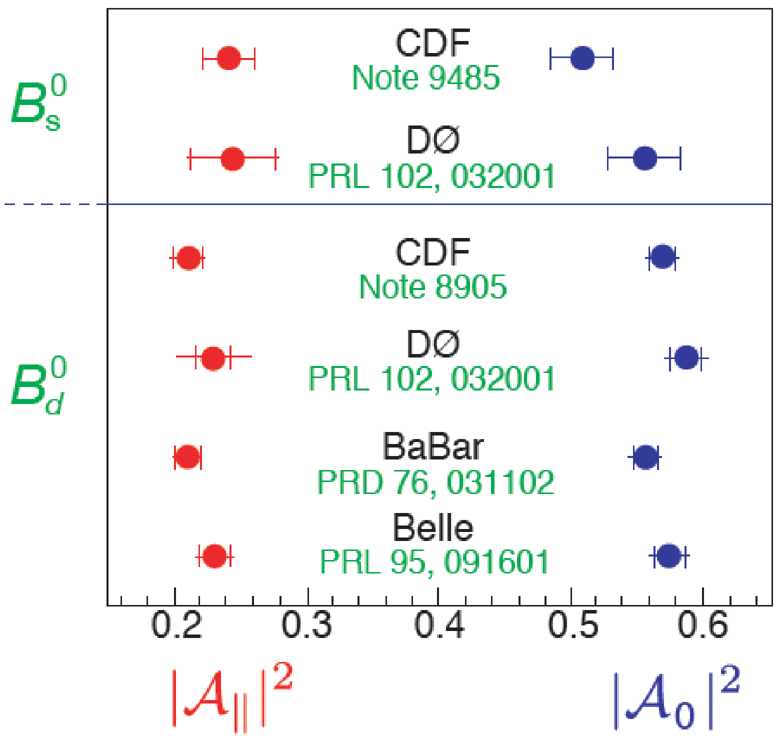
- Ambiguities:

$$2\beta_s^{J/\psi\phi} \to \pi - 2\beta_s^{J/\psi\phi};\ \Delta\Gamma_s \to -\Delta\Gamma_s;\ \delta_\parallel \to 2\pi - \delta_\parallel;\ \delta_\perp \to \pi - \delta_\perp$$

Phases in Transversity Analysis
$B_s \Rightarrow J/\psi\ \phi$ and $B_d \Rightarrow J/\psi\ K^*$

- Same phases? (SU(3) symmetry?)





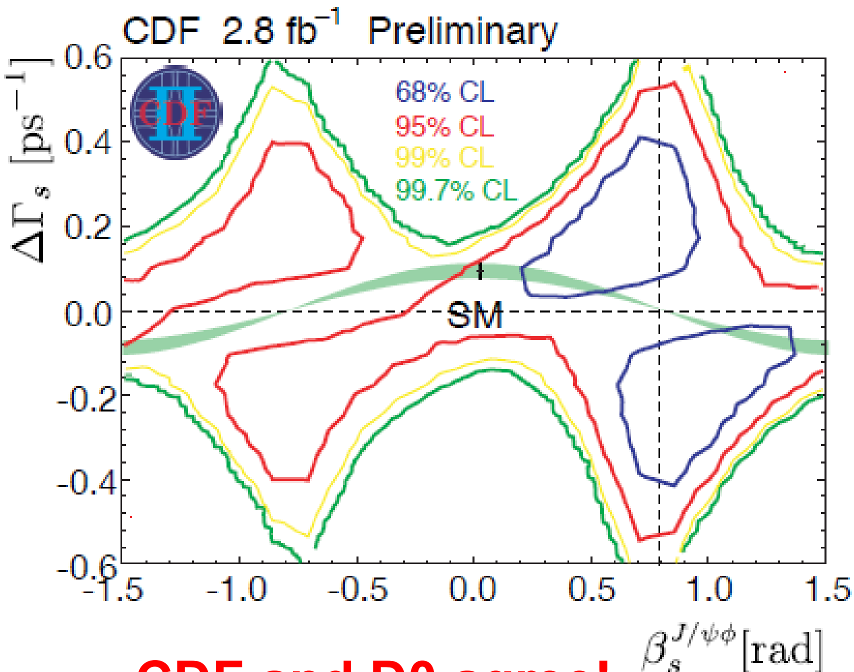
M. Gronau, J.L. Rosner, Phys. Lett. B669, 321 (2008): Strong phases δ_0 and $\delta_{||}$ should be equal to ~10^o for B_s and B^o.

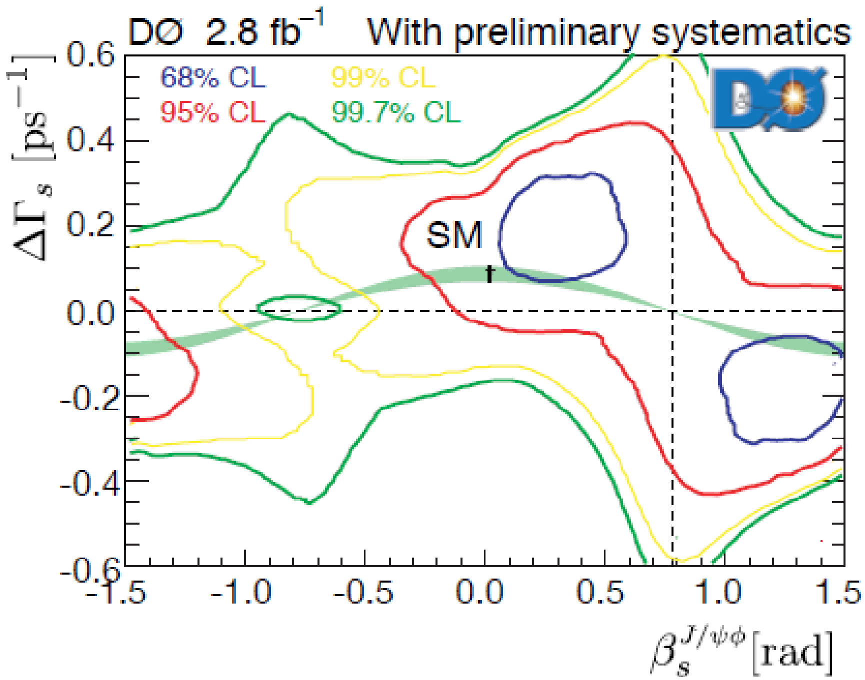
CDF/DØ: $B_s \to J/\psi\ \phi$ w/o phase constraints

For the B_s the weak phase is $\phi_s = \arg[-M_{12}/\Gamma_{12}]$. The SM prediction for ϕ_s : $\phi_s^{SM} = 0.004$ But new physics could change this to: $\phi_s = \phi_s^{SM} + \phi_s^{NP}$. Or alternatively using the CKM triangle (α, β, γ) notation: $2\beta_s = 2\beta_s^{SM} - \phi_s^{NP}$

The relative phase between the B_s mixing amplitude and that of specific $b \to c\bar{c}s$ quark transitions such as for :

$$\overline{B}_s^0 \; or \; B_s^0 \to J/\psi\ \phi \text{ in the SM is: } 2\beta_s^{SM} = 2\arg[-V_{ts}V_{tb}^* / V_{cs}V_{cb}^*] \approx 0.04$$



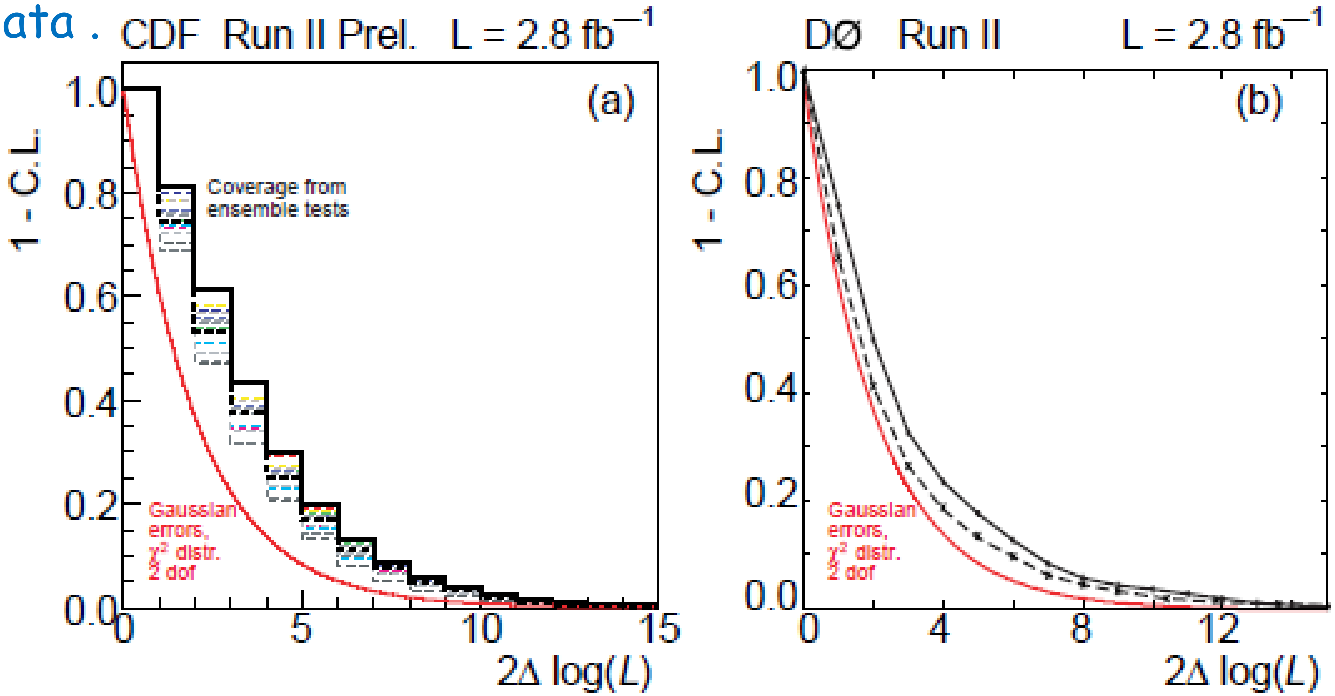


CDF and D0 agree!

From publication: PRL 101, 241801 (2008); DØ Note 5933-CONF

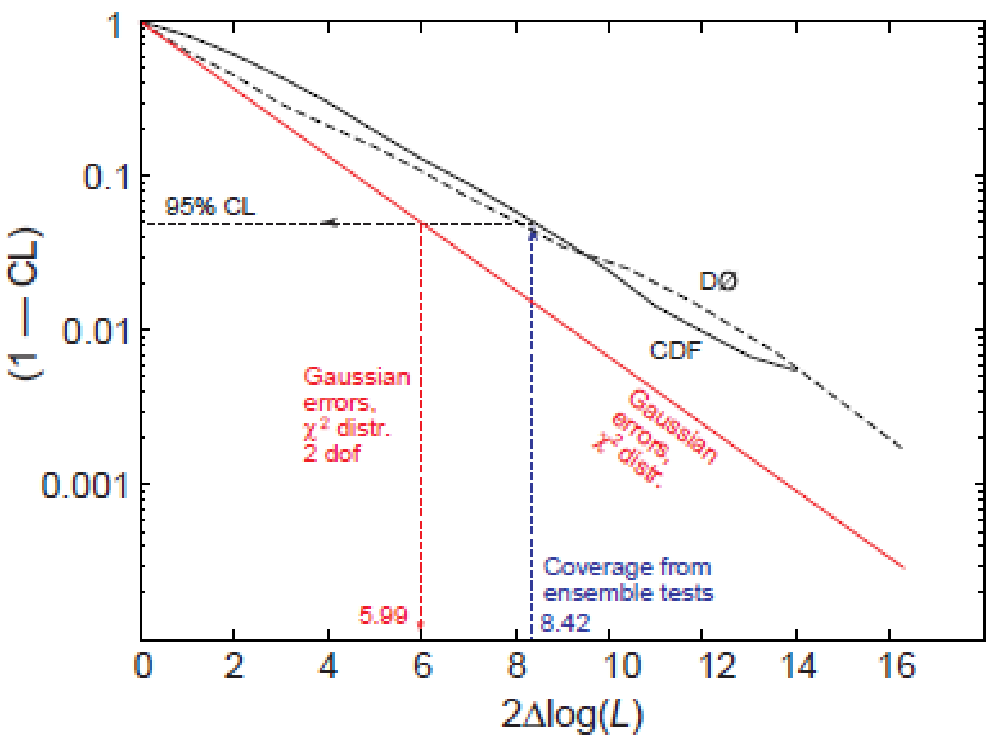
Combining CDF and D0 Results

If the analysis results are correct the likelihood functions in terms of: $\beta_s^{J/\psi\phi}$ and $\Delta\Gamma_s$ should demonstrate it. To verify that the derived values of β_s and $\Delta\Gamma_s$ and their errors are correct, CDF and D0 separately generated 10,000 and 2,000 MC experiments, each with the number of events in their collider data .



From each generated experiment the 2-D likelihood function is determined and from that confidence levels are established. To the extent that the two histograms disagree with the Gaussian predictions (red curves) likelihoods, including systematic errors, are adjusted (next transparency).

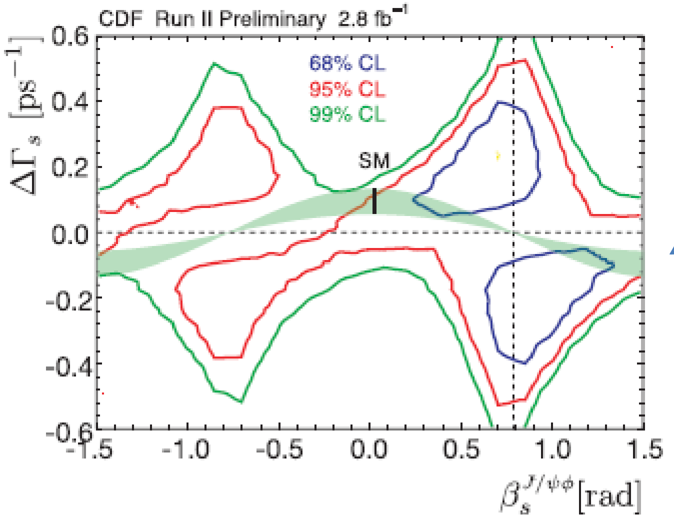
Likelihood Adjustment Example



In the CDF example shown Here, the ensemble coverage tests indicate that a value of $2\Delta \log L = 8.42$ corresponds to the 95% CL. Since the 95% CL should be 5.99 for Gaussian errors, 8.42 is replaced with 5.99., i.e. the 95% χ^2 CL with two degrees of freedom.

Although CDF and D0 start with different coverage this procedure assures a uniform way to combine results.

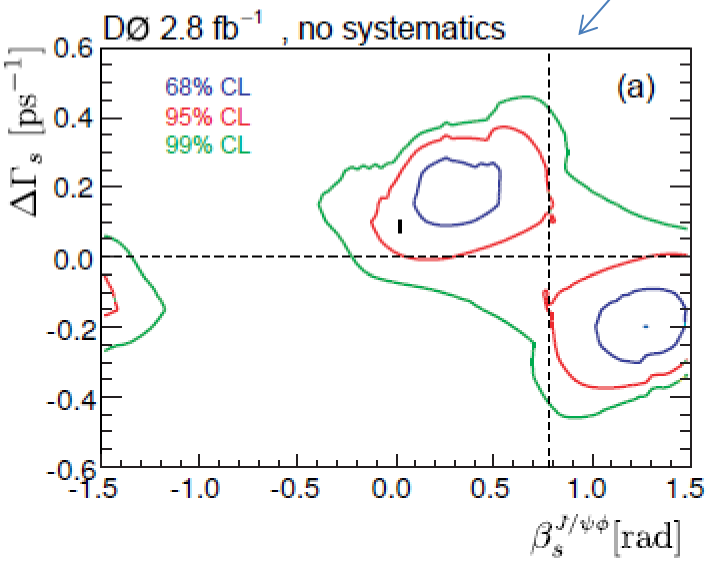
CDF's $\Delta\Gamma_s$ vs. $\beta_s^{J/\psi\phi}$ Scans

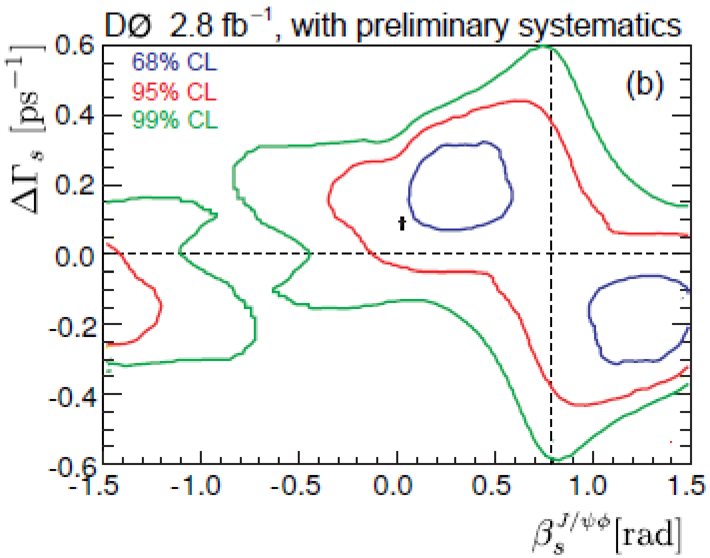


Before Likelihood Adjustment

After Likelihood Adjustment; no systematics

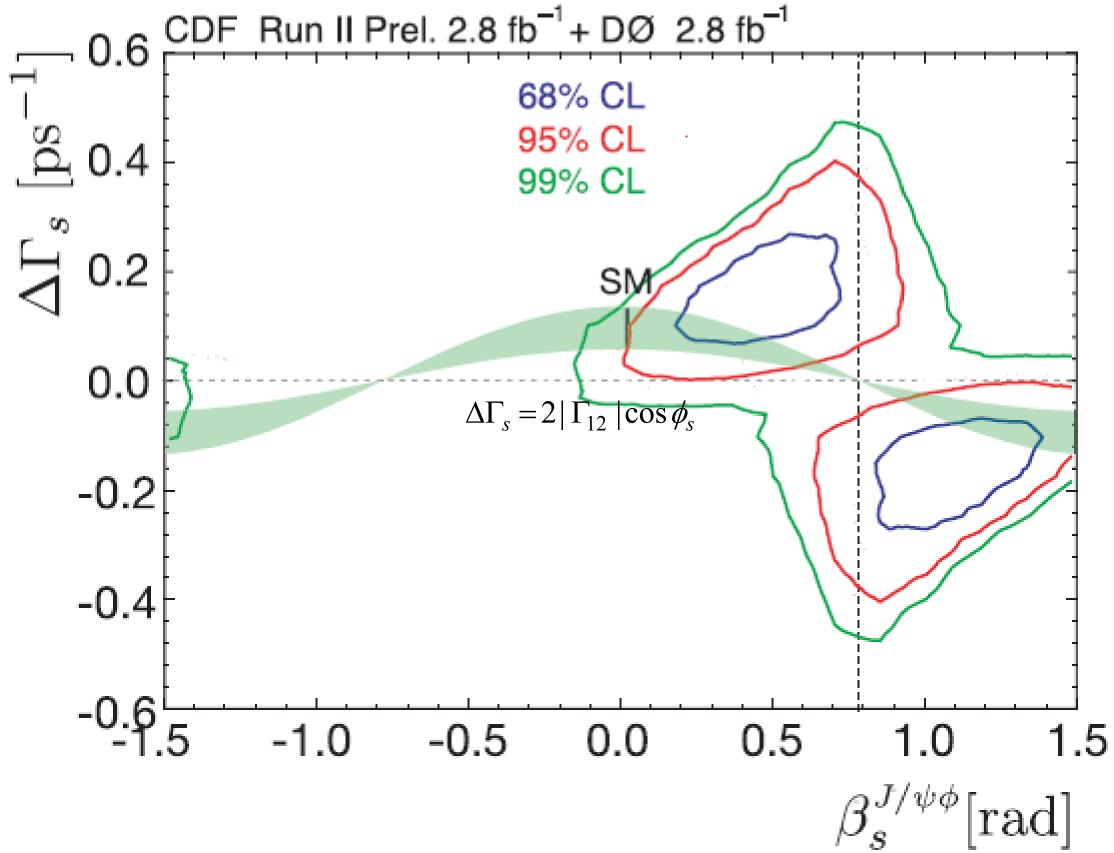
After Likelihood Adjustment; with systematics





CDF/DO Combined $B_s \to J/\psi\ \phi$

PRELIMINARY



Variation allowed by $\Delta\Gamma_s = 2|\Gamma_{12}|\cos\phi_s$ i.e. CPV in the Interference between mixing and decay amplitudes.

CPV in Semi-leptonic B_s Decays?

$$\mathcal{A}_{\rm SL}^{s} = \frac{N(\bar{B}_s^0(t) \to \ell^+ \nu_\ell X) - N(B_s^0(t) \to \ell^- \bar{\nu}_\ell X)}{N(\bar{B}_s^0(t) \to \ell^+ \nu_\ell X) + N(B_s^0(t) \to \ell^- \bar{\nu}_\ell X)} = \frac{|p/q|_s^2 - |q/p|_s^2}{|p/q|_s^2 + |q/p|_s^2}$$

$$|q/p|^2 \neq 1$$

CP violation in mixing

Experimentally, fit to:

Need flavor tagging

Unmixed

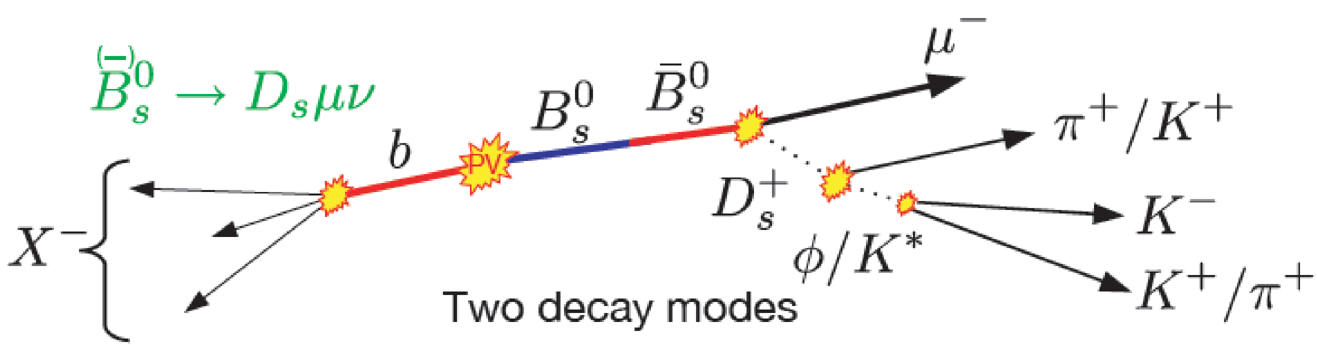
$$\left.\begin{array}{l}\Gamma(B_s^0 \to \mu^+ X) \\ \Gamma(\bar{B}_s^0 \to \mu^- X)\end{array}\right\} \propto \exp(-\Gamma_s t)[\cosh(\Delta\Gamma_s t/2) + \cos(\Delta m_s t)]$$

Mixed

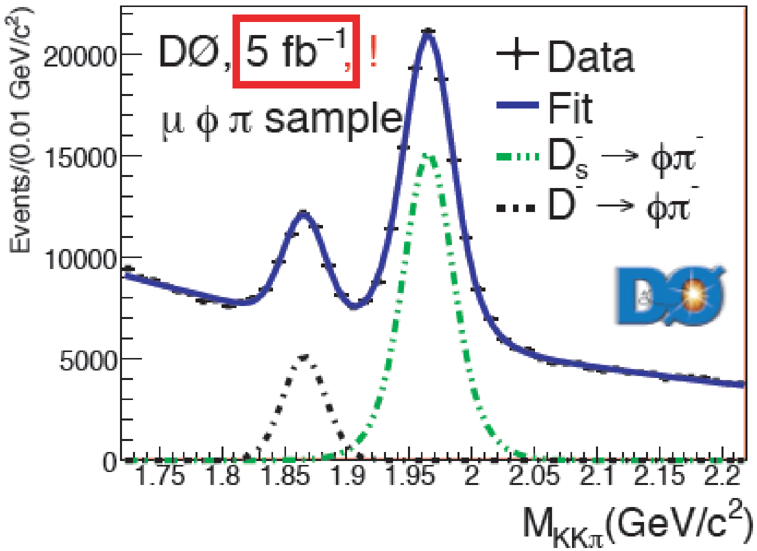
$$\Gamma(\bar{B}_s^0 \to \mu^+ X) \propto (1 + \mathcal{A}_{\rm SL}^{s}) \exp(-\Gamma_s t)[\cosh(\Delta\Gamma_s t/2) - \cos(\Delta m_s t)]$$

$$\Gamma(B_s^0 \to \mu^- X) \propto (1 - \mathcal{A}_{\rm SL}^{s}) \exp(-\Gamma_s t)[\cosh(\Delta\Gamma_s t/2) - \cos(\Delta m_s t)]$$

Flavor tag

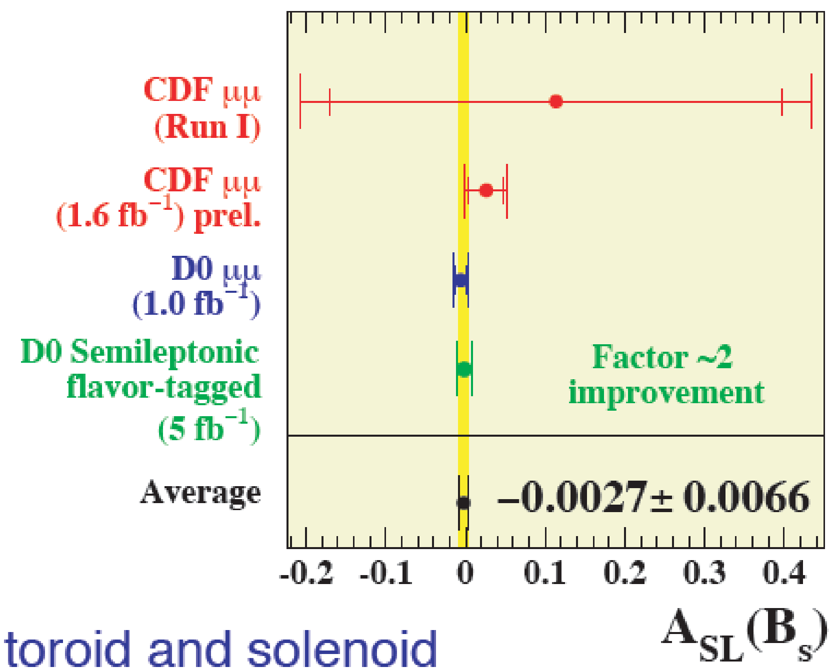


CPV in Semi-leptonic B_s Decays?

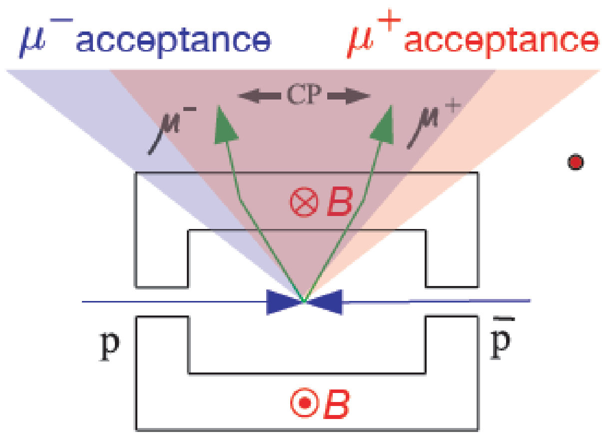


arXiv:0904.3907, sub. to PRL

$$\mathcal{A}_{\rm SL}^{s} = -0.0017 \pm 0.0091^{+0.0012}_{-0.0023}$$



- ~115k total $\overset{(-)}{B}{}^0_s \to D_s \mu\nu$ decays



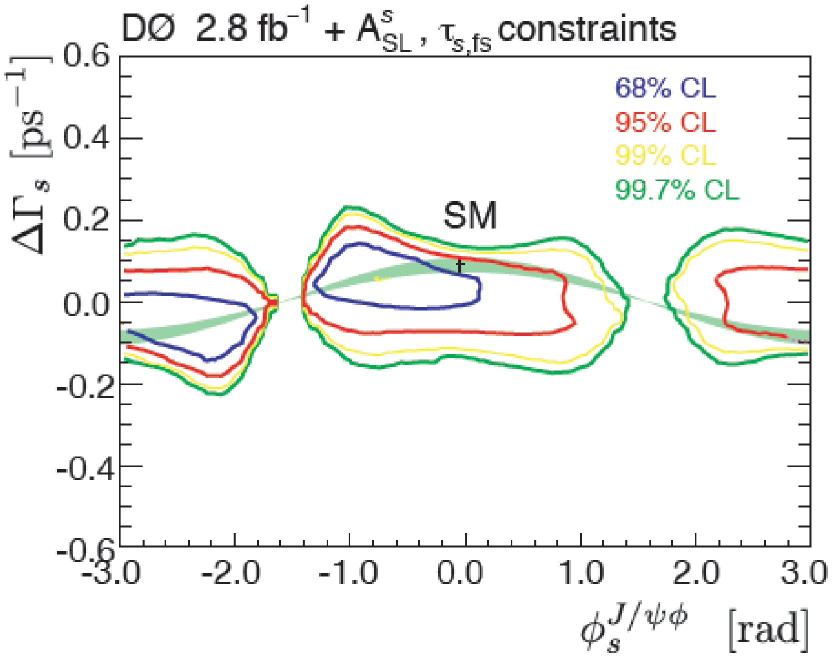
- DØ toroid and solenoid polarities flipped regularly; control & measure detector asymmetries (and then correct, some as large as 3%)

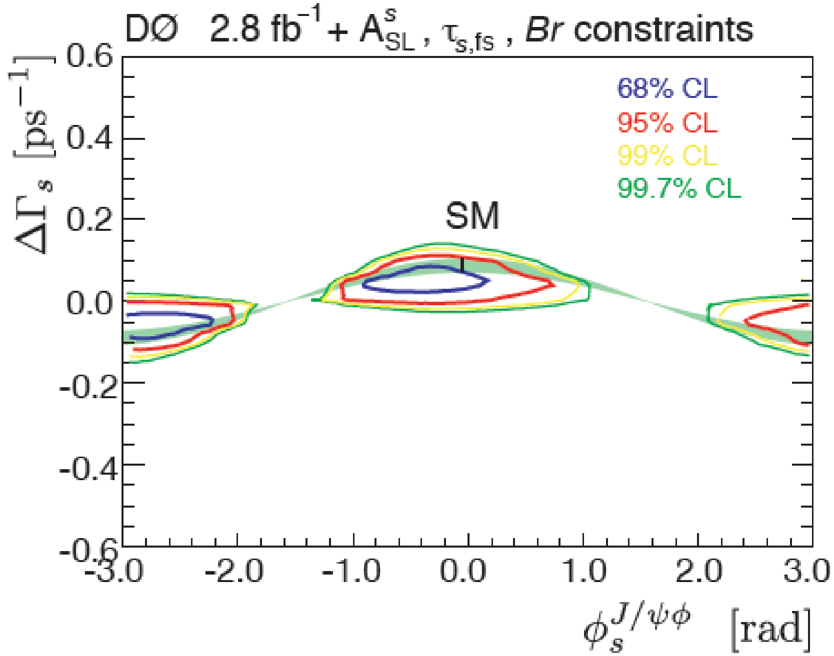
Flavor Specific B_s Lifetime DØ

$$\tau(B_s^0)_{\rm fs} = \frac{1}{\Gamma_s} \frac{1 + \left(\frac{\Delta\Gamma_s}{2\Gamma_s}\right)^2}{1 - \left(\frac{\Delta\Gamma_s}{2\Gamma_s}\right)^2}$$

DØ: Phys. Rev. Lett. 102, 091801 (2009)
(shown as special talk S.Youn last Users' Mtg.)

$$\mathcal{B}(B_s^0 \to D_s^{(*)+} D_s^{(*)-}) = 0.035 \pm 0.015$$



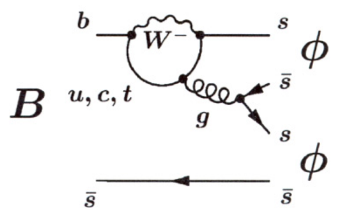


- World average value of B_s^0 flavor-specific lifetime of 1.456 ± 0.030 ps (HFAG) (50% CP-even, 50% CP-odd @ t=0)

- p-value of SM point = 10%
- Again, goal to combine w/ CDF

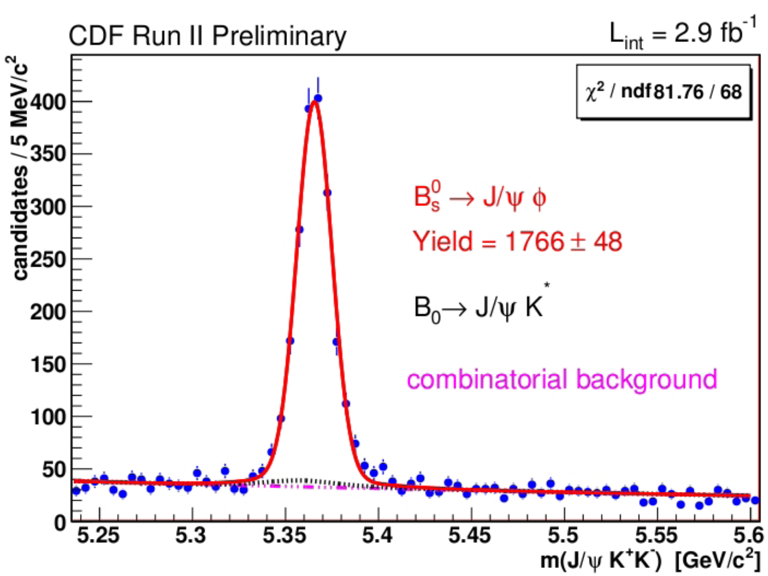
CDF BR($B_s \Rightarrow \phi\,\phi$) Preliminary

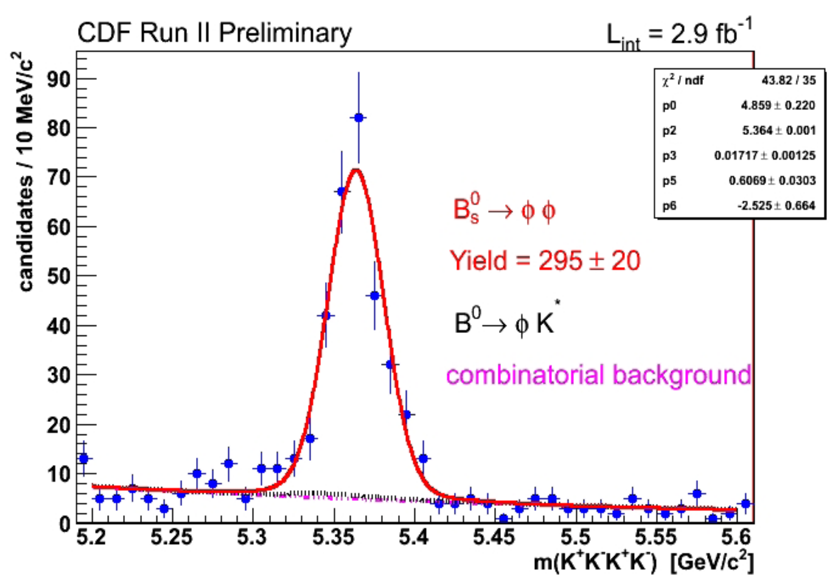
The measurement consists in the evaluation of the ratio:



$$\frac{BR(B_s \to \phi\phi)}{BR(B_s \to J/\psi\,\phi)} = \frac{N_{\phi\phi}}{N_{J/\psi\,\phi}} \bullet \frac{\varepsilon(B_s \to J/\psi\,\phi)}{\varepsilon(B_s \to \phi\phi)} \bullet \frac{BR(J/\psi \to \mu\mu)}{BR(\phi \to KK)} \bullet \varepsilon_{\mu}$$

$$= [1.78 \pm 0.14(stat.) \pm 0.20(syst.)] \bullet 10^{-2}$$





The data plus additional integrated luminosity will be analyzed for B_s mixing and CPV studies.

http://www-cdf.fnal.gov/physics/new/bottom/090618.blessed-Bsphiphi2.9/

Conclusions

- Measurements by CDF/D0 of B_s mixing parameters: Γ_H, Γ_L, Γ_s, $\Delta\Gamma_s$ vs. β_s with good D0/CDF agreement for integrated luminosity of 2.8 fb^{-1} (each experiment).
- Combined result for likelihood contours in $\Delta\Gamma_s$ vs. β_s show the most likely result is ~ 2σ from the SM prediction. Stay tuned!
- D0 measurement of the semi-leptonic flavor specific asymmetry for $B_s \to D_s \mu \nu X$, $\mathcal{A}^s_{\rm SL} = -0.0017 \pm 0.0091^{+0.0012}_{-0.0023}$
  This reduces the world average to $(-2.7 \pm 6.6) \times 10^{-3}$ compared to the SM prediction of $(2.1 \pm 0.57) \times 10^{-5}$.
- CDF has a preliminary measurement of:
  $BR(B_s \to \phi\,\phi) / BR(B_s \to J/\psi\,\phi) = (1.78 \pm 0.14 \pm 0.20) \times 10^{-2}$
  Implies a future CPV angular analysis.

-1

Outlook

- Present integrated luminosity: $6.1fb^{-1}/6.8fb^{-1}$; $2.8fb^{-1}$ just reported.
- D0/CDF Fermilab have asked to run through 2011.
- Should get to $10fb^{-1}$ if nothing breaks and Fermilab gets enough operating money.
- And LHC stays on a good schedule!

Comment!

Thanks to MSU and all participants for a very good meeting!

The End