Looking for Large CP Violation in $B_s^0 \to J/\psi\phi$ Decays

Khaldoun Makhoul

SLAC Experimental Seminar
February 21st 2008

Overview

- *CP* Violation:
  - Standard model
  - $B_s^0 \to J/\psi\phi$
- Measurement:
  - CDF Detector
  - Data Sample & Selection
  - Angular Analysis
  - Flavor Tagging
  - Likelihood Expression
- Results
  - Untagged Analysis
  - Tagged Analysis

CP Violation in the Standard Model

Quark weak flavor eigenstates related to mass eigenstates by CKM Matrix:

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

Wolfenstein parametrization expanded in $\lambda \approx 0.23$, up to λ^5, $V_{CKM} =$

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

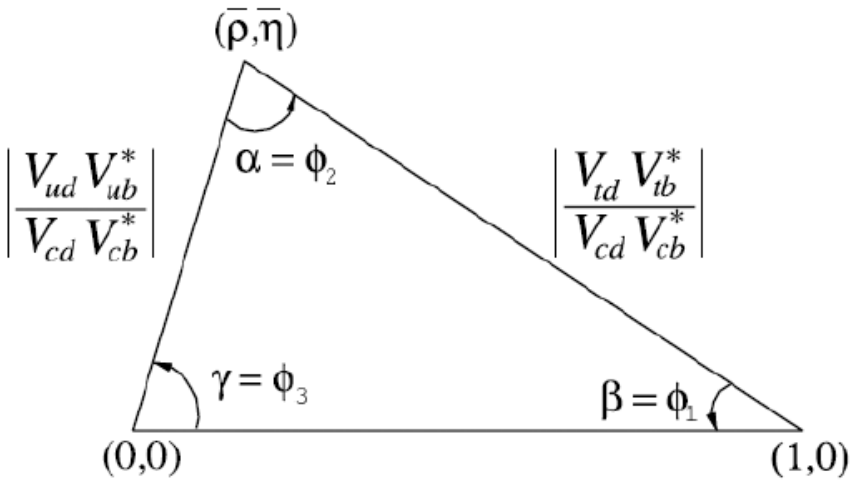
CP violation enters into elements in red. Controlled by one parameter in SM, η

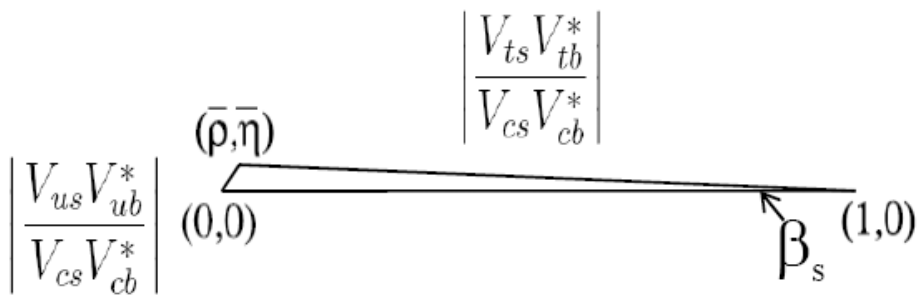
Unitarity Triangles

... or how to get from one SM parameter to a very rich phenomenology.

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

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





- Sides & interior angles can be independently measured
- Goal: to “overconstrain” the triangles
- Hope: that no single choice of CKM parameters will fit all measurements

Selective Review of *CP* Violation Measurements

Discovery of *CP* violation:

- 1964: $K^0_L \to 2\pi$ decay, asymmetry in $K^0 - \overline{K^0}$ mixing

Since then, the standard model description has been (too) successful:

1988, '99	$K^0_{S/L} \to 2\pi^0, \pi^+\pi^-$	Direct *CPV* in decay	NA31, KTeV
2001	$B^0_d \to J/\psi K^0_S$	*CPV* in $B^0_d - \overline{B^0_d}$ mixing	BaBar, Belle
2005, '06	$B^+ \to K^+\rho^0$	Direct *CPV* in decay	BaBar, Belle
2004, '05, '07	$B^0_d \to K^+\pi^-$	Direct *CPV* in decay	BaBar, Belle, CDF
2007	$B^+ \to J/\psi K^+$	Direct *CPV* in decay	DZERO

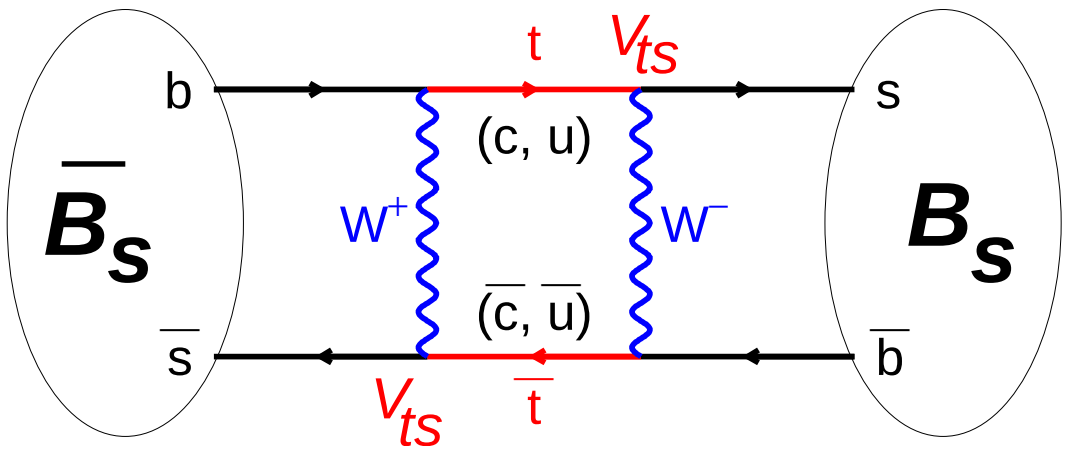
- Success of CKM both from precise determination & agreement, or calculational limitations

"Last hope" for new physics in flavor system: B^0_s decays

- *CP* violation predicted to be very small in Standard Model
- If measured to be otherwise: unambiguous signal for new physics

The Neutral B_s^0 System

"Mixing" of B_s^0 meson refers to $B_s^0 - \overline{B_s^0}$ oscillation, e.g.:



Schröedinger Eq: 2 Masses, Lifetimes

$$i\frac{\partial}{\partial t}\begin{bmatrix} |B_s^0(t)\rangle \\ |\overline{B_s^0}(t)\rangle \end{bmatrix} = \left(\mathbf{M} - \frac{i}{2}\Gamma\right) \times \begin{bmatrix} |B_s^0(t)\rangle \\ |\overline{B_s^0}(t)\rangle \end{bmatrix}$$

$$|B_{L,H}(t)\rangle = p|B_s^0\rangle \pm q|\overline{B_s^0}\rangle\ ,\ q/p = \frac{V_{tb}V_{ts}^*}{V_{tb}^*V_{ts}}$$

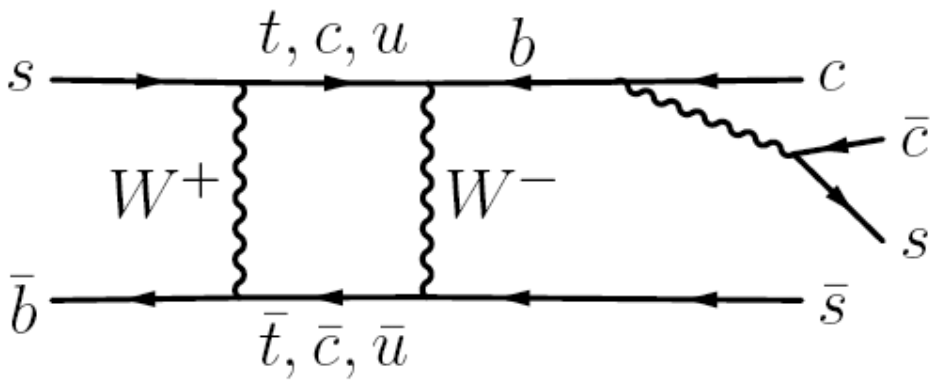
$$\Delta m_s \approx 2\,|M_{12}|$$

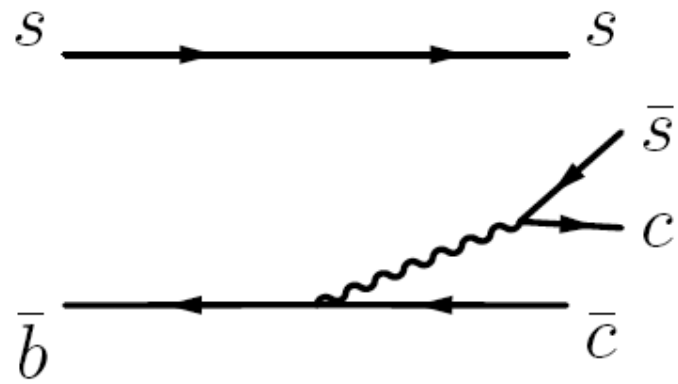
$$\Delta\Gamma_s \approx 2\,|\Gamma_{12}|\cos(\phi_s)$$

$$\phi_s^{SM} = \arg(-M_{12}/\Gamma_{12}) \approx 4\times 10^{-3}$$

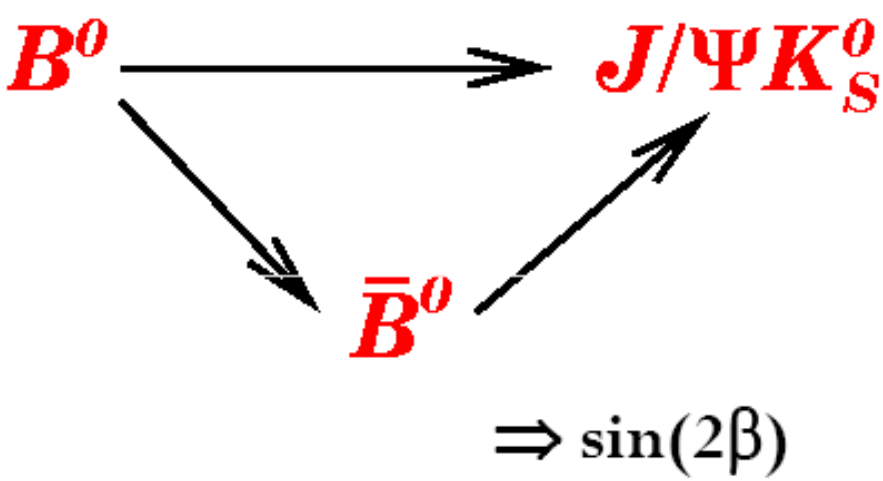
$$\beta_s^{SM} = \arg(-V_{ts}V_{tb}^*/V_{cs}V_{cb}^*) \approx 0.02$$

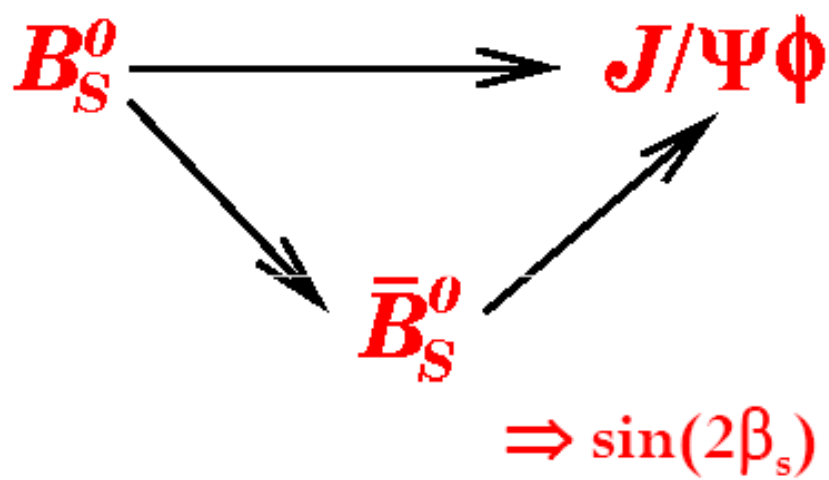
CP Violation in $B_s^0 \to J/\psi\phi$





- $J/\psi\phi$ available as a decay for both B_s^0 and $\overline{B_s^0}$
- *CP* violation occurs in the **interference of mixing and decay**
- This is in analogy to the well-studied case of $B_d^0 \to J/\psi K_S^0$

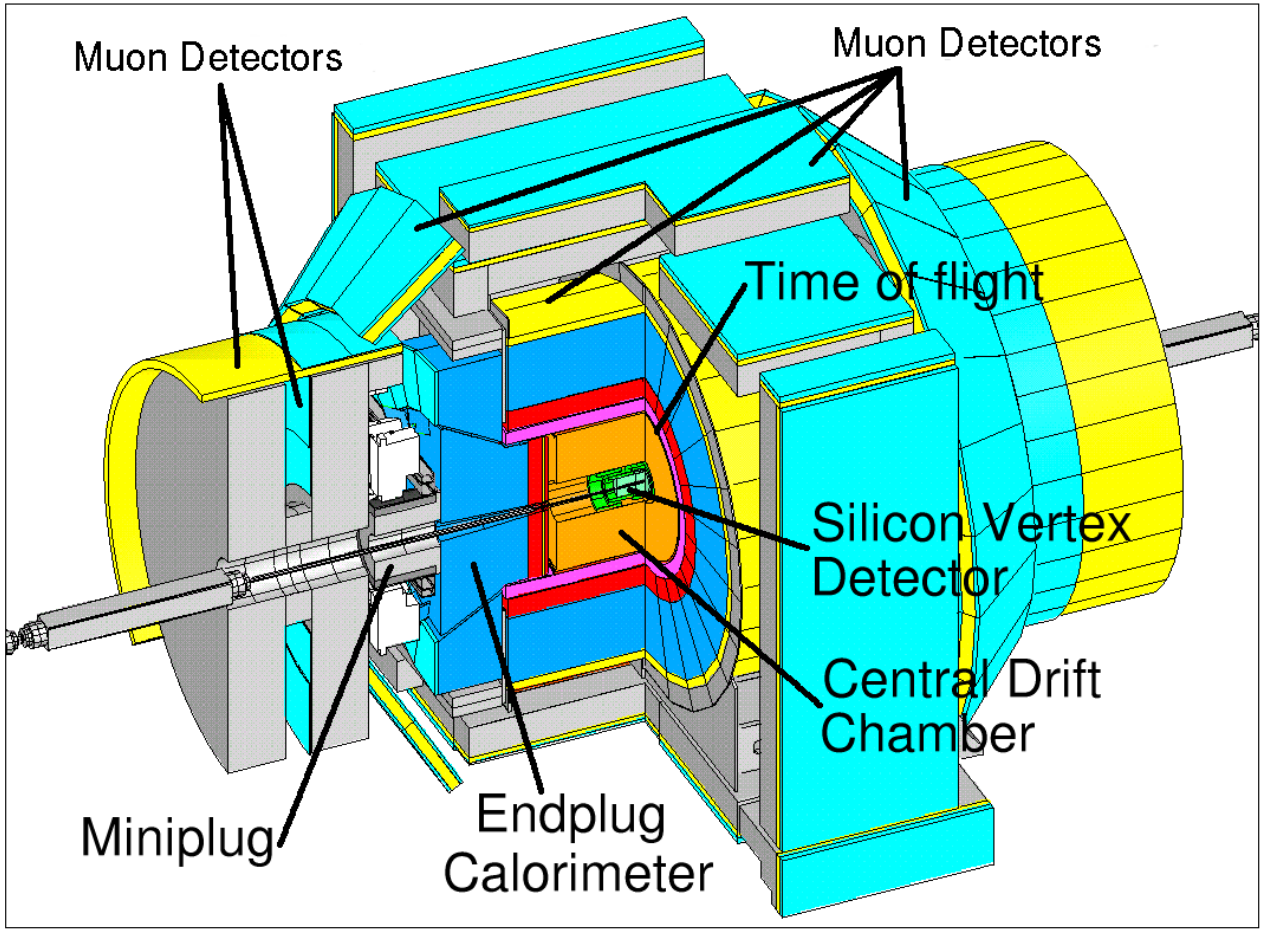




Measurement

- *CP* Violation:
  - Standard model
  - $B_s^0 \to J/\psi\phi$
- Measurement:
  - CDF Detector
  - Data Sample & Selection
  - Angular Analysis
  - Flavor Tagging
  - Likelihood Expression
- Results
  - Untagged Analysis
  - Tagged Analysis

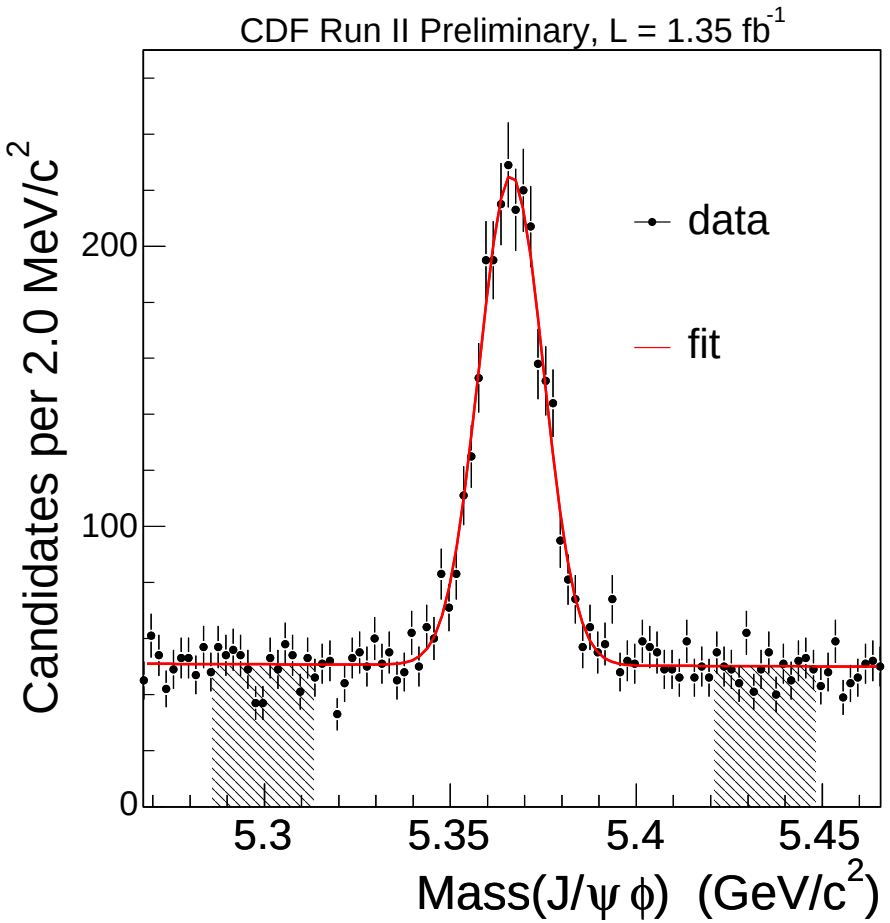
CDF Detector, B Physics Focus



- Silicon SVXII + Layer00:
  - B physics triggers
  - Proper time resolution
- COT drift chamber:
  - Momentum resolution $\sigma_p/p < 0.1\%$
  - dE/dx for particle ID (selection, tagging)
- Time-Of-Flight:
  - Particle ID (selection, tagging)
- Muon det., EM cal:
  - Lepton triggers
  - Lepton ID: tagging

Data Sample and Selection

- Data w/ 1.35fb^{-1}(1.7)
- Di-muon trigger
- Soft precuts followed by neural network selection
- NN Trained on:
  - Simulated events for signal
  - B_s^0 mass sidebands for bkg
- Selection maximizes $S/\sqrt{S+B}$ in signal peak
- ~ 2000 $B_s^0 \to J/\psi\phi$ signal evts



General Analysis Strategy

Reconstruct decays from stable products:

- $B_s^0 \to J/\psi[\mu^+\mu^-]\phi[K^+K^-]$
- $B_d^0 \to J/\psi[\mu^+\mu^-]K^*[K^+\pi^-]$
- With B_d^0 as control sample

Identify $B_s^0/\overline{B_s^0}$

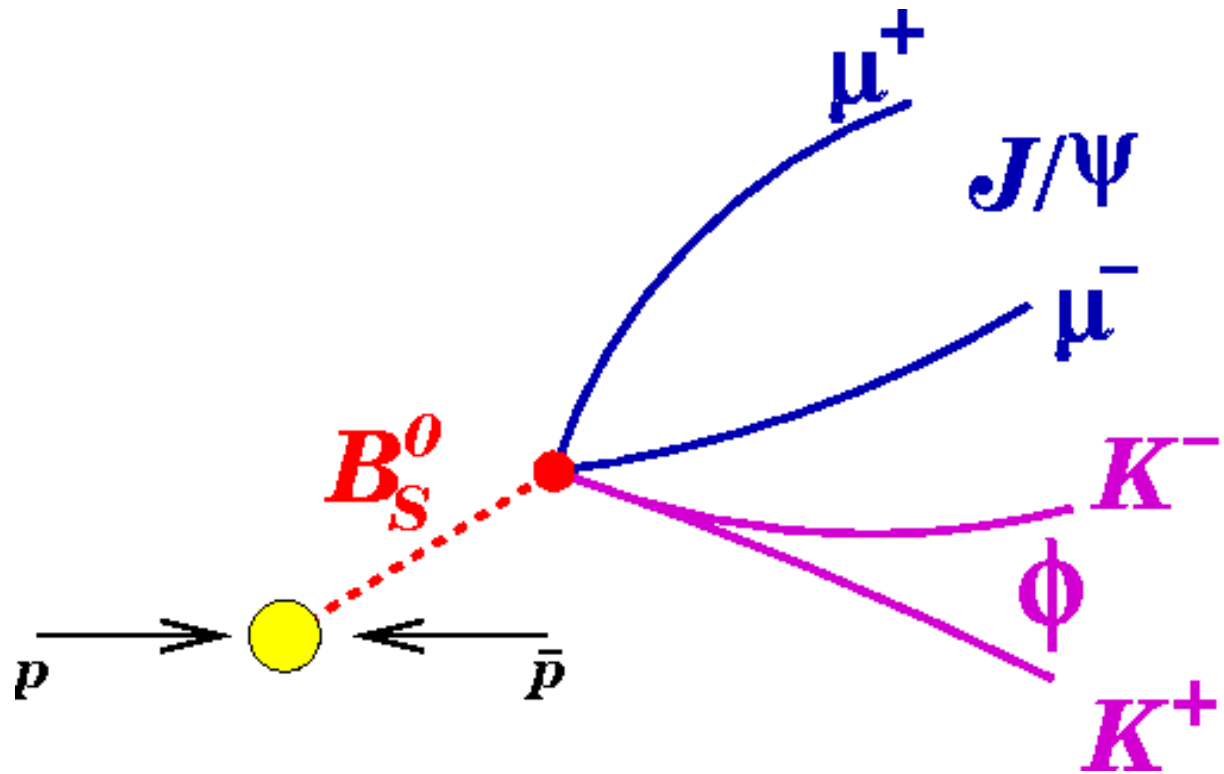
- Flavor tagging

Event variables:

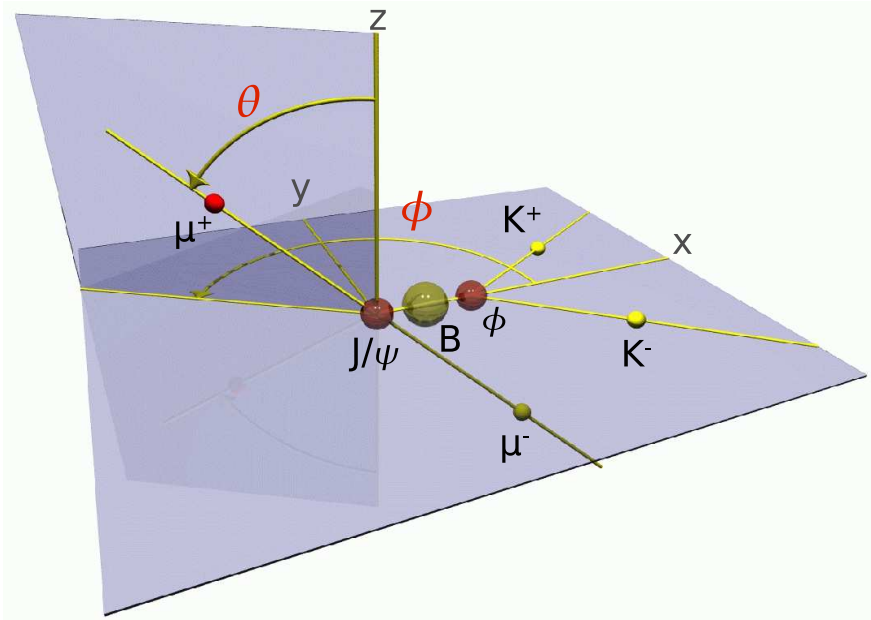
- Mass
- Lifetime $ct = m_B L_{xy}/p_T$
- $\vec{\rho} \equiv \theta_T, \phi_T, \psi_T$
- Tag decision ξ

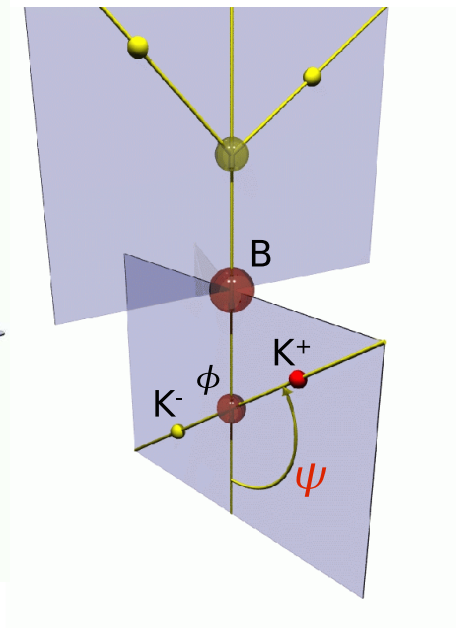
Perform maximum likelihood fit:

- Likelihood in $m, ct, \vec{\rho}, \xi$



$B_s^0 \to J/\psi\phi$ Angular Analysis





Angular momentum:

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

Transversity Basis:

- 3 Angles:
  - θ_T (J/ψ frame)
  - ϕ_T (J/ψ frame)
  - ψ_T (ϕ frame)

- Since $J/\psi\phi$ is C-odd, parity determines CP
- In Transversity basis, polarization of VV:
  - longitudinal (0), transverse and parallel ($\|$) $\to$ *CP*-even
  - transverse and perpendicular ($\perp$) $\to$ *CP*-odd

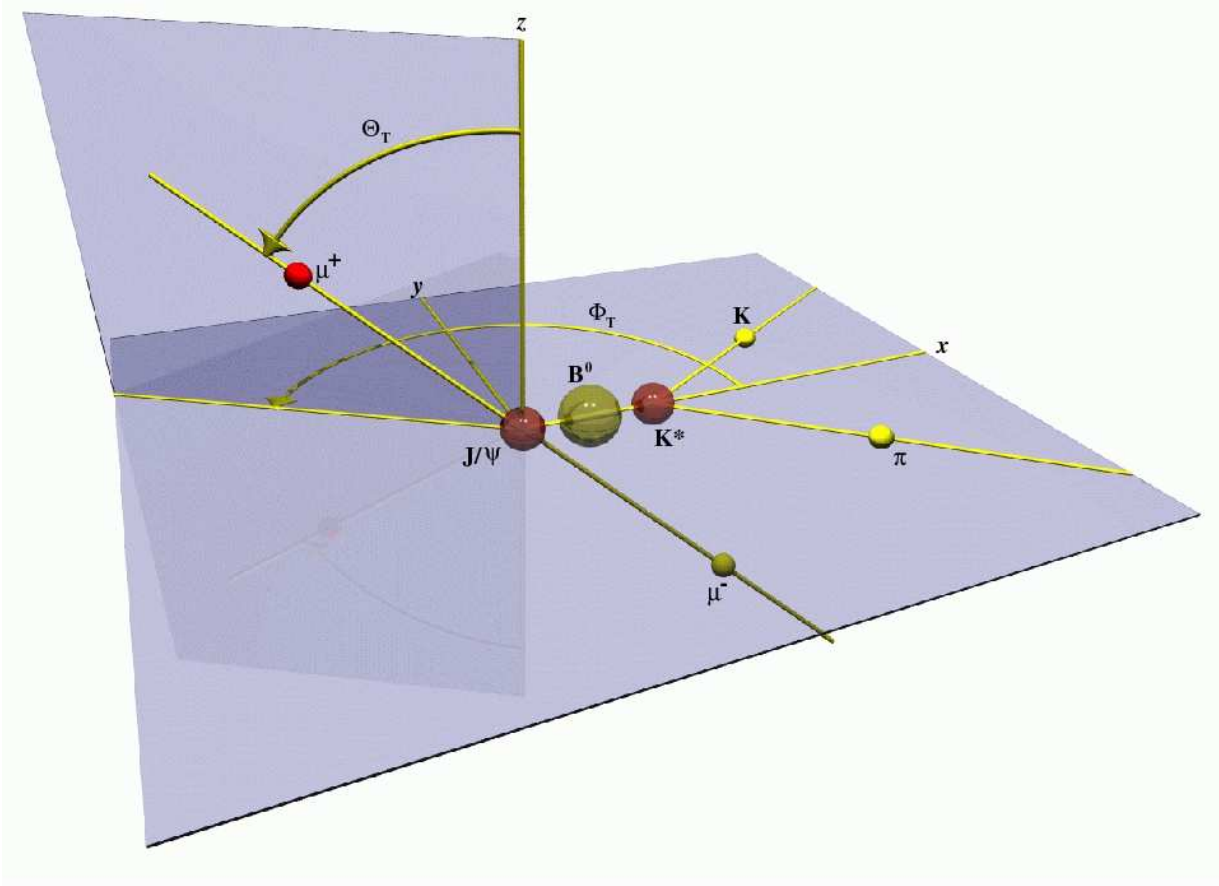
$B_d^0 \to J/\psi K^*$ Angular Analysis

Similar Angular Decay:

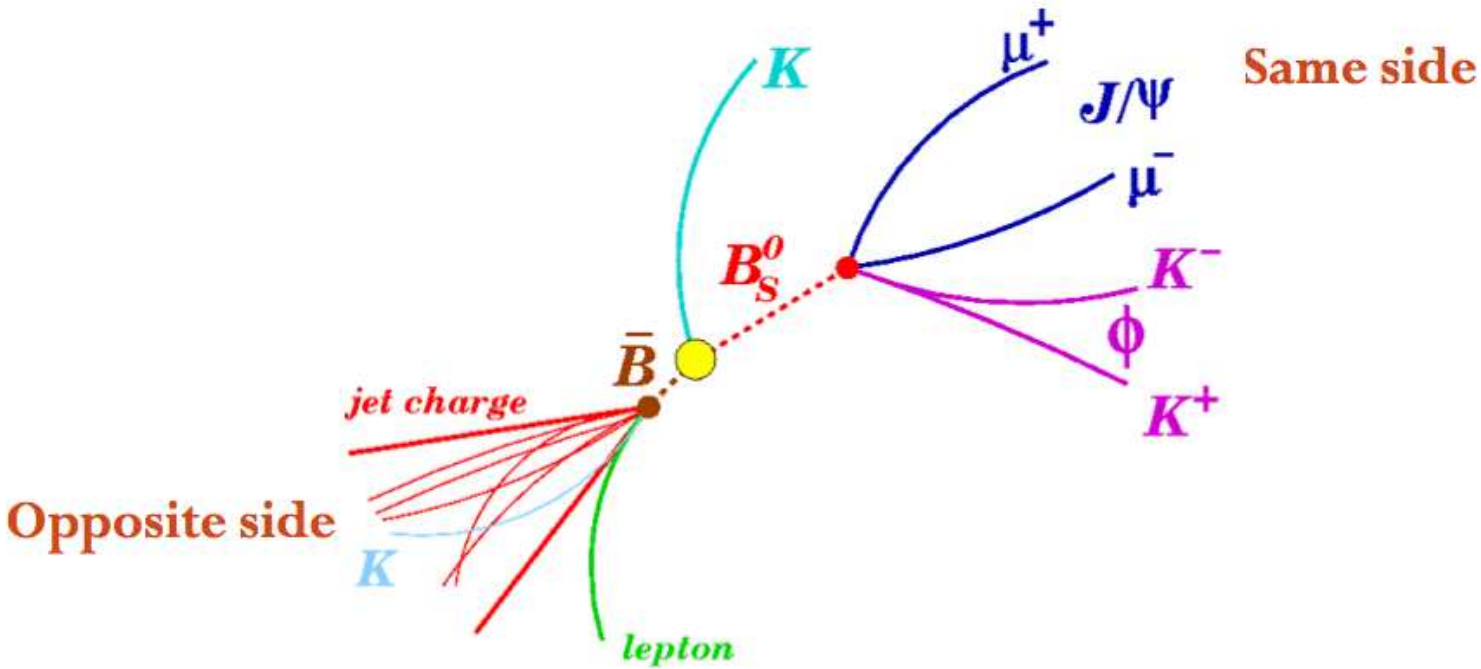
- $P \to VV$
- Similar phase space available

Control:

- Detector efficiency in $\vec{\rho}$
- Measure $|A_0|$, $|A_{\parallel}|$, $|A_{\perp}|$



Flavor Tagging



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

Opposite Side Flavor Tagging

Exclusive algorithms:

Soft Lepton Tagger

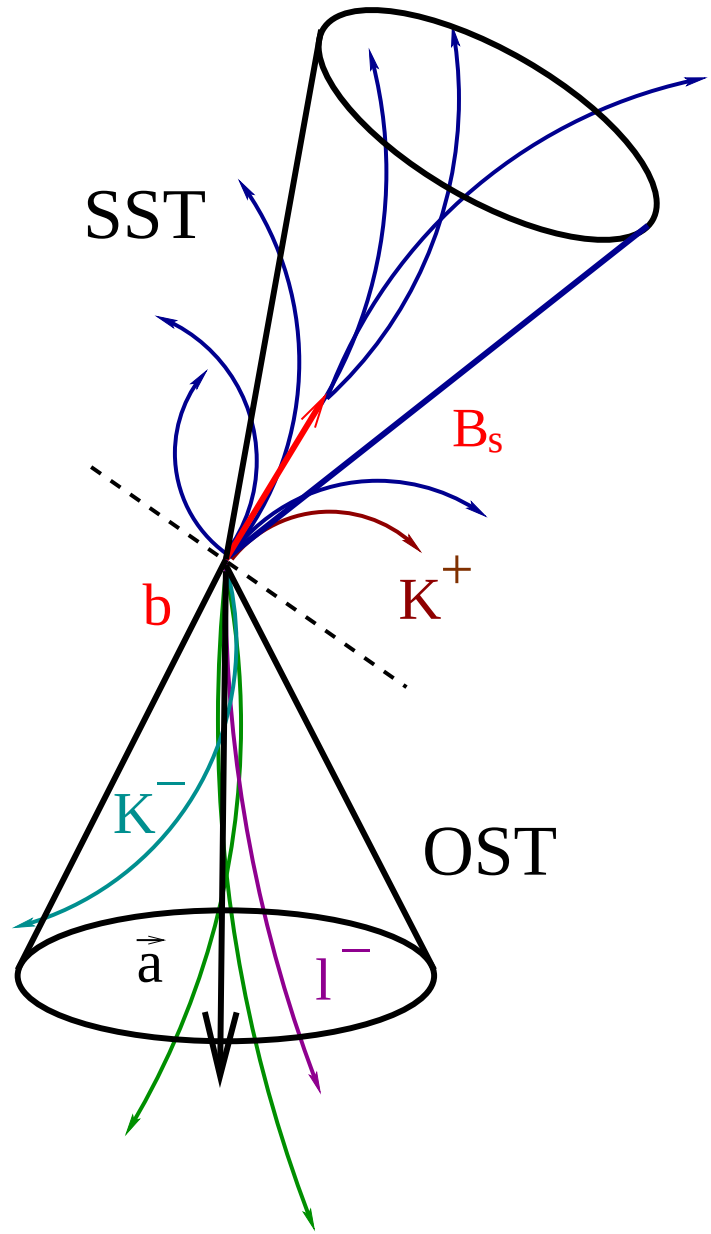
- look for semileptonic B decay on OS
- lepton charge indicates *b*-flavor
- μ, e tagger

Jet Charge Tagger

- look for jet or secondary vertex on OS
- jet charge indicates *b*-flavor

Performance

- Efficiency: $\varepsilon = 0.96 \pm 0.01$
- Avg Dilution: $\mathcal{D} = 0.11 \pm 0.02$



Same Side Flavor Tagging

Most Powerful Tagger:

Fragmentation Track

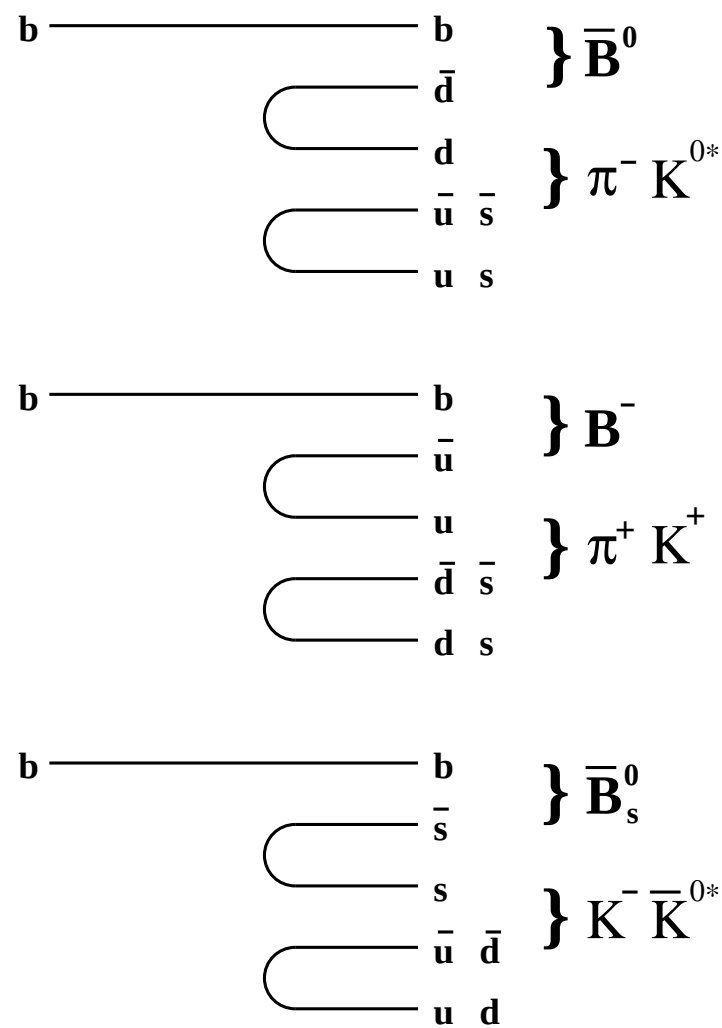
- Look for Kaon assoc. w/ B_s^0 production
- Use TOF & COT for $\pi - K$ separation

Calib using Monte Carlo

- B_s^0, B_d^0, B^+ different
- Use PYTHIA simulation

Performance

- Efficiency: $\varepsilon = 0.50 \pm 0.01$
- Avg Dilution: $\mathcal{D} = 0.27 \pm 0.04$



Likelihood for Decay to $J/\psi\phi$ (1/3)

$B_s^0/\overline{B_s^0} \to J/\psi\phi$ differential decay rates depend on 4 event variables:

- ct: Proper decay length
- $\vec{\rho}$: vector formed by the 3 angles that characterize the decay
- ξ: tag decision ($+1 \to B_s^0$, $-1 \to \overline{B_s^0}$, $0 \to$ no tag)

... and quite a few parameters describing the physics

- $|A_\alpha|$, $\alpha = 0, \|, \perp$: amplitudes for decay to longitudinal, parallel (both *CP*-even), or perpendicular (*CP*-odd) polarizations of J/ψ, ϕ

- δ_α: Phases associated with those amplitudes
- $\Gamma, \Delta\Gamma$: Average lifetime and lifetime difference

$$P(ct, \vec{\rho}|\xi) = \frac{1+\xi\mathcal{D}}{1+|\xi|} \cdot P_{\mathrm{B}}(ct, \vec{\rho}) + \frac{1-\xi\mathcal{D}}{1+|\xi|} \cdot P_{\overline{\mathrm{B}}}(ct, \vec{\rho})$$

Likelihood for Decay to J/$\psi\phi$ (2/3) (KM: WILL CHANGE)

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

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 due to initial state flavor tagging

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

'strong' phases:

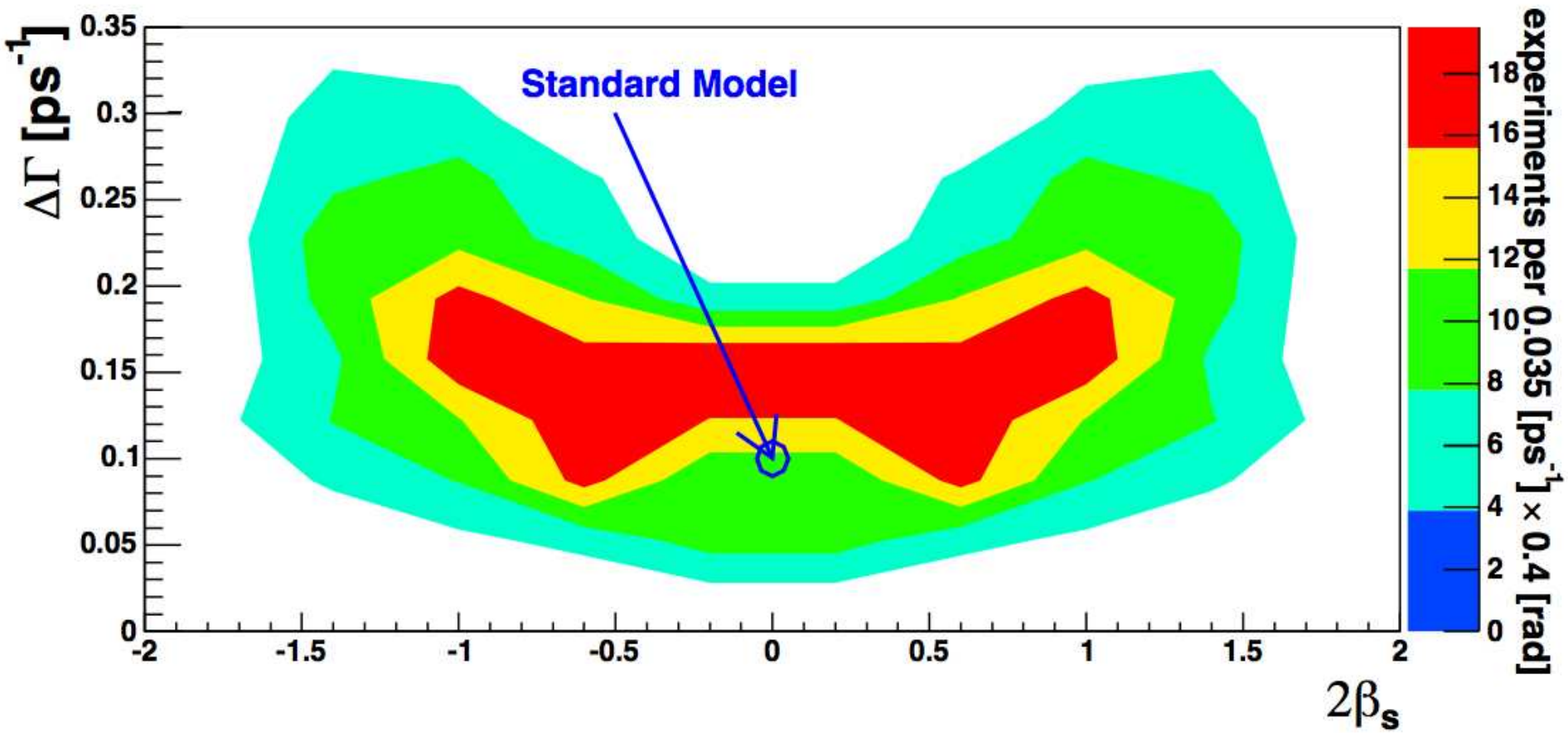
$$\delta_{\|} \equiv \arg(A_{\|}^* A_0)$$
$$\delta_\perp \equiv \arg(A_\perp^* A_0)$$

Likelihood for Decay to $J/\psi\phi$ (3/3)

Difficulties arise

- Likelihood exhibits symmetry to following transformation:
  - $2\beta_s \to \pi - 2\beta_s$
  - $\Delta\Gamma \to -\Delta\Gamma$
  - $\delta_{\|} \to 2\pi - \delta_{\|}$
  - $\delta_{\perp} \to \pi - \delta_{\perp}$
- When β_s is small, we get effective loss of degrees of freedom
  - We see biases in straightforward max. likelihood fit
  - The biases are input parameter dependence
  - The uncertainties are input parameter dependence
- These problems go away with very large statistics, but not for our sensitivity
- This will motivate later discussion of confidence interval technique

Example of Fit Difficulties (Tagging Turned Off)



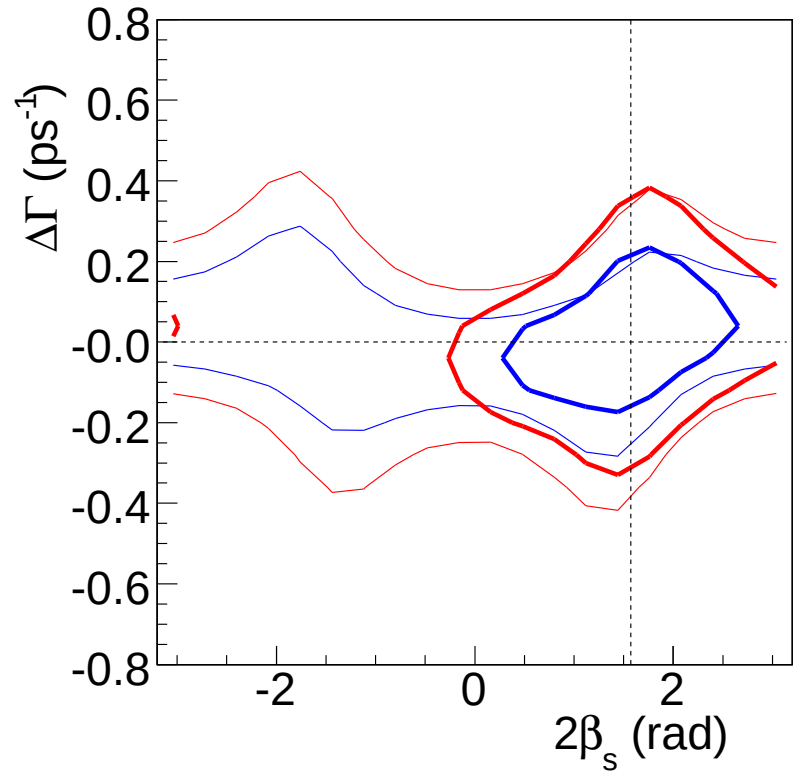
- Toy study with $\Delta\Gamma - \beta_s$ generated at SM values
- Plotting result of fit in 2D plane

Effect of Flavor Tagging on Symmetries, etc

Separate time evolution of mesons produced as B_s^0 or $\overline{B_s}$. Utility:

Three ways to think of utility of flavor-tagging:

- In short: $B_s^0/\overline{B_s}$ differential decay rates $\frac{dP}{dt d\vec{p}}(t, \vec{p})$ dependent on β_s differently
- Likelihood: with tagging, gain sensitibity 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)
- Visually: Toy MC study comparing 68%, 95% likelihood contours for tagged(thick line) /untagged(thin line) in $\Delta\Gamma - \beta_s$ plane



2D confidence Region Method

- Problems arise from limited sensitivity: biases observed in pseudo-experiments depending on input value of β_s
- We use a likelihood ordering suggested by Feldman and Cousins to estimate a confidence interval
- Calculate a p-value for each point on the $\Delta\Gamma - \beta_s$ plane
- Verify that we have proper coverage in the confidence region for alternative true values of the parameters
- Construct a confidence region rather than quote a point estimate

Systematic Effects

Evaluated for the following

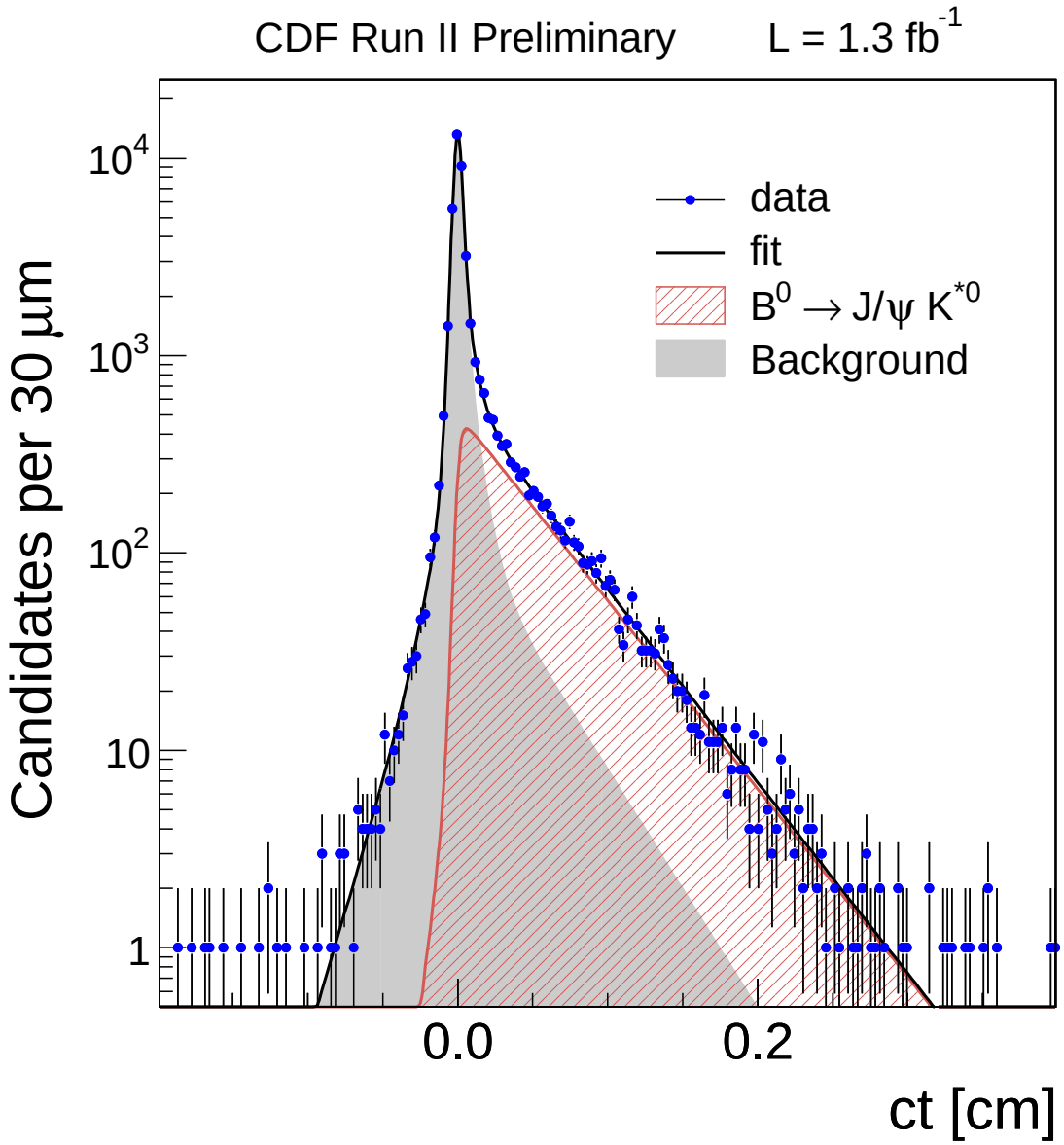
- $B_d^0 \to J/\psi K^*$ decays misreconstructed as B_s^0: $\mathcal{O}(3\%)$ contamination
- Signal mass model
- Lifetime resolution model
- Detector angular acceptance
- Silicon detector alignement

But all are overwhelmed by the confidence region estimation

Results

- *CP* Violation:
  - Standard model
  - $B_s^0 \to J/\psi\phi$
- Measurement:
  - CDF Detector
  - Data Sample & Selection
  - Angular Analysis
  - Flavor Tagging
  - Likelihood Expression
- Results
  - Untagged Analysis
  - Tagged Analysis

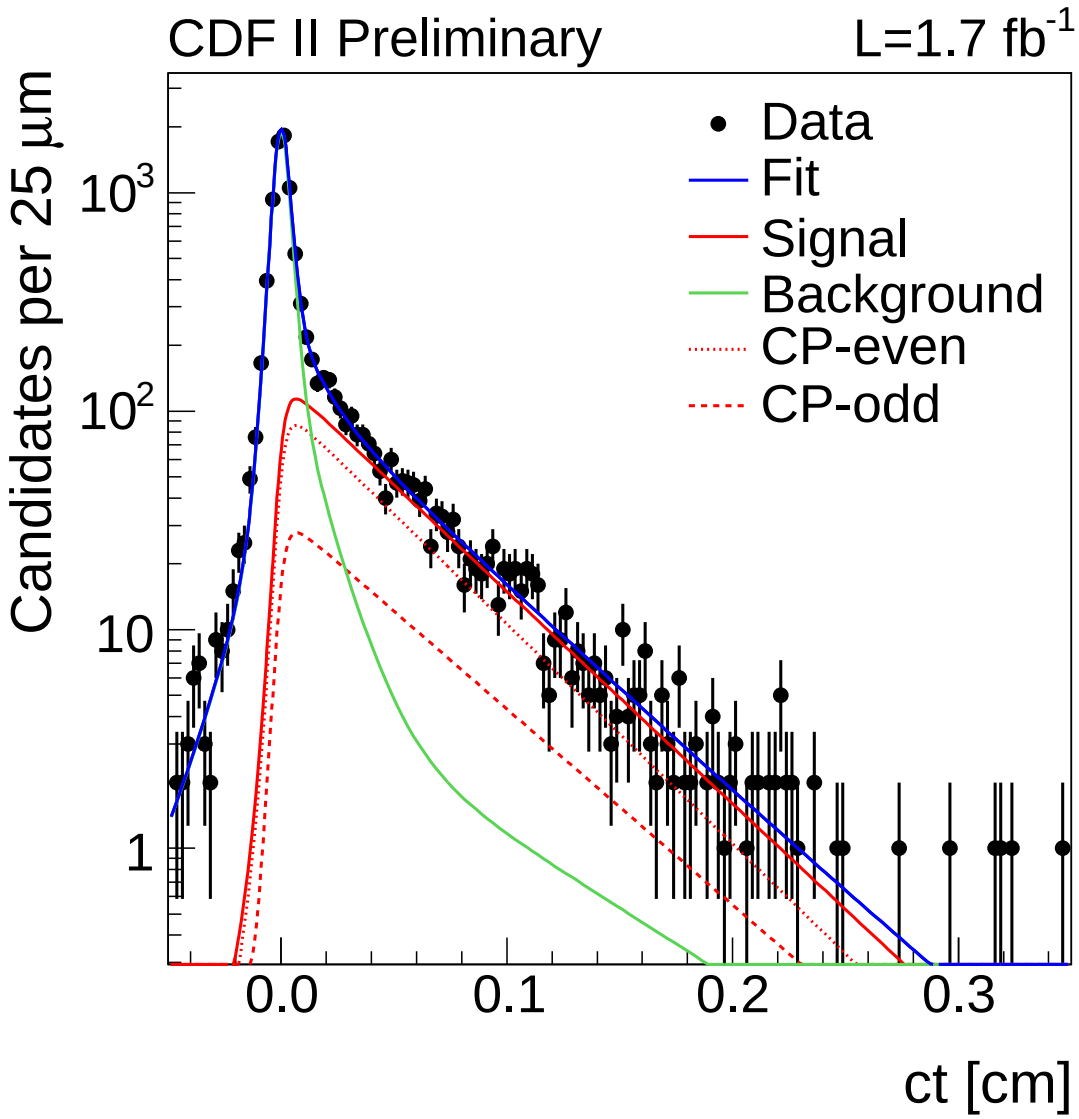
B_d^0 Results: $c\tau$, Angular Parameters



Param = *Val* ± *Stat* ± *Syst*

- $c\tau = 456 \pm 6 \pm 6\ \mu\text{m}$
- $|A_0|^2 = 0.569 \pm 0.009 \pm 0.009$
- $|A_{\|}|^2 = 0.211 \pm 0.012 \pm 0.006$
- $\delta_{\|} = -2.97 \pm 0.08 \pm 0.03$
- $\delta_{\perp} = +2.97 \pm 0.06 \pm 0.01$

B_s^0 Untagged Results: $\Delta\Gamma$, $c\tau$

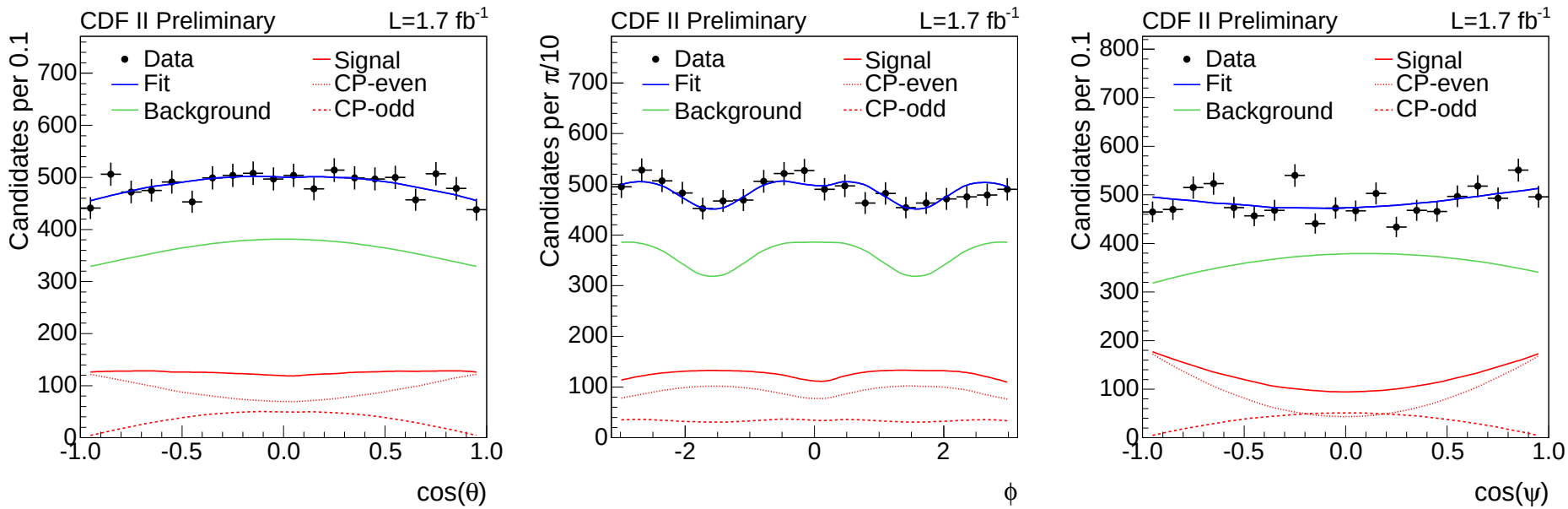


Fixing β_s to 0:

Param = Val ± Stat ± Syst

- $c\tau = 456 \pm 13 \pm 7\ \mu\text{m}$
- $\Delta\Gamma = 0.076^{+0.059}_{-0.063} \pm 0.006\ \text{ps}^{-1}$

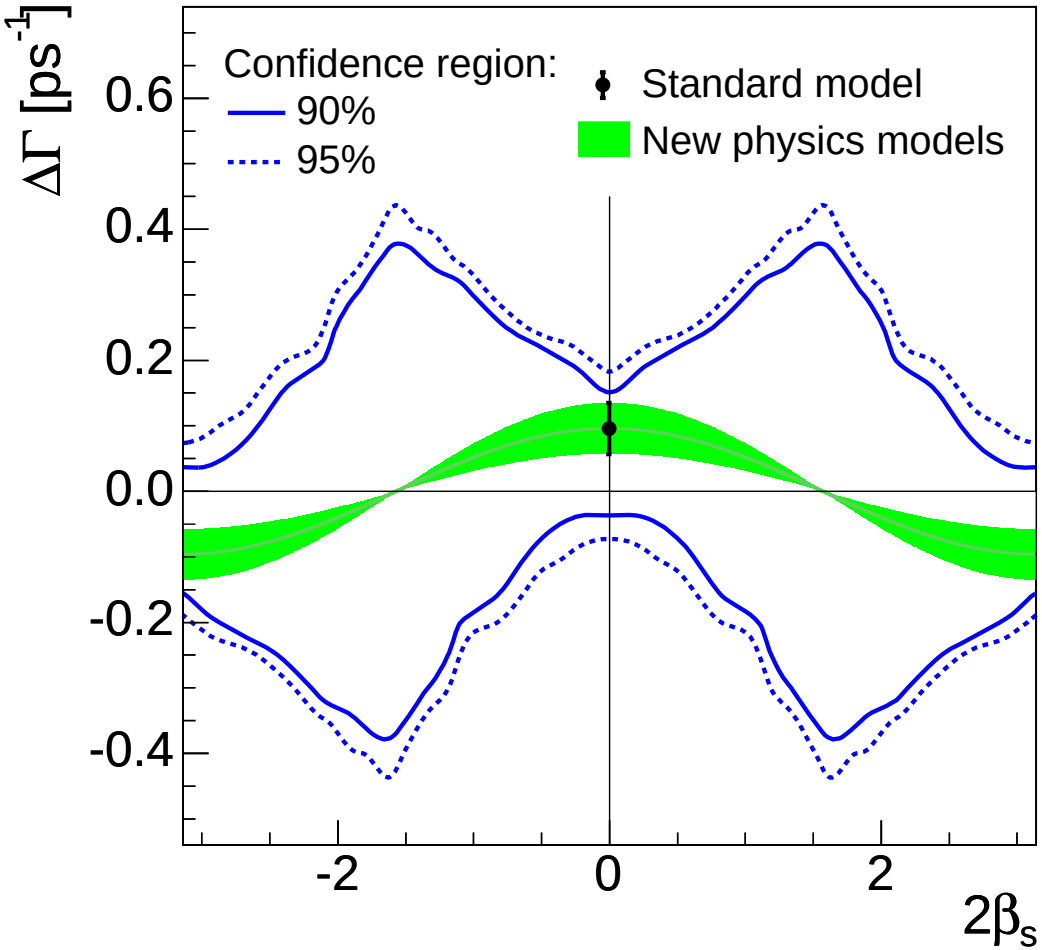
B_s^0 Untagged Results: Angular Parameters



Fixing β_s to 0:

- $|A_0|^2 = 0.531 \pm 0.020 \pm 0.007$
- $|A_{\parallel}|^2 = 0.239 \pm 0.029 \pm 0.011$
- $|A_{\perp}|^2 = 0.230 \pm 0.026 \pm 0.009$

Untagged Results: $\Delta\Gamma - \beta_s$ Confidence Region

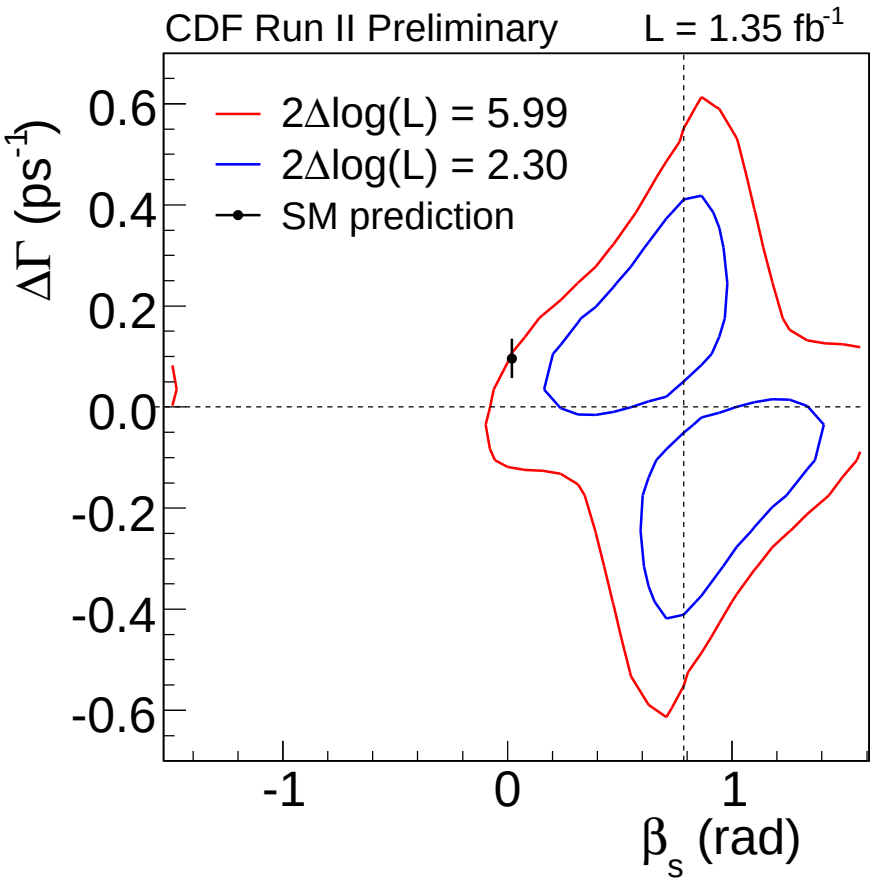


β_s Floating:

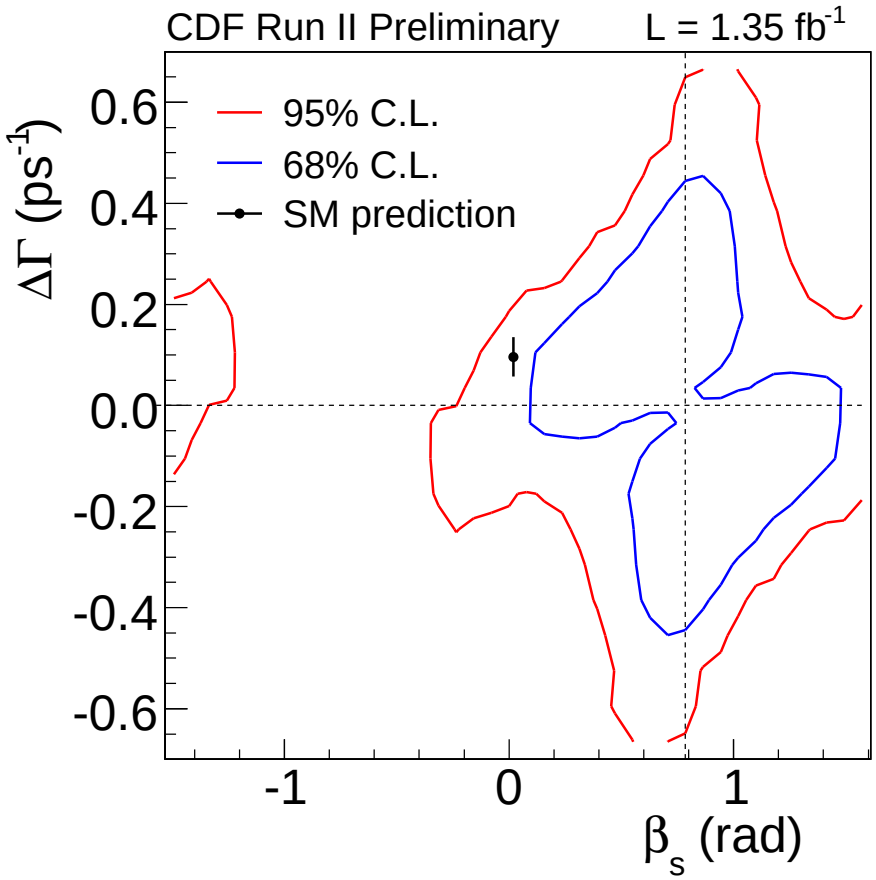
- SM point probability: 22%

Tagged Results: Likelihood & $\Delta\Gamma - \beta_s$ Confidence Region

Likelihood Profile:



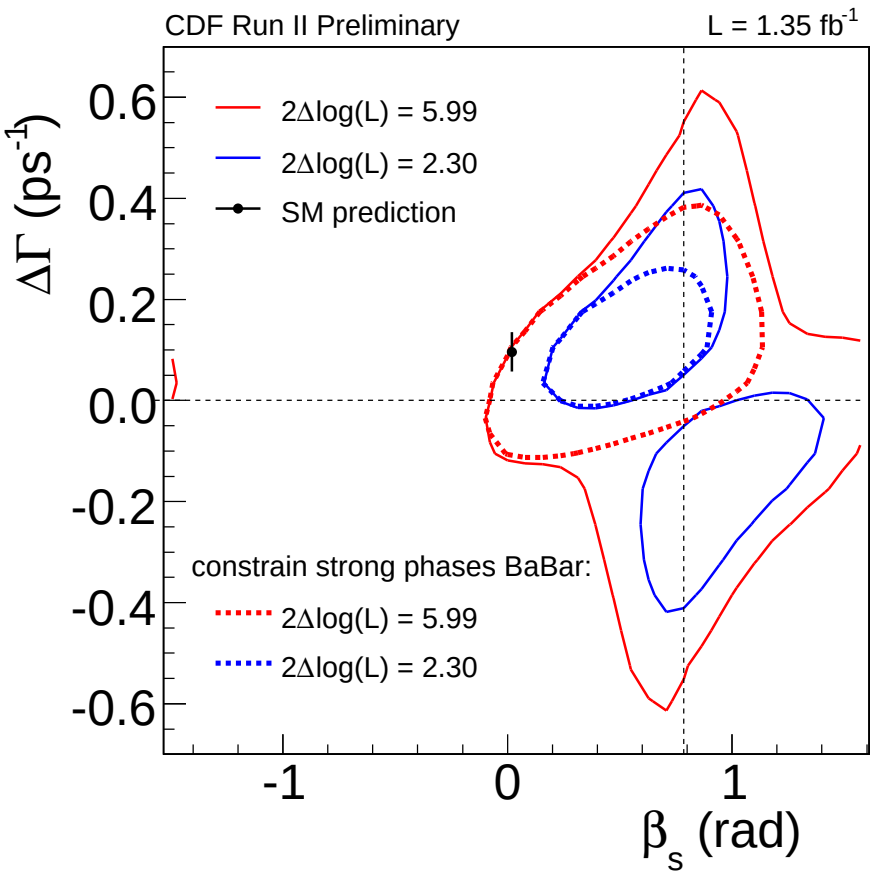
Confidence Region:



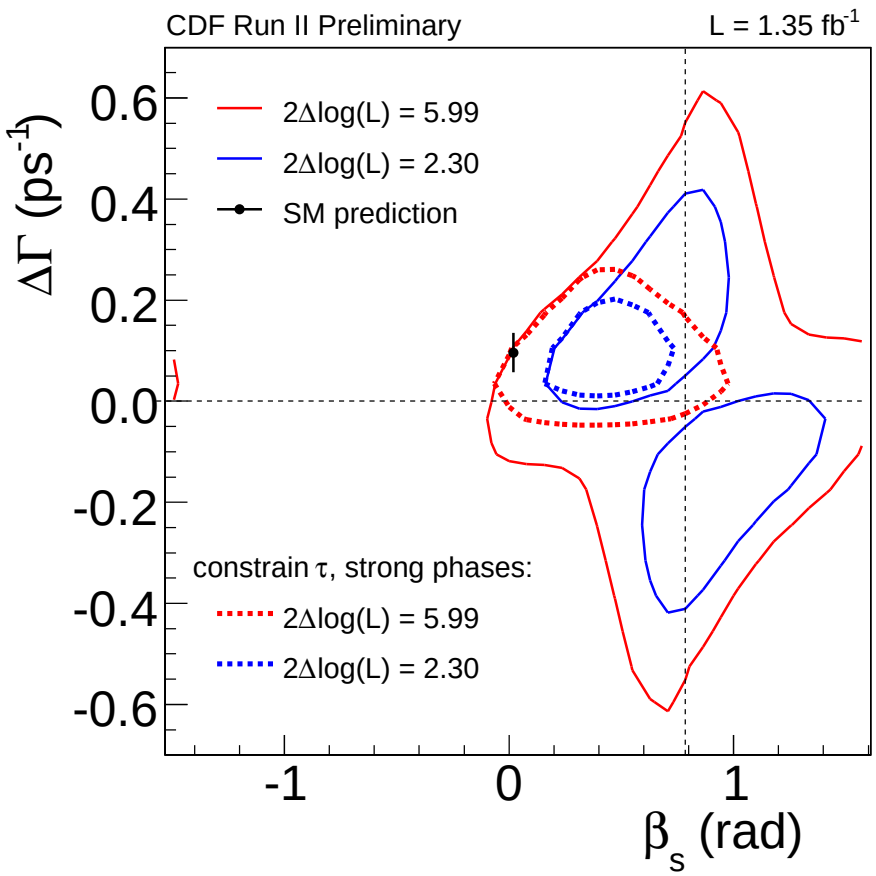
- Assuming SM, we find a probability of a fluctutation as high or higher than what we see in data to be 15%, corresponding to 1.5σ

Tagged Results: β_s with Experimental Constraints

Strong Phases Contrained:

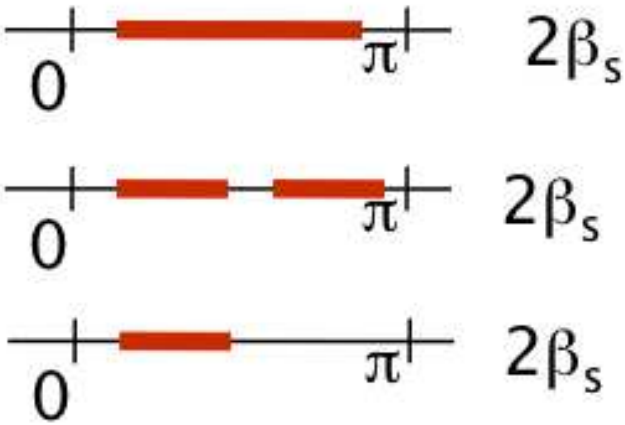


Phases & Lifetime (to B_d^0 $c\tau$):



- Constrained to BaBar results in $B_d^0 \to J/\psi K^*$

Results for β_s: 1-D Confidence Interval, Constraints



If we seek no info on $\Delta\Gamma$, bounding β_s in 1D:

- At 68% C.L. we find $2\beta_s \in [0.32, 2.82]$

Using a theoretical constraint on $|\Gamma_{12}|$:

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

Adding constraint on $\delta_{||}$, $\delta_{\perp}$ from B factories:

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

The latter range is the tightest constraint we can obtain on β_s incorporating all available information

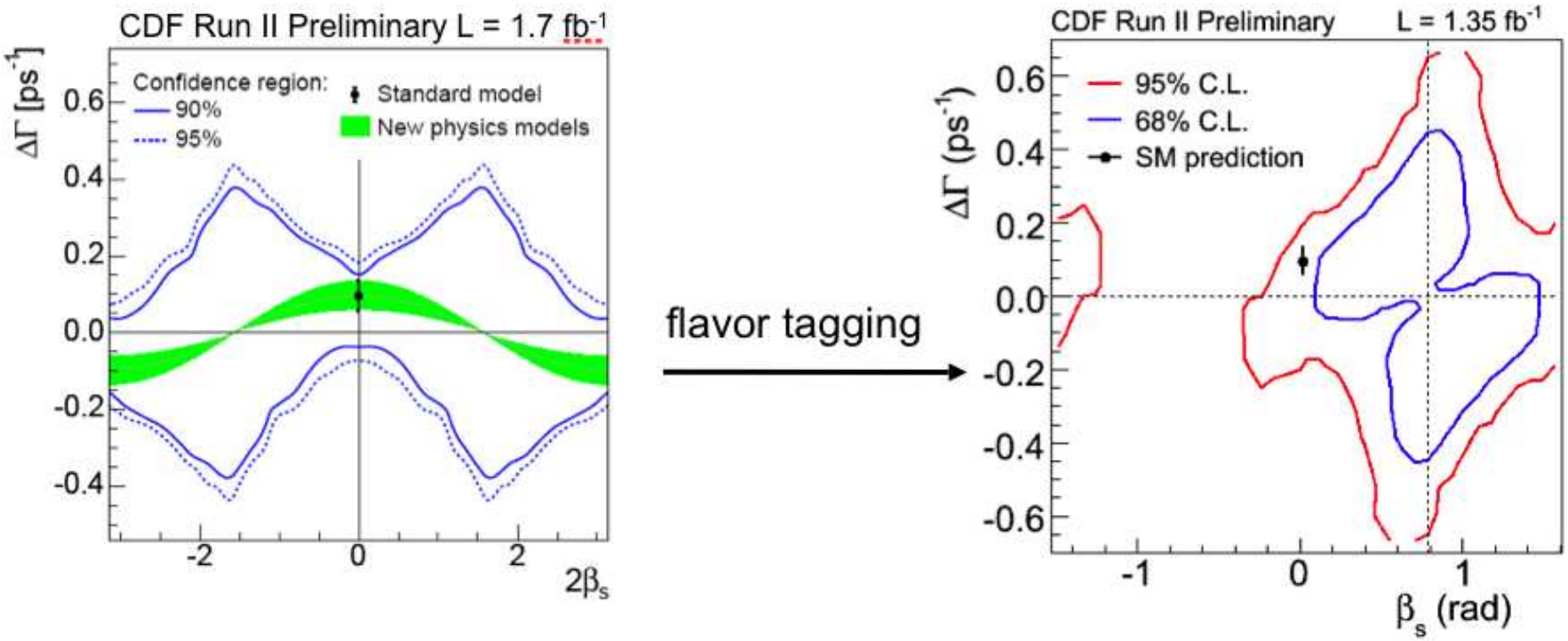
Recent D0 Result

KM: Saw Brand New DZero Result Today! Need to incorporate

Conclusion

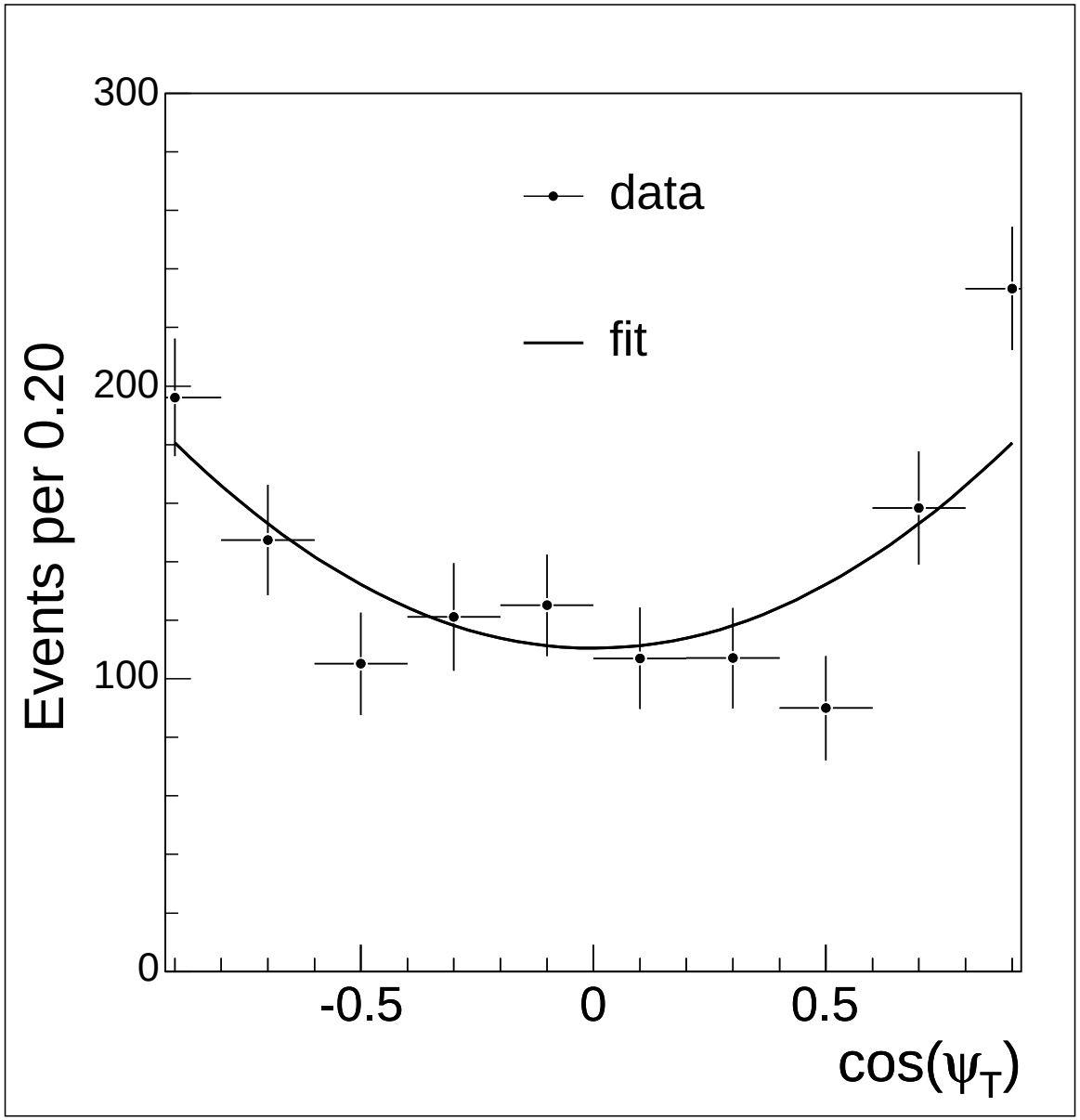
Important result in flavor physics:

- First flavor-tagged measurement of *CP* violating phase in B_s^0 system
- Allowed region in $\Delta\Gamma - \beta_s$ plane is greatly reduced by this measurement

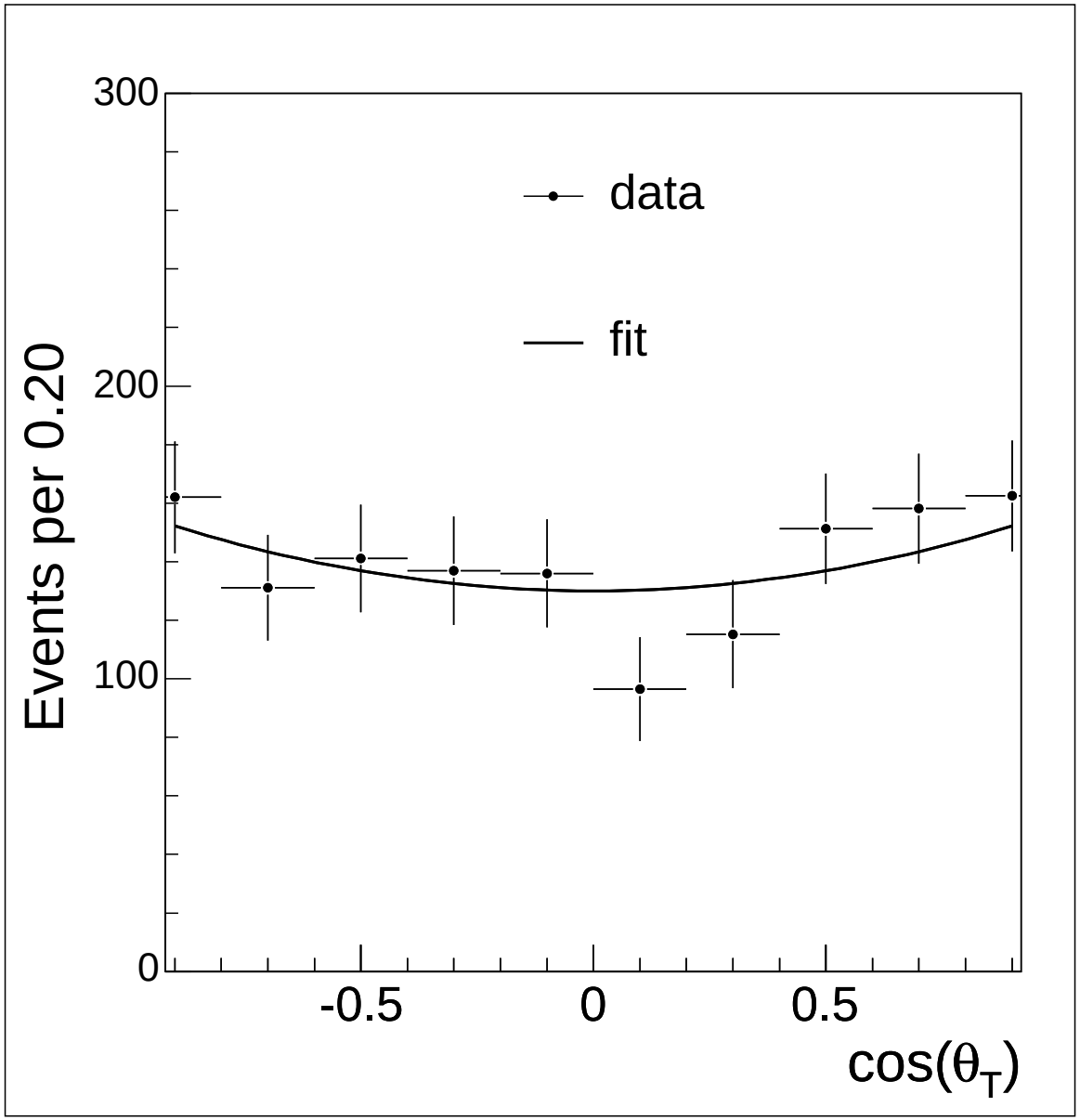


Additional Slides

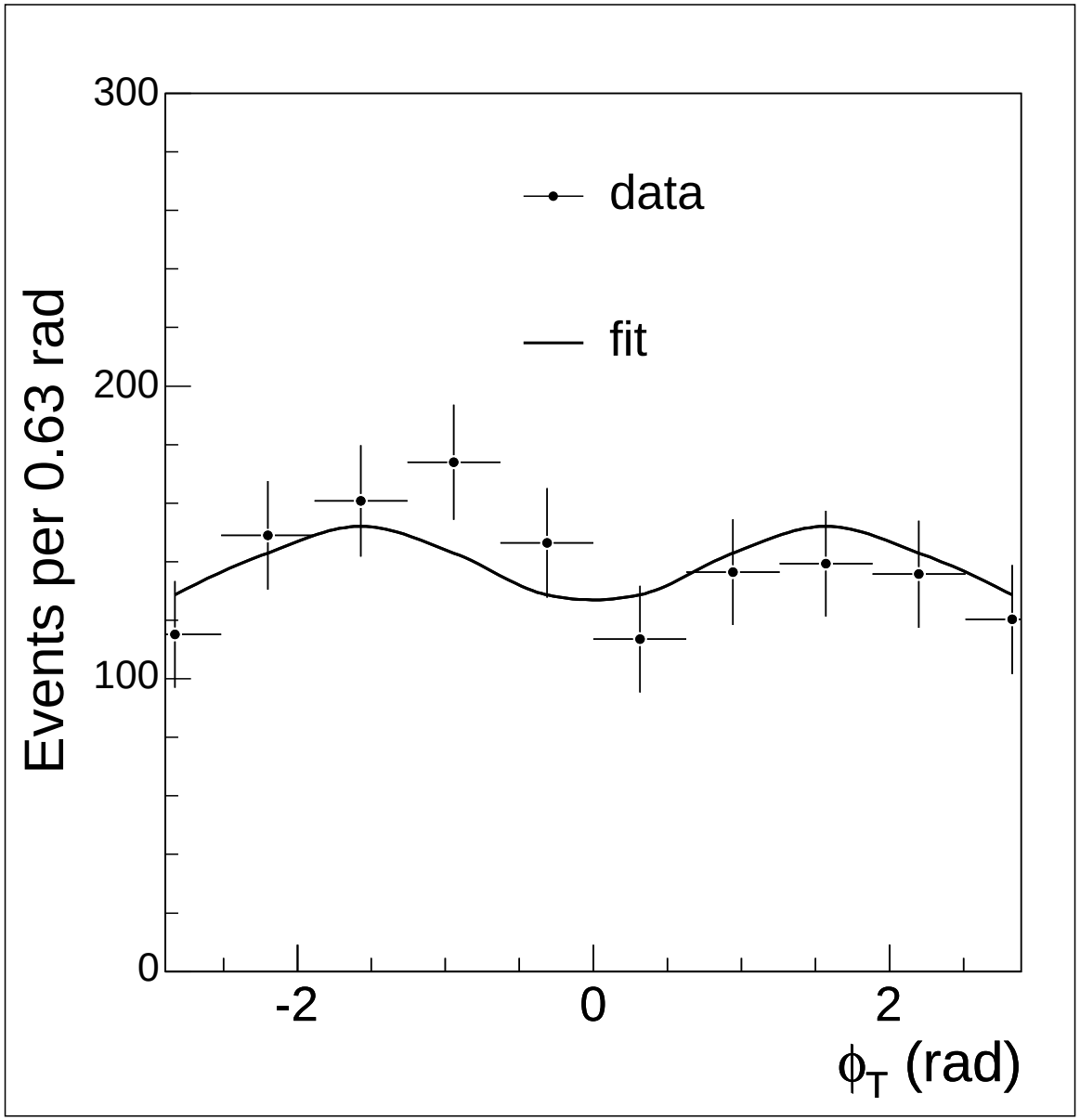
Tagged Analysis: Sideband Subtracted Angular Distrib



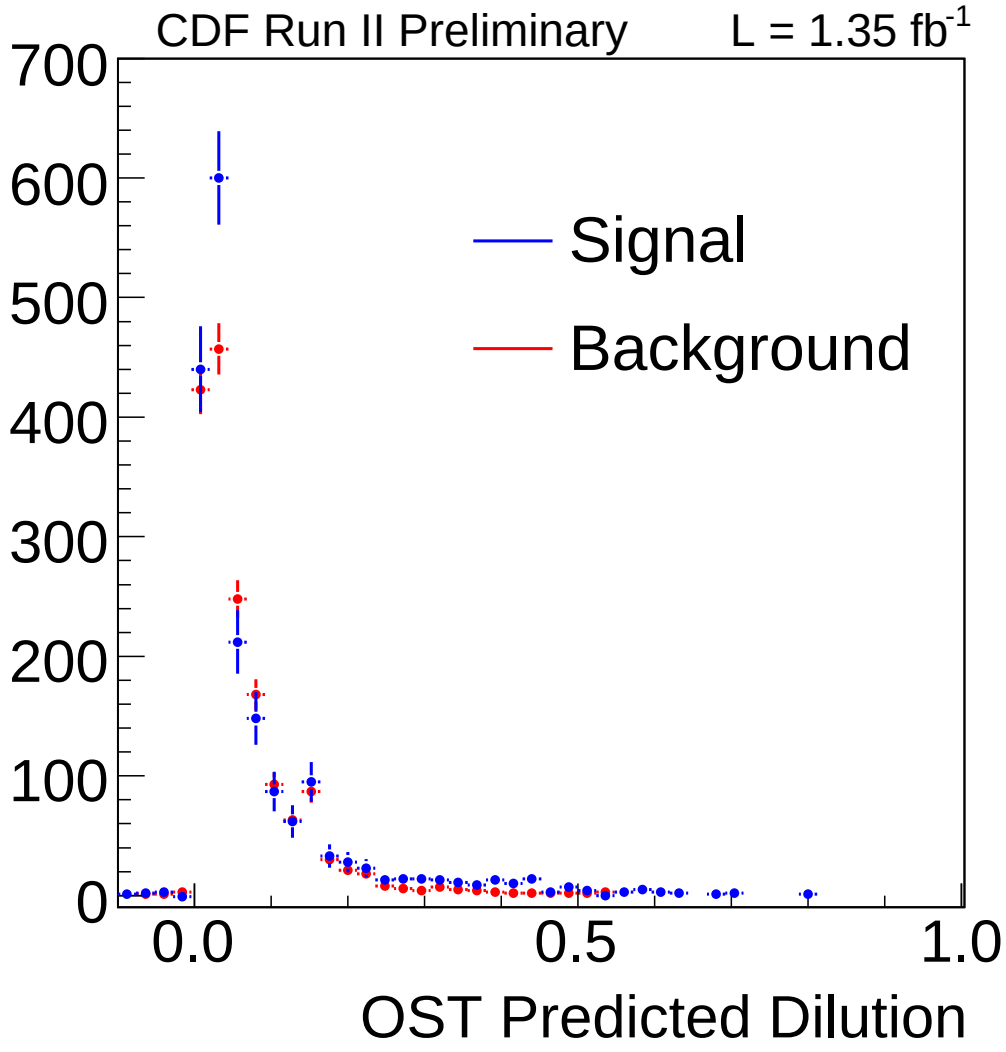
Tagged Analysis: Sideband Subtracted Angular Distrib



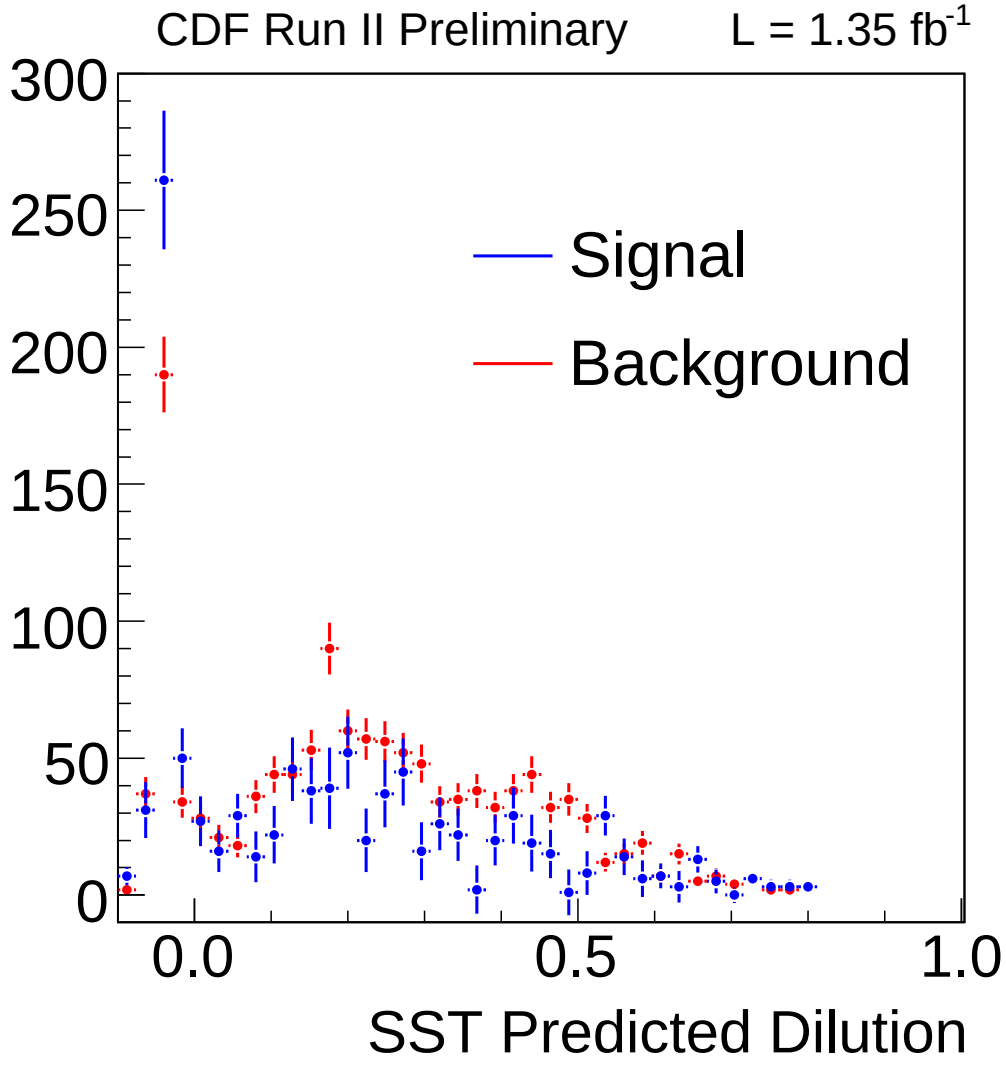
Tagged Analysis: Sideband Subtracted Angular Distrib



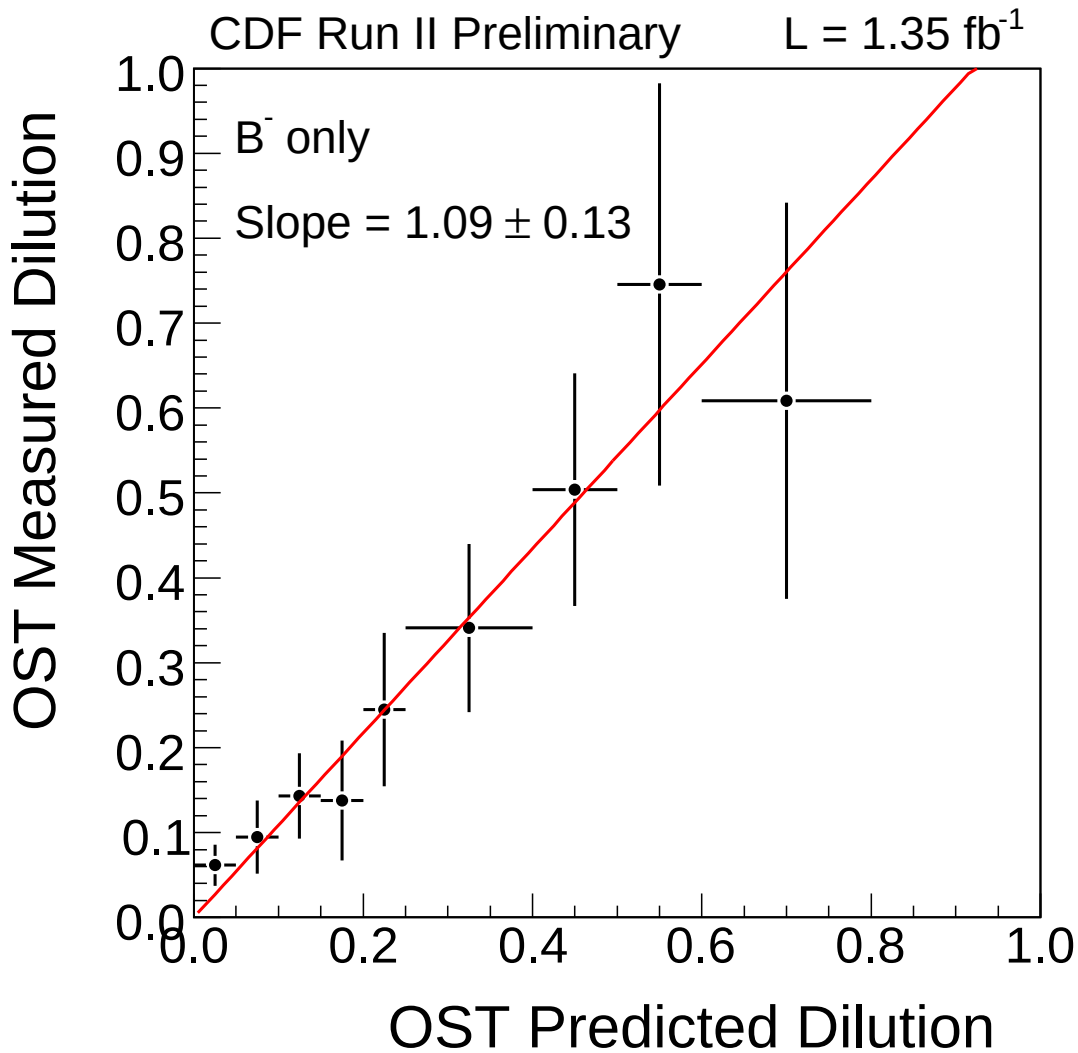
Predicted Dilution: OST



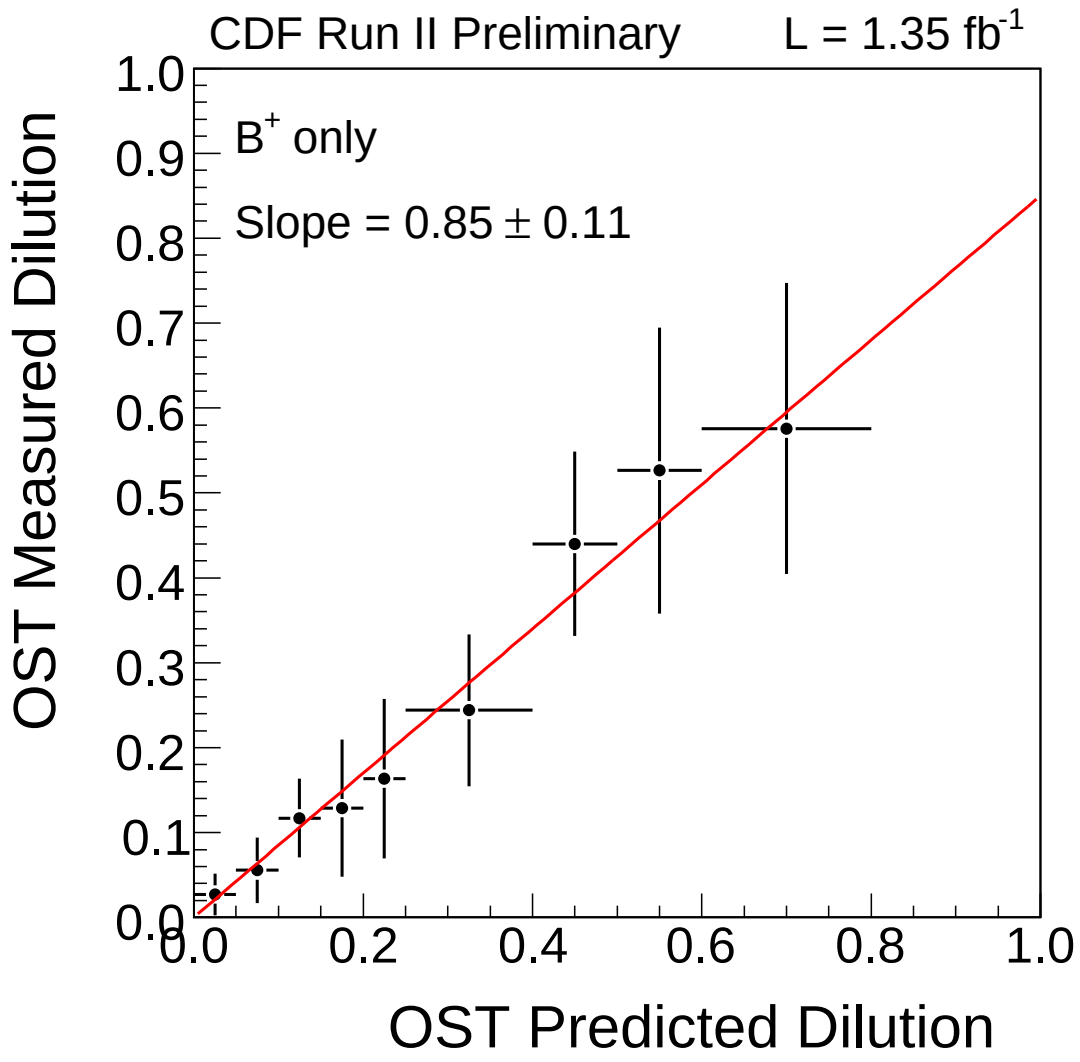
Predicted Dilution: SST



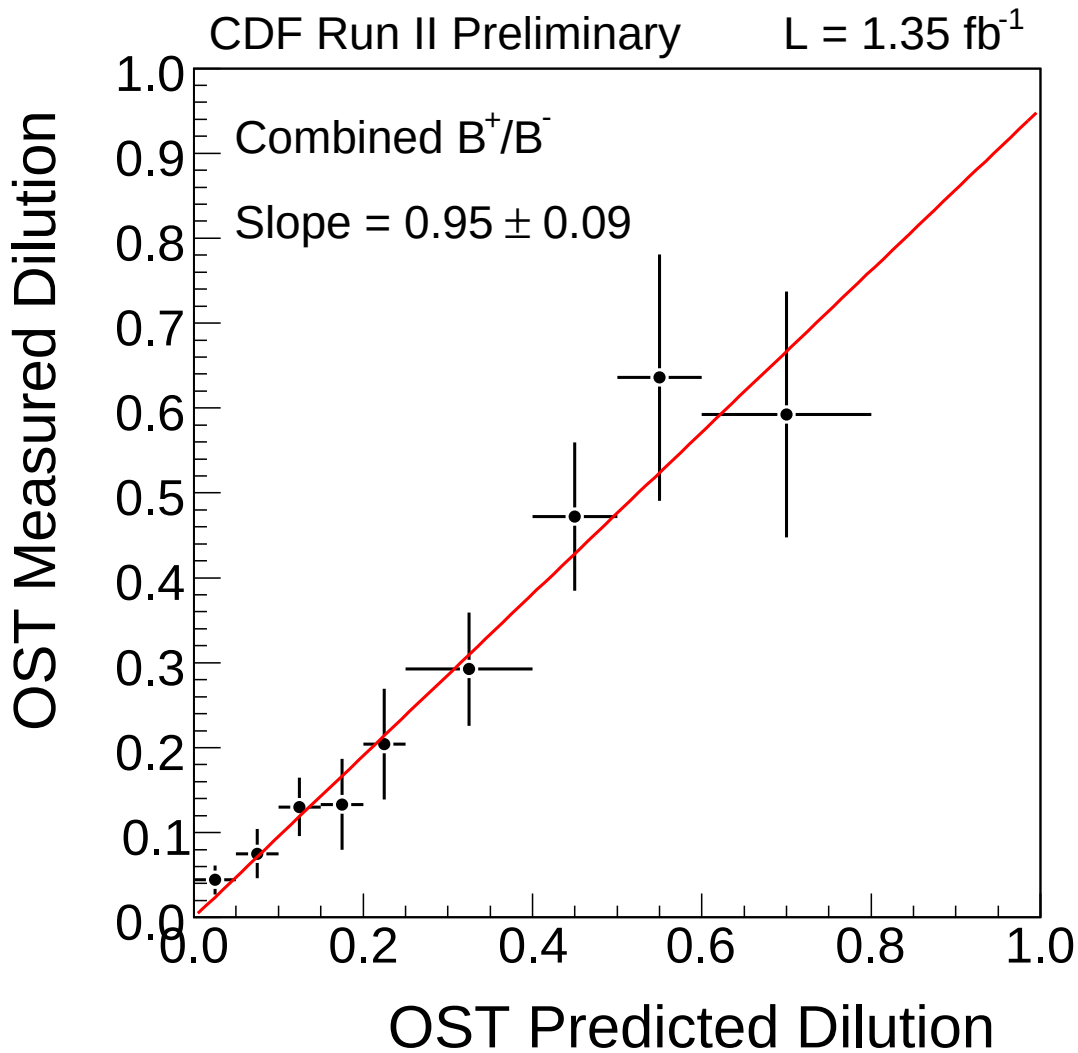
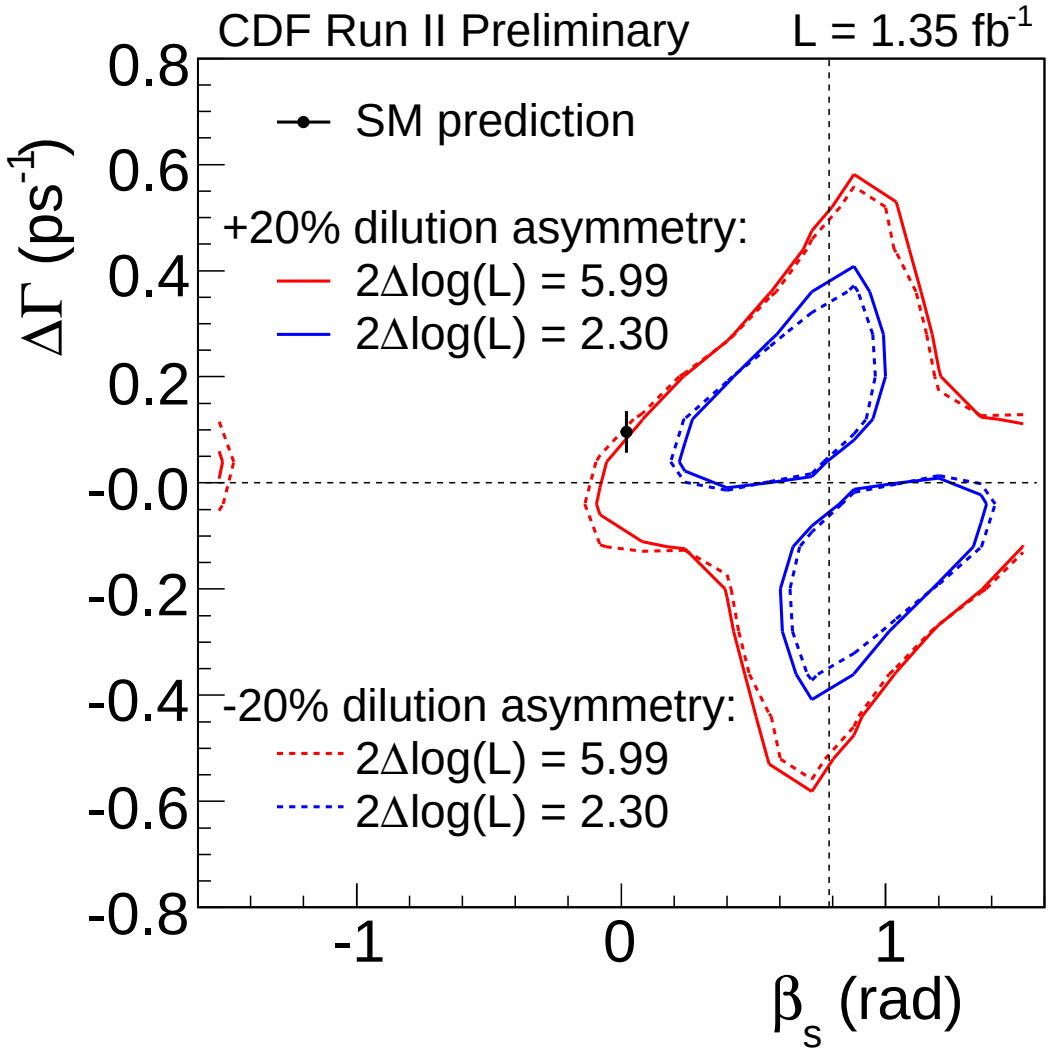
Measured vs. Predicted Dilution: B^-



Measured vs. Predicted Dilution B^+



Measured vs. Predicted Dilution $B^+ + B^-$



Likelihood Profile w/ Additional Asymmetry