New βs measurement at CDF

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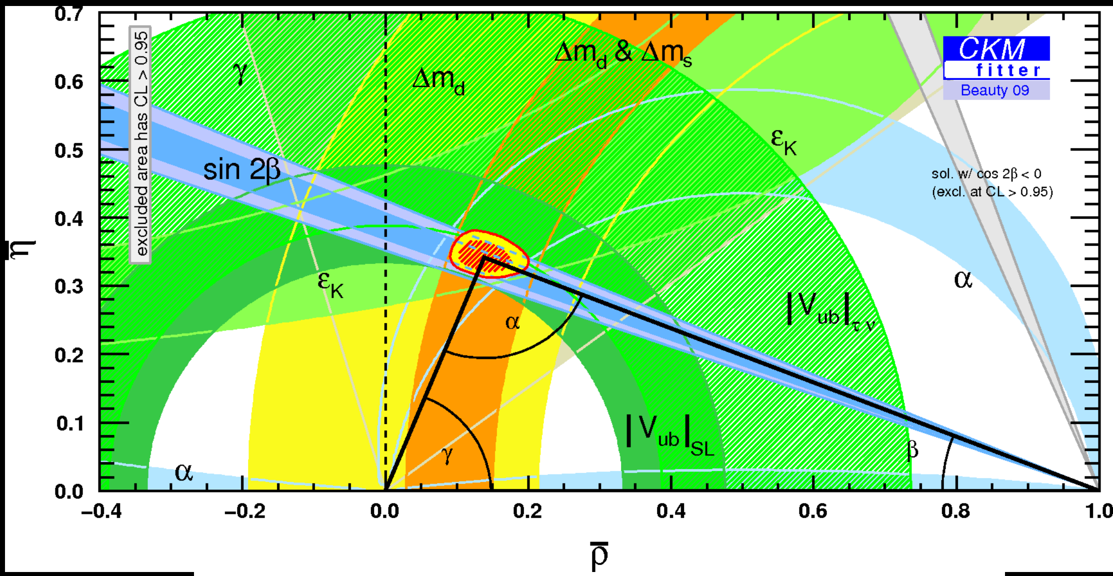
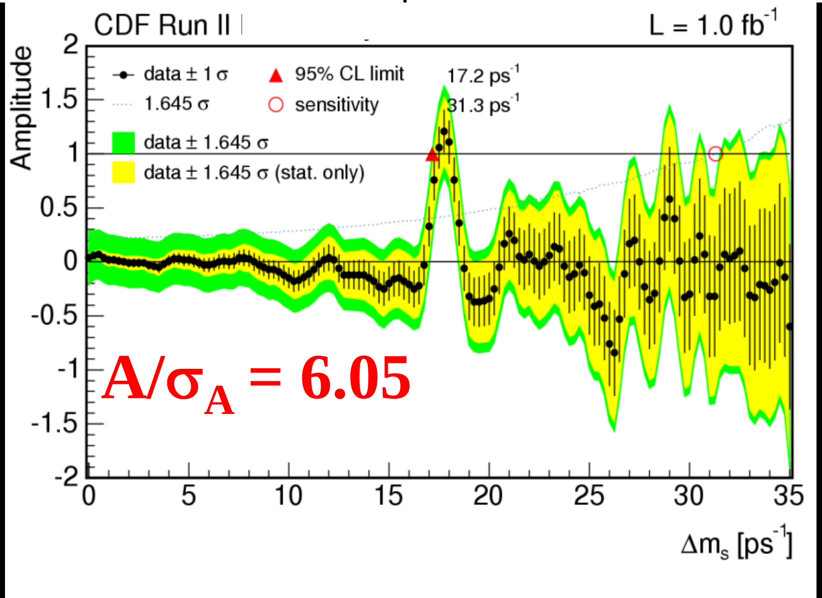
- Introduction
  - Context
  - SM description
- The measurement
  - Fit strategy
  - Signals
  - Flavor tagging
- Results

The Context

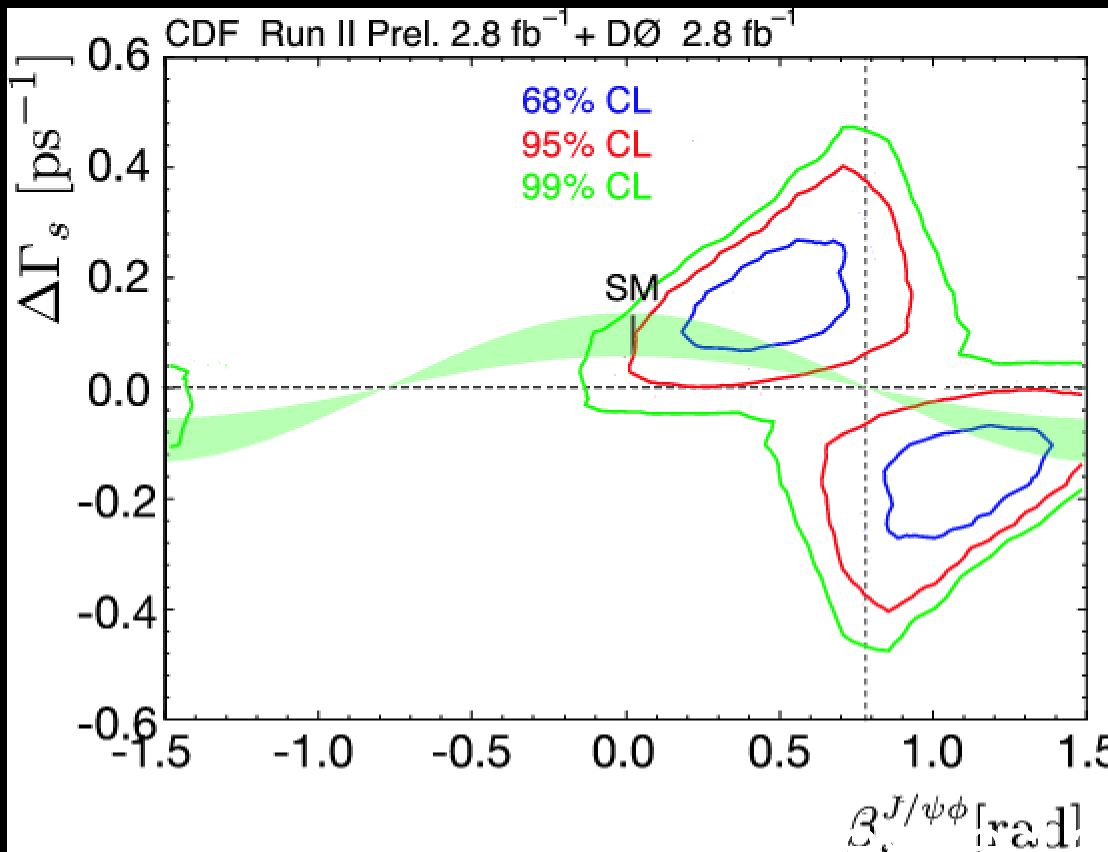
- Great SM success in B_d/B_u sector
  - Thanks B-factories!
  - ...but no evidence for new physics there
- Bs sector can still provide surprises
  - Natural physics for Tevatron experiments
  - In 2006 Δm_s measurement from Bs mixing
    - Right on the SM expectations!
  - Next step is measurement of CP violating phases eg. β_s
    - …some excitement there so far





Status July 2009

- Previous CDF+D0 combined results intriguing

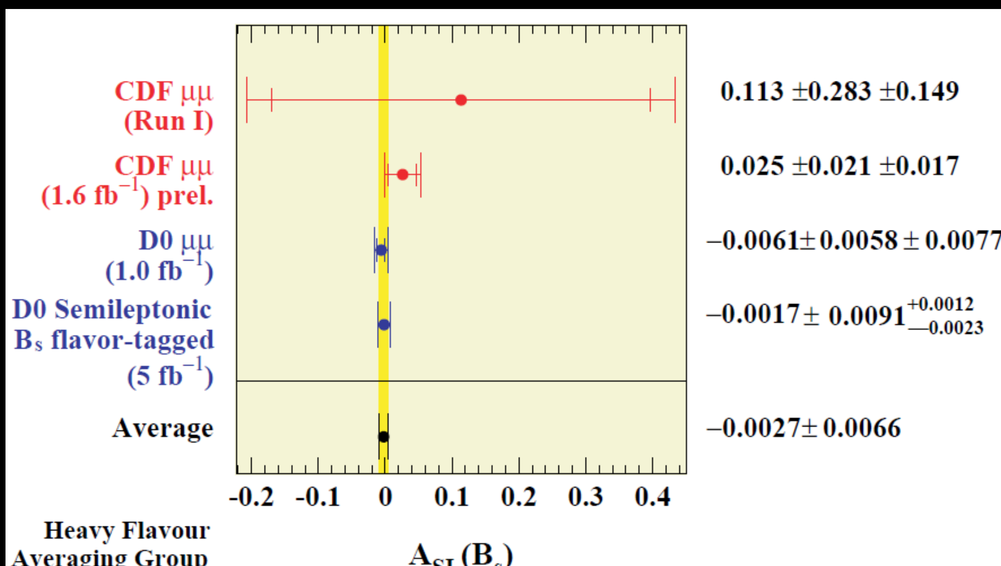


2.1 σ deviation from SM expectations

Related measurements

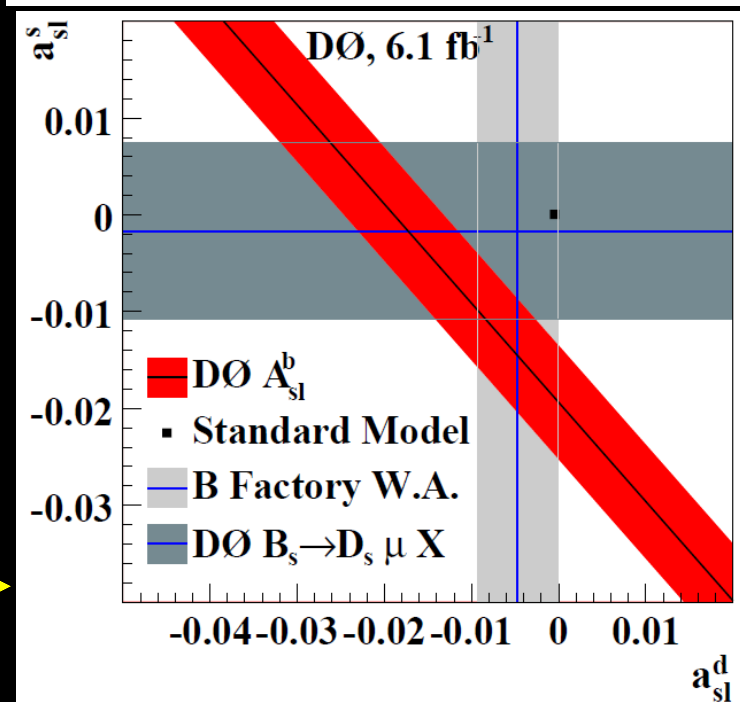
$$a_{sl} = \frac{N_{BB} - N_{\bar{B}\bar{B}}}{N_{BB} + N_{\bar{B}\bar{B}}}$$

- Semileptonic asymmetry
  - Related to $\Delta\Gamma$, Δm and βs
  - SM expectation ~ 10^{-5}
- Old results from CDF and D0:



- Intriguing new D0 result

$$a^s_{sl} = -0.0146 \pm 0.0075$$



βs in SM

- βs is the phase of –Vts
  - ≠ 0 in O(λ[4]) CKM expansion
  - $V_{CKM} = \begin{pmatrix} 1-\frac{\lambda^2}{2}-\frac{\lambda^4}{8} & \lambda & A\lambda^3(\rho-i\eta) \\ -\lambda-A^2\lambda^5(\rho+i\eta-\frac{1}{2}) & 1-\frac{\lambda^2}{2}-(\frac{1}{8}+\frac{A}{2})\lambda^4 & A\lambda^2 \\ A\lambda^3[1-(\rho+i\eta)(1-\frac{\lambda^2}{2})] & -A\lambda^2-A\lambda^4(\rho+i\eta-\frac{1}{2}) & 1-\frac{1}{2}A^2\lambda^4 \end{pmatrix} + \mathcal{O}(\lambda^6)$
  - Quite well constrained assuming SM and very small

CKM fitter. Sept. 2009

$$\beta_s^{SM} = \arg[-V_{ts}V_{tb}^*/(V_{cs}V_{cb}^*)] = 0.01812 \pm 0.0008$$

All real

Basic Theory

- 2 state effective theory:

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

  - Describes mixing and CP violation
  - M, Γ hermitian
    - CPT invariance: $M_{11} = M_{22}$, $\Gamma_{11} = \Gamma_{22}$

$$M = \begin{pmatrix} m & m_{12} \\ m_{12}^* & m \end{pmatrix}$$

$$\Gamma = \begin{pmatrix} \gamma & \gamma_{12} \\ \gamma_{12}^* & \gamma \end{pmatrix}$$

  - After diagonalization:
    - Eigenvalues:

$$\lambda_\pm = (m \pm \Delta m) - \frac{i}{2}(\gamma \pm \Delta\gamma)$$

$$= m - \frac{i}{2}\gamma \pm \sqrt{(m_{12} - \frac{i}{2}\gamma_{12})(m_{12}^* - \frac{i}{2}\gamma_{12}^*)}$$

    - Eigenstates:

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

q ¼ jm12j 12

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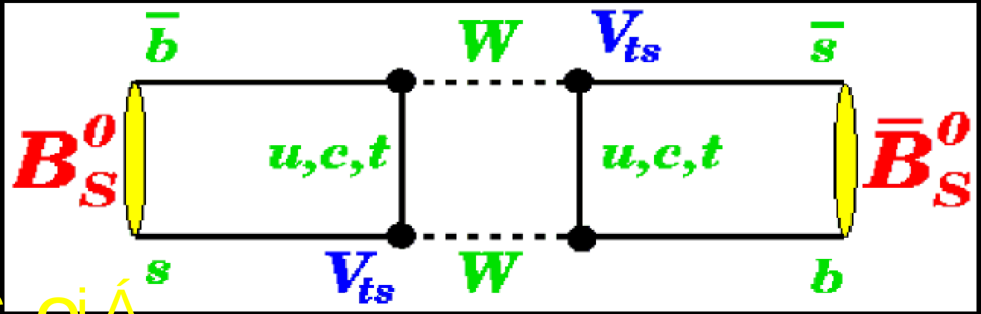
Origin of off-diagonal terms

- m_{12} from box diagram
  - Top quark dominant
  - $M_{12} \propto V^2_{ts} \propto e^{-2i\beta_s}$
- New physics possible in loops!

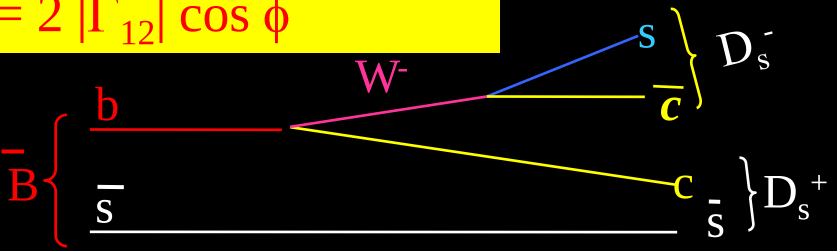
$$M_{12} = M_{12}^{SM} ¢ e^{iÁ_{NP}}$$



- Γ_{12} from common final states
  - For B_s dominated by $D_s^+ D_s^-$
    - $\Delta\Gamma/\Gamma \sim 0.10$
      - Γ_{12} mostly real: $\phi_s \sim -2\beta_s$
  - Tree level dominated
    - Hard to see new physics here

$$\Gamma_{12} = \sum_f < B|f > \rho_f < f|\bar{B} >$$

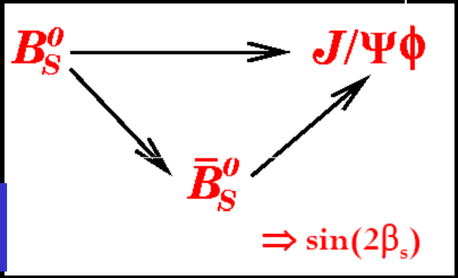
$$\Delta\Gamma = 2\mathrm{Re}\{\Gamma_{12}/ m_{12}\}|m_{12}| = 2\,|\Gamma_{12}| \cos\phi$$



Measured quantities

- Mixing frequency (theory limited):
  - $\Delta M = 2\,|M_{12}|$
- Width difference (statistics limited):
  - $\Delta\Gamma = 2|\Gamma_{12}|\cos\phi$
- Semileptonic asymmetry (stat.+syst. limited)
  - $A_{SL} = \left|\frac{\Gamma_{12}}{M_{12}}\right| \sin\phi = \frac{\Delta\Gamma}{\Delta M}\tan\phi$

- Bs – Bs bar interference in decay to common final state such as J/ψ φ (statistics limited)
  - $-\mathrm{Im}(p/q) \sim \sin(2\beta_s) \sim -\sin\phi$



This measurement

Analysis strategy

Simplified time evolution ($\Delta\Gamma=0$) and f = CP-eigenstate

$$< f|B(t)> = e^{-imt} e^{-\Gamma t/2} A_f \left[\cos(\Delta m t/2) - i \frac{\bar{A}_f}{A_f}\frac{q}{p} \sin(\Delta m t/2) \right]$$

$$< f|\bar{B}(t)> = e^{-imt} e^{-\Gamma t/2} \bar{A}_f \left[\cos(\Delta m t/2) - i \frac{A_f}{\bar{A}_f}\frac{p}{q} \sin(\Delta m t/2) \right]$$

- Study time evolution of $Bs \rightarrow J/\psi\phi$ decay
  - No SM weak phases in $A_f \rightarrow \frac{\bar{A}_f}{A_f} = \pm 1$
    - Sign depends on CP of final state
  - ... but $J/\psi\phi$ is vector-vector → mixture of CP-even and CP-odd
    - Need to perform full angular analysis to separate the components
      - L=0 and L=2 are CP-even, L=1 is CP-odd
      - prefer to use “transversity basis”: A_0, $A_{//}$: CP-even, $A_\perp$: CP-odd
        - Phys. Lett. B 369, 144 (1996), 184 - hep-ph/9511363
    - Need to introduce more hadronic decay amplitudes and their phases:
      - A_0, $A_{//}$, $A_\perp$ ($|A_0|^2 + |A_{//}|^2 + |A_\perp|^2 = 1$), $\delta_{//}$, $\delta_\perp$ (phases relative to A_0)

Full Bs decay rate formula

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

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)

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

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

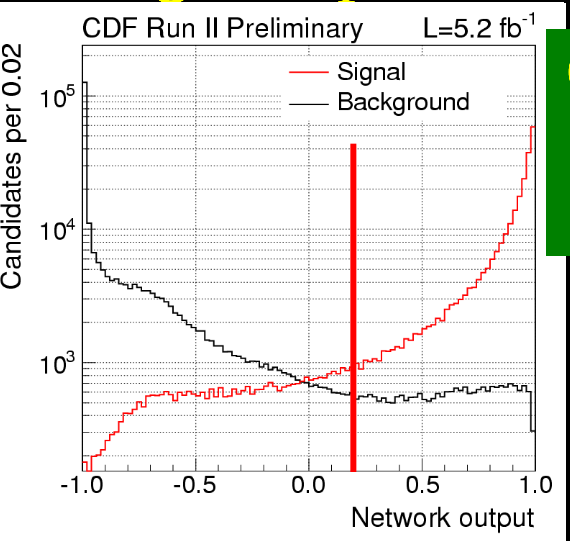
$$\delta_\parallel \equiv \mathrm{Arg}(A_\parallel(0)A_0^*(0))$$

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

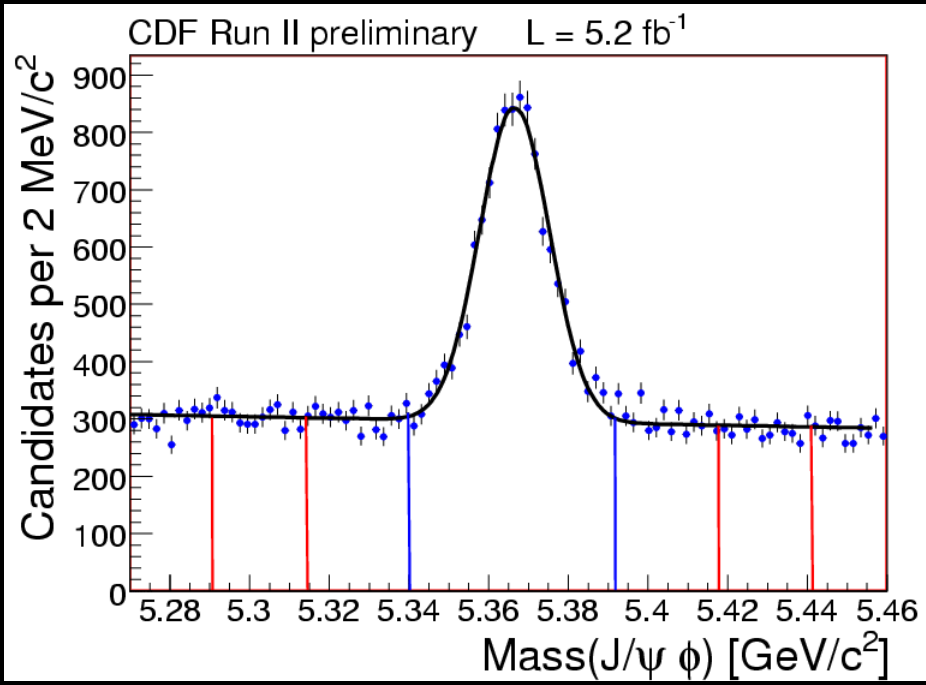
- **Identification of *B* flavor at production (flavor tagging) → better sensitivity to β_s**

Improvements over past

- Luminosity: 2.9 → 5.2 fb^{-1}
- Signal optimization with NN



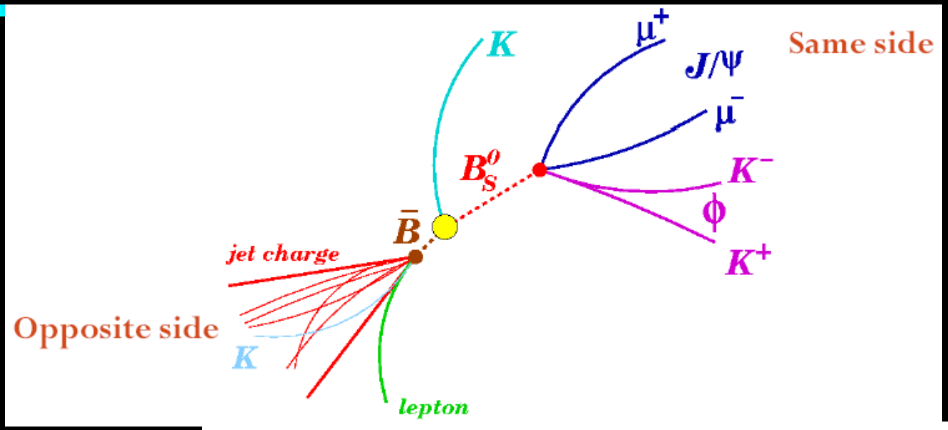
Optimized for best βs resolution

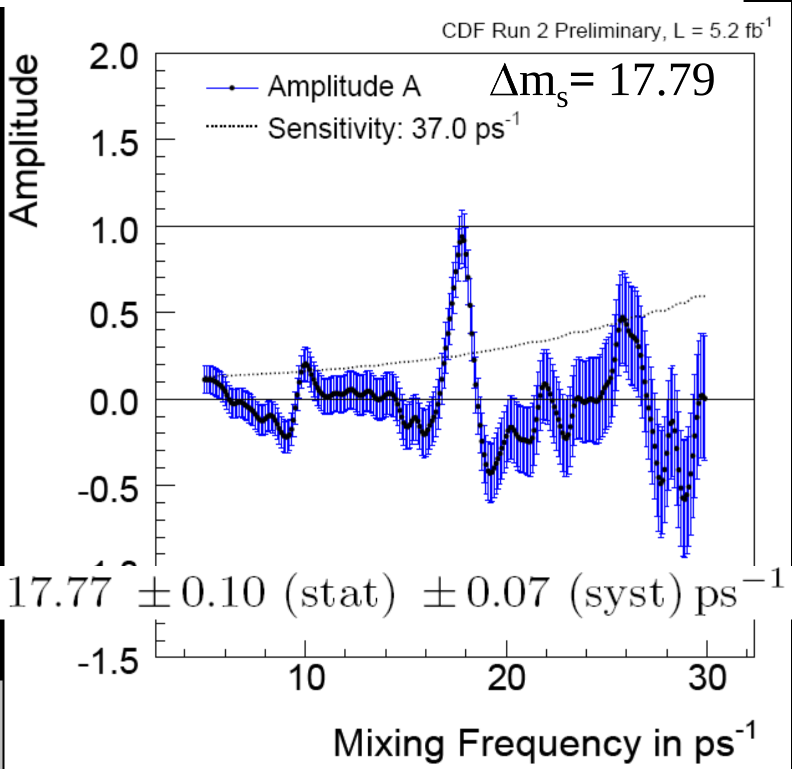


  - ~ 6500 Bs→J/ψϕ, S/N ~ 1
- Improved flavor tagging completely recalibrated (see later)
- Inclusion of f_0 scalar component (Bs→J/ψf_0) (see later)

Flavor tagging

- Opposite side (OST)
  - Jet / lepton charge
  - Combined with NN
  - Calibrate with 52,000 J/ψK+
  - ε = 94.2 0.4%, D = 11.5 0.2%
    - εD^2 = 1.2%
- Same side Kaon (SSKT)
  - Sign of soft kaon near Bs
  - Dilution from simulation
  - Calibrate with ~ 13,000 Bs→Ds(3)pi
    - From mixing amplitude scan
    - εD^2 = 3.2 1.4%





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

Old CDF result

Results: Bs lifetime & ΔΓ

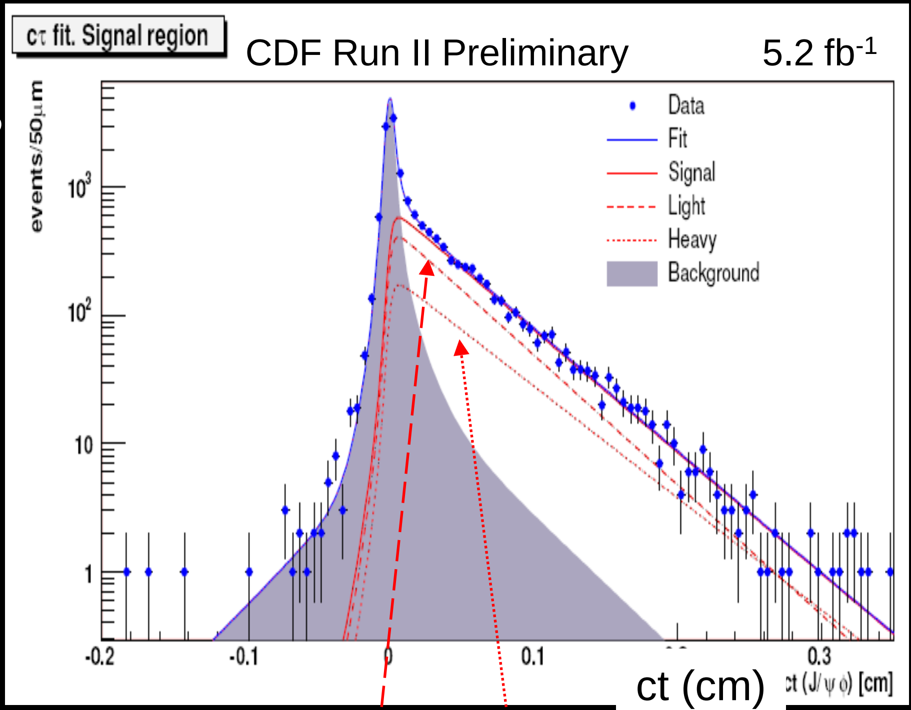
- Point measurement assuming SM
  - Set βs = 0
  - Most precise measurement of Bs lifetime and ΔΓ

$$\tau_s = 1.53 \pm 0.025\ (\text{stat.})\ \pm 0.012\ (\text{syst.})\ \text{ps}$$
$$\Delta\Gamma = 0.075 \pm 0.035\ (\text{stat.}) \pm 0.01\ (\text{syst.})\ ps^{-1}$$

PDG 2009 averages:

$\tau_s = 1.472^{+0.024}_{-0.026}\ ps$

$\Delta\Gamma_s = 0.062^{+0.034}_{-0.037}\ ps^{-1}$



CP-even (B_s^{light}) and *CP*-odd (B_s^{heavy}) components have different lifetimes

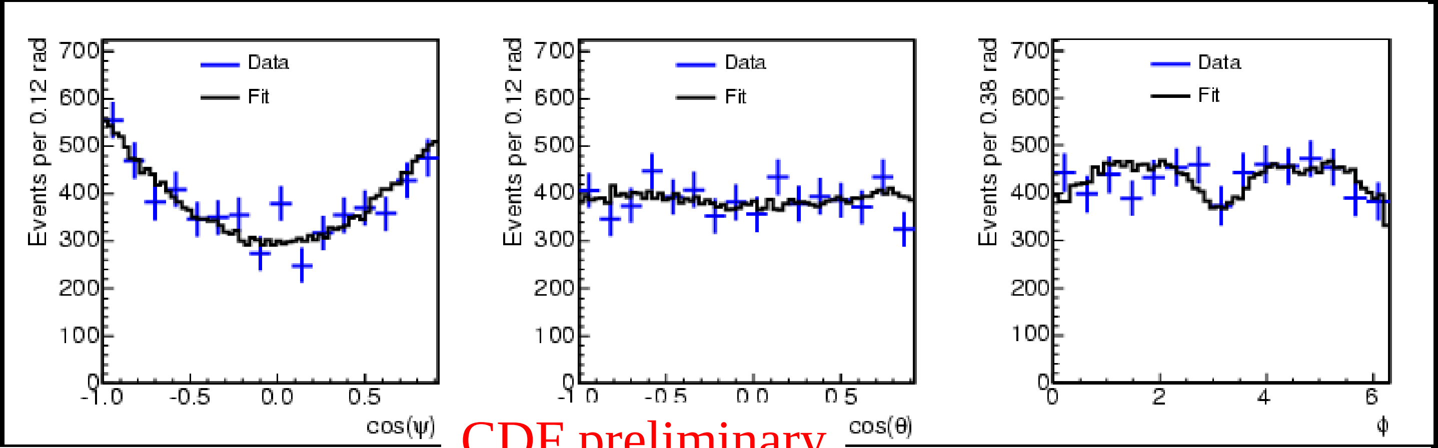
$\rightarrow \Delta\Gamma \neq 0$

Results: polarization amplitudes

- βs = 0 fit
  - Most precise measurement

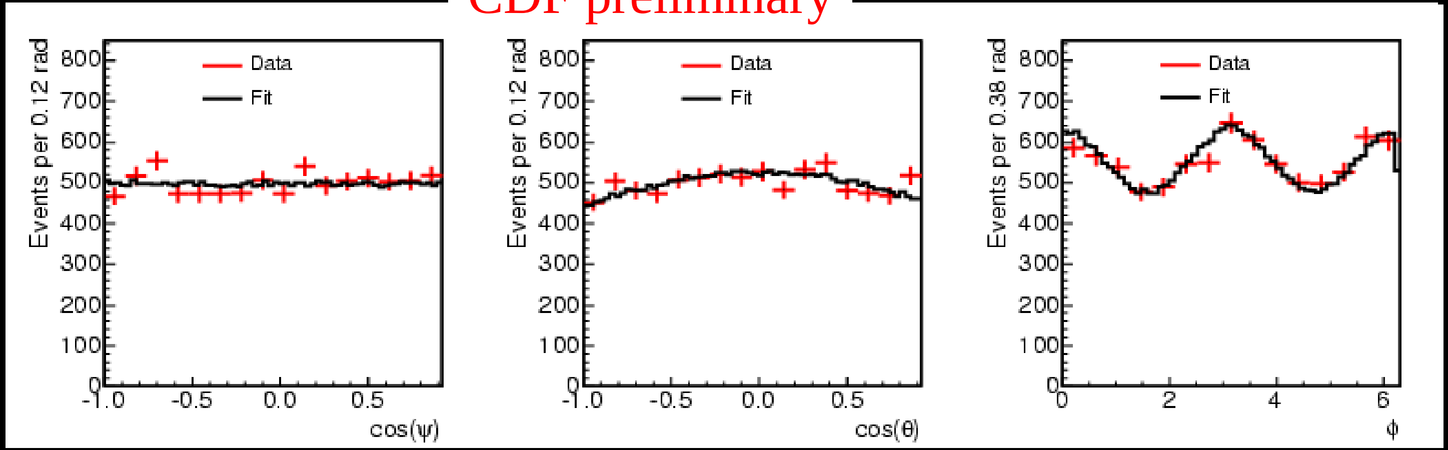
$$
\begin{aligned}
|A_{\parallel}(0)|^2 &= 0.231 \pm 0.014\ (\text{stat}) \pm 0.015\ (\text{syst.}) \\
|A_0(0)|^2 &= 0.524 \pm 0.013\ (\text{stat}) \pm 0.015\ (\text{syst.}) \\
\phi_{\perp} &= 2.95 \pm 0.64\ (\text{stat}) \pm 0.07\ (\text{syst.}).
\end{aligned}
$$

Signal fit projection



CDF preliminary

Background fit projection



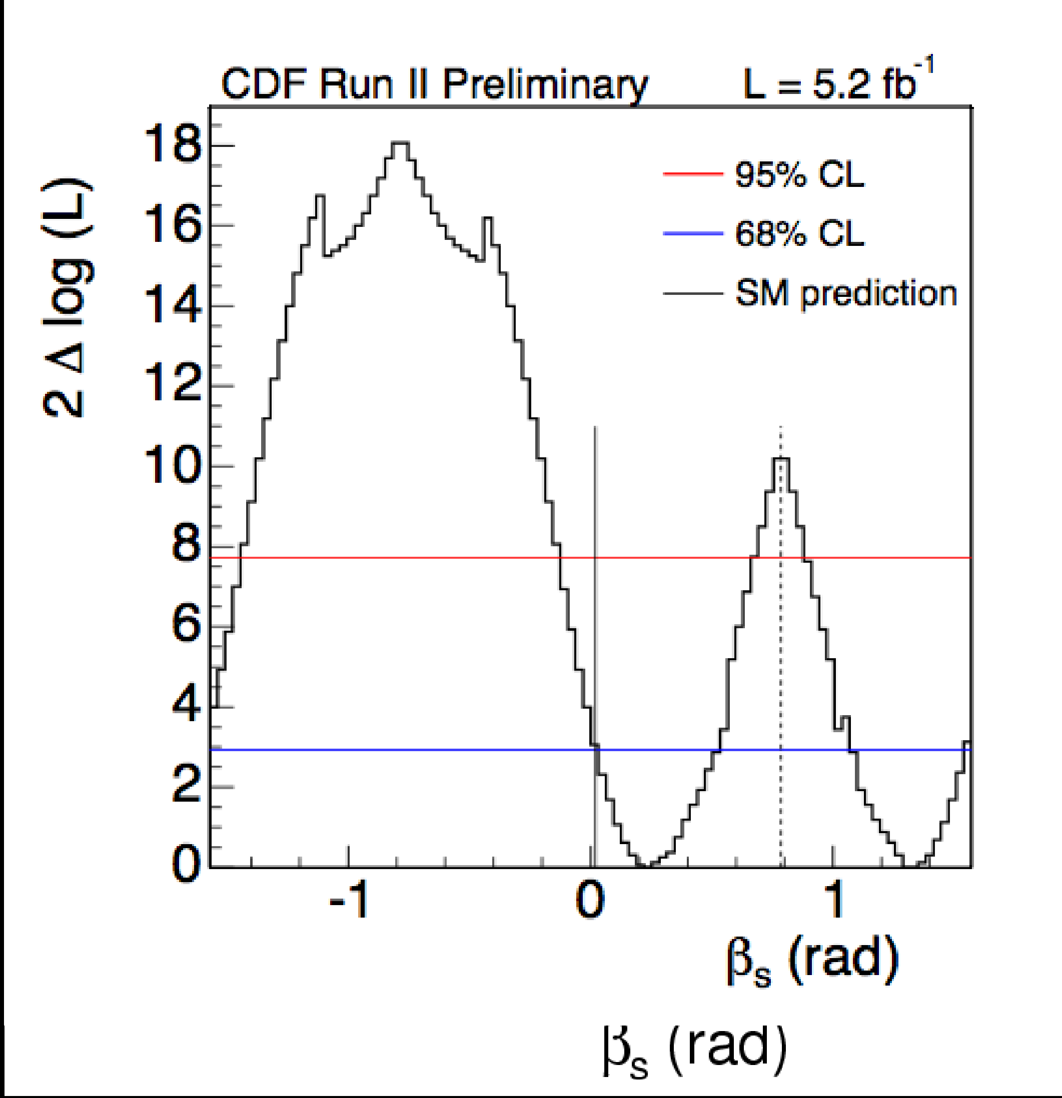
CP Violation Phase β_s with 5.2 fb^{-1} at CDF

- Full fit results
  - Low statistics & dilutions
    - Some parameters very non-Gaussian, including βs
  - Contours corrected for
    - Non-gaussian effects
    - Systematics
  - Note fit symmetry

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

$\delta_{||} \to 2\pi - \delta_{||}$, $\delta_\perp \to \pi - \delta_\perp$

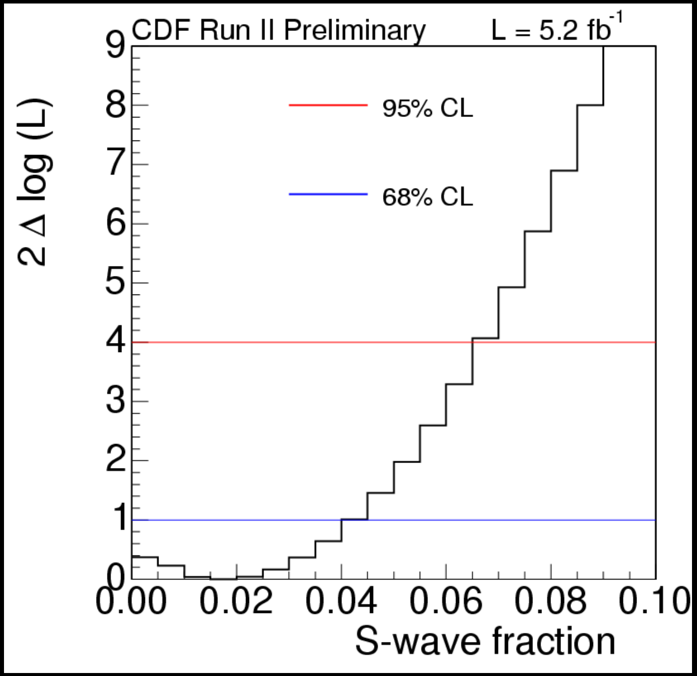
- βs projection
  - [0.02, 0.52] U [1.08, 1.55] at 68% C.L.

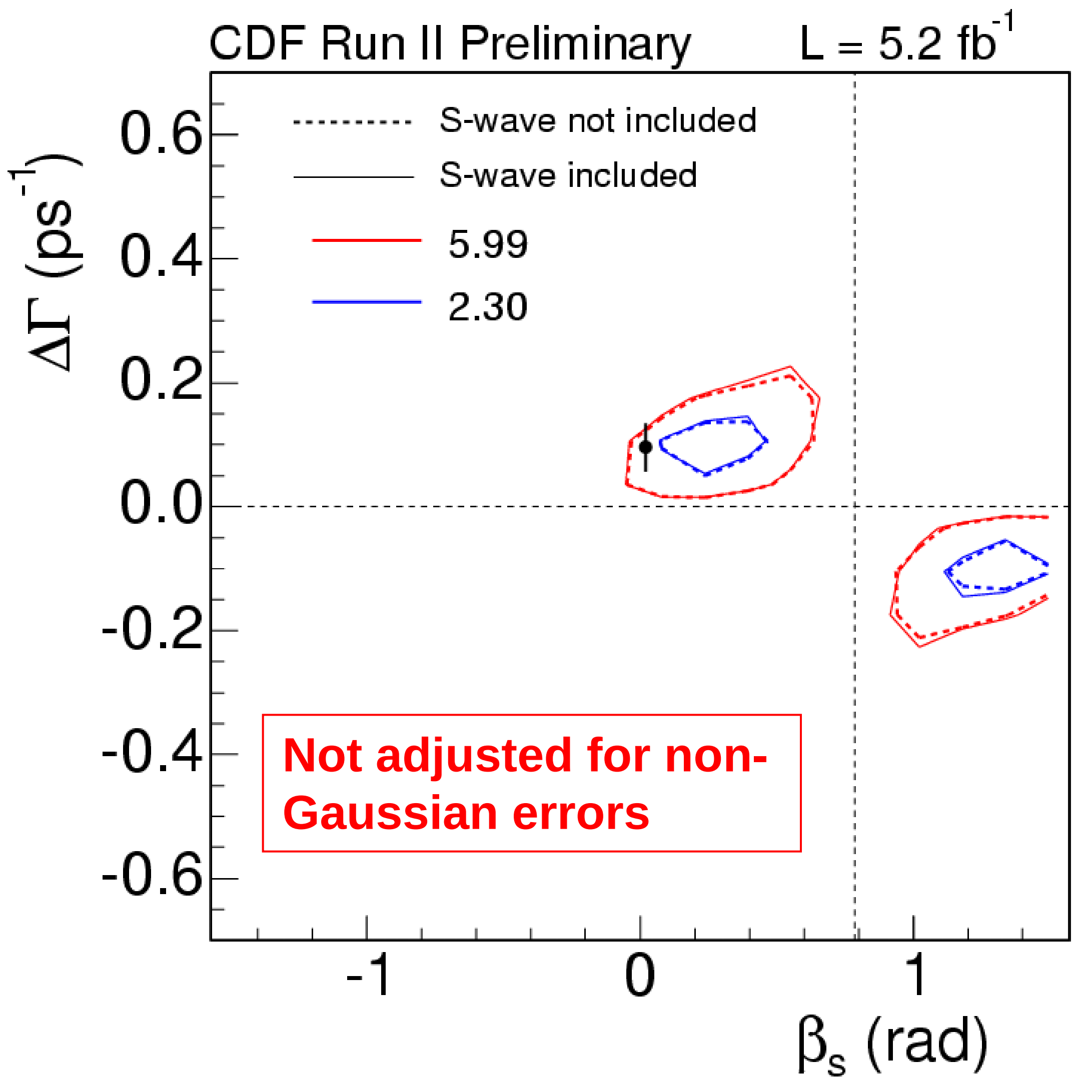


Effect of s-wave resonance

(Suggested in arXiv:0908.3627v1 [hep-ph] 25 Aug 2009)

- Effect of $Bs \to J/\psi\ f_0$
  - Fit prefers ~ 2%
    - Consistent with m(KK) fit
    - < 6.7% @ 95% CL

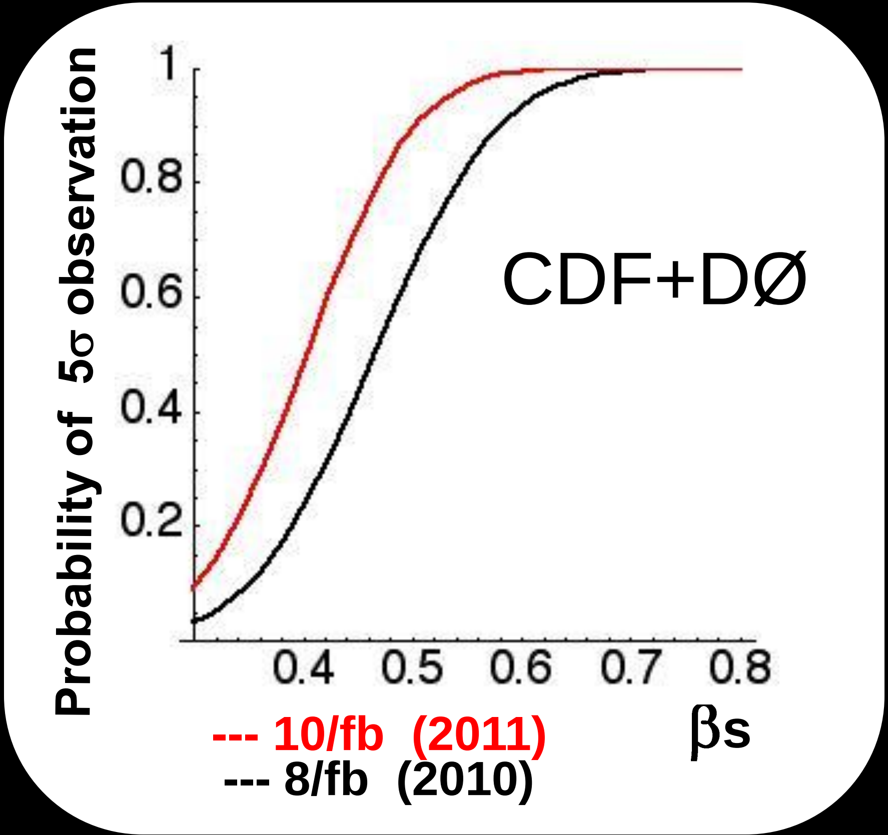


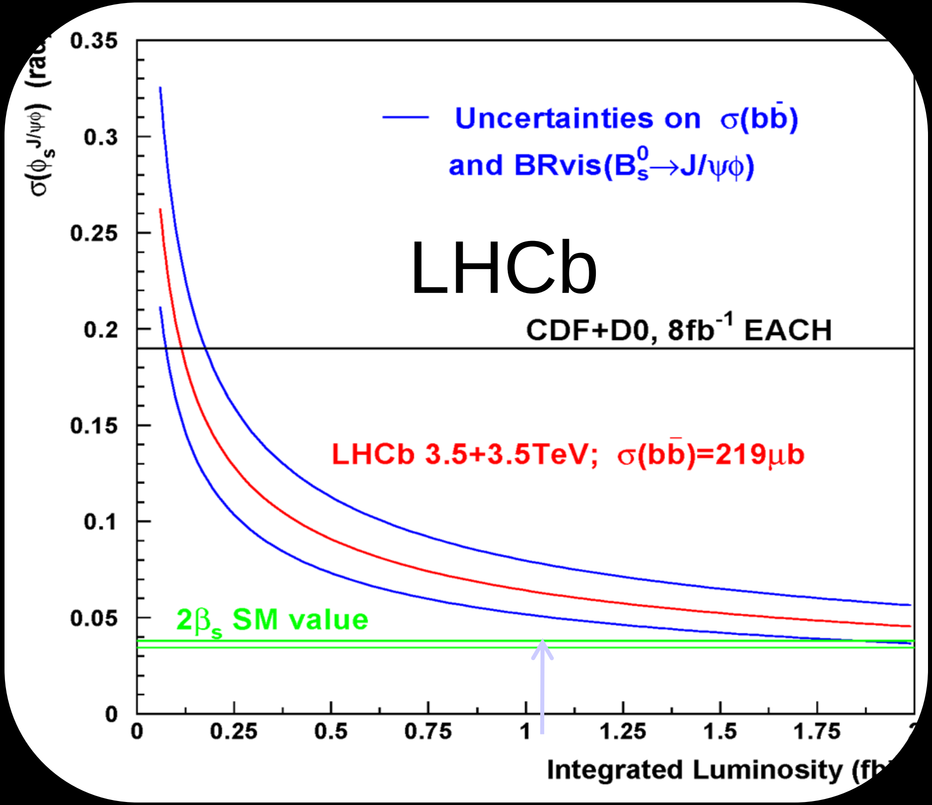


Conclusions & prospects

- Best measurement of Bs lifetime, $\Delta\Gamma$ and polarization amplitudes
- Tighter constraints on βs
  - Improved agreement with SM ($\sim 1\sigma$)
- Future improvements
  - Statistics doubled (10 fb^{-1}) by end of 2011 Tevatron run
  - More data ~ 25-30% from track based triggers
  - Additional decay modes:
    - $\psi(2S)\phi$
    - $J/\psi\ f_0,\ f_0 \rightarrow \pi\pi$ (CP-eigenstate)

Getting hot





Tevatron 2011: discover or exclude NP in wide range of phases.

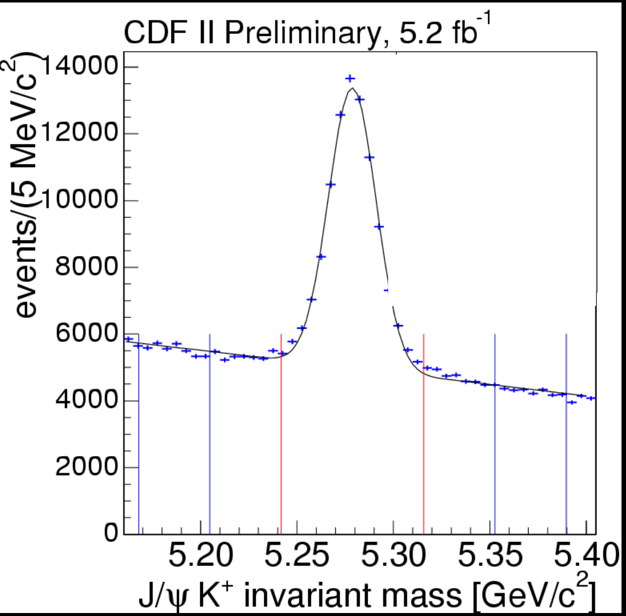
LHCb competitive (if everything turns out as expected)

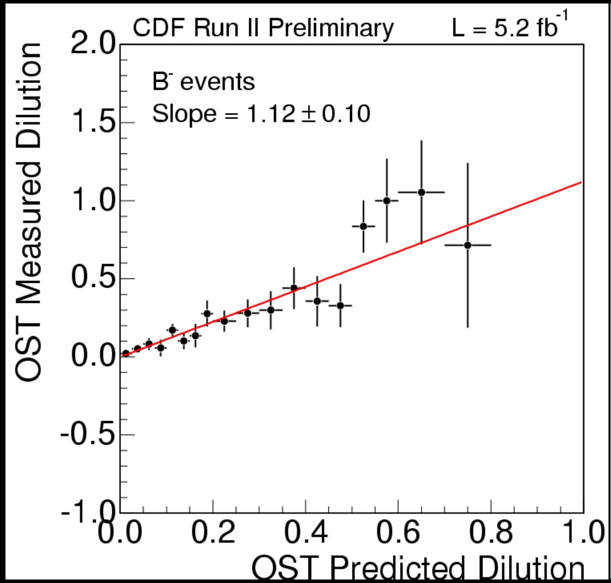
Backup slides

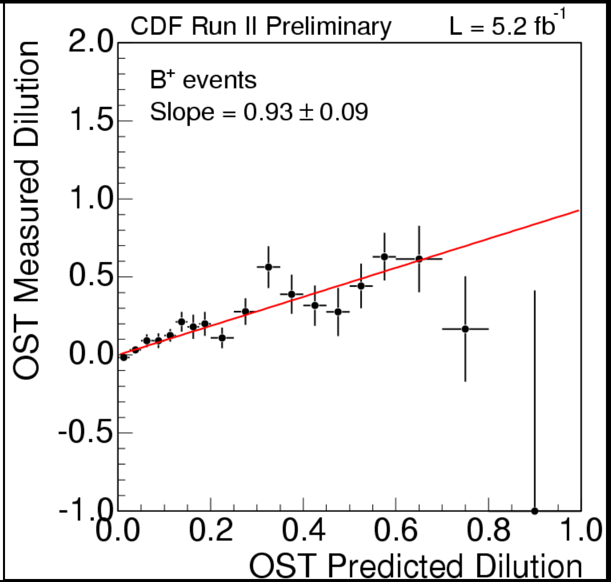
Backup slides

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 ≈ 52,000 $B^{+/-} \rightarrow J/\Psi\, K^{+/-}$ decays







-OST efficiency = 94.2 +/- 0.4%, OST dilution = 11.5 +/- 0.2 %

- Total tagging power = 1.2%

Same Side Tagging Calibration

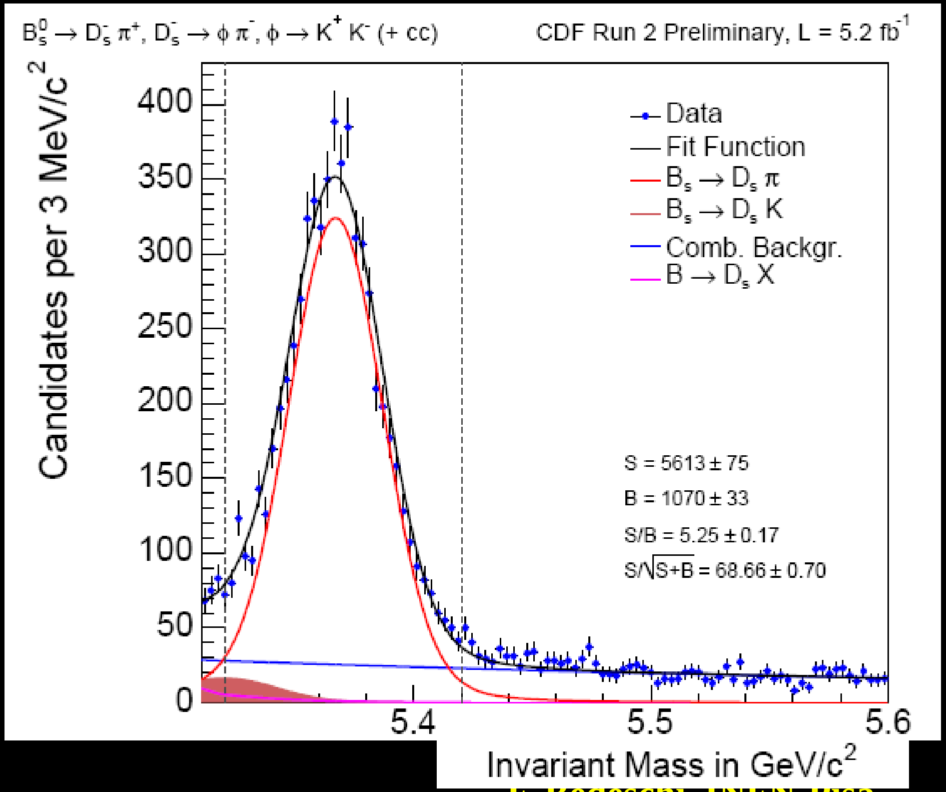
- Event-by-event predicted dilution based on simulation
- Calibrated with 5.2 fb^{-1} of data
- Simultaneously measuring the B_s mixing frequency Δm_s and the dilution scale factor A

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

- D – event by event predicted dilution
- ξ – tagging decision = +1, -1, 0 for B_s, $\bar{B}_s$ 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**

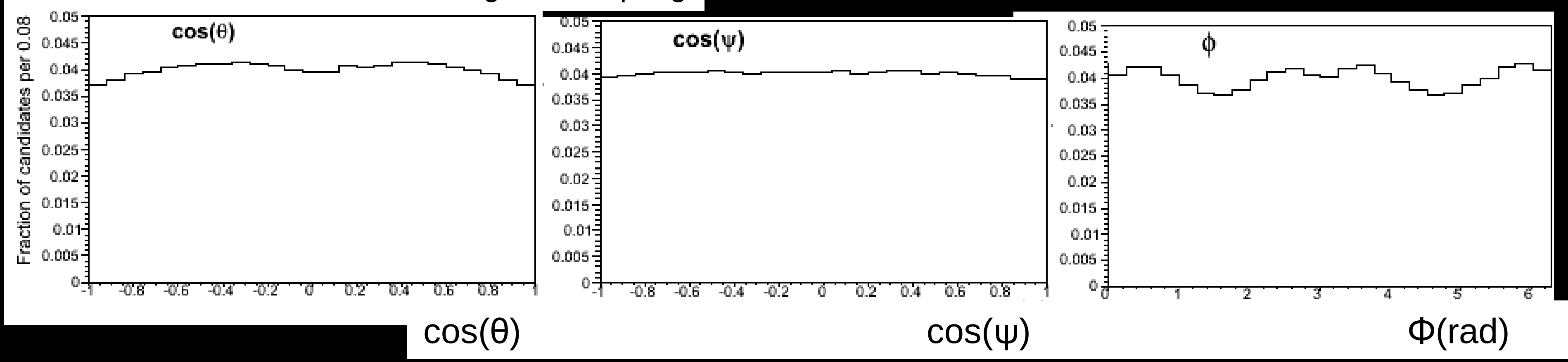


Detector Angular Efficiency

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



S-Wave

- As noted in arxiv:0812.2832v3, the final state in $B_s \rightarrow J/\Psi\, KK$ decays can be in an s-wave state with a ~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 where it is shown that:
  - 10% un-accounted s-wave contamination in the Φ region leads to
    - 10% bias in the measured $2b_s$, towards the SM prediction
    - 15% increase in statistical errors

- S-wave contribution can be either non-resonant 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 $A_\perp$

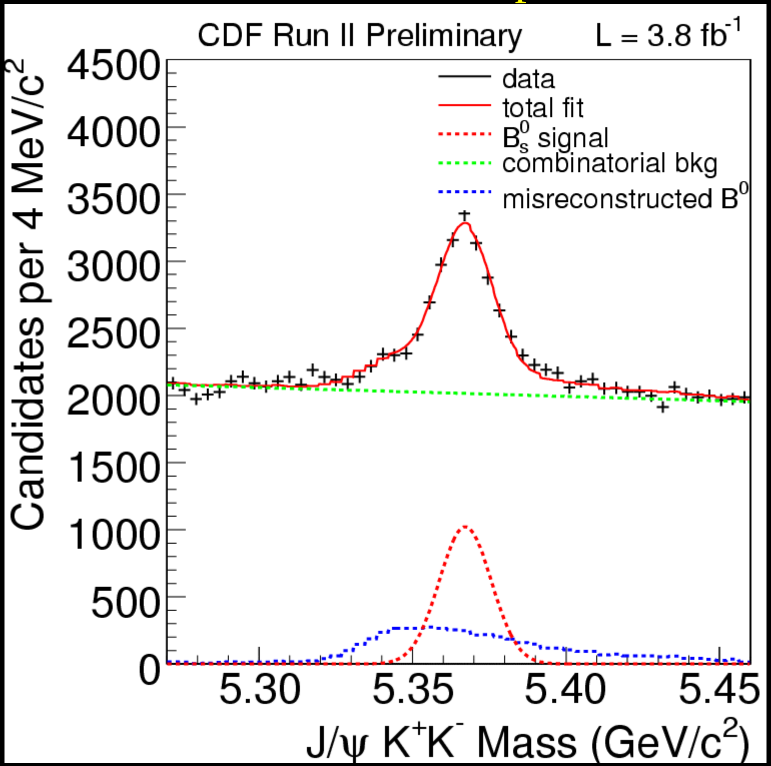
- Mass and phase of s-wave component are assumed flat (good approximation in a narrow +/- 10 MeV around the Φ mass)

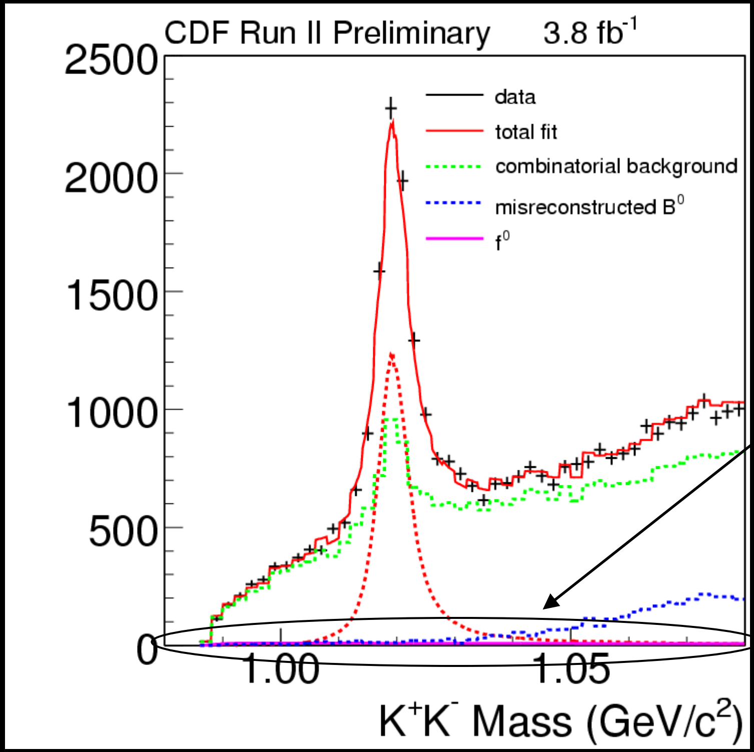
S-Wave Cross Check Using KK Mass Spectrum

- 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

Non-Gaussian Regime

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

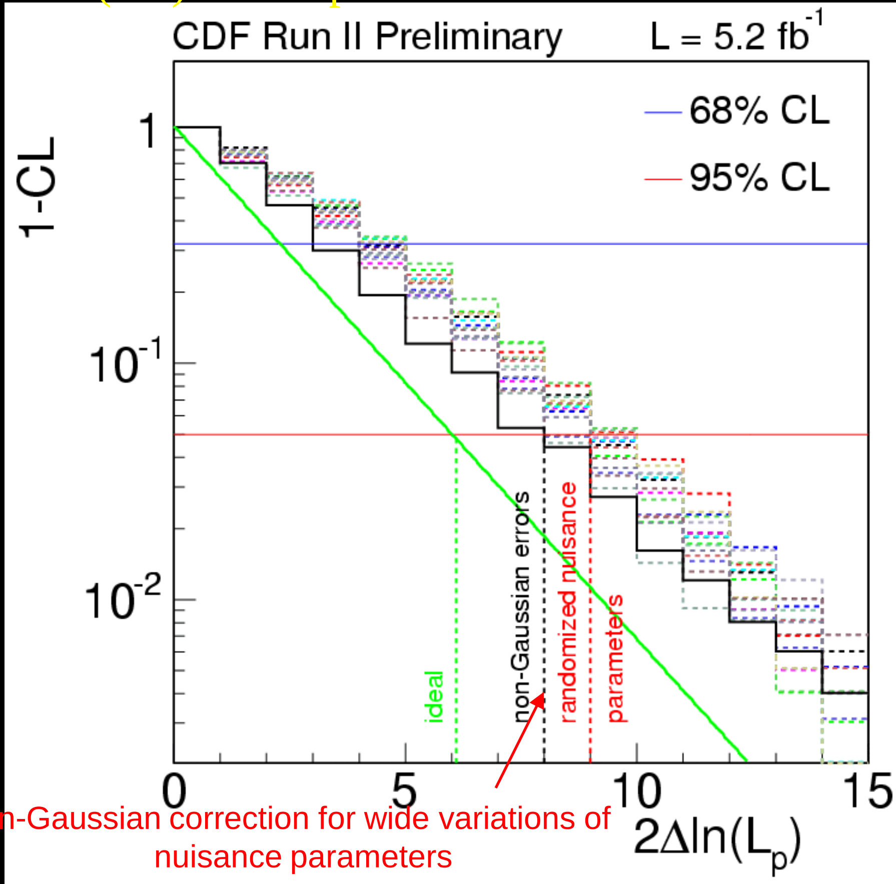
- In ideal case (high statistics, Gaussian likelihood), to get the 2D 68% (95%) C.L. regions, take a slice through profiled likelihood at 2.3 (6.0) units up from minimum

- In this analysis integrated likelihood ratio distribution (black histogram) deviates from the ideal c^2 distribution (green continuous curve)

- Using pseudo-experiments establish a "map" between Confidence Level and 2Dlog(L)

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

- To establish final confidence regions use most conservative case



Systematic Uncertainties

Systematic	$\Delta\Gamma$	$c\tau_s$	$\lvert A_\parallel(0)\rvert^2$	$\lvert A_0(0)\rvert^2$	$\phi_\perp$
Signal efficiency:					
Parameterisation	0.0024	0.96	0.0076	0.008	0.016
MC reweighting	0.0008	0.94	0.0129	0.0129	0.022
Signal mass model	0.0013	0.26	0.0009	0.0011	0.009
Background mass model	0.0009	1.4	0.0004	0.0005	0.004
Resolution model	0.0004	0.69	0.0002	0.0003	0.022
Background lifetime model	0.0036	2.0	0.0007	0.0011	0.058
Background angular distribution:					
Parameterisation	0.0002	0.02	0.0001	0.0001	0.001
$\sigma(c\tau)$ correlation	0.0002	0.14	0.0007	0.0007	0.006
Non-factorisation	0.0001	0.06	0.0004	0.0004	0.003
$B^0 \to J/\psi K^*$ crossfeed	0.0014	0.24	0.0007	0.0010	0.006
SVX alignment	0.0006	2.0	0.0001	0.0002	0.002
Mass error	0.0001	0.58	0.0004	0.0004	0.002
$c\tau$ error	0.0012	0.17	0.0005	0.0007	0.013
Pull bias	0.0028		0.0013	0.0021	
Totals	0.01	3.6	0.015	0.015	0.07