New Measurement of B_s Mixing Phase at CDF

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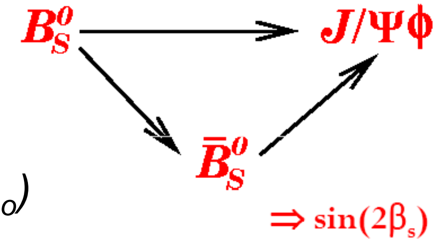
CP Violation in $B_s \to J/\Psi\Phi$ Decays



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

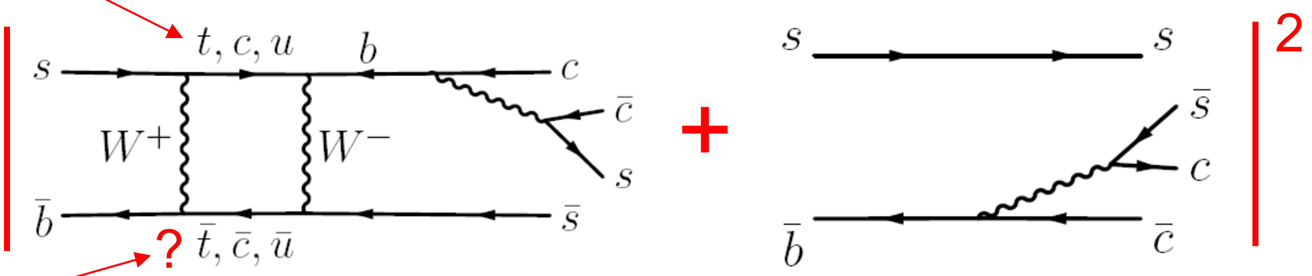
- In SM, *CP* violation phase β_s is predicted to be very small ~$\sin^2(\theta_{Cabibbo})$

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

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

dominant
contribution
from top quark

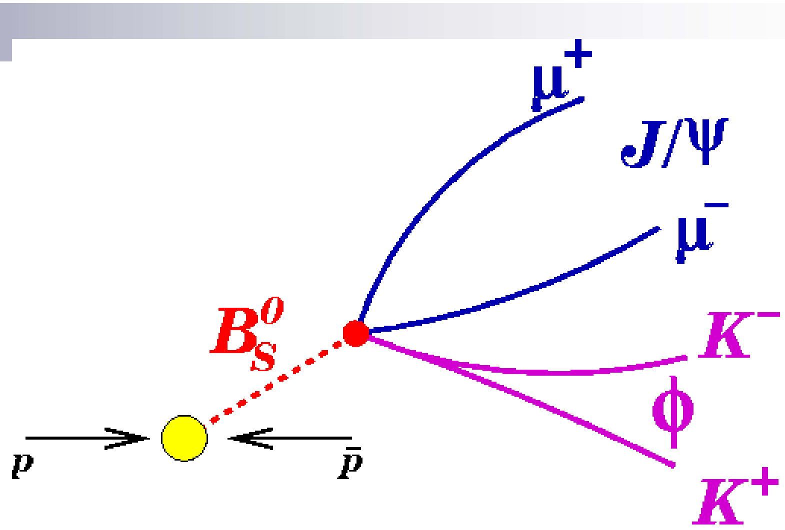
Decay rate ~



New Physics particles ?

- New physics particles running in the mixing diagram may enhance β_s
  - large β_s → clear indication of New Physics !

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

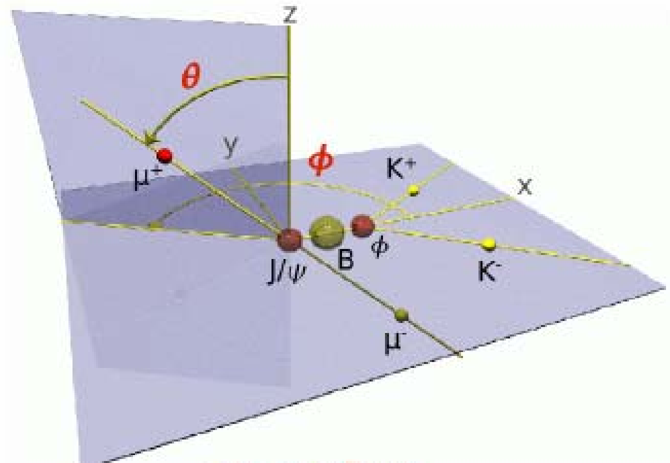


- Measure:
  - B_s lifetime τ_s
  - B_{sH}, B_{sL} decay width difference $\Delta\Gamma_s$
  - *CP* violating phase β_s

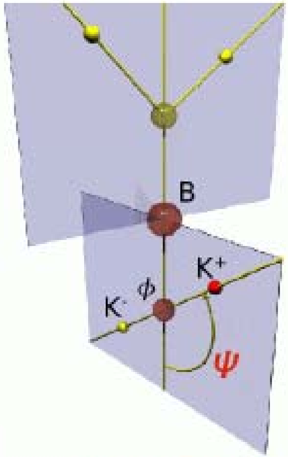
- Decay of B_s (spin 0) to J/Ψ (spin 1) and Φ (spin 1) leads to three different angular momentum final states:

$L = 0$ (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*)



J/ψ rest frame



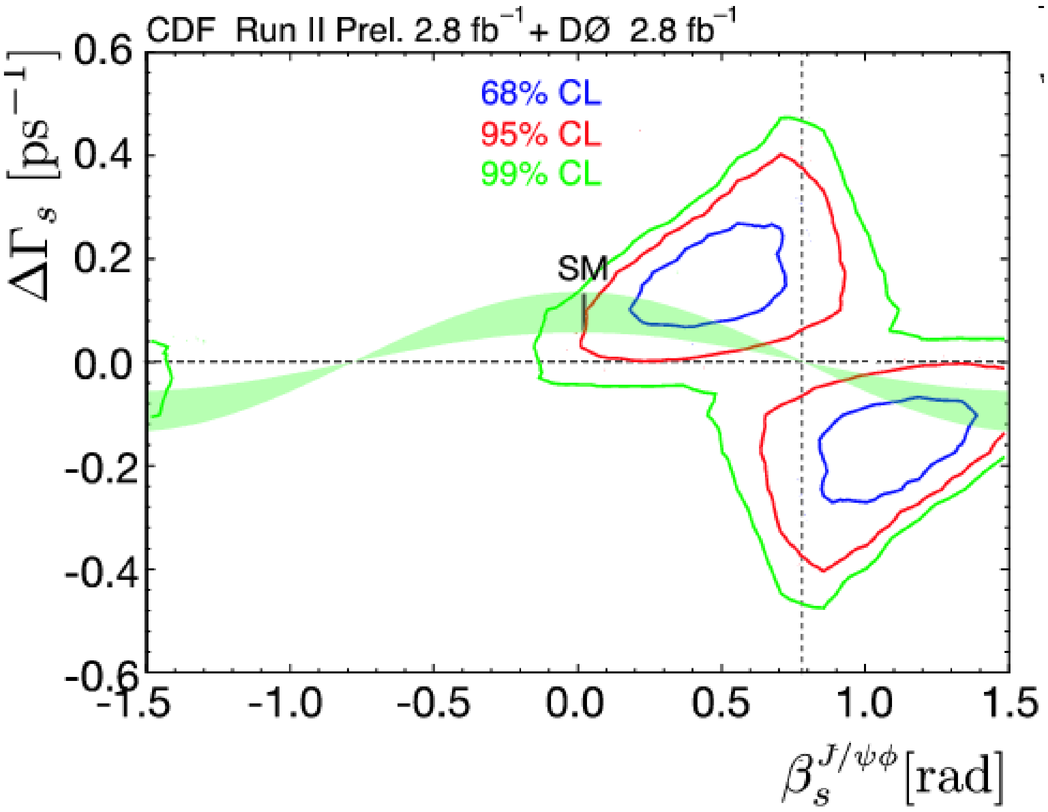
φ rest frame

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

Status Before This Update: CDF + DØ Combination

- CDF + DØ combination done by the Tevatron B Working Group:
  http://tevbwg.fnal.gov/

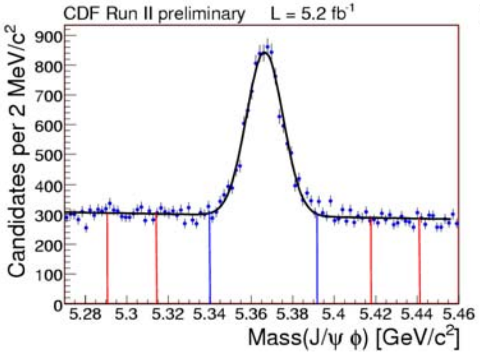
- Shows intriguing 2.1σ deviation from SM expectation (CDF note 9787)



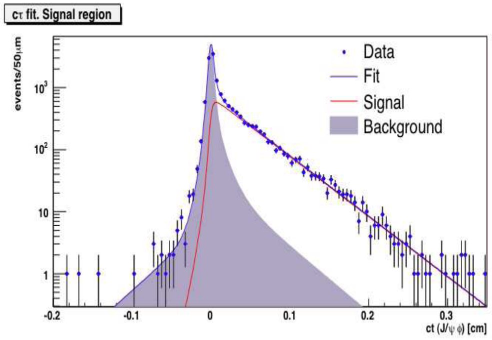
Analysis Components

- Multi-dimensional likelihood fit

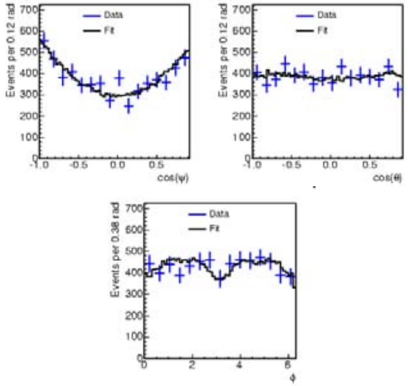
$$f_s P_s(m|\sigma_m) P_s(t,\vec{\rho},\xi|\mathcal{D},\sigma_t) P_s(\sigma_t) P_s(\mathcal{D})$$



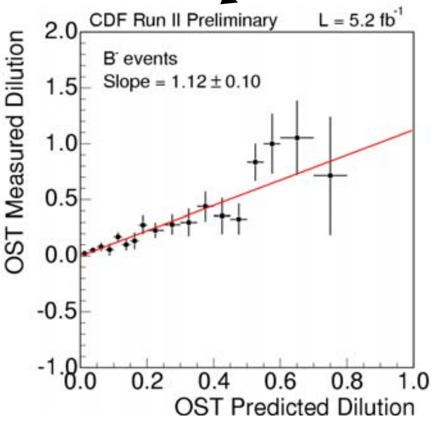
Mass
discriminate signal against background



Decay-time
determines lifetime of each mass eigenstate



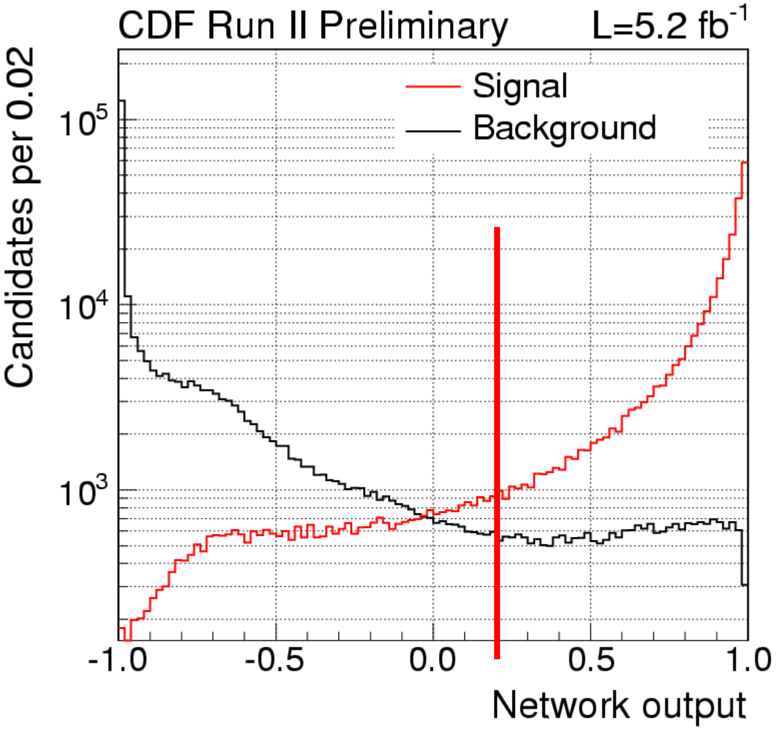
Angles
separate CP-even from CP-odd final states

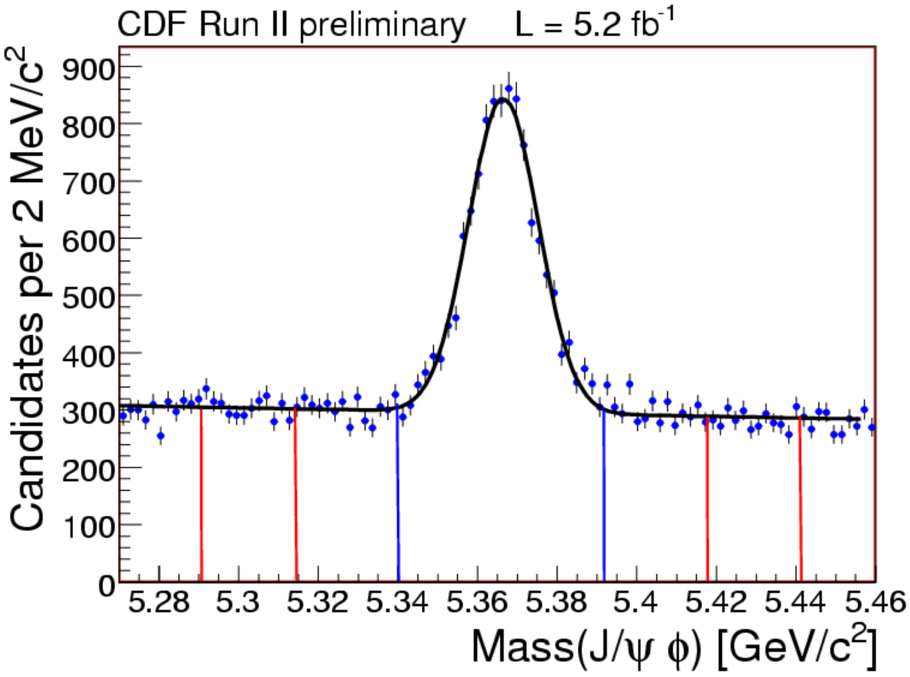


Tagging
determines flavor of initial B_s state

Signal Reconstruction

- Reconstruct $B^0_s \rightarrow J/\psi\Phi$ in 5.2 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 ~6500 signal B_s events with $S/B \sim 1$ (compared to ~3150 in 2.8 fb^{-1})





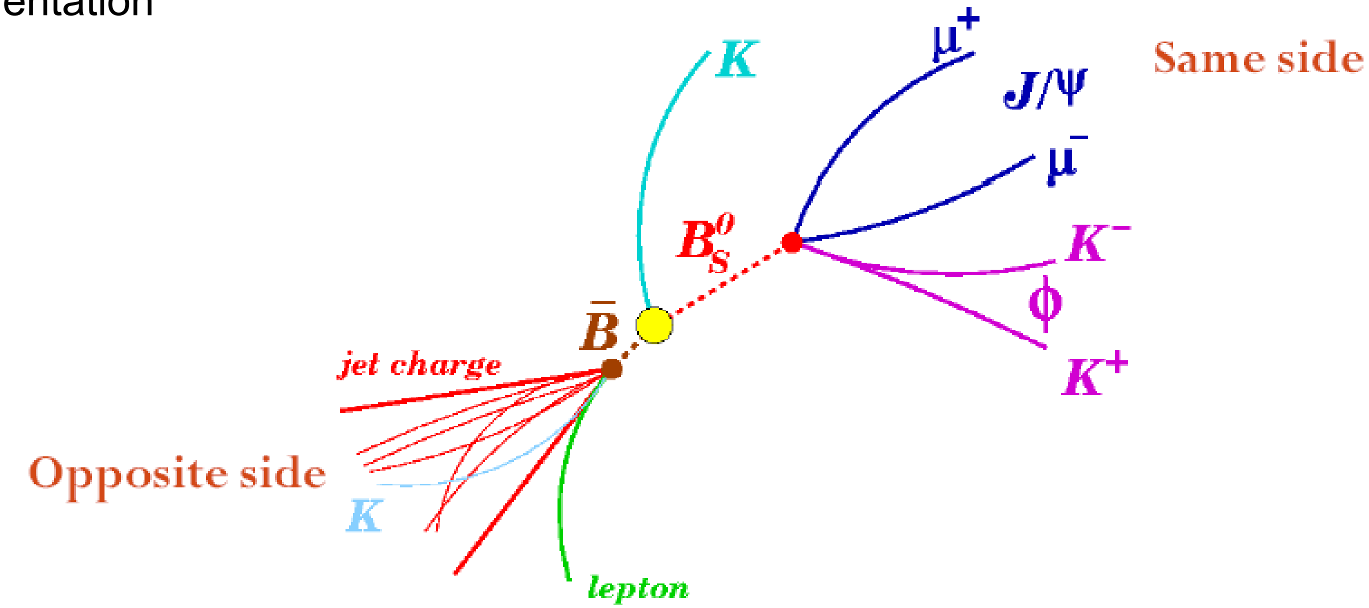
Flavor Tagging

- 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

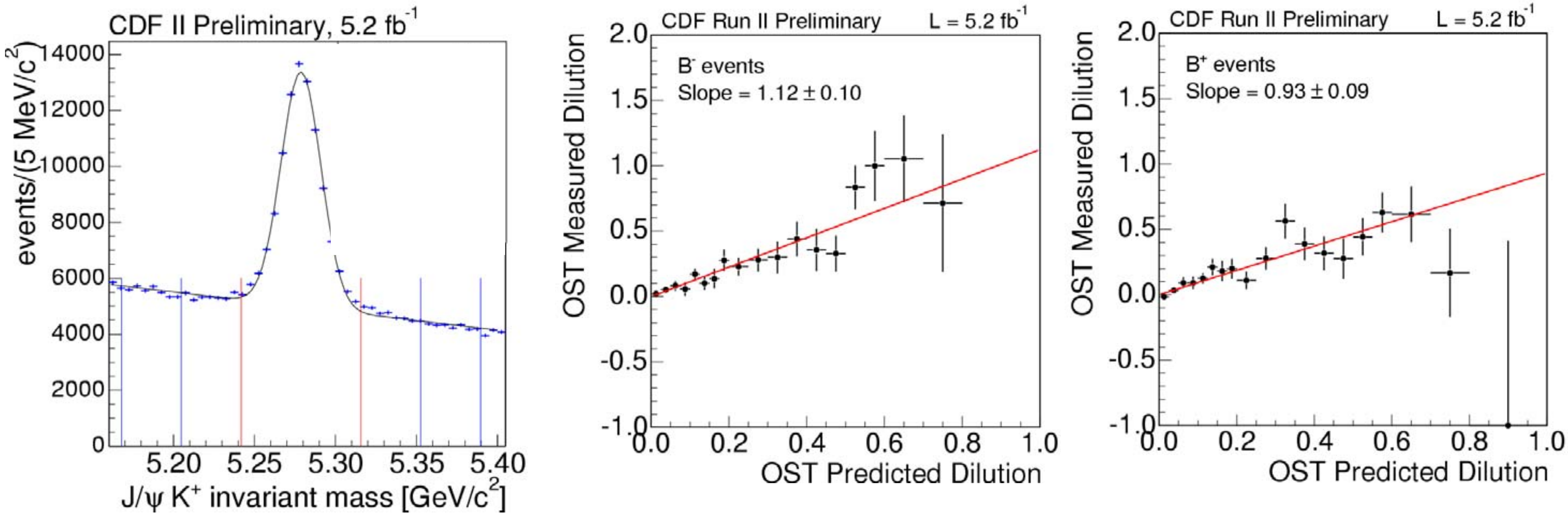
- Same Side Kaon Tagger (SSKT): exploits correlations with particles produced in fragmentation



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



- OST efficiency = 94.2 +/- 0.4%, OST dilution = 11.5 +/- 0.2 % (correct tag probability ~56%)
- Total tagging power = 1.2%

Same Side Tagging Calibration

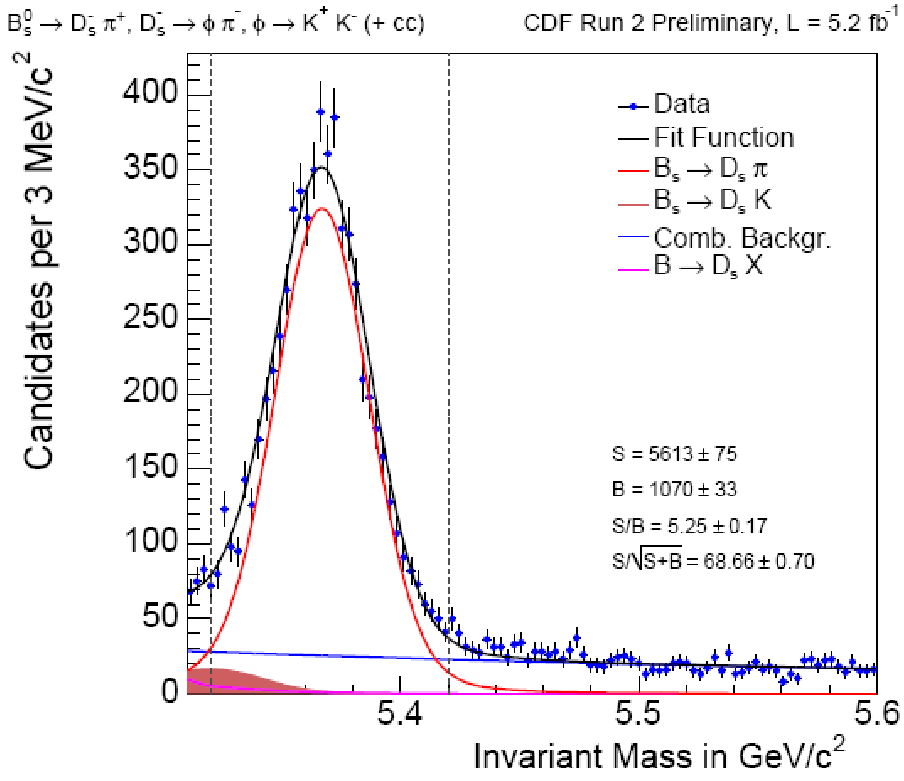
- Event-by-event predicted dilution based on simulation
- Calibrated with 5.2 fb^{-1} of data
- Simultaneously measuring the B_s mixing frequency Δm_s and the dilution scale factor A

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

- 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	$\mathbf{12877 \pm 113}$



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

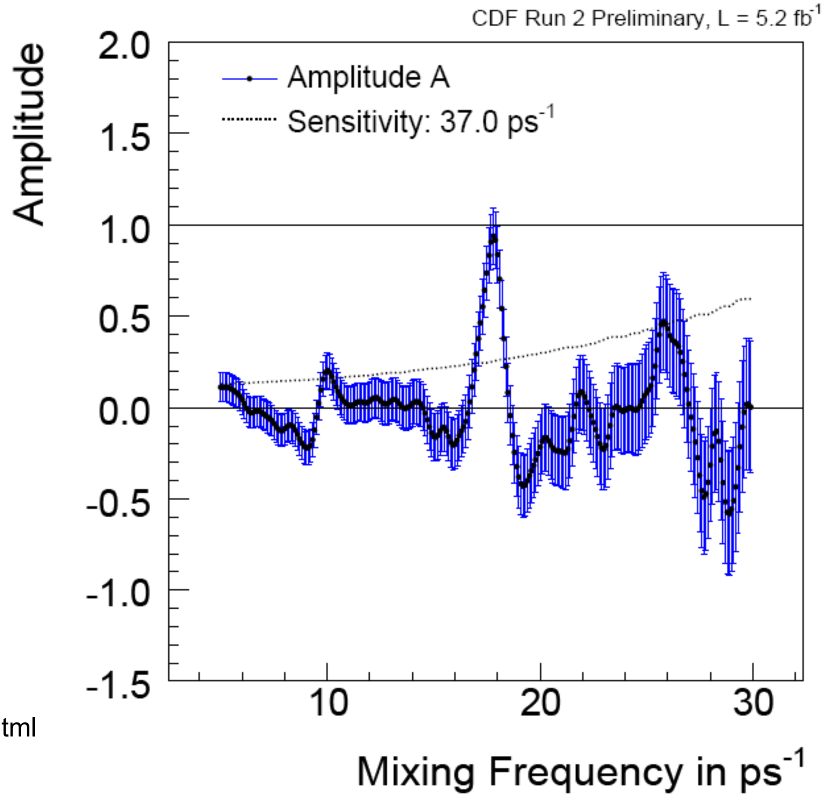
- Dilution scale factor (amplitude) in good agreement with 1:

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

- 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

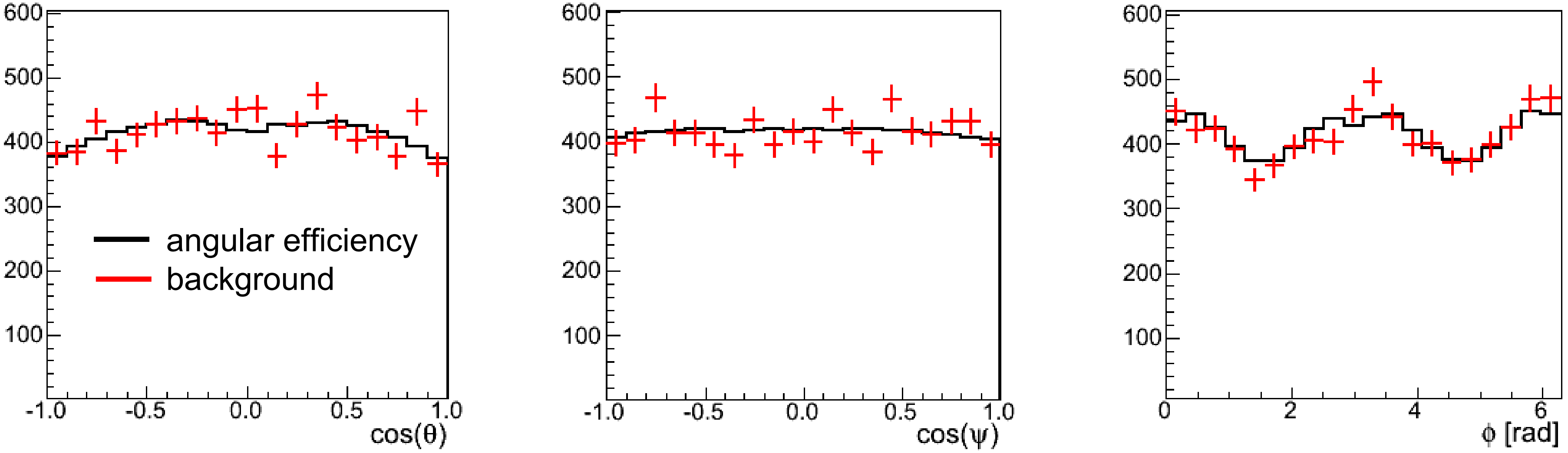
Detector Angular Efficiency

- *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

- Cross check angular efficiency by comparing with background angular distributions
  - good agreement indicates good modeling of angular efficiency

CDF Simulation of Detector Angular Sculpting



B_s Lifetime and Decay Width Difference

- Assuming no *CP* violation ($\beta_s = 0$) obtain most precise measurements of lifetime τ_s and decay width difference $\Delta\Gamma_s$:

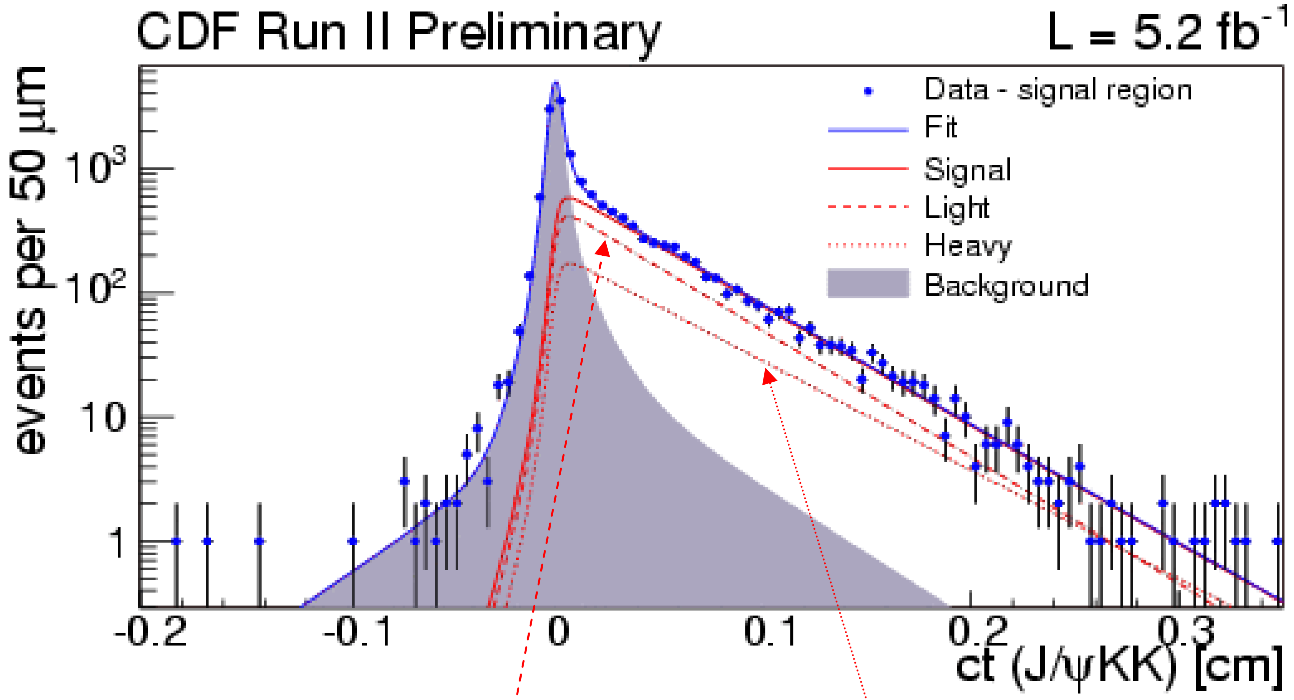
$$\tau_s = 1.53 \pm 0.025\ (\text{stat.})\ \pm 0.012\ (\text{syst.})\ \text{ps}$$

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

compared to 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

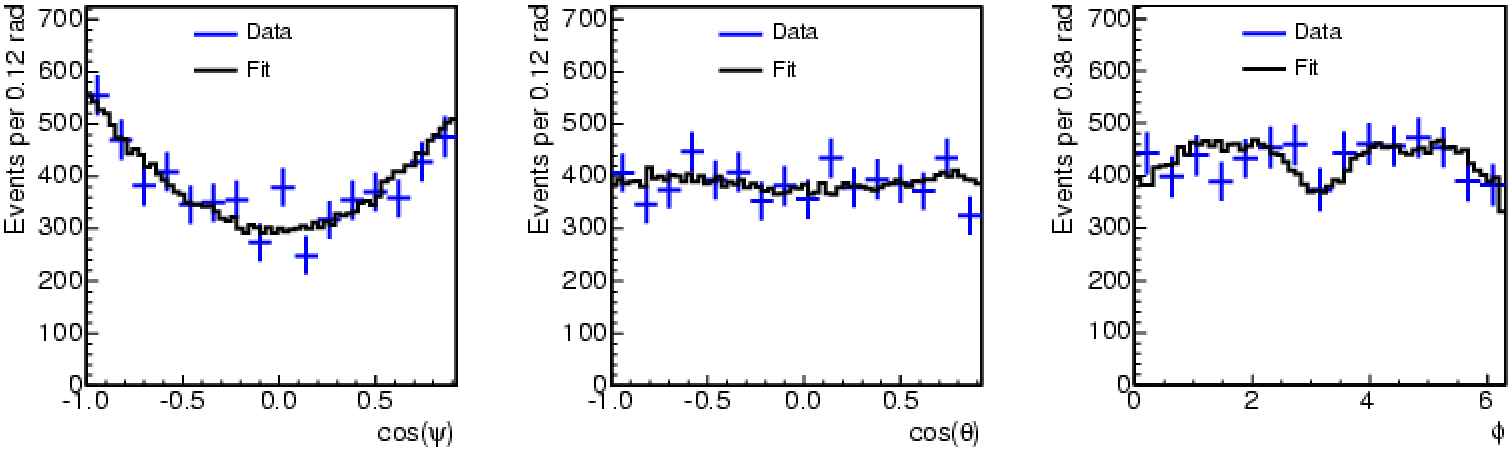
→ $\Delta\Gamma \neq 0$

Polarization Amplitudes

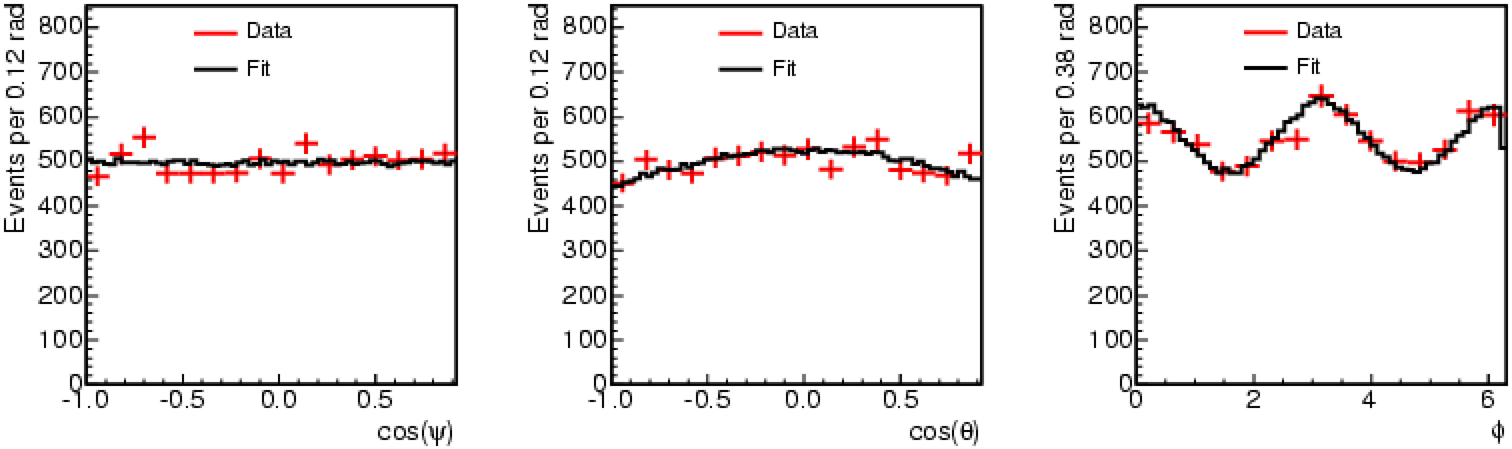
Most precise measurement of polarization amplitudes

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

Signal fit projections



Background fit projections

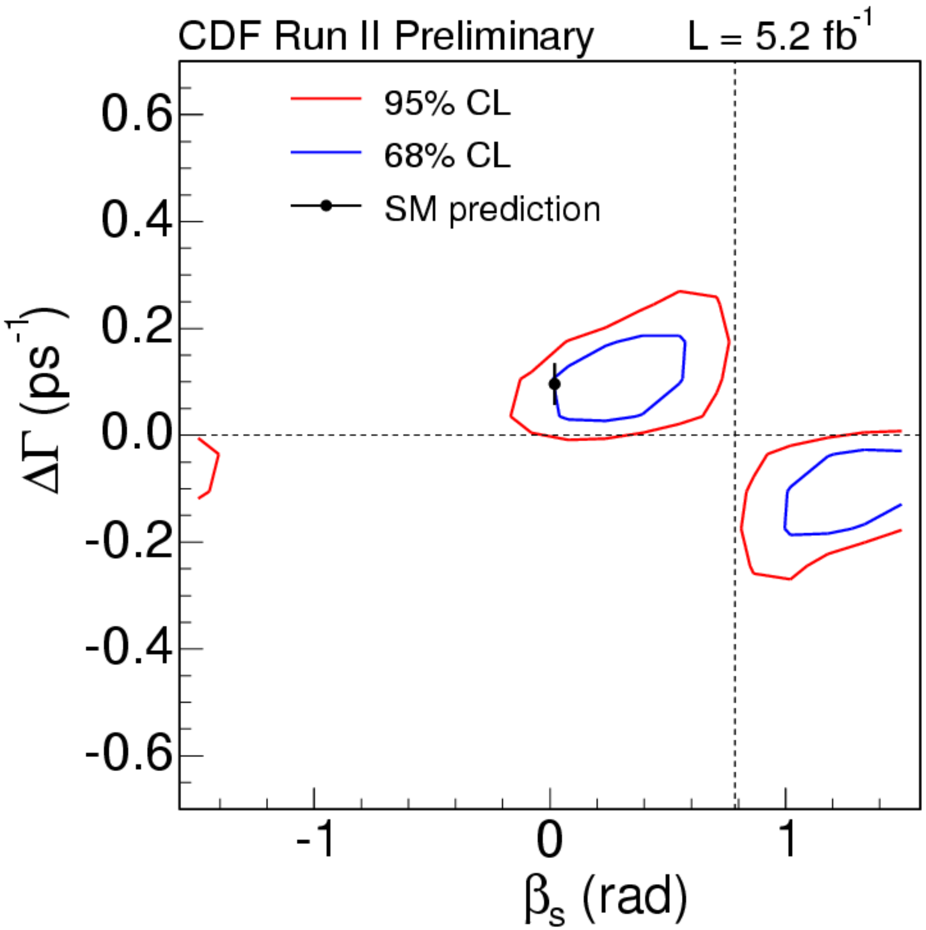


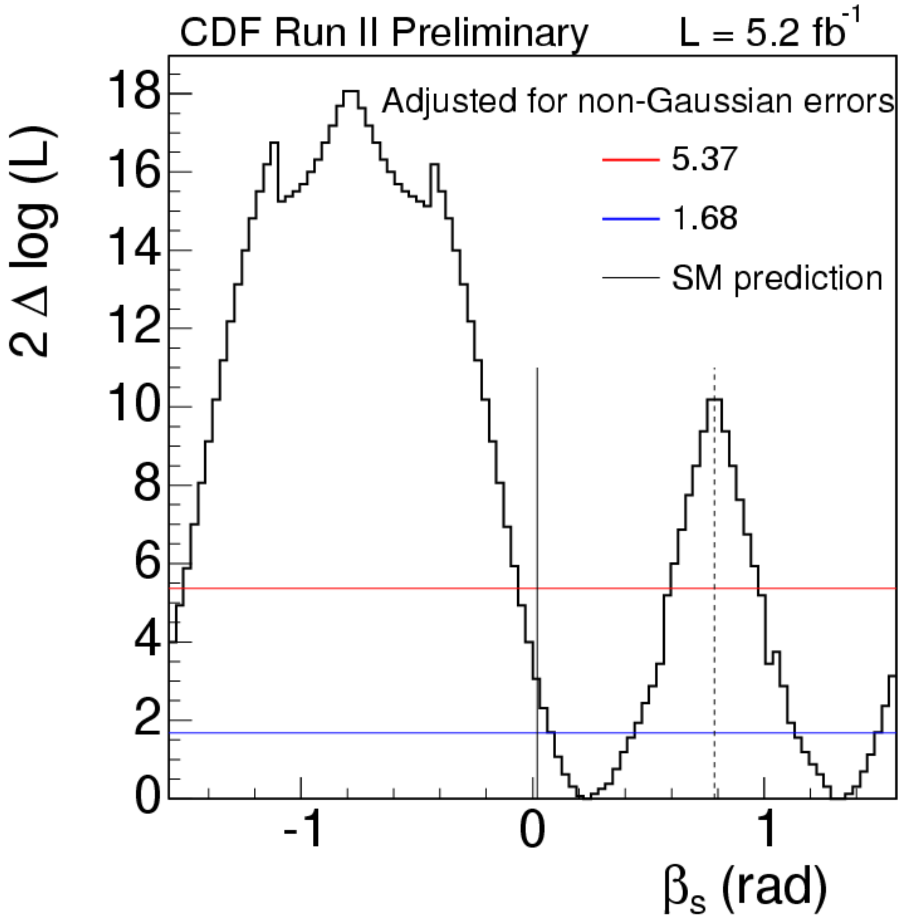
CP Violation Phase β_s with 5.2 fb^{-1} at CDF

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

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

- Agreement with SM at ~1σ level





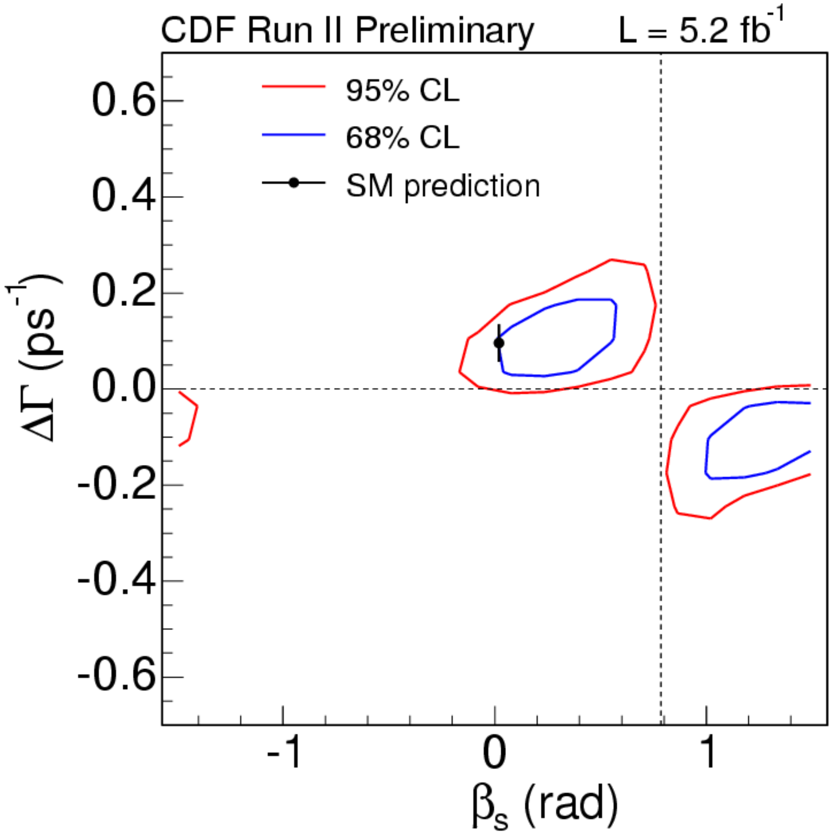
Conclusions

- Measurement of CP violation in B_s system updated by CDF with 5.2 fb^{-1}

- Tightened constraints in β_s space: [0.02, 0.52] U [1.08, 1.55] at 68% C.L.

- Improved agreement with SM expectation at ~1σ level

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



Prospects

- Possible analysis improvements:

  - Improve statistics by ~25-30% by adding $B_s \rightarrow J/\Psi\Phi$ decays from displaced track trigger (difficult due to trigger effects on decay time)

  - Addition of new decay modes:
    - $B_s \rightarrow J/\Psi f^0$, *with* $f^0 \rightarrow \pi\pi$ (less statistics but no angular analysis needed since final state is *CP* eigen-state)
    - $B_s \rightarrow \psi(2s)\Phi$

- Add more data !

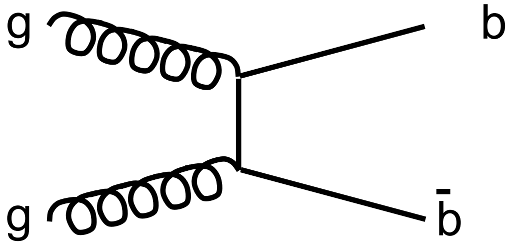
  - 7 fb^{-1} already recorded

  - expect to double sample size (~10 fb^{-1}) by end of Tevatron running in 2011

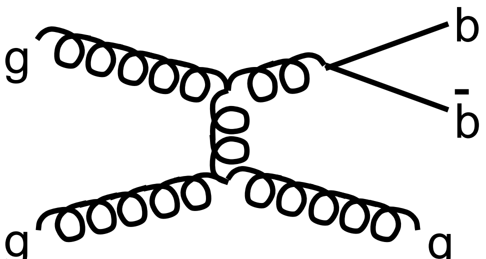
Backup Slides

B Physics at the Tevatron

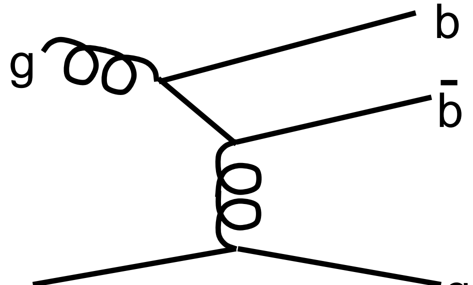
- Mechanisms for b production in $p\bar{p}$ collisions at 1.96 TeV



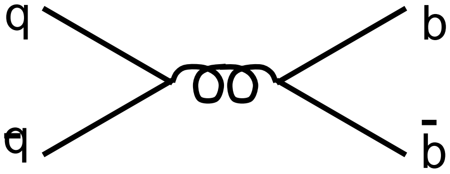
Flavor Creation (gluon fusion)



Gluon Splitting



Flavor Excitation



Flavor Creation (annihilation)

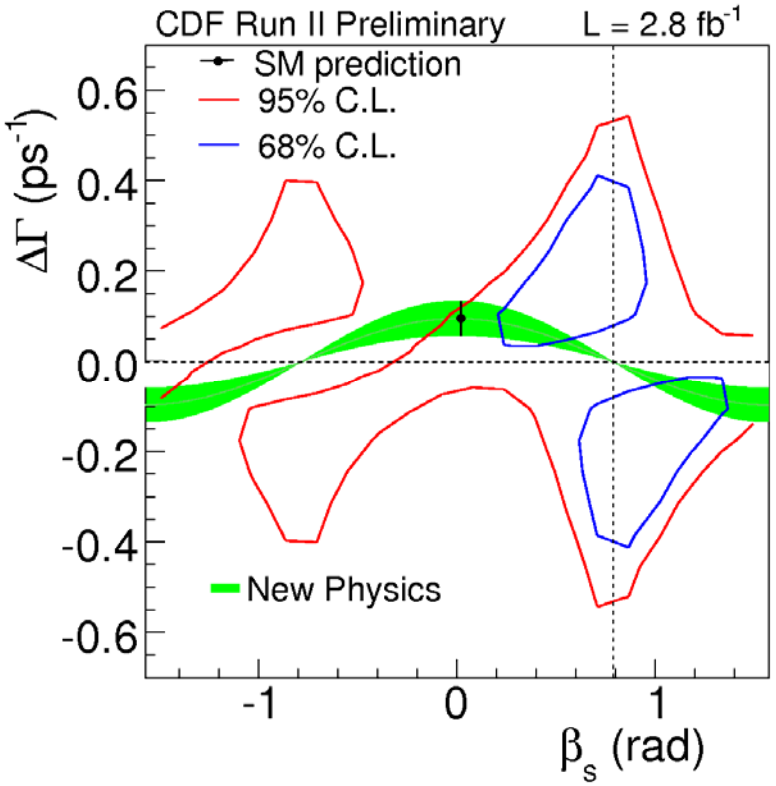
- At Tevatron, b production cross section is much larger compared to B-factories
  → Tevatron experiments CDF and DØ enjoy rich B Physics program

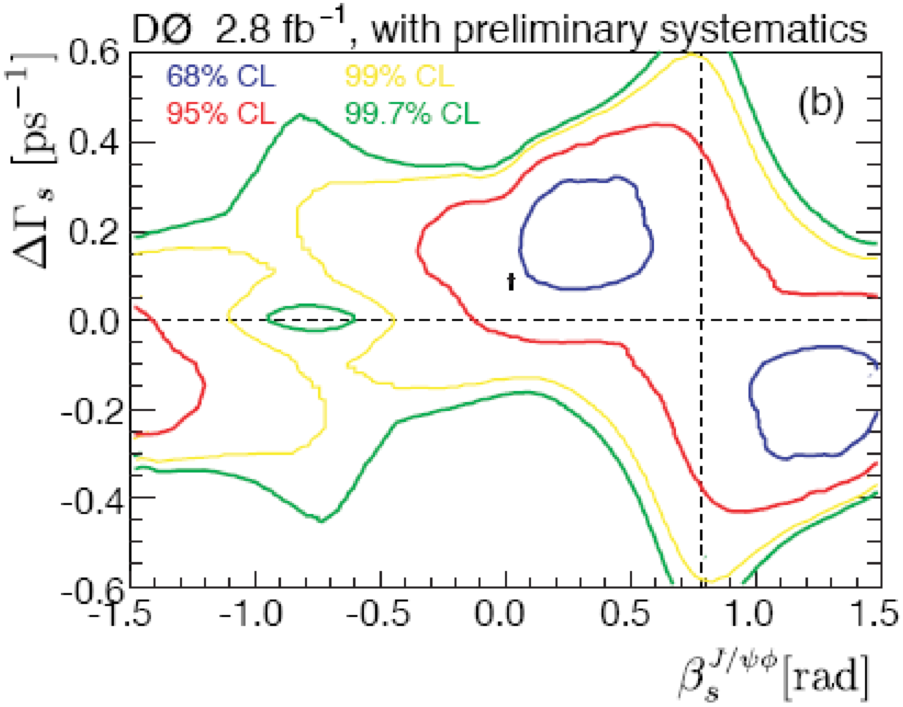
- Plethora of states accessible only at Tevatron: B_s, B_c, Λ_b, Ξ_b, Σ_b…
  → complement the B factories physics program

- Total inelastic cross section at Tevatron is ~1000 larger than b cross section
  → large backgrounds suppressed by triggers that target specific decays

Status Before This Update

- Both CDF (public note 9458) and DØ (conference Note 5933-CONF) showed ~1.5σ deviations from SM in the same direction





β_s vs ϕ_s

- Up to now, introduced two different phases:

$\phi_s^{SM} = \arg\left(-\frac{M_{12}}{\Gamma_{12}}\right) \approx 4\times10^{-3}$ and $\beta_s^{\mathrm{SM}} = \arg(-V_{ts}V_{tb}^*/V_{cs}V_{cb}^*) \approx 0.02$

- New Physics affects both phases by same quantity ϕ_s^{NP} (arxiv:0705.3802v2):

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

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

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

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

Decay Rate

- $B_s \rightarrow J/\Psi\Phi$ decay rate (A.S. Dighe *et al.*, Phys. Lett. B **369** 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:

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

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

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

Decay Rate with S-Wave Included

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

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

CP-odd

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:

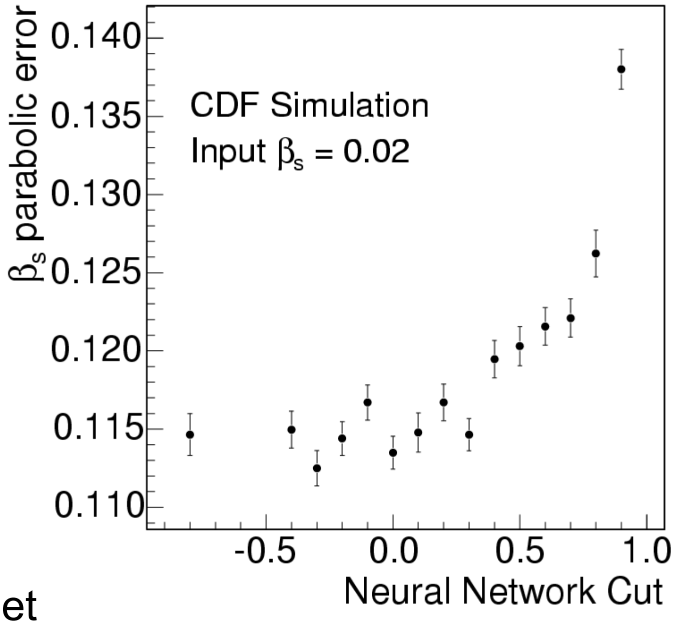
$$\begin{aligned}\rho_B(\theta,\psi,\phi,t) &= (1-F_s)\cdot P_B(\theta,\psi,\phi,t)+F_sQ_B(\theta,\psi,\phi,t)\\ &+\ 2\frac{\sqrt{27}}{16\pi}Re\left[\mathcal{I}_\mu\left((\mathbf{A}_-\times\hat{n})\cdot(\mathbf{B}\times\hat{n})\cdot|f_-(t)|^2+(\mathbf{A}_+\times\hat{n})\cdot(\mathbf{B}\times\hat{n})\cdot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

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

Analysis Improvements with Respect To 2008 Update

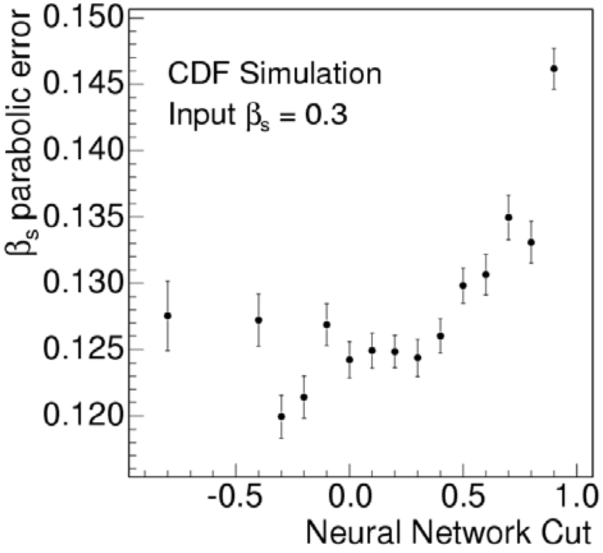
- Almost doubled data sample (from 2.8 fb^{-1} in 2008 to 5.2 fb^{-1} now)

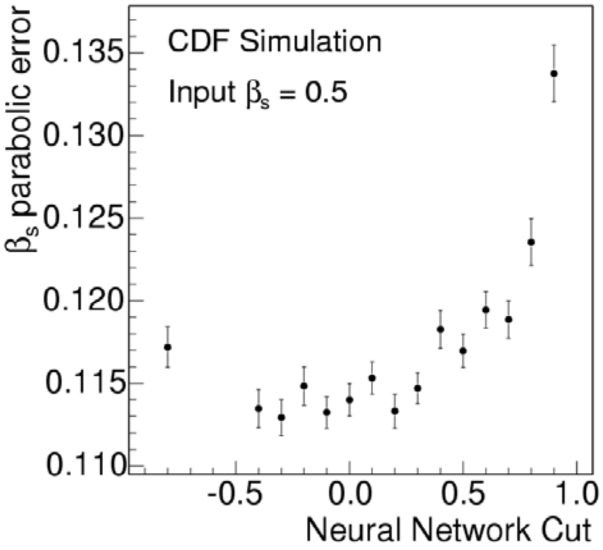
- Improved signal selection:
  - use particle ID (dE/dx and TOF) for full dataset
  - use pseudo-experiments to optimize neural network selection to minimize β_s statistical uncertainty (previously used $S/(S+B)^{1/2}$ as figure of merit)



- Same side kaon tagger (SSKT) used for the full dataset
  - re-calibrated by measuring B_s mixing frequency with 5.2 fb^{-1}

- Inclusion of S-wave contamination in the likelihood fit


CDF Simulation
Input β_s = 0.3
β_s parabolic error
0.150
0.145
0.140
0.135
0.130
0.125
0.120
-0.5
0.0
0.5
1.0
Neural Network Cut


CDF Simulation
Input β_s = 0.5
β_s parabolic error
0.135
0.130
0.125
0.120
0.115
0.110
-0.5
0.0
0.5
1.0
Neural Network Cut

Comparison between tagged and un-tagged fit with and without accounting for S-wave

$$\begin{aligned} c\tau &= 458.64 \pm 7.54 \text{ (stat.) } \mu m \\ \Delta\Gamma &= 0.075 \pm 0.035 \text{ (stat.) } ps^{-1} \\ |A_{\parallel}|^2 &= 0.231 \pm 0.014 \text{ (stat.)} \\ |A_0|^2 &= 0.524 \pm 0.013 \text{ (stat.)} \\ \phi_{\perp} &= 2.95 \pm 0.64 \text{ (stat.)} \end{aligned}$$

Tagged, with S-wave

$$\begin{aligned} c\tau &= 459.1 \pm 7.7 \text{ (stat.) } \mu m \\ \Delta\Gamma &= 0.073 \pm 0.03 \text{ (stat.) } ps^{-1} \\ |A_{\parallel}|^2 &= 0.232 \pm 0.014 \text{ (stat.)} \\ |A_0|^2 &= 0.523 \pm 0.012 \text{ (stat.)} \\ \phi_{\perp} &= 2.80 \pm 0.56 \end{aligned}$$

Tagged, no S-wave

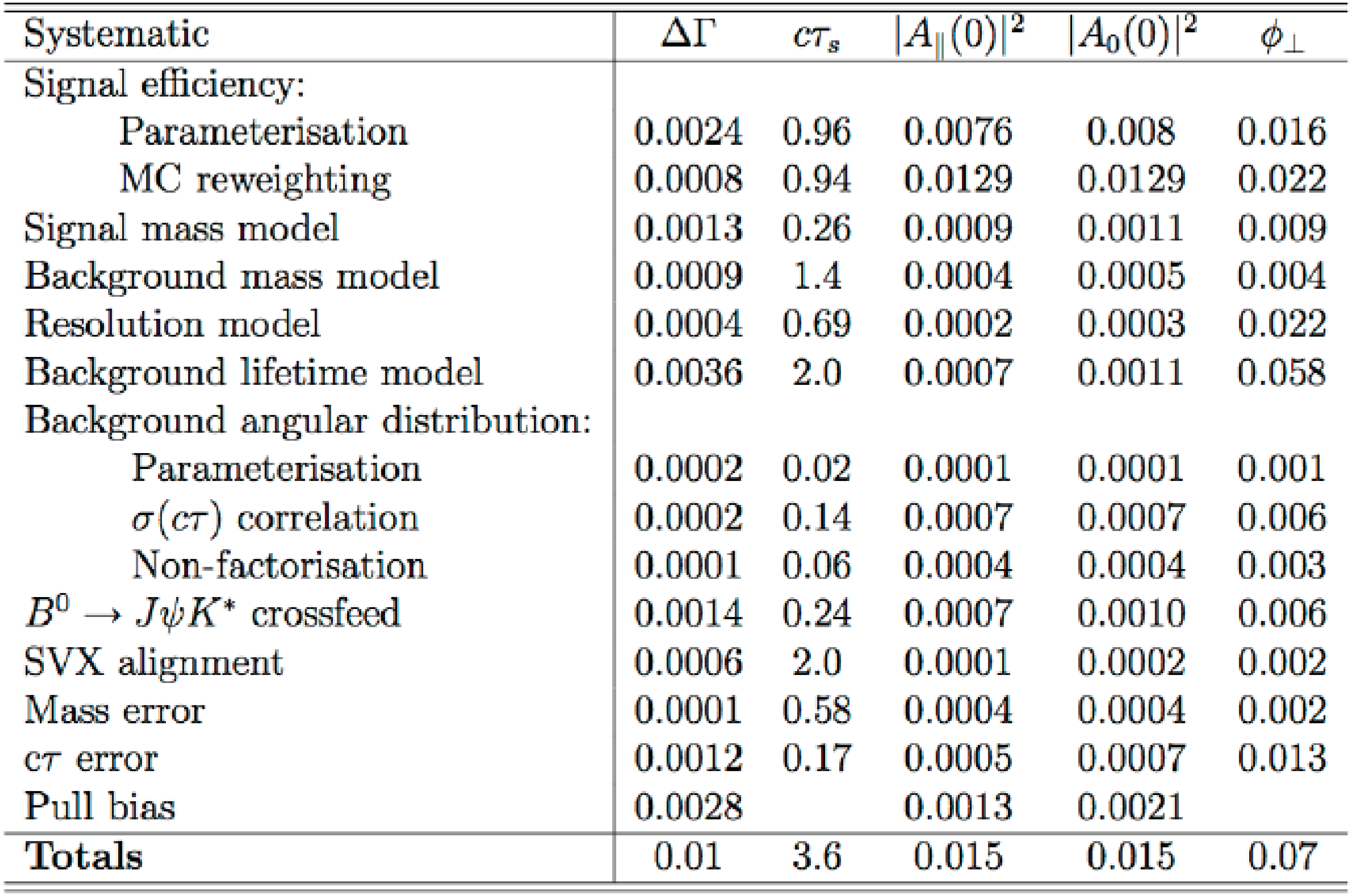
Untagged, with S-wave

$$\begin{aligned} c\tau &= 456.93 \pm 7.69 \text{ (stat.) } \mu m \\ \Delta\Gamma &= 0.071 \pm 0.036 \text{ (stat.) } ps^{-1} \\ |A_{\parallel}|^2 &= 0.233 \pm 0.015 \text{ (stat.)} \\ |A_0|^2 &= 0.521 \pm 0.013 \text{ (stat.)} \end{aligned}$$

Untagged, no S-wave

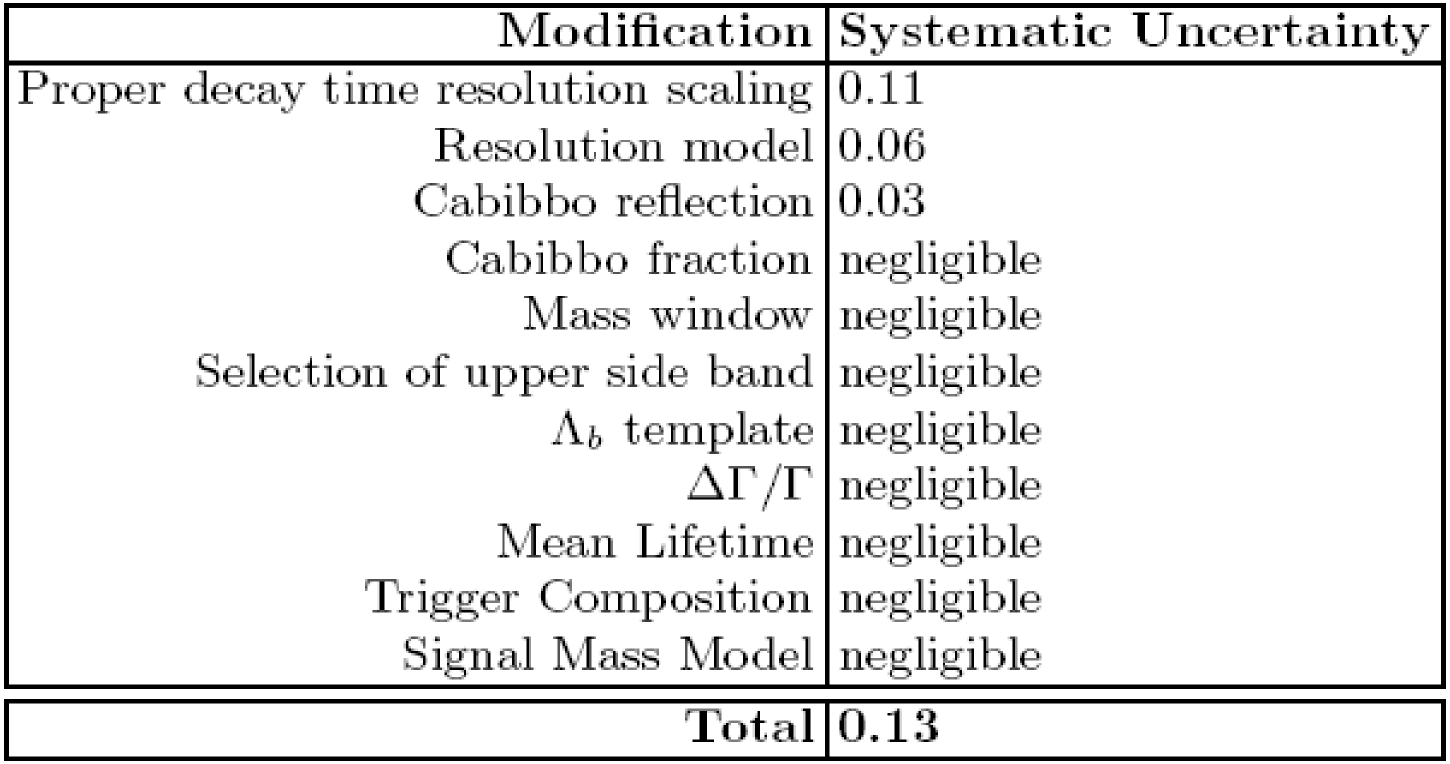
$$\begin{aligned} c\tau &= 457.2 \pm 7.9 \text{ (stat.) } \mu m \\ \Delta\Gamma &= 0.070 \pm 0.04 \text{ (stat.) } ps^{-1} \\ |A_{\parallel}|^2 &= 0.233 \pm 0.016 \text{ (stat.)} \\ |A_0|^2 &= 0.520 \pm 0.013 \text{ (stat.)} \end{aligned}$$

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

Dilution Scale Factor Systematic Uncertainties



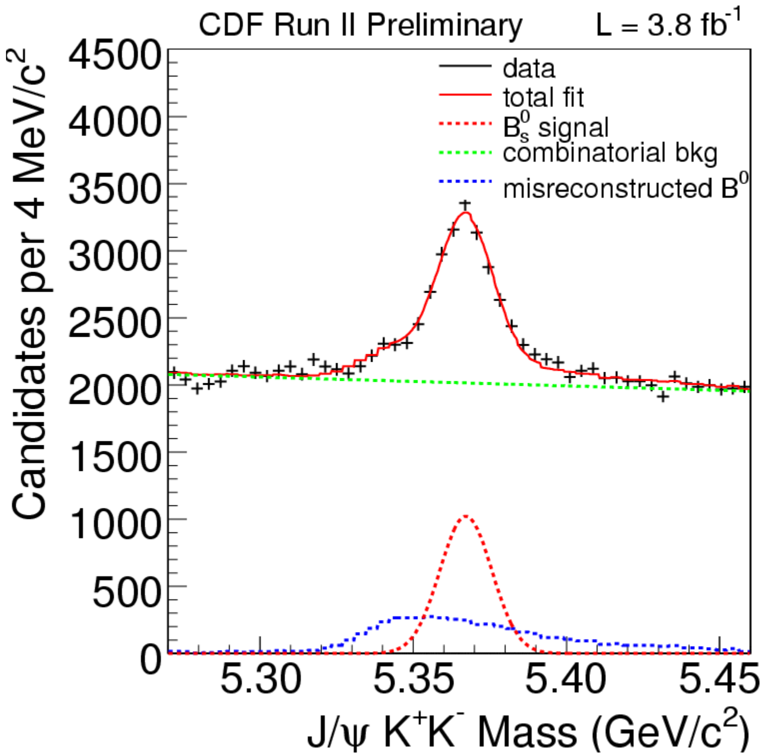
Modification	Systematic Uncertainty
Proper decay time resolution scaling	0.11
Resolution model	0.06
Cabibbo reflection	0.03
Cabibbo fraction	negligible
Mass window	negligible
Selection of upper side band	negligible
Λ_b template	negligible
$\Delta\Gamma/\Gamma$	negligible
Mean Lifetime	negligible
Trigger Composition	negligible
Signal Mass Model	negligible
Total	**0.13**

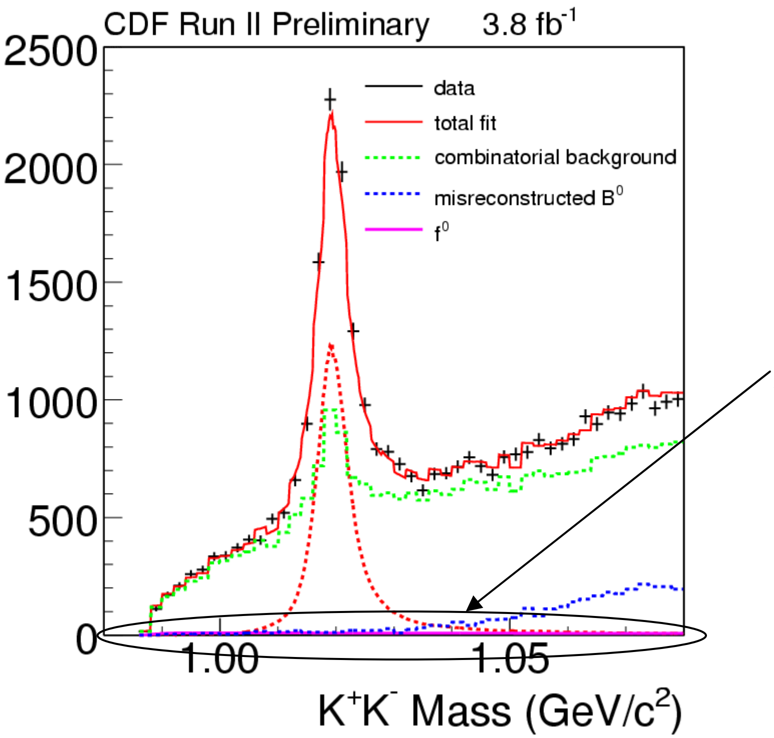
S-Wave Cross Check Using KK Mass Spectrum

- 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

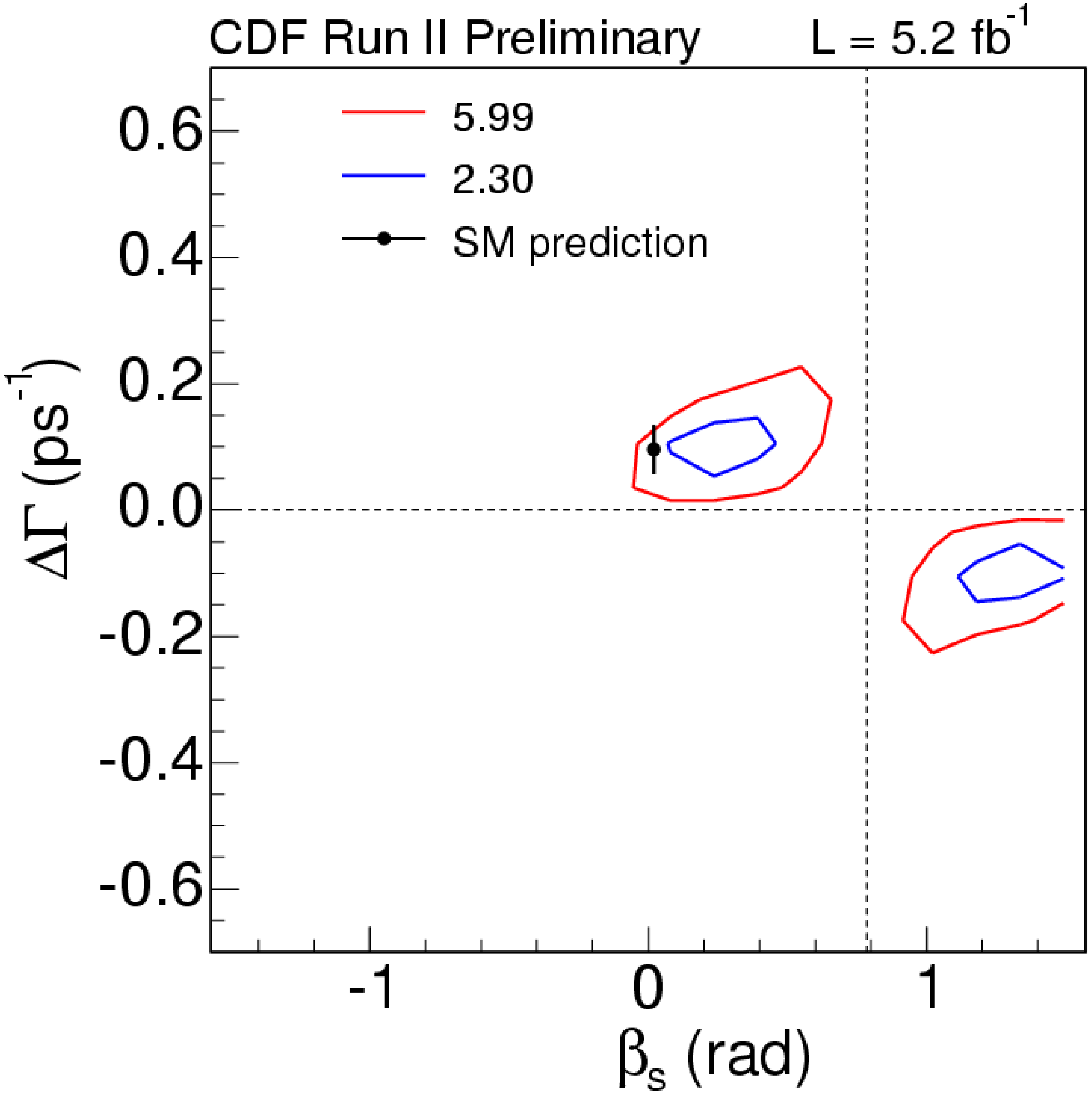
- Good fit of the KK mass spectrum with 2% f^0 contributions



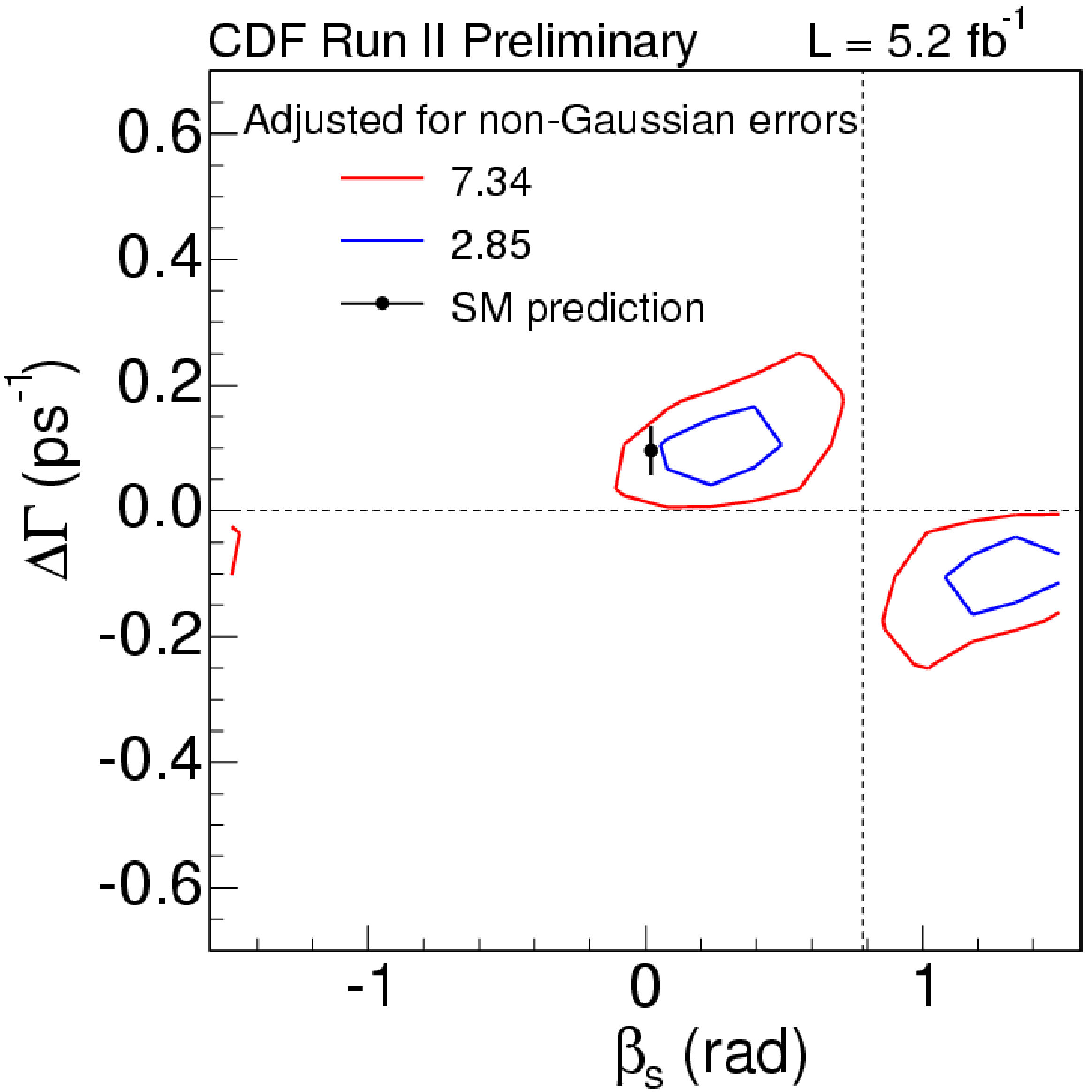


Barely visible S-wave component

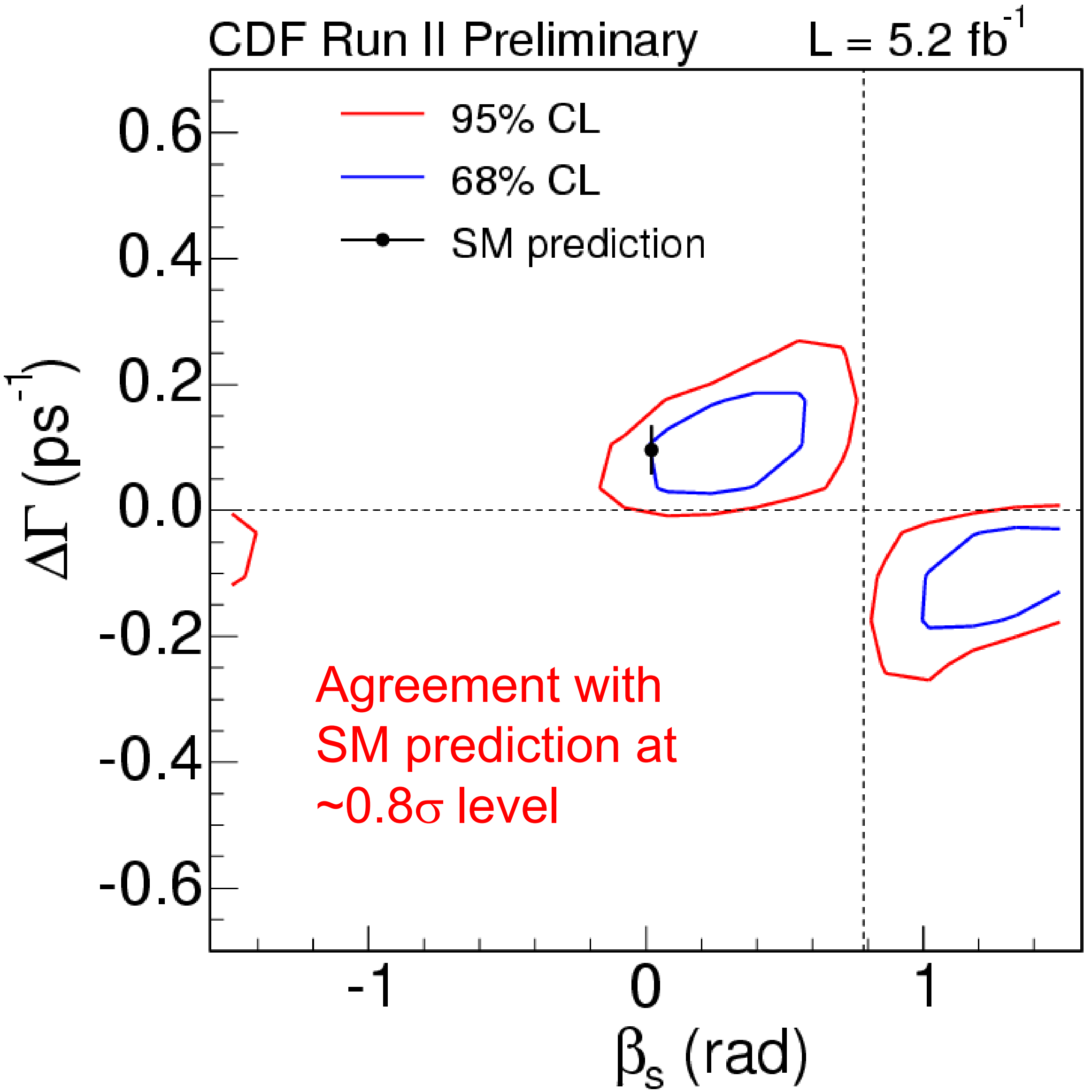
β_s-$\Delta\Gamma$ Contours Without Coverage Adjustment



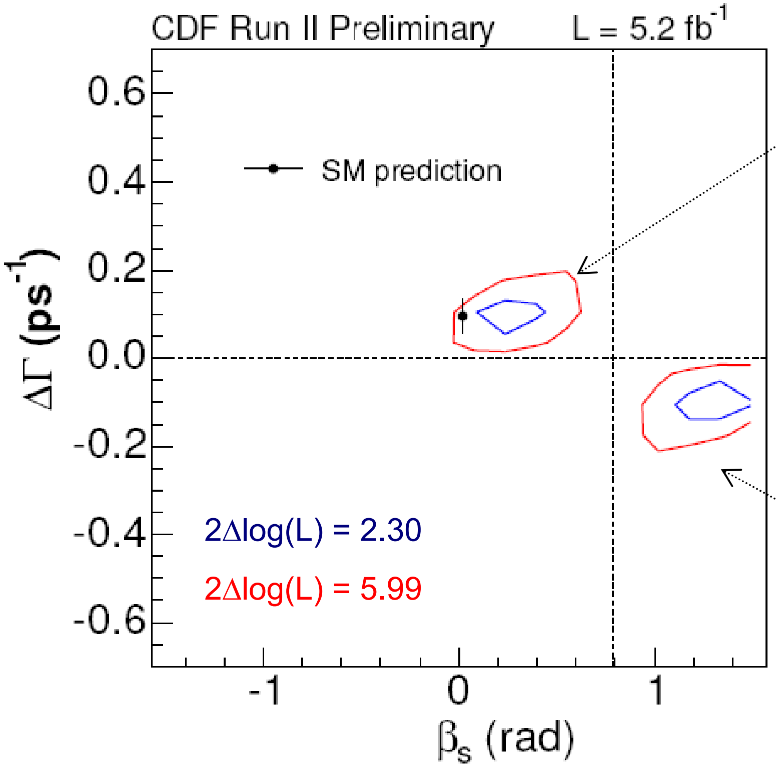
β_s-$\Delta\Gamma$ Contours With Coverage Adjustment



β_s-$\Delta\Gamma$ Contours With Systematics on Coverage



Agreement with SM prediction at ~0.8σ level

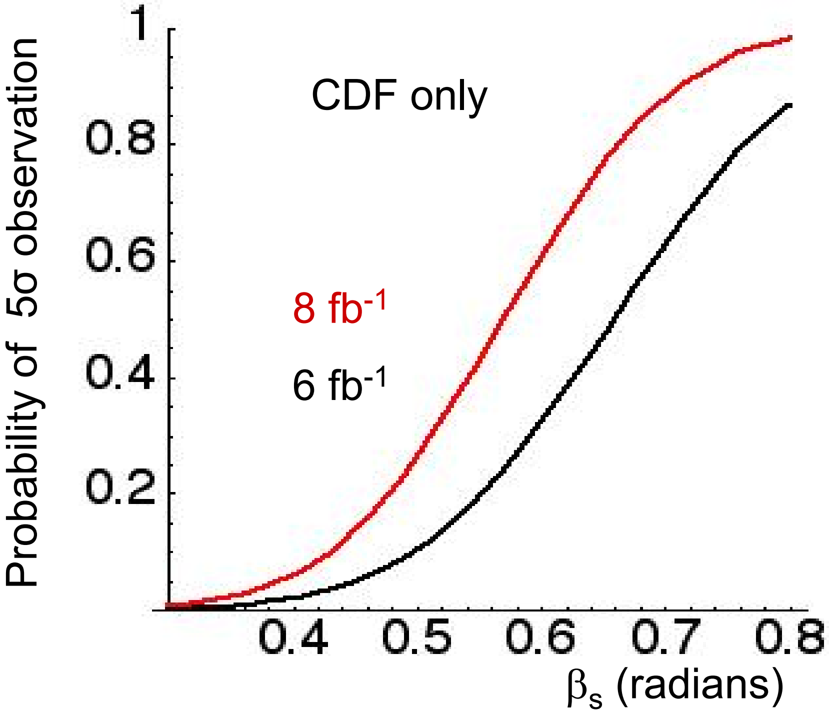


$\cos(\delta_\perp) < 0$
$\cos(\delta_\perp - \delta_\parallel) > 0$

strong phases
could separate
the two minima

$\cos(\delta_\perp) > 0$
$\cos(\delta_\perp - \delta_\parallel) < 0$

Sensitivity



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

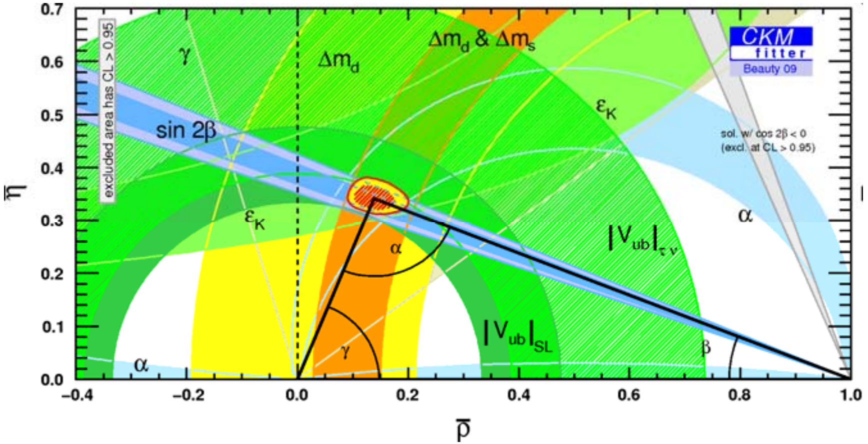
James Cronin

Val Fitch

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

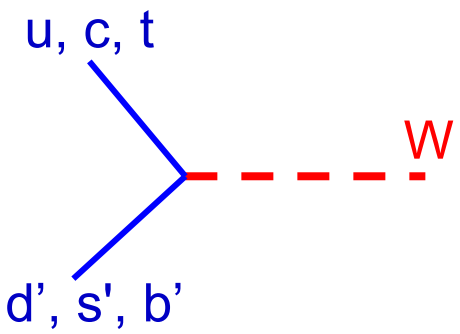
- Could still find large *CP* violation within the SM in the lepton sector
  - initial asymmetry between leptons and anti-leptons may induce baryon asymmetry through baryon number violation processes (lepto-genesis)
  - long baseline neutrino experiments will investigate CP violation in neutrino sector

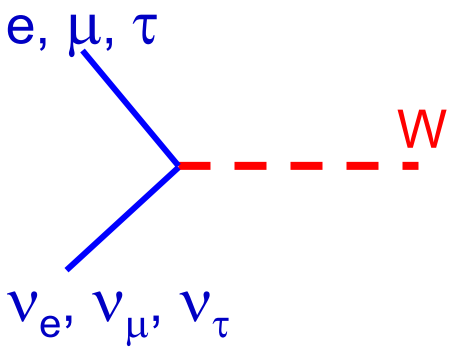
- Alternatively we look for sources of *CP* violation beyond the SM in the quark sector

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

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 $\lambda = V_{us} = \sin(\theta_{Cabibbo}) \approx 0.23$

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

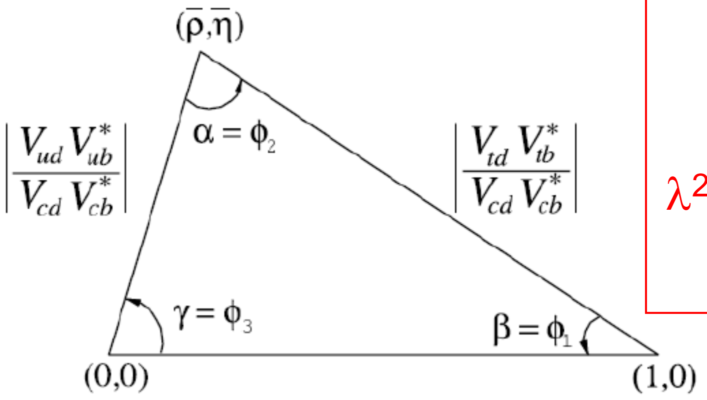
- To conserve probability CKM matrix must be unitary
  → Unitary relations can be represented as "unitarity triangles"

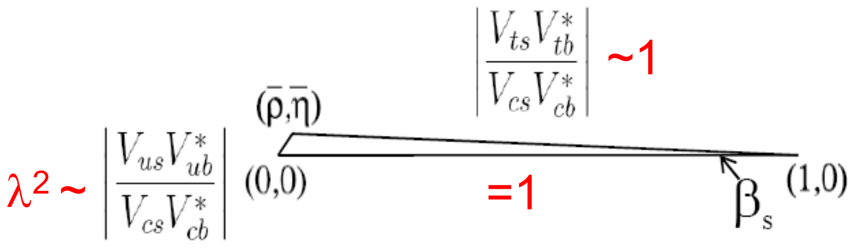
unitarity relations:

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

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

unitarity triangles:



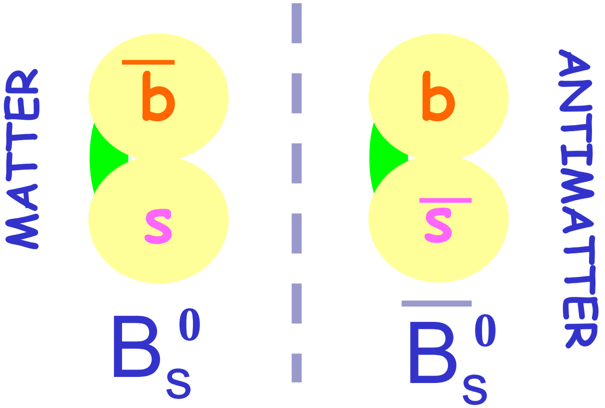


Small *CP* violation phase β_s accessible in $B_s \to J/\psi\Phi$ decays

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:

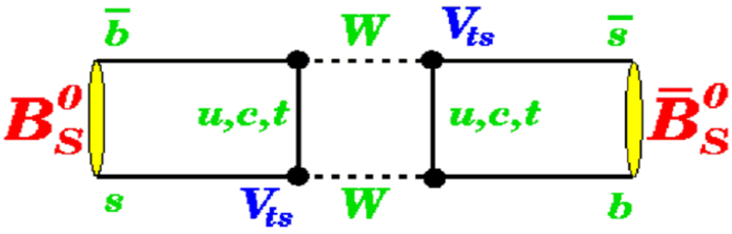
$\Delta m_s = m_H - m_L \approx 2|M_{12}|$

→ B_s oscillates with frequency Δm_s

precisely measured by

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

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



- Mass eigenstates have different decay widths

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

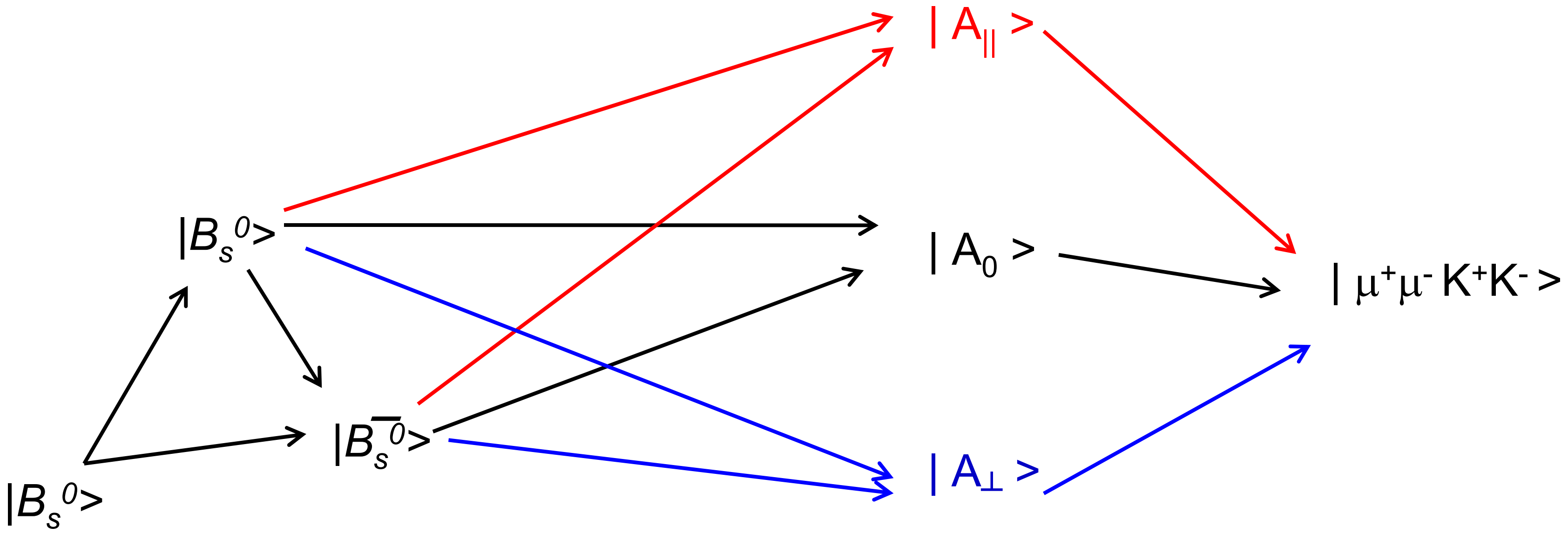
Transversity Basis

- 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 ($\parallel$ parallel to each other) → *CP even*
- longitudinal (0) → *CP even*

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



Decay Rate

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

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

time dependence terms

angular dependence terms

terms with β_s dependence

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

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

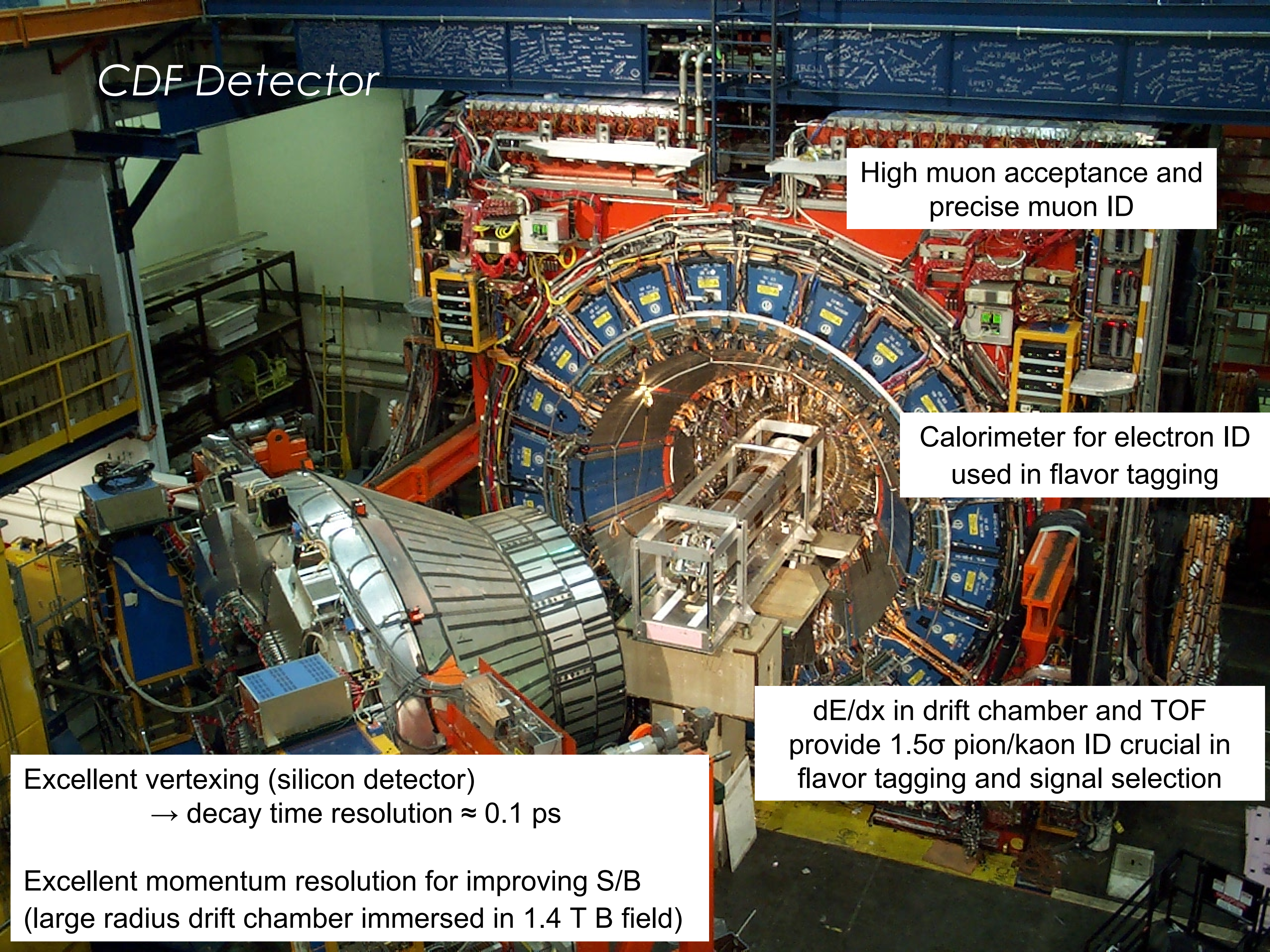
$$\begin{aligned}\mathcal{U}_\pm = \pm e^{-\Gamma t} \times\ & [\sin(\delta_\perp - \delta_\parallel)\cos(\Delta m_s t) \\ & - \cos(\delta_\perp - \delta_\parallel)\cos(2\beta_s)\sin(\Delta m_s t) \\ & \pm \cos(\delta_\perp - \delta_\parallel)\sin(2\beta_s)\sinh(\Delta\Gamma t/2)] \\ \mathcal{V}_\pm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

‘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

CDF Detector



High muon acceptance and
precise muon ID

Calorimeter for electron ID
used in flavor tagging

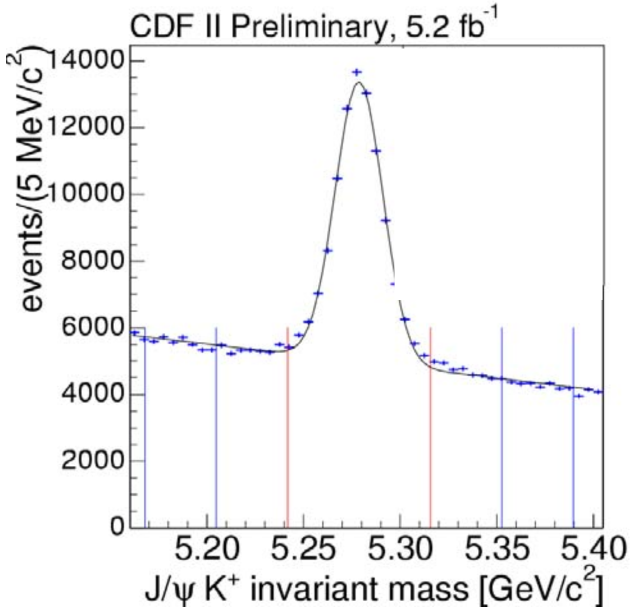
dE/dx in drift chamber and TOF
provide 1.5σ pion/kaon ID crucial in
flavor tagging and signal selection

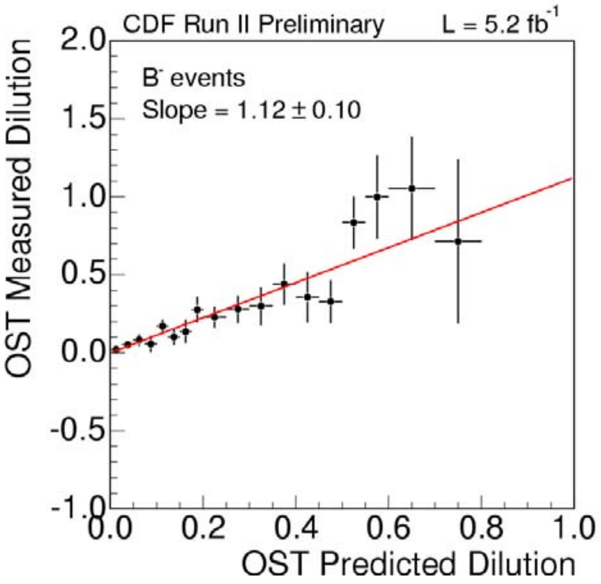
Excellent vertexing (silicon detector)
→ decay time resolution ≈ 0.1 ps

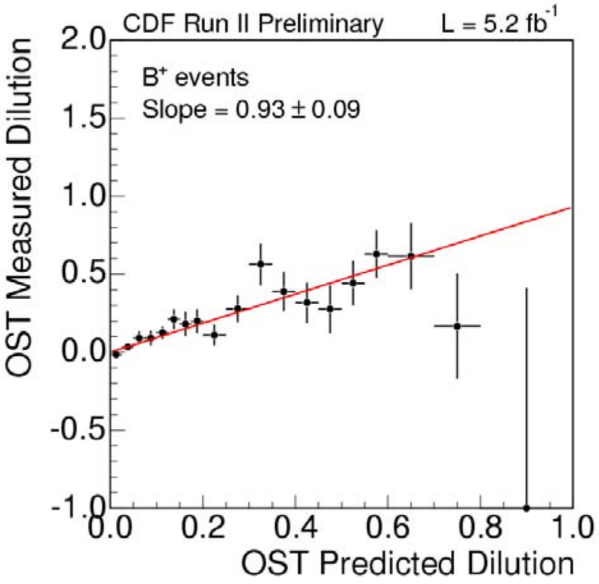
Excellent momentum resolution for improving S/B
(large radius drift chamber immersed in 1.4 T B field)

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 % (correct tag probability ~56%)
- Total tagging power = 1.2%

Same Side Tagging Calibration

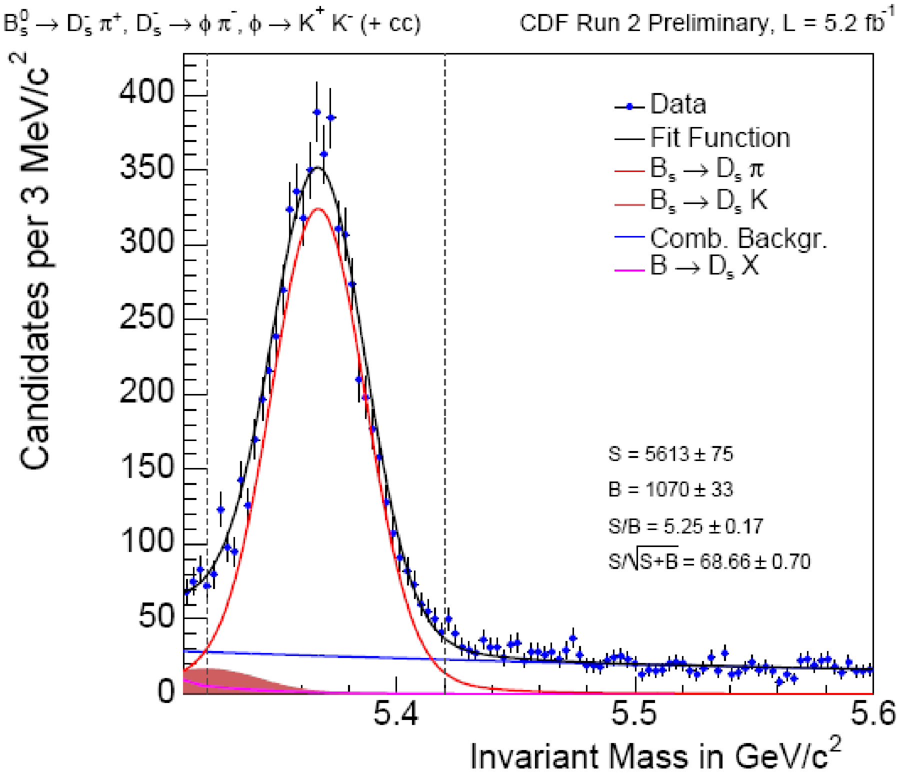
- Event-by-event predicted dilution based on simulation
- Calibrated with 5.2 fb^{-1} of data
- Simultaneously measuring the B_s mixing frequency Δm_s and the dilution scale factor A

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

- 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	$\mathbf{12877 \pm 113}$



Same Side Tagging Performance

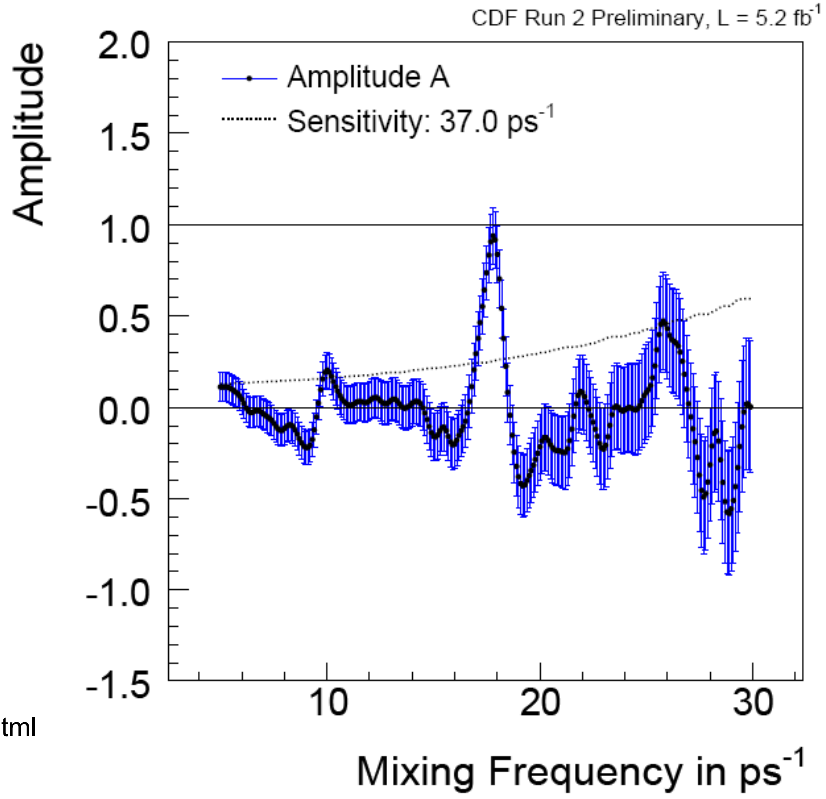
- B_s oscillation frequency measured $\Delta m_s = (17.79 \pm 0.07)\ \mathrm{ps}^{-1}$ (statistical error only)

- 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

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 where it is shown that:
    - 10% un-accounted s-wave contamination in the *Φ* region leads to
        - 10% bias in the measured $2\beta_s$, 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 $A_\perp$

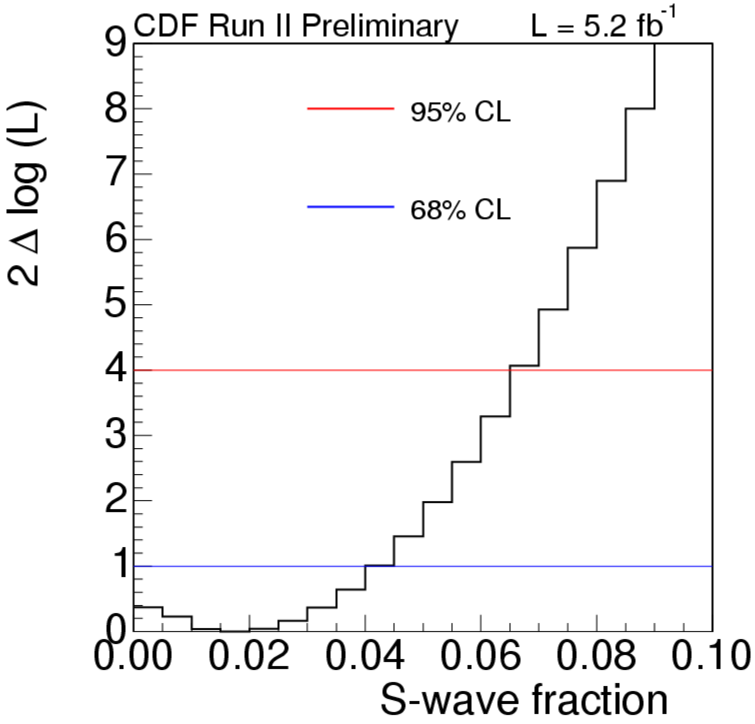
- Mass and phase of s-wave component are assumed flat (good approximation in a narrow +/- 10 MeV around the *Φ* mass)

S-Wave Measurement

- 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 < 6.7% at 95% C.L.

- To be compared with expectation from arxiv:0812.2832v3 of 6.3% s-wave contribution in a range of +/- 10 MeV around the Φ peak



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

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

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

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

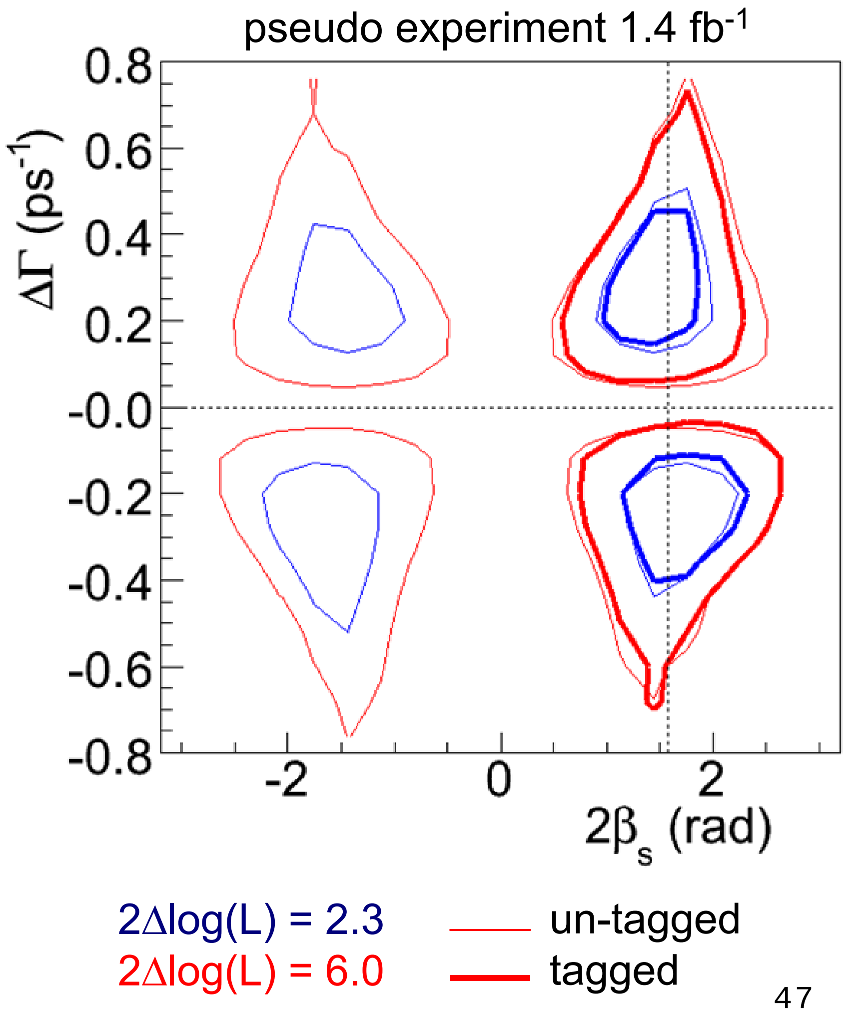
- Study expected effect of tagging using pseudo-experiments

- Improvement of parameter resolution is small due to limited tagging power (εD^2 ~ 4.5% compared to B factories ~30%)

- However, $\beta_s \rightarrow -\beta_s$ no longer a symmetry → 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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$$\delta_{||} \to 2\pi - \delta_{||} \qquad \delta_{\perp} \to \pi - \delta_{\perp}$$

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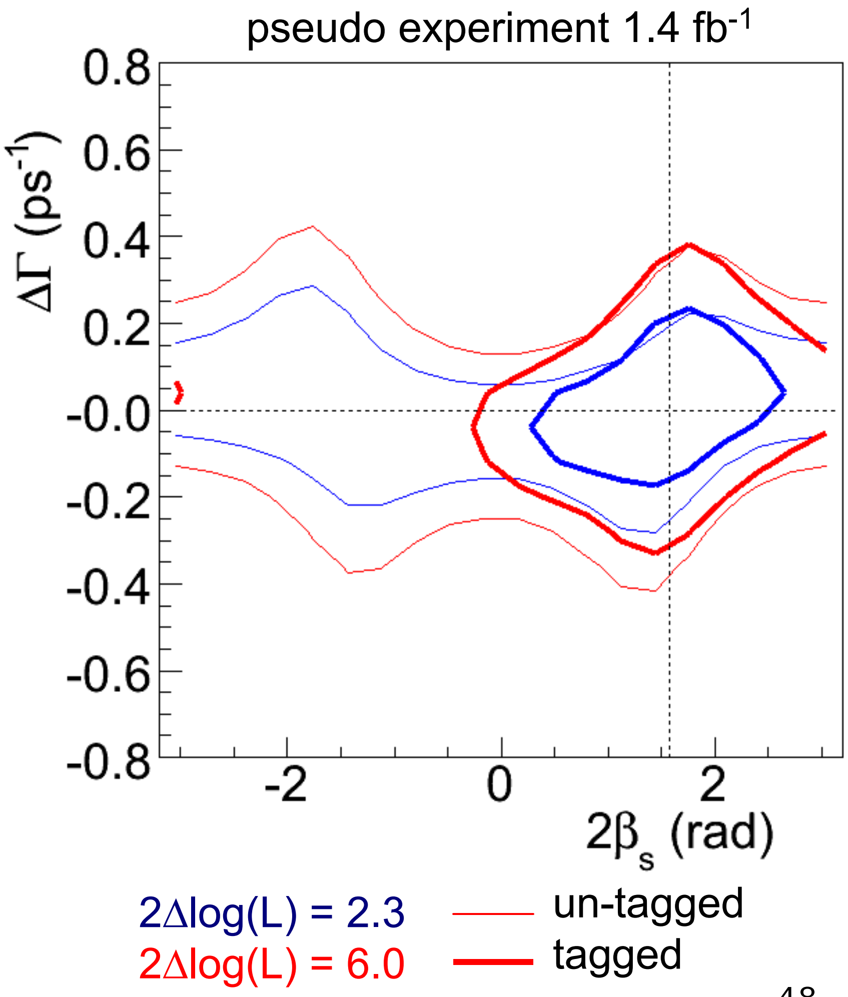


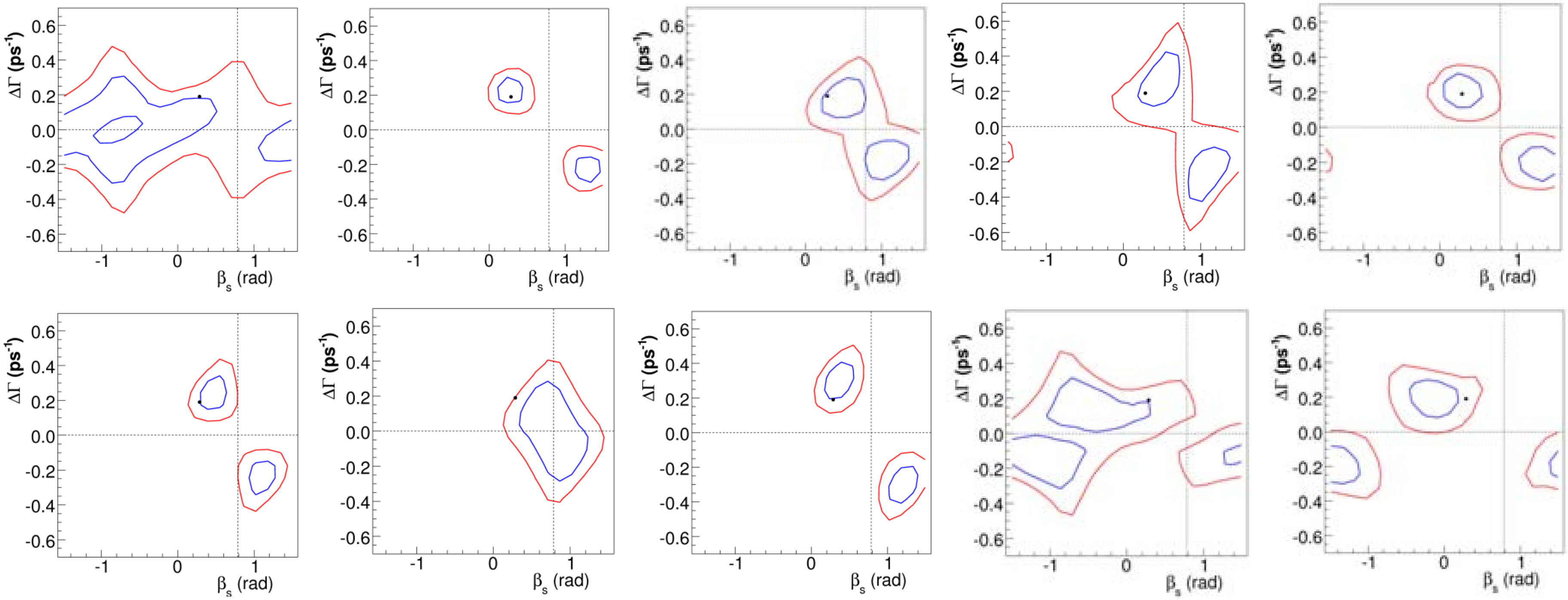
Cross Checks With Pseudo-Experiments

- 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

——— 2Δlog(L) = 2.3

——— 2Δlog(L) = 6.0



Non-Gaussian Regime

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

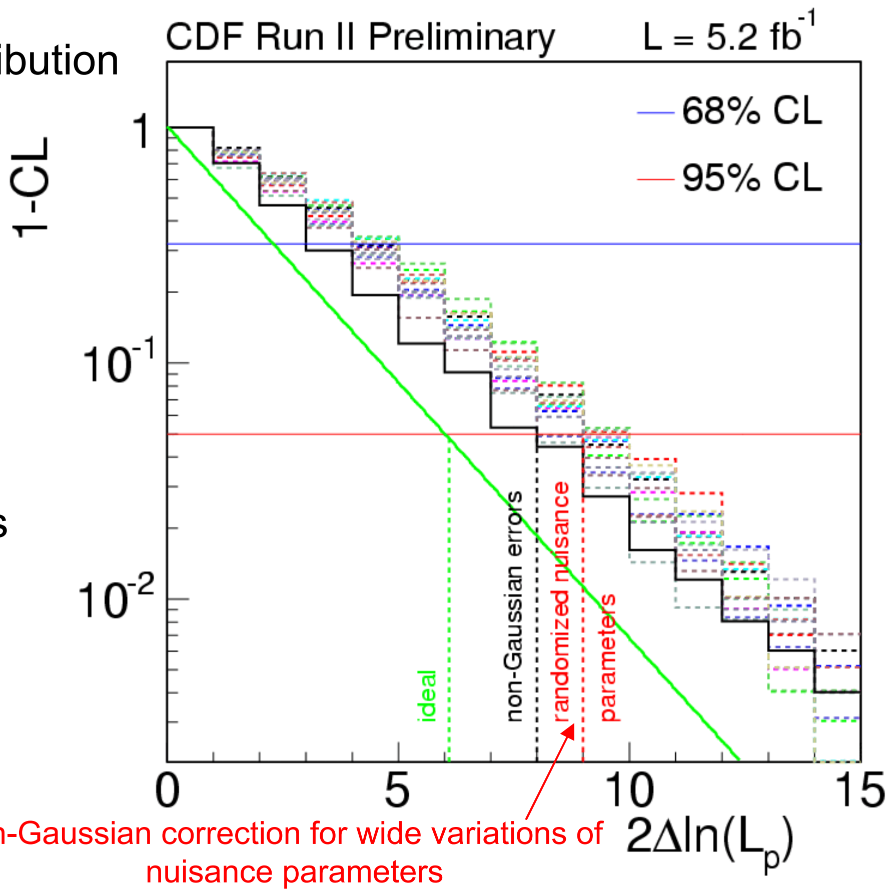
- In ideal case (high statistics, Gaussian likelihood), to get the 2D 68% (95%) C.L. regions, take a slice through profiled likelihood at 2.3 (6.0) units up from minimum

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

- 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

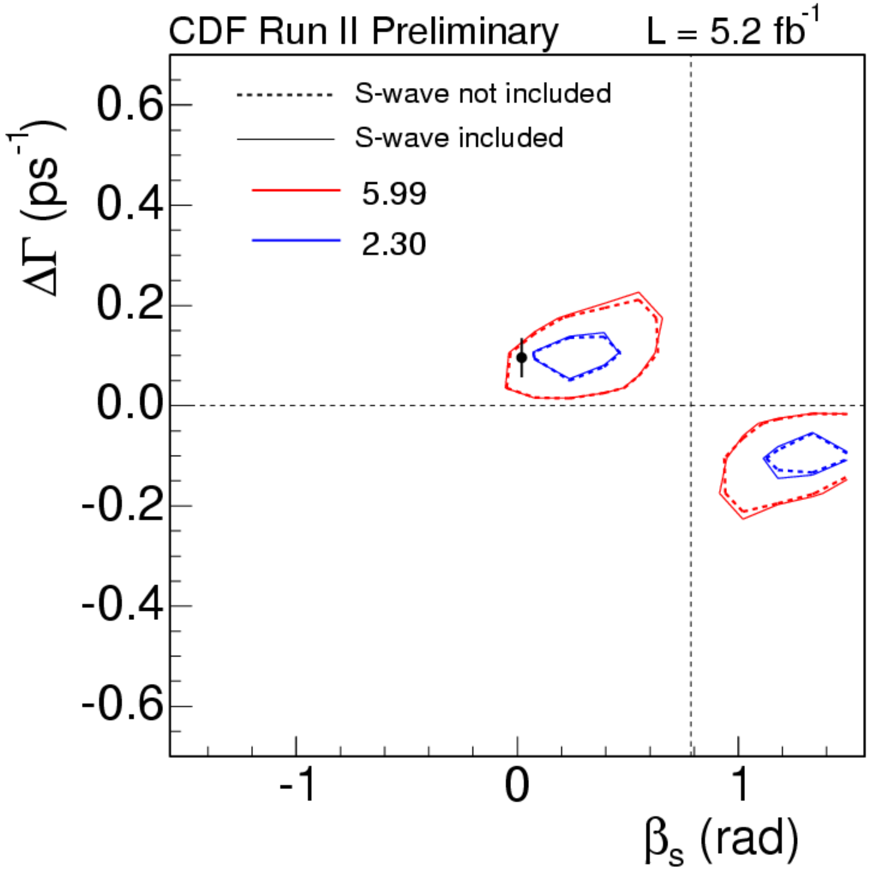
- To establish final confidence regions use most conservative case



non-Gaussian correction for wide variations of nuisance parameters

β_s-$\Delta\Gamma$ Contours with and without Including the S-Wave

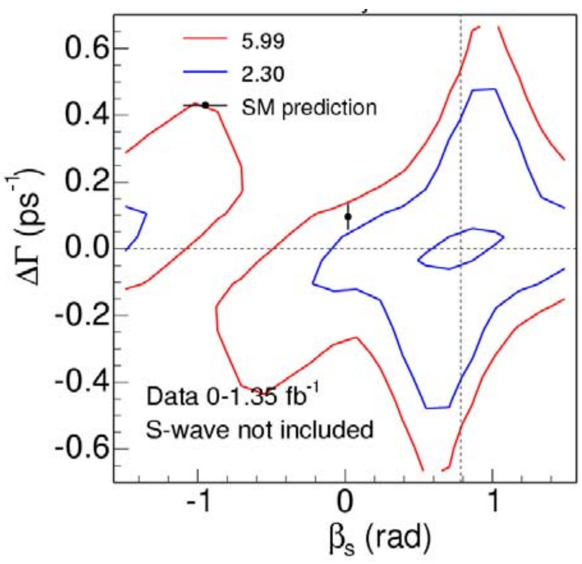
- Compare likelihood contours with and without including the s-wave
- Very small effect on β_s and $\Delta\Gamma$

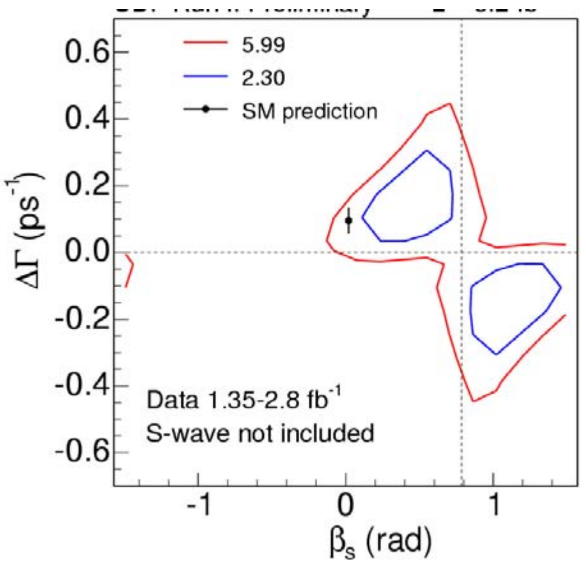


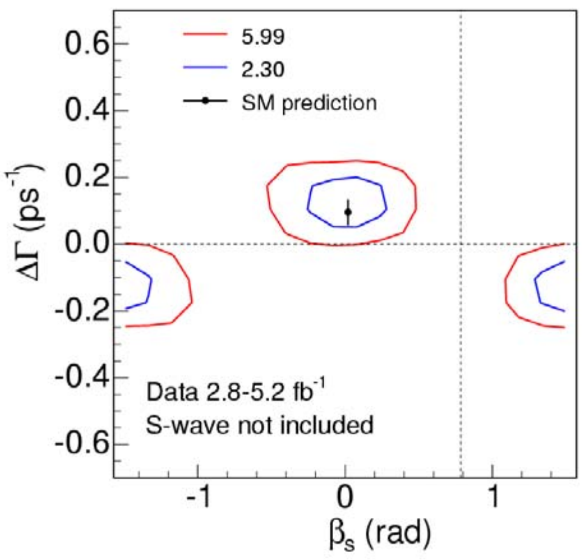
Comparison Between Different Data Periods

- Divide 5.2 fb^{-1} sample in three sub-samples corresponding to three public releases:
  - 0 - 1.4 fb^{-1} (initial result released at the end of 2007, PRL 100, 161802 (2008), arXiv:0712.2397)
  - 1.4 - 2.8 fb^{-1} (added for 2008 ICHEP update)
  - 2.8 - 5.2 fb^{-1} (added for this update)

- Previous results reproduced with updated analysis
- Clearly, improved agreement with the SM expectation comes from the second half of data (2.8 – 5.2 fb^{-1})





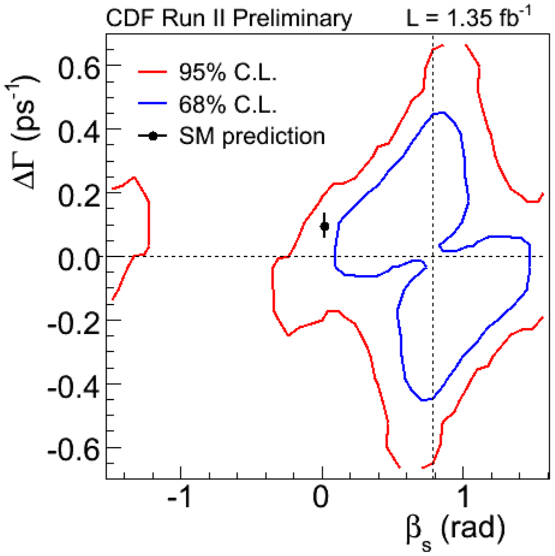


Comparison with Previous Results

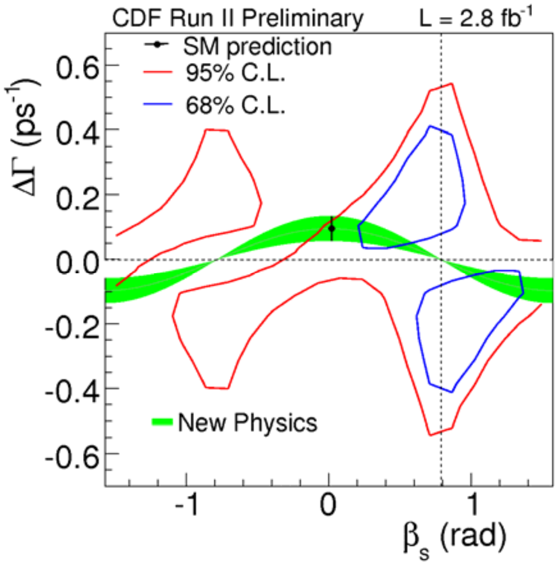
– β_s and $\Delta\Gamma_s$ allowed parameter space greatly reduced

- Agreement with SM expectation improves with higher statistics

Initial result released at the end of 2007, PRL 100, 161802 (2008) arXiv:0712.2397
~2000 signal events



2008 ICHEP update with preliminary PID and tagging
~3150 signal events



This update
~6500 signal events