Measurement of B_s mixing phase β_s at the Tevatron

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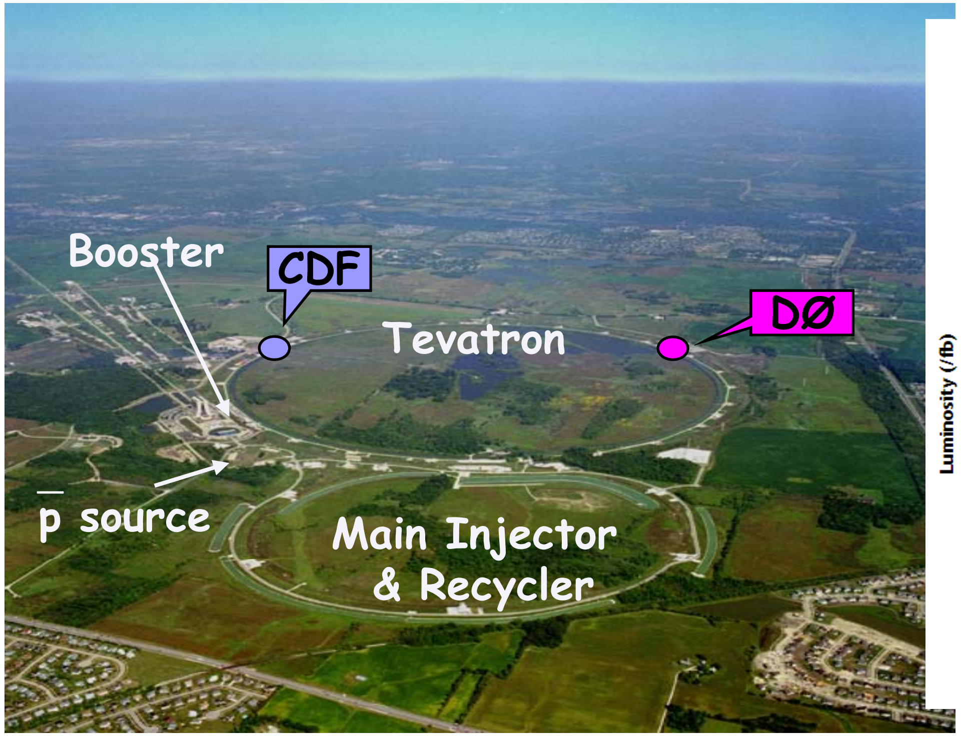
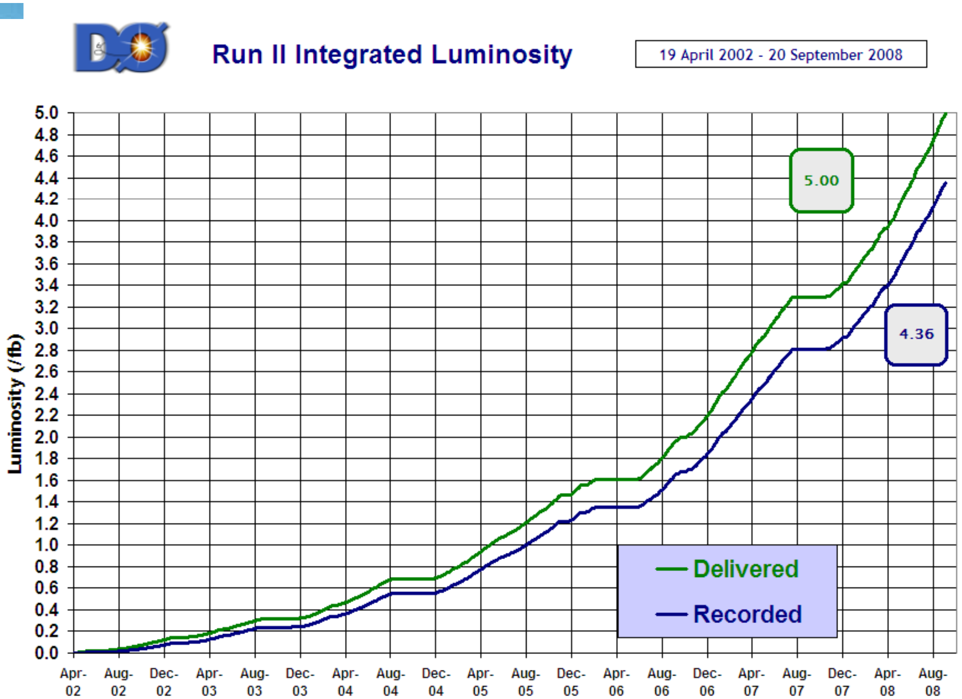
Tevatron

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

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





CDF II Detector

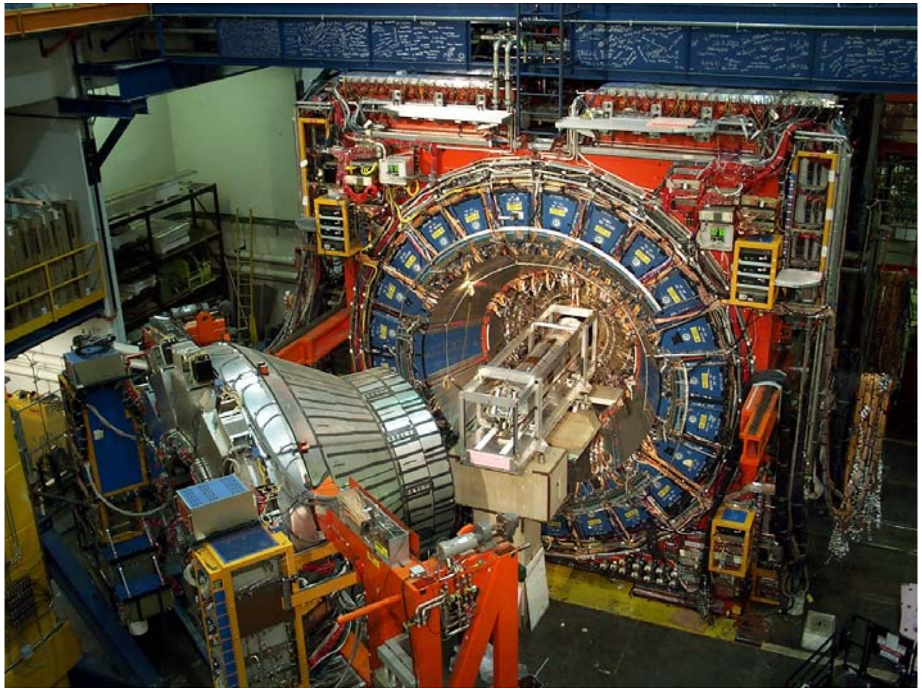
DØ Detector

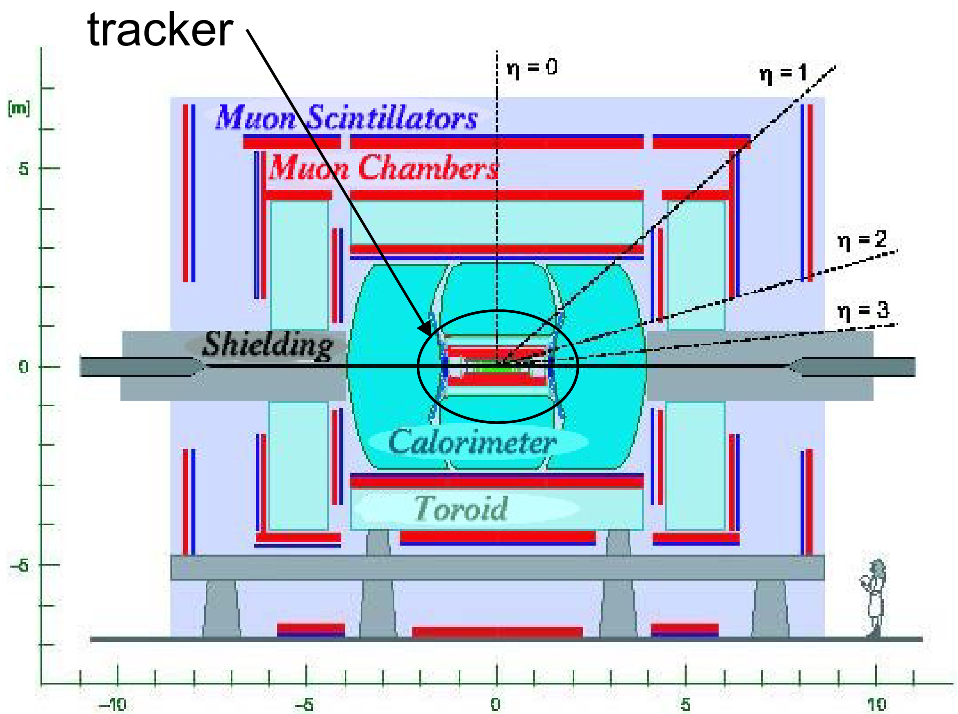
- Central tracking: - silicon vertex detector
  - drift chamber

  $\delta p_T/p_T = 0.0015\ p_T$

  $\rightarrow$ excellent mass resolution
- Particle identification: dE/dX and TOF
- Good electron and muon ID by calorimeters and muon chambers

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





β_s Phase and the CKM Matrix

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

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

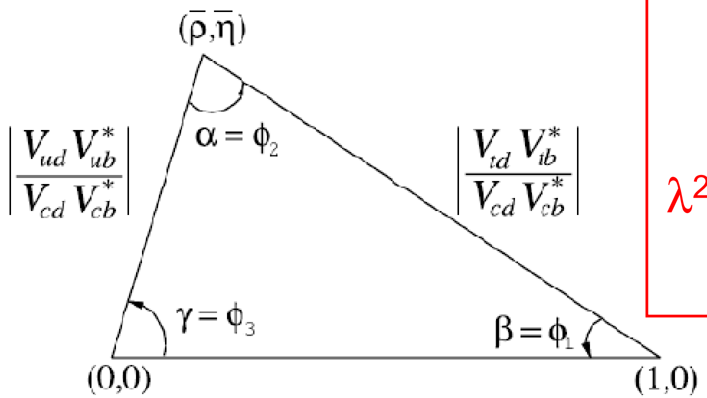
- To conserve probability CKM matrix must be unitary
  → Unitary relations can be represented as “unitarity triangles”

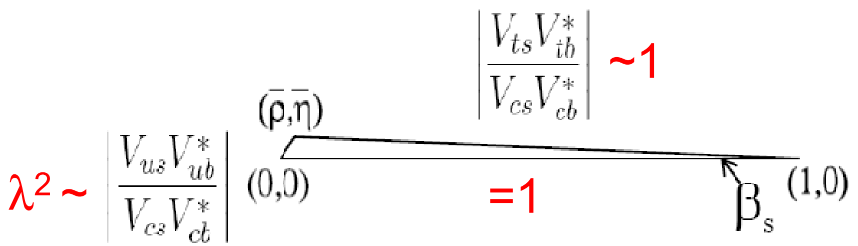
unitarity relations:

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

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

unitarity triangles:





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

Neutral B_s System

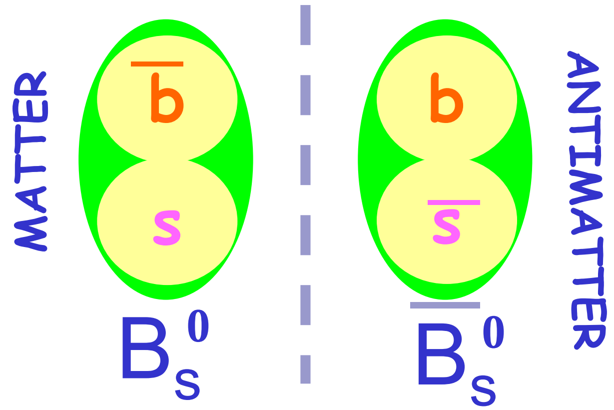
- Time evolution of B_s flavor eigenstates described by Schrodinger equation:

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

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

→ mass eigenstates :

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

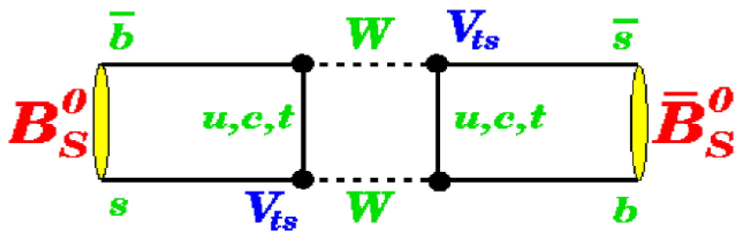


- Flavor eigenstates differ from mass eigenstates and mass eigenvalues are different ($\Delta m_s = m_H - m_L \approx 2|M_{12}|$)

→ B_s oscillates with frequency Δm_s precisely measured by

CDF Δm_s = 17.77 +/- 0.12 ps^{-1}

DØ Δm_s = 18.56 +/- 0.87 ps^{-1}



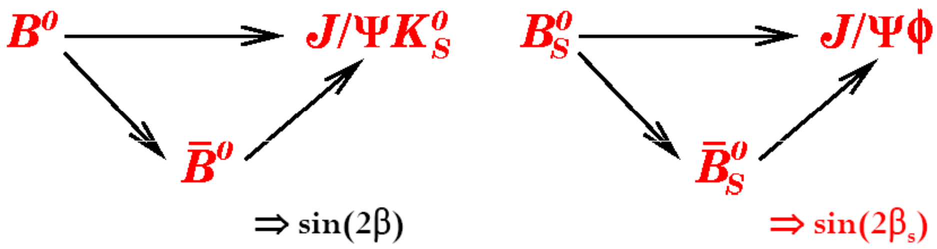
- Mass eigenstates have different decay widths

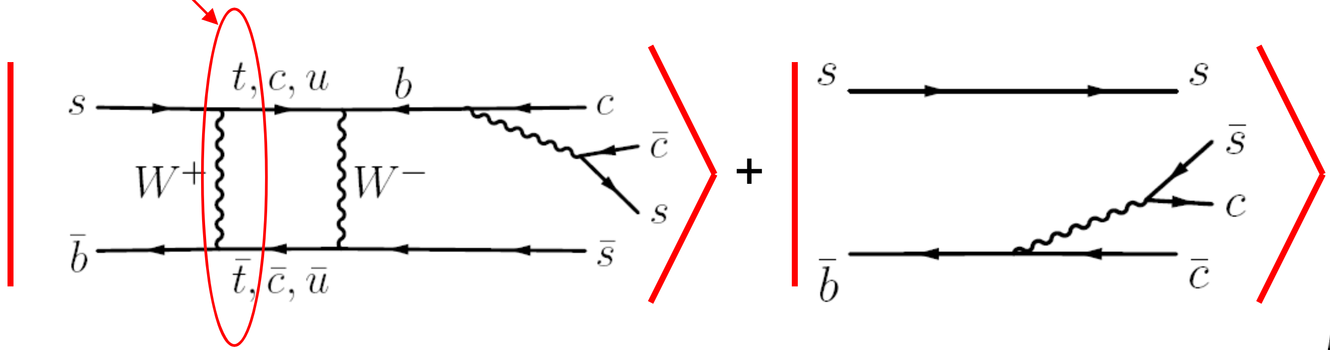
$\Delta\Gamma = \Gamma_L - \Gamma_H \approx 2|\Gamma_{12}|\cos(\Phi_s)$ where $\phi_s^{SM} = \arg\left(-\frac{M_{12}}{\Gamma_{12}}\right) \approx 4 \times 10^{-3}$

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

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

dominant contribution from top quark





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

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

- CP violation phase β_s in SM is predicted to be very small, $O(\lambda^2)$

$\rightarrow$ New Physics CPV can compete or even dominate over small Standard Model CPV

- Ideal place to search for New Physics

β_s vs ϕ_s

- Up to now, introduced two different phases:

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

- New Physics affects both phases by same quantity $\phi_s^{\rm NP}$ (arxiv:0705.3802v2):

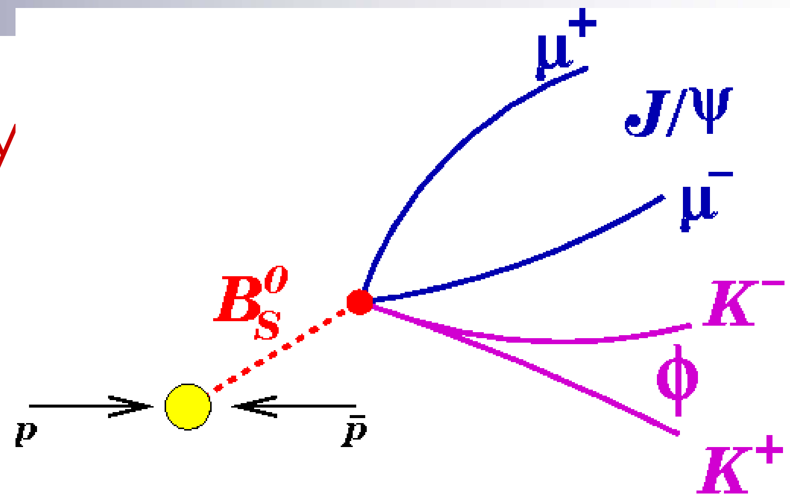
$$2\beta_s = 2\beta_s^{\rm SM} - \phi_s^{\rm NP}$$

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

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

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

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



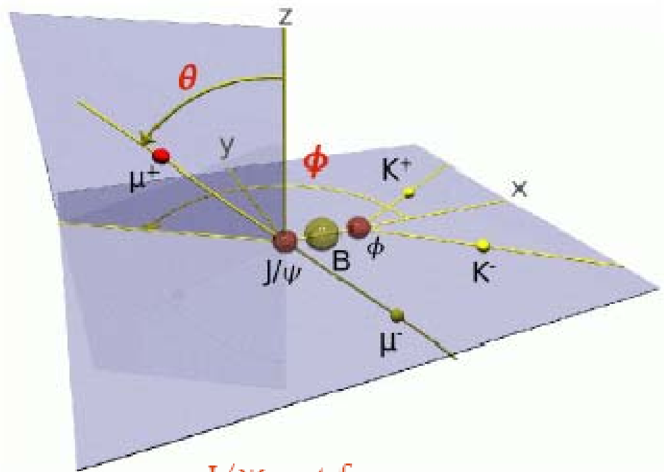
- Extremely physics rich decay mode

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

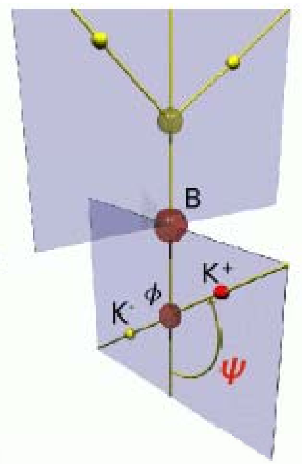
- Decay of B_s (spin 0) to J/Ψ(spin 1) Φ(spin 1) leads to three different angular momentum final states:

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

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



J/ψ rest frame



φ rest frame

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

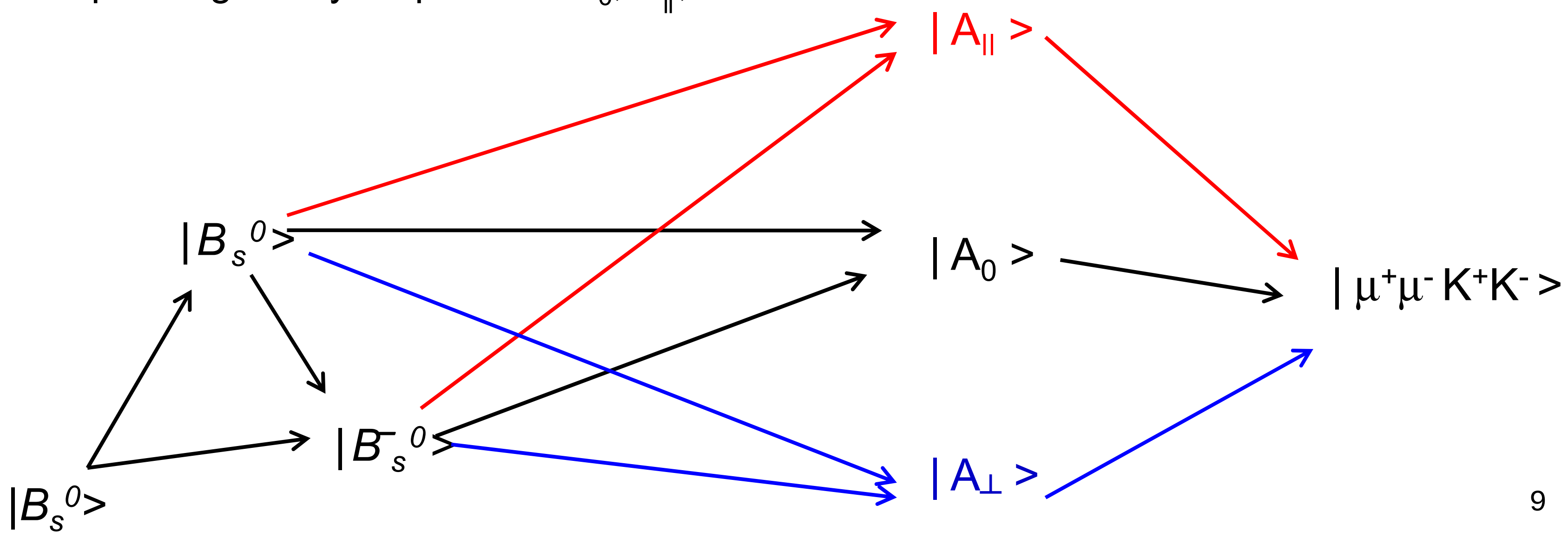
$B_s \rightarrow J/\Psi\Phi$ Phenomenology (2)

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

- Use alternative "transversity basis" in which the vector meson polarizations w.r.t. direction of motion are either (Phys. Lett. B 369, 144 (1996), 184 hep-ph/9511363):

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

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



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

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

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

time dependence terms

angular dependence terms

terms with β_s dependence

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

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

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

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

'strong' phases:

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

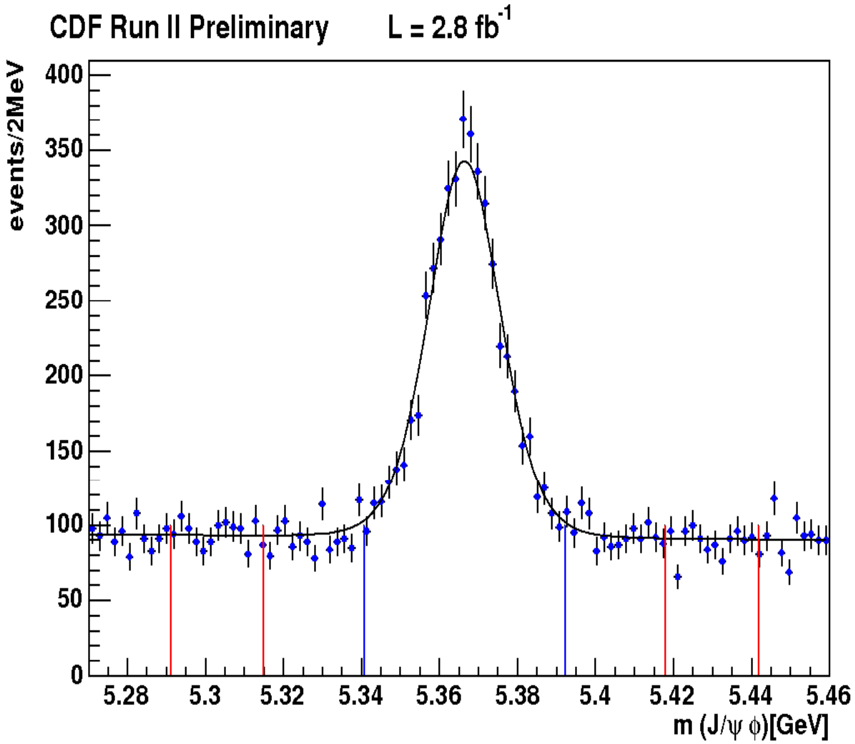
- Identification of B flavor at production (flavor tagging) → better sensitivity to β_s

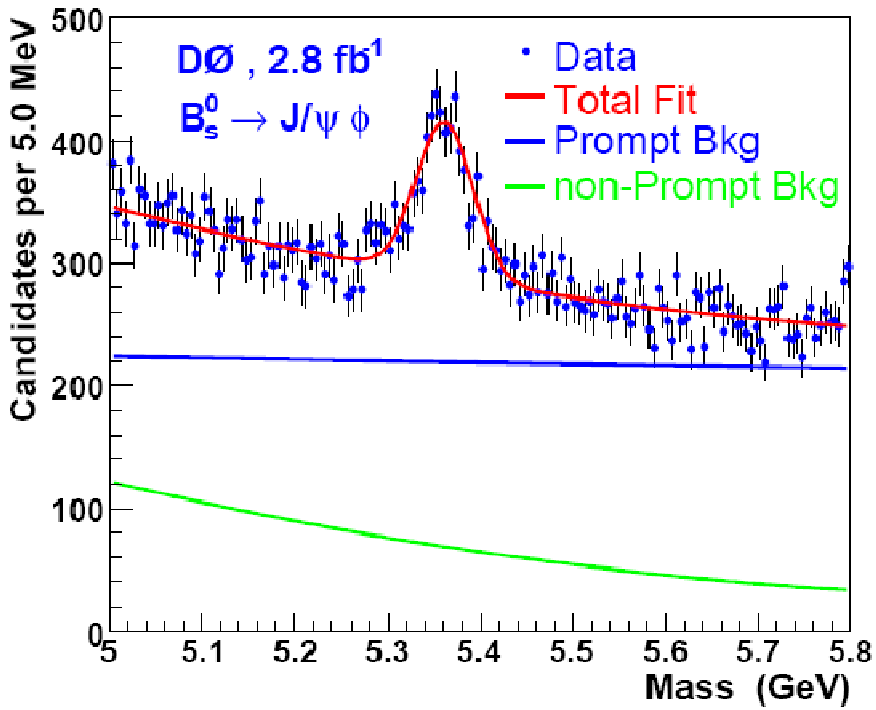
Signal Reconstruction

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

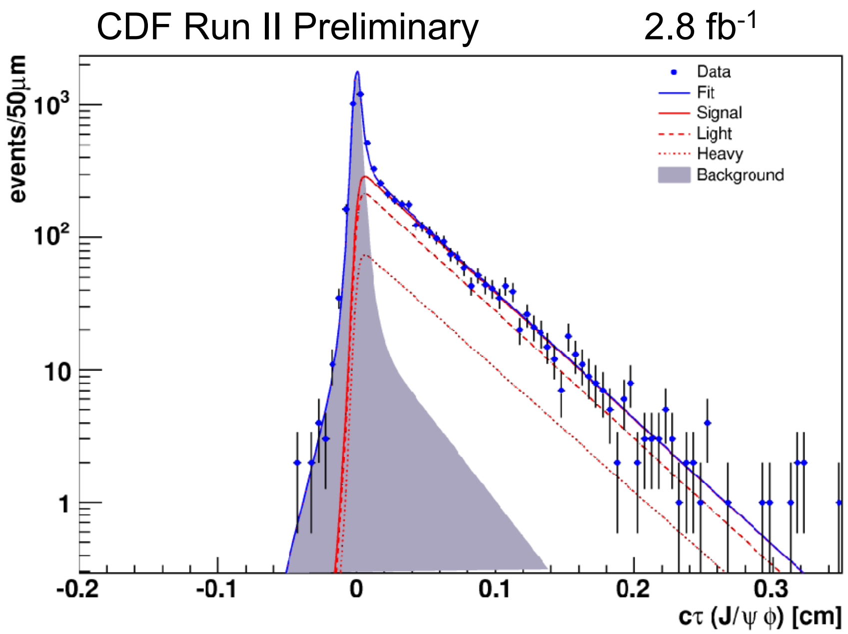
CDF ~3200 signal events
(expect ~4000 with PID signal selection)

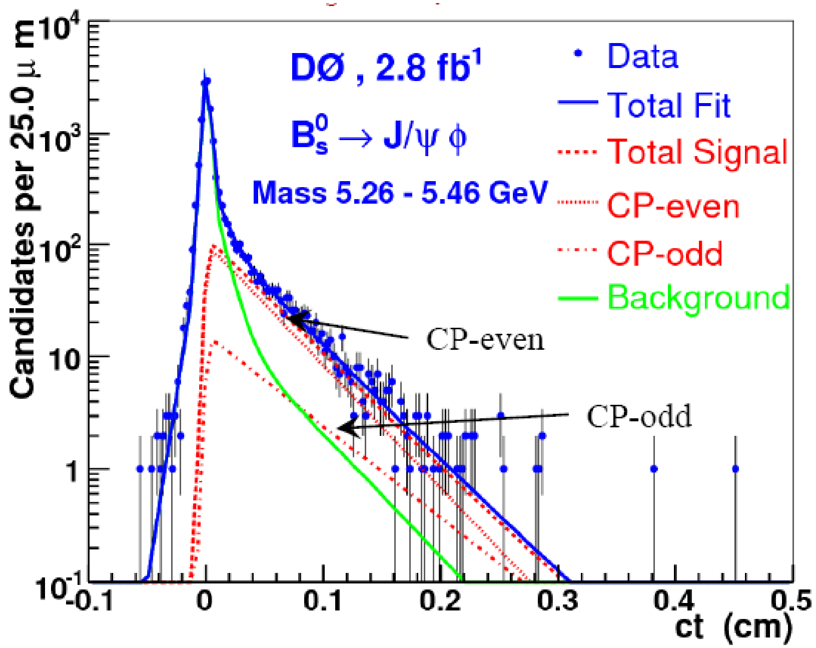
DØ ~2000 signal events





Lifetime and Lifetime Difference





- Average B_s lifetime:

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

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

- Decay width difference $\Delta\Gamma$:

$\beta_s = 0$:

$$\Delta\Gamma = 0.02 \pm 0.05 \text{ (stat.)} \pm 0.01 \text{ (syst.)}\ \mu\text{m}$$

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

β_s free:

- - -

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

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

- Likelihood expression predicts better sensitivity to β_s but still double minima due to symmetry:

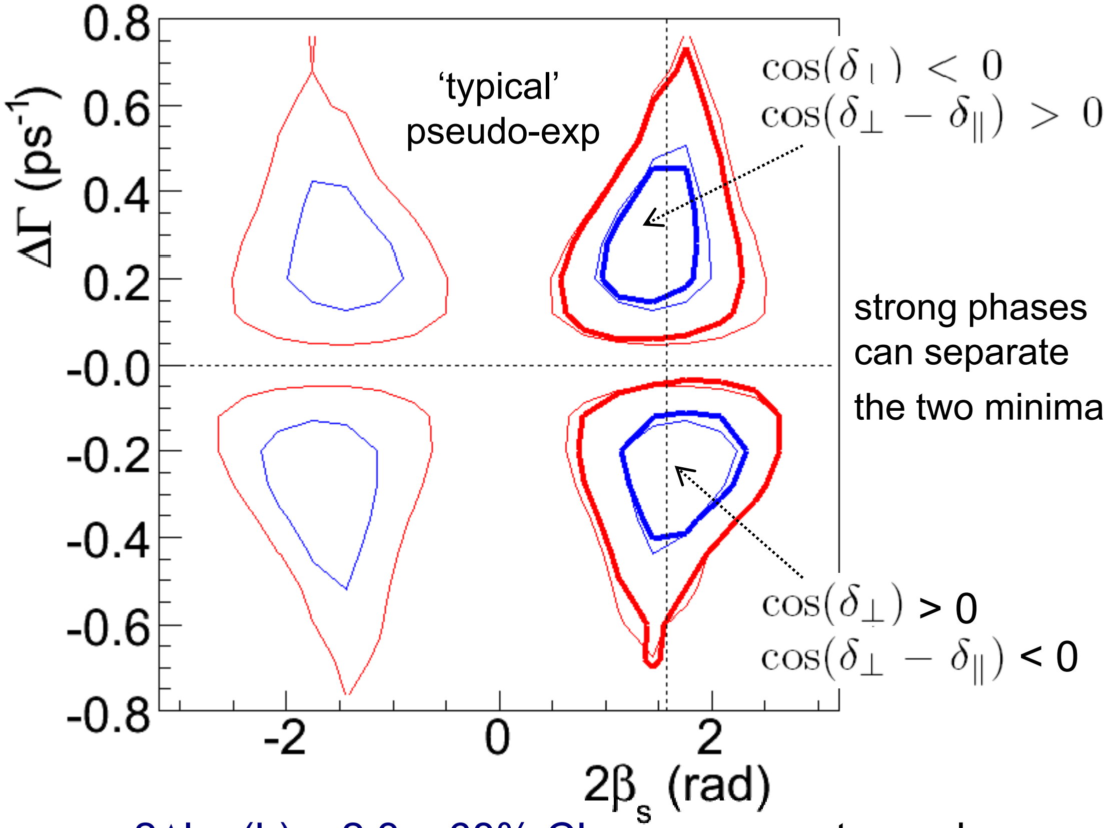
$$2\beta_s \rightarrow \pi - 2\beta_s$$
$$\Delta\Gamma \rightarrow -\Delta\Gamma$$
$$\delta_{\|} \rightarrow 2\pi - \delta_{\|}$$
$$\delta_{\perp} \rightarrow \pi - \delta_{\perp}$$

- Study expected effect of tagging using pseudo-experiments

- Improvement of parameter resolution is small due to limited tagging power ($\varepsilon D^2 \sim 4.5\%$ compared to B factories ~30%)

- However, $\beta_s \rightarrow -\beta_s$ no longer a symmetry
  - $\rightarrow$ 4-fold ambiguity reduced to 2-fold ambiguity
  - $\rightarrow$ allowed region for β_s is reduc to half

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



strong phases can separate the two minima

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

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

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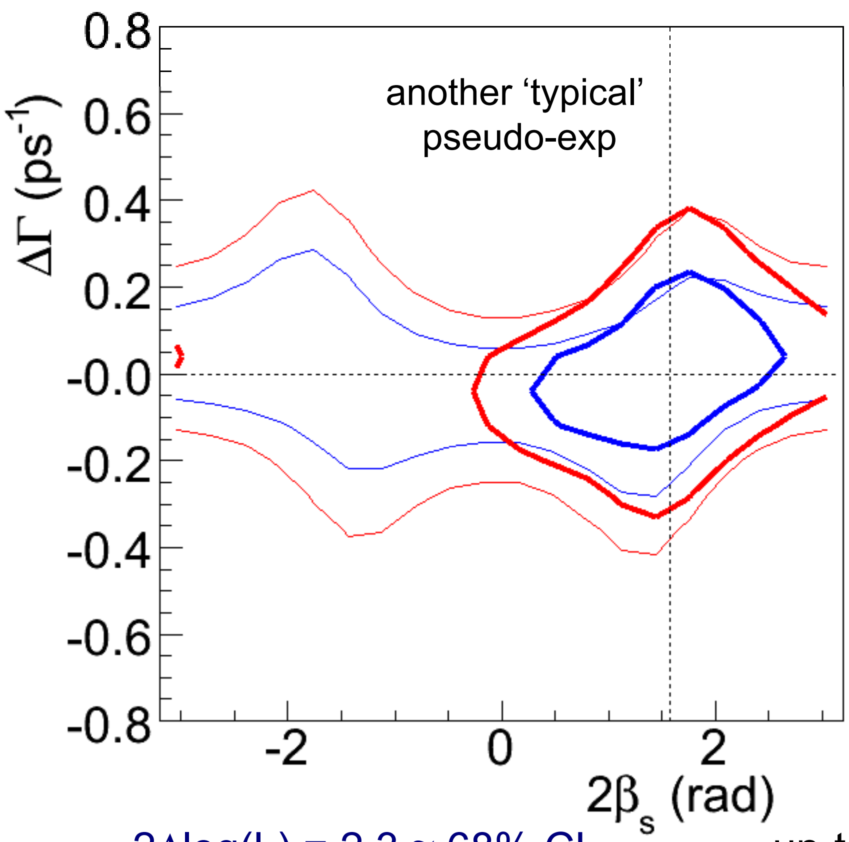

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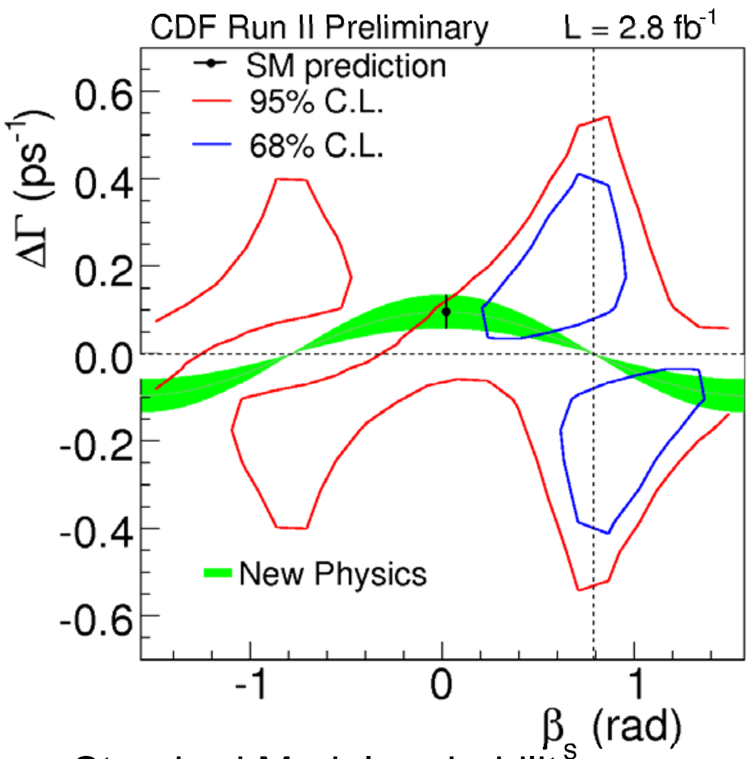
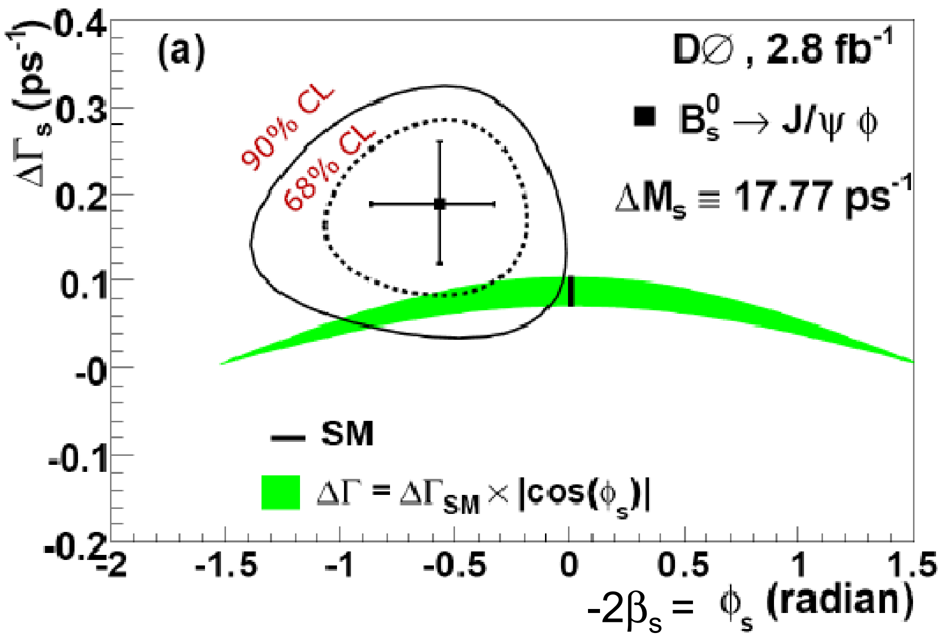
CP Violation Phase β_s in Tagged $B_s \to J/\Psi\Phi$ Decays

- Both DØ and CDF results fluctuate in the same direction 1-2σ from SM prediction
  ($\Phi_s = -2\beta_s$)

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





- Standard Model probability

CDF: 7%, ~1.8σ

DØ: 6.6%, ~1.8σ

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

arXiv:/0802.2255

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

Non-Gaussian Regime

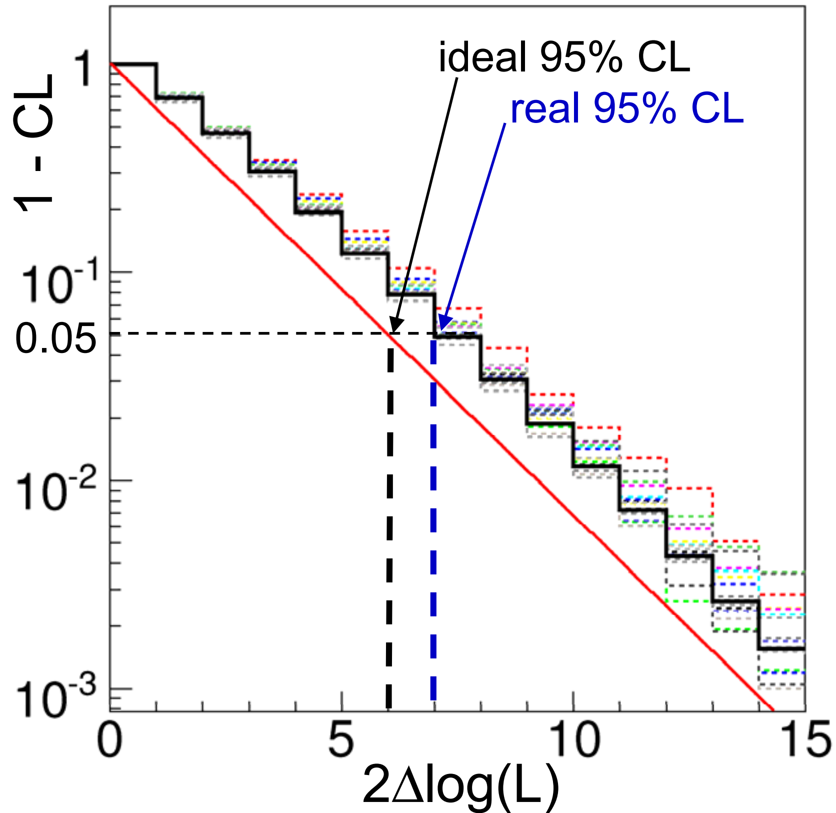
- In ideal case (high statistics, Gaussian likelihood), to get the 2D 68% (95%) C.L. regions, take a slice through profile likelihood at 2.3 (6) units up from minimum

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

-To get 95% CL need to go up ~7 instead of 6 units from minimum

- Procedure used by both CDF and DØ

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

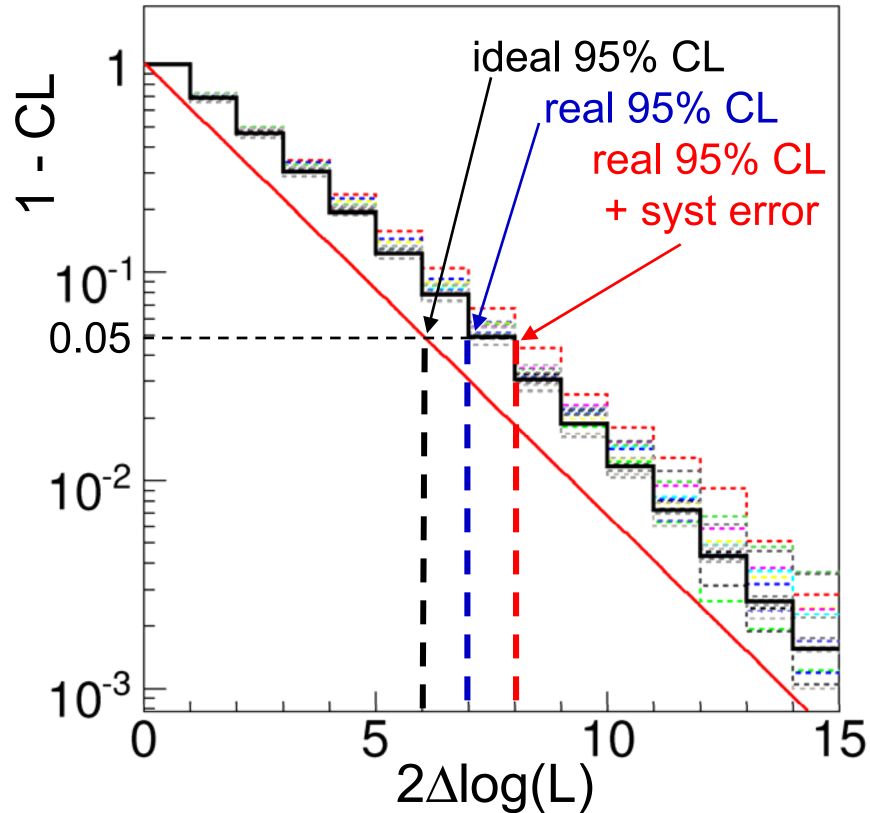


CDF Systematics

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

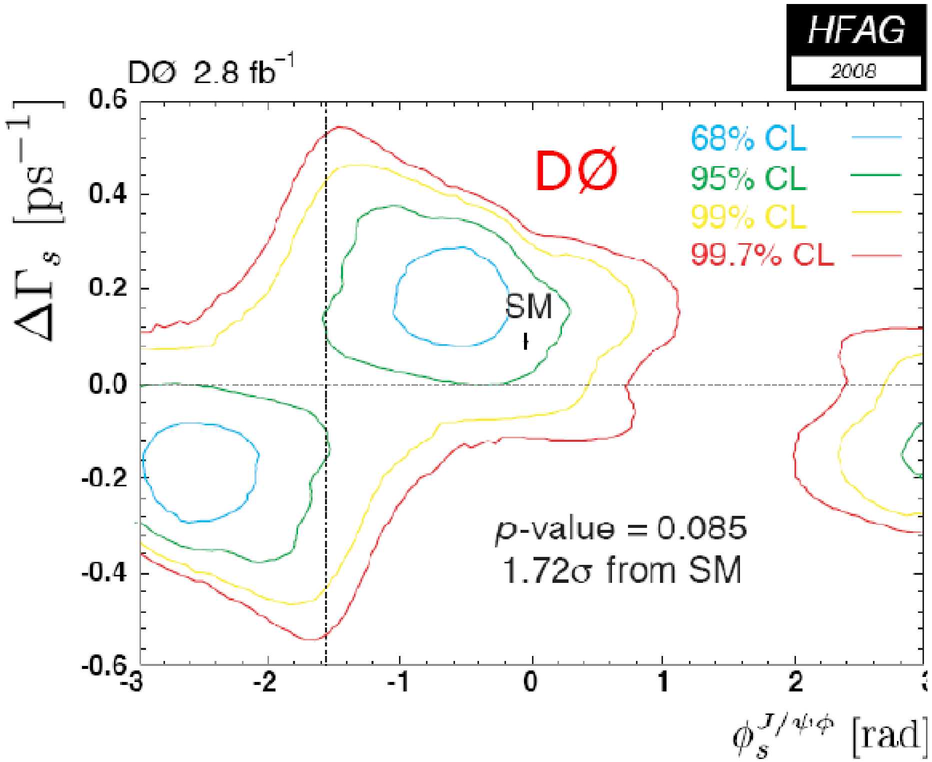
- Nuisance parameters:
    - lifetime, lifetime scale factor uncertainty,
    - strong phases,
    - transversity amplitudes,
    - background angular and decay time parameters,
    - dilution scale factors and tagging efficiency
    - mass signal and background parameters
    - …

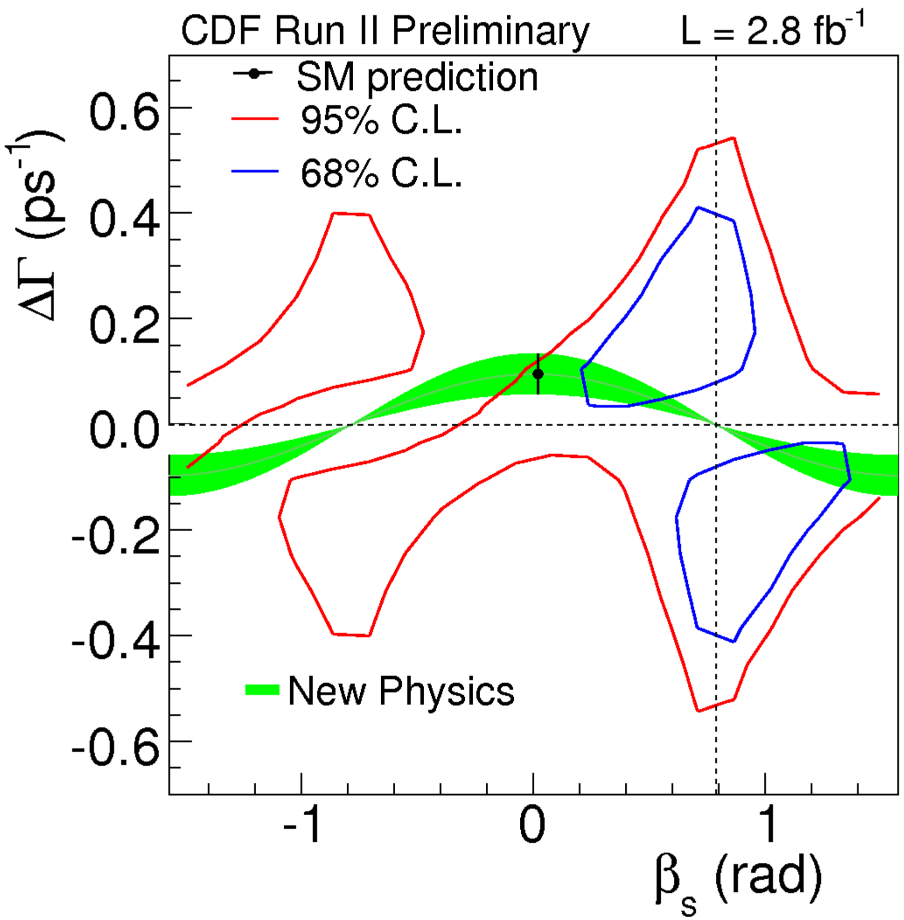
- Take the most conservative curve (dotted red histogram) as final result



Comparison Between CDF and DØ

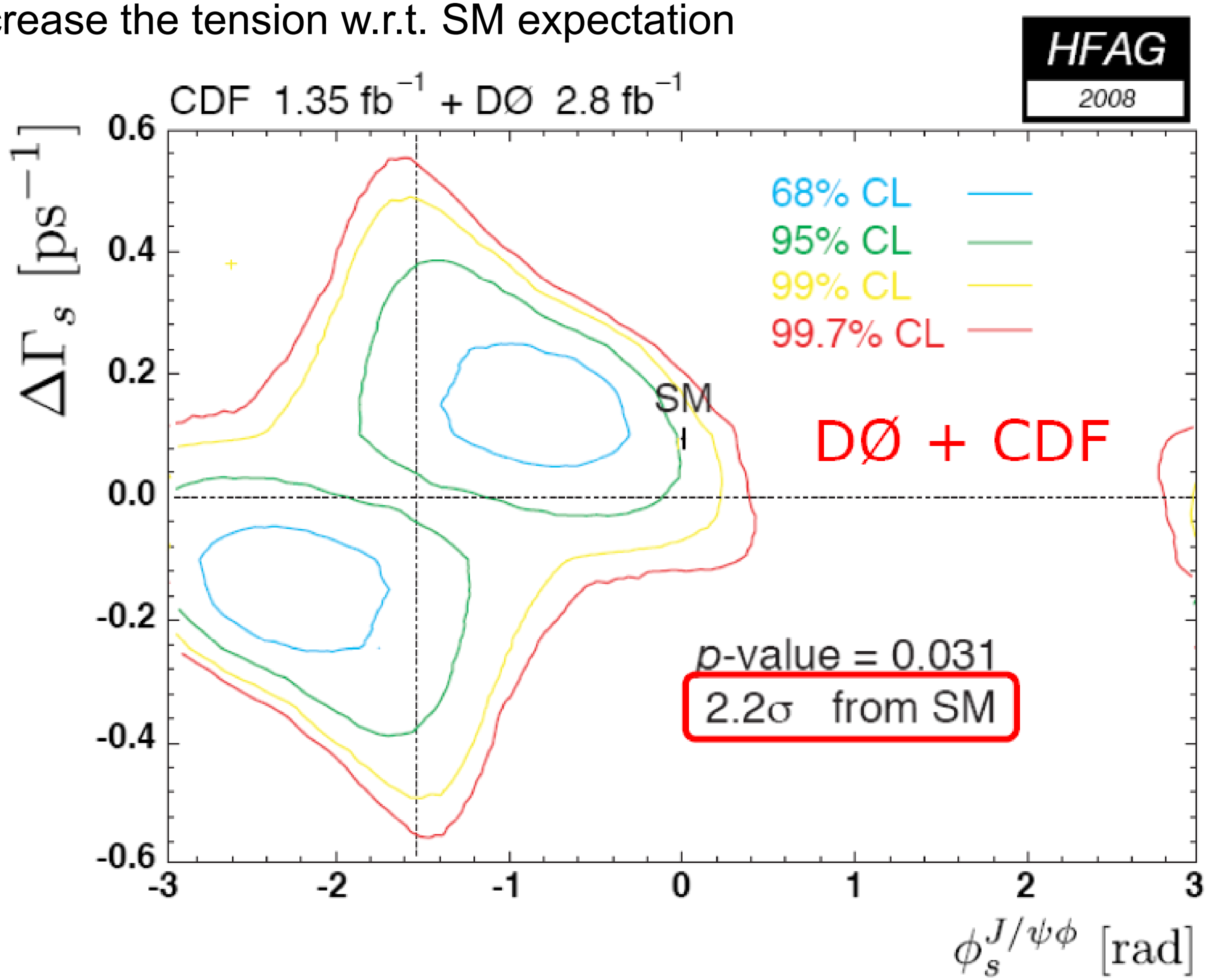
- DØ releases constraints on strong phases → double minimum solution
- CDF and DØ are in good agreement and both favor negative values of $\Phi_s = -2\beta_s$ (positive values of β_s)





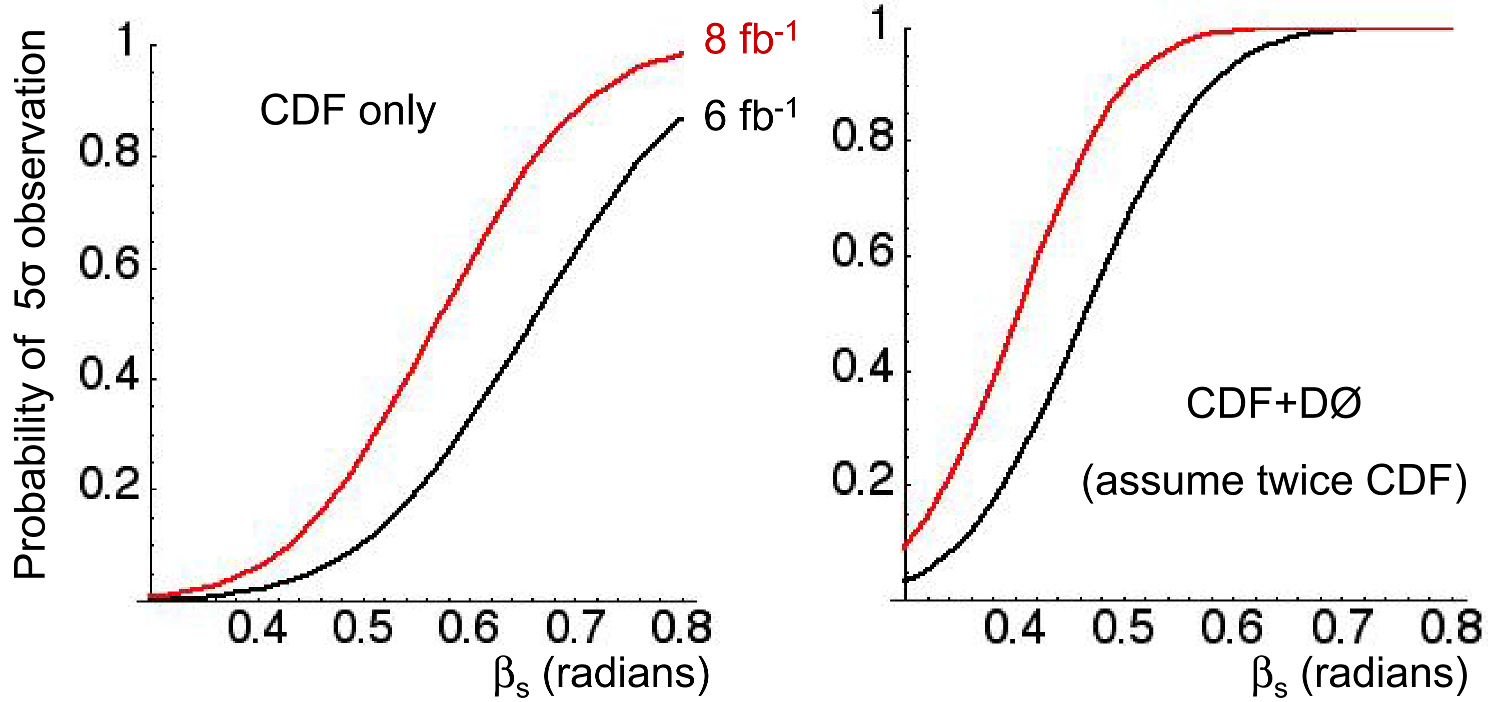
Combining CDF and DØ Results

- HFAG combines old CDF (1.4 fb^{-1}, 1.5 σ from SM) and DØ (2.8 fb^{-1}, 1.7 σ from SM) results yield a 2.2 σ deviation from SM (similar results found by UTFit and CKM collaborations)
- The latest CDF analysis (2.8 fb^{-1}, 1.8 σ from SM) not yet included, but will slightly increase the tension w.r.t. SM expectation



Future

- CPV in B_s system is one of the main topics in LHCb B Physics program → will measure β_s with great precision
- Meanwhile Tevatron can search for anomalously large values of β_s
- Shown results with 2.8 fb^{-1}, but 4 fb^{-1} already on tape to be analyzed soon
- Expect 6/8 fb^{-1} by the end of 2009/2010



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

Conclusions

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

- Significant regions in β_s space are ruled out

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

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

- Combined HFAG result 2.2 σ w.r.t SM expectation

- Interesting to see how these effects evolve with more data

Backup Slides

Analysis

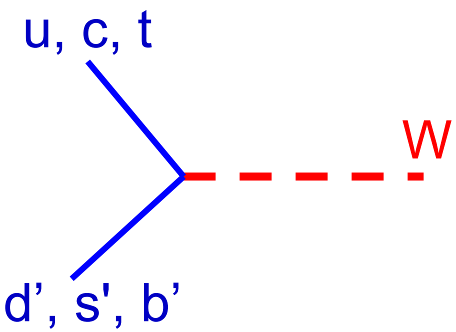
- Ingredients:
  - Signal reconstruction
  - B flavor identification (tagging)
  - Angular analysis
  - Maximum likelihood fit
  - Statistical analysis

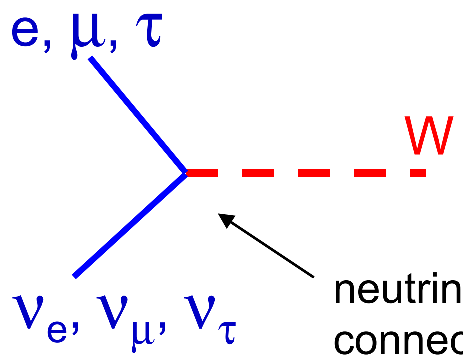
Introduction

- Charge Parity violation (CPV) is a necessary ingredient to explain matter - antimatter asymmetry in Universe

- CP symmetry is broken in Nature by the weak interaction

- Weak interaction Lagrangean is not invariant under CP transformation
  → due to complex phases in mixing matrices that connect up-type fermions with down-type fermions via W bosons:





neutrino mixing matrix connects neutrino mass and weak eigenstates

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

Cabibbo Kobayashi Maskawa (CKM) quark mixing matrix transforms quark mass eigenstates into weak eigenstates

Why Look for CPV in B_s System ?

- CP violation has been measured in various Kaon and B-meson decays

1. Indirect CP violation in the kaon system (εK)
2. Direct CP violation in the kaon system ε'/ε
3. CP Violation in the interference of mixing and decay in $B^0 \to J/\psi\ K^0$.
4. CP Violation in the interference of mixing and decay in B^0->h'K0
5. CP Violation in the interference of mixing and decay in B^0->K+K-Ks
6. CP Violation in the interference of mixing and decay in B^0->π+π-
7. CP Violation in the interference of mixing and decay in B^0->D*+D-
8. CP Violation in the interference of mixing and decay in B^0->$f^0 K^0$s
9. CP Violation in the interference of mixing and decay in B^0->$\psi\pi^0$
10. Direct CP Violation in the decay $B^0 \to K$-π+
11. Direct CP Violation in the decay $B \to \rho\pi$
12. Direct CP Violation in the decay $B \to \pi$+π-

- CKM matrix well constrained

- Within the SM framework, CP violation in the quark sector is orders of magnitude too small to explain the matter - antimatter asymmetry

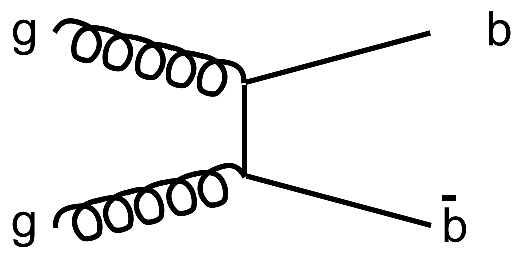
- Only place left to find large CP violation without invoking new physics is lepton sector in long baseline neutrino oscillation experiments

- … or we can look for non-SM sources of CP violation

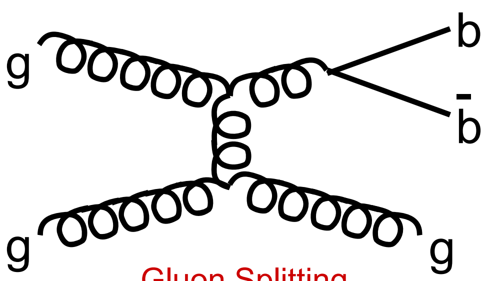
- Ideal place to look for non-SM CPV is the neutral B_s meson system

B Physics at the Tevatron

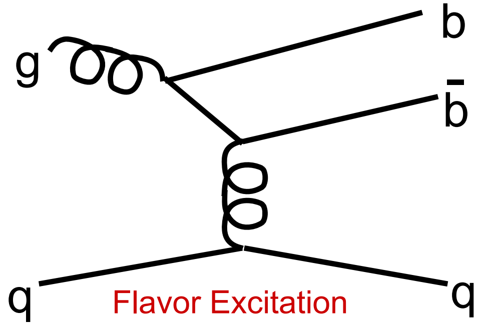
- Mechanisms for b production in $p\bar{p}$ collisions at 1.96 TeV



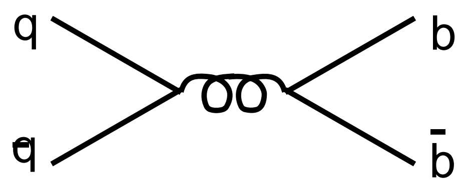
Flavor Creation (gluon fusion)



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

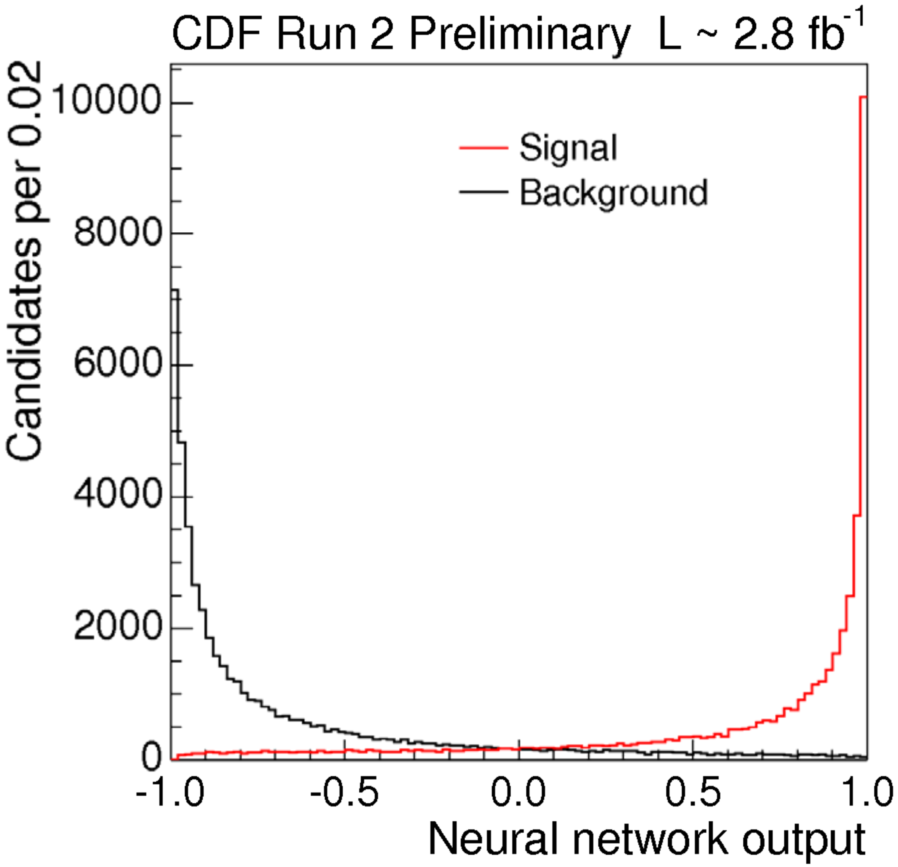
- Plethora of states accessible only at Tevatron: B_s, B_c, Λ_b, Ξ_b, Σ_b…
  → complement the B factories physics program

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

CDF Selection of B_s Signal Using ANN

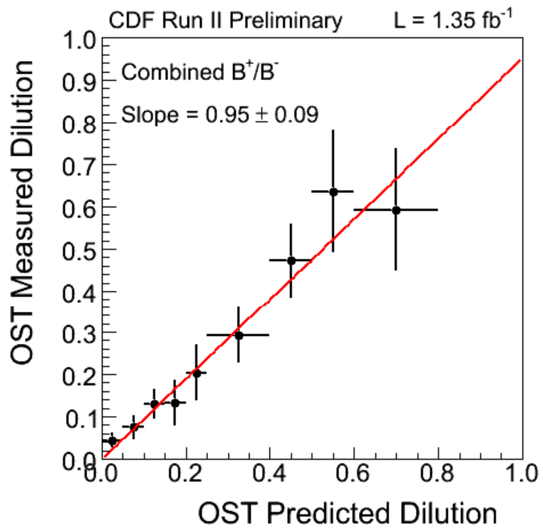
- NN maximizes $S/\sqrt{(S+B)}$, trained on MC for signal and mass sidebands for background

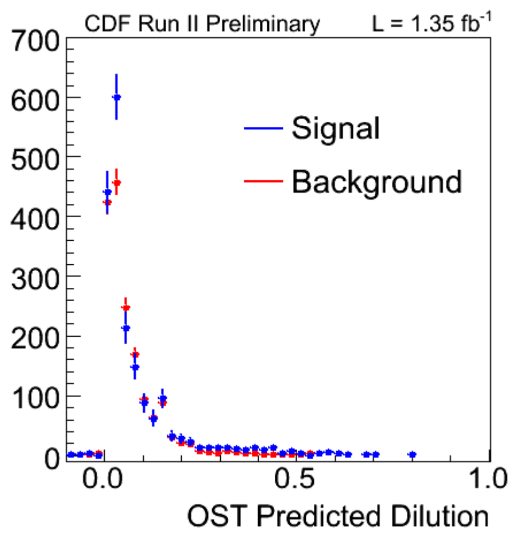
- Variables used by NN
- B^0_s : use p_T and vertex quality
- J/ψ : use p_T and vertex prob.
- Φ : use mass and vertex quality
- PID (dE/dx + TOF) for Kaons from Φ
- …



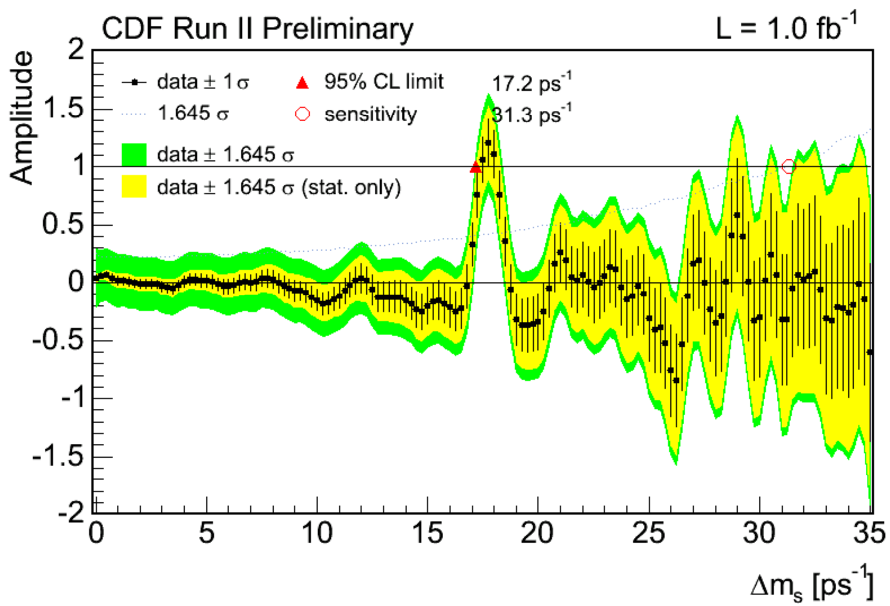
CDF Tagging Calibration and Performance

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





correct tag probability = (1 + dilution) / 2



OST efficiency = 96 +/- 1%

dilution = 11 +/- 2%

SST efficiency = 50 +/- 1%

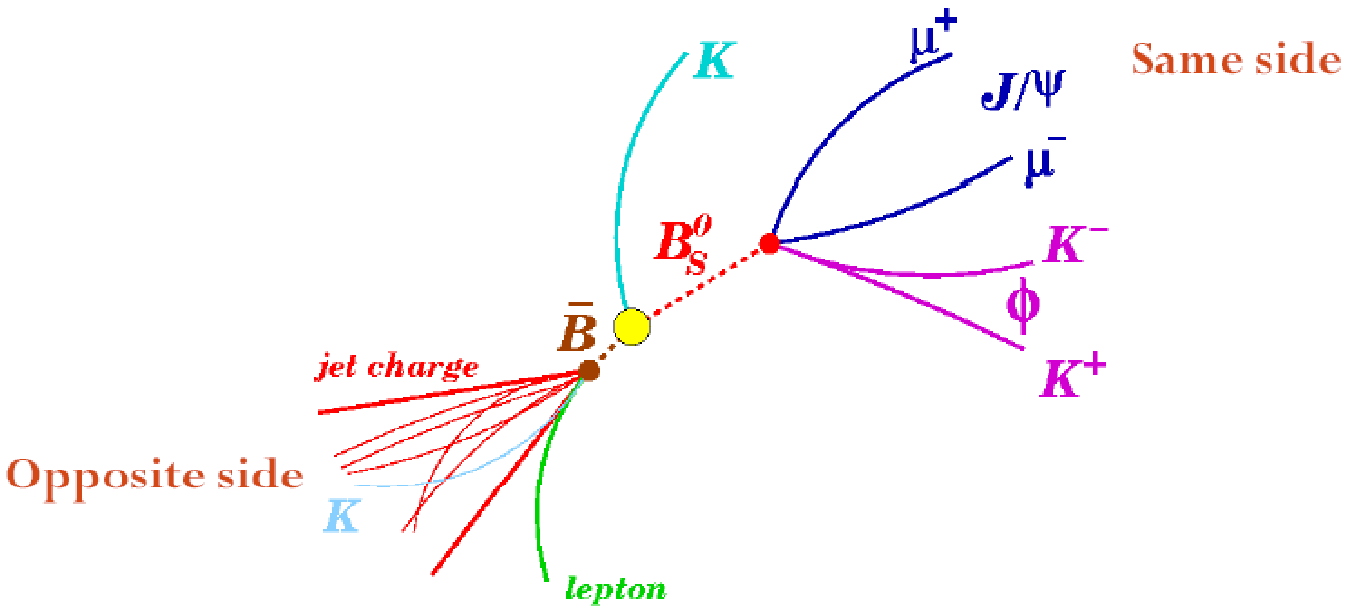
dilution = 27 +/- 4%

Flavor Tagging

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

→ flavor of the B meson at production inferred with

- OST: exploits decay products of other *b*-hadron in the event
- SST: exploits the correlations with particles produced in fragmentation



- Output: decision (*b*-quark or anti-*b*-quark) and probability the decision is correct
- Similar tagging power for both CDF and DØ ~4.5% (compared to ~30% at B factories)

CDF Angular Analysis

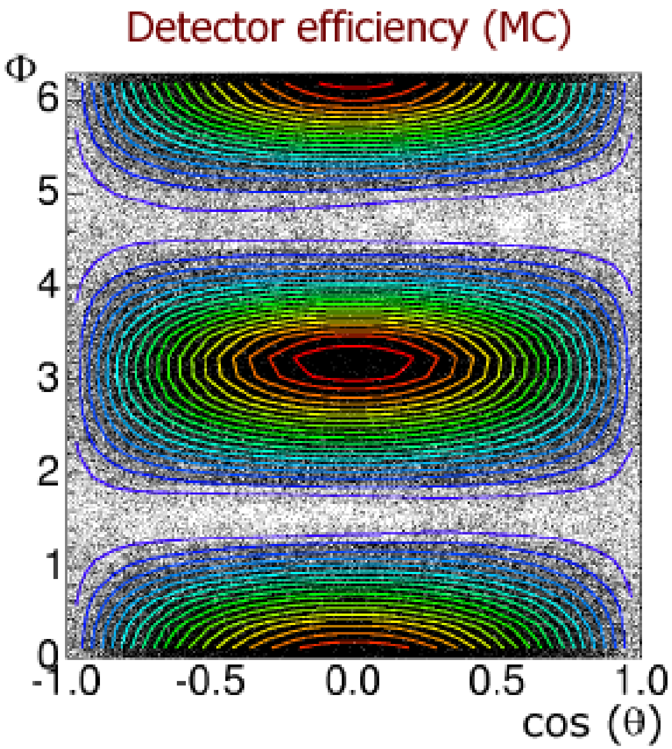
- CP even and CP odd final states have different angular distributions

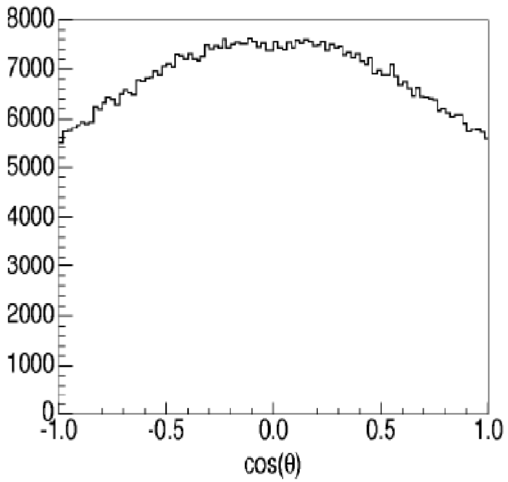
  → use angles $\rho = (\theta,\phi,\psi)$ to separate CP even and CP odd components

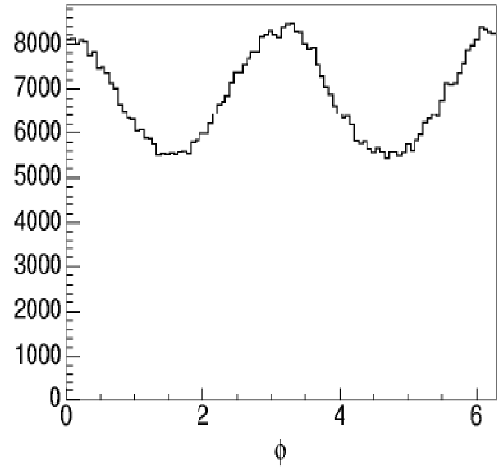
- Detector acceptance distorts the theoretical distributions

  → determine 3D angular efficiency functions from simulation and check in data

- Example 2D and 1D angular efficiency projections in ϕ and $\cos(\phi)$ (3rd dimension, ψ, not shown)





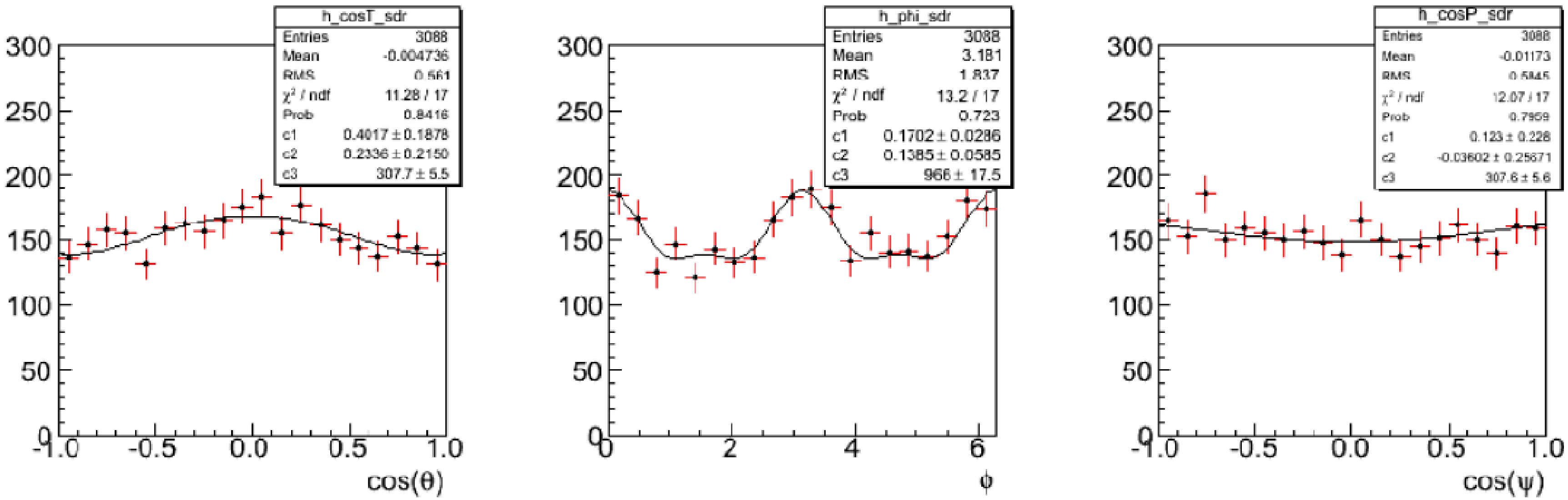


- deviations from flat indicate detector effects

CDF Background Angular Analysis

- Angular background distributions are determined from data B_s mass sidebands

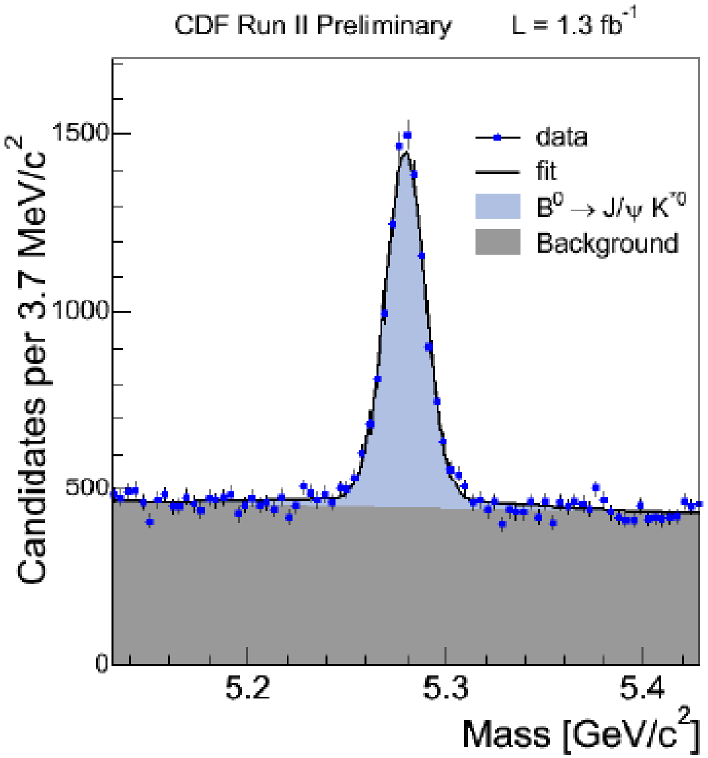
- Notice consistency between background angular distributions and detector sculpting efficiencies on previous page



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

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

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

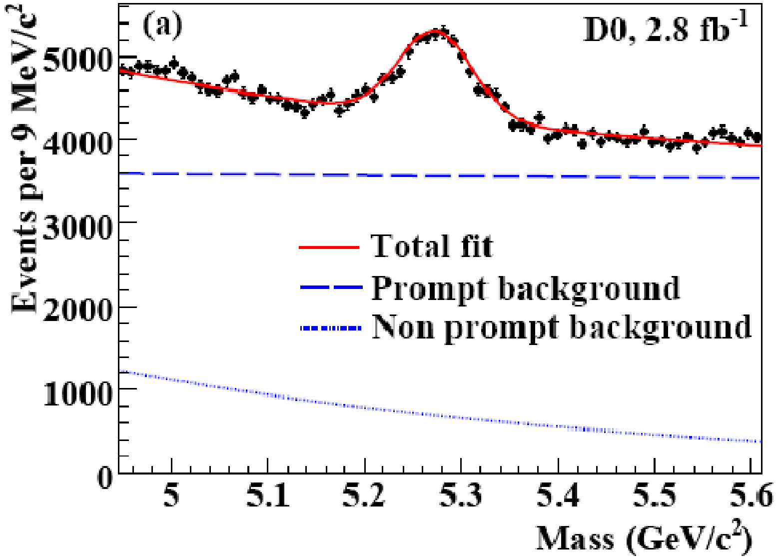


- Not only agree with latest BaBar results, (PRD 76,031102 (2007)) but also competitive

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

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

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



- Consistency of amplitudes and strong phase between Bs and B0

arXiv:0810.0037v1

Analysis without Flavor Tagging

- Drop information on production flavor
- Simpler but less powerful analysis

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

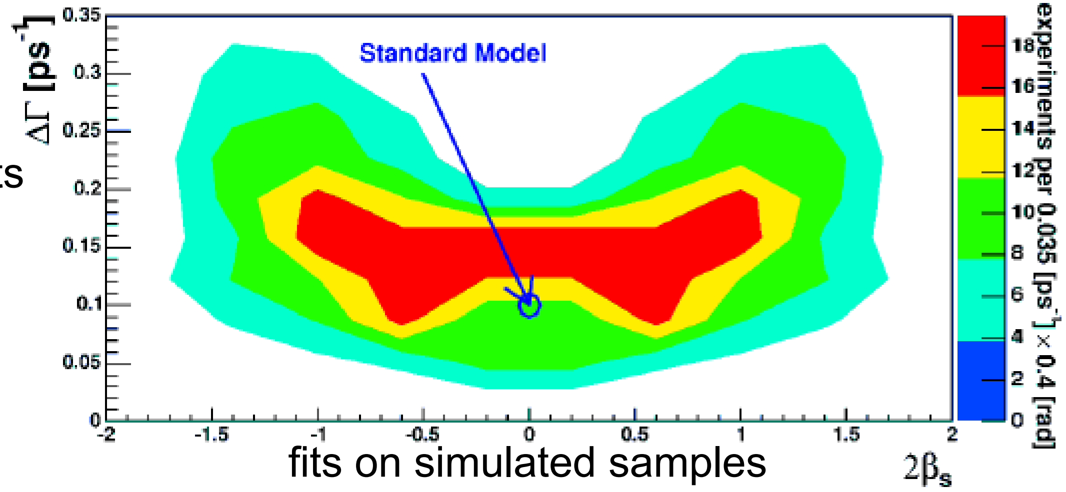
$$\begin{aligned}\mathcal{U}_{\pm} = \pm e^{-\Gamma t} \times & \left[\cancel{\sin(\delta_{\perp} - \delta_{\parallel}) \cos(\Delta m_s t)}\right.\\ & - \cancel{\cos(\delta_{\perp} - \delta_{\parallel}) \cos(2\beta_s) \sin(\Delta m_s t)}\\ & \left.\pm \cos(\delta\_ - \delta_{\parallel}) \sin(2\beta_s)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

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

- Still sensitive to CP-violation phase β_s
- Suited for precise measurement of width-difference and average lifetime

CDF β_s in Untagged Analysis

- Fit for the CPV phase
- Biases and non-Gaussian estimates in pseudo-experiments
- Strong dependence on true values for biases on some fit parameters.



fits on simulated samples

a) Dependence on one parameter in the likelihood vanishes for some values of other parameters:

e.g., if $\Delta\Gamma=0$, $\delta_\perp$ is undetermined $\cos(\delta_\perp)\sin(2\beta_s)\sinh(\Delta\Gamma t/2)]$

b) L invariant under two transformations:

$$2\beta_s \to -2\beta_s,\ \delta_\perp \to \delta_\perp + \pi$$
$$\Delta\Gamma \to -\Delta\Gamma,\ 2\beta_s \to 2\beta_s + \pi$$

→ 4 equivalent minima

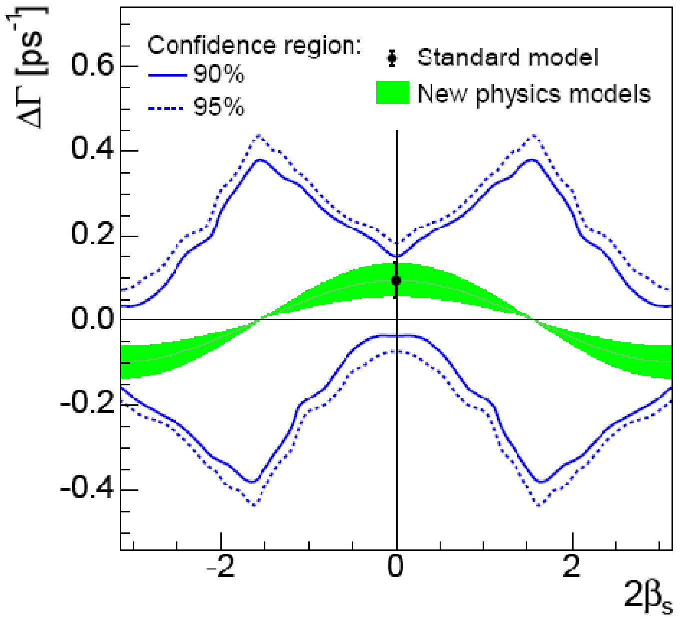
β_s in Untagged Analysis

- Irregular likelihood and biases in fit
  → CDF quotes Feldman-Cousins confidence regions: Standard Model probability 22%

- DØ quotes point estimate: $\Phi_s = -0.79 \pm 0.56\ (stat)\ ^{+0.14}_{-0.01}\ (syst)$

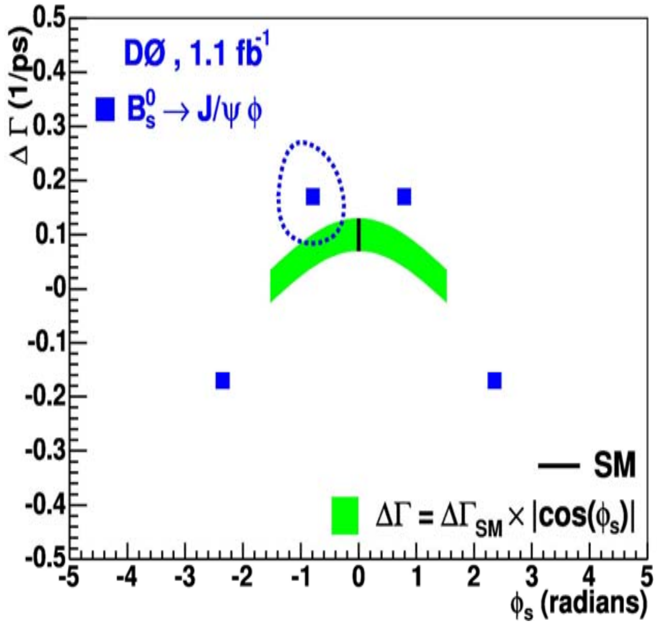
- Symmetries in the likelihood → 4 solutions are possible in $2\beta_s$-$\Delta\Gamma$ plane

CDF: 90%, 95% C.L 1.7 fb^{-1}



Phys. Rev. Lett. 100, 121803 (2008)

DØ: 39% C.L. 1.1 fb^{-1}

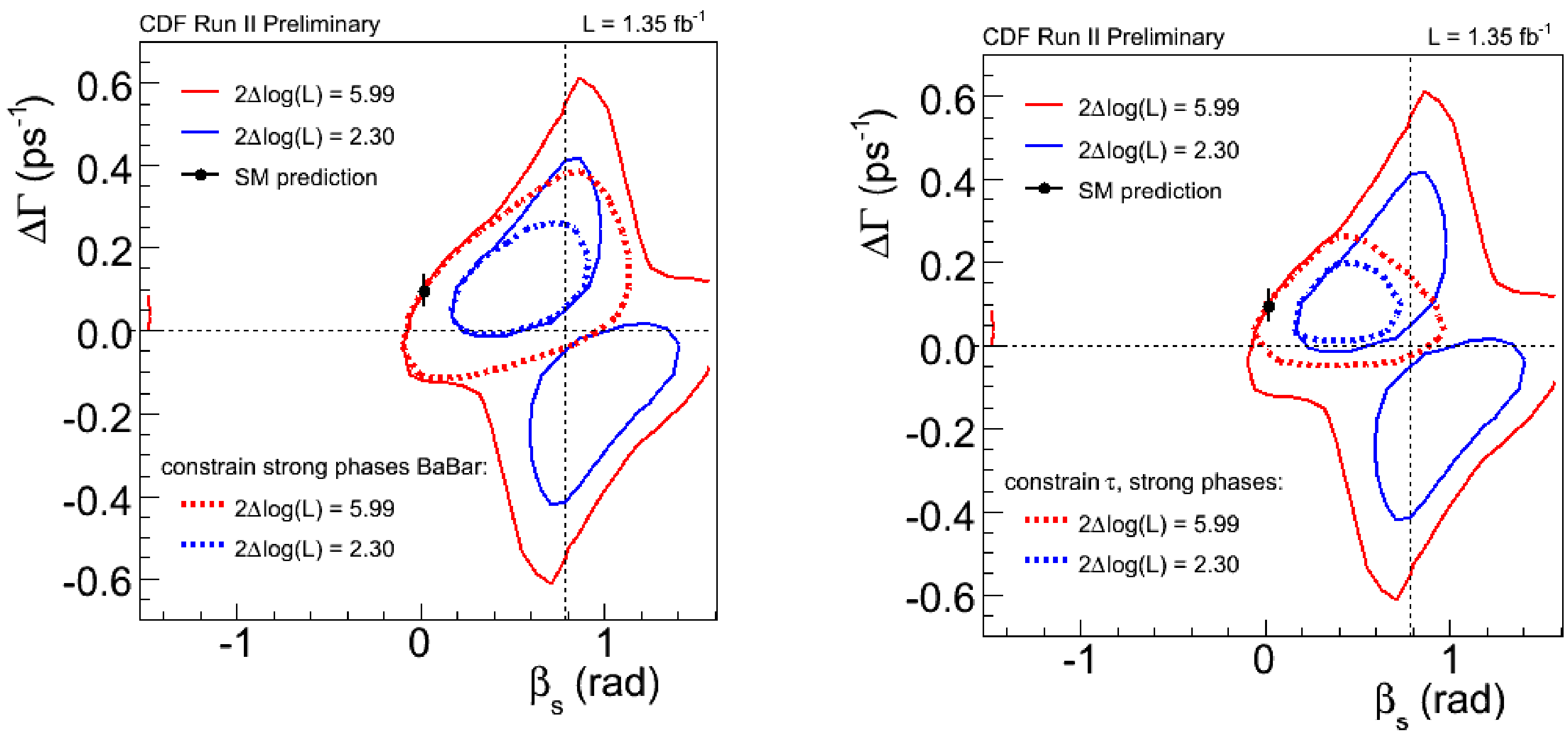


PRL 98, 121801 (2007)

CDF External Constraints in Tagged Analysis (1.4 fb^{-1})

- Spectator model of B mesons suggests that B_s and B^0 have similar lifetimes and strong phases
- Likelihood profiles with external constraints from B factories:

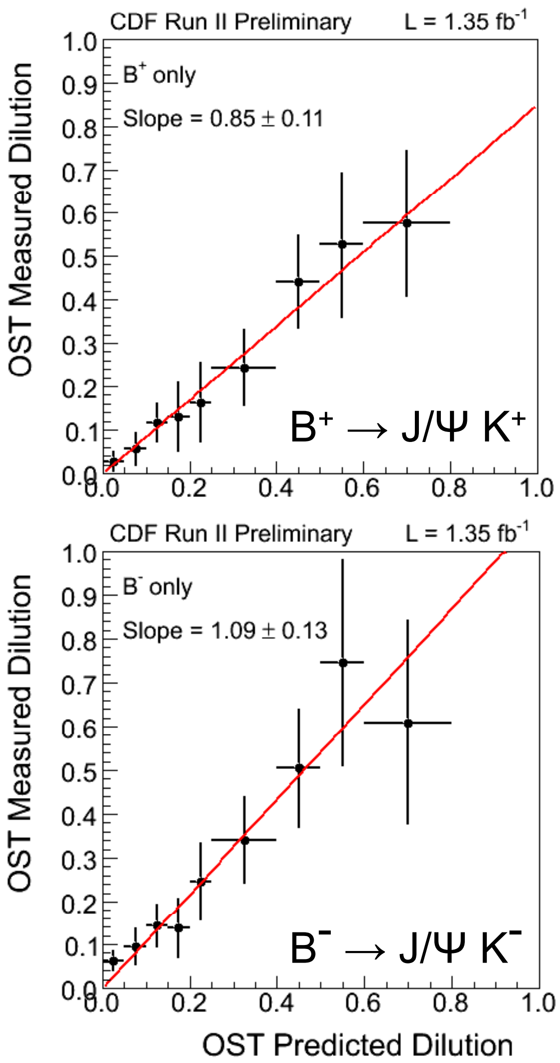
constrain strong phases: constrain lifetime and strong phases:

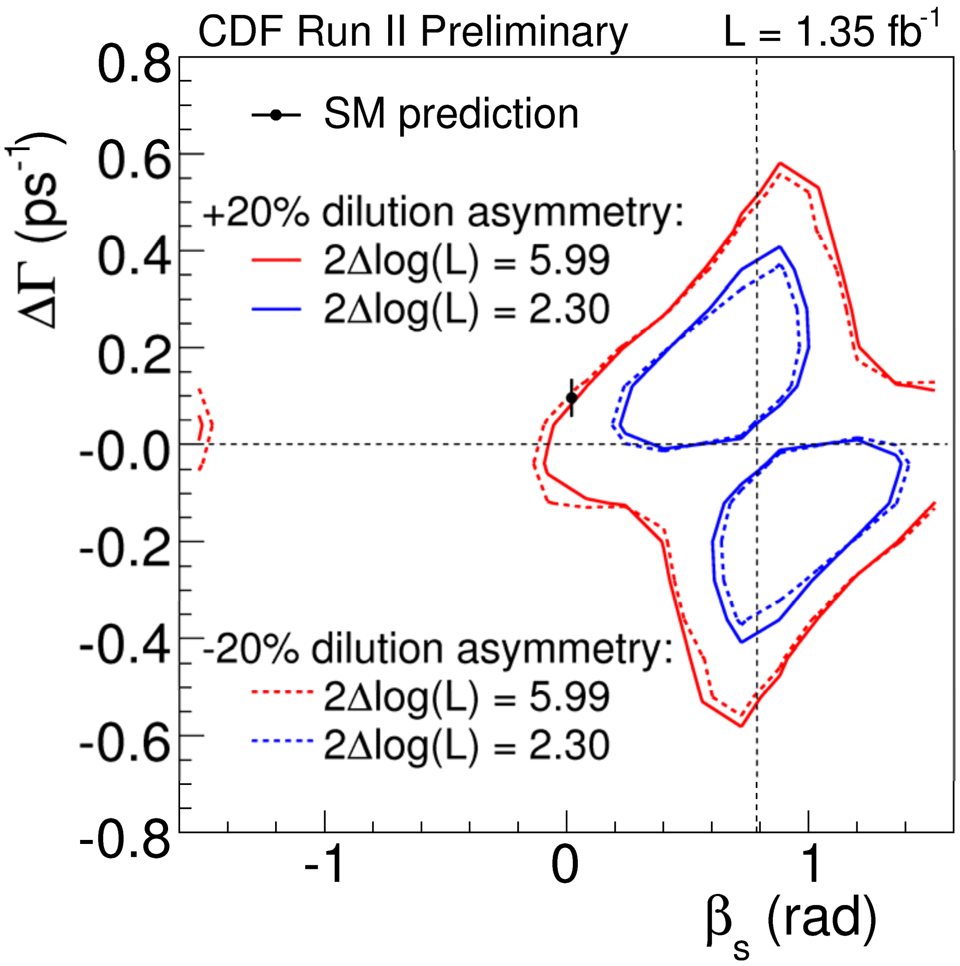


- External constraints on strong phases remove residual 2-fold ambiguity

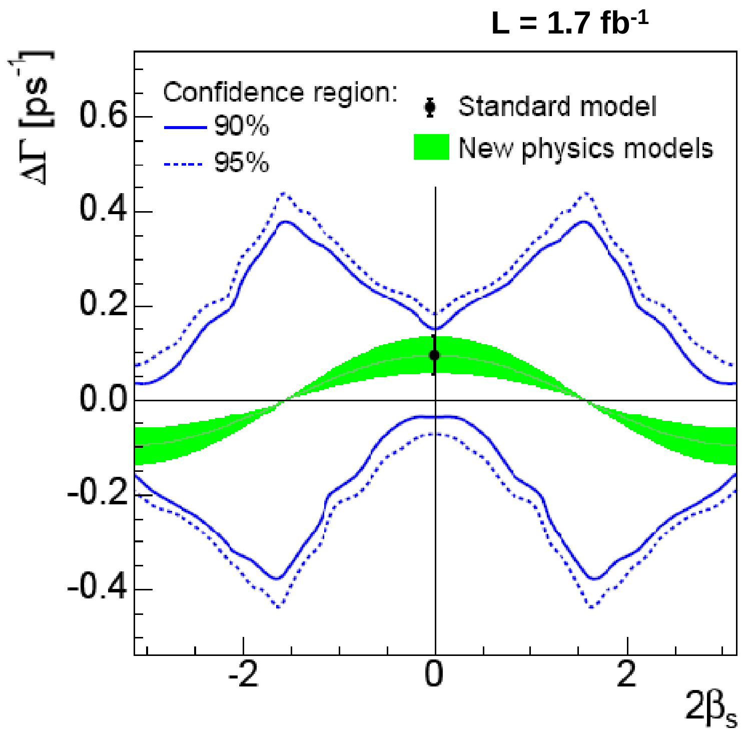
Effect of Dilution Asymmetry on β_s

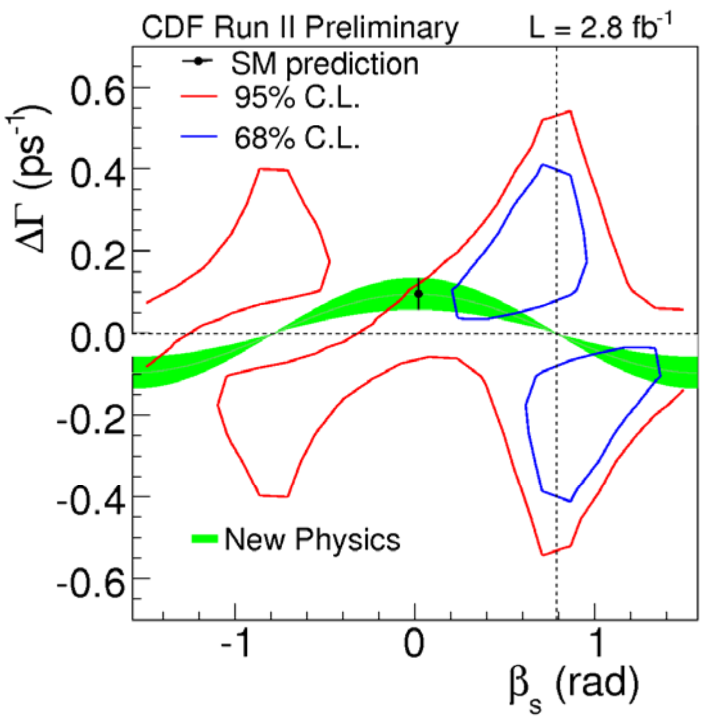
- Effect of 20% b-bbar dilution asymmetry is very small





Comparison Between CDF Tagged and Untagged Analysis

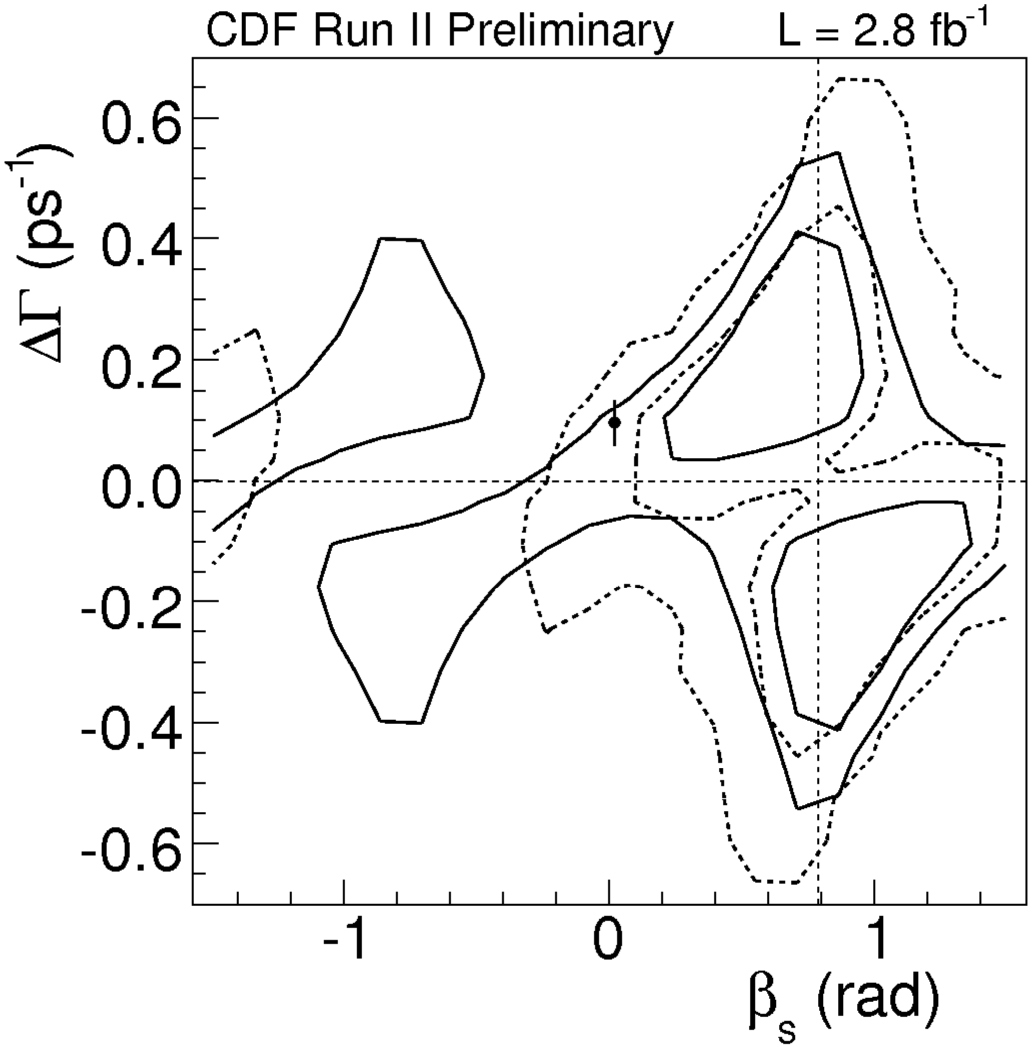




- Allowed parameter space significantly reduced by using B_s flavor tagging
- Negative β_s values are suppressed

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

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



Non-Gaussian Regime

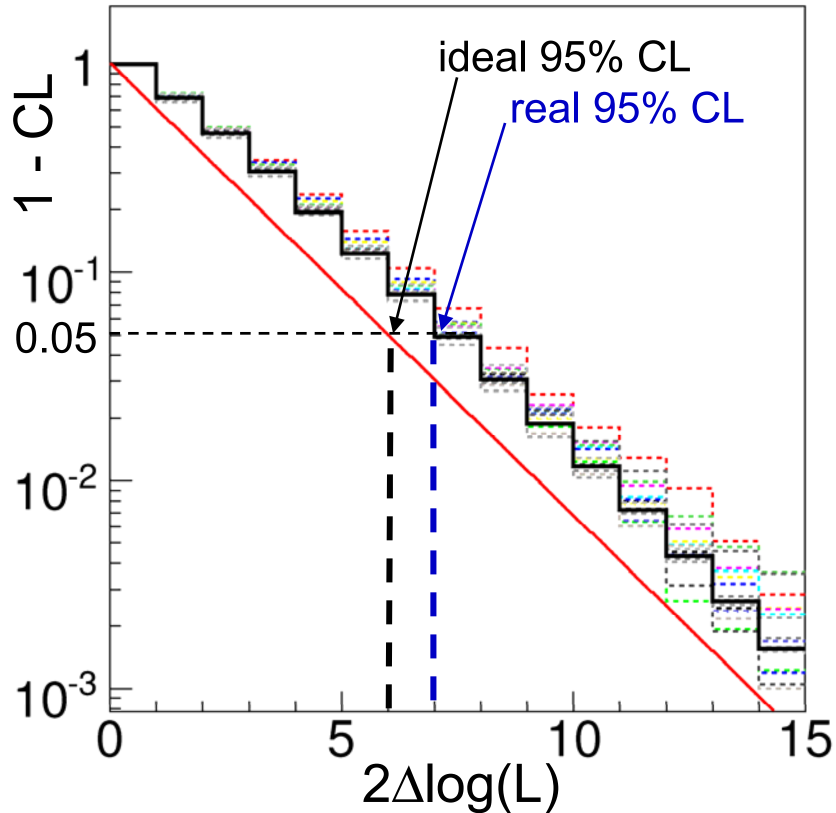
- In ideal case (high statistics, Gaussian likelihood), to get the 2D 68% (95%) C.L. regions, take a slice through profile likelihood at 2.3 (6) units up from minimum

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

-To get 95% CL need to go up ~7 instead of 6 units from minimum

- Procedure used by both CDF and DØ

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

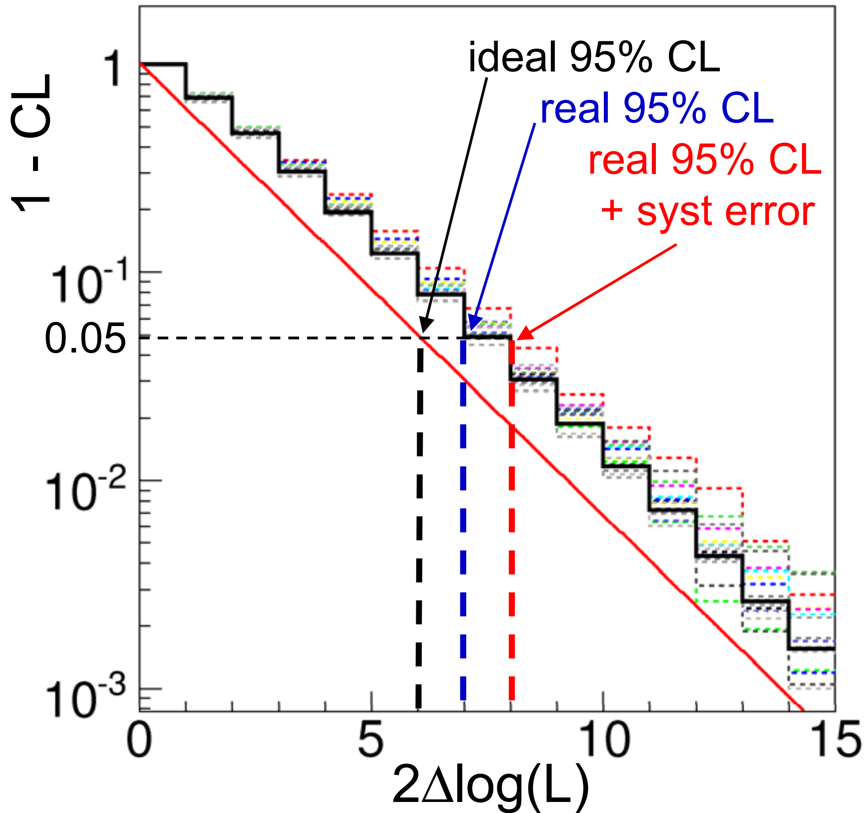


CDF Systematics

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

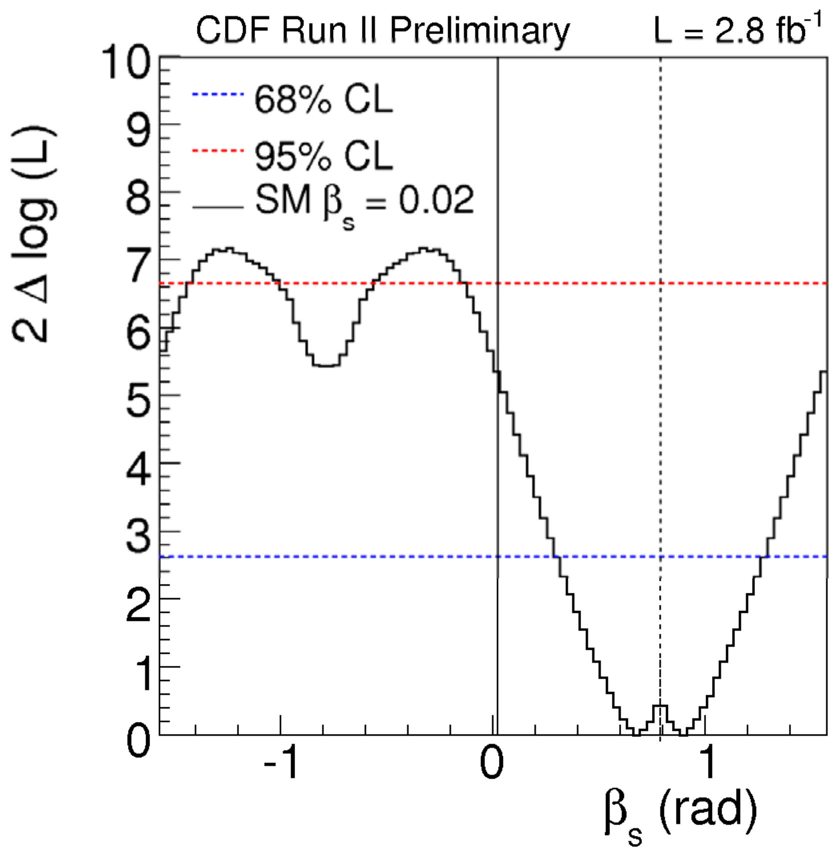
- Nuisance parameters:
  - lifetime, lifetime scale factor uncertainty,
  - strong phases,
  - transversity amplitudes,
  - background angular and decay time parameters,
  - dilution scale factors and tagging efficiency
  - mass signal and background parameters
  - …

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

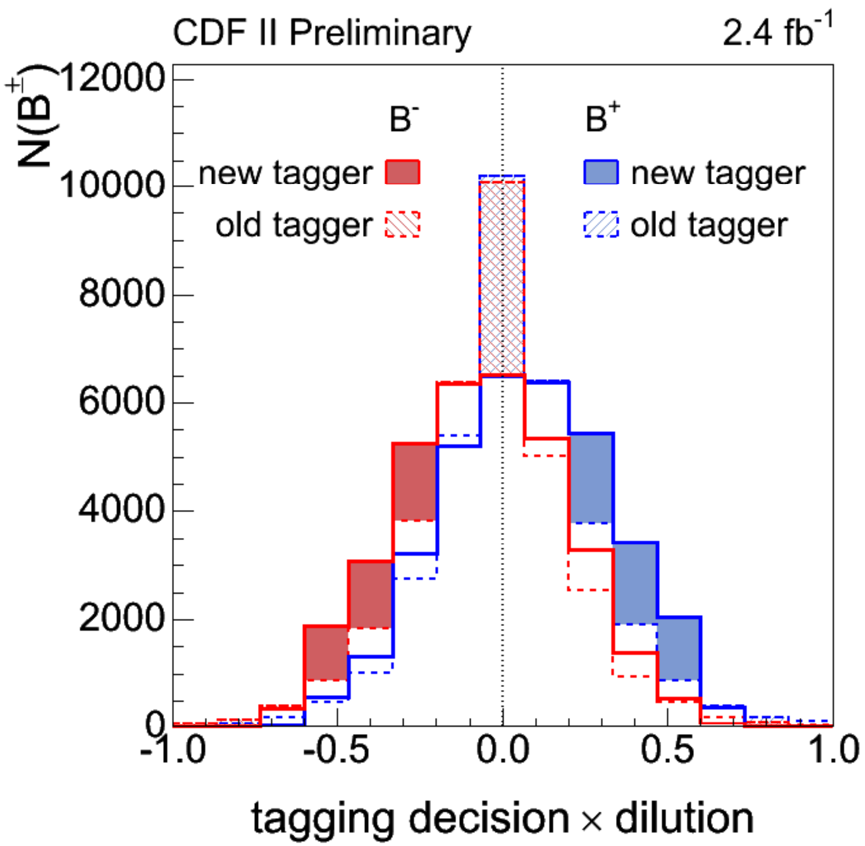


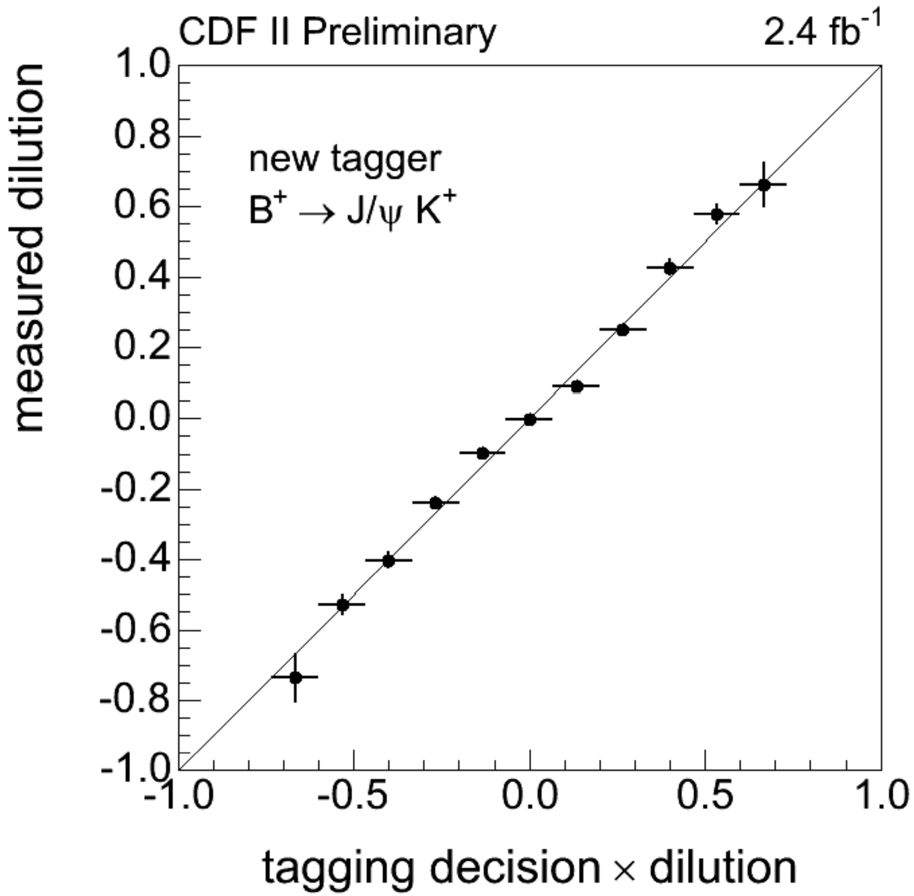
CDF 1D Profile Likelihood

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



CDF Updated Tagger Coming Soon





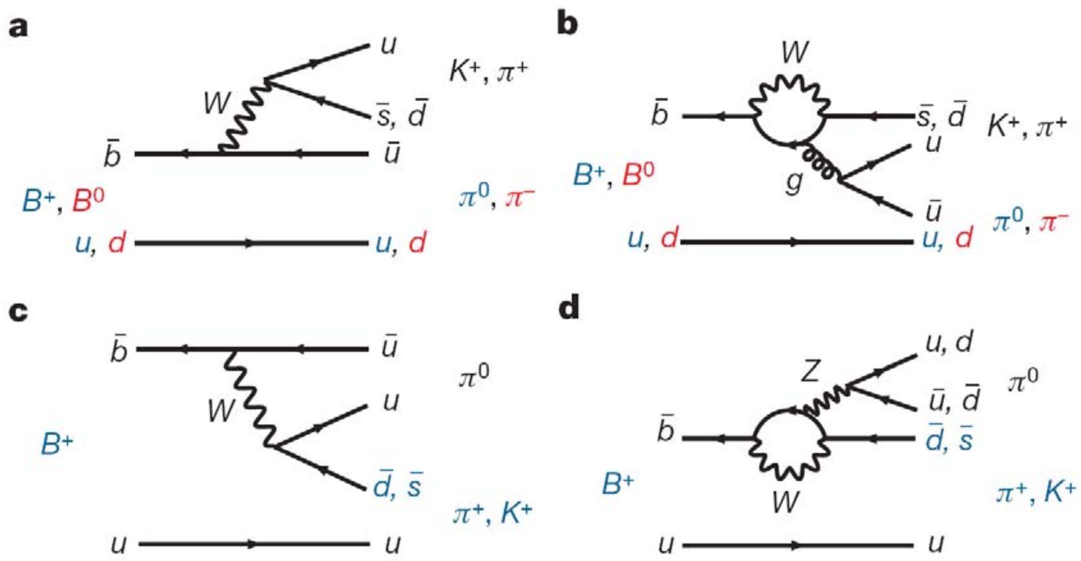
Another Related Puzzle ?

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

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

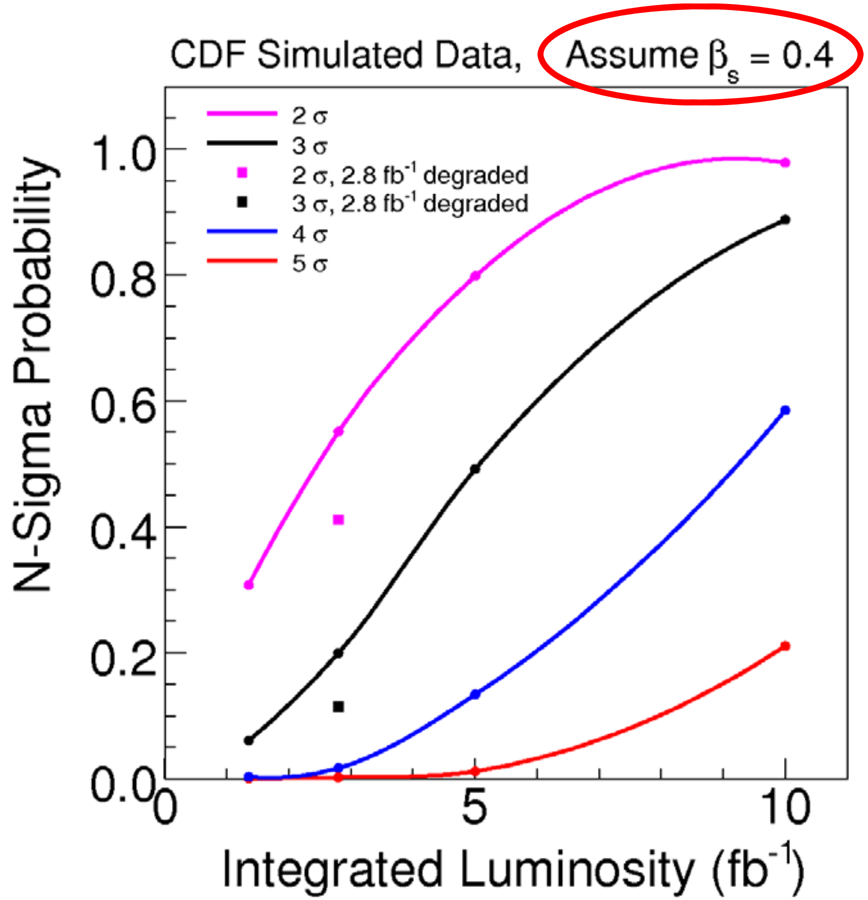
Lin, S.-W. et al. (The Belle collaboration) Nature 452,332–335 (2008)

- Including BaBar measurements: > 5σ



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

Future (2)



CDF Simulated Data, Assume β_s = 0.4
2 σ
3 σ
2 σ, 2.8 fb^{-1} degraded
3 σ, 2.8 fb^{-1} degraded
4 σ
5 σ
N-Sigma Probability
0.0
0.2
0.4
0.6
0.8
1.0
0
5
10
Integrated Luminosity (fb^{-1})