B physics results from the Tevatron mixing and CP violation

Avdhesh Chandra

UNIVERSITY of CALIFORNIA Riverside

for the CDF and DØ collaborations

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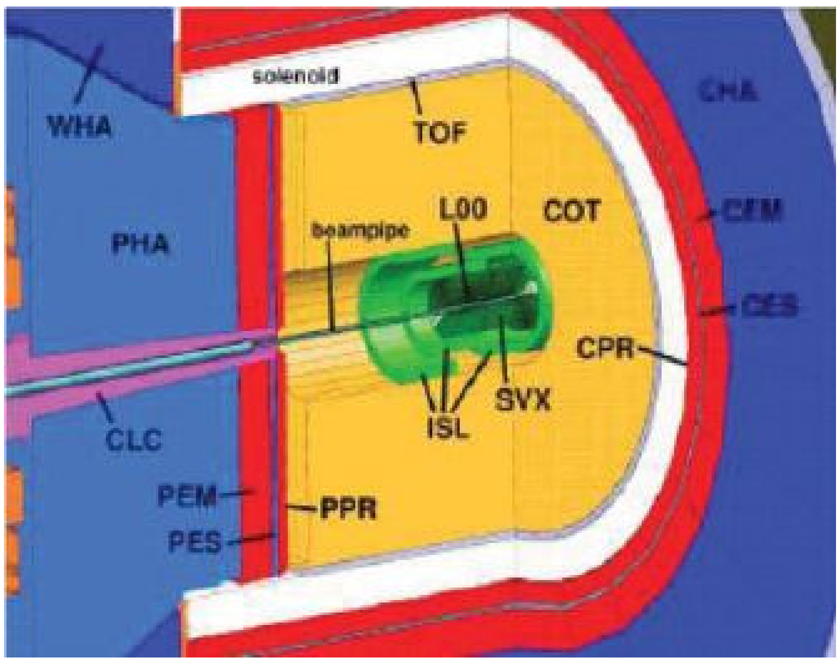
Outline

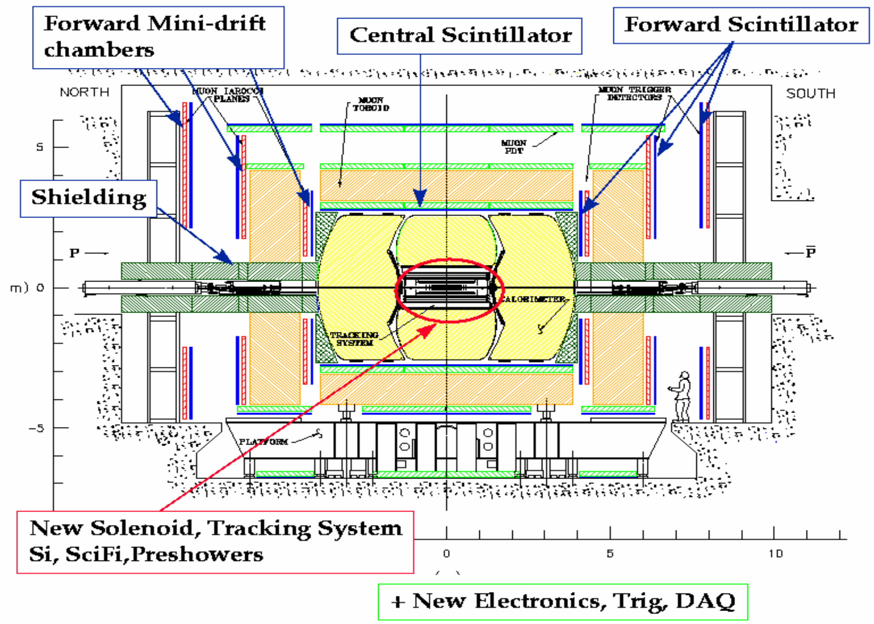
- Introduction
- Mixing measurement
  - ΔM_s (DØ & CDF)
  - Semileptonic asymmetry A_{sl}^s (DØ & CDF)
- Mixing interference measurement
  - $\Delta\Gamma_s$, ϕ_s (DØ & CDF)
- Direct CP violation measurement
  - $B_s \to K\pi$ (CDF)
  - $B^- \to D^0 K^-$ (CDF)
  - $B^\pm \to J/\psi K^\pm(\pi^\pm)$ (DØ)
- Summary & Outlook

Tevatron is a unique place to study B_s mesons
in this talk I will cover mostly B_s results

The CDF & DØ Detector

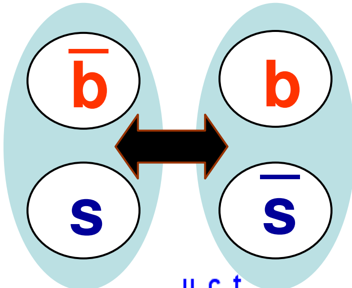
- **Excellent tracking & mass resolution**
  - **Silicon $|\eta| < 2$, 90 cm long**
  - **96 layer drift chamber 44 to 132 cm**
- **Triggered Muon coverage**
  - **$p_T > 1.5$ GeV, $|\eta| < 1$**



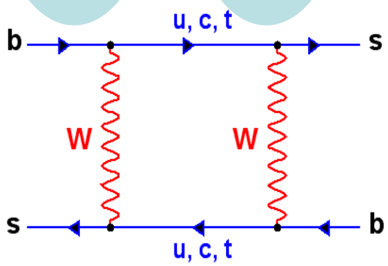


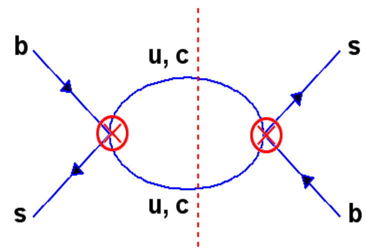
- **Low p_T Muon identification**
  - **$p_T > 1.5$ GeV, $|\eta| < 2$**
- **High tracking efficiency:**
  - **95% $|\eta| < 3$ (Silicon disks)**

B_s Mixing



Schrödinger Equation: $$i\frac{\partial}{\partial t}\begin{pmatrix}|B_s^0(t)\rangle \\ |\overline{B_s^0}(t)\rangle\end{pmatrix} = \begin{pmatrix} M_{11}-\frac{i}{2}\Gamma_{11} & M_{12}-\frac{i}{2}\Gamma_{12} \\ M_{21}-\frac{i}{2}\Gamma_{21} & M_{22}-\frac{i}{2}\Gamma_{22}\end{pmatrix}\begin{pmatrix}|B_s^0(t)\rangle \\ |\overline{B_s^0}(t)\rangle\end{pmatrix}$$





- M_{12} stems from the real part of the box diagram, dominated by top
- Γ_{12} stems from the imaginary part, dominated by charm

Diagonalization gives two physically observed "Light" and "Heavy" mass eigenstates

$$|B_L\rangle = \frac{1}{\sqrt{p^2+q^2}}\left(p|B_s^0\rangle + q|\overline{B_s^0}\rangle\right) \rightarrow \text{CP even}$$

$$|B_H\rangle = \frac{1}{\sqrt{p^2+q^2}}\left(p|B_s^0\rangle - q|\overline{B_s^0}\rangle\right) \rightarrow \text{CP odd}$$

with $|p|^2 + |q|^2 = 1$

for $\frac{q}{p} = 1$

i.e. **no CP *violation***

'squashed' triangle → 'flat' triangle

$\Delta\Gamma_s$ & ϕ_s from $B_s \rightarrow J/\psi\ \phi$

- Golden decay mode, equivalent to $B_d \rightarrow J/\psi K_s$ for $\sin(2\beta)$ measurement
- Flavor mixing CPV angle $\phi_{12} = \arg(M_{12}/\Gamma_{12})$ very small in SM (~0.004)
- CPV phase, $\phi_s = \arg(-V_{ts}V_{tb}^{*}/V_{cs}V_{cb}^{*})$ for $J/\psi\phi$ is also small in SM (~0.04)
- New physics contributions are same to both the quantities
  - **Significant large measurement of ϕ_s is a unambiguous sign of NP**

✓ **Angular analysis in transversity basis**

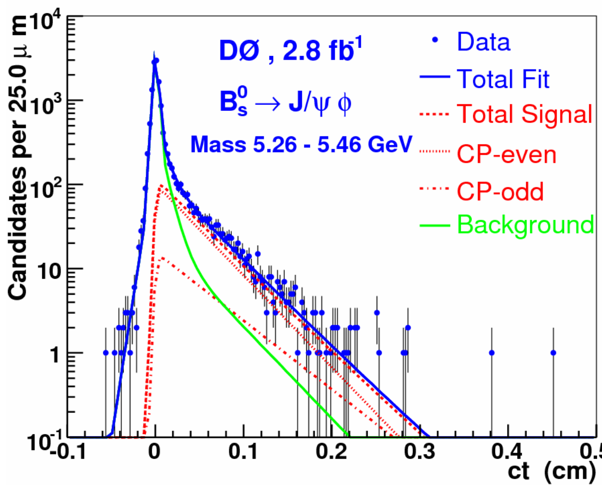
✓ **Different distributions in the time-angular space for B_s and $\bar{B}_s$**

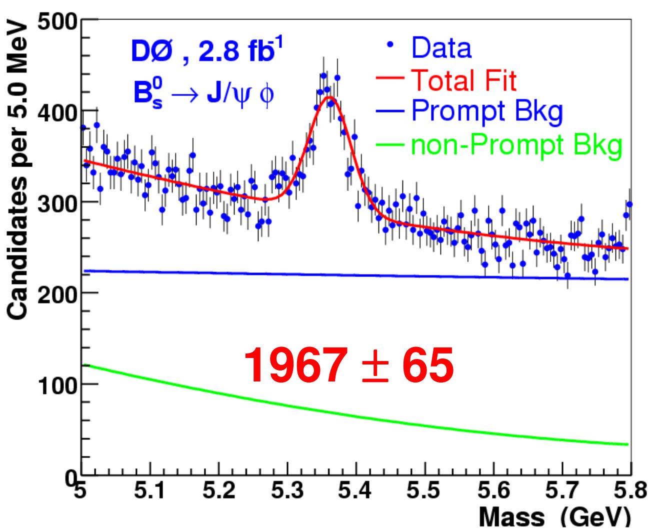
✓ **Unbinned maximum likelihood fit to mass, lifetime and decay angles**

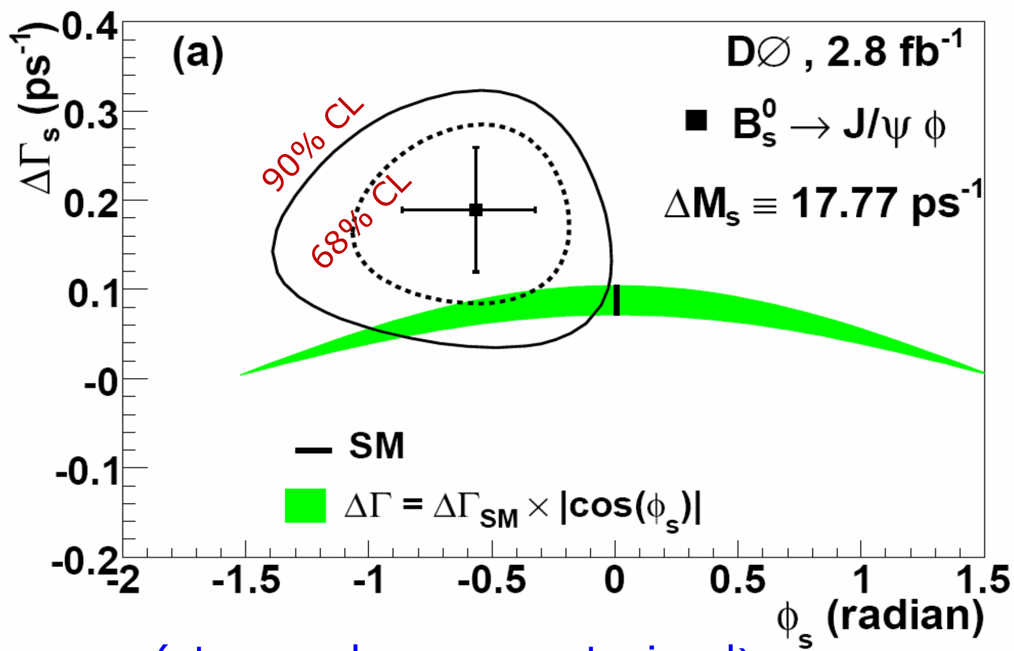
✓ **Weight applied to the angular distribution of B_s and $\bar{B}_s$ according to tagging probability (p), whenever available, otherwise p = 0.5**

✓ **Two fold ambiguity due to angular distribution equations, can be removed for fixed strong phases.**

$\Delta\Gamma_s$ & ϕ_s from DØ







(strong phases constrained)

$$\phi_s = -0.57\,^{+0.24}_{-0.30}\,(stat)\,^{+0.07}_{-0.02}\,(syst)\ \ rad$$

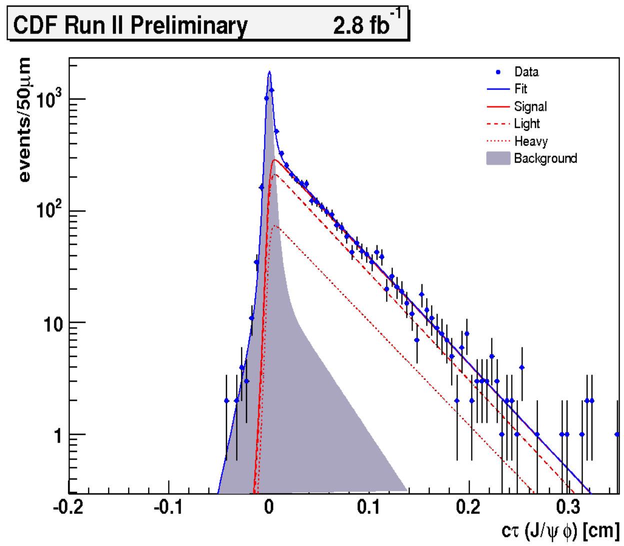
$$\Delta\Gamma_s = 0.19 \pm 0.07\,(stat)\,^{+0.02}_{-0.01}\,(syst)\ \ ps^{-1}$$

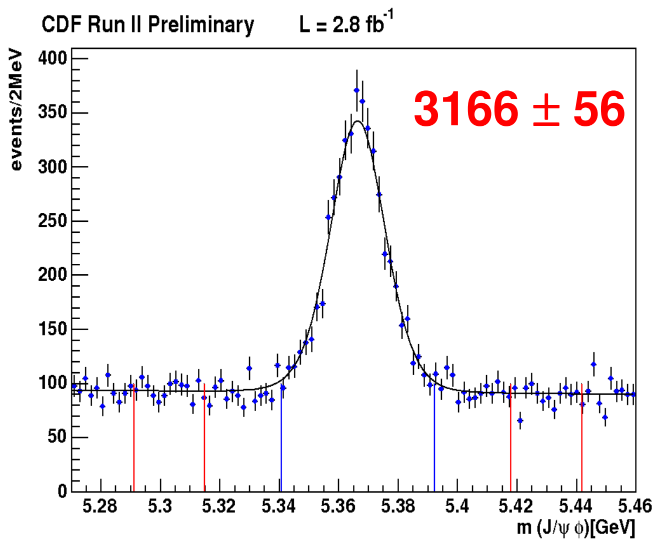
$$\overline{\tau_s} = 1.52 \pm 0.05(stat) \pm 0.01(syst)\ \ ps$$

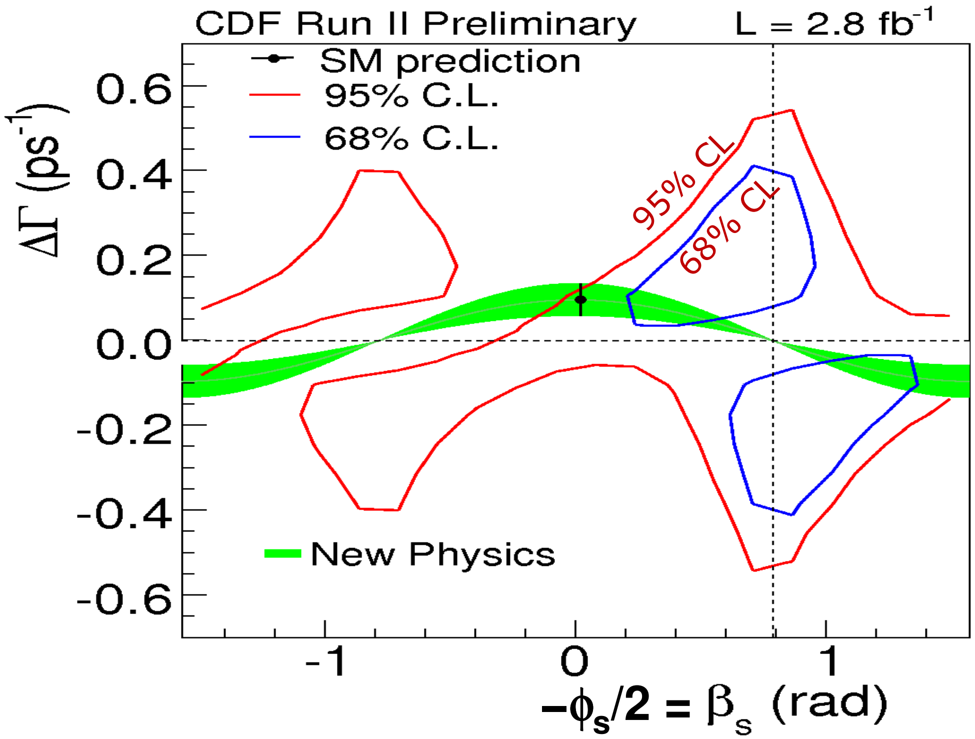
PRL 101, 241801 (2008)

Probability of SM = 6.6% ~1.8σ

$\Delta\Gamma_s$ & ϕ_s from CDF







$$-\phi_s / 2 = \beta_s = [0.28, 1.29] \; rad$$

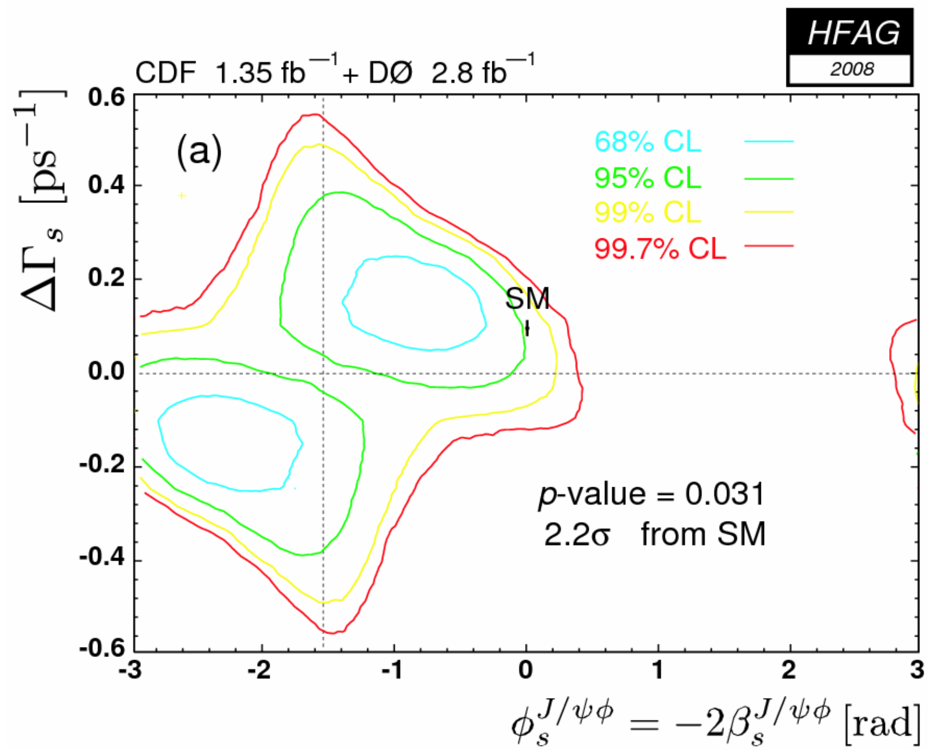
PRL 100, 161802 (2008)

Probability of SM = 7.0% ~1.8σ

$\Delta\Gamma_s$ & ϕ_s from Tevatron

Combination of results, ***with strong phases free***

- **Combination for CDF 1.35 fb^{-1} & DØ 2.8 fb^{-1}**
  - **2.2σ deviation from SM**
- **DØ result combined without strong phase constraint but without syst error (small compare to stat)**



90% CL Region

$$\phi_s \in [-2.85, -1.65], \quad [-1.47, -0.29] \ rad$$

$$\Delta\Gamma_s \in [-0.264, -0.036], \quad [0.036, 0.264] \ ps^{-1}$$

Mixing frequency, ΔM_s

The probability of mixing is given by

$$P_{B\to\bar{B}} = \frac{e^{-\Gamma t}}{2}[\cosh\frac{\Delta\Gamma t}{2} + \cos(\Delta M t)]$$

$$P_{\bar{B}\to B} = \frac{e^{-\Gamma t}}{2}[\cosh\frac{\Delta\Gamma t}{2} - \cos(\Delta M t)]$$

For $\Delta\Gamma = 0$

$$P = \frac{1}{2\tau} e^{-t/\tau}(1 \pm \cos \Delta M t)$$

Tagging efficiency — Proper decay length resolution

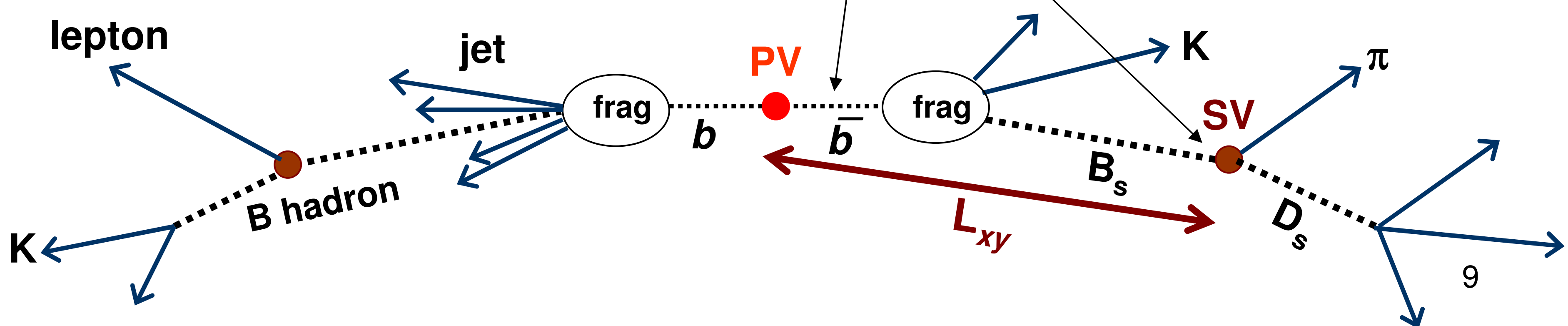
$$Sig = \sqrt{\frac{\varepsilon D^2_{\text{Dilution}}}{2}} \frac{S_{\text{Signal}}}{\sqrt{S + B_{\text{Background}}}} \times e^{-(\Delta M \sigma_t)^2/2}$$

One needs three ingredients:

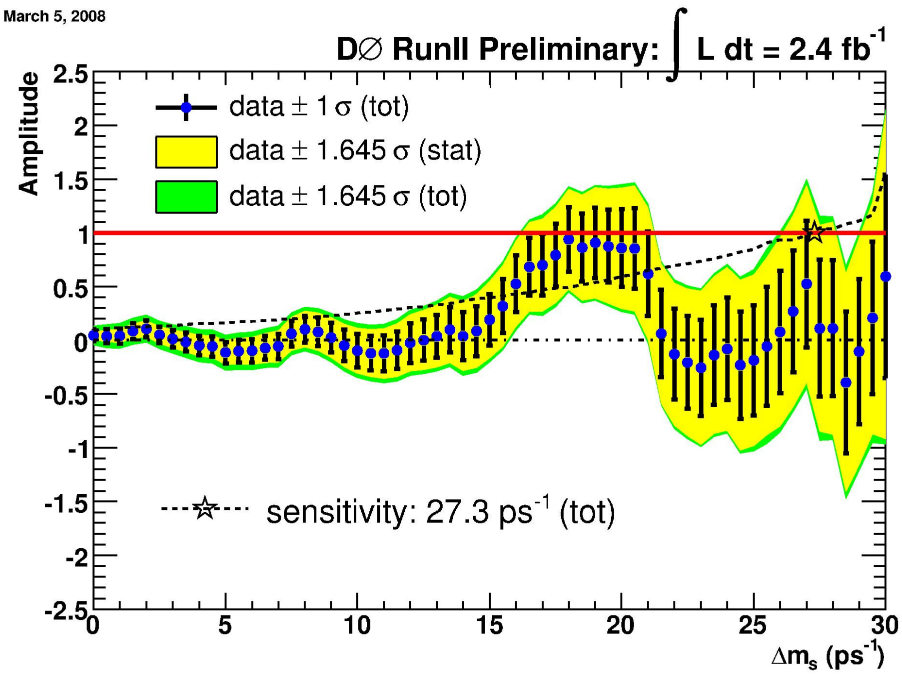
- ✓ B_s flavor at decay
- ✓ B_s flavor at production
- ✓ Good proper decay length resolution

Transverse decay length $L_{xy} = (\vec{x}_{SV} - \vec{x}_{PV}) \frac{\vec{p}_T}{p_T}$

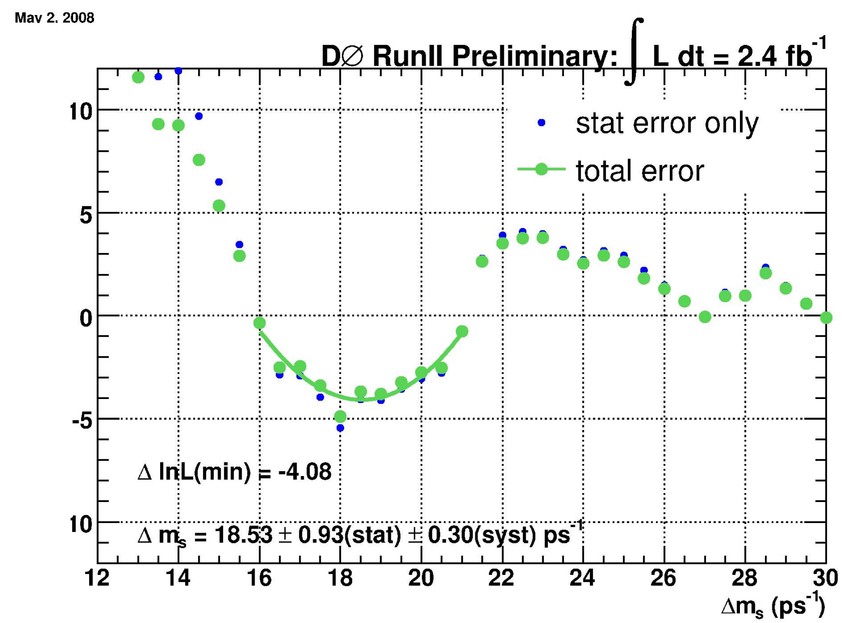
Proper decay length $ct = L_{xy} \frac{M}{p_T}$



DØ ΔM_s result



Combined amplitude scan



ΔM_s (ps^{-1})

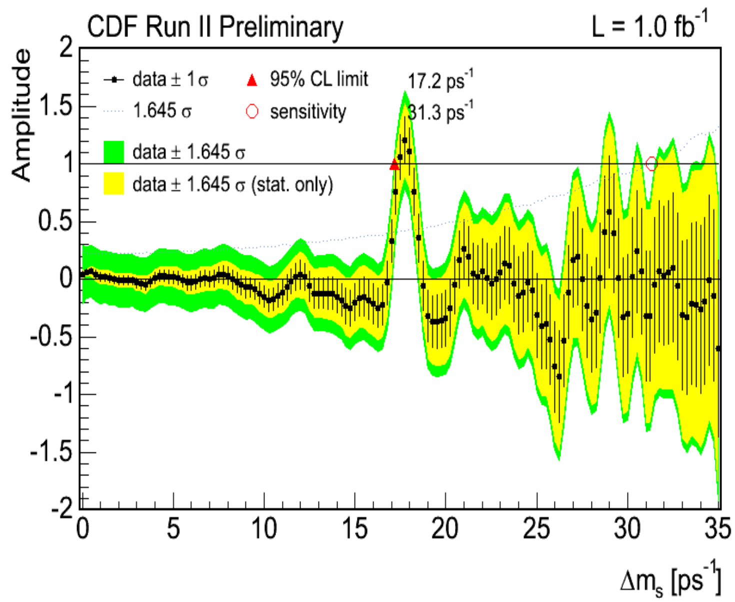
Sensitivity : 27.3 ps^{-1}

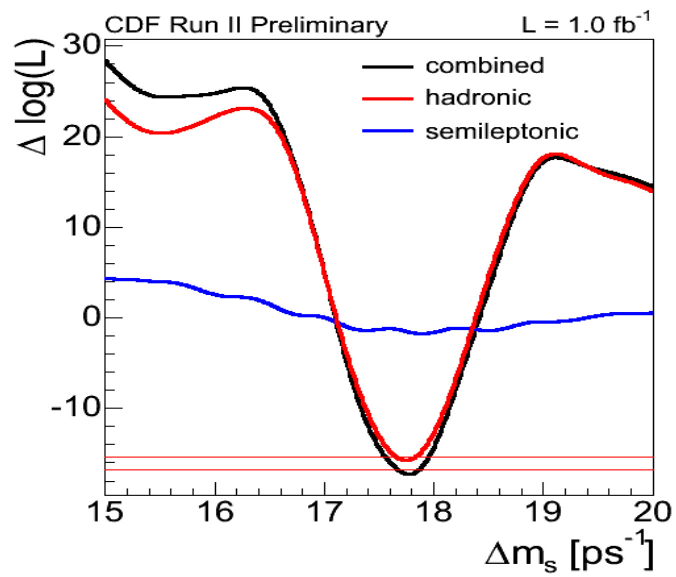
- ✓ **A parabolic fit to likelihood scan for ΔMs returns:**

  $\Delta M_s = 18.53 \pm 0.93 \pm 0.30$ ps^{-1}

- ✓ **2.9σ significance**

CDF ΔM_s result





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

✓ 5.4σ statistical significance

a_{sl}^s in semileptonic B_s decays

- ✓ Useful quantity called, semileptonic CP asymmetry for B_s decays, its SM expected value is very small (~2.06±0.57).10^{-5}
- ✓ Directly related with physical quantites $Im(\Gamma_{12}/M_{12}) = (\Delta\Gamma_s/\Delta M_s)\tan\phi_s$, hence also useful in constraining ϕ_s measurement

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Measurement of the charge asymmetry using a time-dependent analysis of

$$B_s^0 \to D_s^- \mu^+ \nu X,\ (D_s^- \to \phi\pi^-,\ \phi \to K^+ K^-)$$

Charge of the muons gives final state tagging, while initial state tagging using standard flavor tagging method (SST+OST+EvtCharg)

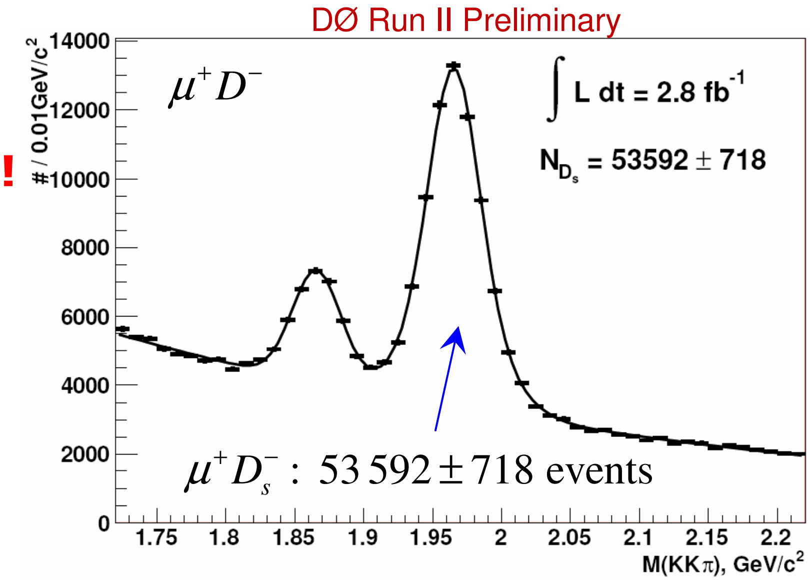
Result:

$$a_{sl}^s = -0.0024 \pm 0.0117(stat)^{+0.0015}_{-0.0024}(syst)$$

Most precise direct measurement to date!

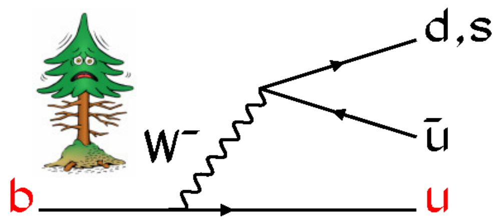
CDF also make indirect measurement of same quantity using "dimuon charge asymmetry" from 1.6 fb-1

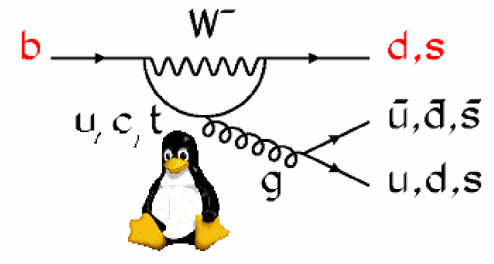
$$a_{sl}^s = 0.020 \pm 0.021(stat) \pm 0.018(syst)$$



Direct CP violation

➢ **Charmless B decays proceed though b→u CKM suppressed tree diagram and b→{s,d} loop diagram**





➢ **Similar amplitudes and their interference it may lead to sizable direct CPV**

➢ **New particles in loop diagram can change the SM expectation values**

➢ **For $B^{\pm}\rightarrow f^{\pm}$ decays, direct CP violation can be associated to non-zero charge asymmetry**

$$A_{ch} = \frac{\Gamma(B^- \rightarrow f^-) - \Gamma(B^+ \rightarrow f^+)}{\Gamma(B^- \rightarrow f^-) + \Gamma(B^+ \rightarrow f^+)}$$

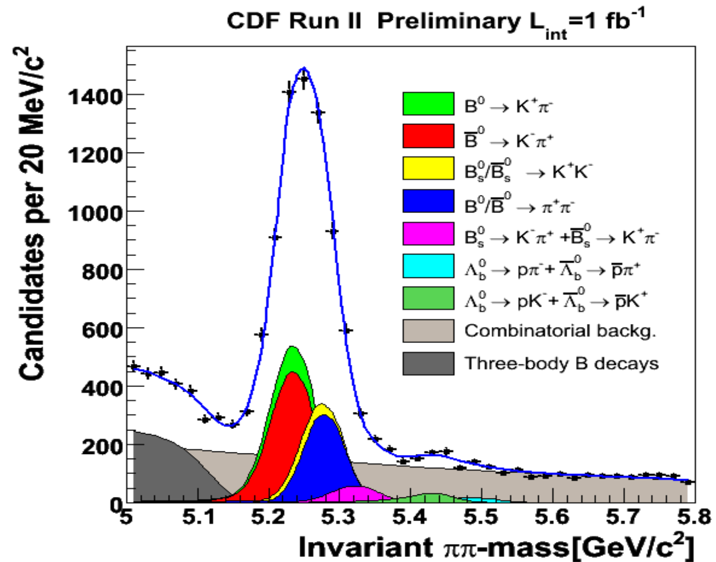
For neutral B decay to charge particles , a similar charge asymmetry is defined based on associated particle's charge with K/π , in decay

CP violation in $B_s \rightarrow K\pi$

Direct CPV for $B_s \rightarrow K\pi$ decay is defined as

$$A_{CP} = \frac{N(\overline{B}_s^0 \rightarrow K^+\pi^-) - N(B_s^0 \rightarrow K^-\pi^+)}{N(\overline{B}_s^0 \rightarrow K^+\pi^-) + N(B_s^0 \rightarrow K^-\pi^+)}$$

- **Using impact parameter displaced track trigger data**
- **$B^0 \rightarrow K\pi$, $B^0 \rightarrow \pi\pi$, $B_s \rightarrow KK$, $B_s \rightarrow K\pi$ and $\Lambda_b \rightarrow pK/\pi$ decays are inlcuded**



Unbinned maximum likelihood fit is performed using kinematics and PID, where PID for each track is defined as

$$PID = \frac{dE/dx]_{meas} - dE/dx]_{\pi}}{dE/dx]_{K} - dE/dx]_{\pi}}$$

Result: $A_{CP}(B_s^0 \rightarrow K^-\pi^+) = 0.39 \pm 0.15(stat) \pm 0.08(syst)$

- ✓ **1st Measurement of Direct CPV from $Bs \rightarrow K\pi$ decay, 2.5σ away from 0**
- ✓ **Compatible with expected value of ~0.37 , H.J.Lipkin, PLB 6212, 126, 2005**
- ✓ **ACP from $B^0 \rightarrow K\pi$ is in agreement with B-factories results.**

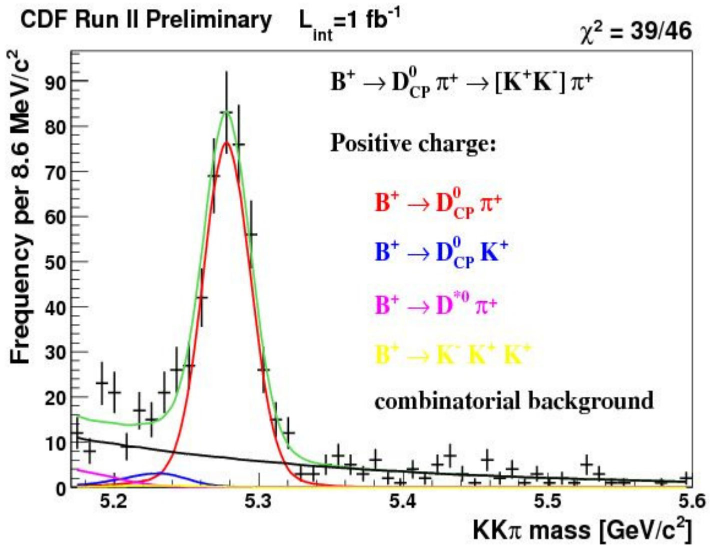
CP violation in B⁻→D⁰K⁻

Direct CPV for B⁻→D⁰K⁻ decay is defined as

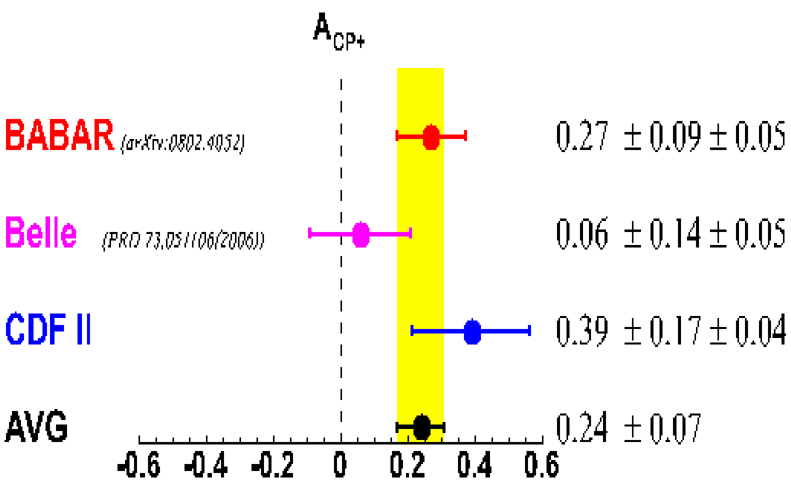
$$A_{CP+} = \frac{BR(B^- \to D^0K^-) - BR(B^+ \to D^0K^+)}{BR(B^- \to D^0K^-) + BR(B^+ \to D^0K^+)}$$

D⁰ is CP-even, i.e. either from KK or ππ

Unbinned maximum likelihood fit is performed using invariant mass, kinematics and PID



Result: $A_{CP+}(B^- \to D^0K^-) = 0.39 \pm 0.17(stat) \pm 0.04(syst)$



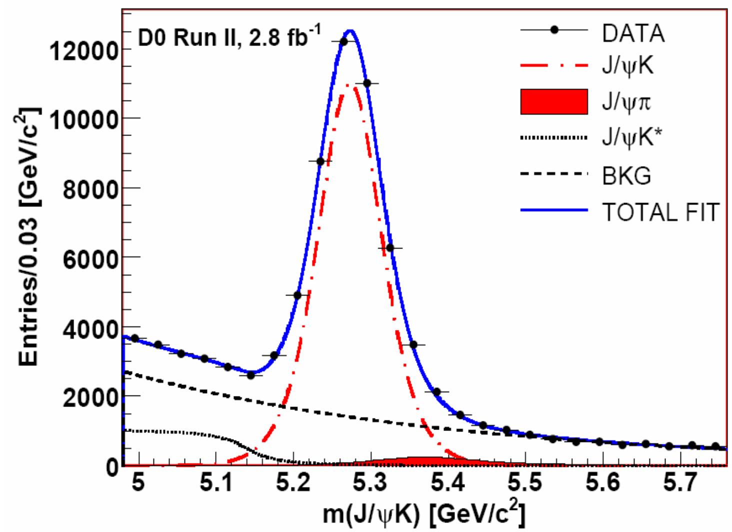
In agreement with the other measurement

CP violation in $B^{\pm} \rightarrow J/\psi K^{\pm}(\pi^{\pm})$

Charge asymmetry in $B^{\pm} \rightarrow J/\psi K^{\pm}(\pi^{\pm})$ decay

$$A_{CP} = \frac{N(B^- \to J/\psi K^-(\pi^-)) - N(B^+ \to J/\psi K^+(\pi^+))}{N(B^- \to J/\psi K^-(\pi^-)) + N(B^+ \to J/\psi K^+(\pi^+))}$$

Reconstructed events include $B \rightarrow J/\psi K$, $B \rightarrow J/\psi \pi$, $B \rightarrow J/\psi K^*$ and combinatorial background (BKG)



- ✓ **Fit assigns, ~40K events due to $B \rightarrow J/\psi K$ & ~1.6K due to $B \rightarrow J/\psi \pi$**
- ✓ **Possible production/detector asymmetries effects are taken care**

Result:

$$A_{CP}(B^+ \to J/\psi K^+) = +0.0075 \pm 0.0061(stat) \pm 0.0027(syst)$$

$$A_{CP}(B^+ \to J/\psi \pi^+) = -0.09 \pm 0.08(stat) \pm 0.03(syst)$$

SM predictions are
~0.003 for $B^+ \rightarrow J/\psi K^+$ (W.-S. Hou, M. Nagashima, A. Soddu, arXiv:hep-ph/0605080)
~0.01 for $B^+ \rightarrow J/\psi \pi^+$ (I. Dunietz, Phys. Lett. **B** 316, 561 (1993))

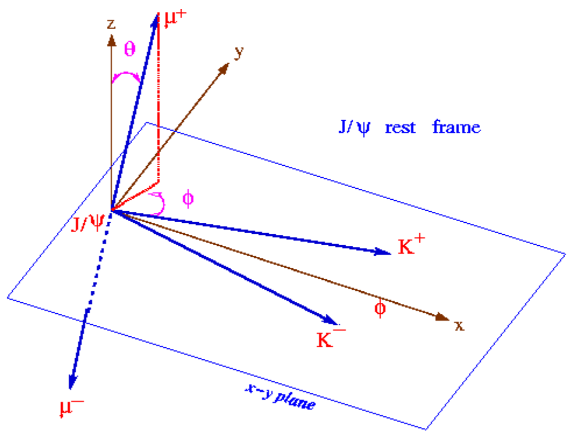
Summary and Outlook

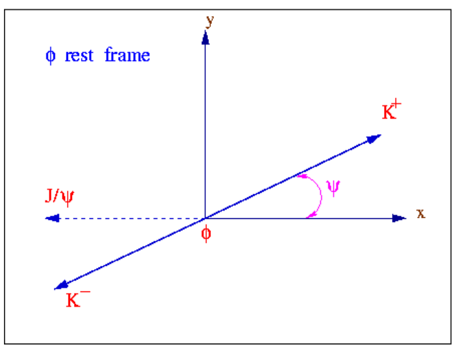
- Tevatron has rich program for CP violation studies , many measurement are 1st and most precise
- All the analysis presented in this talk used data sets of up to 2.8 fb^{-1}. We are expecting updated results with twice as much data.
- Measurement of CP violation phase, ϕ_s provides direct window for New Physics search, updated measurement and combination will be interesting
- Search for direct CP violation in B_s sector can also show new physics hint with more precise measurement
- Tevatron is expected to deliver 6 fb^{-1} by 2009, more than 4.5 fb^{-1} is available for analyses, more results soon, stay tuned!

Additional Slides

Angular Distribution

- $B_s \rightarrow$ V1 + V2 ($J/\psi + \phi$) i.e. Spin 0 $\rightarrow$ 1+1 L= 0,1,2
- L = 0 and 2 corresponds to CP even; L=1 CP odd
- Angular distribution can be written in helicity basis , BUT generally Transversity basis is used to write angular distribution , where polar coordinates are defined in "J/ψ rest frame" and "ϕ rest frame"





$$\frac{d^3\Gamma\left[B_s^0(t) \rightarrow J/\psi(\rightarrow \mu^+\mu^-)\phi(\rightarrow K^+K^-)\right]}{d\cos\theta \;\; d\varphi \;\; d\cos\psi} \propto$$

$$2\cos^2\psi(1-\sin^2\theta\cos^2\varphi) \quad |A_0(t)|^2$$

$$+ \sin^2\psi(1-\sin^2\theta\sin^2\varphi) \quad |A_\parallel(t)|^2$$

$$+ \sin^2\psi\sin^2\theta \quad |A_\perp(t)|^2$$

$$+ \frac{1}{\sqrt{2}}\sin 2\psi\sin^2\theta\sin 2\varphi \quad Re(|A_0^*(t)||A_\parallel(t)|)$$

$$+ \frac{1}{\sqrt{2}}\sin 2\psi\sin 2\theta\cos\varphi \quad Im(|A_0^*(t)||A_\perp(t)|)$$

$$- \sin^2\psi\sin 2\theta\sin\varphi \quad Im(|A_\parallel(t)||A_\perp(t)|)$$

Polarization Amplitudes

Polarization Amplitudes

hep-ph/9804253 & hep-ph/0012219

$$|A_0(t)|^2 = |A_0(0)|^2 \left[\mathcal{T}_+ \pm e^{-\overline{\Gamma}t} \sin\phi_s \; \sin(\Delta M_s t)\right]$$

$$|A_\parallel(t)|^2 = |A_\parallel(0)|^2 \left[\mathcal{T}_+ \pm e^{-\overline{\Gamma}t} \sin\phi_s \; \sin(\Delta M_s t)\right]$$

$$|A_\perp(0)|^2 = |A_\perp(0)|^2 \left[\mathcal{T}_- \mp e^{-\overline{\Gamma}t} \sin\phi_s \; \sin(\Delta M_s t)\right]$$

$$\mathcal{T}_+ = \tfrac{1}{2}\left\{(1+cos\phi_s)e^{-\Gamma_L t} + (1-cos\phi_s)e^{-\Gamma_H t}\right\}$$

$$\mathcal{T}_- = \tfrac{1}{2}\left\{(1-cos\phi_s)e^{-\Gamma_L t} + (1+cos\phi_s)e^{-\Gamma_H t}\right\}$$

$$Re(A_0^*(t)A_\parallel(t)) = |A_0(0)||A_\parallel(0)|\cos(\delta_2-\delta_1)\left[\mathcal{T}_+ \pm e^{-\overline{\Gamma}t}\sin\phi_s \; \sin(\Delta M_s t)\right]$$

$$Im(A_0^*(t)A_\perp(t)) = |A_0(0)||A_\perp(0)|\left[e^{-\overline{\Gamma}t}\left(\pm\sin\delta_2\cos(\Delta M_s t) \mp \cos\delta_2\sin(\Delta M_s t)\cos\phi_s\right) - \frac{1}{2}\left(e^{-\Gamma_H t} - e^{-\Gamma_L t}\right)\sin\phi_s \; \cos\delta_2\right]$$

$$Im(A_\parallel^*(t)A_\perp(t)) = |A_\parallel(0)||A_\perp(0)|\left[e^{-\overline{\Gamma}t}\left(\pm\sin\delta_1\cos(\Delta M_s t) \mp \cos\delta_1\sin(\Delta M_s t)\cos\phi_s\right) - \frac{1}{2}\left(e^{-\Gamma_H t} - e^{-\Gamma_L t}\right)\sin\phi_s \; \cos\delta_1\right]$$

Upper sign corresponds to: Time evolution of pure $B_s^0 \rightarrow J/\psi\,\phi$ at t=0

Lower sign corresponds to: Time evolution of pure $\overline{B}_s^0 \rightarrow J/\psi\,\phi$ at t=0

- ✓ $\overline{\Gamma}$ → average decay width of two physical eigenstates
- ✓ δ_1 δ_2 → CP-conserving strong phase ; ~ |π| and 0
- ✓ $A_0(0)$, $A_\parallel(0)$ → CP-even linear polarization amplitude at t=0
- ✓ $A_\perp(0)$ → CP-odd linear polarization amplitude at t=0

Constraining strong phases

Under flavor SU(3) symmetry , strong phases and amplitudes are expected to be similar for $B_s \rightarrow J/\psi\phi$ & $B_d \rightarrow J/\psi K^*$

arXiv:0808.3761v5 [hep-ph] , Michael Gronau, Jonathan L. Rosner

δ_1 and δ_2 have 2-fold ambiguity , the one with $\cos(\delta_1)<0$ is disfavored theoretically and experimentally, see hep-ex 0607081 (p8)

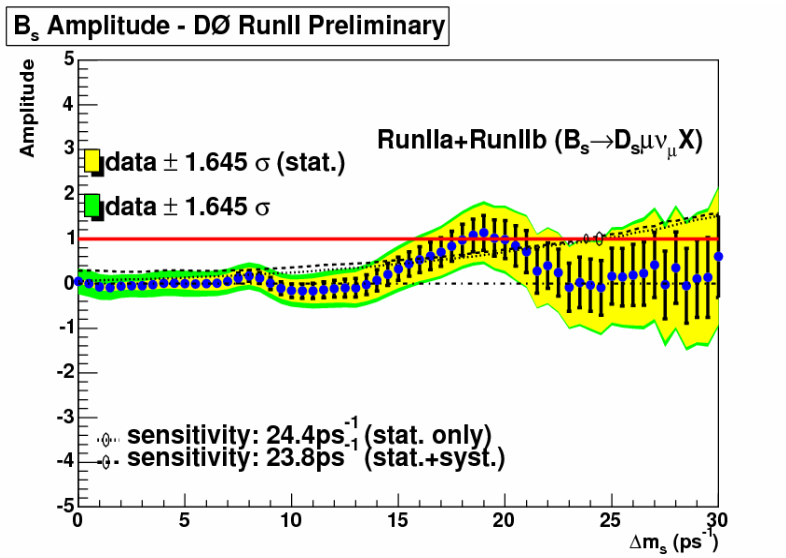
"The relative strong phases are known to have a two-fold ambiguity when measured in an angular analysis alone. In contrast with earlier publications [1, 2, 5] we use here the set of phases predicted by Suzuki [15] using arguments based on the conservation of the s quark helicity in the decay of the b quark. We have confirmed experimentally this prediction by the study of the variation with Kπ invariant mass of the phase deference between the K.(892) amplitude and a non-resonant Kπ S-wave amplitude [3]."

[15] M. Suzuki, "Large violation of s-quark helicity conservation in B → J/psi K*," Phys. Rev. D 64, 117503 (2001).

Amplitude Scan

Scan ΔM_s, for each value find $\mathcal{A} \pm \sigma_{\mathcal{A}}$

$$p^{\pm} \sim \left(1 \pm \mathcal{D} \cos\left(\Delta M_s \cdot Kt\right) \cdot \mathcal{A}\right)$$



If sample frequency is ΔM_s amplitude $\mathcal{A} = 1$

otherwise $\mathcal{A} = 0$

From QCD

$$M_{12} = -\frac{G_F^2 m_W^2 \eta_{B_s} M_{B_s} f_{B_s}^2 B_{B_s}}{12\pi^2} S_0(m_t^2/m_W^2)(V_{tq}^* V_{tb})^2$$

Weak decay constant

Bag parameter

$$\Gamma_{12} = -\frac{G_F^2 m_b^2 \eta'_{B_s} M_{B_s} f_{B_s}^2 B_{B_s}}{8\pi} \Big[(V_{tq}^* V_{tb})^2 + V_{tq}^* V_{tb} V_{cq}^* V_{cb} O\Big(\frac{m_c^2}{m_b^2}\Big) + (V_{cq}^* V_{cb})^2 O\Big(\frac{m_c^4}{m_b^4}\Big)\Big]$$

Large uncertainty cancels out

$$\frac{\Gamma_{12}}{M_{12}} \approx O\Big(\frac{m_b^2}{m_t^2}\Big)$$

$$\phi_{12} \equiv agr\Big(\frac{M_{12}}{\Gamma_{12}}\Big) \approx O\Big(\frac{m_c^2}{m_b^2}\Big)$$

$$\Delta M \approx 2|M_{12}|$$

$$\Delta\Gamma \approx 2|\Gamma_{12}| \cos\phi_{12}$$