Time Dependent Angular Analysis of $B_s \rightarrow J/\Psi\phi$ and $B_d \rightarrow J/\Psi K^*$ decays, and a Lifetime Difference in the B_s System (A Short Summary)

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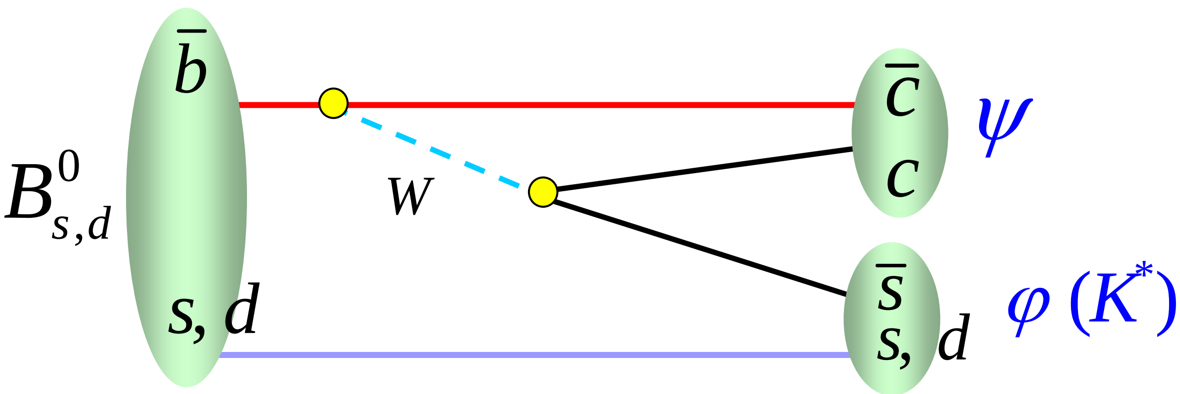
Overview

- We look for evidence of two lifetimes in B decays
- Examine two similar decay modes

$$B_s \to J/\psi\varphi$$
$$B_d \to J/\psi K^{*0}$$



- In the B_s system, we find (among other things ...)

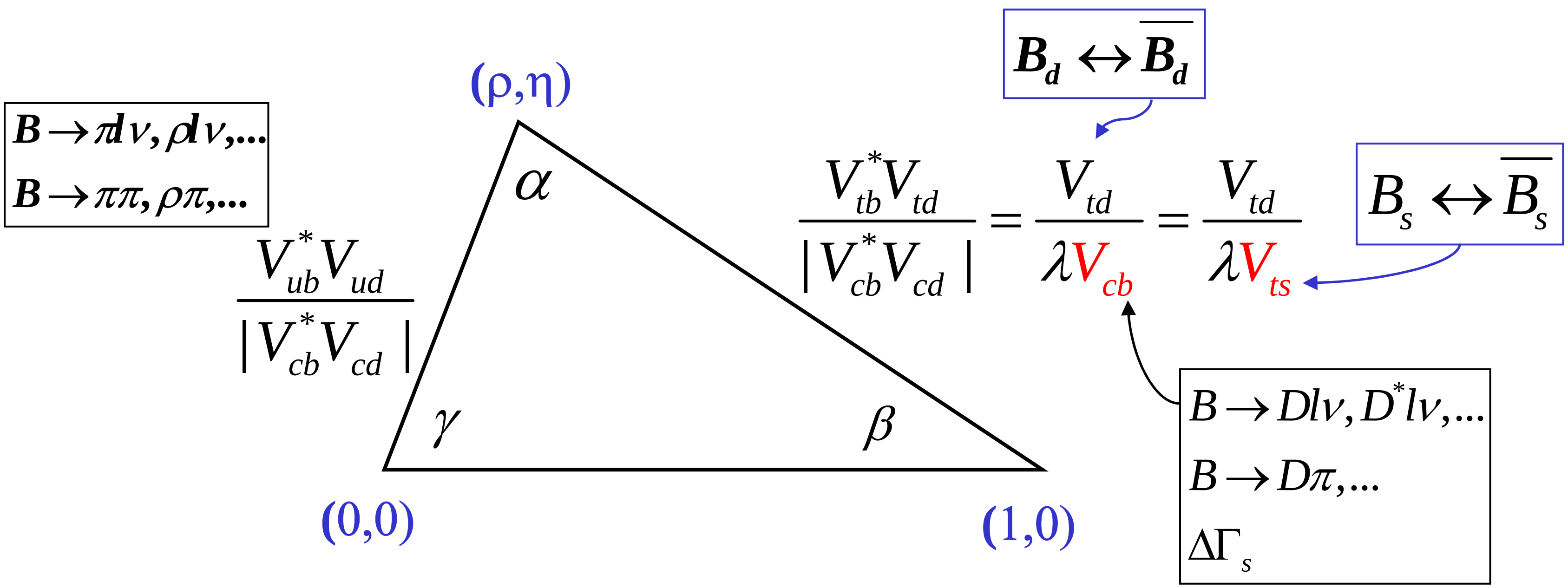
$$\tau_L = 1.13^{+0.13}_{-0.09} \pm 0.02\,\text{ps}$$
$$\tau_H = 2.38^{+0.56}_{-0.43} \pm 0.03\,\text{ps}$$

$$\Delta\Gamma_s = 0.46 \pm 0.18 \pm 0.01\ \text{ps}^{-1}$$
$$\frac{\Delta\Gamma_s}{\Gamma_s} = 0.71^{+0.24}_{-0.28} \pm 0.01$$

Unitarity Triangle

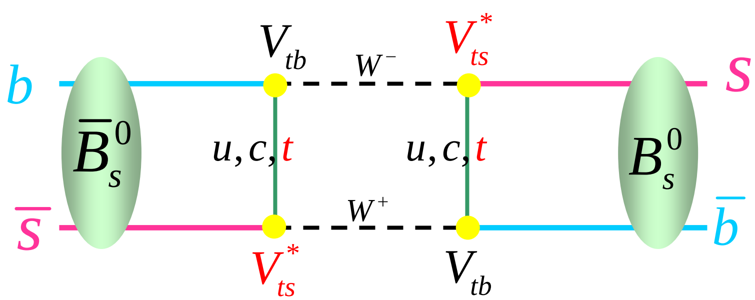
- Wolfenstein parameterization of CKM Matrix

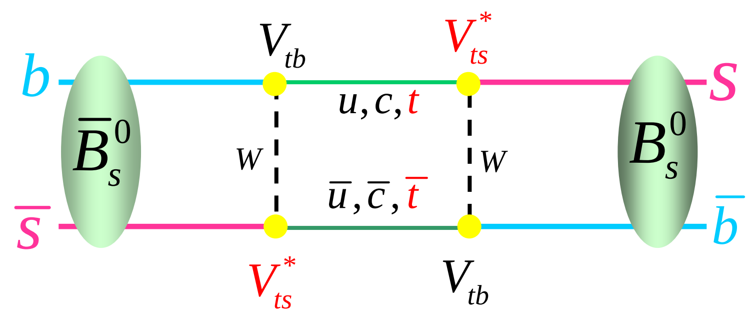
$$U = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \cong \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$



B Oscillations

- Second order weak diagram gives non-zero matrix element $\langle \overline{B} | H | B \rangle$
  - In $\overline{B} - B$ basis have a non-diagonal Hamiltonian





$$H = \begin{pmatrix} M & M_{12} \\ M_{12}^* & M \end{pmatrix} - \frac{i}{2}\begin{pmatrix} \Gamma & \Gamma_{12} \\ \Gamma_{12}^* & \Gamma \end{pmatrix}$$

- Diagonalize and get two states with eigenvalues

$$\lambda = M - \tfrac{i}{2}\Gamma \pm \frac{q}{p}(M_{12} - \tfrac{i}{2}\Gamma_{12})$$

$$M_{H,L} = M \pm \mathrm{Re}(\tfrac{q}{p}(M_{12} - \tfrac{i}{2}\Gamma_{12}))$$

$$\Gamma_{H,L} = \Gamma \pm 2\,\mathrm{Im}(\tfrac{q}{p}(M_{12} - \tfrac{i}{2}\Gamma_{12}))$$

$$\frac{q}{p} = \pm\sqrt{\frac{M_{12}^* - \frac{i}{2}\Gamma_{12}^*}{M_{12} - \frac{i}{2}\Gamma_{12}}} = \underbrace{\begin{cases} e^{2i\beta}, & B_d \\ 1, & B_s \end{cases}}_{SM}$$

Eigenstates

- Choose phase convention $CP|B_s\rangle = -|\bar{B}_s\rangle$
- E.g. in the Bs case, where we expect no phase from CKM

$$|B_s^H\rangle = p|B_s\rangle + q|\bar{B}_s\rangle = \frac{1}{\sqrt{2}}(|B_s\rangle + |\bar{B}_s\rangle) \quad \text{CP-Odd}$$

$$|B_s^L\rangle = p|B_s\rangle - q|\bar{B}_s\rangle = \frac{1}{\sqrt{2}}(|B_s\rangle - |\bar{B}_s\rangle) \quad \text{CP-Even}$$

- An initial particle or antiparticle is then

$$|B_s> = \frac{1}{\sqrt{2}}(|B_s^H> + |B_s^L>)$$

$$|\bar{B}_s> = \frac{1}{\sqrt{2}}(|B_s^H> - |B_s^L>)$$

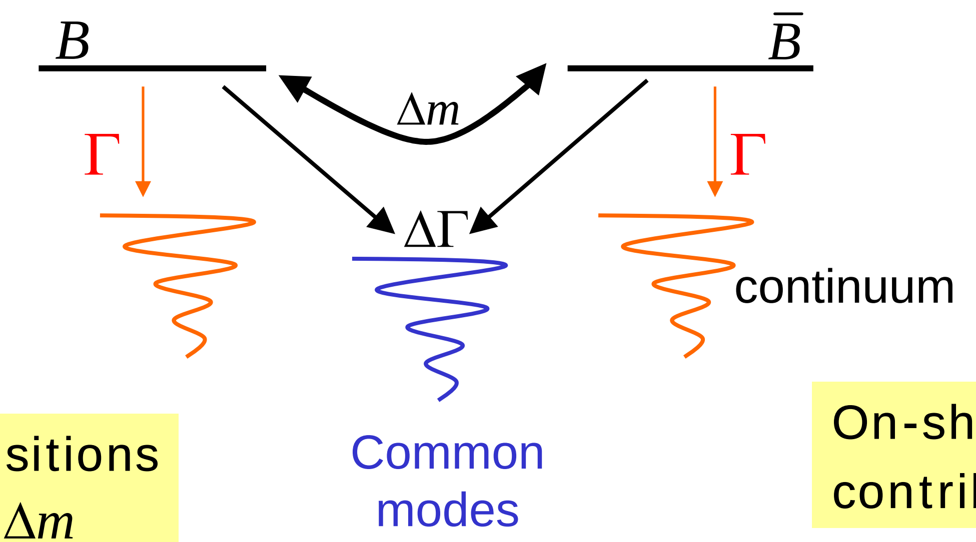
Kaon Expert Apology:

s=Strange, not Short

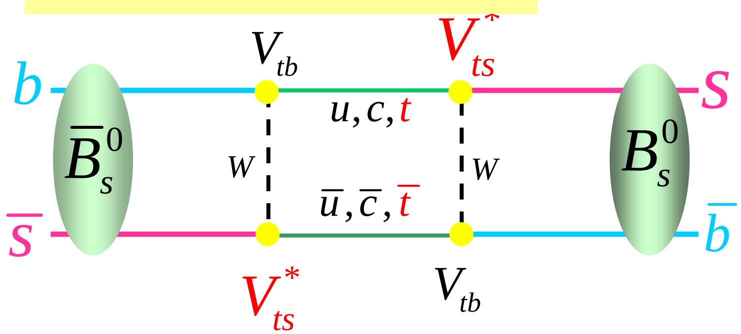
L=Light, not Long

H=Heavy

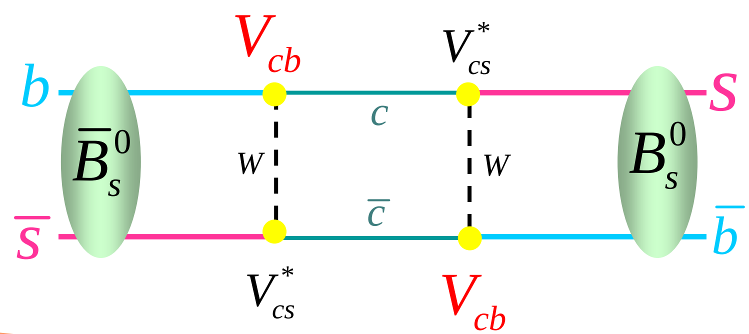
Calculating Matrix Elements



Off-shell transitions contribute to Δm



On-shell transitions contribute to $\Delta\Gamma$



$$|V_{ts}| \overset{O(\lambda^4)}{=} |V_{cb}|$$

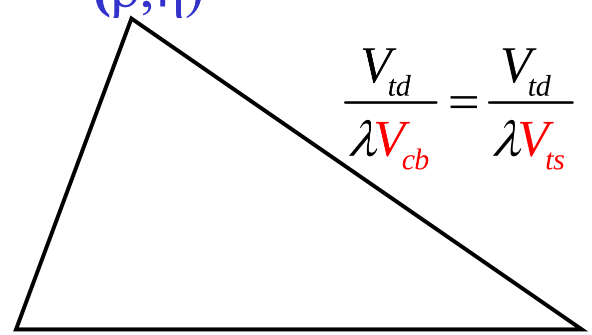
Lifetime difference measures "same" CKM element as mass difference (oscillation frequency)

Constraining Unitarity Triangle

$$\Delta m_d = \frac{G_F^2}{6\pi^2} m_B f_{B_d}^2 B_{B_d} \eta_B m_t^2 F(m_t^2 / M_W^2) |V_{td}^* V_{tb}|^2 = 0.502 \pm 0.006\,\mathrm{ps}^{-1}$$

- Determines an annulus centered at (1,0), but large errors

$$f_{B_d}\sqrt{B_{B_d}} = 228 \pm 32\,\mathrm{MeV}$$



- B decay constant and Bag parameter are almost common to B_s
  => Good to measure ratio

$$\frac{\Delta m_d}{\Delta m_s} = \frac{m_{B_d}}{m_{B_s}} \frac{f_{B_d}^2 B_{B_d}}{f_{B_s}^2 B_{B_s}} \frac{|V_{td}|^2}{|V_{ts}|^2}$$

$$\frac{f_{B_d}^2 B_{B_d}}{f_{B_s}^2 B_{B_s}} = 1.21 \pm 0.06$$

$\Delta\Gamma_s$ also suffers from needing f_{B_s} and B_{B_s} and depends upon V_{cb}, so $\frac{\Delta m_d}{\Delta\Gamma_s}$ good too

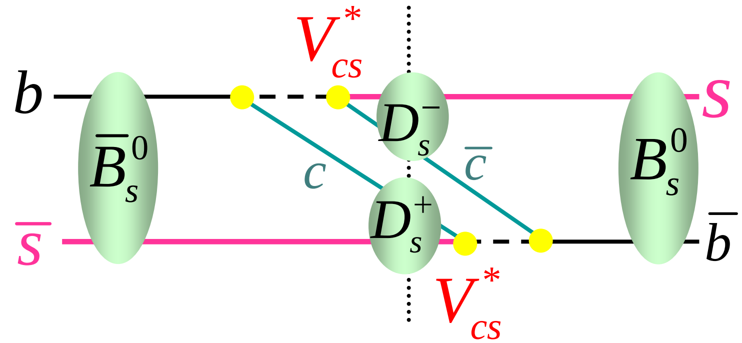
SM Expectations

- $\frac{\Delta m_d}{\Delta m_s} \approx \lambda^2 = 0.05$ from CKM elements
- $|\frac{\Gamma_{12}}{M_{12}}| \propto \frac{m_b^2}{m_t^2}$ suppressed since lifetime = on-shell transitions
- $\Delta\Gamma$ expected small in B_d system ($\Delta\Gamma / \Gamma \approx 1\%$)

- Just as $\Delta m_s \gg \Delta m_d$, $\Delta\Gamma_s \gg \Delta\Gamma_d$ can still be sizeable

$\Delta\Gamma_s / \Gamma_s = 0.12 \pm 0.06$ Dunietz, Fleischer, Niertse hep-ph/0012219

- (Intermediate D_s states, e.g., are Cabibbo-allowed)



SM Expectations

- To first approx $\frac{\Delta\Gamma}{\Delta m} = \frac{3}{2}\pi \frac{m_b^2}{m_t^2} = 3.7^{+0.8}_{-1.5} \times 10^{-3}$

  (but see Beneke et al for full form NLO analysis, hep-ph/9808385)

- In the following, we define

$$\Gamma = \tfrac{1}{2}(\Gamma_L + \Gamma_H) \equiv \frac{1}{\tau}$$
$$\Delta\Gamma = \Gamma_L - \Gamma_H$$

so that

$$\frac{1}{\tau_L} = \Gamma_L = \Gamma + \frac{\Delta\Gamma}{2},$$
$$\frac{1}{\tau_H} = \Gamma_H = \Gamma - \frac{\Delta\Gamma}{2}$$

Analysis Sketch

$$B_s \to J/\psi\varphi$$
$$B_d \to J/\psi K^{*0}$$

$$\begin{cases} J/\psi \to \mu^+\mu^- \\ \varphi \to K^+K^- \\ K^{*0} \to K^-\pi^+ \end{cases}$$

- Angular momenta:

$$P \to VV$$

- Total J of final state = 0
- Two spin-1 => J = 0, 1, 2
- Orbital L = 0, 1, 2 (S,P,D wave)

=> Need 3 amplitudes (partial wave, helicity, or transversity)

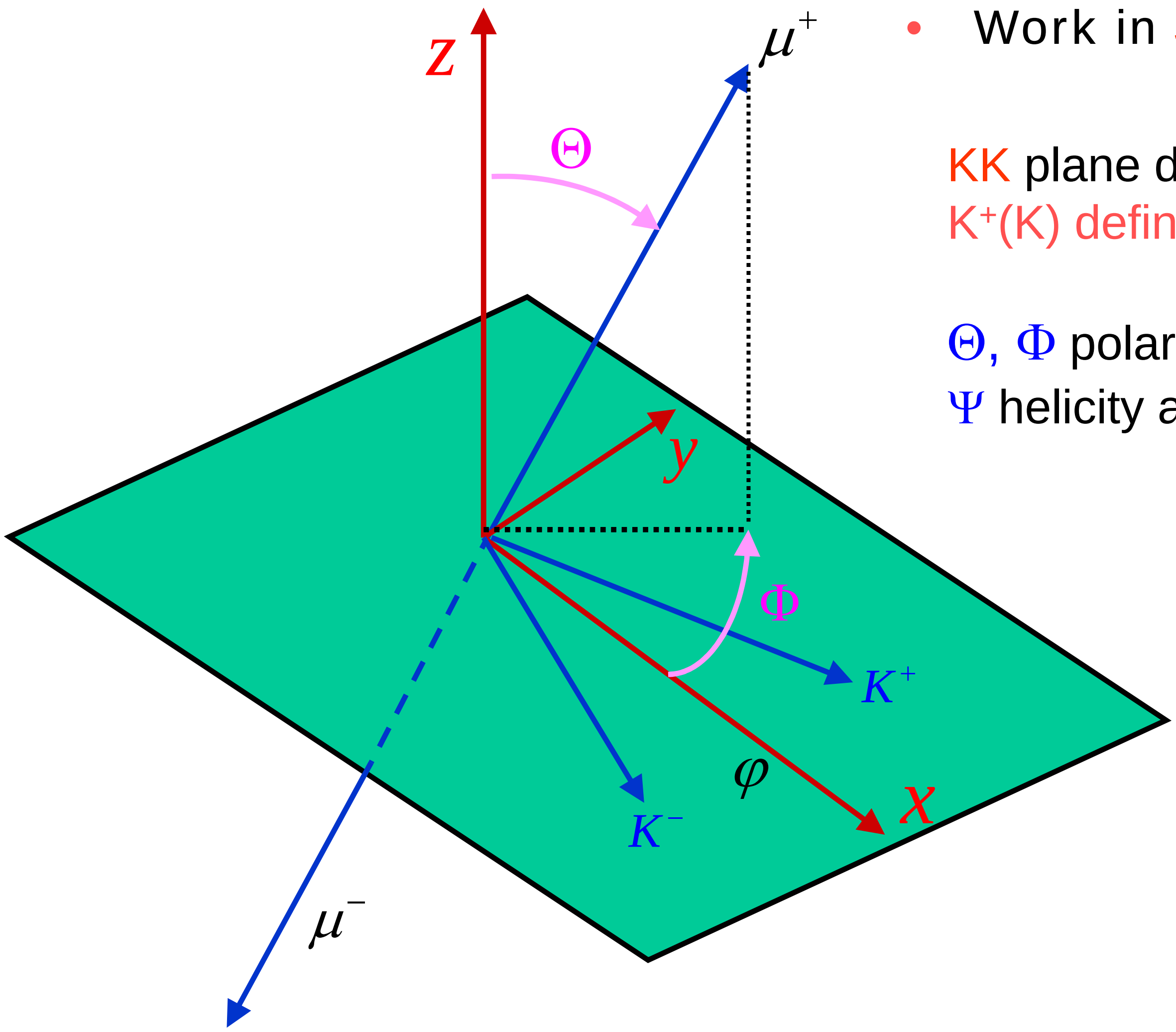
Isolates P-odd nicely

- S,D wave = Parity Even, (CP Even for $J/\psi\varphi$)
- P wave = Parity Odd, (CP Odd for $J/\psi\varphi$)

$$B_s^H = \frac{1}{\sqrt{2}}(|B_s\rangle + |\overline{B}_s\rangle) = CP - odd$$
$$B_s^L = \frac{1}{\sqrt{2}}(|B_s\rangle - |\overline{B}_s\rangle) = CP - even$$

Disentangle different L-components
of decay amplitudes => isolate two B states

Transversity Angles



- Work in J/Ψ rest Frame

KK plane defines (x,y) plane
K^+(K) defines +y direction

Θ, Φ polar & azimuthal angles of μ+
Ψ helicity angle of ϕ (K*)

Decay Angular Distributions

$$\frac{d^4\mathcal{P}}{d\vec{\rho}\,dt} \propto |A_0|^2 \cdot g_1(t)\cdot f_1(\vec{\rho}) + |A_{||}|^2 \cdot g_2(t)\cdot f_2(\vec{\rho}) + |A_\perp|^2 \cdot g_3(t)\cdot f_3(\vec{\rho}) \pm Im(A_{||}^* A_\perp)\cdot g_4(t)\cdot f_4(\vec{\rho}) + Re(A_0^* A_{||})\cdot g_5(t)\cdot f_5(\vec{\rho}) \pm Im(A_0^* A_\perp)\cdot g_6(t)\cdot f_6(\vec{\rho}) \equiv \sum_{i=1}^{6} \mathcal{A}_i \cdot g_i(t)\cdot f_i(\vec{\rho})$$

$$\begin{aligned}
f_1(\vec{\rho}) &= 2\cos^2\psi(1-\sin^2\theta\cos^2\phi) \\
f_2(\vec{\rho}) &= \sin^2\psi(1-\sin^2\theta\sin^2\phi) \\
f_3(\vec{\rho}) &= \sin^2\psi\sin^2\theta \\
f_4(\vec{\rho}) &= -\sin^2\psi\sin 2\theta\sin\phi \\
f_5(\vec{\rho}) &= \frac{1}{\sqrt{2}}\sin 2\psi\sin^2\theta\sin 2\phi \\
f_6(\vec{\rho}) &= \frac{1}{\sqrt{2}}\sin 2\psi\sin 2\theta\cos\phi
\end{aligned}$$

$g_i(t)$ different for B_d and B_s and are rather non-trivial

A. Dighe et. al., Eur. Phys. J. C 6, 647-662

A_0 = longitudinal pol. amplitude

$A_{||}, A_\perp$ = transverse pol. amplitudes

Fit Functions

B_s:

$$\frac{d^4\mathcal{P}}{d\vec{\rho}\,dt} \propto |A_0|^2 \cdot e^{-\Gamma_L t} \cdot f_1(\vec{\rho}) + |A_\parallel|^2 \cdot e^{-\Gamma_L t} \cdot f_2(\vec{\rho}) + |A_\perp|^2 \cdot e^{-\Gamma_H t} \cdot f_3(\vec{\rho}) + Re(A_0^* A_\parallel) \cdot e^{-\Gamma_L t} \cdot f_5(\vec{\rho})$$

$\Gamma_L = CP - \text{even}$

$\Gamma_H = CP - \text{odd}$

- flavor blind decay
- $\delta\phi_{CPV} \approx 0.03$
- Δm_s is large

B_d:

$$\frac{d^4\mathcal{P}}{d\vec{\rho}\,dt} \propto \Big\{ |A_0|^2 \cdot f_1(\vec{\rho}) + |A_\parallel|^2 \cdot f_2(\vec{\rho}) + |A_\perp|^2 \cdot f_3(\vec{\rho}) \pm Im(A_\parallel^* A_\perp) \cdot f_4(\vec{\rho}) + Re(A_0^* A_\parallel) \cdot f_5(\vec{\rho}) \pm Im(A_0^* A_\perp) \cdot f_6(\vec{\rho}) \Big\} \cdot e^{-\Gamma_d t}$$

- flavor specific decay
- $\delta\phi_{CPV} = 2\beta$

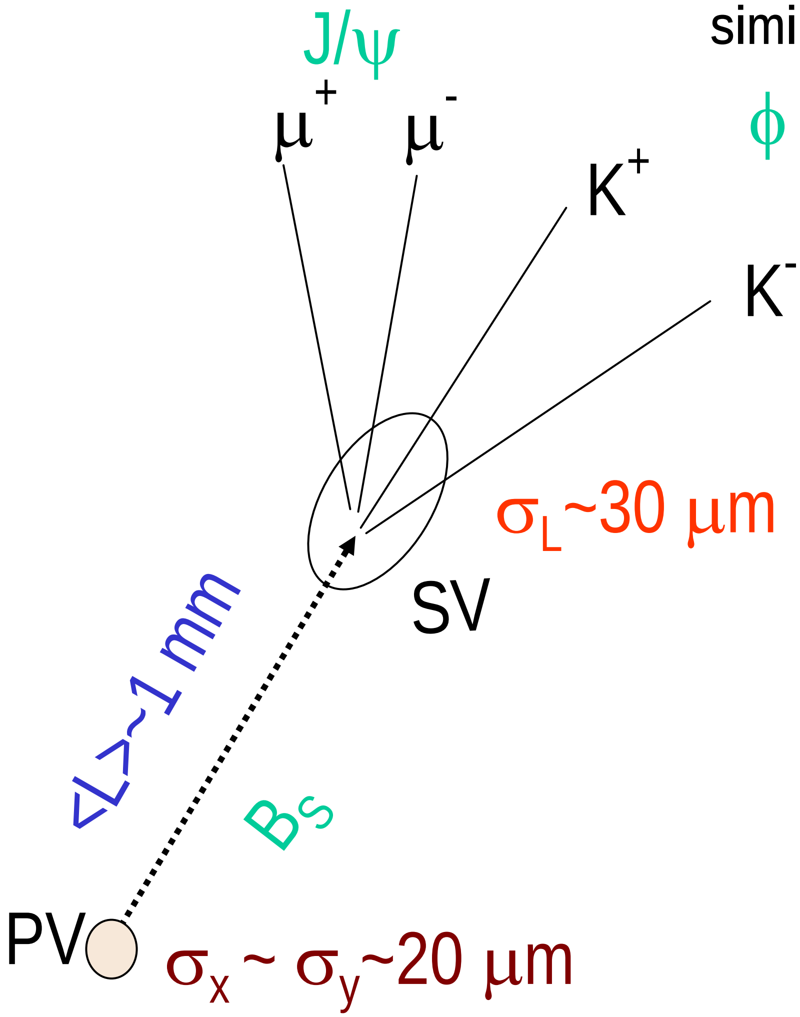
- UNTAGGED analysis
  - Don't try to tell if initial state is B or $\overline{B}$

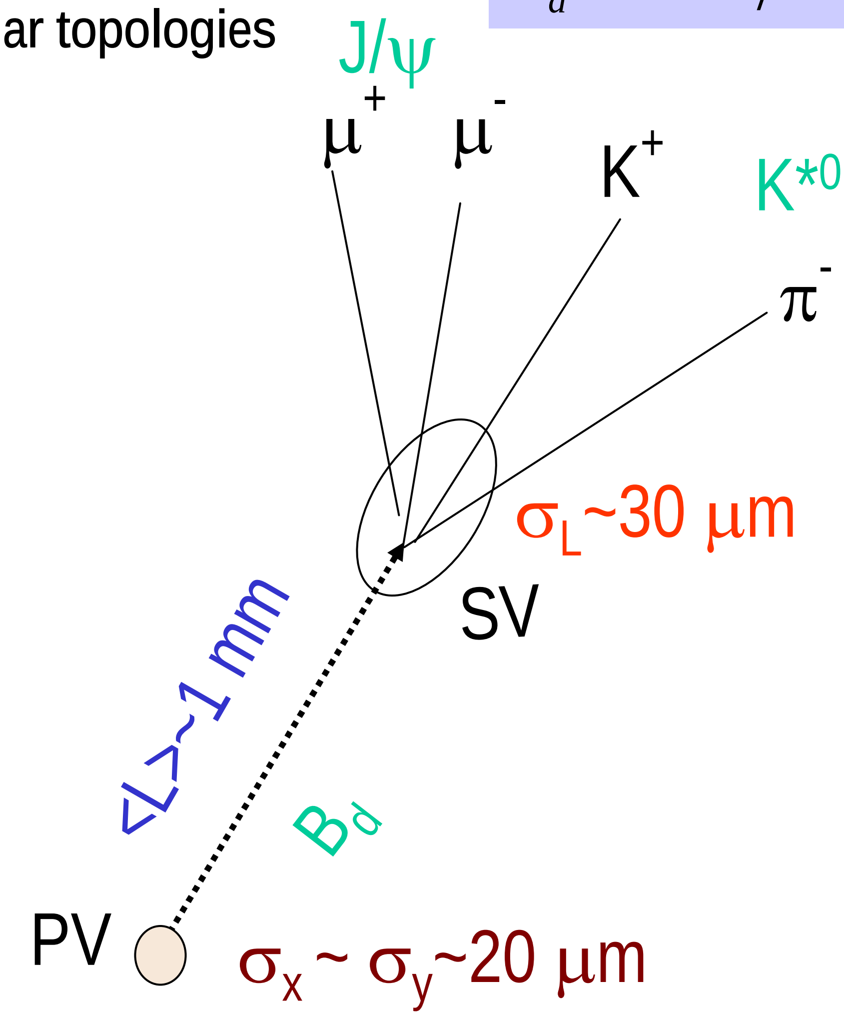
Decay Modes

$B_s \rightarrow J/\psi\phi$

Compare the two similar topologies

$B_d \rightarrow J/\psi K^*$





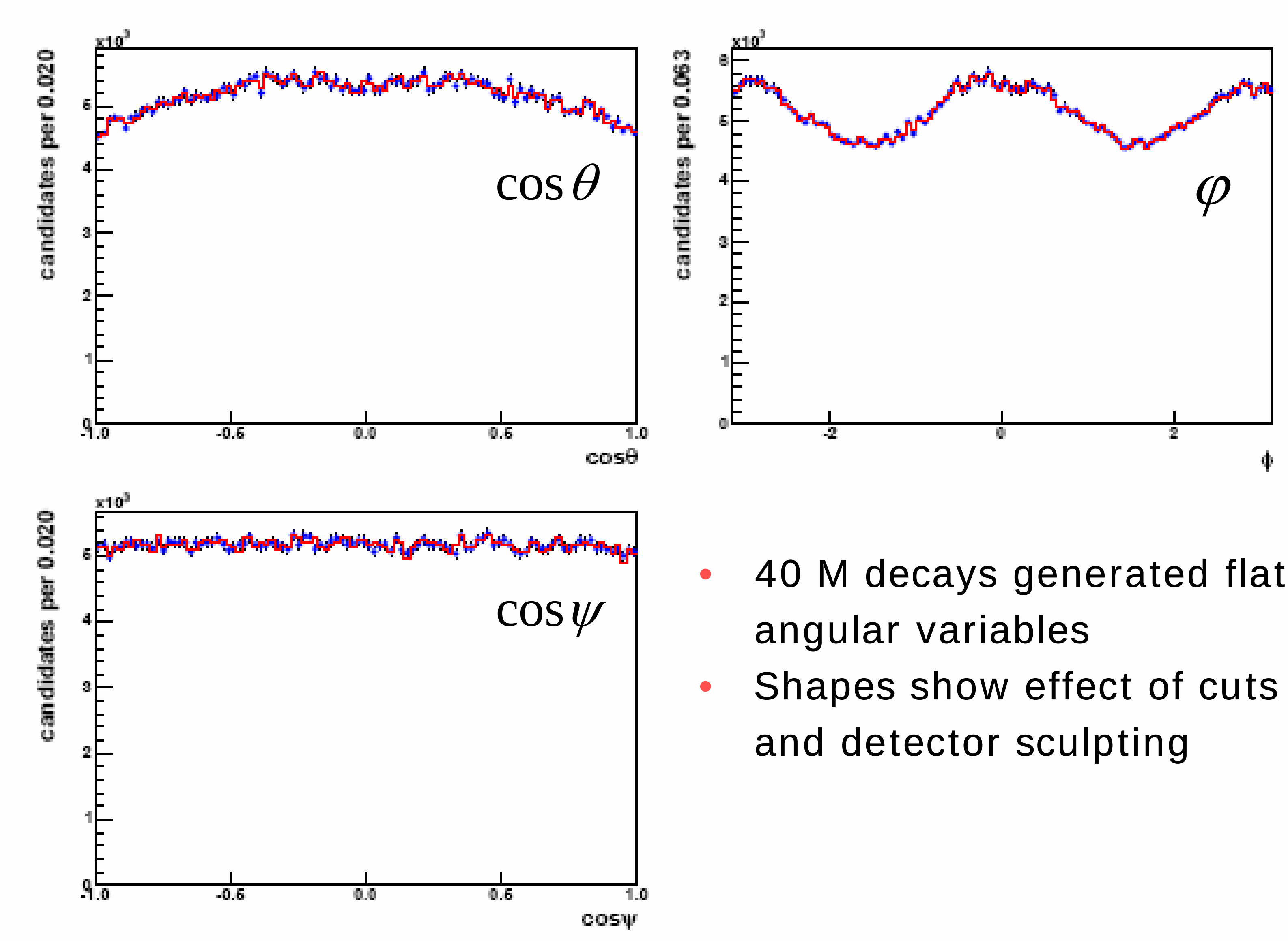
Sample Selection

- ~260 pb-1 taken up to Feb 2004 (start of COT problem–now fixed!!)

- Track Selection
  - $P_T > 0.4$ GeV
  - Well-measured in Central Tracker
  - All 4 tracks have Silicon Detector hits
- J/Ψ Selection
  - $P_T > 1.5$ GeV
  - Mass within 80 MeV of PDG
  - J/Ψ trigger path (unbiased in lifetime)

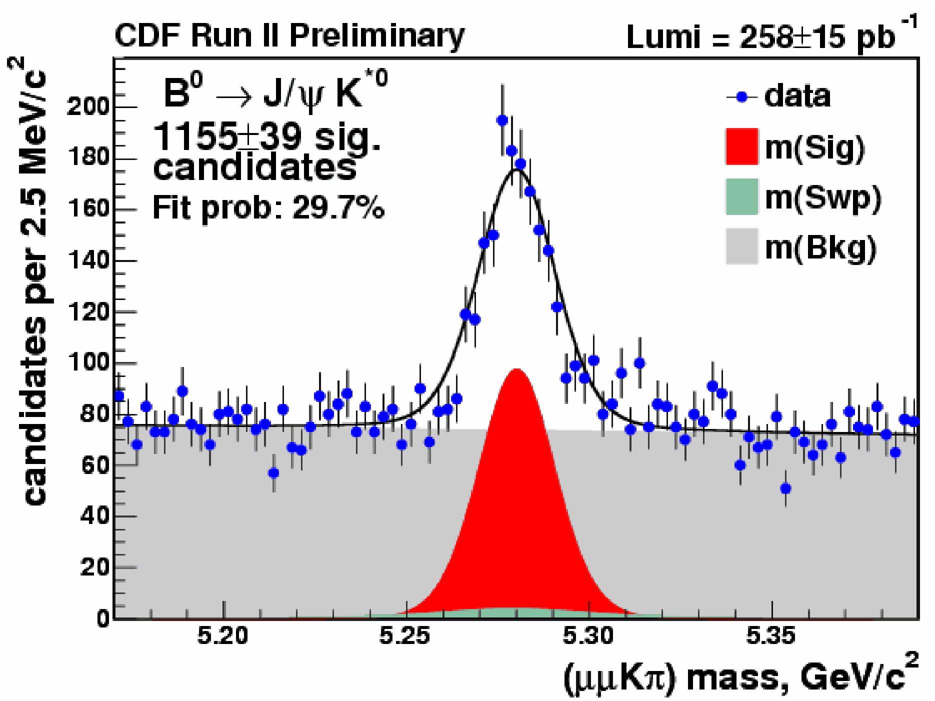
- Momenta (P_T)
  - K^* > 2.6 GeV, B_d > 6.0 GeV
  - ϕ > 2.0 GeV, B_s > 6.0 GeV
- Mass windows
  - ϕ : 6.5 MeV
  - K^* : 50 MeV
    - Closest $K\pi$ assignment to K^* chosen (=swaps~10 %)
- B meson Vertex:
  - Constrain J/Ψ mass
- Primary vertex from beamline

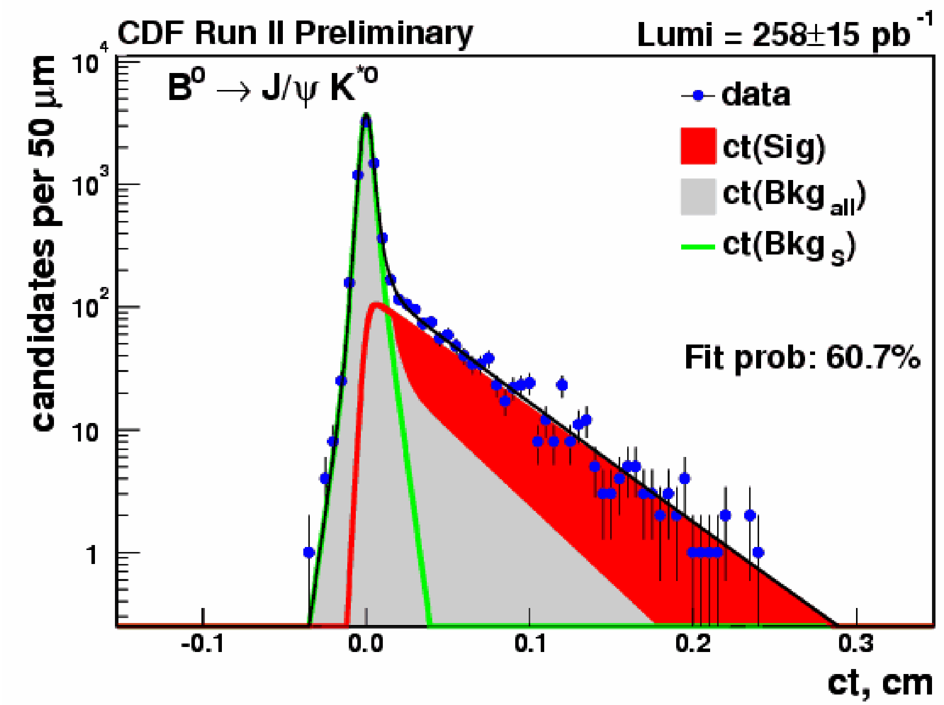
Detector Acceptance



- 40 M decays generated flat in angular variables
- Shapes show effect of cuts and detector sculpting

Mass and Lifetime Projections (B_d)





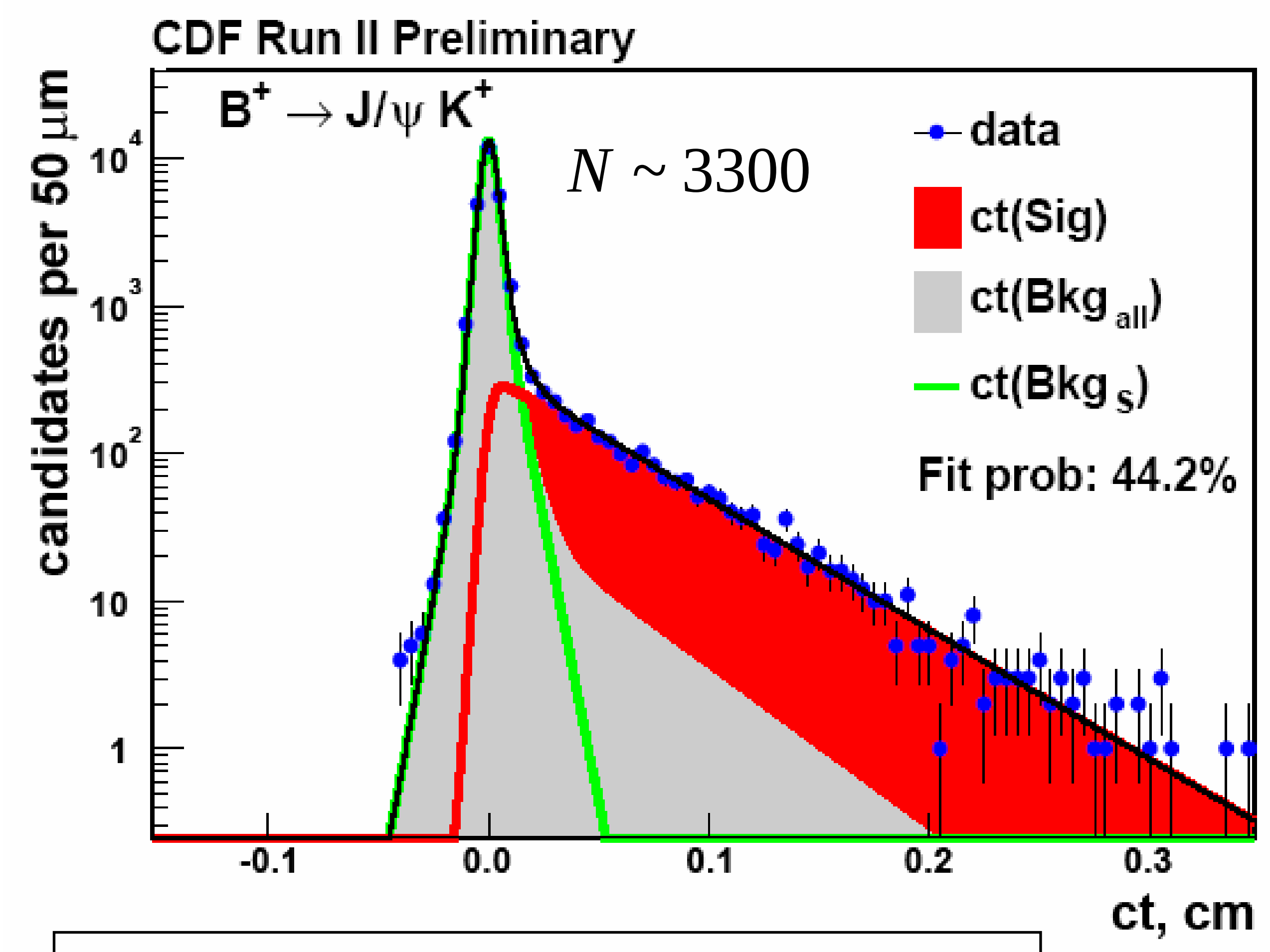
$$\frac{\Delta\Gamma_d}{\Gamma_d} \leq .01$$ is small in SM

=>Fit to 1 lifetime

$$c\tau_{B^0} = 462 \pm 15 \pm 4\,\mu m$$

$$PDG = 460.8 \pm 4.2\,\mu m$$

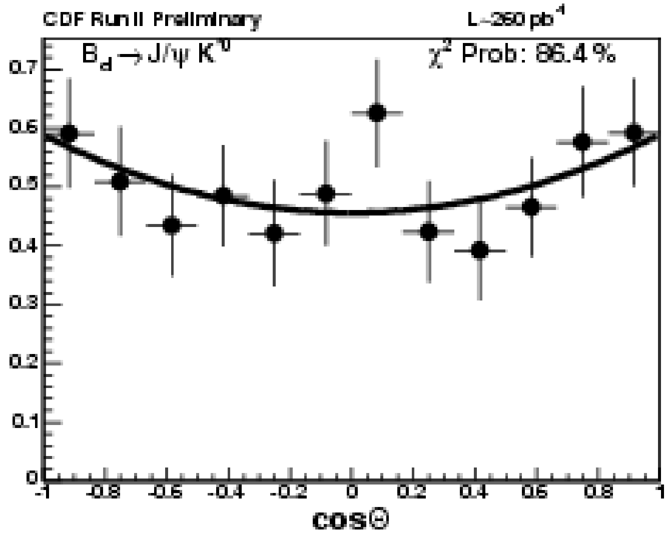
B+ Lifetime

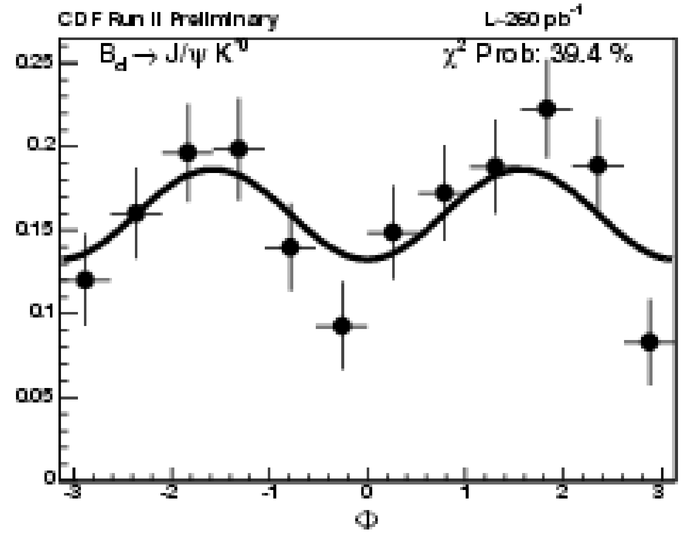


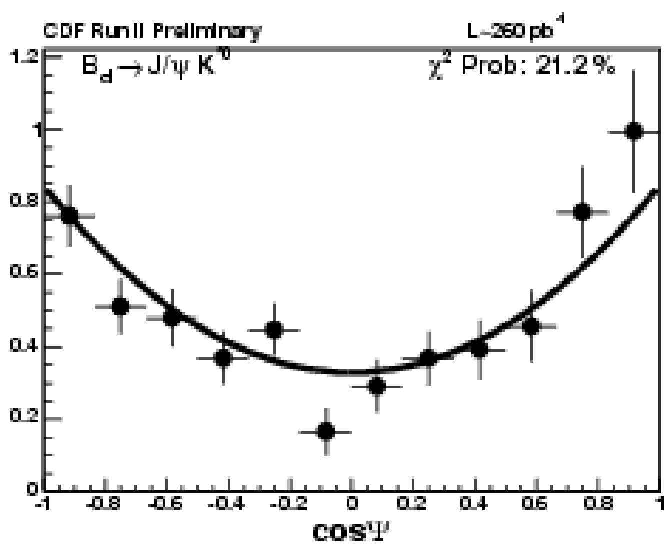
CDF Run II: $\tau_u = 1.660 \pm 0.033 \text{ ps}^{-1}$

PDG: $\tau_u = 1.671 \pm 0.018 \text{ ps}^{-1}$

Angular Projections (B_d)

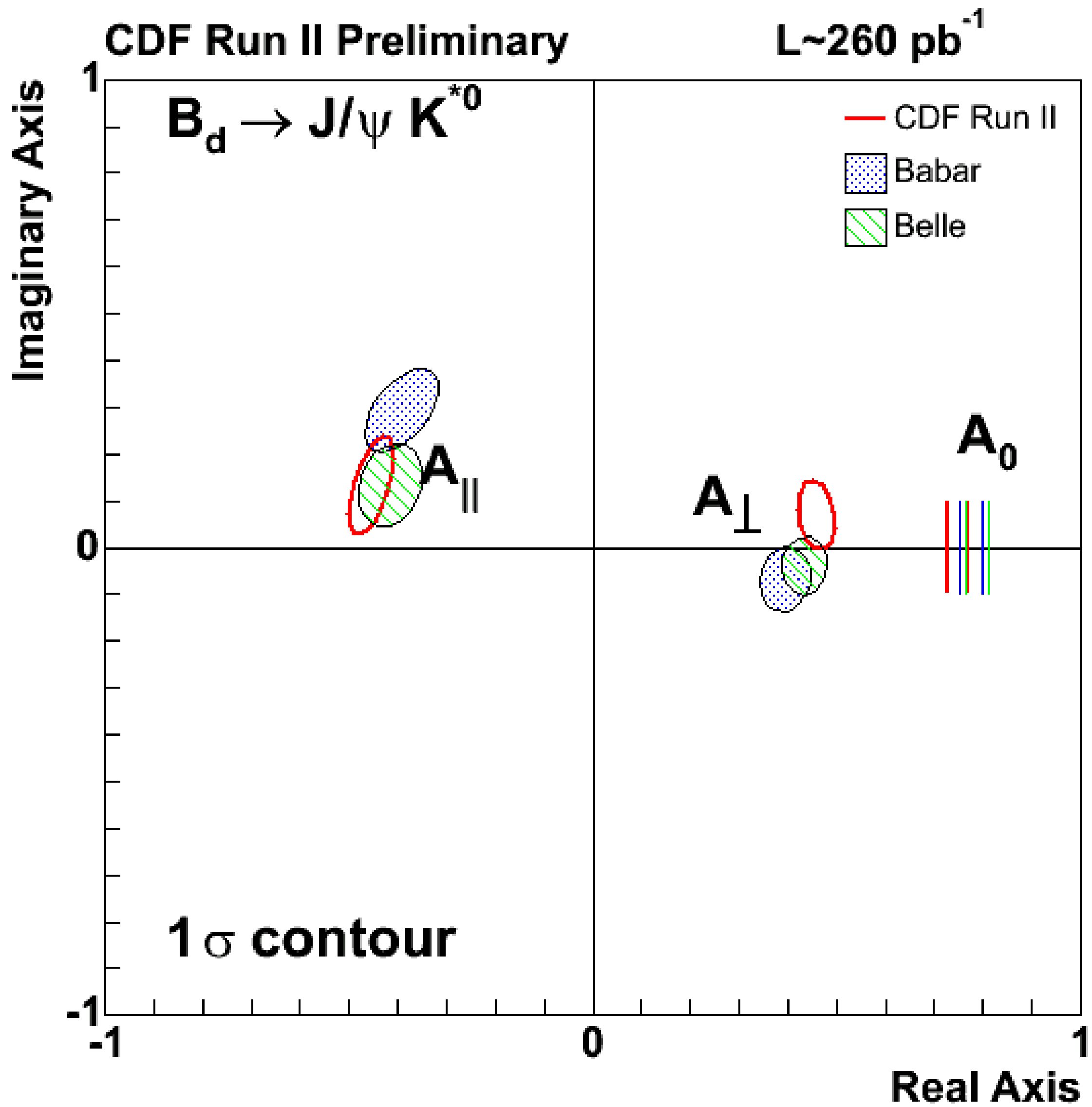






- Sideband subtracted, acceptance corrected projections
- Full Likelihood Fit is simultaneous in angular variables
- Can't see correlations in these projections

B_d Amplitudes vs. BaBar/Belle



B_s Results

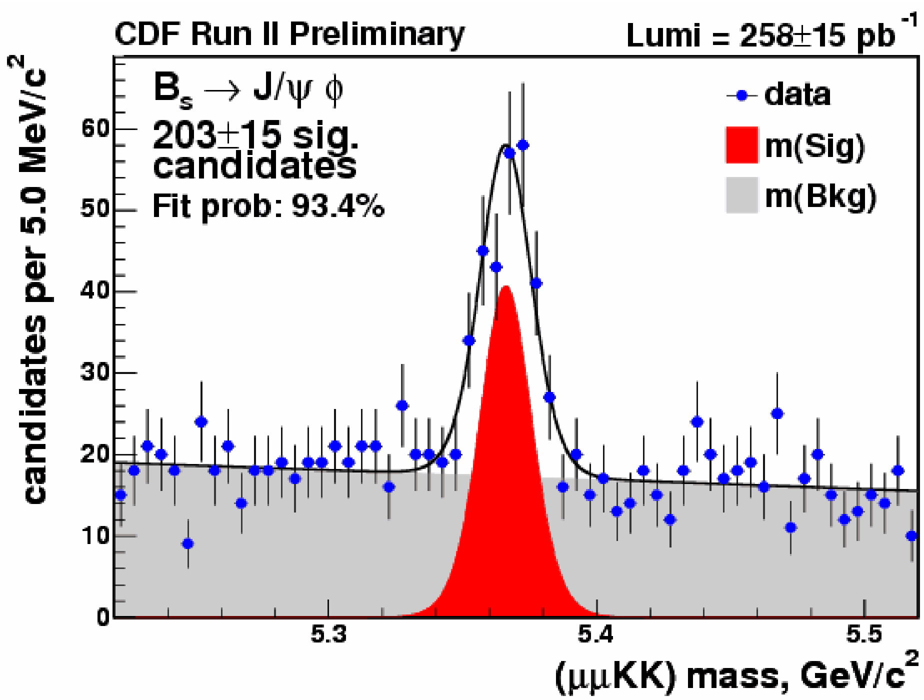
- Perform two fits
  1. Unconstrained: Fit data as described
  2. Constrained: Invoke SM constraint $\Gamma_s = \frac{1}{2}(\Gamma_H + \Gamma_L) = \Gamma_d$
     (Expected true to ~1%)

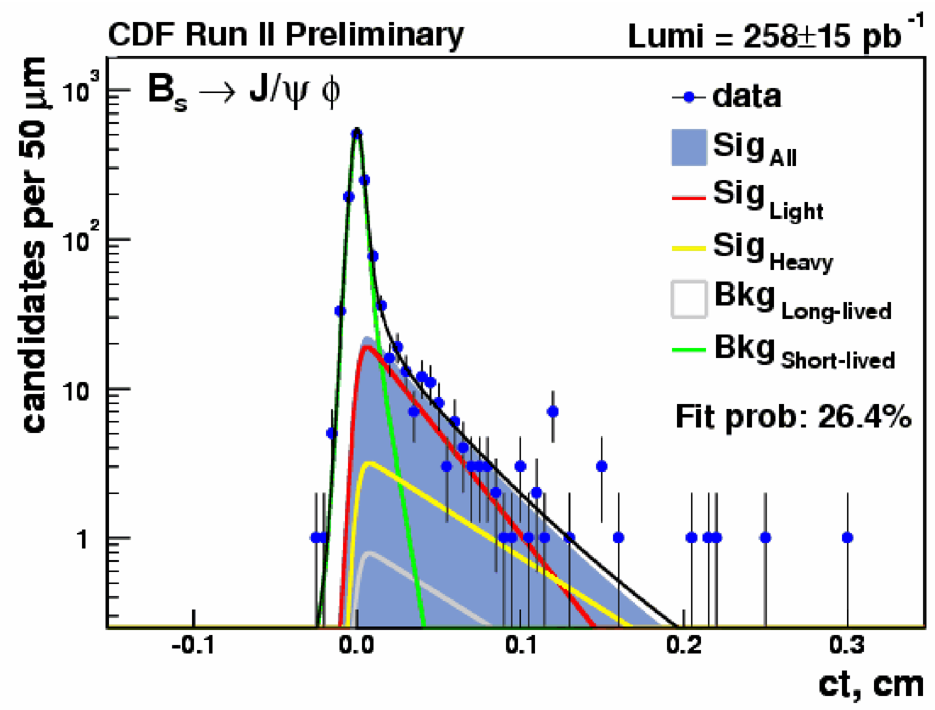
  Since $\tau_d = 1.54 \pm 0.014\,\text{ps}$

  set

$$\frac{1}{\Gamma_s} = \frac{2\tau_L \tau_H}{\tau_L + \tau_H} = 1.54 \pm 0.021\,\text{ps}$$

Mass and Lifetime Projections (Bs) — Unconstrained Fit





$$\tau_L = 1.05^{+0.16}_{-0.13} \pm 0.02\,\text{ps}$$

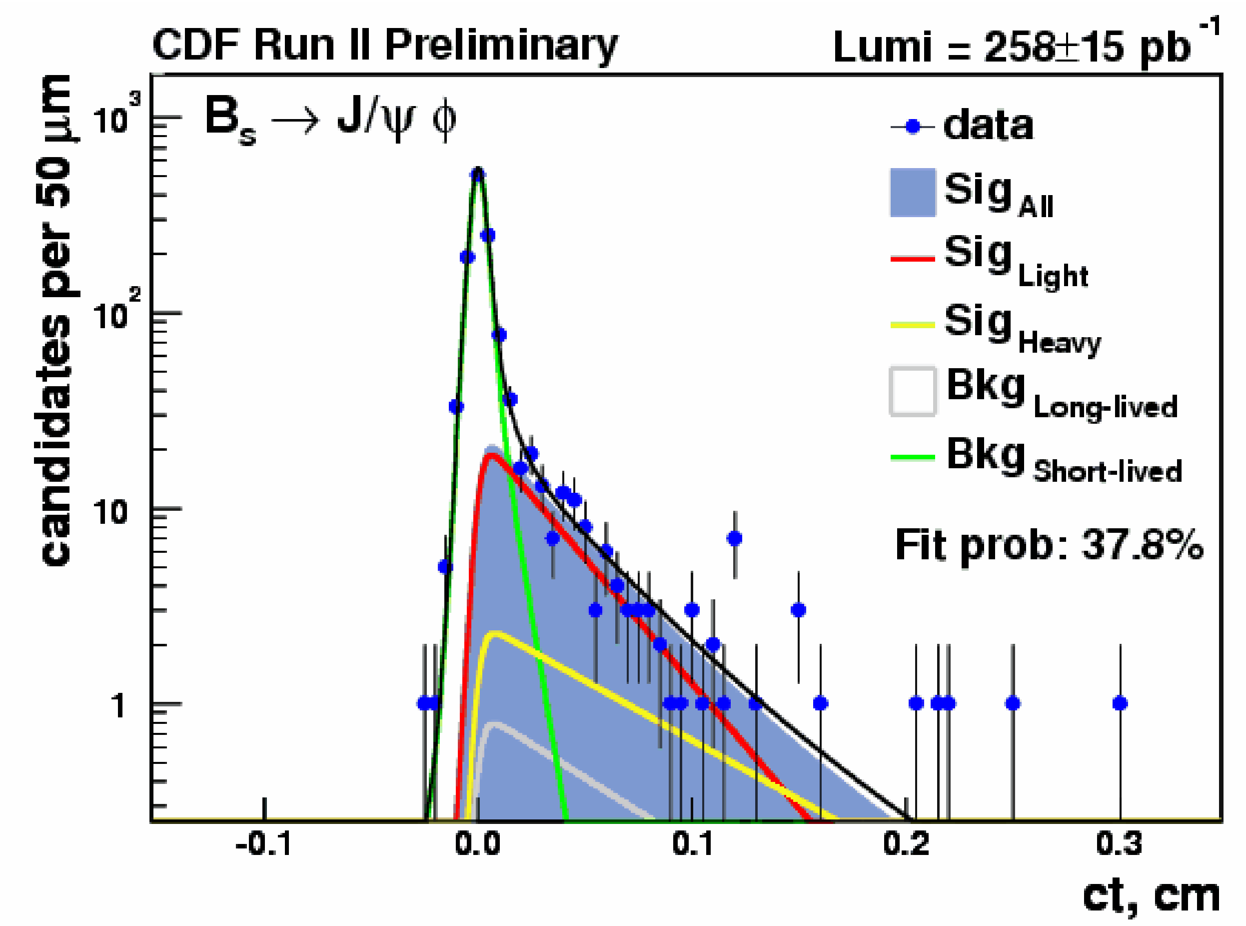
$$\tau_H = 2.07^{+0.58}_{-0.46} \pm 0.03\,\text{ps}$$

$$\Delta\Gamma_s = 0.47^{+0.19}_{-0.24} \pm 0.01\ \text{ps}^{-1}$$

$$\frac{\Delta\Gamma_s}{\Gamma_s} = 0.65^{+0.25}_{-0.33} \pm 0.01$$

CP-odd fraction (τ_H) ~ 22%

Lifetime Projection (B_s)— Constrained Fit



- SM Predicts $\Gamma_s = \Gamma_d$ to ~1% : constrain in fit
- Remember, can't see angular separation of CP eigenstates in projection

$$\tau_L = 1.13^{+0.13}_{-0.09} \pm 0.02\,\text{ps}$$
$$\tau_H = 2.38^{+0.56}_{-0.43} \pm 0.03\,\text{ps}$$

$$\Delta\Gamma_s = 0.46 \pm 0.18 \pm .01\ \text{ps}^{-1}$$
$$\frac{\Delta\Gamma_s}{\Gamma_s} = 0.71^{+0.24}_{-0.28} \pm 0.01$$

Main Fitting results

	B_d	B_s Unconstrained Fit	B_s Constrained Fit	unit
M_B	5280.2 ± 0.8	5366.1 ± 0.8	5366.0 ± 0.8	MeV/c^2
A_0	0.750 ± 0.017	0.784 ± 0.039	0.783 ± 0.038	
$A_{\parallel}$	0.473 ± 0.034	0.510 ± 0.082	0.539 ± 0.070	
$A_{\perp}$	0.464 ± 0.035	0.354 ± 0.098	0.308 ± 0.087	
$\delta_{\parallel}$	2.86 ± 0.22	1.94 ± 0.36	1.91 ± 0.32	
$\delta_{\perp}$	0.15 ± 0.15			
$c\tau_B$	462 ± 15			μm
$c\tau_L$		$316\ ^{+48}_{-40}$	$340\ ^{+40}_{-28}$	μm
$c\tau_H$		$622\ ^{+175}_{-138}$	$713\ ^{+167}_{-129}$	μm
$c\tau_s$		$419\ ^{+45}_{-38}$	$\mathbf{460 \pm 6.2}$	μm
$\Delta\Gamma_s/\Gamma_s$		$65\ ^{+25}_{-33}$	$71\ ^{+24}_{-28}$	%
$\Delta\Gamma_s$		$0.47\ ^{+0.19}_{-0.24}$	$0.46\ ^{+0.17}_{-0.18}$	ps^{-1}
N_{sig}	1155 ± 39	203 ± 15	201 ± 15	

Any two at a time ($c\tau_L$, $c\tau_H$, $c\tau_s$, $\Delta\Gamma_s/\Gamma_s$, $\Delta\Gamma_s$)

Systematics

- Alignment
- Lifetime Fit model
- Procedure Bias
- Cross-feed
- Detector Acceptance
- Monte Carlo - data matching
- K-π swap
- Non-resonant decays
- Background angular model
- Unequal amounts of $B-\overline{B}$

(Alignment, Lifetime Fit model, Procedure Bias:) From high-statistics B^{+} and J/ψ studies

Systematics

B_d	$c\tau$, μm	$\|A_0\|$	$\|A_\parallel\|$	$\|A_\perp\|$	$arg(A_\parallel)$	$arg(A_\perp)$
Bkg. ang. model	3.9	0.009	0.006	0.006	0.01	0.01
Eff. and acc.	–	–	–	–	–	–
K $\leftrightarrow \pi$ swap	–	0.002	0.002	0.002	0.01	–
Non-resonant decays	–	0.007	0.001	0.004	0.07	0.04
Bkg. lft. model	1.7	–	–	–	–	–
SVX alignment	1.0	–	–	–	–	–
Lft. bias	1.3	–	–	–	–	–
B_s cross-feed	–	–	–	–	–	–
Total	4.6	0.012	0.006	0.007	0.07	0.04

B_s	$c\tau_L$, μm	$\Delta\Gamma/\Gamma$	$\|A_0\|$	$\|A_\parallel\|$	$\|A_\perp\|$	$\arg(A_\parallel)$
Bkg. ang. model	3.7	0.007	0.007	0.013	0.003	0.03
Eff. and acc.	–	–	–	–	–	–
Unequal # B_s,$\bar{B}_s$	–	–	–	–	–	–
Bkg. lft. model	1.7	–	–	–	–	–
SVX alignment	1.0	–	–	–	–	–
Lft. bias	1.3	–	–	–	–	–
B_d cross-feed	5.0	0.008	–	0.003	0.001	–
Total	6.7	0.011	0.007	0.013	0.003	0.03

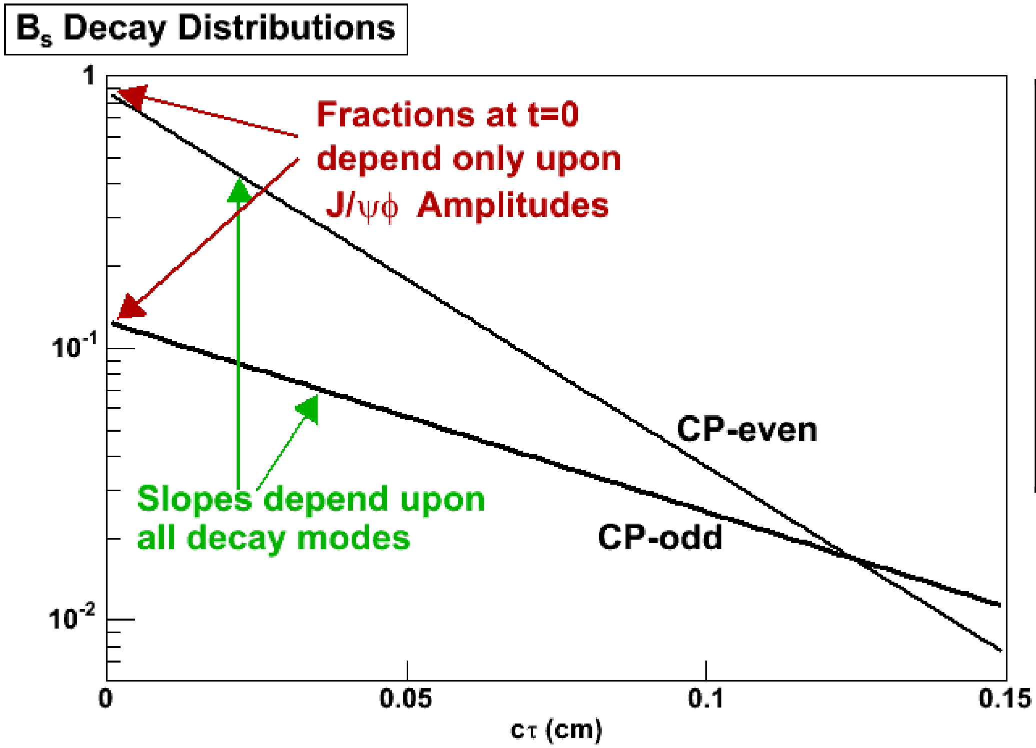
Cross Check: B_d Fit

- Bd sample is ~4 times as large as Bs
  - Fit Bd sample with Bs fit function
  - Split sample into 4 subsamples of size ~ Bs sample size

Fit	$\Delta\Gamma/\Gamma(\%)$	$c\tau_L(\mu m)$
Full sample one $c\tau$	–	461 ± 15
Full sample	14.5 ± 12.1	444 ± 21
1st sub sample	13.7 ± 27.9	422 ± 34
2nd sub sample	25.1 ± 22.3	437 ± 39
3rd sub sample	26.1 ± 23.0	437 ± 50
4th sub sample	-7.6 ± 27.6	475 ± 41

- Note: This is not a measurement of $\Delta\Gamma_d / \Gamma_d$

Cross Check: B_s and B_d CP odd fraction



- Fit to amplitudes ONLY, using different minimum lifetime cuts.
- Clear CP odd fraction increase suggests relative large lifetime difference on the two components
- Angular distribution is saying the same thing as the lifetime information

B_s CP-odd fraction

Cut (μm)	Fitted (%)	Predicted (%)
>0	20.1 ± 9.0	--20.1--
>150	24.2 ± 10.3	24.1
>300	29.6 ± 12.7	28.6
>450	38.7 ± 11.6	33.6

B_d CP-odd fraction

Cut (μm)	Fitted (%)
>0	21.6 ± 4.4
>150	23.0 ± 3.6
>300	23.0 ± 4.0
>450	23.6 ± 4.9

Expect constant

Prob(0), Prob(SM)

Performed 10,000 Toy MC fits to estimate the probability of a fluctuation

Input $\Delta\Gamma/\Gamma$ = 0

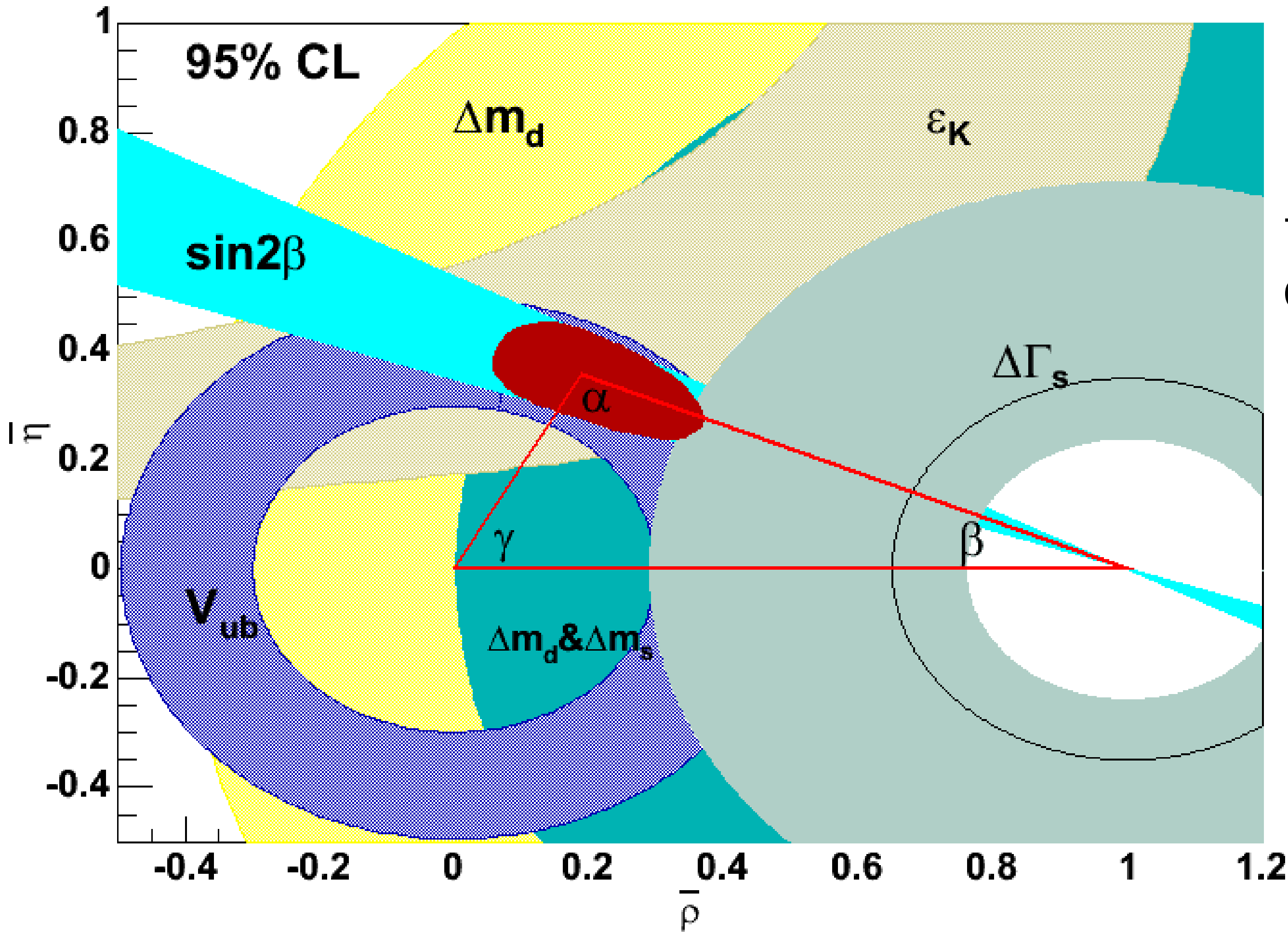
- Unconstrained Fit
  - 1/315 give $\Delta\Gamma/\Gamma$ > 0.65
- Constrained Fit
  - 1/718 give $\Delta\Gamma/\Gamma$ > 0.71

Input $\Delta\Gamma/\Gamma$ = 0.12 (SM prediction)

- Unconstrained Fit
  - 1/84 give $\Delta\Gamma/\Gamma$ > 0.65
- Constrained Fit
  - 1/204 give $\Delta\Gamma/\Gamma$ > 0.71

- Note: These answer the question:
  - If true value = X, what is the chance to see our measurement
- Not the same as asking:
  - If true value=our measurement, what is the chance of measuring X

Unitarity Triangle



*(based on constrained fit, toy MC estimate + Gaussian theory error)

Conclusions

- We need more data!
- Combination of amplitude and lifetime analysis very powerful tool
- $B_d \to J/\psi K^*$ amplitudes measured with precision comparable to BaBar/Belle and agree well
- B_d lifetime agrees with PDG $462 \pm 16\,\mu m$

- ~200 $B_s \to J/\psi\varphi$ show evidence of two lifetime components
- $\Delta\Gamma = 0$ ruled out at 1 in 700 odds (with $\Gamma_s = \Gamma_d$ constraint)
  - First measurement of lifetime difference
  - 1/200 odds that SM central value (0.12) gives our measurement

$$\Delta\Gamma_s = 0.46 \pm 0.18 \pm .01\ \mathrm{ps}^{-1} \qquad \frac{\Delta\Gamma_s}{\Gamma_s} = 0.71^{+0.24}_{-0.28} \pm 0.01$$