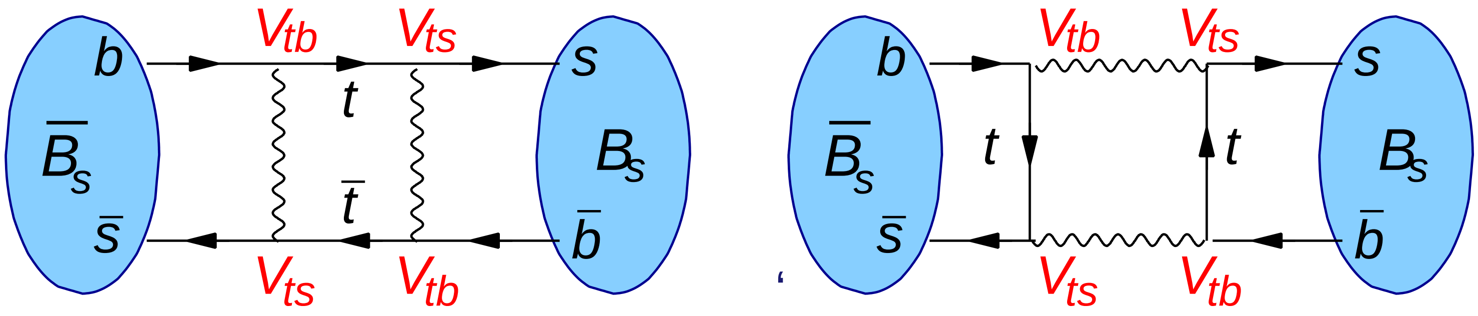
Measurement of CP violation in B_s decays @ LHCb

Christoph Langenbruch, Stephanie Hansmann-Menzemer

Neckarzimmern, 13. März 2008

- Short Reminder on B Mixing & CP violation
- CP violation in $B_s \to J/\Psi\phi$:
  Summary of Recent Measurements from CDF & D0
- Ingredients to the analysis
- Cooking up all ingredients: The Likelihood-Fit
- Sensitivity on $\Delta\Gamma$ and ϕ_s @ LHCb

Phenomology of Mixing



Schrödinger equation: $i\frac{d}{dt}\begin{pmatrix} B^0 \\ \bar{B}^0 \end{pmatrix} = \left(M - \frac{i}{2}\Gamma\right)\begin{pmatrix} B^0 \\ \bar{B}^0 \end{pmatrix}$

Diagonalizing of $(M - \frac{i}{2}\Gamma) \longrightarrow$ mass eigen states:

$|B_L>= p|B^0> +q|\bar{B}^0>$, with m_L, Γ_L

$|B_H>= p|B^0> -q|\bar{B}^0>$, with m_H, Γ_H

$|p|^2 + |q|^2 = 1$ complex coefficients

Flavour eigen states:

$|B^0>= \frac{1}{2p}(|B_L> +|B_H>)$

$|\bar{B}^0>= \frac{1}{2q}(|B_L> +|B_H>)$

Time Evolution

$$|B_{H,L},t\rangle = b_{H,L}(t)|B_{H,L}\rangle \quad \text{mit} \quad b_{H,L}(t) = e^{-\Gamma_{H,L}t} e^{-im_{H,L}t}$$

$$|\psi_{B^0}(t)\rangle = \frac{|B_L,t\rangle + |B_H,t\rangle}{2p} = \frac{1}{2p}\left(b_L(t)\cdot\left(p|B^0\rangle + q|\overline{B}^0\rangle\right) + b_H(t)\cdot\left(p|B^0\rangle - q|\overline{B}^0\rangle\right)\right)$$

$$= f_+(t)\cdot|B^0\rangle - \frac{q}{p} f_-(t)\cdot|\overline{B}^0\rangle$$

$$|\psi_{\overline{B}^0}(t)\rangle = f_+(t)\cdot|\overline{B}^0\rangle + \frac{p}{q} f_-(t)\cdot|B^0\rangle$$

$$f_\pm(t) = \frac{1}{2}\cdot\left[e^{-im_H t}e^{-\Gamma_H t/2} \pm e^{-im_L t}e^{-\Gamma_L t/2}\right]$$

B^0

$$P(B^0 \to B^0, t) = |f_+(t)|^2$$

$$P(B^0 \to \overline{B}^0, t) = \left|\frac{q}{p}\right|^2 |f_-(t)|^2$$

$\overline{B}^0$

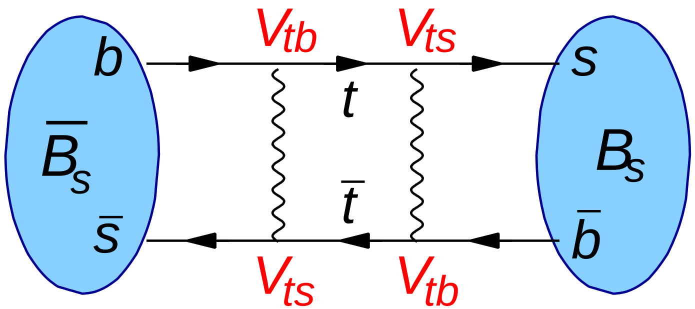
$$P(\overline{B}^0 \to \overline{B}^0, t) = |f_+(t)|^2$$

$$P(\overline{B}^0 \to B^0, t) = \left|\frac{p}{q}\right|^2 |f_-(t)|^2$$

CP-violation in mixing: $P(B^0 \to \bar{B}^0) \neq P(\bar{B}^0 \to B^0) \Leftrightarrow |\frac{q}{p}| \neq 1$

Note: There is a phase difference between f_+ & f_-

Mixing 1×1



flavour eigenstates B & $\bar{B} \neq$ mass eigenstates B_H & B_L

	B_d	B_s
$\Delta m = m_H - m_L$	0.5 ps^{-1}	17.8 ps^{-1}
$\Delta\Gamma = \Gamma_L - \Gamma_H$	$\mathcal{O}(0.01)\Gamma_d$	$\mathcal{O}(0.1)\Gamma_s$
ϕ	$arg(V_{tb}V_{td}^*)$ (=2β)	= $arg(V_{tb}V_{ts}^*)$ (=2β_s)
	$\sin(2\beta) \approx$ 0.7	$\approx$ 0.04 (SM prediction)

B_d: slow mixing, not measurable $\Delta\Gamma$, large mixing phase

B_s: fast mixing, significant $\Delta\Gamma$, tiny mixing phase (in SM)

CP Violation

CP violation: $|\mathcal{A}(B \to f)|^2 \neq |\mathcal{A}(\bar{B} \to \bar{f})|^2$

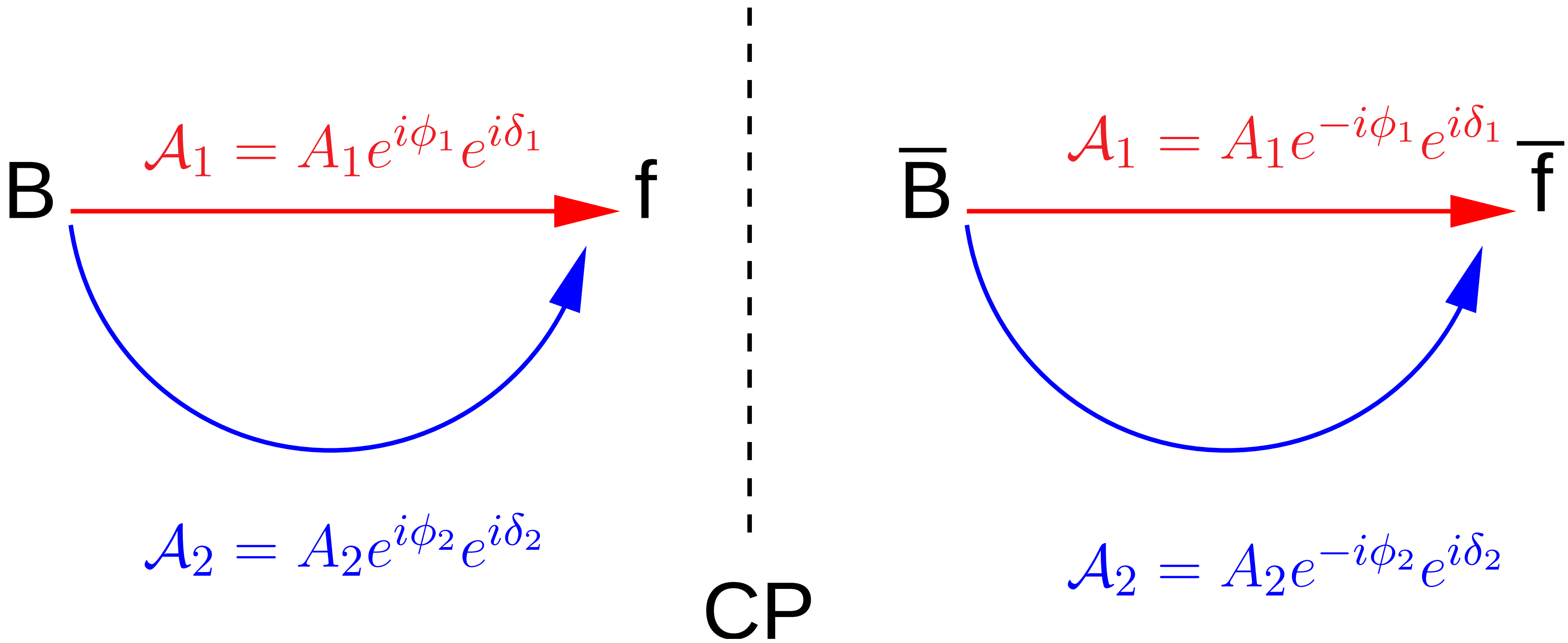
Within weak interaction, moving from particle to antiparticle, system amplitudes are complex conjugated.

No CP violation if:

- There is only one amplitude contributing to the decay: $|\mathcal{A}|^2 = |\mathcal{A}^*|^2$
- The sum of two amplitudes, where both are complex conjugated by moving from particle to antiparticle system: $|\mathcal{A}_1 + \mathcal{A}_2|^2 = (\mathcal{A}_1 + \mathcal{A}_2)(\mathcal{A}_1^* + \mathcal{A}_2^*) = |\mathcal{A}_1^* + \mathcal{A}_2^*|^2$

For CP violation one needs two complex amplitudes, where one of them is complex conjugated and one not by moving from particle to antiparticle system.

CP Violation



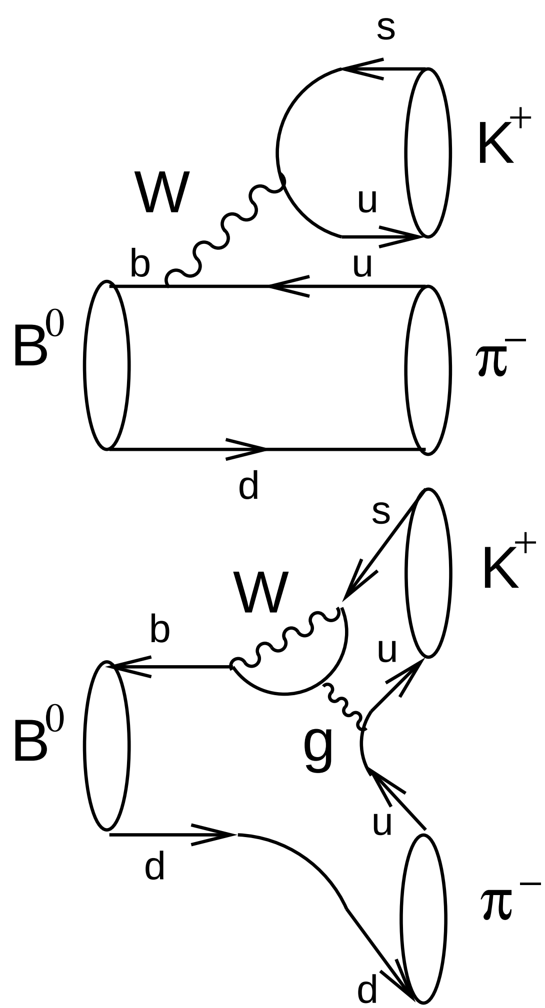
$$|\mathcal{A}|^2 = A_1^2 + A_2^2 + 2A_1A_2\cos(\Delta\phi + \Delta\delta)$$

$$|\mathcal{A}|^2 = A_1^2 + A_2^2 + 2A_1A_2\cos(\Delta\phi - \Delta\delta)$$

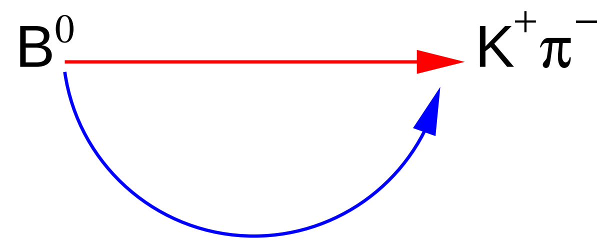
$\mathcal{A}_1$ and $\mathcal{A}_2$ need to have different weak phases ϕ and different (e.g. strong) phases δ.

3 “ways” of CP Violation

1) Direct CP violation:



$\mathcal{A}_1 e^{i*arg(V_{ub}^* V_{us})} e^{i\delta_1}$



$\mathcal{A}_2 e^{i*arg(V_{tb}^* V_{ts})} e^{i\delta_2}$

CP Asymmetrie:

$$|\bar{\mathcal{A}}|^2 - |\mathcal{A}|^2 = 2|A_1||A_2|[\cos(arg(V_{tb}^* V_{ts} + \delta)) - \cos(arg(V_{tb}^* V_{ts} - \Delta\delta))]$$

3 “ways” of CP Violation

2) CP violation in mixing

CP eigenstates $\neq$ mass eigenstates ($|\frac{q}{p}| \neq 0$)
$\rightarrow CP$ violation in mixing.

Model independent: CP Violation in mixing $< \mathcal{O}(\frac{\Delta\Gamma}{\Delta m})$

	B_d	B_s
Δm = m_H - m_L	0.5 ps^{-1}	17.8 ps^{-1}
$\Delta\Gamma/\Gamma$ = $(\Gamma_L$ - $\Gamma_H)/\Gamma$	$\mathcal{O}(0.01)$	$\mathcal{O}(0.1)$
τ = $1/\Gamma$	1.5 ps	1.5 ps
$\rightarrow$ CP in mixing	$\mathcal{O}(0.01)$	$\mathcal{O}(0.01)$

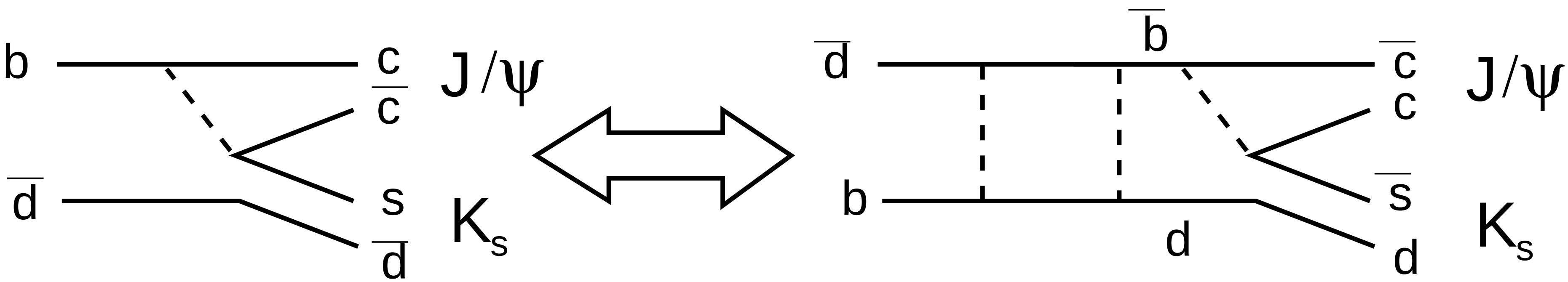
In first order, CP violation in mixing negligible in B system, however

it is important in the kaon system

3 “ways” of CP Violation

3) CP violation in interference between mixing and decay

Same final state through decay & mixing + decay

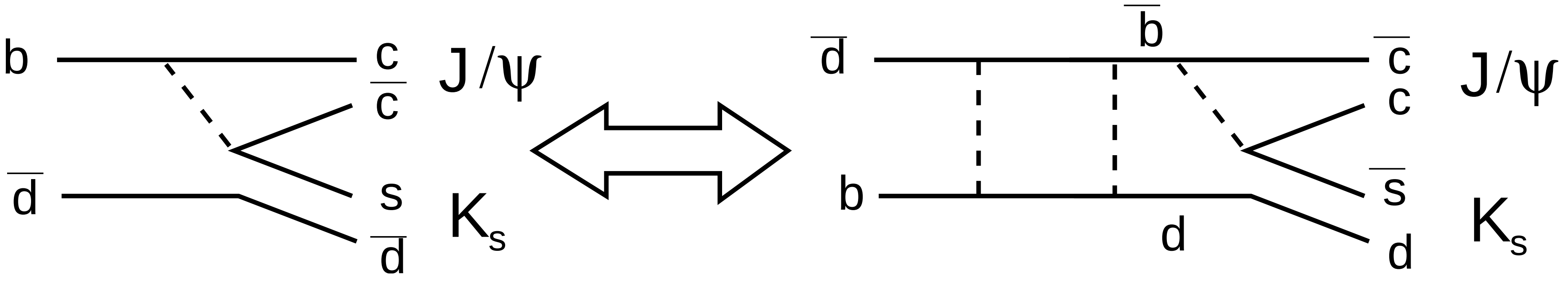


$$
\begin{aligned}
\mathcal{A}_1 &= \mathcal{A}_{mix}(B^0 \to B^0) * \mathcal{A}_{decay}(B^0 \to J/\Psi K_s) \\
&= \cos(\frac{\Delta m t}{2}) * A * e^{i\omega} \\
\mathcal{A}_2 &= \mathcal{A}_{mix}(B^0 \to \bar{B}^0) * \mathcal{A}_{decay}(\bar{B}^0 \to J/\Psi K_s) \\
&= i \sin(\frac{\Delta m t}{2}) * e^{+i\phi} * A * e^{-i\omega}
\end{aligned}
$$

$\Delta\phi = \phi - 2\omega$ (assume no CP violation in mixing and in decay)

$\Delta\delta = \pi/2 \Leftarrow$ mixing introduce second phase difference

$B_d \rightarrow J/\psi K_s$



$$\mathcal{A}(t) = \frac{\Gamma(\bar{B} \rightarrow J/\psi K_s)(t) - \Gamma(B \rightarrow J/\psi K_s)(t)}{\Gamma(\bar{B} \rightarrow J/\psi K_s)(t) + \Gamma(B \rightarrow J/\psi K_s)(t)}$$

$$= \eta_{J/\Psi K_s} * \sin(\phi_{mix} - 2\omega) * \sin(\Delta m_d t)$$

$$CP|J/\psi K_s >= \eta_{J/\psi K_s}|J/\psi K_s >= -1|J/\psi K_s >$$

$$\phi_{mix} = arg(V_{td}V_{tb}^*) = 2\beta$$

$$\omega = arg((V_{cb}V_{cs}^*)(V_{us}V_{ud}^*)) = 0$$

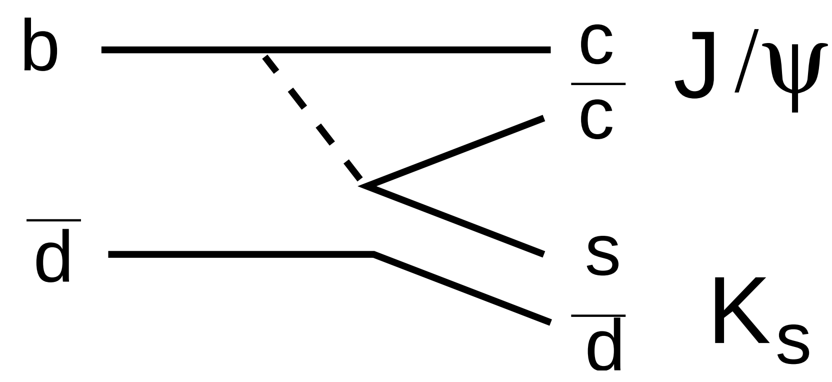
$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1 - \frac{\lambda}{2} & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1 - \frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1 - \rho - i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$

$CP|J/\psi K_s>$

B_d : J^P = 0^{-1} (pseudo scalar)

J/ψ: : J^{CP} = 1^{-1-1} (vector)

K_s: : J^{CP} = 0^{-1-1} (pseudo scalar)



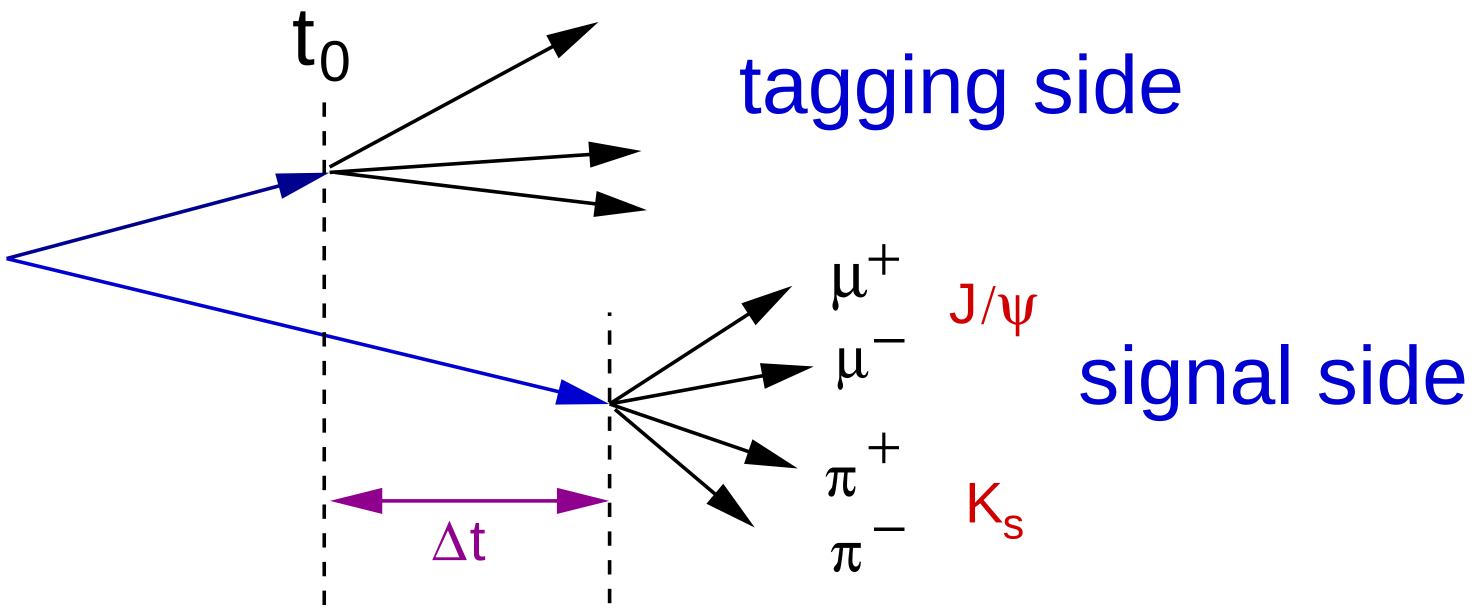
Angular momentum conservation:

0 = J ($J/\psi K_s$) = $|\vec{S} + \vec{L}|$; $\longrightarrow$ L = 1

$$\begin{aligned} P(J/\psi K_s) &= P(J/\psi) * P(K_s) * (-1)^L \\ CP(J/\psi K_s) &= CP(J/\psi) * CP(K_s) * (-1)^L \\ &= -1; \end{aligned}$$

$\longrightarrow$ CP odd final stage ($\eta_{J/\psi K_s}$ = -1)

$B_d \to J/\psi K_s$

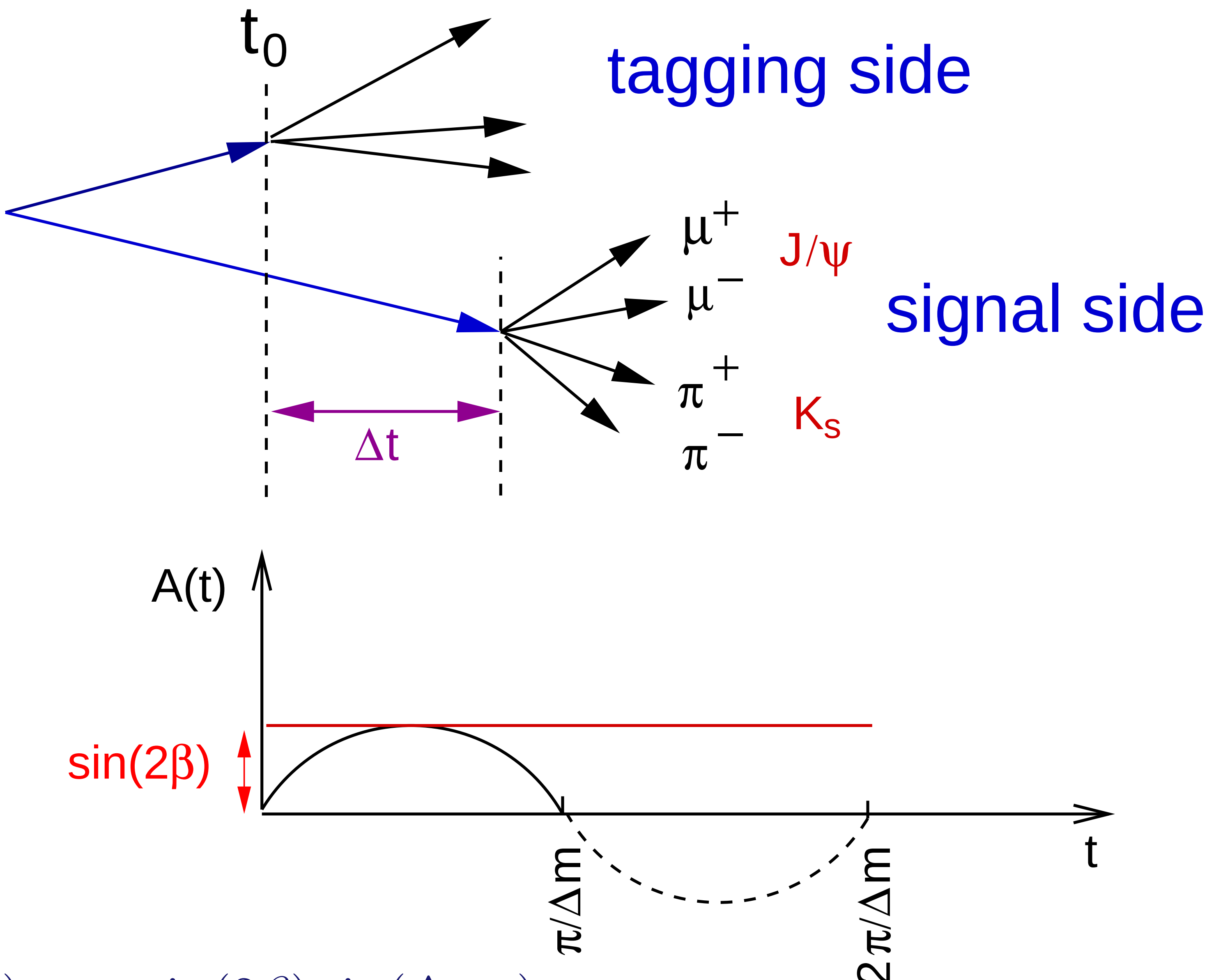


$$\mathcal{A}(t) = \frac{\Gamma(\bar{B}\to J/\psi K_s)(t) - \Gamma(B\to J/\psi K_s)(t)}{\Gamma(\bar{B}\to J/\psi K_s)(t) + \Gamma(B\to J/\psi K_s)(t)}$$

Correlated final states at B factories

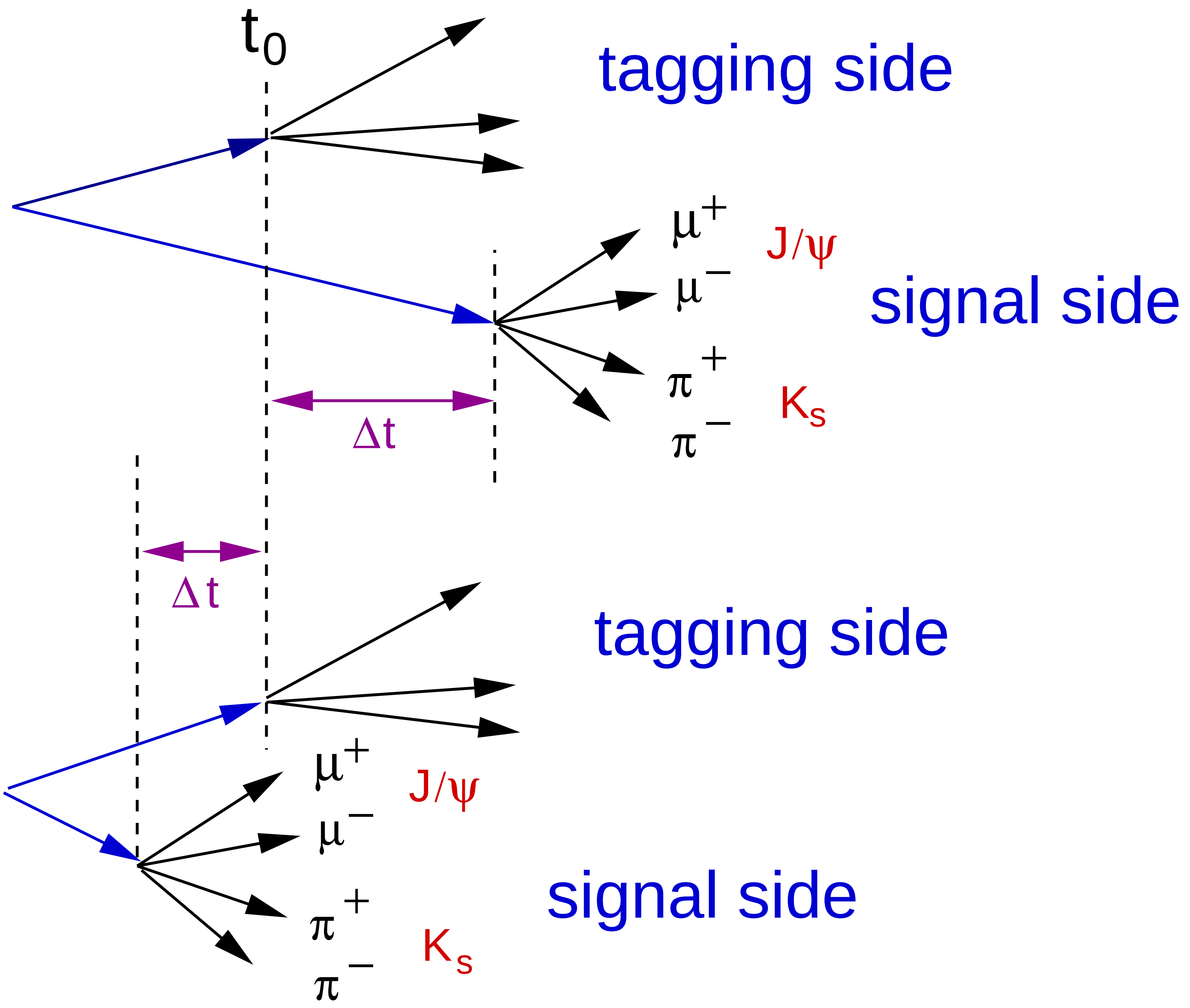
$\longrightarrow$ at $t = t_0$ flavour of signal B fixed by flavour of tagging B.

$B_d \to J/\psi K_s$

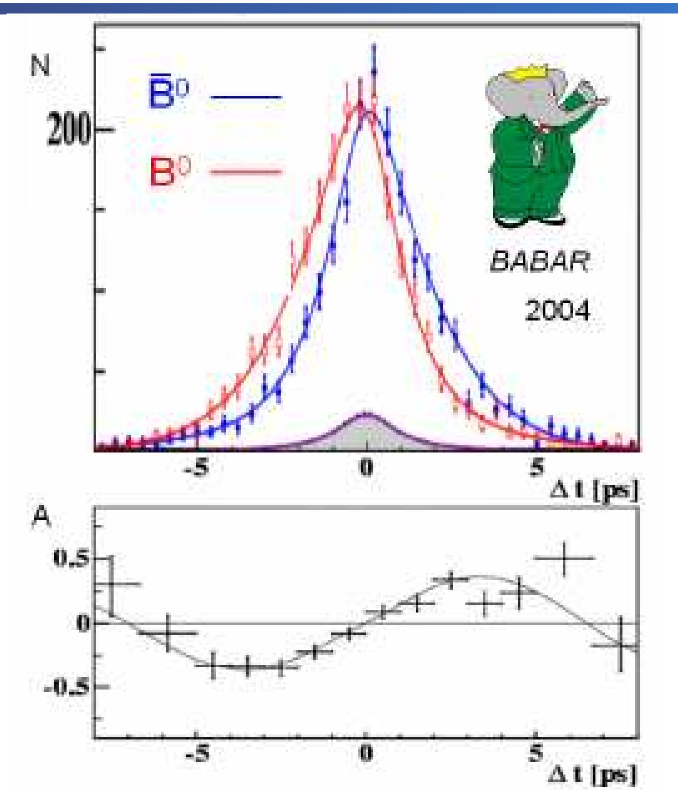


$$\mathcal{A}(t) = -\sin(2\beta)\sin(\Delta m t)$$

$B_d \to J/\psi K_s$


t0
tagging side
μ+
μ−
J/ψ
signal side
π+
π−
Ks
Δt
Δt
tagging side
μ+
μ−
J/ψ
π+
π−
Ks
signal side

$B_d \to J/\psi K_s$



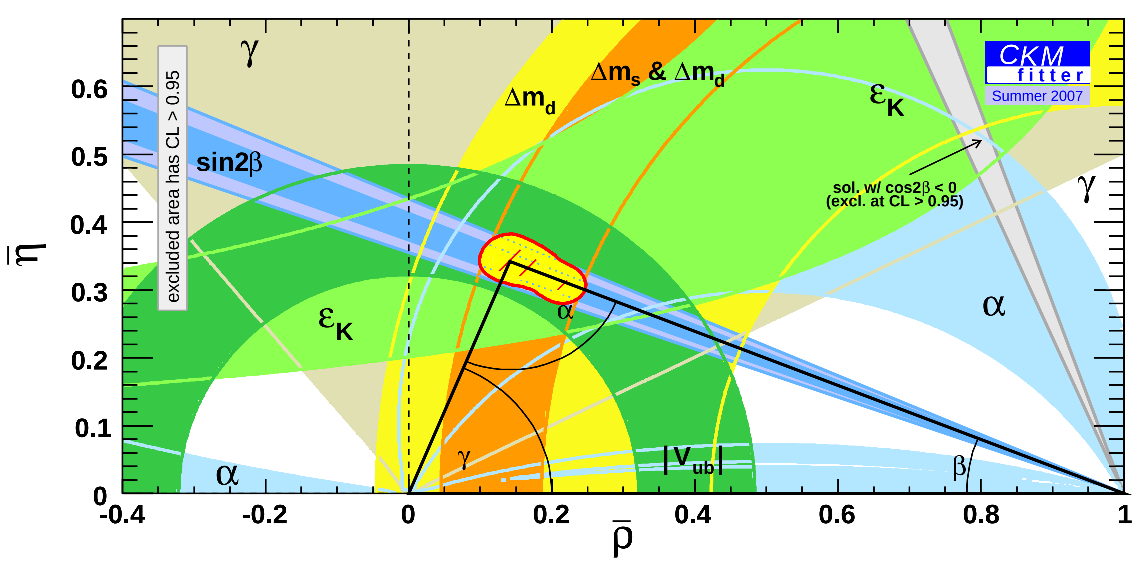
$\mathcal{A}(t)$ = -$\sin(2\beta)$ $\sin(\Delta m_d t)$

Babar:

$\sin(2\beta)$ = 0.722 $\pm$ 0.040 $\pm$ 0.023

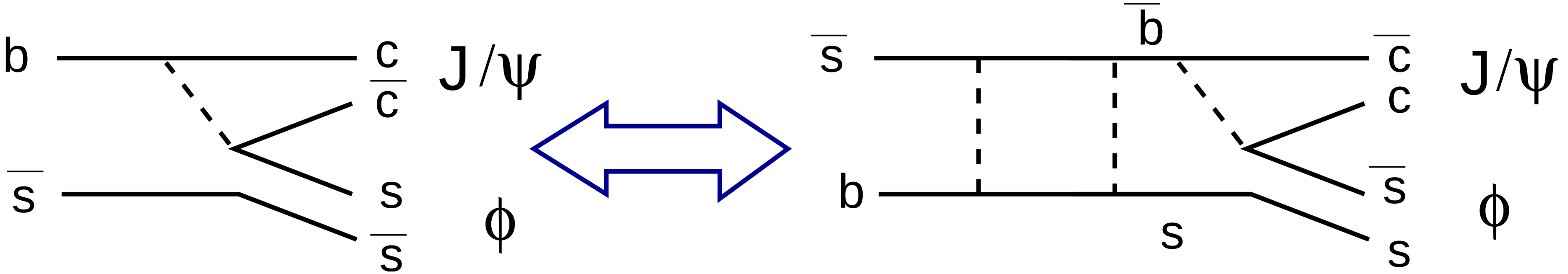
Belle:

$\sin(2\beta)$ = 0.652 $\pm$ 0.039 $\pm$ 0.020



$B_s \to J/\psi\phi$

Basic idea similar to measurement of $\sin(2\beta)$:



- No CP violation in mixing
- No CP violation in decay

$\phi_{mix} = arg((V_{ts}V_{tb}^*)^2) = 2\beta_s \approx 0.04(SM)$,
however potentially large contributions in NP ($\longrightarrow$ Uli N.)

$\omega = arg((V_{cb}V_{cs}^*)(V_{us}V_{us}^*)) = 0$

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1-\frac{\lambda}{2} & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$

$B_s \rightarrow J/\psi\phi$

B_s : J^P = 0^{-1} (pseudo scalar)

J/ψ: : J^{CP} = 1^{-1-1} (vector)

ϕ: : J^{CP} = 1^{-1-1} (vector)

Angular momentum conservation:

0 = J ($J/\psi\phi$) = $|\vec{S}+\vec{L}|$; $\longrightarrow$ L = 0,1,2

P($J/\psi\phi$) = P(J/ψ)*P(ϕ)*(-1)^L

CP($J/\psi\phi$) = CP(J/ψ)*CP(ϕ)*(-1)^L

L = 0,2 $\longrightarrow$ CP even final state

L = 1 $\longrightarrow$ CP odd final state

Final state no CP eigenstate but linear combination!

Angular analysis, to separate CP even/odd contributions.

Three decay amplitudes: $|A_\perp|$ (L=1), $|A_{||}|$, $|A_0|$ (L=0,2),

+ two rel. strong phases: $\delta_1 = arg(A_{||}(0)A_\perp)$, $\delta_2 = arg(A_0(0)A_\perp(0))$

Additional complication: $\Delta\Gamma$ is not negligible in B_s system.

$\Rightarrow$ add. time modulation on top of mixing, Γ_H & Γ_L both have to be taken into account

$$|\bar{A}_0(t)|^2 = \frac{|A_0(0)|^2}{2}\Big[(1+\cos\phi_s)\,e^{-\Gamma_{\mathrm{L}}t} + (1-\cos\phi_s)\,e^{-\Gamma_{\mathrm{H}}t} - 2e^{-\bar{\Gamma}_s t}\sin(\Delta m_s t)\sin\phi_s\Big]$$

$$|\bar{A}_{\|}(t)|^2 = \frac{|A_{\|}(0)|^2}{2}\Big[(1+\cos\phi_s)\,e^{-\Gamma_{\mathrm{L}}t} + (1-\cos\phi_s)\,e^{-\Gamma_{\mathrm{H}}t} - 2e^{-\bar{\Gamma}_s t}\sin(\Delta m_s t)\sin\phi_s\Big]$$

$$|\bar{A}_{\perp}(t)|^2 = \frac{|A_{\perp}(0)|^2}{2}\Big[(1-\cos\phi_s)\,e^{-\Gamma_{\mathrm{L}}t} + (1+\cos\phi_s)\,e^{-\Gamma_{\mathrm{H}}t} + 2e^{-\bar{\Gamma}_s t}\sin(\Delta m_s t)\sin\phi_s\Big]$$

$$\mathrm{Re}\{\bar{A}_0^*(t)\bar{A}_{\|}(t)\} = \frac{1}{2}|A_0(0)||A_{\|}(0)|\cos(\delta_2-\delta_1)\Big[(1+\cos\phi_s)\,e^{-\Gamma_{\mathrm{L}}t} + (1-\cos\phi_s)\,e^{-\Gamma_{\mathrm{H}}t} - 2e^{-\Gamma_s t}\sin(\Delta m_s t)\sin\phi_s\Big]$$

$$\mathrm{Im}\{\bar{A}_{\|}^*(t)\bar{A}_{\perp}(t)\} = -|A_{\|}(0)||A_{\perp}(0)|\Big[e^{-\Gamma_s t}\{\sin\delta_1\cos(\Delta m_s t) - \cos\delta_1\sin(\Delta m_s t)\cos\phi_s\} + \frac{1}{2}\left(e^{-\Gamma_{\mathrm{H}}t} - e^{-\Gamma_{\mathrm{L}}t}\right)\cos\delta_1\sin\phi_s\Big]$$

$$\mathrm{Im}\{\bar{A}_0^*(t)\bar{A}_{\perp}(t)\} = -|A_0(0)||A_{\perp}(0)|\Big[e^{-\Gamma_s t}\{\sin\delta_2\cos(\Delta m_s t) - \cos\delta_2\sin(\Delta m_s t)\cos\phi_s\} + \frac{1}{2}\left(e^{-\Gamma_{\mathrm{H}}t} - e^{-\Gamma_{\mathrm{L}}t}\right)\cos\delta_2\sin\phi_s\Big]$$

Summary

No CP violation in $B_{d/s}$ mixing.

No CP violation in decay $B_d \rightarrow J/\psi K_s$, $B_s \rightarrow J/\psi \phi$

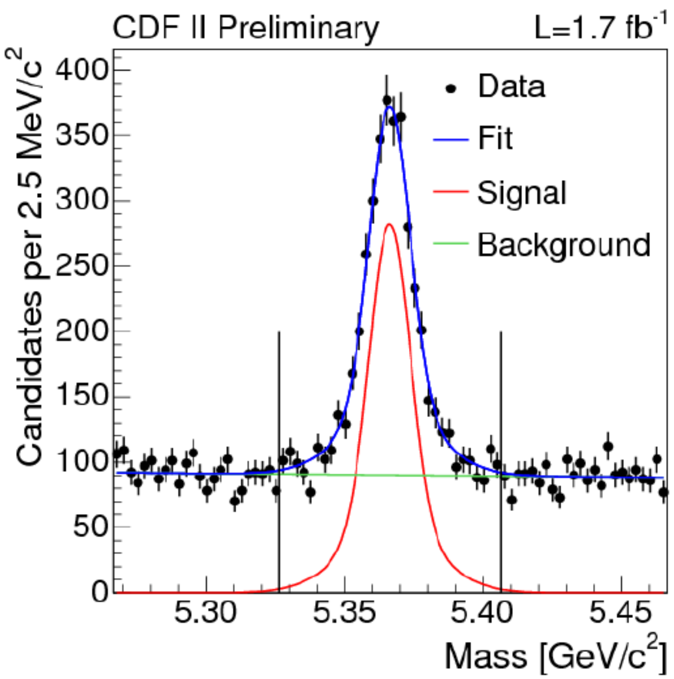
Sensitivity to $\phi_{d/s} = 2\beta_{d/s}$ via CP violation in interference of mixing & decay.

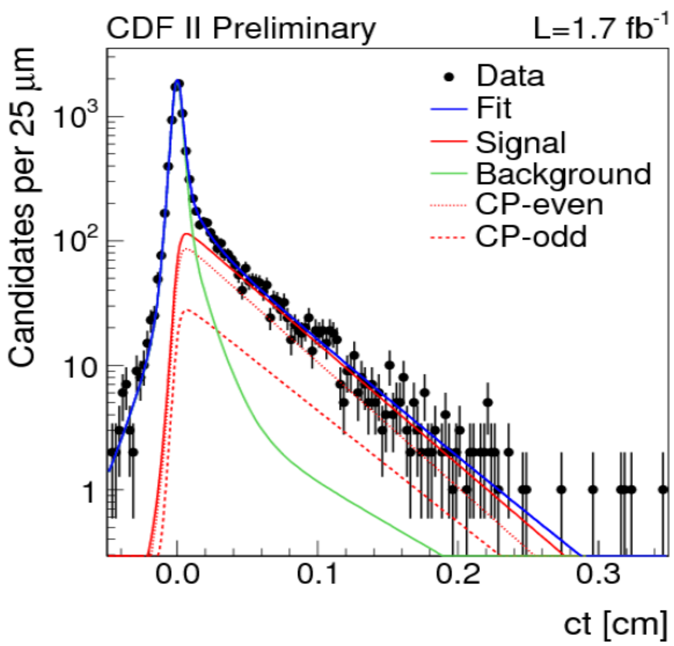
	$B_d \rightarrow J/\psi K_s$	$B_s \rightarrow J/\psi \phi$
CP	CP odd eigenstate	comb. of even/odd eigen states $\rightarrow$ angular analysis
$\Delta\Gamma$	too small, no sensitivity	$\Delta\Gamma$ measurable
$\phi\ (= 2\beta)$	only tagged analyses	in untagged analysis due to large $\Delta\Gamma_s$; higher sensitivity in tagged analyses

$J/\psi\phi$ @ CDF

	CDF analysis	LHCb prospects
signal events	2.500/1.7fb^{-1}	130.000/2fb^{-1}
ϵD^2	5%	10%
proper time resolution	100 fs	40 fs
S/B	1/1	0.1 ???

D0 numbers similar to CDF.



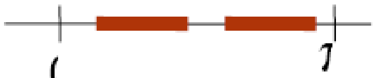


$J/\psi\phi$ @ CDF

- 1D Feldman-Cousins procedure without external constraints:
  $2\beta_s$ in [0.32, 2.82] at the 68% C.L.

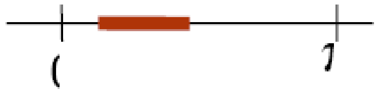
$2\beta_s$

- with theoretical input $\Delta\Gamma$ = 0.096+/- 0.039
  $2\beta_s$ in [0.24, 1.36] U [1.78, 2.90] at 68% C.L.



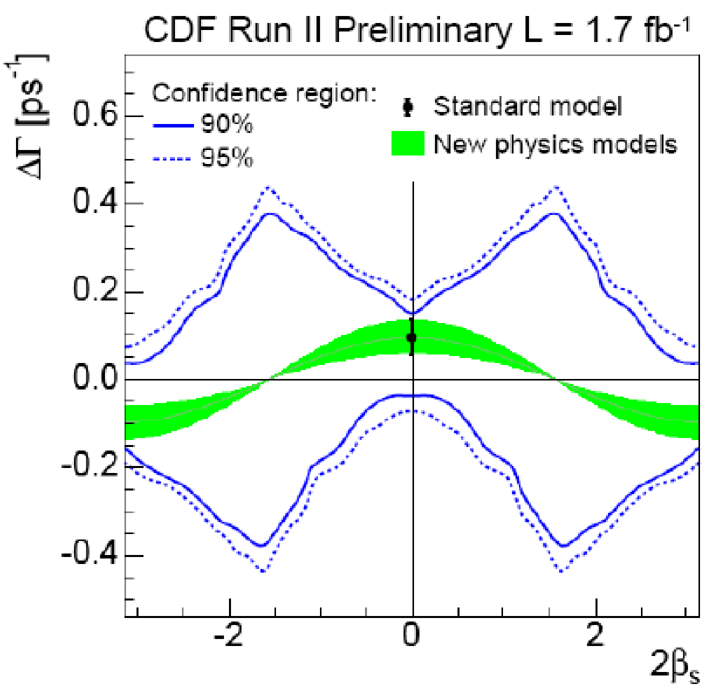
$2\beta_s$

- with external constraints on strong phases, lifetime and $\Delta\Gamma$
  $2\beta_s$ in [0.40, 1.20] at 68% C.L.

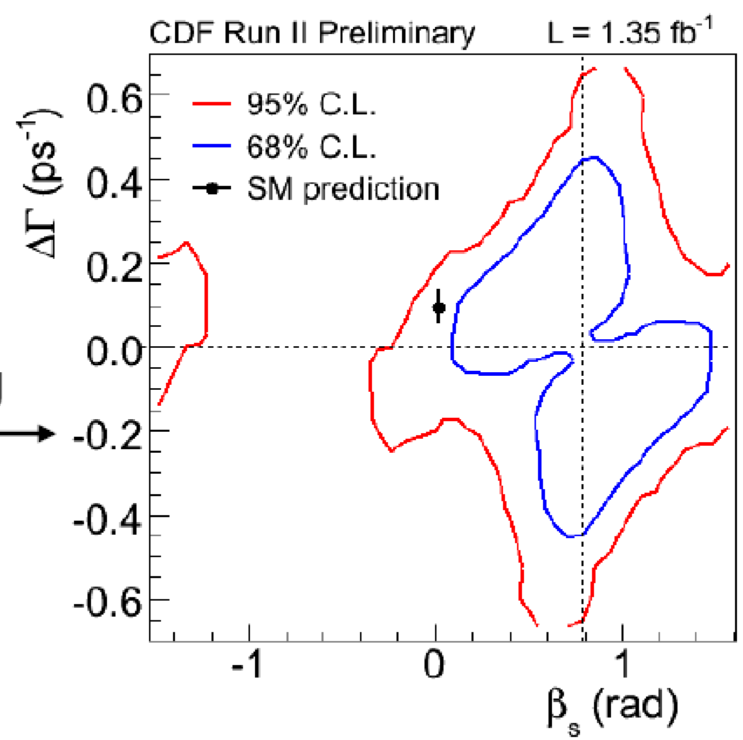


$2\beta_s$

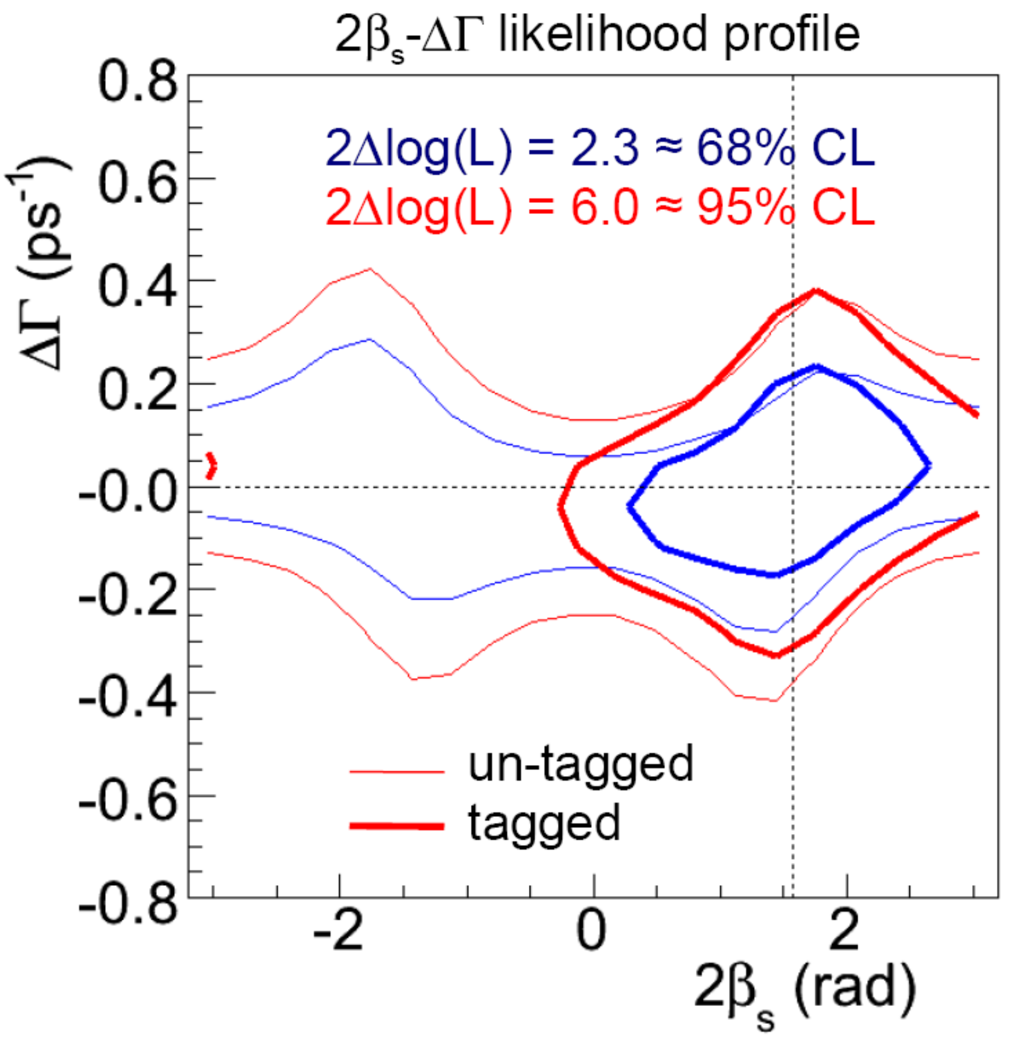
- β_s parameter space is greatly reduced when using flavor tagging:



flavor tagging →



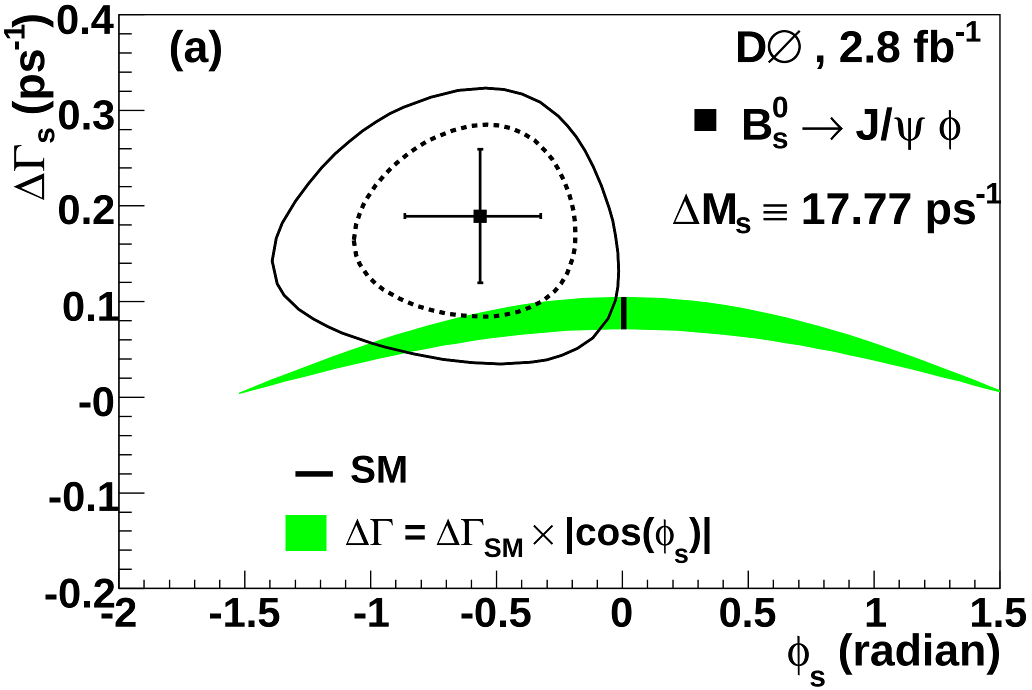
Tagged vs. Untagged



Tagging helps to reduce 4 folded ambiguity to 2 folded one

Otherwise tagging has very little impact ...

$J/\psi\phi$ @ D0



dotted line 68% CL, solid line 90% CL

Fit performed with constraint on strong phases to B_d system.

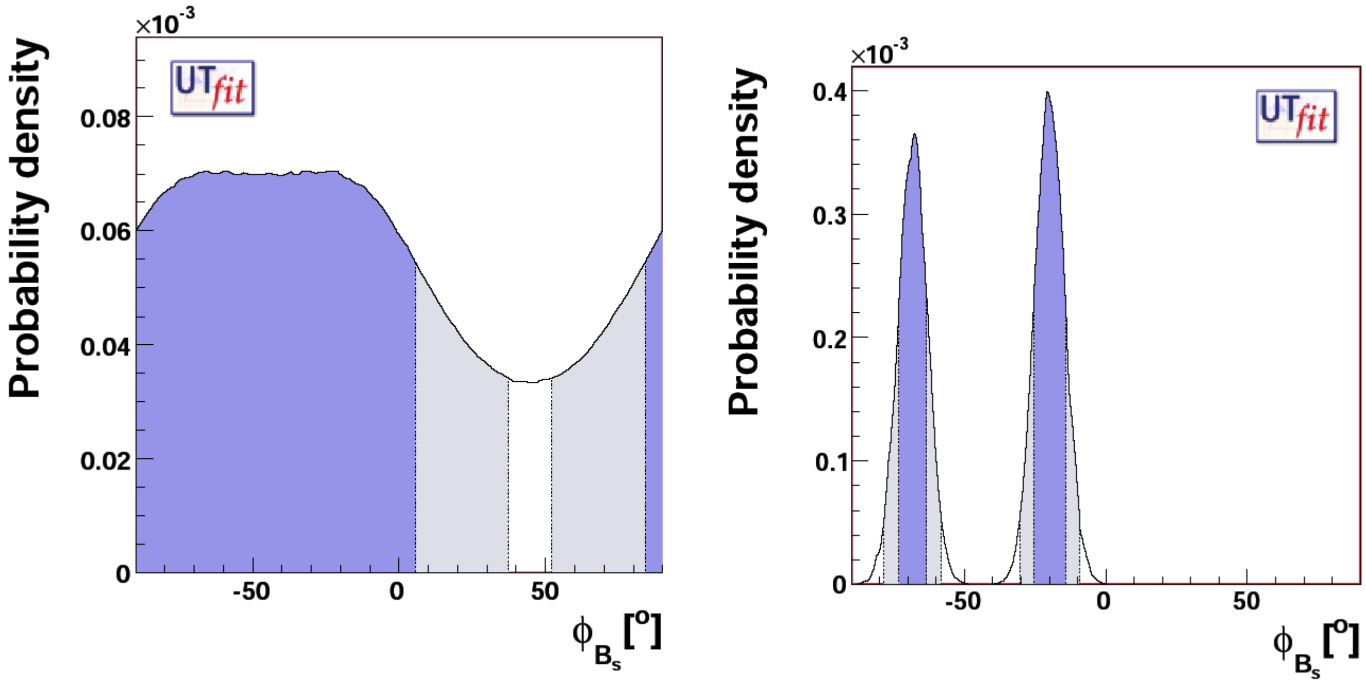
(sign of ϕ_s is defined with opposite side compared to CDF; Two folded amgiguity resolved by constraining strong phases:

$\phi_s \to \pi - \phi_s$; $\Delta\Gamma \to -\Delta\Gamma$; $\delta_{||} \to 2\pi - \delta_{||}$; $\delta_\perp \to \pi - \delta_\perp$)

2 independent results with 2 σ deviation each!

UT-fit Combination

Without/with CDF/D0 $J/\psi\phi$ analysis



3σ evidence for non SM B_s mixing phase.

$\longrightarrow$ Minimal Flavour Violation NP models ruled out @ 3σ.

Be careful with 3σ effects ...