CP violation in oscillations measured with the BaBar experiment

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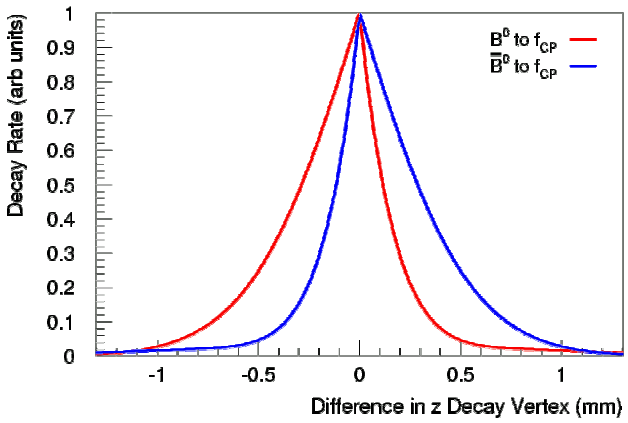
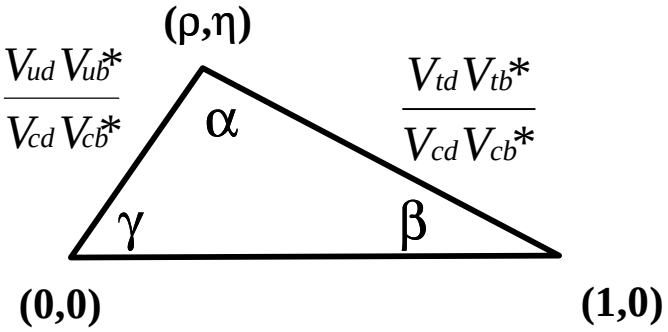




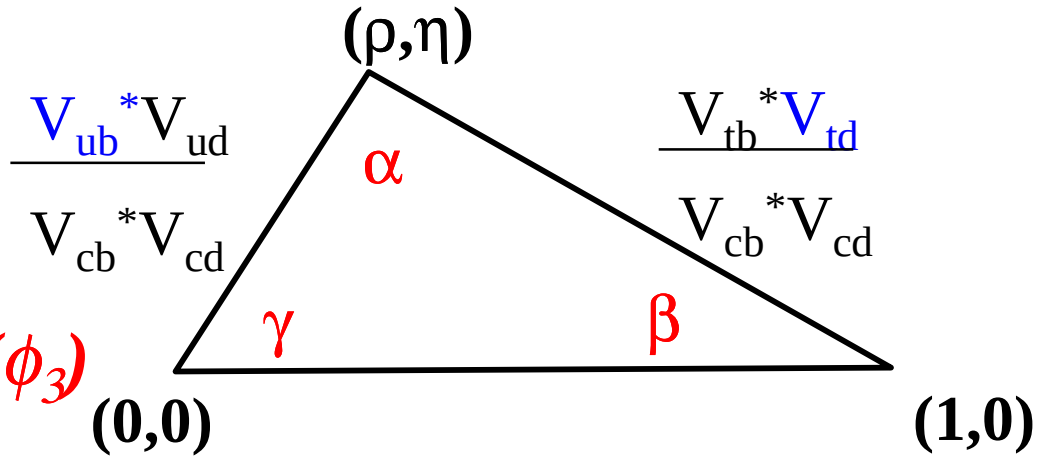
The 'Triangle'

B_d system

- CKM matrix is unitary

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

phases $\rightarrow$

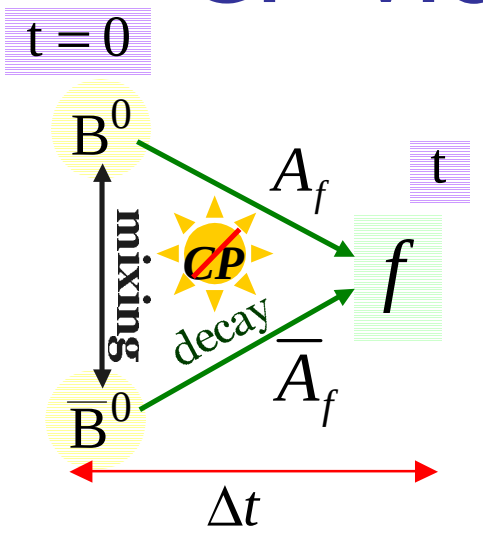


angles $\alpha(\phi_2)$, $\beta(\phi_1)$, ***and*** $\gamma(\phi_3)$

CP violation proportional to triangle area:

measure sides and angles independently

CP violation in mixing and decay



Consider B decays to a mode *f*

interference between mixing and decay

$$\wp(B^0(t) \to f) \sim$$

f is not necessarily a CP eigenstate

$$1+\lambda^2 \pm (1-\lambda^2)\cos(\Delta M t) \pm 2\,\mathrm{Im}(\lambda)\sin(\Delta M t)$$

$$\lambda = \frac{A(\overline{B} \to f)V_{td}^* V_{tb}}{A(B \to f)V_{td}V_{tb}^*} \cong \frac{\overline{A}}{A} e^{-i2\beta}$$

Mixing phase

Examples:

	f	$Arg(\frac{\overline{A}}{A})$	$\lvert\lambda\rvert$	output
mixing	$B_0 \to l\nu X, D^{(*)}\pi,\rho,a_1$	0	~0	ΔM_{B0}
"sin2β"	$B_0 \to J/\Psi K^0$ + …	0	1	sin2β
"sin2α"	$B_0 \to \pi\pi,\rho\pi,\pi\pi\pi$	~(-2γ)	~1	sin2α
sin(2β+γ)	$B_0 \to D^{(*)+}\pi^-$	~(-γ)	~0.02	sin(2β+γ)

CP parameters

- $|\lambda| \neq 1$ if direct CP Violation
- If "f" is a CP eigenstate, only one $|\lambda|$: fit for $|\lambda|$ and $\mathrm{Im}(\lambda)$ or for $C = \frac{1-|\lambda|^2}{1+|\lambda|^2}$ and $S = \frac{2\mathrm{Im}\lambda}{1+|\lambda|^2}$
- If "f" is not a CP eigenstate , need also

$$\bar{\lambda} \cong \frac{A(B \to \bar{f})}{A(B \to f)} e^{-i2\beta} \quad \text{and} \quad A_{CP} = \frac{N(f) - N(\bar{f})}{N(f) + N(\bar{f})}$$

  - 5 parameters: A_{CP} and

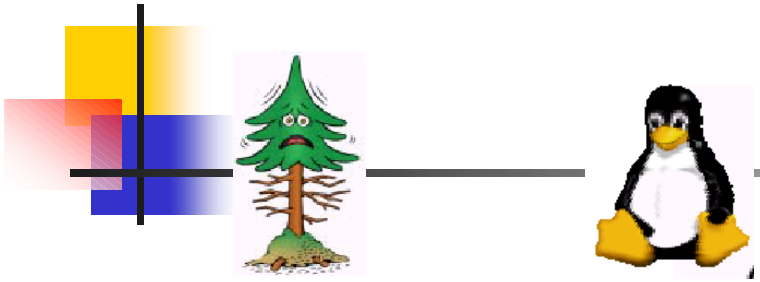
CPV in mixing $\longrightarrow$

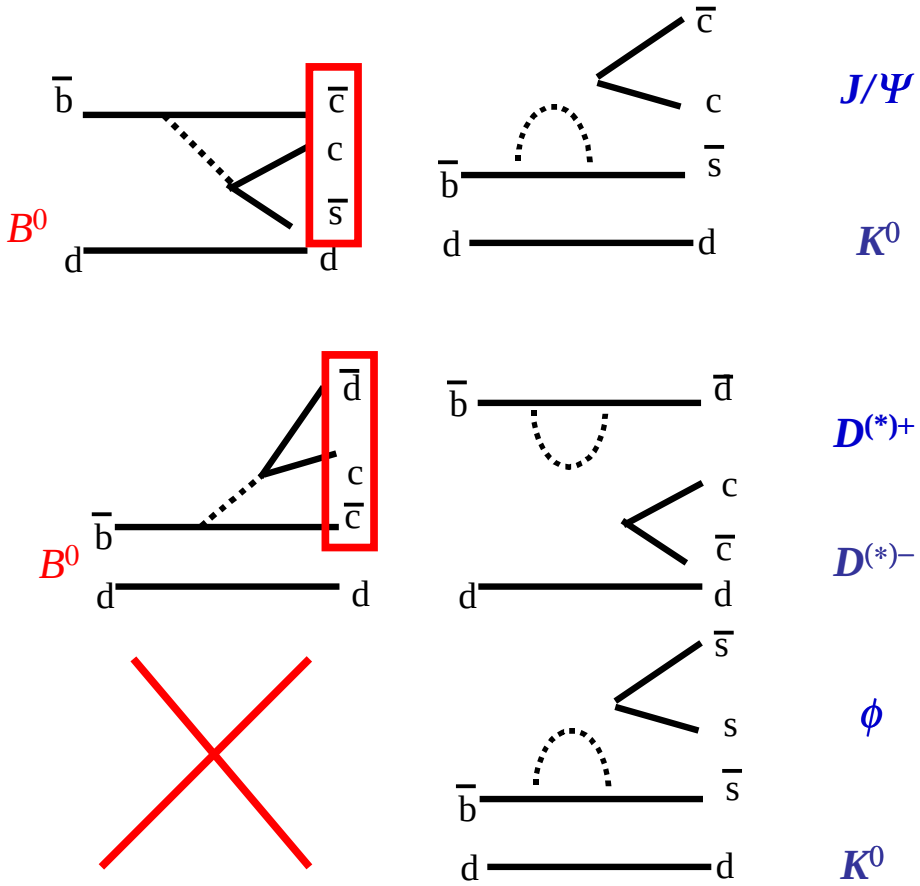
$$C^{+-} = \frac{1-|\lambda|^2}{1+|\lambda|^2} \qquad C^{-+} = \frac{1-|\bar{\lambda}|^2}{1+|\bar{\lambda}|^2}$$

$$S^{+-} = \frac{2\,\mathrm{Im}\,\lambda}{1+|\lambda|^2} \qquad S^{-+} = \frac{2\,\mathrm{Im}\,\bar{\lambda}}{1+|\bar{\lambda}|^2}$$

$\longleftarrow$ direct CPV

Measurements of β





Charmonium K^0

Penguin and tree have the same weak phase

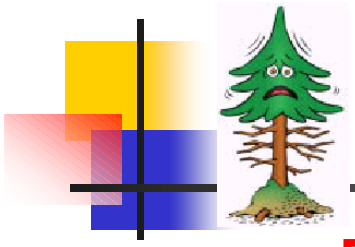
$D^{(*)}D^{(*)}$ and $J/\Psi\pi^0$

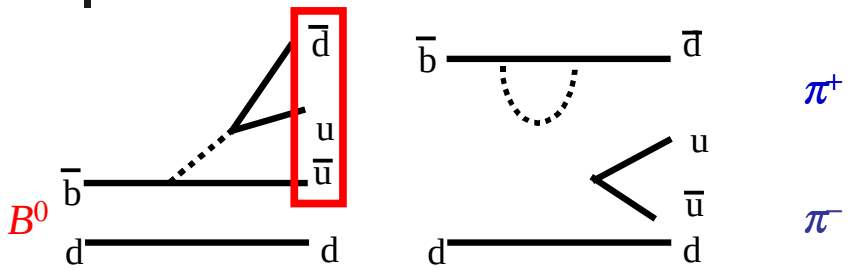
Penguin and tree have different weak phases: asymmetry not necessarily = sin2β

ϕK^0 and $\eta^{(\prime)}K^0$

Mostly penguin. In principle measures sin2β, but sensitive to new physics

Measurements of α





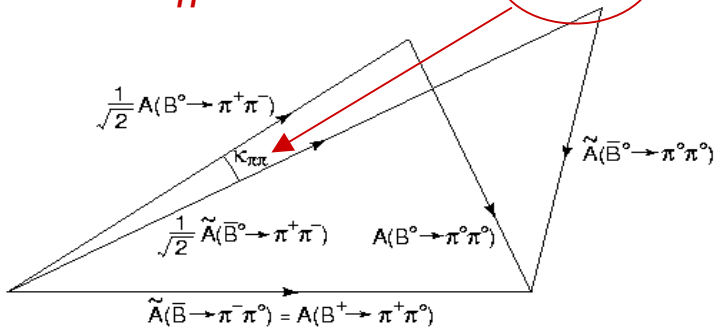
$\pi^+\pi^-$, $\rho^+\pi^-$, $\pi^+\pi^-\pi^0$

Penguin and tree have different weak phases: asymmetry measures $\sin 2\alpha_{eff}$

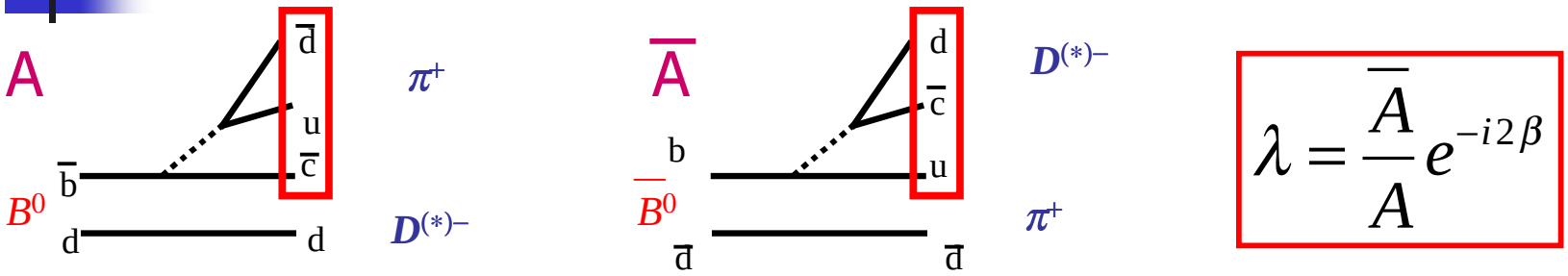
From $\sin 2\alpha_{eff}$ to $\sin 2\alpha$

- $\pi^+\pi^-$, $\rho^+\pi^-$ require isospin analysis (see talk from S. Laplace)
- Long term:3-body dalitz analysis. Penguin to Tree ratio is fit in each point of the Dalitz plot

$$2\alpha_{eff} = 2\alpha + \kappa_{\pi\pi}$$



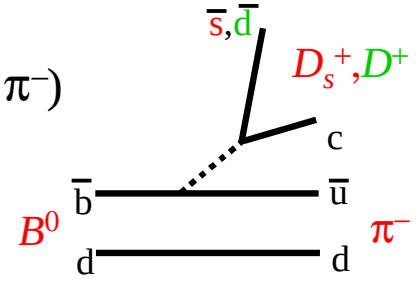
Measurements of sin(2β+γ) in $B0 \to D^{*-}\pi^+, \rho^+, a_1^+$



$$\lambda = \frac{\bar{A}}{A} e^{-i2\beta}$$

- γ enters via the Cabibbo suppressed amplitude $\bar{A}$.
- Small asymmetry : $|\lambda| \sim 0.02$
- need to measure $|\lambda| \rightarrow$ measure $\mathrm{BF}\,(B^0 \to D_s^+ \pi^-)$

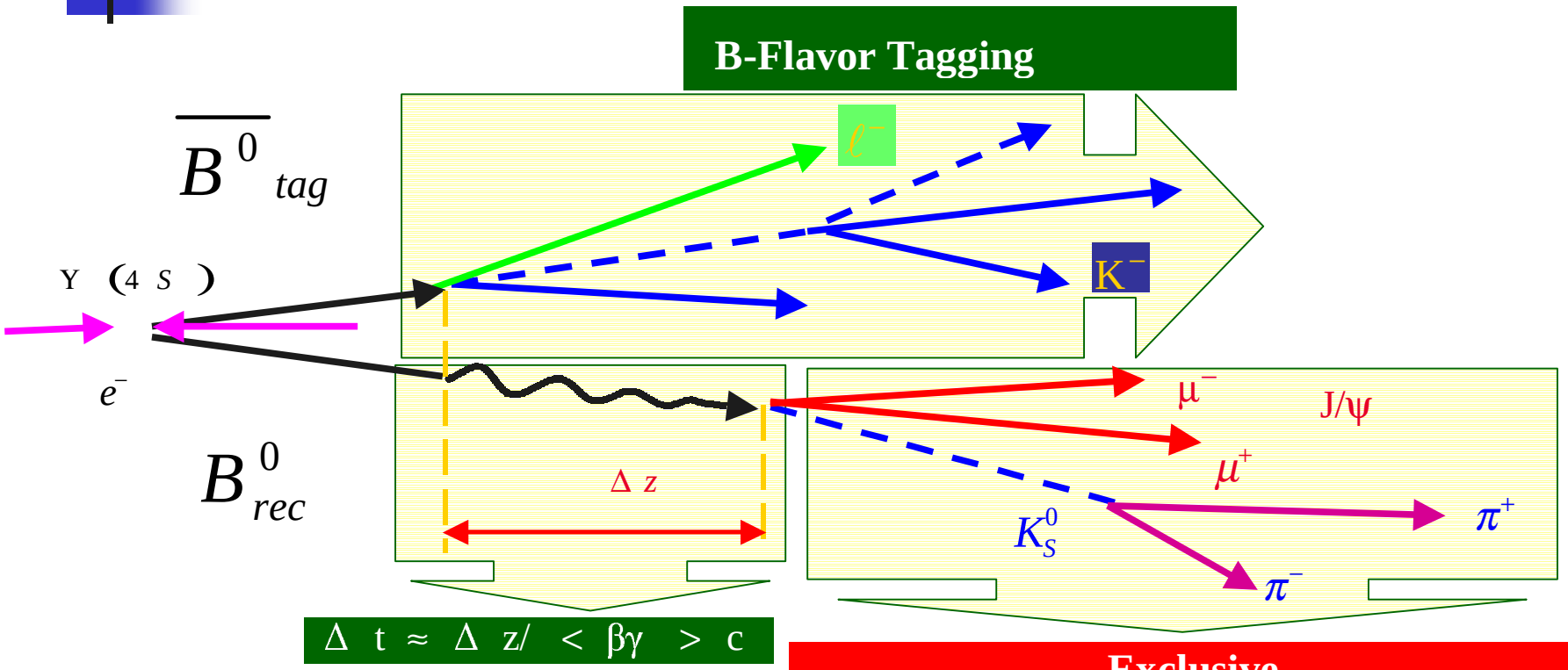
$$\mathrm{BF}\,(B^0 \to D_s^+ \pi^-) \approx \frac{\mathrm{BF}\,(\bar{B}^0 \to D^- \pi^+)}{\tan^2\theta_C} \left(\frac{f_{Ds}^2}{f_D^2} \right) \times \lambda^2_{D\pi}$$



D*ρ,a_1 more complicated but will not require |λ| (angular analysis)

Experimental Technique

Analyses presented on ~88M BB decays (run1+2) collected by the BaBar experiment @ PEP-II



Accurate and unbiased measurement of the vertices

Low BR (10^{-5}) means high luminosity

Tagging and Vertexing

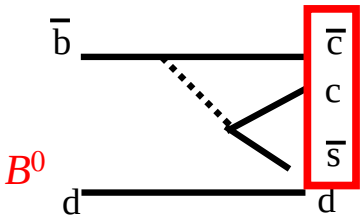
- Lepton's and Kaon's sign tags B flavor

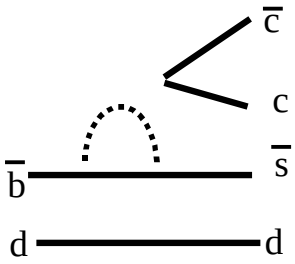
Category	Efficiency (ε)	Mistag Fr. (w)	$Q=\varepsilon(1-2w)^2$ $\sigma(\sin 2\beta) \sim \frac{1}{\sqrt{Q}}$
Lepton	9.1 ± 0.2	3.3 ± 0.6	7.9 ± 0.3
Kaon1	16.7 ± 0.2	9.9 ± 0.7	10.7 ± 0.4
Kaon2	19.8 ± 0.3	20.9 ± 0.8	6.7 ± 0.4
Inclusive	20.0 ± 0.3	31.6 ± 0.9	2.7 ± 0.3
Total	$\mathbf{65.6 \pm 0.5}$		$\mathbf{28.1 \pm 0.7}$

- Δz resolution 180μm

Tagging efficiency and vertex resolution measured from the data

sin2β in $b \to c\bar{s}c$





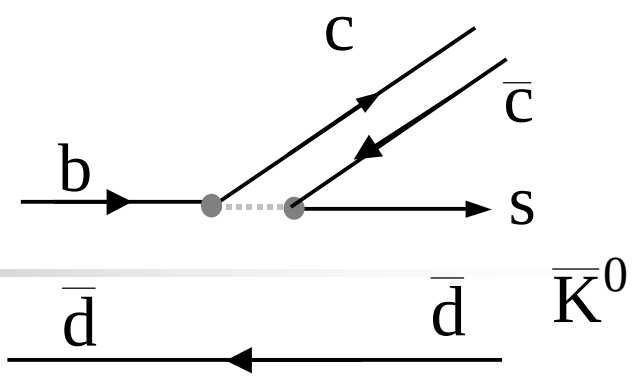
J/Ψ

K^0

Charmonium K^0

Penguin and tree have the same weak phase

Charmonium states



η_{CP} **= -1**

$B^0 \to J/\psi\, K^0_S$

$B^0 \to \psi(2s)\, K^0_S$

$B^0 \to \chi_{c1}\, K^0_S$

$B^0 \to \eta_c\, K^0_S$

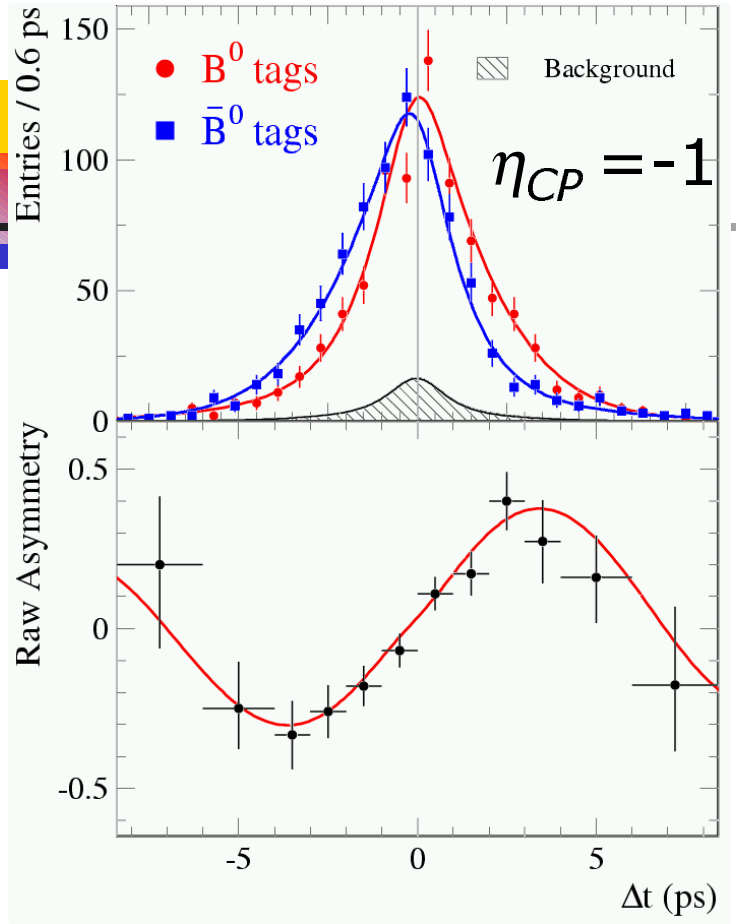
η_{CP} **= +1**

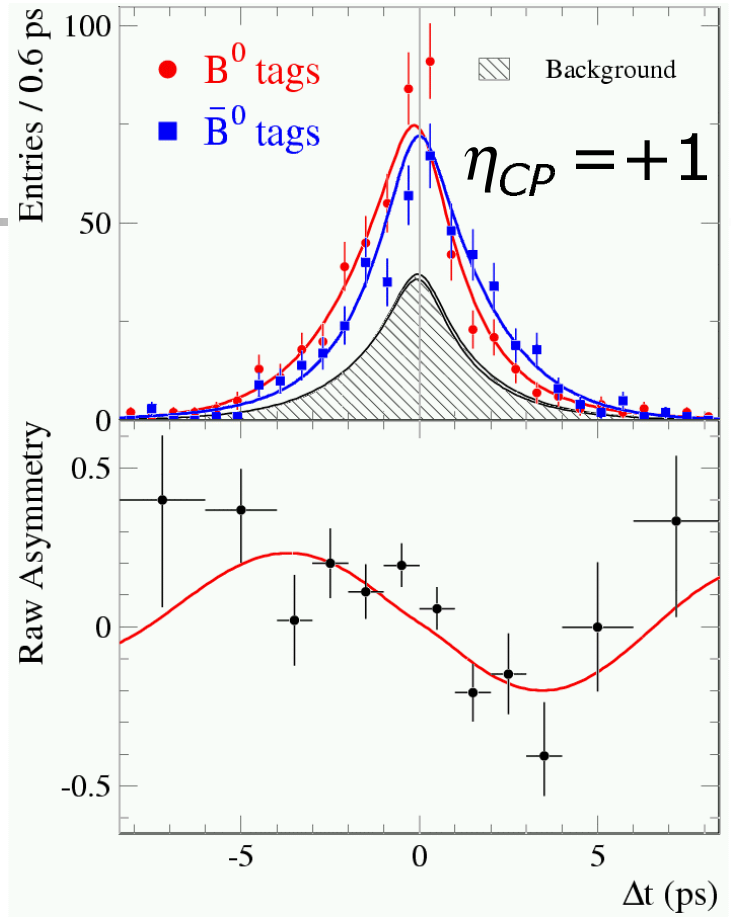
$B^0 \to J/\psi\, K^0_L$

η_{CP} **= (1-2R$_T$)**

$B^0 \to J/\psi\, K^*(K^0_S\pi^0)$

$$A_{CP}(t) = \frac{f(\bar{B}^0_{phys} \to f_{CP}) - f(B^0_{phys} \to f_{CP})}{f(\bar{B}^0_{phys} \to f_{CP}) + f(B^0_{phys} \to f_{CP})} = -\eta_{CP} \sin 2\beta \sin(\Delta m \Delta t)$$



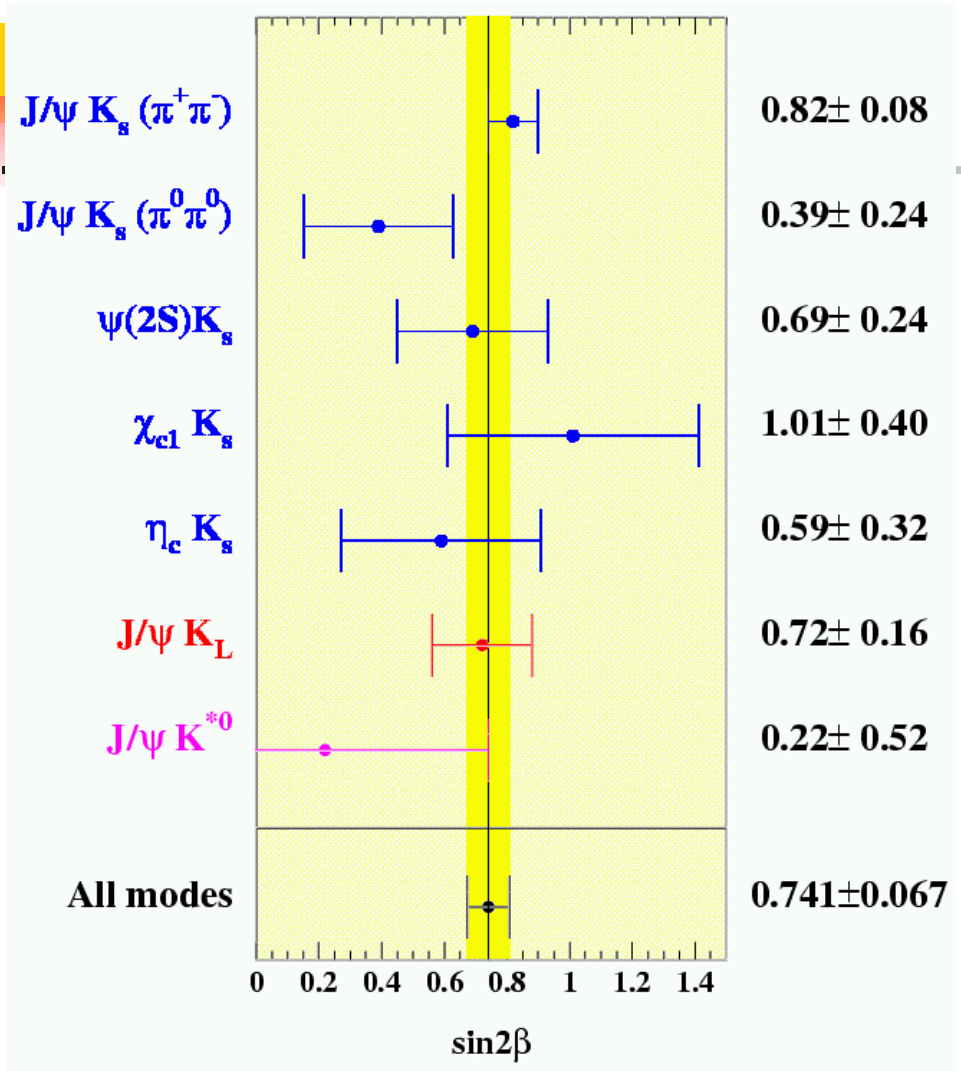


sin2β = 0.755 $\pm$ 0.074

sin2β = 0.723 $\pm$ 0.158

sin2β = 0.741 $\pm$ 0.067 (stat) $\pm$ 0.034 (sys)

sin2β fit results by decay

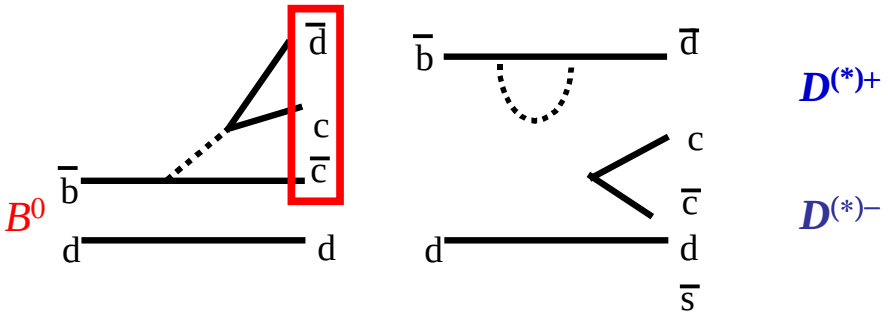


Direct CP search yields no evidence:

$|\lambda| = 0.948 \pm 0.051(stat) \pm 0.030\ (syst)$

Consistency of CP Channels: $P(\chi^2) = 57\%$

sin2β in b→cdc̄



$D^{(*)}D^{(*)}$ and $J/\Psi\pi^0$

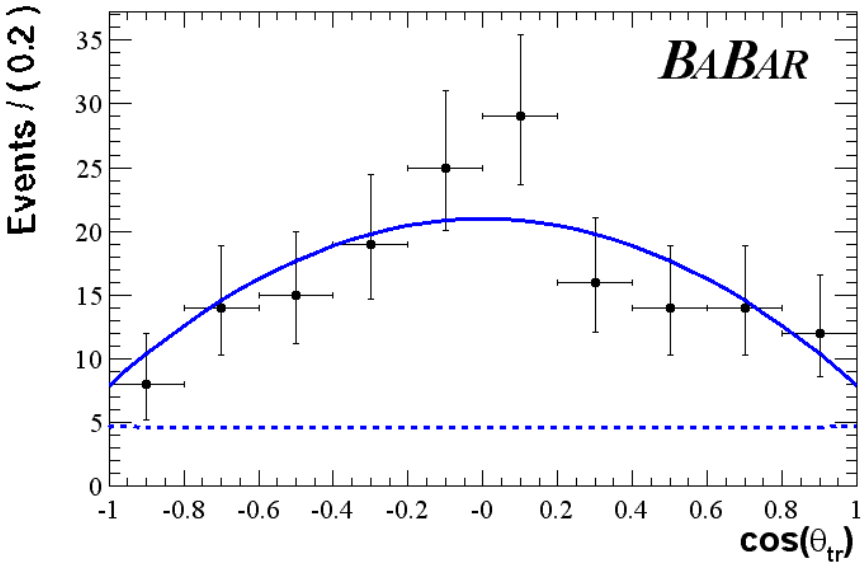
Penguin and tree have different weak phases: asymmetry not necessarily = sin2β

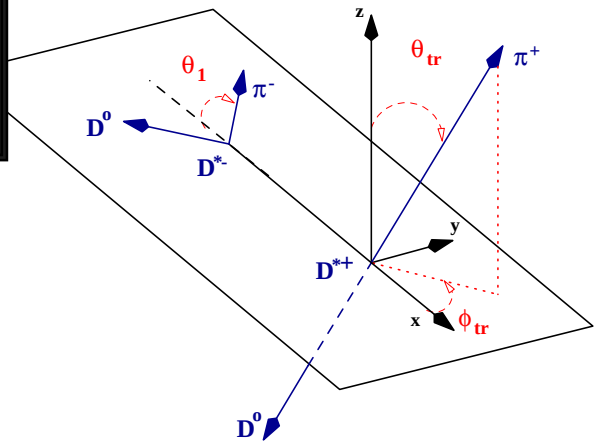
$B^0 \to D^{*+} D^{*-}$

- $D^{*+}D^{*-}$, is not a CP eigenstate (L=0,2 and L=1)
- CP odd fraction $R_\perp$
- Transversity analysis

$$R_\perp = \frac{|A_\perp|^2}{|A_0|^2 + |A_\parallel|^2 + |A_\perp|^2}$$

$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta_{tr}} = \frac{3}{4}(1-R_\perp)\sin^2\theta_{tr} + \frac{3}{2}R_\perp\cos^2\theta_{tr}$$





CP-odd fraction

$R_\perp = 0.07 \pm 0.06 \pm 0.03$

sin2β from $B^0 \to D^{*+}D^{*-}$

If no penguins we should measure $Im(\lambda^+) = -\sin 2\beta$

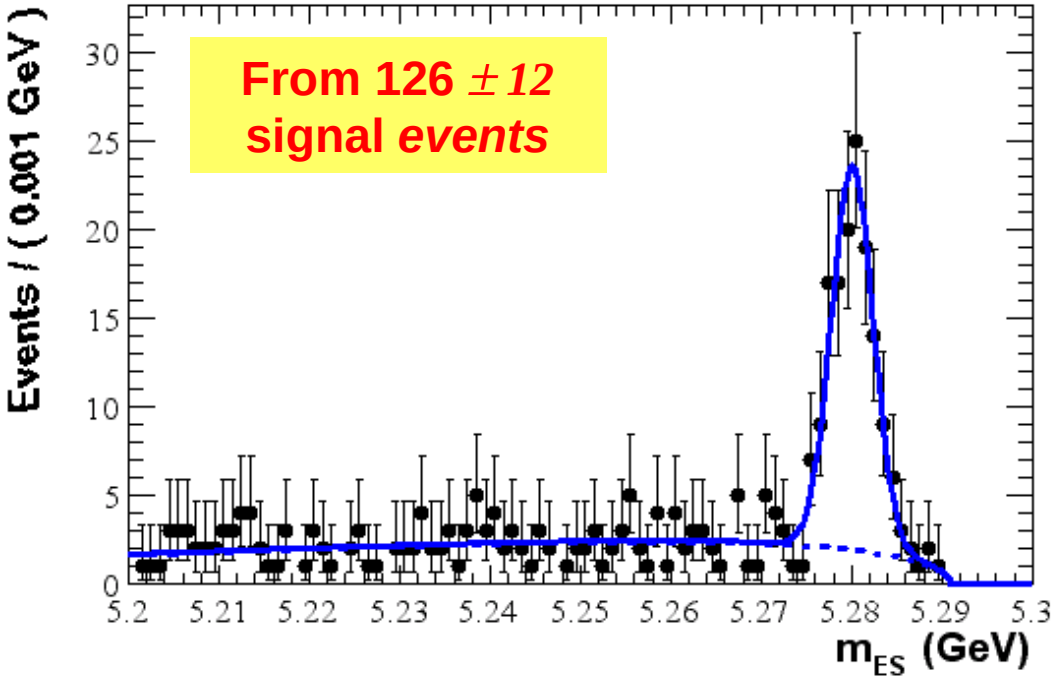
We also measure $|\lambda_+|$

$B^0 \to D^{*+}D^{*-}$

$$Im(\lambda_+) = 0.31 \pm 0.43\ (stat) \pm 0.13\ (syst)$$

$$-\sin 2\beta = -0.741 \pm 0.067$$

$$|\lambda_+| = 0.98 \pm 0.25\ (stat) \pm 0.09\ (syst)$$



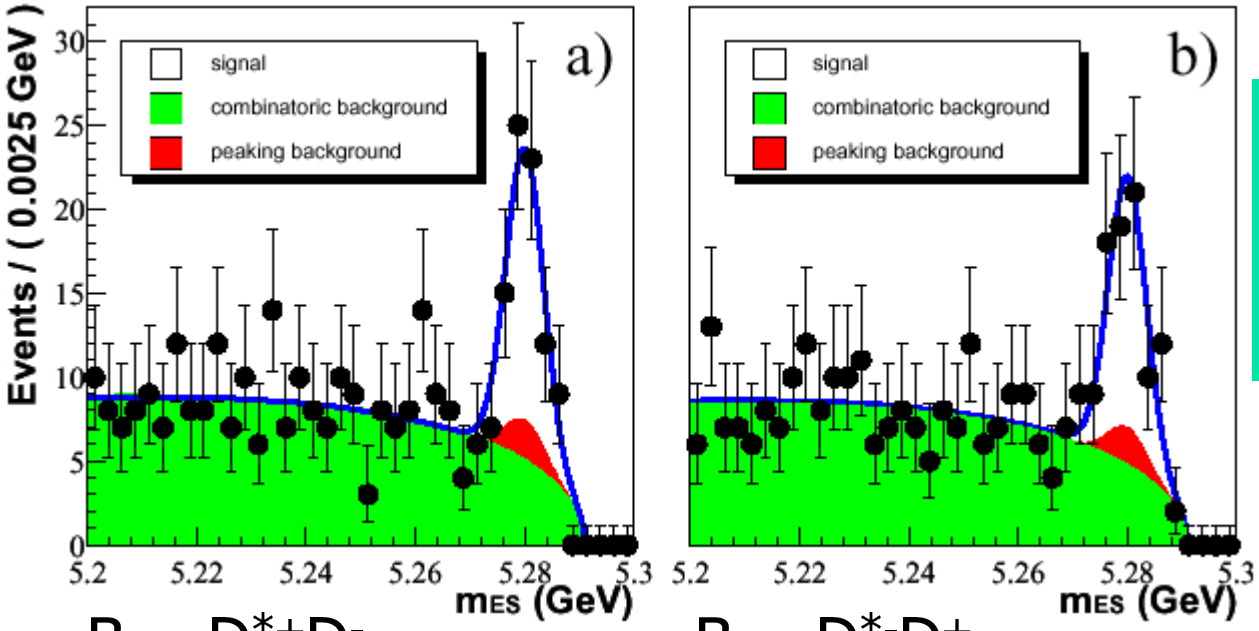
In SM with no penguins

$S^{+-}=S^{-+}= -\sin 2\beta \quad C^{+-}=C^{-+}=0$

sin2β from $B^0 \to D^{*+}D^-$

Not a CP eigenstate: use the S & C parametrization

Vector-PseudoScalar : no angular analysis required



$B \to D^{*+}D^-$ $B \to D^{*-}D^+$

$S^{+-} = -0.24 \pm 0.69 \pm 0.12$

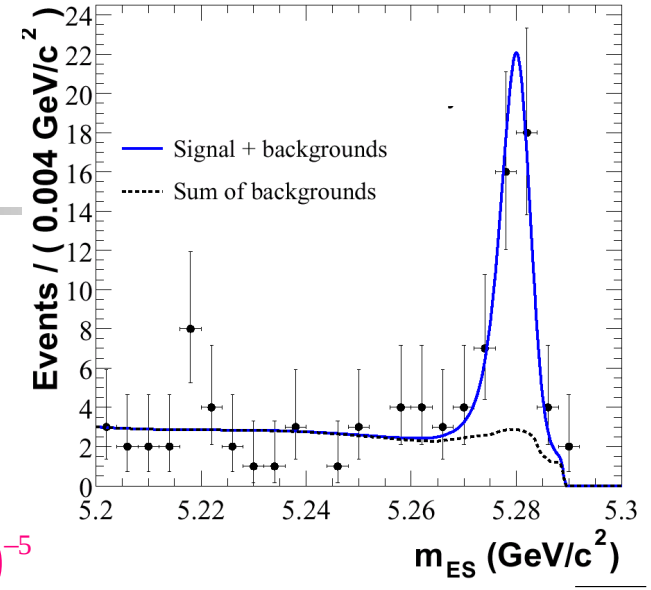
$C^{+-} = -0.22 \pm 0.37 \pm 0.10$

$S^{-+} = -0.82 \pm 0.75 \pm 0.14$

$C^{-+} = -0.47 \pm 0.40 \pm 0.12$

40±7 events

$B^0 \to J/\psi\, \pi^0$

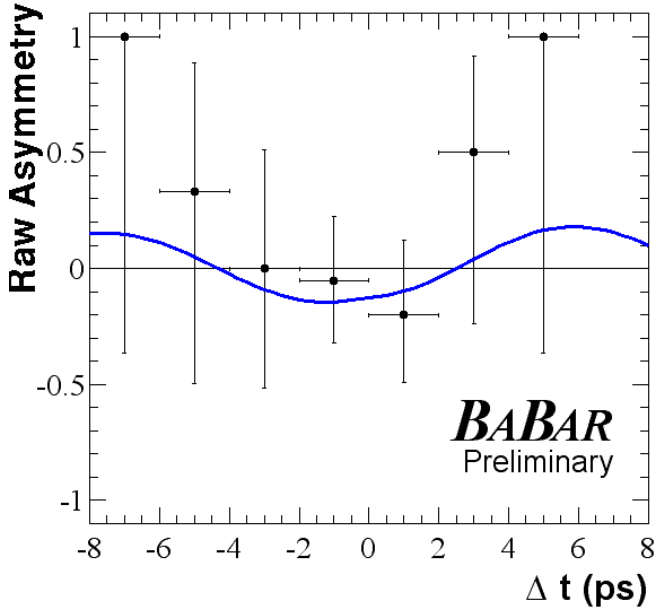


If no penguins we would measure S=-sin2β

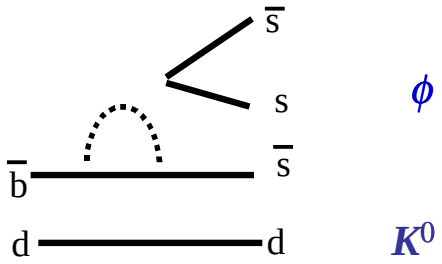
$$BR(B \to J/\psi\pi^0) = (2.0 \pm 0.6 \pm 0.2) \times 10^{-5}$$

$$S_{J/\psi\pi^0} = 0.05 \pm 0.49(stat) \pm 0.16(syst)$$

$$C_{J/\psi\pi^0} = 0.38 \pm 0.41(stat) \pm 0.09(syst)$$

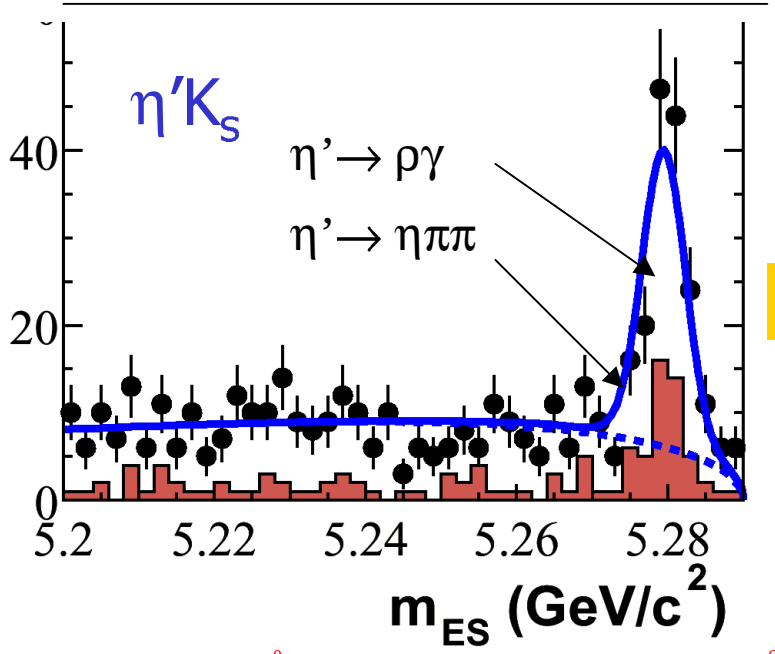


sin2β in $b \to s s \bar{s}$



ϕK^0 and $\eta^{(\prime)} K^0$

Only penguin. In principle measures sin2b, but sensitive to new physics



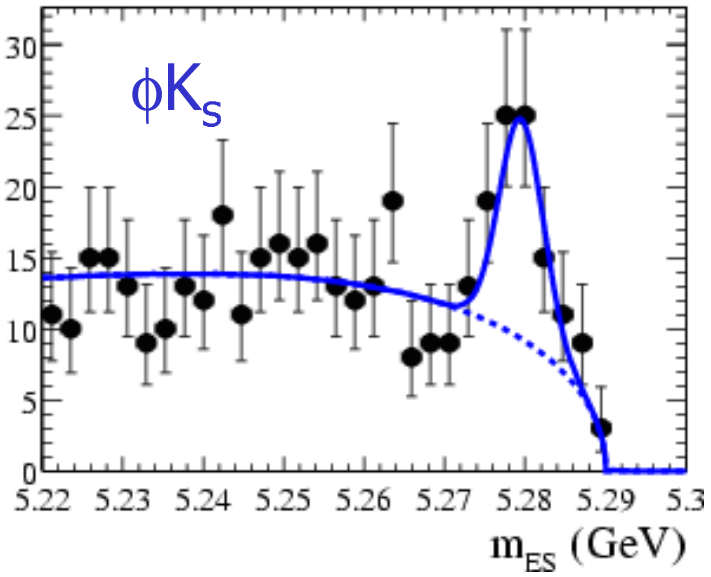
$BR(B \to \eta' K^0) = (76.9 \pm 5.2 \pm 4.0) \times 10^{-6}$

Penguin dominated (quark composition unknown)

-S= 0.02±0.34±0.03=sin2β in SM (no Tree)

N.B. Charmonium modes:

0.741 ± 0.067

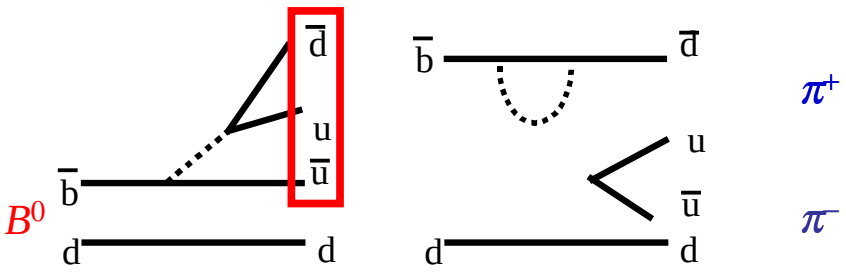


-S=-0.19±0.52±0.09 =sin2β in SM

Assuming $|\lambda|=1$

$BR(B \to \varphi K^0) = (8.1^{+3.1}_{-2.5} \pm 0.8) \times 10^{-6}$

sin2α in $b \to u\bar{d}\bar{d}$



$\pi^+\pi^-$, $\rho^+\pi^-$, $\pi^+\pi^-\pi^0$

Penguin and tree have different weak phases: asymmetry measures $\sin 2\alpha_{eff}$

$\sin 2\alpha_{eff}$ from $B \to \pi\pi$

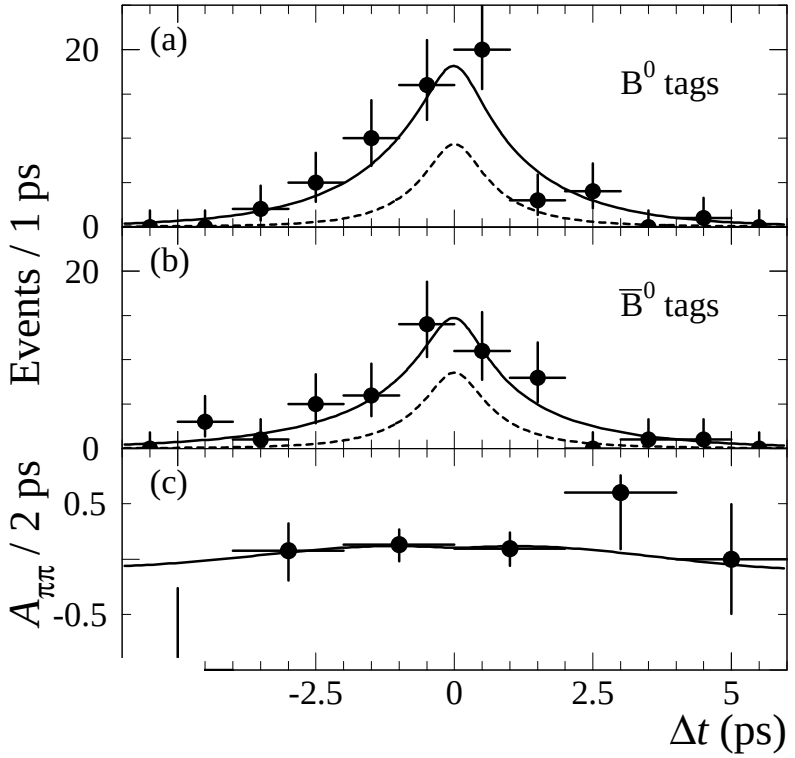
- Analysis proceeds in two steps:
  - Time-independent fit for yields and $K\pi$ charge asymmetry (see talk from S. Laplace)
  - Time-dependent fit for S, and C

$$S = 0.02 \pm 0.34 \pm 0.05$$

$$C = -0.30 \pm 0.25 \pm 0.04$$

$$S = \frac{2\,|\lambda|\sin 2\alpha_{eff}}{1 + |\lambda|^2}$$

$$C = \frac{1 - |\lambda|^2}{1 + |\lambda|^2}$$



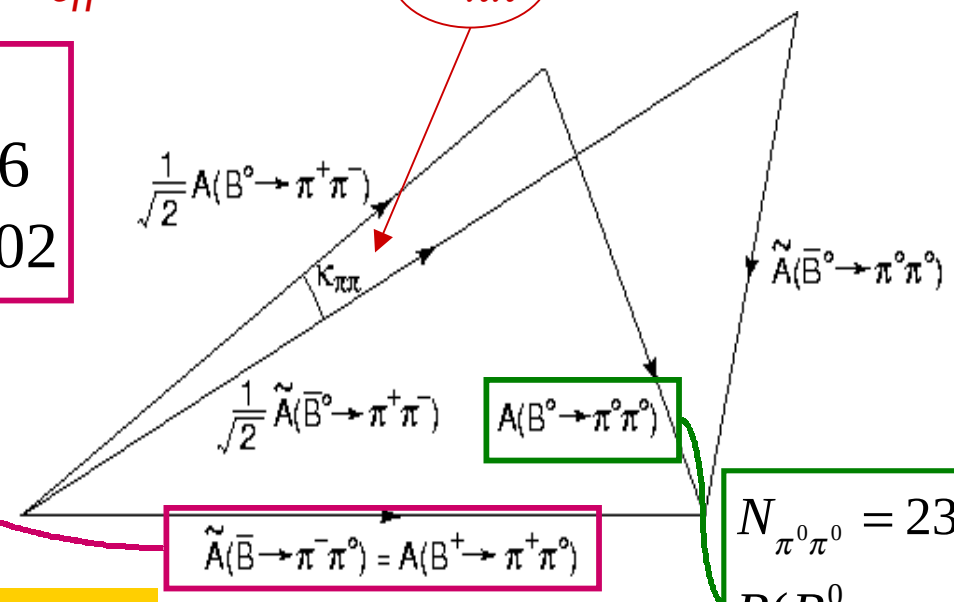
Taming the Penguins: Isospin Triangle

Triangle relations allow determination of penguin-induced shift in α (see talk from S. Laplace)

$$2\alpha_{eff} = 2\alpha + \kappa_{\pi\pi}$$

$Br(B\to\pi\pi^0)10^6 = 5.5^{+1.0}_{-0.9} \pm 0.6$

$A_{CP} = -0.03^{+0.18}_{-0.17} \pm 0.02$



$N_{\pi^0\pi^0} = 23^{+10}_{-9}$

$B(B^0\to\pi^0\pi^0) < 3.6\times10^{-6}$ @ 90% C.L.

$|\alpha_{eff} - \alpha| < 51^\circ$ @ 90% C.L.

CP-Violating Asymmetries in $B^0 \to \rho^+\pi^-, \rho^+K^-$

- Much more difficult than $\pi^+\pi^-$
  - Three-body topology with neutral pion (combinatorics, lower efficiency)
  - Significant fraction of misreconstructed signal events and backgrounds from other B decays
  - Need much larger sample than currently available to extract α cleanly
- We perform a "quasi-two-body" analysis:
  - Select the ρ-dominated region of the $\pi^+\pi^-\pi^0/K^+\pi^-\pi^0$ Dalitz plane
  - Use multivariate techniques to suppress qq backgrounds
  - Simultaneous fit for $\rho^+\pi^-$ and ρ^+K^-

$B^0 \to \rho\pi$ time-dependent asymmetry

Yields: $N_{\rho\pi} = 413^{+34}_{-33}$

$N_{\rho K} = 147^{+22}_{-21}$

hep-ex/0207068

$$\frac{C^{+-} + C^{-+}}{2} = 0.45^{+0.18}_{-0.19}(stat) \pm 0.09(syst)$$

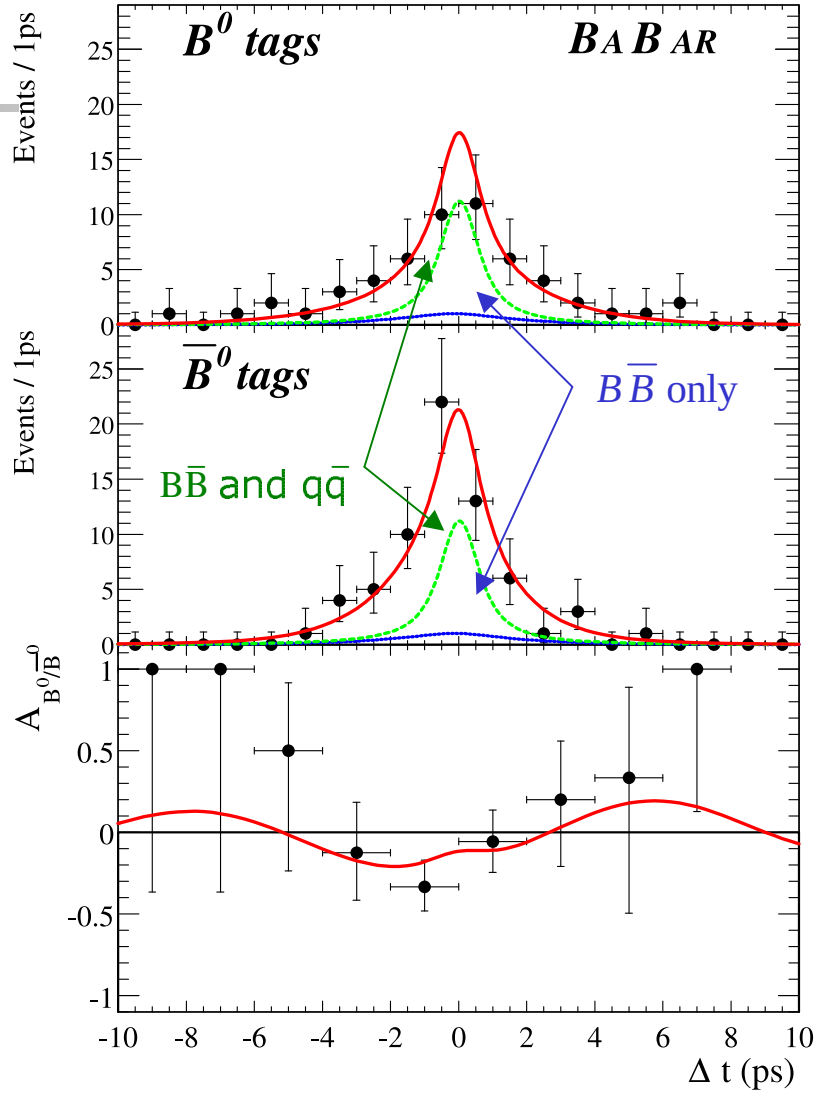
$$\frac{S^{+-} + S^{-+}}{2} = 0.16^{+0.25}_{-0.25}(stat) \pm 0.07(syst)$$

Preliminary

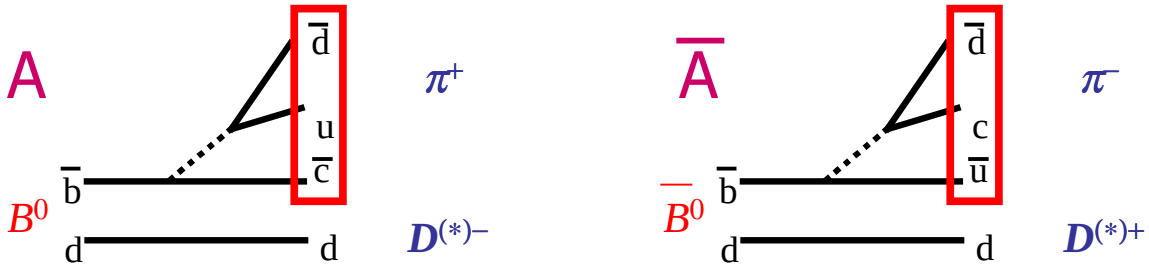
$$\frac{C^{+-} - C^{-+}}{2} = 0.38^{+0.19}_{-0.20}(stat) \pm 0.11(syst)$$

$$\frac{S^{+-} - S^{-+}}{2} = 0.15^{+0.25}_{-0.25}(stat) \pm 0.05(syst)$$

Systematic error dominated by uncertainty on B backgrounds



sin2β+γ in b→cd̄d



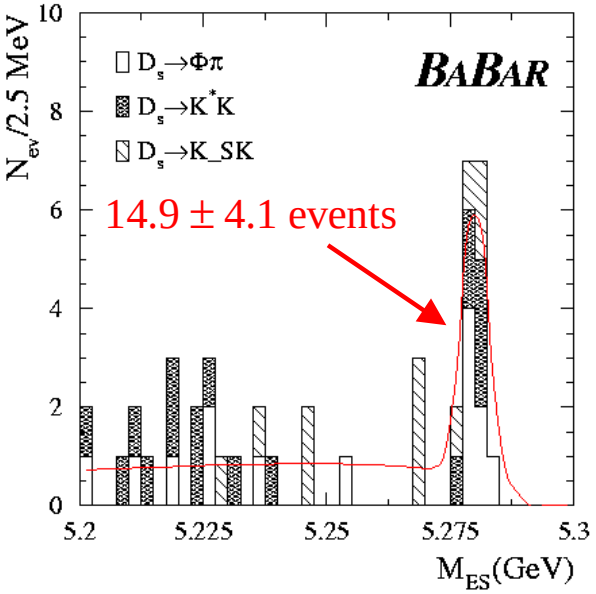
$$\lambda = \frac{\overline{A}}{A} e^{-i2\beta} = |\lambda| e^{-2i(\beta+\gamma)}$$

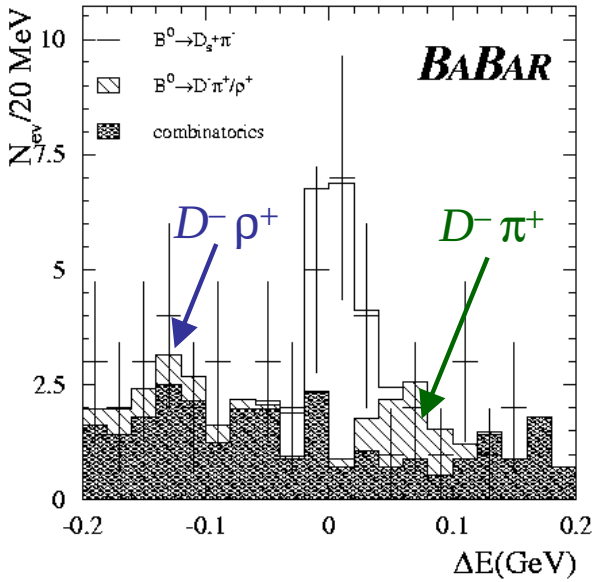
Ready to measure on run1+run2

|λ| already determined @ 30% level from

$$\mathbf{BF}\,(B^0 \to D_s^+ \pi^-) \approx \frac{\mathbf{BF}\,(\bar{B}^0 \to D^- \pi^+)}{\tan^2\theta_C} \left(\frac{f_{Ds}^2}{f_D^2} \right) \times \lambda^2_{D\pi}$$

$B^0 \to D_s^+ \pi^-$ yield





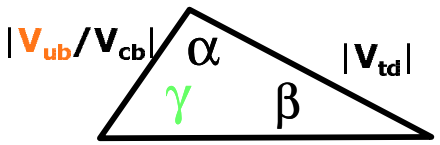
Evidence of reflected $D_s^+ \leftrightarrow D^+$ background

- Systematic error mostly from uncertainty on BF of secondary decays, peaking background uncertainty, selection criteria

significance of the signal = 3.5 σ

$$BF(B^0 \to D_s^+ \pi^-)^{(*)} = (3.1 \pm 1.0 \pm 1.0) \times 10^{-5}$$
$$BF(B^0 \to D_s^+ \pi^-) \times BF(D_s^+ \to \phi \pi^+) = (1.11 \pm 0.37 \pm 0.24) \times 10^{-6}$$

(*) 25% uncertainty from PDG $BF(D_s^+ \to \phi \pi^+)$



$|\lambda| \sim 0.020 \pm 0.005(\text{stat.+sys.}) \pm 0.007\ (\text{th.})$

Sum…

- Starting to measure direct CPV and sin2α_{eff} in b→uud transitions

$B^0 \to \rho\pi$

$$\frac{C^{+-} + C^{-+}}{2} = 0.45^{+0.18}_{-0.19}(stat) \pm 0.09(syst)$$

$$\frac{S^{+-} + S^{-+}}{2} = 0.16^{+0.25}_{-0.25}(stat) \pm 0.07(syst)$$

$B^0 \to \pi\pi$

$$C = -0.30 \pm 0.25 \pm 0.04$$

$$S = 0.02 \pm 0.34 \pm 0.05$$

- If it weren't for penguins **$\sigma(\sin 2\alpha) \sim 0.2$** → isospin triangle desperately needed: so far

$$|\alpha_{\text{eff}} - \alpha| < 51^\circ \ @ \ 90\% \text{ C.L.}$$

...mary

- sin2β starts to be measured in a lot of different environments
- Ignoring penguins, within the SM →
- Hints for interesting developments?