Study of CP Violation at BABAR

Roland Waldi, Univ. Rostock

- Introduction
- Direct CP Violation in B Decay
- The Easy Part: β
- Additional Information: β'
-     and α…
- Summary and Outlook

CP Violation

= asymmetry
between particles and anti-particles (**C**)
when summed over left and right

since P-violation of weak interaction
has opposite sign for particles and anti-particles

use CP instead of C for left/right individually

CP Violation: History

1964 CP Violation in K^0 Observed (Cronin, Fitch…)

1973 Quark Mixing Matrix $\Rightarrow$ CPV (Kobayashi, Maskawa)

1987 $B^0\bar{B}^0$ Oscillation Observed (ARGUS)

1988 Era of B Factory Proposals, Using $\Upsilon(4S) \to B\bar{B}$

Europe:	BETA @ PSI
	ISR-B @ CERN
	Helena @ DESY
USA:	CESR-B @ Cornell
	PEP-2 @ SLAC
Japan:	**KEK-B @ KEK**

1999 B Factories (PEP-2, KEK-B) Start Operation

2001 CPV in B^0 Observed (BABAR, BELLE)

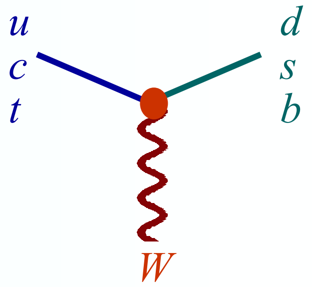
2004 Direct CPV in B^0 Observed (BABAR, BELLE)

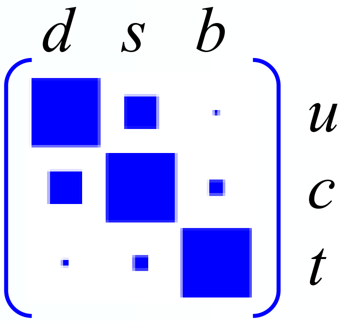
CP Violation

in the Standard Model:

CP-violation = **interference**

due to
the **unitary**
Cabibbo-Kobayashi-Maskawa matrix **V**



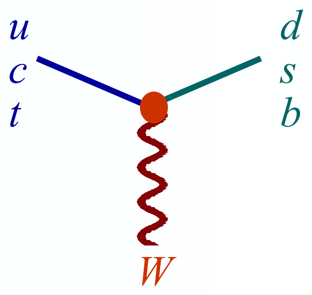


CP Violation

in the Standard Model:

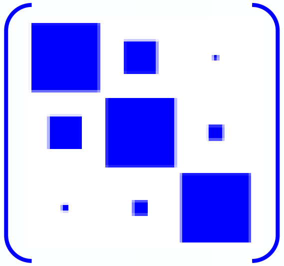
CP-violation = **interference**

due to **one** non-trivial phase in the **unitary** Cabibbo-Kobayashi-Maskawa matrix $\mathbf{V}$



with standard choice of 5 trivial phases:

$$\mathbf{V} = \begin{pmatrix} |V_{ud}| & |V_{us}| & |V_{ub}|e^{-i\tilde{\gamma}} \\ -|V_{cd}|e^{i\phi_4} & |V_{cs}|e^{-i\phi_6} & |V_{cb}| \\ |V_{td}|e^{-i\tilde{\beta}} & -|V_{ts}|e^{i\phi_2} & |V_{tb}| \end{pmatrix} =$$



Another Choice of Phases

$$\begin{pmatrix} |V_{ud}| & |V_{us}| & |V_{ub}|e^{-i\tilde{\gamma}} \\ -|V_{cd}|e^{i\phi_4} & |V_{cs}|e^{-i\phi_6} & |V_{cb}| \\ |V_{td}|e^{-i\tilde{\beta}} & -|V_{ts}|e^{i\phi_2} & |V_{tb}| \end{pmatrix}$$

$\phi_n \approx \eta\lambda^n$ are small phases

free choice of 5 more arbitrary phases

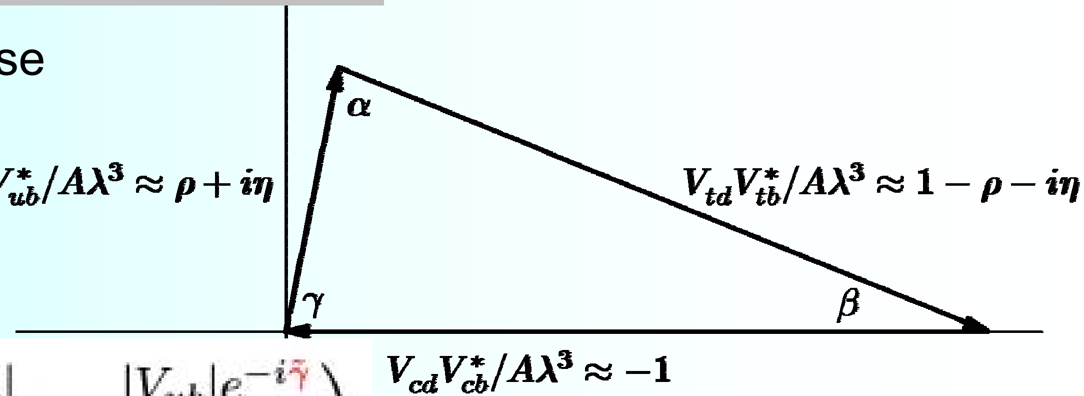
example:

$$\begin{pmatrix} -|V_{ud}|e^{-i(\pi \overbrace{-\tilde{\beta}-\tilde{\gamma}}^{\alpha})} & |V_{us}|e^{i\tilde{\gamma}} & |V_{ub}| \\ -|V_{cd}|e^{i(\phi_4+\tilde{\beta})} & |V_{cs}|e^{-i\phi_6} & |V_{cb}| \\ |V_{td}| & -|V_{ts}|e^{i\phi_2} & |V_{tb}| \end{pmatrix}$$

Two (of 6) Unitarity Triangles

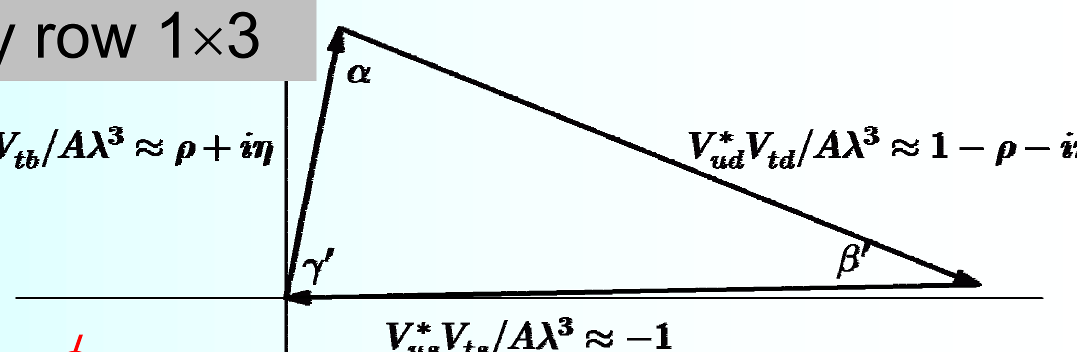
CKM matrix unitarity column 1×3

shape independent of phase convention $\Rightarrow$ **sides** and **angles** are **observables**



$$\mathbf{V} = \begin{pmatrix} |V_{ud}| & |V_{us}| & |V_{ub}|e^{-i\tilde{\gamma}} \\ -|V_{cd}|e^{i\phi_4} & |V_{cs}|e^{-i\phi_6} & |V_{cb}| \\ |V_{td}|e^{-i\tilde{\beta}} & -|V_{ts}|e^{i\phi_2} & |V_{tb}| \end{pmatrix}$$

CKM matrix unitarity row 1×3

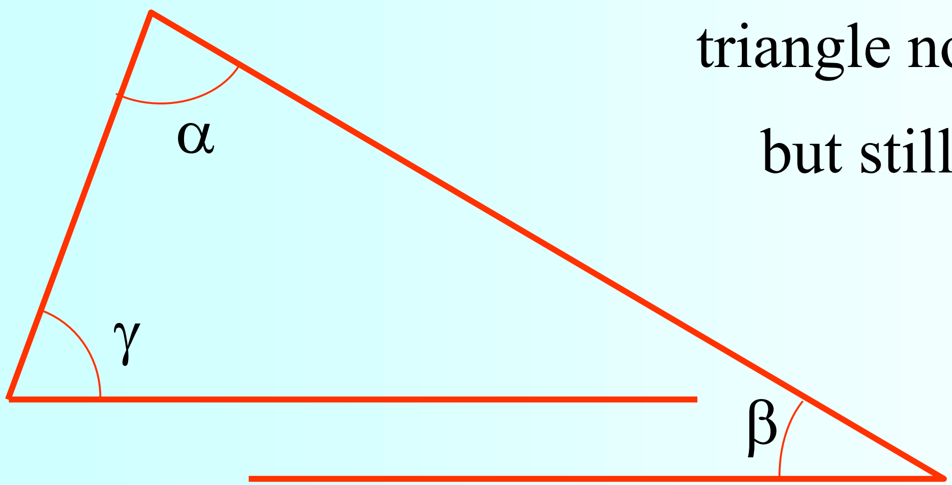


$$\beta = \tilde{\beta} + \phi_4$$

$$\gamma = \tilde{\gamma} - \phi_4$$

$$\delta\gamma = \gamma - \gamma' = \beta' - \beta \approx \phi_2$$

if CKM Matrix **not** Unitary



triangle not closed

but still $\alpha+\beta+\gamma = 180°$

if $\alpha+\beta+\gamma \neq 180°$ we have additional amplitudes,
i.e. we have not measured the angle in the triangle

…which can also be found by measuring one angle in two different channels!

Hunt for New Physics

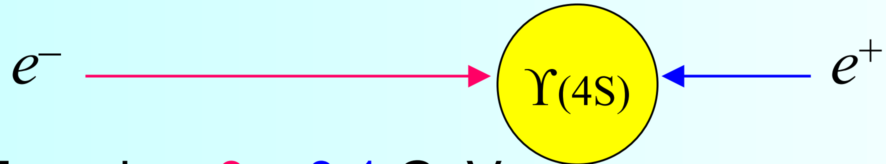
- measure $\alpha, \beta(\beta'), \gamma(\gamma')$ in different modes and look out for discrepancies
- favoured candidates: loop-dominated decays (penguins)

PEP-2 / BABAR

Collaboration:
ca. 550 physicists from
10 Nations

- Canada
- China
- Germany
- France
- Great Britain
- Italy
- Netherlands
- Norway
- Russia
- USA

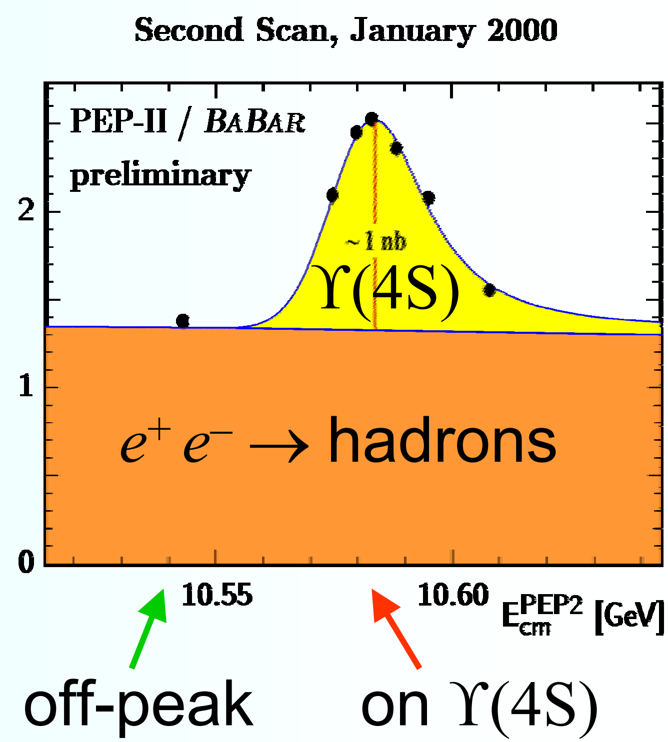
Asymmetric B Factory PEP II



Energies: 9 + 3.1 GeV

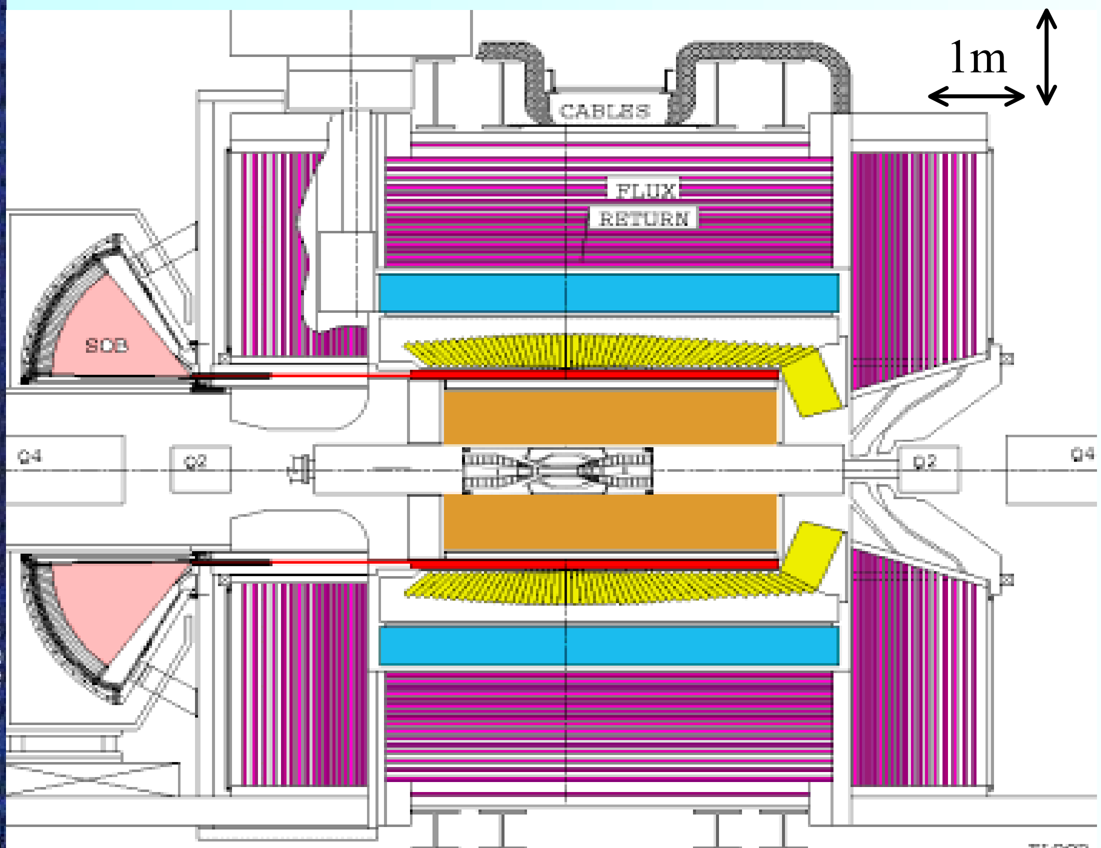
velocity: $\beta\gamma$=0.55

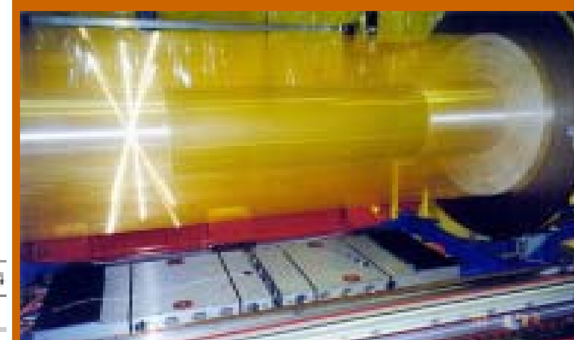
$\Upsilon(4S) \rightarrow B\bar{B}$



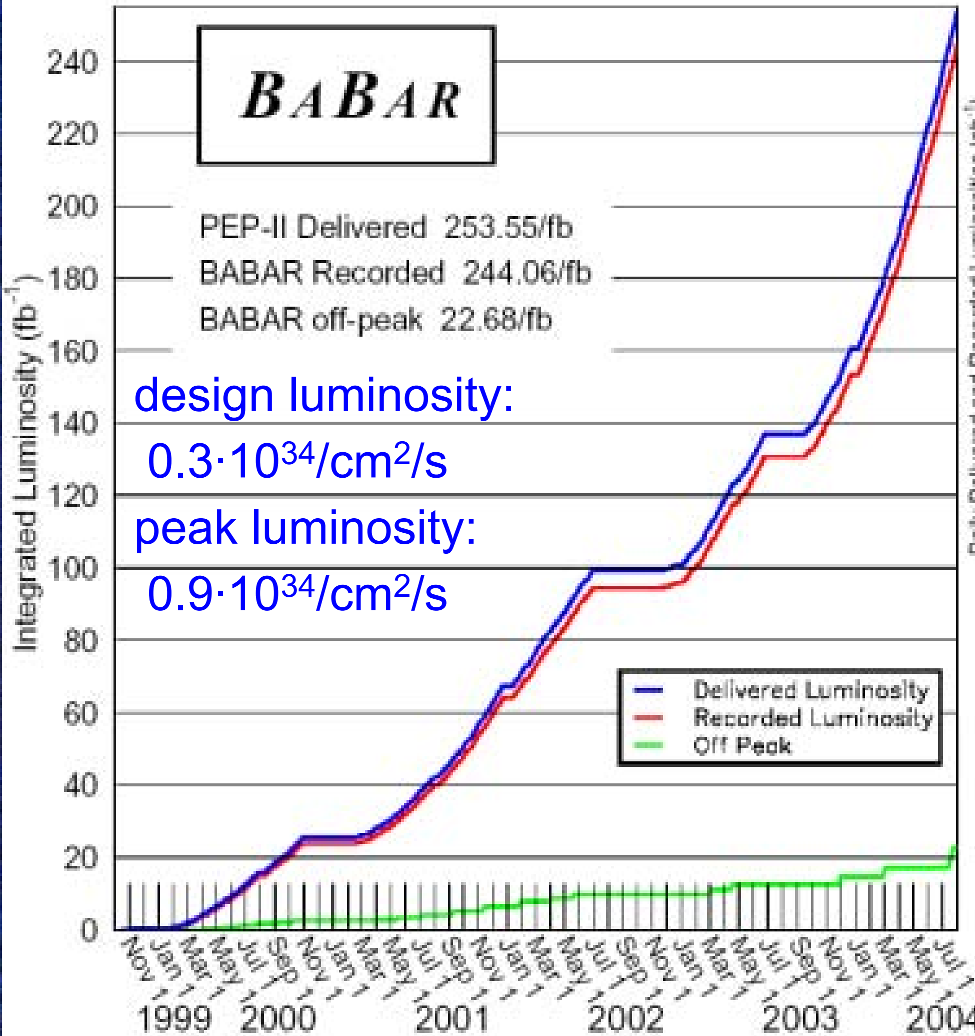
BABAR Detector

Iron Yoke + RPCs/LSTs, Superconducting Coil
DIRC (Cherenkov), CsI-Calorimeter
Drift Chamber, Si Vertex-Tracker

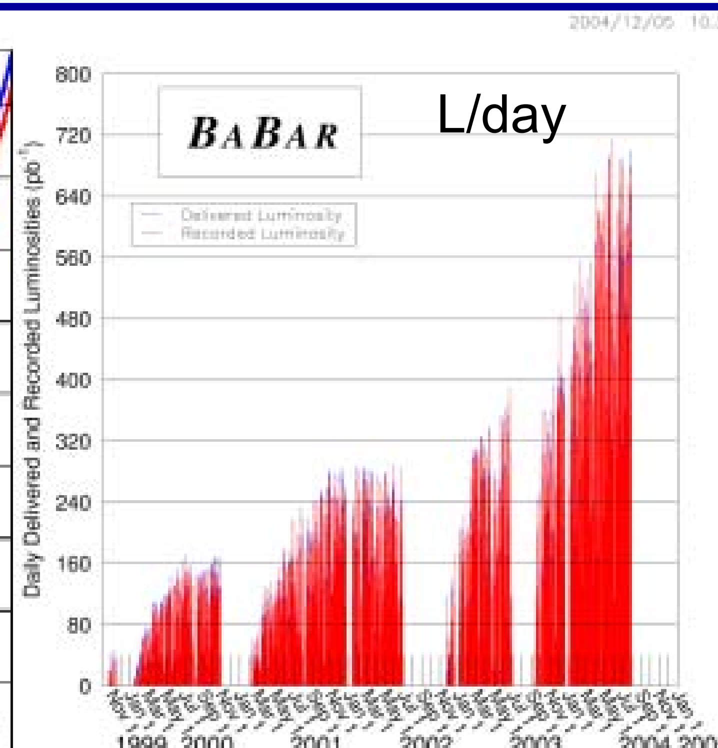




Data Sample



design luminosity:
$0.3 \cdot 10^{34}/\mathrm{cm}^2/\mathrm{s}$
peak luminosity:
$0.9 \cdot 10^{34}/\mathrm{cm}^2/\mathrm{s}$



245 million $B\bar{B}$ pairs
(1000×ARGUS)

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Direct CP Violation: 2 Interfering Amplitudes

$$A(B^0 \to X) = |A_1|e^{i\phi_1 + i\delta_1} + |A_2|e^{i\phi_2 + i\delta_2}$$
$$\bar{A}(\bar{B}^0 \to \bar{X}) = |A_1|e^{-i\phi_1 + i\delta_1} + |A_2|e^{-i\phi_2 + i\delta_2}$$

under CP: $\delta \to \delta$ and $\phi \to -\phi$

$$|A|^2 = |A_1|^2 + |A_2|^2 + |A_1||A_2|\cos(\phi_1 - \phi_2 + \delta_1 - \delta_2)$$
$$|\bar{A}|^2 = |A_1|^2 + |A_2|^2 + |A_1||A_2|\cos(\phi_2 - \phi_1 + \delta_1 - \delta_2)$$
$$|\bar{A}|^2 - |A|^2 = |A_1||A_2|\sin(\phi_1 - \phi_2)\sin(\delta_1 - \delta_2)$$

Asymmetry

$$a = \frac{\mathcal{B}(\bar{B} \to \bar{X}) - \mathcal{B}(B \to X)}{\mathcal{B}(\bar{B} \to \bar{X}) + \mathcal{B}(B \to X)}$$

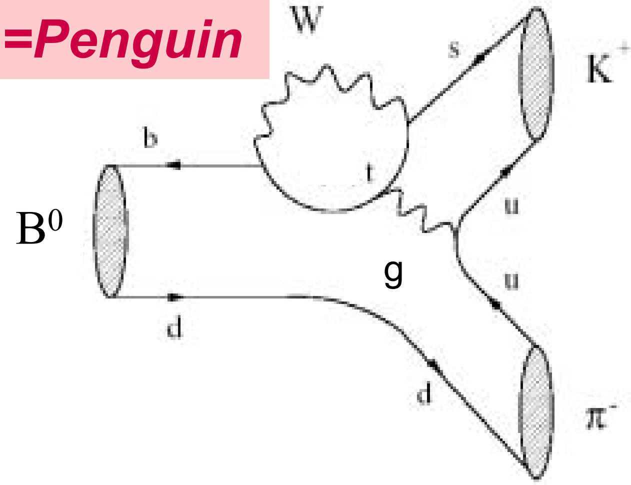
Direct CP Violation: B $\rightarrow$ K$^{+}\pi^{-}$

Asymmetry $\quad a = \dfrac{n_{\overline{B}} - n_B}{n_{\overline{B}} + n_B}$

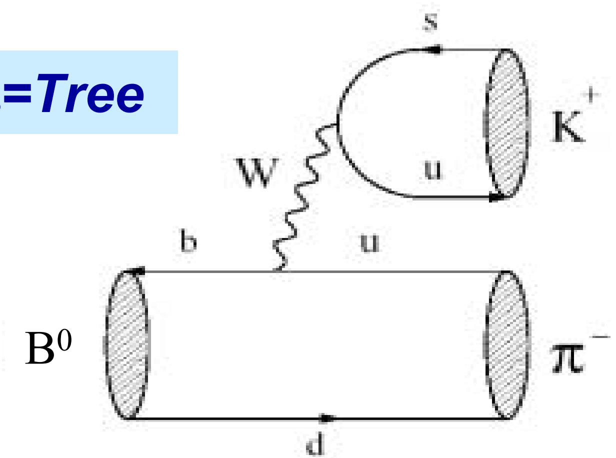
$a \propto \sin(\phi_1 - \phi_2)\,\sin(\delta_1 - \delta_2)$

$\phi_1 - \phi_2 = \gamma'$

A_1=Penguin

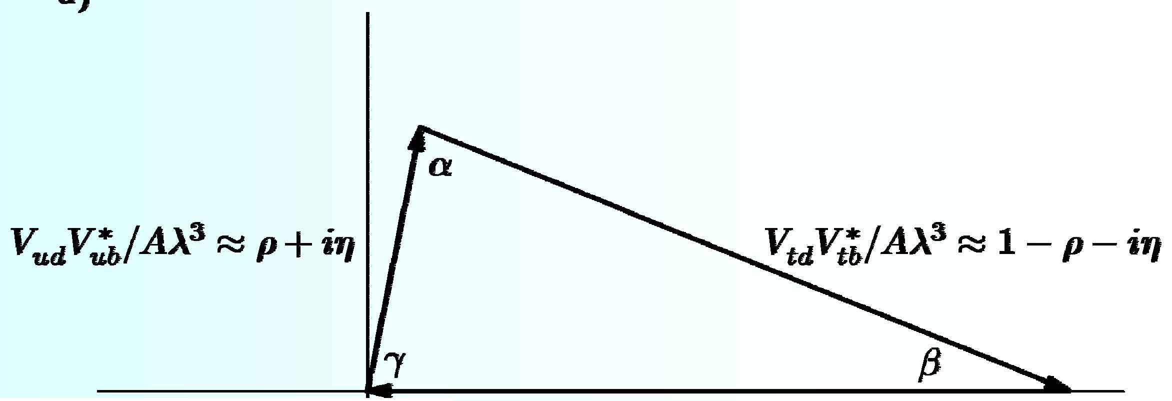


A_2=Tree

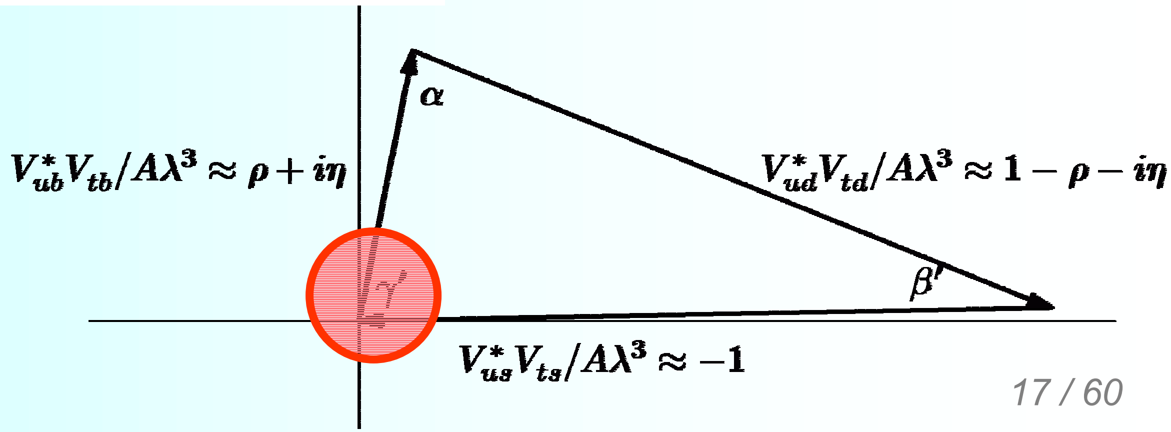


Unitarity Triangles

a)



$$\mathbf{V} = \begin{pmatrix} |V_{ud}| & |V_{us}| & |V_{ub}|e^{-i\tilde{\gamma}} \\ -|V_{cd}|e^{i\phi_4} & |V_{cs}|e^{-i\phi_6} & |V_{cb}| \\ |V_{td}|e^{-i\tilde{\beta}} & -|V_{ts}|e^{i\phi_2} & |V_{tb}| \end{pmatrix}$$



$$\gamma' = \tilde{\gamma} - \phi_2$$

$$\delta\gamma = \gamma - \gamma' \approx \phi_2$$

Direct CP Violation: $B \to K^+\pi^-$

Asymmetry $$a = \frac{n_{\overline{B}} - n_B}{n_{\overline{B}} + n_B}$$

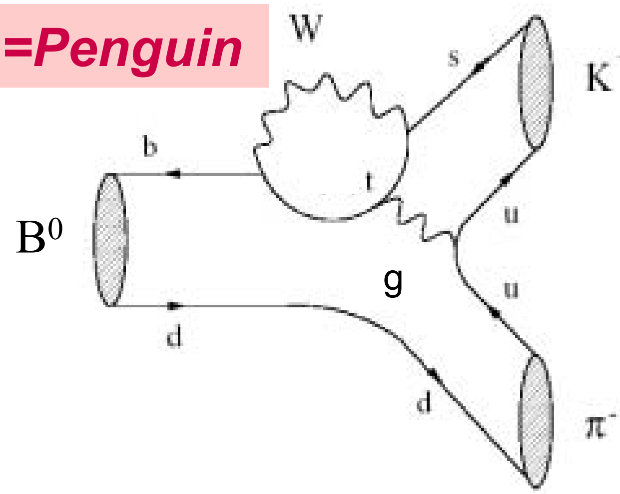
$a \propto \sin(\phi_1 - \phi_2)\sin(\delta_1 - \delta_2)$

$\phi_1 - \phi_2 = \gamma'$

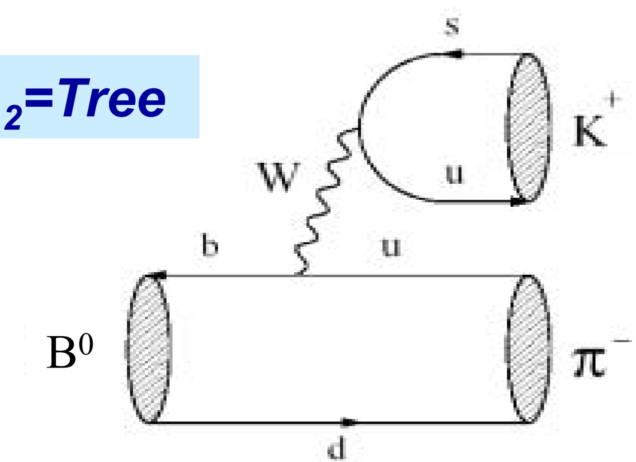
$\delta_1 - \delta_2 = ???$

$|A_1| / |A_2| = ?$

A_1=Penguin



A_2=Tree



Signal Event Selection

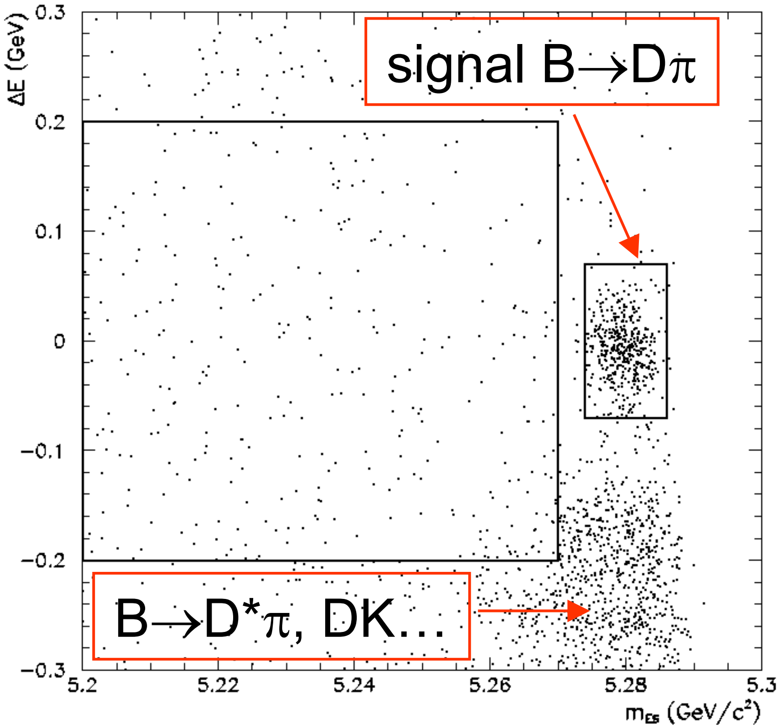
b-jet:
1 constraint = B-mass

Υ(4S):
2 constraints = E_B and p_B

in **cms**

$$\Delta E \equiv \boxed{(E_D + E_\pi)} - E_{beam}$$

example



B candidate

$$m_{ES} = \sqrt{E_{beam}^2 - \boxed{(\vec{p}_D + \vec{p}_\pi)}^2}$$

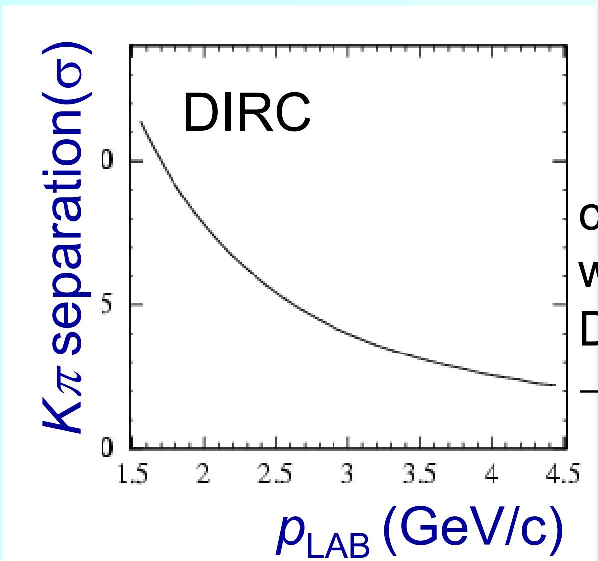
Data Analysis of $K^+\pi^-$

Maximum Likelihood Fit determines yields $n_{\pi\pi}$, $n_{K\pi}$, n_{KK}, and asymmetries $a_{K\pi}$ and a(bgrd) simultaneously:

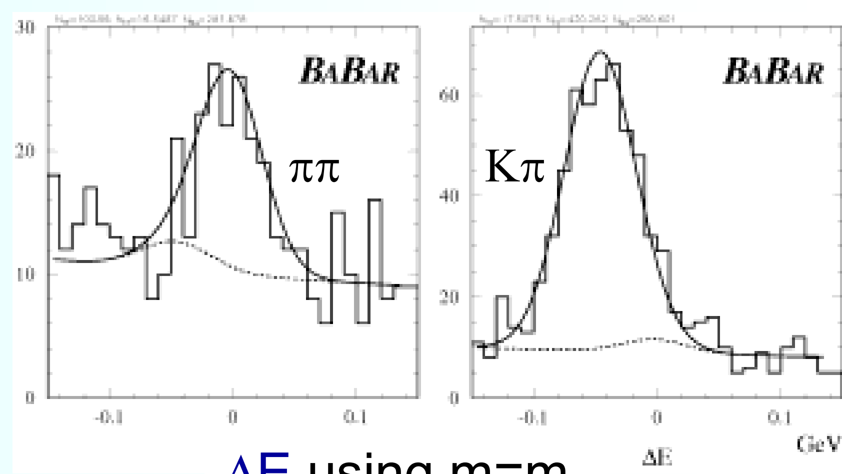
- Event shape (Fisher discr.)
- *B* mass m_{ES}
- *B* energy (ΔE)
- Particle ID ($\theta_{\check{C}}$)

separate signal from $q\bar{q}$ background

separate K from π



calibrated with $D^{*+} \to D^0\pi^+ \to (K^-\pi^+)\pi^+$



ΔE using $m=m_\pi$

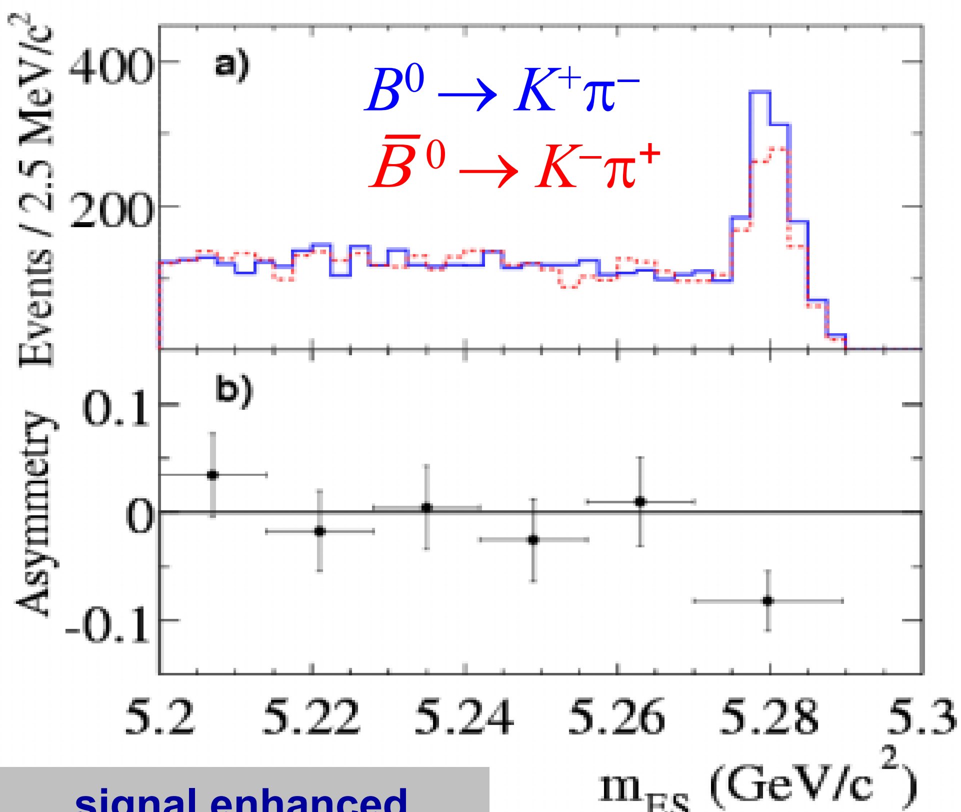
First Observation of Direct CP Violation in B decay

fit

$$a = \frac{n_{\overline{B}} - n_B}{n_{\overline{B}} + n_B} = -0.133 \pm 0.030 \pm 0.009$$

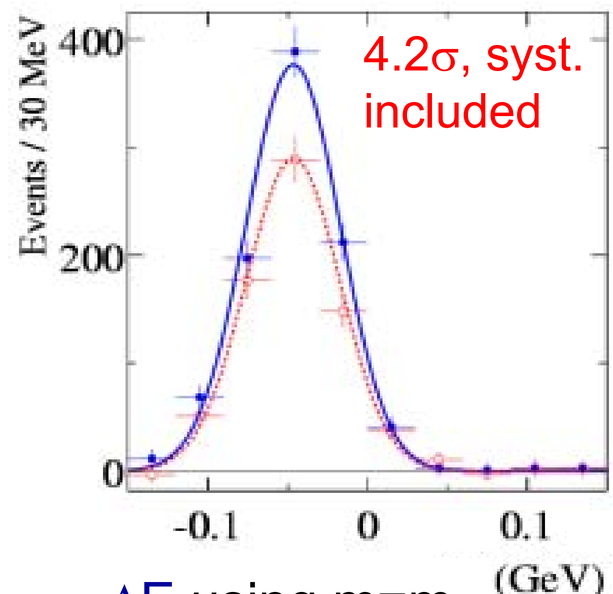
$$n\left(B^0 \to K^+\pi^-\right) = 910$$

$$n\left(\overline{B}^0 \to K^-\pi^+\right) = 696$$



signal enhanced

"sPlot" = signal fraction fit



ΔE using $m=m_\pi$

Systematics for $B \to K^+\pi^-$

Asymmetries consistent

- in different K momentum ranges
- in different running periods
- when including decay time

Source	Sys. Error
Signal Fisher PDF	0.001
DIRC θ_c PDF	0.001
Potential MC bias	0.003
Potential charge bias	0.008
Total	0.009

BABAR:

$a = -0.133 \pm 0.030 \pm 0.009$

Belle:

$a = -0.101 \pm 0.025 \pm 0.005$

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Interference mixed/unmixed

$$
\begin{tikzcd}
B^0 \arrow[rr, bend left] \arrow[dr, bend right] & & f \\
& \overline{B}^0 \arrow[ur, bend right] &
\end{tikzcd}
$$

$$\lambda_f := \frac{\langle f|\mathcal{H}|\overline{B}^0\rangle}{\langle f|\mathcal{H}|B^0\rangle}\frac{\langle \overline{B}^0|B_L\rangle}{\langle B^0|B_L\rangle} = \frac{1-\epsilon_f}{1+\epsilon_f}$$

$$\frac{\overline{A}}{A}\cdot\frac{q}{p}$$

time-dependent asymmetries

CP-Asymmetry Example: B_s

$$a(T) = \left.\frac{\dot N(\bar B_s \to X) - \dot N(B_s \to X)}{\dot N(\bar B_s \to X) + \dot N(B_s \to X)}\right|_T = \frac{\Theta_0 \cos xT + \Lambda_0 \sin xT}{\cosh yT + \Omega_0 \sinh yT}$$

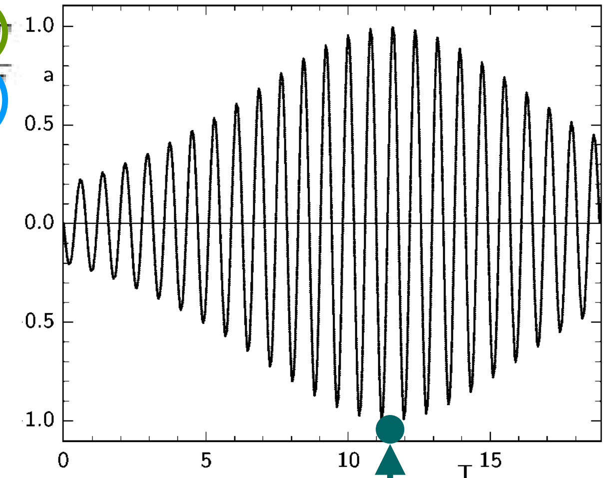
where

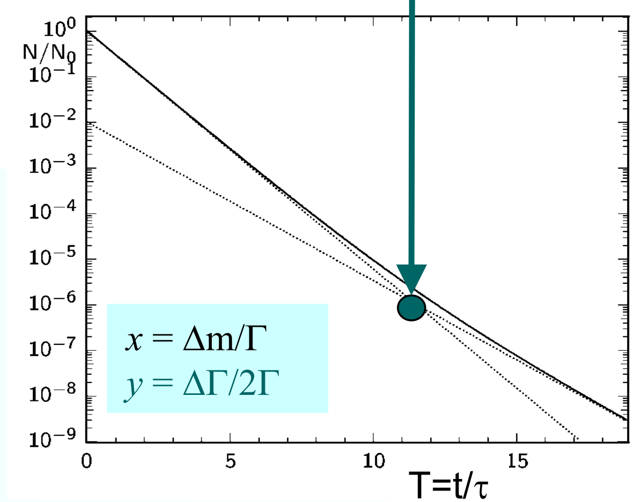
$$\Theta_0 = -\frac{2\,\mathcal{R}e\,\epsilon_f}{1+|\epsilon_f|^2} = \frac{|\lambda|^2-1}{|\lambda|^2+1}$$

$$\Lambda_0 = -\frac{2\,\mathcal{I}m\,\epsilon_f}{1+|\epsilon_f|^2} = \frac{2\,\mathcal{I}m\,\lambda}{1+|\lambda|^2} = D_P \sin\arg\lambda$$

$$\Omega_0 = \frac{1-|\epsilon_f|^2}{1+|\epsilon_f|^2} = \frac{2\,\mathcal{R}e\,\lambda}{1+|\lambda|^2} = D_P \cos\arg\lambda$$

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





$x = \Delta m/\Gamma$: $B\bar{B}$ oscillation frequency

$xT = \Delta m\, t$

$y = \Delta\Gamma/2\Gamma$: $B\bar{B}$ lifetime difference

$yT = (\Delta\Gamma/2)\, t$

CP-Asymmetry Example: $B^0 \to J/\psi\, K_S$

$$a(T) = \left.\frac{\dot{N}(\bar{B}_s \to X) - \dot{N}(B_s \to X)}{\dot{N}(\bar{B}_s \to X) + \dot{N}(B_s \to X)}\right|_T = \frac{\Theta_0 \cos xT + \Lambda_0 \sin xT}{\cosh yT + \Omega_0 \sinh yT}$$

time dependent asymmetry

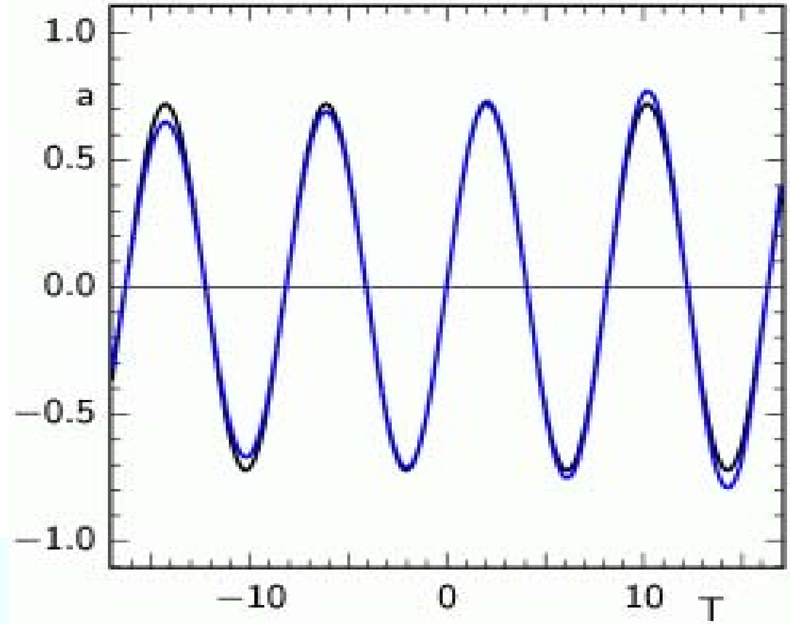
where $\boxed{\lambda = -e^{-2i\beta}}$

$$\Theta_0 = -\frac{2\,\mathcal{R}e\,\epsilon_f}{1+|\epsilon_f|^2} = \frac{|\lambda|^2 - 1}{|\lambda|^2 + 1} = 0$$

$$\Lambda_0 = -\frac{2\,\mathcal{I}m\,\epsilon_f}{1+|\epsilon_f|^2} = \frac{2\,\mathcal{I}m\,\lambda}{1+|\lambda|^2} = \sin 2\beta$$

$$\Omega_0 = \frac{1-|\epsilon_f|^2}{1+|\epsilon_f|^2} = \frac{2\,\mathcal{R}e\,\lambda}{1+|\lambda|^2} = -\cos 2\beta$$

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



$x = 0.77 \pm 0.01$

blue: $y = -0.01$

black: $y = 0$

BABAR 2004: $|y| < 0.08$

Theory: $-0.01 < y < 0.00$

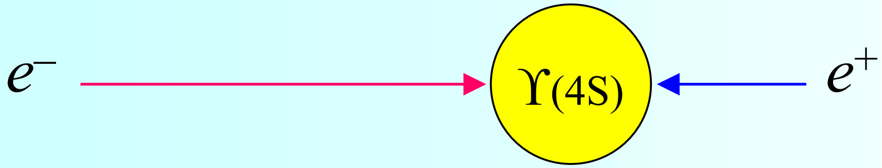
other conventions:

$\Lambda_0 = S$ sin coefficient

$\Theta_0 = A = -C$ cos coefficient

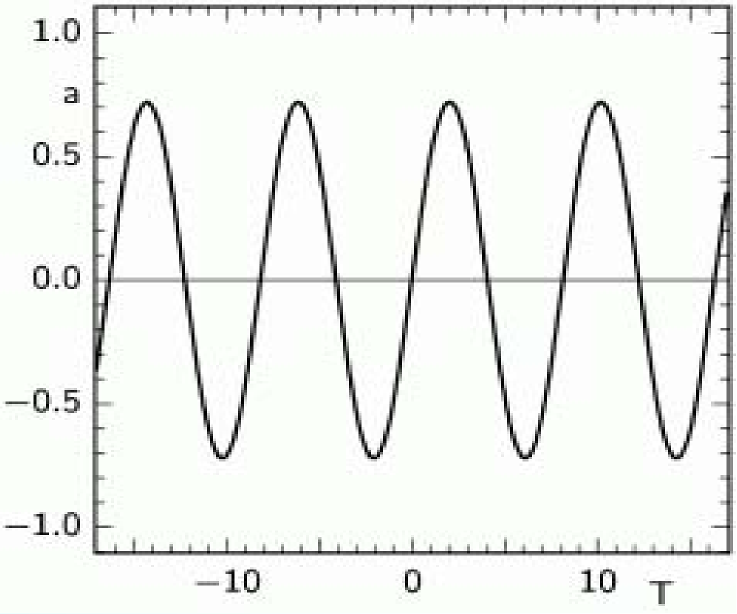
$B^0 \to J/\psi\, K_S$ at $\Upsilon(4S)$

CP-Asymmetry: $a(T) = \Lambda_0 \sin xT = \sin 2\beta \cdot \sin \Delta m \Delta t$

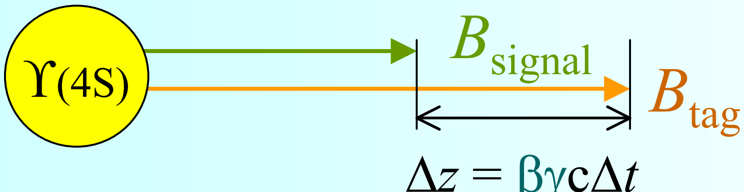


Energies: 9 + 3.1 GeV

velocity: $\beta\gamma=0.55$



$T = \Delta t / \tau$ at $\Upsilon(4S) \to BB$, $\Delta t = t_s - t_t$

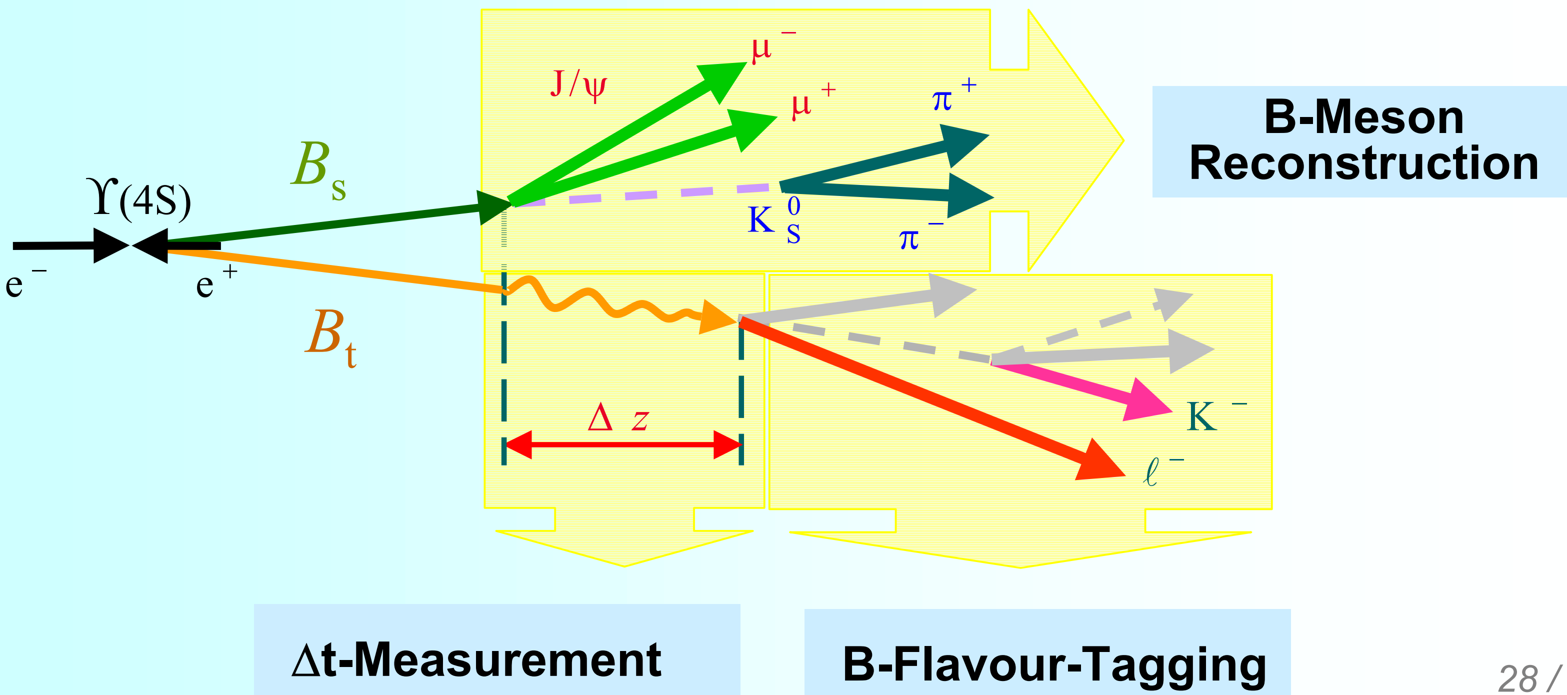


Signal-***B*****,** Lifetime t_s

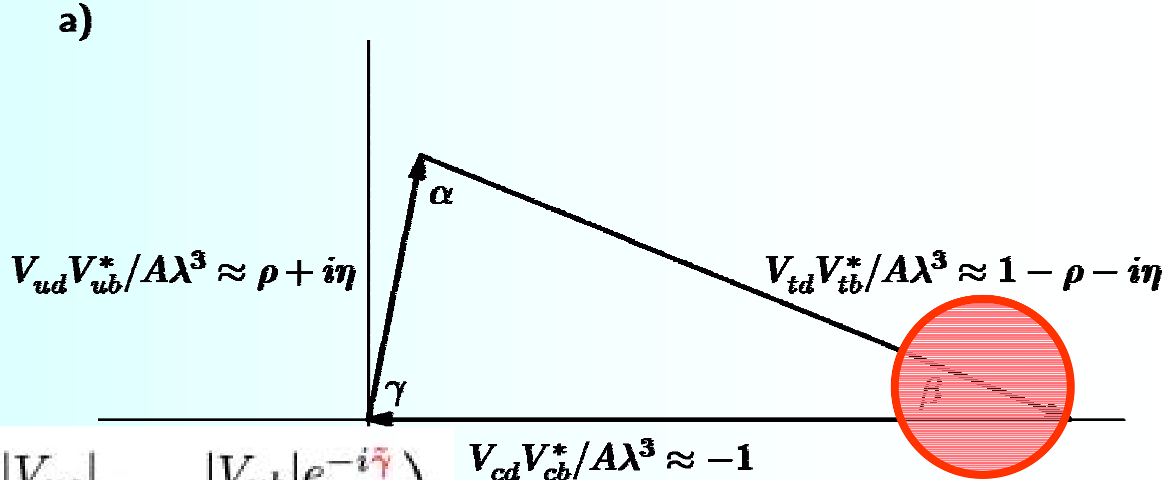
Tag-***B*****,** Lifetime t_t

Measurement of sin 2β at the ϒ(4S)

- measure decay rates $R_1(T)$, $R_2(T)$
- for B^0 or anti-B^0 at time $T = 0$
- calculate $a(T) = \dfrac{R_2(T) - R_1(T)}{R_2(T) + R_1(T)} = \Lambda_0 \sin xT$

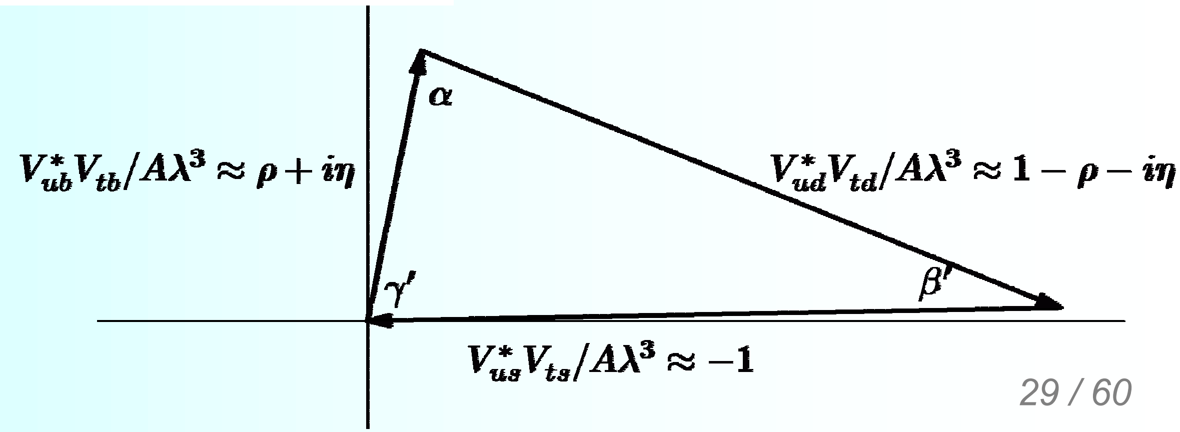


Unitarity Triangles: β



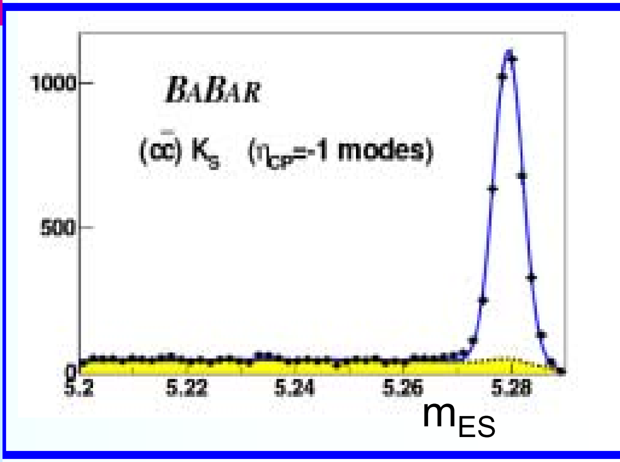
$$\mathbf{V} = \begin{pmatrix} |V_{ud}| & |V_{us}| & |V_{ub}|e^{-i\tilde{\gamma}} \\ -|V_{cd}|e^{i\phi_4} & |V_{cs}|e^{-i\phi_6} & |V_{cb}| \\ |V_{td}|e^{-i\tilde{\beta}} & -|V_{ts}|e^{i\phi_2} & |V_{tb}| \end{pmatrix}$$

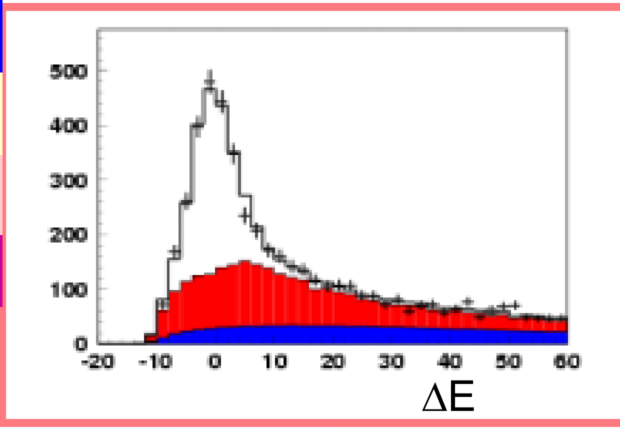
$$\beta = \tilde{\beta} + \phi_4$$



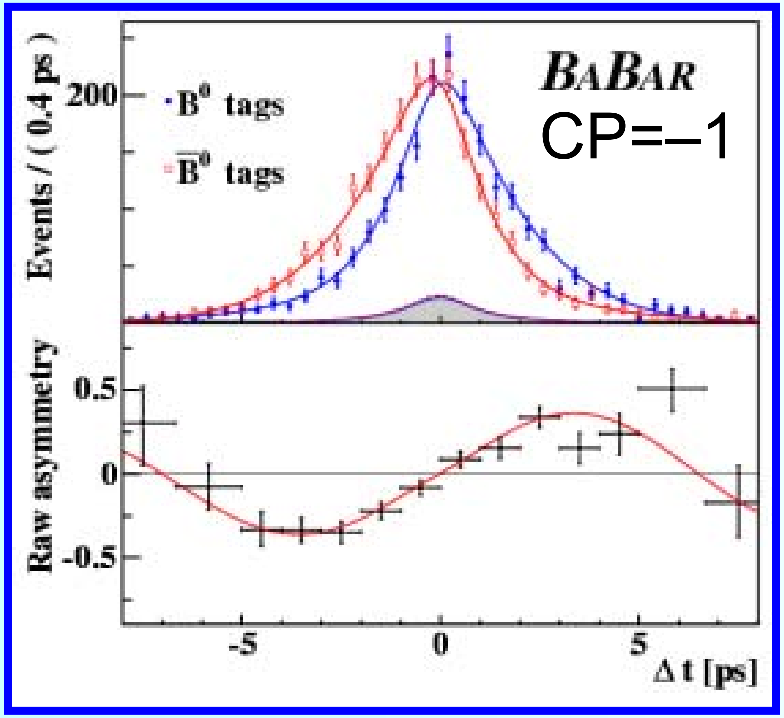
Tagged $(c\bar{c})K$ Decays

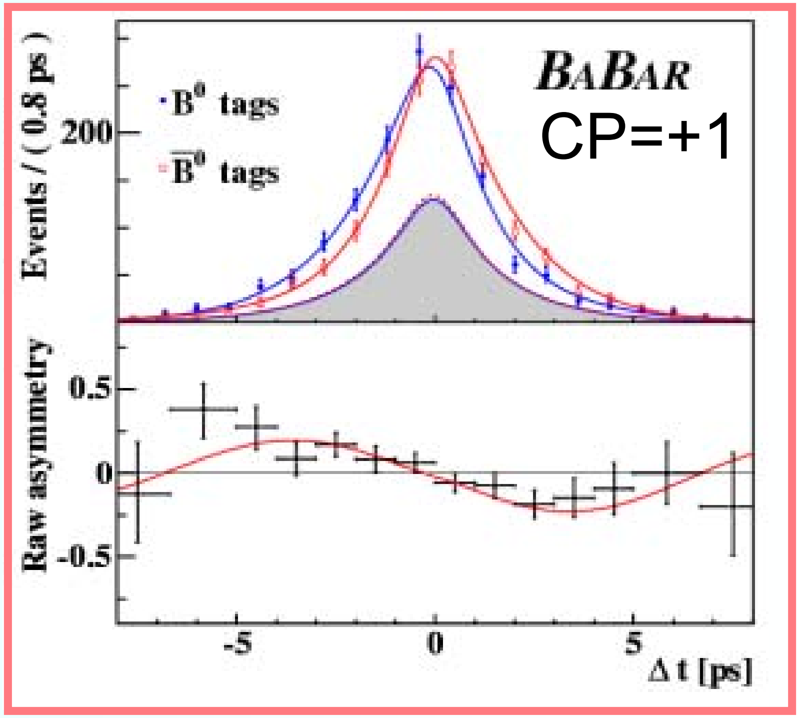
CP sample	N_{tag}	purity	CP
$J/\psi\ K_S\ (K_S \rightarrow \pi^+\pi^-)$	2751	96%	-1
$J/\psi\ K_S\ (K_S \rightarrow \pi^0\pi^0)$	653	88%	-1
$\psi(2S)\ K_S\ (\rightarrow \pi^+\pi^-)$	485	87%	-1
$\chi_{c1}\ K_S\ (K_S \rightarrow \pi^+\pi^-)$	194	85%	-1
$\eta_c\ K_S\ (K_S \rightarrow \pi^+\pi^-)$	287	74%	-1
Total CP=–1	**4370**	**92%**	**-1**
$J/\psi\ K^{*0}(K^{*0} \rightarrow K_S\pi^0)$	572	77%	+0.51
$J/\psi\ K_L$	2788	56%	+1
Total	**7730**	**78%**	





Results on sin2β from (cc̄)K





$$\pm\Lambda_0 = \sin 2\beta = 0.722 \pm 0.040 \pm 0.023$$

$$|\lambda| = 0.950 \pm 0.031 \pm 0.013$$

B $\rightarrow$ Vector-Vector

B: Spin 0

$\Rightarrow$ VV: L=S, $\Sigma\, S_z=0$

Clebsch-Gordan-Table:

		$L=$	0	1	2
		$L_z=$	0	0	0
A_{+1}	$S_z=$	+1,–1	1/3	1/2	1/6
A_0		0,0	–1/3	0	2/3
A_{-1}		–1,+1	1/3	–1/2	1/6
		CP =	**+1**	**–1**	**+1**

Amplitudes: “longitudinal”: A_0 (CP +)

“transversal”: A_{+1}, A_{-1}

or better: $A_{||} = A_{+1} + A_{-1}$ (CP +)

(“circular” $\rightarrow$ “linear” polarisation) $A_{\perp} = A_{+1} - A_{-1}$ (CP –)

Tagged $(c\bar{c})K$ Decays

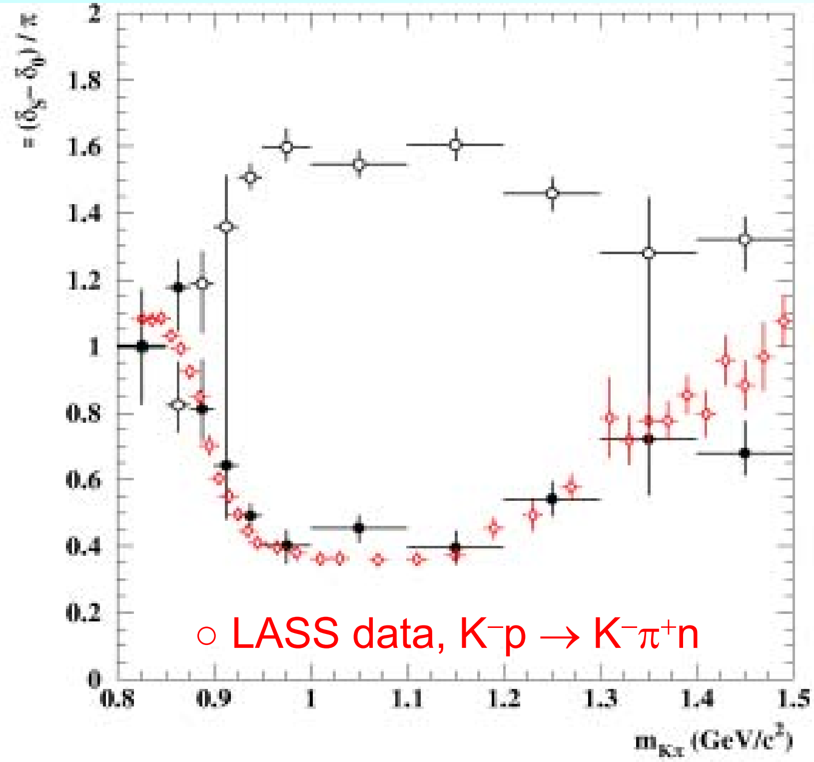
CP sample	N_{tag}	purity	CP
$J/\psi\ K_S\ (K_S \to \pi^+\pi^-)$	2751	96%	-1
$J/\psi\ K_S\ (K_S \to \pi^0\pi^0)$	653	88%	-1
$\psi(2S)\ K_S\ (\to \pi^+\pi^-)$	485	87%	-1
$\chi_{c1}\ K_S\ (K_S \to \pi^+\pi^-)$	194	85%	-1
$\eta_c\ K_S\ (K_S \to \pi^+\pi^-)$	287	74%	-1
Total CP=–1	**4370**	**92%**	**-1**
$J/\psi\ K^{*0}(K^{*0} \to K_S\pi^0)$	572	77%	+0.54
$J/\psi\ K_L$	2788	56%	+1
Total	**7730**	**78%**	

CP odd fraction ($|A_\perp|^2$):
(23±2)% [BABAR*]
(21±1)% [world av.]

* of accepted events

cos(2β) with $B^0 \to J/\psi\, K^{*0}(K_S \pi^0)$

$$\ldots \pm e^{-\Gamma|\Delta t|}[f_4|A_\perp||A_\parallel|\cos(\delta_\perp - \delta_\parallel) + f_6|A_\perp||A_0|\cos(\delta_\perp - \delta_0)]\cos(2\beta)\sin(xT)$$



CP +/– interference

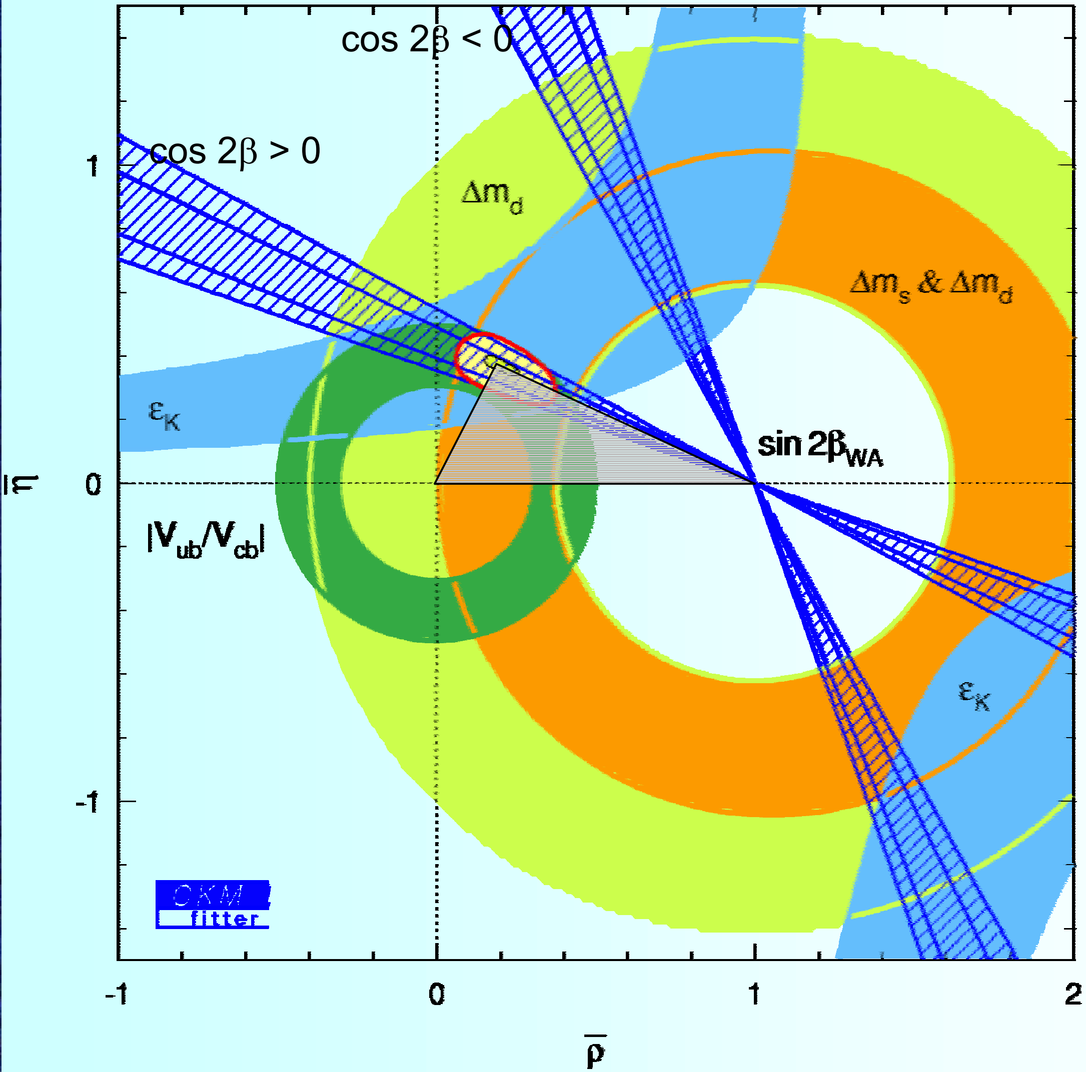
amplitudes and phases use also non-CP charged final states

resolve sign ambiguity of strong phase δ differences using Kπ scalar/vector interference

cos2β = 2.7 ± 0.8(stat) ± 0.3 (syst)   > 0 @ 86% CL

possible from sin 2β: +0.69, –0.69

Status of Unitarity Triangle



world average now:
$\beta = 23.2° \pm 1.5°$

J/ψ K-modes also theoretically „clean“, i.e. β precise at the 0.1% level

Study of CP Violation at BABAR

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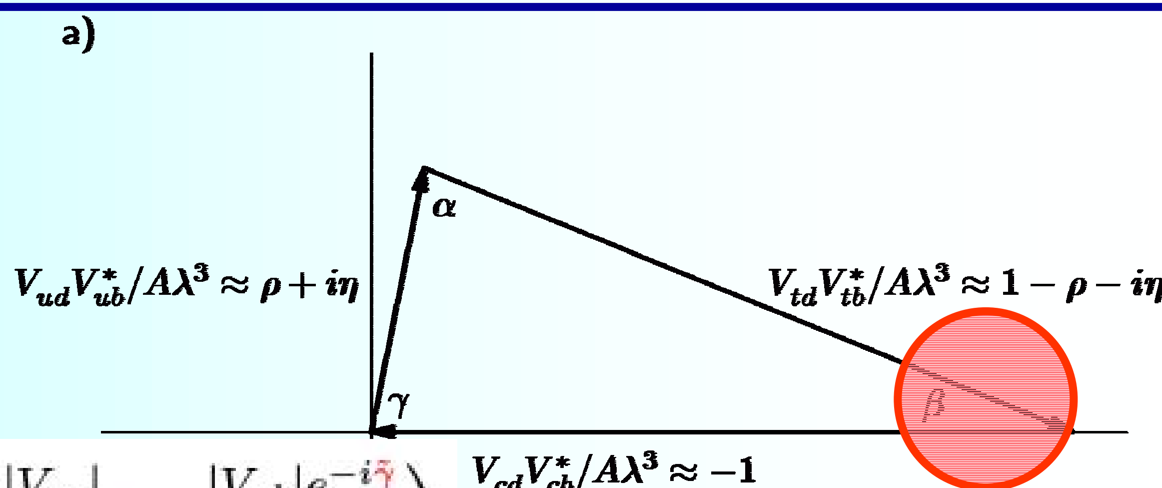
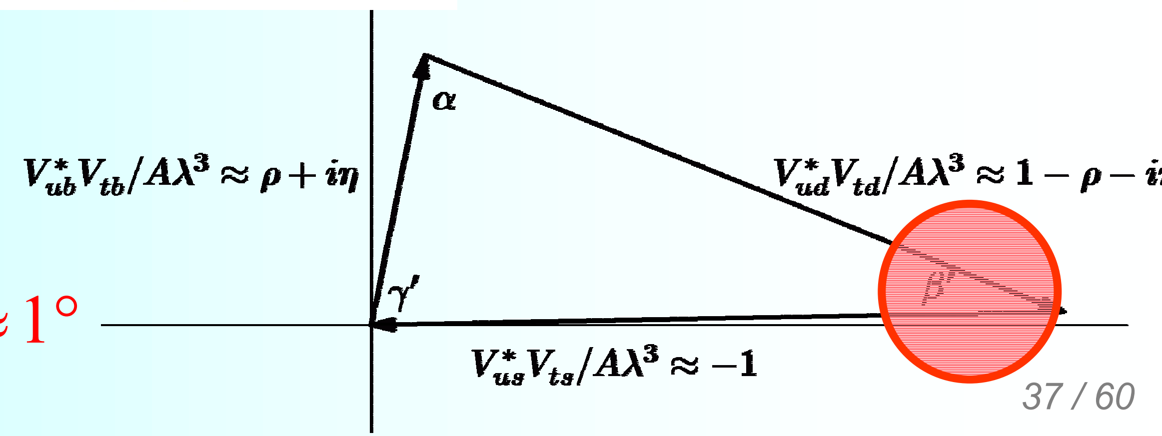
Unitarity Triangles: β & β′



$$\mathbf{V} = \begin{pmatrix} |V_{ud}| & |V_{us}| & |V_{ub}|e^{-i\tilde{\gamma}} \\ -|V_{cd}|e^{i\phi_4} & |V_{cs}|e^{-i\phi_6} & |V_{cb}| \\ |V_{td}|e^{-i\tilde{\beta}} & -|V_{ts}|e^{i\phi_2} & |V_{tb}| \end{pmatrix}$$

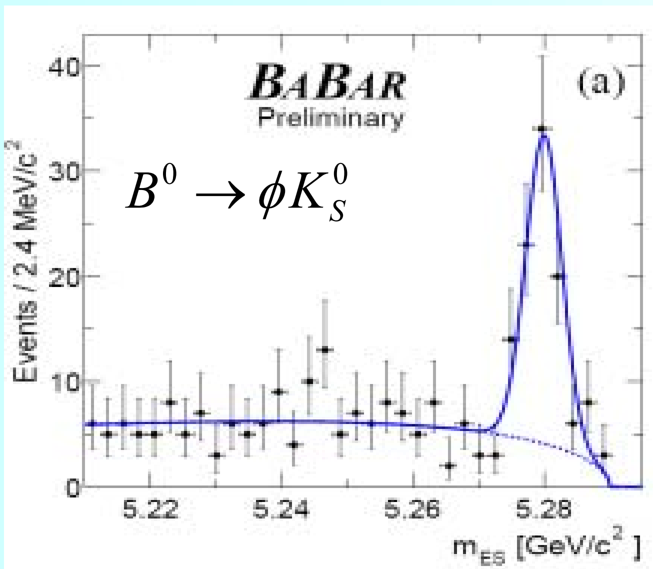


$$\beta = \widetilde{\beta} + \phi_4$$

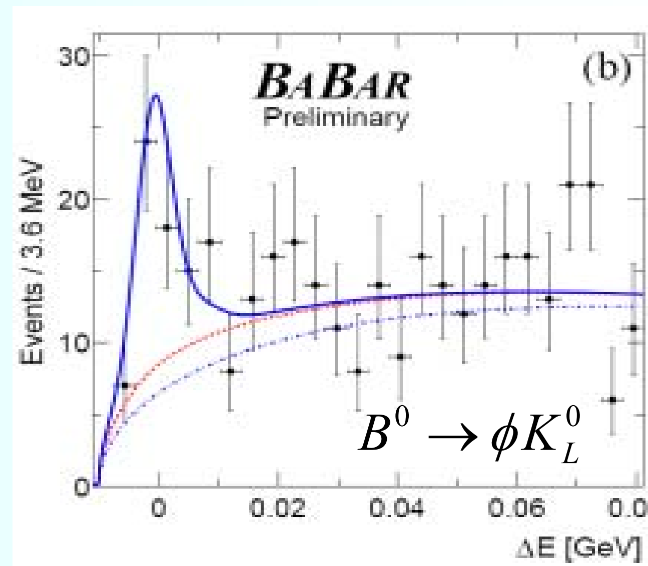
$$\beta' - \beta = \phi_2 - \phi_4 \approx 1^\circ$$

sin(2β′) in s$\bar{s}$s Final States

$B^0 \rightarrow \phi K^0_{S,L}$ CP+ and CP– eigenstates



114 ± 12 signal events



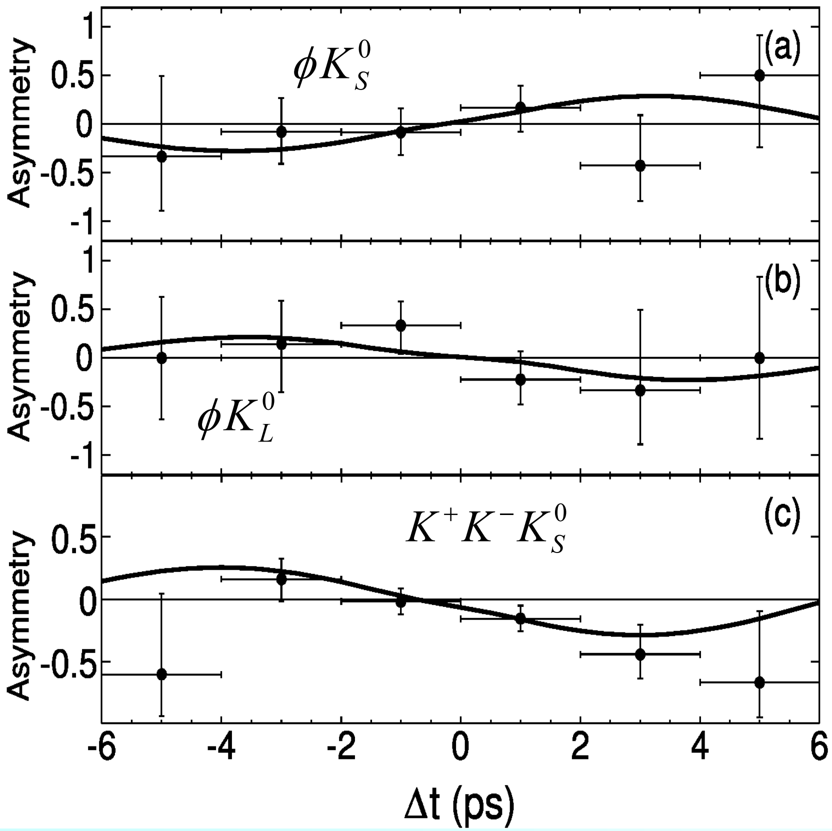
98 ± 18 signal events

$B^0 \rightarrow K^+K^-K^0_S$ mixture CP+/–

452 ± 28 signal events

in Dalitz plot, excluding ϕ region

sin(2β′) in $s\bar{s}s$ Final States



$$\pm\Lambda_0 = \sin 2\beta' = 0.50 \pm 0.25^{+0.07}_{-0.04}$$

$$\Theta_0 = 0.00 \pm 0.23 \pm 0.05$$

$$\sin 2\beta' = 0.55 \pm 0.22 \pm 0.04 \pm 0.11$$

$$f_{CP+} = 0.89 \pm 0.08 \pm 0.06$$

sin(2β′) in s$\bar{s}$s Final States

$$B^0 \to K_S^0 K_S^0 K_S^0$$

CP+ eigenstate

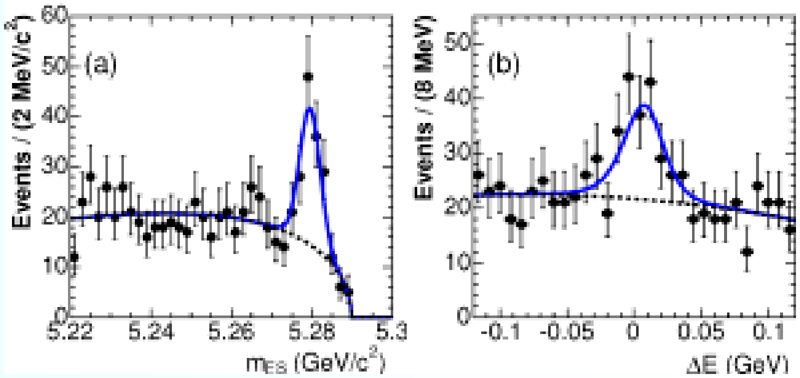
$$BF = \left(6.9^{+0.9}_{-0.8} \pm 0.6\right)\cdot 10^{-6}$$

$$\Lambda_0 = -0.71^{+0.38}_{-0.32} \pm 0.04$$

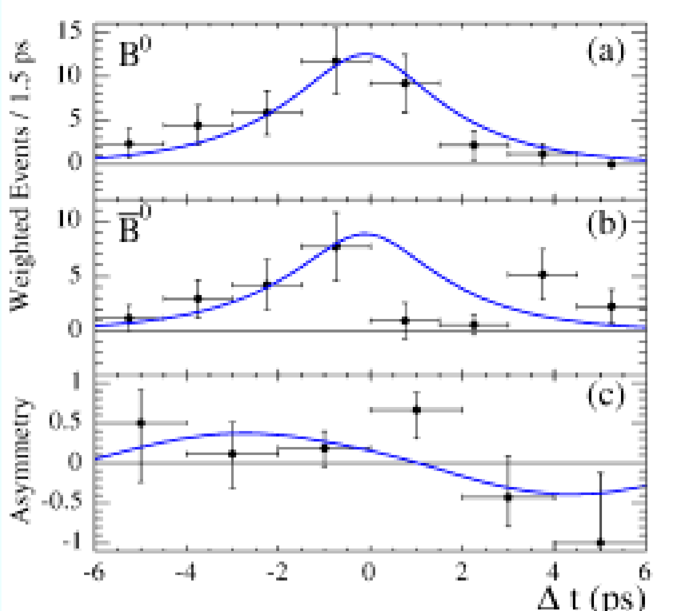
$$\Theta_0 = 0.34^{+0.25}_{-0.28} \pm 0.05$$

$$\Theta_0 := 0$$

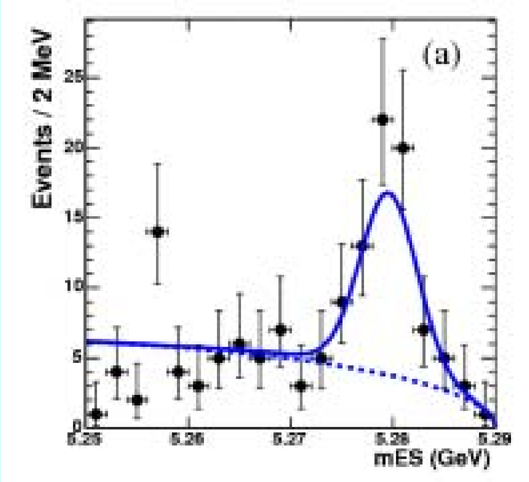
$$\Rightarrow \sin 2\beta' = 0.79^{+0.29}_{-0.36} \pm 0.04$$



88 ± 10 signal events

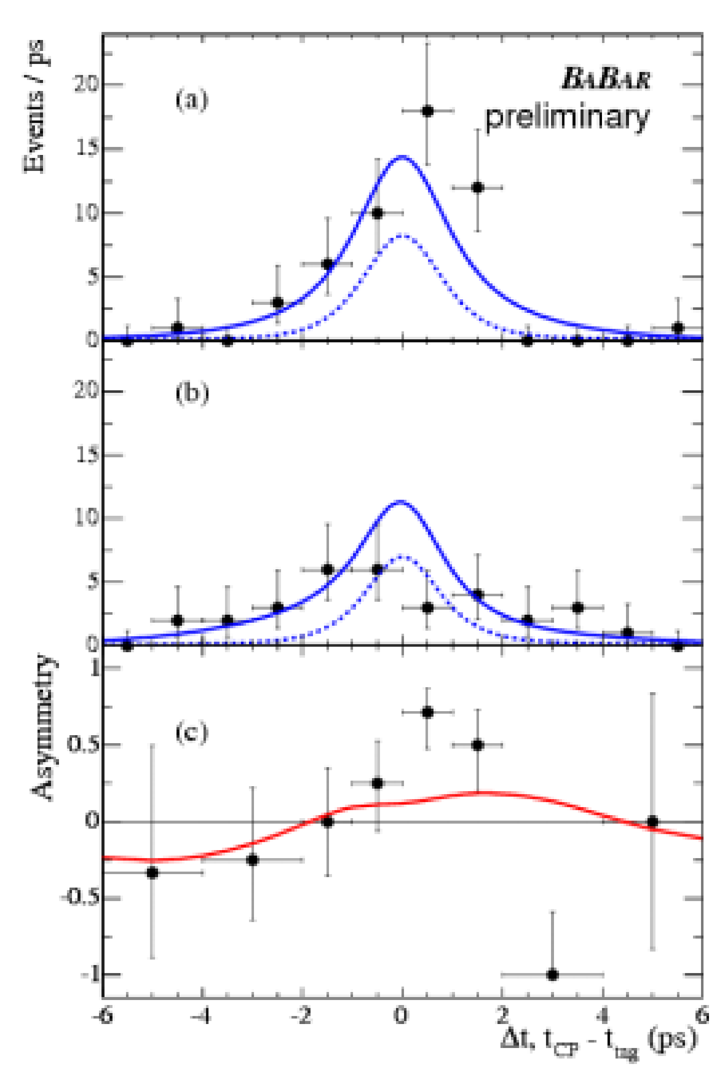


More Penguins: $B^0 \rightarrow \omega K_S$

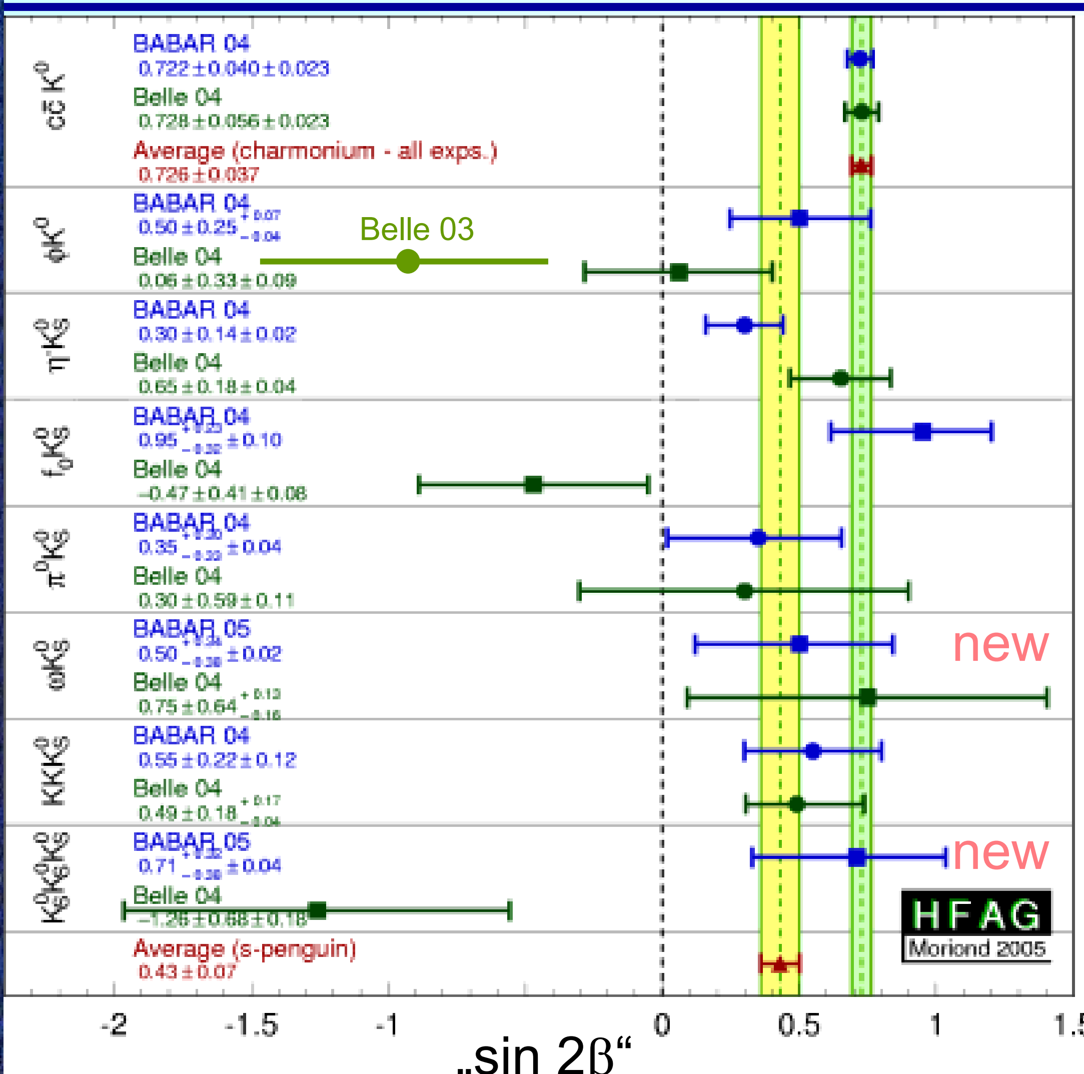


96 ± 14 signal events

$$\Lambda_0 = +0.50\pm^{0.34}_{0.38}\pm 0.02$$
$$\Theta_0 = +0.56\pm^{0.29}_{0.27}\pm 0.03$$



sin(2β) Comparison



BABAR & Belle:

$(c\bar{c})K$
$\sin 2\beta = 0.725 \pm 0.037$

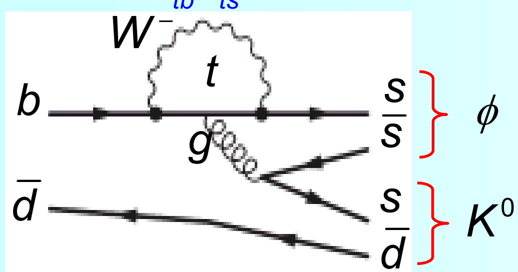
penguins
$\sin 2\beta' = 0.43 \pm 0.07$

3.7σ discrepancy

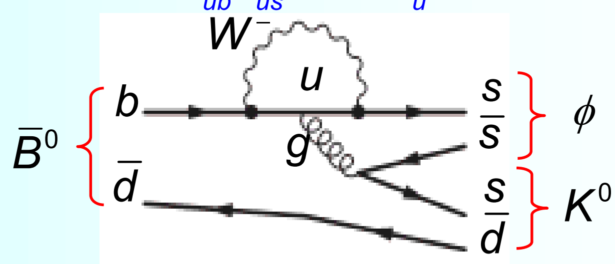
but…

$\Lambda_0 \neq \sin 2\beta'$: SM corrections

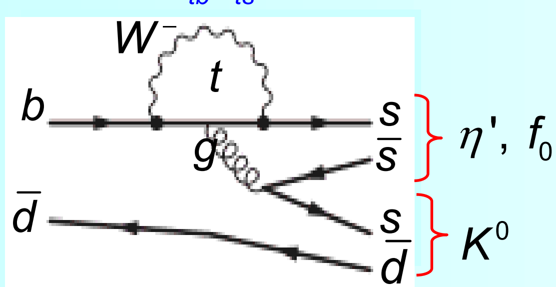
$\propto V_{tb}V_{ts}^{*} \sim \lambda^2$



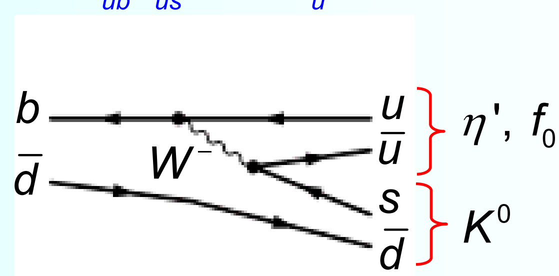
$\propto V_{ub}V_{us}^{*} \sim \lambda^4 R_u e^{-i\gamma}$



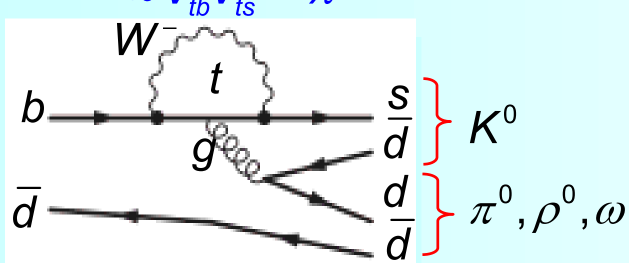
$\propto V_{tb}V_{ts}^{*} \sim \lambda^2$



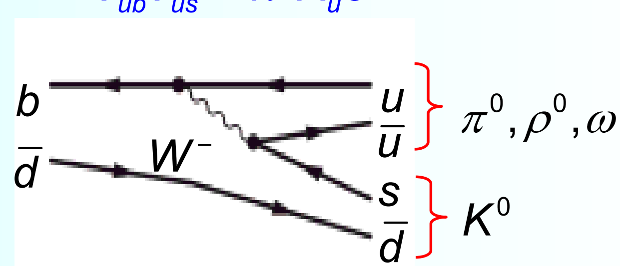
$\propto V_{ub}V_{us}^{*} \sim \lambda^4 R_u e^{-i\gamma}$



$\propto V_{tb}V_{ts}^{*} \sim \lambda^2$



$\propto V_{ub}V_{us}^{*} \sim \lambda^4 R_u e^{-i\gamma}$



up to 20% corrections for relation $\Lambda_0 \leftrightarrow \sin 2\beta'$ possible

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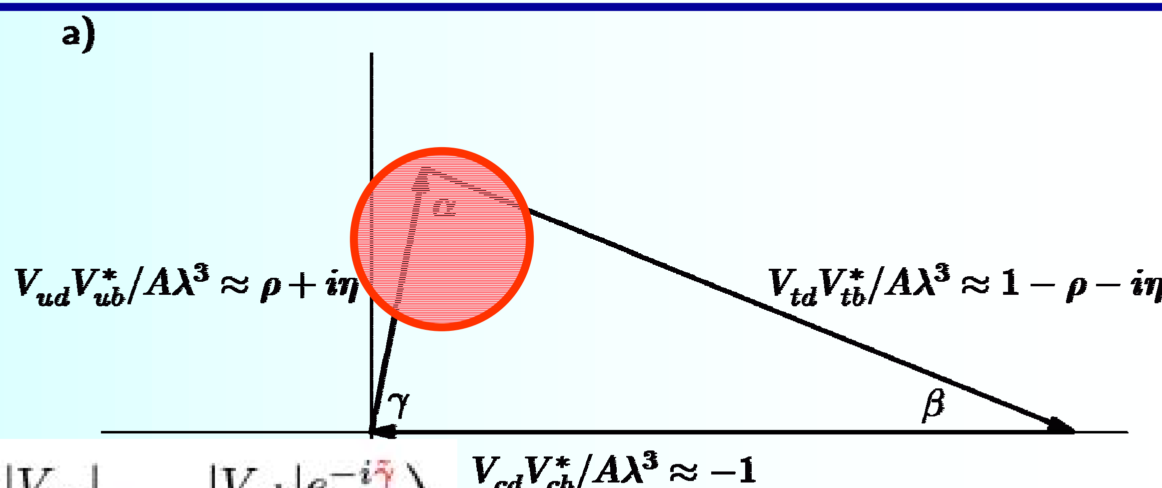
Unitarity Triangles: α

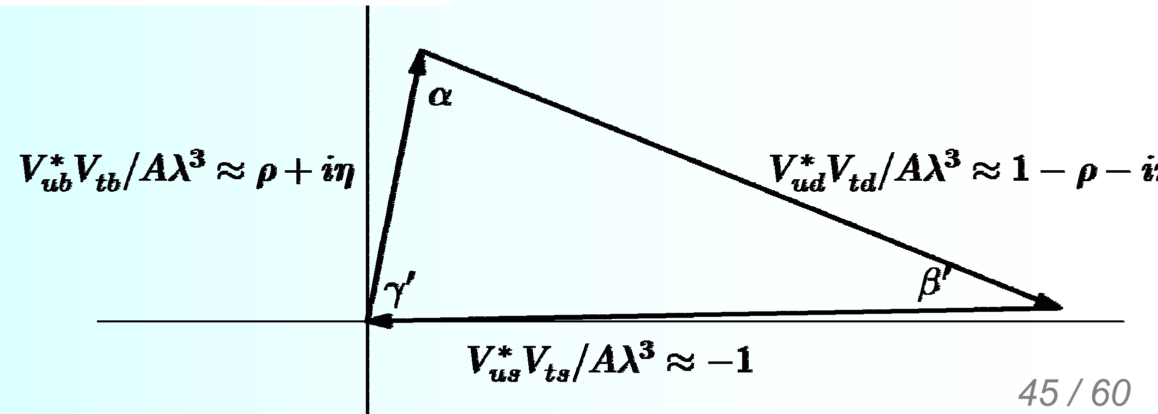
b → $u\bar{u}d$

like $B^0 \to \pi^+\pi^-$

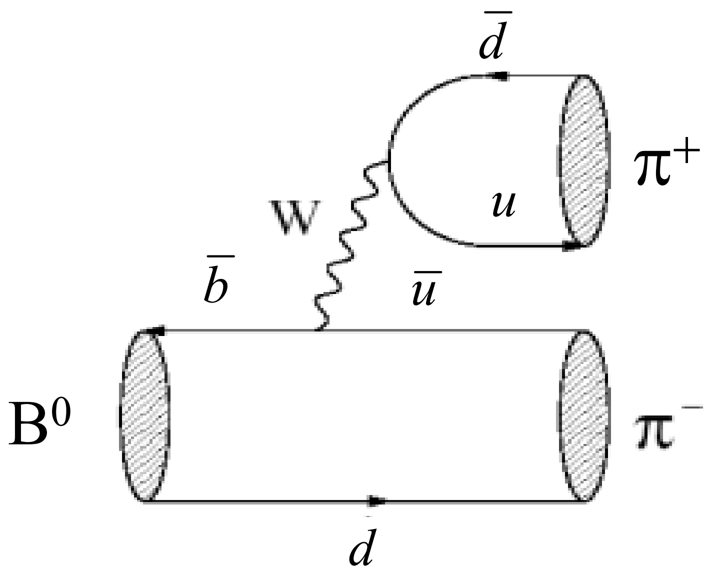


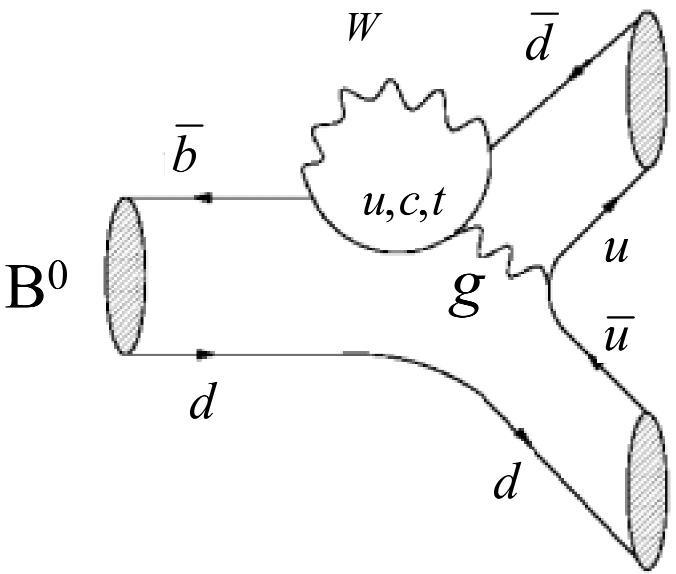
$$\mathbf{V} = \begin{pmatrix} |V_{ud}| & |V_{us}| & |V_{ub}|e^{-i\tilde{\gamma}} \\ -|V_{cd}|e^{i\phi_4} & |V_{cs}|e^{-i\phi_6} & |V_{cb}| \\ |V_{td}|e^{-i\tilde{\beta}} & -|V_{ts}|e^{i\phi_2} & |V_{tb}| \end{pmatrix}$$

$$\alpha = \pi - \tilde{\beta} - \tilde{\gamma}$$



α: the Penguin Pollution

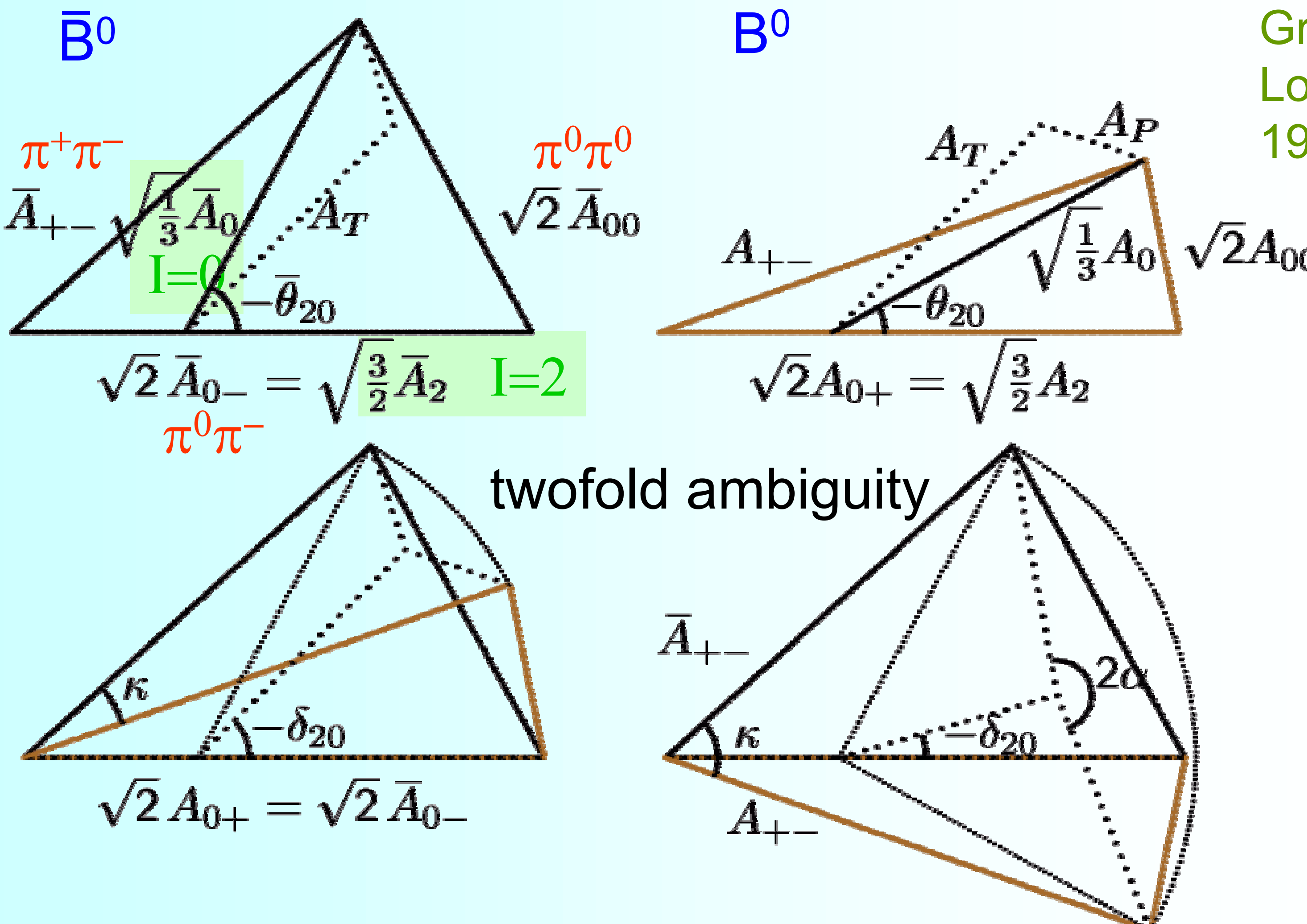




$$\Theta_0 \propto \sin(\delta)$$

$$\Lambda_0 = (\pm)\sqrt{1-\Theta_0^2}\,\sin(2\alpha+\kappa)$$

Isospin Analysis



Gronau, London, 1990

α from B → π π

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

$$BF = (4.7 \pm 0.6 \pm 0.2) \times 10^{-6}$$

$$\Lambda_{\pi^+\pi^-} = -0.30 \pm 0.17 \pm 0.03$$

$$\Theta_{\pi^+\pi^-} = 0.09 \pm 0.15 \pm 0.04$$

$$B^0 \to \pi^0\pi^0$$

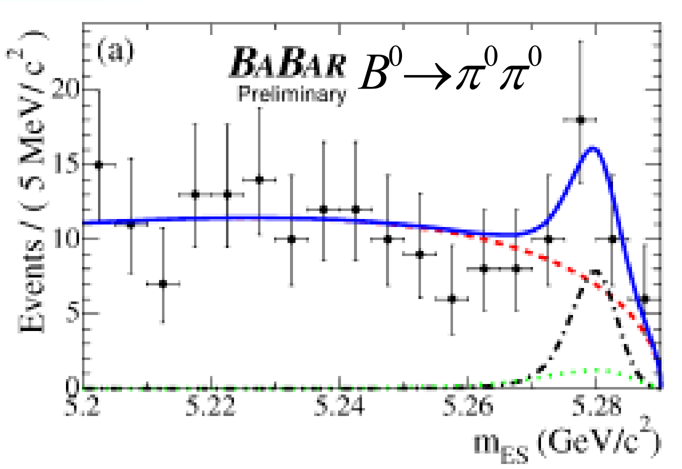
$$BF = (1.17 \pm 0.32 \pm 0.10) \times 10^{-6}$$

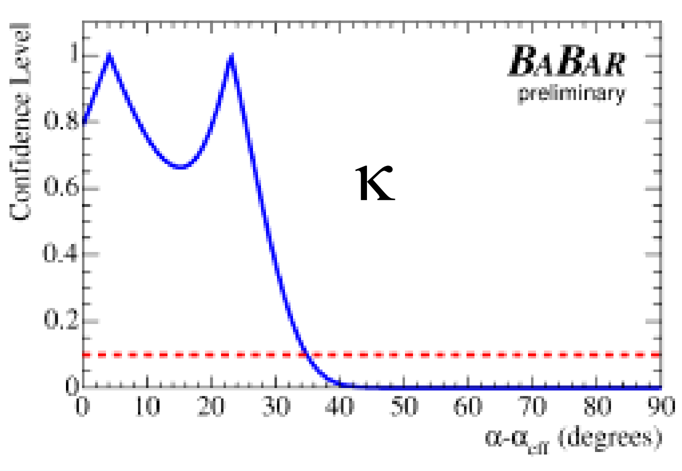
$$\Theta_{\pi^0\pi^0} = 0.12 \pm 0.56 \pm 0.06$$

$$B^\pm \to \pi^\pm\pi^0$$

$$BF = (5.8 \pm 0.6 \pm 0.4) \times 10^{-6}$$

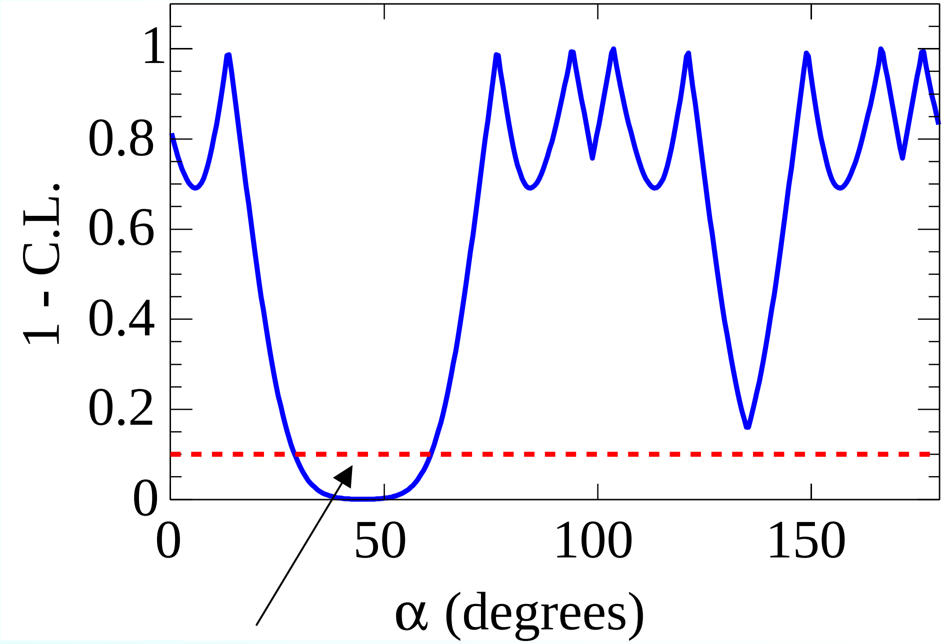
$$a = -0.01 \pm 0.10 \pm 0.02$$





Isospin analysis: $|\alpha - \alpha_{eff}| < 35^o$ at 90% CL

α from B → π π



small range excluded @ 90% CL

$B \to$ Vector-Vector

B: Spin 0

$\Rightarrow$ VV: L=S, $\Sigma\, S_z=0$

Clebsch-Gordan-Table:

		L=	0	1	2
		L_z=	0	0	0
A_{+1}	S_z=	+1,–1	1/3	1/2	1/6
A_0		0,0	–1/3	0	2/3
A_{-1}		–1,+1	1/3	–1/2	1/6
		CP =	**+1**	**–1**	**+1**

Amplitudes:

	"longitudinal":	A_0 (CP +)
	"transversal":	A_{+1}, A_{-1}
	"parallel":	$A_{\parallel} = A_{+1} + A_{-1}$ (CP +)
	"perpendicular":	$A_{\perp} = A_{+1} - A_{-1}$ (CP –)

$B \rightarrow \rho^+\rho^-$

the $\rho^+\rho^-$ system is longitudinally polarized!

$f(A_0)$ = 0.978±0.014±0.028

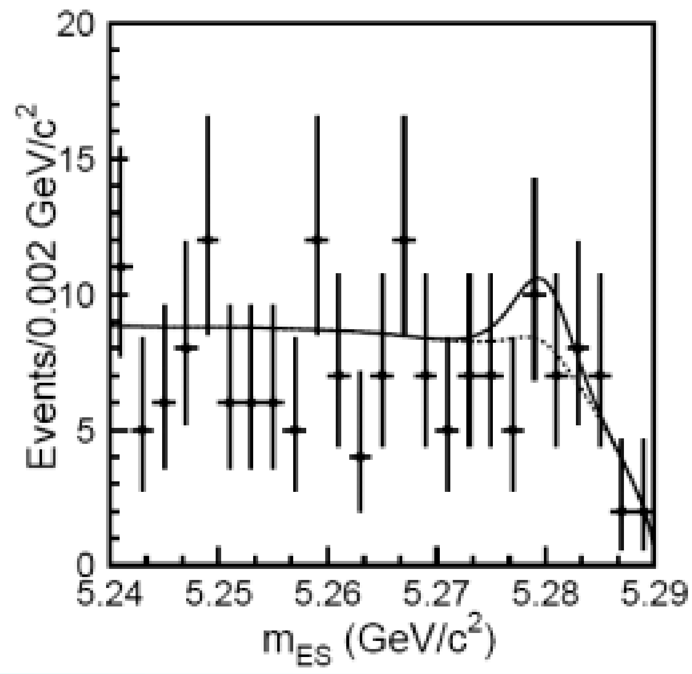
CP = +

617 ± 52 signal events

BF = $(3.0 \pm 0.4 \pm 0.5) \cdot 10^{-5}$

$B \to \rho^0 \rho^0$

$$BF(B^0 \to \rho^0 \rho^0) = (0.54^{+0.36}_{-0.32} \pm 0.19) \cdot 10^{-6}$$
$$< \ 1.1 \cdot 10^{-6} \quad 90\%\ \mathrm{CL}$$



33 ± 24 signal events

Isospin analysis gives correction to α:

$\kappa < 11°$ @ 68% CL

α with $B \to \rho\rho$

$B^0 \to \rho^+ \rho^-$

$$\Lambda_{\rho^+\rho^-} = -0.33 \pm 0.24^{+0.08}_{-0.14}$$

$$\Theta_{\rho^+\rho^-} = 0.03 \pm 0.18 \pm 0.09$$

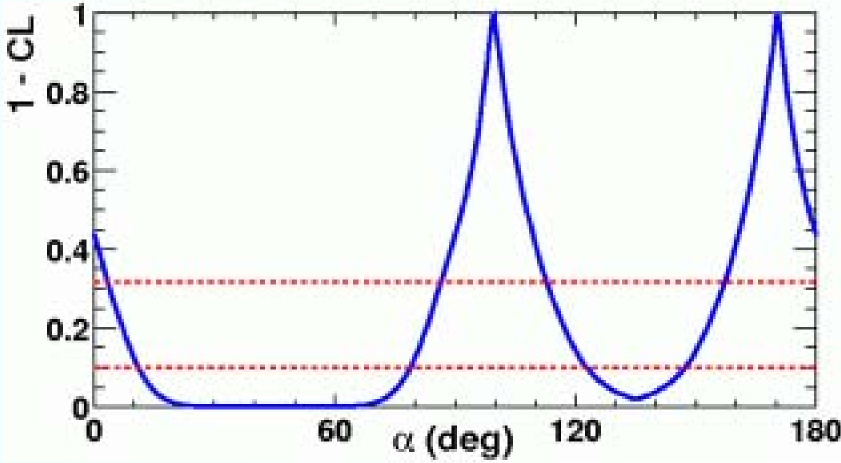
$B^0 \to \rho^0 \rho^0$

$$BF < 1.1 \times 10^{-6}$$

$B^\pm \to \rho^\pm \rho^0$

$$BF = \left(26.4^{+6.1}_{-6.4}\right) \times 10^{-6}$$

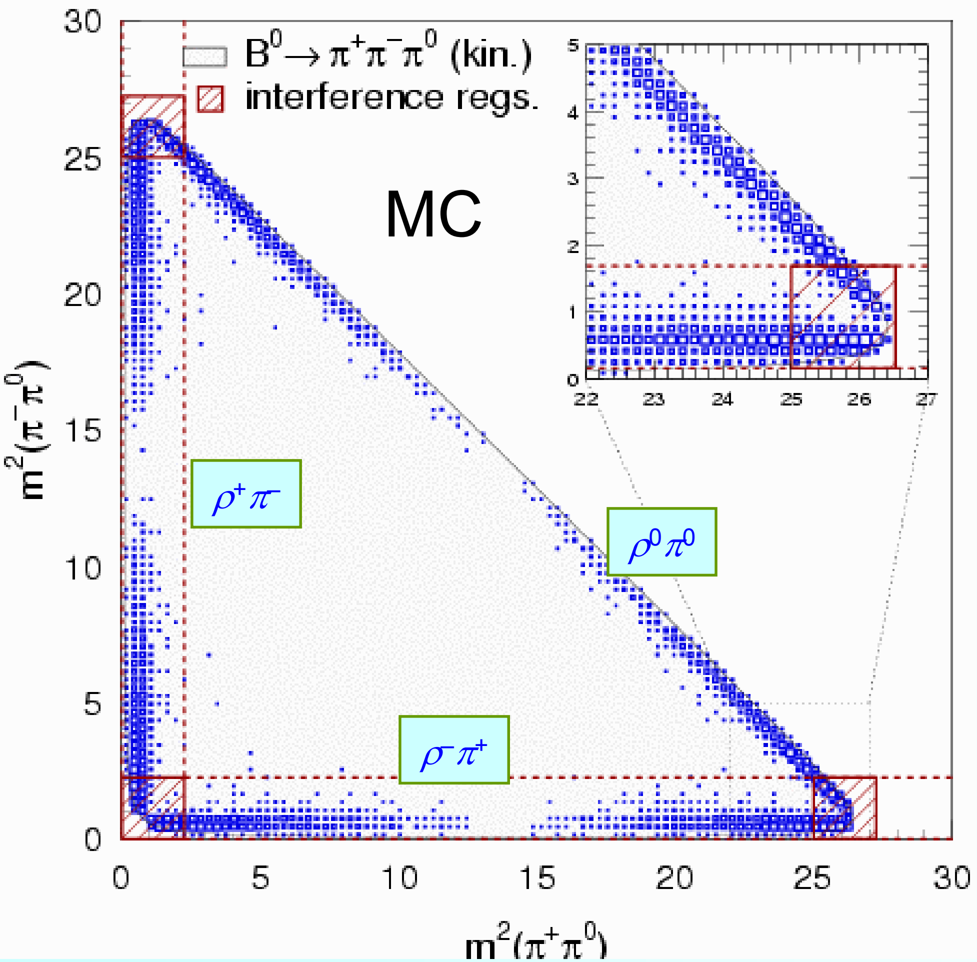
$$f(A_0) = 0.96^{+0.05}_{-0.07}$$



$$\alpha = 100° \pm 13°$$

including ±11° from κ (penguin)

α with $B^0 \to (\rho\pi)^0$



Dalitz plot has $\rho^+\pi^-$, $\rho^-\pi^+$, $\rho^0\pi^0$ and radial excitations

1184 ± 58 signal events

α with $B^0 \to (\rho\pi)^0$

$\rho^0\pi^0$ very small; still many asymmetry parameters

$B^0 \to \rho^+\pi^-$

strong Phase δ_{+-}

$B^0 \to \rho^-\pi^+$

a_{CP}

$\Lambda_{+-}, \Theta_{+-}$

$A_{\rho\pi}^{+-}$

$\Lambda_{-+}, \Theta_{-+}$

$\bar{B}^0 \to \rho^+\pi^-$

$\bar{B}^0 \to \rho^-\pi^+$

$\Lambda_{+-}, \Theta_{+-}, \Lambda_{-+}, \Theta_{-+} \to$ average $\langle\Lambda,\Theta\rangle$ and difference

α with $B^0 \to (\rho\pi)^0$

$$a_{CP} = -0.088 \pm 0.049 \pm 0.013$$

$$\langle \Lambda_{\rho\pi} \rangle = -0.10 \pm 0.14 \pm 0.04$$

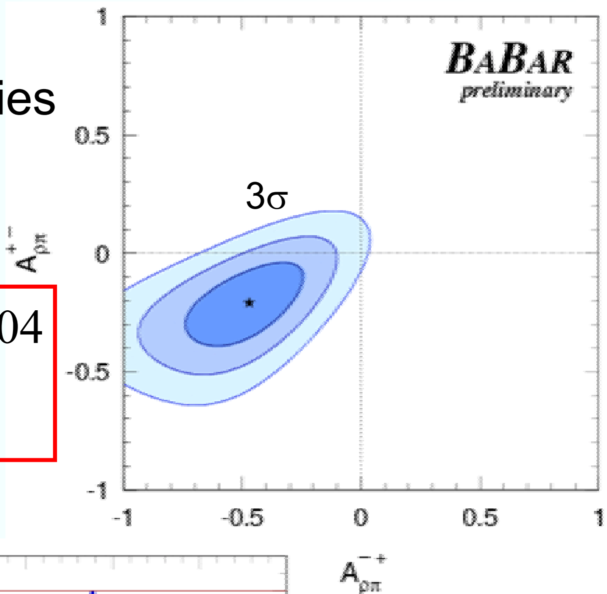
$$\langle \Theta_{\rho\pi} \rangle = -0.34 \pm 0.11 \pm 0.05$$

$$\Delta\Lambda = 0.22 \pm 0.15 \pm 0.03$$

$$\Delta\Theta = 0.15 \pm 0.11 \pm 0.03$$

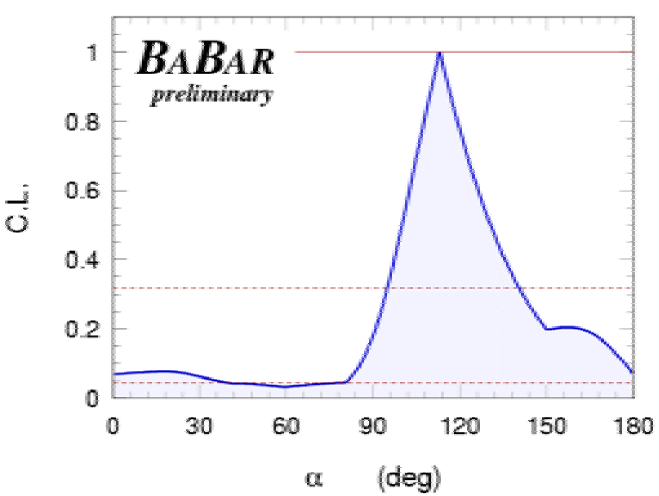
BF asymmetries

$$\boxed{\begin{aligned} A_{\rho\pi}^{+-} &= -0.21 \pm 0.11 \pm 0.04 \\ A_{\rho\pi}^{-+} &= -0.47^{+0.14}_{-0.15} \pm 0.06 \end{aligned}}$$

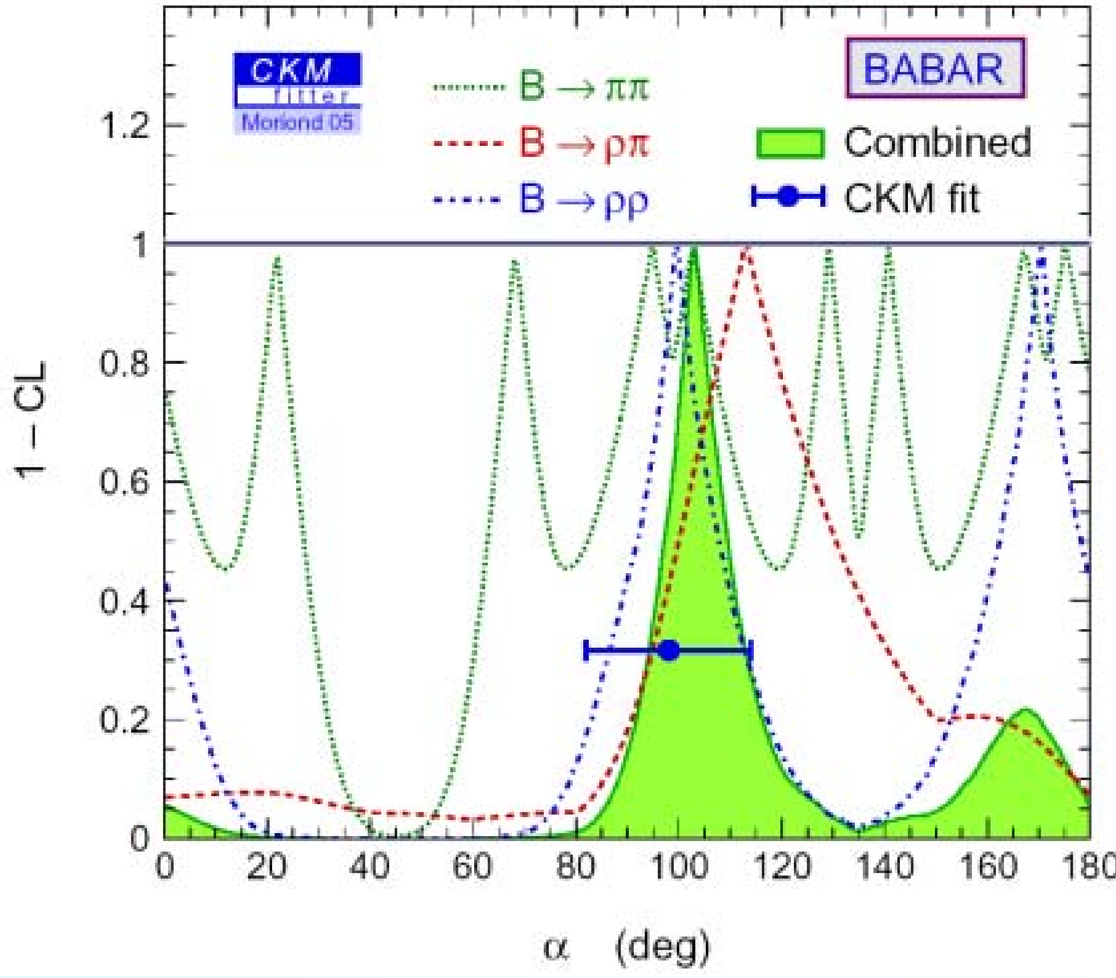


$$\delta_{+-} = \left(-67^{\circ}{}^{+28^\circ}_{-31^\circ} \pm 7^\circ\right)$$

$$\alpha = 113^{\circ}{}^{+27^\circ}_{-17^\circ} \pm 6^\circ$$

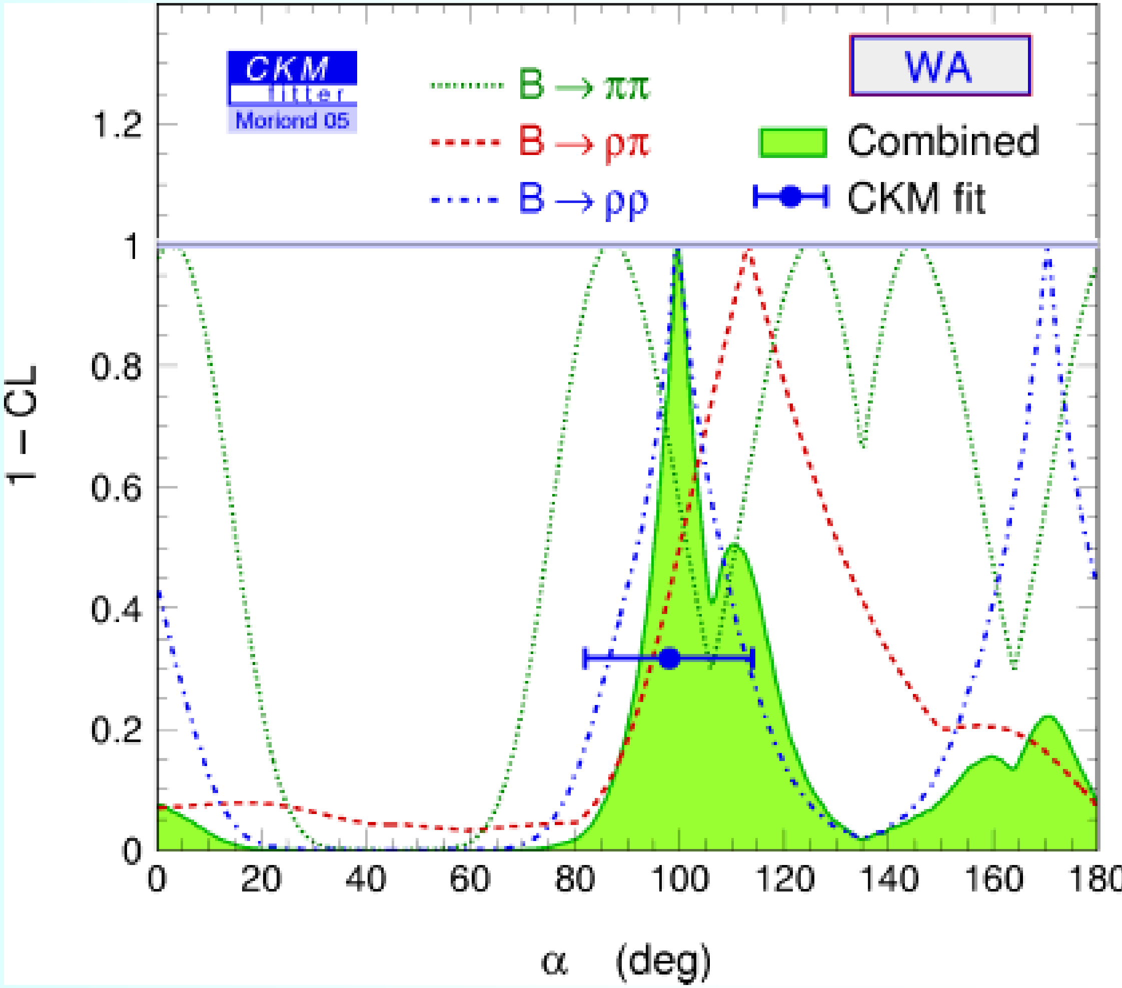


Combined Constraints on α



$$\alpha = 103^\circ \,{}^{+11^\circ}_{-10^\circ}$$

Combined Constraints on α



$$\alpha = 101^\circ\,{}^{+16^\circ}_{-9^\circ}$$

Summary

- observation of direct CPV in B decay
- various measurements of $\beta(\beta')$ differ (2–4σ)
- more data will distinguish new physics from statistical fluctuation
- sensible α measurements available from 3 channels
  (γ also started, errors still large)
- Standard Model (still?) in good shape

Outlook

- BABAR just restarted
- expect datasample × 2 by summer 2006
- expect datasample × 4 by end 2008
- then we need a
  next generation collider
  with $L = 10^{36}/\mathrm{cm}^2/\mathrm{s}$