

Measurement of α

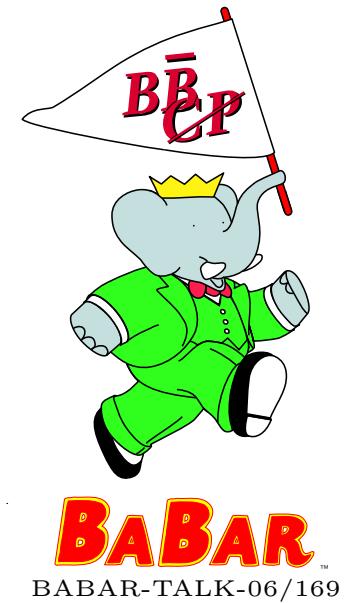
Taming the Mischievous Penguin



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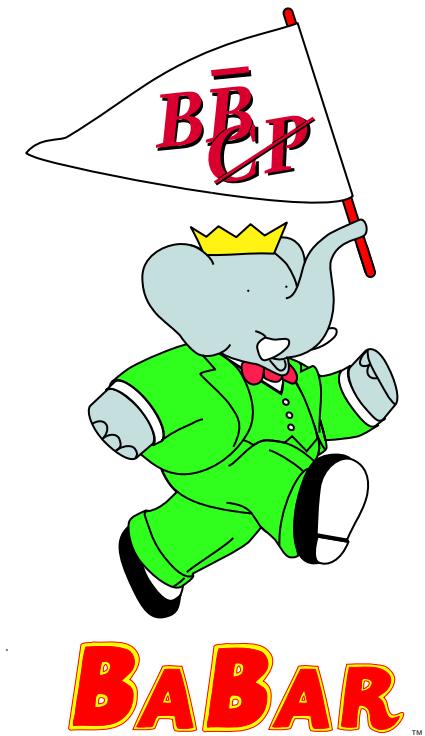


Fermilab

Joint Experimental-Theoretical Seminar

Outline

- Why measure α
- B -physics laboratory – *BABAR*
- Latest results on hadronic $b \rightarrow u$:
 - $B \rightarrow \pi\pi$
 - $B \rightarrow \rho\pi$
 - $B \rightarrow \rho\rho$
 - $B \rightarrow a_1\pi$
- Penguin pollution and α
- Prospects with α
- Do we understand penguin



Standard Model of Matter

- Fermions ($\text{spin}=\frac{1}{2}$) \Rightarrow occupy **space** and constitute **matter**

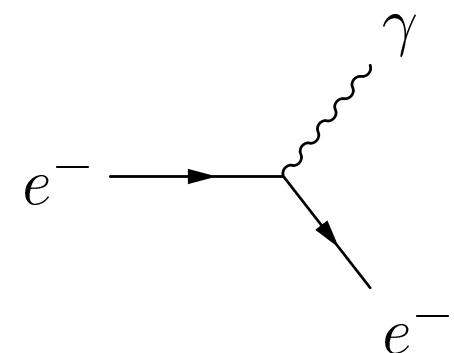
matter		anti-matter	
quarks	leptons	anti-quarks	anti-leptons
(d)	(u)	(\bar{d})	(\bar{u})
s	c	(\bar{s})	(\bar{c})
b	t	(\bar{b})	(\bar{t})
$-e/3$	$2e/3$	$e/3$	$-2e/3$
	$-e$	0	e
		Q	0

- “Forces” (bosons mediate interactions):

Electro-Weak (γ , Z^0 , W^\pm)

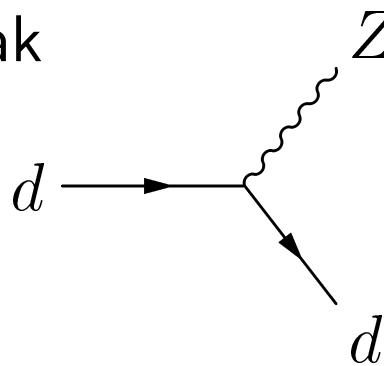
Strong (gluons)

Gravity (not in model yet...)

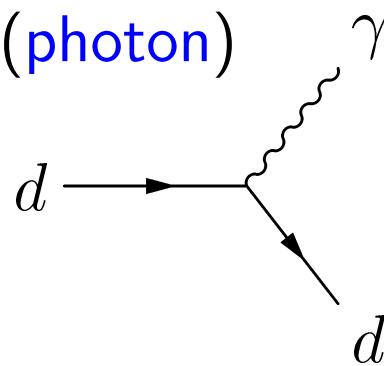


Standard Model of Interactions

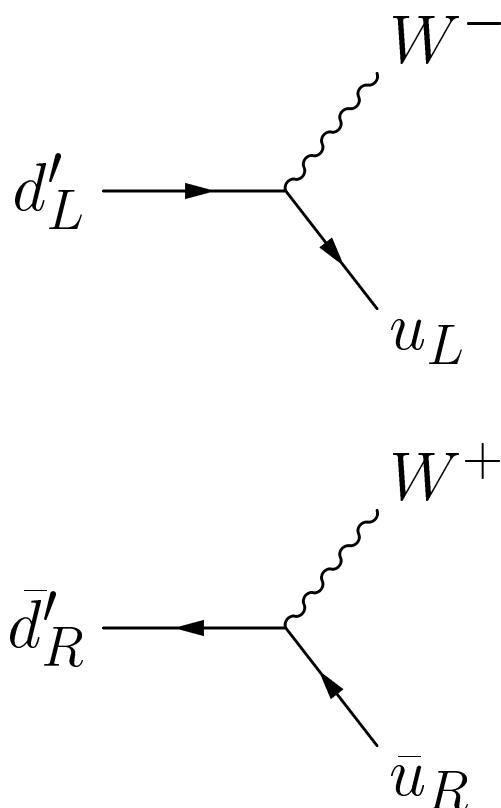
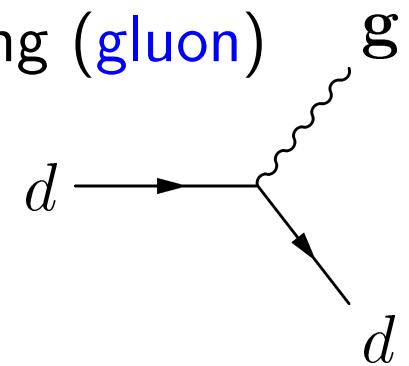
- Weak



- EM (photon)



- Strong (gluon)



- Weak interactions are special:
change of “flavor” and “family”
(e.g. $b \rightarrow u$)

$$|d'\rangle = V_{ud} \cdot |d\rangle + V_{us} \cdot |\text{s}\rangle + V_{ub} \cdot |\text{b}\rangle$$

violate C harge and P arity symmetry
weak violation of CP

Look Beyond the Standard Model

- Why does MATTER dominate (Sakharov):

- CP -asymmetry
- baryon non-conservation
- non-equilibrium

- Need something beyond the SM

- CP -asymmetry not enough
- dark matter ...
- Higgs and mass hierarchy problem

- New Models (e.g. SUperSYmmetry)

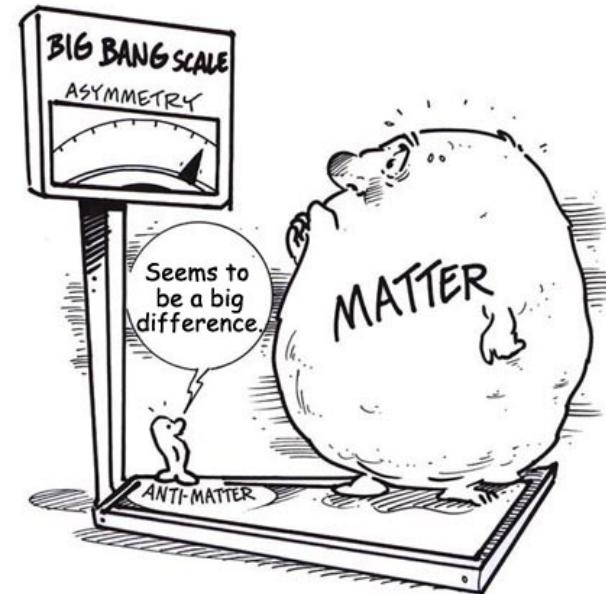
$$\text{quarks (spin}=\frac{1}{2}\text{)} \begin{pmatrix} d \\ s \\ b \end{pmatrix} \begin{pmatrix} u \\ c \\ t \end{pmatrix}$$

$$\text{squarks (spin}=0\text{)} \begin{pmatrix} \tilde{d} \\ \tilde{s} \\ \tilde{b} \end{pmatrix} \begin{pmatrix} \tilde{u} \\ \tilde{c} \\ \tilde{t} \end{pmatrix}$$

heavy \rightarrow

bosons (spin=1/0) $W, Z/H$

$\tilde{\chi}_i^0, \tilde{\chi}_i^\pm$ (spin= $\frac{1}{2}$) (dark matter?)



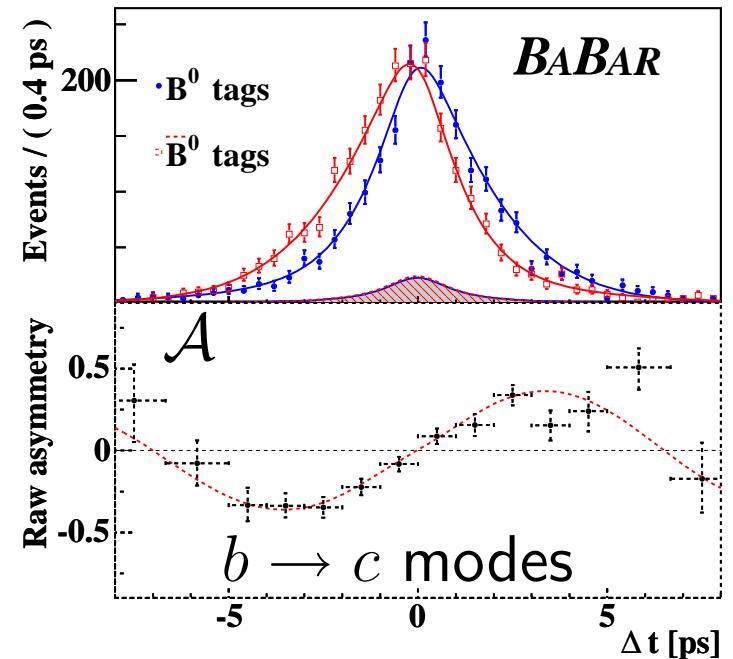
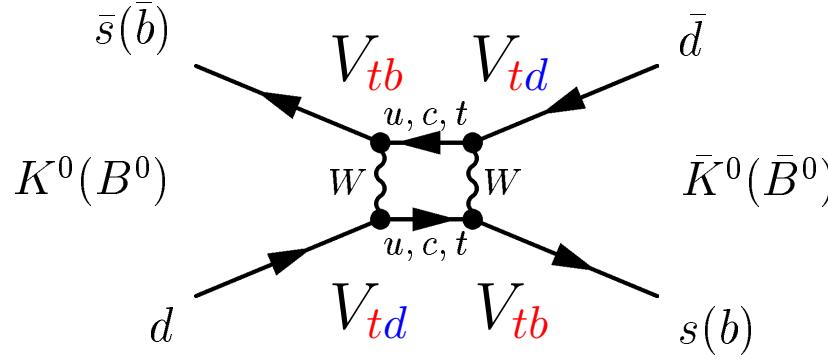
B -Factory Design Measurements

- Rate $B \rightarrow X$ $\Rightarrow |A|^2 = |\langle X | \mathcal{H}_{\text{int}} | B \rangle|^2 \Rightarrow \text{learn } \mathcal{H}_{\text{int}}$
- Rates $B \rightarrow X$ vs. $\bar{B} \rightarrow \bar{X}$ $|A| \neq |\bar{A}| \Rightarrow \text{direct } CP\text{-violation}$
- Rate with time $B^0 \rightarrow B^0(t) \rightarrow X$ and $\bar{B}^0 \rightarrow \bar{B}^0(t) \rightarrow \bar{X}$

$$\Gamma(t) \propto e^{-t/\tau_B} (1 \pm C \times \cos(t/\tau_{\text{mix}}) \mp S \times \sin(t/\tau_{\text{mix}}))$$

$$C \propto |A| - |\bar{A}|$$

$$S \propto \sin(\arg(\text{mix}) + 2 \arg(A/\bar{A}))$$



$$\mathcal{A} = (N_B - N_{\bar{B}})/(N_B + N_{\bar{B}})$$

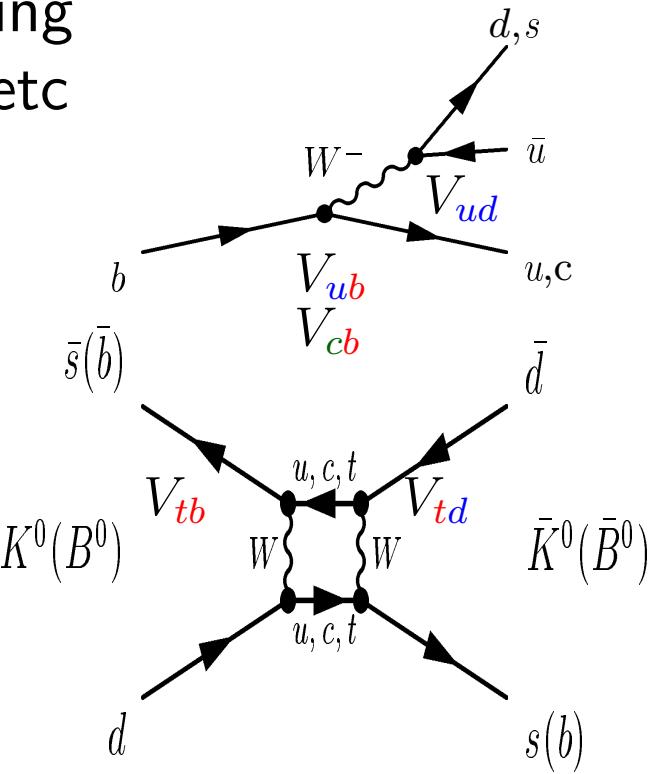
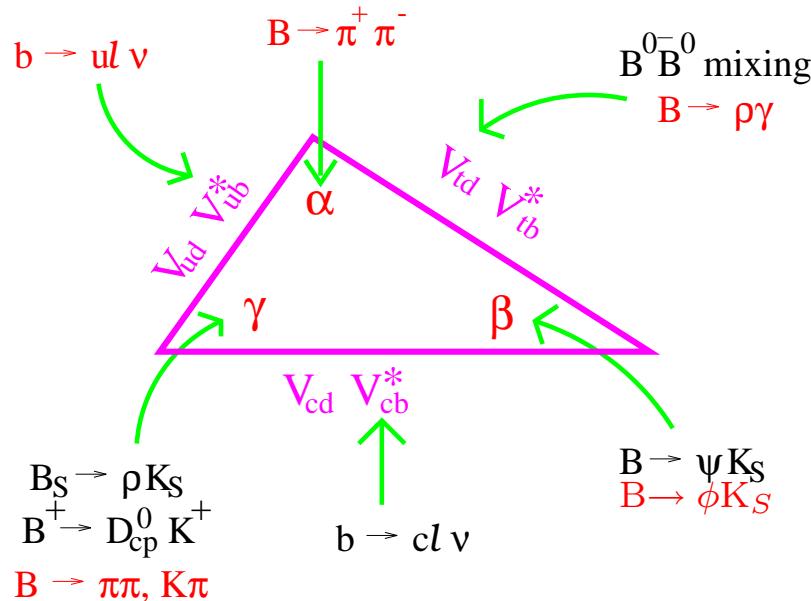
B -Factory “Physics Book”

- Measure sizes and phases of quark-mixing

$$|d'\rangle = V_{ud} \cdot |d\rangle + V_{us} \cdot |\text{green}\rangle + V_{ub} \cdot |\text{red}\rangle, \text{ etc}$$

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

- Overconstrain Unitarity Triangle:



(•) Phases $\Rightarrow CP$ -violation

$$\alpha = \arg[-V_{td} V_{tb}^*/V_{ud} V_{ub}^*]$$

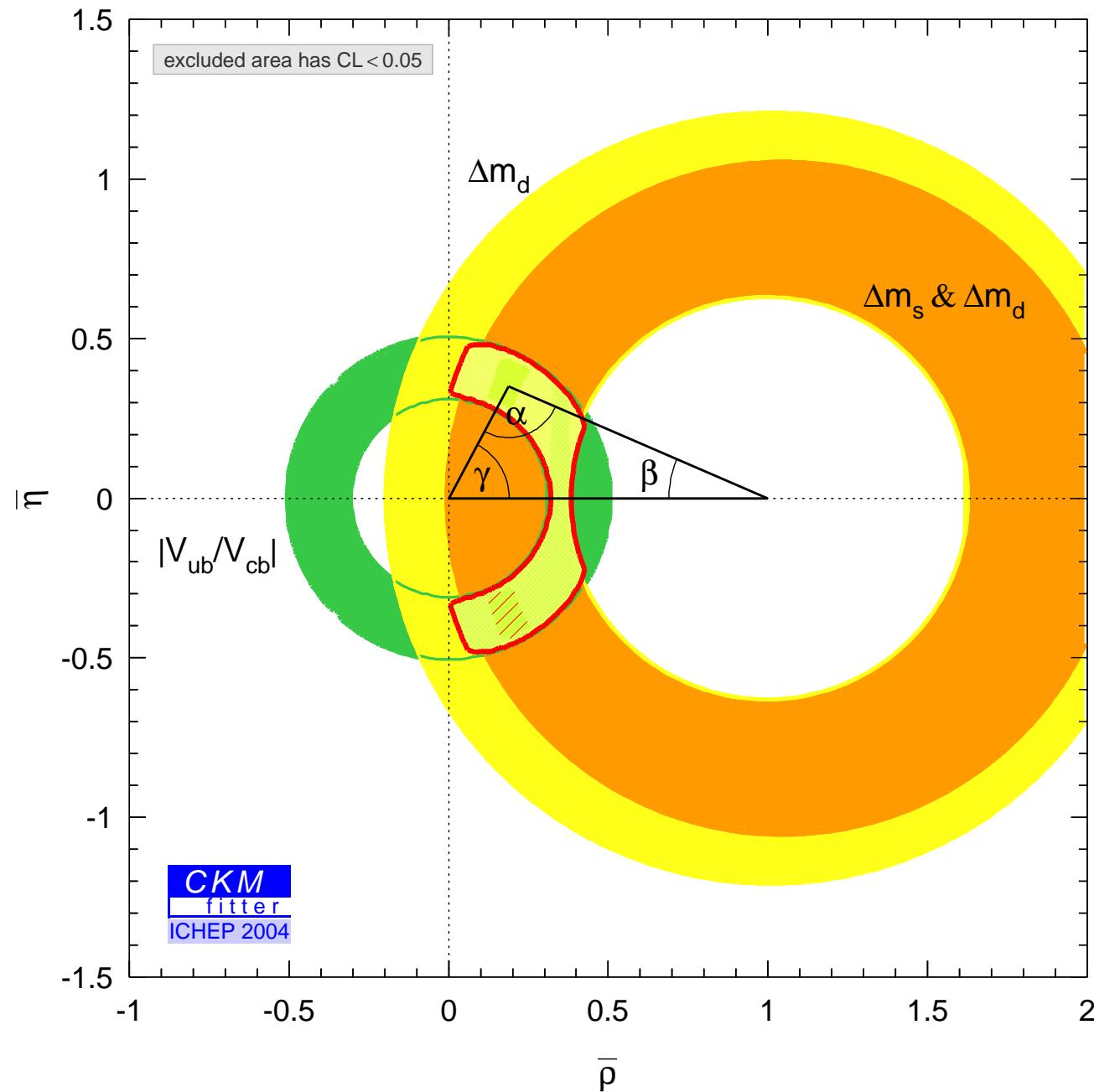
$$S = \sin(2\alpha) \text{ with } b \rightarrow u \quad (B^0 \rightarrow \pi^+ \pi^-)$$

$$\beta = \arg[-V_{cd} V_{cb}^*/V_{td} V_{tb}^*]$$

$$S = \sin(2\beta) \text{ with } b \rightarrow c \quad (B^0 \rightarrow J/\psi K^0)$$

Unitarity Triangle in 2004 (“before α ”)

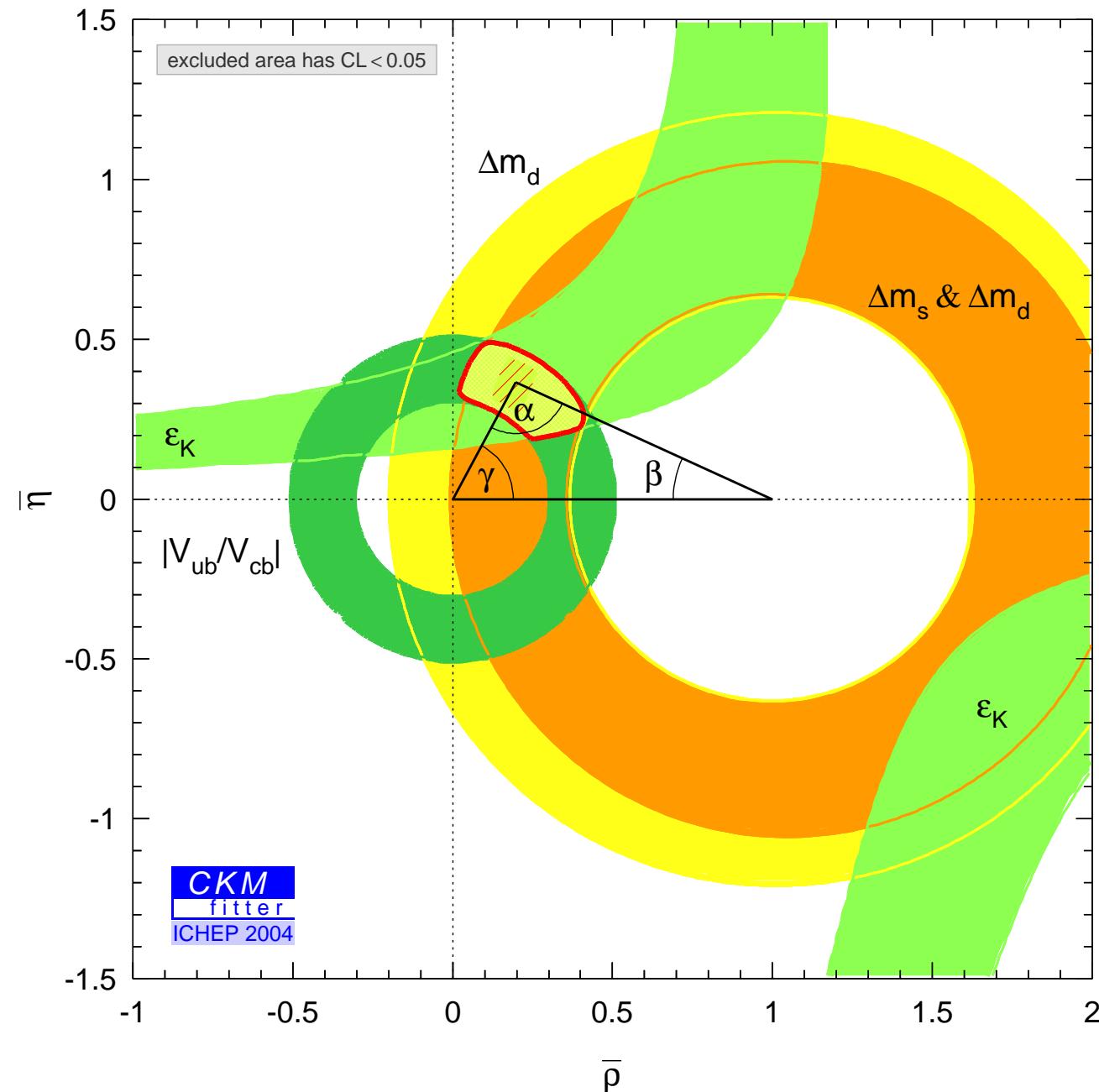
(1) Sides



Unitarity Triangle in 2004 (“before α ”)

(1) Sides

(2) ϵ_K

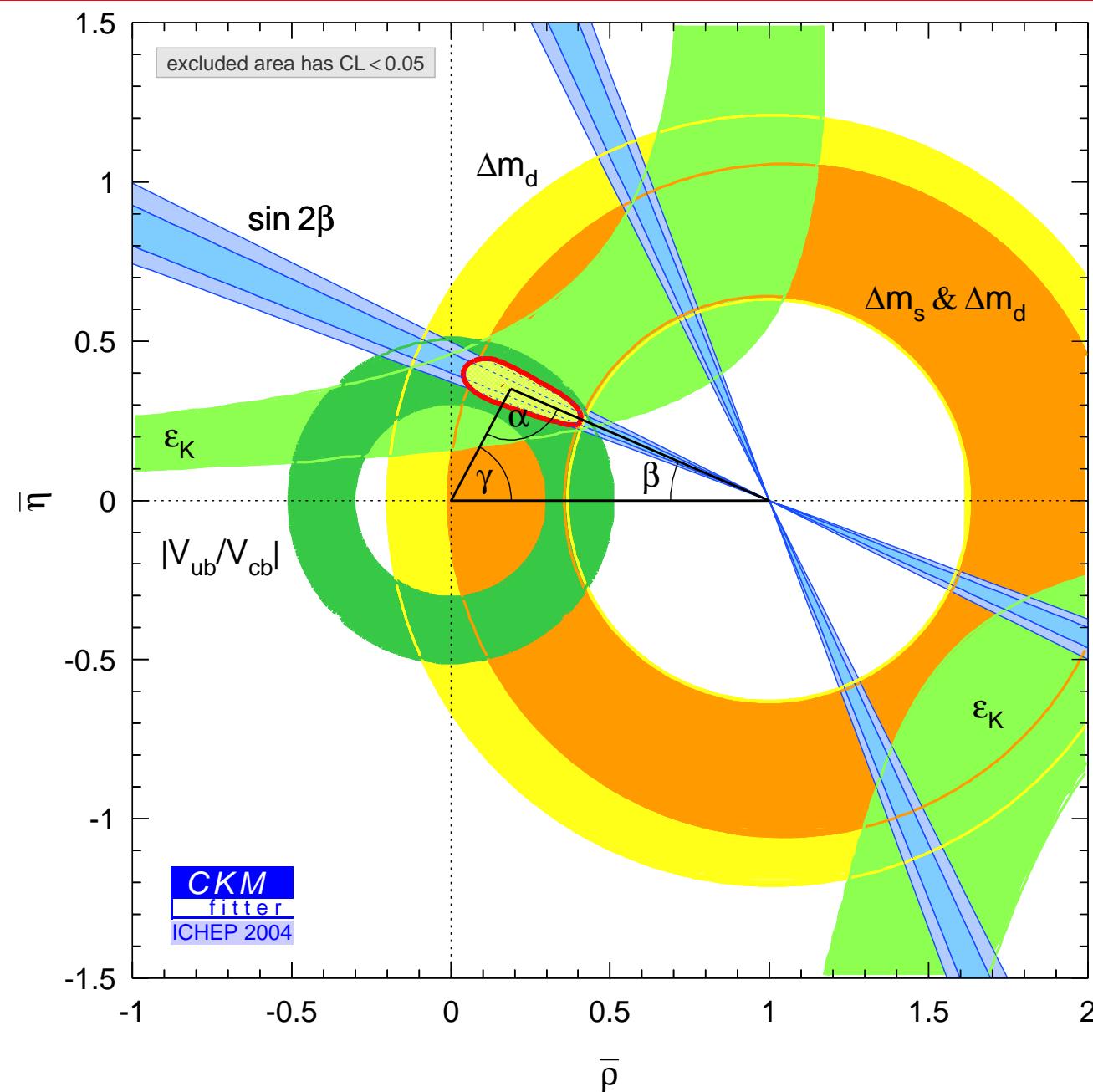


Unitarity Triangle in 2004 (“before α ”)

(1) Sides

(2) ϵ_K

(3) Angle β

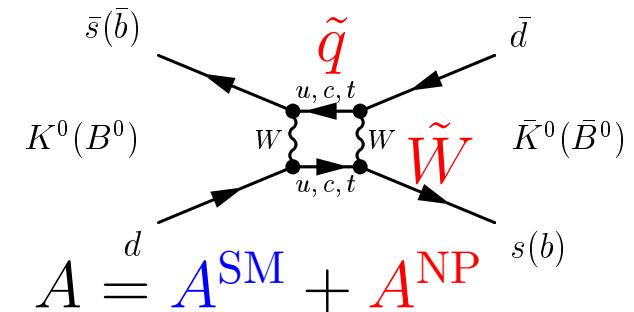


New Physics in Unitarity Triangle

- What if there is New Physics in mixing loop:

$$\Delta m_d \rightarrow \Delta m_d |1 + \frac{|A^{\text{NP}}|}{|A^{\text{SM}}|} e^{i\phi^{\text{NP}}} |$$

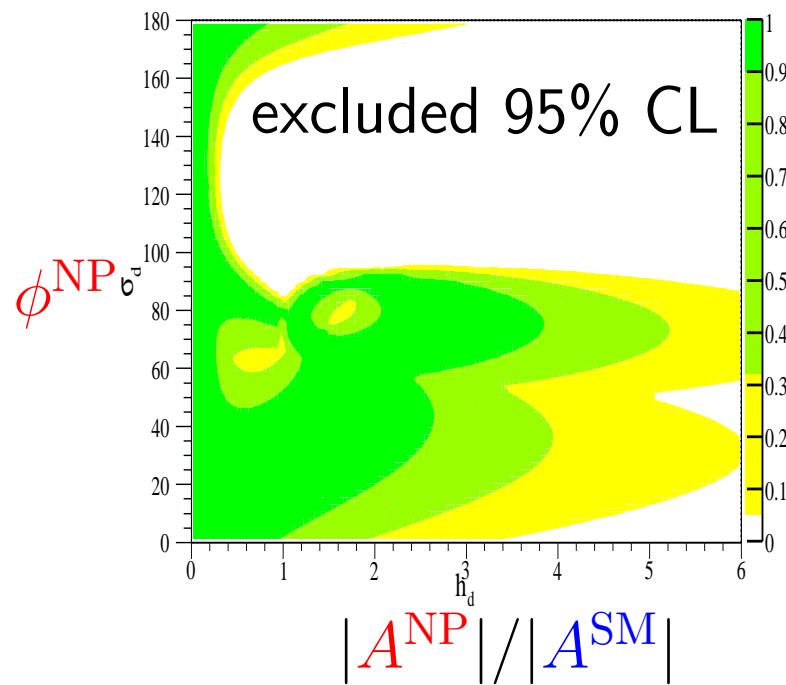
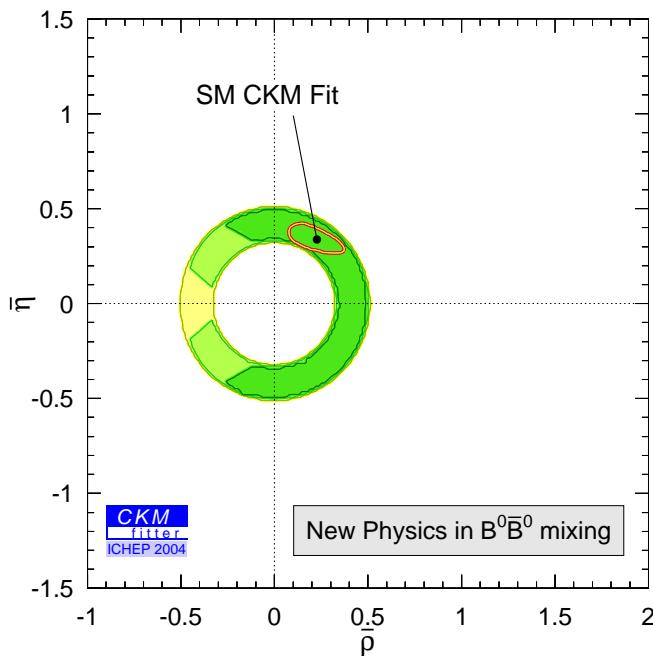
$$\sin(2\beta) \rightarrow \sin(2\beta + \arg(1 + \frac{|A^{\text{NP}}|}{|A^{\text{SM}}|} e^{i\phi^{\text{NP}}}))$$



- Not much constraint without α or γ (e.g. Agashe *et. al.*, hep-ph/0509117):

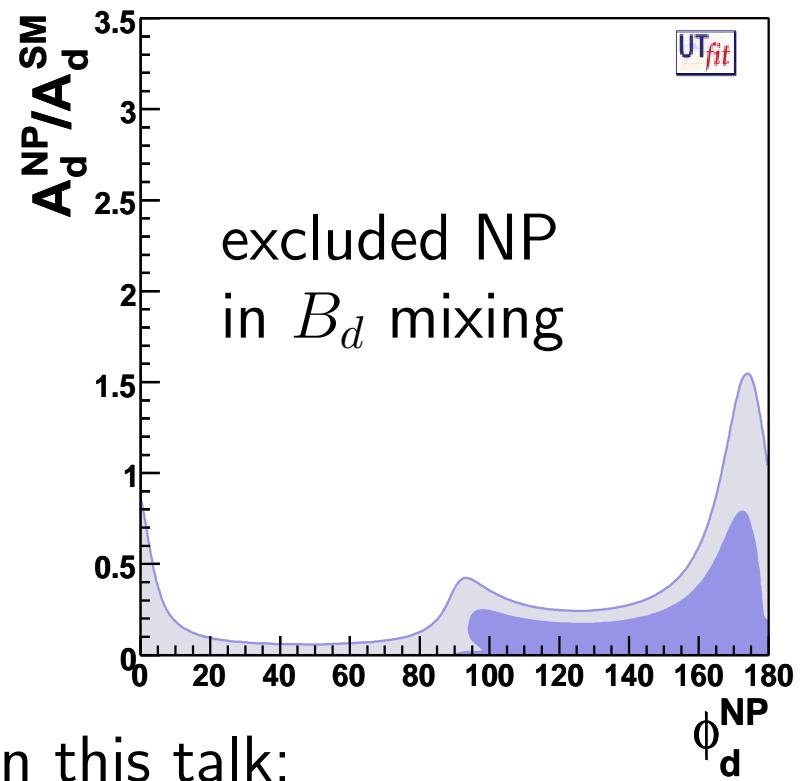
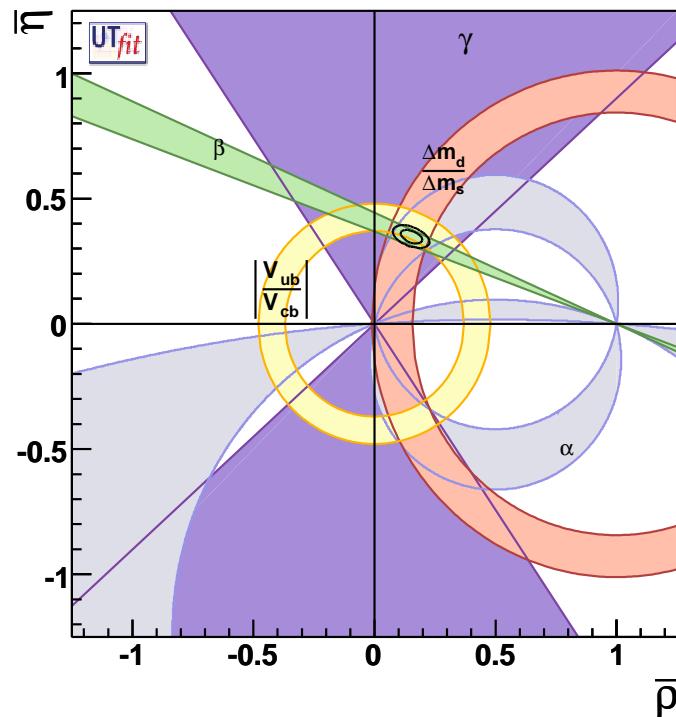
$$\sin(2\alpha) \rightarrow \sin(2\alpha - \arg(1 + \frac{|A^{\text{NP}}|}{|A^{\text{SM}}|} e^{i\phi^{\text{NP}}}))$$

$\gamma = \pi - (\alpha + \beta)$ not affected



Unitarity Triangle in 2006

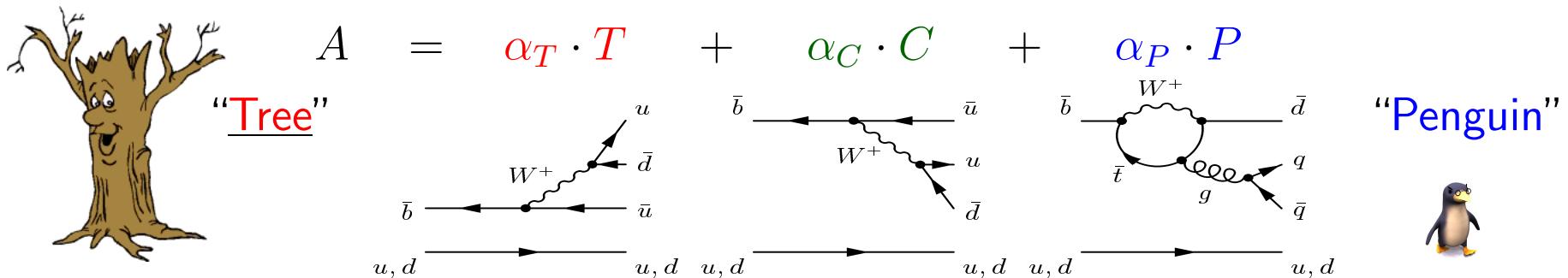
- Recent results:
 - Δm_s in 2006
 - α in 2004-2006 \Rightarrow overconstrain UT \Rightarrow NP constraints



- Statistical methods for illustration in this talk:
 - CKMfitter (www.slac.stanford.edu/xorg/ckmfitter)
 - UTFit (www.utfit.org)
 - other fitting packages (Frequentist/Bayesian)

“Physics Book” $\sin(2\alpha)$: $B \rightarrow \pi\pi$

- With ideal $b \rightarrow u$: $S = \sin 2\alpha$ with $B(t) \rightarrow \pi^+ \pi^-$
but “penguin pollution” $\Delta\alpha \Rightarrow \sin(2\alpha + 2\Delta\alpha)$



	isospin factors			Branching (10^{-6})
	α_T	α_C	α_P	
$B \rightarrow \pi^+ \pi^-$	$\sqrt{2}$	0	$\sqrt{2}$	5.2 ± 0.2
$B \rightarrow \pi^+ \pi^0$	1	1	0	5.7 ± 0.4
$B \rightarrow \pi^0 \pi^0$	0	1	-1	1.3 ± 0.2

- Note isospin triangle:
 - (1) $A(\pi^+ \pi^-)/\sqrt{2} + A(\pi^0 \pi^0) = A(\pi^+ \pi^0)$
 - (2) no “penguin” in $A(\pi^+ \pi^0)$

note: ignore small EW penguin, can include

Measuring α with $B \rightarrow \pi\pi$

- $\mathcal{A}_{\pi^-\pi^+}(t) = C \cos(\Delta m_B t) - S \sin(\Delta m_B t)$

$$S = \frac{2 \operatorname{Im}(\lambda)}{1 + |\lambda|^2} \quad \lambda = \left(\frac{q}{p} \right)_{\text{mix}} \begin{pmatrix} \bar{A}^{+-} \\ A^{+-} \end{pmatrix}$$

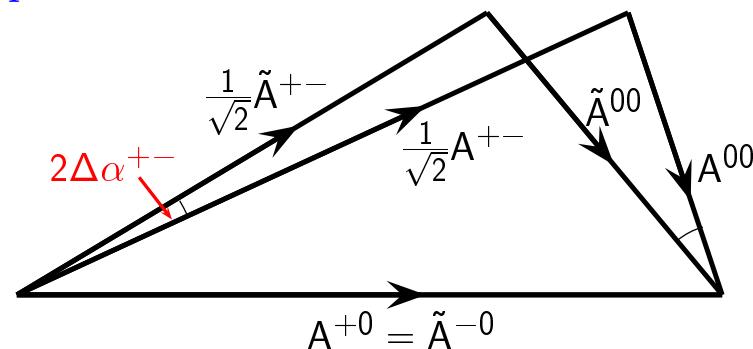
$$C = \frac{1 - |\lambda|^2}{1 + |\lambda|^2}$$

- Gronau/London construction: measure all $B \rightarrow \pi\pi$

$$(1) \text{ no "penguin" in } A(\pi^+\pi^0) \Rightarrow \exp(i2\alpha) = \frac{q}{p} \frac{\bar{A}^{-0}}{A^{+0}}$$

$$(2) 2\Delta\alpha = \arg\left(\frac{A^{+-}}{A^{+0}}\right) - \arg\left(\frac{\bar{A}^{+-}}{\bar{A}^{-0}}\right)$$

from isospin triangles:



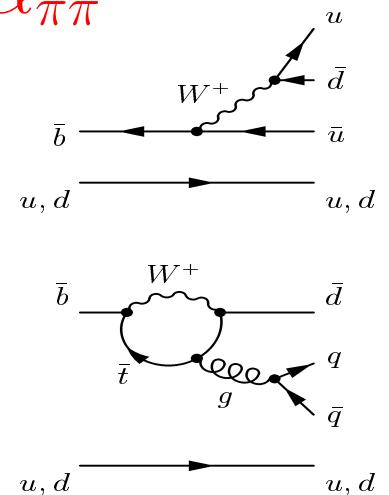
$$\sin(2\alpha - 2\Delta\alpha) = \operatorname{Im}\left(\frac{q}{p} \frac{\bar{A}^{+-}}{A^{+0}}\right) / |\lambda| = S / \sqrt{1 - C^2}$$

$$\alpha = \frac{1}{2} \sin^{-1} \left(\frac{S}{\sqrt{1 - C^2}} \right) + \Delta\alpha$$

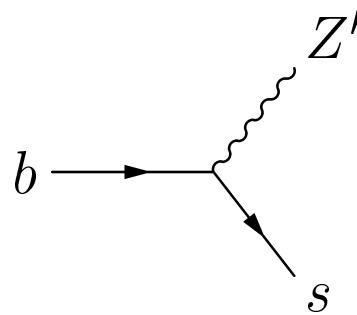
Measuring α : Taming the Penguin

- $B \rightarrow \pi\pi$

$$\alpha = \frac{1}{2} \sin^{-1} \left(S_{\pi\pi} / \sqrt{1 - C_{\pi\pi}^2} \right) + \Delta\alpha_{\pi\pi}$$
 - $S_{\pi\pi}$ and $C_{\pi\pi}$ in $B \rightarrow \pi^+\pi^-$
 - taming penguin pollution $\Delta\alpha_{\pi\pi}$ - main challenge
- $B \rightarrow \rho^\pm\pi^\mp$
 - not CP eigenstate, more parameters
 - interference \Rightarrow complexity, resolve ambiguities and penguin
- $B \rightarrow \rho\rho$
 - similar to $B \rightarrow \pi\pi$, but vector-vector, unique $B \rightarrow \rho^0\rho^0$ (**new**)
 - three triangles: A_0 , $A_{||}$ (P-even), A_\perp (P-odd)
- $B \rightarrow a_1^\pm\pi^\mp$ (**new**)
 - similar to $B \rightarrow \rho\pi$



Another Aspect of “Penguin”



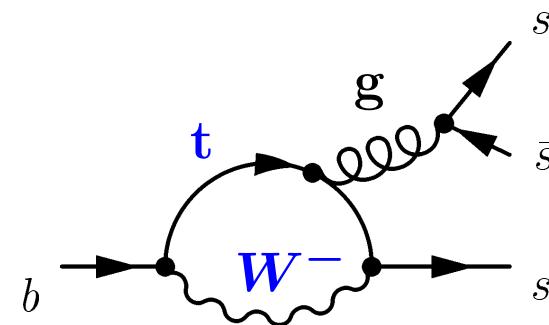
- No neutral quark-mixing (e.g. $b \rightarrow s, d$) beyond the Standard Model



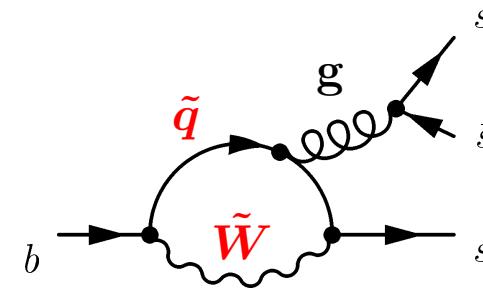
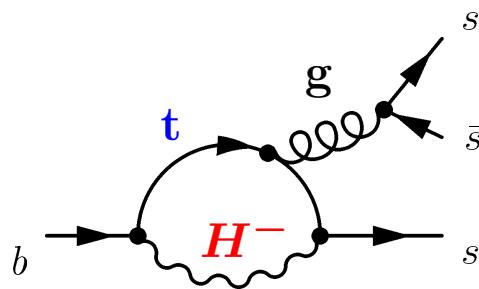
- Possible with virtual loop (**penguin**):

heaviest known particles in loops

t (~ 180 GeV) and W (~ 80 GeV)



- Sensitive to New Physics, e.g. H^\pm , \tilde{H}/\tilde{W} ($\tilde{\chi}_i^0/\tilde{\chi}_i^\pm$) to ~ 500 GeV



- First **gluonic penguins** (1996/97): $B \rightarrow \eta' K, \pi K, \dots$ (CLEO, PRL 80, 3710)
SU(3) relate $b \rightarrow s$ to $b \rightarrow d$ penguin in $B \rightarrow \pi\pi \Rightarrow$ large **penguin pollution!**

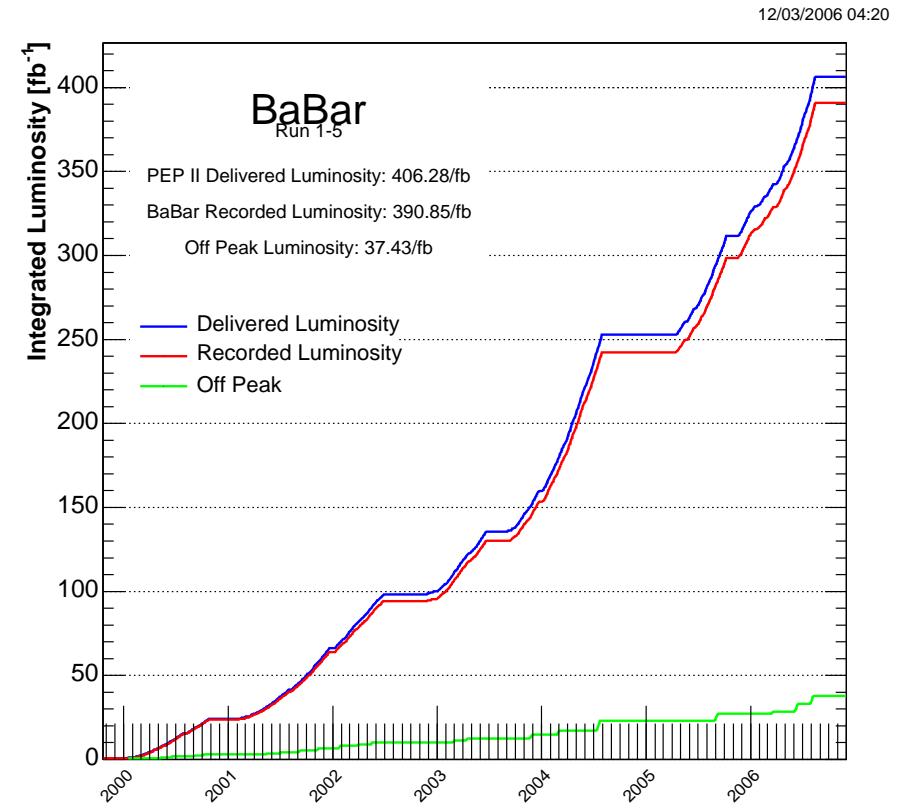
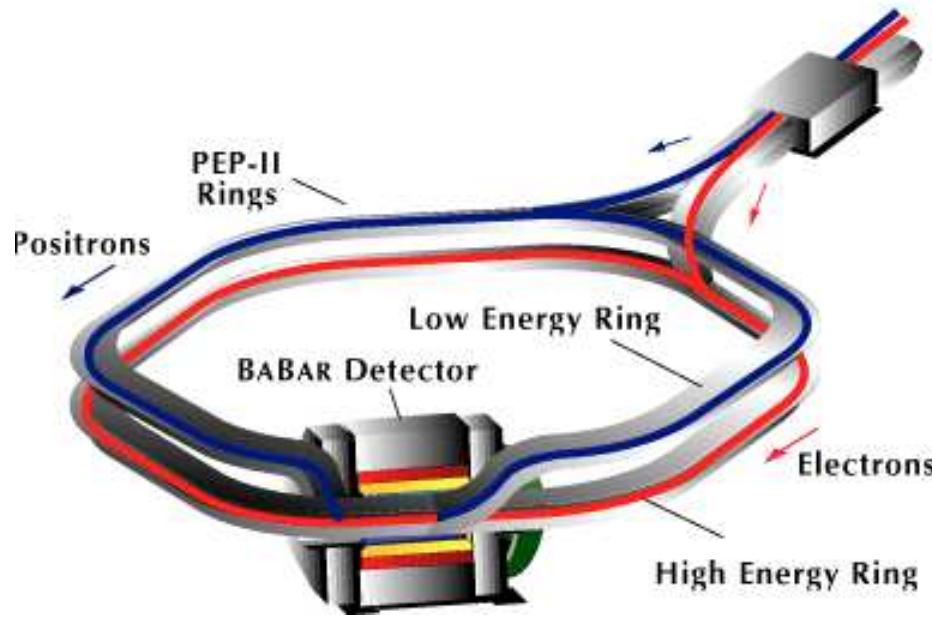
Getting the *B*'s

Producing B Mesons

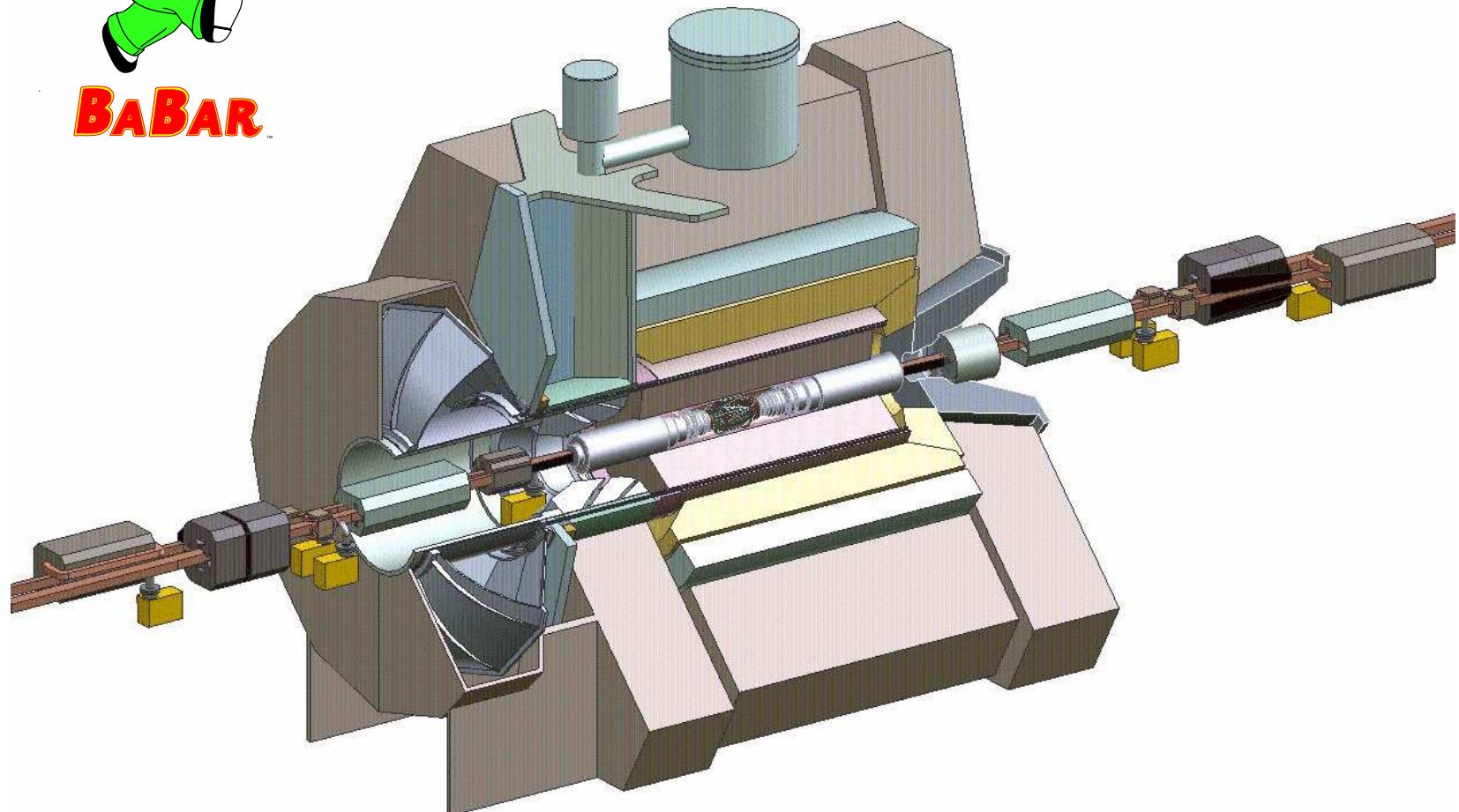
- Need hundreds of millions B mesons to study $\sim 10^{-6}$ decays
 - e^+e^- collider PEP-II
 - $E(e^-) > E(e^+)$ \Rightarrow boost B to measure decay time

“signal”: $e^+e^- \rightarrow \gamma(4S)(b\bar{b}) \rightarrow B\bar{B}$

“background”: $e^+e^- \rightarrow q\bar{q} \rightarrow \text{“jets”}$ $N_{B\bar{B}} \sim 384 \times 10^6$



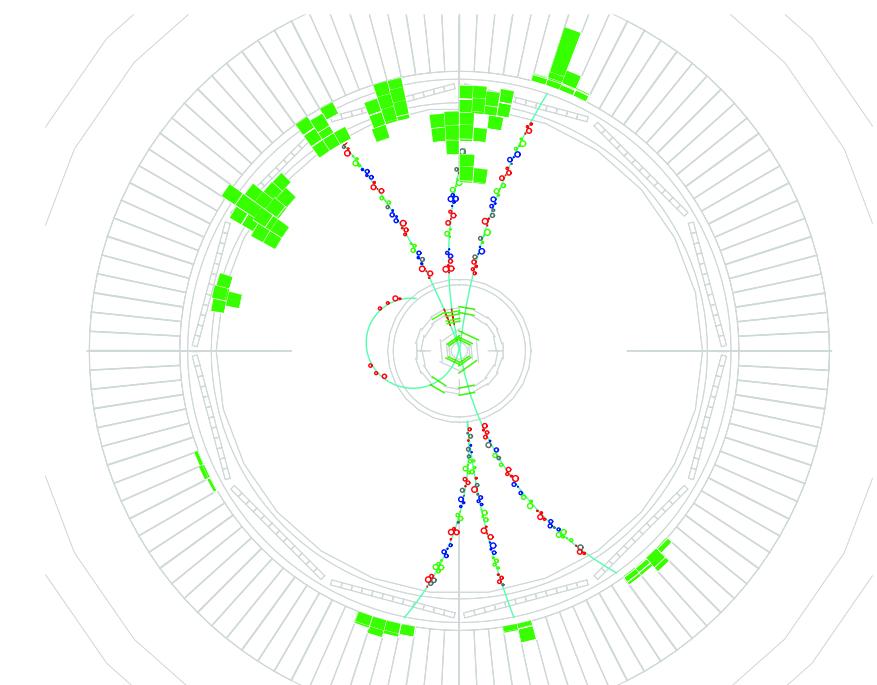
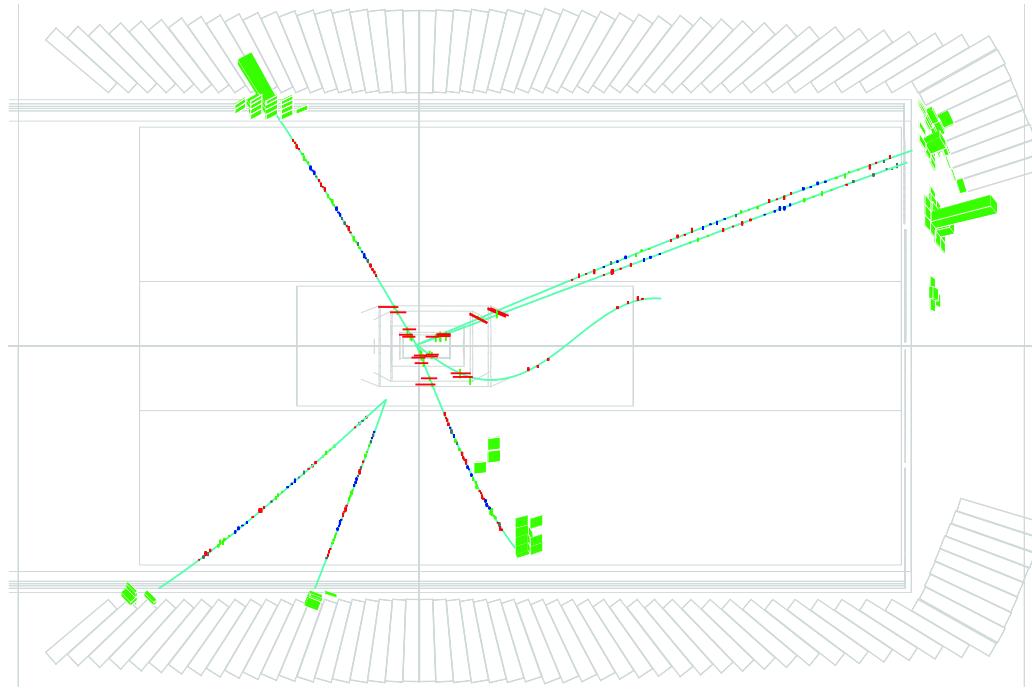
*B*_A*B*_{AR} Detector



- Silicon Vertex Tracker
- Drift Chamber
- Cherenkov Detector
- Electro-Magnetic Calorimeter
- Muon/Magnet system

Event Reconstruction

- Fully reconstruct B decay products, trigger $\sim 100\%$, photons
e.g. $B^0 \rightarrow \pi^+\pi^-$, $(\gamma\gamma)(\gamma\gamma)$, $\pi^+\pi^-(\gamma\gamma)(\gamma\gamma)$, $\pi^+\pi^-\pi^+\pi^-$, ...
- Do not fully reconstruct the other B , inclusive
from $\gamma(4S) \rightarrow B\bar{B}$



B -decay Analysis

Fully reconstruct e.g. $B \rightarrow \pi^+ \pi^- (\gamma\gamma)(\gamma\gamma)$

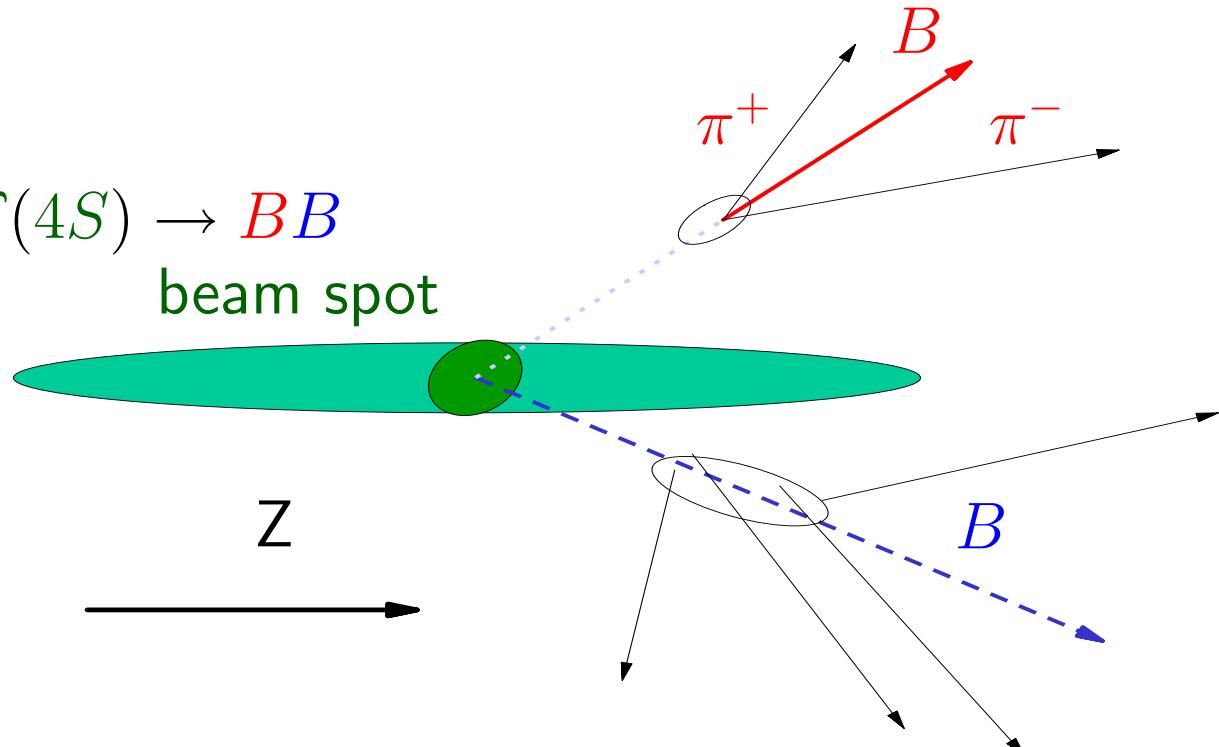
- Vertex
- Momentum
- Energy
- Particle Type ID

Constrain $e^+ e^- \rightarrow \Upsilon(4S) \rightarrow BB$

- $e^+ e^-$ beam momenta
- $e^+ e^-$ beam spot

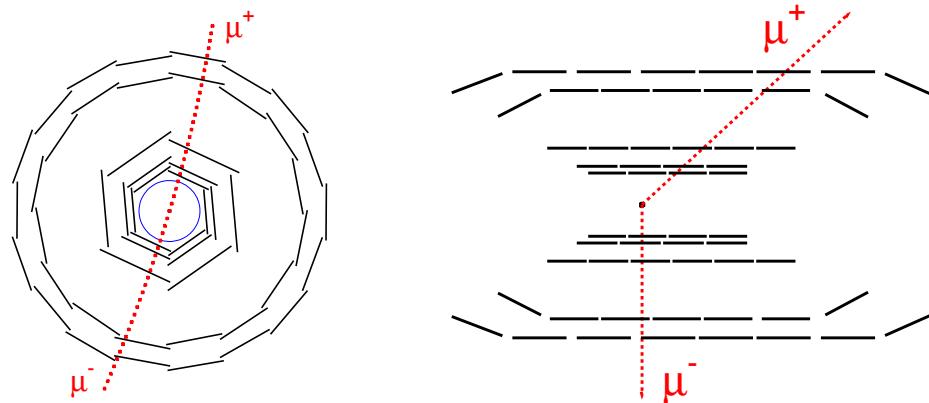
Look at the other B

- Event “shape”
- Vertex
- Flavor tagging (B/\bar{B})

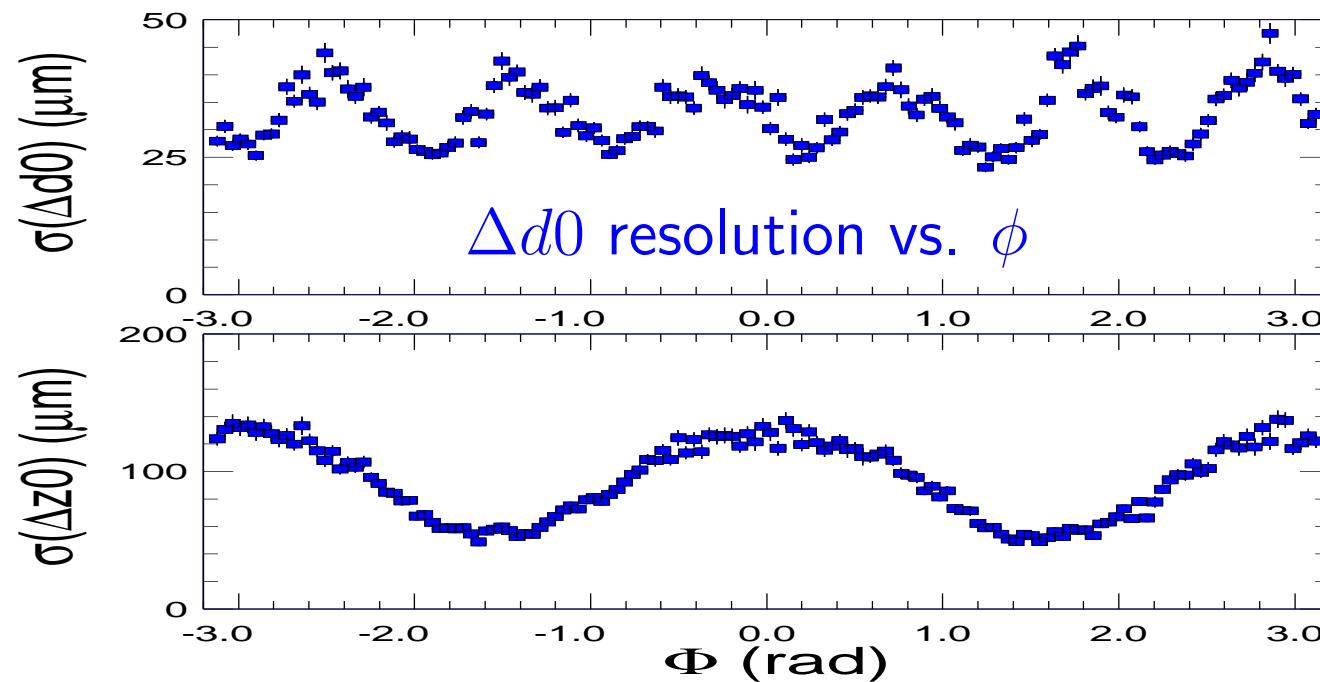


Silicon Tracker Resolution

- Impact parameter
(high p_T) $\sim 30\mu\text{m}$
- Beam-spot $\sigma(x,y,z)$
 $\sim(150, 5, 10000)\mu\text{m}$



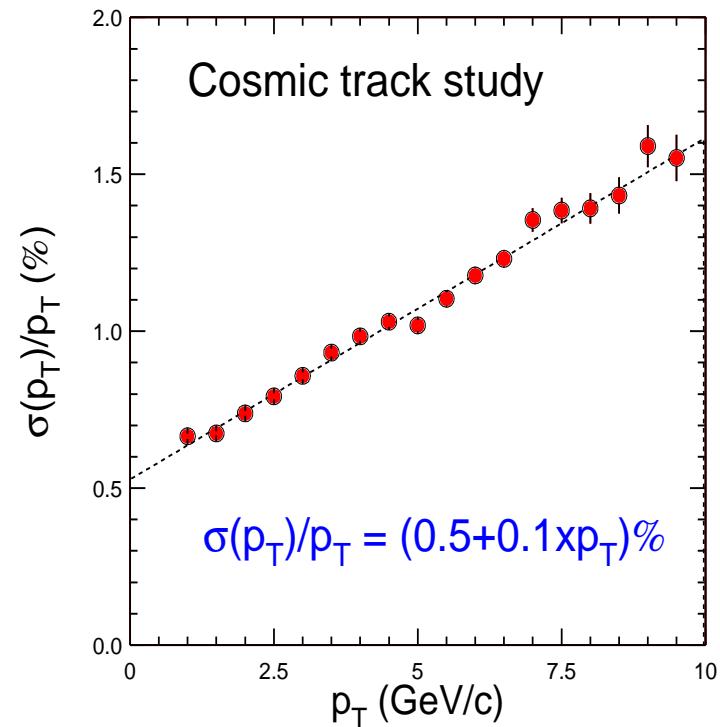
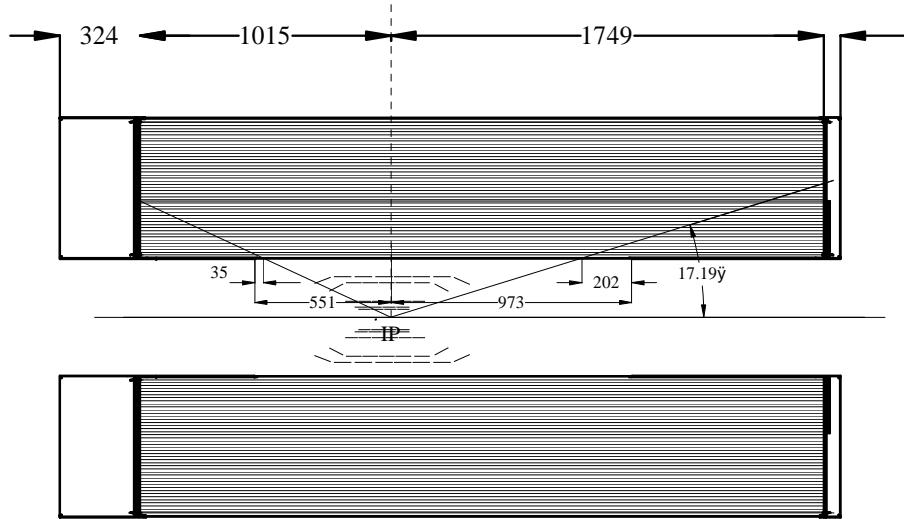
compare $\sigma_{\Delta Z_B} \sim 180\mu\text{m}$, $\beta\gamma c\tau_B \sim 250\mu\text{m}$



Tracking System

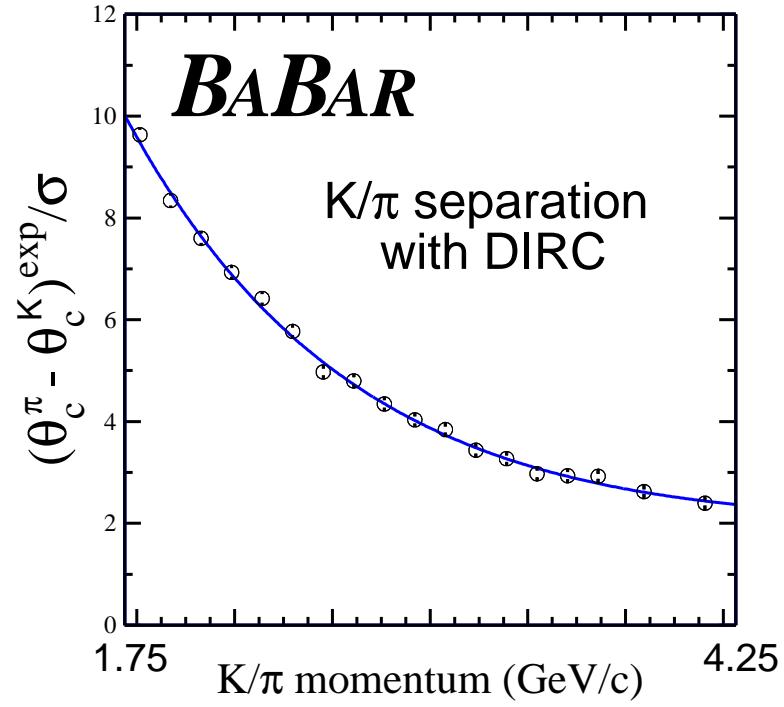
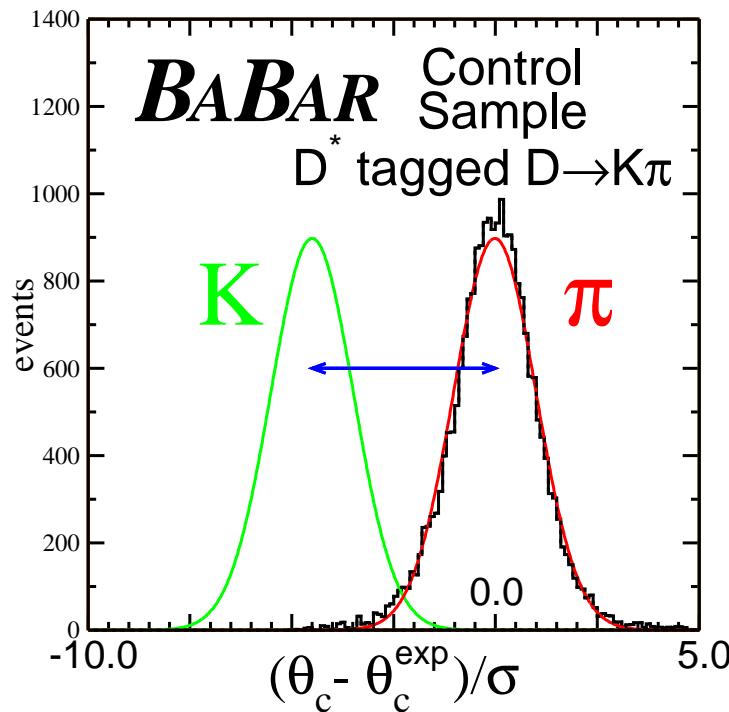
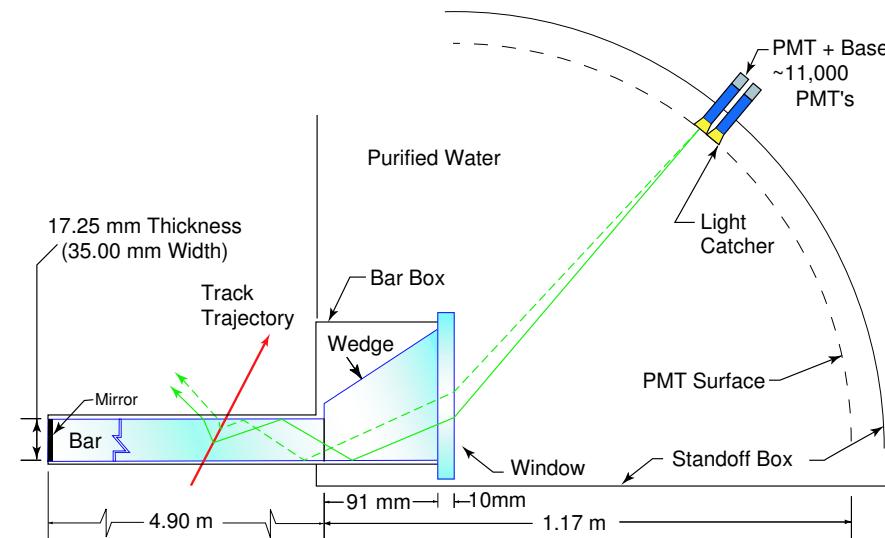
- Silicon Tracker (1) + Drift Chamber (2) \Rightarrow Particle Tracking
 - (1) dominates **position** and **angular**
 - (2) curvature (**momentum**) in the magnetic field

momentum $p_T \sim 1.5 \text{ GeV}/c$, $\sigma_{p_T} \sim 10 \text{ MeV}/c$



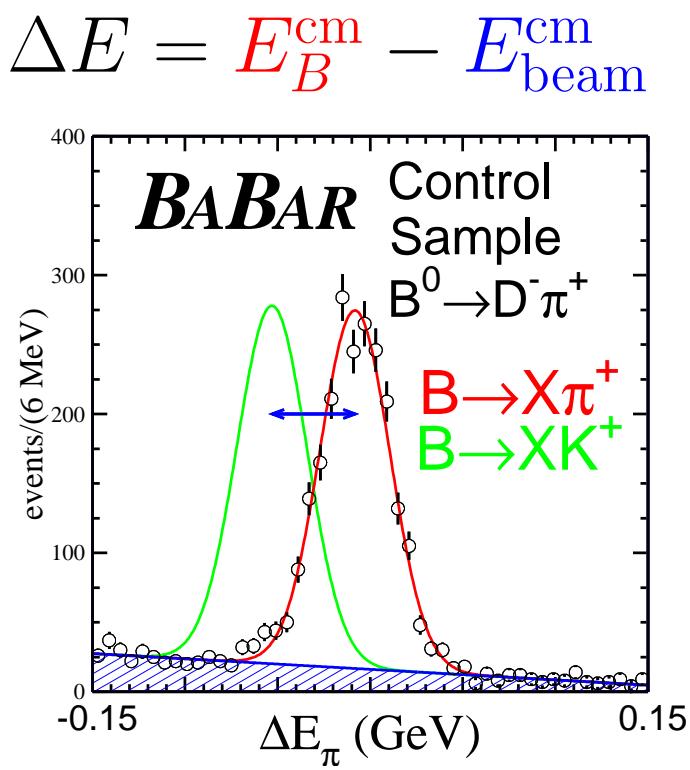
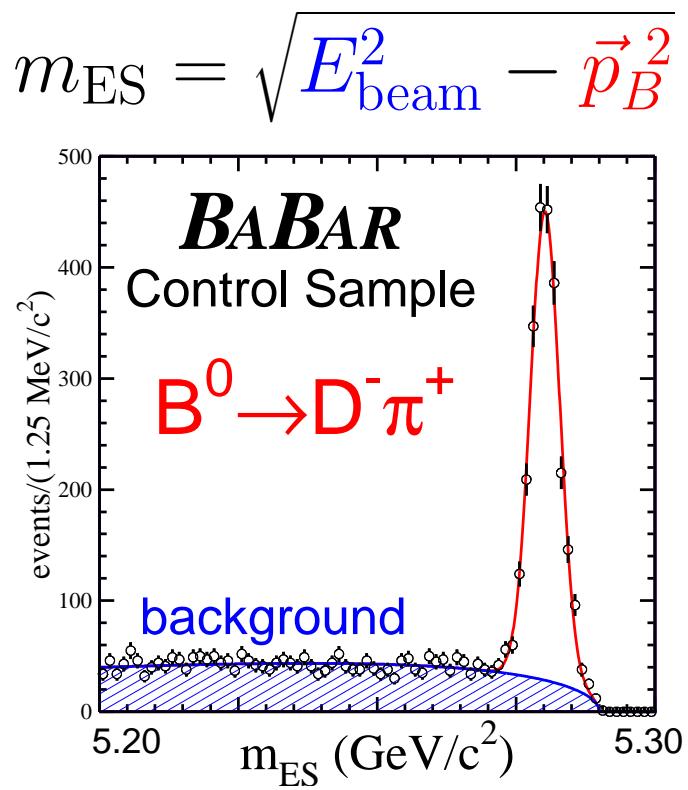
Particle Identification

- Cherenkov angle θ_c from DIRC
 - primary K/π separation
 - $\cos(\theta_c) = 1/\beta n$, $\theta_c = f(p, \text{mass})$
 - from 2.5 to $\sim 10\sigma$ separation
 - boost \Rightarrow momentum/angle correlation



Kinematic Observables

- Reconstruct e.g. $B \rightarrow \rho^0 \rho^+ \rightarrow (\pi^+ \pi^-)(\pi^+ \pi^0)$
 - Vector resonance **masses** ($m_{\pi\pi}$)
- Separate **signal/background** ($e^+ e^- \rightarrow \gamma \rightarrow B \bar{B}$)



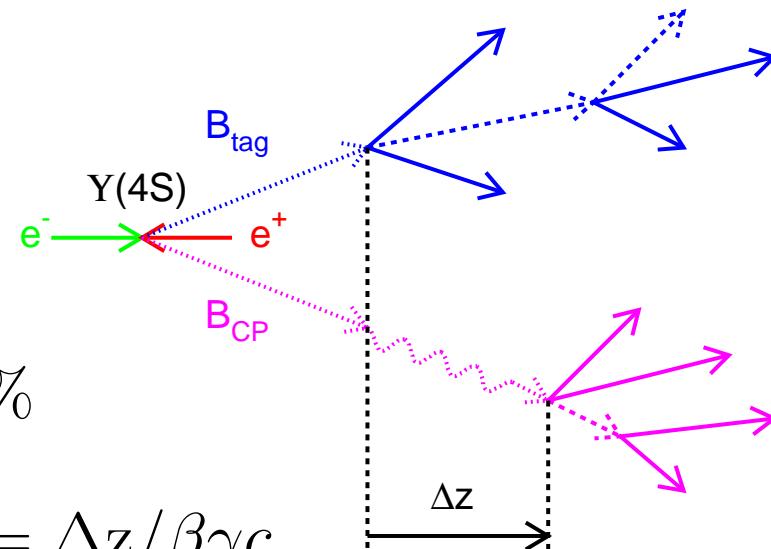
Explore the Other B

- Tag flavor B vs \bar{B} : Q_{tag}

$$B_{\text{tag}} \rightarrow K^+, \mu^+, \text{ etc}$$

$$\bar{B}_{\text{tag}} \rightarrow K^-, \mu^-, \text{ etc}$$

effective $Q = \sum \epsilon_i (1 - 2w_i)^2 \simeq 30\%$



- Measure proper decay time $\Delta t = \Delta z / \beta \gamma c$

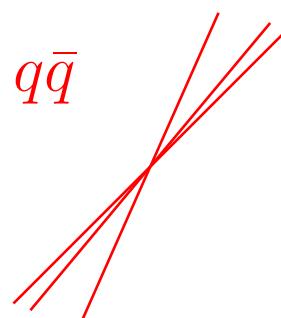
$$e^{-|\Delta t|/\tau_B} \times (1 \pm S(1-2w) \sin(\Delta m_d \Delta t) \dots)$$

$\otimes \mathcal{R}\text{es.}(\Delta z) \sim 180 \mu\text{m}$

study with $B \rightarrow D^{(*)-} \pi^+$, etc

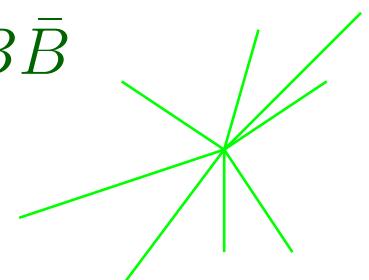
- Suppress “jetty” background:

$$e^+ e^- \rightarrow q\bar{q}$$



event-shape \mathcal{E} (NN, Fisher,...)

$$e^+ e^- \rightarrow B\bar{B}$$



Computing and Analysis

- BABAR \sim Petabyte of data

- (1) Select $N \sim$ few k events/analysis:



$$\vec{x}_j = (m_{\text{ES}}, \Delta E, m_k, \theta_k, \dots, \mathcal{E}, Q_{\text{tag}}, \Delta t)$$



- (2) Extract signal yield (vs. background) and parameters:

$$\text{likelihood } \mathcal{L} = \exp \left(- \sum_i n_i \right) \prod_{j=1}^N \left(\sum_i n_i \mathcal{P}_i(\vec{x}_j; \vec{\xi}) \right) = \text{maximum}$$

- Probability Density Function:

$$\mathcal{P}_i(\vec{x}_j) = \mathcal{P}_{i1}(m_{\text{ES}}) \cdot \mathcal{P}_{i2}(\Delta E) \cdot \mathcal{P}_{i3}(\mathcal{E}) \cdot \mathcal{P}_{i4}(\Delta t, Q_{\text{tag}}, S, C)$$

or in more complex case (angular/mass/Dalitz analysis)

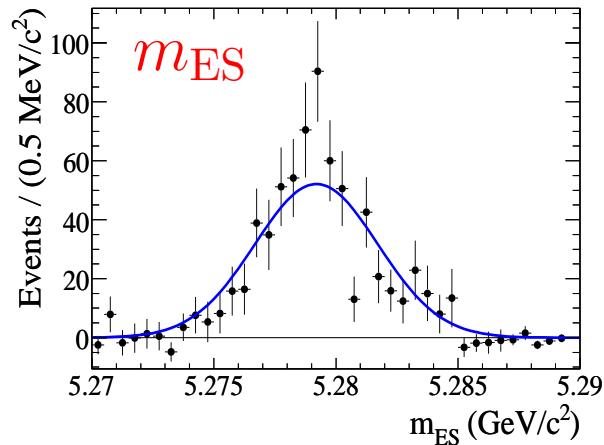
$$\times \mathcal{P}_{i4}(\theta_k, m_k, \dots, \Delta t, Q_{\text{tag}}, S, C, \vec{\xi})$$

$$B\rightarrow \pi\pi$$

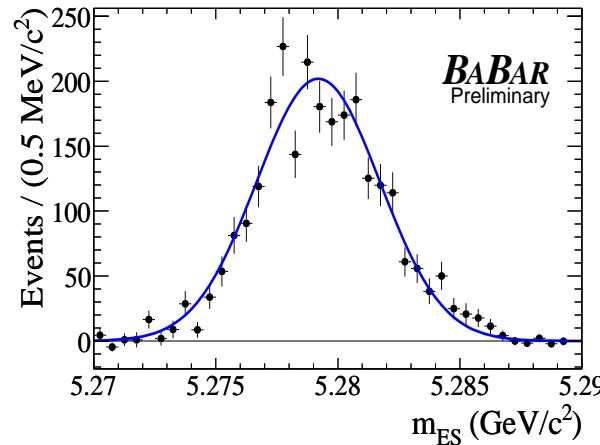
$B^0 \rightarrow \pi^+ \pi^-$

- Combined fit of $B^0 \rightarrow \pi^+ \pi^-$ and $K^\pm \pi^\mp$, DIRC PID in the fit

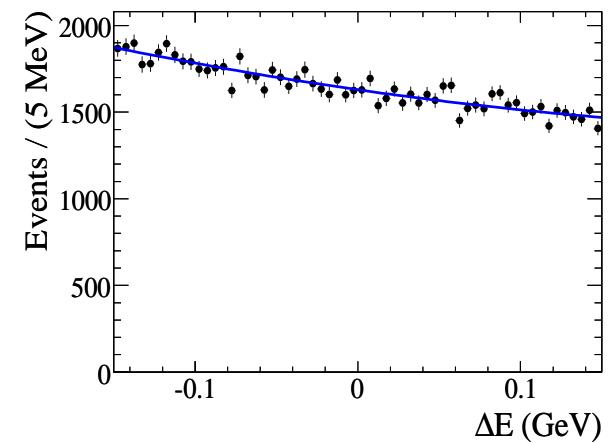
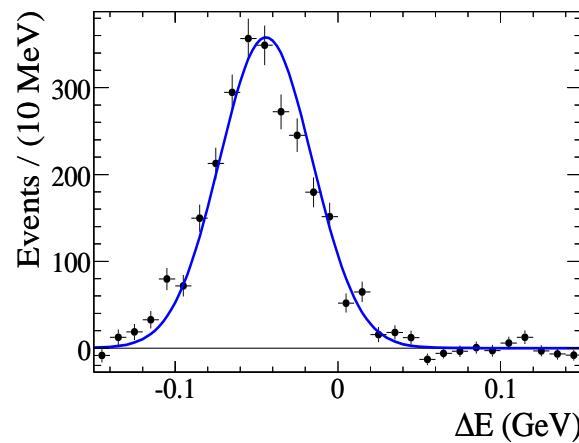
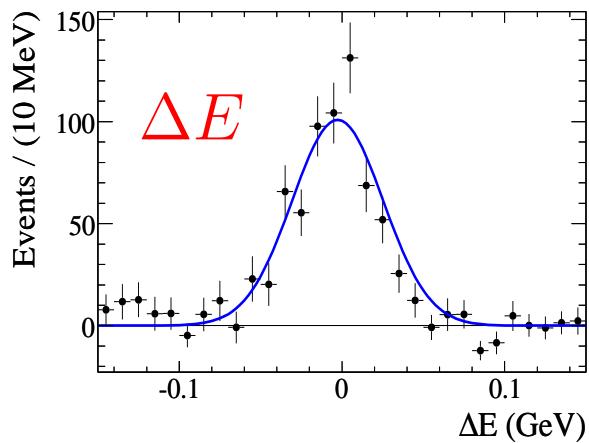
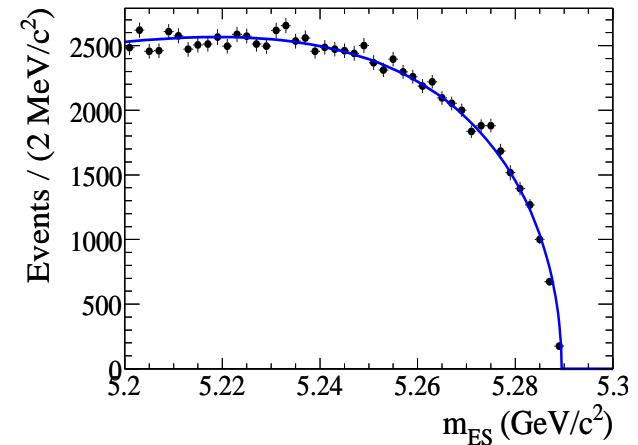
$$N_{\pi\pi} = 675 \pm 42$$



$$N_{K\pi} = 2542 \pm 67$$



combinatorics

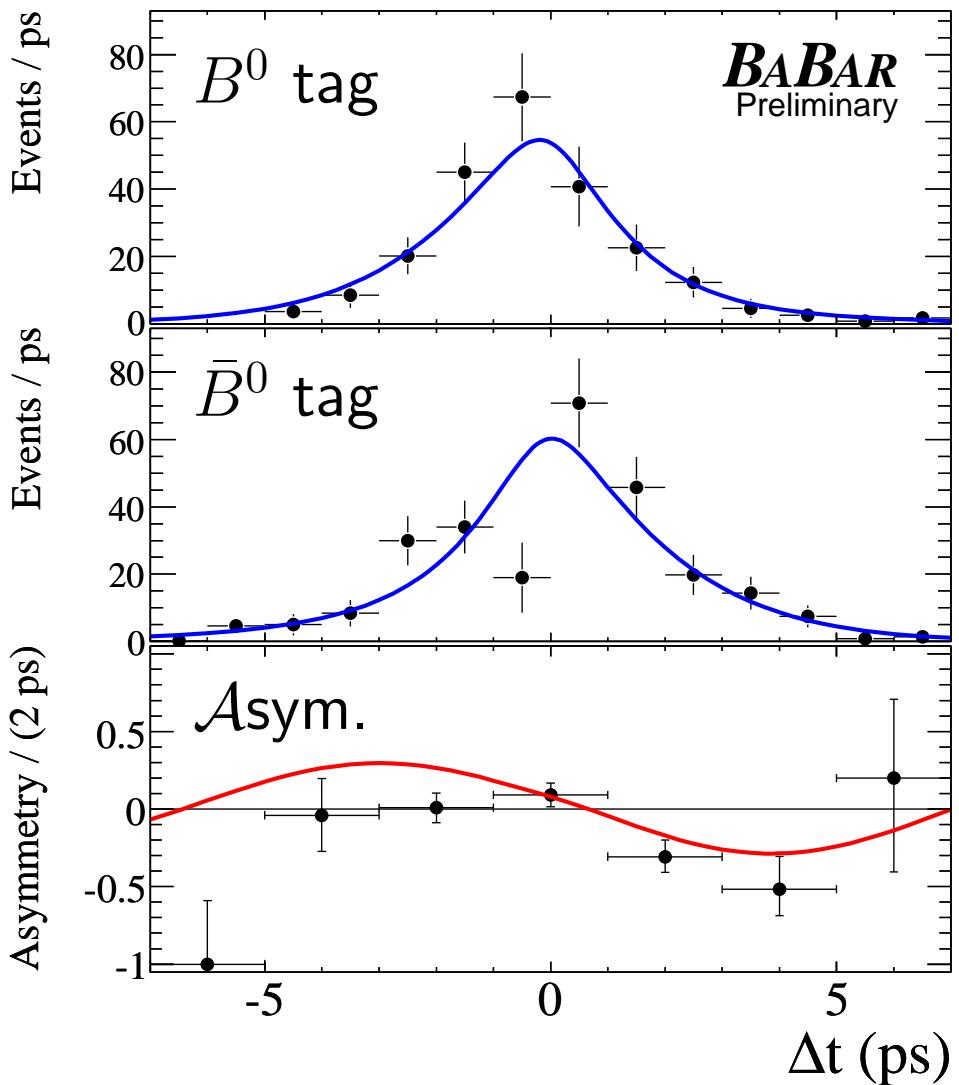


“sPlots” arXiv:[physics/0402083](https://arxiv.org/abs/physics/0402083)

[hep-ex/0607106](https://arxiv.org/abs/hep-ex/0607106)

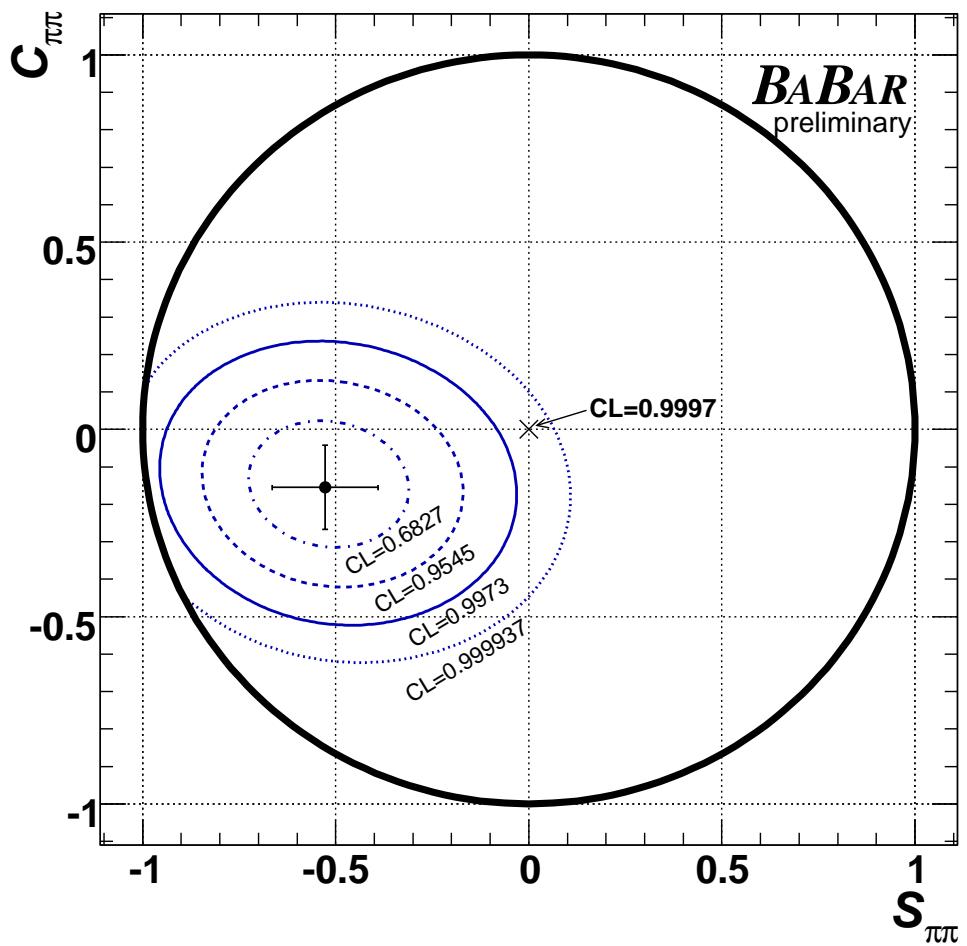
$CP(t)$ in $B^0 \rightarrow \pi^+ \pi^-$

$$S \sin(\Delta m \Delta t) - C \cos(\Delta m \Delta t)$$



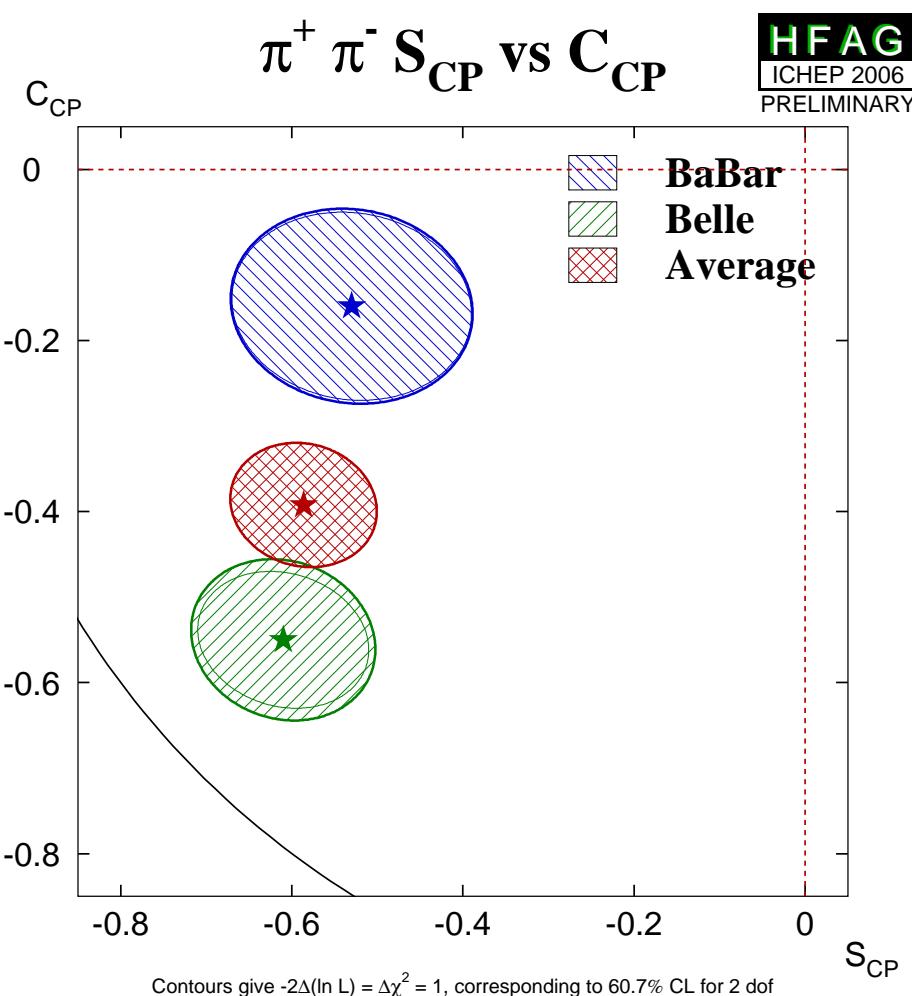
$$S = -0.53 \pm 0.14 \pm 0.02$$

$$C = -0.16 \pm 0.11 \pm 0.03$$



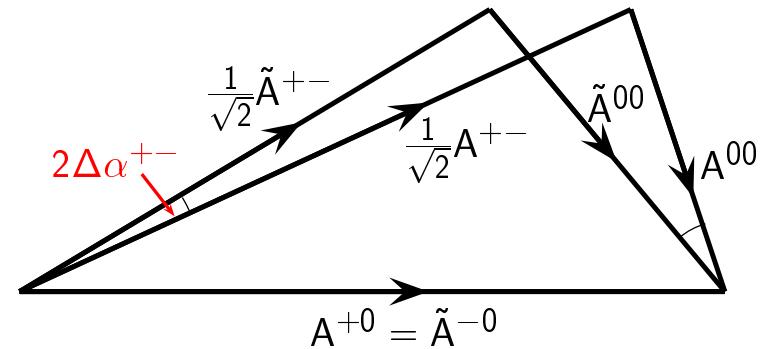
$B^0 \rightarrow \pi^+ \pi^-$

- CP violation established in $B^0 \rightarrow \pi^+ \pi^-$, in part due to penguin
 \Rightarrow getting α is difficult



$$\alpha_{\text{eff}} = \frac{1}{2} \sin^{-1} \left(\frac{S}{\sqrt{1 - C^2}} \right)$$

$$\alpha = \alpha_{\text{eff}} + \Delta\alpha^{+-}$$



need to measure:

$$B^+ \rightarrow \pi^0 \pi^+$$

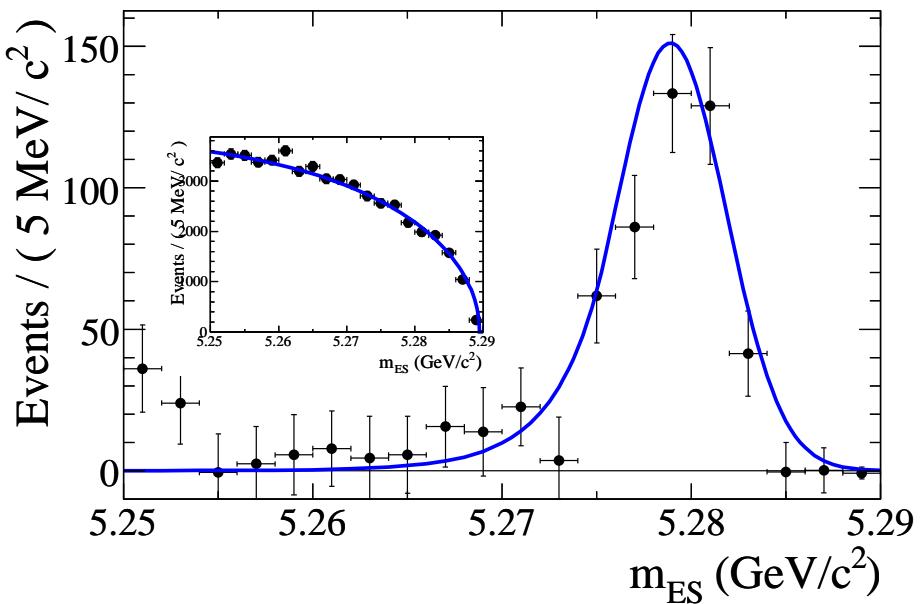
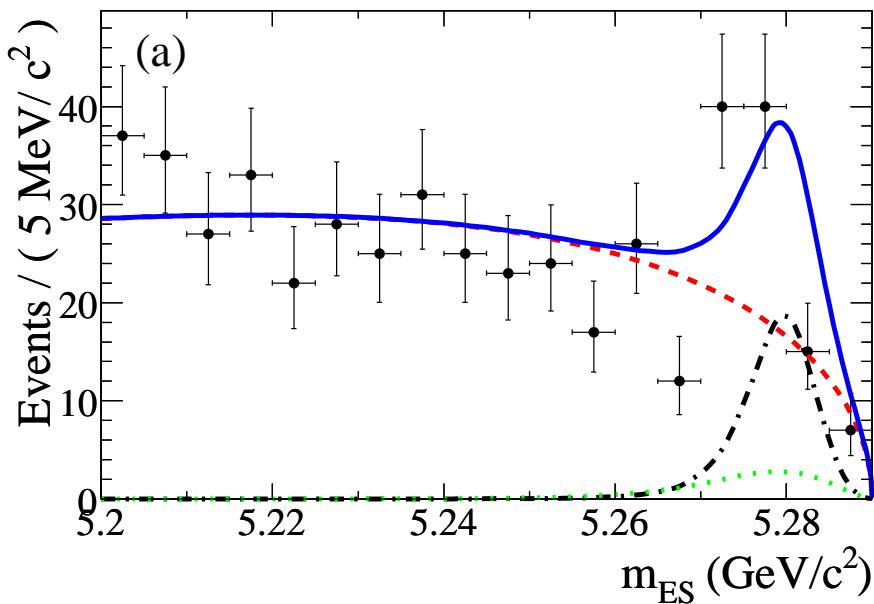
$$B^0 \rightarrow \pi^0 \pi^0$$

$B^0 \rightarrow \pi^0\pi^0$ and $B^+ \rightarrow \pi^+\pi^0$

- Significant signal in both modes:

$$N(B^0 \rightarrow \pi^0\pi^0) = 140 \pm 25$$

$$N(B^+ \rightarrow \pi^+\pi^0) = 572 \pm 53$$



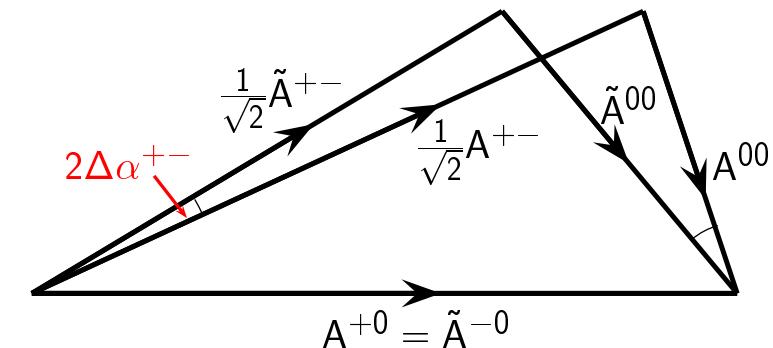
- No S^{00} possible with $B^0 \rightarrow \pi^0\pi^0$ (no vertex):

$$\mathcal{B}^{00} = (1.48 \pm 0.26 \pm 0.12) \times 10^{-6} \quad \mathcal{B}^{0+} = (5.12 \pm 0.47 \pm 0.29) \times 10^{-6}$$

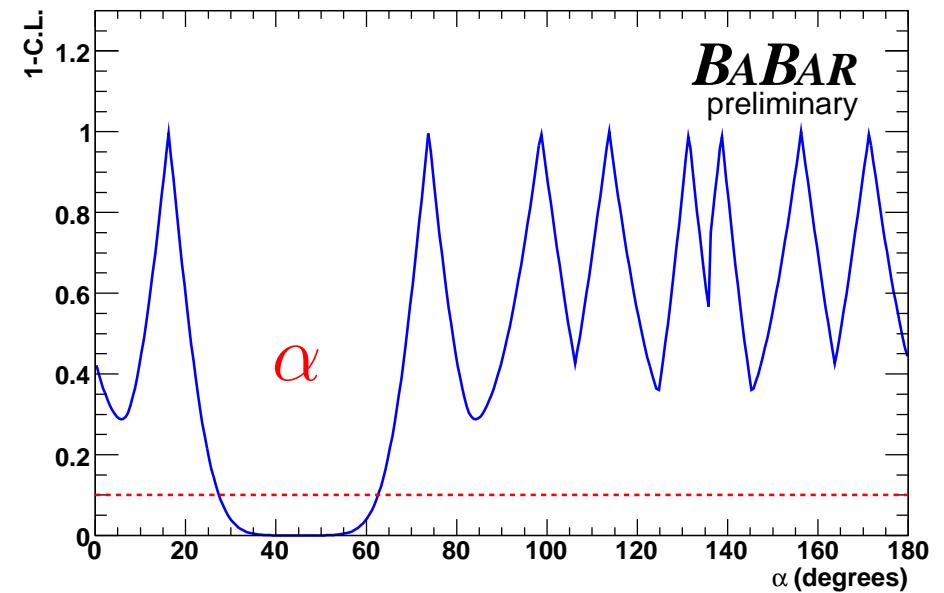
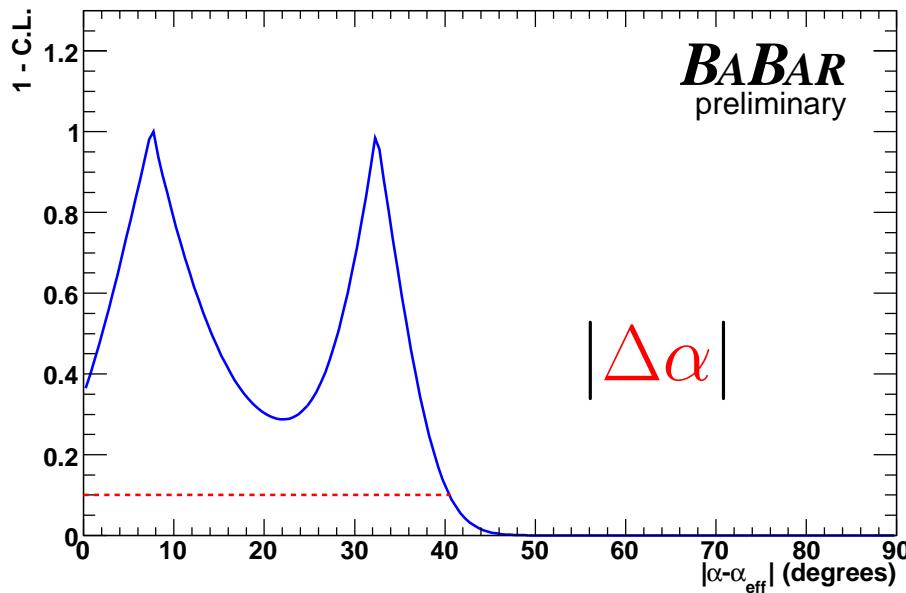
$$C^{00} = -0.33 \pm 0.36 \pm 0.08$$

Penguin Pollution and α with $B \rightarrow \pi\pi$

	α_T	α_C	α_P	$\mathcal{B}(10^{-6})$	C
$\pi^+\pi^-$	$\sqrt{2}$	0	$\sqrt{2}$	$5.8 \pm 0.4 \pm 0.3$	$-0.16 \pm 0.11 \pm 0.03$
$\pi^+\pi^0$	1	1	0	$5.1 \pm 0.5 \pm 0.3$	—
$\pi^0\pi^0$	0	1	-1	$1.5 \pm 0.4 \pm 0.1$	$-0.33 \pm 0.36 \pm 0.08$



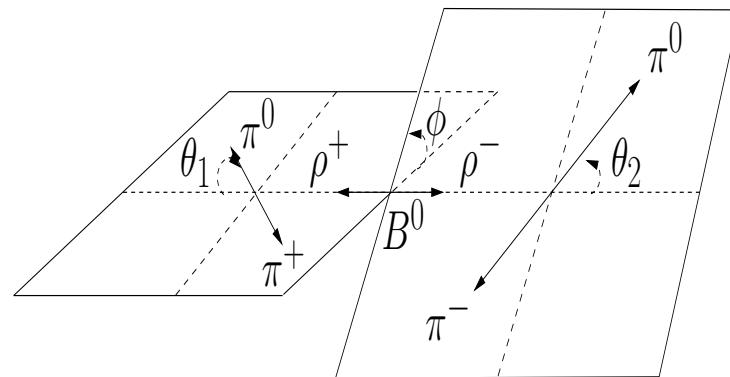
- Ambiguities: 4 triangle orientations \Rightarrow 4-fold $\Delta\alpha$
 $\alpha \leftrightarrow (90^\circ - \alpha) \Rightarrow \times 2 \Rightarrow$ 8-fold α
- penguin pollution: $|\Delta\alpha| < 41^\circ$ at 90% CL vs. $\sigma(\alpha_{\text{eff}}) \sim 5^\circ$



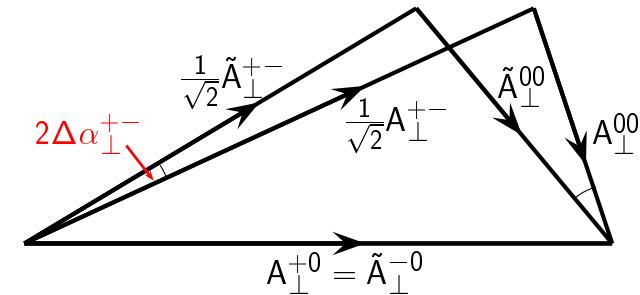
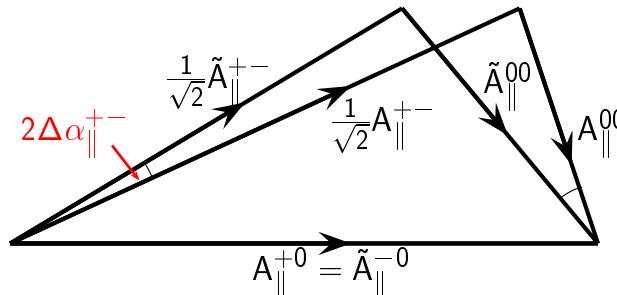
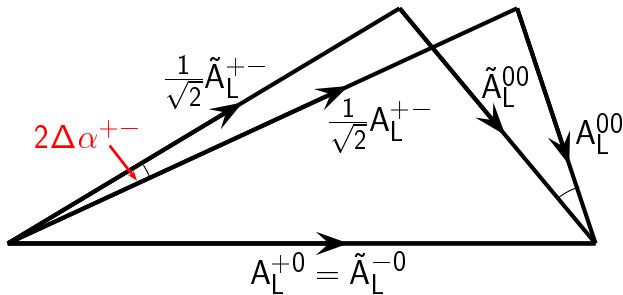
$$B\rightarrow \rho\rho$$

$B \rightarrow \rho\rho$

- $B \rightarrow \rho\rho$ like $B \rightarrow \pi\pi$
 - but 3 amplitudes:
 A_0 , $A_{||}$ (P-even), A_{\perp} (P-odd)



- Three sets of $S_{L/\parallel/\perp}$ and $C_{L/\parallel/\perp}$, and triangles:



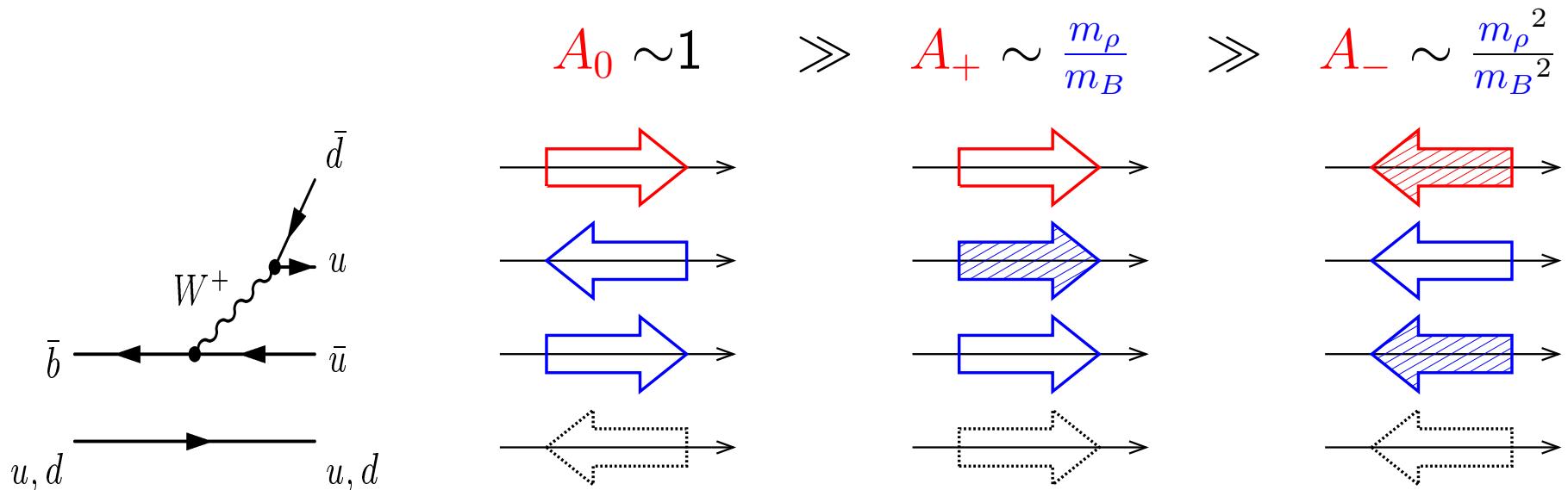
- Need angular analysis to separate A_0 , $A_{||}$, A_{\perp} :

$$d\Gamma \propto \cos^2 \theta_1 \cos^2 \theta_2 |A_0|^2 + \frac{1}{4} \sin^2 \theta_1 \sin^2 \theta_2 (|A_{||}|^2 + |A_{\perp}|^2)$$

- Do not need full angular analysis ...

Longitudinal Polarization in $B \rightarrow \rho\rho$

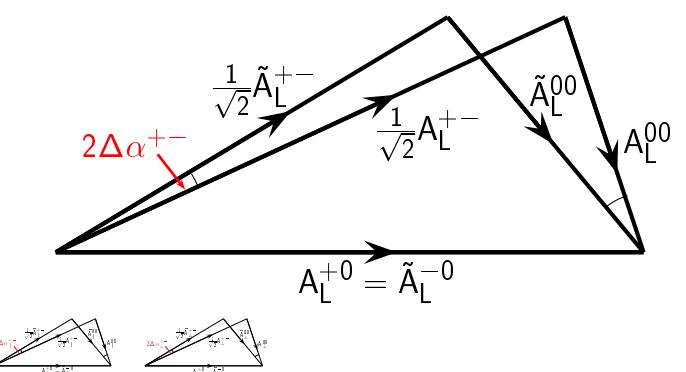
- Fortunately A_0 dominates \Rightarrow just like $B \rightarrow \pi\pi$
 $(V - A)$ of weak interactions and spin flip suppression:



- Experimentally:

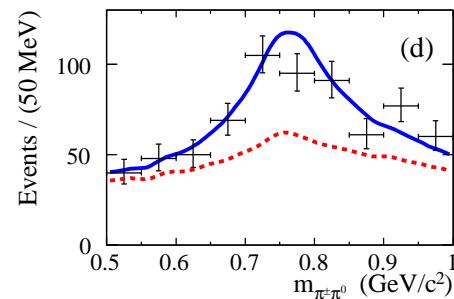
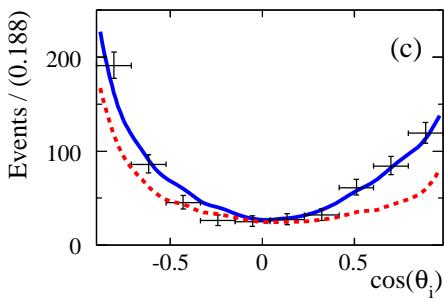
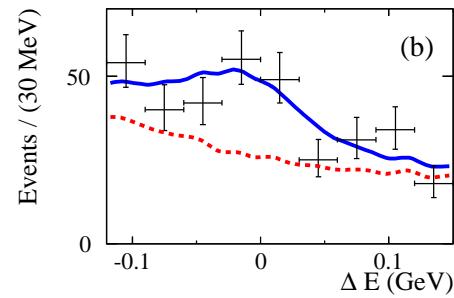
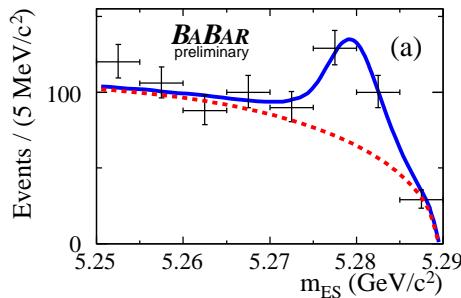
$$f_L(\rho^+\rho^-) = |A_0^{+-}|^2 / \sum |A_\lambda^{+-}|^2 = 0.97 \pm 0.02$$

$$f_L(\rho^+\rho^0) = |A_0^{+0}|^2 / \sum |A_\lambda^{+0}|^2 = 0.91 \pm 0.05$$

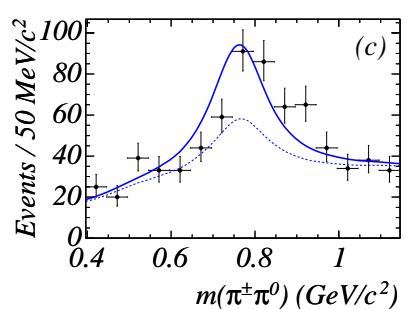
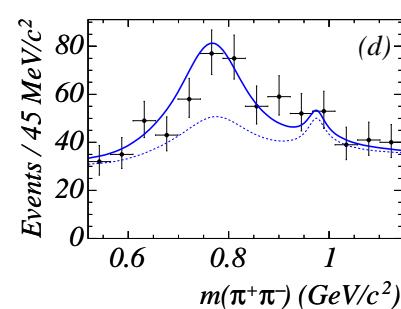
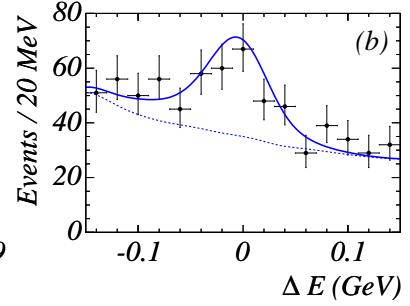
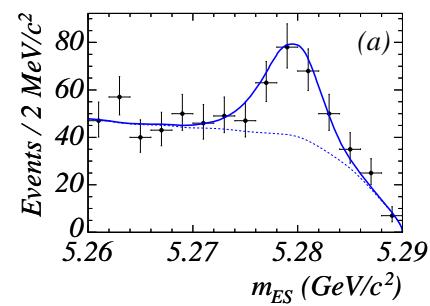


$B \rightarrow \rho^+ \rho^-$

$$N(\rho^+ \rho^-) = 615 \pm 57$$



$$N(\rho^+ \rho^0) = 390 \pm 49$$



$$\mathcal{B}^{+-} = (23.5 \pm 2.2 \pm 4.1) \times 10^{-6}$$

$$\mathcal{B}^{+0} = (16.8 \pm 2.2 \pm 2.3) \times 10^{-6}$$

$$f_L = 0.977 \pm 0.024^{+0.015}_{-0.013}$$

$$f_L = 0.905 \pm 0.042^{+0.023}_{-0.027}$$

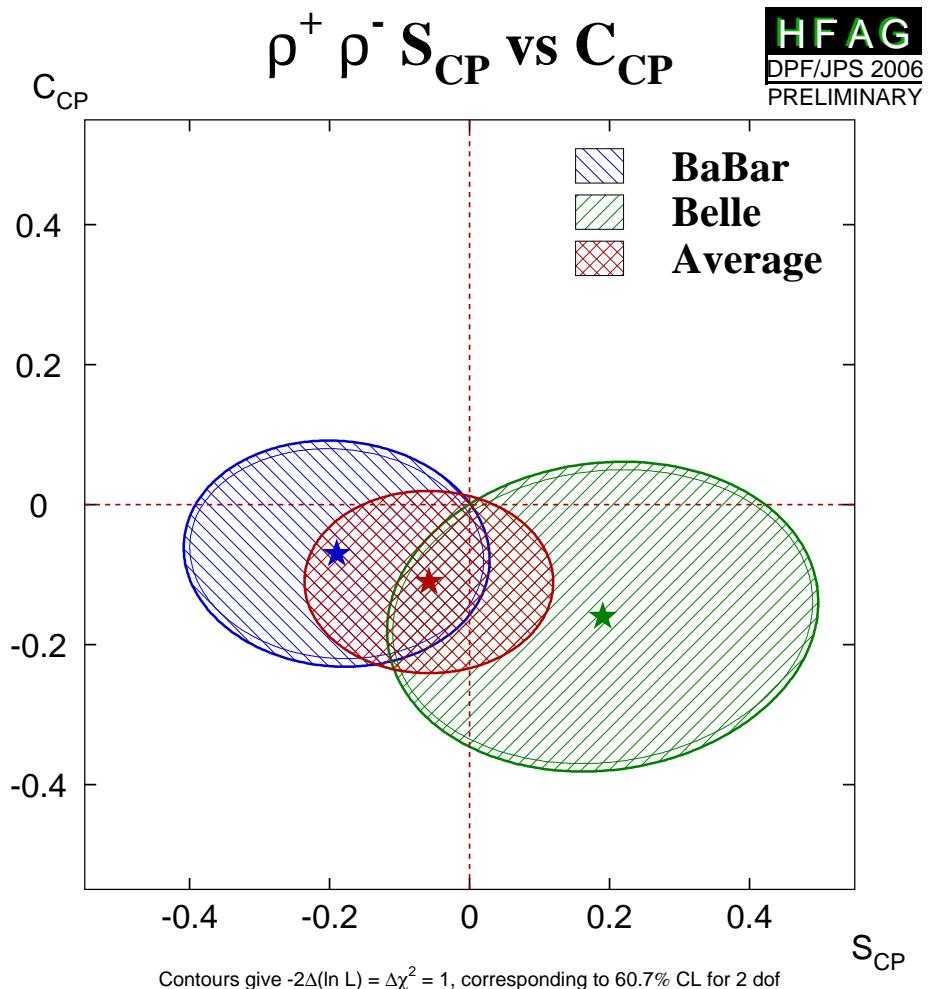
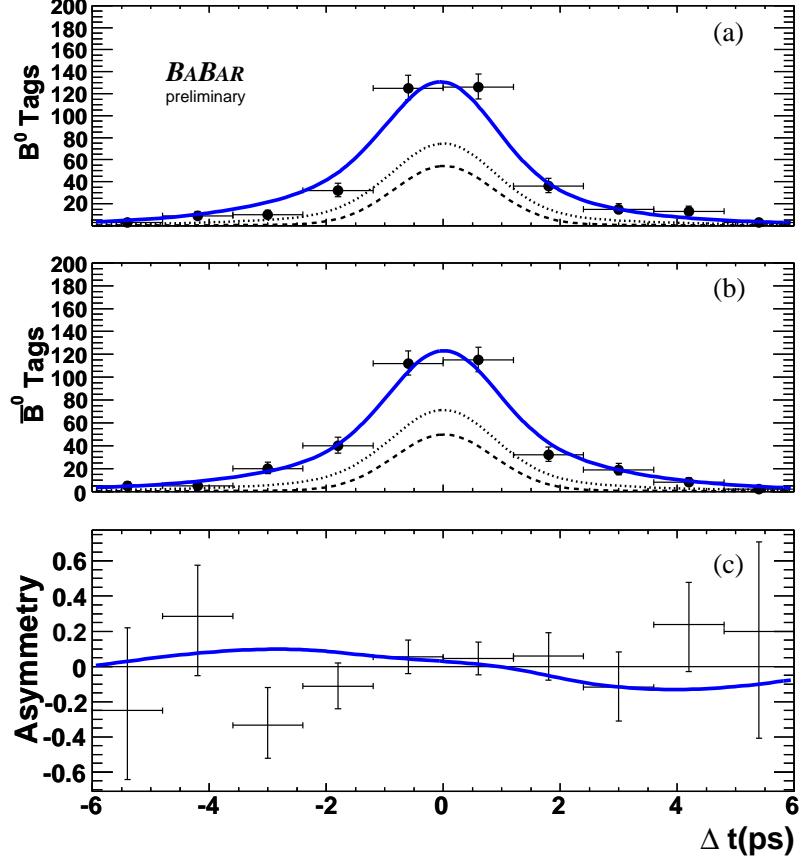
- Note: $\mathcal{B}(\rho^+ \rho^-) > \mathcal{B}(\pi^+ \pi^-)$; $f_L(\rho^+ \rho^-) \sim 1$

hep-ex/0607092, 0607098

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

- CP in $B^0 \rightarrow \rho^+ \rho^-$ $\alpha_{\text{eff}} = \frac{1}{2} \sin^{-1} (\textcolor{red}{S}_L / \sqrt{1 - \textcolor{red}{C}_L^2}) = (95.5^{+6.9}_{-6.2})^\circ$

$$\textcolor{red}{S}_L = -0.19 \pm 0.21^{+0.05}_{-0.07} \quad \textcolor{red}{C}_L = -0.07 \pm 0.15 \pm 0.06$$



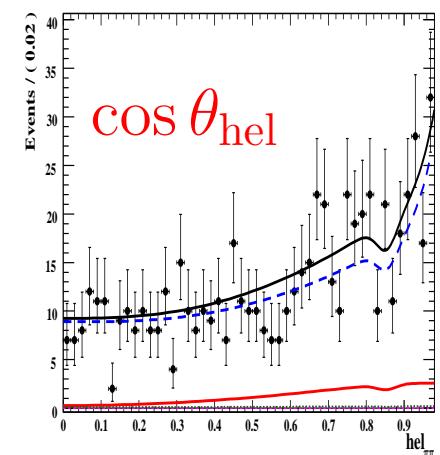
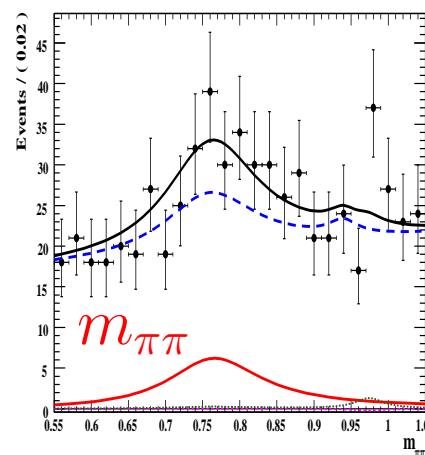
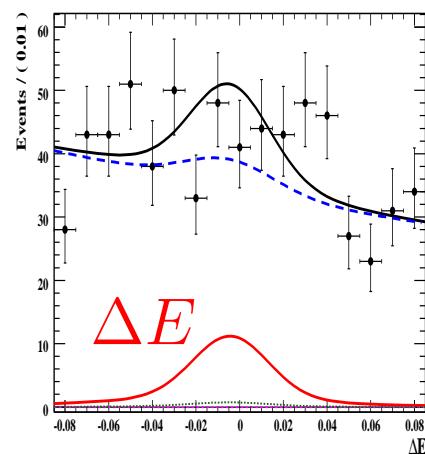
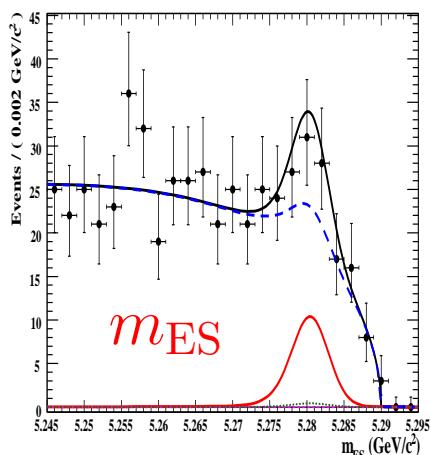
Taming the Penguin with $B \rightarrow \rho^0 \rho^0$ (**new**)

$$N(\rho^0 \rho^0) = 100^{+32}_{-31} \pm 17 \quad \Rightarrow \quad 3.5\sigma \text{ evidence} \quad \text{hep-ex/0612021}$$

$$f_L = 0.87^{+0.12}_{-0.13} \pm 0.04$$

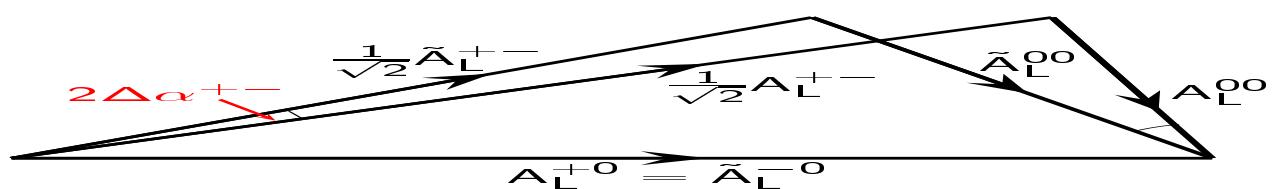
$$\mathcal{B} = (1.07^{+0.34+0.19}_{-0.32-0.18}) \times 10^{-6}$$

note: $\mathcal{B}(\rho^0 \rho^0) < \mathcal{B}(\pi^0 \pi^0)$



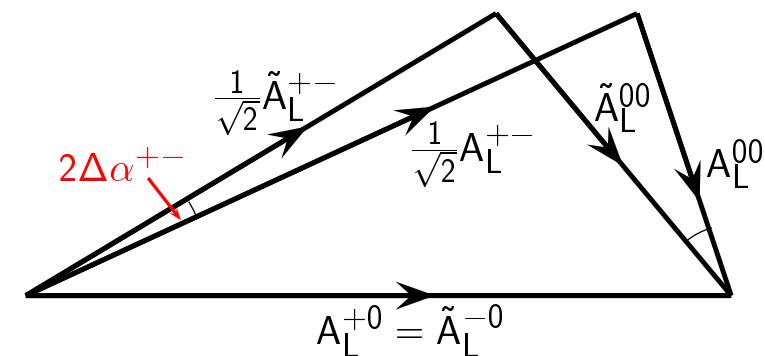
interference with $B^0 \rightarrow a_1^\pm \pi^\mp \rightarrow (\rho^0 \pi^\pm) \pi^\mp$ systematics

- Uncertainty on α is very sensitive to $B \rightarrow \rho^0 \rho^0$:



Penguin Pollution and α with $B \rightarrow \rho\rho$

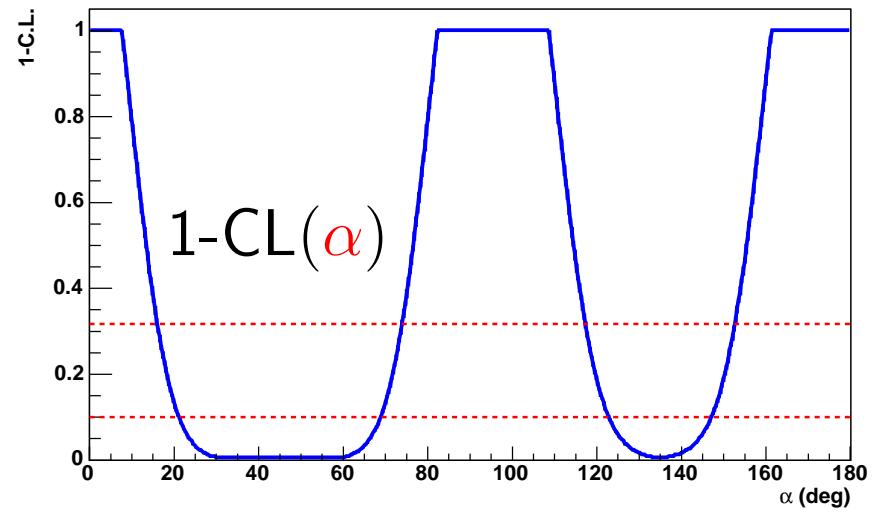
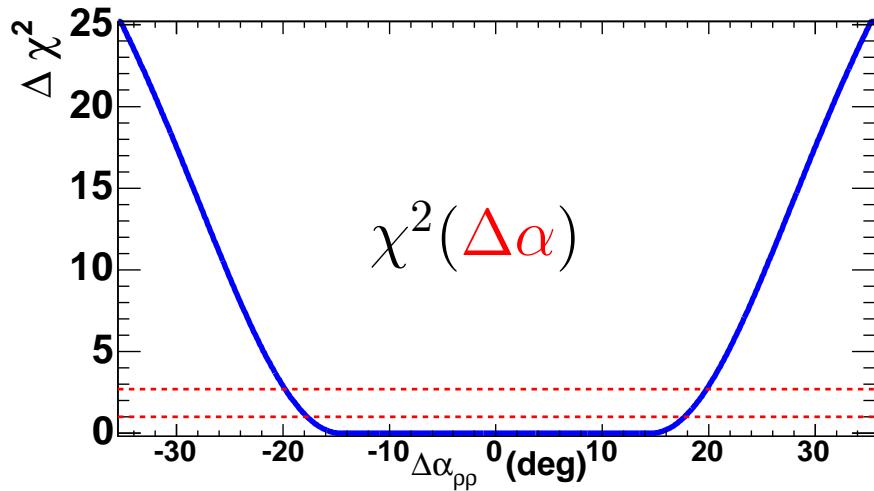
	α_T	α_C	α_P	$\mathcal{B}(10^{-6})$	f_L
$\rho^+ \rho^-$	$\sqrt{2}$	0	$\sqrt{2}$	$23.5 \pm 2.2 \pm 4.1$	$0.977 \pm 0.024^{+0.015}_{-0.013}$
$\rho^+ \rho^0$	1	1	0	$16.8 \pm 2.2 \pm 2.3$	$0.905 \pm 0.042^{+0.023}_{-0.027}$
$\rho^0 \rho^0$	0	1	-1	$1.07^{+0.34}_{-0.32} {}^{+0.19}_{-0.18}$	$0.87^{+0.12}_{-0.13} \pm 0.04$



- Ambiguities: 4 triangle orientations \Rightarrow merged into one $\Delta\alpha$ range
 $\alpha \leftrightarrow (90^\circ - \alpha)$ (no C^{00} measured yet)

penguin: $|\Delta\alpha| < 18^\circ$ at 68% CL

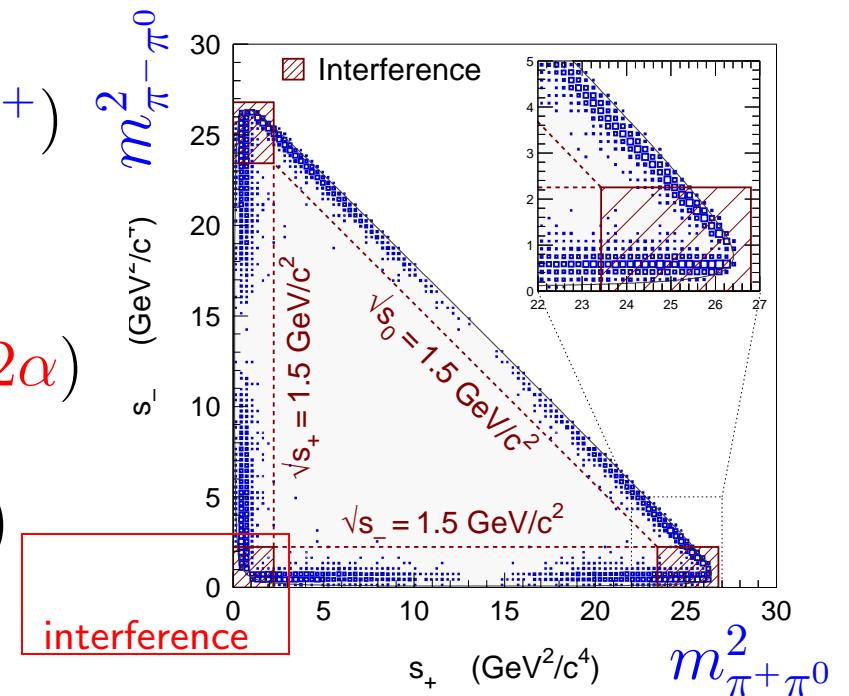
$\alpha \in (74^\circ, 117^\circ)$ at 68% CL



$$B\rightarrow \rho\pi$$

Resolving $(90^\circ - \alpha)$ Ambiguities

- $\sin(2\alpha) \Rightarrow$ ambiguity $\alpha \leftrightarrow (90^\circ - \alpha)$, e.g. $B \rightarrow \pi\pi, \rho\pi, (\rho\rho)_L$, etc
- Angular-time analysis of $B^0 \rightarrow \rho^+ \rho^-$ could solve:
 - $\mathcal{Im}(A_0(t)A_\perp(t)^*) \Rightarrow \cos(2\alpha) \sin(\Delta m \Delta t)$
 - hopeless with $f_L \sim 98\%$
- Dalitz-time analysis of $B^0 \rightarrow \pi^+ \pi^- \pi^0$
 - interference $A^+(\rho^+ \pi^-)$ and $A^-(\rho^- \pi^+)$
 - $\mathcal{Im}(f_+ f_-^* e^{-i2\alpha}) =$
 - $\mathcal{Im}(f_+ f_-^*) \cos(2\alpha) + \mathcal{Re}(f_+ f_-^*) \sin(2\alpha)$
 - f_+ and f_- Dalitz params. (e.g. BW)



Dalitz analysis of $B \rightarrow \rho\pi$

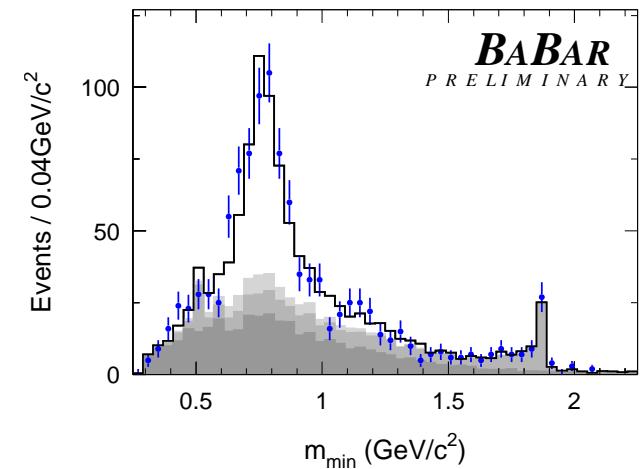
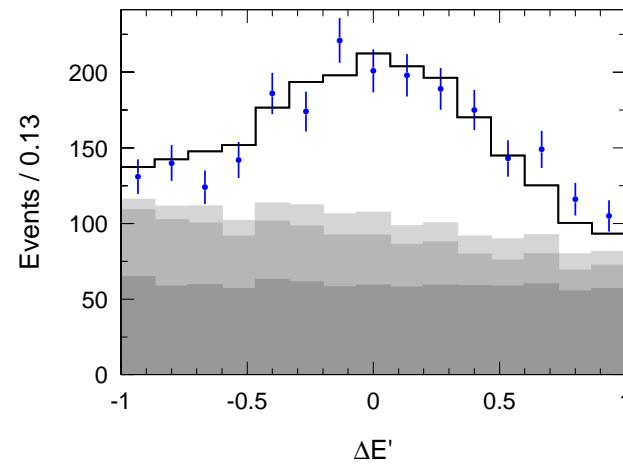
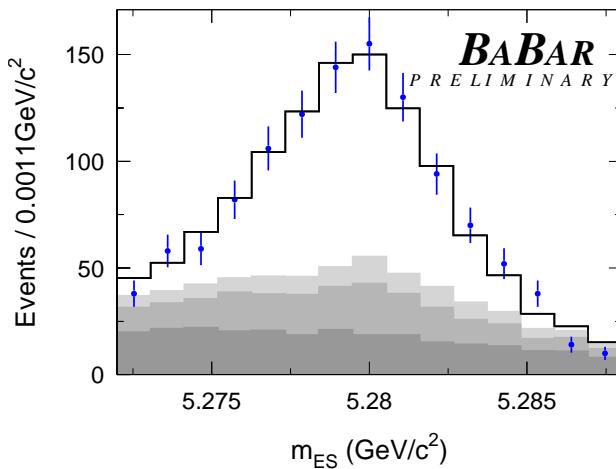
- Dalitz-time analysis of $B \rightarrow \pi^+\pi^-\pi^0$ $N(3\pi) = 1847 \pm 69$

– key: **time**-dependence and **interference** of $\rho^+\pi^-$ and $\rho^-\pi^+$

$$|\mathcal{A}_{3\pi}^\pm(t)|^2 = \frac{e^{-|t|/\tau_{B^0}}}{4\tau_{B^0}} \left[|\mathcal{A}_{3\pi}|^2 + |\bar{\mathcal{A}}_{3\pi}|^2 \mp (|\mathcal{A}_{3\pi}|^2 - |\bar{\mathcal{A}}_{3\pi}|^2) \cos(\Delta mt) \right. \\ \left. \pm 2\mathcal{I}m[(q/p)\bar{\mathcal{A}}_{3\pi}\mathcal{A}_{3\pi}^*] \sin(\Delta mt) \right]$$

- Function of Dalitz plot (s_1, s_2): $\cos(2\alpha)$ & $\sin(2\alpha)$

$$\mathcal{A}_{3\pi} = f_+(s_1, s_2) A^+(\rho^+\pi^-) + f_-(s_1, s_2) A^-(\rho^-\pi^+) + f_0(s_1, s_2) A^0(\rho^0\pi^0)$$



Dalitz analysis of $B \rightarrow \rho\pi$

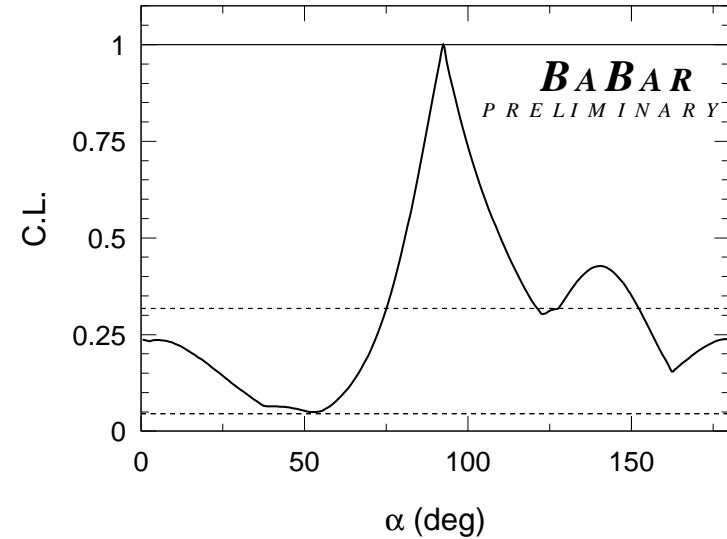
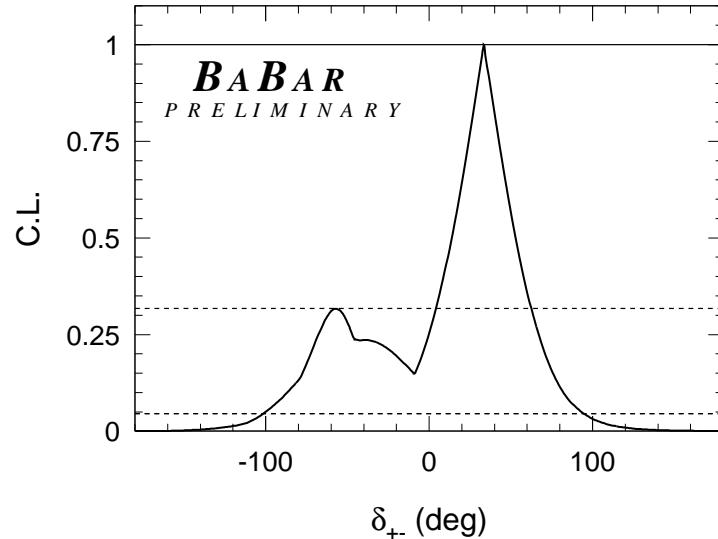
- Get Q2B parameters: $S = -0.01 \pm 0.12 \pm 0.028$ $\Delta S = 0.06 \pm 0.13 \pm 0.029$
 $C = -0.154 \pm 0.090 \pm 0.037$ $\Delta C = 0.377 \pm 0.091 \pm 0.021$

- SM penguin pollution $P(\rho^\pm\pi^\mp)$ and phases from interference:

$$A(B^0 \rightarrow \rho^+\pi^-) = T(\rho^+\pi^-)e^{-\alpha i} + P(\rho^+\pi^-)$$

$$\bar{A}(\bar{B}^0 \rightarrow \rho^-\pi^+) = T(\rho^+\pi^-)e^{+\alpha i} + P(\rho^+\pi^-), \text{ etc ...}$$

$$\delta_{+-} = \arg \left[\frac{A(\rho^-\pi^+)}{A(\rho^+\pi^-)} \right] = (34 \pm 29)^\circ \quad \alpha \in (75^\circ, 152^\circ) \text{ at 68% CL}$$



Put Everything Together: α

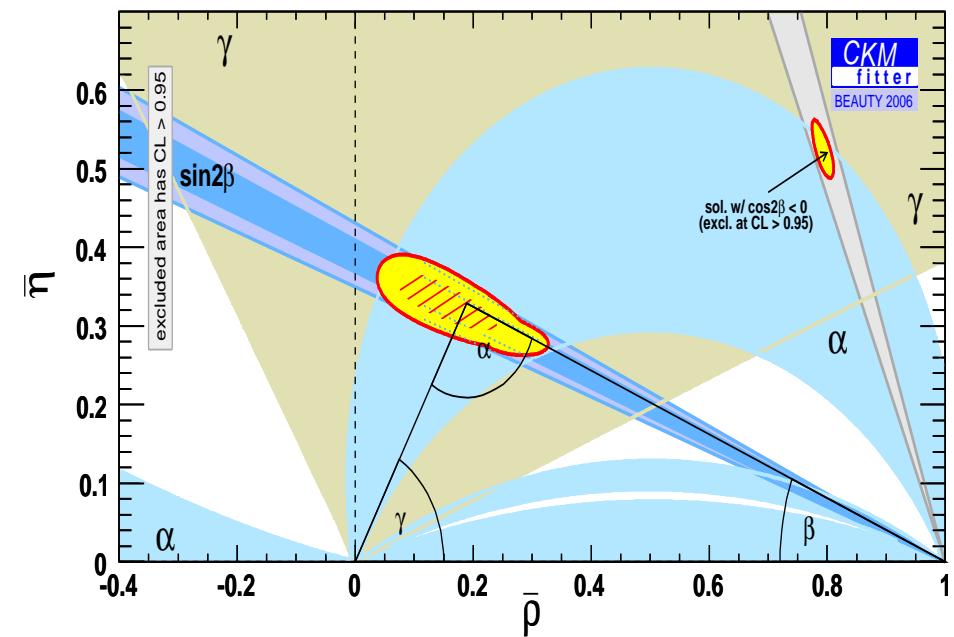
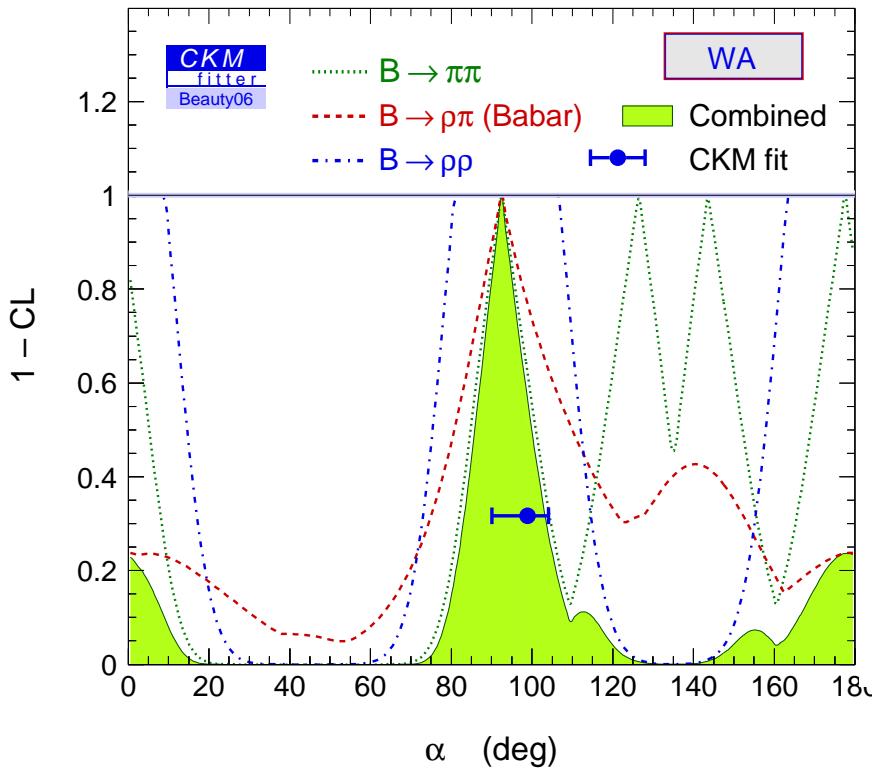
Put Everything Together

- Combine all three sets:

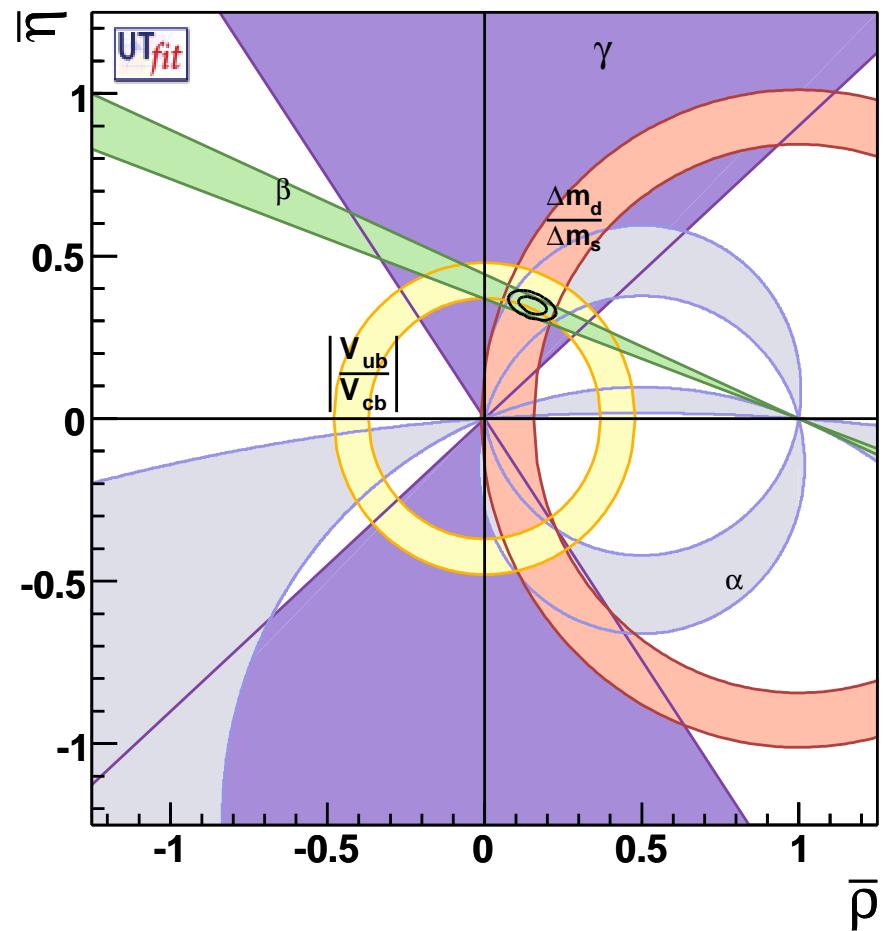
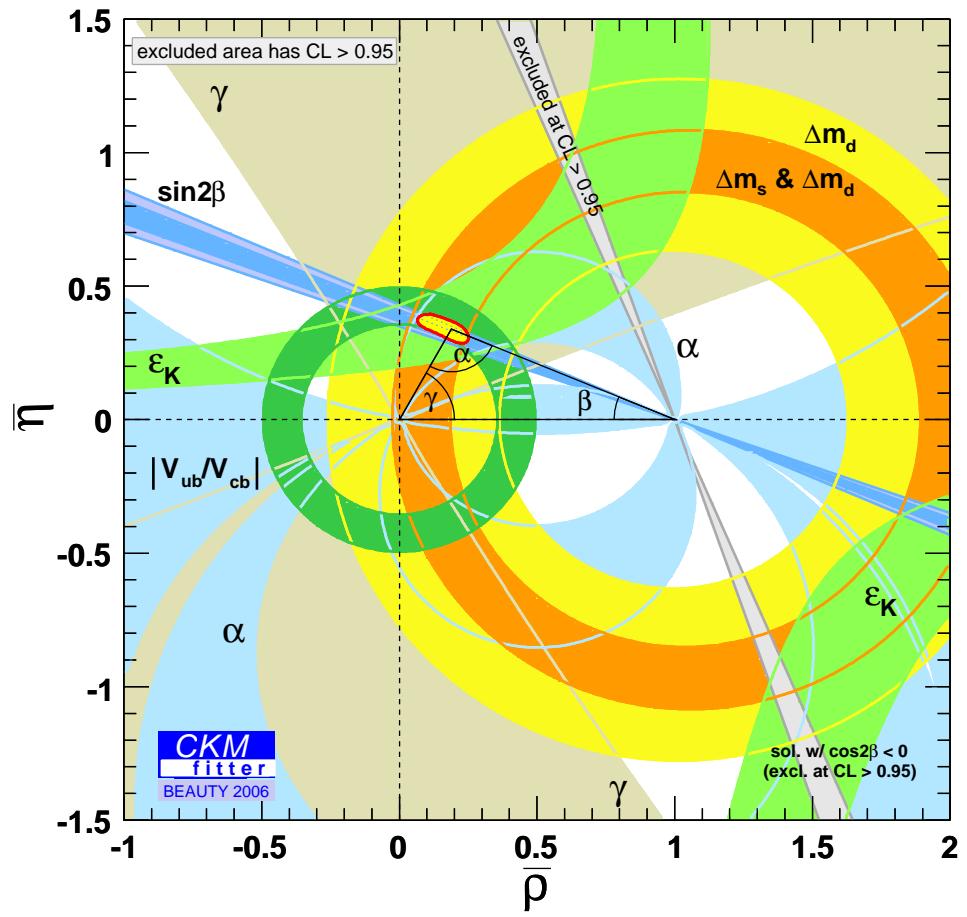
- $B \rightarrow \pi\pi$ (combined with BELLE reduces ambiguities)
- $B \rightarrow \rho\rho$ ($\rho^0\rho^0$ B_{ABAR} only)
- $B \rightarrow \rho\pi$ (B_{ABAR} only)

$$\alpha = (92.6^{+10.7}_{-9.3})^\circ$$

(larger of CKMfitter and UTfit)



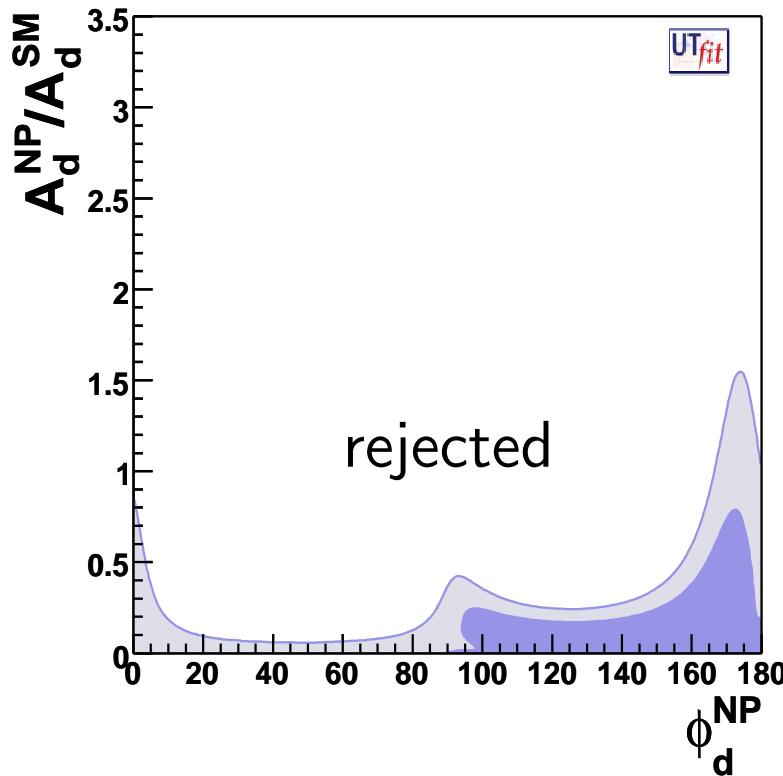
CKM Unitarity Triangle



New Physics Constraints from Unitarity Triangle

- New Physics in B_d mixing (model-independent):

$$A^{\text{NP}} / A^{\text{SM}}$$

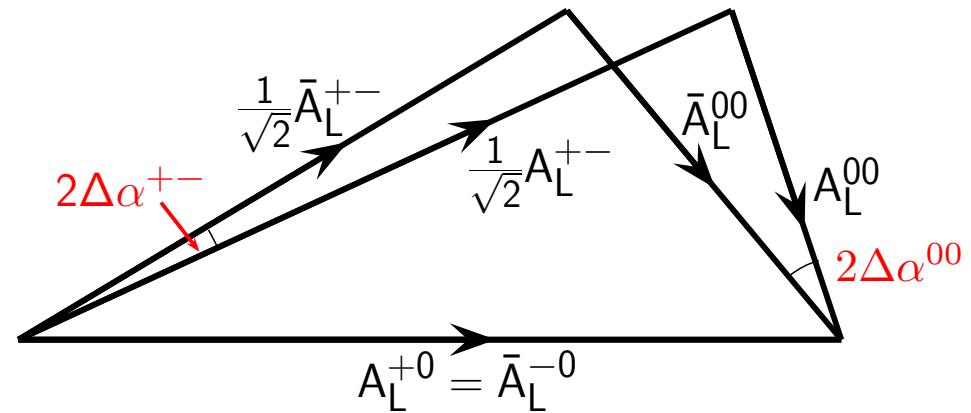


- Constraint on α is critical: β , Δm , V_{xb} not enough

Future of α

- Taming the penguin:

- unique to $B \rightarrow \rho\rho$ (vs. $\pi\pi$): vertex $B^0 \rightarrow \rho^0\rho^0 \rightarrow \pi^+\pi^-\pi^+\pi^-$
- measure S^{00} and C^{00} with $\mathcal{A}_{\rho^0\rho^0}(t)$
- $\Delta\alpha^{00}$ from the same triangle
- resolve triangle ambiguities



- New $b \rightarrow u$ modes ($B \rightarrow a_0\pi, a_1\pi, b_1\pi, \dots$)

- new: $B^0 \rightarrow a_1^\pm\pi^\mp \rightarrow (\rho^0\pi^\pm)\pi^\mp \rightarrow \pi^+\pi^-\pi^+\pi^-$
similar to $B^0 \rightarrow \rho^\pm\pi^\mp$

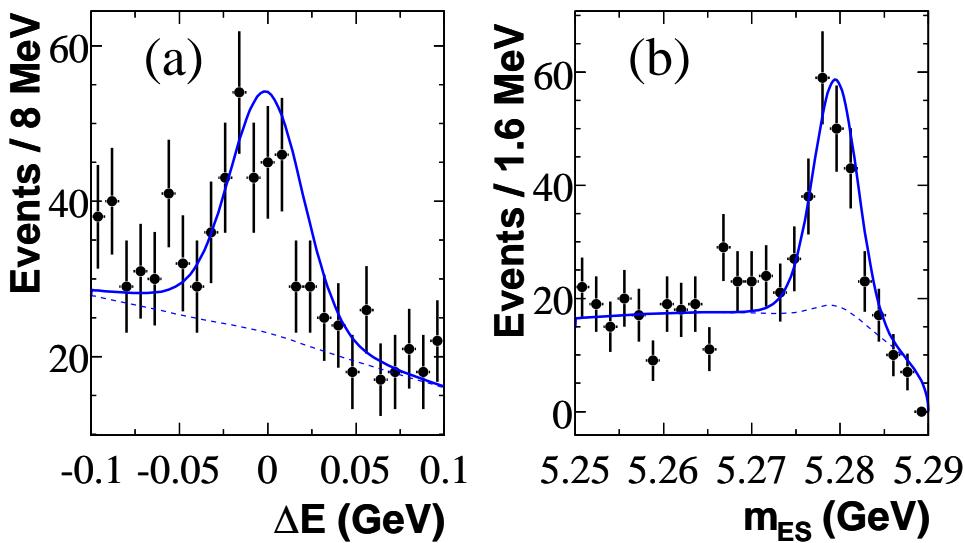


$B^0 \rightarrow a_1^\pm \pi^\mp$ (**new**)

$$\mathcal{B}(a_1^\pm \pi^\mp) = (40 \pm 4) \times 10^{-6}$$

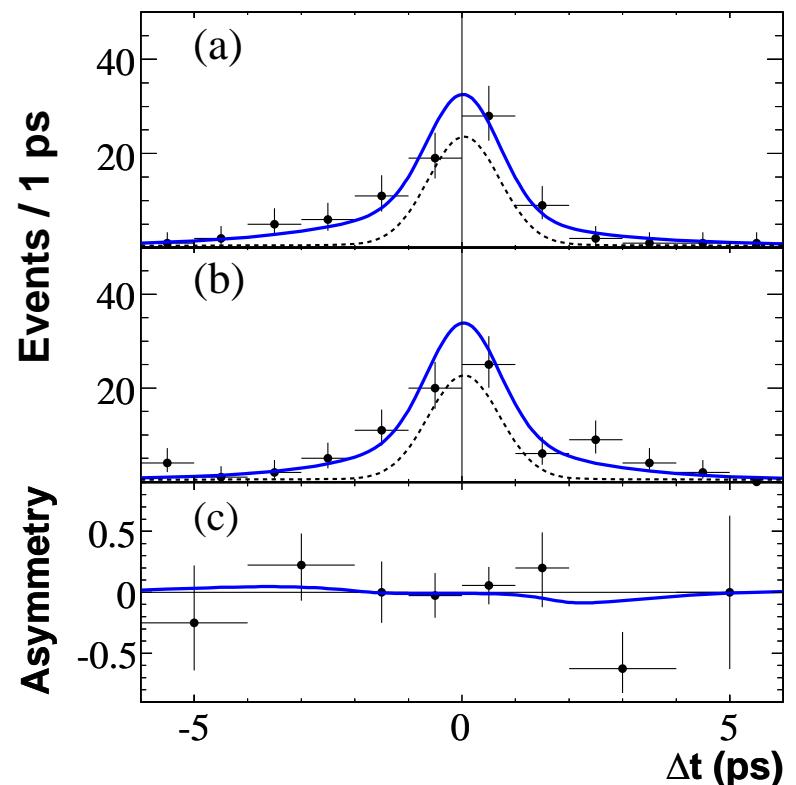
$$N(a_1^\pm \pi^\mp) = (608 \pm 53)$$

errors same as $B \rightarrow \rho\rho \rightarrow$



- Challenge: bound penguin in α
 - use **SU(3)** with $B \rightarrow K_1\pi, a_1\pi$
 - Dalitz analysis like $B^0 \rightarrow \rho\pi$

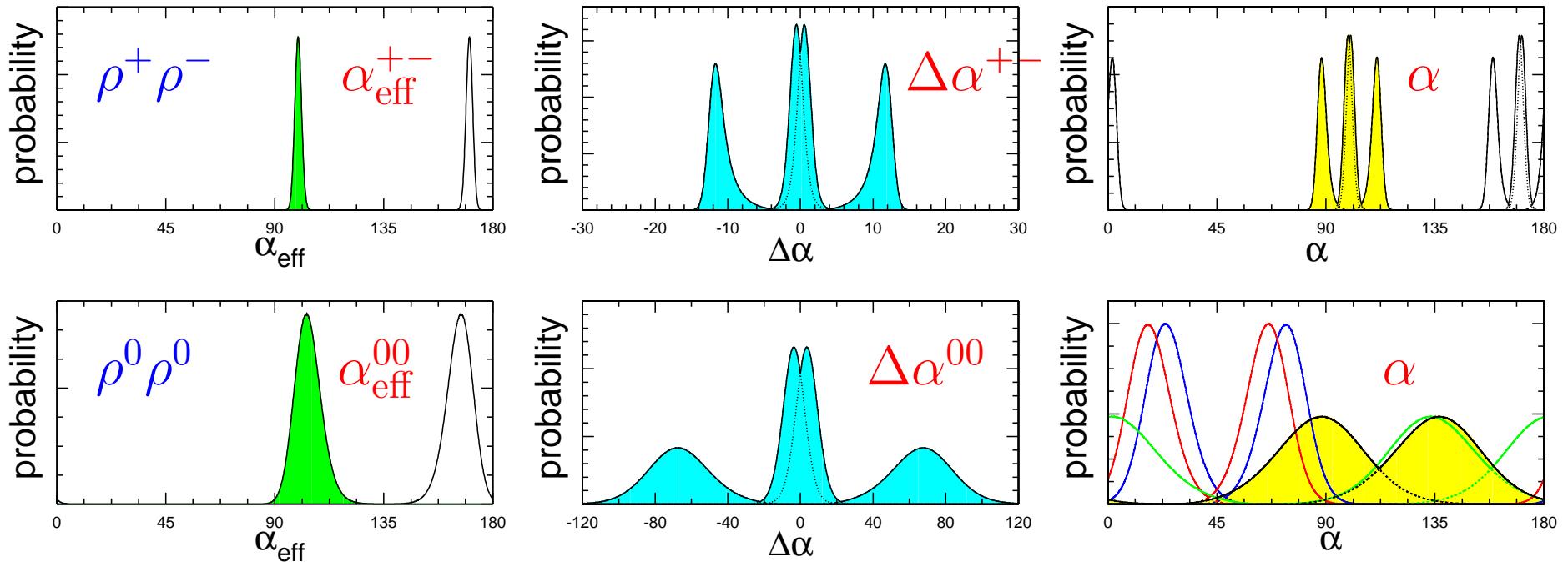
$$\begin{aligned} S &= 0.37 \pm 0.21 \pm 0.07 \\ C &= -0.10 \pm 0.15 \pm 0.09 \\ \Delta S &= -0.14 \pm 0.21 \pm 0.06 \\ \Delta C &= 0.26 \pm 0.15 \pm 0.07 \end{aligned}$$



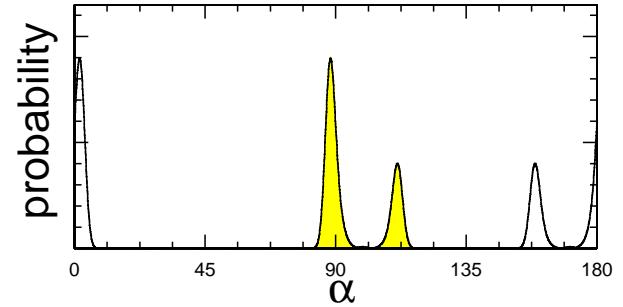
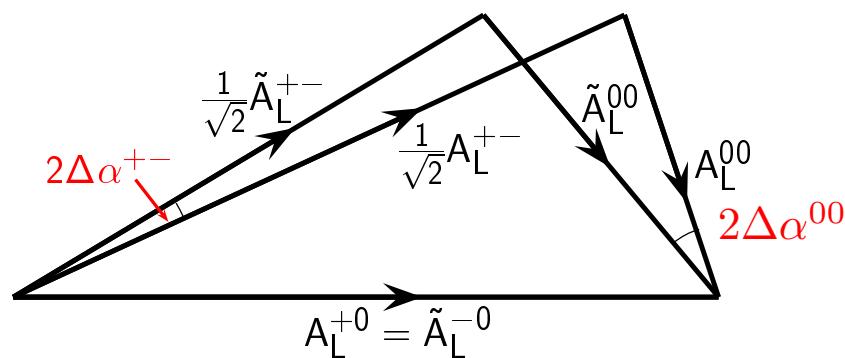
$$\begin{aligned} \mathcal{A}(a_1^\pm \pi^\mp) &= (S \pm \Delta S) \sin(\Delta m \Delta t) \\ &\quad - (C \pm \Delta C) \cos(\Delta m \Delta t) \end{aligned}$$

Measuring α with $\rho^0\rho^0$ (future)

- Toy MC with $\times 20$ data



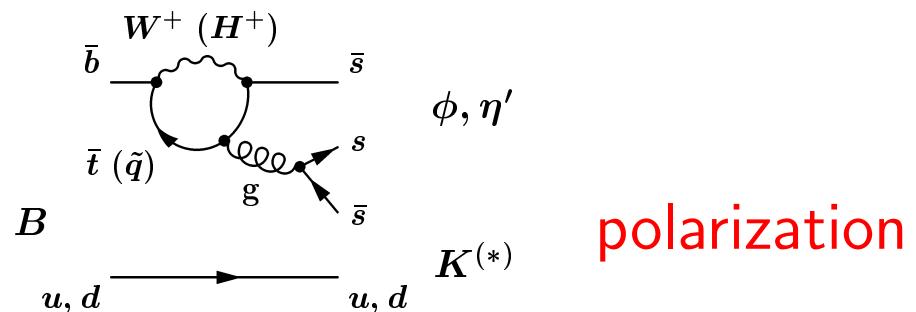
- Triangle orientations match $\Delta\alpha^{+-}$ and $\Delta\alpha^{00}$, resolve ambiguities



Do We Understand Penguins After All ?

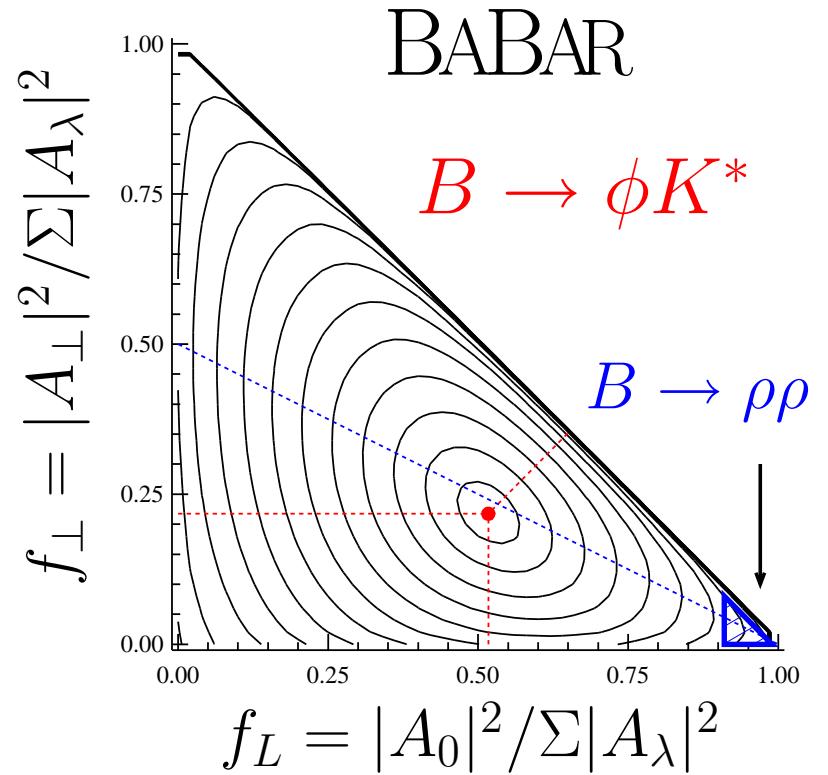
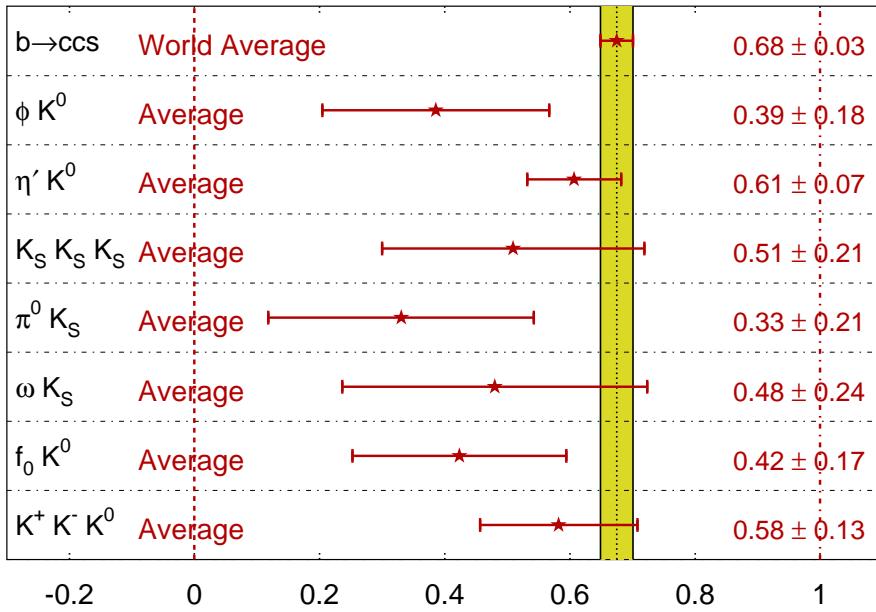
- New Physics in penguins (?)

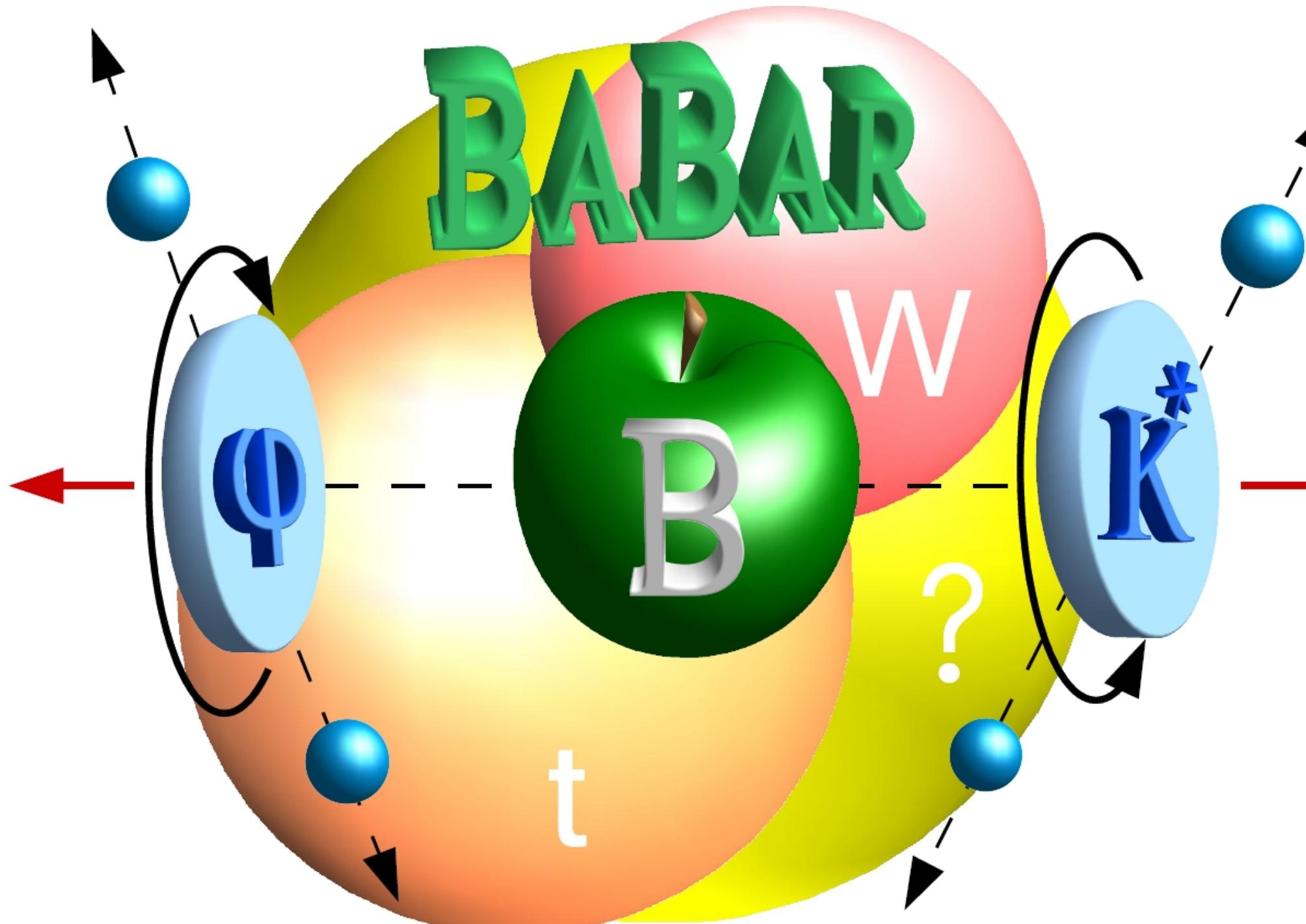
$\sin(2\beta)$



$$\sin(2\beta^{\text{eff}}) \equiv \sin(2\phi_1^{\text{eff}})$$

HFAG
DPF/JPS 2006
PRELIMINARY



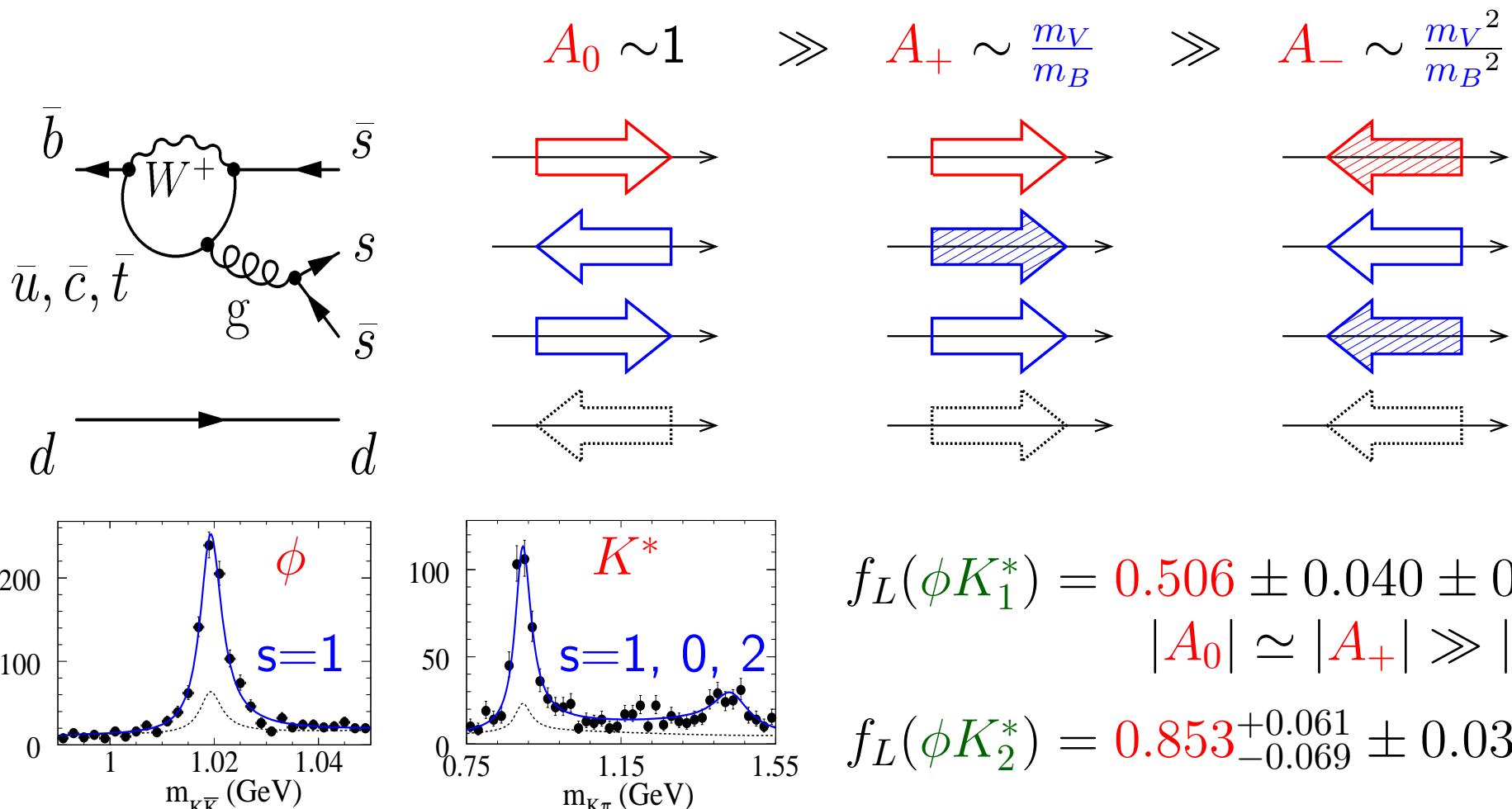


arXiv:hep-ex/0610073

SLAC Today 10/26/2006

Polarization Puzzle in Penguins

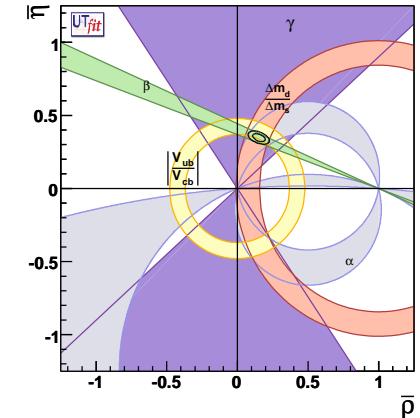
- Standard Model ($V - A$), similar to $B \rightarrow \rho\rho$



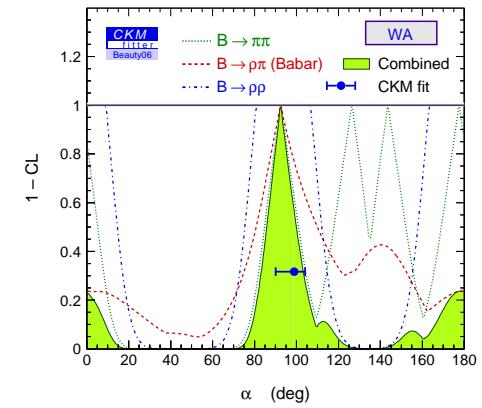
- Conflict models: QCD, EW, annihilation, NP; would affect $\rho^0 \rho^0$ (?)

Summary

- Measurement of α
 - important CKM UT parameter: CP -violation
 - needed for New Physics constraint in mixing



- Experimentally difficult
 - rare modes $B \rightarrow \pi\pi, \rho\pi, \rho\rho$
 - penguin pollution
 - nonetheless obtain $\alpha = (92.6^{+10.7}_{-9.3})^\circ$



- Future
 - constrain penguin, e.g. $CP(t)$ in $B \rightarrow \rho^0\rho^0, a_1\pi$
 - is there New Physics in penguin?



BACKUP

$B \rightarrow \rho\pi$ Decays: Quasi-Two-Body Approach

- $B \rightarrow \rho^\pm \pi^\mp$ not CP eigenstate

$$(S \pm \Delta S) \sin(\Delta m \Delta t) - (C \pm \Delta C) \cos(\Delta m \Delta t)$$

B decay	HFAG \mathcal{B} (10^{-6})
$\rho^0 \pi^0$	1.8 ± 0.6
$\rho^+ \pi^-$	24.0 ± 2.5
$\rho^- \pi^+$	
$\rho^+ \pi^0$	10.8 ± 1.5
$\rho^0 \pi^+$	8.7 ± 1.1

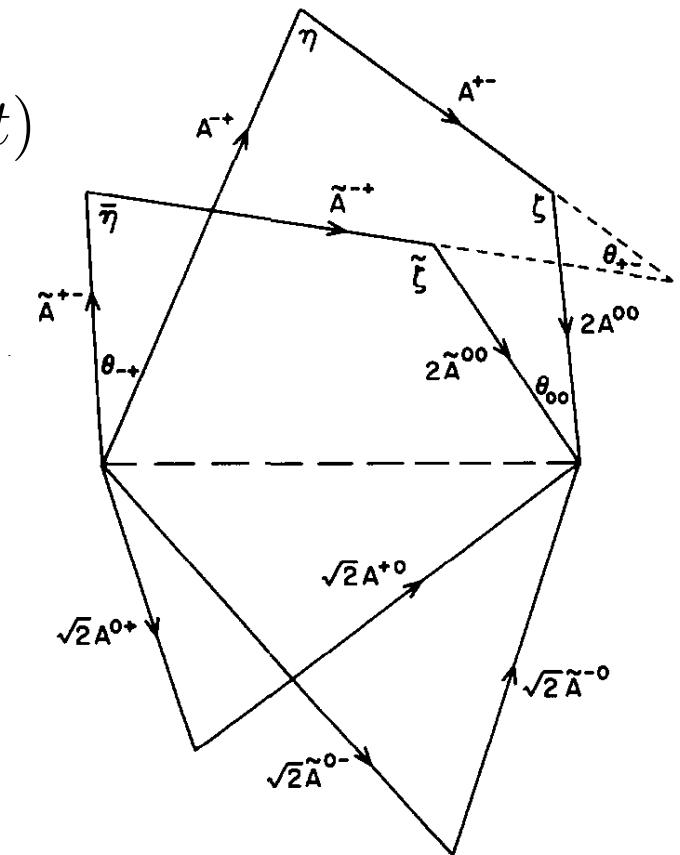
- Q2B isospin analysis unfruitful (12 params):

$$\sin(2\alpha + \theta_{+-}), \sin(2\alpha + \theta_{-+}), \sin(2\alpha + \theta_{00})$$

$$\frac{A^{+-}}{\sqrt{2}} + \frac{A^{-+}}{\sqrt{2}} + \sqrt{2}A^{00} = A^{+0} + A^{0+} = T_1$$

$$A^{+-} - A^{-+} + \frac{A^{0+}}{\sqrt{2}} - \frac{A^{+0}}{\sqrt{2}} = T_2$$

– better if very small $\rho^0 \pi^0$



Lipkin/Nir/Quinn/Snyder, Gronau