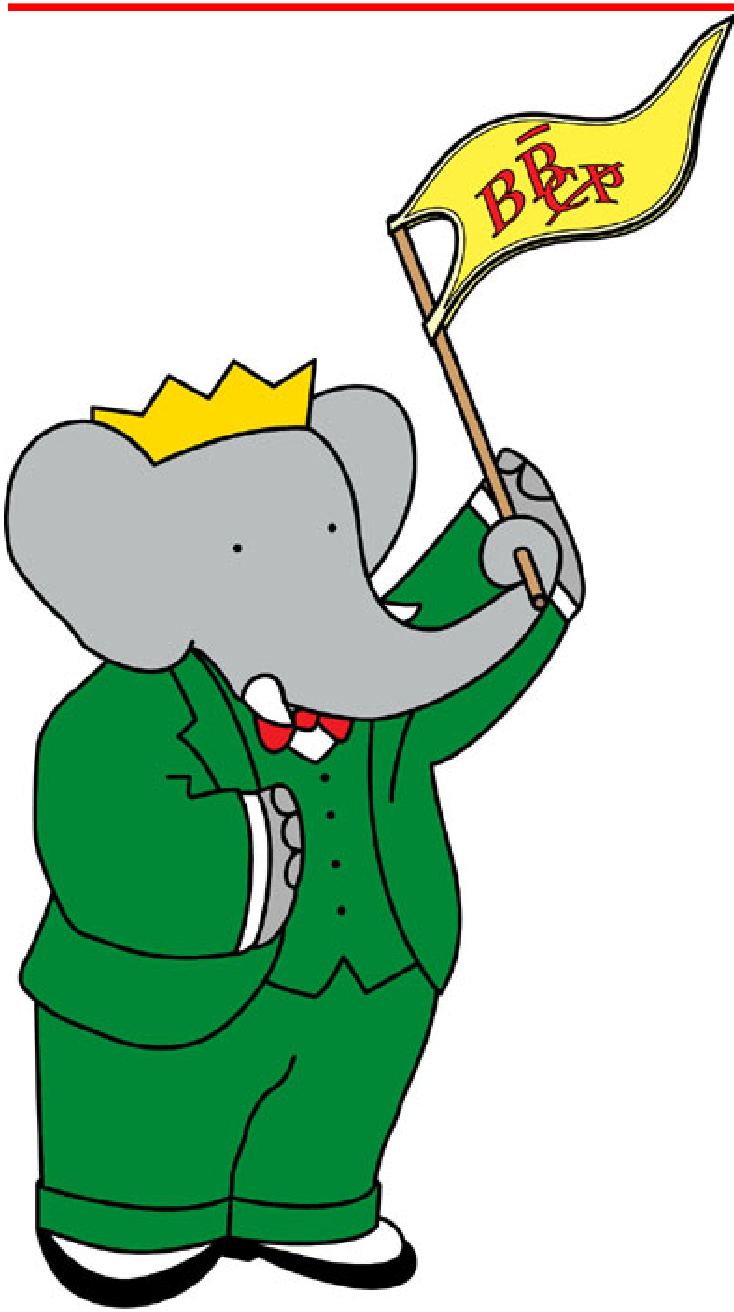

Measurements of the CKM angle α at BaBar

Simone Stracka
on behalf of the BaBar collaboration

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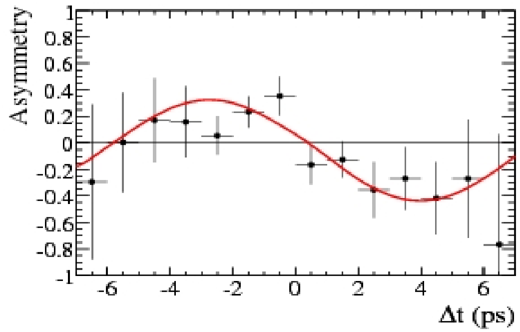
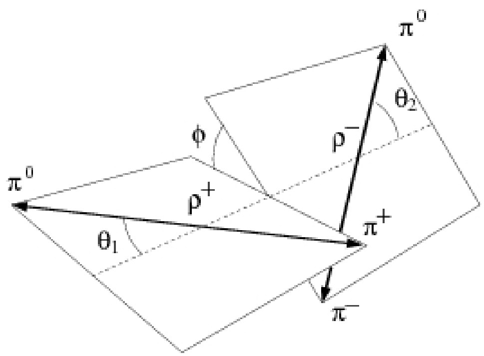
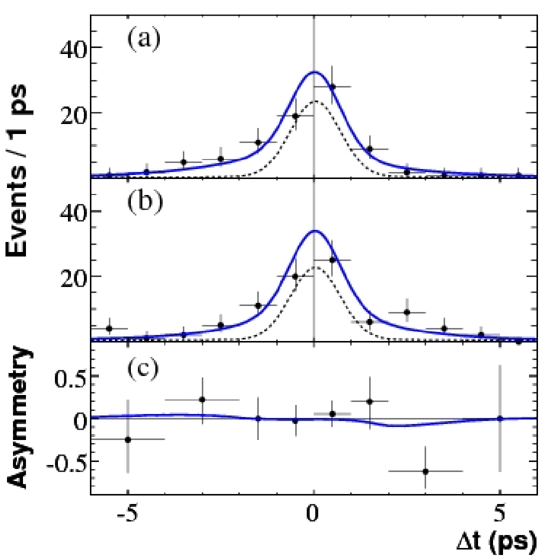
[2] INFN Milano

DPF 2009 – 26-31 July 2009
Wayne State University, Detroit (MI)

Outline







- $B \to \pi\pi$
  - HOT: $B \to h^+h^-$, $B \to \pi^0\pi^0$ 2008 updates arXiv:0807.4226 (2008)
  - CPV observed @ 6.7σ
- $B \to \rho\rho$
  - HOTTER: $B \to \rho^+\rho^0$ 2009 update PRL102, 141802 (2009)
  - Best precision for α
- $B \to \rho\pi$
  - Still to update
- $B \to a_1\pi$

  New!

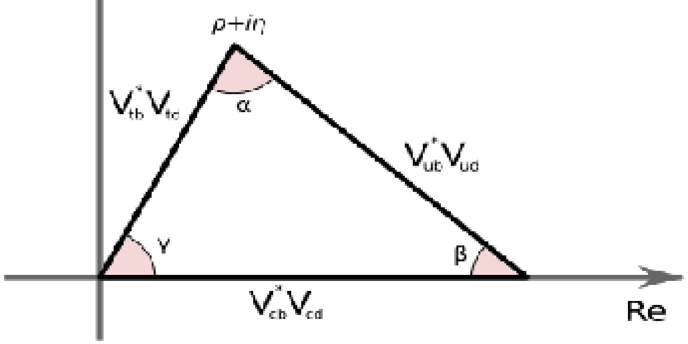
  - FRESH FROM THE OVEN: $B \to K_1\pi$ + $\Delta\alpha$ to be submitted to PRD
  - Fourth channel (after $\pi\pi$, $\rho\rho$, $\rho\pi$)

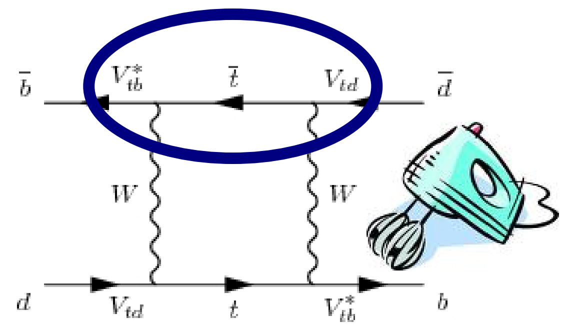
$B \to \pi\pi$ as a prototype

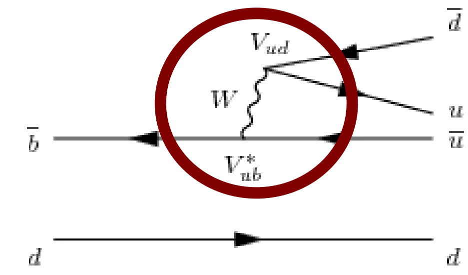
- α extracted from TD CPV asymmetries in $b \to u\bar{u}d$ channels

$\pi\pi$, $\rho\rho$, $\rho\pi$, $a_1\pi$

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

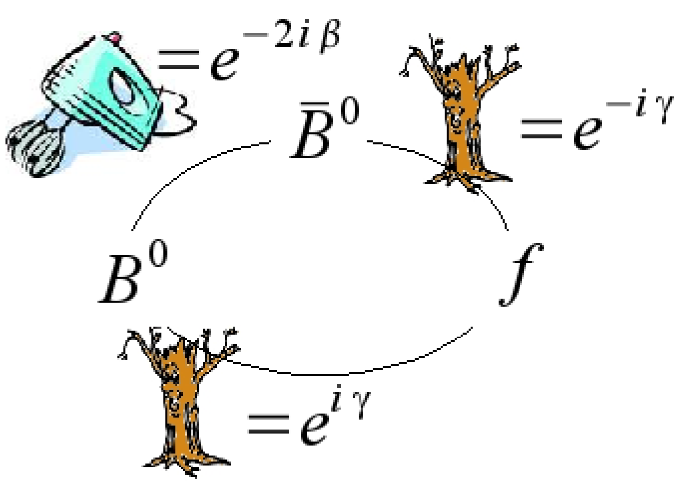






$$\Gamma(B^0(t) \to f) = \langle\Gamma\rangle e^{-\Gamma t}[1 + C\cos(\Delta m t) - S\sin(\Delta m t)]/2$$
$$\Gamma(\bar{B}^0(t) \to f) = \langle\Gamma\rangle e^{-\Gamma t}[1 - C\cos(\Delta m t) + S\sin(\Delta m t)]/2$$

- Assuming only one CKM amplitude contributes to the decay



$$arg[e^{-2i\beta} A(\bar{B}^0 \to \pi^+\pi^-) A^*(B^0 \to \pi^+\pi^-)] = 2\alpha$$

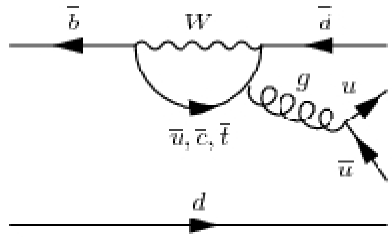
$$\lambda = \frac{q}{p}\frac{\bar{A}}{A} = e^{2i\alpha} \Rightarrow$$

$$S = \frac{2\,Im\,\lambda}{1+|\lambda|^2} = \sin(2\alpha)$$

$$C = \frac{1-|\lambda|^2}{1+|\lambda|^2} = 0$$

Enter penguin

- Penguin has different strong and weak phases



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

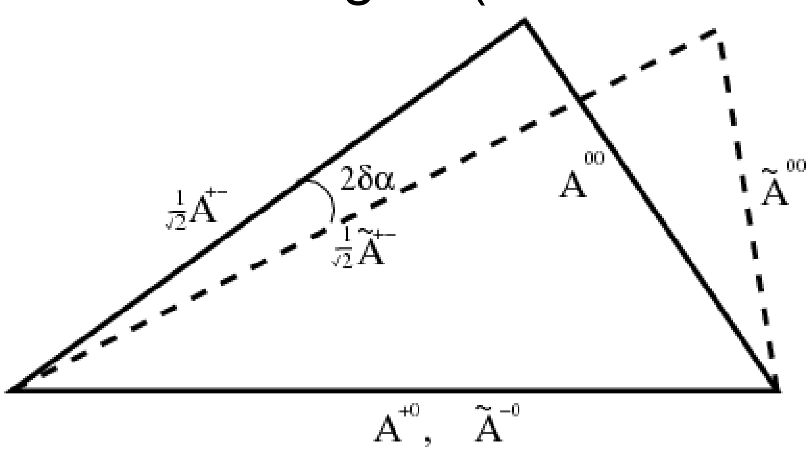
$C \neq 0$ allowed

$$arg[e^{-2i\beta} A(\bar{B}^0 \to \pi^+\pi^-) A^*(B^0 \to \pi^+\pi^-)] = 2\alpha_{eff} = 2\alpha - 2\Delta\alpha^{+-}$$

- Use SU(2) or SU(3) symmetries to constrain $\Delta\alpha$

SU(2)

- geometric representation
  - 2 triangles (B and anti-B)



Gronau, London, PRL65, 3381 (1990)

SU(3)

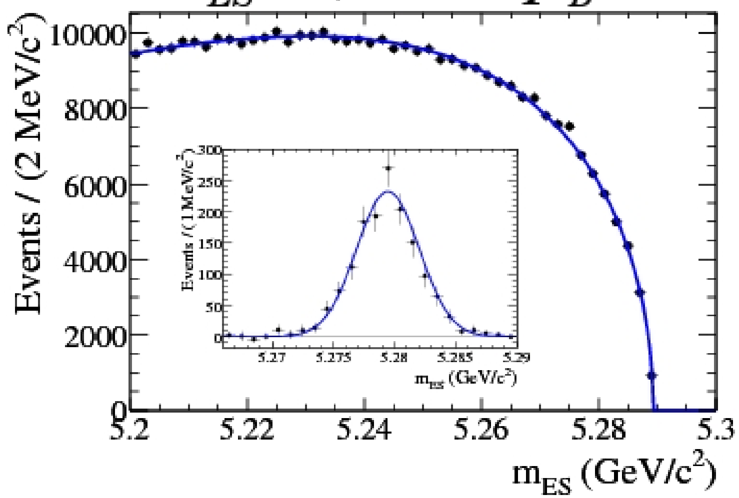
- $\Delta S=0$ decays
  - $|P| \sim |V_{ub}V^*_{ud}|$, $|P| \sim |V_{cb}V^*_{cd}|$
- $\Delta S=1$ decays
  - $|T'| \sim |V_{ub}V^*_{us}|$, $|P'| \sim |V_{cb}V^*_{cs}|$
- P'/T' CKM enhanced over P/T

Gronau, Zupan, PRD70, 074031 (2004)
Gronau, Zupan, PRD73, 057502 (2006)

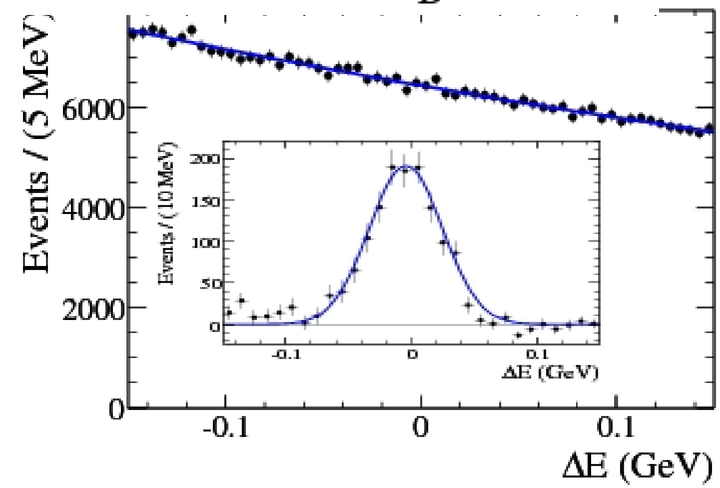
Charmless (quasi) two-body analysis

- Kinematic variables: energy subsituted mass, energy difference

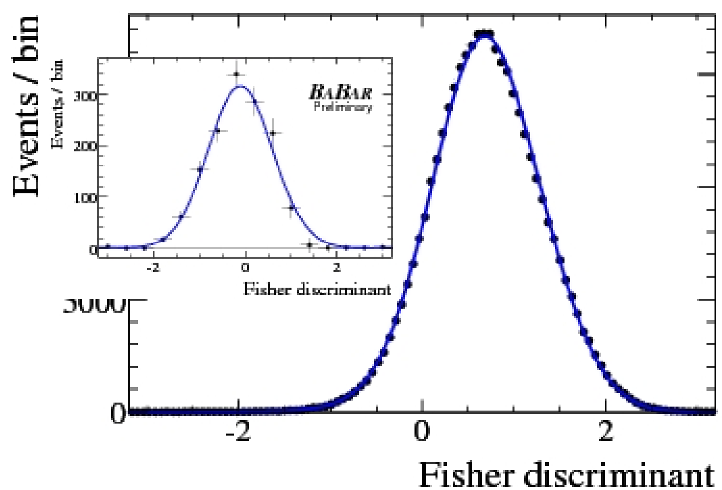
$$m_{ES}=\sqrt{s/4-p_B^2}$$

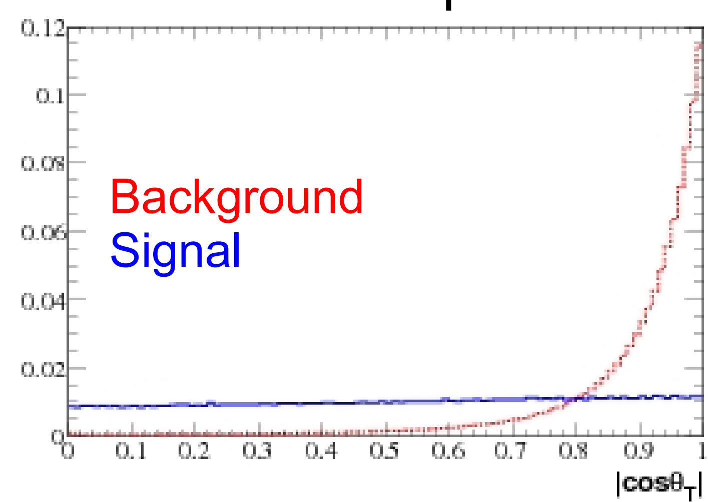


$$\Delta E=E_B-\sqrt{s}/2$$



- Event shape: distinguish “jet-like” qq events and more isotropic B decays

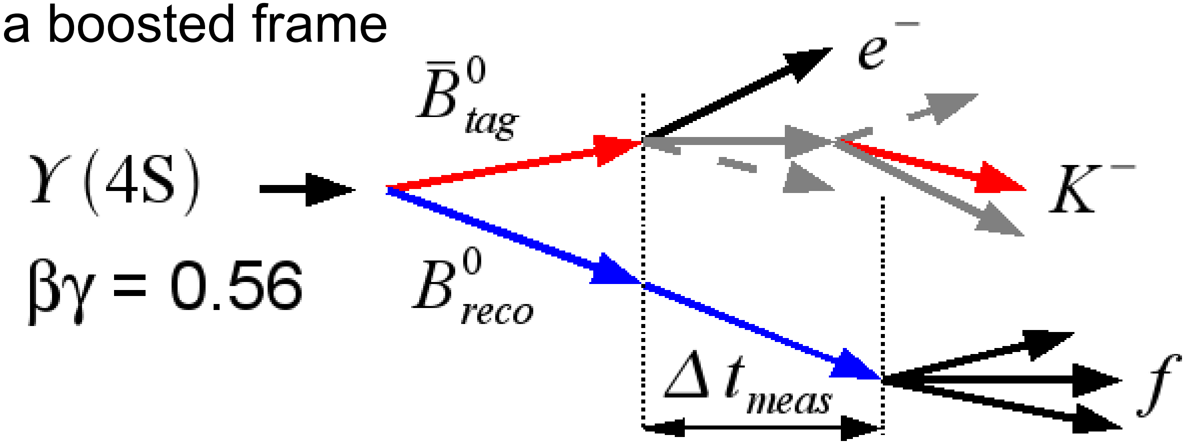




- Extract the signal yield and CP asymmetries via an unbinned Maximum Likelihood fit to several observables

Time dependent analysis

B mesons are produced coherently
in a boosted frame



Identify flavor and vertex of the other B: NN based tagging algorithm with 6 categories

Fully reconstruct signal final state

$$\Delta t_{meas} = t_{reco} - t_{tag} \qquad \Delta z = \beta\gamma c \Delta t_{meas} \approx 260\,\mu m$$

$$F^{\pm}(\Delta t_{meas}) = \frac{e^{-|\Delta t|/\tau}}{4\tau}\left\{1 \mp \Delta w \pm (1-2w)\left[S\sin(\Delta m_d \Delta t) - C\cos(\Delta m_d \Delta t)\right]\right\} \otimes R(\Delta t_{meas} - \Delta t, \sigma_{\Delta t})$$

Include tagging performance

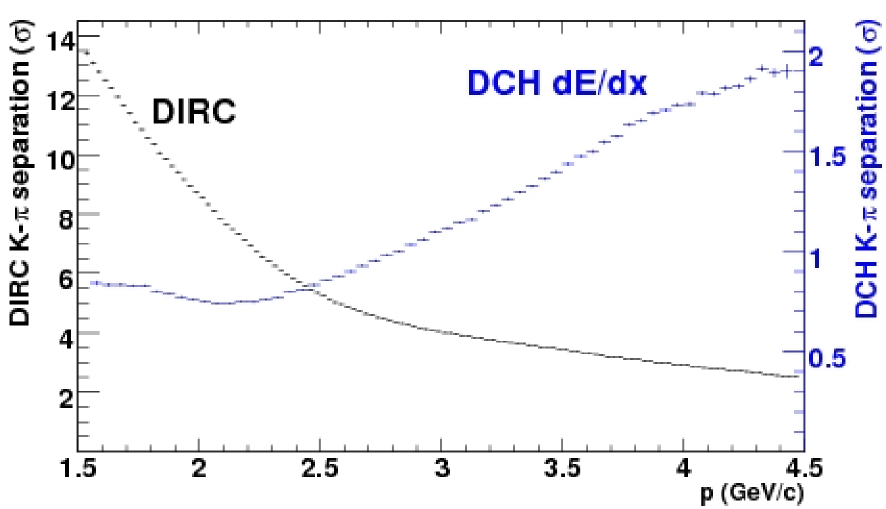
Experimental Δt resolution: convolution with triple gaussian, with parameters obtained from a large sample of fully reconstructed B decays, and free to differ between tagging category

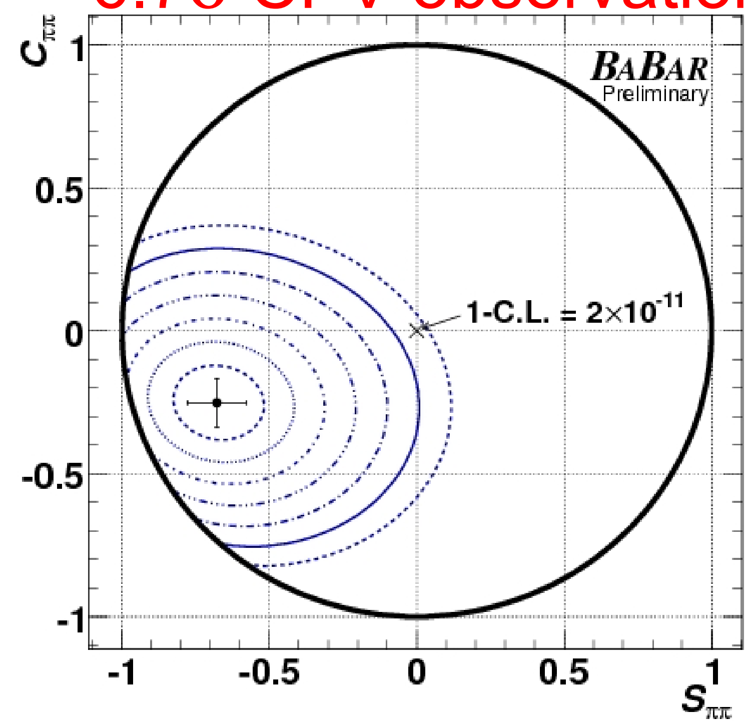
$B \to \pi\pi$

h^+h^-

- Simultaneous ML fit to $\pi^+\pi^-$, π^+K^-, π^-K^+, K^+K^-
- Increased K-π separation
  - PID in the fit: dE/dx in DCH and Cherenkov angle in DIRC
    - DCH $\Rightarrow$ PID also for tracks outside DIRC acceptance
  - Additional $\pi^+\pi^-$, π^+K^-, π^-K^+, K^+K^- separation from ΔE
- Yield = 1394 ± 54

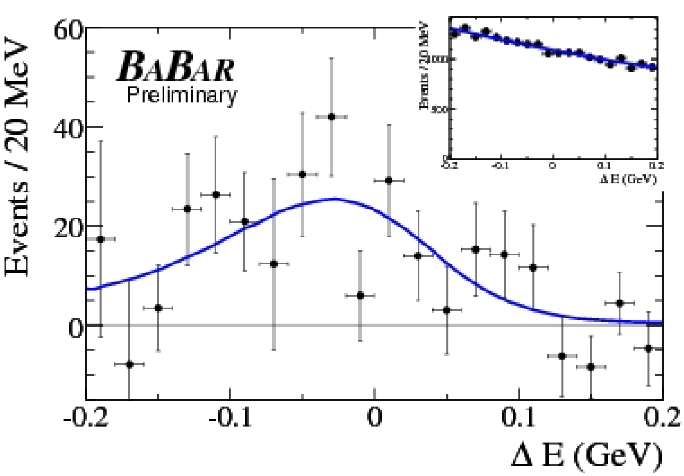
6.7σ CPV observation

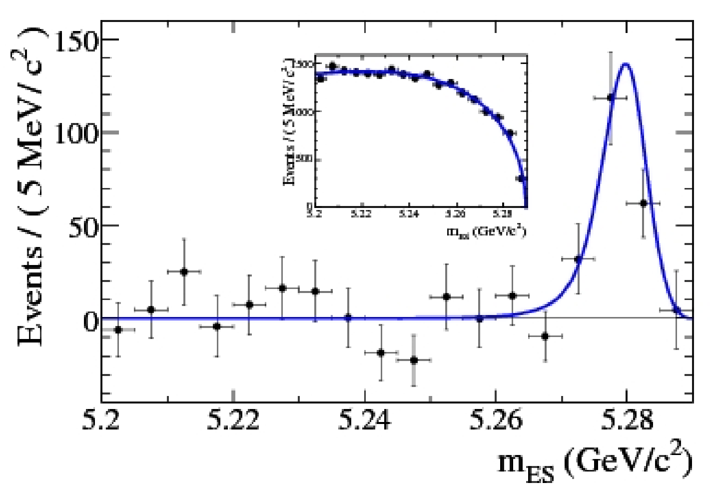


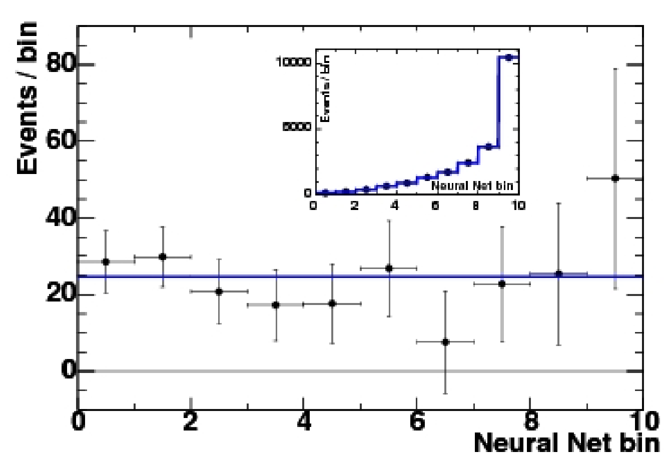


$\pi^0\pi^0$

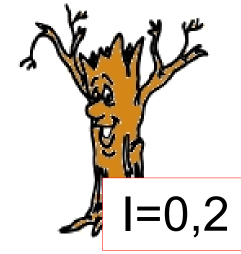
- Reconstruct $\pi^0 \to \gamma\gamma$, and include photon conversions $\gamma \to e^+e^-$
- Use NN to improve signal vs. background separation
  - Background model accounts for NN-m_{ES} correlations
- ML fit to ΔE, m_{ES}, NN and flavor tag
- Yield = 247 ± 29
- BF = $(1.83 \pm 0.21 \pm 0.13) \times 10^{-6}$
- $C^{00} = -0.43 \pm 0.26 \pm 0.05$ (flavor tag- and time-integrated); no S^{00} (no vtx)

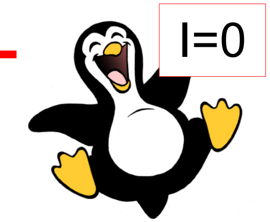






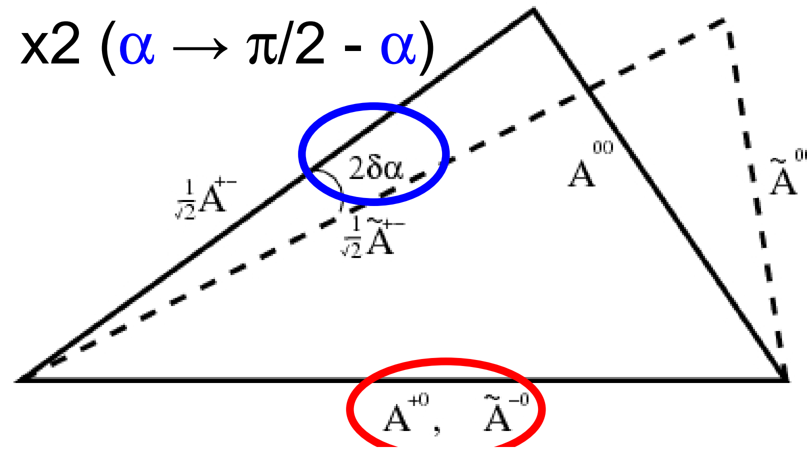
Isospin analysis for ππ



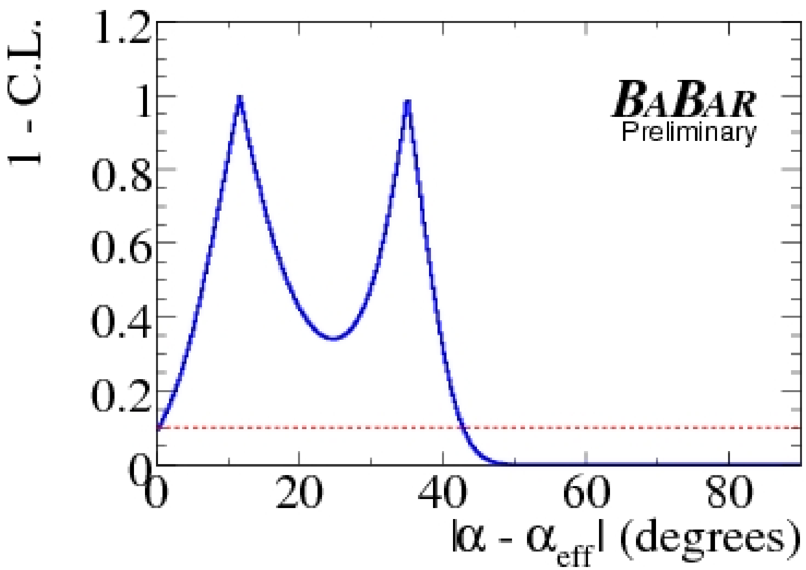


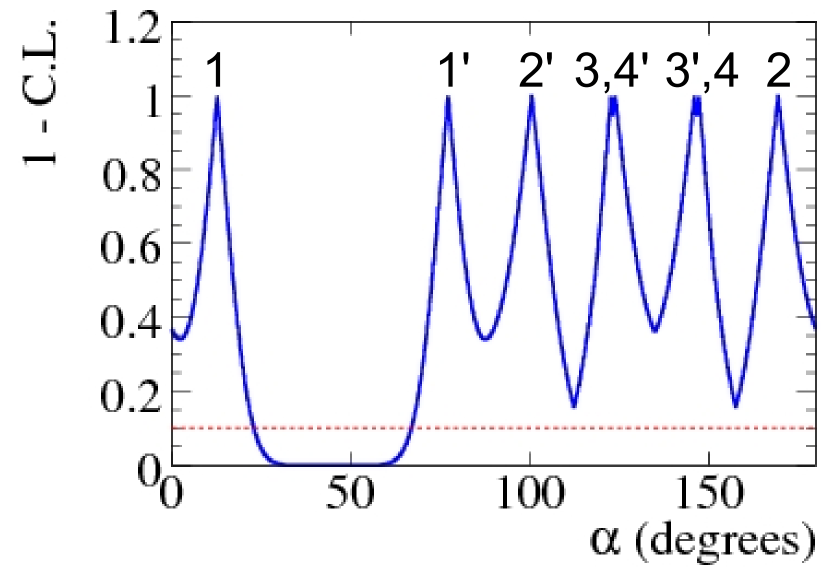
- Decompose $B \to \pi\pi$ in isospin amplitudes (A_0, A_2)
  - I=1 forbidden by Bose statistics
- 8-fold ambiguity: x4 ($\Delta\alpha$ triangles can flip), x2 ($\alpha \to \pi/2 - \alpha$)

	$\mathcal{B}(\times 10^{-6})$	C
$\pi^+\pi^-$	$5.5 \pm 0.4 \pm 0.3$	$-0.25 \pm 0.08 \pm 0.02$
$\pi^+\pi^0$	$5.02 \pm 0.46 \pm 0.29$	$(-0.03 \pm 0.08 \pm 0.01)$
$\pi^0\pi^0$	$1.83 \pm 0.21 \pm 0.13$	$-0.43 \pm 0.26 \pm 0.05$



No gluon penguin $\Rightarrow |A^{+0}| = |\tilde{A}^{-0}|$



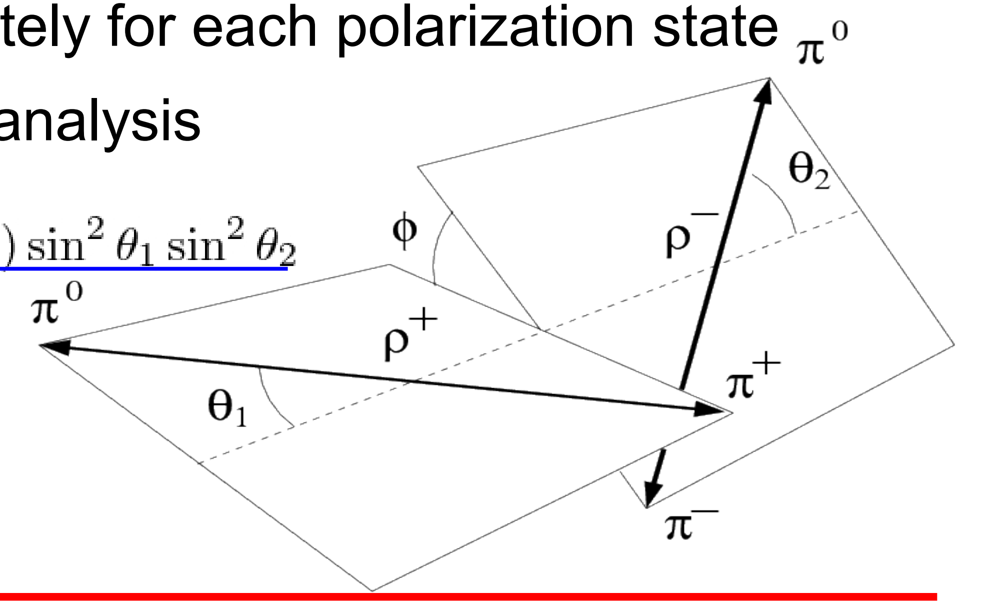


$B \to \rho\rho$

Isospin analysis for ρρ

- BF($B\to\rho^+\rho^-$) ≈ 5 × BF($B\to\pi^+\pi^-$) but:
  - I=1 allowed in $B\to\rho\rho$ if $m_1 \neq m_2$ (wave function can be anti-symmetric)
    - but measurements stable when decreasing allowed Δm range
  - EW penguin can have I=2 and contribute to $B\to\rho^+\rho^0$
    - no sign of direct CP asymmetry in $B\to\rho^+\rho^0$
  - $B\to VV$ allows L=0,1,2 CP=$(-1)^L$
    - 3 polarizations: longitudinal H^0 (L=0,2), transverse $H_{\pm1}$ (L=0,1,2)
    - Isospin relations hold separately for each polarization state
    - $f_L\approx1$ (CP even) from angular analysis

$$\frac{1}{\Gamma}\frac{d^2\Gamma}{(d\cos\theta_1 d\cos\theta_2)} \propto 4 f_L \cos^2\theta_1\cos^2\theta_2 + (1-f_L)\sin^2\theta_1\sin^2\theta_2$$



Falk et al., PRD69, 011502 (2004)
Kagan, PLB601, 151 (2004)

$\rho^+\rho^0$ update

- Higher signal efficiency and background rejection
- x2 increase in data sample w.r.t. previous measurement
- Improved charged particle reconstruction
- Improved background model
  - 3D model for BB and continuum components

$$\mathcal{P}_{3D} = [\mathcal{P}(m_{\pi^+\pi^-}|\cos\theta_{\rho^0})\times\mathcal{P}(\cos\theta_{\rho^0}|NN)]\times[\mathcal{P}(m_{\pi^+\pi^0}|\cos\theta_{\rho^+})\times\mathcal{P}(\cos\theta_{\rho^+}|NN)]\times\mathcal{P}(NN)$$

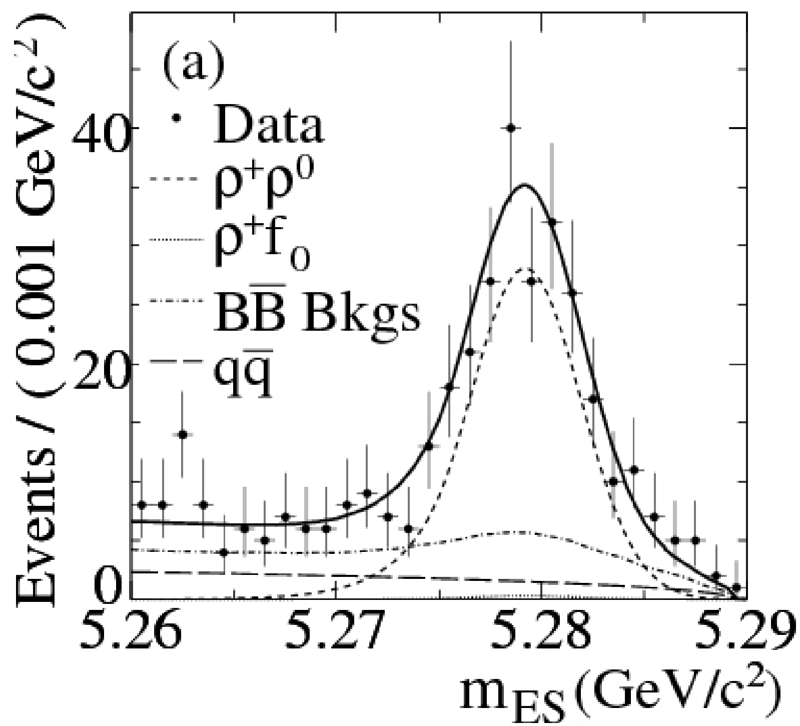
1) $A_{CP}(\rho^+\rho^0) \approx 0 \Rightarrow$ EW penguin is negligible

$$A_{CP} \equiv \frac{\Gamma_{B^-} - \Gamma_{B^+}}{\Gamma_{B^-} + \Gamma_{B^+}} = -0.054 \pm 0.055 \pm 0.010$$

2) both BF and f_L increase

$$BF(B^+ \to \rho^+\rho^0) = (23.7 \pm 1.4 \pm 1.4) \times 10^{-6} \nearrow 2\sigma$$

$$f_L \equiv \Gamma_L / \Gamma = 0.950 \pm 0.015 \pm 0.006$$



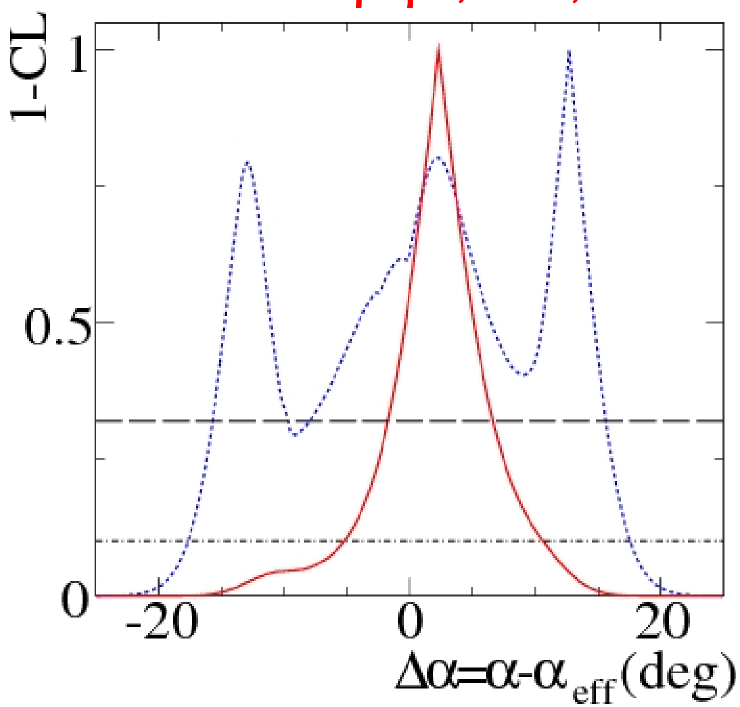
$\rho^+\rho^0$ results

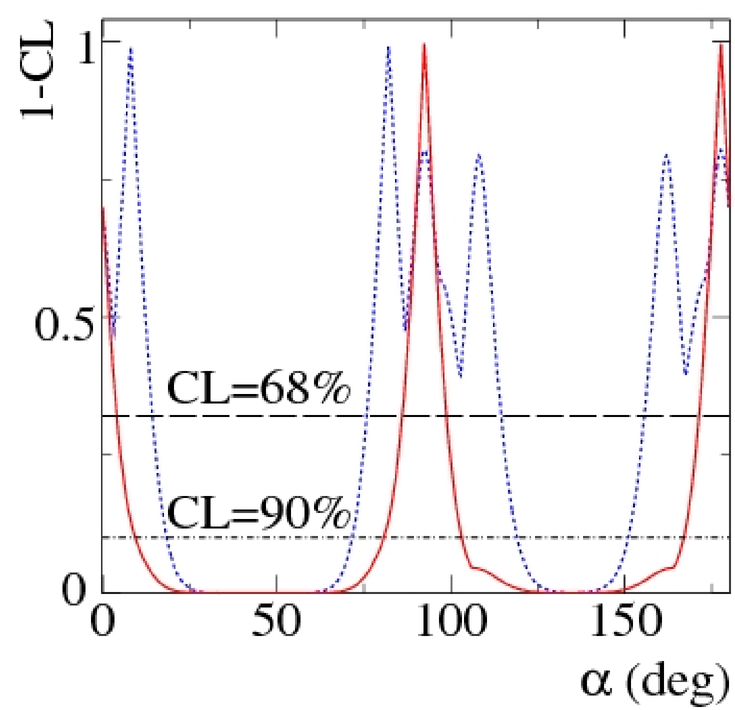
	$\mathcal{B}(\times 10^{-6})$	f_L	$C = -A_{CP}$	S
$\rho^+\rho^-$	$25.5 \pm 2.1^{+3.6}_{-3.9}$	$0.992 \pm 0.024^{+0.026}_{-0.013}$	$0.01 \pm 0.15 \pm 0.06$	$-0.17 \pm 0.20^{+0.05}_{-0.06}$
$\rho^+\rho^0$	$23.7 \pm 1.4 \pm 1.4$	$0.950 \pm 0.042 \pm 0.006$	$(0.054 \pm 0.055 \pm 0.010)$	$-$
$\rho^0\rho^0$	$0.92 \pm 0.32 \pm 0.14$	$0.75^{+0.11}_{-0.14} \pm 0.04$	$0.2 \pm 0.8 \pm 0.3$	$0.3 \pm 0.7 \pm 0.2$

- $A_{CP}(\rho^+\rho^0) \approx 0 \Rightarrow$ EW penguin is negligible $\Rightarrow$ isospin analysis holds within 1-2°
- S^{00} provides relative suppression of $\Delta\alpha$ ambiguities

Include C^{00}, S^{00}

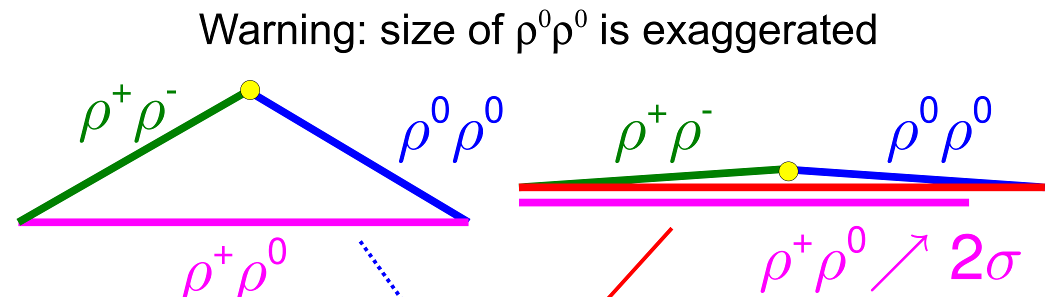
Include $\rho^+\rho^0$, C^{00}, S^{00}

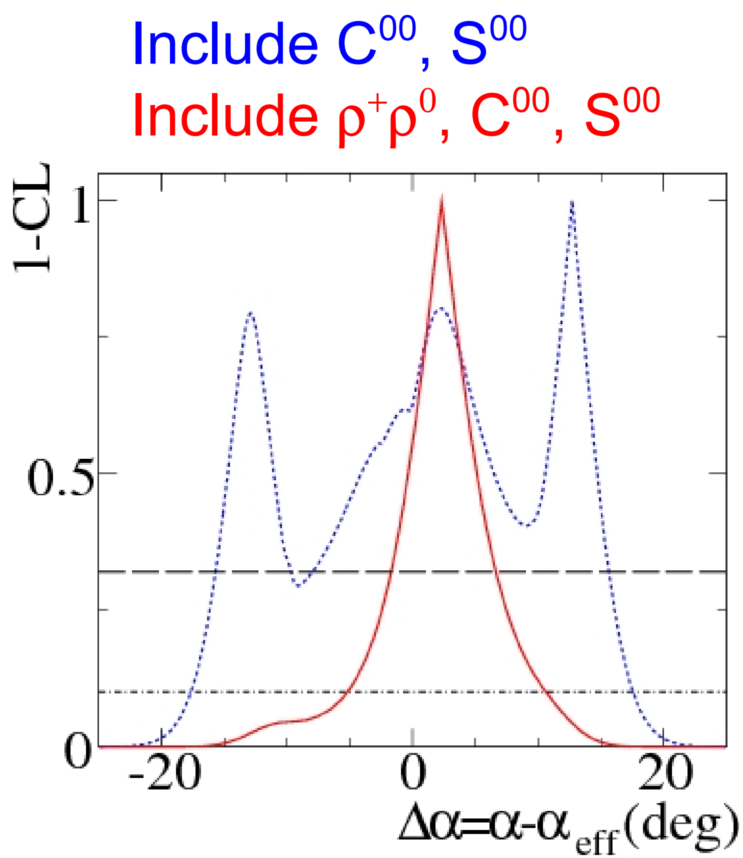


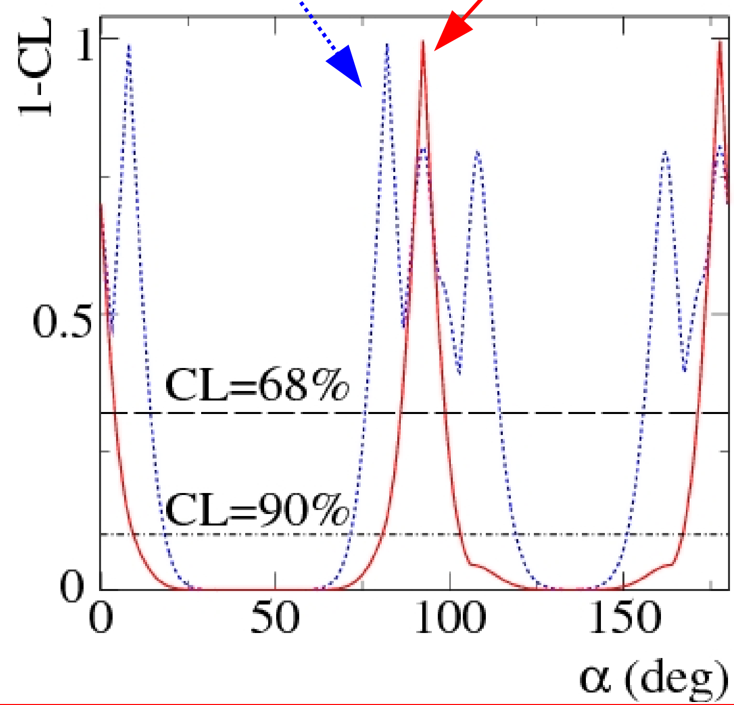


$\rho^+\rho^0$ results

- $BF(\rho^+\rho^0)$ and $f_L(\rho^+\rho^0)$ increase $\Rightarrow$ isospin triangle flattens out







$$\alpha = \left(82.6^{+32.6}_{-6.3}\right)^\circ$$
$$|\Delta\alpha| < 15.7^\circ \ @ 68\ CL$$

$\Rightarrow$

$$\alpha = \left(92.4^{+6.0}_{-6.5}\right)^\circ$$
$$-1.8^\circ < \Delta\alpha < 6.7^\circ \ @ 68\ CL$$

$B \to a_1 \pi$

$B \to a_1 \pi$

- Not a CP eigenstate

$$A_+ = A(B^0 \to a_1^+ \pi^-) \qquad \bar{A}_+ = A(\bar{B}^0 \to a_1^- \pi^+)$$
$$A_- = A(B^0 \to a_1^- \pi^+) \qquad \bar{A}_- = A(\bar{B}^0 \to a_1^+ \pi^-)$$

$$S \pm \Delta S \equiv \frac{2\, Im(e^{-2i\beta} \bar{A}_\mp A_\pm^*)}{|A_\pm|^2 + |\bar{A}_\mp|^2}$$

$$C \pm \Delta C \equiv \frac{|A_\pm|^2 - |\bar{A}_\mp|^2}{|A_\pm|^2 + |\bar{A}_\mp|^2}$$

PRL98, 181803 (2007)

A_{CP}	$-0.07 \pm 0.07 \pm 0.02$
S	$0.37 \pm 0.21 \pm 0.07$
ΔS	$-0.14 \pm 0.21 \pm 0.06$
C	$-0.10 \pm 0.15 \pm 0.09$
ΔC	$0.26 \pm 0.15 \pm 0.07$

$$F_{Q_{\rm tag}}^{a_1^\pm \pi^\mp}(\Delta t) = (1 \pm A_{CP}) \frac{e^{-|\Delta t|/\tau}}{4\tau} \left\{ 1 - Q_{\rm tag}\Delta w + Q_{\rm tag}(1-2w) \left[(S \pm \Delta S)\sin(\Delta m_d \Delta t) - (C \pm \Delta C)\cos(\Delta m_d \Delta t) \right] \right\}$$

- Extraction of α_{eff}

$$2\alpha_{eff}^{\pm} \equiv arg[e^{-2i\beta} \bar{A}_\pm A_\pm^*] \qquad 2\alpha_{eff}^{\pm} \pm \hat{\delta} = arg[e^{-2i\beta} \bar{A}_\pm A_\mp^*] = \arcsin \frac{S \mp \Delta S}{\sqrt{1-(C \mp \Delta C)^2}}$$

$$\hat{\delta} \equiv arg[A_+ A_-^*] \qquad \alpha_{eff} = \frac{1}{2}(\alpha_{eff}^+ + \alpha_{eff}^-)$$

  - For small penguins, $\delta \approx$ strong phase between tree amplitudes

$\Delta\alpha$ from SU(3)

- Penguin (P) is CKM ($1/\lambda = |V_{cs}|/|V_{cd}|$) enhanced in $\Delta S=1$ decays
- Use SU(3) symmetry and ratios of CP-averaged rates for $\Delta S=1$ ($B\to a_1 K$, $B\to K_{1A}\pi$) and $\Delta S=0$ ($B\to a_1\pi$)

$$R_{+}^{0,+} \equiv \frac{\lambda^2 f_{a_1}^2 BF(K_{1A}^{+,0}\pi^{-,+})}{f_{K_{1A}}^2 BF(a_1^+\pi^-)}$$

K_{1A} = SU(3) partner of a_1

PRL97, 051802 (2006)
PRL100, 051803 (2008)

and similarly for $R_{-}^{0,+}$ from $a_1 K$ decays

- Get $|\alpha_{eff}^{+,-}-\alpha|$ by solving the system:

$$\cos 2(\alpha_{\rm eff}^{\pm} - \alpha) \geq \frac{1 - R_{\pm}^{0}}{\sqrt{1 - \mathcal{A}_{CP}^{\pm\,2}}}$$

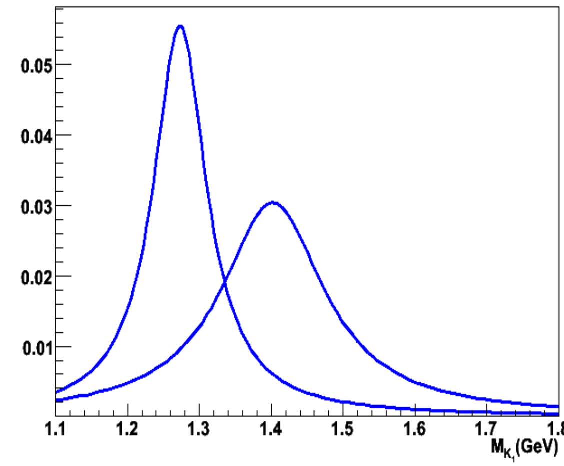
$$\cos 2(\alpha_{\rm eff}^{\pm} - \alpha) \geq \frac{1 - R_{\pm}^{+}}{\sqrt{1 - \mathcal{A}_{CP}^{\pm\,2}}}$$

$A_{CP}^{\pm}$ = CP asymmetries

- $|\Delta\alpha| = (|\alpha_{eff}^{+}-\alpha|+|\alpha_{eff}^{-}-\alpha|)/2$

B decays to $K_1(1270)\pi$ and $K_1(1400)\pi$

- $BF(B \to K_{1A}\pi)$ is the only missing piece for extracting α from $B \to a_1\pi$
- SU(3) octet states K_{1A} (C= +1 octet) and K_{1B} (C= -1 octet) mix
  - $|K_1(1400)\rangle = |K_{1A}\rangle \cos\theta + |K_{1B}\rangle \sin\theta$
    $|K_1(1270)\rangle = -|K_{1A}\rangle \sin\theta + |K_{1B}\rangle \cos\theta$



- Need to measure these to get $BF(B \to K_{1A}\pi)$
  - Upper limits by ARGUS:
    - $BF(B^0 \to K_1(1400)^+\pi^-) < 1.1\times10^{-3}$ @ 90% C.L.
    - $BF(B^+ \to K_1(1400)^0\pi^+) < 2.6\times10^{-3}$ @ 90% C.L.

      Argus coll., PLB 254, 288 (1991)
  - Theoretical predictions
    - ~ $O(10^{-6})$

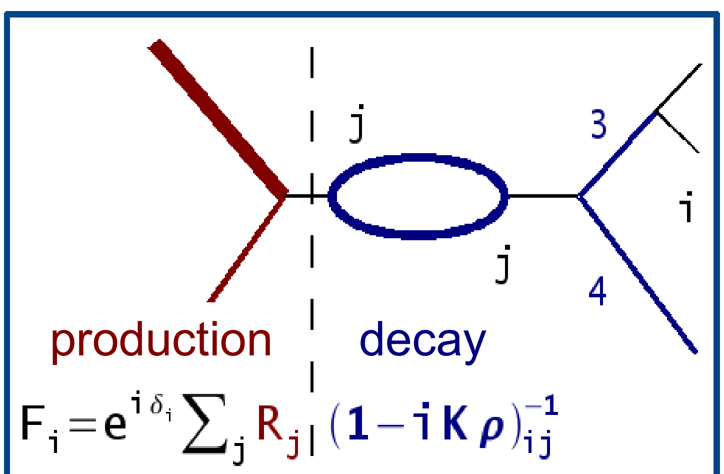
      Laporta et al., PRD 74, 054035 (2006)
      Calderon et al., PRD 76, 094019 (2007)
      Cheng et al., PRD 76, 114020 (2007)

$K_1\pi$ analysis

- Other consequences of mixing:
  - broad resonances with nearly equal masses
  - same quantum numbers and final state ($K\pi\pi$)
  - intermediate decays almost at threshold $\Rightarrow$ PHSP overlap

  } Interference effects

- Use $K\pi\pi$ mass spectrum to distinguish between $K_1(1270)$ and $K_1(1400)$
  - Include interference effects in the signal model
- Highest statistics data from WA3 exp. ACCMOR, NPB 187, 1 (1981)
  - $K\pi\pi$ analyzed using a six-channel, two-resonance K-matrix model



$$R_j = \frac{f_{pa} f_{aj}}{M_a - M_{K\pi\pi}} + \frac{f_{pb} f_{bj}}{M_b - M_{K\pi\pi}}$$

$$K_{ij} = \frac{f_{ai} f_{aj}}{M_a - M_{K\pi\pi}} + \frac{f_{bi} f_{bj}}{M_b - M_{K\pi\pi}}$$

$$\rho_{ij}(M_{K\pi\pi}) = \frac{2\delta_{ij}}{M_{K\pi\pi}} \left[\frac{2 m_3^* m_4}{m_3^* + m_4} \left(M_{K\pi\pi} - m_3^* - m_4 + i\frac{\Gamma_3}{2} \right) \right]^{1/2}$$

$K_1\pi$ analysis

- Model signal $K\pi\pi$ mass from MC implementing the K-matrix model
  - $$f = \sum_{i \neq \omega K} F_i \langle K\pi\pi | i \rangle = \sum_{i \neq \omega K} F_i C_i BW_i^{\ell} A_i^{\ell}$$
- decay parameters fixed to the values extracted from fit to WA3 data
  - Include background terms
  - 6^{th} channel (ωK) not fitted

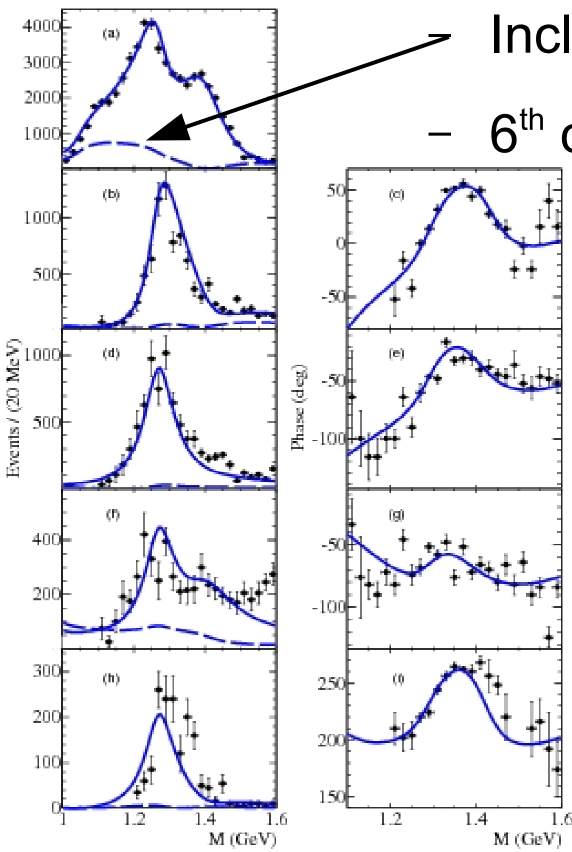
$(K^*\pi)_S$

ρK

$K^*_0\pi$

f_0K

$(K^*\pi)_D$

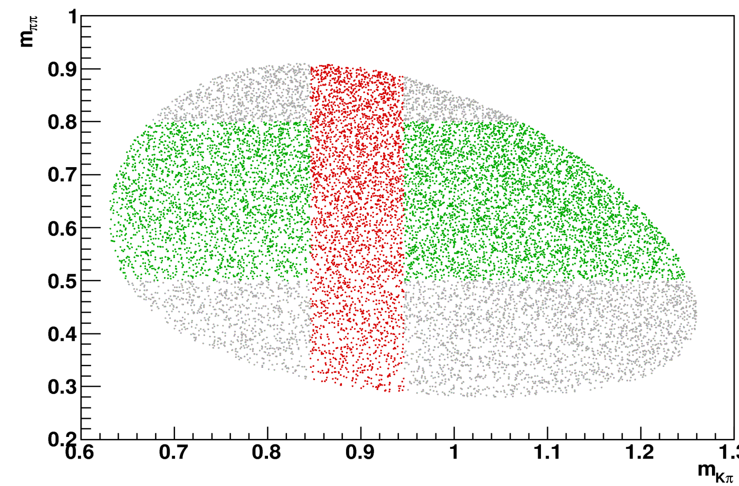


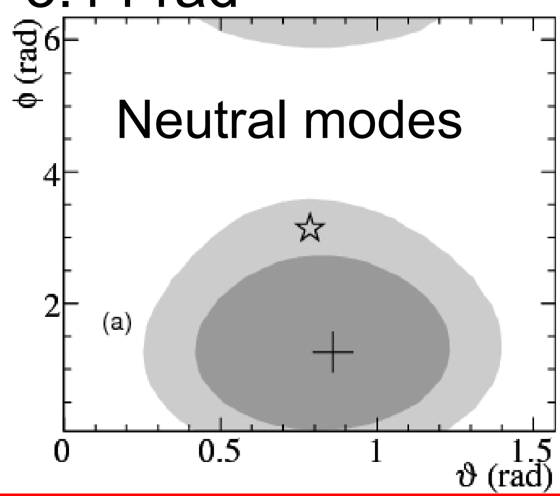
Parameter	Fitted value
M_a	1.40 ± 0.02
M_b	1.16 ± 0.02
θ	$72^\circ \pm 3^\circ$
γ_+	0.75 ± 0.03
γ_-	0.44 ± 0.03
f_{a3}	0.02 ± 0.03
f_{b3}	0.32 ± 0.01
f_{a4}	-0.08 ± 0.02
f_{b4}	0.16 ± 0.01
f_{a5}	0.06 ± 0.01
f_{b5}	0.21 ± 0.04
δ_2	$-31^\circ \pm 1^\circ$
δ_3	$82^\circ \pm 2^\circ$
δ_4	$78^\circ \pm 4^\circ$
δ_5	$20^\circ \pm 9^\circ$

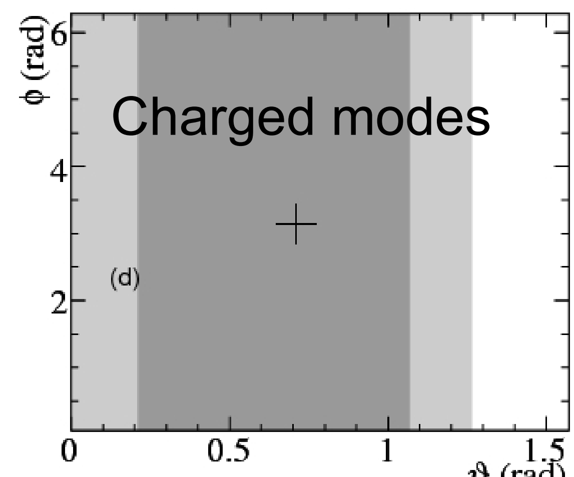
- production parameters left floating in the analysis of B decays
  - ($f_{pa}=\cos\vartheta, f_{pb}=\sin\vartheta\, e^{i\phi}$) $\Rightarrow$ finite ranges for (ϑ,ϕ)

$K_1\pi$ analysis

- NLL scan over (ϑ,ϕ) + extended ML fit for BF (m_{ES}, ΔE, Fisher, $m_{K\pi\pi}$, $|H|$)
  - Use nonparametric templates for signal $P(m_{K\pi\pi}|\vartheta,\phi)$
- Include $K^*(1410)\pi$ and $K^*\pi\pi + \rho K\pi$ as individual components
- Neutral modes
  - simultaneous fit to "K^*" and "ρ" bands
    - helps in resolving ambiguities on ϕ
- Charged modes
  - fit to "K^*" band only
  - not sensitive to ϕ: fix ϕ=3.14 rad
- Results of NLL scan:







$K_1\pi$ results

- $BF(B^0 \to K_1(1400)^+\pi^- + K_1(1270)^+\pi^-) \sim (3.1^{+0.8}_{-0.7}) \times 10^{-5}$ S=7.5σ
- $BF(B^+ \to K_1(1400)^0\pi^+ + K_1(1270)^0\pi^+) \sim (2.9^{+3.0}_{-1.7}) \times 10^{-5}$ S=3.2σ

Neutral modes

$BF(B^0 \to K_1(1400)^+\pi^-) = (1.6^{+0.8}_{-0.9}) \times 10^{-5}$

$BF(B^0 \to K_1(1270)^+\pi^-) = (1.6^{+0.9}_{-1.0}) \times 10^{-5}$

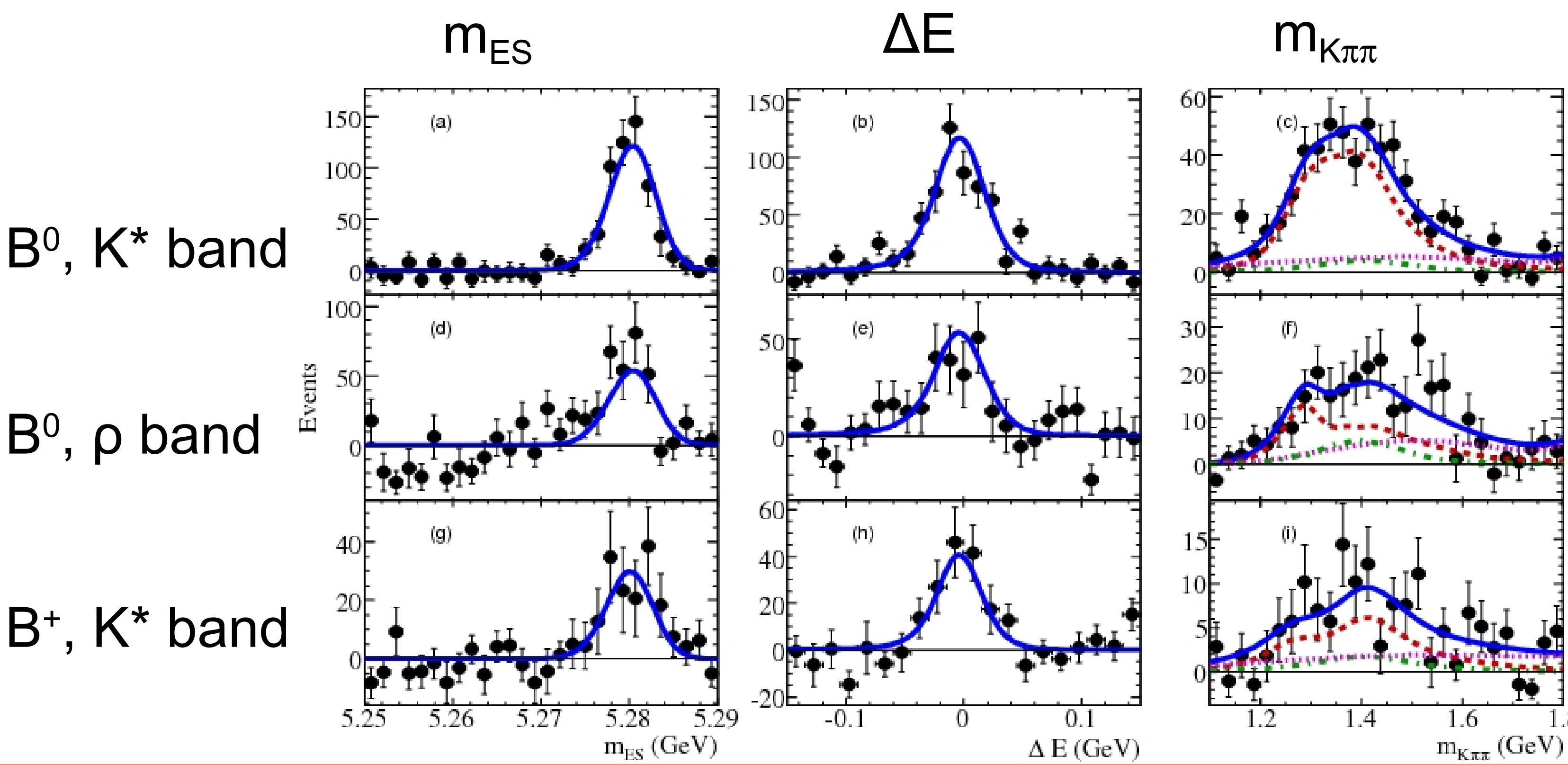
$BF(B^0 \to K_{1A}{}^+\pi^-) = (1.4^{+0.9}_{-1.0}) \times 10^{-5}$

Charged modes

$BF(B^+ \to K_1(1400)^0\pi^+) < 3.9 \times 10^{-5}$

$BF(B^+ \to K_1(1270)^0\pi^+) < 4.0 \times 10^{-5}$

$BF(B^+ \to K_{1A}{}^0\pi^+) < 3.6 \times 10^{-5}$



$a_1\pi$ results

$\mathcal{B}(a_1^{\pm}\pi^{\mp})(\times 10^{-6})$	$\mathcal{B}(a_1^{-}K^{+})(\times 10^{-6})$	$\mathcal{B}(a_1^{+}K^{0})(\times 10^{-6})$	$\mathcal{B}(K_1^{+}\pi^{-})(\times 10^{-5})$	$\mathcal{B}(K_1^{0}\pi^{+})(\times 10^{-5})$
$(33.2 \pm 3.8 \pm 3.0)$	$(16.3 \pm 2.9 \pm 2.3)$	$(33.2 \pm 5.0 \pm 4.4)$	$(1.4^{+0.9}_{-1.0})$	< 3.6
f_π(MeV)	f_K(MeV)	f_{a_1}(MeV)	$f_{K_{1A}}$(MeV)	$\theta_{mix}(^\circ)$
130.4 ± 0.2	155.5 ± 0.9	203 ± 18	207 ± 20	72

Assume BF($a_1^+ \to \pi^+\pi^-\pi^+$)=50%

- Evaluate the bounds on $|\Delta\alpha|$ by a MC based method
  - Generate input according to the experimental distributions
  - For each set of generated values, evaluate the bounds
  - Get limits by counting the fraction of bounds within a given value
- 8 ambiguities on α: 11°, 41°, 49°, 79°, 101°, 131°, 139°, 169°
  - 2 ($\alpha \to \pi/2 - \alpha$) x 2 (roughly $2\alpha \leftrightarrow \delta$) x 2 (average)
  - assume $\delta \sim 0$ (from factorization) $\Rightarrow$ 2 ambiguities

$|\Delta\alpha| < 11^\circ$ (13°) @ 68% (90%) CL

$\alpha = (79 \pm 7 \pm 11)^\circ$

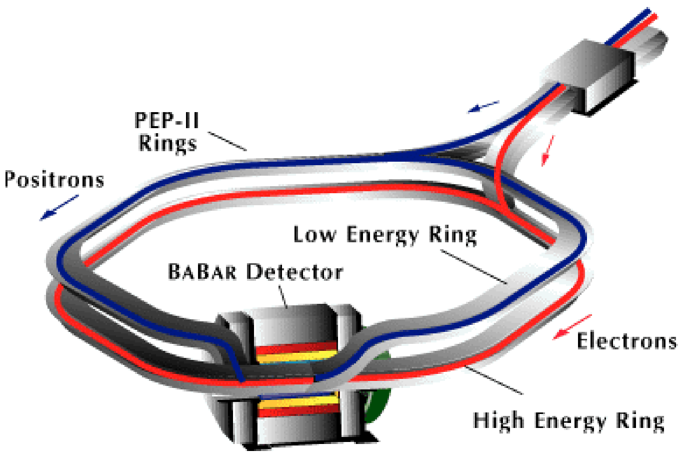
Conclusions

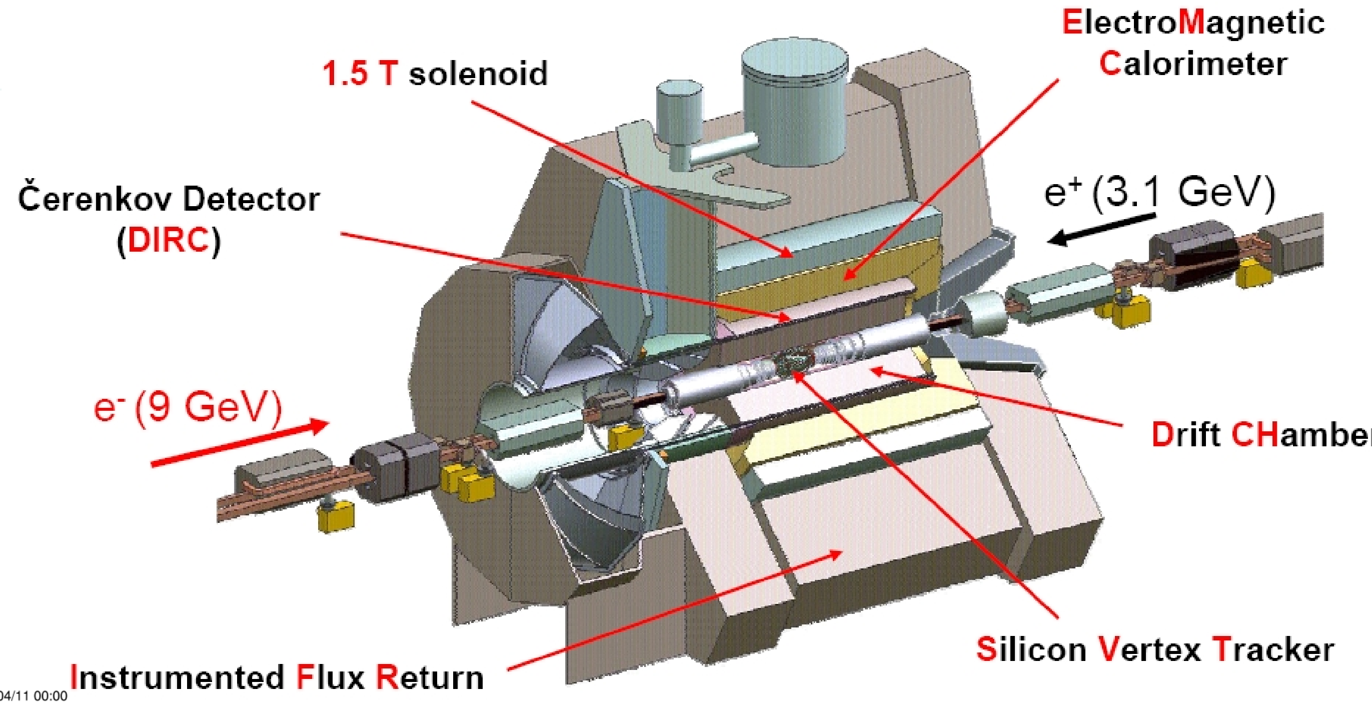
- Much improvement has come from constraining model uncertainties
- Time dependent CPV observed in $\pi^+\pi^-$
- In $\rho\rho$ reached 7% precision in α, comparable to 5.3% in $\sin 2\beta$
- $\pi^+\pi^-\pi^0$ still to update (not in this talk)
- $a_1\pi$ now provides a fourth independent determination of α

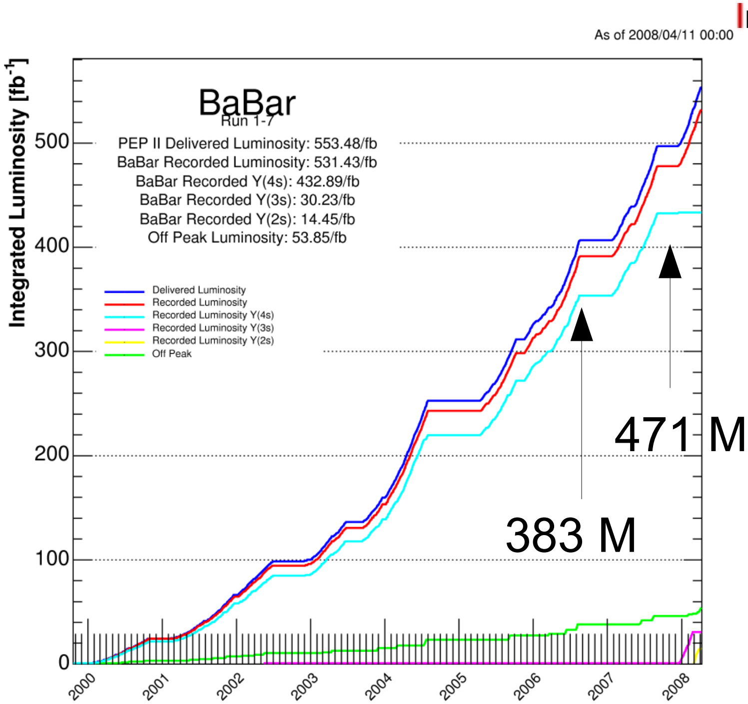
$$(P/T)_{\rho\rho} < (P/T)_{a_1\pi} < (P/T)_{\pi\pi}$$

- Used the final BaBar data sample
  - Many measurements still limited by statistics

BaBar detector and dataset







- Final sample @ $\Upsilon(4S)$:
  - 439 fb^{-1}
  - 471×10^6 BB pairs