$B \rightarrow \pi\pi$ and the CKM Angle α

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$B \rightarrow \pi\pi$ and the CKM Angle α

- $B \rightarrow \pi\pi$: Isospin Analysis and α.
- The Individual Modes:
  - $B^0 \rightarrow \pi^+ \pi^-$
  - $B^0 \rightarrow \pi^0 \pi^0$
  - $B^\pm \rightarrow \pi^\pm \pi^0$
- Putting it together: Measuring α

CKM Angle α

- CKM Matrix describes mixing between flavor and weak eigenstates.

$$V = \begin{array}{c} \\ u \\ c \\ t \end{array} \begin{array}{c} \begin{array}{ccc} d & s & b \end{array} \\ \begin{pmatrix} 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} \end{array}$$

Unitary up to $O(\lambda^4)$, with CP violating phases in V_{ub} and V_{td} .

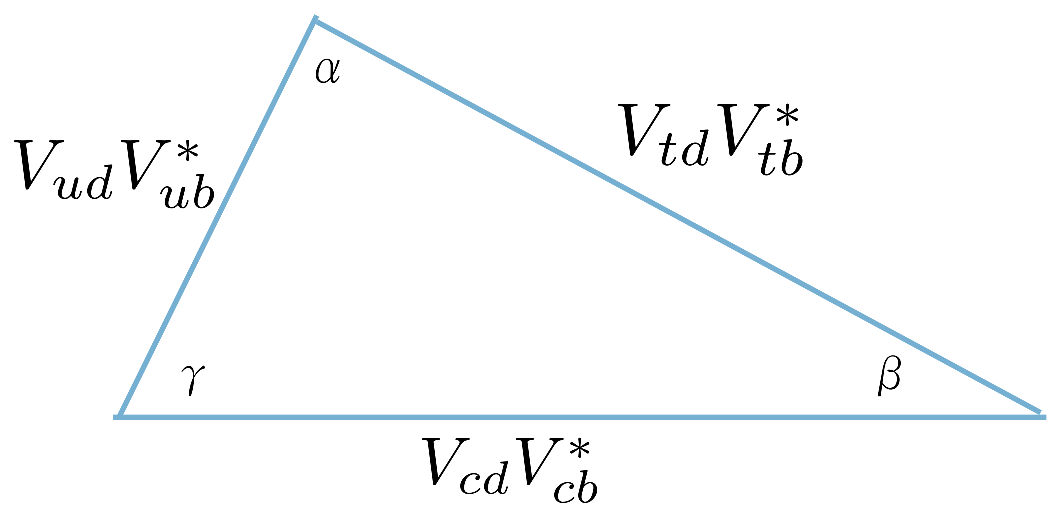
Because of the unitarity condition:

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

$$\alpha \equiv \phi_2 \equiv arg\left(-\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}\right)$$

$$\beta \equiv \phi_1 \equiv arg\left(-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right)$$

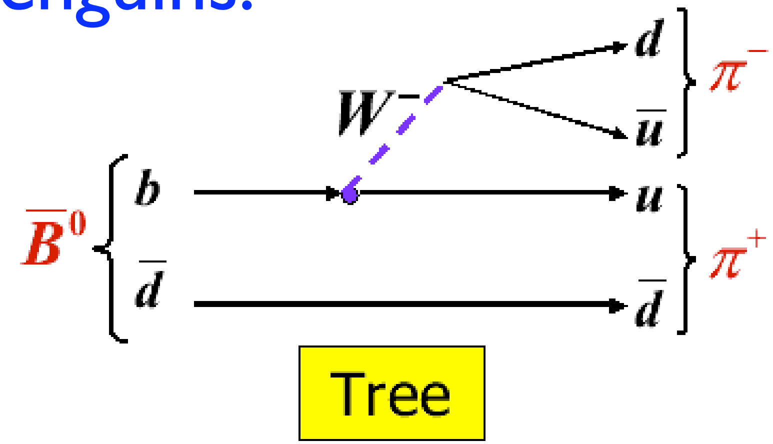
$$\gamma \equiv \phi_3 \equiv arg\left(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right)$$



CKM Angle α and $B \rightarrow \pi^+ \pi^-$

In the absence of penguins:

$$a_{\pi^+\pi^-}(\Delta t) = \frac{\Gamma(B^0 \rightarrow \pi^+\pi^-) - \Gamma(\overline{B}^0 \rightarrow \pi^+\pi^-)}{\Gamma(B^0 \rightarrow \pi^+\pi^-) + \Gamma(\overline{B}^0 \rightarrow \pi^+\pi^-)}$$



$$a_{\pi^+\pi^-}(\Delta t) = \frac{(1 - |\lambda_{\pi^+\pi^-}|^2) cos(\Delta m \Delta t) - 2 \Im m(\lambda_{\pi^+\pi^-}) sin(\Delta m \Delta t)}{(1 + |\lambda_{\pi^+\pi^-}|^2)}$$

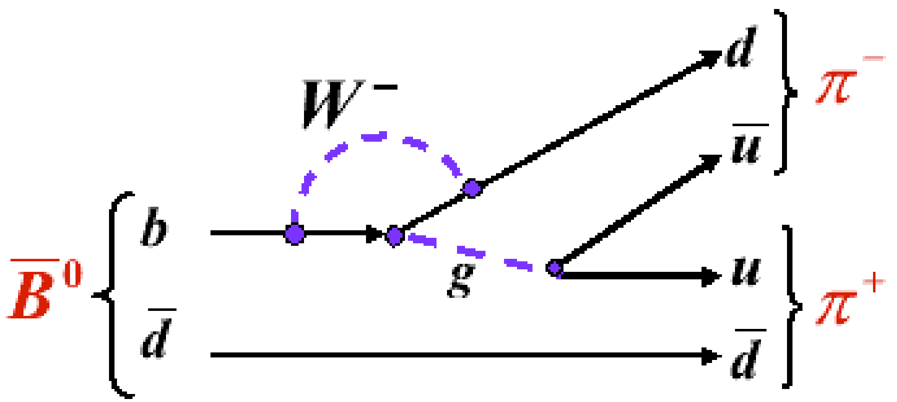
$$\lambda_{\pi^+\pi^-} = \left(\frac{V_{tb}^* V_{td}}{V_{tb} V_{td}^*}\right)\left(\frac{V_{ud}^* V_{ub}}{V_{ud} V_{ub}^*}\right) \Longrightarrow \Im m \lambda_{\pi^+\pi^-} = sin(2\alpha)$$

CKM Angle α and $B \to \pi^+ \pi^-$

Penguin Pollution

$$\lambda_{\pi^+\pi^-} = |\lambda| e^{2i\alpha_{eff}} = \frac{e^{-i\alpha} T + P}{e^{+i\alpha} T + P}$$

$$= e^{-2i\alpha} \frac{1 + |Z| e^{i(\delta+\alpha)}}{1 + |Z| e^{i(\delta-\alpha)}}$$



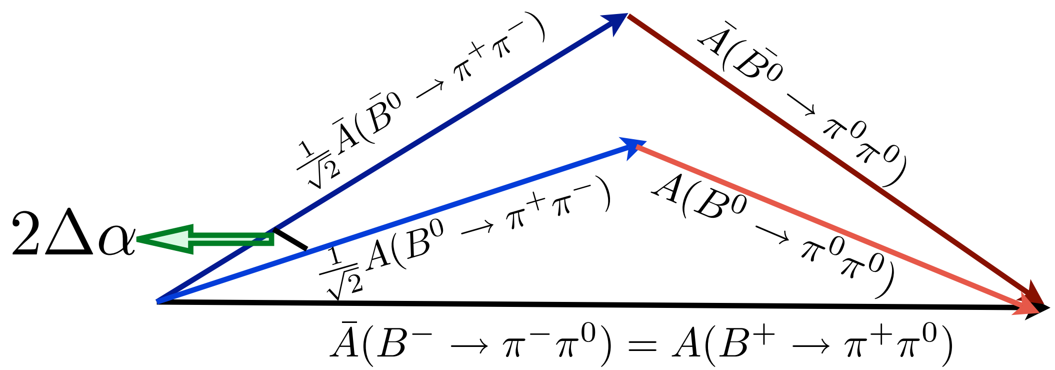
Penguin

Here, $Z = \frac{P}{T}$ is the ratio of the penguin amplitude (P) to the tree amplitude (T), and $\delta = \delta_P - \delta_T$, the difference in the strong phases between P and T.

Isospin Analysis: B→ππ

$$\Delta\alpha = \alpha - \alpha_{eff}$$

$$A^{+0} \equiv A(B^+ \to \pi^+\pi^0)$$
$$A^{+-} \equiv A(B^0 \to \pi^+\pi^-)$$
$$A^{00} \equiv A(B^0 \to \pi^0\pi^0)$$



The key observation: $B^\pm \to \pi^\pm\pi^0$ is a purely tree decay (no $\Delta I = 1/2$ amplitude)

So (after a rotation):

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

$$\frac{1}{\sqrt{2}}A^{+-} + A^{00} = A^{+0}$$

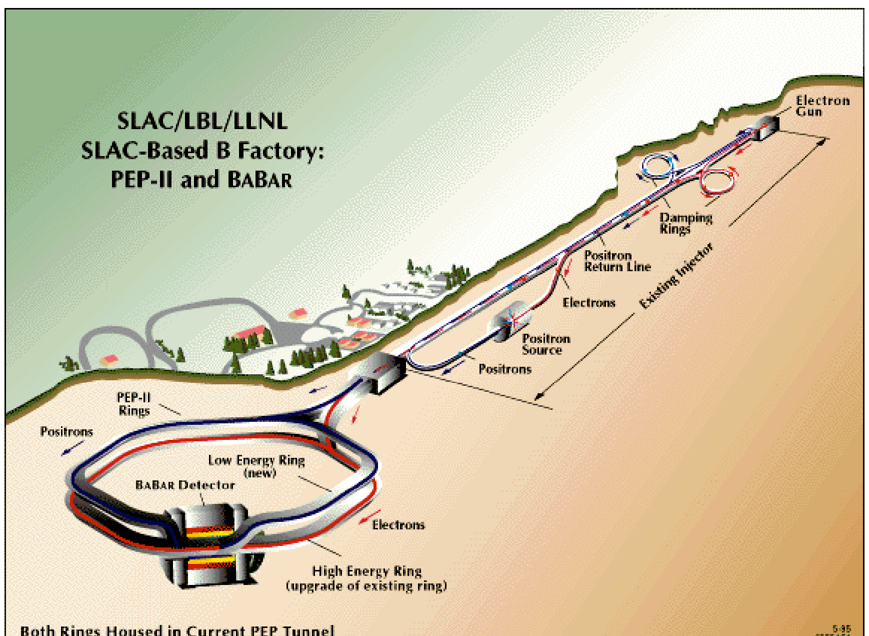
$$\frac{1}{\sqrt{2}}\bar{A}^{+-} + \bar{A}^{00} = \bar{A}^{-0}$$

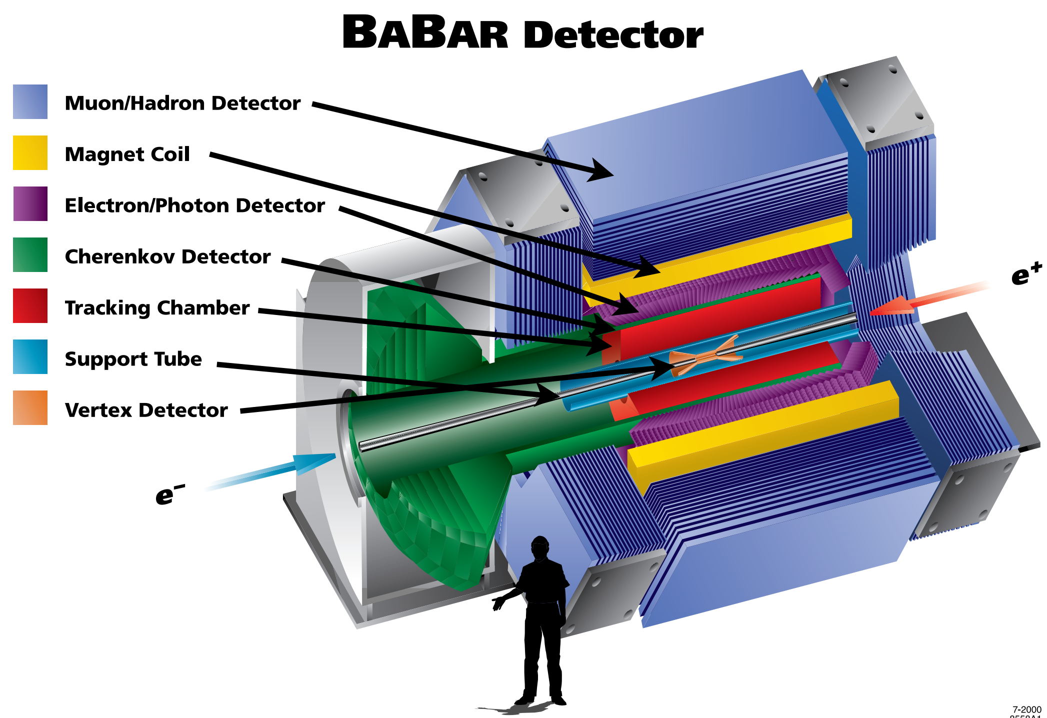
[M. Gronau and D. London, Phys Rev. Lett. 65, 3381 (1990)]

<u>Eight-fold ambiguity in α.</u>

BaBar at PEP II

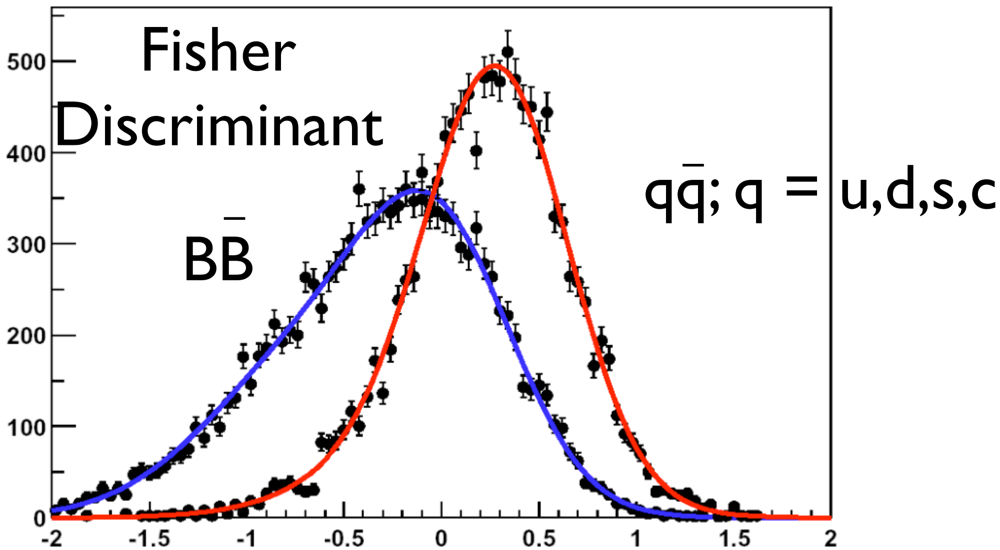
- Asymmetric-energy electron-positron collider.
- CM energy at the $\Upsilon(4S)$ resonance.
- All analyses here use 316 fb^{-1} of data taken through June 2006.

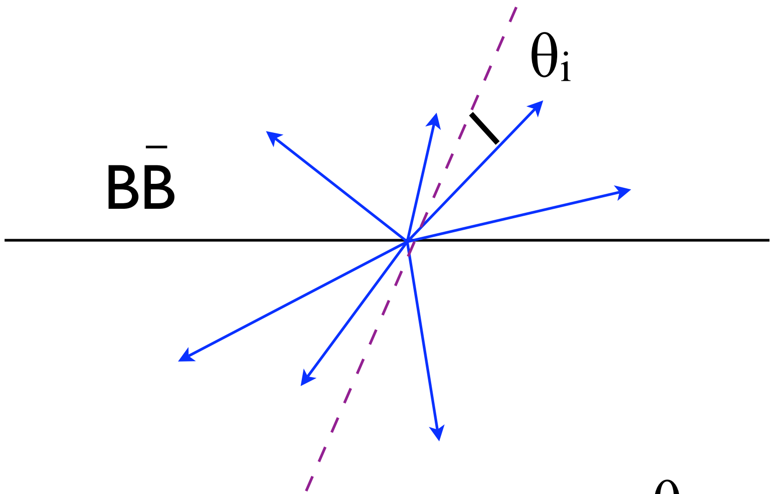


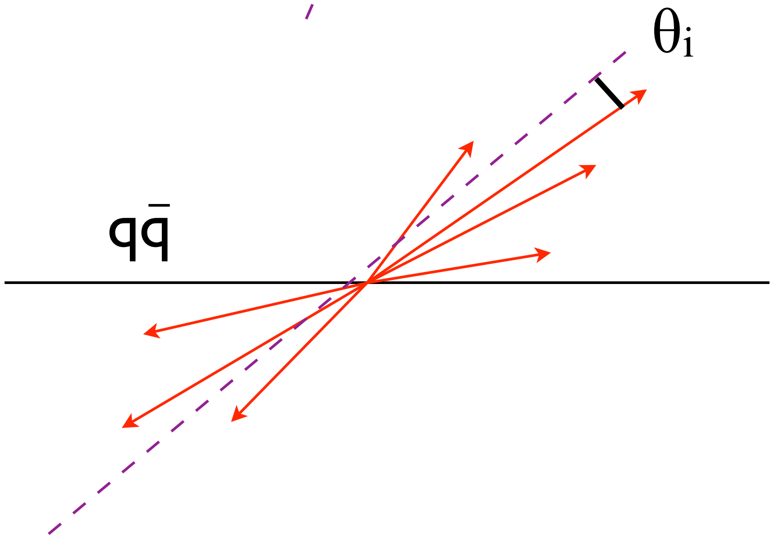


Common Analysis Techniques

- $m_{ES} = \sqrt{(s/2 + p_0 \cdot p_B)^2 / E_0^2 - p_B^2}$
- $\Delta E = E_B - \frac{1}{2} E_{beam}$
- $\mathcal{F} = c_0 \sum_i p_i + c_2 \sum_i p_i \times (cos\theta_i)^2$

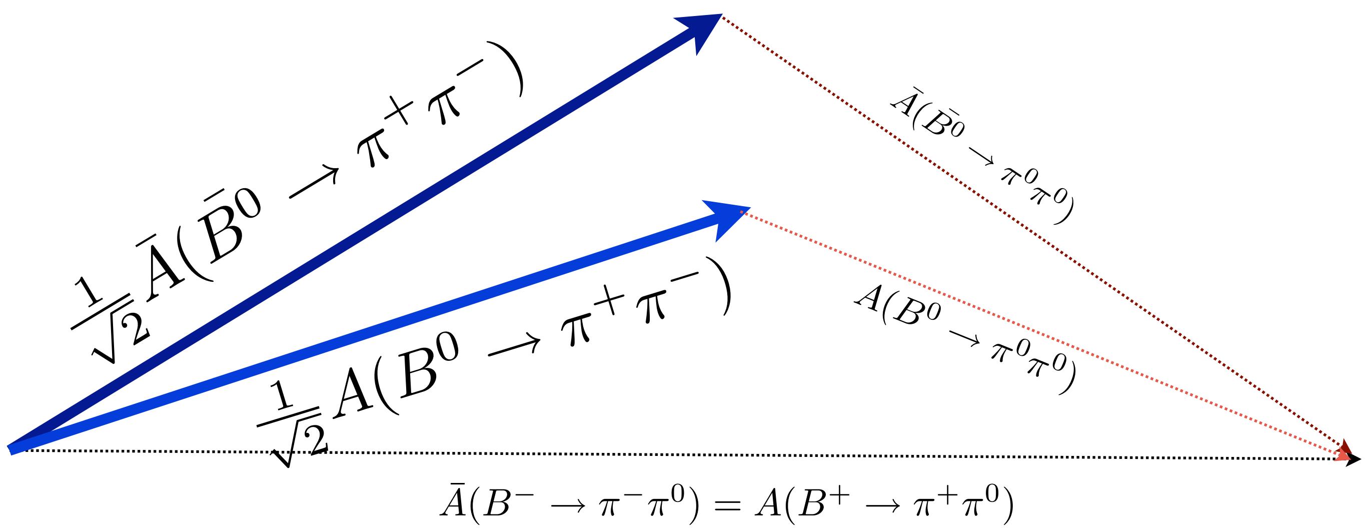






$B^0 \rightarrow \pi^+ \pi^-$

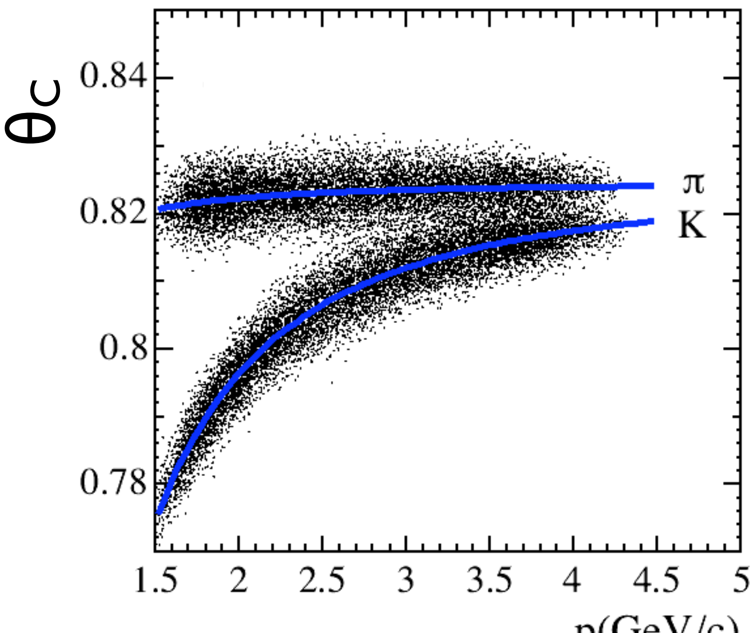
- Two charged tracks
  - Time dependent CP Violation
- Most precise of the $B \rightarrow \pi\,\pi$ modes.

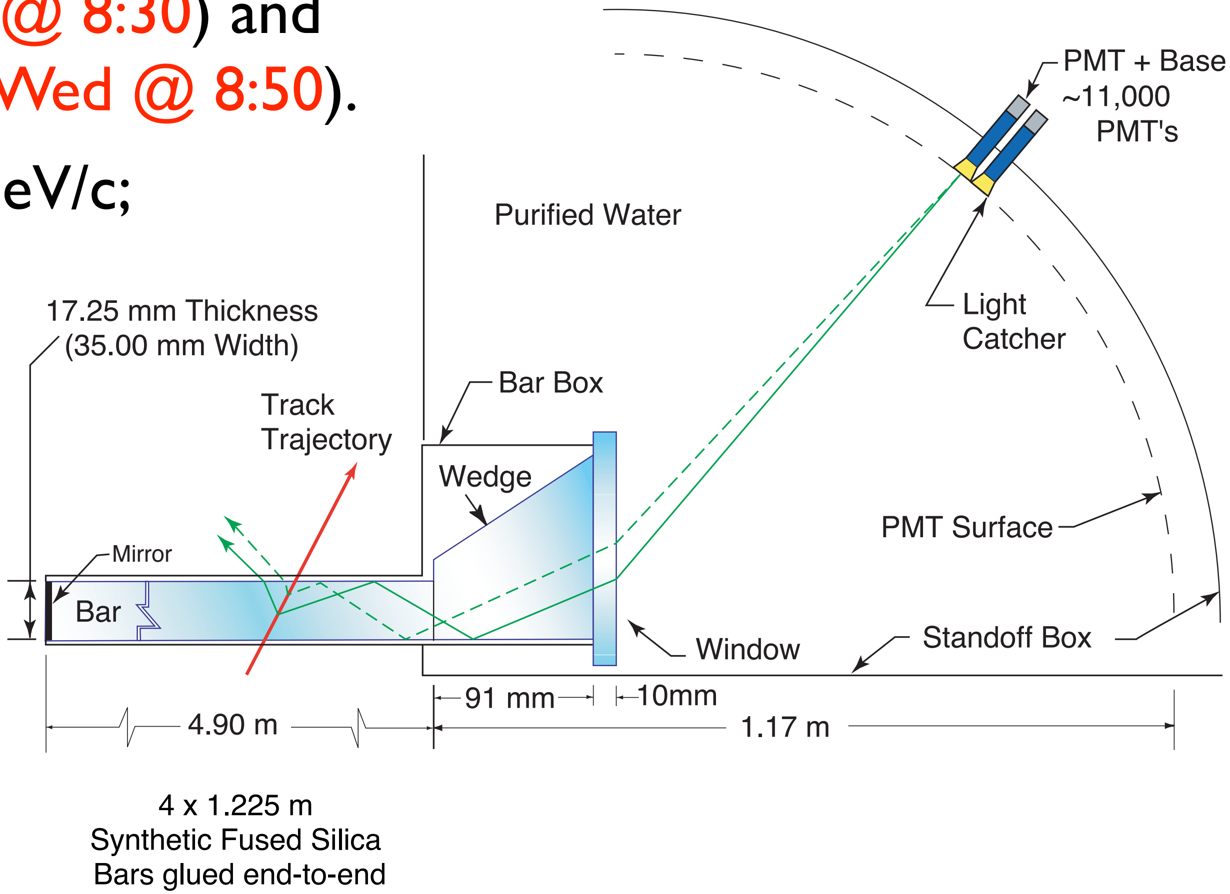


$B^0 \to \pi^+ \pi^-$: K/π separation

- DIRC: Cherenkov detector used for particle identification

- Simultaneous fit for
  - $B^0 \to K^\pm \pi^\mp$ (see X. Li; Wed @ 8:30) and
  - $B^0 \to K^+ K^-$ (see: J. Biesiada: Wed @ 8:50).
- 12σ K/π separation @ 1.5 GeV/c;
- 2σ @ 4.5GeV/c





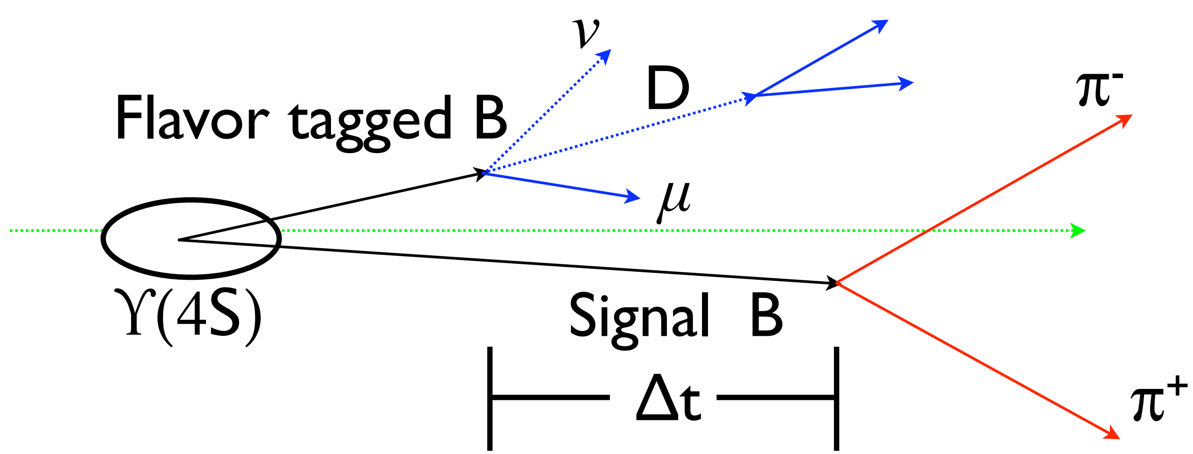
$B^0 \to \pi^+ \pi^-$: CP Asymmetry

- Time dependent CP Asymmetry
- B flavor tagging: NN-based; 6 independent categories (plus untagged).
- Mistag rate measured from large sample of fully reconstructed B's.
- $\beta\gamma = 0.56$

$$a_{\pi^+\pi^-}(\Delta t) = \frac{\Gamma(B^0 \to \pi^+\pi^-) - \Gamma(\overline{B}^0 \to \pi^+\pi^-)}{\Gamma(B^0 \to \pi^+\pi^-) + \Gamma(\overline{B}^0 \to \pi^+\pi^-)}$$

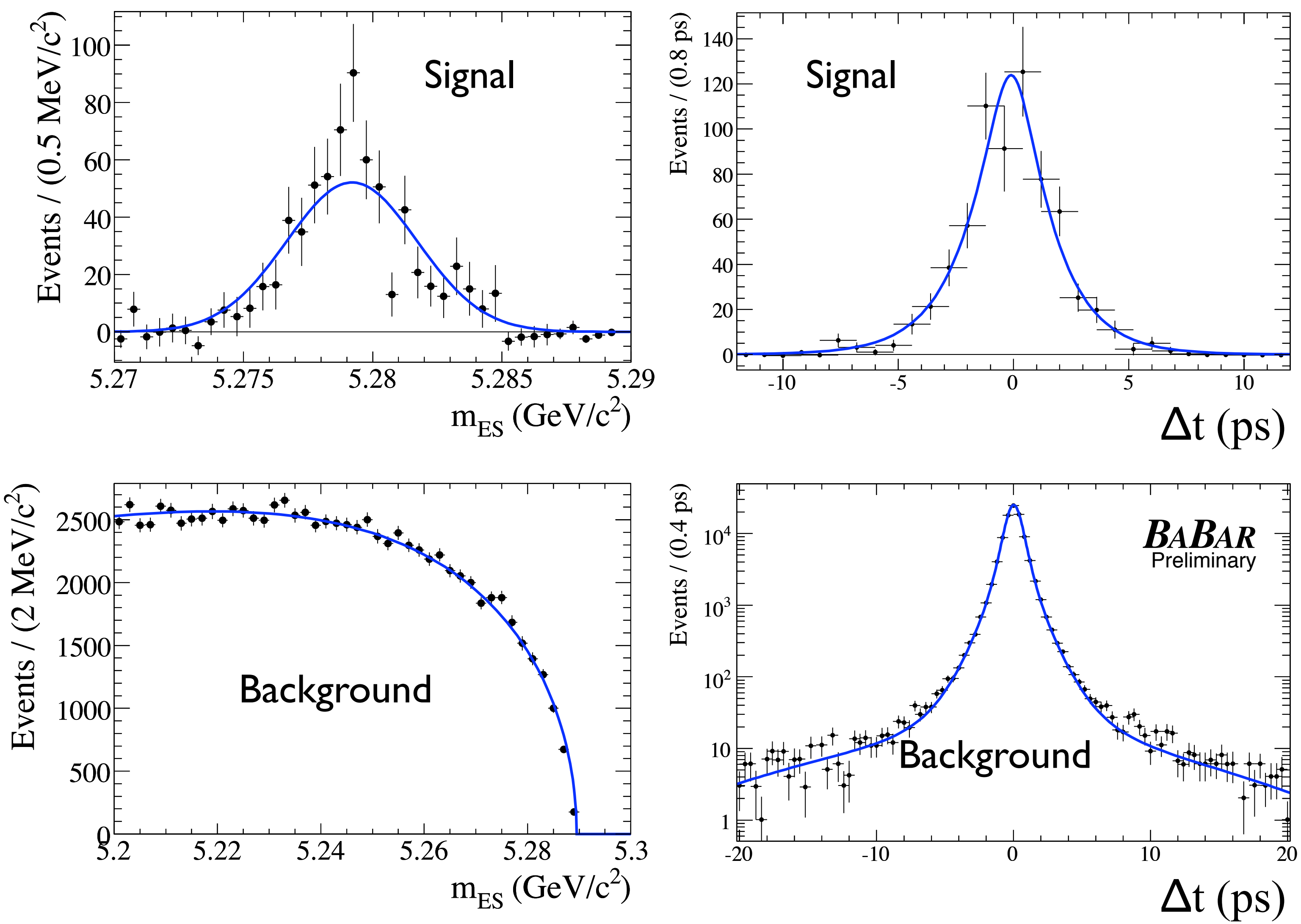
$$= -S_{\pi^+\pi^-} sin(\Delta m_d \Delta t) + C_{\pi^+\pi^-} cos(\Delta m_d \Delta t)$$

$$\frac{S_{\pi^+\pi^-}}{\sqrt{1 - C^2_{\pi^+\pi^-}}} = sin(2\alpha_{eff})$$



$B^0 \rightarrow \pi^+ \pi^-$: Results I

- 675±42 events

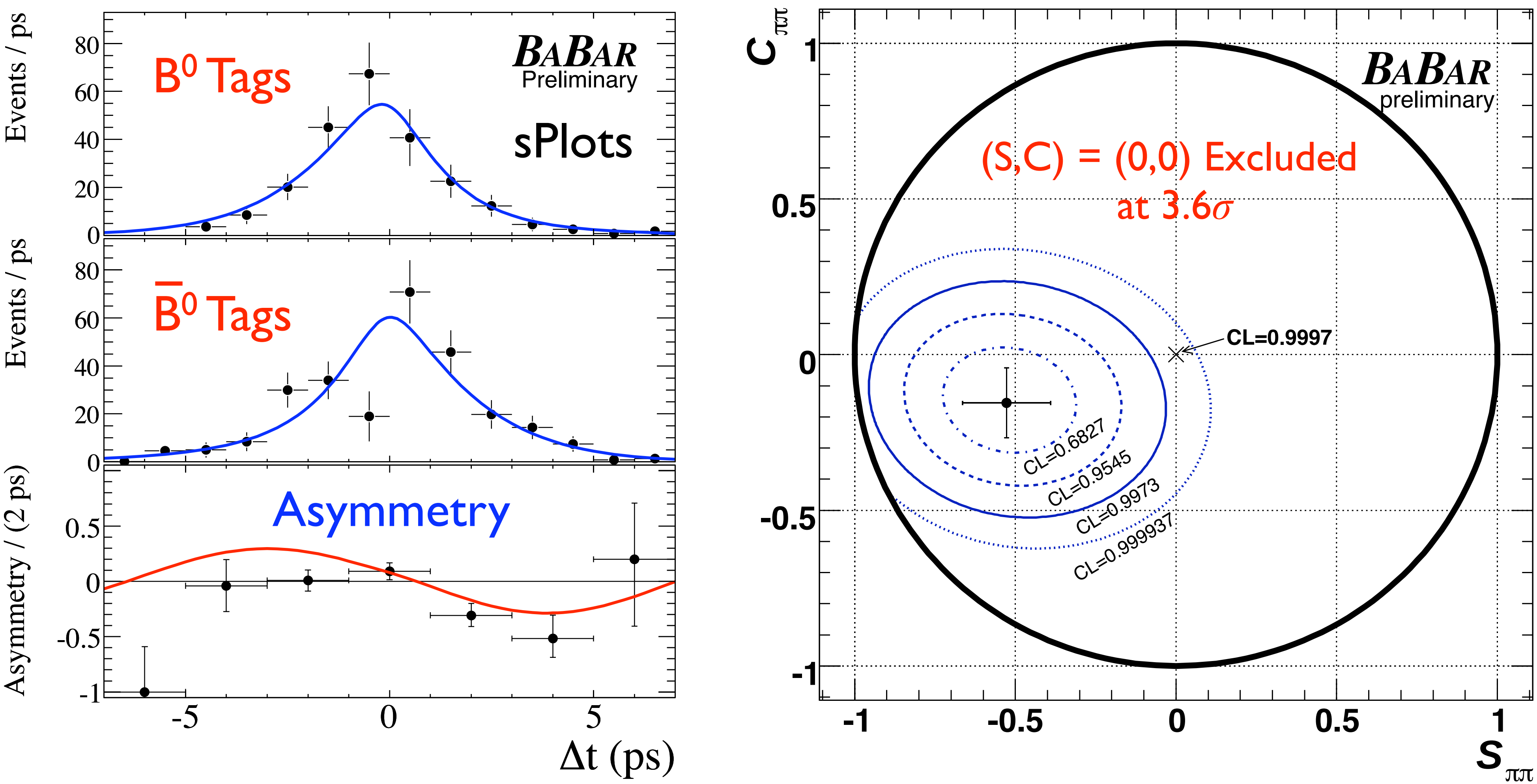


- Maximum likelihood fit includes $K\pi$, KK
- m_{ES}, ΔE, Fisher, DIRC angle, Δt, tagging.
- Two sequential fits: yield (h h' modes), then those parameters fixed for TDCP fit.
- Plots of likelihood weighted events (sPlots)

  M.Pivk and F.R. LeDiberder, [Nucl. Instrum. Meth. A **555**, 356 (2005)]

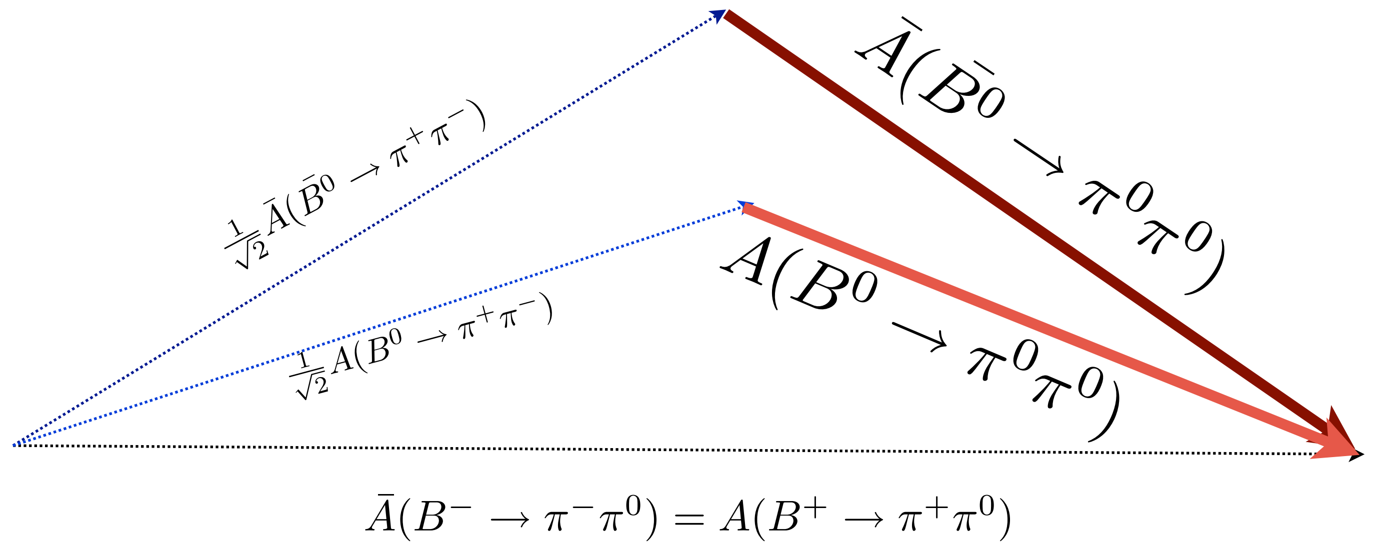
$B^0 \to \pi^+ \pi^-$: Results II

$C(B^0 \to \pi^+ \pi^-)$	$-0.16 \pm 0.11 \pm 0.03$
$S(B^0 \to \pi^+ \pi^-)$	$-0.53 \pm 0.14 \pm 0.02$

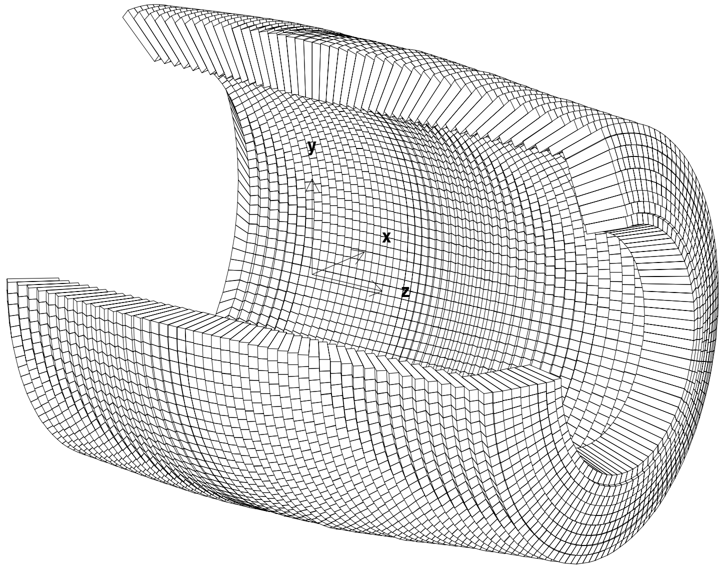


$B^0 \to \pi^0 \pi^0$

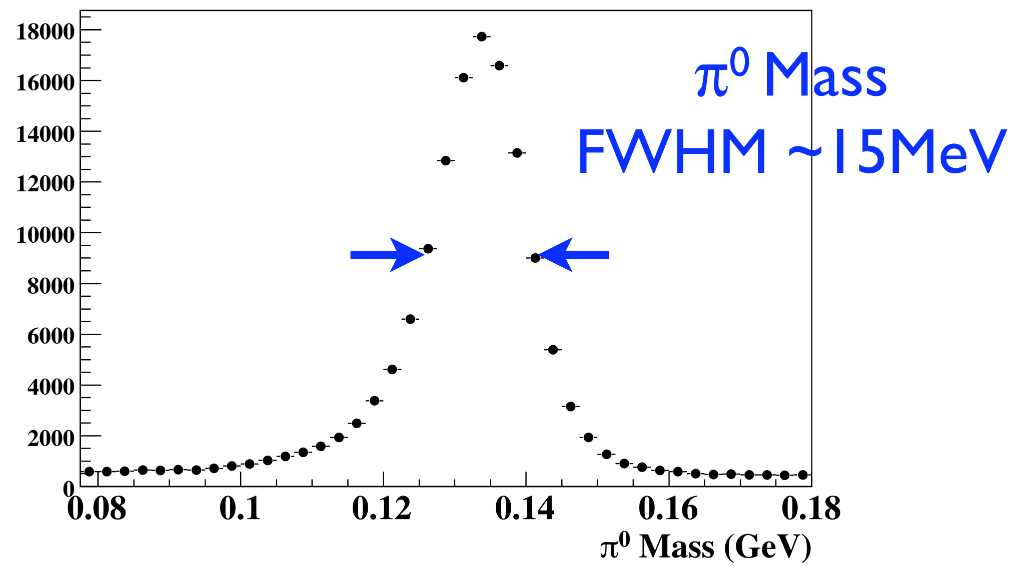
- No charged particles: Still have tagging.
  - $\rightarrow$ Time integrated ACP measurement
- Least precise mode
  - Energy Resolution; Efficiency; Smallest Branching Fraction



$B^0 \to \pi^0 \pi^0$: The EM Calorimeter



- 6580 CsI(Tl) Crystals
- Full range in azimuth, 90% coverage.
- For calibration we use a radioactive source, symmetric π^0s and Bhabha events.
- Energy Resolution:
  - $\frac{\sigma_E}{E} = \frac{2.32\%}{E(GeV)^{1/4}} \oplus 1.85\%$
- Angular Resolution
  - $\sigma_\theta = \sigma_\phi = \frac{3.87}{\sqrt{E(GeV)}}$ mrad

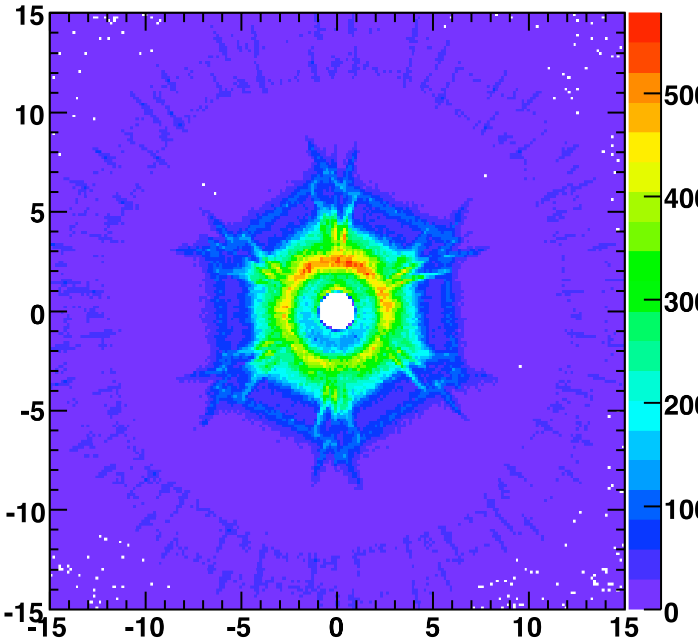


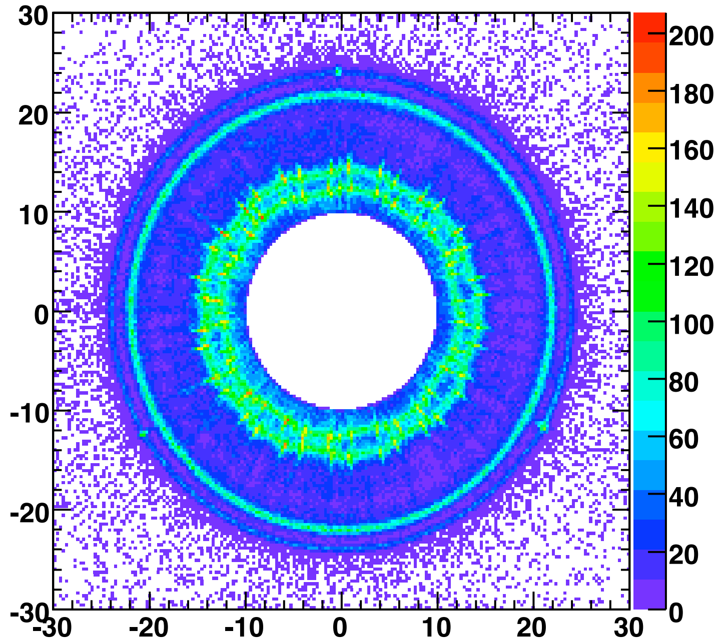
$B^0 \rightarrow \pi^0\, \pi^0$: Improvements

- In addition to $\pi^0 \rightarrow \gamma\gamma$, we include:

- $\gamma \rightarrow e^+ e^-$ Conversions
- 'Merged' π^0s
- $M^2_{\pi^0} \approx E^2_{\pi^0}(S_{\pi^0} - S_\gamma)$

View along Z-axis of $e^+ e^-$ vertex





~ 4% per π^0 improvement in efficiency from merged π^0s

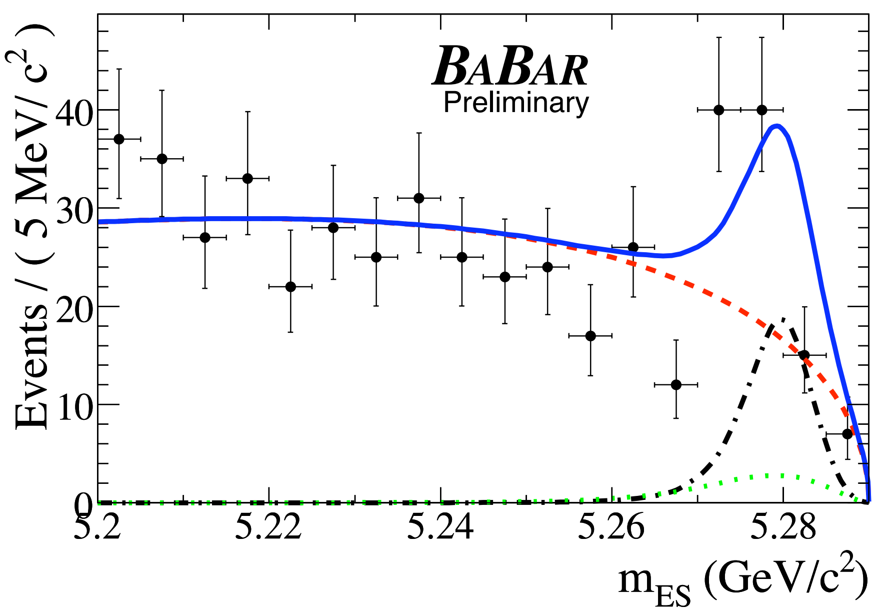
~ 6% per π^0 improvement in efficiency from conversions

Use a large statistics sample of $\tau \rightarrow \rho\nu$ decays for validation.

$B^0 \rightarrow \pi^0 \pi^0$: Results

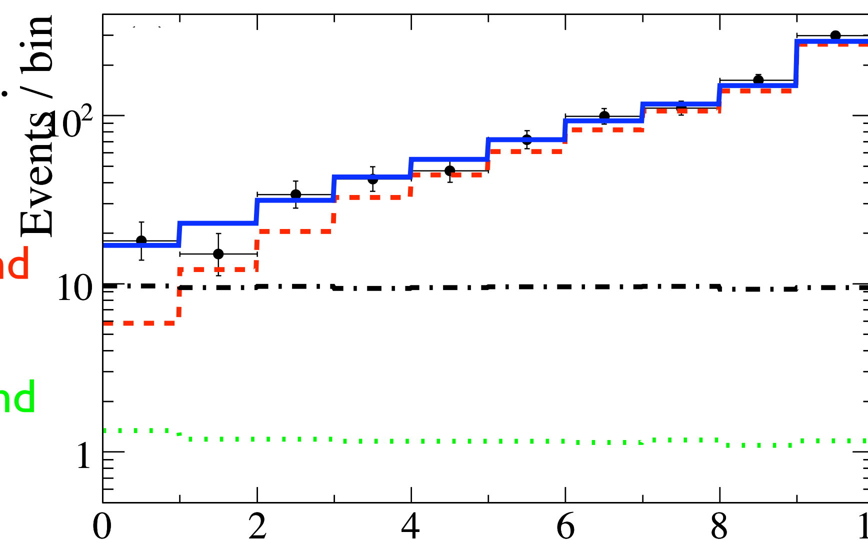
Events	140 ± 25
$BR(B^0 \rightarrow \pi^0 \pi^0)$	$(1.48 \pm 0.26 \pm 0.12) \times 10^{-6}$
$C(B^0 \rightarrow \pi^0 \pi^0)$	-0.33 ± 0.36 ± 0.08

- Maximum Likelihood fit
- m_{ES}, ΔE, Fisher, tagging.



Plots w/ likelihood-cut.

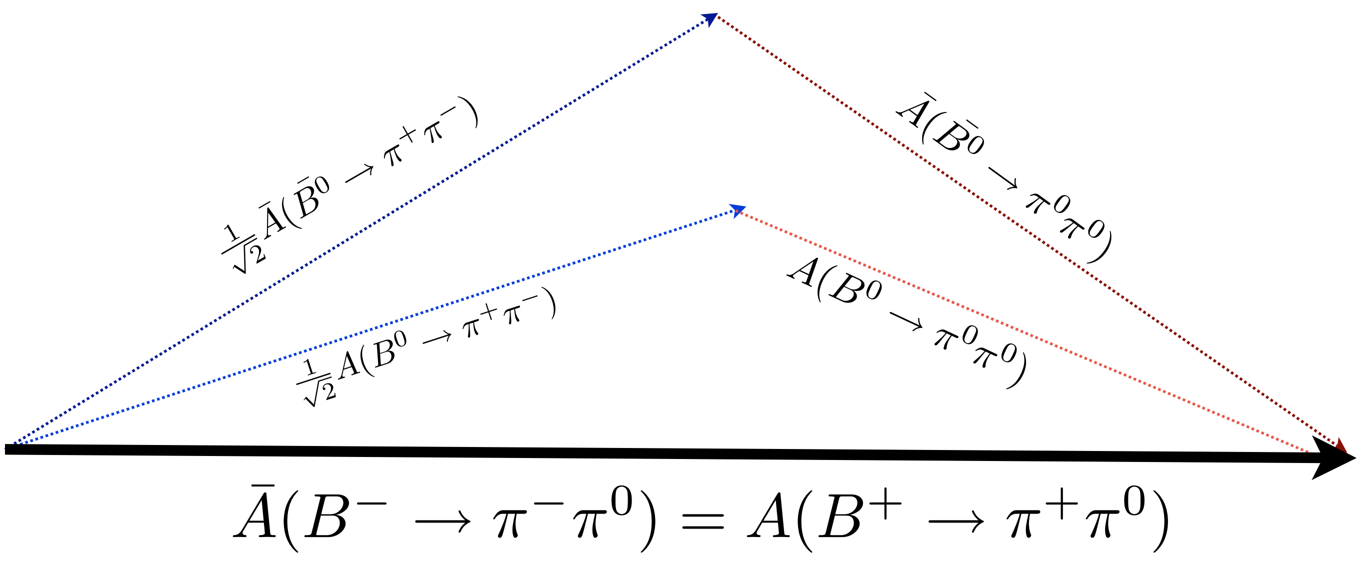
Total
$q\bar{q}$ background
Signal
$B\bar{B}$ background



Event shape Fisher discriminant rebinned from 0 - 10

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

- 1 π^0; 1 charged track
  - hybrid of the two neutral B modes

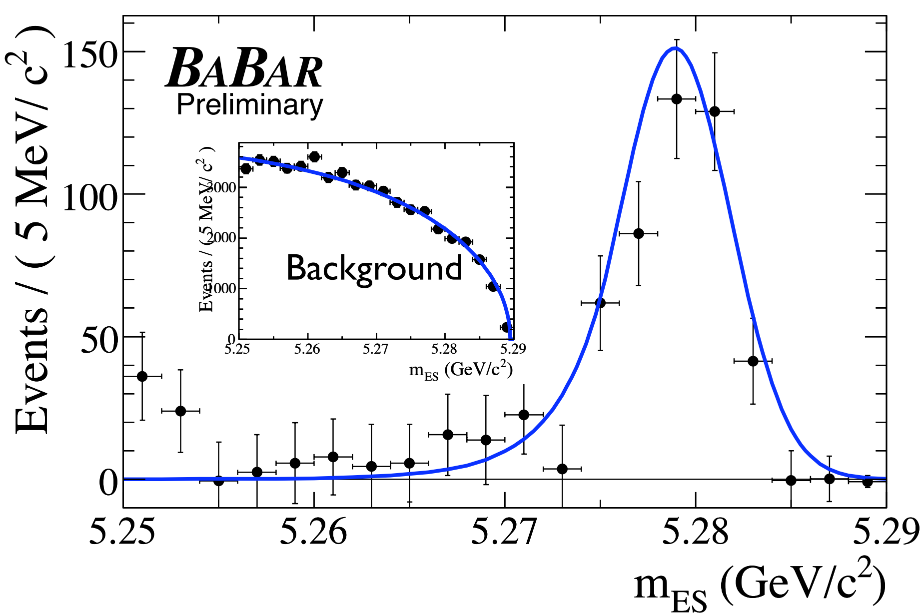


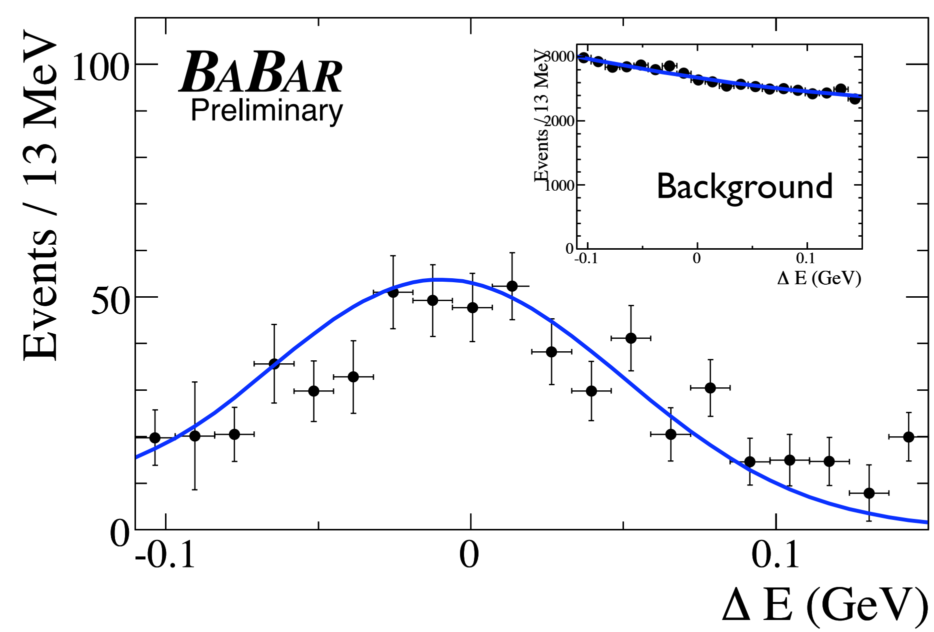
$B^{\pm} \rightarrow \pi^{\pm} \pi^0$: Results

Events	572 ± 53
$BR(B^{\pm} \rightarrow \pi^{\pm} \pi^0)$	$(5.12 \pm 0.47 \pm 0.29) \times 10^{-6}$
$A(B^{\pm} \rightarrow \pi^{\pm} \pi^0)$	$-0.019 \pm 0.088 \pm 0.014$

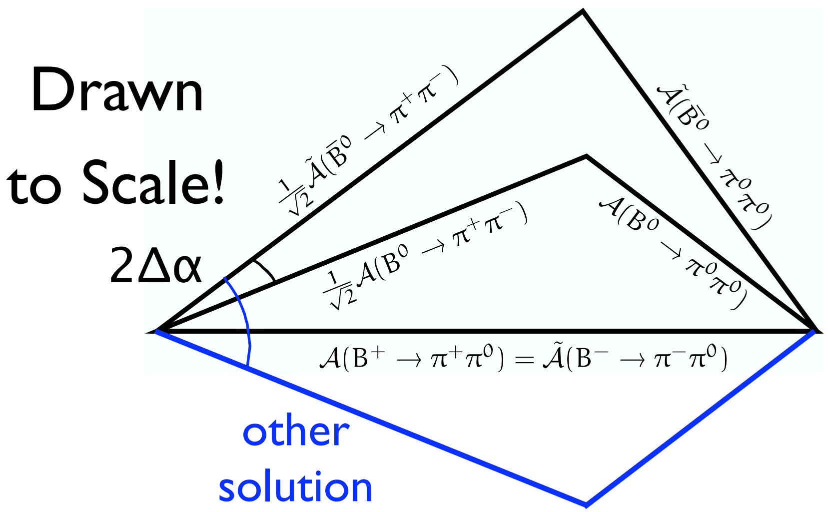
- Maximum Likelihood fit includes $B^{\pm} \rightarrow K^{\pm} \pi^0$

- m_{ES}, ΔE, Fisher, DIRC angle.

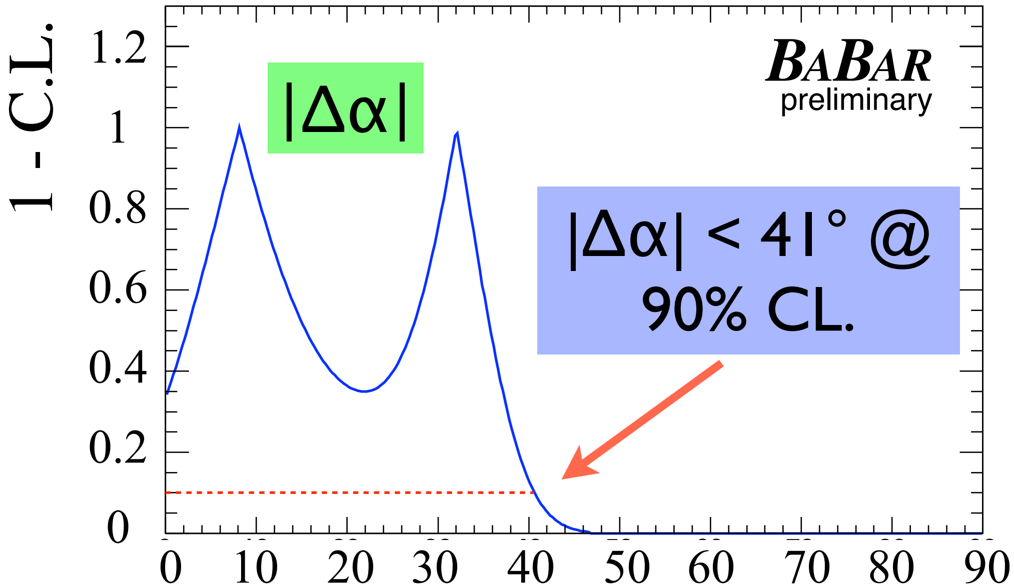


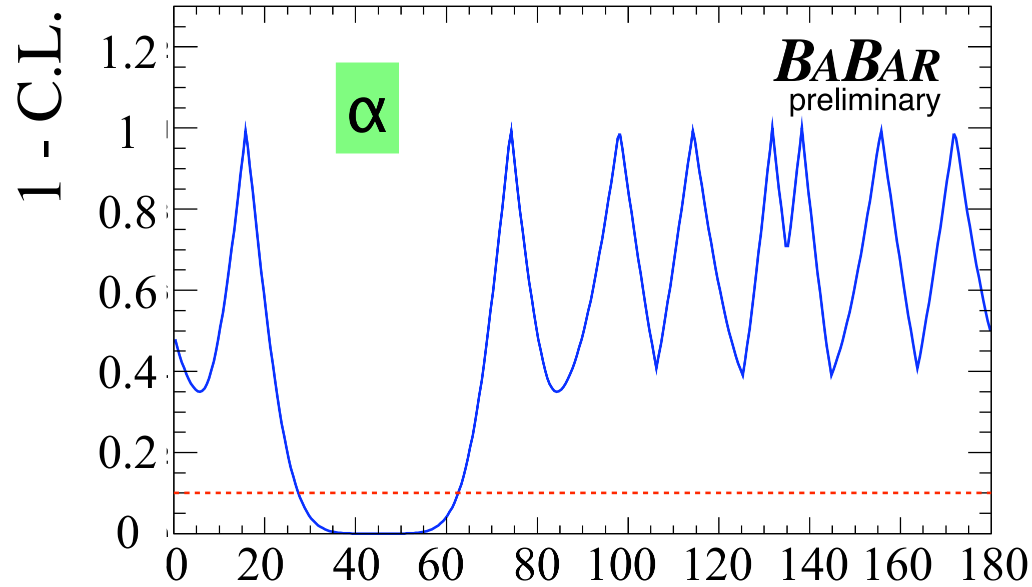


Measuring α, |Δα|

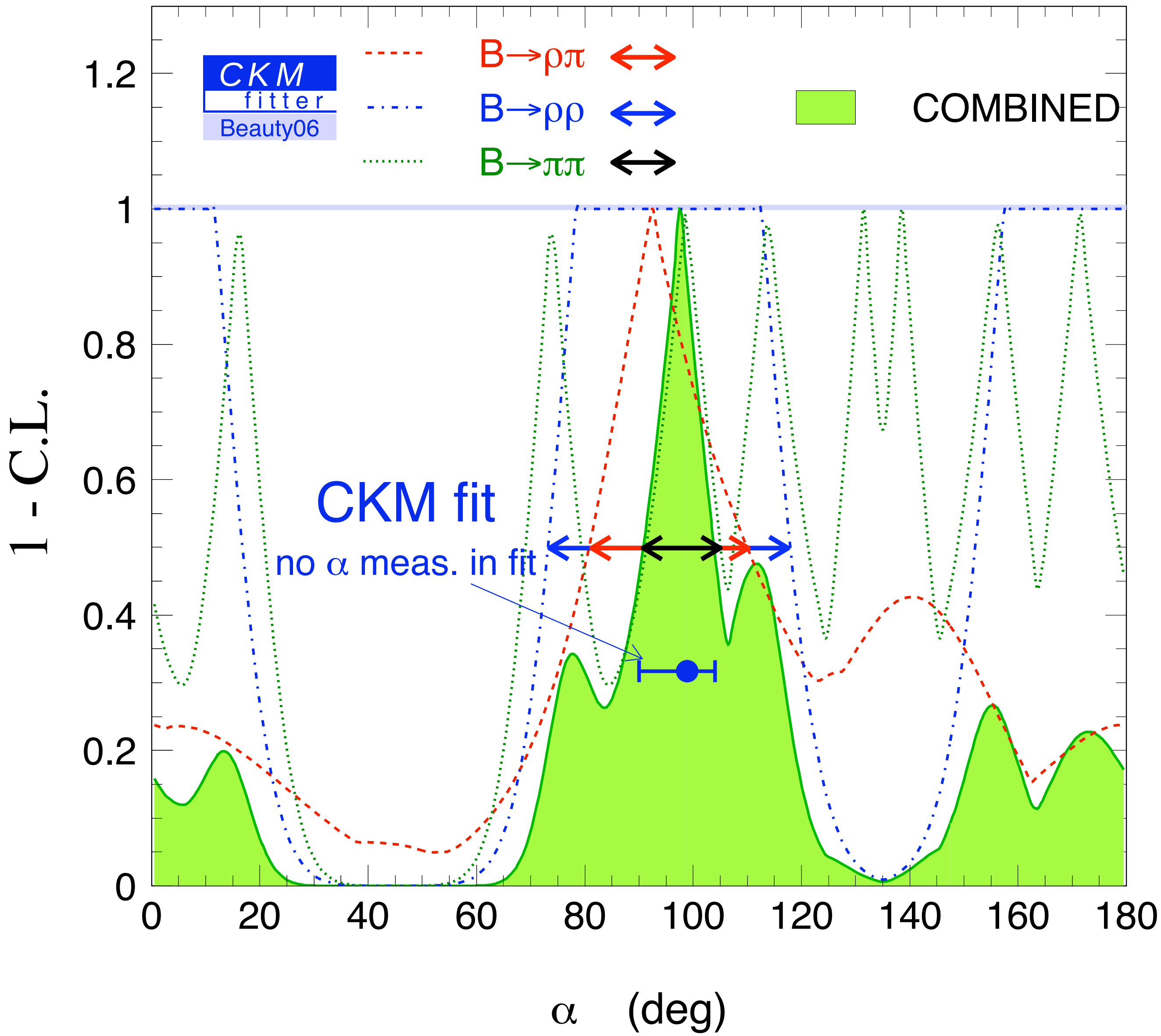


- CKM fitter (Frequentist approach.)
  CKMfitter Group (J.Charles et al.), Eur. Phys. J. C41, 1-131 (2005), [hep-ph/0406184]
- Using only the B→ππ isospin constraints on α and |Δα|.





Including other results



- Combined Babar-only α measurement.
- See Y. Kolomensky talk on B→ρπ, B→ρρ.
- Ignoring multiple solutions, B→ππ is most narrow of CL curves.

Conclusion

- Active program in measuring α using B→ππ modes at Babar

$C(B^0 \to \pi^+ \pi^-)$	$-0.16 \pm 0.11 \pm 0.03$
$S(B^0 \to \pi^+ \pi^-)$	$-0.53 \pm 0.14 \pm 0.02$
$BR(B^0 \to \pi^0 \pi^0)$	$(1.48 \pm 0.26 \pm 0.12) \times 10^{-6}$
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$BR(B^\pm \to \pi^\pm \pi^0)$	$(5.12 \pm 0.47 \pm 0.29) \times 10^{-6}$
$A(B^\pm \to \pi^\pm \pi^0)$	$-0.019 \pm 0.088 \pm 0.014$