Measurements of α at BaBar

Mark Allen, SLAC
for the BaBar Collaboration
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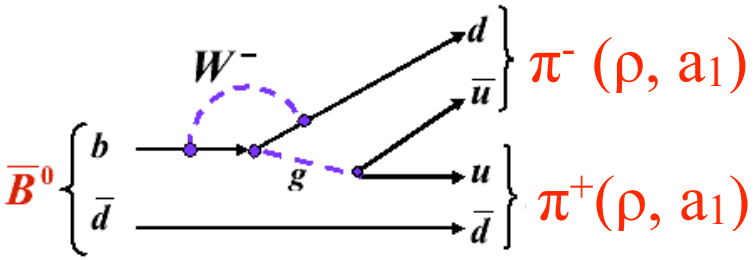
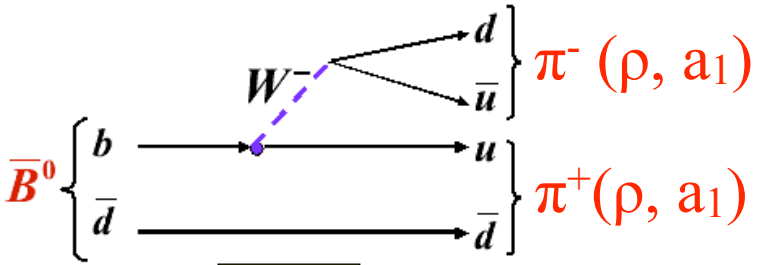
EPS Manchester, UK

CKM Angle α and b → uūd



Penguin



Tree

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

$$a_{\pi^+\pi^-}(\Delta t) = \mathrm{C}cos(\Delta m\Delta t) + \mathrm{S}sin(\Delta m\Delta t)$$

Mixing Tree decay

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

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

GOAL: Disentangle tree and penguin contributions.

Measurements of α

No single "gold-plated" mode

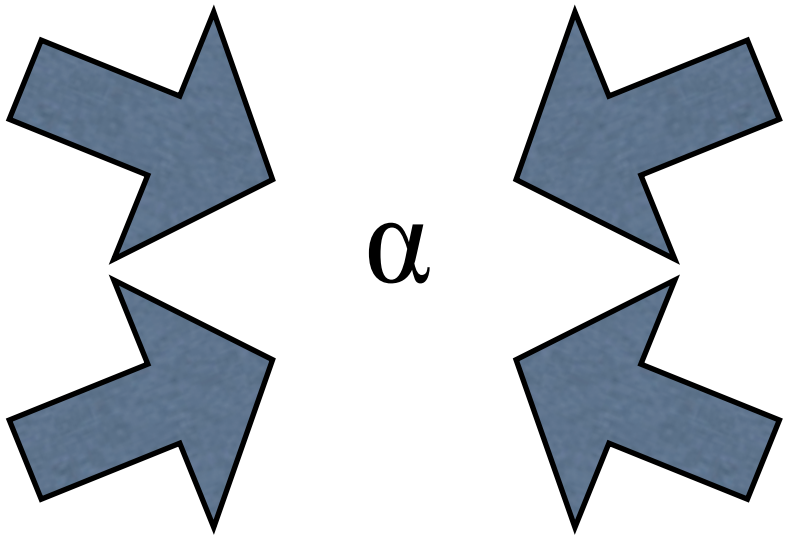
$B^0 \to \pi^+ \pi^-$

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

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

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

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



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

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

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

$B^0 \to a_1^\pm \pi^\mp$

$B^0 \to K_1^+ \pi^-$

$B^0 \to a_1^- K^+$

$B \to \pi\pi$

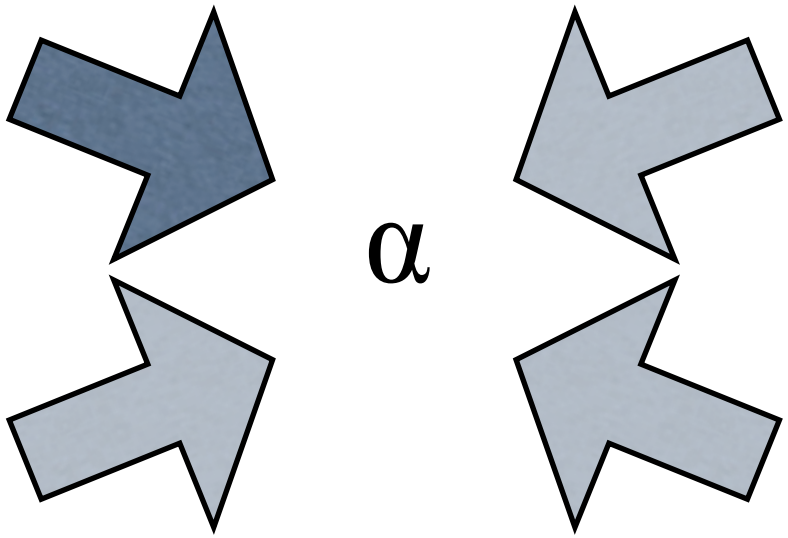
$B^0 \to \pi^+ \pi^-$

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

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

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

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



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

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

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

$B^0 \to a_1^\pm \pi^\mp$

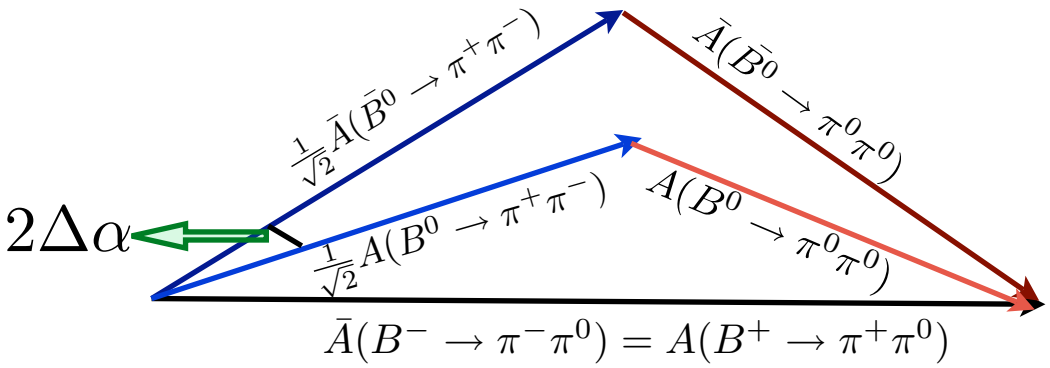
$B^0 \to K_1^+ \pi^-$

$B^0 \to a_1^- K^+$

Isospin Analysis: B→ππ, ρρ

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

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



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

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

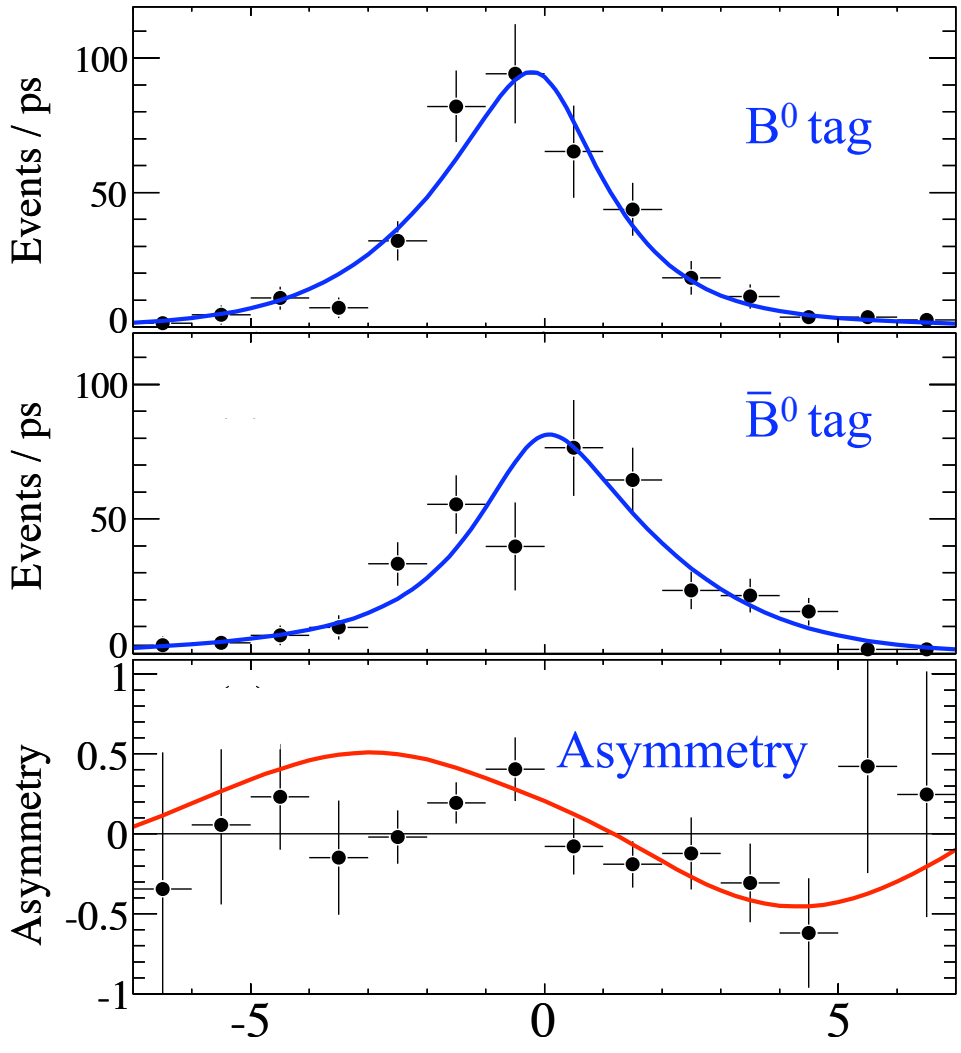
The key observation: $B^\pm \to \pi^\pm\pi^0$ is a purely tree decay (no $\Delta I = 1/2$ amplitude)
So (after a rotation):
$\bar{A}(B^- \to \pi^-\pi^0) = A(B^+ \to \pi^+\pi^0)$

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

Eight-fold ambiguity in α.

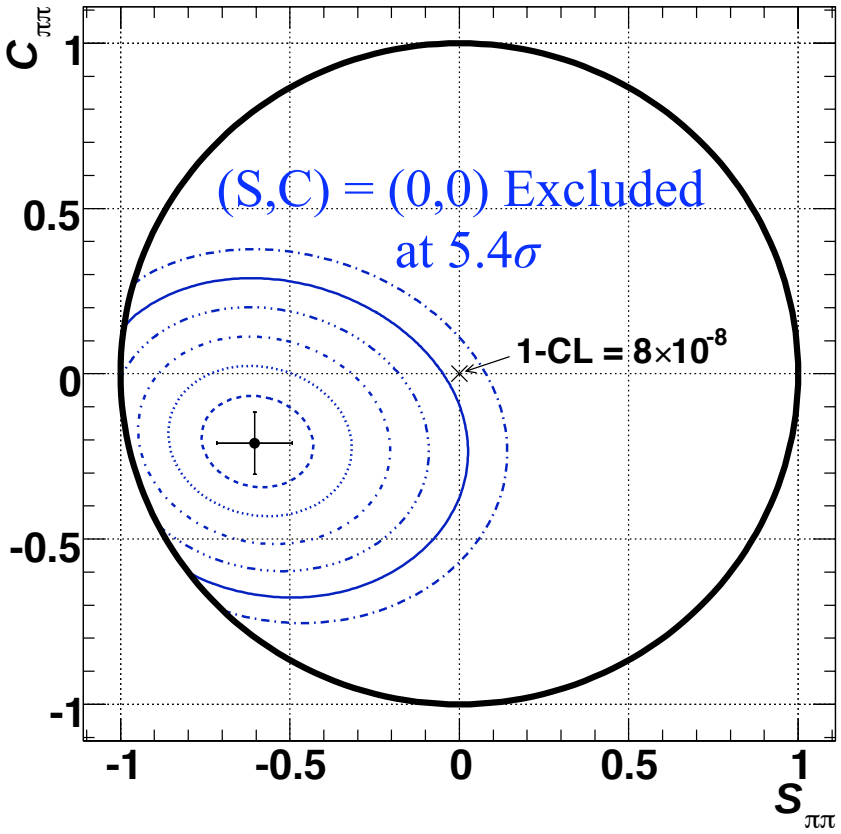
$B^0 \to \pi^+ \pi^-$

PRL: 99, 021603 (2007)



- Events: 1139 ± 49
- $C(B^0 \to \pi^+\pi^-) = -0.21 \pm 0.09 \pm 0.02$
- $S(B^0 \to \pi^+\pi^-) = -0.60 \pm 0.11 \pm 0.03$

- ML Fit: m_{ES}, ΔE, F, θ_C, dE/dx, Δt

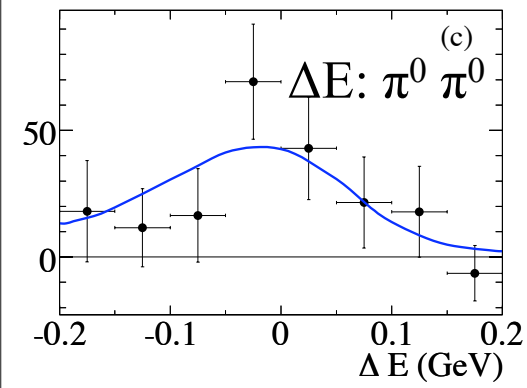


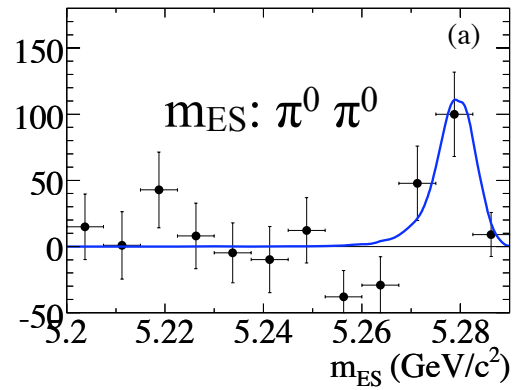
[(sPlots) M.Pivk and F.R. LeDiberder, Nucl. Instrum. Meth. A 555, 356 (2005)]

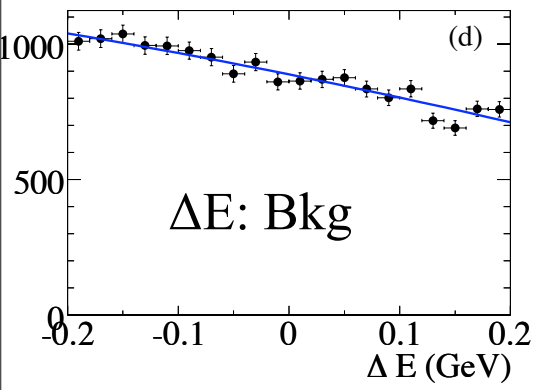
$B \to \pi^0 \pi^0, \pi^\pm \pi^0$

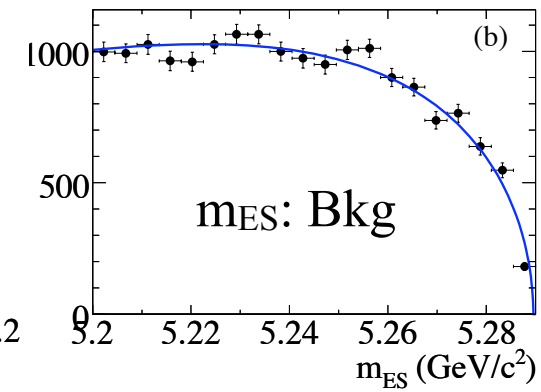
Submitted to PRD-RC: arXiv:0707.2798 [hep-ex]

- Events: $\pi^0 \pi^0$: 154 ± 26
- BR($B^0 \to \pi^0 \pi^0$) = $(1.47 \pm 0.25 \pm 0.12) \times 10^{-6}$
- C($B^0 \to \pi^0 \pi^0$): $-0.49 \pm 0.35 \pm 0.05$

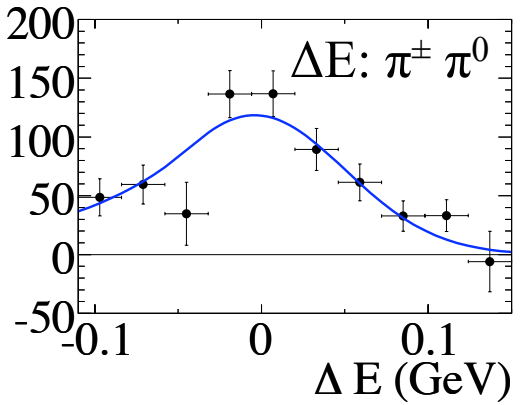


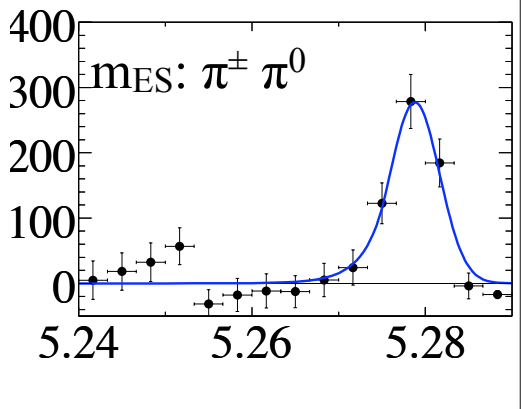


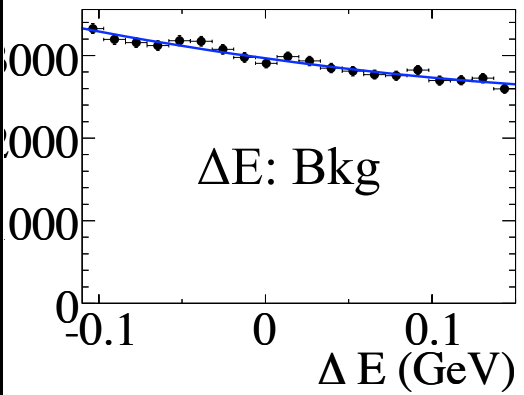


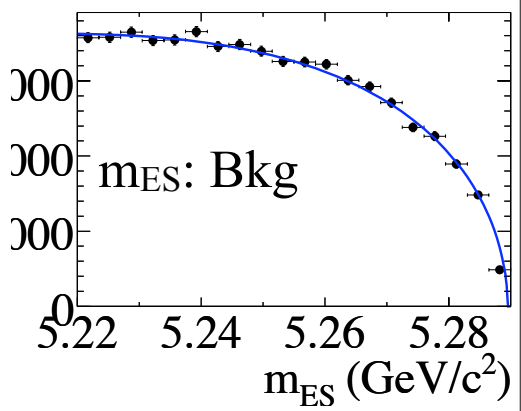


- Events: $\pi^\pm \pi^0$: 627 ± 58
- BR($B^\pm \to \pi^\pm \pi^0$) = $(5.02 \pm 0.46 \pm 0.29) \times 10^{-6}$
- A($B^\pm \to \pi^\pm \pi^0$): $0.03 \pm 0.08 \pm 0.01$



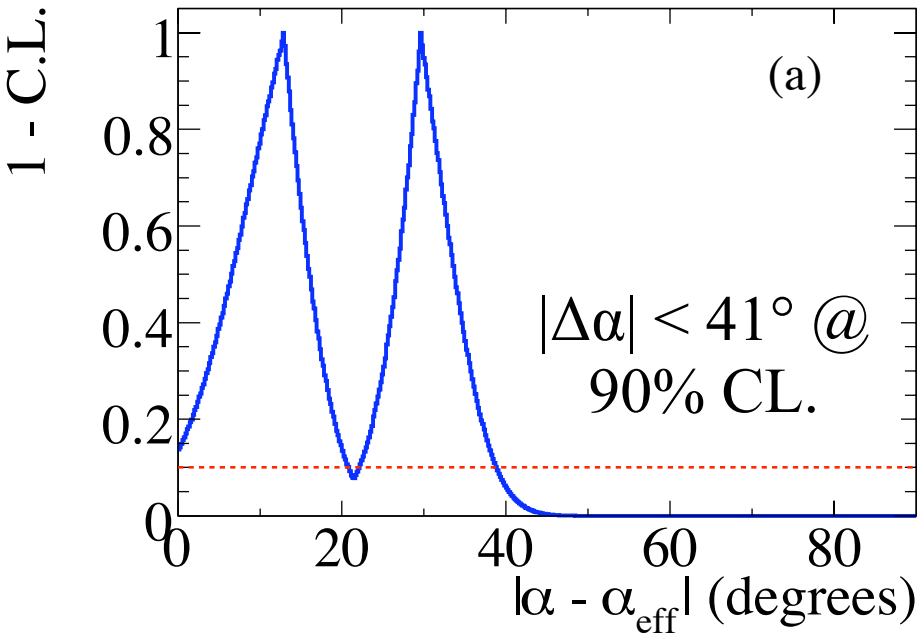






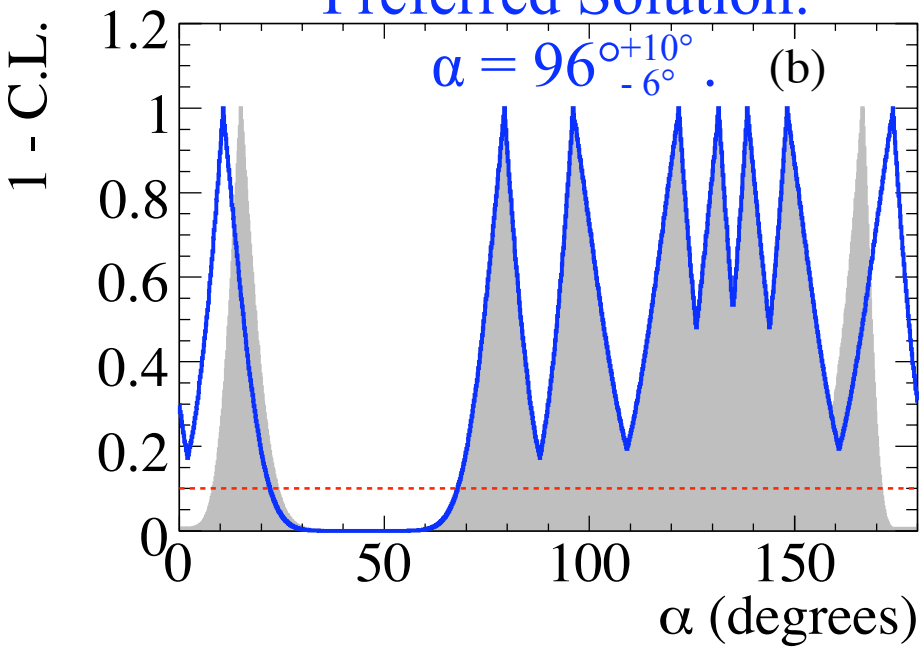
Isospin Triangle: B→ ππ

- Confidence Levels calculated using toy method.
- 25°< α < 66° excluded at 90% C.L.
- Blue line: Gronau & London method
- Grey shade: L&G after requirement on size of penguin amplitude. [**UTFit Collaboration, M. Bona et al, hep-ph/0701204, to appear in PRD**]
- $B \to \pi^+ \pi^-$ BR: **PRD 75 (2007) 012008**

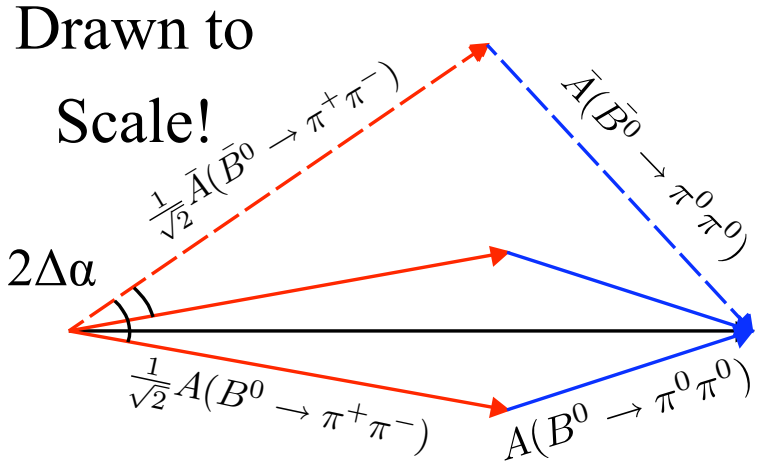


Preferred Solution:

$\alpha = 96^{\circ}{}^{+10^{\circ}}_{-6^{\circ}}$.



Drawn to Scale!



$B \to \rho\rho$

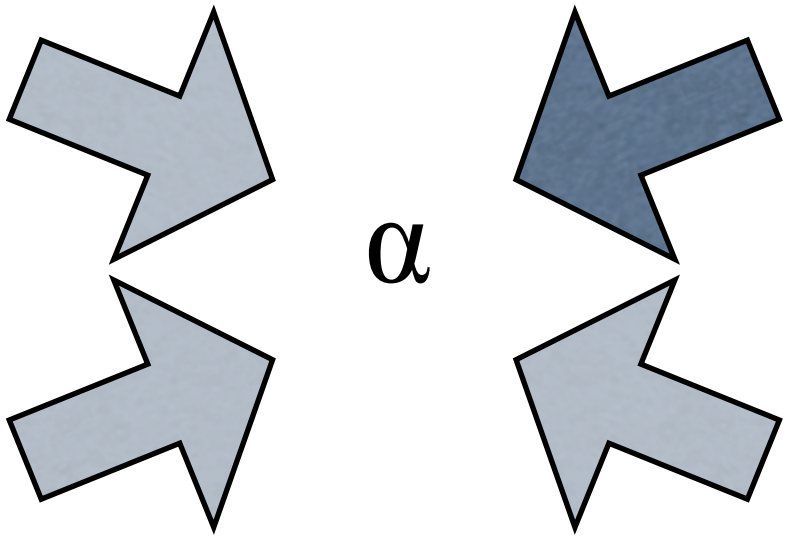
$B^0 \to \pi^+ \pi^-$

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

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

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

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



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

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

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

$B^0 \to a_1^\pm \pi^\mp$

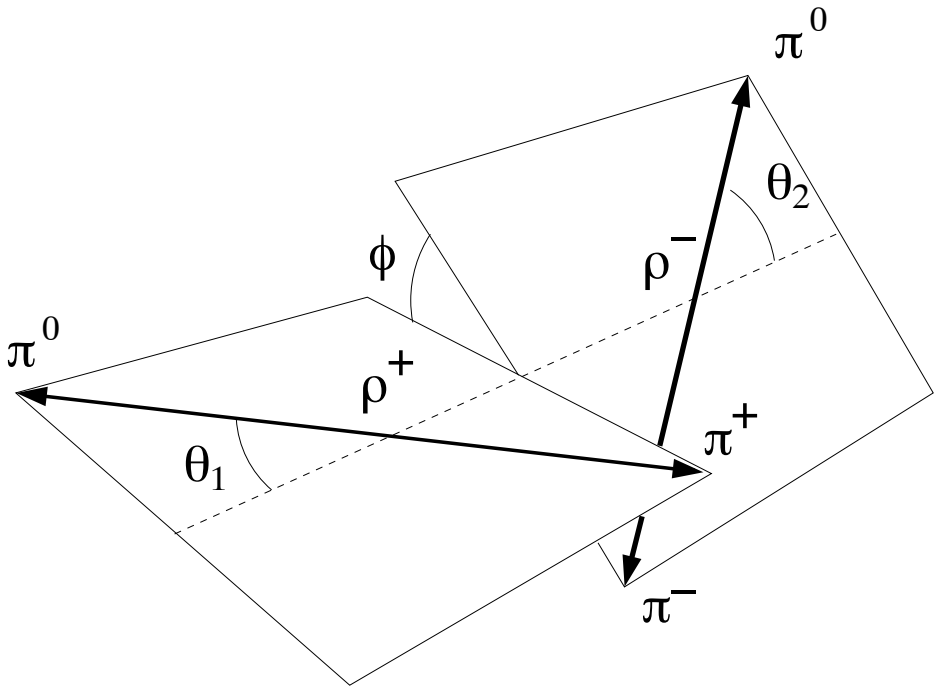
$B^0 \to K_1^+ \pi^-$

$B^0 \to a_1^- K^+$

$B \to \rho\,\rho$

Much like $B \to \pi\pi$:

- Two triangle formulation same.
- Advantage:
  - Can do time dependent CP measurement on $\rho^0\,\rho^0$ mode. (4-fold ambiguity)
  - SU(3) arguments ($B \to K^*\,\rho$)
- Disadvantage:
  - $B^0 \to \rho^0\,\rho^0$ small
  - Longitudinal/Transverse components of differing CP.



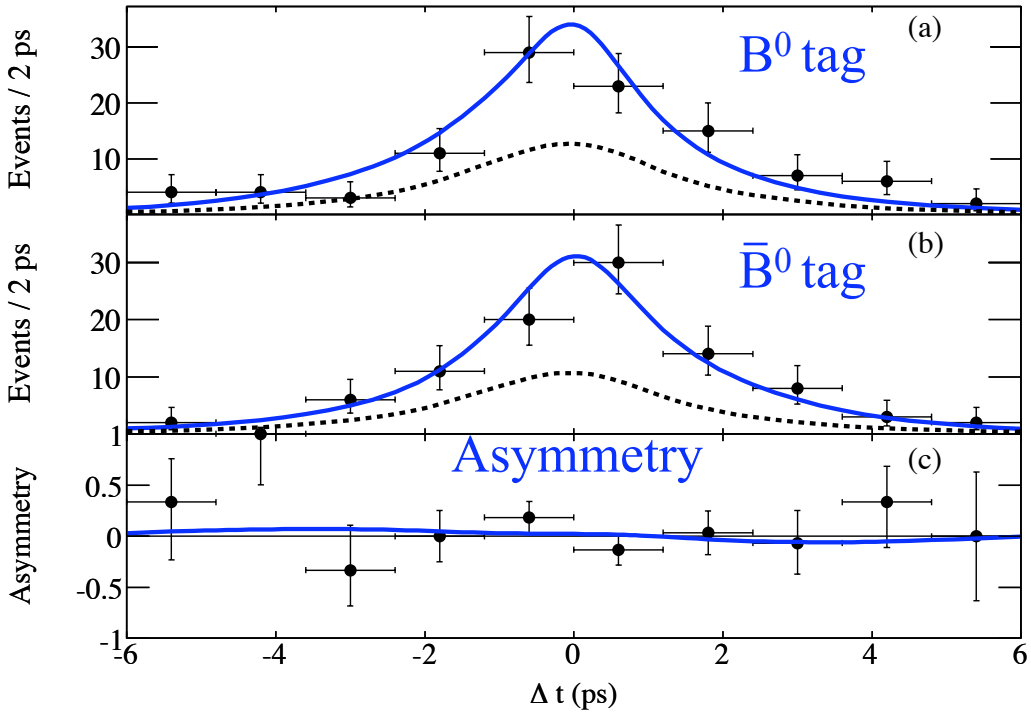
$$\frac{d^2\Gamma}{\Gamma(d\cos\theta_1)(d\cos\theta_2)} = \frac{9}{4}\,[f_L\cos^2\theta_1\cos^2\theta_2 + \frac{1}{4}(1-f_L)\sin^2\theta_1\sin^2\theta_2]$$

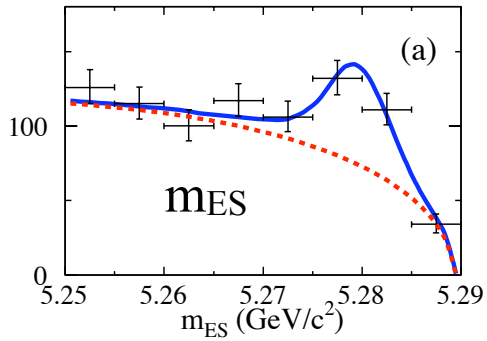
$B^0 \to \rho^+ \rho^-$

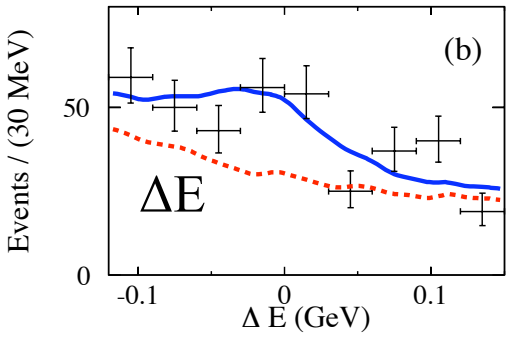
Submitted to PRD: arXiv 0705.2157 [hep-ex]

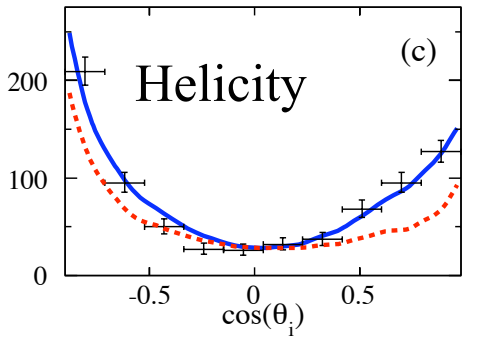
- ML fit variables:
  - m_{ES}, ΔE, NN, Helicity, ρ mass Δt
- Largest Systematic Errors:
  - Self cross-feed fraction (76 events)
  - PDF parameterization (+23/-41 events)

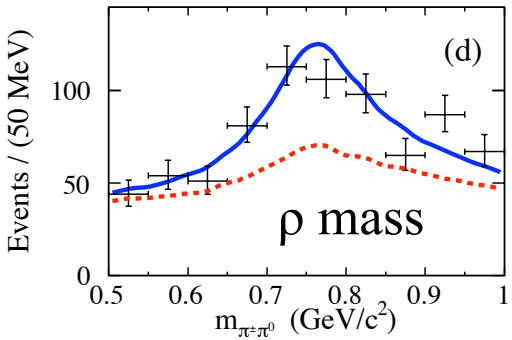
- Events: $729 \pm 60\ ^{+94}_{-102}$
- $BR(B^0 \to \rho^+ \rho^-) = (25.5 \pm 2.1\ ^{+3.6}_{-3.9}) \times 10^{-6}$
- $C(B^0 \to \rho^+ \rho^-) = 0.01 \pm 0.15 \pm 0.06$
- $S(B^0 \to \rho^+ \rho^-) = -0.17 \pm 0.20\ ^{+0.05}_{-0.06}$
- $f_L = 0.992 \pm 0.024\ ^{+0.026}_{-0.013}$











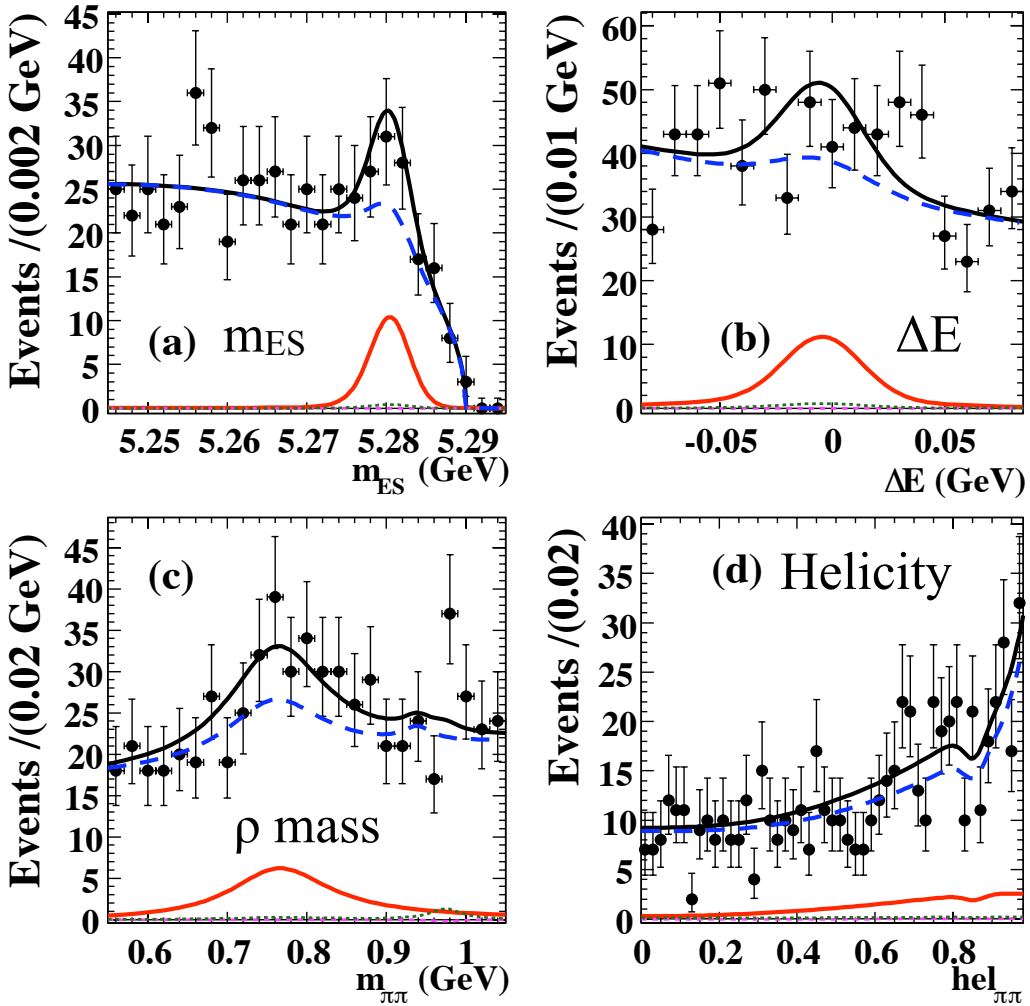
$B \rightarrow \rho^0 \rho^0$

PRL 98, 111801 (2007)

- Events: $100 \pm 32 \pm 17$
- $BR(B^0 \rightarrow \rho^+ \rho^-) = (1.07 \pm 0.33 \pm 0.19) \times 10^{-6}$
- $f_L = 0.87 \pm 0.13 \pm 0.04$

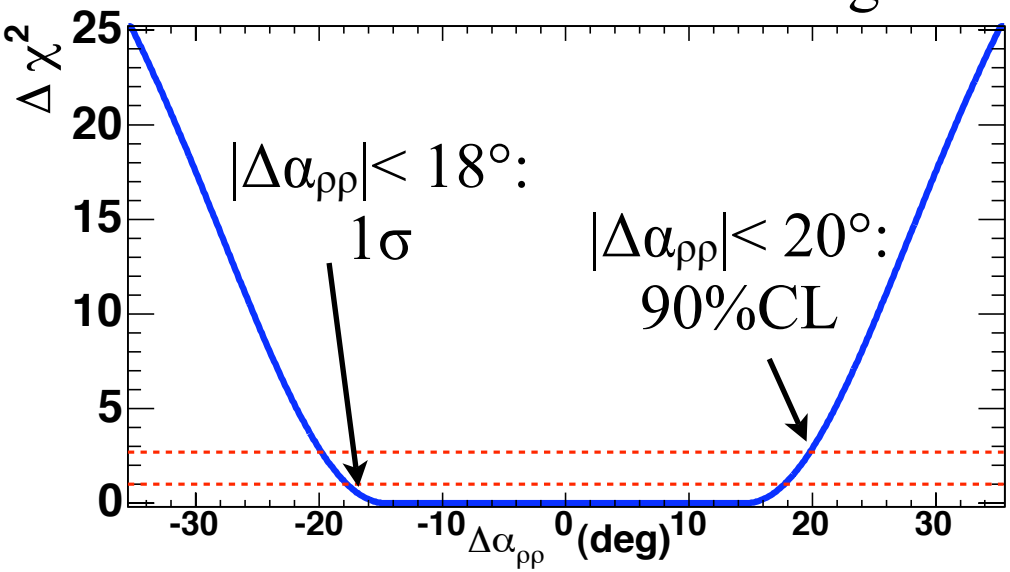
- ML fit variables:
  - m_{ES}, ΔE, NN, Helicity, ρ mass, tagging information
- Largest Systematic Errors:
  - Interference with $a_1^{\pm} \pi^{\mp}$ (14 events)
  - PDF parameters (10 Events)

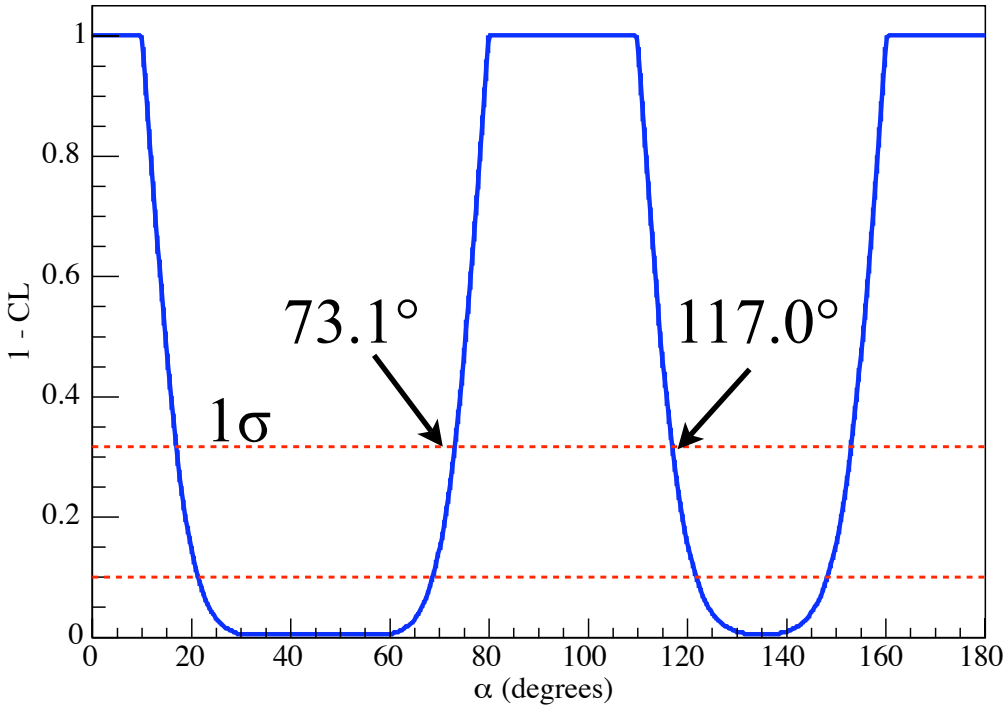
3.5σ significance!



Isospin Triangle: B → ρ ρ

Flat regions: No measurement of C_{00}

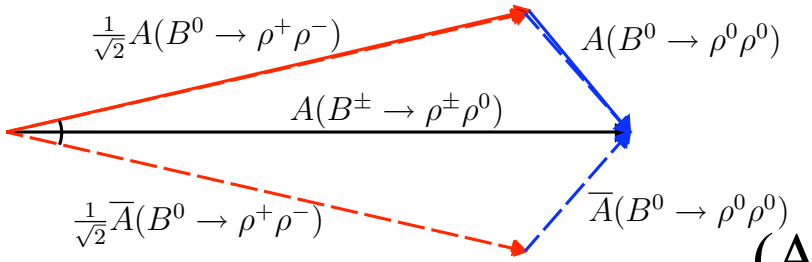




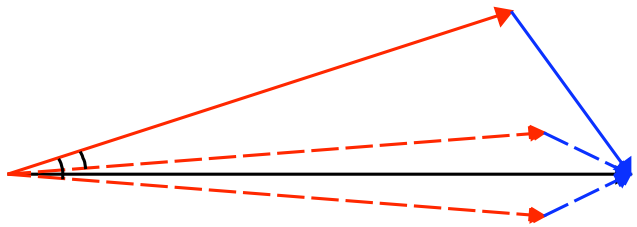
$B^+ \to \rho^+ \rho^0$ BR: $(16.8 \pm 2.2 \pm 2.3) \times 10^{-6}$

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

PRL 97, 261801 (2006)



ρρ Isospin triangles
Drawn to scale
(Assuming $C_{00} = 0, 0.7$):



$B \to \rho\pi$

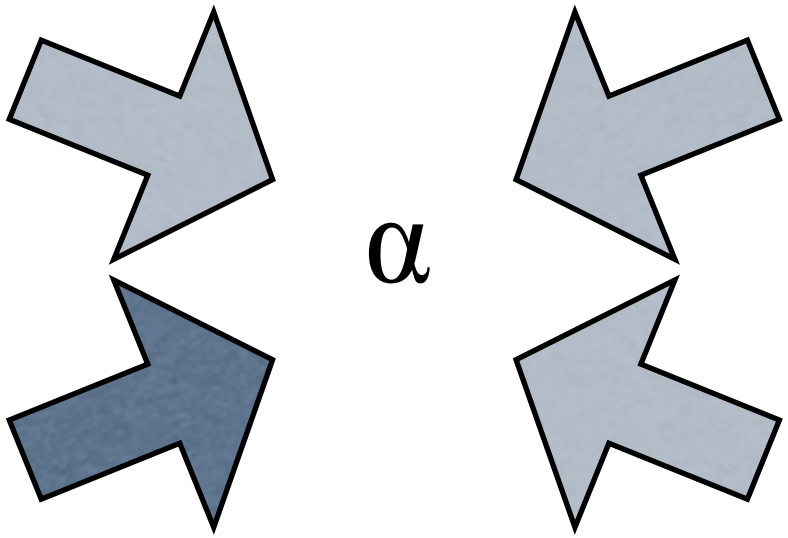
$B^0 \to \pi^+ \pi^-$

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

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

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

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



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

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

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

$B^0 \to a_1^\pm \pi^\mp$

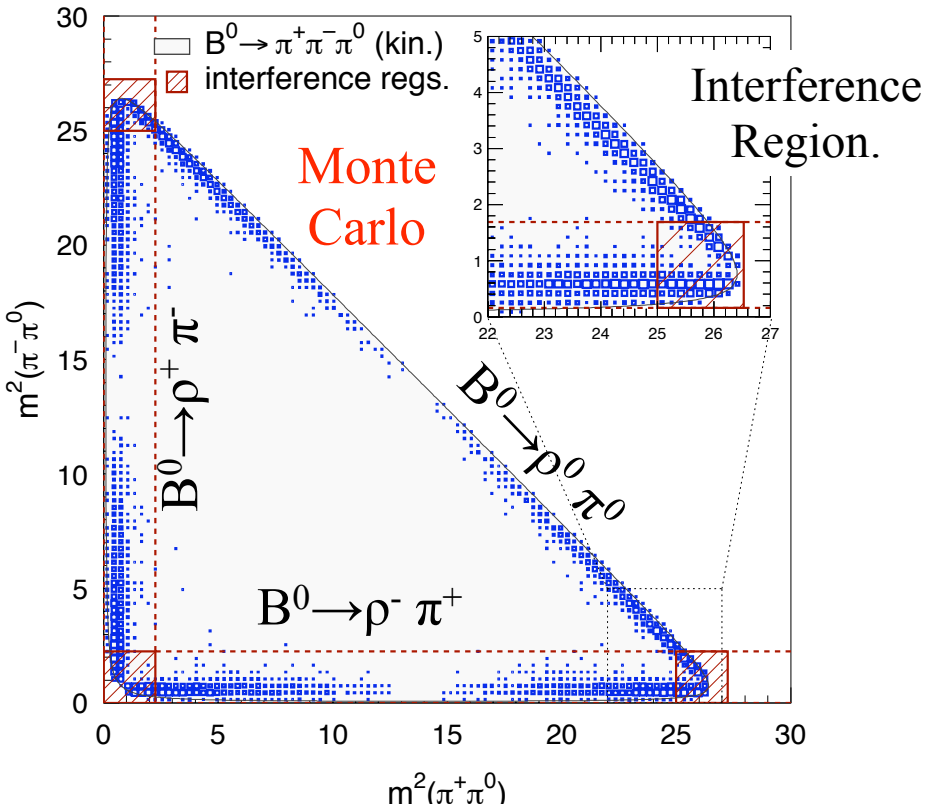
$B^0 \to K_1^+ \pi^-$

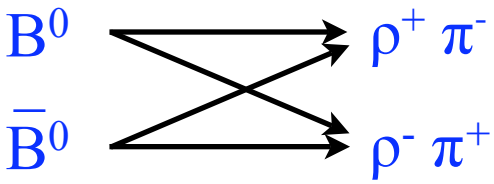
$B^0 \to a_1^- K^+$

$B^0 \rightarrow (\rho\pi)^0$

Full Dalitz plot analysis!

Measure 26 separate Dalitz parameters
(Bilinear coefficients, U's and I's)





$$f_{Qtag} \propto (1 - A_{\rho\pi}) \times [1 + Q_{tag} (S \pm \Delta S) \sin(\Delta m_d \Delta t) - Q_{tag} (C \pm \Delta C) \cos(\Delta m_d \Delta t)]$$

- $Q_{tag} = 1(-1)$ for B^0 ($\bar{B}^0$) tag
- $A_{\rho\pi}$: Time & flavor integrated charge asymmetry
- S, C: Mixing induced CP parameters (related to α)
- ΔC: asymmetry between:
  $\Gamma(B^0 \rightarrow \rho^+ \pi^-) + \Gamma(\bar{B}^0 \rightarrow \rho^- \pi^+)$ &
  $\Gamma(B^0 \rightarrow \rho^- \pi^+) + \Gamma(\bar{B}^0 \rightarrow \rho^+ \pi^-)$
- ΔS: related to strong phase differences among amplitudes
- ΔC, ΔS: not sensitive to CP violation

$B^0 \rightarrow \rho^0 \pi^0$: CP eigenstate

$B^0 \to (\rho\pi)^0$

To appear in PRD:hep-ex/0703008

$N(B^0 \to \pi^+ \pi^- \pi^0) =$	2067 ± 86
$A_{\rho\pi}\ (\rho^\pm \pi^\mp) =$	$-0.14 \pm 0.05 \pm 0.02$
$C\ (\rho^\pm \pi^\mp) =$	$0.15 \pm 0.09 \pm 0.05$
$S\ (\rho^\pm \pi^\mp) =$	$-0.03 \pm 0.11 \pm 0.04$
$\Delta C\ (\rho^\pm \pi^\mp) =$	$0.39 \pm 0.09 \pm 0.09$
$\Delta S\ (\rho^\pm \pi^\mp) =$	$-0.01 \pm 0.14 \pm 0.06$
$C_{00}\ (\rho^0 \pi^0) =$	$-0.10 \pm 0.40 \pm 0.53$
$S_{00}\ (\rho^0 \pi^0) =$	$0.02 \pm 0.22 \pm 0.09$

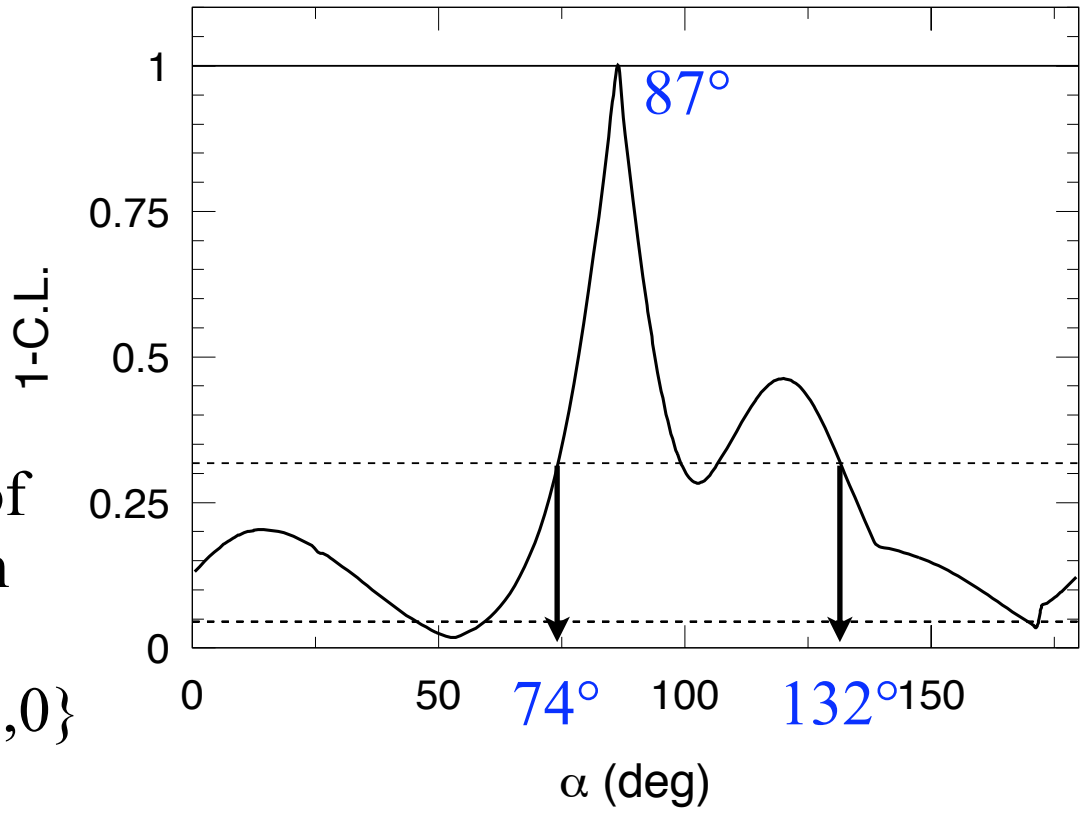
Amplitudes expressed as a sum of Isospin related Tree and Penguin

$$A^+ = A(B^0 \to \rho^+ \pi^-)$$

$$A^\kappa = T^\kappa e^{-i\alpha} + P^\kappa ; \kappa = \{+,-,0\}$$

$$(q/p)\bar{A}^\kappa = T^{\bar{\kappa}} e^{+i\alpha} + P^{\bar{\kappa}}$$

α over-constrained:
9 free parameters, 26 parameters fit.
Constraints on α from a least squares minimization



$B \to a_1 \pi$, SU(3)

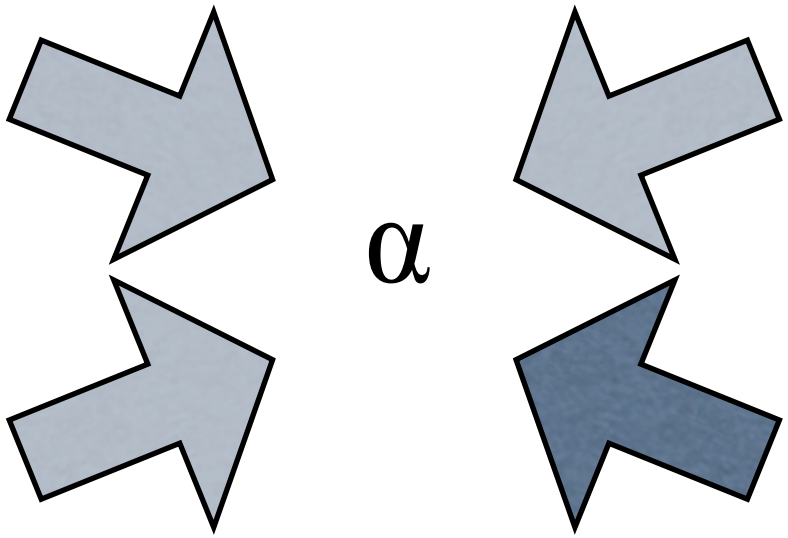
$B^0 \to \pi^+ \pi^-$

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

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

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

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



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

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

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$B^0 \to a_1^\pm \pi^\mp$

$B^0 \to K_1^+ \pi^-$

$B^0 \to a_1^- K^+$

$B^0 \to a_1^{\pm} \pi^{\mp}$ & SU(3)

Getting to α

- "Isospin pentagon" not effective.
- Measure α_{eff}, with $B^0 \to a_1^{\pm}\pi^{\mp}$ and limits on $|\Delta\alpha| = |\alpha_{eff} - \alpha|$ from SU(3) related decays: $B^0 \to a_1^{\pm} K^{\mp}$, $B^0 \to K_{1A}^{\pm} \pi^{\mp}$.
- K_{1A}^{+} :SU(3) partner of a_1^{+}
  - Nearly equal admixture of $K_1^{+}(1270)$ & $K_1^{+}(1400)$
- [Gronau & Zupan, PRD **73**, 057502 (2006)]

Similar to $B \to \rho \pi$:

- Not a CP eigenstate
- Quasi-2 body approach.

- BR:$(B \to K_1^{+}(1270)\,\pi^{-}) = (12.0 \pm 3.1^{+9.3}_{-4.5}) \times 10^{-6}$
  $(< 25.2 \times 10^{-6}$ @ 90% C.L.)
- BR:$(B \to K_1^{+}(1400)\,\pi^{-}) = (16.7 \pm 2.6^{+3.5}_{-5.0}) \times 10^{-6}$
  $(< 21.8 \times 10^{-6}$ @ 90% C.L.)

$$\alpha_{eff} = \frac{1}{4}\left[\arcsin\left(\frac{S_{a_1\pi} + \Delta S_{a_1\pi}}{\sqrt{1-(C_{a_1\pi} + \Delta C_{a_1\pi})^2}}\right) + \arcsin\left(\frac{S_{a_1\pi} - \Delta S_{a_1\pi}}{\sqrt{1-(C_{a_1\pi} - \Delta C_{a_1\pi})^2}}\right)\right]$$

$B^0 \to a_1^{\pm} \pi^{\mp}$

CP:PRL 98 181803. BR: PRL 97, 051802 (2006).

Use ML fit to
ΔE, m_{ES}, Fisher, m_{a1}, Helicity, Δt

$\alpha_{eff} = 78.6° \pm 7.3°$

$N(B^0 \to a_1^{\pm} \pi^{\mp}) = 608 \pm 53$

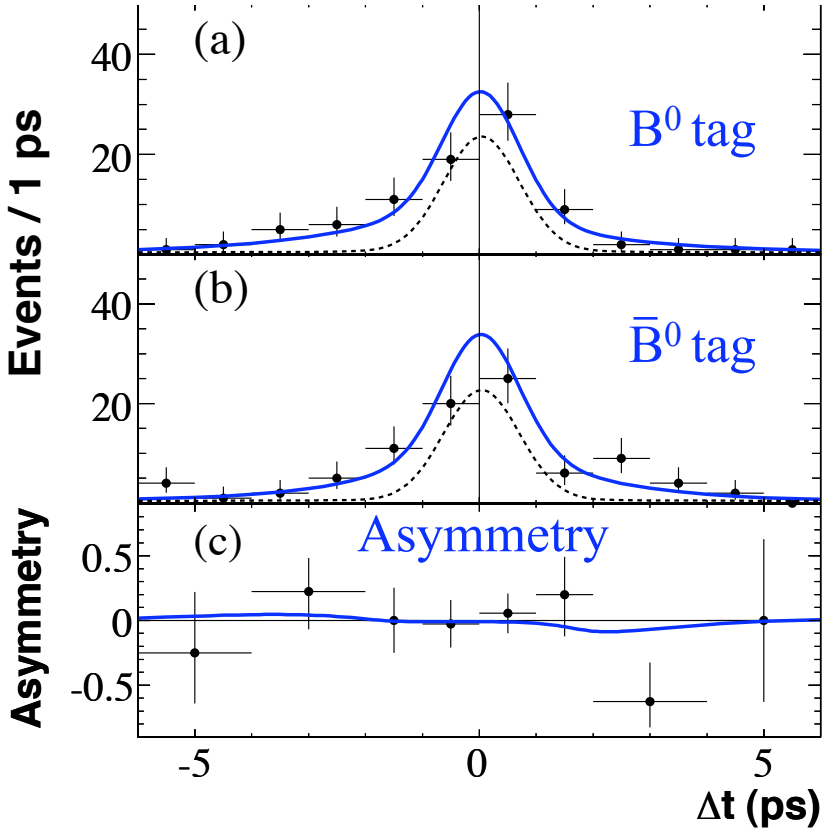
$A(a_1^{\pm} \pi^{\mp}) = -0.07 \pm 0.07 \pm 0.02$

$C(a_1^{\pm} \pi^{\mp}) = -0.10 \pm 0.15 \pm 0.09$

$S(a_1^{\pm} \pi^{\mp}) = 0.37 \pm 0.21 \pm 0.07$

$\Delta C(a_1^{\pm} \pi^{\mp}) = 0.26 \pm 0.15 \pm 0.07$

$\Delta S(a_1^{\pm} \pi^{\mp}) = -0.14 \pm 0.21 \pm 0.06$



Largest systematic errors:

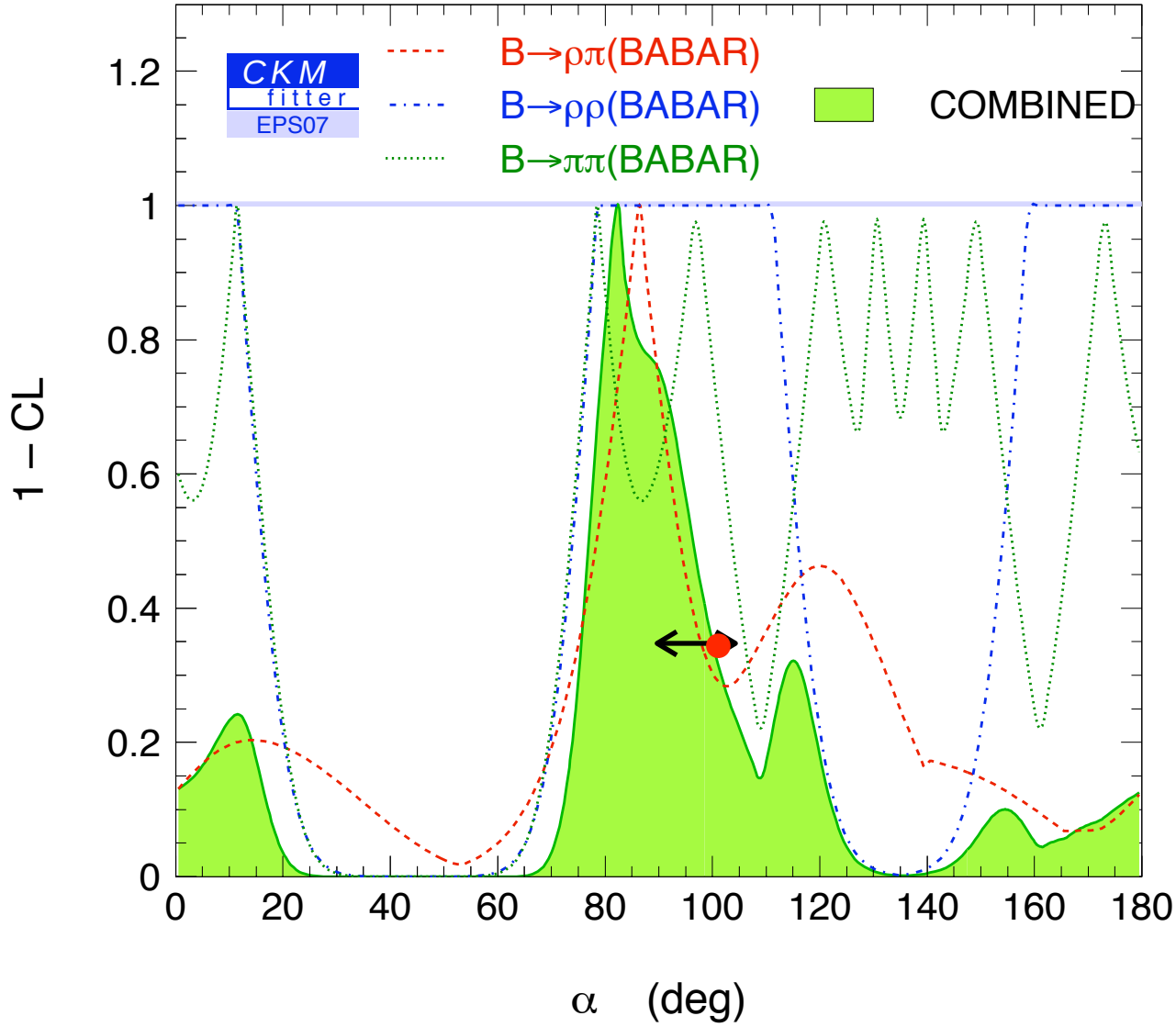
- PDF parameterization
- B background CP content
- $B \to a_2 \pi$ contribution and interference

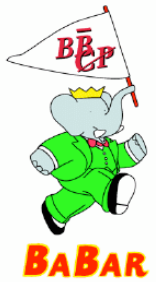
Conclusion

CKMFitter average α **not** using direct measurements
$102^{\circ}\ ^{+3^{\circ}}_{-12^{\circ}}$.

CKMFitter average α **only** using direct measurements
$82.5^{\circ}\ ^{+18^{\circ}}_{-\ 7.3^{\circ}}$.

Thanks to the CKM Fitter group for the plot and numbers.

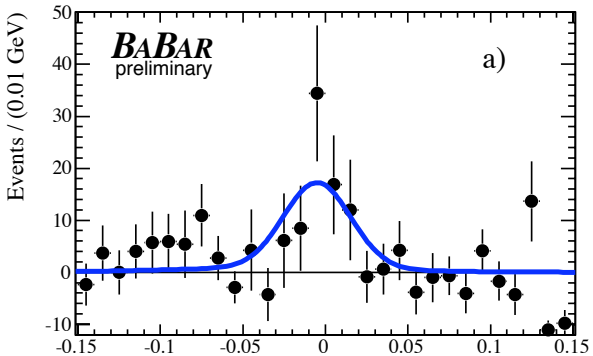




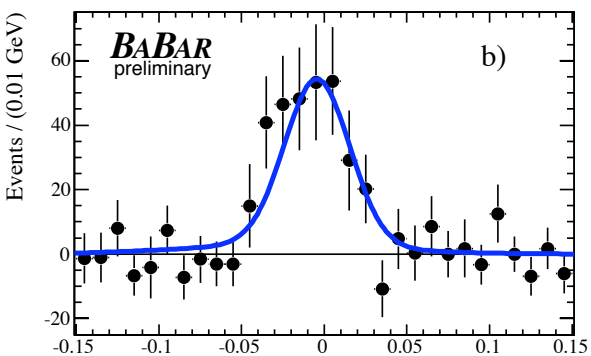
Extra Slides

$B \to K_1^{\pm} \pi$

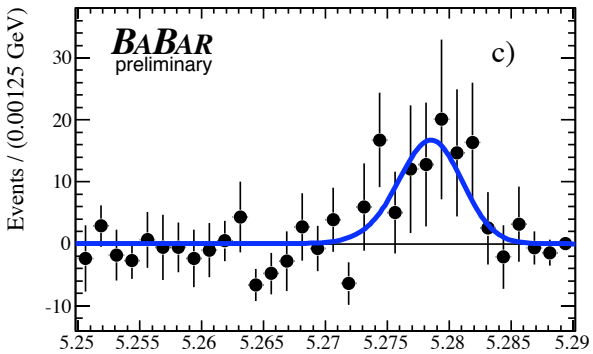
- Events: $K_1^+(1270)\,\pi^-$: $109 \pm 29\ ^{+85}_{-38}$
- Events: $K_1^+(1400)\,\pi^-$: $318 \pm 46\ ^{+56}_{-90}$
- BR:($B \to K_1^+(1270)\,\pi^-$): $(12.0 \pm 3.1\ ^{+9.3}_{-4.5}) \times 10^{-6}$ (< 25.2)
- BR:($B \to K_1^+(1400)\,\pi^-$): $(16.7 \pm 2.6\ ^{+3.5}_{-5.0}) \times 10^{-6}$ (< 21.8)



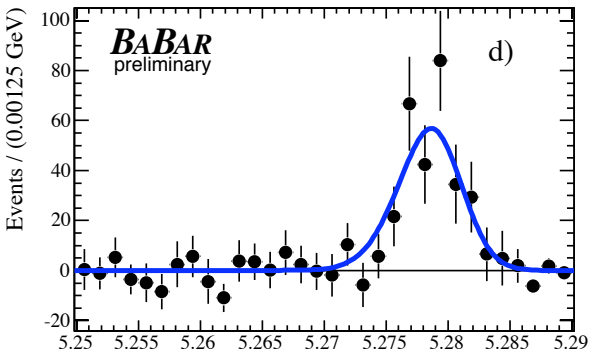
ΔE: $K_1(1270)\,\pi$



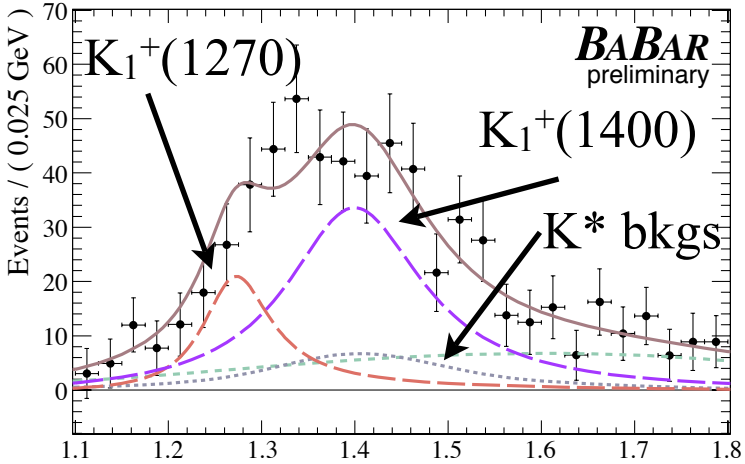
ΔE: $K_1(1400)\,\pi$



m_{ES}: $K_1(1270)\,\pi$



m_{ES}: $K_1(1400)\,\pi$



K_1 mass sPlot using only ΔE, m_{ES}, Fisher

- $K_1(1270)$ Submodes:
  - $K^{*0}(870,1430)\,\pi^+$, $K^+\rho^0$
- $K_1(1400)$ Submodes:
  - $K^{*0}(870)\,\pi^+$
- Use ML fit to:
  - ΔE, m_{ES}, Fisher, m_{K1}, Hel.
- Main systematic: Interference