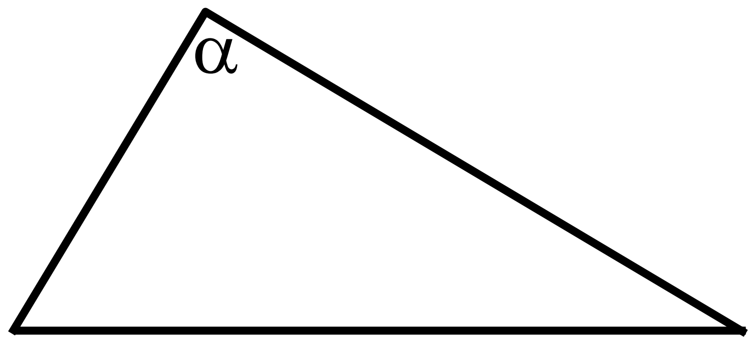
CP Violation in $B \to \rho\rho$ and Measurement of the Unitarity Triangle Angle α

CKM Workshop 2005 San Diego, CA



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Talk Overview

- Physics Motivation
  - $B \rightarrow VV$ decays (quick reminder)
  - CP Violation (v. quick reminder)
  - Isospin analysis (even quicker reminder)

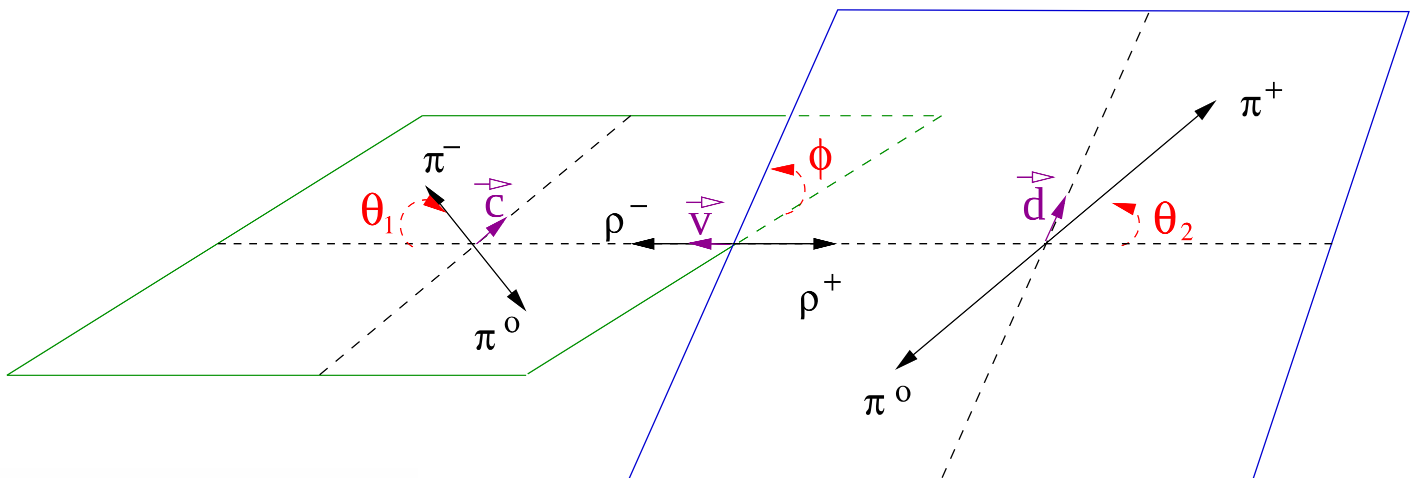
- Results
  - $\rho^0\rho^0$ Result from ICHEP ($210 fb^{-1}$)
  - new! $\rho^+\rho^-$ ($210 fb^{-1}$)
  - a few words on $\rho^+\rho^0$

- Impact on the Unitarity Triangle

- Conclusions

$B \to \rho\rho$

- VV final state
- L=0,1,2 partial wave components – need angular analysis to determine CP content of decay
- ρρ is almost 100% longitudinally polarised (f_L~1)



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

Longitudinal
(CP even)
SLong & CLong

Transverse
(Mixed CP state)
Set $S_{Tran}=C_{Tran}=0$
& vary for systematics

Like ππ etc., analyse time evolution of $B^0\bar{B}^0$ system

(assume $\Delta\Gamma=0$):

$$f(B^0/\overline{B}^0_{phys} \rightarrow f/\overline{f}, \Delta t) =$$

$$\tfrac{\Gamma}{4} e^{-\Gamma|\Delta t|}\left[1+\eta S \sin(\Delta m_d \Delta t) - \eta C \cos(\Delta m_d \Delta t)\right]$$

$$\eta = +1(-1) \text{ for } B^0(\overline{B}^0)$$

Indirect CP violation → $S \neq 0$

Direct CP violation → $C \neq 0$

$$\lambda_{f_{CP}} = \frac{q}{p} \cdot \frac{\overline{A}_{\overline{f}_{CP}}}{A_{f_{CP}}}$$

$$S_{f_{CP}} = \frac{2\,\mathrm{Im}\,\lambda_{f_{CP}}}{1+|\lambda_{f_{CP}}|^2}$$

$$C_{f_{CP}} = \frac{1-|\lambda_{f_{CP}}|^2}{1+|\lambda_{f_{CP}}|^2}$$

$$C = -A_{CP}$$

$$BaBar : Belle$$

Also need to worry about: tagging dilution

: resolution function

But it's a bit more complicated for ρρ...

- In general want to do a time dependent angular analysis (D*D*).
- As f_L~1, most information is in a single CP even amplitude.
- Δt dependence is:

$$P_{LONG} \propto \frac{\Gamma}{4} e^{-\Gamma|\Delta t|}\left[1+\eta S_{LONG}\sin(\Delta m_d \Delta t)-\eta C_{LONG}\cos(\Delta m_d \Delta t)\right]$$

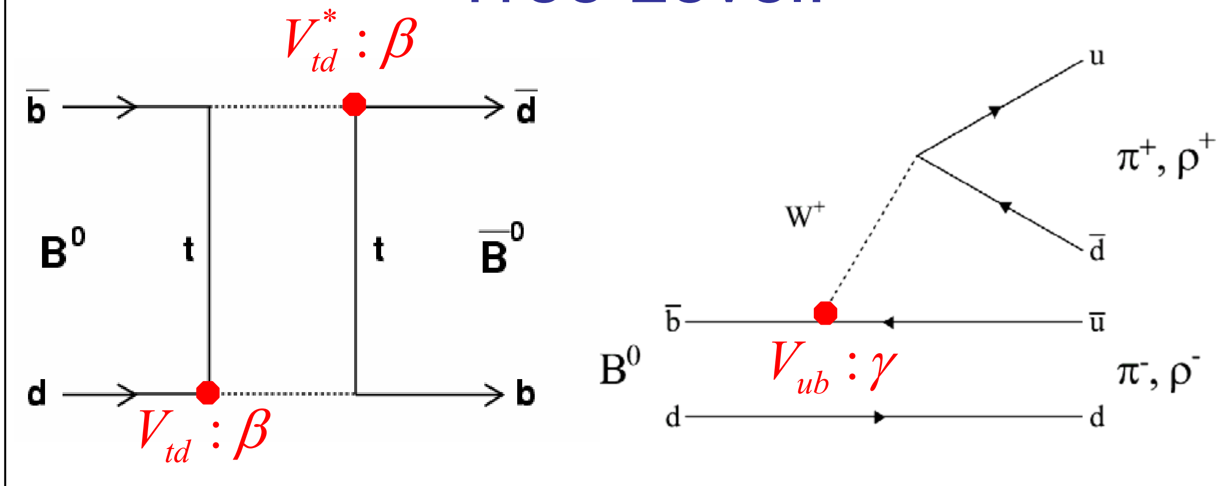
$$P_{TRAN} \propto \frac{\Gamma}{4} e^{-\Gamma|\Delta t|}\left[1+\eta S_{TRAN}\sin(\Delta m_d \Delta t)-\eta C_{TRAN}\cos(\Delta m_d \Delta t)\right]$$

- Don't care about disentangling CP admixture of the transverse polarisation into CP eigen states.

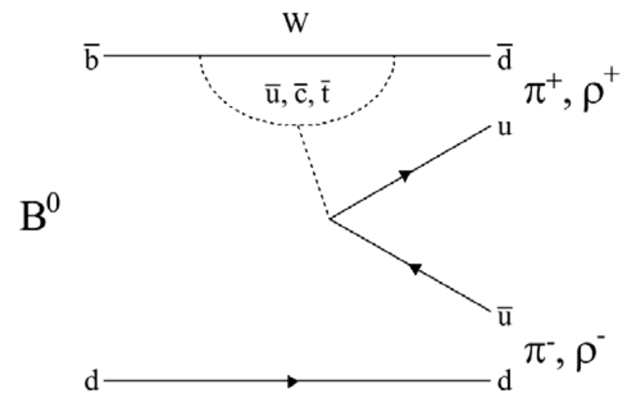
> So as there are very few transverse events
> just set $S_{TRAN}=C_{TRAN}=0$ in fit to data
> vary between ±1 when evaluating systematic error

CP Violation in $B^0 \to \rho^+\rho^-$

Tree Level:



+Loops (penguins)



$$C_{\rho\rho} = 0$$

$$S_{\rho\rho} = \sin(2\alpha)$$

$$C_{\rho\rho} \propto \sin(\delta)$$

$$S_{\rho\rho} = \sqrt{1 - C_{\rho\rho}^2}\,\sin(2\alpha_{\text{eff}})$$

$$\delta = \delta_P - \delta_T$$

→ Same Physics as $\pi\pi/\rho\pi$

→ measure α_{eff}

→ need to bound $|\alpha_{\text{eff}} - \alpha|$ (shift from loops)

Isospin Analysis

- Bounds α_{eff}-α
- SU(2) relates different $\rho\rho$ final states
  $\Rightarrow$triangles for $\rho\rho$

Gronau-London: PRL**65**, 3381 (1990)

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

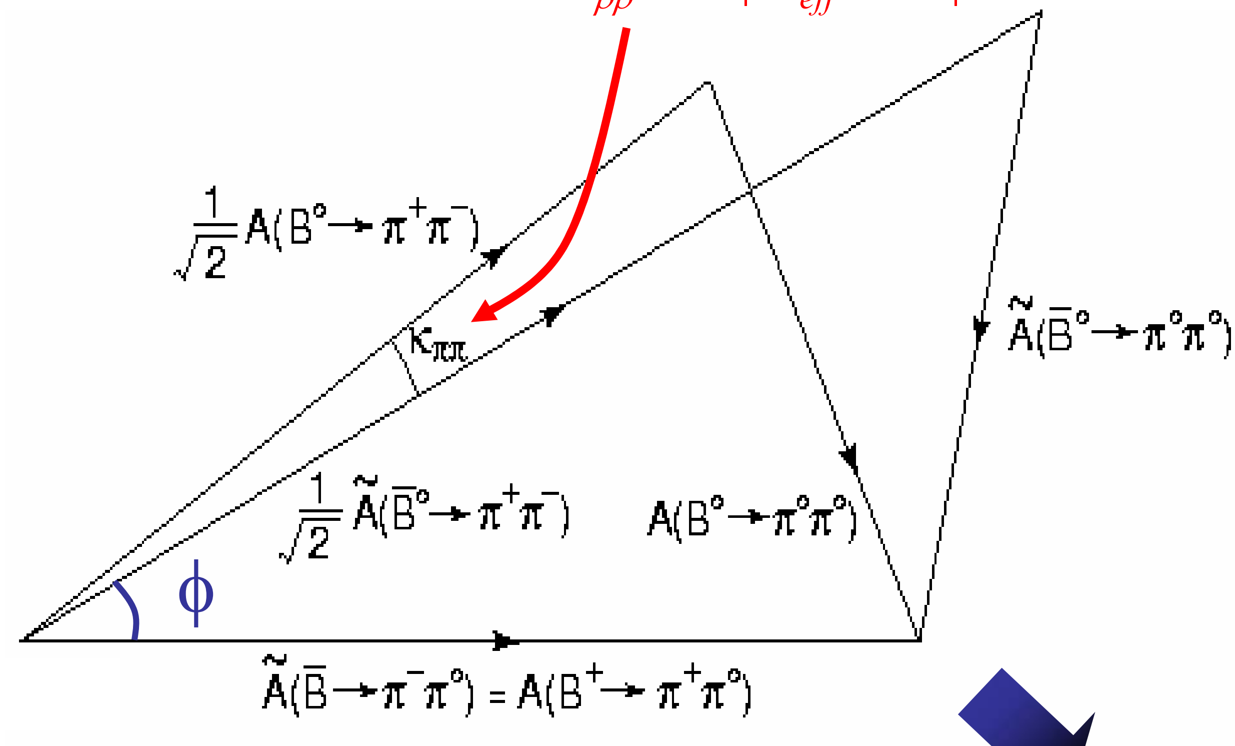
$$\frac{1}{\sqrt{2}} \overline{A}^{-+}_{Long} + \overline{A}^{00}_{Long} = \overline{A}^{-0}_{Long}$$

similar relations for each transversity amplitude
$\Rightarrow$ only care about longitudinal events as $f_L \sim 1$

- So if $A^{00}=0$, we would expect $|A^{+-}|^2=2|A^{+0}|^2$

Isospin Analysis/determination of α

$$\kappa_{\rho\rho} = 2\,|\,\alpha_{eff} - \alpha\,|$$



For ρρ we require:

$A(B^0 \to \rho^+\rho^-) + C.C.$

$A(B^0 \to \rho^0\rho^0) + C.C.$

$A(B^+ \to \rho^+\rho^0) + C.C.$

$S_{\rho^+\rho^-}$

$+Polarization: f_L^{+-}, f_L^{+0}, f_L^{00}$

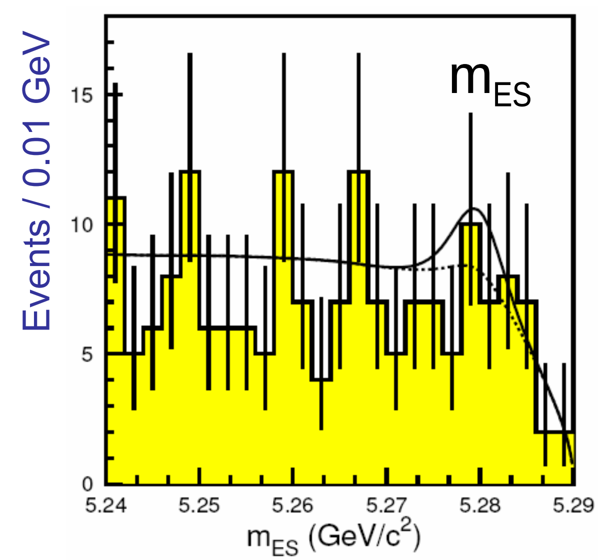
$$\alpha_{\text{eff}} = \tfrac{1}{2}\arcsin\left(\frac{S_{+-}}{\sqrt{1-C_{+-}^2}}\right)$$

→ α

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

(227e6 B Pairs)

- Limiting factor in the ρρ isospin analysis
- First result published in PRL **91**, 171802 (2003)
  - $BF(B^0 \rightarrow \rho^0 \rho^0) < 1.1 \times 10^{-6}$ (90% CL)
    $N_{signal} = 33^{+22}_{-20} (stat)$
- ML fit using 8 inputs:
  m_{ES}, ΔE, tagging,
  $m_{\pi+\pi-}$, $\cos\theta_H$, MVA ($\times 2$ for $m_{\pi+\pi-}$, $\cos\theta_H$)
- Dominant Systematics:
  - $a_1\pi$ interference: ±7.5 events
  - PDF variations: ±6 events
  - *B* bkgd: ±5.8 events



hep-ex/0412067 (accepted for publication)

Previous $\rho^+\rho^-$ results from BaBar

- Runs 1+2 (results published in PRL, PRD):

$$BR(B^0 \to \rho^+\rho^-) = (30 \pm 4 \pm 5) \times 10^{-6}$$

$$f_L = 0.99 \pm 0.03^{+0.04}_{-0.03}$$

$$S_{Long} = -0.42 \pm 0.41 \pm 0.14 \quad C_{Long} = -0.17 \pm 0.27 \pm 0.14$$

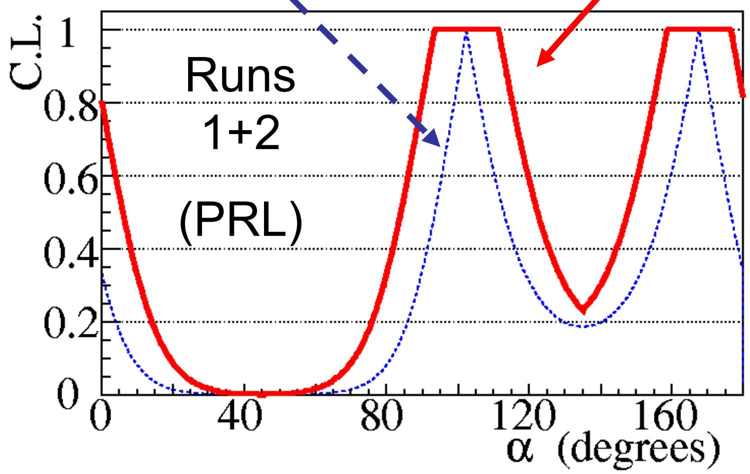
- Runs 1+2+3 (presented at Moriond EW 2004):

$$S_{Long} = -0.19 \pm 0.33 \pm 0.11 \quad C_{Long} = -0.23 \pm 0.24 \pm 0.14$$

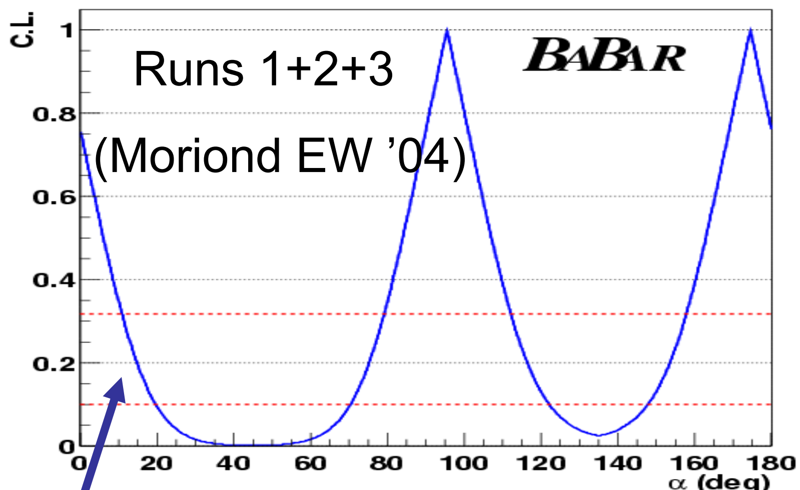
$$\sin^2\delta \leq \frac{f^{00}_{Long} \times \mathcal{B}(B^0/\overline{B}^0 \to \rho^0\rho^0)}{f^{+0}_{Long} \times \mathcal{B}(B^\pm \to \rho^\pm\rho^0)}$$

Using Grossman Quinn Bound to constrain penguin pollution

α_{eff}



$$\alpha = 102^{\circ}\,{}^{+16^0}_{-12^0}\,{}_{stat}\,{}^{+5^\circ}_{-4}\,{}_{syst} \pm 13^{\circ}_{penguin}$$



$$\alpha = 96^{\circ} \pm 10^{\circ}_{stat} \pm 4^{\circ}_{syst} \pm 13^{\circ}_{penguin}$$

Isospin Analysis

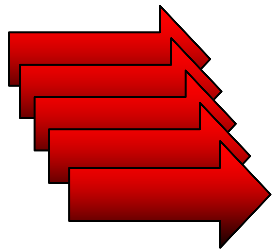
New $\rho^+\rho^-$ Result

- Essentially same method; but there are a few changes
- 210 fb^{-1} of data used (BaBar's full data set)
- CP fit still uses untagged events to constrain $q\bar{q}$ background shape from data
- new result is an update of S_{Long}, C_{Long}, and f_L
- some improvements in the analysis
  - Δt model for signal is improved
  - better B-background model (updated according to HFAG)
  - interference calculation for systematic errors
- use toy MC to extract CL on α

• Unbinned extended maximum likelihood fit

other modes have similar analysis methodology

m_{ES} – B mass
ΔE – energy difference
Δt – proper time difference
NN_{out} – neural network
$m_{\pi\pi}$ (x2) – ρ masses
$\cos\theta_{hel}$ (x2) – ρ helicity



5 exclusive tagging Categories:
- Leptons
- High Purity Kaons
- Lower Purity Kaons
- Other
- Un-tagged

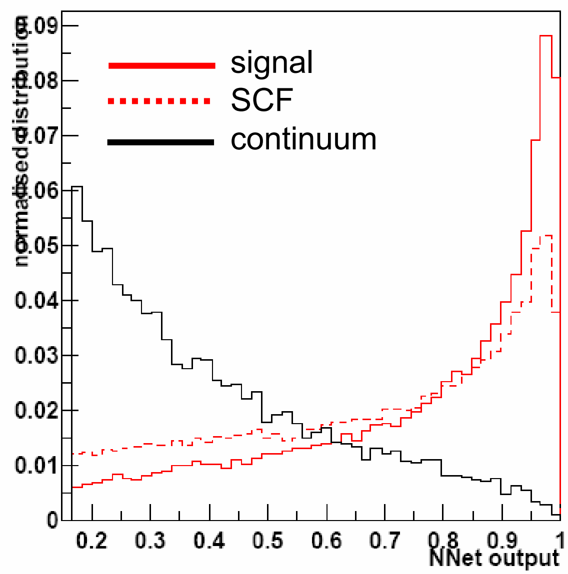
NN_{out}: 10 inputs to a multi layer perceptron to discriminate between signal and $e^+e^- \rightarrow$ continuum

$$\sum_{ROE} |p_i^*|$$

$$\sum_{ROE} |p_i^*| \cos^2\theta_i$$

for neutral and charged sums over ROE used separately in MVA

$$\sum_{ROE} p_T$$

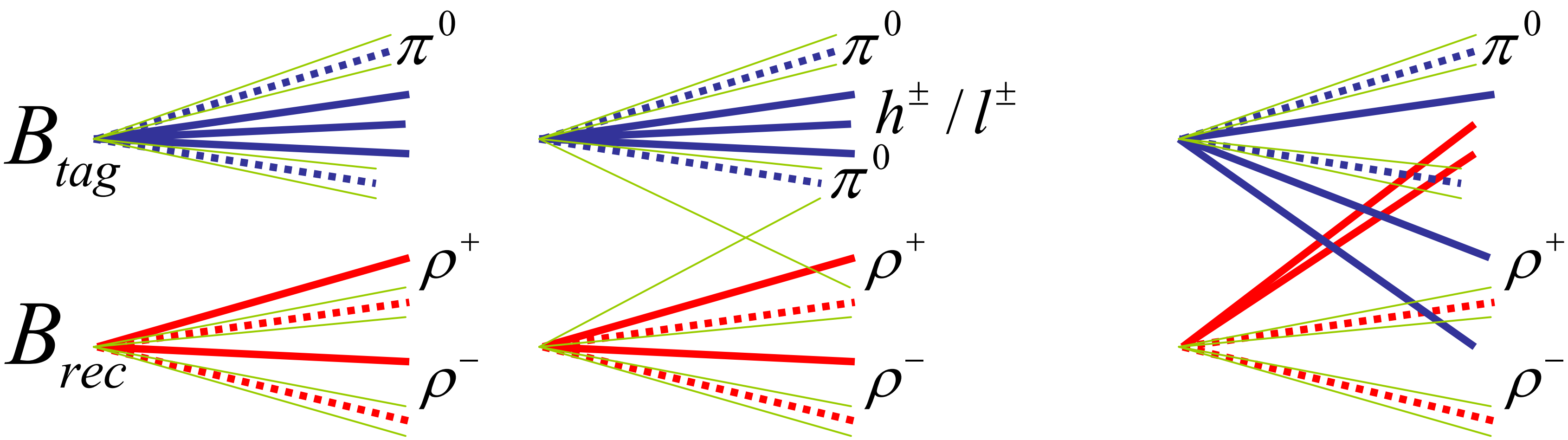


π^0 decay angle (x2)
|cos| of angle between direction of B and Z axis
|cos| of angle between the B thrust and Z axis
|cos| of angle between the B thrust axis and thrust of ROE

Improvements in Δt model for latest result

Signal is the sum of:

true signal	(51.8%)
correct track SCF	(34.6%)
wrong track SCF	(13.6%)



(Correct Tracks used to form vertex)
- calculating the correct Δz/Δt

(Wrong Track(s) used)
- wrong Δz/Δt: 'junk' for CP fit

Wrong track SCF

- pick up one or all tracks from other B meson
- leads to biased S and C for part of the signal

Solution: describe S and C for correct track signal and wrong track signal separately.

$$PDF_{signal} = PDF_{signal}^{long} + PDF_{signal}^{tran}$$

$$PDF_{signal}^{long} = (P_{true}^{long} + P_{correct\ \ track}^{long}) \times f[S_{Long}, C_{Long}, \Delta t, \sigma_{\Delta t}]$$
$$+ P_{wrong\ \ track}^{long} \times f[S_{Long}^{W}, C_{Long}^{W}, \Delta t, \sigma_{\Delta t}]$$

- Use the correct track signal only for measuring S_{LONG} and C_{LONG}
- Set $S_{Long}{}^{w}$=$C_{Long}{}^{w}$=0 in the fit & apply systematic error for wrong track CP on the final result.
- Benefits of this solution
  - remove bias on CP result due to these events (~1.3° effect).
  - no need for additional systematic errors to cover this.

Brief Summary of Time Dependence of fit

- split the longitudinal and transverse polarisation

- longitudinal signal:
  - correct track S and C are the S_{Long} and C_{Long} of our result. We use this for α

  - wrong track S and C are set to zero in the nominal fit. Then vary these parameters to ± 1 for systematic errors

- transverse signal:
  - do not distinguish between CP odd/even components. Just allow for a common S and C. Vary between ± 1 for systematics

- Correct track events have a common resolution function

- Wrong track events have their own resolution function

Background Summary

In addition to the signal (1% of fit sample)
→continuum background (92% of fit sample)
→B background 7% of fit sample)

The Main B backgrounds Considered In the fit (38 different modes are included in our background model):

B→charm dominates

$$B^+ \to charm = 2551$$

$$B^+ \to (a_1\pi)^+ = 87$$

$$B^+ \to \rho^+\rho^0 = 82$$

$$B^+ \to a_1\rho^+ = 65$$

$$B^+ \to \rho\pi^0 = 51$$

$$B^0 \to charm = 1316$$

$$B^0 \to a_1\rho = 145$$

$$B^0 \to a_1\pi = 65$$

$$B^0 \to K^{**}\pi = 56$$

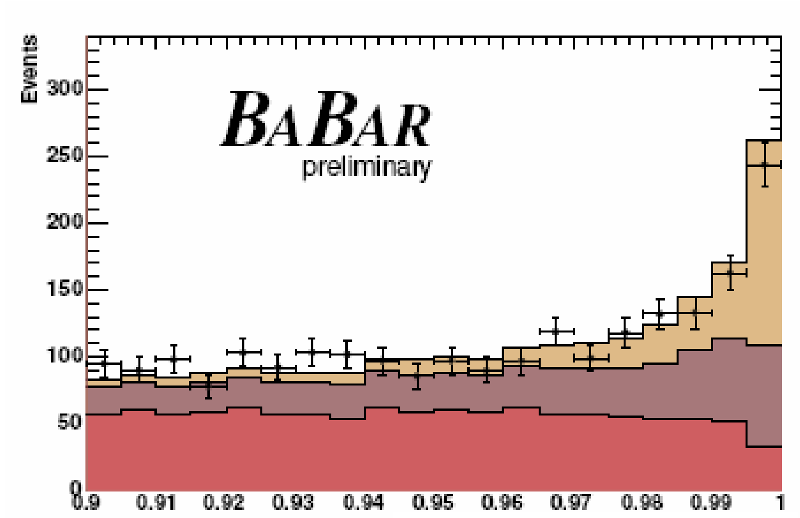
$$B^0 \to \rho\pi = 31$$

Final states with charged ρ mesons contribute a lot in our background model.

Fit Results

A total of 26 parameters are floated.

signal yield
S_L, C_L, f_L
22 background parameters



Data sample = 68703 events

$$N_{signal} = 685 \pm 52 \rightarrow N_{signal} = 617 \pm 52$$

$$R = \frac{L_{signal}}{L_{signal} + L_{background}}$$

$$f_L = 0.978 \pm 0.014$$

$$S_L = -0.33 \pm 0.24$$

$$C_L = -0.03 \pm 0.18$$

- Correct signal yield for bias coming from correlations that are neglected in the fit model
- These have a small impact on the other parameters (see systematics)

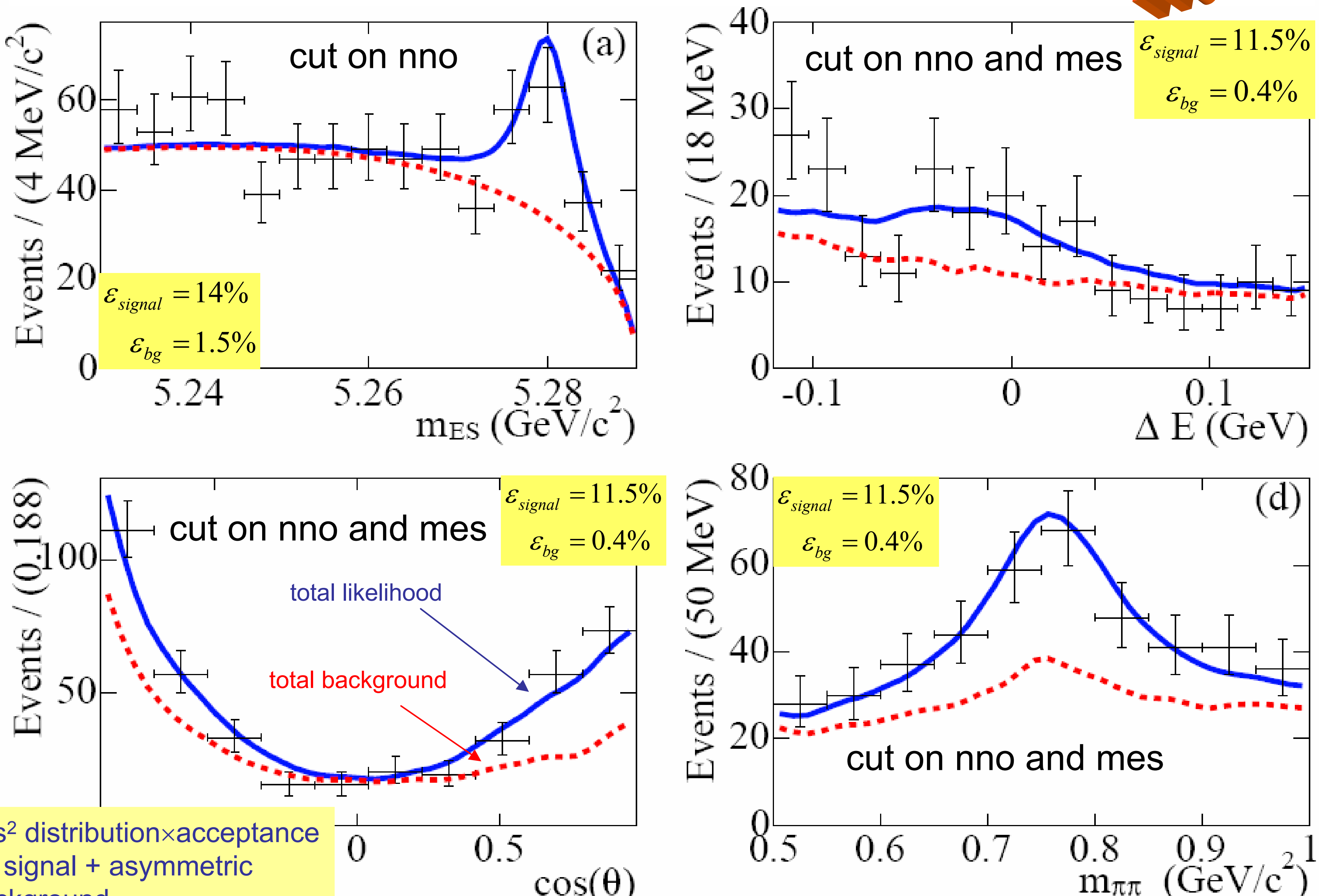
•compatible with previous results

all new results

Preliminary

Signal Projection Plots –Lepton and Kaon1 categories only

Preliminary



cos² distribution×acceptance for signal + asymmetric background

Interference calculation (systematic error)

1. Generate toy MC in 5D phase space: m_1, m_2, θ_1, θ_2, ϕ for $A_{\rho\rho}$ and A_{xx}.
   [$xx = a_1\pi$, $\rho\pi\pi$, $\pi\pi\pi\pi$] using BW for resonances

2. Calculate Matrix element including interference term

3. Cut on allowed m_i and θ_i to match $\rho\rho$ selection cuts

4. Calculate effective S and C from toy data: e.g.

$$\lambda(x_i) = \frac{q}{p}\frac{A(\overline{B}^0 \to \rho^+\rho^-) + A(\overline{B}^0 \to a_1^+\pi^-) + A(\overline{B}^0 \to a_1^-\pi^+)}{A(B^0 \to \rho^+\rho^-) + A(B^0 \to a_1^+\pi^-) + A(B^0 \to a_1^-\pi^+)} \quad \Rightarrow S(x_i) = \frac{2\,\mathrm{Im}(\lambda(x_i))}{1-|\lambda(x_i)|^2}$$

$$S^{eff}(x_i) = \frac{\int S(x_i)\left|A(\overline{B}^0 / B^0 \to a_1^+\pi^-)\right|^2 d^5x_i}{\int \left|A(\overline{B}^0 / B^0 \to a_1^+\pi^-)\right|^2 d^5x_i}$$

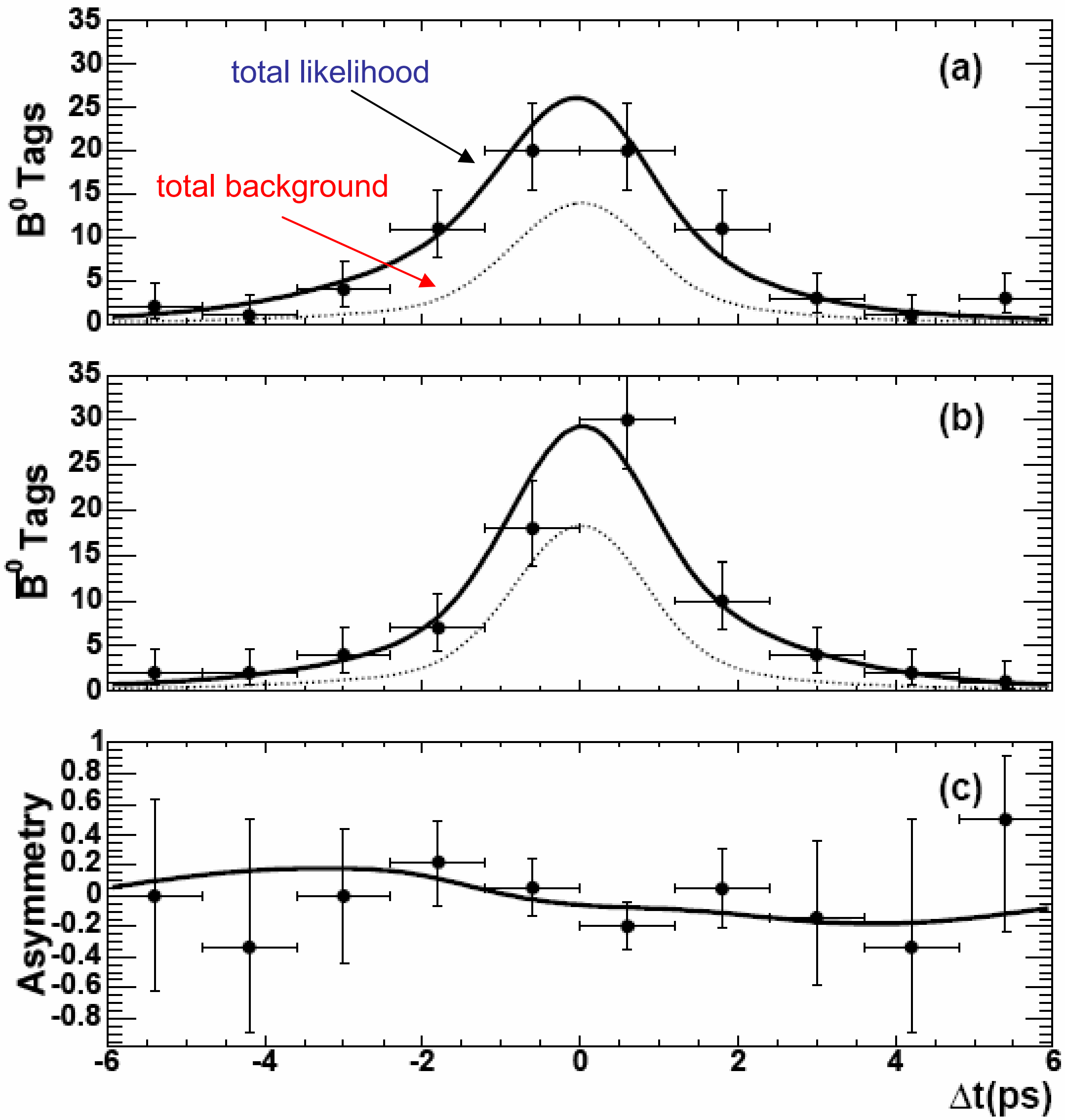
5. Take the RMS deviation of O_{eff}-O as the systematic error.

- also looked at $\sigma(400)\pi\pi$, but ignored this final state as it has a small efficiency relative to the other final states included here.

Total Systematic Uncertainty

Contribution	f_L	S_{long}	C_{long}
B-background yield	± 0.003	± 0.027	$^{+0.002}_{-0.003}$
B-background CP	± 0.001	± 0.027	± 0.045
non-resonant events	0.015	0.030	0.001
Floating B- background	-0.020	-0.12	+ 0.008
Neglecting Interference	0.0036	0.023	0.022
DCSD	–	0.012	0.037
SVT LA (alignment)	–	0.034	0.005
Fit bias	0.010	0.04	0.05
CPV in wrong track SXF	0.0005	$^{+0.007}_{-0.002}$	± 0.012
.			
.			
.			
Total	$^{+0.021}_{-0.029}$	$^{+0.08}_{-0.14}$	$\pm$ 0.09

Table 1: Summary of the main systematic errors contribution to f_L, S_{long} and C_{long}



Events from the Lepton and Kaon1 tagging categories only.

$$S_{Long} = -0.33 \pm 0.24^{+0.08}_{-0.14}$$

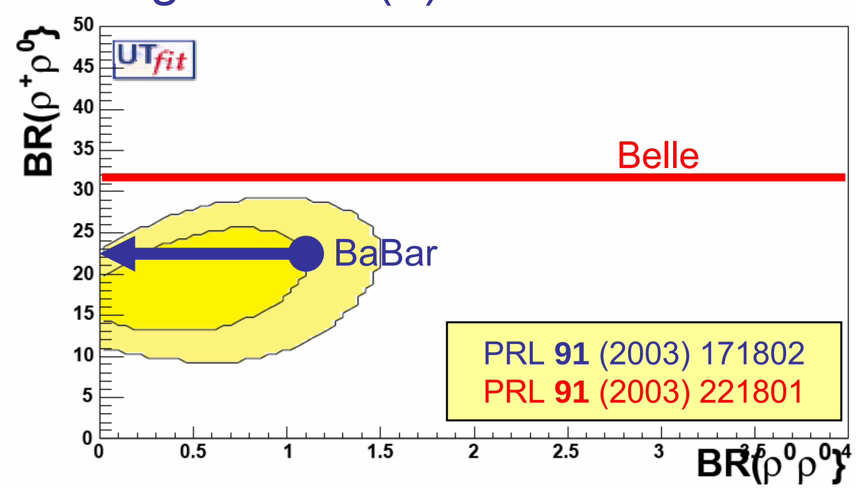
$$C_{Long} = -0.03 \pm 0.18 \pm 0.09$$

$$f_L = 0.978 \pm 0.014^{+0.020}_{-0.028}$$

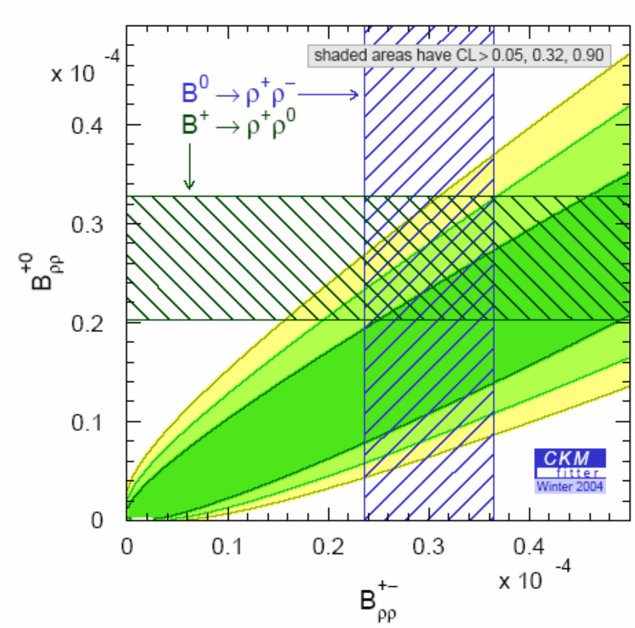
Preliminary

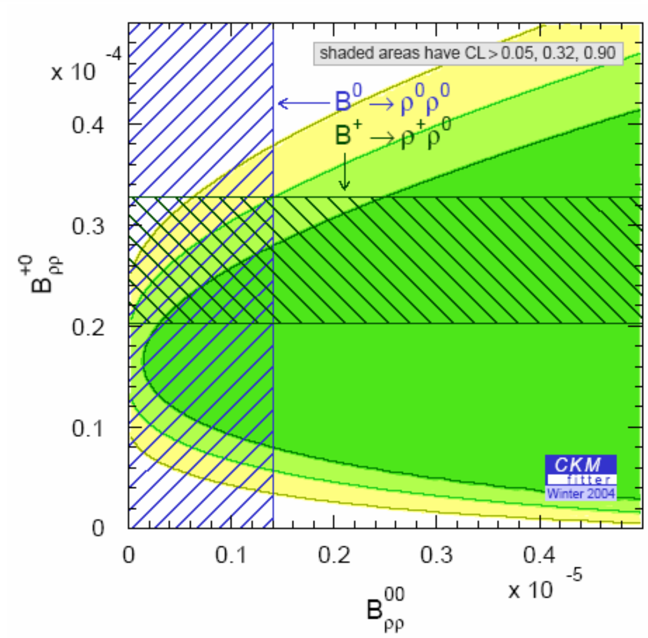
$B \to \rho^+\rho^0$

- UT Fit and CKM Fitter predict that the central value of $BF(B^+ \to \rho^+\rho^0)$ is a little too large for SU(2).



- An updated measurement of this mode is long overdue & we're eagerly awaiting it!

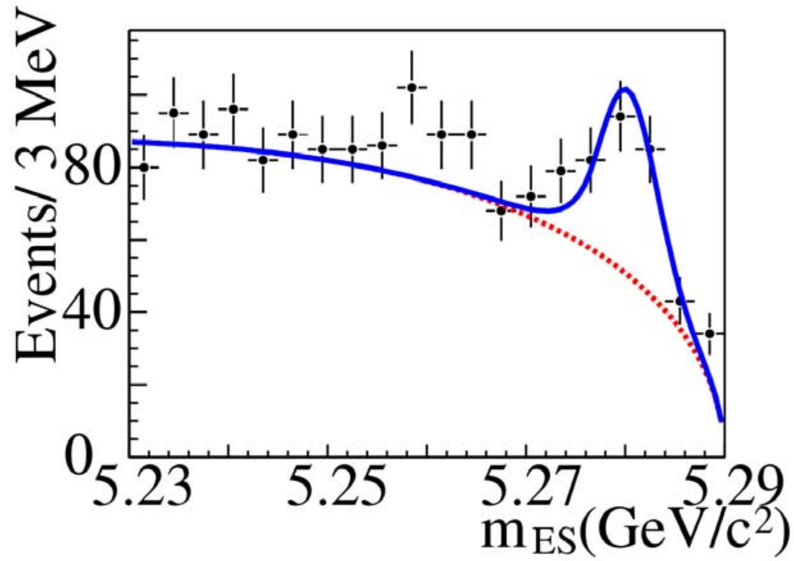




Measuring α

➡ Use Isospin analysis for longitudinal polarisation

$B^0 \to \rho^+\rho^-$ (BaBar) PRL **93** 231801 (2004)



$$BF = (30 \pm 4 \pm 5) \times 10^{-6}$$

(88e6 B Pairs)

new $$f_L = 0.978 \pm 0.014^{+0.021}_{-0.028}$$

(230e6 B Pairs)

$B^+ \to \rho^+\rho^0$ (Belle & BaBar)

$$BF = (26.4 \pm 6.4) \times 10^{-6}$$

$$f_L = 0.96^{+0.05}_{-0.07}$$

PRL **91** (2003) 171802
PRL **91** (2003) 221801

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

$$BF < 1.1 \times 10^{-6} (90\% C.L.)$$

hep-ex/0412067 (227e6 B Pairs)

Penguins are small in B→ρρ

$$|\alpha_{eff} - \alpha| < 11^\circ (68\% CL)$$

- Build a χ^2_{min} from the measured observables (S,C, f_L and BR) each of which can be related to the amplitudes that make up the isospin triangles.

  χ^2 scan in α $$\Delta\chi^2(\alpha) = \chi^2_{\min}(\alpha) - \chi^2_{\min 0}$$

  To obtain the CL: we use toy MC to reproduce what happens with data: i) Generate toy for each alpha scanned

  ii) calculate $1 - \mathrm{CL}(\alpha)$: fraction of toys with

$$\Delta\chi^2(\alpha)_{toy} > \Delta\chi^2(\alpha)_{data}$$

  Toy MC techniques work better in this case as the isospin triangle is not closed (so is unphysical):

$$1/\sqrt{2}\left|A^{+-}_{Long}\right| + \left|A^{00}_{Long}\right| \le \left|A^{+0}_{Long}\right|$$

Assumptions in the use of SU(2) with $\rho^+\rho^-$

- Assume Gronau-London Isospin analysis (use SU2 without electroweak penguins)

- Neglect I=1 component of amplitude (should be $O(\Gamma_\rho/m_\rho)^2 \approx 4\%$) Falk et al, PRD **69** 011502 (2004)

- (implicitly we also neglect higher ρ resonances in the final state when extracting S and C)

The α Result

$$S_{Long} = -0.33 \pm 0.24^{+0.08}_{-0.14}$$

$$C_{Long} = -0.03 \pm 0.18 \pm 0.09$$

$$f_L = 0.978 \pm 0.014^{+0.020}_{-0.028}$$

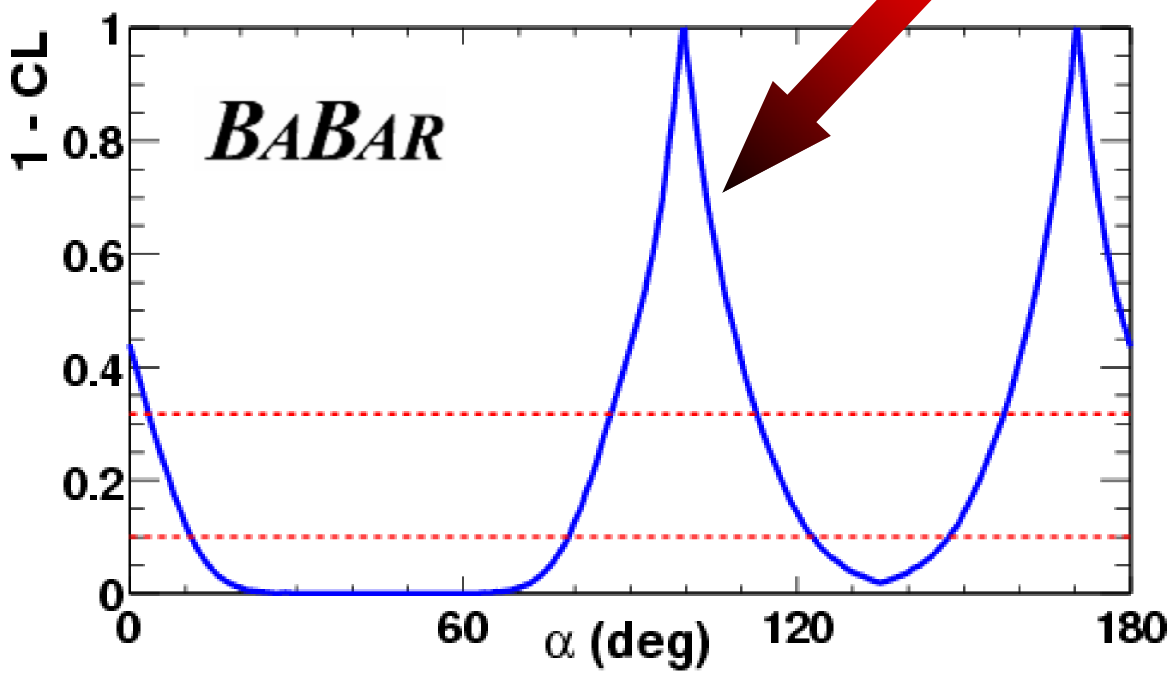
+ Inputs from other ρρ measurements

$$\alpha \in [79^\circ, 123^\circ] \text{ at } 90\% CL$$

Neglect:

- EW penguins (1-2°) effect (CKM Fitter/Gronau & Zupan)
- Possible I=1 amplitudes

Penguin error is ±**11°** at 1σ.



The solution in agreement with the SM is: $\alpha = 100^\circ \pm 13^\circ$

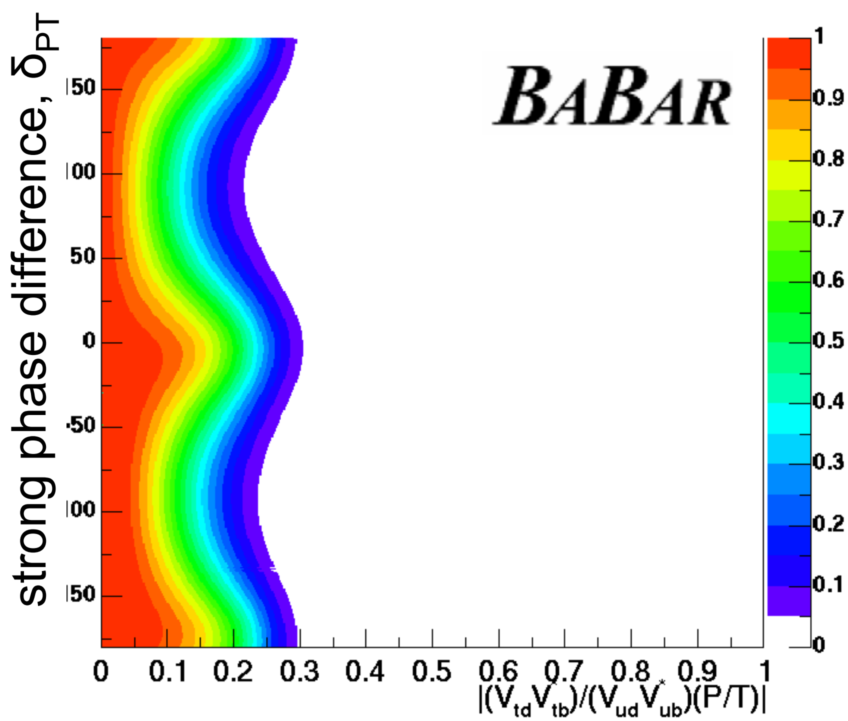
Preliminary

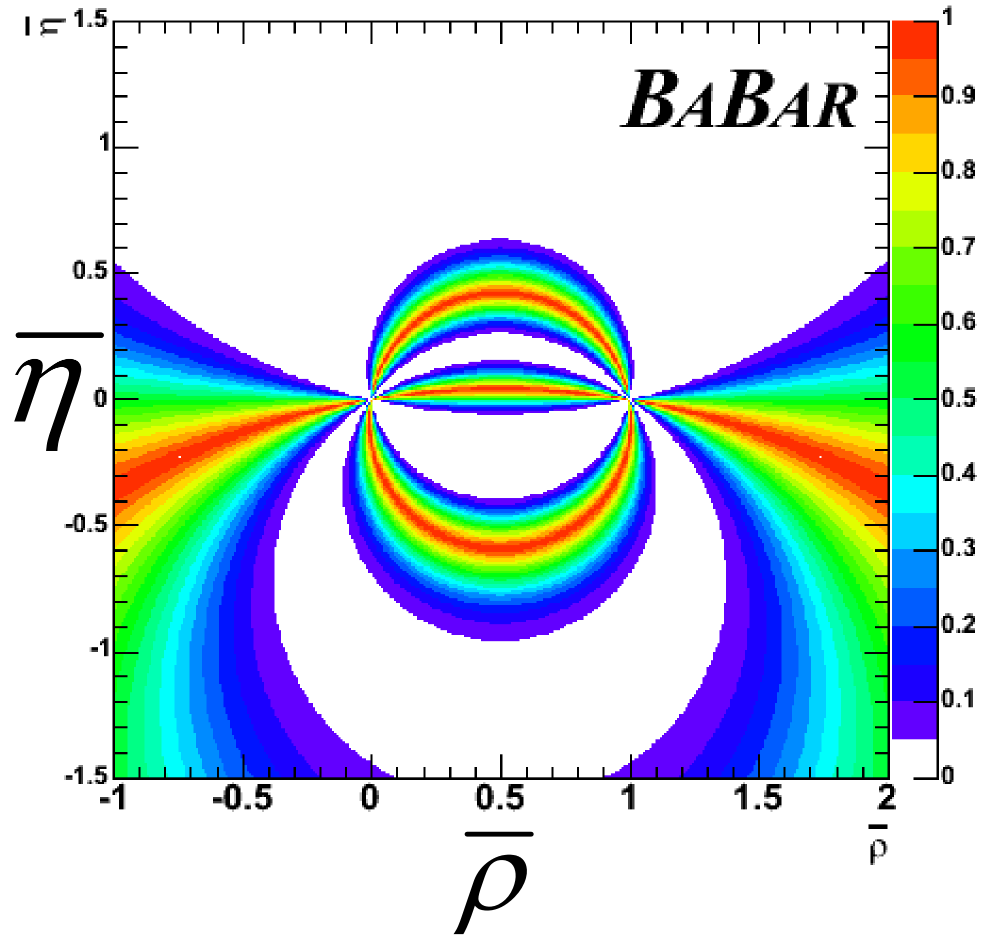
- Using these results, we can constrain |P/T| in ρρ
- and also show the α constrain in the $\bar{\eta}\bar{\rho}$ plane.

Preliminary

$$P = P_t - P_c$$

$$T = T + P_u - P_c$$





$$|P/T| = 0.07^{+0.14}_{-0.07}$$

(same P, T convention as CKM Fitter for the |P/T| plot)

Summary

- New result on $\rho^0\rho^0$ last summer
- New result this winter for $\rho^+\rho^-$

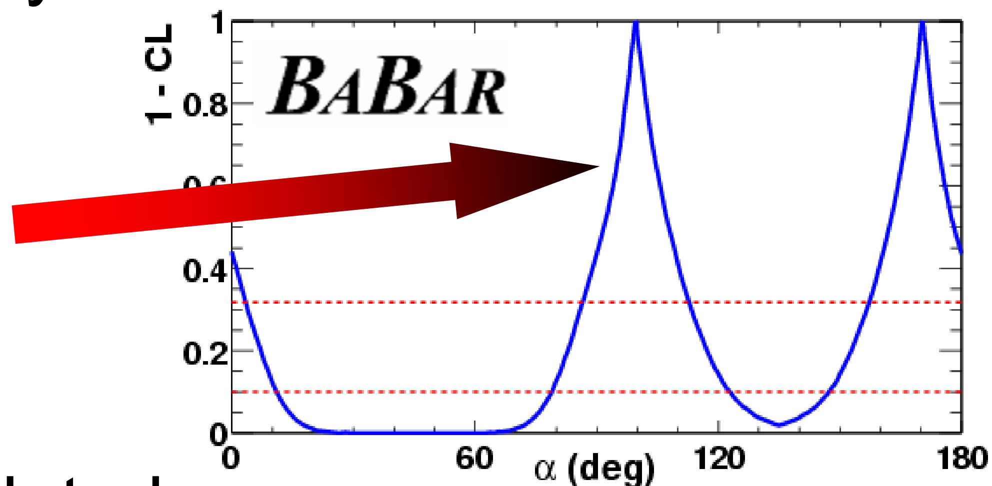
→updated CP + f_L measurement

$$S_{Long} = -0.33 \pm 0.24^{+0.08}_{-0.14} \qquad C_{Long} = -0.03 \pm 0.18 \pm 0.09$$

$$f_L = 0.978 \pm 0.014^{+0.021}_{-0.029}$$

- Updated Isospin analysis result

$$\alpha = 100^\circ \pm 13^\circ$$



- need to see $\rho^+\rho^0$ updated soon.