CP-violation in $B^0 \to (\rho\pi)^0 \to \pi^+\pi^-\pi^0$ using a time-dependent Dalitz plot analysis

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DPF, 2004,

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The CKM matrix and Unitarity Triangle

The CKM mixing matrix relates the quarks in the weak interaction basis (d',s',b'), and the quark mass eigenstates (d,s,b): $(d',s',b')=V_{CKM}\,(d,s,b)$

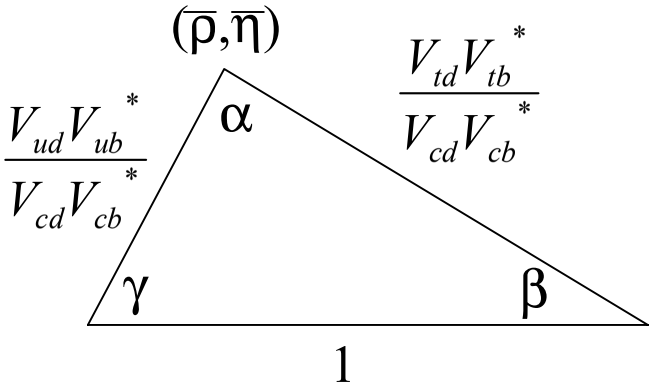
$$V_{CKM}=\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

Wolfenstein parametrization:

$$V_{CKM}\approx\begin{pmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho-i\eta) \\ -\lambda(1+iA^2\lambda^4\eta) & 1-\frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2(1+i\lambda^2\eta) & 1 \end{pmatrix}$$

Unitarity leads to:

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



$\lambda=\sin\theta_C$ (Cabibbo angle)

Independent parameters: λ,ρ,η, A

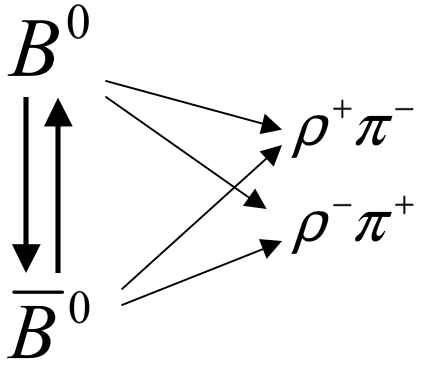
The angles of the triangle are related to CP–violation.

Measure α from CP-asymmetries in b→uūd processes.

$B\to\pi\pi$, $B\to\rho\pi$, $B\to\rho\rho$

Previous $B^0 \to \rho^+\pi^-$ Results (non-Dalitz approach)

ρπ is not a CP eigenstate:



Time dependent decay rate:

$$\Gamma(B^0 \to \rho^{\pm}\pi^{\mp}) \propto (1 \pm A_{CP})(1 - (S \pm \Delta S)\sin(\Delta m \Delta t) + (C \pm \Delta C)\cos(\Delta m \Delta t))$$

C: direct CPV

S: CPV in interference between mixing and decay

ΔC, ΔS: parameters related to ρπ not being a CP eigenstate.

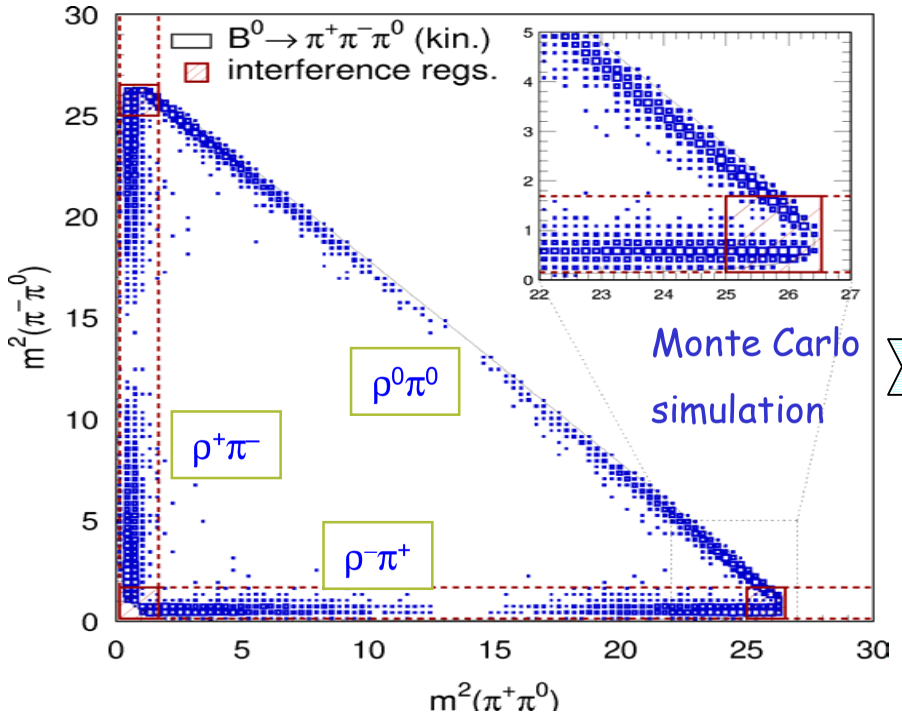
A_{CP}: asymmetry between $\rho^+\pi^-$ and $\rho^-\pi^+$

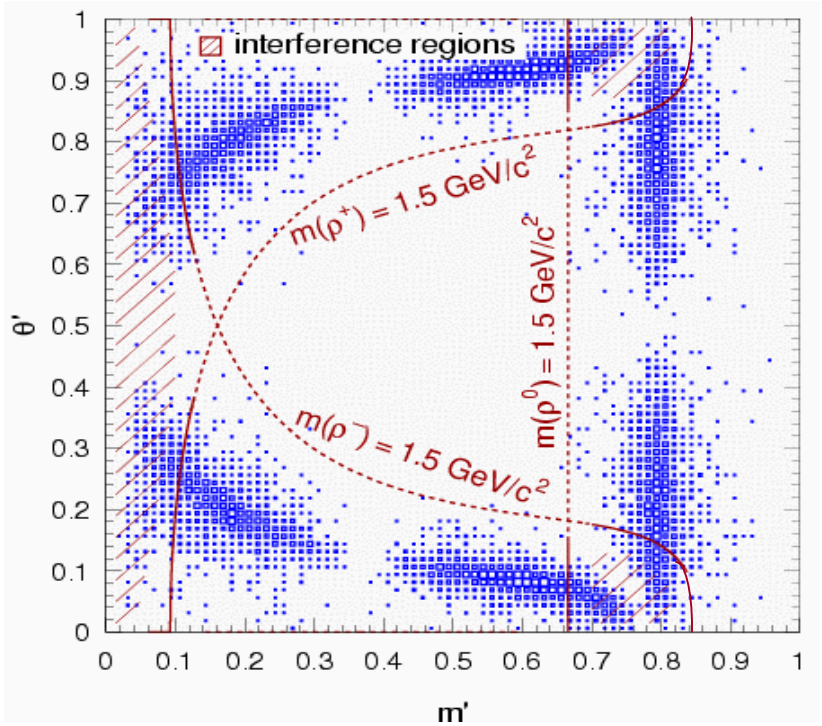
Babar results from 113 fb^{-1} with a quasi-2-body approach. (Select the ρ bands on the Dalitz plot, cut away interference regions)

PRL 91, 201802 (2003)

$$S = -0.13 \pm 0.18 \pm 0.04, \; C = 0.35 \pm 0.13 \pm 0.05$$
$$\Delta S = 0.33 \pm 0.18 \pm 0.03, \; \Delta C = 0.20 \pm 0.13 \pm 0.05$$
$$A_{CP} = -0.11 \pm 0.06 \pm 0.03$$

$B^0 \to (\rho\pi)^0 \to \pi^+\pi^-\pi^0$ Dalitz plot





Square Dalitz plot: more uniform repartition of events. Better parametrization.

$$m' \equiv \frac{1}{\pi}\arccos\left(2\frac{m_{+-} - m_{+-}[\min]}{m_{+-}[\max] - m_{+-}[\min]} - 1\right), \qquad \theta' \equiv \frac{1}{\pi}\theta_{+-}$$

$$m_{+-}[\max] = m_{B^0} - m_{\pi^0}$$

$$m_{+-}[\min] = 2m_{\pi^+}$$

θ_{+-} is the angle between the pos. track and neg. B^0 momentum in the {+-} rest frame

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

Snyder-Quinn approach, PRD 48, 2139 (1993)

Extract α and the strong phases using the interference between the $B^0 \to \pi^+\pi^-\pi^0$ amplitudes.

$$A_{3\pi} = f_+ A^{+-} + f_- A^{-+} + f_0 A^{00}$$
$$\overline{A}_{3\pi} = f_+ \overline{A}^{+-} + f_- \overline{A}^{-+} + f_0 \overline{A}^{00}$$

$f_{+,-,0}$ are relativistic Breit-Wigner functions, that depend on the Dalitz plot variables. $A^{+-,-+,00}$ are decay amplitudes to $\rho^+\pi^-$, $\rho^-\pi^+$ and $\rho^0\pi^0$.

$$\Gamma(\Delta t) \propto \left(|A_{3\pi}|^2 + |\overline{A_{3\pi}}|^2 \right) \frac{e^{-|\Delta t|/\tau}}{4\tau}$$

Q_{tag}=+1 for B^0 and -1 for $\overline{B}^0$

$$\left(1 + 2Q_{tag} \frac{\mathrm{Im}\left[\overline{A}_{3\pi} A^*_{3\pi} \right]}{|A_{3\pi}|^2 + |\overline{A_{3\pi}}|^2} \sin(\Delta m_d \Delta t) - Q_{tag} \frac{|A_{3\pi}|^2 - |\overline{A_{3\pi}}|^2}{|A_{3\pi}|^2 + |\overline{A_{3\pi}}|^2} \cos(\Delta m_d \Delta t) \right)$$

Fit Strategy

Expand $A_{3\pi}$ as the sum of the form factors, $f_{+,-,0}$, multiplied by observable coefficients, U and I. PRD **62**, 054002 (2000)

$$\left|A_{3\pi}\right|^2 \pm \left|\overline{A}_{3\pi}\right|^2 = \sum_{\kappa\in\{+,0,-\}} \left|f_\kappa\right|^2 U_\kappa^{\pm} + 2 \sum_{\sigma<\kappa\in\{+,0,-\}} \left(\mathrm{Re}\left[f_\kappa f_\sigma^*\right] U_\kappa^{\pm} - \mathrm{Im}\left[f_\kappa f_\sigma^*\right] U_{\kappa\sigma}^{\pm,\mathrm{Im}}\right)$$

$$\mathrm{Im}\left(\overline{A}_{3\pi} A_{3\pi}^*\right) = \sum_{\kappa\in\{+,0,-\}} \left|f_\kappa\right|^2 I_\kappa + \sum_{\sigma<\kappa\in\{+,0,-\}} \left(\mathrm{Re}\left[f_\kappa f_\sigma^*\right] I_{\kappa\sigma}^{\mathrm{Im}} + \mathrm{Im}\left[f_\kappa f_\sigma^*\right] I_{\kappa\sigma}^{\mathrm{Re}}\right)$$

Assume that the amplitude is dominated by $\rho^{+,-,0}$ and the radial excitations $\rho(1450)$, $\rho(1700)$

U's and I's are determined in the likelihood fit. 27 observables.

$\rho^0\pi^0$ is small, (set some params. to zero) → 16 observables

Other resonances such as f_0 are included in the background model.

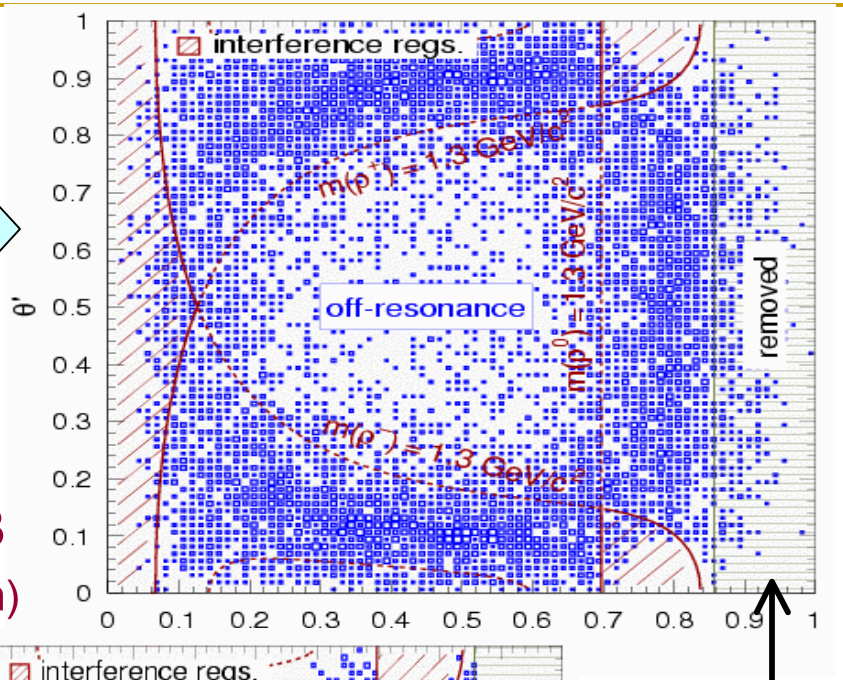
A possible σ resonance is not considered. (expected to be insignificant in neutral B decays.)

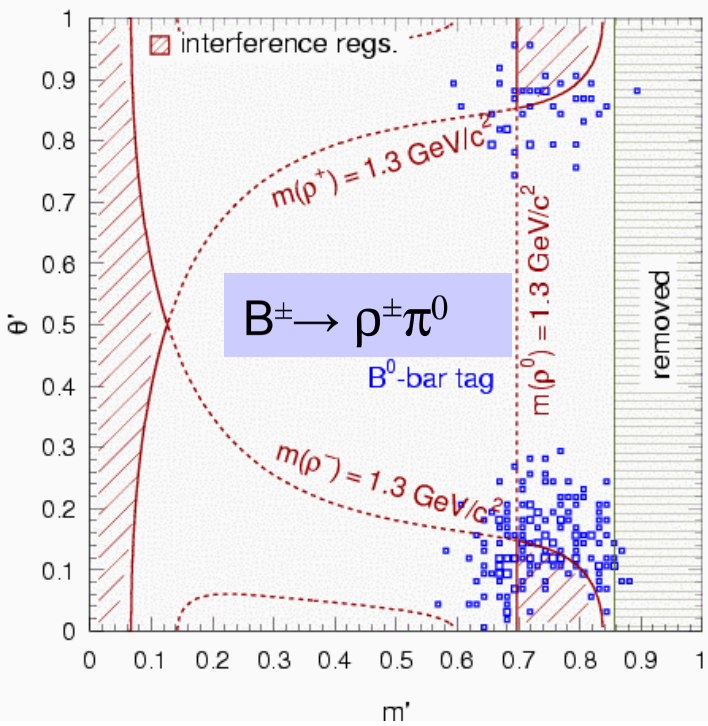
Backgrounds

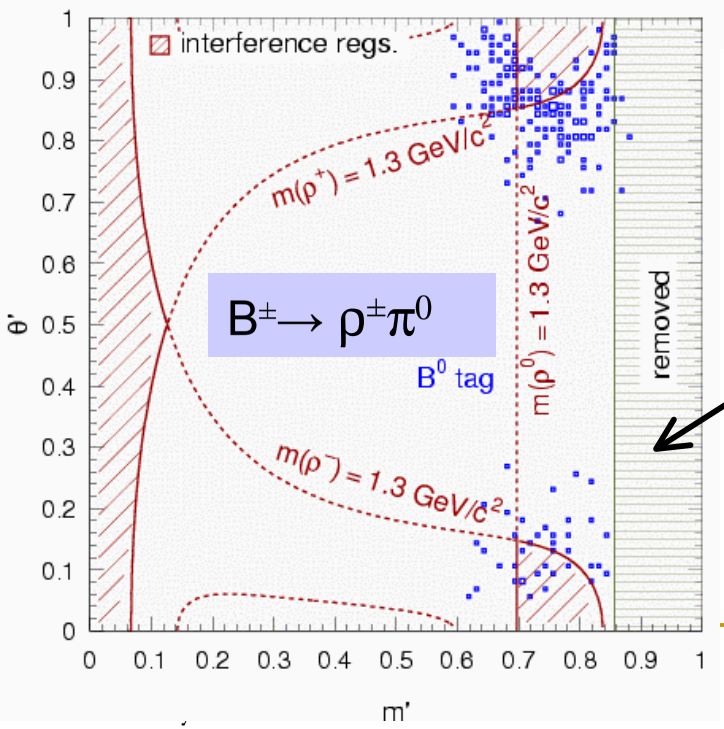
Dominant: $q\bar{q}$ continuum:

Model 38 B-background modes, including B → charm decays.

Use different fixed Dalitz-plot background shapes for different B tags. (asymmetry from misreconstruction)







Cut removes most of $K_s^0\pi^0$ decays

Analysis Features

Build a maximum likelihood using PDFs for 5 discriminating variables:

Energy difference: $\Delta E = E_B^* - E_{\text{beam}}^*$
transformed range (-1,1)

Energy substituted mass: $m_{\text{ES}} = \sqrt{E_{\text{beam}}^{*2} - p_B^{*2}}$

B-decay: isotropic
Continuum $q\bar{q}$: jet-like

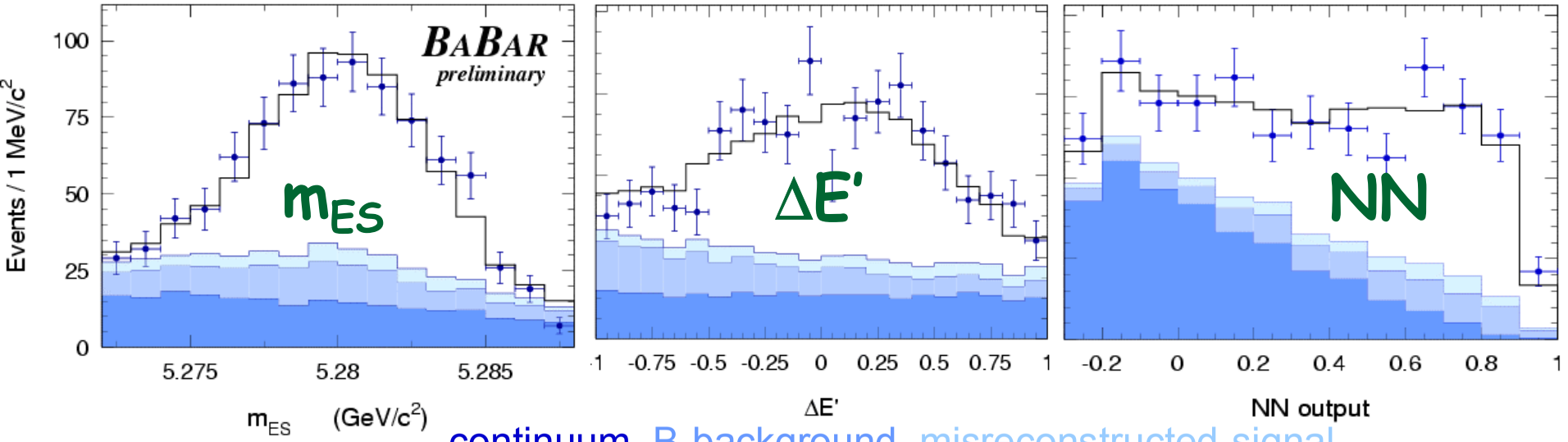
} Combine event shape variables into a Neural Network (NN).

$$Likelihood \propto Pdf(m_{ES}) \times Pdf(\Delta E) \times Pdf(NN) \times Pdf(\Delta t) \times Pdf(DP)$$

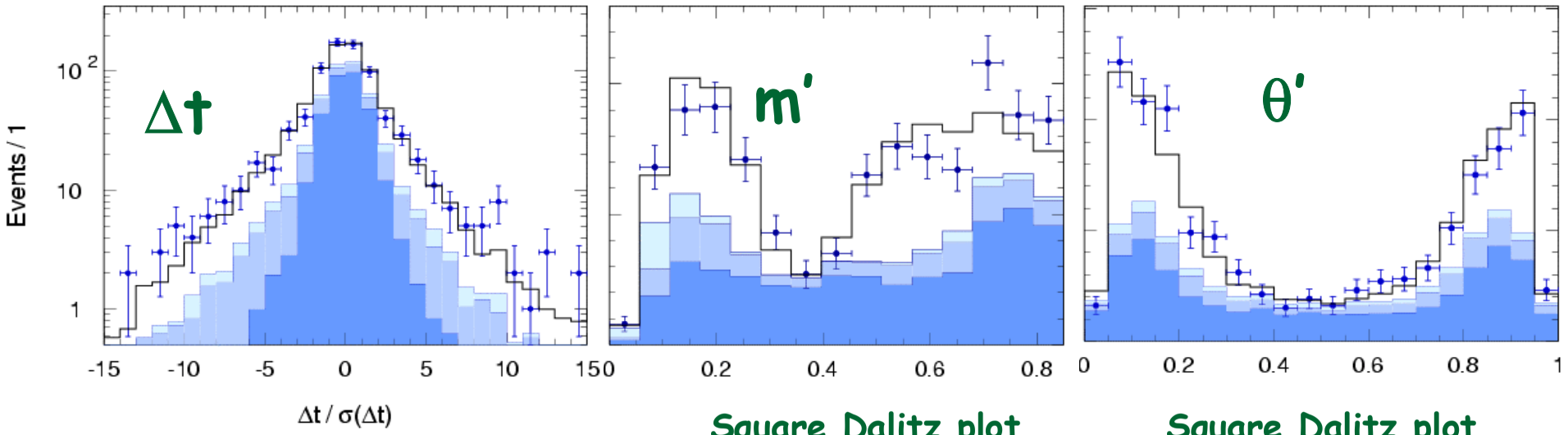
- Model signal efficiency variation across the Dalitz Plot. 24% average.
- Variation of signal misreconstruction rate across the Dalitz Plot. 19% on average, mostly from low momentum neutrals.
- Take into account the correlations: DP-NN, DP-ΔE

Data Projections

Use **192 fb^{-1}** of data. 17031 events selected, 80% are continuum background



continuum, B-background, misreconstructed-signal



Results

$B^0 \to \pi^+\pi^-\pi^0$ event yield: 1184 ± 58 (stat.)

Extract the physics parameters from the fitted U's and I's

The trigonometrical functions of α are "hidden" in the U's and I's

$$C = \frac{1}{2}\left(\frac{U_+^-}{U_+^+} + \frac{U_-^-}{U_-^+}\right) \qquad S = \frac{I_+}{U_+^+} + \frac{I_-}{U_-^+} \qquad A_{CP} = \frac{U_+^+ - U_-^+}{U_+^+ + U_-^+}$$

$$\Delta C = \frac{1}{2}\left(\frac{U_+^-}{U_+^+} - \frac{U_-^-}{U_-^+}\right) \qquad \Delta S = \frac{I_+}{U_+^+} - \frac{I_-}{U_-^+}$$

	Q2B(113 fb^{-1}), LP03	Dalitz(192 fb^{-1}) New!
$A_{\rho\pi}$	–0.114 ± 0.062 ± 0.027	–0.088 ± 0.049 ± 0.013
C	0.35 ± 0.14 ± 0.05	0.34 ± 0.11 ± 0.05
ΔC	0.20 ± 0.14 ± 0.05	0.15 ± 0.11 ± 0.03
S	–0.13 ± 0.18 ± 0.04	–0.10 ± 0.14 ± 0.04
ΔS	0.33 ± 0.18 ± 0.03	0.22 ± 0.15 ± 0.03

Parameters related to direct CP

Direct CP results

Define physically more intuitive quantities:

$$A_{\rho\pi}^{+-} \propto N(B^0 \to \rho^+\pi^-) - N(\bar{B}^0 \to \rho^-\pi^+)$$

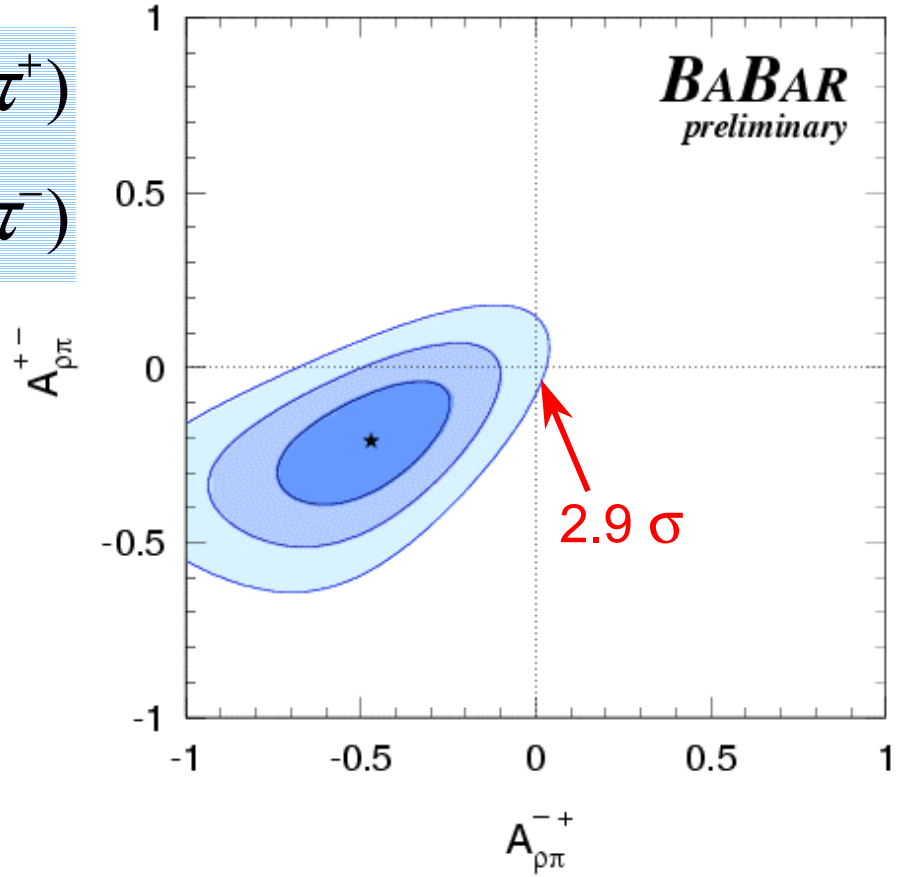
$$A_{\rho\pi}^{-+} \propto N(B^0 \to \rho^-\pi^+) - N(\bar{B}^0 \to \rho^+\pi^-)$$

$$A_{\rho\pi}^{-+} \equiv \frac{A_{\rho\pi} - C - A_{\rho\pi}\Delta C}{1 - C - A_{\rho\pi}\Delta C}$$

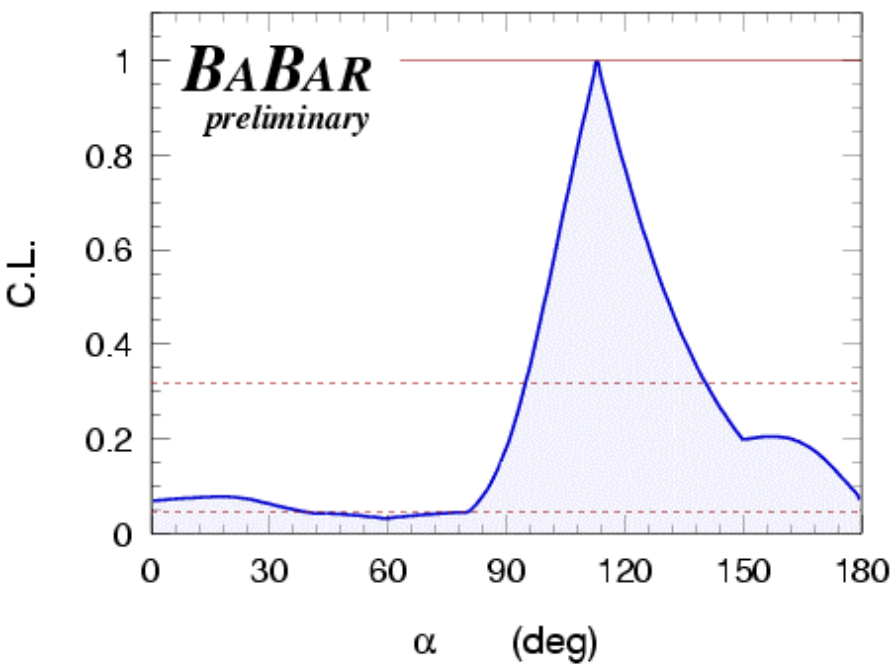
$$= -0.47^{+0.14}_{-0.15} \pm 0.06$$

$$A_{\rho\pi}^{+-} \equiv \frac{A_{\rho\pi} + C + A_{\rho\pi}\Delta C}{1 + \Delta C + A_{\rho\pi}C}$$

$$= -0.21 \pm 0.11 \pm 0.04$$

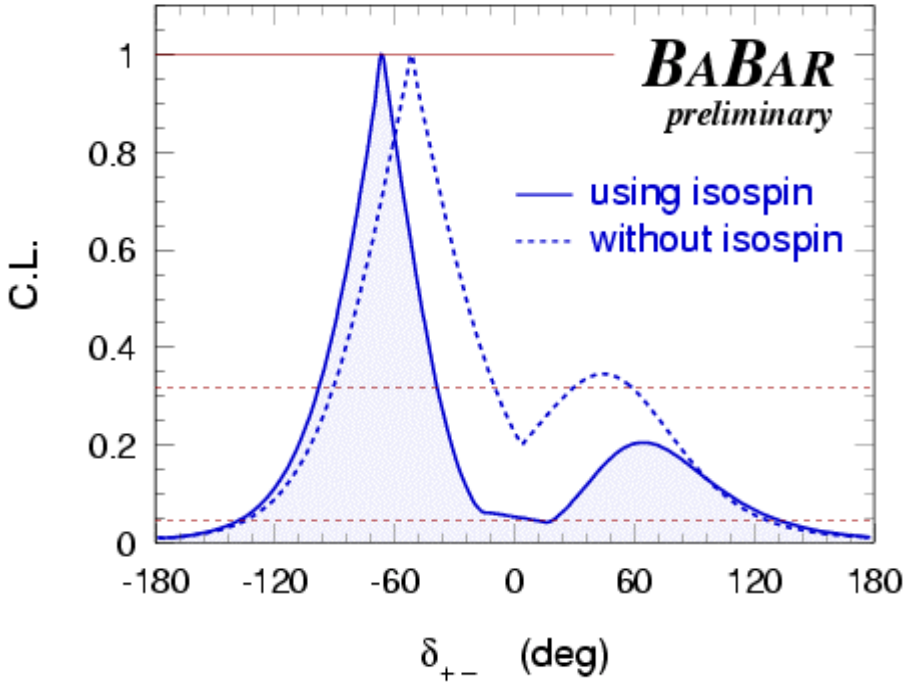


α and strong phase results



$$\alpha = \left(113^{+27}_{-17} \pm 6\right)^{\circ}$$

<u>weak</u> constraint at two standard deviations

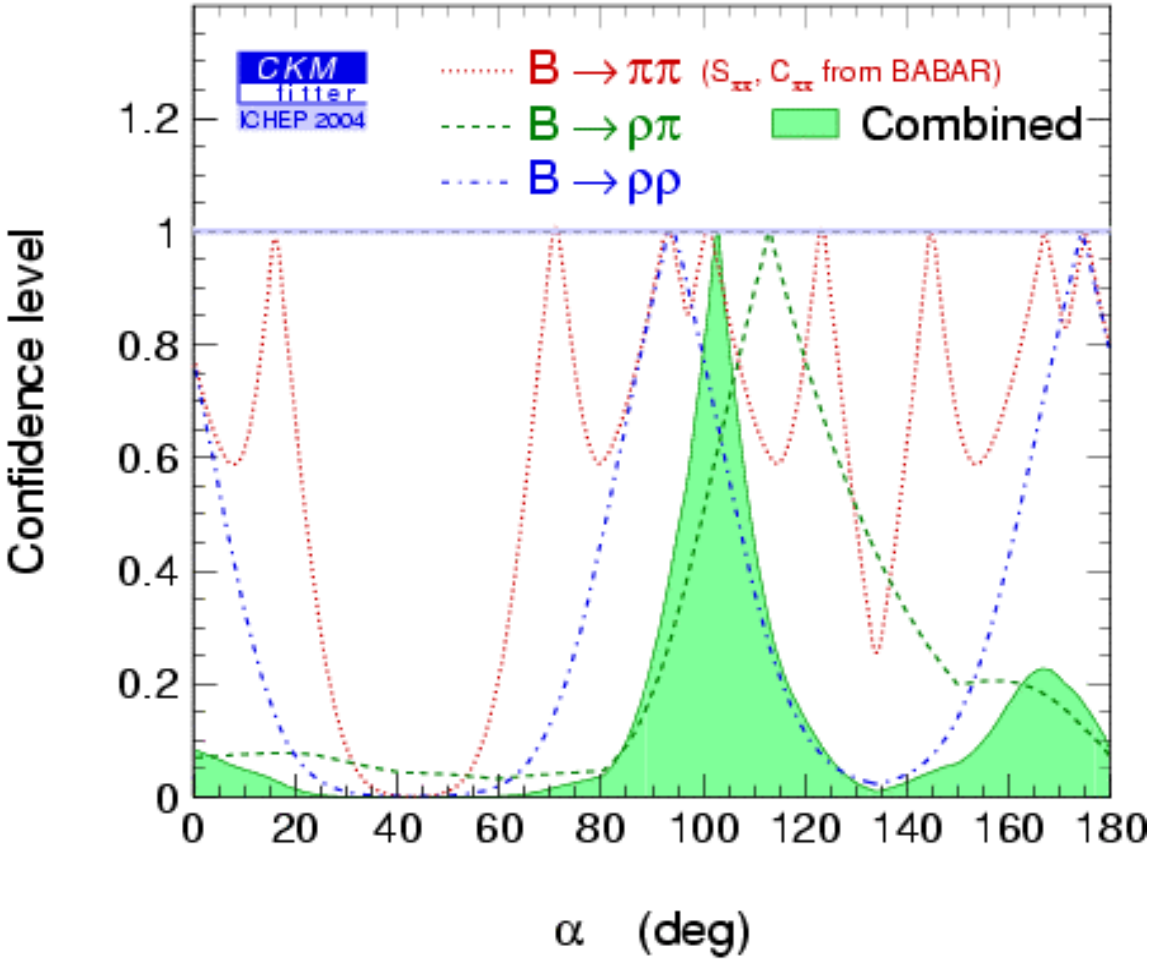


(Isospin relations reduce the number of parameters)

Strong phase between $B^0 \to \rho^+\pi^-$ and $B^0 \to \rho^-\pi^+$:

$$\delta_{+-} = \arg(A^{+-*} A^{-+}) = (-67^{+28}_{-31} \pm 7)^{o}$$

α at BaBar



Combined value from all 3 channels:

$$\alpha = (103\ ^{+10}_{-11})^{o}$$

Conclusions

- The first time-dependent Dalitz plot analysis of the decay $B^0 \to \pi^+\pi^-\pi^0$ has been carried out at BaBar.

  hep-ex/0408099, SLAC-PUB-10658

- The new CP parameters are in good agreement with earlier published results.
- Measure direct CP violation at 2.9σ.
- Obtain constraints on
  - CKM angle $\alpha = \left(113^{+27}_{-17} \pm 6\right)^\circ$
  - Relative strong phase between $\rho^+\pi^-$ and $\rho^-\pi^+$:

    $\delta_{+-} = (-67^{+28}_{-31} \pm 7)^o$

Backup Slides

Fit Results

U_{-}^{+}	Coeff. of $\|f(\rho^-)\|^2$	1.19 ± 0.12 ± 0.03
I_{-}	Coeff. of $\|f(\rho^-)\|^2 \sin(\Delta m \Delta t)$	–0.19 ± 0.11 ± 0.02
I_{+}	Coeff. of $\|f(\rho^+)\|^2 \sin(\Delta m \Delta t)$	0.06 ± 0.11 ± 0.02
U_{-}^{-}	Coeff. of $\|f(\rho^-)\|^2 \cos(\Delta m \Delta t)$	0.22 ± 0.16 ± 0.05
U_{+}^{-}	Coeff.of $\|f(\rho^+)\|^2 \cos(\Delta m \Delta t)$	0.50 ± 0.17 ± 0.05
$U_{+-}^{-,Im}$	Coeff. of $Im[f(\rho^+)\, f(\rho^-)^*] \cos(\Delta m \Delta t)$	0.25 ± 1.4 ± 0.3
$U_{+-}^{-,Re}$	Coeff. of $Re[f(\rho^+)\, f(\rho^-)^*] \cos(\Delta m \Delta t)$	2.0 ± 1.2 ± 0.2
$U_{+-}^{+,Im}$	Coeff. of $Im[f(\rho^+)\, f(\rho^-)^*]$	0.16 ± 0.70 ± 0.14
$U_{+-}^{+,Re}$	Coeff. of $Re[f(\rho^+)\, f(\rho^-)^*]$	–0.26 ± 0.65 ± 0.17
I_{+-}^{Im}	Coeff. of $Im[f(\rho^+)\, f(\rho^-)^*] \sin(\Delta m \Delta t)$	–5.2 ± 1.9 ± 0.7
I_{+-}^{Re}	Coeff. of $Re[f(\rho^+)\, f(\rho^-)^*] \sin(\Delta m \Delta t)$	–0.3 ± 2.0 ± 0.5
U_{0}^{+}	Coeff. of $\|f(\rho^0)\|^2$	0.16 ± 0.05 ± 0.05
$U_{+0}^{+,Im}$	Coeff. of $Im[f(\rho^+)\, f(\rho^0)^*]$	0.25 ± 0.35 ± 0.18
$U_{+0}^{+,Re}$	Coeff. of $Re[f(\rho^+)\, f(\rho^0)^*]$	–0.34 ± 0.39 ± 0.15
$U_{-0}^{+,Im}$	Coeff. of $Im[f(\rho^-)\, f(\rho^0)^*]$	0.34 ± 0.43 ± 0.17
$U_{-0}^{+,Re}$	Coeff. of $Re[f(\rho^-)\, f(\rho^0)^*]$	–0.98 ± 0.44 ± 0.18

Q2B terms $U^{+}_{+}=1$

Interfering terms

$\rho^0\pi^0$ related terms

Systematic Uncertainites

- Parameters that measure the interference effects:

  Systematic errors dominated by the uncertainty in the signal DP model. (ρ resonance tail description). Vary the masses and widths of ρ(770), ρ(1450), relative amounts, phase and amplitude of ρ(1700).

  (The phase and amplitude of the ρ(1450) is floated in the nominal fit.)

  The resulting errors from the signal model range from 0.6 on $\mathbf{I_{+-}^{Im}}$ to 0.08 on $\mathbf{U_{+-}^{+Im}}$

- Parameters not sensitive to interference effects:

  Systematic errors dominated by B-background and fit bias uncertainties.

- Systematic errors from fixing some of the $\rho^0\pi^0$ parameters is evaluated with Monte Carlo. Largest effect is 0.11, on $\mathbf{U_{+0}^{+Im}}$