$B^0 \to \pi^+\pi^-\pi^0$ time-dependent Dalitz analysis at BaBar

Gianluca Cavoto
INFN Roma La Sapienza

CKM workshop 06 at Nagoya

WG4 parallel session

Time-dependence

Time-dependent Dalitz analysis

$$d\Gamma(B^0 \to \pi^+\pi^-\pi^0) = \frac{1}{(2\pi)^3}\frac{|A_{3\pi}|^2}{8m^3_{B^0}}ds_+ds_-$$

Mandelstam variables

$$s_+ = (p_+ + p_0)^2$$
$$s_- = (p_- + p_0)^2$$

$$|\mathcal{A}^{\pm}_{3\pi}(\Delta t)|^2 = \left[|A_{3\pi}|^2+|\overline{A}_{3\pi}|^2 \mp \left(|A_{3\pi}|^2 - |\overline{A}_{3\pi}|^2\right)\cos(\Delta m_d \Delta t) \pm 2\mathrm{Im}\left[\overline{\mathcal{A}}_{3\pi}A^*_{3\pi}\right]\sin(\Delta m_d \Delta t)\right]$$

\+ (-)
B^0bar (B^0))
decaying

$$A_{3\pi} = f_+A^+ + f_-A^- + f_0A^0$$
$$\overline{A}_{3\pi} = f_+\overline{A}^+ + f_-\overline{A}^- + f_0\overline{A}^0$$

charge of the ρ

Isobar model: $f(s_i,s_j)$

Weak and strong phase

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

Bilinear coefficients, U and I

$$|A_{3\pi}|^2 \pm |\overline{A}_{3\pi}|^2$$

$$\sum_{\kappa\in\{+,-,0\}} |f_\kappa|^2 U_\kappa^{\pm} \;+\; 2\sum_{\kappa<\sigma\in\{+,-,0\}} \left(\mathrm{Re}\left[f_\kappa f_\sigma^*\right] U_{\kappa\sigma}^{\pm,\mathrm{Re}} - \mathrm{Im}\left[f_\kappa f_\sigma^*\right] U_{\kappa\sigma}^{\pm,\mathrm{Im}}\right)$$

$$\mathrm{Im}\left(\overline{\mathcal{A}}_{3\pi} A_{3\pi}^*\right)$$

$$\sum_{\kappa\in\{+,-,0\}} |f_\kappa|^2 I_\kappa \;+\; \sum_{\kappa<\sigma\in\{+,-,0\}} \left(\mathrm{Re}\left[f_\kappa f_\sigma^*\right] I_{\kappa\sigma}^{\mathrm{Im}} + \mathrm{Im}\left[f_\kappa f_\sigma^*\right] I_{\kappa\sigma}^{\mathrm{Re}}\right)$$

27 real parameters

- Normalized to U_+^+ determined from the fit
- Unique solution, gaussian!!
- Easy combination among exp.'s

κ,σ: charge of the ρ

$$\begin{aligned}
U_\kappa^{\pm} &= |A^\kappa|^2 \pm |\overline{A}^\kappa|^2 \,, \\
U_{\kappa\sigma}^{\pm,\mathrm{Re(Im)}} &= \mathrm{Re(Im)}\left[A^\kappa A^{\sigma *} \pm \overline{A}^\kappa \overline{A}^{\sigma *}\right] \,, \\
I_\kappa &= \mathrm{Im}\left[\overline{A}^\kappa A^{\kappa *}\right] \,, \\
I_{\kappa\sigma}^{\mathrm{Re}} &= \mathrm{Re}\left[\overline{A}^\kappa A^{\sigma *} - \overline{A}^\sigma A^{\kappa *}\right] \,, \\
I_{\kappa\sigma}^{\mathrm{Im}} &= \mathrm{Im}\left[\overline{A}^\kappa A^{\sigma *} + \overline{A}^\sigma A^{\kappa *}\right] \,.
\end{aligned}$$

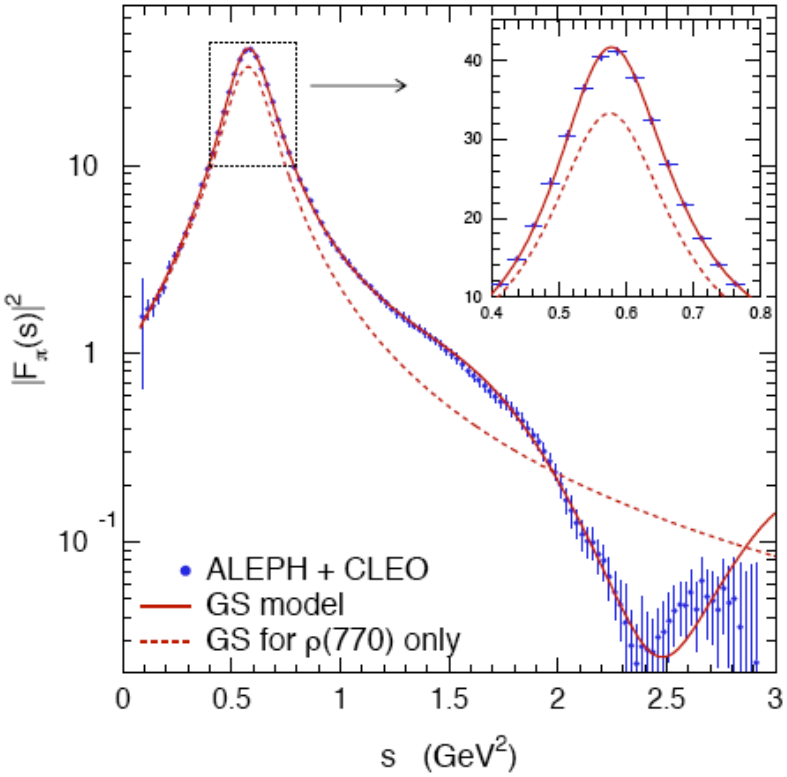
Branching fractions and direct CPV

Mixing induced CPV

Sensitive to interference pattern!

Dalitz Model

- ρ dominated
  - Rel. BW Gounaris-Sakurai
    - » ρ(770), ρ(1450),ρ(1700) mass and width from τ and e^+e^- data (Aleph & CMD-2)
    - » $\pi^+\pi^-$ scalar allowed in systematics evaluation
    - » Crosscheck relative phase on signal data

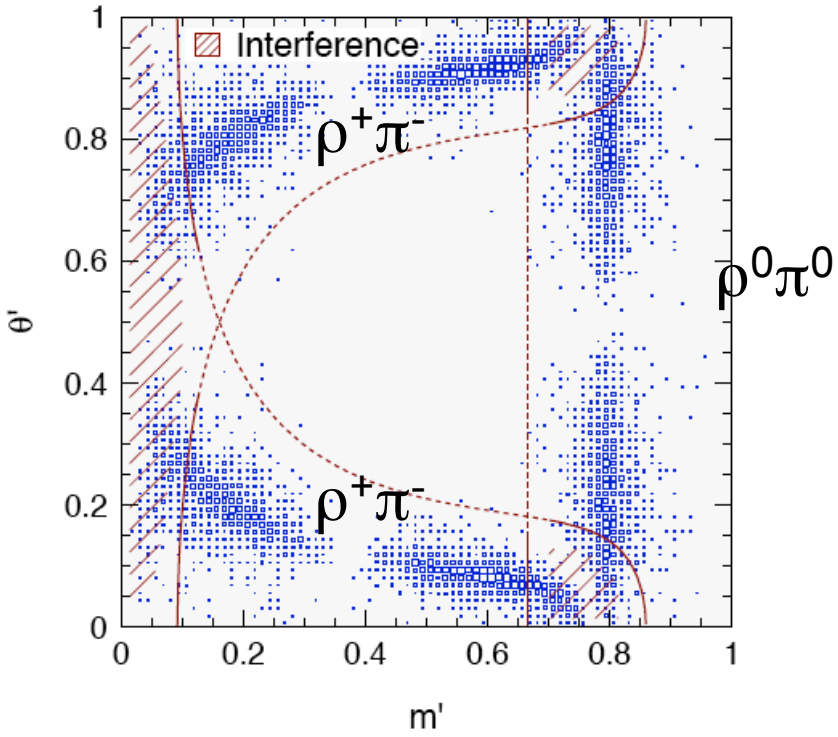


Square Dalitz Plot

$$m' \equiv \frac{1}{\pi}\arccos\left(2\frac{m_0 - m_0^{\min}}{m_0^{\max} - m_0^{\min}} - 1\right), \quad \theta' \equiv \frac{1}{\pi}\theta_0,$$

Helicity angle

Signal only MC



Most of sensitivity from interference region!

Measure terms like $\cos(2\alpha)\sin(\Delta m_d \Delta t)$

Extract strong phases directly

Dashed lines: isocontour for $\sqrt{s_{+,-,0}} = 1.5\ \mathrm{GeV}/c^2$

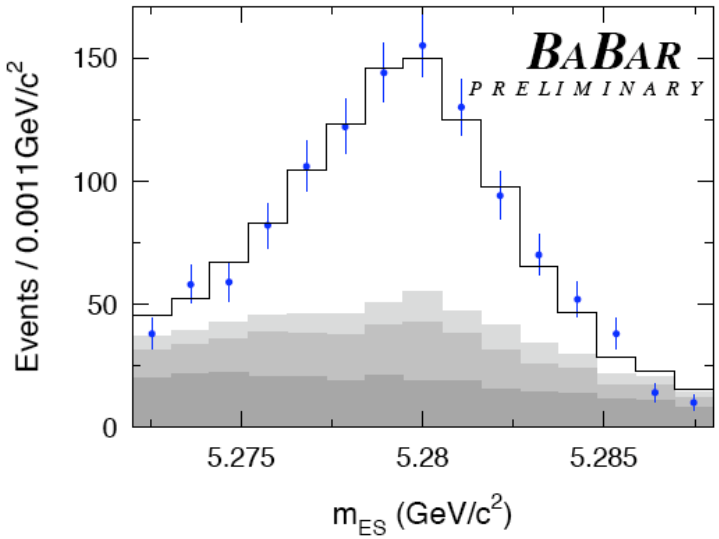
Events selection

- Kinematics and topology
  - » To suppress continuum background

c_+ = 0.080 GeV
c_- = -0.140 GeV
$\bar{c}$ = 0.045 GeV

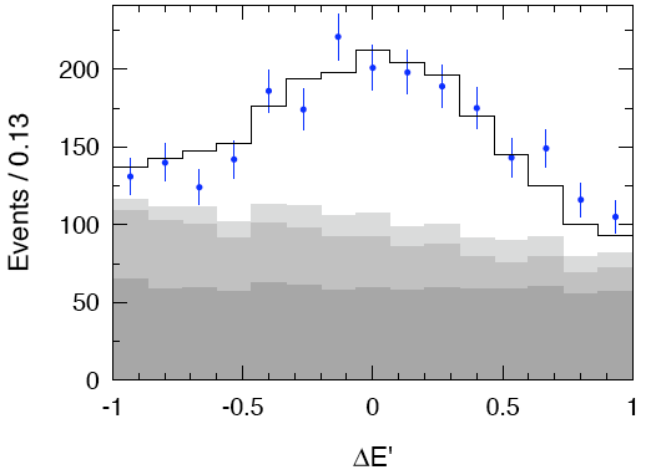
$$\Delta E_{\pm}(m_0) = c_{\pm} - (c_{\pm} \mp \bar{c})\,(m_0/m_0^{\max})^2$$

$$\Delta E' = (2\Delta E - \Delta E_+ - \Delta E_-)/(\Delta E_+ - \Delta E_-)$$



$$5.272 < m_{\rm ES} < 5.288\,{\rm GeV}/c^2$$

Remove ΔE dependence on π^0 momentum



$$-1 < \Delta E' < 1$$

$$N_{\pi^+\pi^-\pi^0} = 1847 \pm 69$$

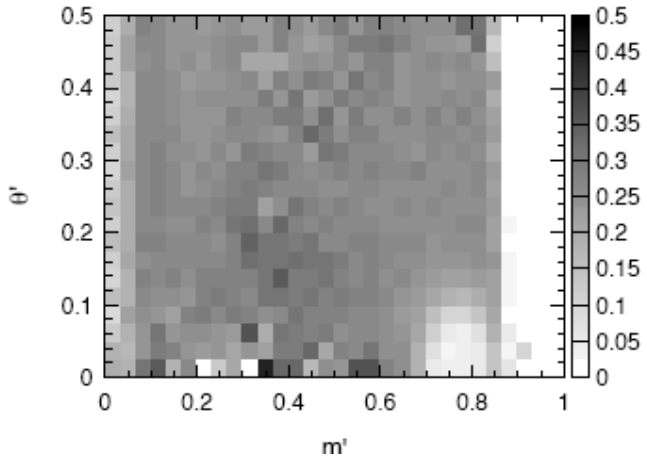
$$\varepsilon_{\rho^+\pi^-} = 24\%$$

Signal description

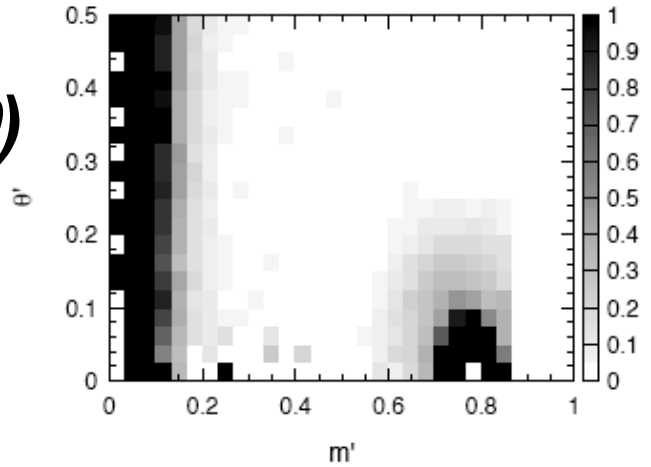
- 22% $\rho^+\pi^-$ and 13% $\rho^0\pi^0$ are misrecontructed (track or cluster from other B)
  - » Self-Cross Feed events
  - » Concentrate in corners: where interference sits…

- Detailed parametrization on Dalitz
  - efficiency $\varepsilon(m',\theta)$
  - SCF rate $f_{SCF}(m',\theta)$ and
  - SCF resolution function on Dalitz
- Δt resolution

$\varepsilon(m',\theta)$

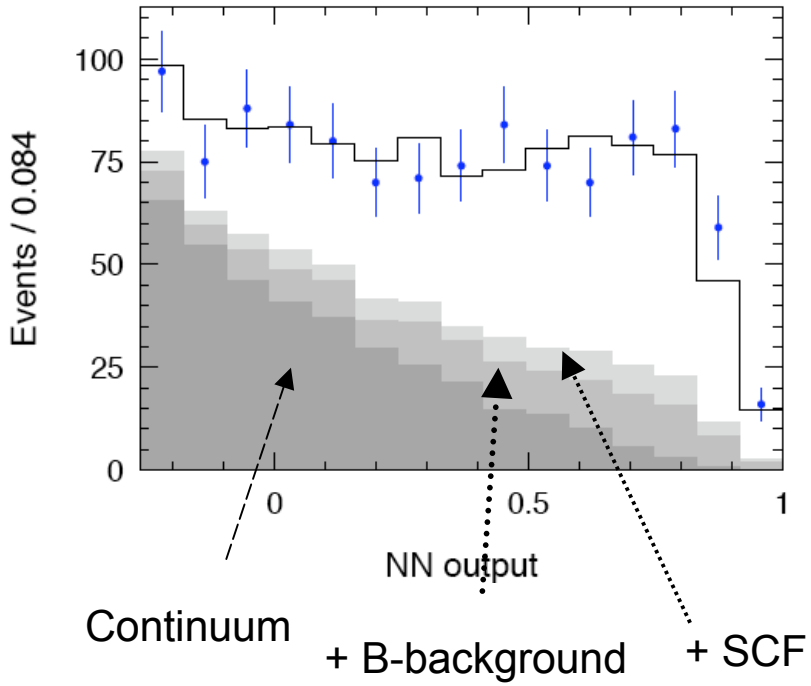


$f_{SCF}(m',\theta)$



Backgrounds

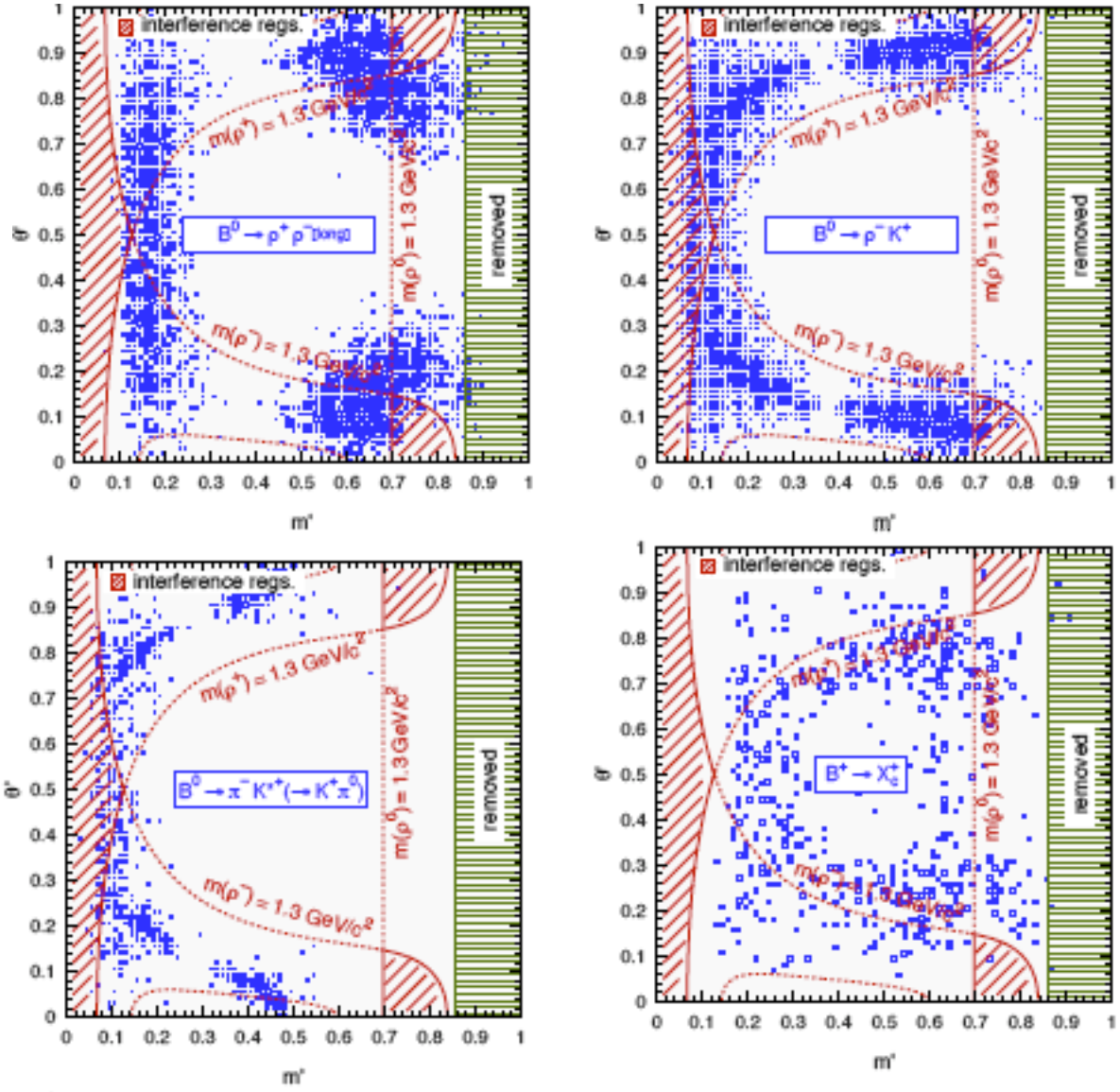
- Mainly continuum
  - » Neural Network with several inputs
- Neutral and charged B
  - » Hundred exclusive final states analyzed
  - » 18 categories
- 6 B^0 charmless decays
- 8 B^+ charmless decays
- 2 b→c decays
  - » $(\rho\pi)^+, \rho\rho, \rho K, K\pi\pi, a_1\pi, D\pi, \ldots$
- Flavor- Dalitz correlation accounted for



Maximum likelihood fit

B-background Dalitz distributions

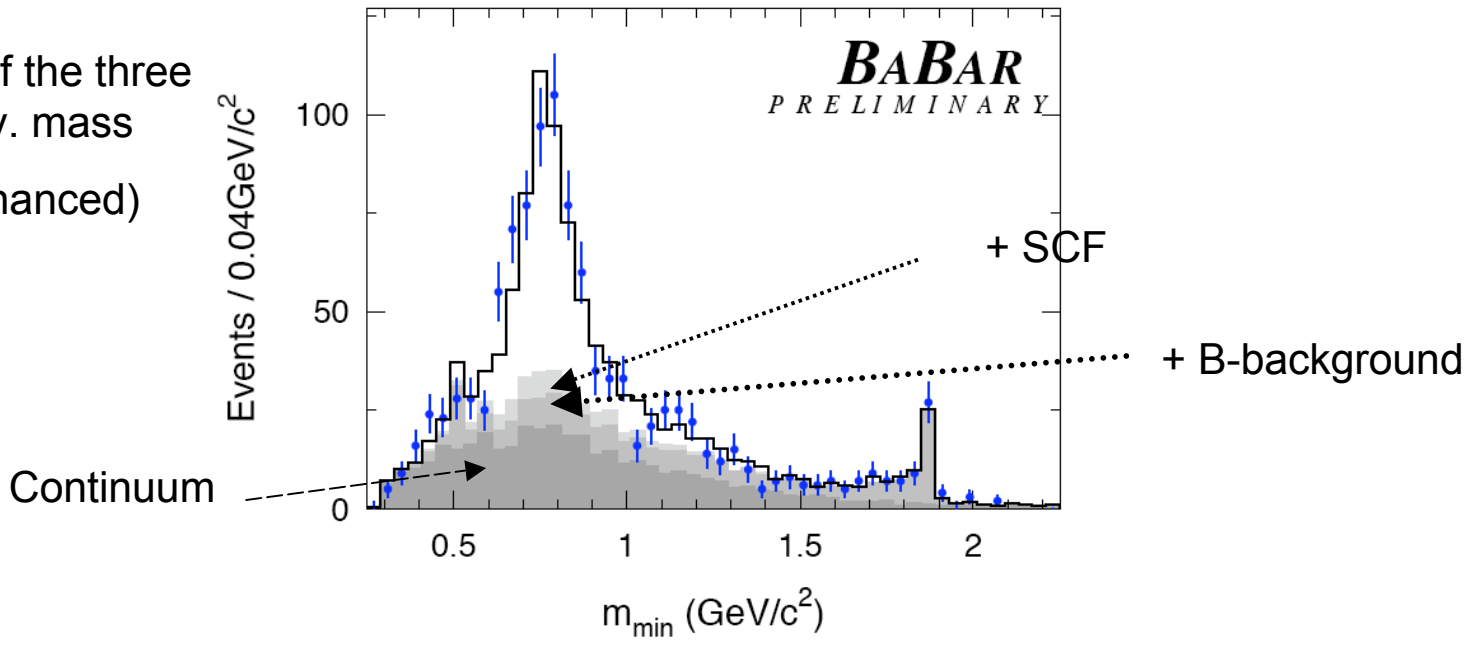
MC simulation

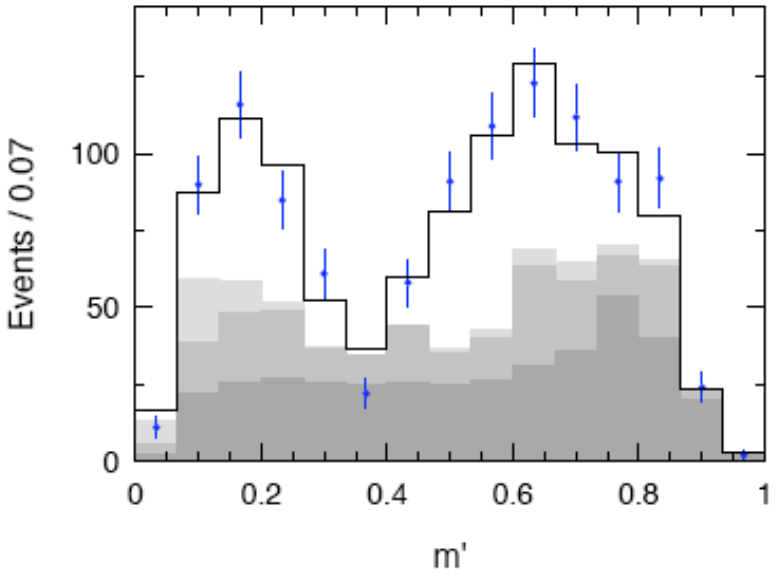


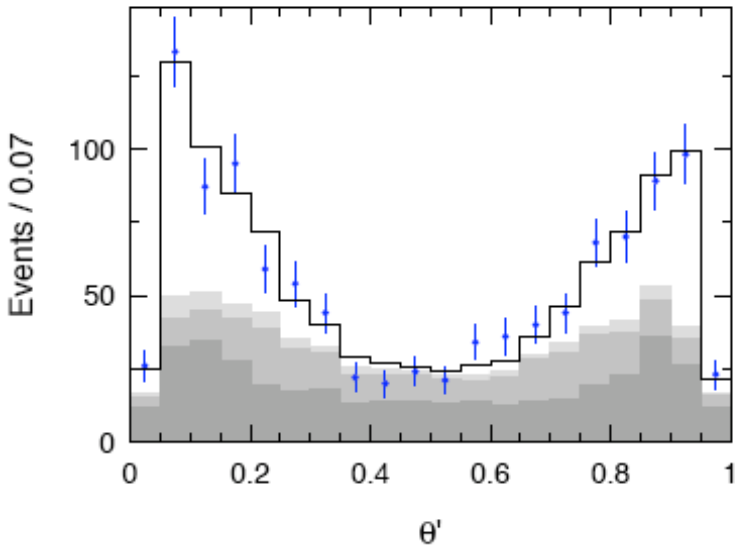
Dalitz distributions

Smallest of the three di-pion inv. mass

(signal enhanced)







Fit results

Parameter		Description	Result
U_0^+	"Q-2body"	Coefficient of $\|f_0\|^2$	$0.237 \pm 0.053 \pm 0.043$
U_-^+	"Q-2body"	Coefficient of $\|f_-\|^2$	$1.33 \pm 0.11 \pm 0.04$
U_0^-	"Q-2body"	Coefficient of $\|f_0\|^2 \cos(\Delta m_d \Delta t)$	$-0.055 \pm 0.098 \pm 0.13$
U_-^-	"Q-2body"	Coefficient of $\|f_-\|^2 \cos(\Delta m_d \Delta t)$	$-0.30 \pm 0.15 \pm 0.03$
U_+^-	"Q-2body"	Coefficient of $\|f_+\|^2 \cos(\Delta m_d \Delta t)$	$0.53 \pm 0.15 \pm 0.04$
I_0	"Q-2body"	Coefficient of $\|f_0\|^2 \sin(\Delta m_d \Delta t)$	$-0.028 \pm 0.058 \pm 0.02$
I_-	"Q-2body"	Coefficient of $\|f_-\|^2 \sin(\Delta m_d \Delta t)$	$-0.03 \pm 0.10 \pm 0.03$
I_+	"Q-2body"	Coefficient of $\|f_+\|^2 \sin(\Delta m_d \Delta t)$	$0.039 \pm 0.097 \pm 0.02$
$U_{+-}^{+,\mathrm{Im}}$	"interference"	Coefficient of $\mathrm{Im}[f_+ f_-^*]$	$0.62 \pm 0.54 \pm 0.72$
$U_{+-}^{+,\mathrm{Re}}$	"interference"	Coefficient of $\mathrm{Re}[f_+ f_-^*]$	$0.38 \pm 0.55 \pm 0.28$
$U_{+-}^{-,\mathrm{Im}}$	"interference"	Coefficient of $\mathrm{Im}[f_+ f_-^*] \cos(\Delta m_d \Delta t)$	$0.13 \pm 0.94 \pm 0.17$
$U_{+-}^{-,\mathrm{Re}}$	"interference"	Coefficient of $\mathrm{Re}[f_+ f_-^*] \cos(\Delta m_d \Delta t)$	$2.14 \pm 0.91 \pm 0.33$
I_{+-}^{Im}	"interference"	Coefficient of $\mathrm{Im}[f_+ f_-^*] \sin(\Delta m_d \Delta t)$	$-1.9 \pm 1.1 \pm 0.1$
I_{+-}^{Re}	"interference"	Coefficient of $\mathrm{Re}[f_+ f_-^*] \sin(\Delta m_d \Delta t)$	$-0.1 \pm 1.9 \pm 0.3$
$U_{+0}^{+,\mathrm{Im}}$	"interference"	Coefficient of $\mathrm{Im}[f_+ f_0^*]$	$0.03 \pm 0.42 \pm 0.12$
$U_{+0}^{+,\mathrm{Re}}$	"interference"	Coefficient of $\mathrm{Re}[f_+ f_0^*]$	$-0.75 \pm 0.40 \pm 0.15$
$U_{+0}^{-,\mathrm{Im}}$	"interference"	Coefficient of $\mathrm{Im}[f_+ f_0^*] \cos(\Delta m_d \Delta t)$	$-0.93 \pm 0.68 \pm 0.08$
$U_{+0}^{-,\mathrm{Re}}$	"interference"	Coefficient of $\mathrm{Re}[f_+ f_0^*] \cos(\Delta m_d \Delta t)$	$-0.47 \pm 0.80 \pm 0.3$
I_{+0}^{Im}	"interference"	Coefficient of $\mathrm{Im}[f_+ f_0^*] \sin(\Delta m_d \Delta t)$	$-0.1 \pm 1.1 \pm 0.3$
I_{+0}^{Re}	"interference"	Coefficient of $\mathrm{Re}[f_+ f_0^*] \sin(\Delta m_d \Delta t)$	$0.2 \pm 1.1 \pm 0.4$
$U_{-0}^{+,\mathrm{Im}}$	"interference"	Coefficient of $\mathrm{Im}[f_- f_0^*]$	$-0.03 \pm 0.40 \pm 0.23$
$U_{-0}^{+,\mathrm{Re}}$	"interference"	Coefficient of $\mathrm{Re}[f_- f_0^*]$	$-0.52 \pm 0.32 \pm 0.08$
$U_{-0}^{-,\mathrm{Im}}$	"interference"	Coefficient of $\mathrm{Im}[f_- f_0^*] \cos(\Delta m_d \Delta t)$	$0.24 \pm 0.61 \pm 0.2$
$U_{-0}^{-,\mathrm{Re}}$	"interference"	Coefficient of $\mathrm{Re}[f_- f_0^*] \cos(\Delta m_d \Delta t)$	$-0.42 \pm 0.73 \pm 0.28$
I_{-0}^{Im}	"interference"	Coefficient of $\mathrm{Im}[f_- f_0^*] \sin(\Delta m_d \Delta t)$	$0.7 \pm 1.0 \pm 0.3$
I_{-0}^{Re}	"interference"	Coefficient of $\mathrm{Re}[f_- f_0^*] \sin(\Delta m_d \Delta t)$	$0.92 \pm 0.91 \pm 0.4$

"Q-2body"

"interference"

U_+^+ average BF($\rho^+\pi^-$)

U_+^+ is fixed to 1

Excess of $\rho^0\pi^0$

U_k^- Direct CPV $\rho^+\pi^-$

Mixing induced CPV

Statistical and systematic errors

Full covariance Matrix available

(both statistical and systematics)

Systematics studies

- Dalitz plot model:
  - toyMC: Generate with alternative models:
    - Nonresonant (uniform) component
    - Scalar $\pi^+\pi^-$ component
      - » [low mass scalar, $f_0(980)$,$f_2(1270)$]
- ρ lineshape
    - Check relative amplitude assumption
  - Vary mass and width
- B-background
  - Assumption on CP contents
- And more
  - Fit bias (negligible)
  - Parameters other PDF (background Dalitz, f_{SCF})

Relevant for interference parameters

Relevant for Q-2b parameters

Quasi-2body parameters

$$\mathcal{A}(\rho^{\pm}\pi^{\mp}) \sim (S \pm \Delta S)\sin\Delta m\Delta t - (C \pm \Delta C)\cos\Delta m\Delta t$$

asymmetry

$$C^{+} = \frac{U_{+}^{-}}{U_{+}^{+}}\,, \quad C^{-} = \frac{U_{-}^{-}}{U_{-}^{+}}\,, \quad S^{+} = \frac{2\,I_{+}}{U_{+}^{+}}\,, \quad S^{-} = \frac{2\,I_{-}}{U_{-}^{+}}\,, \quad \mathcal{A}_{\rho\pi} = \frac{U_{+}^{+} - U_{-}^{+}}{U_{+}^{+} + U_{-}^{+}}\,,$$

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

» They include interference effects

» Averaging S and C

$$\begin{aligned}
\mathcal{A}_{\rho\pi} &= -0.142 \pm 0.041 \pm 0.015\,, \\
C &= 0.154 \pm 0.090 \pm 0.037\,, \\
S &= 0.01 \pm 0.12 \pm 0.028\,,
\end{aligned}$$

$$C = (C^{+} + C^{-})/2,\ \Delta C = (C^{+} - C^{-})/2,$$
$$S = (S^{+} + S^{-})/2,\ \text{and}\ \Delta S = (S^{+} - S^{-})/2$$

$$\begin{aligned}
\Delta C &= 0.377 \pm 0.091 \pm 0.021\,, \\
\Delta S &= 0.06 \pm 0.13 \pm 0.029\,.
\end{aligned}$$

Systematics dominated by

B-background CP content

Q-2b interpretation

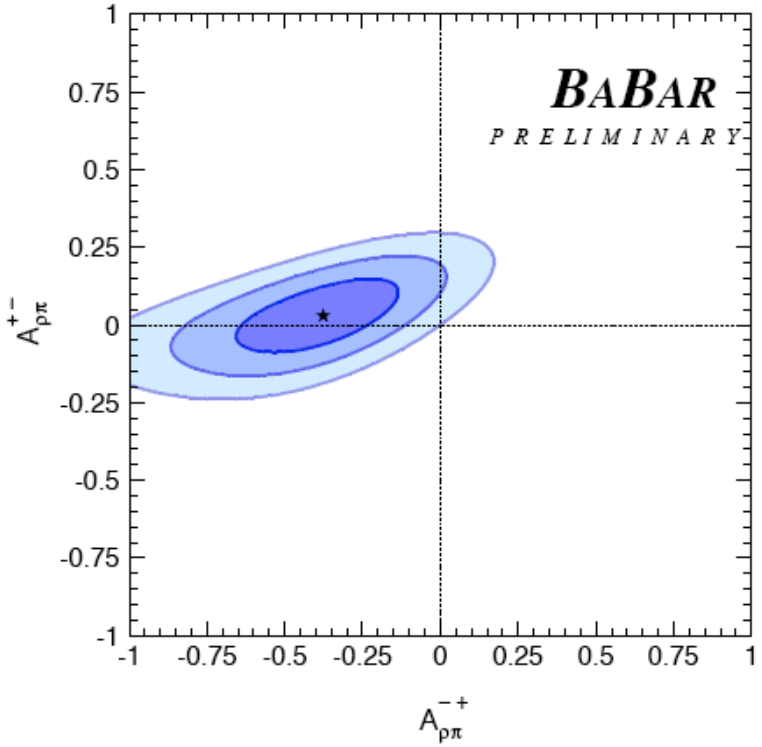
Compare B^0/ρ^+ and $\overline{B}^0/\rho^-$ more intuitively:

$$\kappa^{+-} = (q/p)(\overline{A}^-/A^+)$$

$$\mathcal{A}_{\rho\pi}^{+-} = \frac{|\kappa^{+-}|^2 - 1}{|\kappa^{+-}|^2 + 1}$$

$$\mathcal{A}_{\rho\pi}^{+-} = 0.03 \pm 0.07 \pm 0.03$$

$$\mathcal{A}_{\rho\pi}^{-+} = -0.38\,^{+0.15}_{-0.16} \pm 0.07$$



3σ effect

(syst. included)

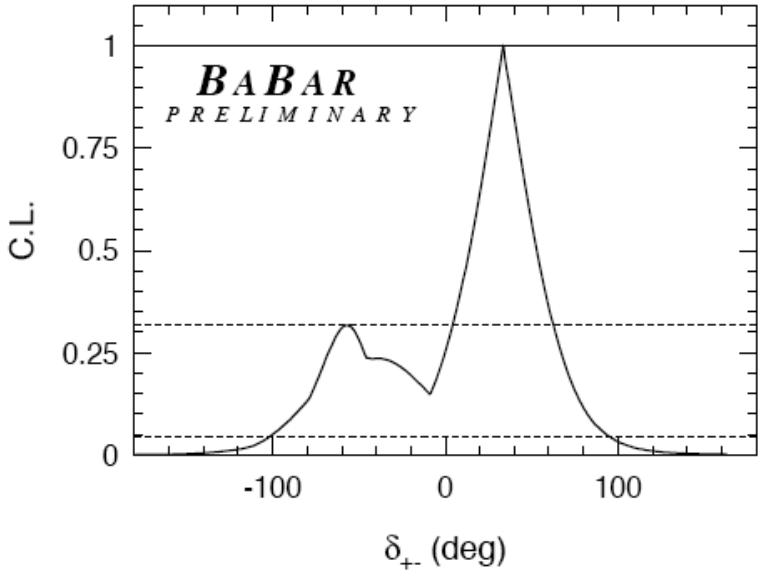
Finally, α and δ

Relative phase $B^0 \to \rho^-\pi^+$ and $B^0 \to \rho^+\pi^-$

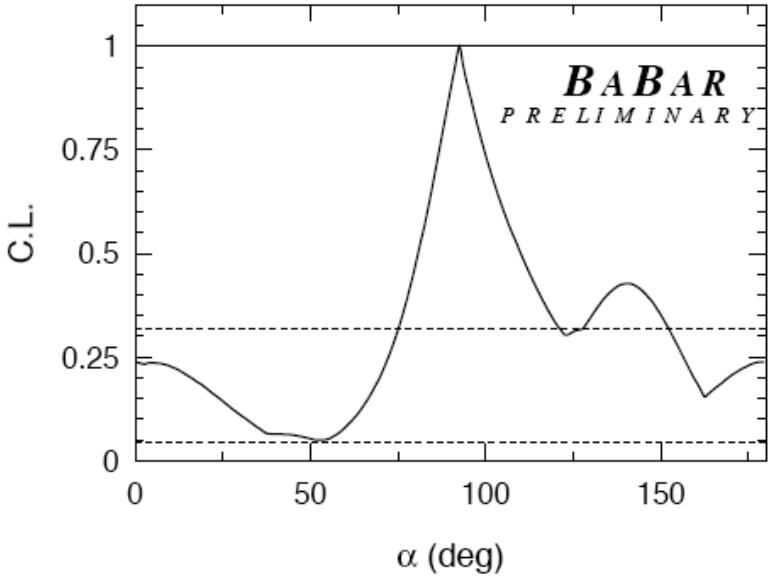
$$\delta_{+-} = \arg\left(A^{+*}A^{-}\right)$$

$$A^{\kappa} = T^{\kappa}e^{-i\alpha} + P^{\kappa}$$
$$\overline{A}^{\kappa} = T^{\overline{\kappa}}e^{+i\alpha} + P^{\overline{\kappa}}$$

Strong isospin: $\dot{P}^0 = -(P^+ + P^-)/2$



$$\delta_{+-} = (34 \pm 29)^{\circ}$$



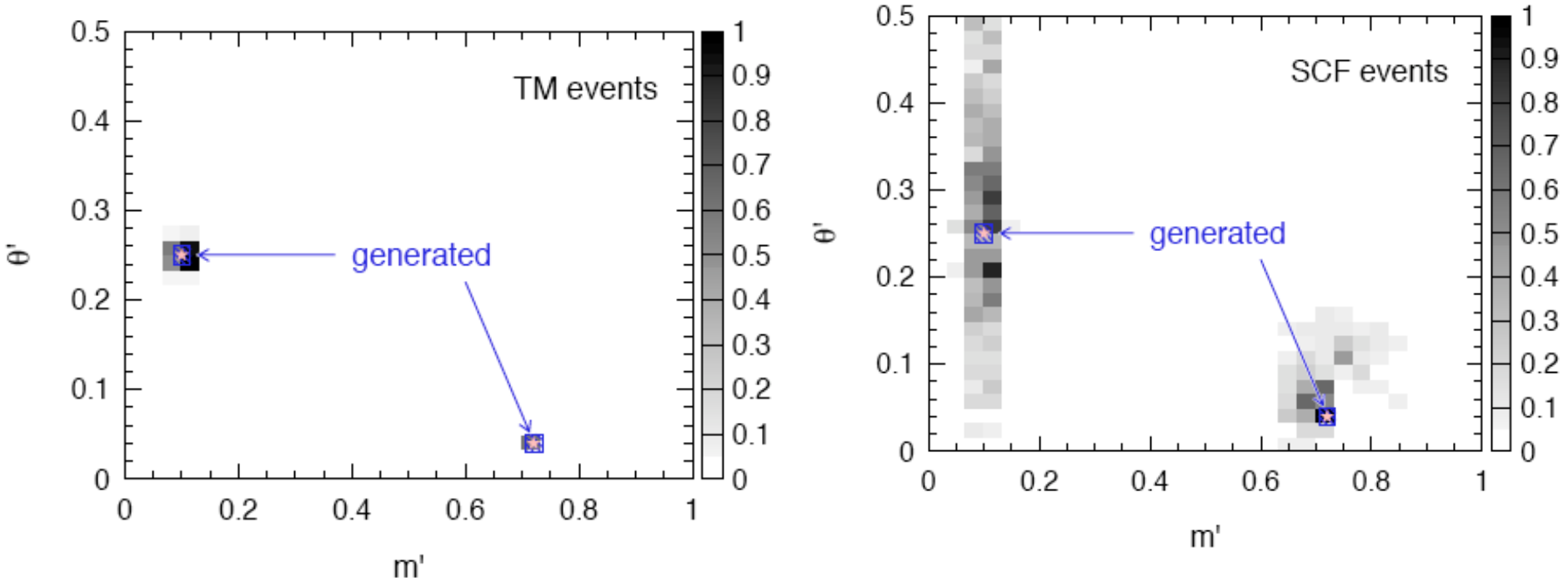
No constraint on α at 2σ

Summary

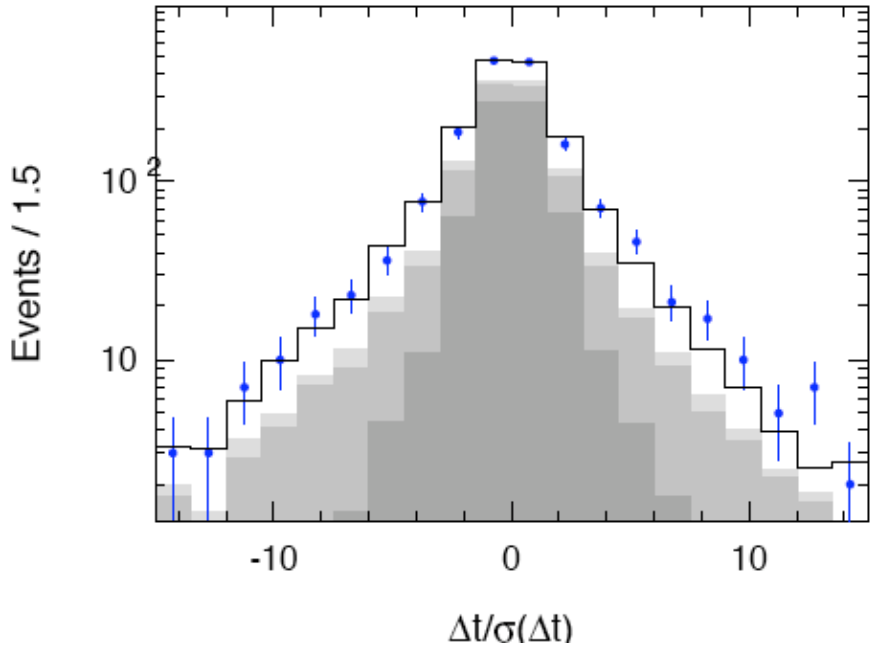
- "Pentagonal" isospin analysis not feasible in $\rho\pi$
- Full Dalitz time dependent analysis
  - Model ρ meson, extract strong and weak phases
  - Interference effects correctly modeled!!! (no Q-2body approximation)
- Current sensitivity limited by statistics
  - Dalitz model is hard systematics eventually
- Ignoring mirror solution
  - α in [75°, 152°] interval at 68% C.L.
- Excess of $\rho^0\pi^0$ events
  - Correlated with $\pi^+\pi^-$ scalar
- Only B-factory can do $B\to\rho\pi$?
  - SCF under control.

Back up

Resolution effects



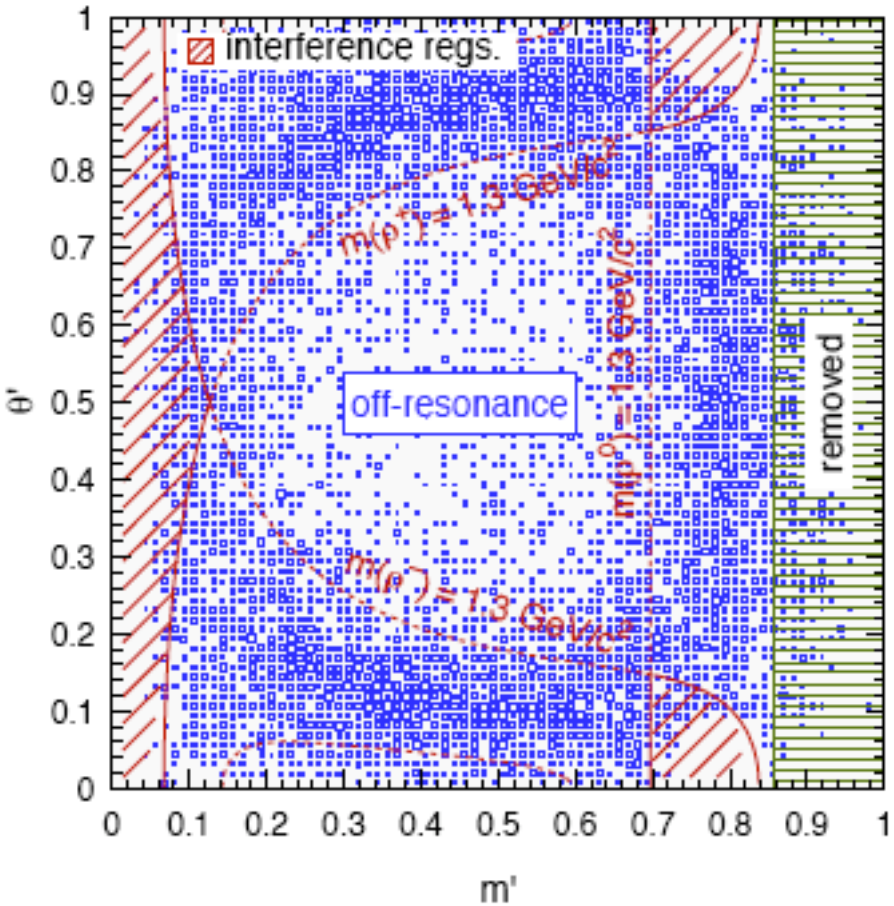
Δt distribution



Summary of B background

Class	Mode	BR $[10^{-6}]$	Expected number of events
0	$B^+ \to \rho^+\rho^0_{[\mathrm{long}]}$	19.1 ± 3.5	52 ± 10
0	$B^+ \to a_1^+(\to (\rho\pi)^+)\pi^0$	20.0 ± 15.0	32 ± 24
0	$B^+ \to a_1^0(\to \rho^{+-}\pi^{-+})\pi^+$	20.0 ± 15.0	19 ± 14
1	$B^+ \to \pi^+\rho^0$	8.7 ± 1.0	73 ± 8
1	$B^+ \to \rho^0 K^+$	4.3 ± 0.6	6 ± 1
2	$B^+ \to \pi^+ K^0_S(\to \pi^+\pi^-)$	8.3 ± 0.4	10 ± 1
3	$B^+ \to \pi^0\rho^+$	10.8 ± 1.4	63 ± 8
3	$B^+ \to \pi^+ K^0_S(\to \pi^0\pi^0)$	3.7 ± 0.2	15 ± 2
4	$B^+ \to \pi^+\pi^0$	5.5 ± 0.6	14 ± 2
4	$B^+ \to K^+\pi^0$	12.1 ± 0.8	8 ± 1
5	$B^+ \to (K^{(**)}(1430)\pi)^+ \to (K^+\pi\pi)^+$	29.0 ± 5.4	38 ± 5
6	$B^0 \to \pi^- K^{*+}(\to K^0_S\pi^+)$	3.3 ± 0.4	2 ± 1
7	$B^0 \to \rho^+\rho^-_{[\mathrm{long}]}$	25.2 ± 3.7	67 ± 10
7	$B^0 \to (a_1\pi)^0$	39.7 ± 3.7	39 ± 4
8	$B^0 \to K^+\pi^-$	18.9 ± 0.7	12 ± 0
9	$B^0 \to \pi^- K^{*+}(\to K^+\pi^0)$	3.3 ± 0.4	20 ± 2
9	$B^0 \to K^{(**)}(1430)\pi \to K\pi\pi^0$	11.2 ± 2.2	212 ± 34
10	$B^0 \to \gamma K^{*0}(892, 1430)(\to (K^+\pi^-)^0)$	27.4 ± 1.5	14 ± 1
10	$B^0 \to \pi^0 K^{*0}(\to K^+\pi^-)$	1.3 ± 0.5	9 ± 4
10	$B^0 \to \eta'(\to \rho^0\gamma)\pi^0$	0.4 ± 0.2	3 ± 2
11	$B^0 \to \rho^- K^+$	9.9 ± 1.6	103 ± 17
12	$B^0 \to K^+\pi^-\pi^0_{[\mathrm{nonres}]}$	4.6 ± 4.6	38 ± 38
13	$B^0 \to \pi^0 K^0_S(\to \pi^+\pi^-)$	5.8 ± 0.5	50 ± 4
14	$B^0 \to D^-(\to \pi^-\pi^0)\pi^+$	7.5 ± 2.3	599 ± 184
15	$B^0 \to \overline{D}^0(\to K^+\pi^-)\pi^0$	11.0 ± 3.2	100 ± 29
16	$B^0 \to \overline{D}^0(\to \pi^+\pi^-)\pi^0$	0.4 ± 0.1	35 ± 9
17	$B^0 \to J/\psi(\to e^+e^-, \mu^+\mu^-)\pi^0$	2.6 ± 0.5	77 ± 15
18	$B^0 \to \{\text{neutral generic } b \to c \text{ decays}\}$	–	173 ± 15
19	$B^+ \to \{\text{charged generic } b \to c \text{ decays}\}$	–	396 ± 20

Off-resonance Dalitz distr.



Q-2b parameters cov. matrix

	$\mathcal{A}_{\rho\pi}$	C	ΔC	S	ΔS
$\mathcal{A}_{\rho\pi}$	1.93				
C	−0.71	9.68			
ΔC	−0.55	2.63	8.93		
S	−0.03	−0.71	−0.13	15.3	
ΔS	−0.03	−0.57	−0.07	3.93	17.08

Multiplied by 1000