CKM2010

Determination of α/ϕ_2 from $B \to a_1\pi$ and $B \to K_{1A}\pi$ decays

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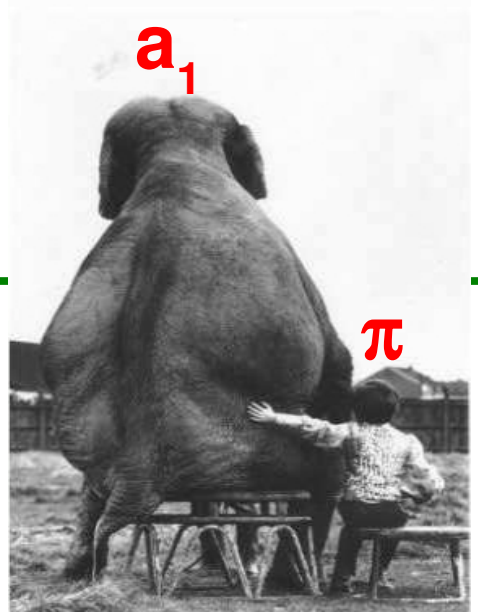
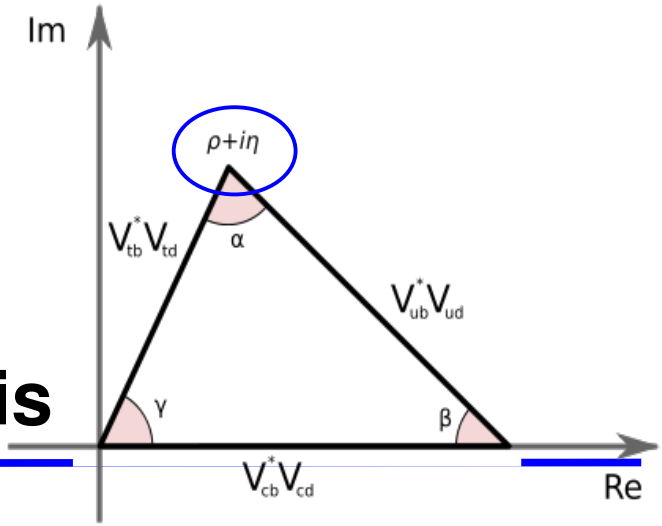
[Representing the BaBar Collaboration]

Outline

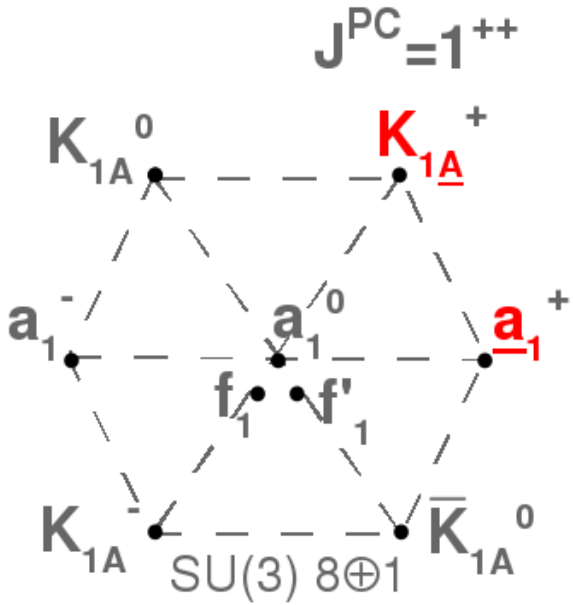


- $B^0 \to a_1^{\pm}\pi^{\mp}$ BF



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

- $B^0 \to a_1^{-}K^{+}$ and $B^{+} \to a_1^{+}K^{0}$
  $B \to K_{1A}\pi$ BF



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

PRL 97, 051802 (2006)

- $a_1(1260)^{\pm} \to (\rho\pi)^{\pm}$ dominant, $J^P=1^+$
  - $\pi^+\pi^-\pi^{\pm}$ ~ 50% - possible $\sigma\pi \Rightarrow$ 2.5% systematic

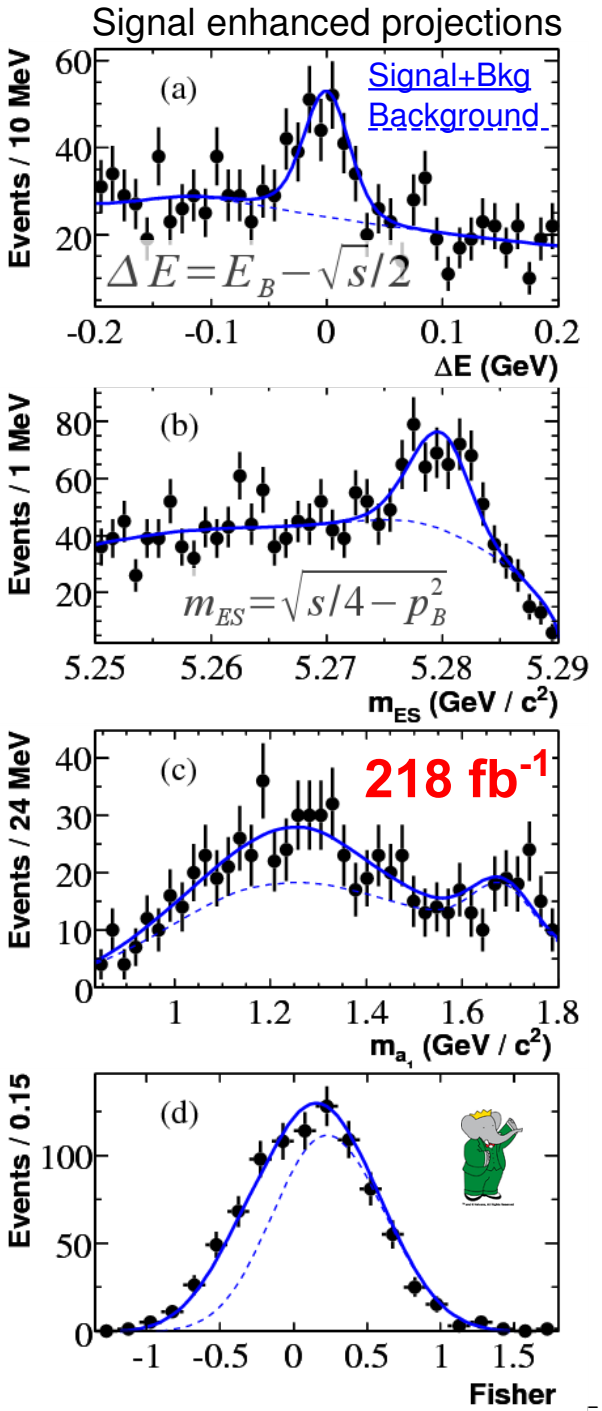
- BaBar: ML fit (ΔE, m_{ES}, Fisher, m_{a_1}, $\cos\theta_H$)
  - $N_{sg} = 421 \pm 48 \Rightarrow$ BF = $(33.2 \pm 3.8 \pm 3.0) \times 10^{-6}$

- $m_{a1(1260)}$ and $\Gamma_{a1(1260)}$ poorly known (model uncertainties) $\Rightarrow$ extract from the fit to the data
  - $m_{a1(1260)} = [1229 \pm 21(\text{stat})]$ MeV *
  - $\Gamma_{a1(1260)} = [393 \pm 62\ (\text{stat})]$ MeV *

  * within ranges allowed by PDG

- Belle BF (535M $B\bar{B}$) is consistent with BaBar
  - 3D fit (ΔE, m_{ES}, $\cos\theta_H$) + 1D fit to m_{a_1}
  - BF = $(29.8 \pm 3.2 \pm 4.6) \times 10^{-6}$ [arXiv:0706.3279]

Signal enhanced projections



α measurement in non CP-eigenstates

- Time-dependence of $B^0(\to \bar{B}^0) \to a_1^{\pm}\pi^{\mp}$ [Aleksan et al.: NPB 361, 141 (1991)]

$$F^{a_1^{\pm}\pi^{\mp}}_{Q_{tag}}(\Delta t) = (1 \pm \mathcal{A}_{CP})\frac{e^{-|\Delta t|/\tau}}{8\tau}\left\{1 + Q_{tag} \times \left[(S \pm \Delta S)\sin(\Delta m_d \Delta t) - (C \pm \Delta C)\cos(\Delta m_d \Delta t)\right]\right\}$$

$S_\pm$ $C_\pm$

- Penguin pollution and strong phase between tree amplitudes

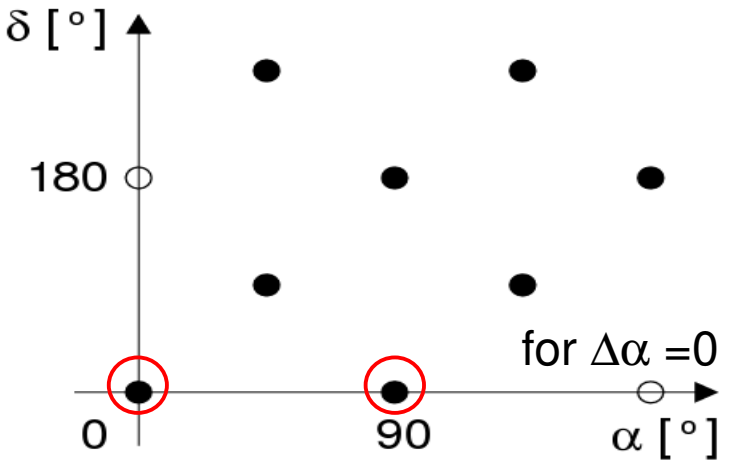
$$S_\pm = \sqrt{1 - C_\pm^2} \times \sin(2\alpha + 2\Delta\alpha \pm \hat{\delta})$$

$2\alpha_{eff}$ $2\alpha_{eff}^{\pm}$

  - get $\alpha_{\rm eff} \equiv \alpha + \Delta\alpha$ by averaging out δ

- 8 trigonometric ambiguities
  - Reduced to 2 (factorization $\Rightarrow |\delta| \ll 90°$)
    - Negligible rescattering

[Gronau and Zupan: PRD 70, 074031 (2004); PRD 73, 057502 (2006)]



$B^0 \to a_1^{\pm}\pi^{\mp}$ time-dependent analysis

PRL 98, 181803 (2007)

- Fit Δt model to data ($N_{tagged} = 461 \pm 46$)

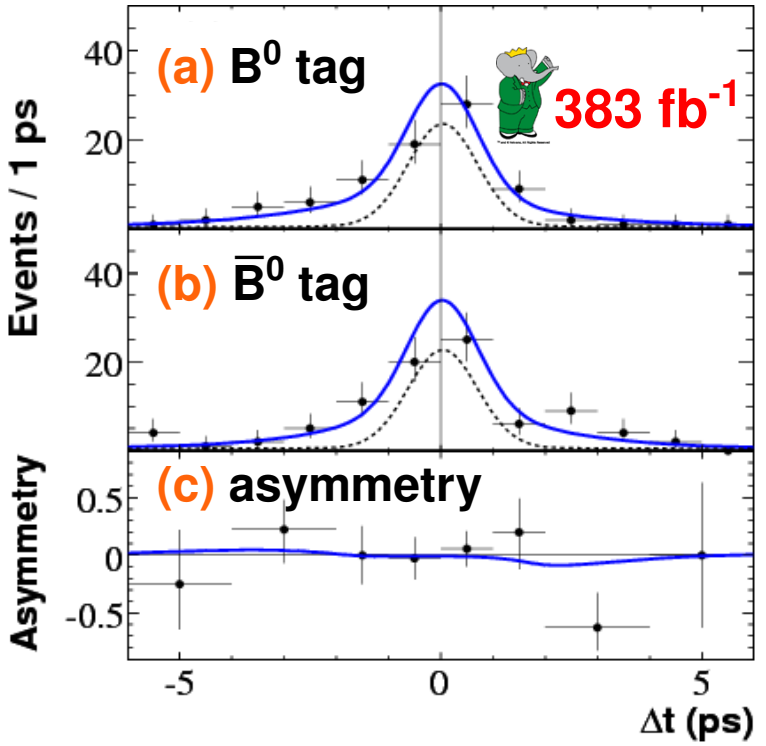
  $S = 0.37 \pm 0.21 \pm 0.07$

  $\Delta S = -0.14 \pm 0.21 \pm 0.06$

  $C = -0.10 \pm 0.15 \pm 0.09$

  $\Delta C = 0.26 \pm 0.15 \pm 0.07$

  $A_{CP} = -0.07 \pm 0.07 \pm 0.02$



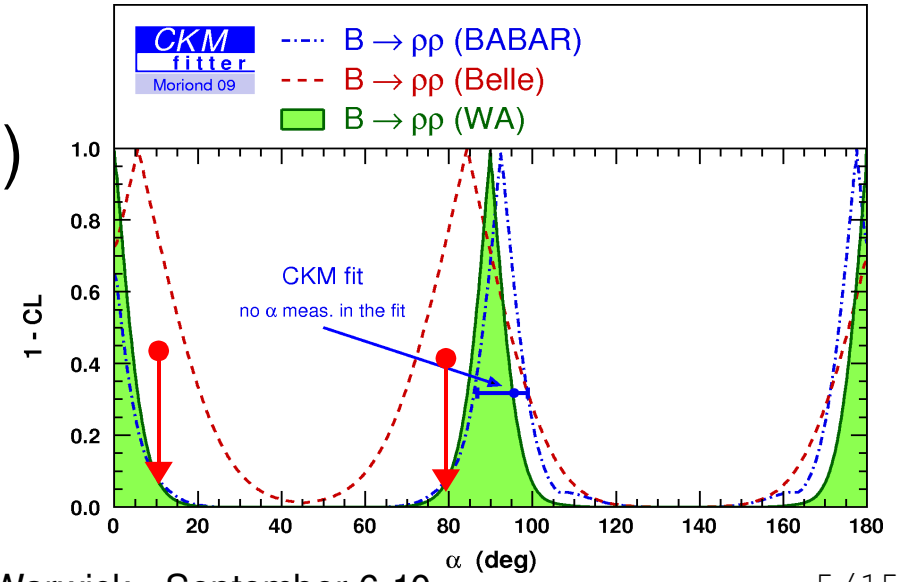
- $m_{a1(1260)} = 1229$ MeV

  $\Gamma_{a1(1260)} = 393$ MeV [PRL 97, 051802 (2006)]

- Correlations are weak (at O(%) level)

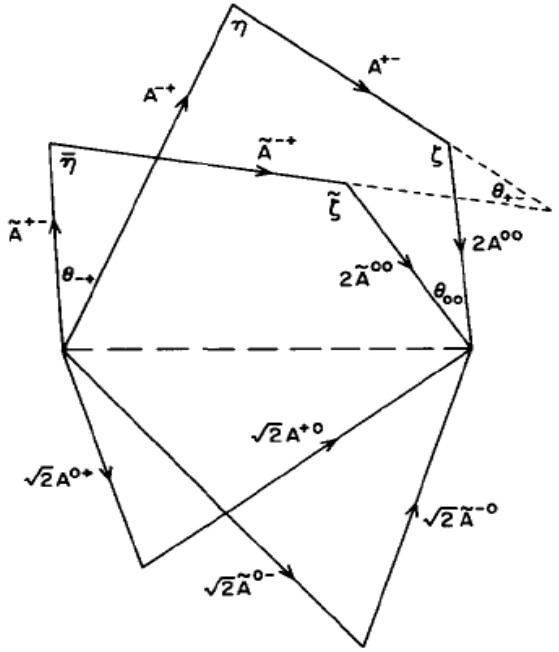
$\alpha_{eff} = (79 \pm 7)^o$

$\{11, 41, 49, 79, 101, 131, 139, 169\}^o$



Constraining penguin contributions

- Use symmetries to constrain $\Delta\alpha \equiv \alpha_{\rm eff} - \alpha$



[Lipkin et al.: PRD 44, 1454 (1991);
Gronau: PLB 265, 389 (1991)]

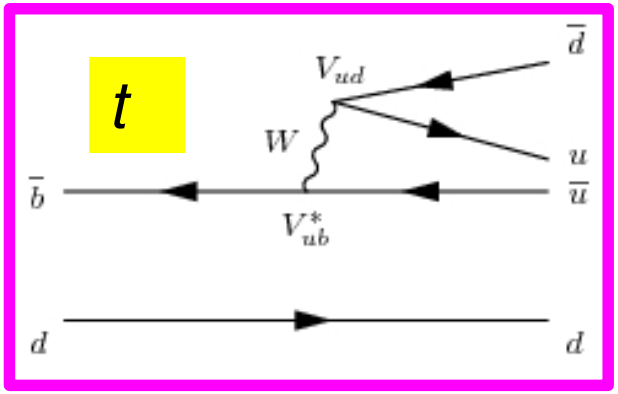
SU(2) not a viable option

→ use approximate flavor SU(3)

[Gronau and Zupan: PRD 70, 074031 (2004);
PRD 73, 057502 (2006)]

- ΔS=0 decays: $A(B^0 \to a_1^+\pi^-) = e^{i\gamma}t_+ + p_+$

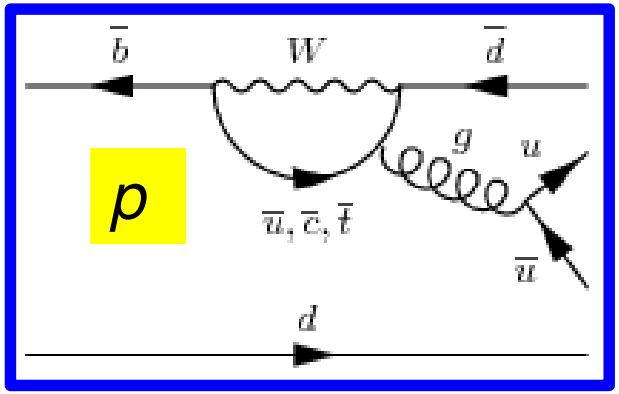
$$A(B^0 \to a_1^-\pi^+) = e^{i\gamma}t_- + p_-$$



- ΔS=1 decays: $A(B^+ \to K_{1A}^0\pi^+) = -(\bar{\lambda})^{-1}\dfrac{f_{K_{1A}}}{f_{a_1}}p_+$

$$A(B^+ \to a_1^+K^0) = -(\bar{\lambda})^{-1}\frac{f_K}{f_\pi}p_-$$

$$\bar{\lambda} = |V_{cd}|/|V_{cs}| \sim 0.23$$



Constraining penguin contributions

- Derive bounds on $\Delta\alpha$ from ratios of CP-averaged rates of $\Delta S=1$ and $\Delta S=0$ B decays:

$$\cos 2(\alpha^{\pm}_{\rm eff} - \alpha) \geq (1 - 2R^0_{\pm})/\sqrt{1-(\mathcal{A}^{\pm}_{CP})^2}$$

$$\cos 2(\alpha^{\pm}_{\rm eff} - \alpha) \geq (1 - 2R^+_{\pm})/\sqrt{1-(\mathcal{A}^{\pm}_{CP})^2}$$

  - Rates for $\Delta S=1$ decays to $K_{1A}\pi$ and $a_1 K$ are *both* necessary

$$R^0_+ \equiv \frac{\bar{\lambda}^2 f^2_{a_1} \mathcal{B}(K^+_{1A}\pi^-)}{f^2_{K_{1A}} \mathcal{B}(a_1^+\pi^-)}$$

$$R^+_- \equiv \frac{\bar{\lambda}^2 f^2_{\pi} \mathcal{B}(a_1^+ K^0)}{f^2_{K} \mathcal{B}(a_1^-\pi^+)}$$

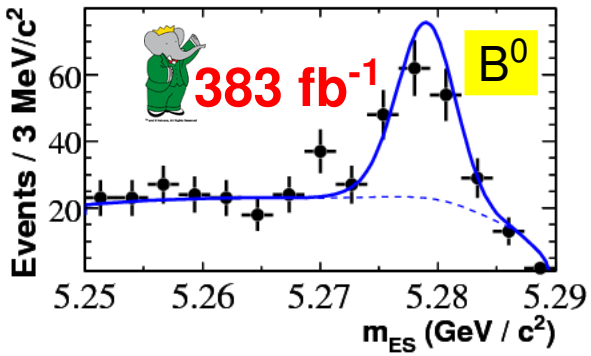
- Include *factorizable* SU(3) corrections
  - Ratios of decay constants
  - Neglect exchange ($\Delta S=0$) and weak annihilation ($\Delta S=1$) diagrams

[Gronau and Zupan: PRD 70, 074031 (2004); PRD 73, 057502 (2006)]

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

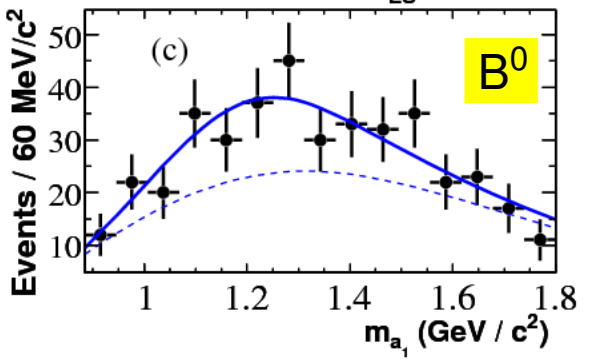
PRL 100, 051803 (2008)

- BaBar: ML fit (ΔE, m_{ES}, Fisher, m_{a_1}, $\cos\theta_H$)



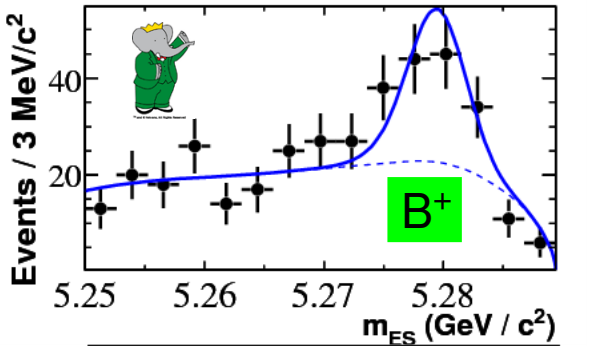
- $BF(B^0 \to a_1^- K^+) = (16.4 \pm 3.0 \pm 2.4) \times 10^{-6}$

  $N_{sg} = 272 \pm 44$ (S=5.1σ); $A_{ch} = -0.16 \pm 0.12 \pm 0.01$



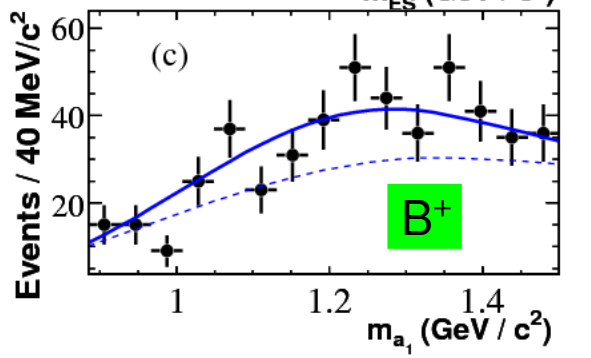
- $BF(B^+ \to a_1^+ K^0) = (34.8 \pm 5.0 \pm 4.4) \times 10^{-6}$

  $N_{sg} = 241 \pm 32$ (S=6.2σ); $A_{ch} = 0.12 \pm 0.11 \pm 0.02$



- Th: $BF(B^+ \to a_1^+ K^0) \sim BF(B^0 \to a_1^- K^+)$)
  - Not consistent with experiment

[Cheng, PRD 76, 114020 (2007)]



K_1 mesons

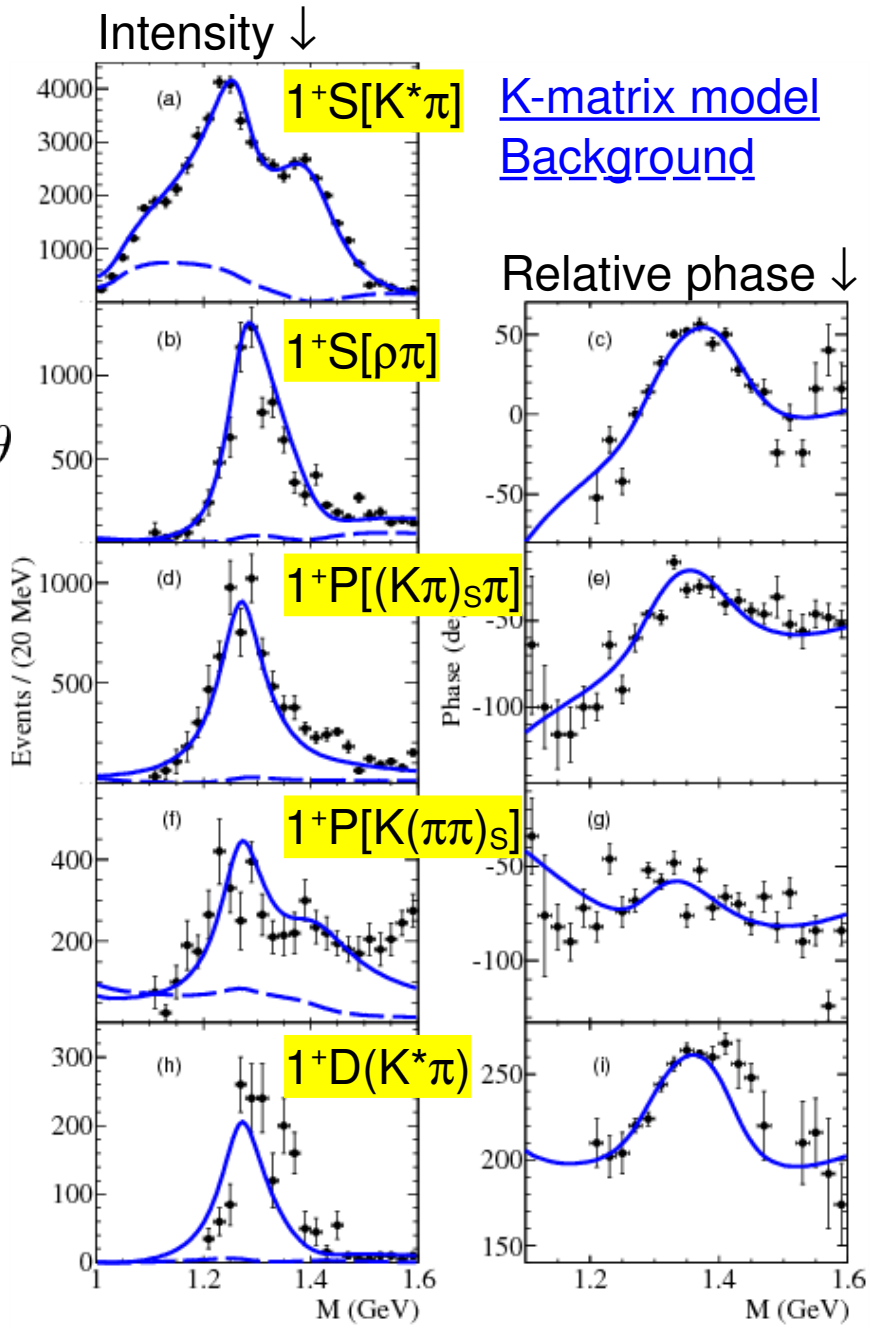
- K_{1A} and K_{1B} mixtures of two mass eigenstates [Brandenburg et al.: PRL 36, 703 (1976) Carnegie et al.: PLB 68, 287 (1977)]
  - K_{1A} & K_{1B}: SU(3) partners of a_1 & b_1

$$|K_1(1400)\rangle = |K_{1A}\rangle \cos\theta + |K_{1B}\rangle \sin\theta$$
$$|K_1(1270)\rangle = -|K_{1A}\rangle \sin\theta + |K_{1B}\rangle \cos\theta$$

- Experimental features in the Kππ system explained by two resonances:

	$K_1(1270)$	$K_1(1400)$
M (MeV)	1273 ± 7	1402 ± 7
Γ (MeV)	90 ± 20	174 ± 13
BF[K*π]	42 ± 6	94 ± 6
BF[ρK]	16 ± 5	3 ± 3
BF$[(K\pi)_{S\text{-wave}}\pi]$	28 ± 4	–
D-wave/S-wave [K*π]	1.0 ± 0.7	0.04 ± 0.01

PWA of diffractive K p → Kππ p data [ACCMOR: PLB 187, 1 (1981)]

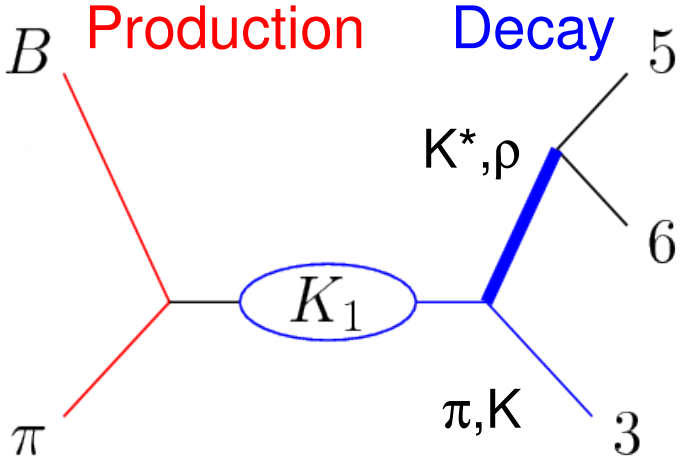


ωK channel not fitted to data

Signal model for $K_1 \to K\pi\pi$

PRD 81, 052009 (2010)

- K-matrix model for interfering resonances [Aitchison, NPA 189, 417 (1972)]
  - 2 resonances x 6 channels [$(K^*\pi)_S$, $K\rho$, $(K\pi)_S\,\pi$, $K\,(\pi\pi)_S$, $(K^*\pi)_D$, $K\omega$]



$$F_i = e^{i\delta_i}\sum_j R_j\left(1 - i\mathbf{K}\boldsymbol{\rho}\right)^{-1}_{ij}$$

$$R_i = \frac{f_{pa}f_{aj}}{M_a - M_{K\pi\pi}} + \frac{f_{pb}f_{bj}}{M_b - M_{K\pi\pi}}$$

a = $K_1(1400)$
b = $K_1(1270)$

$$K_{ij} = \frac{f_{ai}f_{aj}}{M_a - M_{K\pi\pi}} + \frac{f_{bi}f_{bj}}{M_b - M_{K\pi\pi}}$$

No $M_{K\pi\pi}$ dependence for $f_{p\alpha}$ and $f_{\alpha i}$

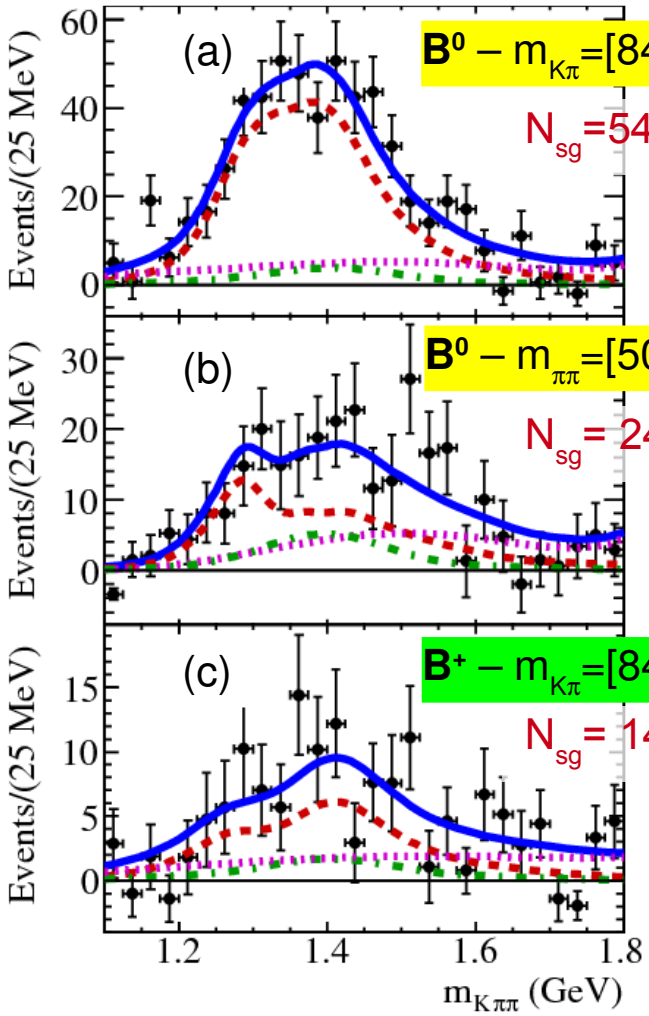
- Decay parameters determined from a fit to the results of PWA of diffractive $K\,p \to K\pi\pi\,p$ data [ACCMOR, NPB 187, 1 (1981)]
- Production parameters determined from a fit to B-decay data
  - overall normalization ⇒ combined BF[$B \to K_1(1270)\pi + K_1(1400)\pi$]
  - $\tan\vartheta = |f_{pb}/f_{pa}|$: relative $K_1(1270)$ and $K_1(1400)$ fraction
  - $\varphi = \arg(f_{pb}/f_{pa})$: interference effects

$K_1\pi$ production parameters

PRD 81, 052009 (2010)

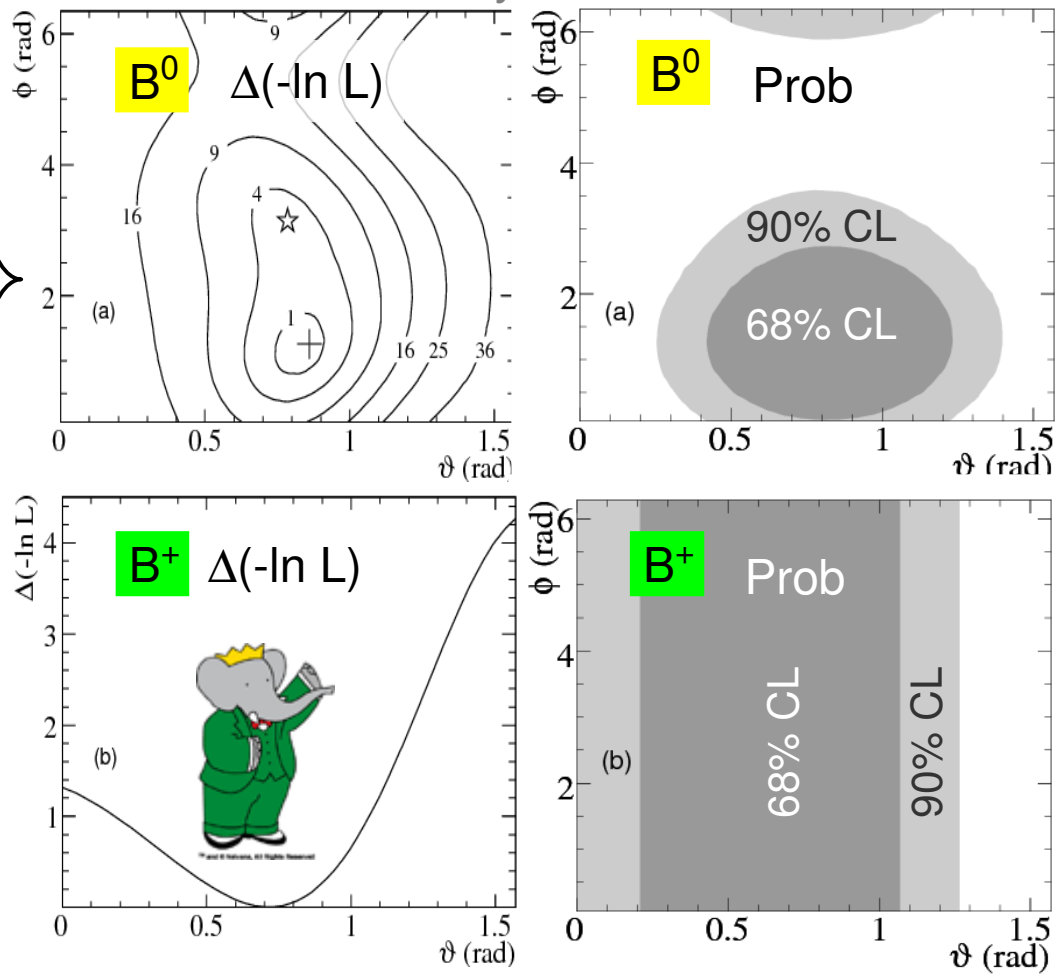
- (ϑ,φ) scan: at each node, ML fit (ΔE, m_{ES}, Fisher, $m_{K\pi\pi}$, $\cos\theta_H$)
  - $m_{K\pi\pi}$ PDF templates modeled upon MC for each $\zeta = (\vartheta,\varphi)$ set:

$$\mathcal{M}(\zeta) = \sum_{i \neq \omega K} F_i(M_{K\pi\pi};\zeta)\, \mathcal{C}_i\, \mathcal{BW}_i(m_{56})\, \mathcal{A}_i(\Theta,\Phi,\beta)$$



sPlot: subtraction of continuum-bkg

include systematics → **413 fb^{-1}**



$B \to K_{1A} \pi$ branching fractions

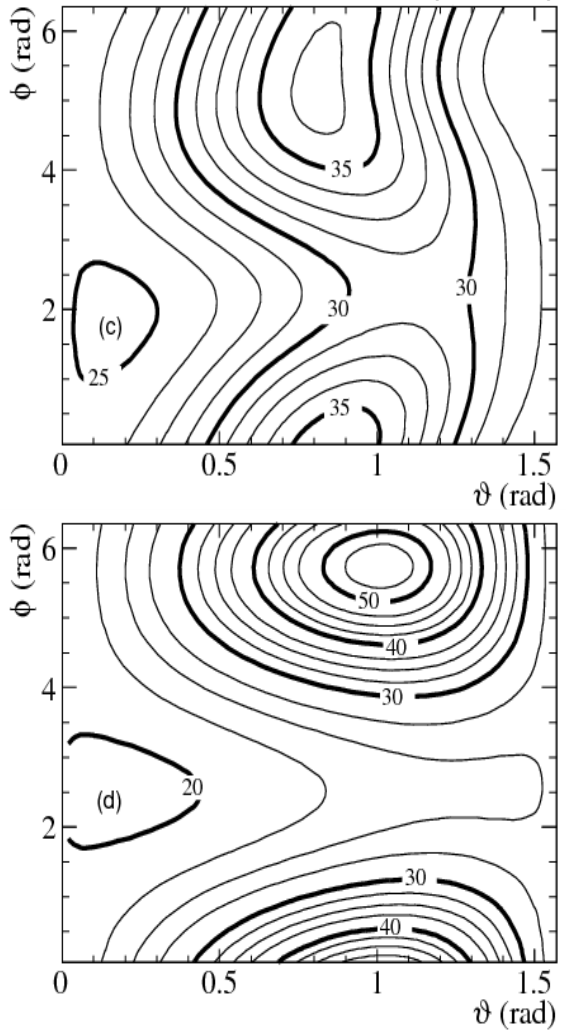
PRD 81, 052009 (2010)

- Weighted average over (ϑ,φ) – weight$(\vartheta,\varphi) = L(\vartheta,\varphi) \otimes$ syst.
  - Systematics on BF_{sum} included (convolution of L[BF] with 1D gaussian)

- In MC, "turn off" one K_1 at a time: $c_a^{(i)} f_{pa} + c_b^{(i)} f_{pb} \to 0$
  - Evaluate $corr_j(\vartheta,\varphi) = BF_j / BF_{sum}$ using MC ($j \neq i$)

Decay	BF ($\times 10^{-6}$)	S (σ)
$B^0 \to K_1(1270)^+\pi^- + K_1(1400)^+\pi^-]$	31^{+8}_{-7}	7.5
$B^+ \to K_1(1270)^0\pi^+ + K_1(1400)^0\pi^+]$	29^{+29}_{-17}	3.2
$B^0 \to K_1(1270)^+\pi^-$	17^{+8}_{-11}	
$B^0 \to K_1(1400)^+\pi^-$	17^{+7}_{-9}	
$B^0 \to K_{1A}{}^+\pi^-$	14^{+9}_{-10}	
$B^+ \to K_1(1270)^0\pi^+$	<40	
$B^+ \to K_1(1400)^0\pi^+$	<39	
$B^+ \to K_{1A}{}^0\pi^+$	<36	

$\sum_i BF_i \neq BF_{sum}$



a_1 and K_{1A} decay constants

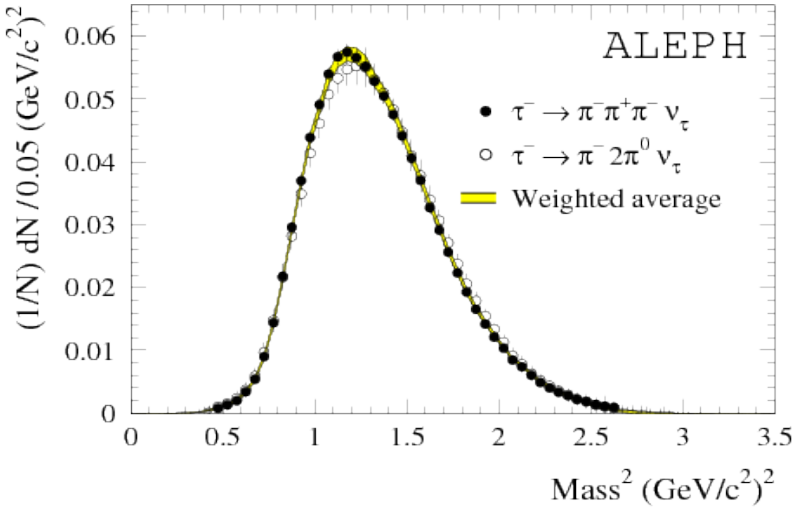
- Agreement between f_{a1} values obtained by different methods:

Method	f_{a1} (MeV)	Ref.
QCD sum rules	238 ± 10	[1]
$f_{K1(1270)}$ + SU(3)	$215 - 223$*	[2]
$\tau^- \to \pi^-\pi^+\pi^-\nu$	203 ± 18	[3]

* depends on K_1 mixing angle

[1] Yang: NPB 776, 187 (2007)
[2] Nardulli: Pham, PLB 623, 65 (2005)
[3] Bloch et al.: PRD 60, 111502R (1999)

[ALEPH: EPJC 4, 409 (1998)]



- $|f_{K1(1270)}|$=175 ± 19 MeV from Br[$\tau \to K_1(1270)\,\nu$]
  [ALEPH: EPJC 11, 599 (1999),
  Cheng: PRD 67, 094007 (2003)]
- f_{K1A} calculated from quark model
  - use $|f_{K1(1270)}|$ and $|f_{a1}|$=203 MeV as input
    [Cheng: PRD 69, 074025 (2004)]

θ_{K1}	$\lvert f_{K1A}\rvert$ (MeV)
37°	293
58°	207

[Cheng, Yang: PRD 76, 114020 (2007)]

- Naive quark model estimate of $|f_{K1A}|$ variation with θ_{K1} = 58°→72°
  ⇒ $|f_{K1A}|$ decreases by O(20 MeV)

(used in K-matrix)

Extraction of bounds on Δα

PRD 81, 052009 (2010)

- MC trials: generate quantities from experimental distributions
  - For each set of values, solve system of inequalities for Δα

$BF(a_1^{\pm}\pi^{\mp})$ [10^{-6}]	$BF(a_1^{-}K^{+})$ [10^{-6}]	$BF(a_1^{+}K^{0})$ [10^{-6}]	$BF(K_{1A}^{+}\pi^{-})$ [10^{-6}]	$BF(K_{1A}^{0}\pi^{+})$ [10^{-6}]
$33.2 \pm 3.8 \pm 3.0$	$16.3 \pm 2.9 \pm 2.3$	$34.8 \pm 5.0 \pm 4.4$	14^{+9}_{-10}	<36
f_π (MeV)	f_K (MeV)	f_{a1} (MeV)	f_{K1A} (MeV)	θ [°]
130.4 ± 0.2	155.5 ± 0.9	203 ± 18	207 ± 20	72

$$\cos 2(\alpha^{\pm}_{\rm eff} - \alpha) \geq (1 - 2R^{0}_{\pm})/\sqrt{1-(\mathcal{A}^{\pm}_{CP})^2}$$

$$\cos 2(\alpha^{\pm}_{\rm eff} - \alpha) \geq (1 - 2R^{+}_{\pm})/\sqrt{1-(\mathcal{A}^{\pm}_{CP})^2}$$

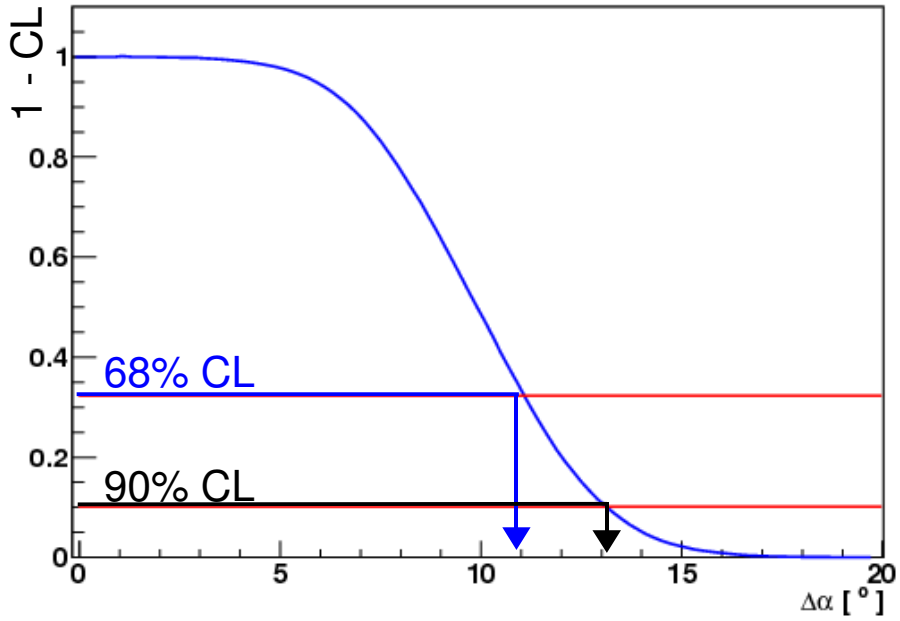
$$(P/T)_{\rho\rho} < (P/T)_{a_1\pi} \lesssim (P/T)_{\rho\pi} < (P/T)_{\pi\pi}$$

$|\Delta\alpha| < 11^\circ$ @ 68% CL

$\Delta\alpha < 13^\circ$ @ 90% CL

$\alpha = (79 \pm 7 \pm 11)^\circ$

Selected solution compatible with global CKM fits



Summary and outlook

- BaBar measured α / ϕ_2 from $a_1\,\pi$ + SU(3) to constrain penguins
  - 8 ambiguities, reduced to 2 with assumptions on strong phase δ
  - $\alpha_{eff} = [11 \pm 7]^o, [79 \pm 7]^o$, $|\alpha - \alpha_{eff}| < 11^o (13^o)$ at 68%(90%) CL
  - 4th independent measurement – awaiting for Belle results

- Will benefit from further input from theory and experiment:
  - Decay constants, K_1 mixing angle
  - Null tests of assumptions, e.g., BF($B^0 \rightarrow K_1^{\pm} K^{\mp}$) (annihilation)

- Future measurements at LHC-b and Super B-factories
  - Statistical error from TD analysis ~ $\rho\rho$
  - $(P/T)_{\rho\rho} < (P/T)_{a_1\pi} \leq (P/T)_{\rho\pi} < (P/T)_{\pi\pi}$
  - Resume full SU(3) fit? Could provide cross check of assumptions

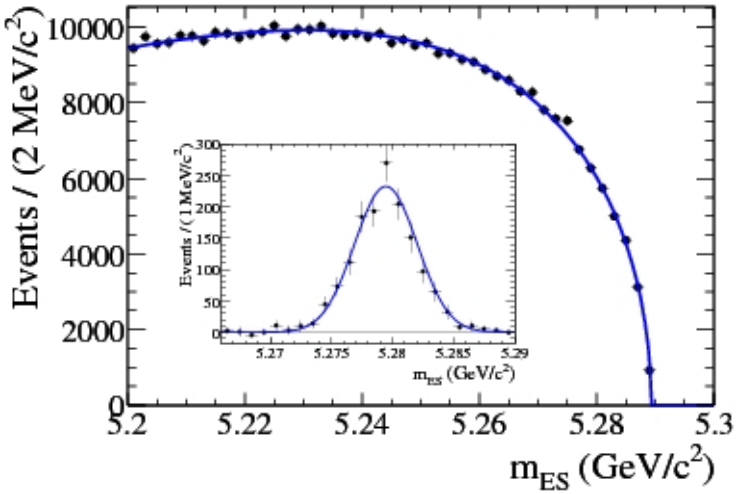
Thank you!

Backup

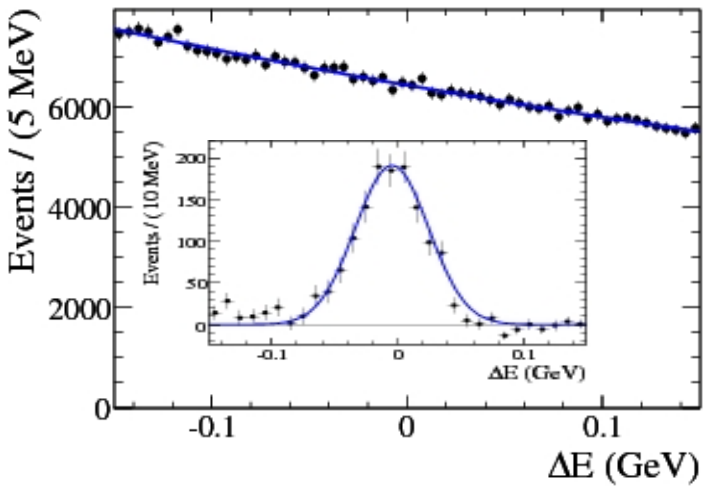
Charmless (quasi) two-body analysis

- Kinematic variables: energy subsituted mass, energy difference

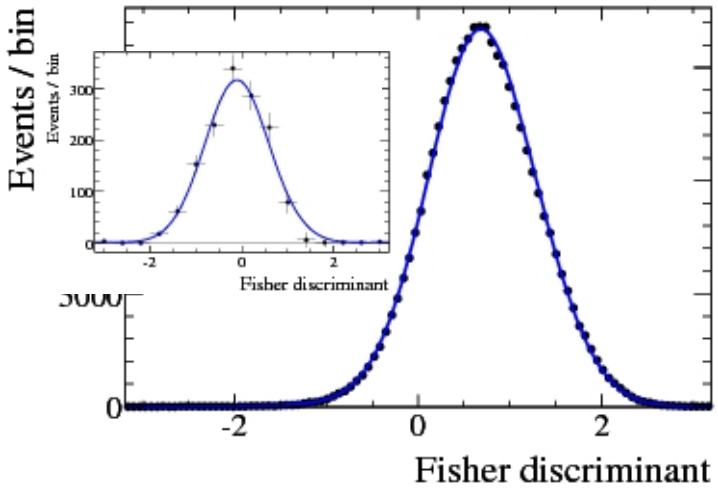
$$m_{ES} = \sqrt{s/4 - p_B^2}$$

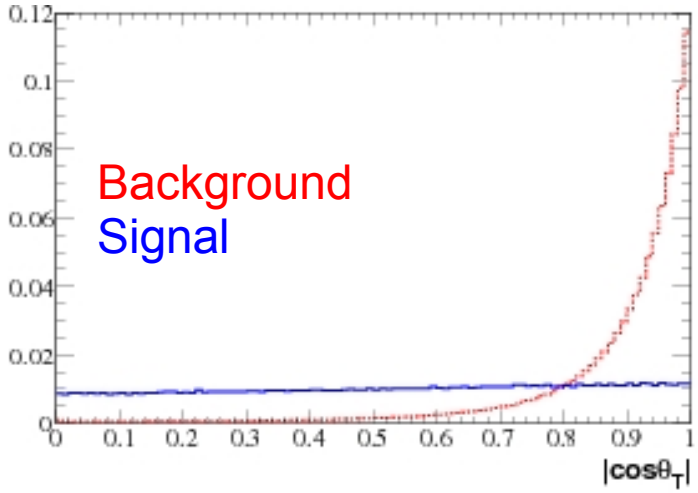


$$\Delta E = E_B - \sqrt{s}/2$$



- Event shape: distinguish "jet-like" qq events and more isotropic B decays

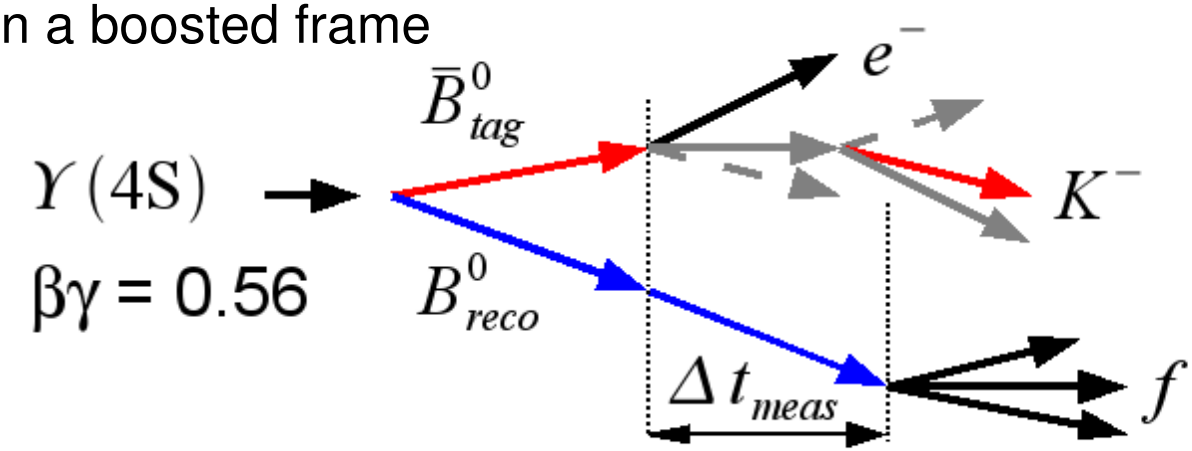




- Extract the signal yield and CP asymmetries via an unbinned Maximum Likelihood fit to several observables

Time dependent analysis

B mesons are produced coherently in a boosted frame



Identify flavor and vertex of the other B: NN based tagging algorithm with 6 categories

Fully reconstruct signal final state

$$\Delta t_{meas} = t_{reco} - t_{tag} \qquad \Delta z = \beta\gamma c \Delta t_{meas} \approx 260\,\mu m$$

$$F^{\pm}(\Delta t_{meas}) = \frac{e^{-|\Delta t|/\tau}}{4\tau}\left\{1 \mp \Delta w \pm (1-2w)\left[S\sin(\Delta m_d \Delta t) - C\cos(\Delta m_d \Delta t)\right]\right\} \otimes R(\Delta t_{meas} - \Delta t, \sigma_{\Delta t})$$

Include tagging performance

Experimental Δt resolution: convolution with triple gaussian, with parameters obtained from a large sample of fully reconstructed B decays, and free to differ between tagging category