

Time-dependent measurements of CP violation related to ϕ_2 (α) from Belle



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- $B^0 \rightarrow \pi^+ \pi^-$ (*PRL 93, 021601*)
- $B^0 \rightarrow \rho^\pm \pi^\mp$ (*hep-ex/0408003, submitted to PRL*)
- $B^0 \rightarrow \rho^+ \rho^-$ (*in progress*)

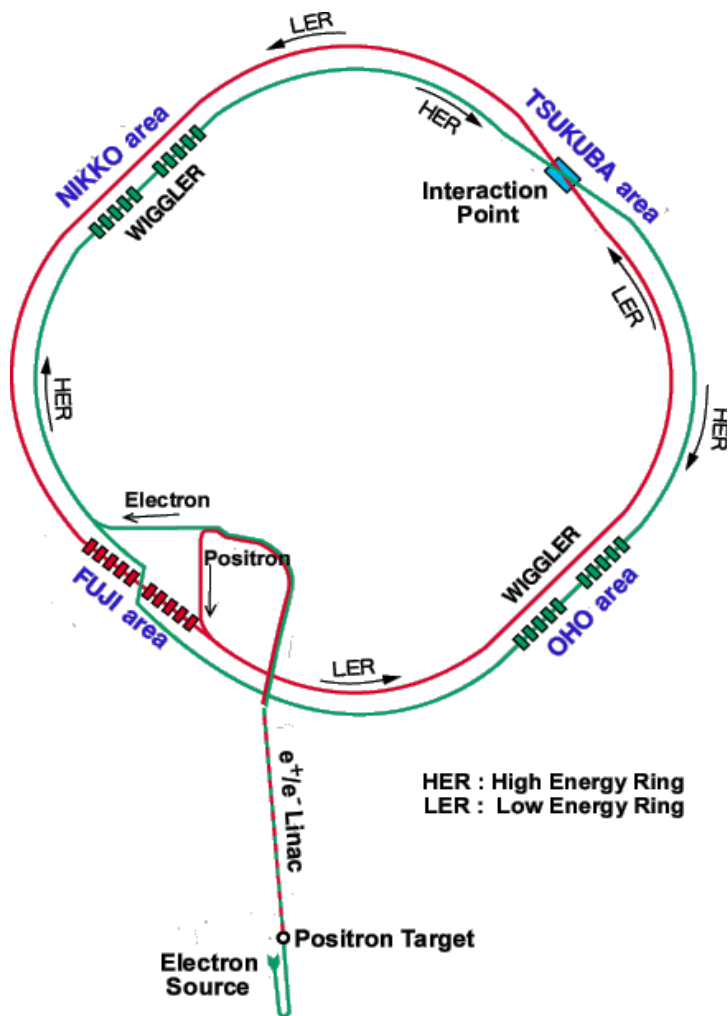
less penguin uncertainty

BUT

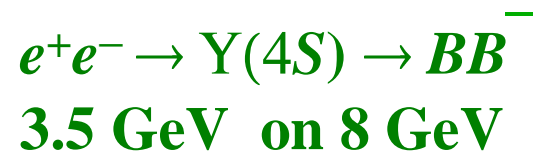
more experimental
challenges & theoretical
assumptions



Belle at KEKB

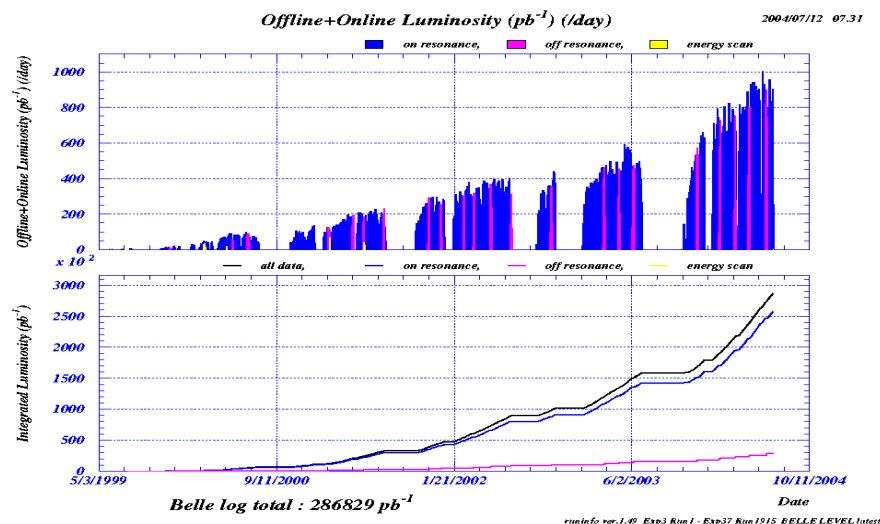


HER : High Energy Ring
LER : Low Energy Ring



$$\int L dt = 287 \text{ fb}^{-1} \text{ on July 12th, 2004}$$

$$(L_{peak} (\text{max}) = 1.13 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1})$$



140 fb⁻¹ on resonance (152M BB)
by June 2003 (results presented here)

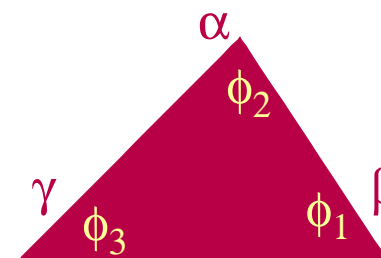


$B^0 \rightarrow \pi^+\pi^-$ formalism

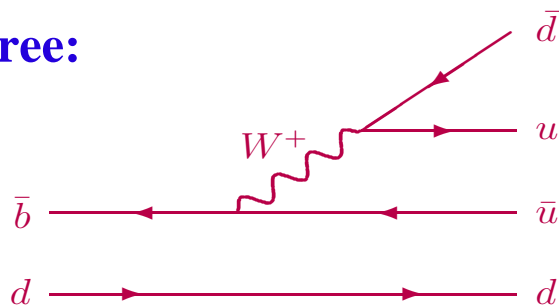
$$\frac{N_{\bar{B}^0 \rightarrow \pi\pi} - N_{B^0 \rightarrow \pi\pi}}{N_{\bar{B}^0 \rightarrow \pi\pi} + N_{B^0 \rightarrow \pi\pi}} = \mathcal{A}_{\pi\pi} \cos(\Delta m \Delta t) + \mathcal{S}_{\pi\pi} \sin(\Delta m \Delta t)$$

$$\mathcal{A}_{\pi\pi} = \frac{1 - |\lambda|^2}{1 + |\lambda|^2} \quad \mathcal{S}_{\pi\pi} = \frac{2\text{Im} \lambda}{1 + |\lambda|^2}$$

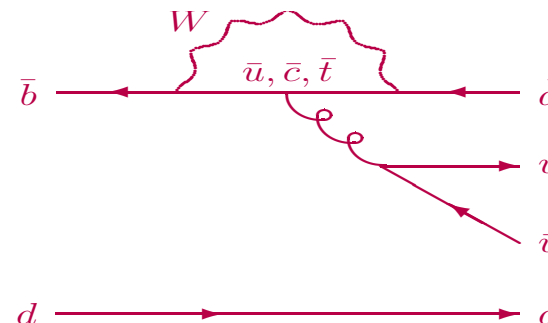
$$\lambda_{\pi\pi} = \left(\frac{q}{p} \right) \frac{A(\bar{B}^0 \rightarrow \pi^+\pi^-)}{A(B^0 \rightarrow \pi^+\pi^-)} = e^{i2\phi_2} \quad (\text{no penguin})$$



Tree:



Penguin:





Analysis Overview

1) $B \rightarrow \pi^+ \pi^- (n\pi^0)$
selection:

$$m_{bc} = \sqrt{(E_{beam}^*)^2 - (p_B^*)^2}$$

$$\Delta E = E_B^* - E_{beam}^*$$

For $B \rightarrow \pi^+ \pi^-$:

$$5.271 < m_{bc} < 5.287 \text{ GeV}/c^2$$

$$|\Delta E| < 0.064 \text{ GeV}$$

2) Flavor tagging:

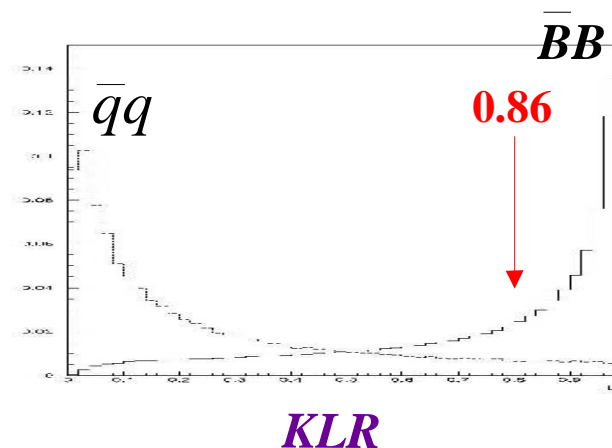
input: K^\pm, μ^\pm, e^\pm

output: $q = \pm 1$, quality $r \in (0, 1)$

3) Continuum suppression:

- Fisher discriminant from Fox-Wolfram moments
- $\cos \theta_B$

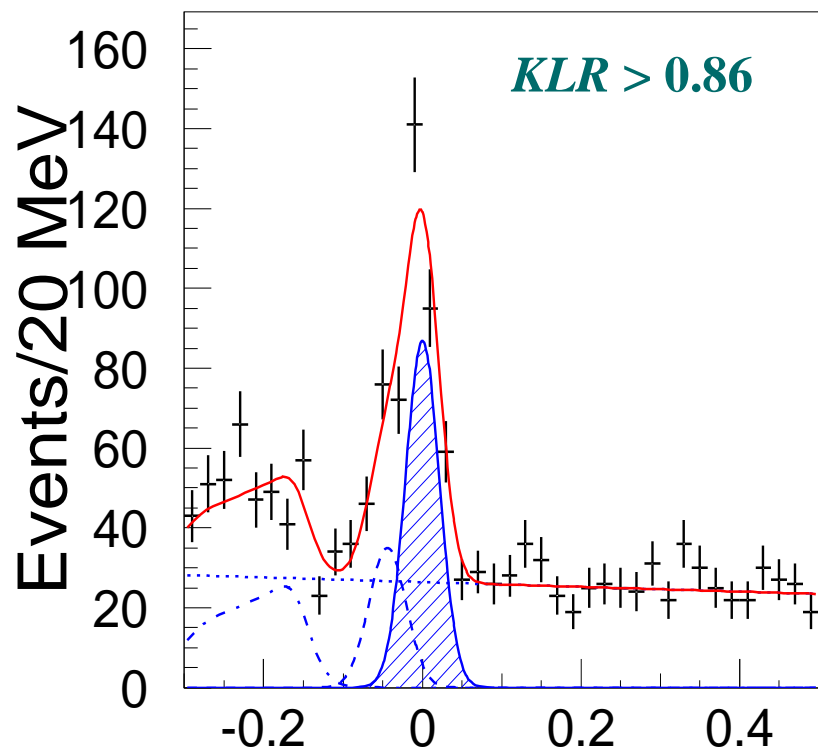
$$KLR \equiv \frac{\mathcal{L}_{B\bar{B}}}{(\mathcal{L}_{B\bar{B}} + \mathcal{L}_{q\bar{q}})}$$



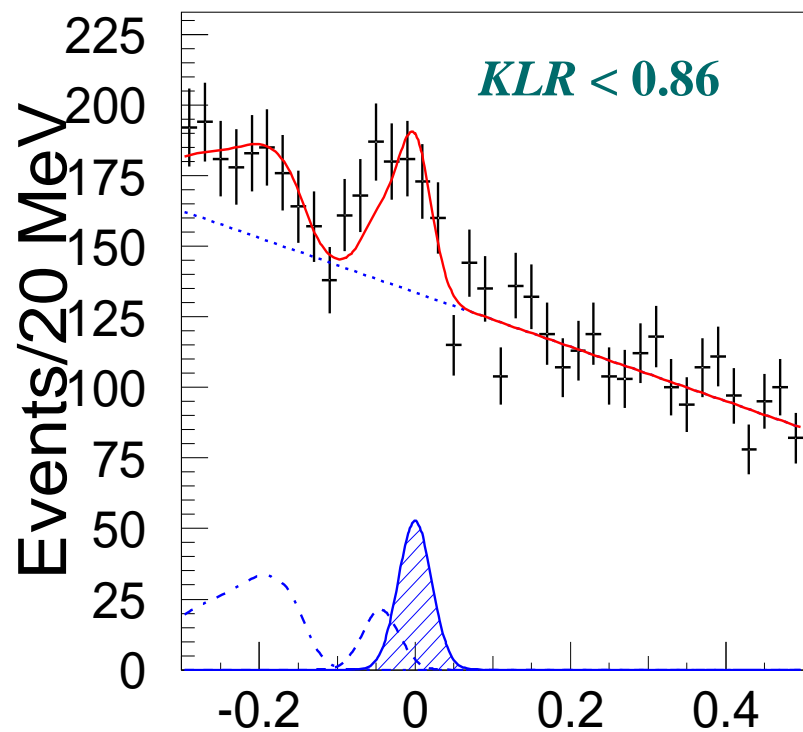
4) Vertexing and Δt fit



$B^0 \rightarrow \pi^+\pi^-$ (140 fb^{-1})



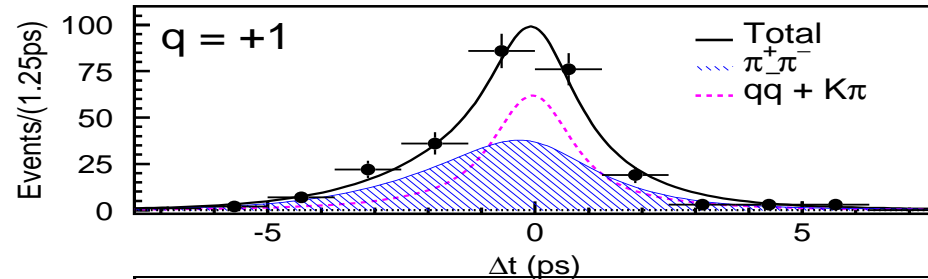
$N_{\pi\pi} = 232$



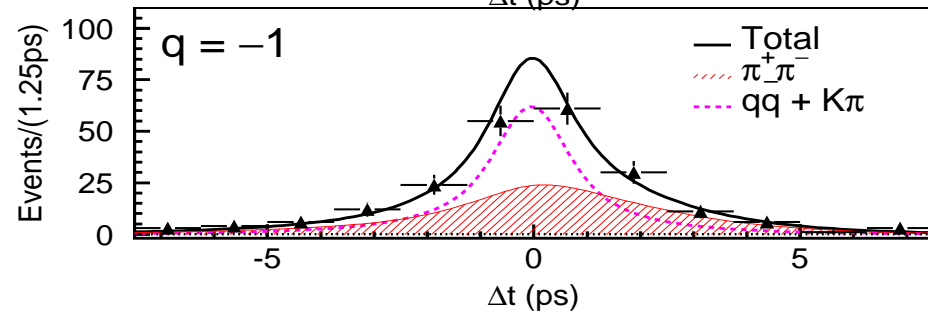
$N_{\pi\pi} = 141$



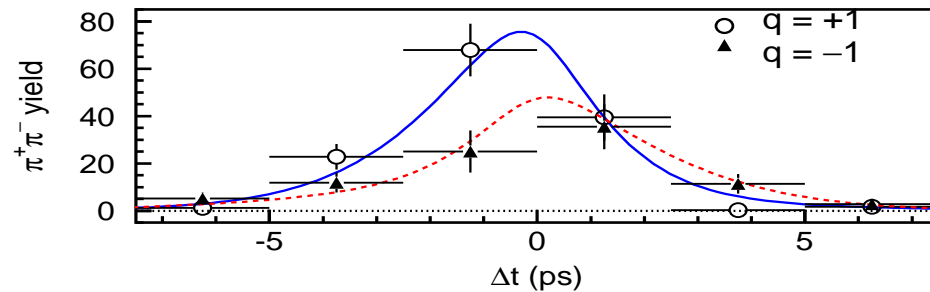
Unbinned max. likelihood fit to Δt (140 fb^{-1})



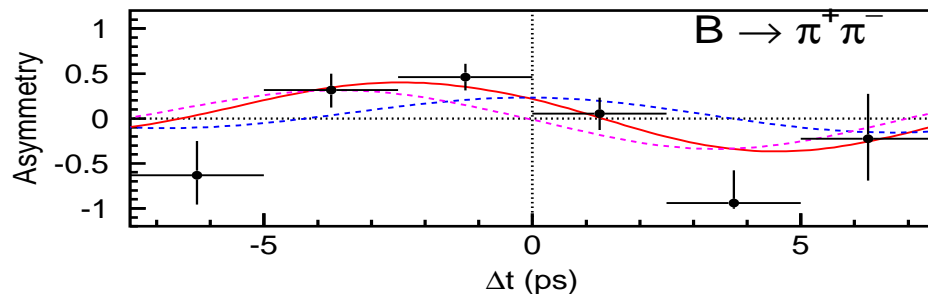
264 events: 140 $\pi\pi$
($KLR > 0.86$)



219 events: 92 $\pi\pi$
($KLR > 0.86$)



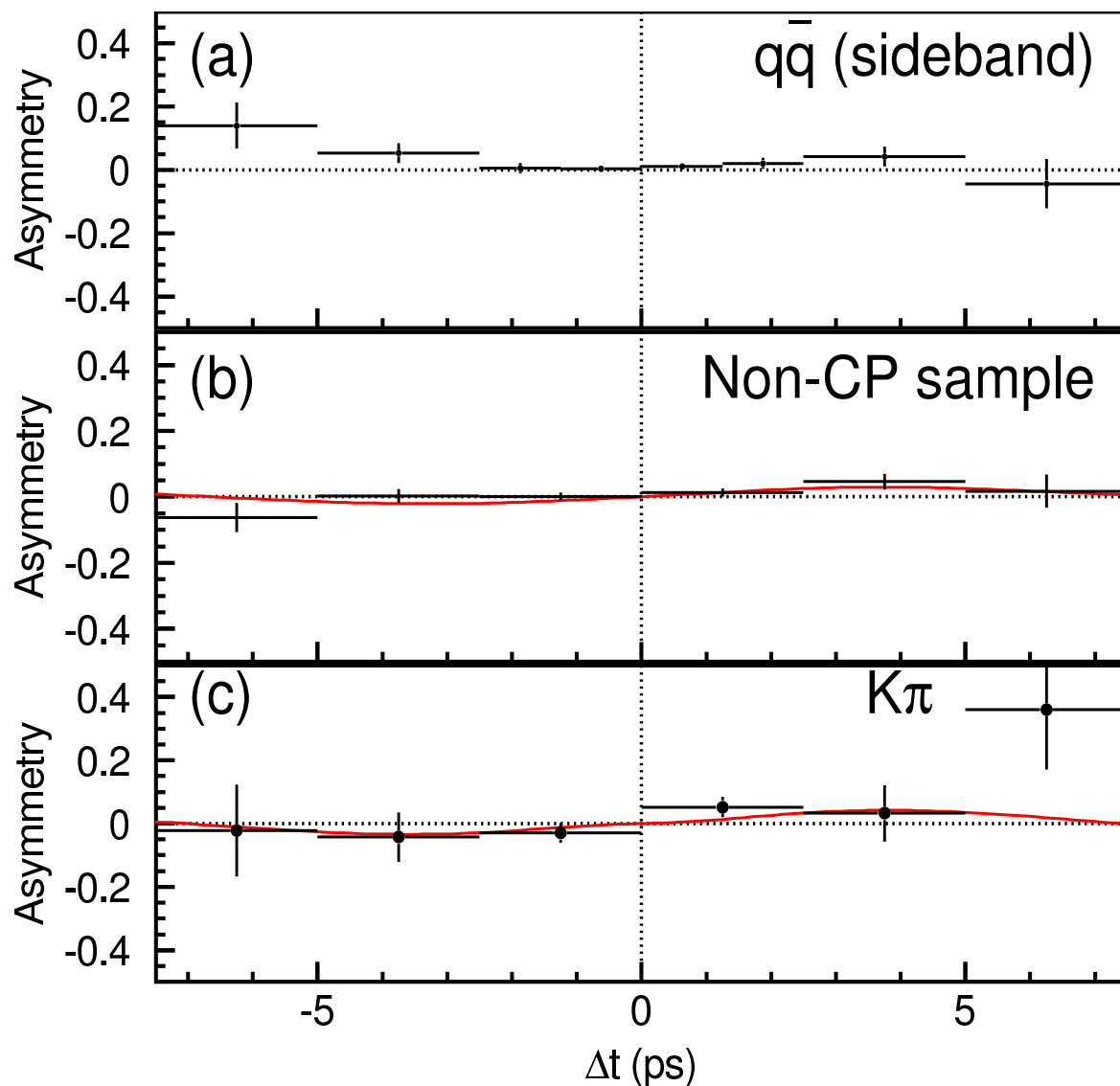
$A_{\pi\pi} = +0.58 \pm 0.15$ (stat.)
 ± 0.07 (syst.)



$S_{\pi\pi} = -1.00 \pm 0.21$ (stat.)
 ± 0.07 (syst.)



Cross checks I: other CP asymmetries



Sideband:

23170 B^0 tags

22736 B^0 tags

$$Asymm = 0.95 \pm 0.47\%$$

9346 $B \rightarrow D^-\pi^+$:

$$A_{\pi\pi} = -0.02 \pm 0.03$$

$$S_{\pi\pi} = 0.11 \pm 0.04$$

10211 $B \rightarrow D^{*-}\pi^+$:

$$A_{\pi\pi} = 0.01 \pm 0.03$$

$$S_{\pi\pi} = 0.05 \pm 0.04$$

2358 $B \rightarrow K^\pm\pi^\mp$:

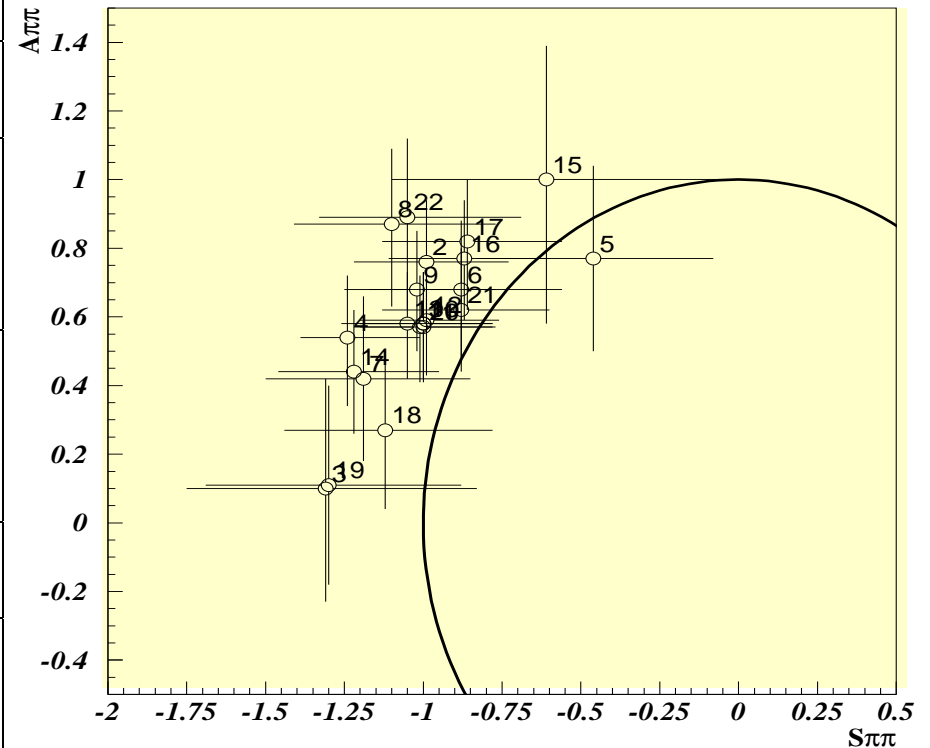
$$A_{K\pi} = -0.02 \pm 0.08$$

$$S_{K\pi} = 0.14 \pm 0.11$$



Cross checks II: various subsamples

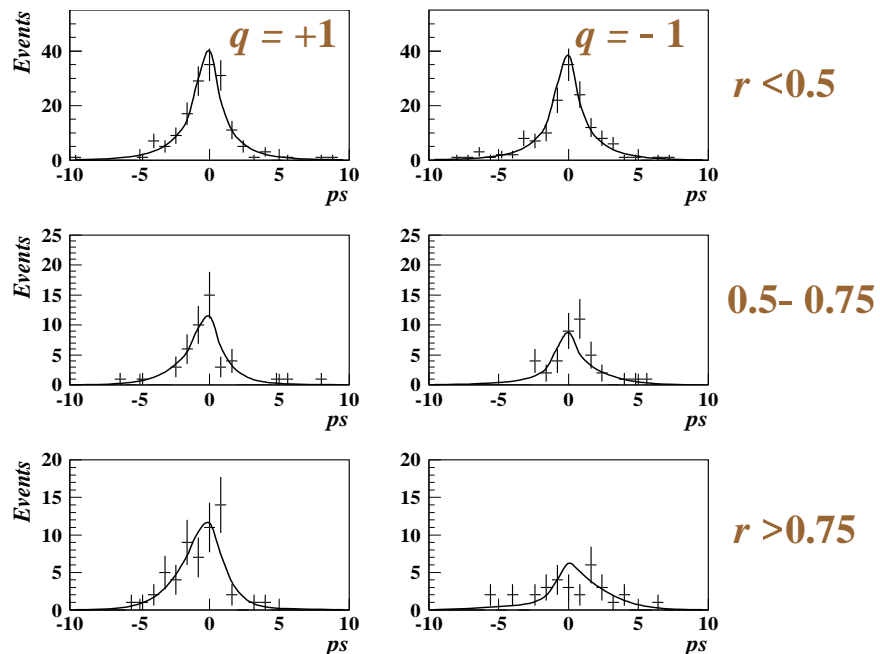
	1529(365.5/135.4/1028.1)	$+0.58^{+0.15}_{-0.16}$	$-1.00^{+0.22}_{-0.20}$
$KLR > 0.86$	483(231.5/83.3/168.3)	$+0.76^{+0.18}_{-0.19}$	$-0.99^{+0.26}_{-0.23}$
$KLR < 0.86$	1046(134/52.1/859.8)	$+0.10^{+0.32}_{-0.33}$	$-1.31^{+0.48}_{-0.44}$
exp.7-exp.19	866(211.1/76.7/578.2)	$+0.54^{+0.18}_{-0.20}$	$-1.24^{+0.23}_{-0.15}$
exp.21-exp.27	663(154.4/58.7/449.9)	$+0.77^{+0.27}_{-0.27}$	$-0.46^{+0.38}_{-0.37}$
$\Delta E < 0$	872(194.8/131.1/546.2)	$+0.68^{+0.20}_{-0.21}$	$-0.88^{+0.32}_{-0.29}$
$\Delta E > 0$	657(170.7/4.4/481.9)	$+0.42^{+0.24}_{-0.24}$	$-1.19^{+0.34}_{-0.31}$
$ \Delta E < 1\sigma_{\Delta E}$	623(171.1/60.0/391.8)	$+0.87^{+0.22}_{-0.24}$	$-1.10^{+0.33}_{-0.31}$
$ \Delta E > 1\sigma_{\Delta E}$	1131(292.7/99.4/738.9)	$+0.68^{+0.17}_{-0.18}$	$-1.02^{+0.25}_{-0.23}$
$ \Delta t < 15(\text{ps})$	1520(364.4/134.8/1020.8)	$+0.58^{+0.15}_{-0.16}$	$-1.00^{+0.22}_{-0.20}$
$ \Delta t < 10(\text{ps})$	1516(363.4/134.3/1018.3)	$+0.57^{+0.15}_{-0.16}$	$-1.01^{+0.23}_{-0.21}$
$ \Delta t < 8(\text{ps})$	1512(360.9/133.7/1017.4)	$+0.59^{+0.15}_{-0.16}$	$-0.99^{+0.23}_{-0.21}$
$ \Delta t < 5(\text{ps})$	1470(351.4/127.9/990.7)	$+0.58^{+0.15}_{-0.16}$	$-1.05^{+0.23}_{-0.21}$
multi tracks	1151(276.4/99.1/775.5)	$+0.44^{+0.18}_{-0.18}$	$-1.22^{+0.27}_{-0.25}$
single track	378(89.1/36.3/252.6)	$+1.00^{+0.39}_{-0.42}$	$-0.61^{+0.57}_{-0.49}$
$ qr > 0.75$	185(81.6/33.7/69.7)	$+0.77^{+0.17}_{-0.18}$	$-0.87^{+0.27}_{-0.24}$
$ qr > 0.875$	94(51.2/22.9/19.9)	$+0.82^{+0.18}_{-0.20}$	$-0.86^{+0.30}_{-0.27}$
$ qr < 0.875$	1435(314.3/112.5/1008.2)	$+0.27^{+0.23}_{-0.23}$	$-1.12^{+0.34}_{-0.32}$
$ qr < 0.75$	1344(283.8/101.7/958.4)	$+0.11^{+0.29}_{-0.29}$	$-1.30^{+0.42}_{-0.39}$
$\xi < 50$	1486(353.5/132.8/999.7)	$+0.57^{+0.16}_{-0.16}$	$-1.00^{+0.23}_{-0.20}$
$\xi < 10$	1125(274.3/97.3/753.5)	$+0.62^{+0.18}_{-0.18}$	$-0.88^{+0.28}_{-0.25}$
$\xi < 3$	597(146.2/52.5/398.3)	$+0.89^{+0.23}_{-0.27}$	$-1.05^{+0.36}_{-0.28}$





Cross checks III: independ. analysis (binned fit)

- binned maximum likelihood fit
- $KLR > 0.86$ (less $q\bar{q}$ background)
- 3 different resolution functions ($|qr| \in 0, 0.50, 0.75, 1$)
- no "outlier" events ($|\Delta t| < 10$ ps)
- analysis done in blind manner



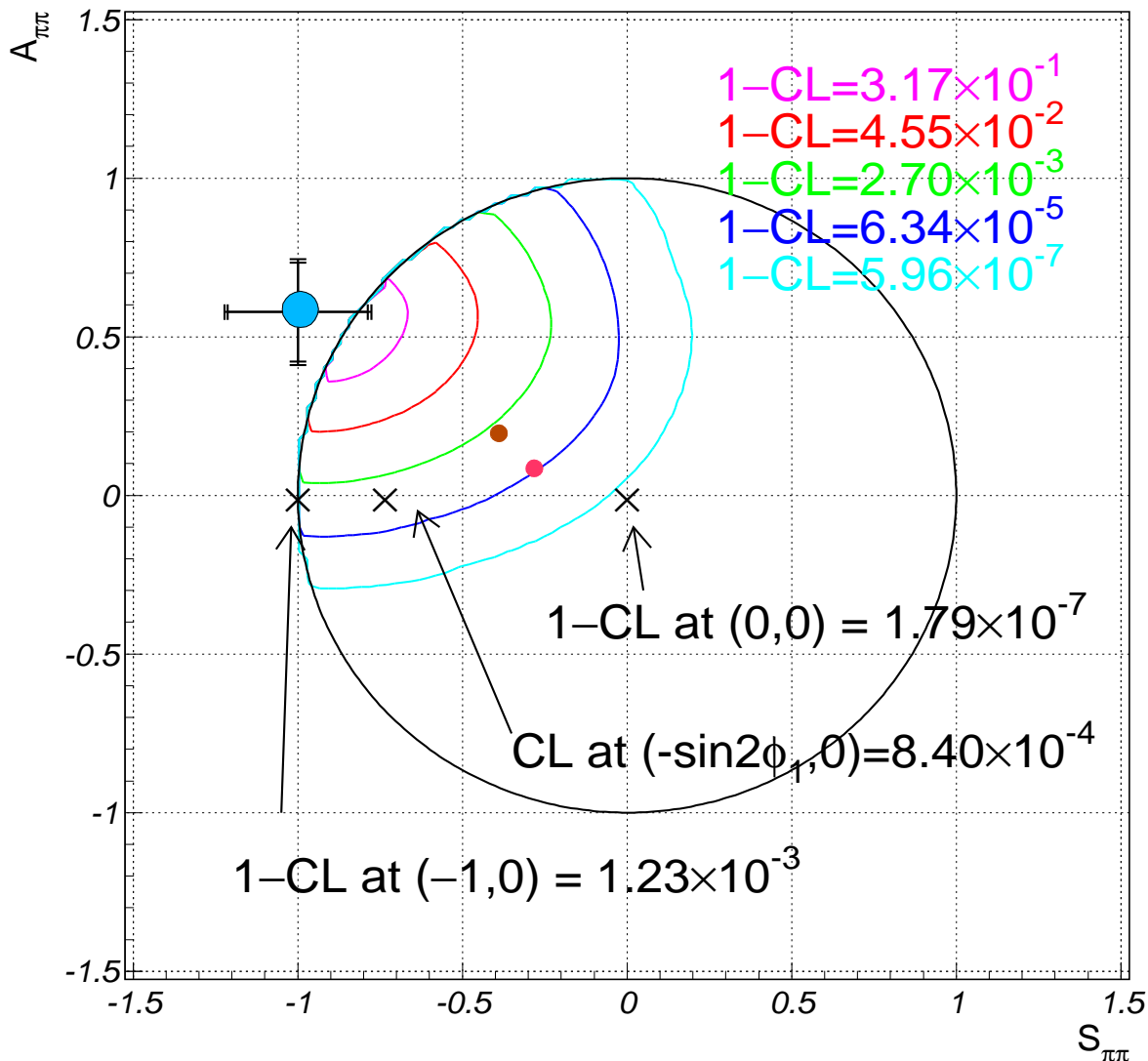
Fit	$A_{\pi\pi}$	$S_{\pi\pi}$	$\chi^2/\text{d.o.f.}$
Binned ($KLR > 0.86$)	$+0.654^{+0.190}_{-0.194}$	$-0.943^{+0.278}_{-0.254}$	0.60
Binned ($KLR > 0.86, \Delta t < 10$ ps)	$+0.738^{+0.228}_{-0.231}$	$-0.913^{+0.312}_{-0.285}$	0.68
Unbinned ($KLR > 0.86$)	$+0.76^{+0.18}_{-0.19}$	$-0.99^{+0.26}_{-0.23}$	—

Results consistent with toy MC expectations ($\sigma_{\Delta A} = 0.12, \sigma_{\Delta S} = 0.20$)



Statistical Significance

Use Toy MC, constructing confidence belts with Feldman-Cousins ordering:



$A_{\pi\pi}, S_{\pi\pi} = (0, 0)$
 corresponds to 5.2σ
 statist. fluctuation \Rightarrow
 observation of
CP violation

$A_{\pi\pi} = 0$ corresponds
 to $\geq 3.2\sigma$ statistical
 fluctuation (any $S_{\pi\pi}$)
 \Rightarrow evidence for direct
CP violation



Constraints upon ϕ_2 (α) and $|P/T|$

Gronau and Rosner,
PRD 65, 093012 (2002)
PRD 66, 053003 (2002):

$$\begin{aligned}
 A(B^0 \rightarrow \pi^+ \pi^-) &= -(|T|e^{i\delta_T}e^{i\phi_3} + |P|e^{i\delta_P}) \\
 A(\bar{B}^0 \rightarrow \pi^+ \pi^-) &= -(|T|e^{i\delta_T}e^{-i\phi_3} + |P|e^{i\delta_P}) \\
 \Rightarrow \lambda_{\pi\pi} &\equiv \frac{q}{p} \frac{\bar{A}_{\pi\pi}}{A_{\pi\pi}} = e^{i\phi_2} \frac{1 + |P/T| e^{i(\delta+\phi_3)}}{1 + |P/T| e^{i(\delta-\phi_3)}} \\
 & \quad (\delta \equiv \delta_P - \delta_T)
 \end{aligned}$$

Take $\phi_1 = 0.736 \pm 0.049$

\Rightarrow 2 constraints &

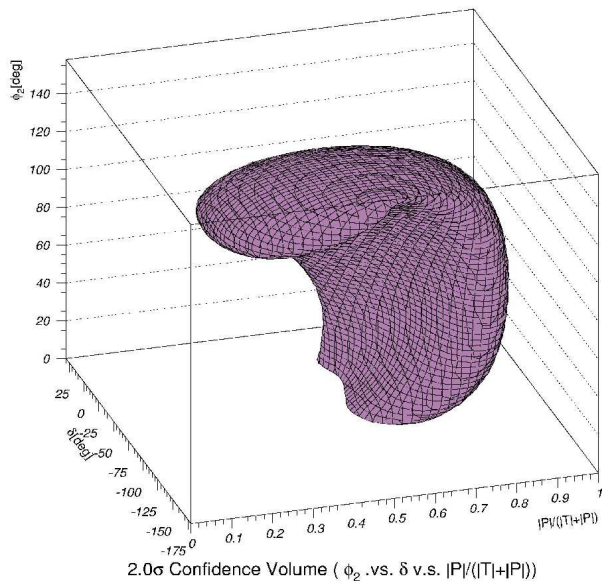
3 unknowns

$(\phi_2, \delta, |P/T|)$

$$\begin{aligned}
 A_{\pi\pi} &\equiv \frac{|\lambda|^2 - 1}{|\lambda|^2 + 1} = \frac{-2|P/T| \sin(\phi_1 + \phi_2) \sin \delta}{1 - 2|P/T| \cos(\phi_1 + \phi_2) \cos \delta + |P/T|^2} \\
 S_{\pi\pi} &\equiv \frac{2\text{Im}\lambda}{|\lambda|^2 + 1} \\
 &= \frac{2|P/T| \sin(\phi_1 - \phi_2) \cos \delta + \sin 2\phi_2 - |P/T|^2 \sin 2\phi_1}{1 - 2|P/T| \cos(\phi_1 + \phi_2) \cos \delta + |P/T|^2}
 \end{aligned}$$



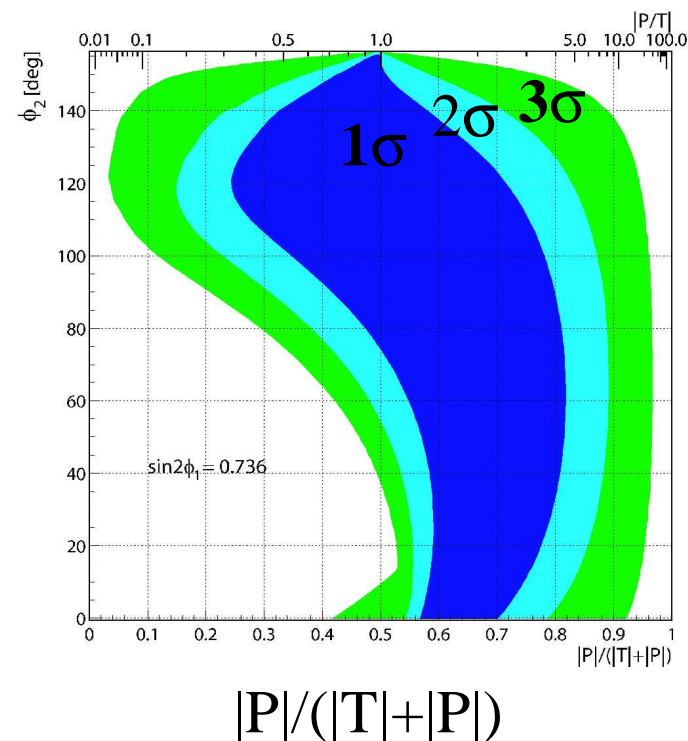
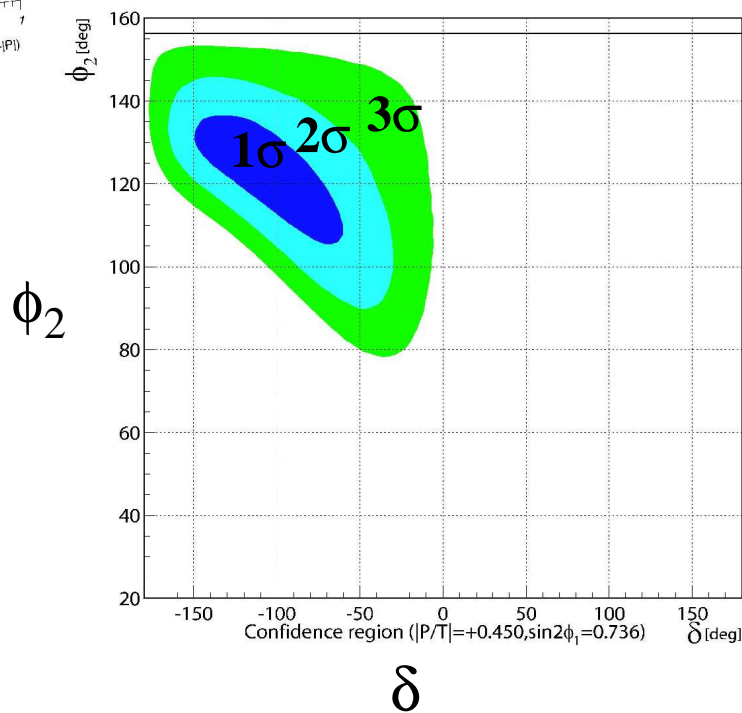
Constraints upon ϕ_2 (α) and $|P/T|$ cont'd



For $|P/T| < 0.45$
(factorization,
perturbative QCD)

$90^\circ \leq \phi_2 \leq 146^\circ$
(95% C.L.)

For any δ
 $|P/T| > 0.17$
(95% C.L.)

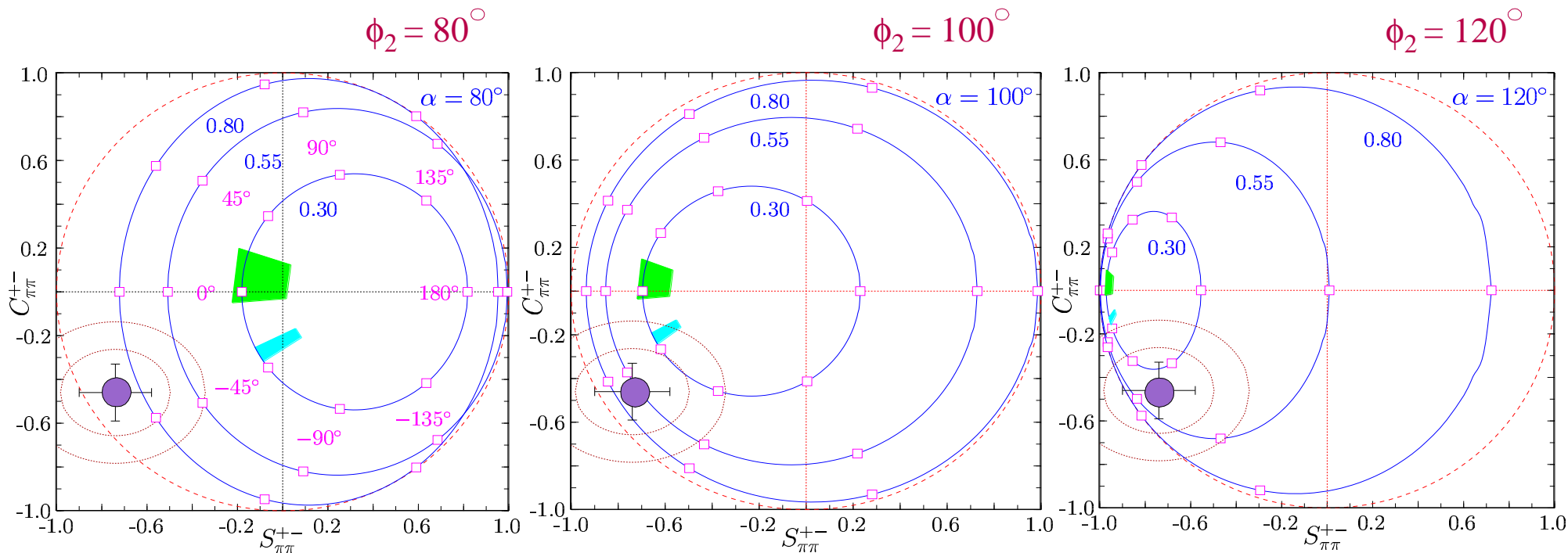




Constraints upon ϕ_2 (α) and $|P/T|$ cont'd

Ali, Lunghi, and Parkhomenko,
EPJ C36, 183 (2004):

Babar + Belle: $C_{\pi\pi} = -0.46 \pm 0.13$, $S_{\pi\pi} = -0.74 \pm 0.16$ (HFAG)



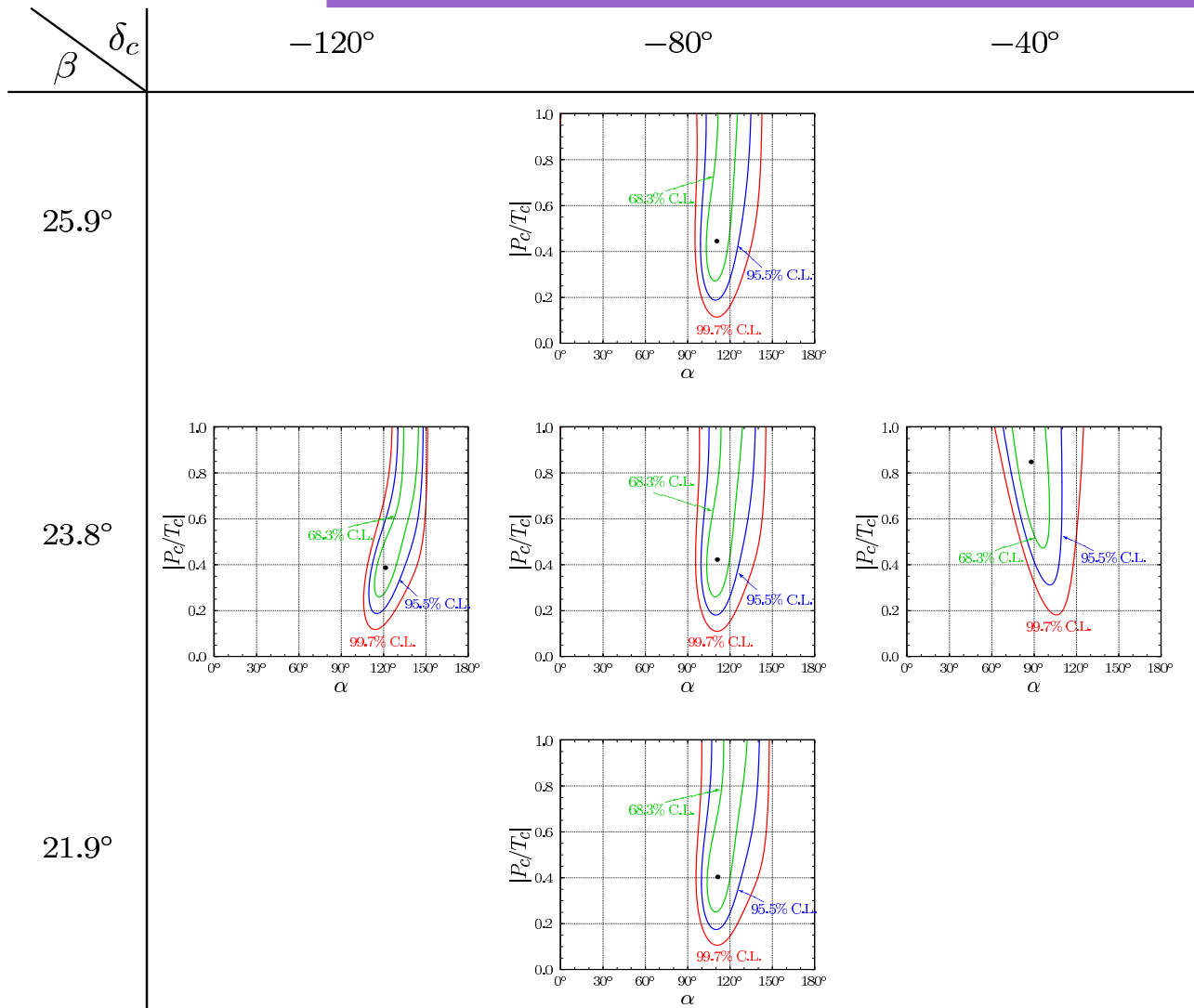
\Rightarrow small ϕ_2 requires large $|P/T|$; large $|P/T|$ allows small ϕ_2
 \Rightarrow small ϕ_2 requires small $|\delta|$; large ϕ_2 allows large $|\delta|$



Constraints upon ϕ_2 (α) and $|P/T|$ cont'd

Ali, Lunghi, and Parkhomenko,
EPJ C36, 183 (2004):

Babar + Belle: $C_{\pi\pi} = -0.46 \pm 0.13$, $S_{\pi\pi} = -0.74 \pm 0.16$ (HFAG)





Constraints upon ϕ_2 (α) and $|P/T|$ cont'd

Gronau and Rosner,
PLB 595, 339 (2004):

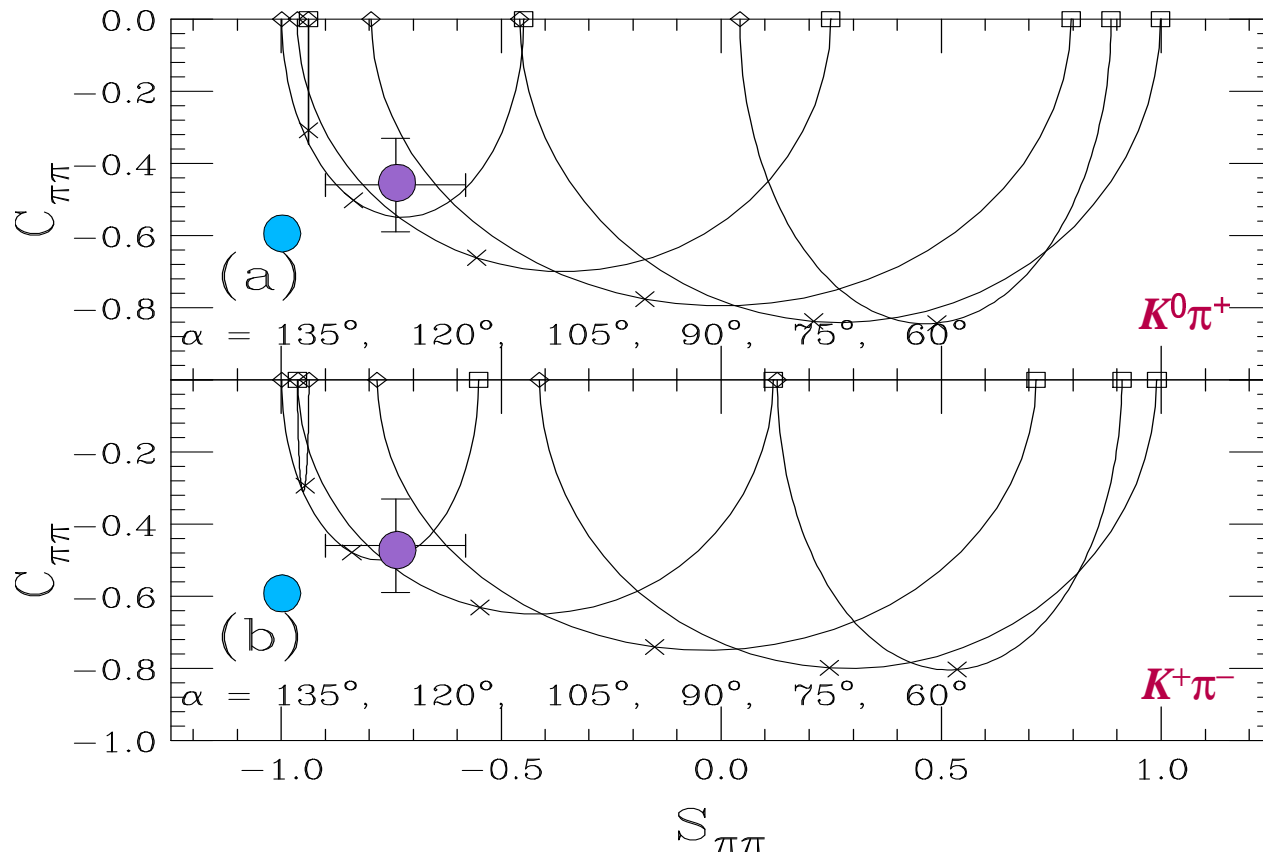
$SU(3)$:

$$T_{K^+\pi^-} = \left(\frac{f_K}{f_\pi}\right) \left(\frac{V_{us}}{V_{ud}}\right) T_{\pi^+\pi^-}$$

$$P_{K^+\pi^-} = \left(\frac{V_{cs}}{V_{cd}}\right) P_{\pi^+\pi^-}$$

$$\Rightarrow \frac{\Gamma(B^0 \rightarrow K^+\pi^-)}{\Gamma(B^0 \rightarrow \pi^+\pi^-)} \text{ or } \frac{\Gamma(B^+ \rightarrow K^0\pi^+)}{\Gamma(B^0 \rightarrow \pi^+\pi^-)}$$

provides the
needed constraint



$\Rightarrow \phi_2 > 86^\circ$
(1 sigma)



Constraints upon ϕ_2 (α) and $|P/T|$ cont'd

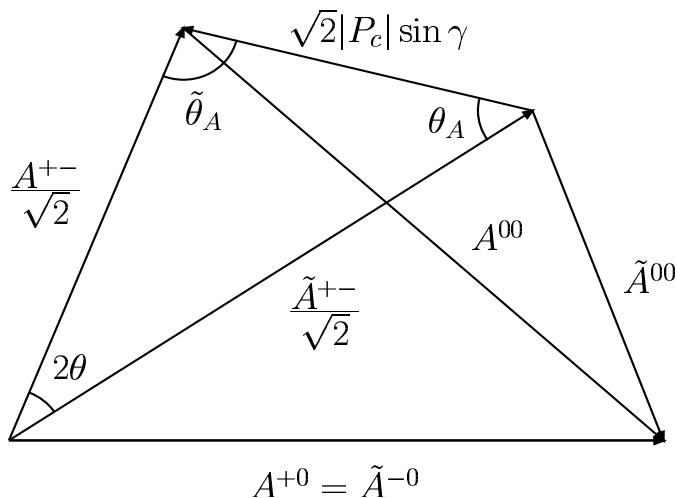
Gronau and London,
PRL 65, 3381 (1990):

SU(2) Isospin:

$$\frac{A(B^0 \rightarrow \pi^+\pi^-)}{\sqrt{2}} + A(B^0 \rightarrow \pi^0\pi^0) = A(B^+ \rightarrow \pi^+\pi^0)$$

$$\frac{A(\bar{B}^0 \rightarrow \pi^+\pi^-)}{\sqrt{2}} + A(\bar{B}^0 \rightarrow \pi^0\pi^0) = A(B^- \rightarrow \pi^-\pi^0)$$

6 parameters + 6 observables \Rightarrow all determined



New measurement (254 fb^{-1}) of $\bar{B}^0 \rightarrow \pi^0\pi^0$
and $B^0 \rightarrow \pi^0\pi^0$ now makes this possible:

$$B = 2.32^{+0.44}_{-0.48} \text{ } ^{+0.22}_{-0.18} \times 10^{-6}$$

$$\mathcal{A}(\pi^0\pi^0) = +0.43 \pm 0.51^{+0.17}_{-0.16}$$

BUT:

- statistical errors too large to determine α_{eff}
- branching fraction large \Rightarrow weaker GLSS bound:

$$\cos 2\theta \geq \frac{(B^{+-}/2 + B^{+0} - B^{00})^2 - B^{+-}B^{+0}}{B^{+-}B^{+0} \sqrt{1 - A_{\pi\pi}^2}}$$

$$\geq 0.498 \Rightarrow \theta < 30^\circ$$

Gronau, London, Sinha, Sinha,
PLB 514, 315 (2001):



$B^0 \rightarrow \rho^\pm \pi^\mp$ formalism

$$P(\rho^\pm \pi^\mp) = (1 \pm A_{CP}^{\rho\pi}) \frac{e^{-|\Delta t|/\tau_B}}{4\tau_B} \left\{ 1 - q(C_{\rho\pi} \pm \Delta C_{\rho\pi}) \cos(\Delta m \Delta t) + q(S_{\rho\pi} \pm \Delta S_{\rho\pi}) \sin(\Delta m \Delta t) \right\}$$

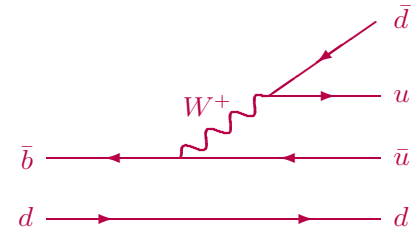
$$A_{CP}^{\rho\pi} = \frac{N(\rho^+ \pi^-) - N(\rho^- \pi^+)}{N(\rho^+ \pi^-) + N(\rho^- \pi^+)} : \text{time \& flavor integrated asymmetry}$$

$C_{\rho\pi}$: direct CP violation

$S_{\rho\pi}$: CP violation arising from mixing

$\Delta C_{\rho\pi}$: difference btwn ($W \rightarrow \rho$) & (spectator $\rightarrow \rho$) rates

$\Delta S_{\rho\pi}$: difference btwn ($W \rightarrow \rho$) & (spectator $\rightarrow \rho$) strong phase



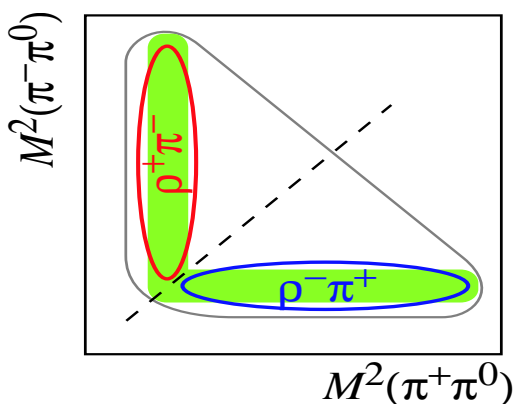
$$A_{+-} \equiv \frac{N(\bar{B}^0 \rightarrow \rho^- \pi^+) - N(B^0 \rightarrow \rho^+ \pi^-)}{N(\bar{B}^0 \rightarrow \rho^- \pi^+) + N(B^0 \rightarrow \rho^+ \pi^-)} = - \frac{A_{CP}^{\rho\pi} + C_{\rho\pi} + A_{CP}^{\rho\pi} \cdot \Delta C_{\rho\pi}}{1 + \Delta C_{\rho\pi} + A_{CP}^{\rho\pi} \cdot C_{\rho\pi}}$$

$$A_{-+} \equiv \frac{N(\bar{B}^0 \rightarrow \rho^+ \pi^-) - N(B^0 \rightarrow \rho^- \pi^+)}{N(\bar{B}^0 \rightarrow \rho^+ \pi^-) + N(B^0 \rightarrow \rho^- \pi^+)} = \frac{A_{CP}^{\rho\pi} - C_{\rho\pi} - A_{CP}^{\rho\pi} \cdot \Delta C_{\rho\pi}}{1 - \Delta C_{\rho\pi} - A_{CP}^{\rho\pi} \cdot C_{\rho\pi}}$$

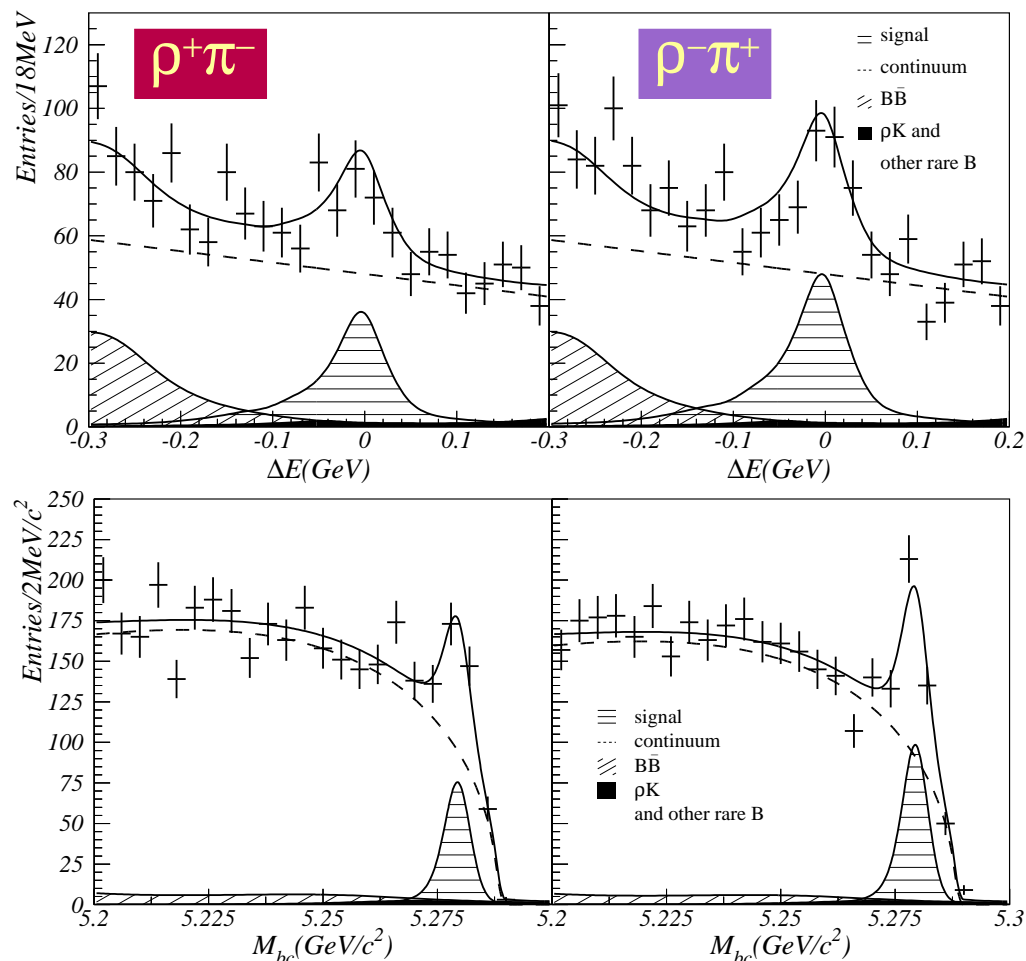


New $B^0 \rightarrow \rho^\pm \pi^\mp$ result (140 fb^{-1})

- $\pi^+ \pi^- \pi^0$ combinations
- $p(\pi^0) > 200 \text{ MeV}/c$
- $\pi^0 \mid \cos(\theta_{\text{helicity}}) \mid < 0.95$
- $\rho^\pm \mid \cos(\theta_{\text{helicity}}) \mid > 0.5$
- if multiple candidates, choose best based on $\Sigma(\chi^2_{\text{vertex fits}})$
- $m(\pi^+ \pi^-) > 0.97 \text{ GeV}/c^2$
- $0.57 < m(\pi^\pm \pi^0) < 0.97 \text{ GeV}/c^2$
& $m(\pi^\mp \pi^0) > 1.22 \text{ GeV}/c^2$



2-d fit for event yields:





New $B^0 \rightarrow \rho^\pm \pi^\mp$ result (140 fb^{-1}): Δt fit

$$\mathcal{L} = \prod_{i=1}^N \left\{ f_{\rho\pi} P_{\rho\pi}(\Delta t_i) + f_{\rho\pi}^{\text{wc}} P_{\rho\pi}^{\text{wc}}(\Delta t_i) + f_{\rho K} P_{\rho K}(\Delta t_i) + f_{q\bar{q}} P_{q\bar{q}}(\Delta t_i) + f_{b \rightarrow c} P_{b \rightarrow c}(\Delta t_i) + f_{b \rightarrow u} P_{b \rightarrow u}(\Delta t_i) \right\}$$

\Rightarrow 4 parameter fit

349 $\rho \pi$
 7 $K \pi$
 903 $\bar{q} q$
 25 $b \rightarrow c$
 16 $b \rightarrow u$

Result:

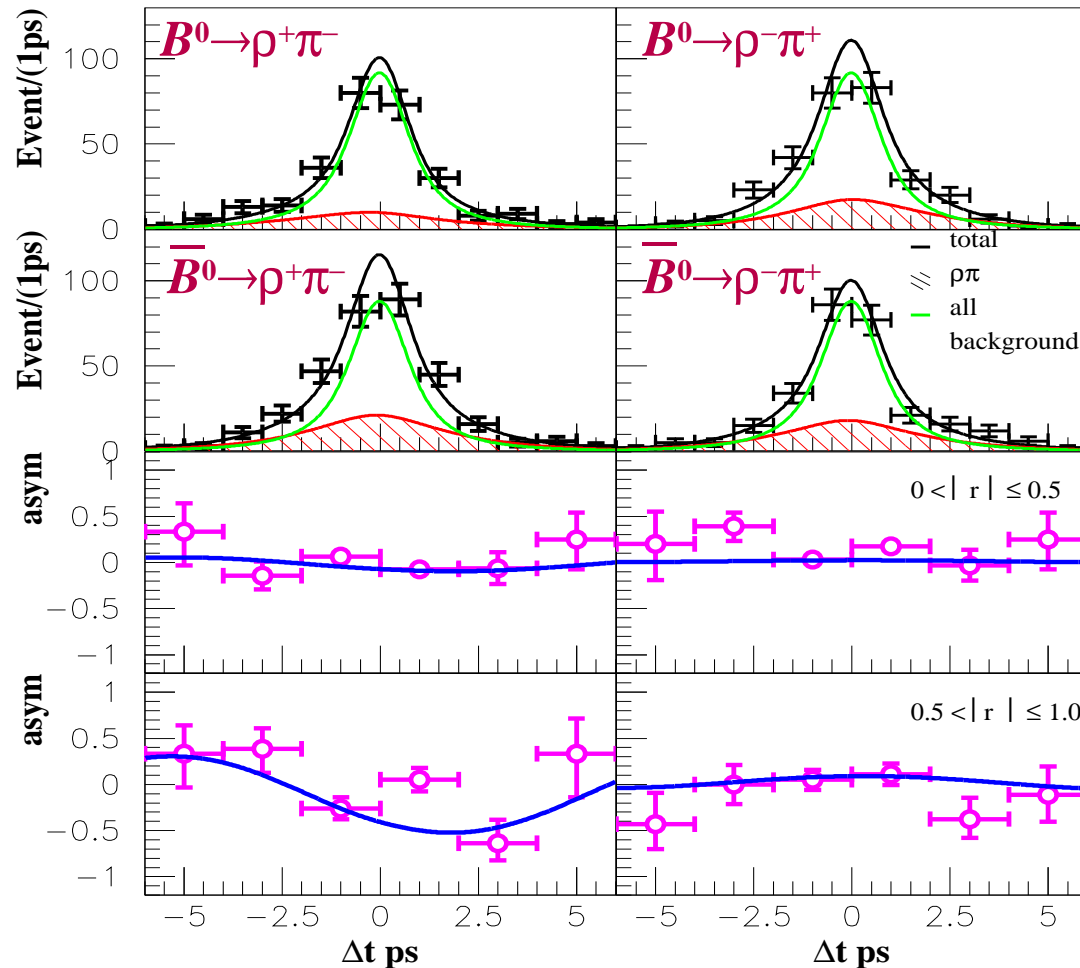
$$A_{CP}^{\rho\pi} = -0.16_{-0.10}^{+0.09} \pm 0.02$$

$$\mathcal{C}_{\rho\pi} = 0.25 \pm 0.17_{-0.06}^{+0.02}$$

$$\mathcal{S}_{\rho\pi} = -0.28 \pm 0.23_{-0.08}^{+0.10}$$

$$\Delta\mathcal{C}_{\rho\pi} = 0.38 \pm 0.18_{-0.04}^{+0.02}$$

$$\Delta\mathcal{S}_{\rho\pi} = -0.30 \pm 0.24 \pm 0.09$$





$B^0 \rightarrow \rho^\pm \pi^\mp$ constraint on ϕ_2

Gronau & Zupan,
hep-ph/0407002:

6 observables: $C, S, \Delta C, \Delta S, \Gamma_+, \Gamma_-$

8 theoretical parameters: $t_+, t_-, p_+, p_-, \delta_\pm = \arg(p_\pm/t_\pm), \delta_t = \arg(t_-/t_+), \phi_2$

⇒ Use judicious reparametrization to reduce to 4 observables
& 6 parameters

⇒ Assume flavor $SU(3)$ and use measured rates/limits for

$B^0 \rightarrow K^{*\pm} \pi^\mp, \rho^\mp K^\pm$ and $B^\pm \rightarrow K^{*0} \pi^\pm, \rho^\pm K^0$ to fully constrain parameters

Result:

$$\begin{aligned}\phi_2 &= 102 \pm 19 \text{ (Belle)} \\ &= 94 \pm 16 \text{ (BaBar)} \\ &= 95 \pm 16 \text{ (average)}\end{aligned}$$

BUT:

- ◆ $SU(3)$ breaking effects
- ◆ assumed δ_t small
- ◆ exists a solution near 170



Summary

$B^0 \rightarrow \pi^+\pi^-$: (140 fb⁻¹):

- $A_{\pi\pi} = +0.58 \pm 0.15 \pm 0.07$
 $S_{\pi\pi} = -1.00 \pm 0.21 \pm 0.07$
- observation of CP violation (5.2σ level)
- evidence for direct CP violation (3.2σ)
- $90 \leq \phi_2 \leq 146$ for $|P/T| < 0.45$ (QCDf, pQCD)
- if ϕ_2 at low end of range, large $|P/T|$ favored
- $|P/T| > 0.17$ (95% C.L.)

($> 2\sigma$ disagreement
between Belle and Babar)

Gronau & Rosner,
hep-ph/0405173: 103 ± 17 (Belle + BaBar)

$B^0 \rightarrow \rho^+\pi^-$:

- $C_{\rho\pi} = +0.25 \pm 0.17 + 0.02 - 0.06$
 $S_{\rho\pi} = -0.28 \pm 0.23 + 0.10 - 0.08$

Gronau & Zupan,
hep-ph/0407002: 95 ± 16 (Belle + BaBar)



Backup Slides



Cross checks IV: τ_B and Δm

9346 $B \rightarrow D^- \pi^+$:

$$\tau_B = 1.569 \pm 0.021 \text{ ps}$$

10211 $B \rightarrow D^{*-} \pi^+$:

$$\tau_B = 1.589 \pm 0.021 \text{ ps}$$

(PDG: $\tau_B = 1.537 \pm 0.015$)

1529 $B \rightarrow \pi\pi$:

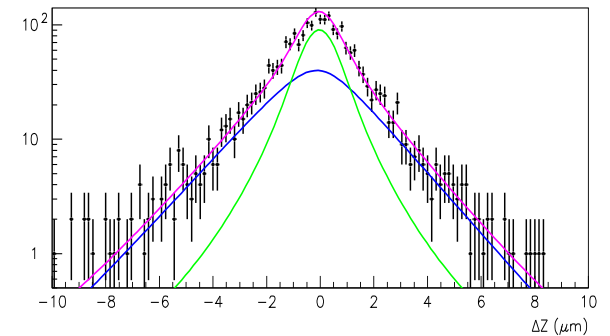
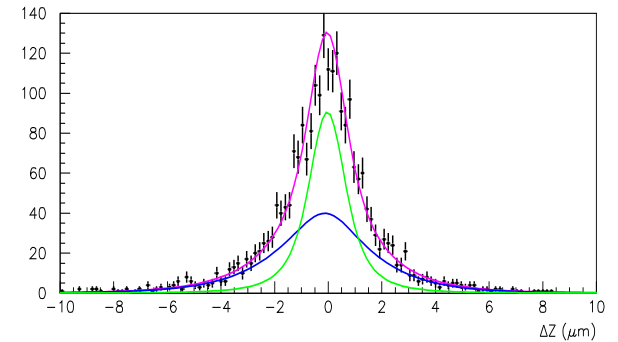
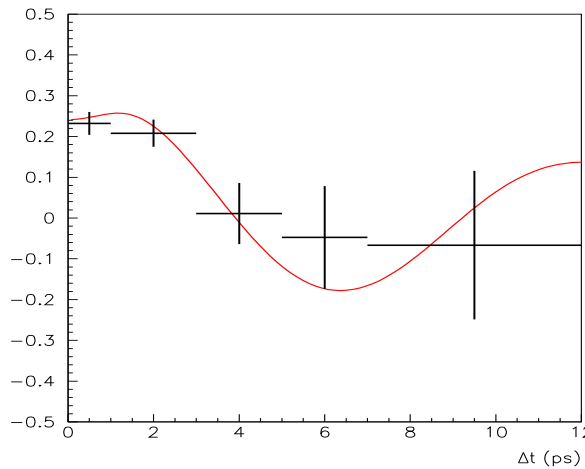
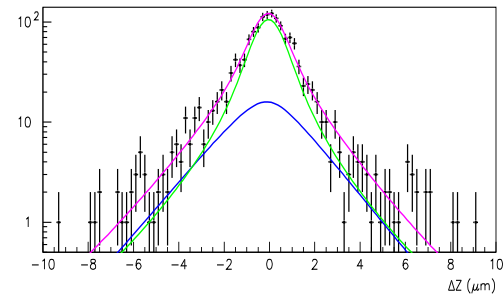
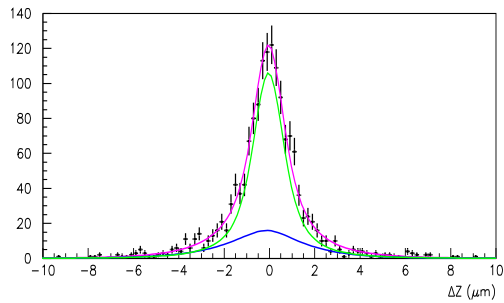
$$\tau_B = 1.46 \pm 0.09 \text{ ps}$$

2358 $B \rightarrow K^\pm \pi^\mp$:

$$\tau_B = 1.52 \pm 0.06 \text{ ps}$$

$$\Delta m = 0.529^{+0.044}_{-0.072}$$

(PDG: $\Delta m = 0.502 \pm 0.007$)





Cross checks V: Toy Monte Carlo (10^7 exps.)

$$A_{\pi\pi} = 0.$$

$$S_{\pi\pi} = 0.$$

$$A_{\pi\pi} = 0.549$$

$$S_{\pi\pi} = -0.836$$

56% out of physical region
27% out of ellipse

