New Results on *CP* Violation from Belle: $B \to \pi^+\pi^-$ with 140 fb^{-1}

(hep−ex/0401029)

Alan Schwartz
University of Cincinnati

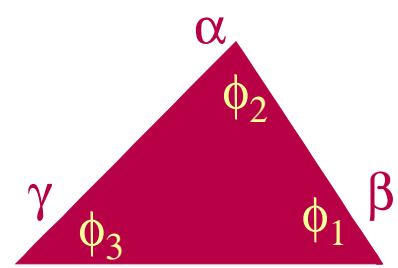
- Introduction
- Event Selection
- Unbinned max. likelihood fit for $A_{\pi\pi}$, $S_{\pi\pi}$
- Cross checks, including binned ML fit
- Constraints on ϕ_2 and $|P/T|$
- Summary

Introduction

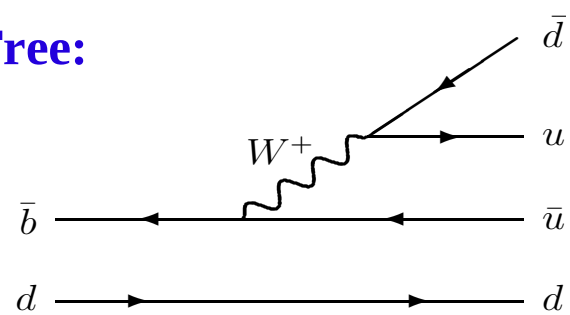
$$\frac{N_{\overline{B}^0\to\pi\pi} - N_{B^0\to\pi\pi}}{N_{\overline{B}^0\to\pi\pi} + N_{B^0\to\pi\pi}} = \mathcal{A}_{\pi\pi}\cos(\Delta m\,\Delta t) + \mathcal{S}_{\pi\pi}\sin(\Delta m\,\Delta t)$$

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

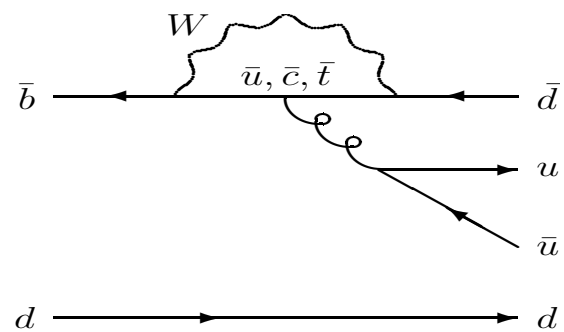
$$\boxed{\lambda_{\pi\pi} = \left(\frac{q}{p}\right)\frac{A(\overline{B}^0\to\pi^+\pi^-)}{A(B^0\to\pi^+\pi^-)} = e^{i2\phi_2} \quad \text{(no penguin)}}$$



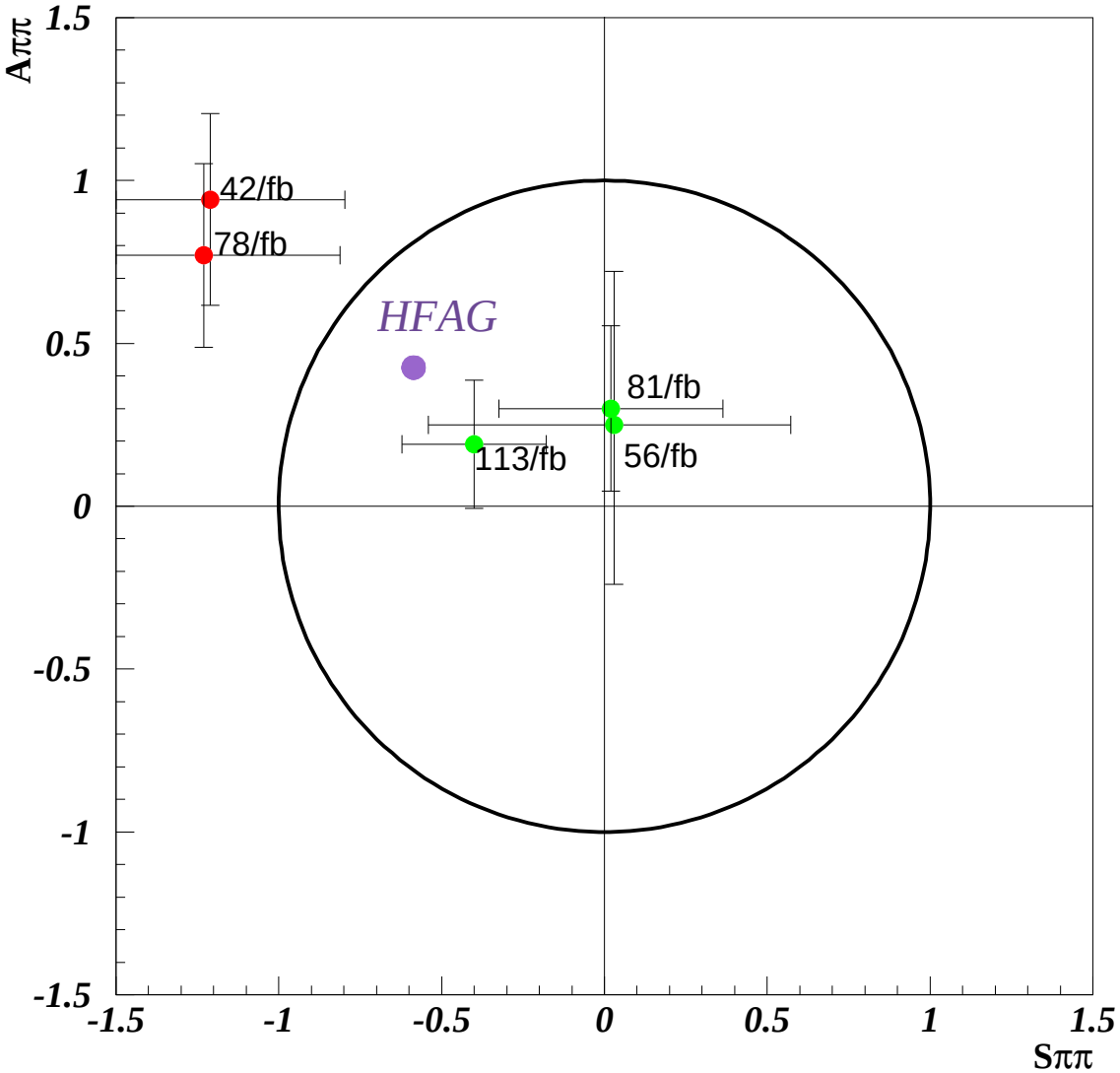
Tree:



Penguin:



Previous status (Aug 2003)



HFAG :

$A_{\pi\pi} = 0.37 \pm 0.16$

$S_{\pi\pi} = -0.56 \pm 0.20$

$\chi^2 = 6.1 \Rightarrow$

CL = 0.047

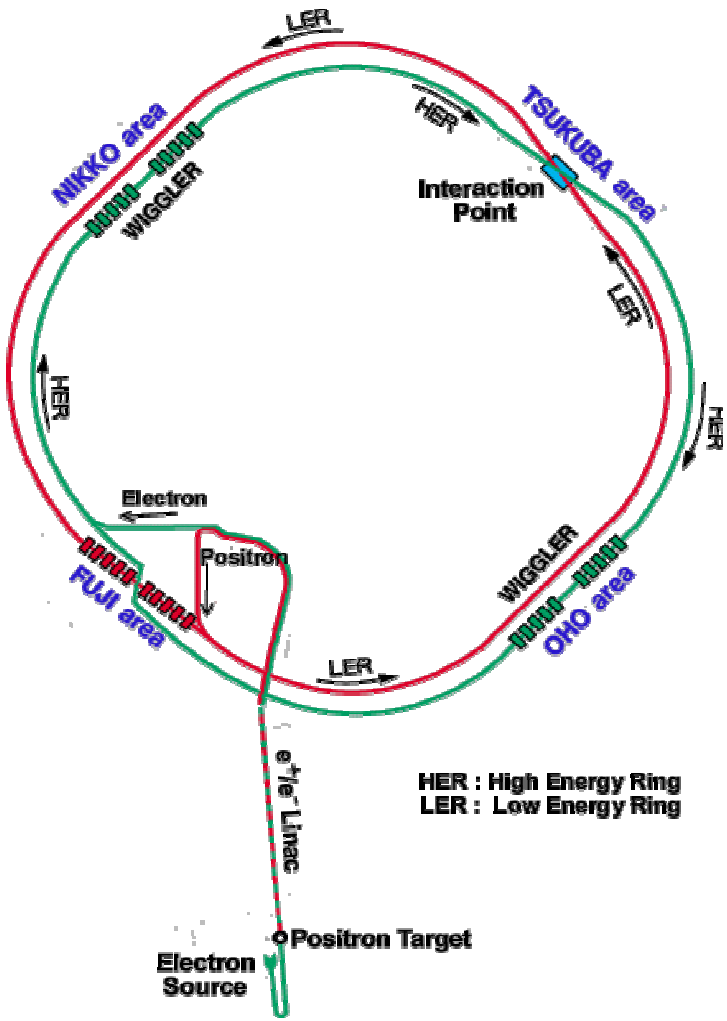
(2σ)

Improvements since last Belle result

- additional data:
  - 2000–2002: 78 fb^{-1} *(re−analyzed)*
  - 2002–2003: 62 fb^{-1}
- signal fraction determined via 2D fit in $\Delta E - m_{bc}$
- more efficient continuum suppression algorithm (also used for $B^0 \to \pi^0\pi^0$ measurement)
- new check: binned maximum likelihood fit to Δt (different resolution functions, done blindly)

- flavor tag, vertexing, resolution function, unbinned ML fitting procedure, are the same as used for $\sin 2\phi_1$ measurement (hep−ex/0308036)

Belle at KEKB

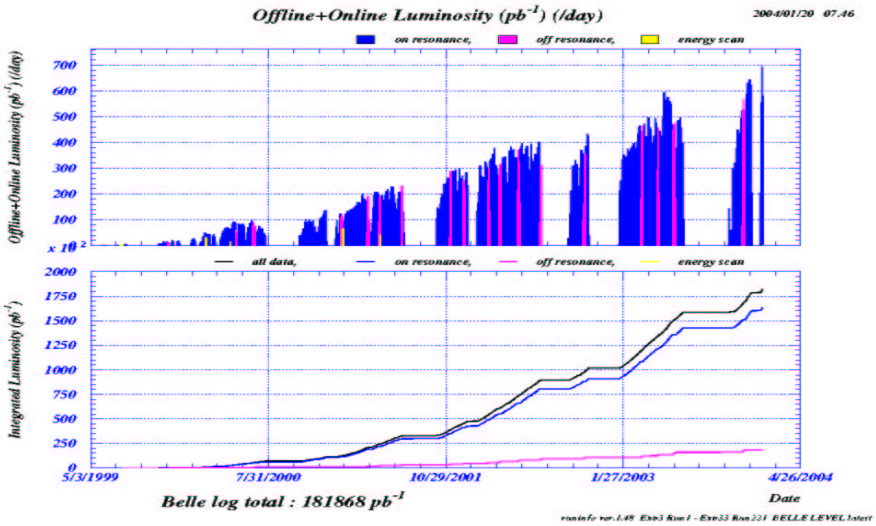


$e^+e^- \rightarrow \Upsilon(4S) \rightarrow B\bar{B}$

3.5 GeV on 8 GeV

$\int L\,dt = 190\ fb^{-1}$ **on Feb 4th, 2004**

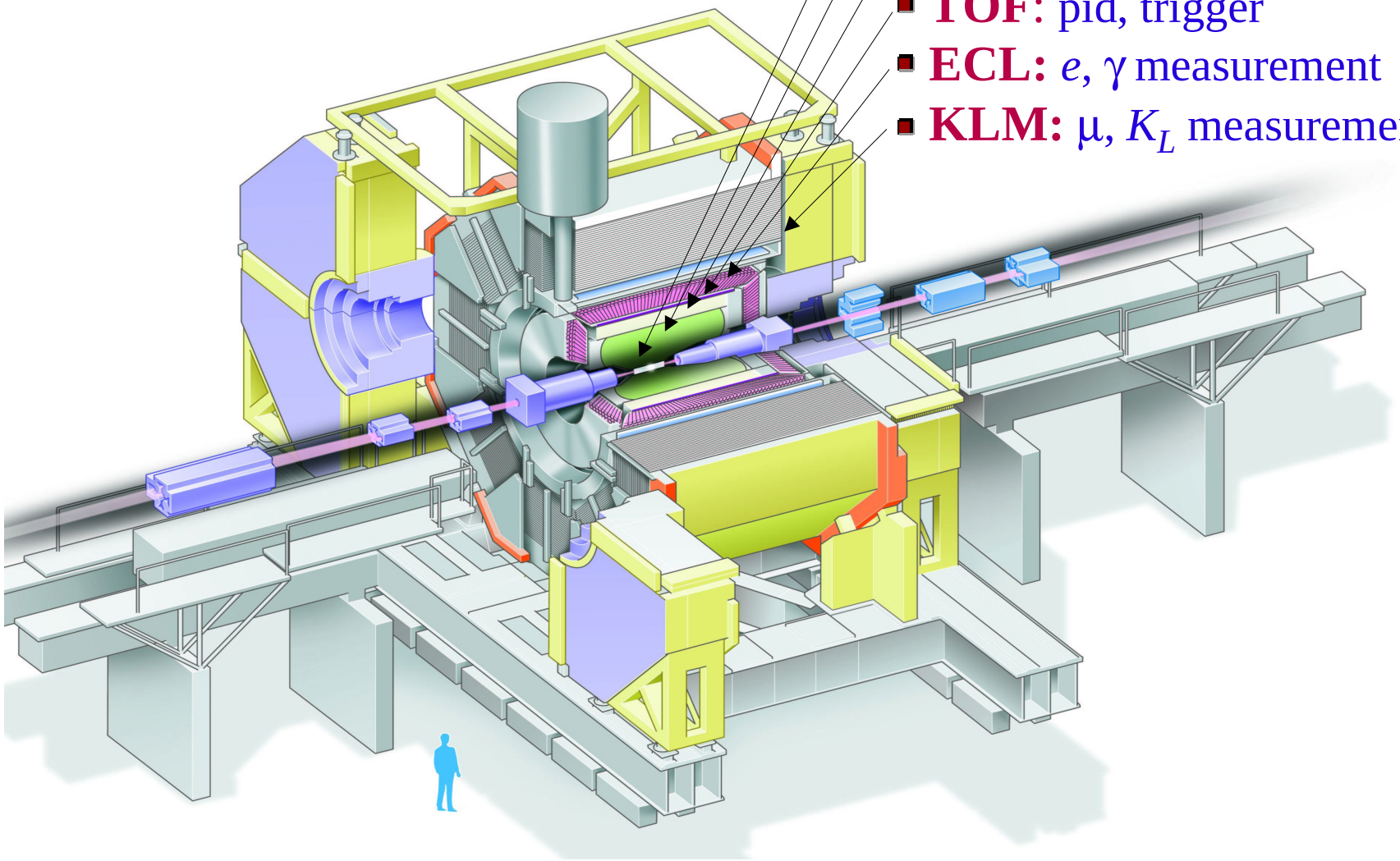
(L_{peak} (max) = 1.13×10^{34} $cm^{-2}\,s^{-1}$)



140 fb^{-1} on resonance (152M BB)
by June 2003 **(results presented here)**

The Belle detector

- **SVD:** vertexing (lifetime)
- **CDC:** tracking, *dE/dx* for pid
- **ACC:** aerogel Cerenk. Counter
- **TOF**: pid, trigger
- **ECL:** e, γ measurement
- **KLM:** μ, K_L measurement



Analysis Overview

1) $B \to \pi^+\pi^-$ selection:

$$m_{bc} = \sqrt{(E^*_{beam})^2 - (p^*_B)^2}$$

$$\Delta E = E^*_B - E^*_{beam}$$

($5.271 < m_{bc} < 5.287$ GeV/c^2)

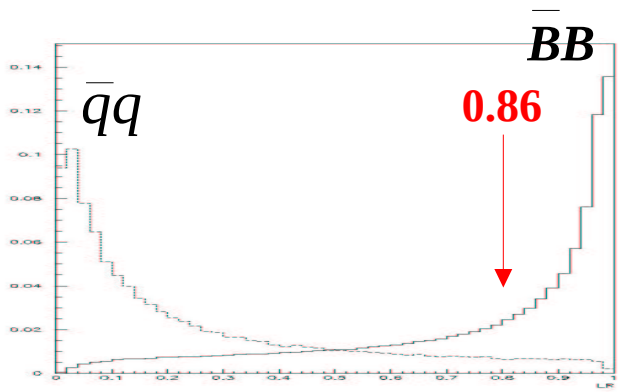
($|\Delta E| < 0.064$ GeV)

2) Flavor tagging:

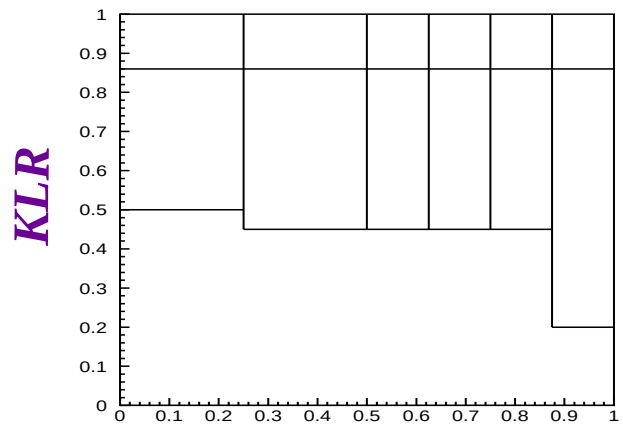
mainly $K^{\pm}$, $\mu^{\pm}$, $e^{\pm}$ output: $q = \pm 1$, quality $r \in (0, 1)$

3) Continuum suppression:

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

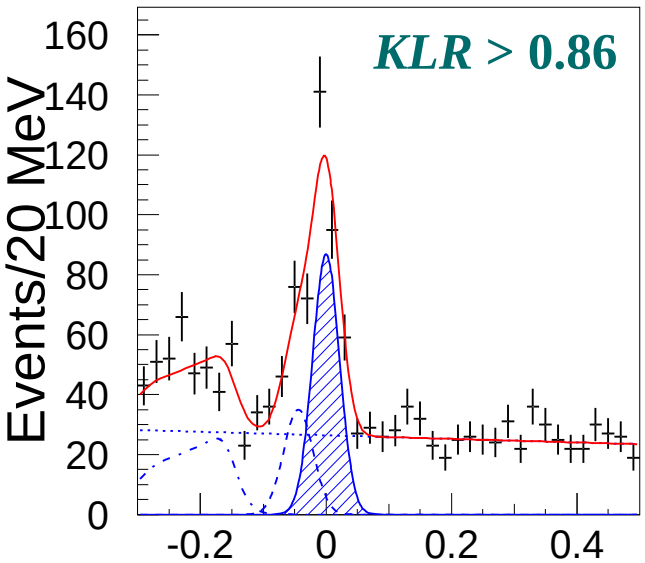


KLR

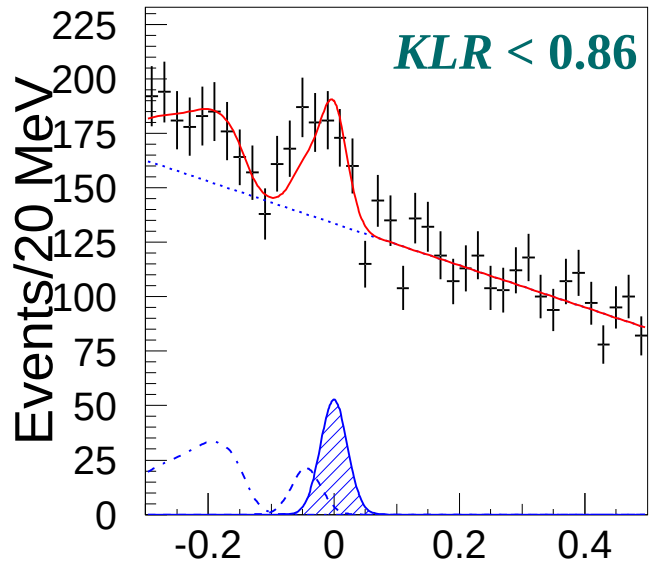


4) Vertexing and Δt fit

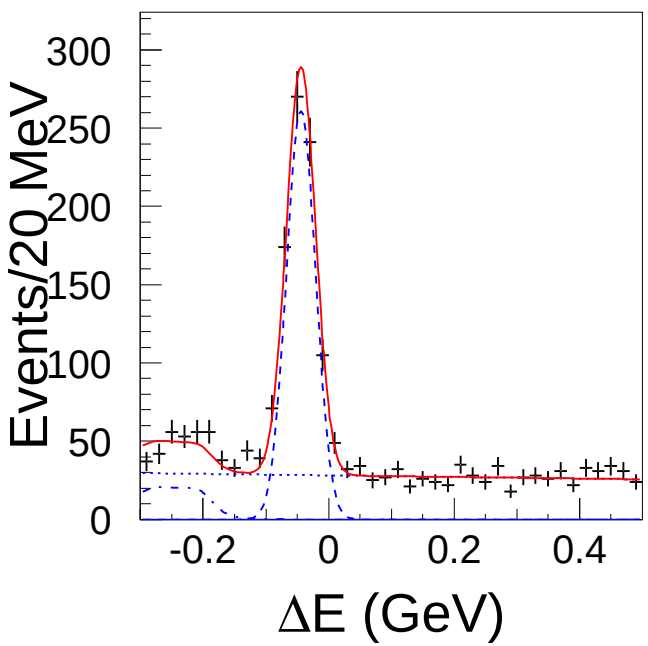
$B^0 \to \pi^+\pi^-$ (and $K^+\pi^-$) final sample



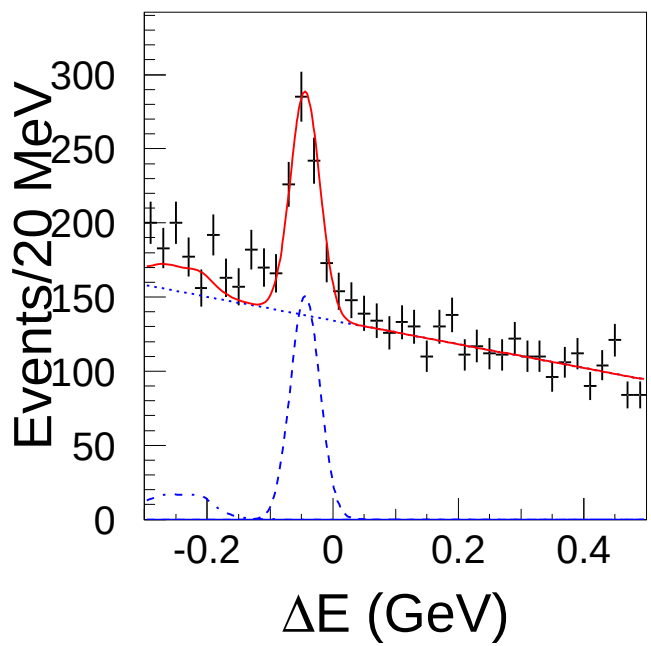
$N_{\pi\pi} = 232$



$N_{\pi\pi} = 141$



$N_{K\pi} = 609$



$N_{K\pi} = 303$

Maximum likelihood fit to Δt

$$\mathcal{L}_i = \int \Big[f_{\pi\pi} P_{\pi\pi}(\Delta t') + f_{K\pi} P_{K\pi}(\Delta t') \Big] \cdot R_{hh}(\Delta t_i - \Delta t') + f_{q\bar{q}} P_{q\bar{q}}(\Delta t') \cdot R_{q\bar{q}}(\Delta t_i - \Delta t')\, dt'$$

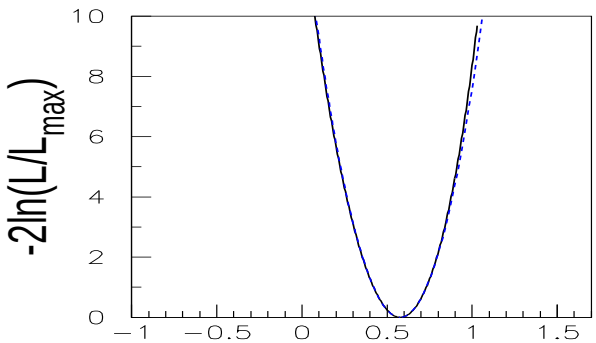
$$P^{(\ell)}_{B^0 \to \pi\pi} = \frac{e^{-|\Delta t|/\tau_B}}{\mathcal{N}} \Big\{ 1 + q(1 - 2\omega_\ell) \big[\mathcal{A}_{\pi\pi} \cos(\Delta m\, \Delta t) + \mathcal{S}_{\pi\pi} \sin(\Delta m\, \Delta t) \big] \Big\}$$

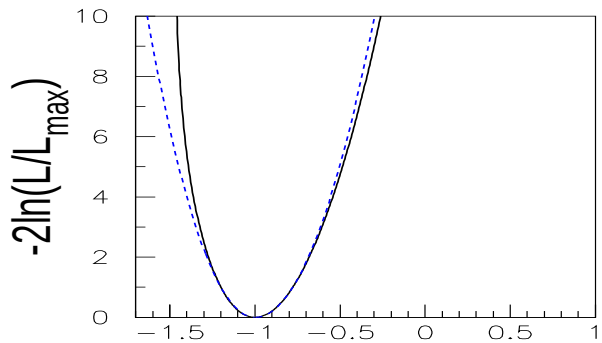
$$P_{K\pi} = \frac{e^{-|\Delta t|/\tau_B}}{2\tau_B}$$

$$P_{q\bar{q}} = f \frac{e^{-|\Delta t|/\tau_{q\bar{q}}}}{2\tau_{q\bar{q}}} + (1 - f)\, \delta(\Delta t)\ ,$$

$$f_{\pi\pi} = \frac{F_{\pi\pi}(\Delta E,\, M_{bc}) \cdot f_\ell(\pi\pi)}{[\, F_{\pi\pi}(\Delta E,\, M_{bc}) + F_{K\pi}(\Delta E,\, M_{bc})\,] \cdot f_\ell(\pi\pi) + F_{q\bar{q}}(\Delta E,\, M_{bc}) \cdot f_\ell(q\bar{q})}$$

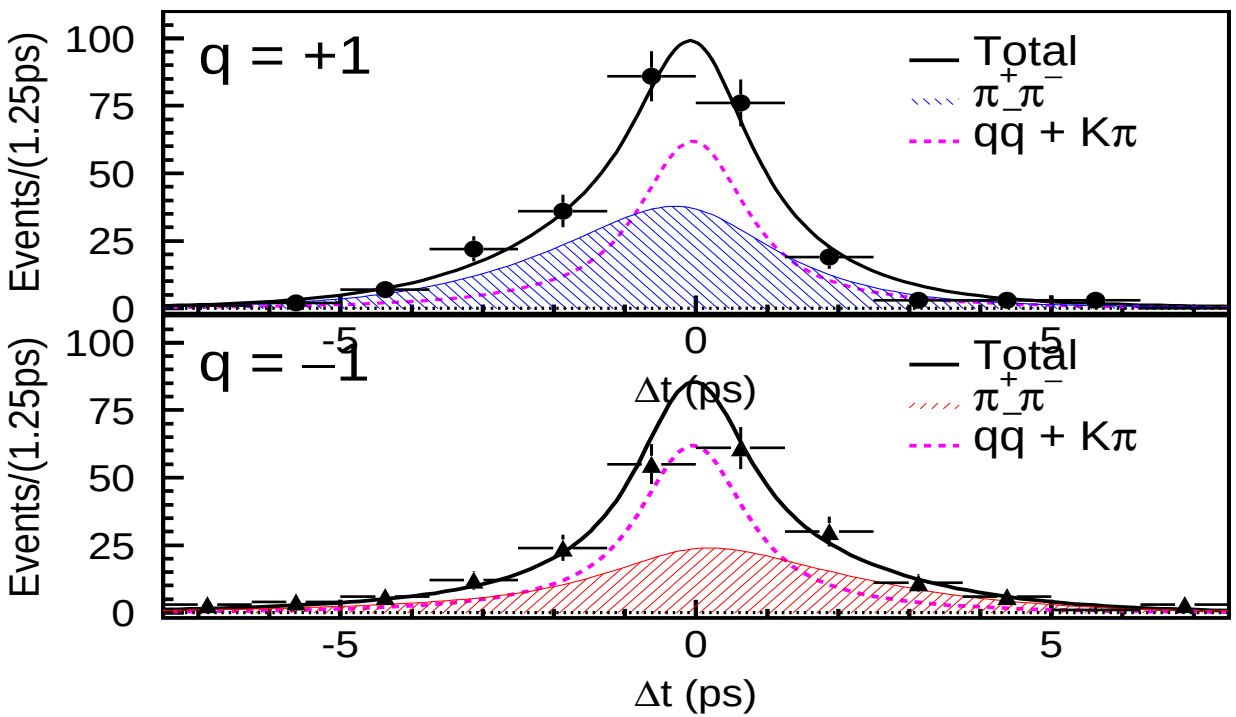
Results of Fit I





$A_{\pi\pi} = 0.58\ ^{+0.15}_{-0.16}$ **(MINOS)**

$S_{\pi\pi} = -1.00\ ^{+0.22}_{-0.20}$ **(MINOS)**



264 events
(*KLR* > 0.86)
χ^2 = 12.5/12

219 events
(*KLR* > 0.86)
χ^2 = 14.7/16

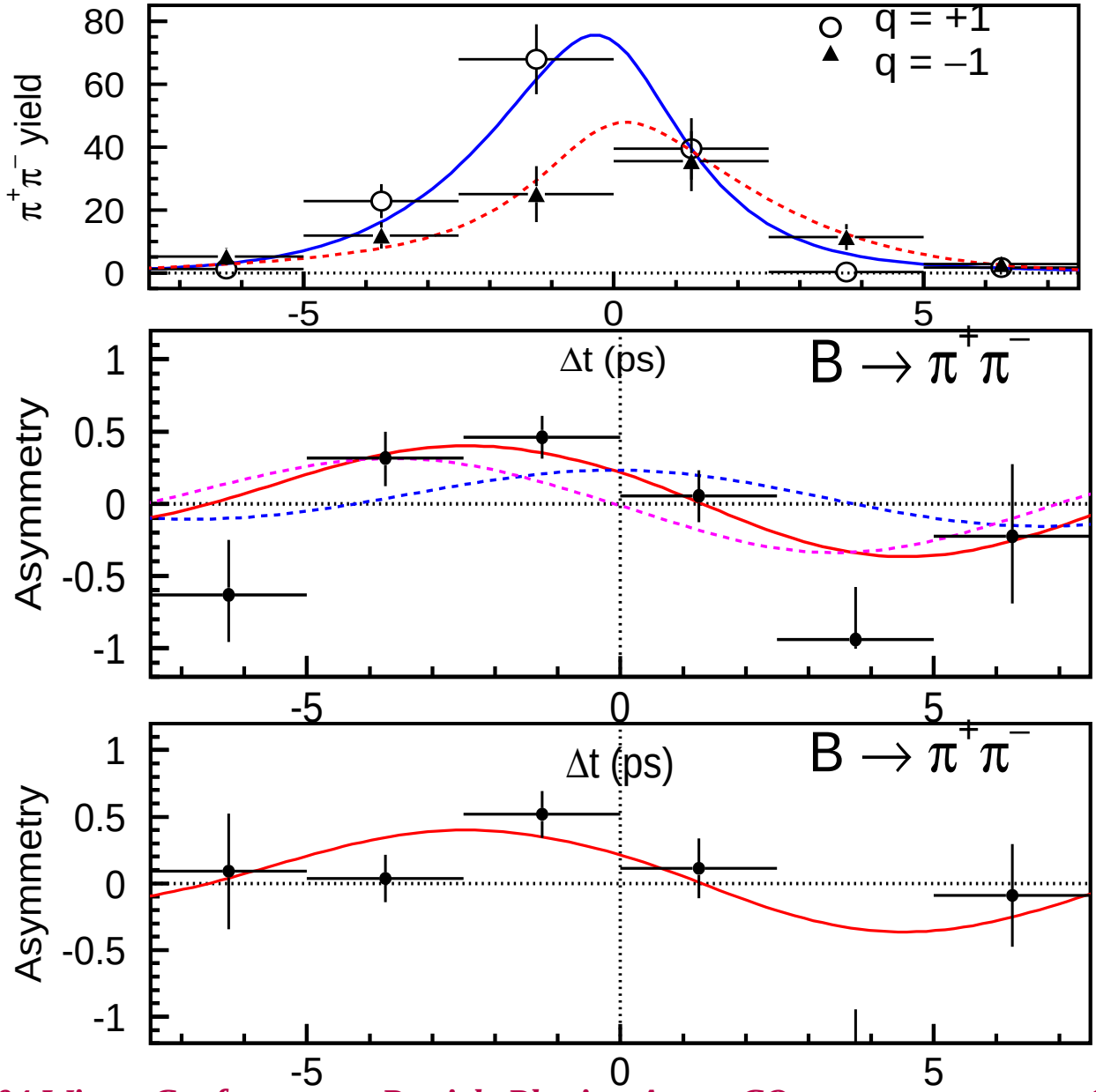
Results of Fit II

Fitting for event yield as function of Δt : (KLR > 0.86)

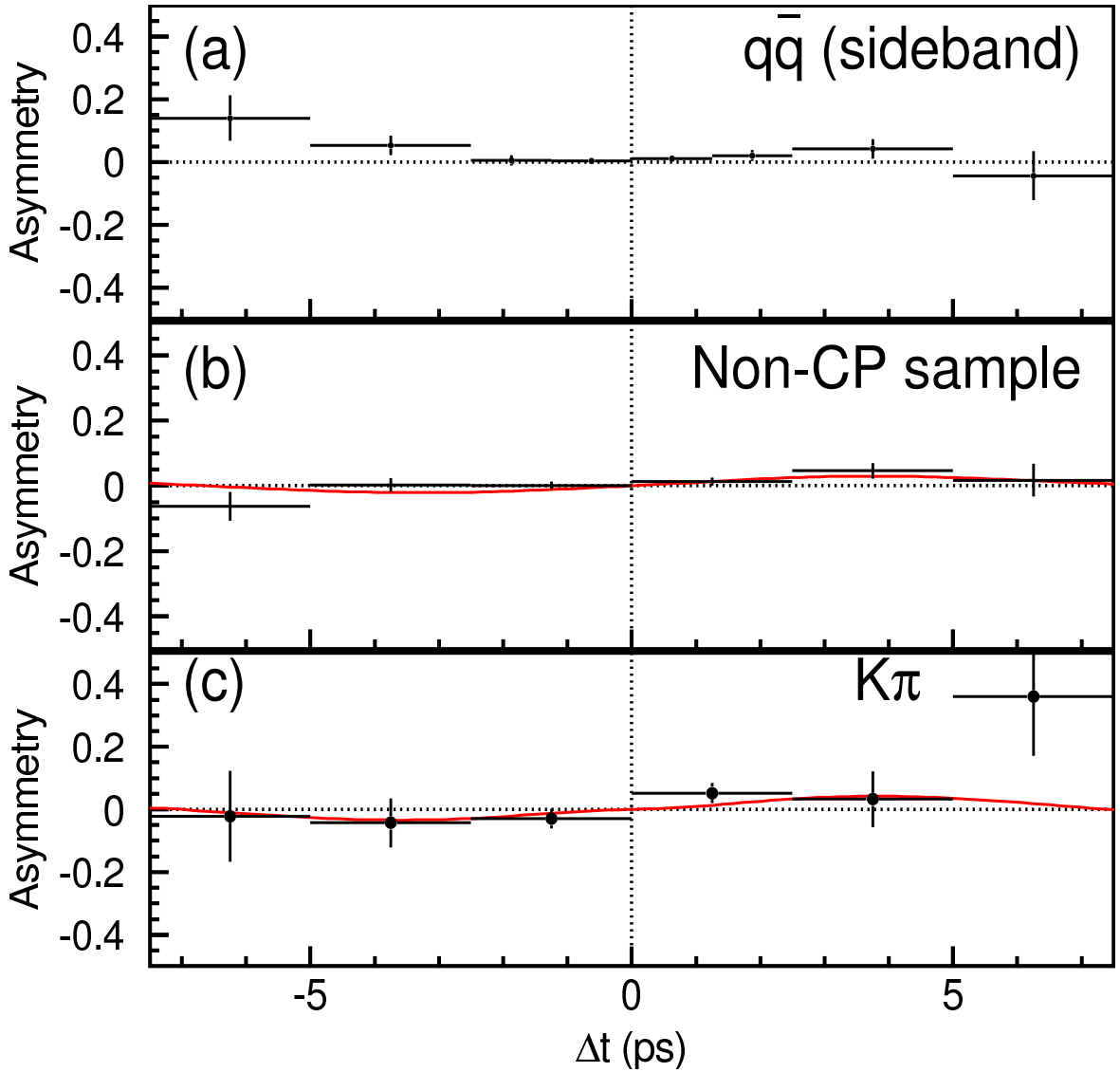
$A_{\pi\pi} = 0.58$

$S_{\pi\pi} = -1.00$

all *KLR*



Cross checks I: other CP asymmetries



Sideband:

23170 B^0 tags

22736 B^0 tags

***Asymm* = 0.95 ±0.47%**

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

$A_{\pi\pi}$ = –0.02 ±0.03

$S_{\pi\pi}$ = 0.11 ±0.04

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

$A_{\pi\pi}$ = 0.01 ±0.03

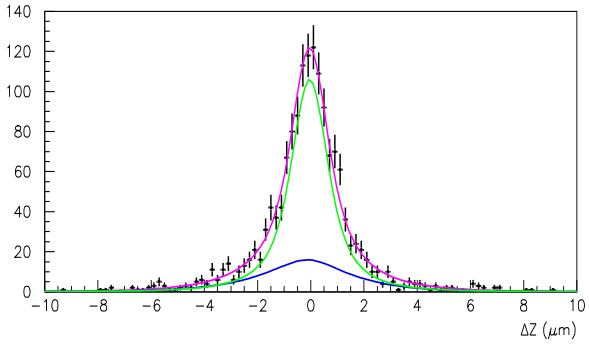
$S_{\pi\pi}$ = 0.05 ±0.04

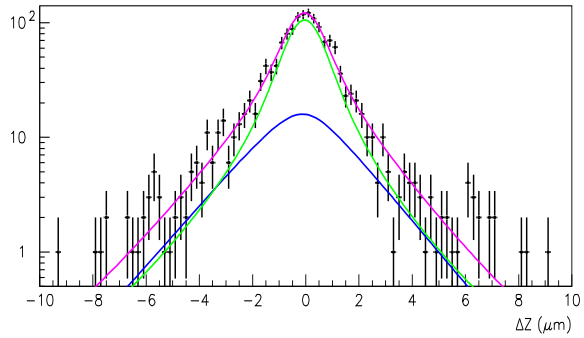
2358 $B \to K^\pm \pi^\mp$:

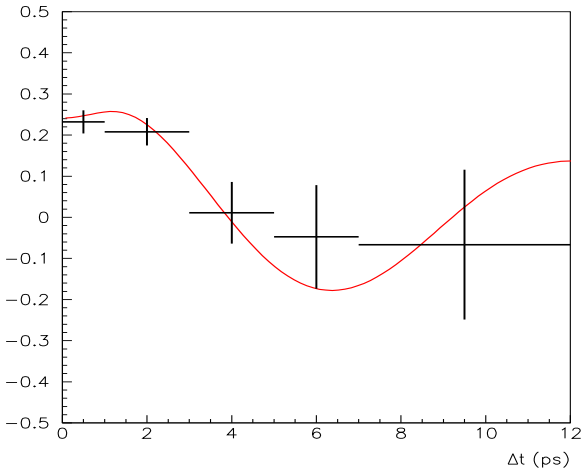
$A_{K\pi}$ = –0.02 ±0.03

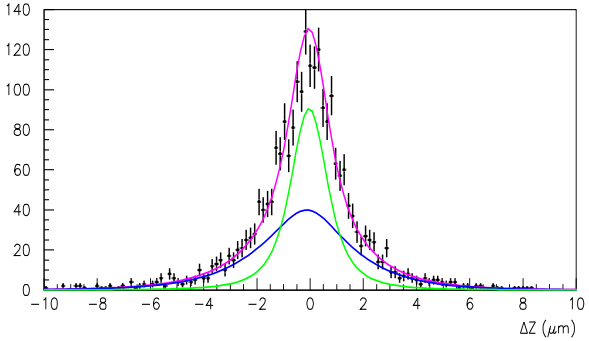
$S_{K\pi}$ = 0.11 ±0.04

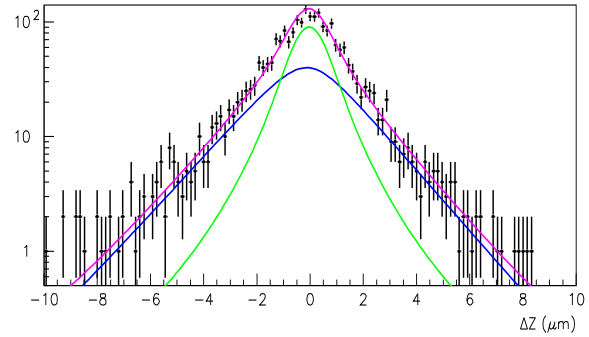
Cross checks II: τ_B and Δm











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

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

2358 $B \to K^{\pm}\pi^{\mp}$:

$\tau_B = 1.52 \pm 0.06$ ps

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

9346 $B \to D^{-}\pi^{+}$:

$\tau_B = 1.569 \pm 0.021$ ps

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

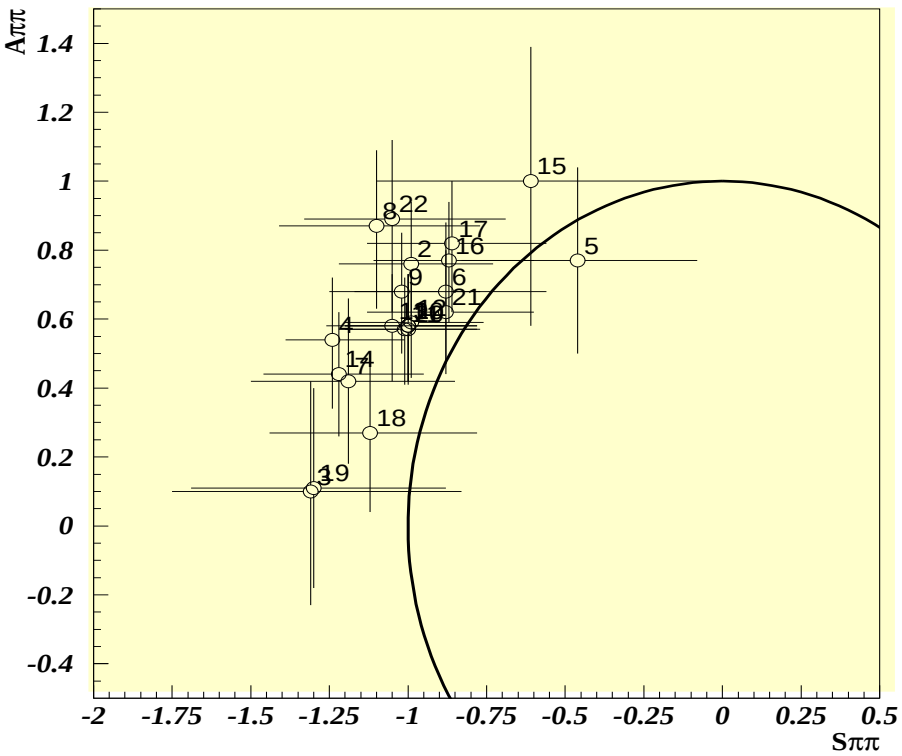
$\tau_B = 1.589 \pm 0.021$ ps

1529 $B \to \pi\pi$:

$\tau_B = 1.46 \pm 0.09$ ps

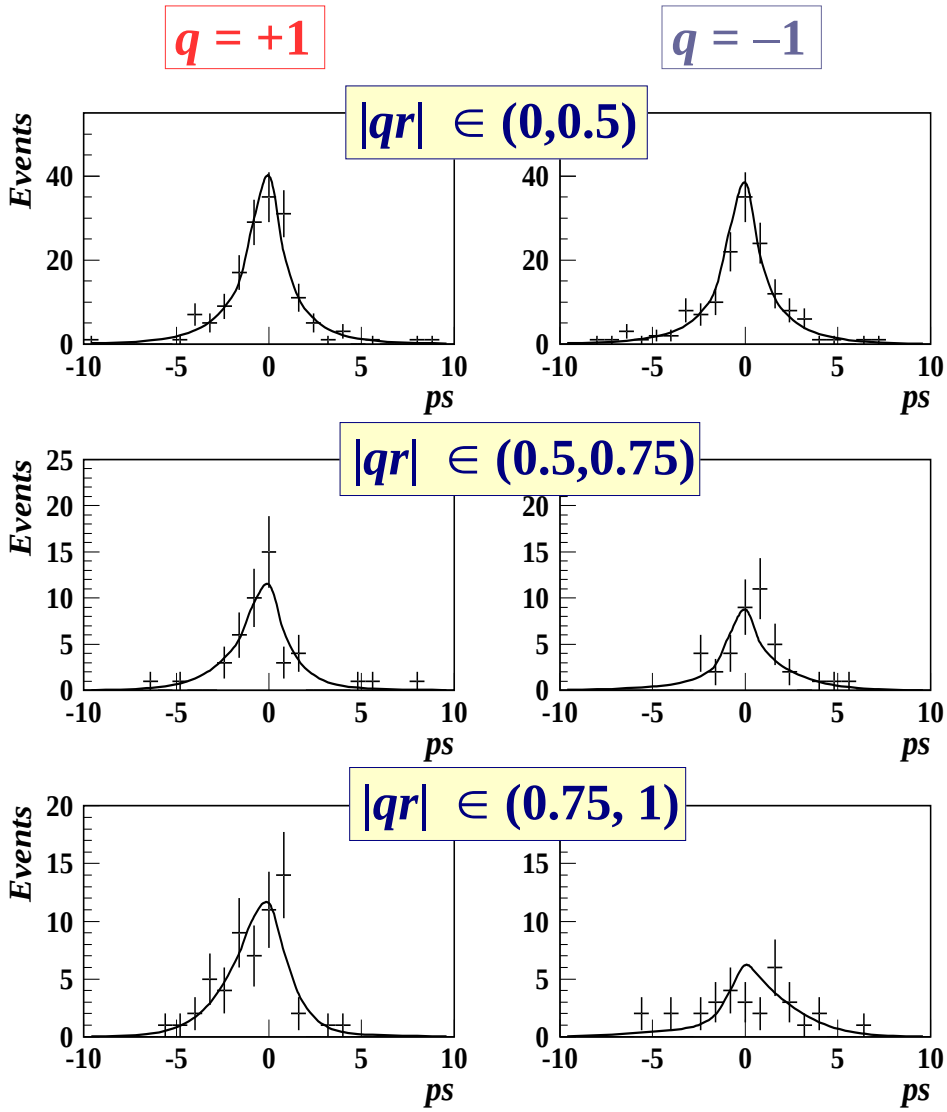
Cross checks III: various subsamples

Subsample	$N_{tot}(\pi\pi/K\pi/\bar{q}q)$	$A_{\pi\pi}$	$S_{\pi\pi}$
default	1529(365.5/135.4/1028.1)	$\mathbf{+0.58^{+0.15}_{-0.16}}$	$\mathbf{-1.00^{+0.22}_{-0.20}}$
$KLR > 0.86$	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)	$+0.42^{+0.24}_{-0.24}$	$-1.19^{+0.34}_{-0.31}$
$\lvert\Delta E\rvert < 1\sigma_{\Delta E}$	623(171.1/60.0/391.8)	$+0.87^{+0.22}_{-0.24}$	$-1.10^{+0.33}_{-0.31}$
$\lvert\Delta E\rvert > 1\sigma_{\Delta E}$	1131(292.7/99.4/738.9)	$+0.68^{+0.17}_{-0.18}$	$-1.02^{+0.25}_{-0.23}$
$\lvert\Delta t\rvert < 15$(ps)	1520(364.4/134.8/1020.8)	$+0.58^{+0.15}_{-0.16}$	$-1.00^{+0.22}_{-0.20}$
$\lvert\Delta t\rvert < 10$(ps)	1516(363.4/134.3/1018.3)	$+0.57^{+0.15}_{-0.16}$	$-1.01^{+0.23}_{-0.21}$
$\lvert\Delta t\rvert < 8$(ps)	1512(360.9/133.7/1017.4)	$+0.59^{+0.15}_{-0.16}$	$-0.99^{+0.23}_{-0.21}$
$\lvert\Delta t\rvert < 5$(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)	$+1.00^{+0.39}_{-0.42}$	$-0.61^{+0.57}_{-0.49}$
$\lvert qr\rvert > 0.75$	185(81.6/33.7/69.7)	$+0.77^{+0.17}_{-0.18}$	$-0.87^{+0.27}_{-0.24}$
$\lvert qr\rvert > 0.875$	94(51.2/22.9/19.9)	$+0.82^{+0.18}_{-0.20}$	$-0.86^{+0.30}_{-0.27}$
$\lvert qr\rvert < 0.875$	1435(314.3/112.5/1008.2)	$+0.27^{+0.23}_{-0.23}$	$-1.12^{+0.34}_{-0.32}$
$\lvert qr\rvert < 0.75$	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 IV: independ. analysis (binned fit)

- binned maximum likelihood fit
- *KLR* > 0.86 (less $\bar{q}q$ 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

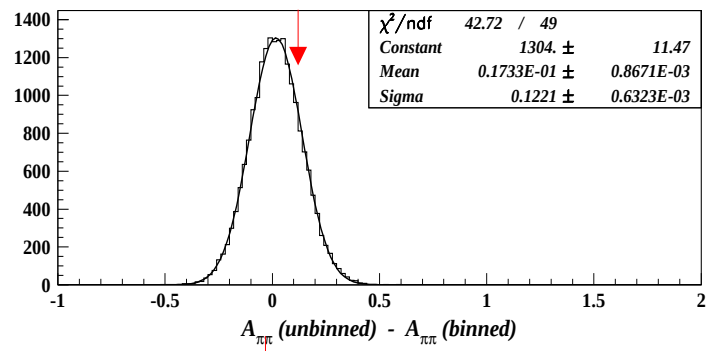


Independ. analysis (binned fit) cont'd

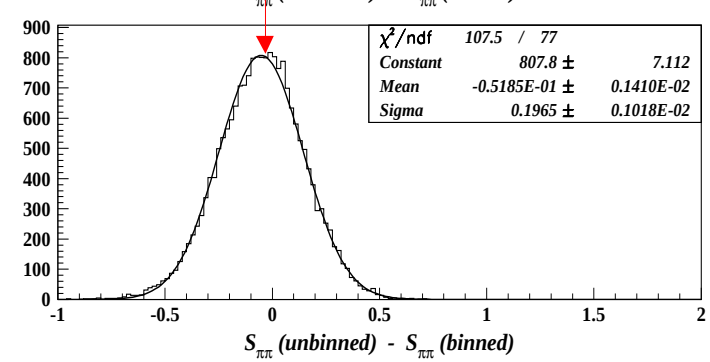
Fit	$A_{\pi\pi}$	$S_{\pi\pi}$	χ^2/d.o.f.
Binned ($KLR > 0.86$)	$+0.654^{+0.190}_{-0.194}$	$-0.943^{+0.278}_{-0.254}$	0.60
Binned ($KLR > 0.86$, $\lvert\Delta t\rvert < 10$ ps)	$+0.738^{+0.228}_{-0.231}$	$-0.913^{+0.312}_{-0.285}$	0.68
Unbinned ($KLR > 0.86$)	$+0.76^{+0.18}_{-0.19}$	$-0.99^{+0.26}_{-0.23}$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

Toy MC study: 20000 expt's

$\sigma(\Delta A_{\pi\pi}) = 0.12$



$\sigma(\Delta S_{\pi\pi}) = 0.20$

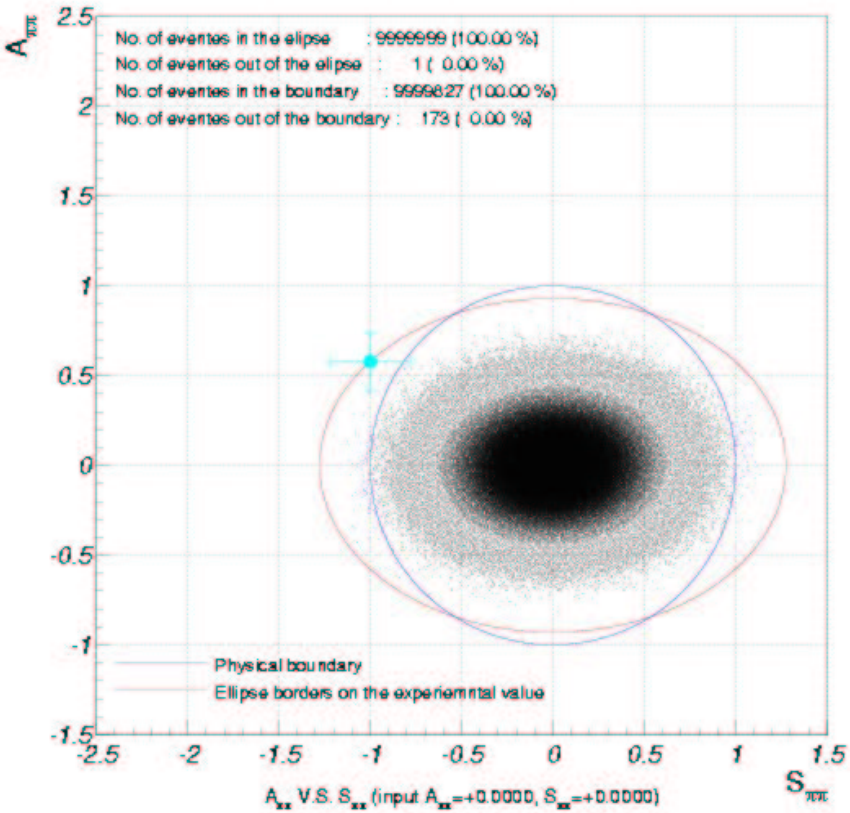


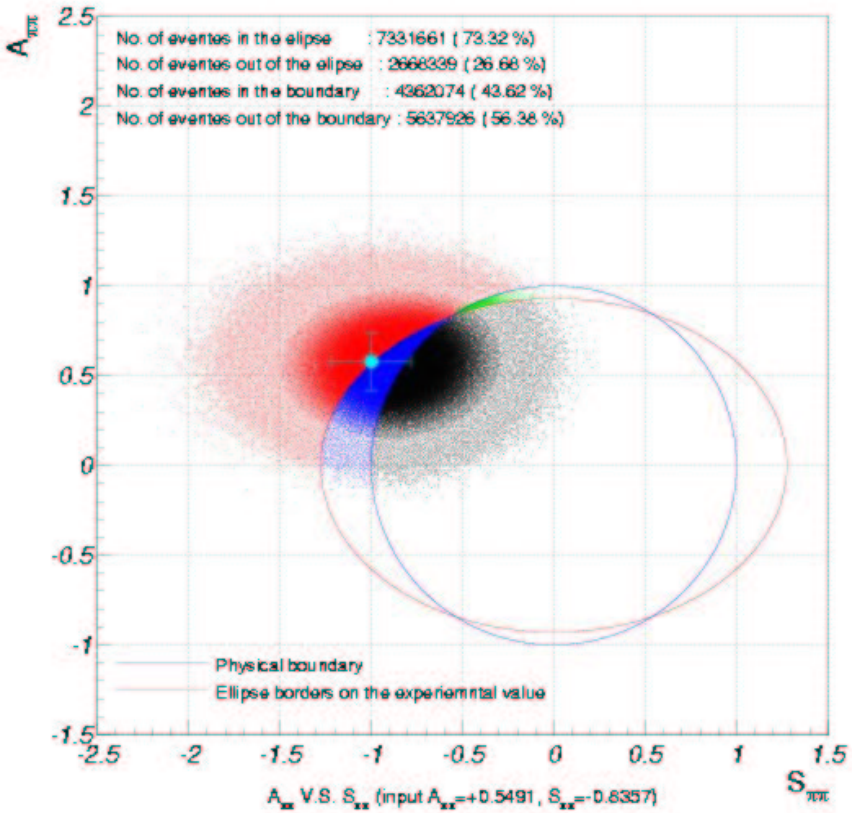
Cross checks V: Toy Monte Carlo (10^7 *exps.*)

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

$A_{\pi\pi} = 0.549$
$S_{\pi\pi} = -0.836$

56% out of physical region
27% out of ellipse



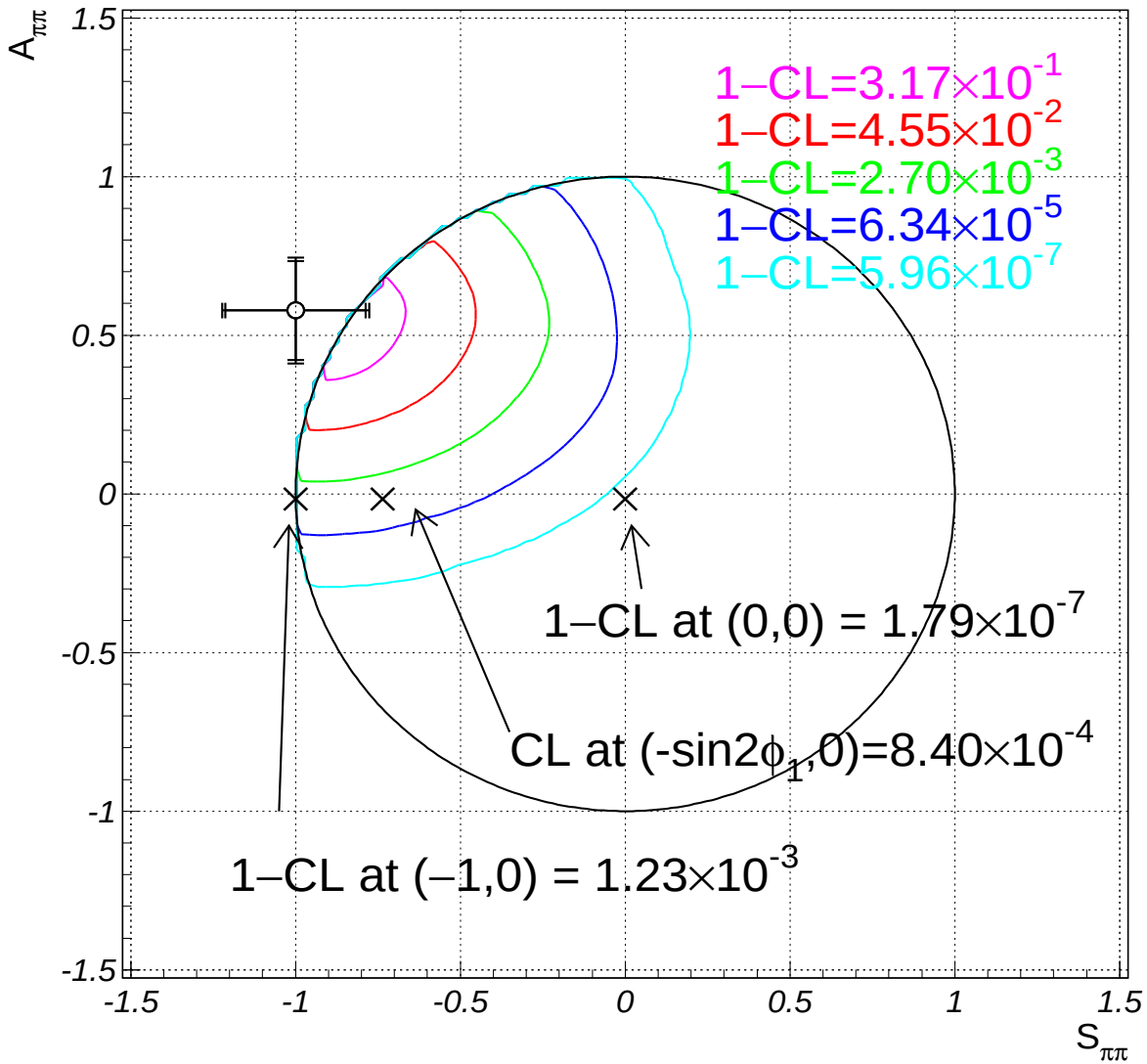


Systematic Uncertainties

Uncertainty	$\boldsymbol{A_{\pi\pi}}$	$\boldsymbol{S_{\pi\pi}}$
Wrong tag fraction	± 0.009	± 0.009
τ_B, Δm, $A_{K\pi}$	± 0.024	± 0.007
Resolution function	± 0.010	± 0.020
Background shape	± 0.014	± 0.021
Background fractions	± 0.028	± 0.025
Fit bias	± 0.018	± 0.023
Vertexing	± 0.039	± 0.045
Tag side interference	± 0.027	± 0.011
Total	$\boldsymbol{\pm 0.066}$	$\boldsymbol{\pm 0.066}$

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 ⇒ observation of *CP* violation

$A_{\pi\pi}$ = 0 corresponds to ≥3.2σ statistical fluctuation (any $S_{\pi\pi}$) ⇒ evidence for direct *CP* violation

Constraints upon ϕ_2 (α) and |P/T|

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

$$A(B^0 \to \pi^+\pi^-) = -\left(|T|e^{i\delta_T}e^{i\phi_3} + |P|e^{i\delta_P}\right)$$
$$A(\overline{B}^0 \to \pi^+\pi^-) = -\left(|T|e^{i\delta_T}e^{-i\phi_3} + |P|e^{i\delta_P}\right)$$

$$\Rightarrow \quad \lambda_{\pi\pi} \equiv Im\left(\frac{q}{p}\frac{\overline{A}_{\pi\pi}}{A_{\pi\pi}}\right) = e^{i\phi_2}\frac{1+|P/T|\,e^{i(\delta+\phi_3)}}{1+|P/T|\,e^{i(\delta-\phi_3)}}$$

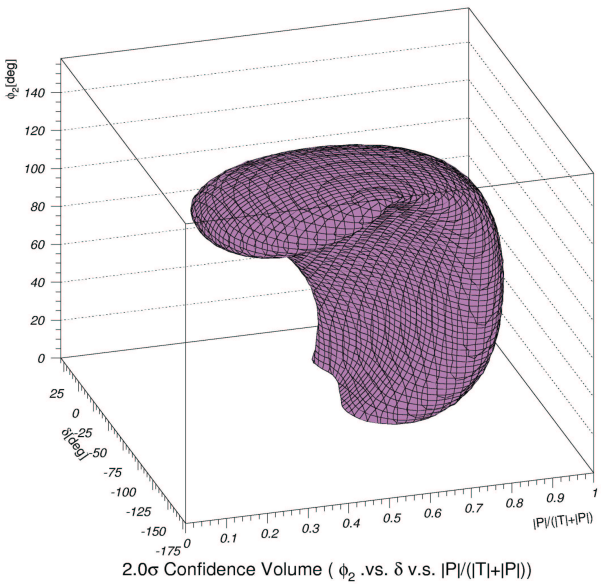
$$(\delta \equiv \delta_P - \delta_T)$$

Take ϕ_1=0.736 $\pm$0.049
$\Rightarrow$ 2 constraints &
3 unknowns
(ϕ_2, δ, |P/T|)

$$A_{\pi\pi} \equiv \frac{|\lambda|^2-1}{|\lambda|^2+1} = \frac{-2|P/T|\sin(\phi_1+\phi_2)\sin\delta}{1-2|P/T|\cos(\phi_1+\phi_2)\cos\delta+|P/T|^2}$$

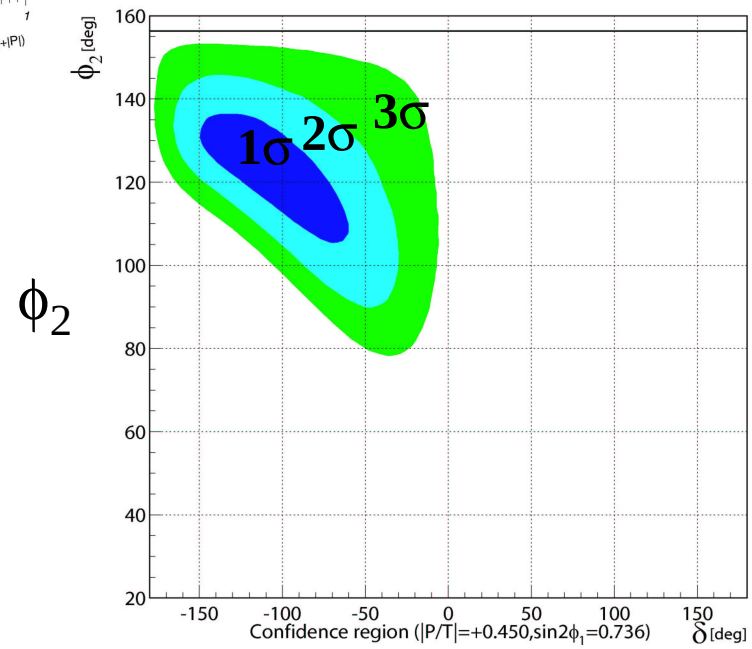
$$S_{\pi\pi} \equiv \frac{2Im\lambda}{|\lambda|^2+1}$$
$$= \frac{2|P/T|\sin(\phi_1-\phi_2)\cos\delta+\sin 2\phi_2-|P/T|^2\sin 2\phi_1}{1-2|P/T|\cos(\phi_1+\phi_2)\cos\delta+|P/T|^2}$$

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



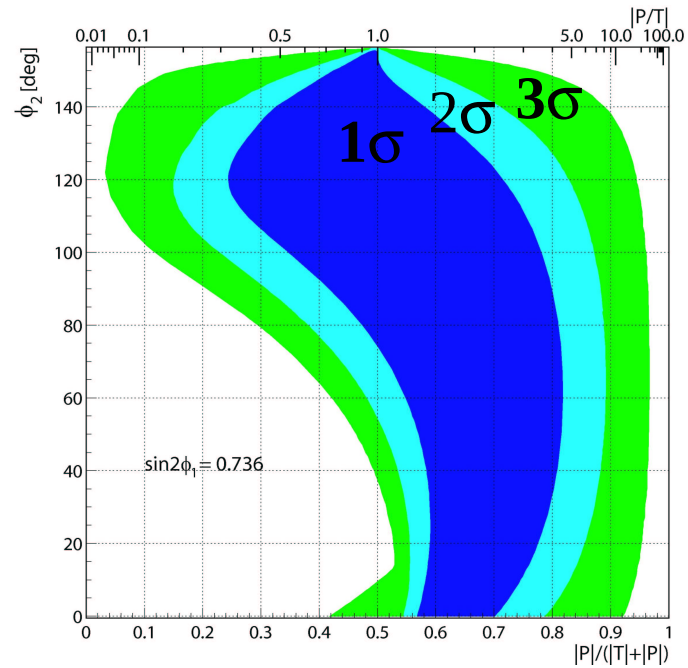
For |P/T|=0.45 (worst case?)
$90^\circ \leq \phi_2 \leq 146^\circ$
(95% C.L.)

For any δ
|P/T| > 0.17
(95% C.L.)



ϕ_2

δ



|P|/(|T|+|P|)

Summary

With 140 fb^{-1} Belle has:

- **Measured a *CP* asymmetry in B→ $\pi^+\pi^-$ decays:**

$$A_{\pi\pi} = +0.58 \pm 0.15 \text{ (stat.)} \pm 0.07 \text{ (syst.)}$$
$$S_{\pi\pi} = -1.00 \pm 0.21 \text{ (stat.)} \pm 0.07 \text{ (syst.)}$$

This is consistent with our 78 fb^{-1} measurement.

- **This constitutes an *observation* of *CP* violation at the 5.2σ level**

- **This constitutes *evidence* for <u>direct</u> *CP* violation at the 3.2σ level**

- **This result gives the model−independent constraints:**

$$90^\circ \leq \phi_2 \leq 146^\circ \text{ (95\% C.L.) for } |P/T| < 0.45$$
$$|P/T| > 0.17 \text{ (95\% C.L.) for all } \delta$$