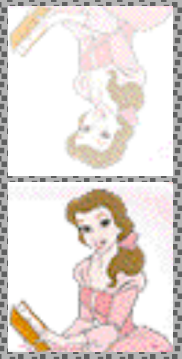
CP Asymmetry in $B^0 \to \pi^+\pi^-$ at Belle



- $B^0 \to \pi^+\pi^-$ and CP asymmetry in CKM
- $e^+e^- \to$ (4S) at KEKB and Belle
- Belle data
  - Measurement of CP asymmetry in $B^0 \to \pi^+\pi^-$
  - Interpretation vis-a-vis CKM
- Future

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Belle Collaboration

$B^0 \to \pi^+\pi^-$ involves ϕ_2 (α) of CKM:

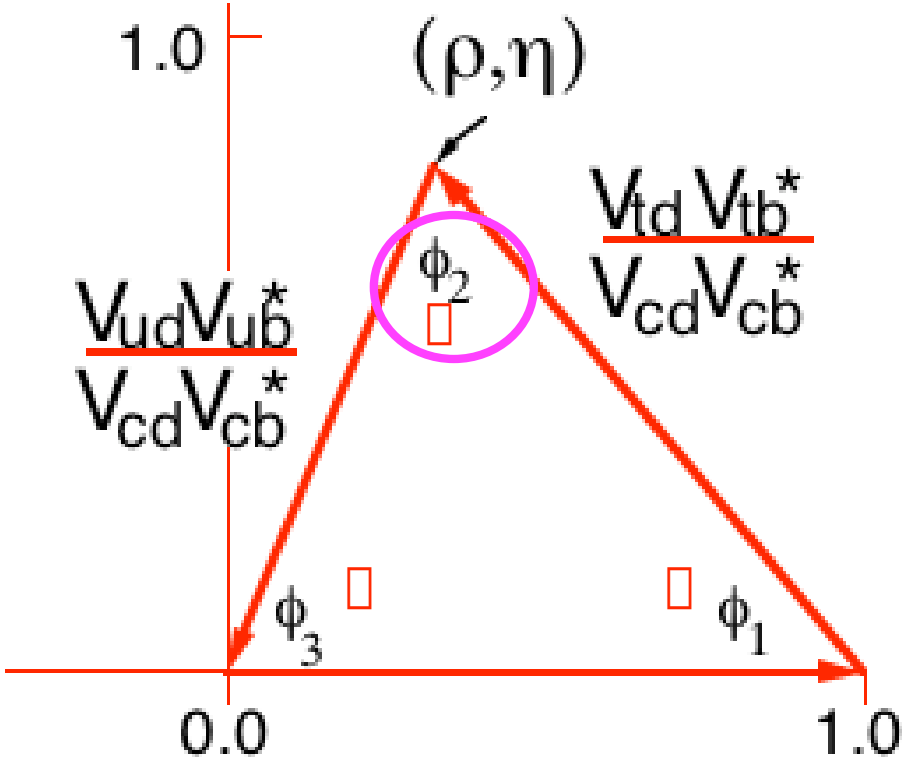
CKM: matrix of W-quark couplings - 3x3, unitary

One condition of unitarity:

$$\frac{V_{ub}^* V_{ud}}{V_{cb}^* V_{cd}} + 1 + \frac{V_{tb}^* V_{td}}{V_{cb}^* V_{cd}} = 0$$

$\rho(\rho+i\eta)$ $\qquad$ $\rho(1-\rho+i\eta)$

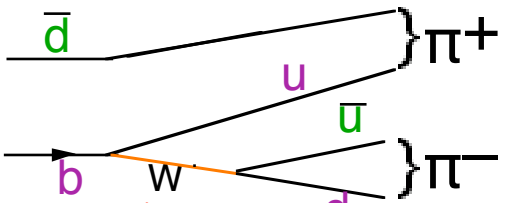
Represented in complex plane as "unitarity triangle"



$B^0 \to \pi^+\pi^-$

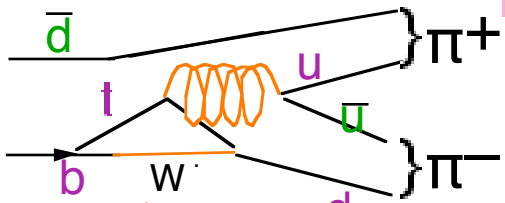
2 paths, each w/wo mixing:

Tree

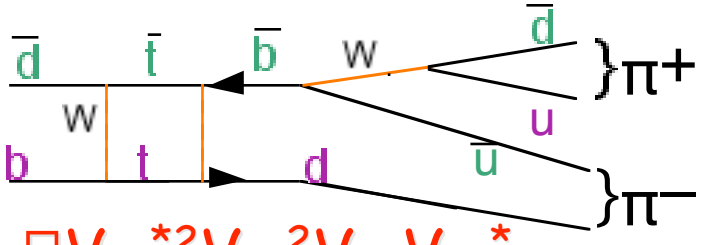


$\propto V_{ub}^* V_{ud}$

Penguin



$\propto V_{tb}^* V_{td}$

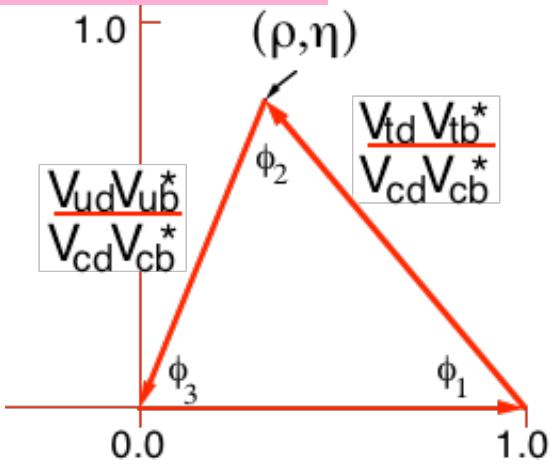


$\propto V_{tb}^{*2} V_{td}^2 V_{ub} V_{ud}^*$

mixing+ "

$\propto V_{tb}^{*2} V_{td}^2 V_{tb} V_{td}^*$

$$\phi_2 = \arg\left(\frac{V_{td}V_{tb}^*}{-V_{ud}V_{ub}^*}\right)$$



$$q = \begin{pmatrix} +1 \text{if } B_{t=0} = B^0 \\ -1 \text{if } B_{t=0} = \bar{B}^0 \end{pmatrix}$$

Bottom line: CP-asymmetric time-dependent rate from x-terms

$$\frac{dN}{dt}(B \to f_{CP}) = \frac{1}{2}\Gamma e^{-\Gamma\Delta t}(1 + q \cdot [\mathcal{A}_{\pi\pi}\cos(\Delta m\Delta t) + \mathcal{S}_{\pi\pi}\sin(\Delta m\Delta t)])$$

"direct" asym

Uncertainty: relative amplitudes of Tree, Penguin

- if T dominates, $A_{\pi\pi}=0$, $S_{\pi\pi}=\sin 2\phi_2$
- if P, T comparable, $A_{\pi\pi}\neq 0$, $S_{\pi\pi}\sim\sin(2\phi_2+2\delta)\cdot 2/(|\lambda|^2+1)$

$A_{\pi\pi}\neq 0$: Direct CP violation

2δ: difference of strong phase

$|\lambda|\neq 1$: if direct CP violation

Previous Belle result {PRL 89, 071801 (2002)} (42 fb^{-1} ~45M B pairs)

$S_{\pi\pi}= -1.21\ ^{+0.38+0.16}_{-0.27-0.13}$

$A_{\pi\pi}= +0.94\ ^{+0.25+0.09}_{-0.31\ -0.09}$

Each 2.9σ from zero; note physical region is

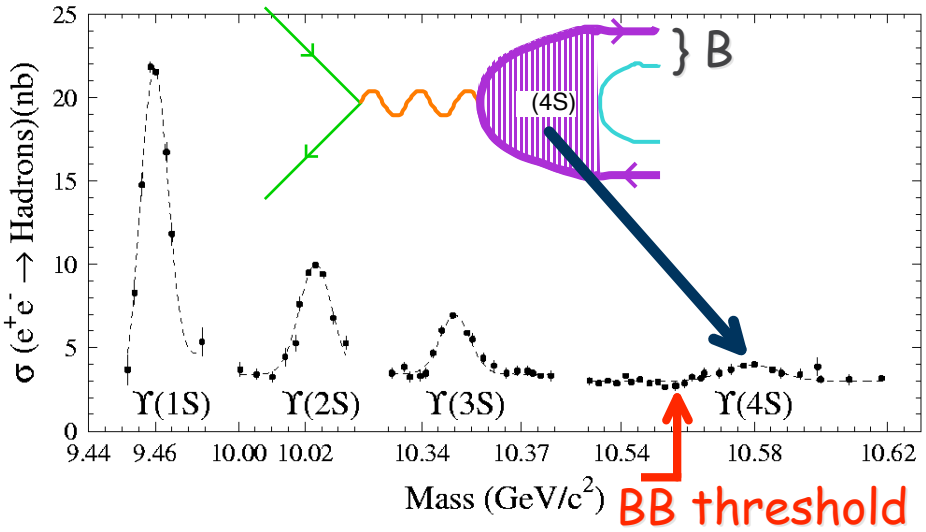
$$\sqrt{S_{\pi\pi}^2 + A_{\pi\pi}^2} \leq 1$$

Now:

- more data - 78 fb^{-1}
- improved analysis - tracking, Δt resolution, event selection
- statistical analysis

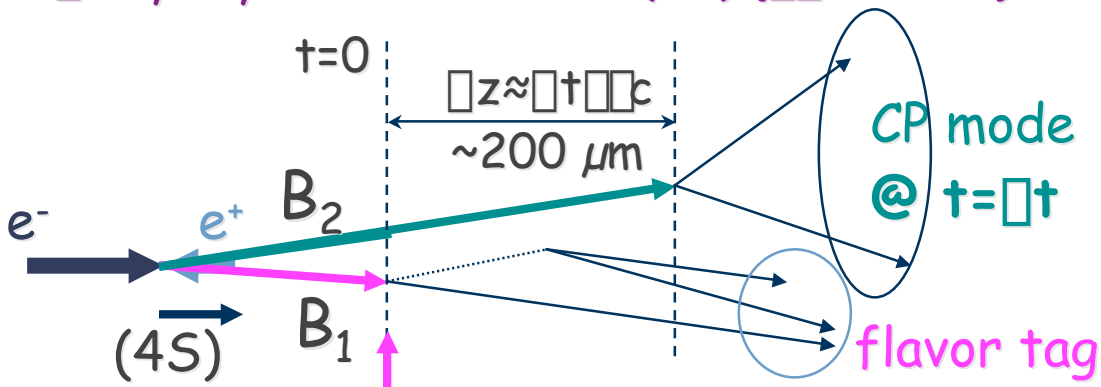
(total 126 fb^{-1}, ~1.3x10^8 B events)

B production: $e^+e^- \to \Upsilon(4S) \to B\bar{B}$



As with sin2β via J/ψK:
- reconstruct CP mode
- tag flavor
- reconstruct vertices
- unbinned max. likelihood fit to Δt

Δt by asymmetric e^+e^- -> (4S) {βγ = 0.425}



Belle detector

Charged tracking/vertexing

- SVD: 3-layer DSSD Si μstrip
- CDC: 50 layers (He-ethane)

Hadron identification

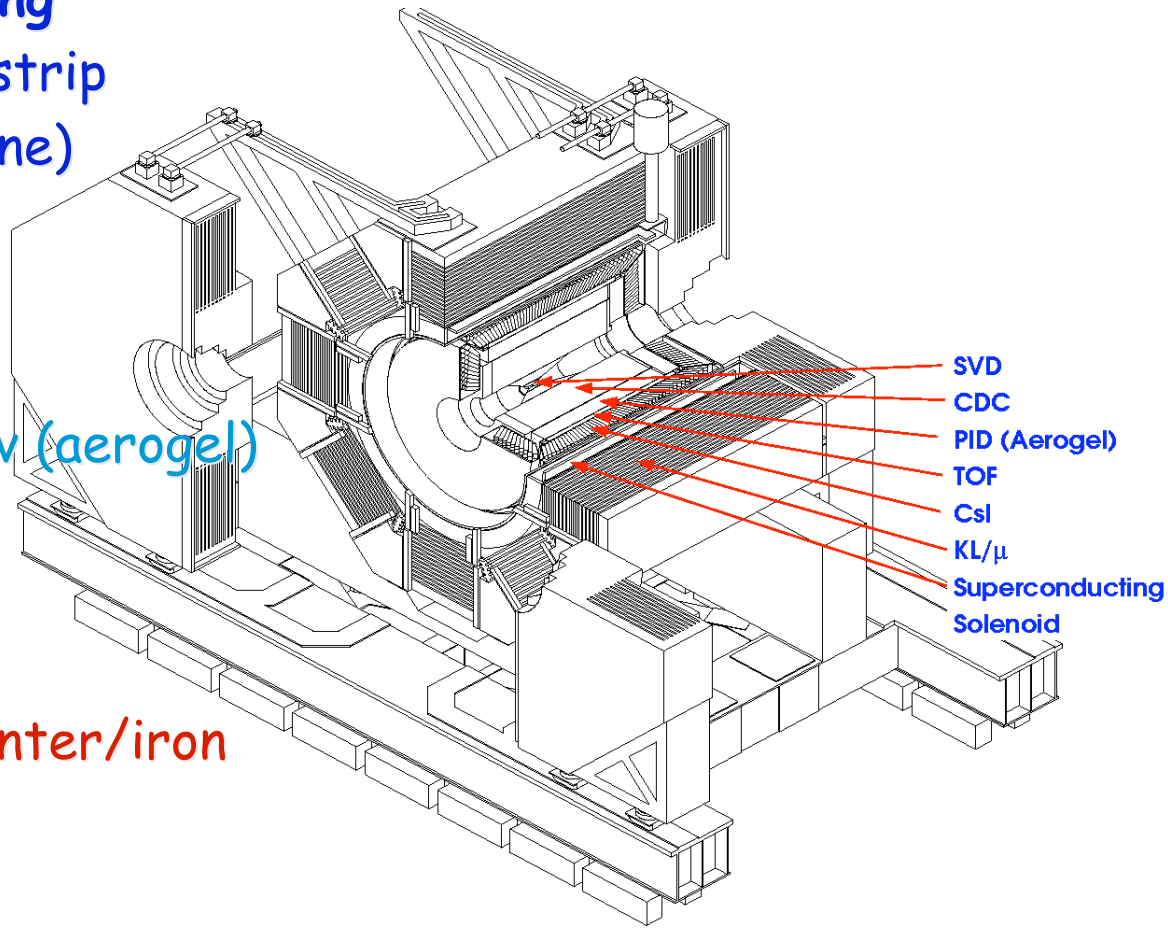
- CDC: dE/dx
- TOF: time-of-flight
- ACC: Threshold Cerenkov (aerogel)

Electron/photon

- ECL: CsI calorimeter

Muon/KL

- KLM: Resistive plate counter/iron



...the people

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Measurement of the CP Violation Parameter $\sin 2\phi_1$ in B_d^0 Meson Decays

A. Abashian,[44] K. Abe,[8] K. Abe,[36] I. Adachi,[8] Byoung Sup Ahn,[14] H. Aihara,[37] M. Akatsu,[19] G. Alimonti,[7] K. Aoki,[8] K. Asai,[20] M. Asai,[5] Y. Asano,[42] T. Aso,[41] V. Aulchenko,[2] T. Aushev,[12] A. M. Bakich,[33] E. Banas,[15] S. Behari,[8] P. K. Behera,[43] D. Beiline,[2] A. Bondar,[2] A. Bozek,[15] T. E. Browder,[7] B. C. K. Casey,[7] P. Chang,[23] Y. Chao,[23] B. G. Cheon,[32] S.-K. Choi,[6] Y. Choi,[32] Y. Doi,[8] J. Dragic,[17] A. Drutskoy,[12] S. Eidelman,[2] Y. Enari,[19] R. Enomoto,[8,10] C. W. Everton,[17] F. Fang,[7] H. Fujii,[8] K. Fujimoto,[19] Y. Fujita,[8] C. Fukunaga,[39] M. Fukushima,[10] A. Garmash,[2,8] A. Gordon,[17] K. Gotow,[44] H. Guler,[7] R. Guo,[21] J. Haba,[8] T. Haji,[37] H. Hamasaki,[8] K. Hanagaki,[29] F. Handa,[36] K. Hara,[27] T. Hara,[27] T. Haruyama,[8] N. C. Hastings,[17] K. Hayashi,[8] H. Hayashii,[20] M. Hazumi,[27] E. M. Heenan,[17] Y. Higashi,[8] Y. Higashino,[19] I. Higuchi,[36] T. Higuchi,[37] T. Hirai,[38] H. Hirano,[40] M. Hirose,[10] T. Hojo,[27] Y. Hoshi,[35] K. Hoshina,[40] W.-S. Hou,[23] S.-C. Hsu,[23] H.-C. Huang,[23] Y.-C. Huang,[21] S. Ichizawa,[38] Y. Igarashi,[8] T. Iijima,[8] H. Ikeda,[8] K. Ikeda,[20] K. Inami,[19] Y. Inoue,[26] A. Ishikawa,[19] H. Ishino,[38] R. Itoh,[8] G. Iwai,[25] M. Iwai,[8] M. Iwamoto,[3] H. Iwasaki,[8] Y. Iwasaki,[8] D. J. Jackson,[27] P. Jalocha,[15] H. K. Jang,[31] M. Jones,[7] R. Kagan,[12] H. Kakuno,[38] J. Kaneko,[38] J. H. Kang,[45] J. S. Kang,[14] P. Kapusta,[15] K. Kasami,[8] N. Katayama,[8] H. Kawai,[3] H. Kawai,[37] M. Kawai,[8] N. Kawamura,[1] T. Kawasaki,[25] H. Kichimi,[8] D. W. Kim,[32] Heejong Kim,[45] H. J. Kim,[45] Hyunwoo Kim,[14] S. K. Kim,[31] K. Kinoshita,[5] S. Kobayashi,[30] S. Koike,[8] S. Koishi,[38] Y. Kondo,[8] H. Konishi,[40] K. Korotushenko,[29] P. Krokovny,[2] R. Kulasiri,[5] S. Kumar,[28] T. Kuniya,[30] E. Kurihara,[3] A. Kuzmin,[2] Y.-J. Kwon,[45] M. H. Lee,[8] S. H. Lee,[31] C. Leonidopoulos,[29] H.-B. Li,[11] R.-S. Lu,[23] Y. Makida,[8] A. Manabe,[8] D. Marlow,[29] T. Matsubara,[37] T. Matsuda,[8] S. Matsui,[19] S. Matsumoto,[4] T. Matsumoto,[19] Y. Mikami,[36] K. Misono,[19] K. Miyabayashi,[20] H. Miyake,[27] H. Miyata,[25] L. C. Moffitt,[17] A. Mohapatra,[43] G. R. Moloney,[17] G. F. Moorhead,[17] N. Morgan,[44] S. Mori,[42] T. Mori,[4] A. Murakami,[30] T. Nagamine,[36] Y. Nagasaka,[18] Y. Nagashima,[27] T. Nakadaira,[37] T. Nakamura,[38] E. Nakano,[26] M. Nakao,[8] H. Nakazawa,[4] J. W. Nam,[32] S. Narita,[36] Z. Natkaniec,[15] K. Neichi,[35] S. Nishida,[16] O. Nitoh,[40] S. Noguchi,[20] T. Nozaki,[8] S. Ogawa,[34] T. Ohshima,[19] Y. Ohshima,[38] T. Okabe,[19] T. Okazaki,[20] S. Okuno,[13] S. L. Olsen,[7] W. Ostrowicz,[15] H. Ozaki,[8] P. Pakhlov,[12] H. Palka,[15] C. S. Park,[31] C. W. Park,[14] H. Park,[14] L. S. Peak,[33] M. Peters,[7] L. E. Piilonen,[44] E. Prebys,[29] J. L. Rodriguez,[7] N. Root,[2] M. Rozanska,[15] K. Rybicki,[15] J. Ryuko,[27] H. Sagawa,[8] S. Saitoh,[3] Y. Sakai,[8] H. Sakamoto,[16] H. Sakaue,[26] M. Satapathy,[43] N. Sato,[8] A. Satpathy,[8,5] S. Schrenk,[5] S. Semenov,[12] Y. Settai,[4] M. E. Sevior,[17] H. Shibuya,[34] B. Shwartz,[2] A. Sidorov,[2] V. Sidorov,[2] J. B. Singh,[28] S. Stanič,[42] A. Sugi,[19] A. Sugiyama,[19] K. Sumisawa,[27] T. Sumiyoshi,[8] J. Suzuki,[8] J.-I. Suzuki,[8] K. Suzuki,[3] S. Suzuki,[19] S. Y. Suzuki,[8] S. K. Swain,[7] H. Tajima,[37] T. Takahashi,[26] F. Takasaki,[8] M. Takita,[27] K. Tamai,[8] N. Tamura,[25] J. Tanaka,[37] M. Tanaka,[8] Y. Tanaka,[18] G. N. Taylor,[17] Y. Teramoto,[26] M. Tomoto,[19] T. Tomura,[37] S. N. Tovey,[17] K. Trabelsi,[7] T. Tsuboyama,[8] Y. Tsujita,[42] T. Tsukamoto,[8] T. Tsukamoto,[30] S. Uehara,[8] K. Ueno,[23] N. Ujiie,[8] Y. Unno,[3] S. Uno,[8] Y. Ushiroda,[16] Y. Usov,[2] S. E. Vahsen,[29] G. Varner,[7] K. E. Varvell,[33] C. C. Wang,[23] C. H. Wang,[22] M.-Z. Wang,[23] T. J. Wang,[11] Y. Watanabe,[38] E. Won,[31] B. D. Yabsley,[8] Y. Yamada,[8] M. Yamaga,[36] A. Yamaguchi,[36] H. Yamaguchi,[8] H. Yamamoto,[7] T. Yamanaka,[27] H. Yamaoka,[8] Y. Yamaoka,[8] Y. Yamashita,[24] M. Yamauchi,[8] S. Yanaka,[38] M. Yokoyama,[37] K. Yoshida,[19] Y. Yusa,[36] H. Yuta,[1] C. C. Zhang,[11] H. W. Zhao,[8] J. Zhang,[42] Y. Zheng,[7] V. Zhilich,[2] and D. Žontar[42]

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We present a measurement of the standard model CP violation parameter $\sin 2\phi_1$ (also known as $\sin 2\beta$) based on a 10.5 fb^{-1} data sample collected at the $\Upsilon(4S)$ resonance with the Belle detector at the KEKB asymmetric e^+e^- collider. One neutral B meson is reconstructed in the $J/\psi K_S$, $\psi(2S)K_S$, $\chi_{c1}K_S$, $\eta_c K_S$, $J/\psi K_L$, or $J/\psi\pi^0$ CP-eigenstate decay channel and the flavor of the accompanying B meson is identified from its charged particle decay products. From the asymmetry in the distribution of the time interval between the two B-meson decay points, we determine $\sin 2\phi_1 = 0.58^{+0.32}_{-0.34}(\text{stat})^{+0.09}_{-0.10}(\text{syst})$.

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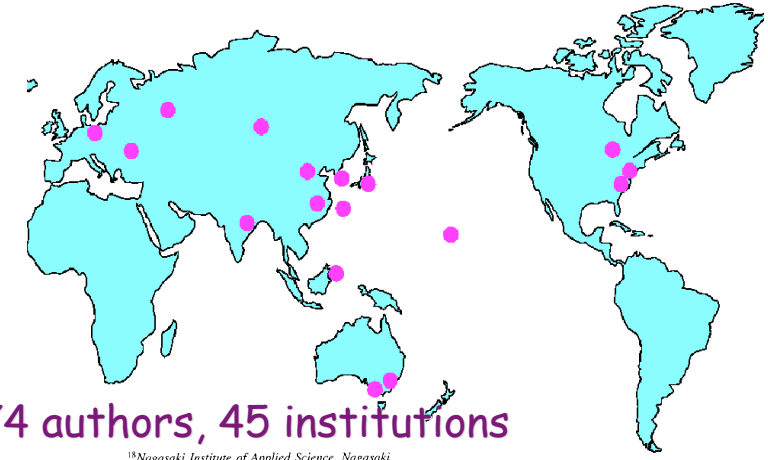


274 authors, 45 institutions

many nations

$B^0 \to \pi^+\pi^-$ reconstruction

final selection:

$\Delta E = E^*_{cand} - E^*_{beam}$: 0 ± 0.057 GeV ($E^*_{beam} = s^{1/2}/2$) {Kπ shift −45 MeV}

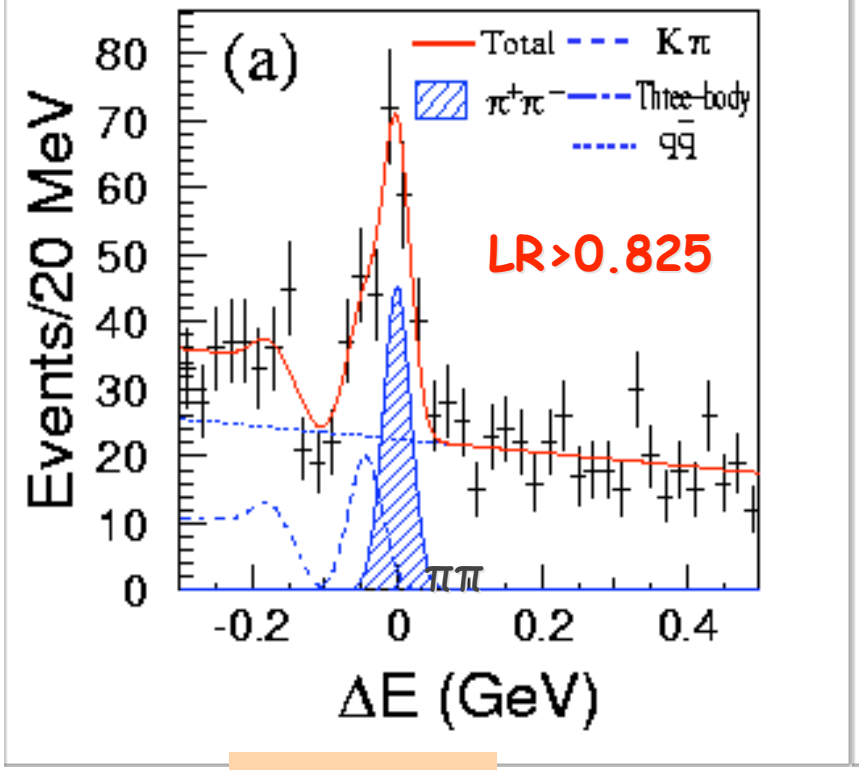
$M_{bc} = (E^*_{beam}{}^2 - p^*_{cand}{}^2)^{1/2}$: 5.271 – 5.287 GeV/$c^2$ (Beam-constrained)

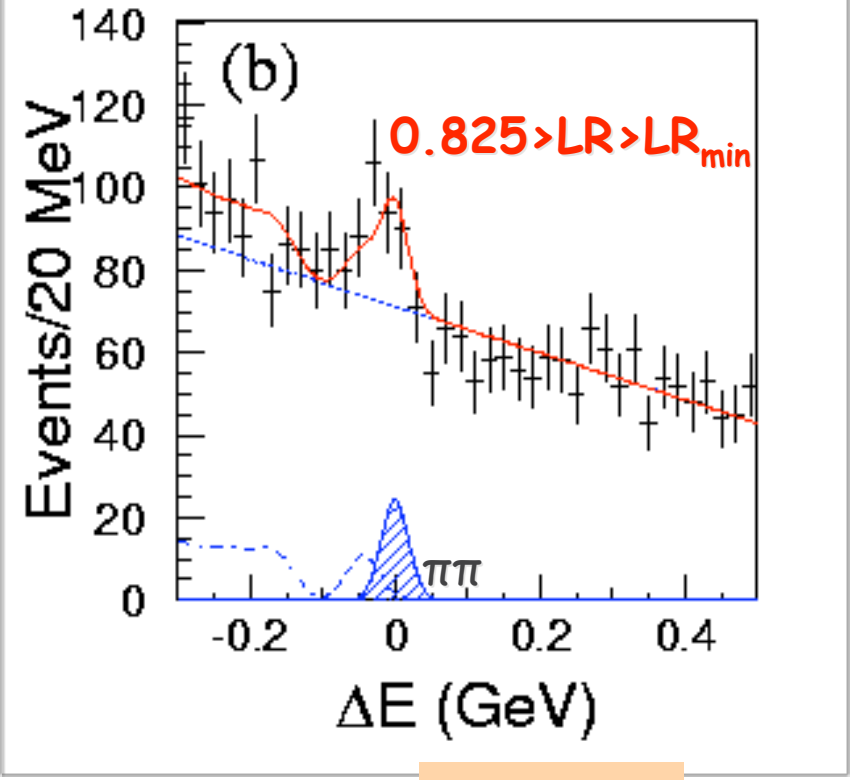
… but less clean than $B^0 \to J/\psi K_s$:

- "physics bg" $B^0 \to K^+\pi^-$ => hadron ID, kinematics
  dE/dx, TOF, Aerogel – "positive ID" $\varepsilon_\pi = 91\%$, $\varepsilon_K = 10\%$
- continuum => event shape {qq "jet-like" vs BB "spherical")
  Fisher discriminant from modified Fox-Wolfram moments
  B candidate direction relative to beam axis
  Construct Likelihood ratio $LR = L_{BB}/[L_{BB}+L_{qq}]$, 2 selections:
  $LR > 0.825$ {$\varepsilon_{BB} = 53\%$, $\varepsilon_{qq} = 5\%$}
  $0.825 > LR > LR_{min}$ (cut depends on flavor tag classification)

$B^0 \to \pi^+\pi^-$ Candidates

760 in signal box - 391 B^0, 369 $\bar{B}^0$



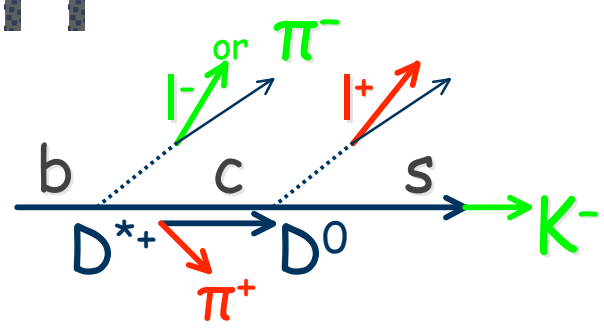


ππ:106±16
Kπ:41±10
qq:128±6

Total signal 163±24

ππ:57±8
Kπ:22±6
qq:406±17

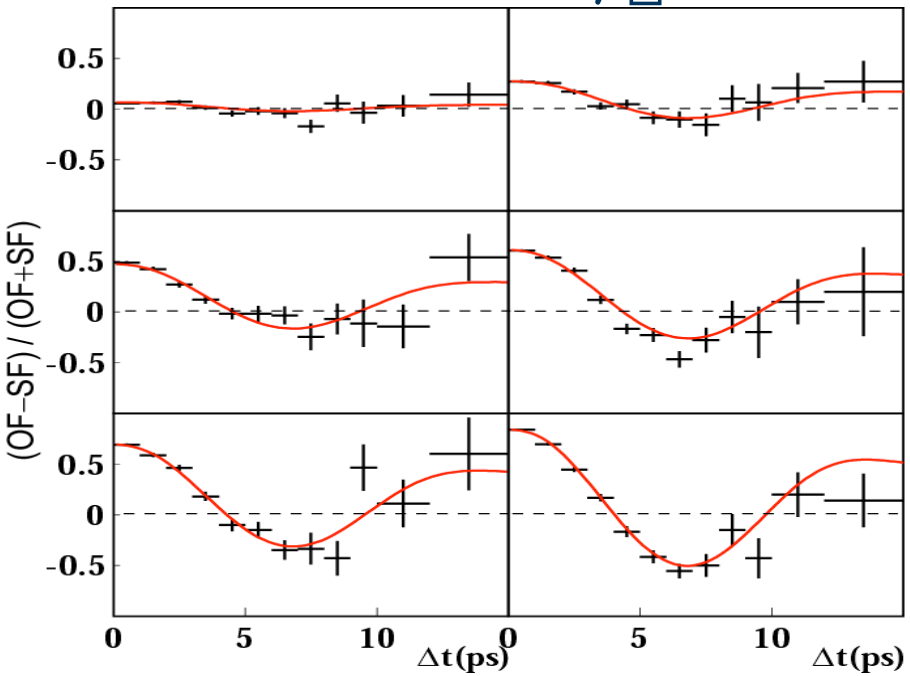
Flavor tagging: same as for sin2ϕ_1



- high-p lepton (p*>1.1 GeV): b->l^-
- net K charge b->K^-
- medium-p lepton, b->c-> l^+
- soft π b->c{D^{*+}->$D^0\pi^+$}
- hard π b->{c}π^-X

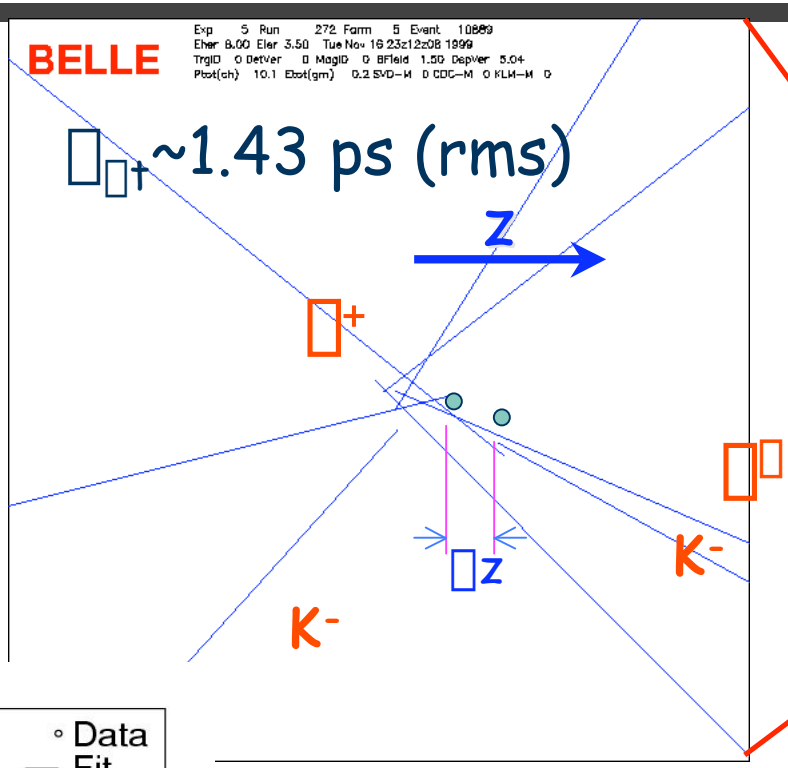
* multidimensional likelihood, ϵ>99%

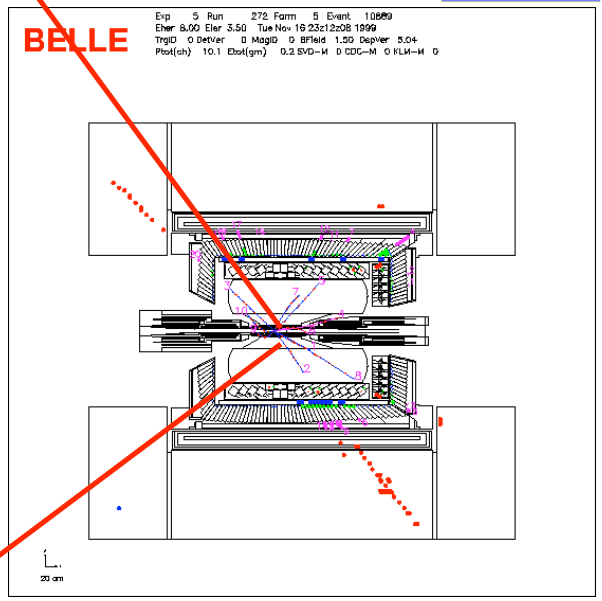
- wrong-tag fraction w
  classify events based on expected w (MC) - 6 bins.
  (B^0 mixing amplitude in data) =>
- effective efficiency
  = ϵ(1-2w): net (28.8±0.5)%

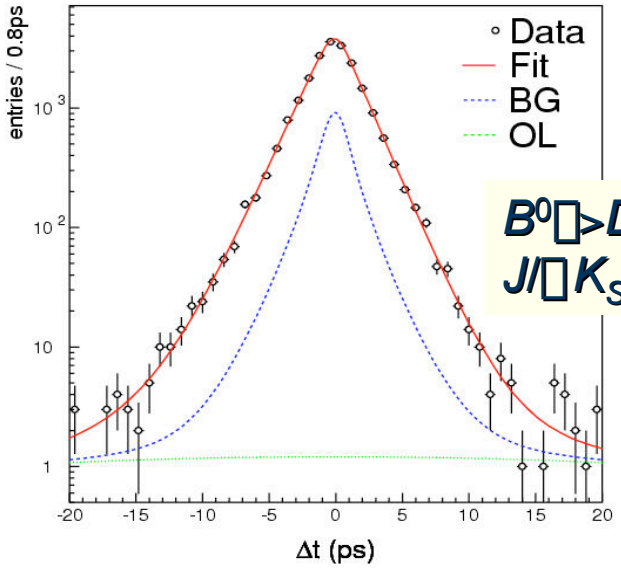


mixing amplitude <-> w

□z vertex reconstruction: same as for sin2□1







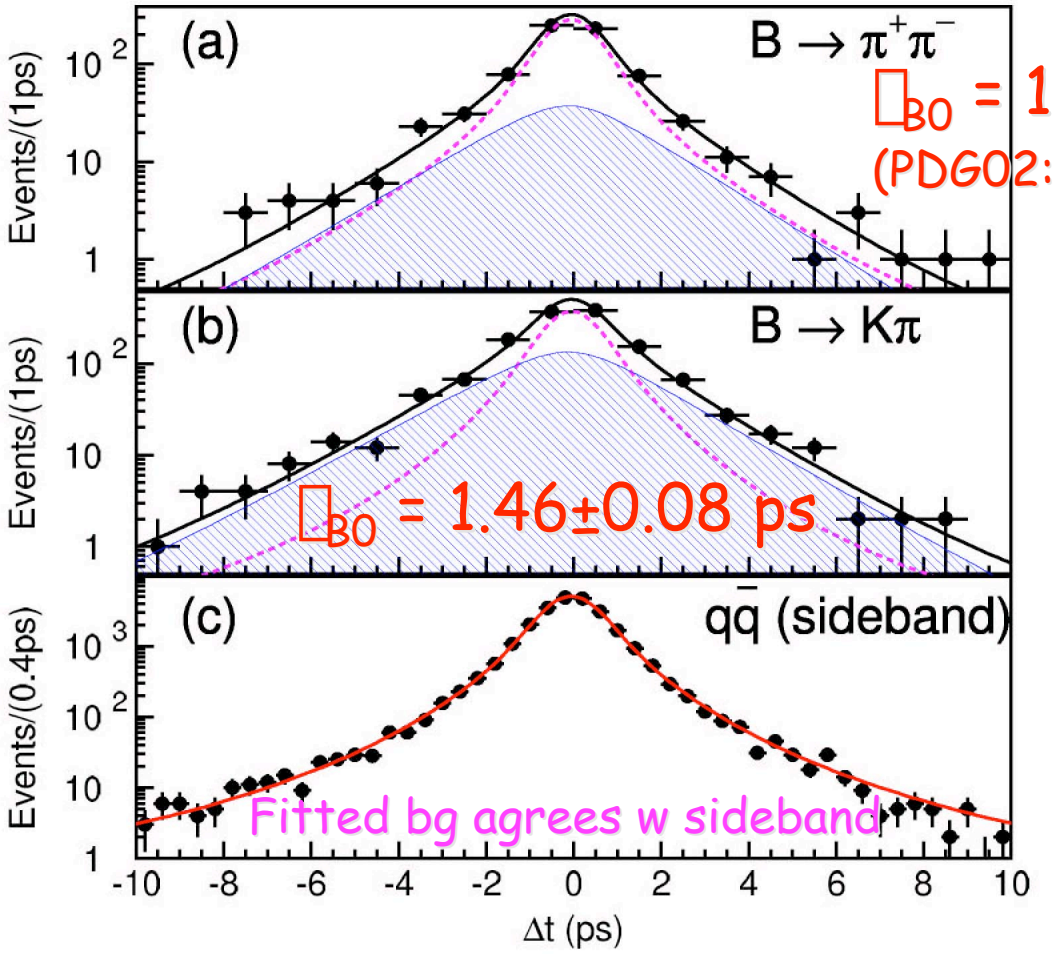
***B*⁰□>*D*⁺□□, *D**⁺□□, *D**⁺□□, *J*/□*K*_S, *J*/□*K**⁰**

Resolution function: validate via lifetime

<= □_B0 = 1.551±0.018 ps

(PDG02: 1.542±0.016)

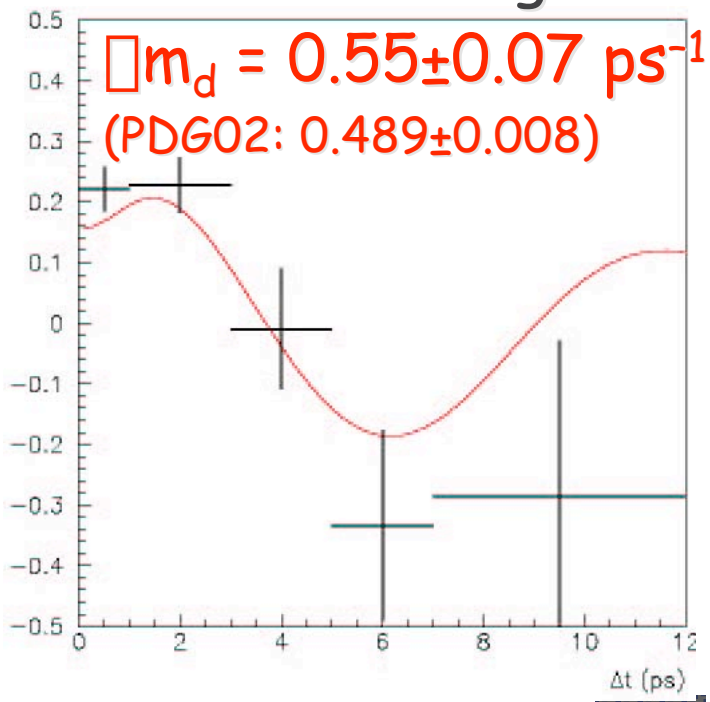
More checks of Δt resolution+flavor tag



τ_{B^0} = 1.42±0.14 ps

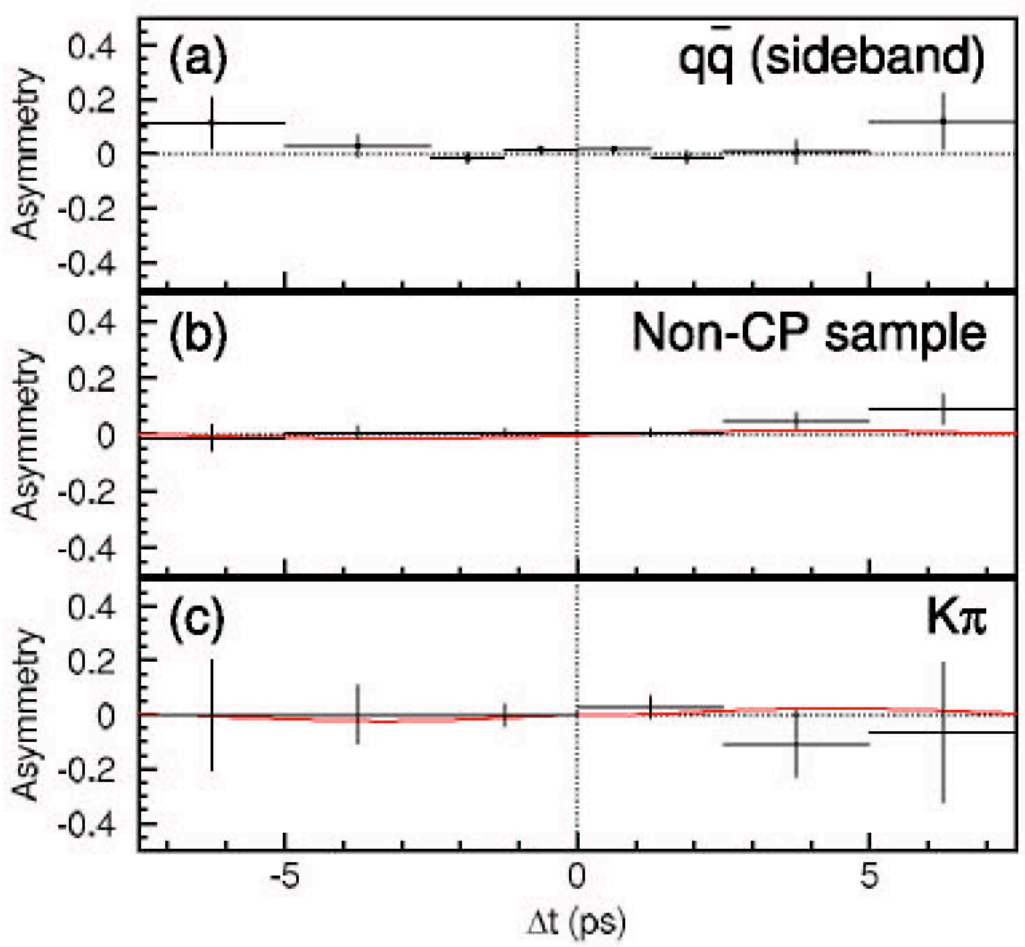
(PDG02: 1.542±0.016)

$B^0 \to K^+\pi^-$ mixing



Check for flavor bias

Look where zero asymmetry expected:



"$S_{\pi\pi}$"= -0.045±0.033

"$A_{\pi\pi}$"= -0.015±0.022

$S_{K\pi}$= -0.03±0.11

$A_{K\pi}$= +0.08±0.16

Fitting for CP asymmetry

Same technique as with sin2ϕ_1

- unbinned maximum likelihood fit
- resolution function event-by-event: tracking, misreconstruction, physics, approximation of $\Delta t = \Delta z / \beta\gamma c$
- wrong tag fraction w, backgrounds

Fit for $A_{\pi\pi}$, $S_{\pi\pi}$:

root

$$\frac{dN}{dt}(B \to f_{CP}) = \frac{1}{2}\Gamma e^{-\Gamma\Delta t}(1 + q \cdot [\mathcal{A}_{\pi\pi}\cos(\Delta m\Delta t) + \mathcal{S}_{\pi\pi}\sin(\Delta m\Delta t)])$$

Diluted

$$\frac{dN}{dt}(\Delta t_{\pi\pi}) = \frac{1}{2}\Gamma e^{-\Gamma\Delta t}[1 \pm (1-2w_i)(S\sin(\Delta m\Delta t) + A\cos(\Delta m\Delta t))]$$

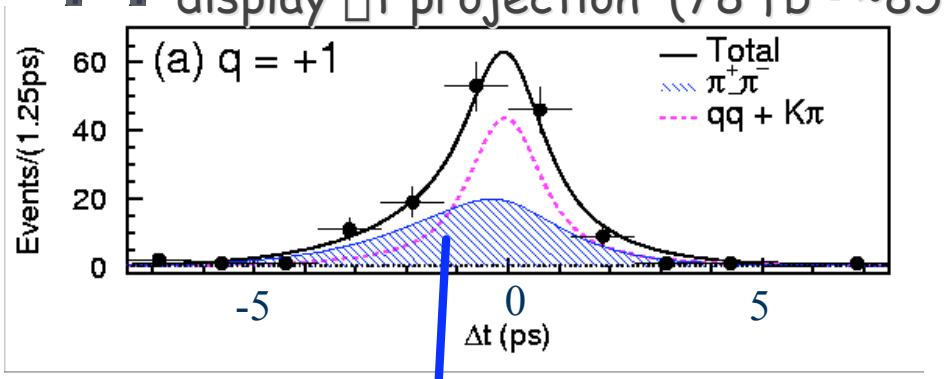
+Kπ (set $A_{K\pi} = 0$)

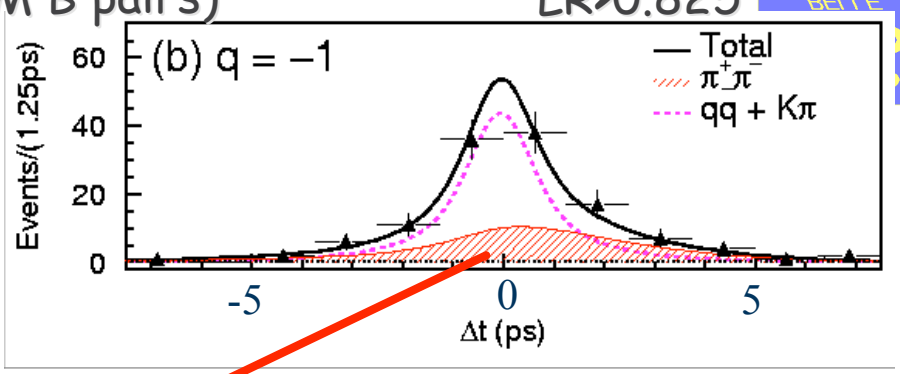
$$\frac{dN}{dt}(\Delta t_{K\pi}) = \frac{1}{2}\Gamma e^{-\Gamma\Delta t}[1 \pm (1-2w_i)(A_{K\pi}\cos(\Delta m\Delta t))]$$

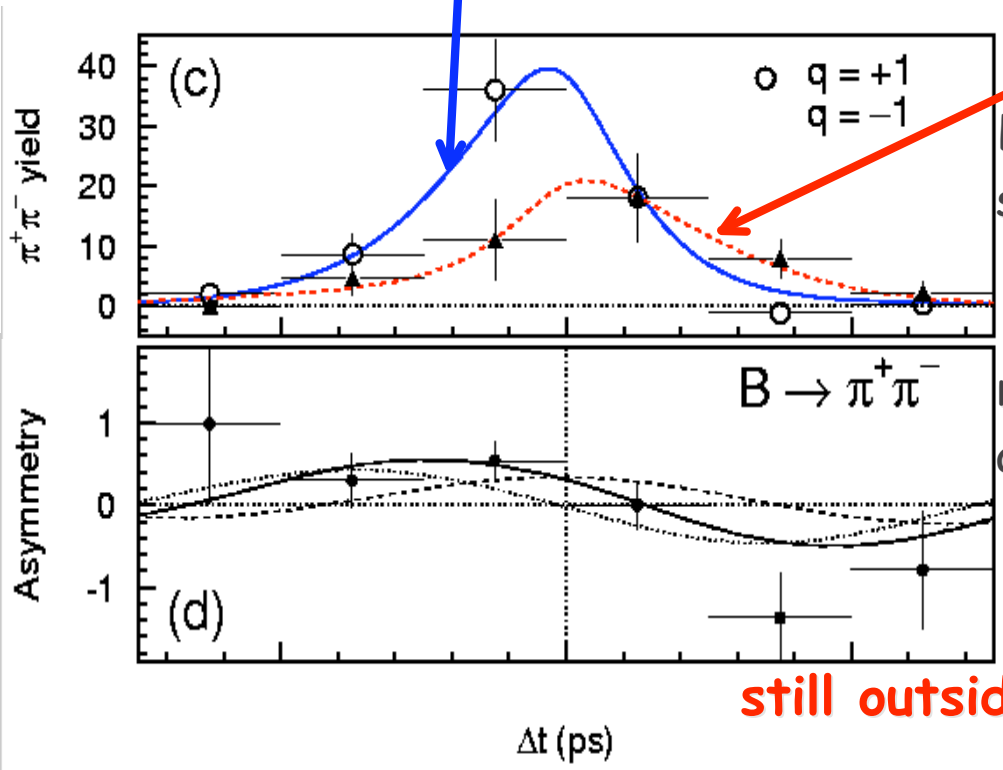
+resolution + bg

Fit Results

display Δt projection (78 fb^{-1} ~85M B pairs) LR>0.825







Background subtracted

raw asymmetry

Likelihood not parabolic -> statistical errors estimated numerically via MC ensemble

$$S_{\pi\pi} = -1.23 \pm 0.41^{+0.08}_{-0.07}$$

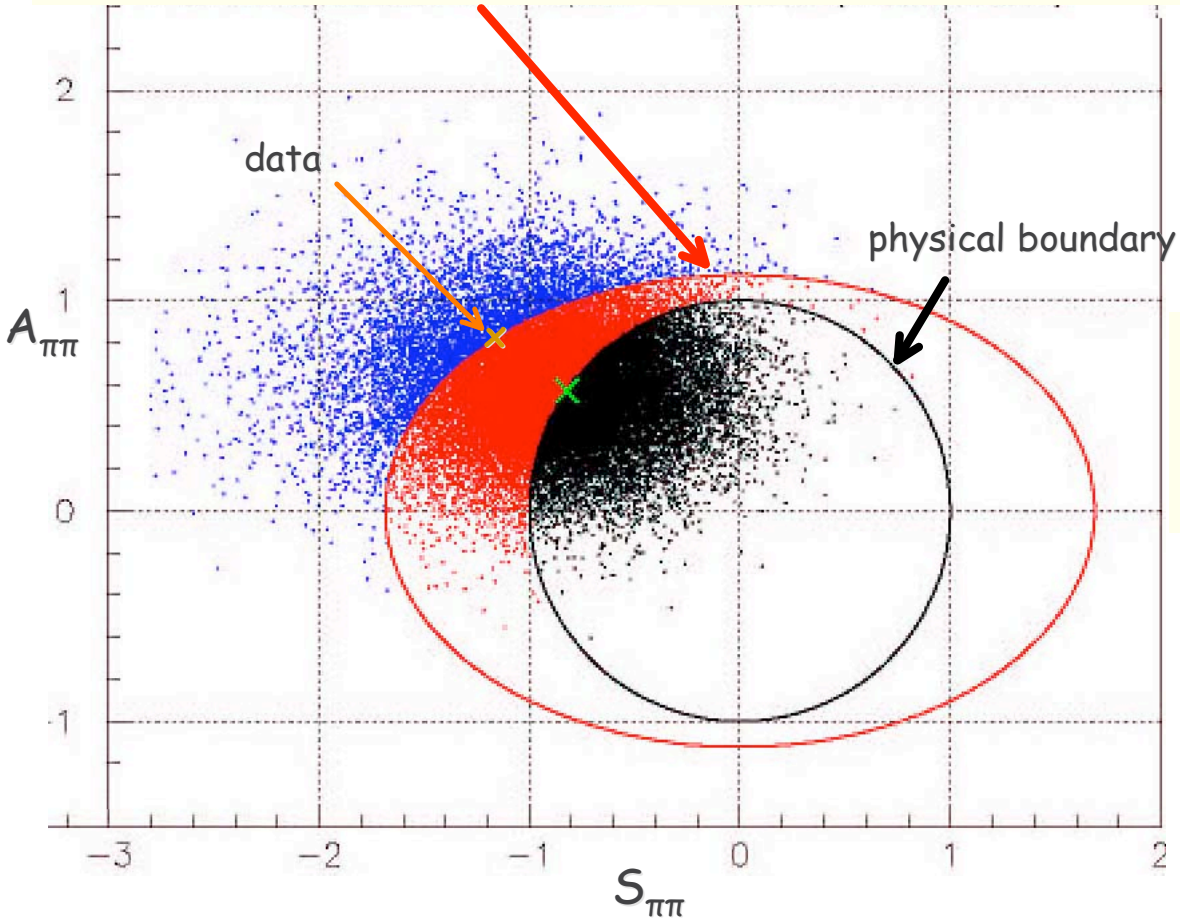
$$A_{\pi\pi} = +0.77 \pm 0.27 \pm 0.08$$

(stat) (sys)

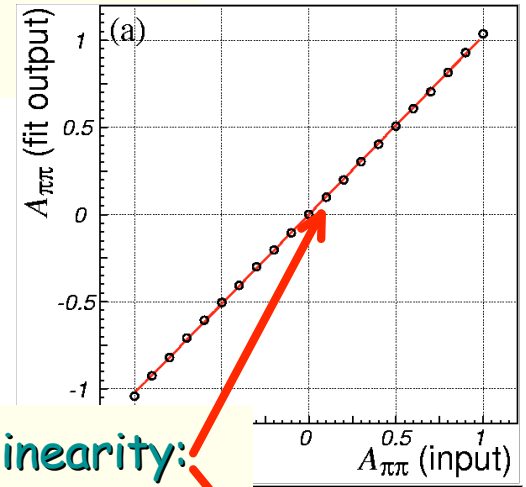
still outside physical region => investigate …

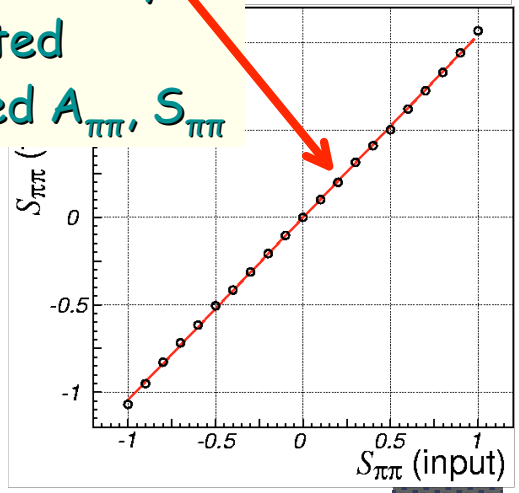
Fit Results: statistical analysis

- MC ensemble - 30k expts, 760 events ea, $A_{\pi\pi}$=0.569, $S_{\pi\pi}$=-0.822
  probability of being outside physical boundary =60.1%
  " further (in □) from (0,0)=16.6%



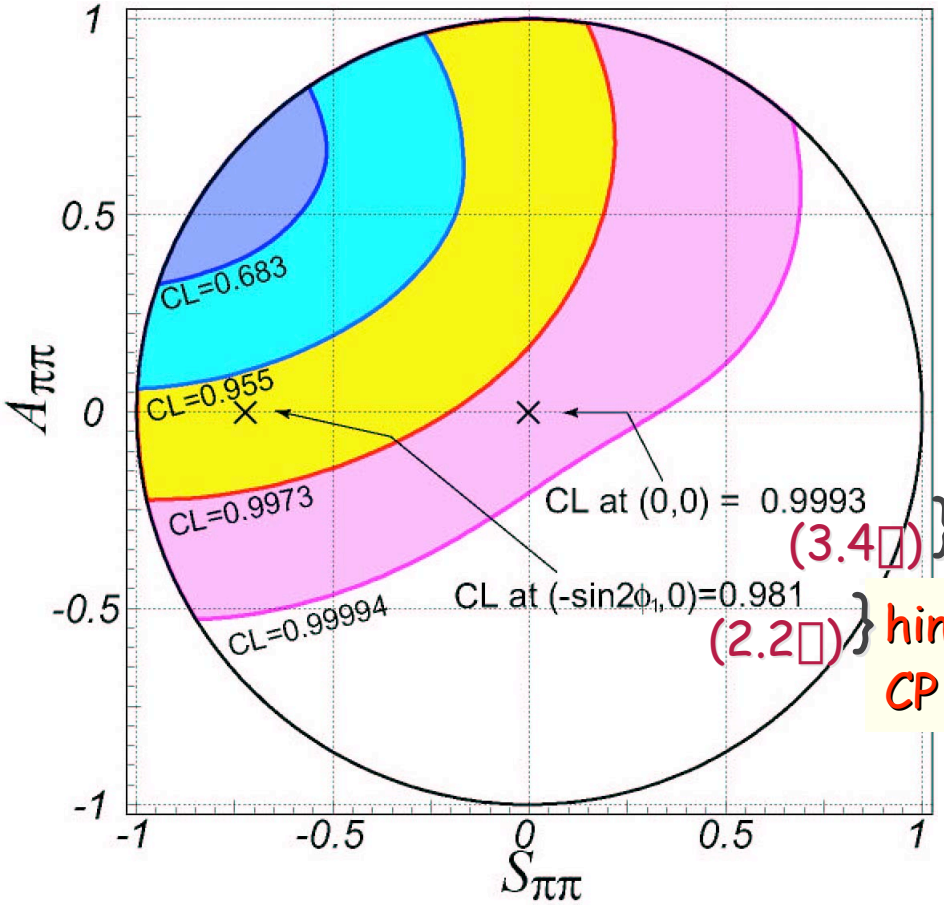
check linearity:
generated
vs fitted $A_{\pi\pi}$, $S_{\pi\pi}$





Confidence regions

- Feldman-Cousins frequentist approach.
- Acceptance regions from MC ensembles.
- Systematic errors included.
- Confidence Level (CL) calculated at each point.



(3.4σ) interpret as evidence for CP non-conservation in $B^0 \to \pi^+\pi^-$

(2.2σ) hint of direct CP non-conservation

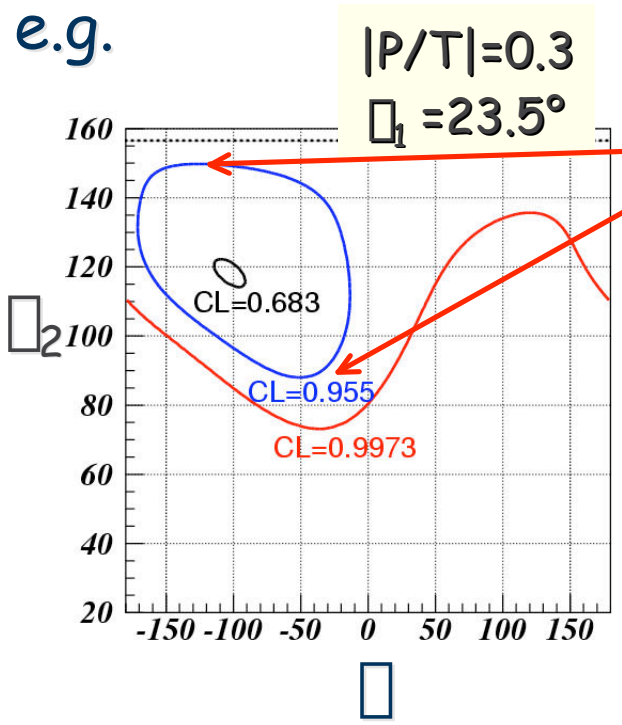
Constraints on the CKM angle ϕ_2

- $S_{\pi\pi}$, $A_{\pi\pi}$ depend on 4 parameters:

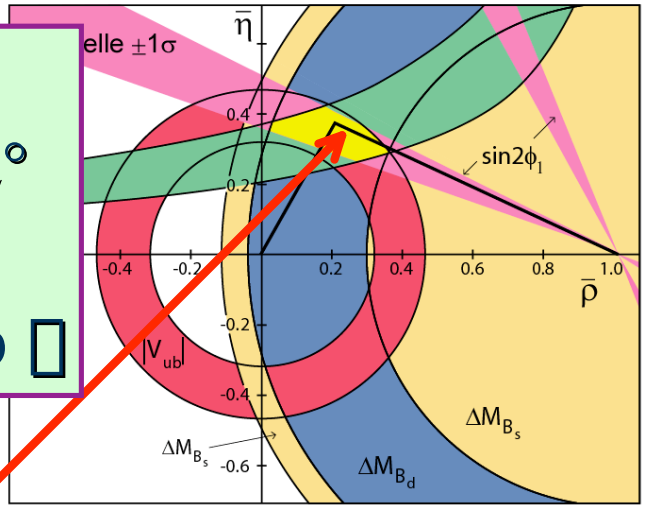
  ϕ_2, ϕ_1[21.3°-25.9°], |P/T|[0.15-0.45], δ

  -> plot confidence contours in (ϕ_2, δ)for various |P/T|

e.g.



Find:
$78° \leq \phi_2 \leq 152°$
(95% C.L.)
insensitive to δ



From other CKM (CKM fitter group, 2002):
$78.3° \leq \phi_2 \leq 121.6°$ (95% C.L.)
=> consistent

Summary

Belle, 2000-2:

- peak $L = 9.5 \times 10^{33} cm^{-2} s^{-1}$ - nearly at design ($1 \times 10^{34} cm^{-2} s^{-1}$)
- passed 100 fb^{-1} in Oct. 2002
- with 78 fb^{-1} on (4S), sensitive to large values of $\sin 2\phi_2$
- measure CP asym in $B^0 \to \pi^+ \pi^-$

  constraints on ϕ_2, consistent with other CKM constraints.

  hint of direct CP non-conservation

  result submitted to PRD.

Next

- ->150 fb^{-1} by summer, 500 fb^{-1} by 2005
- Luminosity >@ design
- the CP challenge: stay tuned on ϕ_2