時間依存性とDalitz plotを用いた$B\to\rho\pi$崩壊過程における*CP*非対称度の測定

April 13th, 2007

HEP seminar at Kyoto University

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Outline

- Introduction
  - KM model (CPV in B) and CKM angle ϕ_2
  - $B \to \rho\pi$ Time-dependent Dalitz plot analysis
- Analysis procedure
  - Event selection and signal extraction
  - Unbinned Maximum Likelihood Fit
- Constraint on ϕ_2
  - Penguin contribution and isospin relation
  - Constraint from $B \to \rho\pi$

hep-ex/0701015
Accepted by PRL

Introduction

Kobayashi-Maskawa (KM) Model

CKM matrix

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

- K and M proposed…
  - For $\not{CP}$, quarks have to have **three generations**.
  - An irreducible **complex phase in quark mixing matrix** violates CP.

Unitarity triangle

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

CKM triangle and ϕ_2

- Why ϕ_2 is important?
  - UT triangle closure = an important SM test.

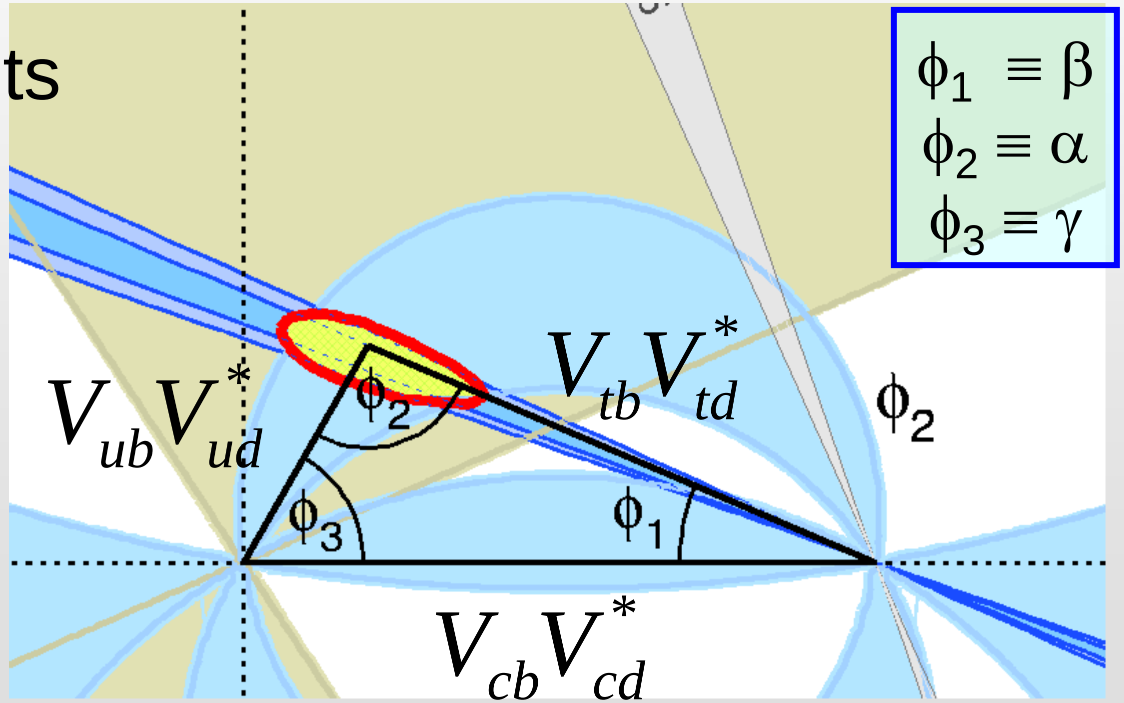
- Current constraints

$$\phi_1 = (21 \pm 1)^\circ$$

$$\phi_2 = (93^{+11}_{-9})^\circ$$

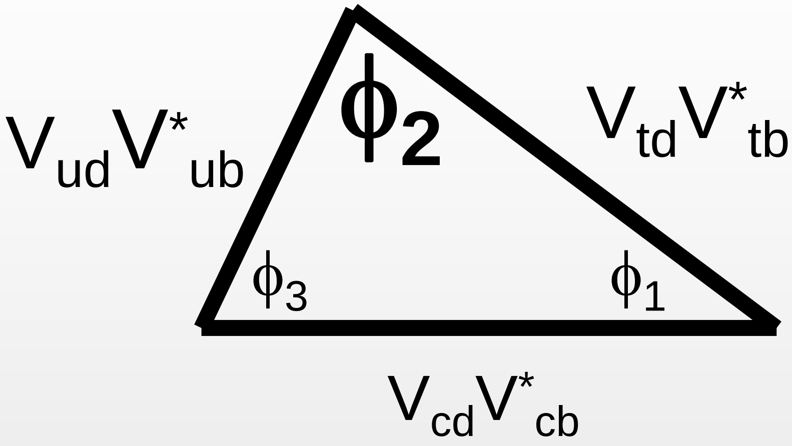
$$\phi_3 = (60^{+38}_{-24})^\circ$$

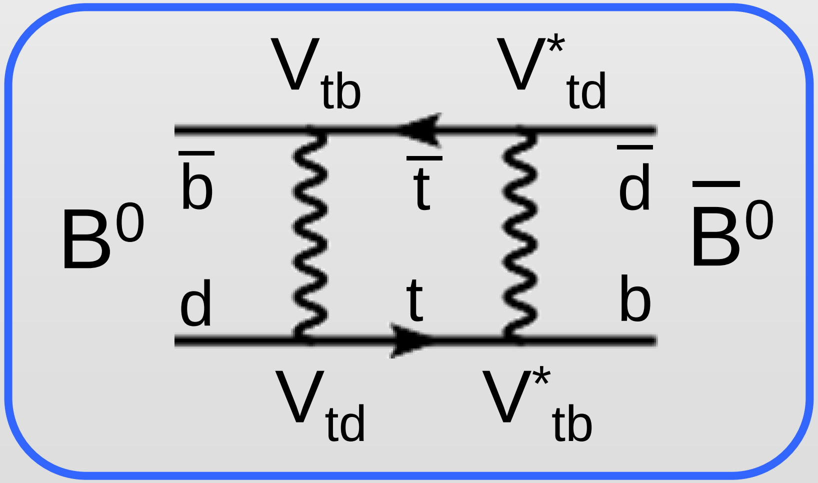
$$\sigma_{\phi_2} >> \sigma_{\phi_1}$$



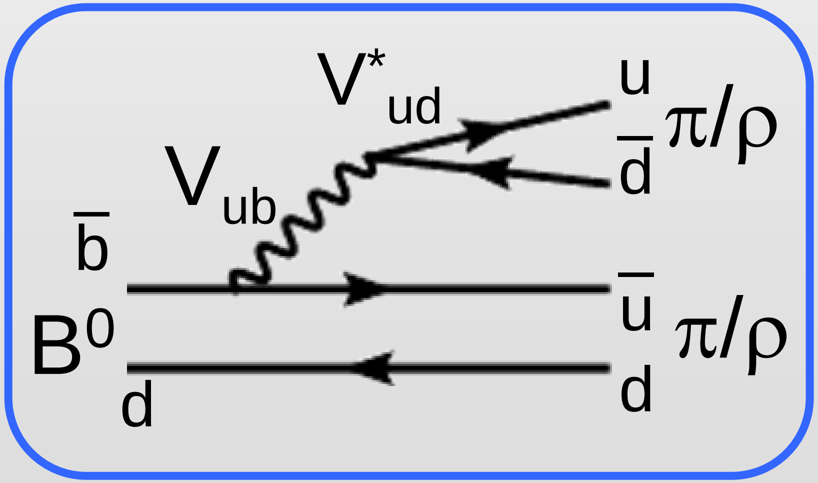
Provided by CKM fitter

CKM triangle and $\phi_2(\alpha)$



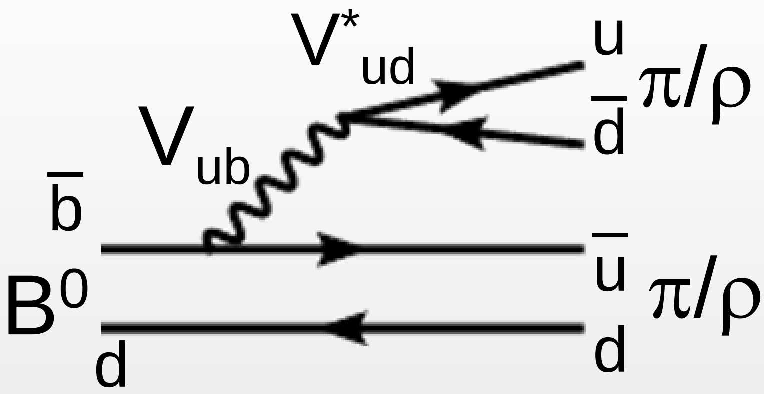


Mixing diagram



Decay diagram (tree)

CKM triangle and $\phi_2(\alpha)$

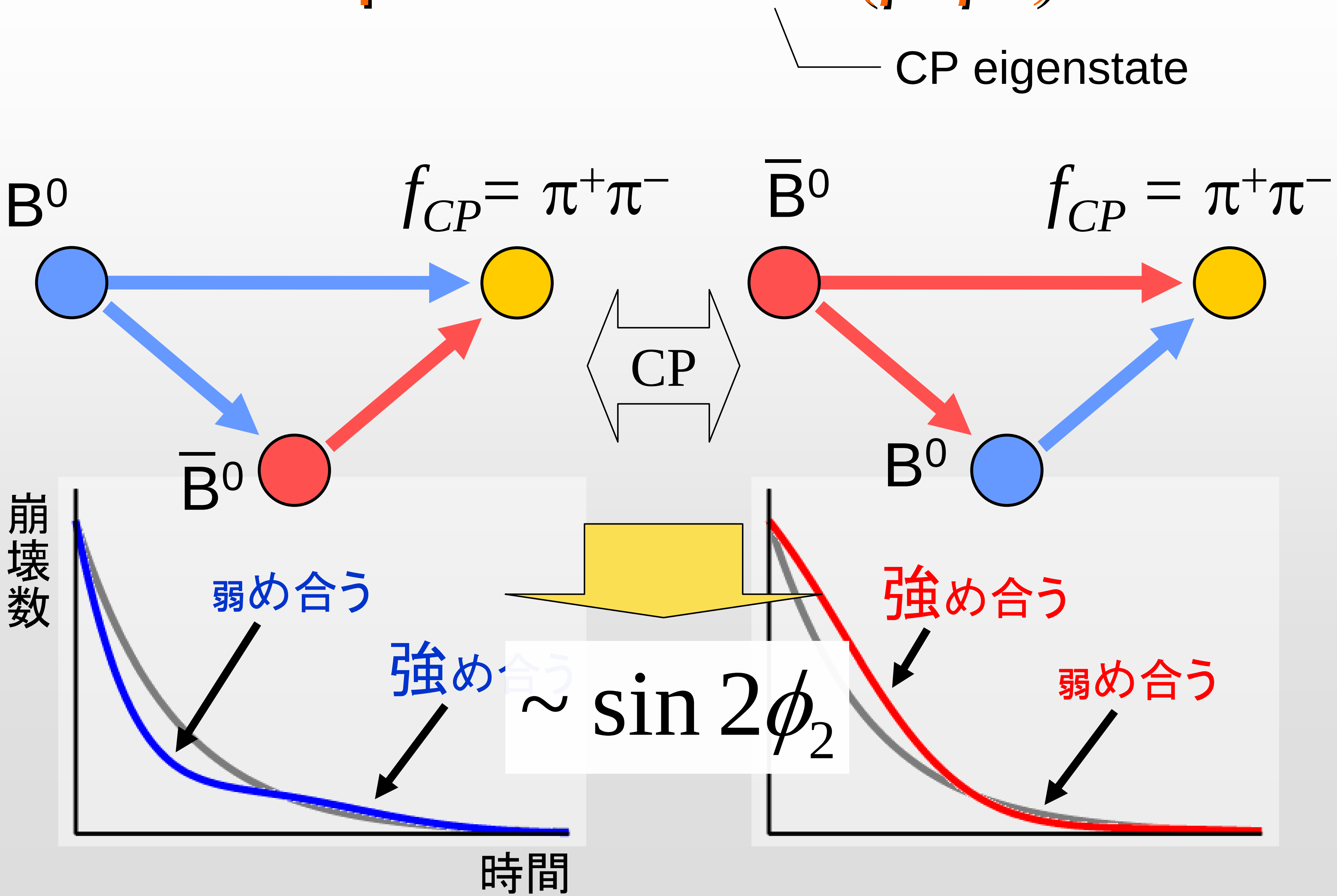


$B^0 \rightarrow \pi^+\pi^-$

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

$B^0 \rightarrow (\rho\pi)^0$

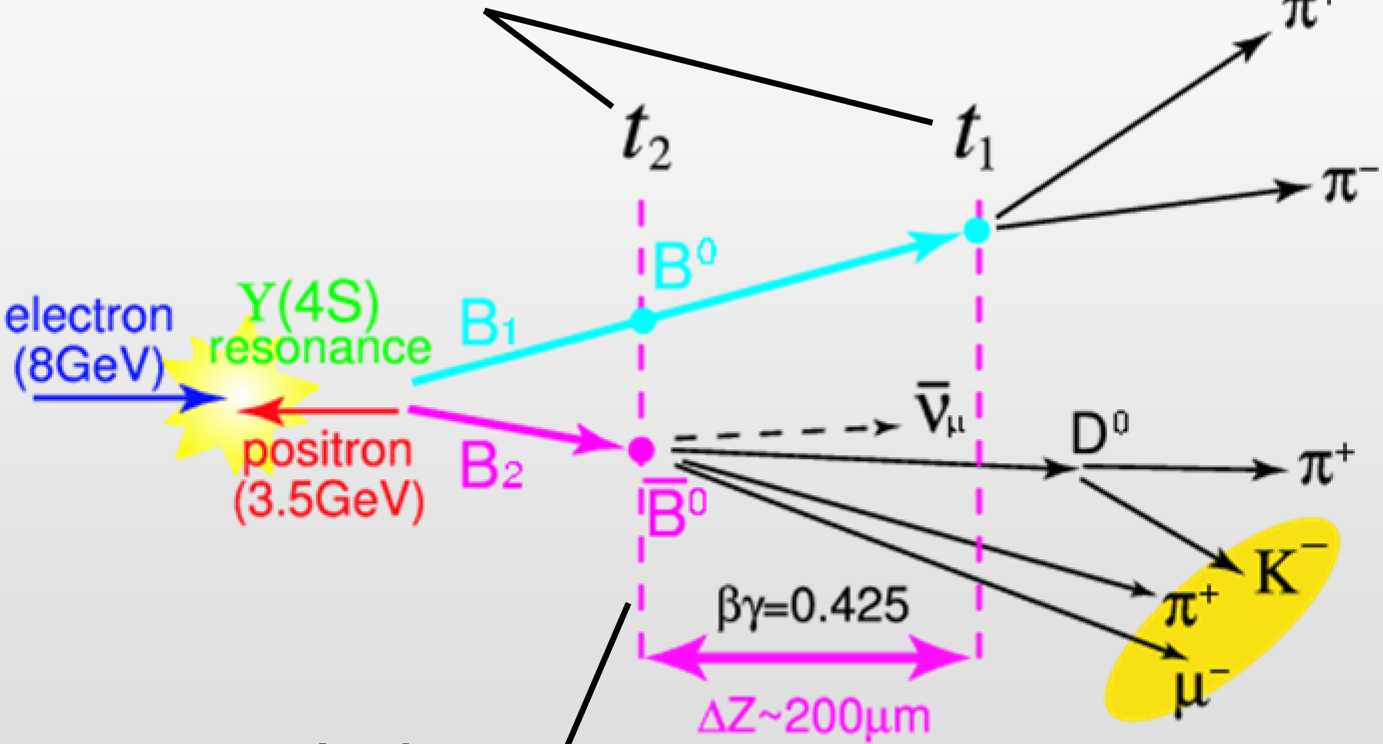
An example: $B^0 \to \pi^+\pi^-(\rho^+\rho^-)$



Determination of Δt and q_{tag}

B's are boosted

→ Δt is measured from vertex positions



B's are entangled

→ flavor of B_1 at time t_2 is determined by B_2 decay

Time-dependent CPV analysis

- The case of $B^0 \to \pi^+\pi^-$

$$A = A(B^0 \to \pi^+\pi^-)$$

$$\overline{A} = A(\overline{B}^0 \to \pi^+\pi^-)$$

Direct CP Violation

Δt from vertex

$$\frac{e^{-|\Delta t|/\tau_{B^0}}}{4\tau_{B^0}}\left[\left(|A|^2+|\overline{A}|^2\right)-q_{\mathrm{tag}}\cdot\left(|A|^2-|\overline{A}|^2\right)\cos\Delta m\Delta t + q_{\mathrm{tag}}\cdot 2\,\mathrm{Im}\left(e^{-2i\phi_1}A^*\overline{A}\right)\sin\Delta m\Delta t\right]$$

Tag side B flavor

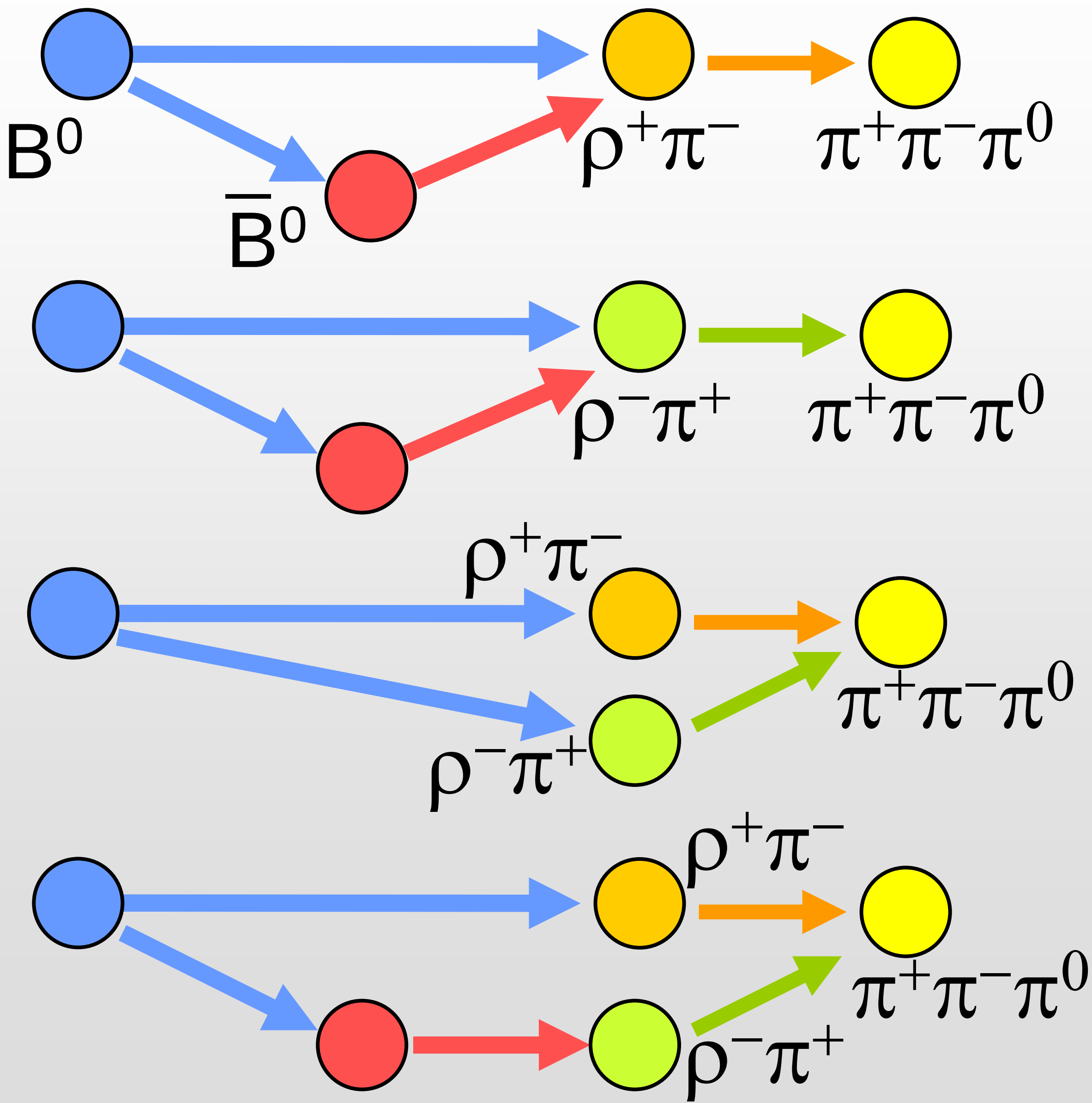
$\sim \sin 2\phi_2$

Why $B \to \rho\pi$?

- $B^0 \to \pi\pi$, $\rho\rho$ has discrete ambiguity
  - Only $\sin 2\phi_2$ is measured
- $B^0 \to \rho\pi$ has a potential to solve the ambiguity.
  - In addition to $\sin 2\phi_2$, $\cos 2\phi_2$ is measured.
- Ambiguity from QCD is dependent on mode
  - It is valuable to measure with various mode.

$B^0 \to \rho\pi$

Snyder & Quinn (1993)



$\sim \sin(2\phi_2 + \delta)$

$\sim \sin(2\phi_2 - \delta)$

$\sim \sin\delta$

$\sim \cos\delta$

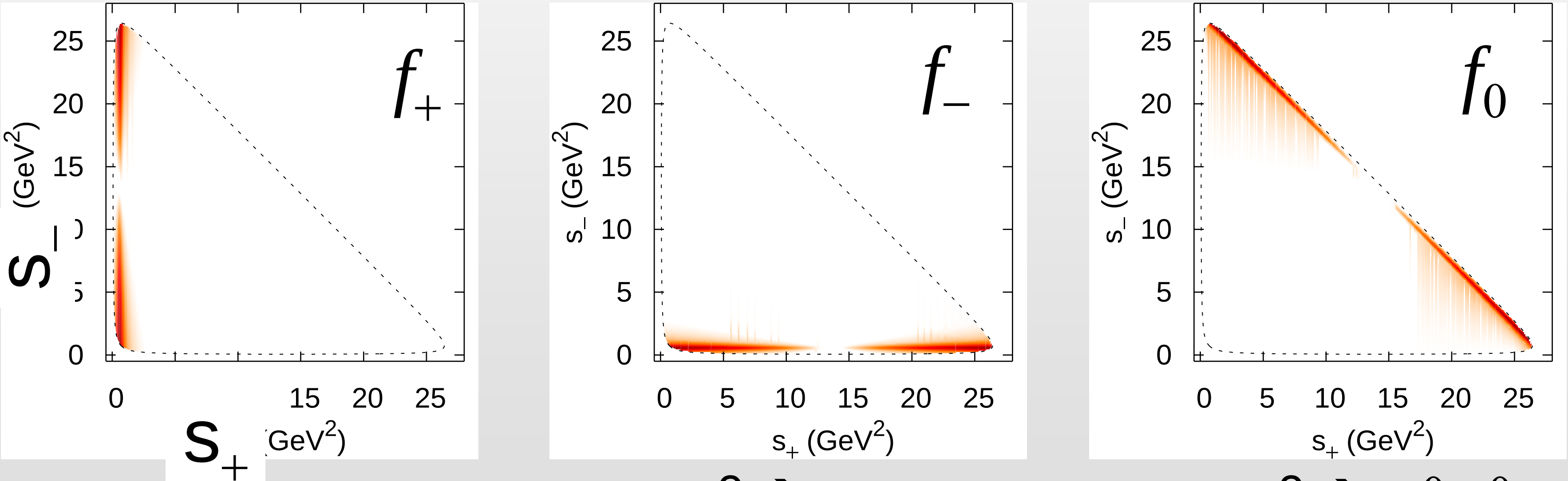
$\sim \sin 2\phi_2$

$\sim \cos 2\phi_2$

How to identify $\rho^{\pm}$: Dalitz plot

$\rho^+\pi^-$, $\rho^-\pi^+$, $\rho^0\pi^0$ → $\pi^+\pi^-\pi^0$: the same final state

$$s_+ \equiv (p_+ + p_0)^2, \; s_- \equiv (p_- + p_0)^2$$



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

Kinematical overlap → Interference

Dalitz plot dependent amplitudes

$$A^{+} = A(B^{0} \to \rho^{+}\pi^{-}) \qquad \overline{A}^{+} = e^{-2i\phi_1} A(\overline{B}^{0} \to \rho^{+}\pi^{-})$$

$$A^{-} = A(B^{0} \to \rho^{-}\pi^{+}) \qquad \vdots$$

$$A^{0} = A(B^{0} \to \rho^{0}\pi^{0})$$

Kinematics (Dalitz plot)

$$A_{3\pi}(s_{+}, s_{-}) = f_{+}A^{+} + f_{-}A^{-} + f_{0}A^{0}$$

$$e^{-2i\phi_1}\overline{A}_{3\pi}(s_{+}, s_{-}) = f_{+}\overline{A}^{+} + f_{-}\overline{A}^{-} + f_{0}\overline{A}^{0}$$

Complex amplitudes to be determined

Time- and Dalitz- dependence

Time-dependence in terms of $A_{3\pi}$

Direct CP violation effect

$$\frac{e^{-|\Delta t|/\tau_{B^0}}}{4\tau_{B^0}}\Big[\left(|A_{3\pi}|^2+|\overline{A}_{3\pi}|^2\right)-q_{\rm tag}\cdot\left(|A_{3\pi}|^2-|\overline{A}_{3\pi}|^2\right)\cos\Delta m\Delta t$$

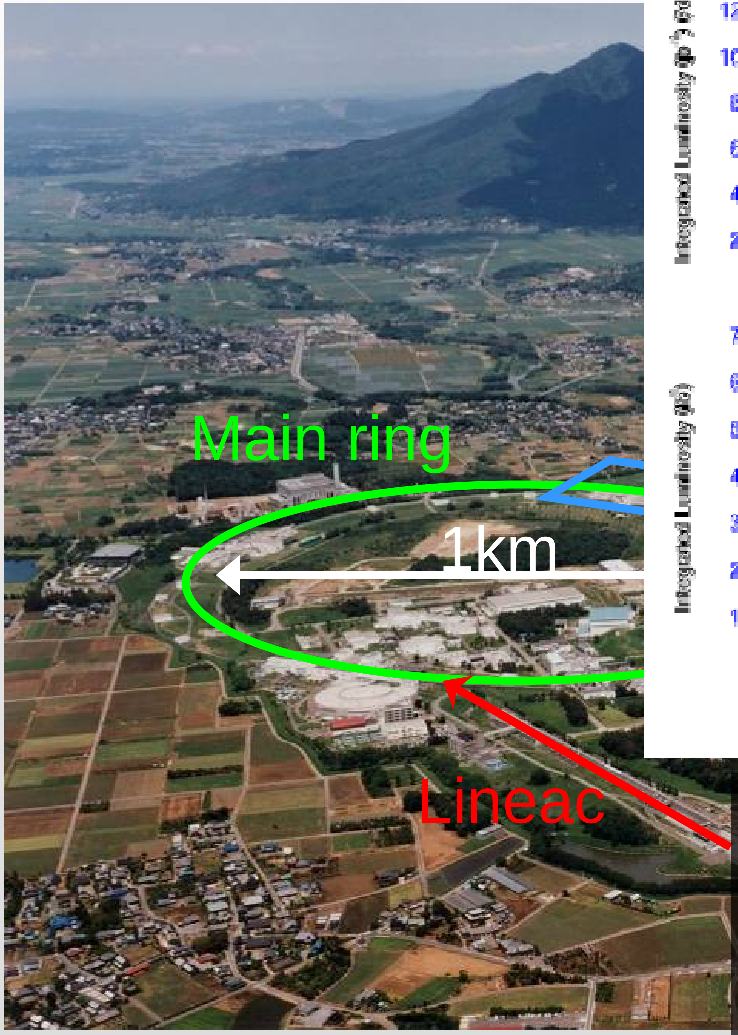
$$+q_{\rm tag}\cdot 2\,{\rm Im}\left(e^{-2i\phi_1}A^*_{3\pi}\overline{A}_{3\pi}\right)\sin\Delta m\Delta t\Big]$$

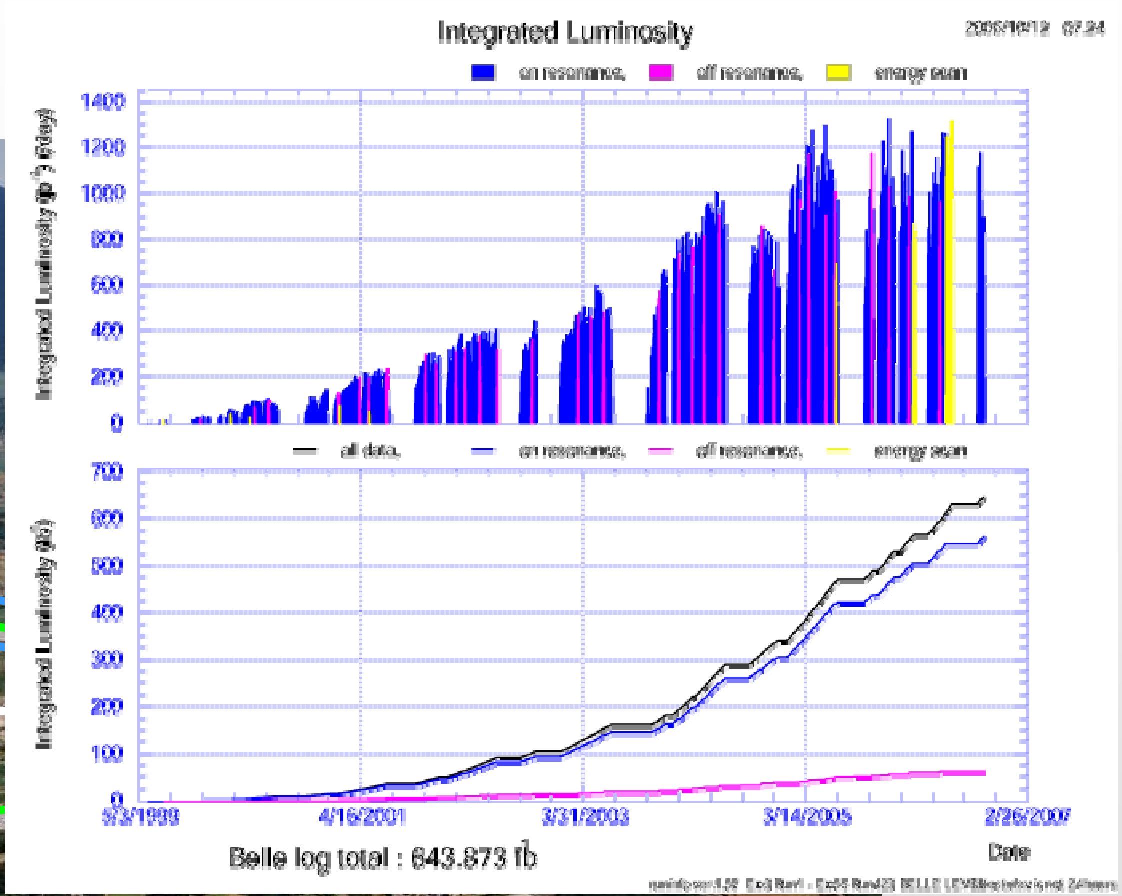
Dependences of

$\sin(2\phi_2+\delta)$
$\sin(2\phi_2)$
$\cos(2\phi_2)$
etc…

Experimental apparatus

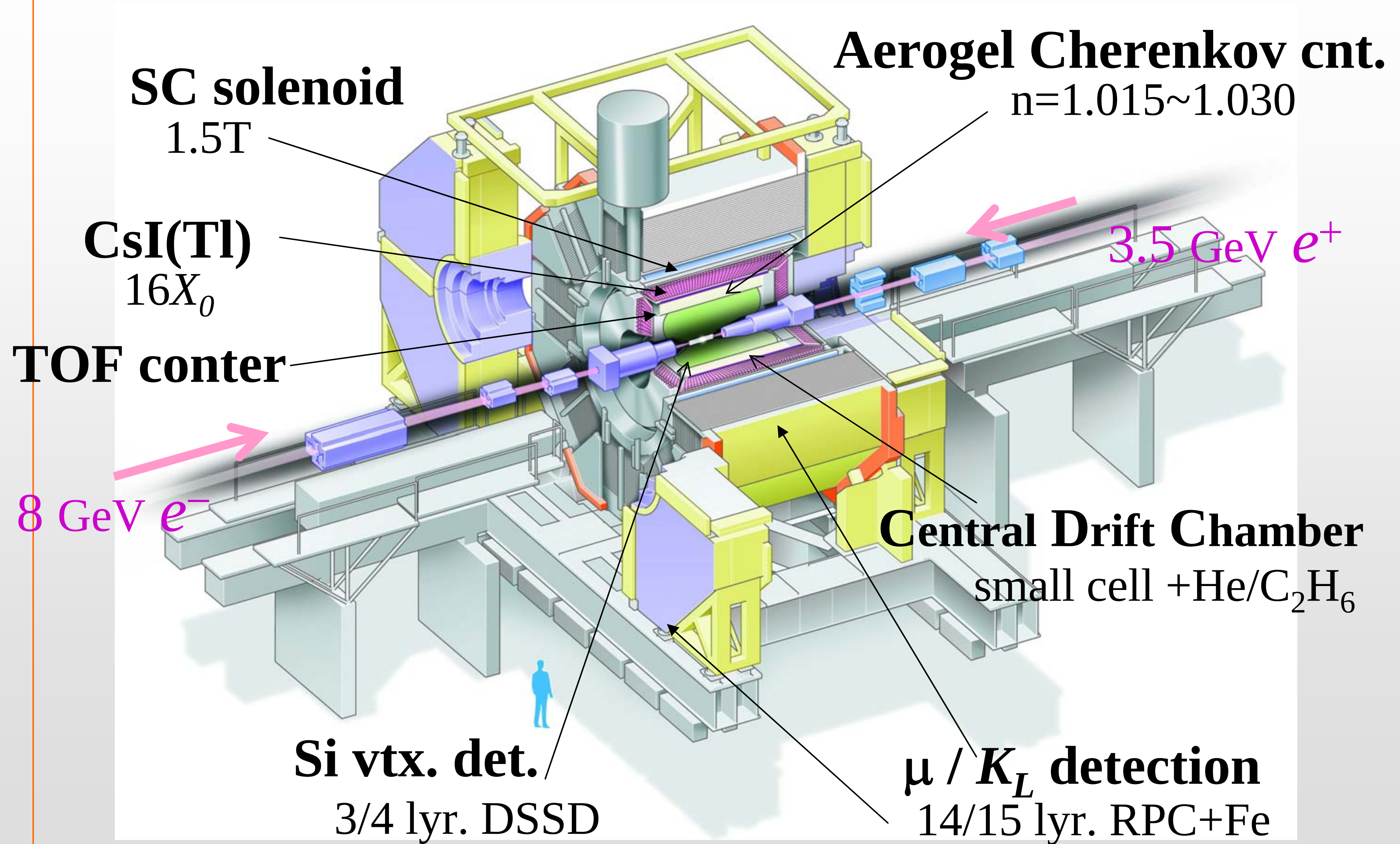
KEKB accelerator



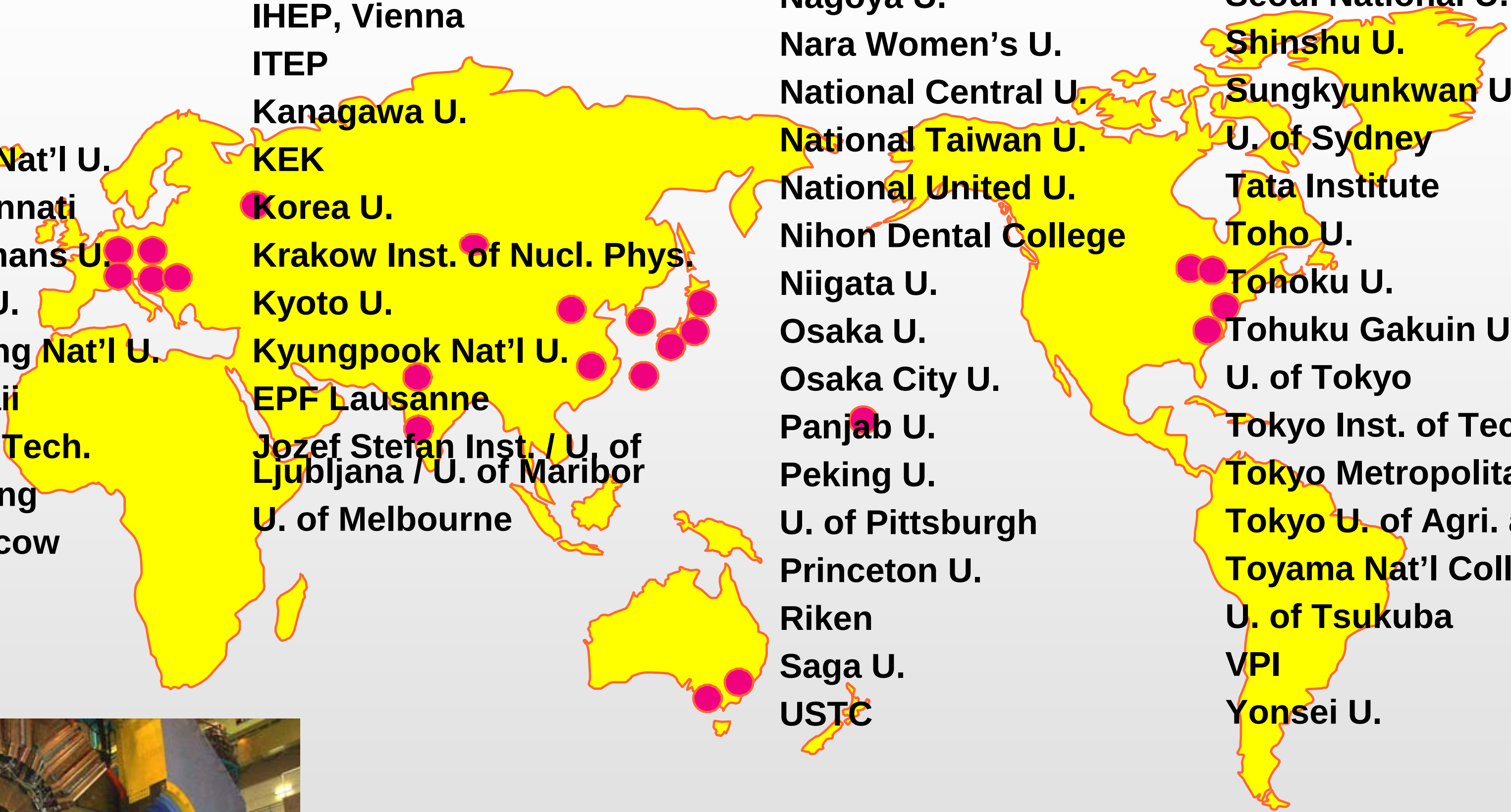


~700/fb until now
This analysis: 414/fb, 449MBB
(until last summer)

Belle Detector



Belle Collaboration



Aomori U.
BINP
Chiba U.
Chonnam Nat'l U.
U. of Cincinnati
Ewha Womans U.
Frankfurt U.
Gyeongsang Nat'l U.
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Hiroshima Tech.
IHEP, Beijing
IHEP, Moscow

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ITEP
Kanagawa U.
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Korea U.
Krakow Inst. of Nucl. Phys.
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Kyungpook Nat'l U.
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Tokyo Metropolitan U.
Tokyo U. of Agri. and Tech.
Toyama Nat'l College
U. of Tsukuba
VPI
Yonsei U.

13 countries, 55 institutes, ~400 collaborators

Analysis

Analysis procedure

- Event selection
- Vertexing & Flavor Tagging
- Unbinned Maximum Likelihood Fit
- ϕ_2 extraction

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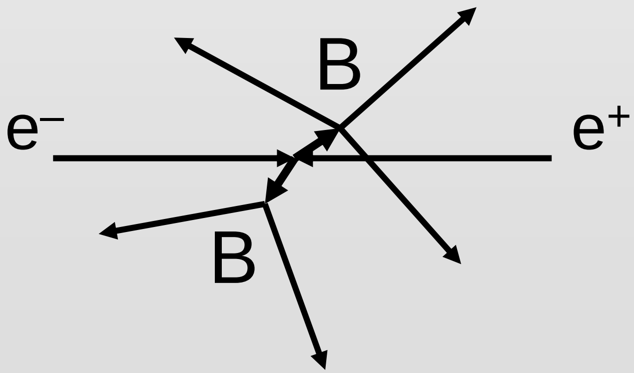
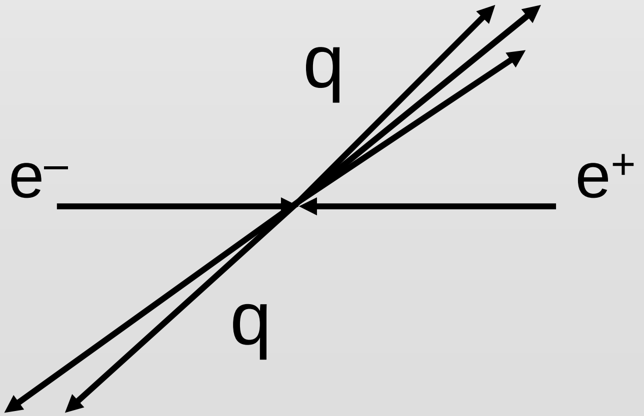
Event selection

- Event ($B^0 \to \pi\pi\pi$) reconstruction
  - π^0 reconstruction
- PID (K/π separation)
- Continuum suppression (event shape)

$$M_{bc} = \sqrt{E_{beam}^2 - p_B^{*\,2}}$$

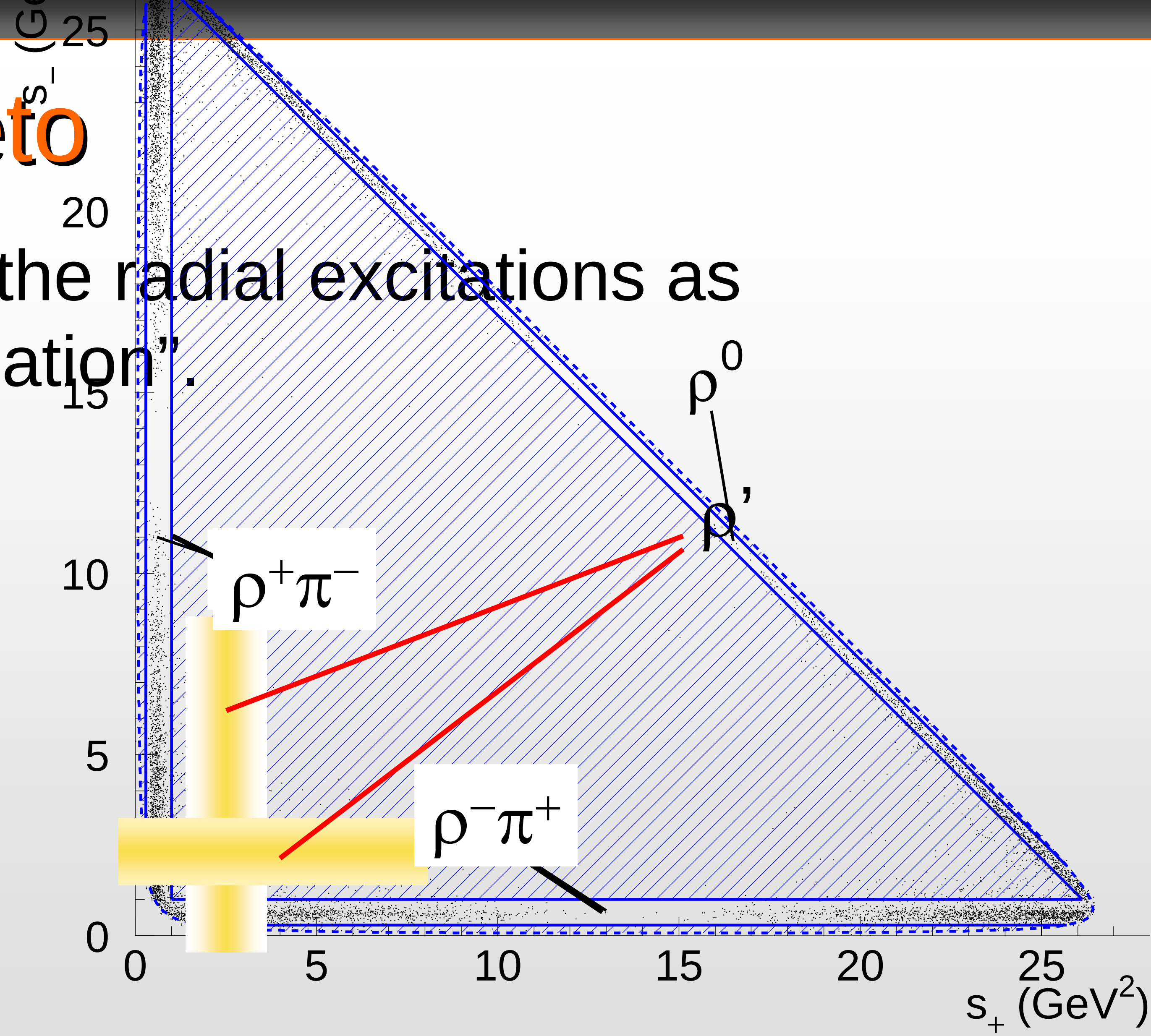
$$\Delta E = E_B^* - E_{beam}$$





Dalitz Veto

- Consider the radial excitations as "contamination".

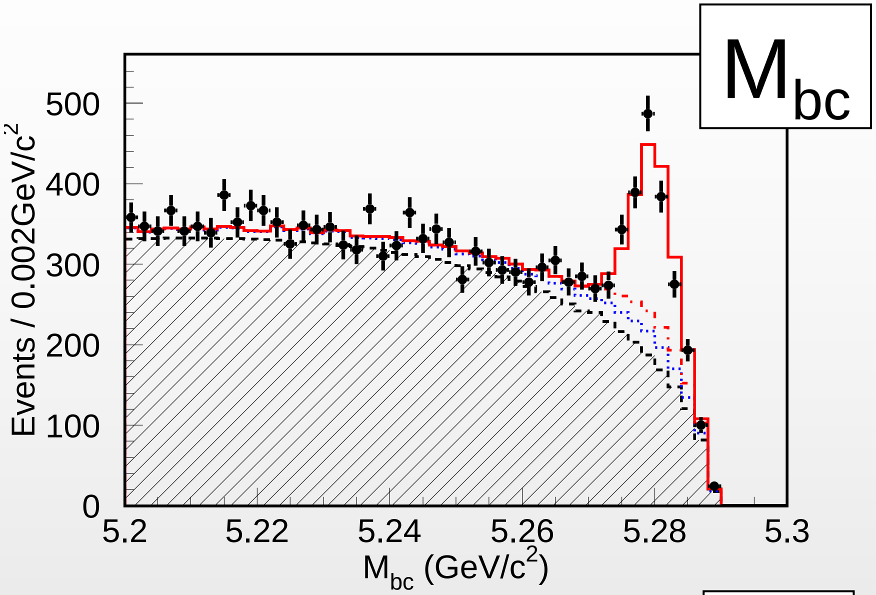


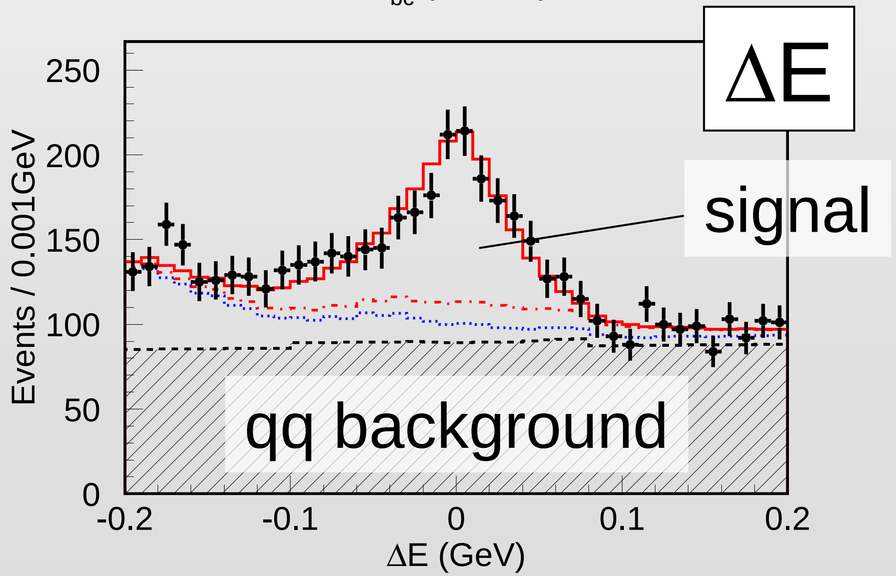
Still the ρ' and ρ'' enters into the mass window

→Systematic error

Event Reconstruction

- 971 ± 42 $B^0 \rightarrow \pi^+\pi^-\pi^0$ candidates
  - Efficiency ~10%
  - Purity ~30%
- Other components
  - SCF (Incorrectly reconstructed signal) ~5%
  - Continuum (qq) ~57%
  - Other B decay ~8%



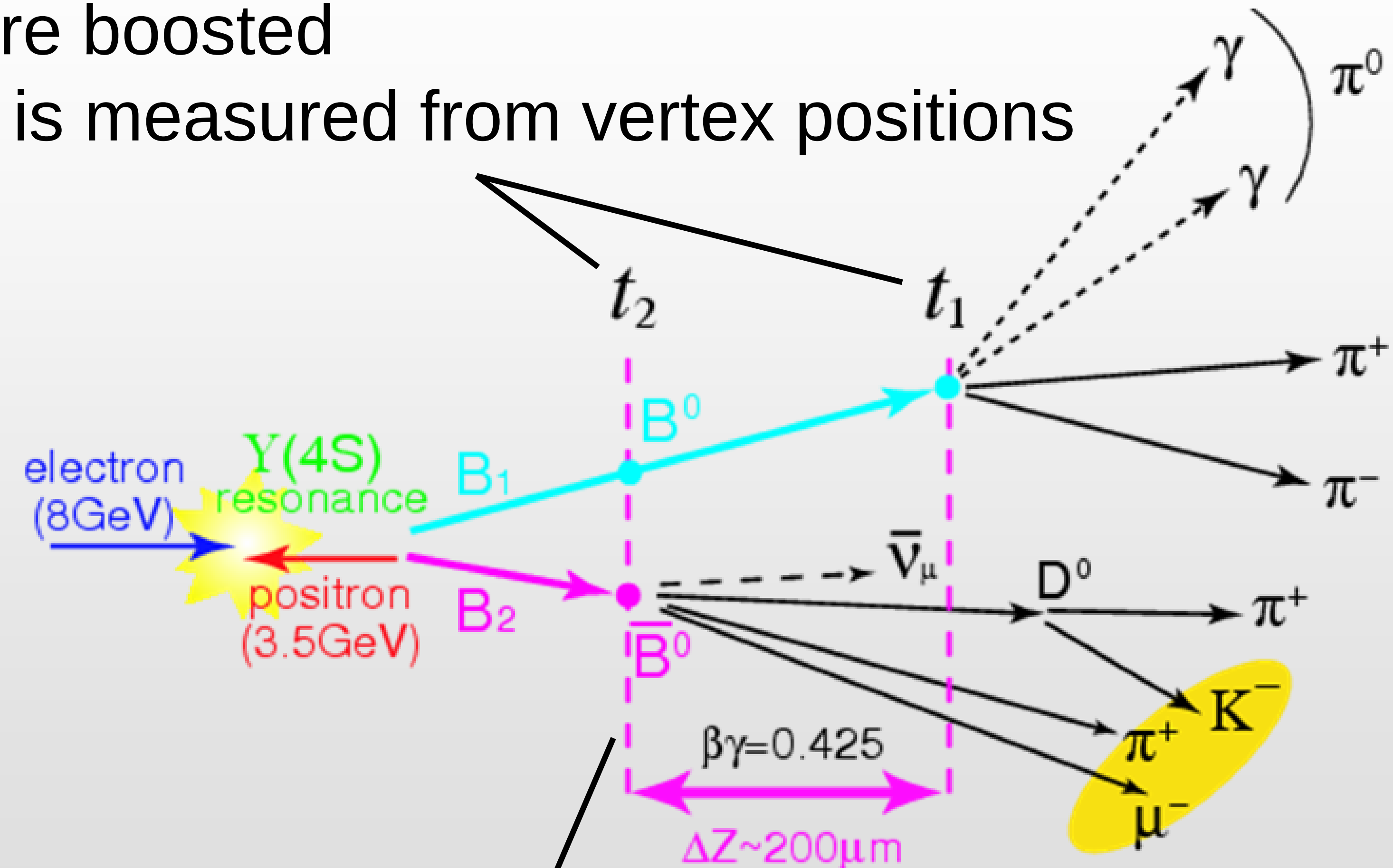


Analysis procedure

- Event selection
- Vertexing & Flavor Tagging
- Unbinned Maximum Likelihood Fit
- ϕ_2 extraction

Vertexing and Flavor Tagging

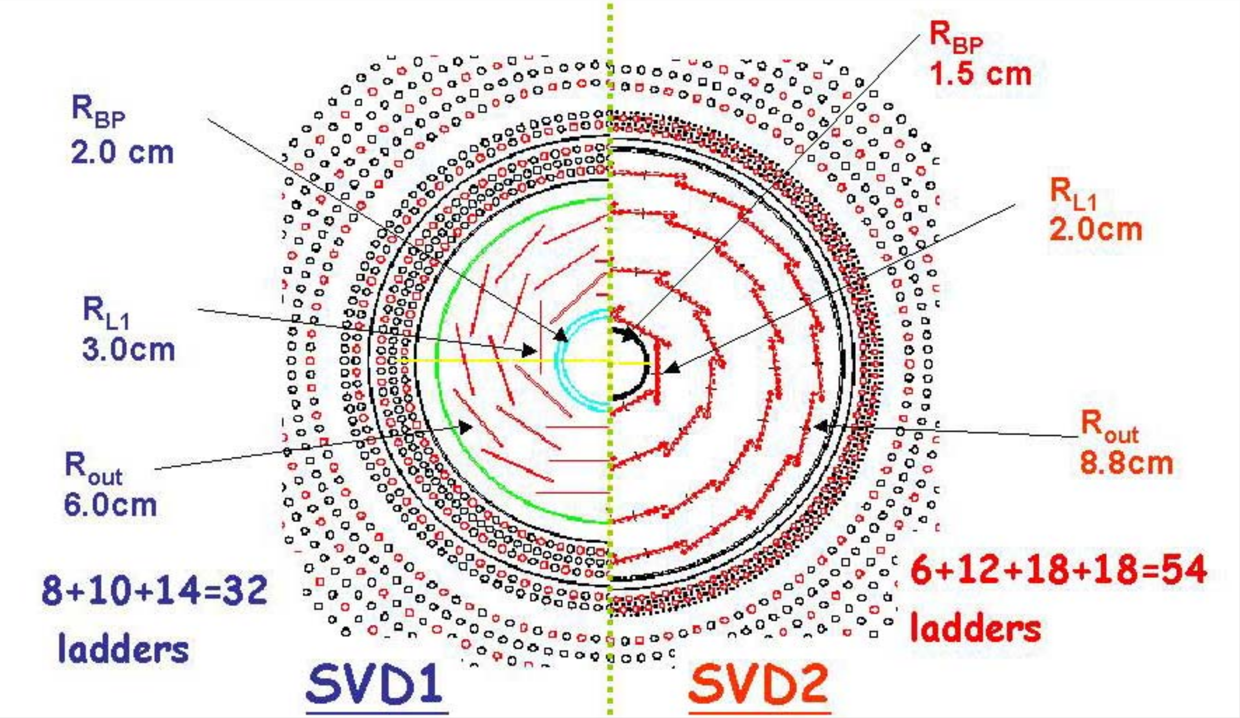
B's are boosted
→ Δt is measured from vertex positions



B's are entangled
→ flavor of B_1 at time t_2 is determined by B_2 decay

Vertexing: Detector

Silicon Vertex Detector (SVD)



3(SVD1)/4(SVD2) layers Double-sided Silicon Strip Detector

beam pipe r=1.5cm (SVD2)

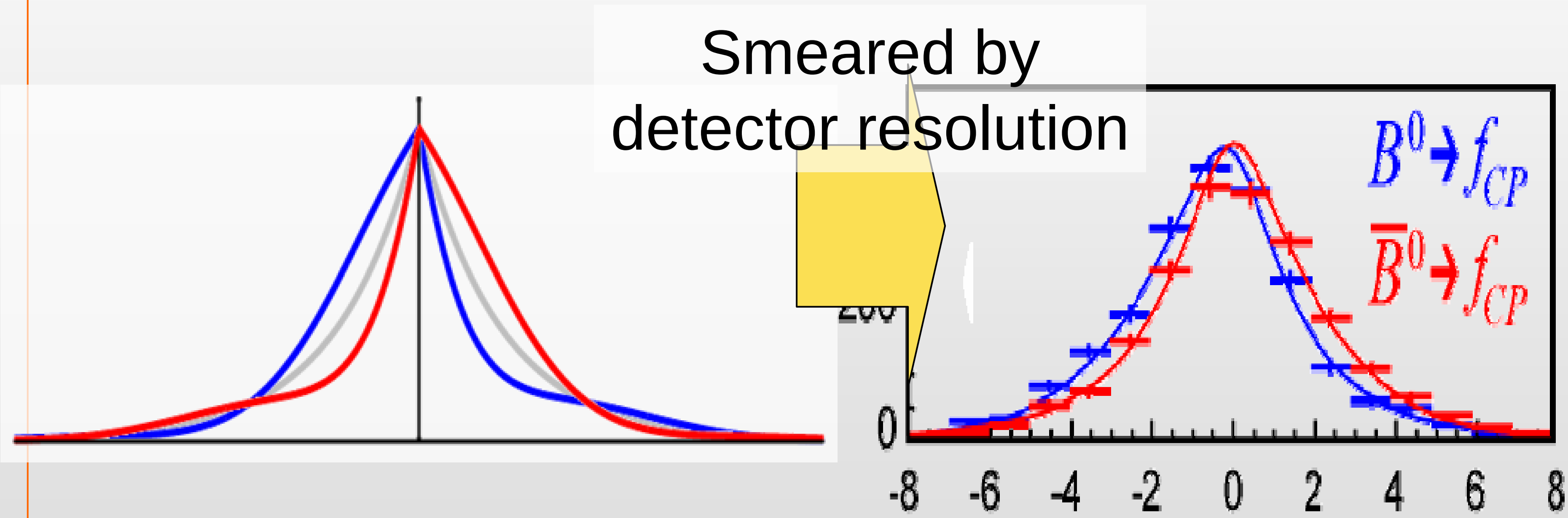
1st layer r=2.0cm (SVD2)

~120k channels (SVD2)

Vertexing: Resolution

Measured Δt is smeared by resolution

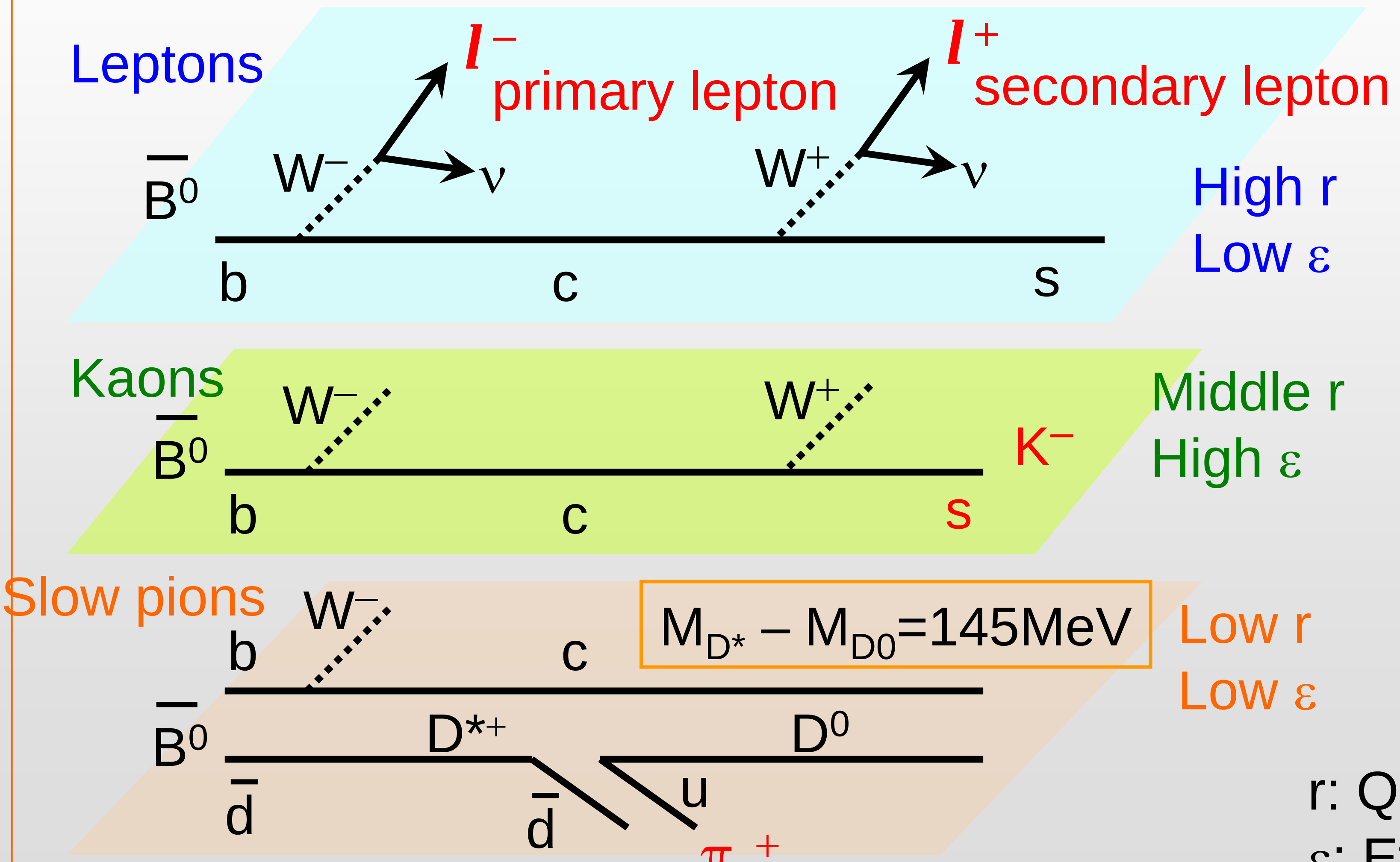
- $\sigma_z \sim 60\mu m$ (CP side)
- $\sigma_{\Delta z} \sim 120\mu m$



$$P(\Delta t) \qquad\qquad P(\Delta t) \otimes R(\Delta t)$$

Flavor Tagging: Algorithm

Likelihood composed of Tag side B information

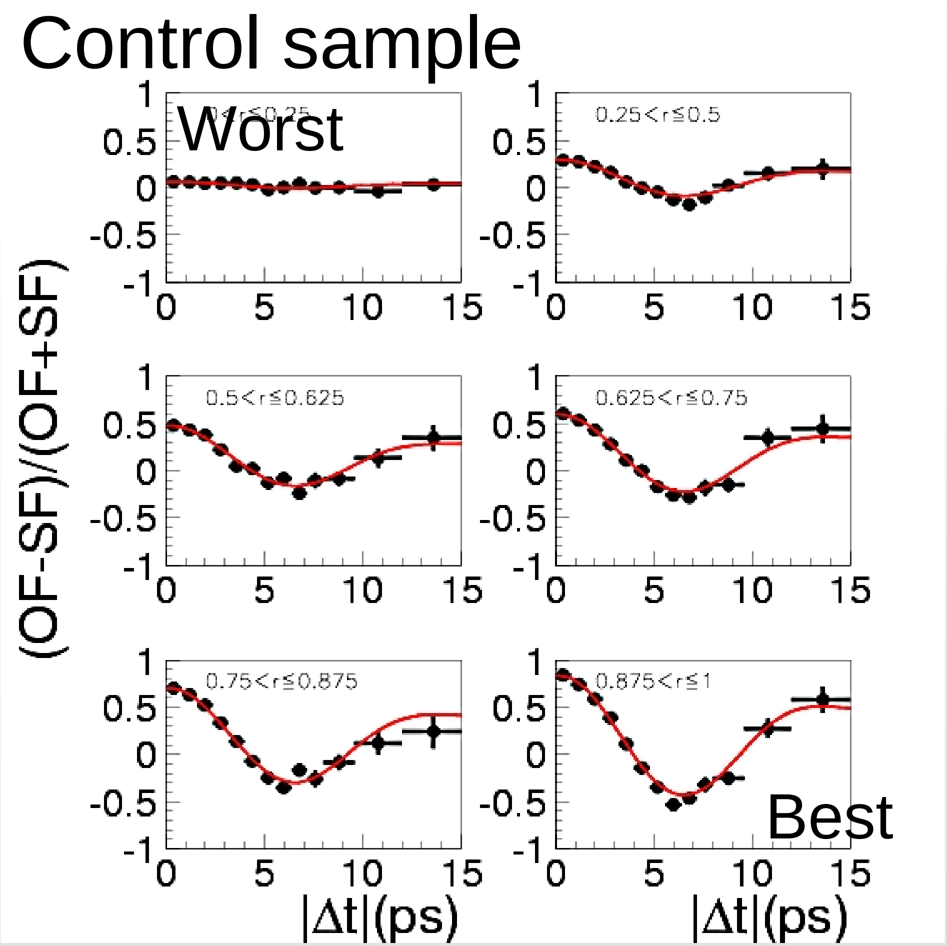


r: Quality

ε: Efficiency

Flavor Tagging: Calibration

- Wrong tag fraction is "measured" using B^0-$\bar{B}^0$ mixing.
  - Real amplitude of mixing is known to be unity.
  - Observed amplitude corresponds to dilution due to wrong tagging.
- Effective tagging efficiency ~30%.



B^0-$\bar{B}^0$ mixing in each tagging quality (r) region

Analysis procedure

- Event selection
- Vertexing & Flavor Tagging
- Unbinned Maximum Likelihood Fit
- ϕ_2 extraction

Unbinned Maximum Likelihood fit

- Likelihood function $\mathcal{L}$

$$\mathcal{L} = \prod_i P(\Delta E, M_{\text{bc}}; s_+, s_-; \Delta t, q_{\text{tag}}, r)$$

Index over events

- Event-by-Event PDF P

$$P(\Delta E, M_{\text{bc}}; s_+, s_-; \Delta t, q_{\text{tag}}, r)$$

$$= (1 - f_{qq} - f_{BB}) P_{\text{sig}} + f_{qq} P_{qq} + f_{BB} P_{BB}$$

Signal

Continuum

Other B decays

Signal PDF

Dalitz plot dependent

$$\mathcal{P}(s_+, s_-; \Delta t, q_{\rm tag}, r)$$

$$= \frac{e^{-|\Delta t|/\tau_{B^0}}}{4\tau_{B^0}} \Big[\left(|A_{3\pi}|^2 + |\overline{A}_{3\pi}|^2 \right) - q_{\rm tag} \cdot \left(|A_{3\pi}|^2 - |\overline{A}_{3\pi}|^2 \right) \cos \Delta m \Delta t$$

$$+ q_{\rm tag} \cdot 2\,{\rm Im}\left(e^{-2i\phi_1} A^*_{3\pi} \overline{A}_{3\pi} \right) \sin \Delta m \Delta t \Big]$$

Dilution due to miss-tagging
is taken account

Resolution function

$$P_{\rm sig} = P(\Delta E, M_{\rm bc}) \cdot \mathcal{P}(s_+, s_-; \Delta t, q_{\rm tag}, r) \otimes R(\Delta t)$$

Quinn & Silva (2000)

26(27) parameters to be fitted

- Signal PDF is a product of Δt and Dalitz PDF

Δt: 3 functions

$$e^{-|\Delta t|/\tau}$$

$$e^{-|\Delta t|/\tau}\cos(\Delta m\Delta t)$$

$$e^{-|\Delta t|/\tau}\sin(\Delta m\Delta t)$$

Dalitz: 9 functions

$$|\rho^+|^2$$

$$\mathrm{Re}[\rho^+ \leftrightarrow \rho^-] \quad \mathrm{Im}[\rho^+ \leftrightarrow \rho^-] \quad |\rho^-|^2$$

$$\mathrm{Re}[\rho^+ \leftrightarrow \rho^0] \quad \mathrm{Im}[\rho^+ \leftrightarrow \rho^0] \quad \mathrm{Re}[\rho^- \leftrightarrow \rho^0] \quad \mathrm{Im}[\rho^- \leftrightarrow \rho^0] \quad |\rho^0|^2$$

Signal PDF: linear combination of 3x9 = 27 functions

Coefficients of them are fit parameters

Quasi-Two-Body Parameters

- Using the information of non-interfering parameters alone.
- Dominant systematic error is from potential $B^0 \to \pi^+\pi^-\pi^0$ (~~ρπ~~) BG.

Δt: 3 functions

$$e^{-|\Delta t|/\tau}$$

$$e^{-|\Delta t|/\tau}\cos(\Delta m \Delta t)$$

$$e^{-|\Delta t|/\tau}\sin(\Delta m \Delta t)$$

Dalitz: 9 functions

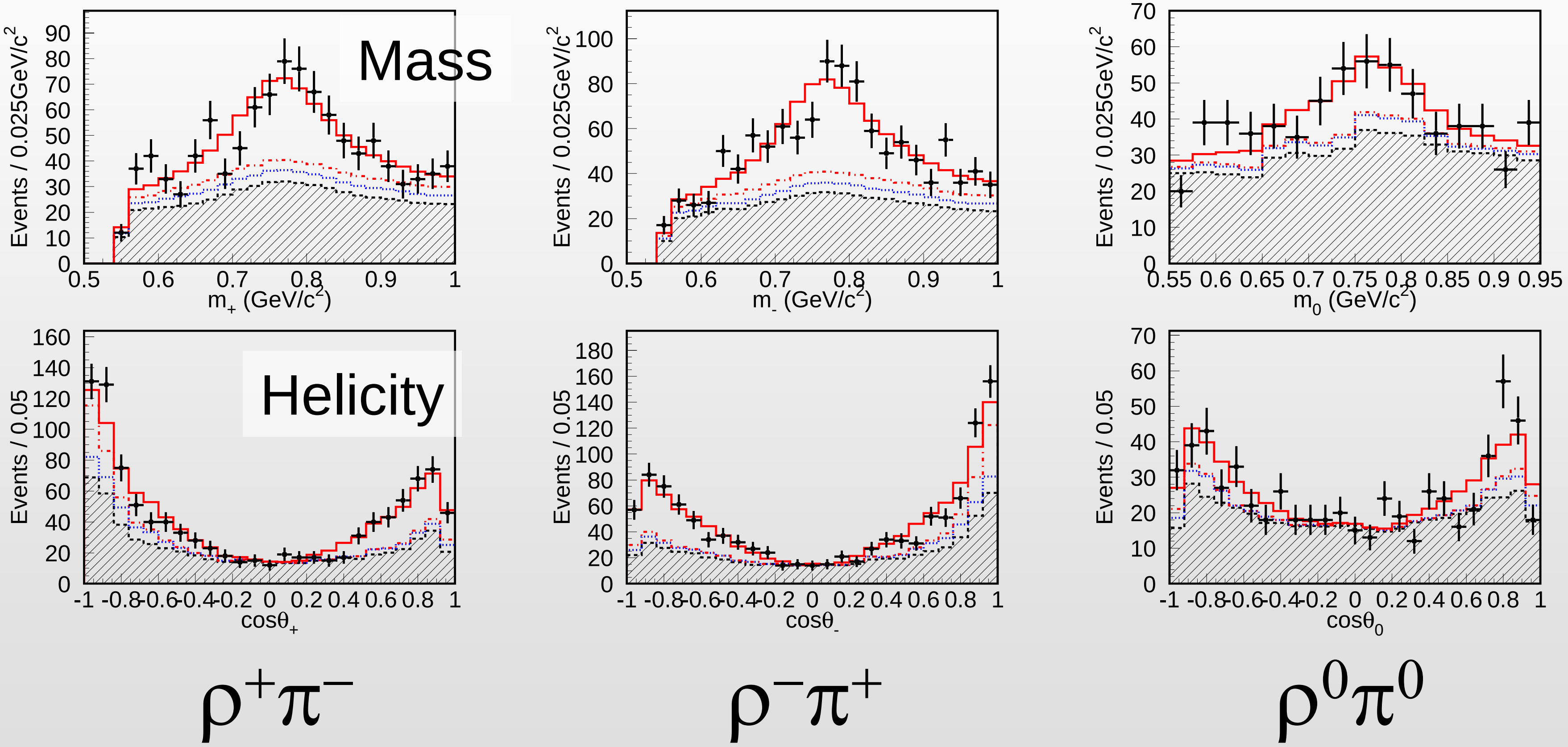
$$|\rho^+|^2$$

$$\mathrm{Re}[\rho^+ \leftrightarrow \rho^-] \quad \mathrm{Im}[\rho^+ \leftrightarrow \rho^-] \quad |\rho^-|^2$$

$$\mathrm{Re}[\rho^+ \leftrightarrow \rho^0] \quad \mathrm{Re}[\rho^- \leftrightarrow \rho^0] \quad \mathrm{Im}[\rho^+ \leftrightarrow \rho^0] \quad \mathrm{Im}[\rho^- \leftrightarrow \rho^0] \quad |\rho^0|^2$$

Fit result: Mass and Helicity

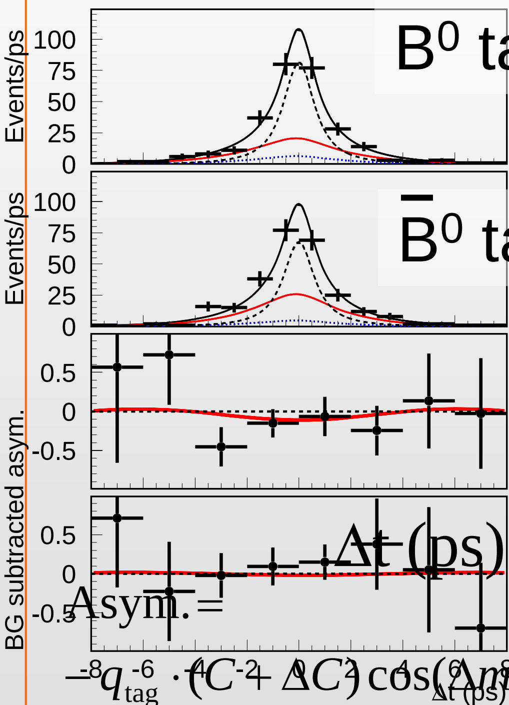
Projections of Dalitz plot



Data distribution is well described by fitted PDF.

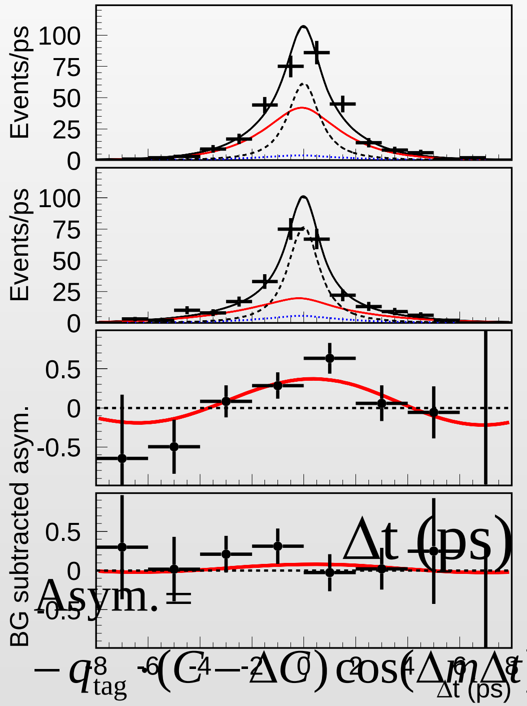
Fit result: Δt distribution

$\rho^+\pi^-$



$$\text{Asym.} = -q_{\text{tag}} \cdot (C + \Delta C)\cos(\Delta m \Delta t) + q_{\text{tag}} \cdot (S + \Delta S)\sin(\Delta m \Delta t)$$

$\rho^-\pi^+$



$$\text{Asym.} = -q_{\text{tag}} \cdot (C - \Delta C)\cos(\Delta m \Delta t) + q_{\text{tag}} \cdot (S - \Delta S)\sin(\Delta m \Delta t)$$

$$C = -0.13 \pm 0.09 \pm 0.05$$
$$\Delta C = +0.36 \pm 0.10 \pm 0.05$$
$$S = +0.06 \pm 0.13 \pm 0.05$$
$$\Delta S = -0.08 \pm 0.13 \pm 0.05$$

CP Violating

Direct CP violation: A^{+-} and A^{-+}

$$A^{+-} = \frac{\Gamma(\overline{B}^0 \to \rho^- \pi^+) - \Gamma(B^0 \to \rho^+ \pi^-)}{\Gamma(\overline{B}^0 \to \rho^- \pi^+) + \Gamma(B^0 \to \rho^+ \pi^-)}$$

$$A^{-+} = \frac{\Gamma(\overline{B}^0 \to \rho^+ \pi^-) - \Gamma(B^0 \to \rho^- \pi^+)}{\Gamma(\overline{B}^0 \to \rho^+ \pi^-) + \Gamma(B^0 \to \rho^- \pi^+)}$$

Calculated from Q2B parameters

$$\mathcal{A}_{\rho\pi}^{+-} \equiv -\frac{\mathcal{A}_{\rho\pi}^{CP} + \mathcal{C} + \mathcal{A}_{\rho\pi}^{CP}\Delta\mathcal{C}}{1 + \Delta\mathcal{C} + \mathcal{A}_{\rho\pi}^{CP}\,\mathcal{C}} ,$$

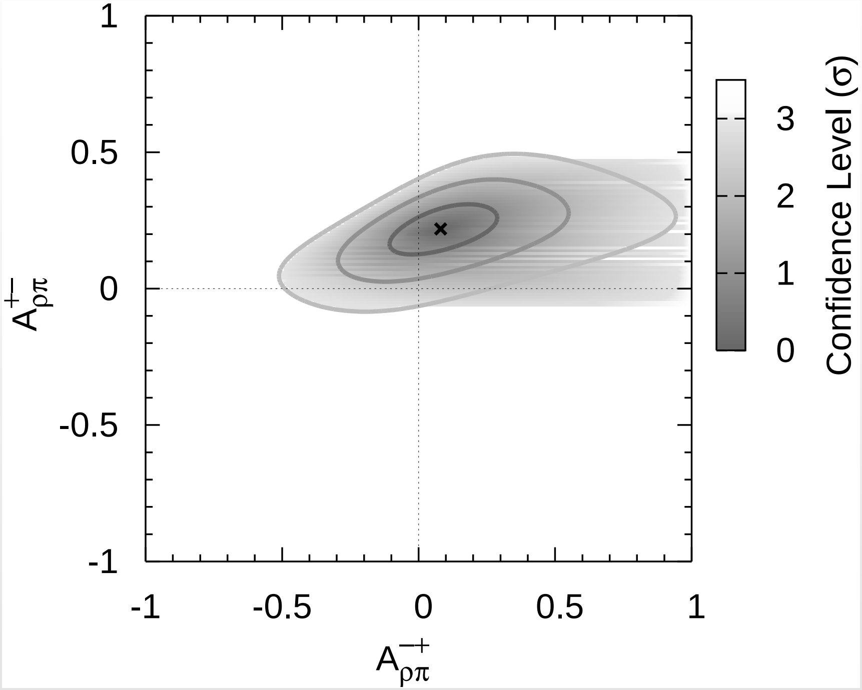
$$\mathcal{A}_{\rho\pi}^{-+} \equiv \frac{\mathcal{A}_{\rho\pi}^{CP} - \mathcal{C} - \mathcal{A}_{\rho\pi}^{CP}\Delta\mathcal{C}}{1 - \Delta\mathcal{C} - \mathcal{A}_{\rho\pi}^{CP}\,\mathcal{C}} ,$$

Quasi-Two-Body: Direct CPV

$$A^{+-} = +0.21 \pm 0.08 \pm 0.04$$

$$A^{-+} = +0.08 \pm 0.17 \pm 0.11$$

Correlation: +0.47



A^{-+} vs. A^{+-}

DCPV Confidence Level ~2.3σ

Quasi-Two-Body: $B^0 \rightarrow \rho^0\pi^0$

$$\text{Asym.} = q_{\text{tag}} \cdot A_{\rho^0\pi^0} \cos(\Delta m \Delta t) + q_{\text{tag}} \cdot S_{\rho^0\pi^0} \sin(\Delta m \Delta t)$$

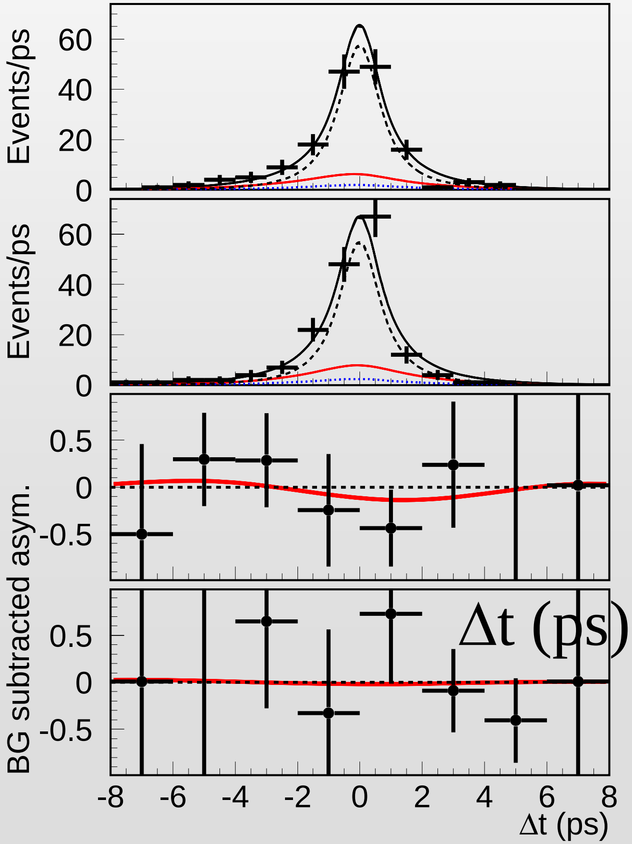
$$A_{\rho^0\pi^0}\,(-C_{\rho^0\pi^0}) = -0.49 \pm 0.36 \pm 0.28$$

$$S_{\rho^0\pi^0} = +0.17 \pm 0.57 \pm 0.35$$

First measurement

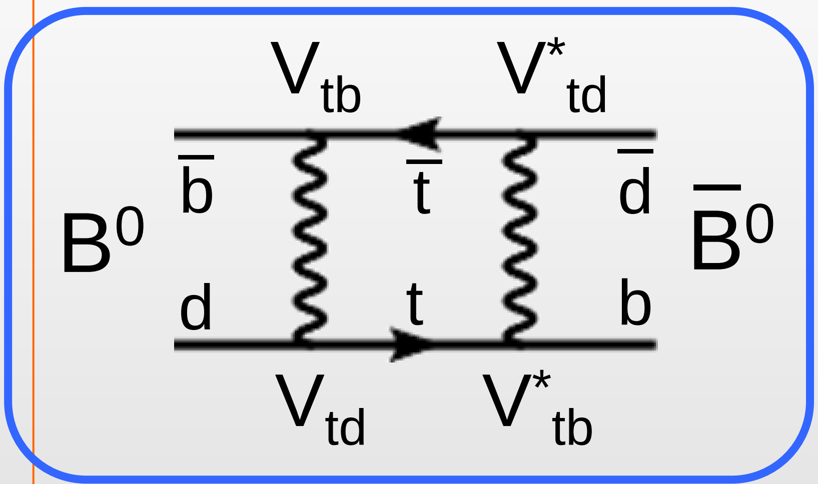
$$\mathcal{A}_{\rho^0\pi^0} = -\frac{U_0^-}{U_0^+}\,, \quad \mathcal{S}_{\rho^0\pi^0} = \frac{2I_0}{U_0^+}\,.$$

Δt distribution of $B^0 \rightarrow \rho^0\pi^0$



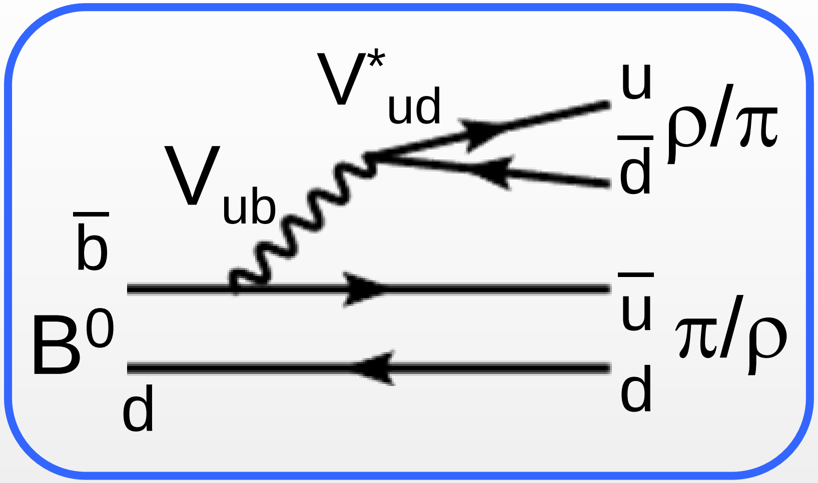
ϕ_2 (α) extraction

Penguin pollution



Mixing diagram

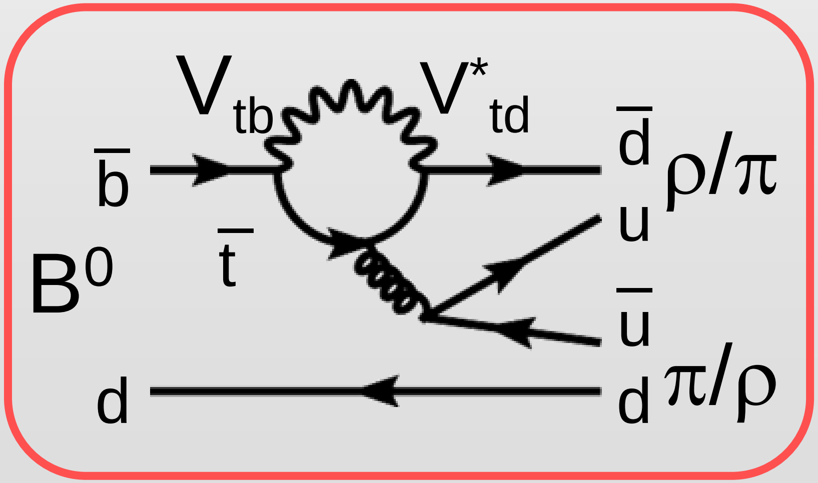
+



Tree diagram

ϕ_2

+



Penguin diagram

0

Dalitz + Isospin Analysis

- Uses both interfering and non-interfering parameters.
- In particular, interfering parameters play important roles.
- Primary systematic error
  - radial excitations (ρ’ and ρ’’)

Δt: 3 functions

$$e^{-|\Delta t|/\tau}$$

$$e^{-|\Delta t|/\tau}\cos(\Delta m \Delta t)$$

$$e^{-|\Delta t|/\tau}\sin(\Delta m \Delta t)$$

Dalitz: 9 functions

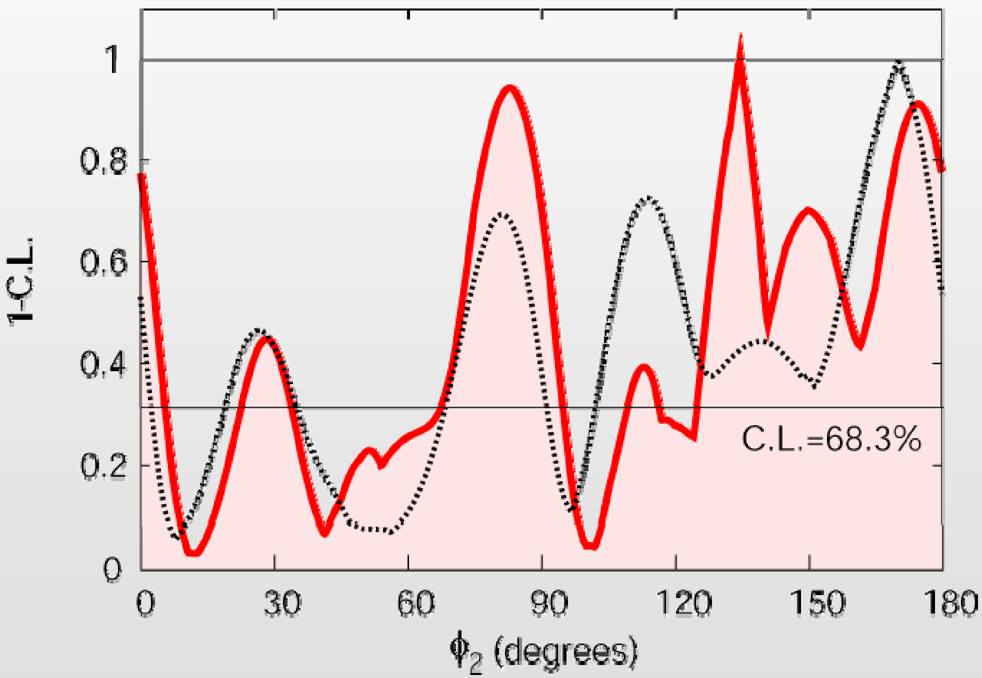
$$|\rho^+|^2$$

$$\mathrm{Re}[\rho^+ \leftrightarrow \rho^-] \quad \mathrm{Im}[\rho^+ \leftrightarrow \rho^-] \quad |\rho^-|^2$$

$$\mathrm{Re}[\rho^+ \leftrightarrow \rho^0] \quad \mathrm{Re}[\rho^- \leftrightarrow \rho^0] \quad \mathrm{Im}[\rho^+ \leftrightarrow \rho^0] \quad \mathrm{Im}[\rho^- \leftrightarrow \rho^0] \quad |\rho^0|^2$$

Dalitz + Isospin Analysis: Result

- Combined analysis of
  - Our result
  - Charged mode info.
- As allowed region, we obtain:
  - $0 < \phi_2 < 5°$
  - $23° < \phi_2 < 34°$
  - $68° < \phi_2 < 95°$
  - $109° < \phi_2 < 180$



Combined analysis

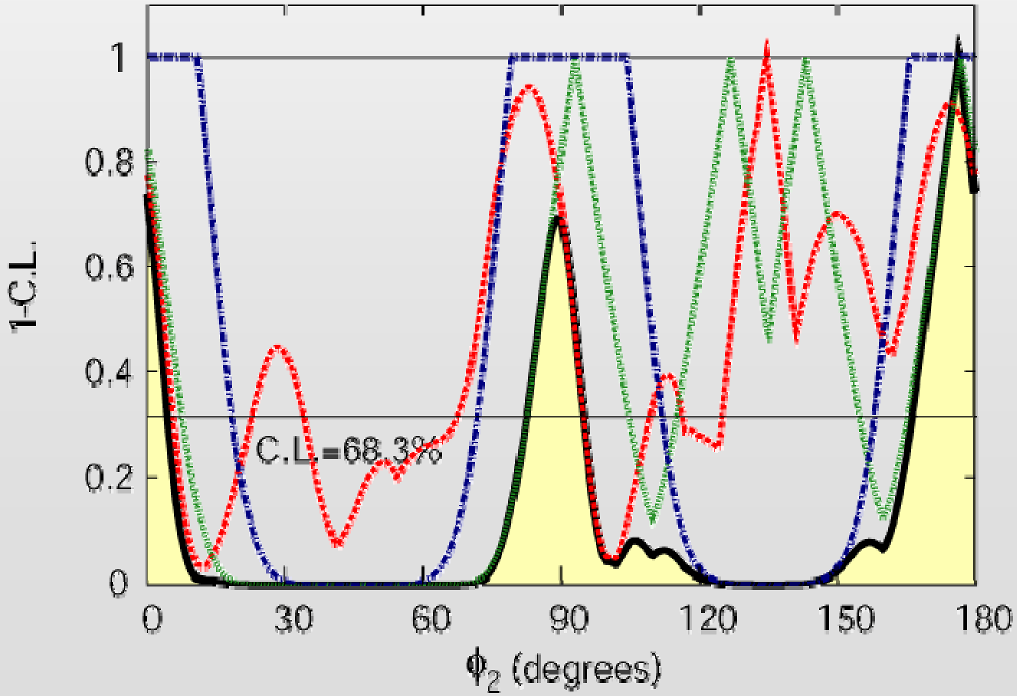
- Gluon penguin contribution is mode dependent

- Addition of $B^0 \rightarrow \pi\pi, \rho\rho, \rho\pi$

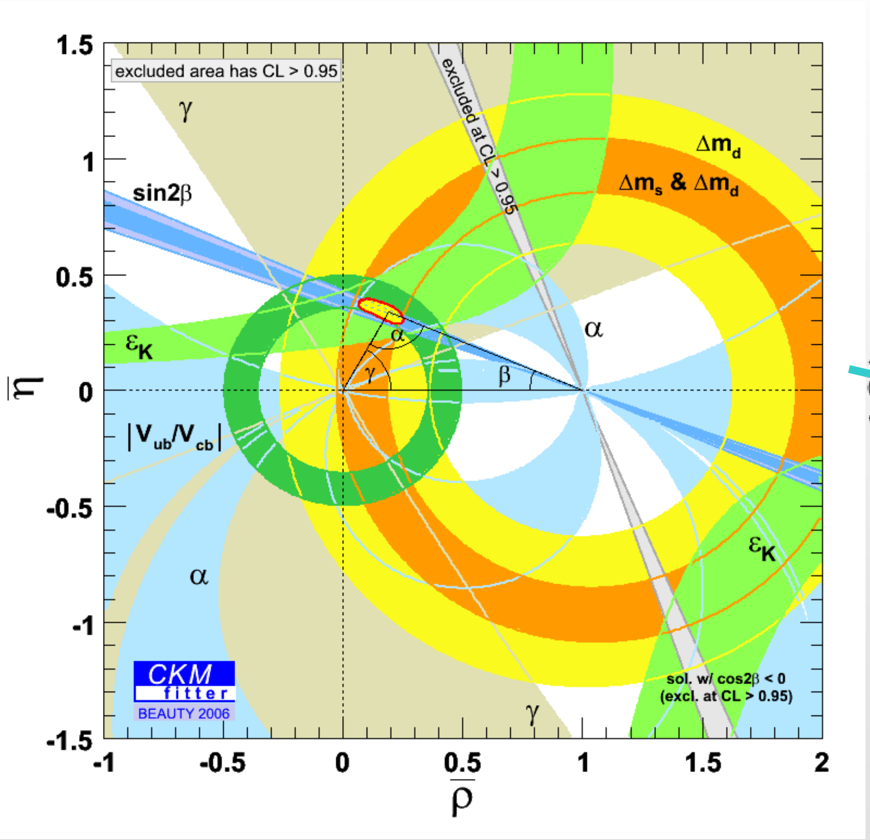
  $\rightarrow$ Decrease the uncertainty from penguin

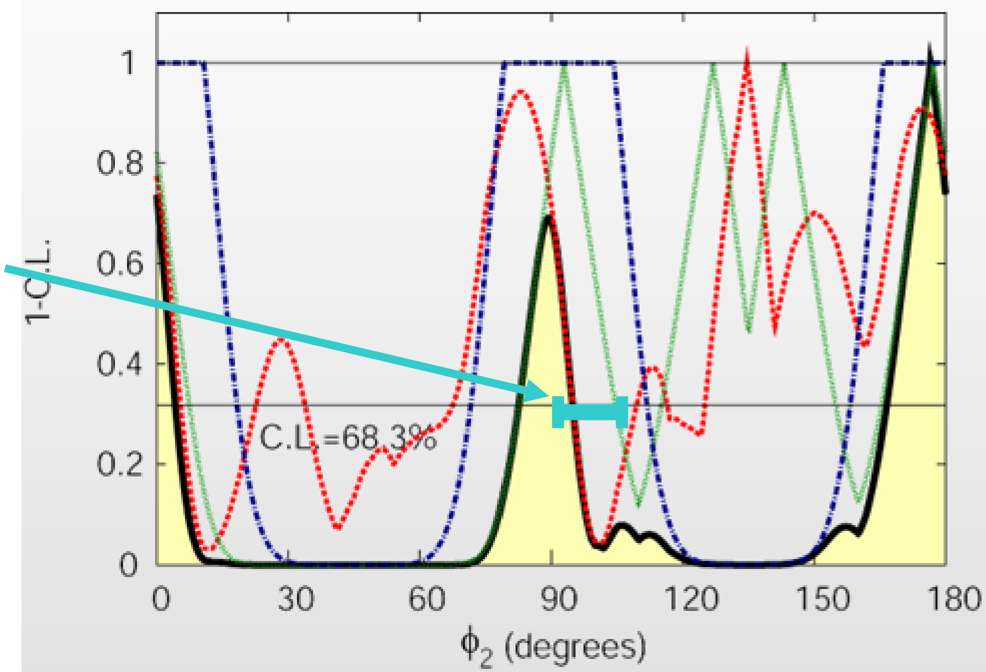
WA (B→ππ, ρρ) + our result

- We obtain $83<\phi_2<95$ (deg.) at 68.3%C.L.
- Our measurement of B→ρπ improves the constraint on ϕ_2.
- To solve the ambiguity, we need more data.



Comparison with Global fit





Global fit w/o direct measurement
$\phi_2 = 100^{+5}_{-7}$ (deg.)

Averaged direct measurement
$83 < \phi_2 < 95$ (deg.)

Conclusion

- B→$\rho\pi$ time-dependent Dalitz plot analysis
  - Potential capability of killing discrete ambiguity solution.
  - Very interesting, but a complex analysis.
- We perform the analysis with 449M BB data collected at Belle/KEKB
  - Indication of direct CP violation
  - First measurement of $\mathcal{S}_{\rho 0 \pi 0}$
- Constraint on ϕ_2
  - Our $\rho\pi$ analysis: $68<\phi_2<95$ (deg.)
  - Combined $\pi\pi$, $\rho\rho$, and our $\rho\pi$: $83<\phi_2<95$ (deg.)
  - Consistent with the expectation from other measurements.

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Accepted by PRL