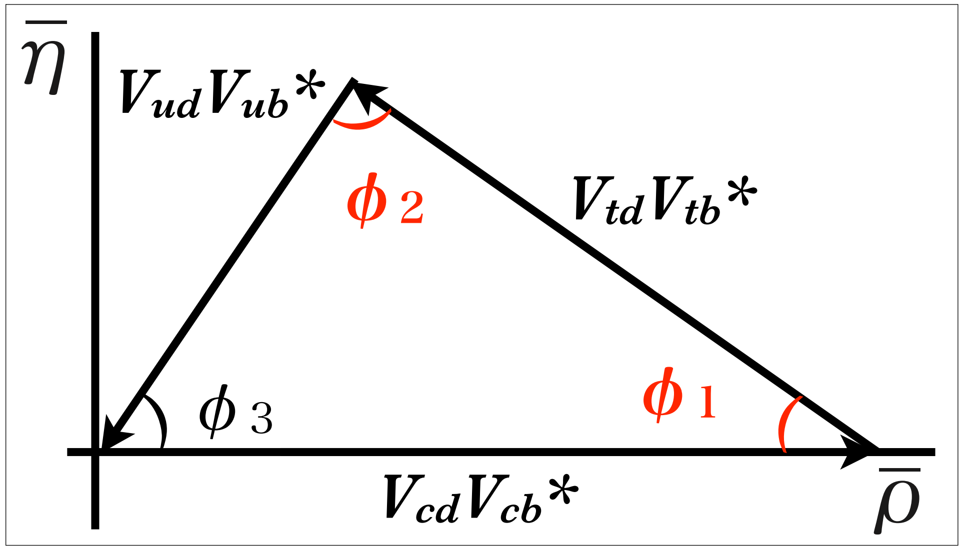
ϕ_1 and ϕ_2 at Belle (II)

Yosuke Yusa
Niigata University



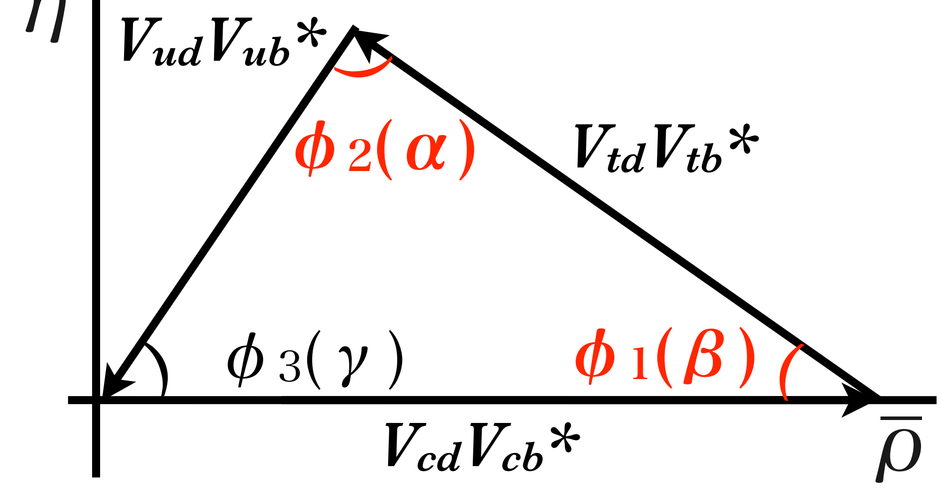
ϕ_1/ϕ_2 — angles of unitary triangle

Quark transition: Cabibbo-Kobayashi-Maskawa (CKM) Matrix

CP violation is induced by complex phase and parameterized as angles of the unitary triangle.

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

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



Decay rate is described as difference of decay time between B^0 mesons.

$$\mathcal{A}_{CP} = \frac{\mathcal{P}(\overline{B^0}(\Delta t) \to f_{CP}) - \mathcal{P}(B^0(\Delta t) \to f_{CP})}{\mathcal{P}(\overline{B^0}(\Delta t) \to f_{CP}) + \mathcal{P}(B^0(\Delta t) \to f_{CP})}$$

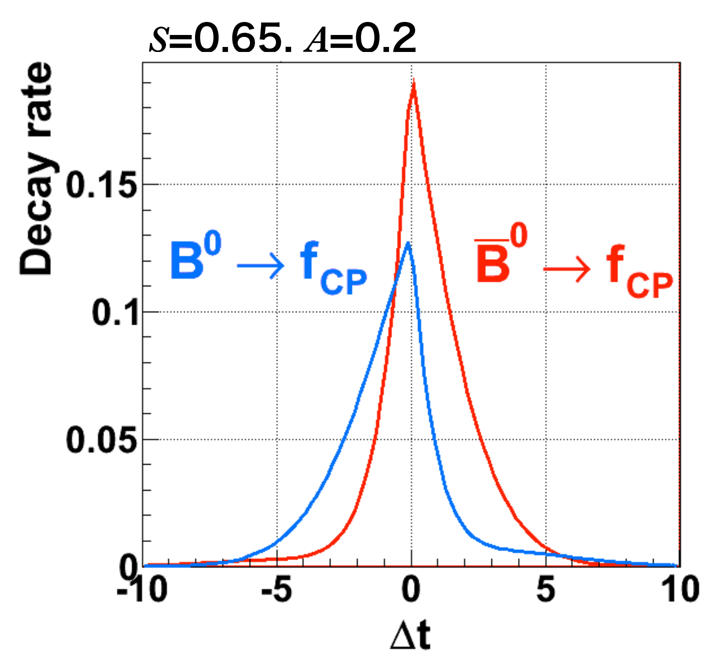
$= S \sin\Delta m \Delta t \quad + \quad A \cos\Delta m \Delta t$

mixing induced CPV — direct CPV

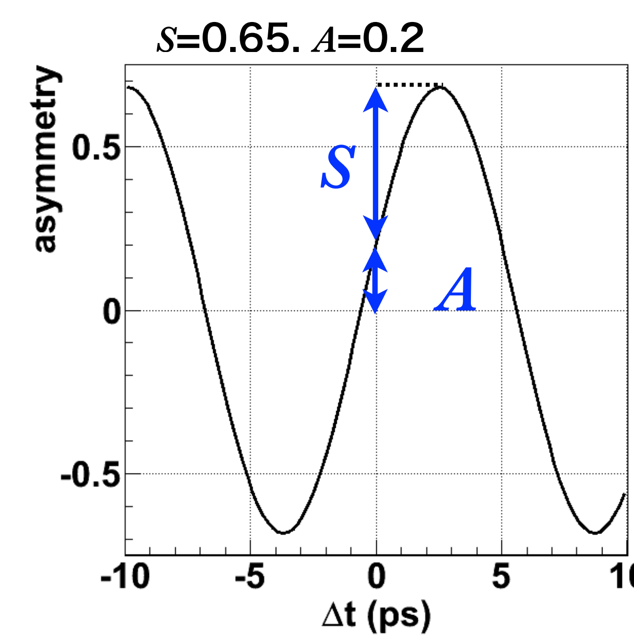
Δm: mass difference of eigenstates

Δt: decay time difference of eigenstates

$\overset{(-)}{B^0} \to f_{CP}$ proper-time distribution



Asymmetry A_{CP} distribution



ϕ_1 measurement

Time-dependent CP violation:

Quantum interference between two diagrams.

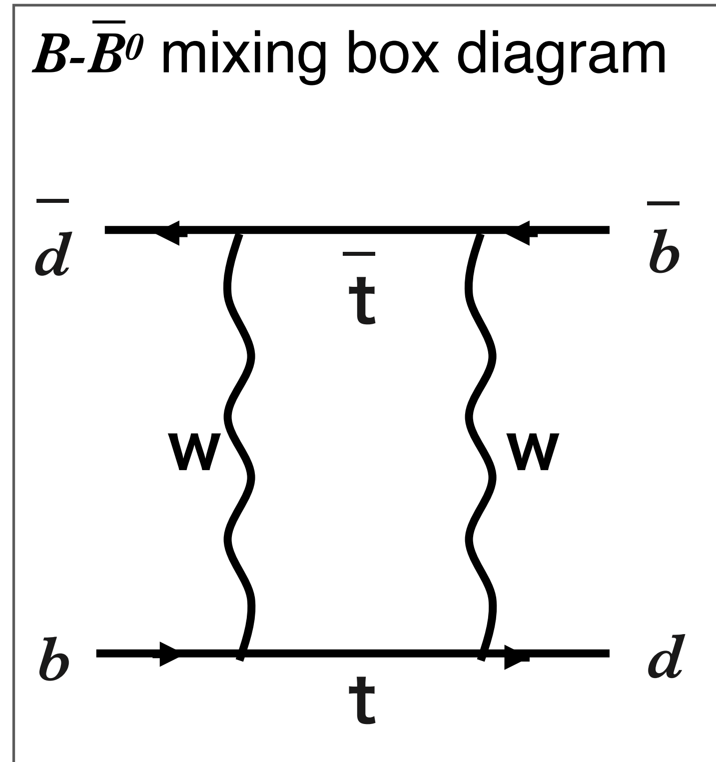
$\phi_1 (= \beta) = \arg(V_{cd} V_{cb}^* / V_{td} V_{tb}^*)$

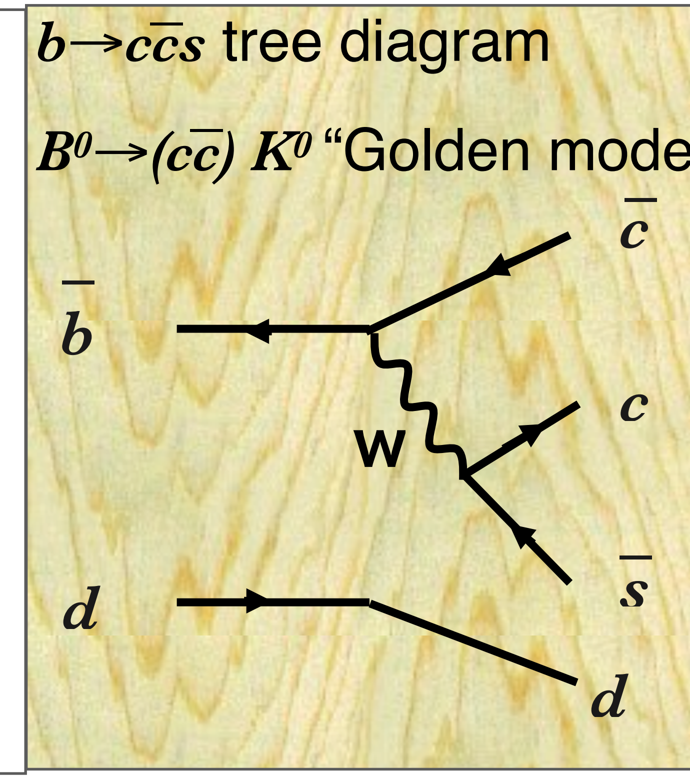
→ Accessible using CP-eigenstates induced by $b \to c\bar{c}s$ tree diagram.

$S = -\xi_f \sin 2\phi_1$

ξ_f: CP eigenvalue :

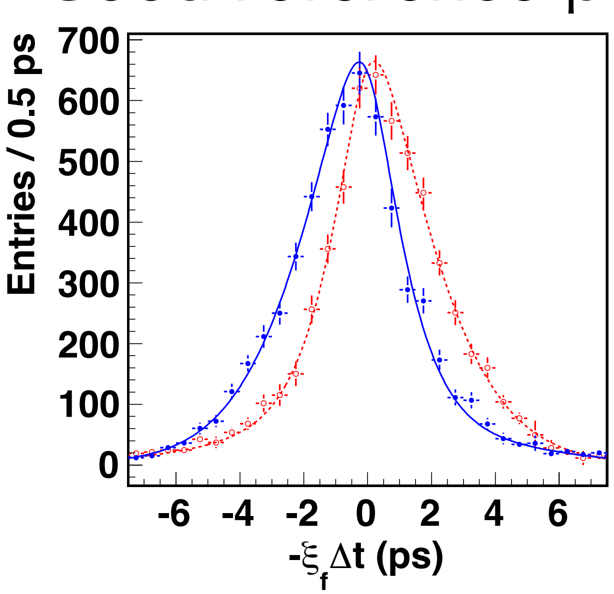
-1 for $(c\bar{c})K^0_S$, $+1$ for $(c\bar{c})K^0_L$

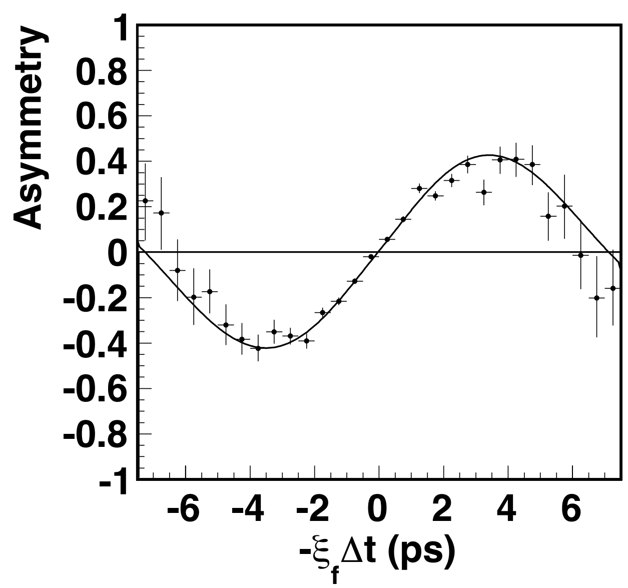




Since contribution from other diagrams are tiny, ϕ_1 measured from these CP-eigenstates are theoretically clean.

→ Good reference point of the Standard Model.





$\sin 2\phi_1 = 0.668 \pm 0.023 \pm 0.013$,

$A = 0.007 \pm 0.016 \pm 0.013$

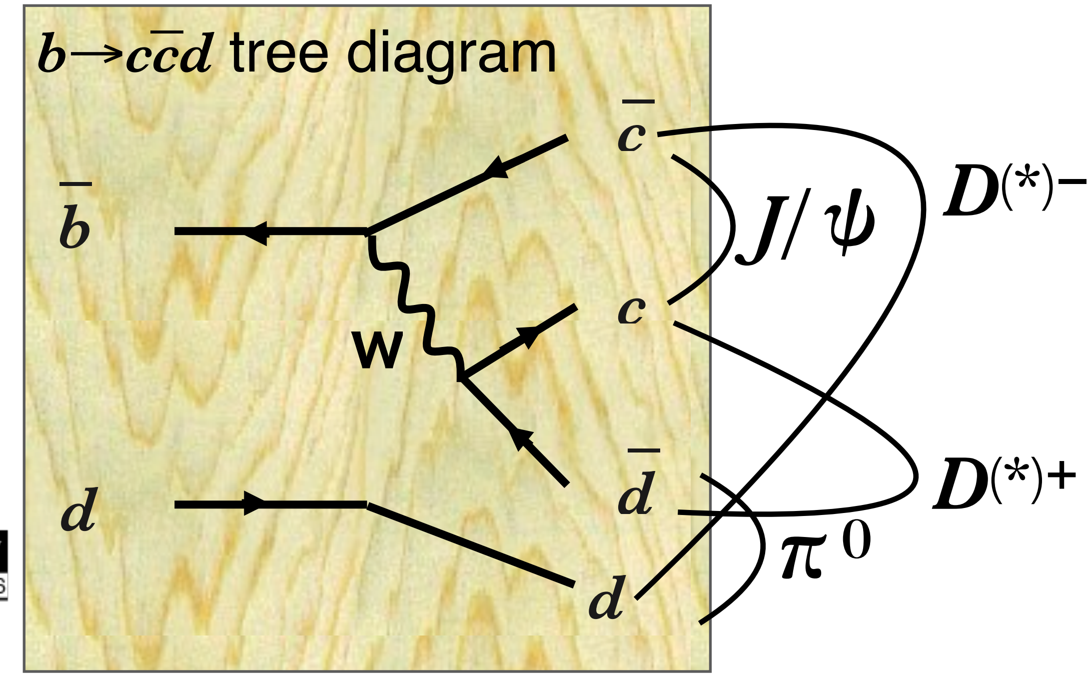
ϕ_1 measurement

ϕ_1 is also measured using CP-eigenstates induced by $b \to c\bar{c}d$ tree diagram.

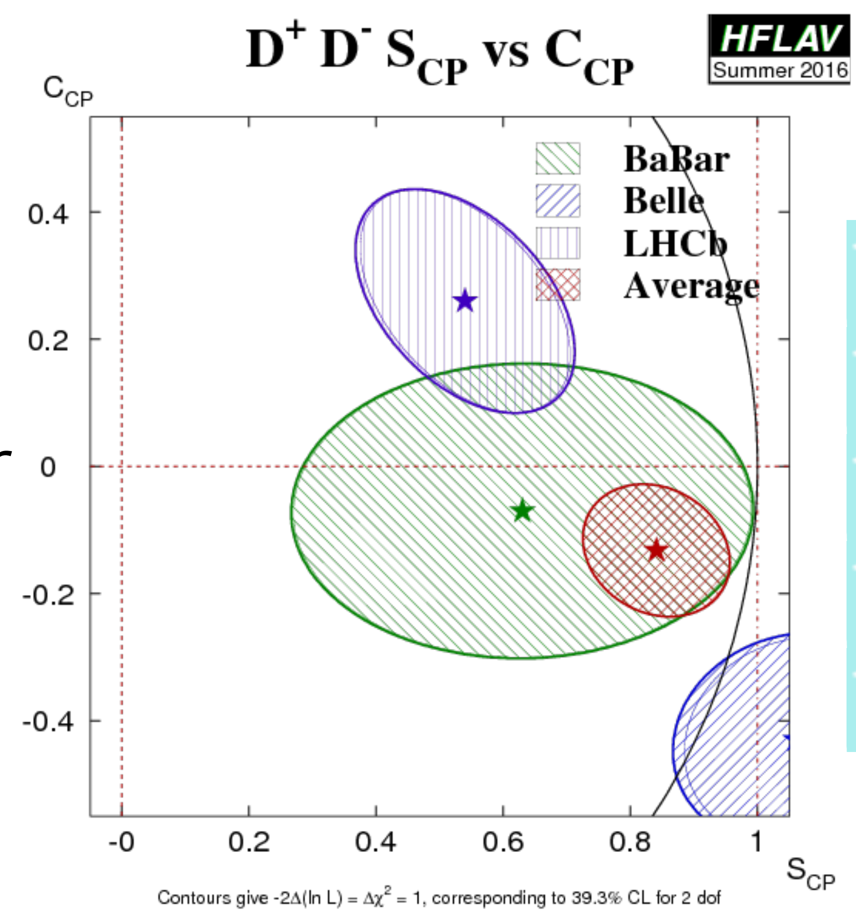
Pollution from penguin diagram can be consdered but effect is expected to be low in SM.

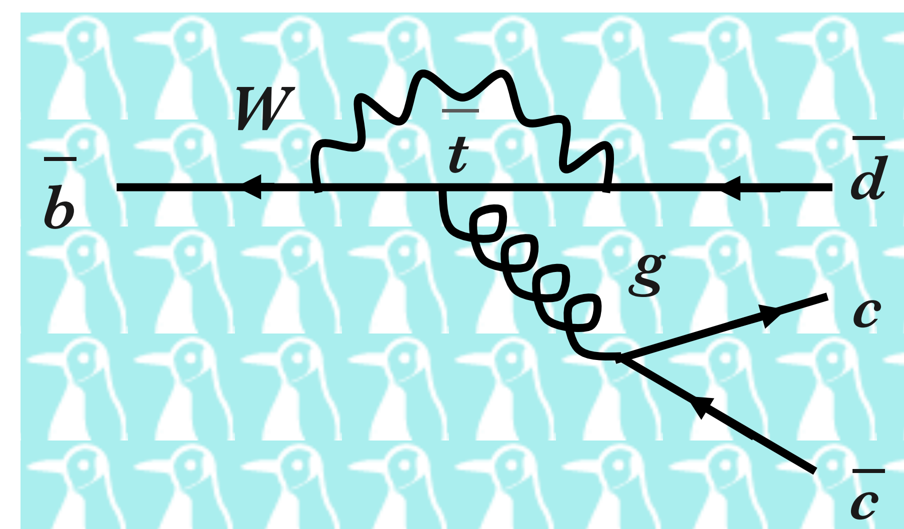
→ If large deviation from $b \to c\bar{c}s$ is seen,

it indicates contribution of new physics.



In $B^0 \to D^+D^-$, large direct CP violation was seen in Belle (4.0σ). Tension is relaxed after update but we need further study using more statistics.





$B^0 \to J/\psi\, \pi^0$ can be used for estimation of possible penguin polution in $B^0 \to J/\psi\, K^0$ (PRL 95, 221804 (2005)) → Necessary information for large statistic measurement.

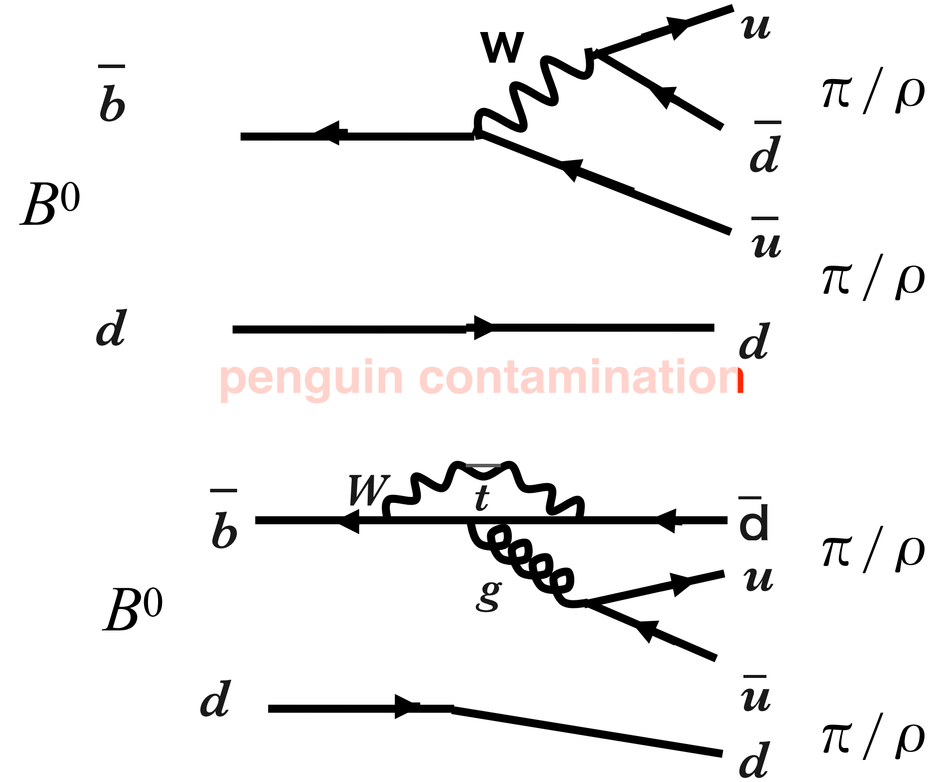
ϕ_2 measurement

$\phi_2 (= \alpha) = \arg(V_{ud} V_{ub}^* / V_{td} V_{tb}^*)$

→ Accessible via b→u tree diagram but contribution from b→d penguin diagram is not negligible.

$S = -\xi_f \sqrt{1-A^2} \sin 2\phi_2^{eff}$

$\phi_2^{eff} = \phi_2 - \Delta\phi_2$ (“effective” ϕ_2)



Strategies to determine ϕ_2 without CP phase from penguin contamination

- Isospin relations between $B \to \pi^i \pi^j$ / $\rho^i \rho^j$ decay amplitudes

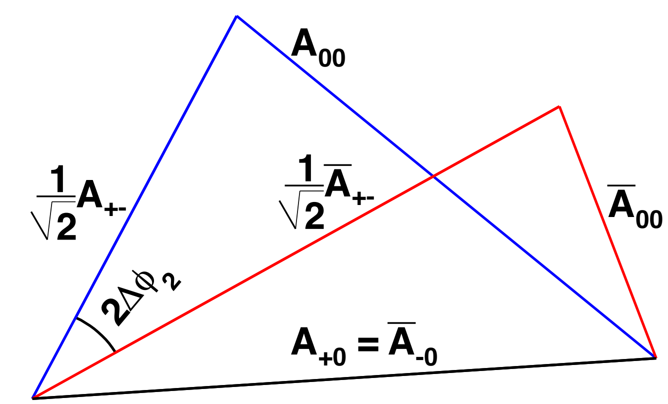
Gronau and London, PRL65 3381 (1990)

$$A^{+0} = \frac{1}{\sqrt{2}} A^{+-} + A^{00}$$

$$\bar{A}^{-0} = \frac{1}{\sqrt{2}} \bar{A}^{+-} + \bar{A}^{00}$$

(A^{ij} : Decay amplitudes of $B \to \pi^i \pi^j / \rho^i \rho^j$)

⇒ Using branching fractions and CP violation parameters, $\Delta\phi_2$ is determined with four-fold ambiguity.

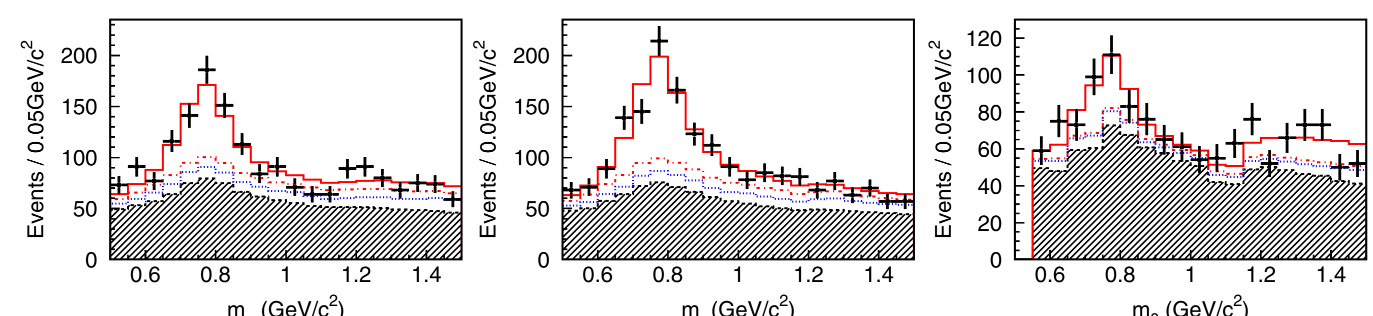


- Dalitz analysis for $\pi \pi \pi^0$ 3-body system

A. Snyder and H. Quinn, PRD 48 2139 (1993)

Interference between three $B \to \rho \pi$ states

Δt fit with coefficients of Dalitz plot functions



⇒ Constrain ϕ_2 with a small ambiguity in theoretical point of view.

$\sin 2\phi_1^{\mathrm{eff}}$ measurement in $b \to sqq$

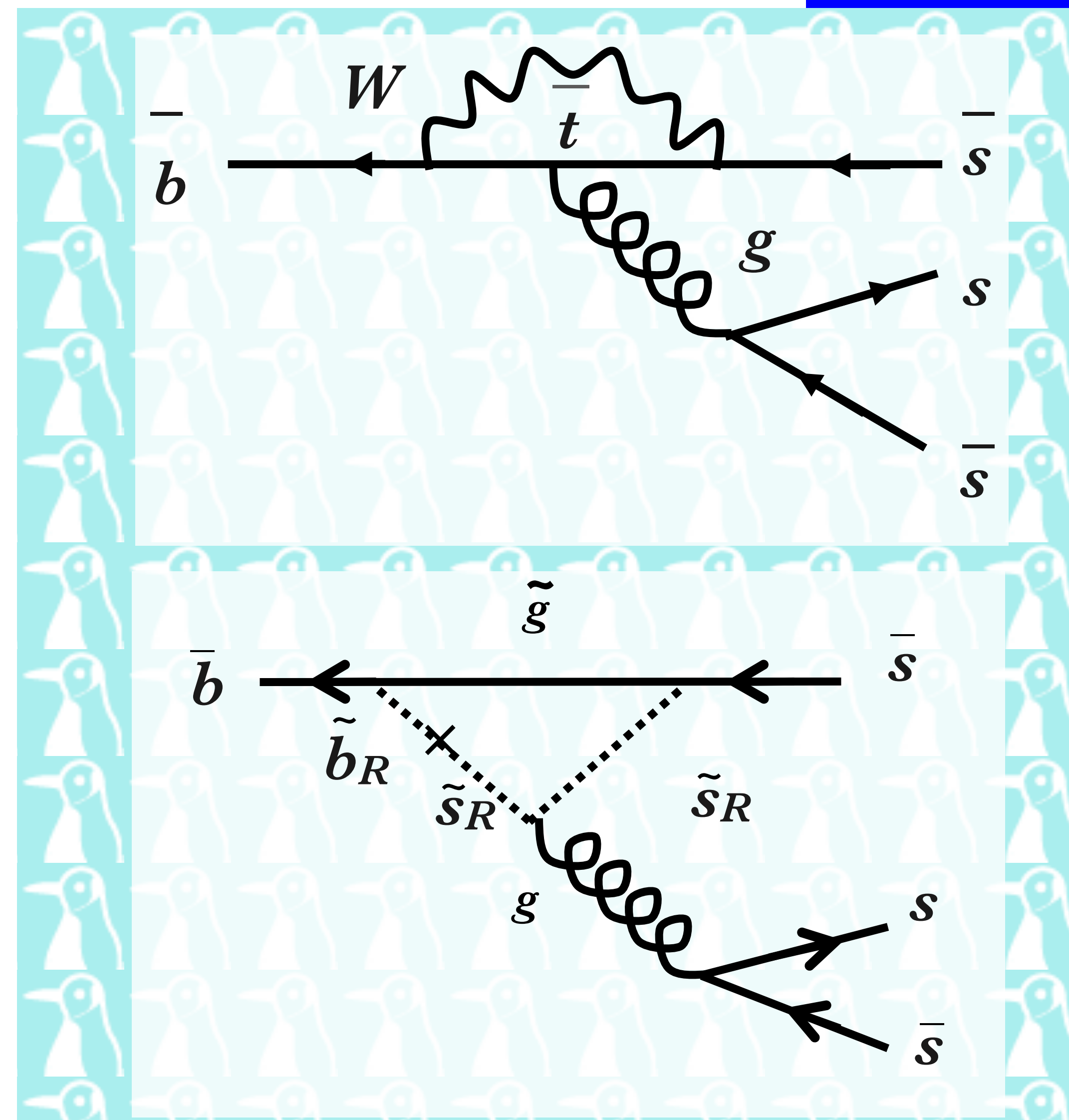
Same weak phase as $b \to c\bar{c}s$

if only SM penguin contributes.

$S \equiv -\xi_f \sin 2\phi_1^{\mathrm{eff}} = -\xi_f \sin 2\phi_1$

Penguin loop is sensitive to the new physics contribution.

$S = -\xi_f \sin 2\phi_1 \oplus$ *extra CP phase from non-SM?*



	ΔS	BF ($\times 10^{-5}$)
$B^0 \to \eta' K^0$	0.01 ± 0.01	6.6
$B^0 \to \phi K^0$	0.02 ± 0.01	0.86
$B^0 \to \omega K^0_S$	0.13 ± 0.08	0.5
$B^0 \to \rho^0 K^0_S$	$-0.08^{+0.08}_{-0.12}$	0.47
$B^0 \to K^0_S \pi^0$	$0.07^{+0.05}_{-0.04}$	0.95

J. Zupan, hep-ph/0707.1323

	ΔS	BF ($\times 10^{-5}$)
$B^0 \to K^+ K^- K^0_S$	$0.03^{+0.02}_{-0.03}$	2.47
$B^0 \to K^0_S K^0_S K^0_S$	$0.02^{+0.02}_{-0.03}$	0.62

Hai-Yang Cheng, hep-ph/0702252

ΔS: S shift from theoretically predicted from other SM diagrams (mainly from $b \to u$ tree)

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$S = -\xi_f \sin 2\phi_{1\oplus}$ *extra CP phase from non-SM?*

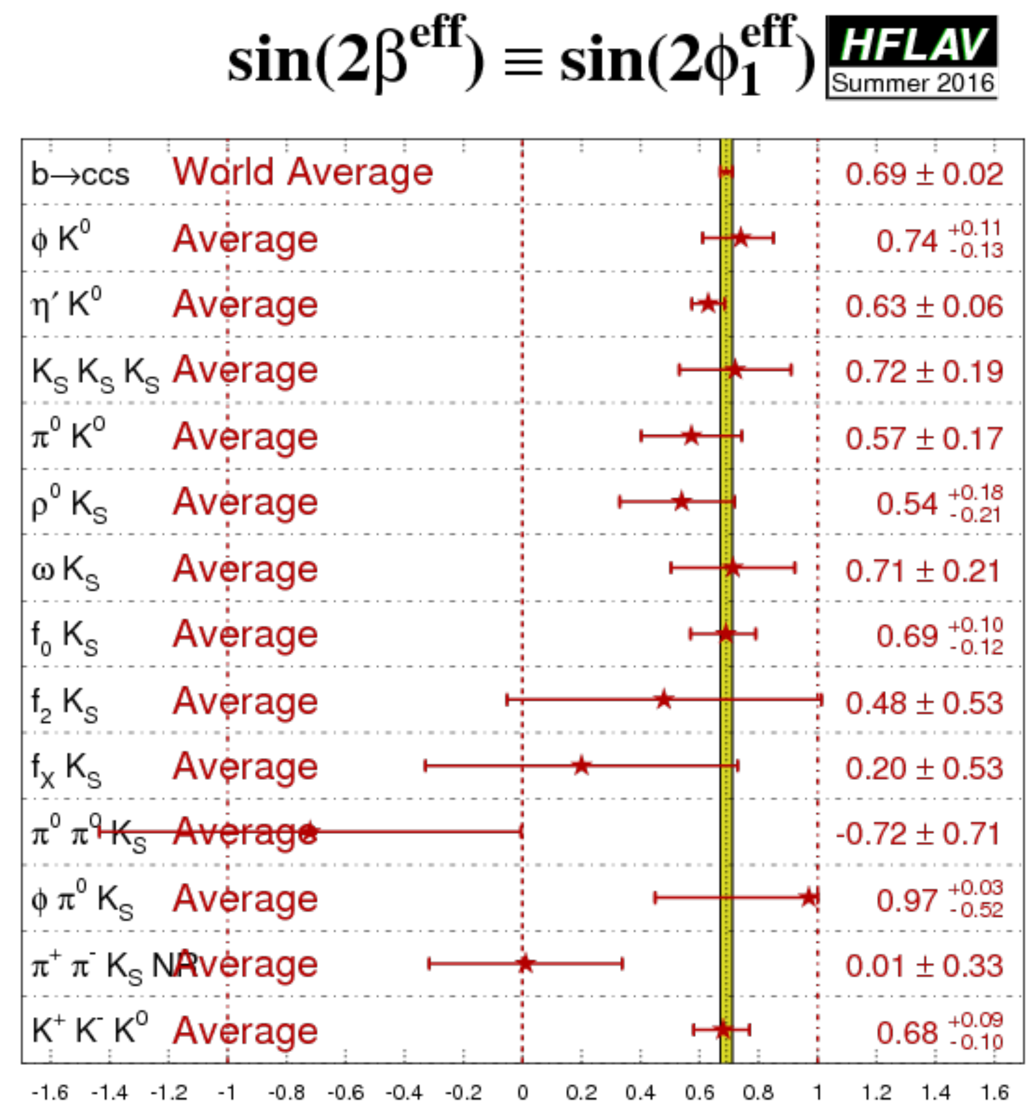
Naiive $b \to s$ penguin average

$\sin 2\phi_1^{\rm eff} = 0.655 \pm 0.032$

$b \to c$ tree average

$\sin 2\phi_1 = 0.699 \pm 0.017$

Theoretical shifts below are not considered for "naiive" average.



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$\sin 2\phi_1^{\rm eff} = 0.655 \pm 0.032$

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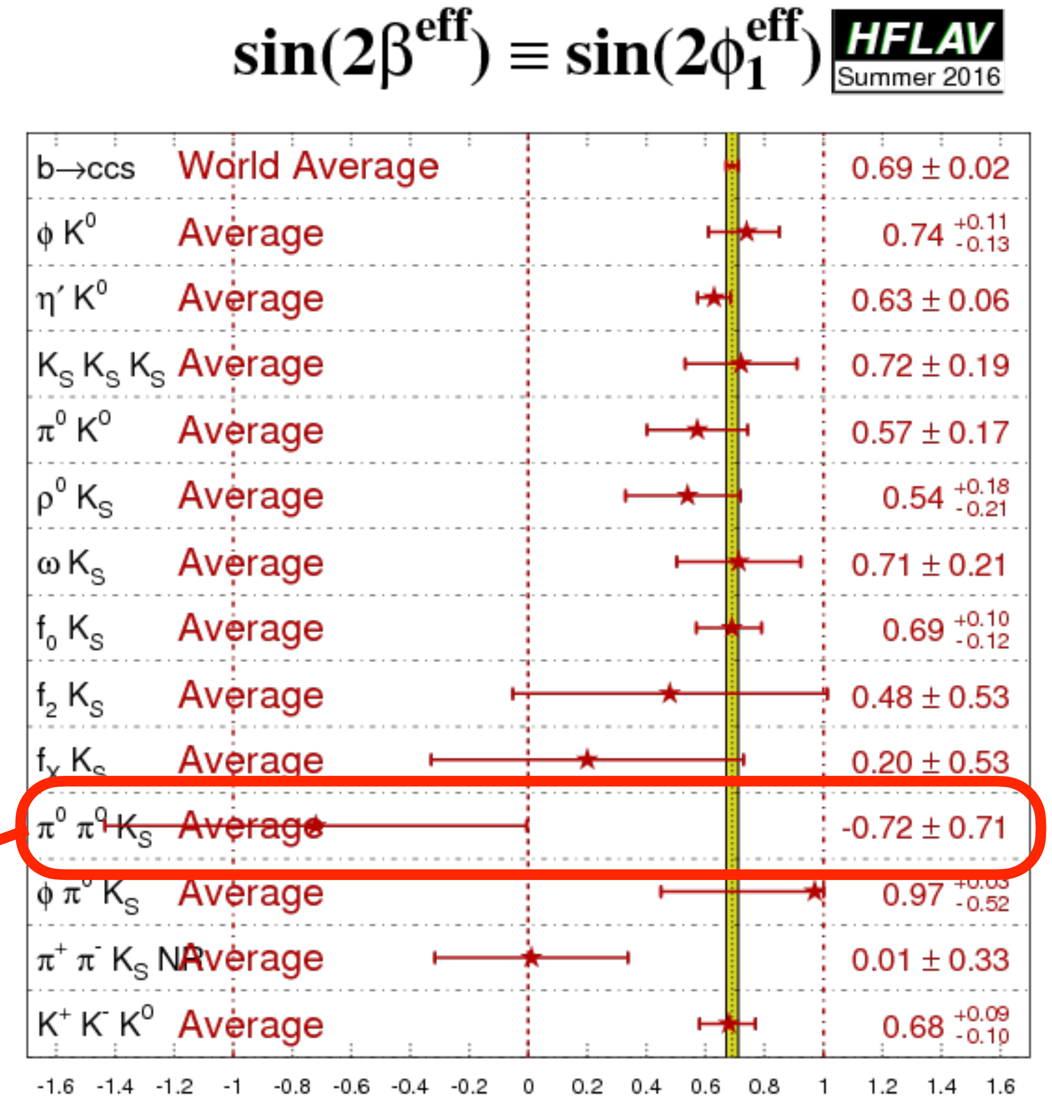
$\sin 2\phi_1 = 0.699 \pm 0.017$

Recently published using Belle full data



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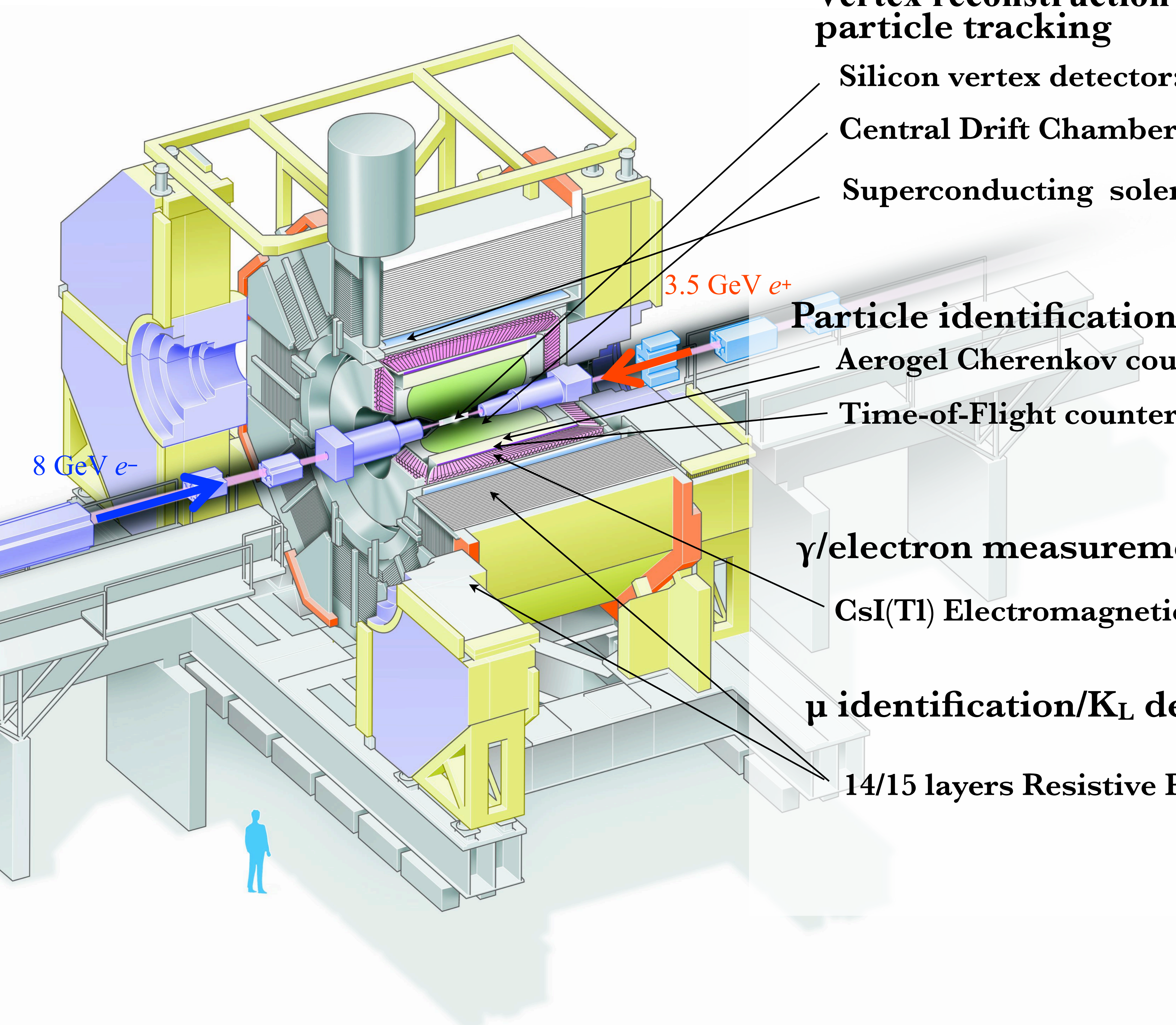
Belle detector



Vertex reconstruction and Charged particle tracking

- **Silicon vertex detector: 3/4 layers DSSD**
- **Central Drift Chamber: small cell +He/C_2H_6**
- **Superconducting solenoid: 1.5T magnetic field**

Particle identification

- **Aerogel Cherenkov counter: Aerogel radiator + PMT**
- **Time-of-Flight counter**

γ/electron measurement

- **CsI(Tl) Electromagnetic calorimeter**

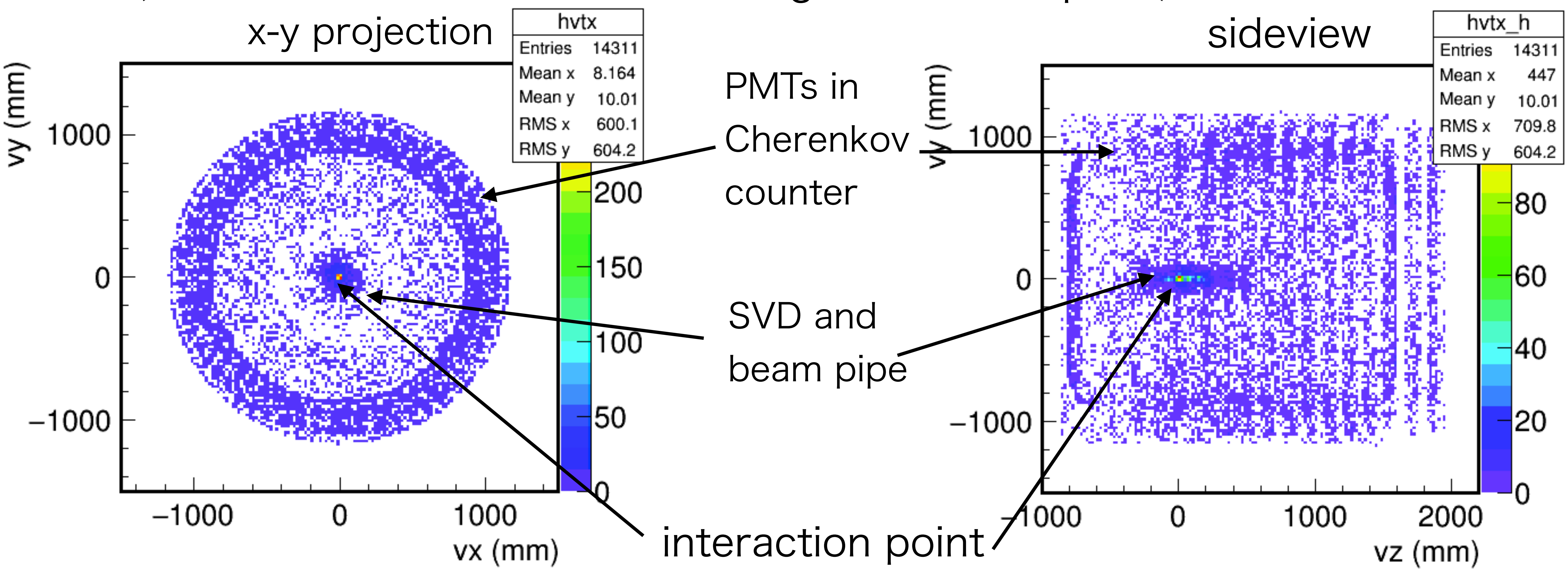
μ identification/K_L detection

- **14/15 layers Resistive Plate Counter+Fe**

Photon detection in Belle

Photon detection efficiency degradation (~10%) due to materials between e^+e^- interaction point and calorimeter.

Photon convert vertex position studied in $B^0 \to \pi^0 \pi^0 K^0_S$ (MC)
(Calorimeter is located outside region of these plots)



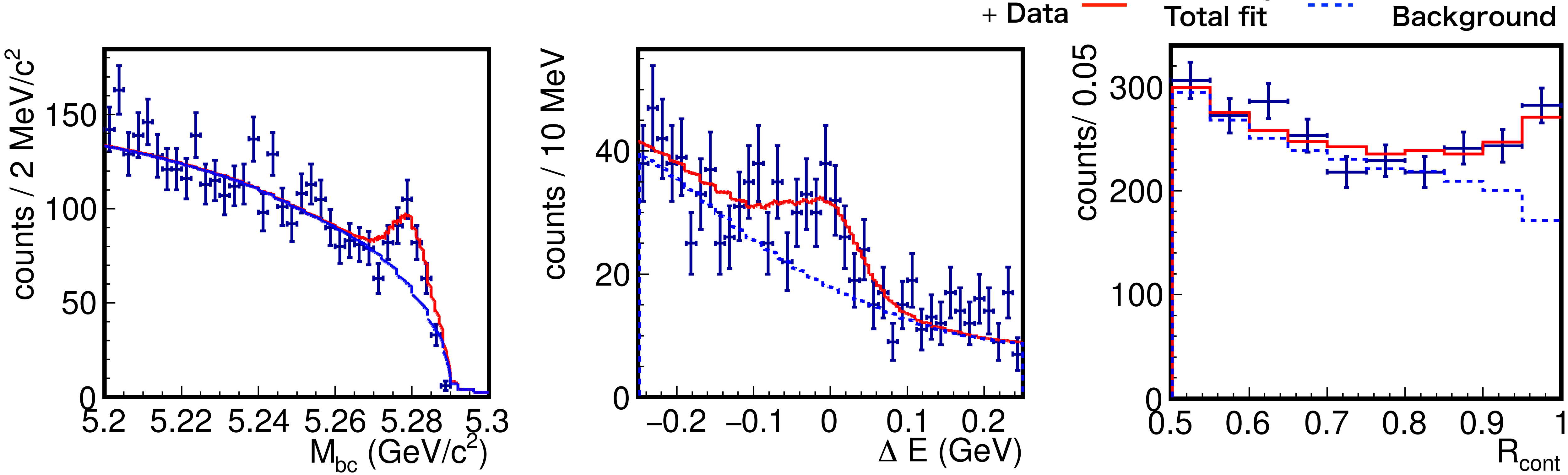
Efficiency to detect 2 π^0 decays into 4 photons is < $(1-0.1)^4$ = 64%.
→ We need large statistics to analyze B decays including multi-π^0.
To solve this issue, Cherenkov counter is replaced to low material devices in Belle II.

How to obtain ϕ_1/ϕ_2 — reconstruction of CP side

Reconstruct CP-side using momentum, energy and particle identification information from detector.

Suppression of continuum background is done using shape variable parameter of all observables in an event.

Reconstruced variables in $B^0 \to \pi^0 \pi^0 K^0_S$ analysis

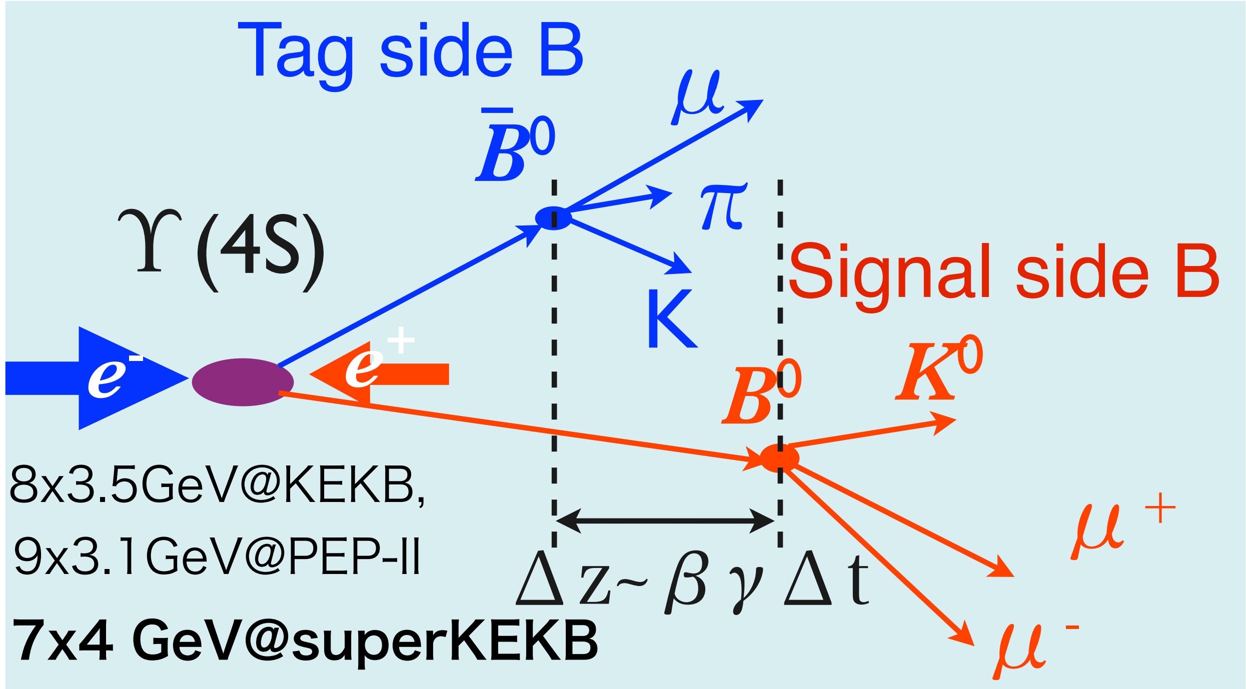


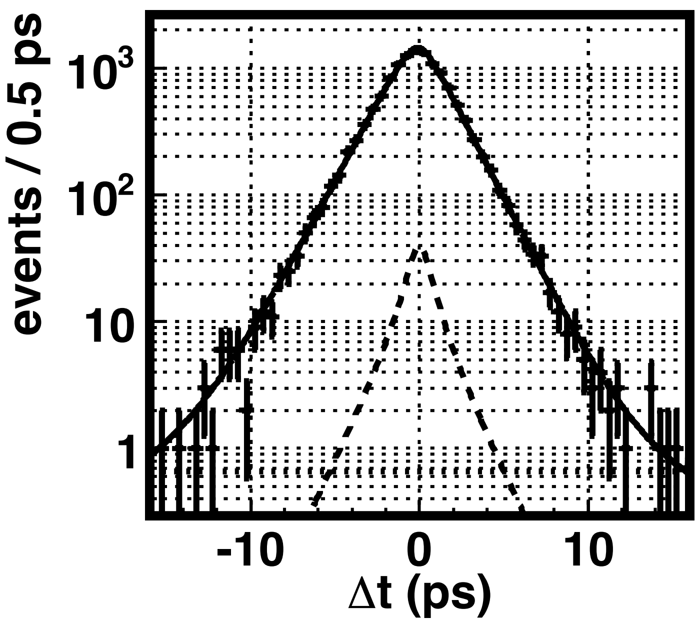
Fraction of signal and background used to extract CP violation parameters is obtained from the fit to kinematic variables togather with that used for continuum suppression.

Signal yield with vertex information = 146.7±23.6 events

How to obtain ϕ_1/ϕ_2 — Fit to Δt and q

- Δt is measured by vertex positions of B and $\bar{B}$.





q-integrated Δt distribution (liftime fit)

$B^0 \to J/\psi K^0_S$ from 772M $B\bar{B}$

- Tag side

  Remaining observables in an event is used for flavor determination

  $\bar{B}^0 \to D^{*+} l^- \nu$, $B^0 \to D^{*\pm} \to D^0 \pi^+$, $D^0 \to K^- l^+ \nu$

  To determine flavor based on integrated information, multi-dimensional likelihood is used in Belle.

  New technologies are introduced in Belle II (Boosted Desision Tree, Artificial Neural Network, Deep Neural Network).

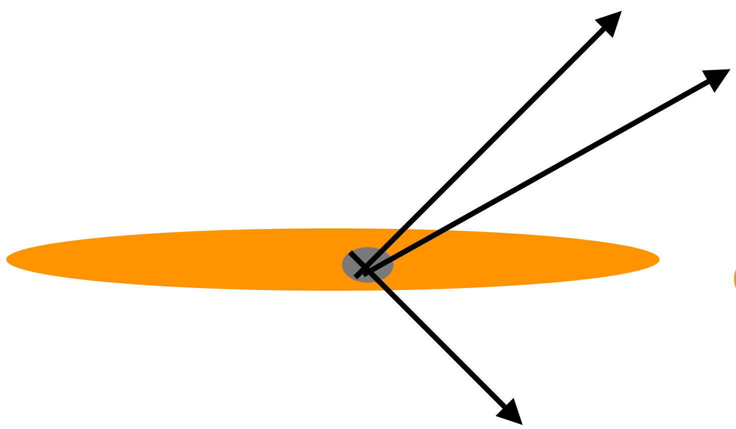
CP violation parameters (S, A) are obtained by the fit to Δt.

$$\text{Signal PDF: } \mathcal{P}(\Delta t) = \frac{e^{-|\Delta t|/\tau_{B^0}}}{4\tau_{B^0}} q(\mathbf{A}\cos\Delta m\Delta t + \mathbf{S}\sin\Delta m\Delta t)$$

Vertex reconstruction with Ks

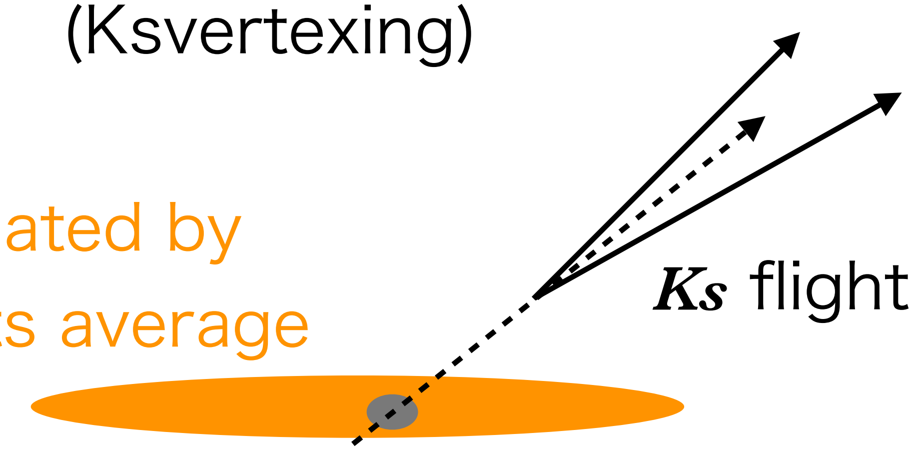
Vertex reconstruction using non-primary tracks is available with constraint on interaction point (IP).

Standard vertex reconstruction



IP constraint calculated by every 10000 events average

Vertex reconstruction usign non-primary tracks from Ks decay (Ksvertexing)

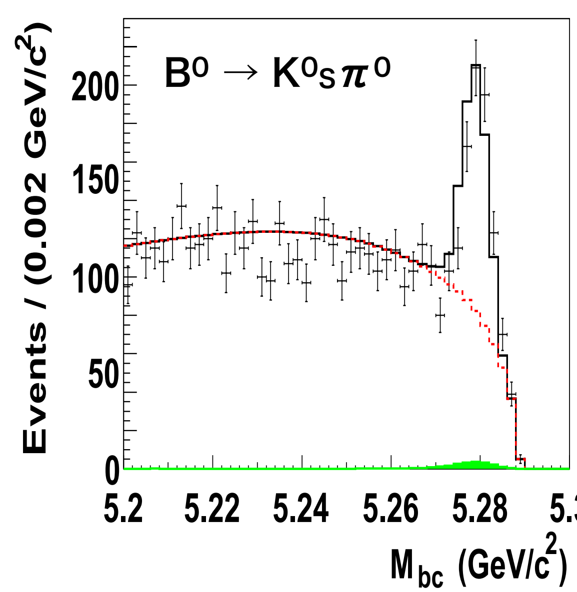


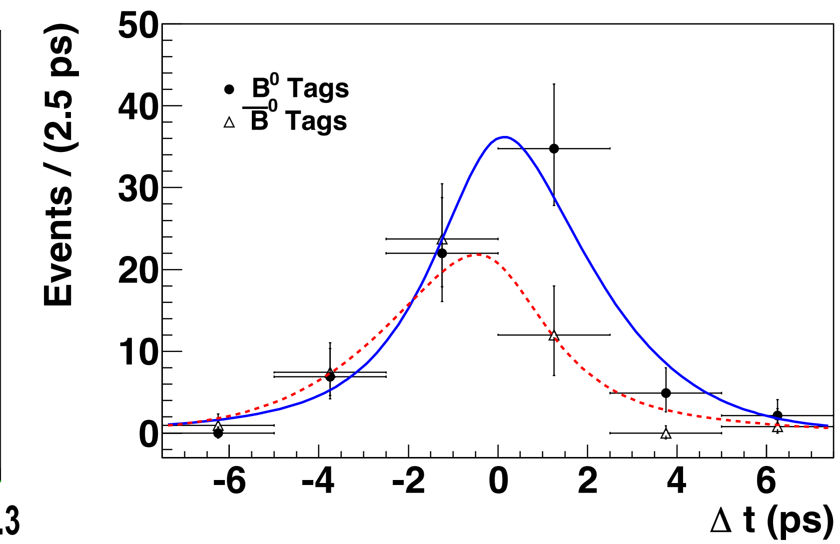
Ks flight direction

This technique enables time-dependent CP violation measurements in CP-eigenstates in which no primary tracks from IP.

"Measurement of CP asymmetries in $B^0 \to K^0 \pi^0$ decays"

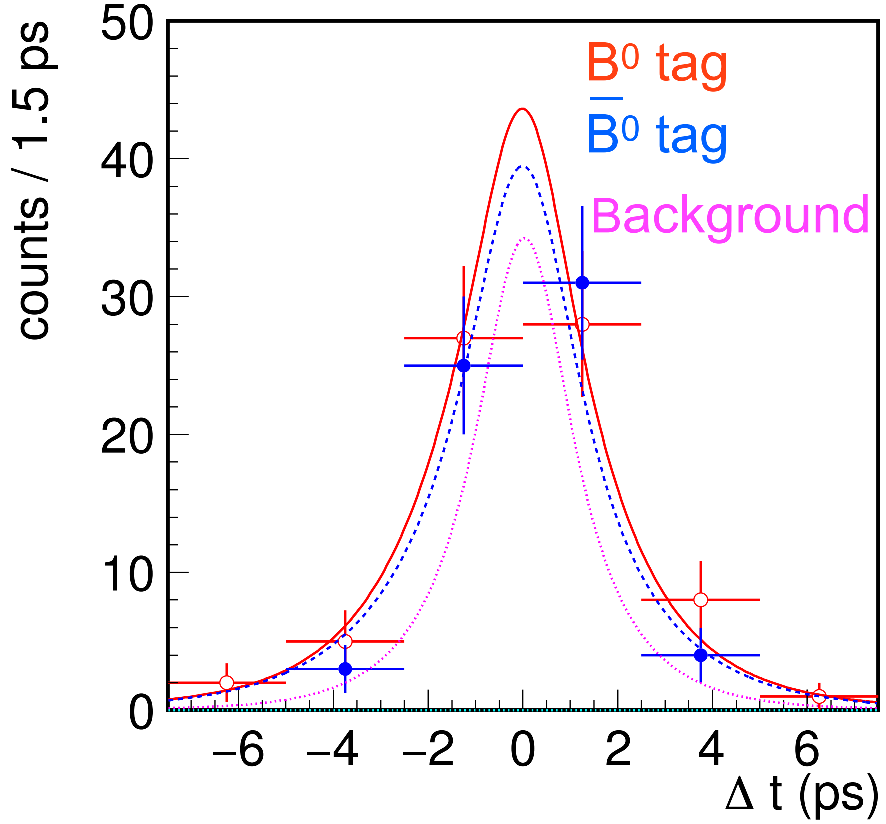
Phys.Rev.D81:011101,2010

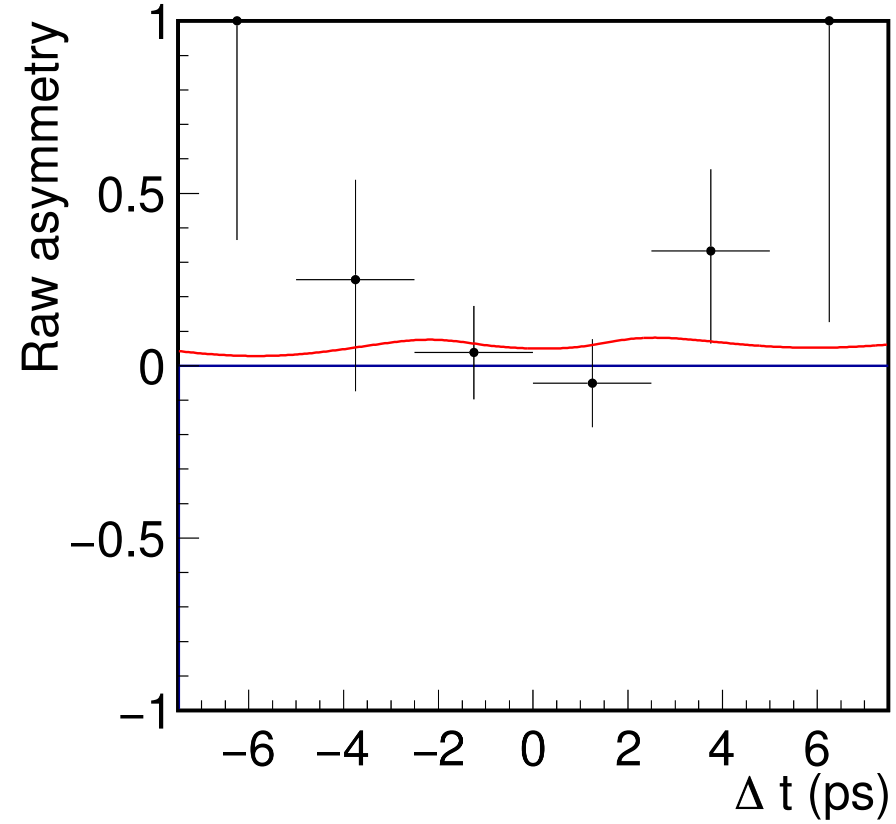




In Belle II, constraint from IP is expected to be better due to nano-beam scheme (demonstrated later). → Vertex quality should be improved.

ϕ_1^{eff} measurement in $B^0 \to \pi^0 \pi^0 K^0_S$





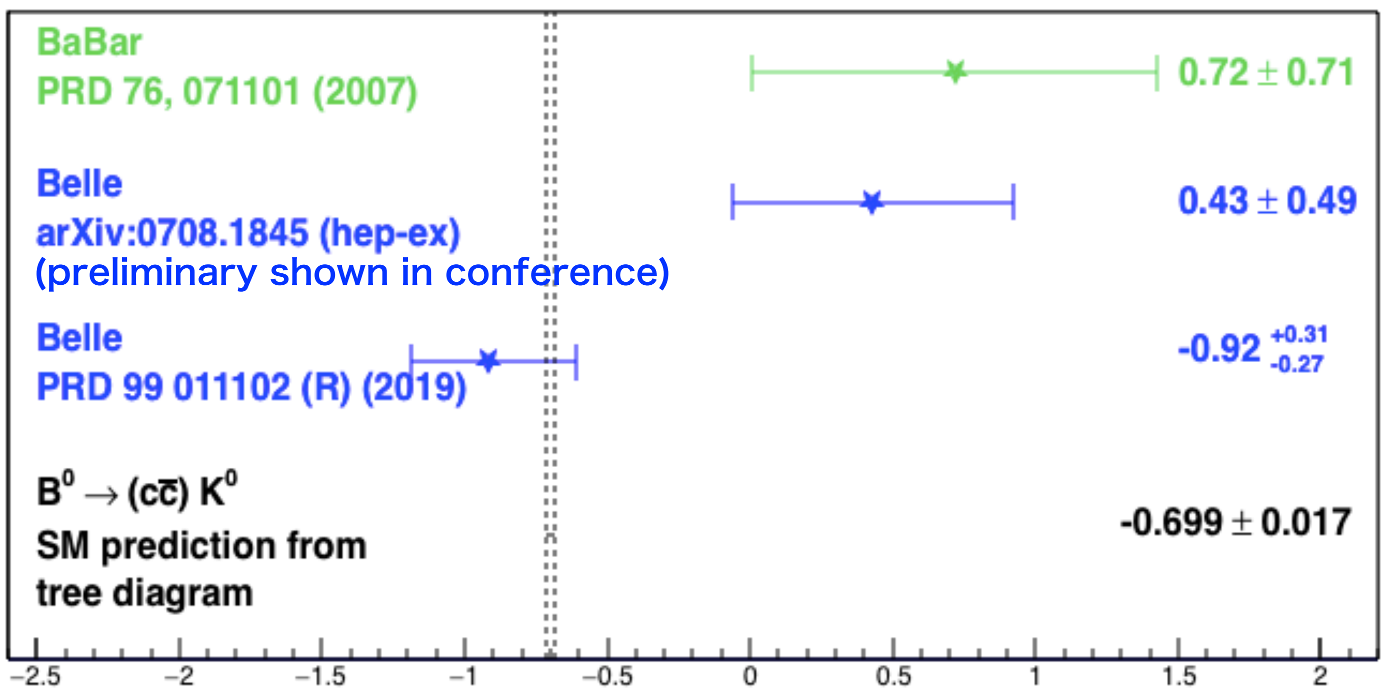
$$\sin 2\phi_1^{\text{eff}} = 0.92^{+0.27}_{-0.31}\ (\text{stat.})\ ^{+0.10}_{-0.11}\ (\text{syst.})$$
$$\mathcal{A} = 0.28 \pm 0.21\ (\text{stat.})\ \pm 0.04\ (\text{syst.})$$

(1.8σ deviation from 0)

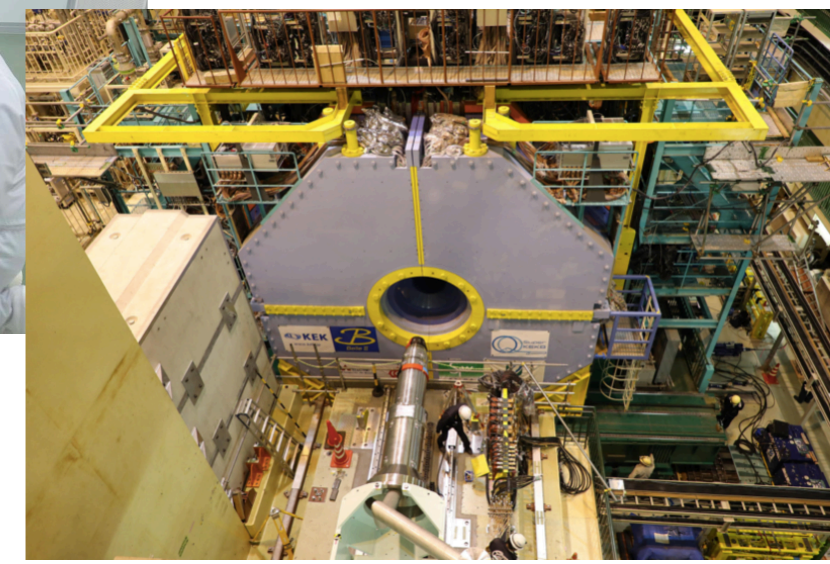
First published result from Belle.
Third measurement of $\sin 2\phi_1^{eff}$ using CP-even eigenstate induced by $b \to sq\bar{q}$ followed by $B^0 \to \eta' K^0_L$ and $B^0 \to \phi K^0_L$.

Consistent with SM expectation.

$\pi^0\pi^0K^0_S\ S_{CP}$



Belle II — Where we are now?



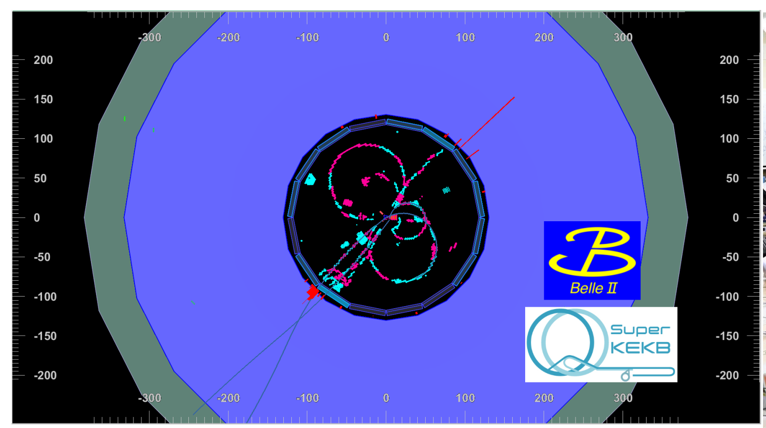
2016

Feb. Phase 1 (w/o Belle,
 w/o final focusing) starts

Jun. Phase 1 ends

2017

Apr. Belle II detector roll in



2018

Mar. Phase 2 (partial VXD,
 w/ final focusing) starts

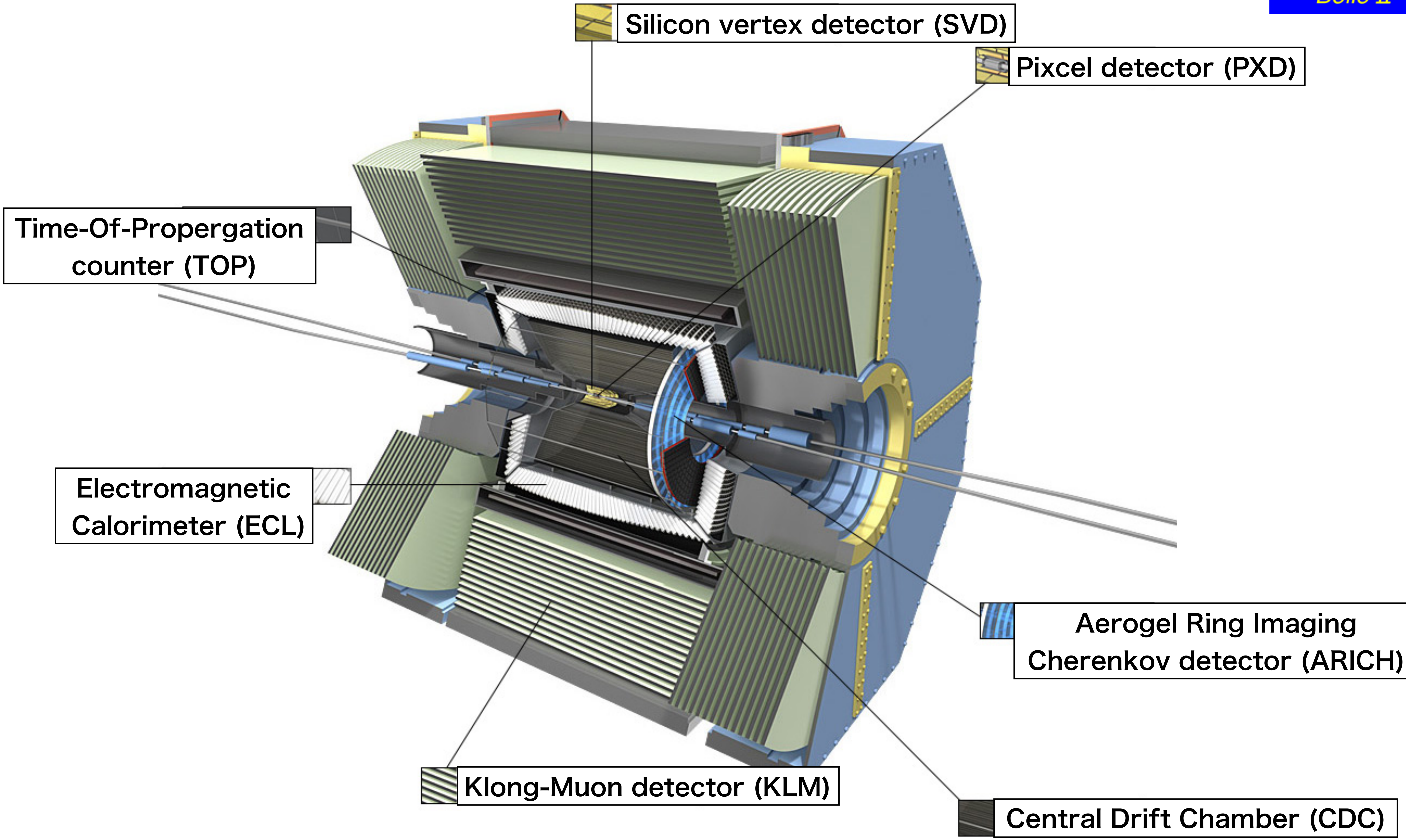
Apr. First collision

Jul. Phase 2 ends
 Integrated luminosity
 ~500 pb^{-1}

2019

Mar. Phase 3 (almost full
 VXD) starts

Belle II detector

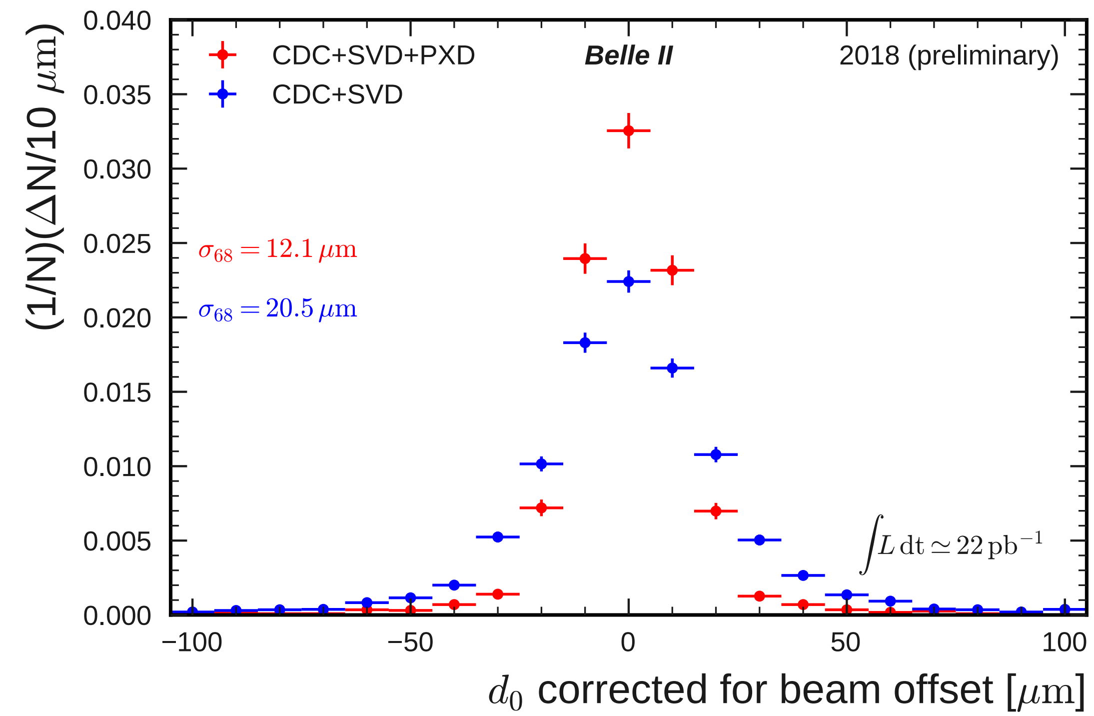


PXD and SVD has been installed after phase 2 and ready now.

Problems of subsystem found in phase 2 operation are fixed.

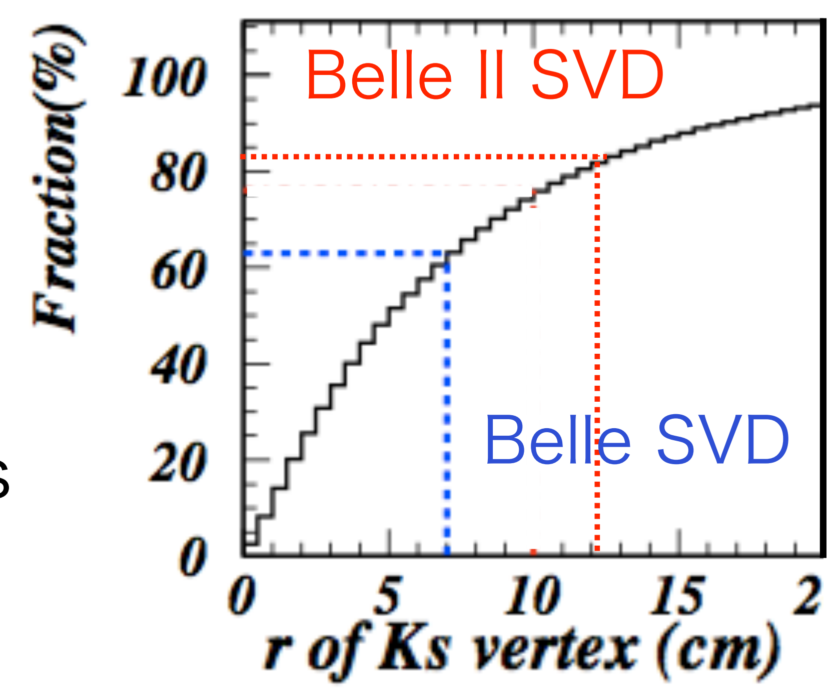
Benefits of upgrade for ϕ_1/ϕ_2 measurements

Smaller radious of inner layers of PXD contributes to improve vertex resolution.
→ Resolution of tracking improves 40%



d_0: closest approach of track in x-y plane

More $K^0{}_S$ decay inside of larger radious of outer SVD layer.
→ $K^0{}_S$ finding efficiency imcreses.
Efficiency of vertex reconstruction using $K^0{}_S$ daughter improves.

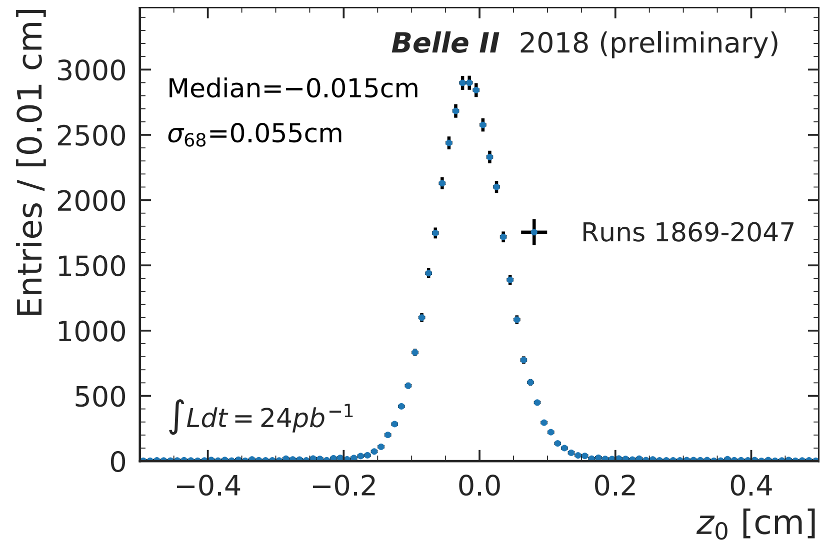


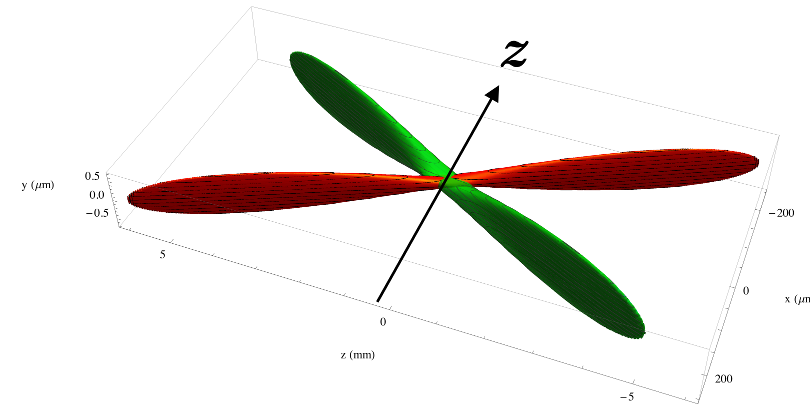
Improvement of particle identification performance contributes to flavor tagging quality.

Photon detection efficiency increases due to less materal of inner part.

Phase2 data analysis

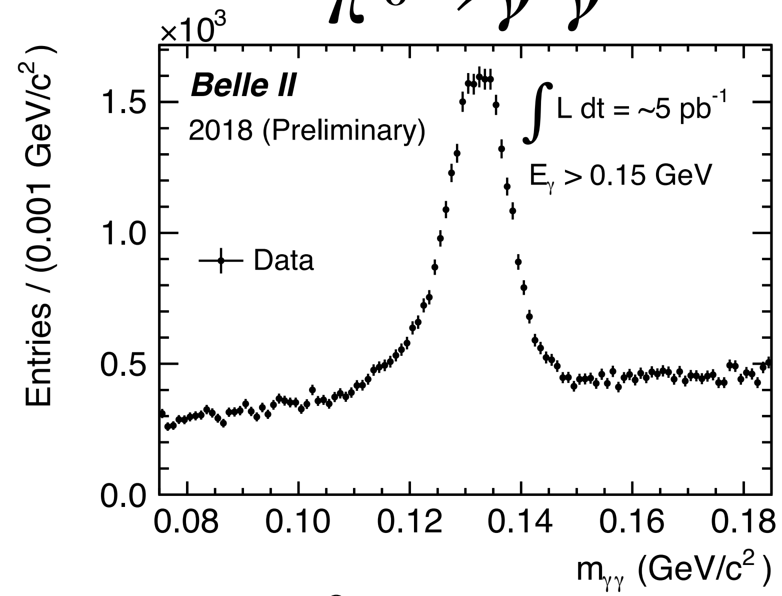
Spread of IP estimated using closest approach of tracks in z-coordinate is consistent with small beam crossing spot size calculated from phase 2 beam optics.



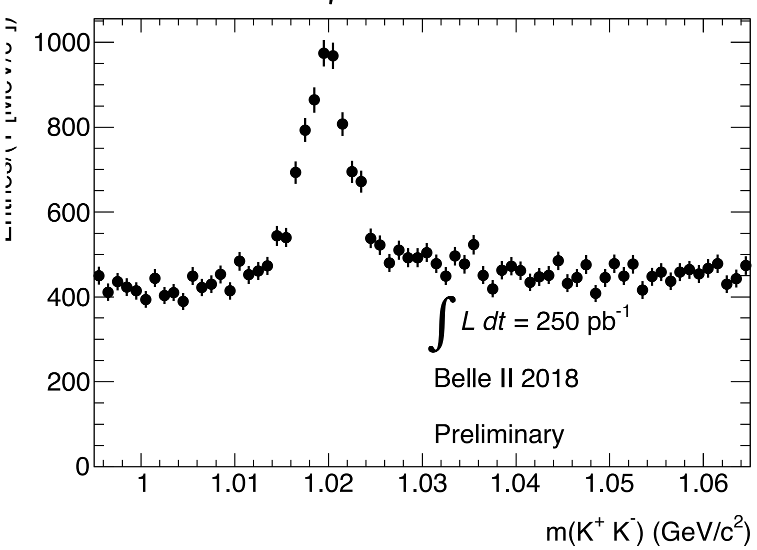


Using 500 pb^{-1} of the data collected during phase 2 operation, we confirm many of particles that are included in CP-eigenstates are reconstructed.

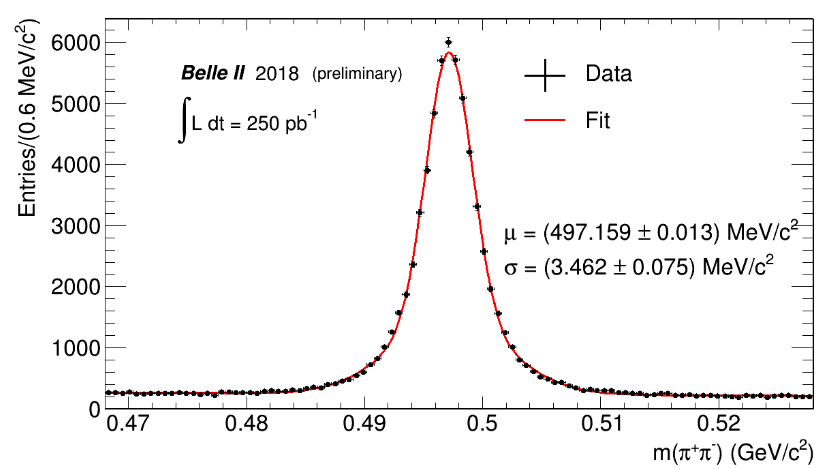
$\pi^0 \to \gamma\ \gamma$



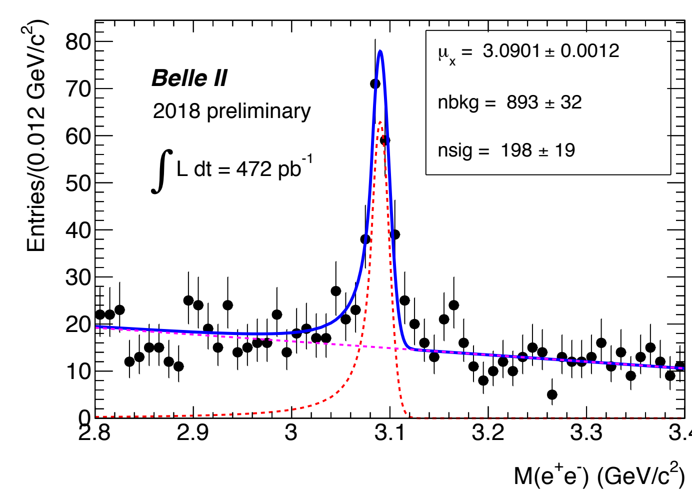
$\phi \to K^+K^-$



$K^0{}_S \to \pi^+\pi^-$



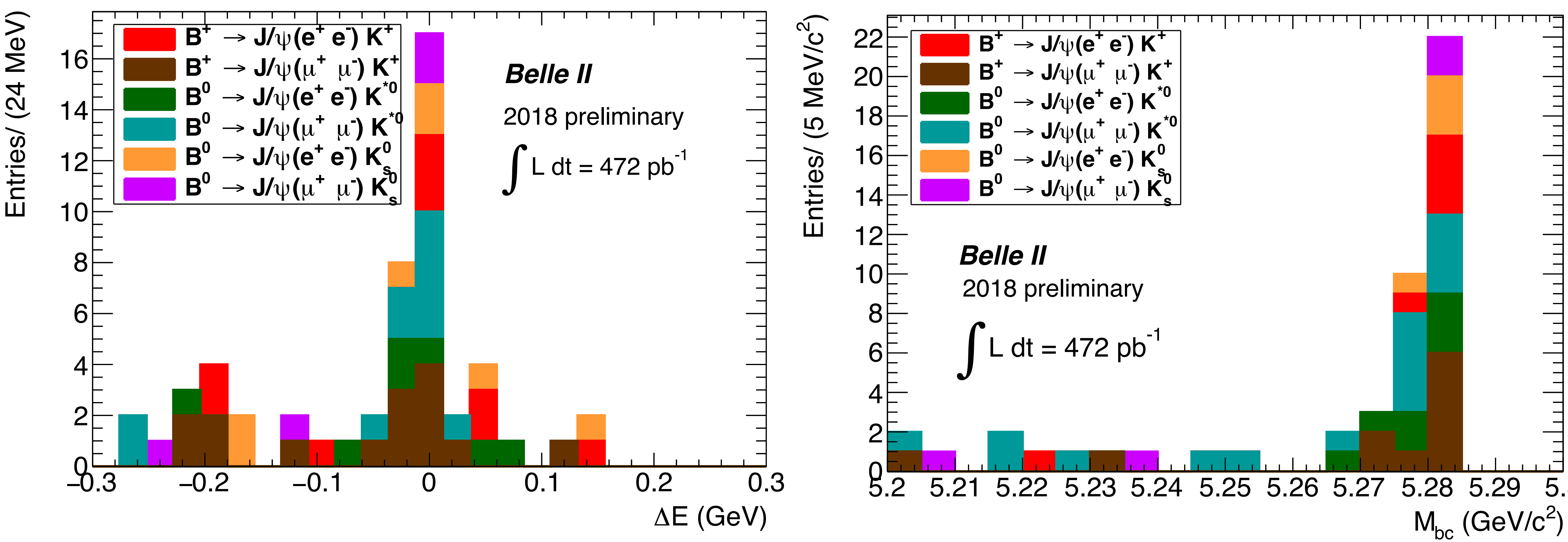
$J/\psi \to e^+e^-$



Phase2 data analysis

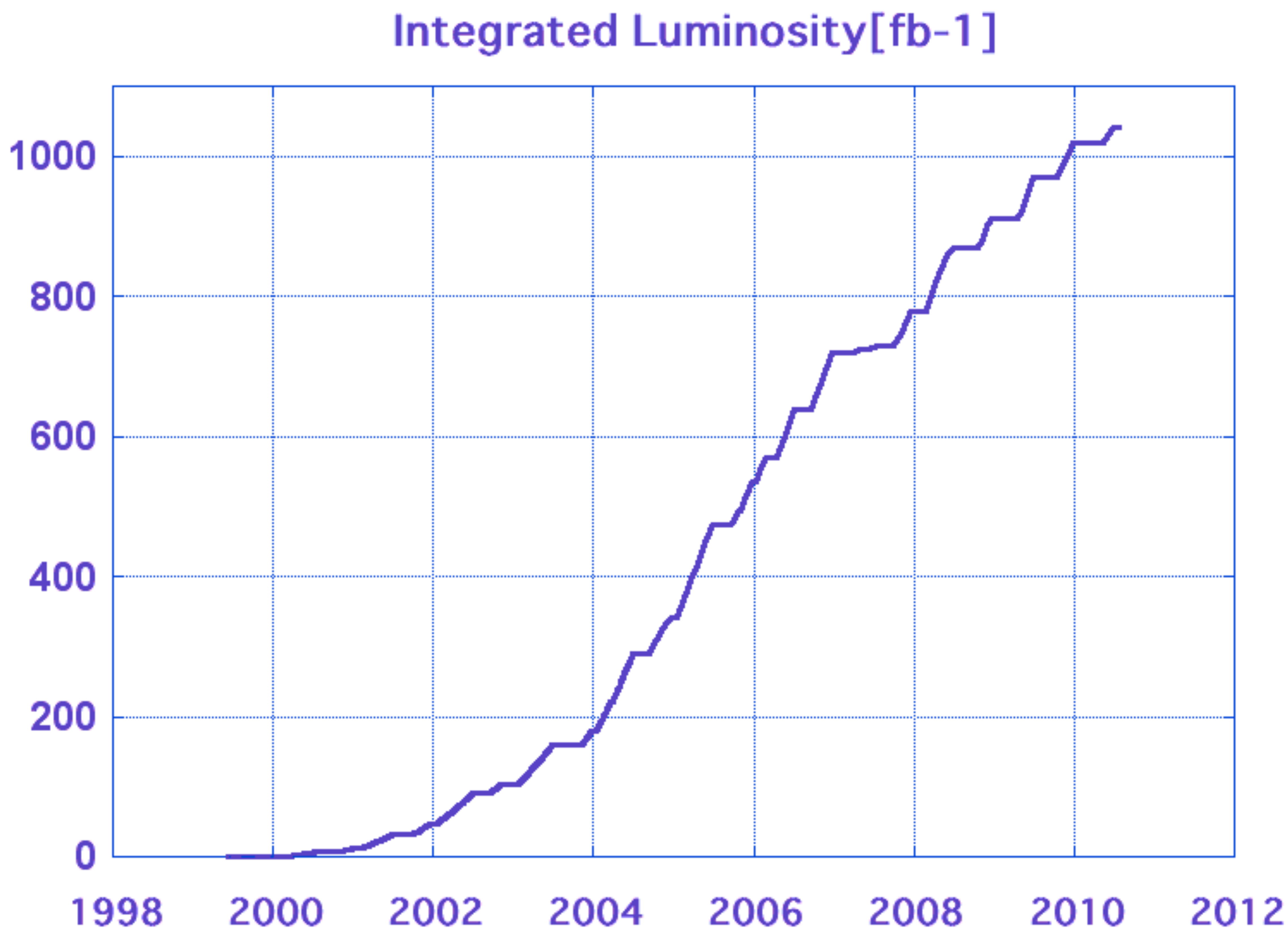
Using 500 pb^{-1} of the data collected during phase 2 operation, we confirm many of particles that are included in CP eigenstates can be reconstructed.

$$B^{0/+} \to J/\psi K^{0(*)/+}$$

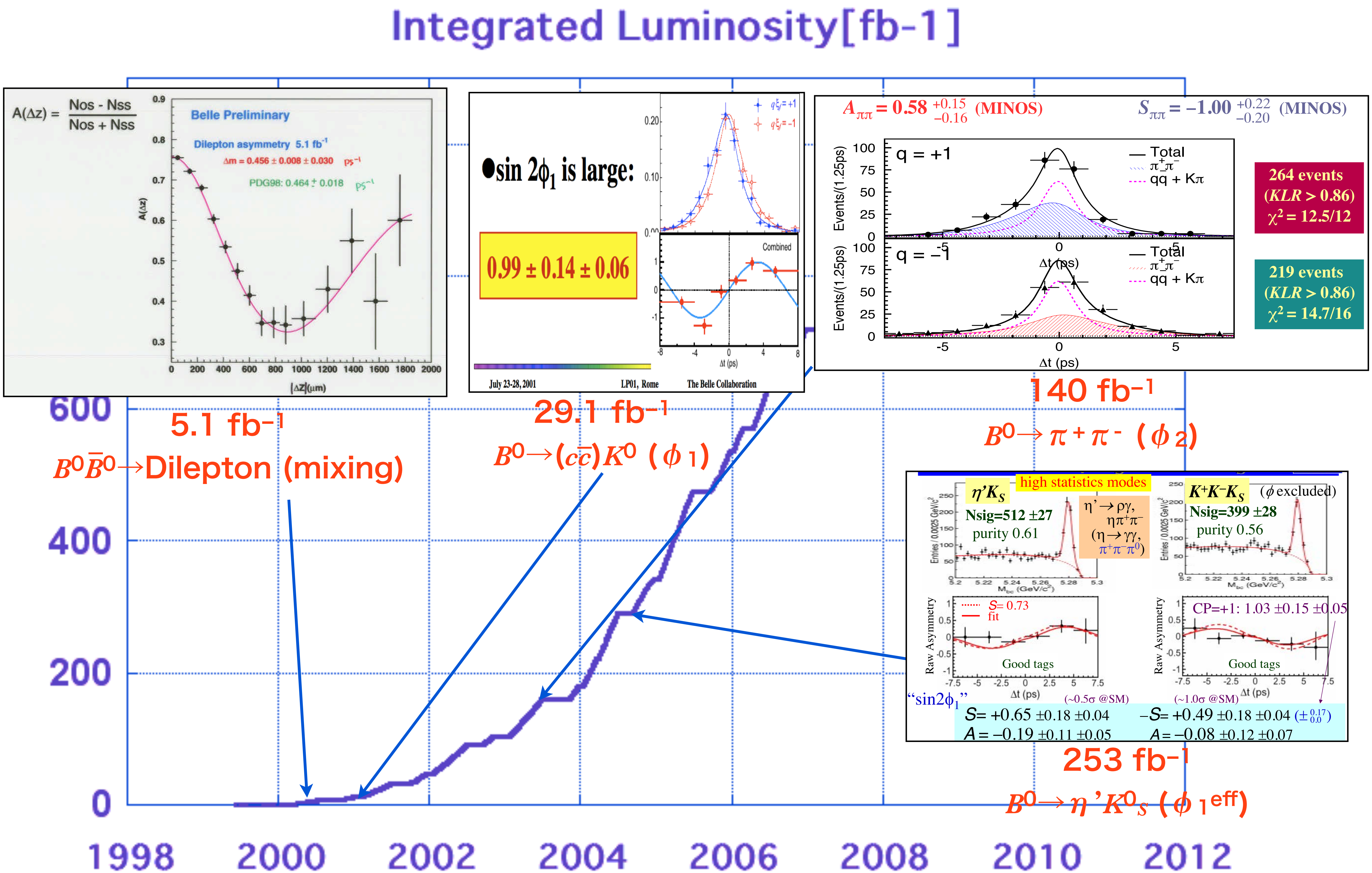


$B^0 \to J/\psi K^0_S$ sign is indicated in reconstructed distributions (orange and magenta).

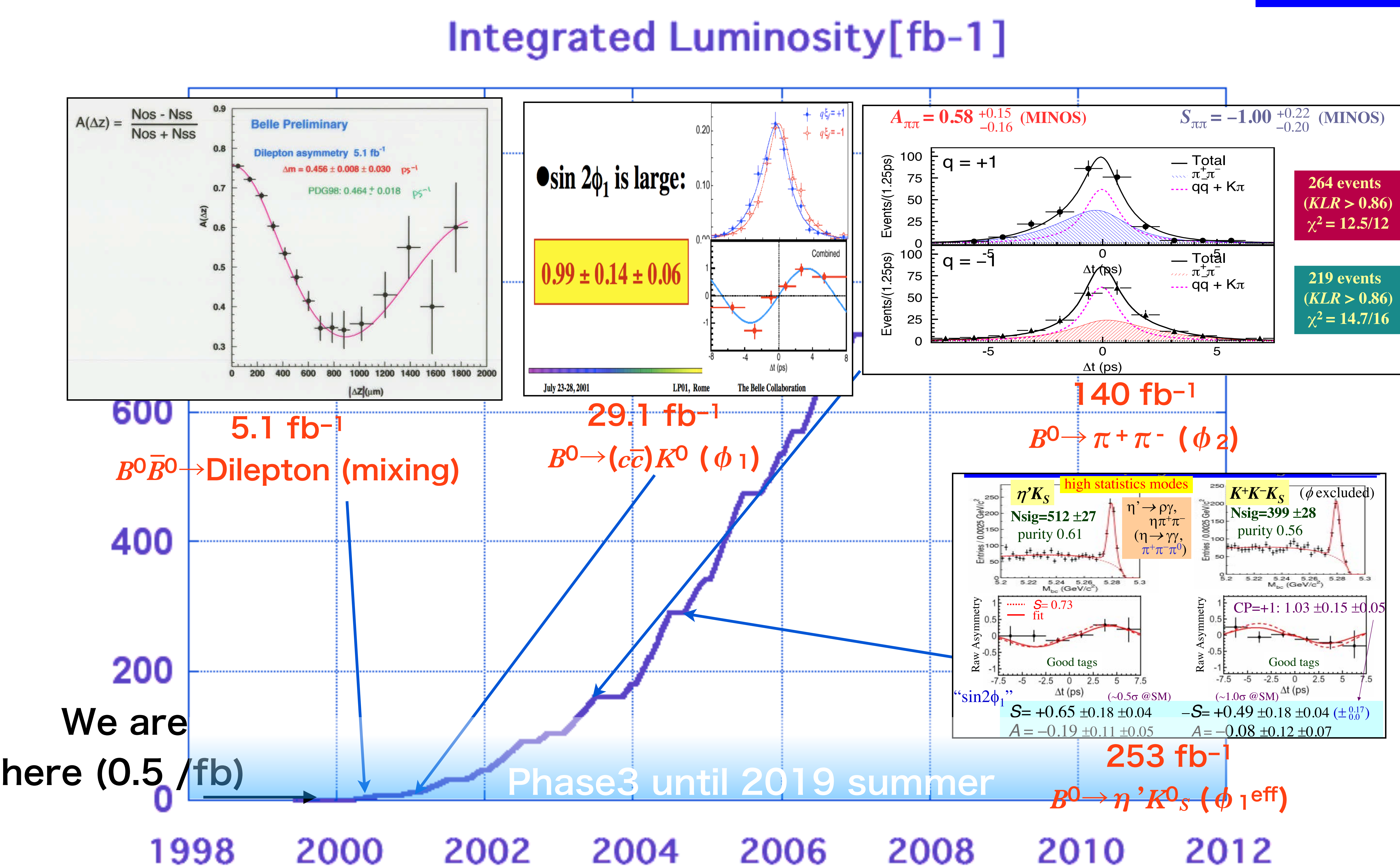
Re-discovery of CP-violation within our reach



Re-discovery of CP-violation within our reach



Re-discovery of CP-violation within our reach



Far milestone — beyond Belle/BABAR results

Decay modes in which first observation of ϕ_1 is expected using a few ab^{-1} data.

Belle II

$b \to c$

Mode	Experiment (# of $B\bar{B}$)	S	significance	A
$B^0 \to J/\psi\,\pi^0$	BABAR (466M)	$-1.23 \pm 0.21 \pm 0.04$	4.0σ	$0.20 \pm 0.19 \pm 0.03$
	Belle (772M)	$-0.59 \pm 0.19 \pm 0.03$	3.0σ	$0.08 \pm 0.16 \pm 0.05$
$B^0 \to D^+D^-$	BABAR (467M)	$-0.63 \pm 0.36 \pm 0.05$	—	$0.07 \pm 0.23 \pm 0.03$
	Belle (772M)	$-1.06^{+0.21}_{-0.14} \pm 0.08$	4.2σ	$0.43 \pm 0.16 \pm 0.05$
	LHCb (3 fb^{-1})	$-0.54^{+0.17}_{-0.16} \pm 0.05$	4.0σ	$-0.26^{+0.18}_{-0.17} \pm 0.05$
$B^0 \to D^{*+}D^{*-}$	BABAR (467M)	$-0.70 \pm 0.16 \pm 0.03$	—	$-0.05 \pm 0.09 \pm 0.0$
	Belle (772M)	$-0.79 \pm 0.13 \pm 0.03$	5.4σ	$0.15 \pm 0.08 \pm 0.02$
$B^0 \to D^{*+}D^-$	BABAR (467M)	$-0.68 \pm 0.15 \pm 0.04$	—	$-0.04 \pm 0.12 \pm 0.0$
	Belle (772M)	$-0.78 \pm 0.15 \pm 0.05$	4.0σ	$0.01 \pm 0.11 \pm 0.04$

←Recently publised. PRD98, 112008 (2018)

$b \to s$

Mode	Experiment (# of $B\bar{B}$)	S	significance
$B^0 \to K^0_S K^0_S K^0_S$	BABAR (468M)	$0.94^{+0.21}_{-0.24} \pm 0.06$	3.8σ
	Belle (535M)	$0.30 \pm 0.32 \pm 0.08$	—
$B^0 \to \pi^0 K^0_S$	BABAR (467M)	$0.55 \pm 0.20 \pm 0.03$	—
	Belle (657M)	$0.67 \pm 0.31 \pm 0.08$	—
$B^0 \to \rho^0 K^0_S$	BABAR (383M)	$0.35^{+0.26}_{-0.31} \pm 0.06 \pm 0.03$	—
	Belle (657M)	$0.64^{+0.19}_{-0.25} \pm 0.09 \pm 0.10$	—
$B^0 \to \omega K^0_S$	BABAR (467M)	$0.55 \pm ^{+0.26}_{-0.29} \pm 0.02$	—
	Belle (772M)	$0.91 \pm 0.32 \pm 0.05$	3.1σ

This will be reviced soon using full data set.

Hopefully not so far

milestone — beyond Belle/BABAR results

Decay modes in which first observation of ϕ_1 is expected using a few ab^{-1} data.

$b \to c$

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$B^0 \to D^{*+}D^-$	BABAR (467M)	−0.68±0.15±0.04	—	−0.04±0.12±0.0
	Belle (772M)	−0.78±0.15±0.05	4.0 σ	0.01±0.11±0.04

$b \to s$

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$B^0 \to \rho^0 K^0_S$	BABAR (383M)	$0.35^{+0.26}_{-0.31}\pm0.06\pm0.03$	—
	Belle (657M)	$0.64^{+0.19}_{-0.25}\pm0.09\pm0.10$	—
$B^0 \to \omega K^0_S$	BABAR (467M)	$0.55^{+0.26}_{-0.29}\pm0.02$	—
	Belle (772M)	0.91±0.32±0.05	3.1 σ

This will be reviced soon using full data set. (→ Belle (535M) $B^0 \to K^0_S K^0_S K^0_S$)

Hopefully not so far

milestone — beyond Belle/BABAR results

Belle II

Decay modes in which first observation of ϕ_1 is expected using a few ab^{-1} data.

$b \to c$

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	Belle (772M)	$-0.78 \pm 0.15 \pm 0.05$	4.0σ	$0.01 \pm 0.11 \pm 0.04$

←Recently publised. PRD98, 112008 (2018)

Anomaly among experiments should be solved in future.

$b \to s$

Mode	Experiment (# of BB)	S	significance
$B^0 \to K^0_S K^0_S K^0_S$	BABAR (468M)	$0.94^{+0.21}_{-0.24} \pm 0.06$	3.8σ
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	Belle (657M)	$0.64^{+0.19}_{-0.25} \pm 0.09 \pm 0.10$	—
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	Belle (772M)	$0.91 \pm 0.32 \pm 0.05$	3.1σ

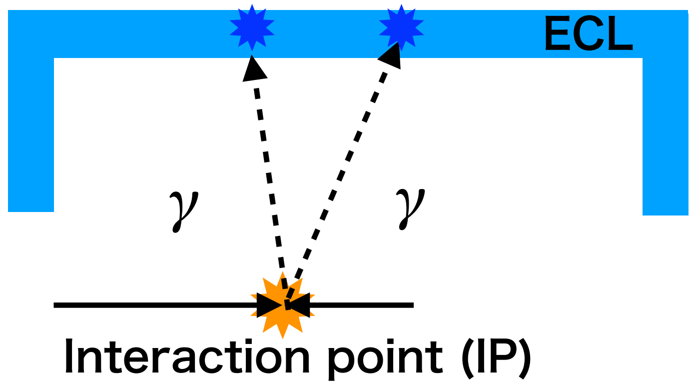
This will be reviced soon using full data set.

Hopefully not so far

milestone — beyond Belle/BABAR results

For ϕ_2, new input for iso-spin relation analysis :

$B^0 \to \pi^0 \pi^0$ time-dependent analysis.

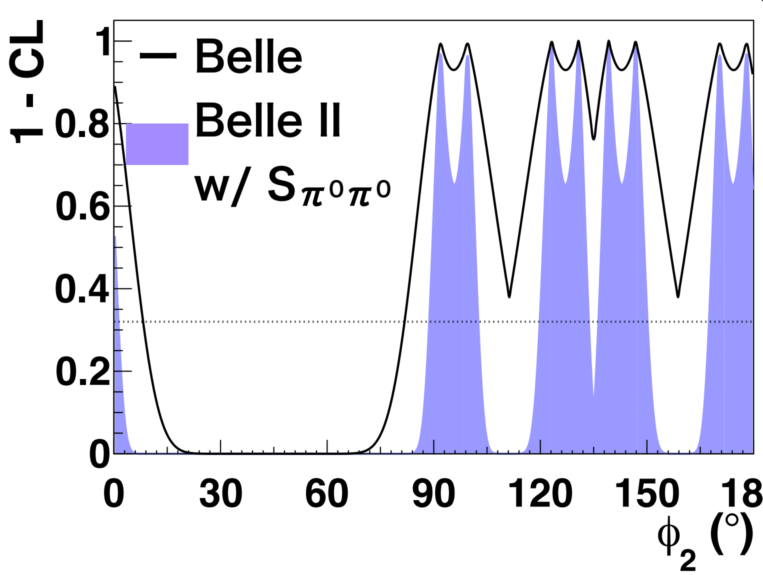


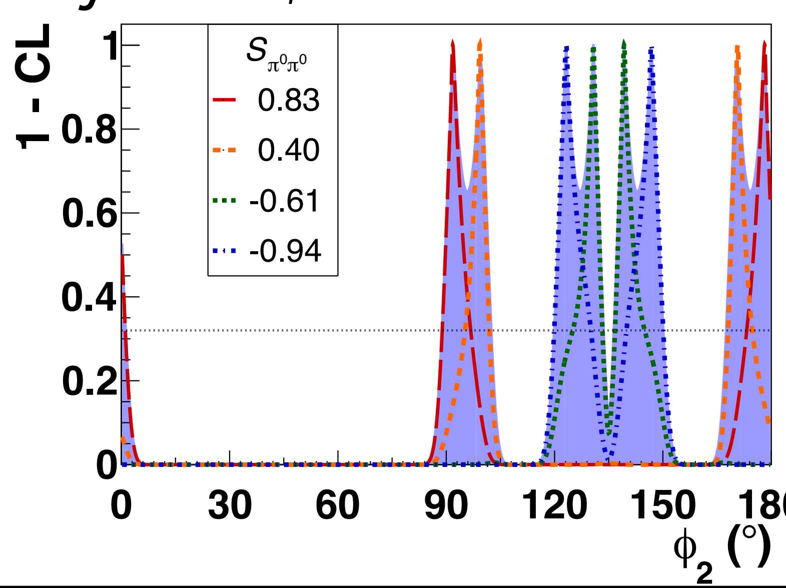
Electromagnetic calorimeter detects hit position of photons.

→ In usual analysis, no B^0 decay vertex information from π^0.

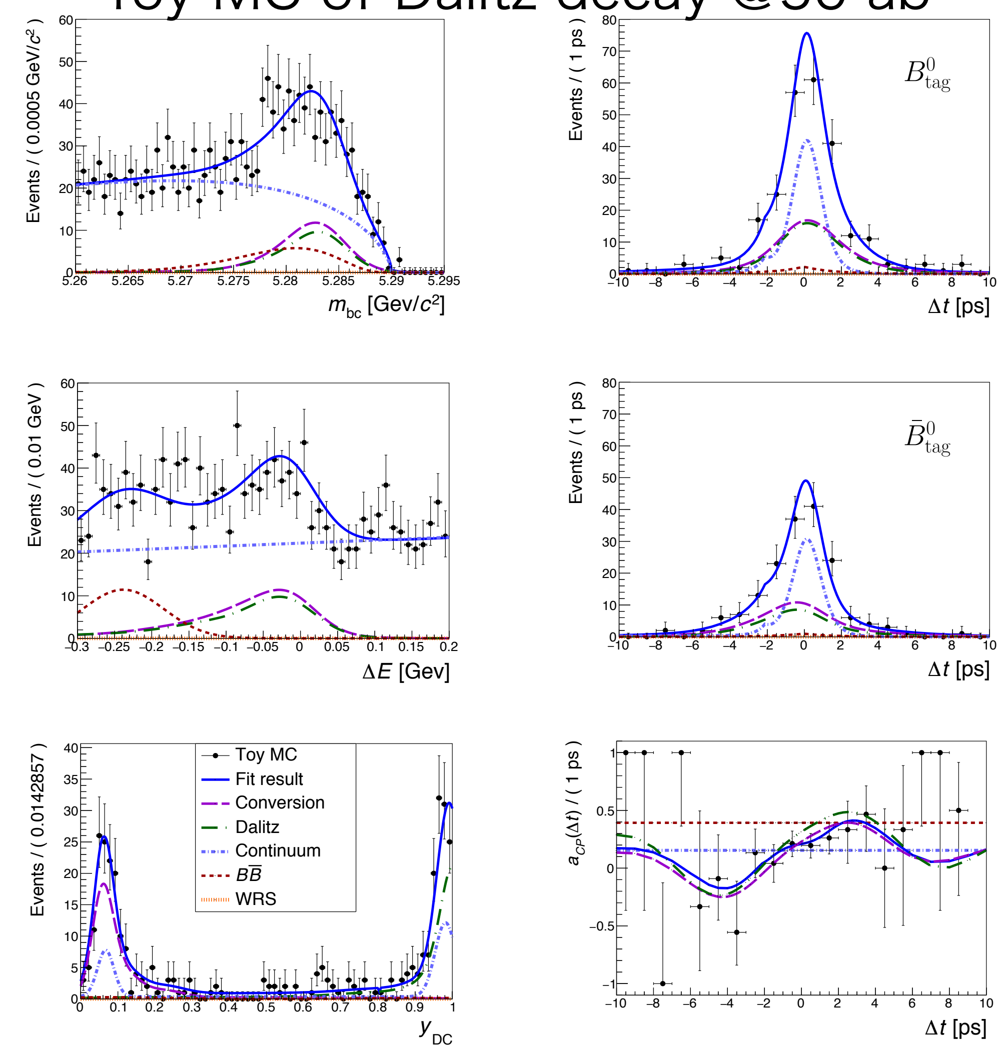
If we use a large data sample in Belle II, we can approach “π^0 vertexing” using Dalitz decay ($\pi^0 \to e^+ e^- \gamma$) or π^0 direction from photon conversion.

Although statistic error is large, (= ±0.28), we can reduce umbiguity for ϕ_2.





Toy MC of Dalitz decay @50 ab⁻¹



(Plots from Belle II Physics Book)

Systematic error in large statistic analysis

We have already been close to systematic limit.

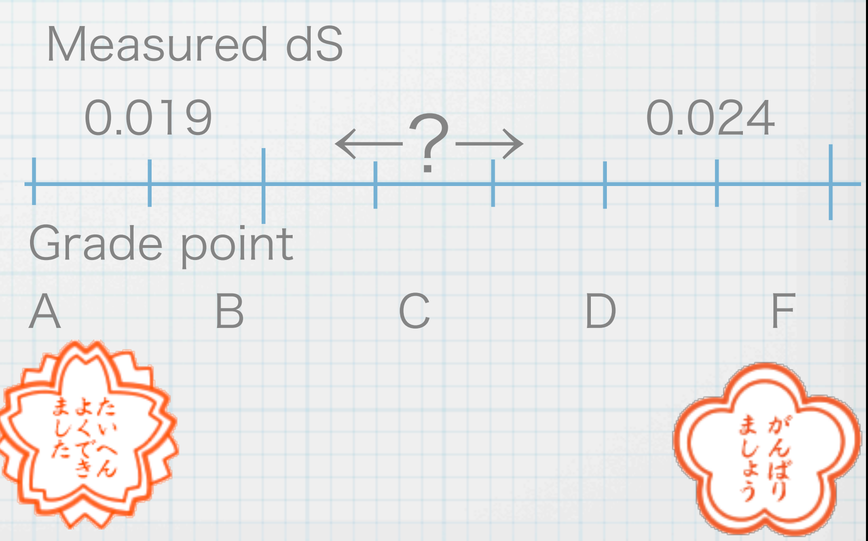
In Belle II, we have to consider this issue in many studies.

Reference point of systematic study

Categories	dS	dA
Vertexing	0.012	0.009
Possible fit bias	0.007	0.004
Δt Resolution function	0.009	0.001
BG fractions ($J/\psi K_L$)	0.005	0.002
Wrong tag probability	0.004	0.003
BG fractions ($J/\psi K_S$)	0.003	0.001
Fixed Physics parameters	0.001	0.001
BG Δt	0.001	0.001
Tag-Side interference	0.001	0.009
Total	**0.019**	**0.014**

Vertexing detail	dS	dA
IP tube constraint vertex fit	0.0072	0.0005
Poor-quality vertex rejection	0.0064	0.0021
Imperfect SVD alignment	0.0056	0.0040
Δz bias	0.0050	0.0073
Track error estimation	0.0033	0.0060
Track rejection in B_{tag} decay vertexing	0.0026	0.0015
Δt fit range	0.0002	0.0004
Total	0.012	0.009

One reference point is systematic error in 2006:
dS = 0.019, dA = 0.014
At worst, same level with statistical error expected from toy study
dS = 0.024, dA = 0.016



Tuesday, November 16, 2010

12

My slide in Belle general meeting for ϕ_1 measurement in $B^0 \to (c\bar{c})K^0$ using full data.

We discussed whether we can set systematic uncertainty enough small comparing to previous analysis and also to expected of statistical error.

Systematic error in large statistic analysis

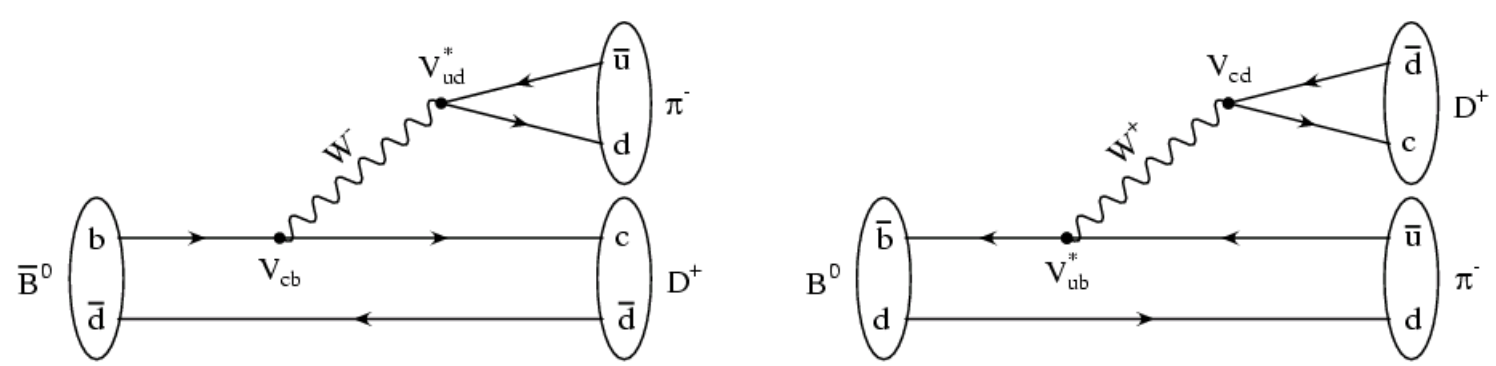
Systematic is expected to be dominant in ϕ_1 measurement using 50 ab^{-1}

Vertex improvement contributes to reduce systematic error of S.

If we use only high momentum leptons (mainly come from semi-leptonic decay) for flaver tagging, uncertainty from tag-side interference on A is largely suppressed. Total error becomes small although statistic is sacrificed.

Error expectation considering luminosity scale (Belle II Physics Book)

	No improvement	Vertex improvement	Leptonic categories
$S_{J/\psi K_S^0}$ (50 ab^{-1})			
stat.	0.0035	0.0035	0.0060
syst. reducible	0.0012	0.0012	0.0012
syst. irreducible	0.0082	0.0044	0.0040
$A_{J/\psi K_S^0}$ (50 ab^{-1})			
stat.	0.0025	0.0025	0.0043
syst. reducible	0.0007	0.0007	0.0007
syst. irreducible	$^{+0.043}_{-0.022}$	$^{+0.042}_{-0.011}$	0.011



CKM-favored amplitude — doubly-CKM suppressed amplitude

Interference between non-zero two diagram
→ CP violation in tag side: $2r' \sin(2\phi_1+\phi_3\pm\delta')$

→ We have to try further idea to suppress systematic error.
In some case, approach from theoretical side is needed.

Summary

ϕ_1 and ϕ_2 angles have been measured in Belle through time-dependent analysis of B^0 decays.

More sensitivity is expexted in Belle II not only incresing of data but also from detector upgrade.

Decay products of CP-eigenstates have been already observed in phase 2 data.

From phase 3 operation with vertex detectors, measurements of ϕ_1 and ϕ_2 in Belle II are within our reach now.

We expect first observation in many decay modes but have to make effort for systematic estimation for high precision study.

Backup

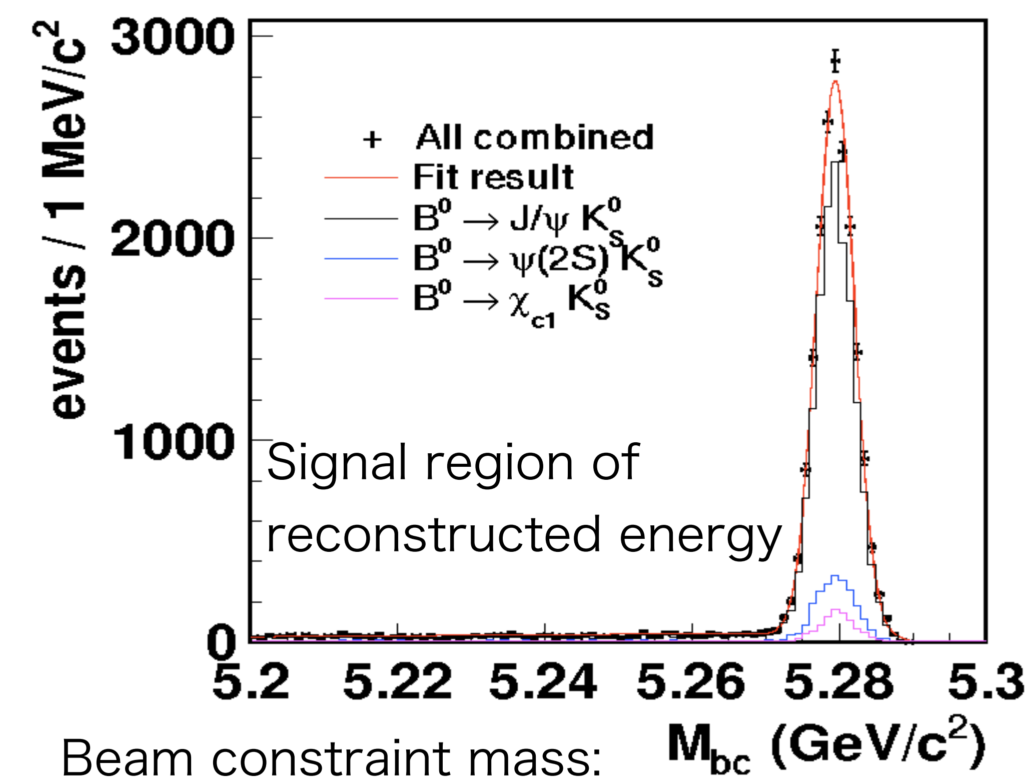
How to obtain ϕ_1/ϕ_2 — signal reconstruction

Reconstruct CP-side using momentum, energy and particle identification information from detector.

ex. $B^0 \to (c\bar{c})K^0_S$: Very clean signal, selected by loose criteria.

$B^0 \to J/\psi\, K^0_L$: Only K^0_L flight direction is detected as hadron cluster in KLM (Cluster energy can not obtained)

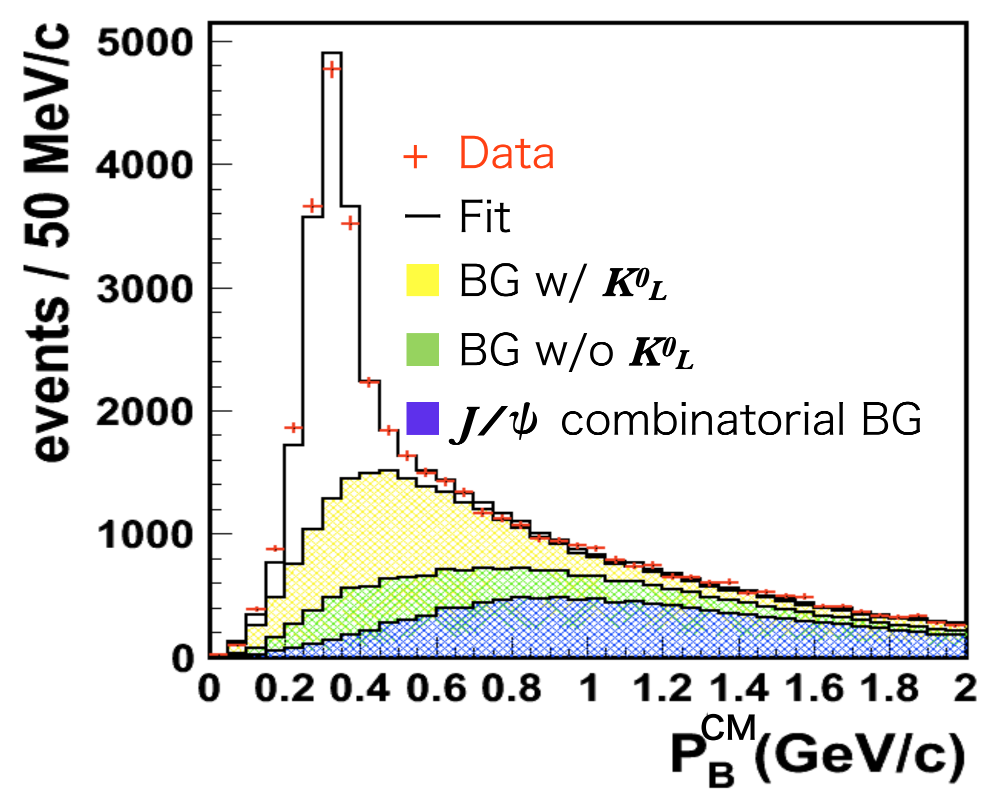
$B^0 \to (c\bar{c})K^0_S$ (CP-odd: $\xi_f = -1$)



Beam constraint mass:

$M_{bc} = \sqrt{E_{beam}^2 - P_B^{CM\,2}}$

$B^0 \to J/\psi\, K^0_L$ (CP-even: $\xi_f = +1$)



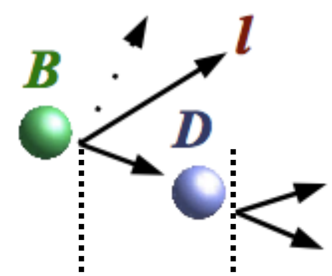
	$J/\psi\, K^0_S$	$\psi(2S) K^0_S$	$\chi_{c1} K^0_S$	$J/\psi\, K^0_L$
Signal yield	12727±115	1981±46	949±33	10087±154
Purity (%)	97	93	89	63

How to obtain ϕ_1/ϕ_2 — correction on Δt and q

q and Δt change due to imperfectness of the measurement.

Δt :

- Detector resolution
- Non-primary track effect
  D lifetime ≠ 0
- Kinematic approximation
  $\Delta t \equiv \Delta z / c\beta\gamma \fallingdotseq \Delta t_{\mathrm{true}}$

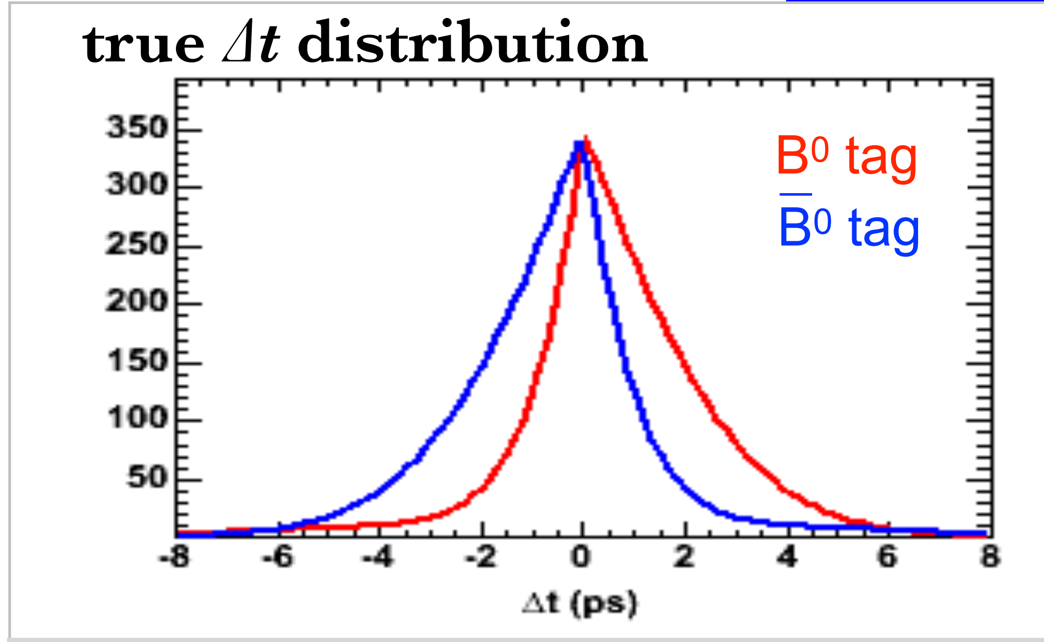


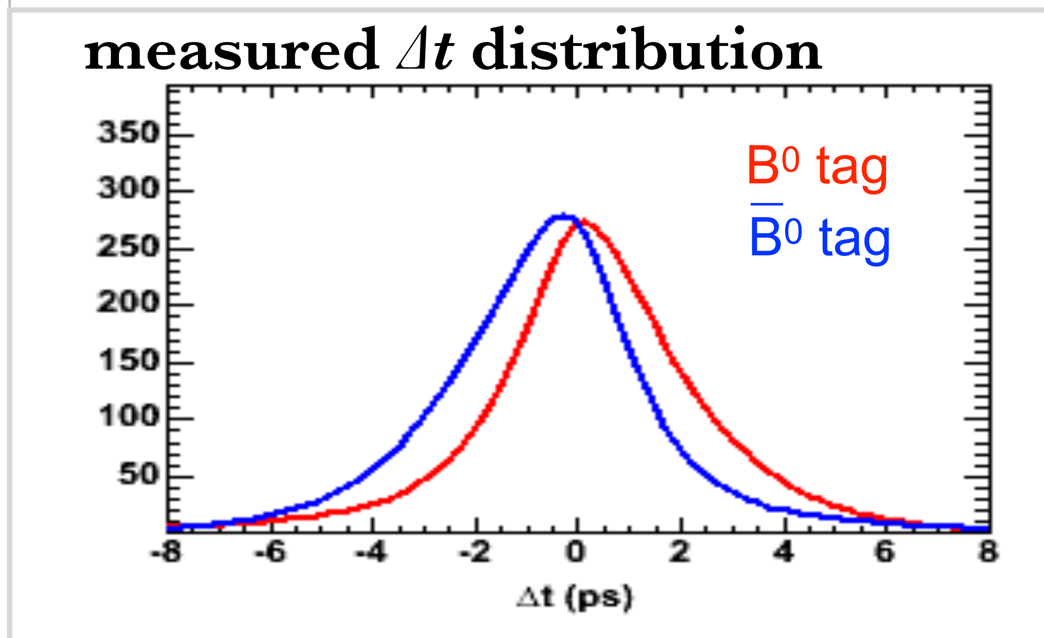
q :

- PID failure
- Ambiguity of flavor determination algorithm

Those effects is estimated using a large number of control sample of $B^0 \to D^{*-}\ell^+\nu$, $B^{0/+} \to D^{(*)}\pi/\rho$ and $B^+ \to J/\psi K^+$

⇒ Observed time-dependent decay rate

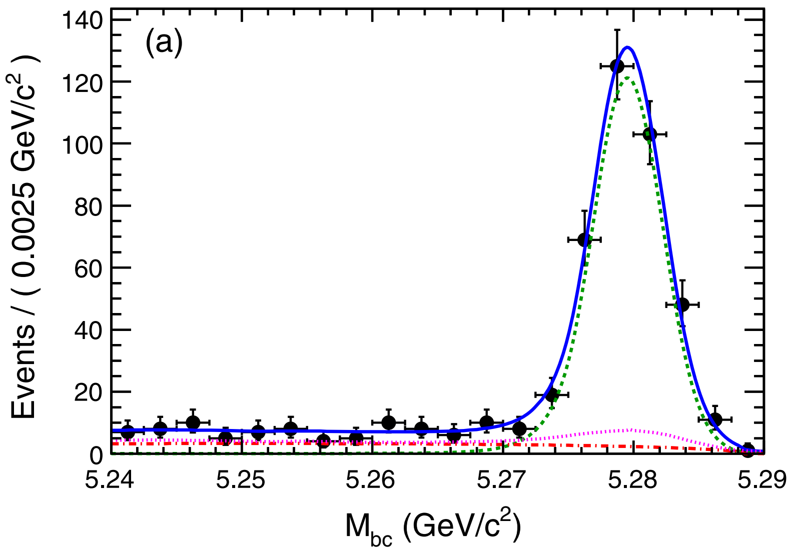


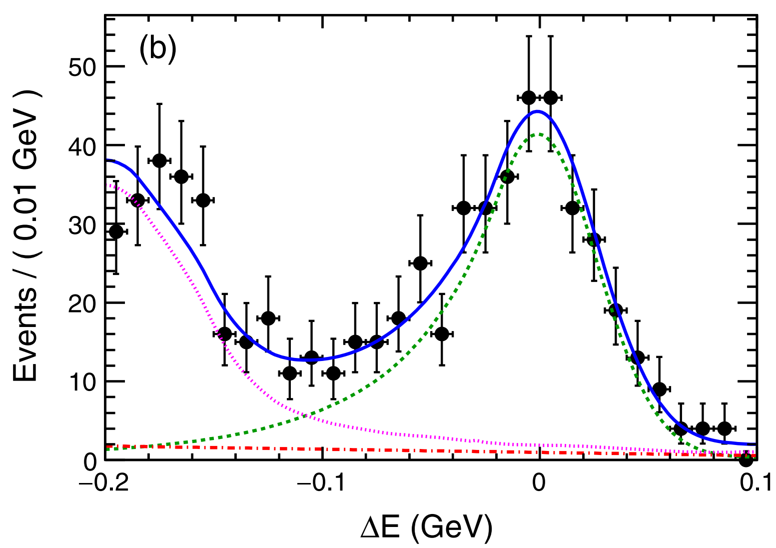


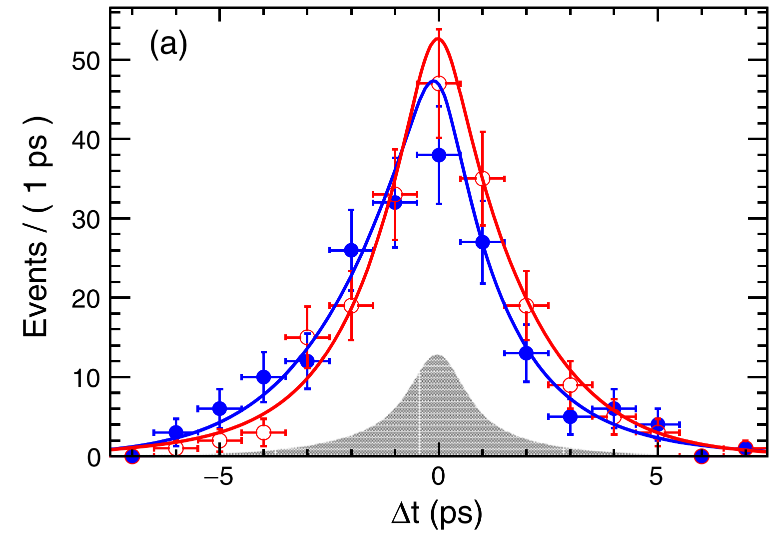
$$P_{sig}(\Delta t, q) = \frac{1}{4\tau} e^{-\frac{|\Delta t|}{\tau_B}} (1-2w)\, q (A\cos\Delta m\Delta t + S\sin\Delta m\Delta t) \otimes R(\Delta t)$$

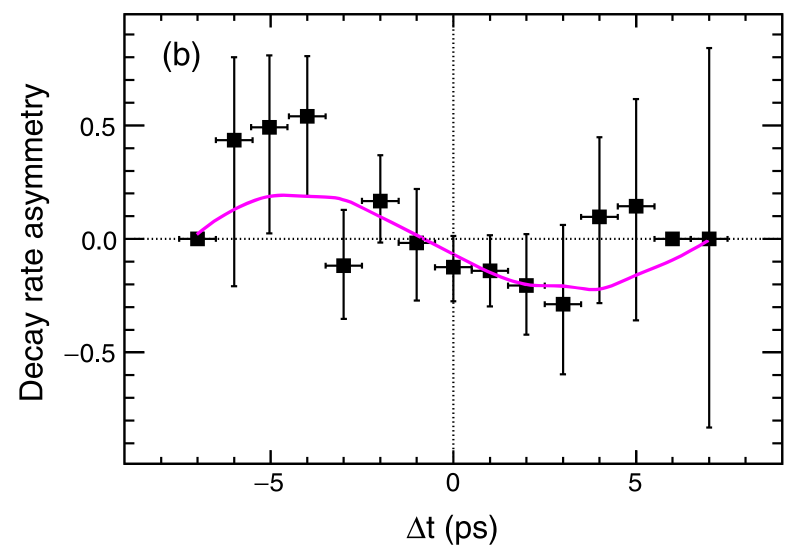
dilution factor — Resolution function

$B^0 \to J/\psi\ \pi^0$









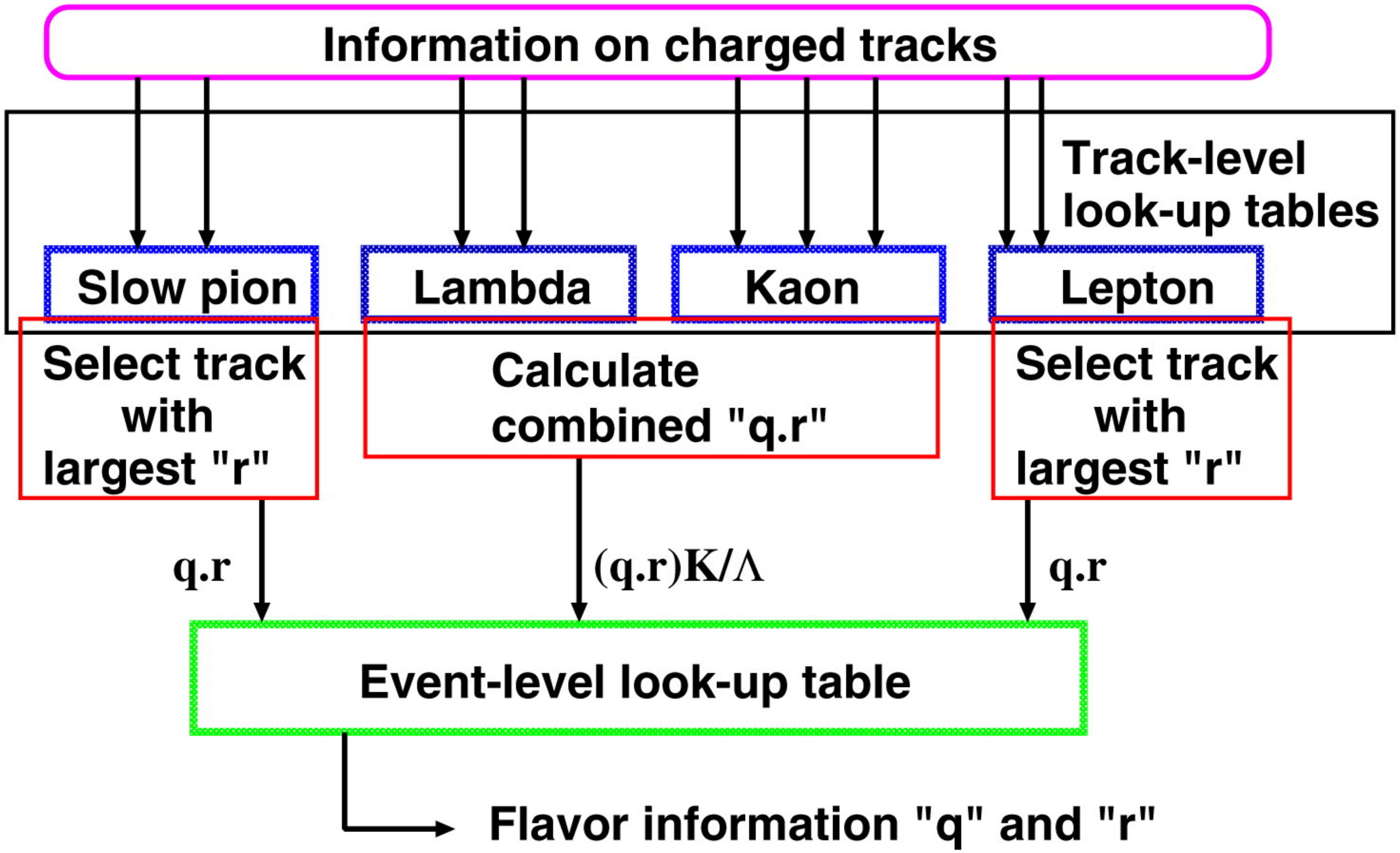
N_{signal} = 332.0±22.1

N_{qq} = 16.3±3.5

$$\mathcal{S} = -0.59 \pm 0.19 \pm 0.03$$

$$\mathcal{A} = -0.15 \pm 0.14^{+0.04}_{-0.03},$$

Flavor tagging analysis stream in Belle



ϕ_2 measurement using isospin relation

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

772M $B\bar{B}$ PRD 88 092003 (2013)

$$\mathcal{A}_{CP}(B^0 \to \pi^+\pi^-) = +0.33 \pm 0.06(\text{stat}) \pm 0.03(\text{syst})$$

$$\mathcal{S}_{CP}(B^0 \to \pi^+\pi^-) = -0.64 \pm 0.08(\text{stat}) \pm 0.03(\text{syst})$$

$$\mathcal{B}(B^0 \to \pi^+\pi^-) = (5.04 \pm 0.21 \pm 0.18) \times 10^{-6}$$

$B^0 \to \pi^0\pi^0$

275M $B\bar{B}$ PRL 94 181803 (2005)

$$\mathcal{A}_{CP} = 0.44^{+0.53}_{-0.52} \pm 0.17$$

$$\mathcal{B}(B^0 \to \pi^0\pi^0) = (2.3^{+0.4+0.2}_{-0.5-0.3}) \times 10^{-6}$$

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

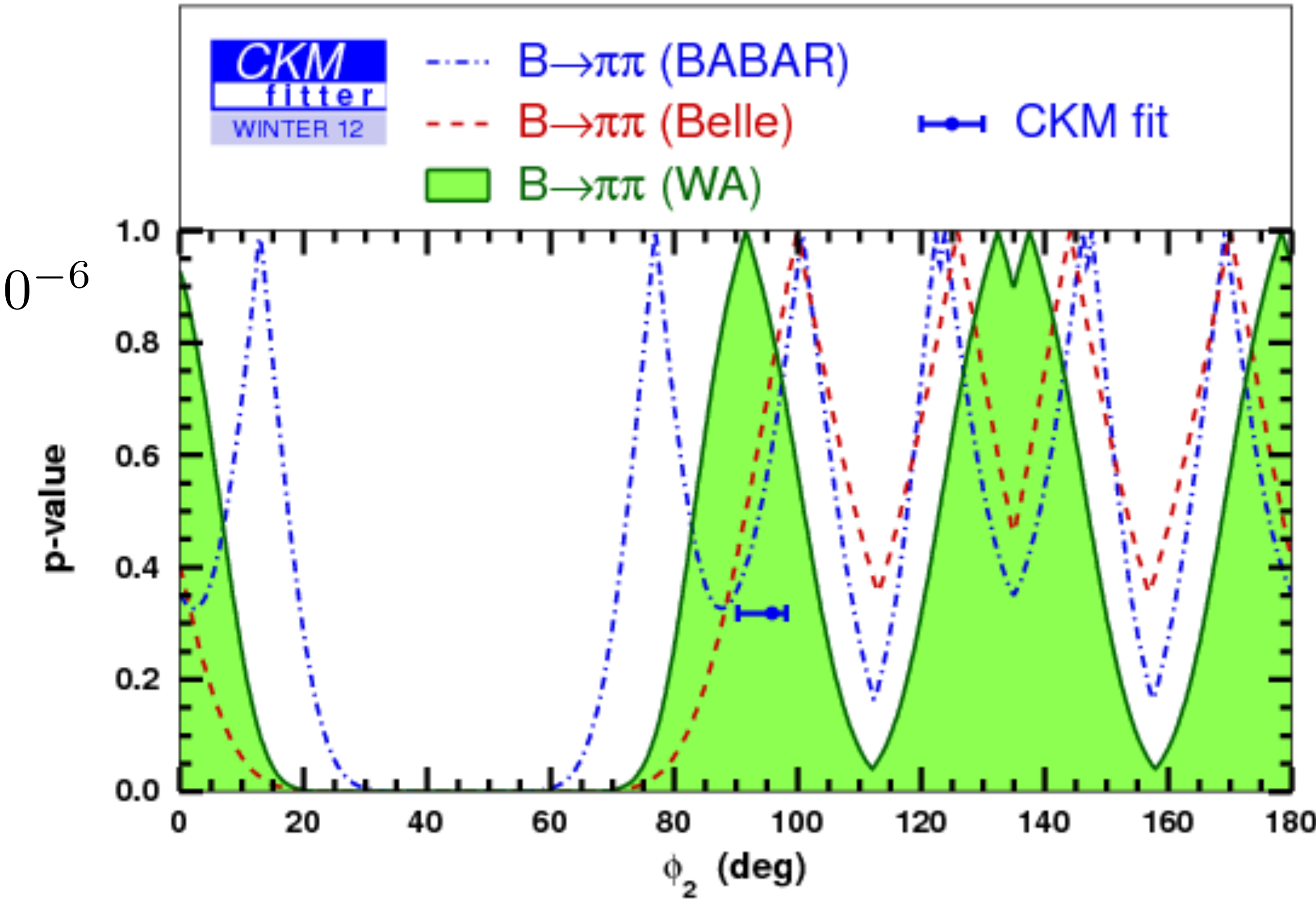
772M $B\bar{B}$ PRD 87 031103(R) (2013)

$$\mathcal{A}_{CP}(B^+ \to \pi^+\pi^0) = 0.025 \pm 0.043 \pm 0.007$$

$$\mathcal{B}(B^+ \to \pi^+\pi^0) = (5.86 \pm 0.26 \pm 0.38) \times 10^{-6}$$

Large uncertainty of ϕ_2 is due to measurements in $B^0 \to \pi^0\pi^0$ decay

- Low branching fraction
- Photon detection efficiency
- (No S_{CP} due to lack of vertex in signal side → eight-fold ambiguity)



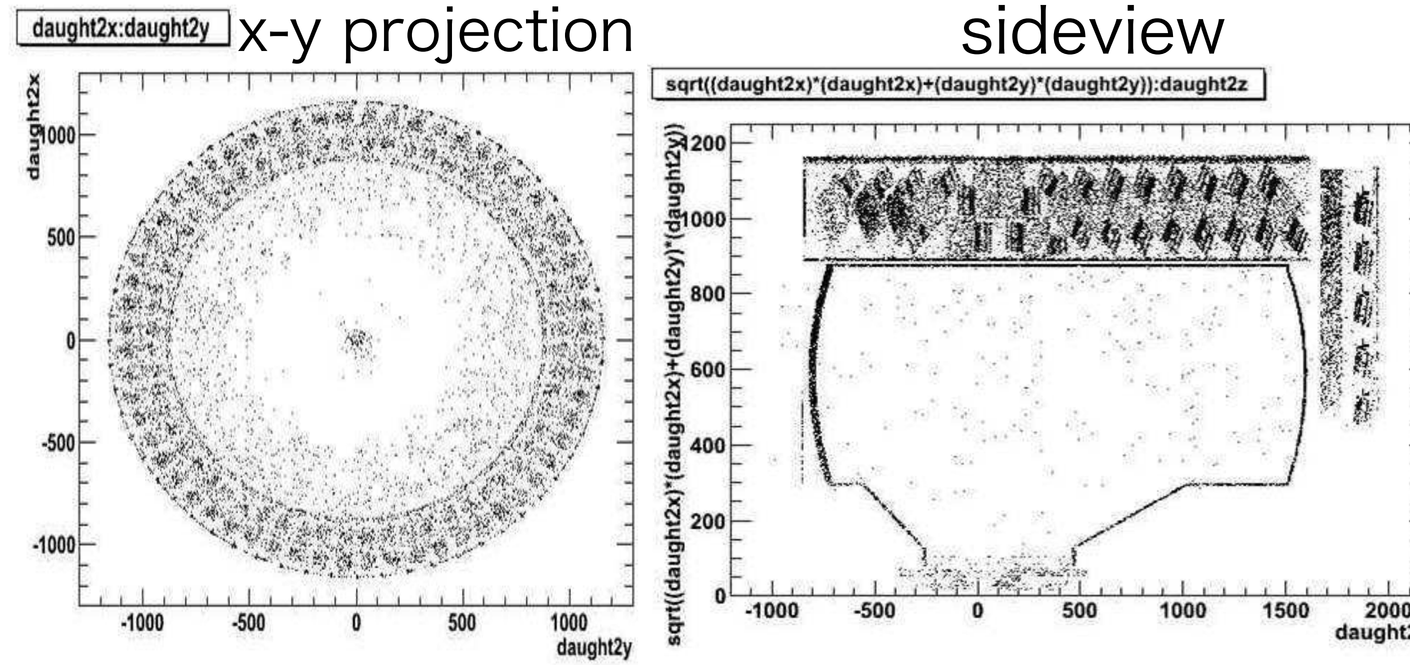
$B^0 \to \pi^0 \pi^0$ measurement

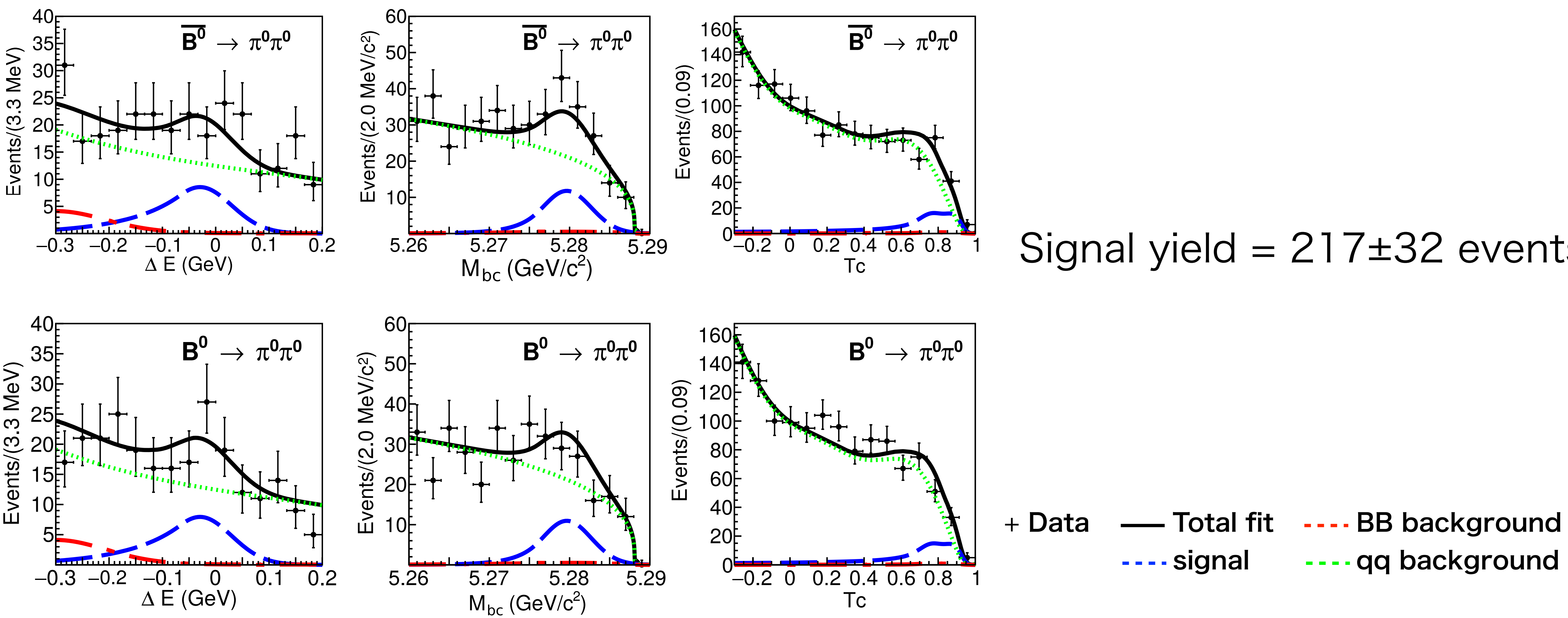
Update using full data set
PRD 96 032007 (2017)

Many photons are lost by conversion with material in front of calorimeter.
→ Converted photon reconstructed by $\gamma \to e^+e^-$ that is apart from IP is also used for π^0 reconstruction.

Photon interaction points (MC)

x-y projection sideview





Signal yield = 217±32 events

$B^0 \to \pi^0 \pi^0$ measurement

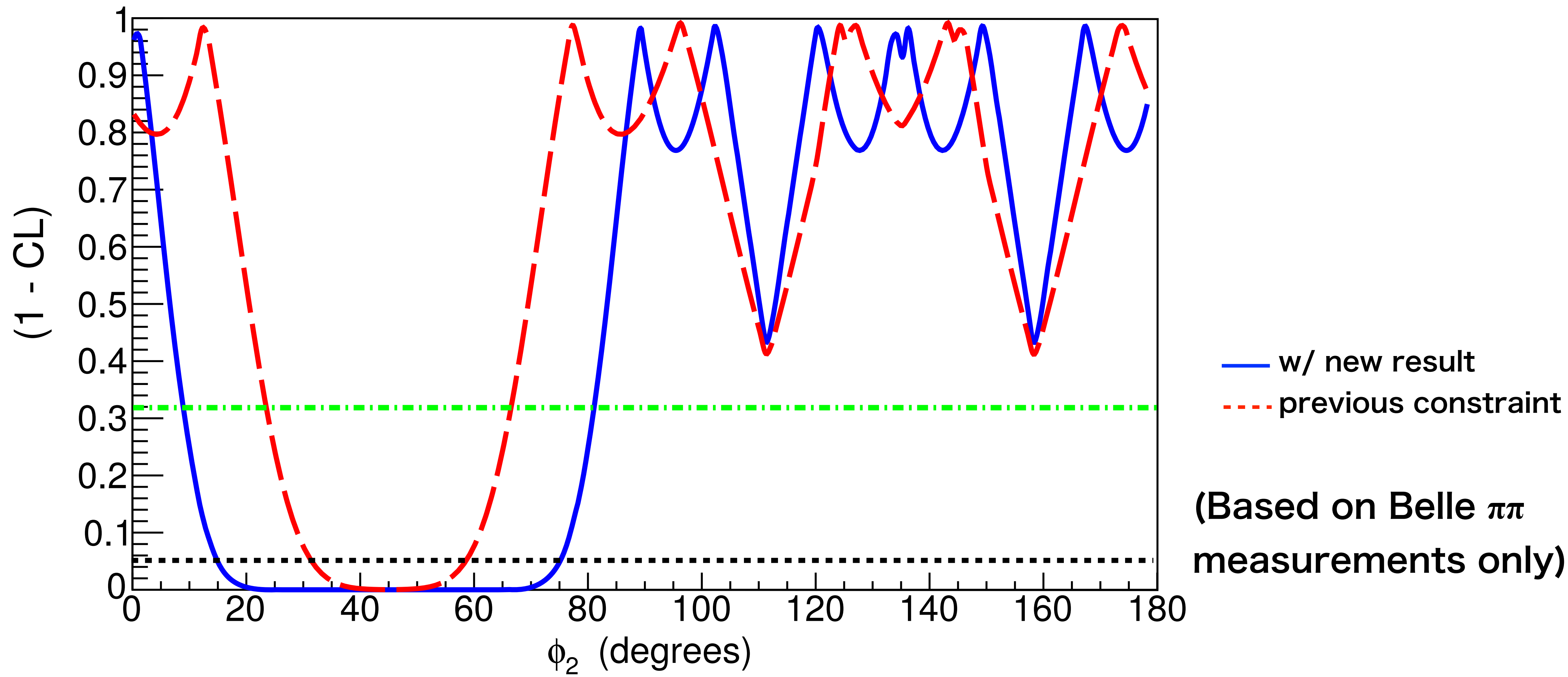
$A_{CP} = +0.14 \pm 0.36 \pm 0.10$

$\mathcal{B}(B^0 \to \pi^0\pi^0) = (1.31 \pm 0.19 \pm 0.19) \times 10^{-6}$

(6.4 σ significance)

ϕ_2 confidence level scan including new observables from $B^0 \to \pi^0 \pi^0$

Excluded region: 9.5° < ϕ_2 < 81.6° (68% C.L.) , 15.5° < ϕ_2 < 75.0° (95% C.L.)



(Based on Belle $\pi\pi$ measurements only)