Overview of Flavor Physics Results at Belle

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on behalf of the Belle collaboration

Introduction

Measurements of various B meson decays with interactions of flavor give hints to the new physics beyond the SM (BSM).

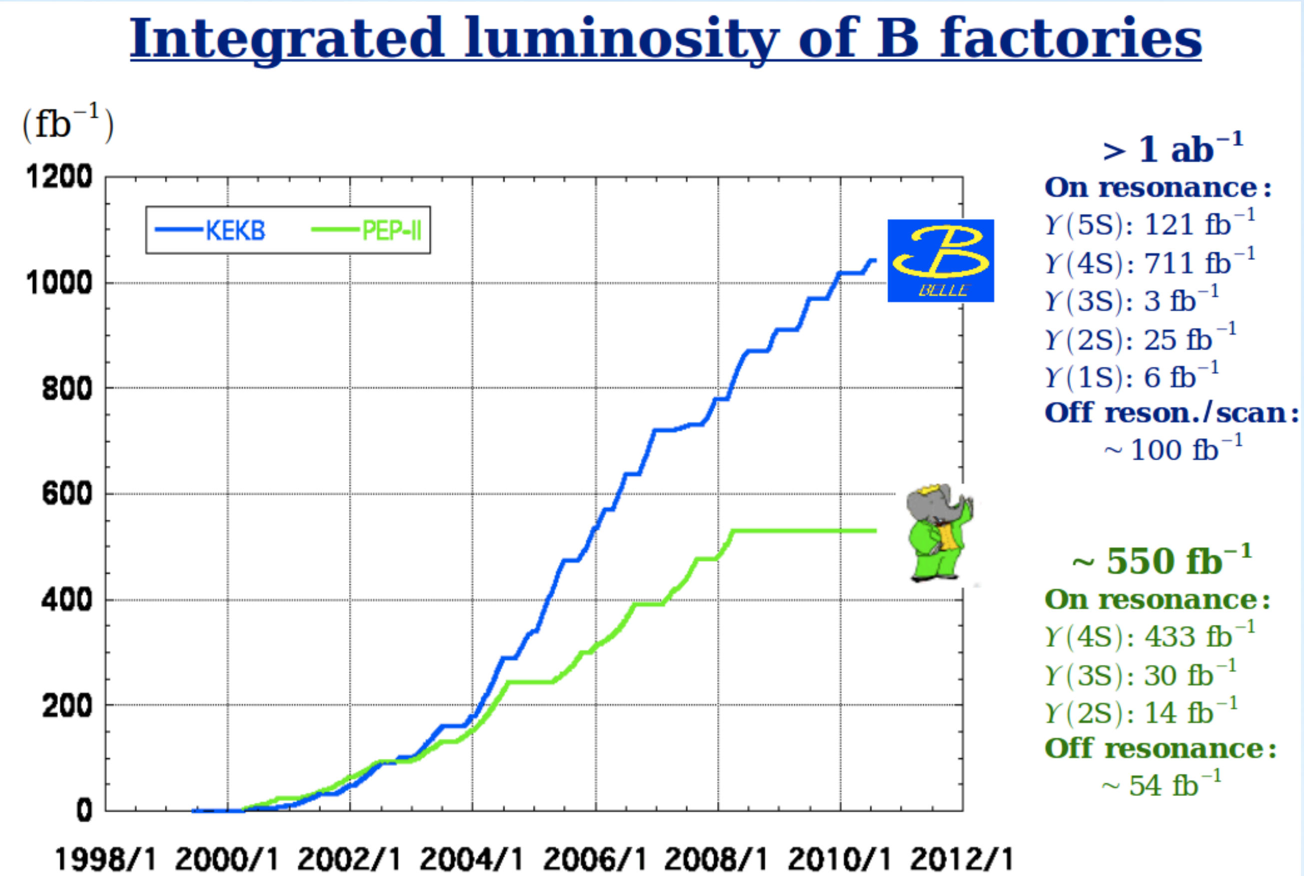
- CP violation
- Branching fractions
- Rare decay search
- New particle search

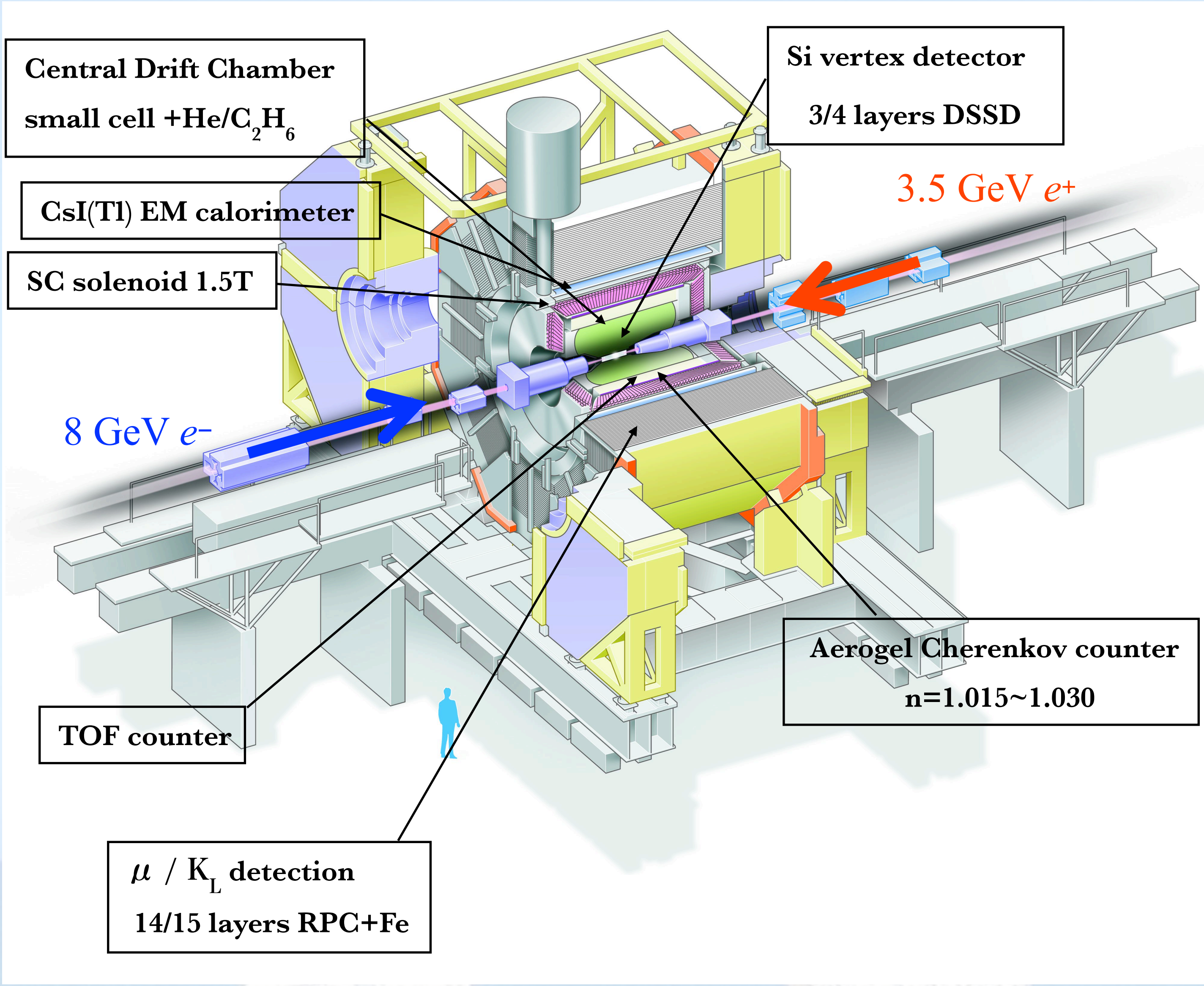
…

Through precise measurement with a high statistic data sample, we can search for a slight signal and open the door to the BSM that appears in very high energy scale.
⇒ Luminosity frontier

In this talk, I review flavor physics results in the Belle experiment together with the most resent updates.

Belle experiment





In total, 772 million $B\bar{B}$ pairs are accumulated. Studies using full data sample are still ongoing. All of the new results shown today is based on the full data set.

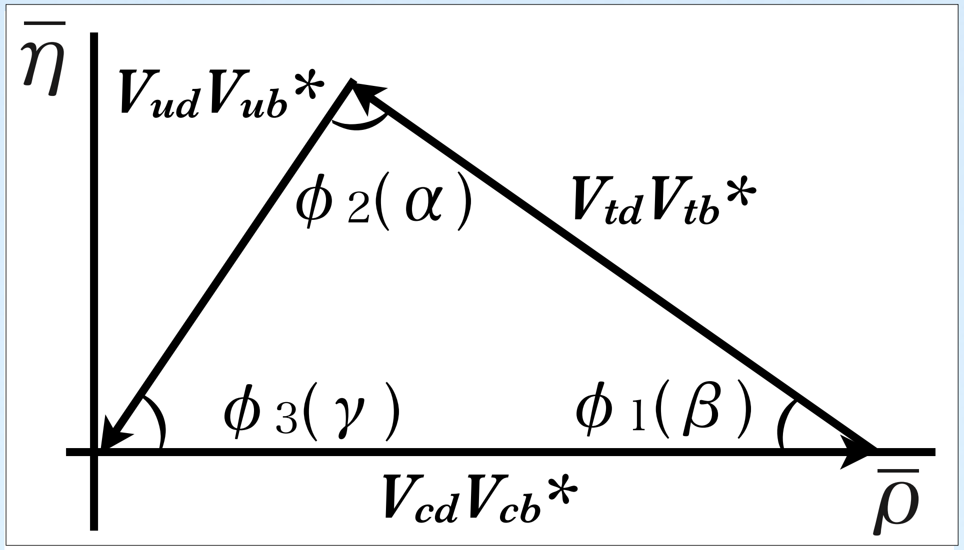
- charged particle tracking
- momentum measurement
- particle identification
- e/γ energy measurement
- K_L cluster detection

CP violation

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

→ CP violation parameters are angles of the unitary triangle.

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



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

In past decade, great breakthrough for CP-violation parameters measurements in B decays has been achieved by B-factries.

Angles from direct measurement (Averages by CKMfitter group in winter 2014)	Typical final states used for the measurements (CP-eigenstates)
$\phi_1\,(\beta) = (21.50^{+0.75}_{-0.74})^\circ$	$B^0 \to (c\bar{c})K^0$
$\phi_2\,(\alpha) = (85.4^{+4.0}_{-3.9})^\circ$	$B \to \pi\pi, \pi\rho, \rho\rho$
$\phi_3\,(\gamma) = (70.0^{+7.0}_{-9.0})^\circ$	$B \to D^{(*)}K^{(*)}$

CP violation in B decays

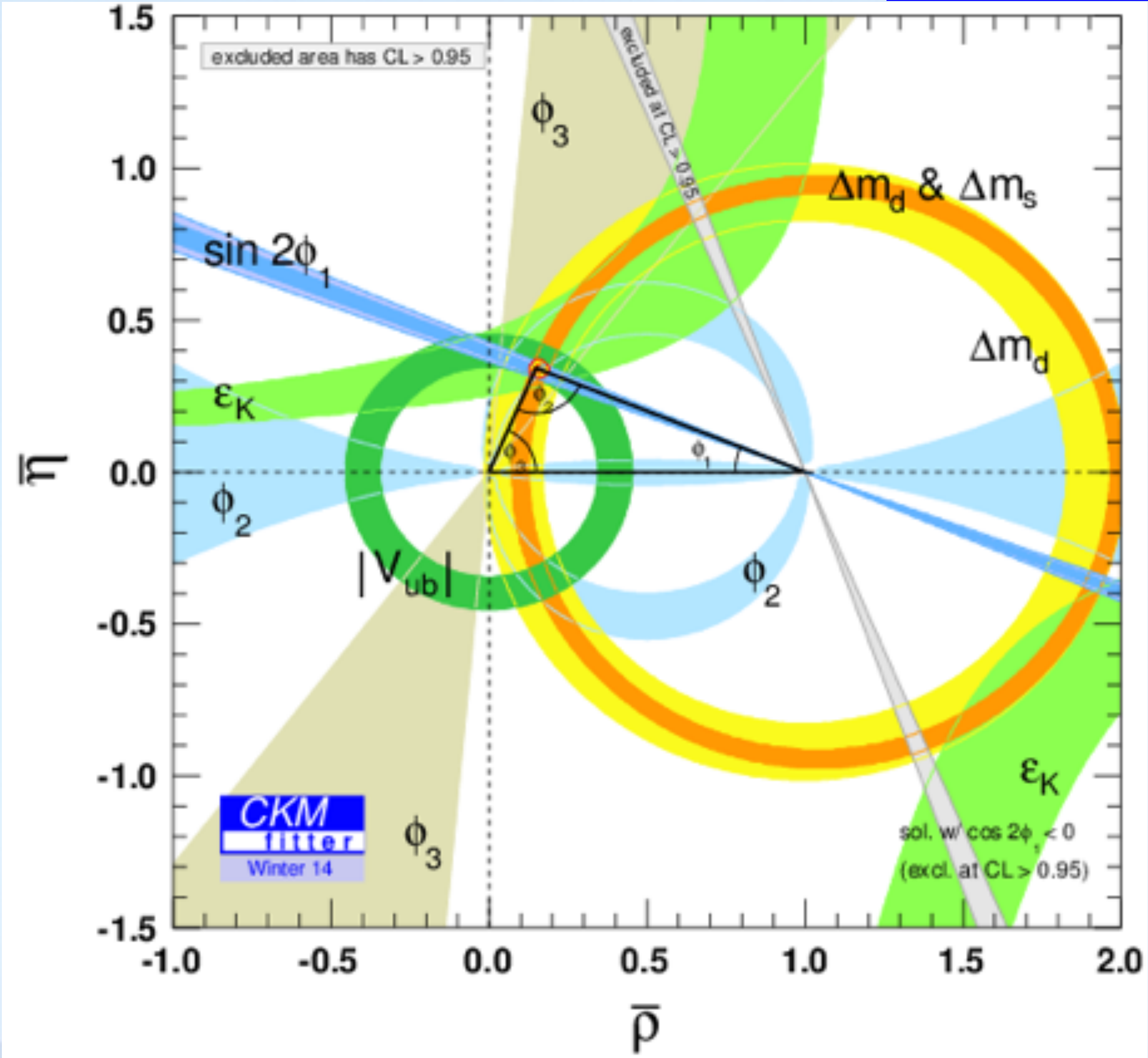
$$\mathcal{A}_{CP} = \frac{\mathcal{P}(\overline{B^0}(\Delta t) \to f_{CP}) - \mathcal{P}(B^0(\Delta t) \to f_{CP})}{\mathcal{P}(\overline{B^0}(\Delta t) \to f_{CP}) + \mathcal{P}(B^0(\Delta t) \to f_{CP})}$$

$= \boldsymbol{S} \sin\Delta m \Delta t$ + $\boldsymbol{A} \cos\Delta m\Delta t$

mixing induced CPV — **direct CPV**

Δm: mass difference of eigenstates

Δt: decay time difference of eigenstates



CP violation parameters S and A are measured using decay to the CP eigenstate.

ex. $b \to c\bar{c}s$ tree diagram

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

"Golden mode"

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

A ~0

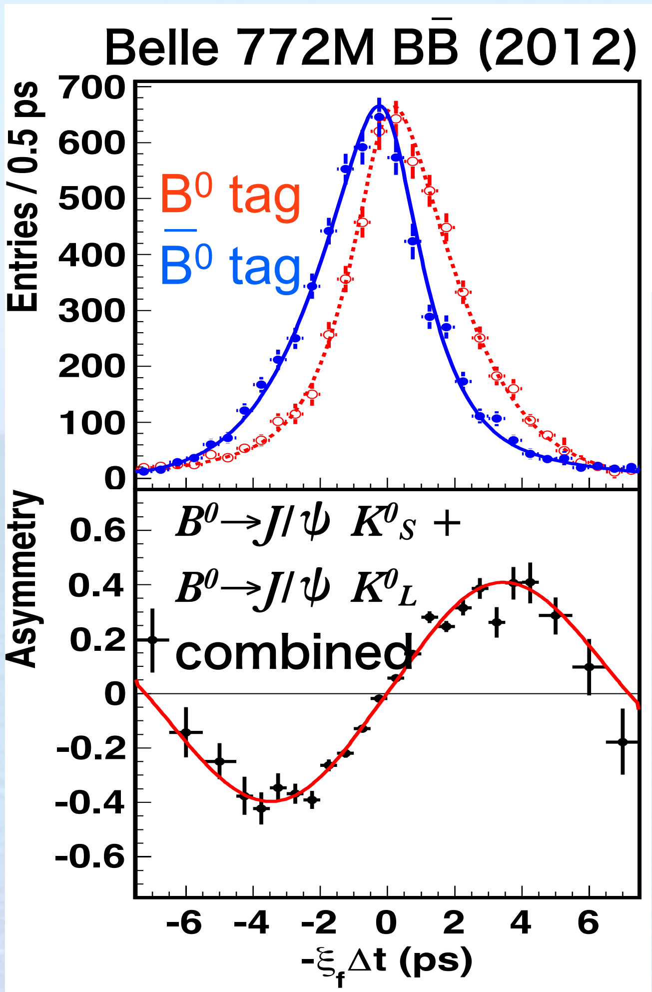
ξ_f: ***CP* eigenvalue**

= −1 for $J/\psi\ K^0_S$

+1 for $J/\psi\ K^0_L$

S= 0.667±0.023±0.012

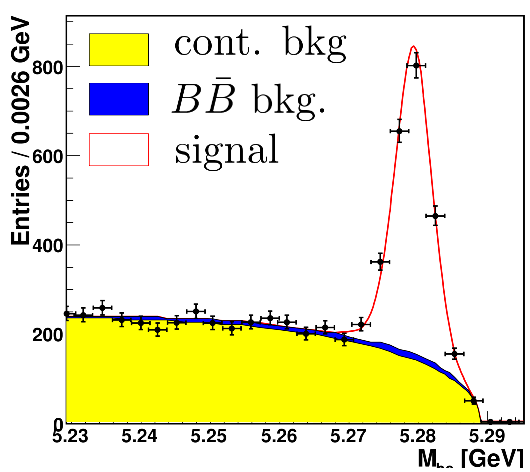
A= 0.006±0.016±0.012



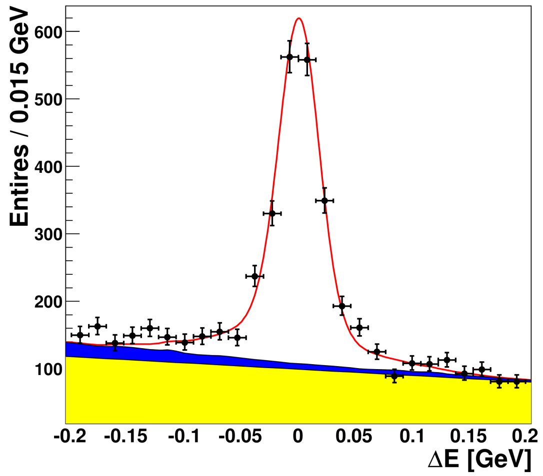
By checking consistency of CP violation parameters, we investigate bias from the BSM: The triangle is closes? ($\phi_1 + \phi_2 + \phi_3$ is just π ? or some additional phases?)

Analysis strategy

- Reconstruct signal B and identify using kinematic variables (mass, energy…)

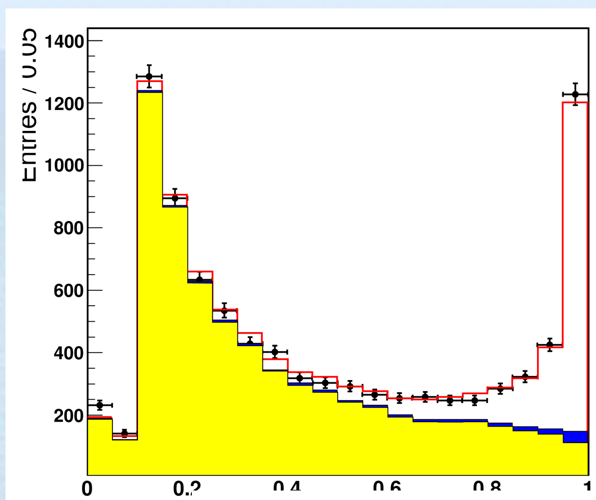


Beam constraint mass:
$M_{bc} = \sqrt{(E_{beam}/2)^2 - p_{rec}^2}$



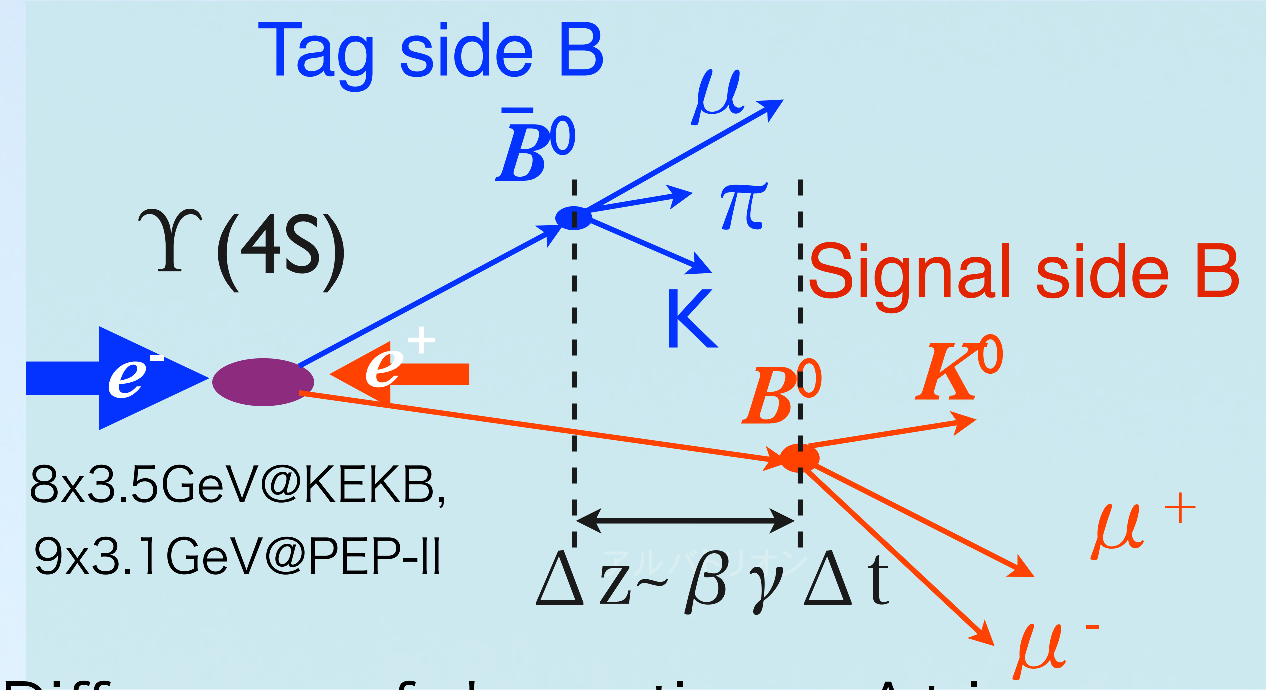
Eenergy difference:
$\Delta E = E_{rec}^{CM} - E_{beam}/2$

- $q\bar{q}$ continuum suppression discriminant (likelihood, neural net, BDT…) based on shape variables of the B decay.
  Distribution of decay products:
  B decay: spherically
  $q\bar{q}$ continuum: jet-like



qq suppression (Likelihood)

Time-dependent CP violation measurement



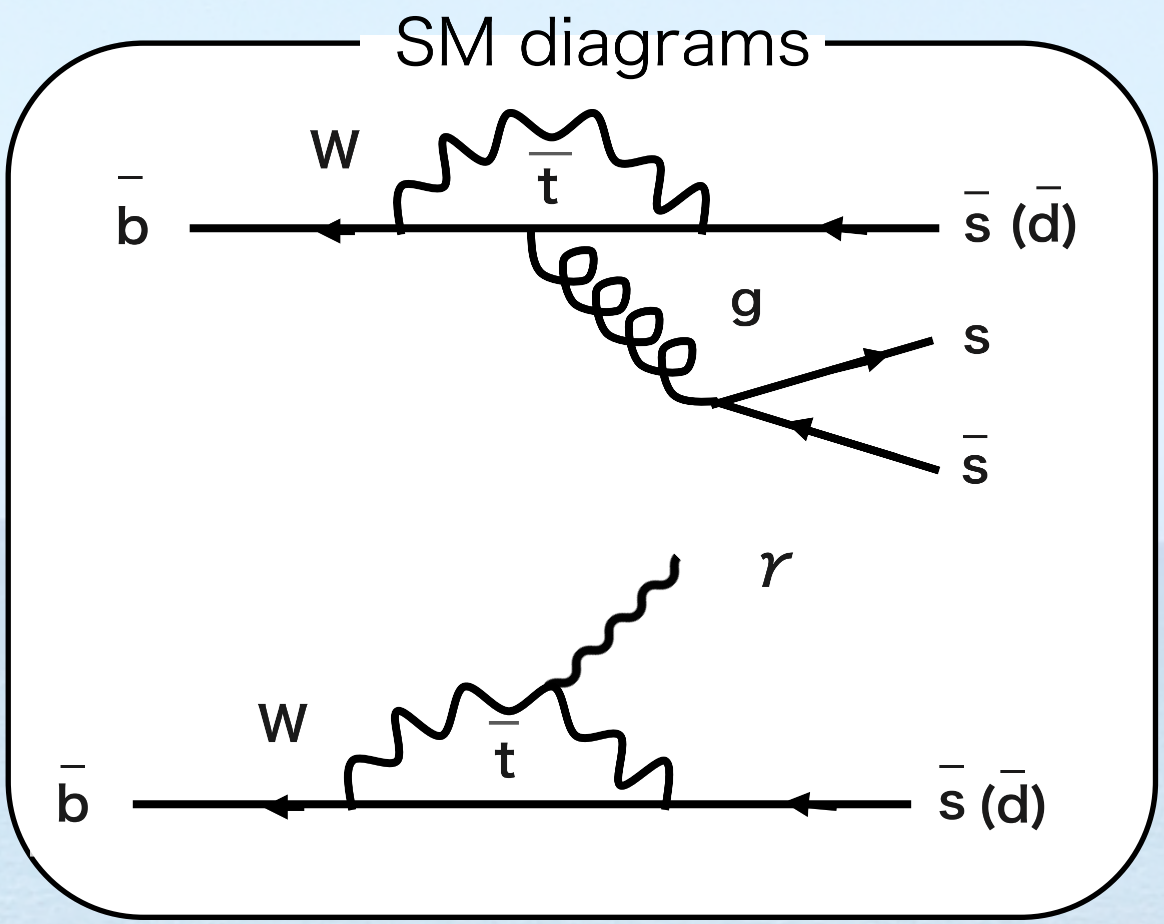
- Difference of decay times, Δt is measured by vertex positions of B and $\bar{B}$.
- Flavor of B^0 is measured from flavor of companion $\bar{B}^0$ decay products. (high momentum lepton, kaon, etc.) Effective tagging efficiency ~30%.
- CP violation parameters are obtained by the fit to Δt and B flavor simultaneously to other variables such as reconstructed B kinematics etc.

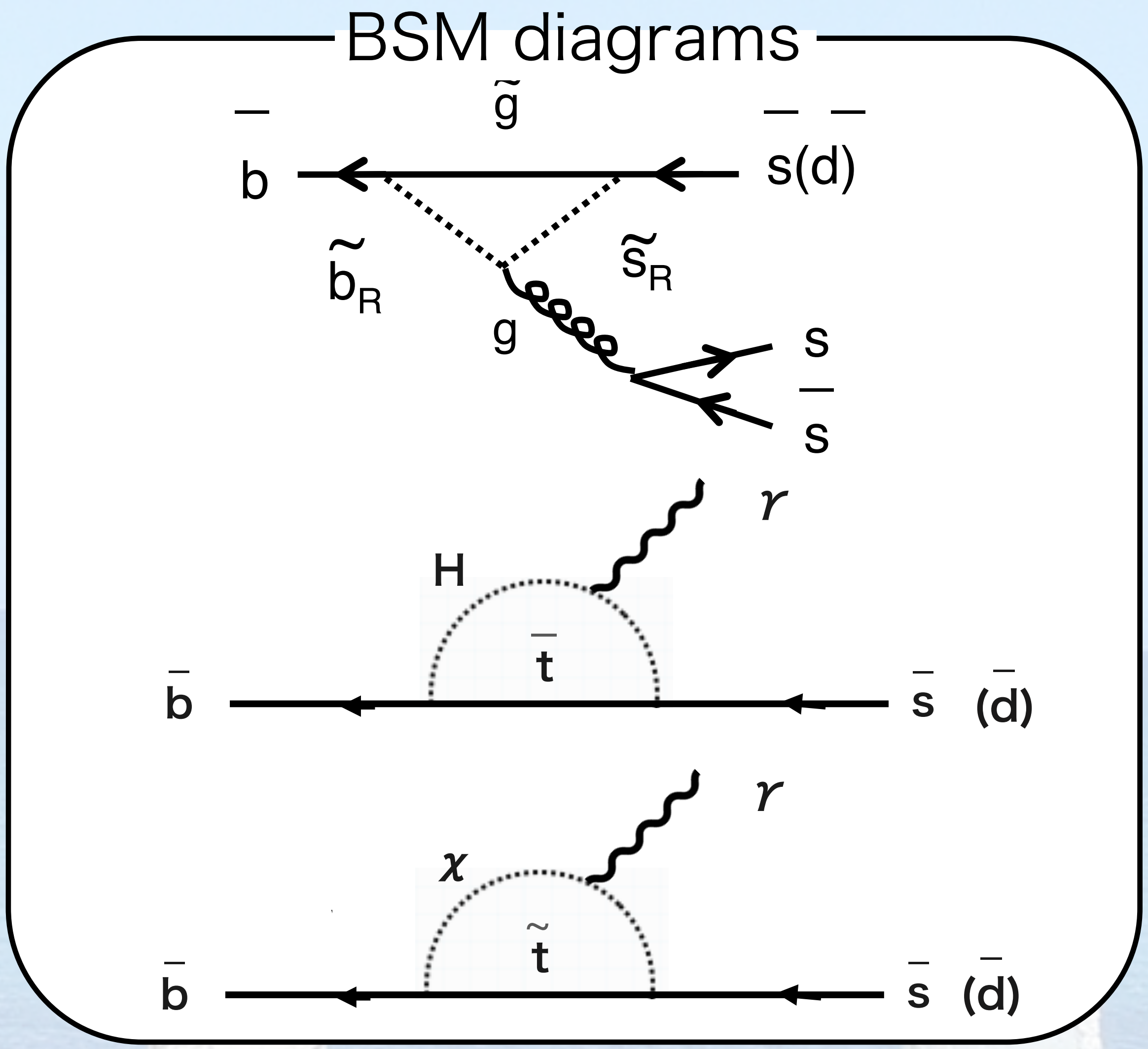
Approach to BSM via penguin diagram

A loop appears in the first order diagrams of Flavor Changing Neutral Current transitions: $b \to sq\bar{q}$ and $b \to s\gamma$.

⇒ Sensitive to the physics beyond the SM (BSM) contribution

The effects can be appeared in parameters we observe: CP phases, branching fractions, forward-backward asymmetries, isospin asymmetries.



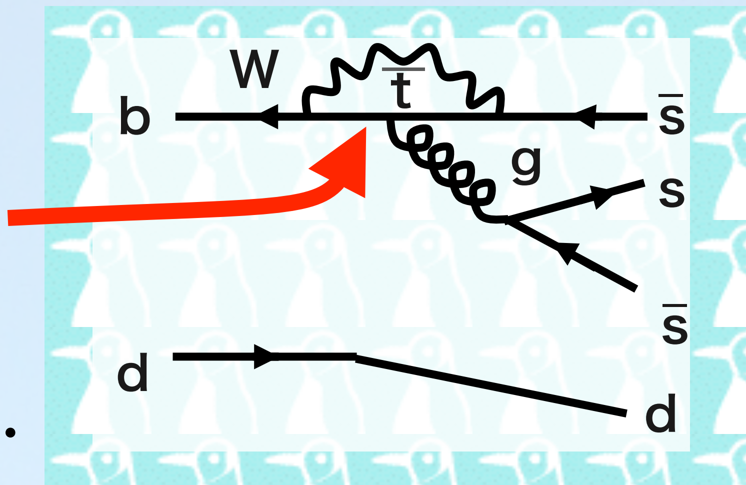


CP violation in decay via penguin diagram

Penguin loop is sensitive to the new physics contribution.

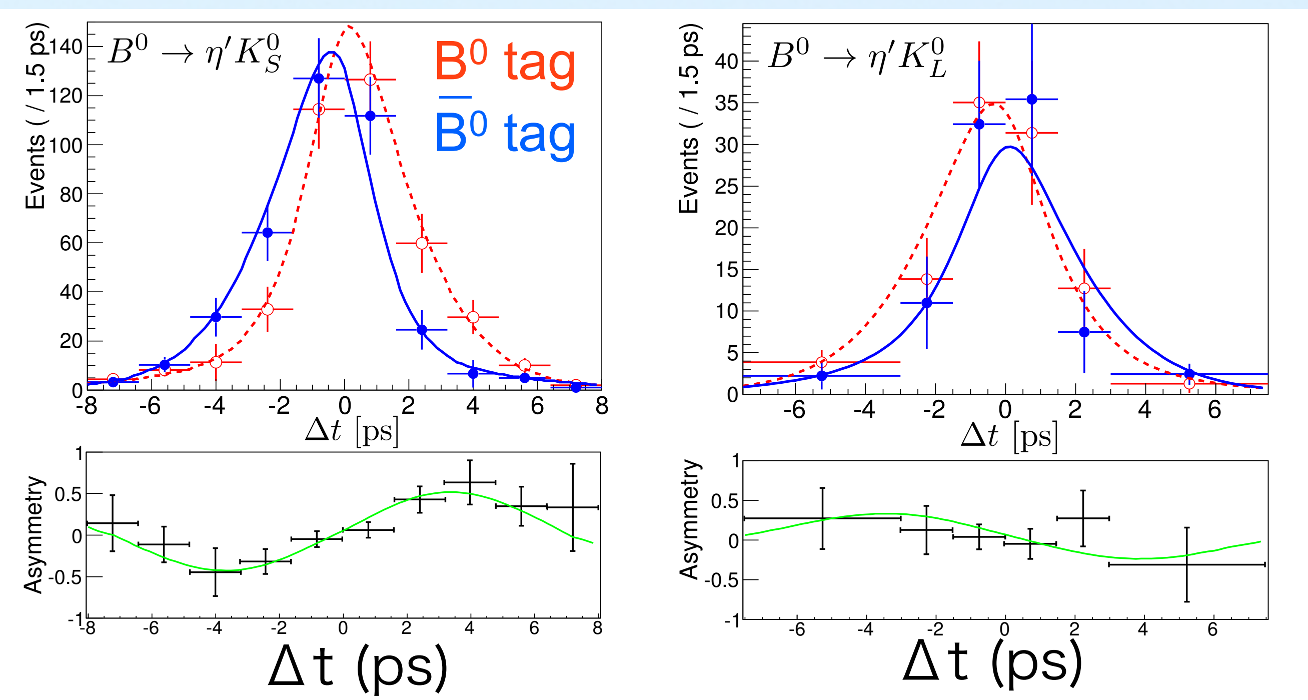
$S \equiv -\xi_f \sin 2\phi_1^{\mathrm{eff}} = -\xi_f \sin 2\phi_1$ from decay with $b \to c\bar{c}s$?

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



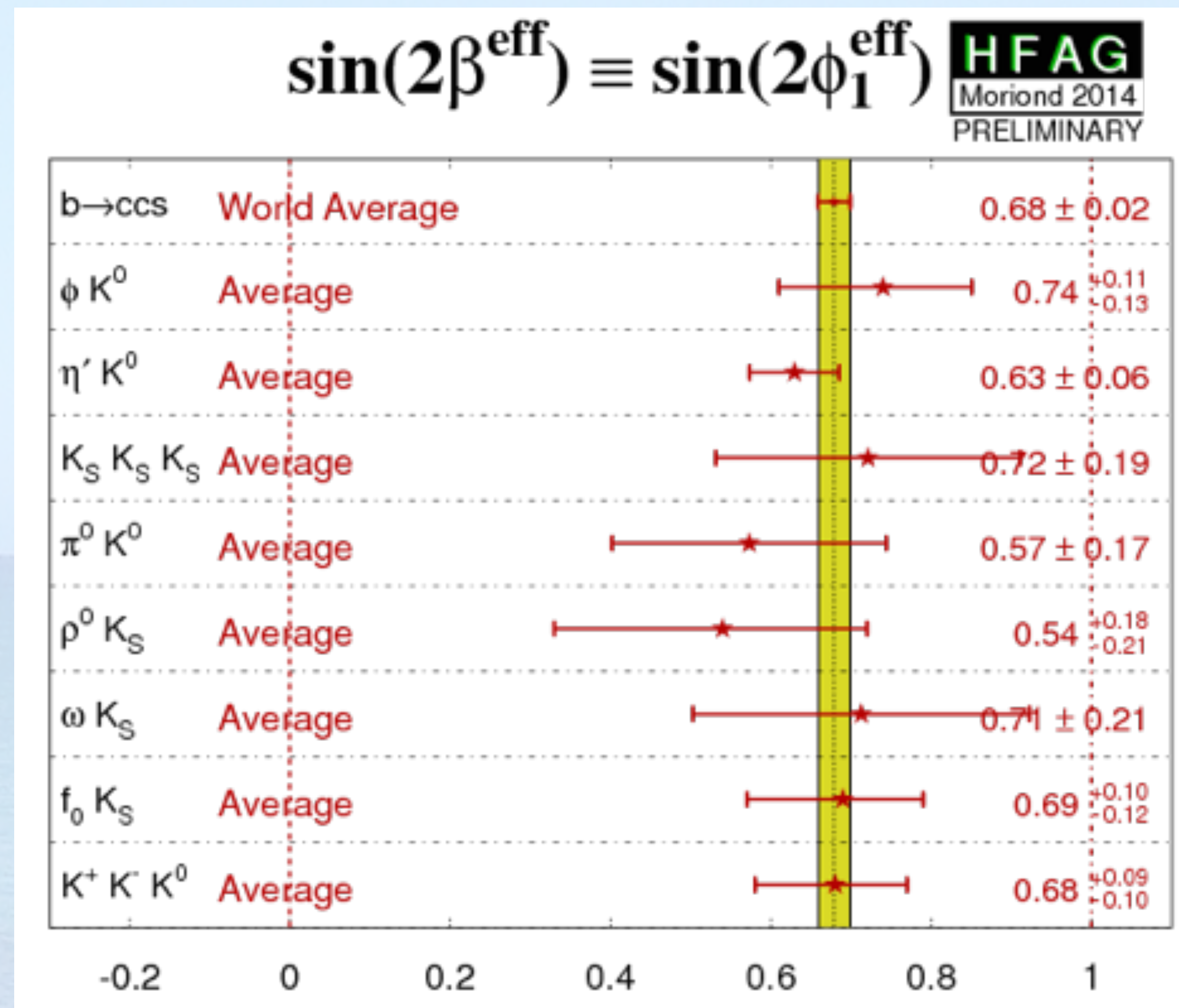
$B^0 \to \eta' K^0$ – "platinum mode" – Large branching fraction and few possible deviation in the SM.

Belle 772M $B\bar{B}$



Decay mode	$-\xi_f \mathcal{S}_f$	$\mathcal{A}_f$
$\eta' K^0_S$	$+0.71 \pm 0.07$	$+0.02 \pm 0.05$
$\eta' K^0_L$	$+0.46 \pm 0.21$	$+0.09 \pm 0.14$
$\eta' K^0$	$+0.68 \pm 0.07 \pm 0.03$	$+0.03 \pm 0.05 \pm 0.04$

preliminary

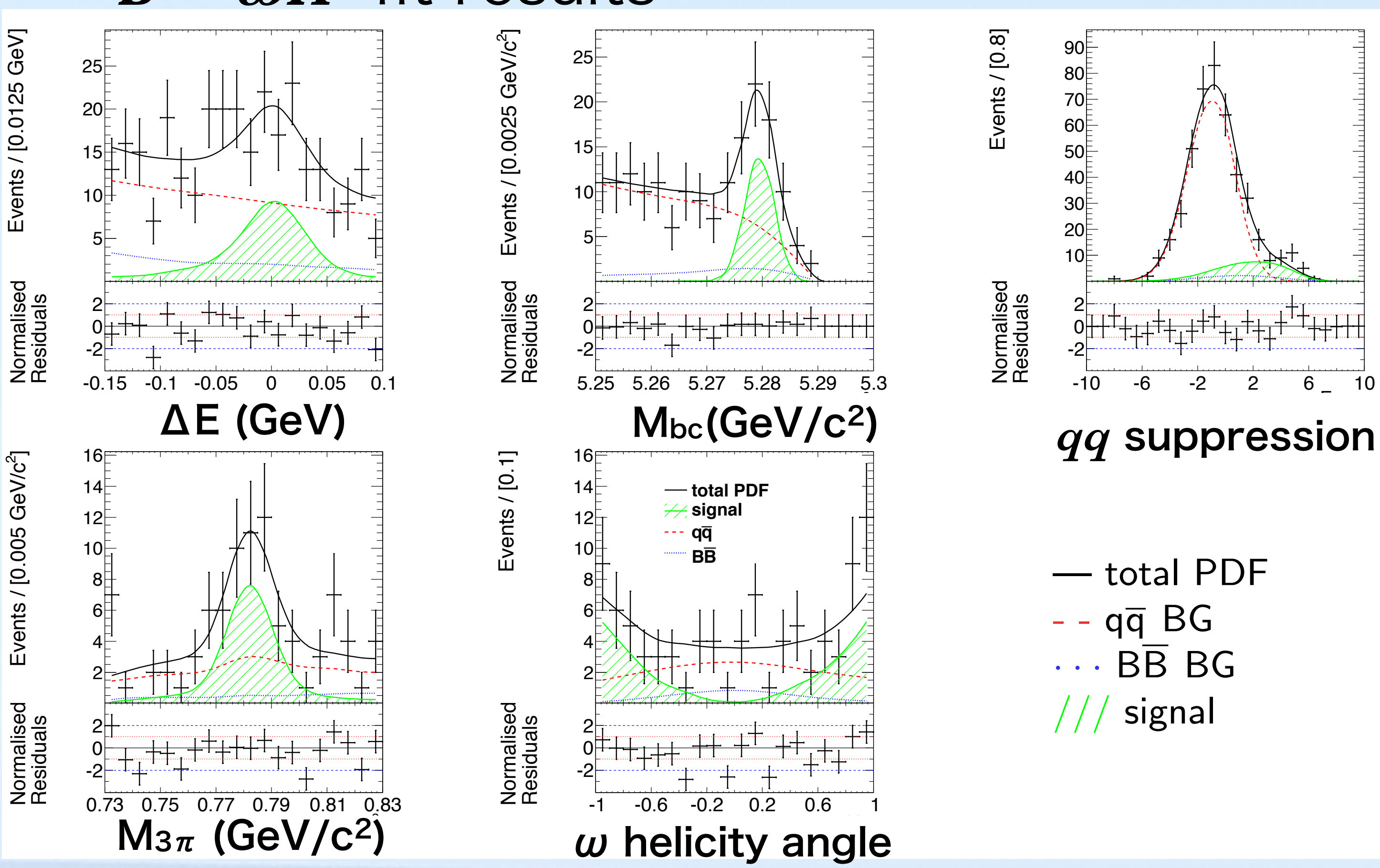


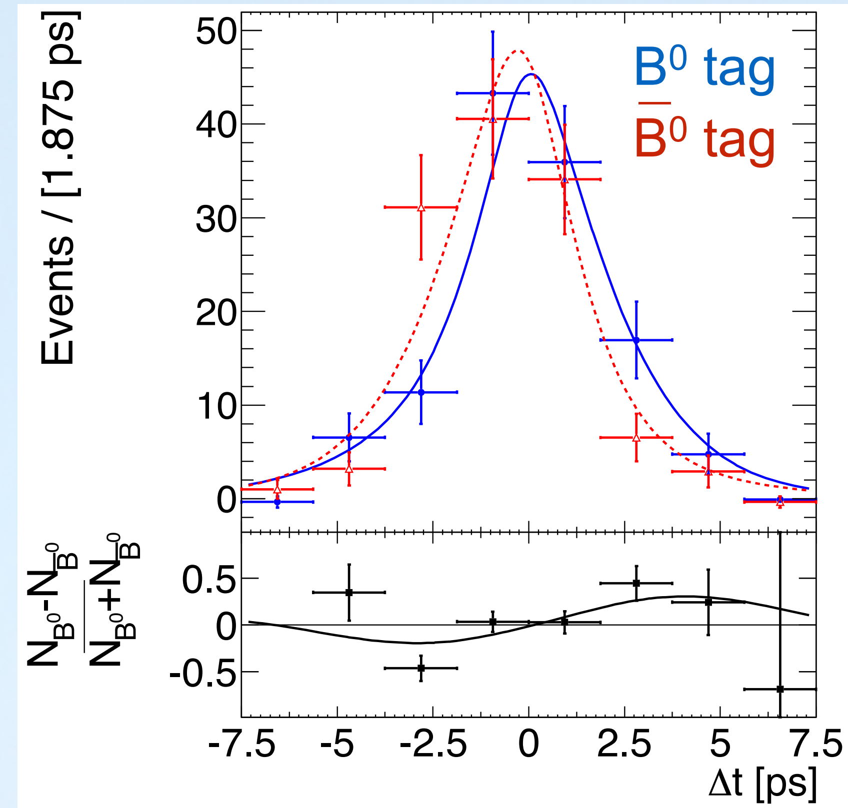
→ Consistent with ϕ_1 from decays via $b \to c\bar{c}s$

CP violation in $B^0 \to \omega K^0$

Simultaneous fit to observables of the candidates of $B^0 \to \omega K^0$ signal decay and $B^+ \to \omega K^+$ control sample decay. (reducing systematic uncertainty)

$B^0 \to \omega K^0$ fit results





	$B\overline{B}$-pairs	$\mathcal{BR}(B^0 \to \omega K^0)$	$\mathcal{A}_{CP}$	$\mathcal{S}_{CP}$
Belle	388×10^6	$(4.4^{+0.8}_{-0.7} \pm 0.4) \times 10^{-6}$	-	-
Belle	535×10^6	-	$-0.09 \pm 0.29 \pm 0.06$	$+0.11 \pm 0.46 \pm 0.07$
BaBar	467×10^6	$(5.4 \pm 0.8 \pm 0.3) \times 10^{-6}$	$+0.52^{+0.22}_{-0.20} \pm 0.03$	$+0.55^{+0.26}_{-0.29} \pm 0.02$
Belle	772×10^6	$(4.5 \pm 0.4 \pm 0.3) \times 10^{-6}$	$-0.36 \pm 0.19 \pm 0.05$	$+0.91 \pm 0.32 \pm 0.05$

	$B\overline{B}$-pairs	$\mathcal{BR}(B^+ \to \omega K^+)$	$\mathcal{A}_{CP}$
Belle	388×10^6	$(8.1 \pm 0.6 \pm 0.6) \times 10^{-6}$	$+0.05^{+0.08}_{-0.07} \pm 0.01$
BaBar	383×10^6	$(6.3 \pm 0.5 \pm 0.3) \times 10^{-6}$	$-0.01 \pm 0.07 \pm 0.01$
Belle	772×10^6	$(6.8 \pm 0.4 \pm 0.4) \times 10^{-6}$	$-0.03 \pm 0.04 \pm 0.01$

Phys. Rev. D 90, 012002 (2014)

Evidence of the time-dependent CP violation is seen. (3.1 σ significance)

Consistent with the results in decays via $b \to c\bar{c}s$.

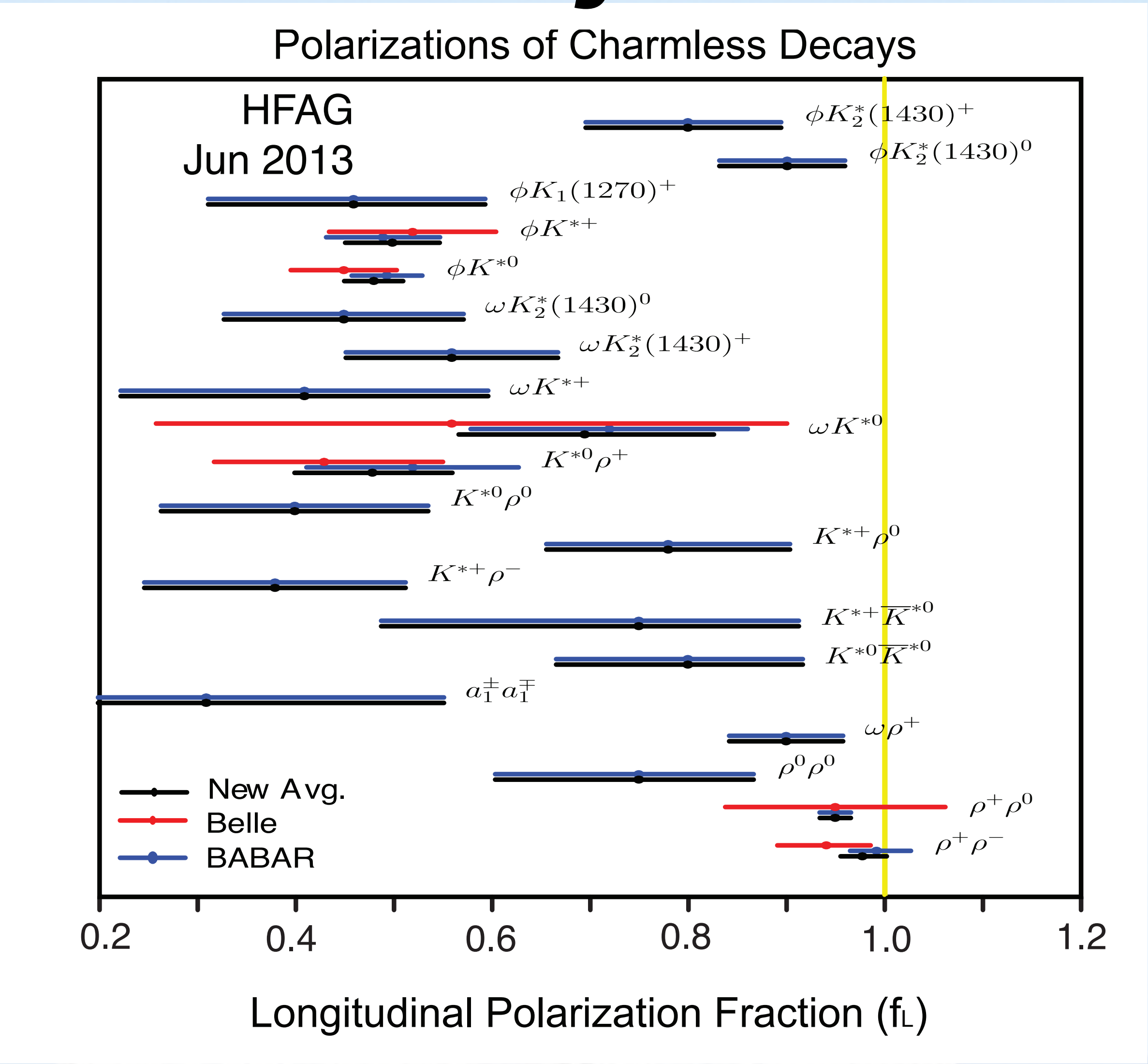
Branching fraction of charmless hadronic B decays

$B^+ \to \bar{K}^*(892)^0 K^*(892)^+$: $b \to d$ penguin

Longitudinal polarization of B decay to 2 vector meson state f_L is expected to be ~1 from QCD.

Recent measurement in $B^0 \to \phi K^*(892)^0$

$f_L = 0.499 \pm 0.030 \pm 0.018$ (Belle 2012)



$B^0 \to \eta' K^*(892)^0$: $b \to s$ penguin

Branching fraction predicted from pQCD: $(3.4 \pm 0.3) \times 10^{-6}$

Large direct CP violation is expected by interference of $b \to s$ penguin and $b \to u$ tree diagram.

$A(B^+ \to \eta K^+) = -0.38 \pm 0.11 \pm 0.01$ (Belle 2012),

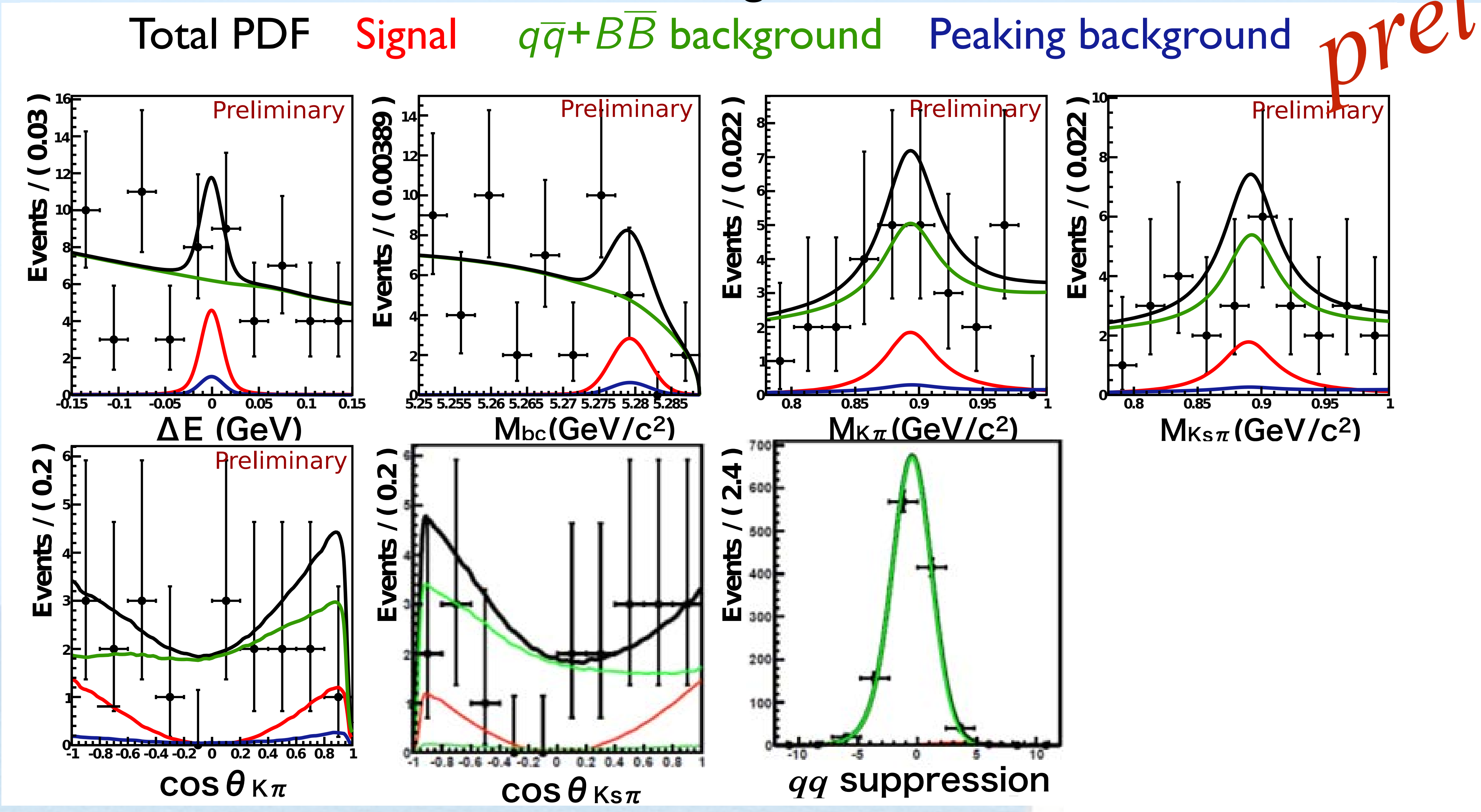
$-0.36 \pm 0.11 \pm 0.03$ (BABAR 2009)

Branching fraction of charmless hadronic B decays

$B^+ \to \bar{K}^*(892)^0 K^*(892)^+$

7-dimensional fit to extract the signal.

preliminary



$\mathcal{B}(B^+ \to \bar{K}^*(892)^0 K^*(892)^+) = (0.77^{+0.35}_{-0.30} \pm 0.12) \times 10^{-6}$ (2.7σ significance)

$f_L = 1.06 \pm 0.30 \pm 0.14$

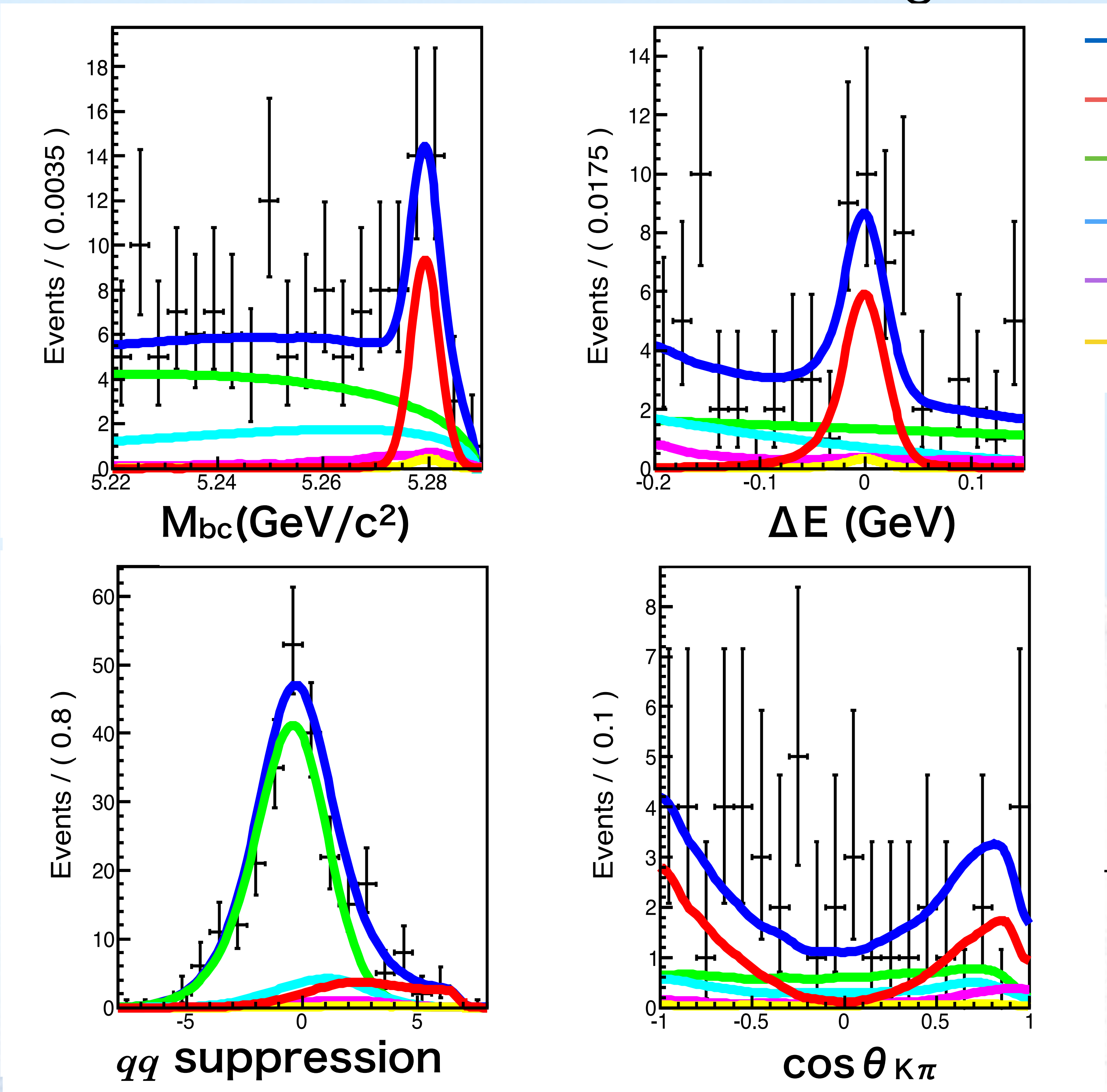
→ Consistent with QCD prediction.

Branching fraction of charmless hadronic B decays

preliminary

$B^0 \to \eta' K^*(892)^0$

4-dimensional fit to extract the signal.



$\mathcal{B}(B^0 \to \eta' K^*(892)^0)$

$= (2.6 \pm 0.7 \pm 0.2) \times 10^{-6}$

(5.0σ significance)

$\mathcal{A}(B^0 \to \eta' K^*(892)^0)$

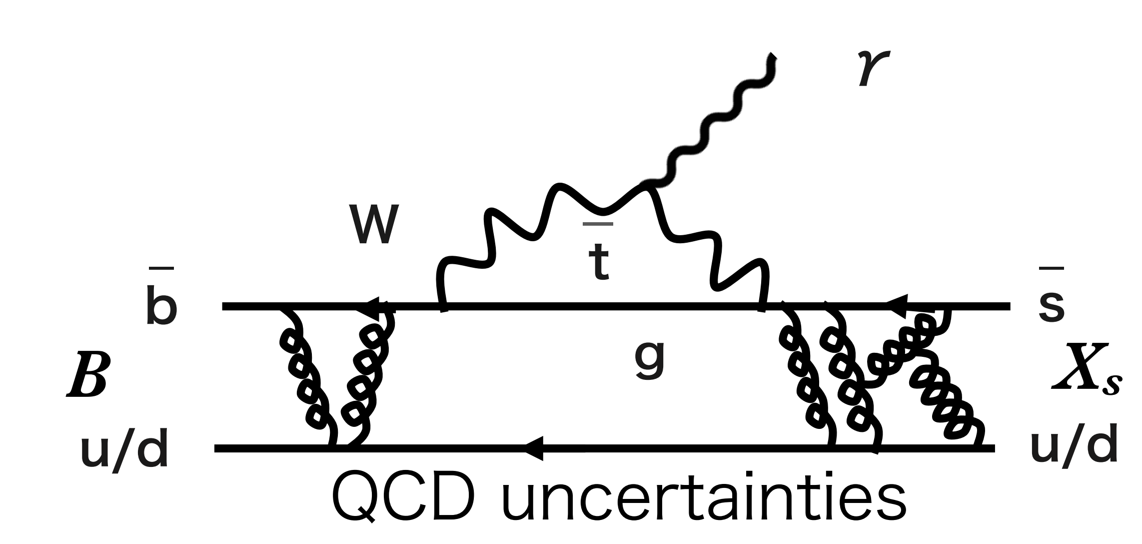
$= -0.22 \pm 0.29^{+0.02}_{-0.03}$

→ Consistent with prediction from pQCD and CPV in $B^+ \to \eta K^+$.

Branching fraction of $B \to X_s \gamma$

Theoretical estimation with NNLO :

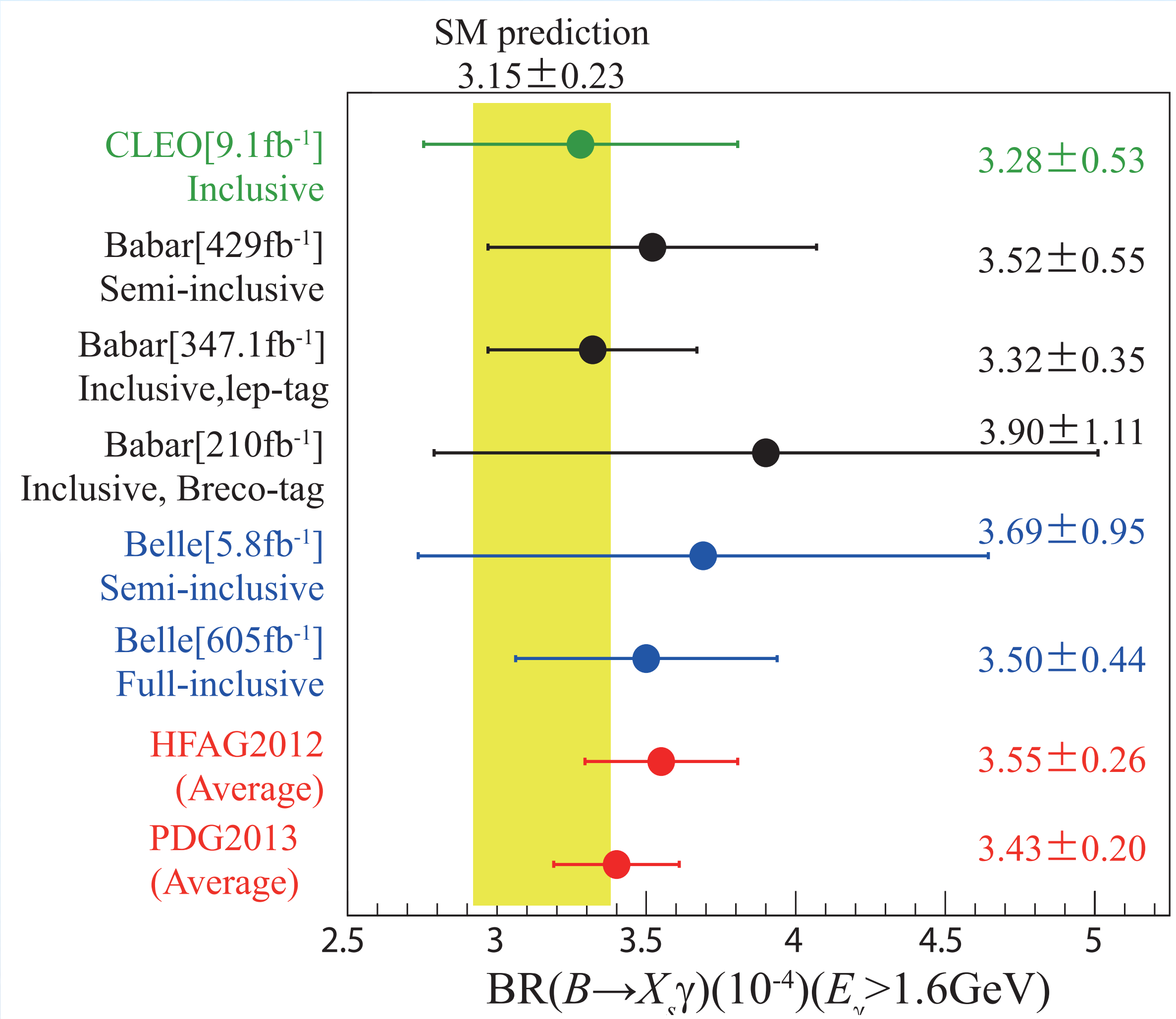
$Br(B \to X_s \gamma)$ = (3.15±0.23)×10^{-4} (E_γ^* > 1.6 GeV)



Several approaches to measure the branching fractions

- Full-inclusive
  Measure signal photon energy spectrum.
- Semi-inclusive
  Reconstruct as much decay modes with X_s as possible and combine the result.
- Exclusive
  Reconstruct specific decay modes ($B \to K^* \gamma$, ...).

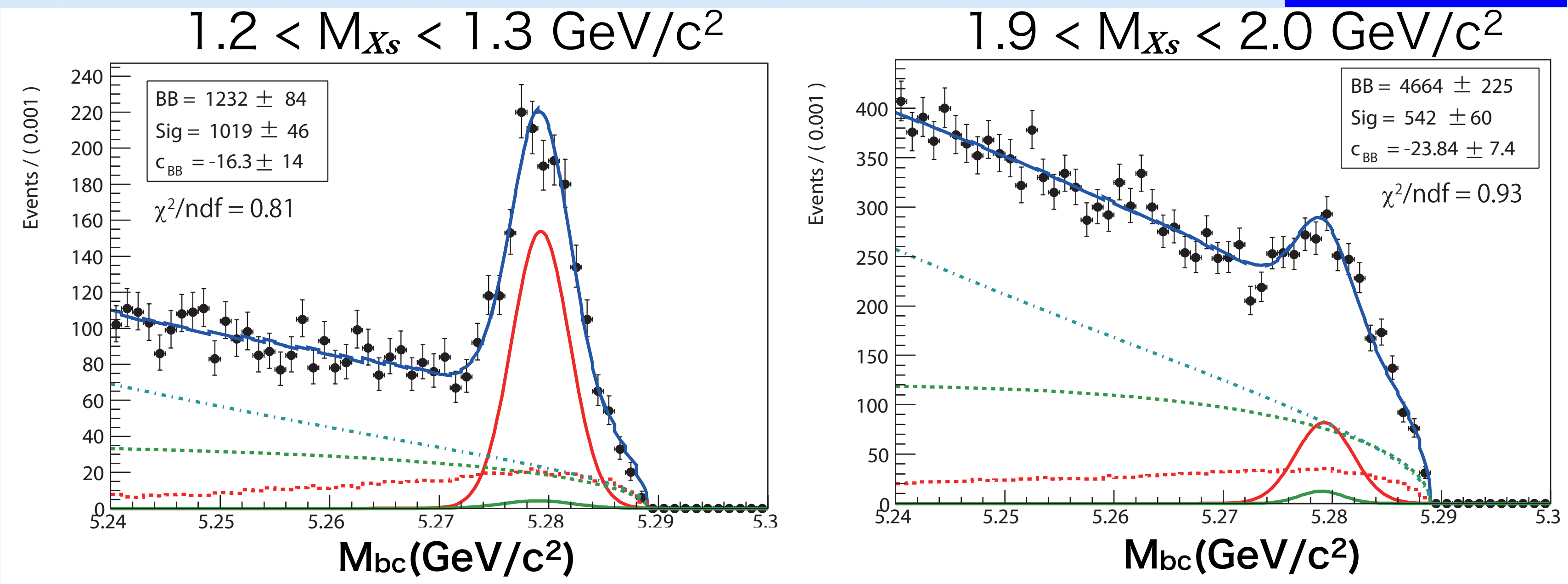
Theoretical uncertainty due to hadronization	Signal purity
small	low
↕	↕
large	high



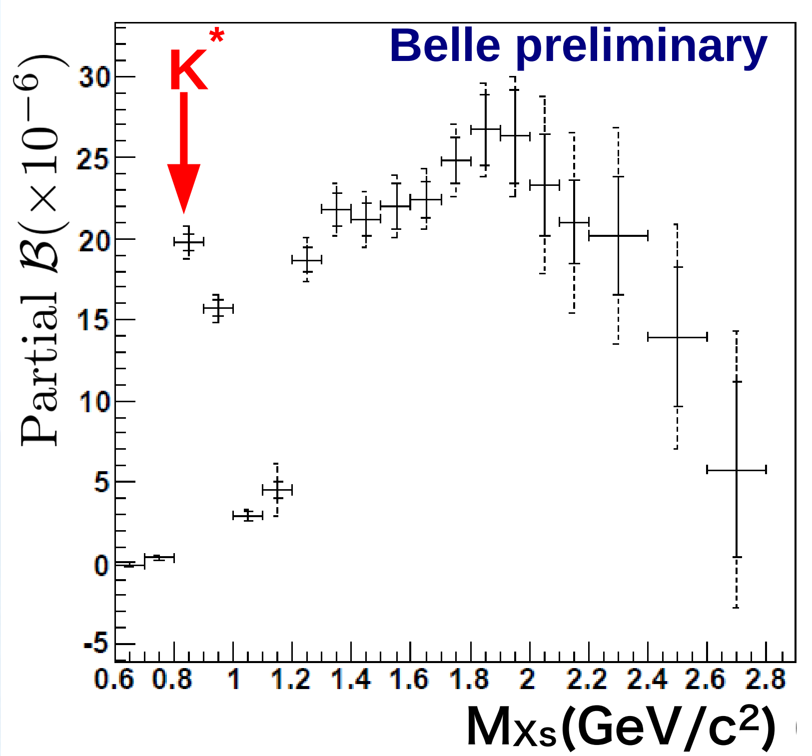
Branching fraction of semi-inclusive $B \to X_s \gamma$

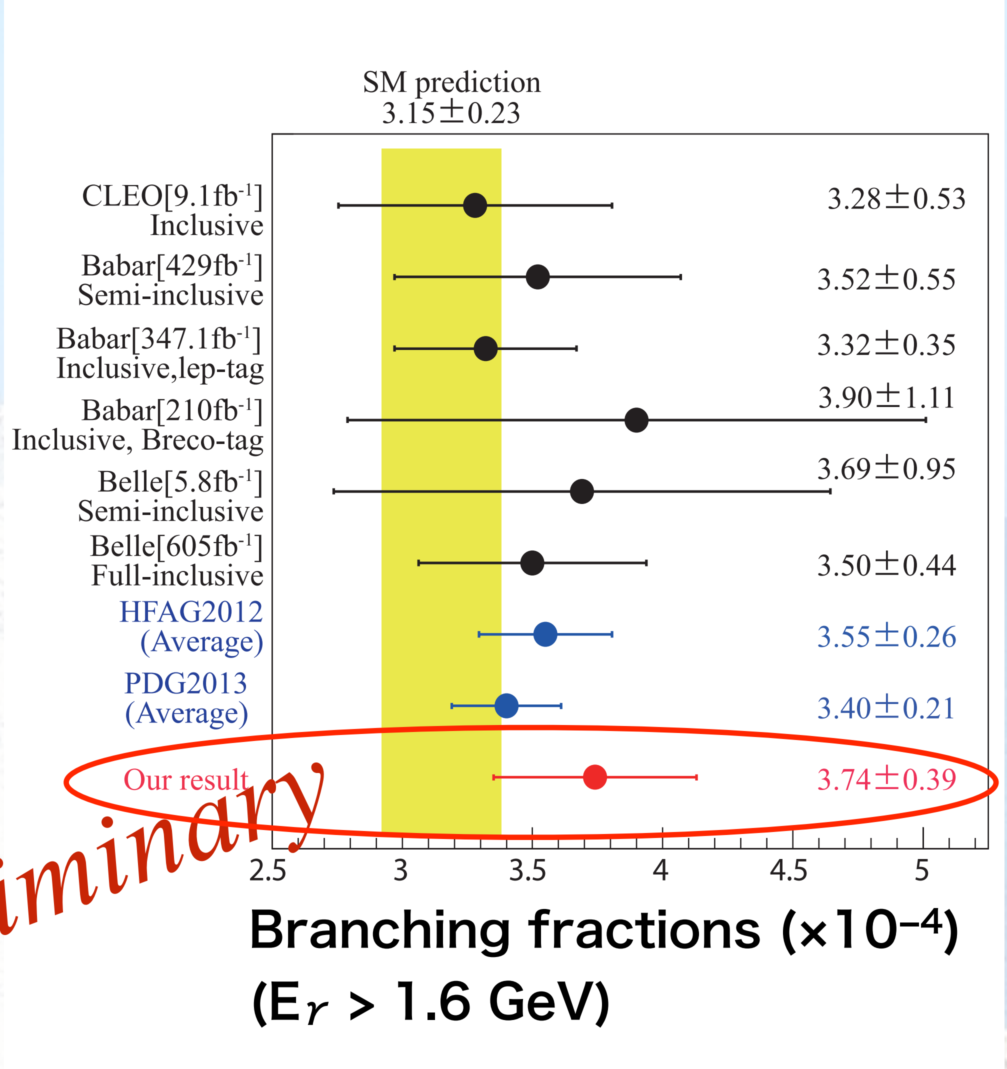
Semi-inclusive reconstruction of X_s using 38 states. ($0.6 < X_s < 2.8$ GeV/c^2) by combinations of K, π and η (~70% of total).

Signal yield is extracted in each X_s mass region.



Total branching fraction is extracted from spectrum of partial one as a function of X_s mass and photon energy.





$E^*_\gamma > 1.8$ GeV and $0.6 \le M_{X_s} \le 2.8$ GeV/c^2

$$\mathcal{B}(B \to X_s\gamma) = (3.51 \pm 0.17 \pm 0.33) \times 10^{-4}$$

preliminary

CP asymmetry in $B \to X_{(s+d)}\gamma$

Measure asymmetry of decay rate from B and $\bar{B}$. (Flavor is tagged by that of a high momentum lepton in accompany B decay)

Channel	A_{CP}(SM)
$B \to X_s\gamma$	[-0.6% , +2.8%]
$B \to X_d\gamma$	[-62% ,+14%]
$B \to X_{s+d}\gamma$	0

PRL 106, 141801 (2011)

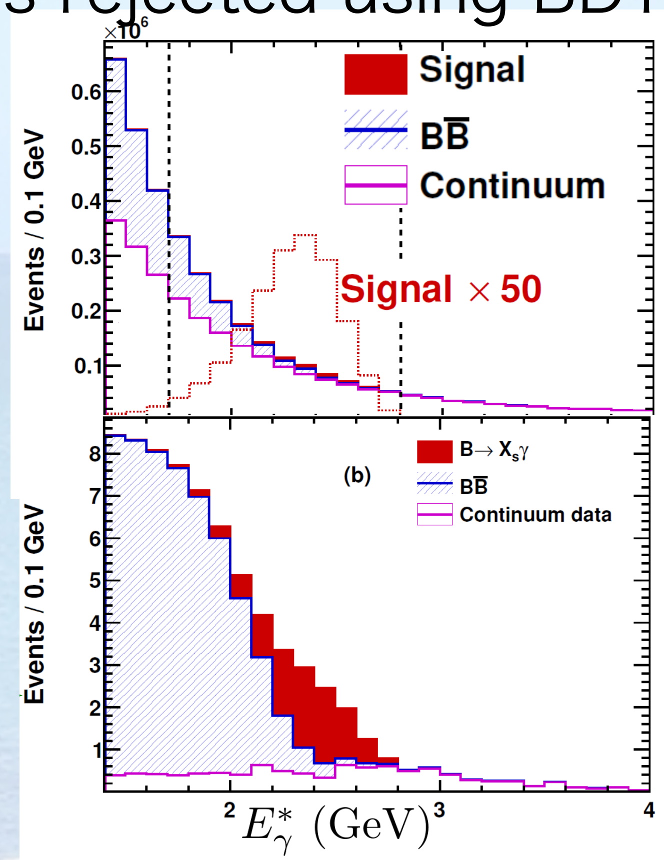
Owing to unitarity, an error from theory cancels when using combined final states of $X_{(s+d)}$.

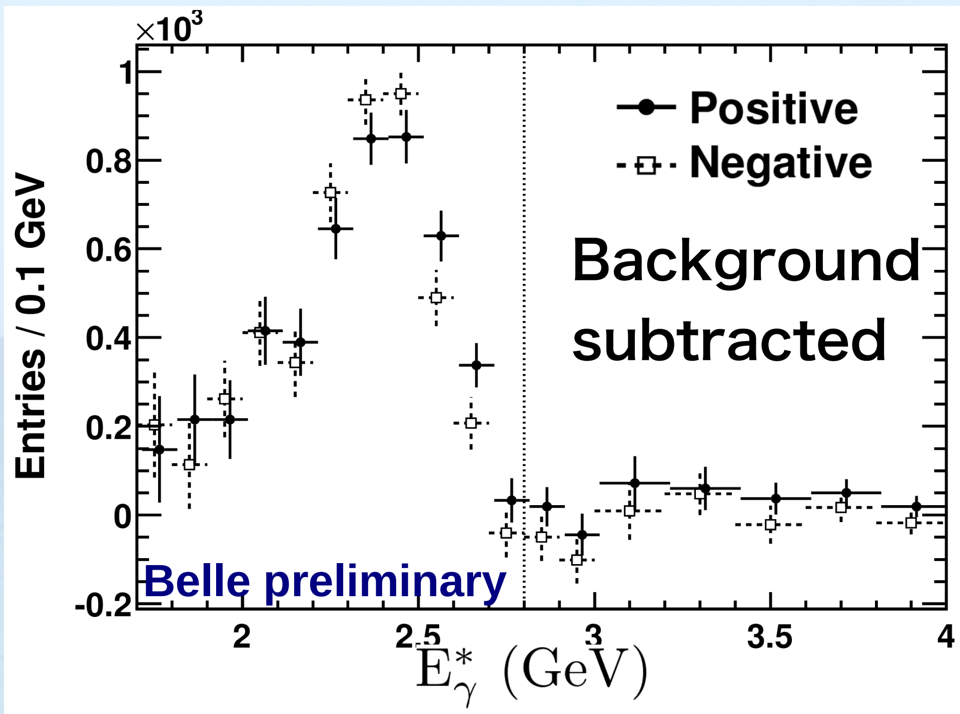
$$A_{CP\,q} = \frac{\Delta_q}{2\Gamma(B \to f)} \longrightarrow \Delta_q \propto \Im(V_{uq}V_{ub}^* V_{cq}V_{cb}^*)$$

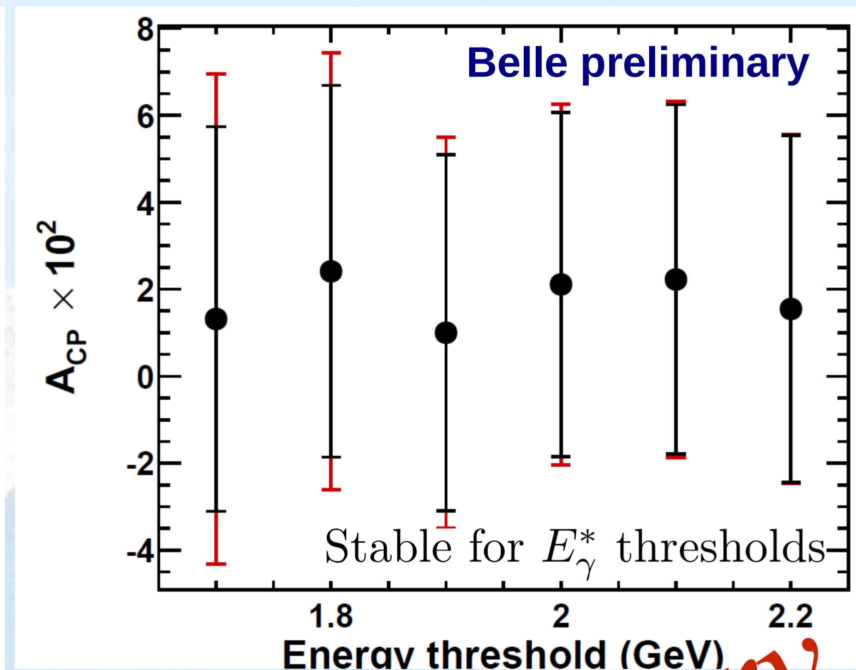
$$\Delta_s = -\Delta_d$$

Nucl.Phys.B704(2005) 56-74

Continuum background is rejected using BDT.







$A_{CP} = (2.2 \pm 4.0 \pm 0.8) \times 10^{-2}$

($E_\gamma^* > 2.1$ GeV)

preliminary

ϕ_2 measurement strategy

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

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

mixing induced CPV — direct CPV

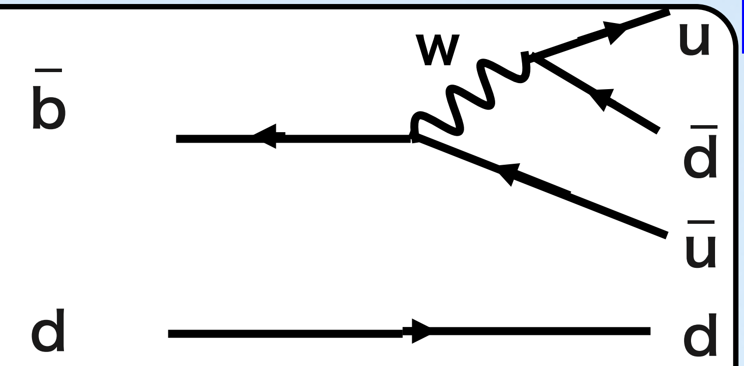
where $S = -\xi_f \sqrt{1-A^2} \sin 2\phi_2^{eff}$

ξ_f: *CP* eigenvalue

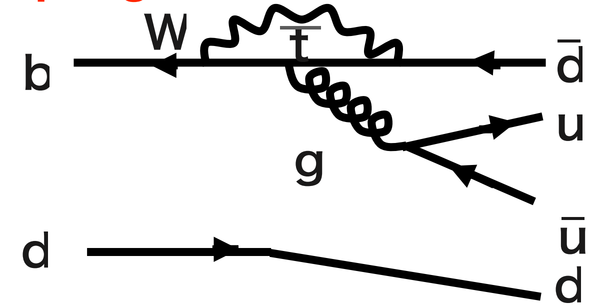
Δm: mass difference of eigenstates

Δt: decay time difference of eigenstates

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



penguin contamination



2 strategy 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

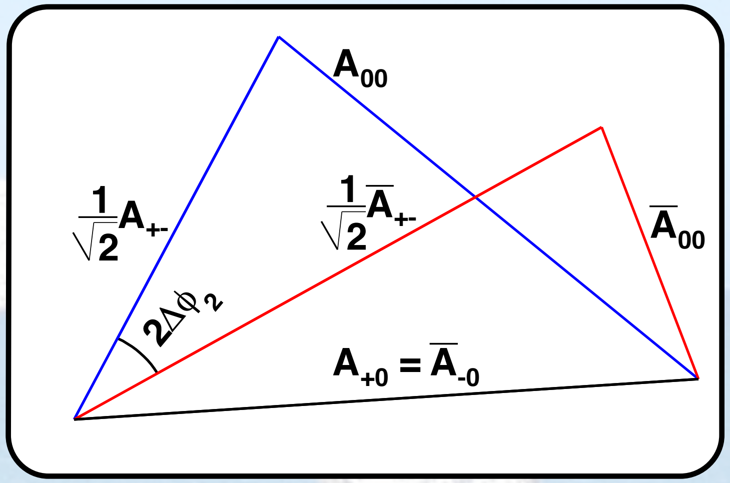
  (Gronau and London, PRL65 3381)

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

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

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

⇒ $\Delta\phi_2$ 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, the most powerful constraint for ϕ_2 at present.

Isospin relation analysis in $B\to\pi\pi$

$B^0\to\pi^+\pi^-$ PRD 88 092003 (2013)

$S= -0.64\pm0.08\pm0.03$

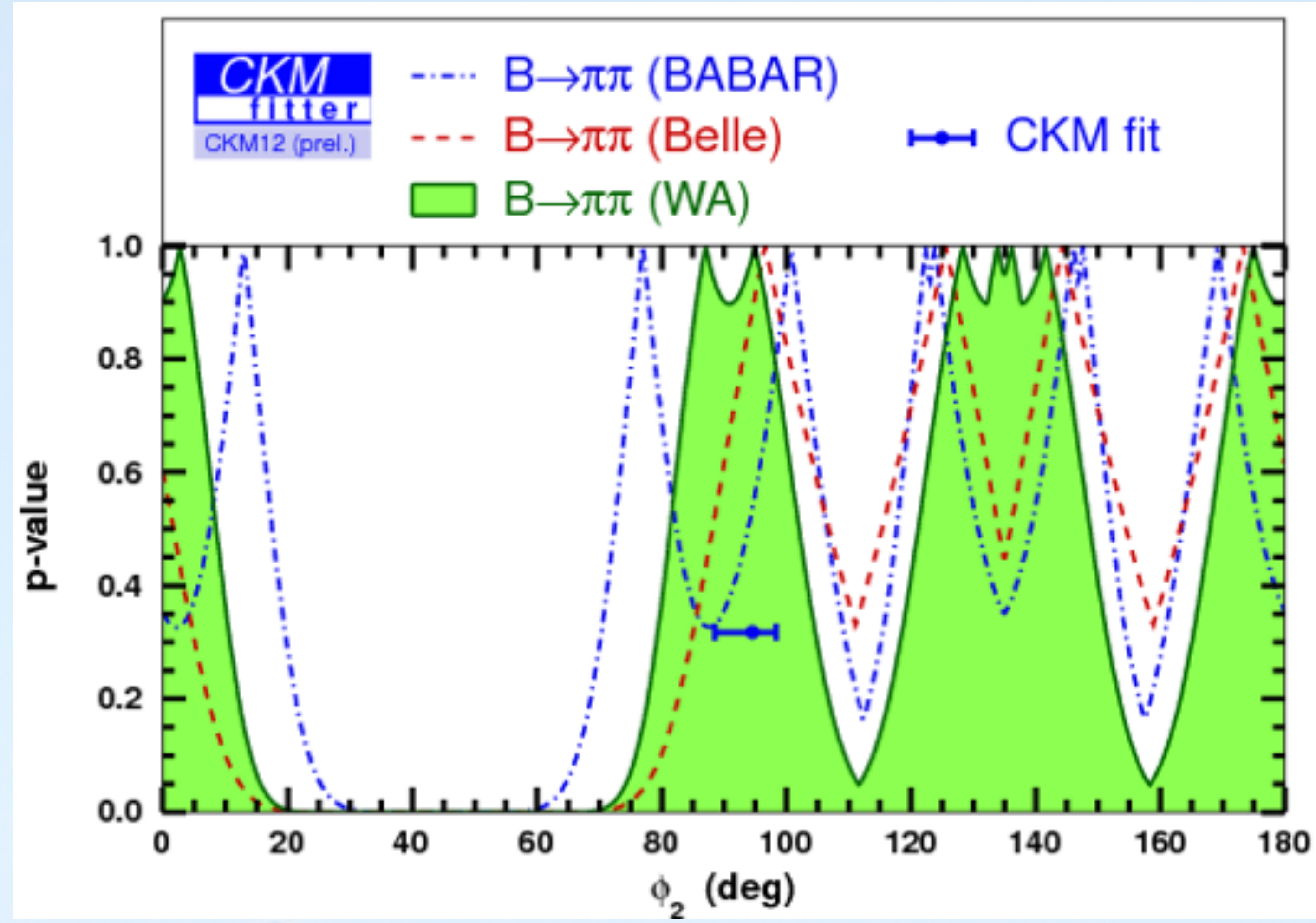
$A= 0.33\pm0.06\pm0.03$

$B^+\to\pi^+\pi^0$ PRD 87 031103(R) (2013)

$A= 0.025\pm0.043\pm0.007$

$B^0\to\pi^0\pi^0$ PRL 94 181803 (2005)

$A= 0.44^{+0.53}_{-0.52}\pm0.17$



$\phi_2 \in [85.0^\circ, 148.0^\circ]$ (Belle results only)

Recently $B^0\to\pi^0\pi^0$ is updated with full data.

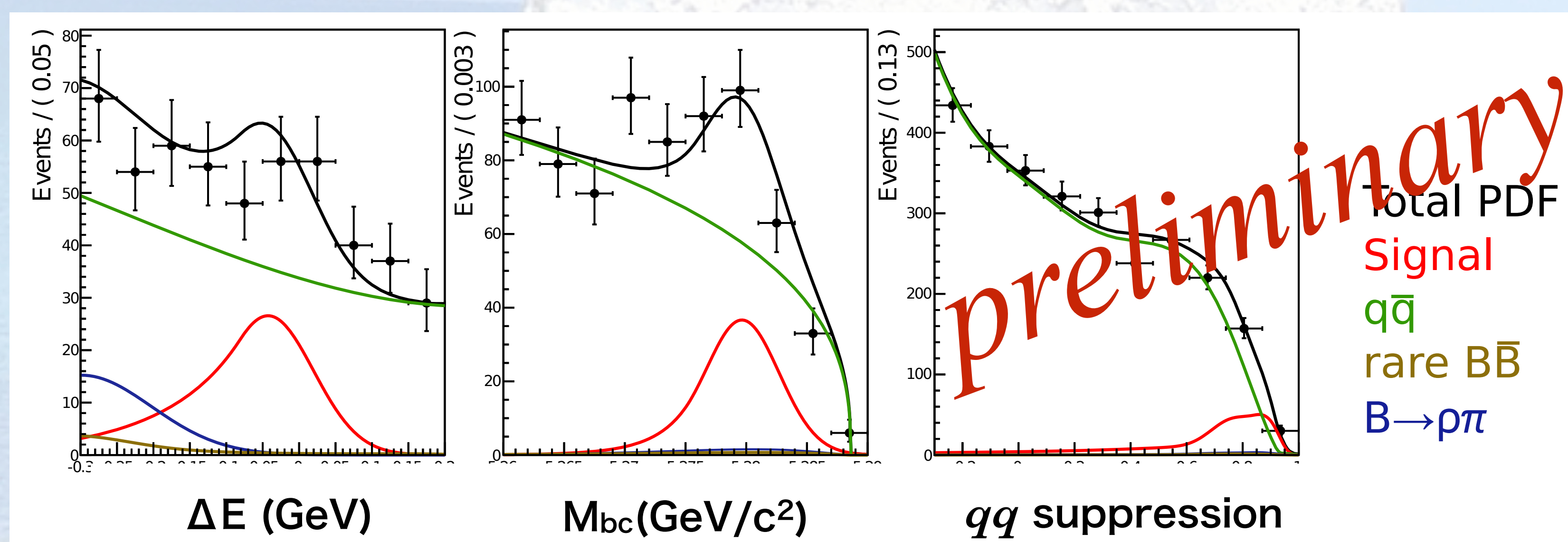
Signal yield = 224±29

⇒ Br($B^0\to\pi^0\pi^0$)

= $(0.90\pm0.12\pm0.10)\times10^{-6}$

(significance level = 6.7σ)

A= -0.054 ± 0.086



Measurements for CKM matrix elements

CKM matrix elements are measured from B decays.

In semi-leptonic decays $\boldsymbol{B \to D^{(*)} l\nu}$, $\boldsymbol{Vcb}$ appears in the differential decay width for a kinematic variable

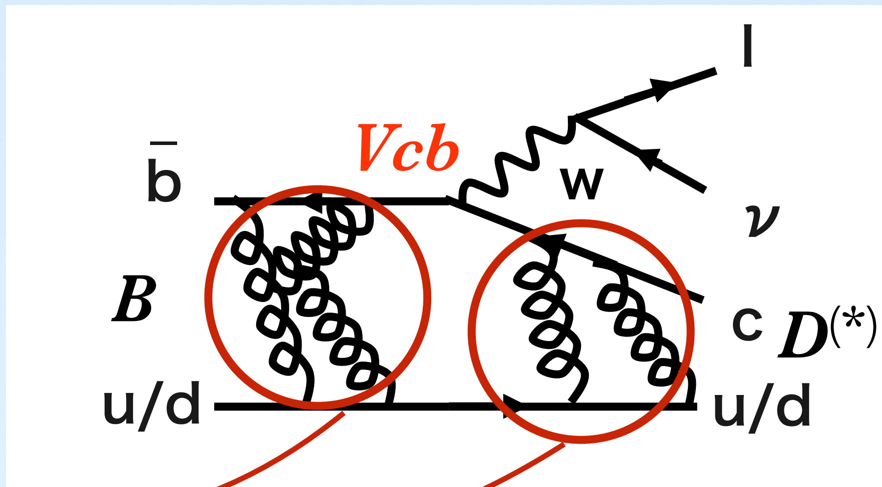
w : inner product of B and D velocities.

$$\frac{d\Gamma}{dw} = \frac{G_F^2 m_D^3}{48\pi^3}(m_B + m_D)^2(w^2-1)^{3/2}|\eta_{\mathrm{EW}}|^2|V_{\mathrm{cb}}|^2|\mathcal{G}(w)|^2$$

constants

electroweak correction

form factor



To cope with the form factor, several measurements are done.

→ Identify signal with high momentum lepton. (inclusive)

Reconstruct many final states and combine results. (semi-inclusive)

Reconstruct specific decay mode. (exclusive)

Signal can not be fully reconstructed due to neutrino in the final state.

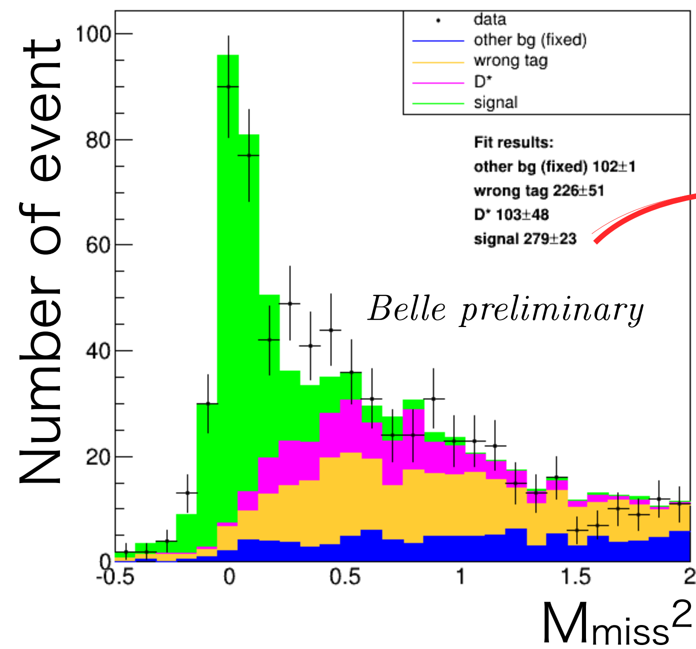
→ Reconstruct companion B and signal is reconstructed using remaining observed particles.

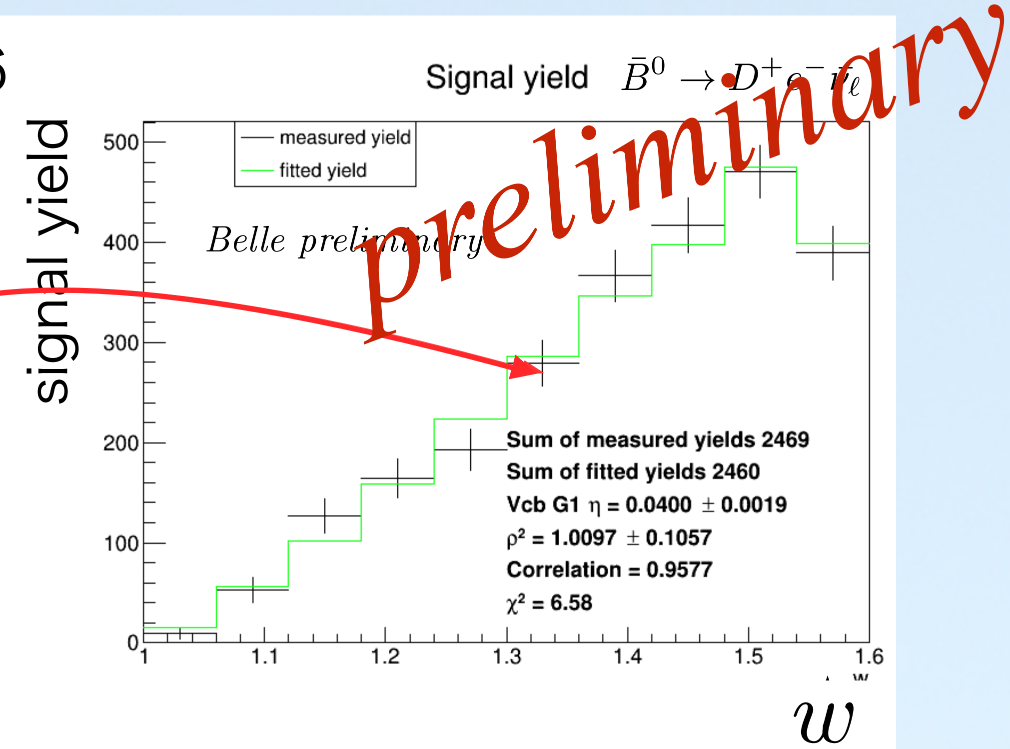
Semi-inclusive $B \to D l \nu$

Reconstruct $\bar{B}^0 \to D^+ l^- \nu$ with 7 D^+ decay modes and $B^- \to \bar{D}^0 l^- \nu$ with 8 $\bar{D}^0$ decay modes.

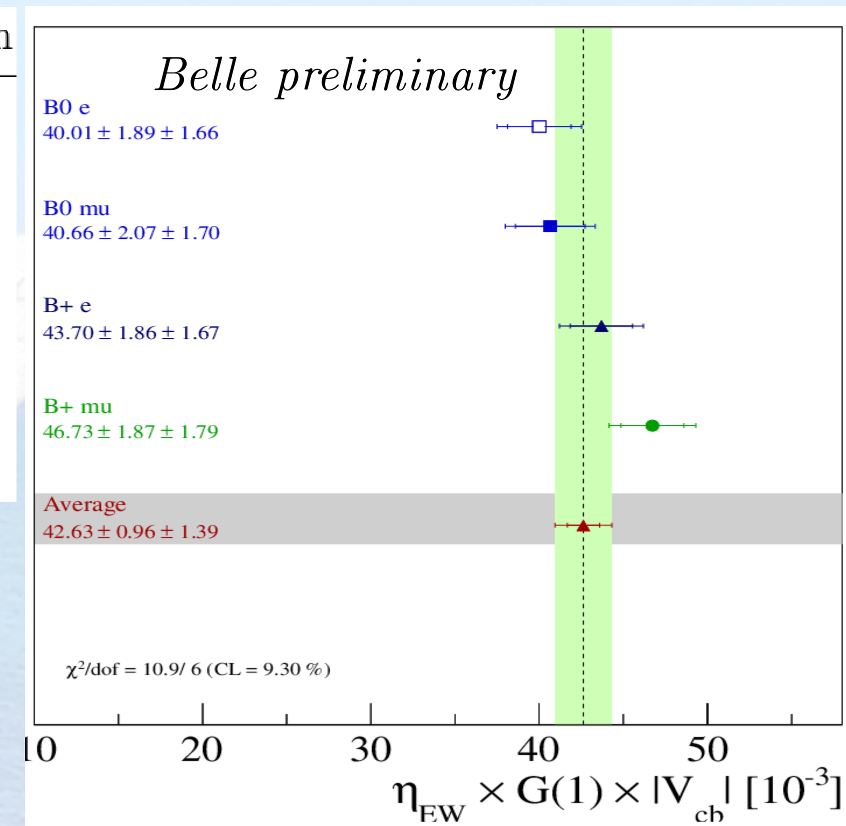
M_{miss} : Missing mass calculated by subtracting energies of all measured particles from a beam energy
→ Correspond to neutrino mass (~0) in the signal.

Data fit in $1.30 < w < 1.36$





Sample	$\eta_{EW}\mathcal{G}(1)\lvert V_{cb}\rvert$ $[10^{-3}]$	ρ^2	correlation
$\bar{B}^0 \to D^+ e^- \bar{\nu}_\ell$	$40.01 \pm 1.89(\text{stat}) \pm 1.66(\text{syst})$	$1.010 \pm 0.106(\text{stat}) \pm 0.029(\text{syst})$	0.692
$\bar{B}^0 \to D^+ \mu^- \bar{\nu}_\ell$	$40.66 \pm 2.07(\text{stat}) \pm 1.70(\text{syst})$	$1.075 \pm 0.115(\text{stat}) \pm 0.031(\text{syst})$	0.713
$B^- \to \bar{D}^0 e^- \bar{\nu}_\ell$	$43.70 \pm 1.86(\text{stat}) \pm 1.67(\text{syst})$	$0.909 \pm 0.099(\text{stat}) \pm 0.014(\text{syst})$	0.711
$B^- \to \bar{D}^0 \mu^- \bar{\nu}_\ell$	$46.73 \pm 1.87(\text{stat}) \pm 1.79(\text{syst})$	$1.075 \pm 0.091(\text{stat}) \pm 0.014(\text{syst})$	0.680
Average	$42.63 \pm 0.96(\text{stat}) \pm 1.39(\text{syst})$	$1.001 \pm 0.051(\text{stat}) \pm 0.018(\text{syst})$	0.494



Consistent with a HFAG average of exclusive measurements.

$$\eta_{EW}\mathcal{G}(1)|V_{cb}| = [42.64 \pm 0.72 \pm 1.35] \times 10^{-3}$$
$$\rho^2 = 1.186 \pm 0.036 \pm 0.041$$

Summary and Prospects

Using a 711 fb^{-1} data sample, we investigate a signal of the BSM in various flavor physics in the B decays:

CP violation, CKM matrix elements, branching fractions and polarization.

Most of the results are obtained with the best accuracy in the world. Evidence of the BSM has not seen.

Further approaches to the luminosity frontier will be expected through new analyses with a full data of the Belle and upcoming 50 ab^{-1} data from the Belle II.