Recent results on CPV and hadronic decays of B mesons at Belle

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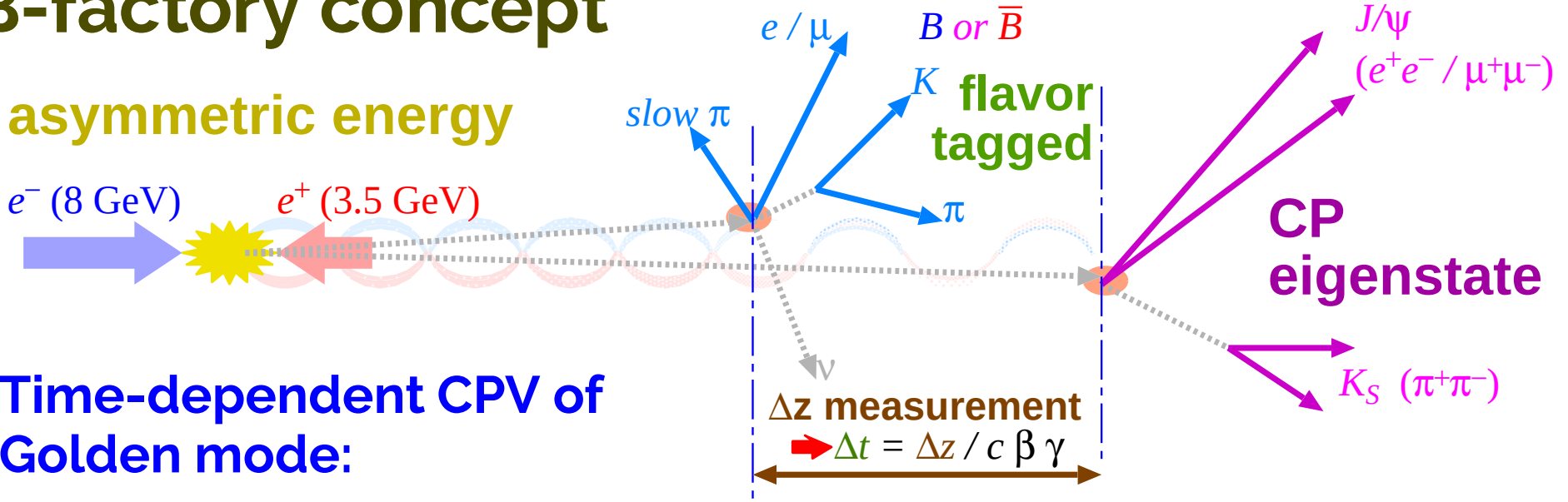
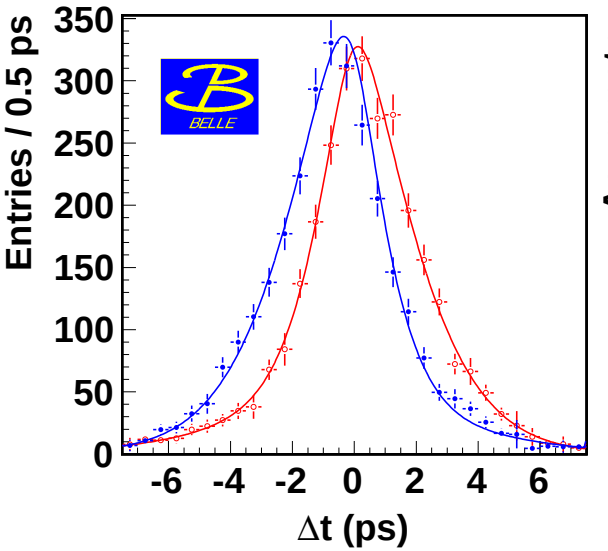
B-factory concept

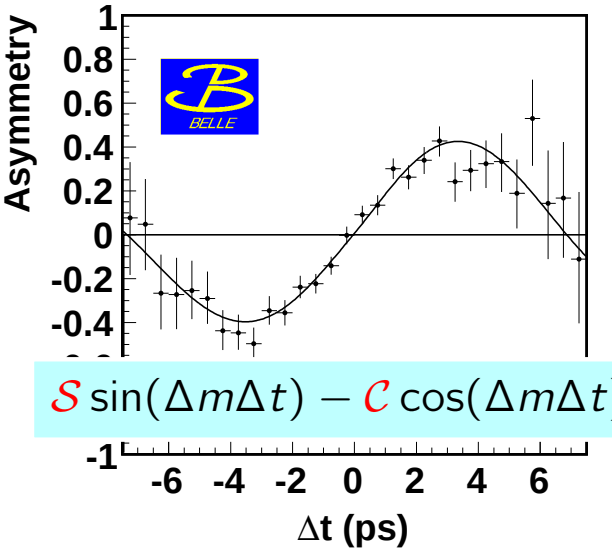
asymmetric energy



Time-dependent CPV of Golden mode:

- ✔ $B^0 \to J/\psi K_S$
- ✔ flavor tag
  $\epsilon_{\text{effective}} \sim 30\%$
- ✔ $\sigma(\Delta z) \sim 100\ \mu\text{m}$
  $\Leftrightarrow \langle \Delta z \rangle \sim 200 \mu\text{m}$





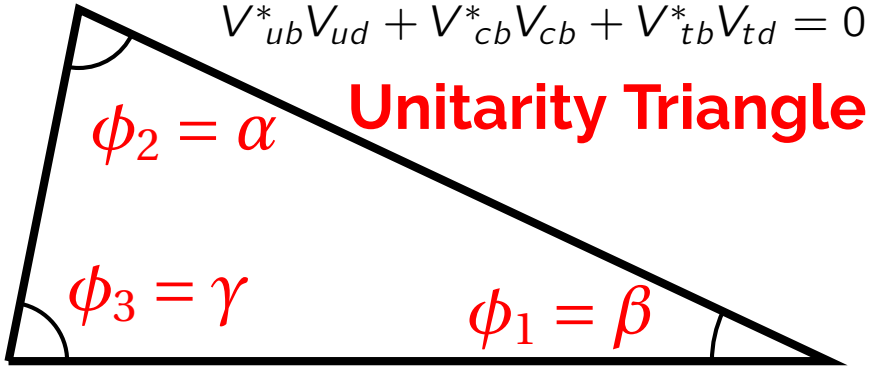
$\mathcal{S} \sin(\Delta m \Delta t) - \mathcal{C} \cos(\Delta m \Delta t)$

$\mathcal{S}_{c\bar{c}s} = \sin 2\phi_1 = +0.667 \pm 0.023 \pm 0.013$ PRL 108, 171802 (2012)

$\mathcal{S}_{c\bar{c}s} = \sin 2\beta = +0.687 \pm 0.028 \pm 0.012$ PRD 79, 072009 (2009)

($\mathcal{C}_{c\bar{c}s} \sim 0$, consistent with SM)

$$2\phi_1 = \phi\left(\overline{B}^0 \xrightarrow{V_{td}} \xrightarrow{V_{td}} B^0\right)$$



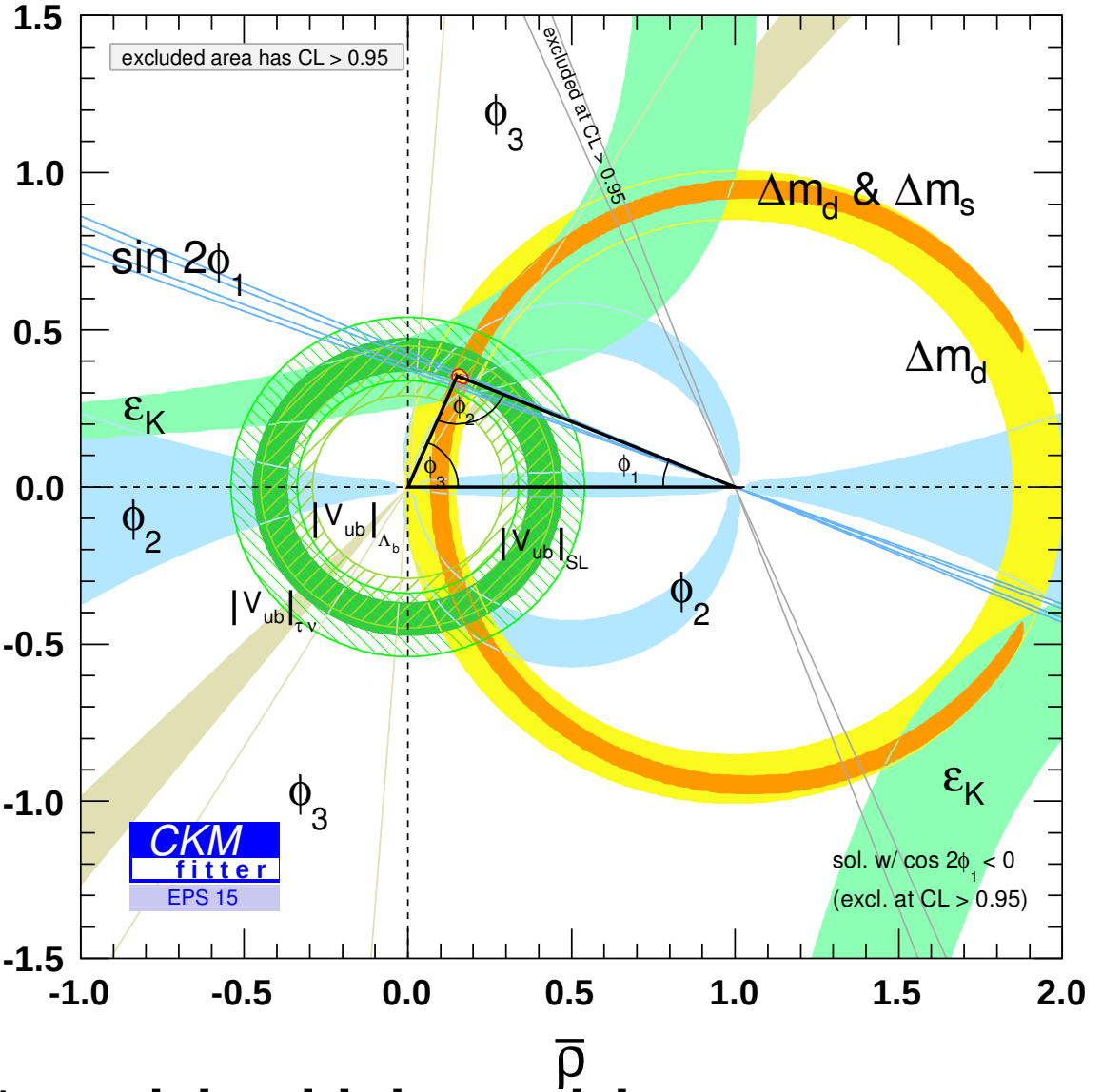
$$2\phi_2 = \phi\left(\text{box}\right) + \phi\left(\xrightarrow{V_{ub}} \Big/ \xrightarrow{V^*_{ub}}\right)$$

$$\phi_3 = \phi\left(\xrightarrow{V_{ub}}\right)$$

- **Golden Mode ($B \to J/\psi K_S$): phase in B^0-$\overline{B}^0$ mixing**
  - Very clean, only tiny SM penguin pollution so far neglected
  - NP phase in mixing **if any** cannot be distinguished
  - Small SM pollution should eventually be problem (O(1–2%))
- **Overconstraint of UT triangle**
  - All angles and sides can be measured
  - CPV parameters from other means: V_{ub}, ϕ_3 (tree, SM)

Success of SM:

- ✔ overconstrained unitarity triangle ⇐



However…

- ⚠ Still problem in V_{ub}
- ⚠ It's only ϕ_1 and $\Delta m_d/\Delta m_s$ giving high precision
- ⚠ Second ϕ_1 solution is not yet excluded with high CL
- 💡 Nothing precludes O(10%) beyond the SM physics(!)

Outline

- **3 topics today**
  - ✔ **sin2ϕ_1 in $B^0 \to D^{(*)}_{CP} h^0$ with Belle+BaBar data**

      [PRL 115, 121604 (2015)]

  - ✔ **sin2ϕ_1 & cos2ϕ_1 in $B^0 \to D^{(*)} h^0$, $D \to K_S \pi\pi$**

     **[preliminary, NEW!]**

  - ✔ **First observation of $B^0 \to \psi(2S)\pi^0$**

     [PRD 93, 031101(R) (2016)]

- **Overflow** (in backup slides)
  - ϕ_2 from $B^0 \to \rho^+\rho^-$  [PRD 93, 032010 (2016)]
  - Evidence for $B^0 \to \eta\pi^0$  [PRD 92, 011101(R) (2015)]

All results based on full dataset of 772M $B\overline{B}$ (+471M from BaBar)

($b \to c$ tree)		
$\Rightarrow b \to c\bar{c}s$	$B \to J/\psi K_S$	(ϕ_1 golden mode)
$\Rightarrow b \to c\bar{c}d$	$B \to J/\psi\pi^0, \psi(2S)\pi^0$	(ϕ_1)
$b \to c\bar{u}s$	$B \to \overline{D}K$	(ϕ_3, tree only)
$\Rightarrow b \to c\bar{u}d$	$B \to \overline{D}\pi$	(ϕ_1, ϕ_3)
($b \to u$ tree, suppressed)		
$b \to u\bar{c}s$	$B \to DK$	(ϕ_3)
$b \to u\bar{c}d$	$B \to D\pi$	(ϕ_1, ϕ_3, suppresed)
$b \to u\bar{u}s$	$B \to K\pi$ tree	
$\Rightarrow b \to u\bar{u}d$	$B \to \pi\pi$	(ϕ_2)
($b \to s$ penguin)		
$\Rightarrow b \to s\bar{c}c$	$B \to J/\psi K_S$	(ϕ_1 pollution)
$b \to s\bar{s}s$	$B \to \phi K$	
$b \to s\bar{u}u$	$B \to K\pi$ penguin	
$b \to s\bar{d}d$	$B \to K\pi$ penguin	
($b \to d$ penguin, suppressed)		
$\Rightarrow b \to d\bar{c}c$	$B \to J/\psi\pi^0, \psi(2S)\pi^0$	(ϕ_1 pollution)
$b \to d\bar{s}s$	$B \to KK$ penguin	
$\Rightarrow b \to d\bar{u}u$	$B \to \pi\pi$ penguin	(ϕ_2 isospin analysis)
$b \to d\bar{d}d$	$B \to \pi\pi$ penguin	(ϕ_2 isospin analysis)

Lots of info to disentangle
many unknowns

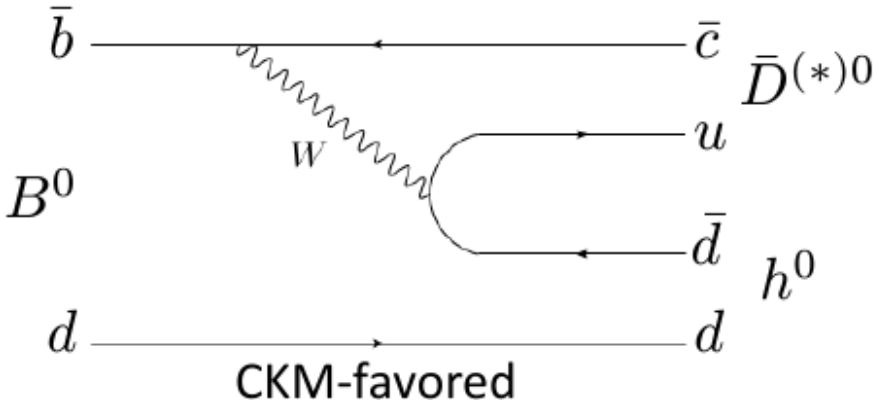
$\phi_1 - B^0 \to D_{cp}^{(*)} h^0$

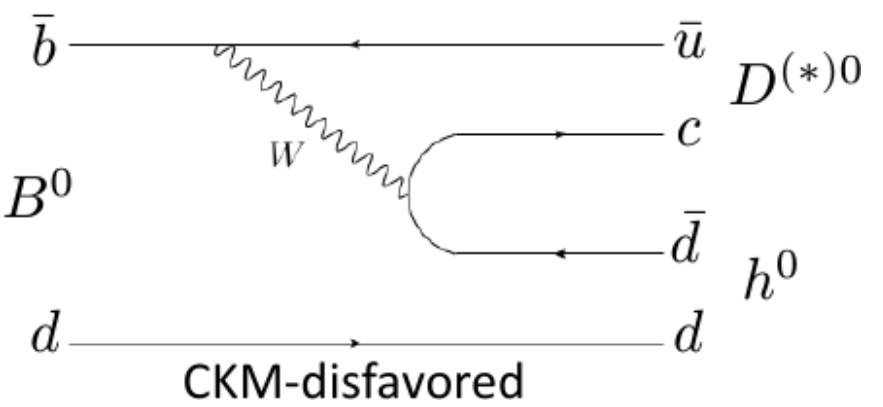
BaBar and Belle Collaborations, Phys. Rev. Lett. 115, 121604 (2015)
(see also talk by Markus Röhrken at EPS-HEP 2015 conference)

$B \to D^{(*)}_{cp} h^0$

- **Decay modes**
  - D_{cp} — $D^0/\overline{D}^0$ decaying into K^+K^- (CP+); $K_S\pi^0$, $K_S\omega$ (CP−)
  - $D^*_{cp} \to D_{cp}\pi^0$ (still CP eigenstate)
  - h^0 — neutral meson: π^0, η, ω (CP−)
  - $D^{(*)}_{cp} h^0$ final states are also CP eigenstates (CP+ or −)
- **Time-dependent CPV analysis gives $\mathcal{S} = -(-1)^{CP} \sin 2\phi_1$**

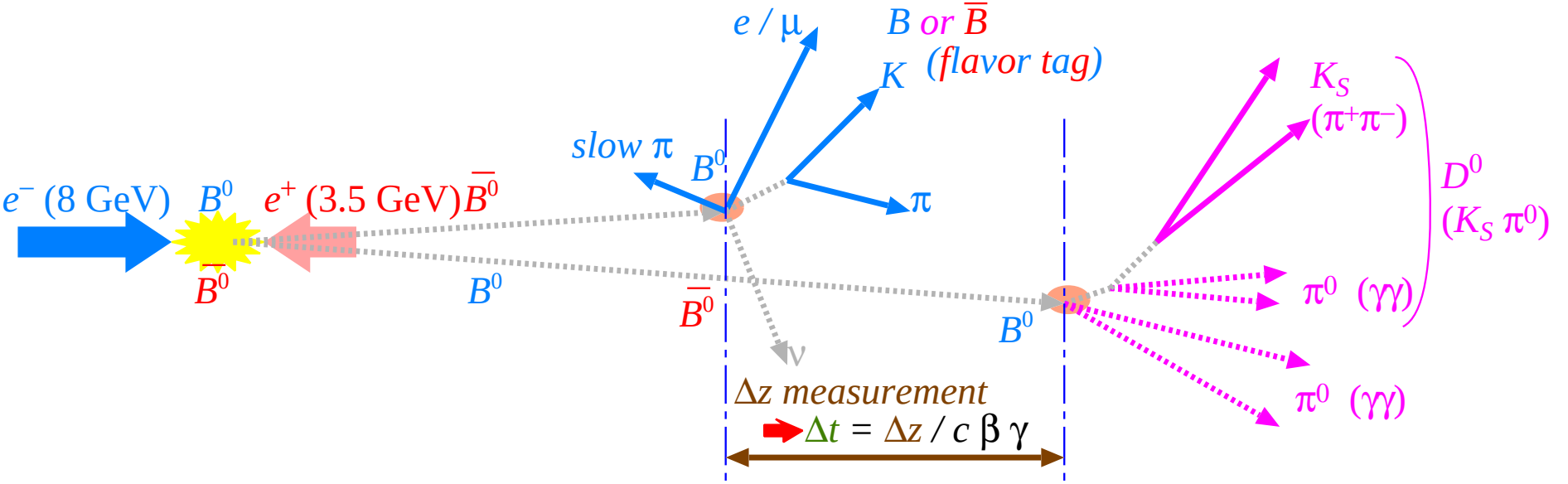
But not only "yet-another" CPV measurement for ϕ_1
tree diagram only and hence **penguin pollution free**





(CPV in D decay is much smaller and neglected)

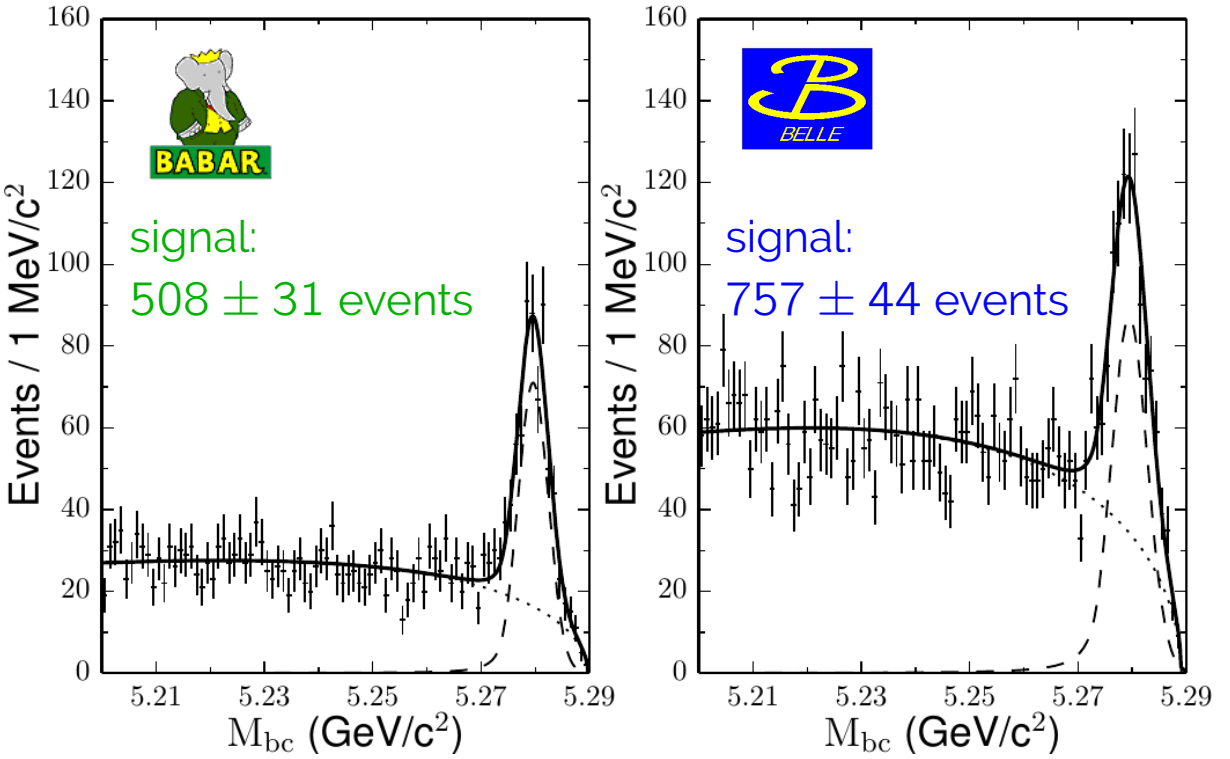
Time-dependent Analysis for $B \to D^{(*)}_{cp} h^0$



- **Average $\Delta z \sim 200\mu$m for Belle, $\sim 250\mu$m for BaBar**
- **Standard time-dependent CPV measurement, but**
  - Vertex extrapolated from $K_S \to \pi^+\pi^-$ for $h^0 \to \gamma\gamma$
  - Trajectory from **displaced D^0 vertex** with IP constraint
  - Resolution $\sim 100\mu$m, depending on final state
- **Standard flavor tagging algorithm**

First Belle-BaBar Joint Analysis

- **Motivation** — small branching fraction ($O(10^{-6})$)
- **Difficulty** — event vertex resolution and tagging efficiency
- **Analysis** — who joined BaBar from Belle and working on both
  - Continuum background — event shape variables (NN)
  - Beam-energy constrained mass — $M_{\rm bc} = \sqrt{(E^*_{\rm beam})^2 - (p^*_B)^2}$



Principle of the Combined Analysis

- Combined by maximizing the **joint log-likelihood function**

$$\ln \mathcal{L} = \sum_i \ln \mathcal{P}_i^{\text{BaBar}} + \sum_j \ln \mathcal{P}_j^{\text{Belle}}$$

- PDFs with **experiment specific resolution functions**

$$\mathcal{P}^{\text{exp}} = \sum_k f_k \int [P_k(\Delta t') R_k(\Delta t - \Delta t')] d\Delta t'$$

[k: signal or background index, P_k: signal or background model, R_k: resolution function]

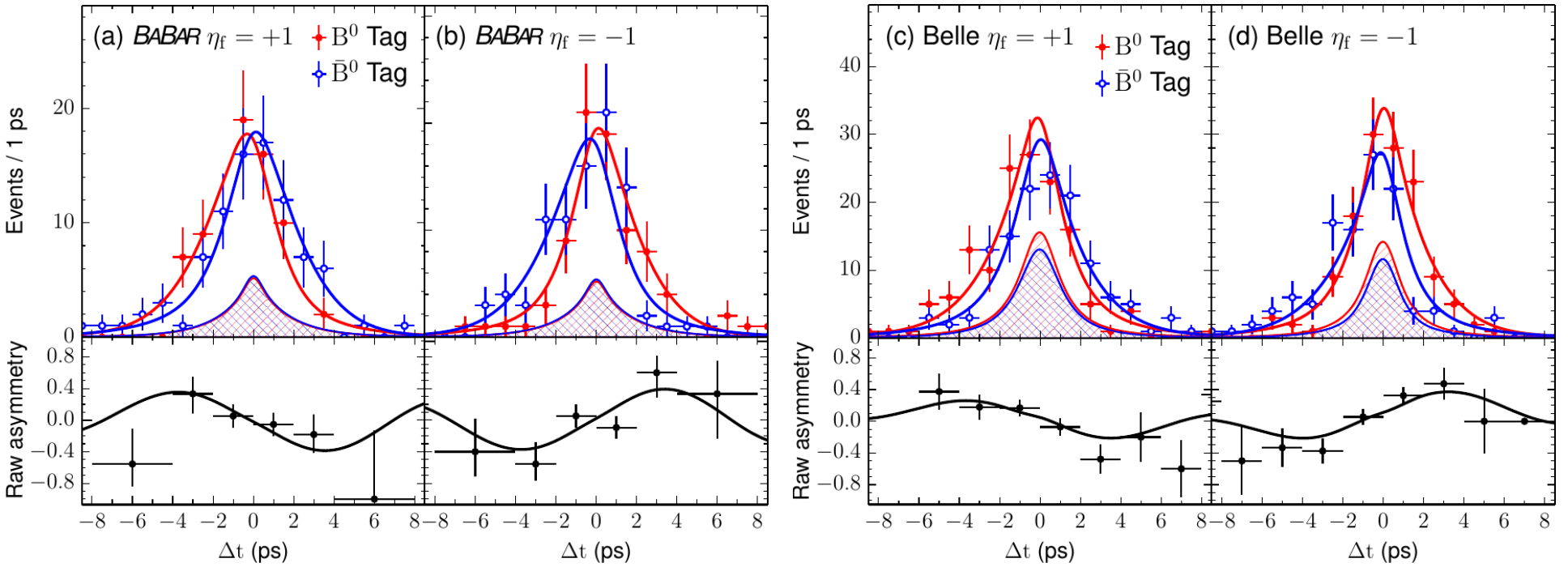
- Event/experiment dependent flavor tagging quality — q
- **Common signal model**

$$P_{\text{sig}}(\Delta t, q) = \frac{1}{4\tau_{B^0}} e^{\frac{-|\Delta t|}{\tau_{B^0}}} [1 + q(\mathcal{S} \sin(\Delta m \Delta t) - \mathcal{C} \cos(\Delta m \Delta t))]$$

$-(-1)^{CP}\mathcal{S} = \sin 2\phi_1$ and $\mathcal{C} = 0$ in the SM

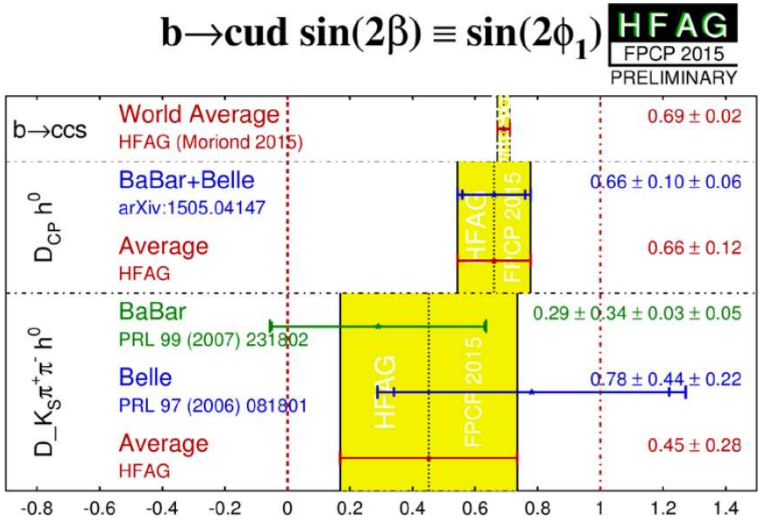
- Background determined from M_{bc} sidebands

$B \to D^{(*)}_{cp} h^0$ Results



$$-(-1)^{CP}\mathcal{S} = +0.66 \pm 0.10 \pm 0.06$$
$$\mathcal{C} = -0.02 \pm 0.07 \pm 0.03$$
(5.4σ non-zero CPV)

First observation in agreement with CPV parameters from $b \to c\bar{c}s$



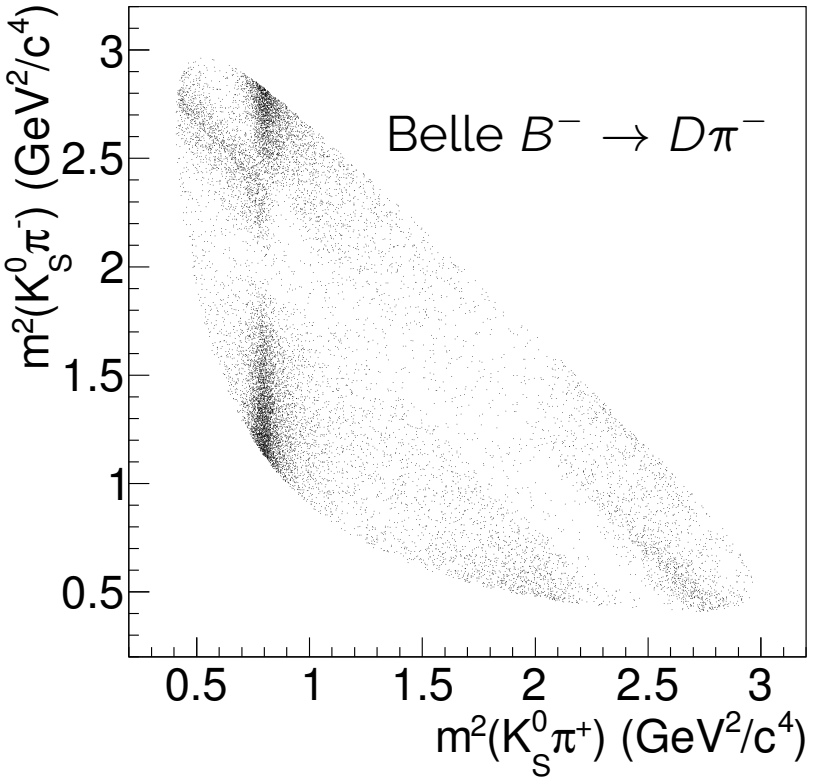
Full Belle II data will allow to address O(10%) NP effect

$B^0 \to D^{(*)0} h^0,\ D \to K_S \pi^+ \pi^-$

Belle Collaborations, preliminary **(first shown today)**

$B^0 \to D^{(*)0} h^0, D \to K_S \pi^+ \pi^-$

- Similar to $B \to D^{(*)}_{cp} h^0$, **but $D \to K_S \pi^+ \pi^-$ is not a CP eigenstate**
  - **Mix** of e.g. $K^{*-}\pi^+$ **(favored)**, $K_S \rho^0$ **(CP)**, $K^{*+}\pi^-$ **(DCS)**
  - **Many** K **resonances:** $K^*(892)$, $K_0^*(1430)$, $K_1(1270)$, $K_2^*(1430)$, ...
  - Dalitz plot provides rich and **measureable** strong phase structure
- **Dalitz model**
  - Sum of known resonances, relative amplitude and phase from a fit to $D^{*+} \to D^0 \pi^+$ **(unbinned, model-dependent)**
  - $|\text{amplitude}|^2$ from $B^- \to D^0 \pi^-$, phase from coherent $\psi(3770) \to D^0 \overline{D}^0$ into $(D \to K_S \pi^+ \pi^-)^2$ and CP-tagged modes by CLEO **(binned, model-independent)**



Time-dependent Dalitz analysis

$$P_{\rm sig}(m_+^2, m_-^2, \Delta t) \propto e^{-\frac{|\Delta t|}{\tau_B}} \left[1 + q_B(\mathcal{A}(m_+^2, m_-^2)\cos(\Delta m_B \Delta t) + \mathcal{S}(m_+^2, m_-^2)\sin(\Delta m_B \Delta t))\right]$$

$$\mathcal{S}(m_+^2, m_-^2) \propto \mathrm{Im}[f(m_-^2, m_+^2) f^*(m_+^2, m_-^2) e^{2\phi_1}]$$

- **Sensitive directly to ϕ_1, or both $\sin 2\phi_1$ and $\cos 2\phi_1$**
  [Bondar,Gershon,Krokovny:PLB624,1(2005)]
- **Combination of widely used techniques**
  - D Dalitz plot analysis developed for ϕ_3
  - Time-dependent Dalitz to measure $\phi_1^{\rm eff}$ in $b \to s$ penguin ($B \to K_S \pi\pi$)
- **Previous model-dependent analysis**
  - Belle (386M $B\overline{B}$) [PRL 97, 081801 (2006)]
  - BaBar (383M $B\overline{B}$) [PRL 99, 231802 (2007)]
  - Exclusion of second ϕ_1 solution only by 98% and 86% CL
- **New analysis with full Belle data** (772M $B\overline{B}$)

Model-independent binned analysis

$$N_i(\Delta t, \phi_1) = h_2 e^{-\frac{|\Delta t|}{\tau_B}} \left[1 + Q_B \frac{K_i - K_{-i}}{K_i + K_{-i}} \cos(\Delta m_B \Delta t) \right.$$
$$\left. + 2 Q_B \xi_{h^0} (-1)^l \frac{\sqrt{K_i K_{-i}}}{K_i + K_{-i}} \sin(\Delta m_B \Delta t)(S_i \cos 2\phi_1 + C_i \sin 2\phi_1) \right]$$

Integrated $|\text{amplitude}|^2$

$$K_i = \int |\mathcal{A}_D(m_-^2, m_+^2)|^2 d\mathcal{D}$$

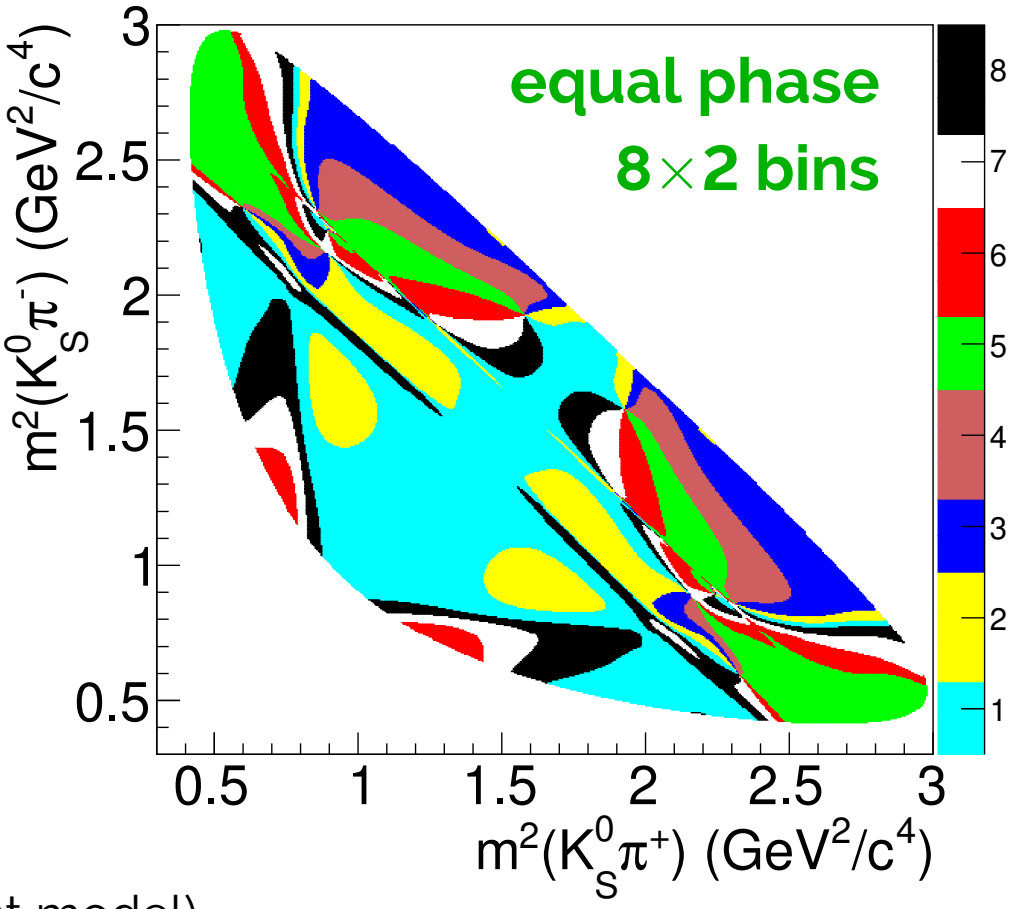
from $B^- \to D^0 \pi^-$ (flavor specific)

Integrated strong phase

$$S_i = \frac{\int |\mathcal{A}_D||\overline{\mathcal{A}}_D| \sin \Delta\delta_D \, d\mathcal{D}}{\sqrt{K_i K_{-i}}},$$

$$C_i = \frac{\int |\mathcal{A}_D||\overline{\mathcal{A}}_D| \cos \Delta\delta_D \, d\mathcal{D}}{\sqrt{K_i K_{-i}}}$$

from coherent $D^0\overline{D}^0$ by CLEO



Measured in 8×2 bins

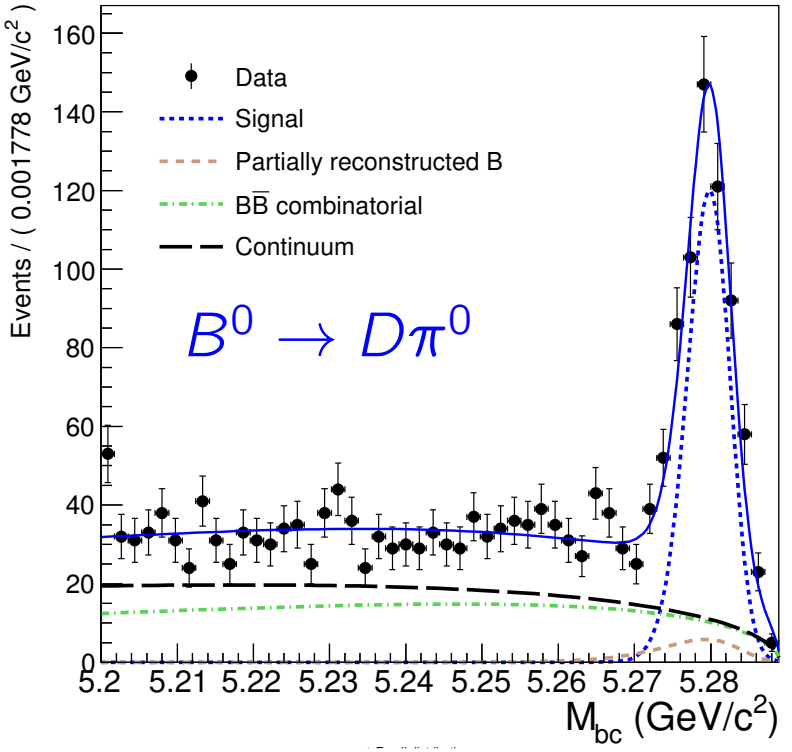
(binning based on a realisting resonant model)

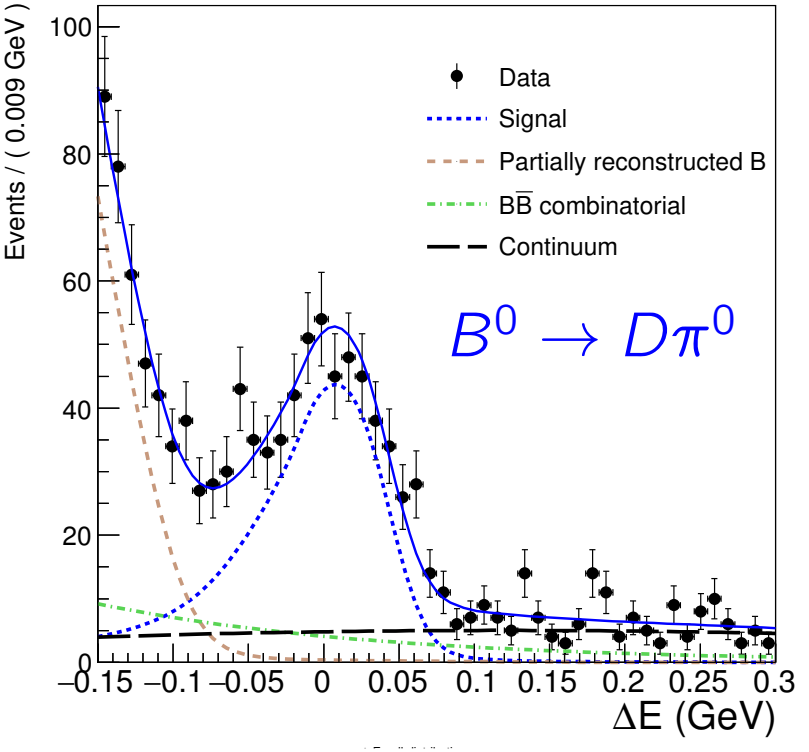
Signal

- Standard M_{bc}-ΔE fit
- Total: 962 ± 41 signal events
- Signal fraction used in the Δt Dalitz fit

mode	N_{sig}	$f_{sig}(\%)$
$D^0\pi^0$	464 ± 26	72 ± 4
$D^0\eta_{\gamma\gamma}$	99 ± 14	51 ± 7
$D^0\eta_{\pi^+\pi^-\pi^0}$	51 ± 9	66 ± 11
$D^0\omega$	182 ± 18	58 ± 6
$D^0\eta'$	28 ± 6	70 ± 16
$D^{*0}\pi^0$	103 ± 17	44 ± 7
$D^{*0}\eta$	36 ± 8	64 ± 13

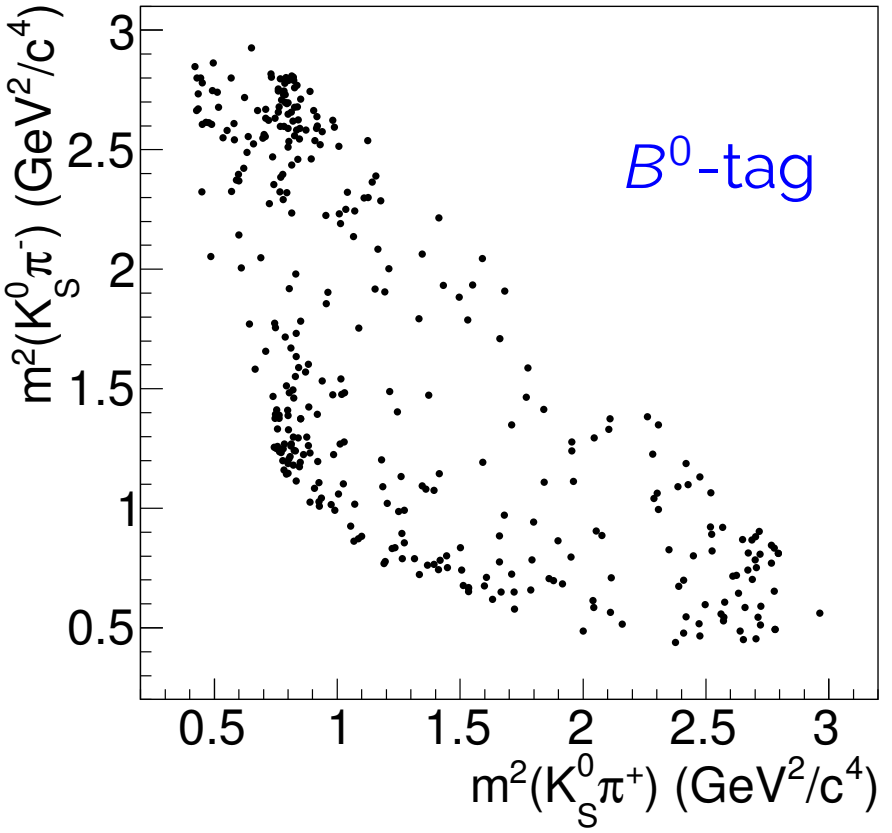
preliminary

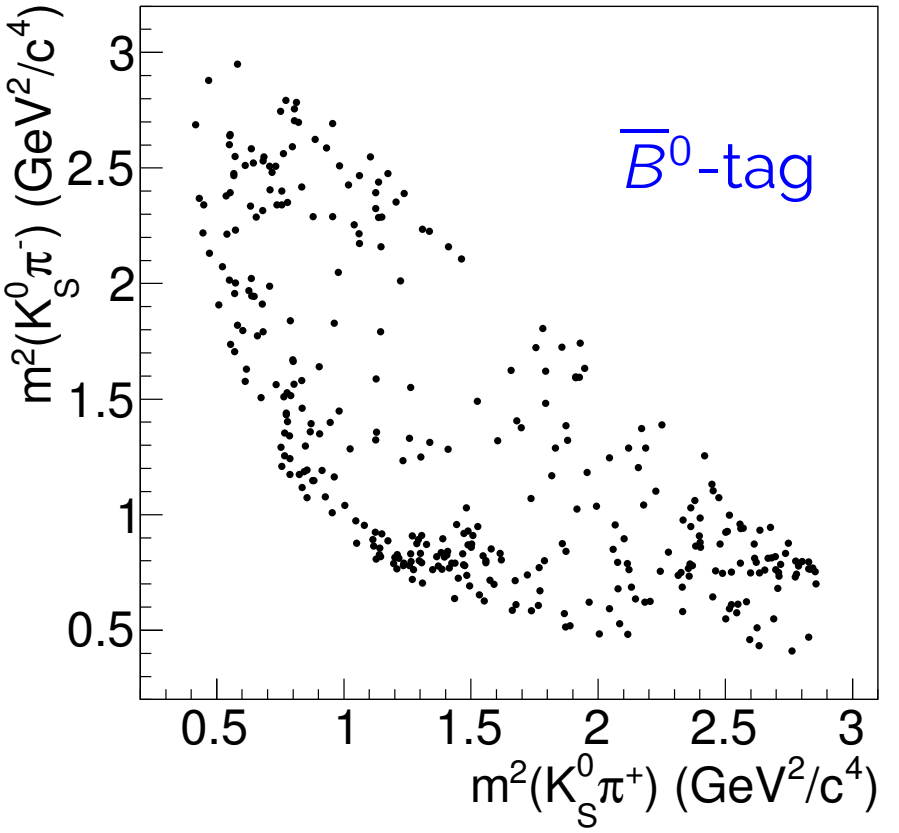




Flavor-tagged Dalitz plot

- Clear pattern visible for B^0 tagged and $\overline{B}^0$ tagged Dalitz plots (selected events with good tag probability)





Results

mode	$\sin 2\phi_1$	$\cos 2\phi_1$
$B^0 \to D\pi^0$	0.61 ± 0.37	$0.88\ ^{+0.46}_{-0.52}$
$B^0 \to D\omega$	-0.12 ± 0.58	$1.28\ ^{+0.62}_{-0.69}$
others	0.44 ± 0.51	$0.89\ ^{+0.49}_{-0.55}$
combined	$0.43 \pm 0.27 \pm 0.08$	$1.06 \pm 0.33\ ^{+0.21}_{-0.15}$

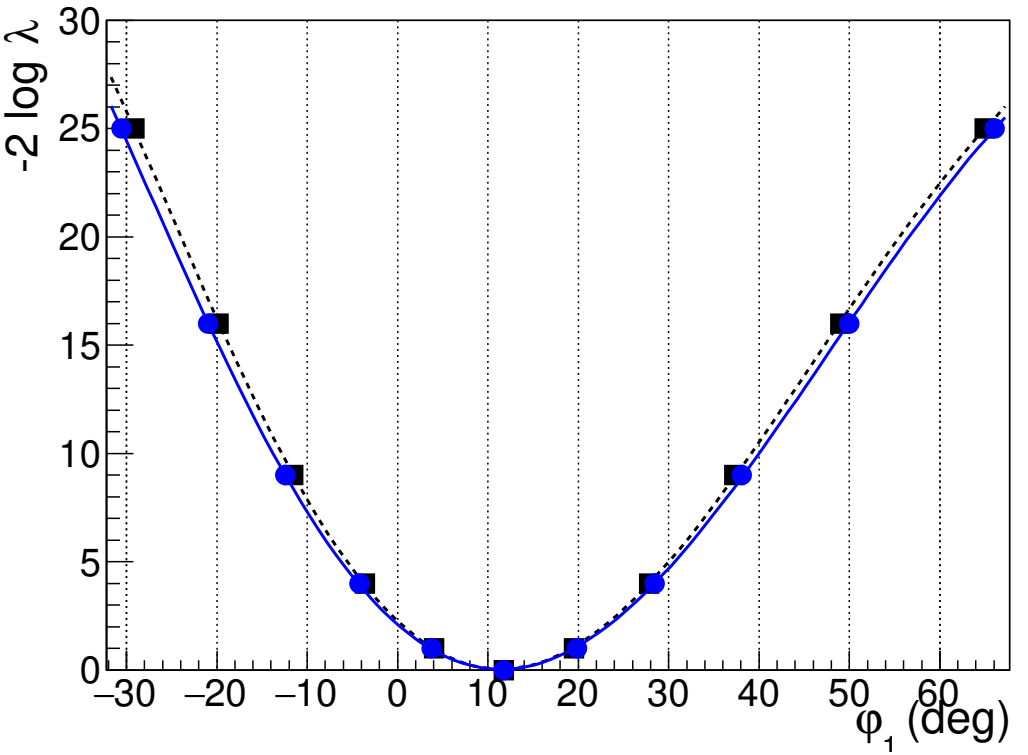
preliminary

$\phi_1 = 11.7^\circ \pm 7.8^\circ \pm 2.1^\circ$
(this analysis)

$\Leftrightarrow$ two solutions
from golden mode

$\phi_1 = 21.9^\circ$ (1.3σ away)
$\phi_1 = 68.1^\circ$ **(5.1σ away)**

Definitely disfavors the second ϕ_1 solution



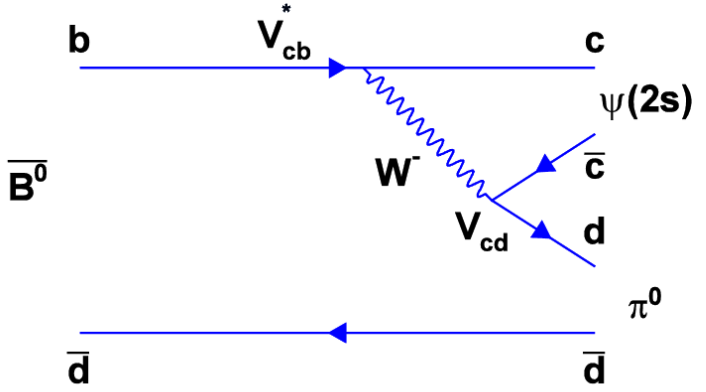
$B^0 \to \psi(2S)\pi^0$ — for future ϕ_1

Belle Collaboration, Phys. Rev. D93, 031101(R) (2016)

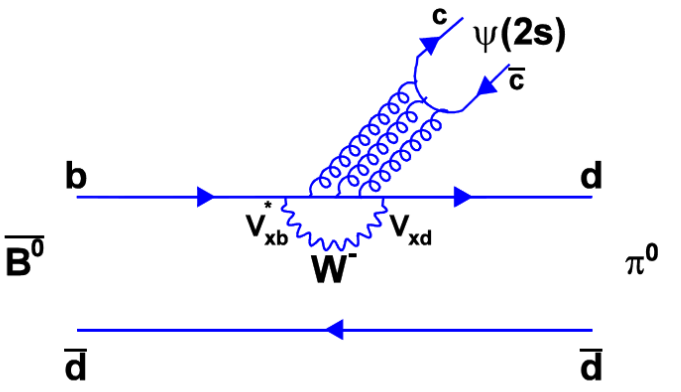
(see also talk by Vipin Gaur at Moriond QCD 2016 conference)

$B \to \psi(2S)\pi^0$ motivation and analysis

- To quantify the penguin pollution to ϕ_1 in $b \to c\bar{c}s$, **let's look at a different diagram:** $b \to c\bar{c}d$



b → cc̄d tree transition (dominant contribution)



b → dcc̄ loop process (strongly suppressed)

- $B \to J/\psi\pi^0$ has been measured: [PRD77,071101R(2008), Belle 535M $B\overline{B}$]
  $\mathcal{S}_{J/\psi\pi^0} = -0.65 \pm 0.21 \pm 0.05$ (consistent with $\sin 2\phi_1$ from $b \to c\bar{c}s$)
  but $B \to \psi(2S)\pi^0$ has not been previously observed
- **Analysis technique:**
  - Decay chain: $\psi(2S) \to \ell^+\ell^-$ or $J/\psi(\to \ell^+\ell^-)\pi^+\pi^-$ ($\ell = e, \mu$), $\pi^0 \to \gamma\gamma$
  - Background: $b \to (c\bar{c})q$ feed-across, $R_2 < 0.5$ for continuum
  - Signal: $M_{\rm bc} = \sqrt{(E^*_{\rm beam})^2 - (p^*_B)^2} \Rightarrow m_B$, $\Delta E = E_B - E^*_{\rm beam} \Rightarrow 0$

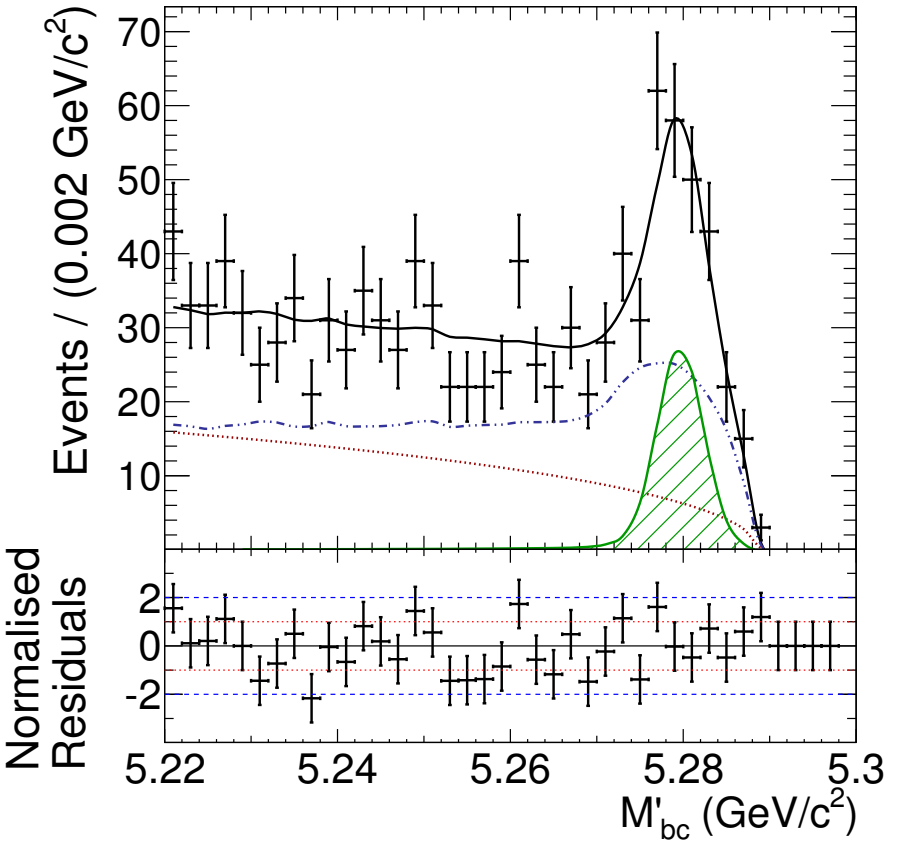
$B \to \psi(2S)\pi^0$ results

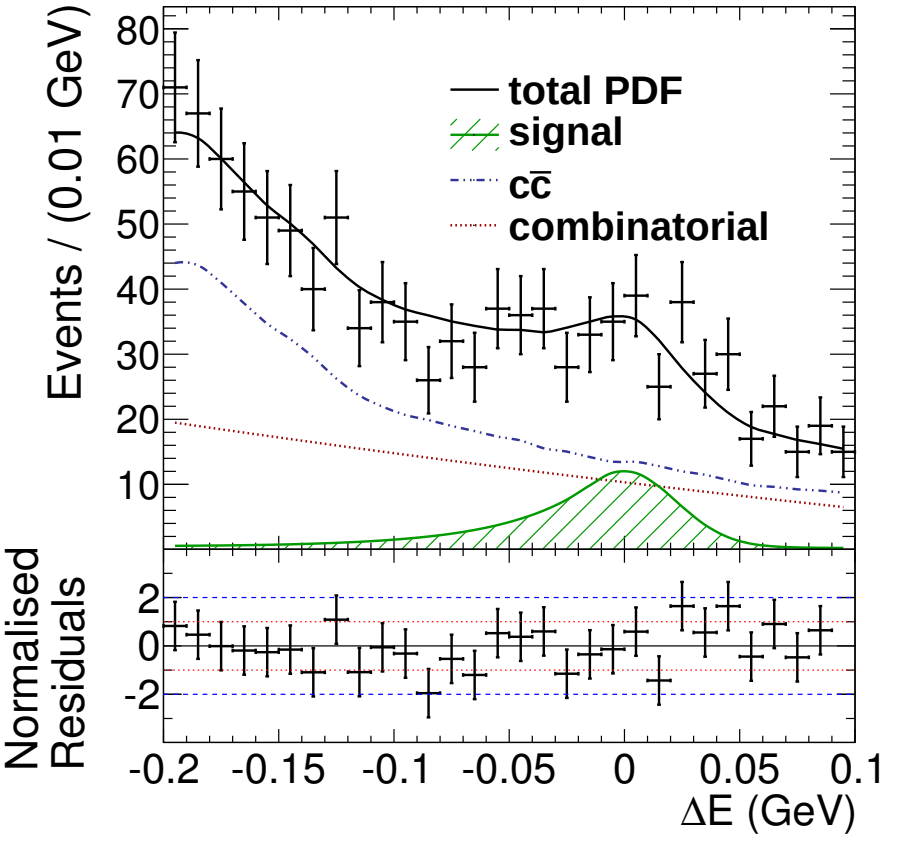
$$\mathcal{B}(B \to \psi(2S)\pi^0) = (1.17 \pm 0.17 \pm 0.08) \times 10^{-5}\ (7.2\sigma)$$

$$\Leftrightarrow \mathcal{B}(B \to J/\psi\pi^0) = (1.76 \pm 0.16) \times 10^{-5}\ \text{(PDG)}$$

85 ± 12 events

first observation, time dependent CP fit with future Belle II data





Summary


TENDER
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- **First observation of CPV in $B \to D^{(*)}_{cp} h^0$** from Belle + BaBar, not possible without combining, **promising for Belle II NP search**
- **New results on $\cos 2\phi_1$** from model-independent and time-dependent Dalitz analysis of $B \to D^{(*)} h^0$, $D \to K_S \pi\pi$
  second ϕ_1 solution is excluded by 5σ
- **Observation of $B \to \psi(2S)\pi^0$** — a new $b \to c\bar{c}d$ mode

Modes with h^0 will be more interesting with Belle II statistics, and may not be so easy by LHCb

But that's not all — **Belle still has number of analyses in preparation for ϕ_1, ϕ_2 and other hadronic B decays**

Stay tuned (even before Belle II turns on)!

Overflow

ϕ_2 — $B^0 \to \rho^+\rho^-$

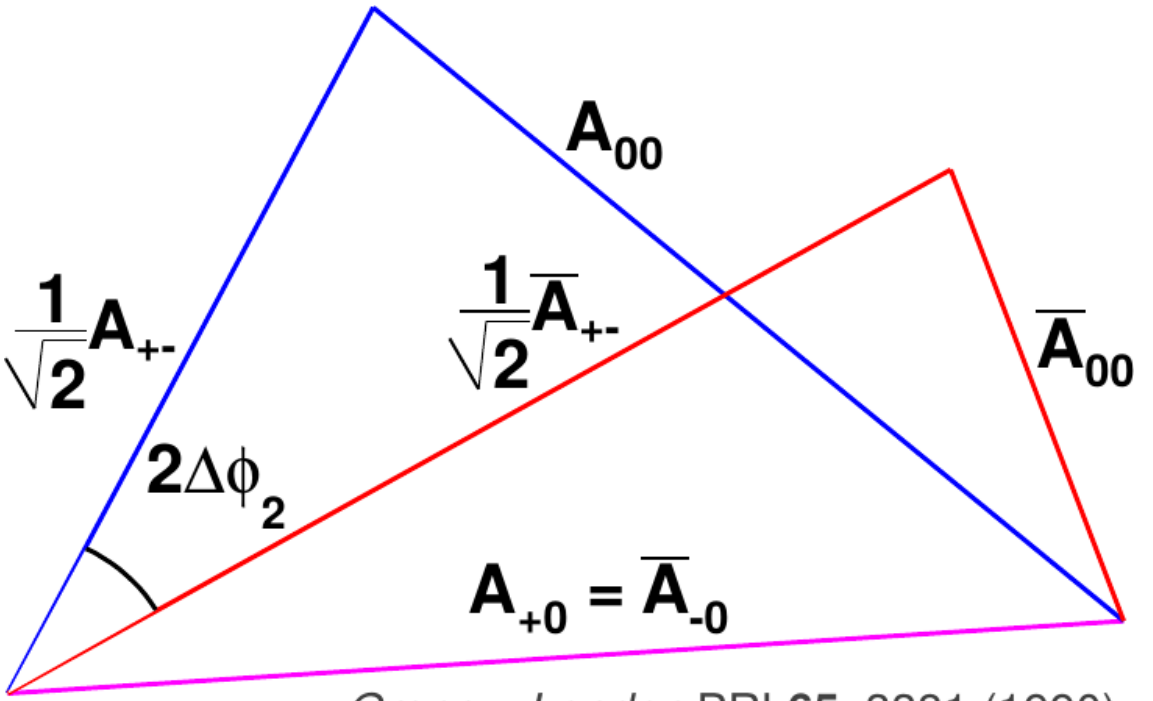
Belle Collaboration, Phys. Rev. D93, 032010 (2016)

(see also talk by Pit Vanhoefer at EPS-HEP 2015 conference)

ϕ_2 and isospin analysis

- $\sin 2\phi_2$ can e extracted from $B \to \pi^+\pi^-$ and $B \to \rho^+\rho^-$, $\mathcal{S} = \sin 2\phi_2$, if there is no "penguin pollution"
- Unfortunately this is not the case, $\mathcal{S} = \sqrt{1-\mathcal{A}^2}\sin 2(\phi_2 + \Delta\phi_2)$, but fortunately size of penguin contribution can be resolved
- Solution using isospin relations:
  3 branching fractions and 2 direct CPV are needed

A_{+-}: $B^0 \to h^+h^-$
$\overline{A}_{+-}$: $\overline{B}^0 \to h^+h^-$
A_{00}: $B^0 \to h^0h^0$
$\overline{A}_{00}$: $\overline{B}^0 \to h^0h^0$
A_{+0}: $B^+ \to h^+h^0$
($h = \pi,\ \rho$)

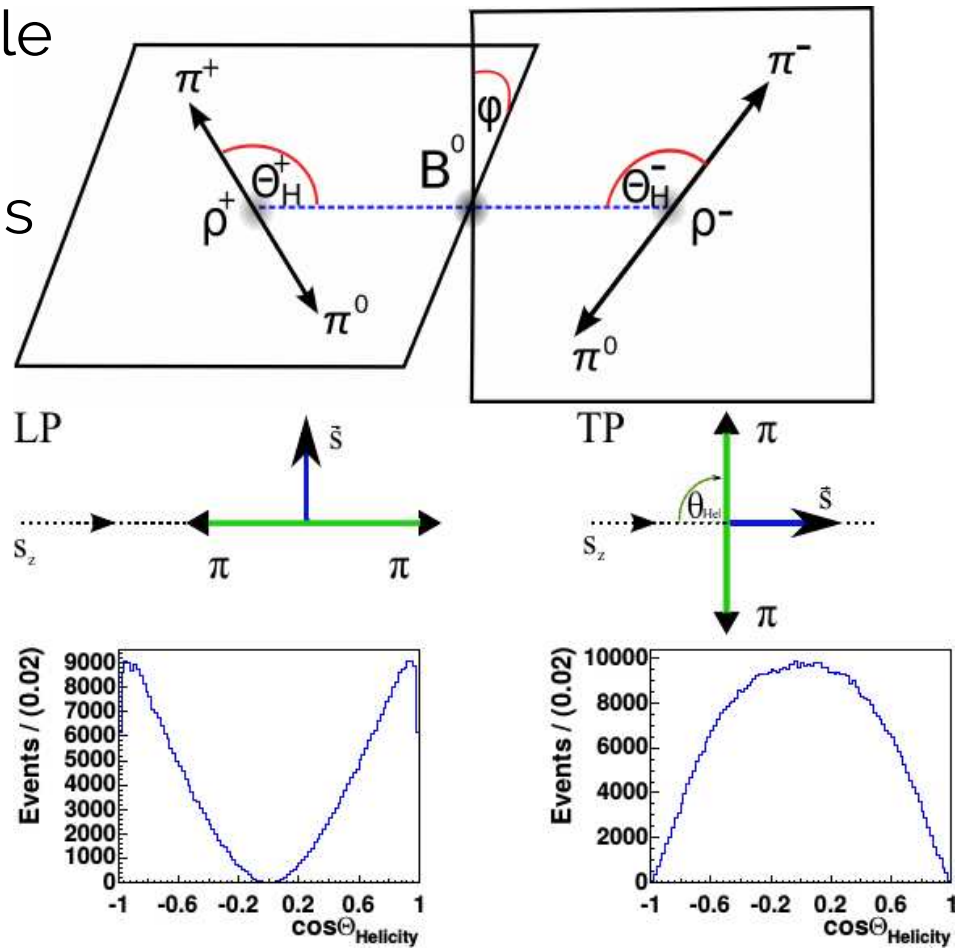


Gronau, London PRL**65**, 3381 (1990)

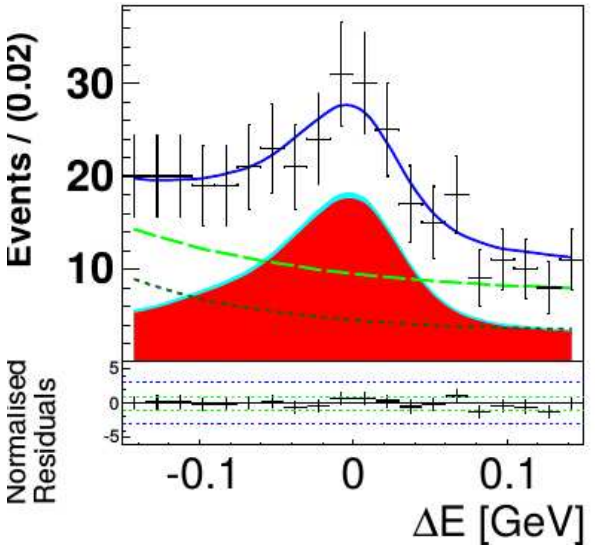
$B^0 \to \rho^+\rho^-$ analysis

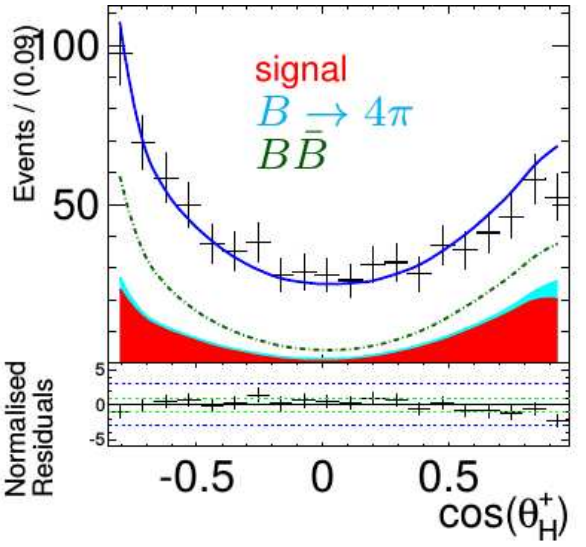
- Polarization has to be resolved as vector-vector final state is mixture of CP-even and CP-odd
- Predicted to be almost fully longitudinally polarized, and hence almost CP-even
- Decomposed by helicity angle
- $\rho^+ \to \pi^+\pi^0$ to be separated from other $\pi^+\pi^0$ contributions
- Standard time-dependent fit
- 9-parameter ML fit

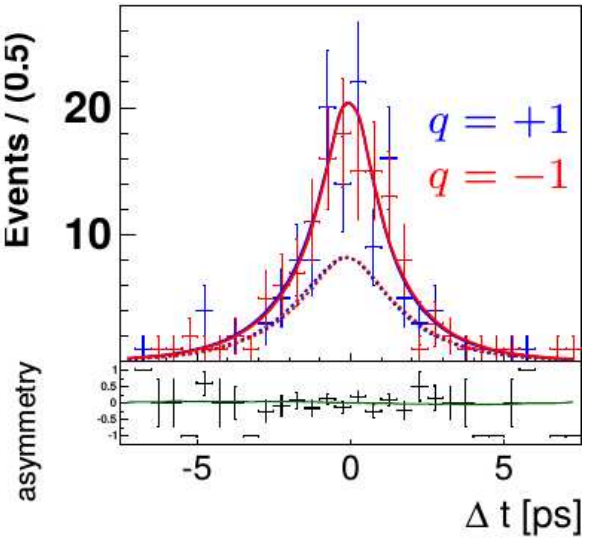
  ΔE, $M_{\rm bc}$, $\mathcal{F}$, m_{+0}, m_{-0}, $\cos\theta_H^+$, $\cos\theta_H^-$, Δt, q



Fit results

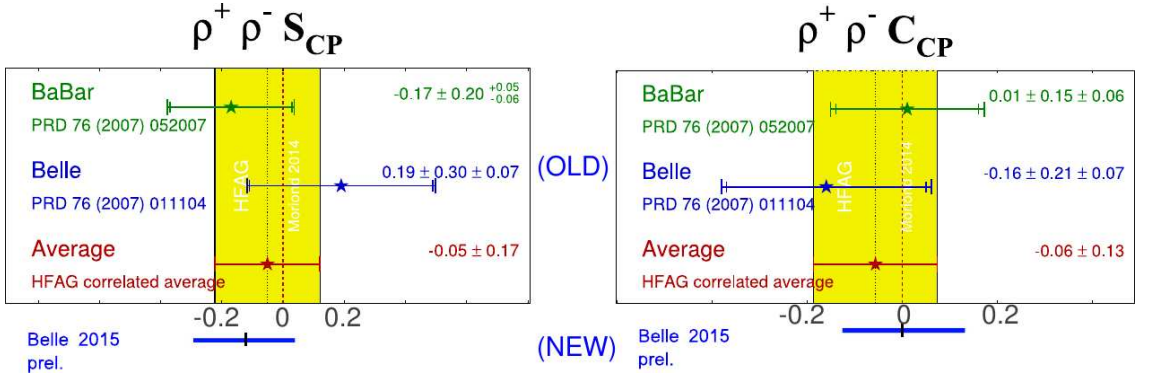






[Belle preliminary]

$$\mathcal{B}(B^0 \to \rho^+\rho^-) = (28.3 \pm 1.5 \pm 1.4) \times 10^{-6}$$
$$f_L = 0.988 \pm 0.012 \pm 0.023$$
$$\mathcal{S} = -0.13 \pm 0.15 \pm 0.05,\ \mathcal{A} = 0.00 \pm 0.10 \pm 0.06$$



Better precision than previous world average

ϕ_2 extraction

From longitudinally polarized (LP) $B \to \rho\rho$ Belle data only:

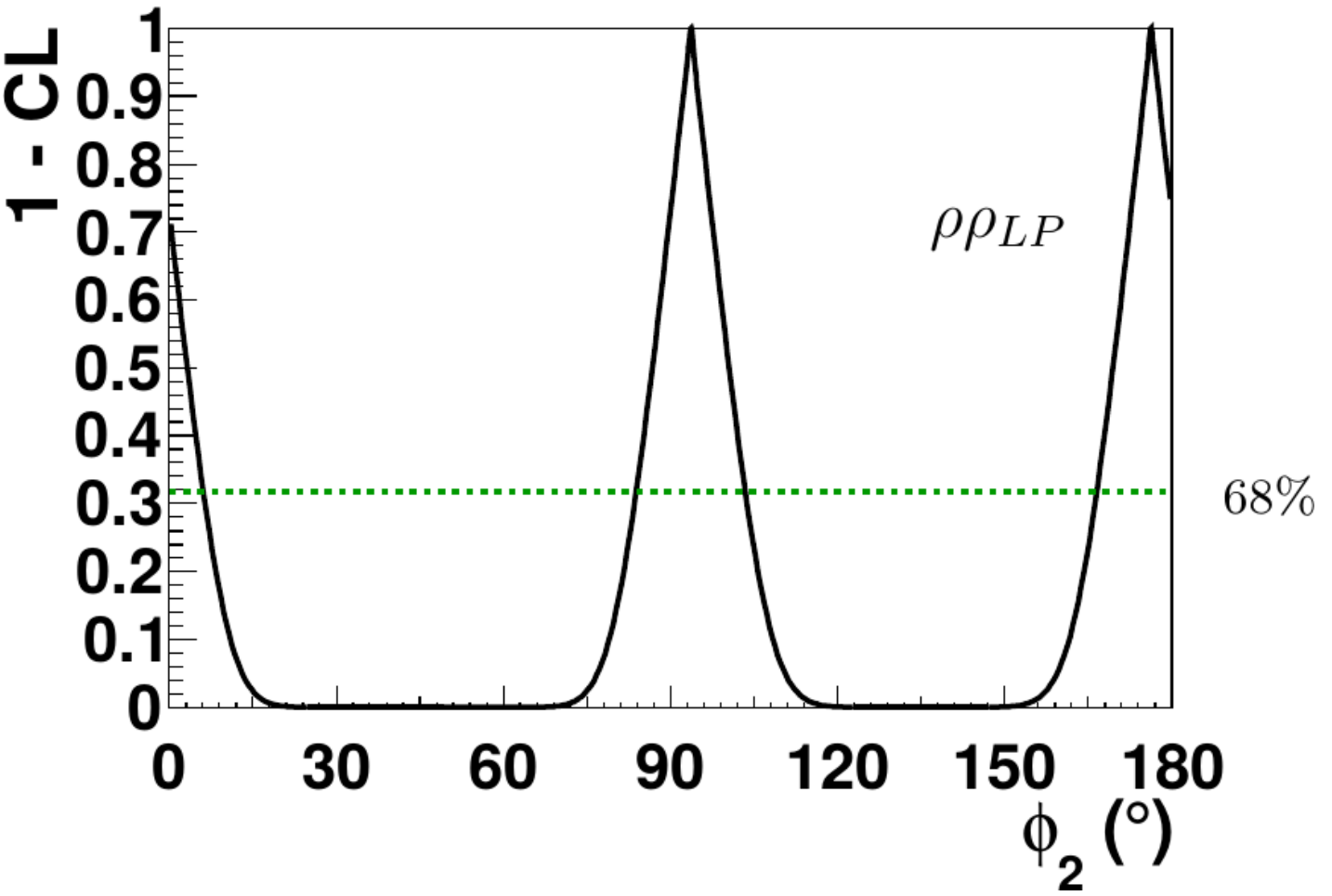
$$\boxed{\phi_2 = (93.7 \pm 10.6)^\circ} \Leftrightarrow \text{WA, all modes: } \phi_2 = (87.6\,^{+3.5}_{-3.3})^\circ$$

Additional input:

$\rho^0\rho^0$ (2014)
PRD89, 072009

$\rho^+\rho^0$ (2003!)
PRL91,221801
(only 10% data!)

Thanks to small $B \to (\rho^0\rho^0)_{LP}$, 4-fold ambiguity reduced to 2-fold



Belle's final ϕ_2 is yet to come, by updating $\rho^+\rho^0$ and $\rho\pi$ analyses

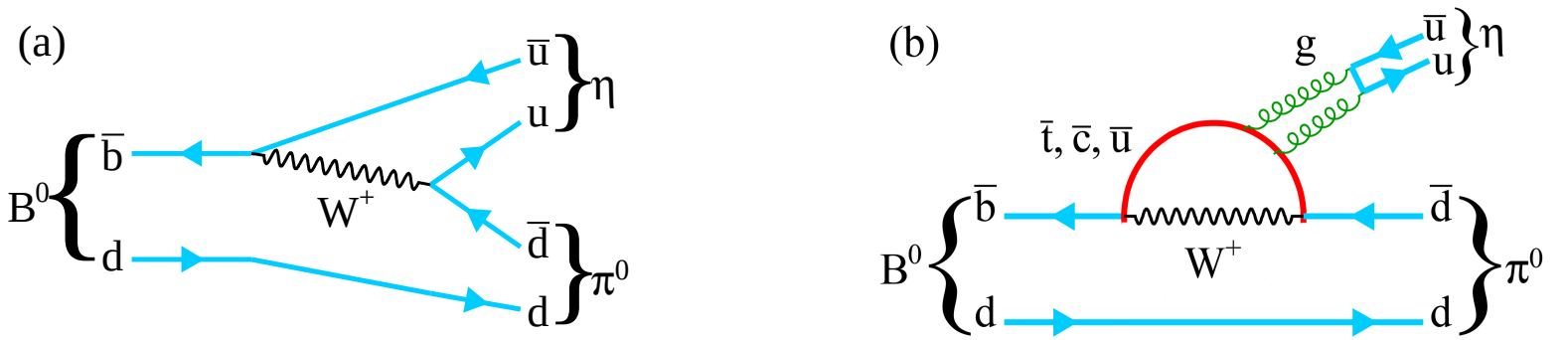
ϕ_2 related — $B^0 \to \eta\pi^0$

Belle Collaboration, Phys. Rev. D92, 011101(R) (2015)

(see also talk by Bilas Pal at CIPANP 2015 conference)

$B^0 \to \eta\pi^0$ motivations

- Color suppressed $b \to u$ and highly suppressed $b \to d$

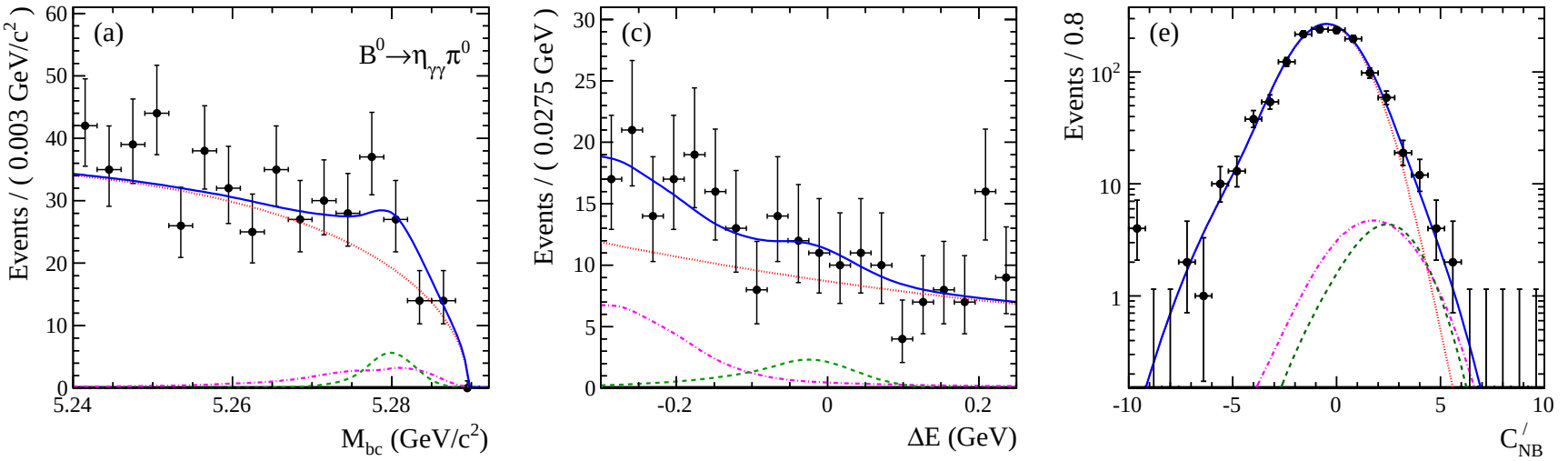


- Useful to constrain isospin breaking in ϕ_2 from $B \to \pi\pi$
  [Gronau et al, PRD71, 074017 (2005); Gardner, PRD72 034015 (2005)]
- Also useful to constrain $\Delta\phi_1 = \phi_1^{\text{eff}} - \phi_1$ from $B \to \eta' K^0$
  [Gronau et al, PLB596, 107 (2004); Gronau et al, PRD74, 093003 (2006)]
- Previous upper limits:
  $\mathcal{B} < 2.5 \times 10^{-6}$ (Belle, 152M $B\overline{B}$, PRD71, 091106R (2005))
  $\mathcal{B} < 1.5 \times 10^{-6}$ (BaBar, 459M $B\overline{B}$, PRD78, 011107R (2008))
- Update with Belle full dataset (753M $B\overline{B}$)

$B^0 \to \eta\pi^0$ results

- $\eta \to \gamma\gamma$ and $\eta \to \pi^+\pi^-\pi^0$
- Fit to $M_{\rm bc}$, ΔE and continuum suppression variable C'_{NB}
- $\mathcal{B}(B \to \eta\pi^0) = (4.1\,^{+1.7\,+0.5}_{-1.5\,-0.7}) \times 10^{-7}$ **(3.0σ), first evidence**
- Limit on isospin breaking effect:
  $|(\Delta\alpha - \Delta\alpha_0)_{\pi^0-\eta-eta'}| < 0.97°$ (90% CL) (previously $< 1.6°$)

(plots for $\eta \to \gamma\gamma$ mode)



(similar plots for $\eta \to \pi^+\pi^-\pi^0$ mode)