Measurement of the γ/ϕ_3 CKM Angle with *Belle II*

Hülya Atmacan

University of South Carolina

On Behalf of the *Belle II* Collaboration

21st Particle and Nuclei International Conference

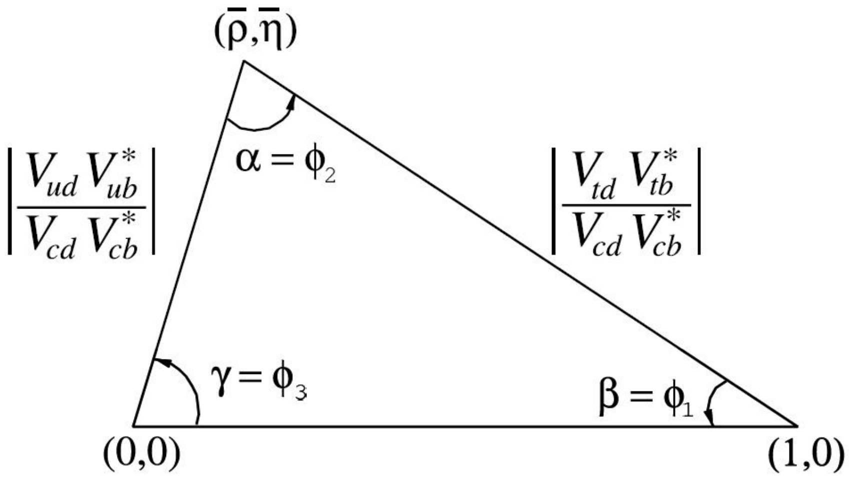
PANIC 2017

September 1, 2017

Outline

- Introduction
- Measurements from $B^{\pm} \longrightarrow D^{(*)}K^{(*)\pm}$
- Current status
- Belle II prospects
- Summary

Introduction



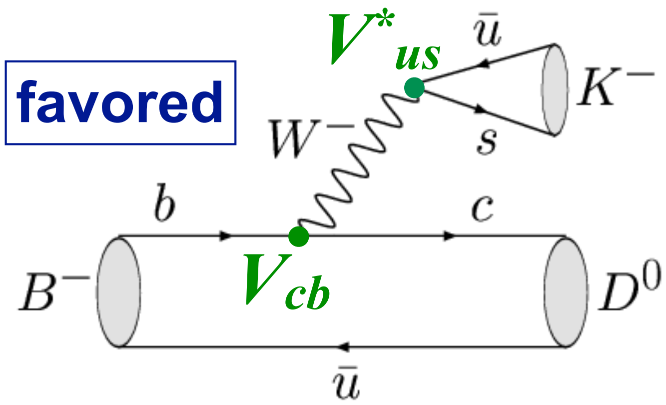
$$\gamma = \phi_3 \equiv \arg\left(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right)$$

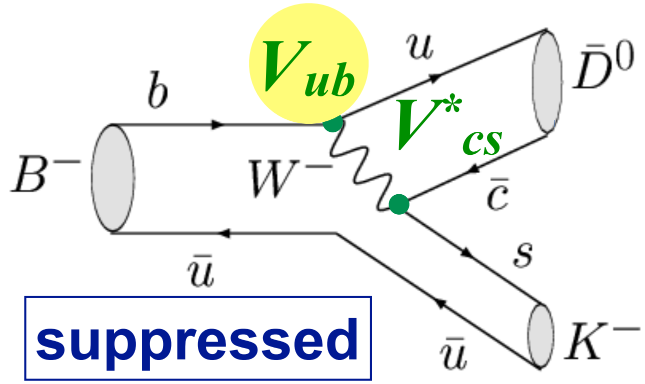
- least well measured CKM angle.
- limited by the small branching fractions of the processes used in its measurement.
- can be determined using tree-level processes only.
- theoretically clean.
- provides a Standard Model (SM) benchmark.

γ/ϕ_3 measurements from $B^{\pm} \to D^{(*)} K^{(*)\pm}$

Tree level determination of γ/ϕ_3 angle

$B^- \to D^0 K^-$ $\qquad\qquad$ $B^- \to \overline{D}^0 K^-$





$$A_1 \qquad\qquad A_1 r_B e^{i(\delta_B - \gamma)}$$

Sensitivity depending on size of hadronic ratio.

$$r_B = \frac{|A_{Suppressed}|}{|A_{Favored}|} \sim \frac{|V_{ub}V^*_{cs}|}{|V_{cb}V^*_{us}|} \times c_{colorSupp} \sim 0.1$$

r_B : magnitude of the ratio of amplitudes.

δ_B : strong phase difference

Different B ($\to DK$, D^*K , DK^*) decays have different hadronic factors (r_B , δ_B)

Three primary methods for measuring γ/ϕ_3 from $B^{\pm} \to D^{(*)} K^{(*)\pm}$

- Reconstruct D in final states accessible to both $D^0\,\overline{D}^0$

GLW Method (Gronau-London-Wyler)

[Phys. Lett., B253:483–488, 1991]

[Phys. Lett., B265:172–176, 1991]

- Interference with *CP* eigenstates
  - *final state of* $D^0 =$ *CP* eigenstates as K^+K^- , $\pi^+\pi^-$, $K_s^0\,\pi^0$

ADS Method (Atwood-Dunietz-Soni)

[Phys. Rev. D, 63:036005, Jan 2001]

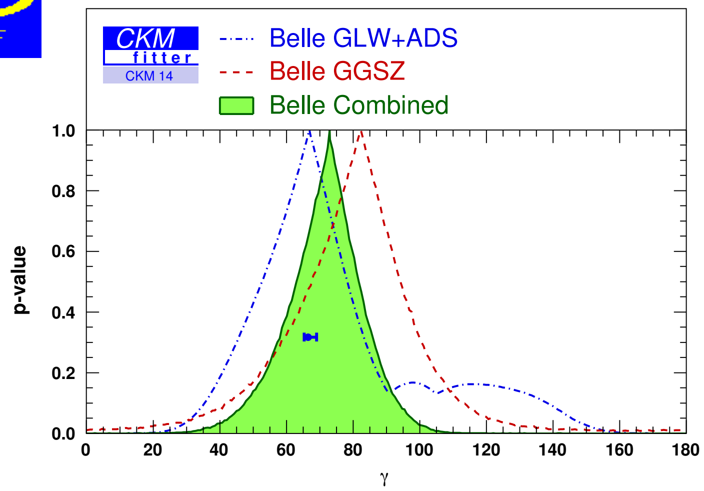
- Interference with flavor specific
  - *final state of* $D^0 =$ Doubly-Cabbibo-Suppressed (DCS) decays as $K^+\,\pi^-$

GGSZ (Dalitz) Method (Giri-Grossman-Soffer-Zupan)

[Phys. Rev. D, 68:054018, Sep 2003]

- Self conjugate D decays using Dalitz plot
  - *final state of* $D^0 =$ Three-body decays as $D \to K_s^0\pi^+\pi^-$, $K_s^0\,K^+\,K^-$

γ/ϕ_3 Current Status @ *B Factories*



$$\gamma / \phi_3 = \left(73^{+13}_{-15}\right)^\circ$$

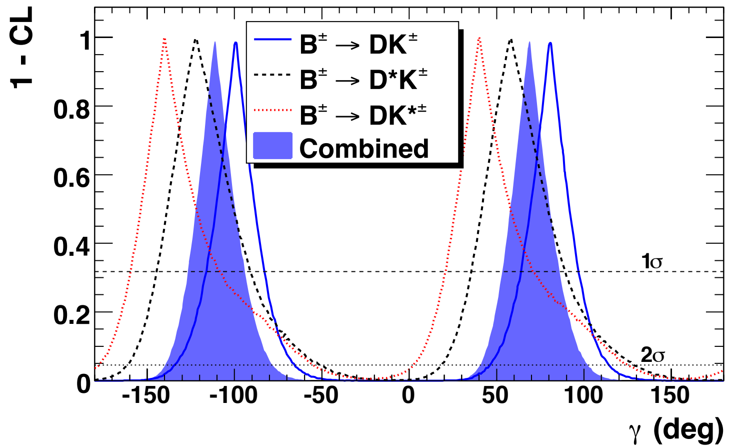
B⁻ → D^(*) K^(*)-

$B^- \to D^{(*)} K^{(*)-}$

$(D^* \to D\,\pi^0, D\,\gamma)$

Type of *D* Final States	Method
$K^+ K^-$, $\pi^+ \pi^-$, $K_s^0 \pi^0$, $K_s^0 \eta$	GLW
$K\pi$, $K^-\pi^+\pi^0$	ADS
$K_s^0\pi^+\pi^-$	GGSZ

[PRD 87 052015 (2013)]



$$\gamma / \phi_3 = \left(69^{+17}_{-16}\right)^\circ$$

$B^- \to D^{(*)} K^{(*)-}$

$(D^* \to D\,\pi^0, D\,\gamma)$

Type of D Final States	Method
$K^+ K^-$, $\pi^+ \pi^-$, $K_s^0 \pi^0$, $K_s^0 \omega$	GLW
$K\pi$, $K^-\pi^+\pi^0$	ADS
$K_s^0\pi^+\pi^-$, $K_s^0K^+K^-$	GGSZ

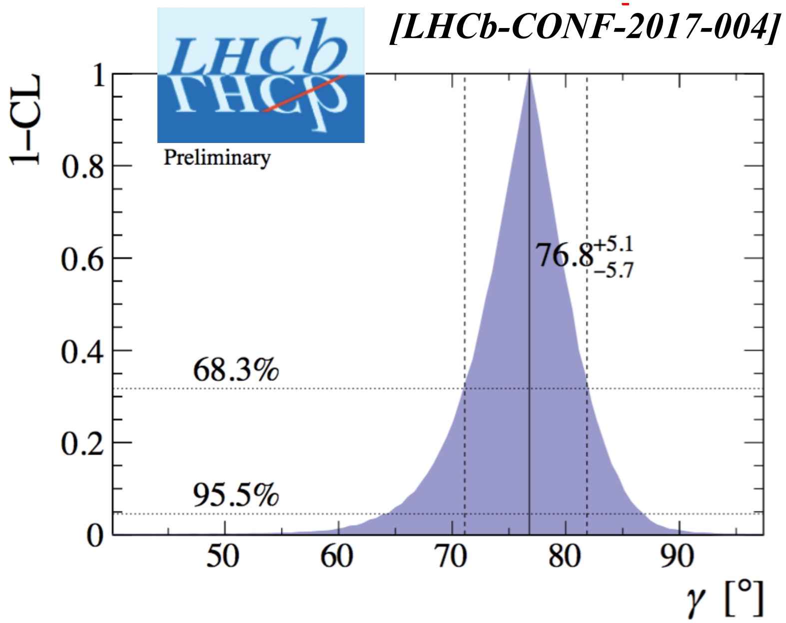
γ/ϕ_3 Current Status @ *LHCb*

list of LHCb measurements used in combination

B decay	D decay	Method	
$B^+ \to DK^+$	$D \to h^+h^-$	GLW	Updated to Run 1 + 2 fb^{-1} Run 2 [LHCb-CONF-2016-014]
$B^+ \to DK^+$	$D \to h^+h^-$	ADS	
$B^+ \to DK^+$	$D \to h^+\pi^-\pi^+\pi^-$	GLW/ADS	
$B^+ \to DK^+$	$D \to h^+h^-\pi^0$	GLW/ADS	
$B^+ \to DK^+$	$D \to K^0_S h^+h^-$	GGSZ	
$B^+ \to DK^+$	$D \to K^0_S K^+\pi^-$	GLS	
$B^+ \to D^*K^+$	$D \to h^+h^-$	GLW	New [LHCb-PAPER-2017-021]
$B^+ \to DK^{*+}$	$D \to h^+h^-$	GLW/ADS	New [LHCb-CONF-2016-014]
$B^+ \to DK^+\pi^+\pi^-$	$D \to h^+h^-$	GLW/ADS	
$B^0 \to DK^{*0}$	$D \to K^+\pi^-$	ADS	
$B^0 \to DK^+\pi^-$	$D \to h^+h^-$	GLW-Dalitz	
$B^0 \to DK^{*0}$	$D \to K^0_S\pi^+\pi^-$	GGSZ	
$B^0_s \to D_s^{\mp}K^{\pm}$	$D_s^+ \to h^+h^-\pi^+$	TD	Updated to 3 fb^{-1} Run 1 [LHCb-PAPER-021]

TD Time-dependent*

[LHCb-CONF-2017-004]

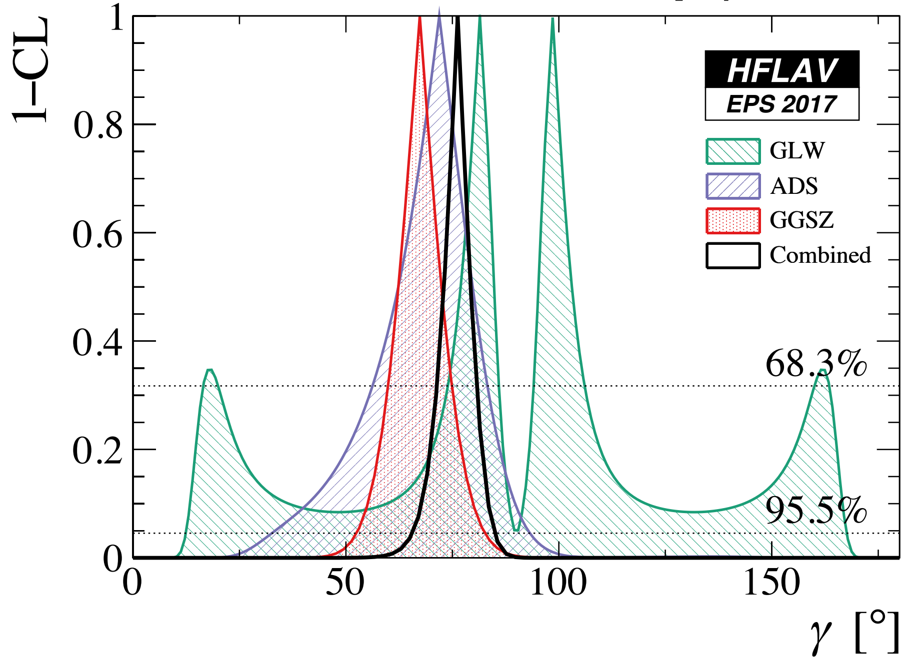


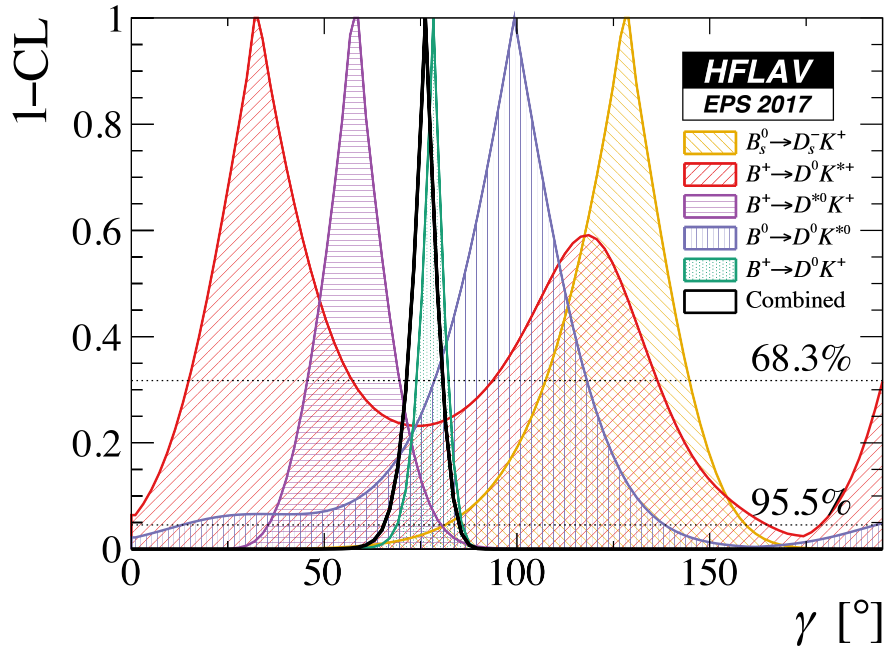
$$\gamma = (76.8^{+5.1}_{-5.7})^\circ$$

- 30% improvement with respect to the 2016 combination.

New HFLAV γ/ϕ_3 combination

[http://www.slac.stanford.edu/xorg/hflav/triangle/summer2017/ index.shtml#gamma_comb]

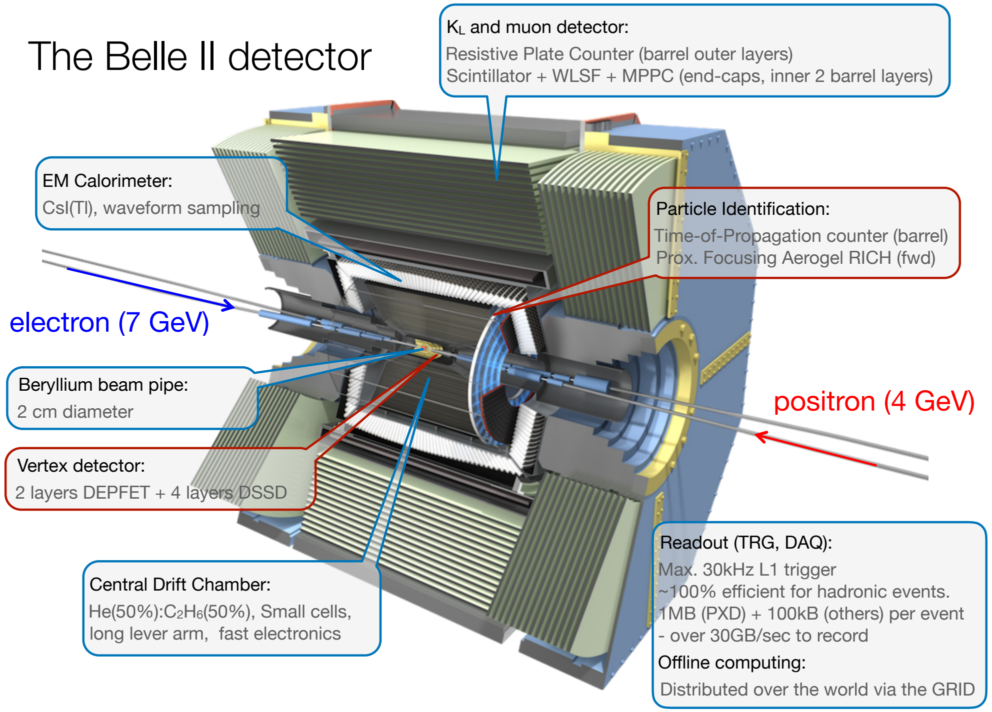


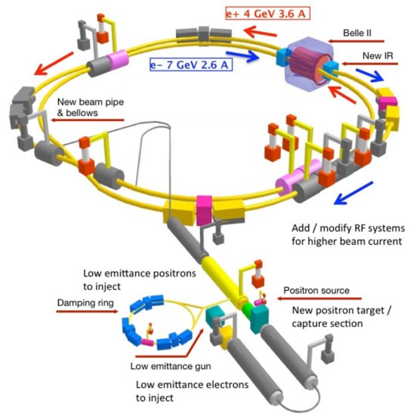


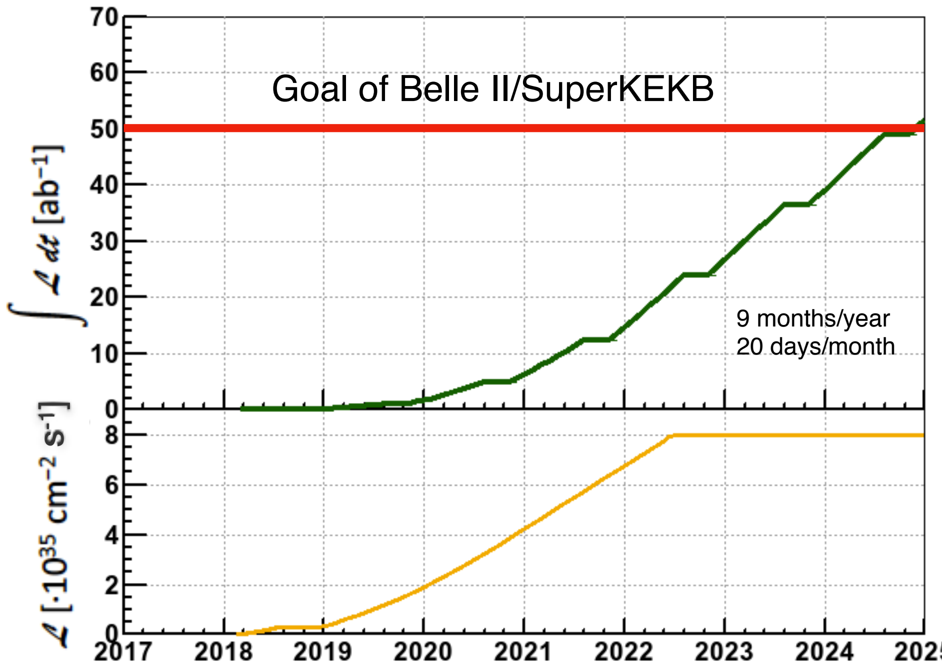
$$\gamma = (76.2^{+4.7}_{-5.0})^\circ$$

- The world average is now slightly better than 5° .

Belle II *Detector* @ *SuperKEKB*







- full solid angle detector; clean event environment; well defined initial state.
- Increase K_s^0 efficiency.
- Improved K / π separation.
- Improved reconstruction, selection and tagging algorithms.

$L_{int} > 50\ ab^{-1}$ by 2025 (50 x *Belle*)

$L_{peak} = 8 \times 10^{35}\ cm^{-2}s^{-1}$ (40 x *KEKB*)

more details by Jake Bennett (September 3)

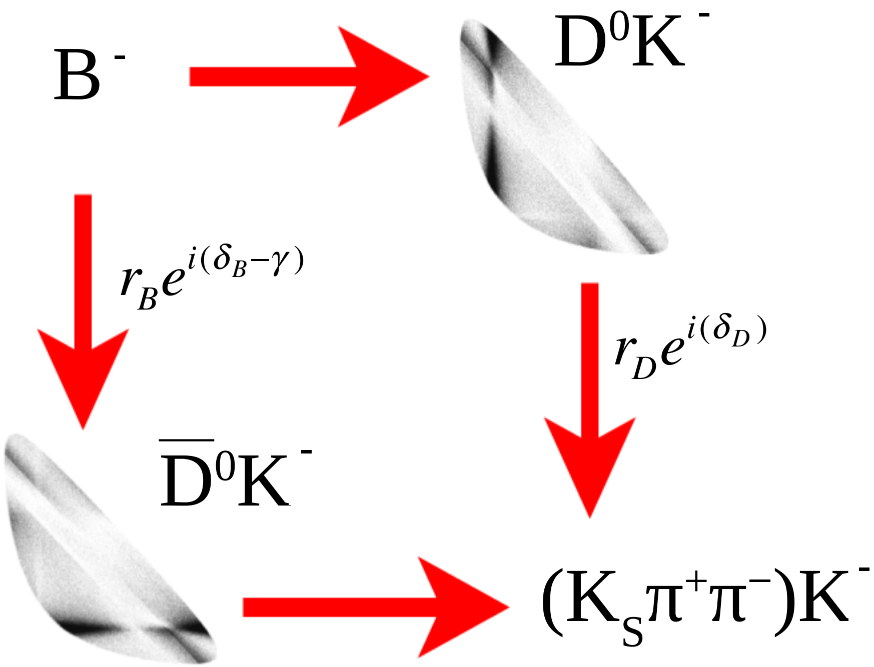
Measurement of γ/ϕ_3 @ *Belle II*

- Determination of $\gamma/\phi_3 \Rightarrow$ **dominated** by **Dalitz-plot (GGSZ) analysis** at *Belle*.
  - $B^{\pm} \rightarrow D\,(\rightarrow K_S^0\,\pi^+\,\pi^-)\,K^{\pm}$ → the most sensitive single analysis.

Each point on the Dalitz plot has different r_D and δ_D.

$$r_D = \left| \frac{A(D^0 \rightarrow f)}{A(\bar{D}^0 \rightarrow f)} \right|$$

δ_D : strong phase difference



- **Model-dependent GGSZ method**
  - r_D and δ_D determined via amplitude model.
  - large systematic uncertainty (i.e. 8.9°) due to amplitude model.
- **Model-independent GGSZ method**

  ☞ used by *Belle II*
  - use quantum coherence in $e^+e^- \rightarrow \gamma^* \rightarrow D\bar{D}$ (CLEO-c, BESIII) to measure amplitude-averaged strong phase differences, c_i, s_i.

$$c_i = \langle \cos \Delta\delta_D \rangle,\ s_i = \langle \sin \Delta\delta_D \rangle$$

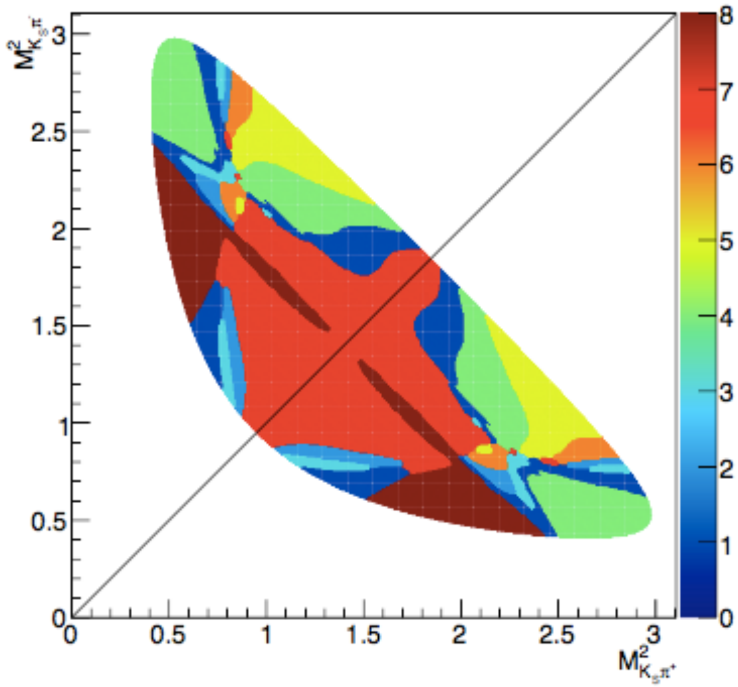
γ/ϕ_3 Sensitivity with $B^{\pm} \to D^0(K_s^0\pi^+\pi^-)\, K^{\pm}$ @ Belle II

Model-independent Dalitz plot analysis of $B^{\pm} \to D^0(K_s^0\pi^+\pi^-)\, K^{\pm}$

- Dalitz plot is divided into symmetrical bins.
- Number of events from D flavor eigenstates, $K_{\pm i}$, measured in $D^{*\pm} \to D\, \pi^{\pm}$.
- c_i and s_i, measured at CLEO or BES III.
- Number of events $N_i^{\pm}$ in a particular bin in a $B^{\pm} \to DK^{\pm}$:

[Belle hep-ex/0604054]

$$N_i^{\pm} \propto K_{\mp i} + r_{\pm}^2 K_{-i} + 2\sqrt{K_i K_{-i}}\,(x_{\pm} c_i \pm y_{\pm} s_i)$$



Dalitz binnings used for model independent analysis

- Fit in $B^{\pm} \to DK^{\pm}$

$$(x_{\pm}, y_{\pm}) = r_B(\cos(\pm\gamma + \delta_B), \sin(\pm\gamma + \delta_B))$$

γ/ϕ_3 Sensitivity with $B^{\pm} \to D^0(K_s^0\pi^+\pi^-) K^{\pm}$ @ Belle II

Belle II

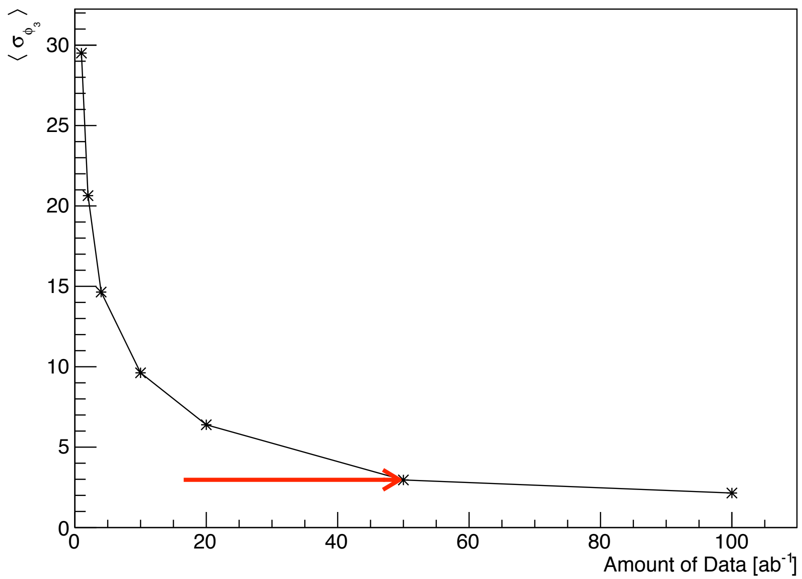
Assuming 10 fb^{-1} $\psi(3770)$ BES III dataset

we estimate for GGSZ

$$\delta(\gamma/\phi_3)^{50\,ab^{-1}} = 3^\circ$$

once the combination of *Belle* GLW, ADS, GGSZ results is extrapolated

$$\delta(\gamma/\phi_3)^{50\,ab^{-1}} = 1.6^\circ$$



Expected uncertainty (based on toy MC studies) vs luminosity on γ/ϕ_3.

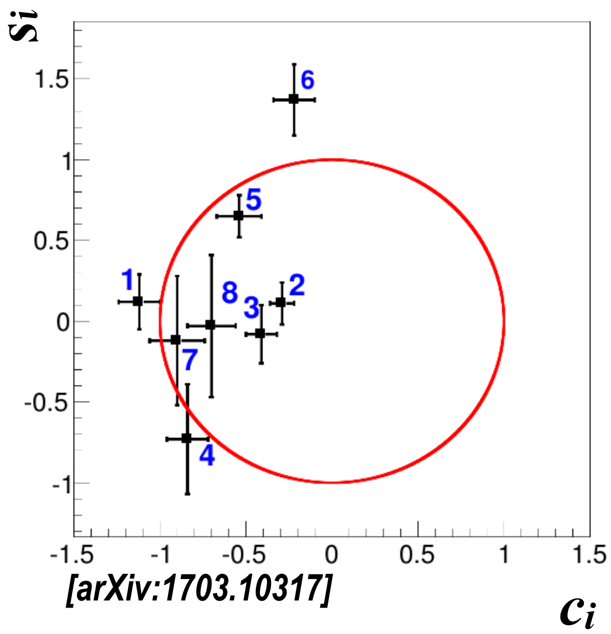
future improvements

- including additional channels such as $K_s^0K^+K^-$ and $B^+\to D^{*0}K^+$.
- including continuum suppression variable in the fit.

γ/ϕ_3 Sensitivity with $B^{\pm} \to D^0(K_s^0\pi^+\pi^-\pi^0)\, K^{\pm}$ @ Belle II

New Decay Mode

- A new model-independent GGSZ measurement in $B^{\pm}\to D(K_s^0\pi^+\pi^-\pi^0)K^{\pm}$.
  - $D^0\to K_s^0\,\pi^+\,\pi^-\,\pi^0$ decays from CLEO-c, BES III.
    - large branching fraction (BF) (5.2 %).
  - Quantum-correlated measurement of $D^0\to K_s^0\,\pi^+\,\pi^-\,\pi^0$ *[arXiv:1703.10317]*
    - 818 pb^{-1} CLEO-c data at the $\psi(3770)$ resonance.
    - CP-even fraction **0.246 ± 0.018**.



[arXiv:1703.10317]

c_i and s_i values in.

The uncertainties shown are statistical only.

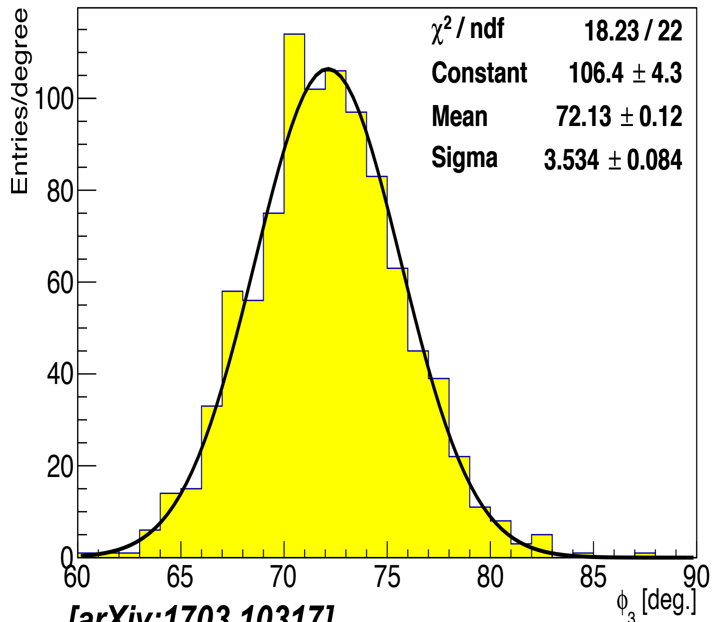
γ/ϕ_3 Sensitivity with $B^{\pm} \rightarrow D^0(K_s^0\pi^+\pi^-\pi^0)\, K^{\pm}$ @ *Belle II*

A toy simulation study:

- **Assuming:** increase in BF is compensated by loss of efficiency due to π^0.
- with 1200 events (from Belle sample of $B^{\pm} \rightarrow D\, (K_s^0\pi^+\pi^-)\, K^{\pm}$) - *under investigation*
- $\delta(\gamma/\phi_3) = 25°$ (c_i , s_i , $K_{\pm i}$ values from ***arXiv:1703.10317)***
- Project to a 50 ab^{-1} *Belle II* sample.

Single mode uncertainty on γ/ϕ_3

$$\delta(\gamma/\phi_3)^{50\,ab^{-1}} = 3.5°$$



[arXiv:1703.10317]

Caveat: background to be studied.

New Physics (NP) in γ/ϕ_3

- The traditional way: compare γ/ϕ_3 from tree-level decays with the one from penguin-dominated processes.

- Recent studies show that NP contributions to tree-level Wilson coefficients C_1 and C_2 of $\mathcal{O}(40\%)$ and $\mathcal{O}(20\%)$ are not excluded.
  [arXiv:1404.2531, arXiv:1412.1446, arXiv:1409.3251]

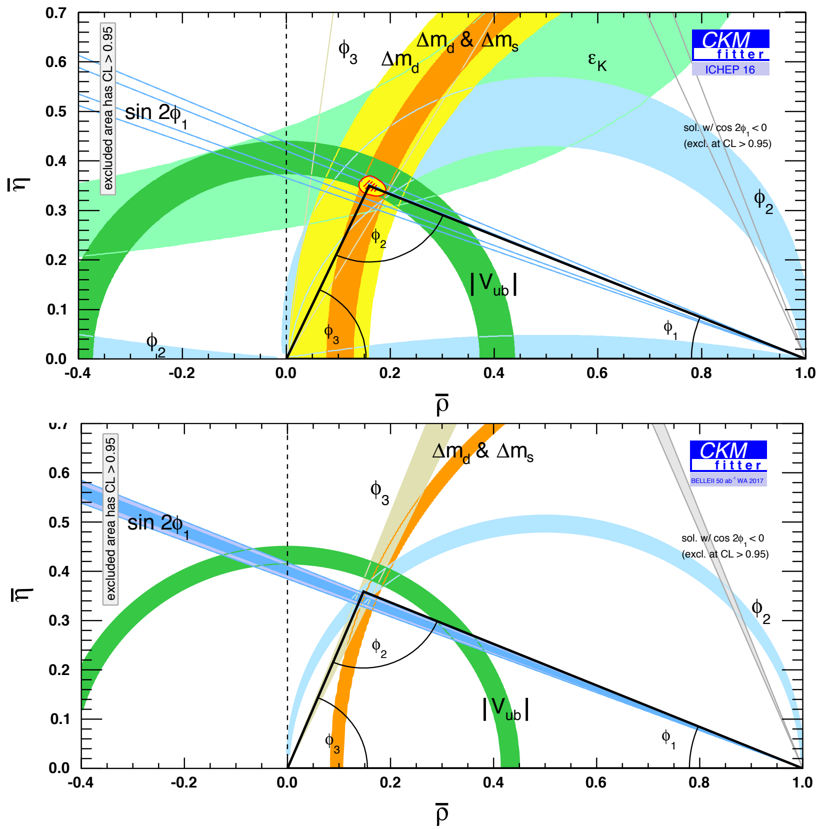
  - Shifts in γ/ϕ_3 of the order of ±4°can not be eliminated ***[arXiv:1412.1446]***.

- Strong motivation to 1° precision.

Summary

- γ/ϕ_3 precision is now better than 5°.
- First preliminary sensitivity analysis at Belle II
  - $B^\pm \to D\,(\to K_s^0\,\pi^+\,\pi^-)\,K^\pm$: at 50 ab^{-1} $\delta(\gamma/\phi_3)$ = **3°**
  - $B^\pm \to D\,(\to K_s^0\,\pi^+\,\pi^-\,\pi^0)\,K^\pm$: at 50 ab^{-1} $\delta(\gamma/\phi_3)$ = **3.5°**
- Conservatively, combined sensitivity:

$$\delta(\gamma/\phi_3)^{50\,ab^{-1}} = \mathbf{1.6°}$$



CKM constraints from tree-dominated decays. Now and at 50 ab^{-1}

EXTRA

γ/ϕ_3 GLW Method

- Both D^0 or $\overline{D^0}$ decay to the same CP eigenstate.
- The four (only three independent) GLW observables are:

$$R_{CP^{\pm}} = 2\frac{\Gamma(B^- \to D_{CP^{\pm}}K^-) + \Gamma(B^+ \to D_{CP^{\pm}}K^+)}{\Gamma(B^- \to D_{fav}K^-) + \Gamma(B^+ \to D_{fav}K^+)}$$

$$A_{CP^{\pm}} = 2\frac{\Gamma(B^- \to D_{CP^{\pm}}K^-) - \Gamma(B^+ \to D_{CP^{\pm}}K^+)}{\Gamma(B^- \to D_{CP^{\pm}}K^-) + \Gamma(B^+ \to D_{CP^{\pm}}K^+)}$$

$$R_{CP^{\pm}} = 1 + r_B^2 \pm 2r_B \cos\delta_B \cos\gamma$$

$$A_{CP^{\pm}} = \pm 2r_B \sin\delta_B \sin\gamma / R_{CP^{\pm}}$$

- no need of external inputs.

γ/ϕ_3 ADS Method

- Select events where the (anti)D^0 from the favored amplitude decays to a DCS final state (and the (anti)D^0 from the suppressed amplitude decays to the same Cabibbo favored final state):

$$B^+ \to \overset{(-)}{D}{}^0 K^+,\ \overset{(-)}{D}{}^0 \to K^-\pi^+$$

$$B^- \to \overset{(-)}{D}{}^0 K^-,\ \overset{(-)}{D}{}^0 \to K^+\pi^-$$

$$R_{ADS} = \frac{\Gamma(B^- \to [K^+\pi^-]_D K^-) + \Gamma(B^+ \to [K^-\pi^+]_D K^+)}{\Gamma(B^- \to [K^-\pi^+]_D K^-) + \Gamma(B^+ \to [K^+\pi^-]_D K^+)}$$

$$= r_B^2 + r_D^2 + 2 r_B r_D \cos(\delta_B + \delta_D)\cos(\gamma)$$

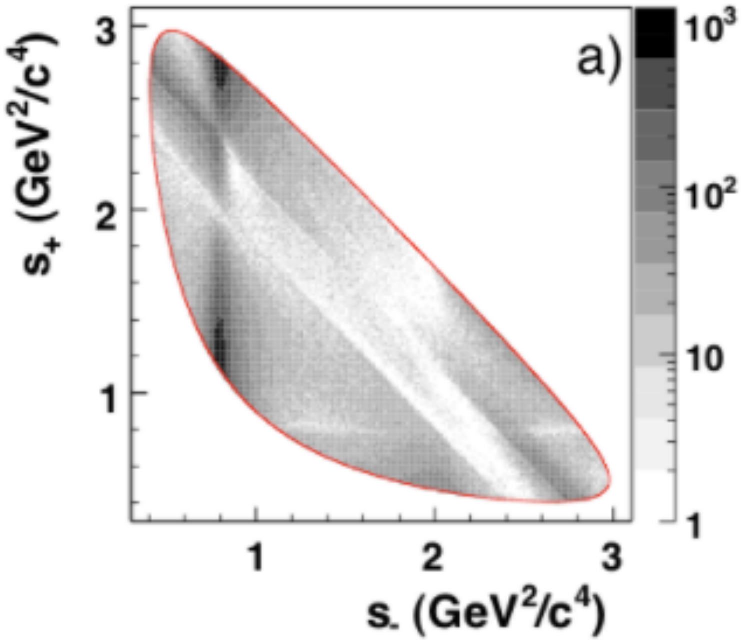
$$A_{ADS} = \frac{\Gamma(B^- \to [K^+\pi^-]_D K^-) - \Gamma(B^+ \to [K^-\pi^+]_D K^+)}{\Gamma(B^- \to [K^-\pi^+]_D K^-) + \Gamma(B^+ \to [K^+\pi^-]_D K^+)}$$

$$= 2 r_B r_D \sin(\delta_B + \delta_D)\sin(\gamma) / R_{ADS}$$

Additional variables $\boldsymbol{r_D}$ and $\boldsymbol{\delta_D}$ can be provided by charm factories.

γ/ϕ_3 GGSZ Method

- For self-conjugate multi-body D final states, i.e $K_s^0\ \pi^+\ \pi^-$
- The amplitude for $B^+ \to DK^+$, with $m_\pm^2 = m_{K_s^0\pi^\pm}^2$



$$A_{B^+}(m_+^2, m_-^2) = \overline{A}_D + r_B e^{i(\delta_B+\gamma)} A_D$$

$$A_{B^-}(m_+^2, m_-^2) = A_D + r_B e^{i(\delta_B-\gamma)} \overline{A}_D$$

- $A_D(m_+^2, m_-^2)$ is the amplitude of the $D^0 \to K_s^0\ \pi^+\ \pi^-$ decay.

γ/ϕ_3 Sensitivity with $B^{\pm} \rightarrow D^0(K_s^0\pi^+\pi^-) K^{\pm}$ @ Belle II

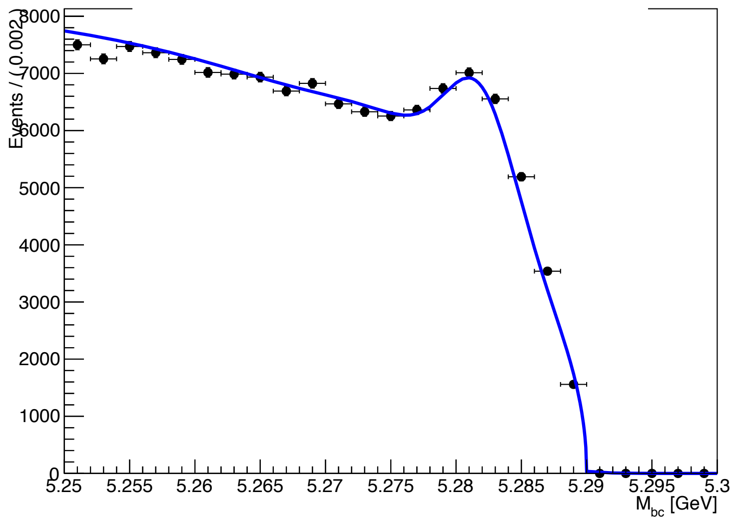
Preliminary Sensitivity Study

- Generic Monte Carlo (MC) corresponding to 2 ab^{-1} data (no beam background).
- $D^{*\pm}\rightarrow D\pi^{\pm}$, $B^{\pm}\rightarrow D\pi^{\pm}$ and $B^{\pm}\rightarrow DK^{\pm}$ with $D\rightarrow K_S{}^0\pi^+\pi^-$.
  - $D^{*\pm}\rightarrow D\pi^{\pm}$ → to find the flavor Dalitz.
  - $B^{\pm}\rightarrow D\pi^{\pm}$ → control mode and background in the signal $B^{\pm}\rightarrow DK^{\pm}$.
- D^* fit in $M(D)$ and $\Delta M = M(D\pi^{\pm})$ - $M(D)$
  - Fit per Dalitz bin to obtain K_i flavor inputs.
- signal and background separation,
  - fit in two dimensions (ΔE, M_{bc})

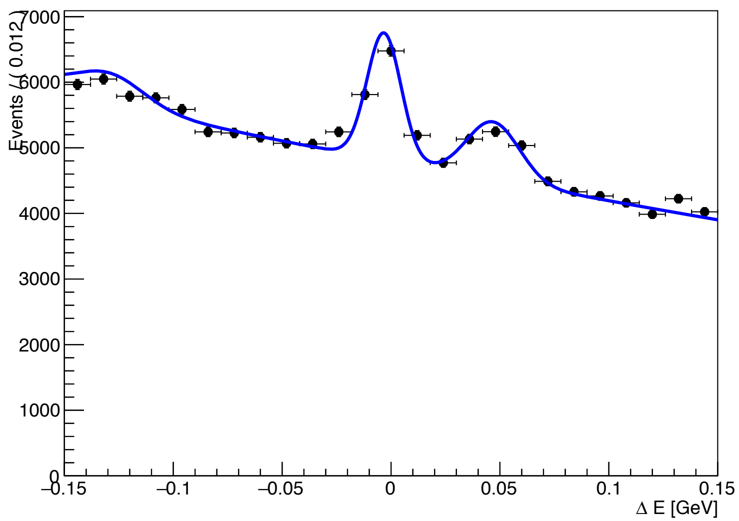
$$\Delta E = E_B^* - E_{beam}^*, \quad M_{bc} = \sqrt{E_{beam}^{*2} - \vec{p}_B^{\,*2}}$$

- Combine fit to all bins in $B^{\pm}\rightarrow D(K_S{}^0\pi^+\pi^-)K^{\pm}$.

M_{bc} Overall Fit



ΔE Overall Fit



Measurement of γ/ϕ_3 @ *Belle II*

Examples of *D* final states that have been studied so far:

Type of D decay	Method	*D* Final states
***CP* - eigenstates**	GLW	*CP*-even: K^+K^-, $\pi^+\pi^-$; *CP*-odd: $K_s^0\pi^0$, $K_s^0\eta$
CF and DCS	ADS	$K^\pm\pi^\mp$, $K^\pm\pi^\mp\pi^0$
Self - conjugate	GGSZ	$K_s^0\pi^+\pi^-$

More modes with neutral particles :

- CP-even: $K_s^0\,\eta\,\pi^0$, $K_L^0\pi^0$, $K_s^0\pi^0\pi^0$, $K_s^0K_s^0K_s^0$
- CP-odd: $K_s^0K_s^0K_L^0$, $\eta\,\pi^0\,\pi^0$, $\eta'\,\pi^0\,\pi^0$, $K_s^0K_s^0\pi^0$, $K_s^0K_s^0\,\eta$
- Self-conjugate: $K_s^0\pi^+\pi^-\pi^0$, $K_s^0K^+K^-$, $\pi^+\pi^-\pi^0$, $K^+K^-\pi^0$, $\pi^+\pi^-\pi^0\pi^0$, $K_L^0\pi^+\pi^-$,
  $K_L^0K^+K^-$, $\pi^+\pi^-\pi^0\pi^0$

*ongoing studies by *Belle*

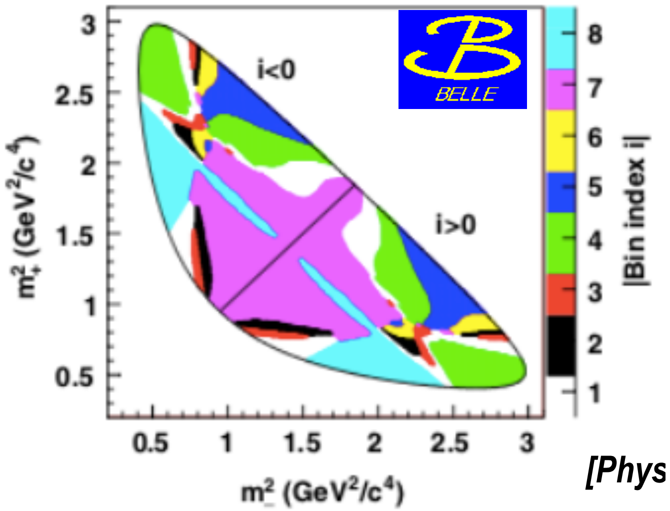
γ/ϕ_3 measurements from $B^{\pm} \to D^{(*)} K^{(*)\pm}$ @ Belle (GGSZ)

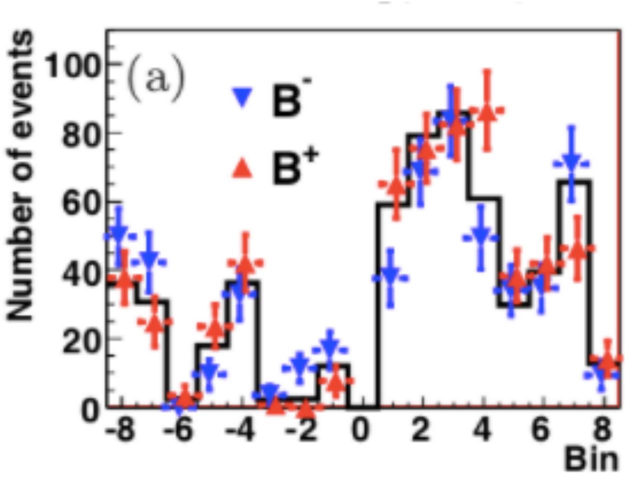
Determination of γ/ϕ_3 is **dominated** by **GGSZ (Dalitz) method.**

$$B^{\pm} \to D^0 K^{\pm},\ D^0 \to K_s^0 \pi \pi$$

- **The first model-independent Dalitz analysis**

  Model uncertainty is replaced by statistical uncertainty from CLEO-c .





[Phys

$$\gamma/\phi_3 = (77.3^{+15.1}_{-14.9} \pm 4.1 \pm 4.3)^{\circ}$$

- **The model-dependent unbinned Dalitz analysis for** $B^{\pm} \to D K^{\pm}$ **and** $B^{\pm} \to D^{*} K^{\pm}$

$$\gamma/\phi_3 = (78.4^{+10.8}_{-11.6} \pm 3.6 \pm 8.9)^{\circ}$$

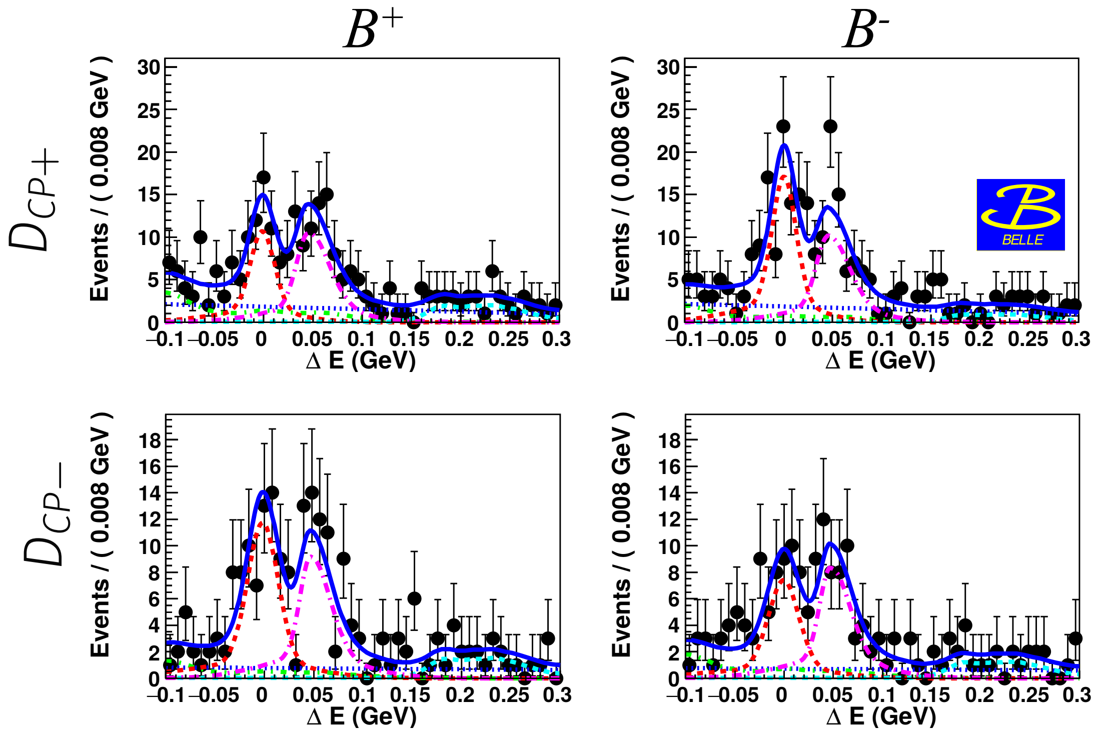
[Phys. Rev. D, 81:112002, Jun 2010]

- Model uncertainty is expected to be dominant for future experiments.
  - More statistics and BES III results will take place CLEO-c

γ/ϕ_3 measurements from $B^{\pm} \to D^{(*)} K^{(*)\pm}$ @ *Belle* (GLW and ADS)

$B^- \to D^{*0} K^-$, $D^* \to D^0 \pi^0$, $D^0 \gamma$

- To be published soon. Full Belle data set: 770 M. BB events.
- involve low energy π^0 or γ .



GLW

- Combining results for $D^* \to D^0 \pi^0$, $D^0 \gamma$ yields:

$$A_{CP^+} = -0.14 \pm 0.10 \pm 0.001$$
$$A_{CP^-} = +0.22 \pm 0.11 \pm 0.001$$

ADS

$$R_{D^*K,D\pi^0} = \left[1.0^{+0.8}_{-0.7}(stat)^{+0.1}_{-0.2}(syst)\right] \times 10^{-2}$$
$$R_{D^*K,D\gamma} = [3.6^{+1.4}_{-1.2}(stat) \pm 0.2(syst)] \times 10^{-2}$$

- $D^* \to D^0 \gamma$ mode → ***3.5 σ*** significance.