γ/ϕ_3 combination at Belle and Belle II

师晓东

东京大学

Submitted to JHEP, arXiv:2404.12817

UTokyo

東京大学 大学院
理学系研究科·理学部
SCHOOL OF SCIENCE, THE UNIVERSITY OF TOKYO

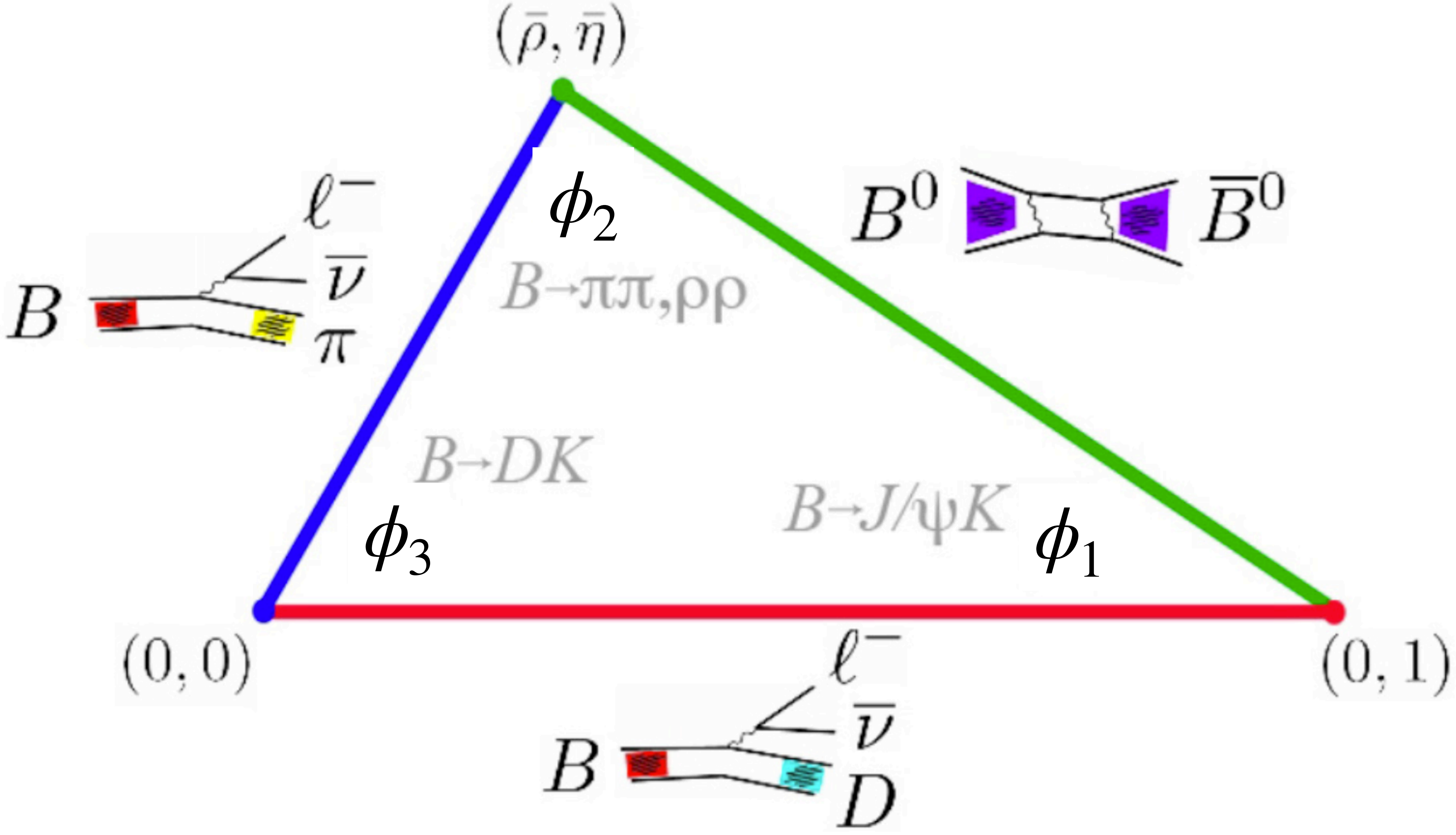
2024.8.13-18
第十四届全国粒子物理学术会议

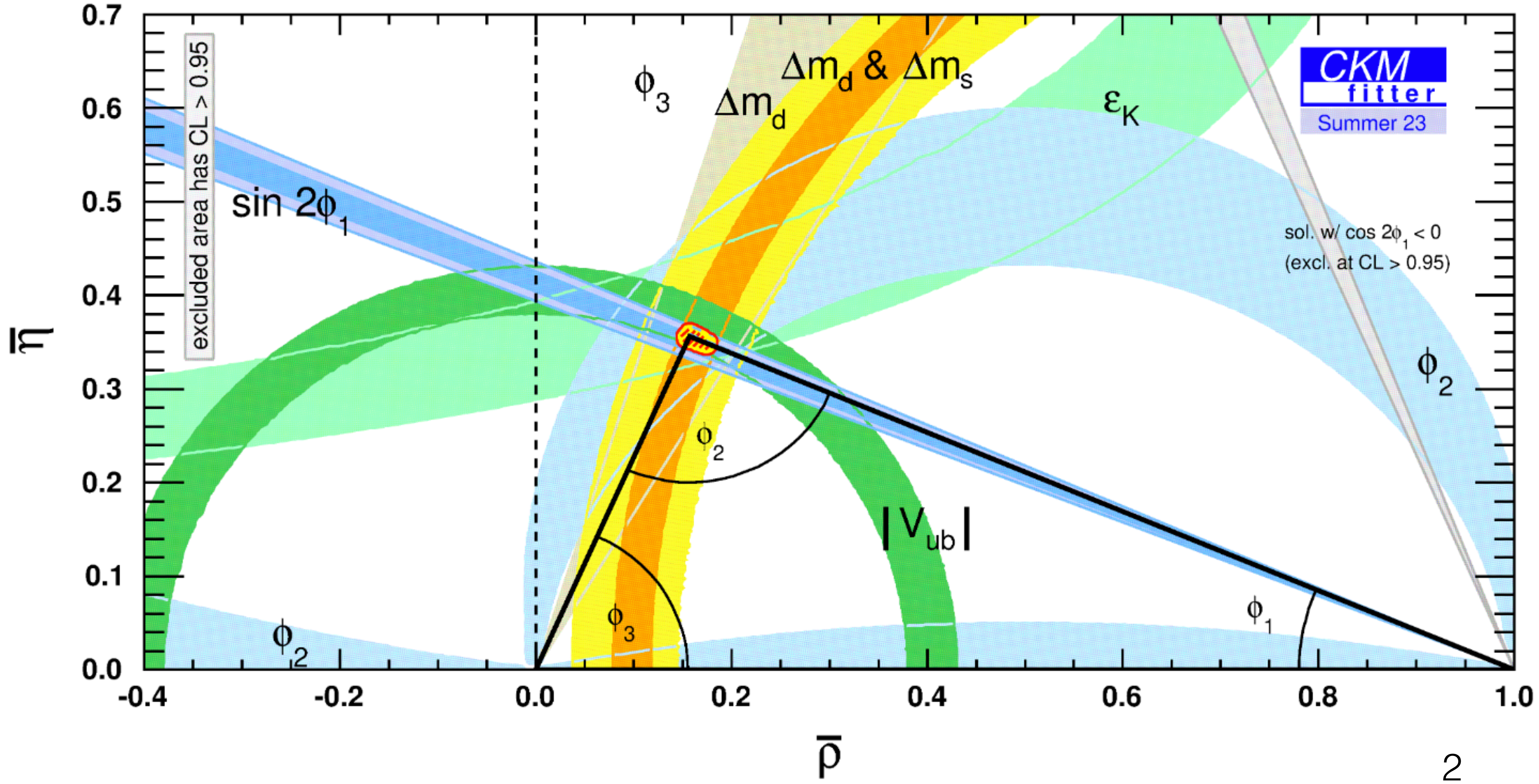
BELLE

Belle II

CKM matrix and the unitary triangle

- In SM, CKM matrix is **unitary**: four free parameter, one of them is the complex phase, the **only one source** of CPV in quark sector in SM!

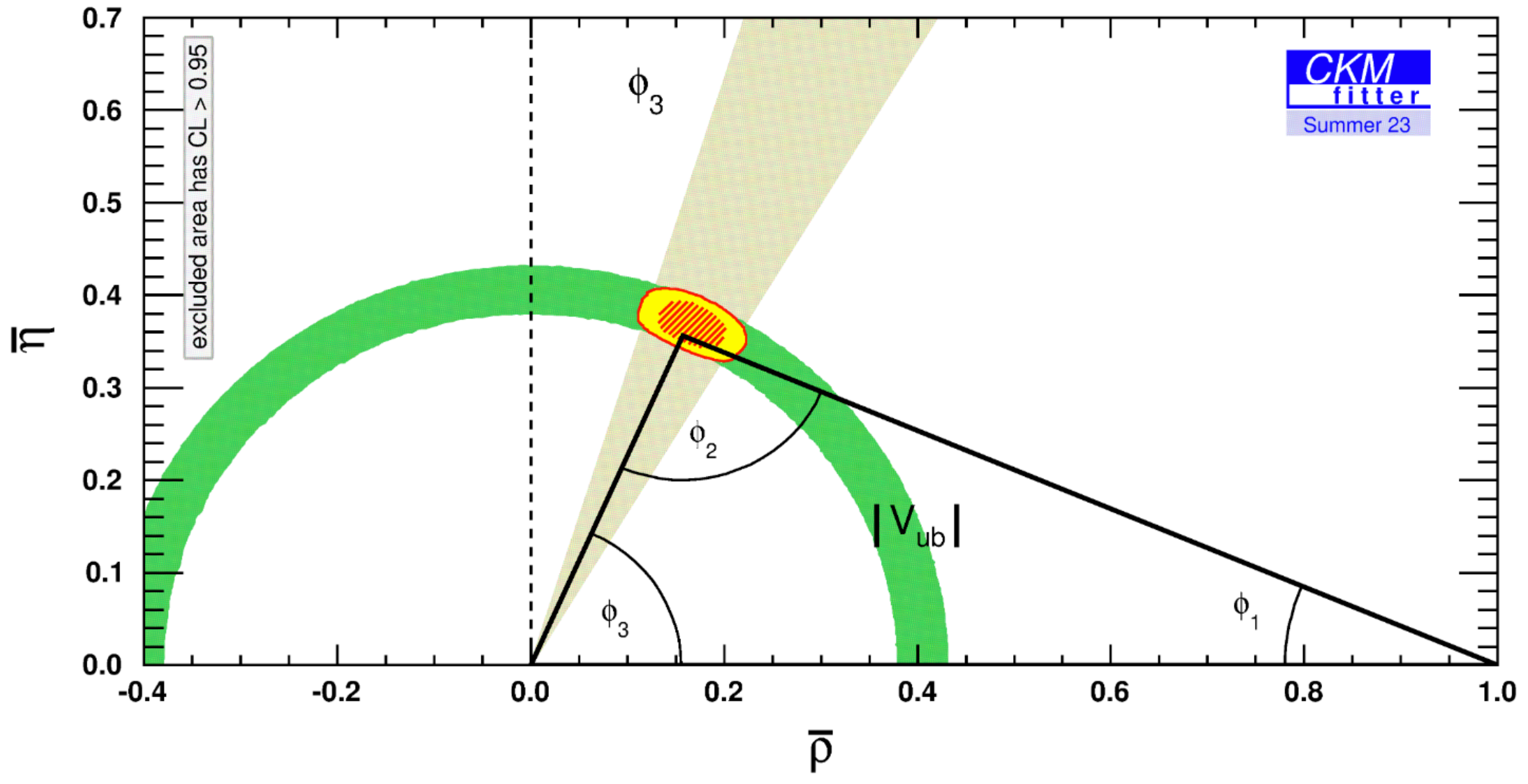




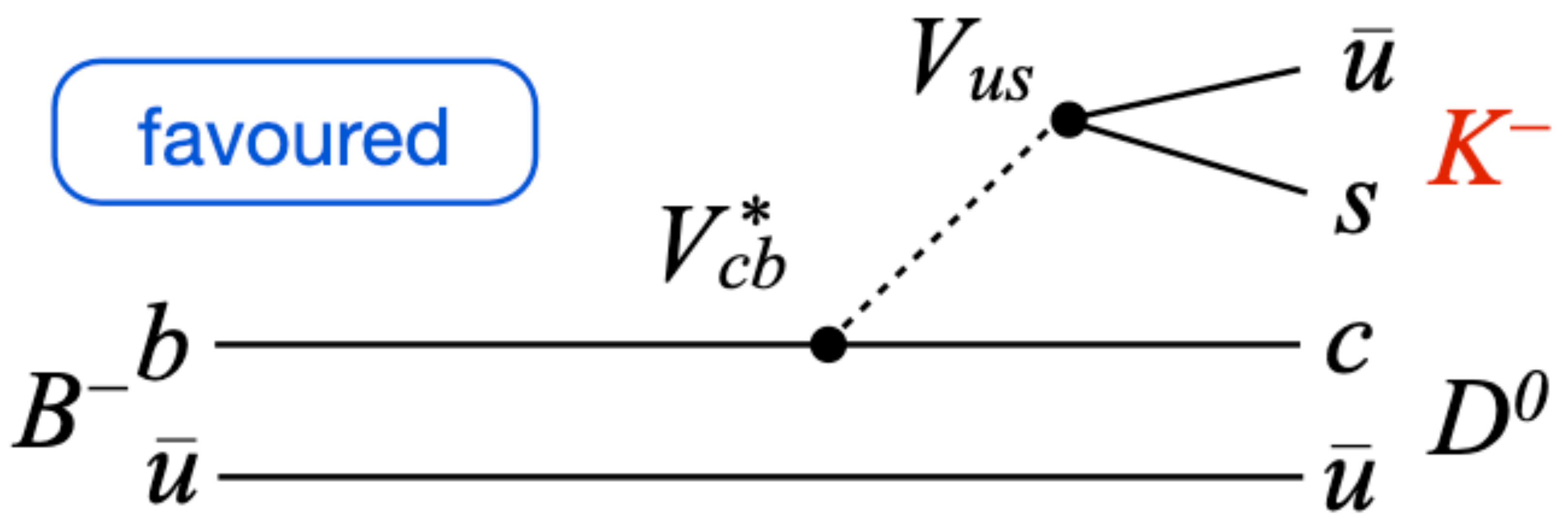
- $\phi_1 = \beta = \arg(-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}), (22.6^{+0.5}_{-0.4})^\circ$
- $\phi_2 = \alpha = \arg(-\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}),(84.1^{+4.5}_{-3.8})^\circ$
- $\phi_3 = \gamma = \arg(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}),(66.4^{+2.8}_{-3.0})^\circ$

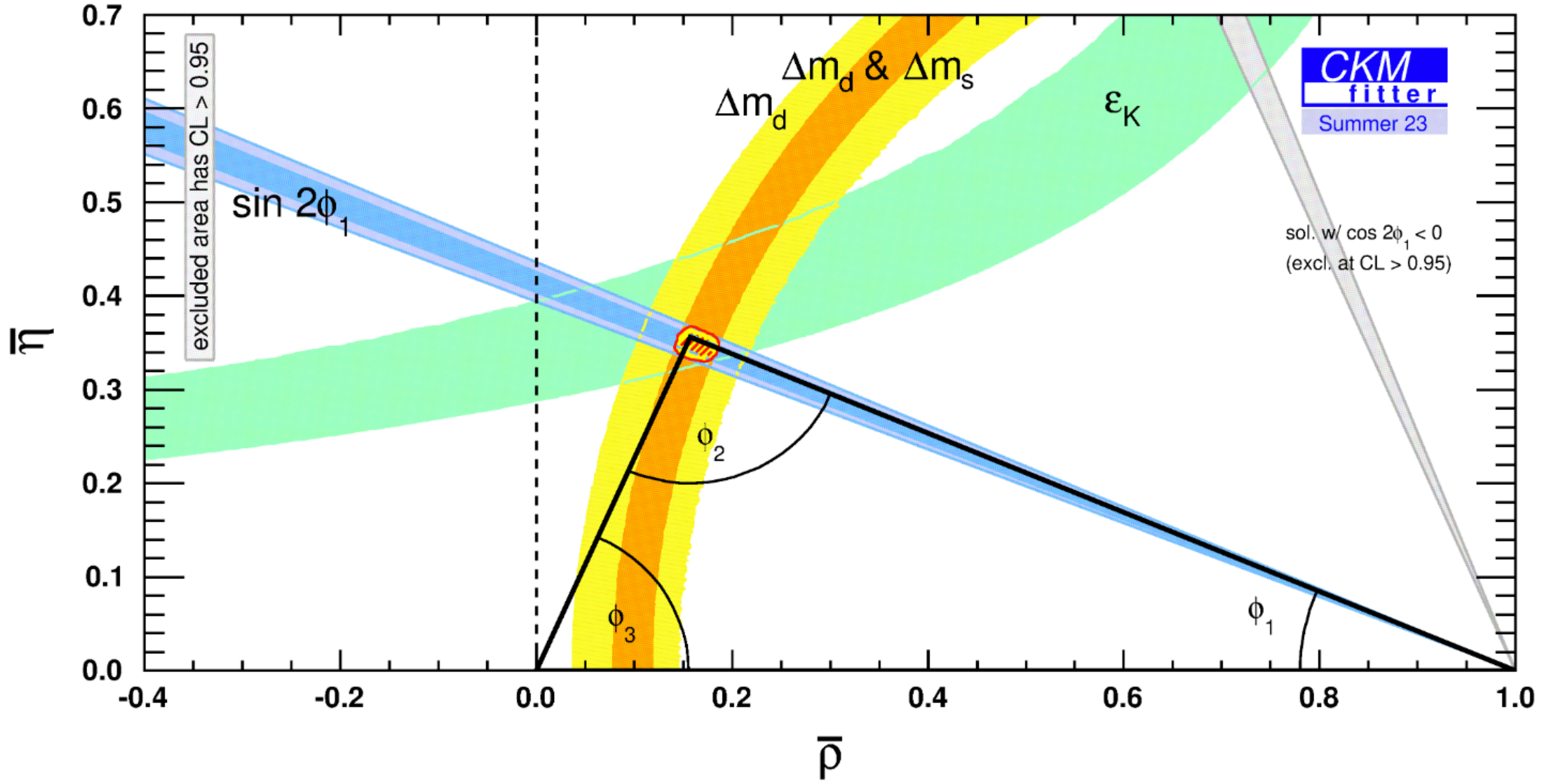
HFLAV 2024

Tree process v.s. loop precess

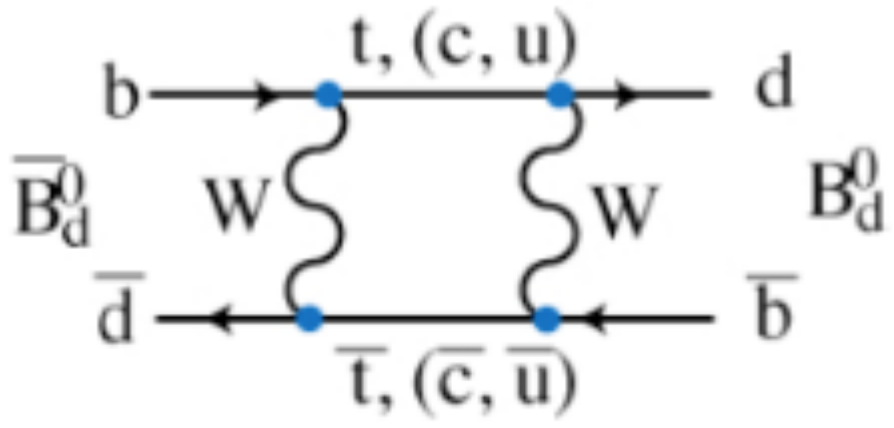


Tree level only



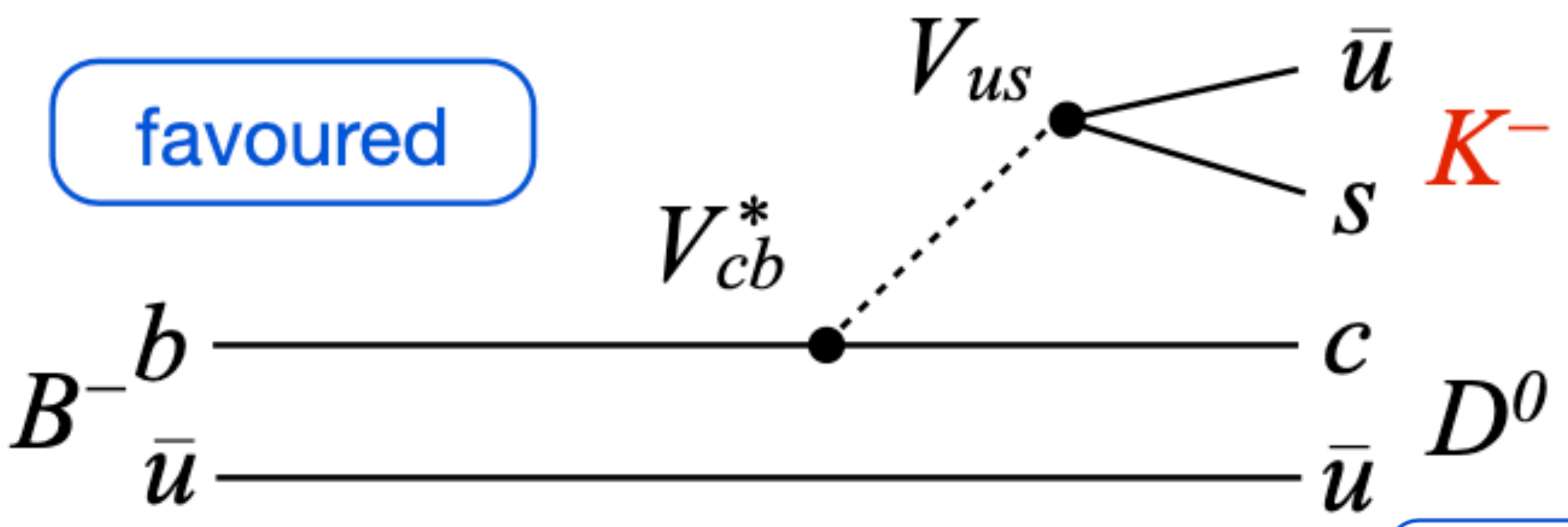


Loop-level only



NP at O(>TeV)?

How to measure ϕ_3: interference in $B^- \to DK^-$



$B^- \to D^0 K^- \sim V_{cb} V^*_{us}$

$\sim A\lambda^3$

relative amplitude:

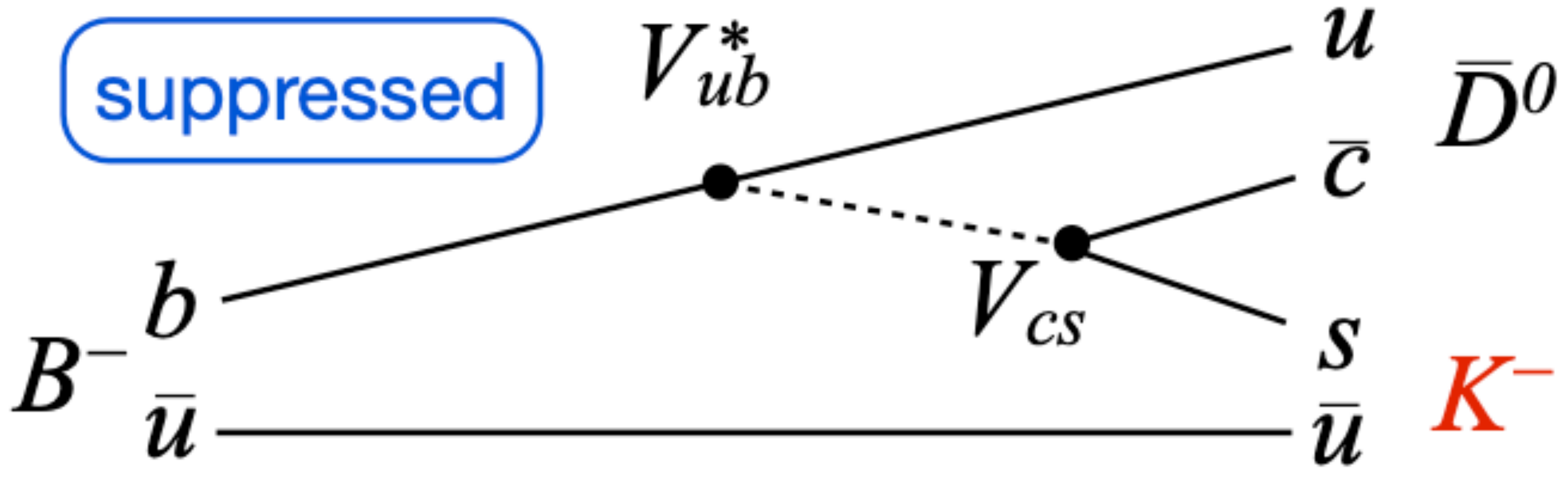
$$\left|\frac{V_{cs} V^*_{ub}}{V_{us} V^*_{cb}}\right| f_{col} = r_B \approx 0.1$$

relative strong phase:

$$= \delta_B$$

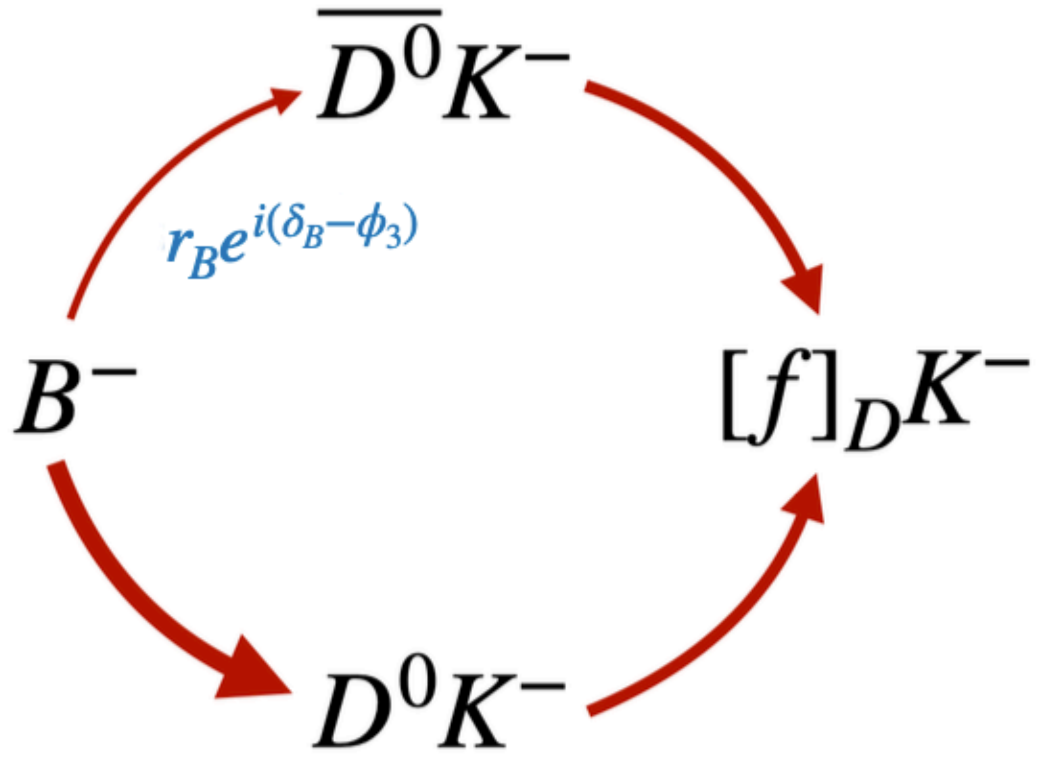
weak phase difference:

$$\arg\left(\frac{V_{cs}\ V^*_{ub}}{V_{us}\ V^*_{cb}}\right) = \arg\left(-\frac{V^*_{ub}}{V^*_{cb}}\right) = \phi_3$$



$B^- \to \bar{D}^0 K^- \sim V_{ub} V^*_{cs}$

$\sim A\lambda^3(\rho + i\eta)$



- Depends on the D decay final states, different methods:
  - **BPGGSZ**: self conjugated multi-body decays, e.g. $K^0_S\pi^+\pi^-, K^0_S\pi^+\pi^-\pi^0, \pi^+\pi^-\pi^+\pi^-$
  - **GLW**: CP eigenstates, e.g. $K^0_S\pi^0, K^+K^-$
  - **ADS**: CF and DCS decays, e.g. $K^-\pi^+, K^-\pi^+\pi^0, K^-\pi^+\pi^\pm\pi^\mp$
  - **GLS**: SCS decays, e.g. $K^0_S K^\mp\pi^\pm$

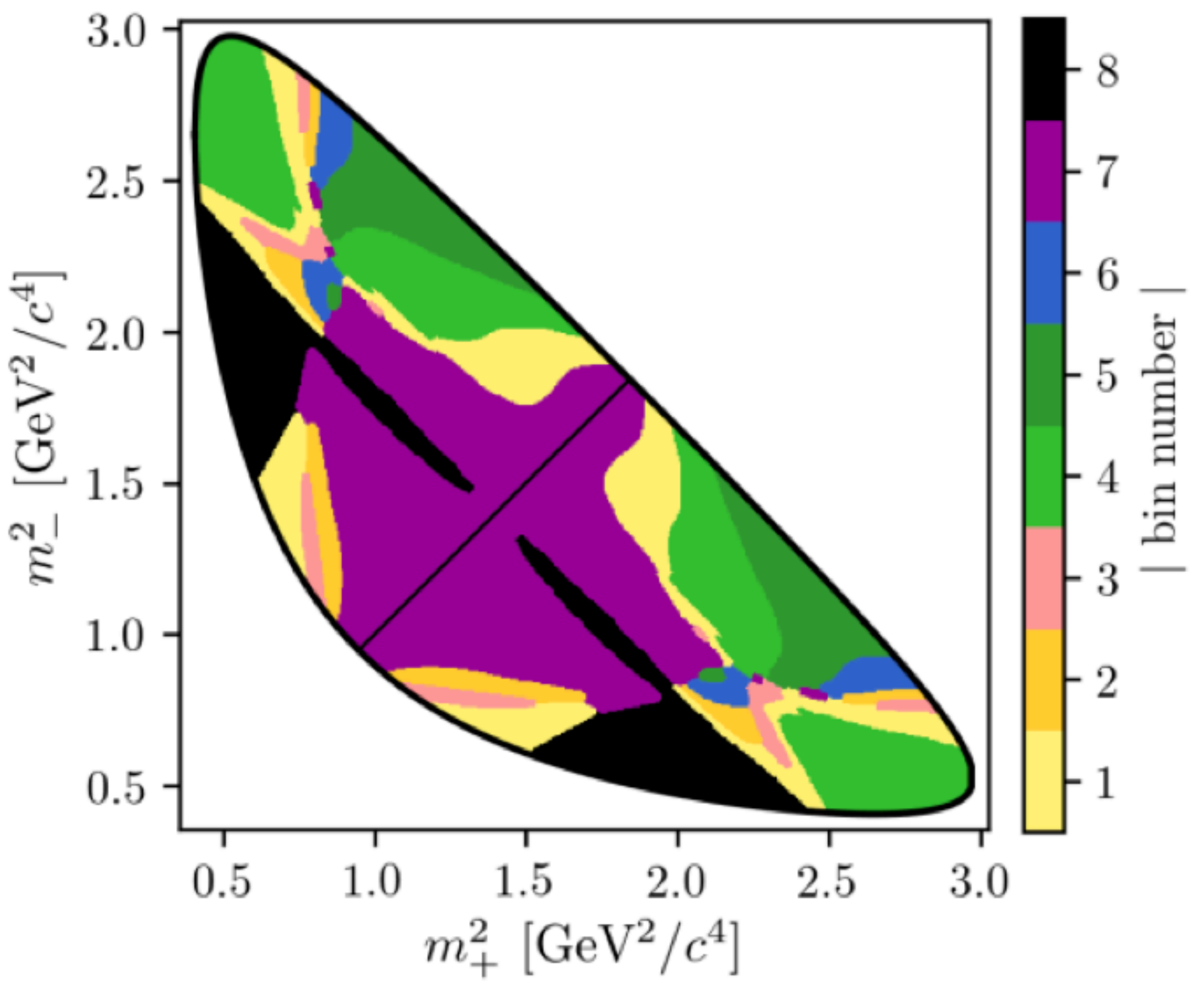
- Need inputs from charm experiments, e.g. strong-phase difference.
  - CLEO-c and BESIII provides **model-independent** external inputs.(**Valuable contribution!**)

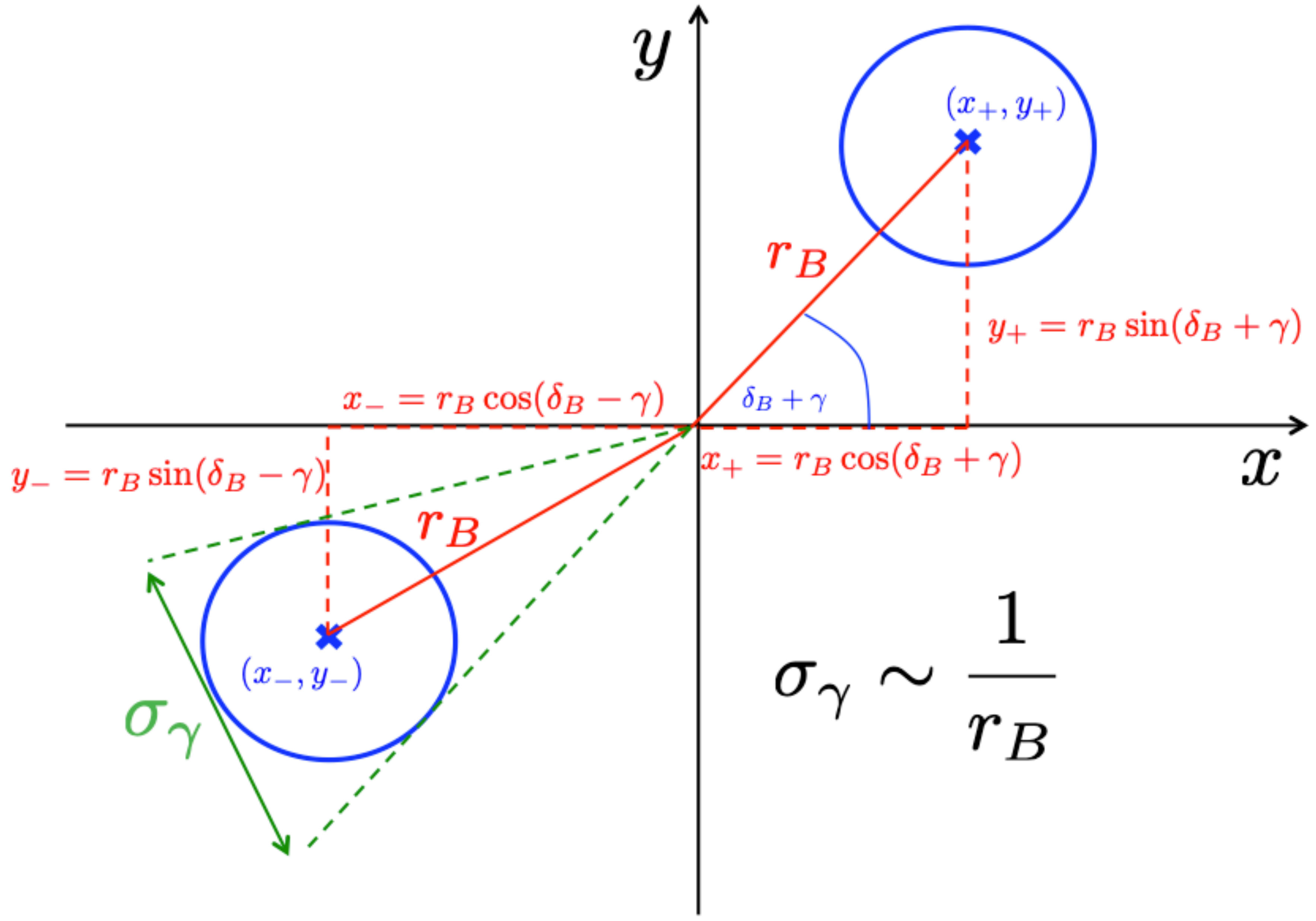
BPGGSZ method (golden channel)

- D decays to self conjugated multi-body final states.
- Binned way to gain more sensitivity from interference between various partial waves in local region(bin).
- D information, $|A|_i, c_i, s_i$, are measured by CLEO-c and BESIII.

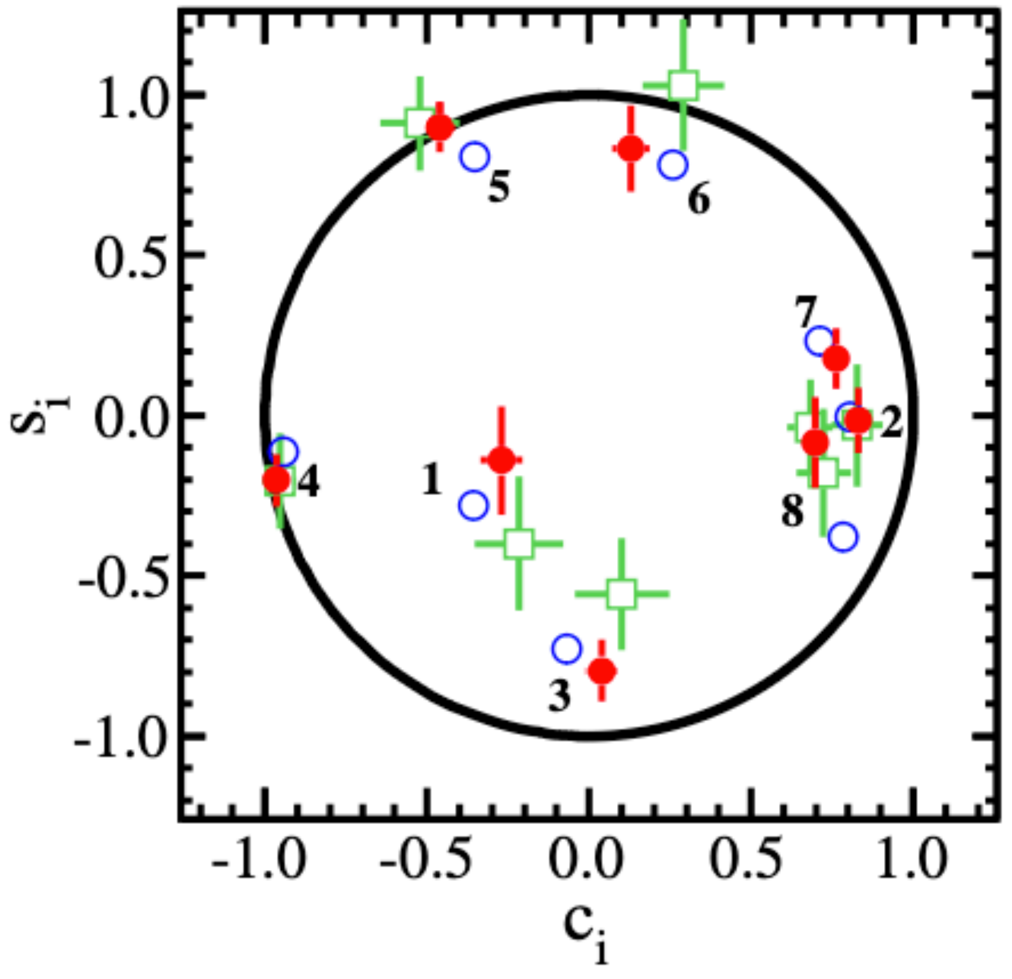
$$d\Gamma_{B^\pm}(\mathbf{x}) = A^2_{(\pm,\mp)} + r_B^2 A^2_{(\mp,\pm)} + 2A_{(\pm,\mp)}A_{(\mp,\pm)}\left[\underbrace{r_B\cos(\delta_B \pm \gamma)}_{x_\pm}\underbrace{\cos(\delta_{D(\pm,\mp)})}_{c_i} + \underbrace{r_B\sin(\delta_B \pm \gamma)}_{y_\pm}\underbrace{\sin(\delta_{D(\pm,\mp)})}_{s_i}\right]$$

$D \to K_S^0\pi^+\pi^-$



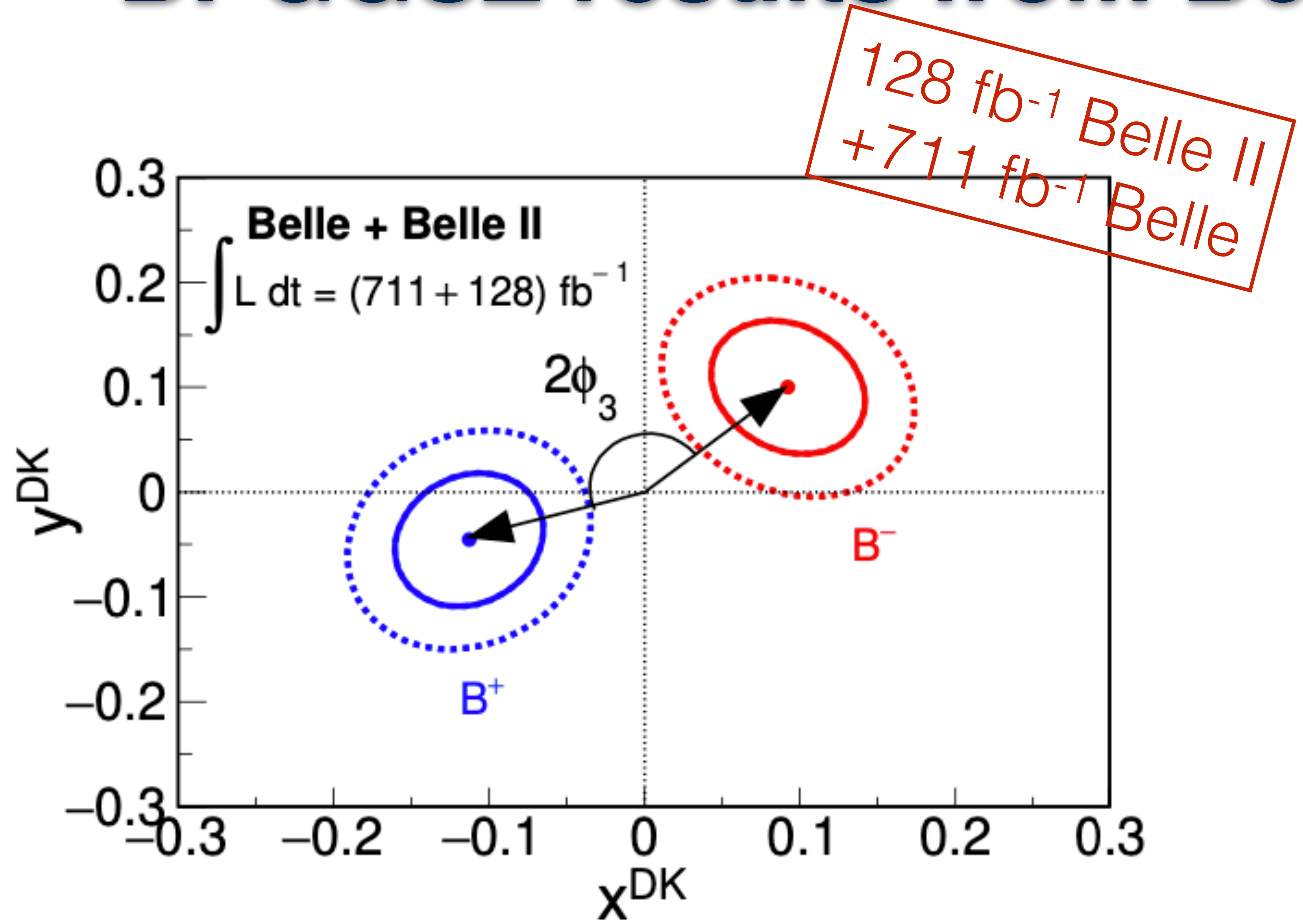


- ϕ_3's precision highly depends on the r_B's value!
- Large r_B -> large interference in B->DK-> more sensitive to ϕ_3.



Blue:model
Red:BESIII
Green:CLEO

BPGGSZ results from Belle and Belle II

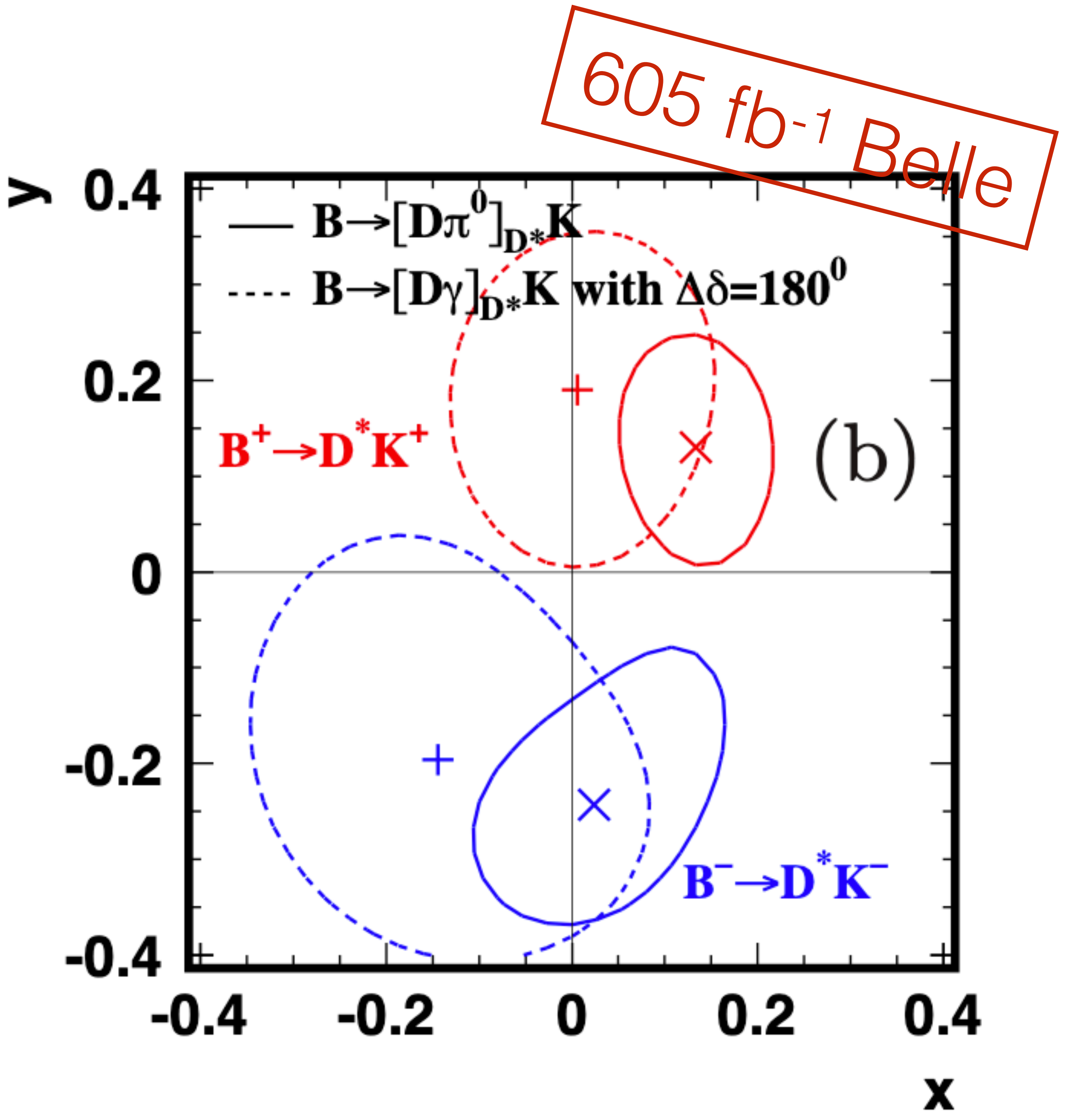


$B^+ \to Dh^+, D \to K_S^0 h^+ h^-$

JHEP 02(2022)063

$(78.4 \pm 11.4 \pm 0.5 \pm 1.0)^\circ$

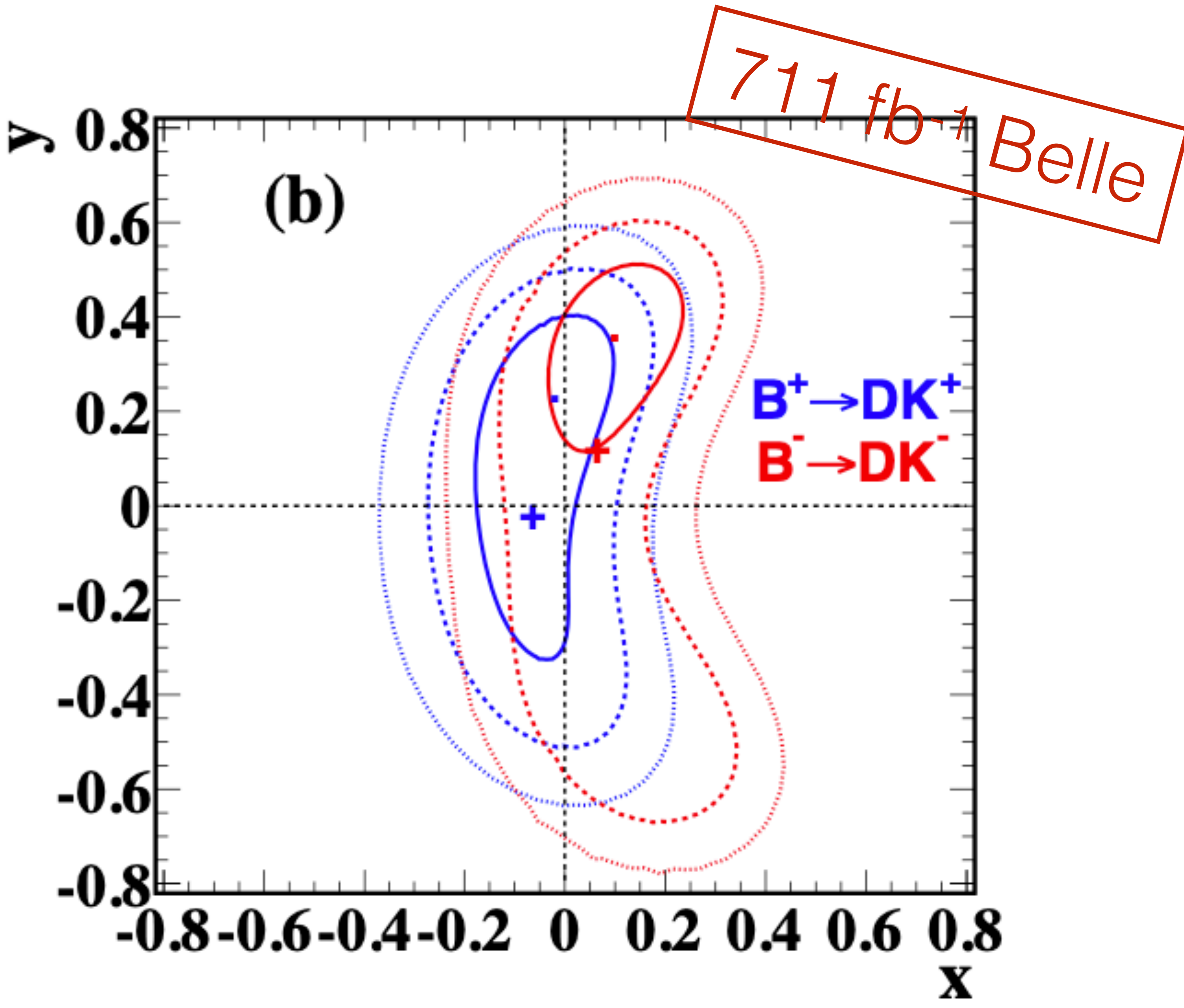
Stat Syst ci/si



$B^+ \to D^* h^+, D \to K_S^0 \pi^+ \pi^-$

Phys. Rev. D 81 (2010) 112002

$(73.9^{+18.9}_{-20.2} \pm 4.2 \pm 8.9)^\circ$



$B^+ \to Dh^+, D \to K_S^0 \pi^+ \pi^- \pi^0$

JHEP 10(2019)178

$(5.7^{+10.2}_{-8.8} \pm 3.5 \pm 5.7)^\circ$

- Many ϕ_3 (and other observables) numbers from different final states. Which one shall we look at?
- Need a combination! Also can check consistent among many results.

Combination of ϕ_3 using results from Belle and Belle II

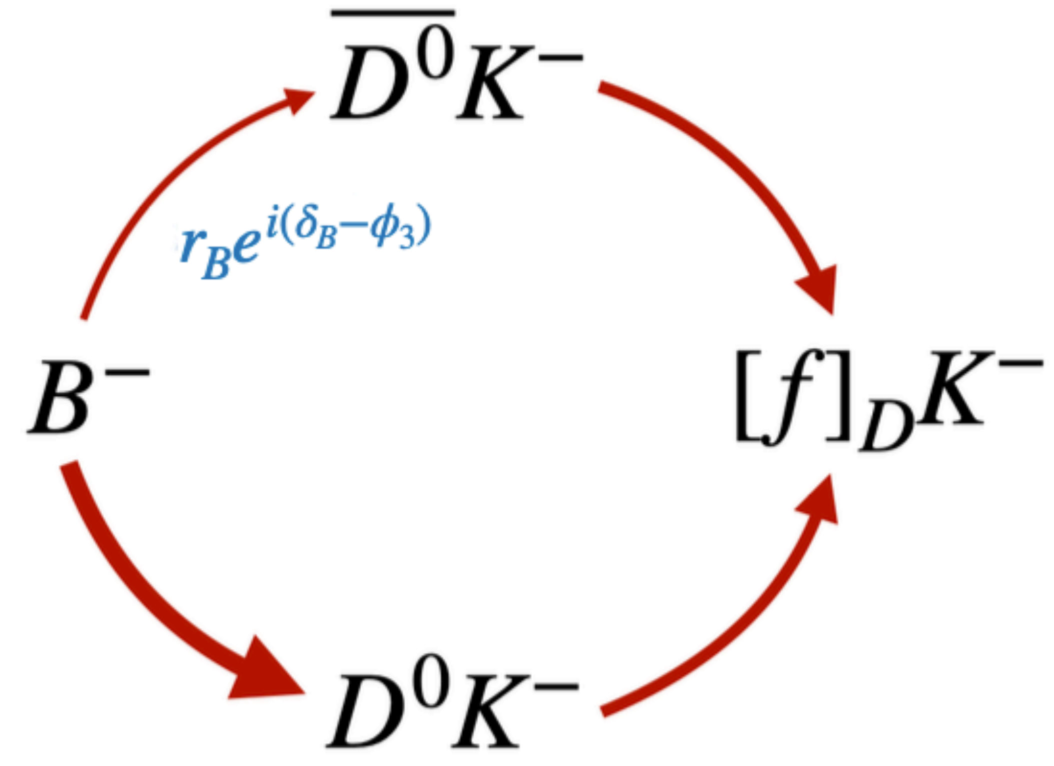
- Combine four different methods, 17 different final states.
- Only 3 results used Belle II Run1 data. (More precise results are expected.)
- Tool: GammaCombo, a dedicated tool for combination by LHCb.

B decay	D decay	Method	Data set (Belle + Belle II)[fb^{-1}]	
$B^+ \to Dh^+$	$D \to K_S^0\pi^0, K^-K^+$	GLW	$711+189$	[JHEP 05 212 (2024)]
$B^+ \to Dh^+$	$D \to K^+\pi^-, K^+\pi^-\pi^0$	ADS	$711+0$	[PRL 106 231803 (2011), PRD 88 091104(2013)]
$B^+ \to Dh^+$	$D \to K_S^0 K^-\pi^+$	GLS	$711+362$	[JHEP 09 146 (2023)]
$B^+ \to Dh^+$	$D \to K_S^0 h^-h^+$	BPGGSZ (m.i.)	$711+128$	[JHEP 02 063 (2022)]
$B^+ \to Dh^+$	$D \to K_S^0\pi^-\pi^+\pi^0$	BPGGSZ (m.i.)	$711+0$	[JHEP 10 178 (2019)]
$B^+ \to D^*K^+$	$D^* \to D\pi^0, D \to K_S^0\pi^0, K_S^0\phi, K_S^0\omega, K^-K^+, \pi^-\pi^+$	GLW	210+0	[PRD 73 051106 (2006)]
$B^+ \to D^*K^+$	$D^* \to D\pi^0, D\gamma, D \to K_S^0\pi^-\pi^+$	BPGGSZ (m.d.)	$605+0$	[PRD 81 112002 (2010)]

- $B^0 \to D^{(*)}h^{(*)}$ results are not used: negligible contribution and extra parameters introduced.

External inputs to ϕ_3 combination

Decay	Observable	Value	Source
$D \to K^+\pi^-$	$R_D^{K\pi}$	$(3.44 \pm 0.02) \times 10^{-3}$	HFLAV
	$\delta_D^{K\pi}$	$(191.7 \pm 3.7)^\circ$	
	$r_D^{K\pi}\cos(\delta_D^{K\pi})$	-0.0562 ± 0.0081	BESIII
	$r_D^{K\pi}\sin(\delta_D^{K\pi})$	-0.011 ± 0.012	
$D \to K^+\pi^-\pi^0$	$r_D^{K\pi\pi^0}$	0.0447 ± 0.0012	CLEO + LHCb
	$\kappa_D^{K\pi\pi^0}$	0.81 ± 0.06	
	$\delta_D^{K\pi\pi^0}$	$(198 \pm 15)^\circ$	
	$r_D^{K\pi\pi^0}$	0.0440 ± 0.0011	BESIII
	$\kappa_D^{K\pi\pi^0}$	0.78 ± 0.04	
	$\delta_D^{K\pi\pi^0}$	$(196 \pm 15)^\circ$	
$D \to K_S^0 K^-\pi^+$	$(r_D^{K_S^0 K\pi})^2$	0.356 ± 0.034	CLEO
	$\kappa_D^{K_S^0 K\pi}$	0.94 ± 0.12	
	$\delta_D^{K_S^0 K\pi}$	$(-16.6 \pm 18.4)^\circ$	
	$(r_D^{K_S^0 K\pi})^2$	0.370 ± 0.003	LHCb
$B^+ \to Dh^+$	R_{GLS}	0.0789 ± 0.0027	PDG

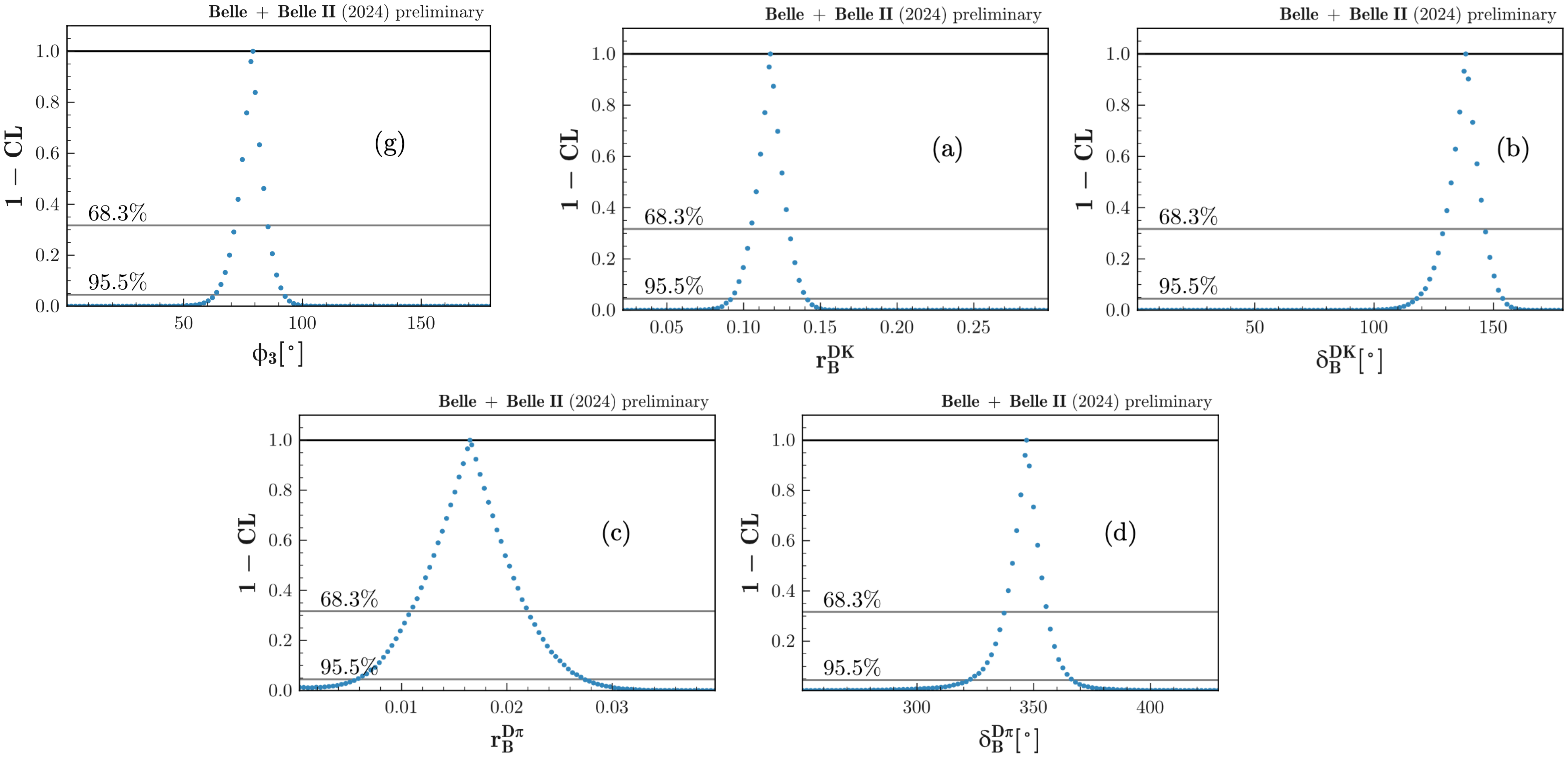


- External inputs: mainly from CLEO and BESIII.
- Looking forward to more precise and valuable results from BESIII!
- Extra wish 🙏: appreciate a lot if BESIII could present the Br($D^0 \to K^-\pi^+\pi^0$)/ Br($D^0 \to K^-\pi^+$) (in the next Kpi,Kpipi0 strong phase difference paper?). This is the major uncertainty in π^0 systematic uncertainty in Belle II.

Results

- 60 input observables and 16 parameters. P-value of the fit quality: 75%.

Preliminary



p-value (PLUGIN): 75% **combining inputs from $B^+ \to D^{(*)}h^+$ decays: $\phi_3 = (78.6 \pm 7.3)^\circ$**

Parameters	$\phi_3(^\circ)$	r_B^{DK}	$\delta_B^{DK}(^\circ)$	$r_B^{D\pi}$	$\delta_B^{D\pi}(^\circ)$	$r_B^{D^*K}$	$\delta_B^{D^*K}(^\circ)$
			PLUGIN method				
Best fit value	78.6	0.117	138.4	0.0165	347.0	0.234	341
68.3% interval	[71.4, 85.4]	[0.105, 0.130]	[129.1, 146.5]	[0.0109, 0.0220]	[337.4, 355.7]	[0.165, 0.303]	[327,355]
95.5% interval	[63, 92]	[0.092, 0.141]	[118, 154]	[0.006, 0.027]	[322, 366]	[0.10, 0.37]	[307, 369]

Discussion about ϕ_3 combination

Preliminary

p-value (PLUGIN): 75%   **combining inputs from $B^+ \to D^{(*)} h^+$ decays: $\phi_3 = (78.6 \pm 7.3)^\circ$**

Parameters	$\phi_3(^\circ)$	r_B^{DK}	$\delta_B^{DK}(^\circ)$	$r_B^{D\pi}$	$\delta_B^{D\pi}(^\circ)$	$r_B^{D^*K}$	$\delta_B^{D^*K}(^\circ)$
PLUGIN method							
Best fit value	78.6	0.117	138.4	0.0165	347.0	0.234	341
68.3% interval	[71.4, 85.4]	[0.105, 0.130]	[129.1, 146.5]	[0.0109, 0.0220]	[337.4, 355.7]	[0.165, 0.303]	[327,355]
95.5% interval	[63, 92]	[0.092, 0.141]	[118, 154]	[0.006, 0.027]	[322, 366]	[0.10, 0.37]	[307, 369]

Comparing to W.A.: [HFLAV]

$\phi_3 = (65.9^{+3.3}_{-3.5})^\circ$

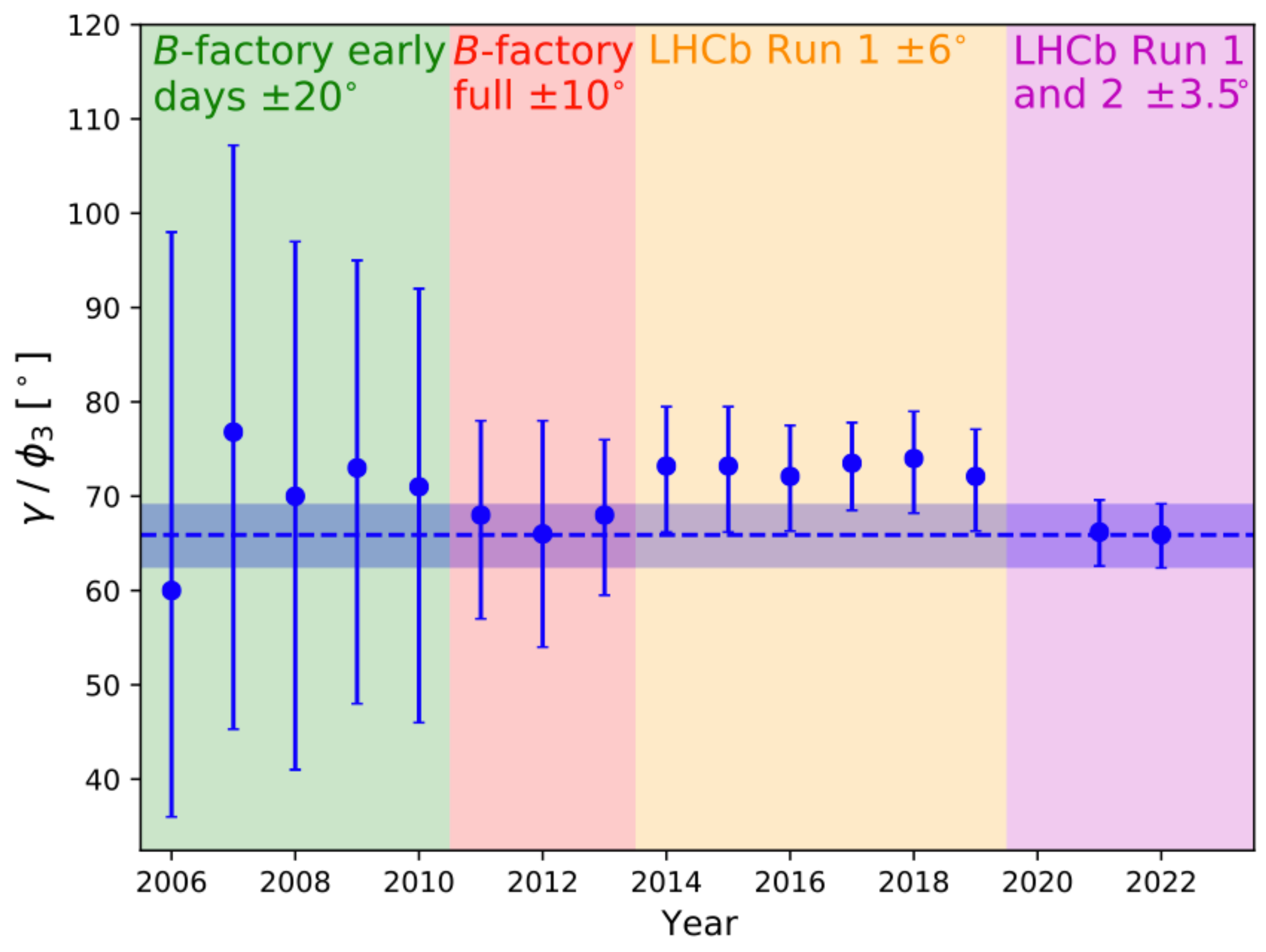
$r_B(DK^-) = (0.0994 \pm 0.0026)$

$\delta_B(DK^-) = (127.7^{+3.6}_{-3.9})^\circ$

$r_B(D\pi^-) = (0.0049 \pm 0.0006)$

$\delta_B(D\pi^-) = (294^{+9.7}_{-11})^\circ$

- Large ϕ_3, but consistent with w.a. in 2 σ



Discussion about ϕ_3 combination

Preliminary

p-value (PLUGIN): 75%   **combining inputs from $B^+ \to D^{(*)} h^+$ decays: $\phi_3 = (78.6 \pm 7.3)^\circ$**

Parameters	$\phi_3(^\circ)$	r_B^{DK}	$\delta_B^{DK}(^\circ)$	$r_B^{D\pi}$	$\delta_B^{D\pi}(^\circ)$	$r_B^{D^*K}$	$\delta_B^{D^*K}(^\circ)$
PLUGIN method							
Best fit value	78.6	0.117	138.4	0.0165	347.0	0.234	341
68.3% interval	[71.4, 85.4]	[0.105, 0.130]	[129.1, 146.5]	[0.0109, 0.0220]	[337.4, 355.7]	[0.165, 0.303]	[327,355]
95.5% interval	[63, 92]	[0.092, 0.141]	[118, 154]	[0.006, 0.027]	[322, 366]	[0.10, 0.37]	[307, 369]

Comparing to W.A.: [HFLAV]

$\phi_3 = (65.9^{+3.3}_{-3.5})^\circ$

$r_B(DK^-) = (0.0994 \pm 0.0026)$

$\delta_B(DK^-) = (127.7^{+3.6}_{-3.9})^\circ$

$r_B(D\pi^-) = (0.0049 \pm 0.0006)$

$\delta_B(D\pi^-) = (294^{+9.7}_{-11})^\circ$

- Large ϕ_3, but consistent with w.a. in 2 σ
- Large r_B, so if future Belle II's data favor the small w.a. r_B, the ϕ_3's precision will be worse a bit.

Discussion about ϕ_3 combination

p-value (PLUGIN): 75% **combining inputs from $B^+ \to D^{(*)}h^+$ decays: $\phi_3 = (78.6 \pm 7.3)^\circ$**

Preliminary

Parameters	$\phi_3(^\circ)$	r_B^{DK}	$\delta_B^{DK}(^\circ)$	$r_B^{D\pi}$	$\delta_B^{D\pi}(^\circ)$	$r_B^{D^*K}$	$\delta_B^{D^*K}(^\circ)$
PLUGIN method							
Best fit value	78.6	0.117	138.4	0.0165	347.0	0.234	341
68.3% interval	[71.4, 85.4]	[0.105, 0.130]	[129.1, 146.5]	[0.0109, 0.0220]	[337.4, 355.7]	[0.165, 0.303]	[327,355]
95.5% interval	[63, 92]	[0.092, 0.141]	[118, 154]	[0.006, 0.027]	[322, 366]	[0.10, 0.37]	[307, 369]

Comparing to W.A.: [HFLAV]

$\phi_3 = (65.9^{+3.3}_{-3.5})^\circ$

$r_B(DK^-) = (0.0994 \pm 0.0026)$

$\delta_B(DK^-) = (127.7^{+3.6}_{-3.9})^\circ$

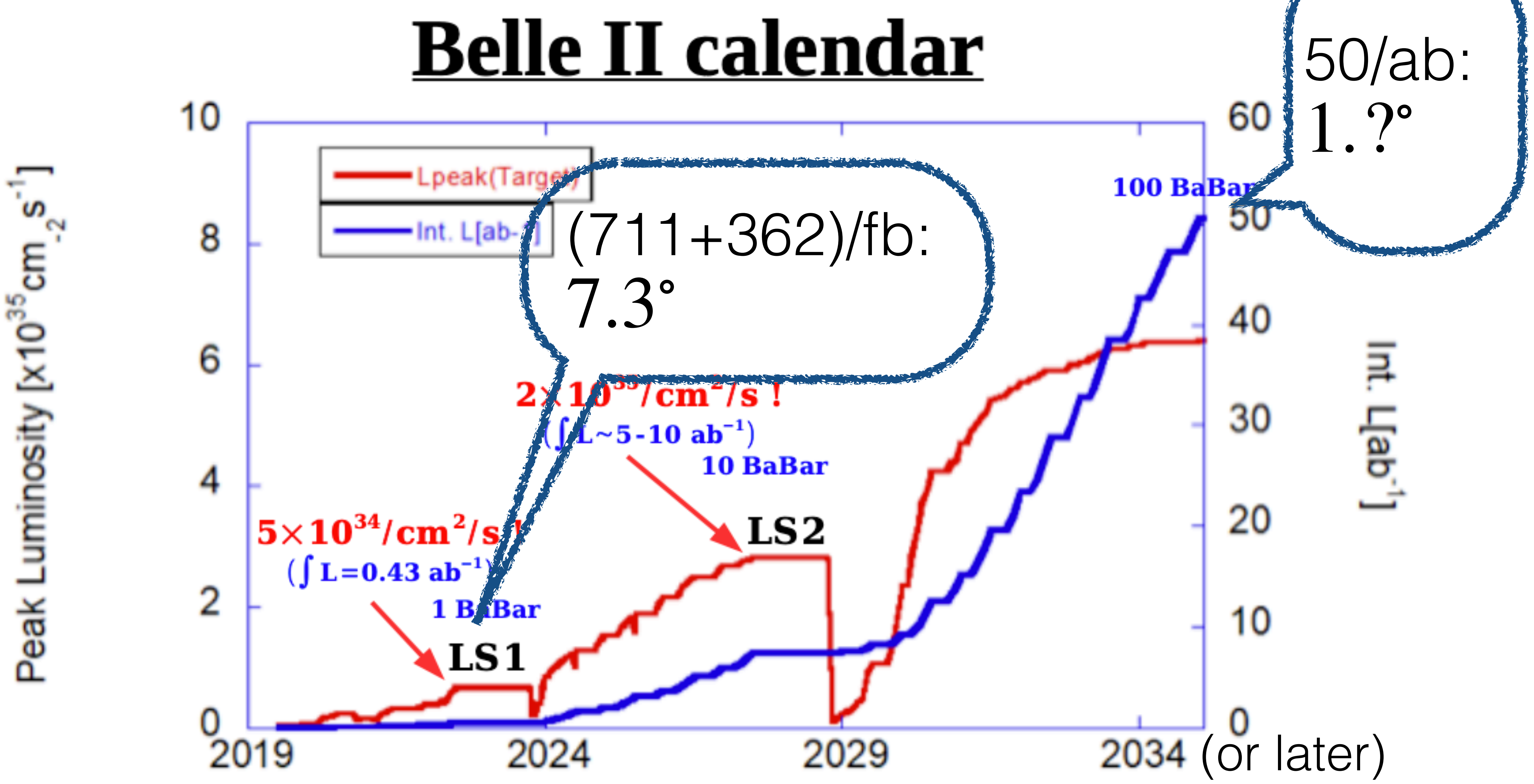
$r_B(D\pi^-) = (0.0049 \pm 0.0006)$

$\delta_B(D\pi^-) = (294^{+9.7}_{-11})^\circ$

- Large ϕ_3, but consistent with w.a. in 2 σ
- Large r_B, so if future Belle II's data favor the w.a. r_B, the ϕ_3's precision will be worse a bit with same data size.
- $(\delta_B(D\pi) + \delta_D) \sim 180^\circ$, $\cos(\delta_B(D\pi) + \delta_D)$'s uncertainty is much smaller than expected -> **unexpected precision** from ADS method. Not true anymore with w.a. $\delta_B(D\pi)$.

$$R_{ADS} = r_B^2 + r_D^2 + 2r_B r_D \cos(\delta_B + \delta_D)\cos(\phi_3)$$

Summary



run 1 (→ June 2022): integrated luminosity ~0.43 ab^{-1}, 4-5×$10^{34}/cm^2/s$
PXD complete (2 layers) to be installed during **LS1** (2022-2023)
(+beampipe + TOP PMTs)
run 2 (→ 2027): integrated luminosity 5-10 ab^{-1}, 2×$10^{35}/cm^2/s$
2027: collider upgrade (QCS+RF) → installation upgraded detector
run 3 (→ 2035): 50 ab^{-1}

- **First ϕ_3 combination** from Belle + Belle II : $(78.6 \pm 7.3)^\circ$. Worse precision comparing to LHCb's due to low statistics.
- On the path to 1 degree (or less) uncertainty on ϕ_3, with more data, more channels, (and possible advanced method).
- BESIII's **precise D results** will be highly appreciated.

- Spoiler alert: our result may change a bit after JHEP review stage, stay tuned!

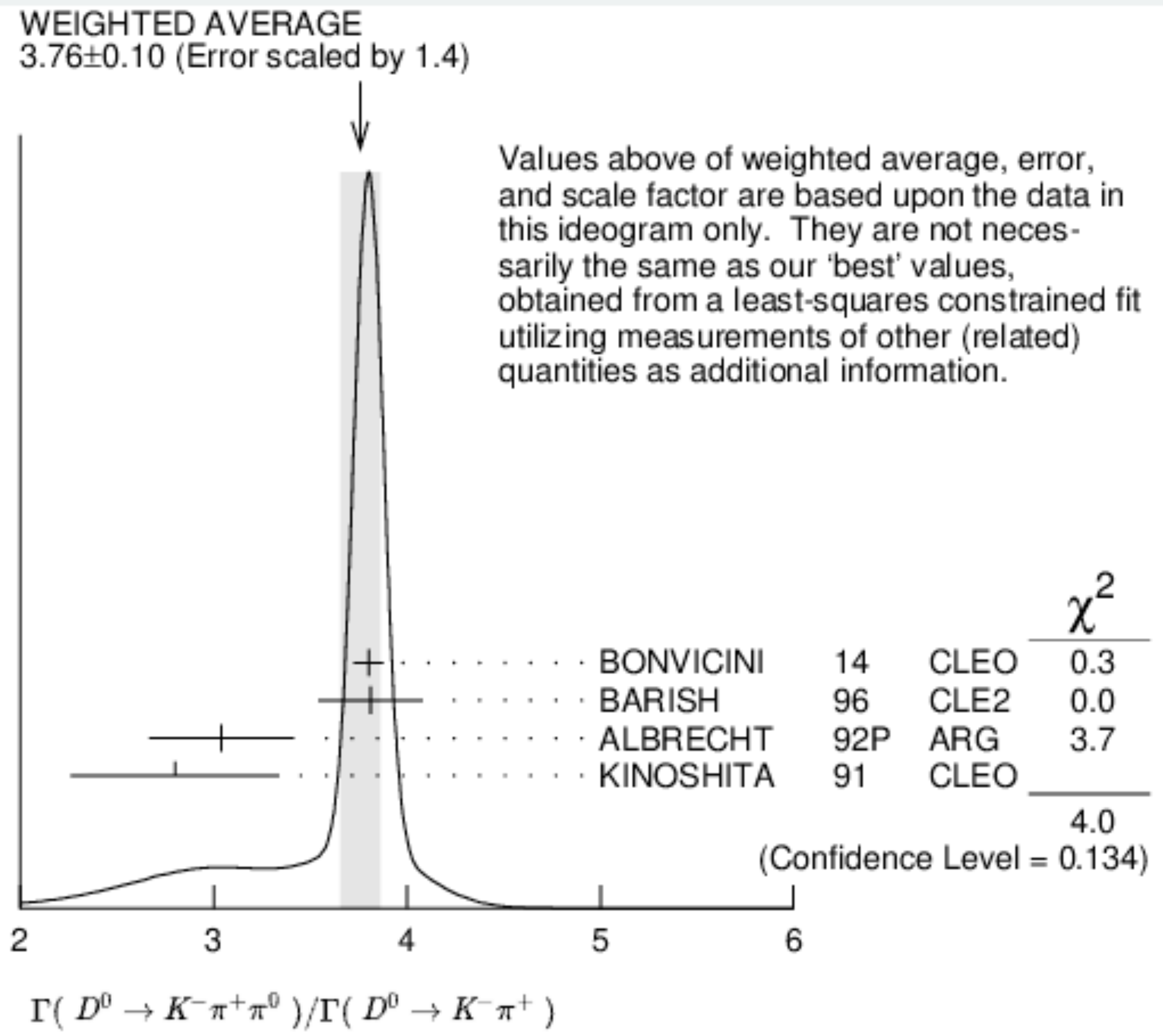
Thank you!

Back-Up

$\Gamma(D^0 \to K^-\pi^+\pi^0)/\Gamma(D^0 \to K^-\pi^+)$ Γ_{58}/Γ_{37}

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
3.65 ± 0.14	OUR FIT Error includes scale factor of 2.3.				
3.76 ± 0.10	OUR AVERAGE Error includes scale factor of 1.4. See the ideogram below.				
3.802 ±0.022 ±0.073		BONVICINI	2014	CLEO	All CLEO-c runs
3.81 ±0.07 ±0.26	10k	BARISH	1996	CLE2	$e^+e^- \approx \Upsilon(4S)$
3.04 ±0.16 ±0.34	931	[1] ALBRECHT	1992P	ARG	$e^+e^- \approx$ 10 GeV
2.8 ±0.14 ±0.52	1050	KINOSHITA	1991	CLEO	$e^+e^- \sim$ 10.7 GeV

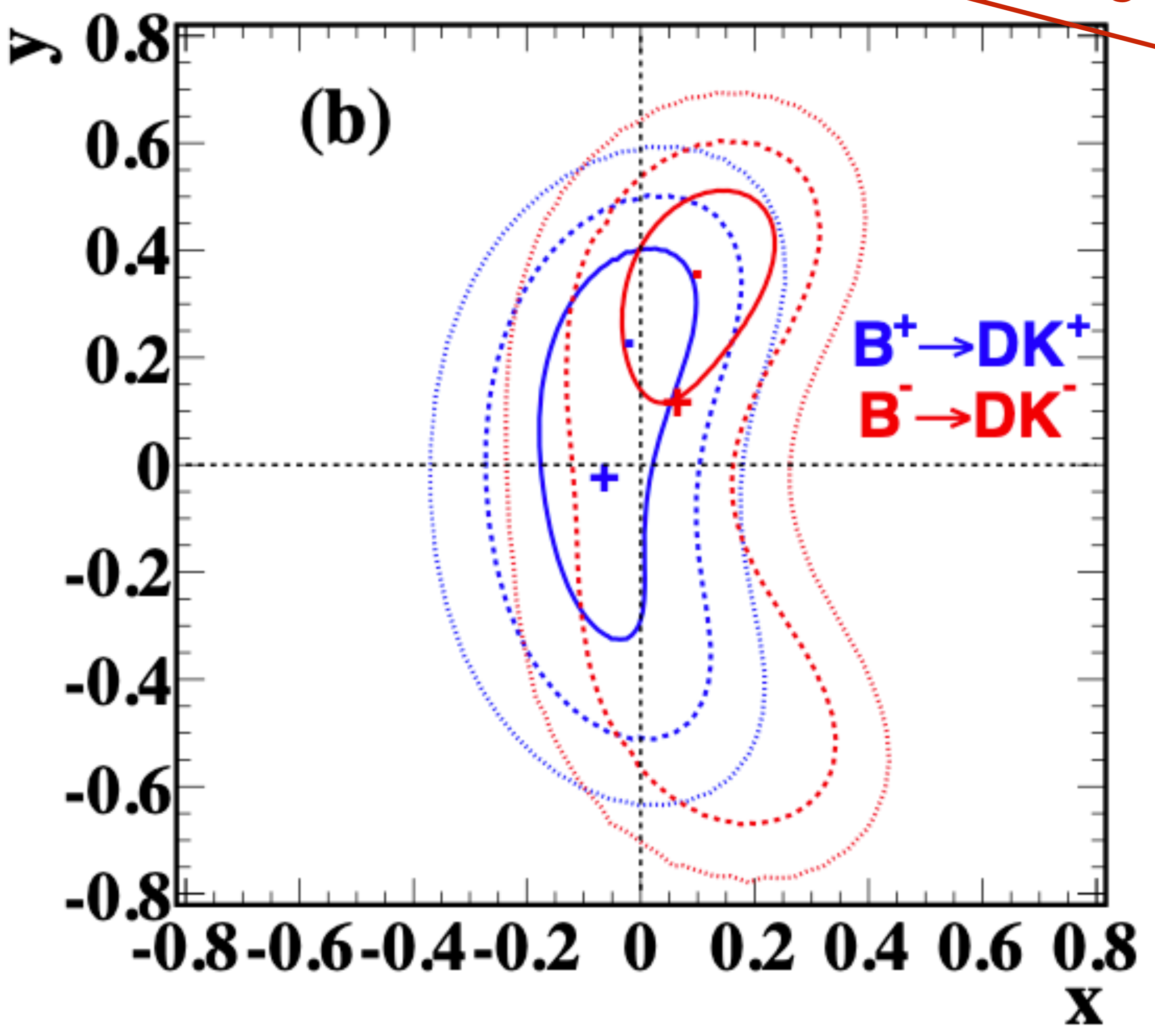
[1] This value is calculated from numbers in Table 1 of ALBRECHT 1992P.

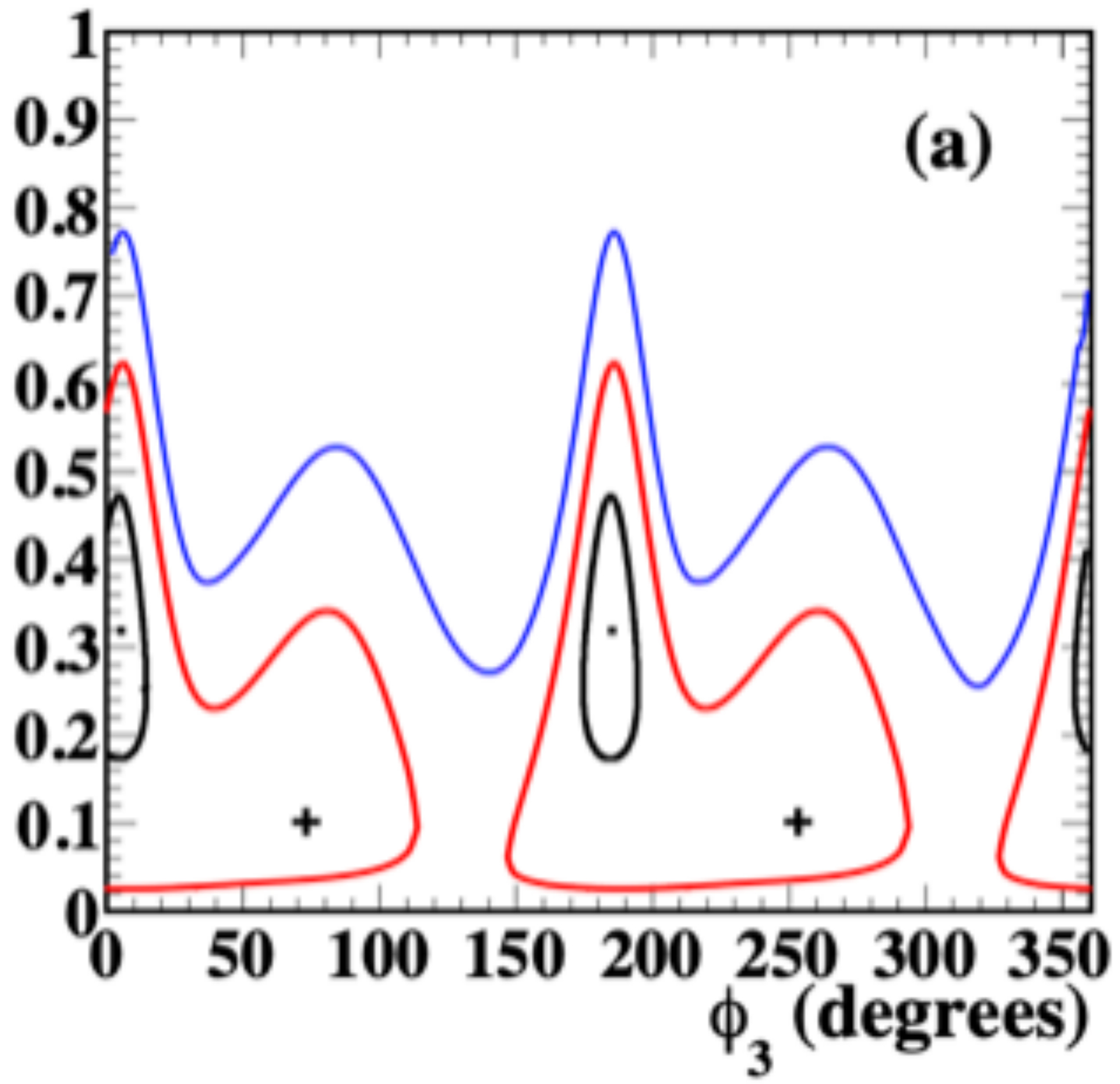


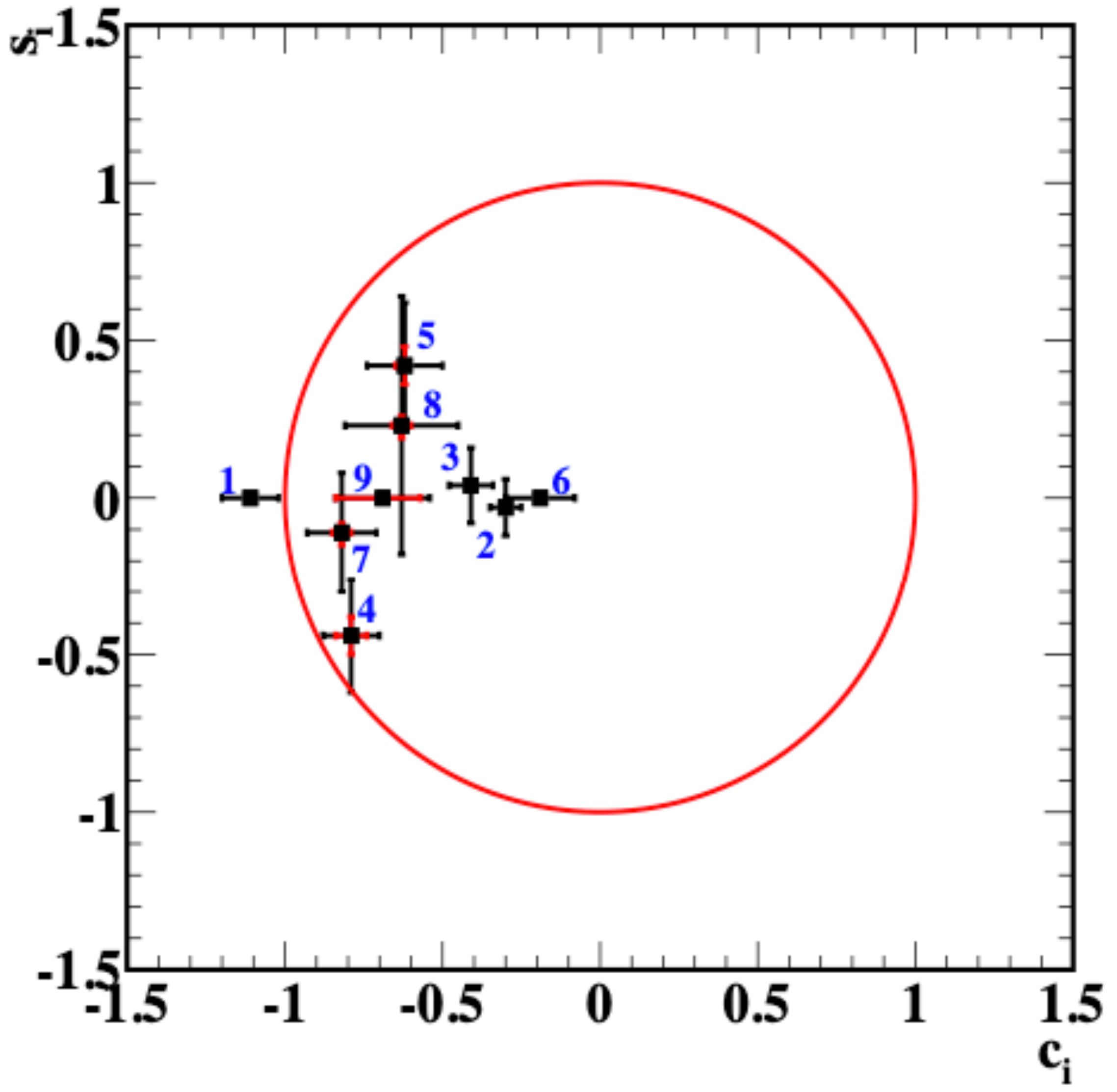
BPGGSZ results from Belle and Belle II

$$N_i^{\pm} = h_B[K_{\pm i} + r_B^2 K_{\mp i} + \sqrt{K_i K_{-i}}(x_{\pm} c_i \pm y_{\pm} s_i)],\quad x_{\pm} = r_B \cos(\delta_B \pm \phi_3)$$
$$y_{\pm} = r_B \sin(\delta_B \pm \phi_3)$$

711 fb-1 Belle







$B^+ \to Dh^+, D \to K_S^0\pi^+\pi^-\pi^0$

JHEP 10(2019)178

$(5.7^{+10.2}_{-8.8} \pm 3.5 \pm 5.7)^{\circ}$

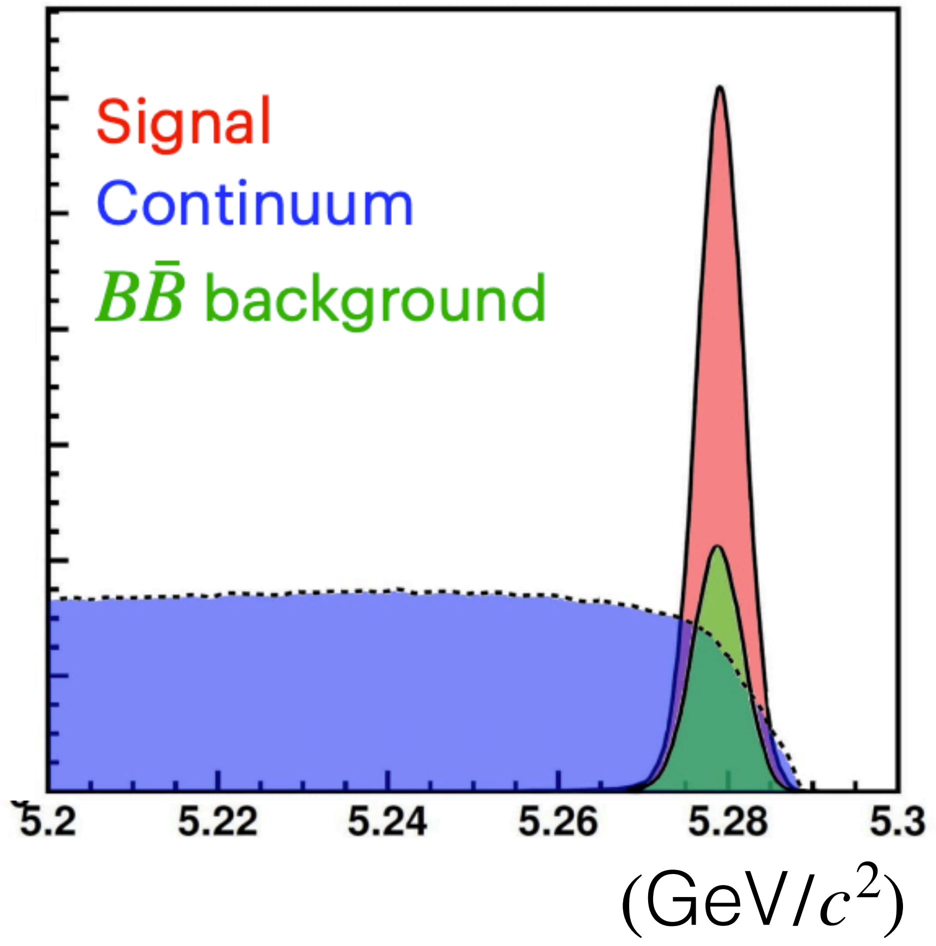
CLEO-c JHEP 01 (2018) 082

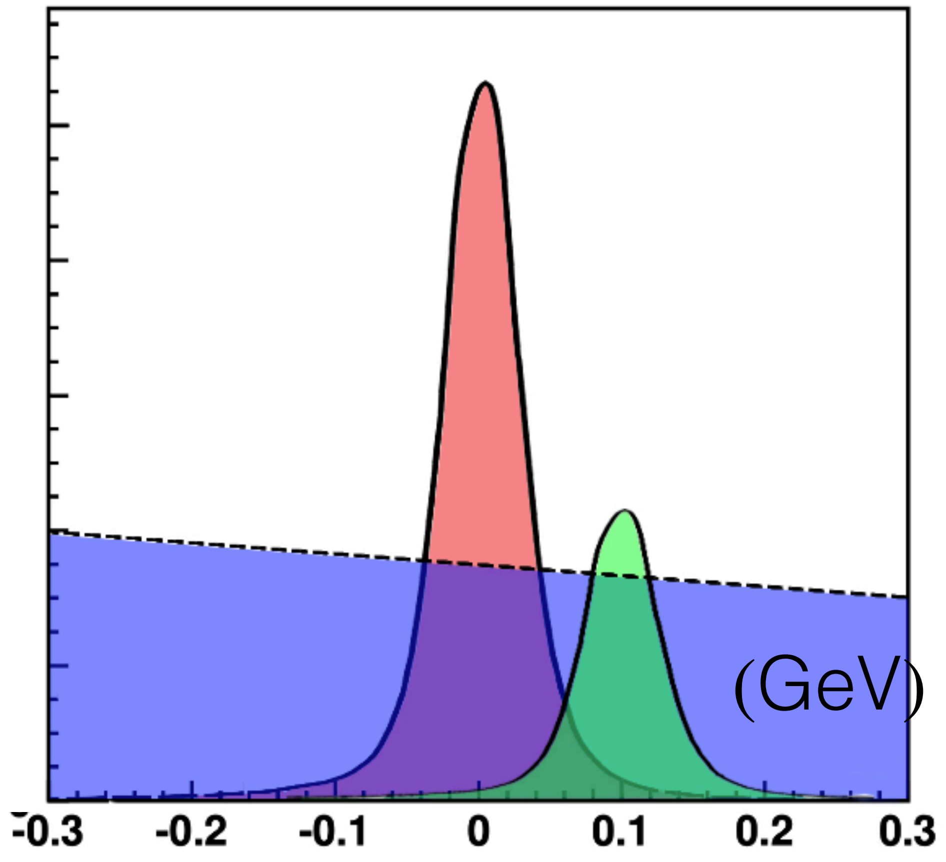
Binning scheme of $D \to K_S^0\pi^+\pi^-\pi^0$ is **not** optimized for ϕ_3.

BESIII will provide the optimized scheme and ci/si. Interesting to see the ϕ_3 from $B^+ \to Dh^+, D \to K_S^0\pi^+\pi^-\pi^0$ with new input from BESIII.

Similar analysis flow

- e^+e^- collide at $\Upsilon(4S)$, just above $B\bar{B}$ threshold: low background and well-known knowledge of initial state





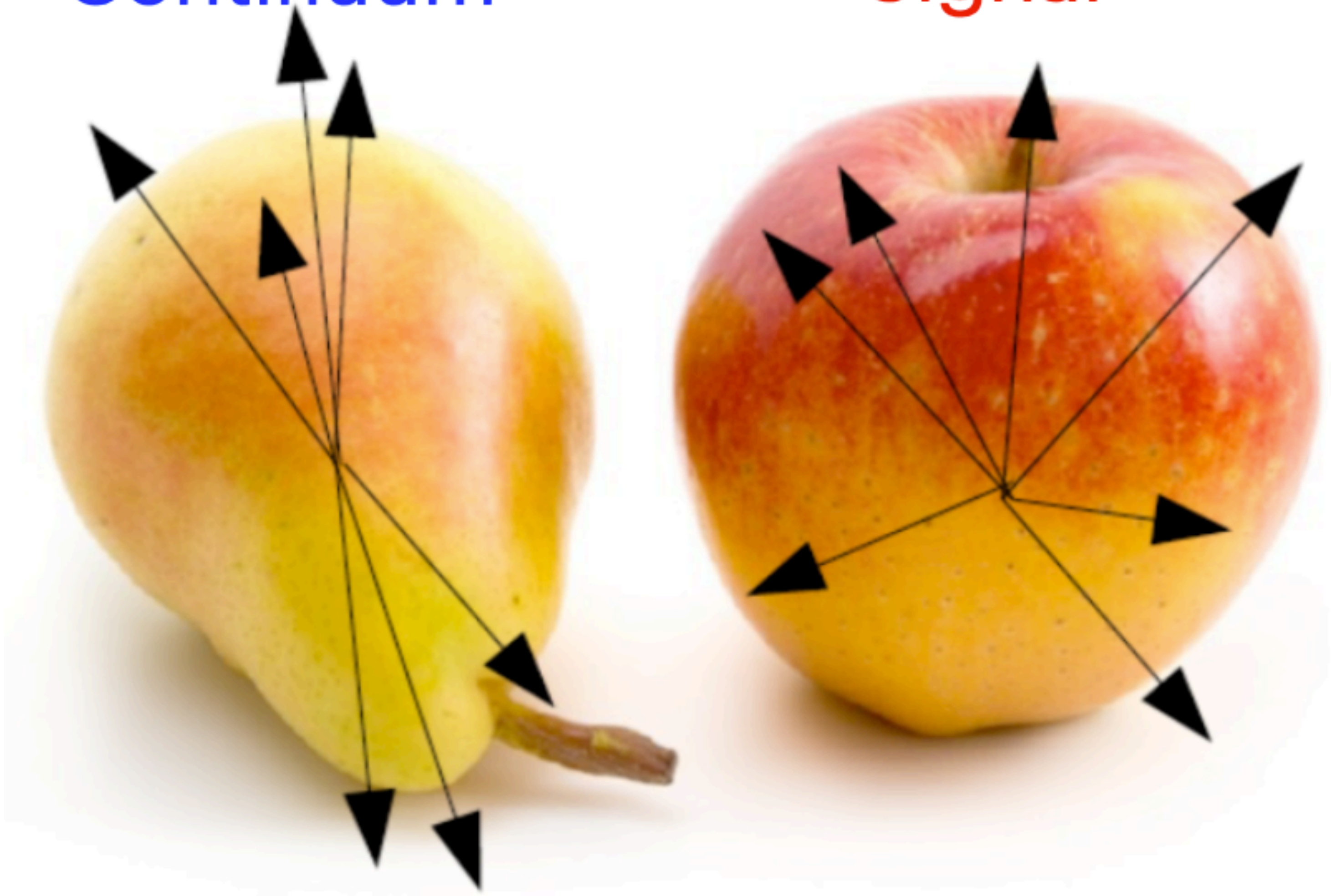
$M_{\rm bc} = \sqrt{s/4 - p_B^{*2}}$

$\Delta E = E_B^* - \sqrt{s}/2$

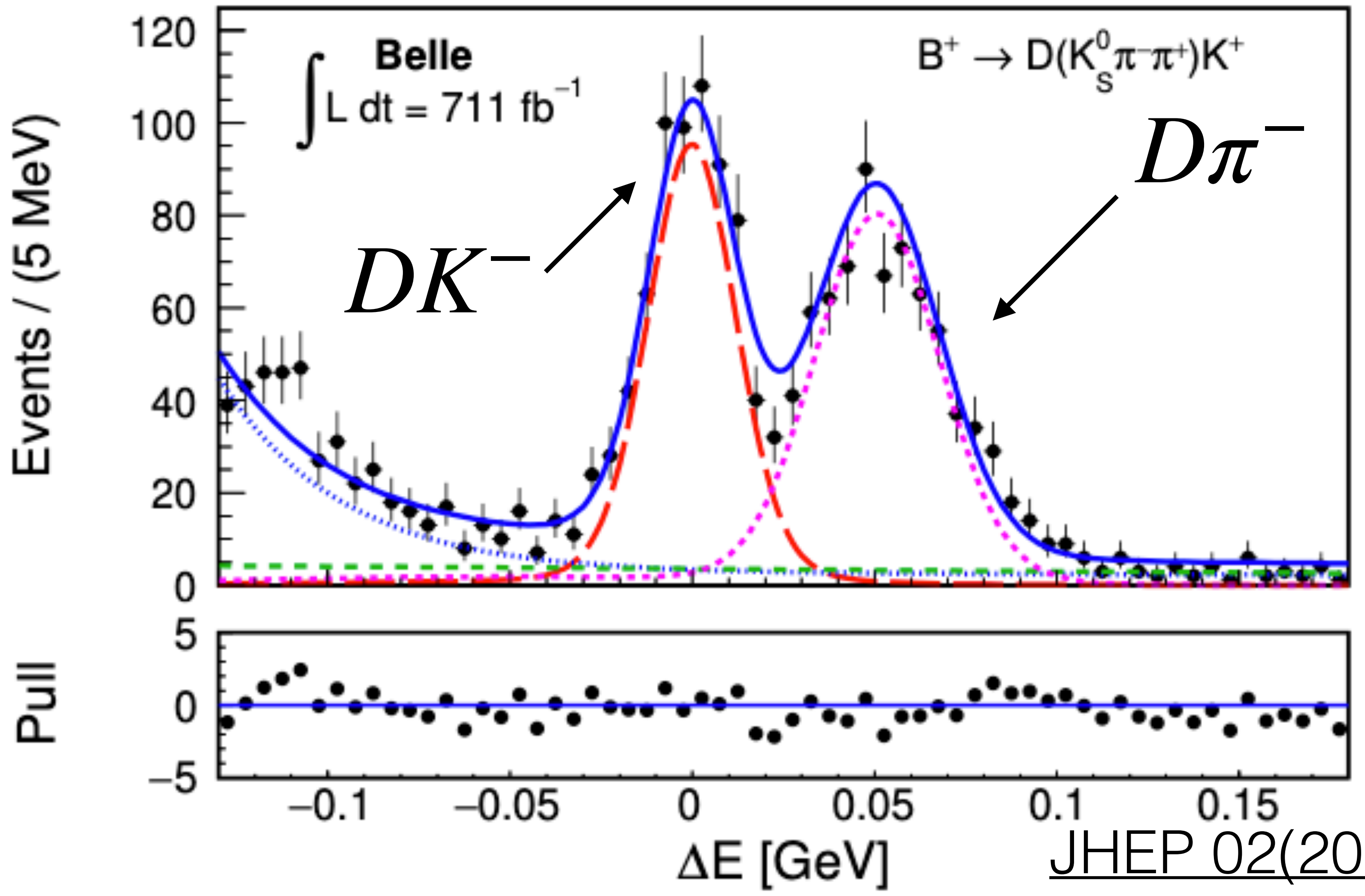
Collision energy

- Use **event shape** to identify continuum background (qqbar).

Continuum Signal



Extract signal on ΔE and BDT output.



JHEP 02(2022)063