WG5

Conveners: Gilberto Tetlamatzi-Xolocotzi , Minakshi Nayak & Melissa Cruz

Direct CP violation (DCPV) including ϕ3/γ from *B* →*DK*, DCPV effects, branching fractions and polarization in *B(s)* Charmless decays

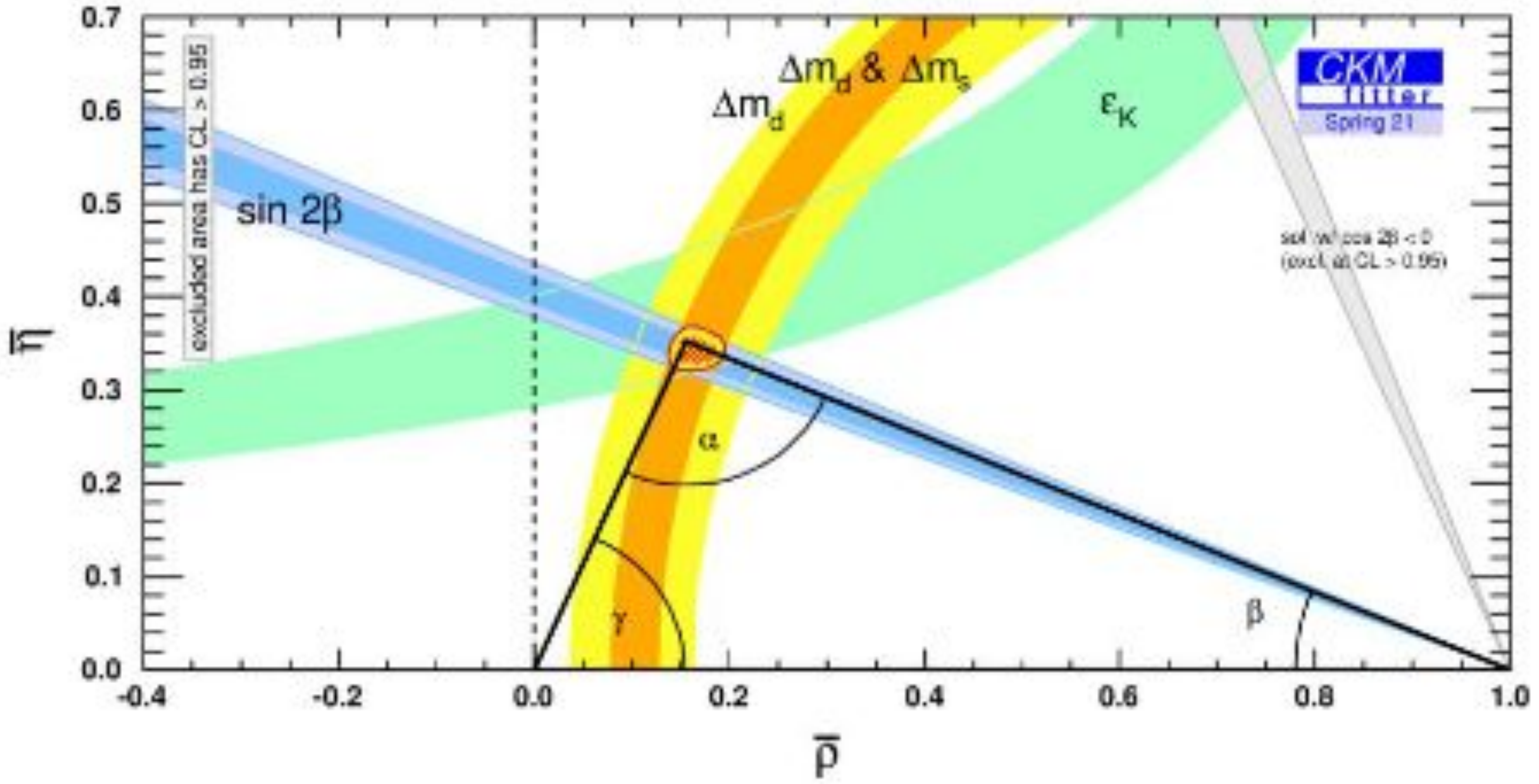
22/09/2023

CKM γ

Why measure γ

$$V_{\mathrm{CKM}} = \begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix} \rightarrow \gamma = arg\left(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right)$$

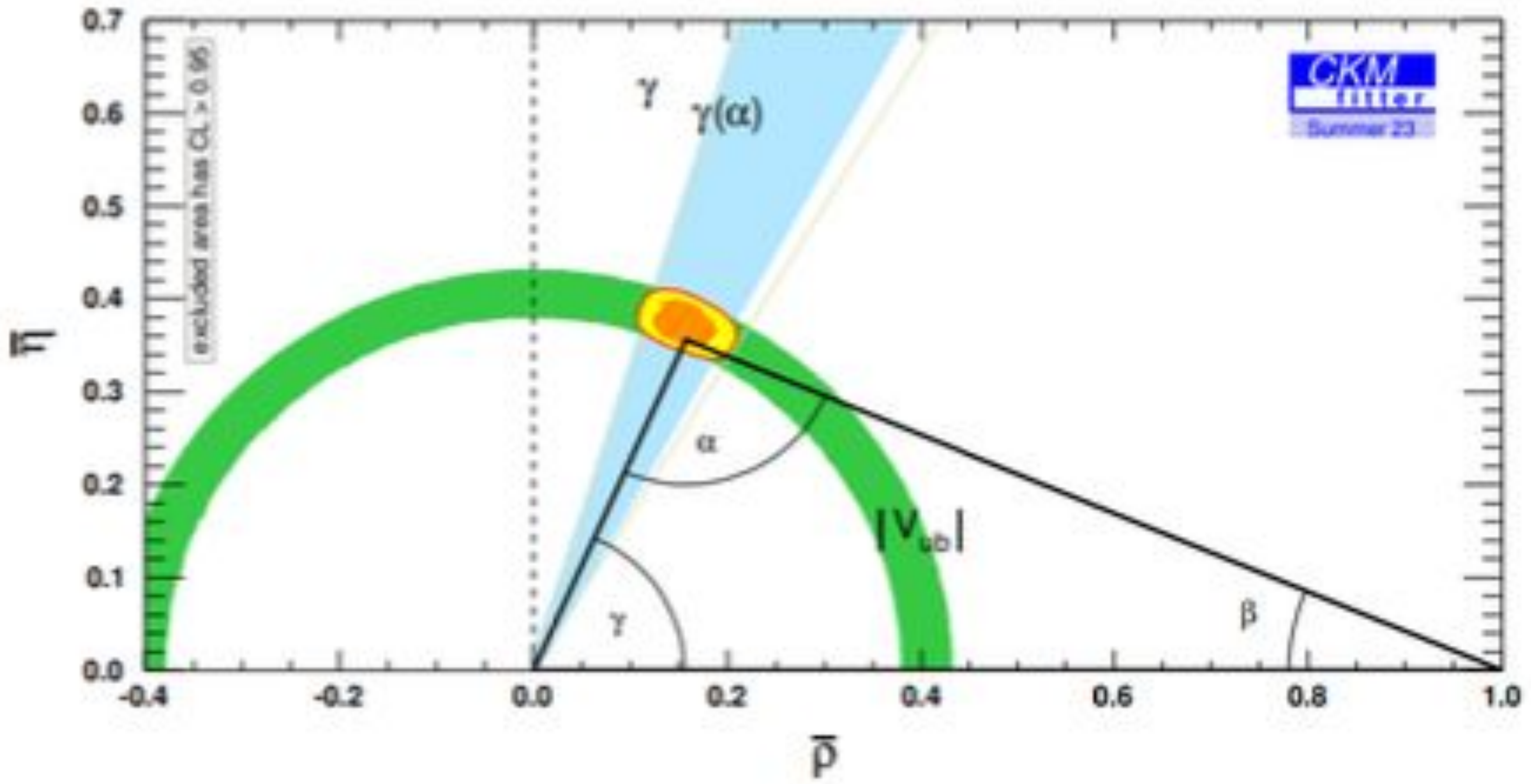
Indirect measurement



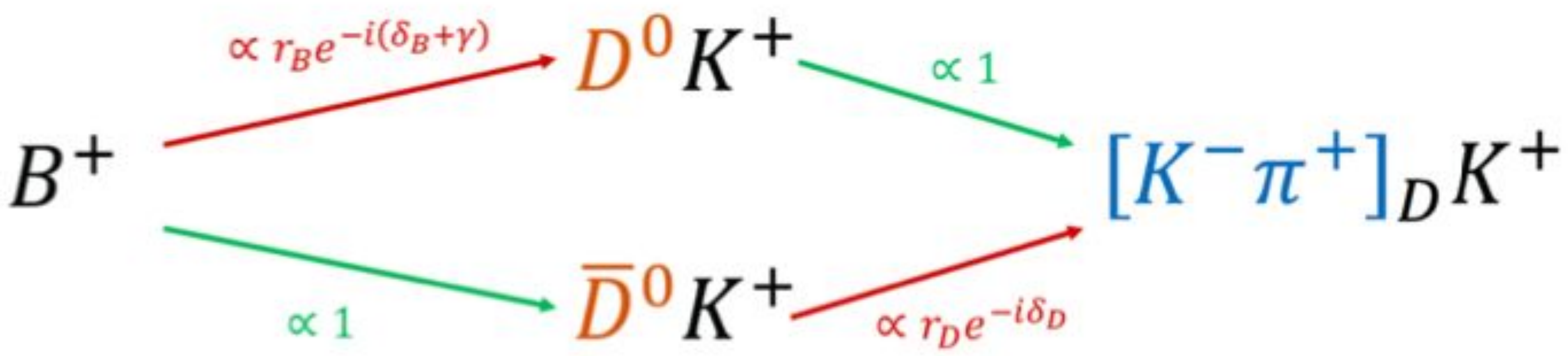
- Extrapolate γ from measurement of α and β
- Measured using loop-level decays: sensitivity to NP
- CKMFitter latest: $\gamma = (66.3^{+0.7}_{-1.9})^o$

Disagreement = New Physics!

Direct measurement



- Measure γ directly using tree-level decays
- Theoretically clean($\delta\gamma/\gamma < 10^{-7}$) *[JHEP 1401(2014)051]*
- HFLAV latest: $\gamma = (65.9^{+3.3}_{-3.5})^o$
- LHCb dominated: $\gamma = (63.8^{+3.5}_{-3.7})^o$ *[LHCb-CONF-2022-003]*



$$\Gamma(B^\pm \to f_D K^\pm) \propto r_B^2 + r_D^2 + 2R_f r_B r_D cos(\delta_B + \delta_D \pm \gamma)$$
$$\Gamma\left(B^\pm \to \bar{f}_D K^\pm\right) \propto 1 + r_B^2 r_D^2 + 2R_f r_B r_D cos(\delta_B - \delta_D \pm \gamma)$$

Need inputs from charm factory

GLW method [Gronau London 1991, Gronau Wyler 1991]

- D decay to CP eigenstate, such as K^+K^-, $\pi^+\pi^-$, $K_S^0\pi^0$.

ADS method [Atwood Dunietz Soni 1996]

- D decay to non-CP eigenstates: $D \to K^\mp\pi^\pm$.

BPGGSZ method [Bondar 2002, Giri Grossman Soffer Zupan 2003, Poluektov & Belle 2004]

- D decays into CP self-conjugate three-body final state, like $K_S\pi^-\pi^+$

Input for γ measurements from BESIII

$D \to K^-\pi^+\pi^-\pi^+/K^-\pi^+\pi^0$ strong parameters measurement

- A binning scheme for $\delta_{K3\pi}$ (*PLB **802**(2020)135188*)
- Obtain corresponding $\delta_{K3\pi}$ and $R_{K3\pi}$

Parameter	Global fit	Binned fit Bin 1	Bin 2	Bin 3	Bin 4
$R_{K3\pi}$	$0.52^{+0.12}_{-0.10}$	$0.58^{+0.25}_{-0.33}$	$0.78^{+0.50}_{-0.21}$	$0.85^{+0.15}_{-0.12}$	$0.45^{+0.33}_{-0.37}$
$\delta_D^{K3\pi}$	$(167^{+31}_{-19})^\circ$	$(131^{+124}_{-16})^\circ$	$(150^{+37}_{-39})^\circ$	$(176^{+57}_{-21})^\circ$	$(274^{+19}_{-30})^\circ$
$r_D^{K3\pi}$ $(\times 10^{-2})$	5.46 ± 0.09	$5.44^{+0.45}_{-0.14}$	$5.80^{+0.14}_{-0.13}$	$5.75^{+0.41}_{-0.14}$	$5.09^{+0.14}_{-0.14}$
$R_{K\pi\pi^0}$	0.78 ± 0.04	0.80 ± 0.04			
$\delta_D^{K\pi\pi^0}$	$(196^{+14}_{-15})^\circ$	$(200\pm11)^\circ$			
$r_D^{K\pi\pi^0}$ $(\times 10^{-2})$	4.40 ± 0.11	4.41 ± 0.11			

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

Method	F_+
CP-tag modes	$0.229 \pm 0.013 \pm 0.002$
$\pi^+\pi^-\pi^0$ tag mode	$0.227 \pm 0.014 \pm 0.003$
$\pi^+\pi^-\pi^+\pi^-$ tag mode	$0.227 \pm 0.016 \pm 0.003$
Self-tag modes	$0.244 \pm 0.019 \pm 0.002$
$K^0_{S,L}\pi^+\pi^-$	$0.244 \pm 0.021 \pm 0.006$
Combined	$0.235 \pm 0.010 \pm 0.002$

$D \to \pi^+\pi^-\pi^+\pi^-$ F^+ measurement

Tag modes	$F_+^{4\pi}$
CP eigenstates	$0.721\pm0.019\pm0.007$
$D\to\pi^+\pi^-\pi^0$	$0.753\pm0.028\pm0.010$
$D\to K^0_{S,L}\pi^+\pi^-$	$0.754\pm0.031\pm0.009$
Combination	$0.735\pm0.015\pm0.005$

$D \to K^+K^-\pi^+\pi^-$ F^+ measurement

$$F_+ = 0.730 \pm 0.037 \pm 0.021$$

used for γ measurement in LHCb

*EPJC **83** (2023) 547*

Update measurement of $\delta_{K\pi}$

$$\delta_D^{K\pi} = (187.6^{+8.9+5.4}_{-9.7-6.4})^\circ$$

New results of γ measurements in ADS and GLW-like decays at LHCb

$$R_{CP} = \frac{\Gamma(B^0 \to [h^+h^-]_D K^{*0}) + \Gamma(\overline{B^0} \to [h^+h^-]_D \overline{K^{*0}})}{\Gamma(B^0 \to [K^-\pi^+]_D K^{*0}) + \Gamma(\overline{B^0} \to [K^+\pi^-]_D \overline{K^{*0}})} \frac{\mathcal{B}(D^0 \to K^-\pi^+)}{\mathcal{B}(D^0 \to h^+h^-)} = \frac{1 + r_B^2 + 2r_B\kappa\cos(\delta_B)\cos(\gamma)}{1 + r_B^2 r_D^2 + 2r_B r_D \kappa\cos(\delta_B - \delta_D)\cos(\gamma)}$$

$$A_{CP} = \frac{\Gamma(B^0 \to [h^+h^-]_D K^{*0}) - \Gamma(\overline{B^0} \to [h^+h^-]_D \overline{K^{*0}})}{\Gamma(B^0 \to [h^+h^-]_D K^{*0}) + \Gamma(\overline{B^0} \to [h^+h^-]_D \overline{K^{*0}})} = \frac{2r_B\kappa\sin(\delta_B)\sin(\gamma)}{1 + r_B^2 + 2\kappa\cos(\delta_B)\cos(\gamma)}$$

Results: GLW Mode $(D \to KK)$

$$A_{CP}^{KK} = -0.047 \pm 0.063 \pm 0.015$$
$$R_{CP}^{KK} = 0.817 \pm 0.057 \pm 0.017$$

Results: ADS Mode $(D \to \pi K)$

$$R_{\pi K}^{+} = 0.069 \pm 0.013 \pm 0.005$$
$$R_{\pi K}^{-} = 0.093 \pm 0.013 \pm 0.005$$

Results: GLW Mode $(D \to \pi\pi\pi\pi)$

$$R_{CP}^{4\pi} = 0.882 \pm 0.086 \pm 0.033$$
$$A_{CP}^{4\pi} = 0.014 \pm 0.087 \pm 0.016$$

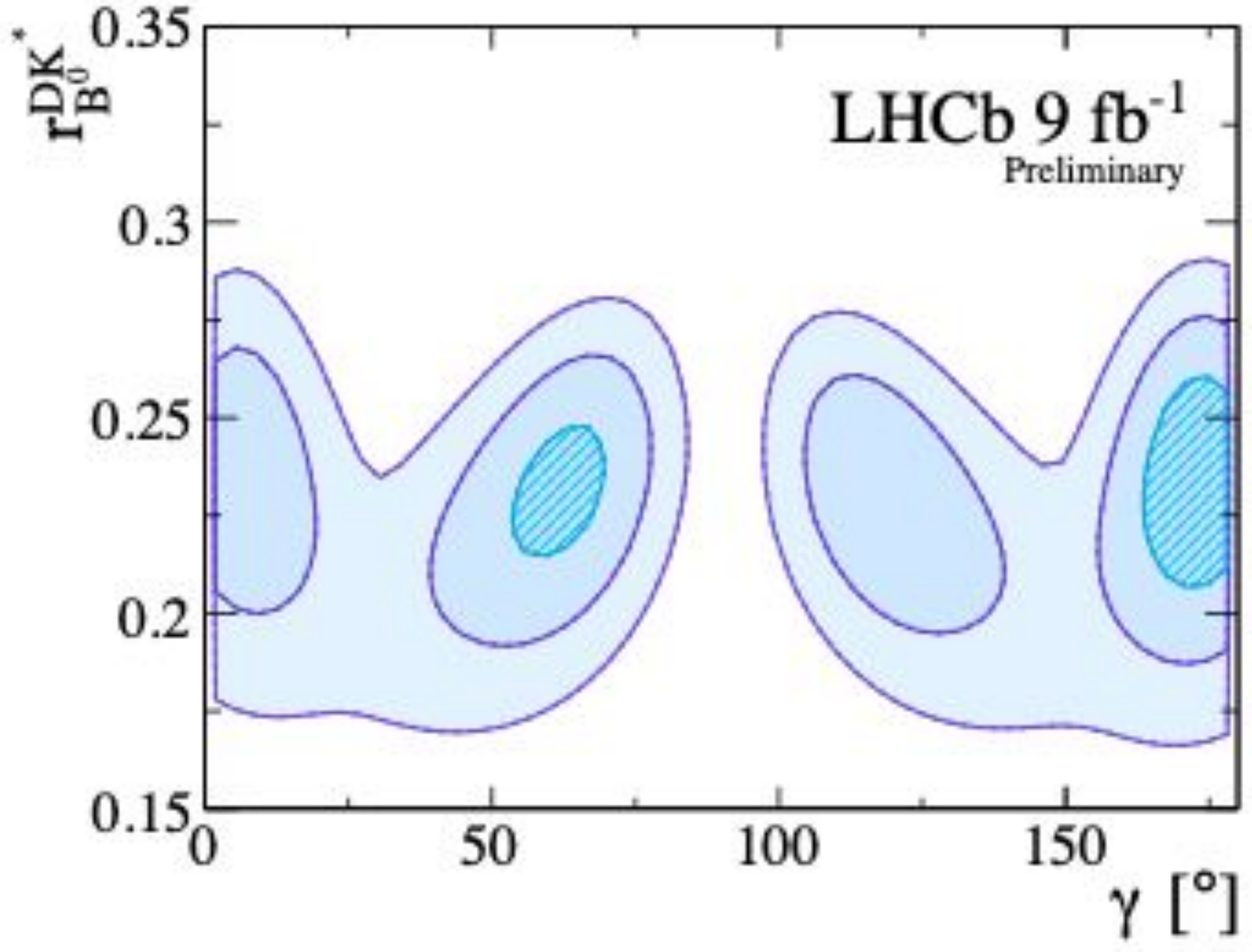
Results: ADS Mode $(D \to \pi K\pi\pi)$

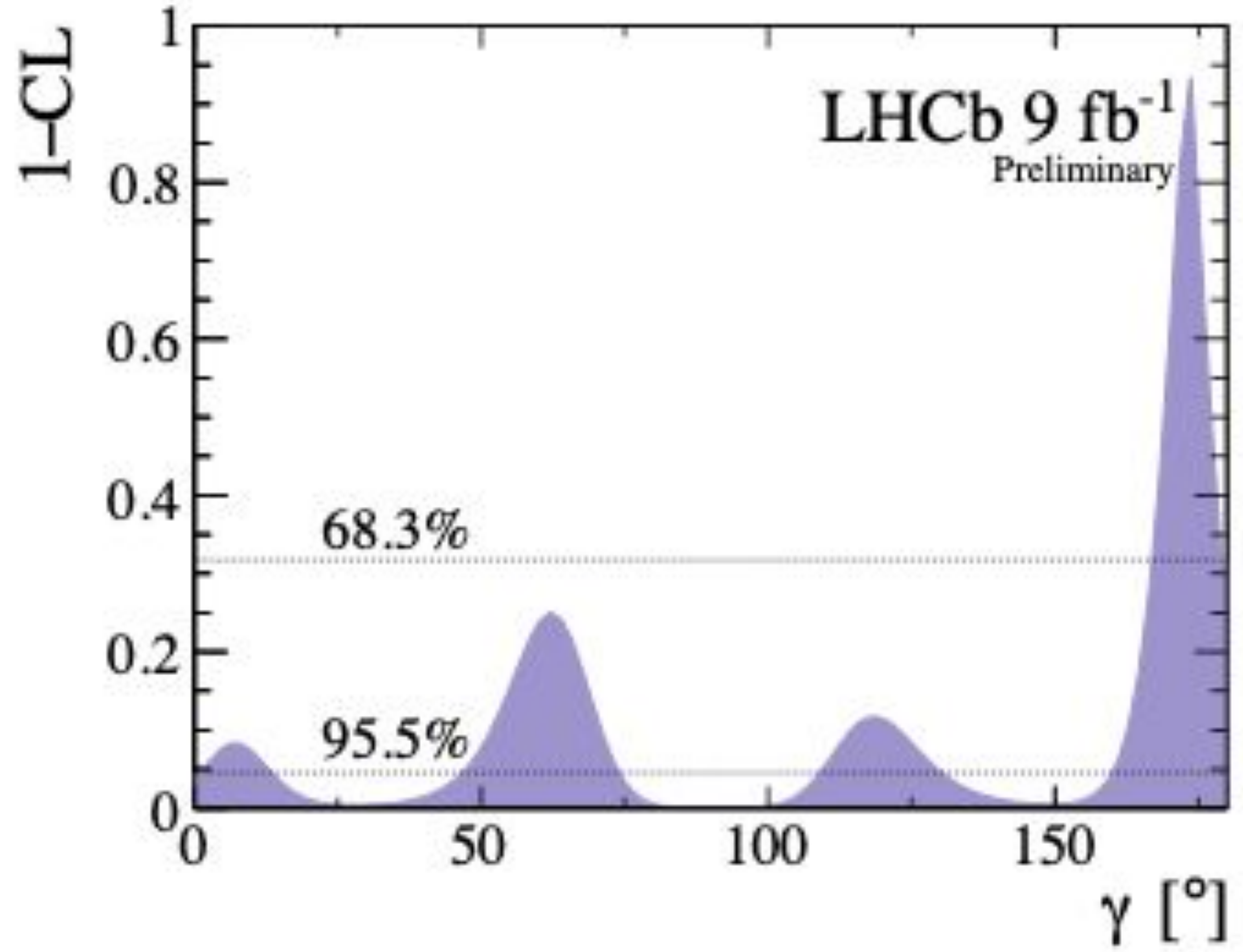
$$R_{\pi K\pi\pi}^{+} = 0.060 \pm 0.014 \pm 0.005$$
$$R_{\pi K\pi\pi}^{-} = 0.038 \pm 0.014 \pm 0.005$$

Results: γ

Interpret asymmetries and ratios in terms of physical observables[2]

Four-fold degeneracy: $(\gamma, \delta_B) \rightarrow (\delta_B, \gamma)$ or $(\pi - \gamma, \pi - \delta_B)$





LHCb-CONF-2023-003

Preferred solution: $\gamma = 172 \pm 6°$

Alternate solution (most consistent with world-average of direct measurements): $\gamma = (62 \pm 8)°$

Results from $B^0 \rightarrow [K^0_S h^+ h^-]_D K^{*0}$ will break the degeneracy

Measurements of CKM angle gamma and parameters related to mixing and CP violation in the charm at LHCb

Presented 3 new LHCb γ measurements, all of which use the $D \to K_S^0 h^+ h^-$ modes

- $B^0 \to DK^{*0}$ [https://doi.org/10.48550/arXiv.2309.05514]
- $B^\pm \to D^* K^\pm$ (fully reconstructed) [LHCb-PAPER-2023-012, in preparation]
- $B^\pm \to D^* K^\pm$ (partially reconstructed) [LHCb-PAPER-023-029, in preparation]

$B^0 \to DK^{*0}$: Results

Not included in the LHCb combination yet

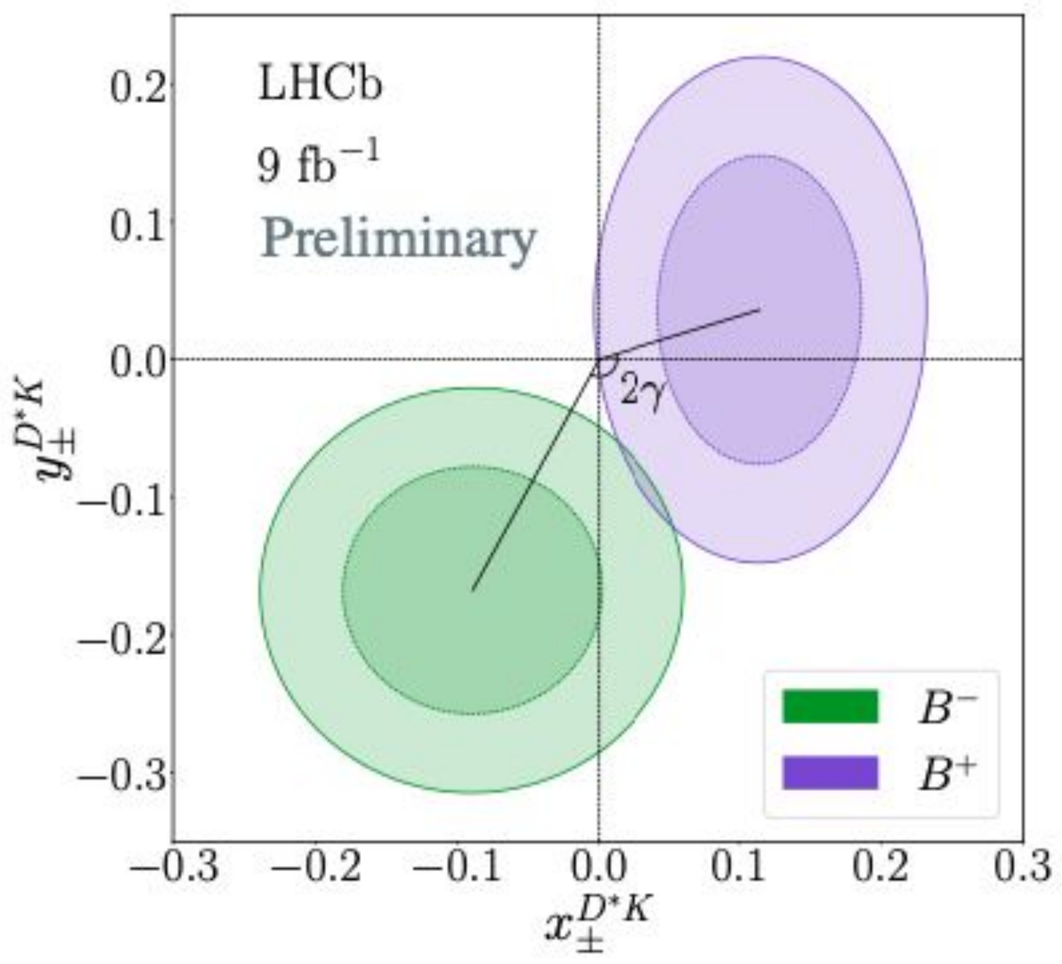
Reduces B^+/B^0 tension → $\gamma = (49^{+23}_{-18})^\circ$,

Consistent with expectations → $r_{B^0} = 0.271^{+0.068}_{-0.066}$,

$$\delta_{B^0} = (236^{+19}_{-21})^\circ.$$

Result useful in combination with measurements in $B^0 \to DK^{*0}$ decays with the ADS and GLW D-decay final states (see Seophine's talk)

Fully reconstructed $B^\pm \to D^* K^\pm$



LHCb-PAPER-2023-012 (in preparation)

$$\gamma = (69^{+13}_{-14})^\circ$$

$$r_B^{D^*K} = 0.15 \pm 0.03$$

$$\delta_B^{D^*K} = (311 \pm 15)^\circ$$

Partially reconstructed $B^\pm \to D^* K^\pm$

- Uncertainty on γ is statistically dominated
- Results consistent with expectations

$$\gamma = (92^{+21}_{-17})^\circ$$

$$r_B^{D^*K} = 0.080^{+0.022}_{-0.023}$$

$$\delta_B^{D^*K} = (310^{+15}_{-20})^\circ$$

Correlated systematic uncertainties on the CKM angle γ

- Uncertainty on γ still statistically dominated, but current level of systematic uncertainty will limit future measurements ($\sim 1.4^{\circ}$)

- Different B^+, B^0, B_s^0 measurements all have effectively decoupled systematics
- Aside from strong-phase inputs, systematics decouple between BelleII and LHCb

- Uncertainties on D strong phases should scale with BESIII data
- $\sim\ 7x$ BESIII data sample for D strong phases by end of 2024
- Questions remain on how to best publish forward-compatible results

New results of the CKM angle γ/ϕ_3 at Belle/Belle II

- **BPGGSZ, GLW, GLS results with Belle + Belle II are recently obtained**
- **first Belle + Belle II combination: $\phi_3 = (78.6 \pm 7.3)^\circ$, consistent with WA within 2σ**

  $(\phi_3 = (66.2^{+3.2}_{-3.6})^\circ)$

inputs: four different methods, 17 different final states

B decay	D decay	Method	Data set (Belle + Belle II) [fb^{-1}]	
$B^+ \to Dh^+$	$D \to K^0_S h^- h^+$	BPGGSZ	$711 + 128$	[JHEP 02 063 (2022)]
$B^+ \to Dh^+$	$D \to K^0_S \pi^- \pi^+ \pi^0$	BPGGSZ	$711 + 0$	[JHEP 10 178 (2019)]
$B^+ \to Dh^+$	$D \to K^0_S \pi^0, K^- K^+$	GLW	$711 + 189$	[arxiv:2308.05048]
$B^+ \to Dh^+$	$D \to K^+\pi^-, K^+\pi^-\pi^0$	ADS	$711 + 0$	[PRL 106 231803 (2011)]
$B^+ \to Dh^+$	$D \to K^0_S K^- \pi^+$	GLS	$711 + 362$	[arxiv:2306.02940]
$B^+ \to D^* K^+$	$D \to K^0_S \pi^- \pi^+$	BPGGSZ	$605 + 0$	[PRD 81 112002 (2010)]
$B^+ \to D^* K^+$	$D \to K^0_S \pi^0, K^0_S \phi, K^0_S \omega, K^- K^+, \pi^- \pi^+$	GLW	210+0	[PRD 73 051106 (2006)]

$B^0 \to D^{(*)} h^{(*)}$ decays are not included: minimal impact and introduce additional external parameters

Towards extracting γ from $B \to DK$ without binning

Key idea: Build optimized observables by (anti-)symmetrizing reduced decay width.

- With respect to $s_{12} = s_{13}$ axis of Dalitz plot:

$$d\Sigma_\pm(s_{12}, s_{13}),\ d\Delta_\pm(s_{12}, s_{13}) \equiv \frac{d\widehat{\Gamma}_\pm(s_{12}, s_{13}) \pm d\widehat{\Gamma}_\pm(s_{13}, s_{12})}{2}\,.$$

- And, additionally, with respect to B meson charge:

$$d\Sigma_{S,A}(s_{12}, s_{13}) \equiv \frac{d\Sigma_+(s_{12}, s_{13}) \pm d\Sigma_-(s_{12}, s_{13})}{2}\,,$$

$$d\Delta_{S,A}(s_{12}, s_{13}) \equiv \frac{d\Delta_+(s_{12}, s_{13}) \pm d\Delta_-(s_{12}, s_{13})}{2}\,.$$

- Smart ratios depend on r_B, δ_B and γ and are constant across the Dalitz plot.

Basis for unbinned method of extracting γ.

$$\left.\frac{\mathrm{d}\Sigma_S}{\mathrm{d}s_{12}\,\mathrm{d}s_{13}}\right|_{\mathrm{sub}} \Big/ \frac{\mathrm{d}\Sigma_A}{\mathrm{d}s_{12}\,\mathrm{d}s_{13}} = -\cot\delta_B \cot\gamma\,,$$

$$\left.\frac{\mathrm{d}\Delta_A}{\mathrm{d}s_{12}\,\mathrm{d}s_{13}}\right._{\mathrm{sub}} \Big/ \frac{\mathrm{d}\Delta_S}{\mathrm{d}s_{12}\,\mathrm{d}s_{13}} = \tan\delta_B \cot\gamma\,,$$

$$\left(\left.\frac{\mathrm{d}\Sigma_S}{\mathrm{d}s_{12}\,\mathrm{d}s_{13}}\right|_{\mathrm{sub}} \left.\frac{\mathrm{d}\Delta_A}{\mathrm{d}s_{12}\,\mathrm{d}s_{13}}\right|_{\mathrm{sub}}\right) \Big/ \left(\frac{\mathrm{d}\Sigma_A}{\mathrm{d}s_{12}\,\mathrm{d}s_{13}}\,\frac{\mathrm{d}\Delta_S}{\mathrm{d}s_{12}\,\mathrm{d}s_{13}}\right) = -\cot^2\gamma\,.$$

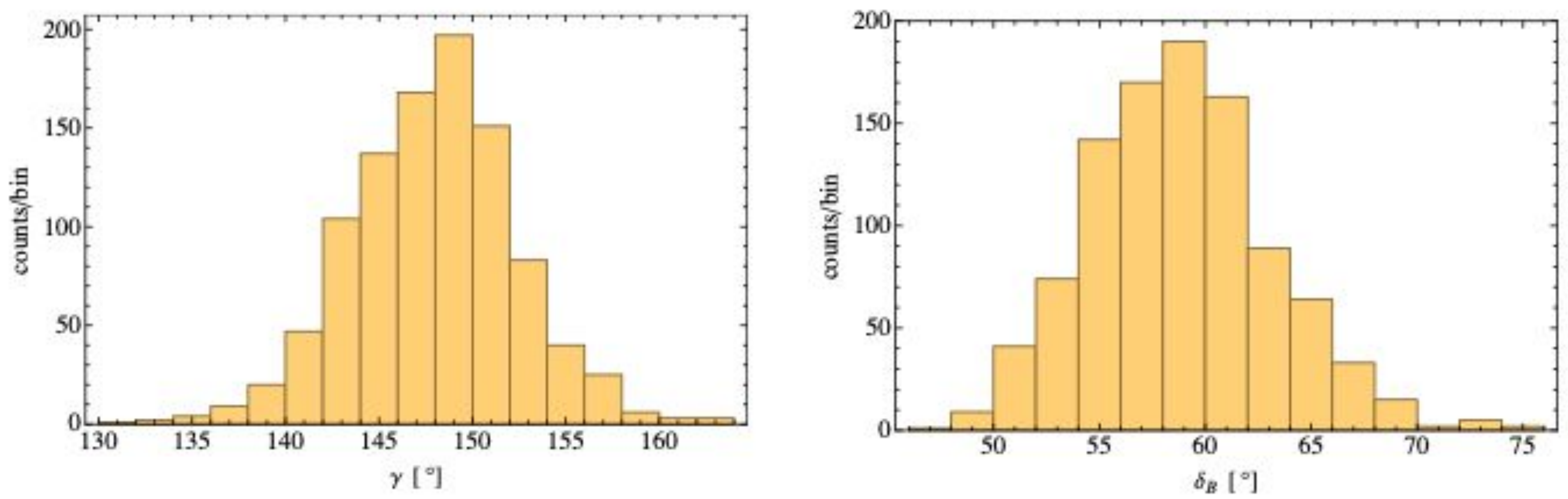
In practice, need cumulative reduced partial decay widths

$$\frac{R_{\Sigma S}|_{\mathrm{sub}}}{R_{\Sigma A}} = -\cot\delta_B \cot\gamma \qquad \frac{R_{\Delta A}|_{\mathrm{sub}}}{R_{\Delta S}} = \tan\delta_B \cot\gamma,$$

$$\left(\frac{R_{\Sigma S}|_{\mathrm{sub}}}{R_{\Sigma A}}\right)\left(\frac{R_{\Delta A}|_{\mathrm{sub}}}{R_{\Delta S}}\right) = -\cot^2\gamma.$$

Proof of Principle

- Check input = output for toy example, based on generated Monte Carlo points.
- Unbinned strategy not yet optimized, but has potential to be competitive with BPGGSZ.
- Presently unclear if our method can provide a superior statistical error.
- Each approach requires different kind of statistical optimization.
- Here: Required optimization = choice of test statistic: Variants of cumulative distribution.



Variable	Input	Output
γ	$150°$	$(148^{+3}_{-5})°$
r_B	0.9	$0.90^{+0.01}_{-0.01}$
δ_B	$60°$	$(59^{+4}_{-4})°$

Updates on Unitarity Triangle fits

Unitarity Triangle update

Result summary

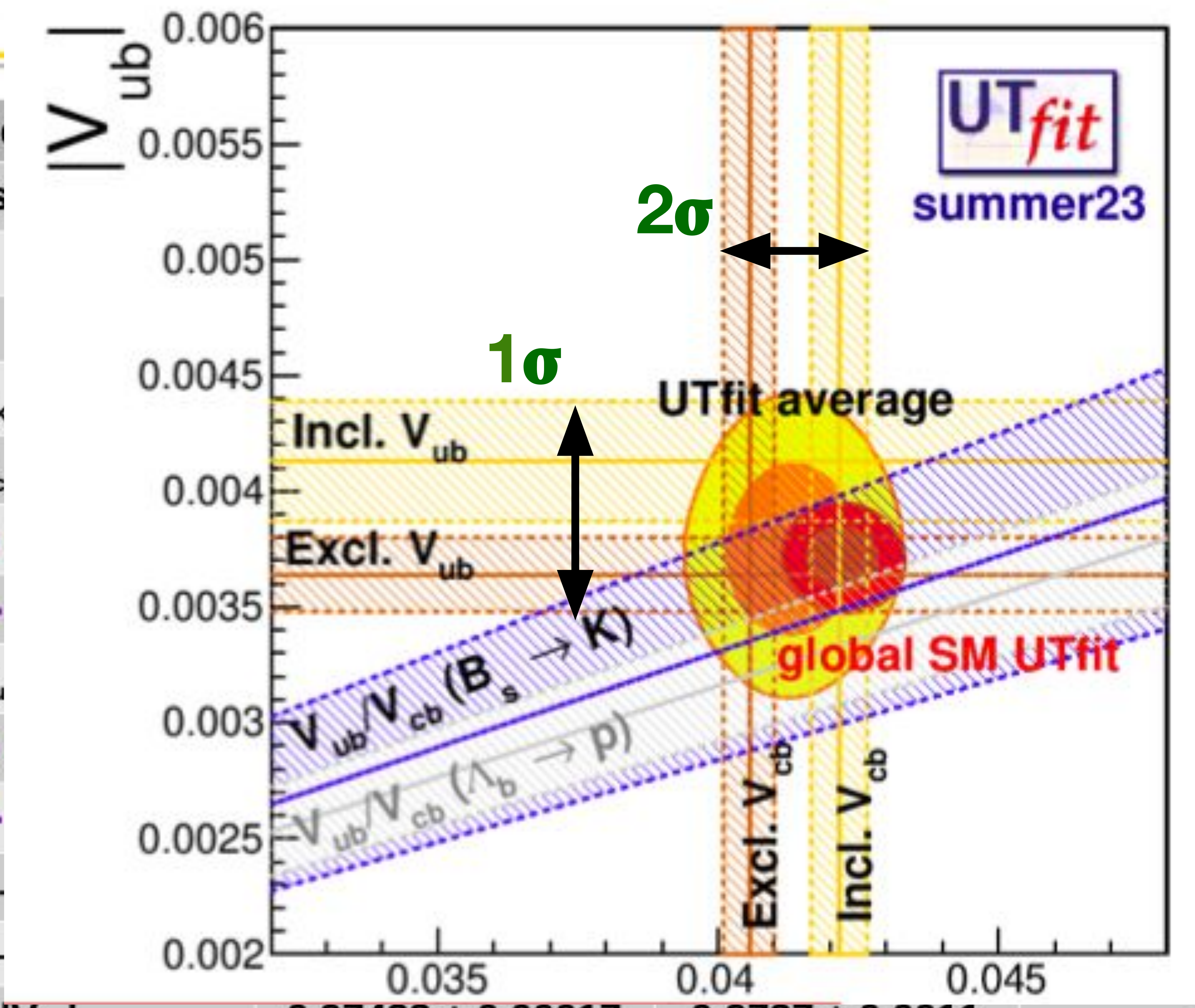
Observables	Measurement	Prediction	Pull (#σ)
$\sin 2\beta$	0.689 ± 0.019	0.739 ± 0.027	~ 1.5
γ	65.4 ± 3.3	65.2 ± 1.5	< 1
α	93.8 ± 4.5	92.3 ± 1.5	< 1
$\varepsilon_K \cdot 10^3$	2.228 ± 0.001	2.01 ± 0.14	~ 1.6
$\lvert V_{cb}\rvert \cdot 10^3$	41.32 ± 0.73	42.21 ± 0.51	~ 1
$\lvert V_{cb}\rvert \cdot 10^3$ (excl)	40.55 ± 0.46		~ 2.5
$\lvert V_{cb}\rvert \cdot 10^3$ (incl)	42.16 ± 0.50		< 1
$\lvert V_{ub}\rvert \cdot 10^3$	3.75 ± 0.26	3.70 ± 0.09	< 1
$\lvert V_{ub}\rvert \cdot 10^3$ (excl)	3.64 ± 0.16	-	< 1
$\lvert V_{ub}\rvert \cdot 10^3$ (incl)	4.13 ± 0.26	-	~ 1.5
$BR(B \to \tau\nu)[10^4]$	1.06 ± 0.19	0.865 ± 0.041	~ 1
$BR(B \to \mu\mu)[10^9]$	3.41 ± 0.29	3.45 ± 0.13	< 1
$\lvert V_{ud}\rvert$	0.97433 ± 0.00017	0.9737 ± 0.0011	< 1

Updates on Unitarity Triangle fits

...rity Triangle update

Result summary

Obs...			...l (#σ)
s...			1.5
			< 1
			< 1
ε_K...			1.6
$\|V_c$...			~ 1
$\|V_{cb}\|$ · ...			2.5
$\|V_{cb}\|$ · ...			< 1
$\|V_u$...			< 1
$\|V_{ub}\|$ · ...			< 1
$\|V_{ub}\|$ · ...			1.5
BR(B ...			~ 1
BR(B ...			< 1
$\|V_{ud}\|$	0.97433 ± 0.00017	0.9737 ± 0.0011	< 1



Lattice result summary

We obtain the predictions for the lattice parameters in different configurations in the fit:

- only lattice parameters ratios
  - (F_{Bs}/F_B, B_{Bs}/B_{Bd} used)
- only B parameters
  - (B_{Bs}[1], B_{Bs}/B_{Bd} used)
- only B_K parameter

Observables	Measurement	Prediction
B_K	0.756 ± 0.016	0.840 ± 0.053
Ratios only		
f_{Bs}	0.2301 ± 0.0012	0.234 ± 0.010
B_{Bs}	1.284 ± 0.059	1.27 ± 0.10
B pars only		
f_{Bs}/f_{Bd}	1.208 ± 0.005	1.201 ± 0.027
f_{Bs}	0.2301 ± 0.0012	0.229 ± 0.006
B_K only		
f_{Bs}	0.2301 ± 0.0012	0.226 ± 0.011
f_{Bs}/f_{Bd}	1.208 ± 0.005	1.07 ± 0.12
B_{Bs}	1.284 ± 0.059	1.32 ± 0.12
B_{Bs}/B_{Bd}	1.015 ± 0.021	1.29 ± 0.29

CP Violation & Multibody

Charmless B decays at Belle II

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

$$\mathcal{B}(B^0 \to \pi^0\pi^0) = (1.38 \pm 0.27 \pm 0.22) \times 10^{-6}$$

$$A_{CP}(B^0 \to \pi^0\pi^0) = 0.14 \pm 0.46 \pm 0.07$$

Achieved Belle precision on BF with 1/3 of Belle sample size thanks to improved photon selection and continuum suppression

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

$$\mathscr{B} = (26.7 \pm 2.8 \pm 2.8) \times 10^{-6}$$

$$f_L = 0.956 \pm 0.035 \pm 0.033$$

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

$$\mathscr{B} = (23.2^{+2.2}_{-2.1} \pm 2.7) \times 10^{-6}$$

$$f_L = 0.943^{+0.035}_{-0.033} \pm 0.027$$

$$A_{CP} = -0.069 \pm 0.069 \pm 0.060$$

$B \to \pi\pi$ decays

$$\mathscr{B}(\pi^+\pi^-) = (5.83 \pm 0.22 \pm 0.17) \times 10^{-6}$$

$$\mathscr{B}(\pi^+\pi^0) = (5.10 \pm 0.29 \pm 0.32) \times 10^{-6}$$

$$\mathscr{A}(\pi^+\pi^0) = -0.081 \pm 0.54 \pm 0.008$$

Competitive with world's best results.
Major systematic uncertainty on BR($B^+ \to \pi^+\pi^0$) from π^0 efficiency.

Summary

Obtained new results on channels sensitive to ϕ_2/α: exceeded expectations on $B^0 \to \pi^0\pi^0$, on par for $B \to \rho\rho$.

Obtained new $K\pi$ sum-rule result in agreement with SM, with precision similar to world average.

CP violation measurements in three-body charmless B decays

$B^\pm \to h^\pm h^+ h^-$

- Measurements of CP asymmetries in charmless three-body:
  - ☑ $B^\pm \to \pi^\pm\pi^+\pi^-$ (First Observation)
  - ☑ $B^\pm \to K^\pm K^+ K^-$ (First Observation)
  - ☑ $B^\pm \to \pi^\pm K^+ K^-$ (Confirmation)
  - ☑ $B^\pm \to K^\pm\pi^+\pi^-$ (No asymmetry)

Phase space integrated asymmetries

$B^\pm \to K^\pm\pi^+\pi^-$

$$A_{CP} = (+1.1 \pm 0.2_{stat} \pm 0.3_{syst} \pm 0.3_{J/\psi K})\,\%$$ ← 2.4σ

$B^\pm \to K^\pm K^+ K^-$

$$A_{CP} = (-3.7 \pm 0.2_{stat} \pm 0.2_{syst} \pm 0.3_{J/\psi K})\,\%$$ ← 8.5σ

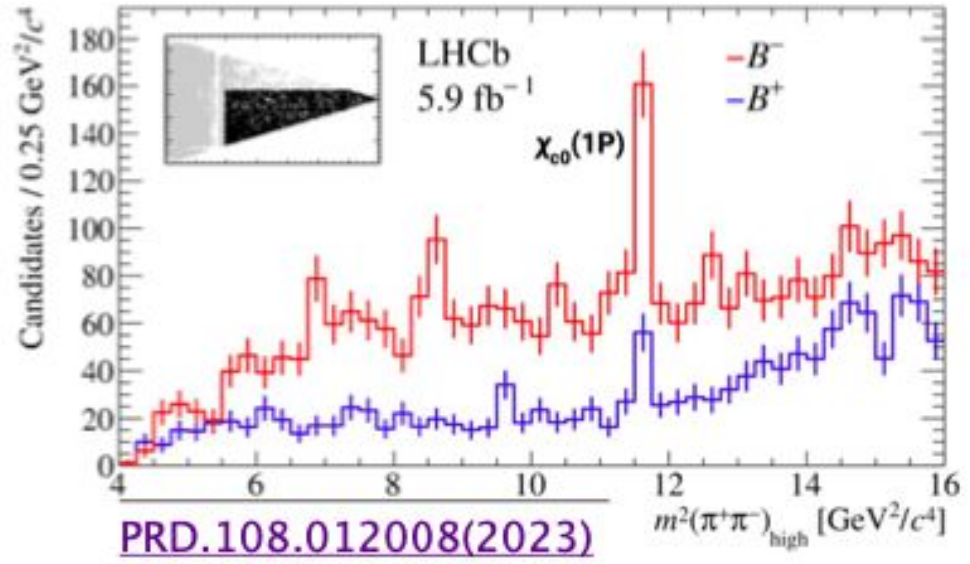
$B^\pm \to \pi^\pm\pi^+\pi^-$

$$A_{CP} = (+8.0 \pm 0.4_{stat} \pm 0.3_{syst} \pm 0.3_{J/\psi K})\,\%$$ ← 14.1σ

$B^\pm \to \pi^\pm K^+ K^-$

$$A_{CP} = (-11.4 \pm 0.7_{stat} \pm 0.3_{syst} \pm 0.3_{J/\psi K})\,\%$$ ← 13.6σ

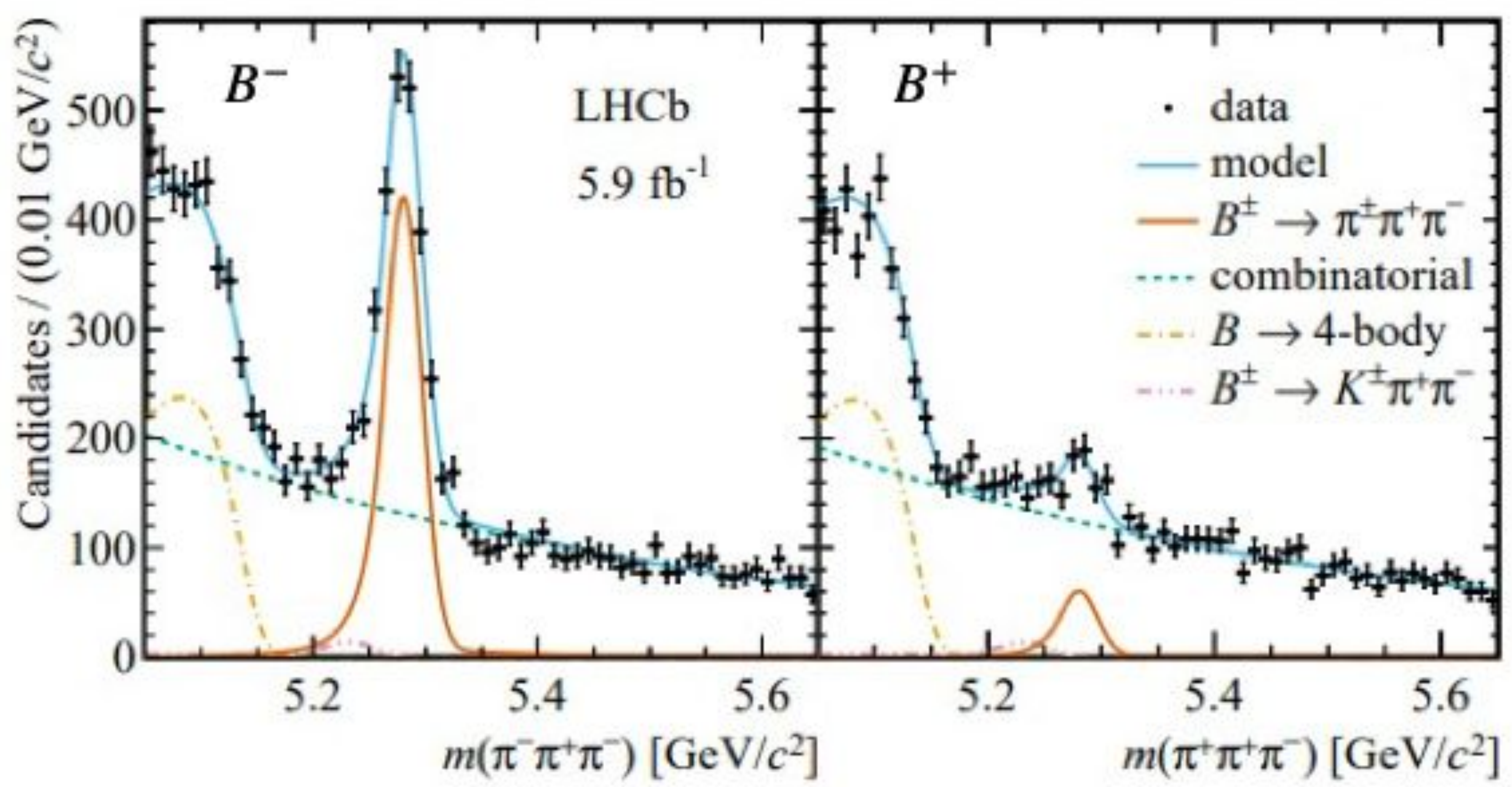
First observation of CPV in $B^\pm \to K^\pm K^+ K^-$, $B^\pm \to \pi^\pm\pi^+\pi^-$



PRD.108.012008(2023)

Localized CP asymmetries

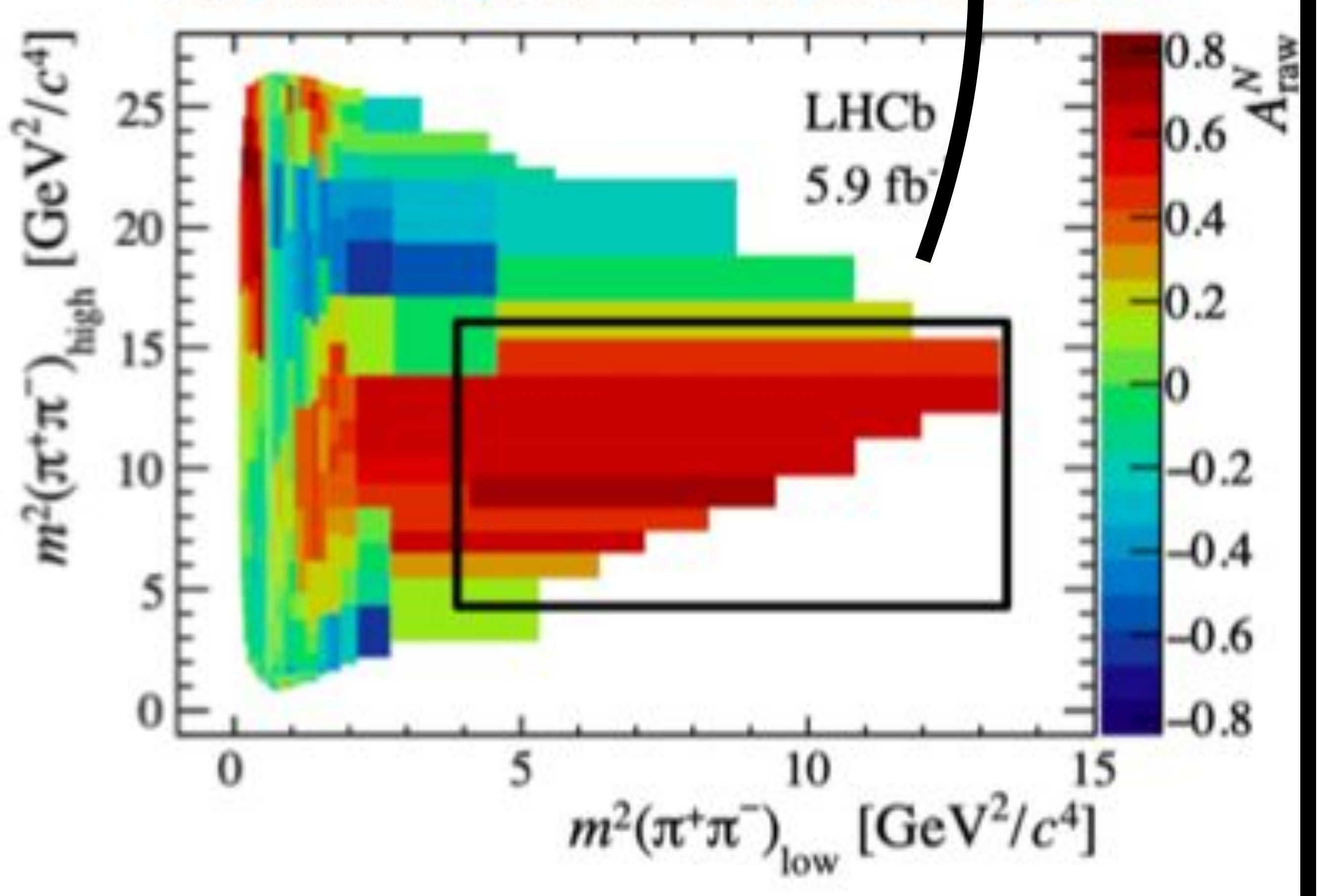
Invariant mass fit region 3



$$A_{CP} = (+74.5 \pm 2.7_{stat} \pm 1.8_{syst} \pm 0.3_{J/\psi K})\,\%$$

Large CPV observed!

Asymmetry in bins of phase space



$B^{\pm}$ decays into a vector + scalar resonance

$B \to PV$

- Measurements of CP asymmetries in $B \to PV$:
  - New method to measure CPV
  - $B^{\pm} \to \rho(770)K^{\pm}$ (First Observation)
  - All other channels (No asymmetry)

Final results for all channels:

Decay channel	This work	Previous measurements
$B^{\pm} \to (\rho(770)^0 \to \pi^+\pi^-)\pi^{\pm}$	$-0.004 \pm 0.017 \pm 0.009$	$+0.007 \pm 0.011 \pm 0.016$ (LHCb)
$B^{\pm} \to (\rho(770)^0 \to \pi^+\pi^-)K^{\pm}$	$+0.150 \pm 0.019 \pm 0.011$	$+0.44 \pm 0.10 \pm 0.04$ (BABAR) $+0.30 \pm 0.11 \pm 0.02$ (Belle)
$B^{\pm} \to (K^*(892)^0 \to K^{\pm}\pi^{\mp})\pi^{\pm}$	$-0.015 \pm 0.021 \pm 0.012$	$+0.032 \pm 0.052 \pm 0.011$ (BABAR) $-0.149 \pm 0.064 \pm 0.020$ (Belle)
$B^{\pm} \to (K^*(892)^0 \to K^{\pm}\pi^{\mp})K^{\pm}$	$+0.007 \pm 0.054 \pm 0.032$	$+0.123 \pm 0.087 \pm 0.045$ (LHCb)
$B^{\pm} \to (\phi(1020) \to K^+K^-)K^{\pm}$	$+0.004 \pm 0.014 \pm 0.007$	$+0.128 \pm 0.044 \pm 0.013$ (BABAR)

Three-body non-leptonic B decays in QCD factorization

Idea / goal

Establish factorization for $\bar{B}^0 \to D^+ M^- \pi^0$ decays ($M = K, \pi$) in phase space region of small $M^-\pi^0$ invariant mass, i.e. $(M\pi)$-system recoils against heavy D meson.

formula for three-body $B \to D(K,\pi)\pi$ decays

- Lagrangian and operators in CMM basis ($x = d, s$)

$$\mathcal{L}_{\rm eff}^{(6)} = -\frac{4G_F}{\sqrt{2}} V_{ux}^* V_{cb} \left(C_1 Q_1 + C_2 Q_2\right) + h.c.\,, \qquad Q_{1,2} = (\bar{c}\gamma^\mu P_L \{T^a, \mathbb{1}\} b)\,(\bar{x}\gamma_\mu P_L \{T^a, \mathbb{1}\} u)$$

Factorization formula at leading power ($L = M^-\pi^0$)

$$\mathcal{A}(\bar{B} \to D^+ L^-) = \frac{4G_F}{\sqrt{2}} V_{ux}^* V_{cb}\, k^-\, F_n^{B\to D} \int_0^1 du\, \left[C_1 T_1(u) + C_2 T_2(u)\right] \Phi_L(u,k)$$

$$a_1(D^+L^-) = \int_0^1 du\, \left[C_1(\mu) T_1(u,\mu) + C_2(\mu) T_2(u,\mu)\right]\, \Phi_L(u,k)$$

Numerical size of amplitude through to NNLO

- Gegenbauer expansion of amplitude

$$a_1(D^+L^-) = \sum_{n\geq 0} \alpha_n^L \left[C_1(\mu)\mathcal{V}_{1n}(\mu) + C_2(\mu)\mathcal{V}_{2n}(\mu)\right] \equiv \sum_{n\geq 0} \alpha_n^L\, \mathcal{G}_n(\mu)$$

Di-meson LCDA

- Normalization

$$\int_0^1 du\, \Phi_{\pi\pi}(u,k^2,\theta_\pi) = \cos\theta_\pi\, \beta_\pi(k^2) F_\pi(k^2)$$

$$\int_0^1 du\, \Phi_{K\pi}(u,k^2,\theta_\pi) = \cos\theta_\pi \frac{\sqrt{\lambda_{K\pi}(k^2)}}{2k^2} f_+^{K\pi}(k^2) + \frac{\Delta m_{K\pi}^2}{2k^2} f_0^{K\pi}(k^2)$$

- Expand in Gegenbauer coefficients:

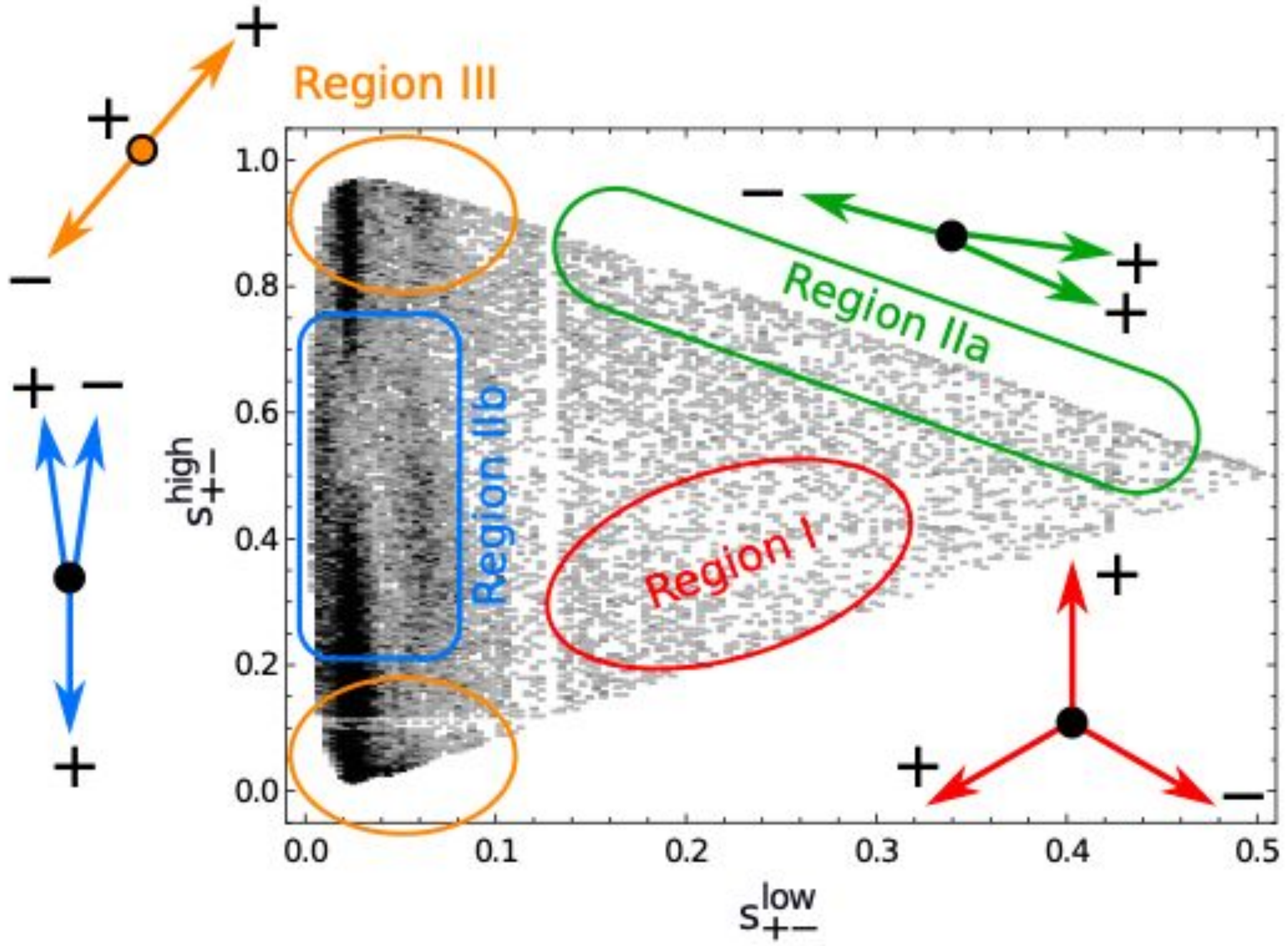
$$\Phi_L(u,k) = 6u\bar{u} \sum_{n=0}^{\infty} \alpha_n^L(k^2,\theta_\pi)\, C_n^{3/2}(u-\bar{u})$$

In $\bar{B}^0 \to D^+\pi^-\pi^0$ case

$$\alpha_n^{\pi\pi}(k^2,\theta_\pi) = \sum_{\ell=1,3,\cdots}^{n+1} B_{n\ell}^{\pi\pi}(k^2)\, P_\ell(\cos\theta_\pi) \qquad (n \text{ even})$$

Three-body charmless nonleptonic B-decays in QCDF

- Focus on $B^+ \to \pi^+\pi^-\pi^+$ in a factorisation approach
  - Identify different regions in Dalitz plot
  - Each region obeys its own factorization formula



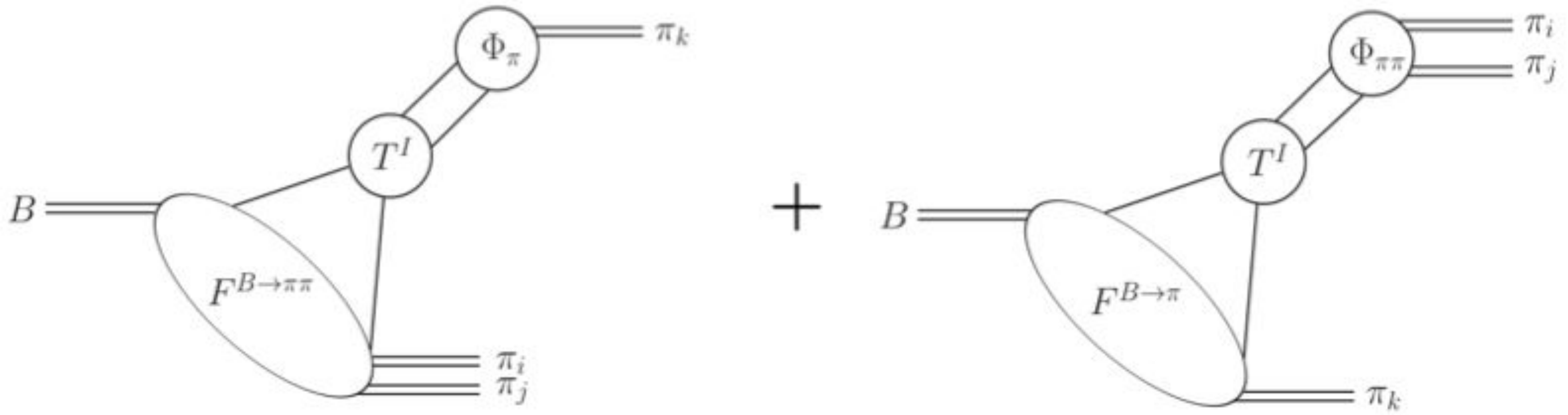
Central region

- Factorization formula

$$\langle \pi^+\pi^+\pi^- | \mathcal{Q}_i | B^+ \rangle_c = T_i^I \otimes F^{B\to\pi} \otimes \Phi_\pi \otimes \Phi_\pi + T_i^{II} \otimes \Phi_B \otimes \Phi_\pi \otimes \Phi_\pi \otimes \Phi_\pi$$

Edges of Dalitz plot

- Features of the edges
  - Three-body decays resemble two-body ones
  - Resonances close to the edges



- Factorisation formula

$$\langle \pi^+\pi^+\pi^- | \mathcal{Q}_i | B \rangle_e = T_i^I \otimes F^{B\to\pi^+} \otimes \Phi_{\pi^+\pi^-} + T_i^I \otimes F^{B\to\pi^+\pi^-} \otimes \Phi_{\pi^+}$$

New nonperturbative input

- $B \to \pi\pi$ form factor
  - Was studied in $B \to \pi\pi\,\ell\,\nu$ decays
- For $B^+ \to \pi^+\pi^-\pi^+$ only vector form factor relevant

$$k_{3\mu}\,\langle \pi^+(k_1)\pi^-(k_2)|\bar{b}\gamma^\mu\gamma^5 u|B^+(p)\rangle = i\,m_\pi\, F_t(s,\zeta)$$

SEARCH FOR CP VIOLATION IN BARYONS WITH THE LHCb DETECTOR

- Up-to-now many channels are being investigated, 3- and 4-body decays of both Ξ_b and Λ_b
  - Also exploring never tried techniques

- Unfortunately, only hints of CP violation have been found, but an evidence of P violation was found

OBSERVATION OF THE SUPPRESSED $\Lambda_b^0 \to D^0 pK^-$ DECAY WITH $D^0 \to K^+\pi^-$ AND MEASUREMENT OF ITS CP ASYMMETRY [arXiv:2109.02621]

OBSERVATION OF THE SUPPRESSED $\Lambda_b^0 \to D^0 pK^-$ DECAY WITH $D^0 \to K^+\pi^-$ AND MEASUREMENT OF ITS CP ASYMMETRY [arXiv:2109.02621]

SEARCH FOR CP VIOLATION IN $\Xi_b^- \to pK^-K^-$ DECAYS [Phys Rev D 104, 052010 (2021)]

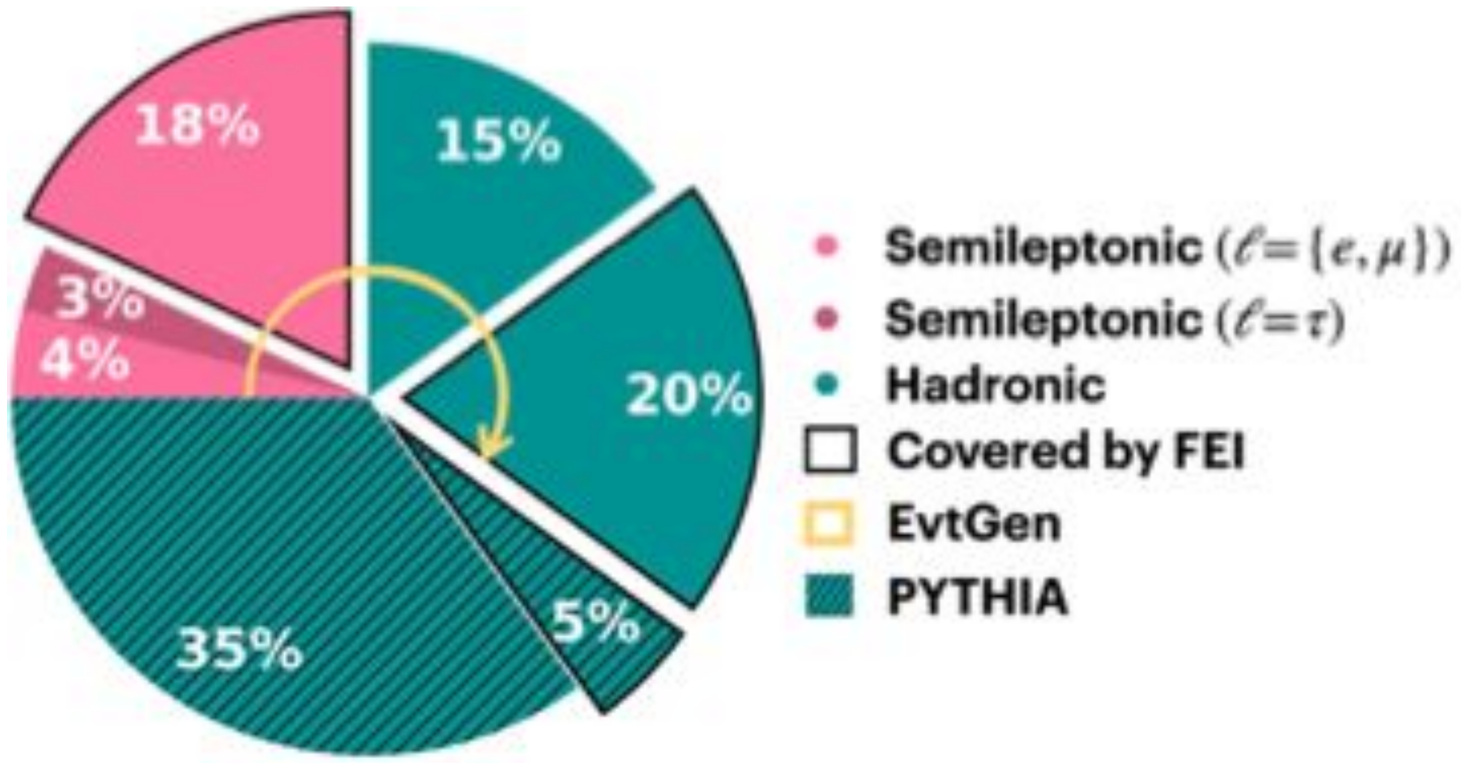
Many analysis are in the pipeline! The search is not stopping

Hadronic B to charm decays at Belle II

Observation of $B \to D^{(*)} K^- K_S^0$

$$\mathcal{B}(\bar{B}^0 \to D^+ K^- K_S^0) = (0.85 \pm 0.11 \pm 0.05) \times 10^{-4},$$
$$\mathcal{B}(B^- \to D^{*0} K^- K_S^0) = (1.57 \pm 0.27 \pm 0.12) \times 10^{-4},$$
$$\mathcal{B}(\bar{B}^0 \to D^{*+} K^- K_S^0) = (0.96 \pm 0.18 \pm 0.06) \times 10^{-4},$$

Belle provided the most precise measurements for $B \to D\pi^+$.
[PRD 105 (2022) 1, 012003 and PRD 105 (2022) 7, 072007]



	Process	Diagram	$\mathcal{B}_{CCQM}$/E	$\mathcal{B}_{PDG}$/E	E
1	$B^0 \to D^- + \pi^+$	D_1	5.34 ± 0.27	2.52 ± 0.13	10^{-3}
2	$B^0 \to \pi^- + D^+$	D_1	11.19 ± 0.56	7.4 ± 1.3	10^{-7}
3	$B^0 \to \pi^- + D_s^+$	D_1	3.48 ± 0.17	2.16 ± 0.26	10^{-5}
4	$B^+ \to \pi^0 + D_s^+$	D_1	1.88 ± 0.09	1.6 ± 0.5	10^{-5}
5	$B^0 \to D^- + \rho^+$	D_1	14.06 ± 0.70	7.6 ± 1.2	10^{-3}
6	$B^0 \to \pi^- + D_s^{*+}$	D_1	3.66 ± 0.18	2.1 ± 0.4	10^{-5}
7	$B^+ \to \pi^0 + D^{*+}$	D_1	0.804 ± 0.04	< 3.6	10^{-6}
8	$B^+ \to \pi^0 + D_s^{*+}$	D_1	0.197 ± 0.01	< 2.6	10^{-4}
9	$B^0 \to D^{*-} + \pi^+$	D_1	4.74 ± 0.24	2.74 ± 0.13	10^{-3}
10	$B^0 \to \rho^- + D_s^+$	D_1	2.76 ± 0.14	< 2.4	10^{-5}
11	$B^+ \to \rho^0 + D_s^+$	D_1	0.149 ± 0.01	< 3.0	10^{-4}
12	$B^0 \to D^{*-} + \rho^+$	D_1	14.58 ± 0.73	6.8 ± 0.9	10^{-3}
13	$B^0 \to \rho^- + D_s^{*+}$	D_1	5.09 ± 0.25	4.1 ± 1.3	10^{-5}
14	$B^+ \to \rho^0 + D_s^{*+}$	D_1	0.275 ± 0.01	< 4.0	10^{-4}
15	$B^0 \to \pi^0 + \overline{D}^0$	D_2	0.085 ± 0.00	2.63 ± 0.14	10^{-4}
16	$B^0 \to \pi^0 + \overline{D}^{*0}$	D_2	1.13 ± 0.06	2.2 ± 0.6	10^{-4}
17	$B^0 \to \rho^0 + \overline{D}^0$	D_2	0.675 ± 0.03	3.21 ± 0.21	10^{-4}
18	$B^0 \to \rho^0 + \overline{D}^{*0}$	D_2	1.50 ± 0.08	< 5.1	10^{-4}
19	$B^+ \to \overline{D}^0 + \pi^+$	D_3	3.89 ± 0.19	4.68 ± 0.13	10^{-3}
20	$B^+ \to \overline{D}^0 + \rho^+$	D_3	1.83 ± 0.09	1.34 ± 0.18	10^{-2}
21	$B^+ \to \overline{D}^{*0} + \pi^+$	D_3	7.60 ± 0.38	4.9 ± 0.17	10^{-3}
22	$B^+ \to \overline{D}^{*0} + \rho^+$	D_3	11.75 ± 0.59	9.8 ± 1.7	10^{-3}

Hadronic B to charm decays at Belle II

Observation of $B \to D^{(*)}K^-K_S^0$

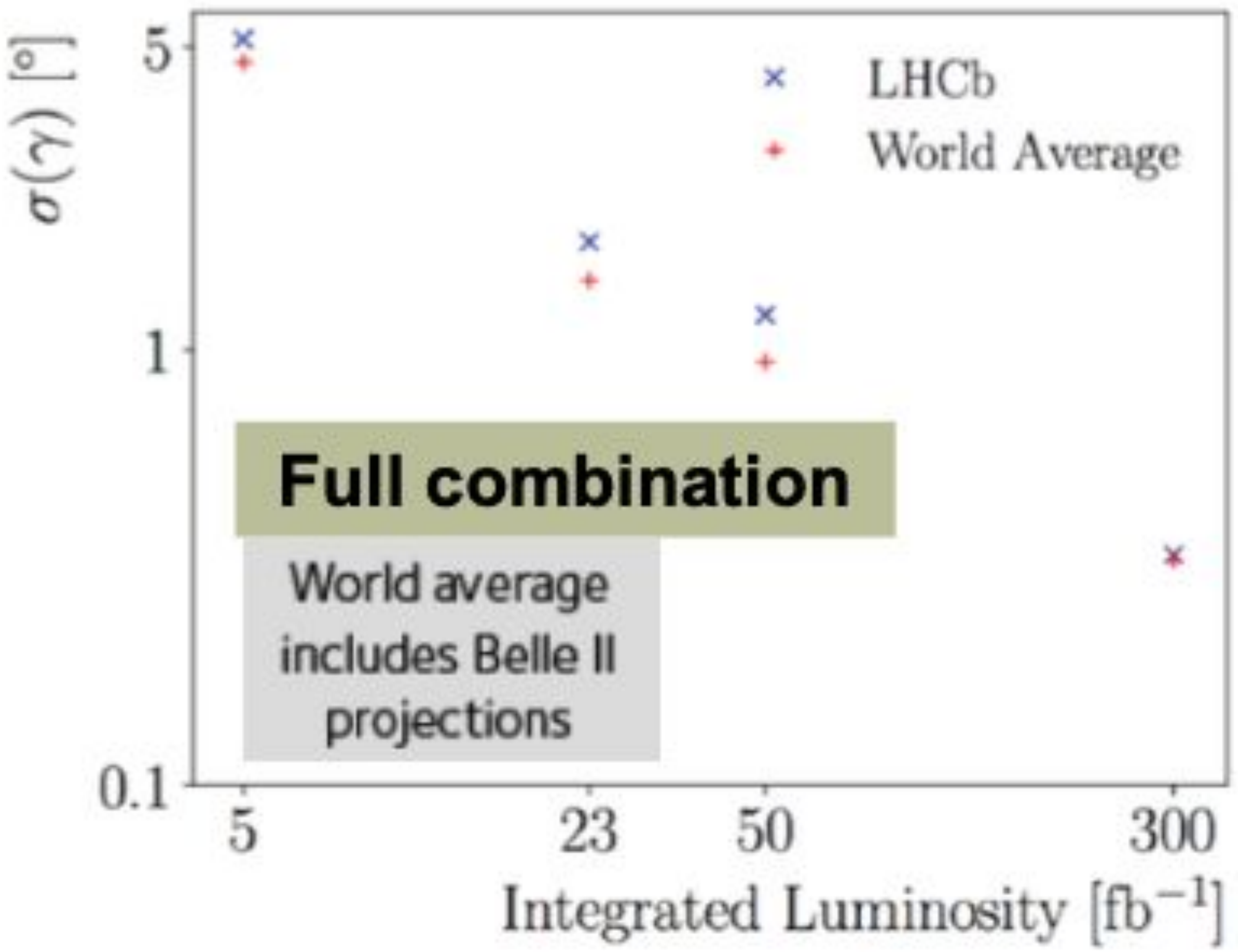
$$\mathcal{B}(\bar{B}^0 \to D^+K^-K_S^0) = (0.85 \pm 0.11 \pm 0.05) \times 10^{-4},$$
$$\mathcal{B}(B^- \to D^{*0}K^-K_S^0) = (1.57 \pm 0.27 \pm 0.12) \times 10^{-4},$$
$$\mathcal{B}(\bar{B}^0 \to D^{*+}K^-K_S^0) = (0.96 \pm 0.18 \pm 0.06) \times 10^{-4}.$$

Belle provided the most precise measurements for $B \to D\pi^+$.
[PRD 105 (2022) 1, 012003 and PRD 105 (2022) 7, 072007]

BF puzzle in $B \to D^{(*)}h$ decays

	Process	Diagram	$\mathcal{B}_{CCQM}/E$	$\mathcal{B}_{PDG}/E$	E
1	$B^0 \to D^- + \pi^+$	D_1	5.34 ± 0.27	2.52 ± 0.13	10^{-3}
2	$B^0 \to \pi^- + D^+$	D_1	11.19 ± 0.56	7.4 ± 1.3	10^{-7}
3	$B^0 \to \pi^- + D_s^+$	D_1	3.48 ± 0.17	2.16 ± 0.26	10^{-5}
4	$B^+ \to \pi^0 + D_s^+$	D_1	1.88 ± 0.09	1.6 ± 0.5	10^{-5}
5	$B^0 \to D^- + \rho^+$	D_1	14.06 ± 0.70	7.6 ± 1.2	10^{-3}
6	$B^0 \to \pi^- + D_s^{*+}$	D_1	3.66 ± 0.18	2.1 ± 0.4	10^{-5}
7	$B^+ \to \pi^0 + D^{*+}$	D_1	0.804 ± 0.04	< 3.6	10^{-6}
8	$B^+ \to \pi^0 + D_s^{*+}$	D_1	0.197 ± 0.01	< 2.6	10^{-4}
9	$B^0 \to D^{*-} + \pi^+$	D_1	4.74 ± 0.24	2.74 ± 0.13	10^{-3}
10	$B^0 \to \rho^- + D_s^+$	D_1	2.76 ± 0.14	< 2.4	10^{-5}
11	$B^+ \to \rho^0 + D_s^+$	D_1	0.149 ± 0.01	< 3.0	10^{-4}
12	$B^0 \to D^{*-} + \rho^+$	D_1	14.58 ± 0.73	6.8 ± 0.9	10^{-3}
13	$B^0 \to \rho^- + D_s^{*+}$	D_1	5.09 ± 0.25	4.1 ± 1.3	10^{-5}
14	$B^+ \to \rho^0 + D_s^{*+}$	D_1	0.275 ± 0.01	< 4.0	10^{-4}
15	$B^0 \to \pi^0 + \bar{D}^0$	D_2	0.085 ± 0.00	2.63 ± 0.14	10^{-4}
16	$B^0 \to \pi^0 + \bar{D}^{*0}$	D_2	1.13 ± 0.06	2.2 ± 0.6	10^{-4}
17	$B^0 \to \rho^0 + \bar{D}^0$	D_2	0.675 ± 0.03	3.21 ± 0.21	10^{-4}
18	$B^0 \to \rho^0 + \bar{D}^{*0}$	D_2	1.50 ± 0.08	< 5.1	10^{-4}
19	$B^+ \to \bar{D}^0 + \pi^+$	D_3	3.89 ± 0.19	4.68 ± 0.13	10^{-3}
20	$B^+ \to \bar{D}^0 + \rho^+$	D_3	1.83 ± 0.09	1.34 ± 0.18	10^{-2}
21	$B^+ \to \bar{D}^{*0} + \pi^+$	D_3	7.60 ± 0.38	4.9 ± 0.17	10^{-3}
22	$B^+ \to \bar{D}^{*0} + \rho^+$	D_3	11.75 ± 0.59	9.8 ± 1.7	10^{-3}

Future prospects for γ



- Status now:
  - Error for γ is about 4°
  - BESIII contribute about 1°
- Around 2030
  - Less than 1° will be achieved
  - BESIII 20fb^{-1} data → improve the error to <0.5°
- (>)2035
  - LHCb upgradeII → sensitivity <0.4°
  - Need more charm factory data (STCF)

dataset	Int. Lum.	year	sensitivity
LHCb Run1 (7,8TeV)	3 fb^{-1}	2012	8°
LHCb Run2 (13TeV)	6 fb^{-1}	2018	4°
BelleII Run	50 ab^{-1}	2025	1-2°
LHCb upgrade (14TeV)	50 fb^{-1}	2030	<1°
LHCb upgradeII (14TeV)	200 fb^{-1}	(>)2035	<0.4°