



**Summary of WG5: Direct CP violation (DCPV)
including ϕ $3/\gamma$ from $B \rightarrow DK$, DCPV effects,
branching fractions and polarisation in charmless B (s)
decays**

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Summary of WG5: Direct CP violation (DCPV) including ϕ_3/γ from $B \rightarrow DK$, DCPV effects, branching fractions and polarisation in charmless $B_{(s)}$ decays

Joachim Brod¹, **Resmi PK**², Wenbin Qian³

11th International Workshop on the CKM Unitarity Triangle (CKM 2021)

22-26 November 2021

¹University of Cincinnati

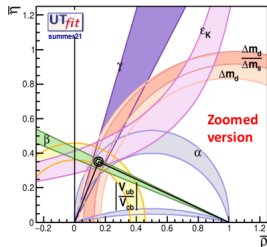
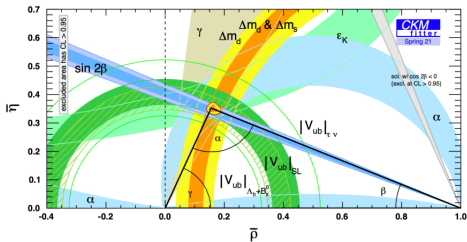
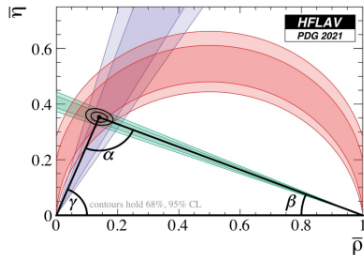
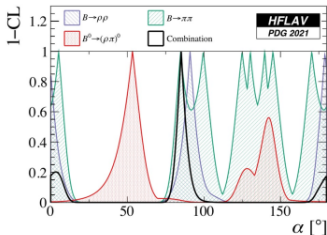
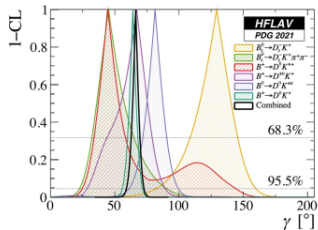
²Aix Marseille Univ, CNRS/IN2P3, CPPM

³University of Chinese Academy of Sciences

- Direct CP violation (DCPV) including ϕ_3/γ from $B \rightarrow DK$, DCPV effects, branching fractions and polarisation in charmless $B_{(s)}$ decays
- Three standalone sessions and one joint session with WG2 and WG4
- 13 talks in WG5 sessions and 6 talks in the joint session
- Huge thanks to all the speakers!

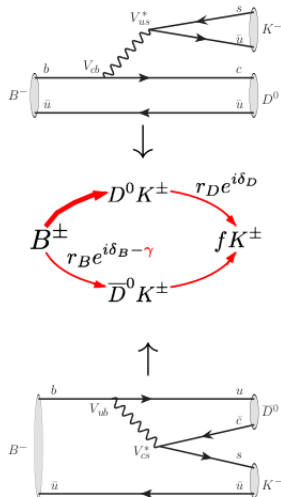
Anton Poluektov, Fidan Suljik, Arnau Brossa Gonzalo, Seema Bahinipati, Niharika Rout, Daniele Manuzzi, Diego Torres Machado, Yun-Tsung Lai, Sagar Hazra, Syuhei Iguro, Matteo Bartolini, Asier Pereiro Castro, Xinyu Shan, Ulrik Egede, Wenbin Qian, Fabio Ferrari, Tobias Huber, Jeremy Peter Dalseno, Eleftheria Malami

- ϕ_3/γ measurements
- Charmless B decays
- Other CPV and polarisation measurements



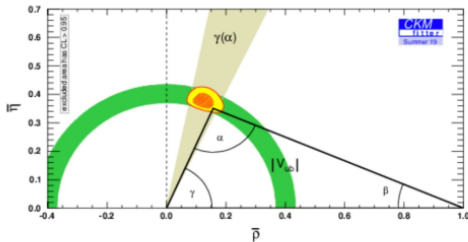
Unitarity Triangle angle γ/ϕ_3

- Measured entirely in tree-level transitions in the interference of $b \rightarrow c$ and $b \rightarrow u$ diagrams.
- All hadronic parameters can be constrained from experiment
 $\Rightarrow$ theoretically very clean (uncertainty $< 10^{-7}$)
[\[Brod, Zupan, JHEP 1401 \(2014\) 051\]](#)
- Combination of many different modes:
 - Time-integrated asymmetries in $B \rightarrow DK$, $B \rightarrow DK^*$, $B \rightarrow DK\pi$ with $D \rightarrow hh, hh\bar{h}\bar{h}$ ("ADS", "GLW")
 - Dalitz plot analyses of $D^0 \rightarrow K_S^0 h^+ h^-$ from $B \rightarrow DK$, $B \rightarrow DK^*$ ("Dalitz" or "BPGGSZ")
 - Time-dependent analyses, e.g. $B_s^0 \rightarrow D_s K$, $B^0 \rightarrow D\pi$



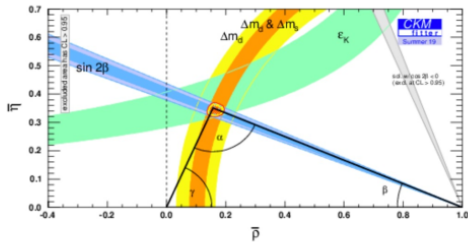
Fidan Suljik

Tree-level (direct measurement)



$$\gamma = (72.1^{+5.4}_{-5.7})^\circ$$

Loop-level (indirect measurement)



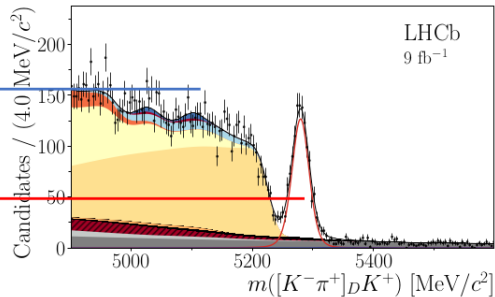
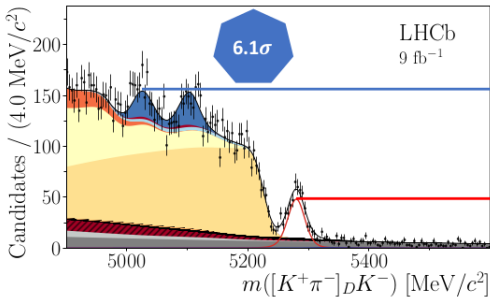
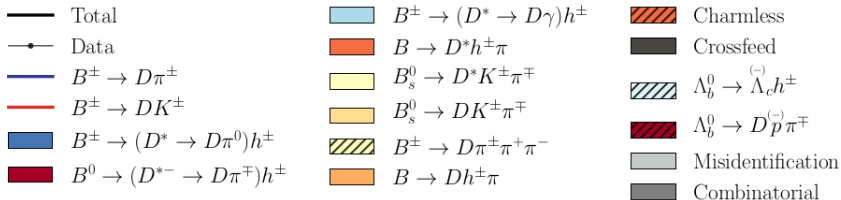
$$\gamma = (65.66^{+0.90}_{-2.65})^\circ$$

CKMfitter² Summer 2019

- Direct measurements of γ at tree-level are expected to be benchmarks of the Standard Model
- Indirect measurements consist of global fits to the unitary triangle, where some inputs include loop processes and assuming closed triangle. New Physics expected to contribute through loop processes
- A discrepancy between direct and indirect measurements would be a clear sign of New Physics

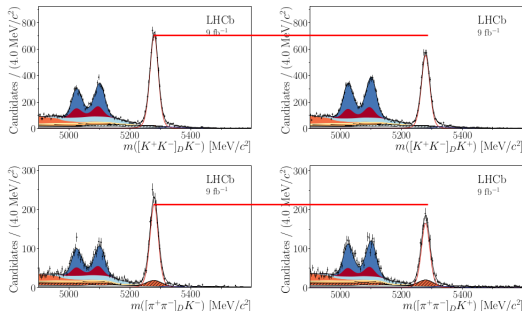
$$B^\pm \rightarrow D^{(*)}K^\pm, D \rightarrow K^\mp\pi^\pm$$

JHEP 04 (2020) 081



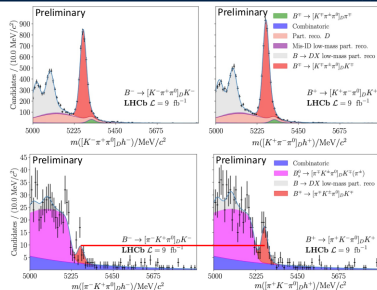
$B^\pm \rightarrow D^{(*)}K^\pm, D \rightarrow h^+h^-$

JHEP 04 (2020) 081



$B^\pm \rightarrow Dh^\pm, D \rightarrow h^\pm h^\mp \pi^0$

LHCb-PAPER-2021-036 (in preparation)

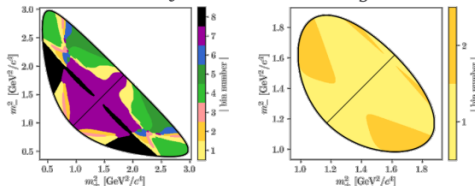


$>7.0\sigma$

- Relatively smaller observable CP violation due to amplitudes of different sizes
- First observation of the suppressed mode in $D \rightarrow h^\pm h^\mp \pi^0$ with $> 7\sigma$

Measurement of γ using $B^+ \rightarrow Dh^+ h^-$ decays with $D \rightarrow K_S^0 h^+ h^-$

- $K_S^0 \pi^+ \pi^-$ and $K_S^0 K^+ K^-$ modes studied
- 8 (2) bins, in the Dalitz plot, maintaining symmetries.
- Defining cosine of δ_B^{DK} as



$$c_i \equiv \frac{\int_i dm_-^2 dm_+^2 |A_D(m_-^2, m_+^2)| |A_D(m_+^2, m_-^2)| \cos [\delta_D(m_-^2, m_+^2) - \delta_D(m_+^2, m_-^2)]}{\sqrt{\int_i dm_-^2 dm_+^2 |A_D(m_-^2, m_+^2)|^2 \int_i dm_-^2 dm_+^2 |A_D(m_+^2, m_-^2)|^2}},$$

- And fraction of pure D decays

$$F_i = \frac{\int_i dm_-^2 dm_+^2 |A_D(m_-^2, m_+^2)|^2 \eta(m_-^2, m_+^2)}{\sum_j \int_j dm_-^2 dm_+^2 |A_D(m_-^2, m_+^2)|^2 \eta(m_-^2, m_+^2)},$$

- $\eta(m_-^2, m_+^2)$: signal efficiency

We can relate the signal yields in each bin with CP parameters

$$\begin{aligned} N_{+i}^+ &= h_{B^+} \left[F_{-i} + \left((x_+^{DK})^2 + (y_+^{DK})^2 \right) F_{+i} + 2\sqrt{F_i F_{-i}} (x_+^{DK} c_{+i} - y_+^{DK} s_{+i}) \right] \\ N_{-i}^+ &= h_{B^+} \left[F_{+i} + \left((x_+^{DK})^2 + (y_+^{DK})^2 \right) F_{-i} + 2\sqrt{F_i F_{-i}} (x_+^{DK} c_{+i} + y_+^{DK} s_{+i}) \right] \\ N_{+i}^- &= h_{B^-} \left[F_{+i} + \left((x_-^{DK})^2 + (y_-^{DK})^2 \right) F_{-i} + 2\sqrt{F_i F_{-i}} (x_-^{DK} c_{+i} + y_-^{DK} s_{+i}) \right] \\ N_{-i}^- &= h_{B^-} \left[F_{-i} + \left((x_-^{DK})^2 + (y_-^{DK})^2 \right) F_{+i} + 2\sqrt{F_i F_{-i}} (x_-^{DK} c_{+i} - y_-^{DK} s_{+i}) \right] \end{aligned}$$

$$x_{\pm}^{DK} \equiv r_B^{DK} \cos(\delta_B^{DK} \pm \gamma) \quad \text{and} \quad y_{\pm}^{DK} \equiv r_B^{DK} \sin(\delta_B^{DK} \pm \gamma).$$

Measurement of γ using $B^+ \rightarrow Dh^+$ decays with $D \rightarrow K_S^0 h^+ h^-$

- CP observables results

$$x_-^{DK} = (5.68 \pm 0.96 \pm 0.20 \pm 0.23) \times 10^{-2}$$

$$y_-^{DK} = (6.55 \pm 1.14 \pm 0.25 \pm 0.35) \times 10^{-2}$$

$$x_+^{DK} = (-9.30 \pm 0.98 \pm 0.24 \pm 0.18) \times 10^{-2}$$

$$y_+^{DK} = (-1.25 \pm 1.23 \pm 0.26 \pm 0.28) \times 10^{-2}$$

$$x_\xi^{D\pi} = (-5.47 \pm 1.99 \pm 0.32 \pm 0.14) \times 10^{-2}$$

$$y_\xi^{D\pi} = (0.71 \pm 2.33 \pm 0.54 \pm 0.18) \times 10^{-2}$$

- Uncertainties are **statistical**, **systematic** and due to **external inputs**
- Systematic uncertainties dominated by partially reconstructed backgrounds

$$\gamma = (68.7_{-5.1}^{+5.2})^\circ,$$

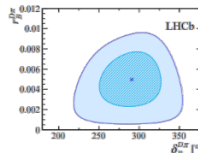
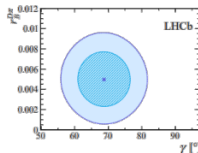
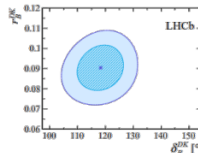
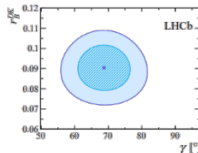
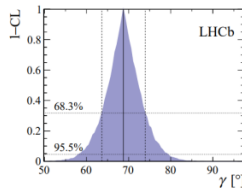
$$r_B^{DK^\pm} = 0.0904_{-0.0075}^{+0.0077},$$

$$\delta_B^{DK^\pm} = (118.3_{-5.6}^{+5.5})^\circ,$$

$$r_B^{D\pi^\pm} = 0.0050 \pm 0.0017,$$

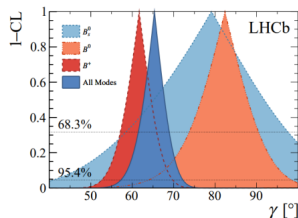
$$\delta_B^{D\pi^\pm} = (291_{-26}^{+24})^\circ.$$

- Most precise single γ measurement to date!



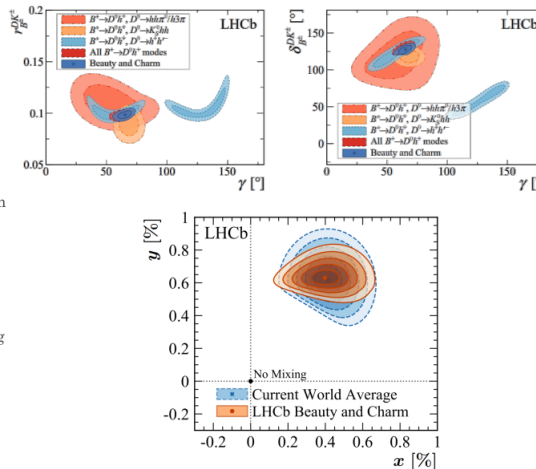
(arXiv:2110.02350)

- First simultaneous determination of CP observables and charm mixing parameters.



- Moderate tension found between initial state B mesons

- Most precise measurement of both γ and charm mixing parameters from a single experiment
- Simultaneous combination has a small effect in γ measurement, but reduces the uncertainty of the charm mixing parameter y by half
- Still room for improvement, sensitivity in the B^0 , B_s^0 and B^+ modes expected to improve significantly when including ongoing analyses

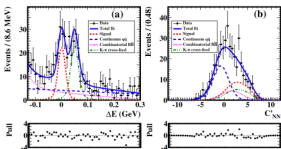
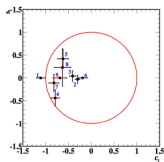


$$B^\pm \rightarrow D(K_S^0 \pi^+ \pi^- \pi^0) K^\pm$$

[JHEP01, 82 (2018)]

GGSZ

Bin	Resonance	Bin	c_i	s_i
1	ω	1	$-1.11 \pm 0.09^{+0.02}_{-0.02}$	0.00
2	$K^{*-} \rho^+$	2	$-0.30 \pm 0.05 \pm 0.01$	$-0.03 \pm 0.09^{+0.01}_{-0.02}$
3	$K^{*+} \rho^-$	3	$-0.41 \pm 0.07^{+0.02}_{-0.02}$	$0.04 \pm 0.12^{+0.01}_{-0.02}$
4	K^{*-}	4	$-0.79 \pm 0.09 \pm 0.05$	$-0.44 \pm 0.18 \pm 0.06$
5	K^{*+}	5	$-0.62 \pm 0.12^{+0.03}_{-0.02}$	$0.42 \pm 0.20 \pm 0.06^*$
6	K^{*0}	6	$-0.19 \pm 0.11 \pm 0.02$	0.00
7	ρ^+	7	$-0.82 \pm 0.11 \pm 0.03$	$-0.11 \pm 0.19^{+0.04}_{-0.03}$
8	ρ^-	8	$-0.63 \pm 0.18 \pm 0.03$	$0.23 \pm 0.41^{+0.04}_{-0.03}$
9	remainder	9	$-0.69 \pm 0.15^{+0.13}_{-0.12}$	0.00



Signal-enhanced fit projections
[JHEP10(2019)178]

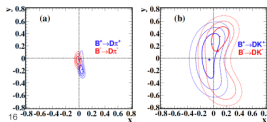
- $\phi_3 = (5.7^{+10.2}_{-8.8}) \pm 3.5 \pm 5.7^\circ$

- 95% CL interval on ϕ_3
($-29.7, 109.5$)° consistent with the current world average

- $r_B = 0.323 \pm 0.147 \pm 0.023 \pm 0.051$

- $\delta_B = (83.4^{+18.3}_{-16.6}) \pm 3.1 \pm 4.0^\circ$

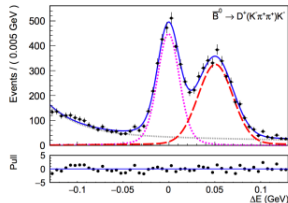
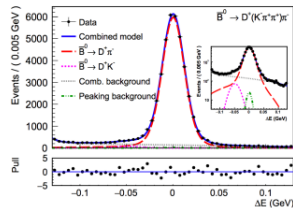
	$B^\pm \rightarrow D\pi^\pm$	$B^\pm \rightarrow DK^\pm$
x_+	$0.039 \pm 0.024^{+0.038+0.014}_{-0.013-0.012}$	$-0.030 \pm 0.121^{+0.017+0.019}_{-0.018-0.018}$
y_+	$-0.196^{+0.080+0.038+0.032}_{-0.059-0.034-0.030}$	$0.220^{+0.182+0.032+0.072}_{-0.541-0.032-0.071}$
x_-	$-0.014 \pm 0.021^{+0.018+0.019}_{-0.010-0.010}$	$0.095 \pm 0.121^{+0.017+0.023}_{-0.016-0.025}$
y_-	$-0.033 \pm 0.059^{+0.018+0.019}_{-0.019-0.010}$	$0.354^{+0.144+0.015+0.032}_{-0.197-0.021-0.049}$



- Single-mode uncertainty of 4.4° achievable with 50 ab^{-1} sample at Belle II
- Further improvements possible once a suitable amplitude model is available
- Precise inputs for c_i, s_i from BESIII will help in reducing the systematic uncertainty

$$\bar{B}^0 \rightarrow D^+ h^- (h = \pi, K)$$

- Analysis using full Belle dataset of 711 fb⁻¹ [arXiv: 2111.04978 (2021)]
- Individual Branching fractions of the Cabibbo favored and the Cabibbo suppressed measured
 $BF(\bar{B}^0 \rightarrow D^+ \pi^-) = (2.48 \pm 0.01 \pm 0.09 \pm 0.04) \times 10^{-3}$
 and the Cabibbo suppressed
 $BF(\bar{B}^0 \rightarrow D^+ K^-) = (2.03 \pm 0.05 \pm 0.07 \pm 0.03) \times 10^{-4}$
- Ratio of branching fractions of CS and CF is measured as $R^D = (8.19 \pm 0.20 \pm 0.23) \times 10^{-2}$
- This ratio facilitates tests of theoretical predictions, particularly those of factorization and SU(3) symmetry breaking in QCD.
- Individual branching fractions are lower than the theory predictions, however, the ratio agrees within uncertainties [arXiv:1606.02888 (2016)].



$$N_{\text{pion enhanced}}^{D\pi} = (1 - \kappa) N_{\text{tot}}^{D\pi}$$

ϵ = kaonID efficiency

$$N_{\text{pion enhanced}}^{DK} = (1 - \epsilon) R^0 N_{\text{tot}}^{D\pi}$$

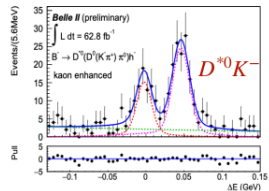
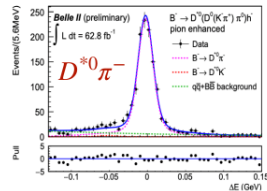
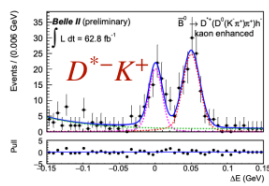
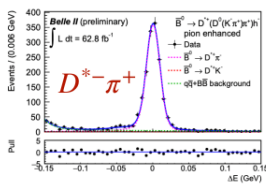
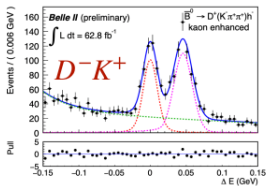
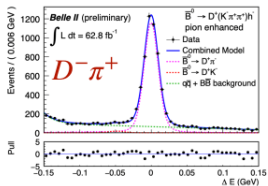
κ = pion fake – rate

$$N_{\text{kaon enhanced}}^{DK} = \epsilon R^0 N_{\text{tot}}^{D\pi}$$

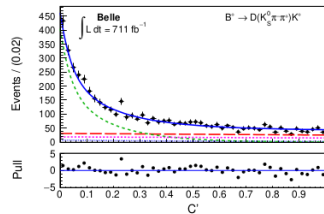
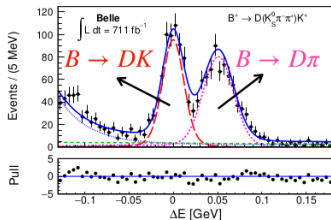
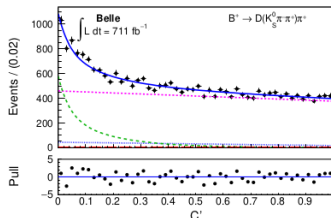
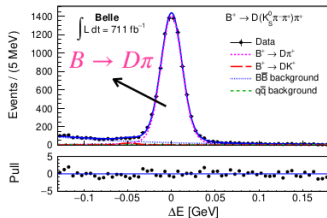
$\kappa, R^0, N_{\text{tot}}^{D\pi}$ are directly extracted from simultaneous fit of $B \rightarrow Dh$

$$N_{\text{kaon enhanced}}^{D\pi} = \kappa N_{\text{tot}}^{D\pi}$$

- Common selection to all the final states
- Common signal extraction strategy
- PID selection prompt h : pion-enhanced and kaon-enhanced



$$B^\pm \rightarrow D(K_S^0 h^+ h^-) K^\pm$$



- 2D (ΔE , C') simultaneous fit of $B \rightarrow D\pi$ and $B \rightarrow DK$
- $K - \pi$ misidentification rate is directly extracted from data

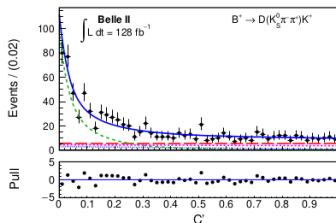
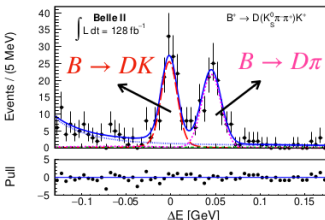
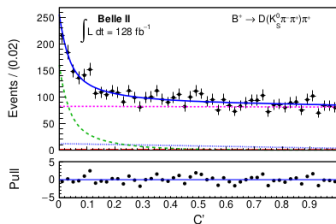
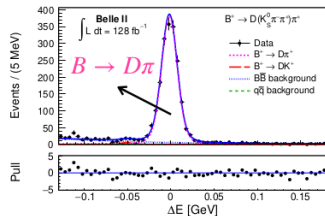
$N_{\text{signal}} : \text{Belle}$

$$K_S^0 \pi \pi = 1467 \pm 53$$

$$K_S^0 K K = 194 \pm 17$$

40% increase in signal yield
as compared to previous
best result of Belle

$$B^\pm \rightarrow D(K_S^0 h^+ h^-) K^\pm$$



- 2D (ΔE , C') simultaneous fit of $B \rightarrow D\pi$ and $B \rightarrow DK$
- $K - \pi$ misidentification rate is directly extracted from data

N_{signal}: Belle II

$$K_S^0 \pi \pi = 280 \pm 21$$

$$K_S^0 K K = 34 \pm 7$$



Additional 17%

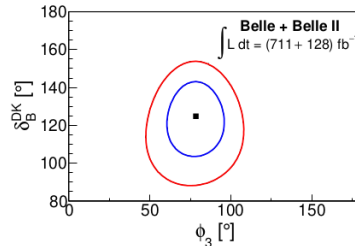
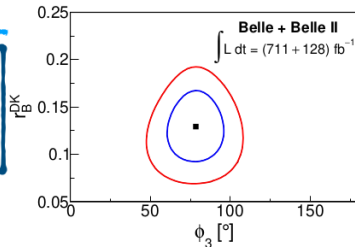
Results

$\delta_B(^{\circ})$	$124.8 \pm 12.9 \text{ (stat.)} \pm 0.5 \text{ (syst.)} \pm 1.7 \text{ (ext. input)}$
r_B^{DK}	$0.129 \pm 0.024 \text{ (stat.)} \pm 0.001 \text{ (syst.)} \pm 0.002 \text{ (ext. input)}$
$\phi_3(^{\circ})$	$78.4 \pm 11.4 \text{ (stat.)} \pm 0.5 \text{ (syst.)} \pm 1.0 \text{ (ext. input)}$

Belle previous results: *PRD 85, 112014 (2012)*

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

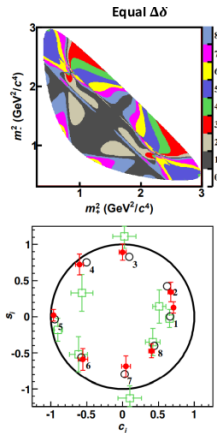
- This result is most precise to date from the B -factory experiments
- New inputs from BESIII on strong-phase has significant impact on systematic uncertainty
Phys. Rev. D 101 (2020) 112002
Phys. Rev. D 102 (2020) 052008
- Use of $B \rightarrow Dh$ decay mode to incorporate efficiency effects reduces the experimental systematic uncertainty



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

(PRL 124, 241802 (2020), PRD 101, 112002 (2020))

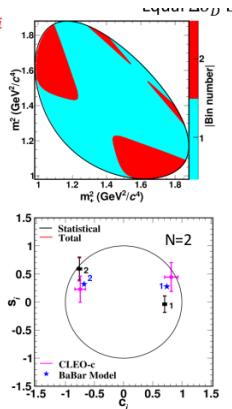
- Strong phase parameters are obtained by MLH fit with expected and observed DT yields
- The strong phase parameters are limited by statistical errors
- On average a factor of ~ 2.5 (2.0) more precise for c_i (s_i) than CLEO-c measurements
- The associated uncertainties on γ are expected to be 0.7° , 1.2° and 0.8° for equal $\Delta\delta$, optimal and modified optimal binning schemes.



$$D^0 \rightarrow K_S^0 K^+ K^-$$

(PRD 102, 052008 (2020))

- Measurement of γ (GGSZ) $\leftarrow c_i, s_i$
- The strong phase parameters are limited by statistical errors
- Compatible with CLEO-c measurement with improved precision
- The associated uncertainty on γ is expected to be $\sim 1.3^\circ$ ($N=3,4$)
- The results of $K_S^0 h^+ h^-$ have been used on γ measurement by LHCb and BelleII. The uncertainty from charm inputs is 1° .



Carefully optimised binning has $\simeq 80\%$ power of the unbinned fit.

Can we do better?

[AP, EPJC (2018) 78: 121]

Weight functions instead of **bins** in phase space $\mathbf{z} = (m_+^2, m_-^2)$:

$$\int_{\mathcal{D}_i} \dots d\mathbf{z} \rightarrow \int_{\mathcal{D}} \dots \times w_i(\mathbf{z}) d\mathbf{z}$$

Treat decay densities as vectors in Hilbert space:

Projecting event density onto basis functions $w_i(\mathbf{z})$.

Works with scattered unbinned data (sum with weights).

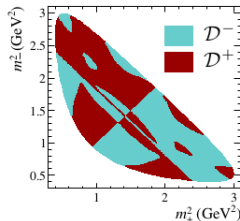
E.g. **Fourier expansion** of strong phase difference:

$$w_{2n}(\mathbf{z}) = \cos(n\Delta\delta_D(\mathbf{z}));$$

$$w_{2n+1}(\mathbf{z}) = \sin(n\Delta\delta_D(\mathbf{z}))$$

Additionally, can **split**

$\mathcal{D}^-$: $|A_D| < |\bar{A}_D|$ and $\mathcal{D}^+$: $|A_D| > |\bar{A}_D|$



Double Dalitz plot analysis

Anton Poluektov

[T. Gershon, AP, PRD 81, 014025 (2010)], [D. Craik, T. Gershon, AP, PRD 97, 056002 (2018)]

- B^0 decays have larger interference term $r_B \sim 0.3$
- 3-body $B \rightarrow DK\pi$: amplitude and strong phase varies $\Rightarrow$ correlated B and D decay Dalitz plots.
- Applying the same model-independent binned technique to $B \rightarrow DK\pi$ decay

$$A_{\text{dblDlz}} = \bar{A}_B \bar{A}_D + e^{i\gamma} A_B A_D,$$

After binning both Dalitz plots, system of equations:

$$\begin{aligned} \langle N_{\alpha i} \rangle = & h_{\text{dblDlz}} \left\{ \bar{\kappa}_{\alpha} K_i + \kappa_{\alpha} K_{-i} \right. \\ & \left. + 2\sqrt{\kappa_{\alpha} K_i \bar{\kappa}_{\alpha} K_{-i}} [(\varkappa_{\alpha} c_i - \sigma_{\alpha} s_i) \cos \gamma - (\varkappa_{\alpha} s_i + \sigma_{\alpha} c_i) \sin \gamma] \right\}, \end{aligned}$$

Can be solved with three classes of events:

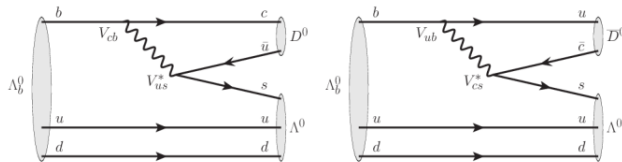
- $B \rightarrow DK\pi, D \rightarrow K^- \pi^+ \ (i=1, c_1 = \cos \delta_{K\pi}, s_1 = \sin \delta_{K\pi}, K_1/K_{-1} = r_{K\pi}^2)$
- $B \rightarrow DK\pi, D \rightarrow K^- K^+, \pi^- \pi^+ \ (i=1, c_1 = +1, s_1 = 0, K_1 = K_{-1})$
- $B \rightarrow DK\pi, D \rightarrow K_S^0 \pi^+ \pi^-$

ADS-like mode contaminated by $B_s^0 \rightarrow D^* K\pi$ decays at LHCb, study if the fit works after removing it (but can be added at Belle II)

Unique measurement for LHC: b -baryons.

[Giri, Mohanta, Khanna, PRD 65 (2002) 073029]

γ -sensitive modes in the case of Λ_b^0 :



$\Lambda_b^0 \rightarrow D \Lambda_{\rightarrow p\pi^-}^0$ mode:

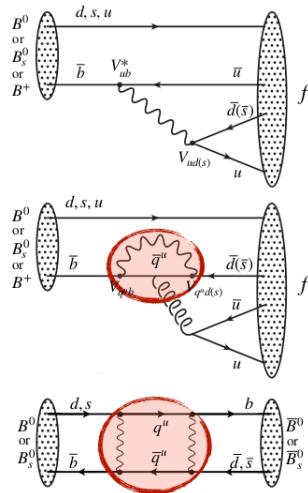
- S - and P -wave amplitudes with different strong parameters. Distinguish in $\Lambda^0 \rightarrow p\pi^-$ angular distribution
- At LHCb, affected by low efficiency to reconstruct long-lived Λ^0 .

First try with excited, strongly decaying $\Lambda^{*0} \rightarrow pK^-$ instead.

- Search for suppressed mode $\Lambda_b^0 \rightarrow DpK^-$ with $D \rightarrow K^+\pi^-$ (ADS-like)
- Measure CP asymmetry

- The $b \rightarrow u$ **tree-level** transitions and the $b \rightarrow s(d)$ **penguin** transitions dominate the charmless B -hadron decays
 - Similar magnitudes due to CKM suppression
 - Physics BSM in the **loops** may be revealed by comparison of measured quantities and SM predictions

- **Relevant quantities:** branching fractions, time-integrated and time-dependent CP asymmetries
 - Sensitive to UT angles and $B_{(s)}^0$ mixing phases,
 - but the combination of several measurements is necessary to extract the CKM parameters



Long-standing $B \rightarrow K\pi$ puzzle

○ Isospin relations $\rightarrow A_{CP}(B^+ \rightarrow K^+\pi^0) = A_{CP}(B^0 \rightarrow K^+\pi^-)$

○ The experimental state of the art was [HFLAV2019]:

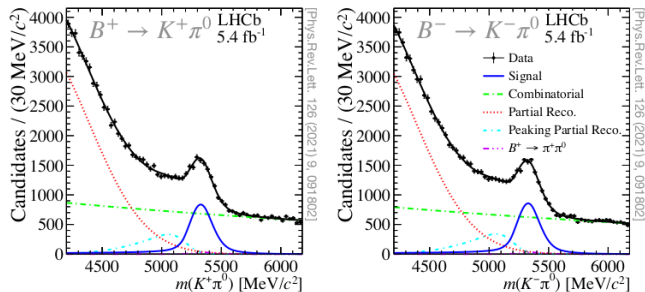
$$\begin{aligned} A_{CP}^{WA}(B^+ \rightarrow K^+\pi^0) &= (+4.0 \pm 2.1) \% \\ A_{CP}^{WA}(B^0 \rightarrow K^+\pi^-) &= (-8.4 \pm 0.4) \% \end{aligned} \quad \rightarrow \text{Almost } 6\sigma \text{ discrepancy!}$$

$\Delta A_{CP}(K\pi) = (12.4 \pm 2.1) \%$

○ Is it due to strong phases and amplitudes
or is new physics emerging from the loops?

○ Full $B \rightarrow K\pi$ puzzle sum rule [PLB627(2005)82]: any deviation from
this would be a sign of new physics

$$A_{CP}(B^0 \rightarrow K^+\pi^-) + A_{CP}(B^+ \rightarrow K^0\pi^+) \frac{\mathbf{B}(B^+ \rightarrow K^0\pi^+) \tau^0}{\mathbf{B}(B^0 \rightarrow K^+\pi^-) \tau^+} = A_{CP}(B^+ \rightarrow K^+\pi^0) \frac{2\mathbf{B}(B^+ \rightarrow K^+\pi^0) \tau^0}{\mathbf{B}(B^0 \rightarrow K^+\pi^-) \tau^+} + A_{CP}(B^0 \rightarrow K^0\pi^0) \frac{2\mathbf{B}(B^0 \rightarrow K^0\pi^0) \tau^0}{\mathbf{B}(B^0 \rightarrow K^+\pi^-) \tau^+}$$



The direct CP asymmetry has been measured to be:

$$A_{CP}^{\text{LHCb}}(B^+ \rightarrow K^+ \pi^0) = (2.5 \pm 1.5 \pm 0.6 \pm 0.3) \%$$

[Phys.Rev.Lett. 126 (2021) 9, 091802]

stat.

syst.

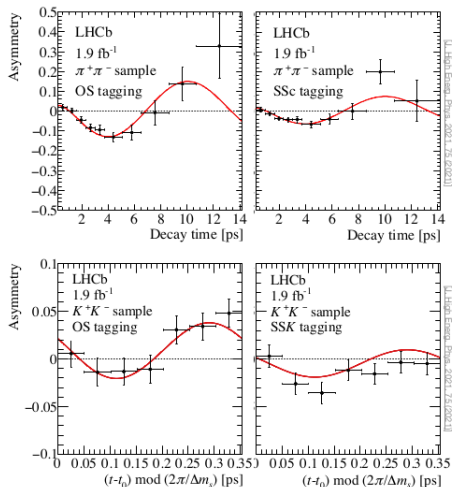
ext.

Most precise
determination
to date

New world average: $A_{CP}^{\text{WA}}(B^+ \rightarrow K^+ \pi^0) = (3.1 \pm 1.7) \%$, which implies:

$$A_{CP}^{\text{WA}}(B^+ \rightarrow K^+ \pi^0) - A_{CP}^{\text{WA}}(B^0 \rightarrow K^+ \pi^-) = (11.5 \pm 1.4) \%$$

nonzero
at 8 σ



Decay time is folded into 1 oscillation period

[Run1: PRD98(2018)032004]
[J. High Energy Phys. 2021, 75 (2021)]
Final combinations with Run1 results:

$$C_{\pi\pi} = (-32.0 \pm 3.8) \%$$

$$S_{\pi\pi} = (-67.2 \pm 3.4) \%$$

$$C_{KK} = (17.2 \pm 3.1) \%$$

$$S_{KK} = (13.9 \pm 3.2) \%$$

$$A_{KK}^{\Delta\Gamma} = (-89.7 \pm 8.7) \%$$

stat.+syst.
uncertainty

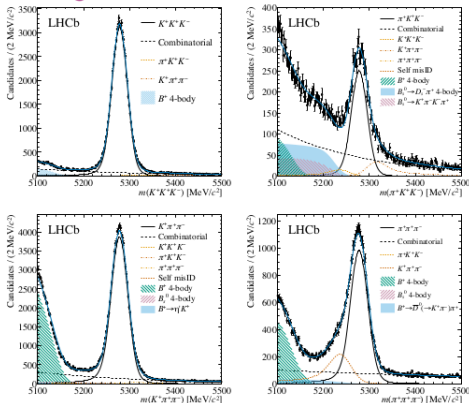
$$\sqrt{(C_{KK})^2 + (S_{KK})^2 + (A_{KK}^{\Delta\Gamma})^2} = 0.93 \pm 0.08 \quad \checkmark$$

- Most precise determination of these quantities to date
- First observation of time-dependent CPV in the B_s sector

Charmless three-body B decays at LHCb

Relative branching fractions of $B^+ \rightarrow h^+ h'^+ h'^-$ (PRD102 (2020) 112010) **Diego Torres Machado**

→ **Signal** + **crossfeed, partially reconstructed and combinatorial background**



Decay	Fit yield
$B^+ \rightarrow K^+ K^+ K^-$	$69\,310 \pm 280$
$B^+ \rightarrow \pi^+ K^+ K^-$	$5\,760 \pm 140$
$B^+ \rightarrow K^+ \pi^+ \pi^-$	$94\,950 \pm 430$
$B^+ \rightarrow \pi^+ \pi^+ \pi^-$	$25\,480 \pm 200$

$$\frac{\mathcal{B}(B^+ \rightarrow h^+ h'^+ h'^-)}{\mathcal{B}(B^+ \rightarrow K^+ K'^+ K'^-)} = \frac{\mathcal{N}_{hh}^{\text{corr}}}{\mathcal{N}_{KK}^{\text{corr}}}$$

$$\mathcal{N}^{\text{corr}} = \frac{1}{\epsilon^{\text{veto}}} \sum_j^{N_{\text{bins}}} \frac{cM_j + \sum_{i \in \text{binj}} w_j}{\epsilon_j^{\text{tot}}}$$

Correction of efficiency across the Dalitz plot via sPlot technique

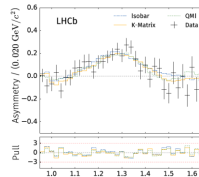
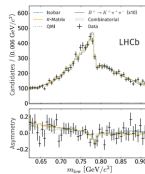
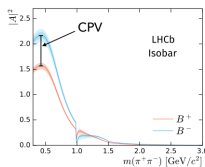
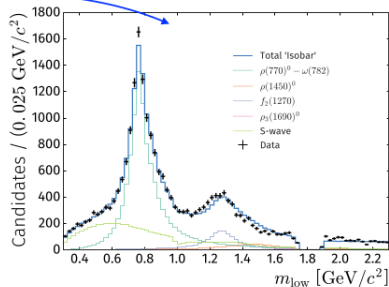
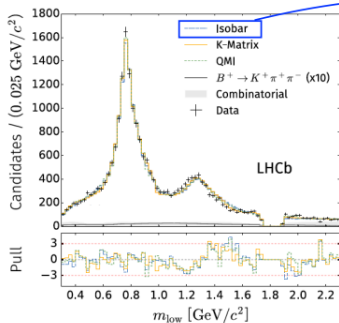
$$\mathcal{B}(B^+ \rightarrow K^+ K^+ \pi^-) / \mathcal{B}(B^+ \rightarrow K^+ K'^+ K'^-) = 0.151 \pm 0.004(\text{stat}) \pm 0.008(\text{syst})$$

$$\mathcal{B}(B^+ \rightarrow K^+ \pi^+ \pi^-) / \mathcal{B}(B^+ \rightarrow K^+ K'^+ K'^-) = 1.703 \pm 0.011(\text{stat}) \pm 0.022(\text{syst})$$

$$\mathcal{B}(B^+ \rightarrow \pi^+ \pi^+ \pi^-) / \mathcal{B}(B^+ \rightarrow K^+ K'^+ K'^-) = 0.488 \pm 0.005(\text{stat}) \pm 0.009(\text{syst})$$

Amplitude analysis of $B^+ \rightarrow \pi^+ \pi^+ \pi^-$ (PRL 124 (2020) 031801, PRD 101 (2020) 012006)

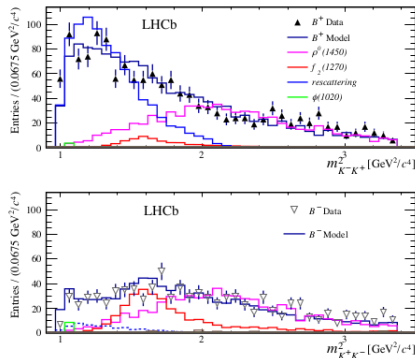
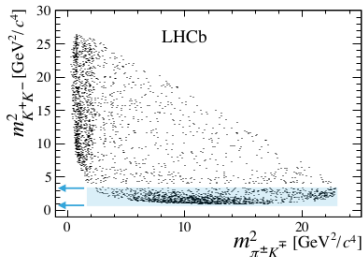
Diego Torres Machado



First observation of CPV in a tensor $f_2(1270)$ at 10σ

Amplitude analysis of $B^+ \rightarrow \pi^+ K^+ K^-$ (PRL 123 (2019) 231802)

Diego Torres Machado



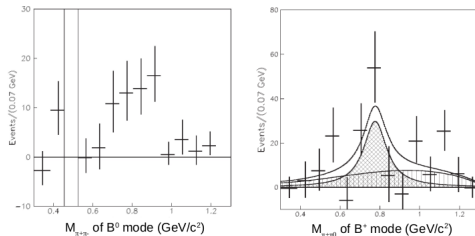
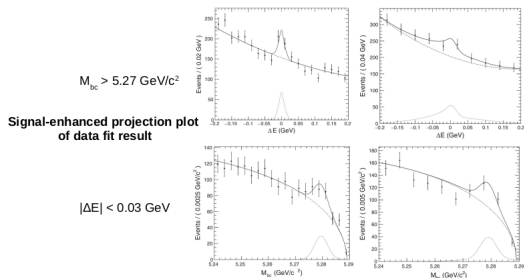
□ Isobar model components:

→ $K^*(892)^0$, $K^*(1430)^0$, single pole, $\rho(1450)^0$, $f_2(1270)$, rescattering, $\phi(1020)$

□ Dominant contribution from the non-resonant component

→ Responsible for almost all CPV observed in $B^\pm \rightarrow \pi^\pm K^+ K^-$ ($-12.3 \pm 2.1\%$)

$$B \rightarrow p\bar{p}\pi\pi \quad (\text{PRD 101, 052012(2020)})$$

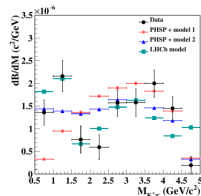
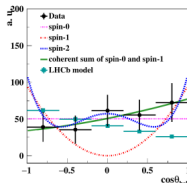
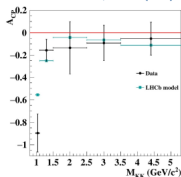
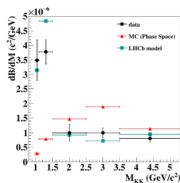


	$B^0 \rightarrow p\bar{p}\pi^+\pi^-$	$B^+ \rightarrow p\bar{p}\pi^+\pi^0$
Signal yield	$73.8^{+15.4}_{-14.9}$	151 ± 39
Significance (σ)	5.5	5.4
BF (10^{-6})	$0.83 \pm 0.17 \pm 0.17$	$4.58 \pm 1.17 \pm 0.67$

- First measurement of the mode; search for ρ mode - yield 86 ± 41

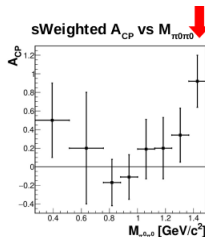
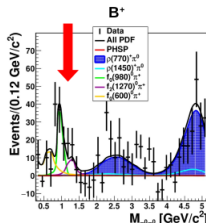
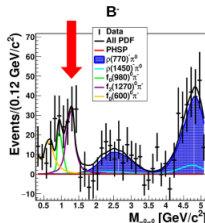
$$B^+ \rightarrow K^+ K^- \pi^+$$

Yun-Tsung Lai



- Consistent with a coherent sum of spin-0 and spin-1

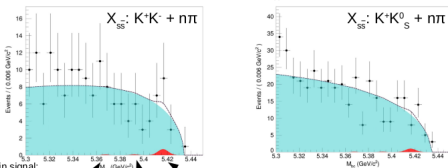
$$B^+ \rightarrow \pi^+ \pi^0 \pi^0$$



A_{CP} measured at
 3.2σ

$$B_s^0 \rightarrow \eta'(X_{s\bar{s}}, \eta, K_S^0) \quad (\text{PRD 104, 012007 (2021), PRD 104, L031101 (2021)})$$

Sum of fits to all $M(X_{s\bar{s}})$ bins



Multiple peaks in signal:

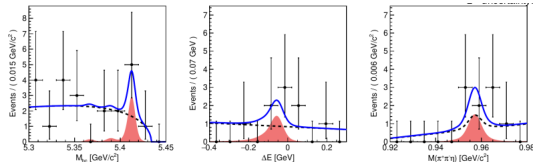
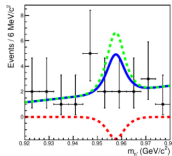
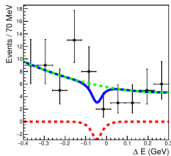
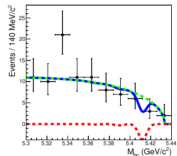
Energy shift due to

missing γ in $B^0 \rightarrow B^0 \gamma$ decay.

$Y(5S) \rightarrow B^0 \bar{B}_s^0$

$Y(5S) \rightarrow B^+ \bar{B}_s^-$

$Y(5S) \rightarrow B^0 \bar{B}_s^0$



UL is set on BF

$$\mathcal{B}(B_s^0 \rightarrow \eta' X_{s\bar{s}}) = (-0.7 \pm 8.1 \pm 0.7 \text{ }^{+3.0}_{-6.0} \pm 0.1) \times 10^{-4}$$

$$- \text{UL: } 1.4 \times 10^{-3} \text{ @ 90 C.L.}$$

$$\mathcal{B}(B_s^0 \rightarrow \eta' \eta) \quad (2.5 \pm 2.2 \pm 0.6) \times 10^{-5} \\ < 6.5 \times 10^{-5} \text{ @ 90\% CL}$$

$$\mathcal{B}(B_s^0 \rightarrow \eta' K_S^0) < 8.16 \times 10^{-6}$$

Isospin sum rule for $B \rightarrow K\pi$

$$\mathcal{B}(B^0 \rightarrow K^+\pi^-) = [18.0 \pm 0.9(\text{stat}) \pm 0.9(\text{syst})] \times 10^{-6}$$

$$A_{CP}(B^0 \rightarrow K^+\pi^-) = -0.16 \pm 0.05(\text{stat}) \pm 0.01(\text{syst})$$

$$\mathcal{B}(B^+ \rightarrow K^0\pi^+) = [21.4^{+2.3}_{-2.2}(\text{stat}) \pm 1.6(\text{syst})] \times 10^{-6}$$

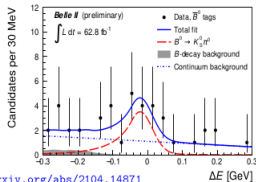
$$A_{CP}(B^+ \rightarrow K^0\pi^+) = -0.01 \pm 0.08(\text{stat}) \pm 0.05(\text{syst})$$

$$\mathcal{B}(B^+ \rightarrow K^+\pi^0) = [11.9^{+1.1}_{-1.0}(\text{stat}) \pm 1.6(\text{syst})] \times 10^{-6}$$

$$A_{CP}(B^+ \rightarrow K^+\pi^0) = -0.09 \pm 0.09(\text{stat}) \pm 0.03(\text{syst})$$

<https://arxiv.org/abs/2105.04111>

$$B^0 \rightarrow K_S^0\pi^0$$

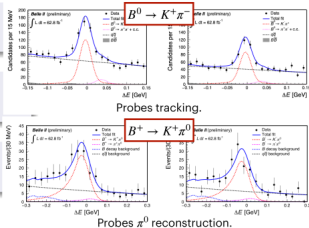
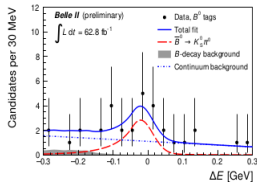


<https://arxiv.org/abs/2104.14871>

$$N(B^0 \rightarrow K^0\pi^0) = 45^{+9}_{-8} \quad \mathcal{B}(B^0 \rightarrow K^0\pi^0) = [8.5^{+1.7}_{-1.6}(\text{stat}) \pm 1.2(\text{syst})] \times 10^{-6}$$

$$A_{K^0\pi^0} = -0.40^{+0.46}_{-0.44}(\text{stat}) \pm 0.04(\text{syst})$$

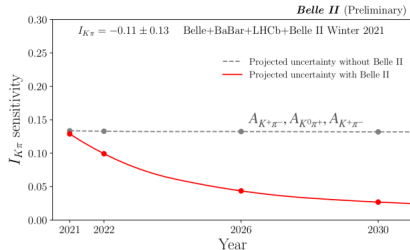
$$\bar{B}^0 \rightarrow K_S^0\pi^0$$



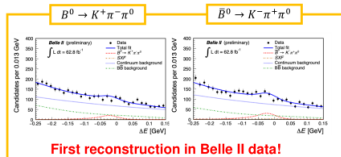
Probes tracking.

Probes π^0 reconstruction.

Sagar Hazra



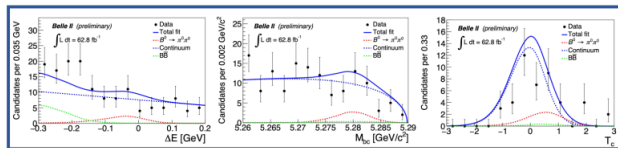
CPV in multibody B decays



First reconstruction in Belle II data!

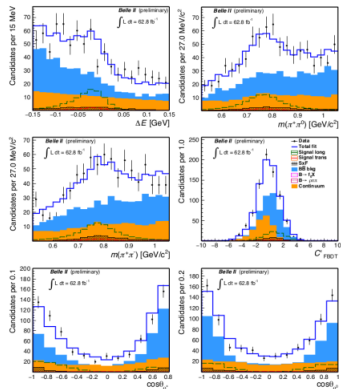
Determining α/ϕ_2

- Possible to study all $B \rightarrow \pi\pi, \rho, \rho$ modes at Belle II
- $B^0 \rightarrow \pi^+\pi^-$, $B^\pm \rightarrow \pi^\pm\pi^0$ benchmark modes to test PID, ΔE resolution, π^0 reconstruction



<https://arxiv.org/pdf/2107.02373.pdf>

$$N(B^0 \rightarrow \pi^0\pi^0) = 14_{-5.6}^{+6.8} \quad \mathcal{B}(B^0 \rightarrow \pi^0\pi^0) = [0.98_{-0.39}^{+0.48}(\text{stat}) \pm 0.27(\text{syst})] \times 10^{-6}$$



<https://arxiv.org/abs/2109.11456>

$$N = 104 \pm 16$$

$$\mathcal{B} = [20.6 \pm 3.2(\text{stat}) \pm 4.0(\text{syst})] \times 10^{-6}$$

$$f_L = 0.936_{-0.041}^{+0.049}(\text{stat}) \pm 0.021(\text{syst})$$

Sub-degree precision in α possible in the near future

Innovation on experimental side important to realising this goal

Amplitude analysis in $B \rightarrow \rho\rho$

Properly handle interference effects, model $I = 1$, resolve α ambiguities

J. Dalseno, JHEP **11** (2018) 193 [\[INSPIRE\]](#)

Opens the possibility for precision SU(3) measurement in $B^0 \rightarrow a_1^\pm \pi^\mp$

Non-factorisable SU(3) can be constrained with amplitude analysis

Consensus on K_1 mixing angle motivated

J. Dalseno, JHEP **10** (2019) 191 [\[INSPIRE\]](#)

Rigorous, coordinated bookkeeping surrounding systematic correlations

Bias in α reduced and uncertainty improved

J. Dalseno, JHEP **10** (2021) 110 [\[INSPIRE\]](#)

Relative branching fraction measurements

Eliminate and reduce dominant branching fractions systematics

LHCb can finally enter the fray in $B \rightarrow \rho\rho$

b -hadron fraction in $\Upsilon(4S)$ at Belle II, and f_u/f_d at LHCb motivated

J. Dalseno, arXiv:2110.08183 [hep-ph] [\[INSPIRE\]](#)

$$\bar{B}_{(s)}^- \rightarrow D_{(s)}^{(*)} K / \pi$$

Possible NP?

	$BR^{exp} \times 10^3$	$BR^{SM, QCDF} \times 10^3$	
$\bar{B}_s \rightarrow D_s^+ \pi^-$	3.00 ± 0.23	4.09 ± 0.21	3.5σ
$\bar{B}^0 \rightarrow D^+ K^-$	0.186 ± 0.020	0.303 ± 0.015	4.7σ
$\bar{B}_s \rightarrow D_s^{*+} \pi^-$	2.0 ± 0.5	4.46 ± 0.22	4.5σ
$\bar{B}^0 \rightarrow D^{*+} K^-$	0.212 ± 0.015	0.327 ± 0.016	5.3σ
PDG	2109.10811		

Theoretical uncertainty mainly comes from $V_{cb} \times FF$

We need a charged mediator (for instance W' , **not** LQ)

The naïve NP scale for this puzzle is estimated as

$$\left| \frac{C_2^{NP}(\Lambda_{NP})}{C_2^{SM}} \right| \sim 10\% = \frac{g_{11} \times g_{33}}{M_V^2} \frac{1}{4\sqrt{2}G_F} = \frac{g_{11} \times g_{33}}{1} \frac{(400\text{GeV})^2}{M_V^2}$$

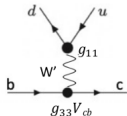
Our model

We will focus on the $SU(2)_1 \times SU(2)_2 \times U(1)_Y$ model

See also for other NP analyses, [Bordone et al 2103.10332](#), [Cai et al 2103.04138](#).

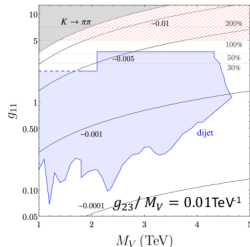
The model contains heavy vector-like quarks and heavy $SU(2)$ gauge multiplet.

(PRD RC 102, 071701, arXiv:2109.10811)



Syuei Iguro

Scenario 2: $g_{11} \times g_{23} \neq 0, g_{33} = 0$



Again, width dependence of the constraint is important!

$$\frac{C_2^{NP}(\Lambda_{NP})}{C_2^{SM}} \sim \frac{g_{11} \times g_{23}}{4\sqrt{2}G_F M_V^2 V_{cb}}$$

Enhancement by $\frac{1}{V_{cb}} \sim 25$

$$g_{ij} = \begin{pmatrix} g_{11} & 0 & 0 \\ 0 & g_{11} & g_{23} \\ 0 & g_{23} & g_{33} \end{pmatrix}$$

Flavor constraint

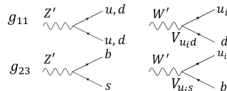
Tree level FCNC in $Z' \rightarrow \Delta M_s$:

$$|g_{23}|/M_V \leq 0.01\text{TeV}^{-1}$$

$$g_{23} \ll g_{11}$$

Collider constraint

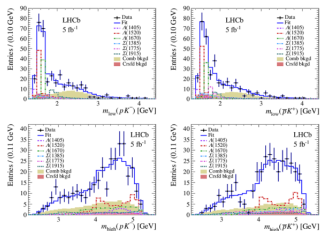
Z', W' decay into 2 jets $\rightarrow$ dijet constraint!



If we evade the collider constraint $C_2^{NP}/C_2^{SM} \sim -0.01$ is possible

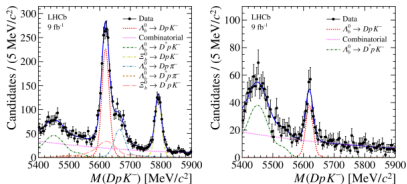
CPV in baryons at LHCb

$$\Xi_b^- \rightarrow pK^-K^- \quad \text{PRD 104, 052010}$$



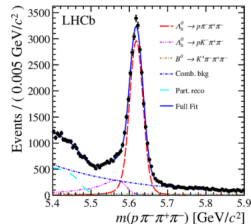
No significant CPV effects

$$\Lambda_b^0 \rightarrow DpK^- \quad \text{arXiv:2109.02621}$$

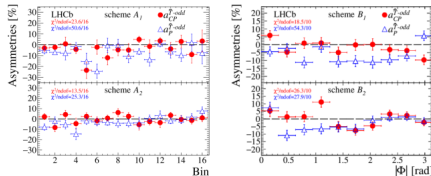


Suppressed decay seen for the first time

$$\Lambda_b^0 \rightarrow p\pi^-\pi^+\pi^- \quad \text{Matteo Bartolini PRD 102, 051101}$$

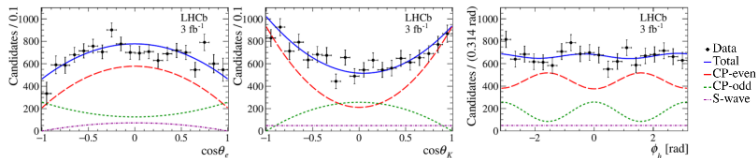


T -odd observable built from triple product correlations of momenta of final state particles



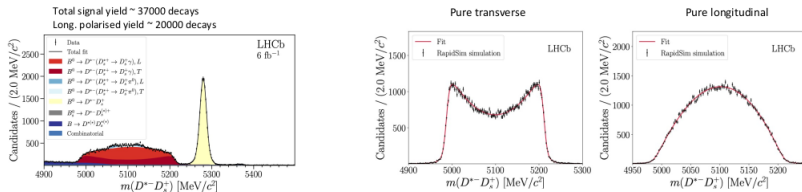
$$B_s^0 \rightarrow J/\psi(\rightarrow e^+e^-)\phi(\rightarrow K^+K^-) \quad (\text{arXiv:2105.14738})$$

Asier Pereiro Castro



$$f_L = 0.530 \pm 0.029 \pm 0.013$$

$$B^0 \rightarrow D^{*-} D_s^{*+} (\rightarrow D_s^+ \gamma) \quad \text{JHEP 2106 (2021) 177}$$



$$f_L = 0.578 \pm 0.010 \pm 0.011$$

Measurements in $B^0 \rightarrow \rho^0 \rho^0$, $B^0 \rightarrow \rho^0 K^{*0}$, $B_s^0 \rightarrow \phi \phi$, $B_{(s)}^0 \rightarrow K^{(*)0} K^{(*)0}$

Deviation of 2.6σ with PQCD for $K^{(*)0} K^{(*)0}$

- Measurements of the CKM angle ϕ_3/γ provide a stringent test of CPV in the SM
 - Precise measurements at LHCb, Belle; expected precision at Run 3 of LHCb and/or Belle II below 1°
 - Novel ideas to aid for further improvements
 - BESIII input a major player
- Charmless B decays - sensitive to UT angles and B mixing phases
 - LHCb and Belle measurements for a variety of two- and three-body modes; Belle II joining the picture too!
- Possible NP in $B_{(s)} \rightarrow D_{(s)} K/\pi$ (?)
- CPV in baryonic decays measured at LHCb and amplitude analysis performed as a first
- Polarisation measurements in $B \rightarrow VV$ decays test the agreement with theoretical calculations