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 Brod, Resmi Pk, Wenbin Qian

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Joachim Brod[1], **Resmi PK**[2], Wenbin Qian[3]

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

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Overview

- Direct CP violation (DCPV) including ϕ_3/γ from $B \to DK$, 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!

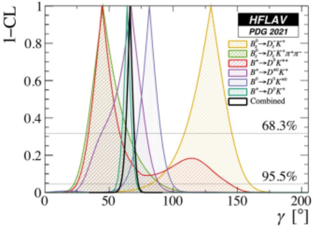
  Anton Poluektov, Fidan Suljik, Arnau Brossa Gonzalo, Seema Bahinipati, Niharika Rout, Daniele Manuzzi, Diego Torres Machado, Yun-Tsung Lai, Sagar Hazra, Syuhei Iguro, Matteo Bartolini, Asier Pereiro Castro, Xinyu Shan, Ulrik Egede, Wenbin Qian, Fabio Ferrari, Tobias Huber, Jeremy Peter Dalseno, Eleftheria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

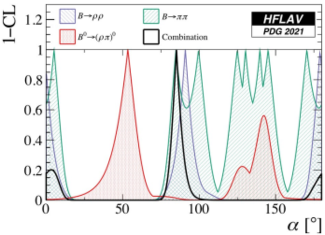
Outline

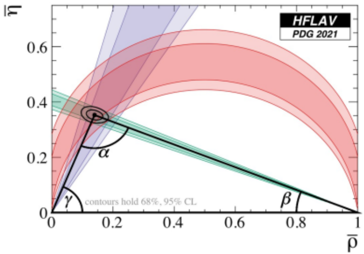
- ϕ_3/γ measurements
- Charmless B decays
- Other CPV and polarisation measurements

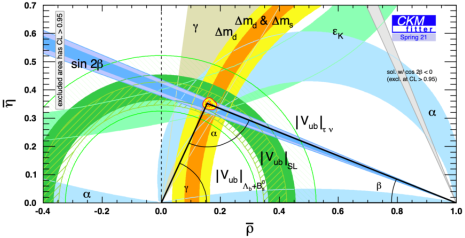
Current Status of CKM parameters

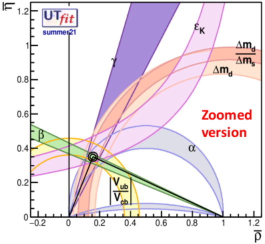
Ulrik Egede, Wenbin Qian, Fabio Ferrari









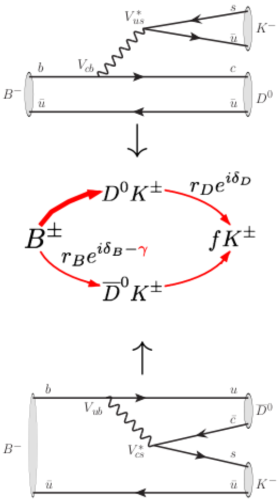


ϕ_3/γ measurements

Anton Poluektov

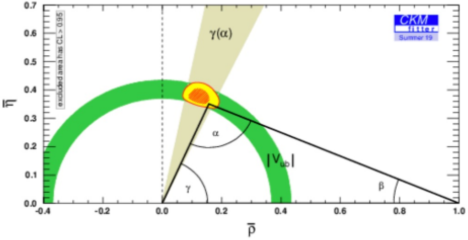
Unitarity Triangle angle γ/ϕ_3

- Measured entirely in tree-level transitions in the interference of $b \to c$ and $b \to u$ 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 $B \to DK$, $B \to DK^*$, $B \to DK\pi$ with $D \to hh, hhhh$ ("ADS", "GLW")
  - Dalitz plot analyses of $D^0 \to K^0_S h^+ h^-$ from $B \to DK$, $B \to DK^*$ ("Dalitz" or "BPGGSZ")
  - Time-dependent analyses, e.g. $B^0_s \to D_s K$, $B^0 \to D\pi$



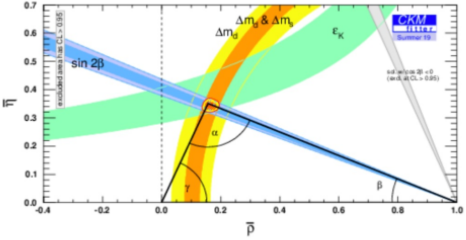
Fidan Suljik

Tree-level (direct measurement)



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

Loop-level (indirect measurement)



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

CKMfitter[2] Summer 2019

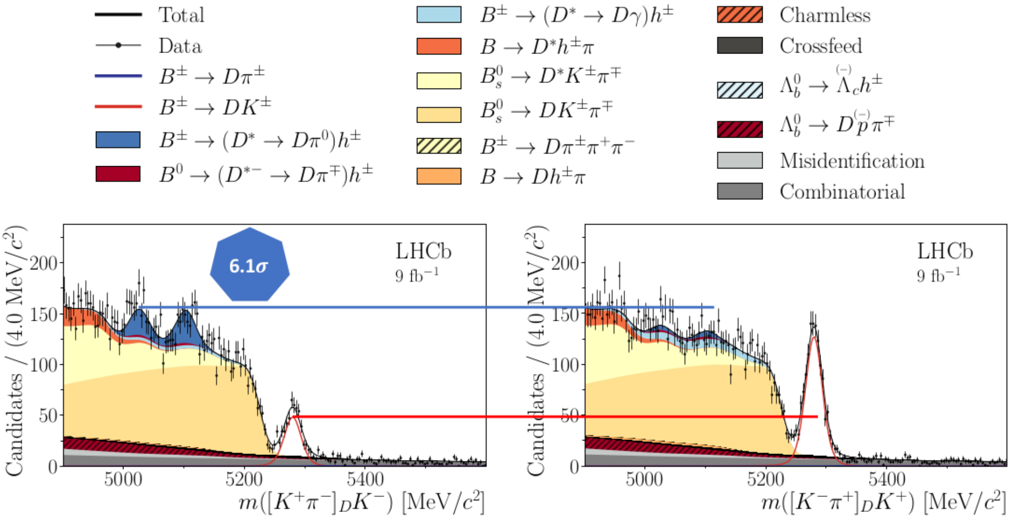
- Direct measurements of γ at tree-level are expected to be benchmarks of the Standard Model
- Indirect measurements consist of global fits to the unitary triangle, where some inputs include loop processes and assuming closed triangle. New Physics expected to contribute through loop processes
- A discrepancy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

ADS measurements at LHCb

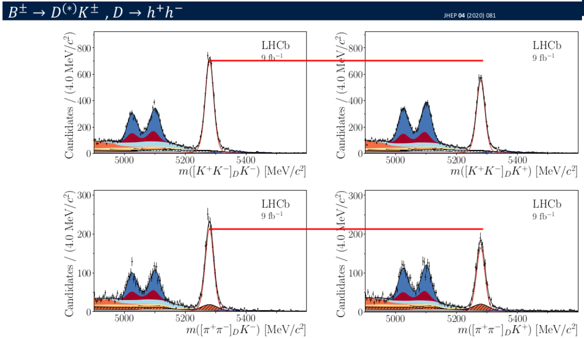
Fidan Suljik

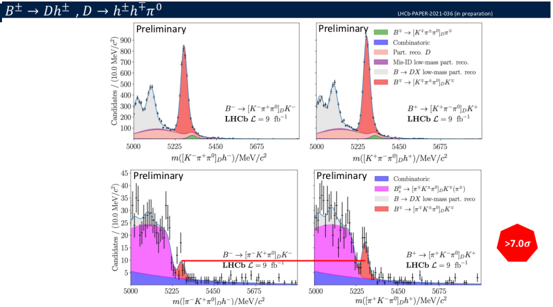
$B^{\pm} \to D^{(*)}K^{\pm}$, $D \to K^{\mp}\pi^{\pm}$

JHEP **04** (2020) 081



Fidan Suljik



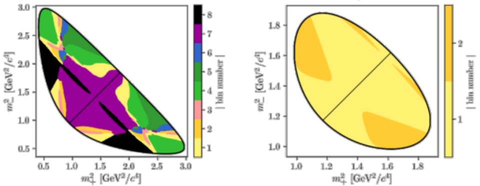


- Relatively smaller observable CP violation due to amplitudes of different sizes
- First observation of the suppressed mode in $D \to h^\pm h^\mp \pi^0$ with $> 7\sigma$

Arnau Brossa Gonzalo

arxiv.org/pdf/2010.08483.pdf

Measurement of γ using $B^+ \to Dh^+$ decays with $D \to K^0_S h^+ h^-$



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

$$c_i \equiv \frac{\int_i dm^2_- \, dm^2_+ \, |A_D(m^2_-, m^2_+)||A_D(m^2_+, m^2_-)| \cos\left[\delta_D(m^2_-, m^2_+) - \delta_D(m^2_+, m^2_-)\right]}{\sqrt{\int_i dm^2_- \, dm^2_+ \, |A_D(m^2_-, m^2_+)|^2 \int_i dm^2_- \, dm^2_+ \, |A_D(m^2_+, m^2_-)|^2}},$$

- 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

$$N^+_{+i} = h_{B^+}\left[F_{-i} + \left((x_+^{DK})^2 + (y_+^{DK})^2\right) F_{+i} + 2\sqrt{F_i F_{-i}}\,(x_+^{DK} c_{+i} - y_+^{DK} s_{+i})\right]$$

$$N^+_{-i} = h_{B^+}\left[F_{+i} + \left((x_+^{DK})^2 + (y_+^{DK})^2\right) F_{-i} + 2\sqrt{F_i F_{-i}}\,(x_+^{DK} c_{+i} + y_+^{DK} s_{+i})\right]$$

$$N^-_{+i} = h_{B^-}\left[F_{+i} + \left((x_-^{DK})^2 + (y_-^{DK})^2\right) F_{-i} + 2\sqrt{F_i F_{-i}}\,(x_-^{DK} c_{+i} + y_-^{DK} s_{+i})\right]$$

$$N^-_{-i} = h_{B^-}\left[F_{-i} + \left((x_-^{DK})^2 + (y_-^{DK})^2\right) F_{+i} + 2\sqrt{F_i F_{-i}}\,(x_-^{DK} c_{+i} - y_-^{DK} s_{+i})\right]$$

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

Arnau Brossa Gonzalo

arxiv.org/pdf/2010.08483.pc

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

- CP observables results

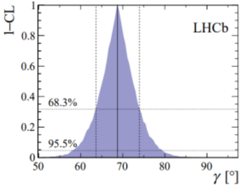
$$x_-^{DK} = (\ \ 5.68 \pm 0.96 \pm 0.20 \pm 0.23) \times 10^{-2}$$
$$y_-^{DK} = (\ \ 6.55 \pm 1.14 \pm 0.25 \pm 0.35) \times 10^{-2}$$
$$x_+^{DK} = (-9.30 \pm 0.98 \pm 0.24 \pm 0.18) \times 10^{-2}$$
$$y_+^{DK} = (-1.25 \pm 1.23 \pm 0.26 \pm 0.28) \times 10^{-2}$$
$$x_\xi^{D\pi} = (-5.47 \pm 1.99 \pm 0.32 \pm 0.14) \times 10^{-2}$$
$$y_\xi^{D\pi} = (\ \ 0.71 \pm 2.33 \pm 0.54 \pm 0.18) \times 10^{-2}$$

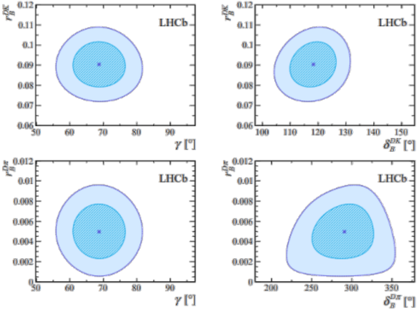
- Uncertainties are statistical, systematic and due to external inputs

- Systematic uncertainties dominated by partially reconstructed backgrounds

$$\gamma = (68.7^{+5.2}_{-5.1})^\circ,$$
$$r_B^{DK^\pm} = 0.0904^{+0.0077}_{-0.0075},$$
$$\delta_B^{DK^\pm} = (118.3^{+5.5}_{-5.6})^\circ,$$
$$r_B^{D\pi^\pm} = 0.0050 \pm 0.0017,$$
$$\delta_B^{D\pi^\pm} = (291^{+24}_{-26})^\circ.$$

- Most precise single γ measurement to date!

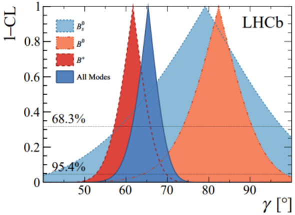




Arnau Brossa Gonzalo

(arXiv:2110.02350)

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

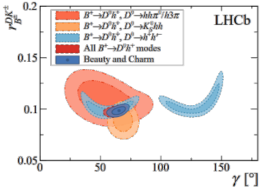


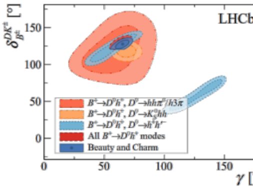
- Moderate tension found between initial state B mesons

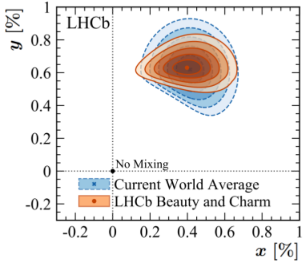
- Most precise measurement of both γ and charm mixing parameters from a single experiment

- 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







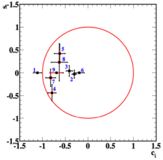
Seema Bahinipati

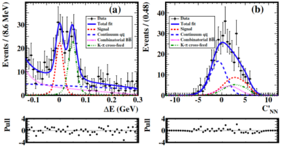
$B^{\pm} \to D(K_S^0\pi^+\pi^-\pi^0)K^{\pm}$ GGSZ

[JHEP01, 82 (2018)]

Bin	Resonance
1	ω
2	$K^{*-}\rho^{+}$
3	$K^{*+}\rho^{-}$
4	K^{*-}
5	K^{*+}
6	K^{*0}
7	ρ^{+}
8	ρ^{-}
9	remainder

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

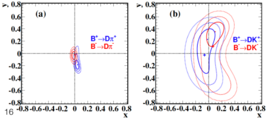




Signal-enhanced fit projections
[JHEP10(2019)178]

- $\phi_3 = (5.7^{+10.2}_{-8.8}) \pm 3.5 \pm 5.7^{\circ}$
- 95% CL interval on ϕ_3 $(-29.7, 109.5)^{\circ}$ consistent with the current world average
- $r_B = 0.323 \pm 0.147 \pm 0.023 \pm 0.051$
- $\delta_B = (83.4^{+18.3}_{-16.6}) \pm 3.1 \pm 4.0^{\circ}$

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

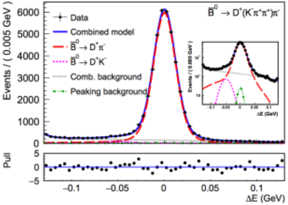


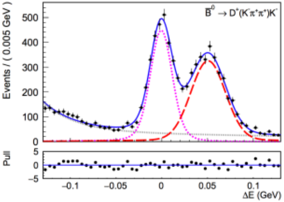
- Single-mode uncertainty of 4.4° achievable with 50 ab^{-1} sample at Belle II
- Further improvements possible once a suitable amplitude model is available
- Precise inputs for c_i, s_i from BESIII will help in reducing the systematic uncertainty

Seema Bahinipati

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

- 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 $BF(\bar{B}^0 \to D^+\pi^-) = (2.48 \pm 0.01 \pm 0.09 \pm 0.04) \times 10^{-3}$ and the Cabibbo suppressed $BF(\bar{B}^0 \to D^+K^-) = = (2.03 \pm 0.05 \pm 0.07 \pm 0.03) \times 10^{-4}$
- 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)].





Niharika Rout

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

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

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

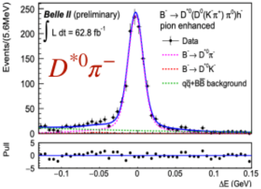
$$N^{D\pi}_{\text{kaon enhanced}} = \kappa N^{D\pi}_{\text{tot}}$$

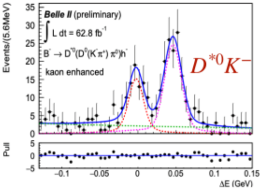
$\epsilon = \text{kaonID efficiency}$

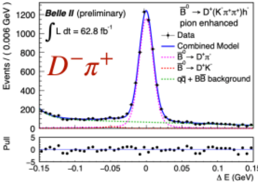
$\kappa = \text{pion fake} - \text{rate}$

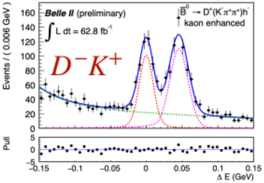
$\kappa, R^{0}, N^{D\pi}_{tot}$ are directly extracted from simultaneous fit of $B \to Dh$

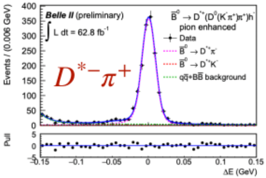
- Common selection to all the final states
- Common signal extraction strategy
- PID selection prompt *h*: pion-enhanced and kaon-enhanced

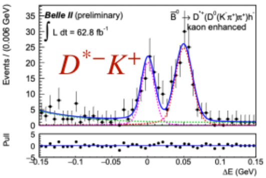








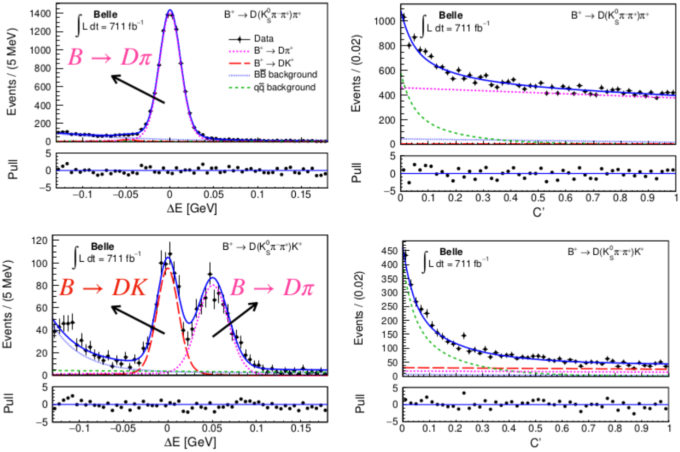




BPGGSZ measurements at Belle + Belle II

Niharika Rout

$B^{\pm} \to D(K_S^0 h^+ h^-)K^{\pm}$



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

N_{signal} : Belle

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

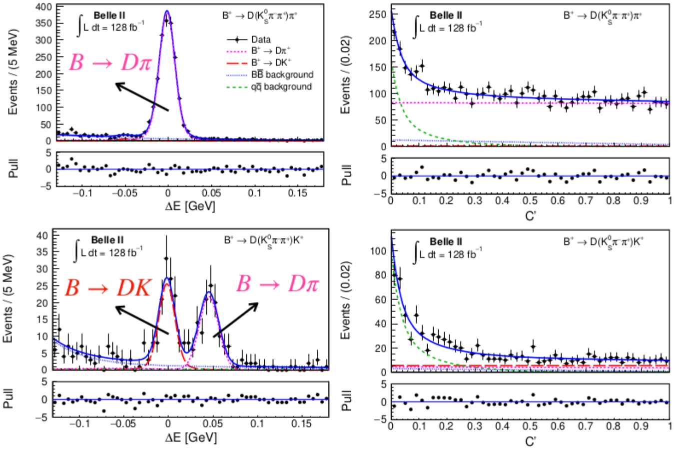
$K_S^0 KK = 194 \pm 17$

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

BPGGSZ measurements at Belle + Belle II

Niharika Rout

$B^\pm \to D(K^0_S h^+ h^-) K^\pm$



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

N_{signal}: Belle II

$K^0_S \pi\pi = 280 \pm 21$

$K^0_S KK = 34 \pm 7$

Additional 17%

Niharika Rout

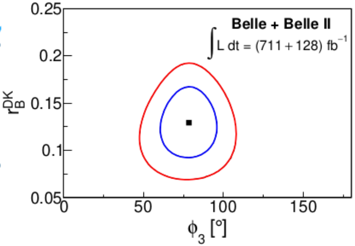
Results

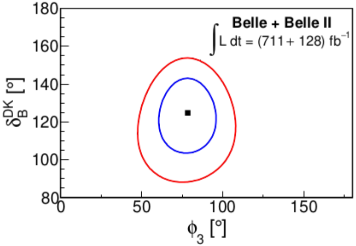
$\delta_B(^\circ)$	124.8 ± 12.9 (stat.) ± 0.5 (syst.) ± 1.7 (ext. input)
r_B^{DK}	0.129 ± 0.024 (stat.) ± 0.001 (syst.) ± 0.002 (ext. input)
$\phi_3(^\circ)$	78.4 ± 11.4 (stat.) ± 0.5 (syst.) ± 1.0 (ext. input)

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 $B \to Dh$ decay mode to incorporate efficiency effects reduces the experimental systematic uncertainty



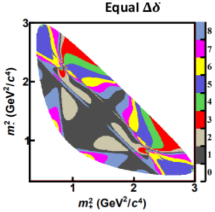


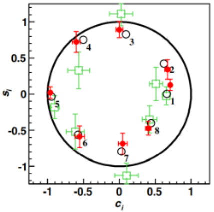
Xinyu Shan

$D^0 \to K^0_S \pi^+ \pi^-$

(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.

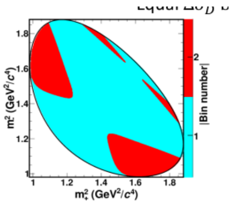


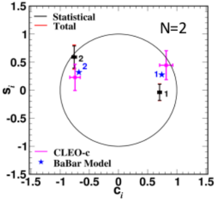


$D^0 \to K^0_S K^+ K^-$

(PRD 102, 052008 (2020))

- Measurement of γ (GGSZ) ← 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 ~1.3° (N=3,4)
- The results of $K^0_S h^+ h^-$ have been used on γ measurement by LHCb and BelleII. The uncertainty from charm inputs is 1°.





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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 $\mathbf{z} = (m_+^2, m_-^2)$:

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

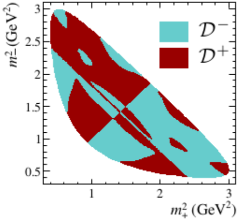
Treat decay densities as vectors in Hilbert space:
Projecting event density onto basis functions $w_i(\mathbf{z})$.

Works with scattered unbinned data (sum with weights).

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

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

Additionally, can **split**
$\mathcal{D}^-$: $|A_D| < |\overline{A}_D|$ and $\mathcal{D}^+$: $|A_D| > |\overline{A}_D|$



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 $B \to DK\pi$: amplitude and strong phase varies $\Rightarrow$ correlated B and D decay Dalitz plots.
- Applying the same model-independent binned technique to $B \to DK\pi$ decay

$$A_{\rm dbl\,Dlz} = \overline{A}_B \overline{A}_D + e^{i\gamma} A_B A_D \, ,$$

After binning both Dalitz plots, system of equations:

$$\begin{aligned}\langle N_{\alpha i}\rangle &= h_{\rm dbl\,Dlz}\Big\{\overline{\kappa}_\alpha K_i + \kappa_\alpha K_{-i} \\ &\quad + 2\sqrt{\kappa_\alpha K_i \overline{\kappa}_\alpha K_{-i}}\,[(\varkappa_\alpha c_i - \sigma_\alpha s_i)\cos\gamma - (\varkappa_\alpha s_i + \sigma_\alpha c_i)\sin\gamma]\Big\} \, ,\end{aligned}$$

Can be solved with three classes of events:

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

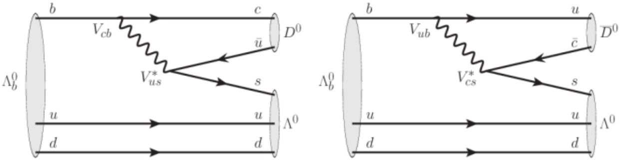
ADS-like mode contaminated by $B^0_s \to D^* K\pi$ decays at LHCb, study if the fit works after removing it (but can be added at Belle II)

Reasonable precision even in worst case $r_B = 0.2$ - $\sigma(\gamma) \simeq 10^\circ$ in Run I+II and 2.5° with 50 fb^{-1}

Anton Poluektov

Unique measurement for LHC: b-baryons. [Giri, Mohanta, Khanna, PRD 65 (2002) 073029]

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



$\Lambda_b^0 \to D\Lambda^0_{\to p\pi^-}$ mode:

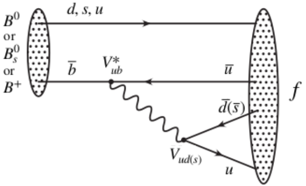
- S- and P-wave amplitudes with different strong parameters. Distinguish in $\Lambda^0 \to p\pi^-$ angular distribution
- At LHCb, affected by low efficiency to reconstruct long-lived Λ^0.

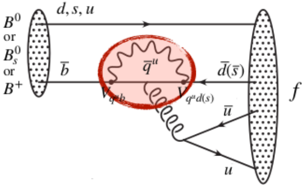
First try with excited, strongly decaying $\Lambda^{*0} \to pK^-$ instead.

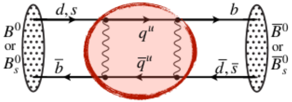
- Search for suppressed mode $\Lambda_b^0 \to DpK^-$ with $D \to K^+\pi^-$ (ADS-like)
- Measure CP asymmetry

Daniele Manuzzi

- The $b \to u$ **tree-level** transitions and the $b \to s(d)$ **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 $B^0_{(s)}$ mixing phases,
  - but the combination of several measurements is necessary to extract the CKM parameters







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

- Isopin relations ➡ $A_{CP}(B^+ \to K^+\pi^0) = A_{CP}(B^0 \to K^+\pi^-)$
- The experimental state of the art was [HFLAV2019]:

$$A_{CP}^{WA}(B^+ \to K^+\pi^0) = (+4.0 \pm 2.1)\,\%$$
$$A_{CP}^{WA}(B^0 \to K^+\pi^-) = (-8.4 \pm 0.4)\,\%$$

→ Almost 6σ discrepancy!

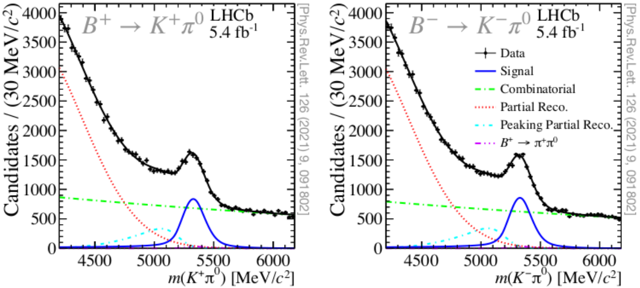
$\Delta A_{CP}(K\pi) = (12.4 \pm 2.1)\,\%$

- **Is it due to strong phases and amplitudes or is new physics emerging from the loops?**
- Full $B \to K\pi$ puzzle sum rule [PLB627(2005)82]: ← any deviation from this would be a sign of new physics

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

Charmless two-body B decays at LHCb

Daniele Manuzzi



The direct CP asymmetry has been measured to be:

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

stat. syst. ext.

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

Most precise determination to date

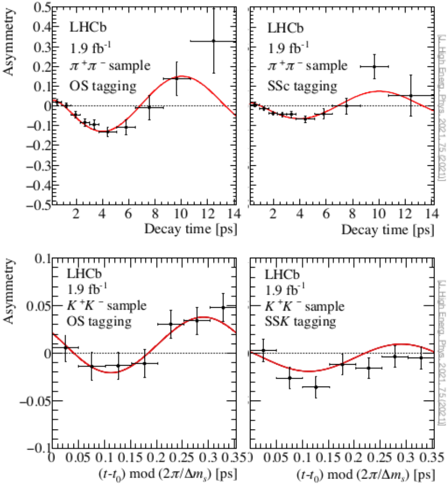
New world average: $A_{CP}^{\text{WA}}(B^+ \to K^+\pi^0) = (3.1 \pm 1.7)\,\%$, which implies:

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

nonzero at 8σ

$B^0_{(s)} \to h^+ h^-$ at LHCb

Daniele Manuzzi



Decay time is folded into 1 oscillation period

[Run1: PRD98(2018)032004]
[J. High Energ. Phys. 2021, 75 (2021)]

Final combinations with Run1 results:

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

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

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

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

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

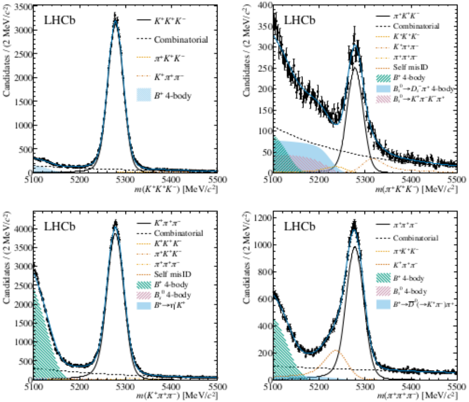
stat.+syst. uncertainty

$$\sqrt{(C_{KK})^2 + (S_{KK})^2 + (A^{\Delta\Gamma}_{KK})^2} = 0.93 \pm 0.08$$ ✓

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

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

→ Signal + crossfeed, partially reconstructed and combinatorial background



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

$$\frac{\mathcal{B}(B^+ \to h^+h'^+h'^-)}{\mathcal{B}(B^+ \to K^+K'^+K'^-)} = \frac{\mathcal{N}^{\rm corr}_{hhh}}{\mathcal{N}^{\rm corr}_{KKK}}$$

$$\mathcal{N}^{\rm corr} = \frac{1}{\varepsilon^{\rm veto}} \sum_j^{N_{\rm bins}} \frac{cM_j + \sum_{i\subset {\rm bin}j} w_j}{\varepsilon_j^{\rm tot}}$$

Correction of efficiency across the Dalitz plot via sPlot technique

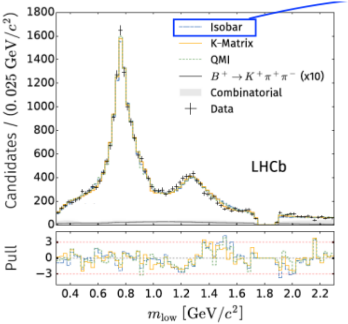
$$\mathcal{B}(B^+ \to K^+K^+\pi^-)/\mathcal{B}(B^+ \to K^+K'^+K'^-) = 0.151 \pm 0.004\,(\text{stat}) \pm 0.008\,(\text{syst})$$

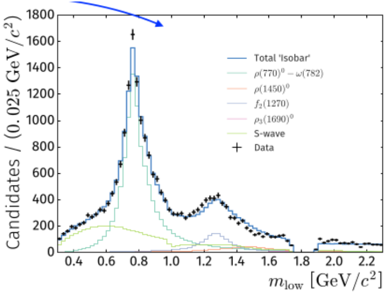
$$\mathcal{B}(B^+ \to K^+\pi^+\pi^-)/\mathcal{B}(B^+ \to K^+K'^+K'^-) = 1.703 \pm 0.011\,(\text{stat}) \pm 0.022\,(\text{syst})$$

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

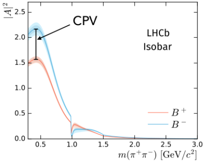
Diego Torres Machado

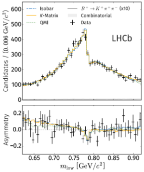
Amplitude analysis of $B^+ \to \pi^+\pi^+\pi^-$ (PRL 124 (2020) 031801, PRD 101 (2020) 012006)

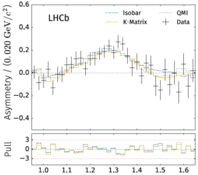




Clear asymmetry below $\rho(770)^0$



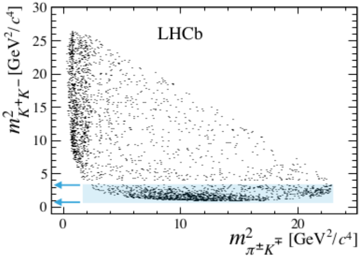


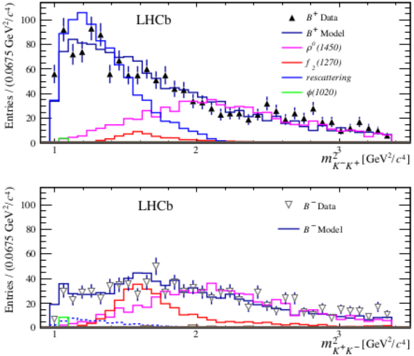


First observation of CPV in a tensor $f_2(1270)$ at 10σ

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

Diego Torres Machado





- Isobar model components:
  - $\to K^*(892)^0, K^*(1430)^0$, single pole, $\rho(1450)^0$, $f_2(1270)$, rescattering, $\phi(1020)$
- Dominant contribution from the non-resonant component
  - $\to$ Responsible for almost all CPV observed in $B^\pm \to \pi^\pm K^+ K^-$ (-12.3±2.1)%

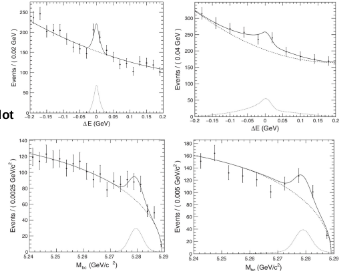
Yun-Tsung Lai

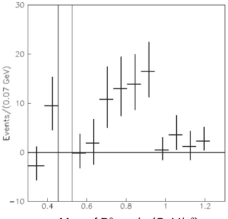
$B \to p\bar{p}\pi\pi$ (PRD 101, 052012(2020))

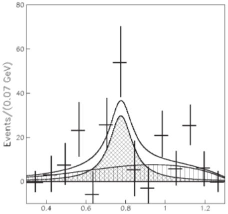
$M_{bc} > 5.27$ GeV/c²

Signal-enhanced projection plot of data fit result

$|\Delta E| < 0.03$ GeV





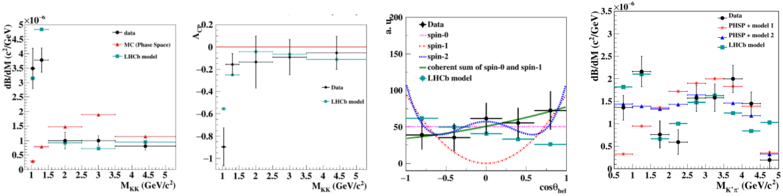


	$B^0 \to p\bar{p}\pi^+\pi^-$	$B^+ \to p\bar{p}\pi^+\pi^0$
Signal yield	$73.8^{+15.4}_{-14.9}$	151 ± 39
Significance (σ)	5.5	5.4
BF (10^{-6})	$0.83 \pm 0.17 \pm 0.17$	$4.58 \pm 1.17 \pm 0.67$

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

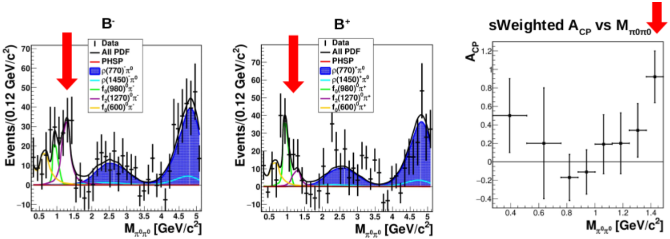
Yun-Tsung Lai

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



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

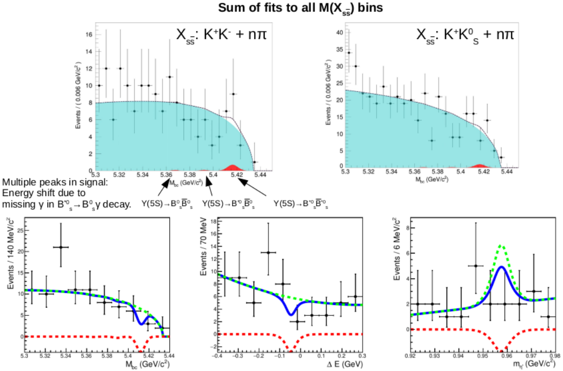
$B^+ \to \pi^+\pi^0\pi^0$

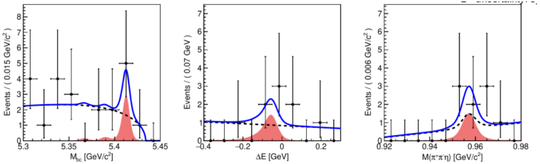


A_{CP} measured at 3.2σ

Yun-Tsung Lai

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





UL is set on BF

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

- UL: 1.4×10^{-3} @ 90 C.L.

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

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

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

Sagar Hazra

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

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

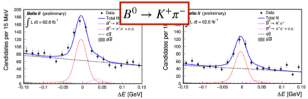
$\mathcal{B}(B^+ \to K^0\pi^+) = [21.4^{+2.3}_{-2.2}(stat) \pm 1.6(syst)] \times 10^{-6}$

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

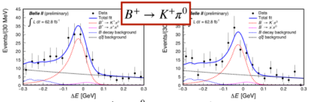
$\mathcal{B}(B^+ \to K^+\pi^0) = [11.9^{+1.1}_{-1.0}(stat) \pm 1.6(syst)] \times 10^{-6}$

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

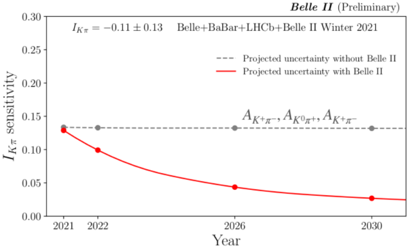
https://arxiv.org/abs/2105.04111



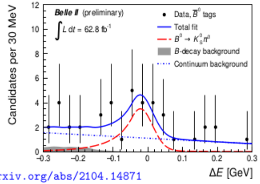
Probes tracking.



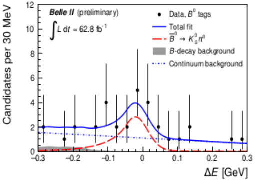
Probes π^0 reconstruction.



$B^0 \to K^0_S\pi^0$



$\bar{B}^0 \to K^0_S\pi^0$

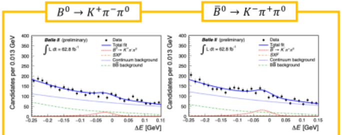


https://arxiv.org/abs/2104.14871

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

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

CPV in multibody B decays

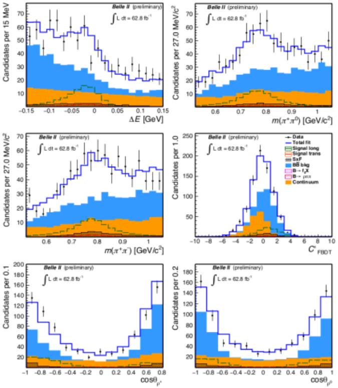


First reconstruction in Belle II data!

Sagar Hazra

Determining α/ϕ_2

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

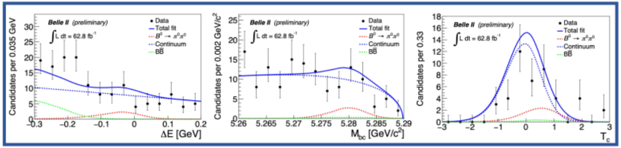


https://arxiv.org/abs/2109.11456

$N = 104 \pm 16$

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

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



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

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

Improvements to measure α

Jeremy Dalseno

- Sub-degree precision in α possible in the near future
- Innovation on experimental side important to realising this goal
- Amplitude analysis in $B \to \rho\rho$
  - 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 $B^0 \to a_1^{\pm}\pi^{\mp}$
  - 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 $B \to \rho\rho$
  - 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]

Possible NP?

Syuhei Iguro

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

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

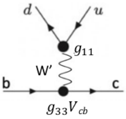
Our model

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)

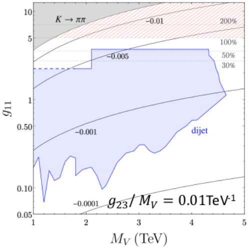


Scenario 2: $g_{11} \times g_{23} \neq 0,\ g_{33} = 0$

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

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

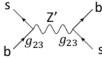
Enhancement by $\frac{1}{V_{cb}} \sim 25$



Again, width dependence of the constraint is important!

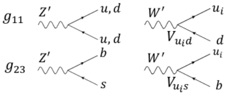
Flavor constraint

Tree level FCNC in Z' -> ΔM_s:
$|g_{23}|/M_V \leq 0.01\mathrm{TeV}^{-1}$
$g_{23} \ll g_{11}$



Collider constraint

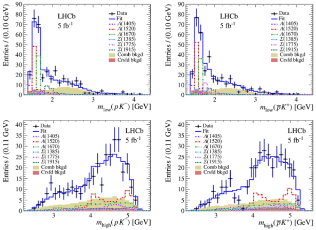
Z', W' decay into 2 jets -> dijet constraint!



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

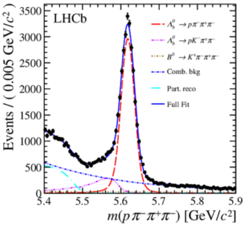
Matteo Bartolini

$\Xi_b^- \to pK^-K^-$ PRD 104, 052010



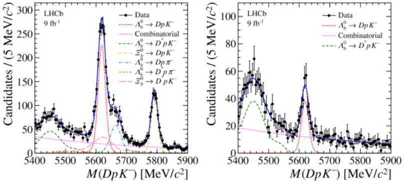
No significant CPV effects

$\Lambda_b^0 \to p\pi^-\pi^+\pi^-$ PRD 102, 051101

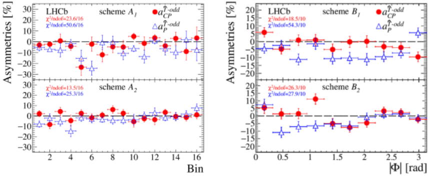


T-odd observable built from triple product correlations of momenta of final state particles

$\Lambda_b^0 \to DpK^-$ arXiv:2109.02621



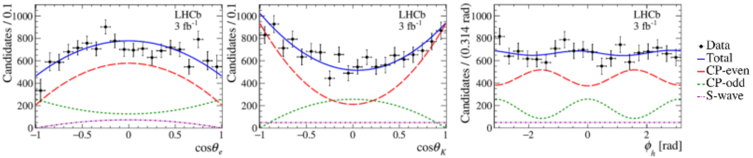
Suppressed decay seen for the first time



f_L in $B \to VV$ decays at LHCb

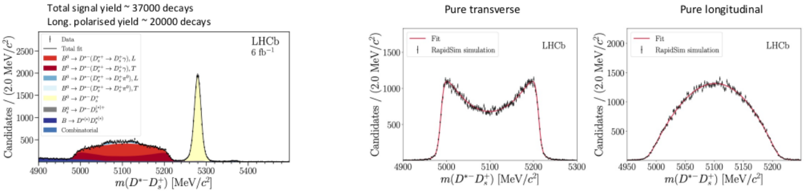
$B_s^0 \to J/\Psi(\to e^+e^-)\phi(\to K^+K^-)$ (arXiv:2105.14738)

Asier Pereiro Castro



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

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



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

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

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

Summary

- 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 $B_{(s)} \to D_{(s)}K/\pi$ (?)
- CPV in baryonic decays measured at LHCb and amplitude analysis performed as a first
- Polarisation measurements in $B \to VV$ decays test the agreement with theoretical calculations