CP violation in charmless b decays at LHCb

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On behalf of the LHCb collaboration

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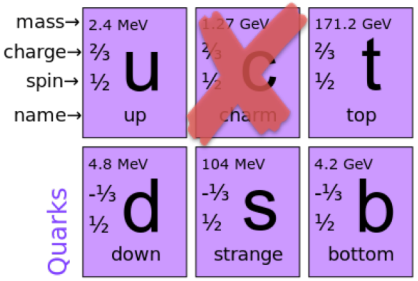
Charmless b decays

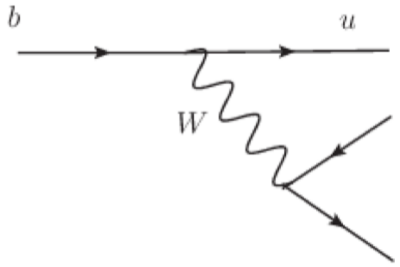


No charm quark in final state particles

~1% of b decays

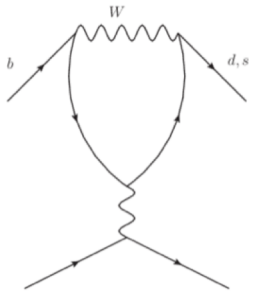
- Competitive contributions from tree-level and loop-level diagrams, leading to large CPV
- New physics contributions easy to enter loop-level diagrams, smoking gun for NP search

$b \to u$

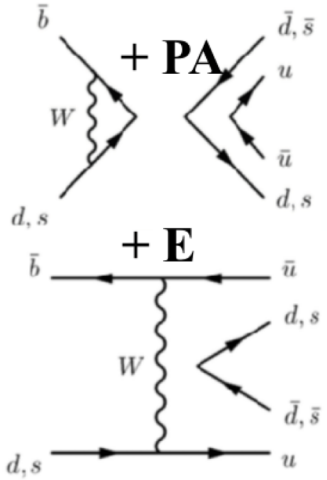


$|V_{ub}|e^{-i\gamma}$

$b \to d, s$



$|V_{td}|e^{i\beta}$ or $-|V_{ts}|e^{-i\beta_s}$



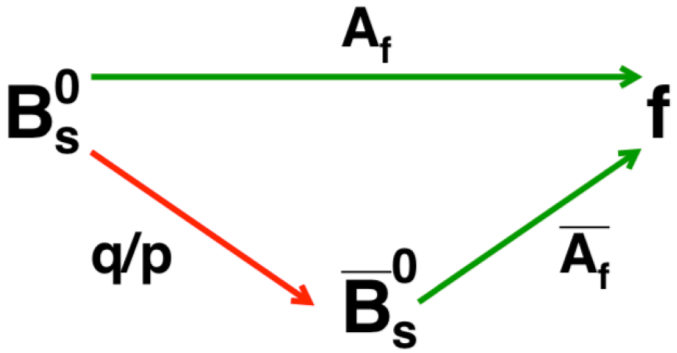
+ New Physics

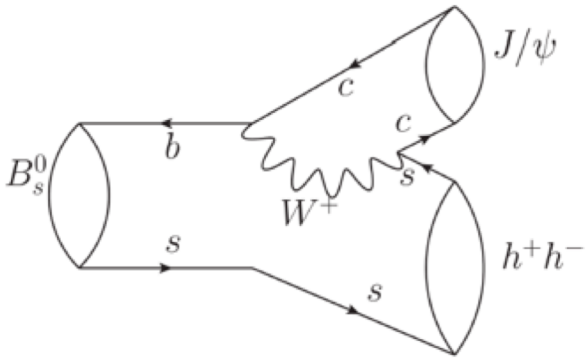
- Selected highlights on new progresses from LHCb

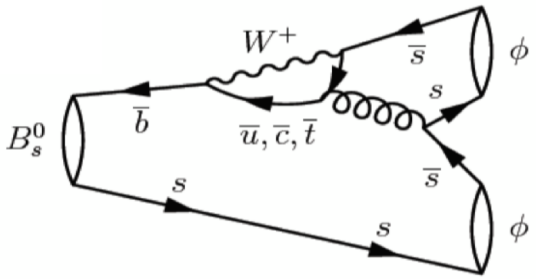
New results from $B \to VV$ decays

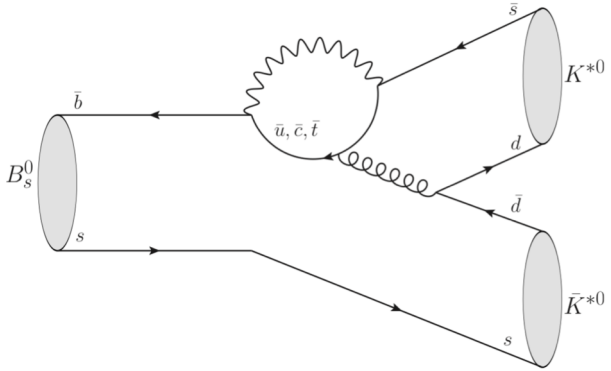
ϕ_s measurements

- ϕ_s: mixing-induced CPV phase in B_s^0 decays
- Depending on final states (quark-level diagram) difference, we have: $\phi_s^{c\bar{c}s}$, $\phi_s^{s\bar{s}s}$, $\phi_s^{d\bar{d}s}$ etc.





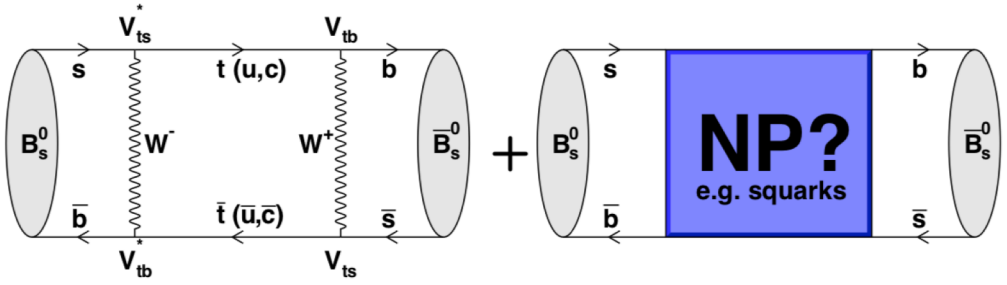




CKMFitter

- SM prediction for $\phi_s^{c\bar{c}s} = -36.8^{+1.0}_{-0.8}$ mrad, and $\phi_s^{s\bar{s}s}$, $\phi_s^{d\bar{d}s}$ very small; NP can contribute and enhance them

Xuesong's talk for new results on $\phi_s^{c\bar{c}s}$ from LHCb



$\phi_s^{s\bar{s}s}$ and $\phi_s^{d\bar{d}s}$ results

LHCb-PAPER-2019-019
JHEP 03 (2018) 140

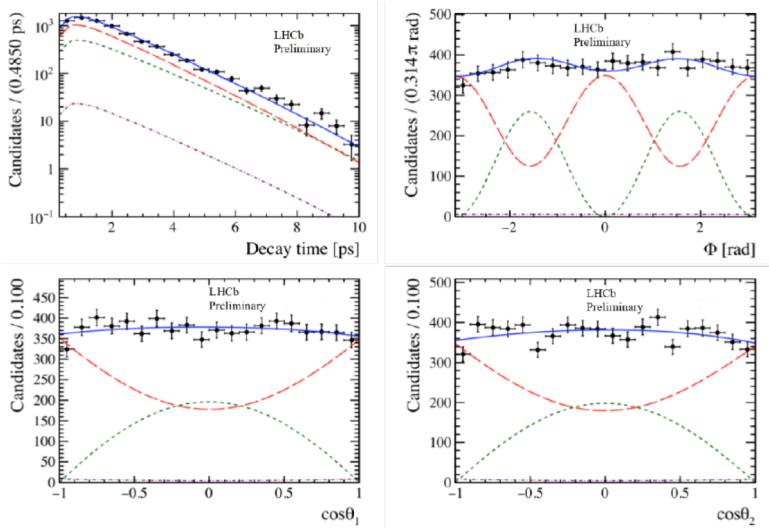
- LHCb has performed measurements of $B_s^0 \to (K^+\pi^-)(K^-\pi^+)$ with 3 fb^{-1} data and gives

$$\phi_s^{s\bar{d}d} = -0.10 \pm 0.13 \pm 0.14 \text{ rad}$$

- New update of $B_s^0 \to \phi\phi$ with 4.9 fb^{-1} data (~8500 signals) and gives

$$\phi_s^{s\bar{s}s} = -0.073 \pm 0.115 \pm 0.027 \text{ rad}$$

- Complicated angular analysis needed to extract CP information



- LHCb prospects for ϕ_s in different processes:

	Run 1 (3 fb^{-1})	Run 2 (9 fb^{-1})	Upgrade I (50 fb^{-1})	Upgrade II (300 fb^{-1})
$\phi_s^{c\bar{c}s}$	37 mrad	15 mrad	4 mrad	2 mrad
$\phi_s^{d\bar{d}s}$	180 mrad	90 mrad	22 mrad	10 mrad
$\phi_s^{s\bar{s}s}$	150 mrad	75 mrad	19 mrad	8 mrad

f_L results

JHEP 07 (2019) 032
JHEP 05 (2019) 026
LHCb-PAPER-2019-019
JHEP 05 (2014) 069

- Large f_L expected for tree-dominated $B \to VV$ decays while not fulfilled for penguin-dominated decays; Interesting place to study strong-interaction effect
- f_L been measured in several $B \to VV$ decays by the LHCb experiment

Decays	f_L	A_{cp}	
$B^0 \to \rho(770)^0 K^*(892)^0$	$0.164 \pm 0.015 \pm 0.022$	$-0.62 \pm 0.09 \pm 0.09$	3 fb^{-1}
$B^0 \to \omega K^*(892)^0$	$0.68 \pm 0.17 \pm 0.16$	$-0.13 \pm 0.27 \pm 0.13$	3 fb^{-1}
$B^0 \to \overline{K^*}(892)^0 K^*(892)^0$	$0.724 \pm 0.051 \pm 0.016$		3 fb^{-1}
$B_s^0 \to \overline{K^*}(892)^0 K^*(892)^0$	$0.240 \pm 0.031 \pm 0.025$		3 fb^{-1}
$B_s^0 \to \phi\phi$	$0.381 \pm 0.007 \pm 0.012$		4.9 fb^{-1}
$B^0 \to \phi K^*(892)^0$	$0.497 \pm 0.019 \pm 0.015$	$-0.003 \pm 0.038 \pm 0.005$	1 fb^{-1}

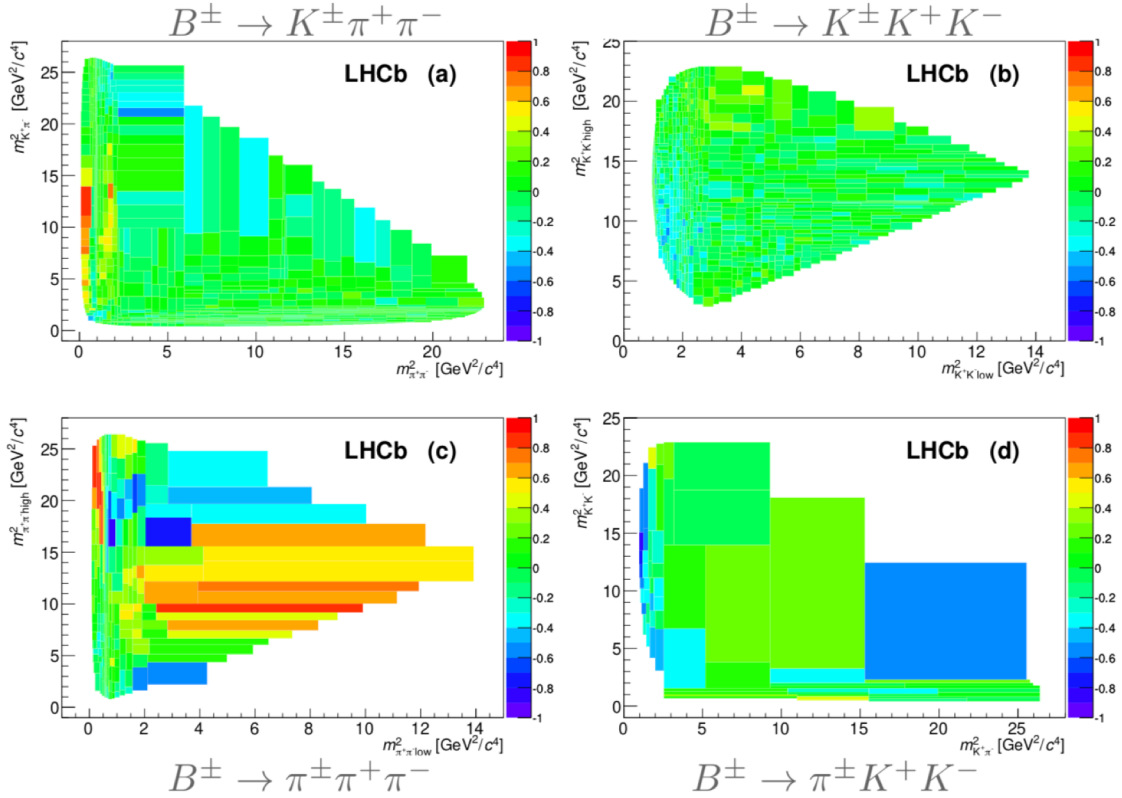
- These results, together with pQCD and QCDF predictions, will help us understand better underlying mechanism

New results from $B \to 3h$ decays

CPV in charmless B decays

PRL 112 (2014) 011081
PRL 111 (2013) 101801
PRD 90 (2014) 112004

- Interesting CPV pattern seen on Dalitz plot of $B \to h'^{+}h^{+}h^{-}, h = K, \pi$
- Dalitz plot analysis needed to shed more light on understanding nature of these CPV



- Now, amplitude analyses of $B^{+} \to \pi^{+}\pi^{+}\pi^{-}$ and $B^{+} \to \pi^{+}K^{+}K^{-}$, with much larger statistics than previous B-factory analyses, has been performed

CPV over Dalitz plot

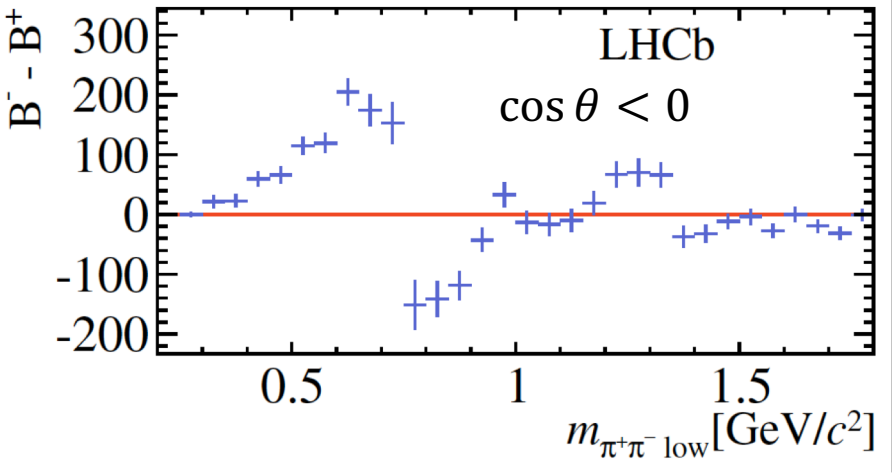
PRD 90 (2014) 112004

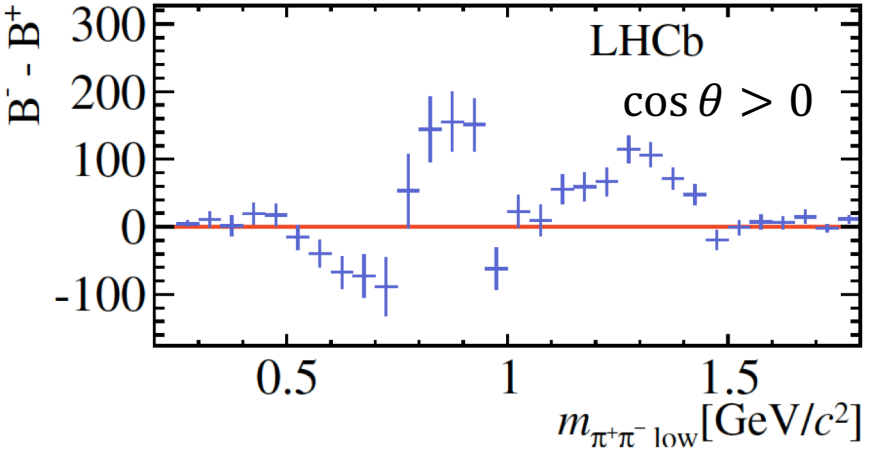
- Two competitive contributions needed to have CPV

$$A = a_1 e^{i(\delta_1+\phi_1)} + a_2 e^{i(\delta_2+\phi_2)} \qquad \bar{A} = a_1 e^{i(\delta_1-\phi_1)} + a_2 e^{i(\delta_2-\phi_2)}$$

$$A_{CP} = \frac{|A|^2 - |\bar{A}|^2}{|A|^2 + |\bar{A}|^2} \propto \sin(\delta_1 - \delta_2)\sin(\phi_1 - \phi_2)$$

- Distributions over PHSP offer possibilities to exam different sources of CPV





Dalitz plot analysis with CPV

- Amplitude with CPV is modelled as

$$A(\Phi_3) = \sum_i A_i(\Phi_3) = \sum_i c_i F_i(\Phi_3)$$ Strong dynamics

$$\bar{A}(\bar{\Phi}_3) = \sum_i \bar{c}_i F_i(\Phi_3)$$ Strong + weak

- CPV then described as

$$c_i = (x_i + \Delta x_i) + i(y_i + \Delta y_i)$$
$$\bar{c}_i = (x_i - \Delta x_i) + i(y_i - \Delta y_i)$$

- Observables:

$$\mathcal{F}_i \equiv \frac{\int d\Phi_3 |A_i(\Phi_3)|^2 + \int d\Phi_3 |\bar{A}_i(\Phi_3)|^2}{\int d\Phi_3 |A(\Phi_3)|^2 + \int d\Phi_3 |\bar{A}(\Phi_3)|^2}$$

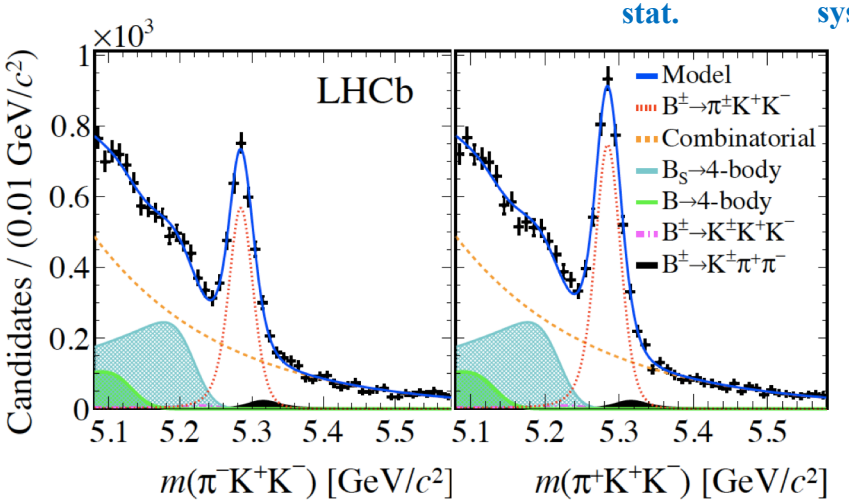
$$\mathcal{A}^i_{CP} \equiv \frac{\int d\Phi_3 |\bar{A}_i(\Phi_3)|^2 - \int d\Phi_3 |A_i(\Phi_3)|^2}{\int d\Phi_3 |\bar{A}_i(\Phi_3)|^2 + \int d\Phi_3 |A_i(\Phi_3)|^2}$$

Dalitz plot analysis with $B \to KK\pi$

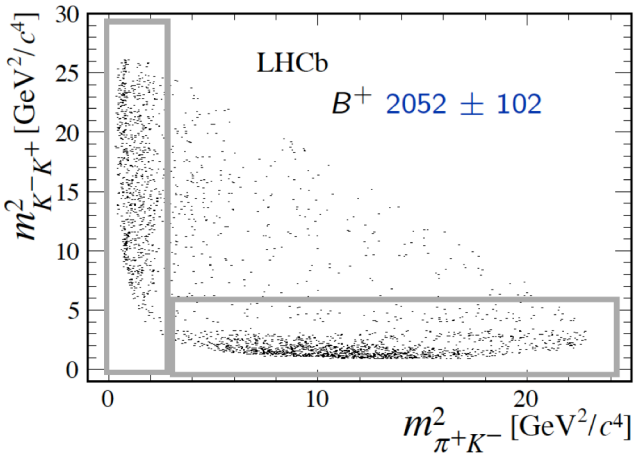
PRD 90 (2014) 112004
arXiv:1905.09244

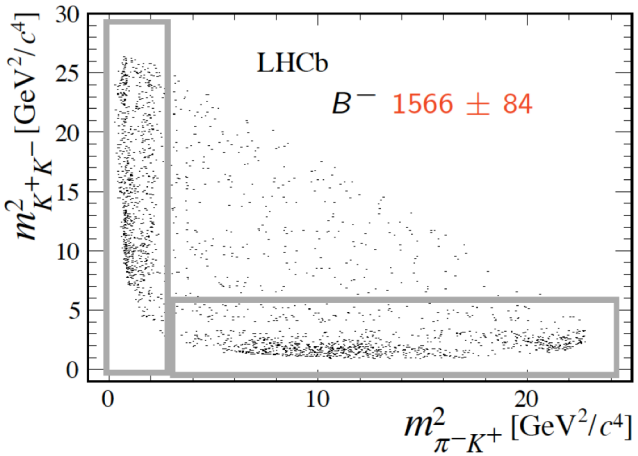
- Global CPV observed previous: $A_{cp} = -0.123 \pm 0.017 \pm 0.012 \pm 0.007$

stat. sys. control channel $B^+ \to J/\psi K^+$



- Clear CPV found over different regions of Dalitz plot (with 3 fb^{-1} data)





Results: $K\pi$ resonances

arXiv:1905.09244

- Resonant contributions:

Contribution	Fit Fraction(%)	A_{CP}(%)
$K^*(892)^0$	$7.5 \pm 0.6 \pm 0.5$	$+12.3 \pm 8.7 \pm 4.5$
$K_0^*(1430)^0$	$4.5 \pm 0.7 \pm 1.2$	$+10.4 \pm 14.9 \pm 8.8$
Single pole	$32.3 \pm 1.5 \pm 4.1$	$-10.7 \pm 5.3 \pm 3.5$
$\rho(1450)^0$	$30.7 \pm 1.2 \pm 0.9$	$-10.9 \pm 4.4 \pm 2.4$
$f_2(1270)$	$7.5 \pm 0.8 \pm 0.7$	$+26.7 \pm 10.2 \pm 4.8$
Rescattering	$16.4 \pm 0.8 \pm 1.0$	$-66.4 \pm 3.8 \pm 1.9$
$\phi(1020)$	$0.3 \pm 0.1 \pm 0.1$	$+9.8 \pm 43.6 \pm 26.6$

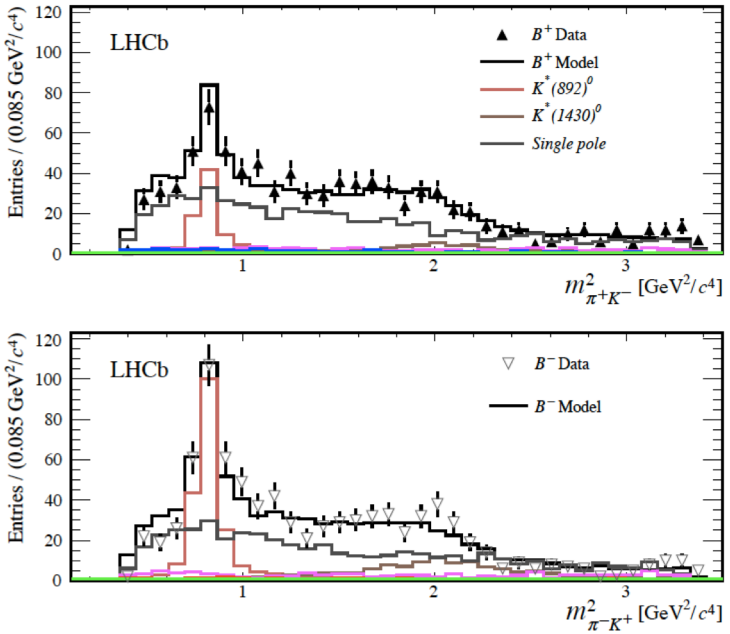
- $K\pi$ non-resonance modelled by

$$\mathcal{A}_{\text{source}} = \left(1 + \frac{s}{\Lambda^2}\right)^{-1}$$

$$s = m^2_{\pi^\pm K^\mp}$$

$$\Lambda = 1\,\text{GeV}/c^2$$

Phys. Rev. D 92 (2015) 054010



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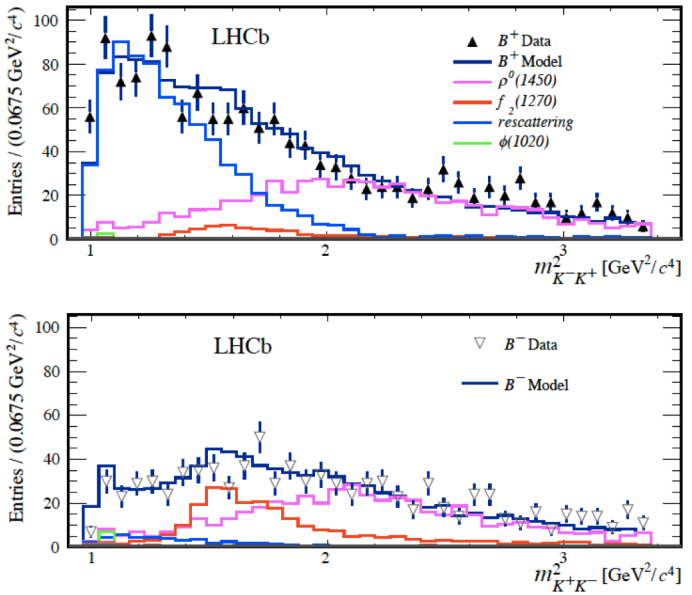
- *KK* non-resonance modelled by rescattering model

$$\mathcal{A}_{\text{rescattering}} = \left(1 + \frac{s}{\Lambda^2}\right)^{-1} \sqrt{1-\nu^2} e^{2i\delta}$$

Phys. Rev. D 71 (2005) 074016

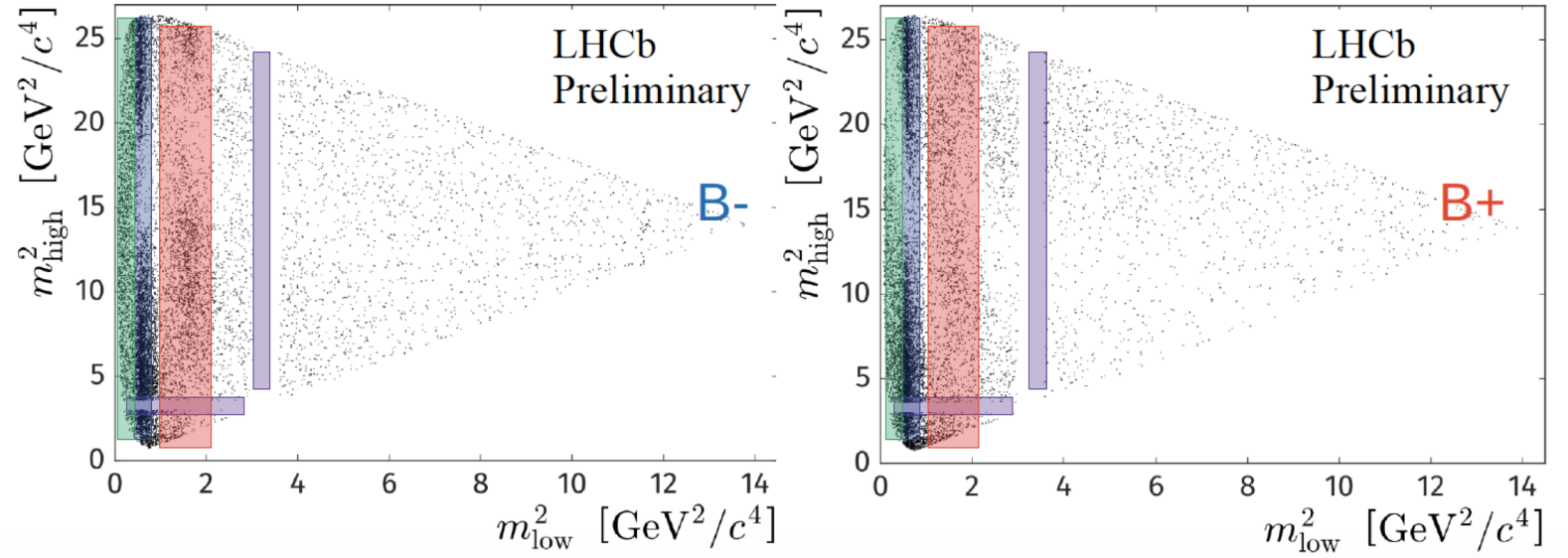


- CPV as larger as -66.4%, largest CPV found in a single decay

Dalitz plot analysis with $B \to \pi\pi\pi$

LHCb-PAPER-2019-017
LHCb-PAPER-2019-018

- Dalitz plot analysis with 20594 ± 1569 events (3 fb^{-1} data)



- Resonant contributions:

  ρ-ω, $f_0(500)$, $f_0(980)$ region: S-P wave interference

  $f_2(1270)$ region: D-S, P wave interference

  High mass: KK-$\pi\pi$ rescattering

- Three different methods to describe S-wave: Isobar model, K-Matrix approach, quasi model independent approach

S-wave results

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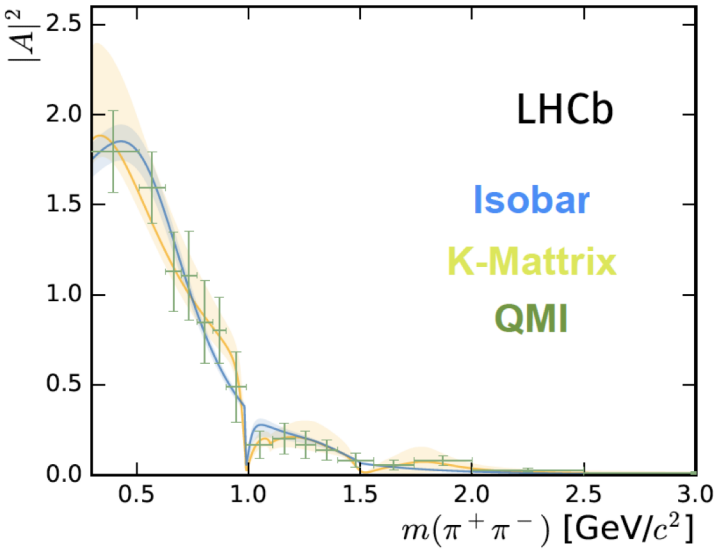
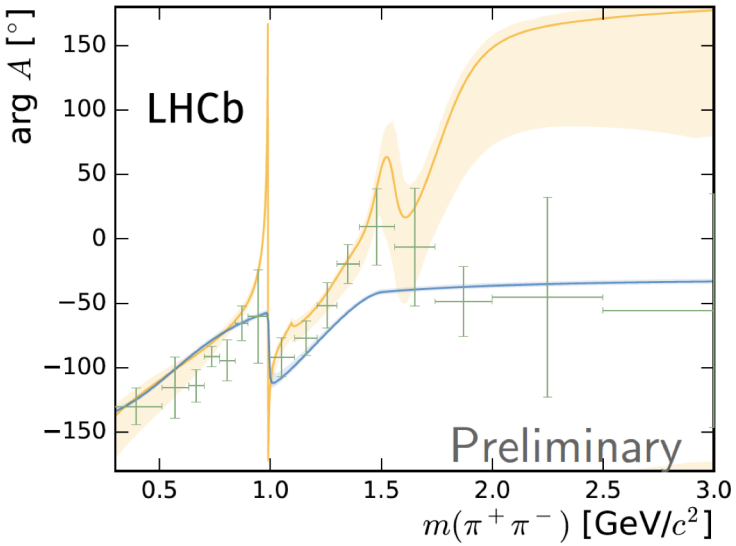
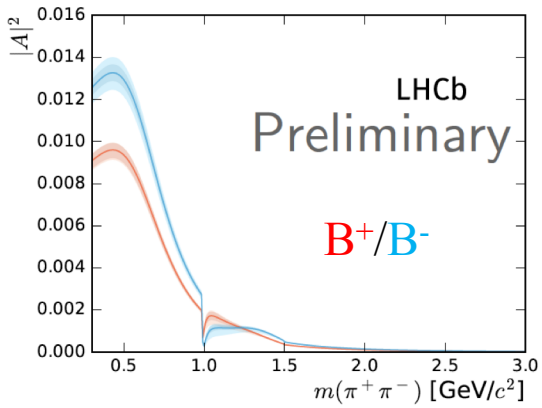
- Good agreement between the three approaches



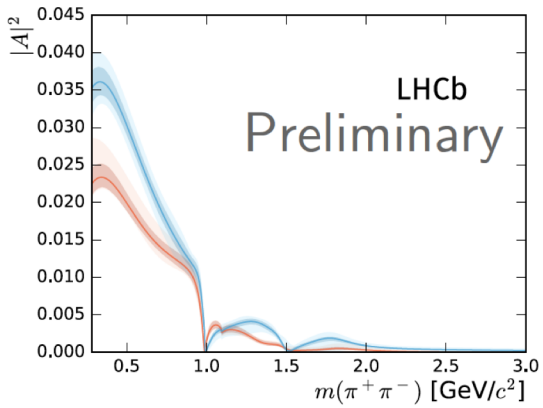


- Similar CPV pattern for the three approaches, as large as 10 σ

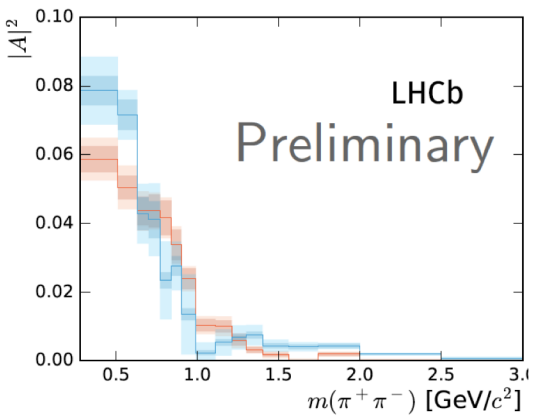
Isobar



KMatrix



QMI



$B \to \pi\pi\pi$ results

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- Fit fractions:

Component	Isobar	K-matrix	QMI
$\rho(770)^0$	$55.5 \pm 0.6 \pm 0.7 \pm 2.5$	$56.5 \pm 0.7 \pm 1.5 \pm 3.1$	$54.8 \pm 1.0 \pm 1.9 \pm 1.0$
$\omega(782)$	$0.50 \pm 0.03 \pm 0.03 \pm 0.04$	$0.47 \pm 0.04 \pm 0.01 \pm 0.03$	$0.57 \pm 0.10 \pm 0.12 \pm 0.12$
$f_2(1270)$	$9.0 \pm 0.3 \pm 0.8 \pm 1.4$	$9.3 \pm 0.4 \pm 0.6 \pm 2.4$	$9.6 \pm 0.4 \pm 0.7 \pm 3.9$
$\rho(1450)^0$	$5.2 \pm 0.3 \pm 0.4 \pm 1.9$	$10.5 \pm 0.7 \pm 0.8 \pm 4.5$	$7.4 \pm 0.5 \pm 3.9 \pm 1.1$
$\rho_3(1690)^0$	$0.5 \pm 0.1 \pm 0.1 \pm 0.4$	$1.5 \pm 0.1 \pm 0.1 \pm 0.4$	$1.0 \pm 0.1 \pm 0.5 \pm 0.1$
S-wave	$25.4 \pm 0.5 \pm 0.7 \pm 3.6$	$25.7 \pm 0.6 \pm 2.6 \pm 1.4$	$26.8 \pm 0.7 \pm 2.0 \pm 1.0$

- Dominant contributions from S-wave and $\rho(770)$
- CP asymmetries:

Component	Isobar	K-matrix	QMI
$\rho(770)^0$	$+0.7 \pm 1.1 \pm 1.2 \pm 1.5$	$+4.2 \pm 1.5 \pm 2.6 \pm 5.8$	$+4.4 \pm 1.7 \pm 2.3 \pm 1.6$
$\omega(782)$	$-4.8 \pm 6.5 \pm 6.6 \pm 3.5$	$-6.2 \pm 8.4 \pm 5.6 \pm 8.1$	$-7.9 \pm 16.5 \pm 14.2 \pm 7.0$
$f_2(1270)$	$+46.8 \pm 6.1 \pm 3.6 \pm 4.4$	$+42.8 \pm 4.1 \pm 2.1 \pm 8.9$	$+37.6 \pm 4.4 \pm 6.0 \pm 5.2$
$\rho(1450)^0$	$-12.9 \pm 3.3 \pm 7.0 \pm 35.7$	$+9.0 \pm 6.0 \pm 10.8 \pm 45.7$	$-15.5 \pm 7.3 \pm 14.3 \pm 32.2$
$\rho_3(1690)^0$	$-80.1 \pm 11.4 \pm 13.5 \pm 24.1$	$-35.7 \pm 10.8 \pm 8.5 \pm 35.9$	$-93.2 \pm 6.8 \pm 8.0 \pm 38.1$
S-wave	$+14.4 \pm 1.8 \pm 2.1 \pm 1.9$	$+15.8 \pm 2.6 \pm 2.1 \pm 6.9$	$+15.0 \pm 2.7 \pm 4.2 \pm 7.0$

- Large CPV from S-wave and $f_2(1270)$

New CPV pattern

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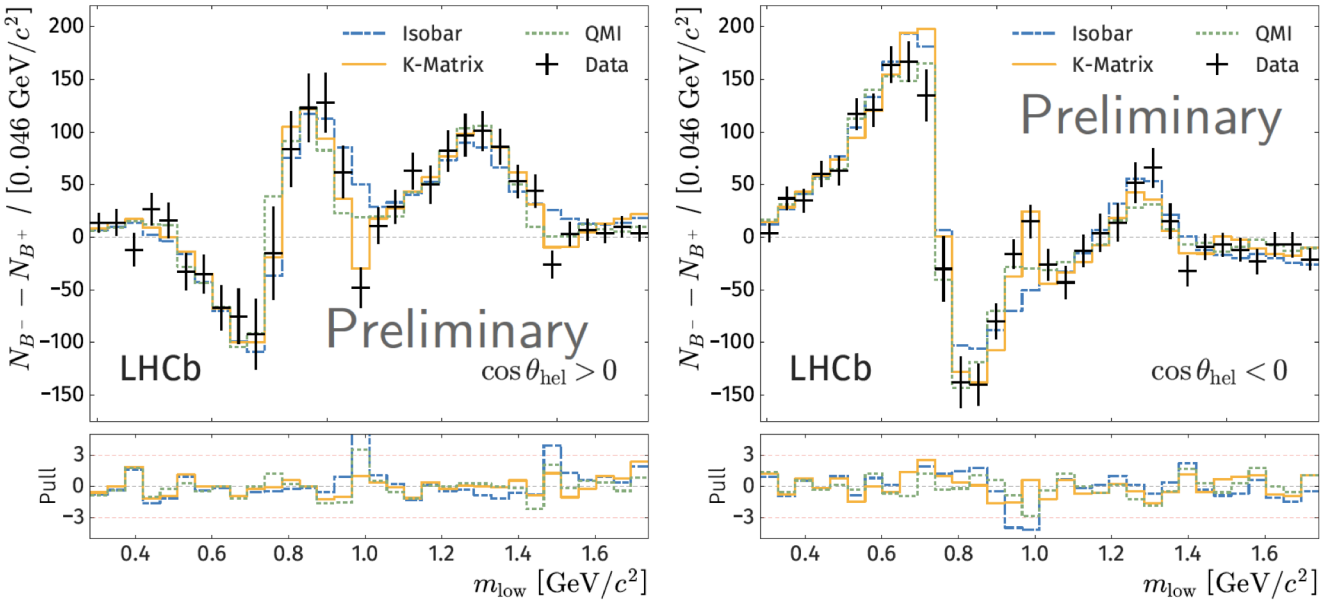
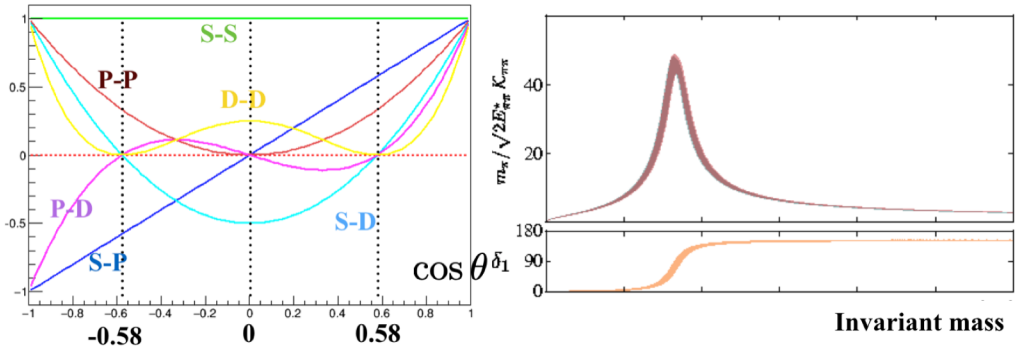
LHCb-PAPER-2019-018

- CPV around $\rho(770)$ pole well described by the three S-wave models



- Over 25σ significance for CPV due to S-P interference, first observation
- Sign-flip due to phase change and helicity angle change
- First observation of large CPV in decays with tensor

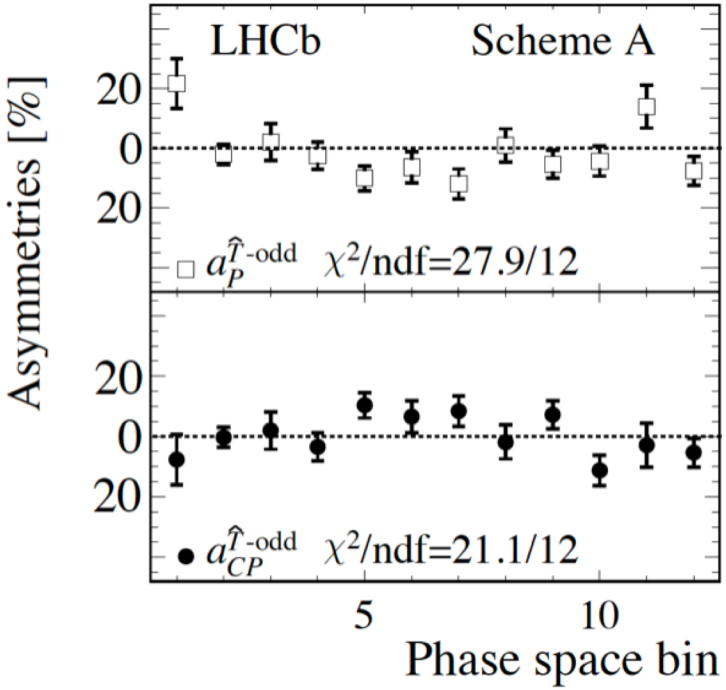


CPV searches in b-baryon decays

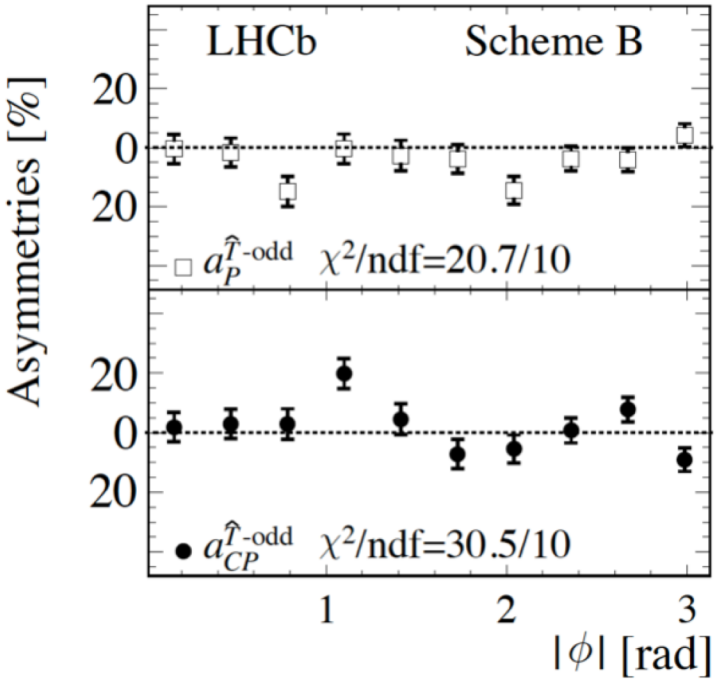
First evidence of CPV in b-baryon decays

Nature Physics 13 (2017) 391
JHEP 08 (2018) 039

- CPV has not yet been found in baryon decays
- We saw first evidence of 3.3σ 2 years ago in $\Lambda_b \to p3\pi$ using triple products using 3 fb^{-1} data



Binning based on resonant structures, e.g. ρ(770), N*, Δ++



Binning based on ϕ angle

- Updates with other $\Lambda_b \to p3h$ decays, no CPV found

A_{CP} measurements in $\Lambda_b/\Xi_b \to 4h$

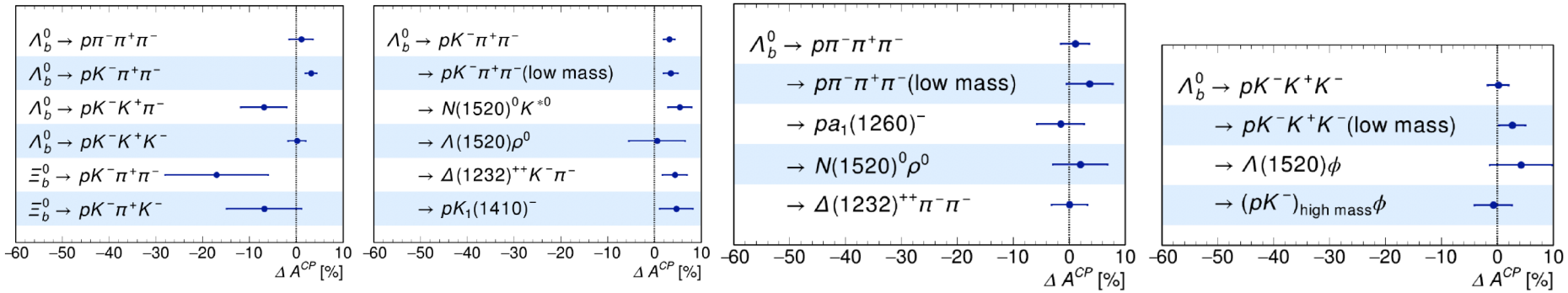
arXiv: 1903.06792

- A_{CP} measurements performed with 3 fb^{-1} data, complementary to triple-product asymmetry measurements
- Six channels studied w.r.t. control channels $\Lambda_b^0 \to \Lambda_c^+\pi^-$ and $\Xi_b^0 \to \Xi_c^+\pi^-$, three of which further divided into specific regions of phase space :

$\Lambda_b^0 \to p\pi^-\pi^+\pi^-$
$\Lambda_b^0 \to pK^-\pi^+\pi^-$
$\Lambda_b^0 \to pK^-K^+\pi^-$
$\Lambda_b^0 \to pK^-K^+K^-$

$\Xi_b^0 \to pK^-\pi^+\pi^-$
$\Xi_b^0 \to pK^-\pi^+K^-$

- Results consistent with no CPV



Conclusion

- Many interesting CPV measurements have been performed by LHCb
- Will put useful information in determining CKM angles, in understanding underlying QCD effects and in constraining new physics
- Stay tuned for more results with LHCb Run 2 data

Thank you for your attention