Recent highlights of CPV measurements in B decays at LHCb

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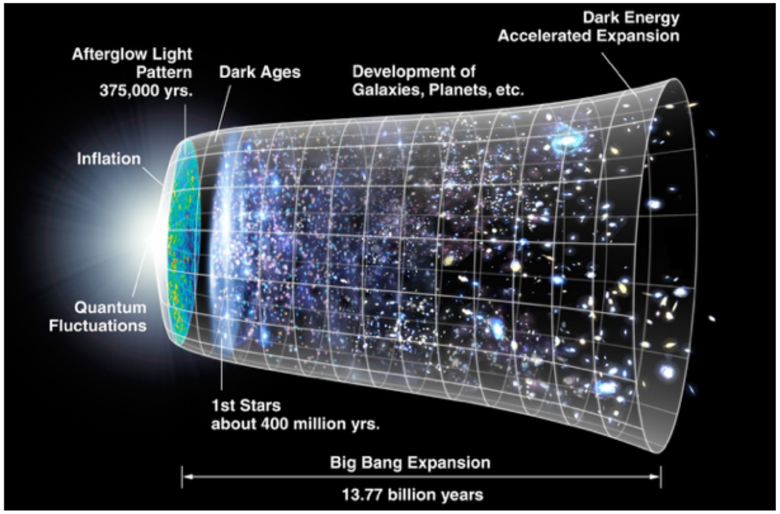
呼和浩特

第17届全国重味物理和CP破坏研讨会

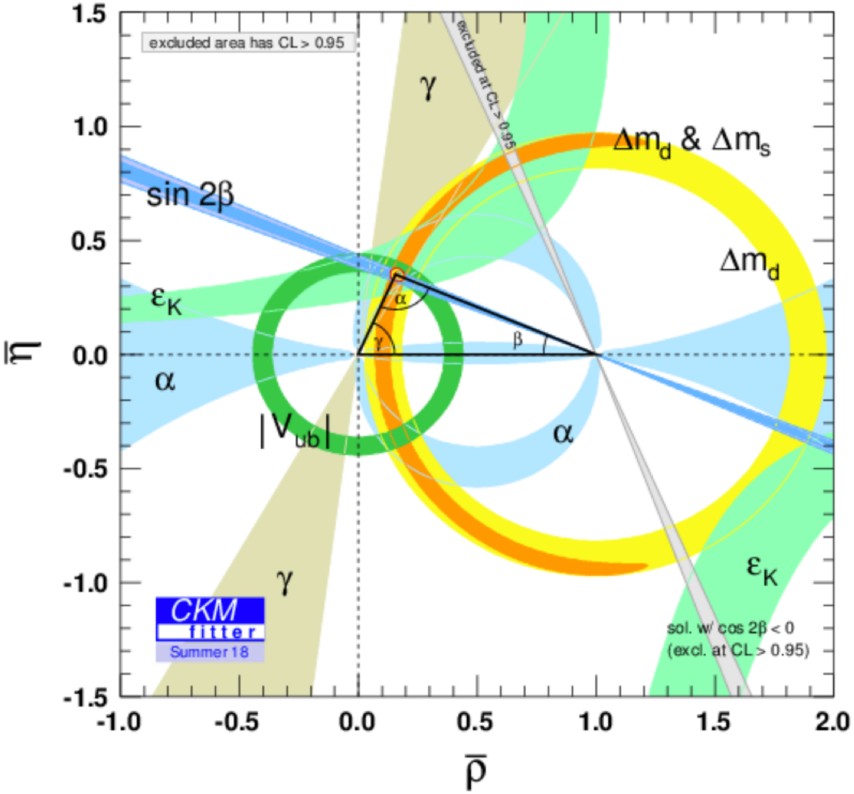
Matter-antimatter asymmetry



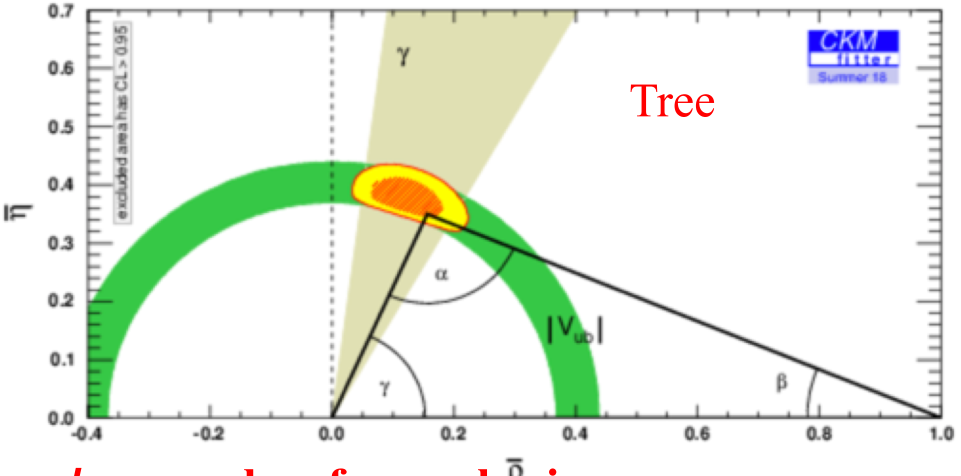
- Central question of physics: how the Universe develops into current matter-dominated state from Big Bang
- Sakharov conditions: C and CP violation required
- Current SM: CKM mechanism, but orders of magnitude smaller! Need to search for new sources of CPV

Global fit

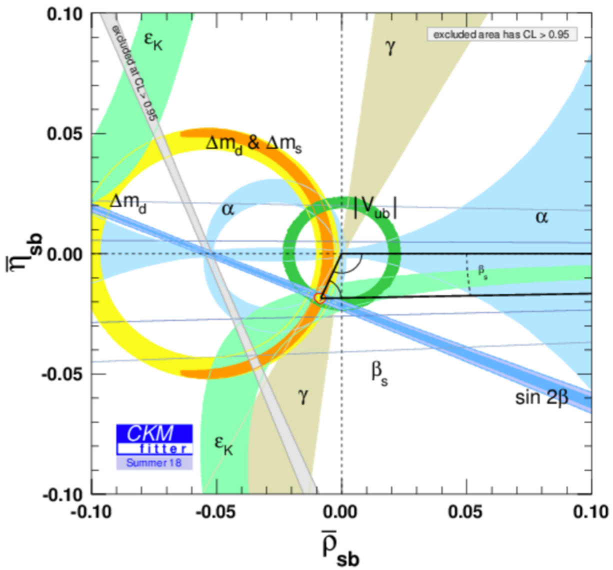
- Precision measurements ⇨ global fit ⇨ deviation from SM and find new CPV sources (NP)



SM baseline，γ least precise measurement



ϕ_s, a probe of new physics



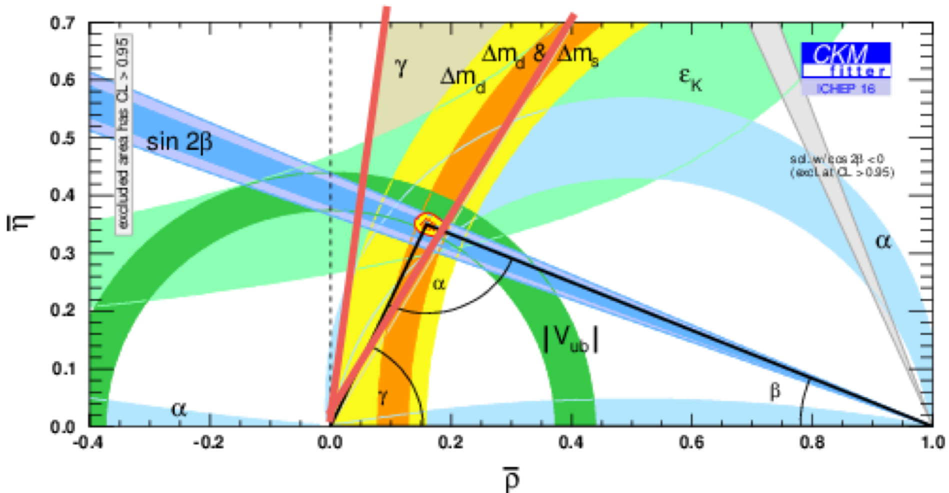
Outline

- **Recent results on γ measurements**
- **Recent updates on ϕ_s**
- **Highlights for CPV in charmless B decays**
- **Conclusion**

Angle γ

- CPV in SM $\propto \sin\gamma$, key element of CKM matrix (mechanism) PRL 55 (1985) 1039

$$\gamma = \arg\left[-V_{ud}V_{ub}^*/(V_{cd}V_{cb}^*)\right]$$



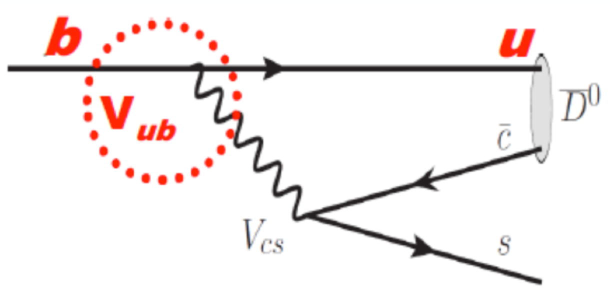
Direct: $\gamma = (73.5^{+4.3}_{-5.0})°$

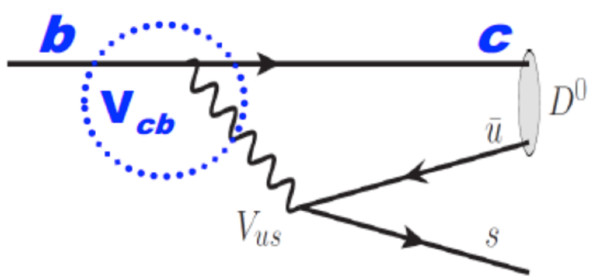
VS

indirect: $\gamma = (65.6^{+1.0}_{-3.4})°$

New Physics?

- γ at tree level: clean theory prediction, $\delta\gamma/\gamma \sim 10^{-7}$ JHEP 1401 (2014) 051

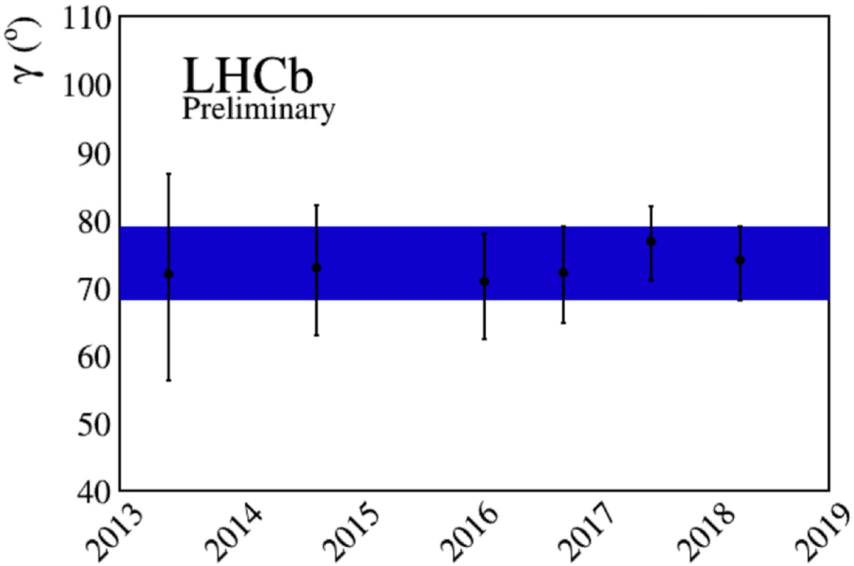




- Least well known CKM parameters before LHCb, bottle net for understanding CKM mechanism

Continuing efforts from LHCb

- LHCb reduces its uncertainties by more than a factor of 2 and will do more



B decay	D decay	Method	Ref.	Dataset[†]
$B^+ \to DK^+$	$D \to h^+h^-$	GLW	[14]	Run 1 & 2
$B^+ \to DK^+$	$D \to h^+h^-$	ADS	[15]	Run 1
$B^+ \to DK^+$	$D \to h^+\pi^-\pi^+\pi^-$	GLW/ADS	[15]	Run 1
$B^+ \to DK^+$	$D \to h^+h^-\pi^0$	GLW/ADS	[16]	Run 1
$B^+ \to DK^+$	$D \to K^0_S h^+h^-$	GGSZ	[17]	Run 1
$B^+ \to DK^+$	$D \to K^0_S h^+h^-$	GGSZ	[18]	Run 2
$B^+ \to DK^+$	$D \to K^0_S K^+\pi^-$	GLS	[19]	Run 1
$B^+ \to D^*K^+$	$D \to h^+h^-$	GLW	[14]	Run 1 & 2
$B^+ \to DK^{*+}$	$D \to h^+h^-$	GLW/ADS	[20]	Run 1 & 2
$B^+ \to DK^{*+}$	$D \to h^+\pi^-\pi^+\pi^-$	GLW/ADS	[20]	Run 1 & 2
$B^+ \to DK^+\pi^+\pi^-$	$D \to h^+h^-$	GLW/ADS	[21]	Run 1
$B^0 \to DK^{*0}$	$D \to K^+\pi^-$	ADS	[22]	Run 1
$B^0 \to DK^+\pi^-$	$D \to h^+h^-$	GLW-Dalitz	[23]	Run 1
$B^0 \to DK^{*0}$	$D \to K^0_S\pi^+\pi^-$	GGSZ	[24]	Run 1
$B^0_s \to D^\mp_s K^\pm$	$D^+_s \to h^+h^-\pi^+$	TD	[25]	Run 1
$B^0 \to D^\mp\pi^\pm$	$D^+ \to K^+\pi^-\pi^+$	TD	[26]	Run 1

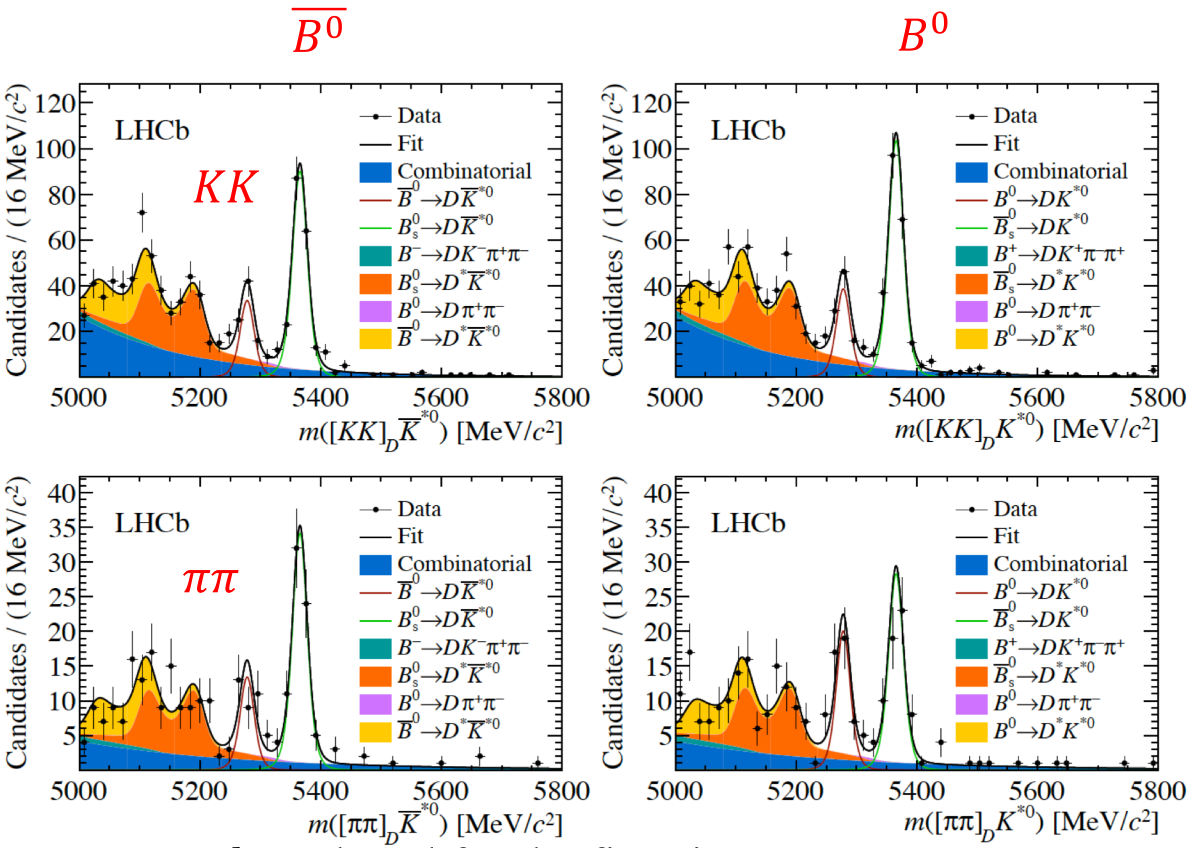
- Tree-level γ： sensitive channels ($B \to D^{(*)}h(h)$ etc.) with small BFs, need to combined them to achieve best sensitivity

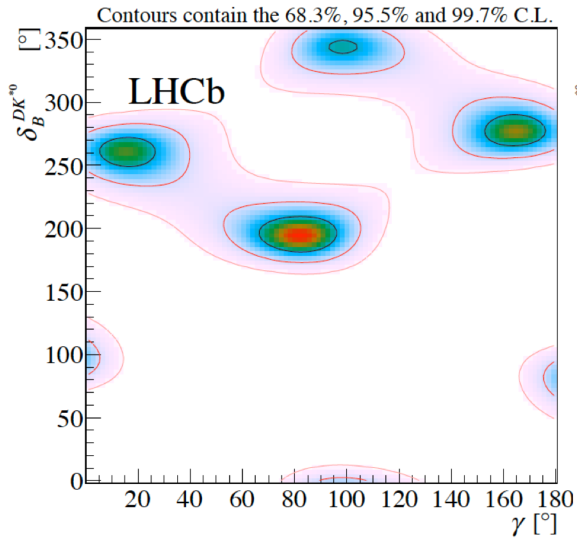
Updates from $B^0 \to DK^*, D \to hh, 4h$

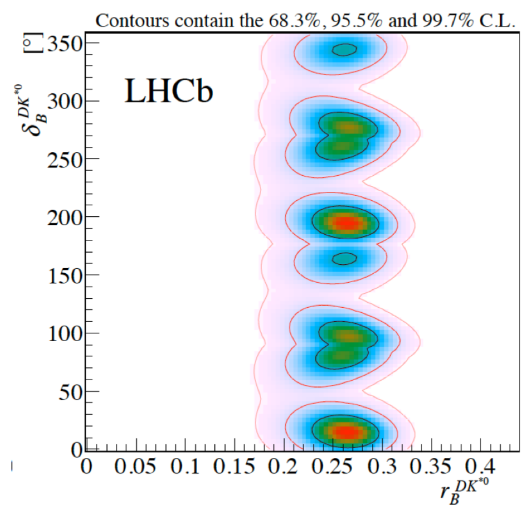
LHCb-PAPER-2019-021

4.8 fb^{-1}

- Updates from previous 3 fb^{-1} analysis with $D \to 2h$, and Dalitz plot analysis of $B \to DK\pi$





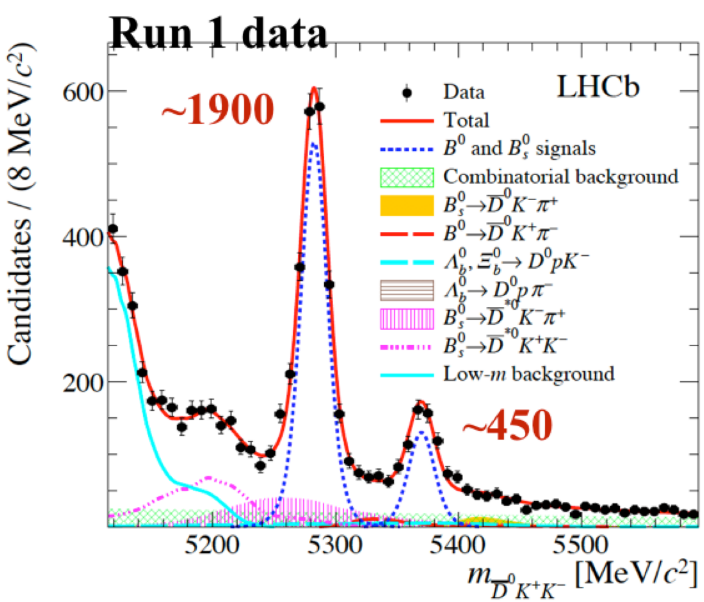


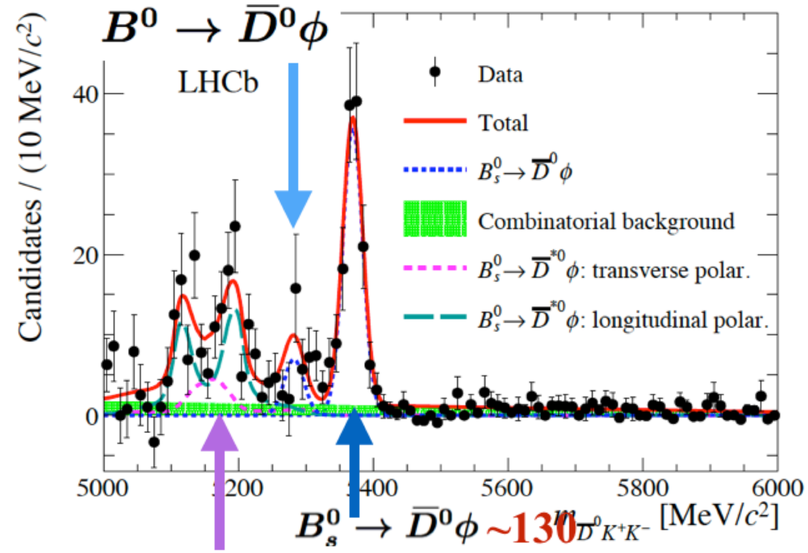
- $D \to 4h$ analyzed for the first time
- First discovery on $B^0 \to D(\pi^+K^-)K^{*0}$ and $B^0 \to D(4\pi)K^{*0}$
- $r_B^{DK^{*0}}$ constrained to 0.265 ± 0.023

Other activities

Phys. Rev. D 98 (2018) 072006
Phys. Rev. D 98 (2018) 071103(R)

- $B^0 \to D\overline{D^0}KK$ and $B_s \to D\overline{D^0}KK$ decays
  - Time-Dependent Dalitz analyses to access CKM angle γ and $\beta_{(s)}$
  - Not only probe $\sin2\beta_{(s)}$, but also $\cos2\beta_{(s)}$
  - Dalitz structures interesting for charm spectroscopy studies
- $B_s \to D^{(*)}\phi$ decays: special cases where final states are in CP eigenstates



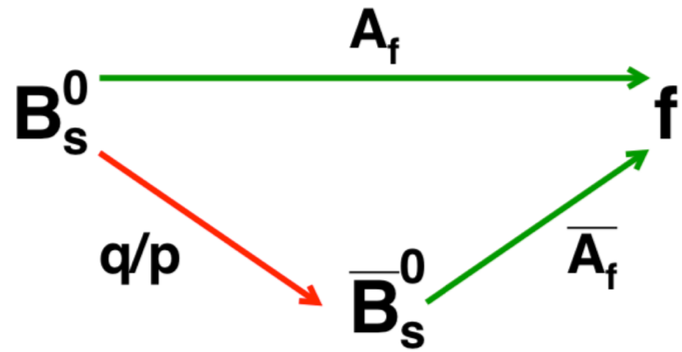


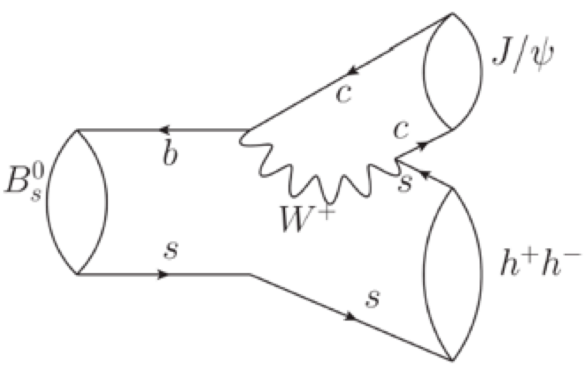
$B_s^0 \to \overline{D}^{*0}\phi$ (Partially reconstructed, Two polarization components) ~160

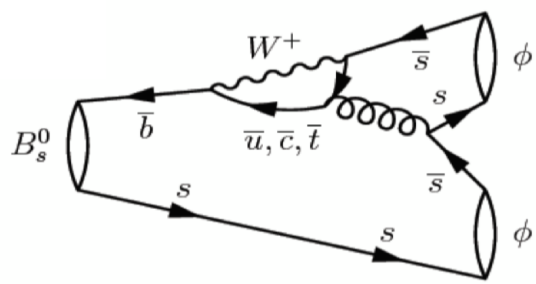
- Comparable sensitivity on γ w.r.t. that of the golden GGSZ mode expected for $B_s \to D^{(*)}\phi$ decays and LHCb-China group are currently working on its measurements

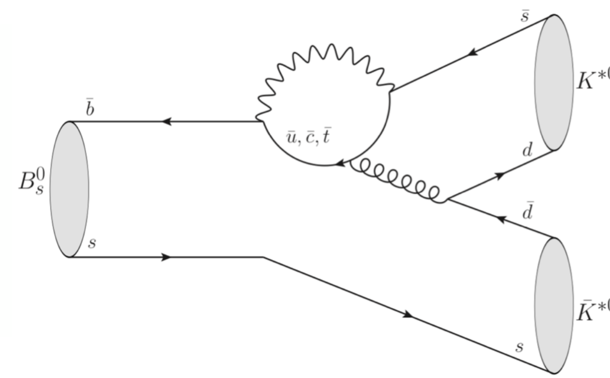
ϕ_s measurements

- 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.

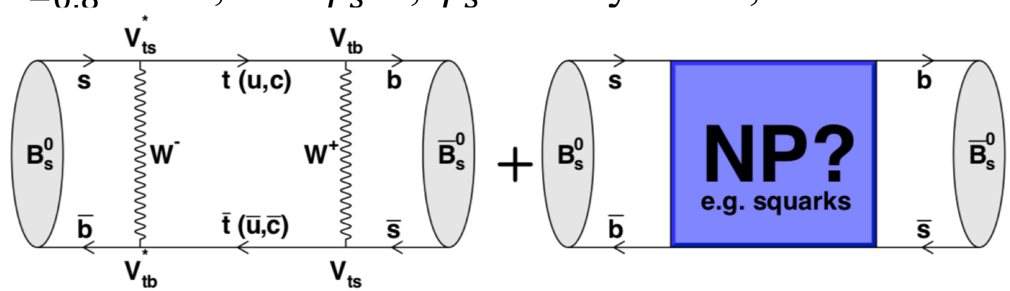








- SM prediction for $\phi_s^{c\bar{c}s} = -36.8^{+1.0}_{-0.8}$ mrad, and $\phi_s^{s\bar{s}s}$, $\phi_s^{d\bar{d}s}$ very small; NP can contribute and enhance them

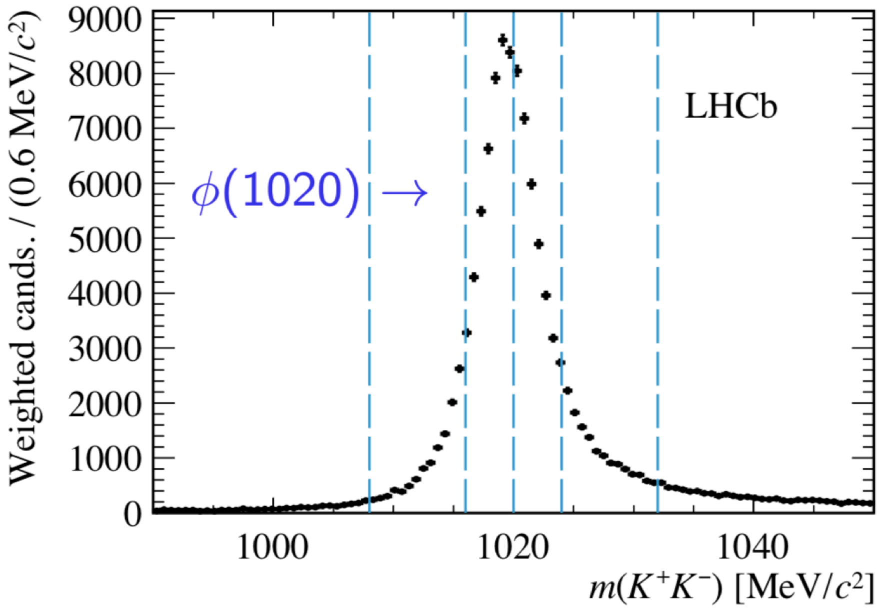


$\phi_s^{c\bar{c}s}$ updates

LHCb-PAPER-2019-013
LHCb-PAPER-2019-003

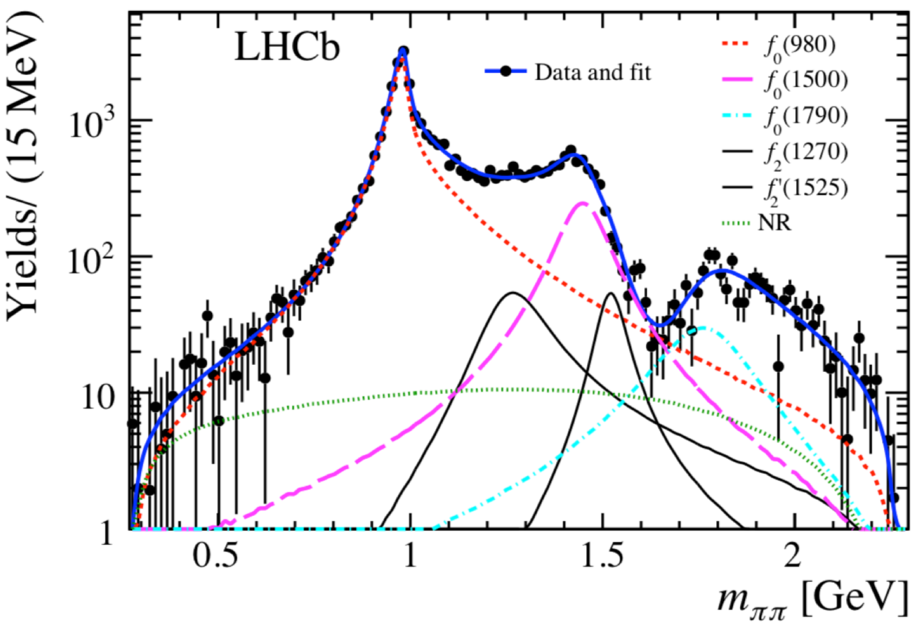
- We have two important updates recently: $B_s^0 \to J/\psi\, \phi$ with 4.9 fb^{-1} and $B_s^0 \to J/\psi \pi^+\pi^-$ with 4.9 fb^{-1}

Fit in six $m(K^+K^-)$ bins



$$\phi_s = -83 \pm 41 \pm 6\,\text{mrad}$$
$$|\lambda| = 1.012 \pm 0.016 \pm 0.006$$
$$\Gamma_s - \Gamma_d = -0.0041 \pm 0.0024 \pm 0.0015\,\text{ps}^{-1}$$
$$\Delta\Gamma_s = 0.077 \pm 0.008 \pm 0.003\,\text{ps}^{-1}$$

Fit to $m(\pi^+\pi^-)$

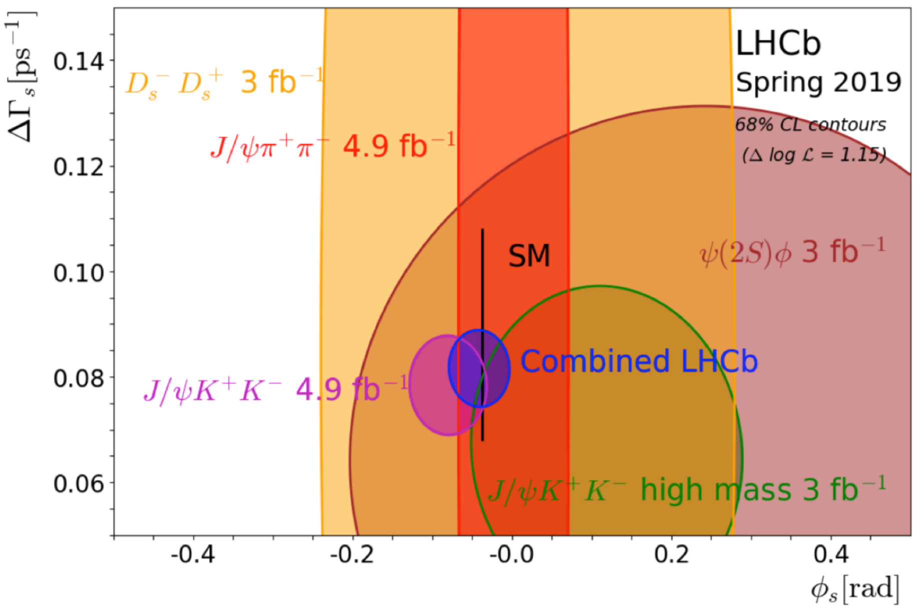


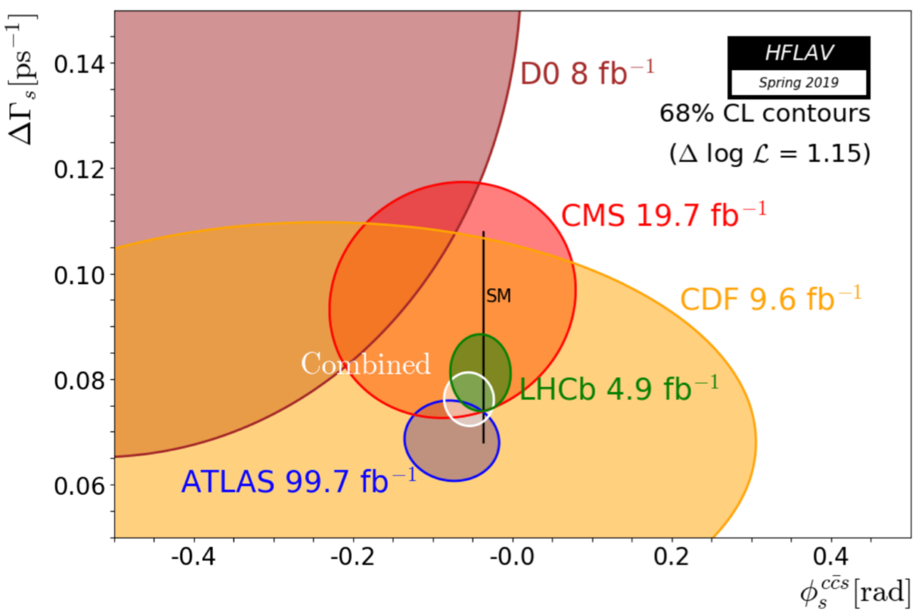
$$\phi_s = -57 \pm 60 \pm 11\,\text{mrad}$$
$$|\lambda| = 1.01^{+0.08}_{-0.06} \pm 0.03$$
$$\Gamma_H - \Gamma_d = -0.050 \pm 0.004 \pm 0.004\,\text{ps}^{-1}$$

$\phi_s^{c\bar{c}s}$ combination

ATLAS-CONF-2019-009
LHCb-PAPER-2019-013
LHCb-PAPER-2019-003

- LHCb combination gives: $\phi_s = -0.041 \pm 0.025$ rad
- B physics now attracts more interests from GPD, there are also results from ATLAS on $B_s^0 \to J/\psi\, \phi$ (see weiming's talk)
- World average: $\phi_s = -0.054 \pm 0.020$ rad vs -0.0370 ± 0.0006 rad from prediction





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

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

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

- Update of $B_s^0 \to \phi\phi$ with 4.9 fb^{-1} data and gives

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

- LHCb prospects for ϕ_s in different processes:

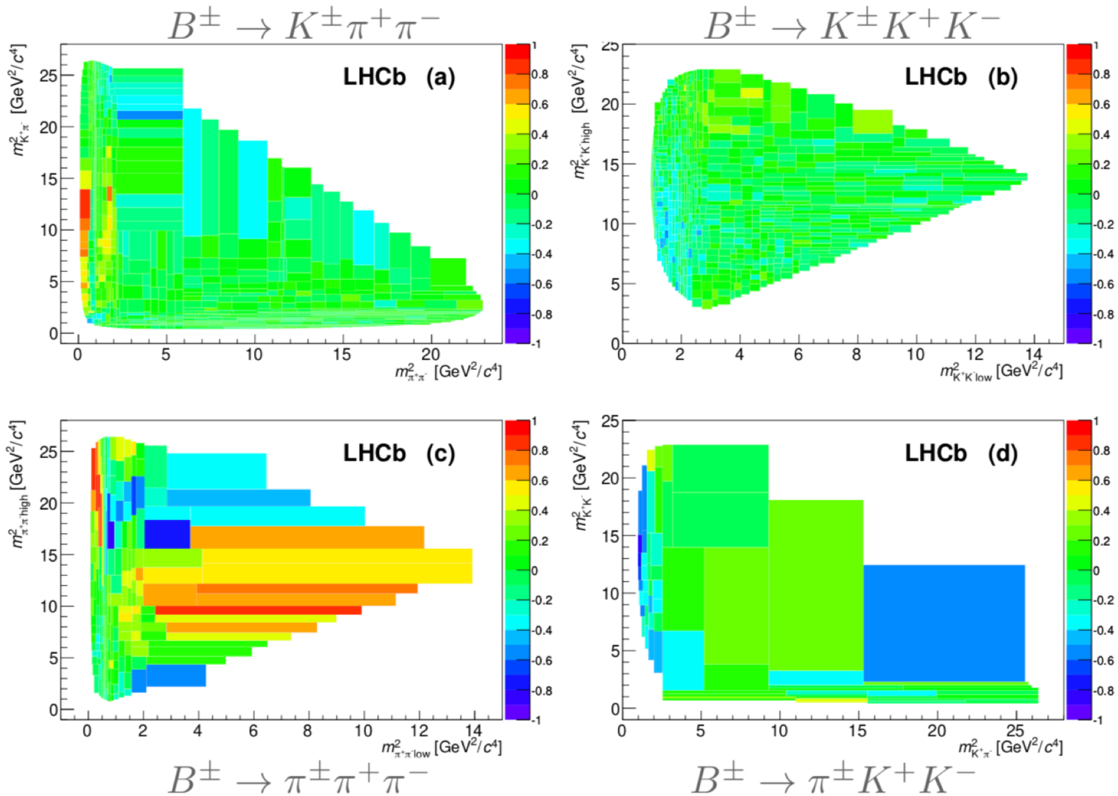
	Run 1	Run 2	Upgrade I	Upgrade II
$\phi_s^{c\bar{c}s}$	37 mrad	15 mrad	4 mrad	2 mrad
$\phi_s^{d\bar{d}s}$	180 mrad	90 mrad	22 mrad	10 mrad
$\phi_s^{s\bar{s}s}$	150 mrad	75 mrad	19 mrad	8 mrad

- LHCb-China group heavily involved in $B_s^0 \to J/\psi\ KK/\pi\pi$ and $B_s^0 \to \phi\phi$

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

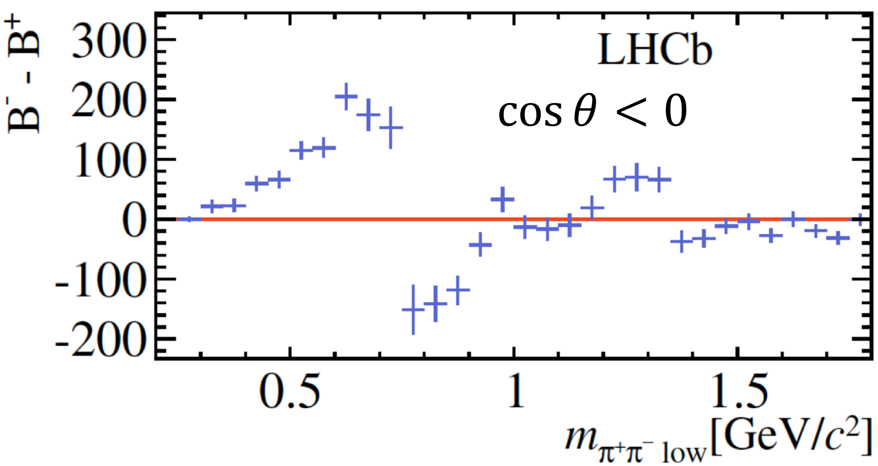
PRD 90 (2014) 112004

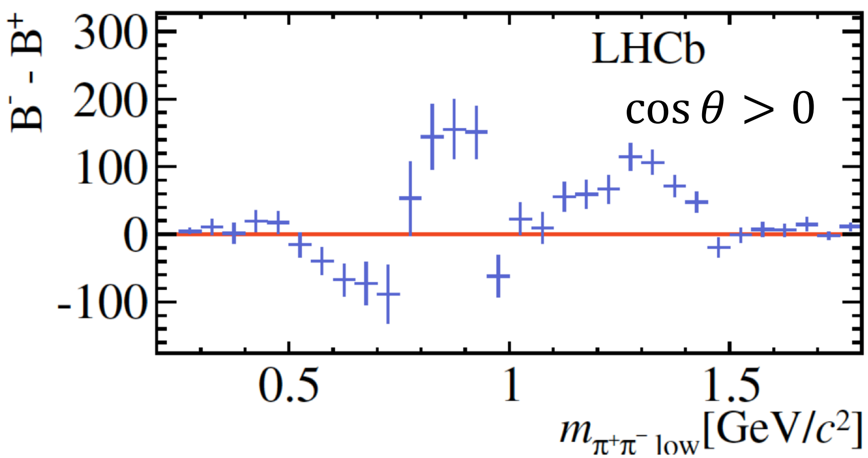
- Two competitive contributions needed to have CPV

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

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

- 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:

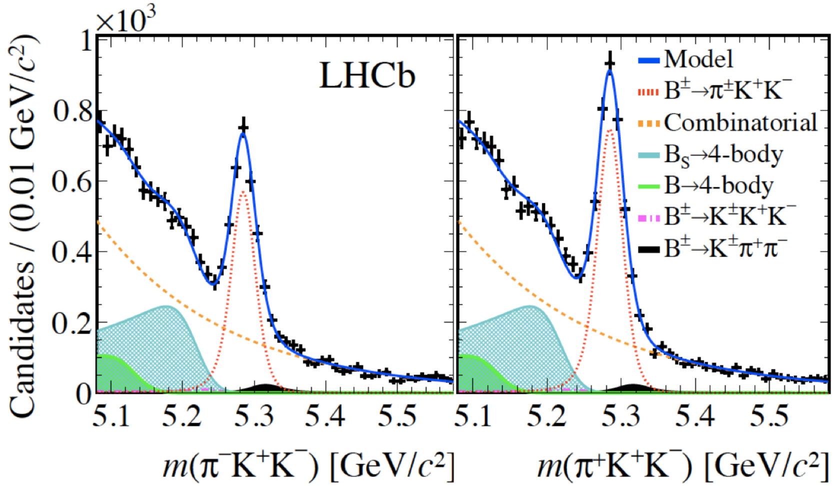
$$\mathcal{F}_i \equiv \frac{\int d\Phi_3 |A_i(\Phi_3)|^2 + \int d\Phi_3 |\bar{A}_i(\Phi_3)|^2}{\int d\Phi_3 |A(\Phi_3)|^2 + \int d\Phi_3 |\bar{A}(\Phi_3)|^2} \qquad \mathcal{A}^i_{CP} \equiv \frac{\int d\Phi_3 |\bar{A}_i(\Phi_3)|^2 - \int d\Phi_3 |A_i(\Phi_3)|^2}{\int d\Phi_3 |\bar{A}_i(\Phi_3)|^2 +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

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

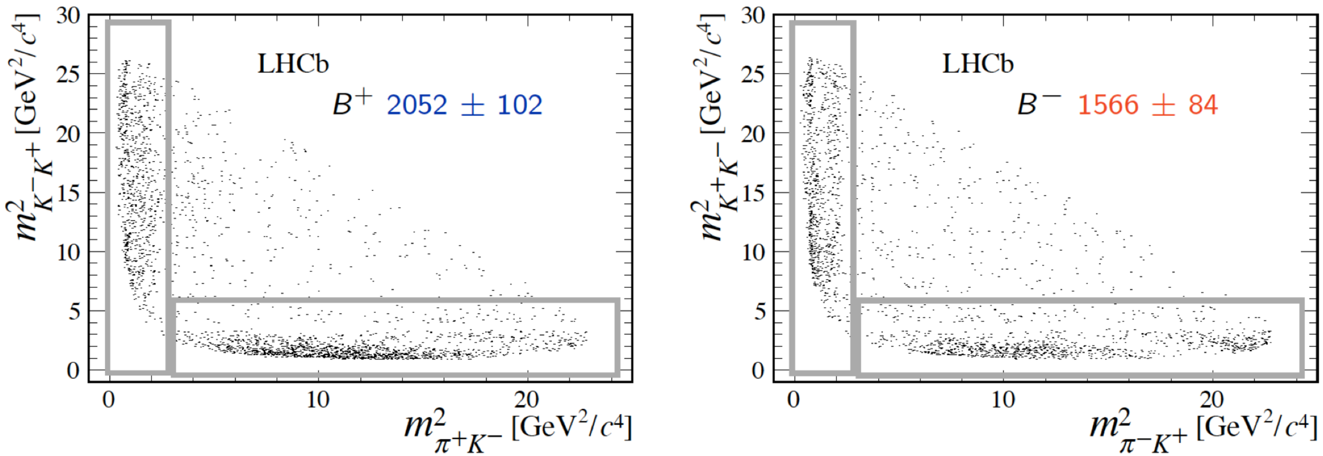
PRD 90 (2014) 112004
arXiv:1905.09244

3 fb^{-1}

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



- Clear CPV found over different regions of Dalitz plot



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	$16.4 \pm 0.8 \pm 1.0$	$-66.4 \pm 3.8 \pm 1.9$
$\phi(1020)$	$0.3 \pm 0.1 \pm 0.1$	$+9.8 \pm 43.6 \pm 26.6$

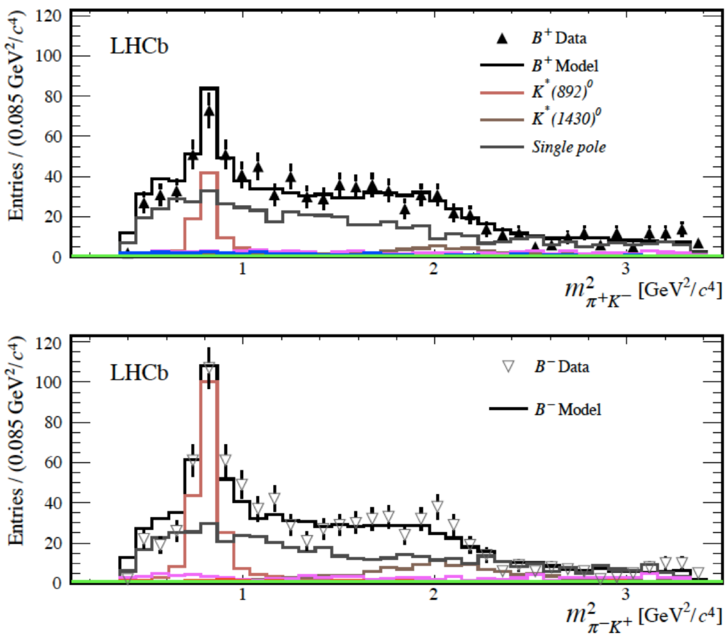
- $K\pi$ non-resonance modelled by

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

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

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

Phys. Rev. D 92 (2015) 054010



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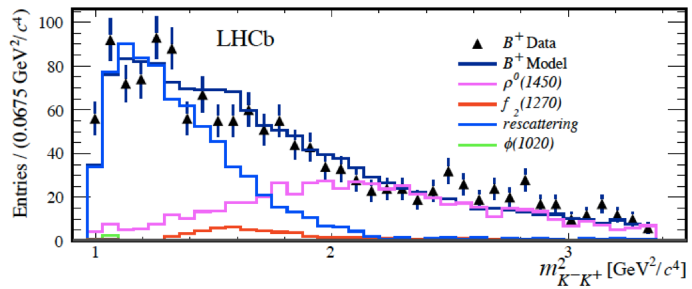
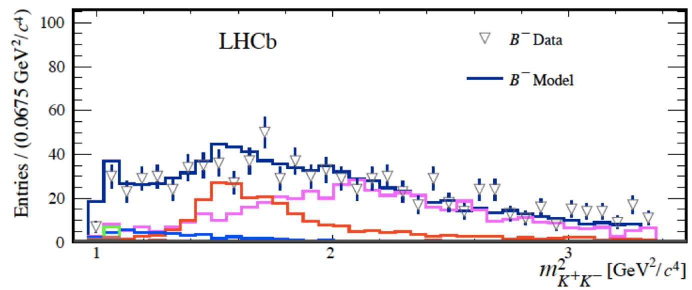
- *KK* non-resonance modelled by rescattering model

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

Phys. Rev. D 71 (2005) 074016





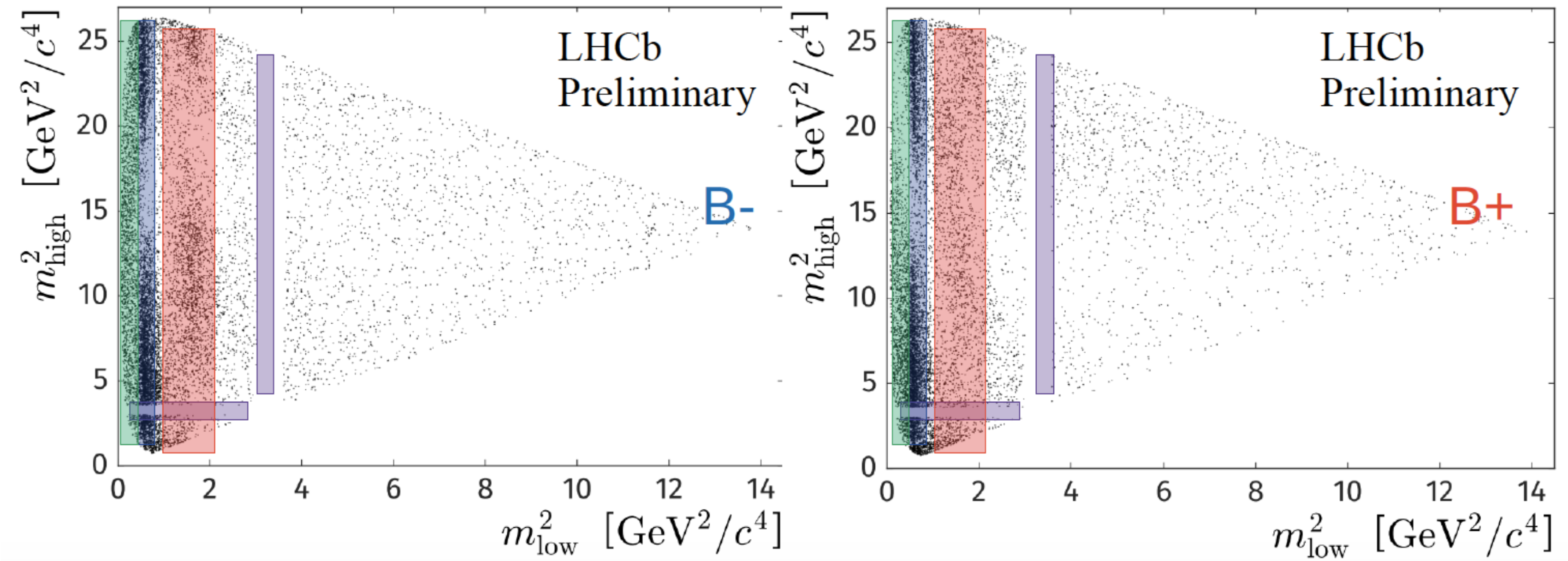
- CPV as larger as -66.4%, largest CPV found in a single decay

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

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

3 fb^{-1}

- Dalitz plot analysis with 20594 ± 1569 events



- 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

S-wave description

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

- General agreed descriptions (RBW, GS) for $\pi\pi$ P- and D-waves;
- More complicated $\pi\pi$ S-wave, modeled in three different approaches:
  - Isobar model: different S-wave contributions are explicitly modeled:

    $f_0(500)$: RBW, complex pole parameterization

    $$T_\sigma(m_{13}) = \frac{1}{m_\sigma^2 - m_{13}^2},$$

    PRD 71 (2005) 054030

    $f_0(980)$: Flatte parametrization

    non-resonant: flat, Belle model, re-scattering model etc

    $$T_{nr}(m_{13}, m_{23}) = c_{nr}(e^{-\alpha_{nr} m_{13}^2} e^{i\delta_1^{nr}} + e^{-\alpha_{nr} m_{23}^2} e^{i\delta_2^{nr}}),$$

    PRL 96 (2006) 251803

    $$T_{nr}(m_{13}) = \frac{a^{nr}}{1 + \frac{m_{13}^2}{\Lambda^2}} e^{i\delta^{nr}}$$

    arXiv:hep-ph/1506.08332

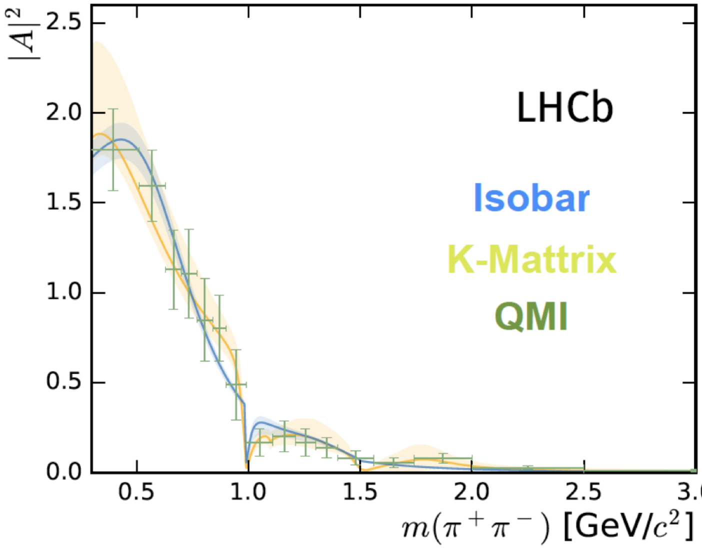
  - K-Matrix approach: 5 poles and 5 decay channels; parameters from global fit to previous data while production vector parameters from fit to data

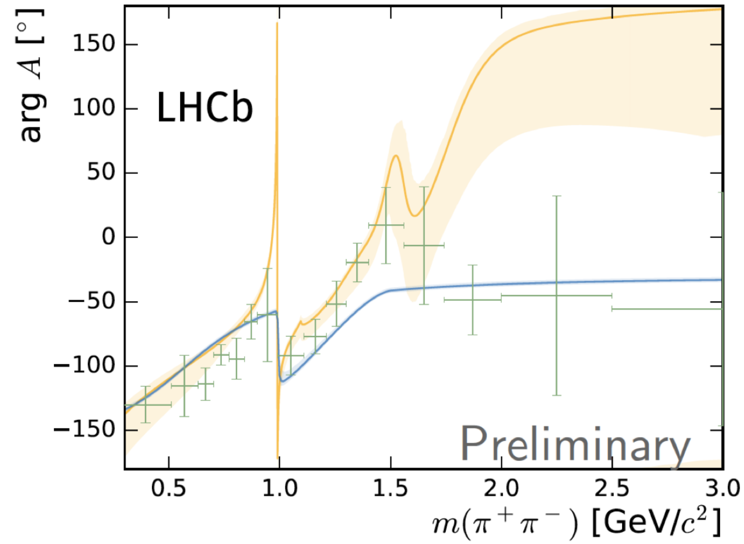
    EPJA 16 (2003) 229

  - Model independent approach (QMI): $\pi\pi$ S-wave binned into 13 bins; amplitudes in each bin obtained from fit to data (26 free parameters)

S-wave results

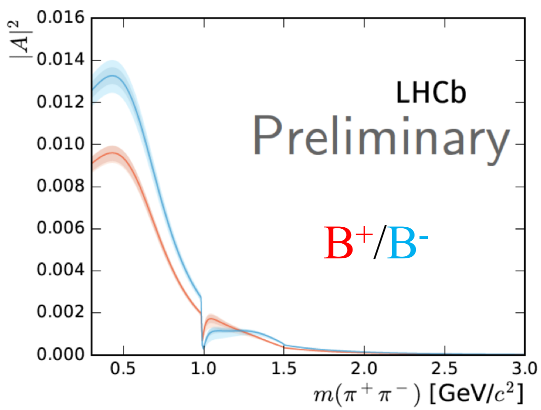
- Good agreement between the three approaches



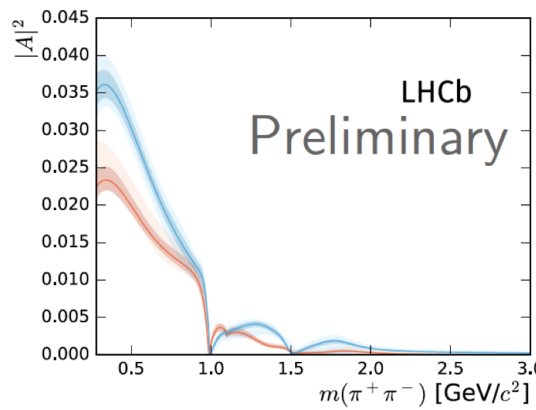


- Similar CPV pattern for the three approaches, as large as 10 σ

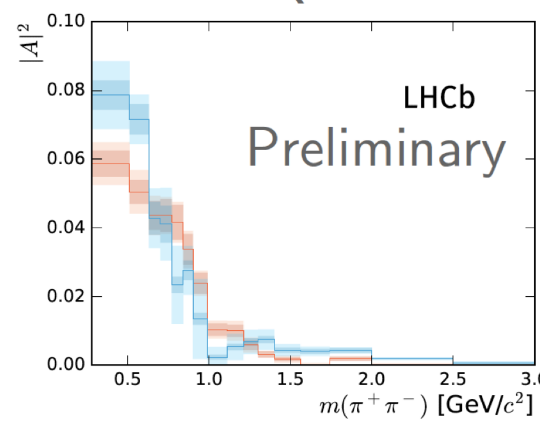
Isobar



KMatrix



QMI



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

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LHCb-PAPER-2019-018

- 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 $f_2(1270)$，not $\rho(770)$
- First observation of large CPV in decays with tensor

New CPV pattern

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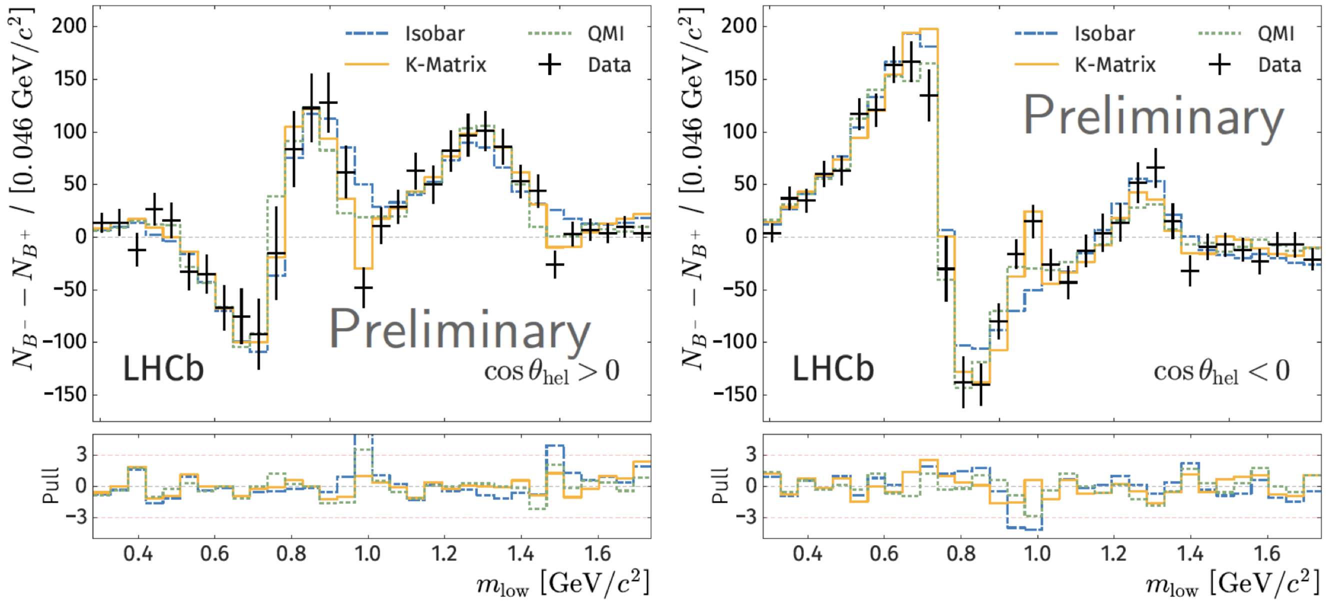
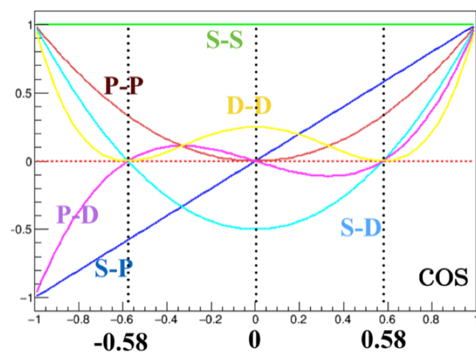
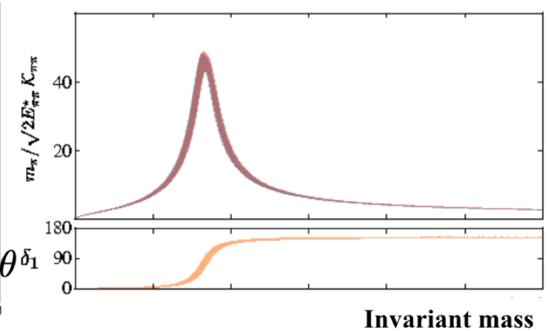
- CPV around $\rho(770)$ pole well described by the three S-wave models



- Over 25σ significance for CPV due to S-P interference, first observation
- Sign-flip due to phase change and helicity angle change





The next CPV

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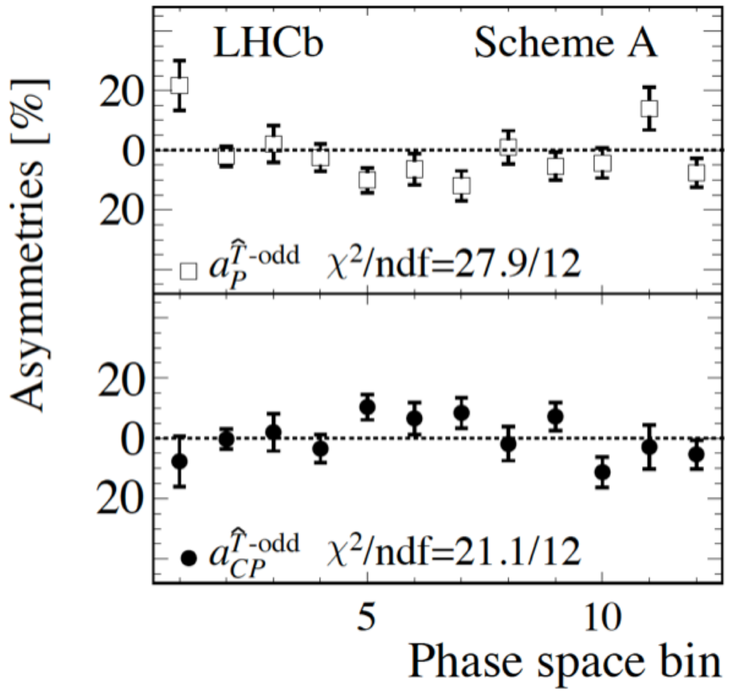
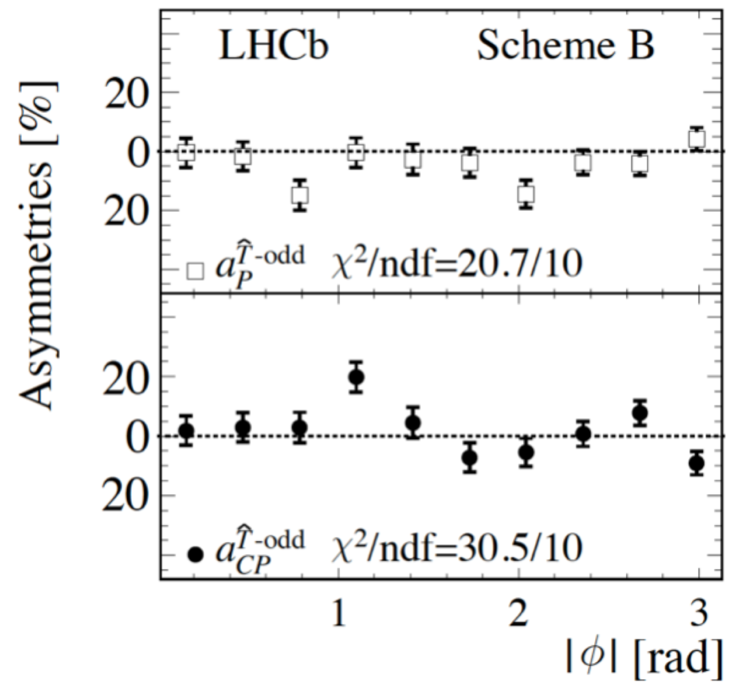
- CPV has not yet been found in baryon decays
- We saw first evidence of 3.3σ 2 years ago in $\Lambda_b \to p3\pi$ using triple products



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



Binning based on ϕ angle

- Searches are performed extensively in LHCb, including $\Lambda_b \to p3\pi$, $\Lambda_b \to pK_S\pi$ (a CPV as large as 20% is predicted in arXiv:1412.1899)

Conclusion

- Plenty of interesting CPV measurements in B decays performed by the LHCb experiments, shedding new lights on our understanding of underlying dynamics
- One of the key goals of LHCb is to search for New physics through precision measurements. New physics may appear anywhere, maybe in flavor sector in year 202x