Recent highlights from the LHCb experiment

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Outline

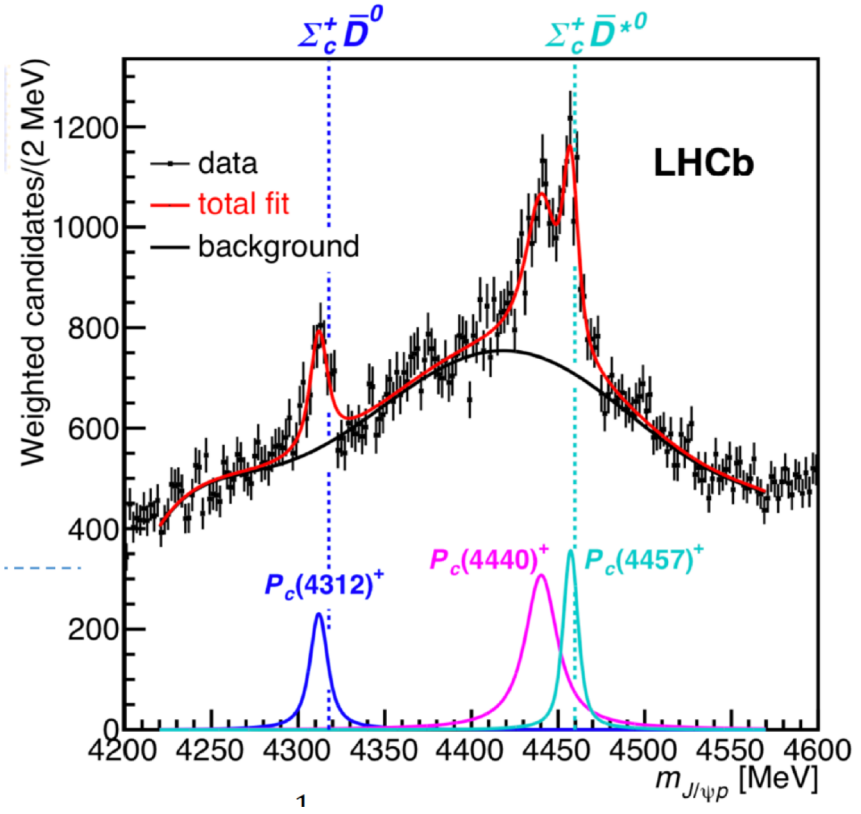
- **Recent highlights on spectroscopy studies**
- **Recent highlights on CPV measurements**
- **Conclusion**

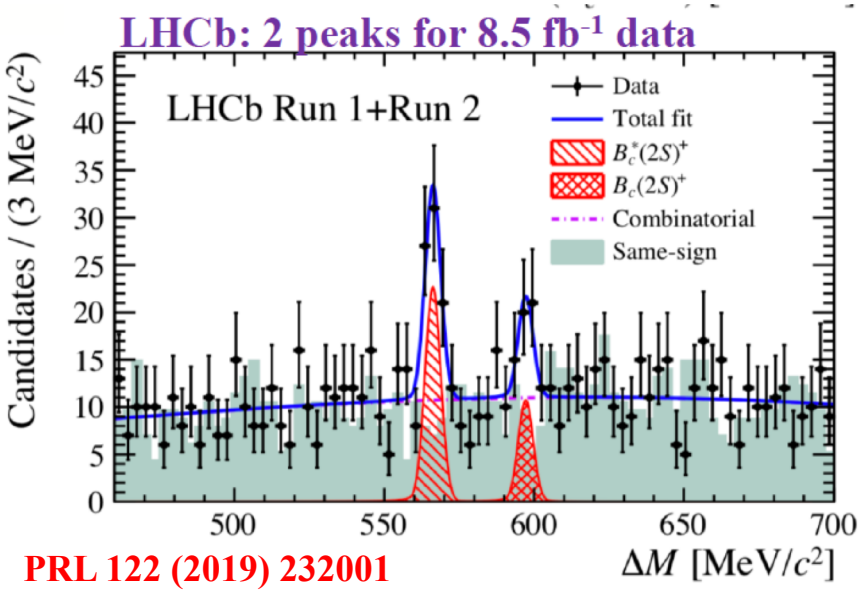
Disclaimer: results of QGP, rare decays, charm CPV etc. from LHCb China group not covered here

Spectroscopy studies by LHCb-China group

- Charmonium production studies
- Charmed and charmonium production at cold nuclear
- Doubly charmed baryons and their extensions
- Properties of charmed baryons
- B_c physics
- Exotic-state searches and property study

PRL 122 (2019) 222001





PRL 122 (2019) 232001

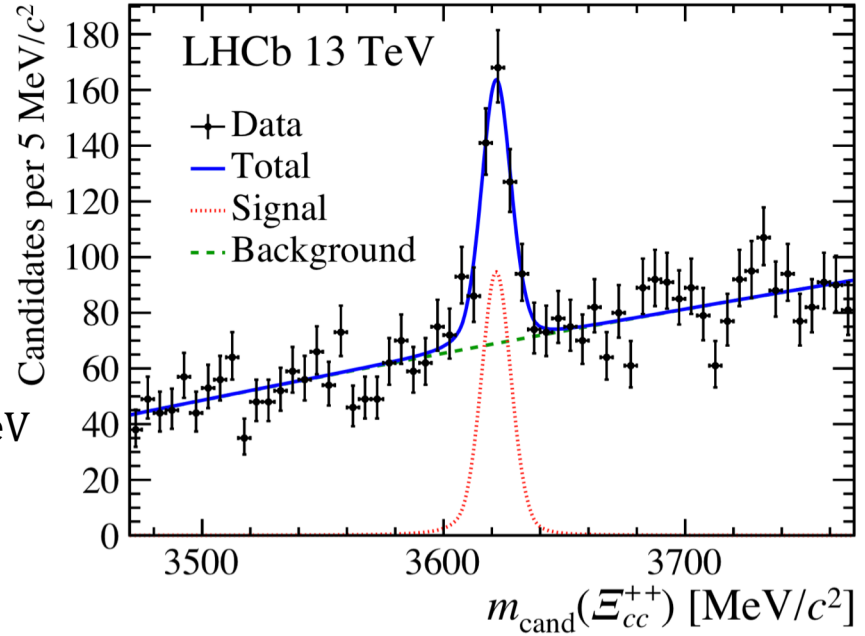
Reminder: Discovery of Ξ_{cc}^{++}

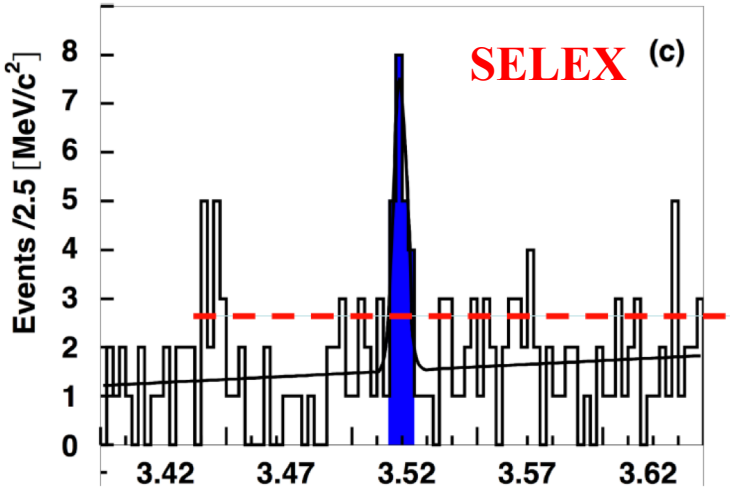
PRL 119 (2017) 112001
PRL 121 (2018) 052002

- Observed in the decay $\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+$ with 1.7 fb^{-1} data at 13 TeV
- Signal yields: 313 ± 33, $>12\sigma$
- Mass measured to be:

  $3621.40 \pm 0.72\,(\text{stat.}) \pm 0.27\,(\text{sys.}) \pm 0.14\,(\Lambda_c^+)$ MeV
- Lifetime measured to be:

  $0.256^{+0.024}_{-0.022}\,(\text{stat.}) \pm 0.014\,(\text{sys.})$ ps
- SELEX observed Ξ_{cc}^+ in the decays $\Lambda_c^+ K^- \pi^+$ and pD^+K^- with mass of 3518.17 ± 1.7 MeV, about 103 MeV lower
- Mass expected to be similar for Ξ_{cc}^+ and Ξ_{cc}^{++}

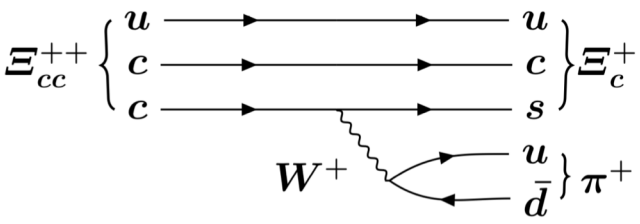




Observation of $\Xi_{cc}^{++} \to \Xi_c^+ \pi^+$

PRL 121 (2018) 162002

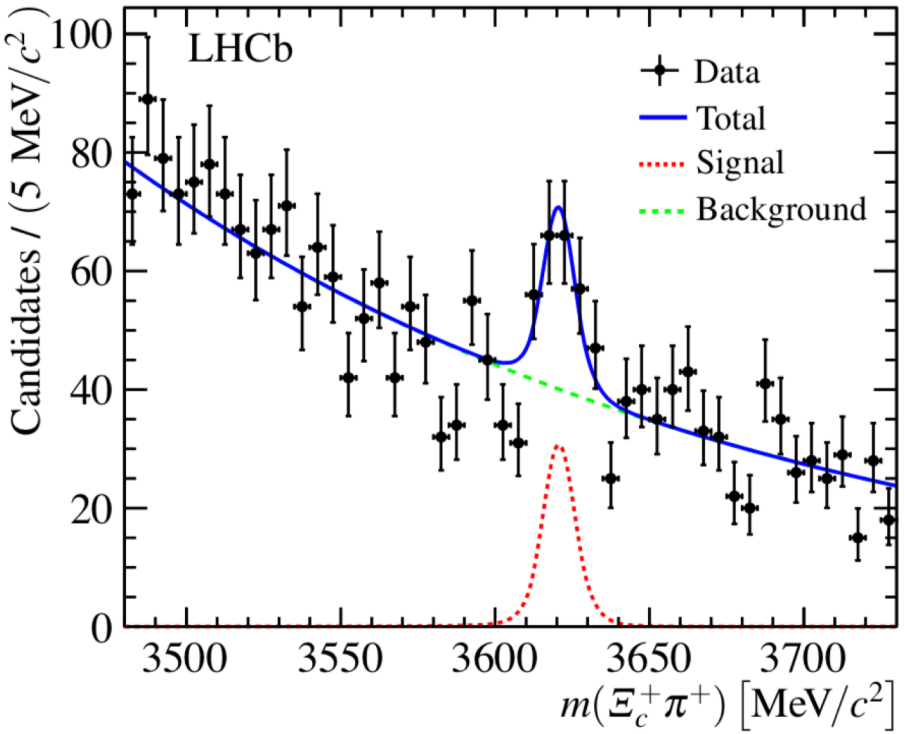
Baryons	Modes	Br	secondary decay Br's	tracks
Ξ_{cc}^{++}	$\Lambda_c^+ K^- \pi^+ \pi^+$	$\mathcal{O}(10\%)$	×6%	6
	$\Xi_c^+ \pi^+$	$(0.2 \sim 5.2)\%$	×(1.6±0.5)%	4
	$\Lambda_c^+ \pi^+$	$(0.1 \sim 0.6)\%$	×6%	4
	pD^+	$(0.1 \sim 0.6)\%$	×9%	4



- Decay channel $\Xi_{cc}^{++} \to \Xi_c^+ \pi^+$ observed using 1.7 fb^{-1} data at 13 TeV
- Signal: 91 ± 20 compared to 289 ± 35 $\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+$ with same data
- Branching ratio measured to be:

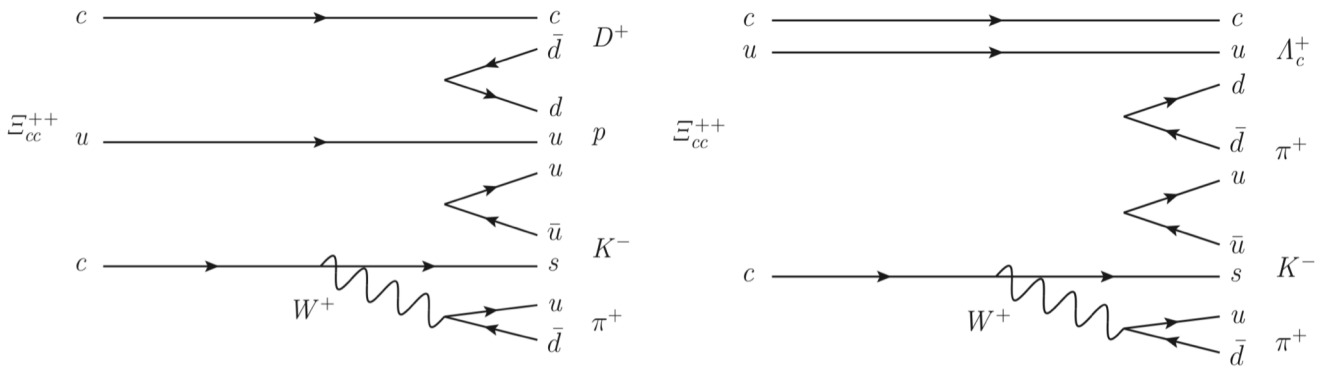
$$\frac{\mathcal{B}(\Xi_{cc}^{++} \to \Xi_c^+ \pi^+) \times \mathcal{B}(\Xi_c^+ \to pK^- \pi^+)}{\mathcal{B}(\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+) \times \mathcal{B}(\Lambda_c^+ \to pK^- \pi^+)} = 0.035 \pm 0.009\,(\text{stat.}) \times 0.003\,(\text{sys.})$$

- Agreed well with expectations



Search for $\Xi_{cc}^{++} \to D^+ p K^- \pi^+$

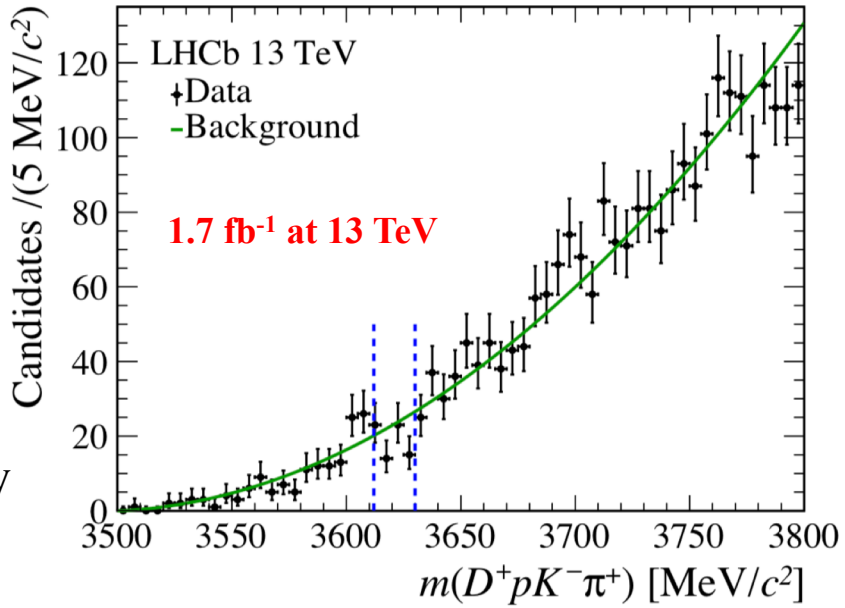
JHEP 10 (2019) 024



- Similar Feynman diagram between $\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+$ and $\Xi_{cc}^{++} \to D^+ p K^- \pi^+$
- $\mathcal{B}(\Lambda_c^+ \to p K^- \pi^+) = (6.28 \pm 0.32)\%$, $\mathcal{B}(D^+ \to K^- \pi^+ \pi^+) = (9.38 \pm 0.16)\%$
- None observed, upper limits set:

$$\frac{\mathcal{B}(\Xi_{cc}^{++} \to D^+ p K^- \pi^+)}{\mathcal{B}(\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+)} < 1.7(2.1) \times 10^{-2} \text{ at } 90(95)\% \text{ CL}$$

- Long distance effects may be important here, stay tuned for results with more data



More properties for Ξ_{cc}^{++}

arXiv:1911.08594
arXiv:1911.01114

- The production of Ξ_{cc}^{++} measured using 1.7 fb^{-1} data at 13 TeV in the LHCb range ($4 < p_T < 15$ GeV and $2.0 < y < 4.5$) w.r.t prompt production of Λ_c^+

$$\frac{\sigma(\Xi_{cc}^{++})\times\mathcal{B}(\Xi_{cc}^{++}\to\Lambda_c^+K^-\pi^+\pi^+)}{\sigma(\Lambda_c^+)} = (2.22 \pm 0.27 \pm 0.29)\times10^{-4}$$

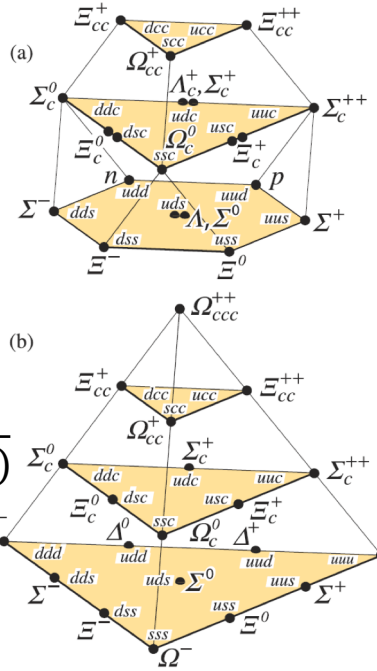
- Note that the predicted $\mathcal{B}(\Xi_{cc}^{++} \to \Lambda_c^+K^-\pi^+\pi^+)$~10%, and B_c production around 0.3%, similar between the two

- An updated mass measurement with full Run2 data (5.6 fb^{-1}) performed using $\Xi_{cc}^{++} \to \Lambda_c^+K^-\pi^+\pi^+$ and $\Xi_{cc}^{++} \to \Xi_c^+\pi^+$ results in $3621.55 \pm 0.23\,(\text{stat.}) \pm 0.30\,(\text{sys.})$ MeV

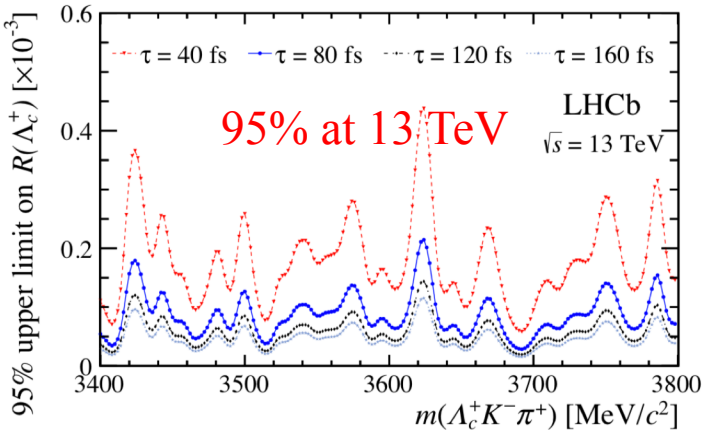
Search for Ξ_{cc}^{+}

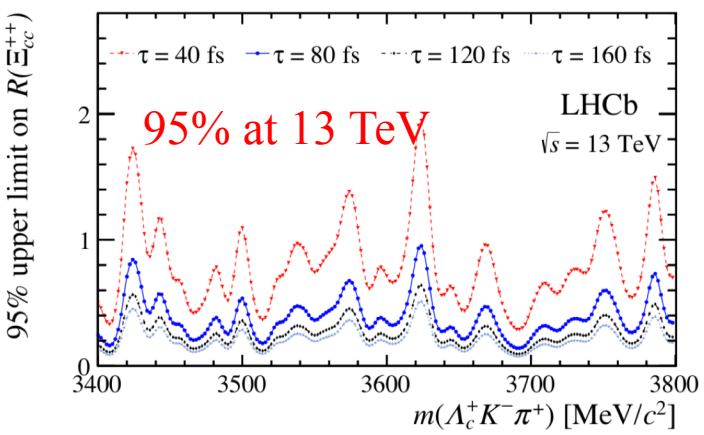
Sci.China.Phys.Mech.Astron. 63 (2020) 221062

- The mass of Ξ_{cc}^{+} observed by SELEX and the mass of Ξ_{cc}^{++} observed by LHCb differ by 103 MeV, interesting to find it also in LHCb
- Searches performed using full Run1 and Run2 data (9.0 fb^{-1}), none found and upper limits set



$$R(\Lambda_c^+) = \frac{\sigma(\Xi_{cc}^+)\times\mathcal{B}(\Xi_{cc}^+ \to \Lambda_c^+ K^-\pi^+)}{\sigma(\Lambda_c^+)} \qquad R(\Xi_{cc}^{++}) = \frac{\sigma(\Xi_{cc}^+)\times\mathcal{B}(\Xi_{cc}^+ \to \Lambda_c^+ K^-\pi^+)}{\sigma(\Xi_{cc}^{++})\times\mathcal{B}(\Xi_{cc}^{++} \to \Lambda_c^+ K^-\pi^+\pi^+)}$$

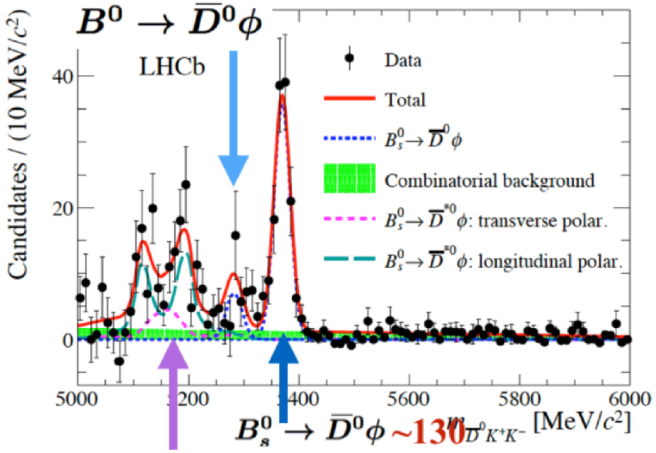


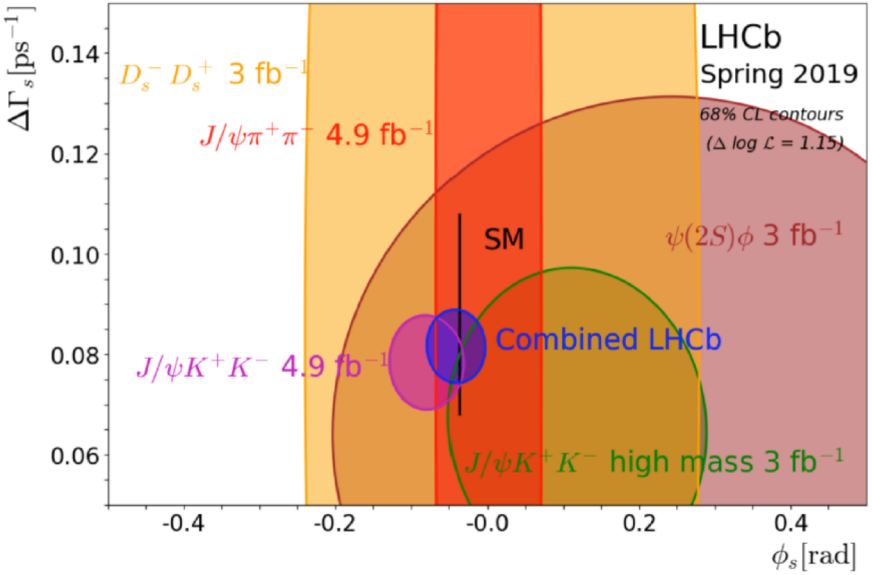


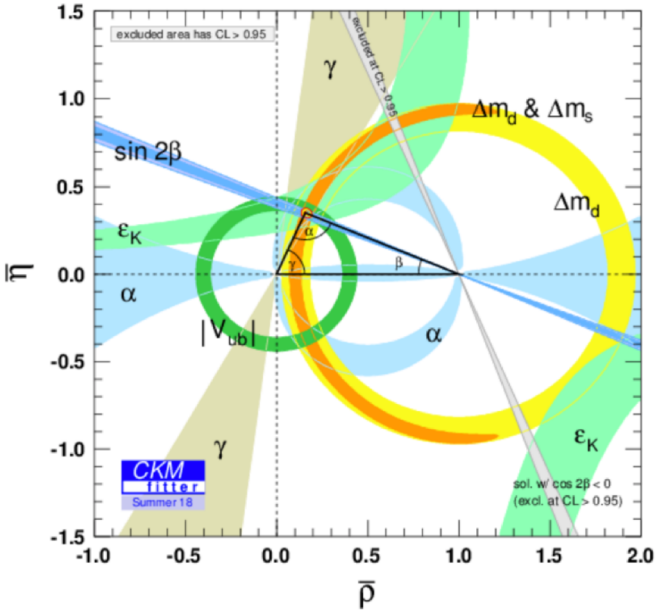
CPV measurements by LHCb-China group

- CKM angle γ measurements
- Precise measurements of angle ϕ_s
- CPV in charmless B decays
- Search for CPV in b-baryon decays
- Search for CPV in charm decays
- Global fit of CKM matrix

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



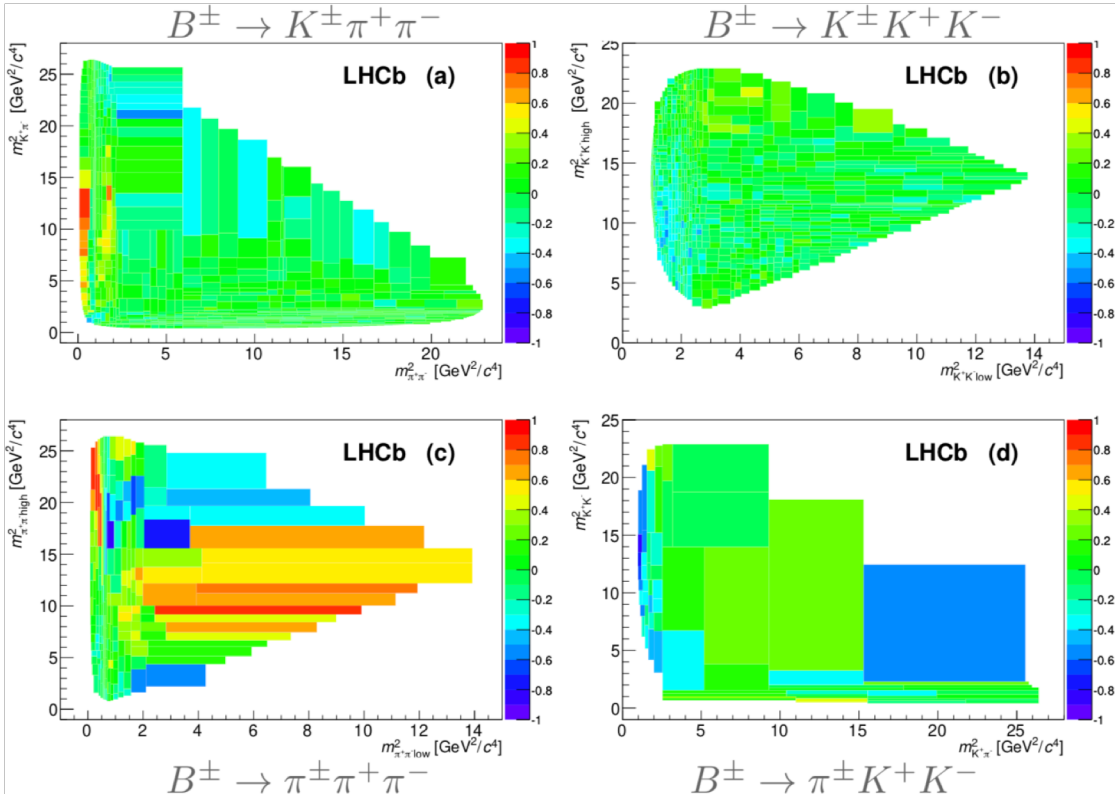




CPV in charmless B decays

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

CPV over Dalitz plot

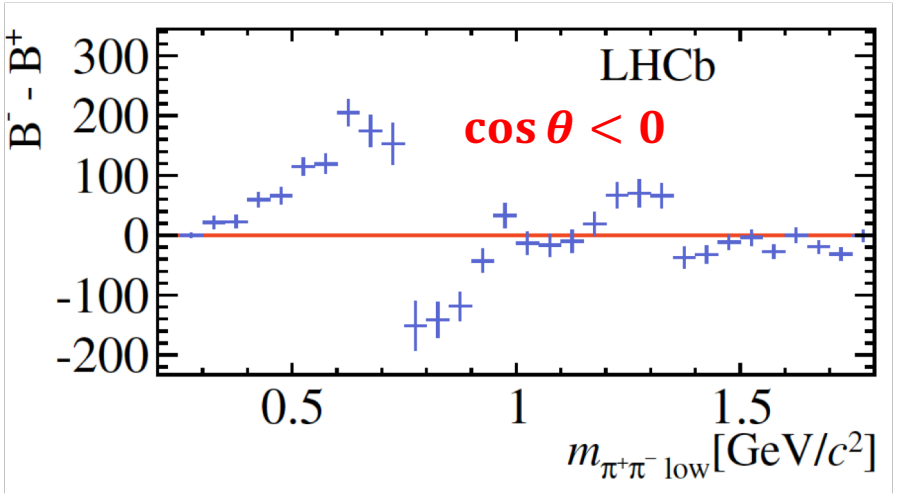
PRD 90 (2014) 112004

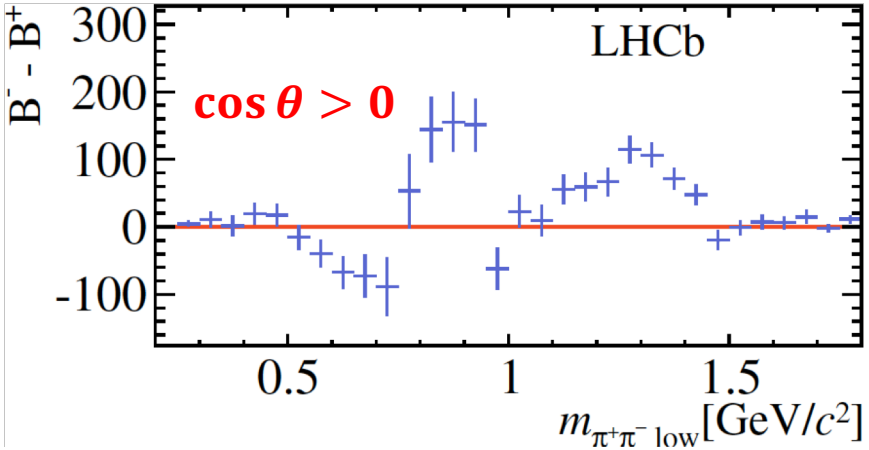
- Two competitive contributions needed to have CPV

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

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

- 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 $B \to \pi\pi\pi$

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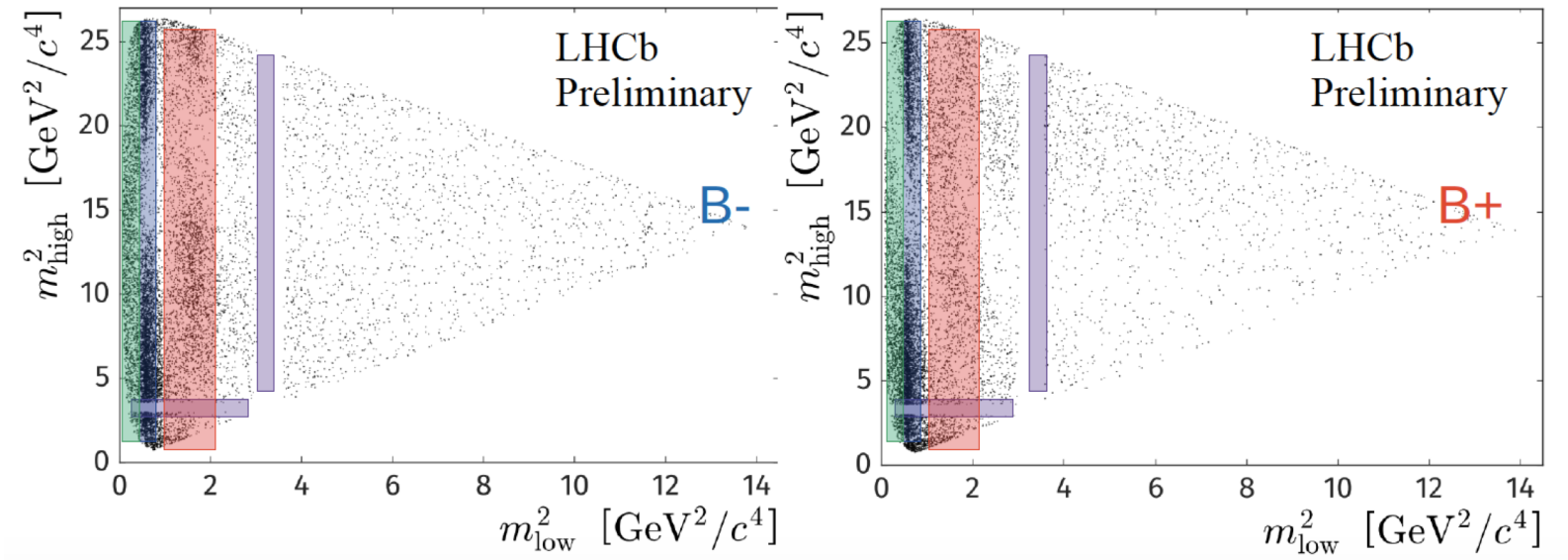
LHCb-PAPER-2019-018

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



- Resonant contributions:

  $\rho - \omega, f_0(500), f_0(980)$ 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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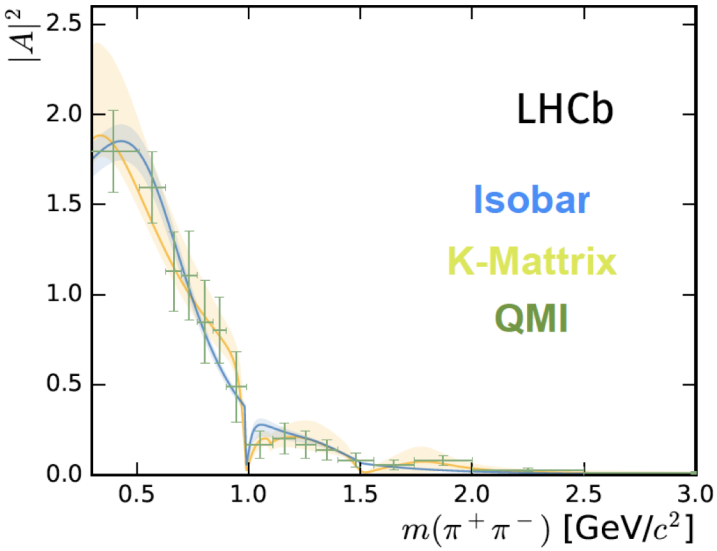
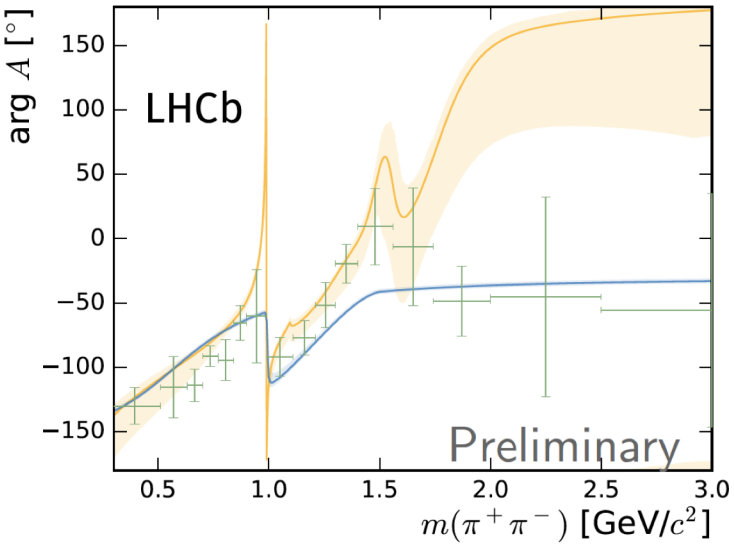
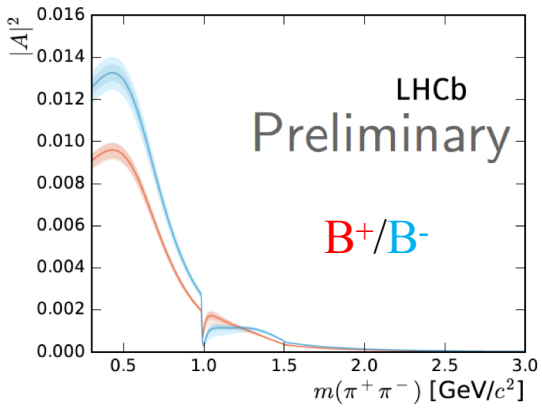
- Good agreement between the three approaches



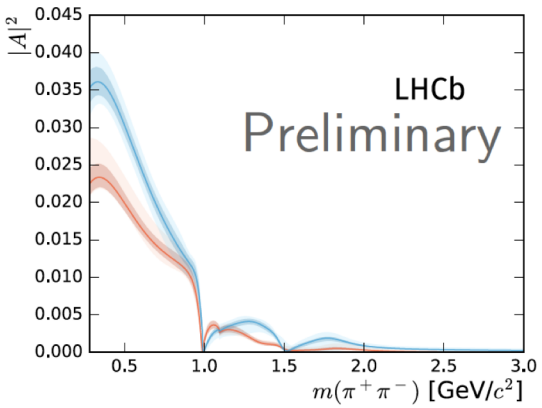


- Similar CPV pattern for the three approaches, as large as 10σ

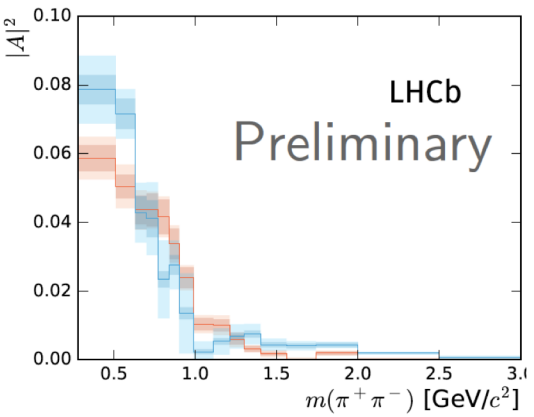
Isobar



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 $f_2(1270)$

New CPV pattern

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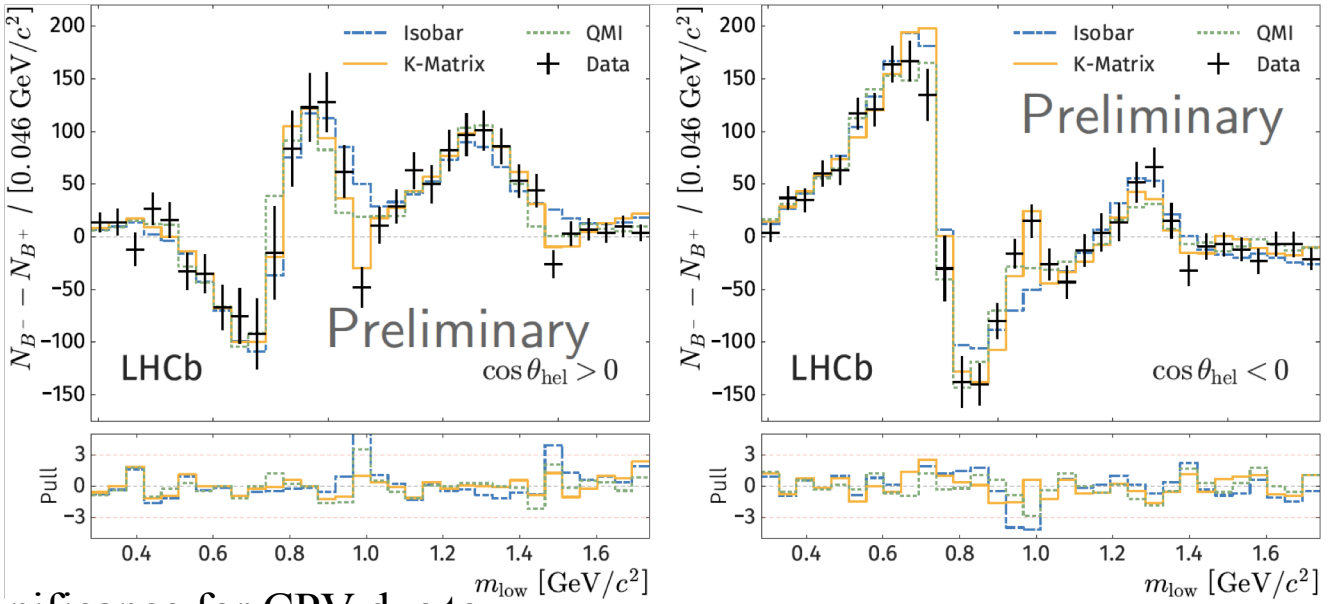
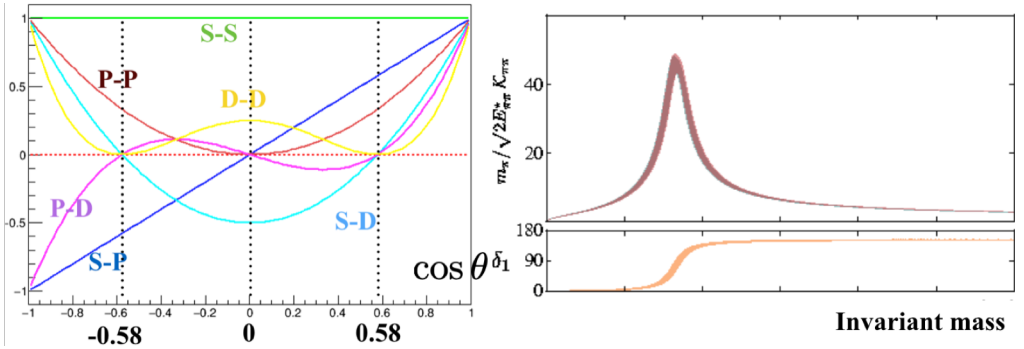
- CPV around $\rho(770)$ pole well described by the three S-wave models

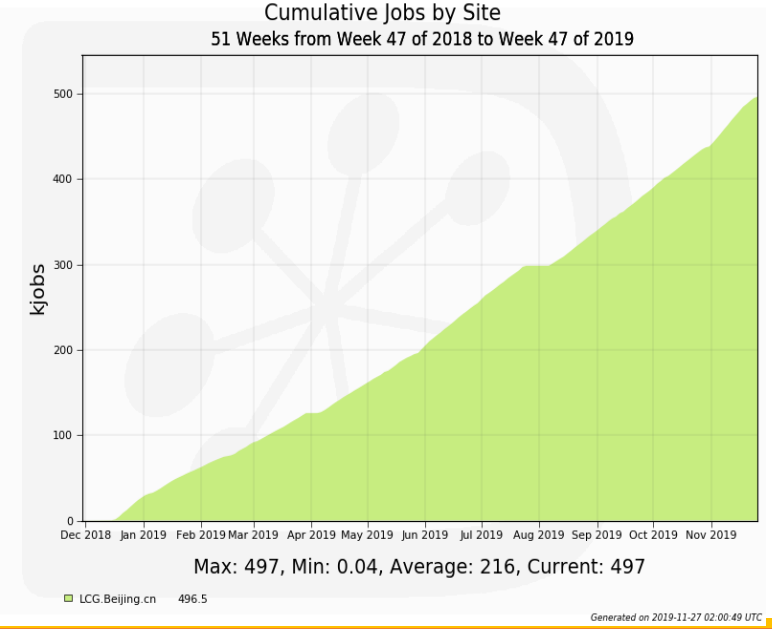


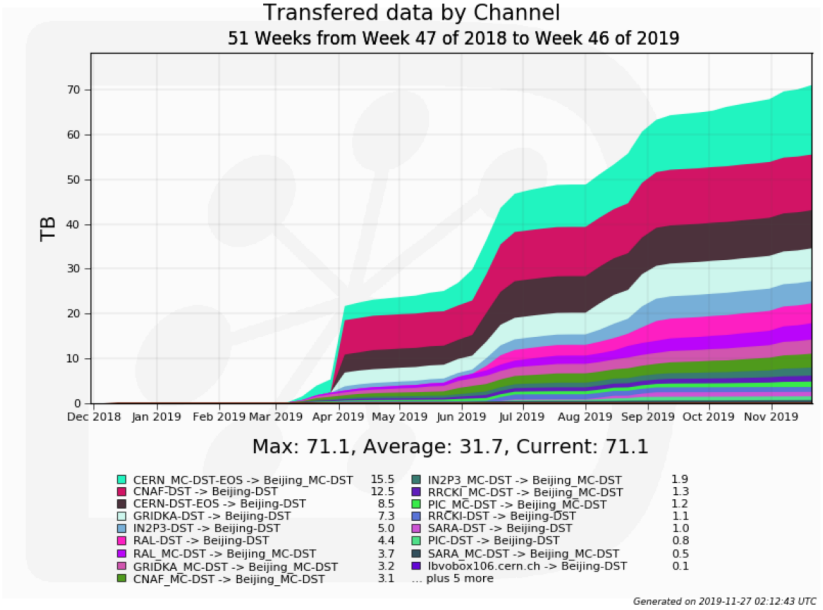
- Over 25σ significance for CPV due to S-P interference, first observation
- Sign-flip due to phase change and helicity angle change
- First observation of large CPV in decays with tensor



LHCb Tier2

- LHCb Tier2 set up late last year with 1008 CPU cores and 360 TB storage
- In the past year, 497K jobs running on site
- Data exchange with ~40 sites over the world
- In coming 71.1 TB and out going 1.53 PB
- Many thanks for IHEP computing center and CAS excellence in particle physics for supporting





Conclusion

- **Many interesting results from LHCb-China group on spectroscopy and CPV studies**
- **Many thanks for the supports from CAS excellence in particle physics**

Thank you for your attention