Conventional spectroscopy at LHCb

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2022/10/20

On behalf of the LHCb collaboration

Implications of LHCb measurements and future prospects 2022

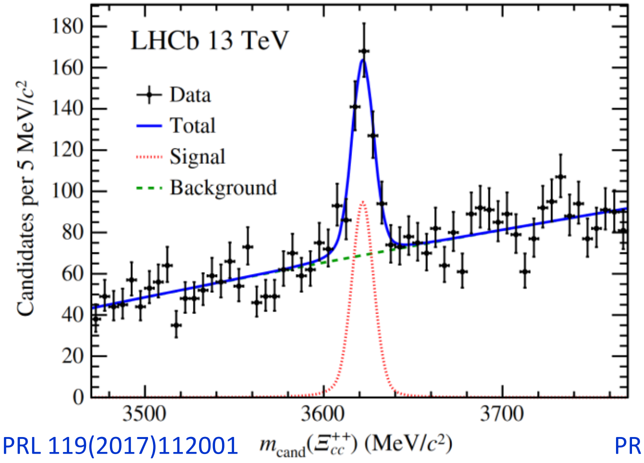
19-21 Oct 2022, CERN

Introduction

- Study of conventional doubly heavy baryons
  - Observation of $\Xi_{cc}^{++} \to \Xi_c'^{+}\pi^+$ JHEP05(2022)038
  - Search for Ξ_{bc}^{+} in $J/\psi\Xi_c^+$ arXiv: 2204.09541
- Study of amplitude structures of charm hadron decays
  - $D_s^+ \to \pi^+\pi^-\pi^+$ arXiv: 2208.03300
  - $D^+ \to \pi^+\pi^-\pi^+$ arXiv: 2209.09840
  - $\Lambda_c^+ \to pK^-\pi^+$ arXiv: 2208.03262, accepted by PRD

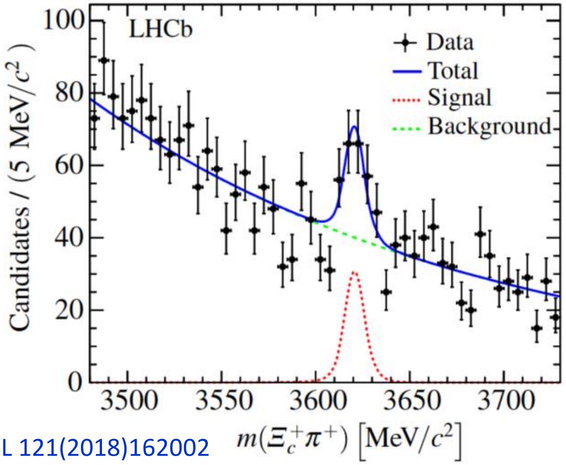
Conventional doubly heavy baryons @ LHCb

Observation of Ξ_{cc}^{++}



PRL 119(2017)112001

New decay: $\Xi_{cc}^{++} \to \Xi_c^+ \pi^+$



PRL 121(2018)162002

Ξ_{cc}^{++} Property measurement

JHEP 02(2020)049

$$m = 3621.55 \pm 0.23 \pm 0.30 \text{ MeV}$$

PRL 121(2018)052002

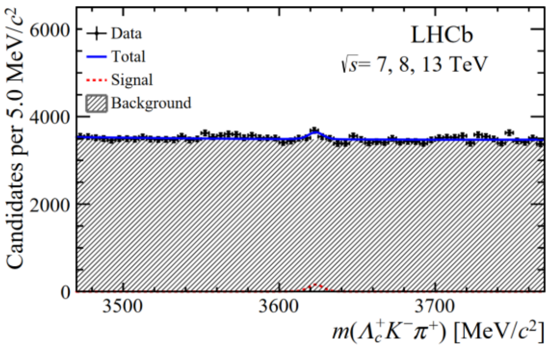
$$\tau = 0.256_{-0.022}^{+0.024} \pm 0.014 \text{ ps}$$

Chin.Phys.C 44(2022)022001

$$\frac{\sigma_{\Xi_{cc}^{++}} B(\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+)}{\sigma_{\Lambda_c^+}} = (2.22 \pm 0.27 \pm 0.29) \times 10^{-4}$$

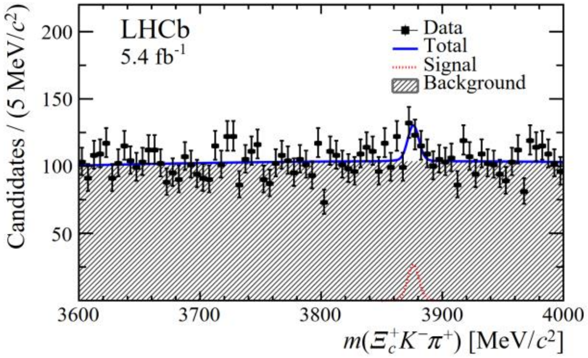
Search for other doubly-heavy baryons, for example:

$\Xi_{cc}^{+} \to \Lambda_c^+ K^- \pi^+$



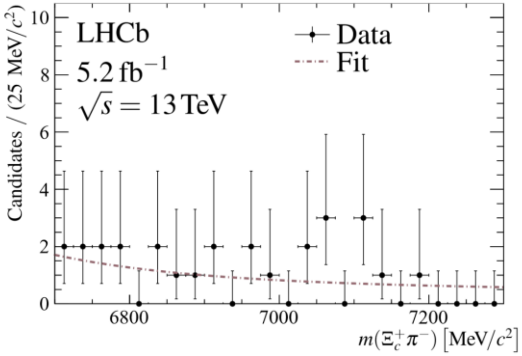
Sci. China-Phys. Mech. Astron. 63(2020)221062
(LHCb-PAPER-2019-029, Supplementary)

$\Omega_{cc}^{+} \to \Xi_c^+ K^- \pi^+$



Sci. China-Phys. Mech. Astron. 64(2021)101062

$\Xi_{bc}^{0} / \Omega_{bc}^{0} \to \Xi_c^+ \pi^-$

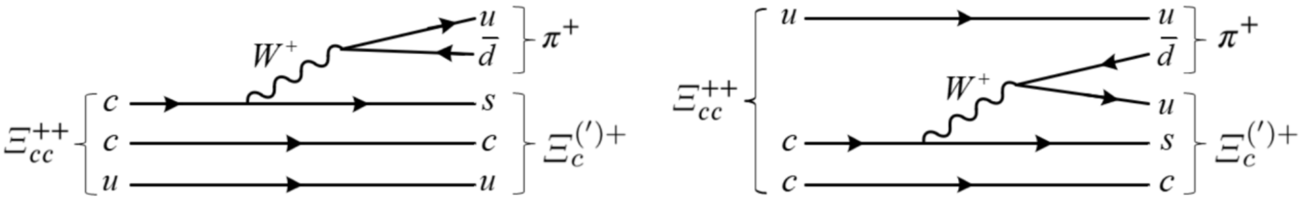


Chin.Phys.C 45(2021)093002

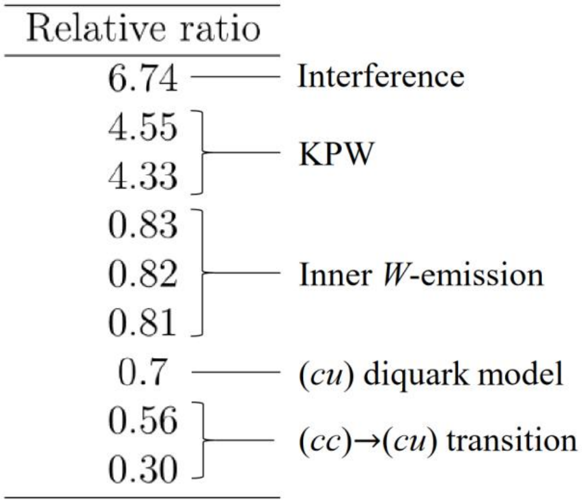
JHEP05(2022)038

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

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



PRD 96(2017)113006, PRD 100(2019)037015, Chin.Phys.C 45(2021)053105, PRD 101(2020)034034, PRD 96(2017)054013, PRD 100(2019)114037, PRD 99(2019)056013, Phys.Part.Nucl. 51(2020)678



Relative ratio	
6.74	Interference
4.55	KPW
4.33	
0.83	Inner W-emission
0.82	
0.81	
0.7	(cu) diquark model
0.56	$(cc)\to(cu)$ transition
0.30	

- $\left[\frac{B(\Xi_{cc}^{++}\to\Xi_c^{\prime +}\pi^+)}{B(\Xi_{cc}^{++}\to\Xi_c^{+}\pi^+)}\right]_{\text{predict}}$ vary between $\mathbf{0.3 \sim 7}$

- Search for $\Xi_{cc}^{++} \to \Xi_c^{\prime +}\pi^+$ and measure branching fraction
  - $\Xi_c^{\prime +} \to \Xi_c^{+}\gamma$, partial Rec. signal in $m(\Xi_c^{+}\pi^+)$
  - **Similar efficiency & comparable production as $\Xi_{cc}^{++} \to \Xi_c^{+}\pi^+$**

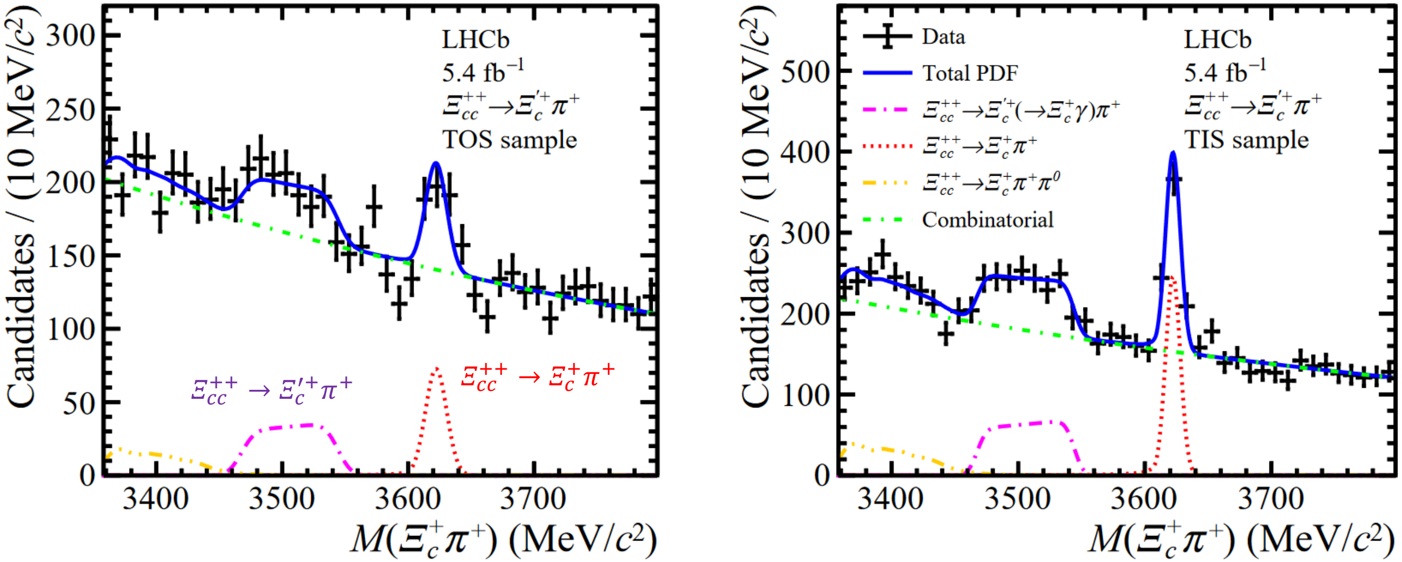
Observed using $\sim 1/3$ of Run2 data

  - **Full Run2 data available now, a promising search**

JHEP05(2022)038

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

- 2016-2018 data, $\mathcal{L}\sim 5.4\ \mathrm{fb}^{-1}$. “Turbo” stream
  - Offline-like real-time rec.&sel. for events with good $\Xi_c^+ \to pK^-\pi^+$ candidate



Significance (stat.) $> 9\sigma$

1st observation of $\Xi_{cc}^{++} \to \Xi_c'^{+}\pi^+$

$$\frac{\mathcal{B}(\Xi_{cc}^{++} \to \Xi_c'^{+}\pi^+)}{\mathcal{B}(\Xi_{cc}^{++} \to \Xi_c^{+}\pi^+)} = 1.41 \pm 0.17 \pm 0.10.$$

Inconsistent with any previous theoretical predictions
A useful input to improve future calculations

Example:

Using light-cone sum rules: Yu-ji Shi et.al., PRD 106(2022)034004
With updated spin-flavor structure of $[us]$ in Ξ_c^+: Hong-Wei Ke et.al., PRD 105(2022)096011

arXiv: 2204.09541

Search for $\Xi_{bc}^{+} \rightarrow J/\psi \Xi_{c}^{+}$

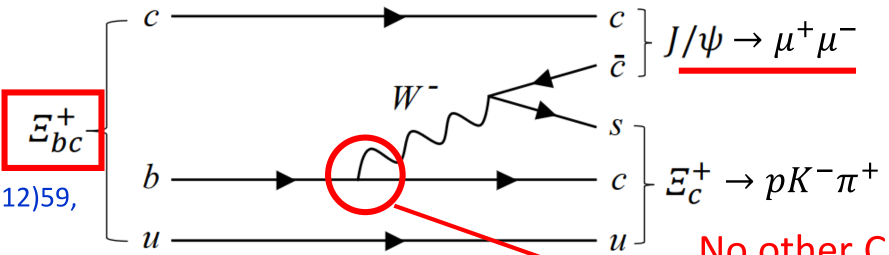
Study of $\Xi_{bc}^{+} \to J/\psi \Xi_{c}^{+}$

- Advantages of $\Xi_{bc}^{+} \to J/\psi \Xi_{c}^{+}$

$\tau(\Xi_{bc}^{+}) > \tau(\Xi_{bc}^{0}, \Omega_{bc}^{0})$
More efficient prompt-bkg subtraction

Phys.Usp.45(2022)455, Nul.Phys.A 895(2012)59, EPCJ 16(2000)461, PRD 98(2018)113004, PRD 99(2019)073006

“golden channel” for signal identification (online & offline)



No other Cabbibo suppression than V_{bc}.
Relatively large branching fraction

- Yield estimation: $B_{c}^{+} \to J/\psi D_{s}^{+}$ as normalization mode

$$\mathcal{R} = \frac{\sigma(\Xi_{bc}^{+}) \times \mathcal{B}(\Xi_{bc}^{+} \to J/\psi \Xi_{c}^{+}) \times \mathcal{B}(\Xi_{c}^{+} \to pK^{-}\pi^{+})}{\sigma(B_{c}^{+}) \times \mathcal{B}(B_{c}^{+} \to J/\psi D_{s}^{+}) \times \mathcal{B}(D_{s}^{+} \to K^{+}K^{-}\pi^{+})} \sim 0.015 \qquad \varepsilon_{\text{sig}}/\varepsilon_{\text{norm}} \sim 1$$

PRD 83(2011)034026,
EPJC 38(2004)267
Chin.Phys.Lett. 27(2010)061302

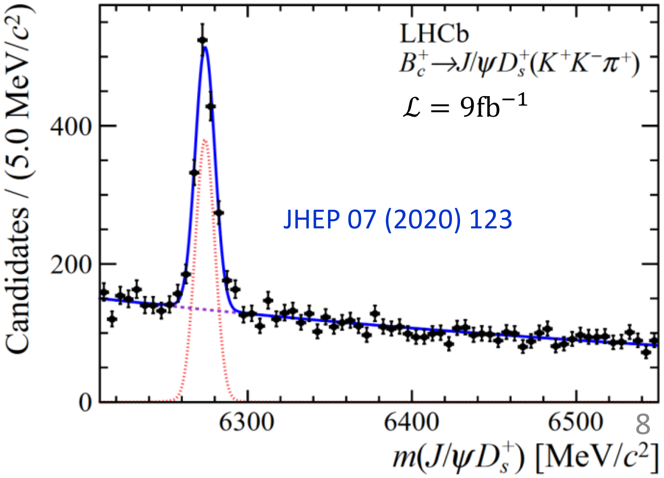
$\sim \frac{1}{3}$ (color suppression)

From PDG

$N_{\text{rec\&sel}}(B_{c}^{+} \to J/\psi D_{s}^{+}) \sim 1000$ in Run1-2 dataset

Expect $N_{\text{rec\&sel}}(\Xi_{bc}^{+} \to J/\psi \Xi_{c}^{+}) \sim 15$

A promising search, especially in high-mass region with low combinatorial background



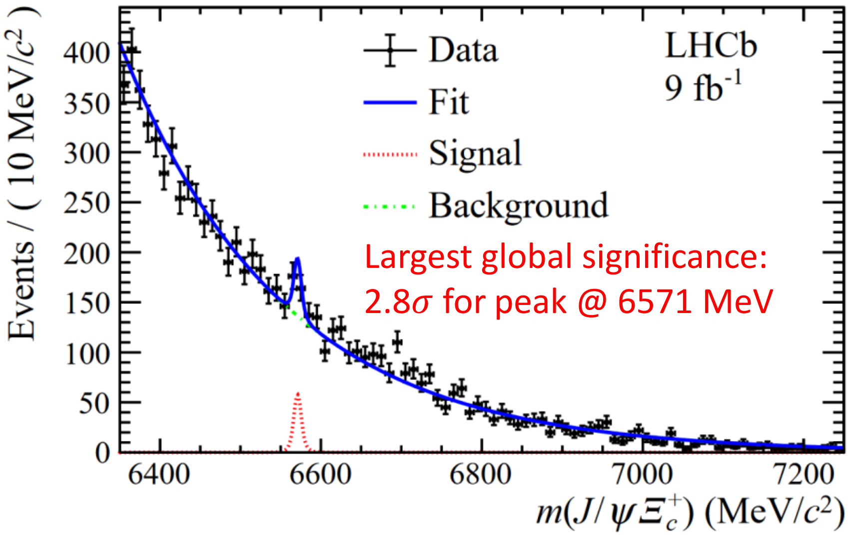
JHEP 07 (2020) 123

arXiv: 2204.09541

Search for $\Xi_{bc}^{+} \to J/\psi\Xi_{c}^{+}$

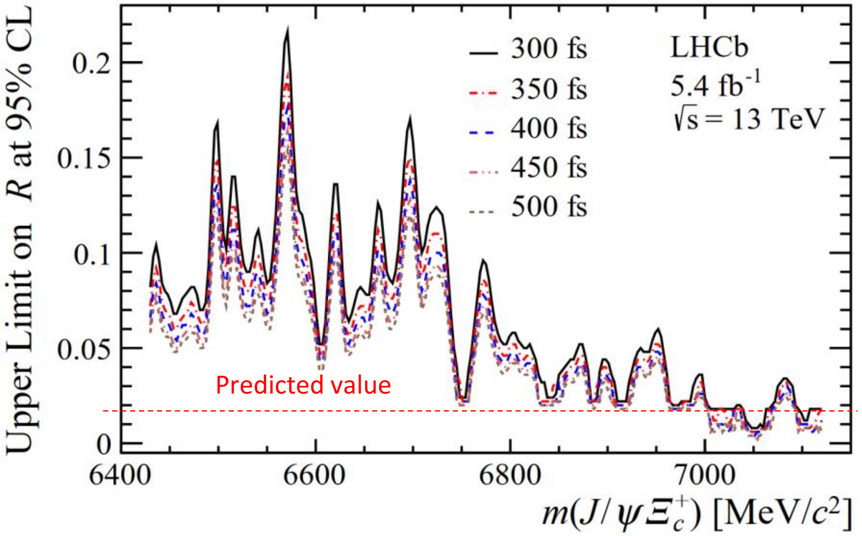
- Full dataset. Dimuon-based online + MVA-based offline selections

Hint of a bump in mass spectrum



Largest global significance: 2.8σ for peak @ 6571 MeV

Upper Limit(UL) of R assigned as $f(m,\tau)$



Predicted value

- Upper limit assigned cannot exclude any mass regions
  - Stay tuned with upcoming Run3 dataset

Amplitude analysis of three-body c decays

LHC: good charm factory
LHCb: good at reconstruction of charm decays

→

Investigate charm-decay amplitudes with competitive precisions

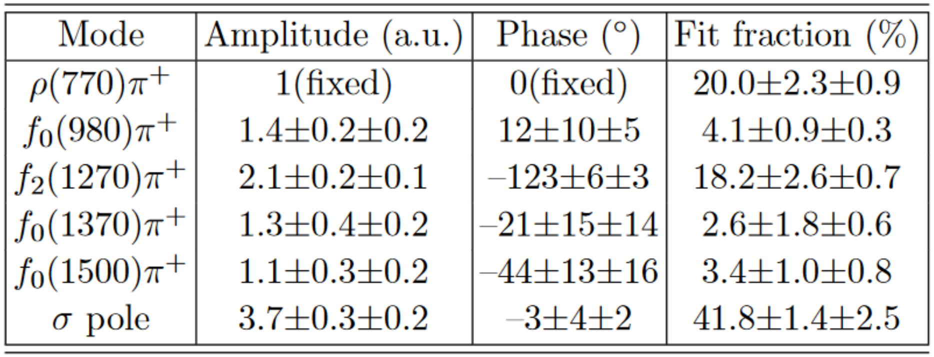
arXiv:2208.03300, arXiv:2209.09840

$$D^+(D_s^+) \to \pi^-\pi^+\pi^+$$

Previous knowledge of amplitudes

- $D^+ \to \pi^+\pi^-\pi^+$ (most recent):

Phys.RD 76 (2007) 012001, CLEO experiment



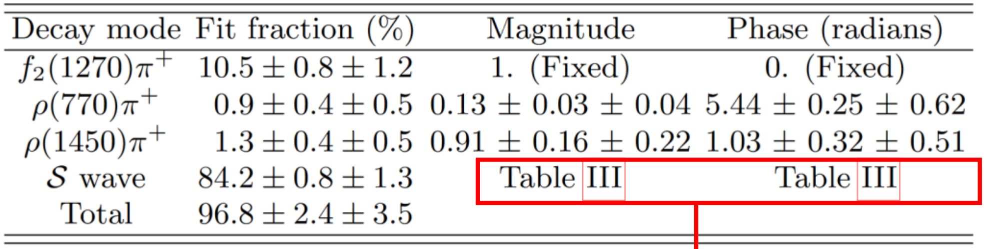
Mode	Amplitude (a.u.)	Phase (°)	Fit fraction (%)
$\rho(770)\pi^+$	1(fixed)	0(fixed)	20.0±2.3±0.9
$f_0(980)\pi^+$	1.4±0.2±0.2	12±10±5	4.1±0.9±0.3
$f_2(1270)\pi^+$	2.1±0.2±0.1	−123±6±3	18.2±2.6±0.7
$f_0(1370)\pi^+$	1.3±0.4±0.2	−21±15±14	2.6±1.8±0.6
$f_0(1500)\pi^+$	1.1±0.3±0.2	−44±13±16	3.4±1.0±0.8
σ pole	3.7±0.3±0.2	−3±4±2	41.8±1.4±2.5

Isobar-model Dalitz-plot analysis

$\sim\mathbf{3k}$ $D^+ \to \pi^+\pi^-\pi^+$ signals

- $D_s^+ \to \pi^+\pi^-\pi^+$(most recent):

arXiv: 2108.10050, submitted in 2021 by BESIII collaboration



Decay mode	Fit fraction (%)	Magnitude	Phase (radians)
$f_2(1270)\pi^+$	$10.5 \pm 0.8 \pm 1.2$	1. (Fixed)	0. (Fixed)
$\rho(770)\pi^+$	$0.9 \pm 0.4 \pm 0.5$	$0.13 \pm 0.03 \pm 0.04$	$5.44 \pm 0.25 \pm 0.62$
$\rho(1450)\pi^+$	$1.3 \pm 0.4 \pm 0.5$	$0.91 \pm 0.16 \pm 0.22$	$1.03 \pm 0.32 \pm 0.51$
$\mathcal{S}$ wave	$84.2 \pm 0.8 \pm 1.3$	Table III	Table III
Total	$96.8 \pm 2.4 \pm 3.5$		

Quasi-model-independent amplitude. Details in arXiv: 2108.10050

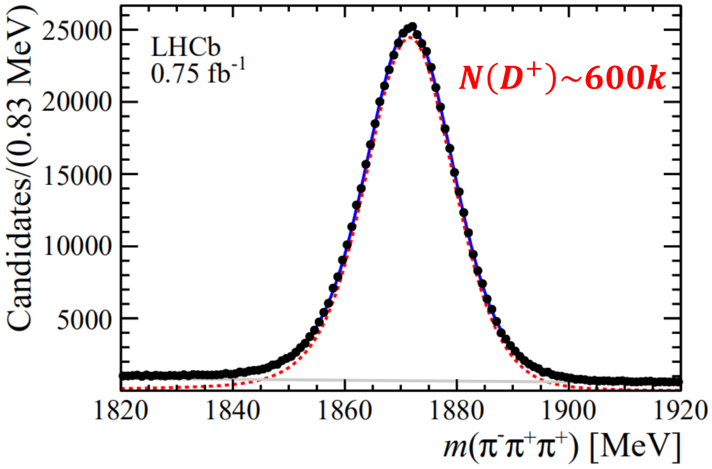
Isobar-model + Quasi-Model-independent amplitude for Dalitz-plot analysis

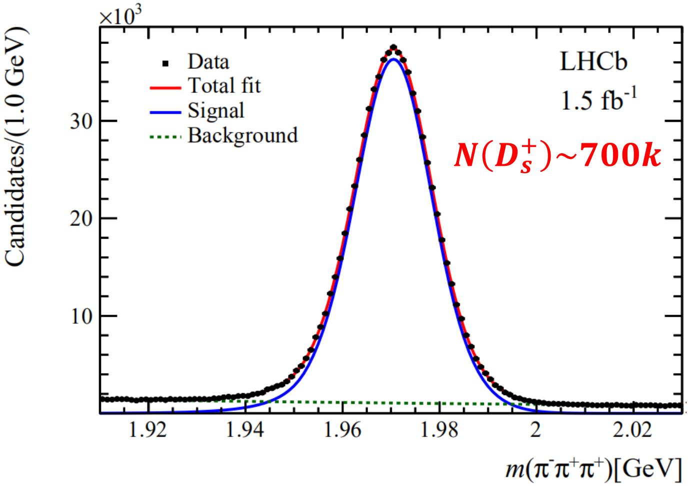
$\sim\mathbf{14k}$ $D_s^+ \to \pi^+\pi^-\pi^+$ signals

arXiv:2208.03300, arXiv:2209.09840

Amplitude analysis of $D^+(D_s^+) \to \pi^-\pi^+\pi^+$

- 2012 data, $\mathcal{L} = 1.5\ \mathrm{fb}^{-1}$. Promptly produced D mesons





  - **Competitive statistical power**

- Methodology for amplitude construction
  - **S-wave**: Quasi-Model Independent approach (**QMIPWA**)

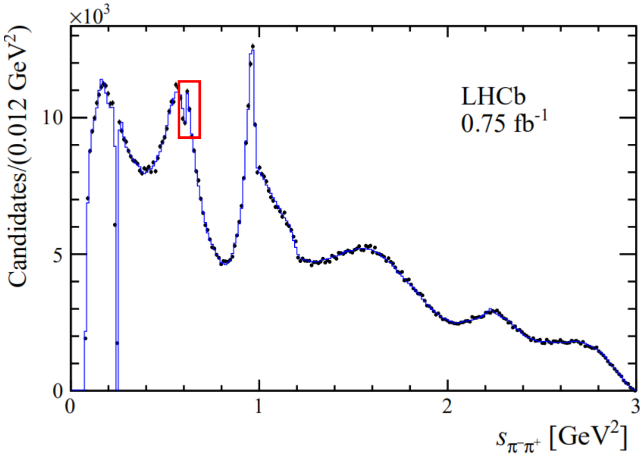
$$\mathcal{A}_S(s_{12}, s_{13}) = \mathcal{A}_S(s_{12}) + \mathcal{A}_S(s_{13}) \qquad \underline{\mathcal{A}_S^k(s_{\pi^+\pi^-}) = c_k e^{i\phi_k}}$$

    - c_k, ϕ_k: Generic functions determined by fit to data
  - **Isobar model for spin-1, spin-2 components**

arXiv:2208.03300, arXiv:2209.09840

Amplitude analysis of $D^+(D_s^+) \to \pi^-\pi^+\pi^+$

- $D^+ \to \pi^-\pi^+\pi^+$

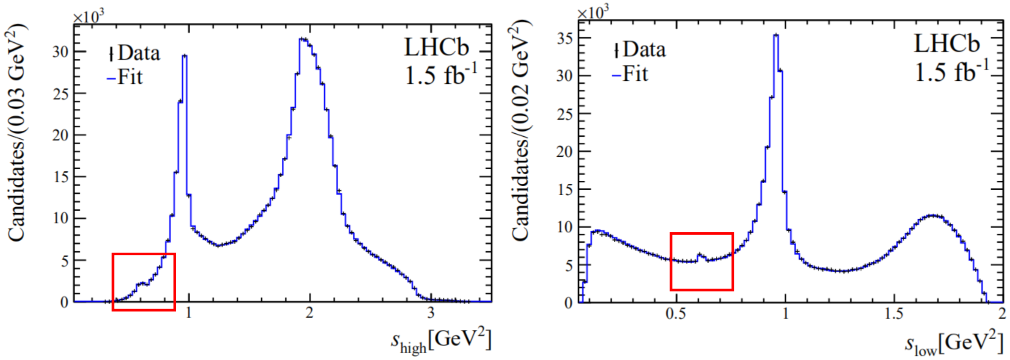


Component	Magnitude	Phase [°]	Fit fraction [%]
$\rho(770)^0\pi^+$	1 [fixed]	0 [fixed]	$26.0 \pm 0.3 \pm 1.6 \pm 0.3$
$\omega(782)\pi^+$	$(1.68 \pm 0.06 \pm 0.15 \pm 0.02) \times 10^{-2}$	$-103.3 \pm 2.1 \pm 2.6 \pm 0.4$	$0.103 \pm 0.008 \pm 0.014 \pm 0.002$
$\rho(1450)^0\pi^+$	$2.66 \pm 0.07 \pm 0.24 \pm 0.22$	$47.0 \pm 1.5 \pm 5.5 \pm 4.1$	$5.4 \pm 0.4 \pm 1.3 \pm 0.8$
$\rho(1700)^0\pi^+$	$7.41 \pm 0.18 \pm 0.47 \pm 0.71$	$-\ 65.7 \pm 1.5 \pm 3.8 \pm 4.6$	$5.7 \pm 0.5 \pm 1.0 \pm 1.0$
$f_2(1270)\pi^+$	$2.16 \pm 0.02 \pm 0.10 \pm 0.02$	$-100.9 \pm 0.7 \pm 2.0 \pm 0.4$	$13.8 \pm 0.2 \pm 0.4 \pm 0.2$
S-wave			$61.8 \pm 0.5 \pm 0.6 \pm 0.5$
$\sum_i \mathrm{FF}_i$			112.8
χ^2/ndof (range)	[1.47 - 1.78]		$-2\log\mathcal{L} = 805622$

Dominated by S-wave, followed by $\rho(770)^0\pi^+$ and $f_2(1270)^0\pi^+$

Contribution from $(\omega(782) \to \pi^+\pi^-)\pi^+$ observed for the first time

- $D_s^+ \to \pi^-\pi^+\pi^+$



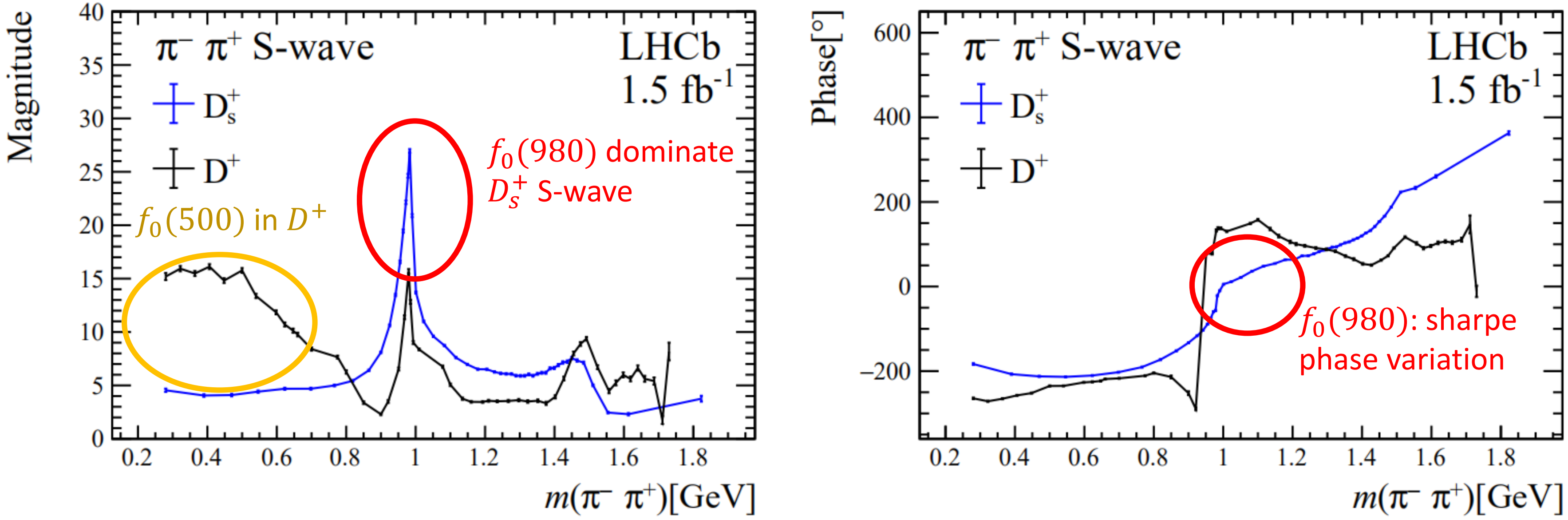
Resonance	Magnitude	Phase [°]	Fit fraction (FF) [%]
S-wave			84.97 ± 0.14
$\rho(770)^0$	0.1201 ± 0.0030	79.4 ± 1.8	1.038 ± 0.054
$\omega(782)$	0.04001 ± 0.00090	-109.9 ± 1.7	0.360 ± 0.016
$\rho(1450)^0$	1.277 ± 0.026	-115.2 ± 2.6	3.86 ± 0.15
$\rho(1700)^0$	0.873 ± 0.061	-60.9 ± 6.1	0.365 ± 0.050
combined	–	–	6.14 ± 0.27
$f_2(1270)$	1 (fixed)	0 (fixed)	13.69 ± 0.14
$f_2'(1525)$	0.1098 ± 0.0069	178.1 ± 4.2	0.0455 ± 0.0070
sum of fit fractions			104.3
χ^2/ndof (range)	$[1.45 - 1.57]$		

Dominated by S-wave, followed by spin-2 resonances

Contribution from $(\omega(782) \to \pi^+\pi^-)\pi^+$observed for the first time

arXiv:2208.03300, arXiv:2209.09840

Comparison of S-wave amplitudes



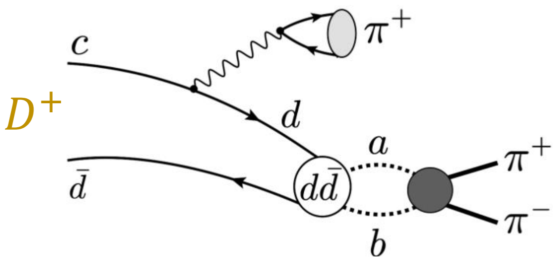
$f_0(500)$ in D^+

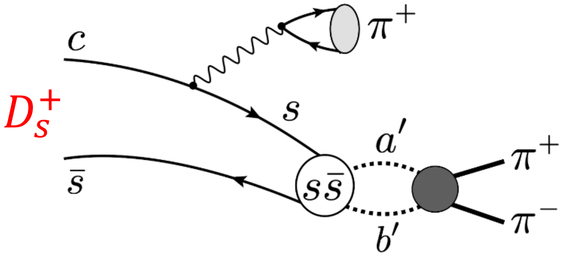
$f_0(980)$ dominate D_s^+ S-wave

$f_0(980)$: sharpe phase variation

unitary chiral model, Int. J. Mod. Phys. **25**(2016)1630001

- Potential interpretation of the difference:





$$\sum_i d\bar{q}_i q_i \bar{d} = \underline{\pi^+\pi^- + \tfrac{1}{2}\pi^0\pi^0} - \tfrac{2}{\sqrt{6}}\pi^0\eta + K^0\overline{K}^0 + \tfrac{1}{3}\eta\eta$$

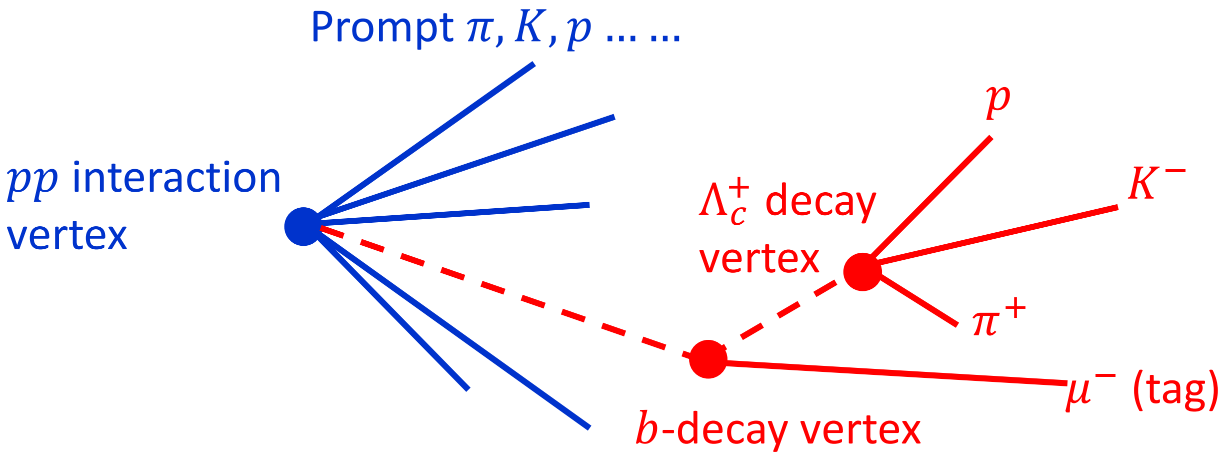
$$\sum_i s\bar{q}_i q_i \bar{s} = \underline{K^+K^- + K^0\overline{K}^0} + \tfrac{1}{3}\eta\eta$$

Indicating $f_0(500)$ as dynamical pole of $\pi\pi \to \pi\pi$ rescattering ?

$f_0(980)$ strongly couples to KK channel

arXiv:2208.03262, accepted by PRD

$$\Lambda_b^0 \to (\Lambda_c^+ \to pK^-\pi^+)\mu^-\bar{\nu}_\nu X$$



Prompt π, K, p … …

pp interaction vertex

Λ_c^+ decay vertex

p

K^-

π^+

μ^- (tag)

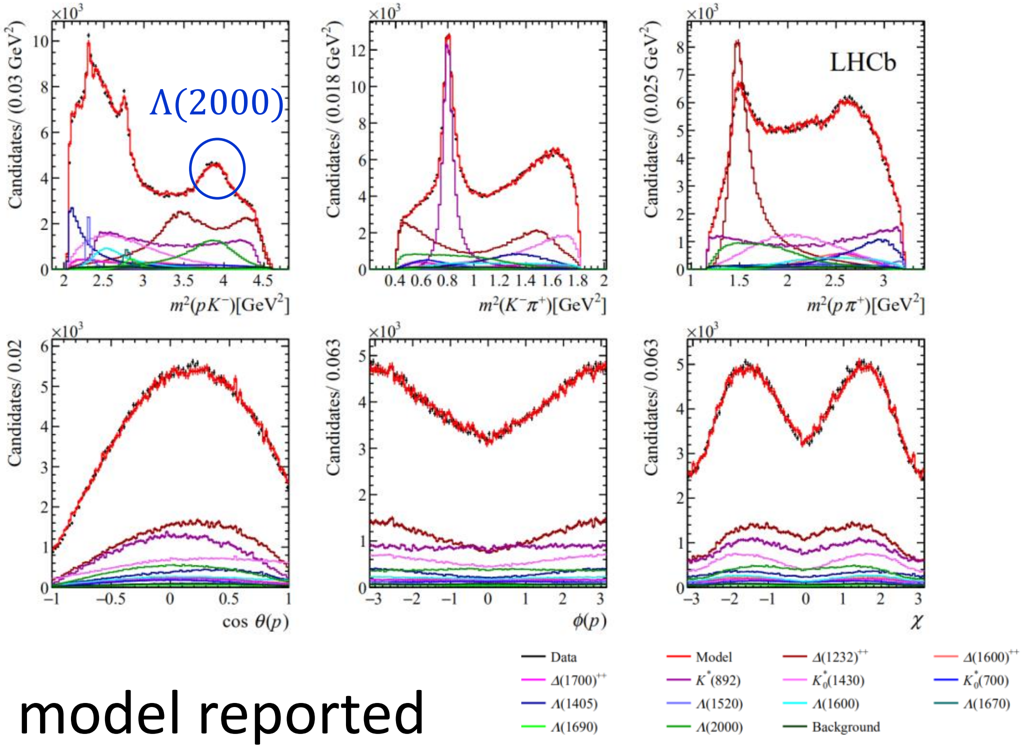
b-decay vertex

arXiv:2208.03262, accepted by PRD

$\Lambda_c^+ \to pK^-\pi^+$ amplitude analysis

- 2016 data, $\mathcal{L} = 0.5\text{fb}^{-1}$; $\sim$400k signals; helicity-based Am.An.

Resonance	J^P	Mass (MeV)	Width (MeV)
$\Lambda(1405)$	$1/2^-$	1405.1	50.5
$\Lambda(1520)$	$3/2^-$	1515 – 1523	10 – 20
$\Lambda(1600)$	$1/2^+$	1630	250
$\Lambda(1670)$	$1/2^-$	1670	30
$\Lambda(1690)$	$3/2^-$	1690	70
$\Lambda(2000)$	$1/2^-$	1900 – 2100	20 – 400
$\Delta(1232)^{++}$	$3/2^+$	1232	117
$\Delta(1600)^{++}$	$3/2^+$	1640	300
$\Delta(1700)^{++}$	$3/2^-$	1690	380
$K_0^*(700)$	0^+	824	478
$K^*(892)$	1^-	895.5	47.3
$K_0^*(1430)$	0^+	1375	190



- All parameters of amplitude model reported
- Mass and width of $\Lambda(2000)$ determined

$$m = 1988 \pm 2 \pm 21\,\text{MeV} \qquad \Gamma = 179 \pm 4 \pm 16\,\text{MeV}$$

arXiv:2208.03262, accepted by PRD

Λ_c^+ Polarization measurement

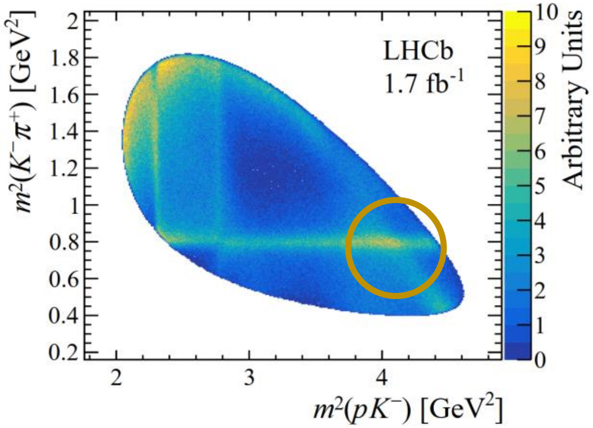
$$\underline{p(\Omega,\boldsymbol{P})} = \frac{1}{\mathcal{N}}\sum_{m_p=\pm1/2}\Big\{(1+\boxed{P_z})|\mathcal{A}_{1/2,m_p}(\Omega)|^2 + (1-\boxed{P_z})|\mathcal{A}_{-1/2,m_p}(\Omega)|^2 + 2\mathrm{Re}\Big[(\boxed{P_x}-\boxed{iP_y})\mathcal{A}^*_{1/2,m_p}(\Omega)\mathcal{A}_{-1/2,m_p}(\Omega)\Big]\Big\},$$

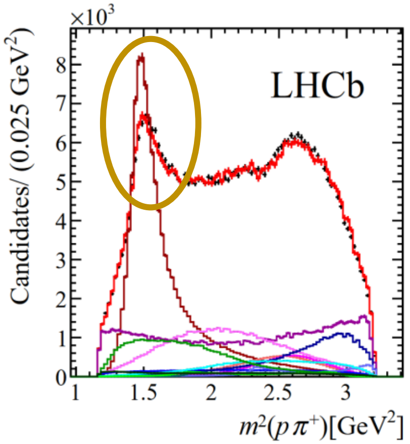
Final-state kinematics

Initial spin structure of Λ_c^+

- Large interference improves sensitivity to initial polarization

Advances in High Energy Physics (2020) 7463073





Large interference between $\Delta(1232)^{++}$ and $K^*(892)$

Λ_c^+ polarization from semileptonic b-decays measured, with 2 different definitions of initial spin axis

Model dependency contributes to the **largest syst.** uncertainty (second term)

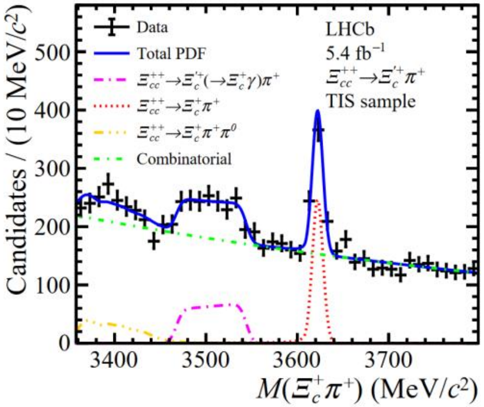
Component	Value (%)
P_x (lab)	$60.32 \pm 0.68 \pm 0.98 \pm 0.21$
P_y (lab)	$-0.41 \pm 0.61 \pm 0.16 \pm 0.07$
P_z (lab)	$-24.7 \pm 0.6 \pm 0.3 \pm 1.1$
P_x $(\tilde{B})$	$21.65 \pm 0.68 \pm 0.36 \pm 0.15$
P_y $(\tilde{B})$	$1.08 \pm 0.61 \pm 0.09 \pm 0.08$
P_z $(\tilde{B})$	$-66.5 \pm 0.6 \pm 1.1 \pm 0.1$

Summary & prospects

Summary

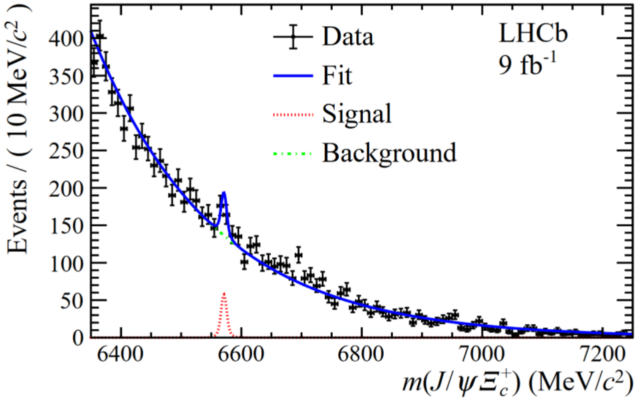
- Many new results about conventional spectroscopy @ LHCb

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



JHEP05(2022)038

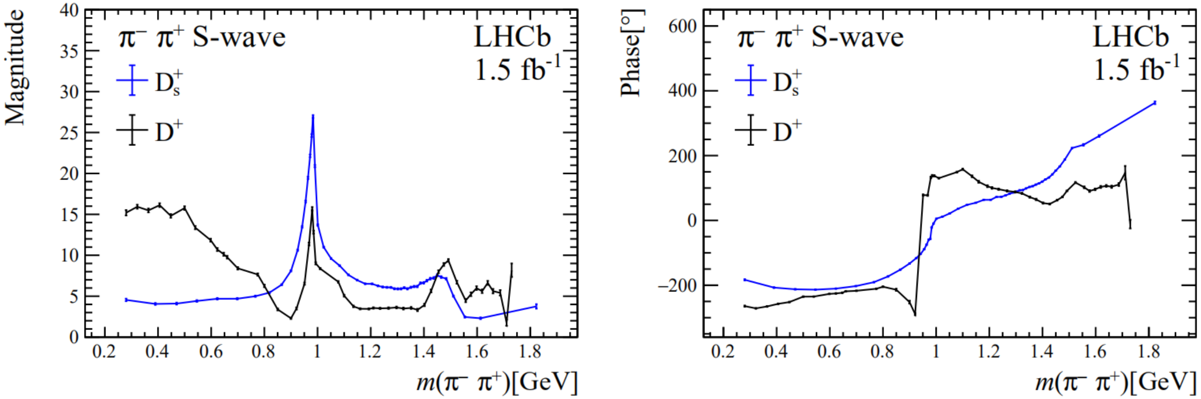
Search for $\Xi_{bc}^{+} \to J/\psi\Xi_c^{+}$



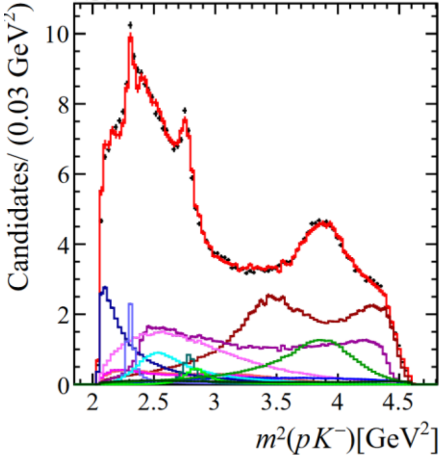
arXiv: 2204.09541

Amplitude analysis of $D^{+} \to \pi^{+}\pi^{-}\pi^{+}, D_s^{+} \to \pi^{+}\pi^{-}\pi^{+}, \Lambda_c^{+} \to pK^{-}\pi^{+}$

arXiv:2208.03300, arXiv:2209.09840



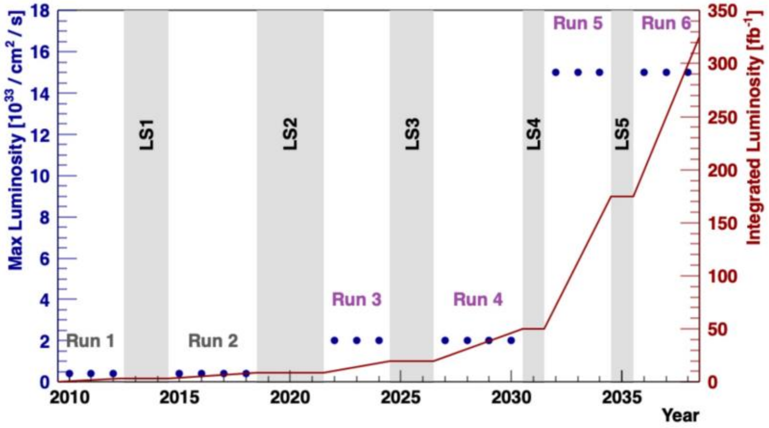
arXiv:2208.03262



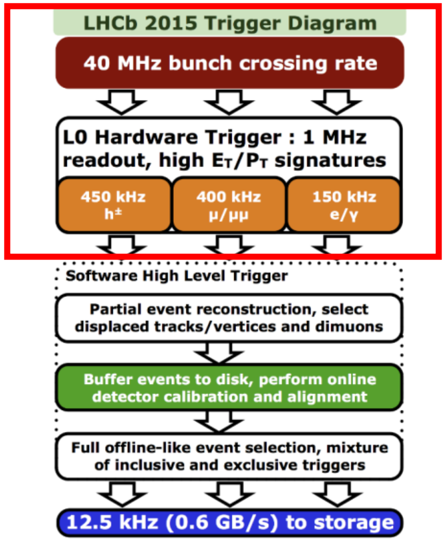
Doubly-heavy hadron study in Run3

New opportunities

Significantly improved integrated luminosity



Fully software-based trigger system



LHCb 2015 Trigger Diagram

40 MHz bunch crossing rate

L0 Hardware Trigger : 1 MHz readout, high E_T/P_T signatures

450 kHz **$h^{\pm}$**	**400 kHz** **$\mu/\mu\mu$**	**150 kHz** **e/γ**

Software High Level Trigger

Partial event reconstruction, select displaced tracks/vertices and dimuons

Buffer events to disk, perform online detector calibration and alignment

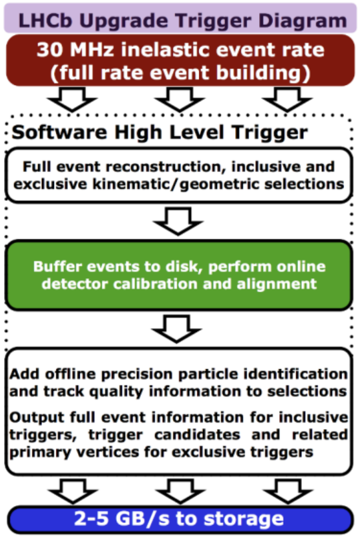
Full offline-like event selection, mixture of inclusive and exclusive triggers

12.5 kHz (0.6 GB/s) to storage

~50% efficiency lost for fully hadronic modes at hardware trigger

Remove hardware trigger

Increased output rate to storage



LHCb Upgrade Trigger Diagram

30 MHz inelastic event rate (full rate event building)

Software High Level Trigger

Full event reconstruction, inclusive and exclusive kinematic/geometric selections

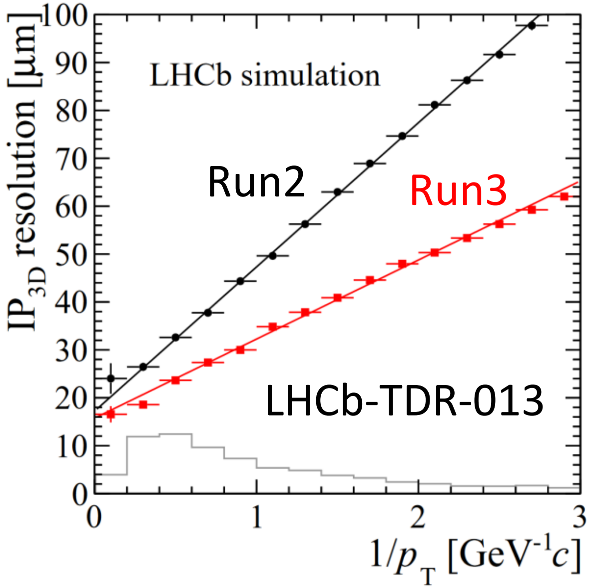
Buffer events to disk, perform online detector calibration and alignment

Add offline precision particle identification and track quality information to selections

Output full event information for inclusive triggers, trigger candidates and related primary vertices for exclusive triggers

2-5 GB/s to storage

Improved performance of subdetectors



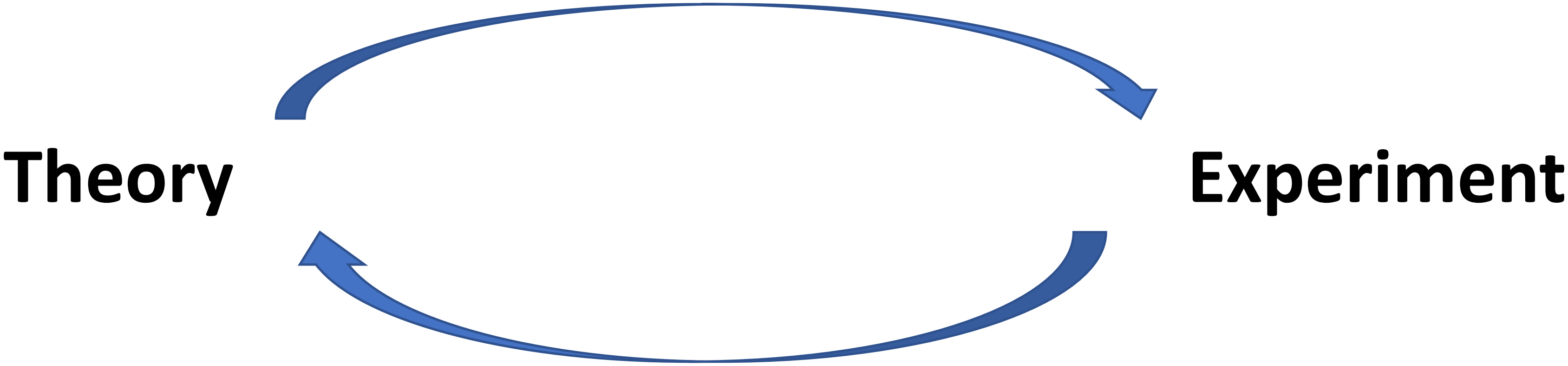
Example:
Better vertex resolution in Run3 Velo
Better separation between prompt background & b, c decay signals

Boost Ξ_{cc}^{+} selection power to that of Ξ_{cc}^{++} at Run2 ?
More efficient bc-baryon Rec.&Sel. ?

Need good collaboration with theory friends

Predictions of mass, lifetime, branching fractions…

Important inputs to help organize the resources of computing, storage & human power



Theory

Experiment

Keep searching for new states/decay modes and measure their properties

Validate theoretical predictions & provide new inputs for calculations

The future of $\Lambda_c^+ \to pK^-\pi^+$

Studies using Λ_c^+ polarization

- Currently already a good precision, further improvement possible

$$P_z\left(\tilde{B}\right) = -66.5 \pm 0.6 \pm \boxed{1.1} \pm 0.1$$

arXiv:2208.03262, accepted by PRD

Due to model dependency

  - Further improve using quasi-model-independent amplitude ?
    - Feasibility established in $D, D_s^+ \to \pi^+\pi^-\pi^+$ analysis
    - Used also for several other on-going b, c decay Dalitz analyses

- What we can learn from Λ_c^+ polarization ?
  - Study the **spin structure of $\boldsymbol{b \to cl\nu}$** ?
  - An on-going study: **$\boldsymbol{\Lambda_c^+}$ EDM/MDM measurement** by quantifying Λ_c^+ **spin-precession** in **strong EM field**

Sensitive tag to New Physics

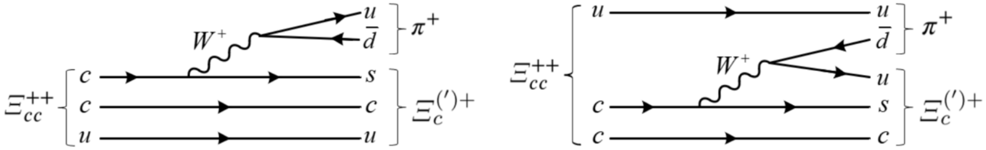
Effectively provided by bent crystal

Impact the Λ_c^+ polarization

    - A recent workshop about this topic: [link]

Thank you for your attention !
Any questions or comments ?

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

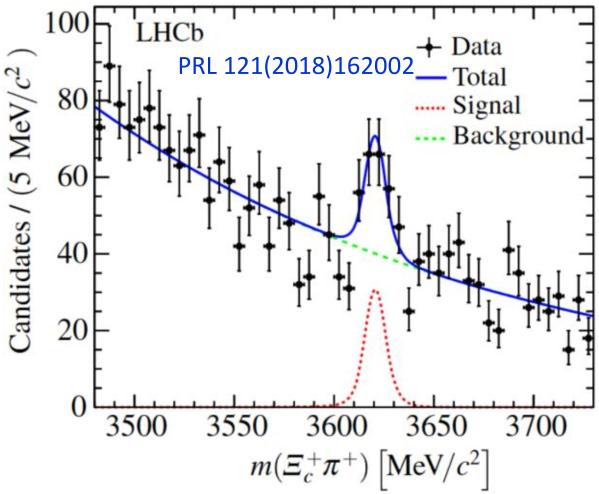


$\Xi_{cc}^{++} \to \Xi_c'^{+}(\to \Xi_c^{+}\gamma)\pi^+$ VS. $\Xi_{cc}^{++} \to \Xi_c^{+}\pi^+$

PRD 96(2017)113006, PRD 100(2019)037015, Chin.Phys.C 45(2021)053105, PRD 101(2020)034034, PRD 96(2017)054013, PRD 100(2019)114037, PRD 99(2019)056013, Phys.Part.Nucl. 51(2020)678

- $\left[\frac{B(\Xi_{cc}^{++}\to\Xi_c'^{+}\pi^+)}{B(\Xi_{cc}^{++}\to\Xi_c^{+}\pi^+)}\right]_{\mathrm{predict}}$ vary between $\mathbf{0.3 \sim 7}$

Significant $\Xi_{cc}^{++} \to \Xi_c^{+}\pi^+$ peak, 2016 data



PRL 121(2018)162002

$\Xi_{cc}^{++} \to \Xi_c'^{+}(\to \Xi_c^{+}\gamma)\pi^+$ V.S. $\Xi_{cc}^{++} \to \Xi_c^{+}\pi^+$

- Partially reconstructed $\Xi_c^+\pi^+$ final state
  - Similar efficiency
- Comparable production yield
- Full Run2 data available ($\mathcal{L} \times \mathbf{3}$)

Promising to study partially reconstructed $\Xi_{cc}^{++} \to \Xi_c'^{+}\pi^+$ signals in $m(\Xi_c^+\pi^+)$ spectrum !