Recent results on hadron spectroscopy from LHCb

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On behalf of the LHCb Collaboration

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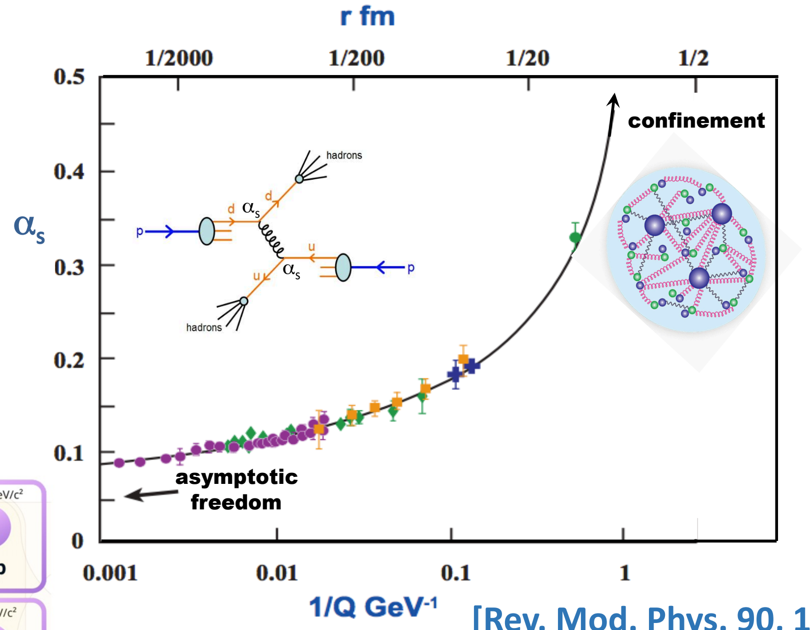
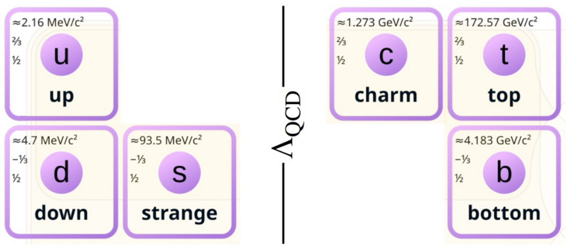
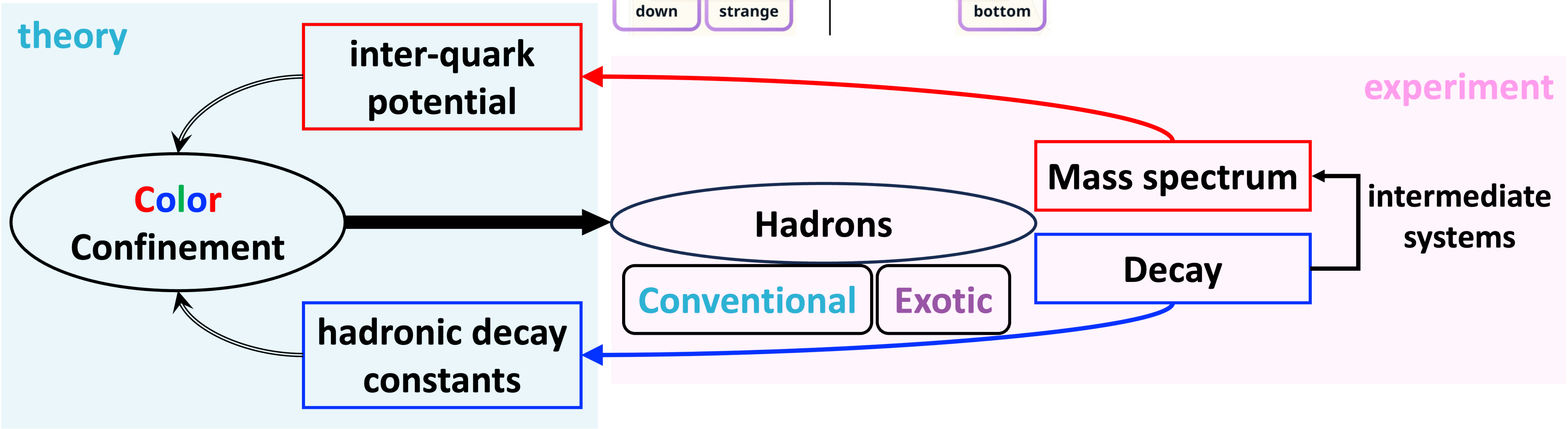
QCD and hadron spectroscopy

- ***QCD dilemma***: understanding the non-perturbative property of QCD at low-energy scale
  - ✓There are no rigorous, first-principle treatments except ***Lattice QCD***, whose application is yet limited
- ***Color confinement***: no analytic proof exists



[Rev. Mod. Phys. 90, 15003 (2018)]





LHCb experiment @ LHC

➢The LHCb experiment is one of the four large experiments at the ***LHC***, dedicated to ***heavy flavor physics***

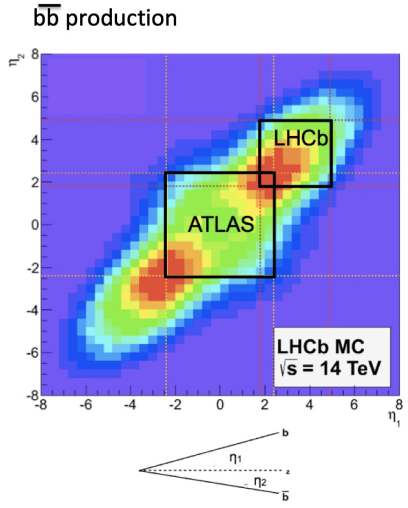
□ ***Largest production cross-sections*** of b- and c-hadrons

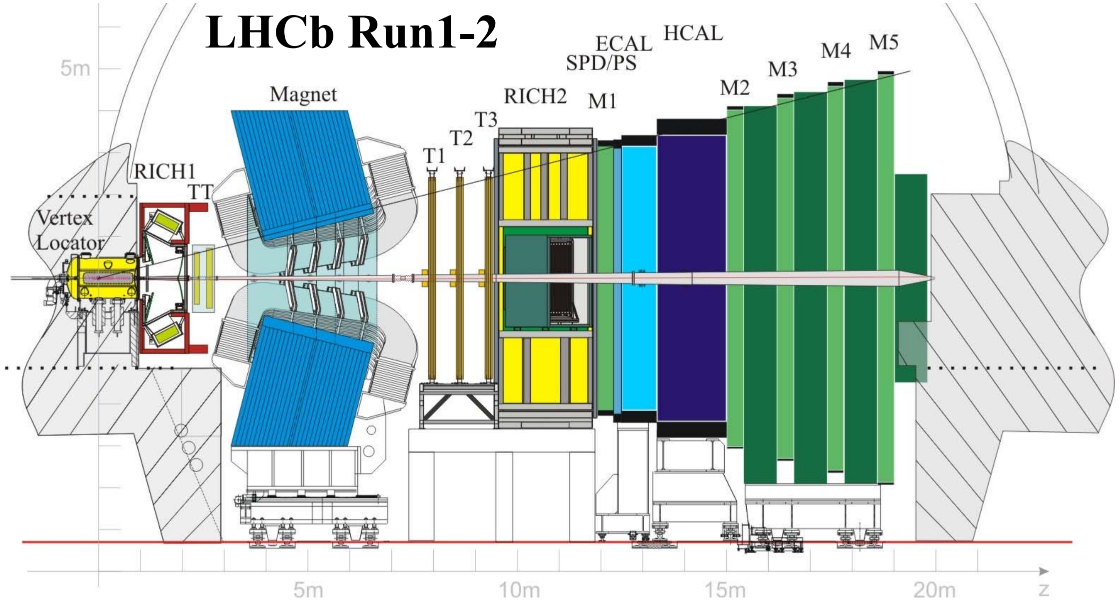
✓ $\sigma(b\bar{b}) \approx 500\ \mu b$ @ 13 TeV & $\sigma(c\bar{c}) \approx 20 \times \sigma(b\bar{b})$

◆A ***single-arm forward spectrometer*** in $2 < \eta < 5$ to effectively cover the dominant kinematic region of heavy quark production

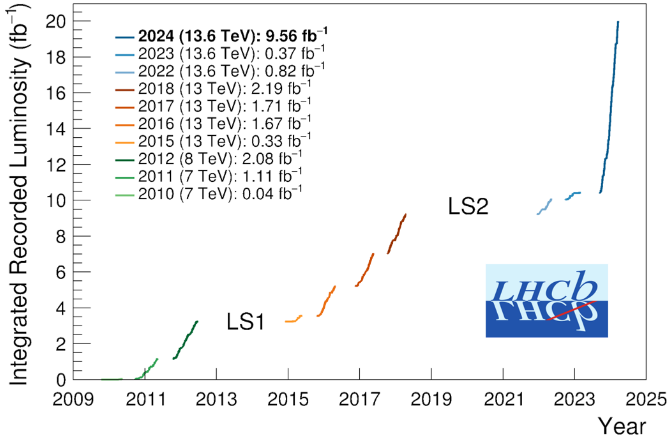
□ ***Huge background*** contamination

◆Excellent ***vertexing***, ***tracking*** and ***particle identification (PID)*** performance allowing for effective detection and background suppression



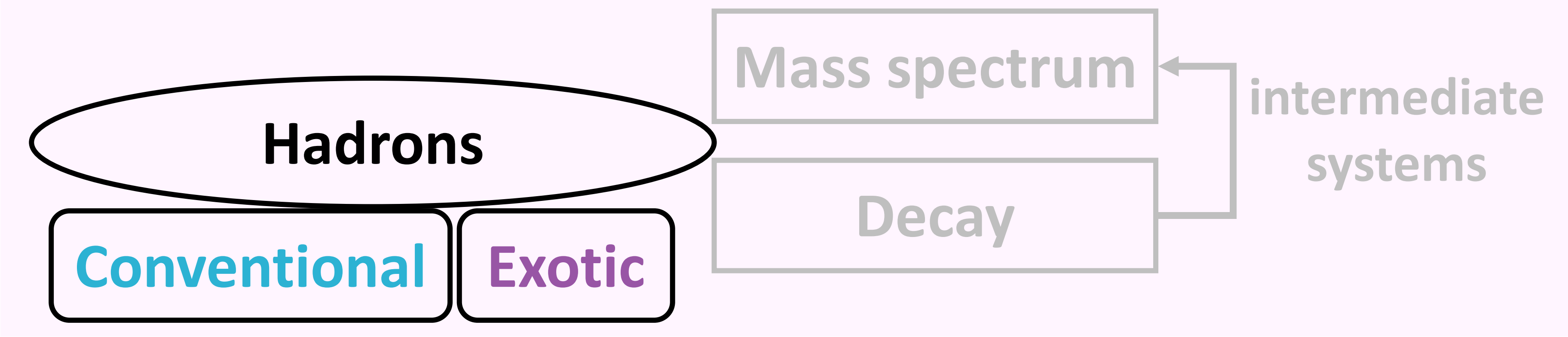


$\mathcal{L}_{\text{int}} = 9\ \text{fb}^{-1}$ @ Run1-2

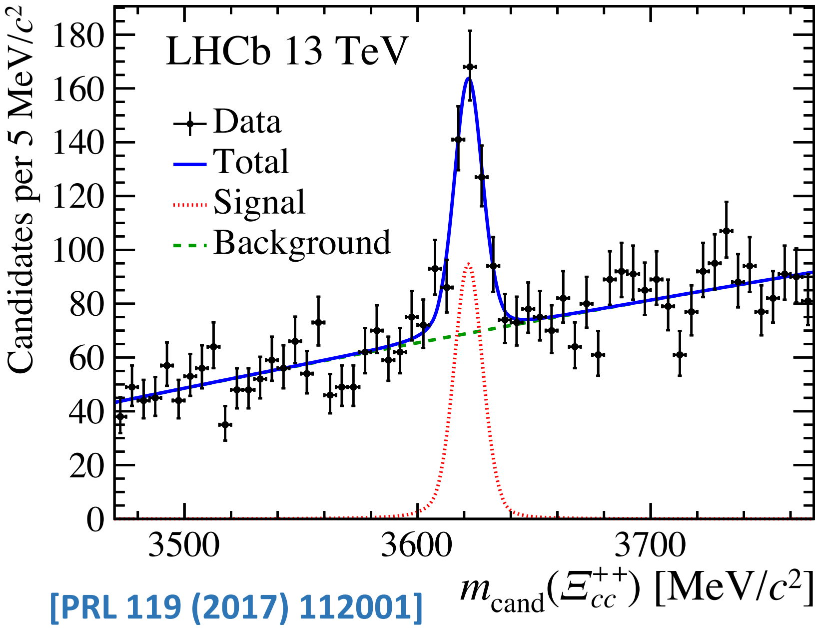


[JINST 3 (2008) S08005]
[IJMPA 30:07 (2015) 1530022]

Hadron spectroscopy study

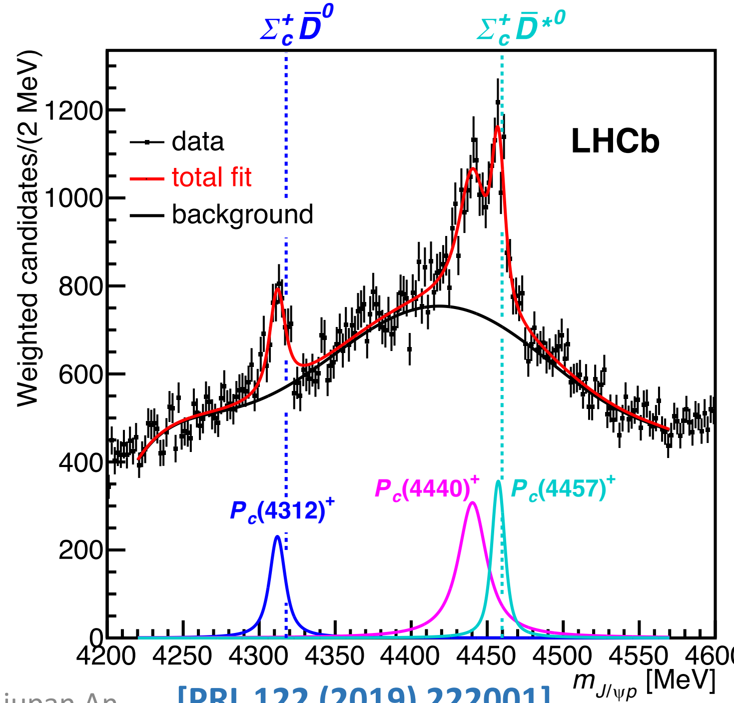


Observation of Ξ_{cc}^{++}



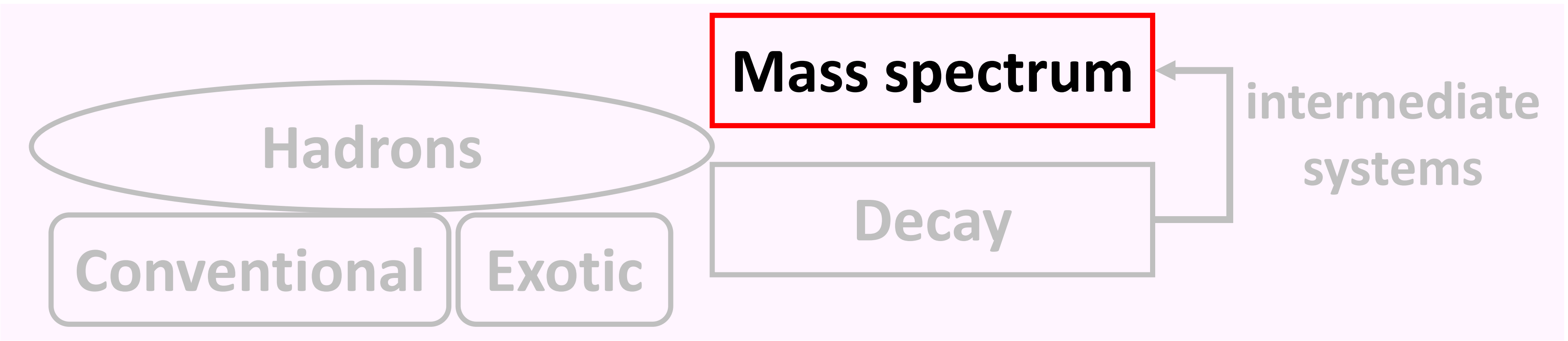
[PRL 119 (2017) 112001]

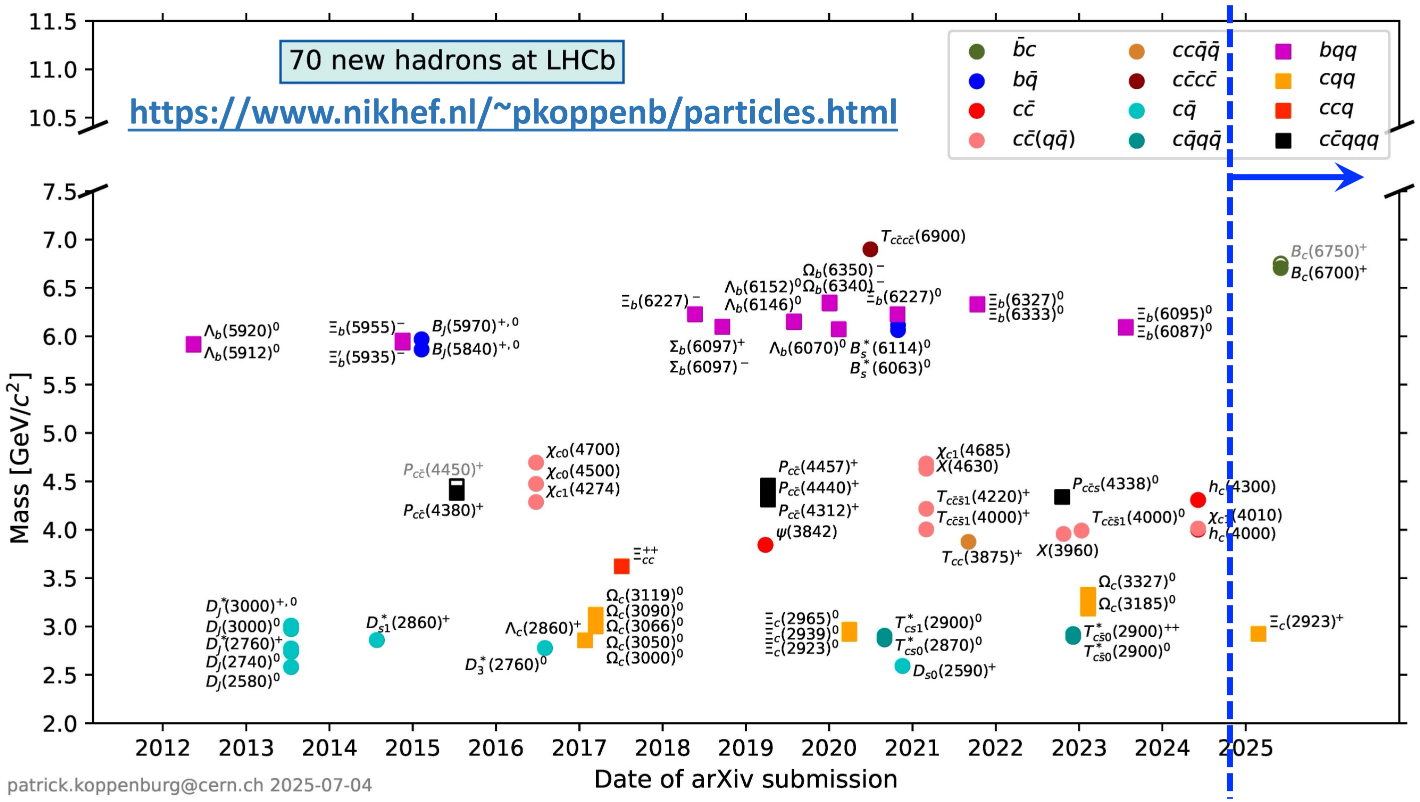
Observation of $P_{c\bar{c}}^{+}$



[PRL 122 (2019) 222001]

Hadron spectroscopy study

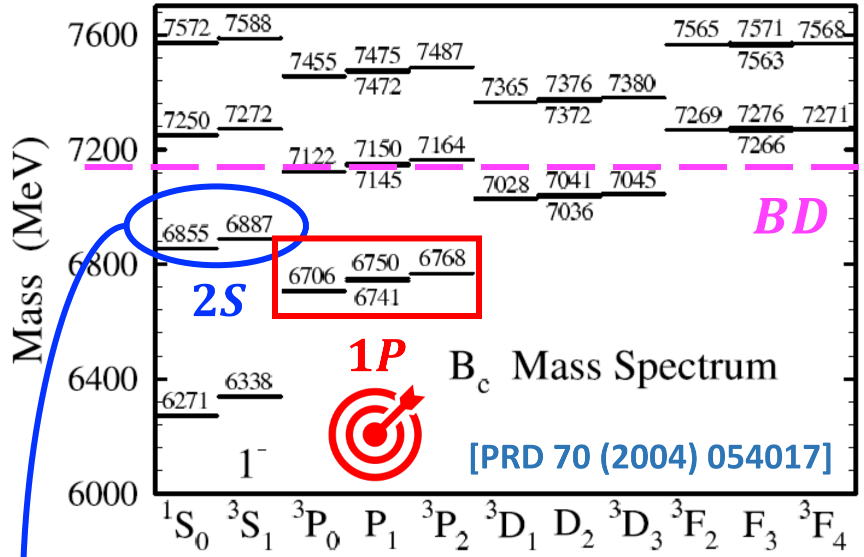




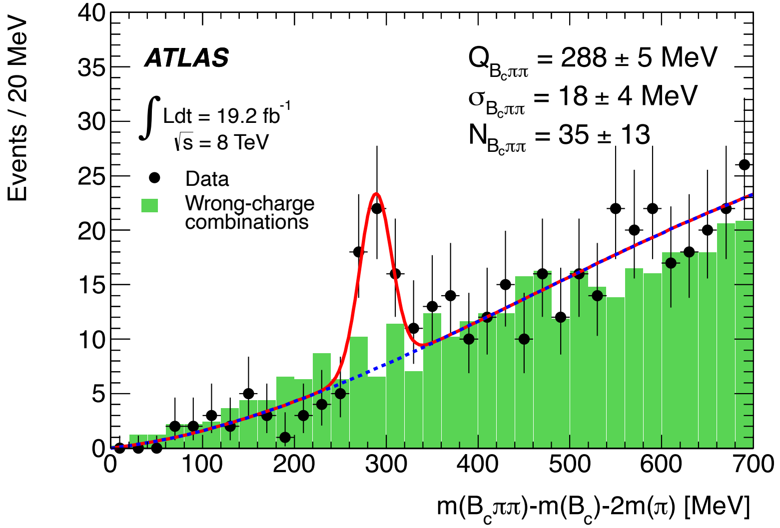
- ➢ Observation of $B_c(1P)^+ \to B_c^+\gamma$
- ➢ Observation of $\Xi_c^{**+} \to \Xi_c^+\pi^+\pi^-$

B_c spectroscopy

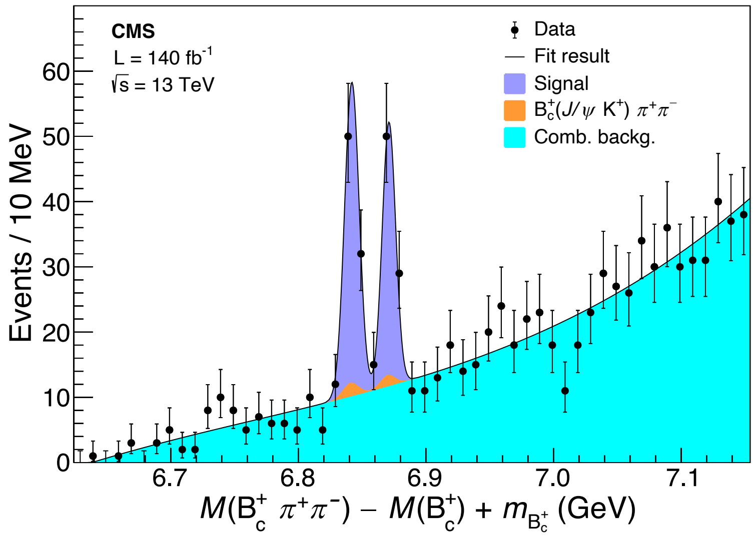
- B_c meson is a **unique and ideal tool to study QCD**
  → the only meson consisting of heavy quarks of different flavors
  → intermediate of the charmonium and bottomonium systems
- Experimental results on B_c spectroscopy are limited
  → **production challenging** compared to quarkonium systems
- Excited B_c^+ states below BD threshold can only undergo radiative or pionic transitions to the ground state B_c^+ $\Rightarrow$ $\mathbf{\Gamma \sim \mathcal{O}(100\ keV)}$



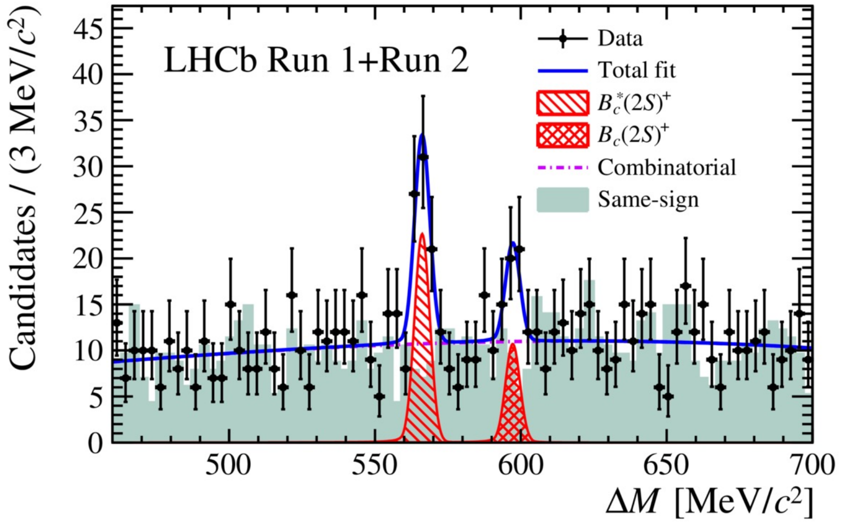
[PRL 113 (2014) 12004]



[PRL 122 (2019) 132001]



[PRL 122 (2019) 232001]



$B_c(1P)^+$ states

Liupan An
Yuhao Wang

$B_c(1P)^+$ states	Decay mode	B. F. prediction (%)
1^3P_0	$B_c^{*+}(\to B_c^+\gamma)\gamma$	100
$1P_1$	$B_c^+\gamma$	17.8
	$B_c^{*+}(\to B_c^+\gamma)\gamma$	82.2
$1P_1'$	$B_c^+\gamma$	87.9
	$B_c^{*+}(\to B_c^+\gamma)\gamma$	12.1
1^3P_2	$B_c^{*+}(\to B_c^+\gamma)\gamma$	100

[PRD 70 (2004) 054017]

	δM	$M(1^3P_0)$	$M(1P_1)$	$M(1P_1')$	$M(1^3P_2)$	θ [°]
Lattice QCD	41	6727	6743	6765	6783	33.4
GKLT	64	6683	6717	6729	6743	17.1
GJ	61	6689	6738	6757	6773	25.6
FUII	55	6701	6737	6760	6772	28.5
EFG	62	6699	6734	6749	6762	20.4
GI	67	6706	6741	6750	6768	22.4
EQ	54	6693	6731	6739	6759	18.7
LLLLGZ	55	6714	6757	6776	6787	35.5
WWLC	55	6705	6739	6748	6762	32.2
LTFWP	53	6712	6770	6761	6783	−24.3
LLWL	67	6701	6745	6754	6773	35.2
HZ	63	6707	6751	6786	6802	55.0

→ $B_c^+\gamma$: peak in $B_c^+\gamma$ mass spectrum

→ $B_c^{*+}(\to B_c^+\cancel{\gamma})\gamma$: peak in $B_c^+\gamma$ mass spectrum but shifted downwards by $\delta M = M(B_c^{*+}) - M(B_c^+)$

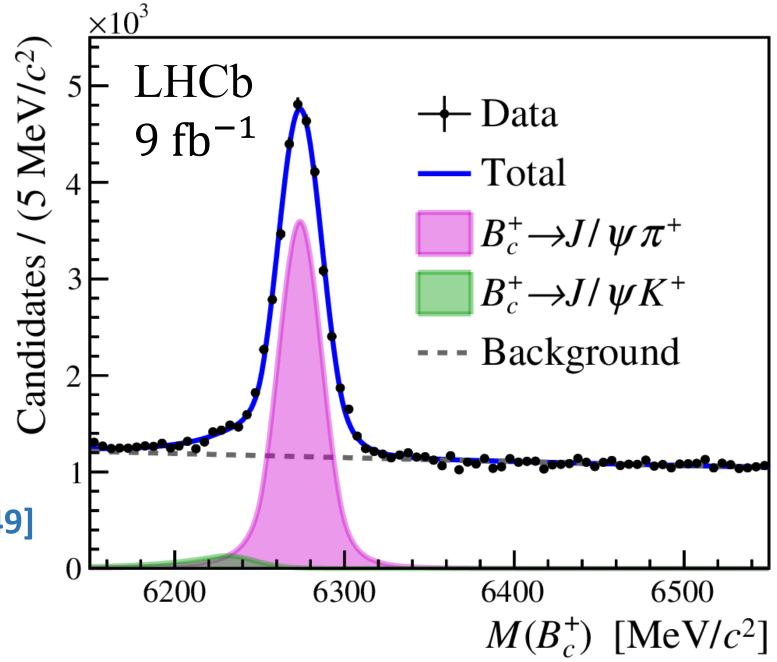
four $B_c(1P)^+$ states → six peaks in $B_c^+\gamma$

- $B_c(1P)^+$ states are searched for in $B_c^+\gamma$ mass spectrum in $340 < M(B_c^+\gamma)_{\rm rec} - M(B_c^+) < 520$ MeV

Study of $B_c^+\gamma$ mass spectrum

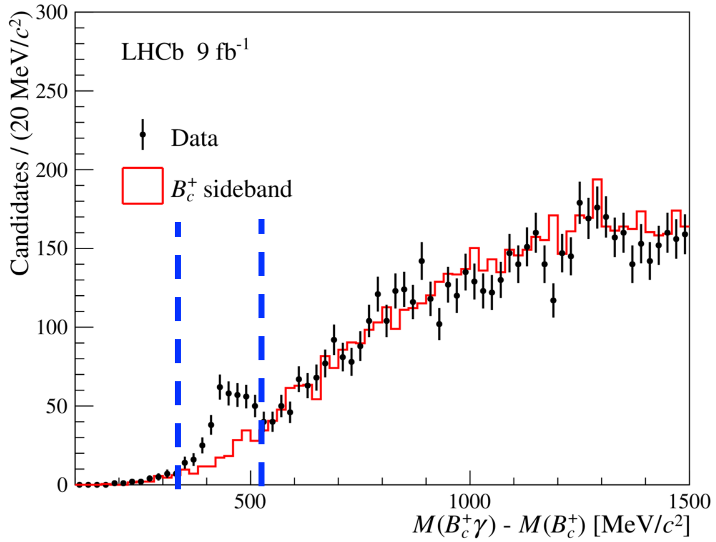
Liupan An
Yuhao Wang

- **Dataset:** Run1 & 2 data at LHCb corresponding to 9 fb^{-1}
- **Decay chain:** $B_c(1P)^+ \to B_c^+\gamma, B_c^+ \to J/\psi\pi^+, J/\psi \to \mu^+\mu^-$ (charge conjugation implied)
- **Candidate reconstruction and selection – photons reconstructed from calo clusters are used**
  - ✓ BDT classifier on B_c^+ to maximize the B_c^+ signal significance
  - ✓ Cut-based selections on $B_c(1P)^+$ to maximize Punzi figure-of-merit $\to$ $E_{\mathrm{T}}(\gamma) > 1$ GeV, $E(\gamma) > 4$ GeV



[arXiv: 2507.02149] accepted by PRL

$N = (24.86 \pm 0.24)\times 10^3$



[arXiv: 2507.02142] accepted by PRD

✓ A **pronounced wide peaking structure** is evident within the predicted mass range for $B_c(1P)^+$

Observation of $B_c(1P)^+$ states

Liupan An
Yuhao Wang

➢ ***Photon energy correction*** is applied to the simulation to eliminate the mismatch to data

◆ Theory-independent fit

✓ The visible width is $\sim 37\ \mathrm{MeV}/c^2$

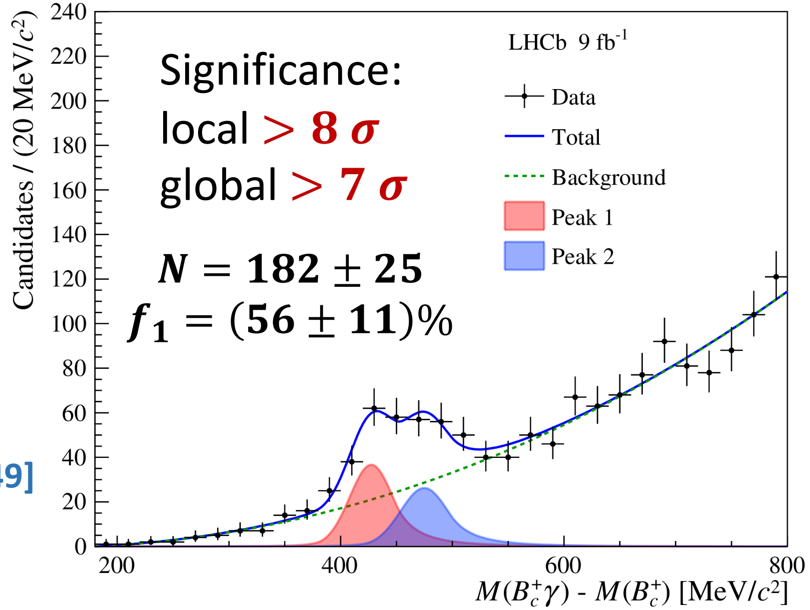
✓ Width of a single peak is $\sim 20\ \mathrm{MeV}/c^2$

⇒ a **minimal effective two-peak model**

$^*\Gamma(B_c(1P)^+) \sim \mathcal{O}(100\ \mathrm{keV})$ negligible

Significance:
local $> 8\,\sigma$
global $> 7\,\sigma$

$N = 182 \pm 25$
$f_1 = (56 \pm 11)\%$



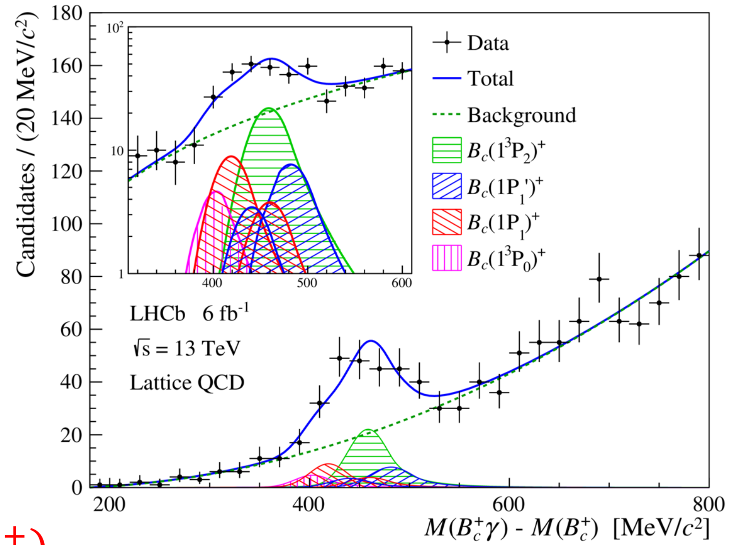
[arXiv: 2507.02149] accepted by PRL

$M_1 = 6704.8 \pm 5.5(\mathrm{stat.}) \pm 2.8(\mathrm{syst.}) \pm 0.3(B_c^+)\ \mathrm{MeV}/c^2$
$M_2 = 6752.4 \pm 9.5(\mathrm{stat.}) \pm 3.1(\mathrm{syst.}) \pm 0.3(B_c^+)\ \mathrm{MeV}/c^2$

◆ Theory-constrained fit

✓ masses and relative yields of six peaks fixed according to predictions

⇒ verification of various QCD models



[arXiv: 2507.02142] accepted by PRD

$$\frac{\sigma(B_c(1P)^+)}{\sigma(B_c^+)} = 0.20 \pm 0.03(\mathrm{stat.}) \pm 0.02(\mathrm{syst.}) \pm 0.03(\mathrm{theo.})$$

for $p_\mathrm{T}(B_c^+) < 20\ \mathrm{GeV}/c, 2.0 < y(B_c^+) < 4.5$ at $\sqrt{s} = 13\ \mathrm{TeV}$

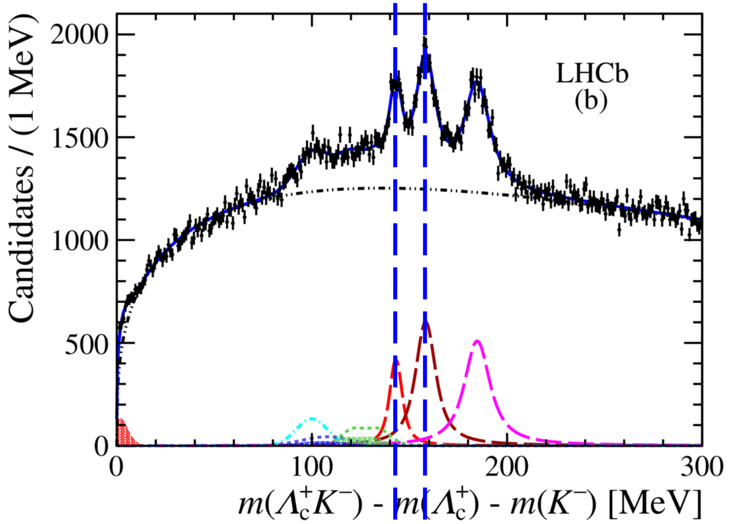
[Comput. Phys. Commun. 197 (2015) 335]

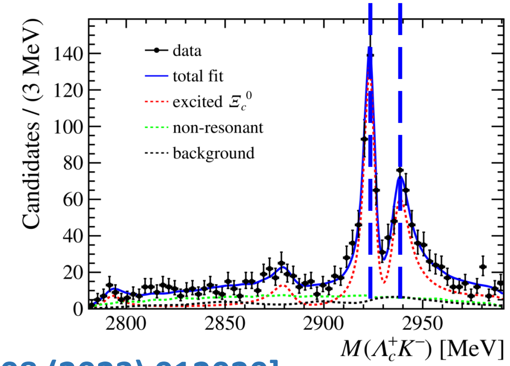
✓ consistent with BcVegPy calculations

$\Xi_c^{0,+}$ spectroscopy

- $\Xi_c^{0,+}$ baryons offer
  - a crucial testbed for ***Heavy Quark Effective Theory***
  - verification of ***diquark model*** with profound implications also for exotic hadrons

[PRL 124 (2020) 222001]





[PRD 108 (2023) 012020]

◆ $\Lambda_c^+K^-$ mass spectrum

Resonance	Mass [MeV]	Γ [MeV]
$\Xi_c(2923)^0$	$2923.04 \pm 0.25 \pm 0.20 \pm 0.14$	$7.1 \pm 0.8 \pm 1.8$
$\Xi_c(2939)^0$	$2938.55 \pm 0.21 \pm 0.17 \pm 0.14$	$10.2 \pm 0.8 \pm 1.1$
$\Xi_c(2965)^0$	$2964.88 \pm 0.26 \pm 0.14 \pm 0.14$	$14.1 \pm 0.9 \pm 1.3$

first observation

✓ $\Xi_c(2965)^0$ inconsistent with the known $\Xi_c(2970)^0$:

$$M = 2967.8^{+0.9}_{-0.7}\ \text{MeV}, \Gamma = 28.1^{+3.4}_{-4.0}\ \text{MeV}$$

◆ $\Lambda_c^+K^-$ in $B^- \to \Lambda_c^+\overline{\Lambda}_c^-K^-$

State	Mass (MeV)	Width (MeV)	Significance
$\Xi_c(2880)^0$	$2881.8 \pm 3.1 \pm 8.5$	$12.4 \pm 5.2 \pm 5.8$	3.8σ
$\Xi_c(2923)^0$	$2924.5 \pm 0.4 \pm 1.1$	$4.8 \pm 0.9 \pm 1.5$	$> 10\sigma$
$\Xi_c(2939)^0$	$2938.5 \pm 0.9 \pm 2.3$	$11.0 \pm 1.9 \pm 7.5$	$> 10\sigma$

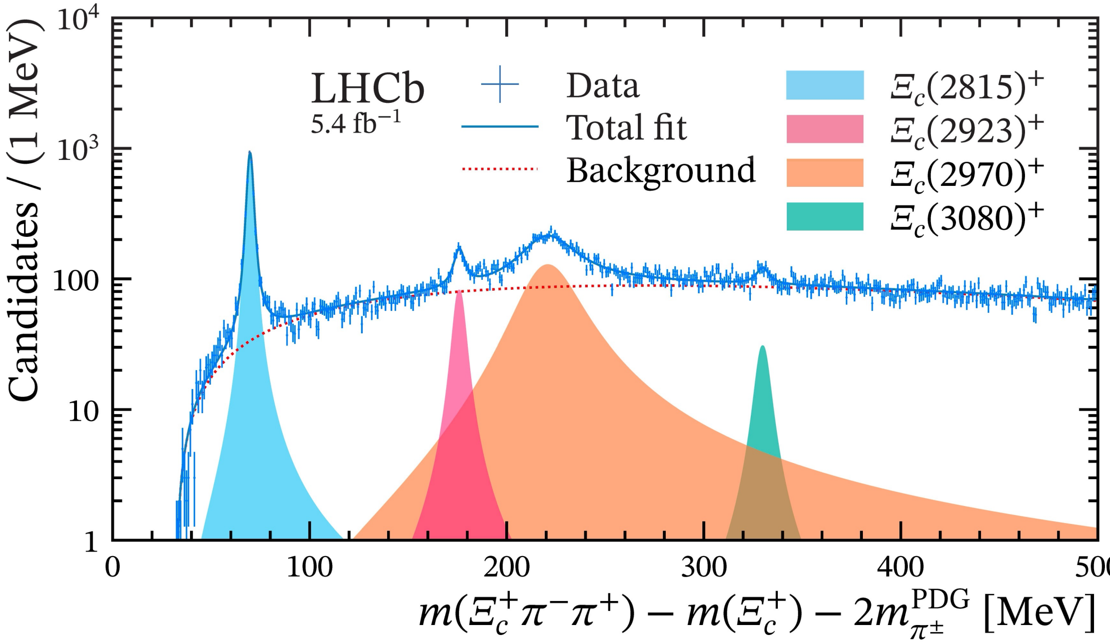
confirmation

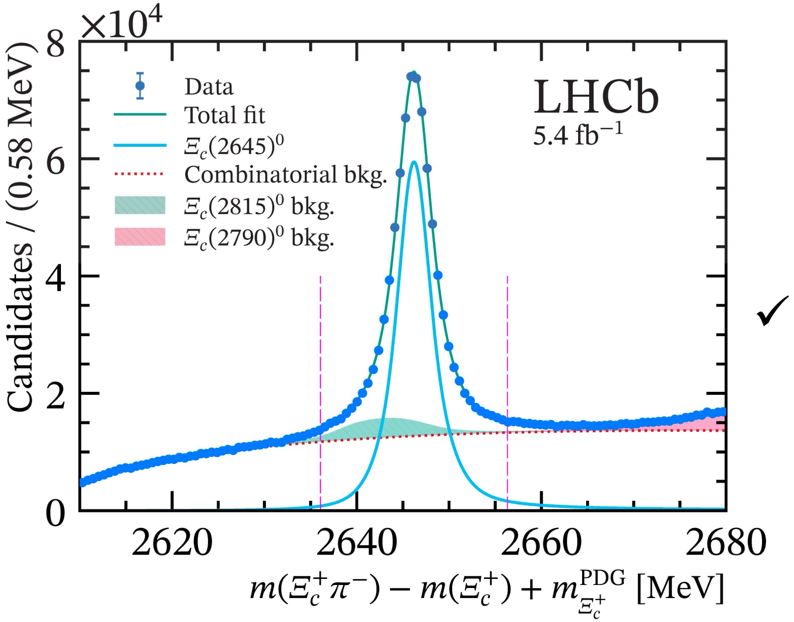
✓ Isospin partners Ξ_c^{**+} can help elucidate their properties

Observation of $\Xi_c^{**+} \to \Xi_c^+\pi^+\pi^-$

[PRL 132 (2025) 161901]

- **Dataset:** $5.4\ \mathrm{fb}^{-1}$ Run2 data from LHCb
- **Decay chain:**
  $\Xi_c^{**+} \to \Xi_c(2645)^0(\to \Xi_c^+\pi^-)\pi^+, \Xi_c^+ \to pK^-\pi^+$
- **Selection:** three-staged MVA classifiers to optimize significance of $\Xi_c^+ \Rightarrow \Xi_c(2645)^0 \Rightarrow \Xi_c^{**+}$ succesively





$N(\Xi_c(2645)^0) \sim 56.5\times 10^4$, purity ~52%

✓ $\Lambda_c^+ K^-$ @ LHCb

$\Xi_c(2923)^0$ → isospin partner

$\Xi_c(2939)^0$ → not seen

$\Xi_c(2965)^0$ → inconsistent width

$m[\Xi_c(2815)^+] = 2816.65 \pm 0.03 \pm 0.03 \pm 0.23\,\mathrm{MeV}$,
$\Gamma[\Xi_c(2815)^+] = 2.07 \pm 0.08 \pm 0.12\,\mathrm{MeV}$,

$m[\Xi_c(2923)^+] = 2922.8 \pm 0.3 \pm 0.5 \pm 0.2\,\mathrm{MeV}$,
$\Gamma[\Xi_c(2923)^+] = 5.3 \pm 0.9 \pm 1.4\,\mathrm{MeV}$,

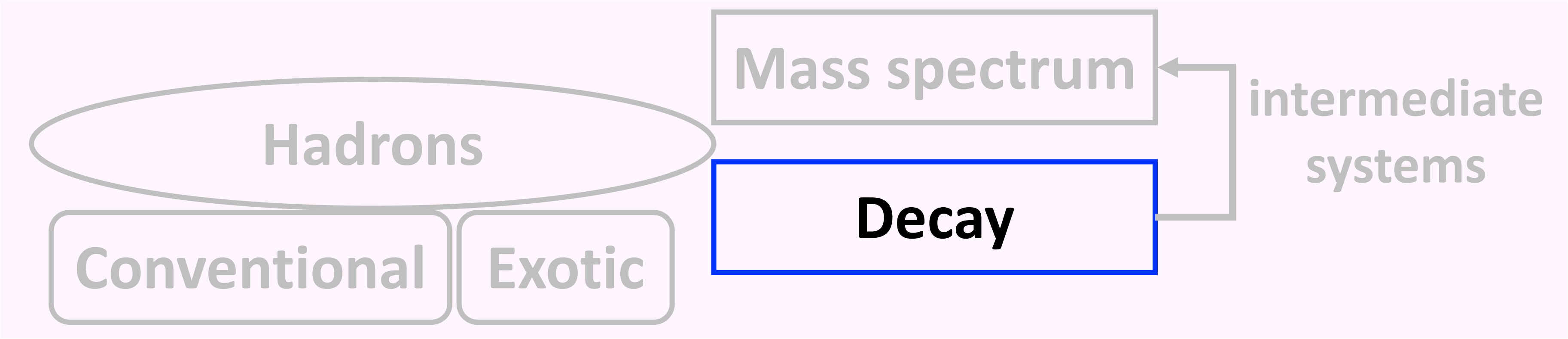
first observation

$m[\Xi_c(2970)^+] = 2968.6 \pm 0.5 \pm 0.5 \pm 0.2\,\mathrm{MeV}$,
$\Gamma[\Xi_c(2970)^+] = 31.7 \pm 1.7 \pm 1.9\,\mathrm{MeV}$,

$m[\Xi_c(3080)^+] = 3076.8 \pm 0.7 \pm 1.3 \pm 0.2\,\mathrm{MeV}$,
$\Gamma[\Xi_c(3080)^+] = 6.8 \pm 2.3 \pm 0.9\,\mathrm{MeV}$,

observation of new decay mode

Hadron spectroscopy study



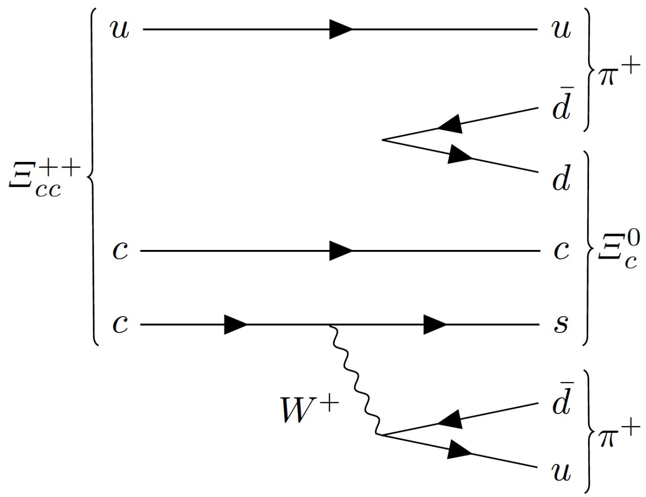
- Observation of $\Xi_{cc}^{++} \to \Xi_c^0 \pi^+ \pi^+$
- Observation of $B_c^+ \to D h^+ h^-$

Observation of $\Xi_{cc}^{++} \to \Xi_c^0 \pi^+ \pi^+$

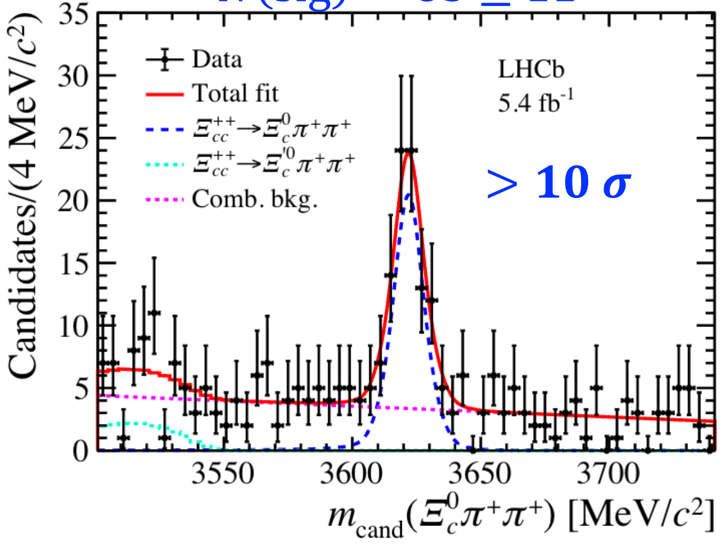
Ao Xu, Xingyu Tong
Yanxi Zhang

[JHEP 10 (2025) 136]

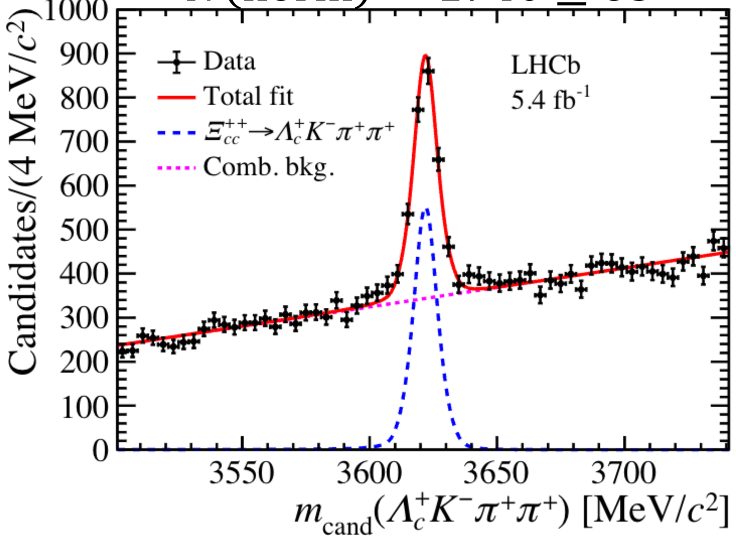
- **Motivation:** only three decay modes of Ξ_{cc}^{++} are observed while more are predicted
  - ✓ Ξ_{cc}^{++} decays can probe nonperturbative interactions in weak decays of doubly heavy baryons
- **Dataset:** $5.4\ \mathrm{fb}^{-1}$ Run2 data from LHCb
- **Decay chain:** $\Xi_{cc}^{++} \to \Xi_c^0 \pi^+ \pi^+, \Xi_c^0 \to p K^- K^- \pi^+$ (signal) vs. $\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+$ (normalisation)
- **Selection:** preselection, BDT classifiers to optimize punzi FoM, veto of physics background



$N(\mathrm{sig}) = 83 \pm 11$



$N(\mathrm{norm}) = 1740 \pm 65$



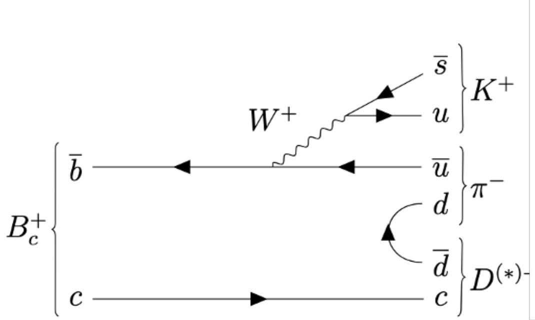
$$\boxed{\frac{\mathcal{B}(\Xi_{cc}^{++} \to \Xi_c^0 \pi^+ \pi^+)}{\mathcal{B}(\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+)} = 1.37 \pm 0.18(\mathrm{stat}) \pm 0.09(\mathrm{syst}) \pm 0.35(\mathrm{ext})}$$

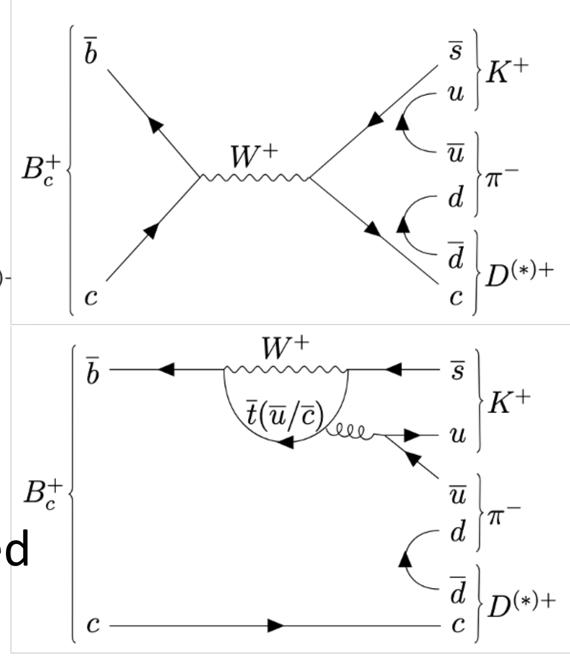
[arXiv: 2509.15873]
submitted to PRL

Observation of $B_c^+ \to D h^+ h^-$

Zeqing Mu, Tianke Wu
Yanxi Zhang

- **Motivation:** B_c^+ weak decays provide an ideal platform to probe nonperturbative QCD and CP-violating effects
  - ✓ $B_c^+ \to D h^+ h^-$ exhibit rich dynamic structures & interfering amplitudes→observable CPV effects





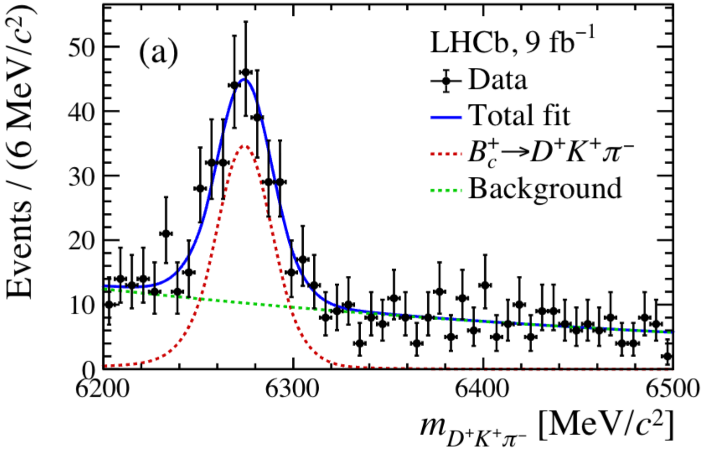
- **Dataset:** Run1 & 2 data at LHCb corresponding to 9 fb^{-1}

$$\boxed{\begin{aligned}
\mathcal{R}(B_c^+ \to D^+K^+\pi^-) &= (1.96 \pm 0.23 \pm 0.08 \pm 0.10) \times 10^{-3} \\
\mathcal{R}(B_c^+ \to D^{*+}K^+\pi^-) &= (3.67 \pm 0.55 \pm 0.24 \pm 0.20) \times 10^{-3} \\
\mathcal{R}(B_c^+ \to D_s^+K^+K^-) &= (1.61 \pm 0.35 \pm 0.13 \pm 0.07) \times 10^{-3}
\end{aligned}}$$

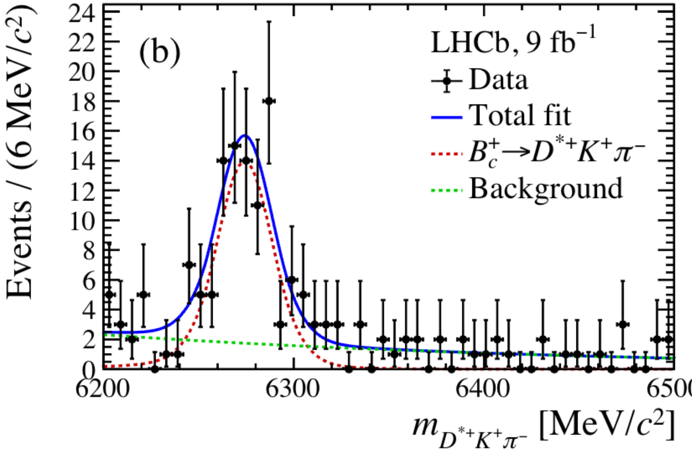
vs. $B_c^+ \to B_s^0 \pi^+$

✓ proceed primarily via excited K^0 or D^0 or ϕ mesons

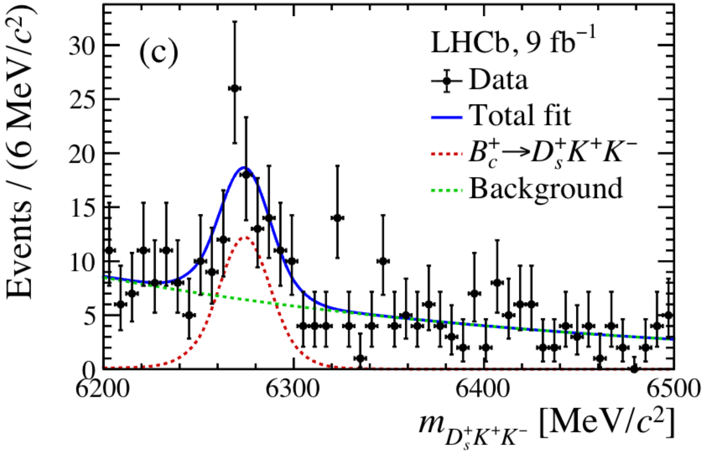
$N(B_c^+ \to D^+K^+\pi^-) = 230 \pm 23$



$N(B_c^+ \to D^{*+}K^+\pi^-) = 87 \pm 12$



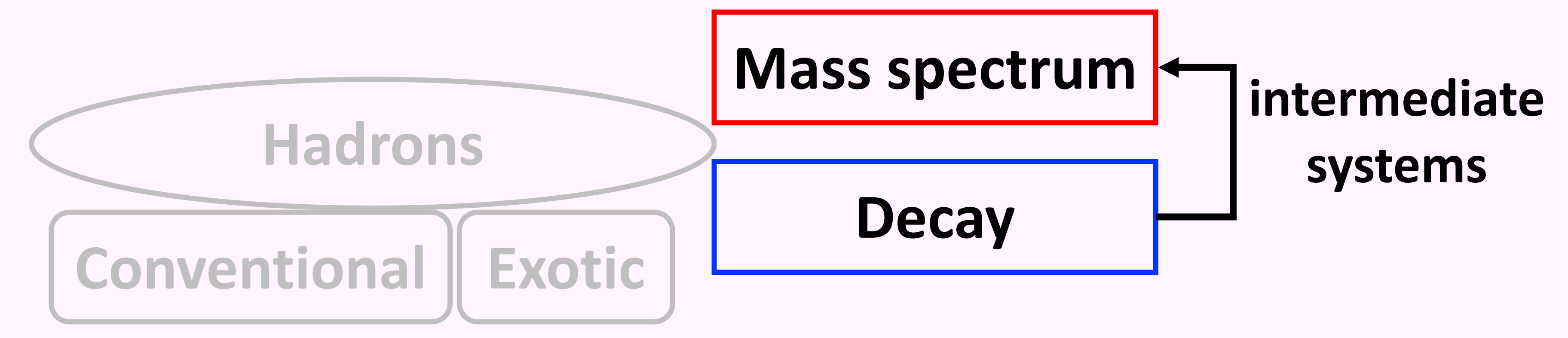
$N(B_c^+ \to D_s^+K^+K^-) = 68 \pm 13$



all > 10 σ

first observation

Hadron spectroscopy study

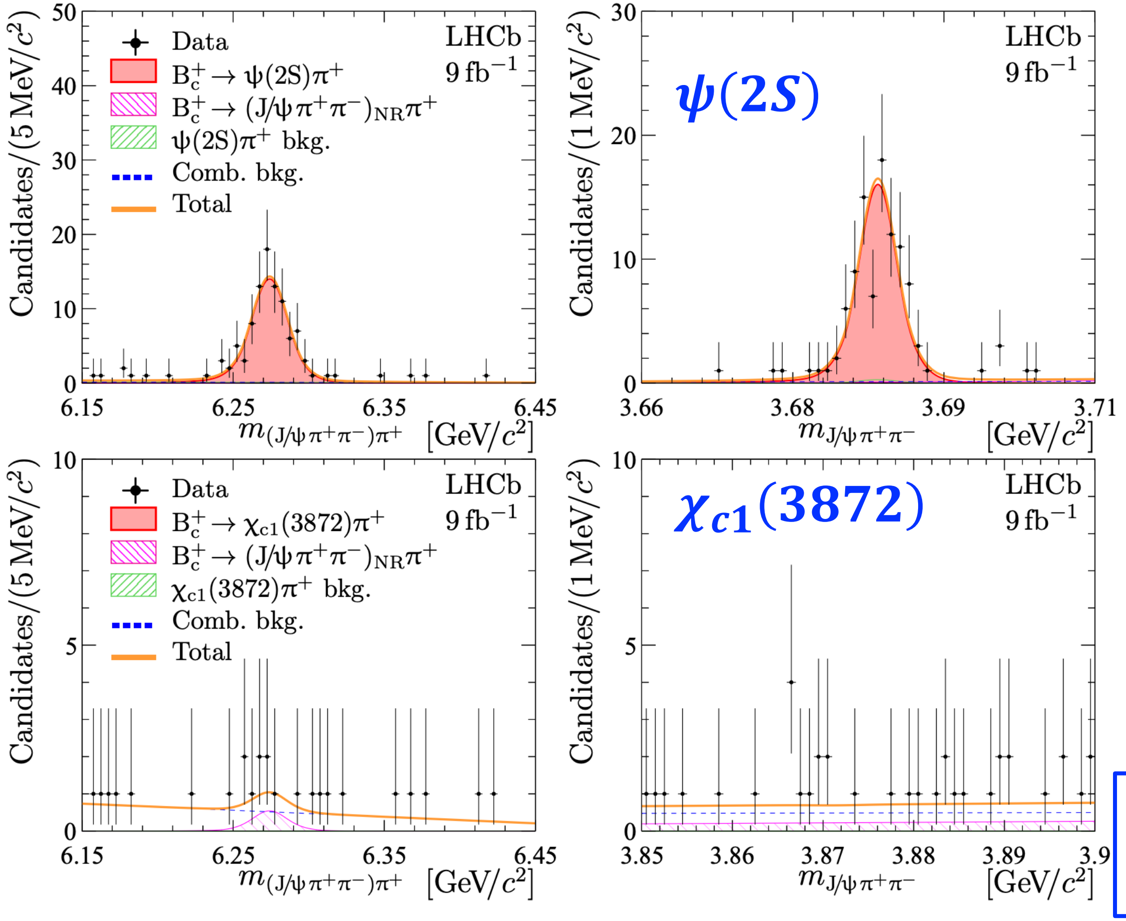


- Search for $B_c^+ \to \chi_{c1}(3872)\pi^+$
- Observation of $\Lambda_b^0 \to \Lambda_c^+ D_s^- K^+ K^-$ and search for $P_{c\bar{c}s} \to \Lambda_c^+ D_s^-$
- Amplitude analysis of $B^0 \to \eta_c(1S) K^+ \pi^-$
- Study of $T_{c\bar{c}1}(4430)^+$ in $B^+ \to \psi(2S) K_S^0 \pi^+$

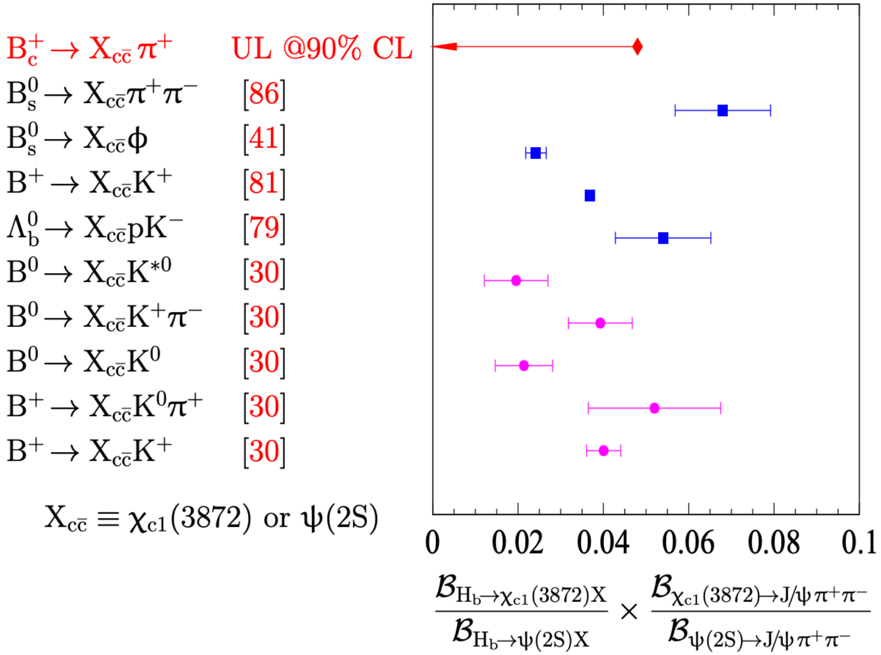
Search for $B_c^+ \to \chi_{c1}(3872)\pi^+$

[JHEP 06 (2025) 13]

- The compact-tetraquark interpretation of $\chi_{c1}(3872)$ predicts enhancement of $\mathcal{B}(B_c^+ \to \chi_{c1}(3872)\pi^+)$ [PR D71 (2005) 014028]
- ATLAS reported significant enhancement of $\chi_{c1}(3872)$ production from B_c^+, assuming short-lived contribution of non-prompt $\chi_{c1}(3872)$ to arise from B_c^+ decays [JHEP 01 (2017) 117]



- No signal observed from 9 fb^{-1} LHCb Run1+2 data



$$\mathcal{R}^{\chi_{c1}(3872)}_{\psi(2S)} = \frac{\mathcal{B}_{B_c^+\to\chi_{c1}(3872)\pi^+}}{\mathcal{B}_{B_c^+\to\psi(2S)\pi^+}} \times \frac{\mathcal{B}_{\chi_{c1}(3872)\to J/\psi\pi^+\pi^-}}{\mathcal{B}_{\psi(2S)\to J/\psi\pi^+\pi^-}} < 0.05\,(0.06) \text{ at } 90\,(95)\%\text{ CL}$$

Observation of $\Lambda_b^0 \to \Lambda_c^+ D_s^- K^+ K^-$

[PRD112 (2025) 052013]

Jinlin Fu, Zan Ren
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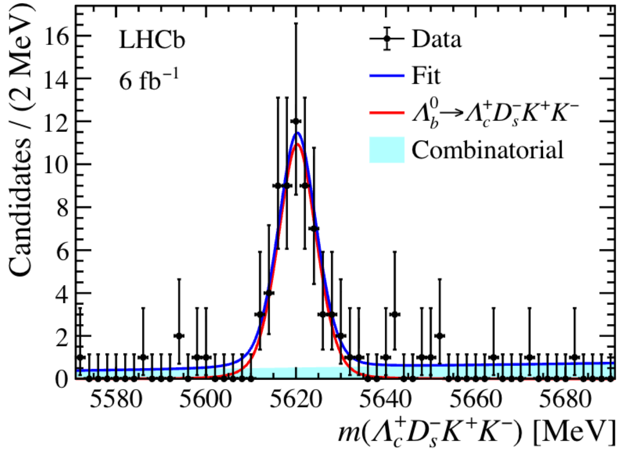
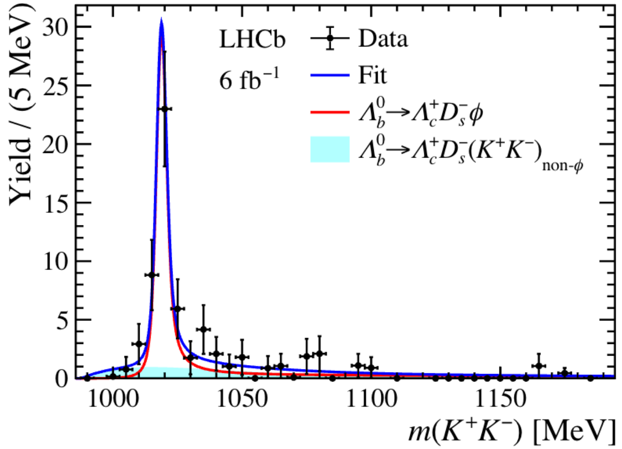
- **Motivation:** search for pentaquark candidates $P_{c\bar{c}s} \to \Lambda_c^+ D_s^-$
- **Dataset:** $6\ \mathrm{fb}^{-1}$ Run2 data from LHCb

$N = 61 \pm 8$

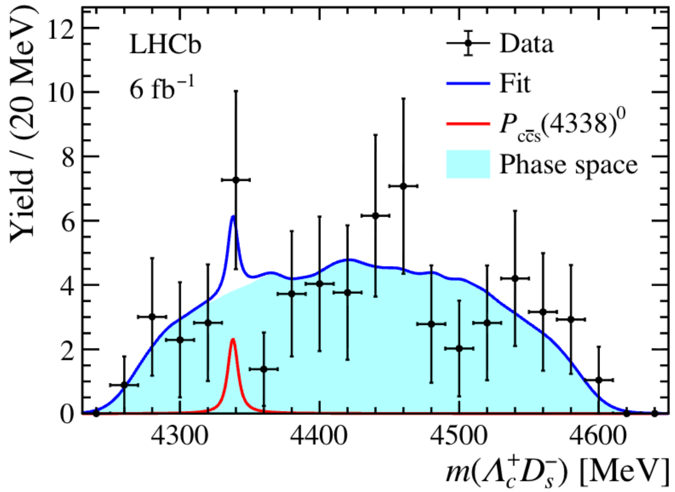
first observation

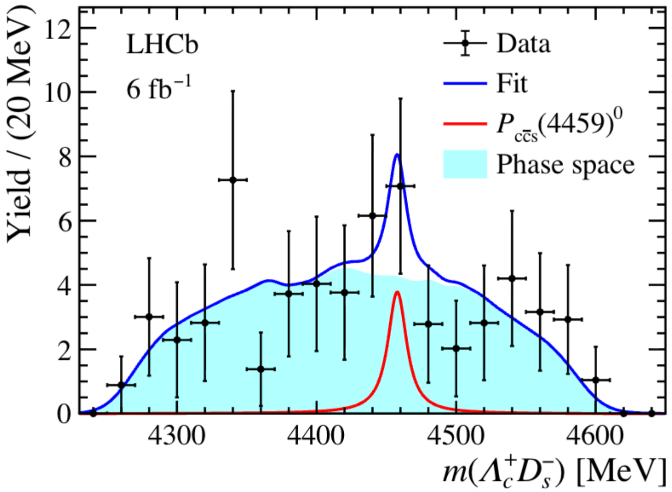


✓ dominated by ϕ component



$$\frac{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ D_s^- K^+ K^-)}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ D_s^-)} = 0.0141 \pm 0.0019 \pm 0.0012$$





✓ no evidence of either $P_{c\bar{c}s}(4338)^0$ or $P_{c\bar{c}s}(4459)^0$

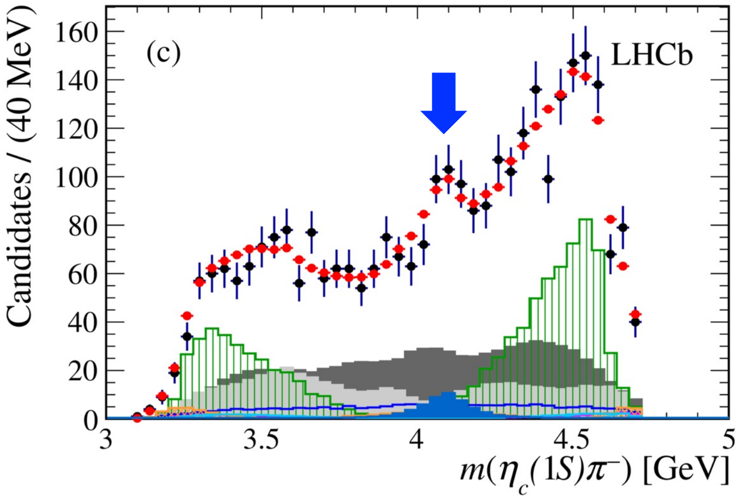
$$\mathcal{R}_{P^0_{c\bar{c}s}} \equiv \frac{\mathcal{B}(\Lambda_b^0 \to P_{c\bar{c}s} K^+ K^-)}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ D_s^- K^+ K^-)} \cdot \mathcal{B}(P^0_{c\bar{c}s} \to \Lambda_c^+ D_s^-)$$

$$\left.\begin{array}{l}\mathcal{R}_{P_{c\bar{c}s}(4338)^0} < 0.12(0.10) \\ \mathcal{R}_{P_{c\bar{c}s}(4459)^0} < 0.20(0.17)\end{array}\right\} @\ 95\%(90\%)\ \mathrm{CL}$$

[arXiv: 2509.03133]
submitted to EPJC

Amplitude analysis of $B^0 \to \eta_c(1S)K^+\pi^-$

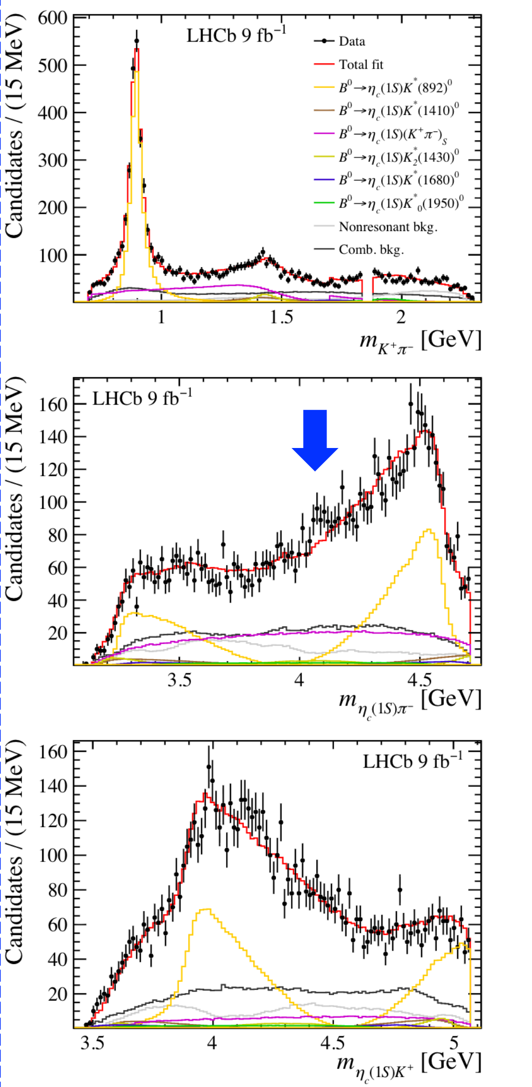
- LHCb saw evidence for an $\eta_c(1S)\pi^-$ resonance in $B^0 \to \eta_c(1S)K^+\pi^-$ with 4.7 fb^{-1} data (2011-2016)



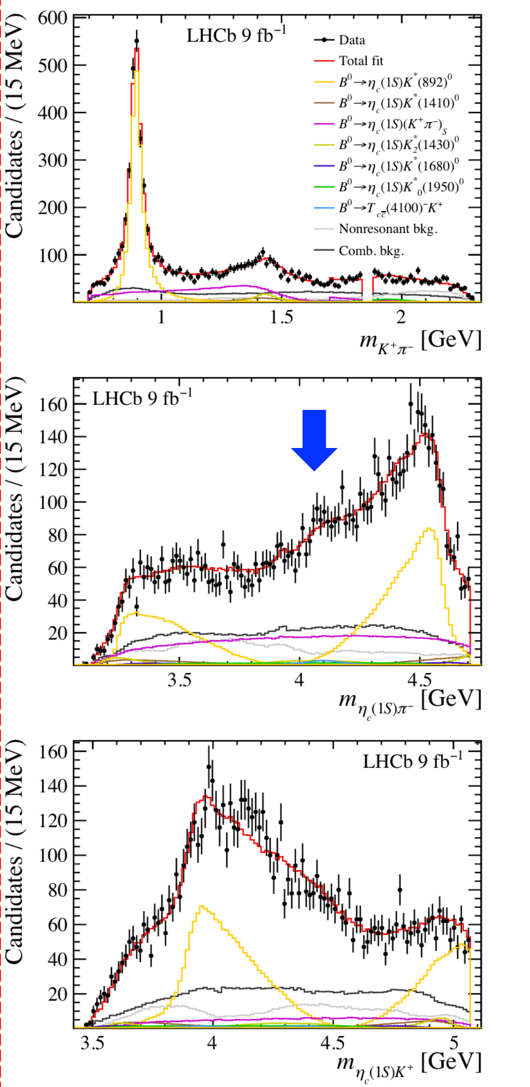
- Update with 9 fb^{-1} Run1&2 data
  - ✓ inclusion of $T_{c\bar{c}}(4100)^- \to \eta_c(1S)\pi^-$ improves the description, but it is ***not significant*** enough after considering systematic uncertainties

$$\boxed{\mathcal{B}(B^0 \to \eta_c(1S)K^+\pi^-) = (5.82 \pm 0.20 \pm 0.23 \pm 0.55) \times 10^{-4}}$$

$K^{*0} \to K^+\pi^-$ only



adding $T_{c\bar{c}} \to \eta_c(1S)\pi^-$



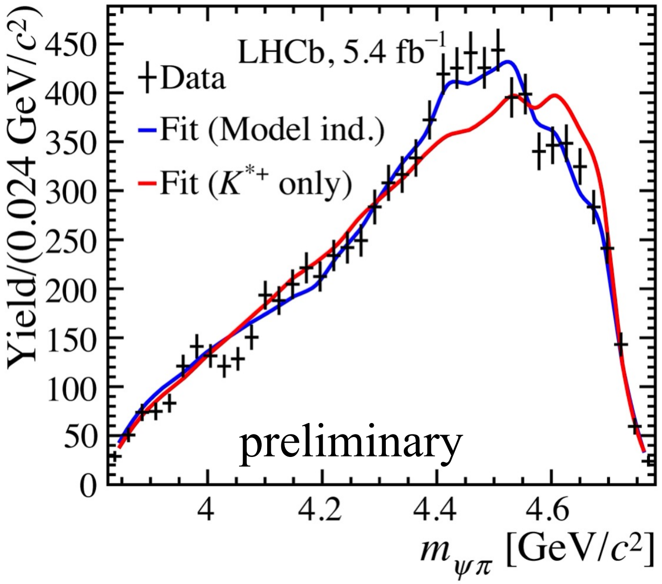
[LHCb-PAPER-2025-039] in preparation

$T_{c\bar{c}1}(4430)^+$ in $B^+ \to \psi(2S)K_S^0\pi^+$

Shuang Zheng
Yanxi Zhang

- First four-dimensional amplitude analysis of $B^+ \to \psi(2S)K_S^0\pi^+$ is performed using 5.4 fb^{-1} Run2 data
  - ✓ related via isospin symmetry to $\bar{B}^0 \to \psi(2S)K^-\pi^+$ where the first charged charmonium-like state $T_{c\bar{c}1}(4430)^+(Z_c(4430)^+, J^P = 1^+)$ was seen [PRL 100 (2008) 142001] [PRL 112 (2014) 222002]

Model independent



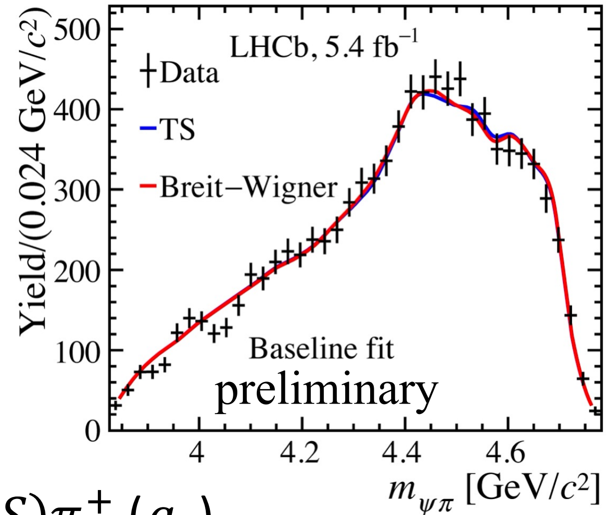
✓ discrepancy resolved by adding $\psi(2S)\pi^+$ component which shows resonant behavior

Model dependent

✓ **Breit Wigner:**

$$M = 4.452 \pm 0.016^{+0.055}_{0.033} \text{ GeV}$$
$$\Gamma = 0.174 \pm 0.019^{+0.083}_{-0.020} \text{ GeV}$$
$$f = (3.7 \pm 0.6^{+4.0}_{-0.7})\%$$
$$J^P = 1^+$$

consistent with $T_{c\bar{c}1}(4430)^+$



◆ **Molecular scenario:** Flatté model with coupling to $\bar{D}_1^*(2600)^0D^+$ (g_2) and $\psi(2S)\pi^+$ (g_1)

$$g_2 = 0.00 \pm 1.78 \pm 2.81 \text{ GeV}/c^2, \left|\frac{g_2}{g_1}\right| < 6.8 \text{ @ 95\% CL}$$

◆ **Triangle singularity mechanism:** model incorporating singularity in $\psi(4230)K^{*+}\pi^+$ triangle diagram gives reasonable description

LHCb detector in Run3

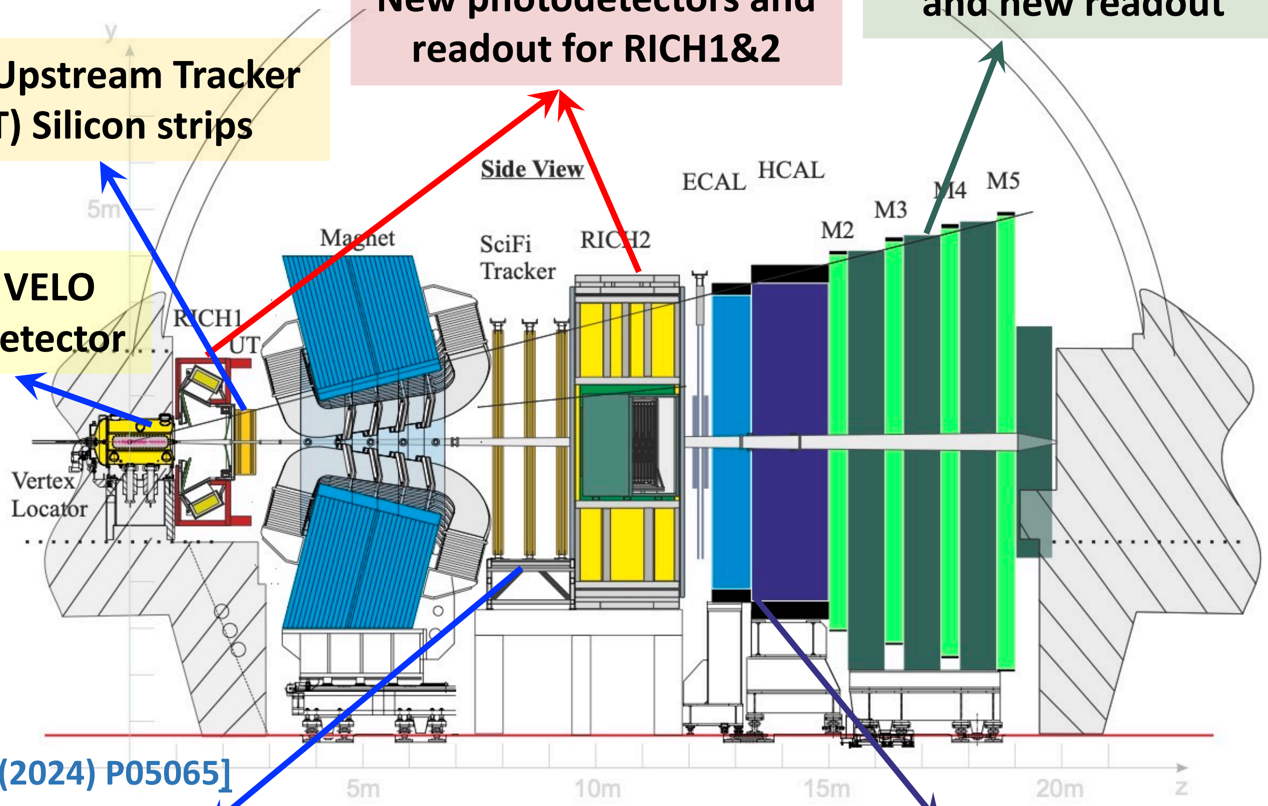
Software-only trigger

New Upstream Tracker (UT) Silicon strips

New VELO Pixel detector

New RICH1 optics
New photodetectors and readout for RICH1&2

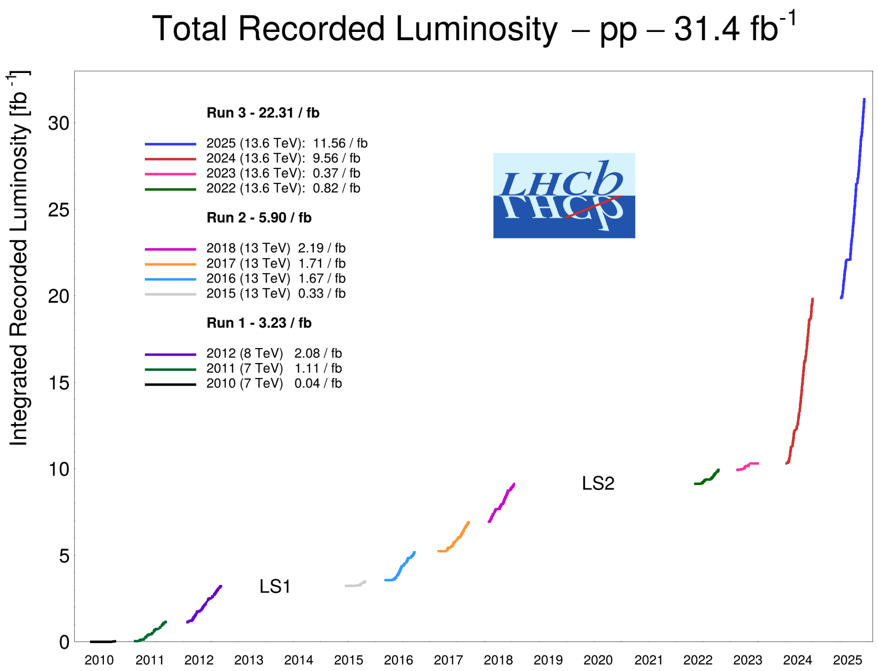
Muon: removed M1 and new readout

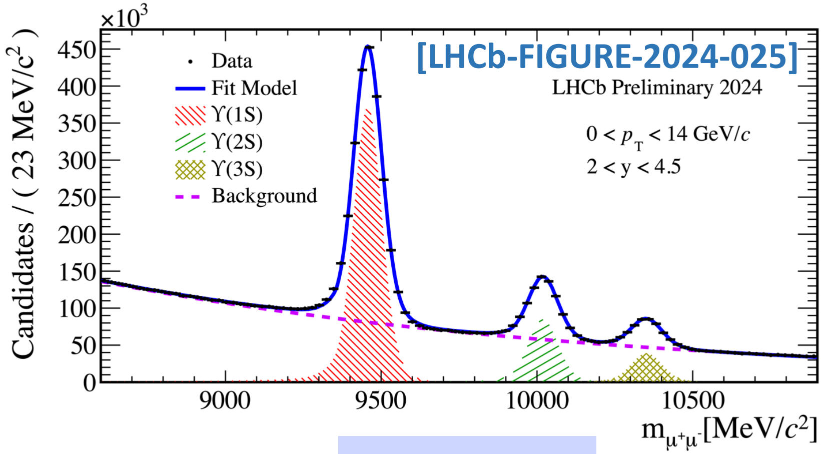


[JINST 19 (2024) P05065]

New SciFi Tracker Scintillating fibres

Calorimeters: removed PreShower (PS) and Scintillating Pad Detector (SPD), new readout





$\Upsilon \to \mu^+\mu^-$

$9\ \mathrm{fb}^{-1}$ @ Run 1-2 → $> 30\ \mathrm{fb}^{-1}$ by Run 3

Conclusion

➢The LHCb experiment maintains a strong momentum in hadron spectroscopy

☐New states

✓Observation of $B_c(1P)^+$ states

✓Observation of $\Xi_c^{**+} \to \Xi_c^+\pi^+\pi^-$

☐New decays

✓Observation of $\Xi_{cc}^{++} \to \Xi_c^0\pi^+\pi^+$

✓Observation of $B_c^+ \to Dh^+h^-$

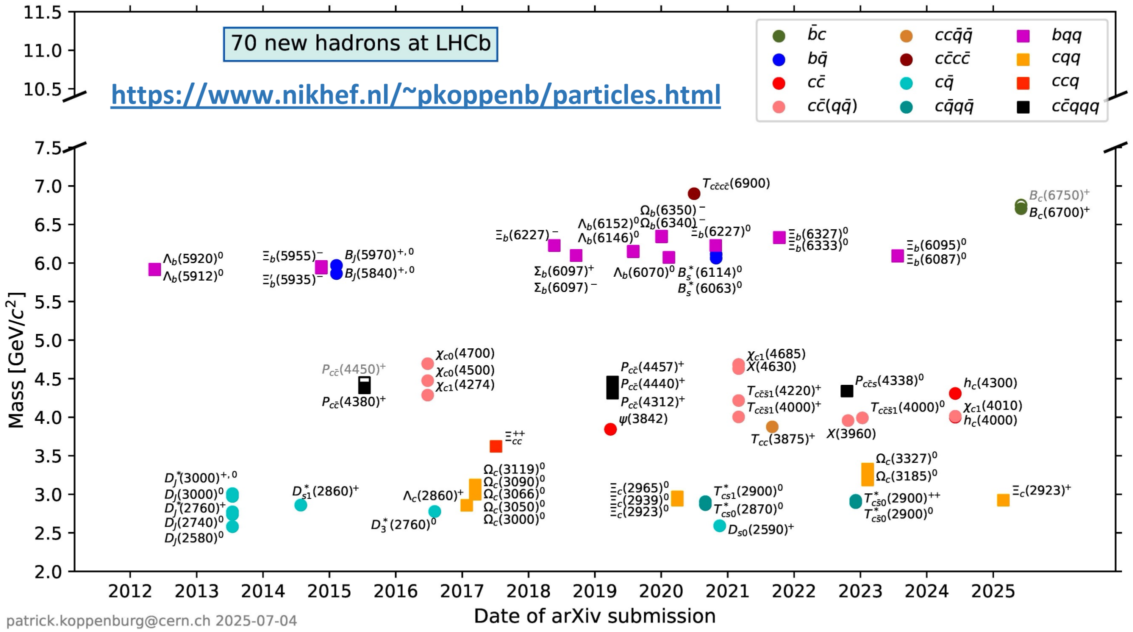
☐Decays for exotic hadron study

✓Search for $B_c^+ \to \chi_{c1}(3872)\pi^+$

✓Observation of $\Lambda_b^0 \to \Lambda_c^+ D_s^- K^+ K^-$ and search for $P_{c\bar{c}s} \to \Lambda_c^+ D_s^-$

✓Amplitude analysis of $B^0 \to \eta_c(1S)K^+\pi^-$

✓Study of $T_{c\bar{c}1}(4430)^+$ in $B^+ \to \psi(2S)K_S^0\pi^+$

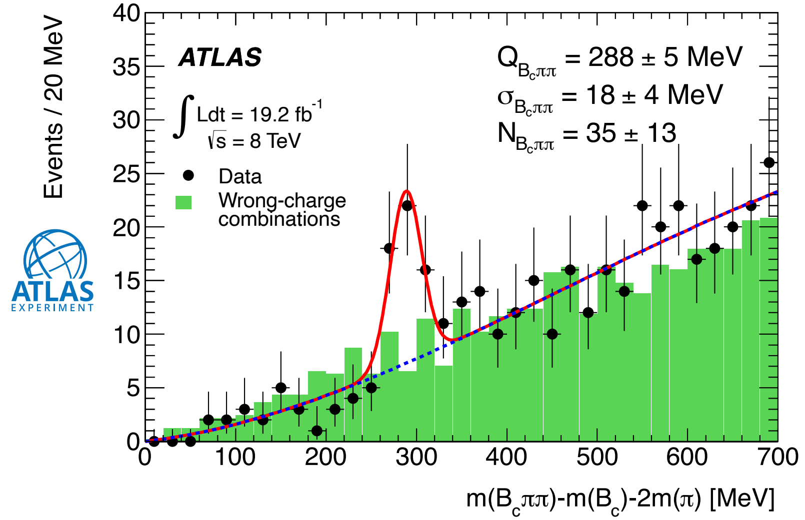


Stay tuned!

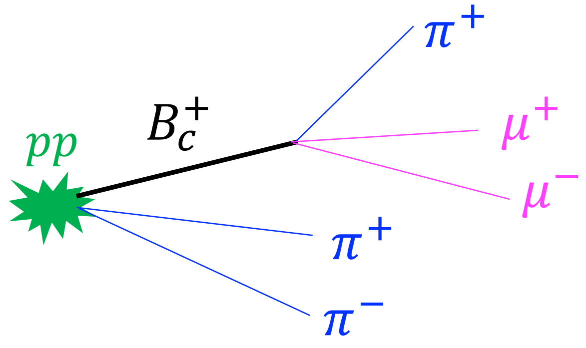
Thank you!

Observation of $B_c(2S)^+$ states

[PRL 113 (2014) 12004]

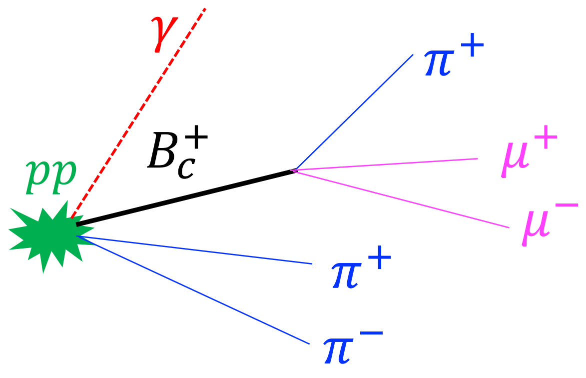


$B_c(2^1S_0)^+ \rightarrow B_c^+\pi^+\pi^-$

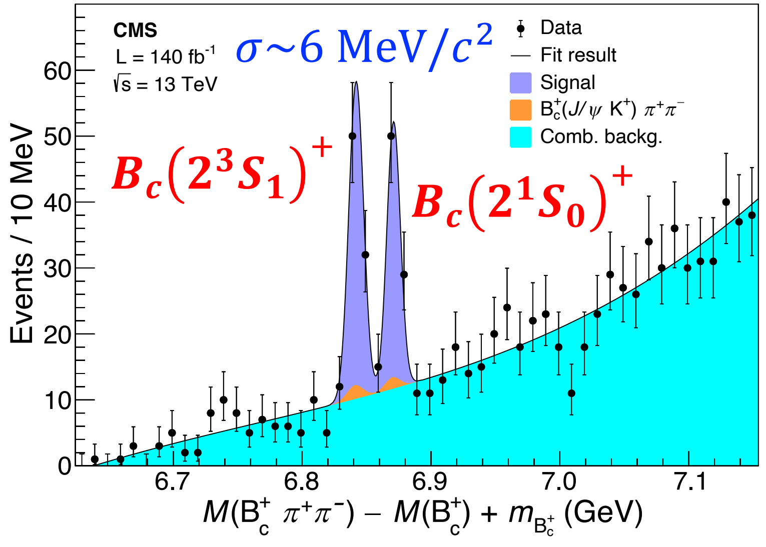


and/or?

$B_c(2^3S_1)^+ \rightarrow B_c^{*+}(\rightarrow B_c^+\cancel{\gamma})\pi^+\pi^-$

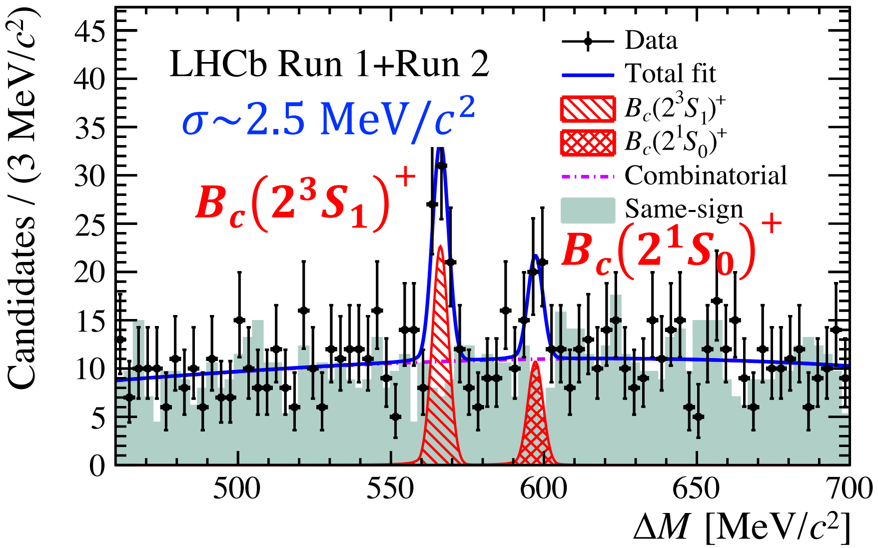


[PRL 122 (2019) 132001]



2^3S_1: **66 ± 10**; 2^1S_0: **51 ± 10**

[PRL 122 (2019) 232001]



2^3S_1: **51 ± 10**; 2^1S_0: **24 ± 9**

$M(2^1S_0)$
$= 6871.0 \pm 1.2(\text{stat}) \pm 0.8(\text{syst})$
$\pm\, 0.8(B_c^+)$ MeV$/c^2$

$M(2^1S_0) - M(2^3S_1)_{\text{rec}}$
$= 29.0 \pm 1.5(\text{stat}) \pm 0.7(\text{syst})$ MeV$/c^2$

$M(2^1S_0)$
$= 6872.1 \pm 1.3(\text{stat}) \pm 0.1(\text{syst})$
$\pm\, 0.8(B_c^+)$ MeV$/c^2$

$M(2^1S_0) - M(2^3S_1)_{\text{rec}}$
$= 31.0 \pm 1.4(\text{stat})$ MeV$/c^2$

$B_c(1P)^+$ states

$$L = 1 \otimes S = \begin{cases} 0 & \Rightarrow \quad \boxed{1^1P_1} \\ 1 & \Rightarrow \quad \mathbf{1^3P_0} \quad \boxed{1^3P_1} \quad \mathbf{1^3P_2} \end{cases}$$

$\rightarrow B_c^+\gamma$: peak in $B_c^+\gamma$ mass spectrum

$\rightarrow B_c^{*+}(\rightarrow B_c^+\cancel{\gamma})\gamma$: peak in $B_c^+\gamma$ mass spectrum but shifted downwards by

$$\delta M = M(B_c^{*+}) - M(B_c^+)$$

mixing

$$\begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} 1^1P_1 \\ 1^3P_1 \end{pmatrix} = \begin{pmatrix} \mathbf{1P_1'} \\ \mathbf{1P_1} \end{pmatrix} \begin{cases} \rightarrow B_c^+\gamma \\ \rightarrow B_c^{*+}(\rightarrow B_c^+\cancel{\gamma})\gamma \end{cases}$$

four states

six peaks

States	1^3P_0	$1P_1$	$1P_1'$	1^3P_2
Decays	$B_c^{*+}(\rightarrow B_c^+\gamma)\gamma$	$B_c^+\gamma$ $B_c^{*+}(\rightarrow B_c^+\gamma)\gamma$	$B_c^+\gamma$ $B_c^{*+}(\rightarrow B_c^+\gamma)\gamma$	$B_c^{*+}(\rightarrow B_c^+\gamma)\gamma$
#peaks	1	2	2	1

Theoretical predictions for $B_c(1P)^+$

& more on predictions of subsets of the parameters

$^*\delta M = M(B_c^{*+}) - M(B_c^+)$

*citations not repeated hereafter

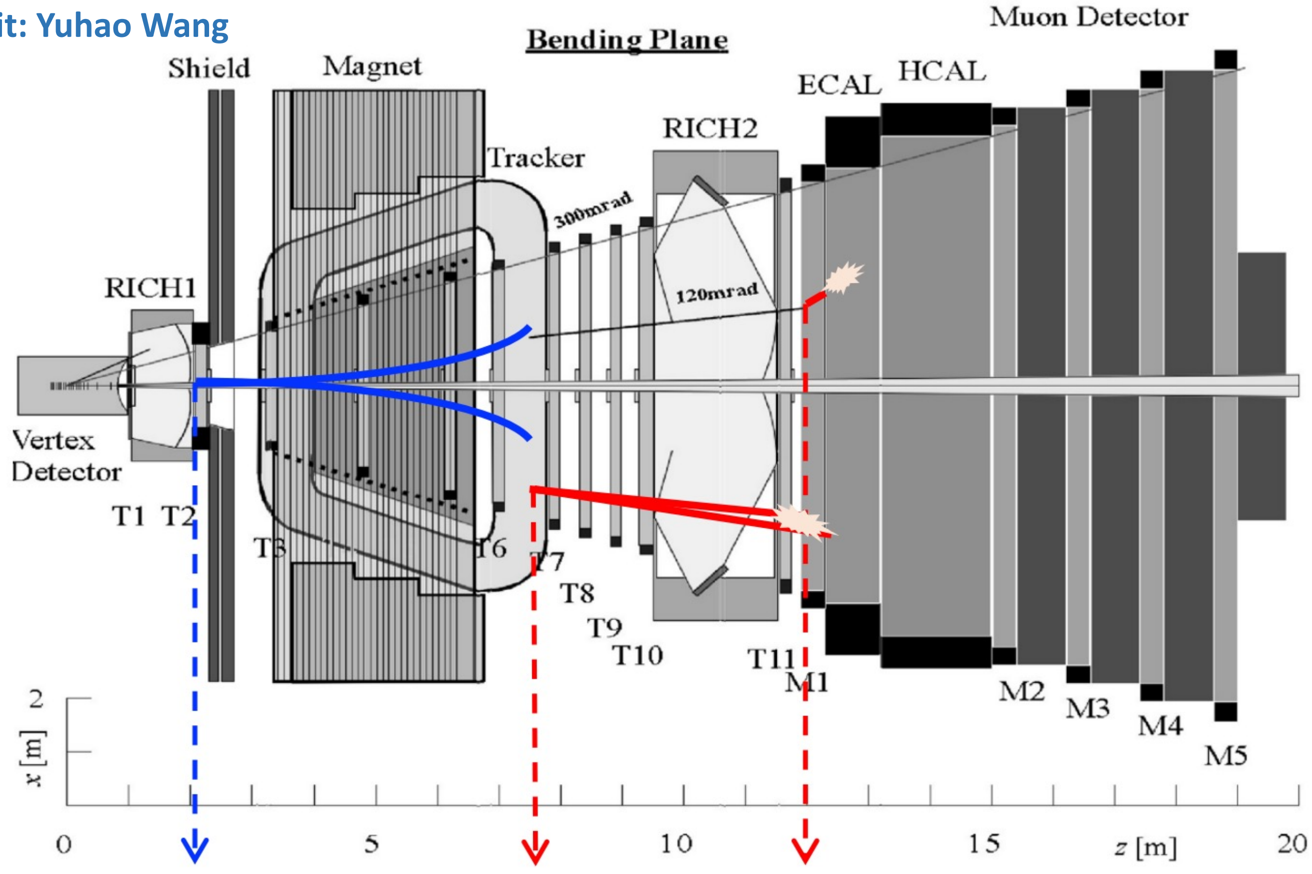
		δM	$M(1^3P_0)$	$M(1P_1)$	$M(1P_1')$	$M(1^3P_2)$	θ [°]
[PL B382 (1996) 131]	Lattice QCD	41	6727	6743	6765	6783	33.4
[PR D51 (1995) 3613]	GKLT	64	6683	6717	6729	6743	17.1
[PR D53 (1996) 312]	GJ	61	6689	6738	6757	6773	25.6
[PR D60 (1999) 074006]	FUII	55	6701	6737	6760	6772	28.5
[PR D67 (2003) 014027]	EFG	62	6699	6734	6749	6762	20.4
[PR D70 (2004) 054017]	GI	67	6706	6741	6750	6768	22.4
[PR D99 (2019) 054025]	EQ	54	6693	6731	6739	6759	18.7
[PR D99 (2019) 096020]	LLLLGZ	55	6714	6757	6776	6787	35.5
[JHEP 05 (2022) 006]	WWLC	55	6705	6739	6748	6762	32.2
[PR D108 (2023) 034019]	LTFWP	53	6712	6770	6761	6783	−24.3
[EPJ C83 (2023) 1080]	LLWL	67	6701	6745	6754	6773	35.2
[CP C48 (2024) 123101]	HZ	63	6707	6751	6786	6802	55.0

➢ $\Delta M_{\mathrm{rec}} = M(B_c^+\gamma)_{\mathrm{rec}} - M(B_c^+)$ is predicted to be in $340 < \Delta M_{\mathrm{rec}} < 520\ \mathrm{MeV}/c^2$

Photon reconstruction at LHCb

$\chi_c \to J/\psi\,\gamma$

Credit: Yuhao Wang



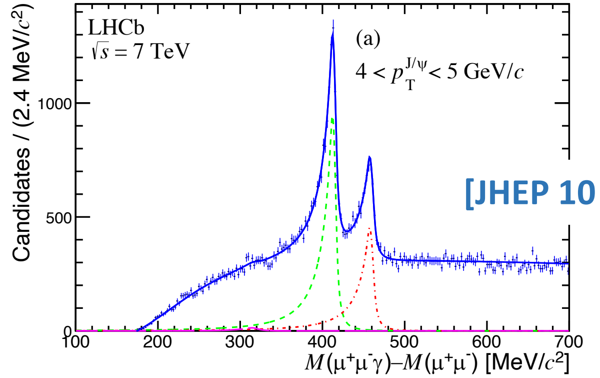
photons convert before magnet

reconstructed from e^+e^-

photons convert after magnet

non-converted photons

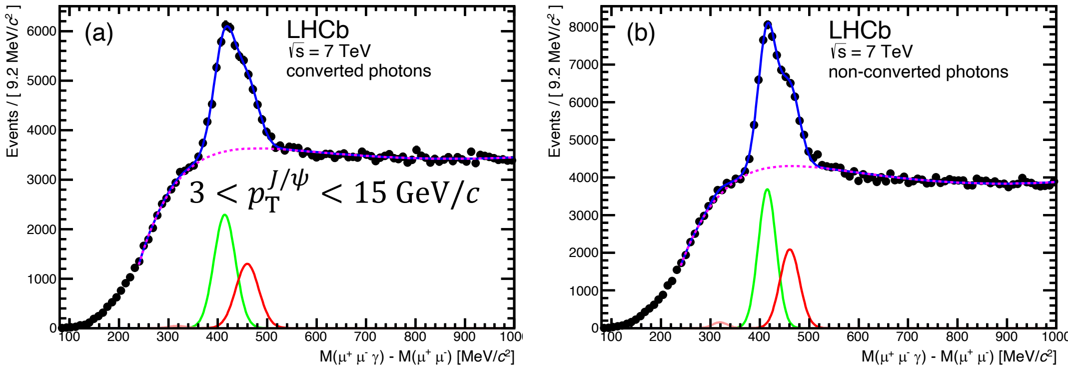
reconstructed as calorimeter clusters



[JHEP 10 (2013) 115]

@1 fb^{-1}

- ✗ Around one order of magnitude smaller statistics, especially at low p_{T}
- ✓ Better mass resolution



[PLB 718 (2012) 431]

- ✓ Much larger statistics
- ✗ Worse mass resolution

@36 pb^{-1}

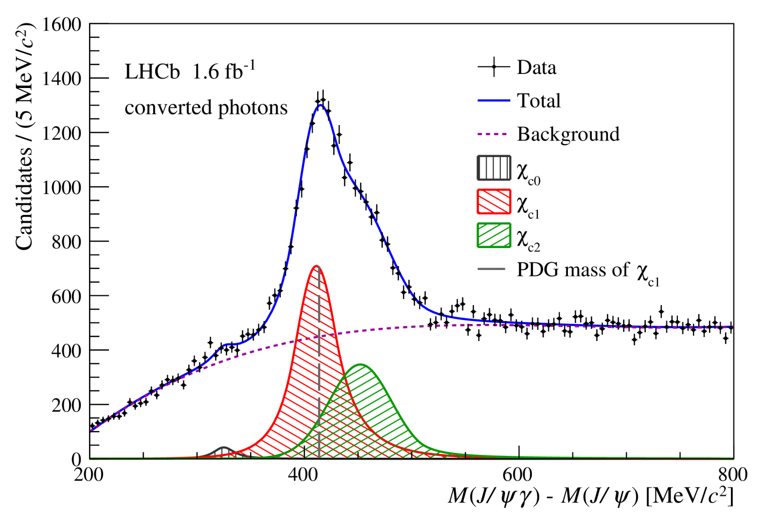
Photon energy correction in simulation

mass measurement | **resolution of multiple peaks**

- Knowledge on ***photon energy scale*** and ***resolution*** is required to interpret the structure
- They can be obtained from simulation, but **photon energy correction** needs to be applied to the simulation to eliminate mismatch between simulation and data

- **Reference mode**: $\chi_{c1} \to J/\psi\gamma$
  - ✓ similar photon energy spectrum to signal decay
  - ✓ identical photon selections are applied
- **Extraction of correction parameters**:
  - ✓ separately for converted and non-converted photons
  - ✓ independently for each data-taking period
  - ✓ in bins of E_γ and n_{tracks} (prominent variables that corrections are dependent on)
  - ✓ **key linear relation** (well established by simulation):

$$\textbf{photon energy bias} \sim M(\chi_{c1}) - M_{\text{PDG}}(\chi_{c1})$$
$$\textbf{photon energy resolution} \sim \sigma(M(\chi_{c1}))$$



- ✓ ***Resonances***: non-relativistic Breit Wigner (width fixed) ⊗ double-sided Crystal Ball (DSCB, Gaussian kernel with tails)
- ✓ ***Background***: third-order polynomial

Check of photon energy correction

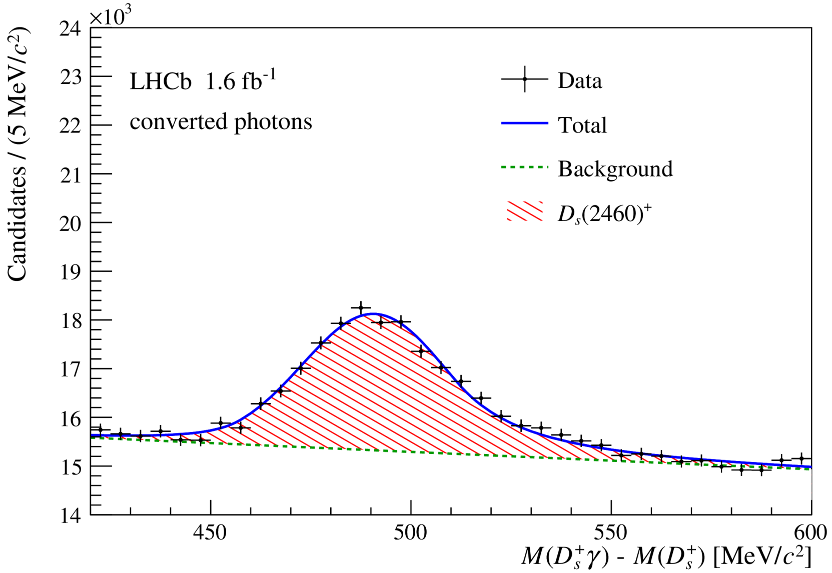
- The corrections are applied to simulated samples on a **per-event** basis, taking the photon energy bias and resolution extracted for the corresponding E_γ and n_{tracks} bin
- The correction parameters and the method are **validated** before application to $B_c^+\gamma$

- **Self-consistency check: good agreement** (e.g. converted photons @2016)
  - ✓ $\chi_{c1} \to J/\psi\gamma$: ΔM: $2.0 \to 0.3\ \text{MeV}/c^2$; $\Delta\sigma$: $0.3 \to 0.1\ \text{MeV}/c^2$
  - ✓ $\chi_{c2} \to J/\psi\gamma$: ΔM: $2.0 \to 0.4\ \text{MeV}/c^2$; $\Delta\sigma$: $0.7 \to 0.4\ \text{MeV}/c^2$

- **Independent validation: $D_{s1}(2460)^+ \to D_s^+\gamma$**
  - ✓ similar photon energy spectrum and decay topology
  - ✓ the largest remaining difference among all categories is

$$\Delta M: 3.6 \to 2.9\ \text{MeV}/c^2$$
$$\Delta\sigma: 4.6 \to 2.6\ \text{MeV}/c^2$$

$\Rightarrow$ scaled to $B_c(1P)^+ \to B_c^+\gamma$ according to energy release as **systematic uncertainty** on peak location measurement



*Measurement on $D_{s1}(2460)^+ \to D_s^+\gamma$ is by itself an interesting topic given $D_{s1}(2460)^+$ is a D^*K molecule candidate

Theory-independent mass fit

- The corrections are applied to simulated samples of $B_c(1P)^+ \to B_c^+\gamma$

$$\Rightarrow \begin{cases} \mu = -0.006\times\Delta M_{\text{true}} - 0.340\ \text{MeV}/c^2 \\ \sigma = 0.041\times\Delta M_{\text{true}} + 1.640\ \text{MeV}/c^2 \end{cases}$$

*$\Gamma(B_c(1P)^+)\sim\mathcal{O}(100\ \text{keV})$ negligible

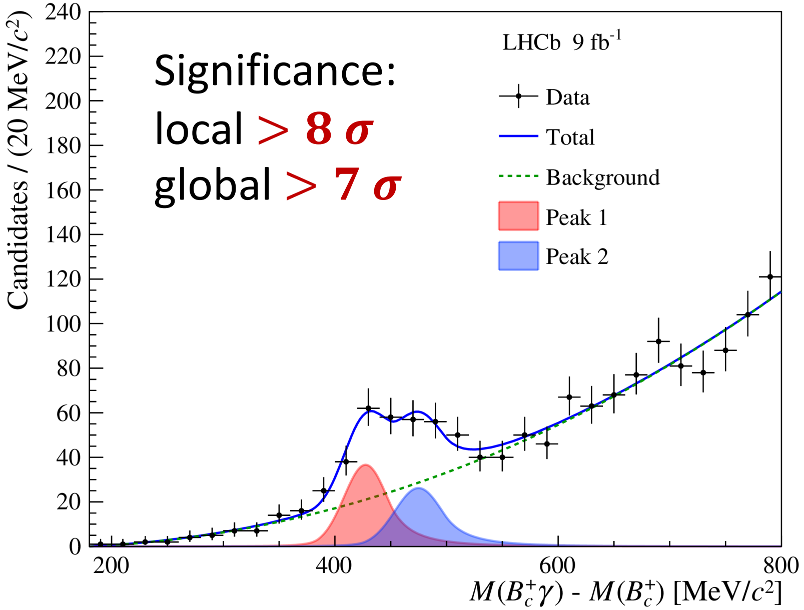
- A theory-independent fit on $B_c^+\gamma$ mass spectrum is performed

✓ The visible width of the peaking structure is $\sim 37\ \text{MeV}/c^2$
✓ Width of a single peak is determined to be $\sim 20\ \text{MeV}/c^2$
⇒ a **minimal two-peak model** is used to describe the structure

$\boldsymbol{N = 182 \pm 25}$
$\boldsymbol{f_1 = (56 \pm 11)\%}$

$\boldsymbol{M_1 = 6704.8 \pm 5.5\ \text{MeV}/c^2}$
$\boldsymbol{M_2 = 6752.4 \pm 9.5\ \text{MeV}/c^2}$

+56% correlation



The two-peak model is **effective**, expected to be composed of contributions from multiple $B_c(1P)^+ \to B_c^+\gamma$ decays, the distinction of which requires larger dataset and better resolution

✓***Peaks***: DSCB with tails fixed to simulation of $B_c(1P)^+ \to B_c^+\gamma$

✓**Background**: monotonically increasing third-order polynomial

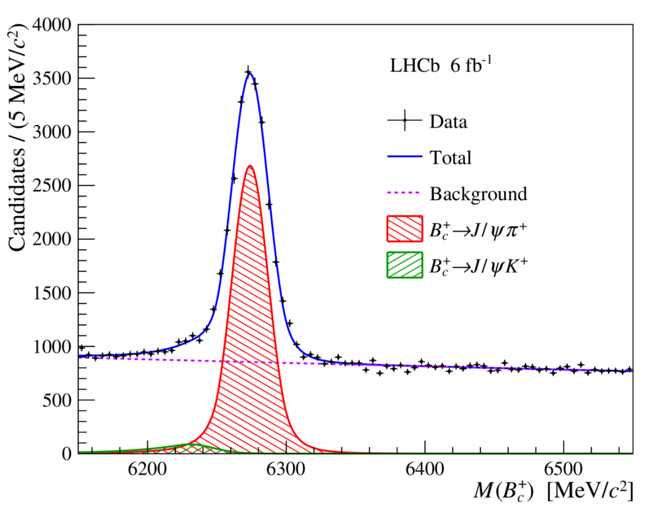
$B_c(1P)^+$ production measurement

- The production cross-section of $B_c(1P)^+$ is measured relative to B_c^+ in the fiducial region $\boldsymbol{p_{\mathrm{T}}(B_c^+) < 20\ \mathrm{GeV}/c, 2.0 < y(B_c^+) < 4.5}$ at $\sqrt{s} = \mathbf{13\ TeV}$ using $\mathbf{6\ fb^{-1}}$ data

$$\mathcal{R} = \frac{N(B_c(1P)^+ \to B_c^+\gamma)}{N(B_c^+)} \times \frac{\varepsilon(B_c^+)}{\varepsilon(B_c(1P)^+ \to B_c^+\gamma)}$$

- $\varepsilon(B_c^+)$: estimated with simulation
- $N(B_c^+)$: determined from fit on $M(J/\psi\pi^+)$
- $\varepsilon(B_c(1P)^+ \to B_c^+\gamma)$: estimated with simulation, differs in $B_c(1P)^+ \to B_c^+\gamma$ and $B_c(1P)^+ \to B_c^{*+}(\to B_c^+\gamma)\gamma$
  $\Rightarrow$ **theory-constrained six-peak models** are used
- $N(B_c(1P)^+ \to B_c^+\gamma)$: determined from **theory-constrained** fit on $M(B_c^+\gamma) - M(B_c^+)$
  $\Rightarrow$ provides verification of various QCD models

$\boldsymbol{N(B_c^+) = (18.70 \pm 0.21)\times 10^3}$



✓ $\boldsymbol{B_c^+ \to J/\psi\pi^+}$ **&** $\boldsymbol{B_c^+ \to J/\psi K^+}$: DSCB with tails fixed to simulation

✓ ***Background***: exponential function

Theory-constrained mass fits (I)

For a given theoretical model,

- ➢masses fixed to prediction
- ➢relative yields of six peaks fixed as $N_i = \sigma_{\text{prod},i} \cdot \mathcal{B}_i \cdot \varepsilon_i$

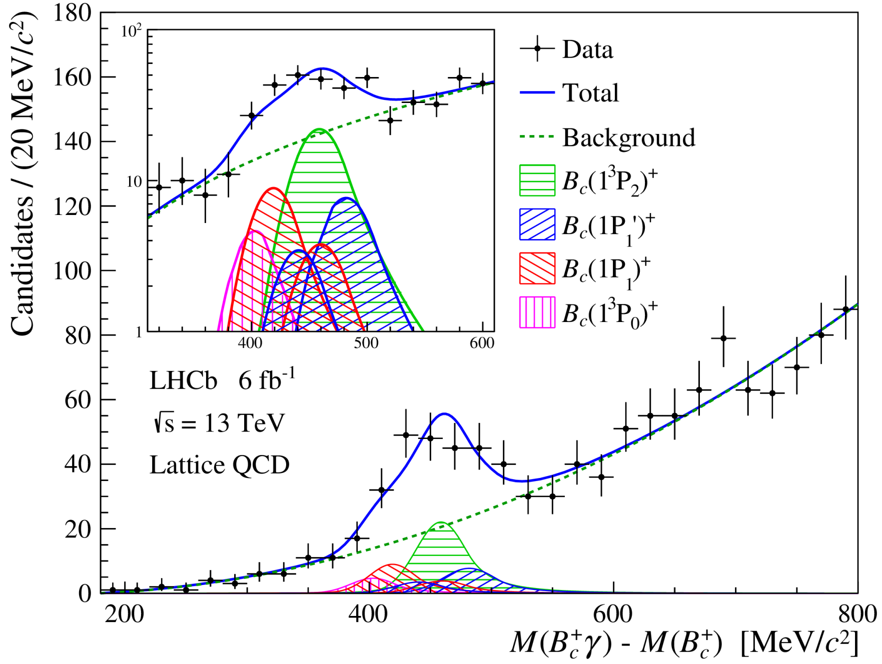
	1^1S_0	1^3S_1	1^1P_1	1^3P_0	1^3P_1	1^3P_2	^1S_0g	^3S_1g	2^1S_0	2^3S_1
σ_{prod} [nb]	18.8	48.7	3.5	1.1	2.7	7.2	0.4	1.55	4.5	11.1

- ✓calculated using BcVegPy [Comput. Phys. Commun. 197 (2015) 335]
- ✓$B_c(2S)^+ \to B_c(1P)^+$ feeddown is considered
  - ✓$\mathcal{B}_i$: obtained from GI model with masses and mixing angle modified for each specific model [PRD 70 (2004) 054017]
  - ✓ε_i: estimated with simulation

◆All considered models provide a generally good description, with p-values ranging from 15% to 90%

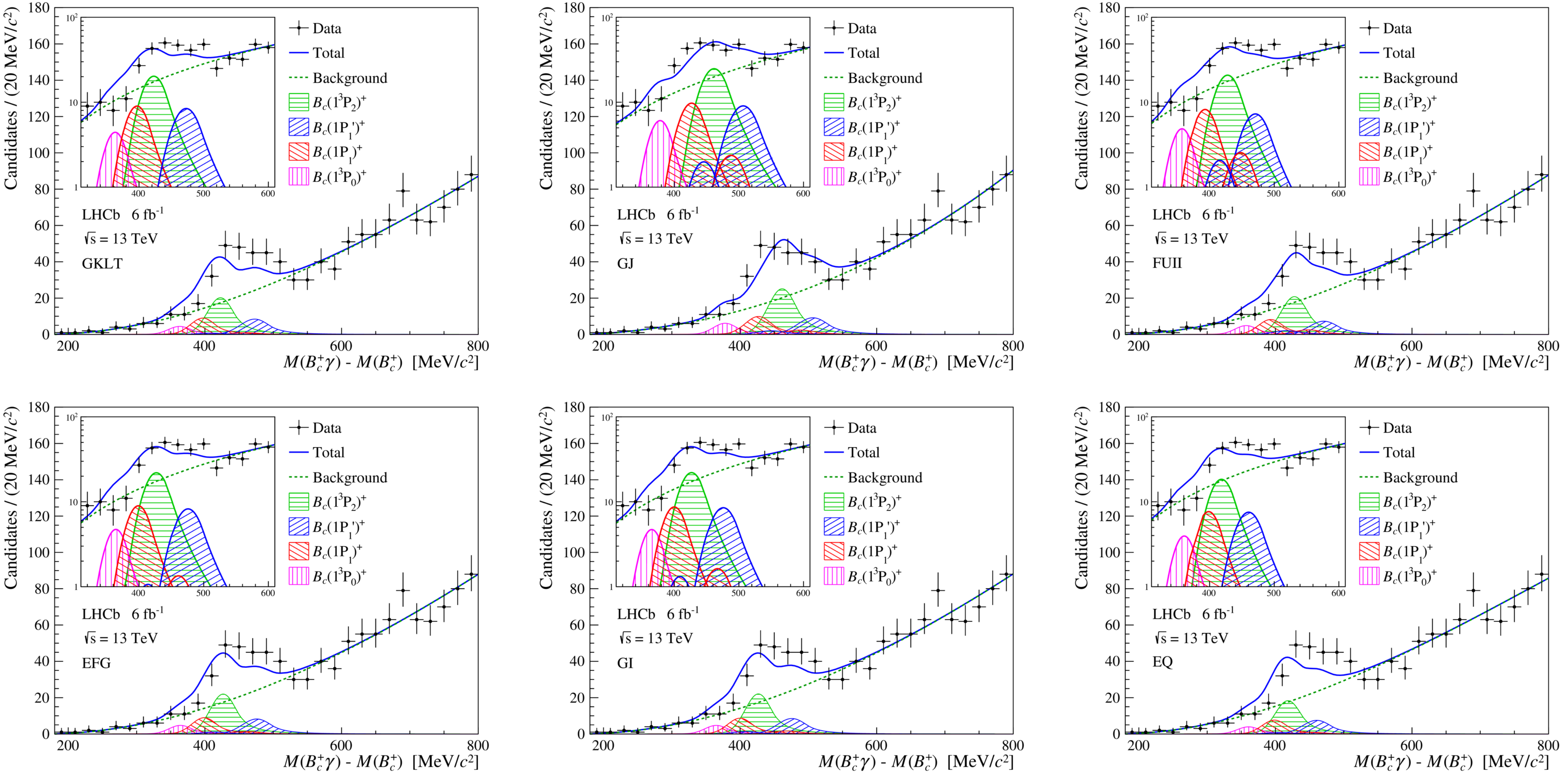
◆**Lattice QCD calculation** by *Davies et al.* is taken as baseline, as it is first-principle & provides highest p-value

	δM	$M(1^3P_0)$	$M(1P_1)$	$M(1P_1')$	$M(1^3P_2)$	θ [°]
Lattice QCD	41	6727	6743	6765	6783	33.4
GKLT	64	6683	6717	6729	6743	17.1
GJ	61	6689	6738	6757	6773	25.6
FUII	55	6701	6737	6760	6772	28.5
EFG	62	6699	6734	6749	6762	20.4
GI	67	6706	6741	6750	6768	22.4
EQ	54	6693	6731	6739	6759	18.7
LLLLGZ	55	6714	6757	6776	6787	35.5
WWLC	55	6705	6739	6748	6762	32.2
LTFWP	53	6712	6770	6761	6783	−24.3
LLWL	67	6701	6745	6754	6773	35.2
HZ	63	6707	6751	6786	6802	55.0

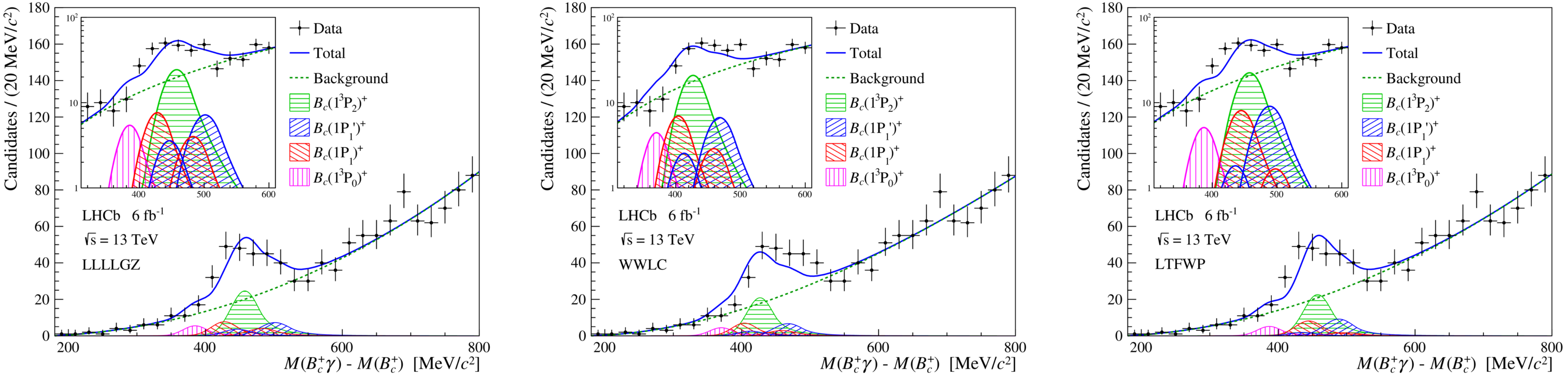


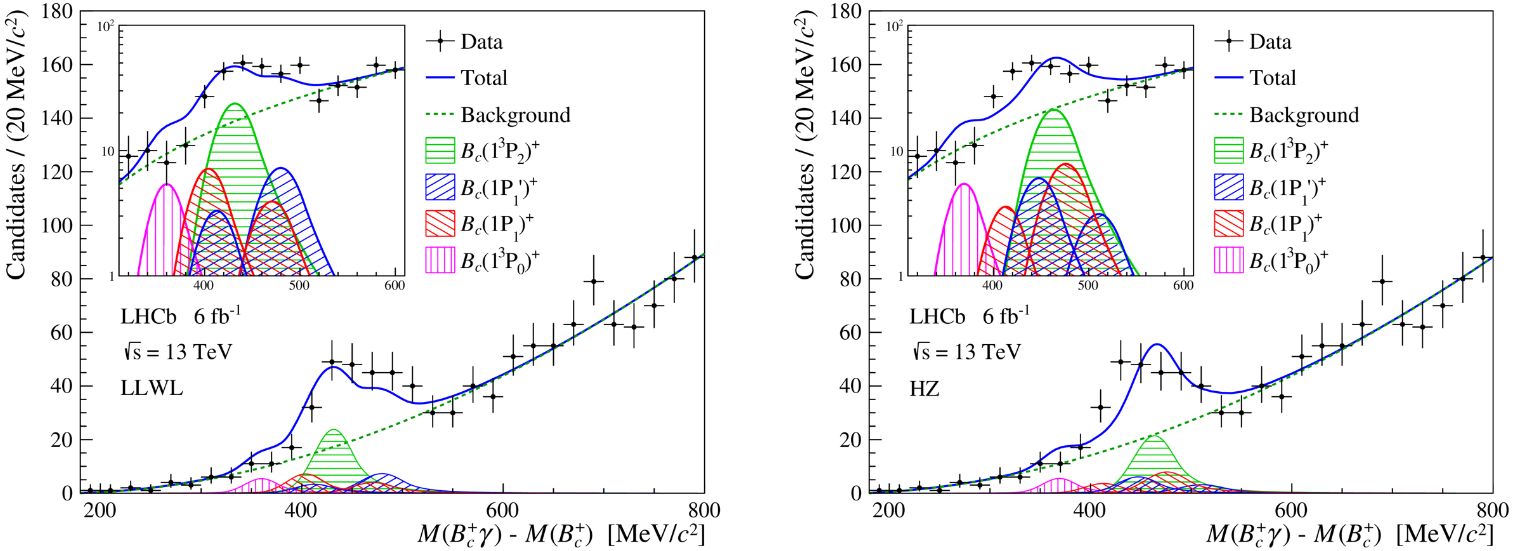
$N = 153 \pm 22$

Theory-constrained mass fits (II)



Theory-constrained mass fits (III)



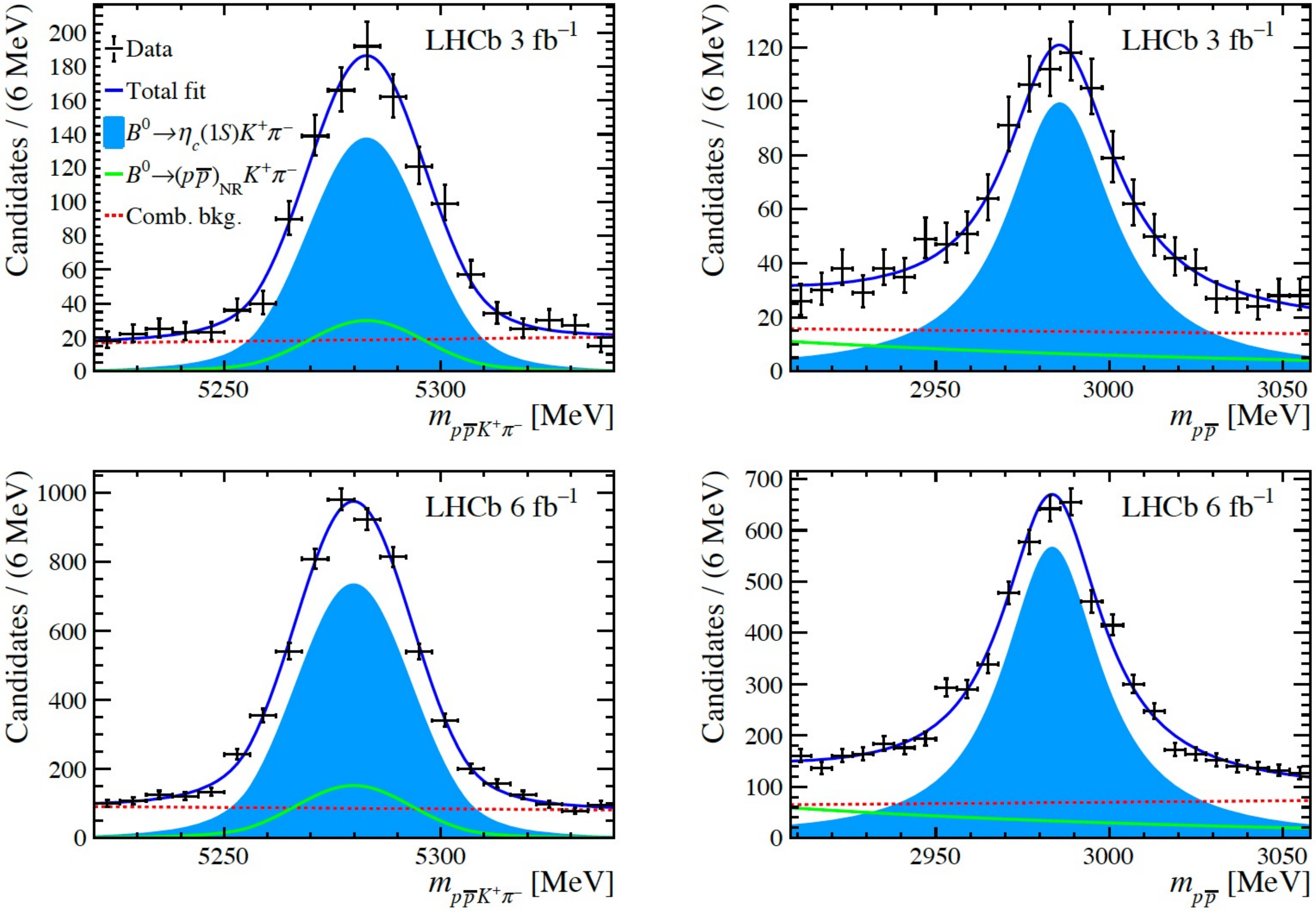


*The fit quality is not solely due to **mass predictions**, but also affected by the **relative yields of six peaks**, according to predictions on ***production***, ***branching fractions*** and ***mixing angle***

[arXiv: 2509.03133]
submitted to EPJC

Amplitude analysis of $B^0 \to \eta_c(1S)K^+\pi^-$

	Yields	
Component	Run 1	Run 2
$B^0 \to \eta_c K^+\pi^-$	772 ± 70	4266 ± 139
$B^0 \to p\overline{p}K^+\pi^-$	168 ± 69	823 ± 139
Combinatorial background	361 ± 34	1665 ± 68

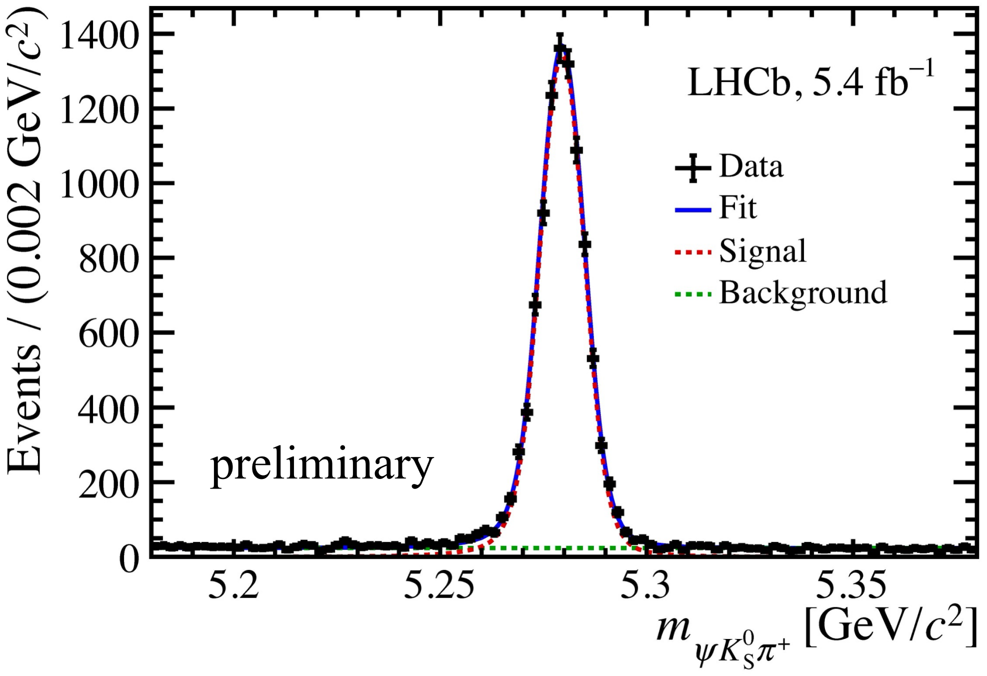


[LHCb-PAPER-2025-039]
in preparation

$T_{c\bar{c}1}(4430)^+$ in $B^+ \to \psi(2S)K_S^0\pi^+$

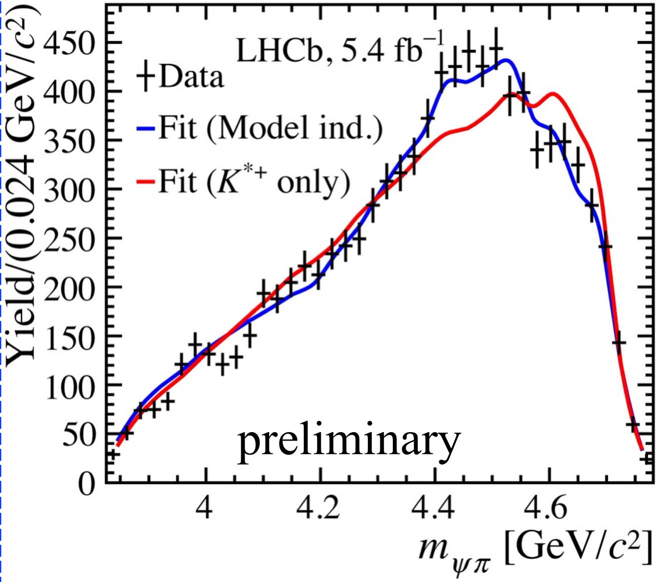
Shuang Zheng
Yanxi Zhang

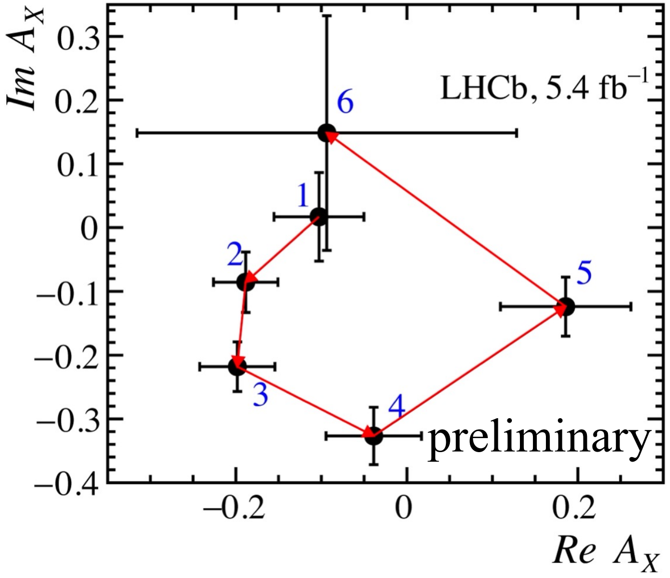
- First four-dimensional amplitude analysis of $B^+ \to \psi(2S)K_S^0\pi^+$ is performed using 5.4 fb^{-1} Run2 data
  - ✓ related via isospin symmetry to $\bar{B}^0 \to \psi(2S)K^-\pi^+$ where the first charged charmonium-like state $T_{c\bar{c}1}(4430)^+ (Z_c(4430)^+, J^P = 1^+)$ was seen [PRL 100 (2008) 142001] [PRL 112 (2014) 222002]



$N = 9600 \pm 100$

Model independent





✓ discrepancy resolved by adding $\psi(2S)\pi^+$ component showing resonant behavior

$T_{c\bar{c}1}(4430)^+$ in $B^+ \to \psi(2S)K_S^0\pi^+$

[LHCb-PAPER-2025-039]
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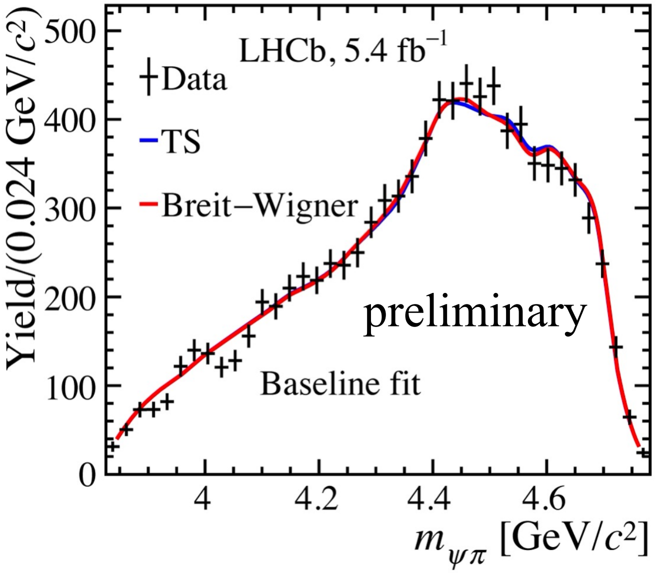
Model dependent



✓ **Breit Wigner:**

$$M = 4.452 \pm 0.016^{+0.055}_{0.033}\ \text{GeV}$$
$$\Gamma = 0.174 \pm 0.019^{+0.083}_{-0.020}\ \text{GeV}$$
$$f = (3.7 \pm 0.6^{+4.0}_{-0.7})\%$$
$$J^P = 1^+$$

consistent with $T_{c\bar{c}1}(4430)^+$

◆ **Molecular scenario**

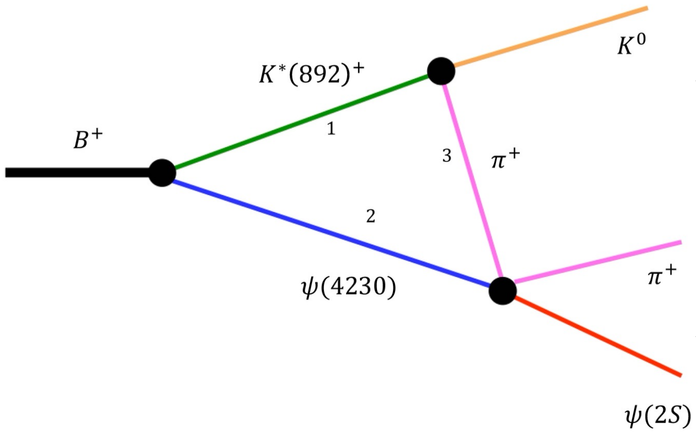
Flatté model to take into account opening of $\bar{D}_1^*(2600)^0 D^+$ decay

$$F = \frac{1}{m_f^2 - m^2 - i(\rho_1 g_1^2 + \rho_2 g_2^2)}$$

g_1: coupling to $\psi(2S)\pi^+$
g_2: coupling to $\bar{D}_1^*(2600)^0 D^+$

$$g_2 = 0.00 \pm 1.78 \pm 2.81\ \text{GeV}/c^2, \left|\frac{g_2}{g_1}\right| < 6.8\ @\ 95\%\ \text{CL}$$

◆ **Triangle singularity mechanism**



✓ Amplitude obtained through integration over the triangle diagram, leaving no free parameter other than an overall complex coupling
✓ A reasonable description is achieved