



Università
di **Genova**

Status and future prospects on heavy spectroscopy at LHCb

Elisabetta Spadaro Norella

University & INFN Genova

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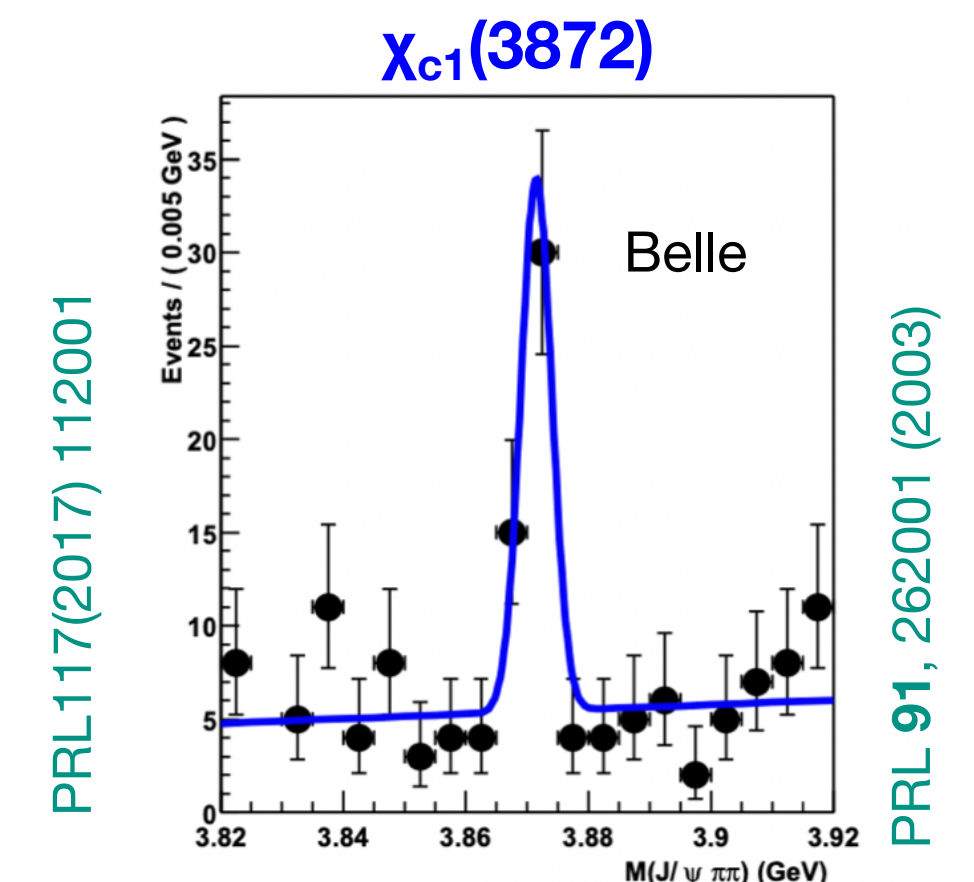
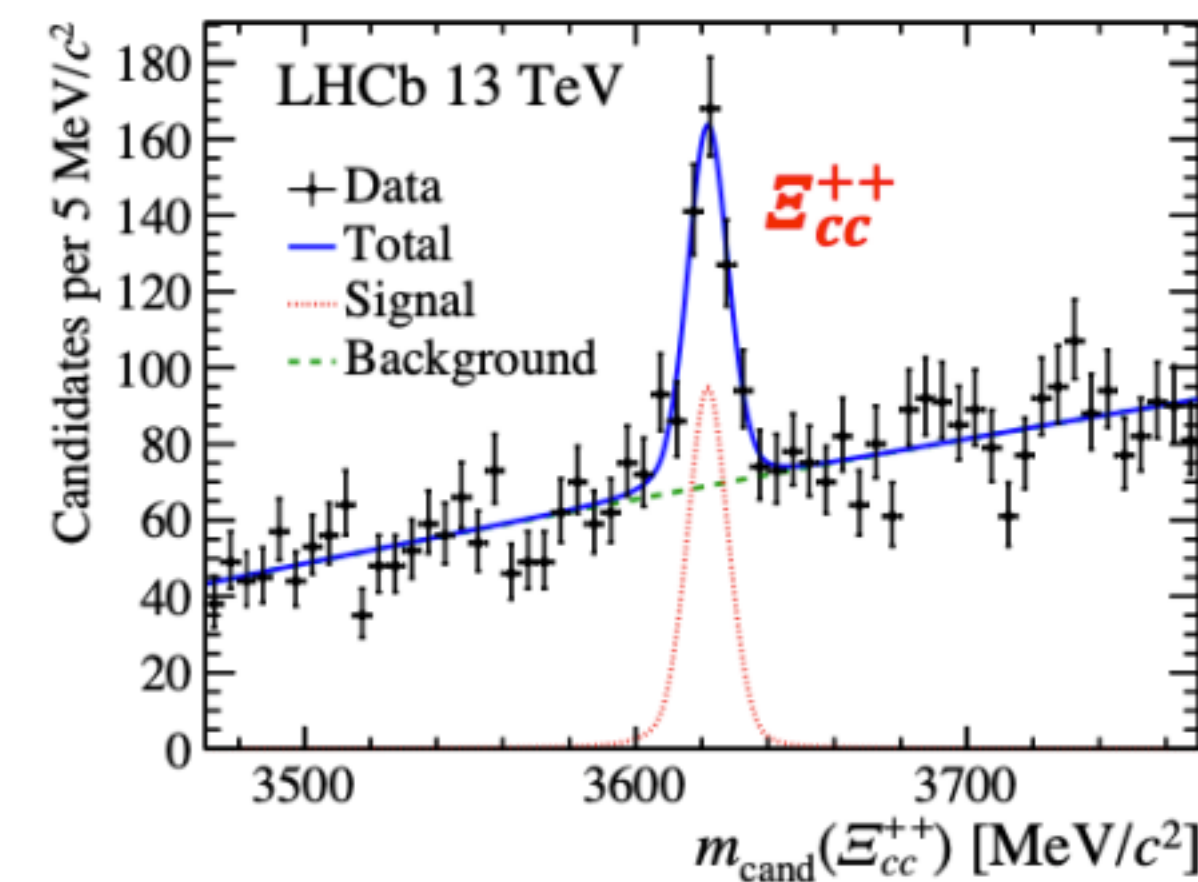
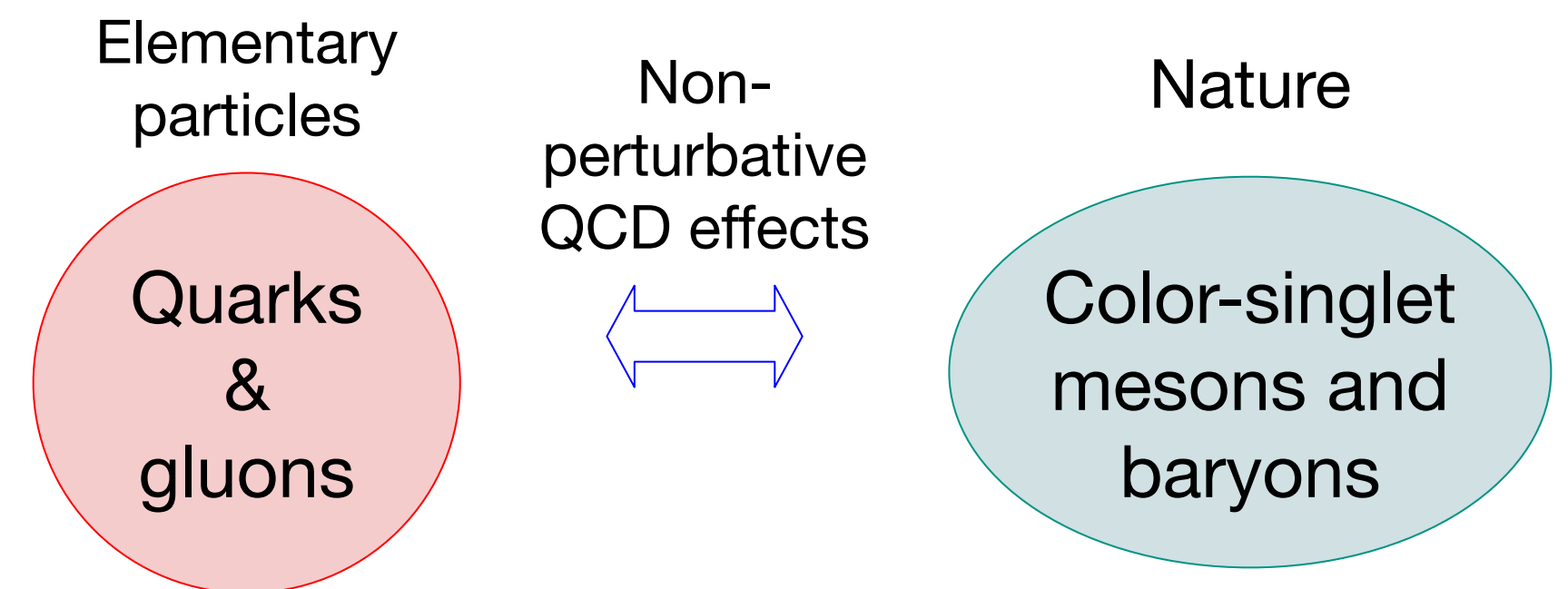
Heavy Hadron spectroscopy

Spectroscopy is a powerful tool to understand QCD at the energy scale of nuclei and hadrons

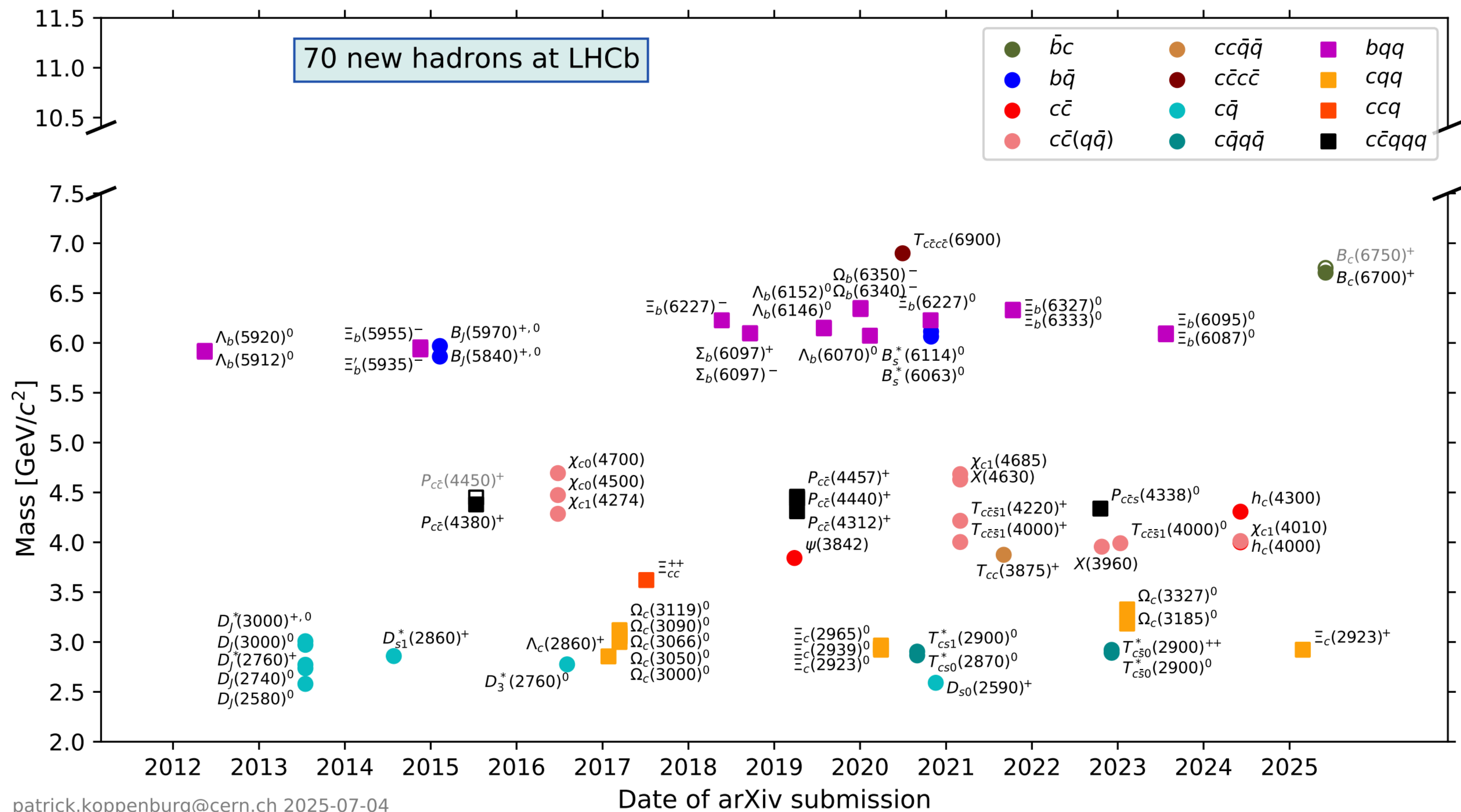
To understand composite matter we study

- conventional and exotic particles/resonances
- existing and new particles/resonances
- in different production mechanisms: from b-hadron decays to prompt production

LHCb benefits from its precision and the LHC's large beauty and charm production in the forward region



New hadrons at LHCb



[Link](#)

LHCb detector

The major player in spectroscopy thanks to its unique dedicated design

- high invariant mass resolution
- PID for separate K , π , p
- highly performant trigger

[JINST 3 \(2008\) S08005](#)

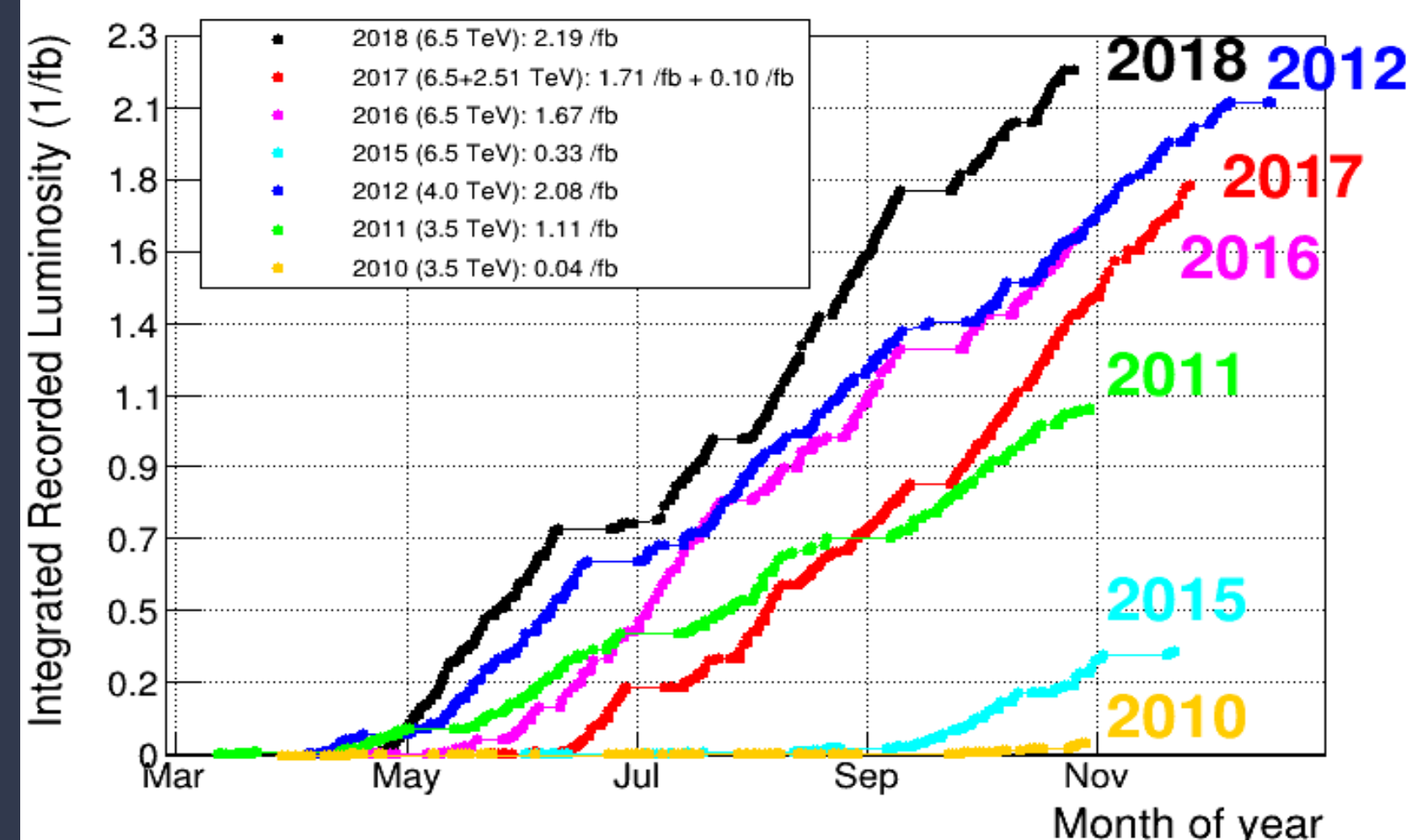
[IJMP A 30, 1530022 \(2015\)](#)

Tracking: momentum resolution of $\sigma_p / p \sim 0,5 - 1\%$

VELO: vertex detector
IP resolution: $\sim 25 \mu\text{m}$

Luminosity:

Run 1 and Run 2: 9 fb^{-1}



Muon chambers, hardware trigger with $\sim 90\%$ efficiency

Calorimeters, hadron trigger with $\sim 50\%$ efficiency

RICH detectors for particle ID. $\text{pid}(p - K) \sim 95\%$

LHCb upgrades

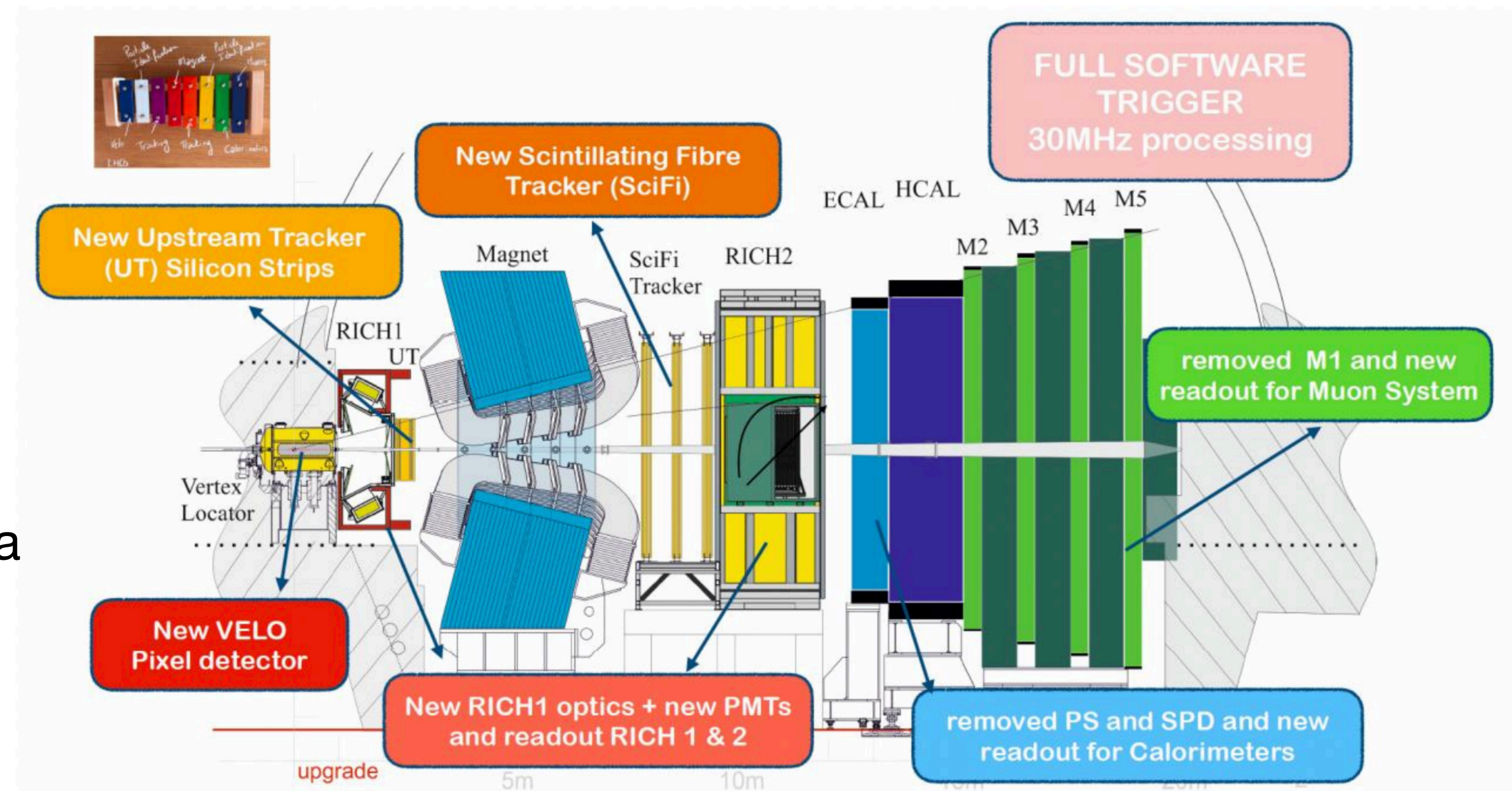


Upgrade I (in Run3 & Run4) -> now at ~end of Run3 ★

Brand-new detector and fully software-based trigger

- x5 luminosity increase: $L = 2 \times 10^{33} \text{cm}^{-2} \text{s}^{-1}$
- Expected luminosity:
 - ⇒ 50fb^{-1} by end of Run4
 - ⇒ 300fb^{-1} by end of Upgrade II (2040)
- Removing the hardware L0 trigger allows triggering on fully hadronic final states, with a ~2–3× improvement in efficiency

LHCb Run 3 detector



The LHCb Upgrade I, JINST 19 (2024) P05065

LHCb upgrades

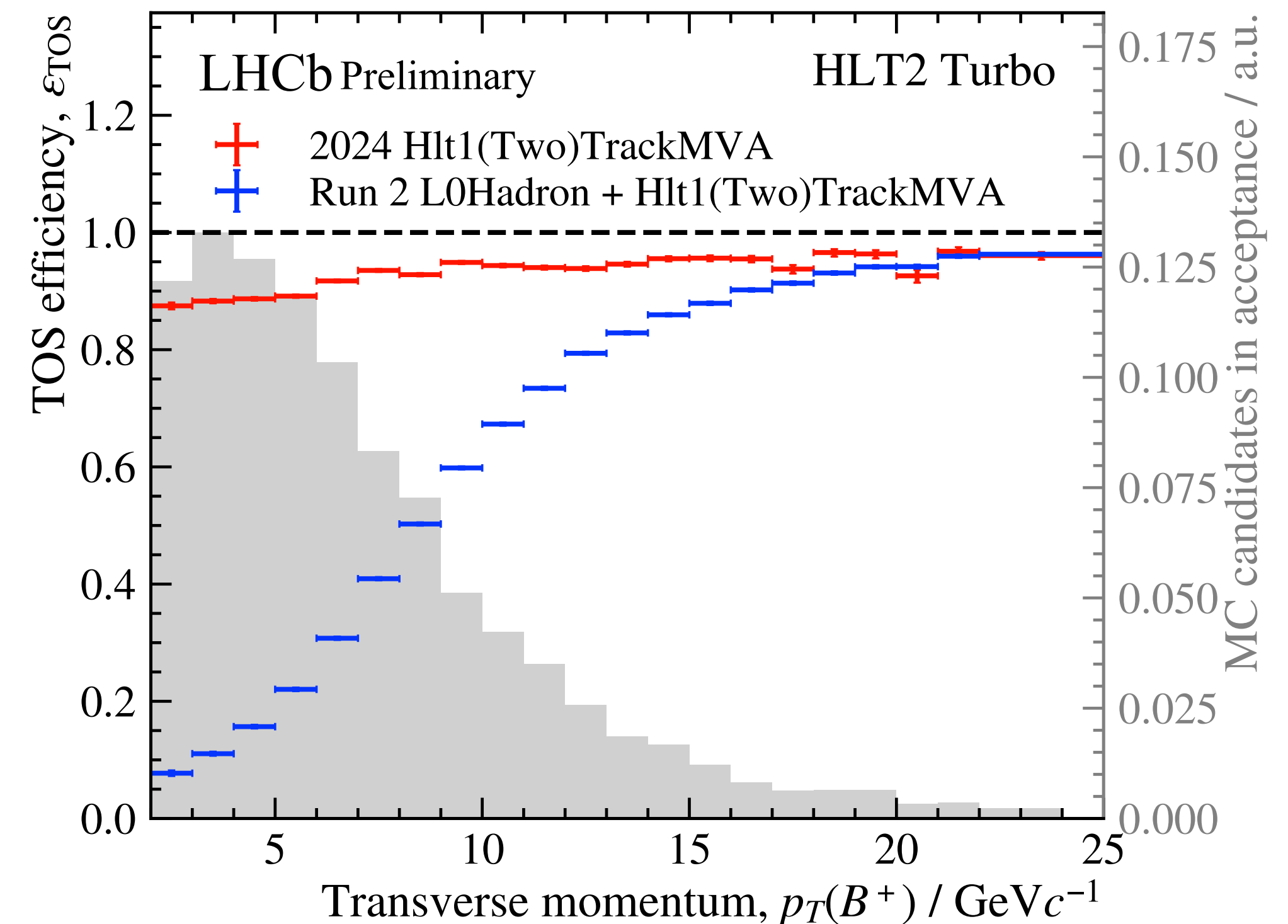


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 - $\Rightarrow 50 \text{ fb}^{-1}$ by end of Run4
 - $\Rightarrow 300 \text{ fb}^{-1}$ by end of Upgrade II (2040)
- Removing the hardware L0 trigger allows triggering on fully hadronic final states, with a $\sim 2\text{--}3\times$ improvement in efficiency

First-level trigger efficiency improvement for B hadrons to $D\pi$ decays compared to Run2



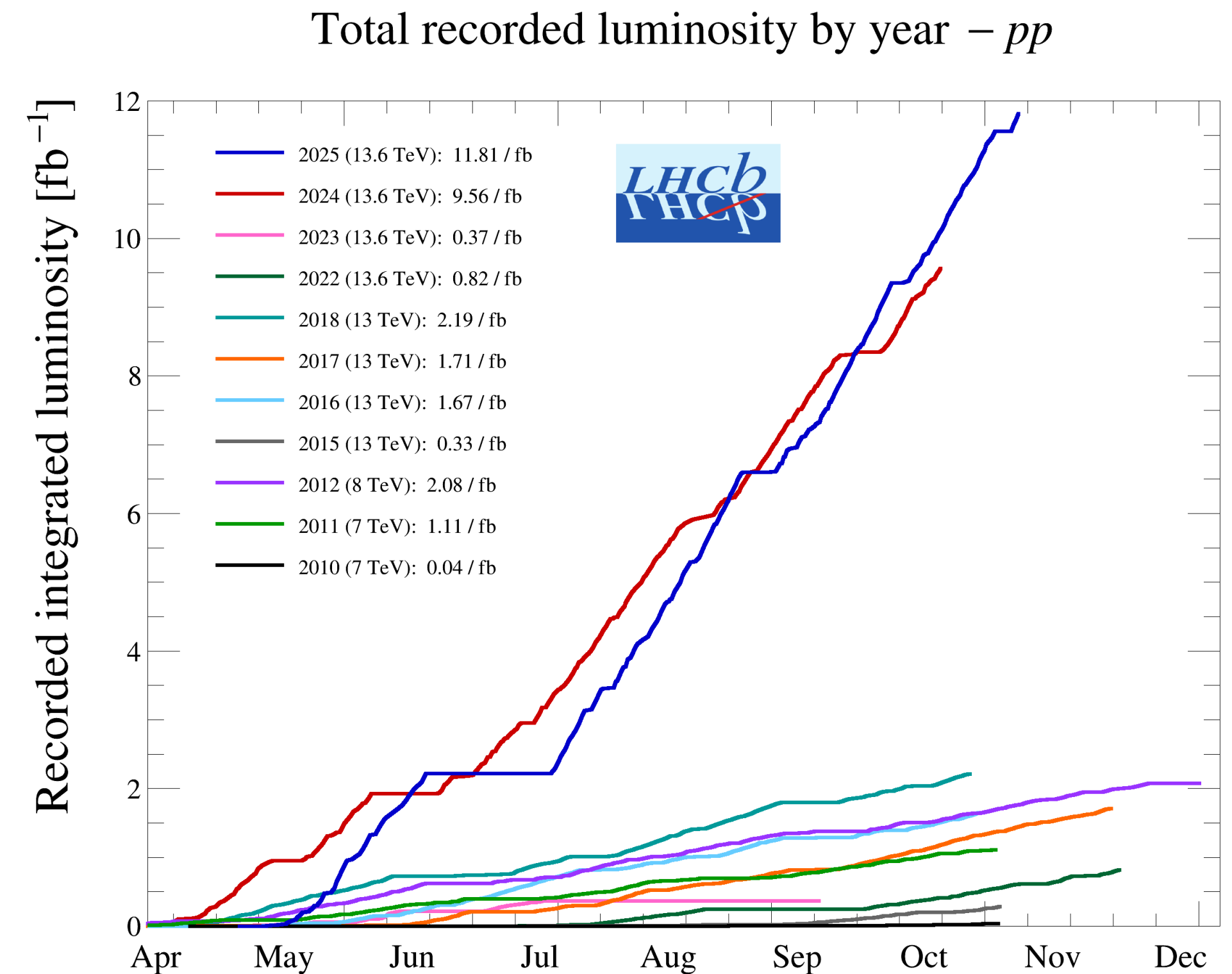
LHCb upgrades



Upgrade I (in Run3 & Run4) -> now at ~end of Run3 ★

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 - ⇒ 50 fb⁻¹ by end of Run4
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Luminosity collected so far: 22 fb⁻¹

⇒ Already about ~3.5x Run2 luminosity

Conventional spectroscopy

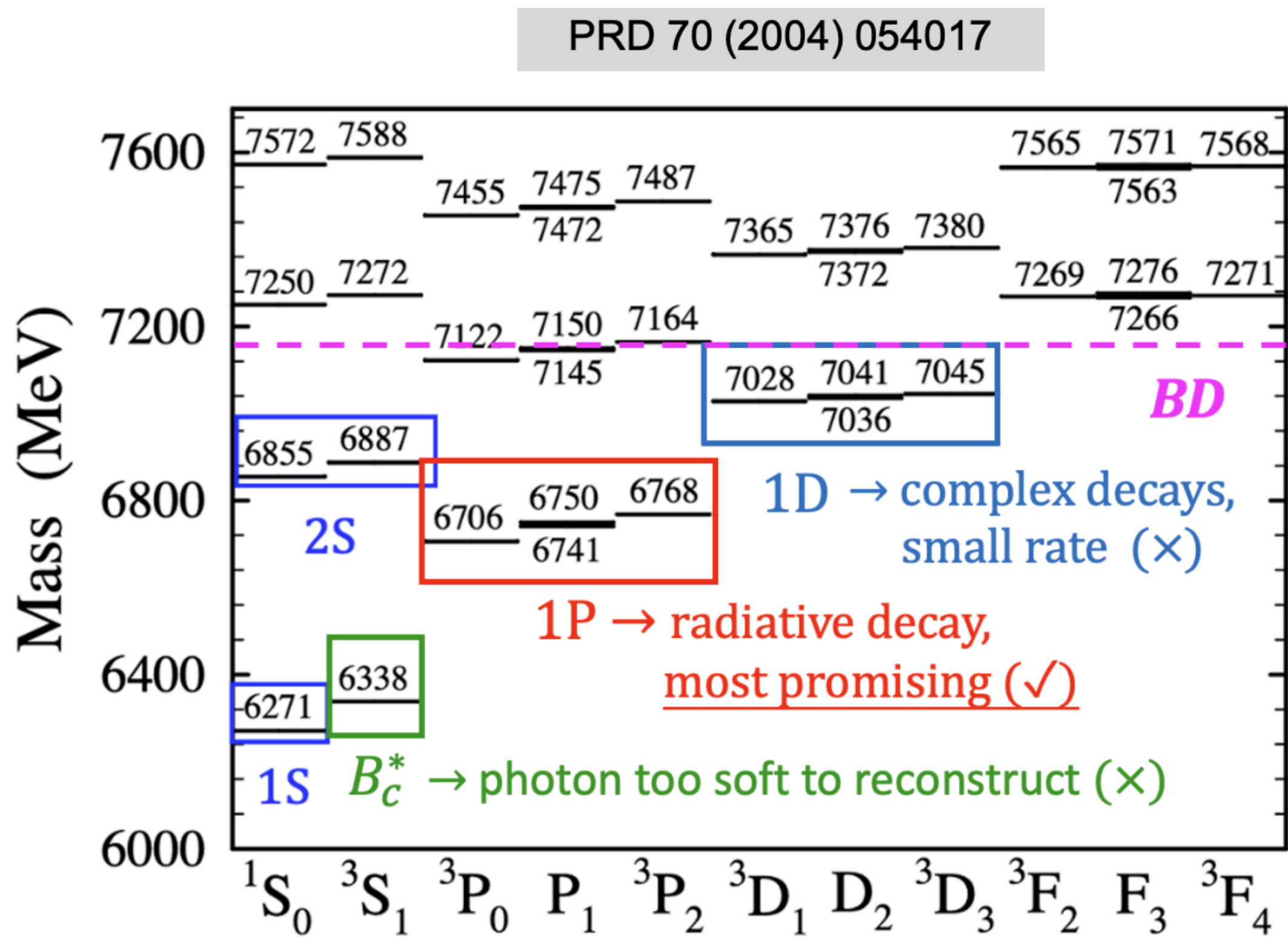
Orbitally excited B_c states

[arXiv:2507.02149](https://arxiv.org/abs/2507.02149)

The B_c^+ meson is the only meson composed of two different heavy quarks (bc), only the 2S excitations are known.

What about 1P? Search for $B_c(1P)^+ \rightarrow B_c^{(*)} + \gamma, B_c^+ \rightarrow J/\psi \pi^+, J/\psi \rightarrow \mu\mu$ in Run 1+2 data

- Four states are expected (but six peaks, due to soft unreconstructed photons from B_c^{*+} decays)



$$(L = 1) \otimes (S = 0, 1) \begin{cases} S = 0 \rightarrow 1^1P_1 \\ S = 1 \rightarrow 1^3P_0, 1^3P_1, 1^3P_2 \end{cases}$$

mixing

Four physical states

$$\begin{pmatrix} 1^3P_0 \\ 1^3P_2 \end{pmatrix} \begin{pmatrix} 1P'_1 \\ 1P_1 \end{pmatrix} = \begin{pmatrix} \cos \theta & \sin \theta \\ -\sin \theta & \cos \theta \end{pmatrix} \begin{pmatrix} 1^1P_1 \\ 1^3P_1 \end{pmatrix}$$

States	1^3P_0	$1P_1$	$1P'_1$	1^3P_2
Decays	$B_c^{*+}(\rightarrow B_c^+ \gamma) \gamma$	$B_c^+ \gamma$	$B_c^+ \gamma$	$B_c^{*+}(\rightarrow B_c^+ \gamma) \gamma$
		$B_c^{*+}(\rightarrow B_c^+ \gamma) \gamma$	$B_c^{*+}(\rightarrow B_c^+ \gamma) \gamma$	
#peaks	1	2	2	1

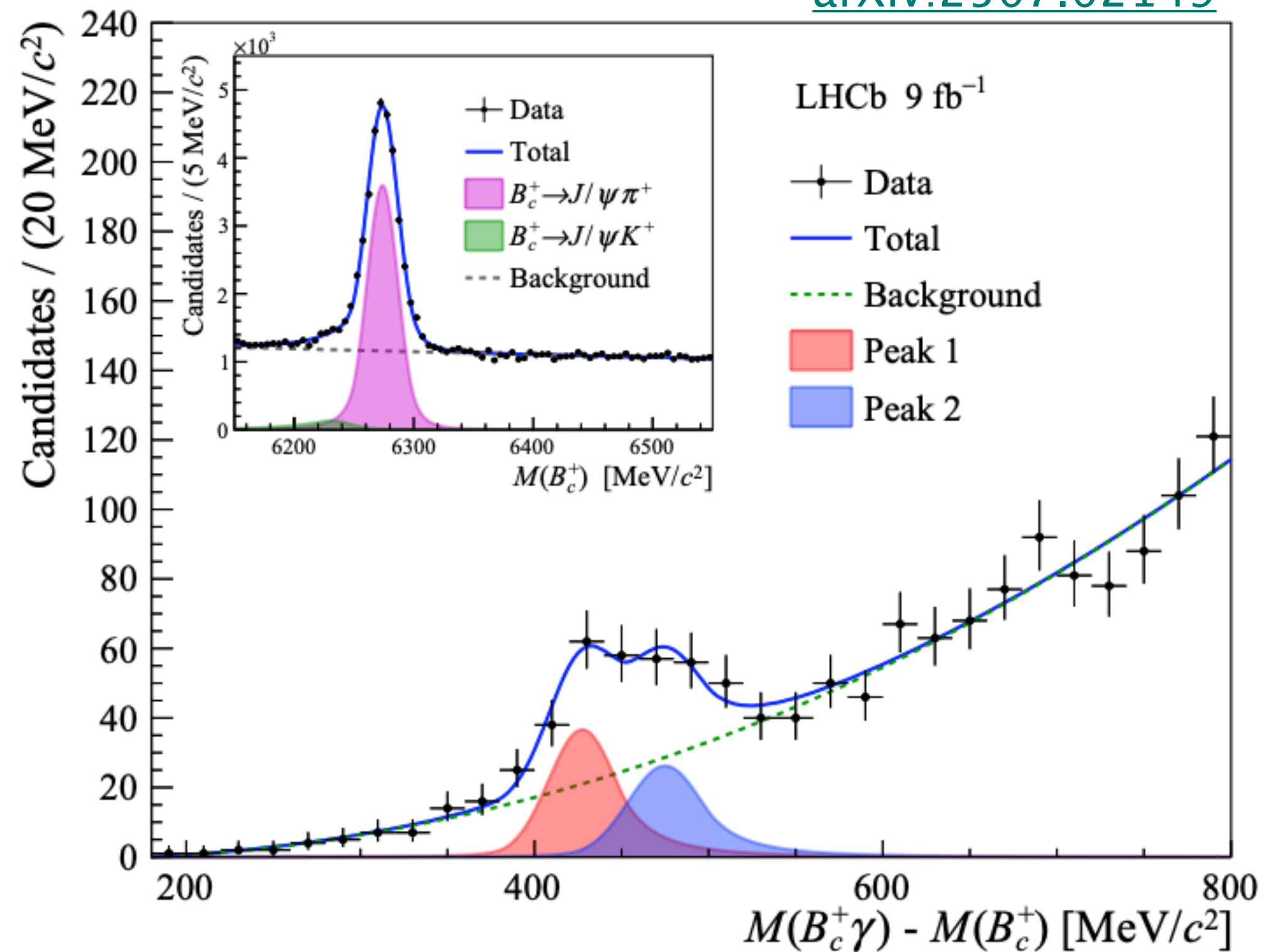
Orbitally excited B_c states

A minimal effective **two-peak model** fit the data, obtained with free masses and widths:

$$m_1 = 6704.8 \pm 5.5 \pm 2.8 \pm 0.3 (B_c \text{ mass}) \text{ MeV}/c^2$$

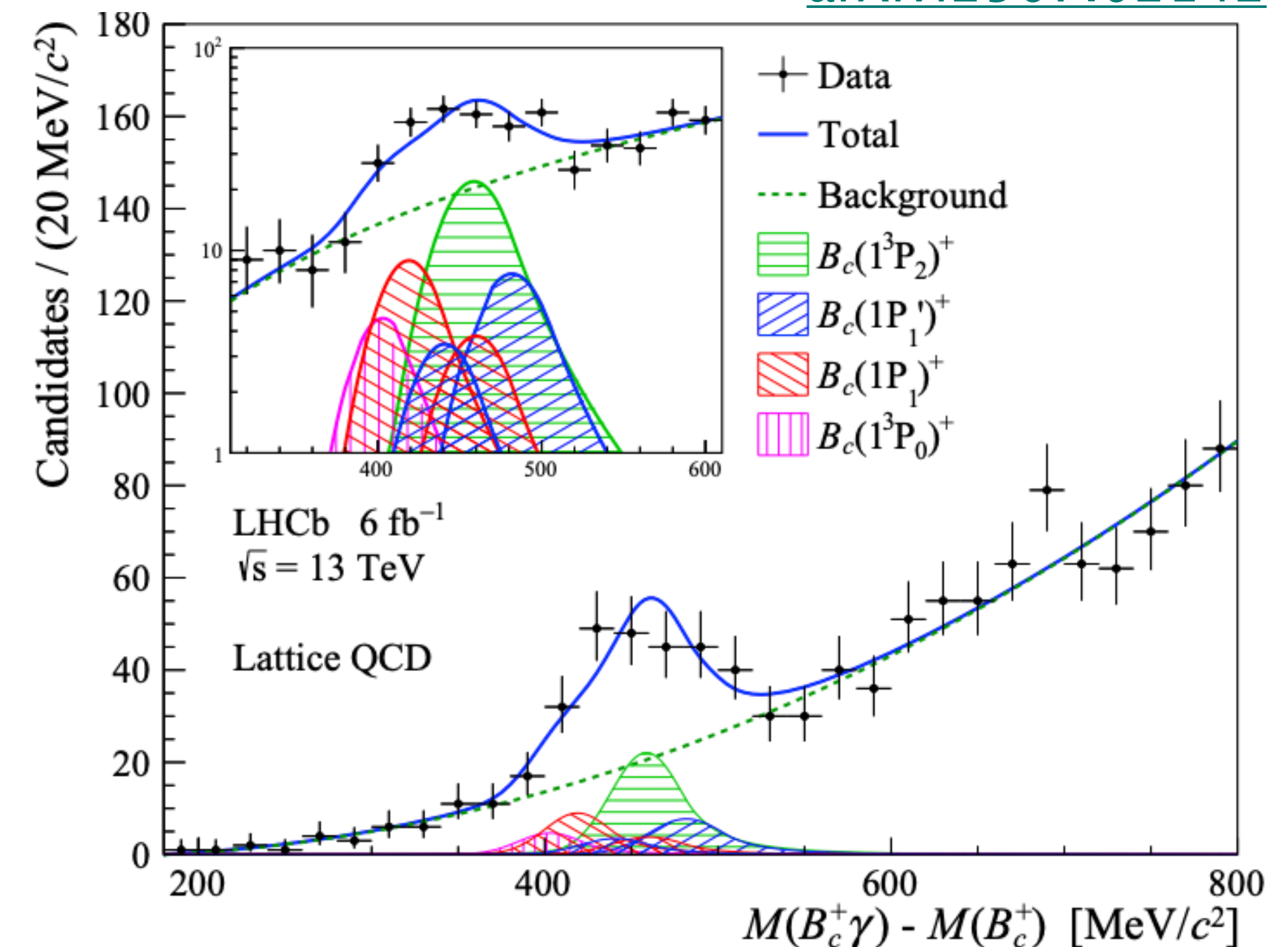
$$m_2 = 6752.4 \pm 9.5 \pm 3.1 \pm 0.3 (B_c \text{ mass}) \text{ MeV}/c^2$$

[arXiv:2507.02149](https://arxiv.org/abs/2507.02149)



Alternative models with 6 peaks all compatible with data,
By fixing masses and relative yields to theoretical expectations

[arXiv:2507.02142](https://arxiv.org/abs/2507.02142)



Relative production cross-section of $B_c(1P)^+$ states compared to B_c^+ :

$$R = 0.20 \pm 0.03 \pm 0.02 \pm 0.03 \text{ (model)}$$

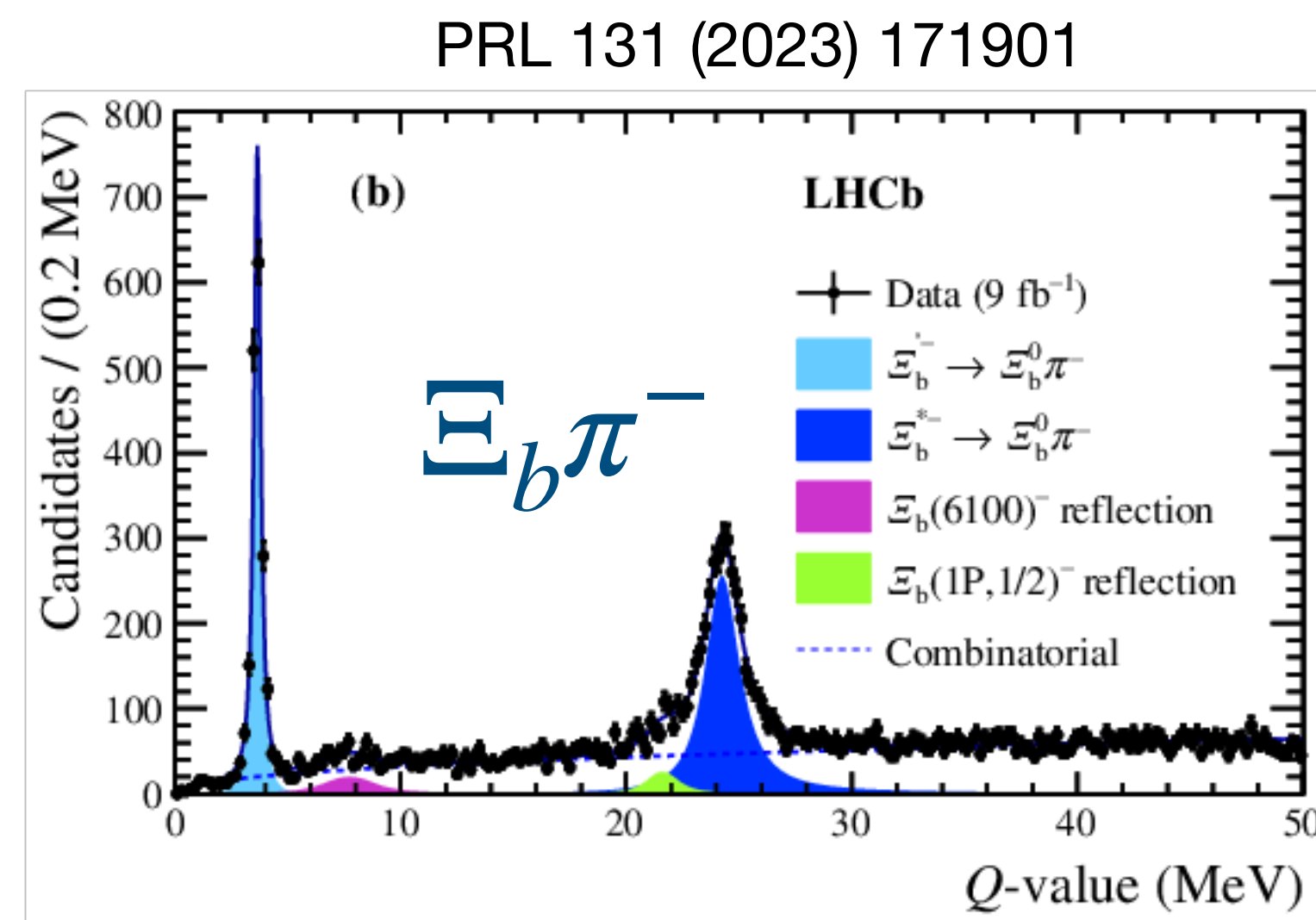
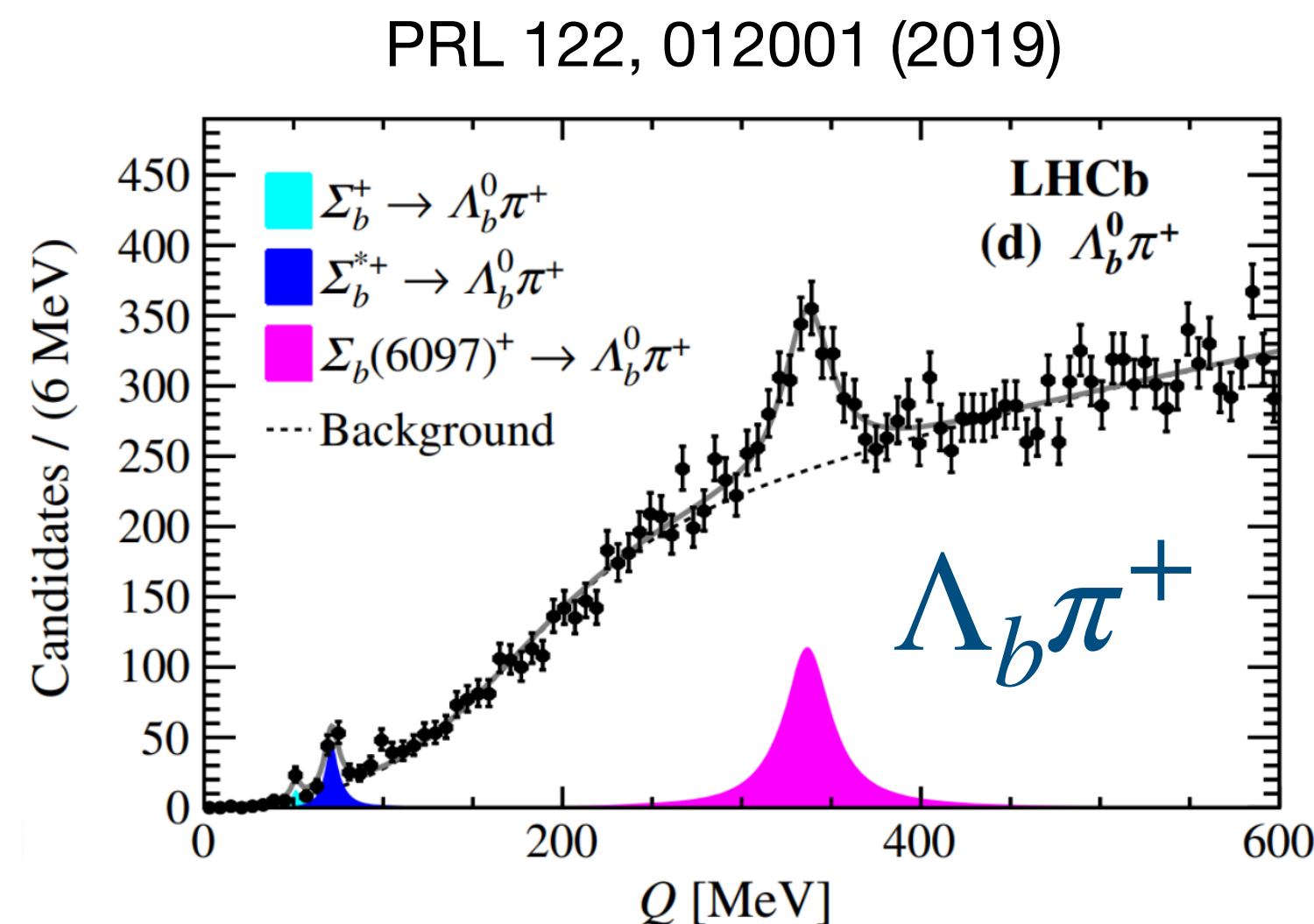
$$(p_T < 20 \text{ GeV}/c \text{ and } 2 < \eta < 4.5)$$

Spectroscopy in beauty

Besides the $B_c\gamma$ channel, a plethora of spectroscopy analyses in beauty are behind the corner:

- Excited $B_{(s)}^0$ and B^+ in $B\pi^0/\gamma$: CMS published results in $B\gamma$ ([arxiv:2508.05820](https://arxiv.org/abs/2508.05820))
- Baryon excitations of Σ_b , Ξ_b in $\Lambda_b\pi^{0/+}$ and $\Lambda_b\pi\pi$, etc.

LHCb analyses: [PRL 122, 012001 (2019), JHEP 06(2020)136, JHEP 06(2020)136, PRL 131 (2023) 171901]



All good channels for Run3 thanks to the trigger on multi-hadron final states

Expected an yield ~x6 (with at least x2 yield/fb)

- Search for **doubly-heavy hadrons**: Ξ_{bc} and Ξ_{bb}
 - First search for $\Xi_{bc} \rightarrow J/\psi\Xi_c$ in LHCb shows only evidences [Chin.Phys.C 47 (2023) 9, 093001]

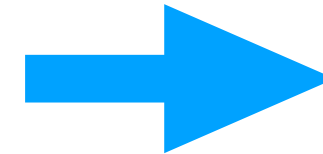
In Run3: Largest sample of b hadrons to conduct searches for higher-mass/excited states!

Spectroscopy in charm

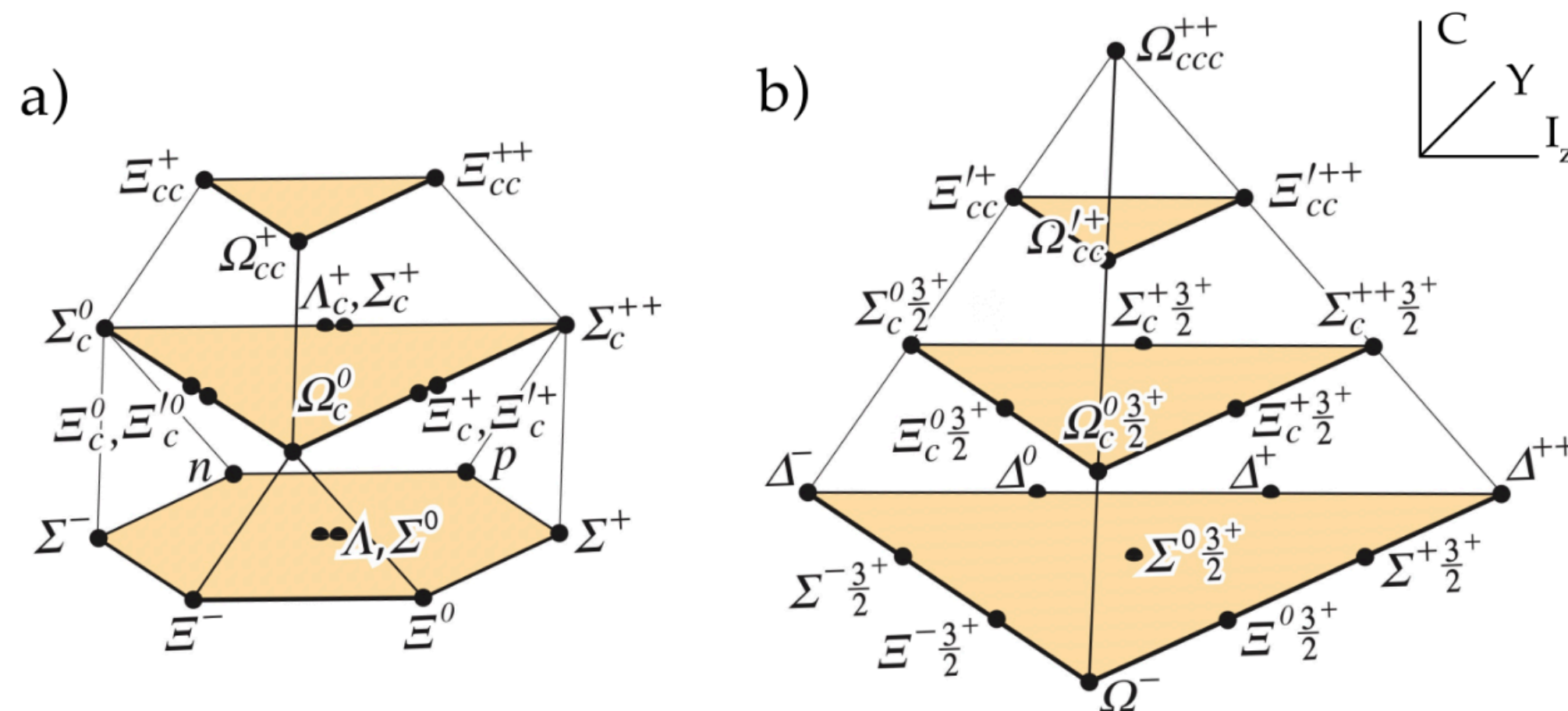
LHCb is also a factory of charm quarks: world's largest samples of inclusively selected charm hadrons

Many studies ongoing for excited charm states:

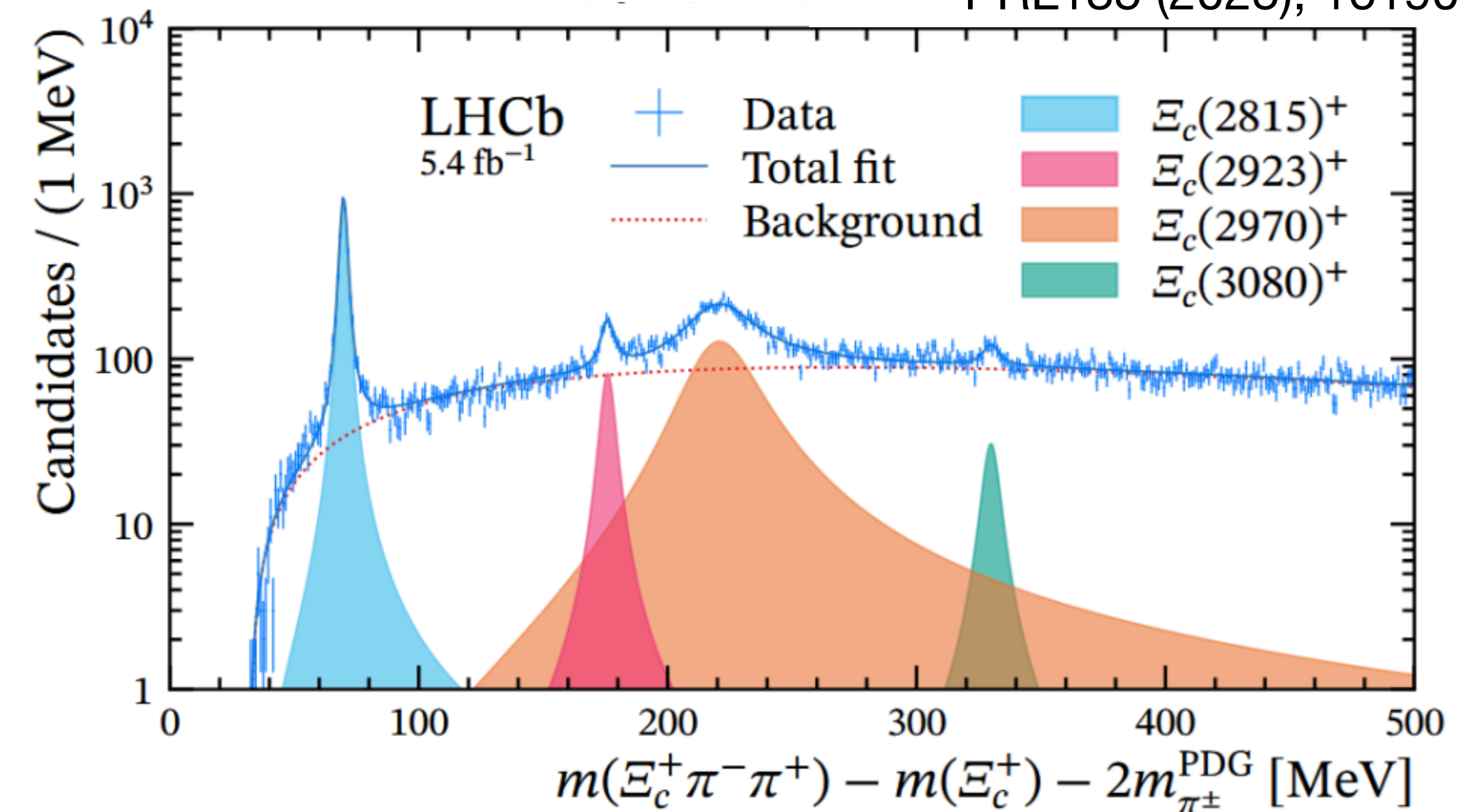
- Discovery of Ξ_{cc}^{++} in 2017 [PRL 119 (2017) 112001]
- Recent results on Ξ_c excited states
 - New $\Xi_c(2923)^+ \rightarrow \Xi_c^+ \pi^- \pi^+$ [PRL135 (2025), 161901]
 - Spin parities $\Xi_c(3055)^{0/+}$ [PRL 134 (2025) 081901]



⇒ Next: search for Ξ_{cc}^+ , Ω_{cc}^+ , Ξ_{cc}^{++} excitations



Prompt $\Xi_c^{**} \rightarrow \Xi_c(2645)^0 (\rightarrow \Xi_c^+ \pi^-) \pi^+$
PRL135 (2025), 161901



Fully hadronic modes have increased efficiency in Run3!

Exotic spectroscopy

Plan of exotic trip

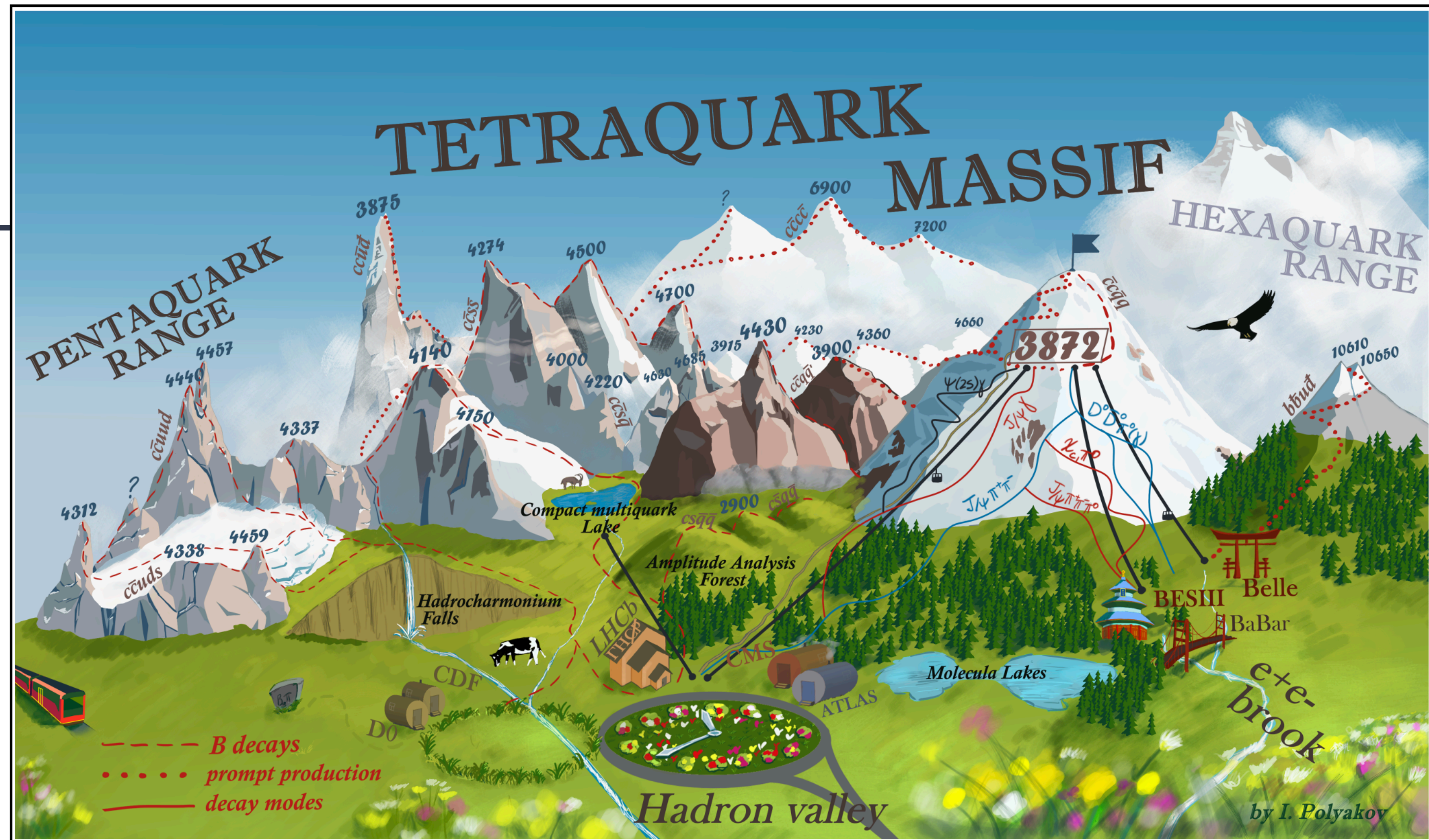
Over the last years, a vast variety of new color-neutral forms (hadrons) is discovered

A brief guide to exotic hadrons

N. Hüsken, E. Spadaro Norella, I. Polyakov

Modern Physics Letters A Vol. 40, No. 17n18, 2530002 (2025)

arXiv:2410.06923



No clear nature, many theoretical phenomenological models :

- Compact tetra/pentaquarks [PRD 71, 014028 (2005), PLB 662 424 (2008)]
 - Hadronic molecules
 - Rescattering effects
- + Lattice-QCD is expected to play a leading role in the future

[PRD 10 (1974) 2445, JHEP 07 (2012) 126...]

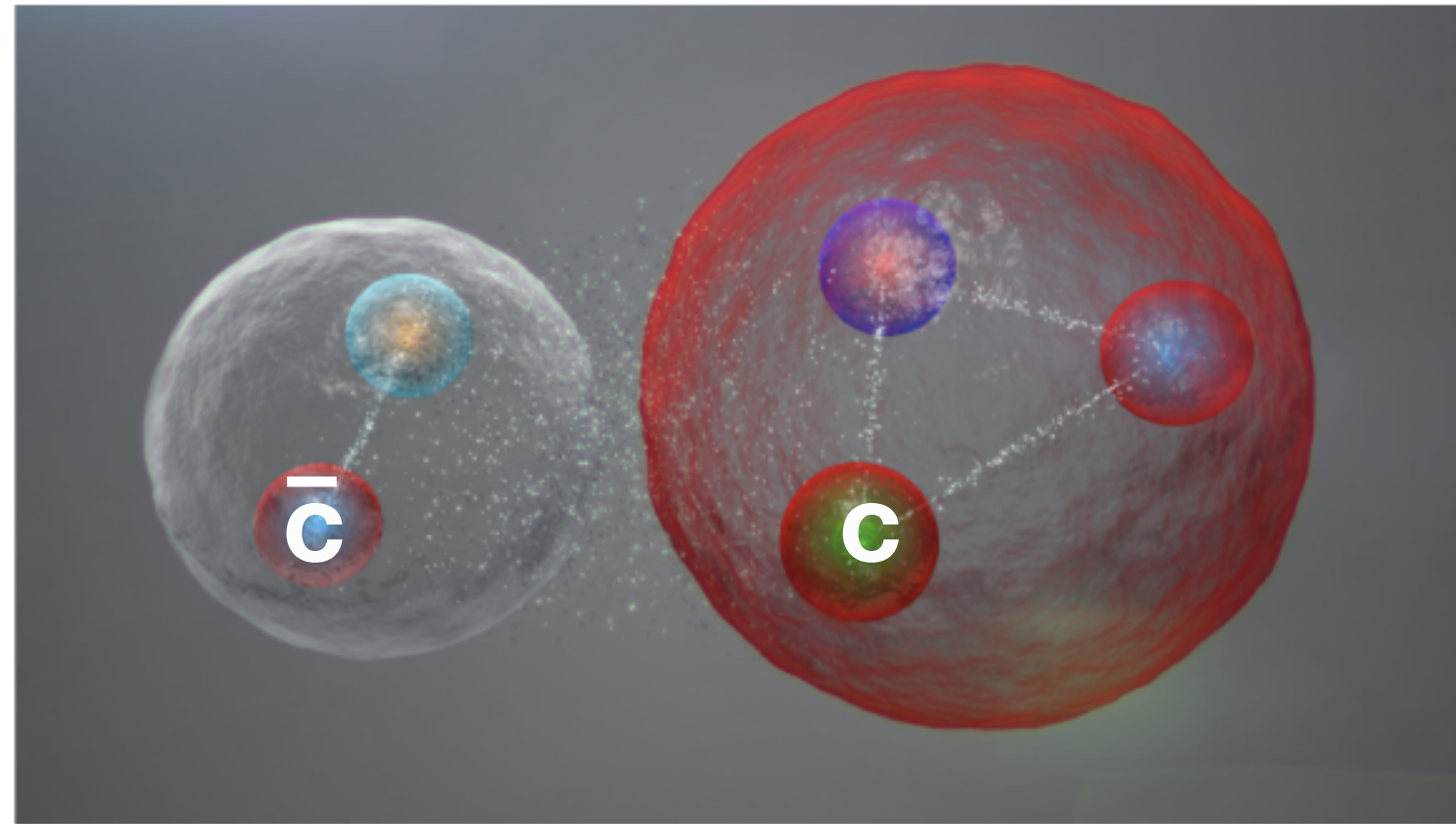
What can we do in experiments?

⇒ Different decays and production

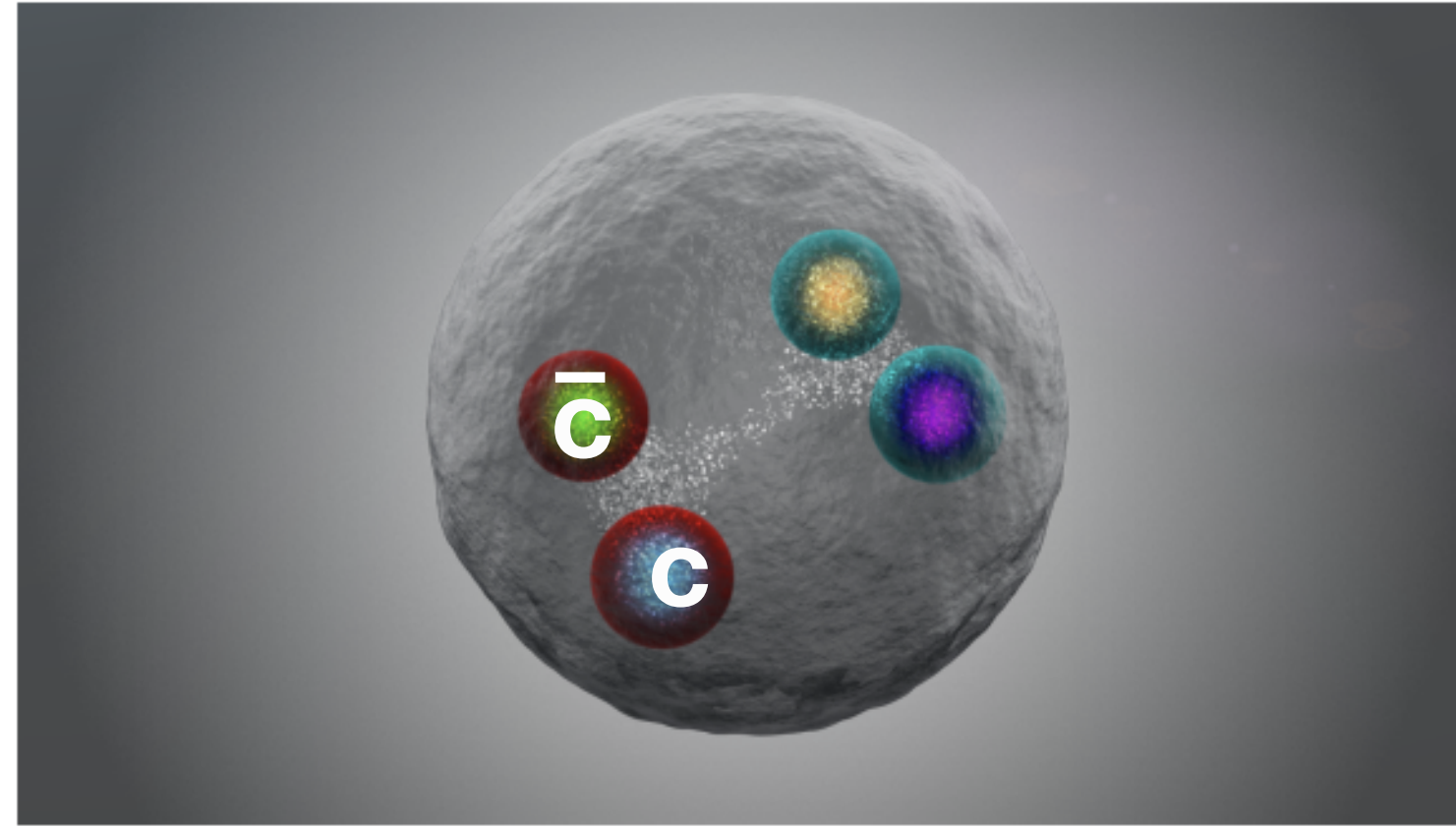
- ⇒ Measure M, Γ, J^P , study lineshape

⇒ Isospin multiplets

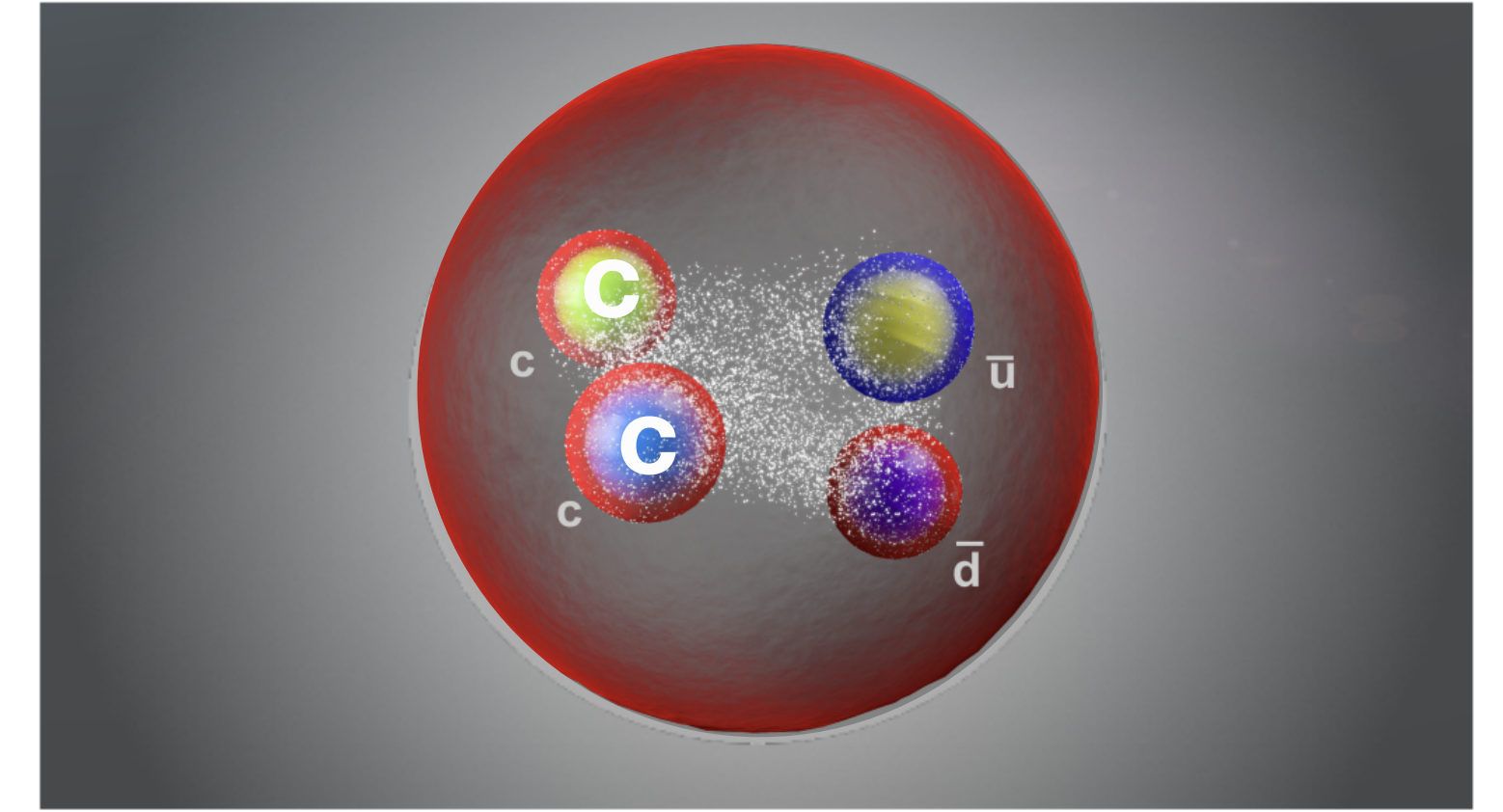
Classifying Exotics...



Hidden-charm pentaquark



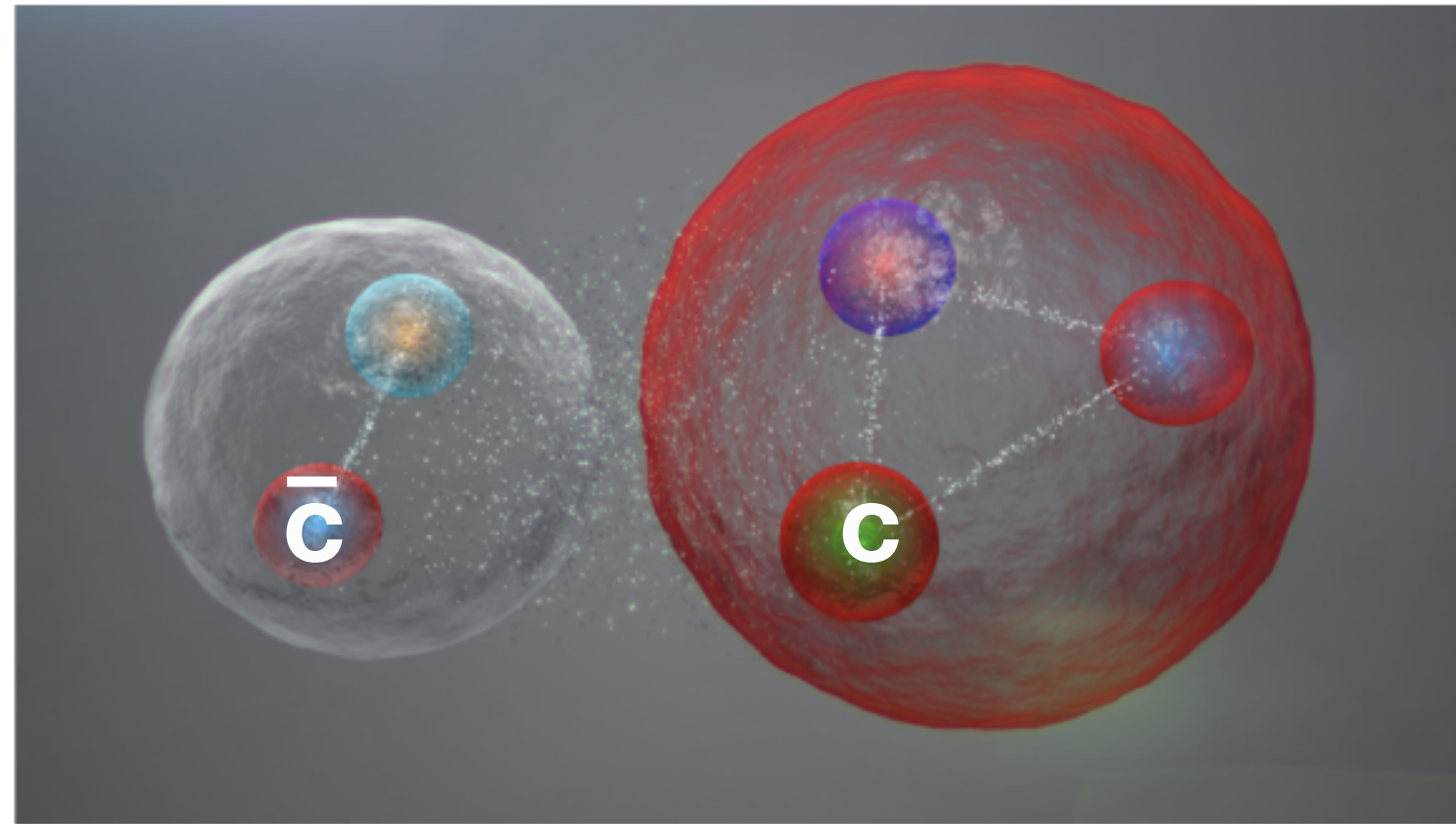
Hidden-charm tetraquarks



Beyond hidden-charm

A selection of some highlights focusing on the prospects in Run3 will be presented

Classifying Exotics...

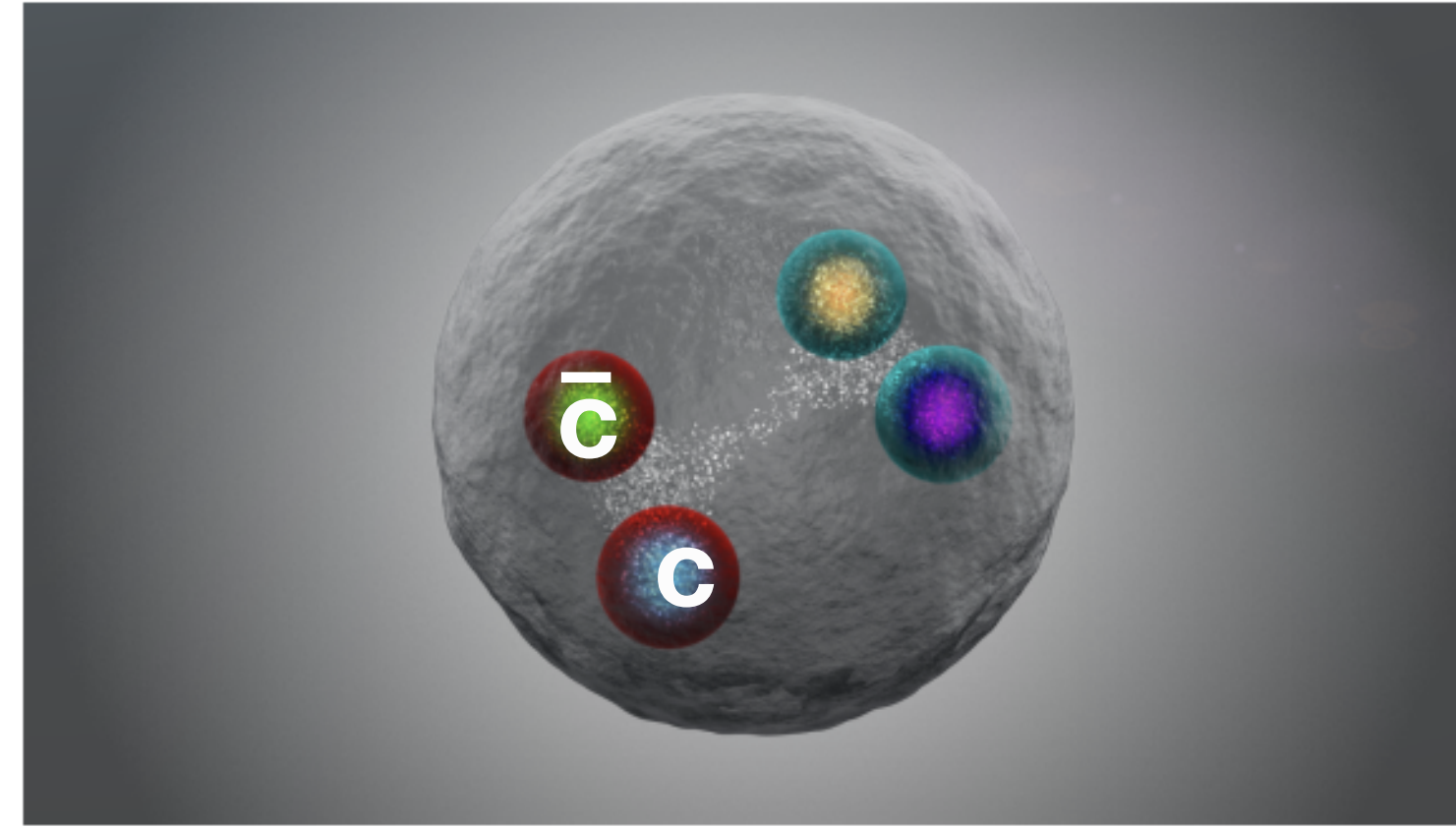


Hidden-charm pentaquark

$P_{c\bar{c}}$ (also known as P_{ψ}^N or P_c)

BARYON-LIKE/HIDDEN CHARM/ISOSPIN=1/2(3/2)
states: $P_{c\bar{c}}(4312)^+$, $P_{c\bar{c}}(4440)^+$, $P_{c\bar{c}}(4457)^+$,
 $P_{c\bar{c}}(4380)^+$, $P_{c\bar{c}}(4337)^+$

PRL 115, 072001 (2015),
PRL 122, 222001 (2019)

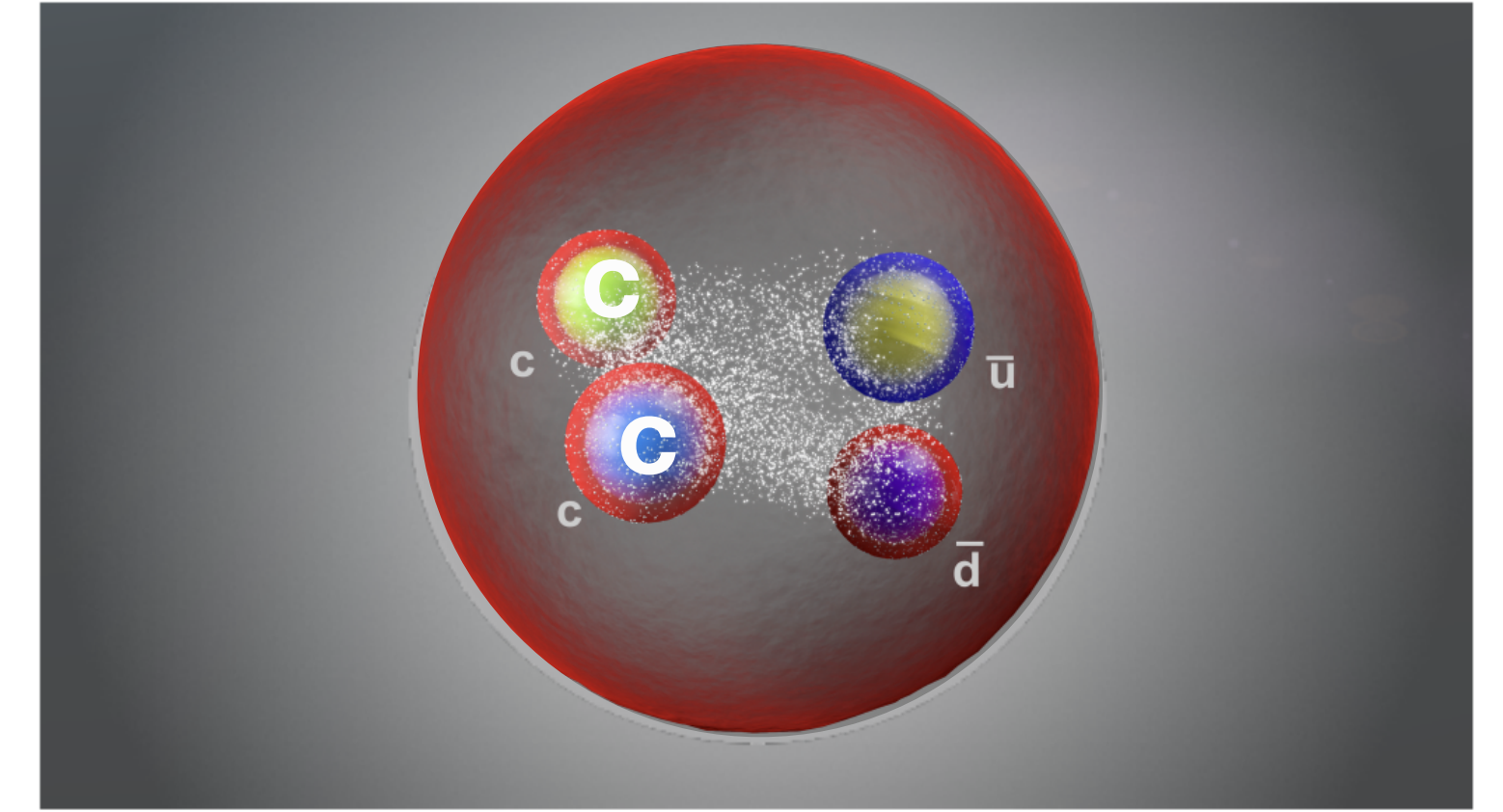


Hidden-charm tetraquarks

$P_{c\bar{c}s}$ (also known as $P_{\psi s}^{\Lambda}$ or P_{cs})

BARYON-LIKE/HIDDEN CHARM/ISOSPIN=0(1)
states:
• $I(J^P) = 0(1/2^-)$: $P_{c\bar{c}s}(4338)^0$
• $I(J^P) = 0(?)$: $P_{c\bar{c}s}(4458)^0$

[PhysRevLett.131.031901](#)

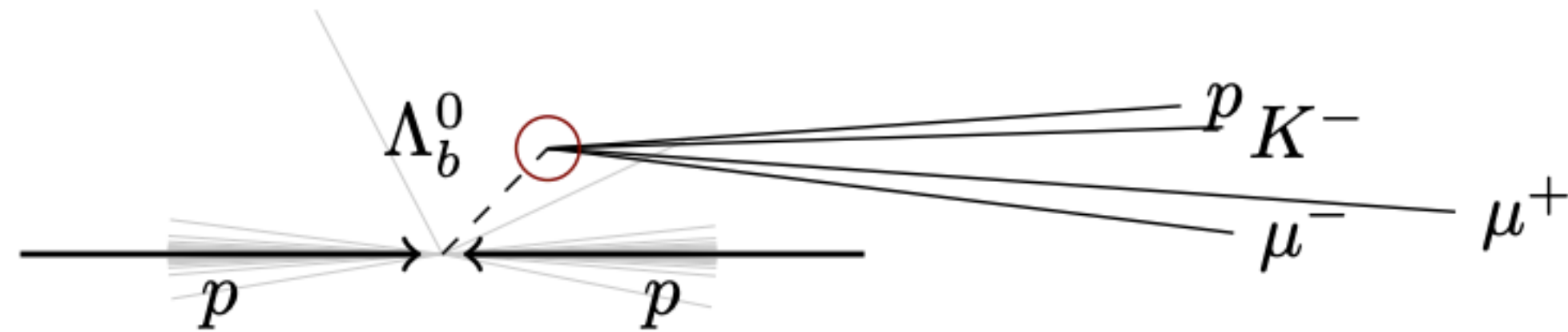


Beyond hidden-charm

The observation of P_c states

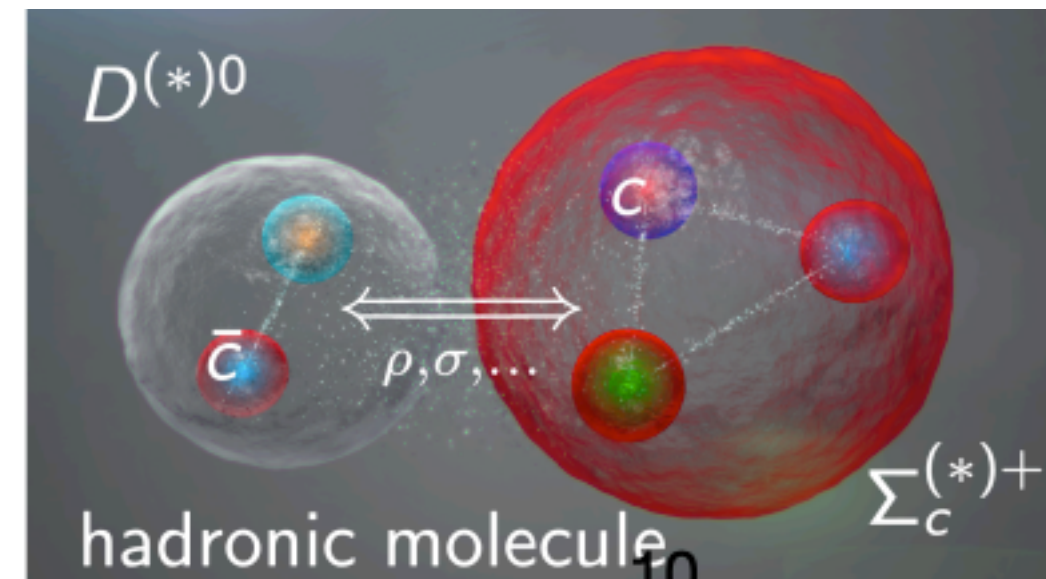
[PRL 115, 072001 (2015),
PRL 122, 222001 (2019)]

First observation by LHCb in $\Lambda_b^0 \rightarrow J/\psi p K$ with Run1 data



Clear resonances in spectrum of $J/\psi[c\bar{c}]p[uud]$

About the rest mass of
 $\Sigma_c^{(*)+}[cud]\bar{D}^{(*)0}[\bar{c}u]$

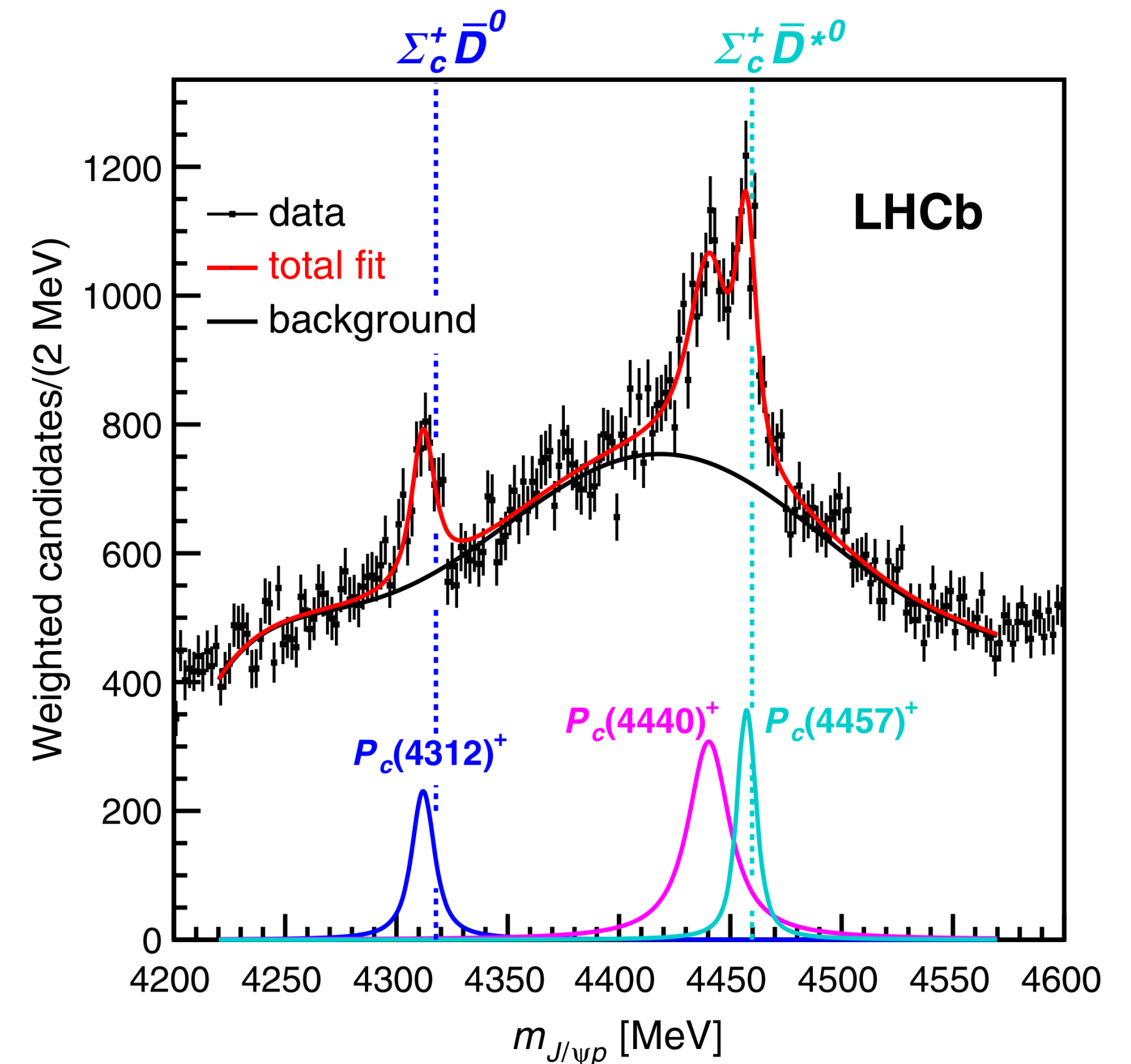


Next: determine quantum numbers with full amplitude analysis

Run 1 + Run 2 dataset:

new state: $P_\psi(4312)^+ + 2$ peaks at 4450 MeV

[PRL 122, 222001 (2019)]



Strange pentaquark

[PhysRevLett.131.031901](#)

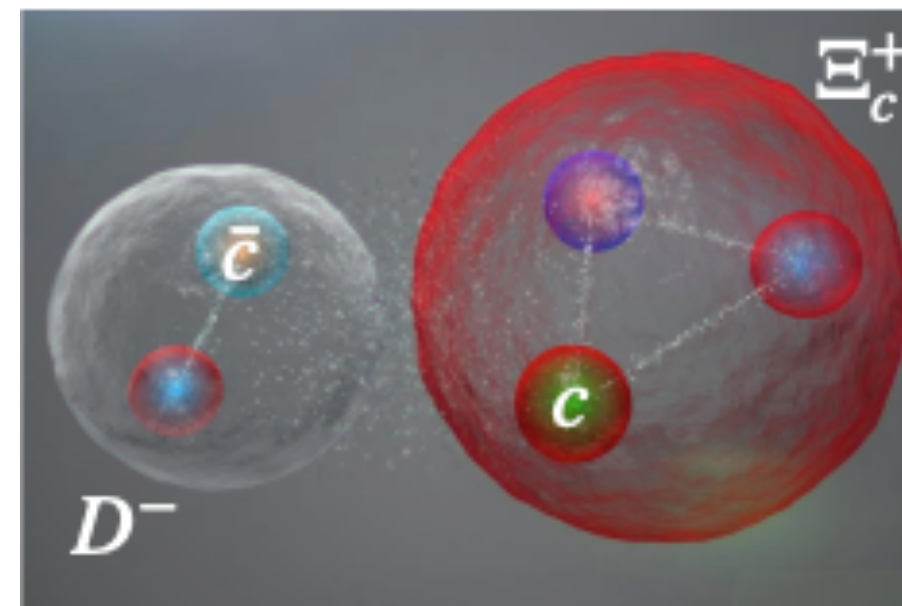
Pentaquark signal is a narrow peak of about 7 MeV width

$$m(P_{\psi s}^{\Lambda}) \quad 4338.2 \pm 0.7 \text{ MeV}$$

$$\Gamma(P_{\psi s}^{\Lambda}) \quad 7.0 \pm 1.2 \text{ MeV}$$

⇒ **Spin-Parity:** $J = 1/2$ determined $P = -1$ favored, $1/2^+$ rejected @90% CL

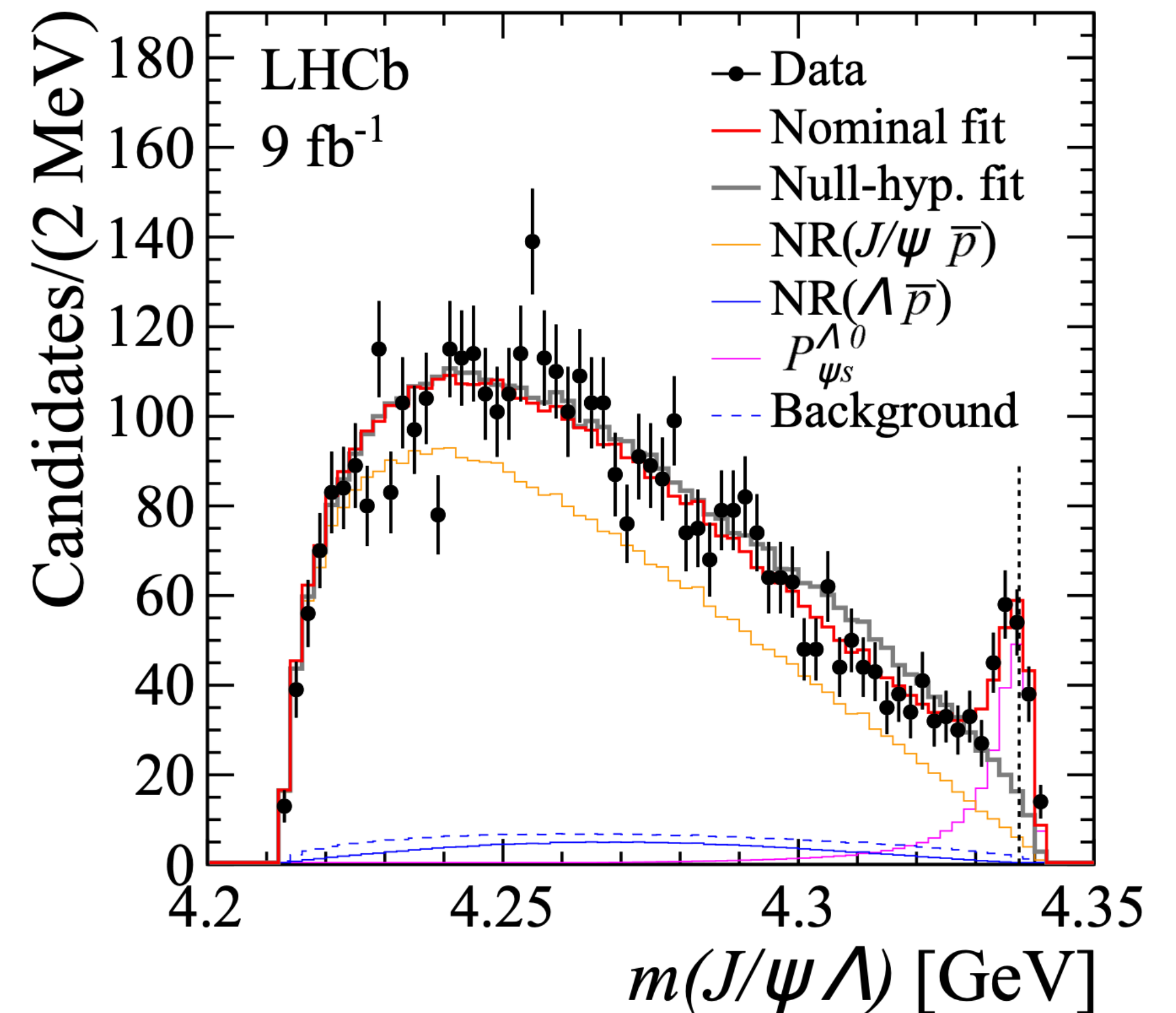
- ✓ Narrow state
- ✓ BW Mass is
 - 0.8MeV above $E_c + D^-$
 - 2.2MeV above $E_c^0 D^0$



Is it a molecular state [1] or triangle singularities [2]?

[1] [PhysRevD.106.036024](#)

[2] [PhysLetB.2023.137715](#)

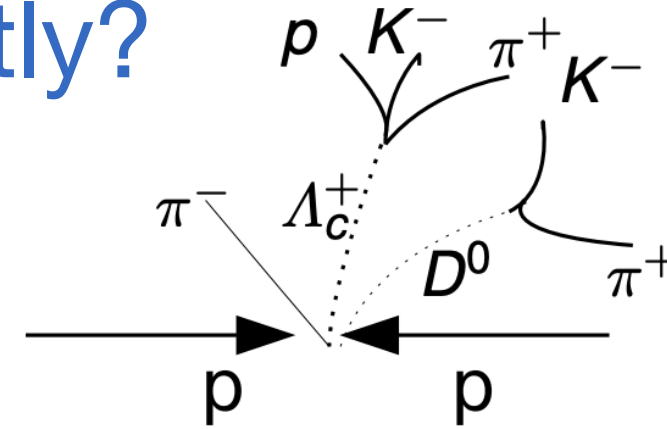


Prompt pentaquarks in $\Sigma_c D$ or $\Lambda_c D$?

[PhysRevD.110.032001](https://arxiv.org/abs/1903.03201)

Observed pentaquarks are close to mass threshold of some charm baryon-meson combinations. [PRD (101), 074030]

- Is it coincidental or evidence of bound states?
- Are pentaquarks produced promptly?



⇒ Inclusive search for pentaquark decays into open-charm Σ_c or Λ_c baryons with D mesons

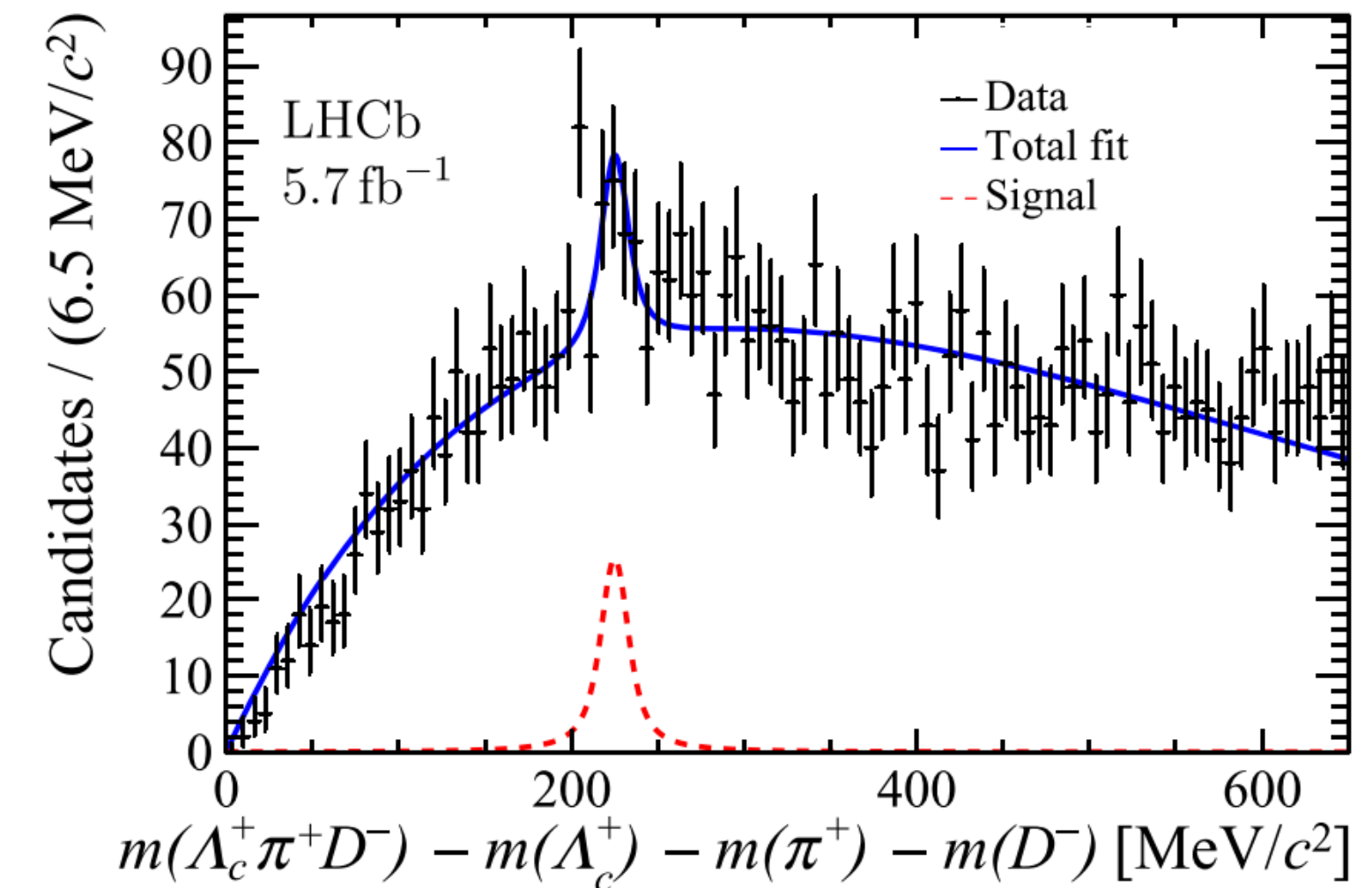
$\Sigma_c^{++} \bar{D}^0$	$\Sigma_c^{++} D^0$	$\Sigma_c^{++} D^-$	$\Sigma_c^{++} D^+$	$\Sigma_c^{++} D^{*-}$	$\Sigma_c^{++} D^{*+}$
$\Sigma_c^0 \bar{D}^0$	$\Sigma_c^0 D^0$	$\Sigma_c^0 D^-$	$\Sigma_c^0 D^+$	$\Sigma_c^0 D^{*-}$	$\Sigma_c^0 D^{*+}$
$\Sigma_c^{*++} \bar{D}^0$	$\Sigma_c^{*++} D^0$	$\Sigma_c^{*++} D^-$	$\Sigma_c^{*++} D^+$	$\Sigma_c^{*++} D^{*-}$	$\Sigma_c^{*++} D^{*+}$
$\Sigma_c^{*0} \bar{D}^0$	$\Sigma_c^{*0} D^0$	$\Sigma_c^{*0} D^-$	$\Sigma_c^{*0} D^+$	$\Sigma_c^{*0} D^{*-}$	$\Sigma_c^{*0} D^{*+}$
$\Lambda_c^+ \bar{D}^0$	$\Lambda_c^+ D^0$	$\Lambda_c^+ D^-$	$\Lambda_c^+ D^+$	$\Lambda_c^+ D^{*-}$	$\Lambda_c^+ D^{*+}$
$\Lambda_c^+ \bar{D}^0 \pi^+$	$\Lambda_c^+ D^0 \pi^+$	$\Lambda_c^+ D^- \pi^+$	$\Lambda_c^+ D^+ \pi^+$	$\Lambda_c^+ D^{*-} \pi^+$	$\Lambda_c^+ D^{*+} \pi^+$
$\Lambda_c^+ \bar{D}^0 \pi^-$	$\Lambda_c^+ D^0 \pi^-$	$\Lambda_c^+ D^- \pi^-$	$\Lambda_c^+ D^+ \pi^-$	$\Lambda_c^+ D^{*-} \pi^-$	$\Lambda_c^+ D^{*+} \pi^-$

Crossed combinations are statistically limited

No evidence is found of new or old states & **UL** are set for all modes (32 modes):

Scan with width of 5, 10, 15 MeV

Highest global significance at 3.6σ for $\Lambda_c \pi^+ D^-$

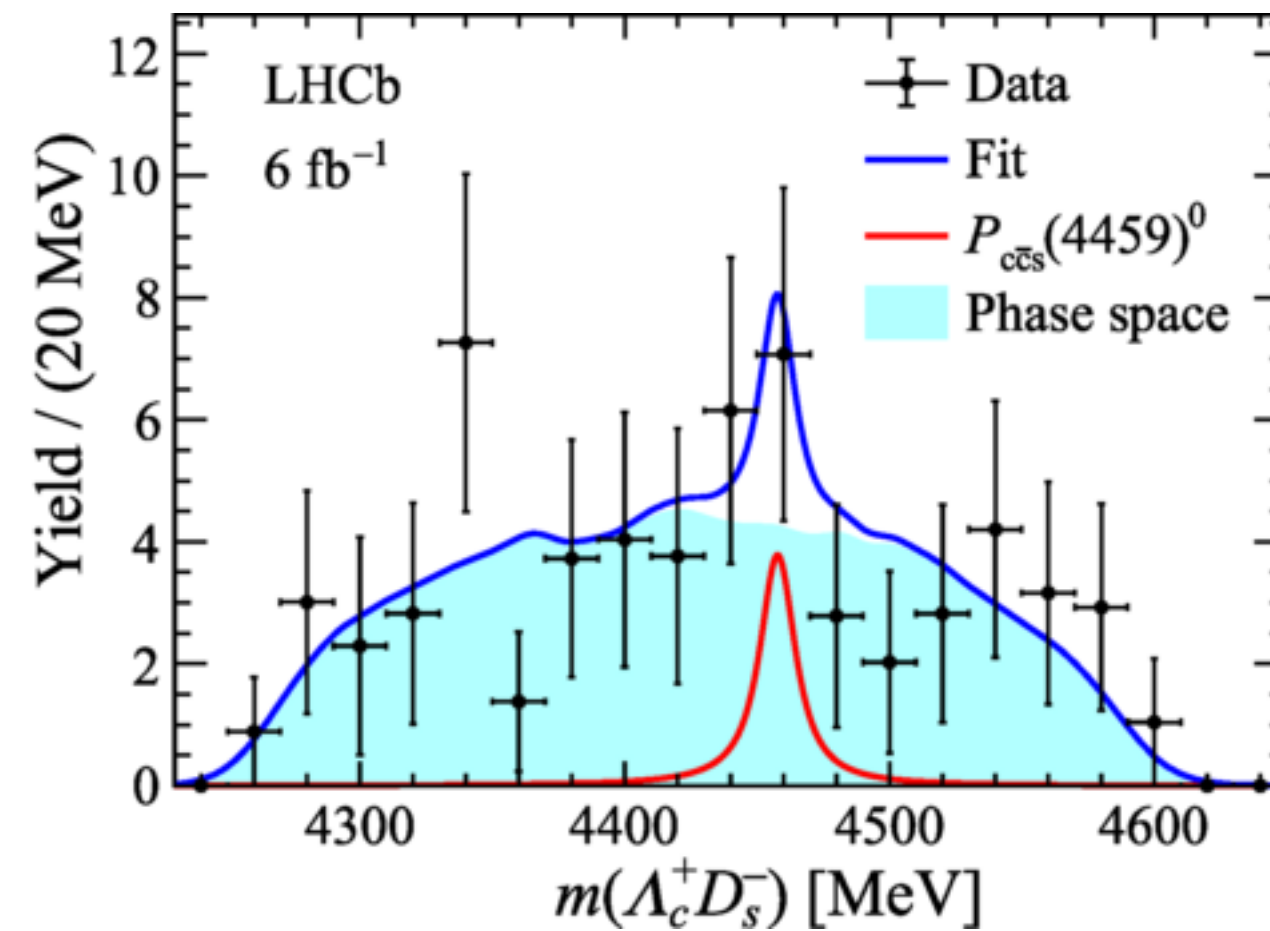
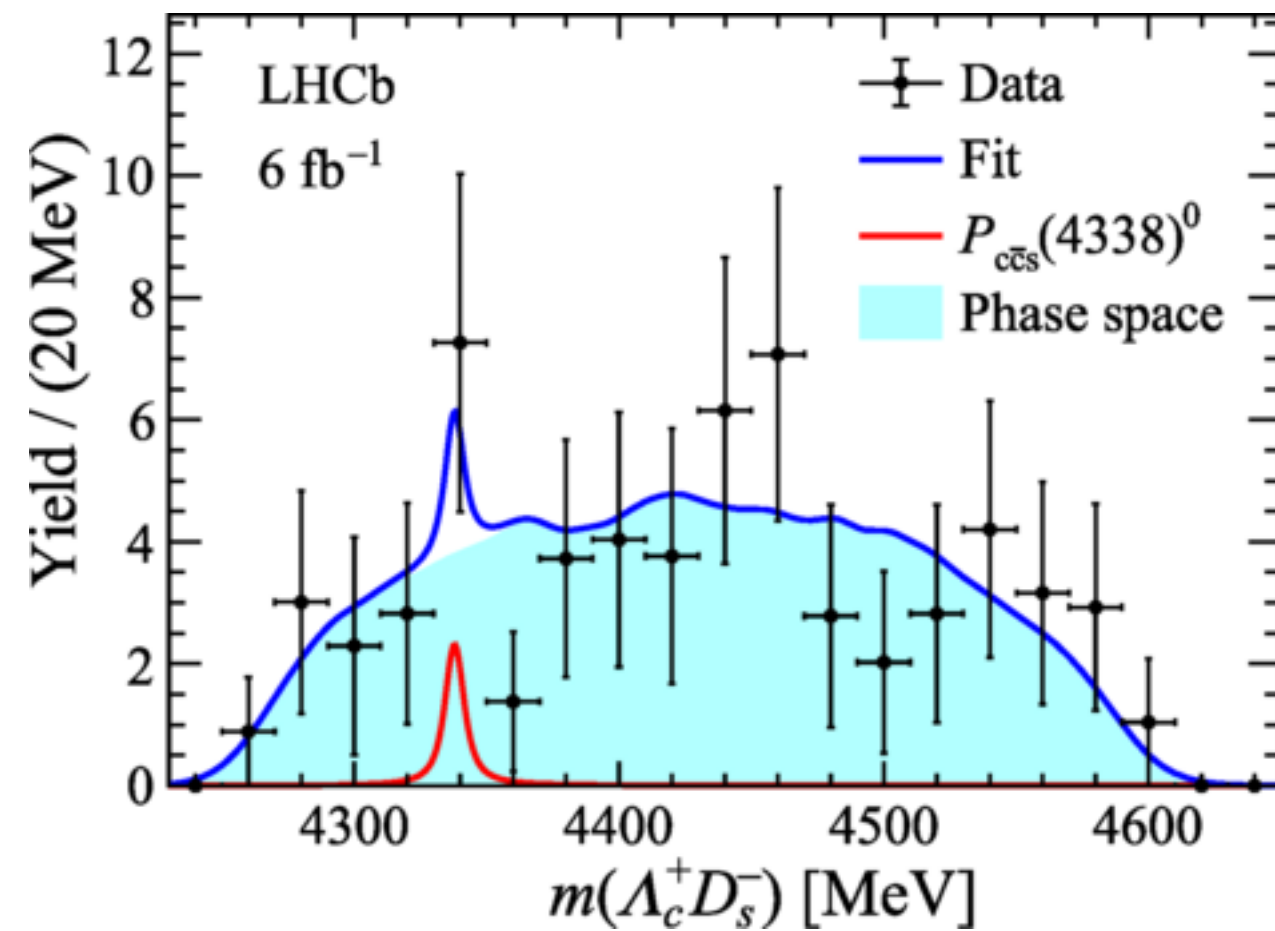


Interesting to update with Run3 data!
+ Search for pentaquark in prompt production
in $J/\psi p$ and $J/\psi \Lambda$

Prospects for other pentaquark decays

Searches in **other B decays to open-charm** final states: $P_{c\bar{c}s} \rightarrow \Lambda_c^+ D_s^- [c\bar{c}sud]$ [Phys. Rev. D 112, 052013](#)

- $\Lambda_b^0 \rightarrow \Lambda_c^+ D_s^- K^+ K^-$ studied with Run2 data: **~60 events** observed



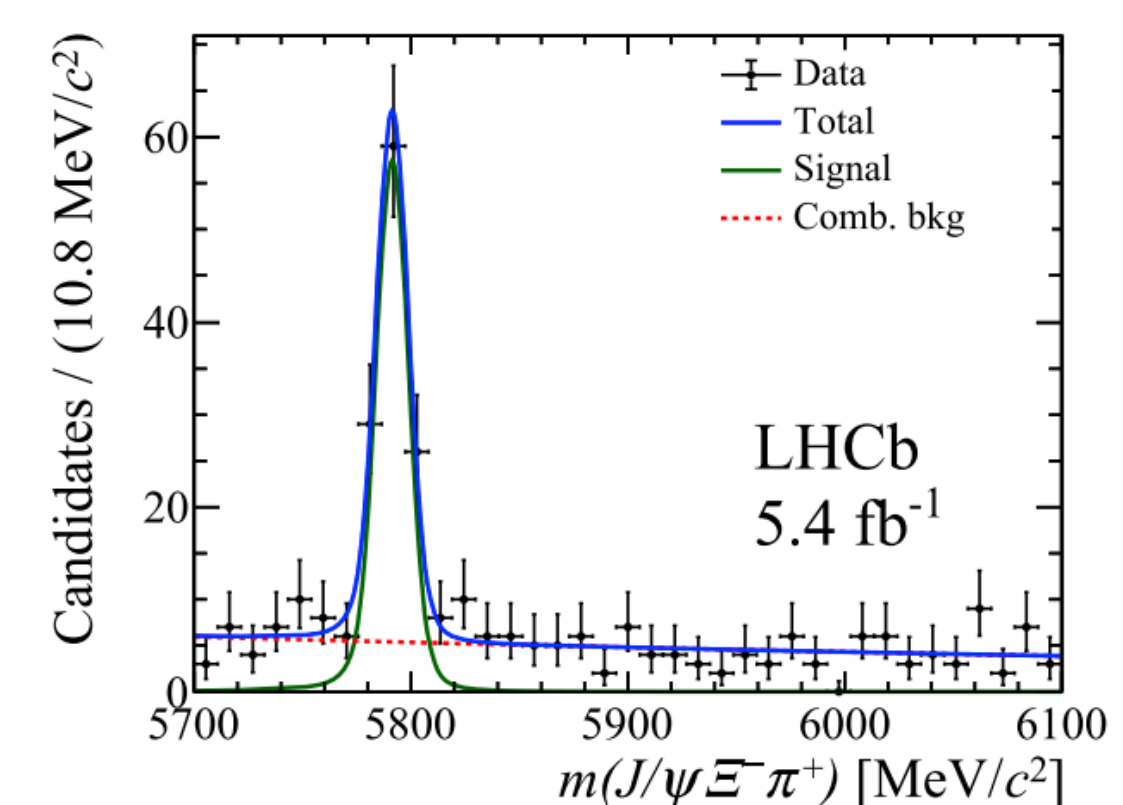
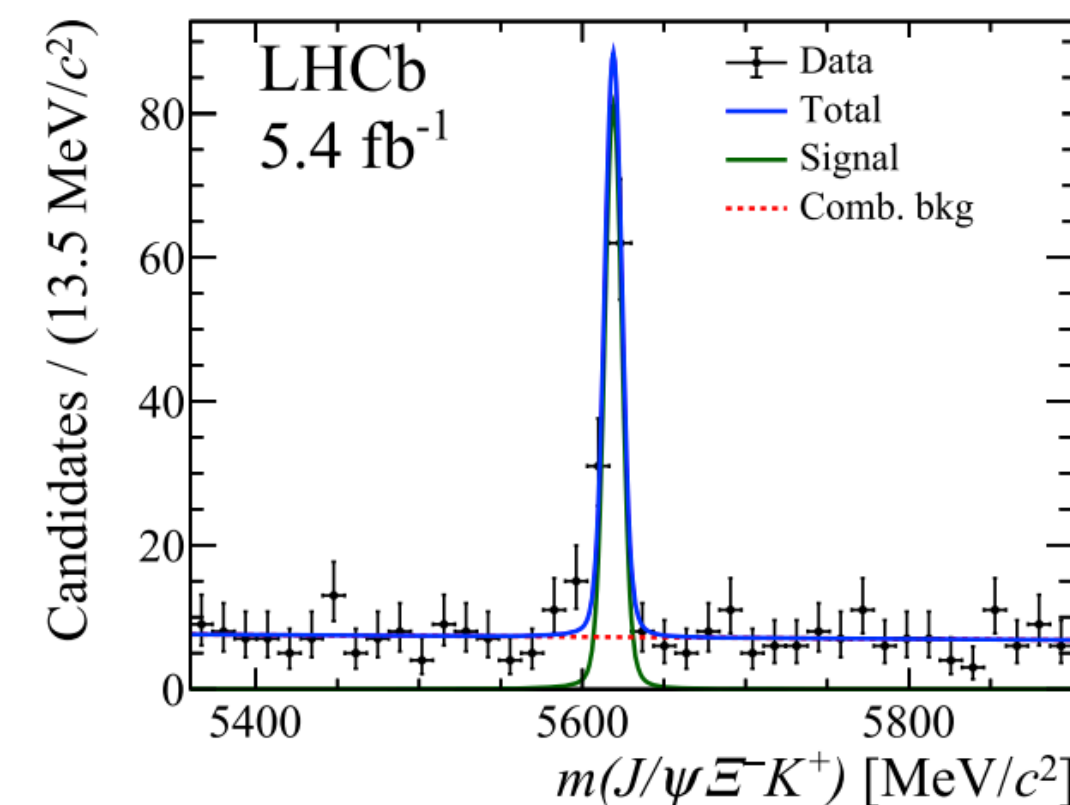
Upper limits are on $P_{c\bar{c}s}$ set at 95% (90%) CLs:
 $\mathcal{R}_{P_{c\bar{c}s}(4338)^0} < 0.12$ (0.10) and $\mathcal{R}_{P_{c\bar{c}s}(4459)^0} < 0.20$ (0.17)

Thanks to the exclusive trigger efficiency for fully hadronic final state:
 Yield expected in **Run3 ~ O(1000) events**

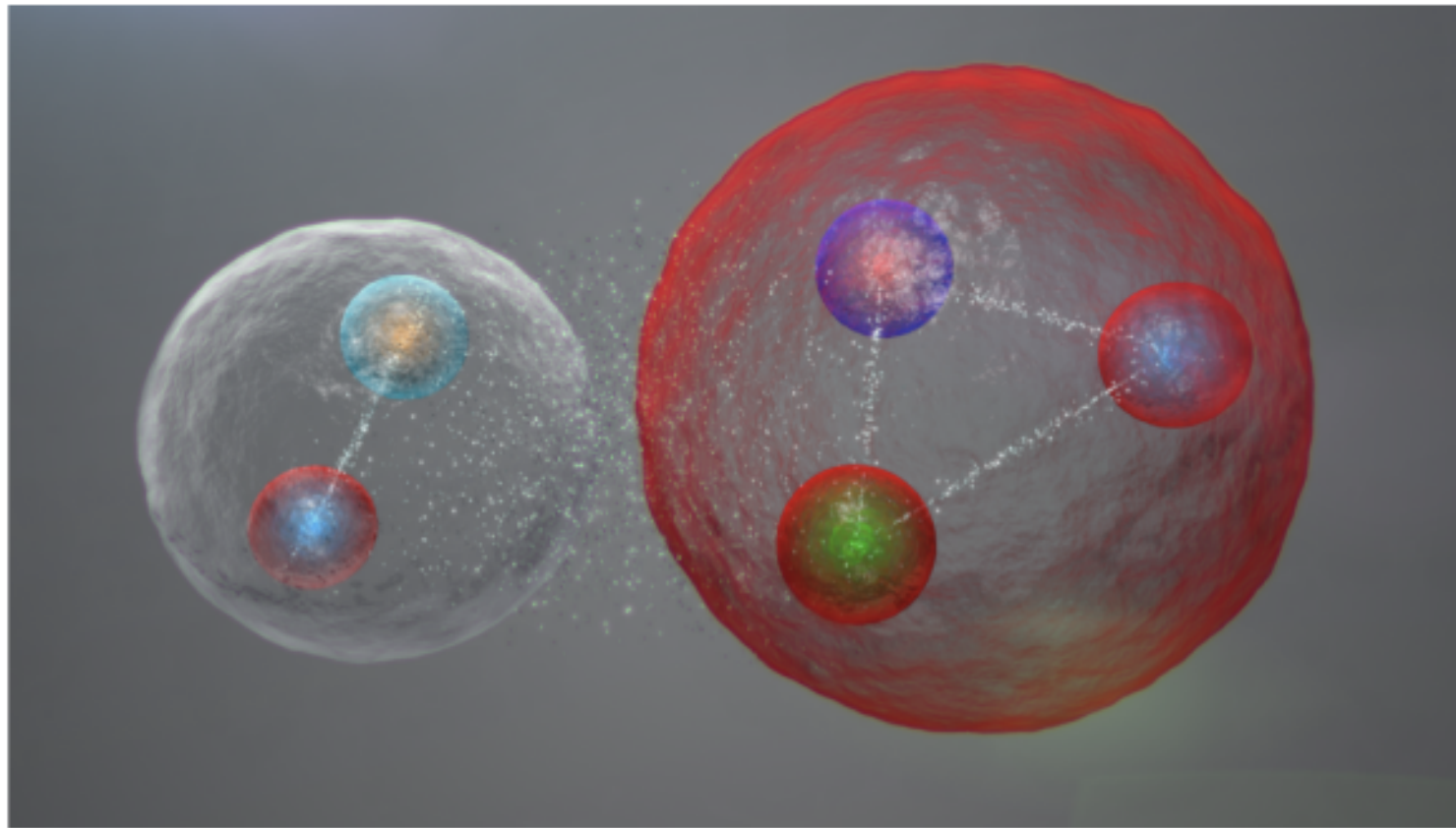
Search for **SU(3) flavor partners**: $P_{c\bar{c}ss} \rightarrow J/\psi \Xi^- [c\bar{c}ssd]$

- First observation of $\Lambda_b^0(\Xi_b^0) \rightarrow J/\psi \Xi^- K(\pi^+)$ with Run2
- No pentaquark state observed so far

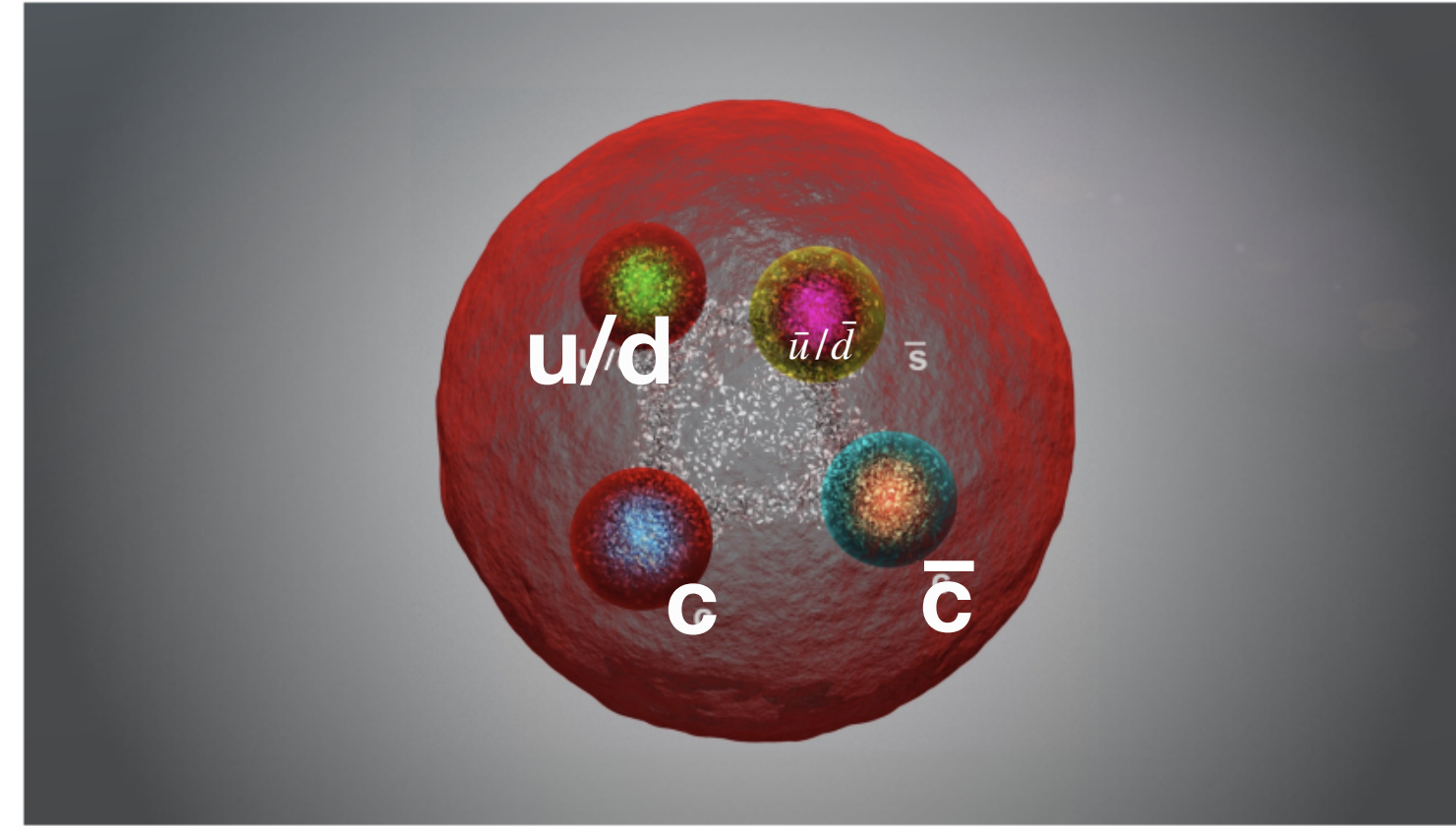
[\[EPJC 85 \(2025\) 812\]](#)



Classifying Exotics...



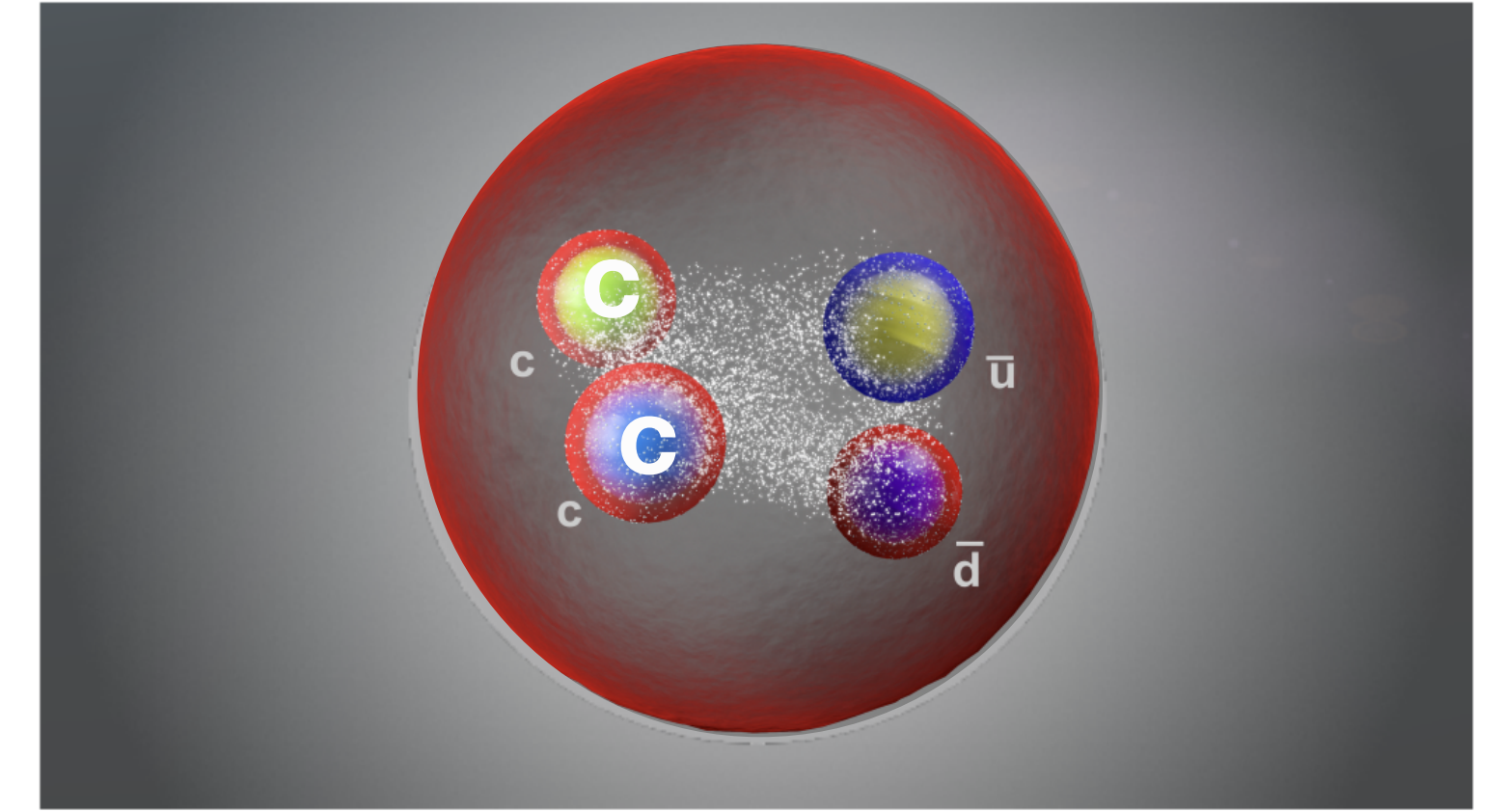
Hidden-charm pentaquark



Hidden-charm tetraquarks

$J/\psi\phi$ states in B decays

- $I(J^{PC}) = 0(0^{++})$: $\chi_{c0}(4500)$, $\chi_{c0}(4700)$
- $I(J^{PC}) = 0(1^{++})$: $\chi_{c1}(4140)$, $\chi_{c1}(4274)$, $\chi_{c1}(4685)$
also known as $X(4140)$, $Y(4140)$, ...
- $I(J^{PC}) = 0(?^{?+})$: $X(4150)$, $X(4630)$, $X(4740)$
also known as $X(4160)$



Beyond hidden-charm

χ_c states in $J/\psi\phi$ in B decays

Some are probably charmonia
and some are exotics!

MESON-LIKE/HIDDEN CHARM/ISOSCALAR
states:

- $I(J^{PC}) = 0(0^{++})$: $\chi_{c0}(4500)$, $\chi_{c0}(4700)$
- $I(J^{PC}) = 0(1^{++})$: $\chi_{c1}(4140)$, $\chi_{c1}(4274)$, $\chi_{c1}(4685)$
also known as $X(4140)$, $Y(4140)$, ...
- $I(J^{PC}) = 0(??^+)$: $X(4150)$, $X(4630)$, $X(4740)$
also known as $X(4160)$

Overall, 9 exotic states (7 X + 2 $T_{c\bar{c}s}$)

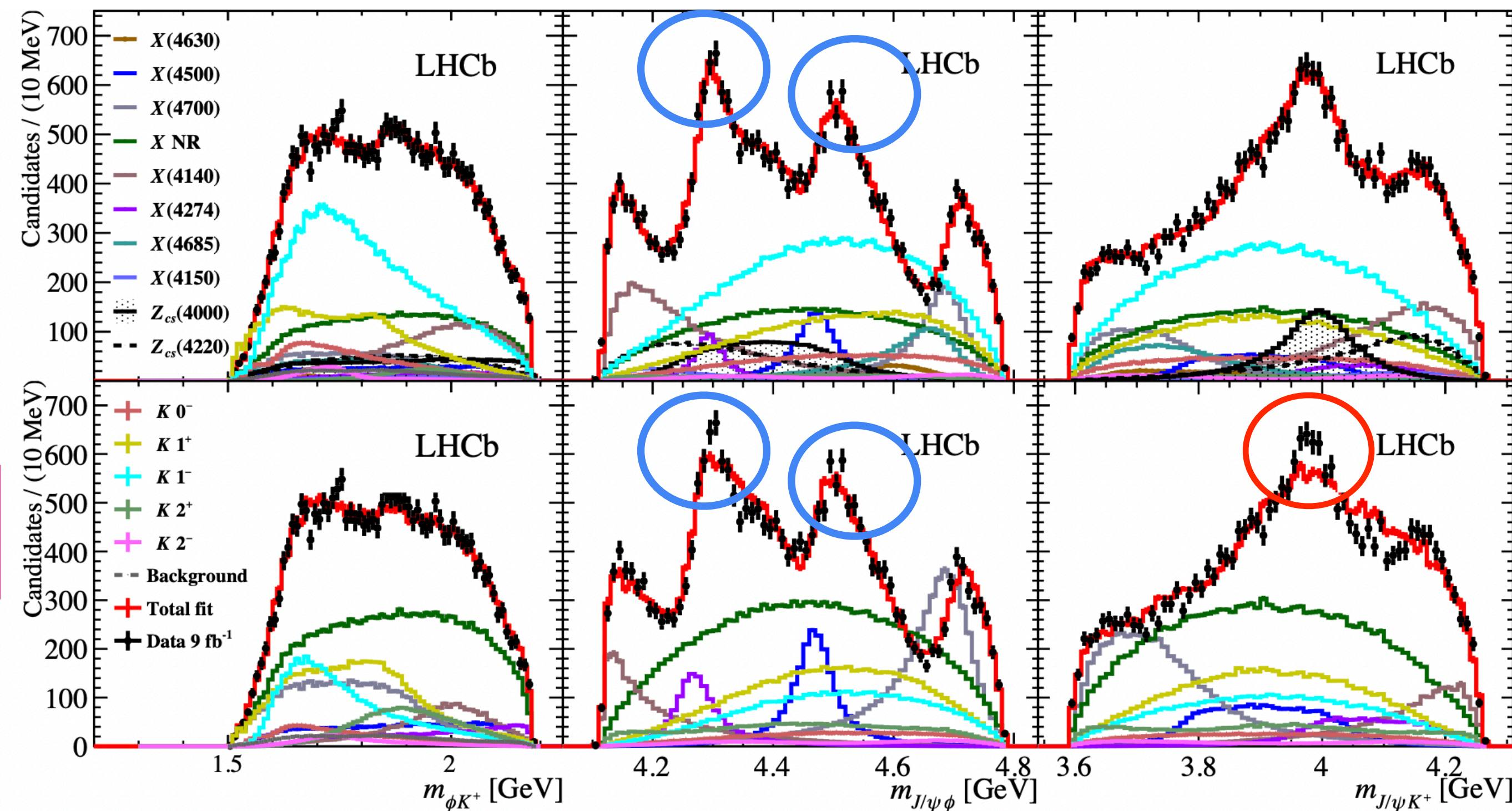
- Isospin partner $T_{c\bar{c}s}(4000)^0$
observed in $B^0 \rightarrow J/\psi\phi K_S^0$ at 4σ
[Phys. Rev. Lett. **131**, 131901]

Run1
model

Study of $B^+ \rightarrow J/\psi\phi K^+$: amplitude analysis by LHCb
with Run1 and later with Run2

LHCb Run1+2

[PhysRevLett.127.082001](https://arxiv.org/abs/1208.4074)



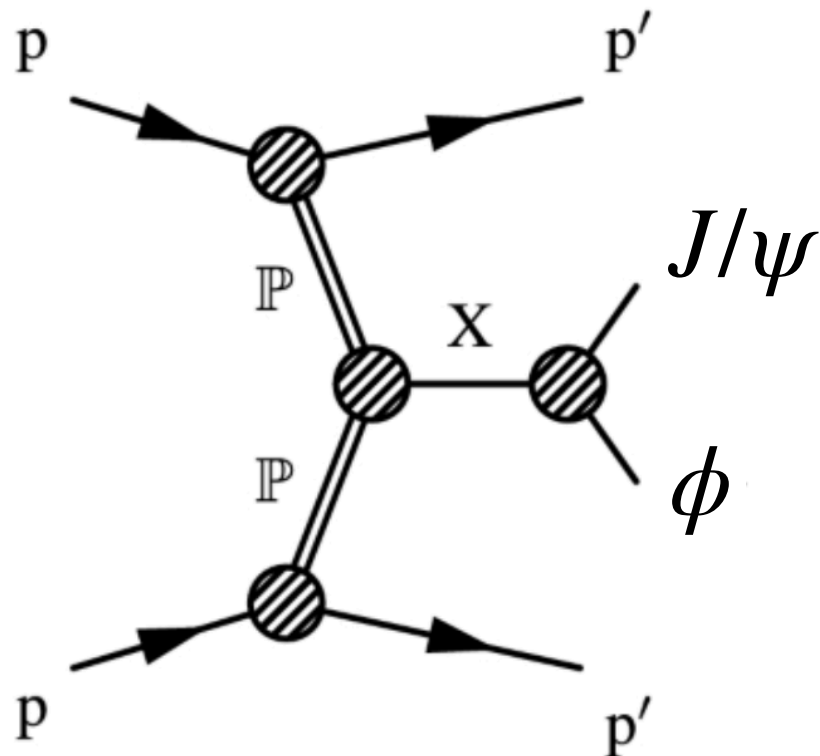
Structures in $J/\psi K^+$: $T_{c\bar{c}s}(4000)^+$

$J/\psi\phi$ in other production processes

Phys.Rev.Lett. 134, 031902 (2025)

Central exclusive production (CEP) provides a clean environment to study the pomeron exchange and exotic hadrons properties $\Rightarrow$ can help clarify the exotic nature

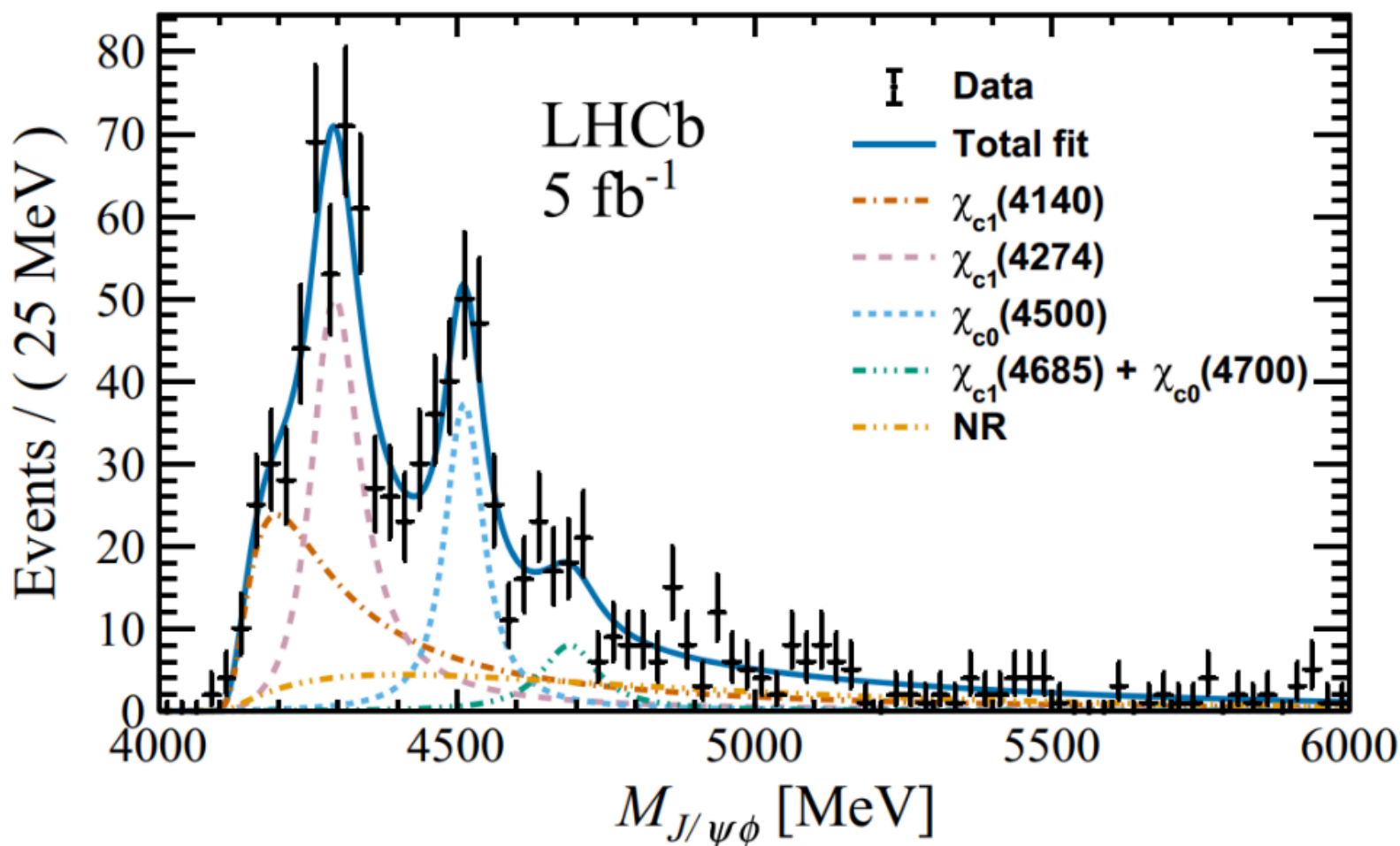
- **HeRSChel**: to extend acceptance $5 < \eta < 10$ [JINST 13 P04017]
- Events with $J/\psi \rightarrow \mu\mu$ and $\phi \rightarrow KK$ with no additional detected activity



First observation of $J/\psi\phi$ states in diffractive processes!

Open the possibility to explore these processes for other exotic states

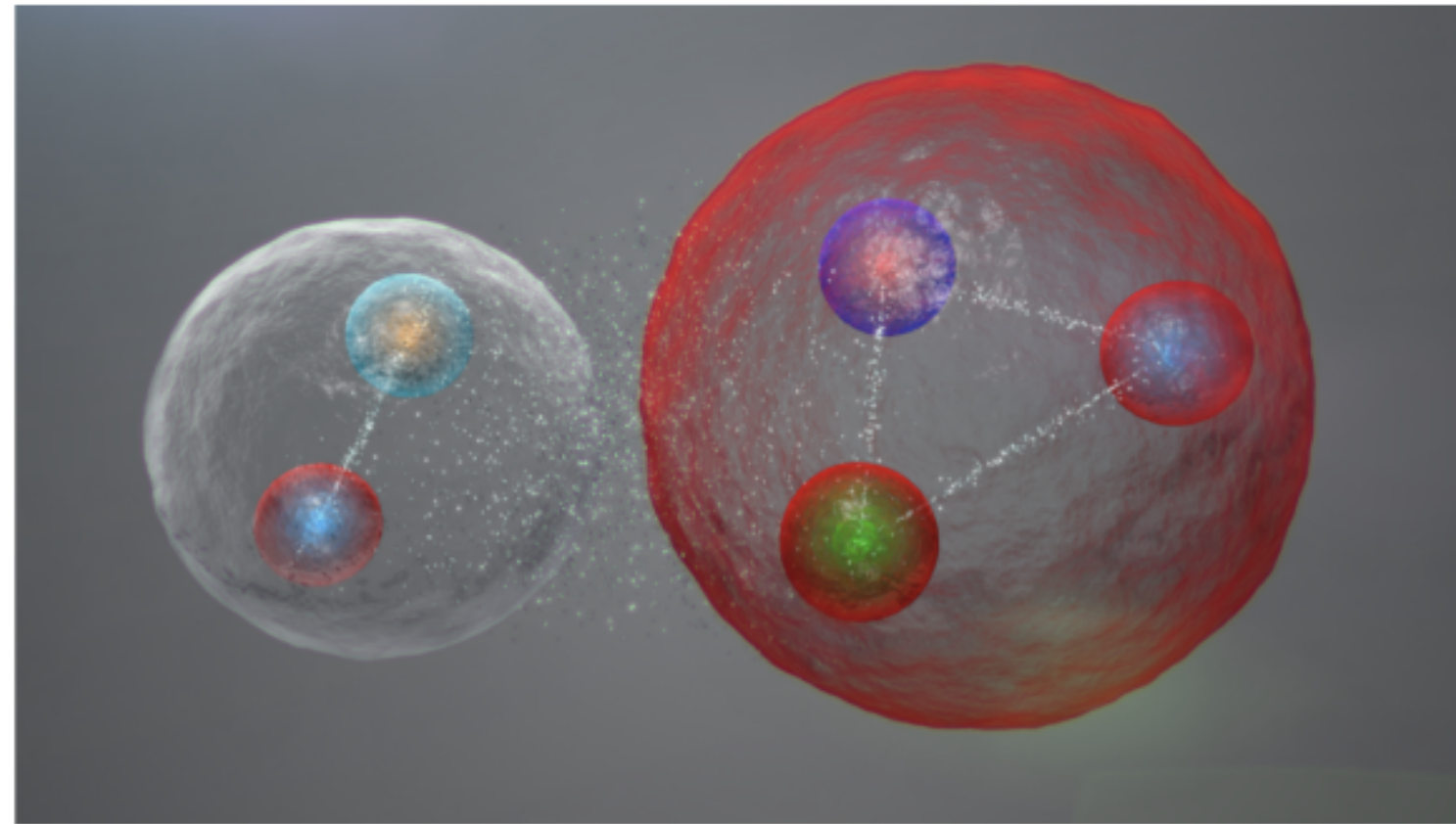
[Phys. Rev. D **104**, 114029, [10.4236/jmp.2013.412193](#), ...]



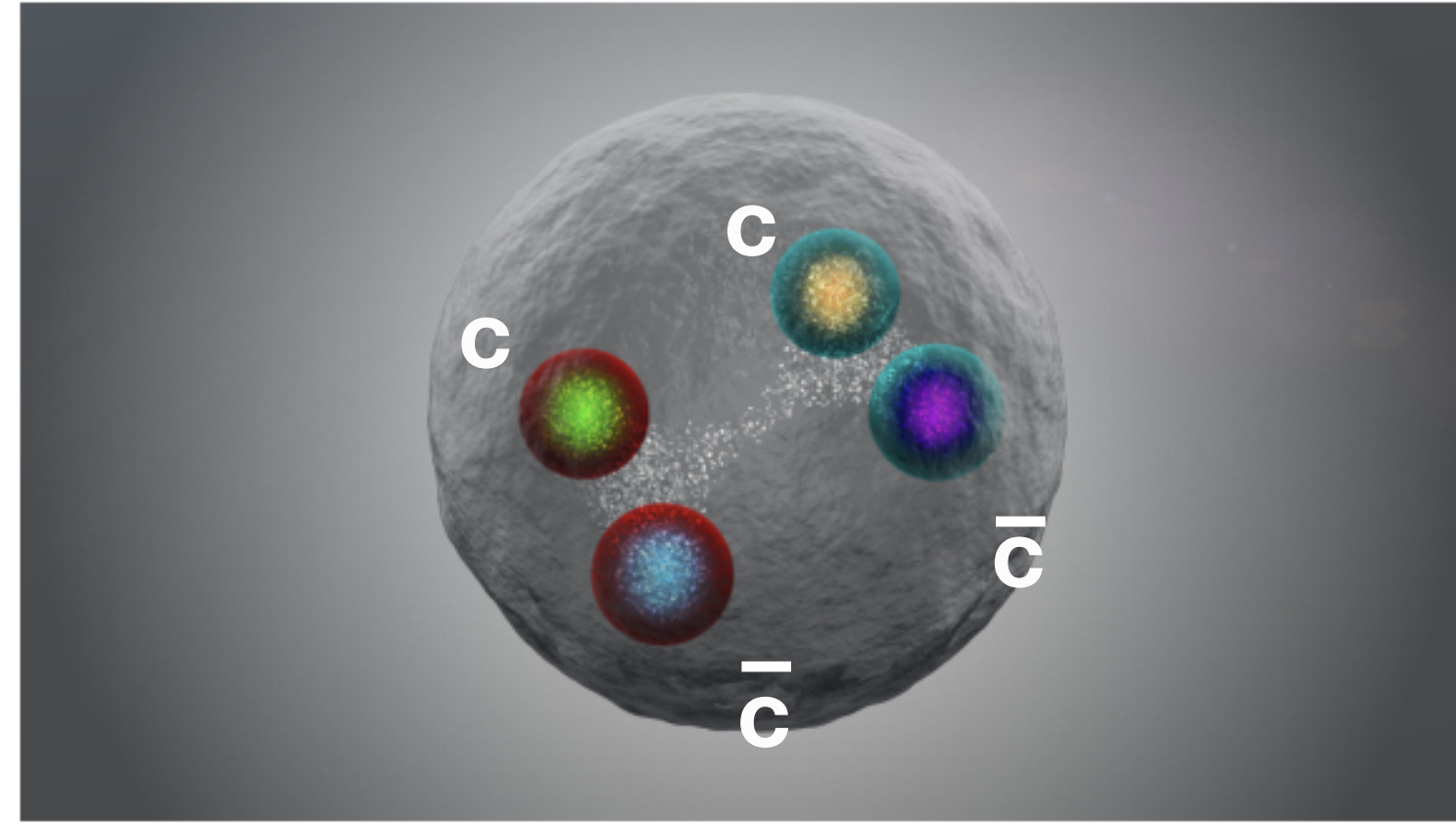
Parameter (MeV)	This work
$M_{\chi_{c1}(4274)}$	$4298 \pm 6^{+4}_{-5}$
$\Gamma_{\chi_{c1}(4274)}$	$92^{+22}_{-18} {}^{+33}_{-19}$
$M_{\chi_{c0}(4500)}$	$4512.5^{+6.0}_{-6.2} {}^{+3.2}_{-2.7}$
$\Gamma_{\chi_{c0}(4500)}$	$65^{+20}_{-16} {}^{+24}_{-9}$

	$\chi_{c1}(4140)$	$\chi_{c1}(4274)$	$\chi_{c0}(4500)$	$\chi_{c1}(4685) + \chi_{c0}(4700)$
$\sigma \times \mathcal{B}_{\text{eff}} \text{ (pb)}$	$0.80 \pm 0.15^{+0.26}_{-0.29}$	$0.73^{+0.14}_{-0.13} {}^{+0.16}_{-0.19}$	$0.42^{+0.09}_{-0.08} {}^{+0.07}_{-0.05}$	$0.14^{+0.07}_{-0.06} {}^{+0.03}_{-0.04}$
Significance	2.3σ	4.1σ	6.1σ	1.8σ

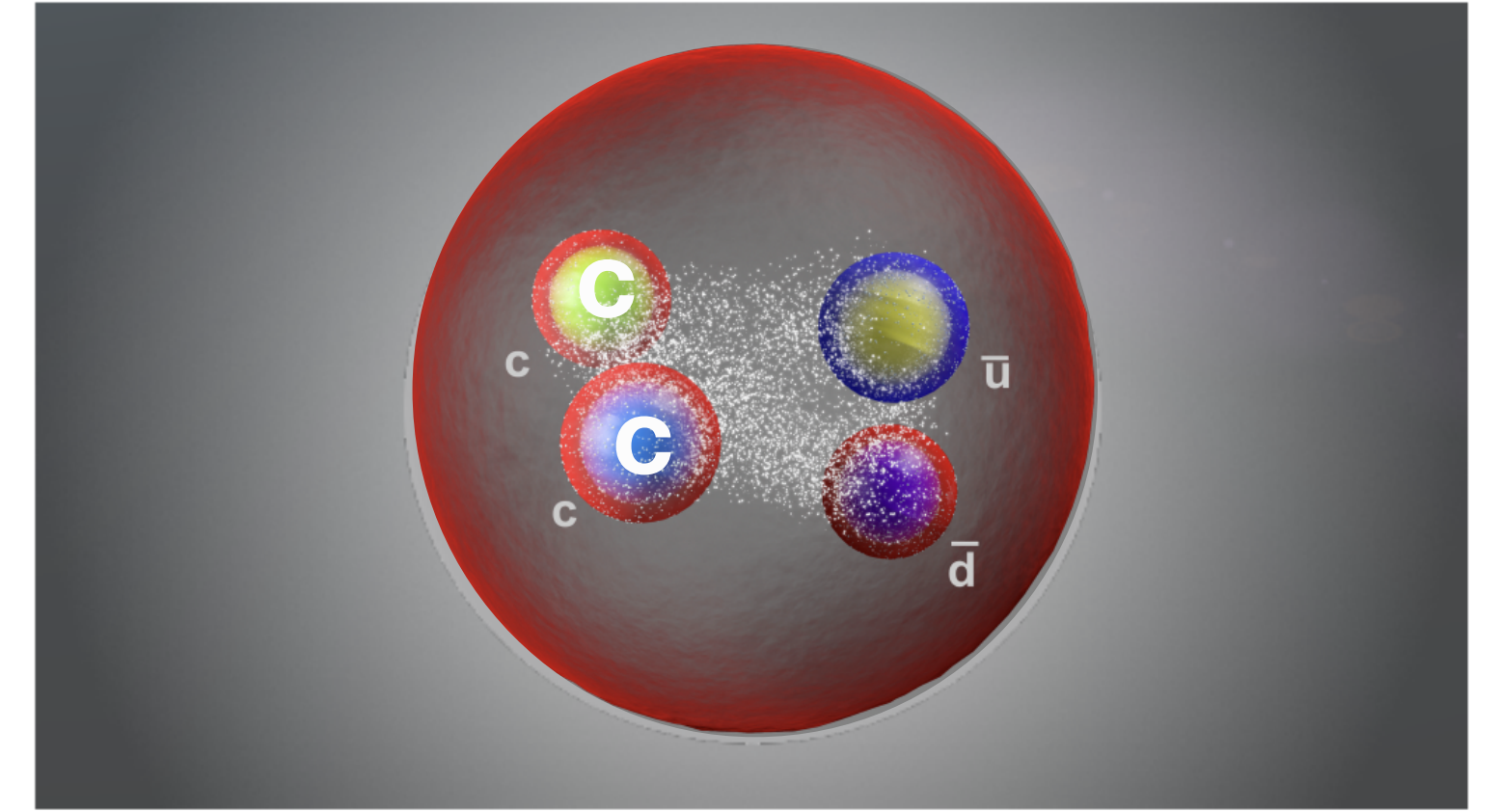
Classifying Exotics...



Hidden-charm pentaquark



Hidden-charm tetraquarks



Beyond hidden-charm

Di- ψ resonance

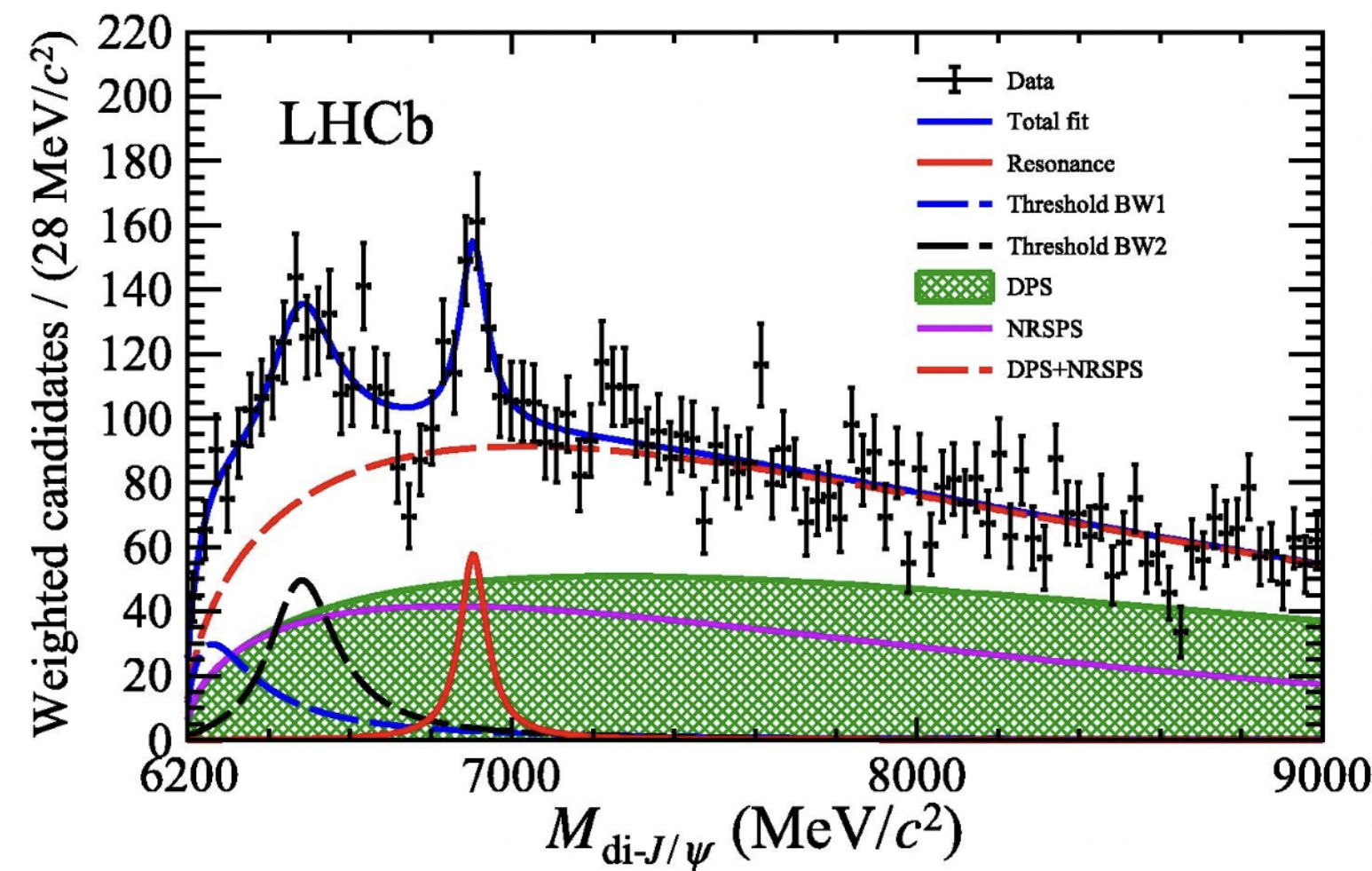
MESON-LIKE/HIDDEN DOUBLE CHARM

states: $T_{c\bar{c}c\bar{c}}(6550)^0$, $T_{c\bar{c}c\bar{c}}(6900)^0$, $T_{c\bar{c}c\bar{c}}(7290)^0$
also known as $T_{\psi\psi}(6900)^0$, ... or $X(6900)$, ...

Sci.Bull. 65 (2020), 23
CMS-PAS-BPH-21-003

Fully charmed states in prompt production

Sci.Bull. 65 (2020), 23

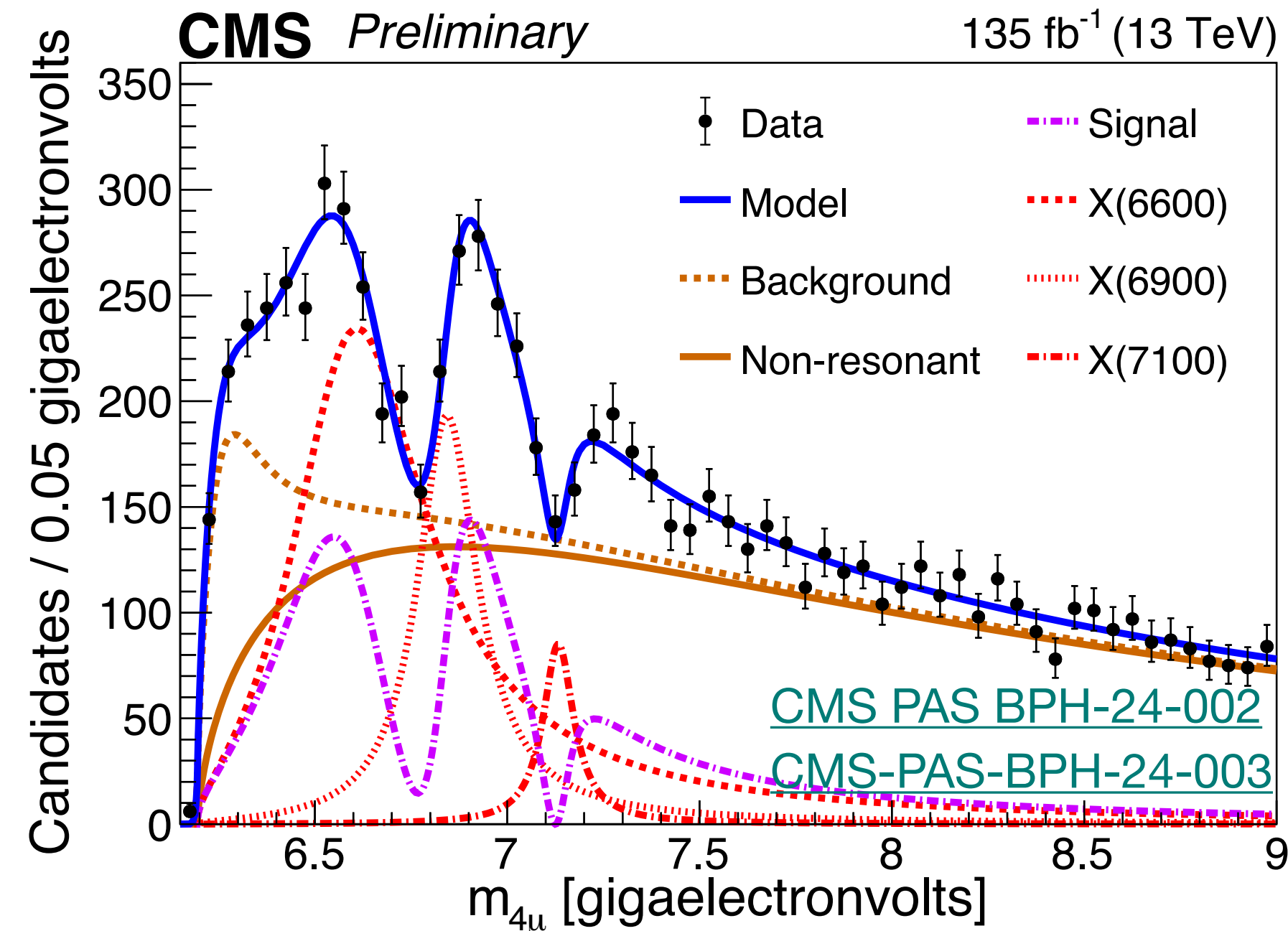


Narrow structure at 6.9 GeV

→ $T_{c\bar{c}c\bar{c}}(6900)$

Broad structure just above double- J/ψ threshold → 5 σ deviation from NR

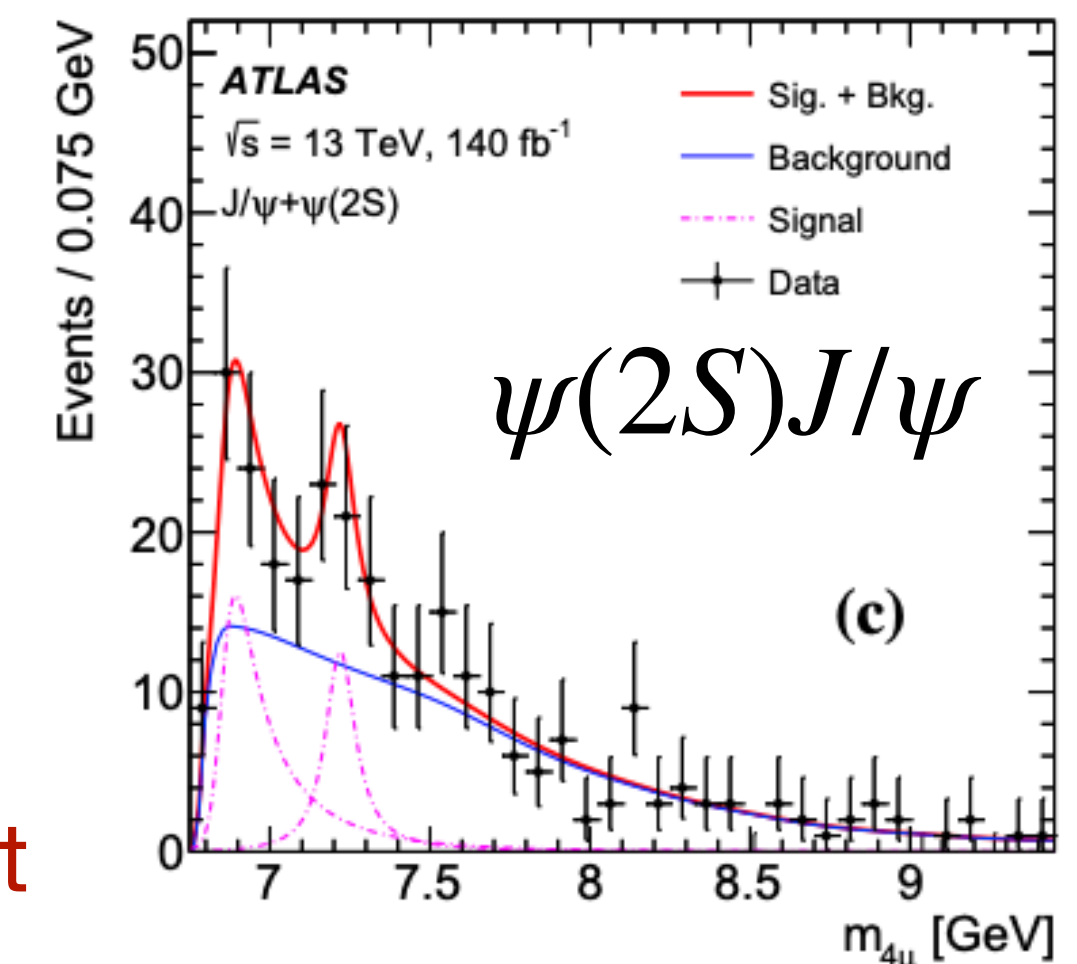
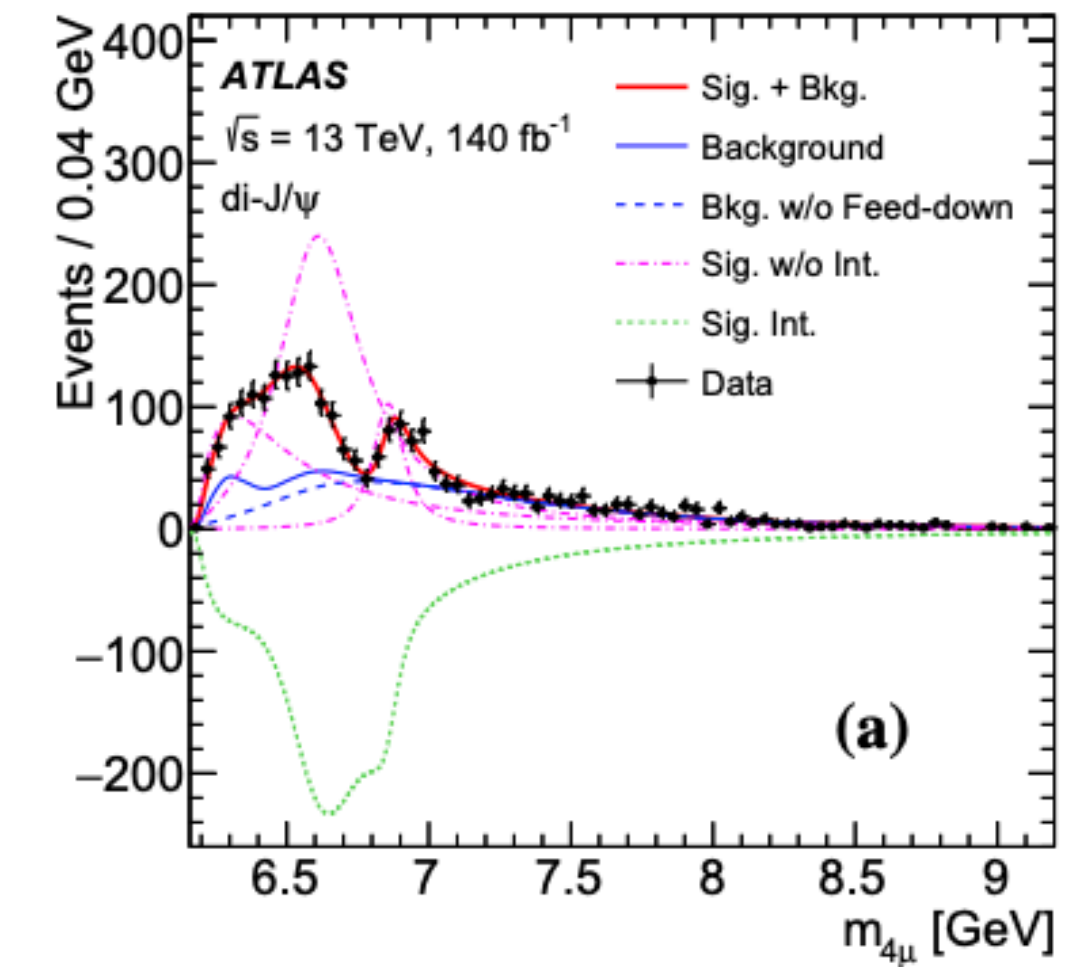
⇒ Need to update LHCb measurement with Run3 data and perform a spin measurement either with full amplitude analysis or with model-independent approach [JHEP 07 (2024) 092]



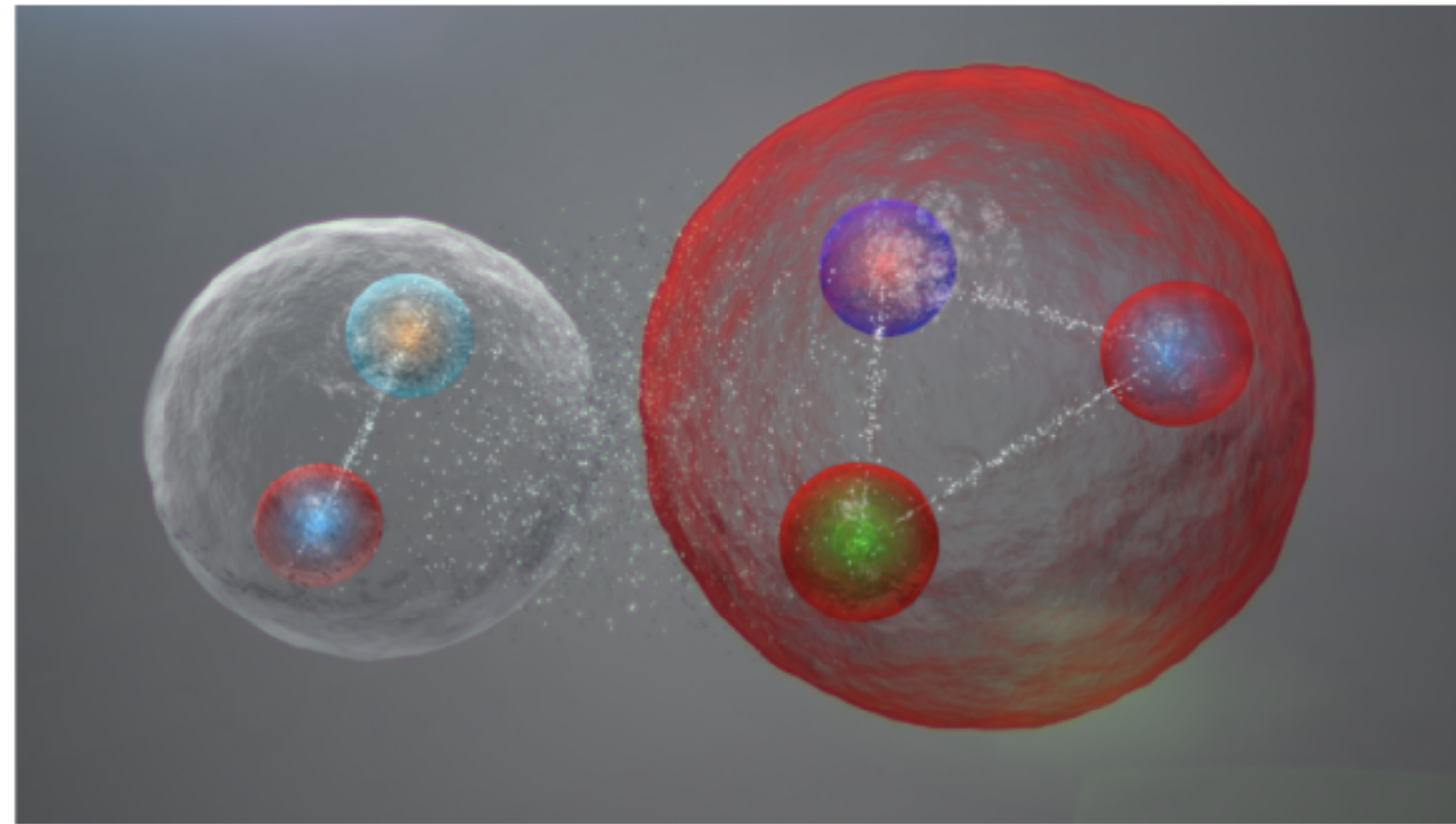
$T_{c\bar{c}c\bar{c}}(6900)$ confirmed & consistent with LHCb + 2 more peaks from CMS but not well distinguished by ATLAS

- $J^{PC} = 2^{++}$ preferred by CMS

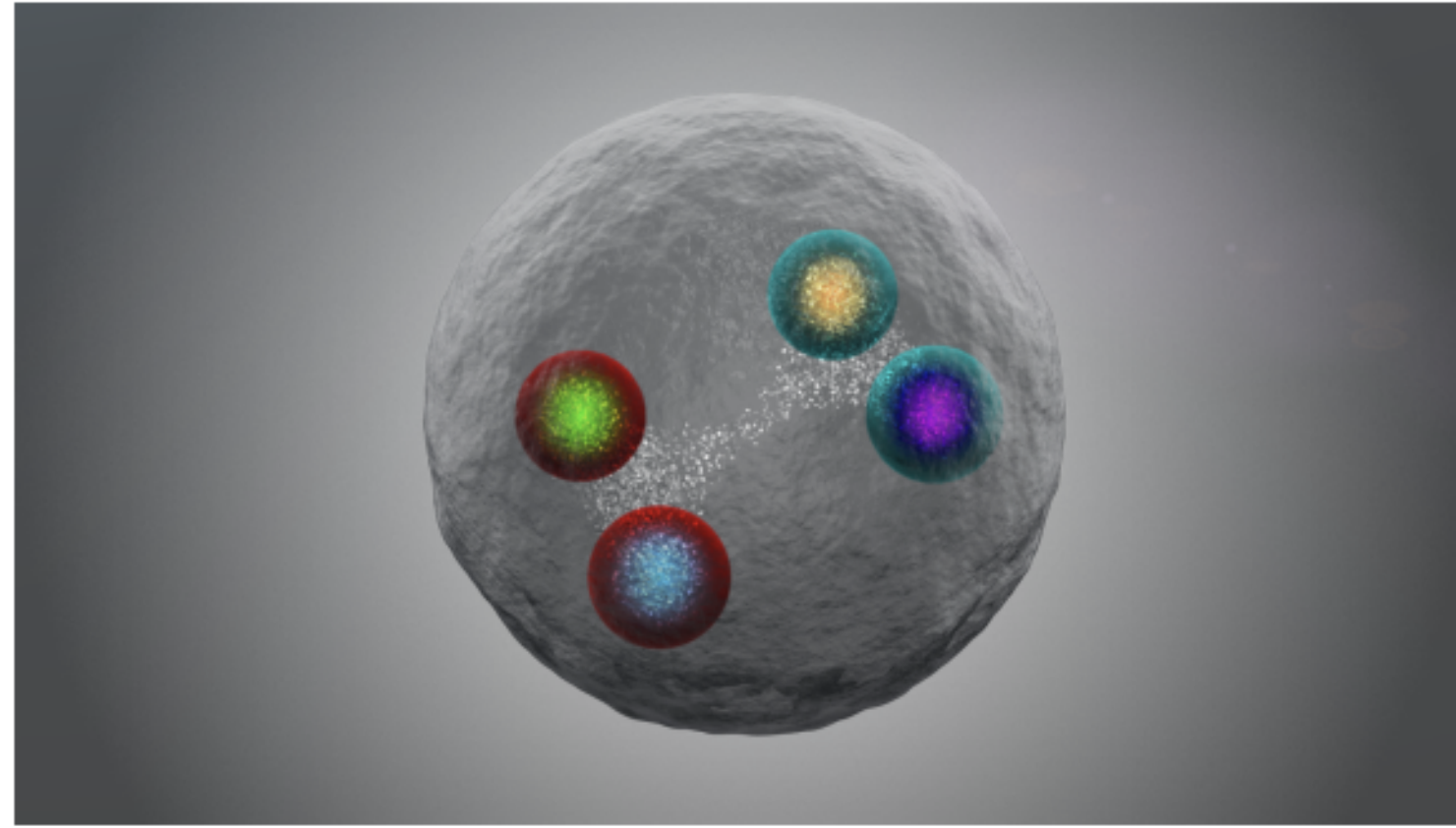
arXiv:2304.08962



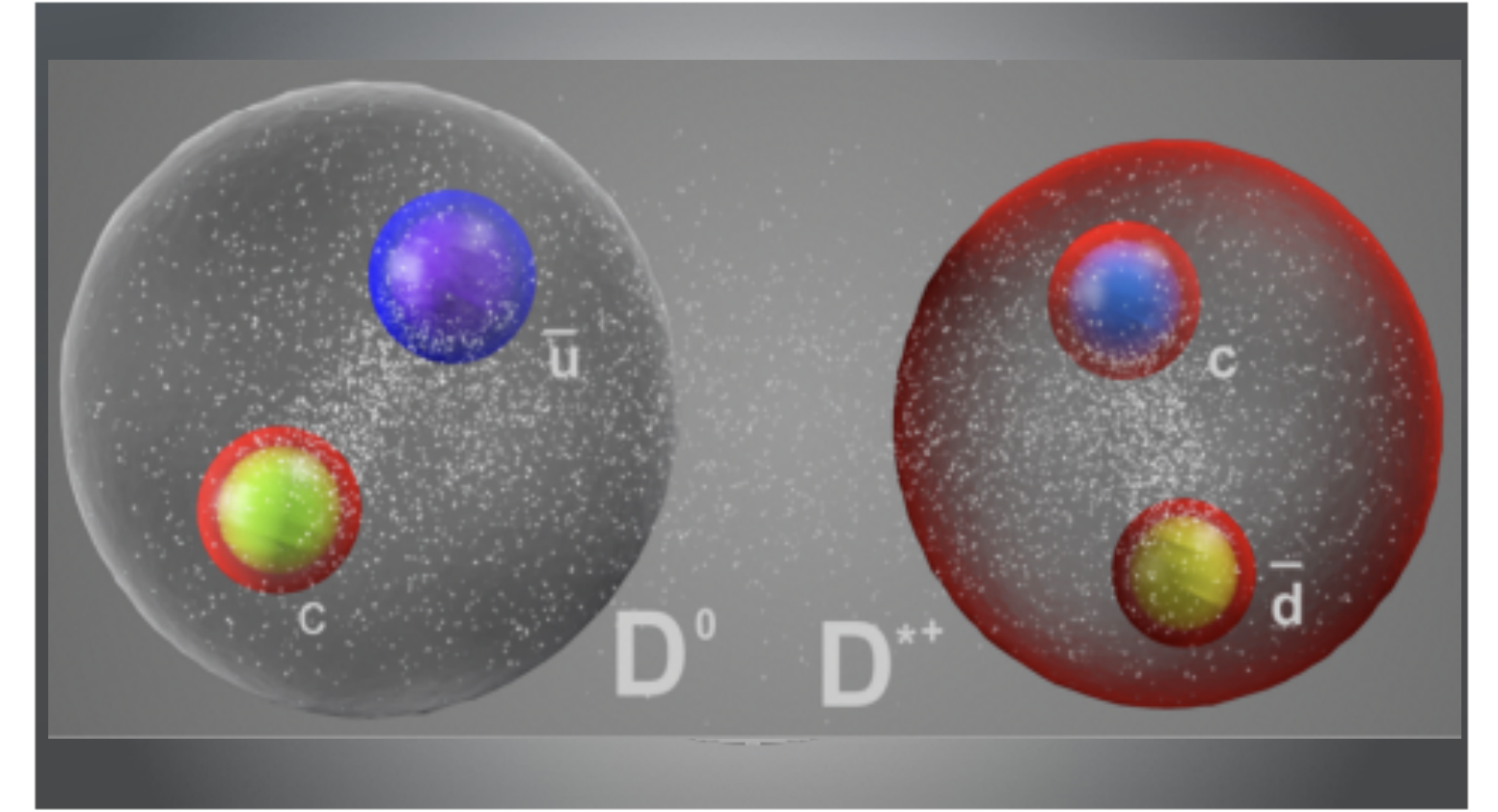
Classifying Exotics...



Hidden-charm pentaquark



Hidden-charm tetraquarks



Beyond hidden charm

Doubly-charm tetraquark

MESON-LIKE/OPEN DOUBLE CHARM

quantum numbers: $I(J^P) = ?(??)$, likely $0(1^+)$

minimal quark content: $[cc\bar{u}\bar{d}]$

experiments: LHCb

production: prompt pp collisions

Nature Physics (2022); [Nat. Comm.](#) 13, 3351 (2022)

Observation of doubly charm tetraquark

Nature Physics (2022); [Nature Communications](#) 13, 3351 (2022)

First observation of same-sign

double charmed tetraquark, $T_{cc}^+(3875) \rightarrow D^0 D^0 \pi^+$

$\Rightarrow$ exotic quark content $cc\bar{u}d$

Mass is below the $D^0 D^{*+}$ threshold and very narrow

$$\delta m = -359 \pm 40_{-6}^{+9} \text{ keV}$$

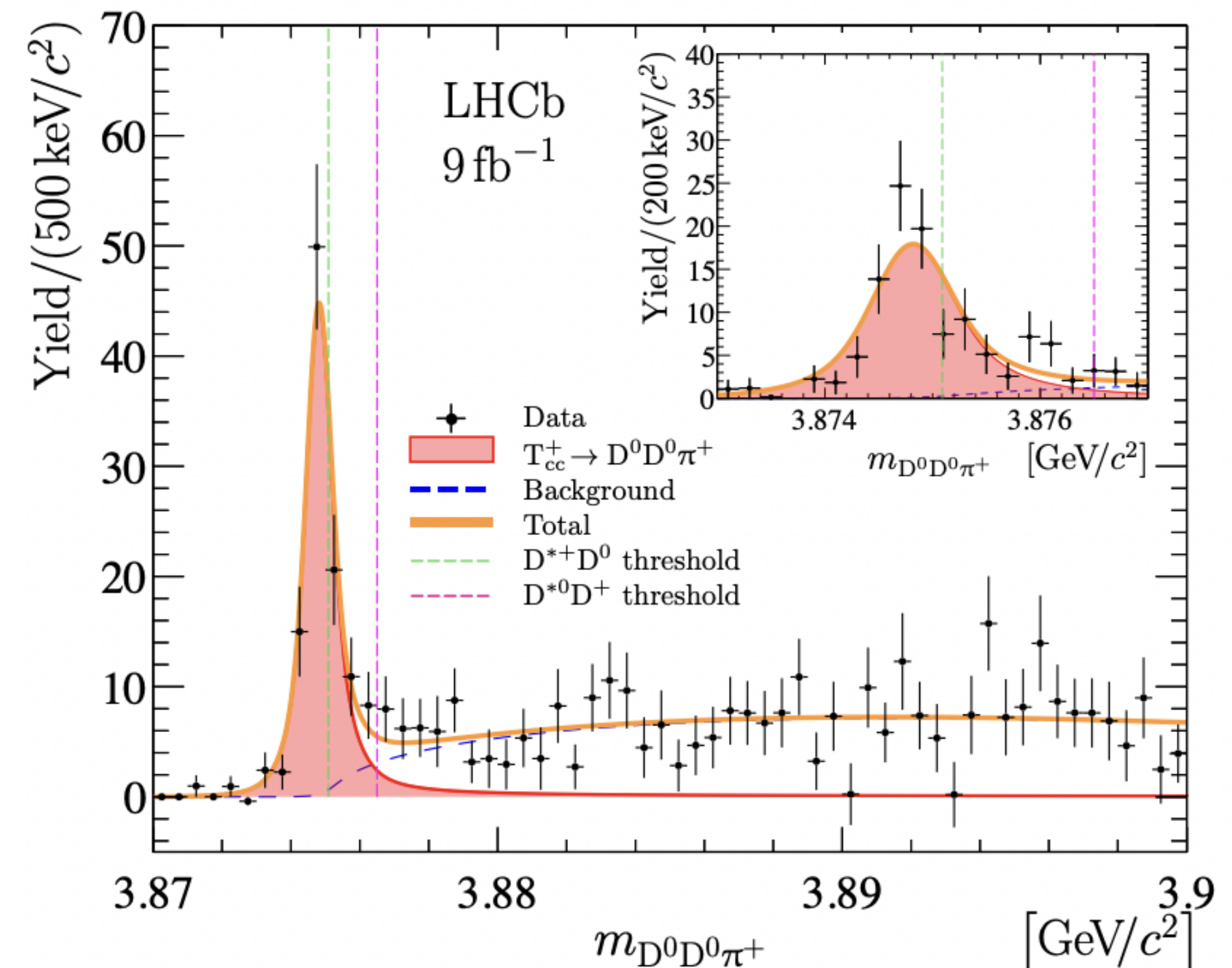
$$\Gamma = 48 \pm 2_{-14}^{+0} \text{ keV}$$

Consistent with an **isoscalar** with $J^P=1^+$

in accordance with expectation for a $cc\bar{u}d$ ground-state

- $l=0$ is supported by no peaks found in $D^+ D^+$ and $D^+ D^0 \pi^+$
- Perfect agreement with model considering only decays to DD^*

[[Nature Communications](#) 13, 3351 (2022)]



Likely it is predominately a DD^* molecule, but also a compact component

[1] [arXiv:hep-ph/0405208](#)

Amplitude analysis to be performed with Run3 data!

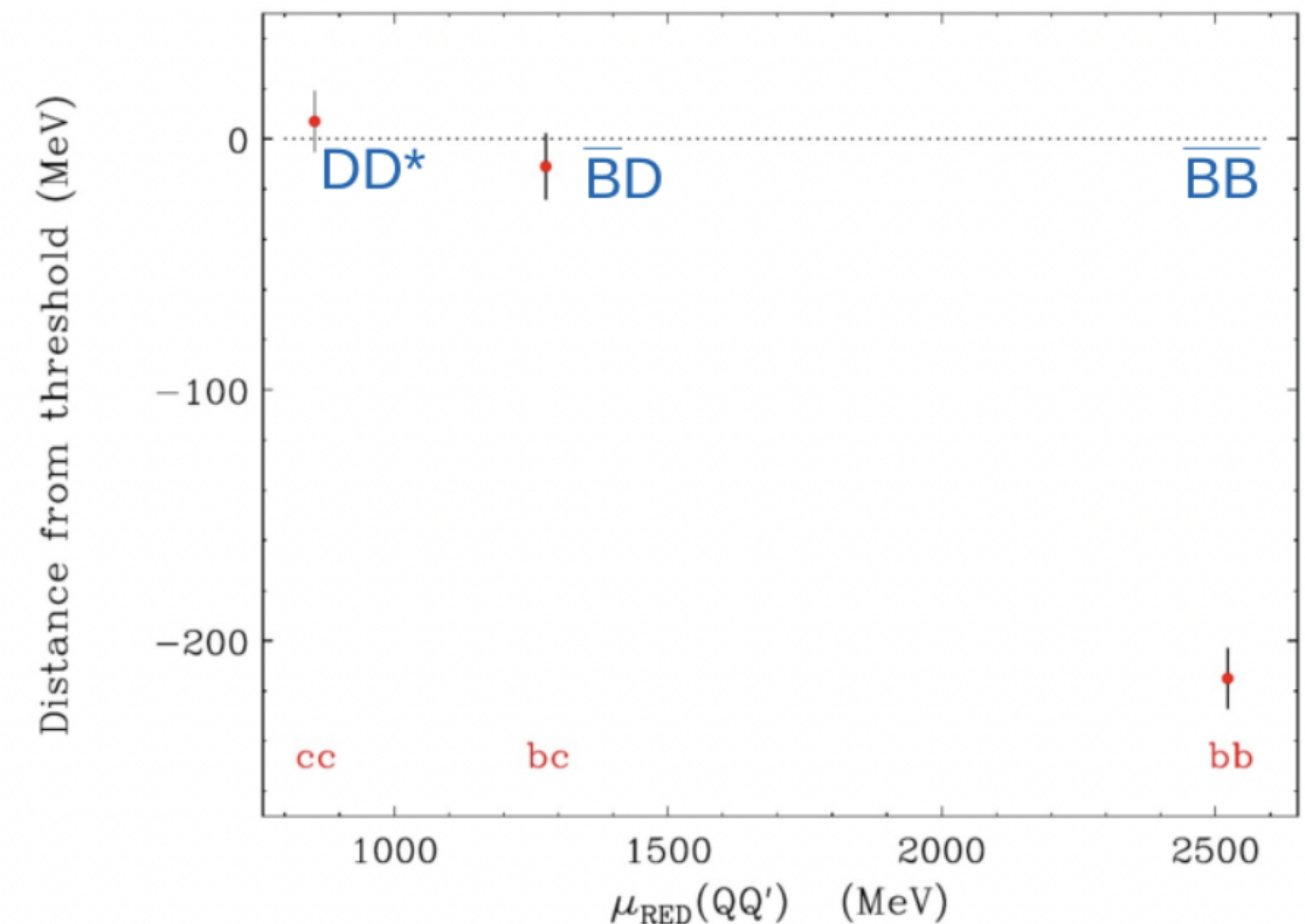
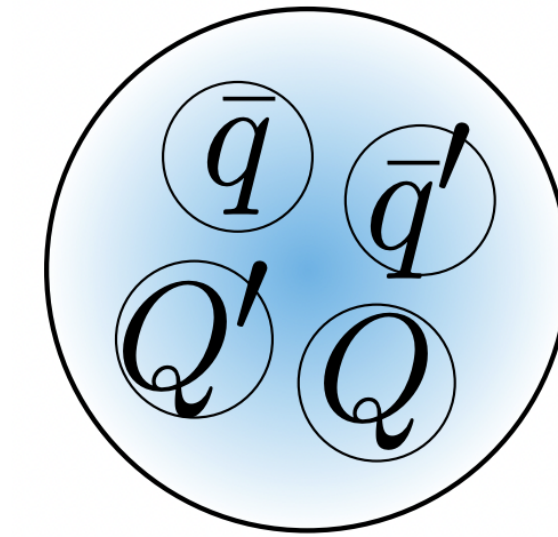
Search for doubly heavy $QQ'\bar{q}\bar{q}'$ states

T_{cc}^+ is the first representee of $(QQ'\bar{q}\bar{q}')$ hadrons
 → almost stable against strong interaction: $\tau \sim 10^{-20}s$

⇒ It supports existence of:

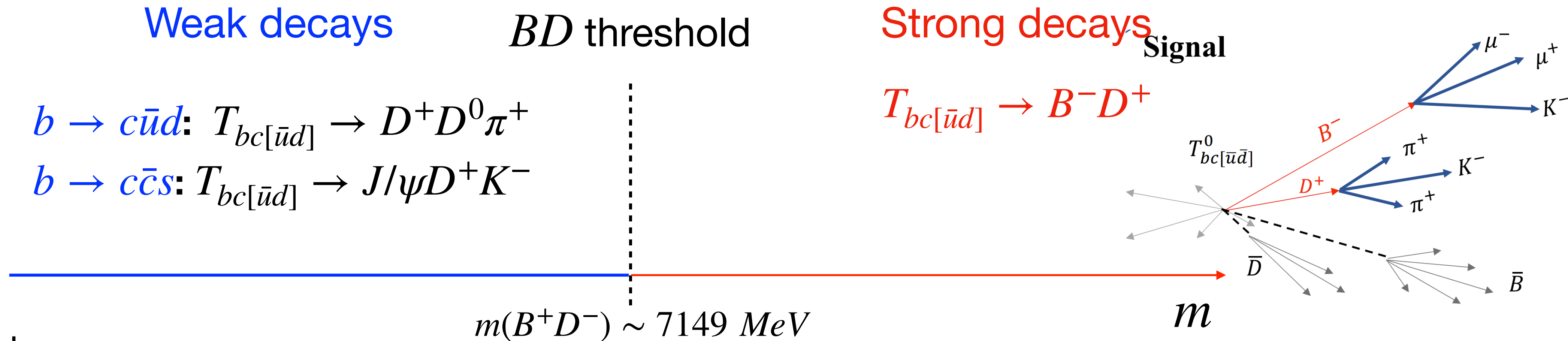
T_{bb}^- ($bb\bar{u}\bar{d}$): stable against QCD with binding energy about 215 MeV with respect to BB^* threshold
 —> Lattice QCD computations show consistent picture [[PhysRevD.110.094503](#)]

T_{bc}^0 ($bc\bar{u}\bar{d}$): either stable or almost, like T_{cc}^+



Phys. Rev. Lett. 119, 202001 (2017)

Search for T_{bc}



Some yield estimates:

$$N_{\text{signal}} = \mathcal{L}_{\text{int}} \sigma \text{BR}(\text{signal}) \text{BR}(\text{daughters}) \epsilon_{\text{tot}}$$

$$T_{bc}[\bar{u}d] \rightarrow J/\psi D^+ K^-$$

- $\sigma \sim 100 \text{ nb}$ at 13 TeV [Phys. Lett. B785 (2018) 605]
 - $\text{BR}(T_{bc} \rightarrow J/\psi D^+ K^-) \sim 1\%$
 - $\epsilon \sim 2.5\% *$
- $\Rightarrow N(50 \text{ fb}^{-1}) = 6800 \text{ events}$

$$T_{bc}[\bar{u}d] \rightarrow B^-(J/\psi K^+) D^+ (\rightarrow K^+ K^- \pi^+)$$

- $\sigma \sim 100 \text{ nb}$
 - $\text{BR}(T_{bc} \rightarrow B^- D^+) \sim 50\%$
 - $\epsilon \sim 2.5\% *$
- $\Rightarrow N(50 \text{ fb}^{-1}) = 350 \text{ events}$

*Preliminary efficiency estimates

$\Rightarrow$ Statistics of O(1000) per channel: combination of many modes within reach in Run3 / Run3+Run4

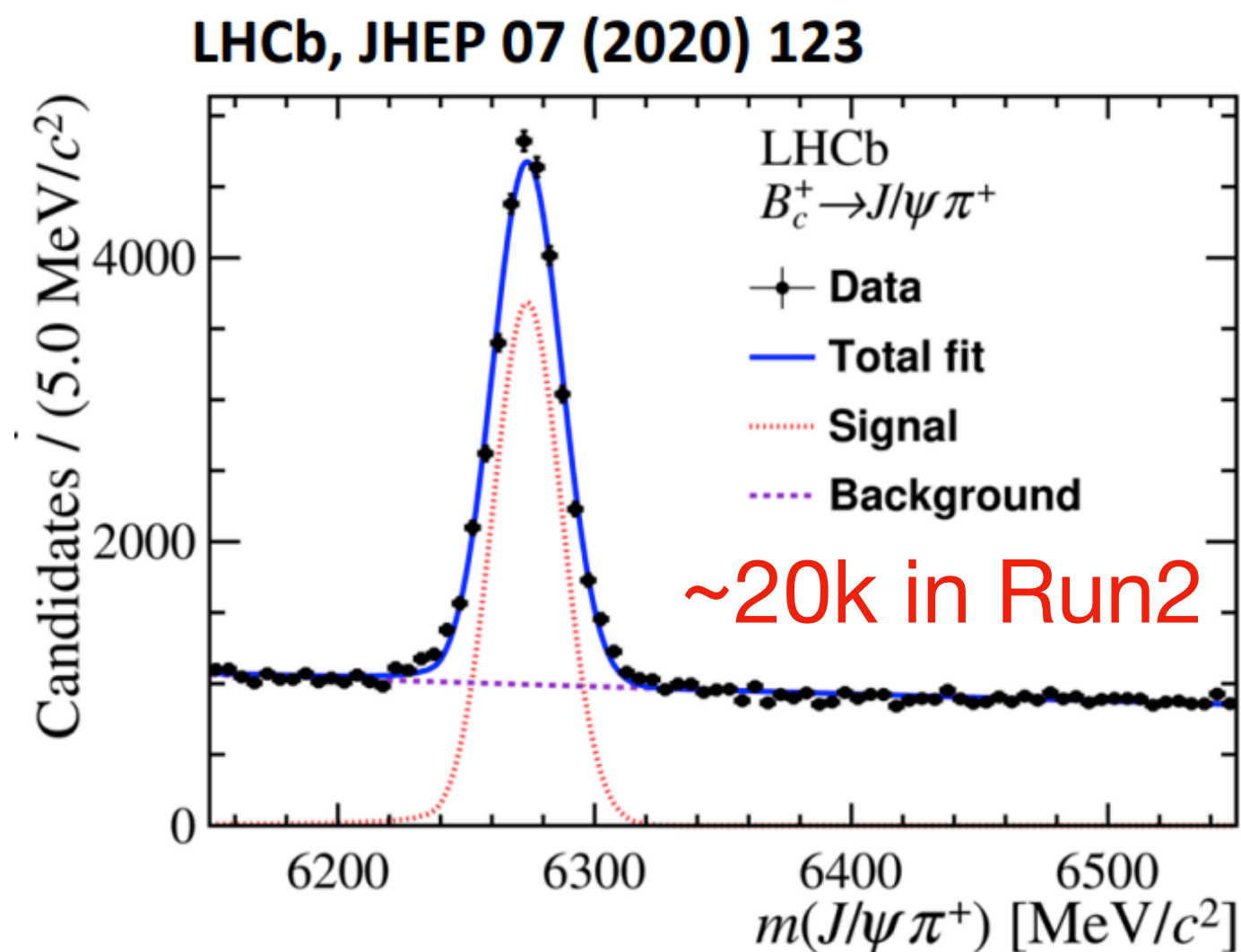
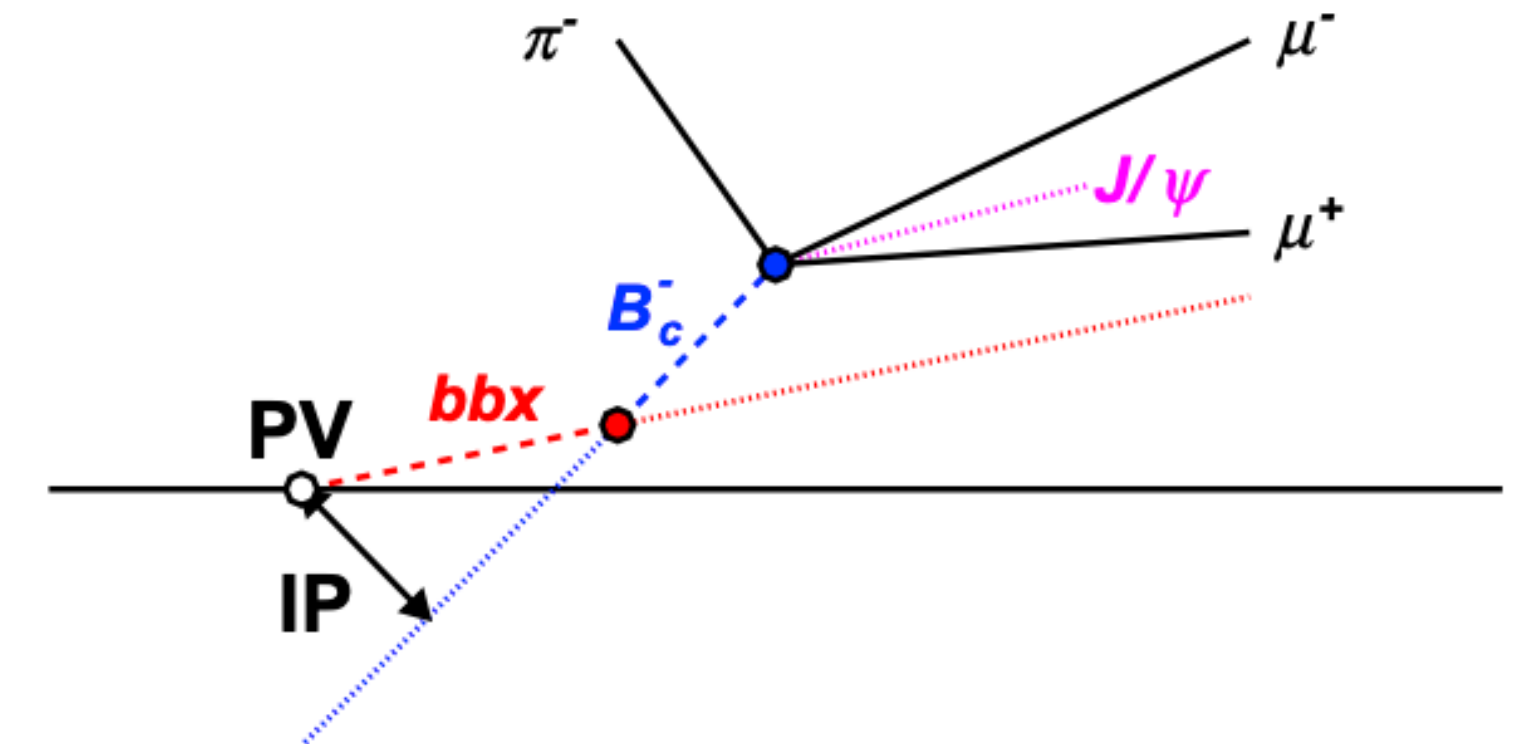
Search for T_{bb}

Cross-section $\sim O(50 - 100)$ times smaller than $\sigma(T_{bc}[\bar{u}d]) \Rightarrow \sigma \sim 1 \text{ nb}$

$\Rightarrow$ Fully exclusive final states seem ‘out of reach’ in Run 3 + 4

Inclusive search in $B_c X$:

- Only need to reconstruct the $B_c \rightarrow J/\psi \pi$
- Only known contribution would be T_{bb} tetraquarks and bbq baryons



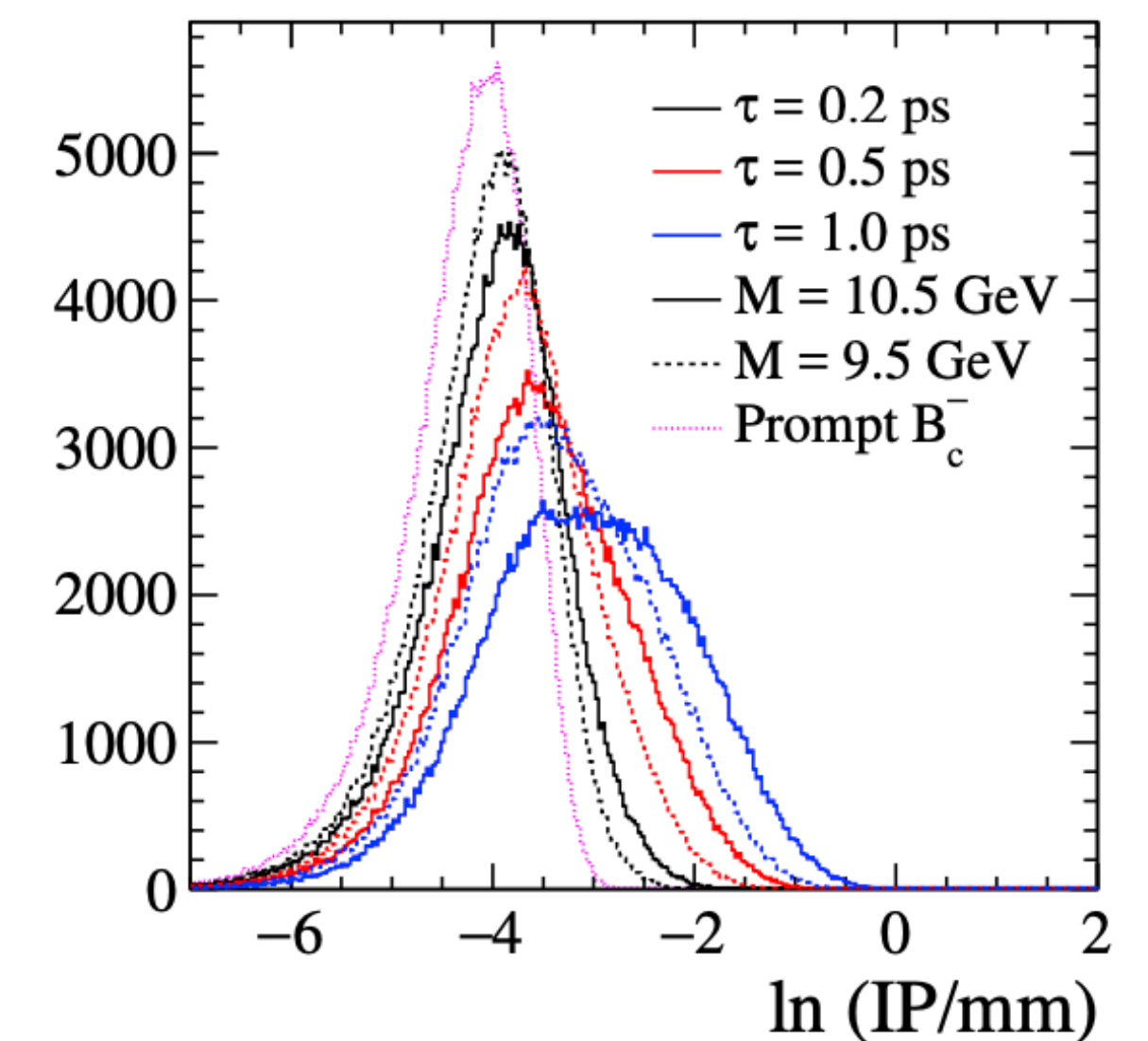
Method: IP distribution can discriminate prompt from secondaries

Yields:

$BR(T_{bb} \rightarrow B_c X) \sim 10\%$, $\epsilon \sim 10\%$

$\Rightarrow \sim 10$ displaced events / fb^{-1} :

$N(50 \text{ fb}^{-1}) \sim 500$ events



(see Gershon & Poluektov, JHEP 01 (2019) 019)

Conclusion

Run1&2: Hadron spectroscopy is one of the leading topics and highlights of LHCb

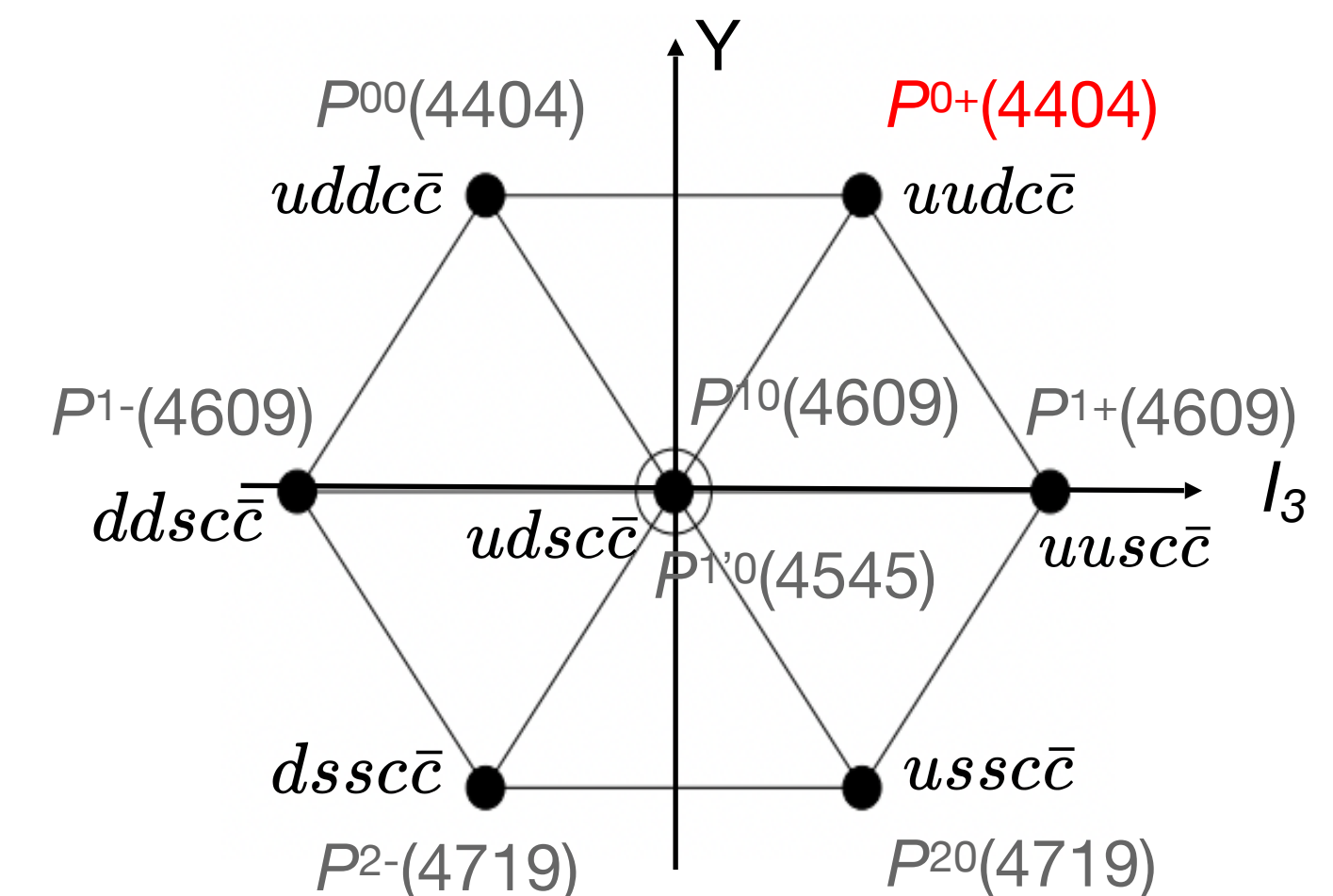
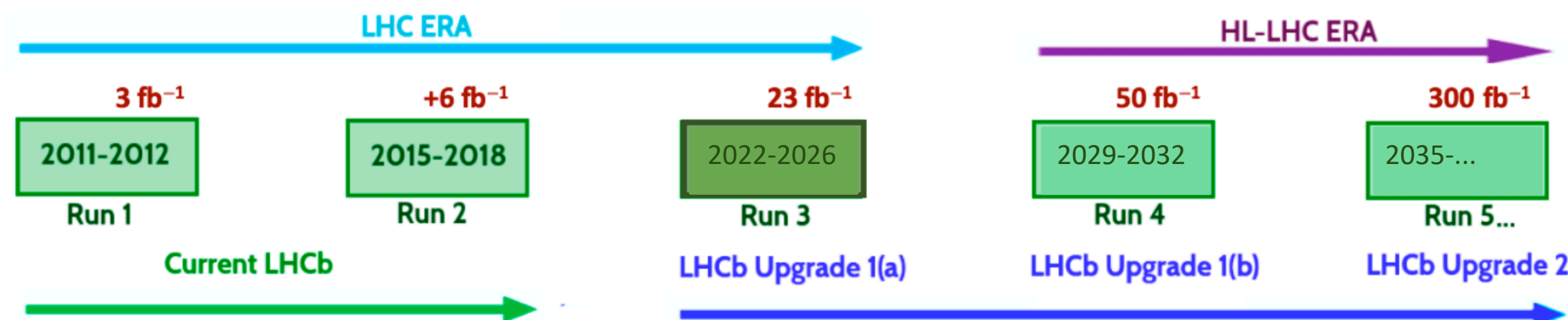
Run3: Upgraded detector & Higher statistics further boosts the spectroscopy studies

Conventional spectroscopy

- LHC experiments are only explorers of Bc decays
- Focus on *bc* and *bb* sector

Exotic spectroscopy

- Access to *bc* tetraquark and pentaquarks and *b $\bar{b}$* spectroscopy
- Search for states in flavour multiplets
- Search for sexaquark



[PhysRevD.96.014014](https://arxiv.org/abs/1907.01401)

Expect LHCb spectroscopy results from Run 3(+) in the near(+) future!

Thank you for the attention!

Backup

Exotics and heavy quark sector



A SCHEMATIC MODEL OF BARYONS AND MESONS

M. GELL-MANN

California Institute of Technology, Pasadena, California

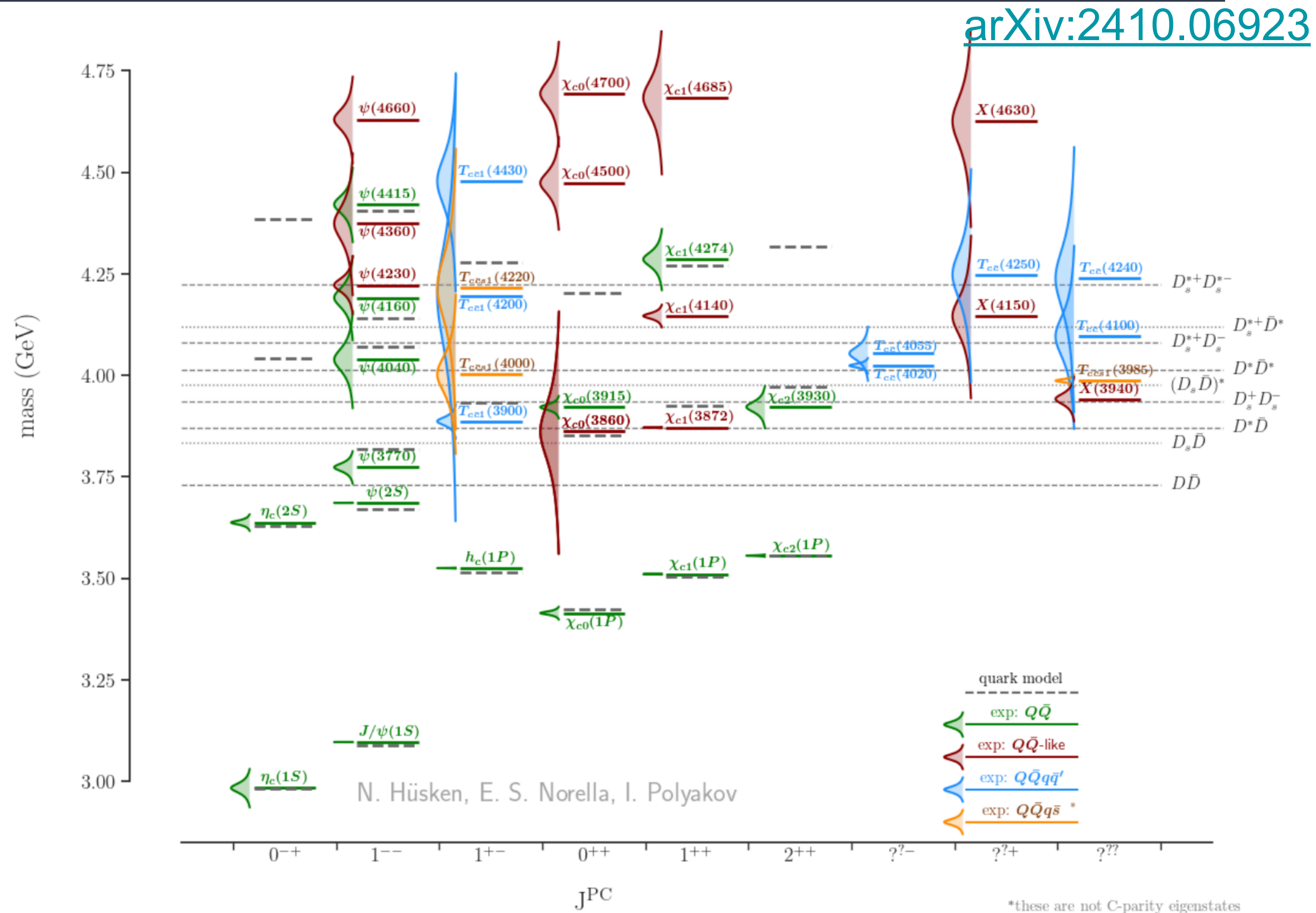
Received 4 January 1964

anti-triplet as anti-quarks $\bar{q}$. Baryons can now be constructed from quarks by using the combinations (qqq) , $(qqq\bar{q})$, etc., while mesons are made out of $(q\bar{q})$, $(q\bar{q}q\bar{q})$, etc. It is assuming that the lowest

Hidden-charm sector is ideal for exotic searches

- Theoretical models well-established for conventional states
- Experimentally easy to measure
 - Narrow and non-overlapping
 - Agreement below $D\bar{D}$ threshold

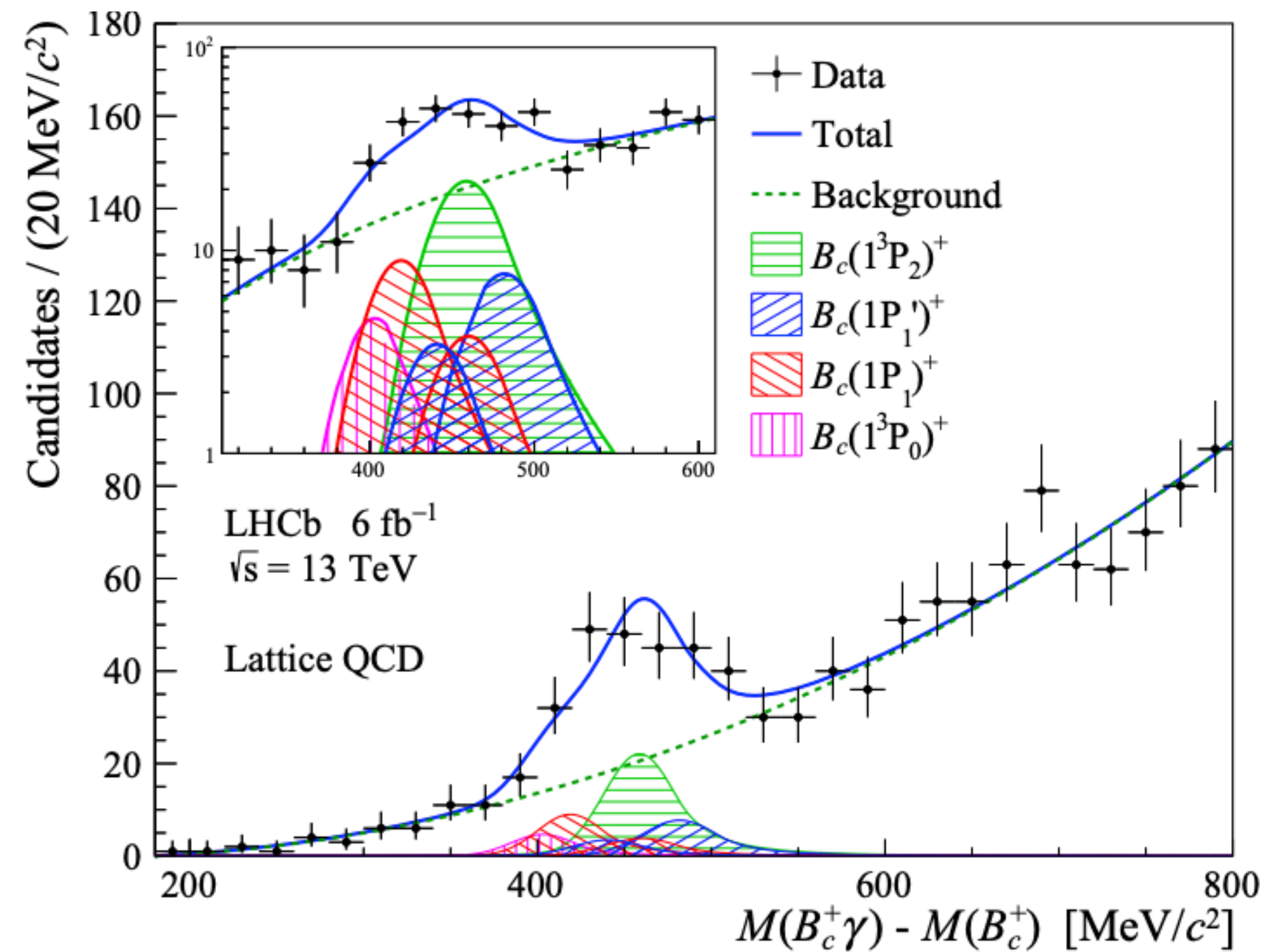
⇒ Exotics easier to identify respect to light and heavy-light sector



Other models

[arXiv:2507.02142](https://arxiv.org/abs/2507.02142)

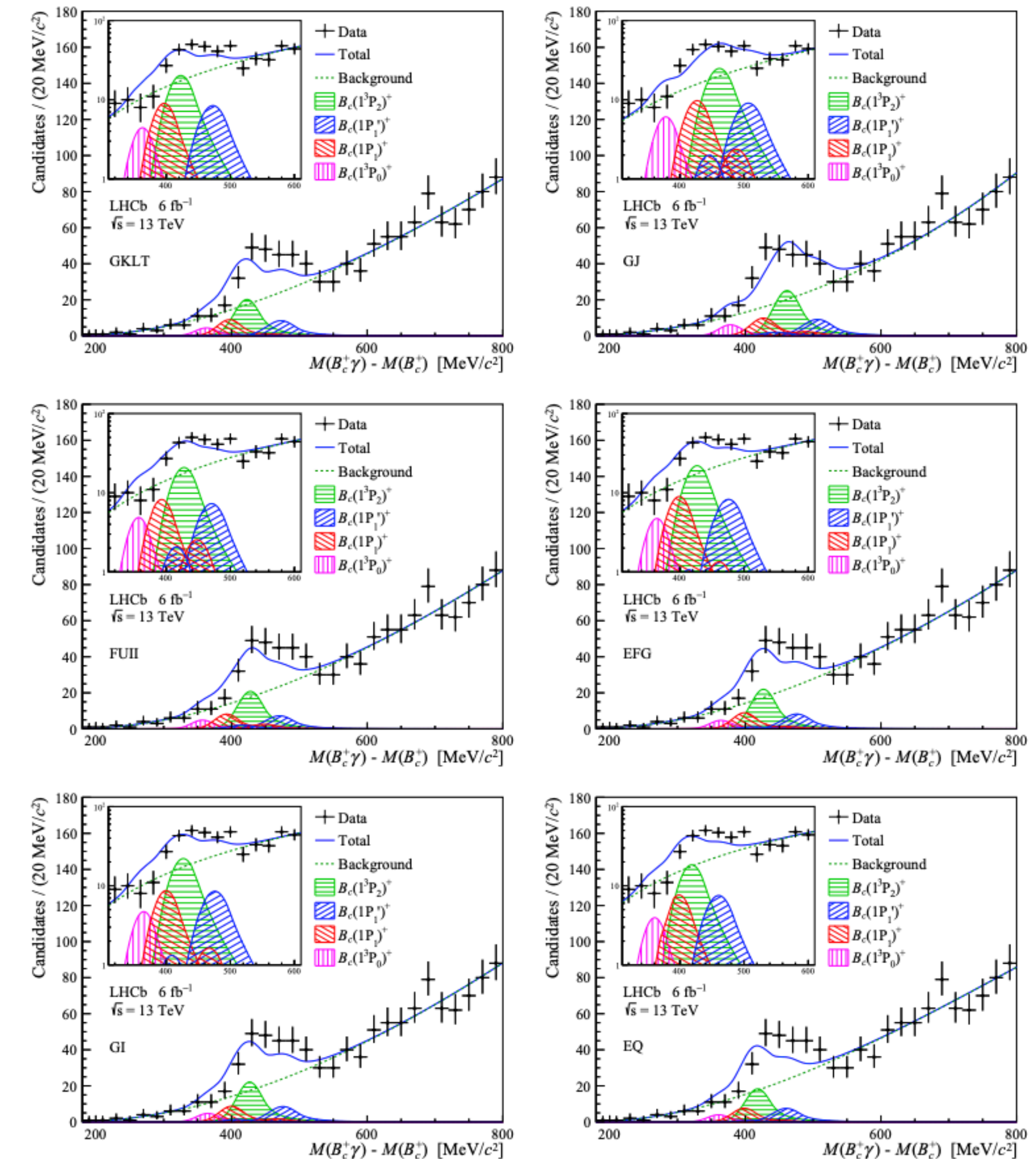
Fix masses and relative yields to theoretical expectations
Investigated several models (Run 2 only) – all compatible with data



Relative production cross-section of $B_c(1P)^+$ states compared to B_c^+ :

$$R = 0.20 \pm 0.03 \pm 0.02 \pm 0.03 \text{ (model)}$$

(pT < 20 GeV/c and 2 < η < 4.5)



Future plans for $T_{QQ'}$ family

Perform amplitude analysis of T_{cc} to determine $J^P \Rightarrow$ with Run3 data

Search for T_{bc} :

- **Above threshold: Strong decay** to BD mesons

Example: $T_{bc[\bar{u}d]} \rightarrow B^- D^+, B^- \rightarrow J/\psi K, D^+ \rightarrow K^+ K^- \pi^+$.

$\Rightarrow$ Assuming $\sigma \sim 100$ nb,

$\Rightarrow N(50 \text{ fb}^{-1}) = 400$ **events**

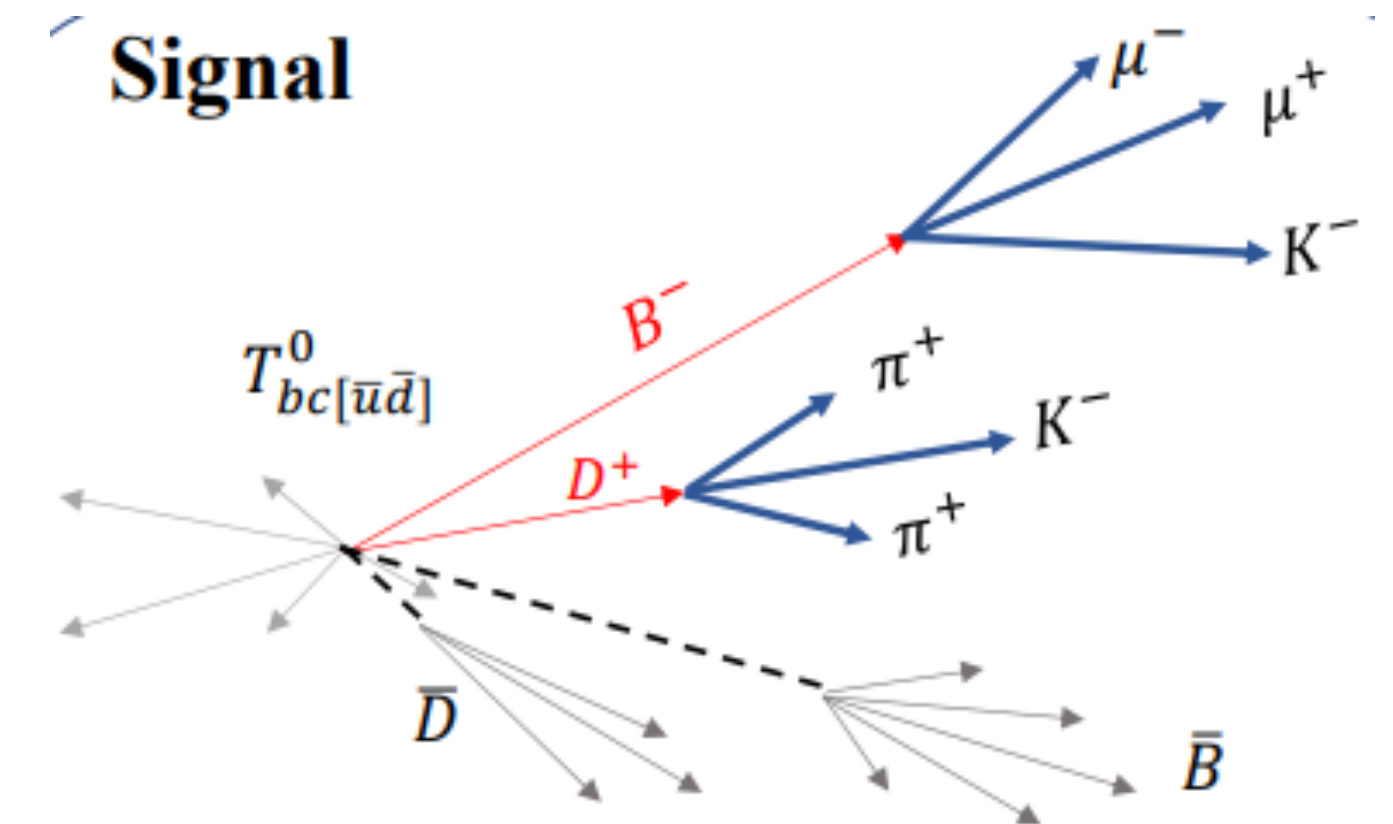
BR $\sim 50\%$ & $\epsilon \sim 10\%$ (x3 wrt Run2)

- **Below threshold: Weak decays:**

$b \rightarrow cud$: $T_{bc[\bar{u}d]} \rightarrow D^+ D^0 \pi^+$: BR $\sim 1\%$, $\epsilon \sim 1\% \Rightarrow N(50 \text{ fb}^{-1}) = 1300$ **events**

$b \rightarrow ccs$: $T_{bc[\bar{u}d]} \rightarrow J/\psi D^+ K^-$: BR $\sim 1\%$, $\epsilon \sim 2.5\% \Rightarrow N(50 \text{ fb}^{-1}) = 6800$ **events**

$\Rightarrow$ could be within reach in Run3 + Run4

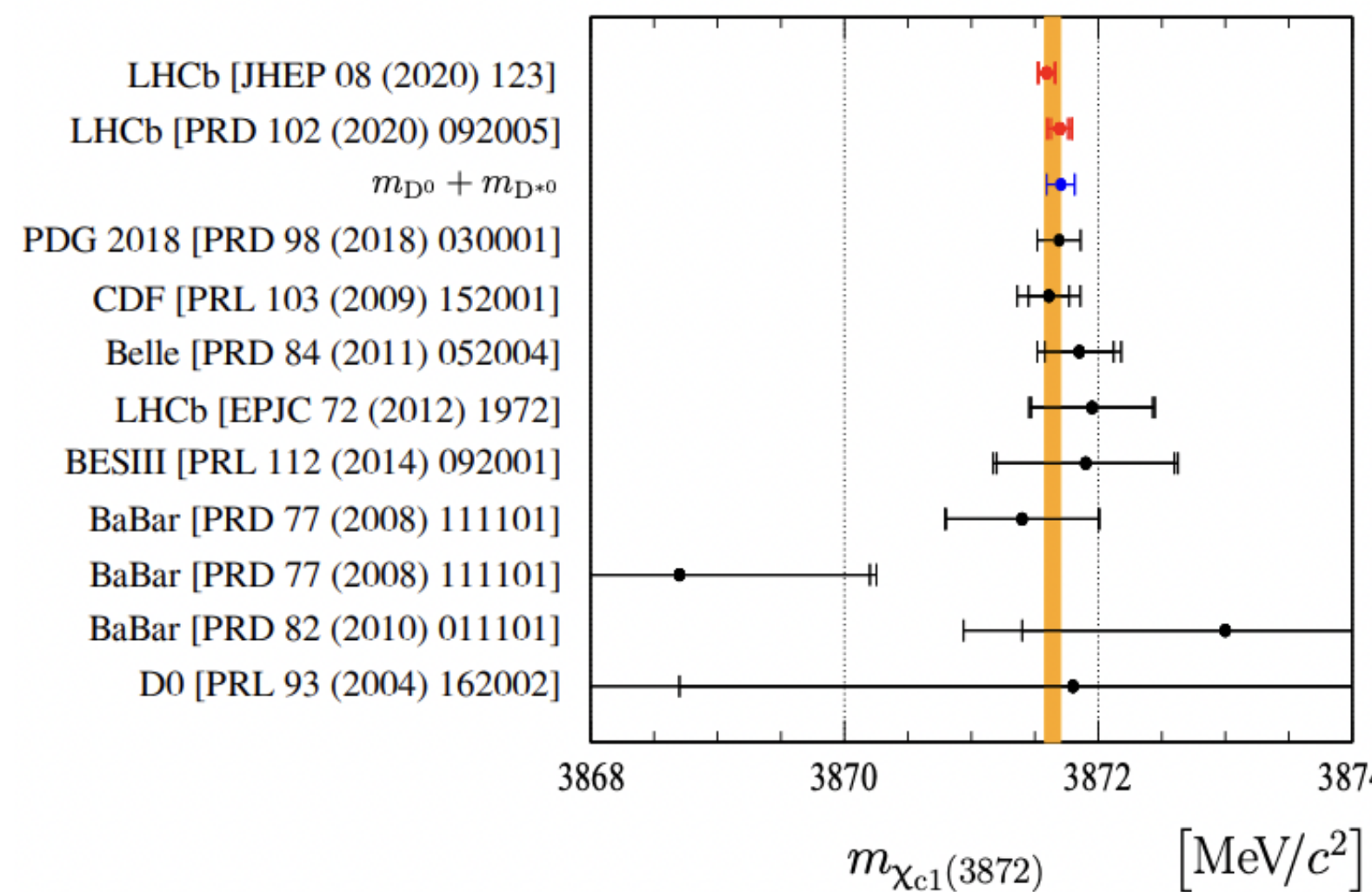


Nature of $\chi_{c1}(3872)$ state

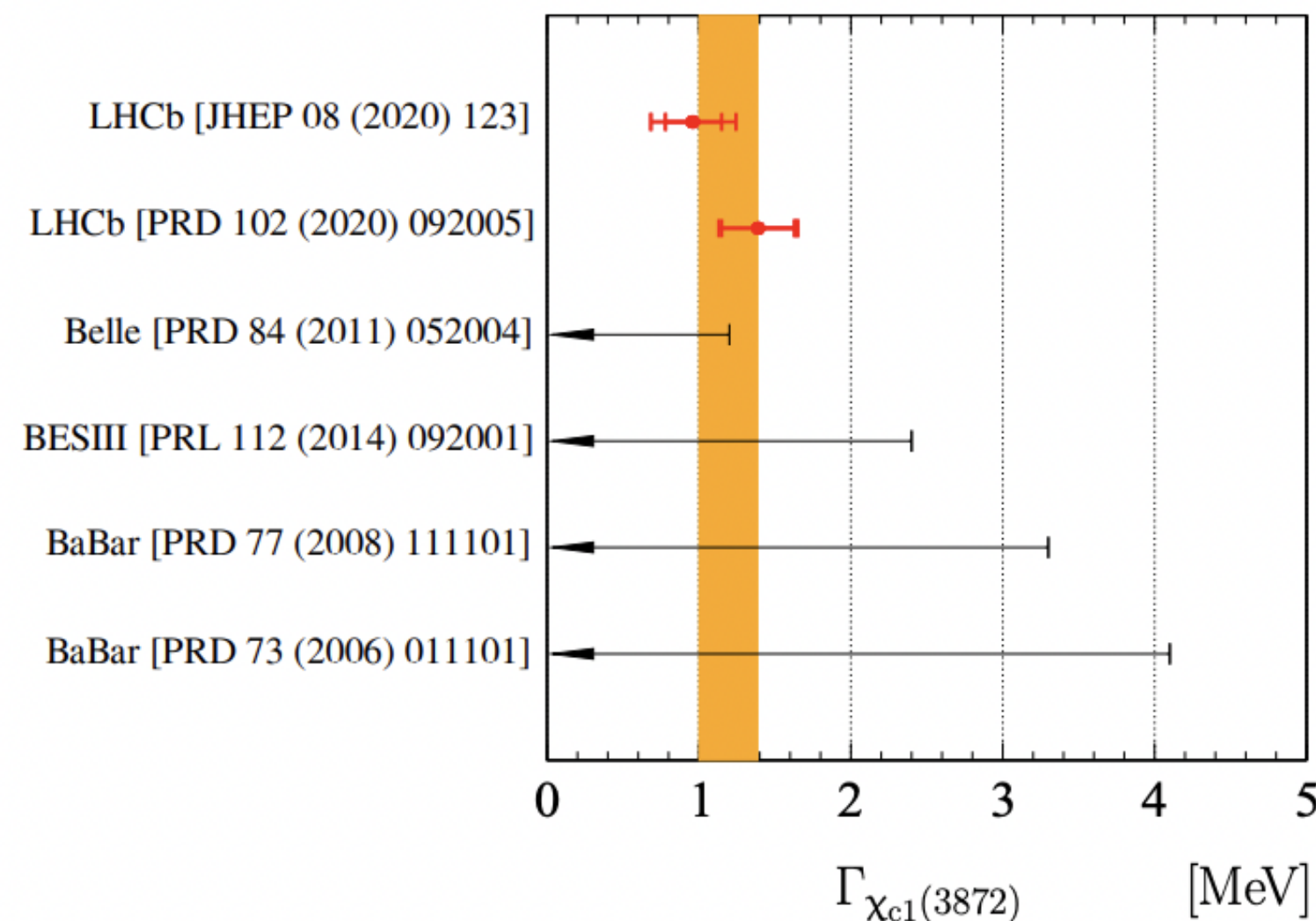
Many experiments contribute to it:

- Spin assignment: $J^{PC} = 1^{++}$ [1] $\Rightarrow$ consistent with $\chi_{c1}(2P)$
- Mass is consistent with $m(\mathbf{D}^0) + m(\mathbf{D}^{*0}) \Rightarrow$ disagree with quark model calculation by 100 MeV [2]
- Width is surprisingly narrow

Its nature is still under debate!
 $\rightarrow$ conventional $\chi_{c1}(2^3P_1)$, DD^* molecular state, tetraquark, hybrid, vector glueball, or mixed?



JHEP 08 (2020) 123



Studying **decay processes**
 can help understand its nature

[1] PRL. 110 (2013) 222001, PRD 92 (2015) 011102(R)
 [2] PhysRevD.69.054008

ω contribution in $\chi_{c1}(3872) \rightarrow J/\psi \pi \pi$

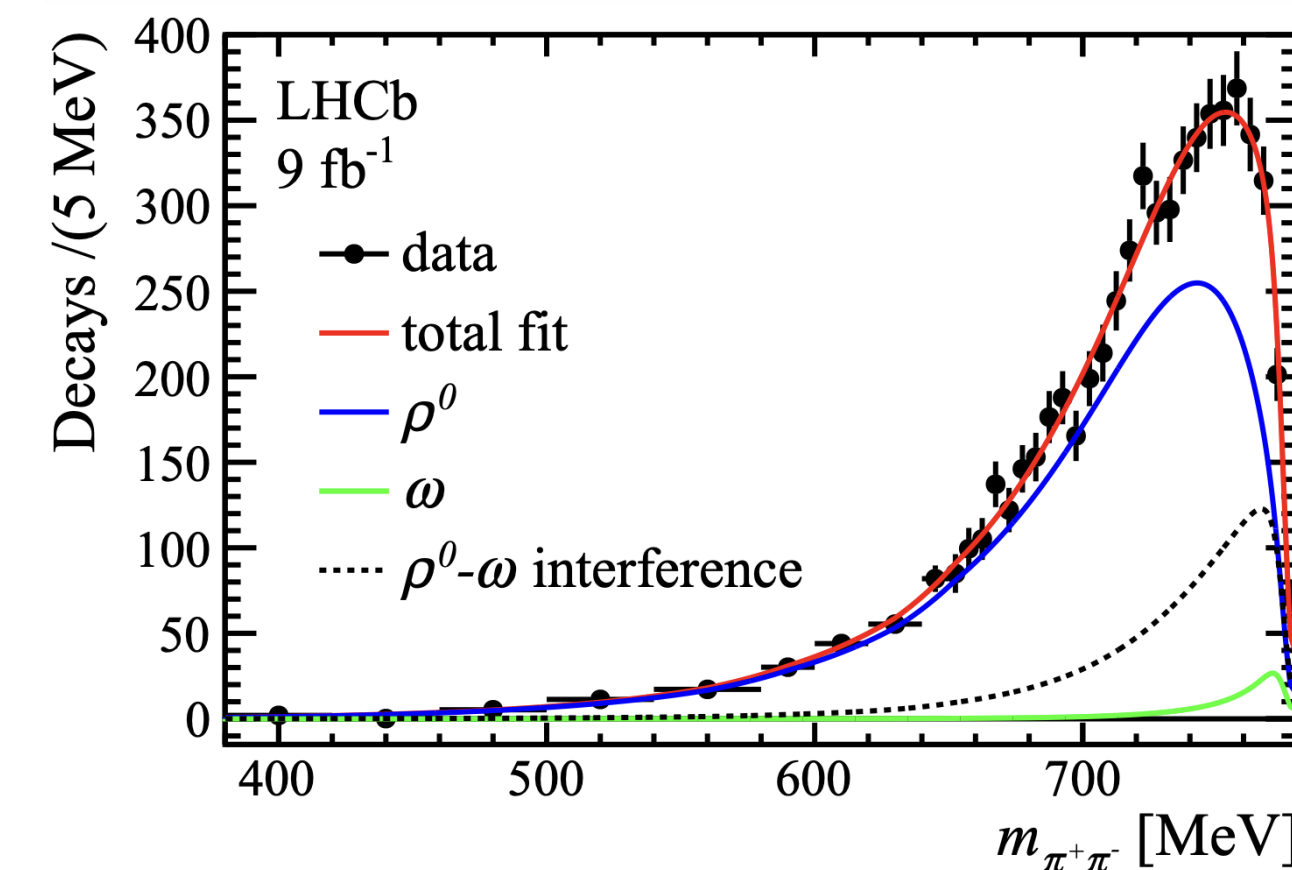
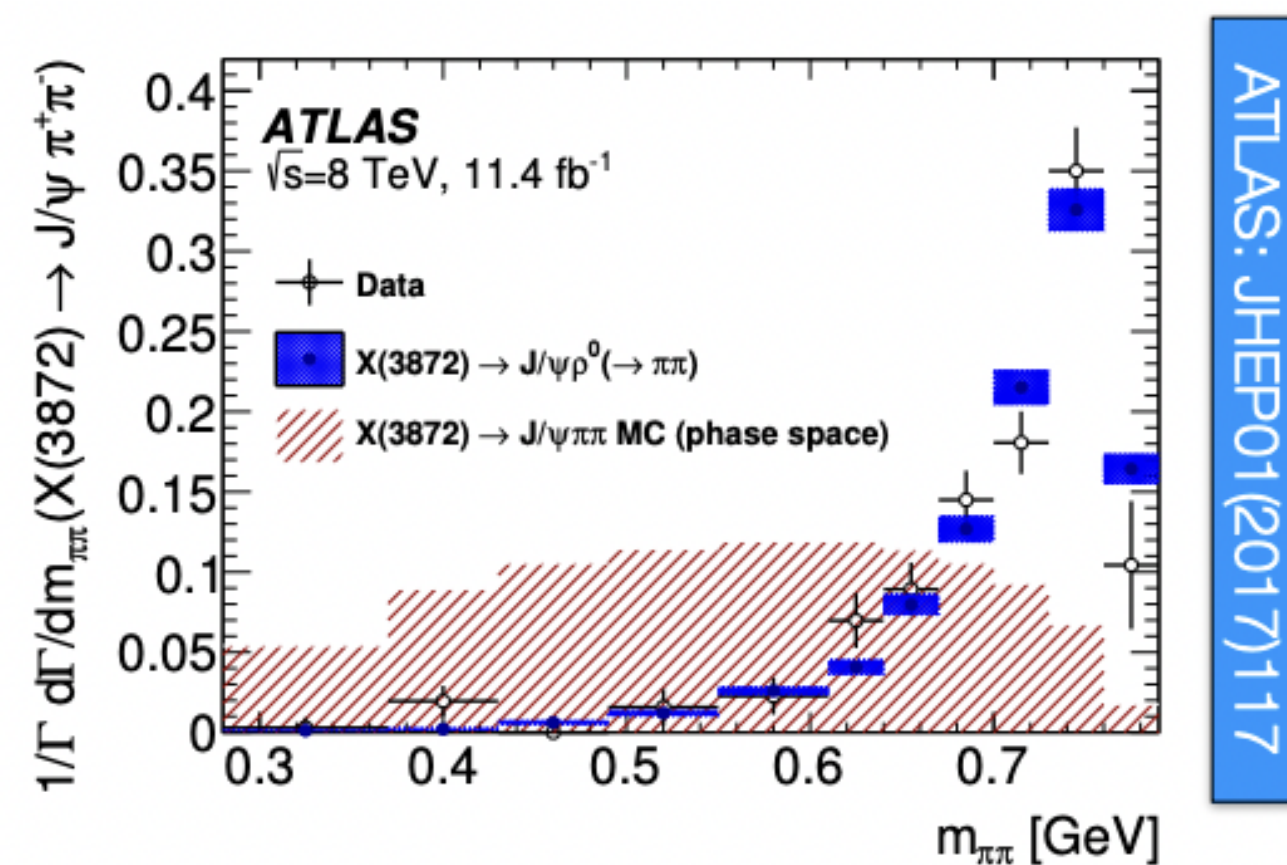
Phys. Rev. D 108 (2023), no. 1 L011103

Large isospin violation observed in $\chi_{c1}(3872)$ decays [Belle, BaBar: Phys. Rev. D 82, 011101 (2010)]

→ How large is it in $\chi_{c1} \rightarrow J/\psi \pi^+ \pi^-$?

Previously only $\chi_{c1}(3872) \rightarrow J/\psi \rho$ (isospin violating decay) dominates the phase space

Now with LHCb: ω contribution of 2%, enhanced by ω - ρ interference (~19%)



Isospin violation = ratio of isospin violating to isospin conserving couplings is much larger than expected for a charmonium

$$\frac{g_{\chi_{c1}(3872) \rightarrow \rho^0 J/\psi}}{g_{\chi_{c1}(3872) \rightarrow \omega J/\psi}} = 0.29 \pm 0.04.$$

$$\frac{g_{\psi(2S) \rightarrow \pi^0 J/\psi}}{g_{\psi(2S) \rightarrow \eta J/\psi}} = 0.045 \pm 0.001$$

⇒ **$\chi_{c1}(3872)$ is not a pure charmonium state;**

Likely related to the ~8 MeV splitting between $\bar{D}^0 D^{*0}$ and $D^{*+} D^-$

$\chi_{c1}(3872)$ radiative decays

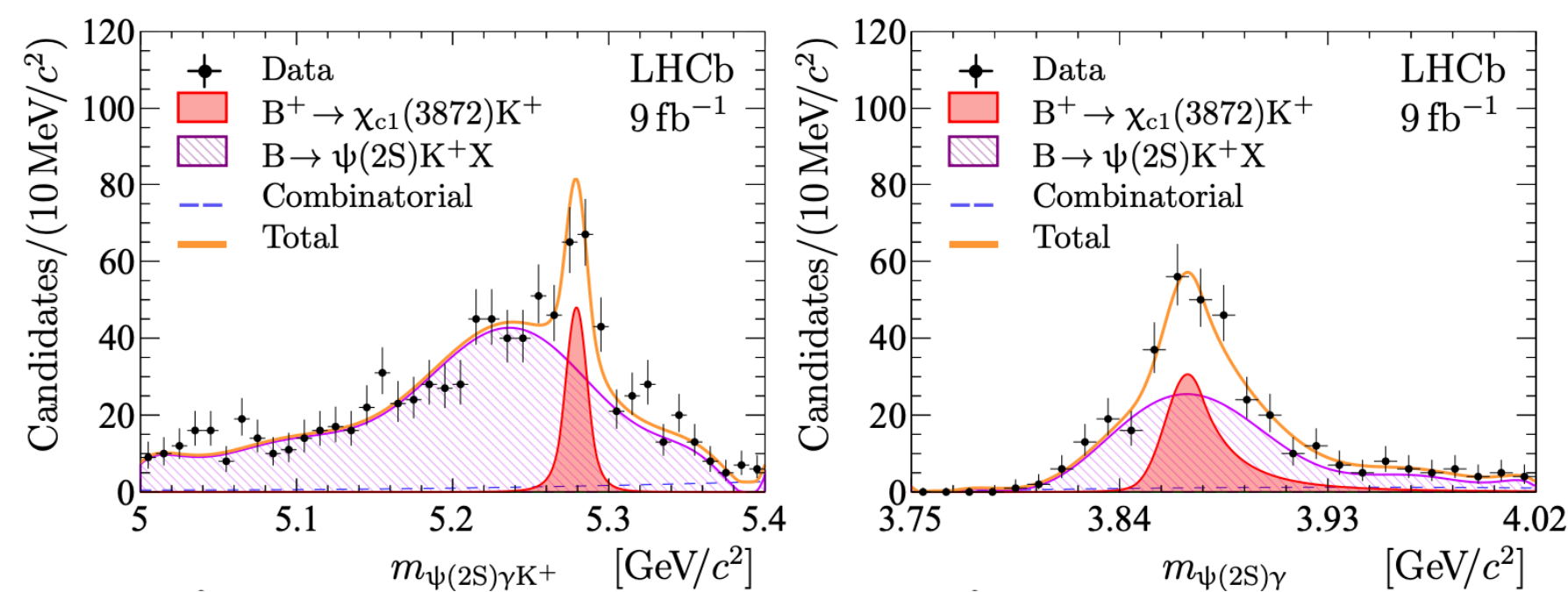
[JHEP11\(2024\)121](#)

Study of $\chi_{c1}(3872) \rightarrow J/\psi\gamma/\psi(2S)\gamma$ in B decays by LHCb

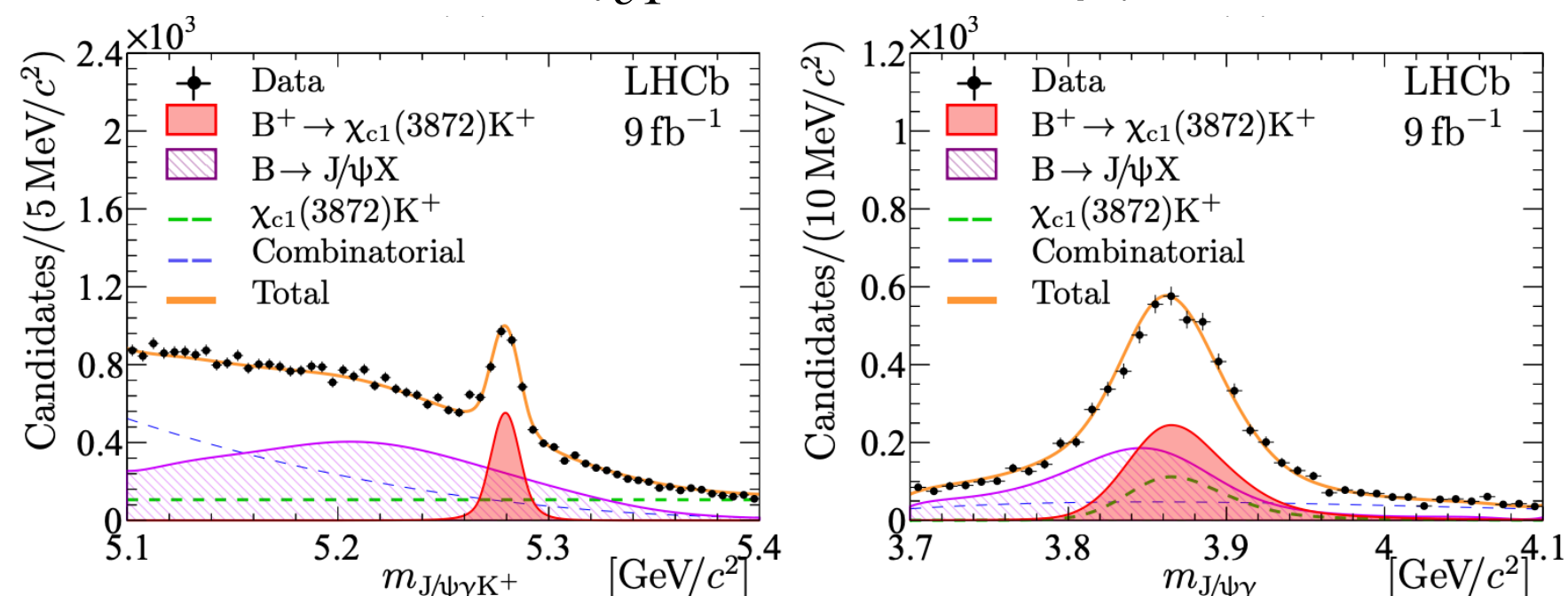
- First observation of $B^+ \rightarrow (\chi_{c1}(3872) \rightarrow \psi(2S)\gamma)K^+$ at 4.8 (6σ) in Run1 (Run2)
- Ratio measured to be:

4D fit over:

$$B^+ \rightarrow (\chi_{c1}(3872) \rightarrow \psi(2S)\gamma)K^+$$

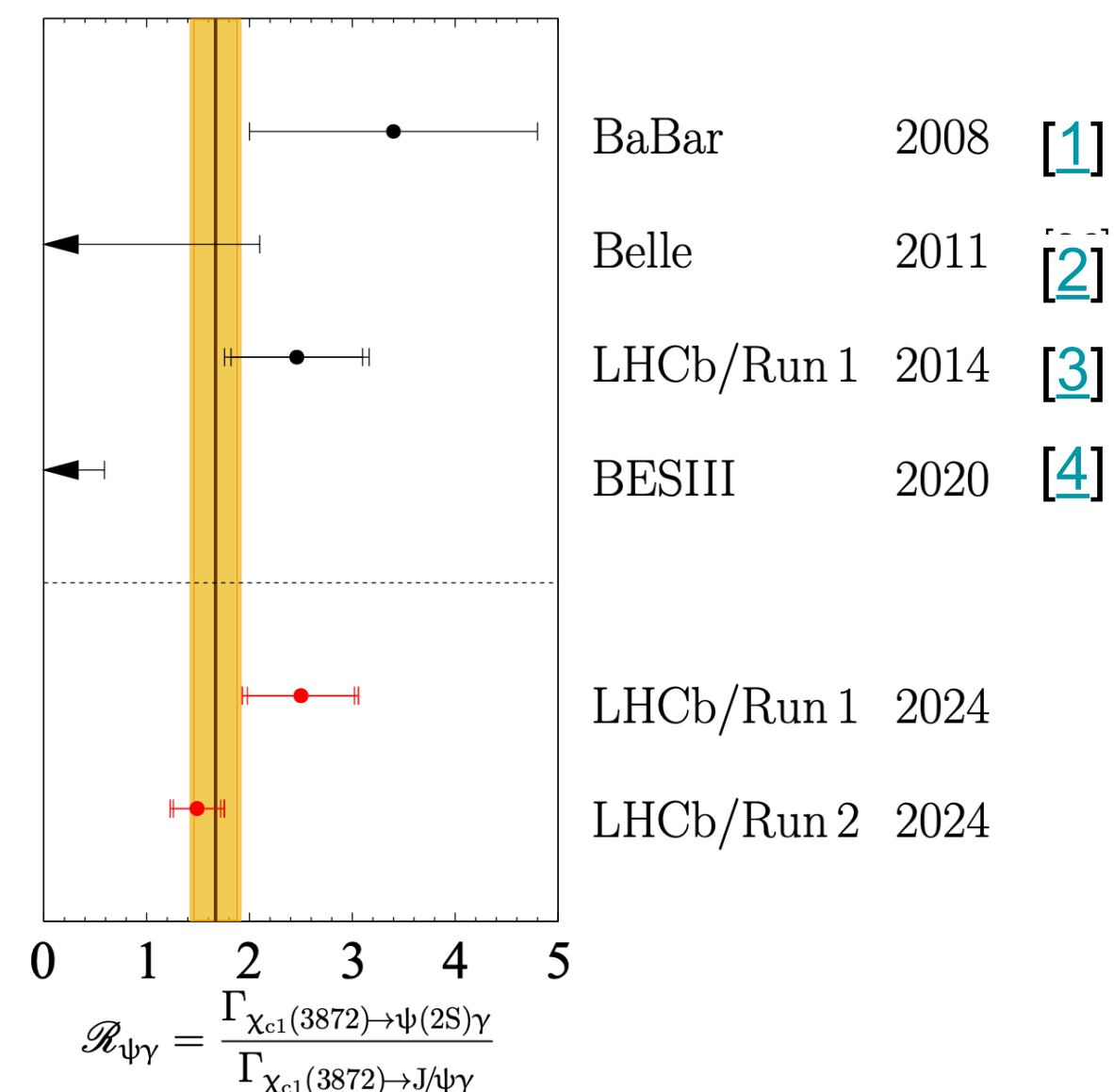


$$B^+ \rightarrow (\chi_{c1}(3872) \rightarrow J/\psi\gamma)K^+$$



$$\frac{\Gamma_{\chi_{c1}(3872) \rightarrow \psi(2S)\gamma}}{\Gamma_{\chi_{c1}(3872) \rightarrow J/\psi\gamma}} = 1.67 \pm 0.21 \pm 0.12 \pm 0.04 \Rightarrow \text{Large ratio}$$

Previous results



Sizable charmonium or compact tetraquark component are more likely

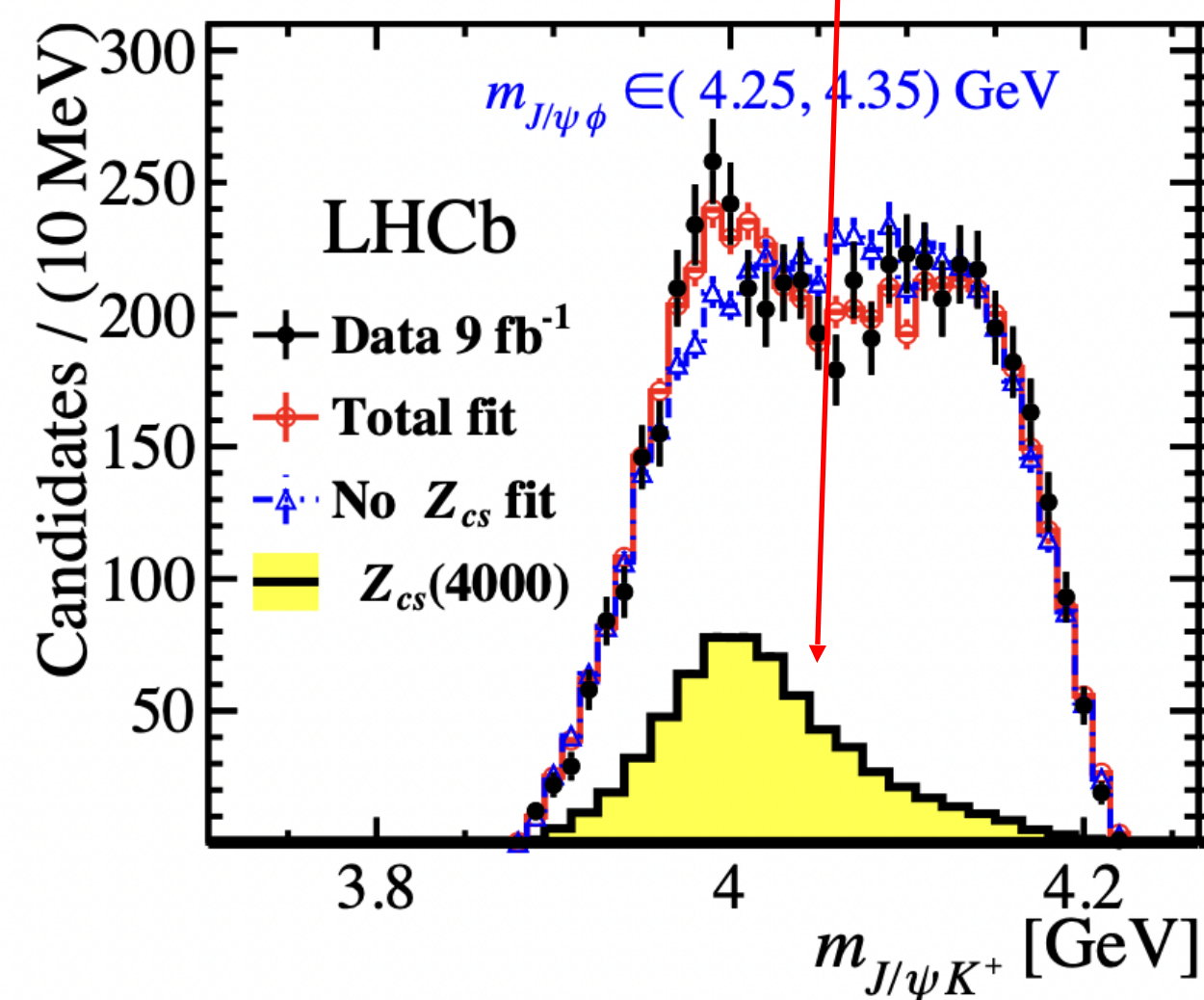
Pure molecular $D\bar{D}^*$ hypothesis is questionable

- But small admixture of $c\bar{c}$ component is sufficient to explain the data [[PhysLettB 2015 0213](#)]

Tetraquark with strangeness

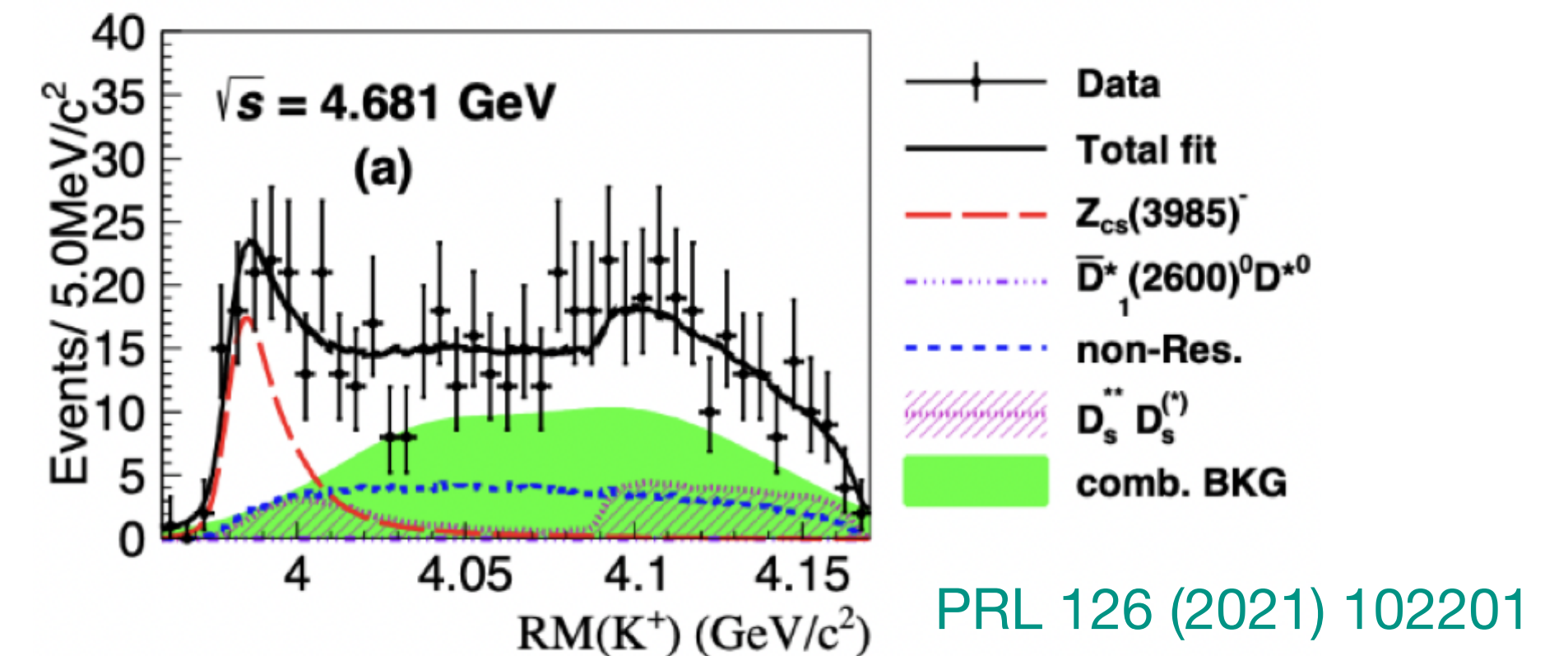
In $B^+ \rightarrow J/\psi \phi K^+$ decays, 2 states with strangeness are observed:

$T_{c\bar{c}s}(4420)^+$ and $T_{c\bar{c}s}(4000)^+$ state by LHCb



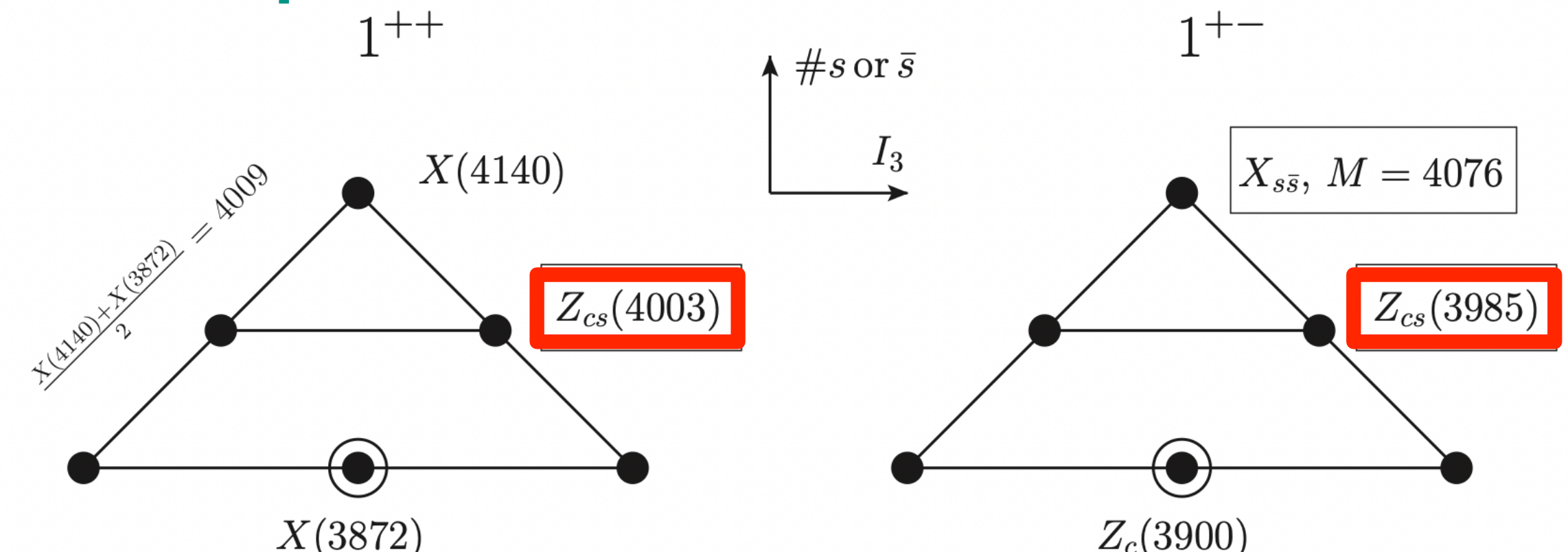
PRL 127, 082001 (2021)

Is it the **same state** as $T_{c\bar{c}s}(3985)^+$ in $D_s^- D^{*0} + D^0 D_s^{*-}$ by BESIII?



PRL 126 (2021) 102201

Degeneracy can be explained in compact tetraquark picture
[\[arXiv:2103.08331v2\]](https://arxiv.org/abs/2103.08331v2)

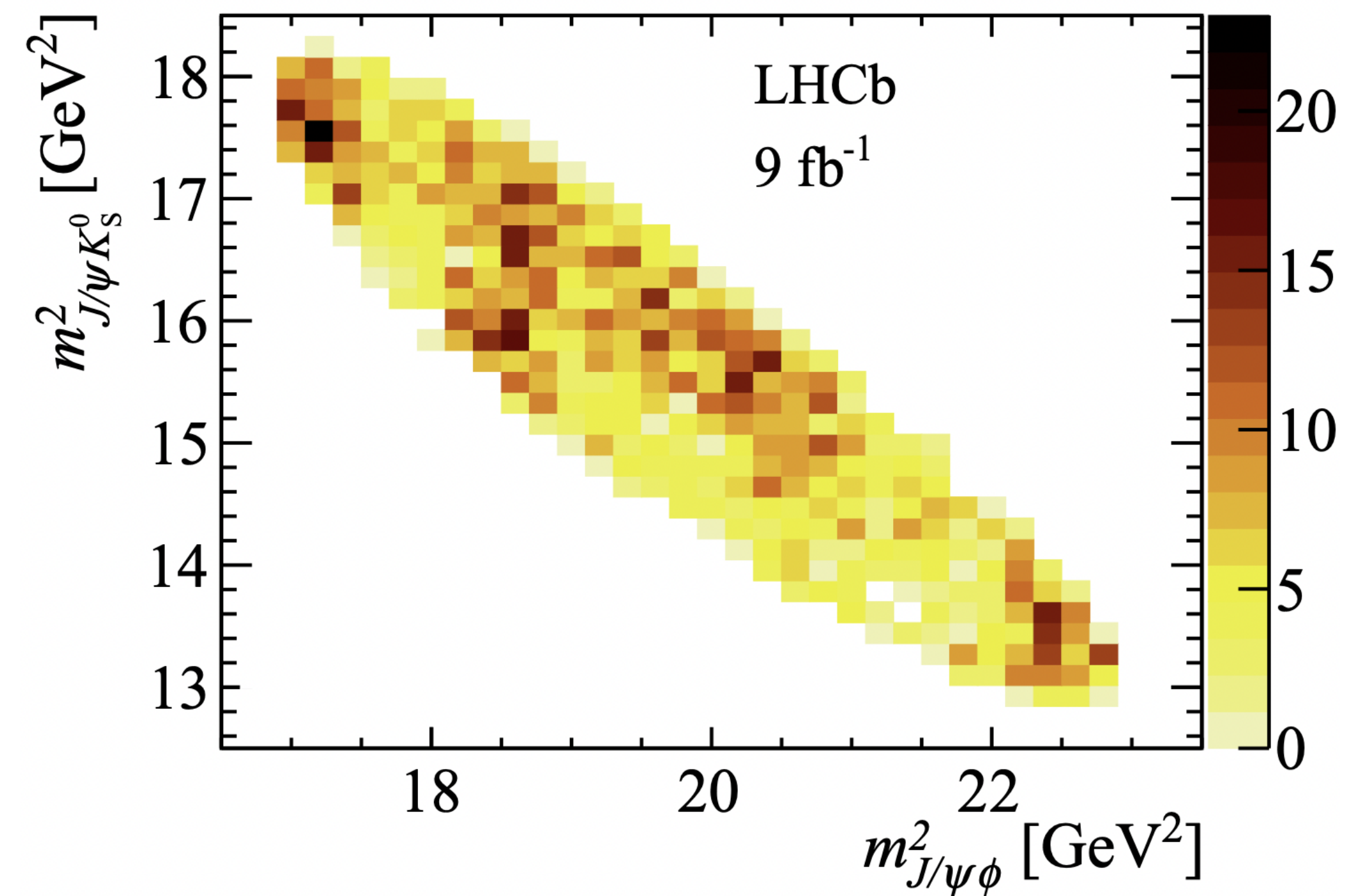
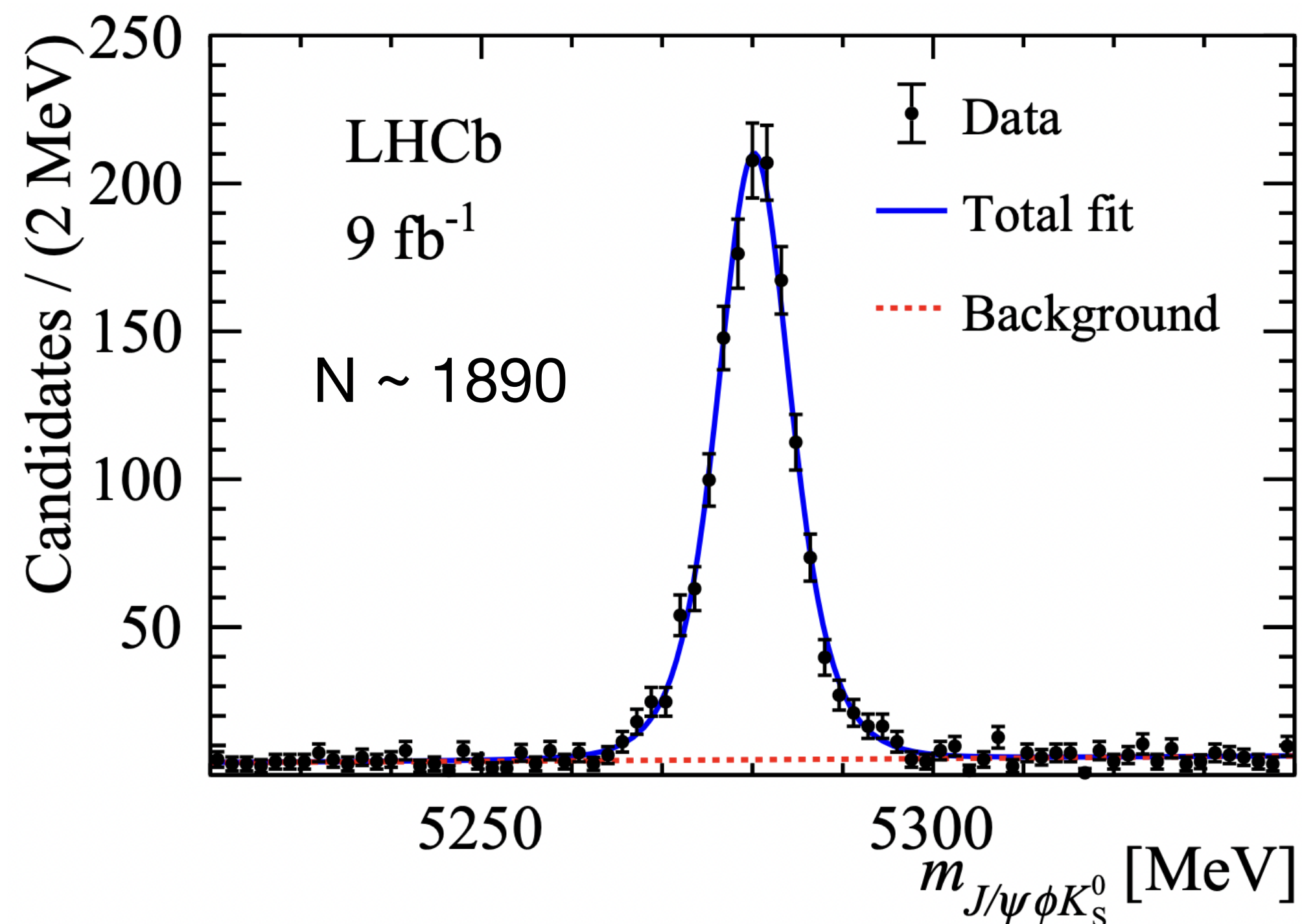


Isospin partners in $B^0 \rightarrow J/\psi\phi K_S^0$ decays

[PhysRevLett.131.131901](#)

Searching for $T_{c\bar{c}s}^0$ states, isospin partners of $T_{c\bar{c}s}^+$ states, is crucial for identifying the complete **SU(3) nonet**

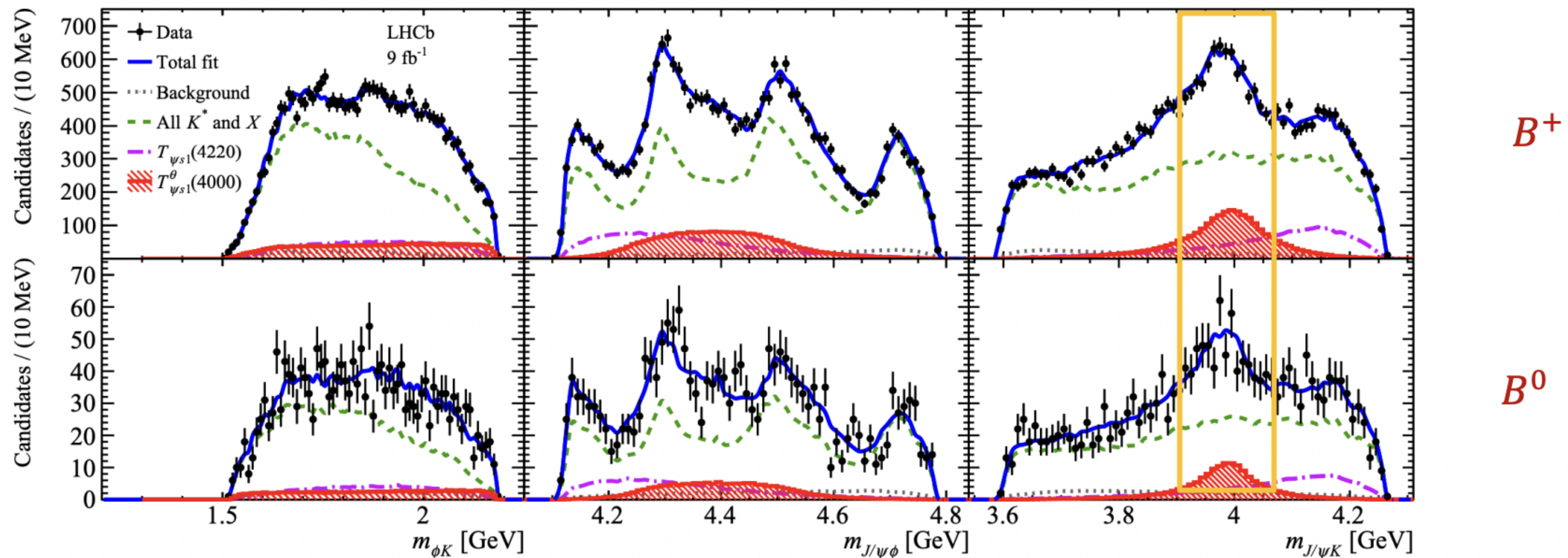
Extension of $B^+ \rightarrow J/\psi\phi K^+$ with $B^0 \rightarrow J/\psi\phi K_S^0$
since the 2 decays are related by isospin symmetry



$B^0 \rightarrow J/\psi \phi K_S^0$ decays

Combined fit to B^+ and B^0 decays:

- All components except $T_{c\bar{c}s}(4000)^0$ in B^0 decay are constrained by those in B^+ decay



Evidence for a new state with 4σ

$$M(T_{\psi s1}^{\theta}(4000)^0) = 3991_{-10}^{+12}_{-17} \text{ MeV},$$

$$\Gamma(T_{\psi s1}^{\theta}(4000)^0) = 105_{-25}^{+29}_{-23} \text{ MeV},$$

$\Rightarrow T_{c\bar{c}s}(4000)^0$ & $T_{c\bar{c}s}(4000)^+$: consistent with being isospin partners, $\Delta M = 12_{-10}^{+11}_{-4} \text{ MeV}$

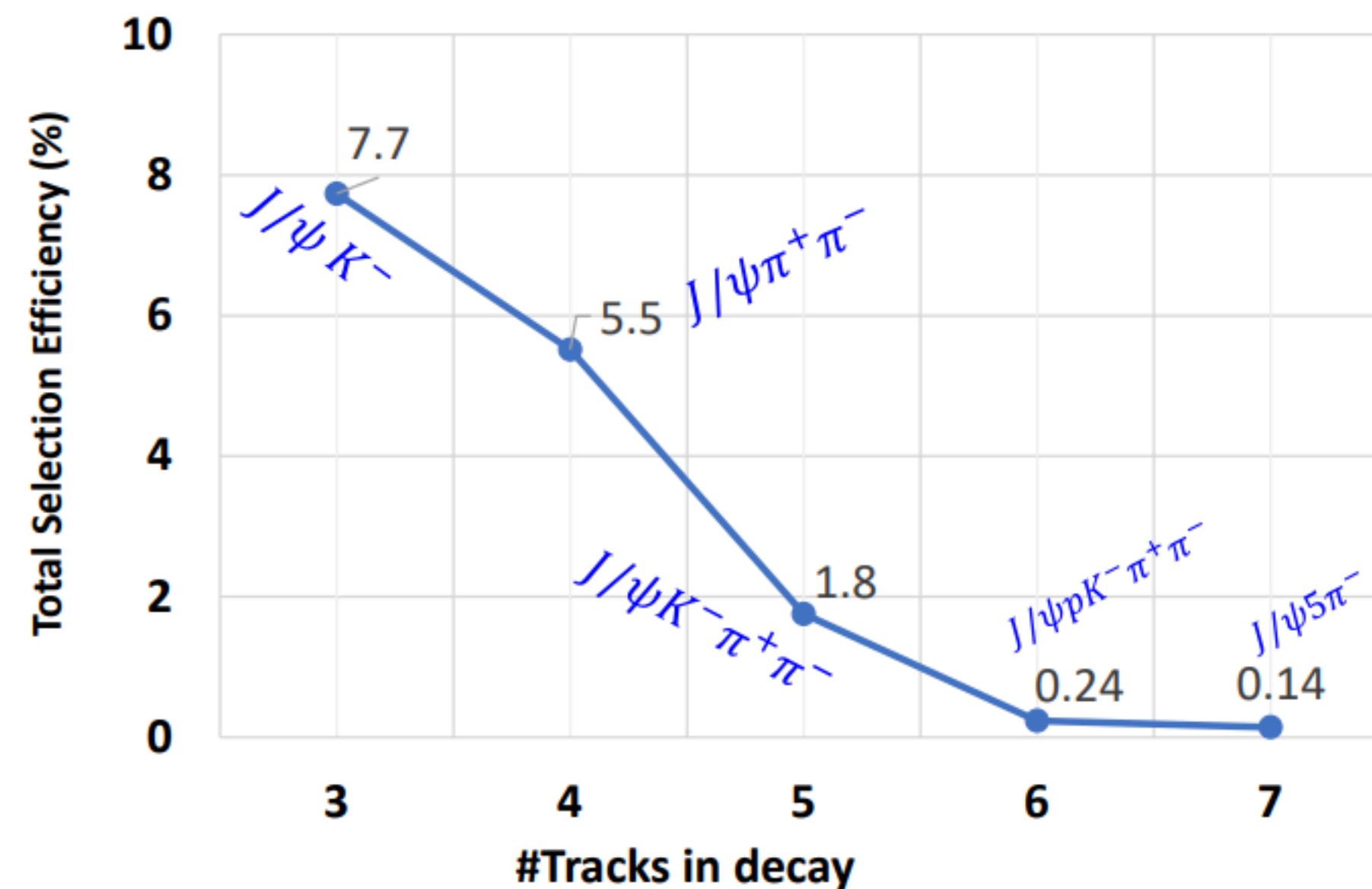
Efficiency estimates for T_{bc}

What can we expect for ε_{tot} ?

□ Let's consider $b \rightarrow J/\psi X$ modes

(Using Run 2 data)

$$\varepsilon_{tot} = \frac{N_{sig}}{\sigma(H_b) \mathcal{L}_{int} \mathcal{B}}$$



□ Very much analysis dependent, so just gives a rough idea.

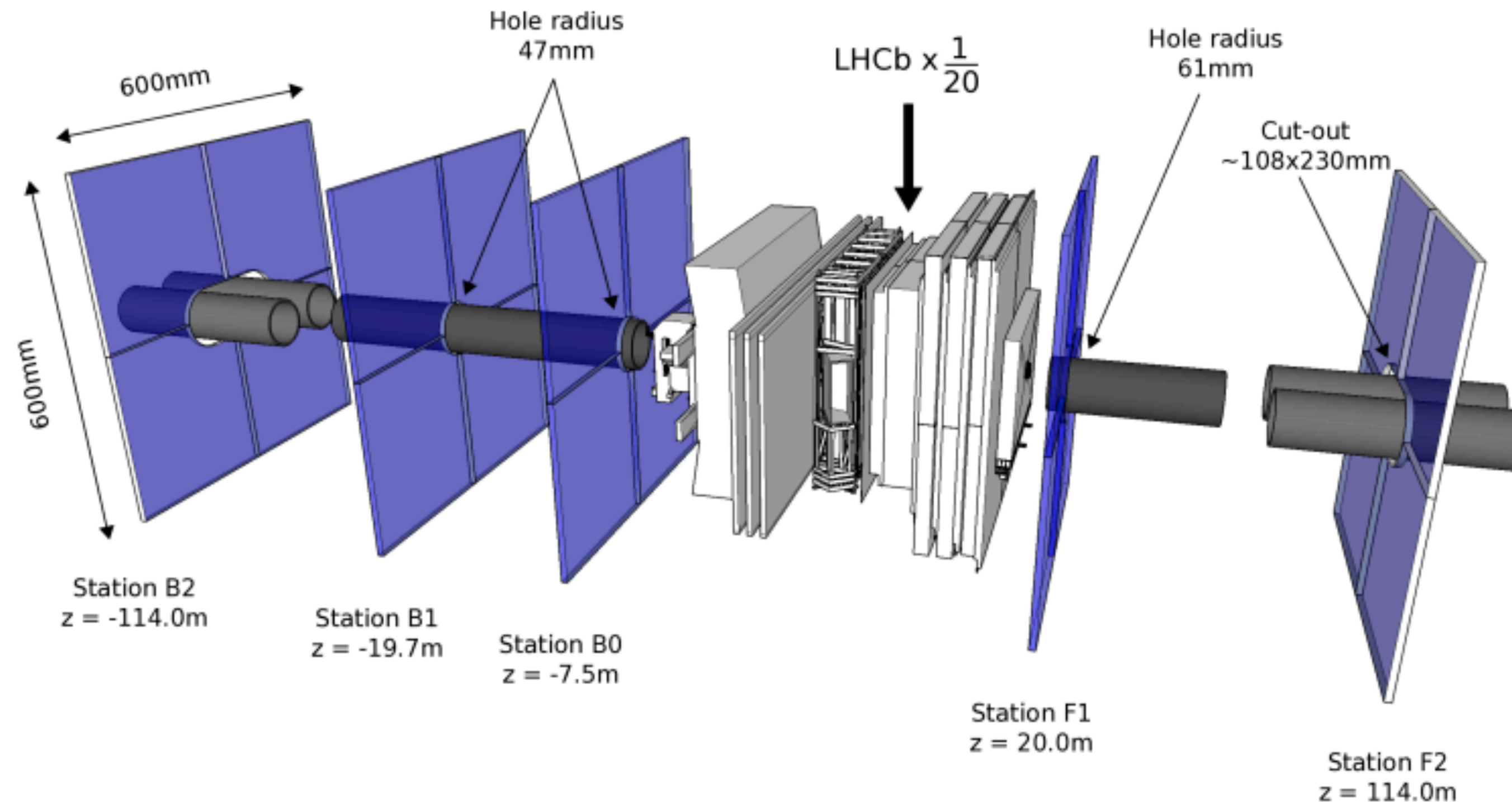
□ Roughly $\varepsilon_{tot}(B^- \rightarrow J/\psi h^-) \approx 0.10$

- Can get a **factor of 3X more B- signal** from $B^- \rightarrow D^0 \pi^-$, $B^- \rightarrow J/\psi K^- \pi^+ \pi^-$ + other modes (including improvements due to removal of high E_T “L0” trigger for hadronic modes)
- Effectively $\varepsilon(B^-) \sim 30\%$

- For **D mesons** produced in association with the fully reconstructed B meson, assume 50% efficiency per final state hadron (LHCb Acc, $p > 2.5$ GeV), and $\varepsilon_D \sim 70\%$ (displaced vertex, IP cuts, etc)
 - $\varepsilon(D^+), \varepsilon(D^{*+}) \sim 0.08$
 - $\varepsilon(D^0 \rightarrow K\pi) \sim 0.17$
 - Could also include $D^0 \rightarrow K\pi\pi\pi$ (~50% extra D^0)

□ The D efficiencies are likely on the optimistic side.

HeRSChel: High Rapidity Shower Counter for LHCb



- Set of plastic scintillator panes, detects showers from particles $5 < |\eta| < 10$
- Used to veto beam-particle dissociation – identifies Central Exclusive Production (CEP)/diffractive and ultra-peripheral collisions (UPC)