

LHC实验上奇特强子态研究进展

张黎明（清华大学）

2026年2月3日，三亚

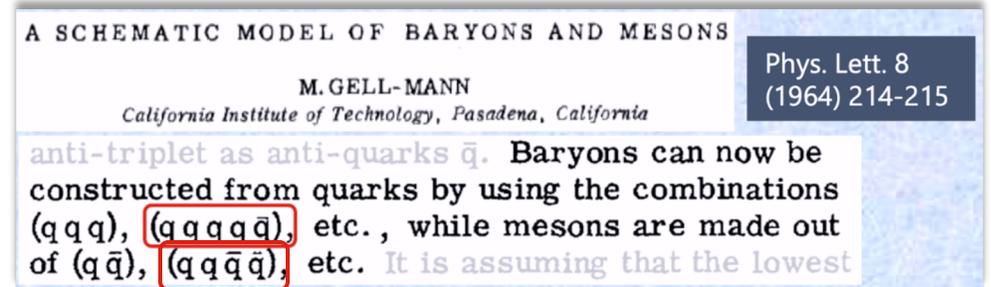


Outlines

- Introduction
- Open flavour tetraquarks
- Hidden(doubly)-charm tetraquarks
- Hidden-charm pentaquarks
- All-charm tetraquarks
- Correlation function

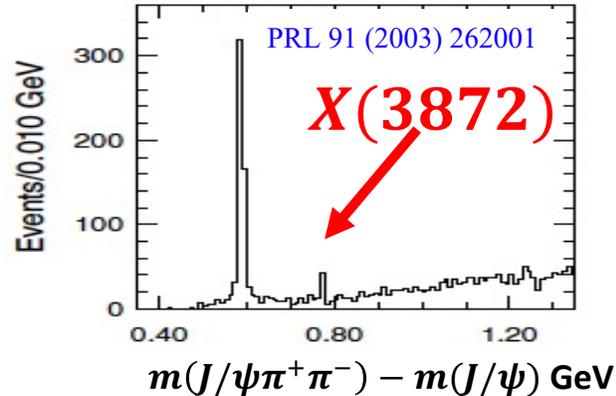
Conventional and exotic hadrons

- In 1964, Gell-Mann and G. Zweig proposed the quark model, which revolutionized our understanding of the structure of matter
- The quark model predicted the existence of exotic hadrons



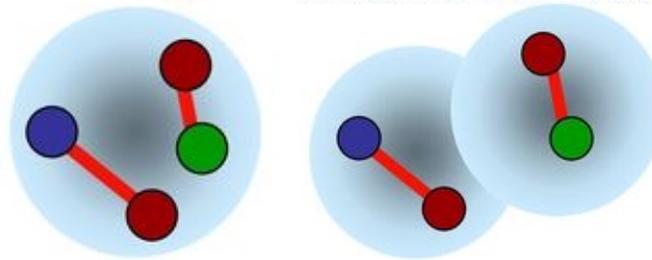
Status and challenges in hadron spectroscopy

Exotic Hadronic States



Numerous new hadronic states have been discovered, many exhibiting "exotic" features incompatible with conventional meson or baryon interpretations.

Theoretical Challenges



No single theoretical model can accommodate all new states. Multiple binding mechanisms or mixtures of different configurations are likely at play.

Broad Implications



As the least-understood sector of SM, it impacts **BSM searches**, neutron star modeling, and understanding strongly coupled theories.

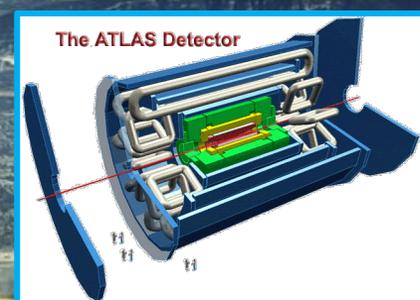
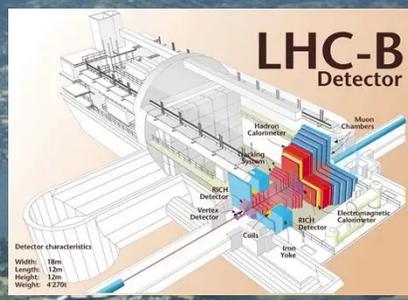
■ Key References

- Seminal works include [Guo et al. \(2025\)](#), [Hüsken et al. \(2024\)](#), [Chen \(2022\)](#), [Lebed \(2022\)](#), [Bicudo \(2022\)](#) and [Dong et al. \(2021\)](#)

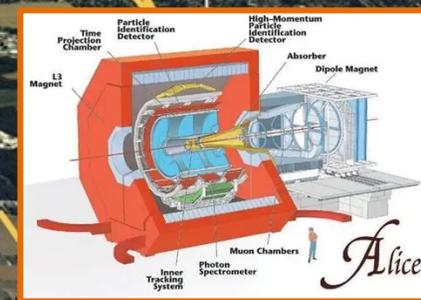
Wishes from experimentalists

1. 系统且精确地测量奇特强子的共振参数，以支持新型强子态的分类并完善强子谱；
2. 确定奇特强子的自旋和宇称量子数，这对揭示其内在结构与性质至关重要；
3. 探索奇特强子的产生与衰变机制，以加深对其内部夸克排列和动力学的理解；
4. 利用更多实验手段研究奇特强子态。

The LHC as a Beauty and Charm factory



The **LHC** is one of the most important facilities for hadron spectroscopy, thanks to its high collision energy, large strong-production cross sections, and high luminosity.



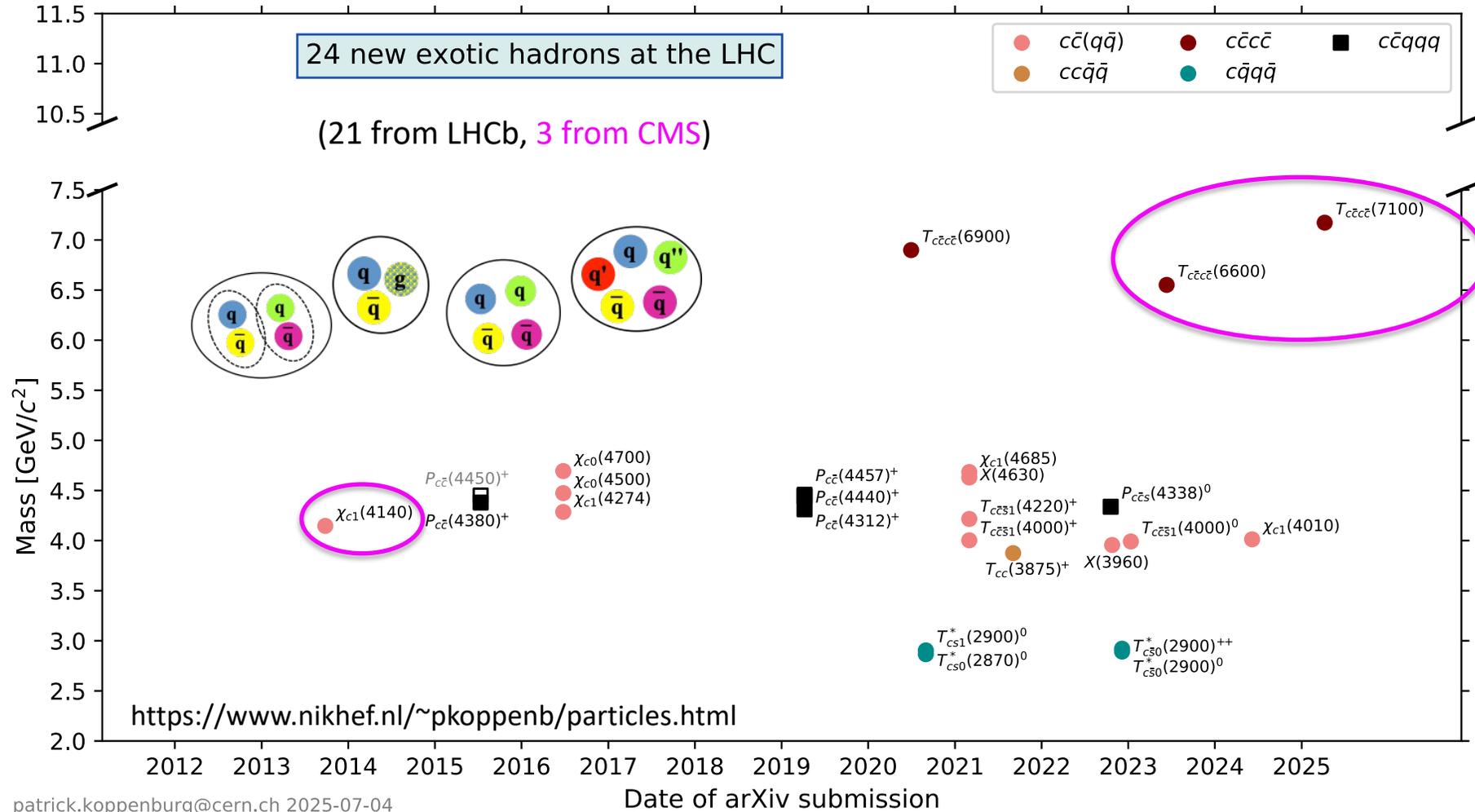
CERN Prévessin

CERN Meyrin

SPS 7 km

LHC 27 km

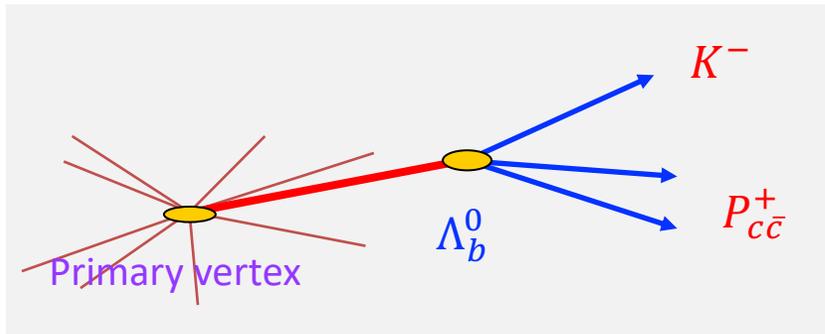
Exotic hadrons @ LHC



Two methods for spectroscopy

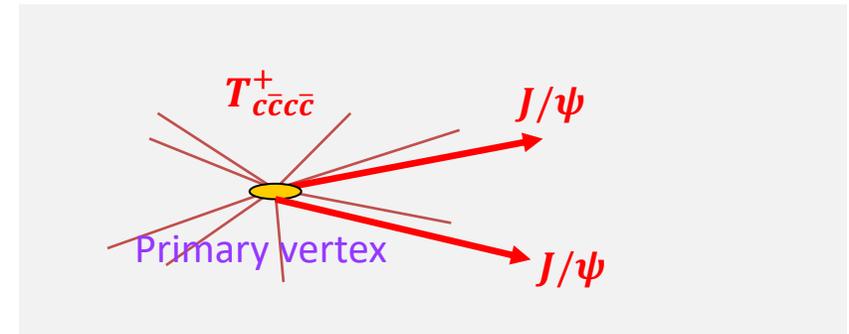
Production by a B or D decays

- Clean environment, suitable for J^P determination, precise measurement
- But limited by mass of B or D
 - $\chi_{c1}(3872), \chi_{c1}(4140)\dots$
 - $T_{c\bar{s}}, T_{c\bar{c}}$
 - $P_{c\bar{c}}, P_{c\bar{c}s}$

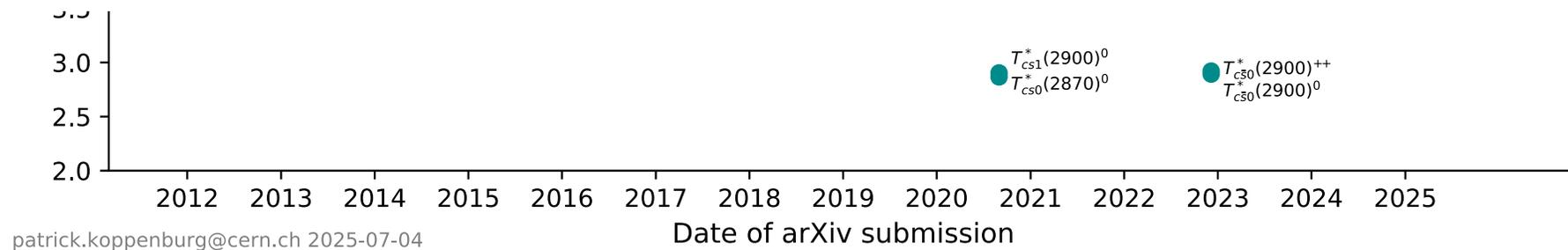


Direct production in pp collisions

- Could generate all possible states, no mass limitations but large background
- Great potential to explore
 - $T_{c\bar{c}}^+$
 - $T_{c\bar{c}c\bar{c}}$

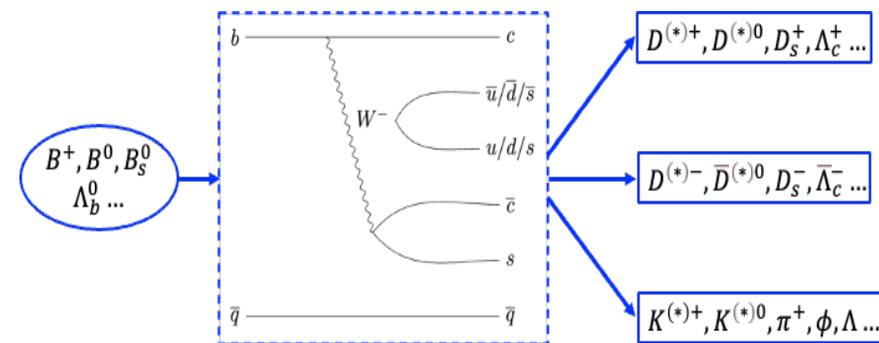


Open flavour tetraquarks



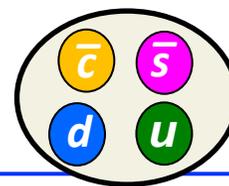
Why $B \rightarrow D\bar{D}h(h')$ decays

- Rich opportunities for spectroscopy studies
 - Charmonium(-like) states in $D^{(*)}\bar{D}^{(*)}, \Lambda_c^+\bar{D}^{(*)}, \Lambda_c^+\bar{\Lambda}_c^- \dots$
 - Excited charm states from $D^{(*)}h, \Lambda_c^+h \dots$
 - Open-flavour exotic states from $\bar{D}^{(*)}h, \bar{\Lambda}_c^-h \dots$
- Summary of results



Quark Content		Candidates	Modes
Q	$cq\bar{q}\bar{q}$	$T_{c\bar{s}0}^*(2870)^0, T_{c\bar{s}1}^*(2900)^0$	$B^+ \rightarrow D^+D^-K^+$
		$T_{c\bar{s}0}^*(2900)^0, T_{c\bar{s}0}^*(2900)^{++}$	$B^0 \rightarrow \bar{D}^0D_s^+\pi^-$ $B^+ \rightarrow D^-D_s^+\pi^+$
		$T_{c\bar{s}0}^*(2300)^{0/++?}$	$B \rightarrow \bar{D}^{(*)}D_s^+\pi^+\pi^-$
$Q\bar{Q}$	$c\bar{c}q\bar{q}$	$X(3960)$	$B^+ \rightarrow D_s^+D_s^-K^+$
		$\chi_{c1}(4010)$	$B^+ \rightarrow D^{*\pm}D^{\mp}K^+$

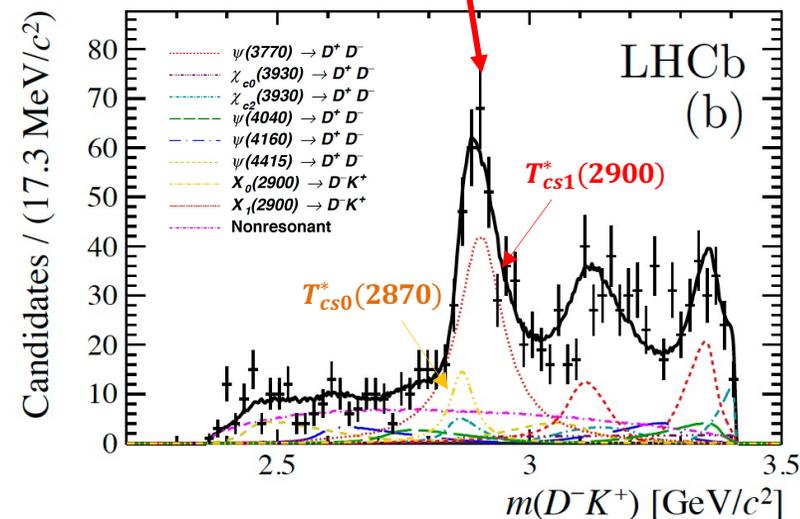
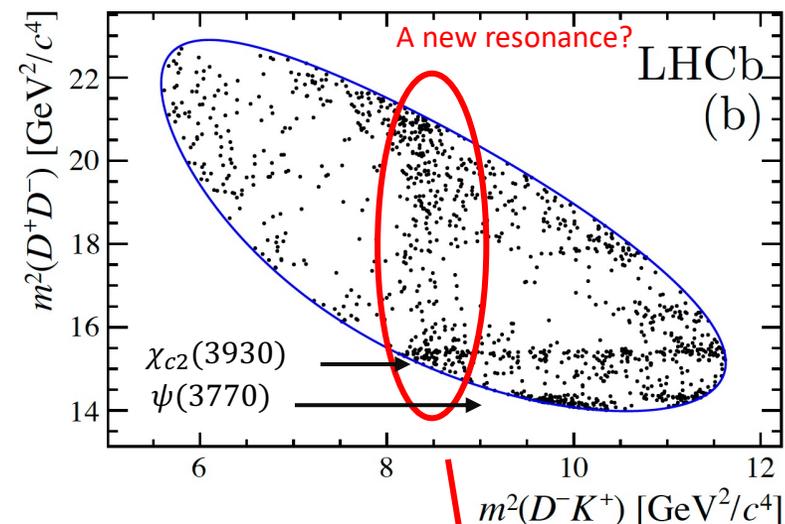
Observation of $T_{cs} \rightarrow D^- K^+$



[PRL 125 (2020) 242001]
[PRD 102 (2020) 112003]

- Amplitude analysis of $B^+ \rightarrow D^+ D^- K^+$ decays (9fb⁻¹)
 - ~1300 signals with purity 99.5%
- Enhancement in $m^2(D^- K^+) \sim 8.5 \text{ GeV}^{-2}$
- Described by $T_{cs1}^*(2900)$ and $T_{cs0}^*(2870)$
- **First discovery of open-charm tetraquarks with four different flavors [$cs\bar{u}\bar{d}$]!**

Resonance	Mass (GeV/c ²)	Width (MeV)
$\chi_{c0}(3930)$	$3.9238 \pm 0.0015 \pm 0.0004$	$17.4 \pm 5.1 \pm 0.8$
$\chi_{c2}(3930)$	$3.9268 \pm 0.0024 \pm 0.0008$	$34.2 \pm 6.6 \pm 1.1$
$T_{cs0}^*(2870)$	$2.866 \pm 0.007 \pm 0.002$	$57 \pm 12 \pm 4$
$T_{cs1}^*(2900)$	$2.904 \pm 0.005 \pm 0.001$	$110 \pm 11 \pm 4$



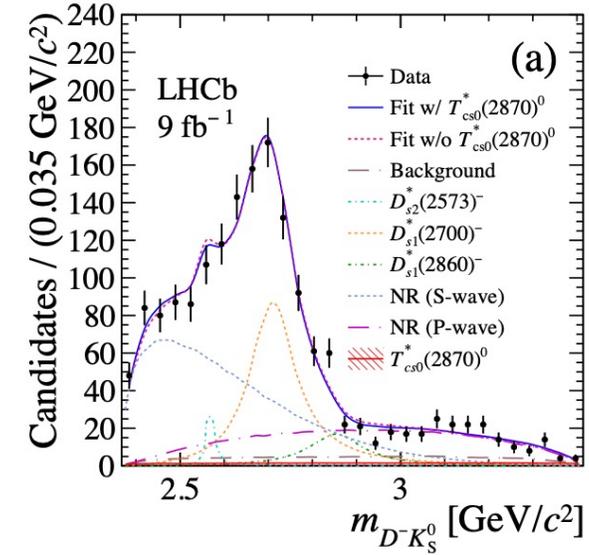
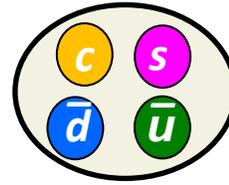
$B^- \rightarrow D^- D^0 \bar{K}^0$: $T_{cs0}^*(2870)^0$ new decay mode

[PRL 134 (2025) 101901]

- Amplitude analysis of $B^- \rightarrow D^- D^0 K_S^0$ finding $T_{cs0}^*(2870)^0$, but not $T_{cs1}^*(2900)^0$ to $D^0 K_S^0$

- $T_{cs0}^*(2870)^0$

- Significance of 5.3σ
- $m = 2883 \pm 11 \pm 8 \text{ MeV}$
- $\Gamma = 87_{-47}^{+22} \pm 17 \text{ MeV}$

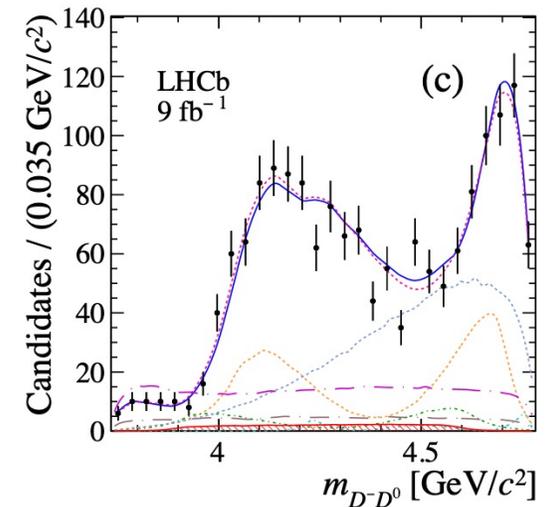
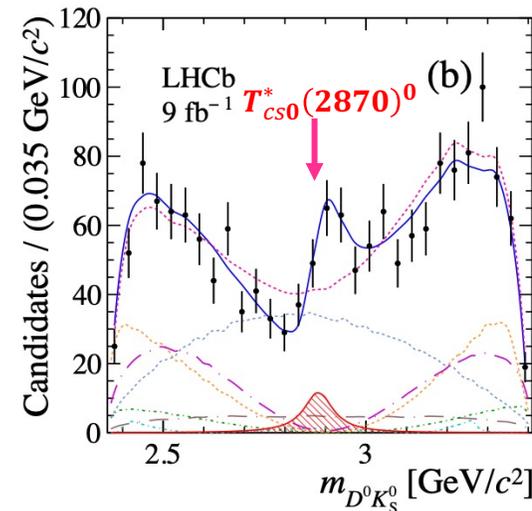


- Branching fraction ratio

$$\frac{T_{cs0}^*(2870)^0 \rightarrow D^0 \bar{K}^0}{T_{cs0}^*(2870)^0 \rightarrow D^+ K^-} = 3.3 \pm 1.1 \pm 1.1 \pm 1.1$$

$$\frac{T_{cs1}^*(2900)^0 \rightarrow D^0 \bar{K}^0}{T_{cs1}^*(2900)^0 \rightarrow D^+ K^-} = 0.15 \pm 0.15 \pm 0.05 \pm 0.05$$

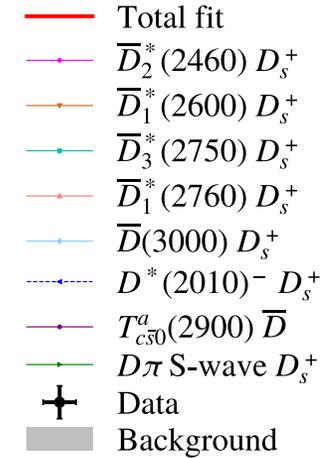
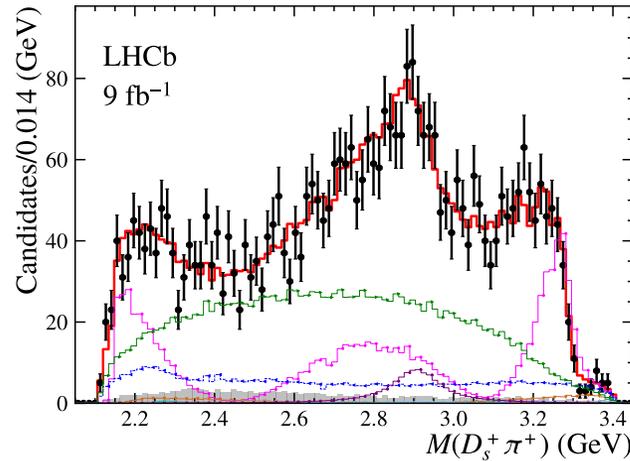
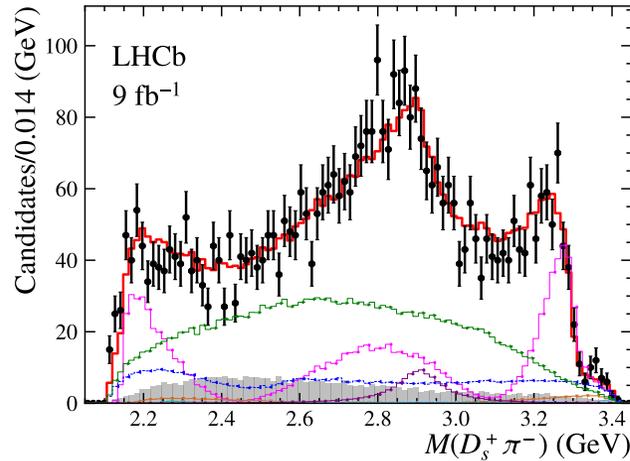
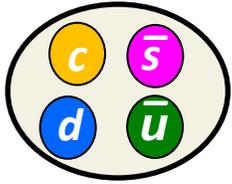
Isospin symmetry: two ratio should be 1



Observation of $T_{c\bar{s}0}^*(2900)^{0/++} \rightarrow D_s^+ \pi^{\mp}$

- Decays from $B^0 \rightarrow \bar{D}^0 D_s^+ \pi^-$ and $B^+ \rightarrow D^- D_s^+ \pi^+$

[PRL 131 (2023) 041902]



➤ $T_{c\bar{s}0}^*(2900)^0 \rightarrow D_s^+ \pi^-$ & $T_{c\bar{s}0}^*(2900)^{++} \rightarrow D_s^+ \pi^+$ **significance $> 9\sigma$**

✓ A second $1^- D_s^+ \pi$ state yields significance of only 1.3σ

✓ Additional $D\pi, D_s^+ \pi, DD_s^+$ resonances disfavored

➤ $J^P = 0^+$ favored over other spin-parity by more than 7.5σ

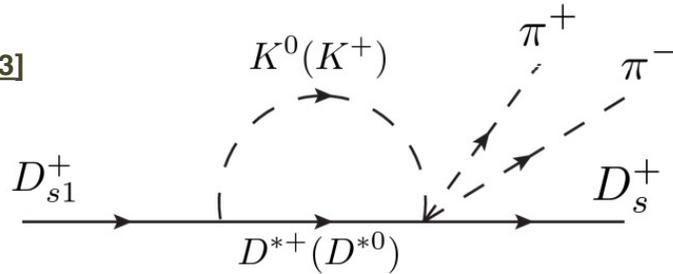
$$M = 2.908 \pm 0.011 \pm 0.020 \text{ GeV}$$

$$\Gamma = 0.136 \pm 0.023 \pm 0.011 \text{ GeV}$$

$D_{s1}(2460)^+ \rightarrow D_s^+ \pi^+ \pi^-$ decays

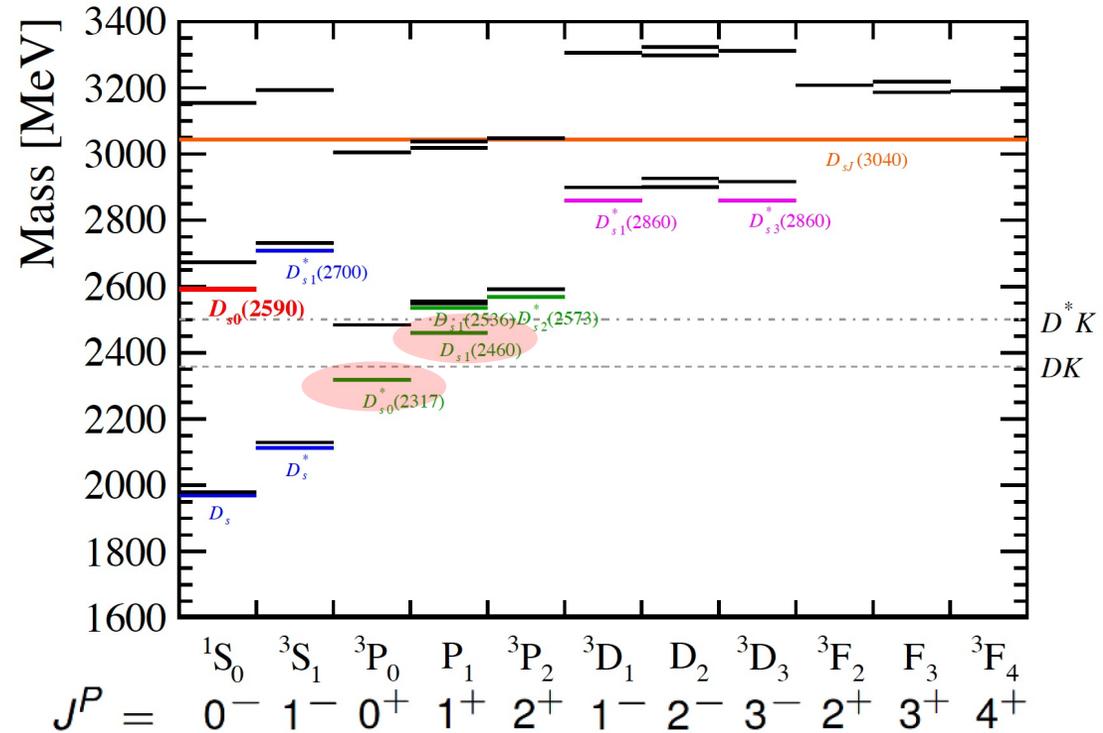
- $D_{s0}^*(2317)$ and $D_{s1}(2460)$ are very special
 - Masses ~ 100 MeV below expectation
 - Isospin-violating decay $D_s^{(*)+} \pi^0$ dominate
- Propose to study of $D_{s1}(2460)^+ \rightarrow D_s^+ \pi^+ \pi^-$
 - Double-bump lineshape in $m(\pi\pi)$ if $D_{s1}(2460)^+$ is a D^*K hadronic molecule

[Tang et. al.
Commun. Theor. Phys. 75 055203]

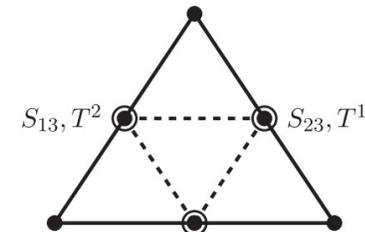


- $I=1$ partners of $D_{s0}^*(2317)$ are proposed
 - Inspired by observation of $I=1$ tetraquark $T_{c\bar{s}}(2900)^{++/0} \rightarrow D_s^+ \pi^\pm$

[PRL 131 (2023) 041902]



$S_{33}(2335 \pm 100) \rightarrow \bar{D}^0 K^0, K^+ K^0 \pi^-$ (weak decay)



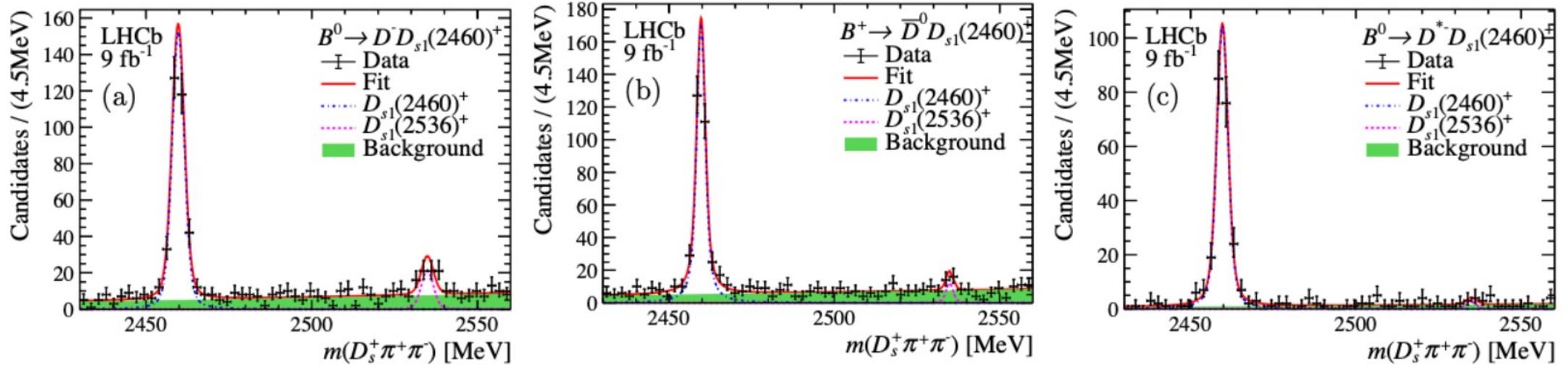
[L. Maiani et. al.
Phys. Rev. D 110, 034014]

$S_{11}(2367 \pm 10) \rightarrow \bar{D}_s^- \pi^-$ or $\bar{D}^- K^-$ $D_{s0}^{*-}(2317)$ + second state $S_{22}(2367 \pm 10) \rightarrow \bar{D}_s^- \pi^+$ or $\bar{D}^0 \bar{K}^0$

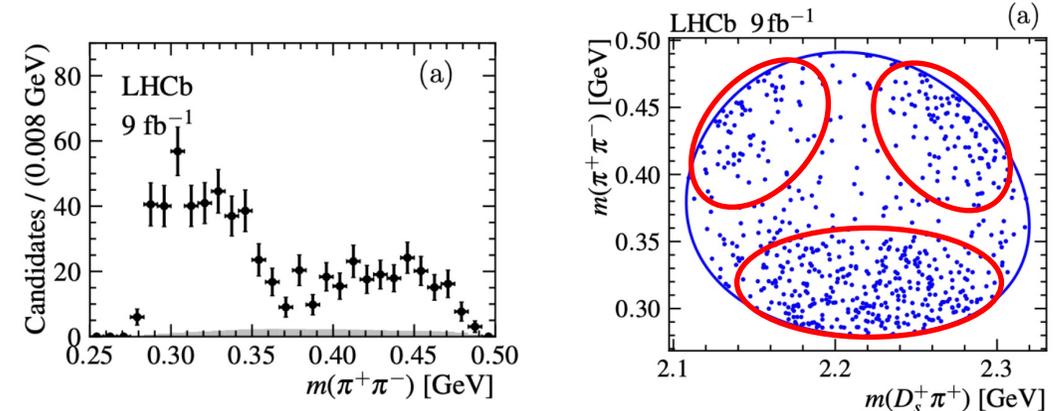
$D_{s1}(2460)^+ \rightarrow D_s^+ \pi^+ \pi^-$ decays

[Sci. Bull. 70 (2025) 1432–1444]

- $\sim 800 D_{s1}(2460)^+ \rightarrow D_s^+ \pi^+ \pi^-$ from three $B \rightarrow D_{s1}(2460)^+ \bar{D}^{(*)}$ decays



- Double-bump structure in $m(\pi\pi)$
- Amplitude analysis performed
 - $f_0(500) + f_0(980)$ and $\pi\pi$ K-matrix cannot describe the data well
 - The model in paper also cannot describe the data well



[Tang et. al.
Commun. Theor. Phys. 75 055203]

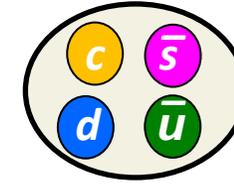
Two resonance models can fit the data well

[Sci. Bull. 70 (2025) 1432–1444]

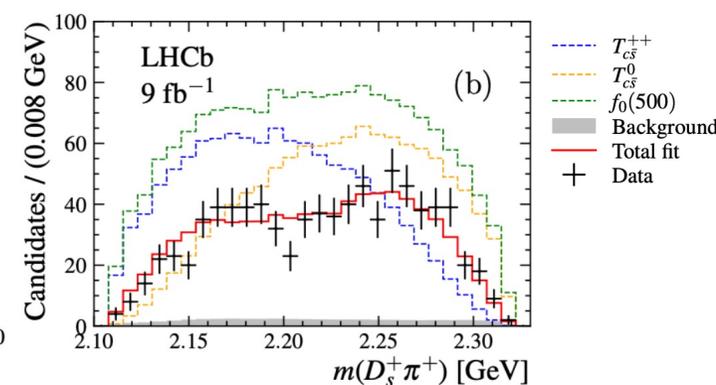
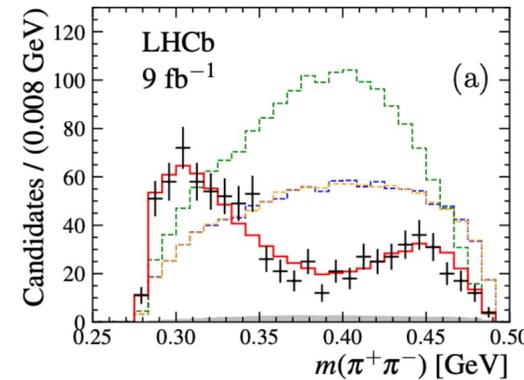
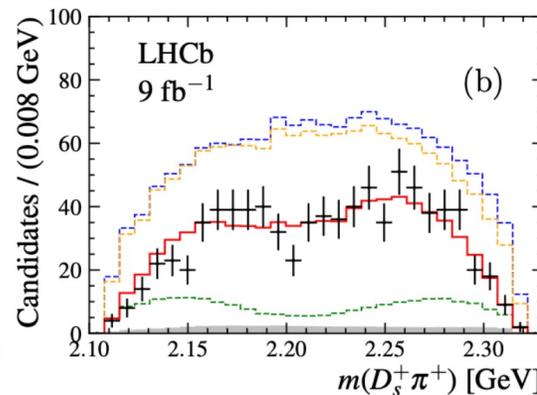
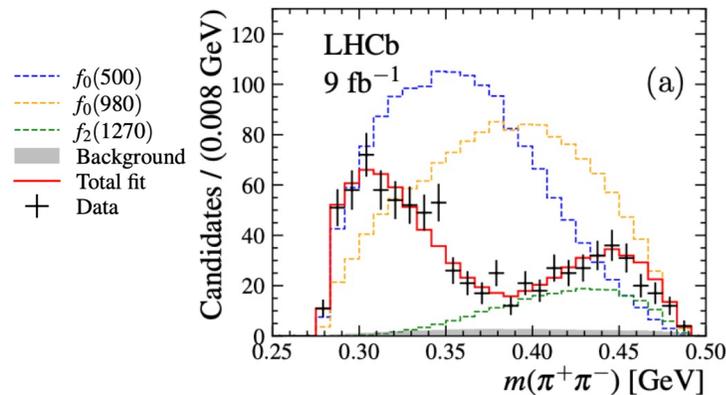
- $f_0(500) + f_0(980) + f_2(1270)$
 - Large contribution from $f_0(980)$ and $f_2(1270)$ above PHSP of $m(\pi\pi)$
 - This model cannot be rejected, but **implausible**

Resonance	Mass (MeV)	Width (MeV)	FF (%)
$f_0(500)$	$376 \pm 9 \pm 16$	$175 \pm 23 \pm 16$	$197 \pm 35 \pm 23$
$f_0(980)$	945.5	167	$187 \pm 38 \pm 43$
$f_2(1270)$	1275.4	186.6	$29 \pm 2 \pm 1$

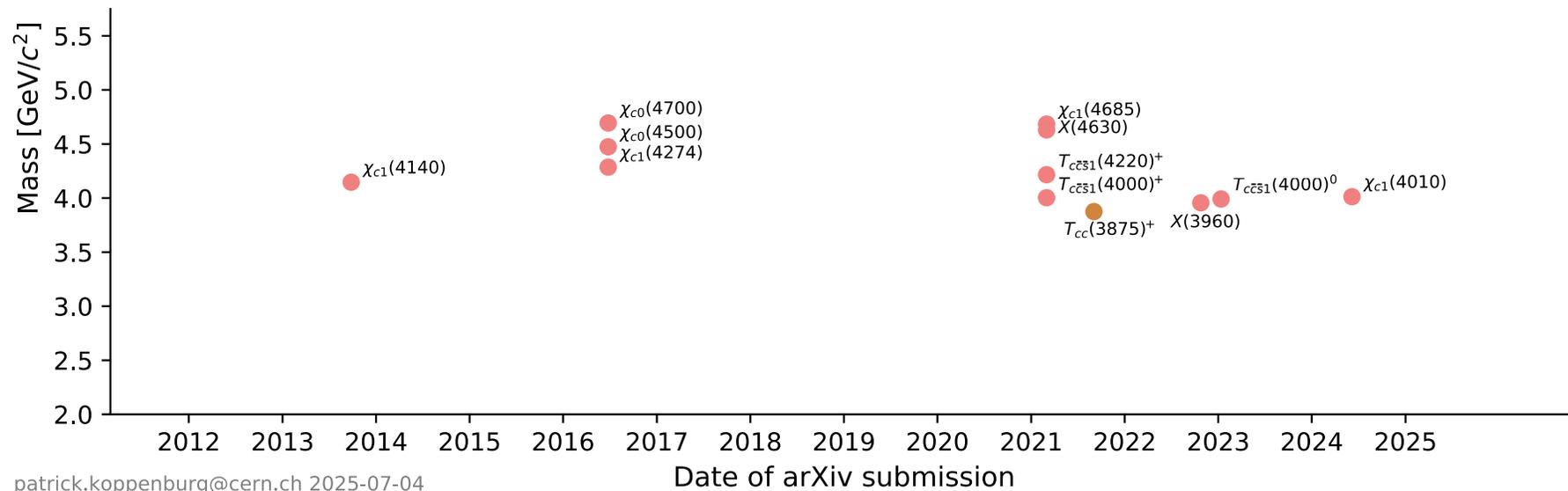
- $f_0(500) + T_{c\bar{s}}^{++} + T_{c\bar{s}}^0$ (new exotics)



Resonance	Mass (MeV)	Width (MeV)	FF (%)
$f_0(500)$	$474 \pm 30 \pm 18$	$224 \pm 23 \pm 16$	$248_{-54}^{+40} \pm 39$
$T_{c\bar{s}}$	$2327 \pm 13 \pm 13$	$96 \pm 16 \pm 23$	$156_{-38}^{+27} \pm 25$

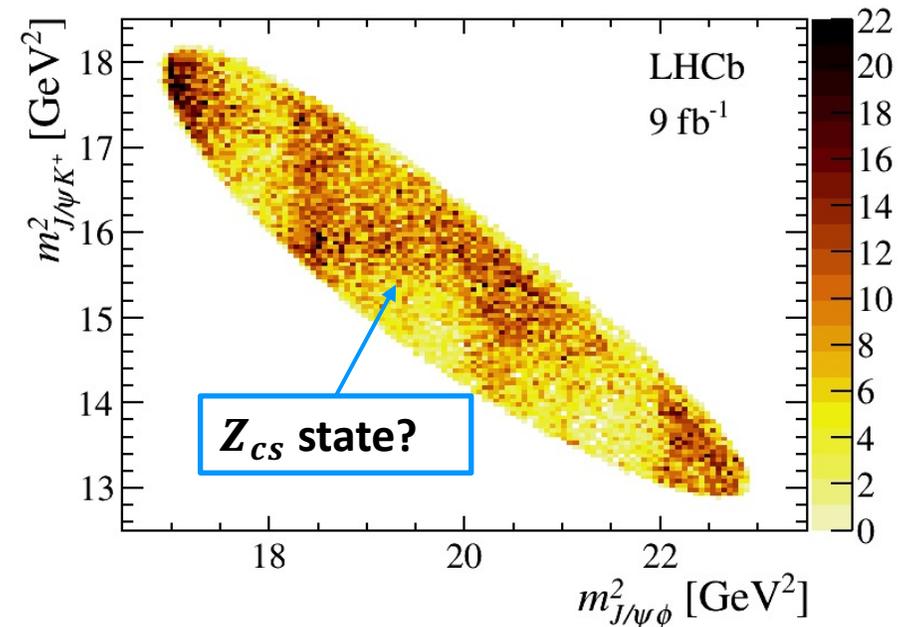
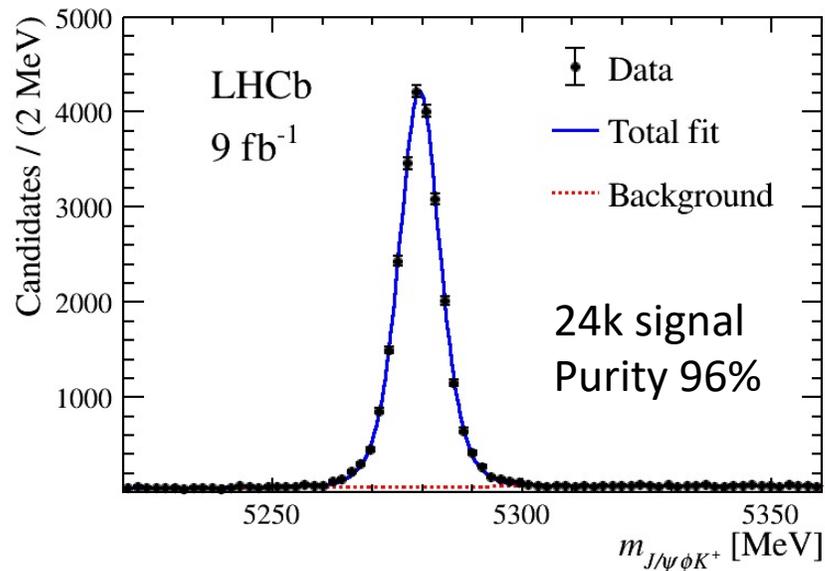


Hidden(doubly)-charm tetraquarks



Exotic states in $B^+ \rightarrow J/\psi\phi K^+$ decays

- $B^+ \rightarrow J/\psi\phi K^+$ decays initially used for study of $J/\psi\phi$ structures
 - $X(4140)$ first observed by CDF and confirmed by CMS
[arXiv:1101.6058] [PLB 734 (2014) 261]
 - With run-1 data, LHCb observed $X(4140)$, $X(4274)$, $X(4500)$ and $X(4700)$ [PRL 118 (2017) 022003]
- With run-1 and 2 data, 6 x signal decays obtained
 - Clearly visible: 4 structures in $J/\psi\phi$ mass and an obvious $J/\psi K^+$ band [PRL 127 (2021) 082001]



Observation of new resonances $\rightarrow J/\psi K^+$ and $J/\psi\phi$

[PRL 127 (2021) 082001]

- Run-1 fit model doesn't work well
- Fit needs more states, in which 4 new exotic-like states are observed

New states:

$$Z_{cs}(4000)^+ J^P = 1^+$$

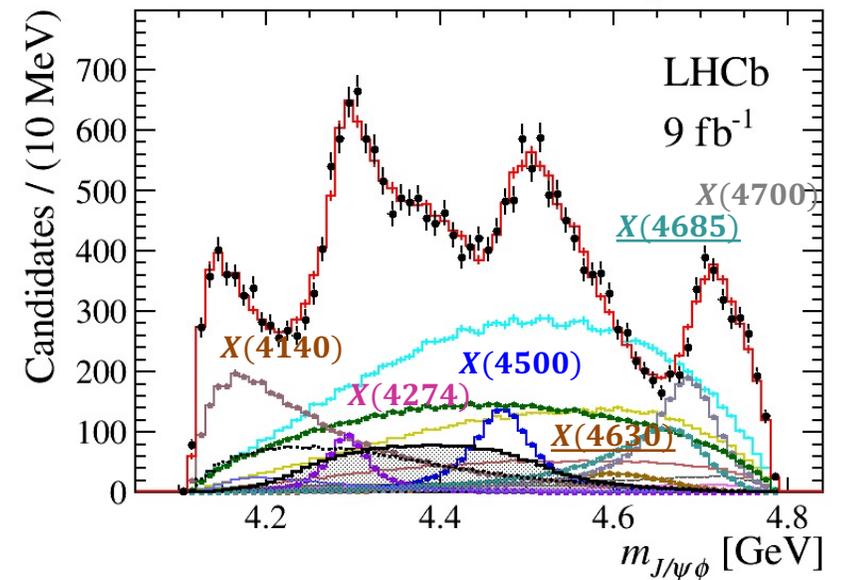
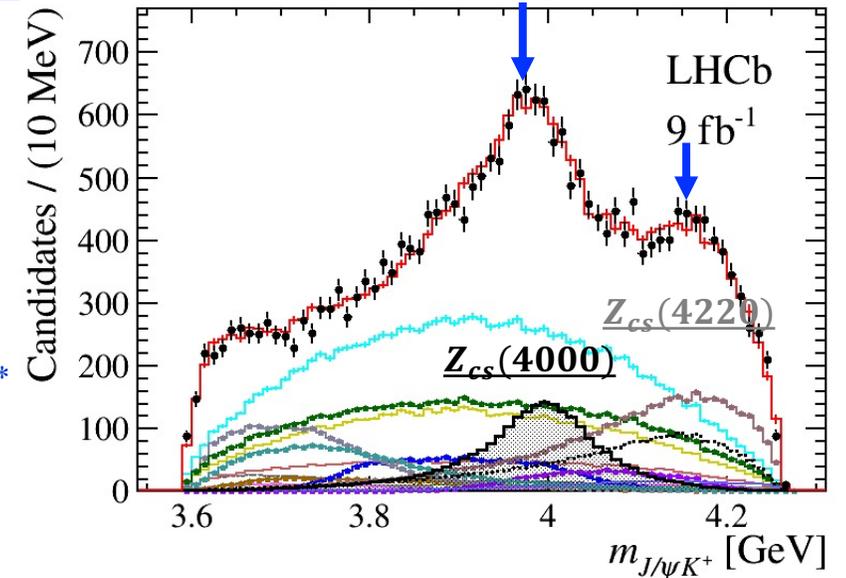
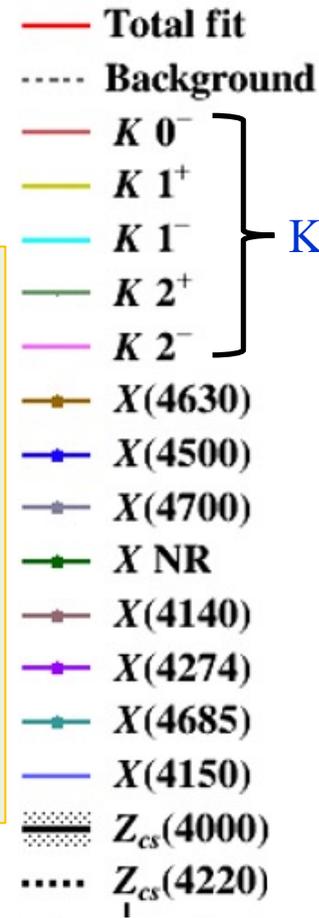
$$Z_{cs}(4220)^+, J^P = 1^{+/-}$$

$$X(4685), X(4630)$$

Confirmed previous observed states:

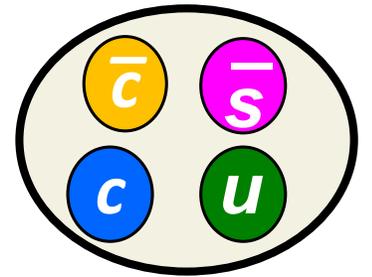
$$X(4140), X(4274),$$

$$X(4500), X(4700)$$

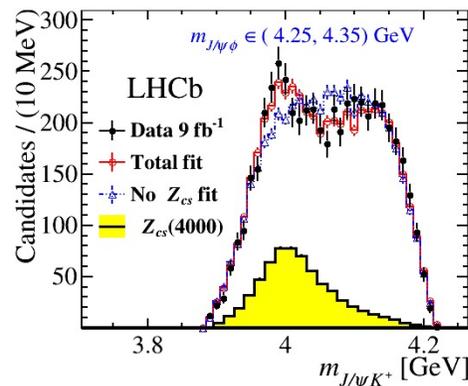


Comparison with BESIII

- BESIII observed a narrow $Z_{cs}(3985)^+$ with different final states $D_s^+ \bar{D}^* + \bar{D} D_s^{*+}$
- Two states have similar masses, but different widths
- No evidence $Z_{cs}(4000)^+$ is the same as $Z_{cs}(3985)^+$ seen by BESIII
 - Fix $Z_{cs}(4000)^+$ to BESIII's result; $2\ln L$ is worse by 160
 - Adding on top of the default model almost doesn't improve the fit likelihood



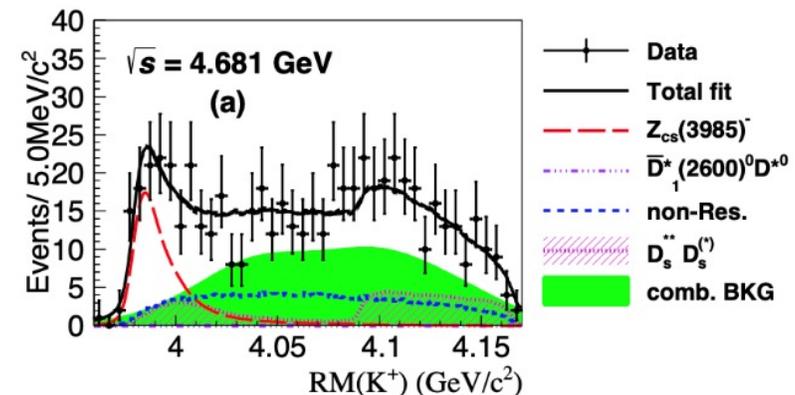
[PRL 127 (2021) 082001]



$$m(Z_{cs}(4000)^+) = (4003 \pm 6_{-14}^{+4}) \text{ MeV}$$

$$\Gamma(Z_{cs}(4000)^+) = (131 \pm 15 \pm 26) \text{ MeV}$$

[PRL 126 (2021) 102001] BESIII

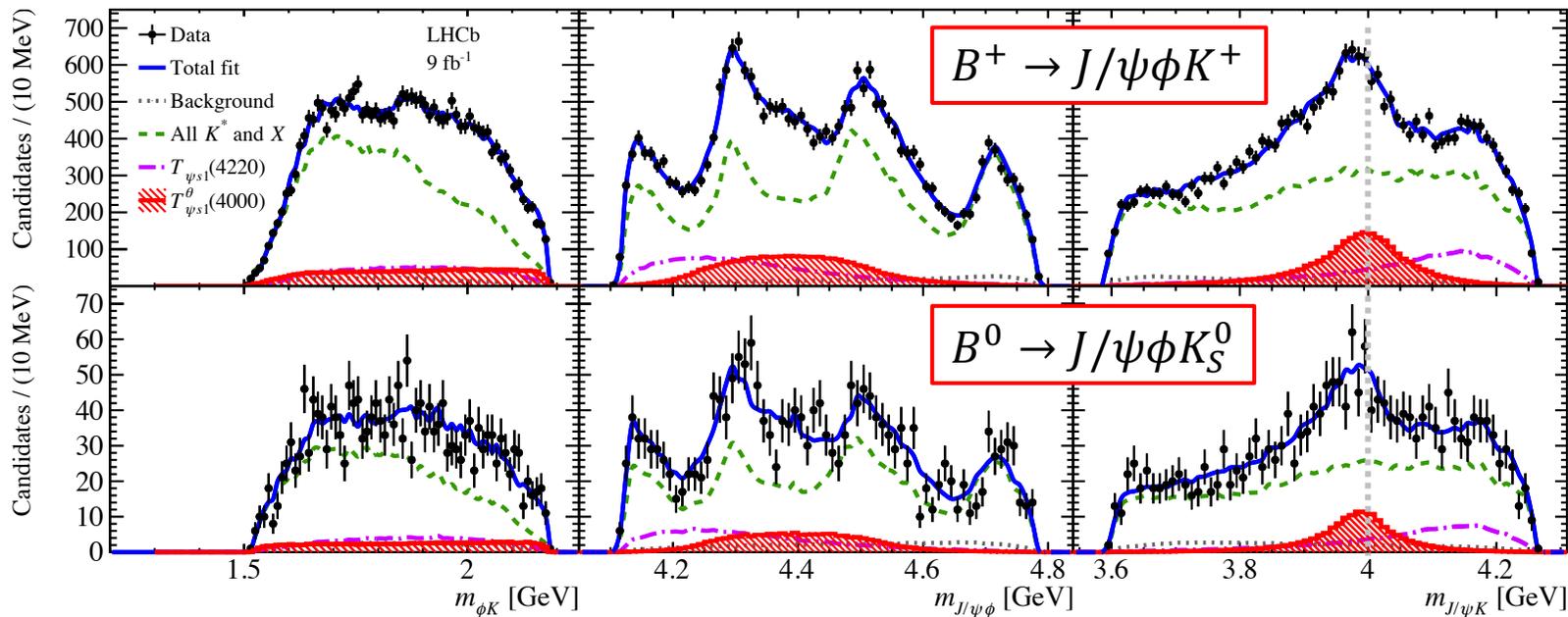
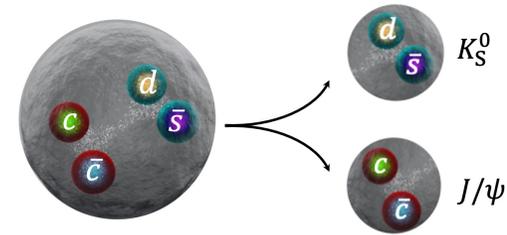


$$m_{\text{pole}}(Z_{cs}(3985)^-) = (3982.5_{-2.6}^{+1.8} \pm 2.1) \text{ MeV}/c^2,$$

$$\Gamma_{\text{pole}}(Z_{cs}(3985)^-) = (12.8_{-4.4}^{+5.3} \pm 3.0) \text{ MeV}.$$

Evidence of $T_{c\bar{c}s_1}(4000)^0$ in $B^0 \rightarrow J/\psi\phi K_S^0$ [PRL 131 (2023) 131901]

- $B^0 \rightarrow J/\psi\phi K_S^0$ and $B^+ \rightarrow J/\psi\phi K^+$ are related by isospin symmetry
- Joint amplitude fit assumes isospin symmetry except for $T_{c\bar{c}s_1}(4000)^0$
- Its significance is 4σ (5.4σ under isospin assumption)
- $T_{c\bar{c}s_1}(4000)^0$ and $T_{c\bar{c}s_1}(4000)^+ \equiv Z_{cS}(4000)^+$ are likely to be isospin partners



$T_{c\bar{c}s}(4000)^0$

$$M(T_{c\bar{c}s_1}(4000)^0) = 3991_{-10}^{+12}_{-17} \text{ MeV}$$

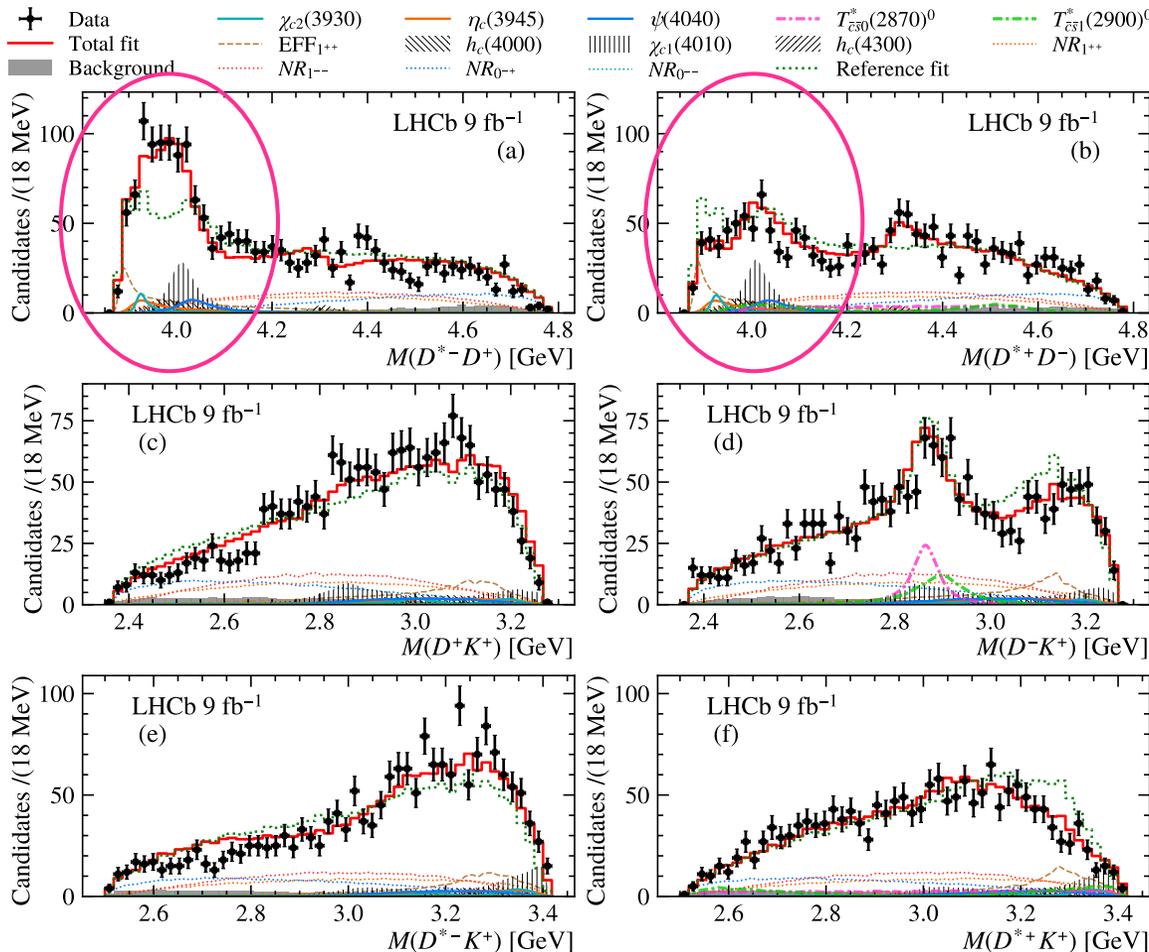
$$\Gamma(T_{c\bar{c}s_1}(4000)^0) = 105_{-25}^{+29}_{-23} \text{ MeV}$$

$$\Delta M(T_{c\bar{c}s_1}^0 - T_{c\bar{c}s_1}^+) = -12_{-10}^{+11}_{-4} \text{ MeV}$$

$B^+ \rightarrow D^{*\pm} D^\mp K^+$: amplitude analysis

[PRL 133 (2024) 131902]

- Amplitudes of $R \rightarrow D^{*+} D^-$ and $R \rightarrow D^{*-} D^+$ linked by **C-parity**
 \Rightarrow allowing determination of C-parities of R resonances



Component	$J^{P(C)}$
EFF ₁₊₊	1 ⁺⁺
$\eta_c(3945)$	0 ⁻⁺
$\chi_{c2}(3930)^\dagger$	2 ⁺⁺
$h_c(4000)$	1 ^{+ -}
$\chi_{c1}(4010)$	1 ⁺⁺
$\psi(4040)^\dagger$	1 ⁻⁻
$h_c(4300)$	1 ^{+ -}
$T_{c\bar{s}0}^*(2870)^{0\dagger}$	0 ⁺
$T_{c\bar{s}1}^*(2900)^{0\dagger}$	1 ⁻
NR ₁₋₋ ($D^{*\mp} D^\pm$)	1 ⁻⁻
NR ₀₋₋ ($D^{*\mp} D^\pm$)	0 ⁻⁻
NR ₁₊₊ ($D^{*\mp} D^\pm$)	1 ⁺⁺
NR ₀₋₊ ($D^{*\mp} D^\pm$)	0 ⁻⁺

- Four charmonium(-like) states are observed decaying to $D^* \bar{D}$ for $>6.1\sigma$
- At least the three of them are new
- J^{PC} for each state is determined for $>5.7\sigma$
- $T_{c\bar{s}}^*$ states, seen in $B^+ \rightarrow D^+ D^- K^+$, are confirmed in $B^+ \rightarrow D^{*+} D^- K^+$ decays

$X(3960)$ in $B^+ \rightarrow D_s^+ D_s^- K^+$ decays [PRL 131 (2023) 071901]

- Strong threshold enhancement found in $D_s^+ D_s^-$ system
- Amplitude analysis is performed
- **$X(3960)$** : threshold enhancement

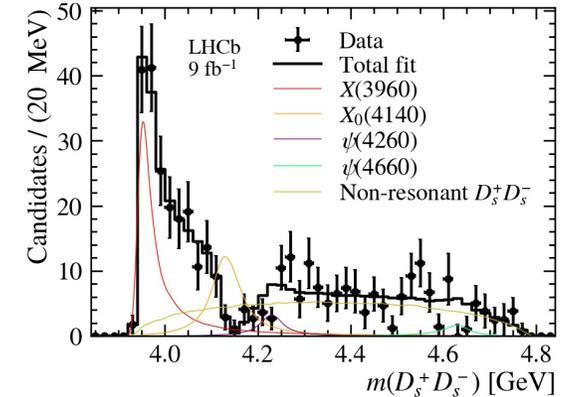
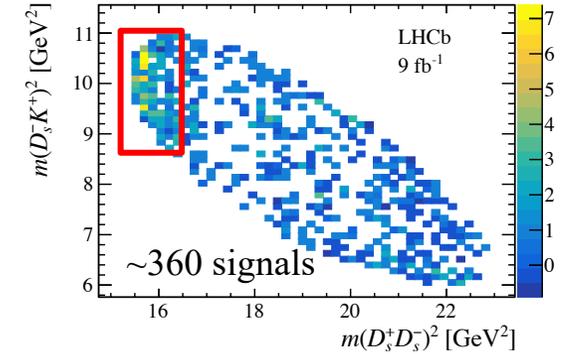
- $J^{PC} = 0^{++}$ preferred over 1^{--} and 2^{++} by 9.3σ and 12.3σ

- Could be a $c\bar{c}s\bar{s}$ tetraquark predicted by Lattice QCD

[JHEP 06 (2021) 035]

- Resonance parameters are consistent with $\chi_{c0}(3915)$ within 3σ

- If $X(3960) = \chi_{c0}(3915)$, $\frac{\mathcal{B}(X \rightarrow D^+ D^-)}{\mathcal{B}(X \rightarrow D_s^+ D_s^-)} = 0.29 \pm 0.09 \pm 0.10 \pm 0.08$



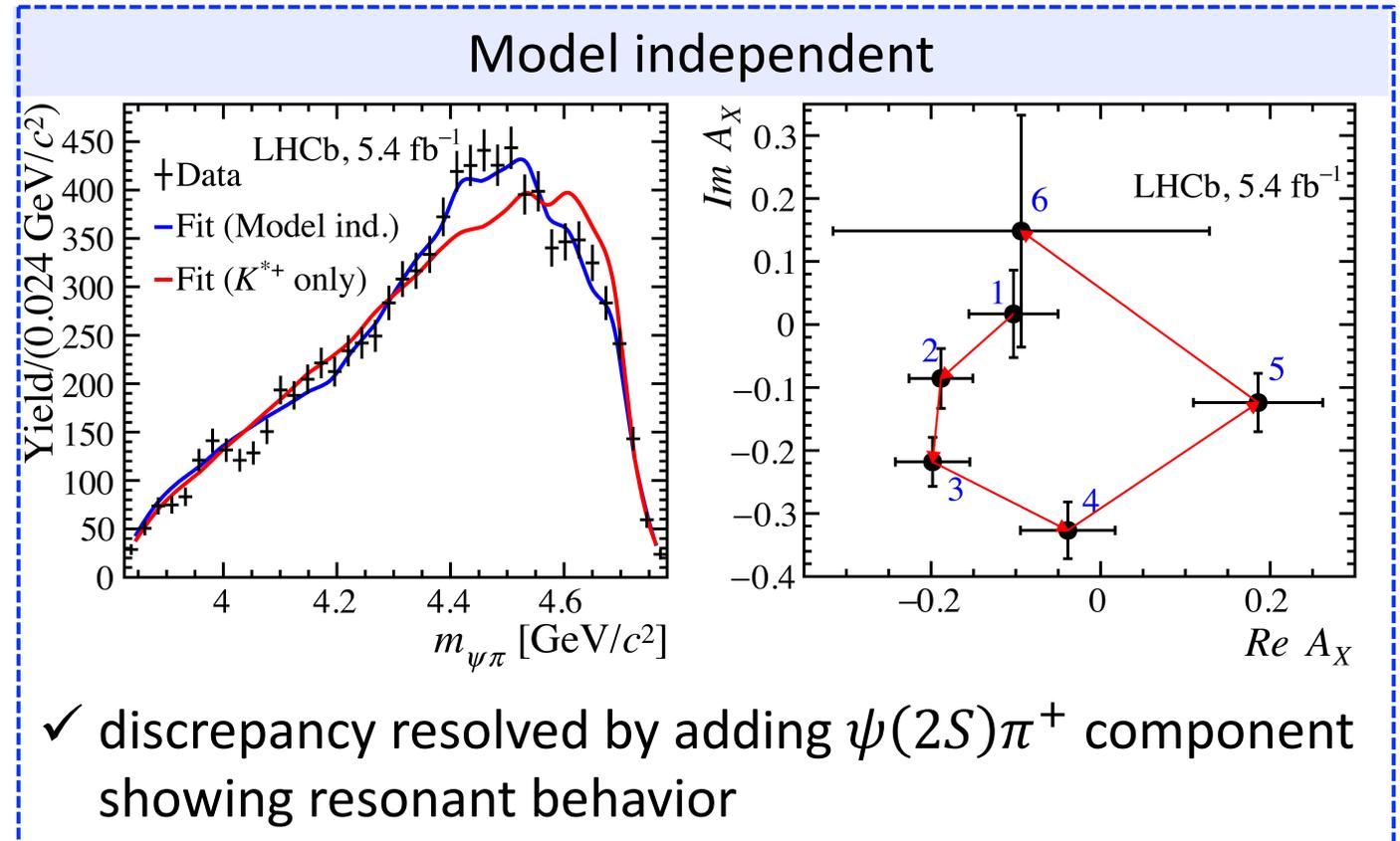
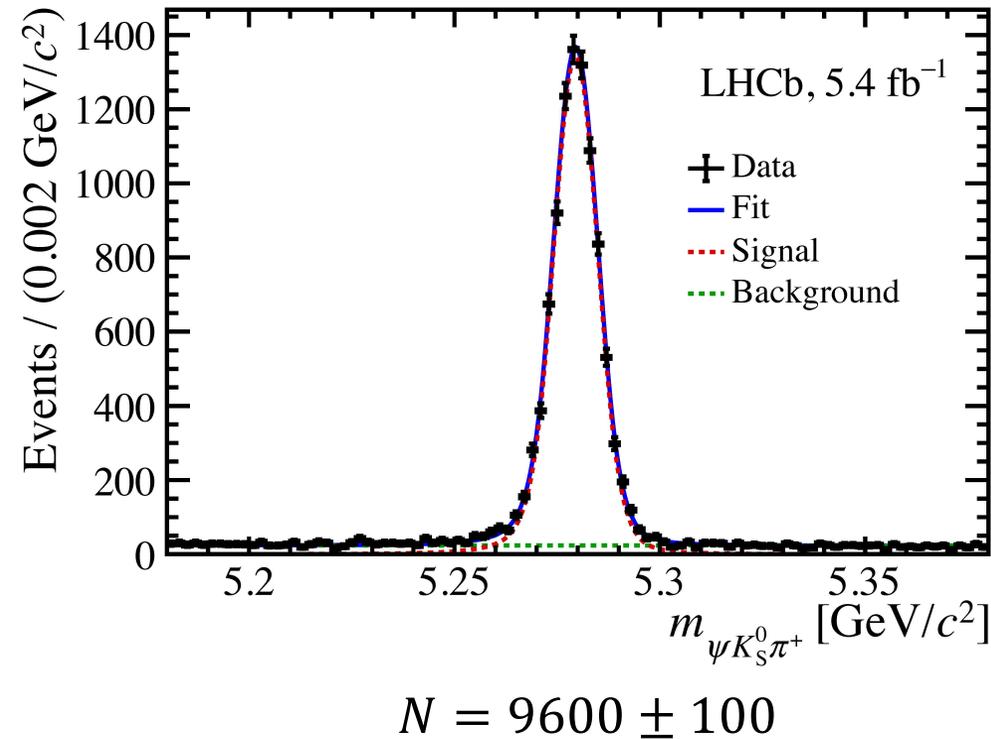
Component	J^{PC}	M_0 (MeV)	Γ_0 (MeV)	\mathcal{F} (%)	\mathcal{S} (σ)
$X(3960)$	0^{++}	$3956 \pm 5 \pm 10$	$43 \pm 13 \pm 8$	$25.4 \pm 7.7 \pm 5.0$	12.6 (14.6)
$X_0(4140)$	0^{++}	$4133 \pm 6 \pm 6$	$67 \pm 17 \pm 7$	$16.7 \pm 4.7 \pm 3.9$	3.8 (4.1)
$\psi(4260)$	1^{--}	4230 [62]	55 [62]	$3.6 \pm 0.4 \pm 3.2$	3.2 (3.6)
$\psi(4660)$	1^{--}	4633 [32]	64 [32]	$2.2 \pm 0.2 \pm 0.8$	3.0 (3.2)
NR	0^{++}	-	-	$46.1 \pm 13.2 \pm 11.3$	3.1 (3.4)

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

[arXiv: 2511.20428]

- First four-dimensional amplitude analysis of $B^+ \rightarrow \psi(2S)K_S^0\pi^+$ is performed using 5.4 fb^{-1} Run2 data
 - related via isospin symmetry to $\bar{B}^0 \rightarrow \psi(2S)K^-\pi^+$ 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]



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

[arXiv: 2511.20428]

Model dependent

✓ Breit Wigner:

$$M = 4.452 \pm 0.016_{-0.033}^{+0.055} \text{ GeV}$$

$$\Gamma = 0.174 \pm 0.019_{-0.020}^{+0.083} \text{ GeV}$$

$$f = (3.7 \pm 0.6_{-0.7}^{+4.0})\%$$

$$J^P = 1^+$$

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

◆ Molecular scenario

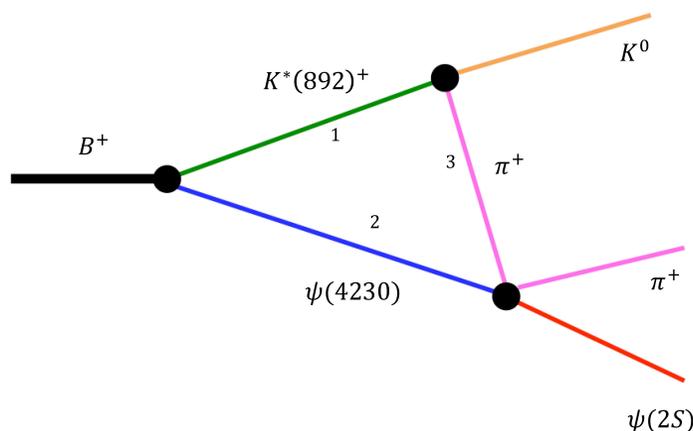
Flatté model to take into account opening of $\bar{D}_1^*(2600)^0 D^+$ decay

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

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

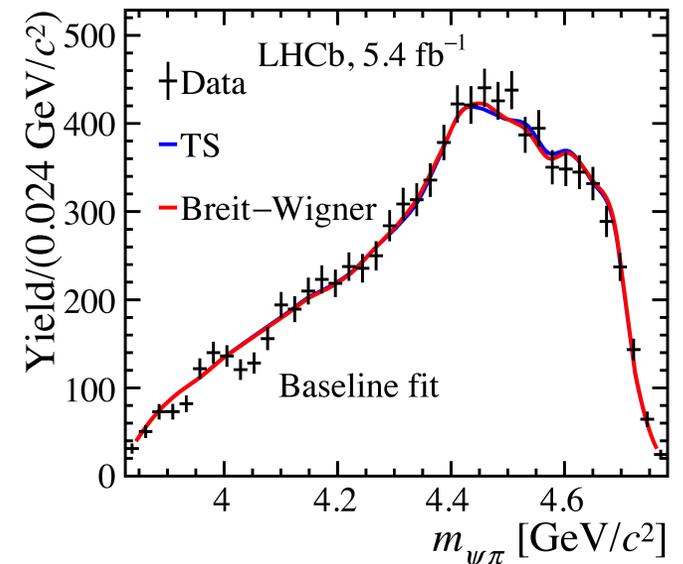
$$g_2 = 0.00 \pm 1.78 \pm 2.81 \text{ GeV}/c^2, \left| \frac{g_2}{g_1} \right| < 6.8 \text{ @ 95\% CL}$$

◆ Triangle singularity mechanism



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

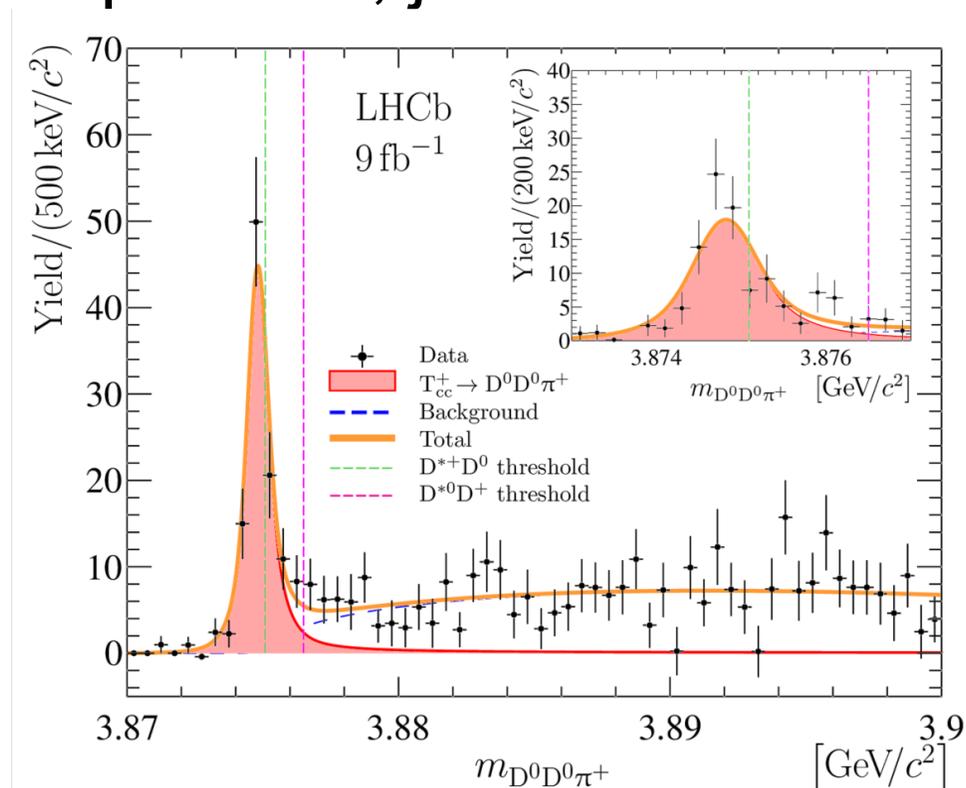
✓ A reasonable description is achieved



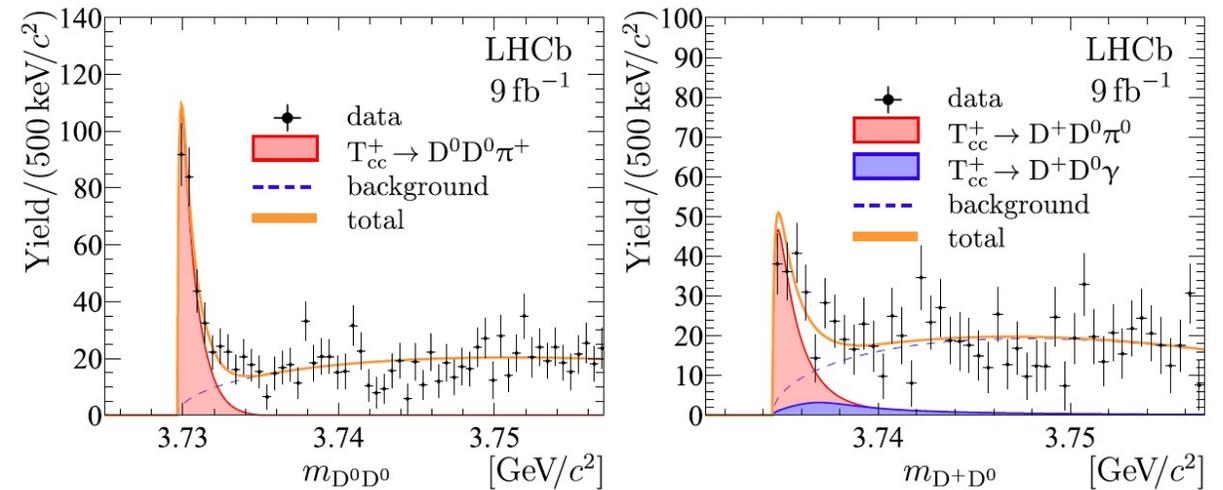
Doubly charmed tetraquark

[Nature Physics 18 (2022) 751]
[Nature Comm. 13 (2022) 3351]

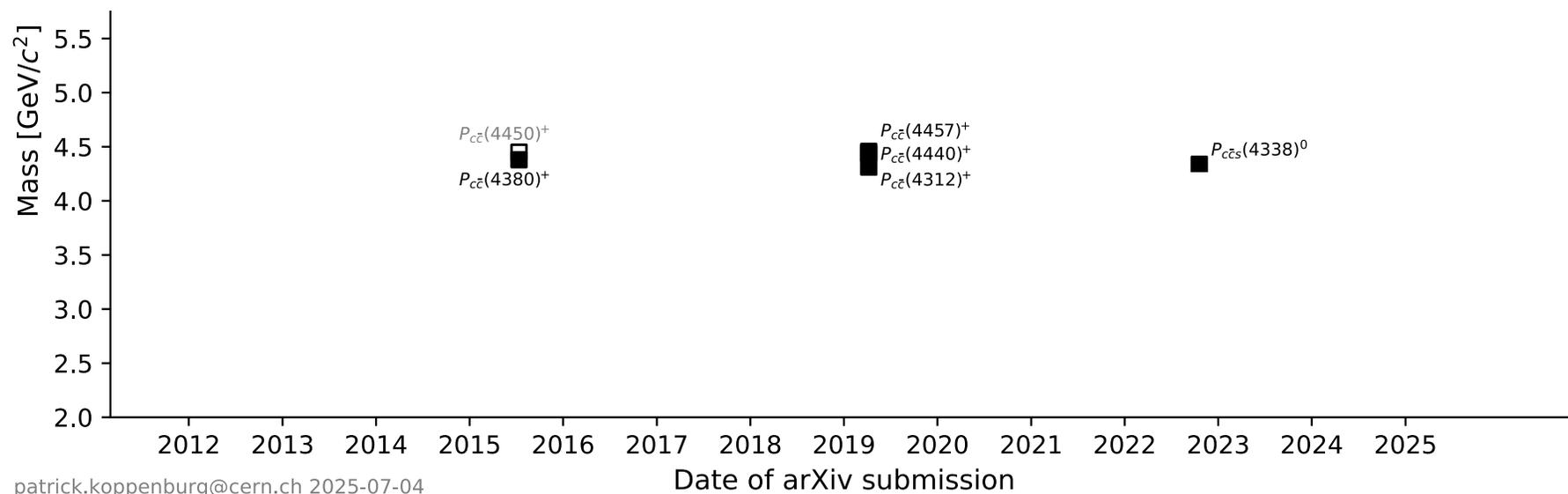
- A narrow resonance T_{cc}^+ ($cc\bar{u}\bar{d}$) discovered in prompt $D^0 D^0 \pi^+$ spectrum, just below the $D^{*+} D^0$



	δm [keV/c ²]	Γ [keV/c ²]
\mathcal{F}^{BW}	-279 ± 59	409 ± 163
\mathcal{F}^{U}	-361 ± 40	47.8 ± 1.9



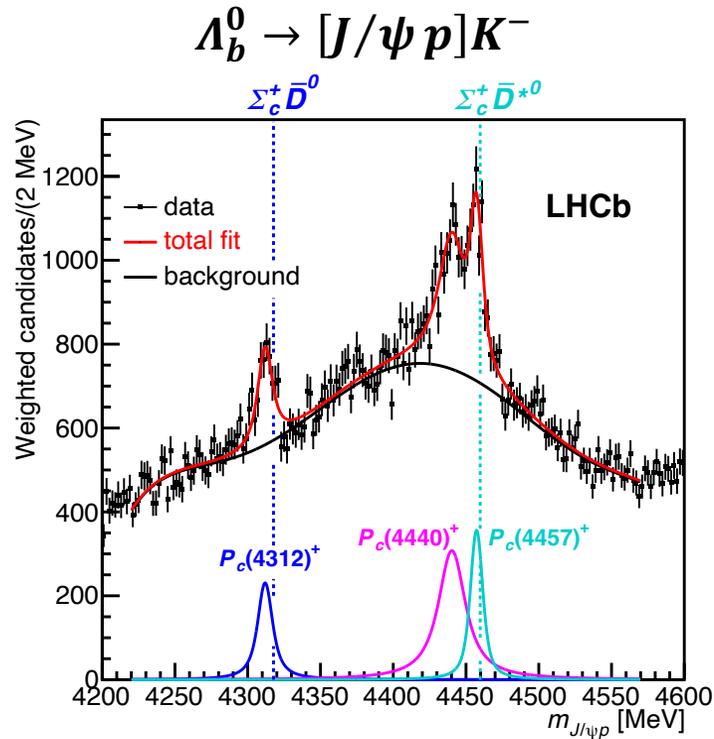
Hidden-charm pentaquarks



Pentaquark study

[PRL 122 (2019) 222001]

- Pentaquark candidates are first observed in 2015, a refined result is presented

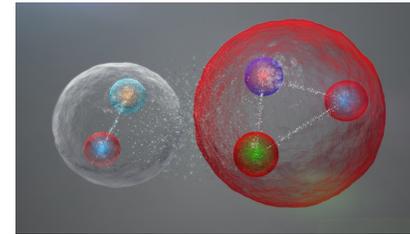


Proximity of $\Sigma_c^+ \bar{D}^0$ and $\Sigma_c^+ \bar{D}^{*0}$ thresholds to the peaks suggests they play an important role in the dynamics

Three narrow structures observed in $m(J/\psi p)$

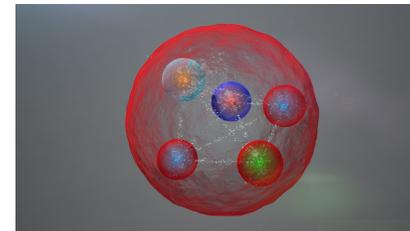
State	M [MeV]	Γ [MeV]	(95% CL)	\mathcal{R} [%]
$P_c(4312)^+$	$4311.9 \pm 0.7_{-0.6}^{+6.8}$	$9.8 \pm 2.7_{-4.5}^{+3.7}$	(< 27)	$0.30 \pm 0.07_{-0.09}^{+0.34}$
$P_c(4440)^+$	$4440.3 \pm 1.3_{-4.7}^{+4.1}$	$20.6 \pm 4.9_{-10.1}^{+8.7}$	(< 49)	$1.11 \pm 0.33_{-0.10}^{+0.22}$
$P_c(4457)^+$	$4457.3 \pm 0.6_{-1.7}^{+4.1}$	$6.4 \pm 2.0_{-1.9}^{+5.7}$	(< 20)	$0.53 \pm 0.16_{-0.13}^{+0.15}$

Hadron molecule



- Mass proximity to threshold **natural**
- Fall-apart decay **dominant**

Compact multiquark



- Mass proximity to threshold **accidental**
- No (strong) hierarchy of couplings

Evidence of a $J/\psi p$ structure

[PRL 128 (2022) 062001]

800 $B_s^0 \rightarrow J/\psi p \bar{p}$ decays

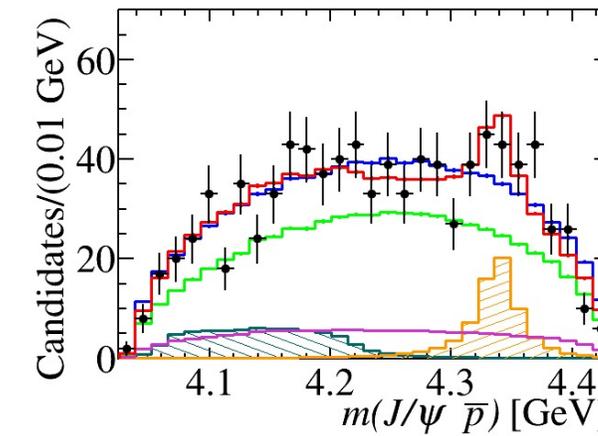
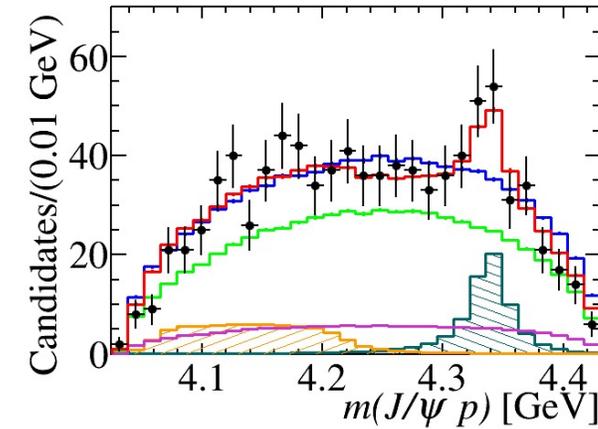
$$M_{P_c} = 4337_{-4}^{+7}(\text{stat})_{-2}^{+2}(\text{syst}) \text{ MeV},$$

$$\Gamma_{P_c} = 29_{-12}^{+26}(\text{stat})_{-14}^{+14}(\text{syst}) \text{ MeV},$$

Can't distinguish J^P due to limited sample size

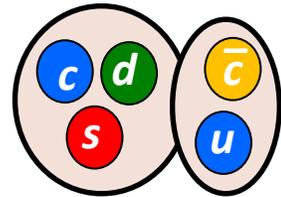
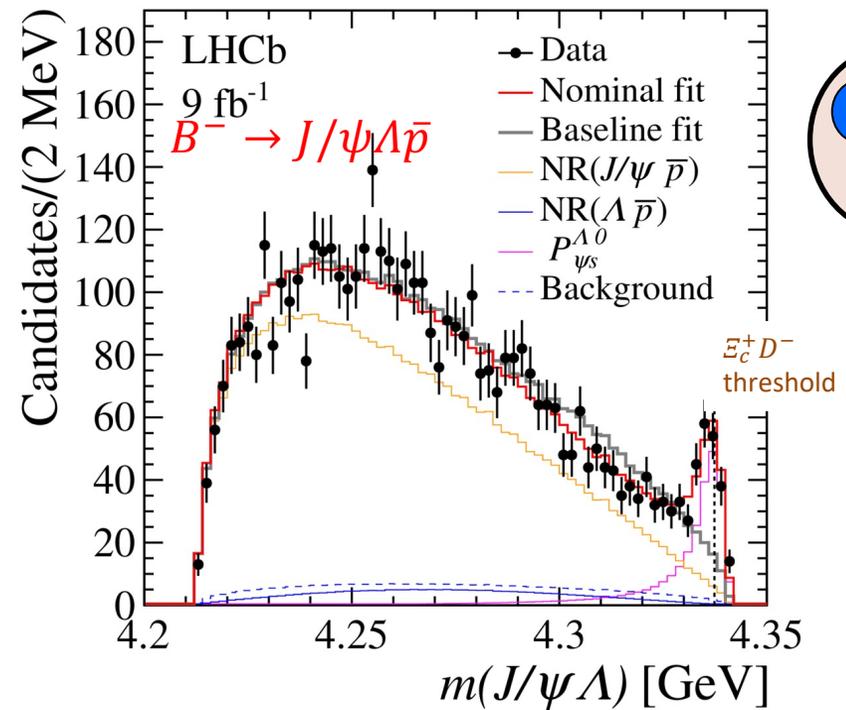
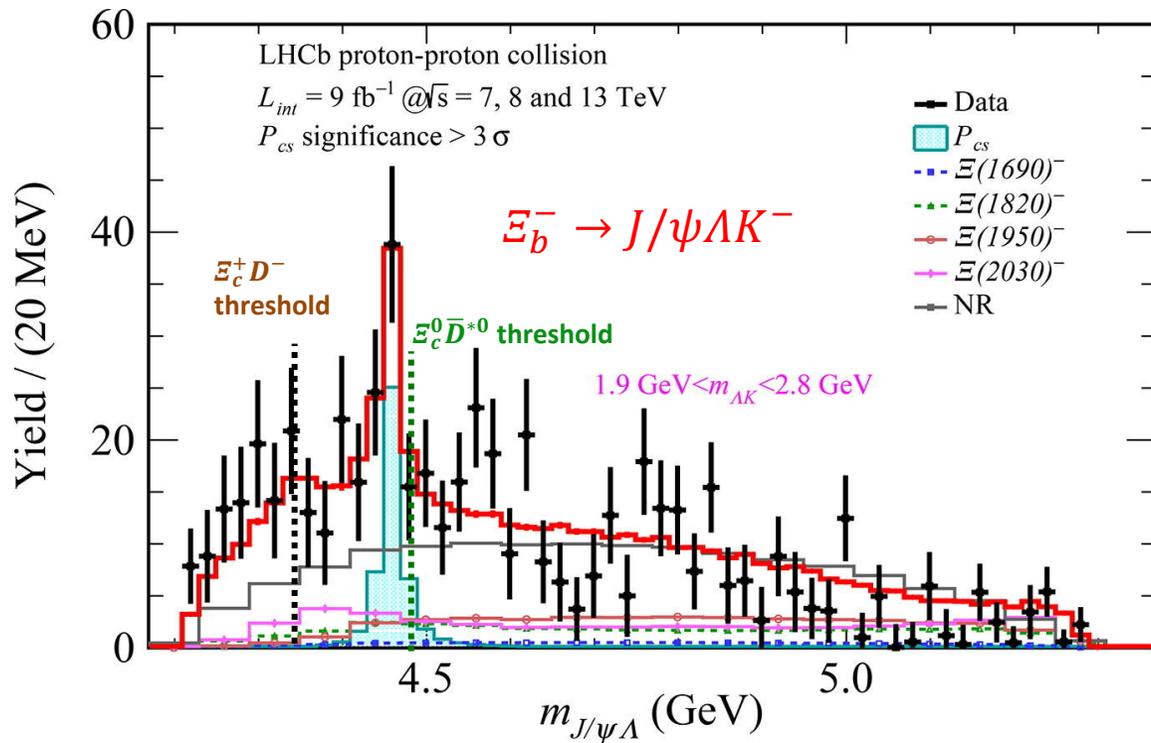
Other contributions are tested, no evidence is seen:

- $P_c(4312)^+$ seen in $\Lambda_b^0 \rightarrow J/\psi p K^-$ [PRL 122 (2019) 222001]
- Predicted glueball state $f_J(2220)(\rightarrow p \bar{p})$ [EPJC 75, 101 (2015)]



$P_{c\bar{c}s} \rightarrow J/\psi\Lambda$

State	M_0 [MeV]	Γ [MeV]	Significance	Threshold	Ref.
$P_{c\bar{c}s}(4459)^0$	$4458.8 \pm 2.9^{+4.7}_{-1.1}$	$17.3 \pm 6.5^{+8.0}_{-5.7}$	3.1σ	$\Xi_c \bar{D}^*$	Science Bulletin 66 (2021) 1278
$P_{c\bar{c}s}(4338)^0$	$4338.2 \pm 0.7 \pm 0.4$	$7.0 \pm 1.2 \pm 1.3$	15σ	$\Xi_c \bar{D}$	PRL 131 (2023) 031901



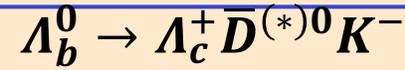
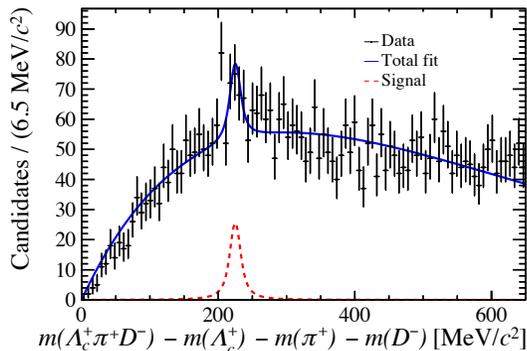
Pentaquark studies via open charm modes

prompt production

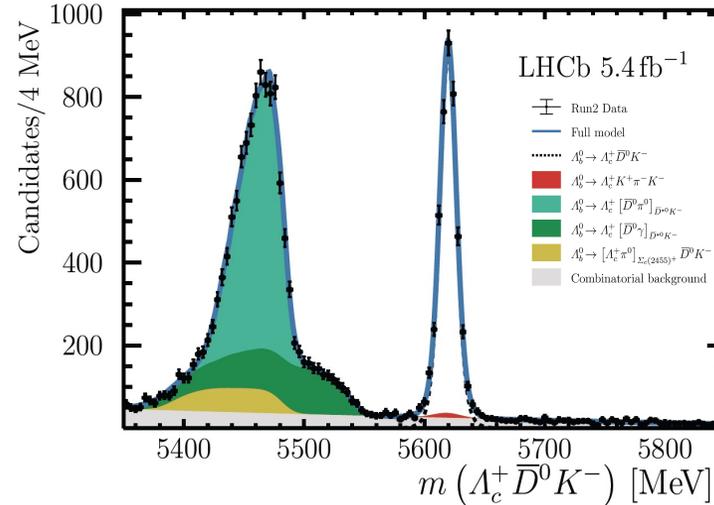
[PR D110 (2024) 032001]

Hadron 1	Hadron 2	Charge	I_3	Y	C	Limit Set
Λ_c^+	\bar{D}^0	+1	1/2	1	0	✓
Λ_c^+	D^-	0	-1/2	1	0	✓
Λ_c^+	D^{*-}	0	-1/2	1	0	✓
Σ_c^{++}	\bar{D}^0	+2	3/2	1	0	✓
Σ_c^{++}	D^-	+1	1/2	1	0	✓
Σ_c^{++}	D^{*-}	+1	1/2	1	0	×
Σ_c^0	\bar{D}^0	0	-1/2	1	0	✓
Σ_c^0	D^-	-1	-3/2	1	0	✓
Σ_c^0	D^{*-}	-1	-3/2	1	0	×
Σ_c^{*++}	\bar{D}^0	+2	3/2	1	0	✓
Σ_c^{*++}	D^-	+1	1/2	1	0	✓
Σ_c^{*++}	D^{*-}	+1	1/2	1	0	✓
Σ_c^{*0}	\bar{D}^0	0	-1/2	1	0	✓
Σ_c^{*0}	D^-	-1	-3/2	1	0	✓
Σ_c^{*0}	D^{*-}	-1	-3/2	1	0	✓

- No significant signals
- Largest deviation from bkg. shown in $\Lambda_c^+ \pi^+ D^- (c\bar{c}uud)$ @ $M \sim 4520.69$ MeV



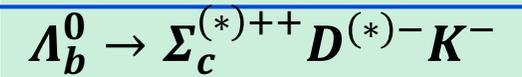
[EPJC 84 (2024) 575]



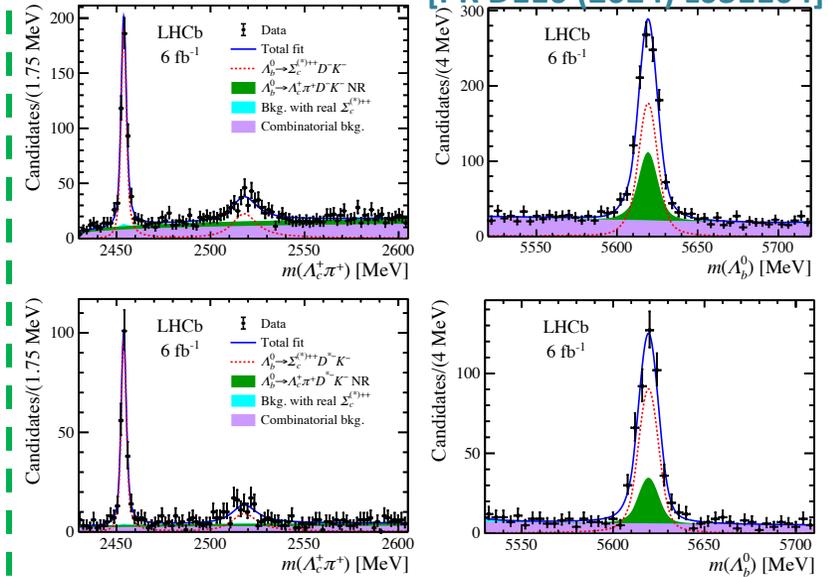
$$\frac{\mathcal{B}(\Lambda_b^0 \rightarrow J/\psi p K^-)}{\mathcal{B}(\Lambda_b^0 \rightarrow \Lambda_c^+ \bar{D}^0 K^-)} = 0.152^{+0.032}_{-0.028},$$

$$\frac{\mathcal{B}(\Lambda_b^0 \rightarrow J/\psi p K^-)}{\mathcal{B}(\Lambda_b^0 \rightarrow \Lambda_c^+ \bar{D}^{*0} K^-)} = 0.049^{+0.011}_{-0.009},$$

- Essential input for extraction of $\mathcal{B}(P_c^+ \rightarrow \Lambda_c^+ \bar{D}^{(*)0})/\mathcal{B}(P_c^+ \rightarrow J/\psi p)$ in the future



[PR D110 (2024) L031104]



$$\frac{\mathcal{B}(\Lambda_b^0 \rightarrow \Sigma_c^{++} D^- K^-)}{\mathcal{B}(\Lambda_b^0 \rightarrow \Lambda_c^+ \bar{D}^0 K^-)} = 0.282 \pm 0.016 \pm 0.016 \pm 0.005,$$

$$\frac{\mathcal{B}(\Lambda_b^0 \rightarrow \Sigma_c^{*++} D^- K^-)}{\mathcal{B}(\Lambda_b^0 \rightarrow \Sigma_c^{++} D^- K^-)} = 0.460 \pm 0.052 \pm 0.028,$$

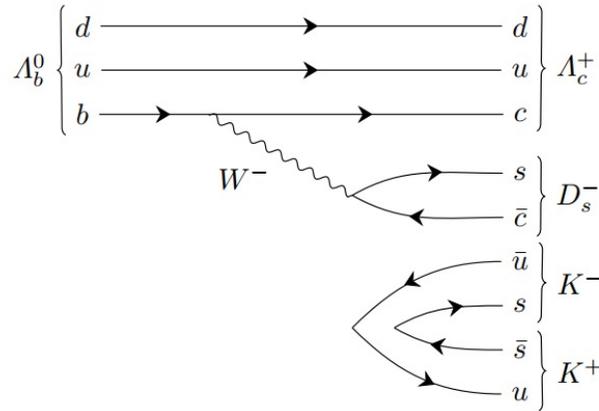
$$\frac{\mathcal{B}(\Lambda_b^0 \rightarrow \Sigma_c^{++} D^{*-} K^-)}{\mathcal{B}(\Lambda_b^0 \rightarrow \Sigma_c^{++} D^- K^-)} = 2.261 \pm 0.202 \pm 0.129 \pm 0.046,$$

$$\frac{\mathcal{B}(\Lambda_b^0 \rightarrow \Sigma_c^{*++} D^{*-} K^-)}{\mathcal{B}(\Lambda_b^0 \rightarrow \Sigma_c^{++} D^- K^-)} = 0.896 \pm 0.137 \pm 0.066 \pm 0.018,$$

- Study of resonant structures calls for larger dataset

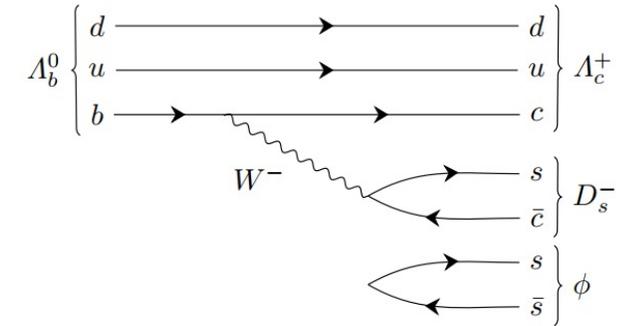
Observation of $\Lambda_b^0 \rightarrow \Lambda_c^+ D_s^- K^+ K^-$ decays

- Can $P_{c\bar{c}s}$ decay into $\Lambda_c^+ D_s^-$



(a) The nonresonant K^+K^- process

[PRD112 (2025) 052013]

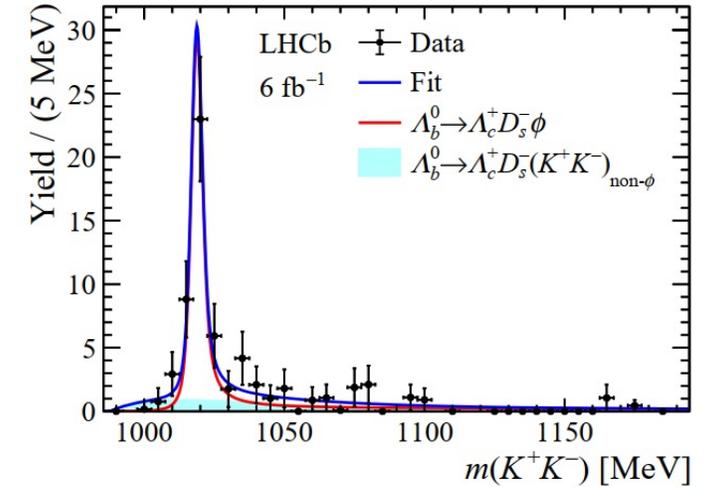
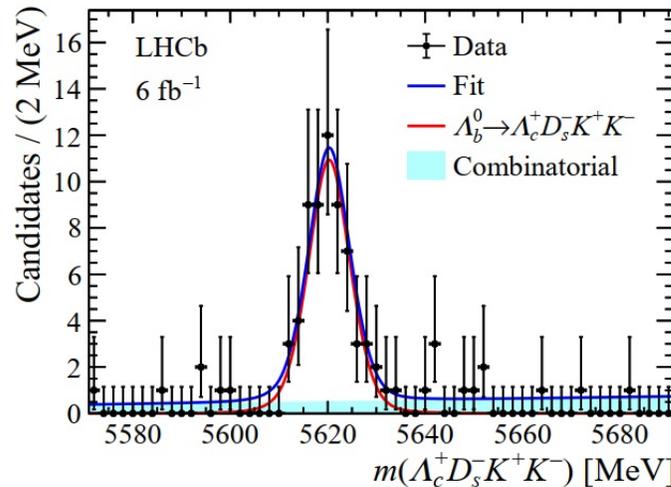


(b) The ϕ -dominated process

- Cut & MVA based selection

- $61 \pm 8 \Lambda_b^0$ decays
- Dominated by $\phi \rightarrow K^+K^-$

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



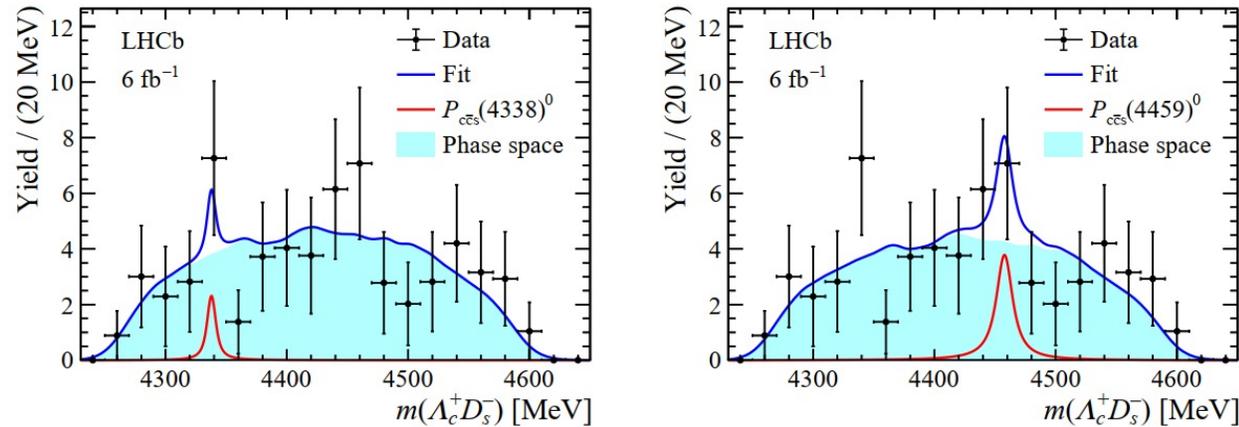
Search for pentaquarks in $\Lambda_c^+ D_s^-$ mass

[PRD112 (2025) 052013]

- $P_{c\bar{c}s}$ contributions (fit fractions) derived from fit to background-subtracted data

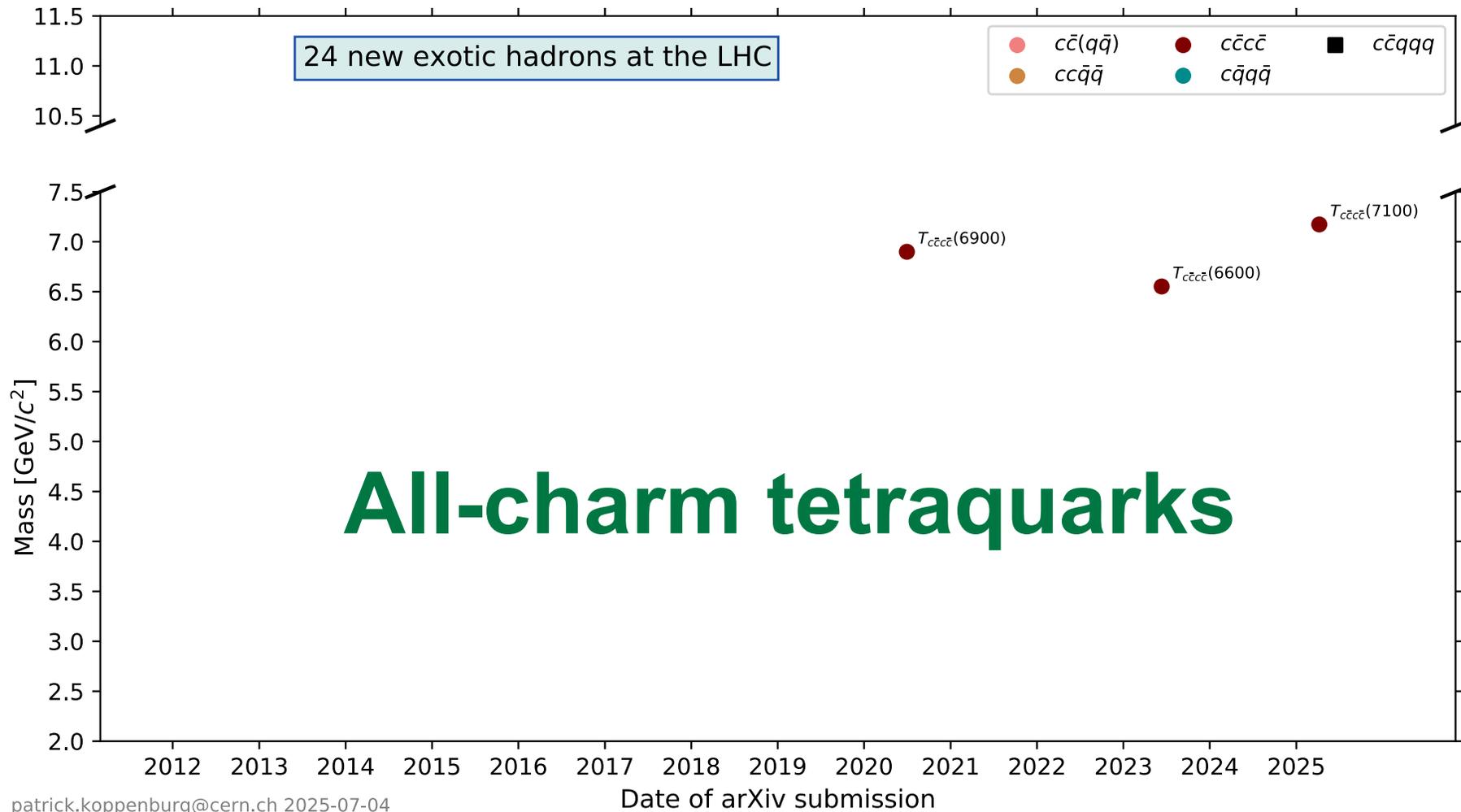
$$\mathcal{R}_{P_{c\bar{c}s}^0} \equiv \frac{\mathcal{B}(\Lambda_b^0 \rightarrow P_{c\bar{c}s} K^+ K^-)}{\mathcal{B}(\Lambda_b^0 \rightarrow \Lambda_c^+ D_s^- K^+ K^-)} \cdot \mathcal{B}(P_{c\bar{c}s}^0 \rightarrow \Lambda_c^+ D_s^-)$$

- Widths and masses are Gaussian constrained to their known values



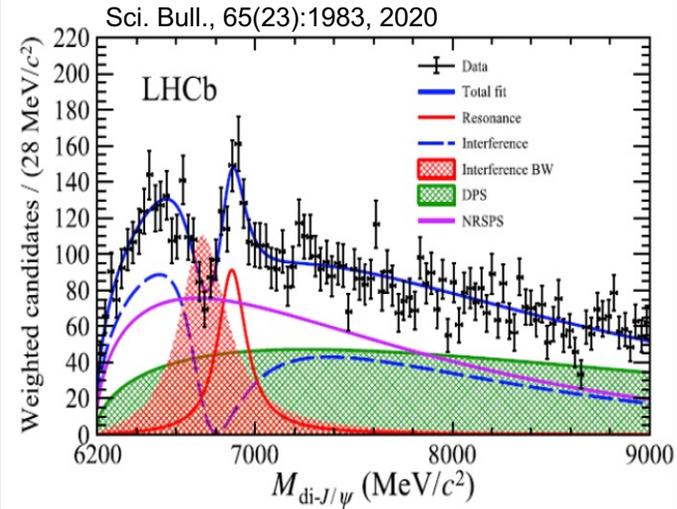
- Upper limits on 90% (95%) CLs:

$$\mathcal{R}_{P_{c\bar{c}s}(4338)^0} < 0.10 \text{ (0.12)} \text{ and } \mathcal{R}_{P_{c\bar{c}s}(4459)^0} < 0.17 \text{ (0.20)}$$

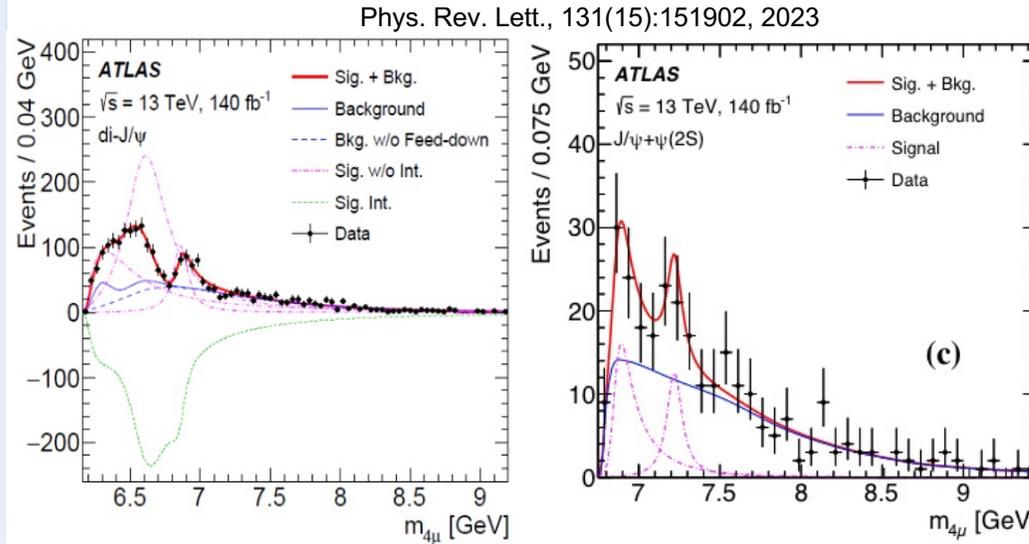


Status of all-charm tetraquark before 2025

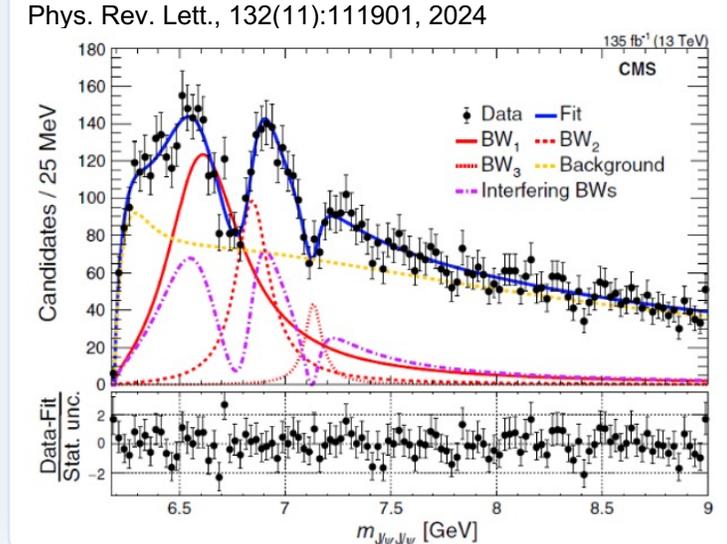
LHCb



ATLAS



CMS



- All exp observe **X(6900)**
- CMS first observed X(6600) & evidence of X(7100)
- All exp use interference, but in different ways
- All exp see a threshold excess, NOT explained! Classified as background
- Many open questions

What is their nature?

Idealized models of potential all-charm structures

Standard Mesons	Exotic Mesons: Tetracharm				Threshold Effects
					e.g. Triangle Singularity

- Found **repulsive between two charmoniums** in Lattice QCD: 2411.11533 [hep-lat]

- **Models of potential quark configurations for $J/\psi J/\psi$ mesons**

Meson-meson “molecule” ($c\bar{c} - c\bar{c}$)

Pair of diquarks ($cc - \bar{c}\bar{c}$)

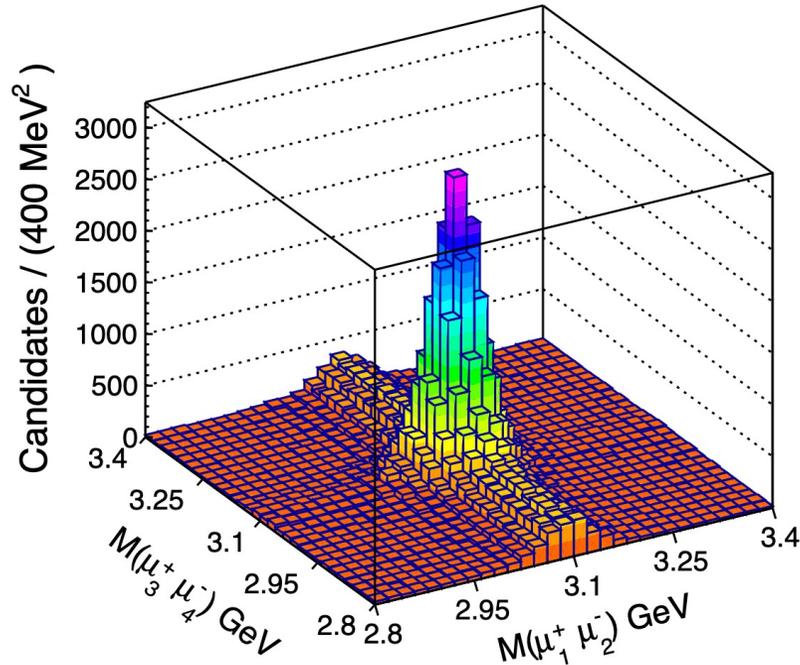
Hybrid with a valence gluon

Peaks as artifact of di-charmonia production thresholds

Properties such as J^{PC} , cross section, new decay channels if resonance?

$J/\psi J/\psi$ updated result

CMS Run 2+3



- **Data samples** [315 fb⁻¹]

Run II: 135 fb⁻¹ data taken in 2016, 2017 and 2018.

Run III: 180 fb⁻¹ data taken in 2022, 2023 and 2024.

- **Luminosity**

Run 2: 135 fb⁻¹

Run 3: 180 fb⁻¹

New triggers in parked data

- **$J/\psi J/\psi$ yield**

Run 2 $\sim 12622 \pm 165$

Run 3 $\sim 31802 \pm 476$

- **$J/\psi J/\psi$ yield per unit luminosity**

Run 2 ~ 93 events / fb⁻¹

Run 3 ~ 177 events / fb⁻¹

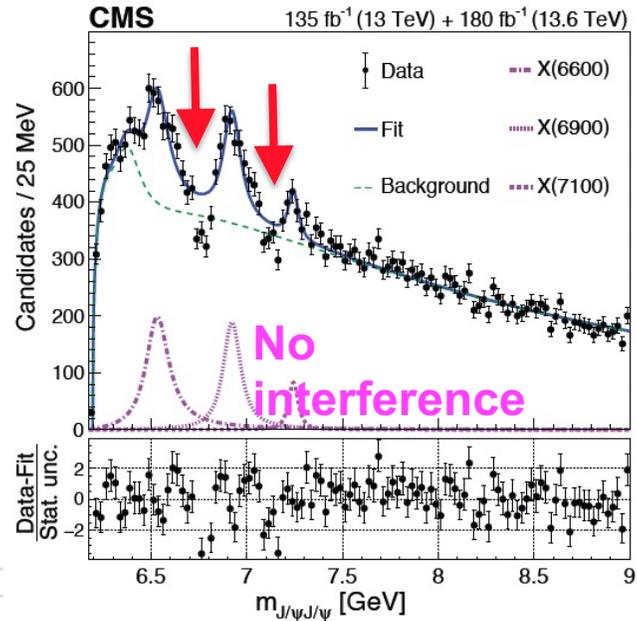
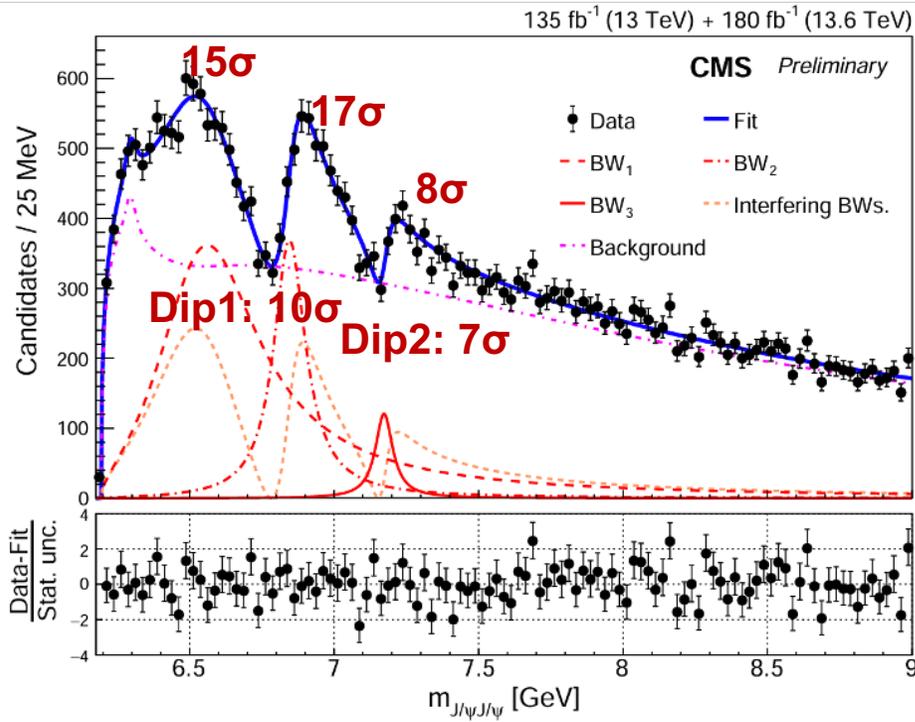
<http://cds.cern.ch/record/2929472>

➤ **Run 2+3 $J/\psi J/\psi$ yield is 3.6X of Run 2**

➤ **Run 2+3 luminosity is 2.3X of Run 2**

Run 2+3 interference fit result

CMS Run 2+3



Params [MeV]	Run II&III Interf.	Run II Interf.
M(BW1)	6593 ⁺¹⁵ ₋₁₄ ± 25	6638 ⁺⁴³⁺¹⁶ ₋₃₈₋₃₁
Γ(BW1)	446 ⁺⁶⁶ ₋₅₄ ± 87	440 ⁺²³⁰⁺¹¹⁰ ₋₂₀₀₋₂₄₀
M(BW2)	6847 ± 10 ± 15	6847 ⁺⁴⁴⁺⁴⁸ ₋₂₈₋₂₀
Γ(BW2)	135 ⁺¹⁶ ₋₁₄ ± 14	191 ⁺⁶⁶⁺²⁵ ₋₄₉₋₁₇
M(BW3)	7173 ⁺⁹ ₋₁₀ ± 13	7134 ⁺⁴⁸⁺⁴¹ ₋₂₅₋₁₅
Γ(BW3)	73 ⁺¹⁸ ₋₁₅ ± 10	97 ⁺⁴⁰⁺²⁹ ₋₂₉₋₂₆

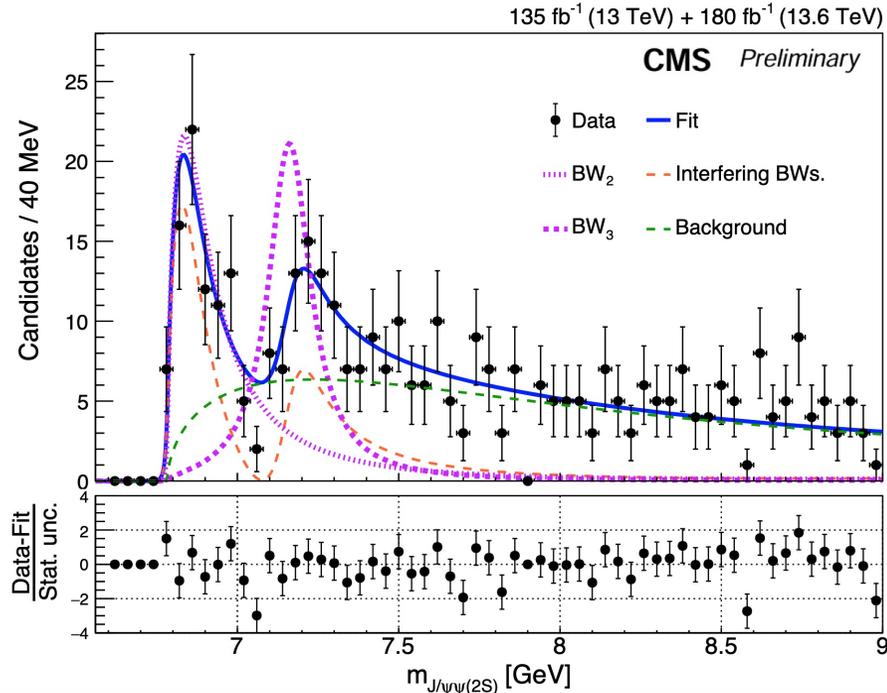
VS. Run II result:

- ✓ Statistical uncertainty reduced by **a factor of 3**
- ✓ Systematic uncertainty reduced by about **a factor of 2**
- ✓ **Statistics & model improvement**

- All states and dips **well above 5 σ !**
- Quantum **interference among structures strengthen!**
- With improved precision, **large mass splittings persist**

$J/\psi\psi(2S)$ Run II & III interference fit result

CMS Run 2+3



- Significance of $X(6900) = 7.9\sigma$
- Significance of $X(7100) = 4.0\sigma$

ATLAS only claim $X(6900) 4.7\sigma$ in $J/\psi\psi(2S)$ channel

Dominant sources	$M_{X(6900)}$	$\Gamma_{X(6900)}$	$M_{X(7100)}$	$\Gamma_{X(7100)}$
Signal shape	± 29	± 79	± 22	± 131
NRSPS shape	± 14	± 54	± 14	± 29
Combinatorial background shape	± 15	± 51	± 15	± 20
Mass resolution	± 5	± 7	± 5	± 9
Efficiency	± 7	± 27	± 7	± 10
Add X(6600) peak	± 104	± 14	± 61	± 31
Fitter bias	+9 -11	+43 -37	+29 -14	0 -80
Total	+110 -110	+120 -120	+74 -70	+140 -160

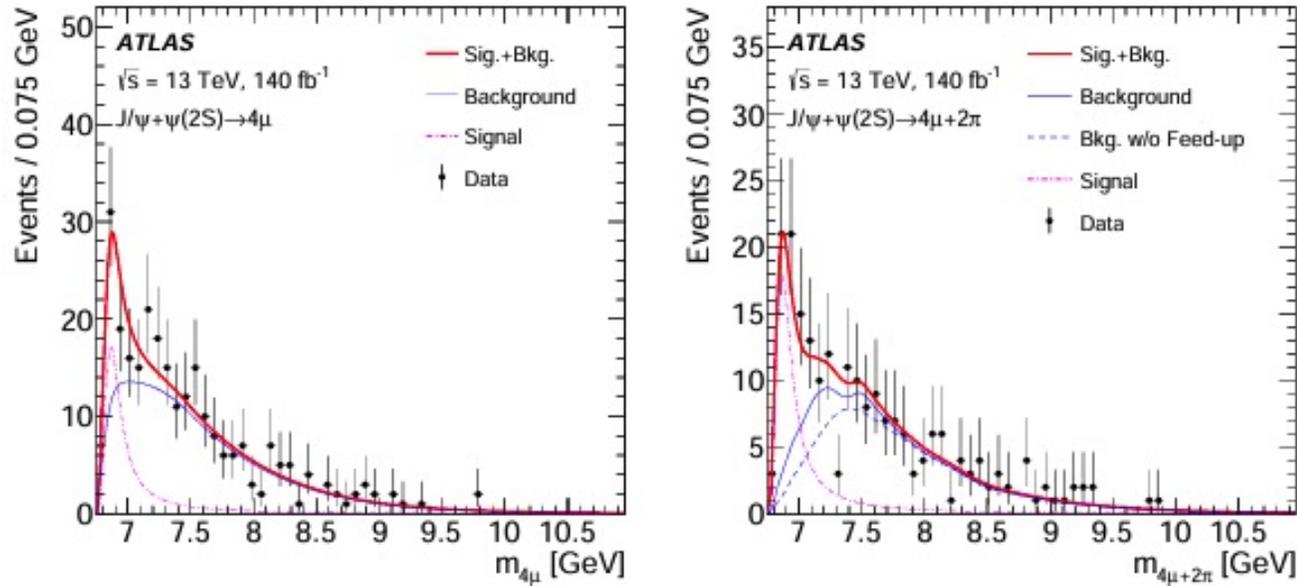
Params	$J/\psi\psi(2S)$ [MeV]	$J/\psi J/\psi$ [MeV]
$M(\text{BW}2)$	$6876^{+46+110}_{-29-110}$	$6847 \pm 10 \pm 15$
$\Gamma(\text{BW}2)$	$253^{+290+120}_{-100-120}$	$135^{+16}_{-14} \pm 14$
$M(\text{BW}3)$	7169^{+26+74}_{-52-70}	$7173^{+9}_{-10} \pm 13$
$\Gamma(\text{BW}3)$	$154^{+110+140}_{-82-160}$	$73^{+18}_{-15} \pm 10$

<http://cds.cern.ch/record/2929529>

Update of $J/\psi\psi(2S)$ from ATLAS

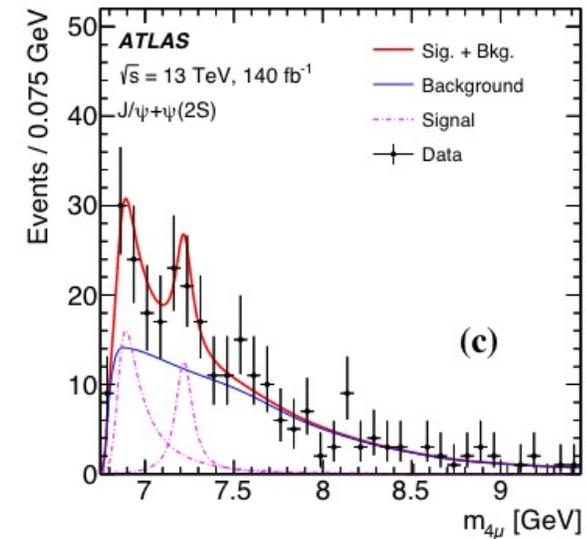
- Simultaneous fit of 3 channels: [arXiv:2509.13101](https://arxiv.org/abs/2509.13101)
 $J/\psi J/\psi$, $J/\psi\psi(2S)$ [4μ], $J/\psi\psi(2S)$ [$4\mu+2\pi$]

Model C: Simultaneous fit for $J/\psi\psi(2S)$ [4μ and $4\mu+2\pi$]



ATLAS 2023 paper

Phys. Rev. Lett., 131(15):151902, 2023



- $X(6900)$ 8.9σ from model C
- Set an upper limit of **0.41 @95%CL** for $X(7200)$
- In ATLAS 2023 paper, $X(7200)$ 3σ in $J/\psi\psi(2S)$ [4μ]

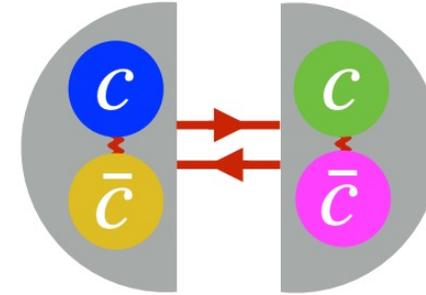
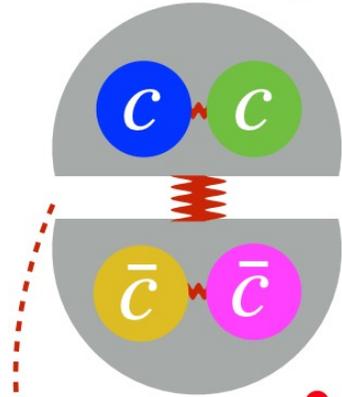
4c States Spin Parity

- Fundamental study of matter at quark level...

– unique **all-heavy** tetraquark states

- Quantum numbers $J^{PC} = ?$

directly related to structure:



- Tightly-bound **tetraquark**:

(cc) or $(\bar{c}\bar{c})$ identical \Rightarrow color anti-triplet (bg-gb,..) $L = 0$, axial vector $S_{1,2} = 1$

$(cc) + (\bar{c}\bar{c}) \Rightarrow L = 0$ (nS) : $S = 0, 2 \Rightarrow J^P = 0^+, 2^+$ ← most likely for a tetraquark

$L = 1$ (nP) : $S = 1 \Rightarrow J^P = 0^-, 1^-, 2^-$ ← less likely

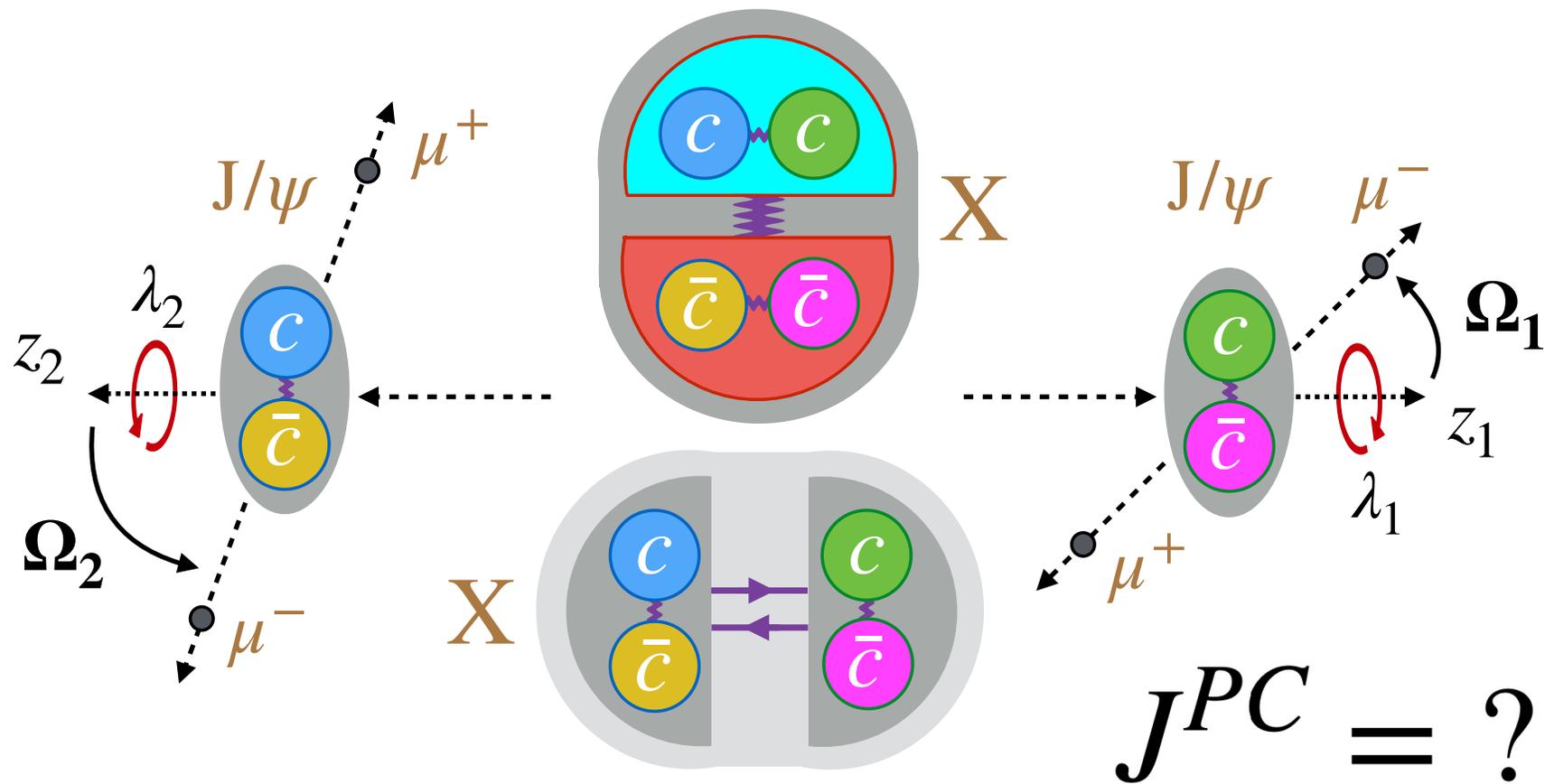
$n = 1, 2, 3, 4, \dots$

$L = 2$ (nD) : $S = 0 \Rightarrow J^P = 2^+$

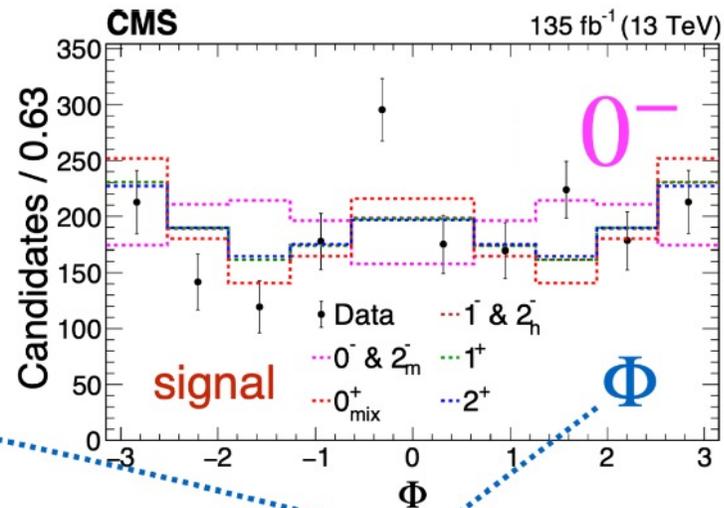
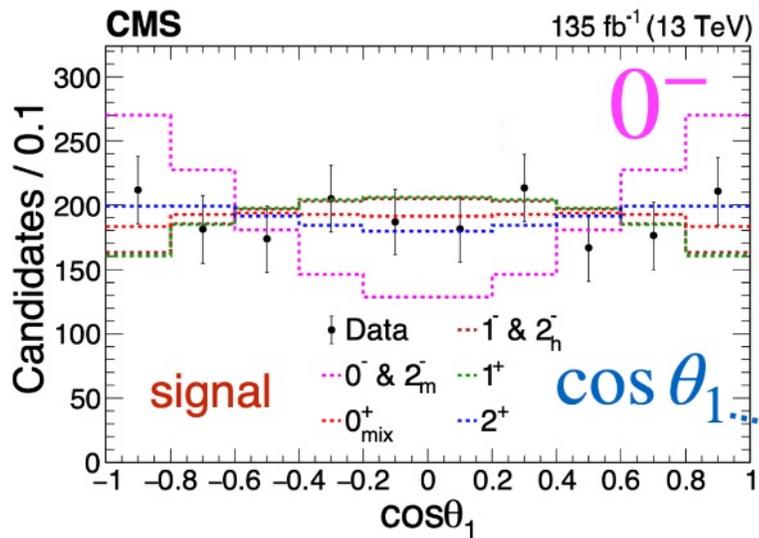
$S = 2 \Rightarrow J^P = 0^+, 1^+, 2^+, 3^+, 4^+ \dots$ ← unlikely

- **Molecular**: less restrictions (e.g. meson $S_{1,2} = 0, 1$): recall $J^P = 1^+$

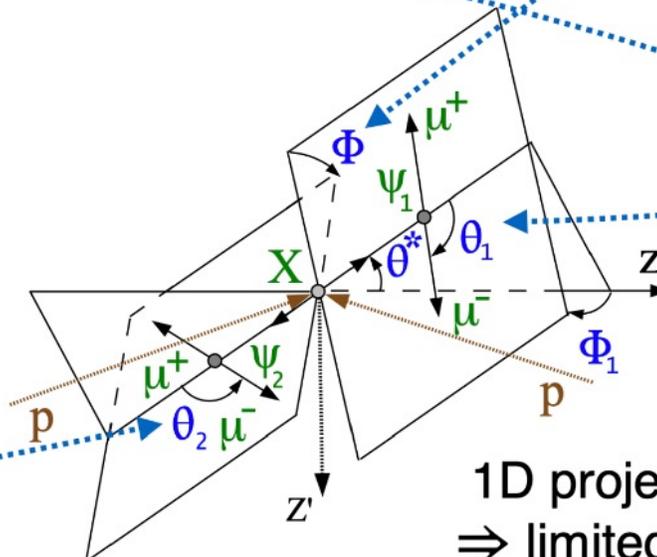
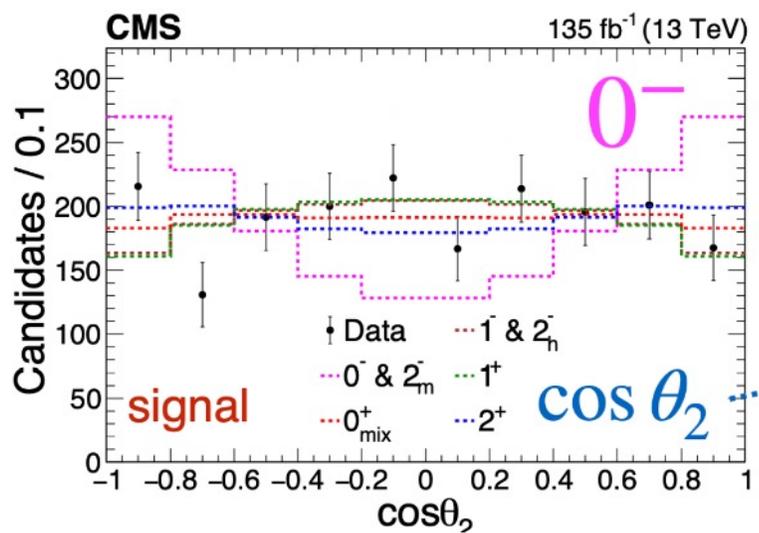
CMS Angular Analysis



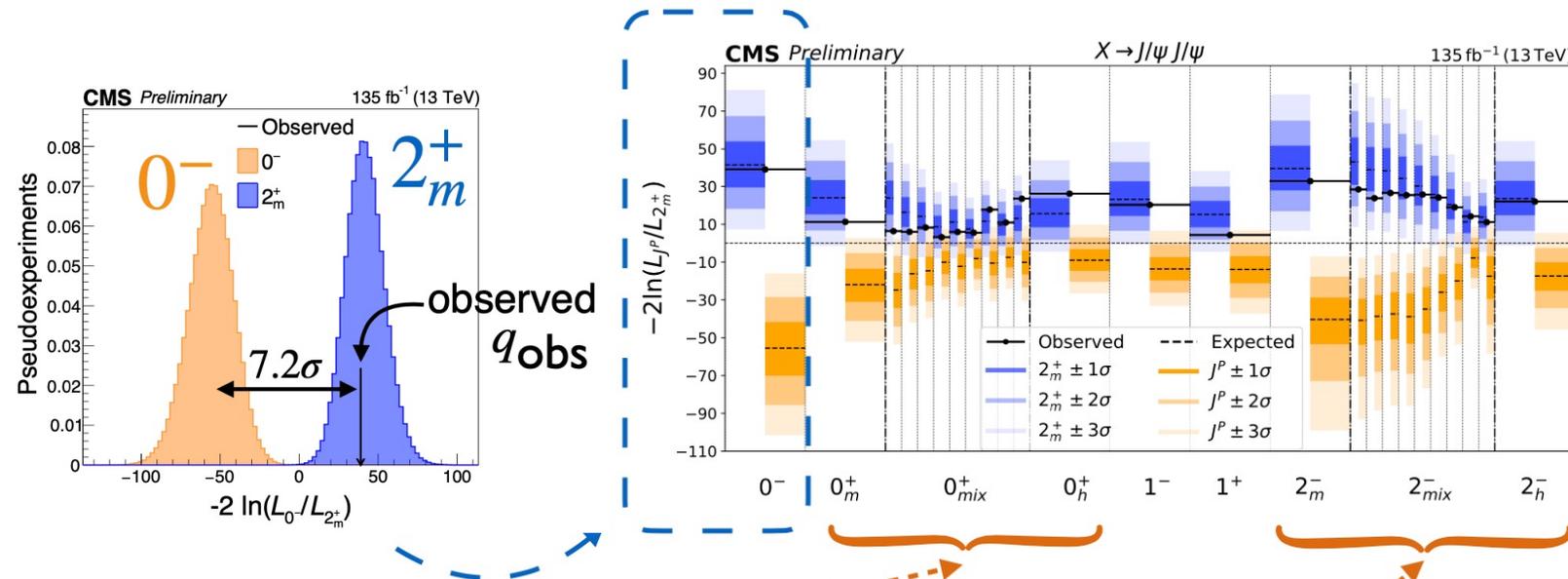
decay angles (consistency check): **distinguish** models



background-subtracted



1D projections from 4D
 \Rightarrow limited information

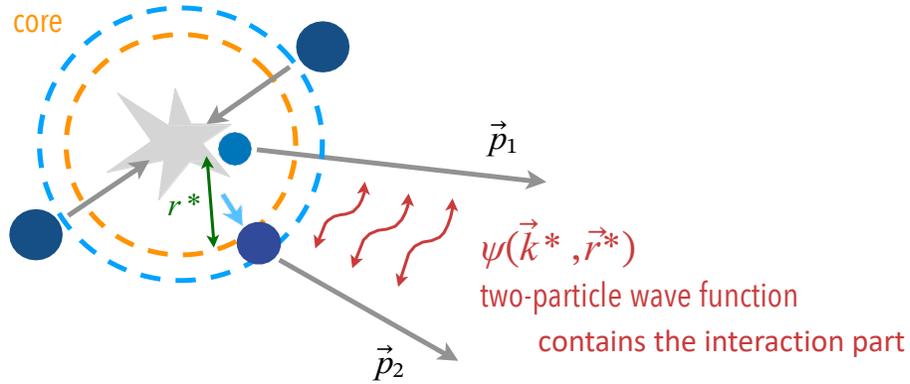


- Scan mixture of two 0^{++} amplitudes (11 steps)
 - constructive interference most conservative
- Scan mixture of two 2^{-+} amplitudes (11 steps)
 - no interference (different spin projections)
- Data are consistent with a 2^{++} model, inconsistent with others

Correlation function

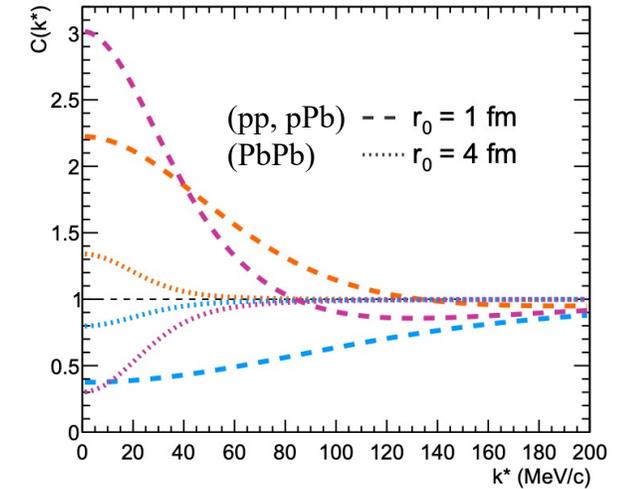
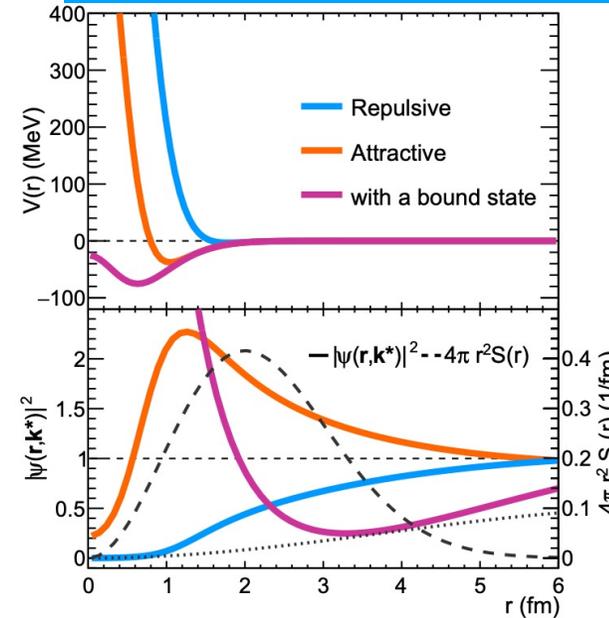
Two-body femtoscopy

Ann. Rev. Nucl. Part. Sci. 71 (2021) 377



$S(r^*)$ the source emitting particles

$$k^* = |\mathbf{p}_2^* - \mathbf{p}_1^*|/2$$



Theo. description
Koonin–Pratt formula

Exp. measurement
mixed-event technique

coincidence measurement?

$$C(k^*) = \int S(\mathbf{r}^*) |\psi(\mathbf{r}^*, \mathbf{k}^*)|^2 d^3r = \xi(k^*) \cdot \frac{N_{SE}(k^*)}{N_{ME}(k^*)}$$

[arXiv: 2506.23476](https://arxiv.org/abs/2506.23476)

spacial structure

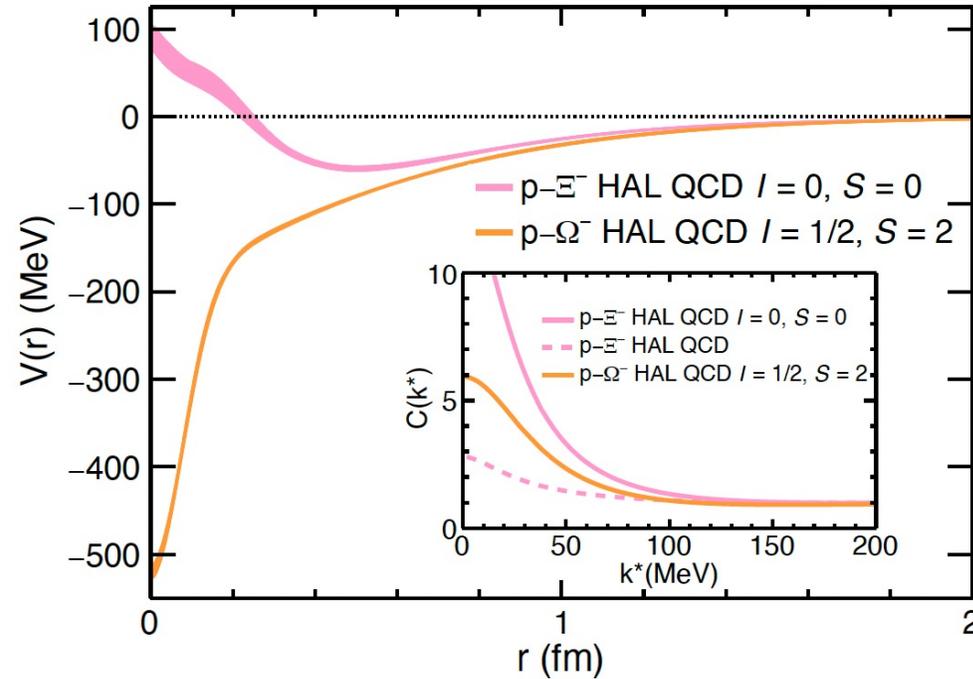
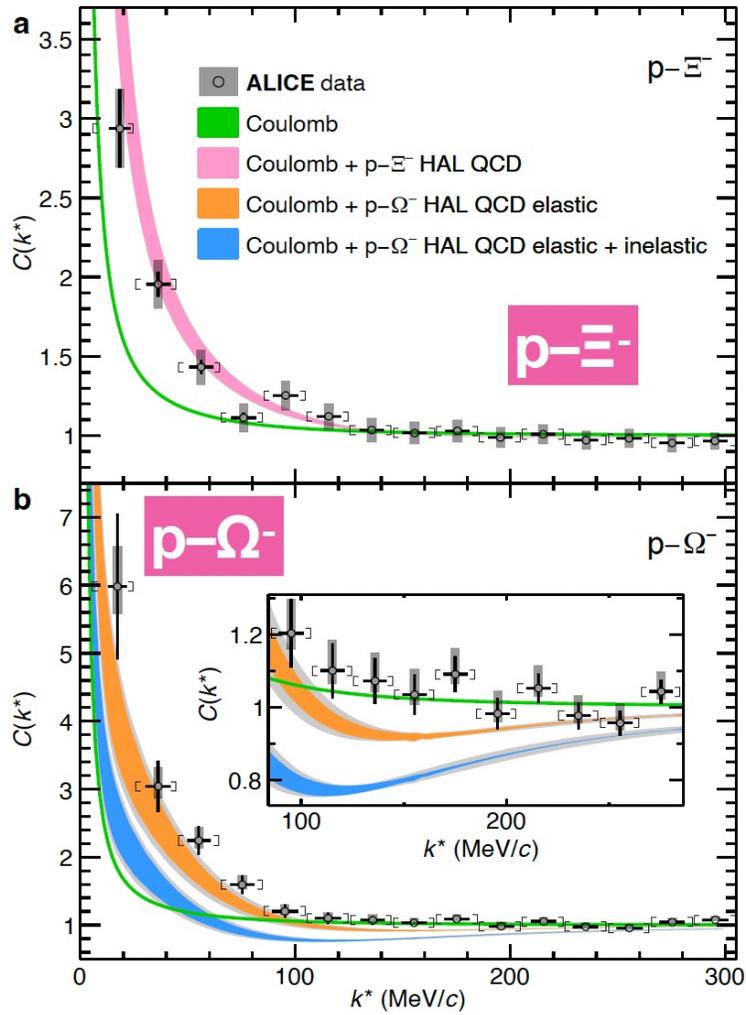
final-state interactions
quantum statistics effects
coupled-channel effects

>1 if the interaction is **attractive**
=1 if there is **no interaction**
<1 if the interaction is **repulsive**

the same and mixed event distributions

the corrections for experimental effects

Proton-hyperon interactions

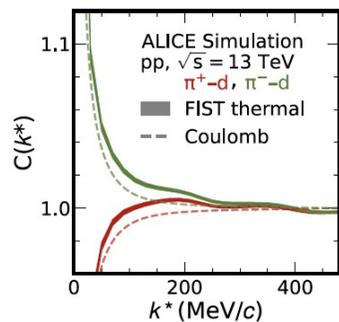
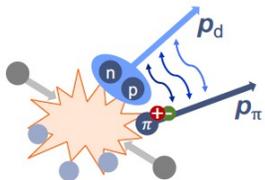


ALICE *Nature Physics* 588 (2020) 232

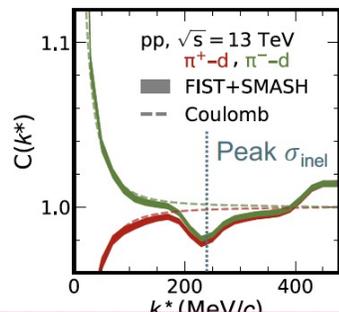
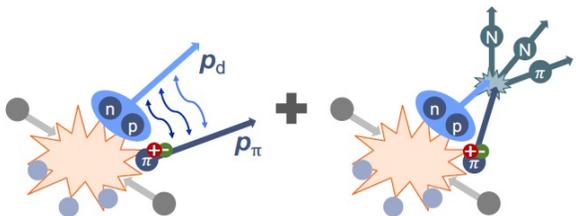
- $p-\Omega^-$ correlation signal is around two times larger than $p-\Xi^-$, large difference in strong interaction
- $p-\Omega^-$ bound-state is not yet observed in data

Δ resonance in π^+d

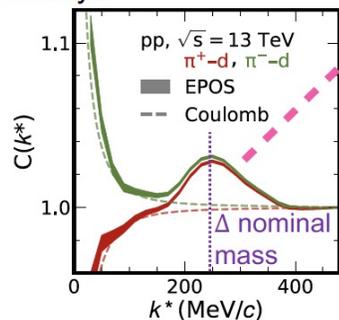
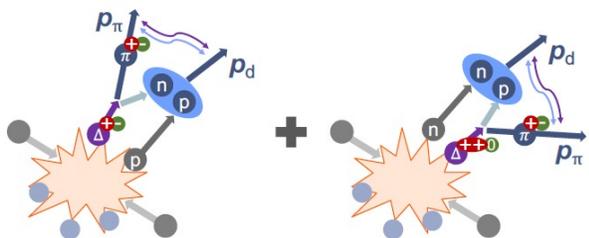
i. Coulomb



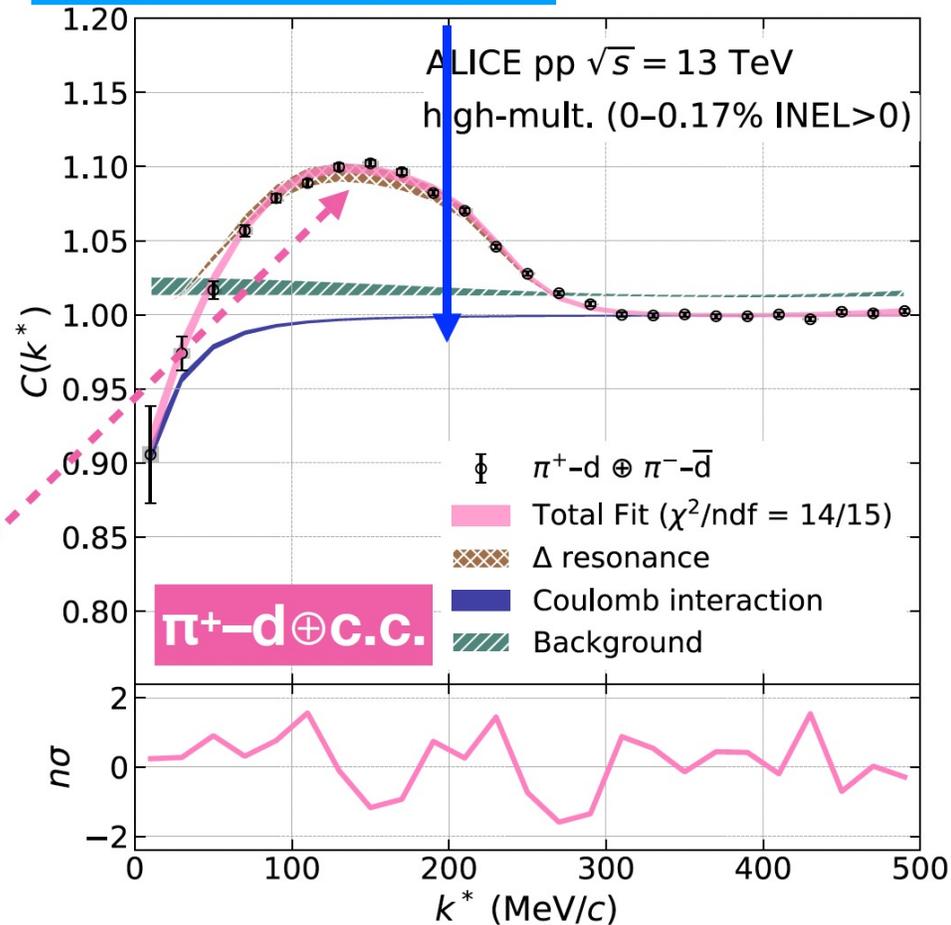
ii. Coulomb + Elastic + Inelastic Interaction



iii. Coulomb + Nuclear fusion after resonance decays



ALICE Nature 648 (2025) 306



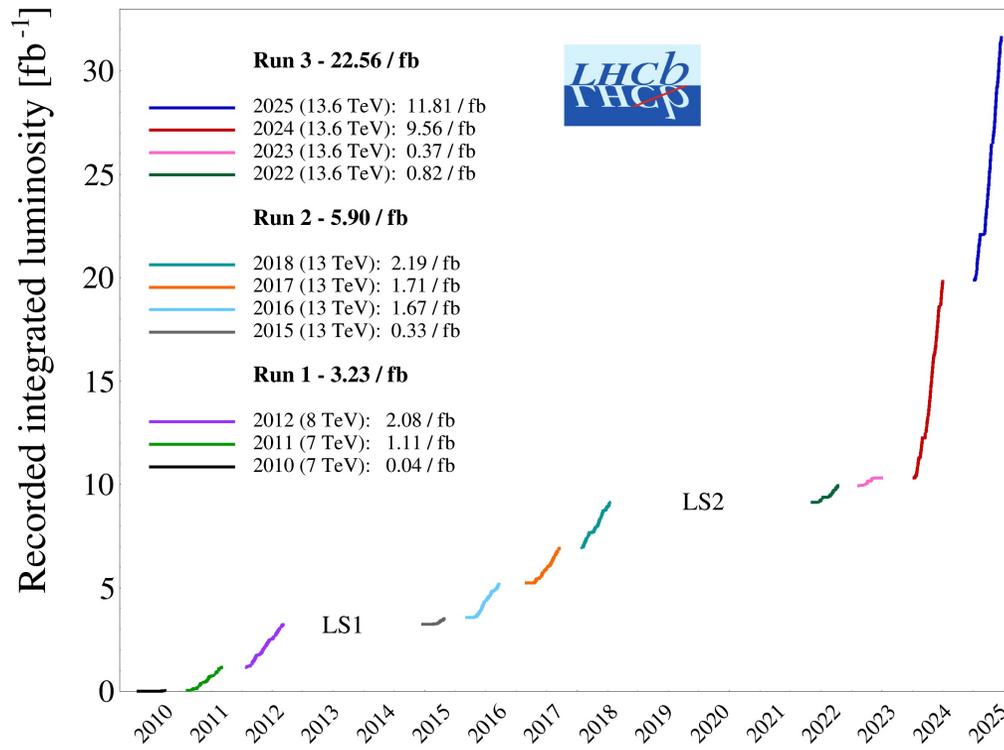
约90%的（反）氘核是通过短寿命共振态（如 $\Delta(1232)$ ）衰变后的核反应产生的

LHCb Run3 performance

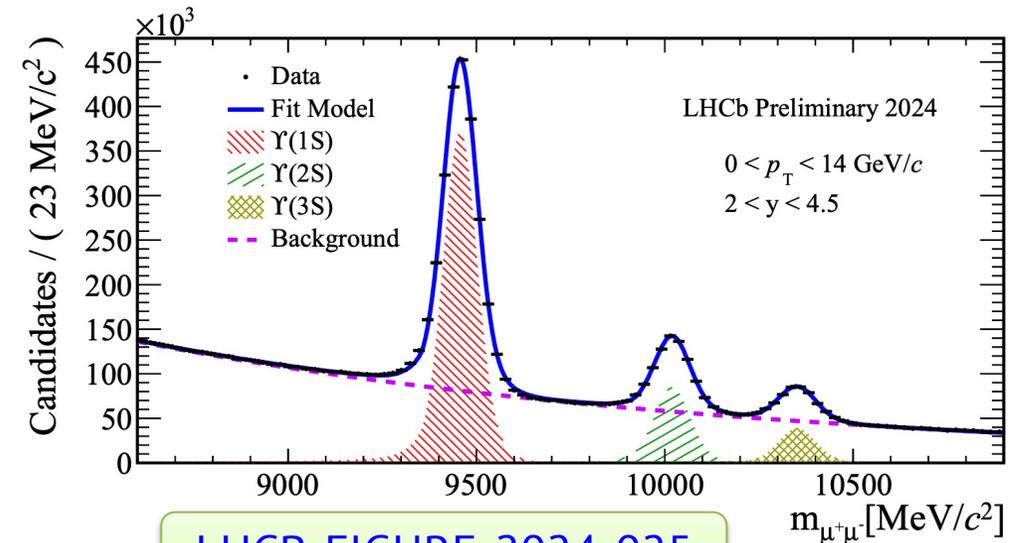
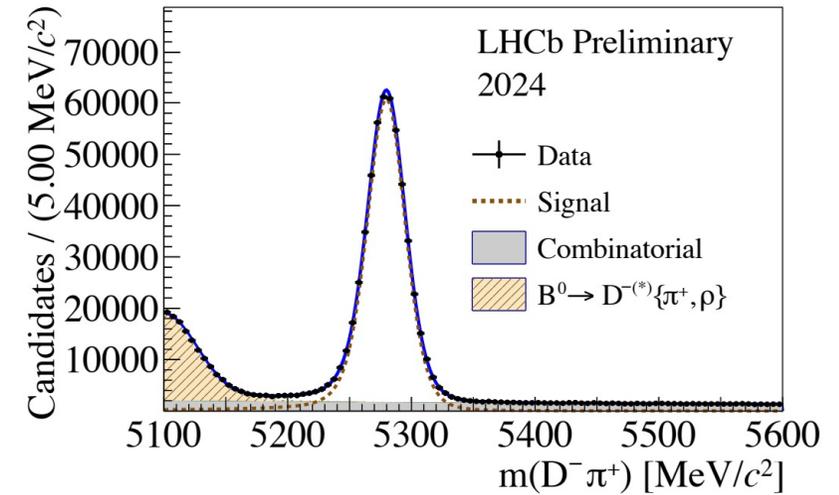
LHCb-FIGURE-2024-021

Reaching Run 2 performance in mass resolution

Total recorded luminosity – pp – 31.7 fb^{-1}



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



LHCb-FIGURE-2024-025

Summary

■ Major Discoveries

- Tetraquarks: confirmed **open-flavor states** (e.g., $T_{cs0}^*(2870)^0$), full-charm structures $X(6600,6900,7100)$, and the **doubly-charmed** T_{cc}^+
- Pentaquarks: Narrow **P_c states** (4312, 4440, 4457) and $P_{cs}(4338)$
- Quantum numbers: Spin-parity of $X(6600,6900,7100)$ determined as $J^{PC} = 2^{++}$

■ Advanced Techniques

- Precision studies rely on amplitude analysis of B hadron decays and direct pp production.
- Femtoscopy (correlation functions) probes strong interactions between hadrons.

■ Future Outlook

- LHCb Run 3 data enable more discoveries and precise measurements

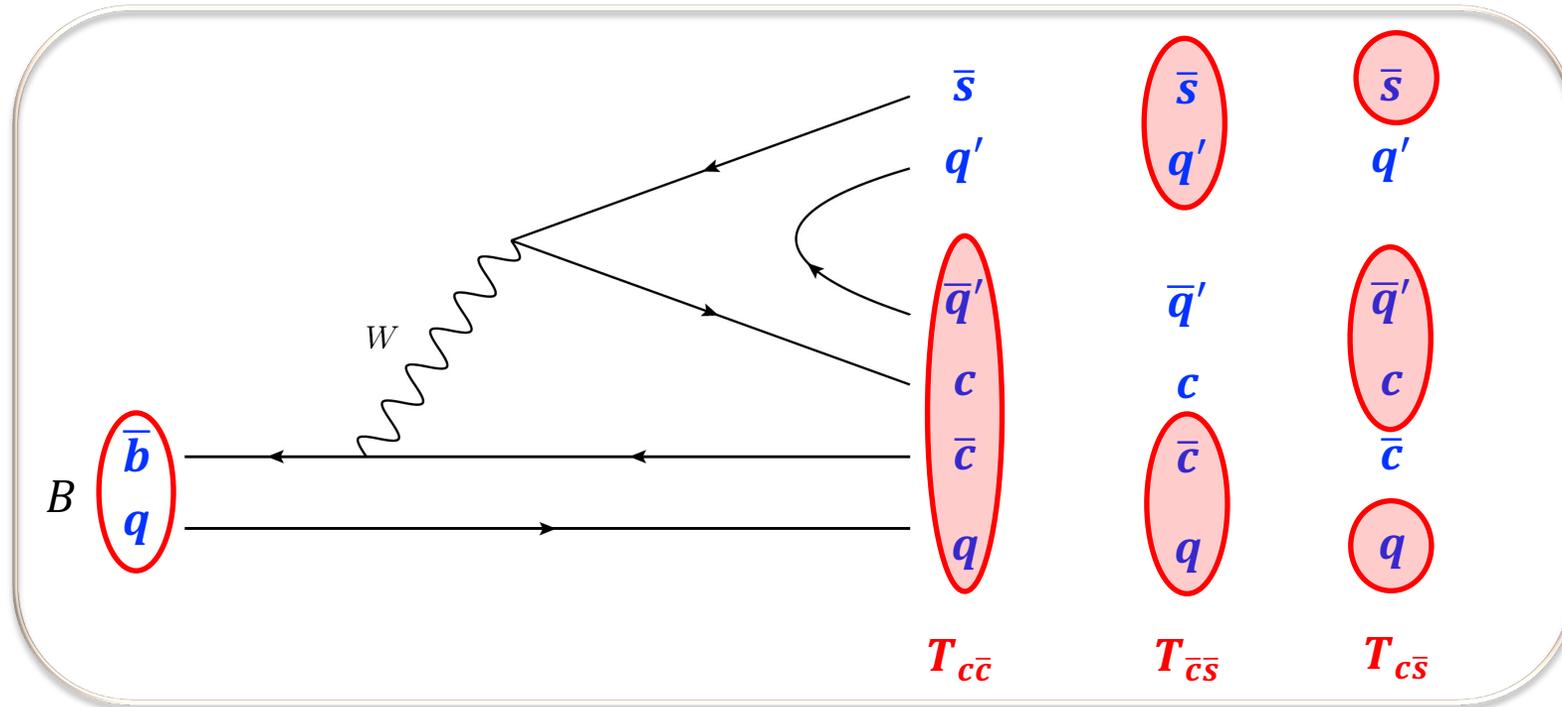
■ More observables?

- production CPV and asymmetry decay parameters (α, β, γ)

BACKUP

Exotic production topology from B decays

- Exotics generated from $b \rightarrow c\bar{c}s$ transition

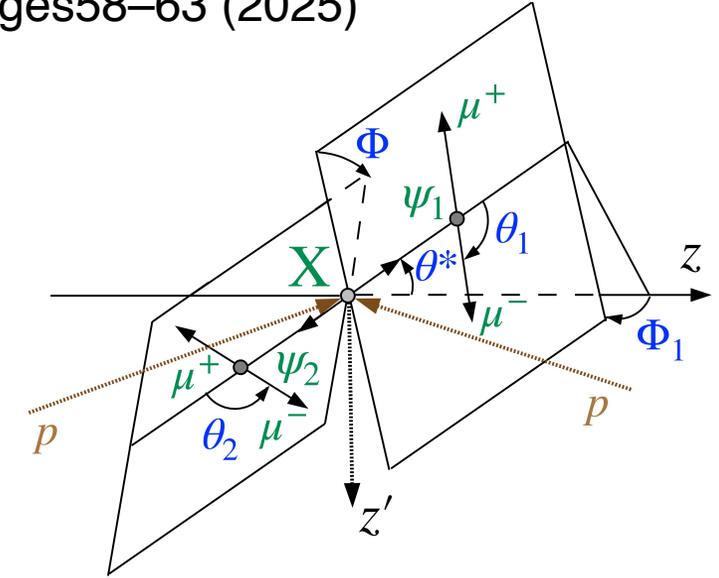


Concept of Analysis: All Input

Nature volume 648, pages58–63 (2025)

□ Framework

- $m_{4\mu}$ spectrum $X \rightarrow 4\mu$ – identical to [Phys. Rev. Lett. 132 \(2024\) 111901](#)
- p_T and p_Z of $X \rightarrow 4\mu$ – match MC to data
- Polarization of X – assume unpolarized



■ Production angles [for data test]

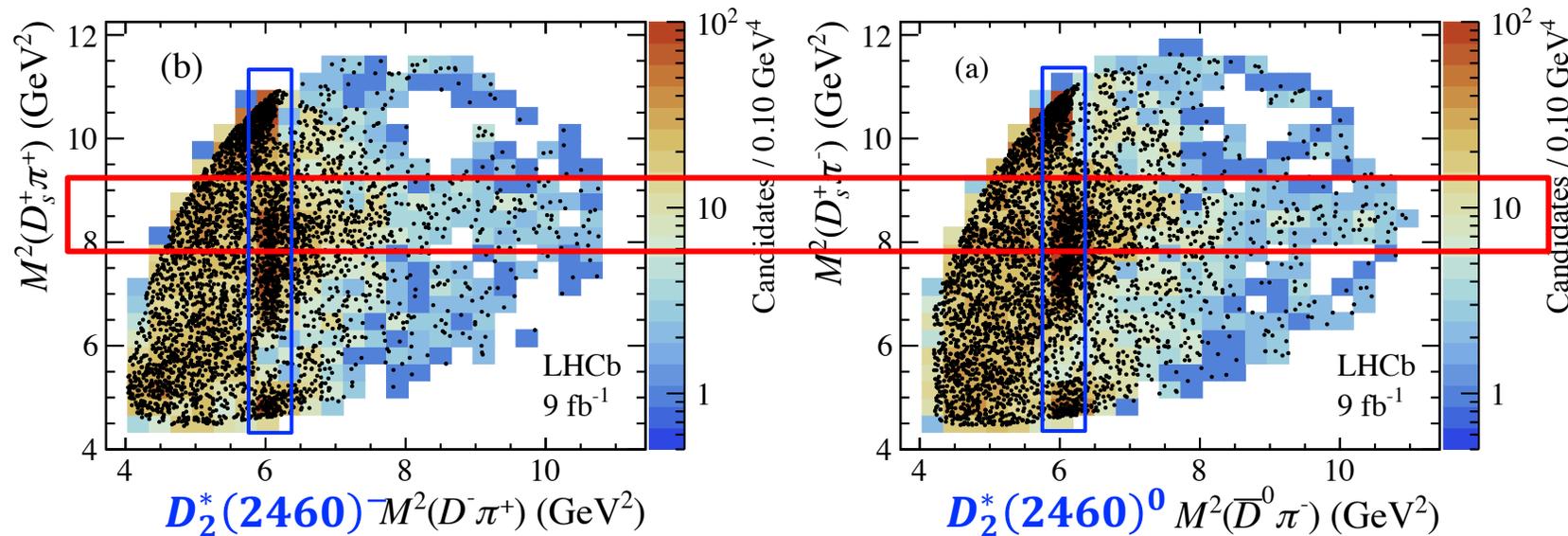
- ϑ^* : angle between beam line and J/ψ momentum in X rest frame
- Φ_1 : azimuthal angle between production plane and decay plane in X rest frame

■ Decay angles [for data analysis]

- Φ : azimuthal angle between two l^+l^- decay planes defined in X rest frame
- ϑ_1 : helicity angle between opposite of J/ψ_2 momentum and l momentum defined in J/ψ_1 rest frame
- ϑ_2 : helicity angle between opposite of J/ψ_1 momentum and l momentum defined in J/ψ_2 rest frame

Study of $B^0 \rightarrow \bar{D}^0 D_s^+ \pi^-$ and $B^+ \rightarrow D^- D_s^+ \pi^+$

- Full 9 fb^{-1} Run1+Run2 LHCb data
 $\Rightarrow 4420 B^0 \rightarrow \bar{D}^0 D_s^+ \pi^-$ and
 $3940 B^+ \rightarrow D^- D_s^+ \pi^+$ candidates

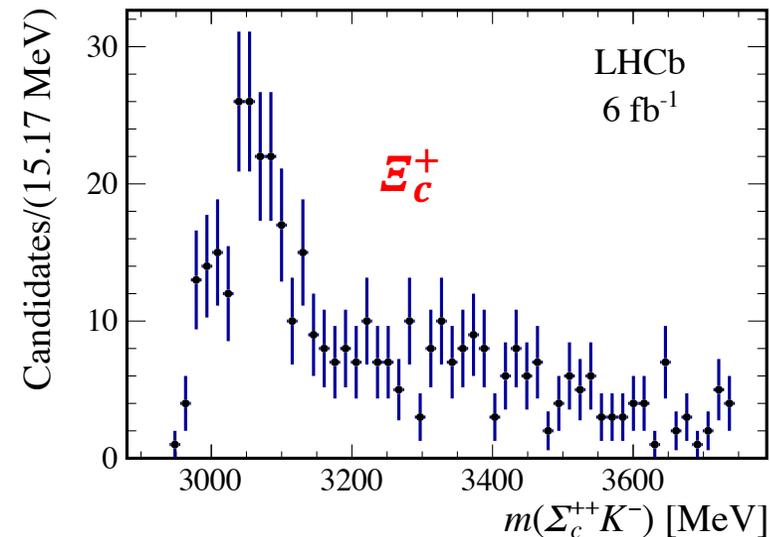
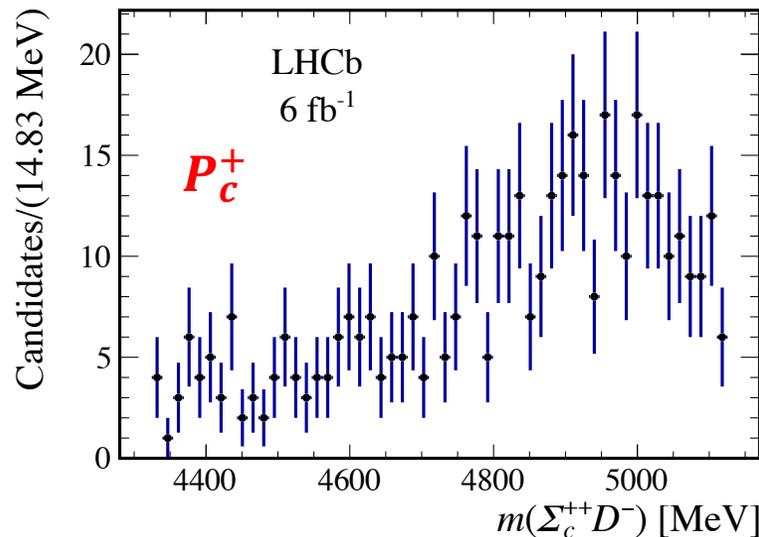
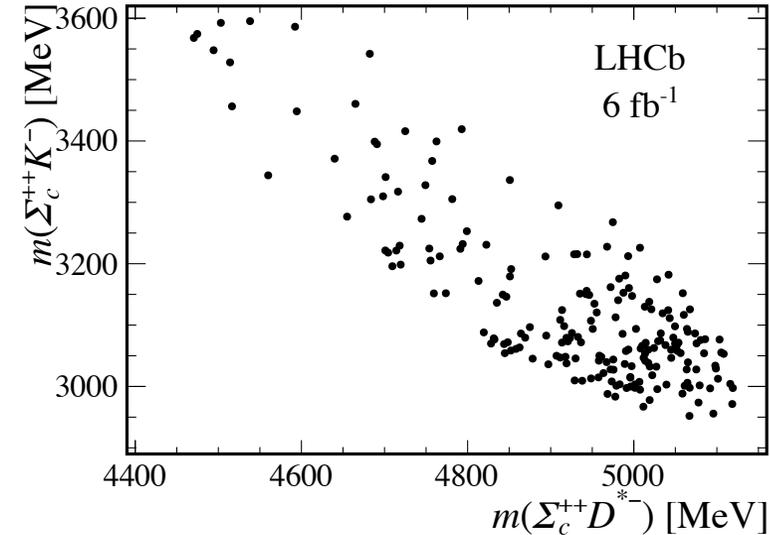
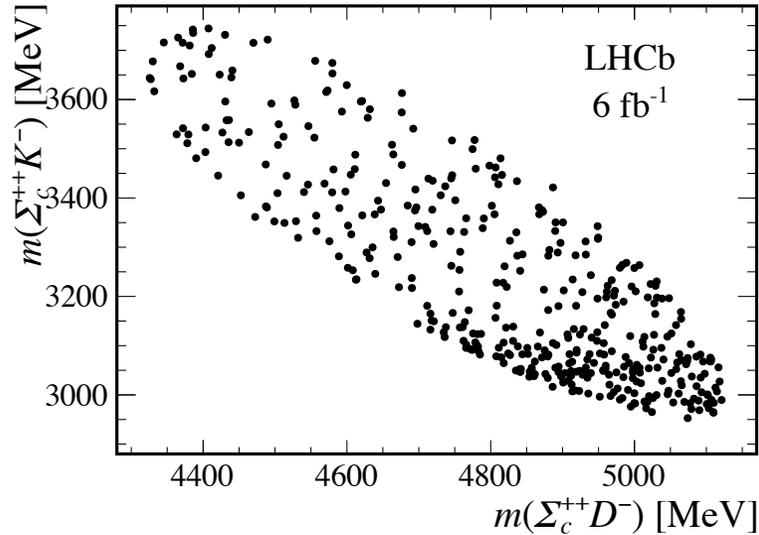


\Rightarrow Joint amplitude analysis where amplitudes of the two decays are related through isospin symmetry

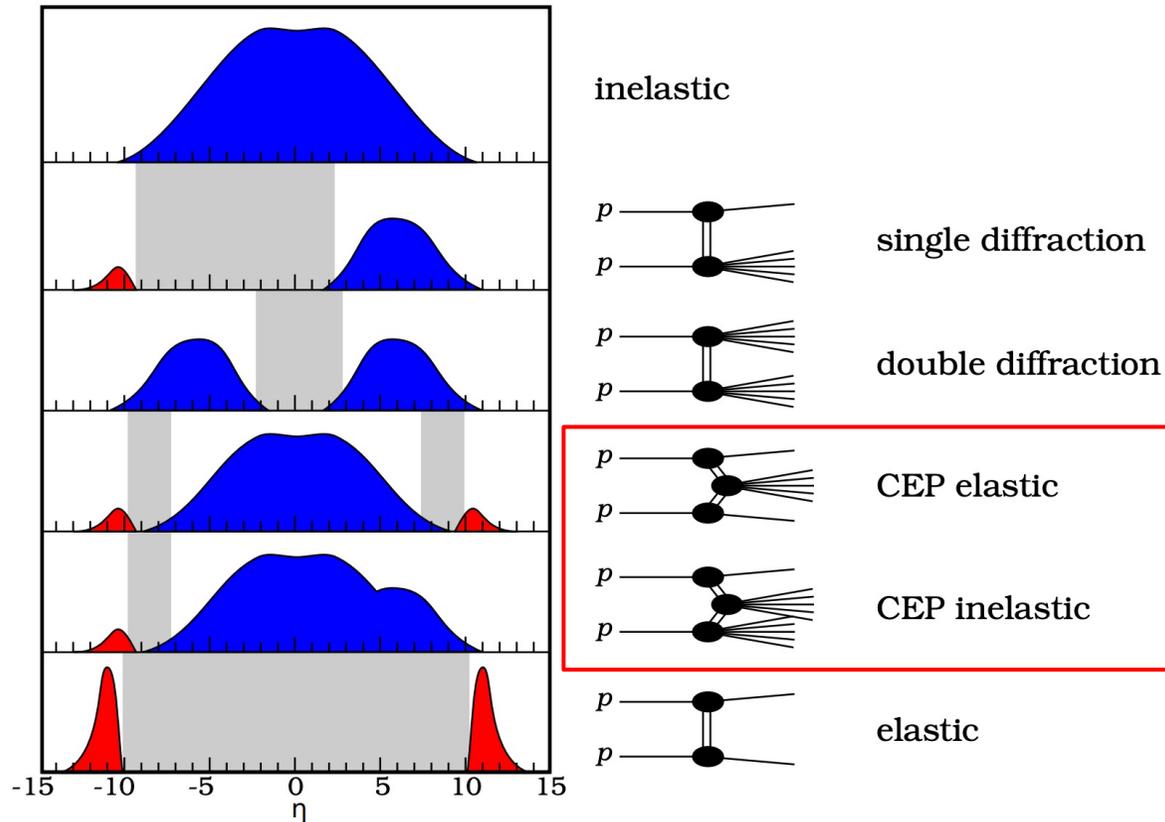
$\Lambda_b^0 \rightarrow \Sigma_c^{(*)++} D^{(*)-} K^-$: intermediate states

[PRD 110 (2024) L031104]

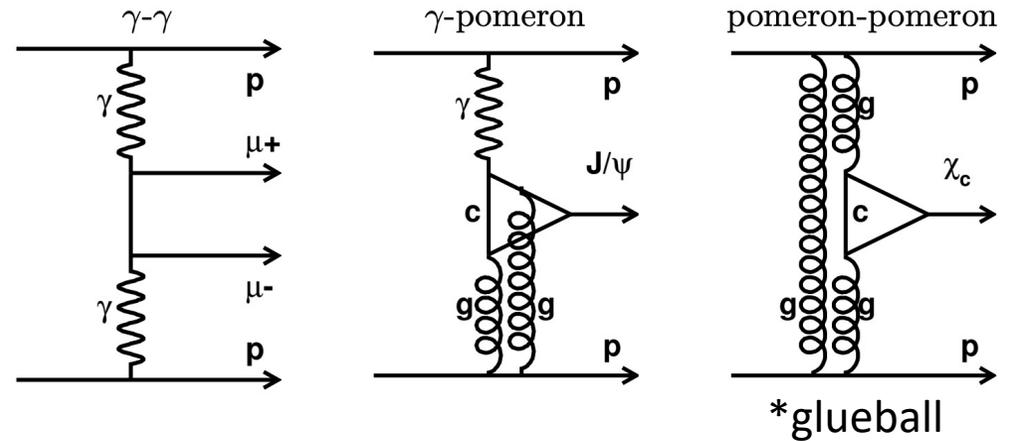
- Larger dataset needed to draw a definitive conclusion



Central exclusive production (CEP)

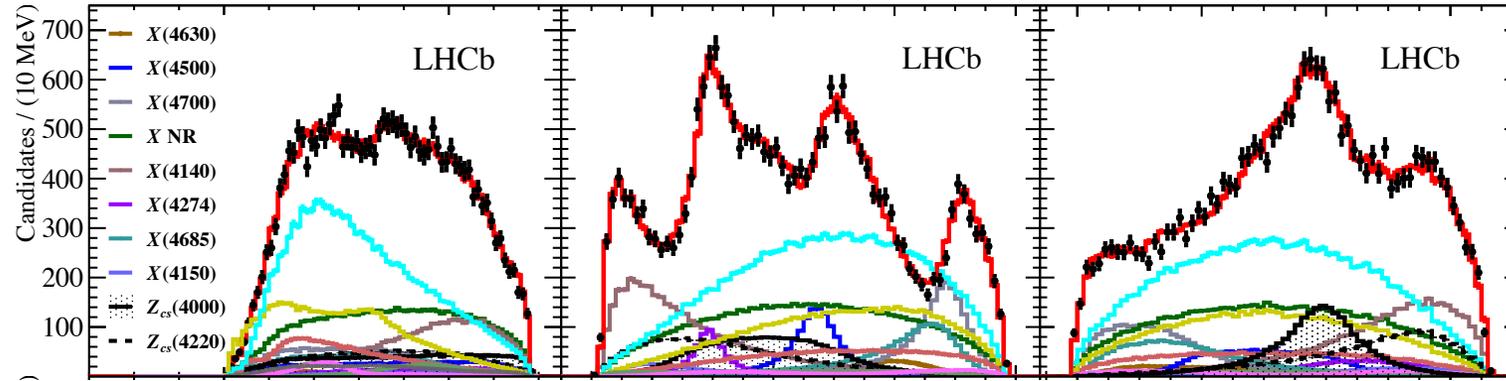


- ✓ Experimentally clean even @LHC
- ✓ Spin-parity option narrowed down
- ✗ Much smaller rate



X in $B^+ \rightarrow J/\psi\phi K^+$

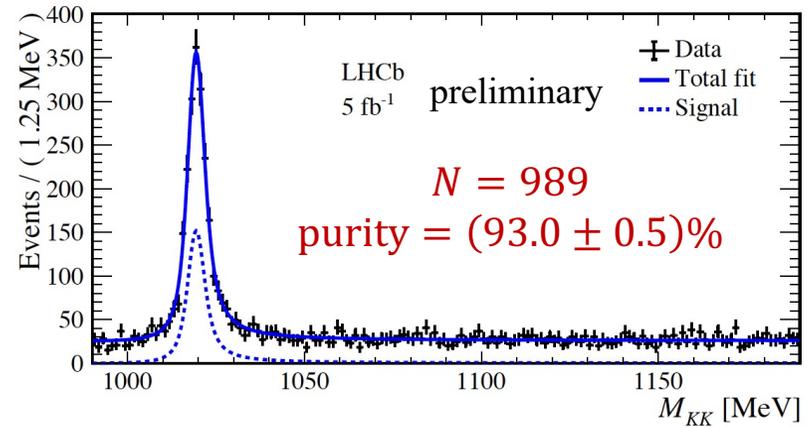
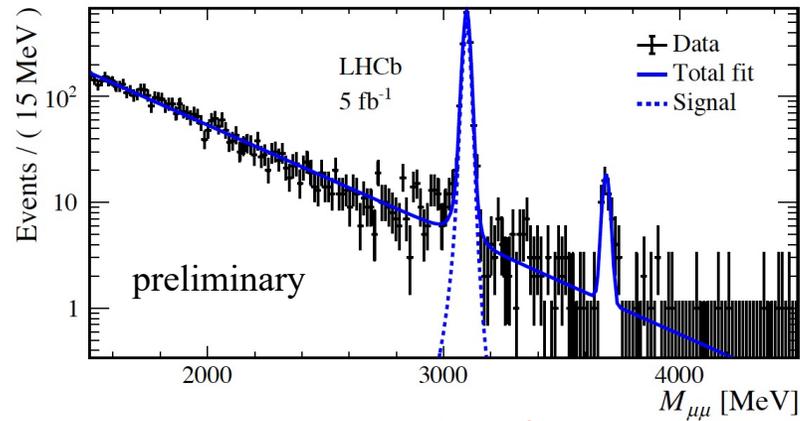
[PRL 127 (2021) 082001]



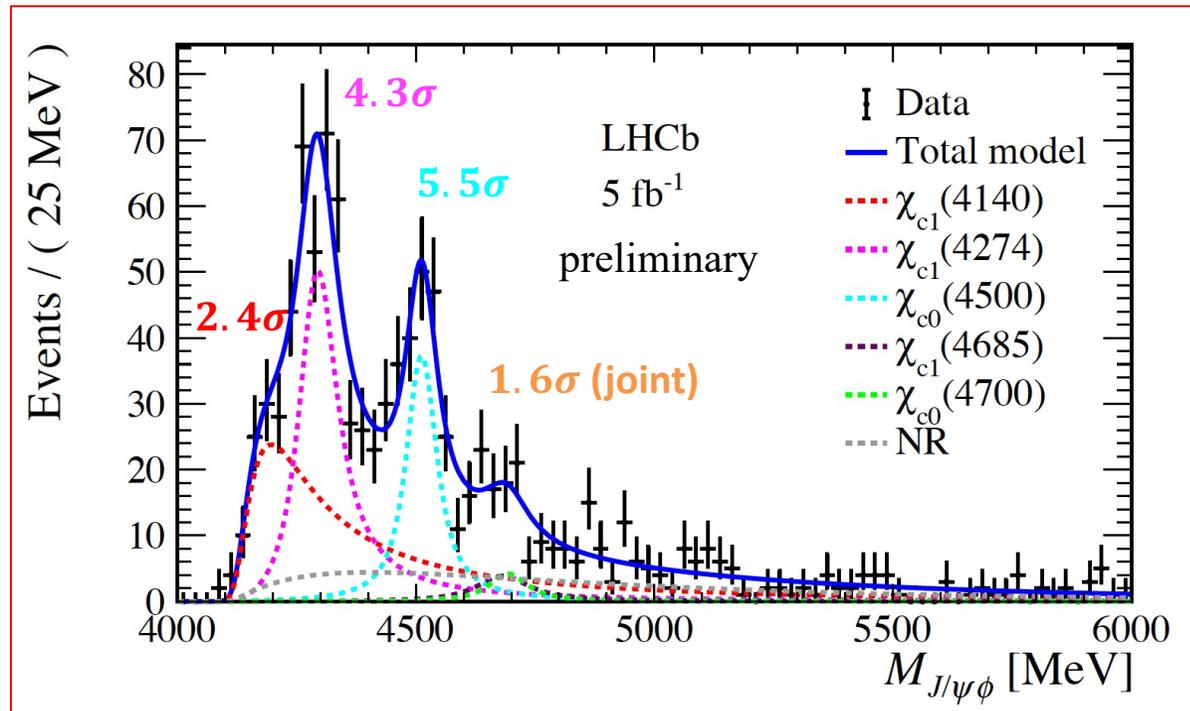
$X(2^-)$				
$X(4150)$	4.8 (8.7)	$4146 \pm 18 \pm 33$	$135 \pm 28^{+59}_{-30}$	$2.0 \pm 0.5^{+0.8}_{-1.0}$
$X(1^-)$				
$X(4630)$	5.5 (5.7)	$4626 \pm 16^{+18}_{-110}$	$174 \pm 27^{+134}_{-73}$	$2.6 \pm 0.5^{+2.9}_{-1.5}$
All $X(0^+)$				$20 \pm 5^{+14}_{-7}$
$X(4500)$	20 (20)	$4474 \pm 3 \pm 3$	$77 \pm 6^{+10}_{-8}$	$5.6 \pm 0.7^{+2.4}_{-0.6}$
$X(4700)$	17 (18)	$4694 \pm 4^{+16}_{-3}$	$87 \pm 8^{+16}_{-6}$	$8.9 \pm 1.2^{+4.9}_{-1.4}$
$\text{NR}_{J/\psi\phi}$	4.8 (5.7)			$28 \pm 8^{+19}_{-11}$
All $X(1^+)$				$26 \pm 3^{+8}_{-10}$
$X(4140)$	13 (16)	$4118 \pm 11^{+19}_{-36}$	$162 \pm 21^{+24}_{-49}$	$17 \pm 3^{+19}_{-6}$
$X(4274)$	18 (18)	$4294 \pm 4^{+3}_{-6}$	$53 \pm 5 \pm 5$	$2.8 \pm 0.5^{+0.8}_{-0.4}$
$X(4685)$	15 (15)	$4684 \pm 7^{+13}_{-16}$	$126 \pm 15^{+37}_{-41}$	$7.2 \pm 1.0^{+4.0}_{-2.0}$
All $Z_{cs}(1^+)$				$25 \pm 5^{+11}_{-12}$
$Z_{cs}(4000)$	15 (16)	$4003 \pm 6^{+4}_{-14}$	$131 \pm 15 \pm 26$	$9.4 \pm 2.1 \pm 3.4$
$Z_{cs}(4220)$	5.9 (8.4)	$4216 \pm 24^{+43}_{-30}$	$233 \pm 52^{+97}_{-73}$	$10 \pm 4^{+10}_{-7}$

$X \rightarrow J/\psi\phi$ in CEP

[LHCb-PAPER-2023-043]
in preparation

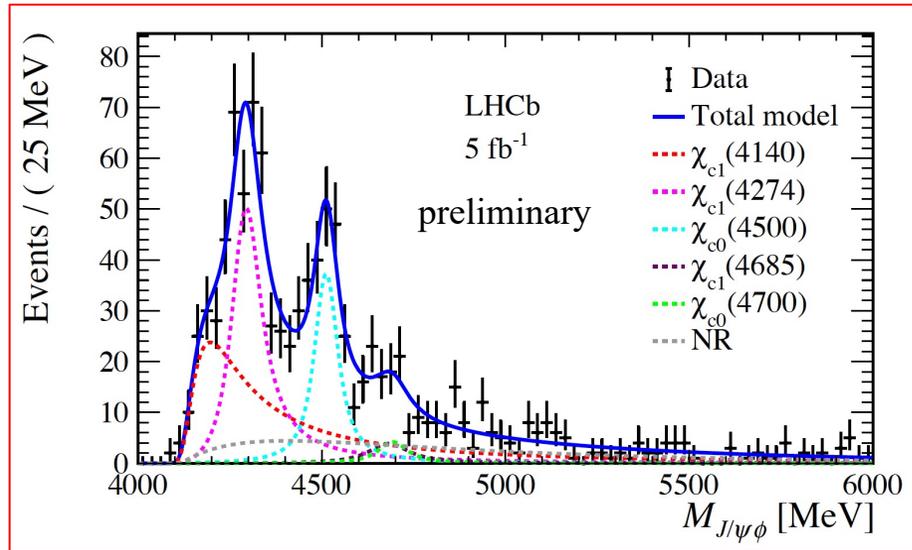


4 tracks



First exotic hadron measurement in CEP!

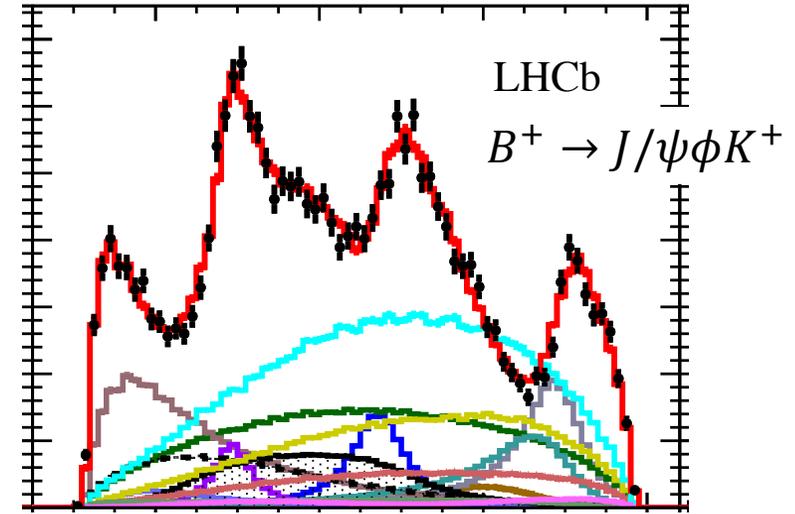
[LHCb-PAPER-2023-043] in preparation



- Mass & width measurements: slightly higher mass of $X(4500)$

Parameter (MeV)	This Letter	Ref. [12]
$M_{\chi_{c1}(4274)}$	$4298 \pm 6 \pm 9$	$4294 \pm 4^{+3}_{-6}$
$\Gamma_{\chi_{c1}(4274)}$	$92^{+22}_{-18} \pm 57$	$53 \pm 5 \pm 5$
$M_{\chi_{c0}(4500)}$	$4512.5^{+6.0}_{-6.2} \pm 3.0$	$4474 \pm 3 \pm 3$
$\Gamma_{\chi_{c0}(4500)}$	$65^{+20}_{-16} \pm 32$	$77 \pm 6^{+10}_{-8}$

[PRL 127 (2021) 082001]



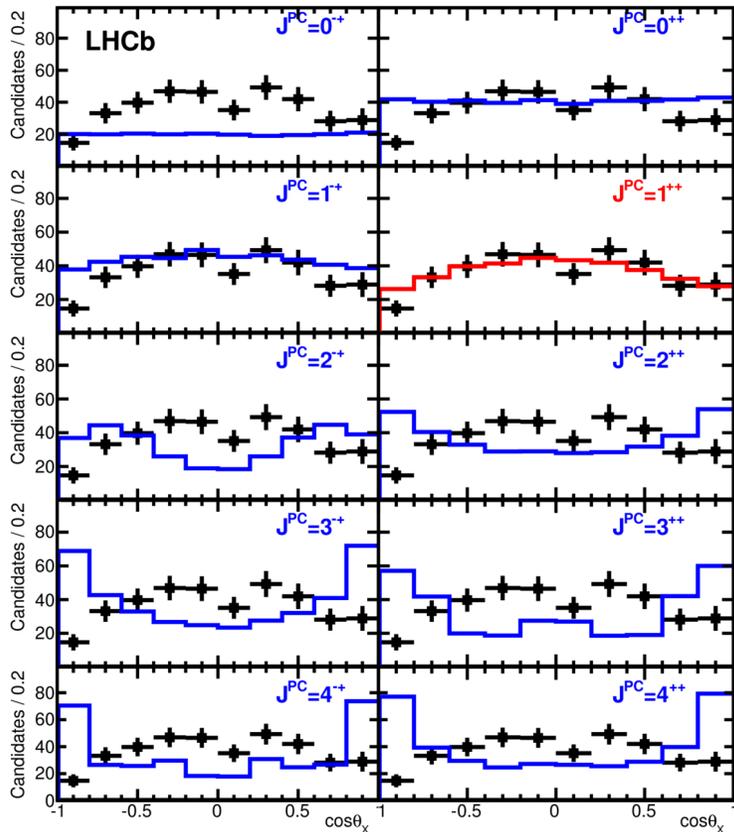
- Cross-section measurements:

$$\begin{aligned} \sigma_{\chi_{c1}(4140)} \times \mathcal{B}_{\text{eff}}^{\chi_{c1}(4140)} &= (0.85 \pm 0.16 \pm 0.30) \text{ pb}, \\ \sigma_{\chi_{c1}(4274)} \times \mathcal{B}_{\text{eff}}^{\chi_{c1}(4274)} &= (0.77^{+0.14}_{-0.13} \pm 0.18) \text{ pb}, \\ \sigma_{\chi_{c0}(4500)} \times \mathcal{B}_{\text{eff}}^{\chi_{c0}(4500)} &= (0.44^{+0.09}_{-0.08} \pm 0.07) \text{ pb}, \\ \sigma_{\chi_{c1}(4685)+\chi_{c0}(4700)} \times \mathcal{B}_{\text{eff}}^{\chi_{c1}(4685)+\chi_{c0}(4700)} &= (0.14^{+0.07}_{-0.06} \pm 0.06) \text{ pb}, \\ \sigma_{NR} \times \mathcal{B}_{\text{eff}}^{NR} &= (0.46^{+0.25}_{-0.19} \pm 0.21) \text{ pb}, \end{aligned}$$

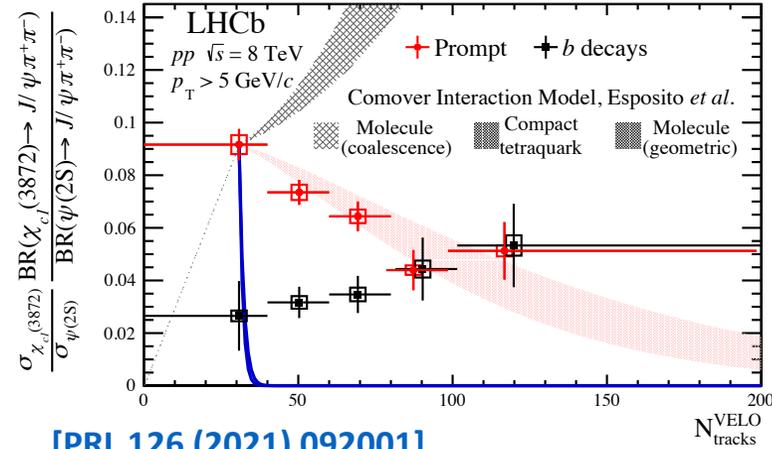
Study of $\chi_{c1}(3872)/X(3872)$

✓ $J^{PC}=1^{++}$

[PRD 92 (2015) 011102 (R)]

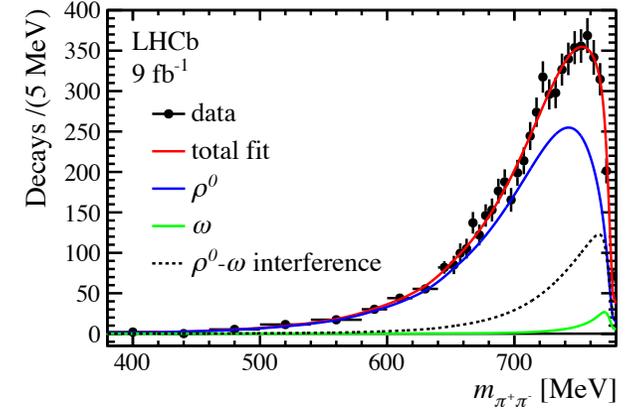


✓ production



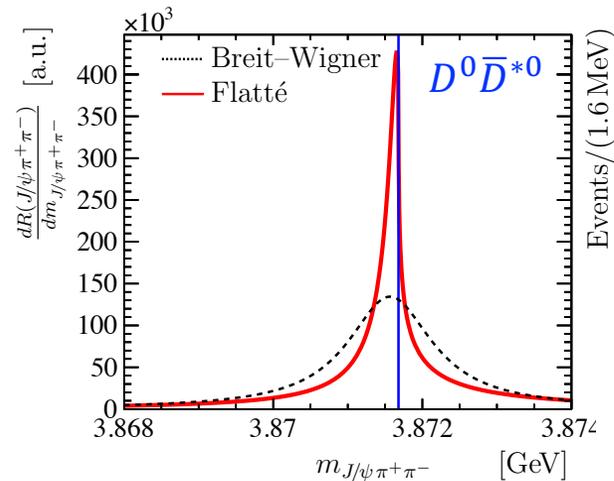
[PRL 126 (2021) 092001]

✓ decay

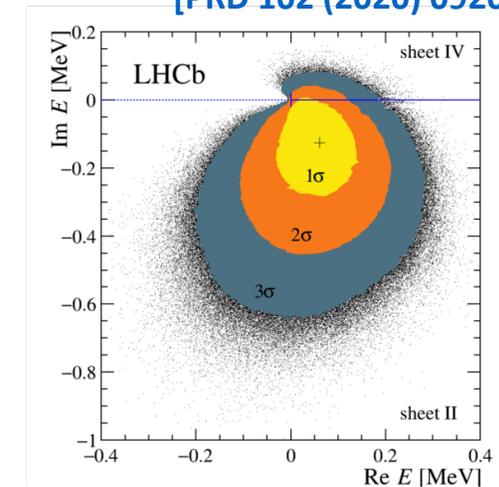


[PRD 131 (2023) L011103]

✓ lineshape

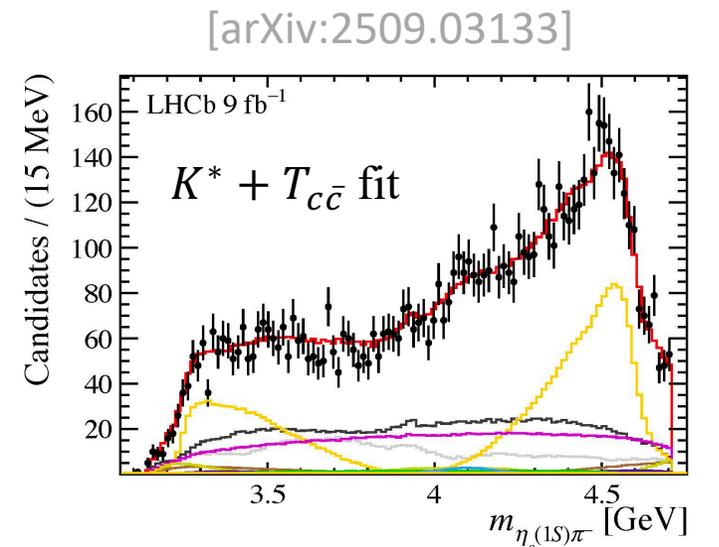
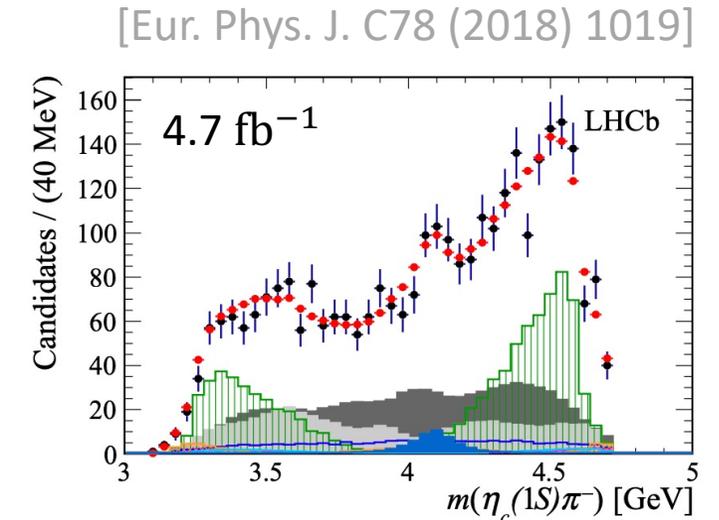


[PRD 102 (2020) 092005]



Amplitude analysis of $B^0 \rightarrow \eta_c K^+ \pi^-$

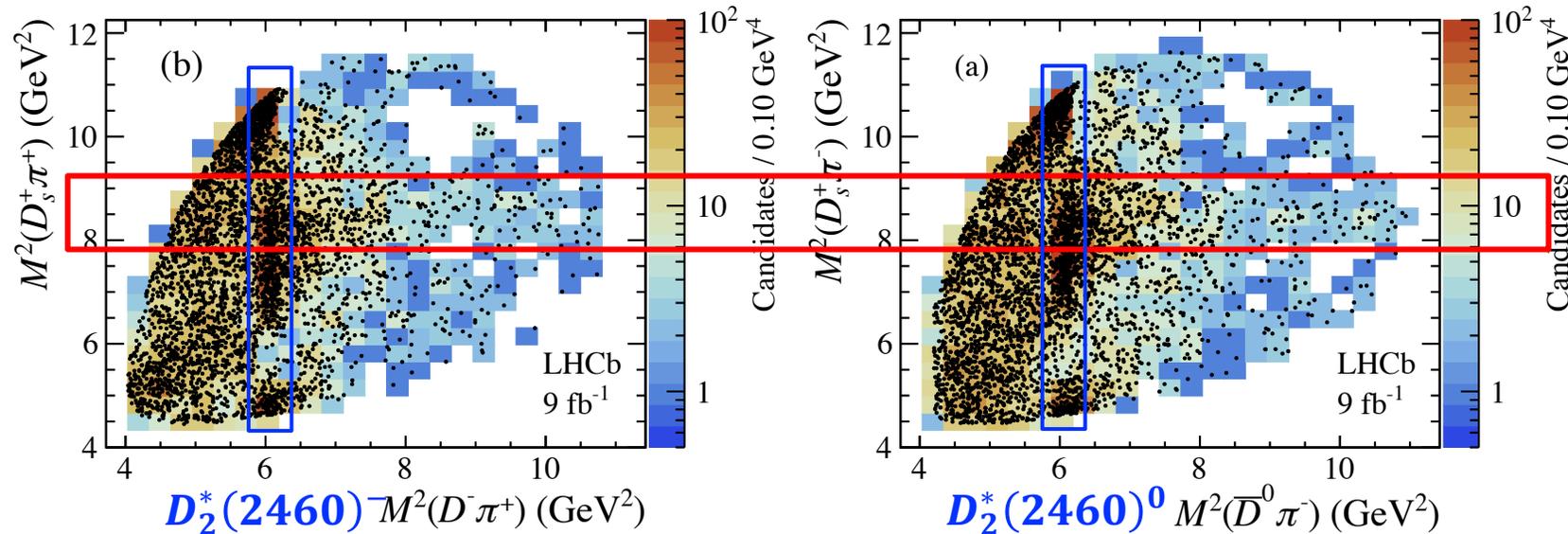
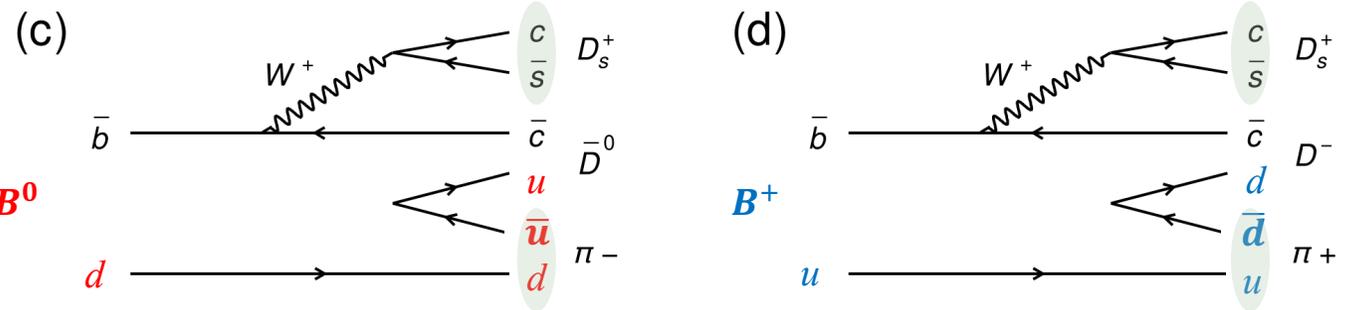
- An evidence of $T_{c\bar{c}}(4100)^- \rightarrow \eta_c \pi^-$ was reported by LHCb with 4.7 fb^{-1} data (3.4σ)
- Update with full 9 fb^{-1} data
- 5000 signal yields (~ 2.5 of previous publication)
- Amplitude results:
 - 3.6σ (2.5σ) significance without (with) systematic uncertainties
 - $J^P = 0^+$ disfavoured by 3.2σ compared to 1^- (stat. only)
 - $m(T_{c\bar{c}}) = 4106 \pm 23 \text{ MeV}$
 - $\Gamma(T_{c\bar{c}}) = 514 \pm 166 \text{ MeV}$
- **$T_{c\bar{c}}(4100)^-$ is not confirmed**



Study of $B^0 \rightarrow \bar{D}^0 D_s^+ \pi^-$ and $B^+ \rightarrow D^- D_s^+ \pi^+$

- Full 9 fb^{-1} Run1+Run2 LHCb data
 $\Rightarrow 4420 B^0 \rightarrow \bar{D}^0 D_s^+ \pi^-$ and
 $3940 B^+ \rightarrow D^- D_s^+ \pi^+$ candidates

[PRL 131 (2023) 041902]



\Rightarrow Joint amplitude analysis where amplitudes of the two decays are related through isospin symmetry

Summary and prospects

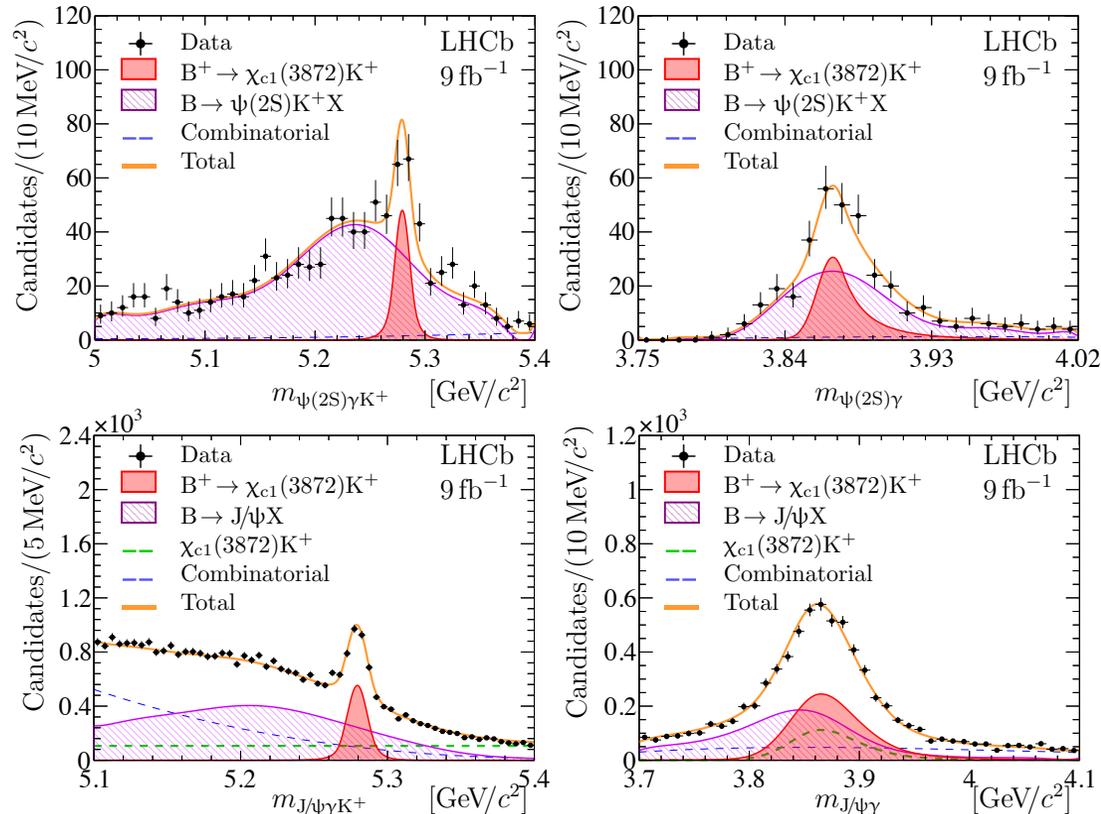
- LHCb keeps making important contributions to heavy hadron spectroscopy, both for conventional or exotic hadrons
- In Run 3, the upgraded LHCb detector and an improved software-only trigger system will be implemented



More exciting results are to come!
More data, more chances & challenges!

Radiative decays of $\chi_{c1}(3872)$

- Nature of $\chi_{c1}(3872)$ still under debate, while study of radiative decays provides a way to probe it
- $\chi_{c1}(3872) \rightarrow \psi(2S)\gamma$ observed for the first time using $B^+ \rightarrow \chi_{c1}(3872)K^+$ decay with 9 fb^{-1} data

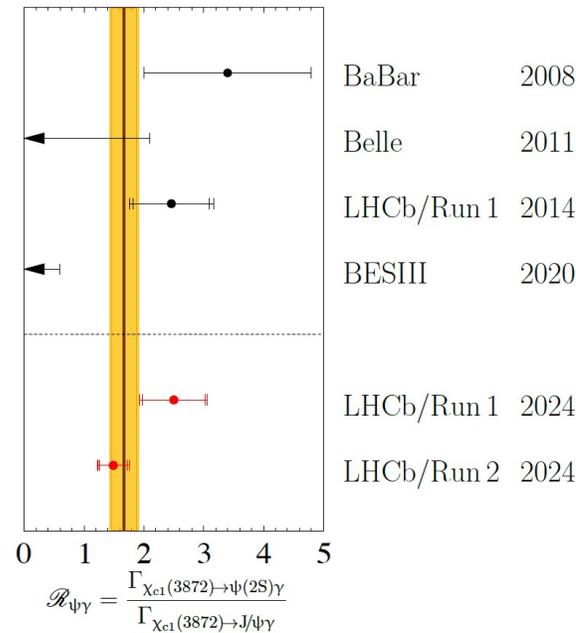


Run1: $N = 40 \pm 8; 5.3\sigma$

Run2: $N = 63 \pm 10; 6.7\sigma$

$$\mathcal{R}_{\psi\gamma} \equiv \frac{\Gamma_{\chi_{c1}(3872) \rightarrow \psi(2S)\gamma}}{\Gamma_{\chi_{c1}(3872) \rightarrow J/\psi\gamma}}$$

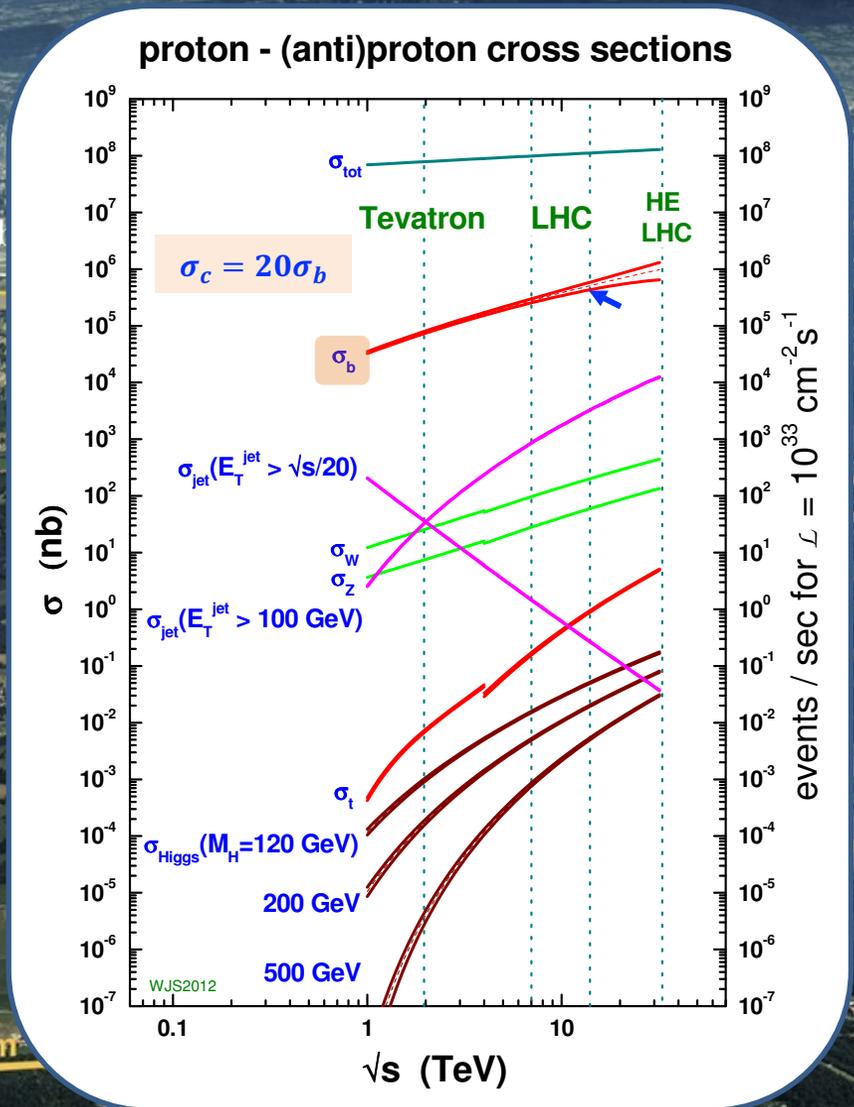
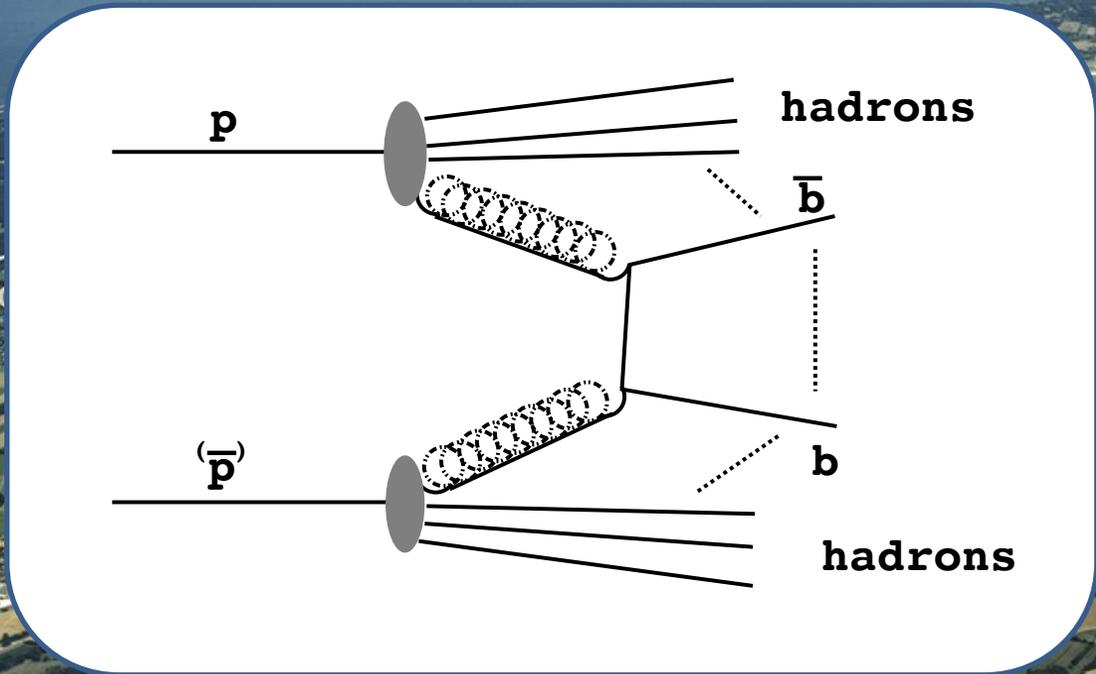
$$\mathcal{R}_{\psi\gamma} = 1.67 \pm 0.21 \pm 0.12 \pm 0.04$$



[arXiv: 2502.04458]

✓ Possible explanation:
different contributions
from W_{c1} , isovector
partner of $\chi_{c1}(3872)$,
in B^+ decays and e^+e^-
annihilations?
→ pp collisions?

The LHC as a Beauty and Charm factory



LHC 27 km

T_{cc}^+ ($cc\bar{u}\bar{d}$)

Nature Comm. 13 (2022) 3351

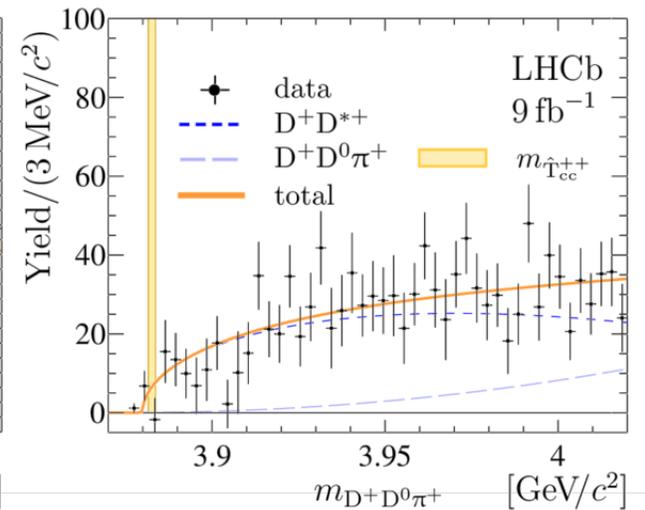
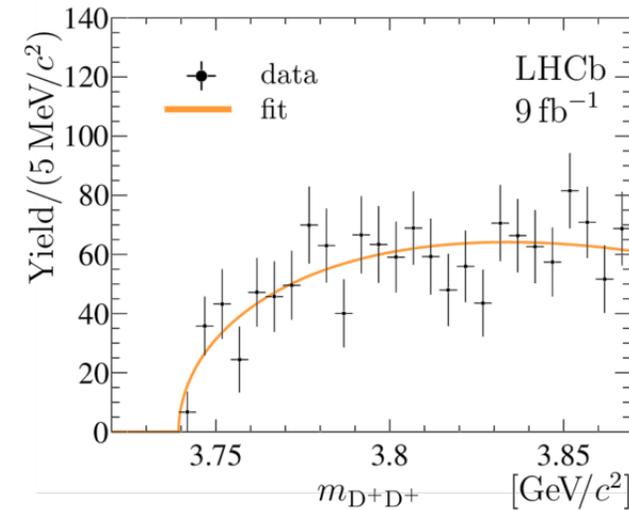
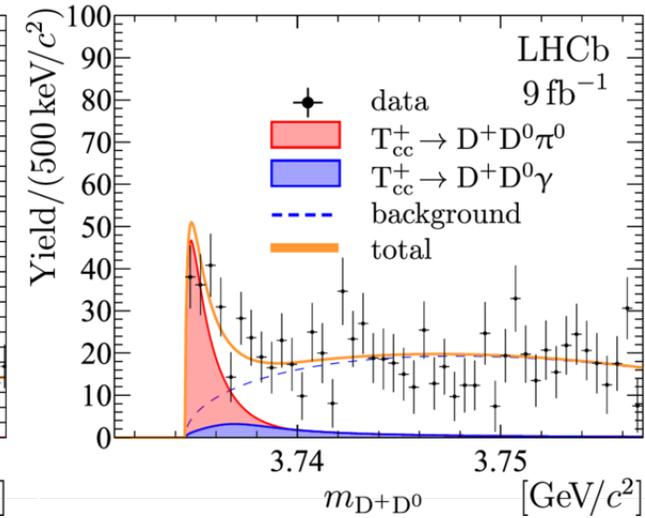
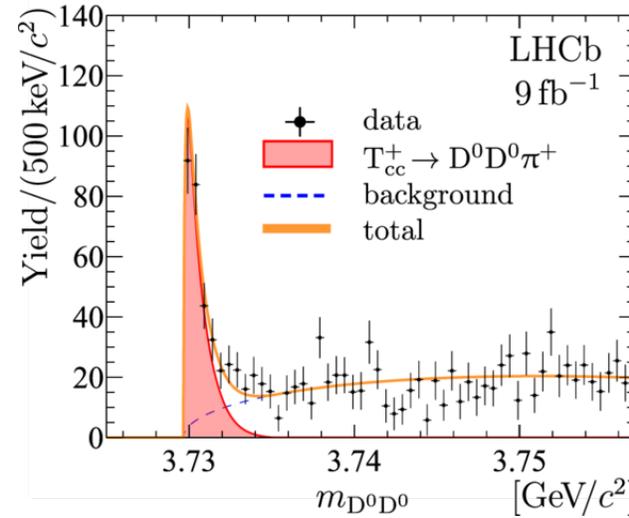
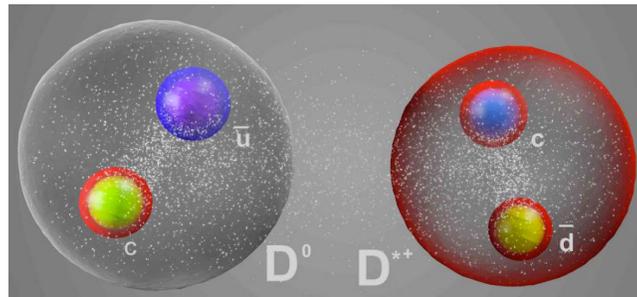
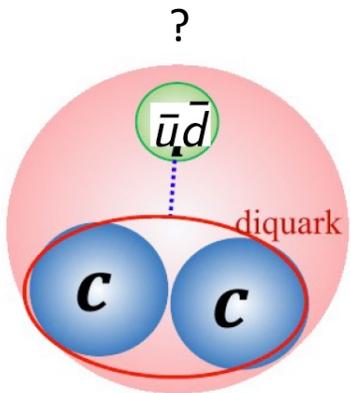
Nature Physics 18 (2022) 751

□ Consist with $J^P = 1^+$ isoscalar

□ Contribute to D^0D^0 and D^0D^+ (π/γ is missing)

□ No peaks in $D^+D^0\pi^+$ and D^+D^+
 $\Rightarrow T_{cc}^{++}$ not found

\Rightarrow Support that T_{cc}^+ is an isoscalar



Answer: To find the predicted deep-bounded $bb\bar{u}\bar{d}$?

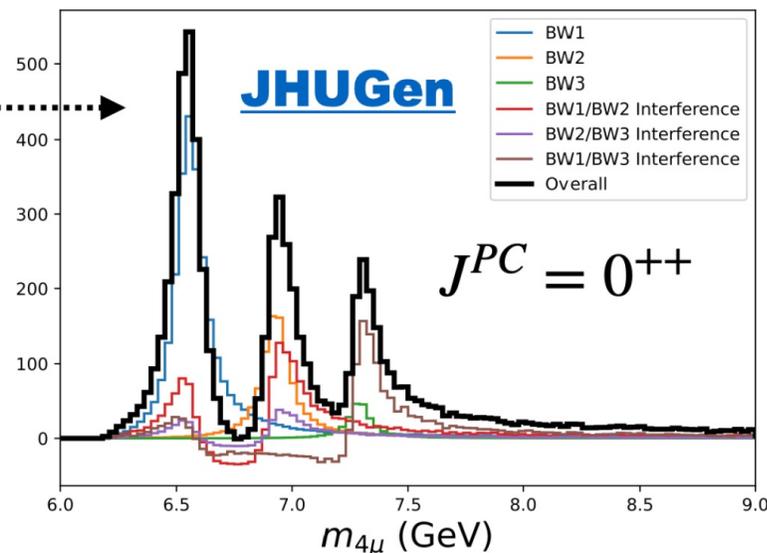
Simplification in Angular Analysis

- Full model possible, but very complex

$$\mathcal{P}(\Phi, \theta_1, \theta_2; m_{4\mu})$$

- (1) Same properties of **3 resonances**:

$$\mathcal{P}(m_{4\mu}, \vec{\Omega}) = \underbrace{\mathcal{P}(m_{4\mu})}_{\text{empirical}} \cdot \underbrace{T(\vec{\Omega} | m_{4\mu})}_{\text{angular}}$$



- (2) Pairwise tests of J_X^P hypotheses i and j :

[arXiv:1208.4018](https://arxiv.org/abs/1208.4018)

$$\text{MELA } \mathcal{D}_{ij}(\vec{\Omega} | m_{4\mu}) = \frac{\mathcal{P}_i(\vec{\Omega} | m_{4\mu})}{\mathcal{P}_i(\vec{\Omega} | m_{4\mu}) + \mathcal{P}_j(\vec{\Omega} | m_{4\mu})}$$

1 optimal observable

- Final 2D model: $\mathcal{P}_{ijk}(m_{4\mu}, \mathcal{D}_{ij}) = \mathcal{P}_k(m_{4\mu}) \cdot T_{ijk}(\mathcal{D}_{ij} | m_{4\mu})$

J/ψ polarizations

- Symmetries:

- angular momentum: $|\lambda_1 - \lambda_2| \leq J$

- identical J/ψ bosons $A_{\lambda_1\lambda_2} = (-1)^J A_{\lambda_2\lambda_1}$

- P & C conserved in QCD:

X with definite J^{PC}

$C = +1$

$A_{\lambda_1\lambda_2} = P(-1)^J A_{-\lambda_1-\lambda_2}$

Test 8+ J_X^P models:

0^{-+}	0^-	$A_{++} = -A_{--}$	
0^{++}	0_m^+ and 0_h^+	$A_{++} = A_{--}$ and A_{00}	← note 2 d.o.f.
1^{-+}	1^-	$A_{+0} = -A_{0+} = A_{-0} = -A_{0-}$	
1^{++}	1^+	$A_{+0} = -A_{0+} = -A_{-0} = A_{0-}$	
2^{-+}	2_m^- and 2_h^-	$A_{++} = -A_{--}$ and $A_{+0} = A_{0+} = -A_{-0} = -A_{0-}$	← note 2 d.o.f.
2^{++}	2_m^+	$A_{++} = A_{--}, A_{00}, A_{+0} = A_{0+} = A_{-0} = A_{0-},$ and $A_{+-} = A_{-+}$	

note 4 d.o.f. for 2^{++} , test one model

