New discoveries of the exotic states at LHCb

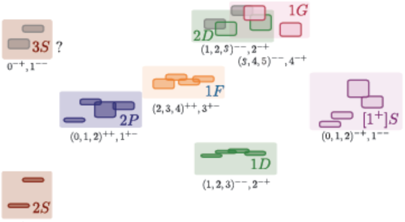
Misha Mikhasenko
on behalf of LHCb

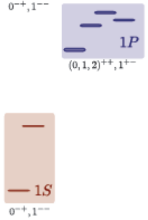
ORIGINS Excellence Cluster

September 6$^{\text{nd}}$, 2022
QNP2022

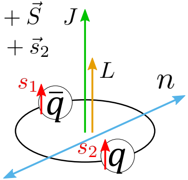
Two ways of building complexity

Hadron variety

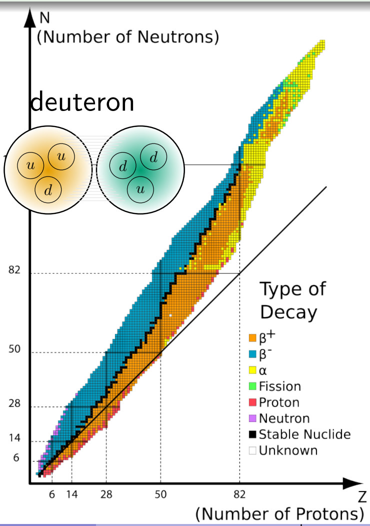




$$\vec{J} = \vec{L} + \vec{S}$$
$$\vec{S} = \vec{s}_1 + \vec{s}_2$$

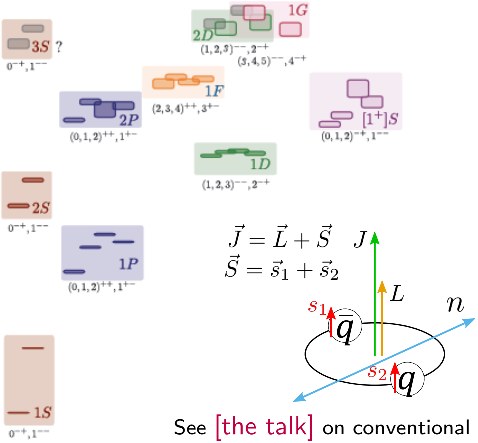


Atomic variety



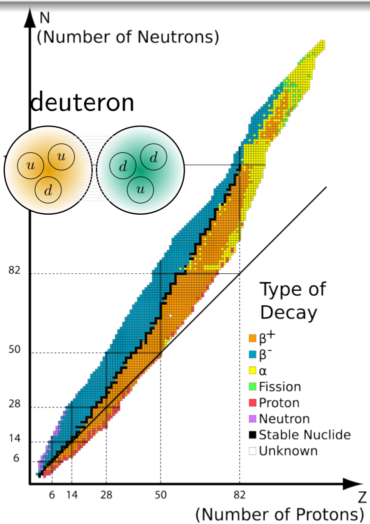
Two ways of building complexity

Hadron variety

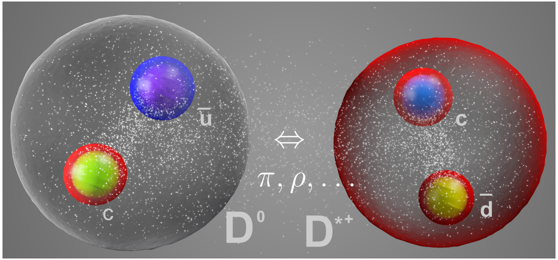


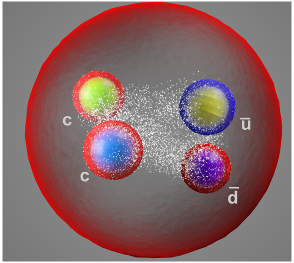
See [the talk] on conventional states at LHCb by Aleksei Dzyuba on Thursday

Atomic variety



Example: innerworking of T_{cc}^+





Molecular configuration:

- two mesons are well separated,
- bound by forces similarly to el.mag. van der Waals,
- entirely coupled to $D^{*+}D^0$,
- lifetime is limited by D^{*+},
- ? spatially-extended object.

Compact configuration:

- genuine QCD state,
- compact (cc) core,
- there is no limit on lifetime, depends on how much it couples to continuum,
- ? typical hadronic size of 1 fm.

Summary of Pentaquarks studies

(*) will be discussed today

$$\boxed{X_b \to (J/\psi p)\ldots}$$

$$\Lambda_b^0 \to (J/\psi p)K^- \quad (*)$$
$$\Lambda_b^0 \to (J/\psi p)\pi^-$$
$$B_s^0 \to (J/\psi p)\bar{p}$$

Thresholds: $\Sigma_c^{(*)+}\overline{D}^{(*)0}$ / $\Sigma_c^{(*)++}D^{(*)-}$

$$P_\psi^N:$$

$$\boxed{X_b \to (J/\psi \Lambda)\ldots}$$

$$\Xi_b^- \to (J/\psi\Lambda)K^- \quad (*)$$
$$B^- \to (J/\psi\Lambda)\bar{p} \quad (*)$$

Thresholds: $\Xi_c^{(*)0}\overline{D}^{(*)0}$ / $\Xi_c^{(*)+}D^{(*)-}$

$$P_{\psi s}^\Lambda:$$

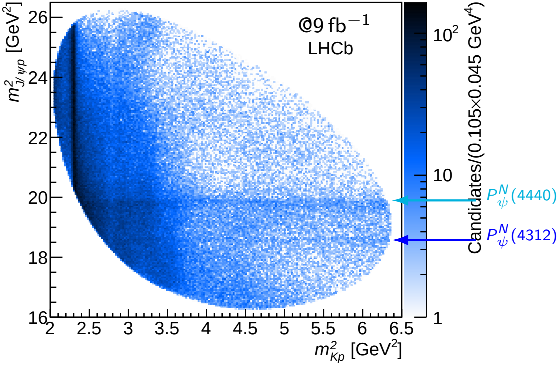
LHCb proposal for the new name convention of exotic hadrons [arXiv:2206.15233]

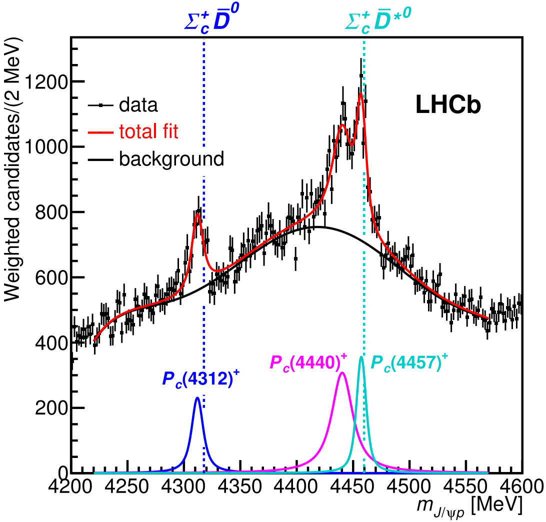
$$\Lambda_b^0 \to \underbrace{J/\psi p}_{P_\psi^N} K^-$$

The first pentaquarks

[PRL 115 (2015), 072001; PRL 122 (2019) 22, 222001]

- Close to the $\Sigma_c \bar{D}^{(*)}$ threshold,
- Multiplicity matches spin combination: $1/2 \otimes 1 = 1/2 \oplus 3/2$
- Narrow(!): 10, 20, and 5 MeV for Γ_{BW}





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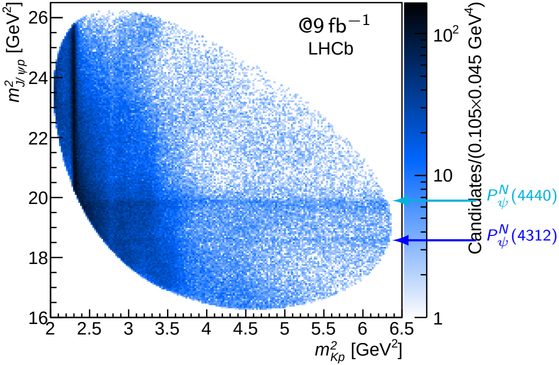
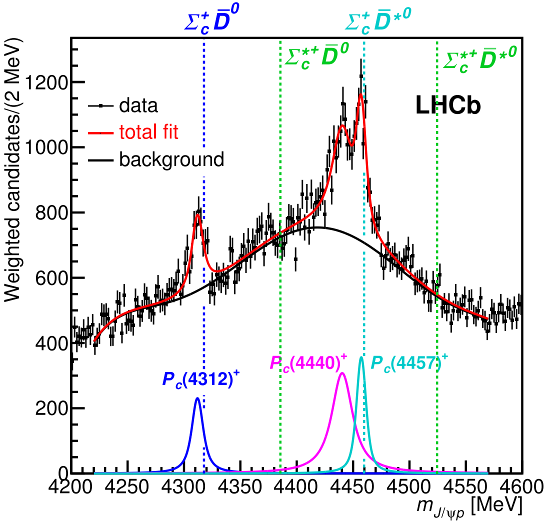


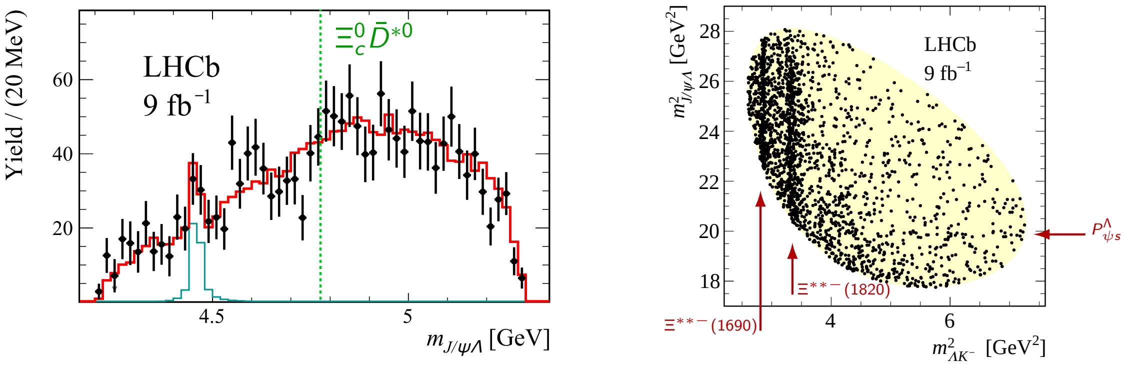


$$\Xi_b^- \to \underbrace{J/\psi \Lambda}_{P_{\psi s}^{\Lambda}} K^-$$

Hint for the strange partners

$\Xi_b^- \to J/\psi(\to \mu^+\mu^-)\Lambda(\to p\pi^-)K^-$ data sample [Sci.Bull. 66 (2021) 1278-1287]

- Full data sample 1750 signals with purity 80%.
- The decay is dominated by the Ξ resonances
- $P_{\psi s}^{\Lambda}(4459)$: $m = 4458.8 \pm 2.9^{+4.7}_{-1.1}$ MeV, $\Gamma = 17.3 \pm 6.5^{+8.0}_{-5.7}$ MeV with 4.3σ significance



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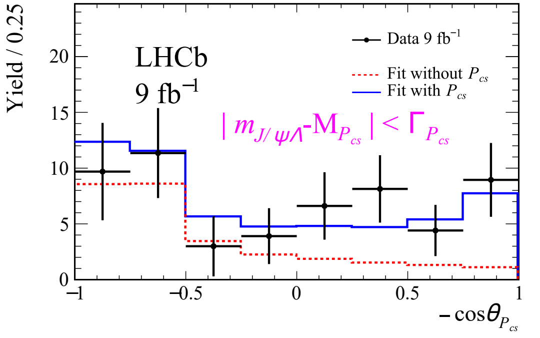
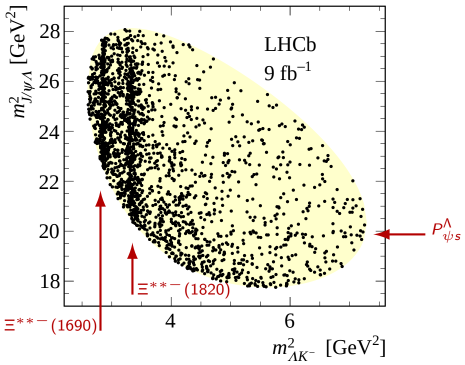


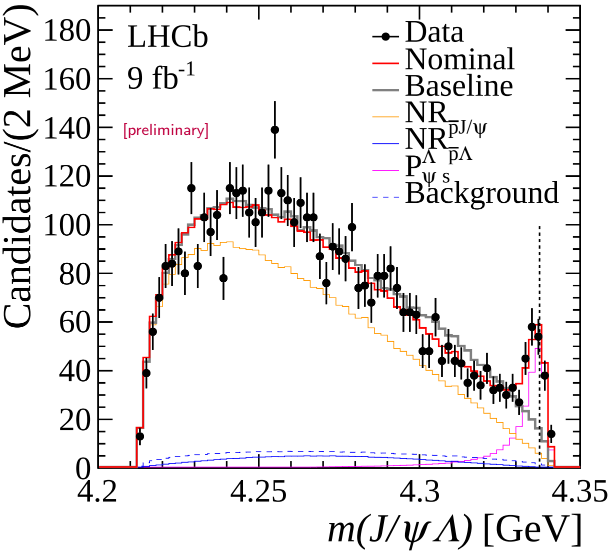


$$B^- \to \underbrace{J/\psi \Lambda}_{P_{\psi s}^{\Lambda}} \bar{p}$$

$B^- \to J/\psi(\to \mu^+\mu^-)\Lambda(\to p\pi)\bar{p}$

[LHCb-PAPER-2022-031 (in preparation)]

- Amplitudes:
  - NR($J/\psi p$), $84.0 \pm 2.2\%$
  - NR($\Lambda\bar{p}$), $11.3 \pm 1.3\%$
  - New $P^{\Lambda}_{\psi s}$, $12.5 \pm 0.7\%$,
  - with parameters
    - $m(P^{\Lambda}_{\psi s}) = 4338.2 \pm 0.7\,\mathrm{MeV}$
    - $\Gamma(P^{\Lambda}_{\psi s}) = 7.0 \pm 1.2\,\mathrm{MeV}$
- $J^P = 1/2^-$ is preferred
- BW mass is close to $\Xi_c \bar{D}$ thresholds:
  - $0.8\,\mathrm{MeV}$ above $\Xi_c^+ D^-$
  - $2.9\,\mathrm{MeV}$ above $\Xi_c^0 \overline{D}^0$



Tetraquarks candidates

(*) will be discussed today

$J/\psi\pi^+$

T_ψ^b (Z_c)

3900, 4430, ...

$J/\psi K^+$

$T_{\psi s}^\theta$ (Z_{cs})

4000, 4220

$J/\psi\phi$ (*)

X $(T_{\psi\phi})$

4140, 4274, 4500, ...

$J/\psi J/\psi$

$T_{\psi\psi}$ $(T_{cc\bar{c}\bar{c}})$

6900, ...(!)

$D^0D^0\pi^+$

T_{cc}

3874

D^+K^- (*)

T_{cs} (X)

2900

$D_s^\pm\pi^+$ (*)

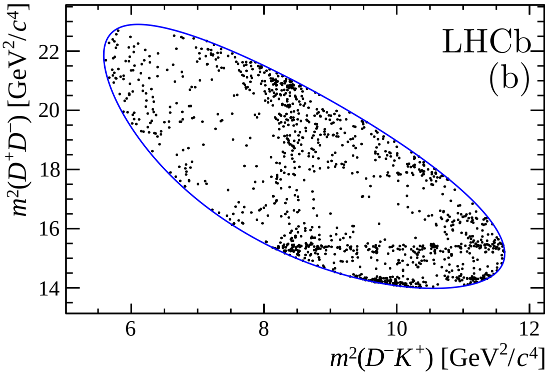
$T_{c\bar{s}}$ (X)

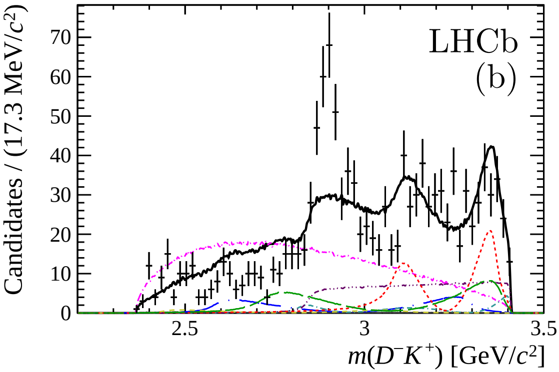
2900

$$B^+ \to D^+ \underbrace{D^- K^+}_{T_{cs}}$$

Dalitz plot for $B^+ \to D^+ D^- K^+$

[LHCb, PRD102 (2020) 112003]





- Horisontal bands are resonances in D^+D^-
- Hint for a vertical band around 8.5 GeV^2 in $m^2(D^-K^+)$
- Exotic candidate $T_{cs}(2900)$: $[\bar{c}\bar{s}ud]$
- Both quantum numbers $J^P = 0^+$ and 1^- are required in the fit

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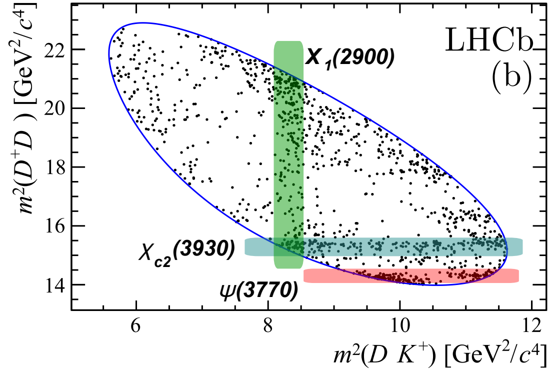

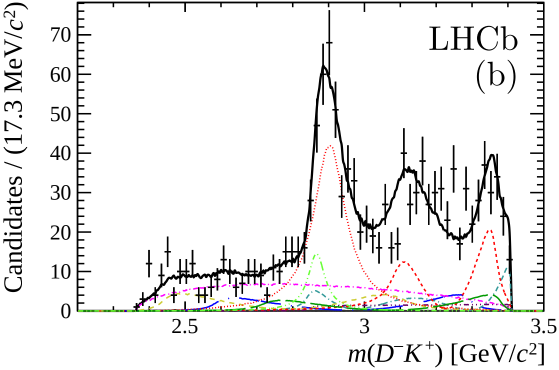

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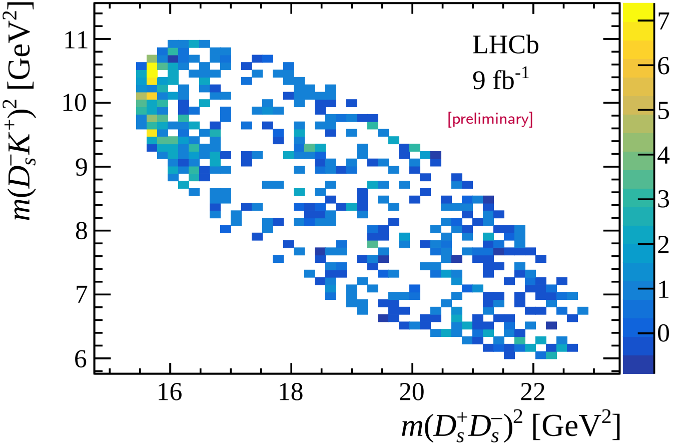
$$B^+ \to \underbrace{D_s^+ D_s^-}_{\chi_{c0}/T_{\psi\phi}} K^+$$

Threshold enhancement at $D_s^+ D_s^-$ in $B^+ \to D_s^+ D_s^- K^+$ decays

[LHCb-PAPER-2022-018, 019 (in preparation)]



- $D_s^+ \to K^+ K^- \pi^+$
- Full data set, 9 fb^{-1}
- 360 signal candidates
- Purity of 84 %

$B^+ \to D_s^+ D_s^- K^+$ amplitude analysis

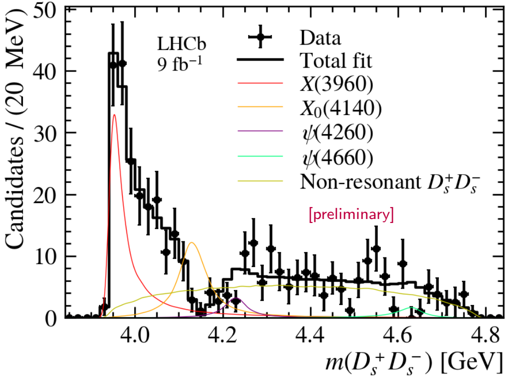
[LHCb-PAPER-2022-018, 019 (in preparation)]

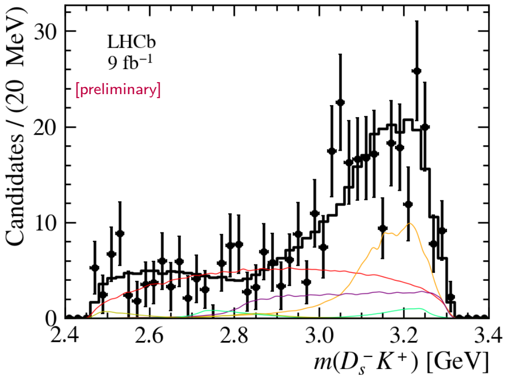
Main features of the data:

- Enhancement at the $D_s^+ D_s^-$ threshold
- Followed by a dip at 4.15 GeV.

Baseline model: $D_s^+ D_s^-$ resonances

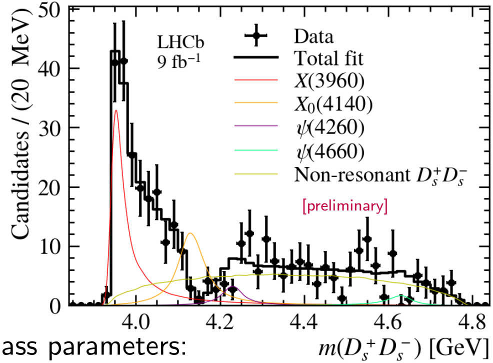
- 1^{--}: $\psi(4260) \sim 4\,\%$, $\psi(4660) \sim 2\,\%$
- 0^{++}: $X(3960) \sim 24\%$, $X(4140) \sim 18\,\%$, NR$\sim 50\,\%$

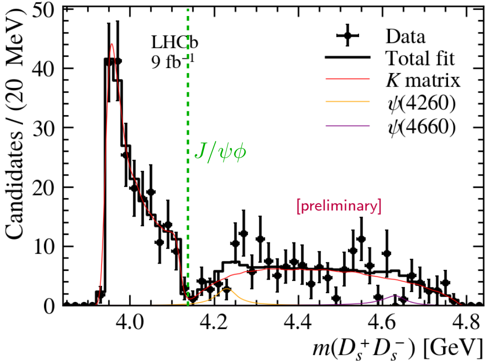




Alternative model using K-matrix [LHCb-PAPER-2022-018, 019 (in preparation)]

Three interfering components in 0^{++} are replaced by the K-matrix.





Mass parameters:

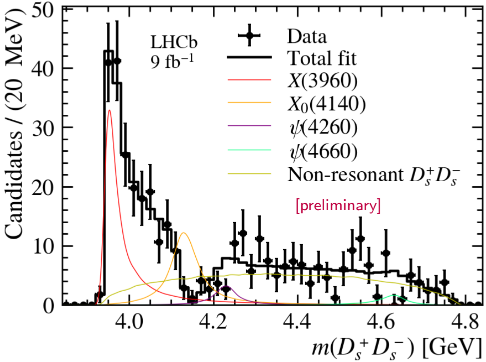
- 3960: $m = 3956 \pm 5 \pm 11\,\text{MeV}$, $\Gamma = 43 \pm 13 \pm 8\,\text{MeV}$
- 4140: $m = 4133 \pm 6 \pm 11\,\text{MeV}$, $\Gamma = 67 \pm 17 \pm 7\,\text{MeV}$

- Coupled channels $D_s^+D_s^- / J/\psi\phi$
- One K-matrix pole + bgd term

Gives equally good fit

Is $X(3960)$ the same as $\chi_{c0}(3930)$ from D^+D^-?

$B^+ \to (D_s^+ D_s^-) K^+$ by LHCb:



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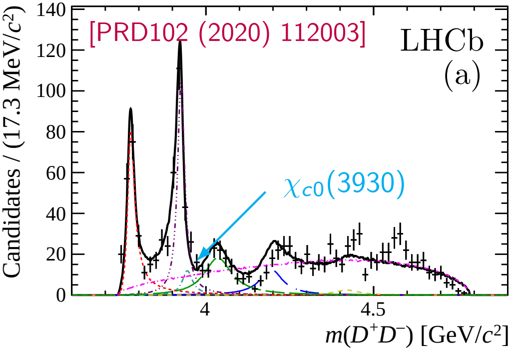
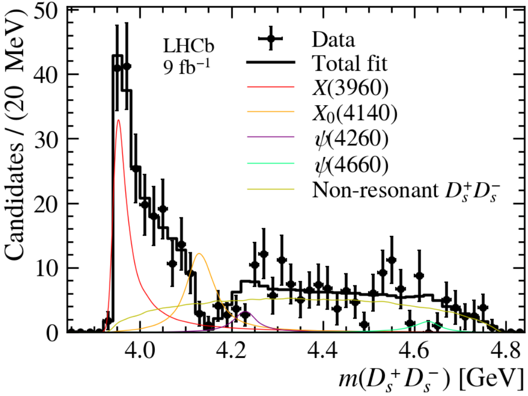


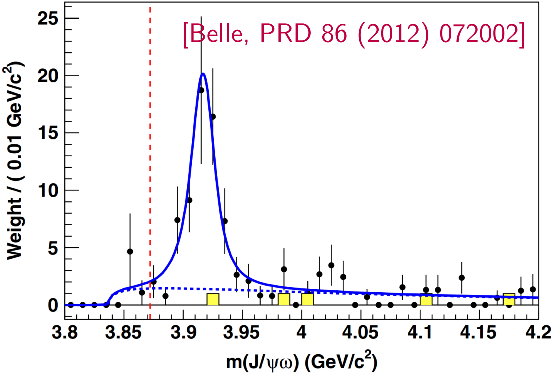
- Assuming to be the same, $\mathcal{B}(\chi_{c0} \to D^+D^-)/\mathcal{B}(\chi_{c0} \to D_s^+D_s^- P) \sim 0.3$
  large molecular component, or large tetraquark component, $T_{\psi\phi}$
- [JHEP 06 (2021) 035] finds a state coupled to $D_s^+D_s^-$ on the lattice

Is $X(3960)$ the same as $\chi_{c0}(3915)$? [LHCb-PAPER-2022-018, 019 (in preparation)]

$B^+ \to (D_s^+ D_s^-) K^+$ by LHCb:



$\gamma\gamma \to J/\psi\omega$ by Belle:



- Belle sees a clean state in $J/\psi\omega$ with $J^P = 0^+$
- The $D_s^+ D_s^-$ signal might be a tail of the $\chi_{c0}(3915)$ state

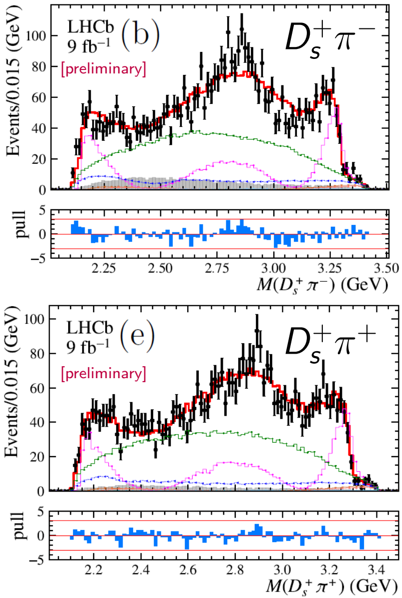
$$B^+ \to D^- \underbrace{D_s^+ \pi^+}_{T^a_{c\bar{s}}}$$

$$B^0 \to \bar{D}^0 \underbrace{D_s^+ \pi^-}_{T^a_{c\bar{s}}}$$

$T^{a}_{c\bar{s}}(2900)$ in the $D_s^{\pm}\pi^{+}$ system

[LHCb-PAPER-2022-026 (in preparation)]

- 4420 B^0 decays and 3940 B^- decays, including charge-conjugated reactions
- Simultaneous fit using the isospin symmetry
- Main components in B^0/B^+ model:
  - $D^* \sim 17/14\,\%$
  - $D_2^* \sim 22/23\,\%$
  - $D\pi$ S-wave$\sim 45/48\,\%$.
- $T^{a}_{cs} \sim 2\,\%$ needed ($> 5\sigma$), $J^P = 0^+$ is favored (7.5σ)
- Mass and width are close to these of $T^{a}_{cs}(2900)$
  - $T^{a0}_{c\bar{s}}$: $m = 2892 \pm 14 \pm 15\,\text{MeV}$, $\Gamma = 119 \pm 26 \pm 12\,\text{MeV}$;
  - $T^{a++}_{c\bar{s}}$: $m = 2921 \pm 17 \pm 19\,\text{MeV}$, $\Gamma = 137 \pm 32 \pm 14\,\text{MeV}$



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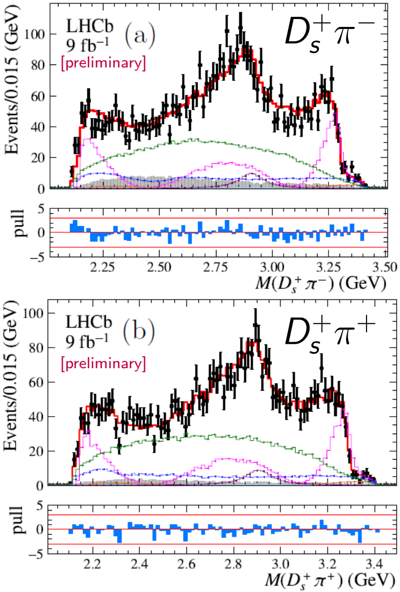


Summary and conclusion

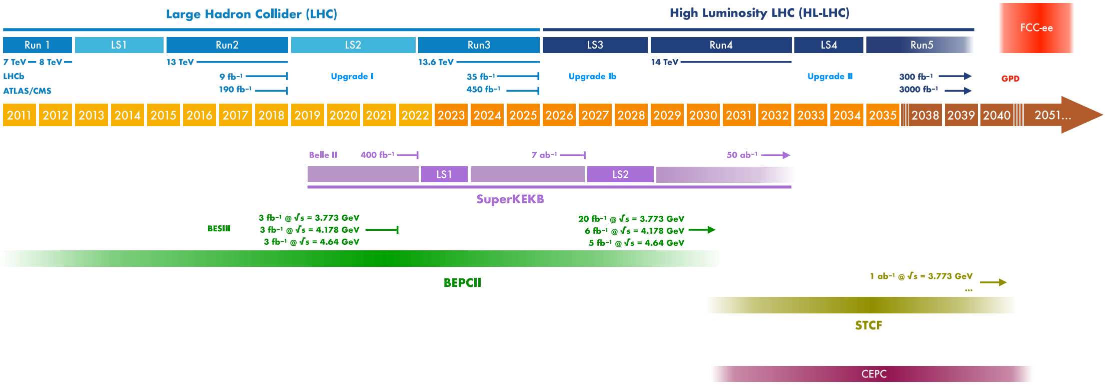
- With excellent performance of LHCb, we are exploring the uncharted waters
- This summer, more puzzle pieces for the quest of understanding nature complexity

Hints for the bigger picture:

- new $P_{\psi s}^{\Lambda}$ in B decays are close to $\Xi_c D$ threshold $\longleftrightarrow$ P_{ψ}^{N} are connected to $\Sigma_c \bar{D}^{(*)}$
  Note, not the SU(3) flavour symmetry(!). Check $\Lambda_c \bar{D}^{(*)}$ and $\Xi_c' \bar{D}^{(*)}$ thresholds
- new $T_{c\bar{s}}^{a}$ appear to be similar to T_{cs}
  HQSS is in action? Where is the good/bad diquark mass difference?
- new $\chi_{c0}/T_{\psi\phi}$ close to the $D_s^+ D_s^-$ threshold.
  A hadronic molecule or the scalar charmonium?

Updated timeline for LHC

[W. Altmannshofer, F. Archilli, arXiv:2206.11331]

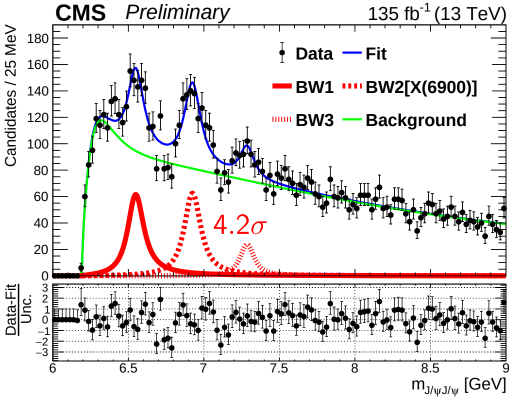


LHCb:

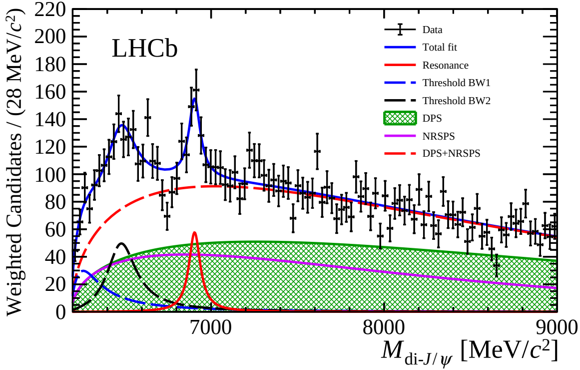
- ramping up after major Upgrade I
- $\times 5$ statistics in Run 3(2023-2025) @13.6 TeV + Run 4(2029-2032) @14 TeV

Thank you for your attention

CMS confirms $T_{\psi\psi}$ structures



[CMS-PAS-BPH-21-003]



[LHCb, Sci.Bull. 65 (2020) 23, 1983-1993]

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- Third state is significant

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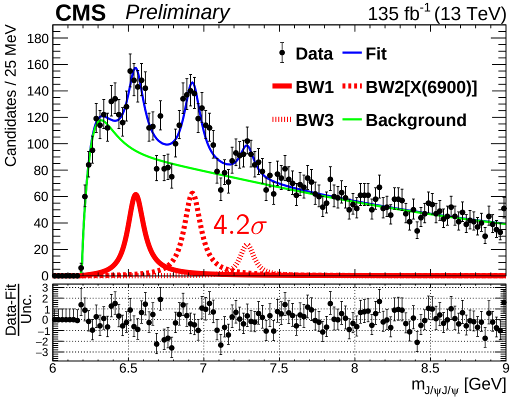
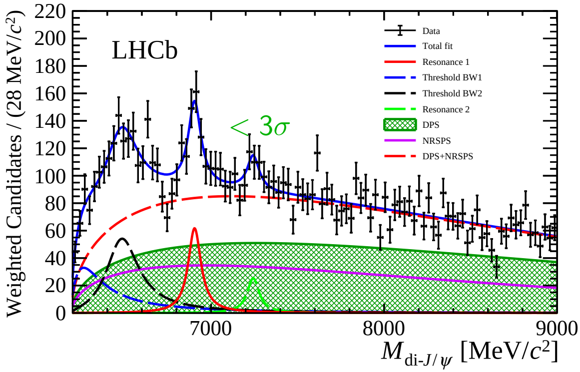


[CMS-PAS-BPH-21-003]



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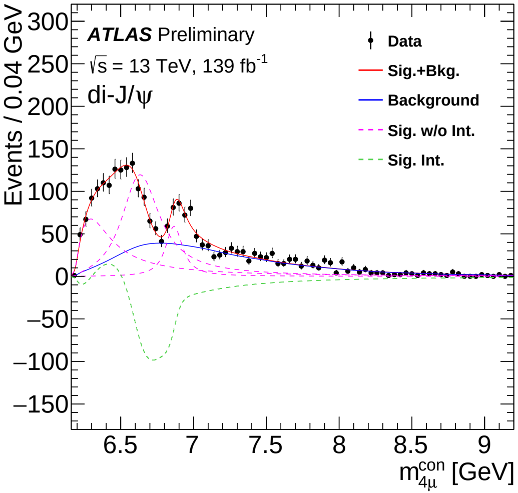
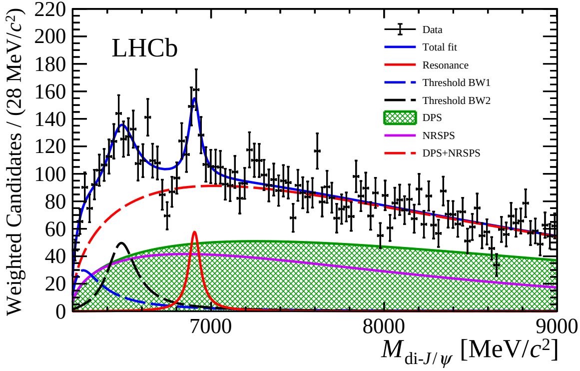
ATLAS also finds structures in $J/\psi J/\psi$



[ATLAS-CONF-2022-040]



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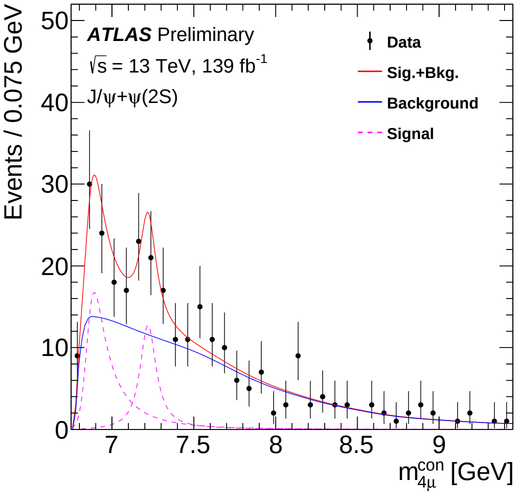
ATLAS also finds structures in $J/\psi J/\psi$ and $\psi' J/\psi$

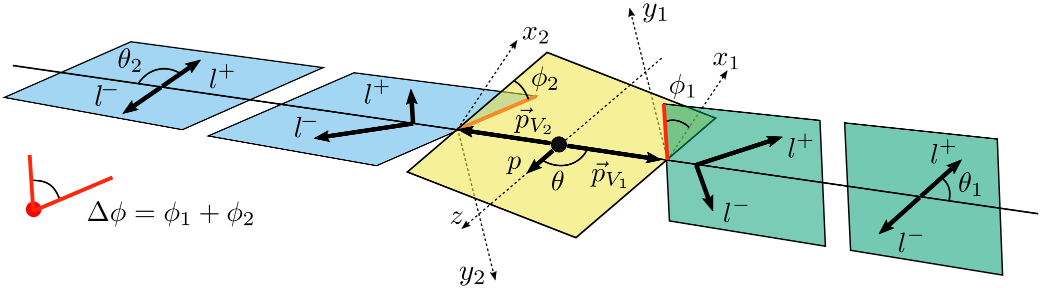


[ATLAS-CONF-2022-040]

- Hints for the near-threshold structure
- Resonances in $\psi' J/\psi$ might produce structures in $J/\psi J/\psi$ as partial-reconstructed decays, $\psi' \to J/\psi +$ neutrals

Four-body decay angles

[MM, L. An, R. McNulty, arXiv:2007.05501]



- θ is the polar angle of $(J/\psi)_1$ with respect to the polarization direction
- (θ_1, ϕ_1) are the spherical angles of μ^+ in the $(J/\psi)_1$ helicity frame
- (θ_2, ϕ_2) are the spherical angles of μ^+ in the $(J/\psi)_2$ helicity frame

No polarization $\Rightarrow$ no z $\Rightarrow$ no decay plane (pink) $\Rightarrow$ only $\phi = \phi_1 + \phi_2$ matters.

Matrix of helicity couplings

[MM, L. An, R. McNulty, arXiv:2007.05501]

$$H_{\lambda_1,\lambda_2} = \begin{pmatrix} h_{1,1} & h_{1,0} & h_{1,-1} \\ h_{0,1} & h_{0,0} & h_{0,-1} \\ h_{-1,1} & h_{-1,0} & h_{-1,-1} \end{pmatrix}$$

The same-color elements are connected by symmetries.

The symmetry relates the couplings

$$H_{\lambda_1,\lambda_2} = (-1)^J \eta_X \, H_{-\lambda_1,-\lambda_2}, \qquad H_{\lambda_1,\lambda_2} = (-1)^J H_{\lambda_2,\lambda_1}.$$

Four categories of possible helicity matrices

[arXiv:2007.05501]

group	$\eta_X(-1)^J, (-1)^J$	J^P	symmetry
I	$+,+$	$\boxed{0^+}$, 2^+, 4^+, 6^+	symmetric, S
II	$-,+$	$\boxed{0^-}$, 2^-, 4^-, 6^-	symmetric, S
III	$+,-$	1^-, 3^-, 5^-, 7^-	antisymmetric, A
IV	$-,-$	$\boxed{1^+}$, 3^+, 5^+, 7^+	antisymmetric, A

$$H^{(I)} \quad \begin{pmatrix} b & a & c \\ a & d & a \\ c & a & b \end{pmatrix}_S \qquad H^{(II)} \quad \begin{pmatrix} b & a & \\ a & & -a \\ & -a & -b \end{pmatrix}_S \qquad H^{(III)} \quad \begin{pmatrix} & a & \\ -a & & -a \\ & a & \end{pmatrix}_A \qquad H^{(IV)} \quad \begin{pmatrix} & a & c \\ -a & & a \\ -c & -a & \end{pmatrix}_A$$

a, b, c, d are still unknown coefficients, complex in general.

Four categories of possible helicity matrices

[arXiv:2007.05501]

group	$\eta_X(-1)^J, (-1)^J$	J^P	symmetry
I	$+, +$	$\boxed{0^+}, 2^+, 4^+, 6^+$	symmetric, S
II	$-, +$	$\boxed{0^-}, 2^-, 4^-, 6^-$	symmetric, S
III	$+, -$	$1^-, 3^-, 5^-, 7^-$	antisymmetric, A
IV	$-, -$	$\boxed{1^+}, 3^+, 5^+, 7^+$	antisymmetric, A

$\boxed{0^+}$

$$\begin{pmatrix} b & & \\ & d & \\ & & b \end{pmatrix}_S$$

$\boxed{0^-}$

$$\begin{pmatrix} b & & \\ & & \\ & & -b \end{pmatrix}_S$$

$\boxed{1^+}$

$$\begin{pmatrix} & a & \\ -a & & a \\ & -a & \end{pmatrix}_A$$

a, b, c, d are still unknown coefficients, complex in general.

Rederivation of the Landau-Yang theorem

[arXiv:2007.05501]

"A massive particle with spin 1 cannot decay into two photons", wikipedia

Photons do not carry the longitudinal polarizarion $\Rightarrow H_{0,i} = H_{i,0} = 0$

$H^{(I)}$

$$\begin{pmatrix} b & a & c \\ a & d & a \\ c & a & b \end{pmatrix}_S \qquad \begin{pmatrix} b & & \\ & d & \\ & & b \end{pmatrix}_S$$

0^+

$H^{(II)}$

$$\begin{pmatrix} b & a & \\ a & & -a \\ & -a & -b \end{pmatrix}_S \qquad \begin{pmatrix} b & & \\ & & \\ & & -b \end{pmatrix}_S$$

0^-

$H^{(III)}$

$$\begin{pmatrix} & a & \\ -a & & -a \\ & a & \end{pmatrix}_A$$

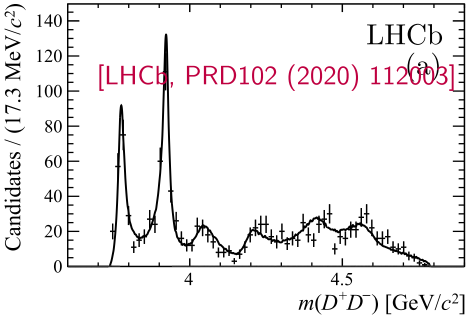
$H^{(IV)}$

$$\begin{pmatrix} & a & c \\ -a & & a \\ -c & -a & \end{pmatrix}_A \qquad \begin{pmatrix} & a & \\ -a & & a \\ & -a & \end{pmatrix}_A$$

1^+

No decay to two photons for 1^+, and group-III: $1^-, 3^-, 5^-, \dots$

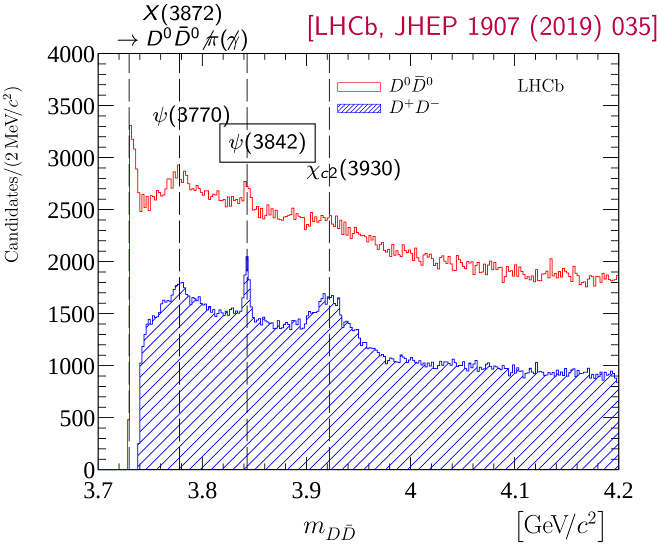
$D\bar{D}$ spectroscopy



Natural parity chanmonia above D^+D^- threshold:

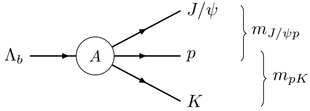
- $\psi(3770)$, $\chi_{c0}(3930)$, $\chi_{c2}(3930)$, $\psi(4040)$, $\psi(4160)$, $\psi(4415)$

Compare to inclusive DD spectra:

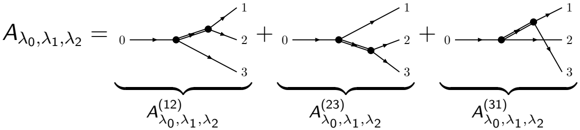


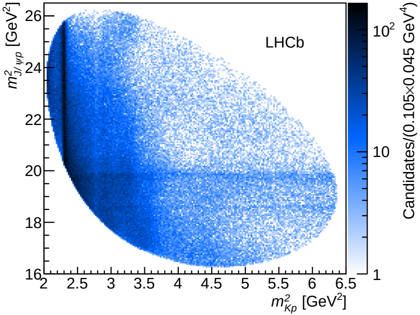
Dalitz Plot Decomposition (DPD)

Update to the angular analysis formalism



Spin in 3-body decays
[MM et al. PRD (2019)]
[Mengzhen Wang et al., 2012.03699 (2020)]





Used in the past

$$A^{(23)}_{\lambda_0,\lambda_1,\lambda_2} = \underbrace{\boxtimes(\phi_i,\theta_i)}_{0\to X,1} \times \underbrace{\boxtimes(\phi'_i,\theta'_i)}_{X\to 2,3} \times \underbrace{\boxtimes(\phi''_i,\theta''_i)}_{\text{spin align.}}$$

- unphysical inhomogenity
- spin 1/2: $A(\pi) \neq A(-\pi)$
- range of ϕ matters $[-\pi,\pi]$ vs $[0,2\pi]$

Proposed in DPD

$$A_{\lambda_0,\lambda_1,\lambda_2} = \sum_{\nu} D^{1/2*}_{\lambda_0,\nu}(\alpha,\beta,\gamma)\, \underbrace{O^{\nu}_{\lambda_1,\lambda_2}(m^2_{12},m^2_{23})}_{O^{(12)}+O^{(23)}+O^{(31)}}$$

$$O^{(23)}_{\nu,\lambda_1,\lambda_2}(m^2_{12},m^2_{23}) = \underbrace{\boxtimes}_{0\to X,1} \times \underbrace{\boxtimes}_{X\to 2,3} \times \underbrace{\boxtimes}_{\text{spin align.}}$$

- correct ϕ dependence by construction