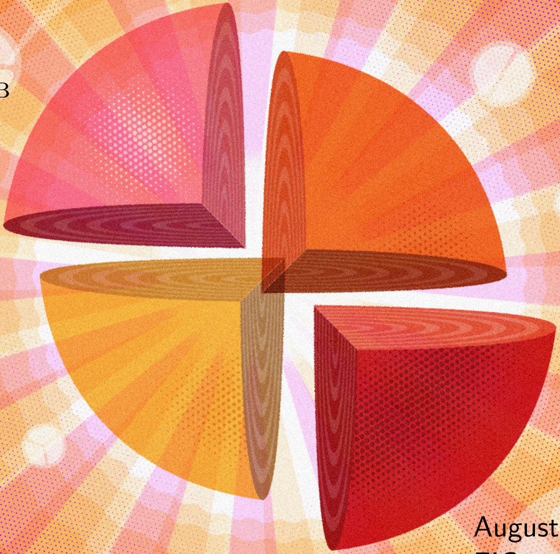
Exotic hadrons at LHCb

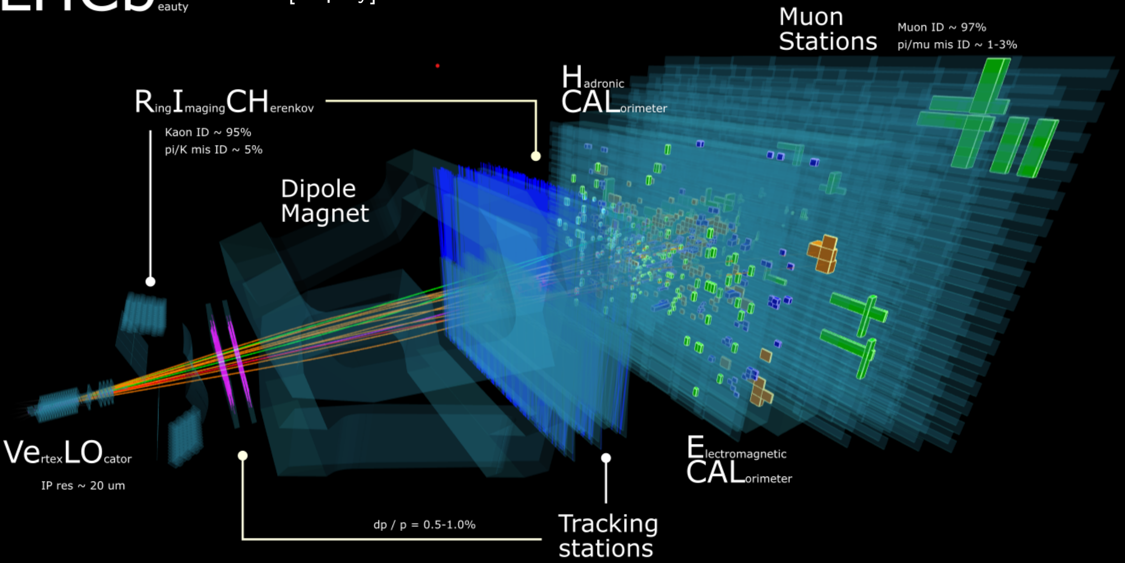
[poster by QuantaMagazine]

Misha Mikhasenko
on behalf of LHCb



August 15$^{\text{nd}}$, 2022
EIC workshop in Stony Brook

LHCb eauty [display]



pp collider (7+7 TeV)

1. Pentaquarks
   - $\Lambda_b^0 \to J/\psi p K^-$
   - $\Xi_b^- \to J/\psi \Lambda K^-$
   - $B^- \to J/\psi \Lambda \bar{p}$
2. Tetraquarks
   - prompt $D^0 D^0 \pi^+$
   - $B^+ \to D^+ D^- K^+$
   - $B^+ \to D_s^+ D_s^- K^+$
   - $B^+ \to D^- D_s^+ \pi^+$ and $B^0 \to \bar{D}^0 D_s^+ \pi^-$
3. Plans

Summary of Pentaquarks studies

(*) will be discussed today

$X_b \to (J/\psi p)\ldots$

$\Lambda_b^0 \to (J/\psi p)K^-$ (*)

$\Lambda_b^0 \to (J/\psi p)\pi^-$

$B_s^0 \to (J/\psi p)\bar{p}$

Thresholds:

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

P_ψ^N:

$X_b \to (J/\psi \Lambda)\ldots$

$\Xi_b^- \to (J/\psi\Lambda)K^-$ (*)

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

Thresholds (?):

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

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

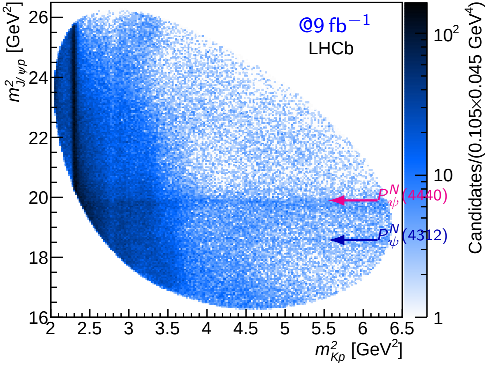
LHCb proposal for the new name convention of exotic hadrons [arxiv: 2206.15233]

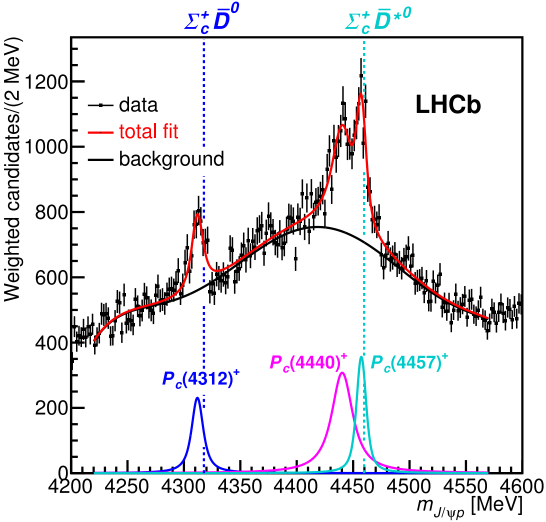
$$\Lambda_b^0 \to \underbrace{J/\psi\, p}_{P_\psi^N} K^-$$

The first pentaquarks

[PRL 115 (2015), PRL 122 (2019) 22]

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





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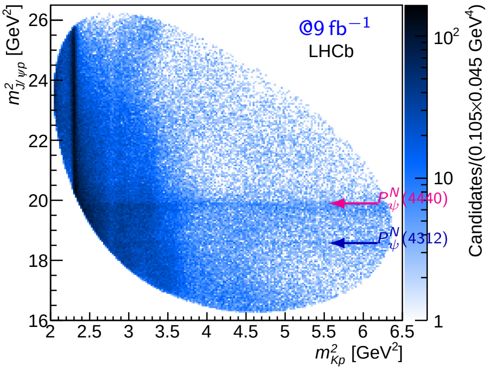
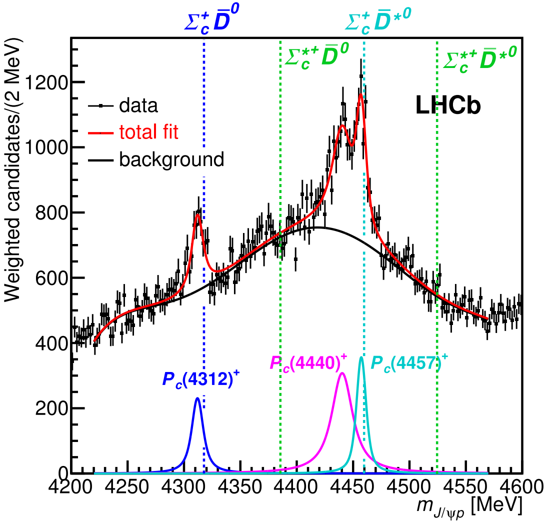


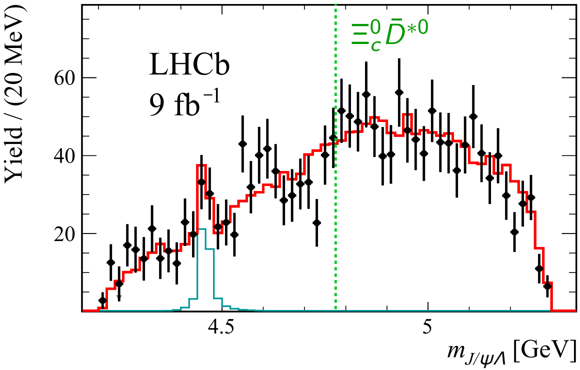


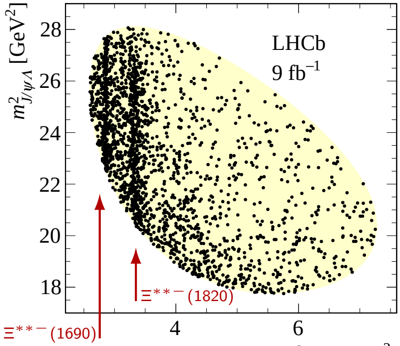
$$\Xi_b^- \to \underbrace{J/\psi \Lambda}_{P_{\psi s}^{\Lambda}} K^-$$

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 amplitude model includes: Ξ
- $P^{\Lambda}_{\psi s}(4459)$: $m = 4458.8 \pm 2.9^{+4.7}_{-1.1}$ MeV, $\Gamma = 17.3 \pm 6.5^{+8.0}_{-5.7}$ MeV



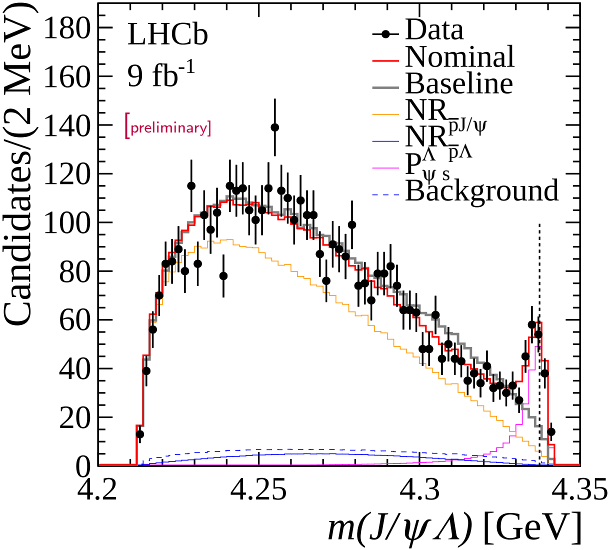


$$B^- \to \underbrace{J/\psi \Lambda}_{P_{\psi s}^{\Lambda}} \bar{p}$$

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

[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, ...(!)

$D^0 D^0 \pi^+$ (*)

T_{cc}

3874

$D^+ K^-$ (*)

T_{cs} (X)

2900

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

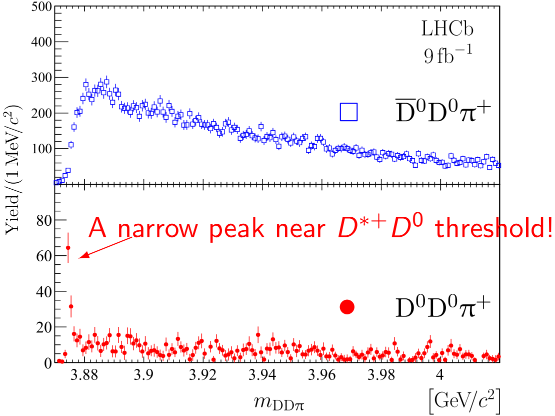
$T_{c\bar{s}}$ (X)

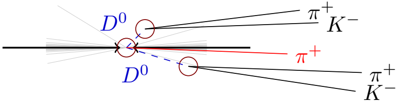
2900

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

The landmark of 2021: a signal in $D^0 D^0 \pi^+$ [Nat. Phys. 18 (2022) 7, 751-754]

Event selection





- Select $D^0 D^0 \pi^+$ candidates from primary vertex with detached $D^0 \to K^- \pi^+$
- Require detached $K^- \pi^+$ with high p_T
- Require good quality of tracks, vertexes, and particle IDs.
- Ensure no K/π candidates belong to one track
- Ensure no reflections via mis-ID
- Subtraction / sWeight for fake-D background

Fit to the spectrum

[NP 18 (2022) 7, 751-754, NC 13 (2022) 1, 3351]

Unitarized model

Two models: Native & Th.-motivated

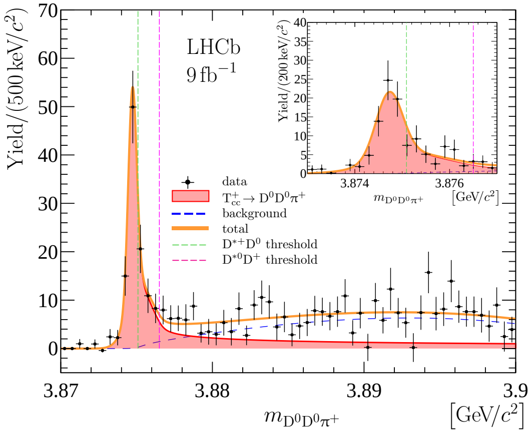
- The peak position is well constrained.
- The width is not, limit to the coupling: $|g| > 7.7(6.2)\,\mathrm{GeV}$ at 90(95)% CL

Parameter	Value
N	117 ± 16
δm_{BW}	-273 ± 61 keV/c^2
Γ_{BW}	410 ± 165 keV

Naive BW

Parameter	Value
N	186 ± 24
δm_{U}	$-359 \pm 40\,\mathrm{keV}/c^2$
$\|g\|$	3×10^4 GeV (fixed)

Advanced Model



Excellent agreement with the data. Reaction amplitude is fully fixed.

Predicted mass spectrum

[Nat.Comm. 13 (2022) 1, 3351]

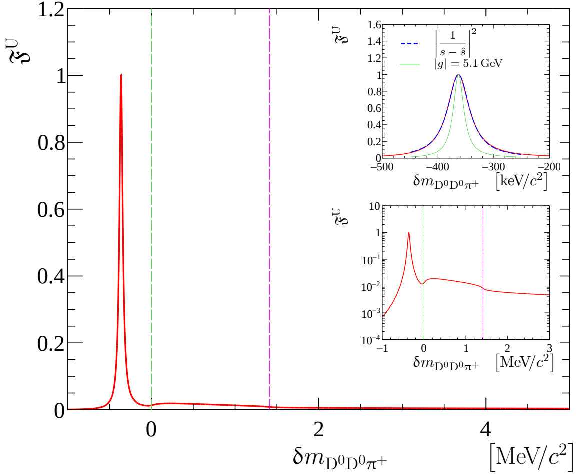
The resolution removed

- Peak position:
  $-359 \pm 40\,\mathrm{keV}$

  (The most precise ever wrt to the threshold)
- FWHM: $47.8 \pm 1.9\,\mathrm{keV}$,
- Lifetime: $\tau \approx 10^{-20}\,s$.

  (Unprecedentedly large for exotic hadrons)
- The pole parameters:

$$\delta m_{\text{pole}} = -360 \pm 40^{+4}_{-0}\,\mathrm{keV}\,,$$
$$\Gamma_{\text{pole}} = 48 \pm 2^{+0}_{-14}\,\mathrm{keV}\,.$$

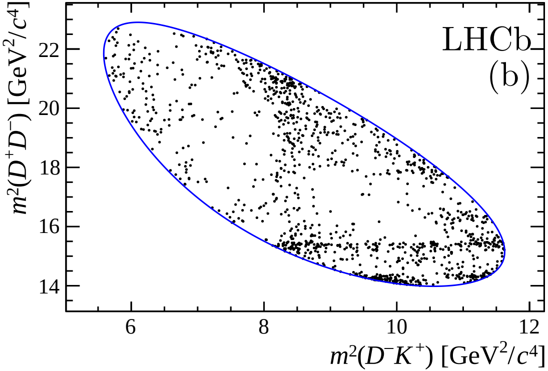


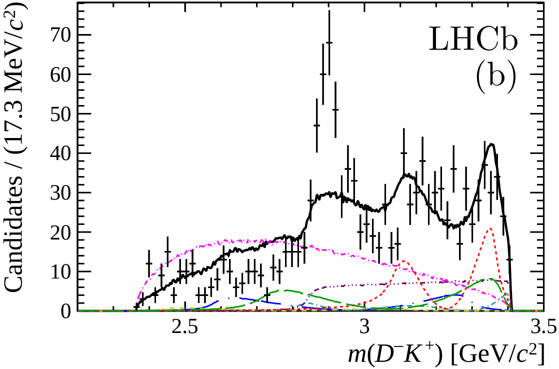
- Nearly-isolated resonance below the $D^{*+}D^0$ threshold
- Long tail with cusps at the $D^{*+}D^0$ and $D^{*0}D^+$ thresholds

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

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 $8,5\,\mathrm{GeV}^2$ in $m^2(D^-K^+)$
- Exotic candidate $T_{cs}(2900)$: $[\bar{c}\bar{s}ud]$
- Both quantum numbers $J^P = 0^+$ and 1^- are wanted by the fit

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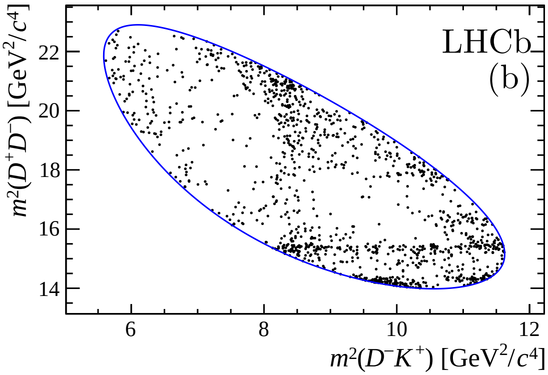

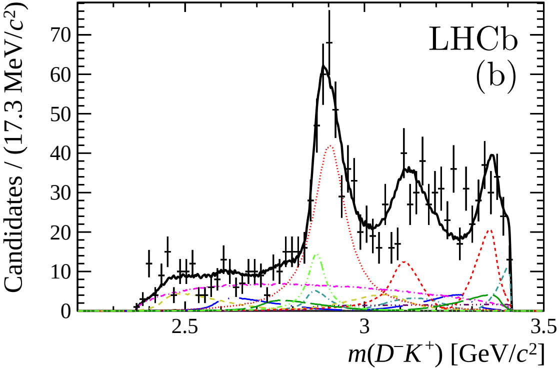

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$$B^+ \to \underbrace{D_s^+ D_s^-}_{\chi_{c0}/\,T_{\psi\phi}} K^+$$

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

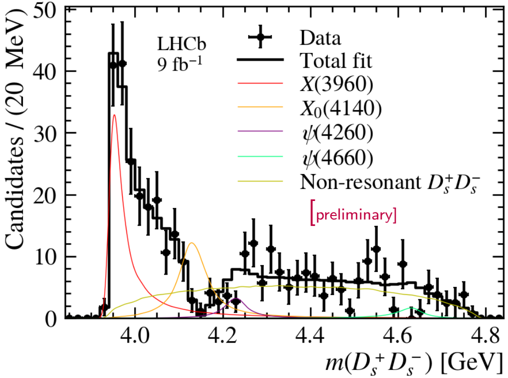
[LHCb-PAPER-2022-018, 019 (in preparation)]

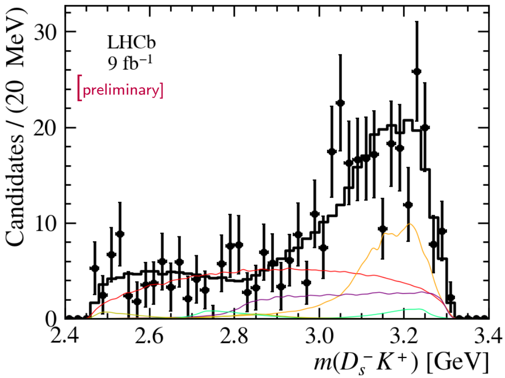
Main features of the data:

- significant structure at the threshold
- a prominent dip at $m(D_s^+ D_s^-) = 4.15\,\text{GeV}$.

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

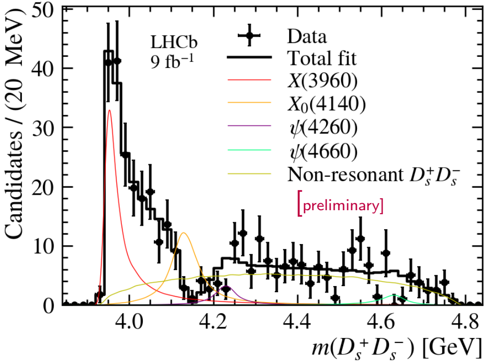
- 1^{--}: $\psi(4260) \sim 4\,\%$, $\psi(4660) \sim 2\,\%$
- 0^{++}: $X(3960) \sim 24\%$, $X(4140) \sim 18\,\%$, NR$\sim 50\,\%$



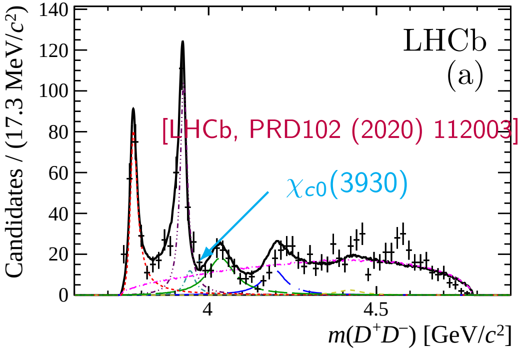


Is $X(3960)$ the same as $\chi_{c0}(3930)$ from D^+D^-?

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



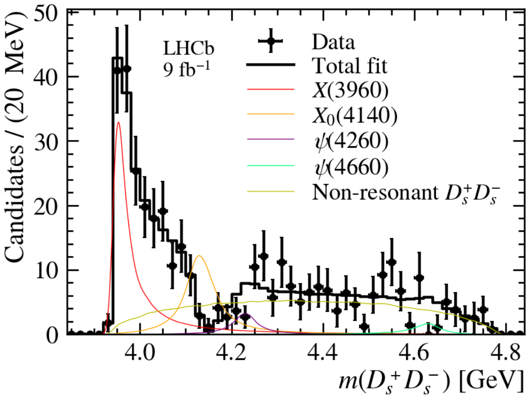
$B^+ \to (D^+ D^-) K^+$ by LHCb:



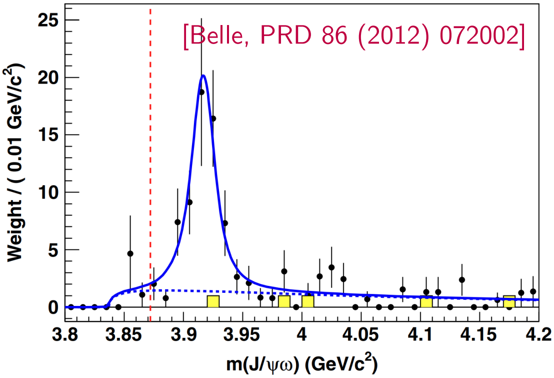
- Assuming to be the same, $\mathcal{B}(\chi_{c0} \to D^+D^-)/\mathcal{B}(\chi_{c0} \to D_s^+ D_s^- P) \sim 0.3$
  large molecular component, or large tetraquark component, $T_{\psi\phi}$
- [JHEP 06 (2021) 035] finds a state coupled to $D_s^+ D_s^-$ on the lattice

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

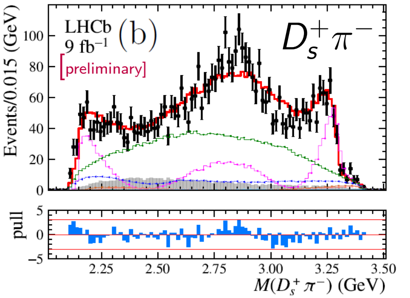
$$B^+ \to D^- \underbrace{D_s^+ \pi^+}_{T^a_{c\bar{s}}(\dots)^{++}}$$

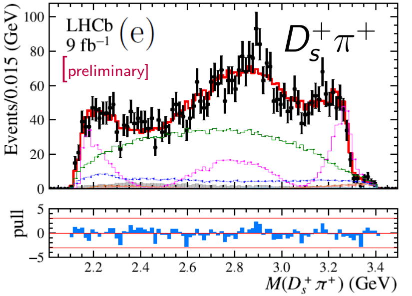
$$B^0 \to \bar{D}^0 \underbrace{D_s^+ \pi^-}_{T^a_{c\bar{s}}(\dots)^{0}}$$

$T^a_{c\bar{s}}(2900)$ 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
- $T^a_{cs} \sim 2\,\%$ needed $(> 5\sigma)$
- T^a_{cs}: $J^P = 0^+$ is favored (7.5σ)
- Mass and width are close to these of $T^a_{cs}(2900)$
  - $T^{a0}_{c\bar{s}}$: $m = 2892 \pm 14 \pm 15\,\text{MeV}$, $\Gamma = 119 \pm 26 \pm 12\,\text{MeV}$;
  - $T^{a++}_{c\bar{s}}$: $m = 2921 \pm 17 \pm 19\,\text{MeV}$, $\Gamma = 137 \pm 32 \pm 14\,\text{MeV}$





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

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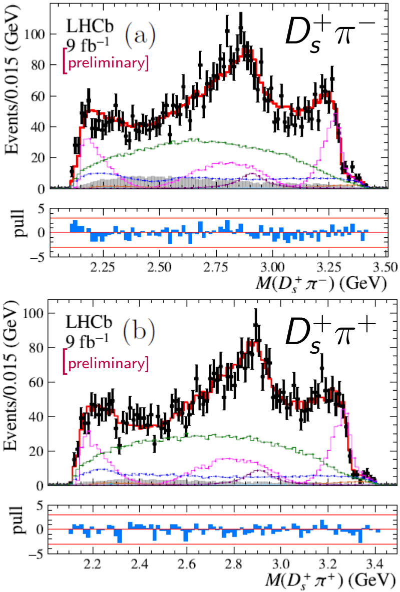
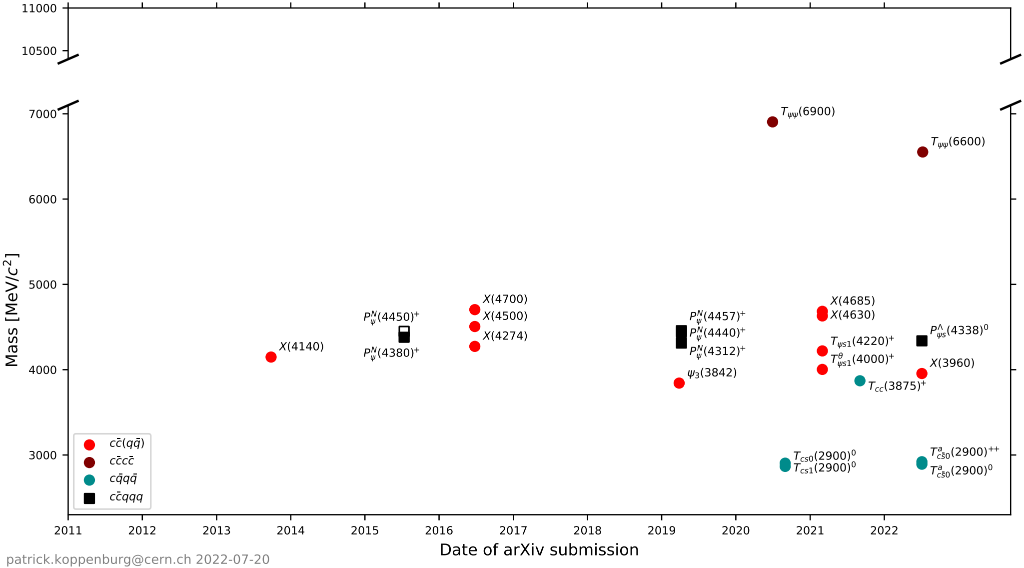


Summary of the new hadronic states



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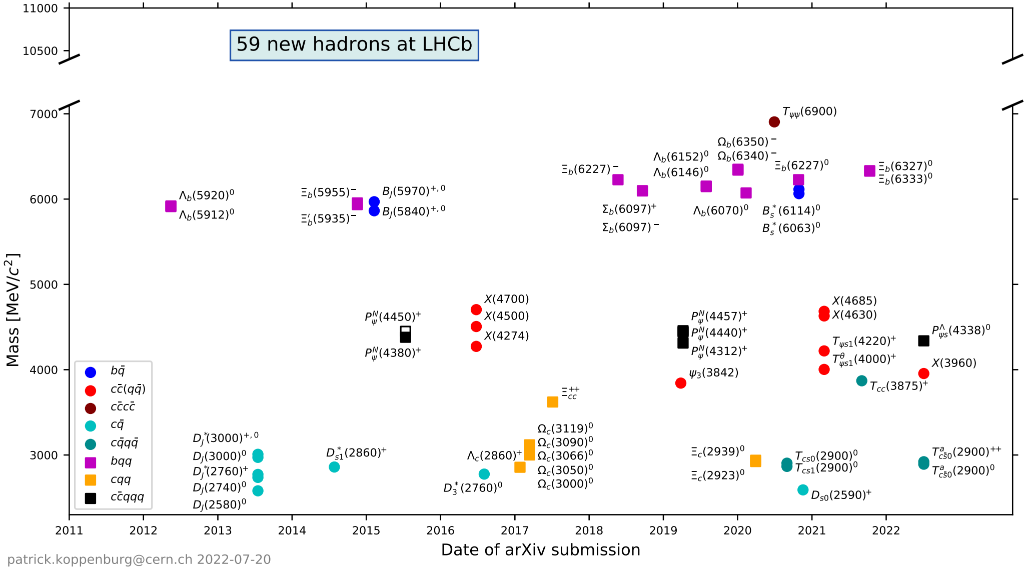
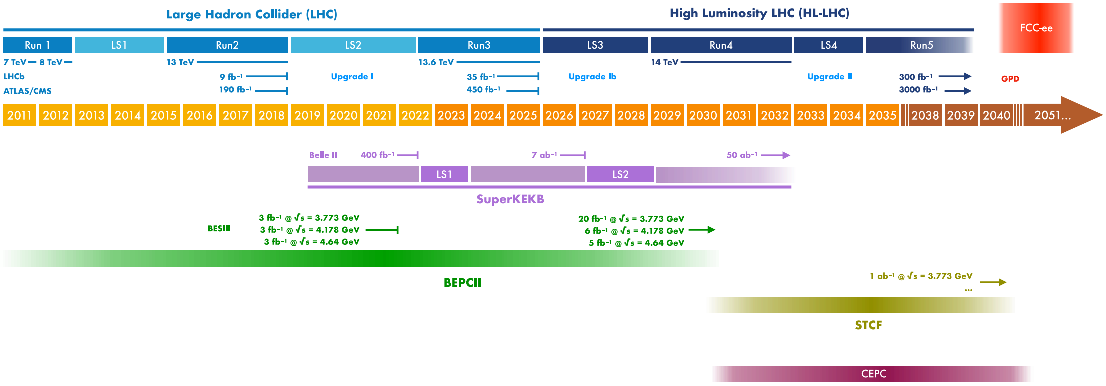


Updated timeline for LHC

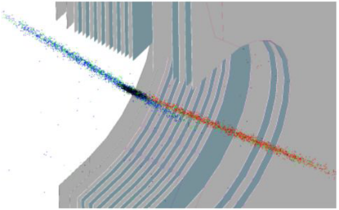
[W. Altmannshofer, F. Archilli, arxiv::2206.11331]



LHCb:

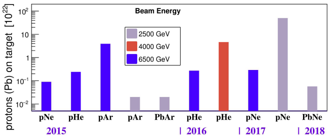
- ramping up after major Upgrade I
- $\times 5$ statistics in Run 3(2023-2025) @13.6 TeV + Run 4(2029-2032) @14 TeV

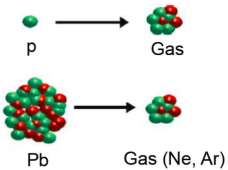
SMOG(2): Fixed Targer LHCb [JINST 9 (2014) 12005, LHCb-PUB-2018-015]



- **System for Measuring Overlap with Gas** (SMOG)
- LHC beam collides with the injected gas (10^{-7} mbar)
- Used to reconstruct the beams transverse profile
- LHCb + gas target $\Rightarrow$ Fixed-target LHCb!

- Unique energy scale: $68 < \sqrt{s} < 110\,\text{GeV}$
- Access to unexplored kinematic region: high-x and intermediate Q^2



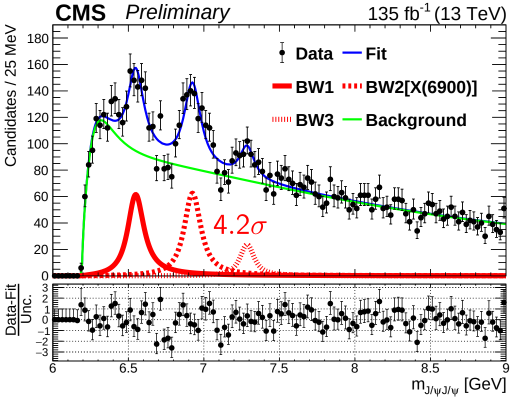


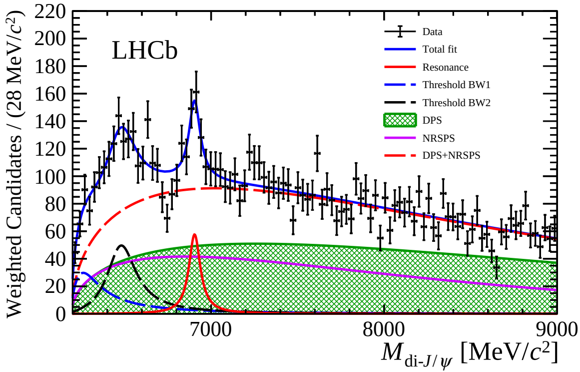
Some physics results

- Detached antiprotons in pHe, [LHCb, arXiv:2205.09009]
- Charmonium production in pNe, [LHCb-PAPER-2022-014]
- J/ψ production in PbNe, [LHCb-PAPER-2022-011]

Thank you for your attentions

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





[CMS-PAS-BPH-21-003]

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

- Clear dips is present that makes the incoherent fit struggles
- Third state is significant

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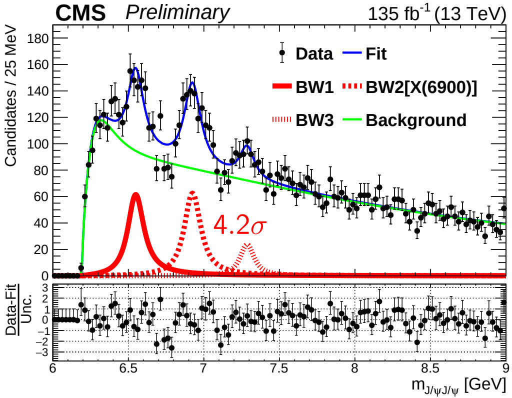

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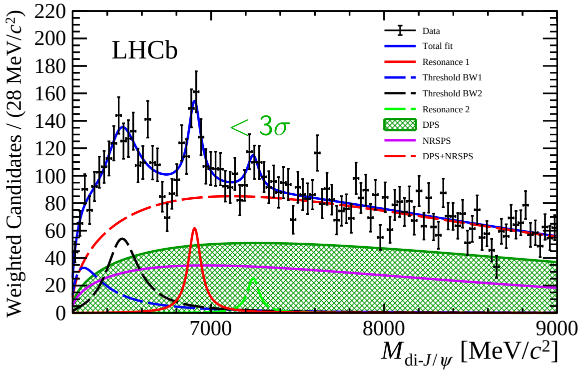

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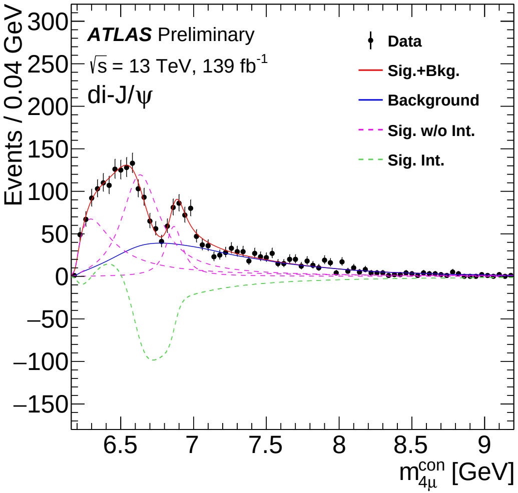
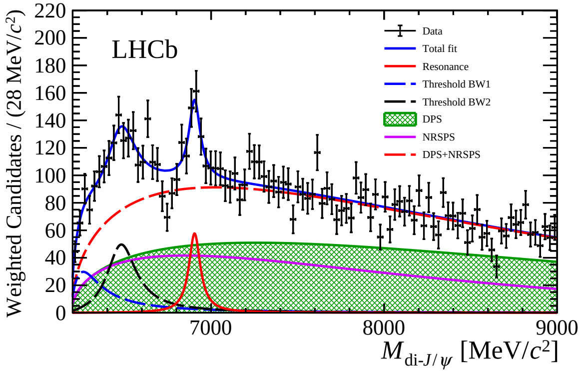
ATLAS also finds structures in $J/\psi J/\psi$

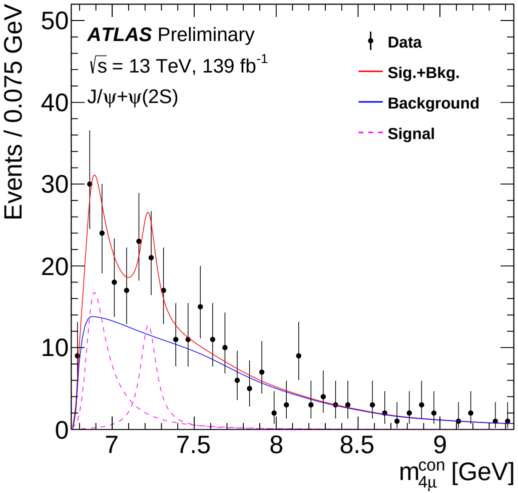


[ATLAS-CONF-2022-040]



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

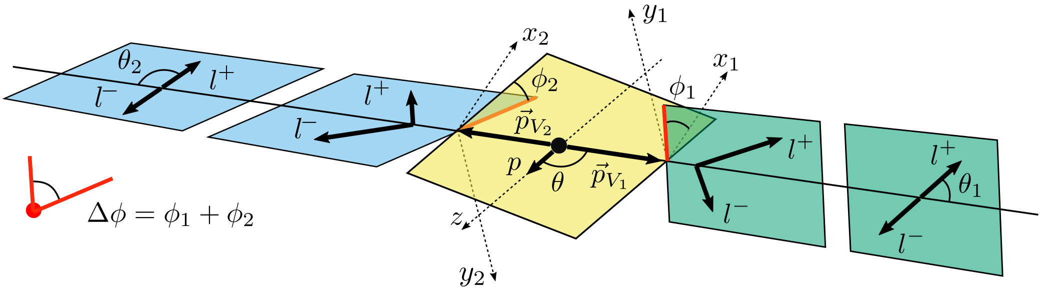
ATLAS also finds structures in $J/\psi J/\psi$ and $\psi' J/\psi$



[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, $\psi' \to J/\psi + \text{neutrals}$

Proposal for $J/\psi J/\psi$ angular analysis [MM, L. An, R. McNulty, arXiv:2007.05501]



Two main angles:

- θ_1, θ_2 decay angle of J/ψ (helicity angle)
- $\Delta\phi$ the azimuthal angle between the decay plans

Symmetry constraints: permutation of identical J/ψ, parity

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

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

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

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$\boxed{0^+}$
$$\begin{pmatrix} b & & \\ & d & \\ & & b \end{pmatrix}_S$$

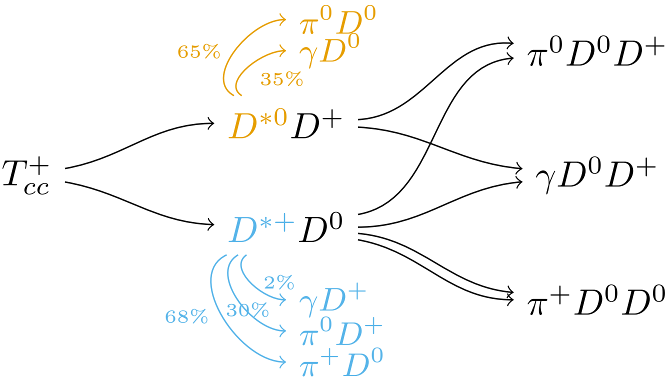
$\boxed{0^-}$
$$\begin{pmatrix} b & & \\ & & \\ & & -b \end{pmatrix}_S$$

$\boxed{1^+}$
$$\begin{pmatrix} & a & \\ -a & & a \\ & -a & \end{pmatrix}_A$$

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

T_{cc}^{+} decay amplitude

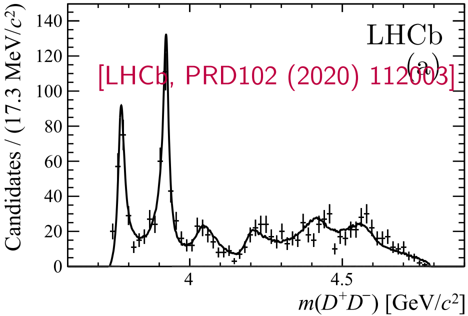
[Nat.Comm. 13 (2022) 1, 3351]



Model assumptions:

- $J^P = 1^+$: S-wave decay to $D^* D$
- T_{cc}^+ is an isoscalar: $|T_{cc}^+\rangle_{I=0} = \left\{ \left|D^{*0} D^+\right\rangle - \left|D^{*+} D^0\right\rangle \right\} / \sqrt{2}$
- No isospin violation in couplings to $D^{*+} D^0$ and $D^{*0} D^+$

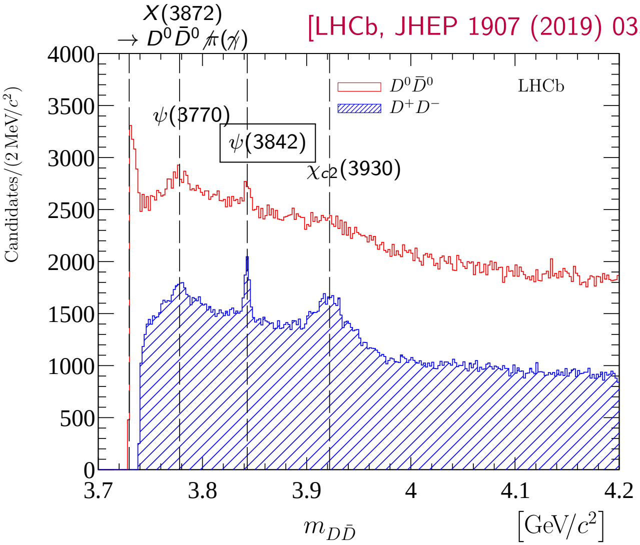
$D\bar{D}$ spectroscopy



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

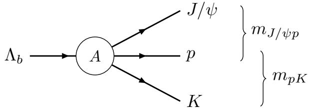
- $\psi(3770)$, $\chi_{c0}(3930)$, $\chi_{c2}(3930)$, $\psi(4040)$, $\psi(4160)$, $\psi(4415)$

Compare to inclusive *DD* spectra:



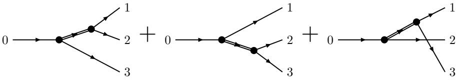
Dalitz Plot Decomposition (DPD)

Update to the angular analysis formalism

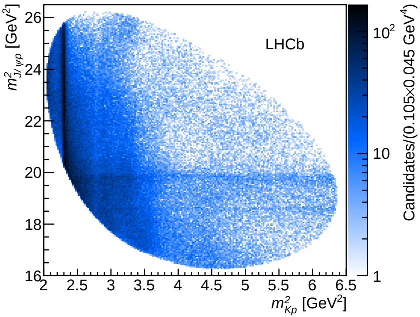


Spin in 3-body decays
[MM et al. PRD (2019)]
[M. Wang et al., CPC (2021)]

$A_{\lambda_0,\lambda_1,\lambda_2} =$



$A^{(12)}_{\lambda_0,\lambda_1,\lambda_2}$ $A^{(23)}_{\lambda_0,\lambda_1,\lambda_2}$ $A^{(31)}_{\lambda_0,\lambda_1,\lambda_2}$



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

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

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

- correct ϕ dependence by construction