Heavy flavour exotics from LHCb

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on behalf of LHCb

Hirschegg 2024

LHCb experiment

1630 members (1118 authors)

96 institutes (21 countries)

An experiment on LHC (symmetric pp collision)

Forward spectrometer: $2 < \eta < 5$

Excellent vertex reconstruction, track reconstruction, particle identification

[LHCb proposal], [Perform. paper]

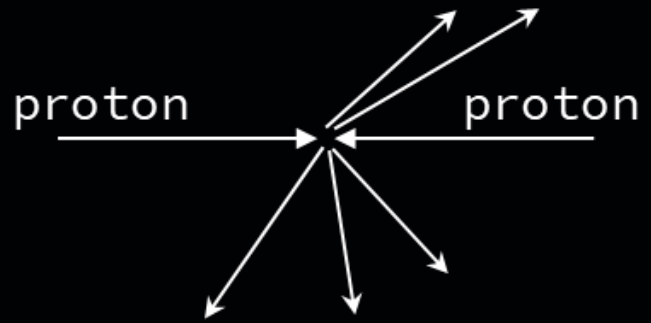
High statistics: $3\text{fb}^{-1} + 6\text{fb}^{-1}$(Run-1+2)

Upgrade I is finished, currently taking data (Run3)

~ 50 fb^{-1} is expected by 2032

[Midjourney 2023, MM] Ultra realistic, cinematic picture of group of scientists at Large hadron Collider emotionally debate

An event in the LHCb experiment

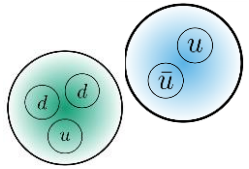


QCD variety

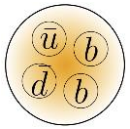
[Midjourney 2023, MM]
Oil pointing, depths of the quantum realm, entangled particles dance gracefully in a cosmic ballet, their movements dictated by the complex interplay of forces and probabilities. Through delicate strokes and swirling colors, capture the particles' intricate choreography, where their trajectories converge and diverge, manifesting the enigmatic beauty of the quantum world.

Possible configurations of hadrons

Conventional Quark Model: $(q\bar{q}, qqq)$



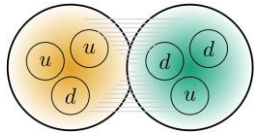
Bigger Quark Model $(q\bar{q}q\bar{q}, qqqq\bar{q}, \dots)$



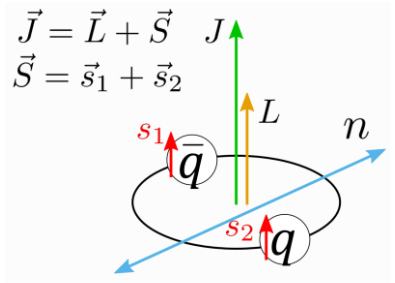
Conventional Hadronic Molecules = Nuclei: $(qqq)(qqq)$

Heavy-Flavor Hadronic Molecules: $(Qqq)(Qqq), (Q\bar{q})(Qqq), \dots$

Admixed Molecules: $q\bar{q} \rightarrow (q\bar{q})(q\bar{q})$



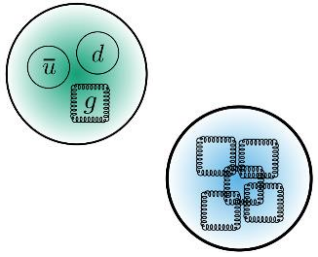
+ nuclei chart



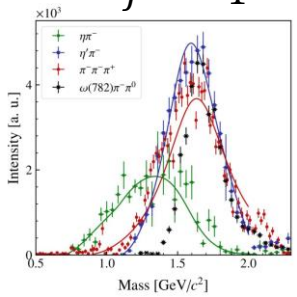
+ excitations

Hybrids: $q{\sim}g{\sim}\bar{q}$

Glueballs: $g{\sim}g$



$J^{PC} = 1^{-+}$



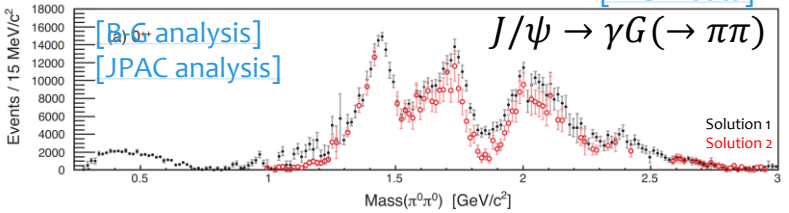
[P.Haas, HADRON2023]

[BESIII data]

[B.G. analysis]

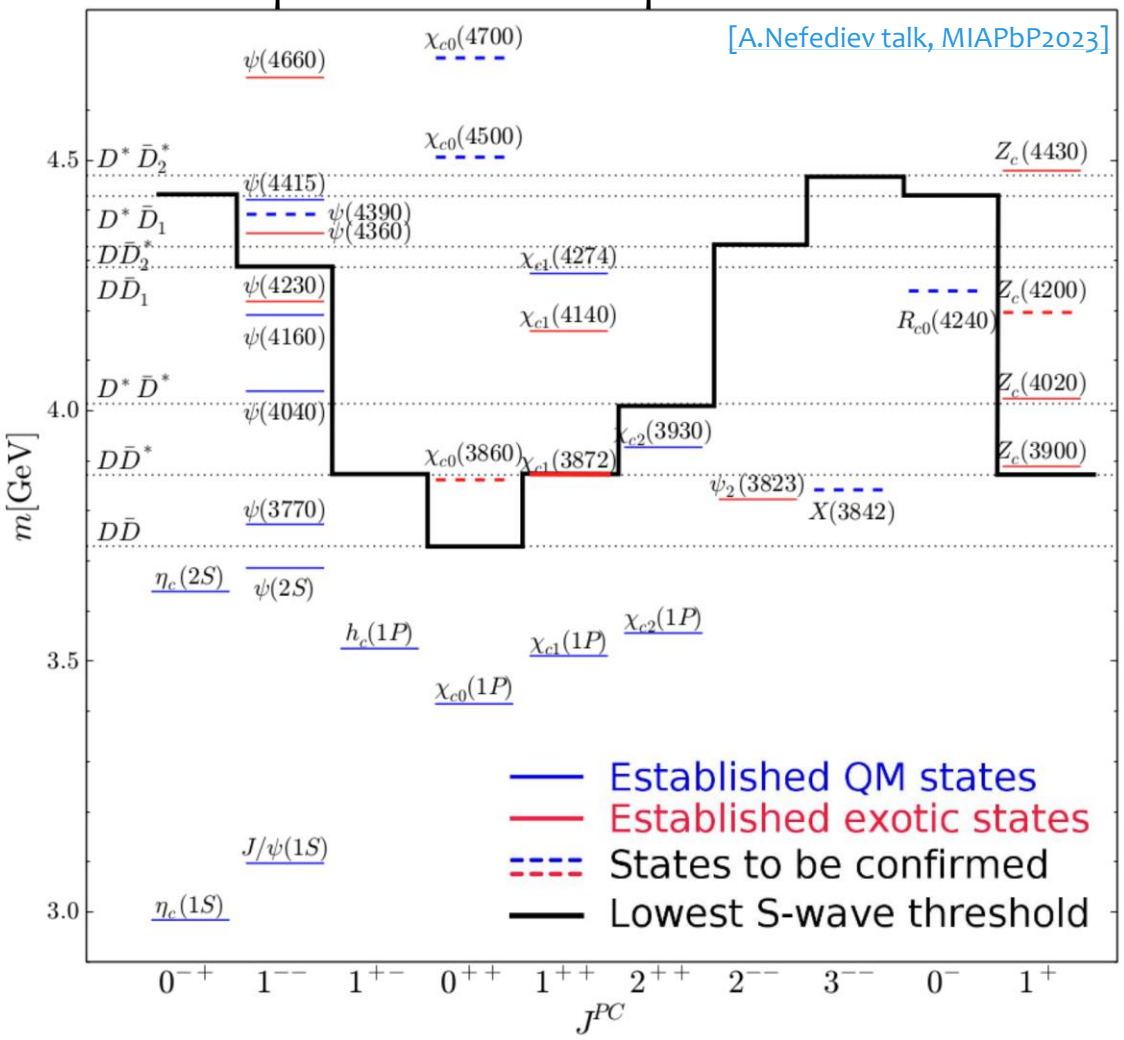
[JPAC analysis]

$J/\psi \rightarrow \gamma G(\rightarrow \pi\pi)$



QM states and thresholds

An example: charmonium spectrum



Most of hadrons are not isolated:

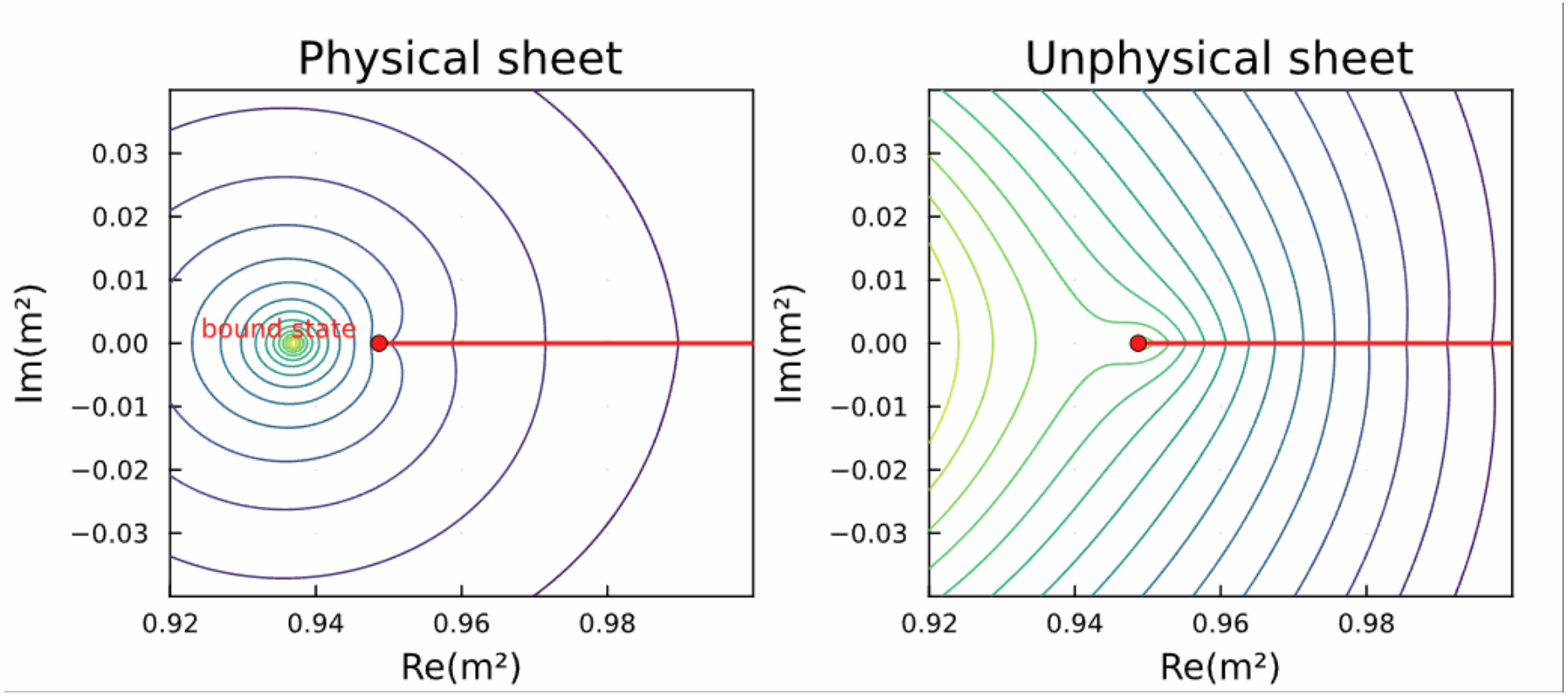
near hadron-hadron threshold,

e.g. $q\bar{q} \rightarrow (q\bar{q})(q\bar{q})$**,**

hadronic states are coupled to hadron-hadron continuum

Molecule component:
a part of the state wave function is $(q\bar{q})(q\bar{q})$

How molecule is often a good model



Transition: **bound state** → **virtual state** → **resonance.** No fundamental difference

The state is mostly **molecular** in vicinity of the threshold

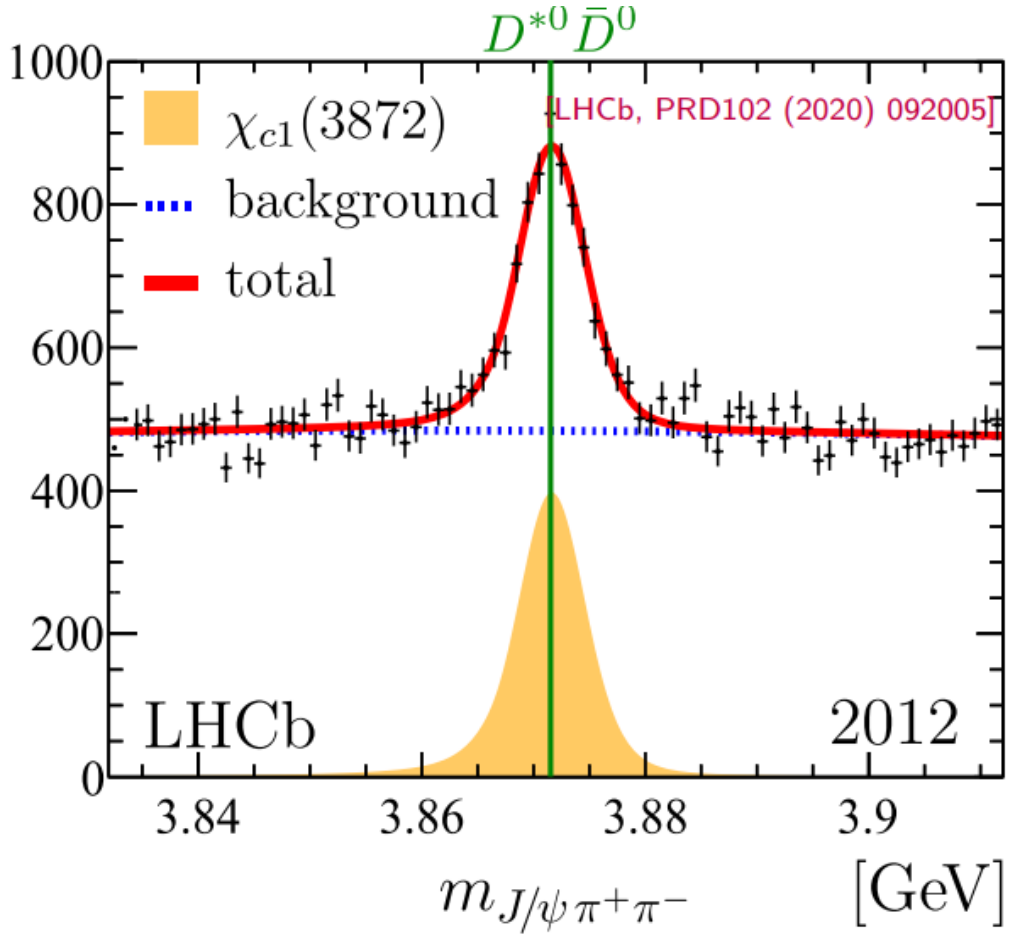
[GitHub/mmikhasenko]

Tetraquarks

[Midjourney 2023, MM] Highly defined macrophotography of a weird unseen quantum world + images

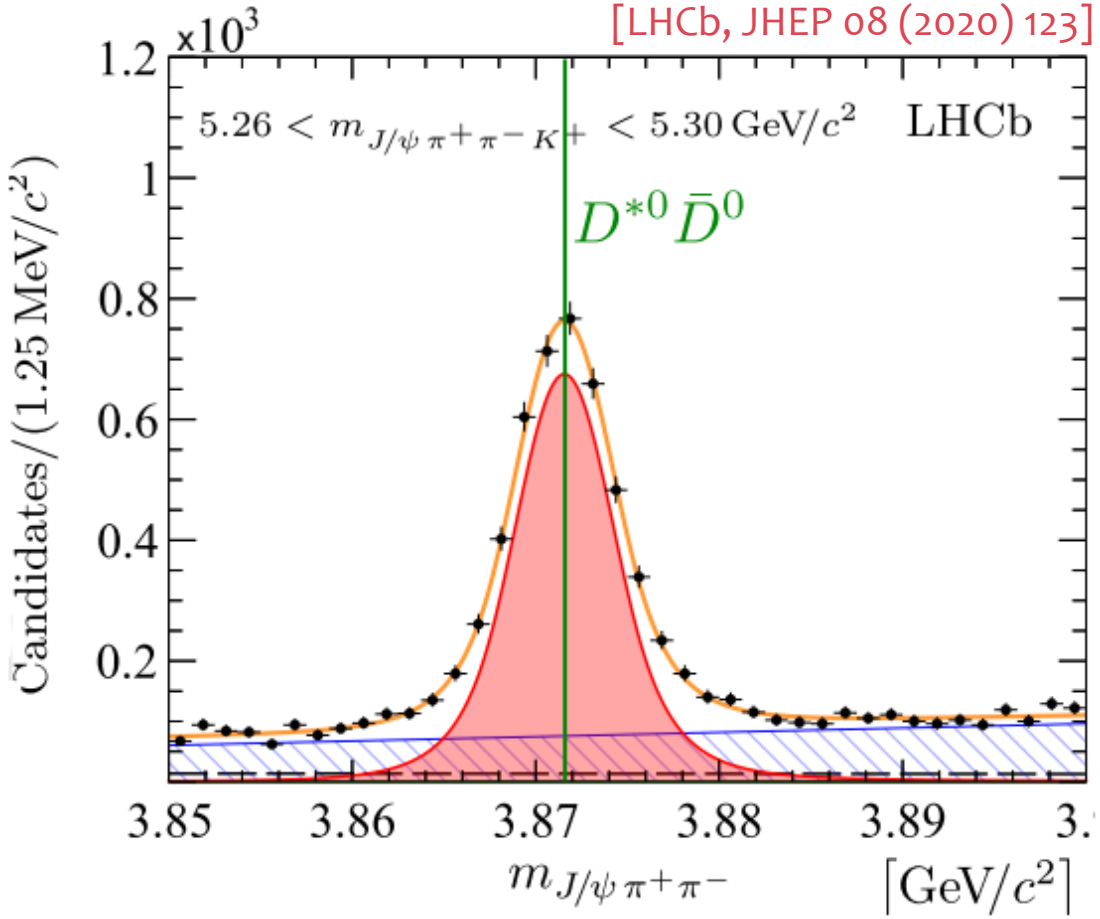
$\chi_{c1}(3872)$ in LHCb

Prompt production ($pp \to \chi_{c1} X$)



From B-decays ($B^+ \to \chi_{c1} K^+$)

[LHCb, JHEP 08 (2020) 123]



$\chi_{c1}(3872)$ lineshape update

General agreement on the pole parameters

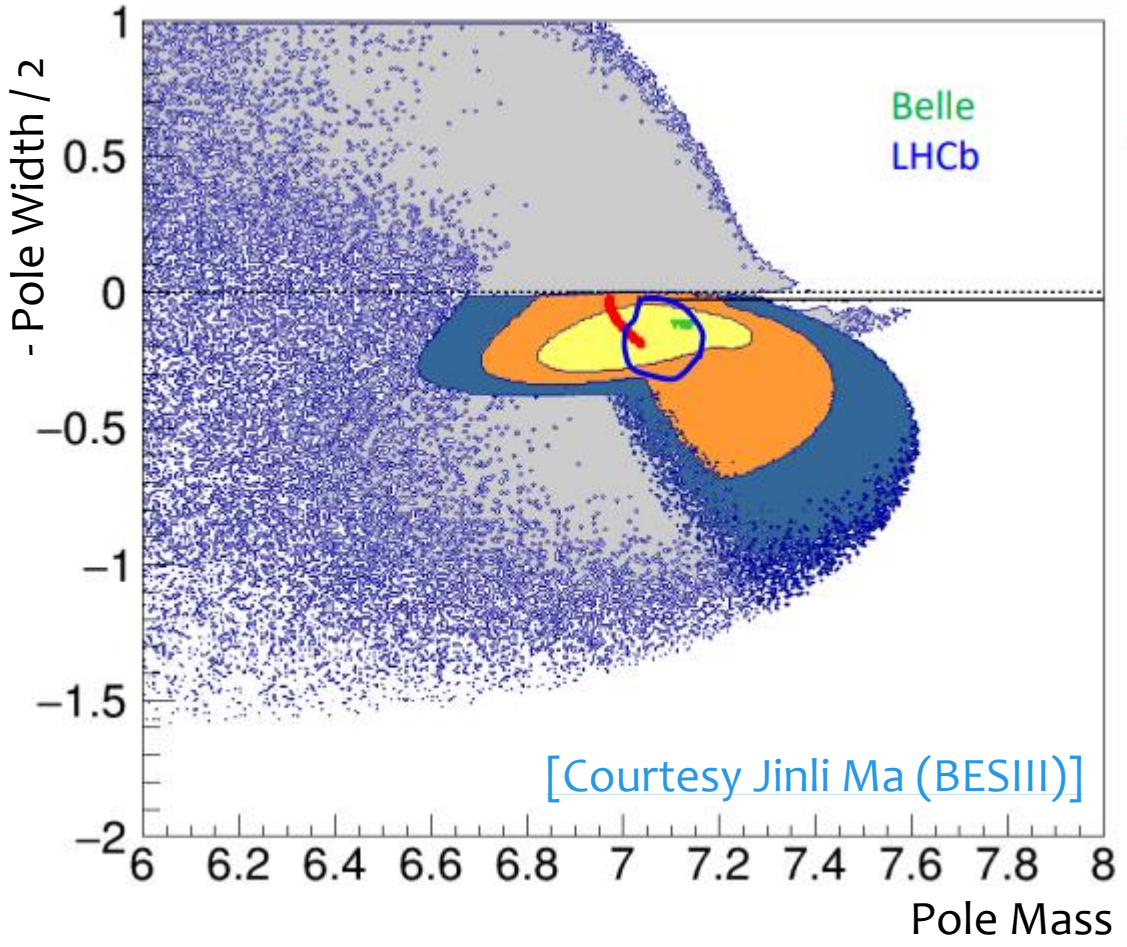
Between BESIII, Belle, LHCb

- Analysis of lineshape by LHCb in $J/\psi\,\pi^+\pi^-$

[LHCb, PRD102 (2020) 092005]

- BESIII analysis gives consistent result

[hep-ex: 2309.01502, see Wolfgang's talk on Monday]



$\pi^+\pi^-$ spectrum in $\chi_{c1}^0 \to J/\psi\,\pi^+\pi^-$

χ_{c1}^0 is mostly isosinglet,

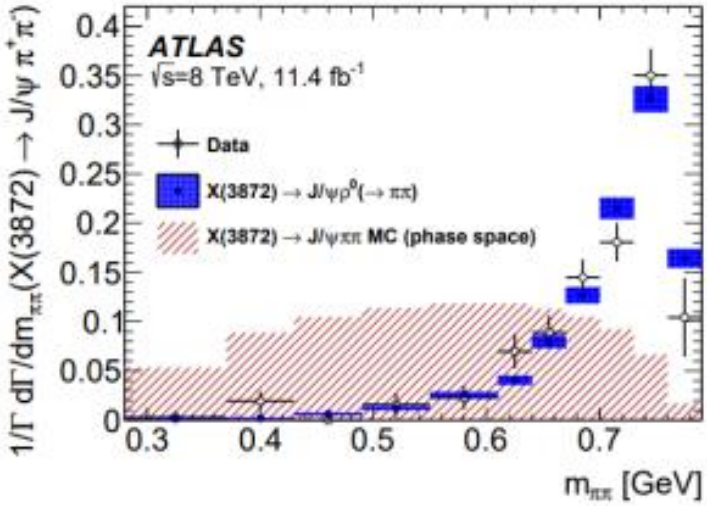
no $\chi_{c1}^0 \to J/\psi\,\pi^+\pi^0$

[BaBar PRD71, 031501 (2005); Belle PRD84, 052004 (2011)]

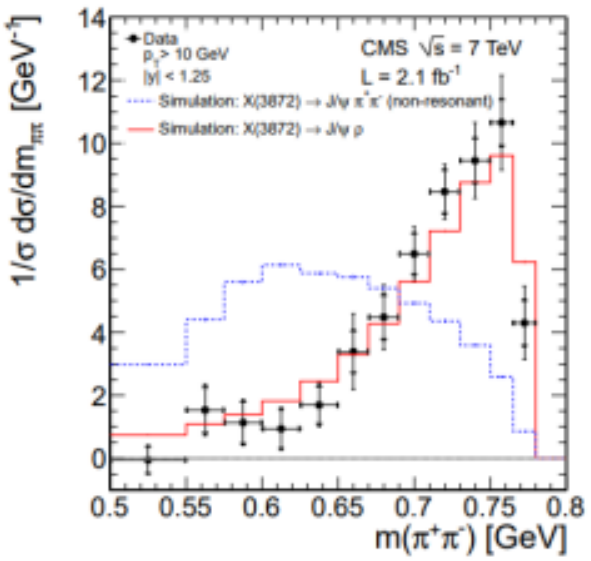
- $\chi_{c1}^0 \to J/\psi\,\omega$ conserves isospin
- $\chi_{c1}^0 \to J/\psi\,\rho$ violates isospin

$pp \to \chi_{c1}X$

[CMS, JHEP 04, 154 (2013)]



[ATLAS, JHEP 01, 117 (2017)]

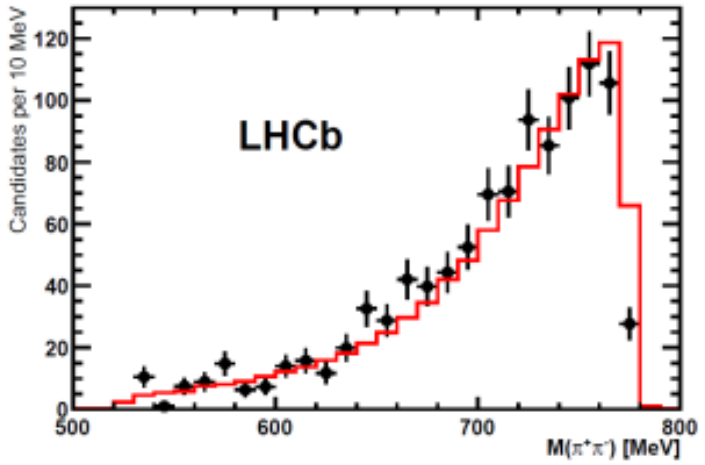


However, ($\pi\pi$) in the decay is in isovector model:

- No in $\chi_{c1}^0 \to J/\psi\,\pi^0\pi^0$ observed
- $\pi^+\pi^-$ distribution is consistent with ρ.

$B^+ \to \chi_{c1}K^+$

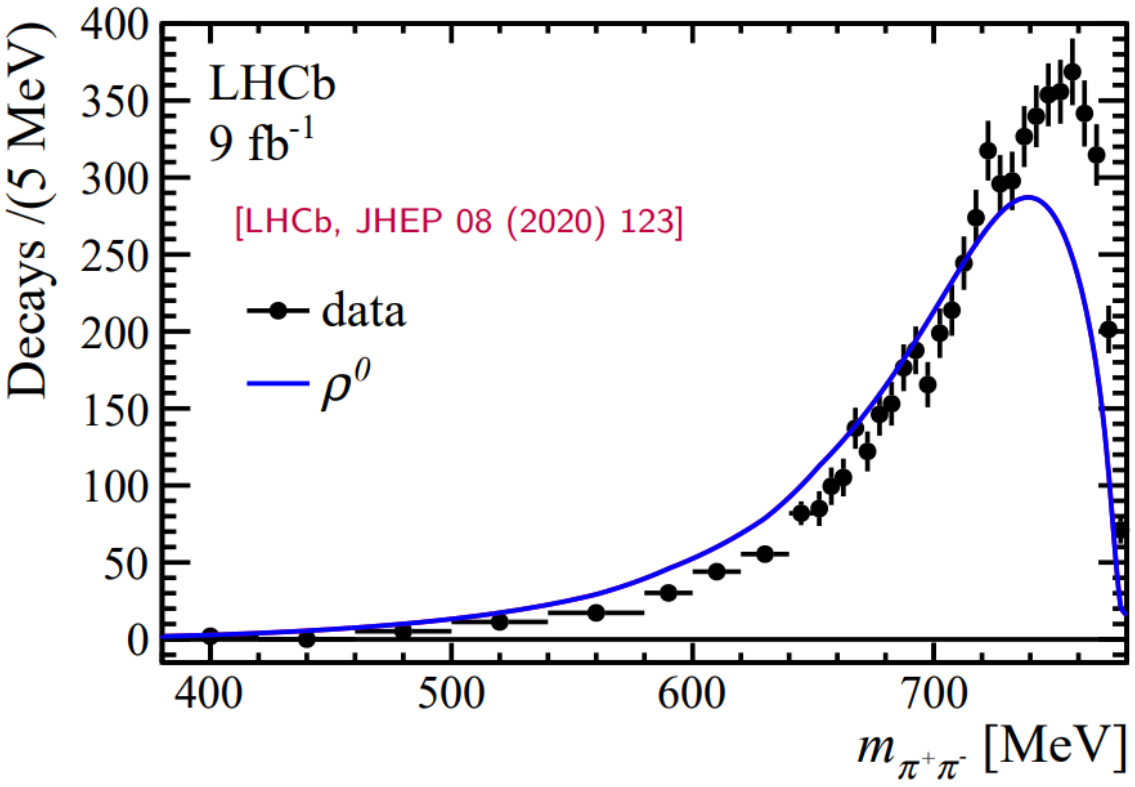
[LHCb, PRD92, 011102 (2015)]



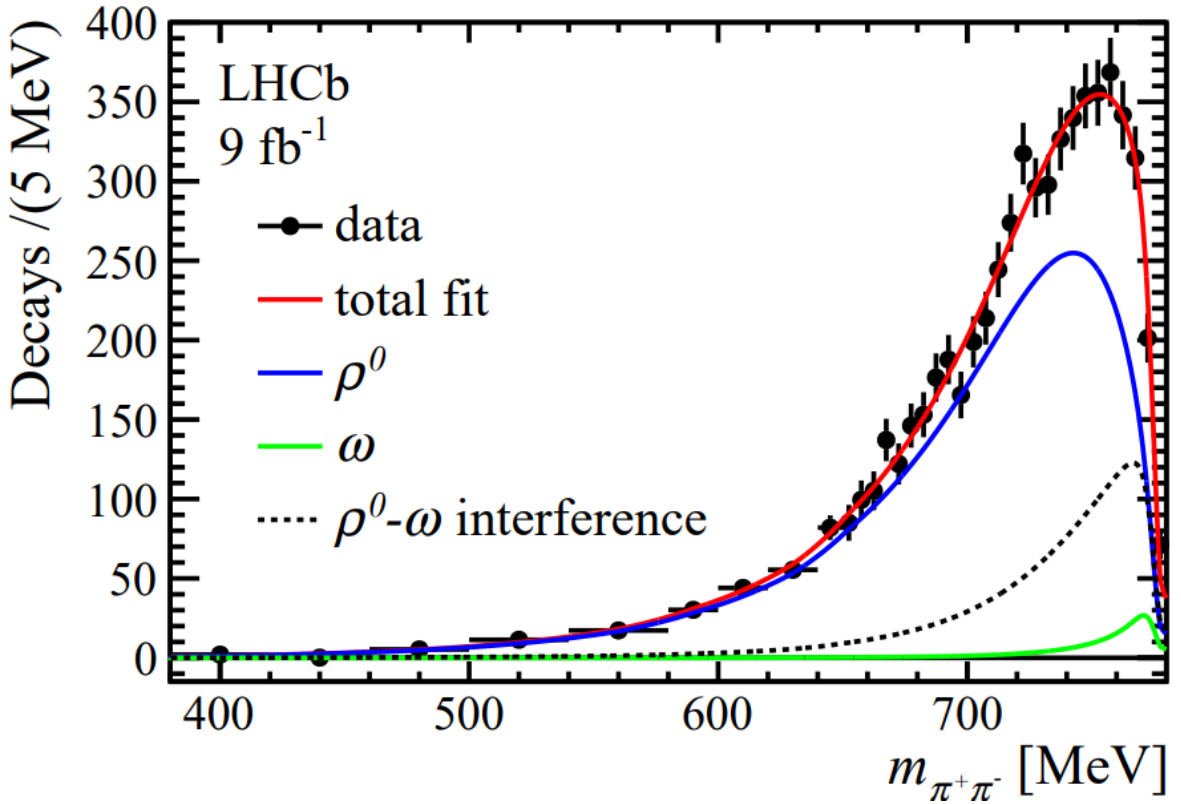
[LHCb, PR D108 (2023) L011103]

Significant ω contribution in $\chi_{c1}^0 \to J/\psi\,\pi^+\pi^-$ decays

Just $\rho^0 \to \pi^+\pi^-$ contradicts the data



$\omega \to \pi^+\pi^-$ is essential:
$\sim \mathrm{BW}_\rho(1 + k_\omega \mathrm{BW}_\omega)$



ρ/ω interference and effect of isospin violation

- Extend the upper limit of ph.sp, m(χ_{c1}^0) → 4 GeV
- Ratio of the integrals:

$$R_{\omega/\rho} = 0.18 \pm 0.05(\text{stat})$$

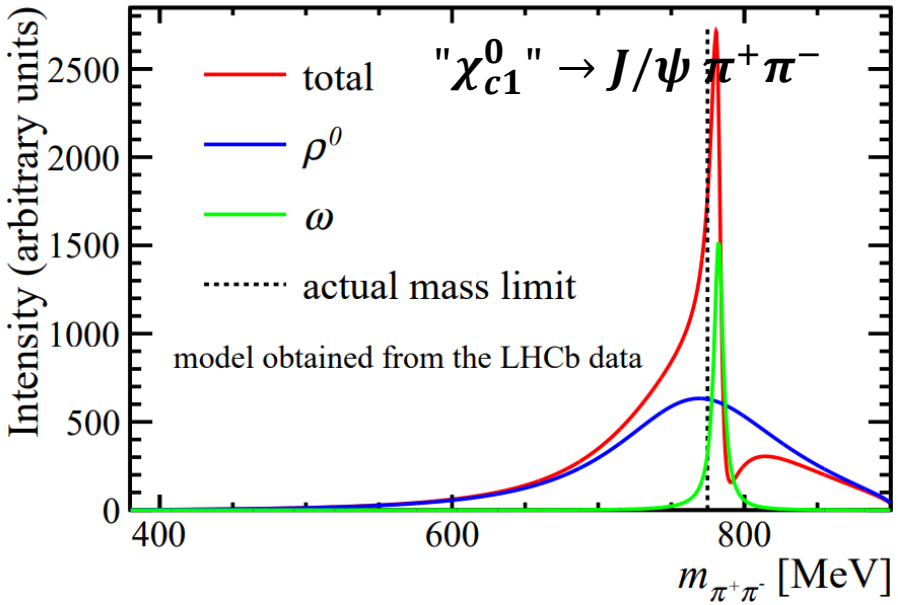
- The estimate for couplings ratio:

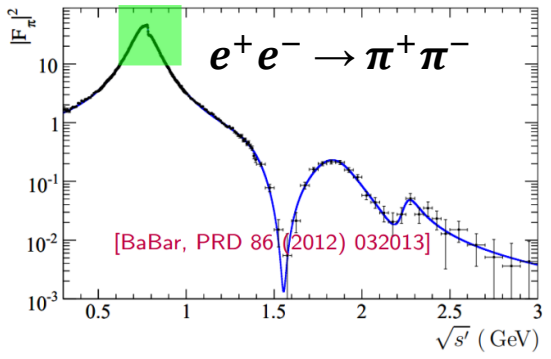
$$\frac{g_{\chi_{c1}\to\rho J/\psi}}{g_{\chi_{c1}\to\omega J/\psi}} = \sqrt{\frac{\mathcal{B}(\omega\to 2\pi)}{\mathcal{B}(\rho\to 2\pi)}\frac{1}{R_{\omega/\rho}}} = 0.29 \pm 0.04$$

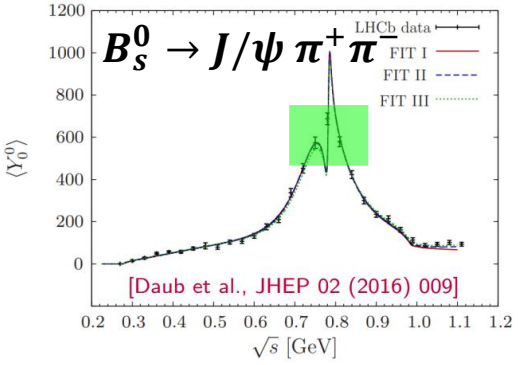
- Can be compared to typical isospin breaking

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

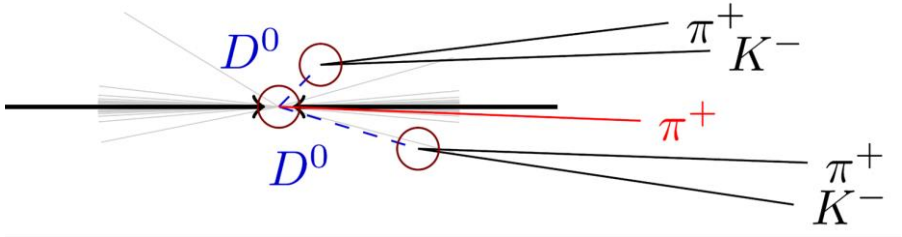
[LHCb, PR D108 (2023) L011103]







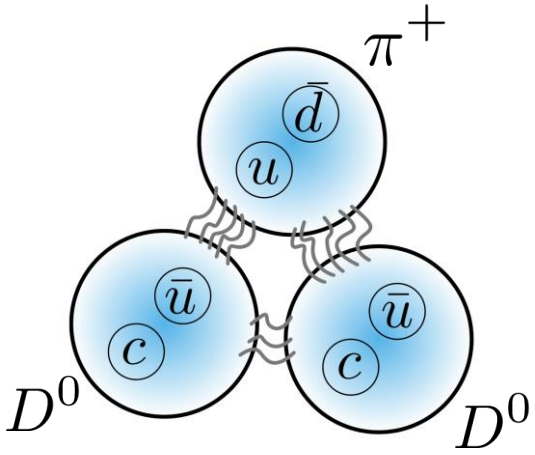
Observation of the doubly-charm tetraquark T_{cc}^{+}



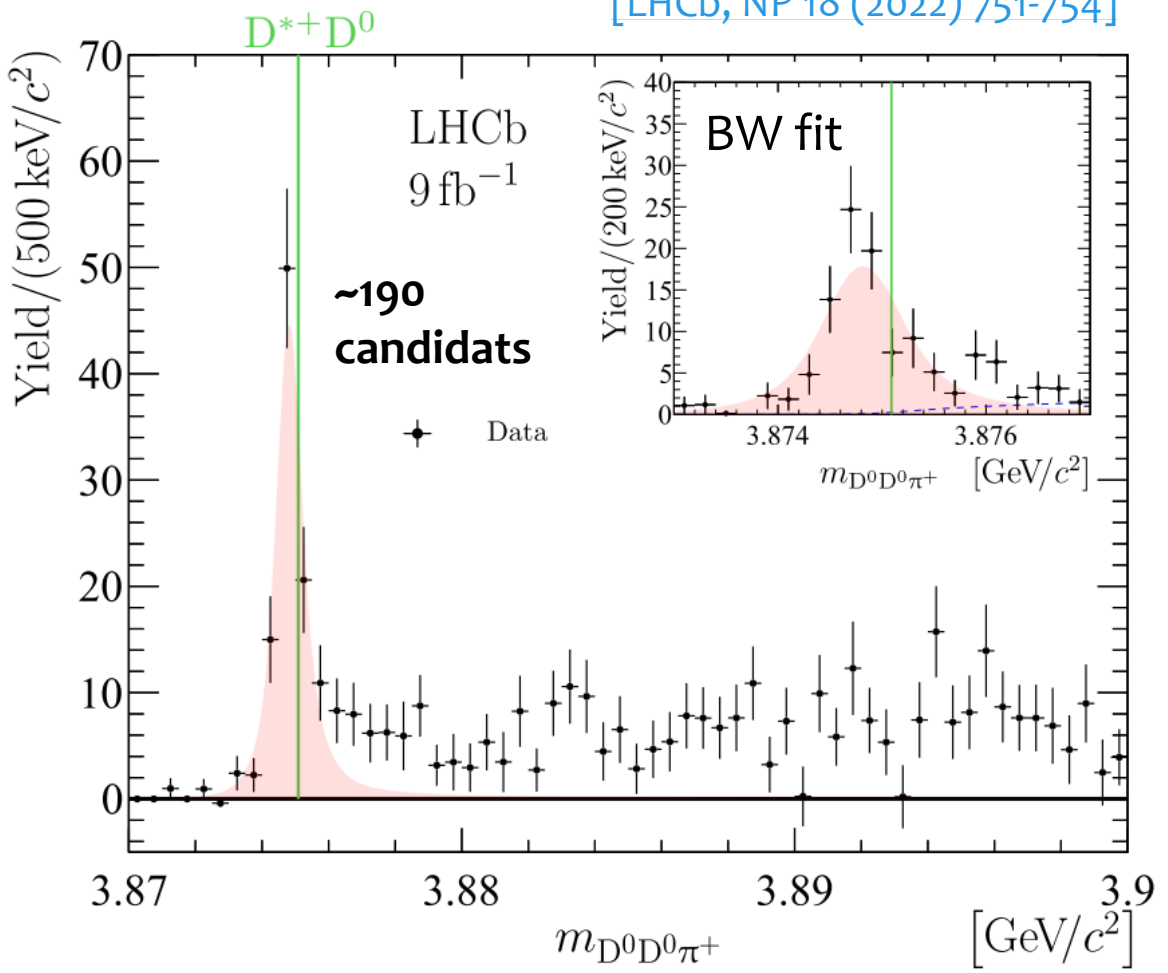
Peak in $D^0D^0\pi^+$ just below $D^{*+}D^0$ threshold

Extremely narrow, ~300keV (resolution)

Needs to be treated as three-body effect

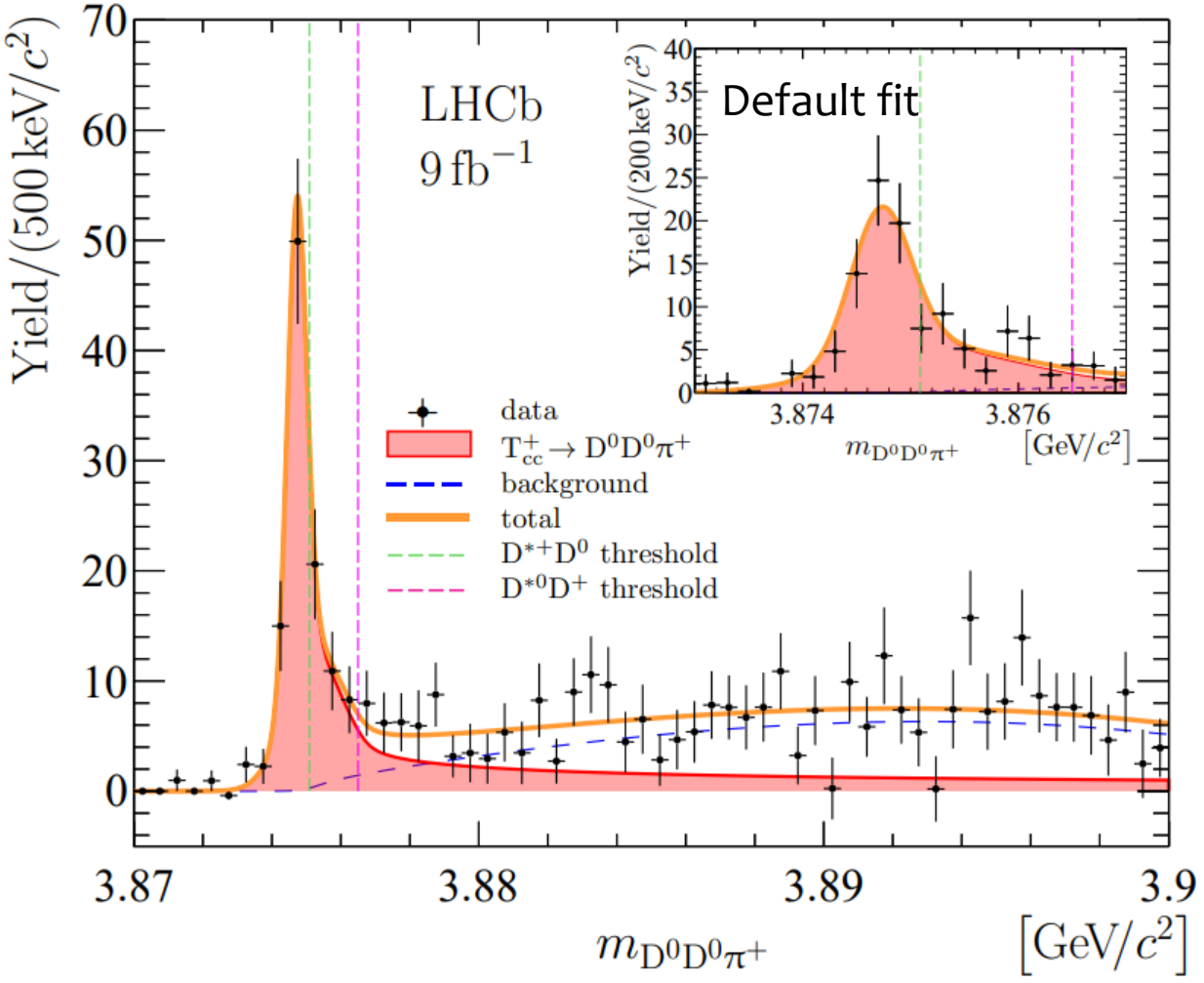


[LHCb, NP 18 (2022) 751-754]



Studies of the doubly-charm tetraquark T_{cc}^{+}

[LHCb, NC 13 (2022) 3351]



QN: isoscalar ($I = 0$), axial ($J^{PC} = 1^{++}$)

Coupled channel model

$$D^{*+}D^0 + D^{*0}D^+$$

$$\to \{D^0D^0\pi^+, D^0D^+\pi^0, D^0D^+\gamma\}$$

Yields pole parameters:

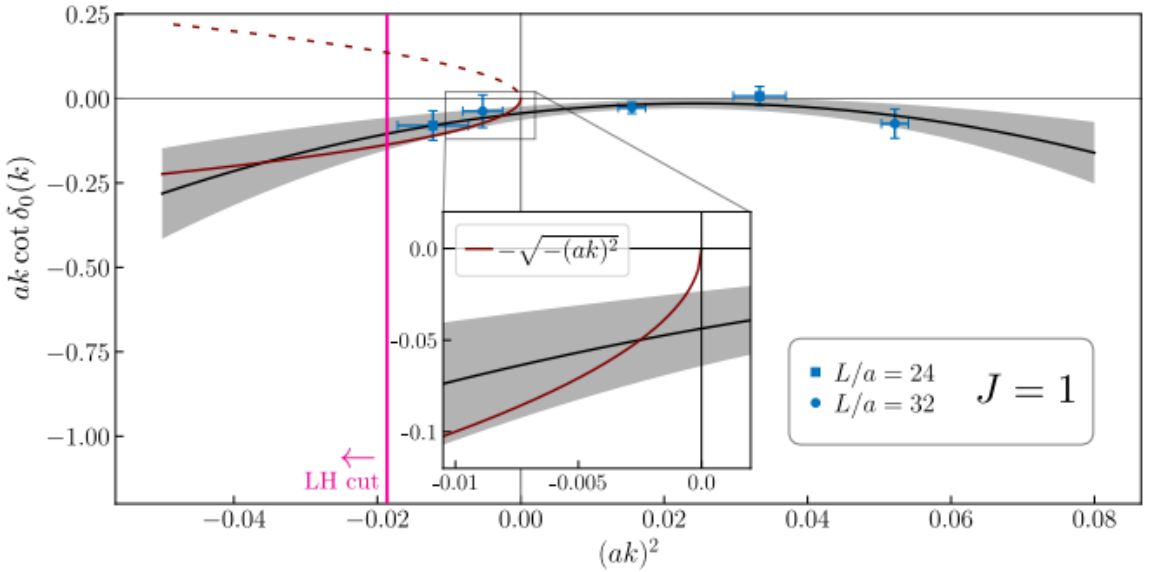
- **Binding energy:** $-360 \pm 40^{+4}_{-0}$ **keV**
- **Width:** $48 \pm 2^{+0}_{-14}$ **keV**

New class of hadrons $QQ\bar{q}\bar{q}$

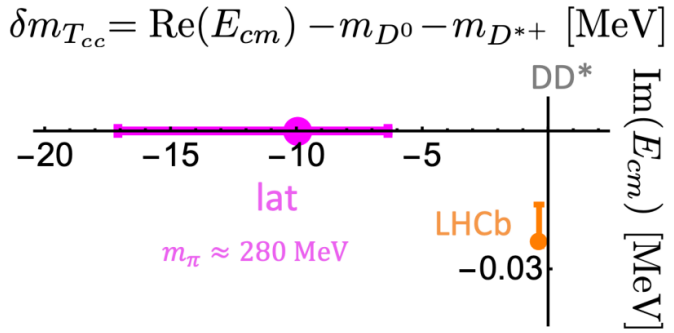
	$J^P = 0^+$	$J^P = 1^+$	
distance from threshold ↑	?	$bb\bar{u}\bar{d}$	stable*
	? $bc\bar{u}\bar{d}$	$bc\bar{u}\bar{d}$	stable (?*)
		$cc\bar{u}\bar{d}$	**nearly stable**
	? $cs\bar{u}\bar{d}$	$cs\bar{u}\bar{d}$	**resonance** (?*)
		$ss\bar{u}\bar{d}$	resonance*

* not yet observed

[C. Alexandrou et al]



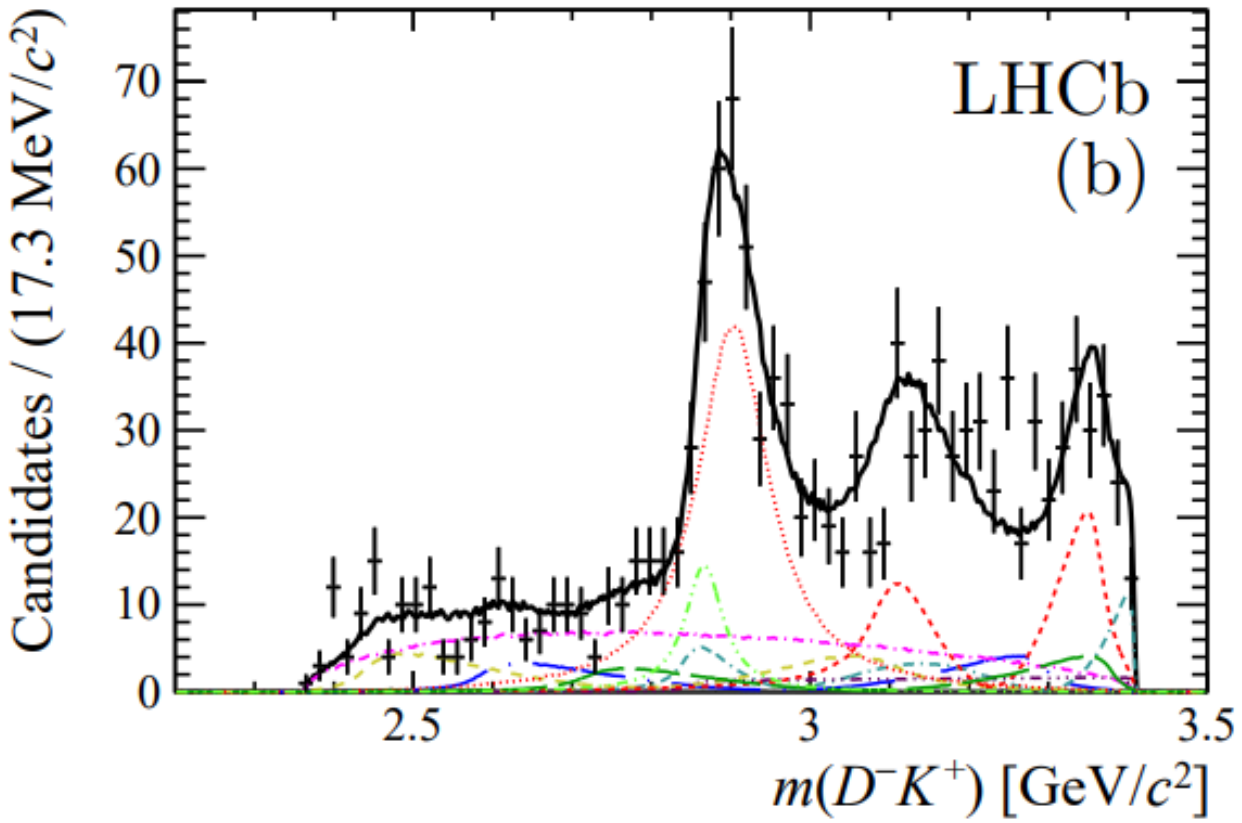
[M. Padmanath, S. Prelovsek]



Resonance in D^-K^+

$B^+ \to D^+D^-K^+$

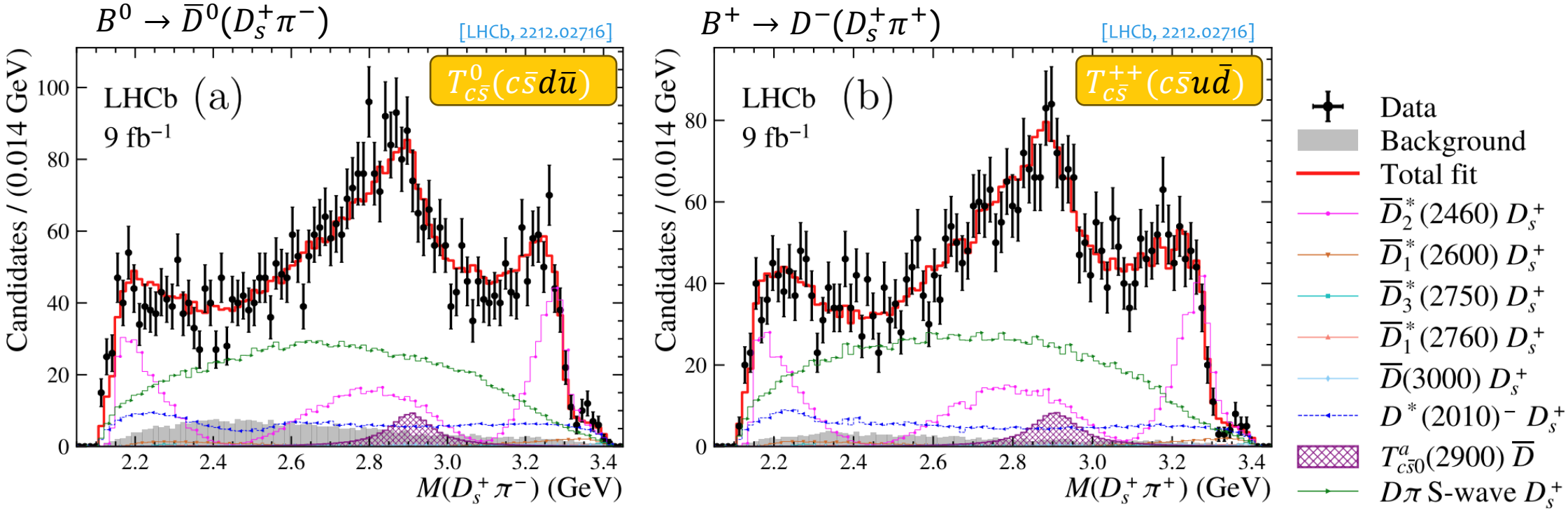
[LHCb, PRD 102 (2020) 112003, PRL 125 (2020) 242001]



Three body decay of B^+ (1374 cand. for R1&2)

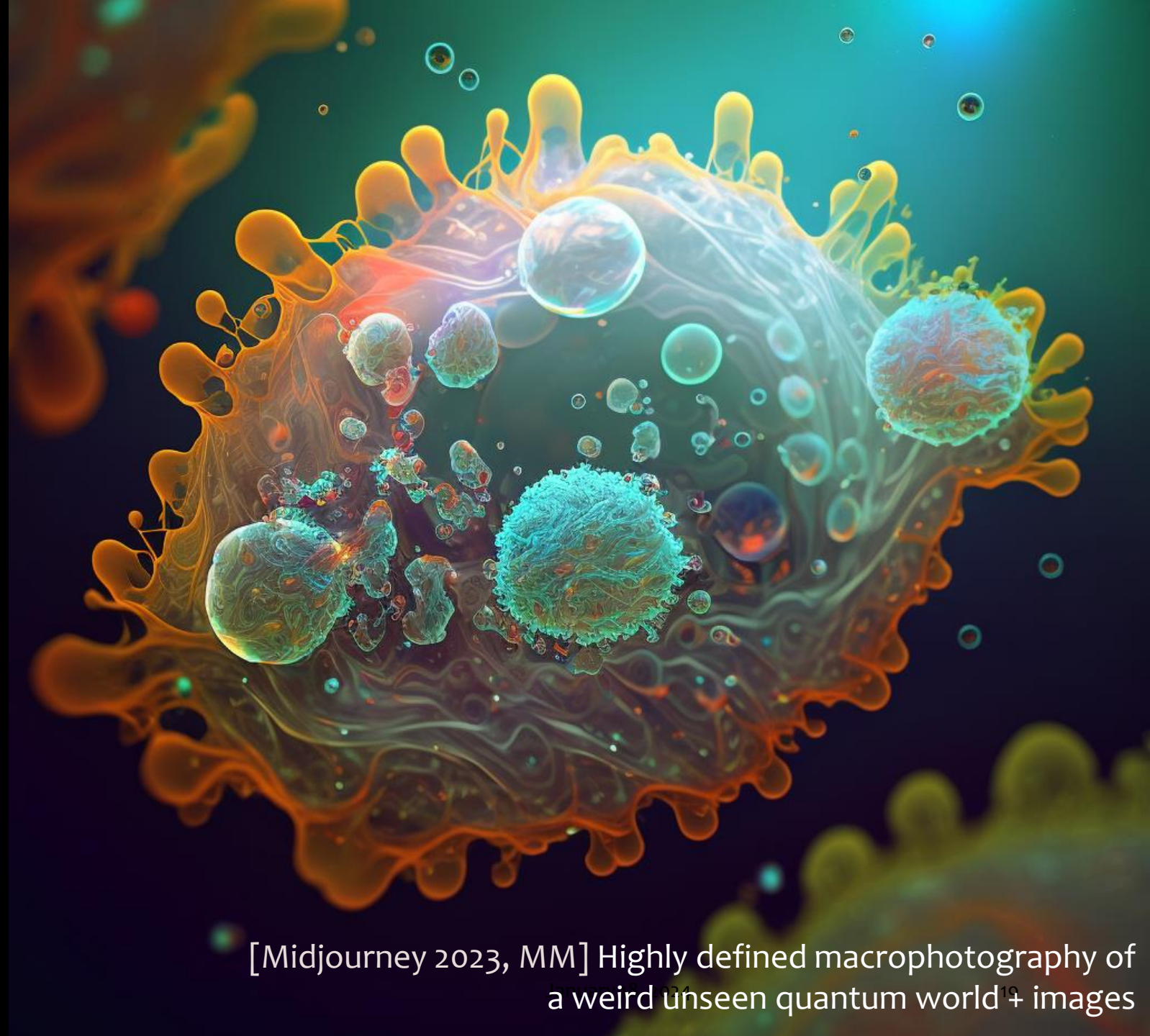
- **Many D^+D^- resonances**
- **Structure at ~8.5 GeV²**
- **Both quantum numbers $J^P = 1^-$ and 0^+ are both wanted in the fit**

$T^0_{cs}(cs\bar{u}\bar{d})$ isoscalar, the lowest $J^P = 0^+$



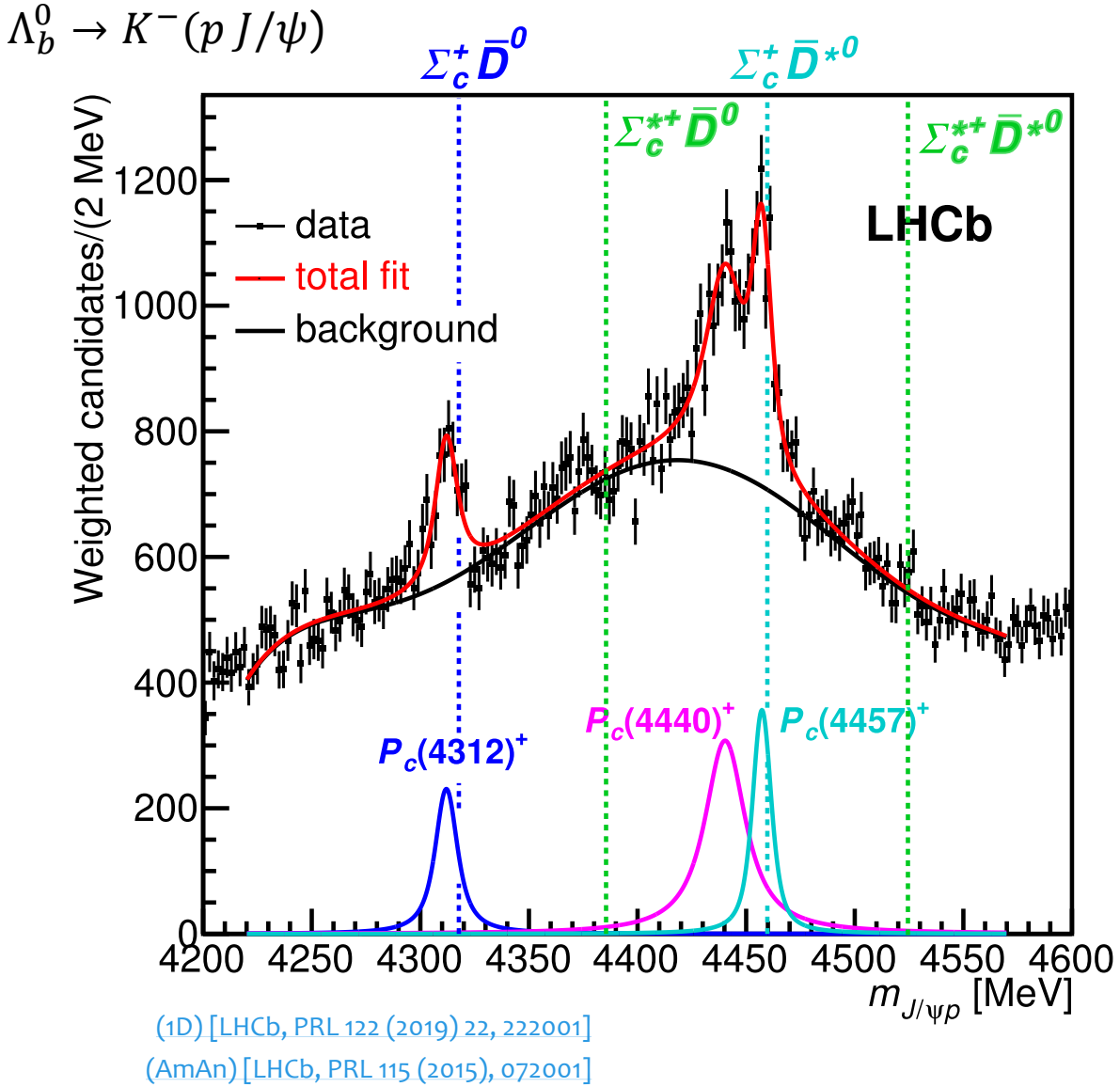
Surprising enhancement again at 2.9 GeV [$T^0_{c\bar{s}}$ & $T^{++}_{c\bar{s}}$]

Pentaquarks



[Midjourney 2023, MM] Highly defined macrophotography of a weird unseen quantum world + images

Famous Pentaquarks



(1D) [LHCb, PRL 122 (2019) 22, 222001]

(AmAn) [LHCb, PRL 115 (2015), 072001]

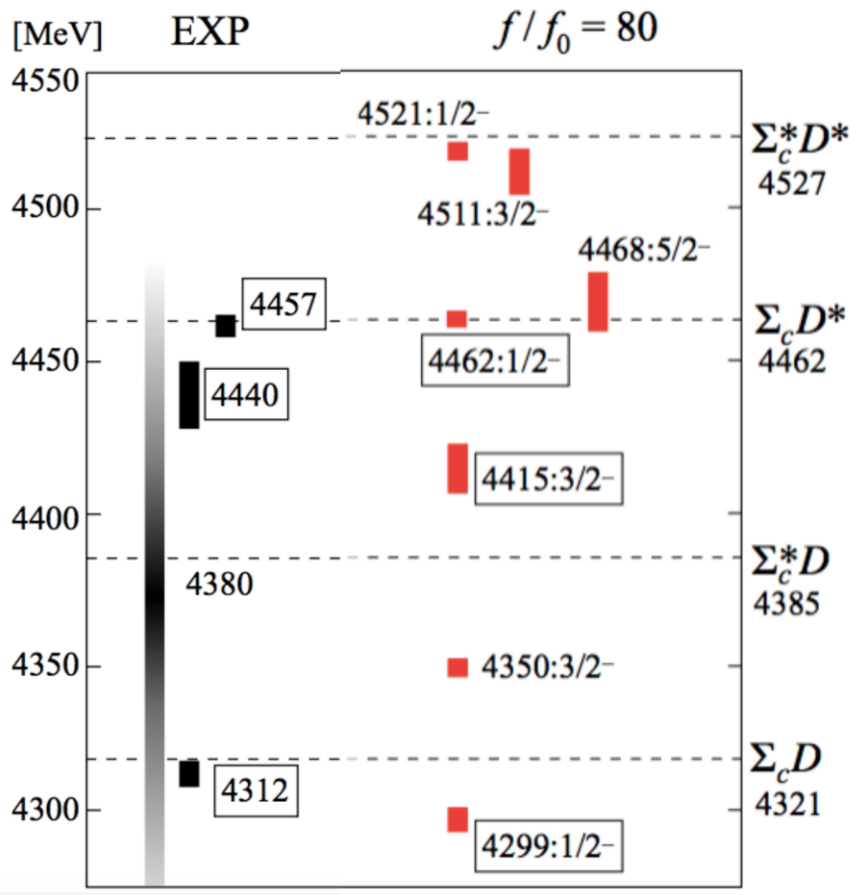
Near threshold

Multiplicity matches threshold spin algebra

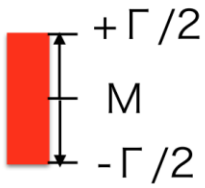
QM states are complex and unknown

A potential model

1.



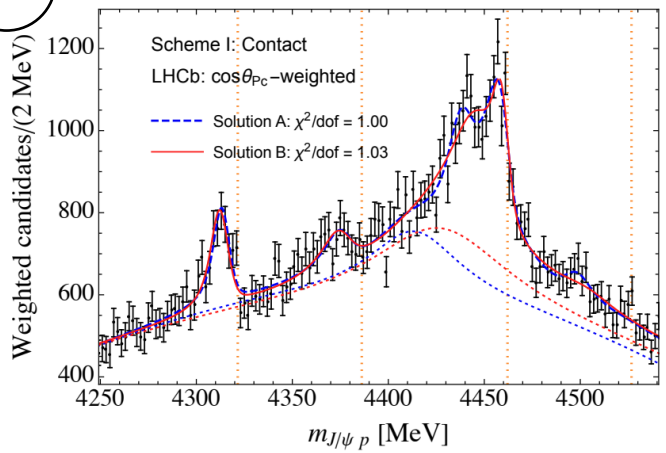
[Yamaguchu et al., 2303.06079]



As an example, molecule spectrum of $P_{c\bar{c}}^{+}$.
It explicitly includes:

- **Contact V_{5q} + One-pion exchange V_π**
- **Tensor interaction is important**

2.

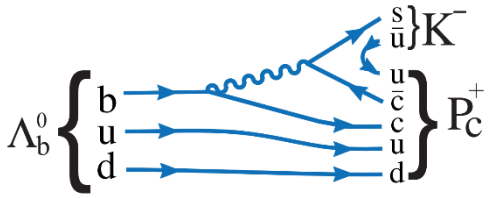


[Meng-Lin Du et al., *JHEP* 08 (2021) 157]

describes the projection with coupled-channel model

Full-dim. fit is the next step

Exploration of similar final states



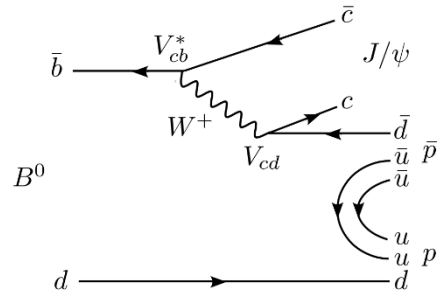
more diff. to produce

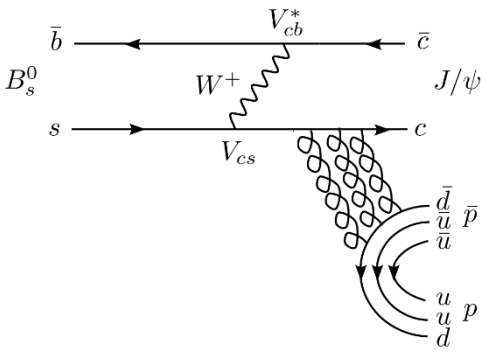
$\Lambda_b^0 \to J/\psi K^- p$ ✓ (2015,2019)

$\Sigma_b^0 \to J/\psi K^- p$

$\Xi_b^- \to J/\psi K^- \Lambda$ ✓ (2021)

$\Omega_b^- \to J/\psi K^- \Xi^0$





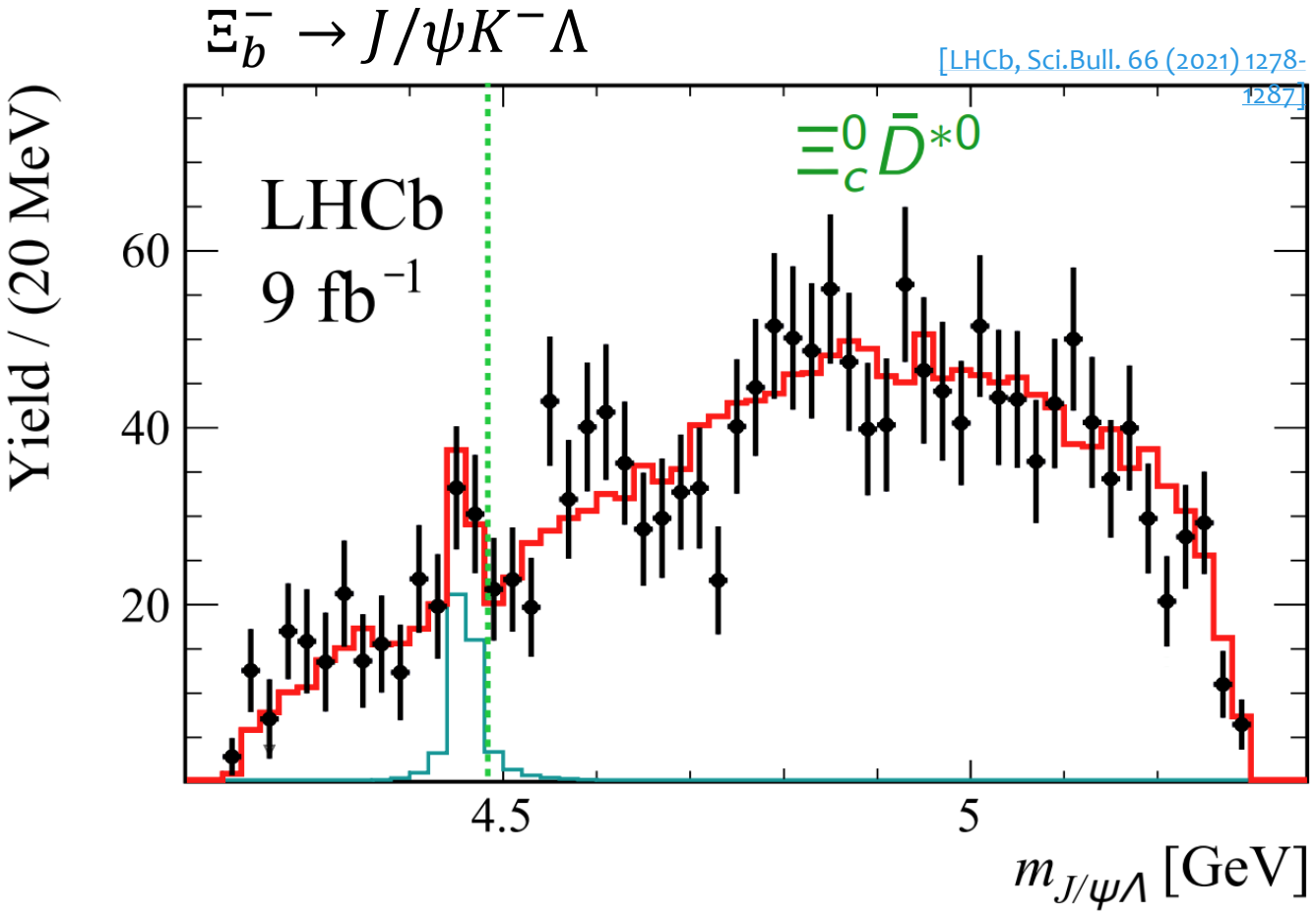
smaller ph.sp

$B^0_{(s)} \to J/\psi p\bar{p}$ ✓ (2021)

$B^- \to J/\psi \Lambda \bar{p}$ ✓ (2022)

$B_s^0 \to J/\psi \Lambda \bar{\Lambda}$

Strange Partner-I*

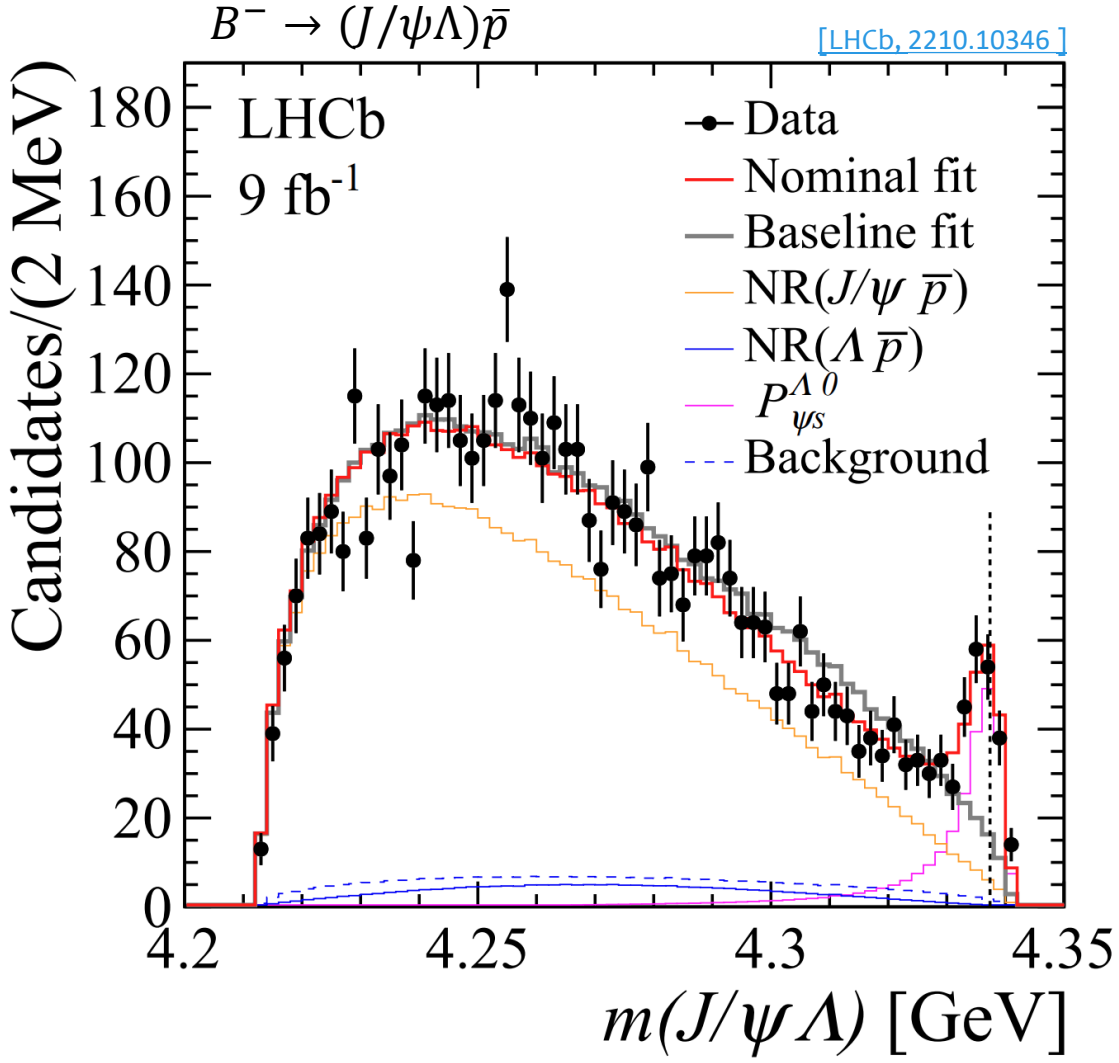


The Ξ_b^- decay amplitude built as

- $\Xi_b^- \to J/\psi \Xi^{**-}$ (dominant)
- $J/\psi\Lambda$ resonance near $\Xi_c^0 \bar{D}^{*0}$ threshold caused by discrepancy for large $(K^-\Lambda)$ mass

$$A \to \overbrace{\blacksquare(m^2_{K^-\Lambda^0}, m^2_{J/\psi\Lambda^0})}^{\text{Dalitz plot}} \times \overbrace{\blacksquare(\theta_{J/\psi}, \phi_{J/\psi})}^{J/\psi\to\mu^+\mu^-)} \times \overbrace{\blacksquare(\theta_{\Lambda^0}, \phi_{\Lambda^0})}^{\Lambda^0\to p\pi^-}.$$

If two states, 1/2, 3/2, they cannot be resolved.



Strange Partner-II*

Prominent peak near $\Xi_c\bar{D}$ threshold

- **0.8±0.7 MeV above $\Xi_c^+ D^-$**
- **2.9±0.7 MeV above $\Xi_c^0 \bar{D}^0$**

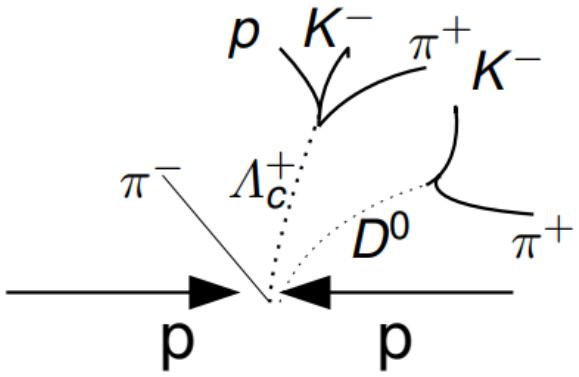
$J^P = 1/2^-$ is preferred

Aligned with $\Xi_c^+ D^-$ molecule

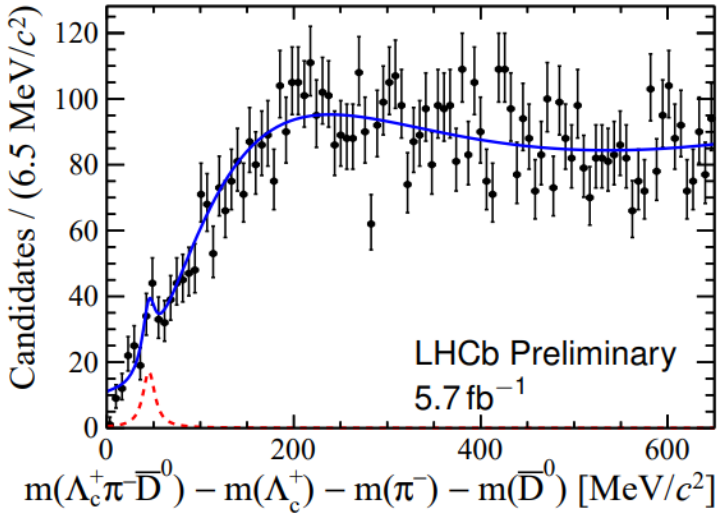
New search of Pentaquarks in open-flavor decays (★)

Pentaquark states seen in $J/\psi\, p$

must leave traces in $\Sigma_c^{(*)++} D^{(*)-}$



[courtesy G. Robertson (LHCb)]



New search in prompt production is performed

in many systems

Statistically limited,

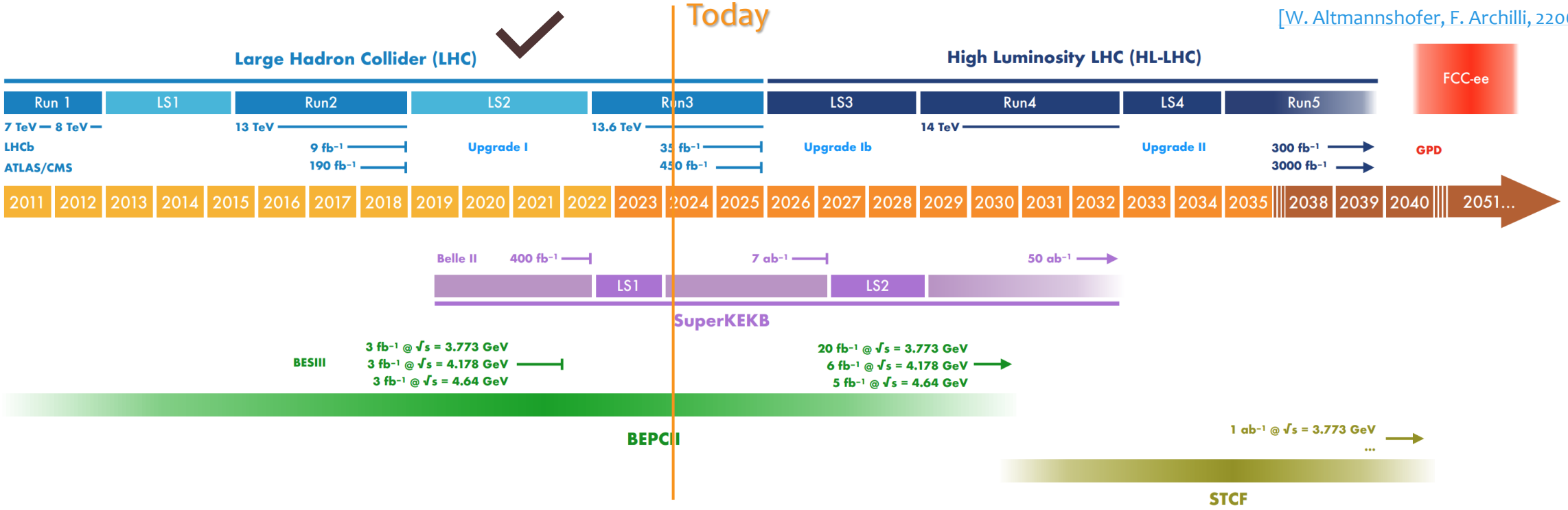
<3 sigma

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

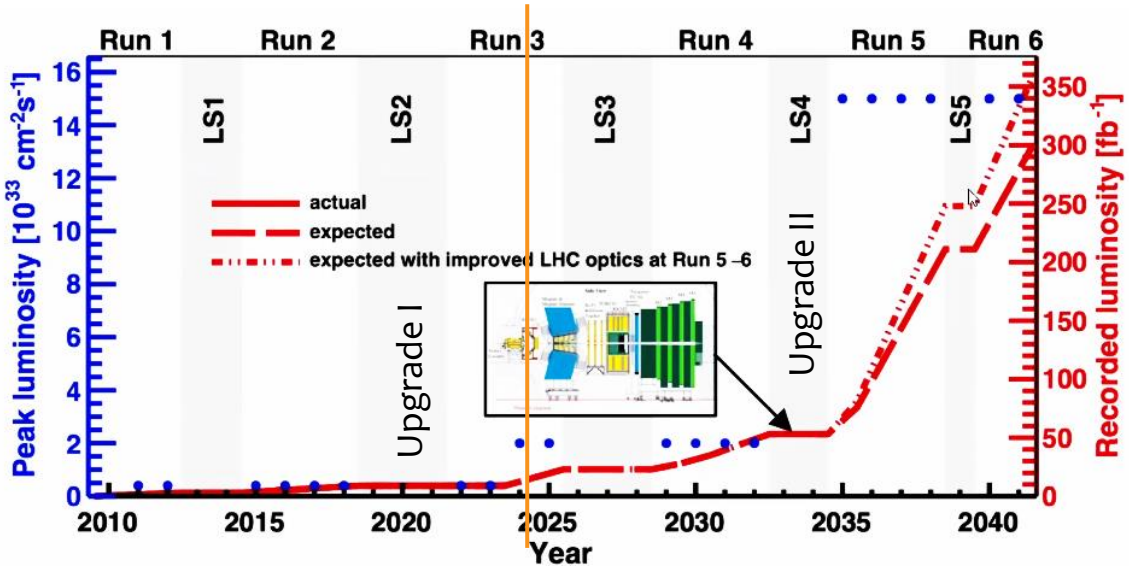
[LHCb-PAPER-2023-018, in preparation]

LHCb Run3 and Outlook

[W. Altmannshofer, F. Archilli, 2206.11331]



Planned schedule



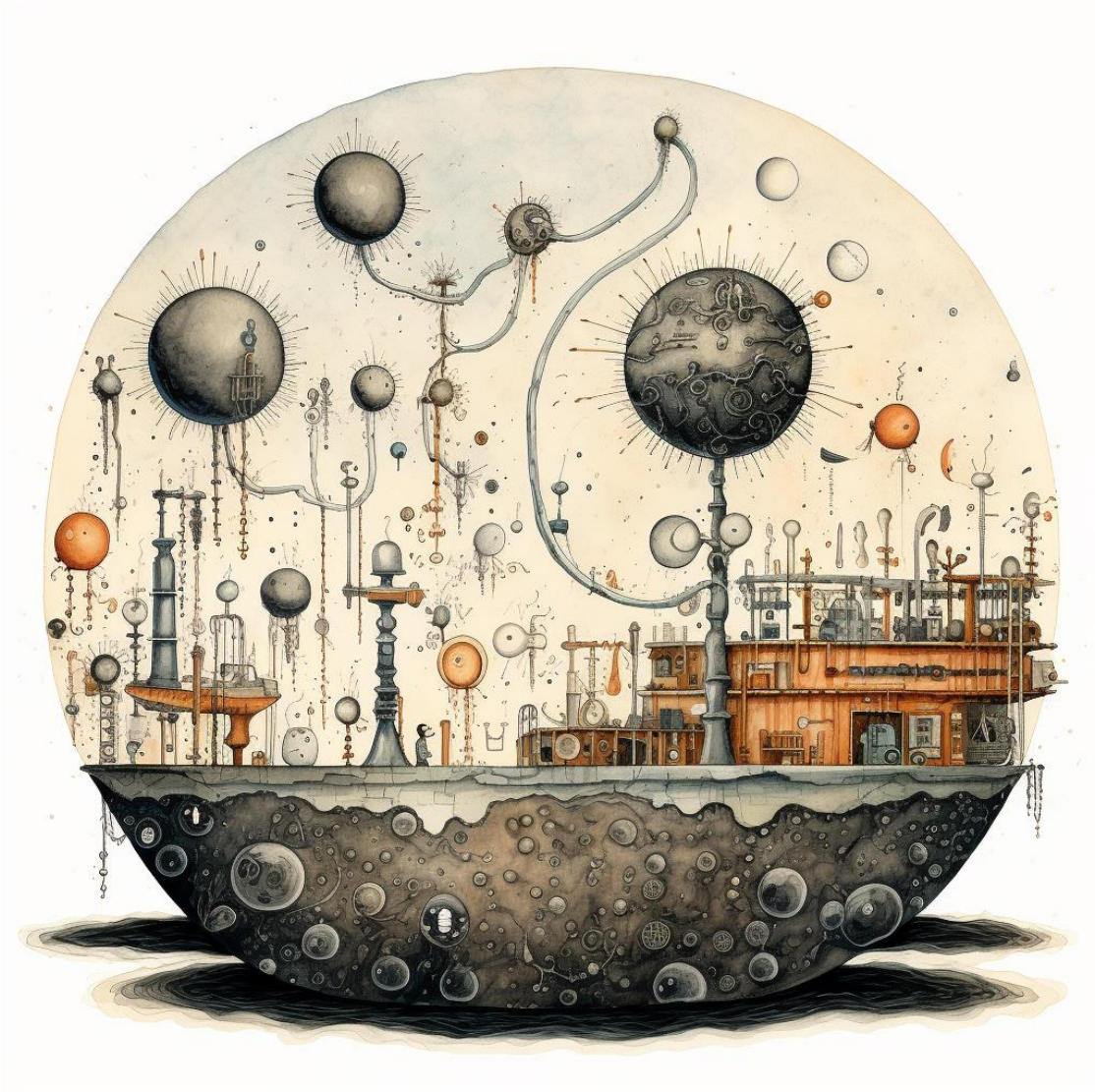
Conclusion

- Huge of progress in heavy flavor exotic spectroscopy.

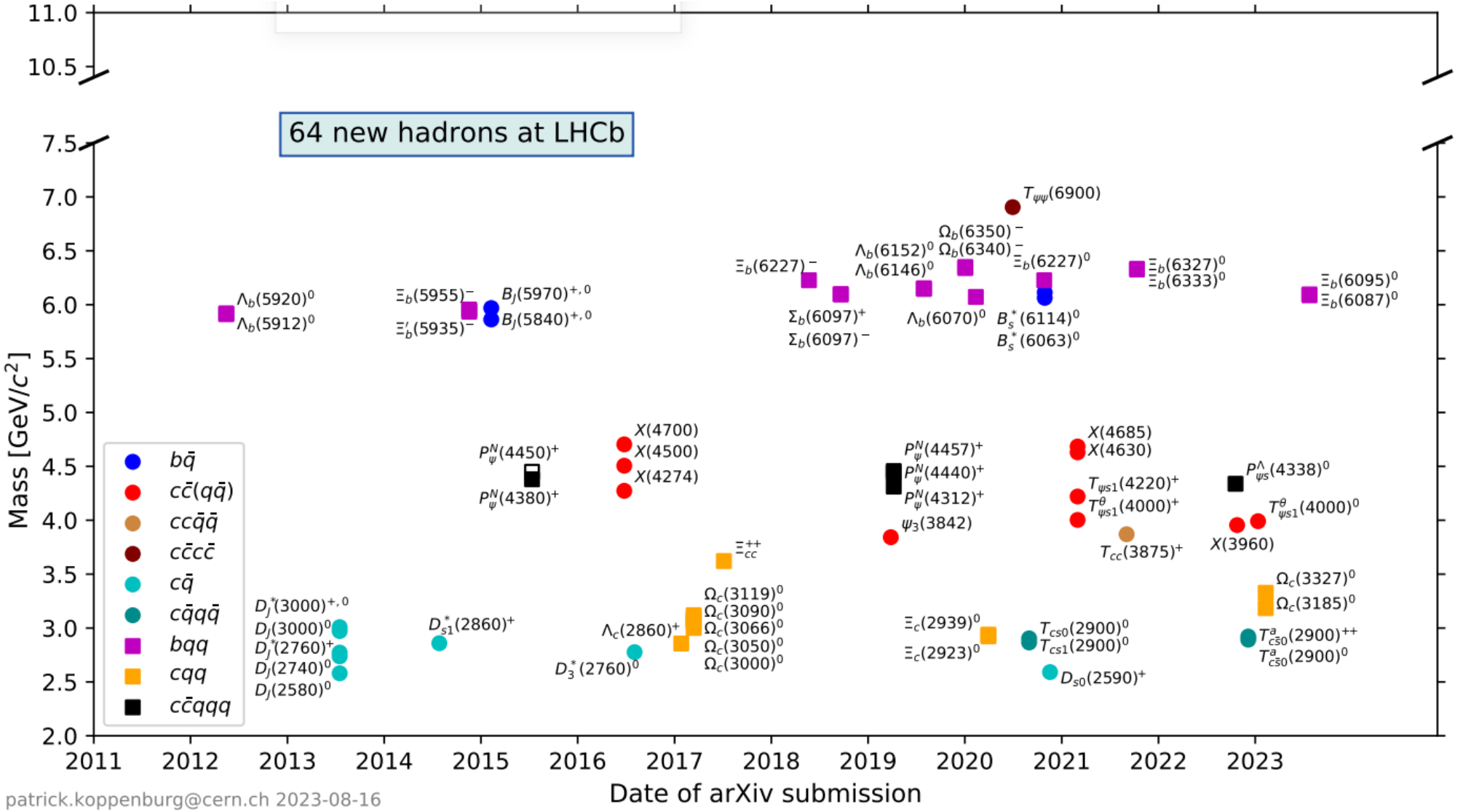
- The hadron spectroscopy is clearly beyond conventional mesons and baryons.
- New classes of hadrons are being unrevealed.

- Effect of Hadronic Continuum is one of the key discovery and main challenge in front of us.

Thank you for the attention



Thank you for the attention



Dip at the place of 4140

Two key structures in Ds-Ds+

- **Threshold expansion**

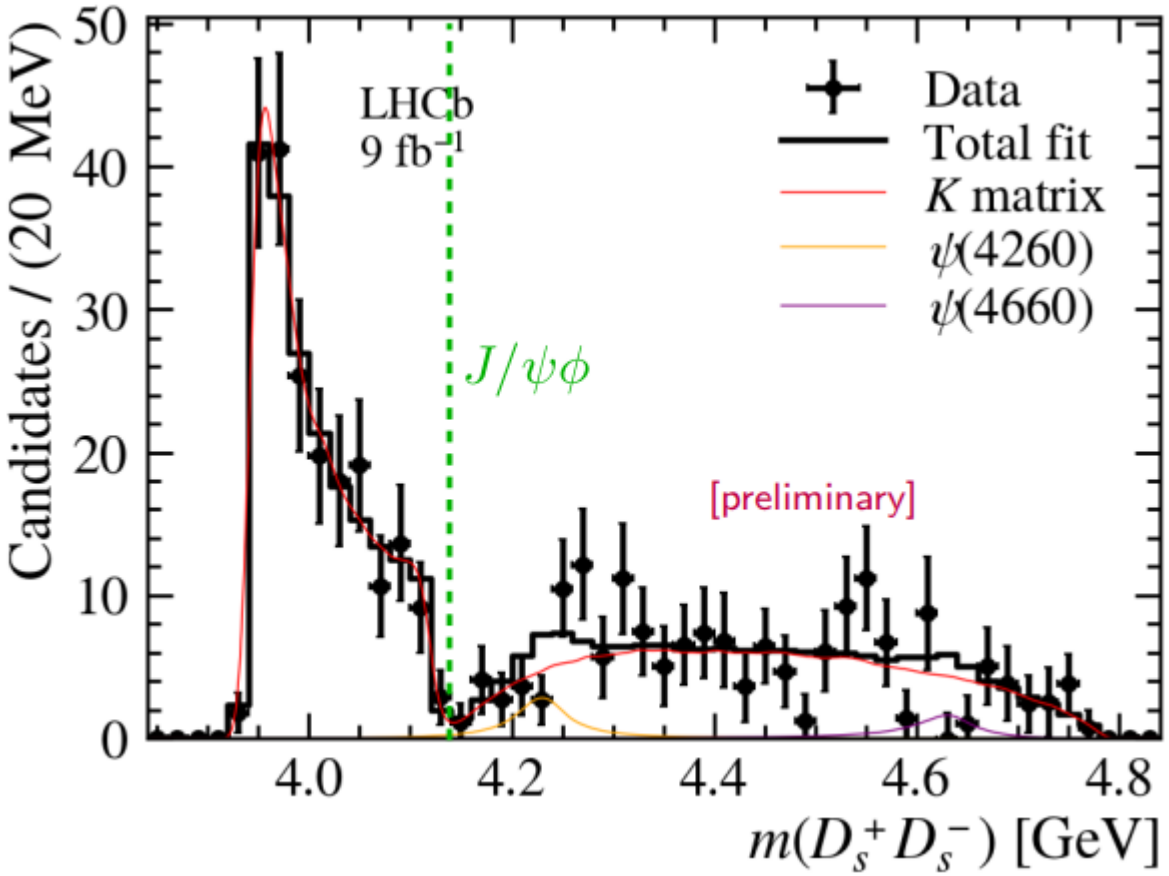
3915 / 3930/ 3930

- **Depletion right at the Jpsi phi threshold**

Also, at the place of 4140, seen by BELLE

[see Elisabeth's talk on Monday]

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



Prediction of the three-body spectrum

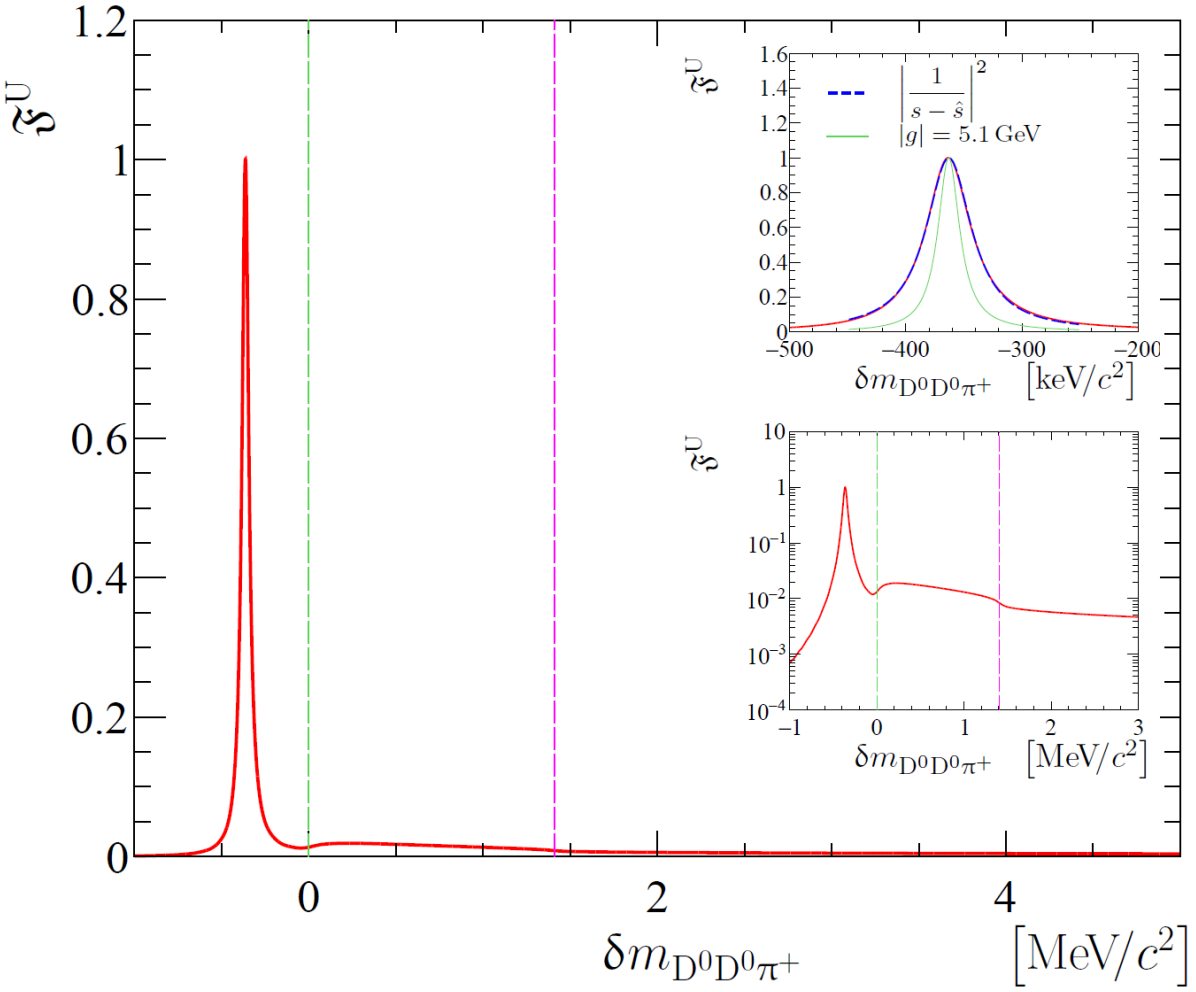
-The narrow peak below the lowest threshold

-Long tail with cusps at the thresholds

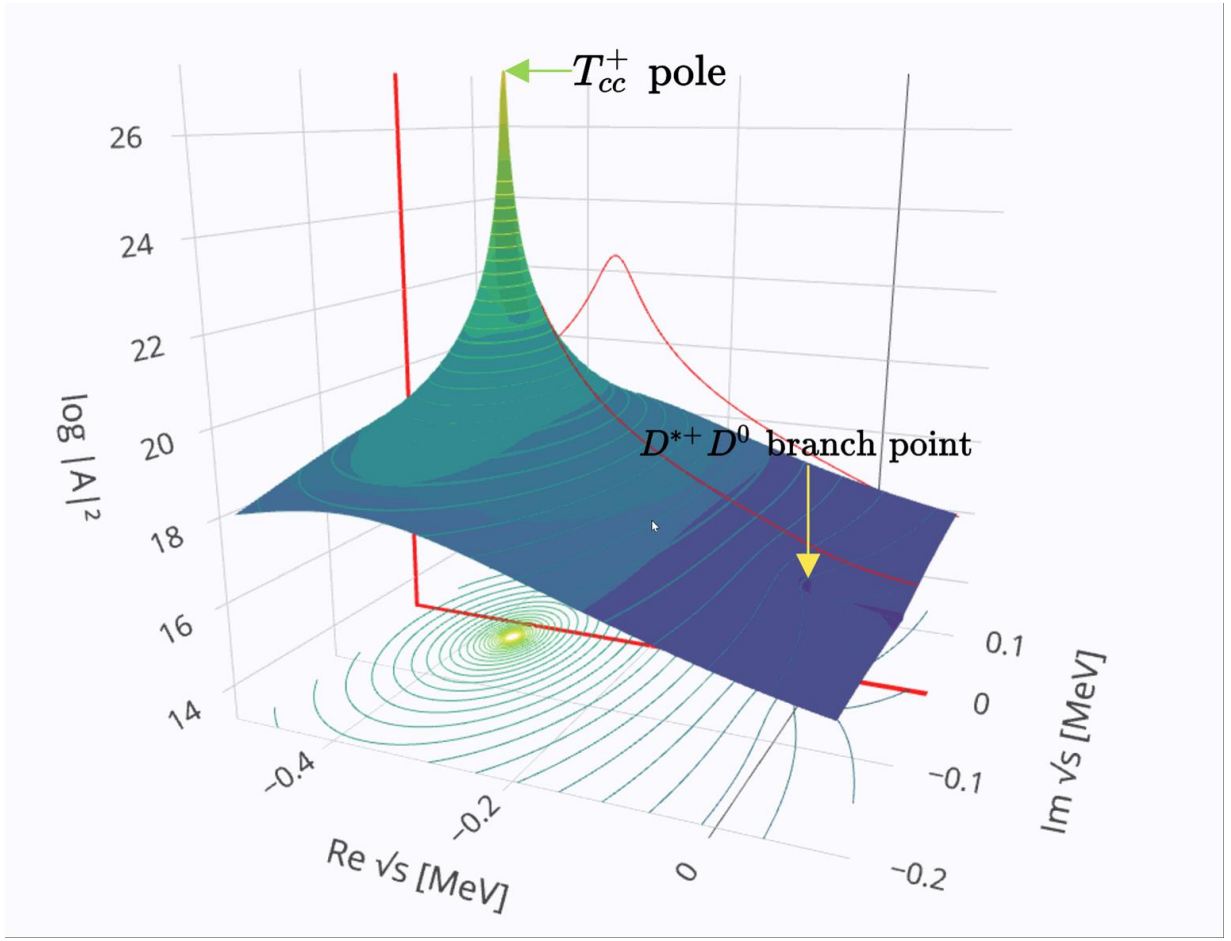
$$T(s) = \frac{\text{production}}{\text{rescattering}(s\,|\,\delta m, g)}$$

Analytic solution enables us:

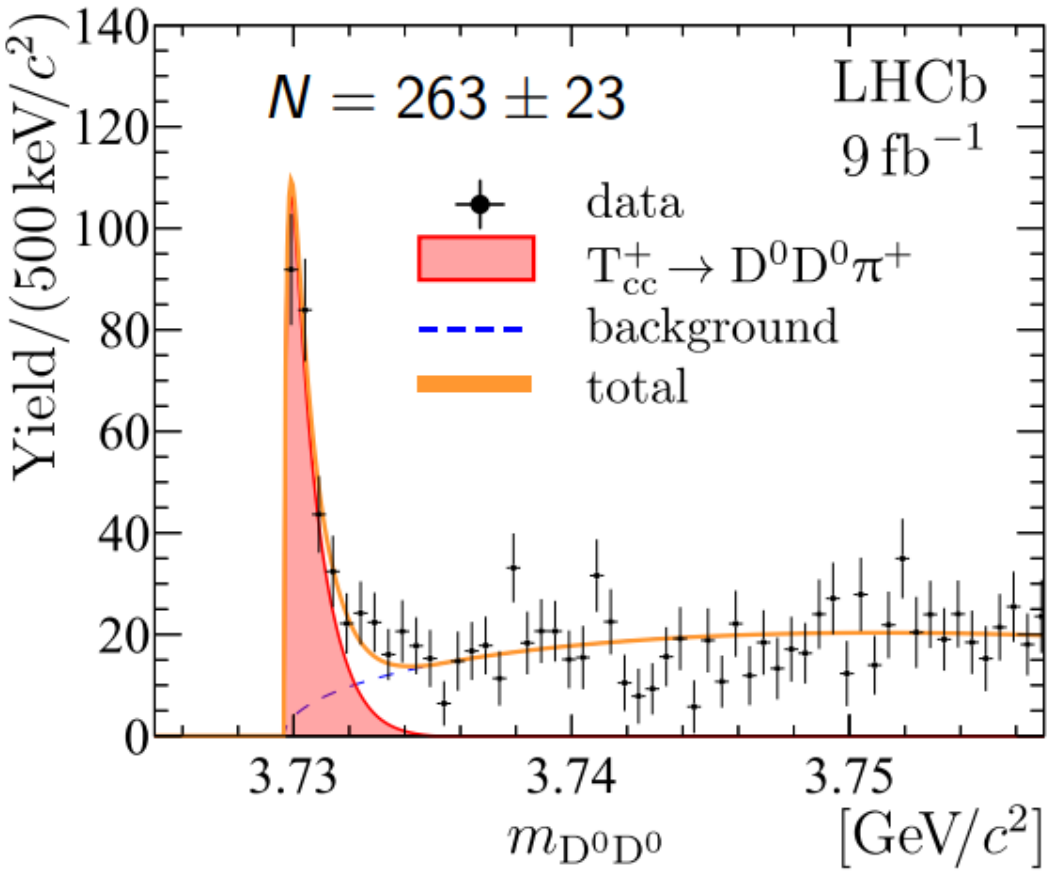
- Obtain pole mass and width
- Compute scattering parameters

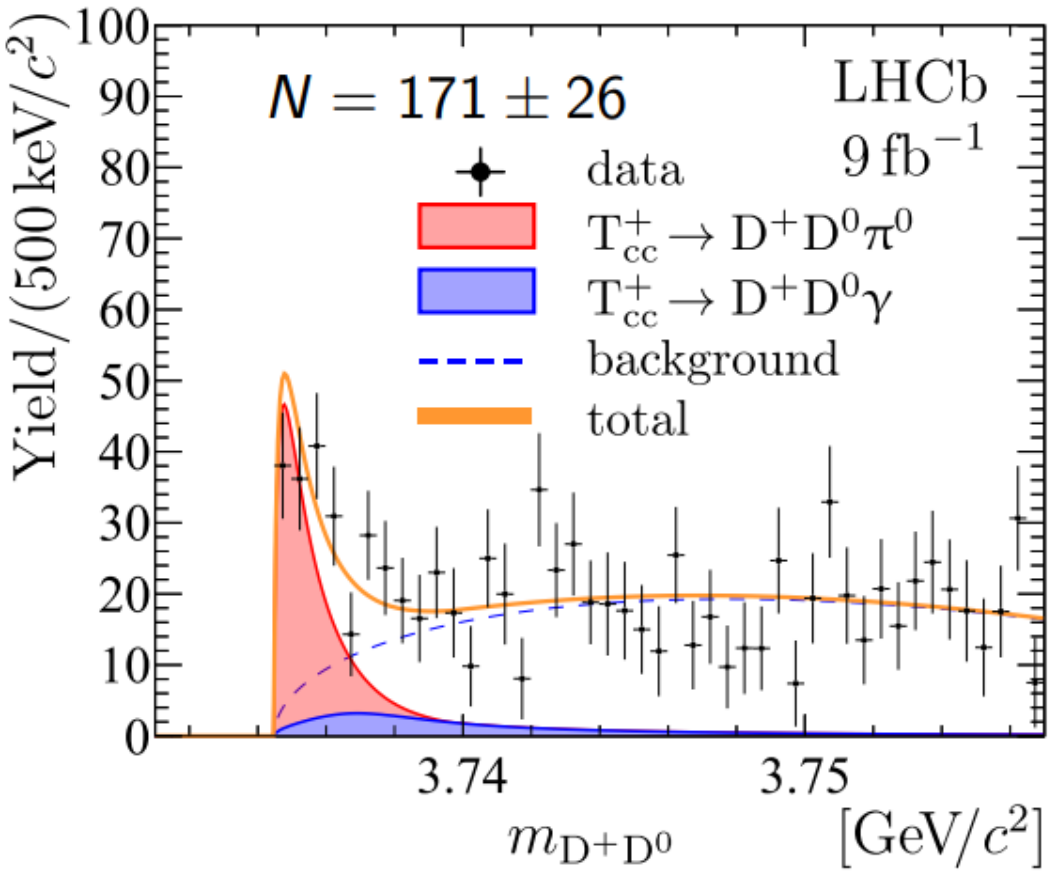


Tcc: Analytic continuation



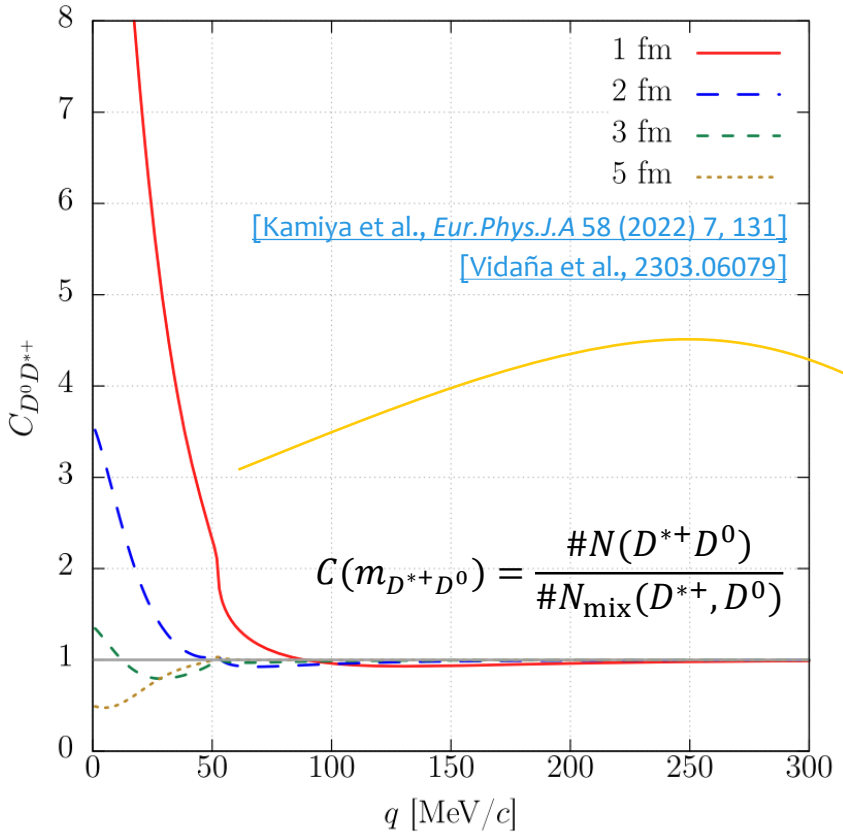
Partially reconstructed T_{cc}^{+}





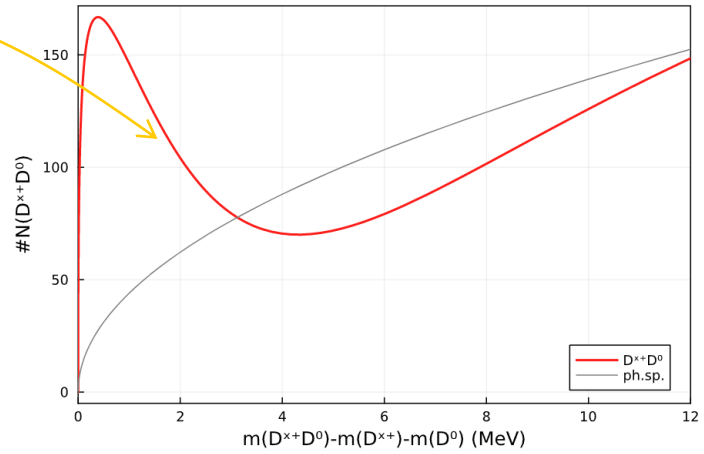
- Lineshape of D^0D^0 and D^0D^+ spectra are predicted well by the model
- Relative yeilds of D^0D^0 and D^0D^+ is in good agreement with the model predictions

Tcc: discussion on production and femtoscopy

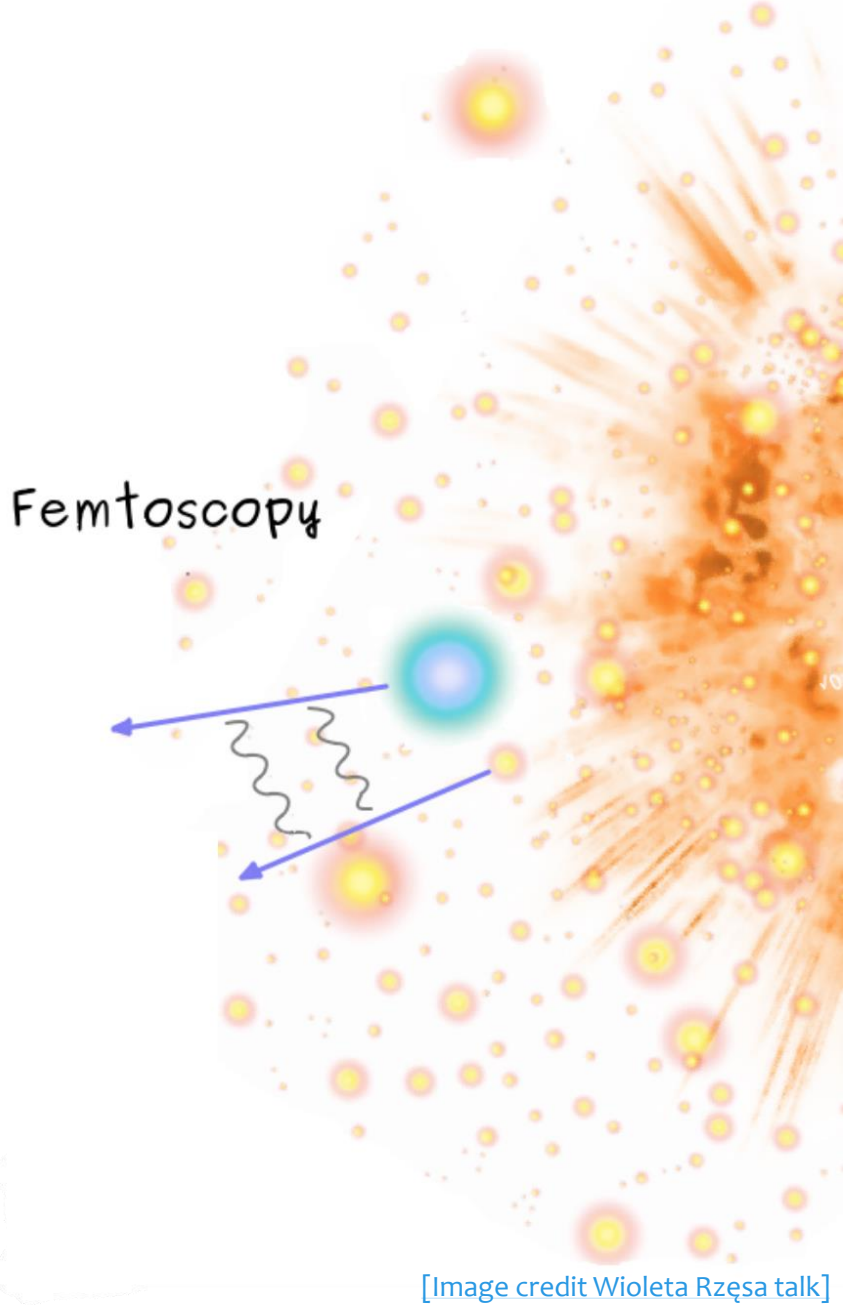


[Kamiya et al., *Eur.Phys.J.A* 58 (2022) 7, 131]
[Vidaña et al., 2303.06079]

On-shell D^{*+}, D^0 produced independently may experience residual T_{cc}^+-interaction



[GitHub/mmikhasenko]



[Image credit Wioleta Rzęsa talk]

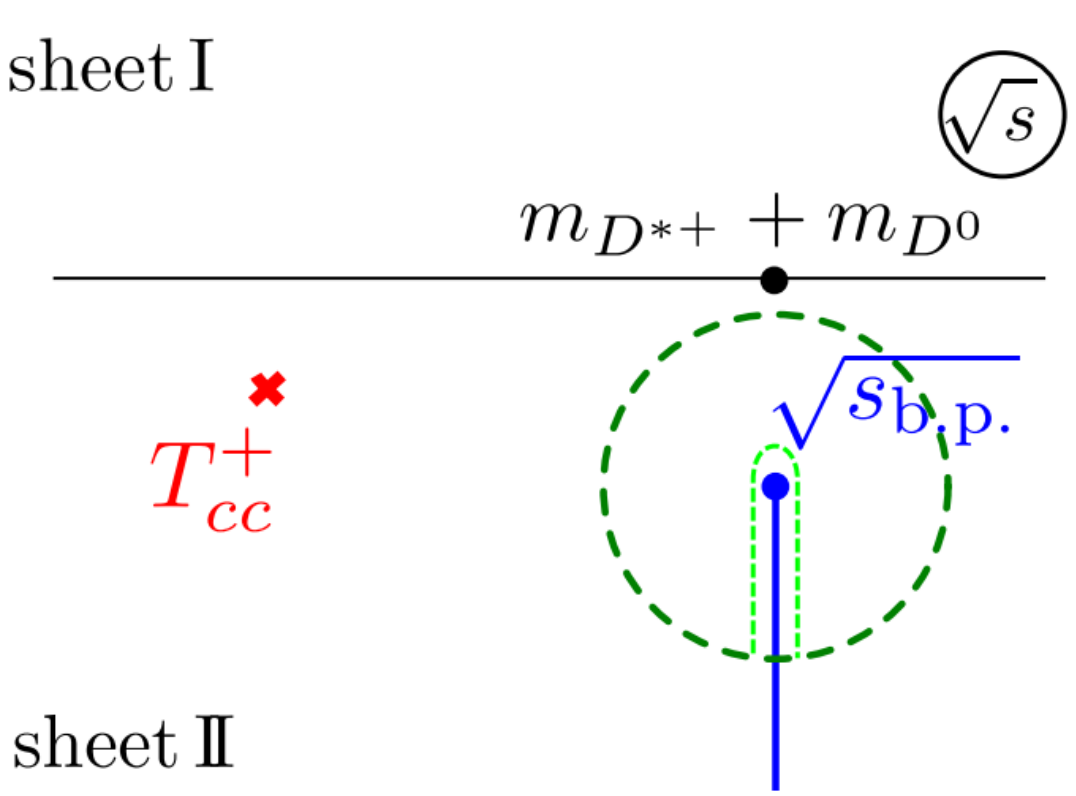
Effective range expansion

$$k \cot \delta(k) = \frac{1}{a} + r\frac{k^2}{2} + O(a^3 k^4)$$

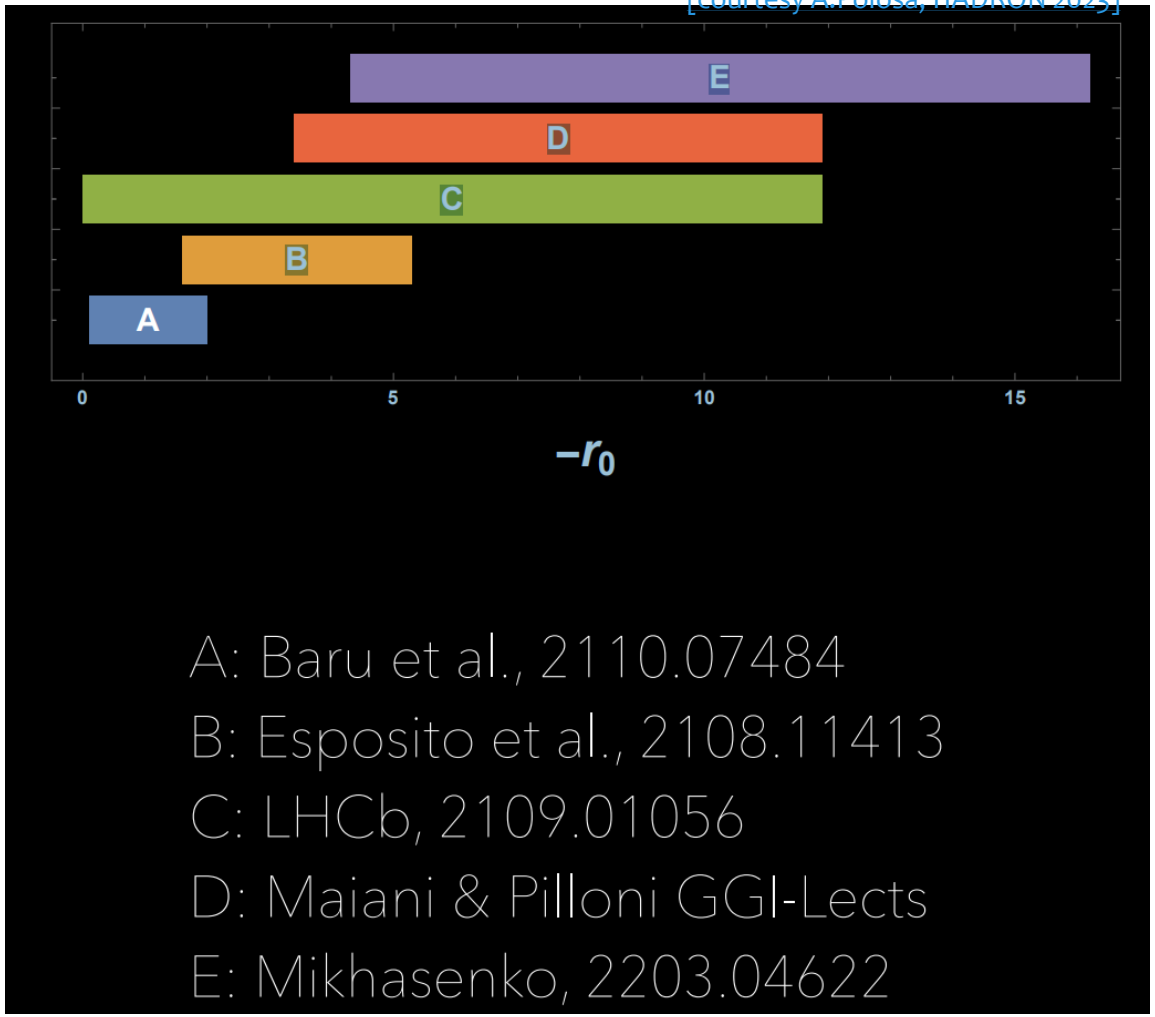
- k is a break-up momentum
- 1/a, r are coefficient in expansion

Can be done by computing derivatives of regular (k cot delta)

D* is unstable, complex branch point



[courtesy A.Polosa, HADRON 2023]



Effective range expansion

Effective range expansion

- **Have you**