Exotic Hadrons from LHCb

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ON BEHALF OF LHCB

MESON 2023, KRAKOW

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)

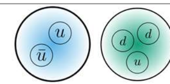
$\sim$50 fb^{-1} is expected by 2032

QCD variety

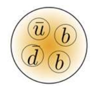

[Midjourney 2023, MM]

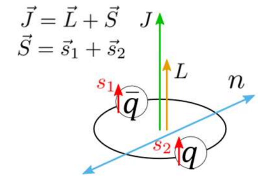
Possible configurations of hadrons

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



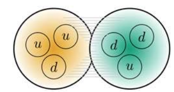
Bigger Quark Model $(q\bar{q}q\bar{q}, qqqq\bar{q}, \dots)$





+ excitations

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



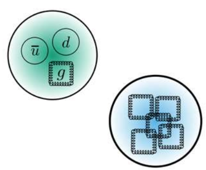
+ nuclei chart

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

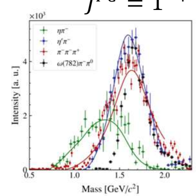
Admixed Molecules: $q\bar{q} \rightarrow (q\bar{q})(q\bar{q})$

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

Glueballs: $g{\sim}g$



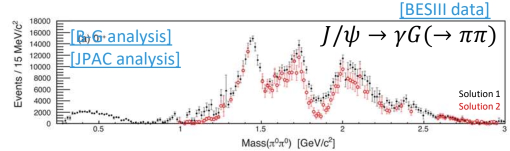
$J^{PC} = 1^{-+}$



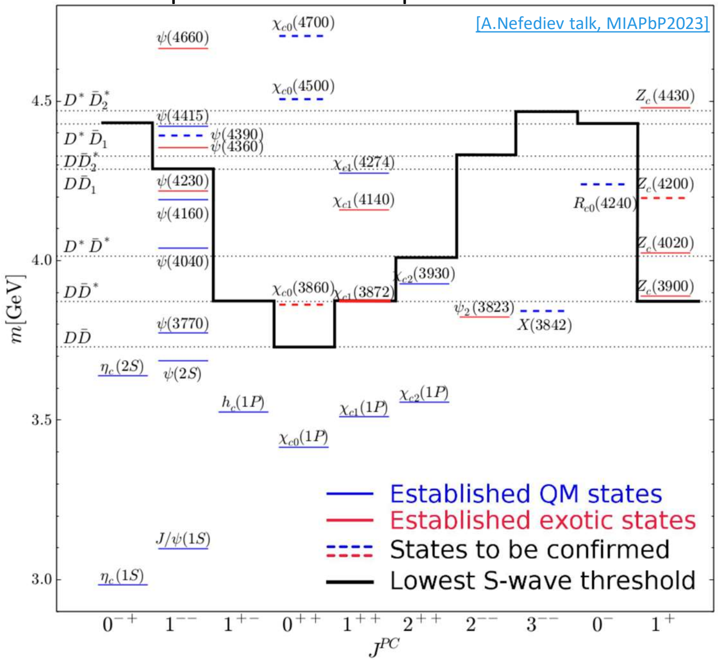
[P.Haas, HADRON2023]

[D. Spülbeck, B3 / 194]

[BESIII data]



An example: charmonium spectrum



QM states and thresholds

Most of hadrons are not isolated:

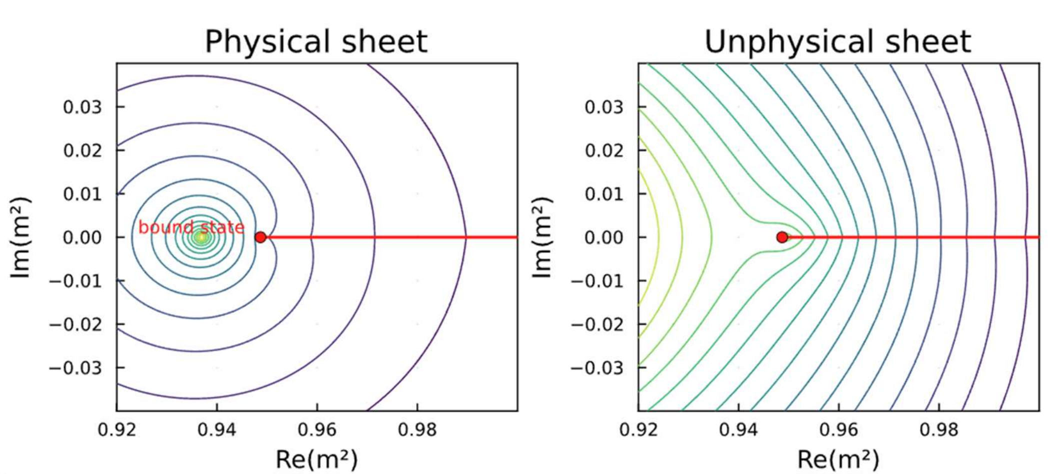
near hadron-hadron threshold,

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

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

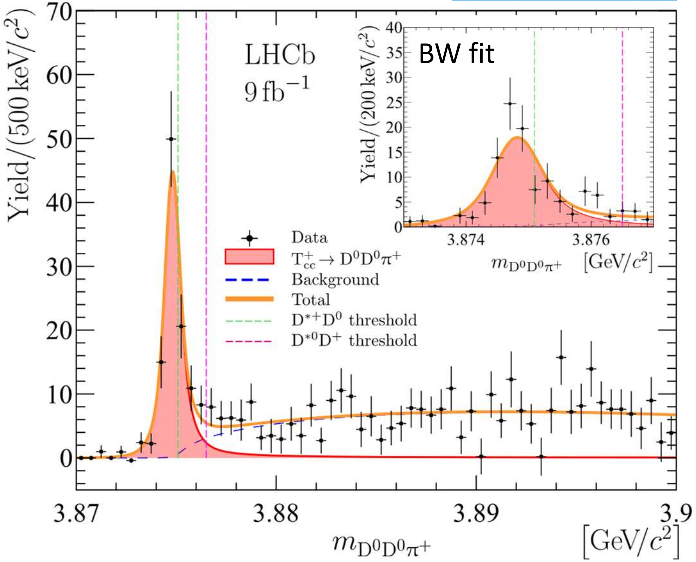
The state is mostly **molecular** in vicinity of the threshold

[GitHub/mmikhasenko]

Tetraquarks

Observation of T_{cc}^+

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



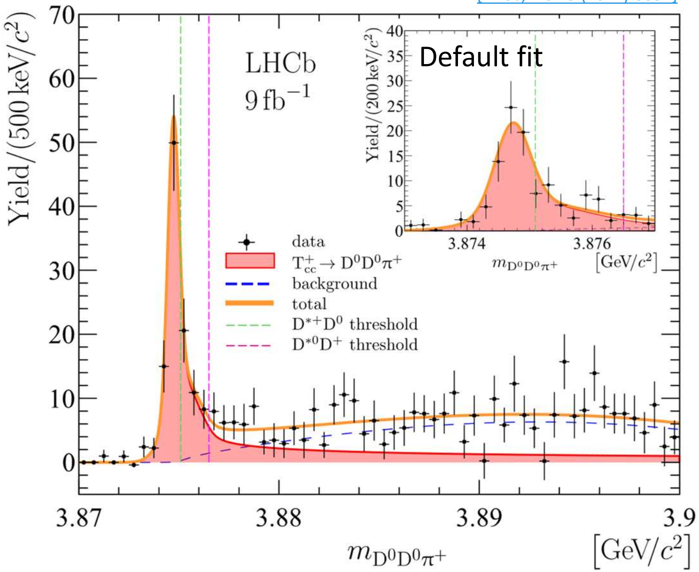
Peak in $D^0D^0\pi^+$ just below $D^{*+}D^0$ threshold

~190 signal events, high significance

Extremely narrow, ~300keV (resolution)

Studies of T_{cc}^{+}

[LHCb, NC 13 (2022) 3351]



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

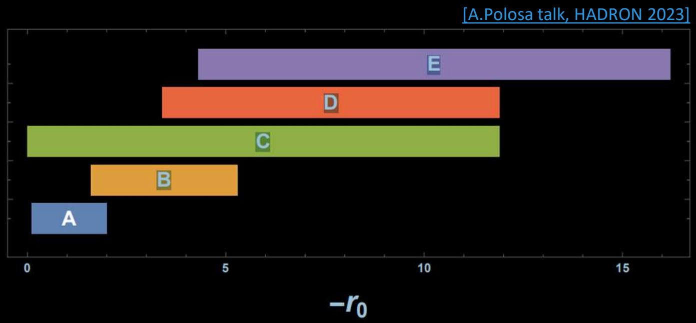
Coupled channel model

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

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

Yields pole parameters:

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



A: Baru et al., 2110.07484
B: Esposito et al., 2108.11413
C: LHCb, 2109.01056
D: Maiani & Pilloni GGI-Lects
E: Mikhasenko, 2203.04622

Effective range discussion

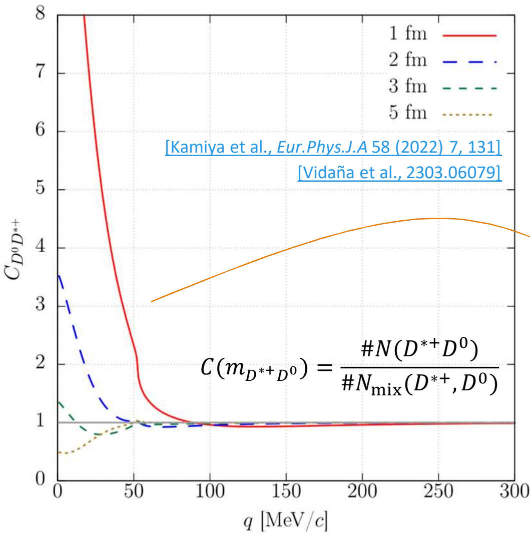
Scattering parameters **(a,r)** gives simplified description of the amplitude near threshold.

Scattering length is well constrained by the binding energy

Limit is set in the **effective range** (related to the width)

High Weinberg compositeness is obtained

Discussion on production

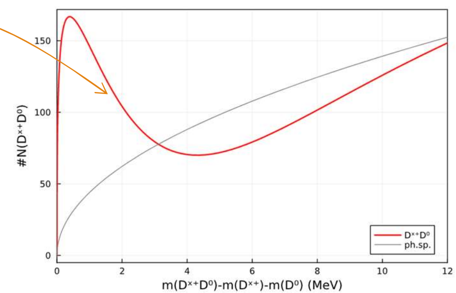


[Kamiya et al., *Eur.Phys.J.A* 58 (2022) 7, 131]

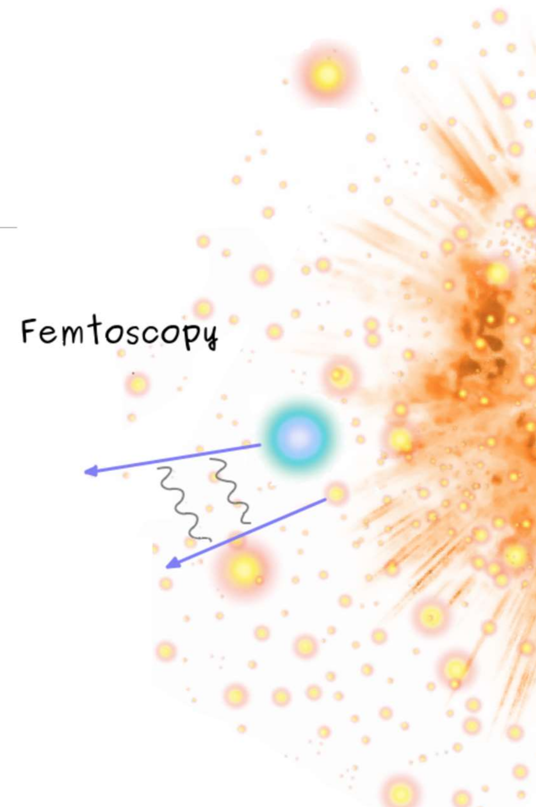
[Vidaña et al., 2303.06079]

$$C(m_{D^{*+}D^0}) = \frac{\#N(D^{*+}D^0)}{\#N_{\text{mix}}(D^{*+}, D^0)}$$

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



[GitHub/mmikhasenko]



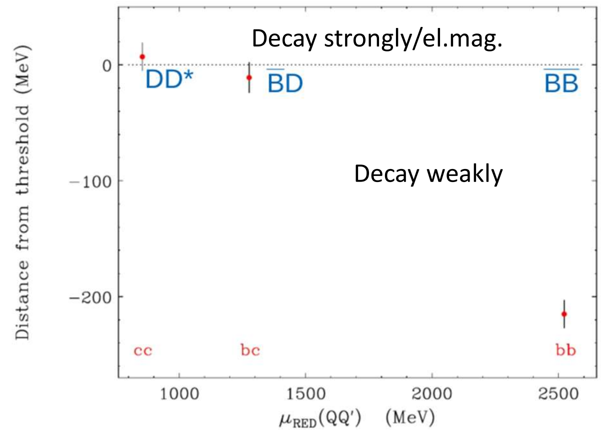
[Image credit Wioleta Rzęsa talk]

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

distance from threshold ↑

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

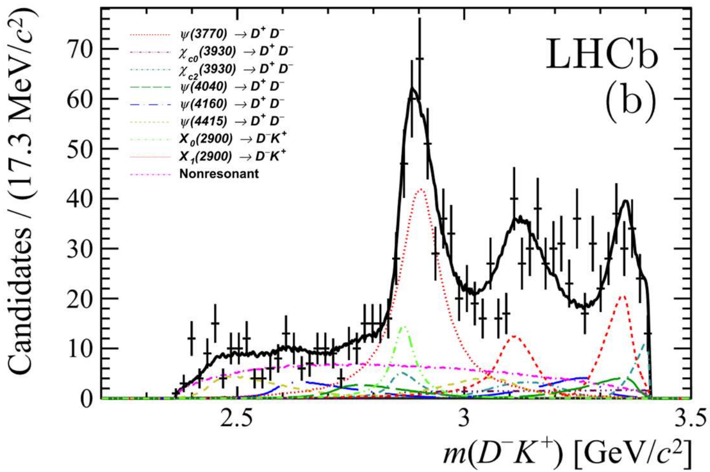
[Karliner, Rosner 1707.07666]



* not yet observed

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

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

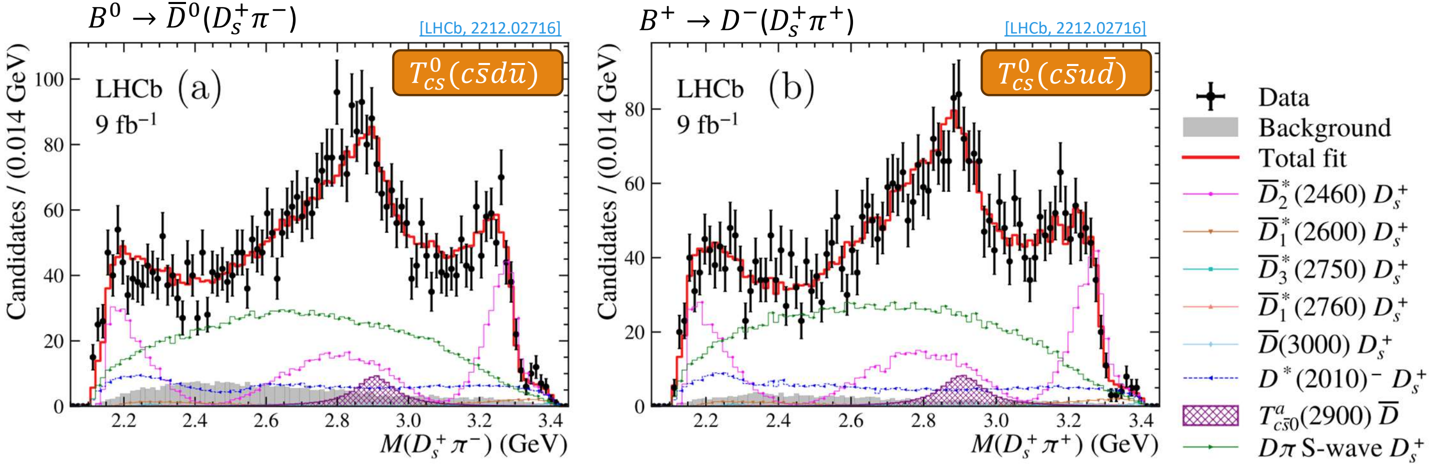


Resonance in $D^- K^+$

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 required in the fit

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

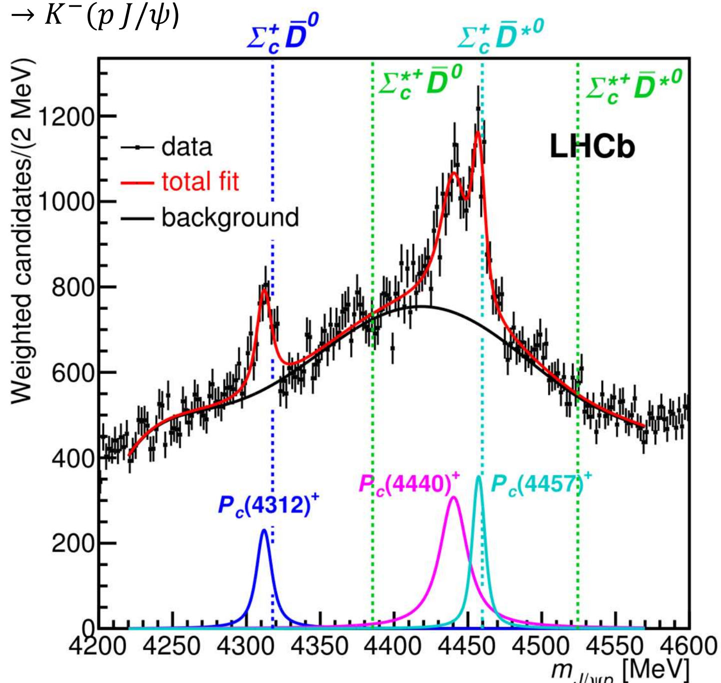


Surprising enhancement at 2.9 GeV

Pentaquarks

Famous Pentaquarks

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



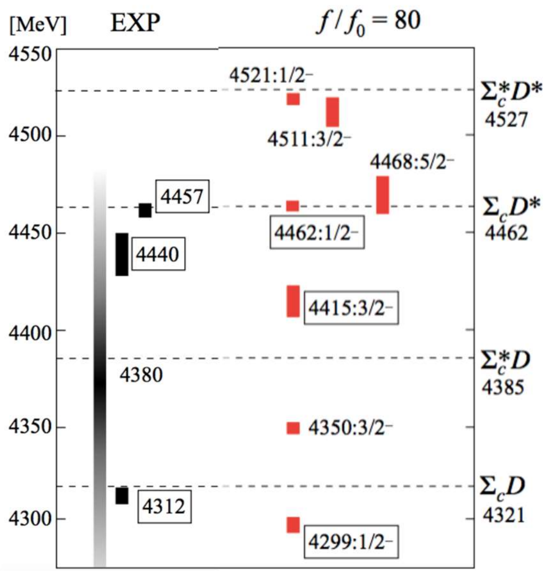
[LHCb, PRL 122 (2019) 22, 222001]

[LHCb, PRL 115 (2015), 072001]

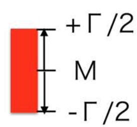
Near threshold

Multiplicity matches threshold spin algebra

QM states are complex and unknown



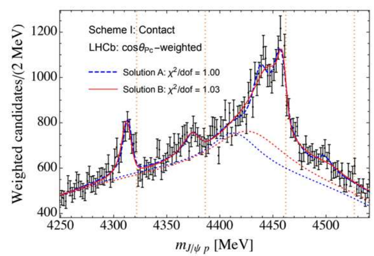
[Yamaguchu et al., 2303.06079]



A potential model

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

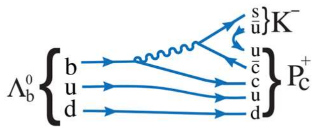


[Meng-Lin Du et al., *JHEP* 08 (2021) 157]

describes the projection with coupled-channel model

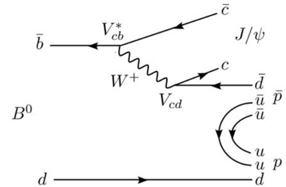
Full-dim. fit is the next step

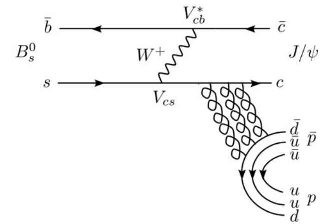
Exploration of similar final states



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



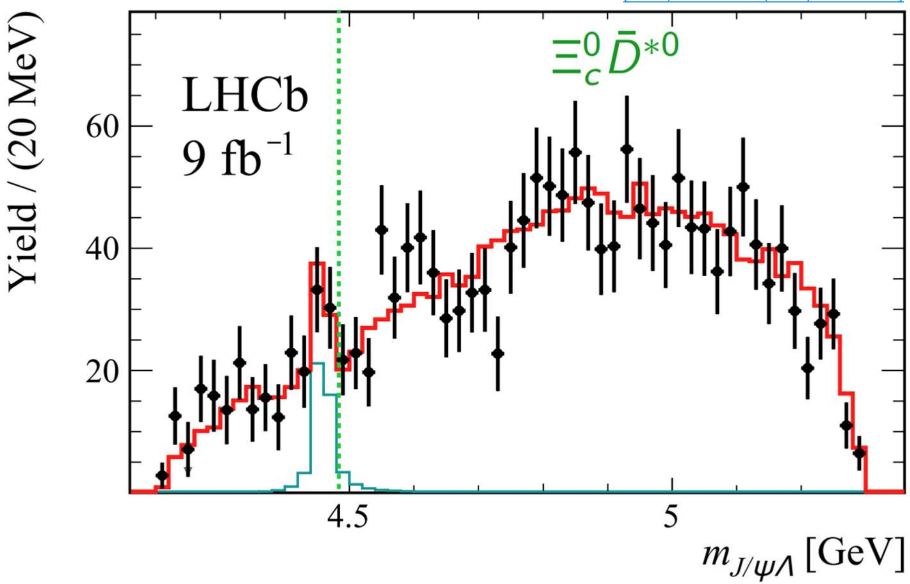


smaller ph.sp

- $B_{(s)}^0 \to J/\psi p\bar{p}$ ✓ (2021)
- $B^- \to J/\psi \Lambda\bar{p}$ ✓ (2022)
- $B_s^0 \to J/\psi \Lambda\bar{\Lambda}$

$\Xi_b^- \to J/\psi K^- \Lambda$

[LHCb, Sci.Bull. 66 (2021) 1278-1287]



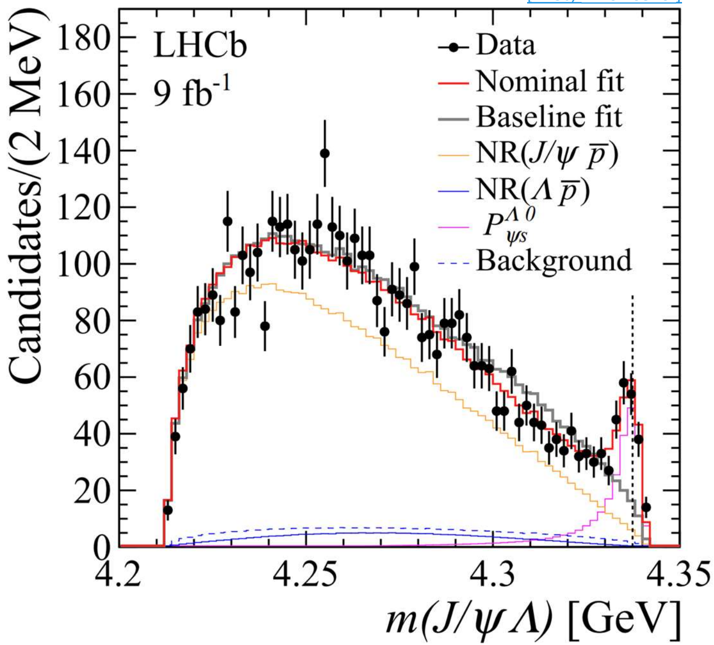
Strange Partner-I

The Ξ_b^- decay amplitude built as

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

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

$B^- \to (J/\psi\Lambda)\bar{p}$ [LHCb, 2210.10346]



Strange Partner-II

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

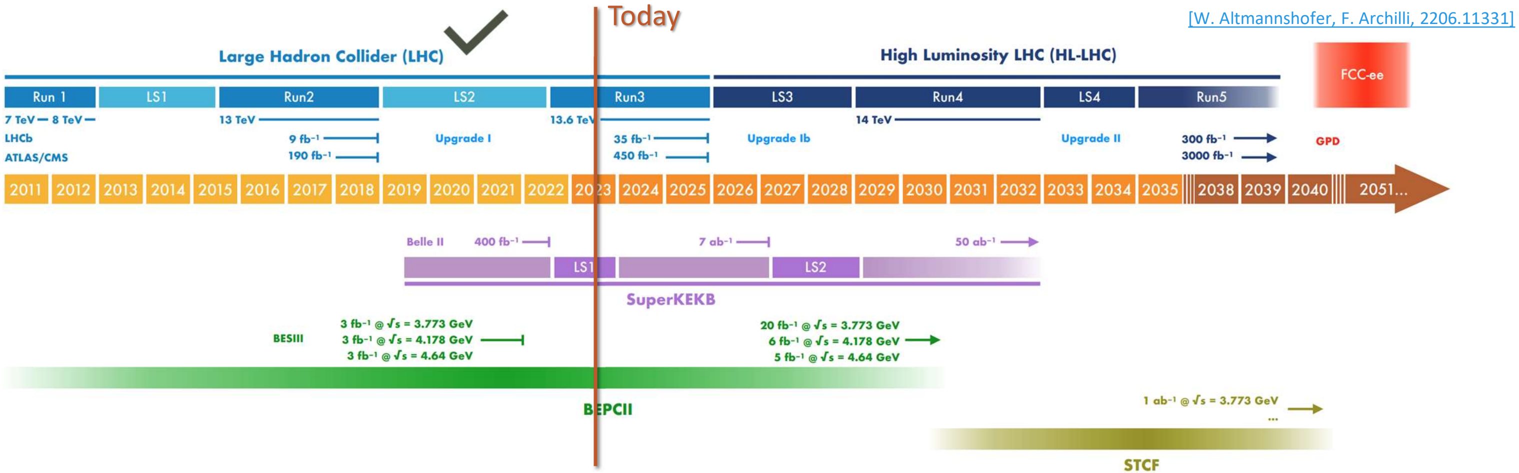
- 0.8±0.7 MeV above $\Xi_c^+ D^-$
- 2.9±0.7 MeV above $\Xi_c^0 \overline{D}^0$

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

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

LHCb Run3 and Outlook

[Midjourney 2023, MM]



Planned schedule

Conclusion

QM states and molecular **components** are closely connected:

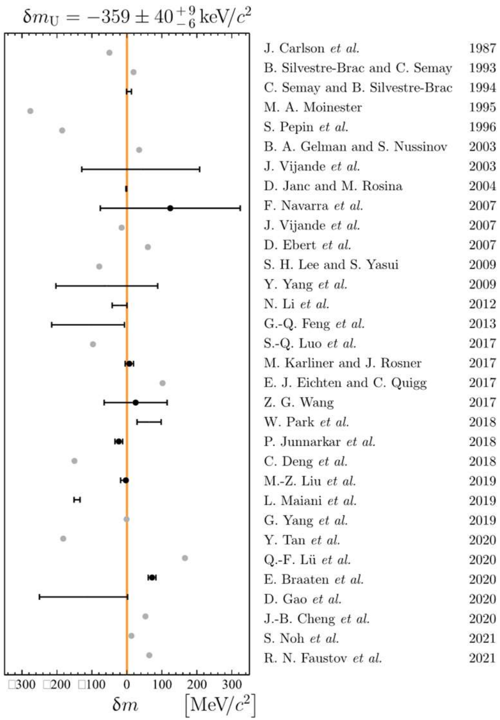
- QM state may look like a pure molecule when appear in a vicinity of the S-wave hadron-hadron threshold

$QQ\bar{q}\bar{q}$ **tetraquarks** is a new class of hadrons:

- T_{cc}^{+} is almost stable, T_{bb}^{-} decays weakly, T_{cs}^{0} could be the seen $D^{-}K^{+}$ resonance.
- There might be a chance to observe stable T_{bc}^{0}

Pentaquarks appearance is consistent with pure molecules.
New states $P_{c\bar{c}s}^{0}$ in $J/\psi\Lambda$ could be SU(3) partners of the $P_{c\bar{c}}^{+}$ states.

Thank you for the attention



More references