Prospects for Exotic Hadron Physics

(QCD connections with astroparticle, hadronic, nuclear physics)

V. Mantovani Sarti (TUM), A. Gérardin (CPT Marseille),
M. Pappagallo (University and INFN Bari)

Open Symposium on the European Strategy for Particle Physics (ESPP2026)
23-27 June 2025, Venice, Italy

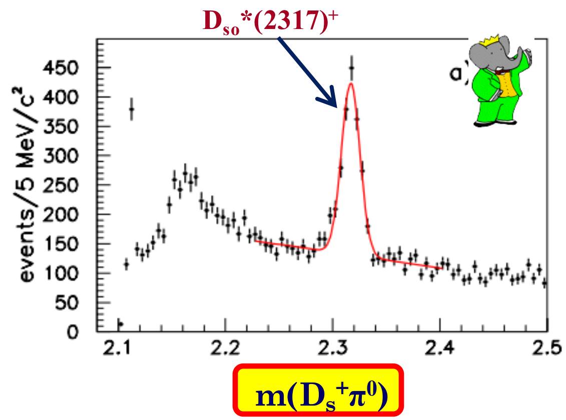
Exotic Hadrons back in spotlight

While the existence of exotic hadrons was predicted since the formulation of the quark model, no hadrons were definitively identified as exotic for many decades.

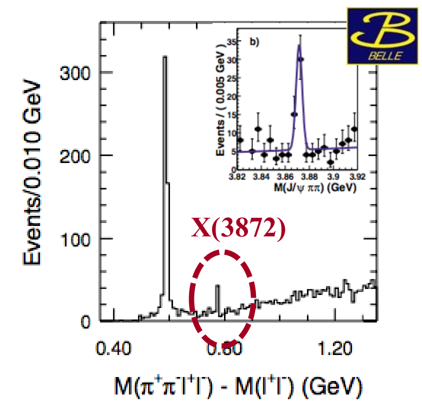
The B-factories shed new light on the field with the discovery of two mesons $D_{s0}^*(2317)^+$ and $\chi_{c1}(3872)$ (a.k.a. X(3872)) exhibiting unexpected properties:

- Masses lower than expected
- Very narrow ($\Gamma \sim O(1\ \mathrm{MeV})$)
- Closeness to hadronic thresholds

[PRL 90 (2003) 242001]



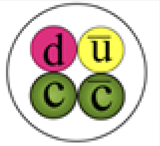
[PRL 91 (2003) 262001]



Observation of Explicit Exotic Hadrons

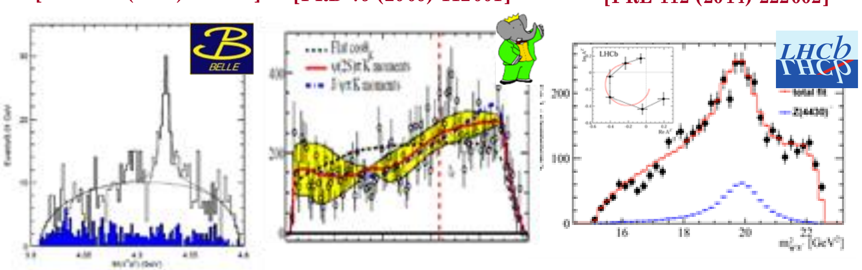
However, despite the precise measurements of their masses and widths, determination of their spin-parities and comprehensive studies of their production in various collision systems, the fundamental nature of these mesons, whether conventional quark-antiquark states or exotic hadrons, remains unresolved.

Observation of first charmonium-like meson: $\mathbf{T_{c\underline{c}1}(4430)^+}$ (a.k.a. Z(4430)+)



- Multidimensional amplitude analysis
- Resonance or rescattering effect?

[PRL 100 (2008) 142001] [PRD 79 (2009) 112001] [PRL 112 (2014) 222002]

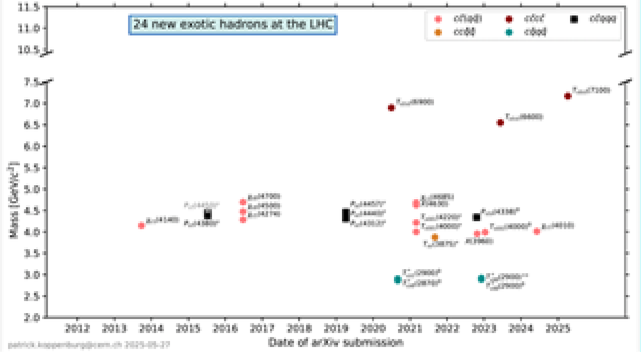


Natural width of Z(4430) [MeV]

State	1D	2D	4D
Belle	$45\,^{+18}_{-13}{}^{+30}_{-13}$	$107^{+86}_{-43}{}^{+74}_{-56}$	$200\,^{+41}_{-46}{}^{+26}_{-35}$
LHCb			$172 \pm 13\,^{+37}_{-34}$

Exotic Hadrons @ LHC

The LHC experiments picked up the baton and firmly established the existence of explicitly exotic hadrons in prompt pp production and from *b*-hadron decays

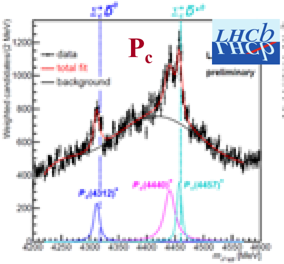


https://koppenburg.ch/particles.html

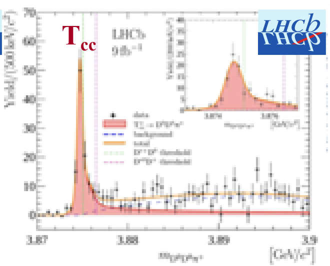
- Pentaquarks $P_c \rightarrow J/\Psi\ p$
- Doubly charmed tetraquark $T_{cc}(3875)^{+} \rightarrow D^0 D^0 \pi^{+}$
- Fully charmed tetraquarks $T_{cccc} \rightarrow J/\psi\ J/\psi$

(Observed by 3 LHC experiments!)

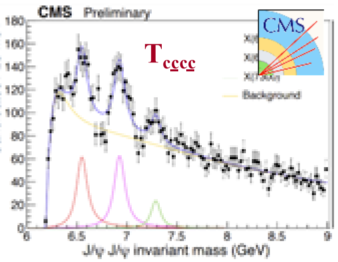
[PRL 122 (2019) 222001]



[Nature Physics 18 (2022) 751]



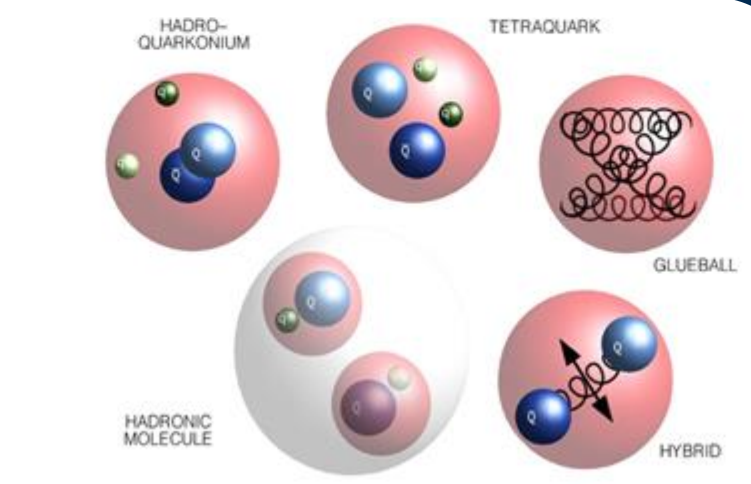
[PRL 132 (2024) 111901]



What's next?

Over the years, an abundance of exotic hadrons has been discovered, so many that PDG2024 has introduced a dedicated naming scheme for them. As with conventional hadrons in the early stages of hadron spectroscopy, recognizing underlying patterns is key to exploring their internal dynamics

- Why do many exotics lack flavour/isospin partners?
- How the quarks are bound together inside the exotic hadrons?
- Do hybrids/glueballs exist?



Credit: C. Hanhart

EXOTIC HADRONS : THEORY INPUTS FROM LATTICE QCD

Lattice QCD is expected to provide important information on exotic hadrons (when not too high above lowest threshold)

➜ First-principle calculations :
- calculations based on path integral formalism (hypercubic lattice used as UV regulator)
- can make **predictions (**quantifiable uncertainties**)**, **guide** experiments
- **complementary** to exp. : e.g. freedom to tune the quark masses, probe internal structure

➜ Path integral evaluated with Markov Chain Monte Carlo
- calculations are affected by statistical uncertainties
  → increasing need of computing resources

➜ Formulated in Euclidean spacetime
- extraction of the mass of stable hadrons (within QCD) is straightforward
- hadronic resonances are not asymptotic states of QCD, **first principle calculations challenging**

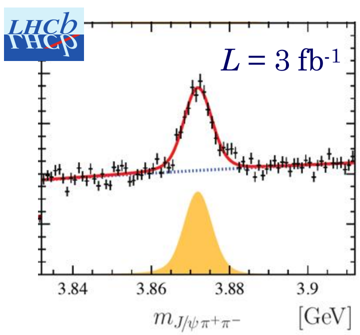
→ no direct access to mass (≠ stable hadrons) : use the finite-volume lattice to extract the scattering amplitude matrix

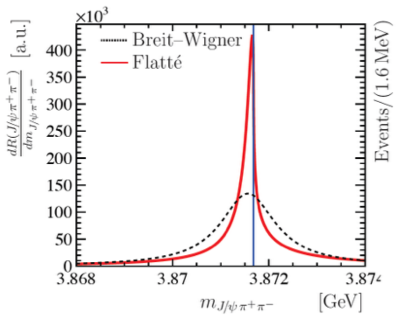
→ significant theory and algorithmic developments in the last decades

Tackling the Nature of $\chi_{c1}(3872)$

- Nature of the $\chi_{c1}(3872)$ state can be elucidated by studies of its lineshape
- Measurements of the compositness (the probability of finding molecular state in the eigenstate) and effective range provided new tools to discriminate between different models

- **LHCb Upgrade II** will increase the sensitivity to the lineshape parameters





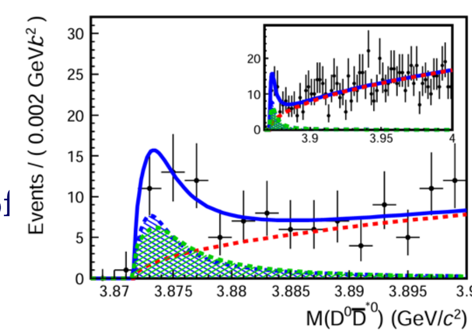
[PRD 102 (2020) 092005]

Table 9.1: Expected data samples at LHCb Upgrade II and Belle II for key decay modes for the spectroscopy of heavy flavoured hadrons. The expected yields at Belle II are estimated by assuming similar efficiencies as at Belle.

Decay mode	LHCb $23\,\mathrm{fb}^{-1}$	LHCb $50\,\mathrm{fb}^{-1}$	LHCb $300\,\mathrm{fb}^{-1}$	Belle II $50\,\mathrm{ab}^{-1}$
$B^+ \to X(3872)(\to J/\psi\,\pi^+\pi^-)K^+$	14k	30k	180k	11k
$B^+ \to X(3872)(\to \psi(2S)\gamma)K^+$	500	1k	7k	4k
$B^0 \to \psi(2S)K^-\pi^+$	340k	700k	4M	140k
$B_c^+ \to D_s^+ D^0 \overline{D}^0$	10	20	100	—
$\Lambda_b^0 \to J/\psi\, pK^-$	340k	700k	4M	—
$\Xi_b^- \to J/\psi\, \Lambda K^-$	4k	10k	55k	—
$\Xi_{cc}^{++} \to \Lambda_c^+ K^-\pi^+\pi^+$	7k	15k	90k	<6k
$\Xi_{bc}^+ \to J/\psi\, \Xi_c^+$	50	100	600	—

[arXiv:1808.08865]

- Belle II targets 40 times more data than previous B-factories
- Efficient photon and π^0 reconstruction makes a lineshape measurement of $\chi_{c1}(3872)$ via $D^0\overline{D}^{*0}$ decays possible together to the first observations of the predicted neutral partners of charged tetraquark states

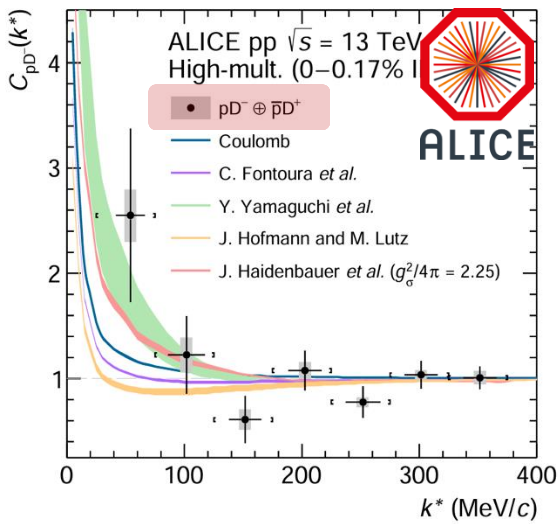


[PRD 107 (2023) 112011]

Femtoscopy as a Probe for Exotic Hadrons

The femtoscopy technique consists of the measurement of correlations in momentum space for hadron-hadron pairs

Correlation functions sensitive to the scattering parameters and the size of the particles emitting source (e.g. pD^- correlation)



Scattering length

Model	f_0 (I = 0)	f_0 (I = 1)	n_σ
Coulomb			(1.1–1.5)
Haidenbauer et al. [22] ($g_\sigma^2/4\pi = 2.25$)	0.67	0.04	(0.8–1.3)
Hofmann and Lutz [23]	−0.16	−0.26	(1.3–1.6)
Yamaguchi et al. [25]	−4.38	−0.07	(0.6–1.1)
Fontoura et al. [24]	0.16	−0.25	(1.1–1.5)

[PRD 106 (2022) 052010]

Femtoscopy as a Probe for Exotic Hadrons

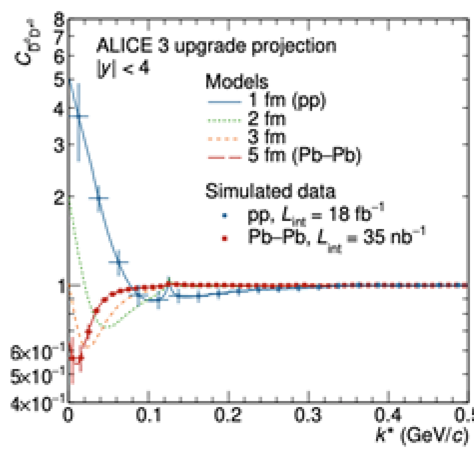
ALICE 3: Complementary experimental constraints on nature of exotic hadrons via correlations in different collision systems

State	Mass (MeV/c^2)	Width (MeV/c^2)	S-wave threshold (MeV/c^2)	Coupled Channels
X(3872) [227]	3872.0 ± 0.2	1.19 ± 0.21	$D^{*0}\bar{D}^0(-0.04)$, $D^{*+}\bar{D}^-(-8.11)$	$\pi^+\pi^-J/\psi$, $\pi^+\pi^-\pi^0 J/\psi$
X(3940) [227]	3942 ± 9	37	$D^*\bar{D}^*$ (-75 ± 9)	$D^*\bar{D}$
X(4140) [227]	4147.0 ± 4.5	83 ± 21	$D_s\bar{D}_s^*$ ($-66^{+4.9}_{-3.2}$)	$\phi J/\psi$
X(4274) [227]	4273.0 ± 8.3	56 ± 11	$D_s\bar{D}_s^*$ ($-49.1^{+19.1}_{-9.1}$)	$\phi J/\psi$
$Z_b(10610)$ [227]	$10\,607.0 \pm 2.0$	18.4 ± 2.4	$B\bar{B}^*(4 \pm 3.2)$	$\pi^\pm\Upsilon(nS)$ $\pi^\pm h_b(nP)$
$Z_b^\pm(10650)$ [227]	$10\,652.2 \pm 1.5$	11.5 ± 2.2	$B^*\bar{B}^*(+2.9)$	$\pi^\pm\Upsilon(nS)$ $\pi^\pm h_b(nP)$
$P_c^+(4312)$ [83]	$4311.9 \pm 0.7^{+6.8}_{-0.6}$		$\Sigma_c\bar{D}(-9.7)$	pJ/ψ
$P_c^+(4440)$ [83]	$4440.3 \pm 1.3^{+4.1}_{-4.7}$	$20.6 \pm 4.9^{+8.7}_{-10.1}$	$\Sigma_c\bar{D}^*(-21.8)$	$pJ/\psi, \Sigma_c\bar{D}\Sigma_c^*\bar{D}$
$P_c^+(4457)$ [83]	$4457.3 \pm 0.6^{+4.1}_{-1.7}$	$6.4 \pm 2.0^{+5.7}_{-1.9}$	$\Sigma_c\bar{D}^*(-4.8)$	$pJ/\psi, \Sigma_c\bar{D}\Sigma_c^*\bar{D}$
T_{cc}^+ [57]	3874.827	0.410	$D^{*+}\bar{D}^0(-0.273)$, $D^{*0}\bar{D}^+(-1.523)$	$D^0D^0\pi^+$

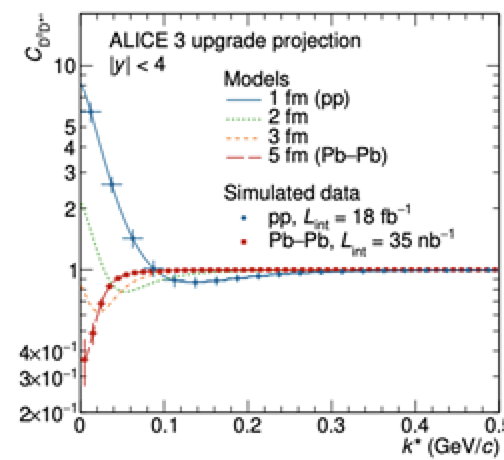
- $\chi_{c1}(3872)$ via $D^0\bar{D}^{*0}$ correlations
  $T_{cc}(3875)^+$ via D^0D^{*+} correlations
- A bound state manifests itself with an inversion of the correlation shape when modifying the emission source radius

[arXiv:2211.02491]

Simulation in a molecular scenario



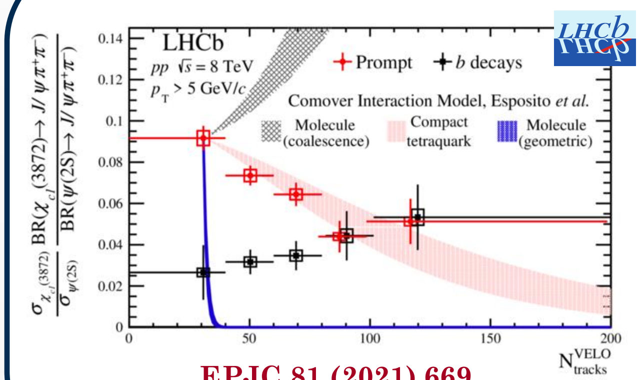
$\chi_{c1}(3872)$



$T_{cc}(3875)^+$

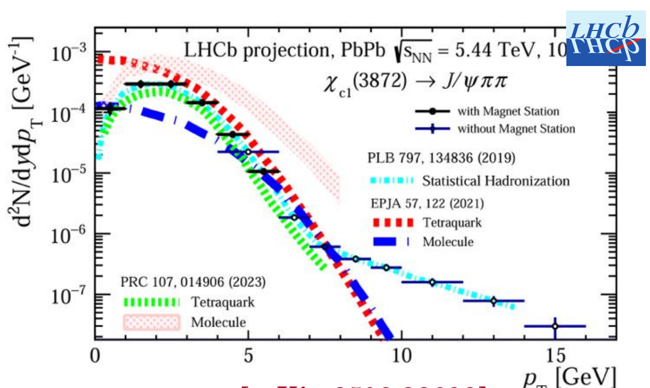
THE EXOTIC NATURE OF $\chi_{c1}(3872)$

Multiplicity dependence in pp, pA and AA collisions is a further handle on the formation mechanism of exotics

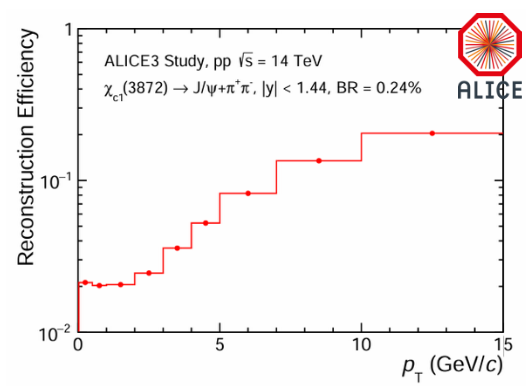


EPJC 81 (2021) 669
PRL 126 (2021) 092001

ALICE 3 and **LHCb Upgrade II** capable to reconstruct the $\chi_{c1}(3872) \rightarrow J/\psi\pi^+\pi^-$ decays at very low p_T, where theoretical models disagree significantly



[arXiv:2503.23093]



[arXiv:2211.02491]

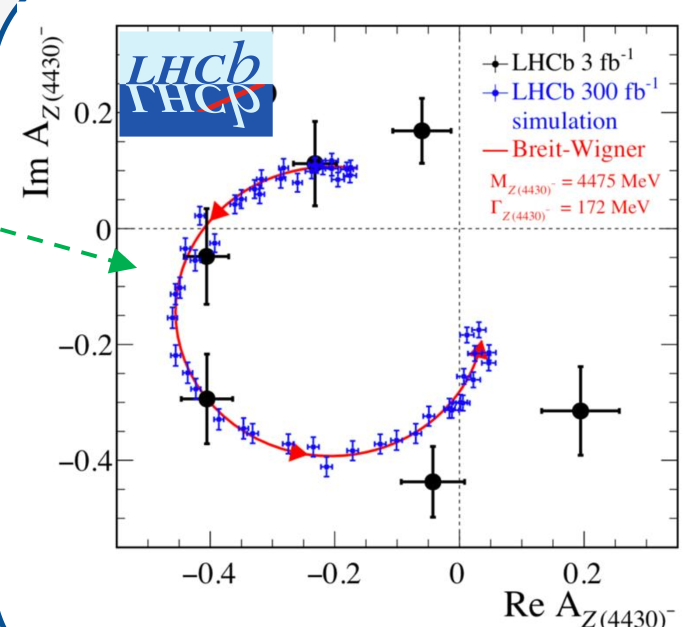
Tackling the Nature of $T_{c\bar{c}1}(4430)^+$

- Observation of several exotic hadronic resonances with hidden charm or beauty in the last decade at LHC and B-factories
- Most of them are quite broad and observed in 3-body decays of *b*-hadrons (e.g. $B^0 \rightarrow Z(4430)^- (\rightarrow \psi(2S)\, \pi^-)\, K^+$)

LHCb Upgrade II would allow to test further their nature by:

- Probing the resonant character
- Searching for isospin partners
- Measurements of quantum numbers J^P

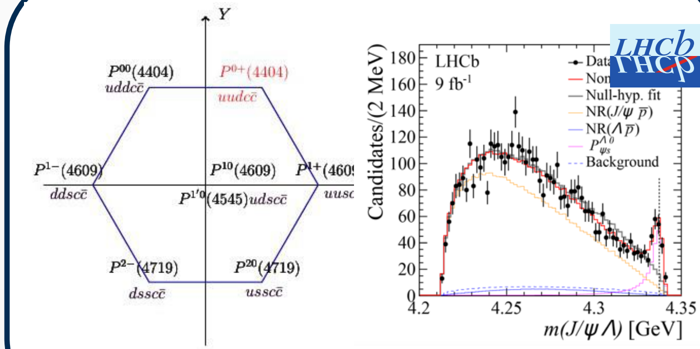
Such goal relies on amplitude analysis techniques. Refinement of theoretical parametrization of hadronic amplitudes and advanced understanding of the light spectroscopy are required in the meantime



[arXiv:1808.08865]

Tackling the Nature of Pentaquarks P_c

- As for other hadrons, multiplets of pentaquarks should exist
- $P_c^+ \to J/\psi\ p\ (uudc\bar{c})$ and $P_{cs}^0 \to J/\psi\ \Lambda\ (udsc\bar{c})$ observed
- **LHCb Upgrade II** could search for other flavour partners and measure quantum numbers



[PRD 96 (2017) 014014] [PRL 131 (2023) 031901]

Probing P_c^+ nature also in different production mechanisms:
e.g. Electroproduction (EIC) or Photoproduction (GlueX)

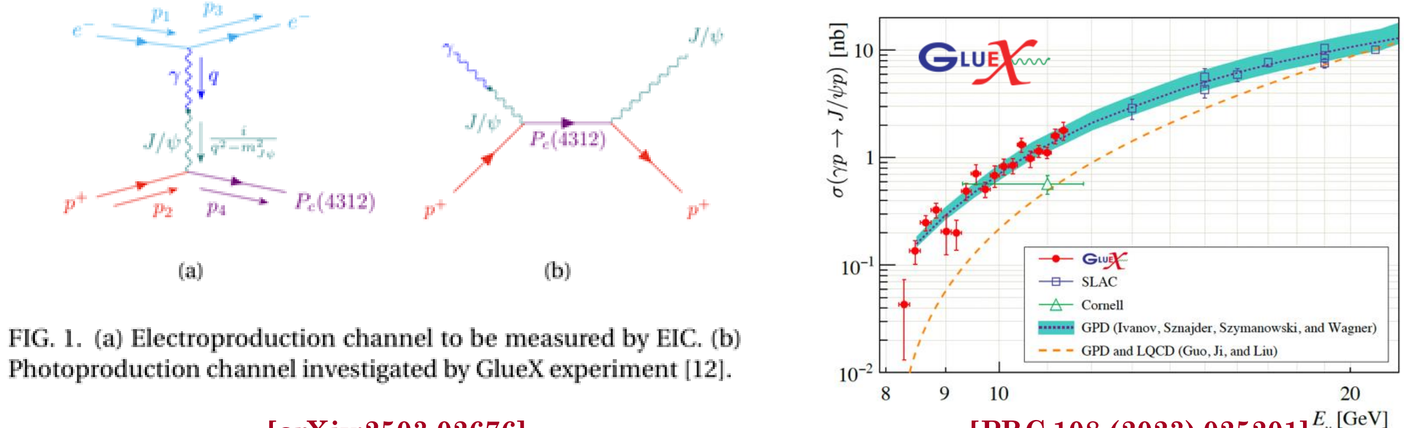
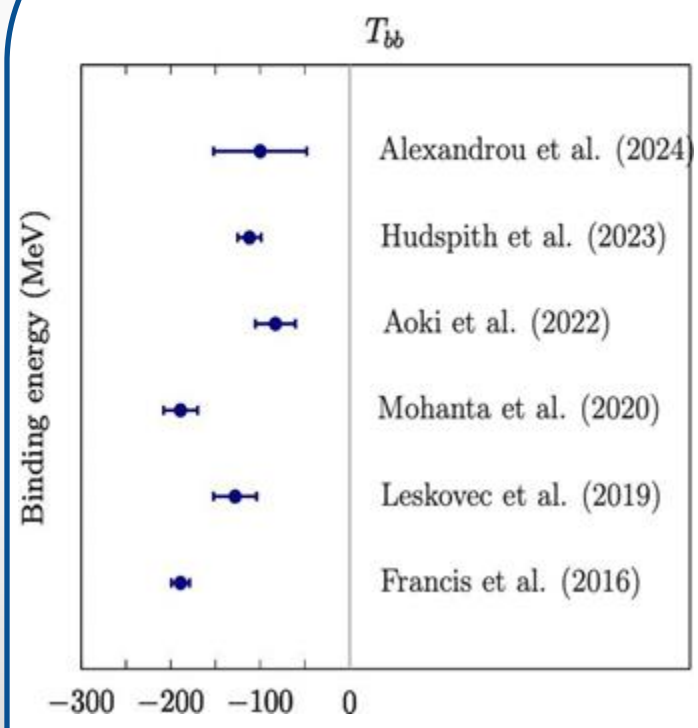


FIG. 1. (a) Electroproduction channel to be measured by EIC. (b) Photoproduction channel investigated by GlueX experiment [12].

[arXiv:2503.02676] [PRC 108 (2023) 025201]

Double Heavy Tetraquark in Lattice QCD



$T_{cc}(3875)^+$ observed in 2021 by LHCb, lies near threshold. Other possibles states : T_{bc}, T_{bb}
What does theory tell us ?

→ T_{bb} benchmark for lattice studies : lattice calculations predict a strongly bound tetraquark
→ first results for T_{bc} and T_{cc} available, lattice finds attraction
→ need to improve on systematics (physical m_π and small a limit)
→ quark mass dependence : study binding mechanism ?

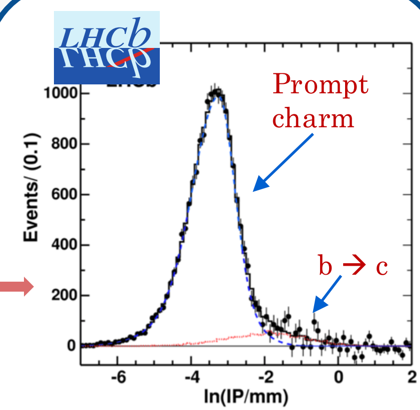
Search for the Doubly Heavy (Exotic) Hadrons (Ξ_{bc}, Ω_{bc}, T_{bc}, Ξ_{bb}, Ω_{bb}, T_{bb}, etc…)

LHCb Upgrade II: Observations of many doubly heavy hadrons, both conventional and exotic, will become within reach. This includes the doubly heavy tetraquark states (T_{bc} and T_{bb}), which are expected to have large enough binding energies such that only weak decays are possible.

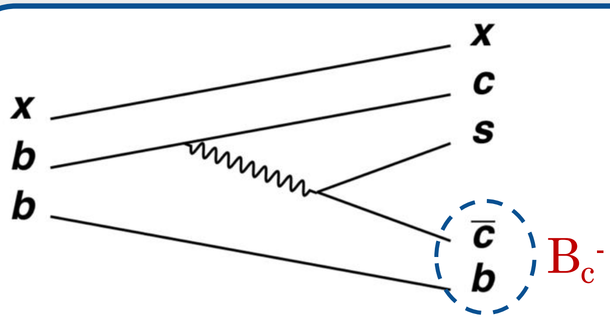
Exclusive approach: e.g. $X_{bb\bar{u}\bar{d}} \to B^- D^+ \pi^-$

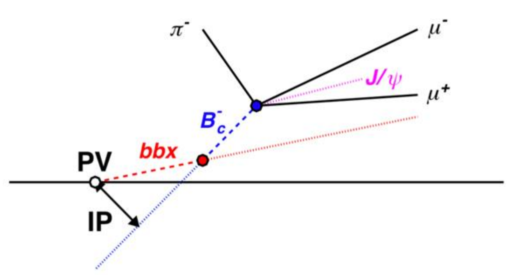
- Suppressed by BFs: 2 x (b → c) x (c → s) x efficiency

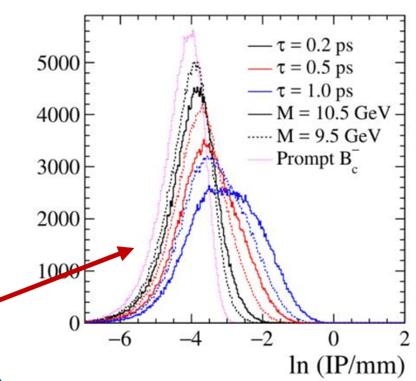
- ➢ Weakly decaying double beauty hadrons are the only possible source of displaced B_c^- mesons
- ➢ What about an inclusive approach? E.g. Displaced charm hadrons used to measure inclusive **σ**($pp \to b\bar{b}X$)



[PLB 694 (2010) 209]







[JHEP 01 (2019) 019]

Yields and shape can return insights on the cross-section, mass and lifetime
Theoretical inputs required to probe the composition of the *bb*-hadron mixture

SUMMARY

Complementarity of experiments essential in exploring spectroscopy

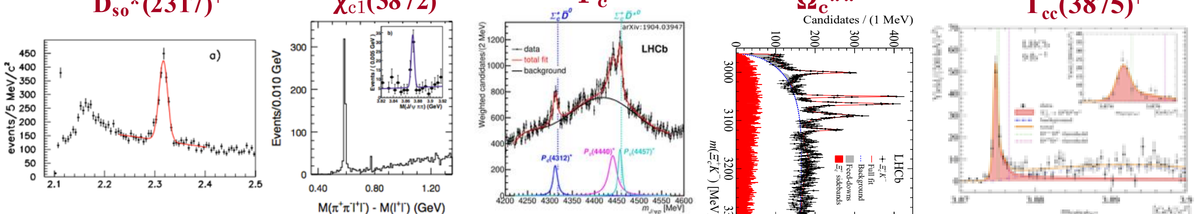
- **LHCb Upgrade II**: large production cross-sections, more performant for decay mode involving charged particles (e.g. $\chi_{c1}(3872) \rightarrow J/\psi\pi\pi$, …), unique in many sectors: $B_s^{(**)}$, $B_c^{(**)}$, $\Xi_{bc}^{(**)}$
- **ALICE 3**: Probing the exotic nature of the hadrons by exploiting the final state correlations
- Belle II: small background, more suitable for decay modes with neutrals in the final state (e.g. $\chi_{c1}(3872) \rightarrow J/\psi\,\gamma$ and its isospin/C-odd partners, …)

Support and resources for the future of **Lattice QCD**

- State-of-the-art simulations are **computationally very demanding**. Access to Tier-0/1 computing resources.
- **Storage** is also important (processing + long term storage : petabytes, more in the future)
- New algorithms/optimizations to exploit new HPC architectures: requires support for training / career-perspectives for research-software engineers.

Predictions are always complicated…even more when concerning unknown states!

$D_{s0}^*(2317)^+$ $\chi_{c1}(3872)$ P_c^+ Ω_c^{**} $T_{cc}(3875)^+$



2003 → 2003 → 2015 → 2017 → 2021 → *…to be continued*

BACKUP

Summary Table

Measurements	Exp./Facility	Observable	Useful for
$\chi_{c1}(3872)$ (a.k.a X(3872))	LHCb U2 ALICE 3 CMS Belle II	DD* correlation Prompt/b-hadron production Low pt production	Standard vs exotic molecule vs tetraqaurk
$T_{cc}(3875)^+$	LHCb U2 ALICE 3	DD* correlation Prompt/bc-hadron production	Exotic molecule vs tetraqaurk
$\Xi_{cc}/\Omega_{cc}/\Xi_{bc}$	LHCb U2 ALICE 3	Exclusive reconstruction	cc and bc bound mechanism Filling SU(4) multiplets
T_{bc}/T_{bb}	LHCb U2	Exclusive reconstruction & Detached Bc production	First weakly decaying Exotic