(Heavy) hadron exotics from lattice QCD

M. Padmanath

IMSc Chennai, a CI of HBNI, India

30^{th} July 2026
The 43rd International Symposium on Lattice Field Theory
University of Maryland, College Park

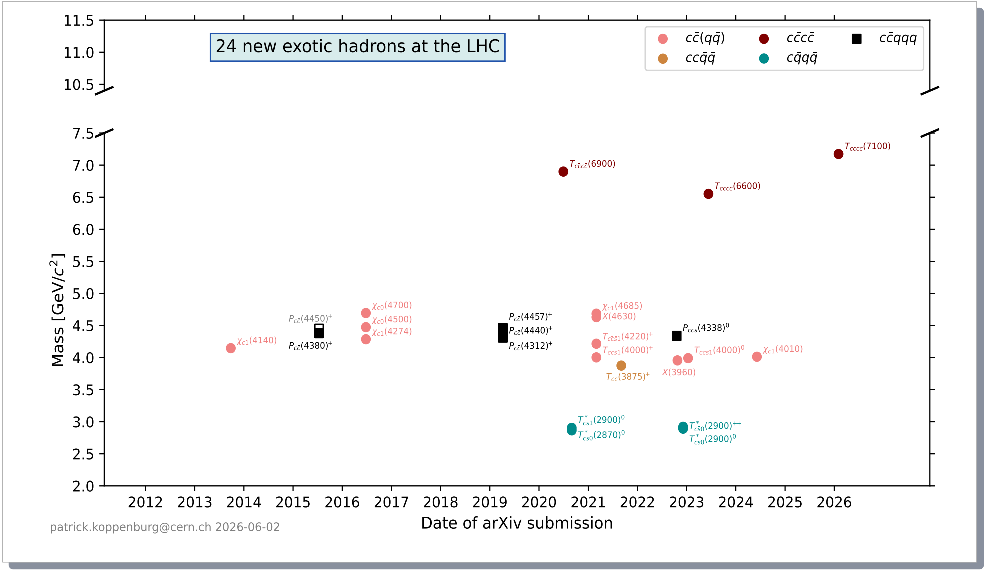
Outline

- **Exotic hadrons and lattice QCD: a quick intro**
- **Charmonium exotics**
- **Heavy flavored tetraquarks**
- **Open charm mesons**
- **Pentaquarks**
- **Summary**

Outline

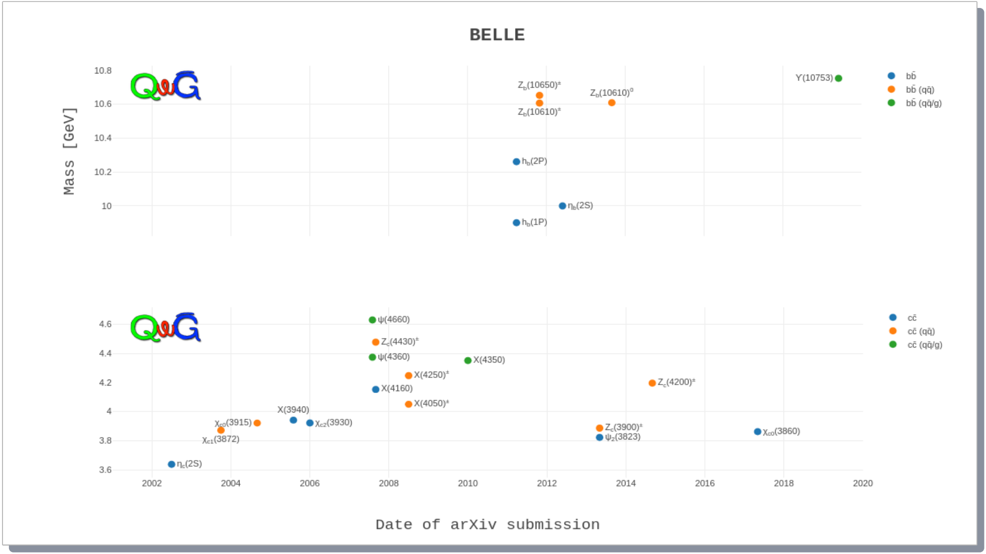
- **Exotic hadrons and lattice QCD: a quick intro**
- Charmonium exotics
- Heavy flavored tetraquarks
- Open charm mesons
- Pentaquarks
- Summary

Exotic discoveries at LHC



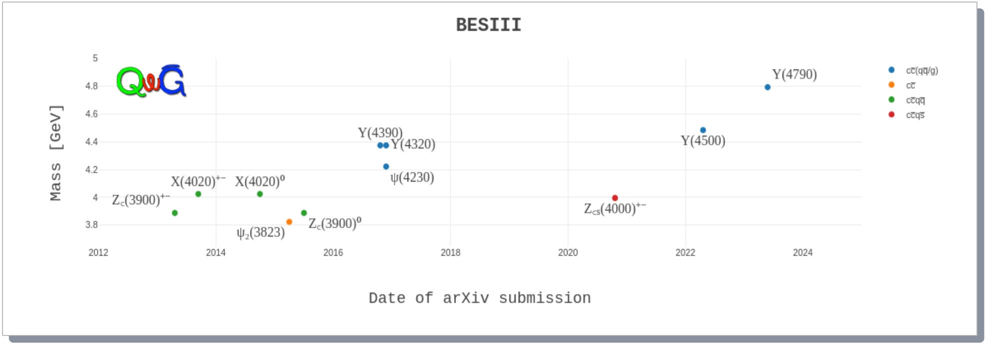
https://www.koppenburg.ch/particles.html

Discoveries at BelleII



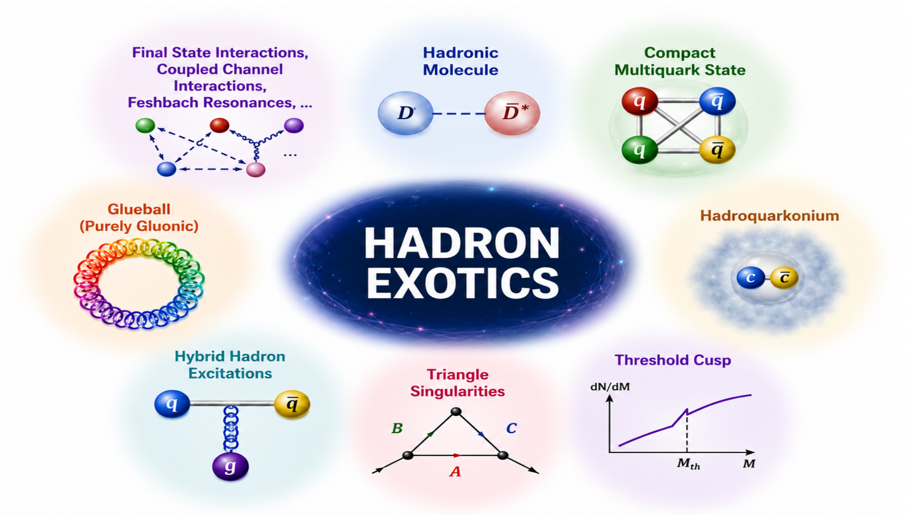
ExoticsHub: https://qwg.ph.nat.tum.de/exoticshub/

Discoveries at BESIII



ExoticsHub: https://qwg.ph.nat.tum.de/exoticshub/

Exotic hadron classifications/interpretations



AI generated cartoon

Workflow in a lattice study of exotic hadrons

Phase 1 – framing

1. Motivation and target selection
   XYZ states, T states, P states, ...
2. Deciding on the lattice setup
   ensemble choice, volume,
   lattice spacing, pion mass, ...

Phase 2 – lattice computation

3. Interpolating operator construction
   Local, derivative-based, bilocal, ...
4. Evaluating correlation matrices
   Smearing programs, all-to-all, ...
5. Variational extraction of spectrum
   GEVP, simultaneous fits, ...

Phase 3 – amplitude analysis

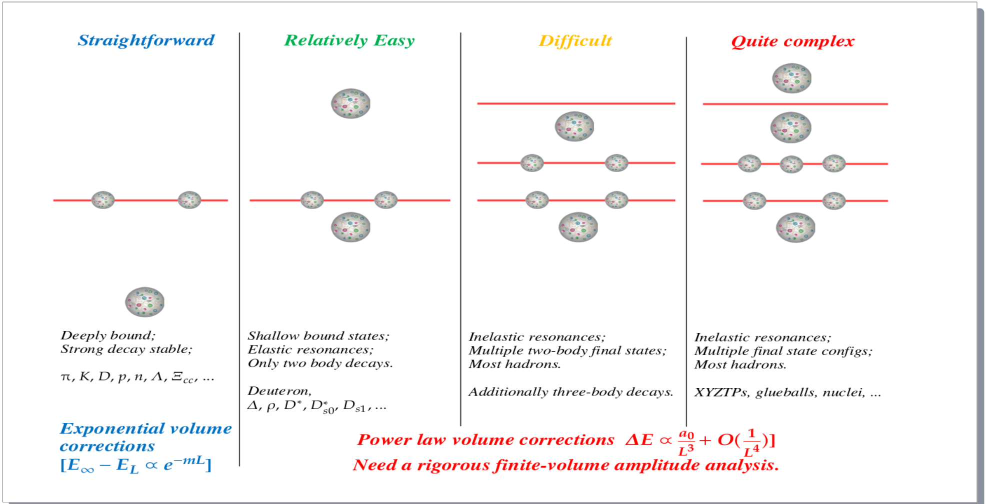
6. Finite volume to Infinite volume mapping
   QC2, QC3, lhc, ...
7. Features in the scattering amplitudes
   (real/virtual) bound poles, resonances, ...
8. Possible physical interpretation
   Residues, channel couplings,
   cross sections, ...

Phase 4 – impact

9. Matching and comparison with phenomenology
   CQM, QCDSR, χPT, EFTs, ...
10. Feedback to experiments
    Scattering parameters, lineshapes,
    branching fractions, form factors, ...

Green PoS LATTICE2025

Complexity in Hadron spectroscopy



Most exotic candidates fall into difficult and quite complex categories. *Mathur LATTICE2024*

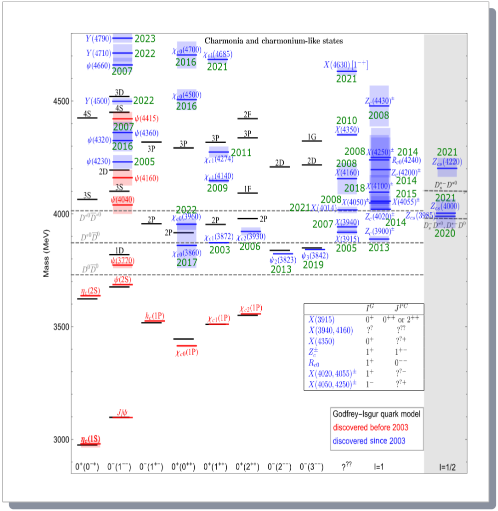
For a previous related lattice plenary talk, see Francis et al. LATTICE2019

Outline

- Exotic hadrons and lattice QCD: a quick intro
- **Charmonium exotics**
- Heavy flavored tetraquarks
- Open charm mesons
- Pentaquarks
- Summary

Charmonium spectrum: the picture we have

- Below threshold, everything is quiet.
- Handful of tensions near and above open charm threshold.
- Some states with exotic quantum numbers
  X(4630) $J^{PC} = 1^{-+}$
- Quantum numbers and state identification often unsettled.
  X(3915), X(3940), X(4160), ...
- Uncertainties in 0^{++} charmonium excitations
  χ_{c0}(3860), X(3915), X(3960), ...
- Isovector vector charmonium states
  $Z_c(3900)^{\pm}$



F.K. Guo Monsoon Hadrons 2026

X(3872): Longest known heavy quark exotic

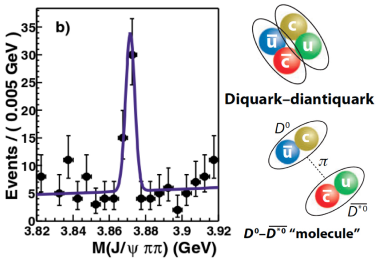
- First observed in Belle 2003

  Belle PRL91 2003

- Later confirmed by CDF (2004), DØ(2004), BaBar (2005).
- Quantum numbers, $J^{PC} = 1^{++}$

  LHCb PRL110 2013

- Appears almost right on top of the $D^0\bar{D}^{*0}$ threshold
- Preferred strong decay modes $D^0\bar{D}^{*0}$, $D^0\bar{D}^0\pi^0$, $J/\psi\ \omega$, $J/\psi\ \rho$, ...



Belle PRL91 2003; *CMS news*

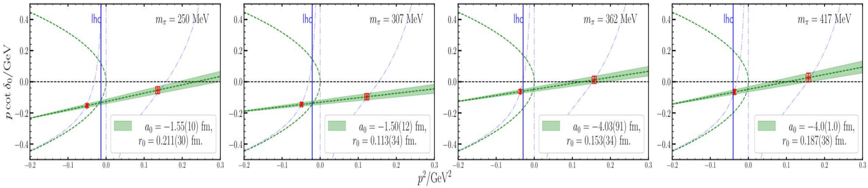
- The isospin assignment is still uncertain. No confirmed isospin partners.
- A quasi bound $D^0\bar{D}^{*0}$ state picture from the analytic structure of the Flatté amplitude.
- Radiative decays to $\psi\gamma$ suggesting compact component *LHCb JHEP11 2024; Koponen Fri 1630 [Stru]*
- First evidence of X(3872) production in Pb-Pb Collisions *CMS PRL128 2022*

  A related topic: Urrea-Niño Fri 1730

- Debates on compactness still alive, despite nearing 25 years since discovery.

  Click here to see a list of interesting talks on X(3872)

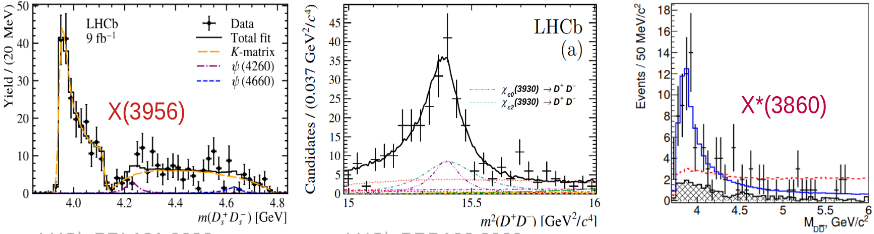
X(3872) on the lattice



Li et al. arXiv:2402.14541

- Not many investigations, owing to complex channel structure.
- Quark mass dependence on relatively coarse ($a_s \sim 0.136$ fm) $N_f = 2$ lattices. Candidate pole for X(3872) from a single $D\bar{D}^*$ in S-wave channel analysis.
- Previous lattice calculations all at single m_π *Chiu&Hsieh PLB646 2007; Bali et al. PRD84 2011; Prelovsek et al. PRL111 2013, PRD92 2015; Lee et al. PoS 2014; Cheung et al.JHEP11 2017;*
- Large FV corrections, role of IB, multichannel analysis, c-quark annihilation, light hadron decay modes, lhc effects ... *Lu Meng's plenary talk for discussion on lhc*
- Similarity to the longest lived exotic hadron T_{cc}^{+}: Will be discussed in the next few minutes.

Excited scalar charmonium as we know



LHCb PRL131 2023 | LHCb PRD102 2020 | Belle PRD95 2017

- $X^*(3860)$ [Belle 2017] the leading candidate for $\chi_{c0}(2P)$, yet not a settled identification. Rests on single Belle measurement, no independent experimental confirmation.
- $X(3915)$ [Belle 2005] has suppressed $D\bar{D}$ mode and prominent OZI suppressed $J/\psi\omega$ mode. Goes against a conventional $\chi_{c0}(2P)$ picture.
- $X(3930)$ feature [LHCb 2020] is probably related to the same pole as for $X(3915)$.
- $X(3960)$ feature [LHCb 2023]: Observed in $B \to D_s^+ D_s^- K^+$ decays. Possible connection to the $D_s^+ D_s^-$ channel. Too low energy to be treated as $\chi_{c0}(3P)$.
- 3.8 - 4.0 GeV hosting a number of features, none of which comfortably fits a $\bar{c}c$ picture. No converged conclusions in the community on number of states and coupled channel dynamics.

Excited scalar charmonium from the lattice (before 2023)

- First attempt of scalar $\bar{D}D$ scattering

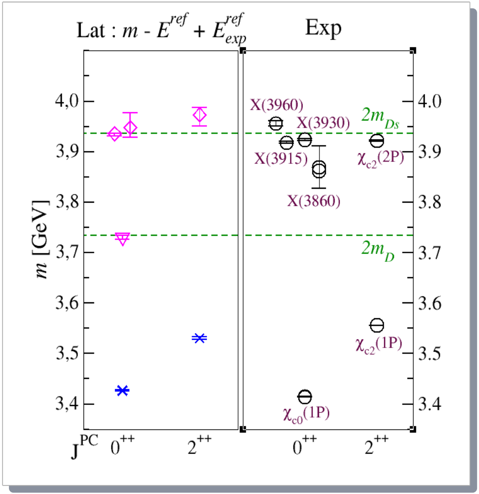
  Lang et al. JHEP09 2015

- First extraction of coupled $\bar{D}D$-$\bar{D}_sD_s$ scattering amplitude. *Prelovsek et al. JHEP06 2021*
  $[\bar{c}c,\ \bar{c}c\bar{q}q;\ q \to u, d, s,$ and $I = 0]$.

- Lattice QCD ensembles : CLS Consortium
  $m_\pi \sim$ 280 MeV, $m_K \sim$ 467 MeV,
  $m_D \sim$ 1927 MeV, $a \sim 0.086$ fm

- Candidates for three scalar excitations
  $\Rightarrow$ yet unobserved shallow $\bar{D}D$ bound state.
  $\Rightarrow$ broad $\bar{D}D$ resonance X(3860).
  $\Rightarrow$ narrow resonance just below and with large coupling to $\bar{D}_sD_s$ threshold.
  X(3960) / X(3930) / X(3915).

- Non-lattice $\bar{D}D$ bound state predictions:
  Gamermann et al. PRD76 2007
  Hidalgo-Duque et al. PLB727 2013
  Baru et al. PLB763 2016
  Deineka et al. PLB827 2022
  Ji et al.SciBull68 2023



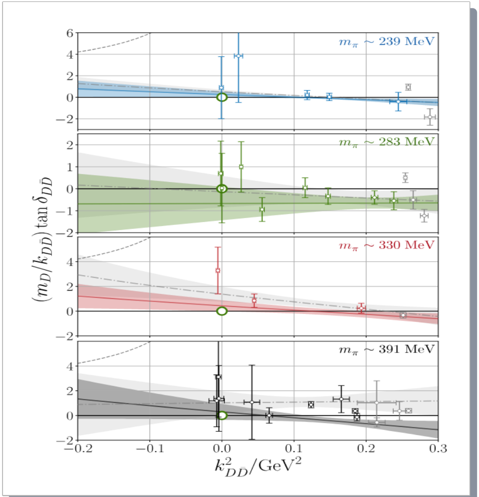
Prelovsek, et al. JHEP06 2021

χPT inspired reanalysis: Shi et al. PRD111 2025

$D\bar{D}$, $D_s\bar{D}_s$, $D^*\bar{D}^*$, $J/\psi\omega$ channels included. $\eta_c\eta$, $\eta_c\eta'$ channels excluded.

Excited scalar charmonium from the lattice (after 2022)

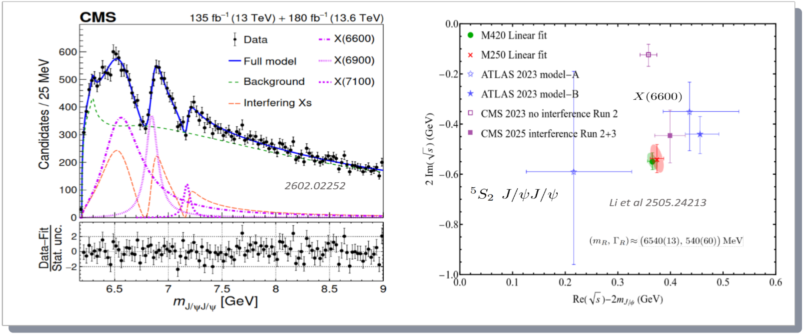
- Analysis involving all kinematically relevant 2-hadron channels and using more than 200 energy levels.
  Wilson et al. PRL132 2024, PRD109 2024.
- Lattice QCD ensembles : Anisotropic clover
  $m_\pi \sim$ 391 MeV, $m_K \sim$ 540 MeV,
  $m_D \sim$ 1852 MeV, $a_s \sim 0.12$ fm
- Only a single scalar resonance below 4 GeV with large coupling to all open charm channels.
- m_q dependence [240-400 MeV] study of $\bar{D}D$ scattering suggesting weak interaction to host any bound pole. *Wilson et al. 2602.09862*
- Conflict with existing lattice results and other phenomenological expectations.
- Continuing tensions calls for more independent and rigorous investigations.



Wilson et al. 2602.09862

$\eta_c\eta$, $\eta_c\eta'$, $D\bar{D}$, $D_s\bar{D}_s$, $D^*\bar{D}^*$, $J/\psi\omega$ channels included.

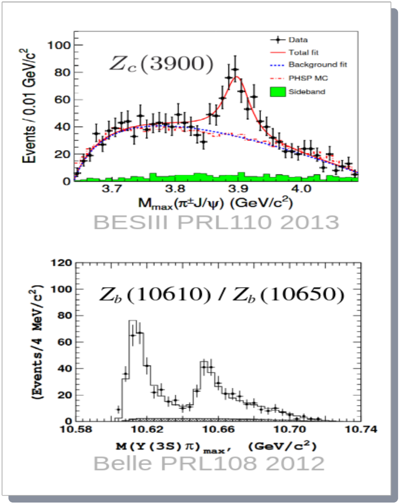
Double charmonium states $T_{cc\bar{c}\bar{c}}$: Expts and Lattice



- Three confirmed features in double charmonium final states *CMS PRL132 2024; 2602.02252*
  X(6600), X(6900), and X(7100) *See also LHCb SciBull65 2020 ATLAS PRL131 2023*
- S-wave $\eta_c\eta_c$ and $J/\psi J/\psi$ elastic scattering:
  genuine 2^{++} resonance around 6540 MeV with width ∼550 MeV
  Consistent with X(6600) *Li et al. 2505.24213; 2505.23220*
- 0^{++} virtual pole 20-40 MeV below $J/\psi J/\psi$ threshold: candidate prediction for X(6200).
- Other related lattice studies:
  Repulsive S-wave $\eta_c\eta_c$ and $J/\psi J/\psi$ interactions *Meng et al.EPJC85 2025*
  Fully beauty tetraquarks: No bound states in $0^{++}/1^{+-}/2^{++}$ channels *Hughes et al. PRD97 2018*

Electrically charged quarkonium Z_c and Z_b

- PDG now refers to these states as $T_{c\bar{c}?}$ and $T_{b\bar{b}?}$.
- $Z_c(3900)/T_{c\bar{c}1}(3900)$ discovered simultaneously in BESIII and Belle. *BESIII PRL110 2013, Belle PRL110 2013*
- Independent confirmation from CLEO-c data *Xiao et al. PLB727 2013*
- Z_c Neutral partner, spin-parity: *BESIII PRL115 2015, PRL119 2017*
- $Z_b/T_{b\bar{b}1}$ discovered by Belle. *Belle PRL108 2012*
- Competing interpretations from phenomenology
  Hadronic molecule *Voloshin, Mehen, Powell, Guo, Hanhart, ...*
  Compact tetraquark *Maiani, Pilloni, Polosa, ...*
  Triangle singularities, threshold cusps *Bugg, Swanson, Chen, Liu, Matsuki, ...*
- Today the question shifted to "what fraction of each?"
  Sizable molecular and compact components *Chen et al. PhysMechAstron67 2024*



Electrically charged quarkonium Z_c and Z_b on the lattice

- Lattice investigations of Z_b based on Born-Oppenheimer static potentials.

  Bicudo et al. PRD101 2019, Prelovsek et al. PLB805 2020, PRD104 2021; Sharma Thu 1710

- Attractive potential in the $B\bar{B}^*$ channel suggesting a bound pole, whereas other explored quantum numbers were not observed to be attractive.

  Prelovsek et al. PLB805 2020, PRD104 2021

- Investigations for $Z_c(3900)$ until 2019: All single volumes, restricted channel sets.

  Prelovsek et al. PLB727 2013, PRD91 2015; Chen et al. PRD89 2014; Lee et al. LATTICE2014; Cheung et al. JHEP12 2016, JHEP11 2017; Chen, Liu et al. CPC43 2019, PRD101 2020

- Coupled channel analysis of $\pi J/\psi$-$\rho\eta_c$-$\bar{D}D^*$ following HALQCD procedure. Argues $Z_c(3900)$ to be a threshold cusp based on strong cross channel potential.

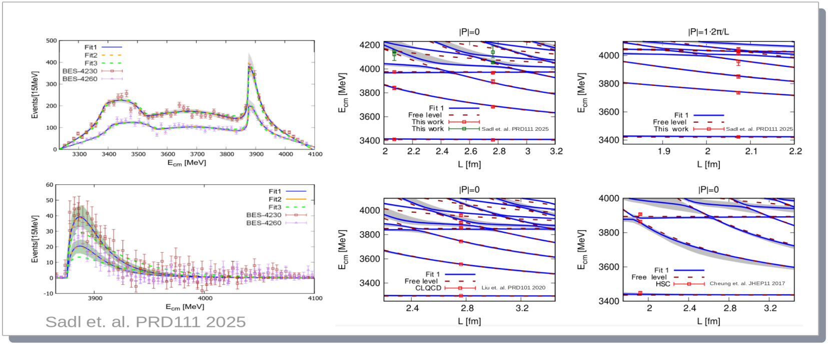
  Ikeda et al. PRL117 2016; JPhysG45 2018

- First analysis to combine multiple volumes, inertial frames and a joint EFT-based fit to lattice and BESIII $J/\psi\pi^\pm$ and $D^0\bar{D}^{*-}$ lineshapes. *Sadl et al. PRD111 2025*

- Joint EFT-based refit to lattice and BESIII lineshapes with enhanced rigor for $\pi^+\pi^-$, $J/\psi\pi^\pm$, K^+K^- and $D^0\bar{D}^{*-}$. *Chen et al. 2604.25607*

- Resonance poles identified for both $Z_c(3900)$ and $Z_{cs}(3985)$. Reinforces cross channel couplings. Sizable molecular and compact components.

Electrically charged quarkonium Z_c and Z_b on the lattice

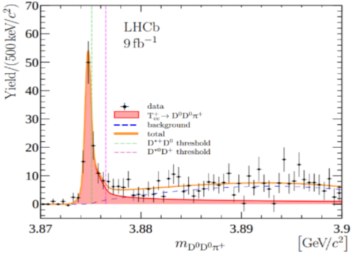


- First analysis to combine multiple volumes, inertial frames and a joint EFT-based fit to lattice and BESIII $J/\psi\pi^{\pm}$ and $D^0\bar{D}^{*-}$ lineshapes. *Sadl et al. PRD111 2025*
- Joint EFT-based refit to lattice and BESIII lineshapes with enhanced rigor for $\pi^+\pi^-$, $J/\psi\pi^{\pm}$, K^+K^- and $D^0\bar{D}^{*-}$. *Chen et al. 2604.25607*
- Resonance poles identified for both $Z_c(3900)$ and $Z_{cs}(3985)$. Reinforces cross channel couplings. Sizable molecular and compact components.

Outline

- Exotic hadrons and lattice QCD: a quick intro
- Charmonium exotics
- **Heavy flavored tetraquarks**
- Open charm mesons
- Pentaquarks
- Summary

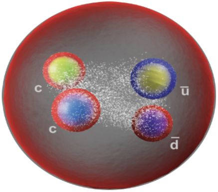
Heavy flavored tetraquarks



LHCb: 2109.01038, 2109.01056

$$\delta m \equiv m_{T_{cc}^+} - (m_{D^{*+}} + m_{D^0})$$

$$\begin{aligned} \delta m_{\rm pole} &= -360 \pm 40^{+4}_{-0} \ \mathrm{keV}/c^2 \,, \\ \Gamma_{\rm pole} &= 48 \pm 2^{+0}_{-14}\, \mathrm{keV} \,. \end{aligned}$$



Courtesy: CERN Courier

- Longest lived tetraquark T_{cc}^+: $I = 0$ and $J^P = 1^+$. *Nature Phys., Nature Comm. 2022*
  Striking similarities with the longest known heavy exotic, X(3872).
- No features observed in $D^0D^+\pi^+$: possibly not $I = 1$.
- Heavy tetraquarks discovered recently, T_{cs}, $T_{c\bar{s}}$, $T_{cc\bar{c}\bar{c}}$. *Mikhasenko ISMD 2025*
  Prospects also for T_{bc} in the near future. *Polyakov at LHCb mini-workshop*
- Heavy flavor tetraquarks: more promising paradigm for exotic hadrons.
  Brambilla et al. PhysRept873 2020; Bicudo PhysRept1039 2023;
  Chen et al. ReptProgPhys86 2023; Francis PPNP140 2025
- Only two lattice calculations before discovery. No amplitude extraction.
  Cheung et al. JHEP11 2017; Junnarkar, et al. PRD99 2019

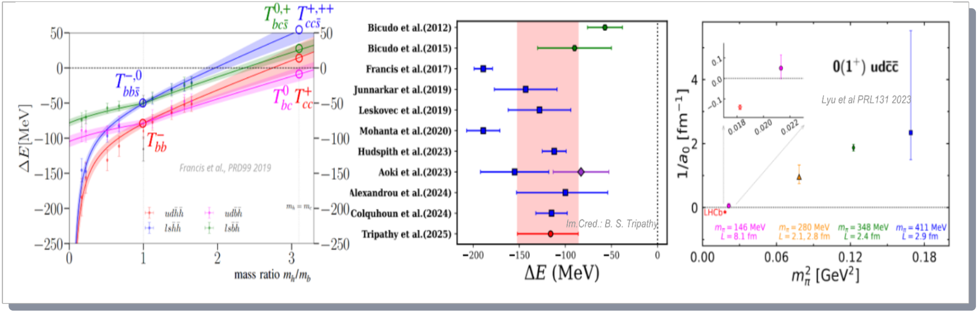
H_{QQ} yield in FCC-ee and HL-LHC

	FCC-ee, 205ab^{-1} at 91GeV	HL-LHC, 300fb^{-1} at LHCb
T_{bb}	<15	<1
Ξ_{bb}	O(50)	O(1)
T_{bc}	<8k	1-5k
Ξ_{bc}	<20k	3-15k
T_{cc}	20k	10k
Ξ_{cc}	70k	150k

- Confirmation of T_{bc}, Ξ_{bc}, T_{cc}, Ξ_{cc}, B_c, ...
  T_{bb} unlikely ...

Polyakov at "Flavours at FCC"

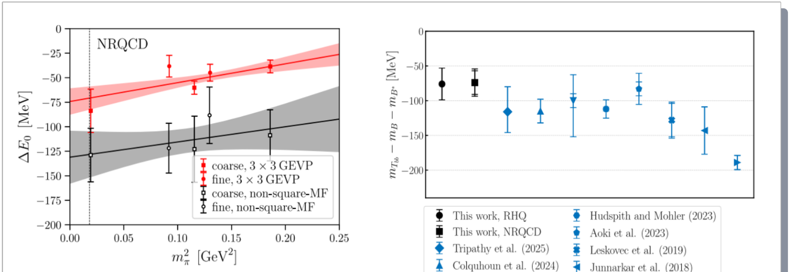
T_{bb} and T_{cc} using lattice QCD: $I(J^P) = 0(1^+)$



- Deeper binding in doubly bottom tetraquarks $\mathcal{O}(100 MeV)$. Generally accepted. Apparent tensions with new reduced binding energy estimates.
- No concrete conclusions in the bottom-charm tetraquark sector.
  Tensions between symmetric *Alexandrou et al. PRL132 2024* and asymmetric setup *MP, et al. PRL132 2024, PRD110 2024*
- Shallow bound state in doubly charm tetraquarks $\mathcal{O}(100 keV)$ in the physical limit. Now a handful of lattice determinations of the DD^* amplitude. Many more challenges!

Lattice focussed reviews: Bicudo PhysRept1039 2023; Francis PPNP140 2025

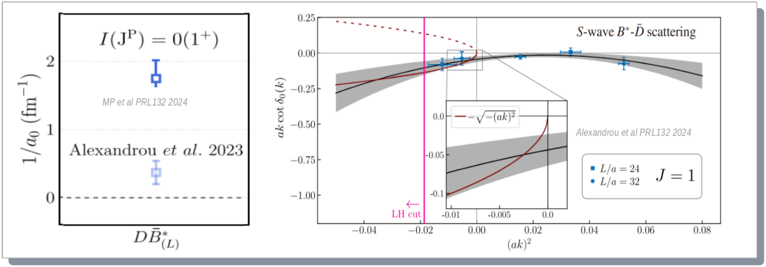
T_{bb} from the lattice



Hoffmann and Meinel PRD113 2026

- Bilocal operators not necessary for the ground state estimation. Crucial for higher excitations, scattering states, amplitude extraction. *Alexandrou et al.PRD110 2024*
- GEVP on symmetric NRQCD-based correlations giving consistent estimates with RHQ-based studies. *Hoffmann & Meinel PRD113 2026*
- Possible plateau identification issues with asymmetric setups.
- Predictions for an isoscalar vector $\bar{b}\bar{b}ud$ resonance 94 MeV above BB threshold. Beyond the static limit, including heavy quark spin effects *Hoffmann & Wagner PRD111 2025*

T_{bc} from the lattice



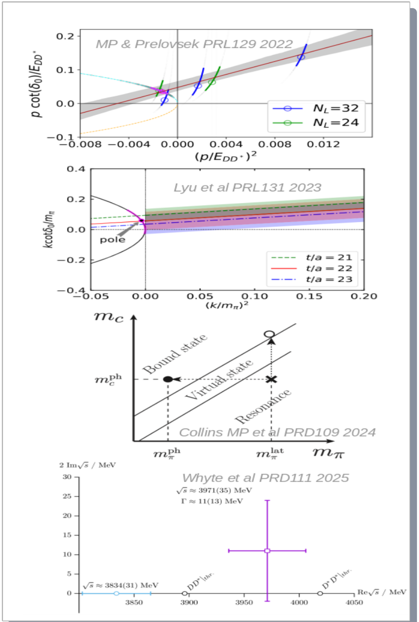
- Two independent measurements on $N_f = 2+1+1$ HISQ lattices, suggesting attractive interactions in $B^{(*)}D$ scattering in isoscalar $J^P = 1^+$ and 0^+ $bc\bar{u}\bar{d}$ systems.
- Relatively deep binding ($\mathcal{O}(40\text{MeV})$) observed on multiple lattice spacings.
  Consistent pattern of decreasing binding observed across $T_{bb} \to T_{bc} \to T_{bs}$.
  Asymmetric correlations utilized. Efforts in progress towards symmetric correlation measurements.
  MP, et al. PRL132 2024, PRD110 2024
- Shallow bindings ($\mathcal{O}(2\text{MeV})$) in the coarsest lattice(s).
  Symmetric correlations involving $\bar{b}\bar{c}ud(p)$ and $\bar{b}u(p_1)\bar{c}d(p_2)$ operators.
  Hints for possible resonances ($\mathcal{O}(100\text{MeV})$) above threshold. *Alexandrou et al. PRL132 2024*
- Recent EFT-based analysis suggests molecular interpretation. *Abolnikov et al. 2602.02176*
- Earlier lattice precedent suggest no observed binding. *Francis PRD99 2019*

T_{cc} on the lattice

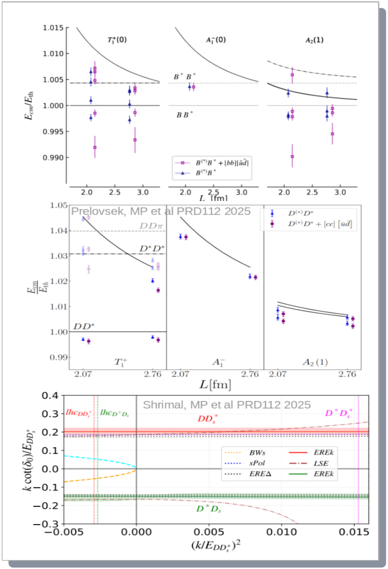
- First extraction of DD^* amplitude at $\sim 2m_\pi^{phys}$
  $2 \to 2$ LQC and ERE $\Rightarrow$ virtual bound pole
  MP & Prelovsek PRL129 2022
- DD^* amplitude immediately above m_π^{phys}.
  HALQCD potential method. *Lyu et al. PRL131 2023*
- Quark mass (m_q) dependence suggesting a real bound state at m_π^{phys}.
  Lyu et al. PRL131 2023; Collins et al. PRD109 2024
- First extraction of coupled DD^*-D^*D^* amplitude.
  Lattice candidate for D^*D^*-bound resonance T'_{cc}.
  Whyte et al. PRD111 2025
- Pion exchange left hand cuts ignored.
- Earlier investigations of DD^* FV spectrum.
  No observed energy shifts at $\sim 3m_\pi^{phys}$
  Cheung et al. JHEP11 2017

  Negative energy shifts
  Junnarkar et al. PRD99 2019

  Shallow negative energy shifts
  Francis et al. PRD99 2019



T_{cc} on the lattice [continues ...]



- Relevance of diquark-antidiquark operators with distillation at $2m_\pi^{phys}$. *Prelovsek et al.PRD112 2025*.
- Insignificant effects in DD^* spectrum near threshold. First excitation in S-wave affected.
- New ground state level emerges BB^* spectrum. Close lying BB^* and B^*B^* thresholds. Elastic analysis questionable.
- Consistent observations in other FV studies at $3m_\pi^{phys}$. *Stump & Green PRD113 2026; Stump Thu 1650*
  Role of tetraquark operators in light meson sector *Hanlon et al. 2603.19192; Meneghini Fri 1500*
- Investigations of the strange partners $T_{cc\bar{u}\bar{s}}$, $T_{bs\bar{u}\bar{d}}$
  No poles observed despite negative energy shifts *Shrimal et al. PRD112 2025; Tripathy et al. PRD111 2025*
- Earlier/Other investigations of strange partners
  Binding in $T_{bb\bar{u}\bar{s}}$ *Francis et al. PRL118 2017; Junnarkar et al. PRD99 2019, Alexandrou et al. PRD110 2024*
  No observed energy shifts in $T_{cc\bar{u}\bar{s}}$ *Cheung et al. JHEP11 2017; Francis et al. PRD99 2019; Junnarkar et al. PRD99 2019*

T_{cc} on the lattice [continues ...]

- $cc\bar{u}\bar{d}$ isospin sectors within same framework. Differing in signature of the coefficients.

$$C_I^{DD^*}(t) = \mathcal{D} - \mathcal{C}_1 + (-1)^{I+1}(\mathcal{D}' - \mathcal{C}_2)$$

Chen et al. PLB833 2022.

- t-channel isovector-vector meson exchange: key in distinguishing the two isospin channels

Meng et al. PRD111 2025.

- Negative energy shifts in isoscalar sector. Attractive interactions. Left hand cuts issues ... *see next slide*

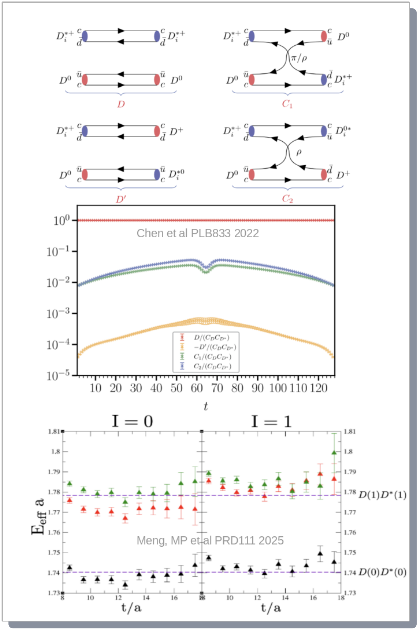
- Positive energy shifts in isovector channel. Repulsive interactions. Consistent with null result in experiments.

- More recent investigation of isospin-1 coupled DD-DD^*-D^*D^* scattering. $\sim 3m_\pi^{phys}$ Reinforces null result in $I = 1$ sector.

Lachini et al. PRD112 2025

- Weak repulsion/attraction in $I(J^P) = 1(0^+)$ and $I(J^P) = 0(1^-)$ elastic DD scattering.

Shi et al. PRD upcoming



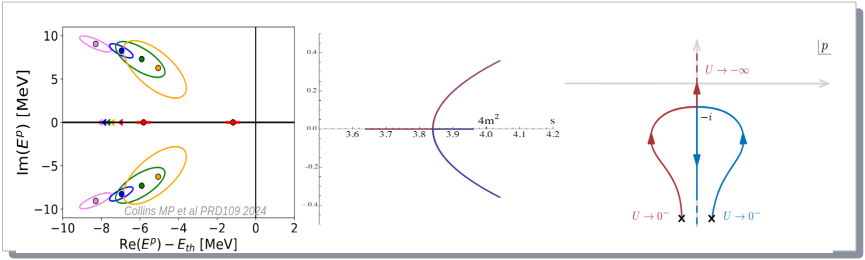
Accommodating three particle effects in T_{cc} studies

- Dedicated plenary talk on solving pion exchange left-hand cuts *Meng Sat 1100*
- Several complementary proposals and attempts

Hansen χDyn2024; Sharpe PoS LATTICE2025; Dawid Wed 0900

Bubna et al.JHEP10 2025; Du et al.PRL135 2025, PRD114 2026;

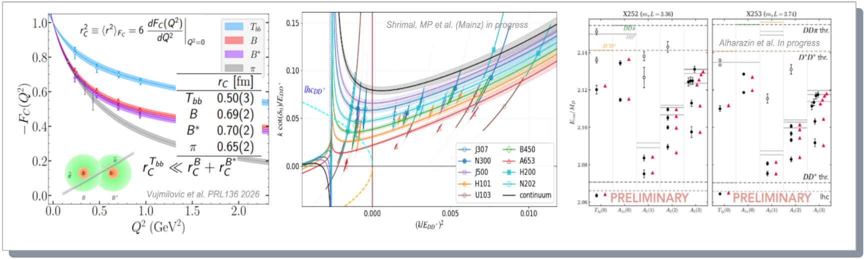
- Upon accommodating the cross-channel effects in DD^* S-wave scattering:
  Virtual bound poles $\Rightarrow$ Virtual resonances



lhc effects in T_{cc} studies: Collins et al.PRD109 2024; Prelovsek et al.PRD112 2025

S-wave pole trajectory discussions: Hyodo PRL111 2013; Hanhart et al. PLB739 2014; Mizera PhysRep1047 2024

Doubly heavy tetraquarks systems: A few other highlights



- First lattice calculation of the EM formfactors of T_{bb} tetraquark. Consistent with a compact state. *Vujmilovic et al. PRL136 2026*

- T_{cc} investigations on multiple lattice spacings (0.038 fm - 0.097 fm). Accommodating lhc effects following LSE-based quantization condition. Addressing lattice systematics in T_{cc} system at $\sim 3m_\pi^{phys}$

  Shrimal et al. (Mainz) in progress; Green et al. PoS Lattice 2023

- T_{cc} study following 3-body RFT formalism at $\sim 2m_\pi^{phys}$. Fits to DD^*+$DD\pi$ spectra involving 2- and 3-particle $\mathcal{K}$-matrices.

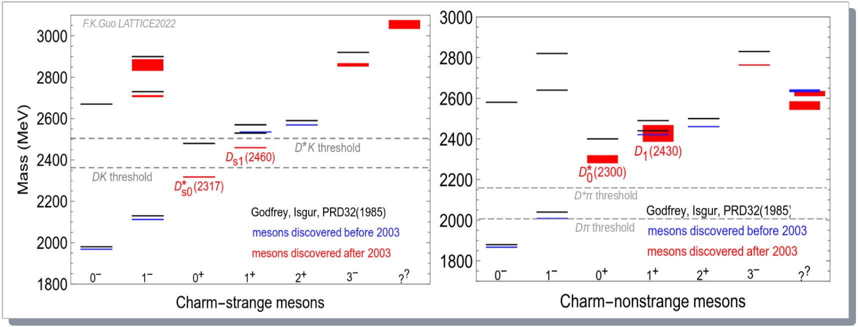
  Sharpe Thu 1630; Raposo PoS LATTICE2025

  Lachini & Briceño 2607.19009; See also Vujmilovic Fri 1400

Outline

- Exotic hadrons and lattice QCD: a quick intro
- Charmonium exotics
- Heavy flavored tetraquarks
- **Open charm mesons**
- Pentaquarks
- Summary

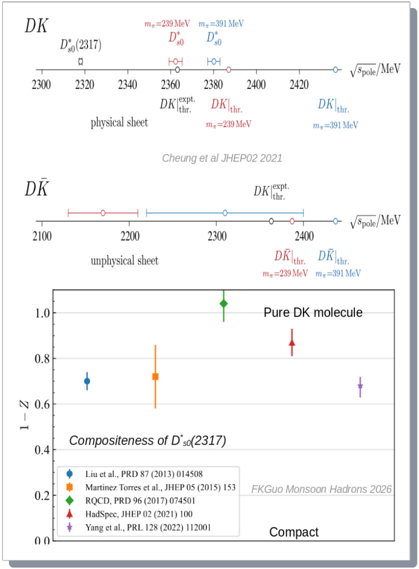
Open charm mesons: three puzzles



- $D^*_{s0}(2317)$ (BaBar 2003) and $D_{s1}(2460)$ (CLEO 2003): narrow, $I = 0$, sitting *below* the DK / D^*K thresholds, ~ 150 MeV below quark model *Godfrey & Isgur PRD32 1985*
- Broad nonstrange partners $D^*_0(2300)$, $D_1(2430)$ (Belle 2004)
- Three puzzles in lowest positive parity excitations: *Du et al. PRD98 2018*
  - (a) Charm strange meson: why so light relative to naïve quark model expectations?
  - (b) Why $M_{D_{s1}} - M_{D^*_{s0}} \simeq 141.8$ MeV $\approx$ $M_{D^*} - M_D \simeq 140.7$ MeV
  - (c) Why is the $D^*_0(2300)$ as heavy as the $D^*_{s0}(2317)$?
- Caveat: $D^*_0(2300)$ BW parameters are suspect. *Kolomeitsev & Lutz PLB582 2004*
  Chiral and coupled channel effects pull down the mass by ~ 100 MeV. *UChPT: Du et al. PRD98 2018*

$D^*_{s0}(2317)$ / $D_{s1}(2460)$: the lattice resolution

- $c\bar{s}$-only interpolators overshoot the mass: the operator basis dictates what you can see
  Moir et al. JHEP05 2013
- $c\bar{s} + DK$ operators + Lüscher FV formalism: DK bound state close to the physical value
  Mohler et al. PRL111 2013
- Near-physical $m_\pi = 150$ MeV: strong m_π dependence of the binding
  Bali et al. PRD96 2017
- Coupled channels: $I{=}0$ DK bound state; $I{=}0$ $D\bar{K}$ virtual; $I{=}1$ repulsive
  Cheung et al. JHEP02 2021
- $D^*_{s0}(2317)$ emerges only when you let it be what it is: a DK system ??
- Bound state: Weak coupling to bilocal DK interpolators and strong coupling to $c\bar{s}$ interpolators. $m_\pi \sim 300$ MeV *Alexandrou et al. PRD101 2020*



The SU(3) skeleton and the double pole nature of $D_0^*(2300)$

- The group theory of $D_{(s)}$ mesons scattering off the light pseudo-NG $J^P = 0^-$ octet mesons.

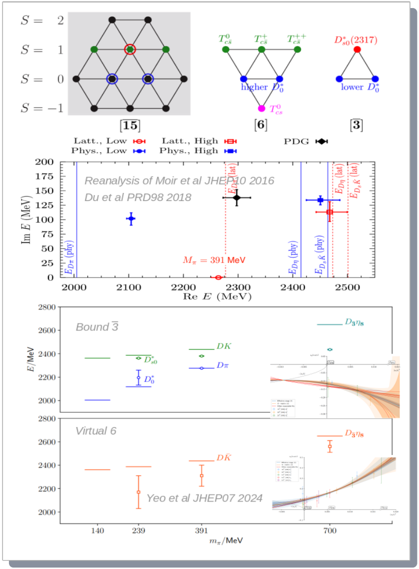
$$[\bar{\mathbf{3}}] \otimes [\mathbf{8}] = [\overline{\mathbf{15}}] \oplus [\mathbf{6}] \oplus [\bar{\mathbf{3}}]$$

- $\bar{\mathbf{3}}$ most attractive, $\mathbf{6}$ attractive, $\overline{\mathbf{15}}$ repulsive. Two D_0^* poles from $\bar{3}$ and 6 split by SU(3) breaking.
  UChPT: Albaladejo et al. PLB767 2017

- Coupled $D\pi$-$D\eta$-$D_s\bar{K}$ studies [HadSpec]:
  $m_\pi = 391$ MeV $\rightarrow$ subthreshold pole
  Moir et al. JHEP10 2016
  $m_\pi = 239$ MeV $\rightarrow$ broad resonance 2.2 GeV
  Gayer et al. JHEP07 2021

- UChPT predicts two $I{=}1/2$ poles (blue/red markers)
  Reproduce FV levels reliably at $m_\pi = 391$ MeV.
  Du et al. PRD98 2018

- SU(3)-symmetric point $m_\pi = m_K \approx 700$ MeV:
  At lighter m_π: $\bar{3} \rightarrow D_{s0}^*$ bound + a low D_0^* resonance, $6 \rightarrow$ a virtual pole.
  Yeo et al. JHEP07 2024



More studies on open charm nonstrange mesons

- $D^*\pi$-$D^*\eta$-$D_s^*\bar{K}$ analysis $\rightarrow$ a similar picture in 1^+.
  bound state + narrow resonance + broad resonance *Lang & Wilson PRL129 2022; JHEP07 2025*

- $D\pi$ scattering at four m_π:
  resonance at $m_\pi \simeq 133, 208$ MeV, virtual pole at $m_\pi \simeq 305, 317$ MeV
  the pole trajectory map anticipated by the EFT *Yan et al. PRD111 2025*
  See also Thoma et al. PoS LATTICE2025

- $m_\pi = m_K = 613$ MeV: 6 attractive, 15 repulsive in both 0^+ and 1^+
  $\Rightarrow$ molecular over compact picture *Gregory et al. EPJA61 2025*
  Quantitative tensions in flavor **6** $D\overline{K}$ scattering with HadSpec observations at m_π =700 MeV
  Yeo et al. JHEP07 2024

- physical-m_π, continuum-limit coupled channels; three-body dynamics ($D^*\pi\pi$ entering the 1^+ sector); left-hand-cut-aware amplitudes, ...

- HQFS: $B_{s0}^* \approx 5720$ MeV, $B_{s1} \approx 5772$ MeV *Du et al.PRD98 2018*
  Lattice predictions 5711(23), 5750(25) MeV, respectively *Lang et al. PLB750 2015*

More on charm strange mesons

- $D_{s1}(2460)^+ \to D_s^+\pi^+\pi^-$ decay assuming D^*K molecular picture.

  Tang et al.CommTheoPhys75 2023

- Dispersive analysis of FSI in $\pi\pi \Rightarrow$ a double bump in the $\pi\pi$ invariant mass

  Tang et al.CommTheoPhys75 2023

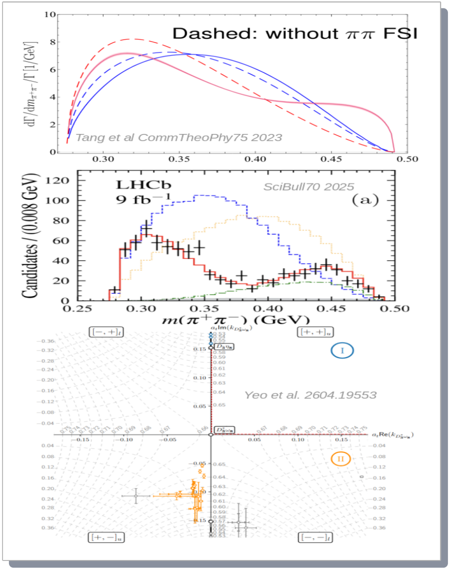
- Experimental evidence: *LHCb SciBull70 2025*

- Molecular-picture predicts - scalar $T_{c\bar{s}}$ resonance with mass ~ 2327 MeV

  Guo & Zou, SciBull70 2025

- An extended investigation at SU(3)-symmetric point $m_\pi = m_K \approx 700$ MeV:
  $6 \to$ a virtual pole plus a resonance.
  Latter identified with $T^*_{cs0}(2870)/T^*_{c\bar{s}0}(2900)$ resonance in the SU(3) symmetric limit.

  Yeo et al. 2604.19553



Outline

- Exotic hadrons and lattice QCD: a quick intro
- Charmonium exotics
- Heavy flavored tetraquarks
- Open charm mesons
- **Pentaquarks**
- Summary

Baryon-meson systems in experiments

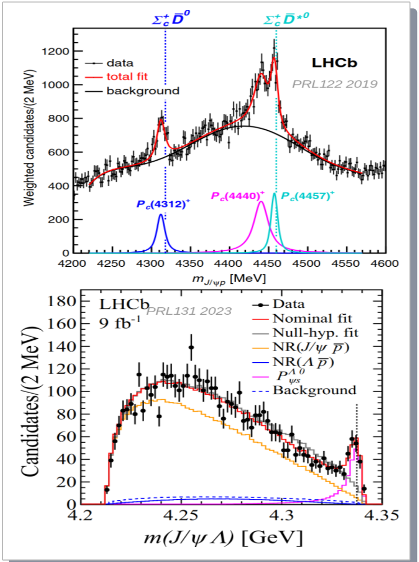
- P_c: Structures just below a $\Sigma_c \bar{D}^{(*)}$ threshold in the $J/\psi p$ spectrum of $\Lambda_b \to J/\psi p K^-$
  LHCb PRL115 2015; PRL122 2019

- $P_{cs}(4338)^0$ / $P_{cs}(4459)^0$ below the $\bar{D}^{(*)}\Xi_c$
  LHCb SciBull66 2021; LHCb PRL131 2023
  Evidence for $P_{cs}(4459)^0$ *BelleII PRL135 2025*

- Femtoscopic correlations in baryon-meson systems: a direct experimental counterpart to lattice scattering amplitudes:
  $K^- p$ *ALICE PRL124 2020; Murakami Fri 1520*
  $K^\pm \Lambda$ ($\Xi(1620)/\Xi(1690)$) *ALICE PLB845 2023*
  $D^{(*)} p$ correlations *ALICE PRD106 2022*

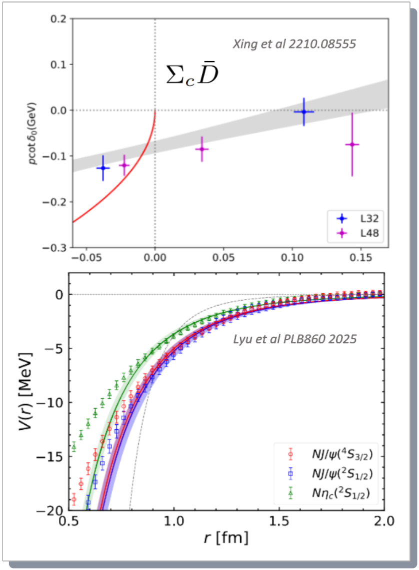
- $N^*(1440)$ in πN partial-wave analysis;
  Lowest N radial excitation *Roper PRL12 1964*
  Three-body $N\pi$-$N\pi\pi$ FV amplitude analysis is crucial. *Wu Fri 1440*

- $\Lambda(1405)$: $J^P = 1/2^-$, just below the $\bar{K}N$ threshold implications for kaonic nuclei and the dense-matter EoS. Recent studies revealing the two-pole structure.
  Bulava et al. PRL132 2024
  Studies at SU(3) point *Sucunza et al.2605.28447*



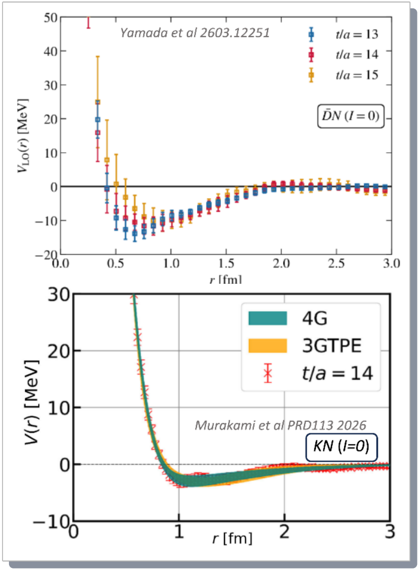
Baryon-meson scattering: hidden charm (P_c sector)

- s-wave $\bar{c}c$-N scattering *à la* Lüscher [quenched]
  Yokokawa et al. PRD74 2006
  $c\bar{c}$–N potentials *à la* HALQCD procedure
  Kawanai, Sasaki, PRD82 2010
- Static $\bar{c}c$ in light hadron cloud [$m_\pi \simeq 223$ MeV]
  Hadroquarkonium $\Rightarrow$ uniformly weak attraction
  Alberti et al. PRD95 2017
- NJ/ψ, $N\eta_c$ scattering at $m_\pi \simeq 266$ MeV,
  J^P up to $5/2^\pm$, no $\Sigma_c\bar{D}^{(*)}$ interpolators.
  Null result within single channel approach.
  Skerbis & Prelovsek PRD99 2019
  See also Liu et al. PoS LATTICE2008 for an earlier study
- $\Sigma_c\bar{D}$, $\Sigma_c\bar{D}^*$ scattering at $m_\pi \simeq 294$ MeV:
  Two shallow bound states, single-channel analysis,
  No NJ/ψ operators, single spacing
  Xing et al. 2210.08555
- N-J/ψ, N-η_c scattering at $m_\pi = 146$ MeV:
  attraction at all distances with a 2π-exchange tail;
  a HALQCD study *Lyu et al. PLB860 2025*



Baryon-meson scattering: open charm

- s-wave $\bar{D}N$ scattering at $m_\pi \simeq 137$ MeV
  HALQCD: repulsive core + shallow attraction
  Not attractive enough to form bound states.
  Yamada et al. 2603.12251; Yamada Fri 1520
- HALQCD based study of KN scattering.
  Weaker binding than in $\bar{D}N$ system.
  Murakami et al. PRD113 2026; Murakami Fri 1520
- Other HAL QCD physical-point results:
  the N-$\bar{\Omega}_{ccc}$ interaction *Zhang et al.PLB871 2025*
- Conspicuous gaps to explore:
  $\pi\Sigma_c$ [$\Lambda_c(2595)$: charm analog of $\Lambda(1405)$],
  D^*N [$\Lambda_c(2940)$, $\Sigma_c(2800)$],
  $\bar{D}^{(*)}\Xi_c$ [$P_{cs}(4338)/P_{cs}(4459)$], ...
- Several challenges ahead: S-D mixing, baryonic SNR, coupled-channel effects, lhc aware amplitudes, ...



Outline

- Exotic hadrons and lattice QCD: a quick intro
- Charmonium exotics
- Heavy flavored tetraquarks
- Open charm mesons
- Pentaquarks
- **Summary**

Summary

- **Exotic hadron landscape keeps growing**: *LHCb, Belle II, BESIII continue discoveries (T_{cc}, T_{cs}, $T_{cc\bar{c}\bar{c}}$, P_{cs}, ...); lattice QCD provides the first-principles framework*
- **X(3872) and T_{cc} share a common challenge**: *Both sit at/near the $D\bar{D}^*$ threshold; understanding now relies on treating pion-exchange left-hand cuts, not just extracting a pole*
- **Scalar charmonium sector remains contested**: *Coupled-channel lattice studies find resonance/bound-state features near $D\bar{D}/D_s\bar{D}_s$; most recent large-scale analysis finds no bound pole$\rightarrow$ genuine tension b/w lattice determinations*
- **The cleanest paradigm of doubly-heavy tetraquarks**: *T_{bb} binding ($\sim$75–100 MeV) robust across actions; T_{cc} a shallow virtual state $\rightarrow$ resonance once lhc effects included; T_{bc} unsettled*
- **Open-charm meson puzzles largely resolved**: *$D_{s0}^*(2317)/D_{s1}(2460)$ as molecular-dominated DK/D^*K states; $D_0^*(2300)$ puzzle explained by SU(3) double-pole structure ($\bar{\mathbf{3}}$ bound + $\mathbf{6}$ resonance)*
- **Relatively less explored frontier of baryon-meson scattering**: *First HALQCD/Lüscher studies of $\Sigma_c\bar{D}^{(*)}$, NJ/ψ, $\bar{D}N$, KN; sector lags behind mesonic channels, clear gaps remain.*
- **Common thread**: *Quark-mass dependence, three-body/lhc-aware formalisms, and cross-validation within the lattice community, ...*

Outlook: what we owe to phenomenology and experiments

- Observables, not just energy levels
  cross sections, lineshapes, scattering parameters, ...
- Rigorous approach to addressing systematics
  Systematics error budget and unaddressed systematics
- Results at the physical point are not the final word
  Quark mass dependence speaks physics
- Transparency in assumptions and approximations made
  Ignored quark line diagrams, channel (in)completeness, ...
- Cross validation within the lattice community
  Comparison of results and methods on same channels.
- Guiding in making the features less exotic
  Understanding their origin and the dynamics within

Thanks for materials and discussions

Constantia Alexandrou
Felipe Ortega Gama
Feng-Kun Guo
Nelson Pitanga Lachini
Nicolas Lang
Zhang Liang
Maxim Mai
Nilmani Mathur
Stefan Meinel
Colin Morningstar
Joseph Moscoso
Ivan Polyakov
Andre Baiao Raposo
Tanishk Shrimal
Andres Stump
Bhabani Sankar Tripathy
Juan Andrés Urrea-Niño
David Wilson
Rento Yamada

I sincerely apologize to colleagues whose important contributions I could not include in this review owing to the limited time available. Any omissions are entirely due to the breadth of the subject and the constraints of the presentation.

Funding acknowledgements

- The Institute of Mathematical Sciences, Chennai
- Anusandhan National Research Foundation, India
- 42nd International Symposium on Lattice Field Theory Organizing committee.

Thank you

Questions & discussion welcome