NSTAR 2026

Exotic hadrons: review and personal perspective

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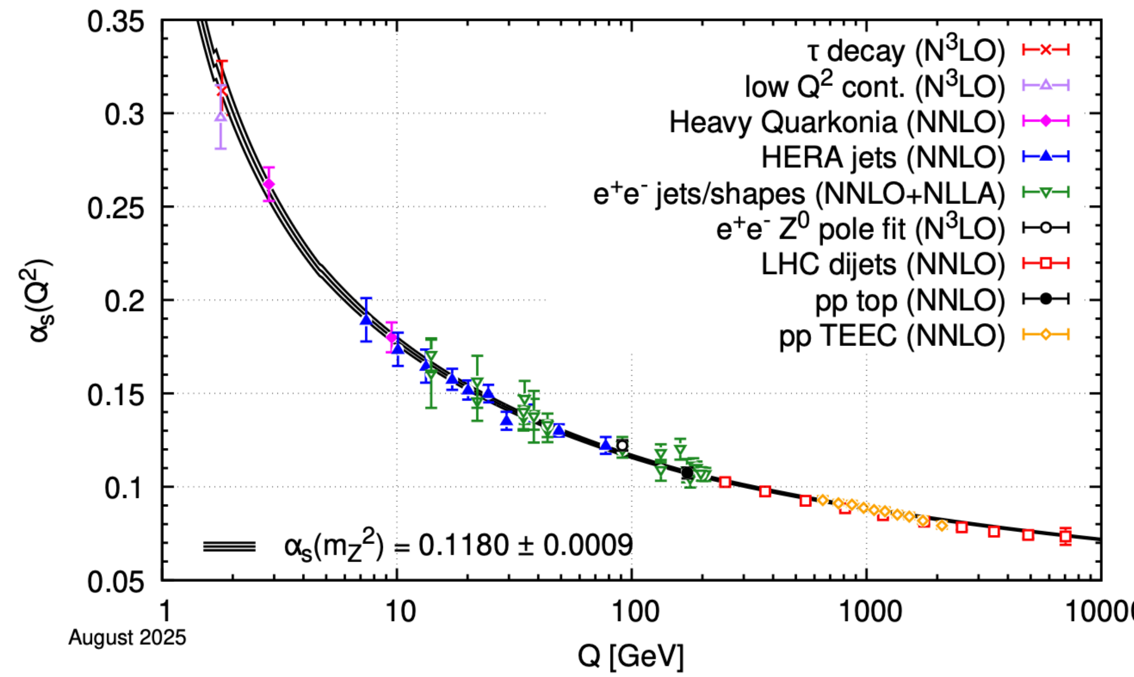
NSTAR2026

Seville, Spanish, September 7th-11st, 2026

Exotic hadrons?

Running Coupling



- Color Confinement

△ Allow all the color neutral objects

① Conventional mesons and baryons in QM

② Hadrons beyond QM, e.g. exotic hadrons

- Quantum numbers in QM

△ For mesons $q\bar{q}$

① $P = (-1)^{L+1}, \quad C = (-1)^{L+S}$

② $0^{-+}, 0^{++}, 1^{--}, 1^{+-}, 1^{++}, 2^{++}, 2^{-+}, 2^{--}, 2^{+-}, \ldots$

△ For baryons qqq

① Allow for all half integer spin

② Allow for both positive and negative parities

- Exotic hadrons

△ With exotic quantum numbers

① $0^{--}, 0^{+-}, 1^{-+}, 2^{+-}, 3^{-+}, \cdots$

② e.g. $\pi_1(1600), \quad J^{PC} = 1^{-+}$

△ With exotic components

① $q\bar{q}g,\ gg, ggg, \cdots$

② $qq\bar{q}q, qqqq\bar{q}, qqqqqq, \cdots$

0^{--} $\bar{D}_s DK$ three-body bound state, Wu et al., PRL135(2025)031902

Prediction of 0^{--} state as $\psi(4260)$ HQSS partner, Ji et al., PRL129(2022)102002

What do we study?

- The physics

① Internal structures, e.g. form factors

② Spectra of various potentials within the QM frame work

③ Production in various processes

④ Various decay modes and partial widthes

⑤ Lineshapes and compositeness

⑥ Partners in various symmetries, e.g. HQS, SU(3) flavor symmetry

⑦ Multi-hadron systems

⑧ Multi-pole structure for a given structure

⑨ Correlation of two/three-hadrons in HIC

⑩ Hadron properties at finite temperature and finite density

⑪ ……

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Which methods do we use?

- The methods

① Various quark models

② DSE

③ pNRQCD

④ QCD sum rule

⑤ Lattice QCD

⑥ Various EFT+Unitarization

⑦ Dispersion relation

⑧ Phenomenological approaches, e.g. effective Lagrangian approach

⑨ Lattice EFT

⑩ Machine learning

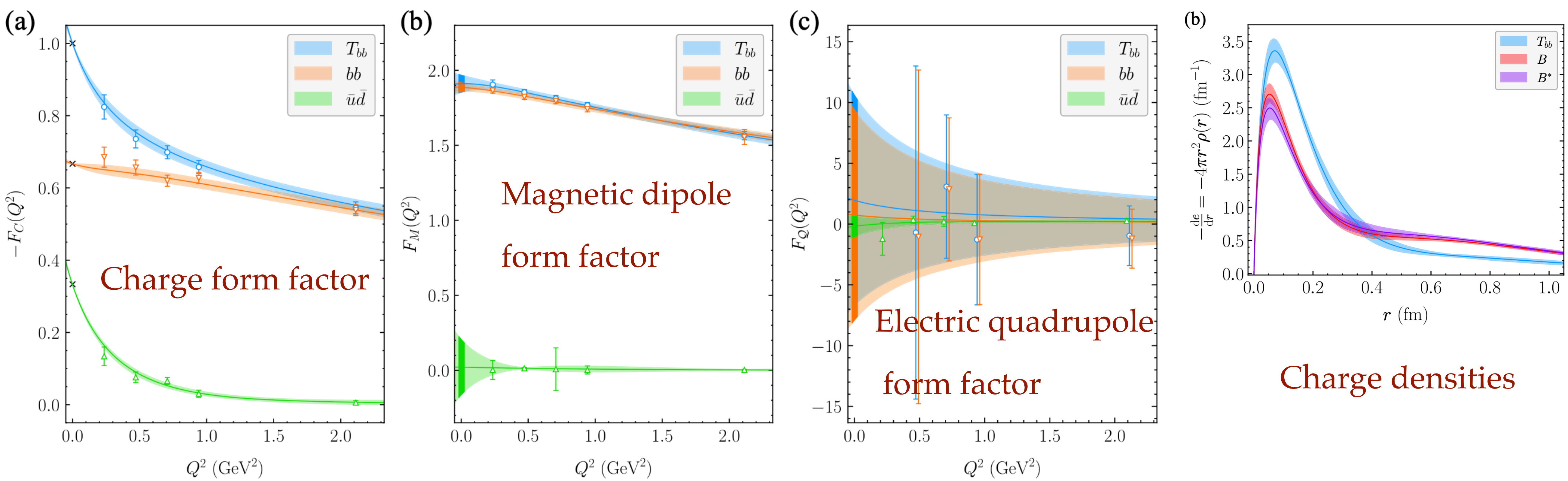
⑪ Hamiltonian EFT

⑫ ….

Form factors

Well defined for stable hadrons

- Electromagnetic form factors of T_{bb} from Lattice QCD



Vujmilovic et al., PRL136(2026)161901

- The first Lattice QCD result on the form factors of exotic hadrons
- Feasible for exotic hadrons stable in strong interaction
- Favor compact object other than hadronic molecule, e.g. $r_{T_{bb}} < r_B + r_{B^*}$
- Diquark anti-diquark picture works well, due to $F_C(Q^2)_{bb}$ and $F_C(Q^2)_{\bar{u}\bar{d}}$ behaviors

Form factors

- Magnetic moments in chiral perturbation theory

  - Motivated by the magnetic moments of decuplet baryons to NNLO in χPT

    Li et al., PRD95(2017)076001

  - Magnetic moments of instable hadrons can be accessed via some special processes, e.g. magnetic moments of Δ can be measured in $\gamma N \to \Delta \to \Delta\gamma \to \pi N\gamma$

    Talk by Luis Albino Fernandez Rangel on Mon. Pascalutsa et al., PRL94(2005)102003, PRD77(2008)014027

  - Magnetic moments of hidden charm pentaquarks in HM, diquark-triquark and diquark-diquark-antiquark pictures

    Wang et al., PRD94(2016)094018

  - Applications to other systems, e.g. P_c, P_{cs}, P_{csss}, $QQQQ\bar{Q}$,

    Li et al., PRD104(2021)054016, Zhang et al., PRD104(2021)114011,Gao et al., CPC46(2022)123111, Zhou et al., PRD106(2022)034034, Wang et al., PRD106(2022)054020, Wang et al., PRD108(2023)034006, Gou et al., EPJC84(2024)392, Zhang et al., EPJC83(2023)727, Li et al.,PRD109(2024)094027, Zhu et al., EPJC86(2026)385….

  - No experimental measurement yet

Spectra in QM

- A simply extension of conventional quark model

- d.o.f $= 3^4 - 3 = 78 \rightarrow 3$ in diquark and antidiquark

Solutions

$\Rightarrow$ Gaussian expansion method (GEM)

Hiyama et al., Prog. Part. Nucl. Phys. 51 (2003)223 Talk by Jean-Marc Richard on Tue.

$\Rightarrow$ explicitly correlated Gaussian (ECG)

Varga, et al., Phys.Rev.C52(1995)2885, Mitroy, et al., Rev. Mod. Phys. 85(2013)693

- Provide the upper limit of the energy, exponential complexity

- Diffusion Monte Carlo (DMC) (sign problem)

Troyer et al., Phys.Rev.Lett.94(2005)170201, Gordillo, et al., Phys.Rev.D110(2024)094024

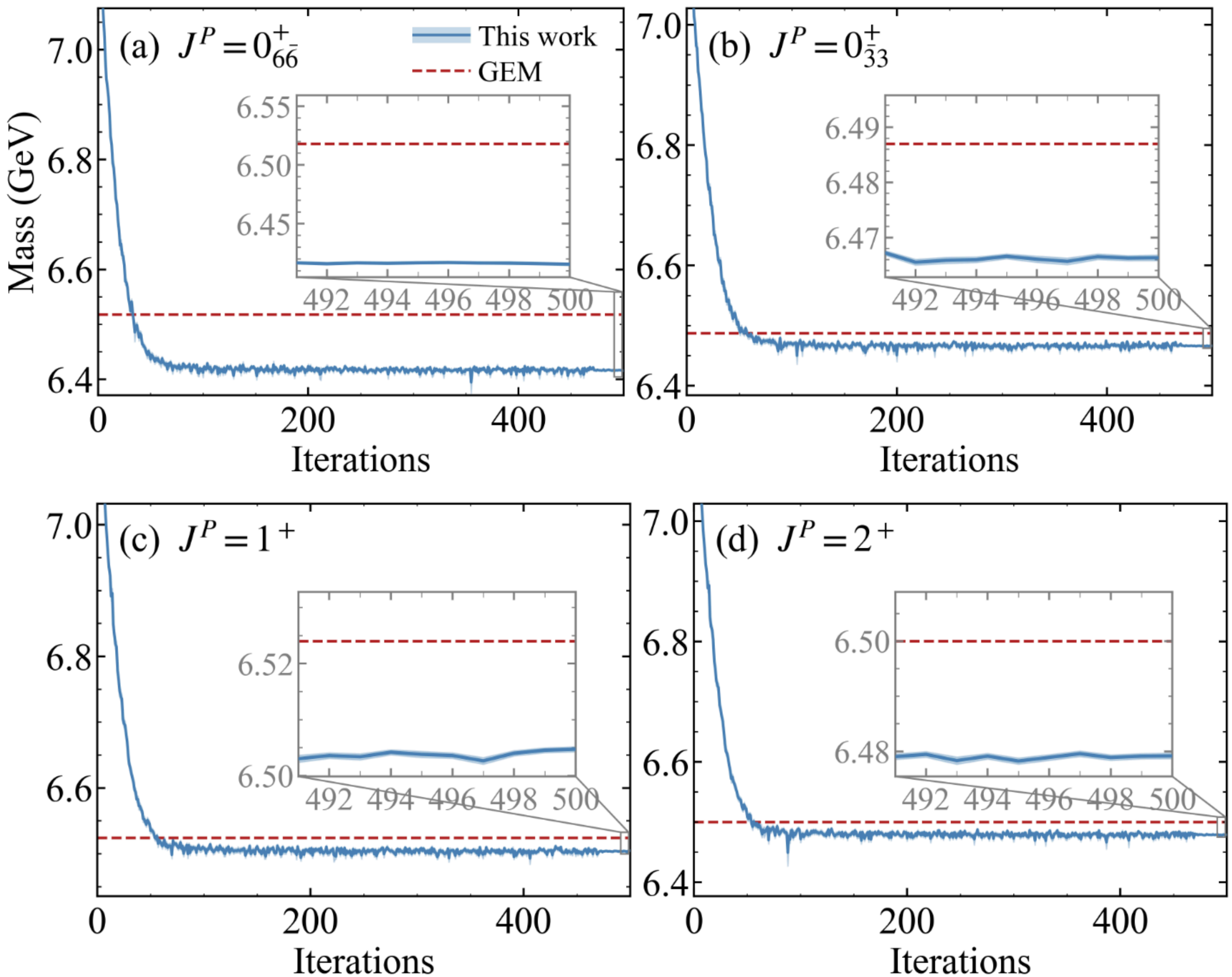
- Neural-network quantum states (NNQS) based on variational Monte Carlo (VMC) framework

Wu et al., PRL136(2026)071901,Li, et al., arXiv:2606.24380[hep-ph]

Spectra in QM

- Fully heavy tetra quark in NNQS

Li, et al., arXiv:2606.24380[hep-ph]



$cc\bar{c}\bar{c}$

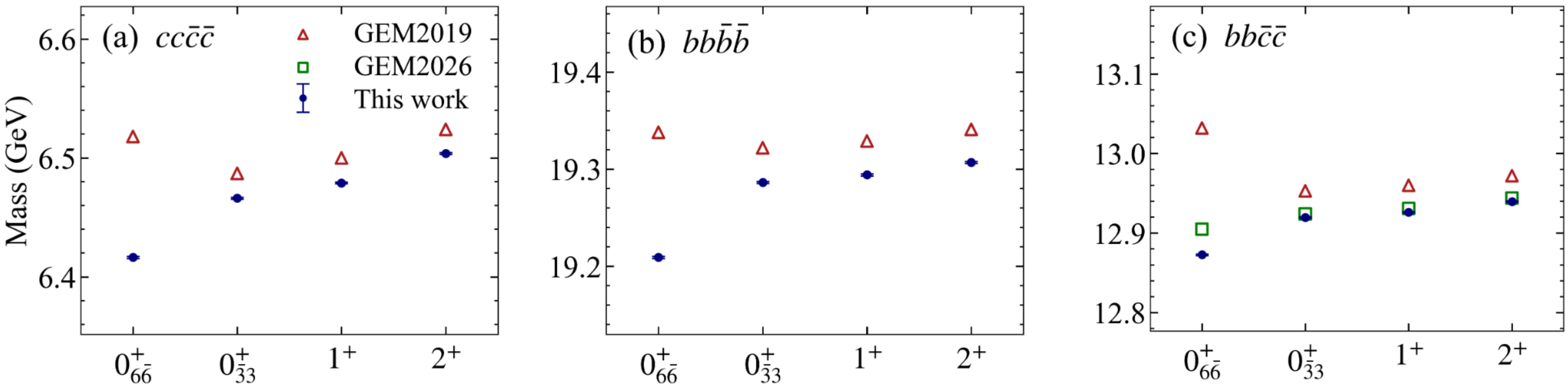
Masses from NNQs is smaller than those from GEM

Liu, et al., PRD100(2019)016006, Wang, et al., arXiv:2604.03047[hep-ph]

Spectra in QM

- Fully heavy tetraquark in NNQS

Li, et al., arXiv:2606.24380[hep-ph]

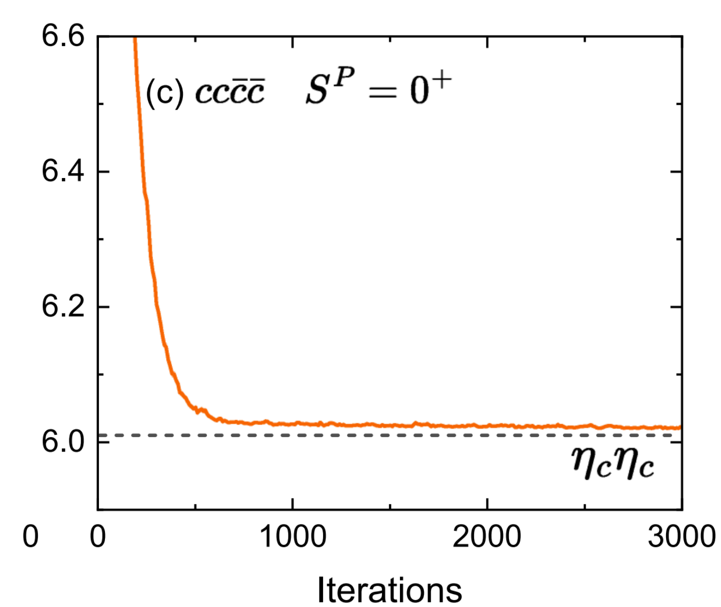


- Eigenenergy strongly depends on the wave functions
- Improved wave functions make the energy closer to those in NNQs, but still larger

Liu, et al., PRD100(2019)016006, Wang, et al., arXiv:2604.03047[hep-ph]

- Design a novel and high-efficiency architecture to solve multi-quark systems problems, i.e. DeepQuark
- The code opens in https://github.com/wlwuphy/DeepQuark

Wu et al., PRL136(2026)071901



Spectra in QM

- Resonances in GEM+Complex scaling

- Some of exotic hadrons are above the threshold of strong decay channels

Olsen et al., RMP90(2018)015003

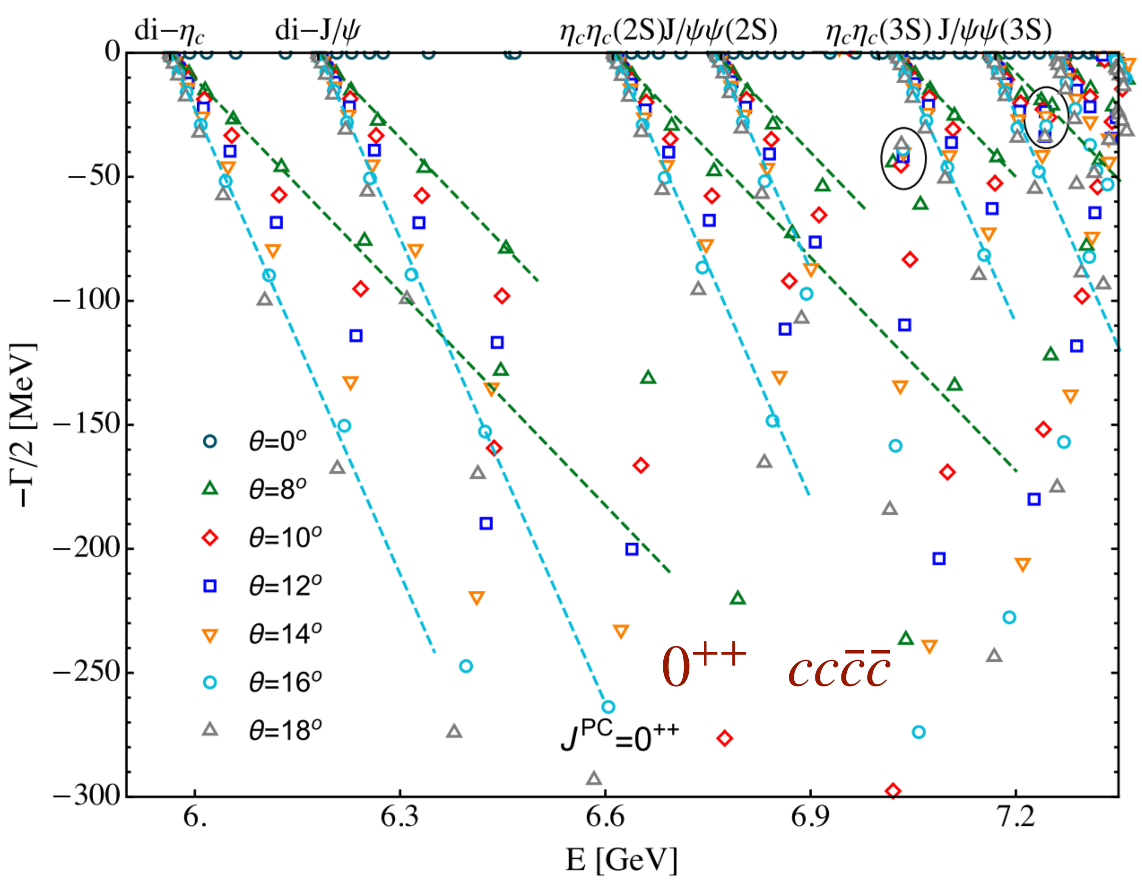
- Borrow complex scaling method from nuclear physics

Aoyama et al., Prog. Theor. Phys. 116(2006)1

- When $r \rightarrow re^{i\theta}$, resonance is stable on complex plane

- S-wave fully charmed tetra quark resonant states

Wang et al., PRD106(2022)096005,
Wang et al., PRD108(2023)071501



- Apply to double charm tetraquarks, hidden charm tetraquarks, double charm hexaquarks

Cheng et al., PRD106(2022)016012, Cheng et al., EPJC 83(2023)1071,
Cheng et al., PRD107(2023)054018, Meng et al., PRD111(2025)014018,
Meng et al., PRD111(2025)014018 ……

Production in various processes

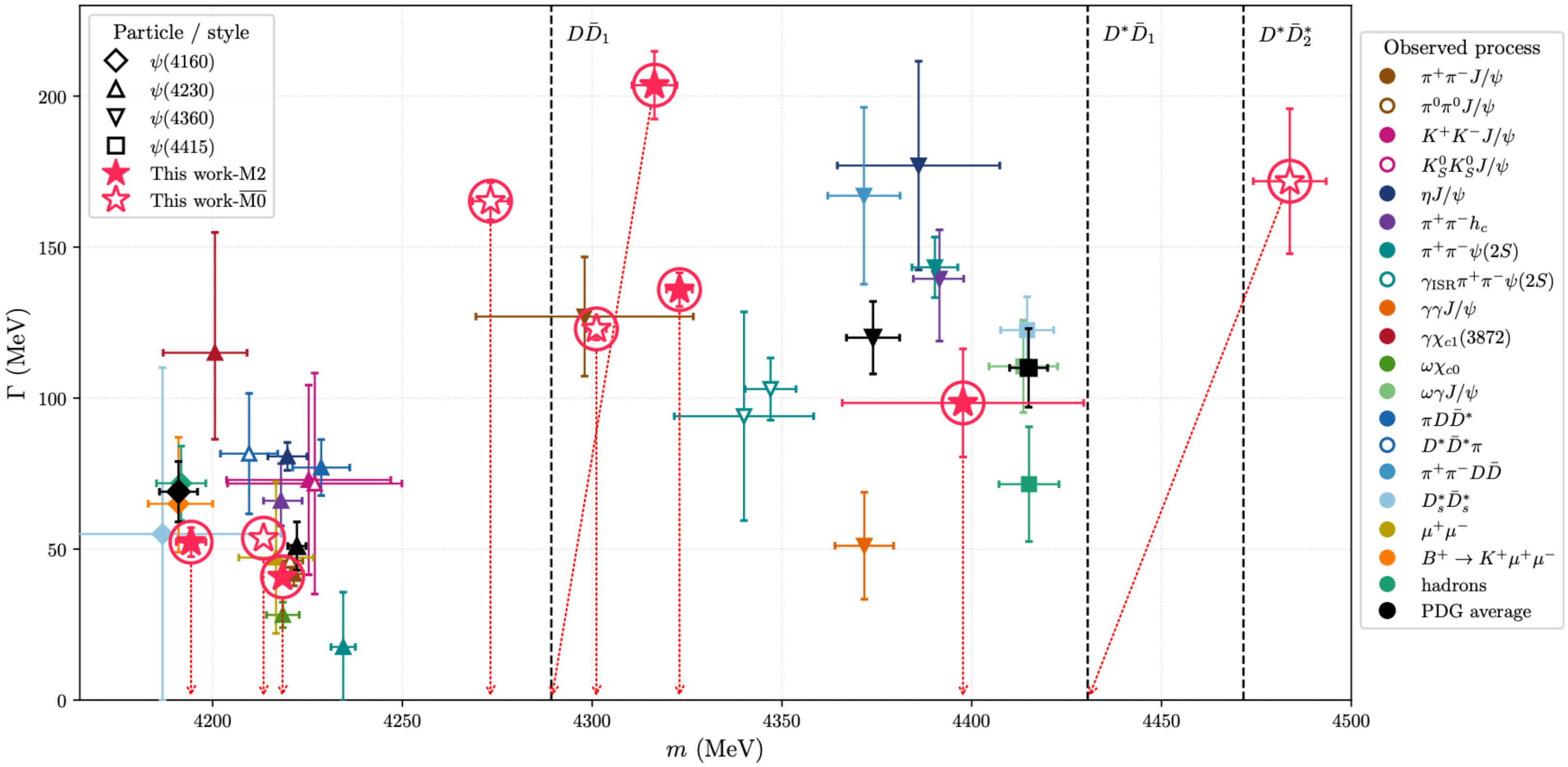
- Several typical processes

- Exotic hadrons in e^+e^- annihilation process

$\Rightarrow$ BESIII detailed scan within the energy region [4.13,4.36] GeV

$\Rightarrow$ Accessible for hidden charm vector exotics

$\Rightarrow$ Fully dynamical coupled-channel analyses



① 19 dynamical channels

② Respect HQSS

③ Satisfy requirement of S-matrix

④ Two dynamical poles around 4.23 GeV and 4.32 GeV

Dong et al., arXiv:2606.06180[hep-ph]

Detten et al., PRD109(2024)116002

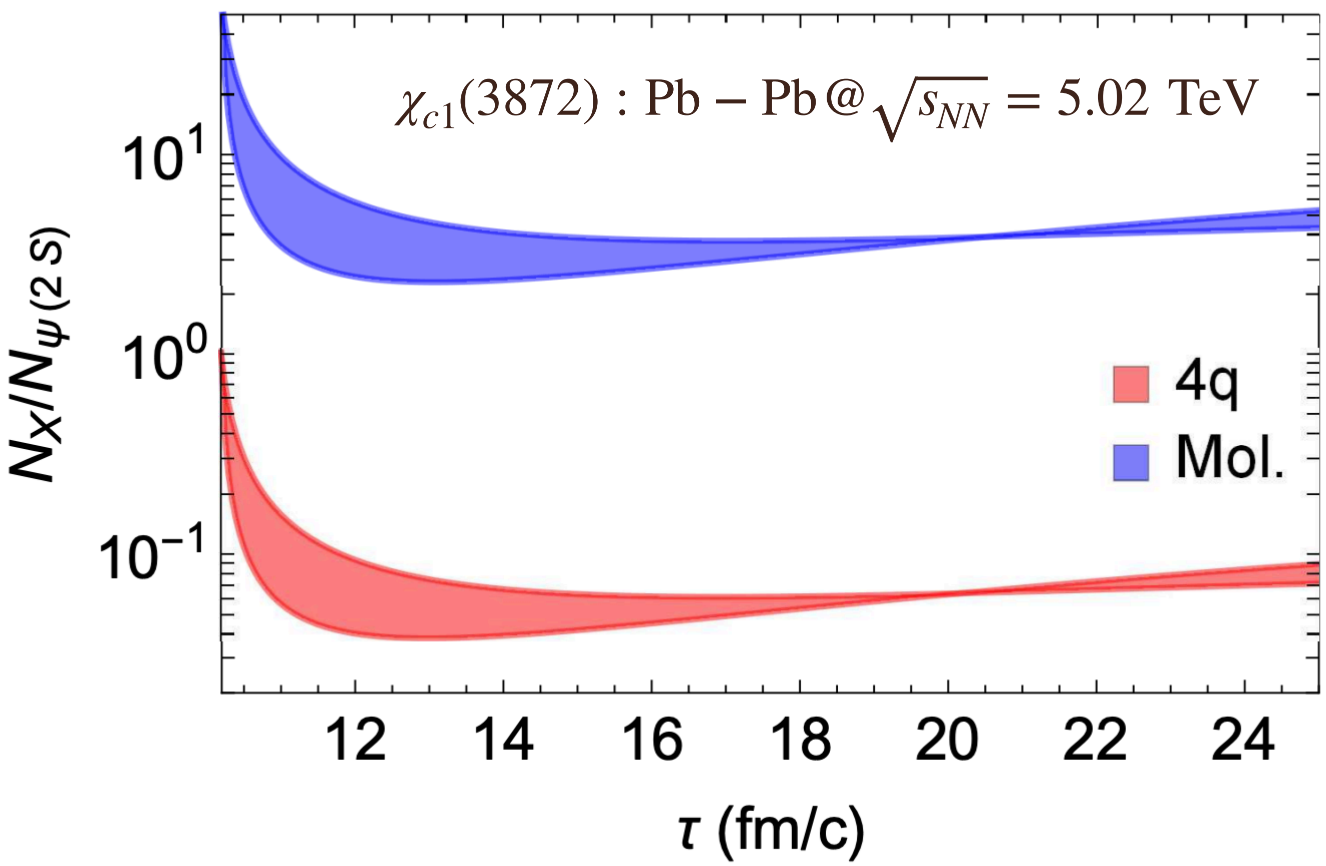
A phenomenological analysis, Nakamura et al., PRD112(2025)054027

Production in various processes

- Several typical processes

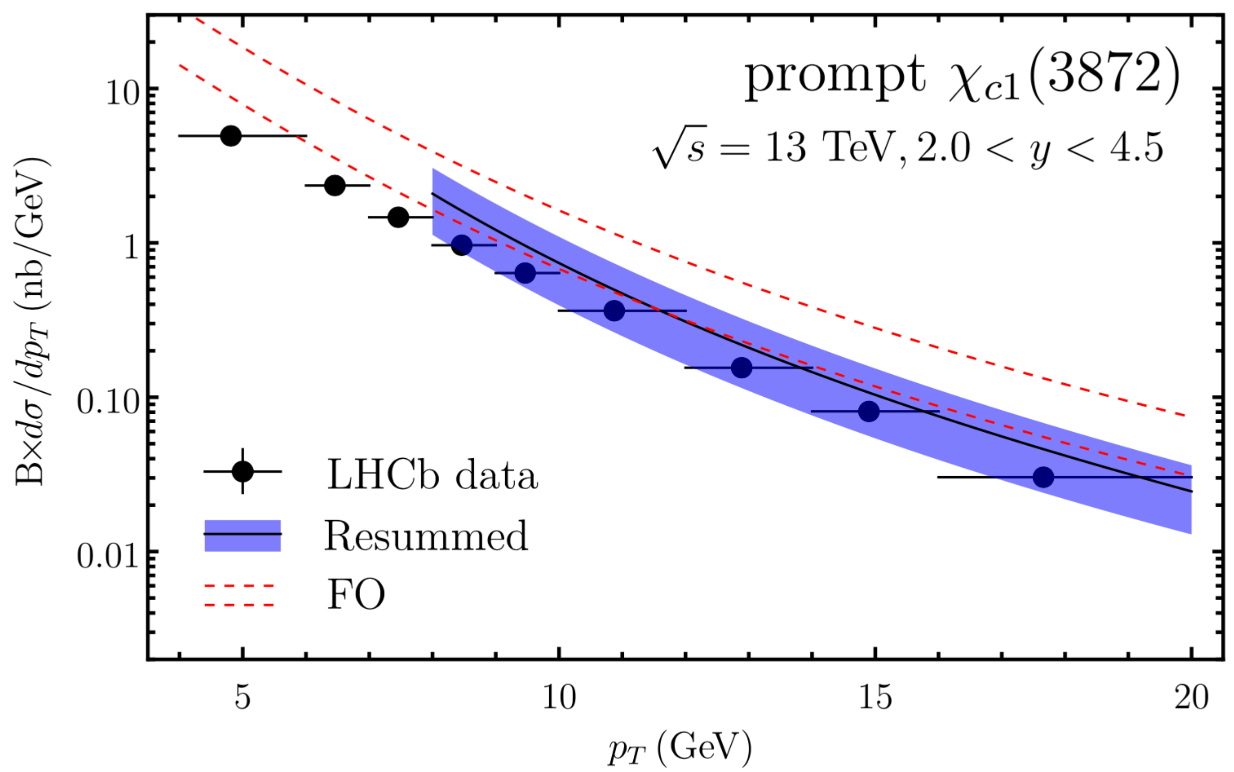
- Exotic hadrons in pp, $p\bar{p}$ and HIC process

$\Rightarrow$ Probe the internal structure in the production



The yield ratio is significant different!

Abreu et al., PRD110(2024)014011



Compact picture can describe the data from CMS, ATLAS and LHCb

Lai et al., PRD112(2025)054005

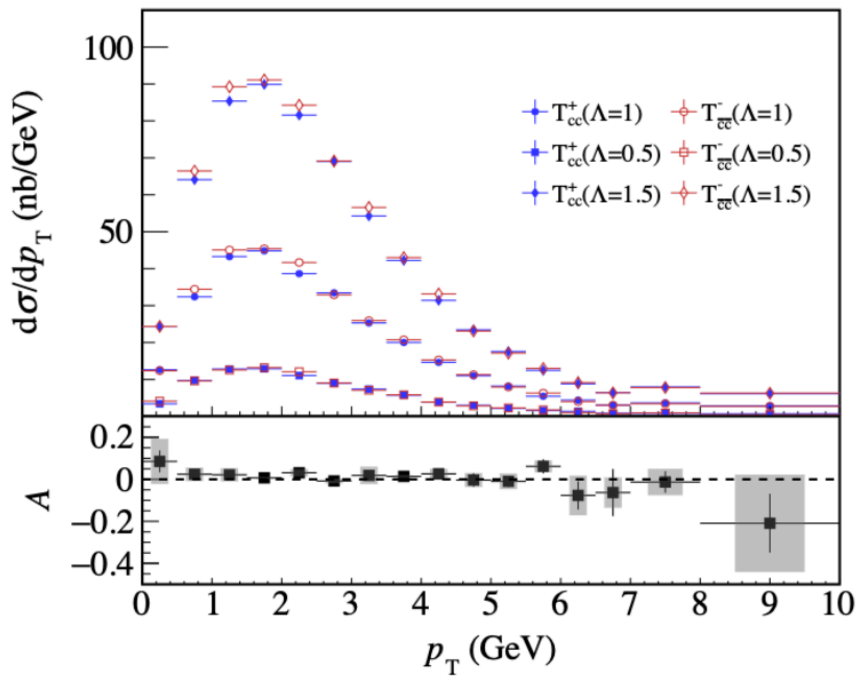
Production in various processes

- Several typical processes

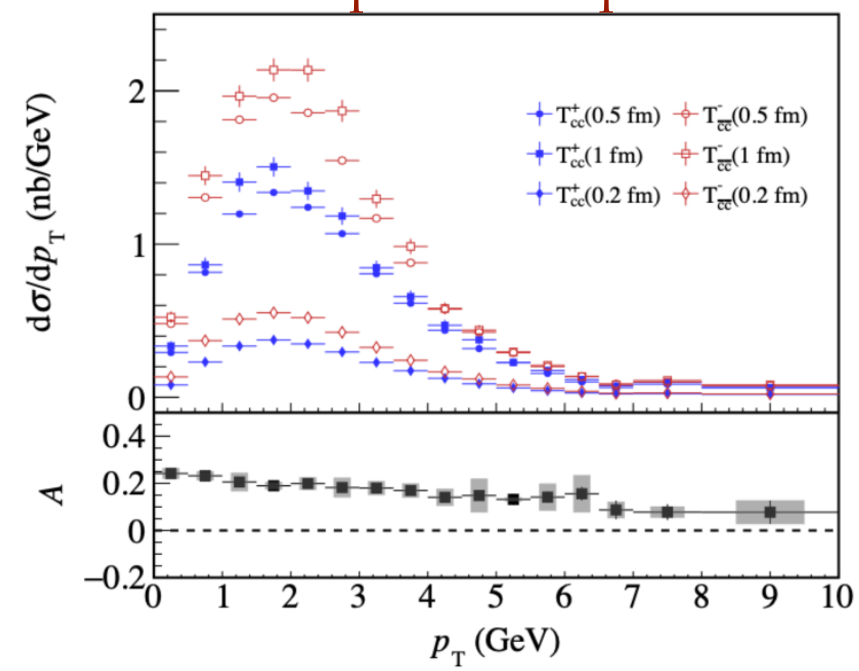
The asymmetry $\mathscr{A} \equiv \dfrac{\sigma^- - \sigma^+}{\sigma^- + \sigma^+}$

- Revealing the nature of the T_{cc} in pp collision

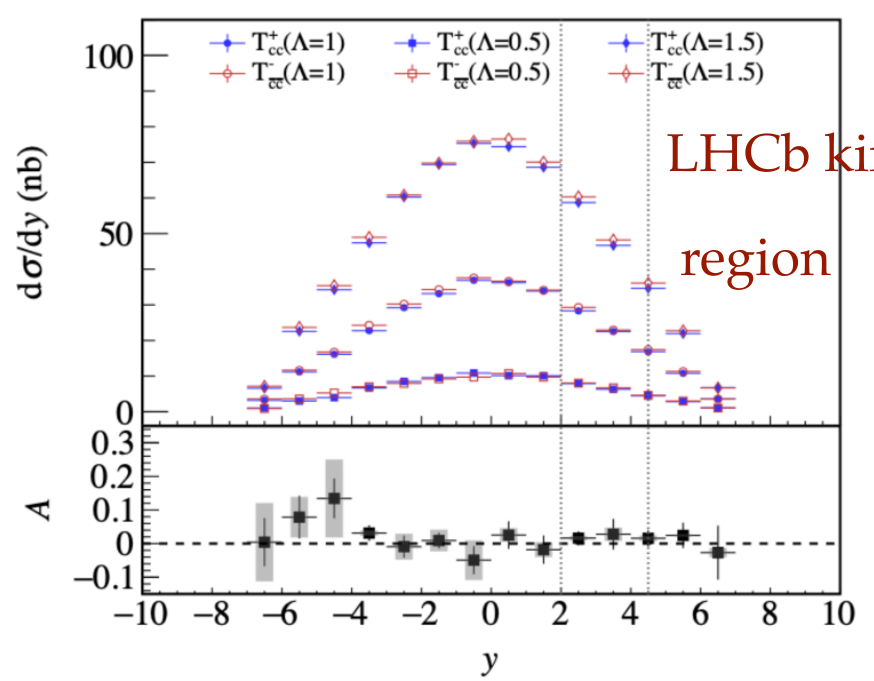
Hadronic molecule



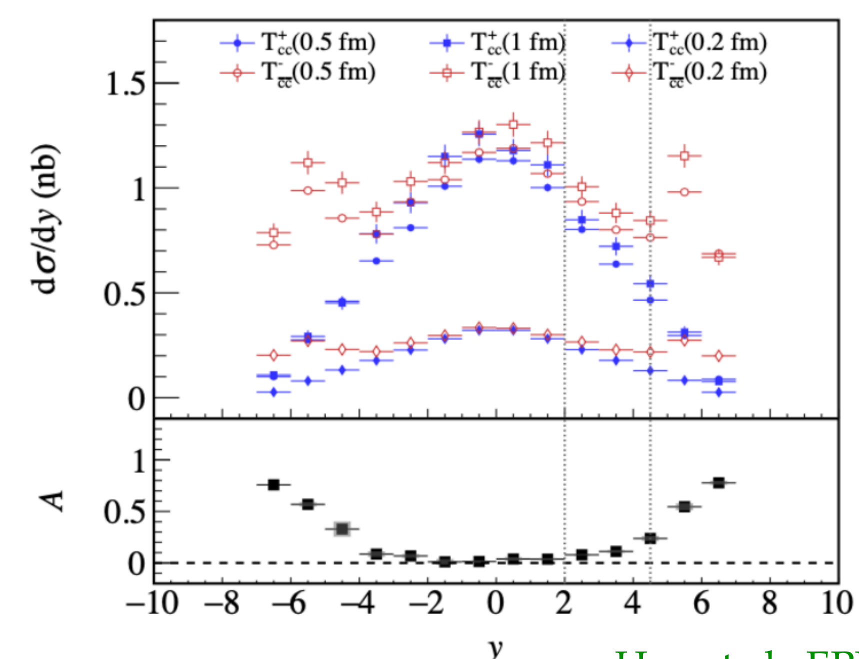
Compact tetra quark



T_{cc} & $\bar{T}_{\bar{c}\bar{c}}$: $\mathrm{Pb-Pb}@\sqrt{s} = 14$ TeV



LHCb kinematic region



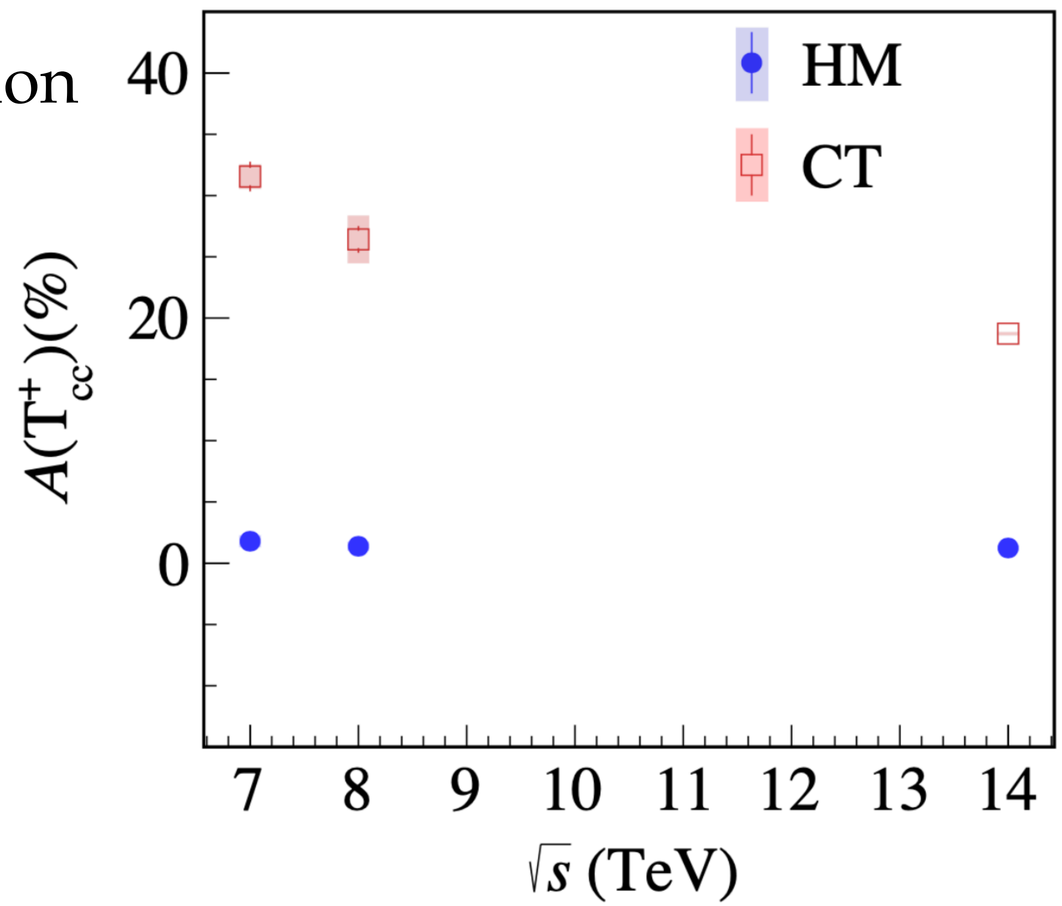
Hua et al., EPJC84(2024)8

Production in various processes

- Several typical processes

  - Revealing the nature of the T_{cc} in pp collision

	HM	CT
Range(GeV)	$\mathcal{A}(\%)$	$\mathcal{A}(\%)$
Full	1.24±0.30±0.20	18.73±0.25±0.14
$4 < p_T < 20$ [114]	2.53±2.01±1.79	7.35±1.48±5.24
$p_T > 0$ [11]	1.64±1.03±0.52	11.42±0.60±0.17
$10 < p_T < 50(30)$ [115]	−13.42±8.44±2.18	−6.62±8.86±7.96
$10 < p_T < 70$ [116]	−16.87±9.33±10.10	0.98±11.04±15.37



① Both asymmetries are positive

② The asymmetry of compact tetraquark is larger than that of hadronic molecule

③ The asymmetry decrease with the increasing c.m. energy

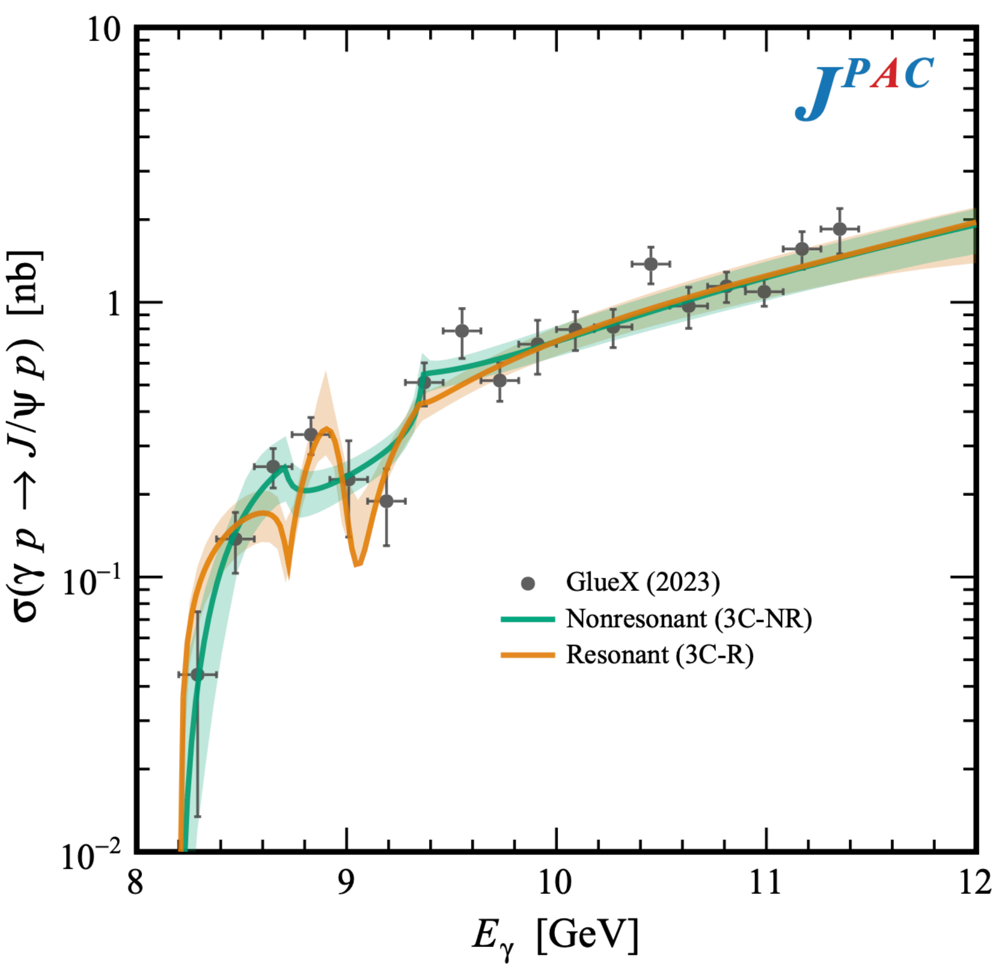
Hua et al., EPJC84(2024)8

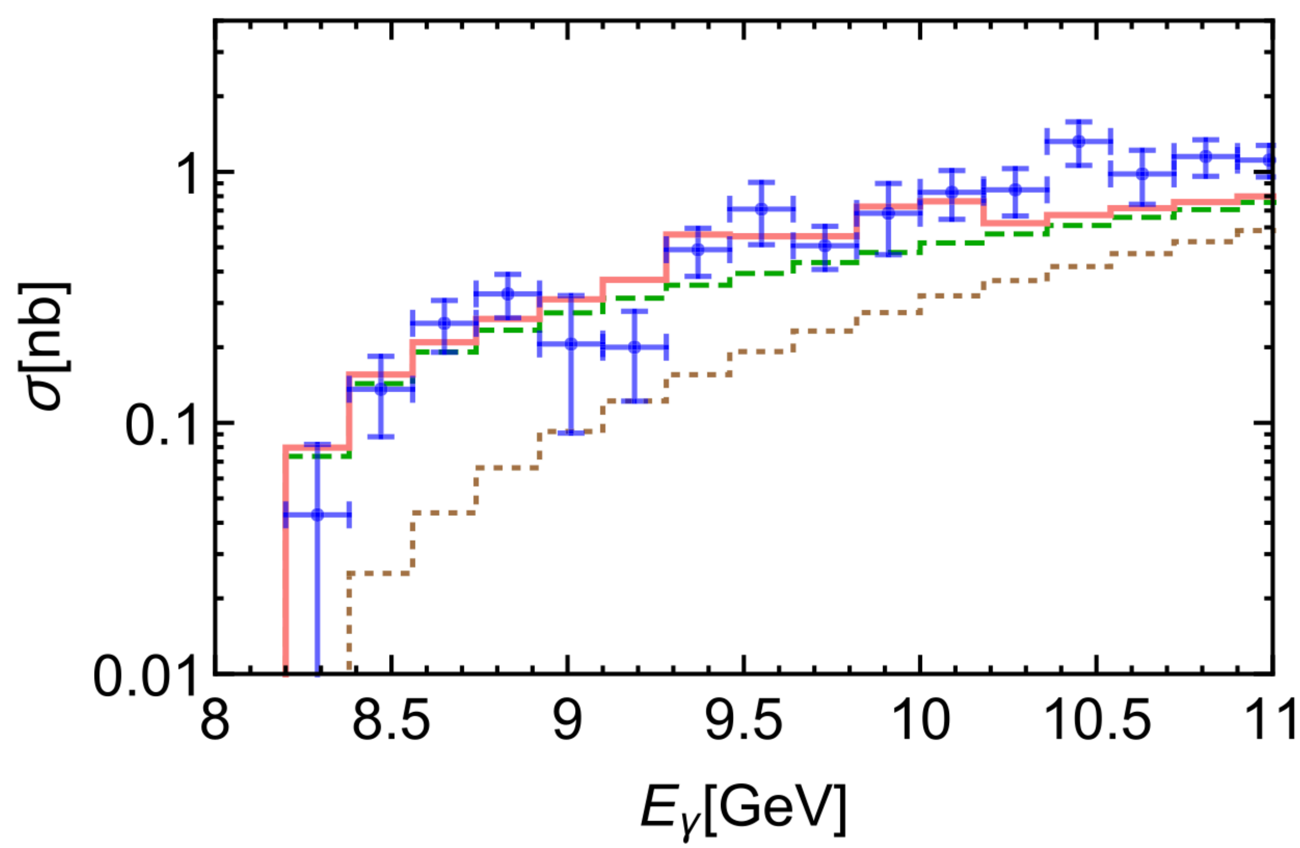
Production in various processes

- Several typical processes

- Exotic hadrons in photo-production, i.e. γp process

$\Rightarrow$ Search for hidden charm pentaquark in J/ψ photo-production (σ and $d\sigma/dt$)





Coupled channel is non-negligible

Not clear about P_c's existence

JPAC Collaboration., PRD108(2023)054018

Coupled channel is non-negligible

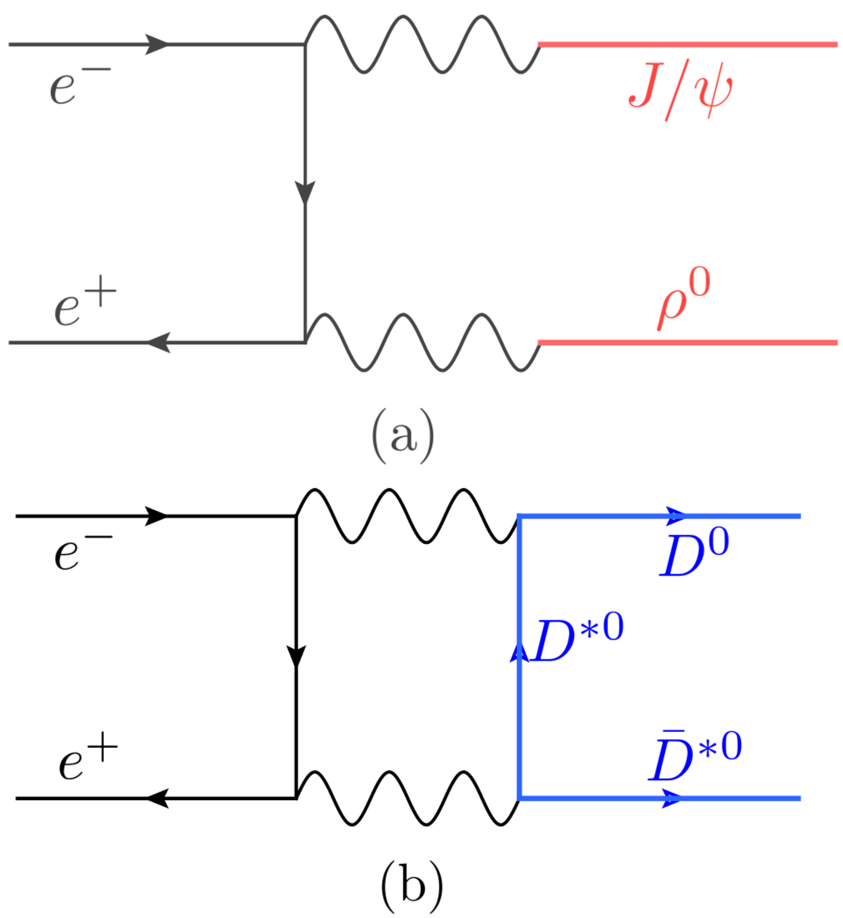
P_cs as dynamic generate states

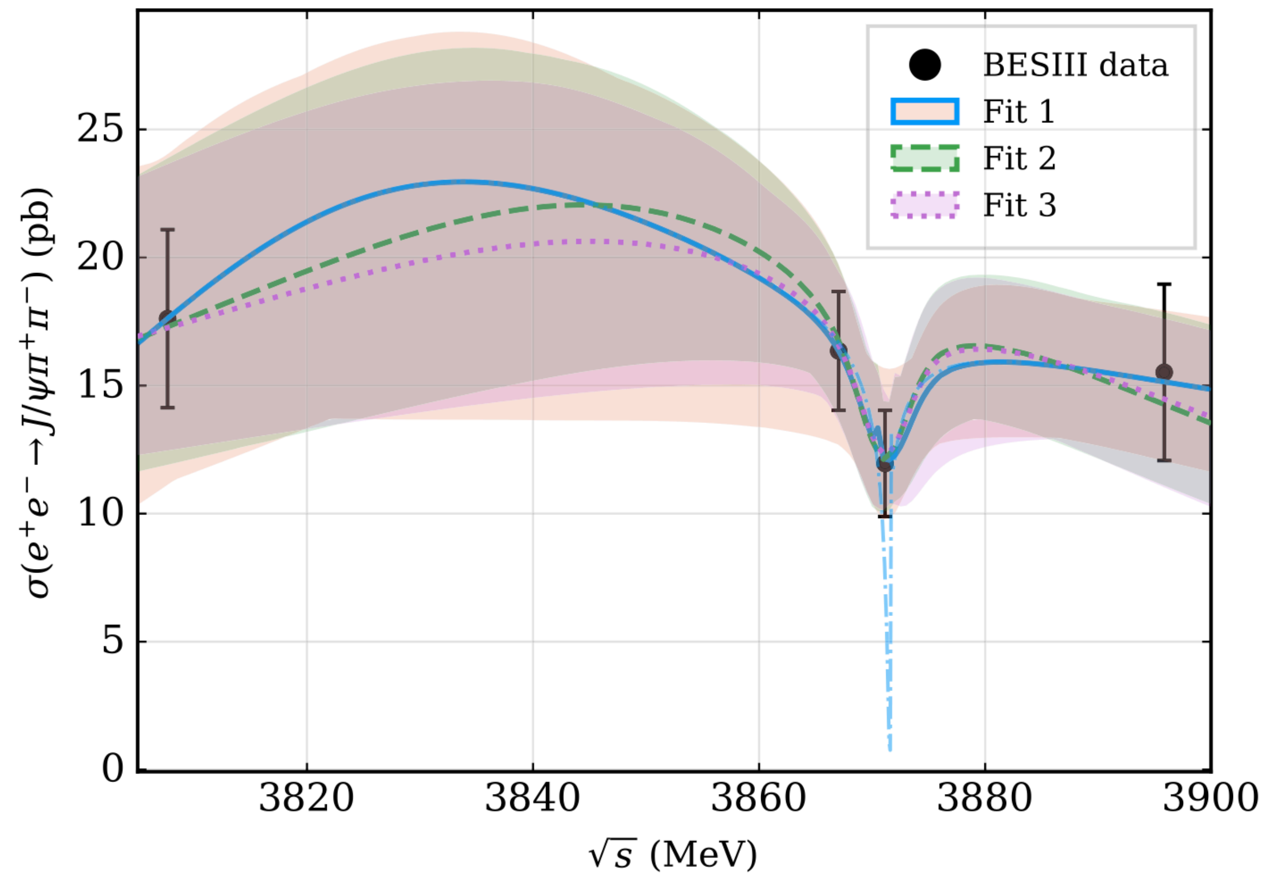
Zhang, EPJC85(2025)1120

Talk by Alessandro Pilloni on Mon.

Lineshapes and compositeness

- A peak or dip in lineshape?



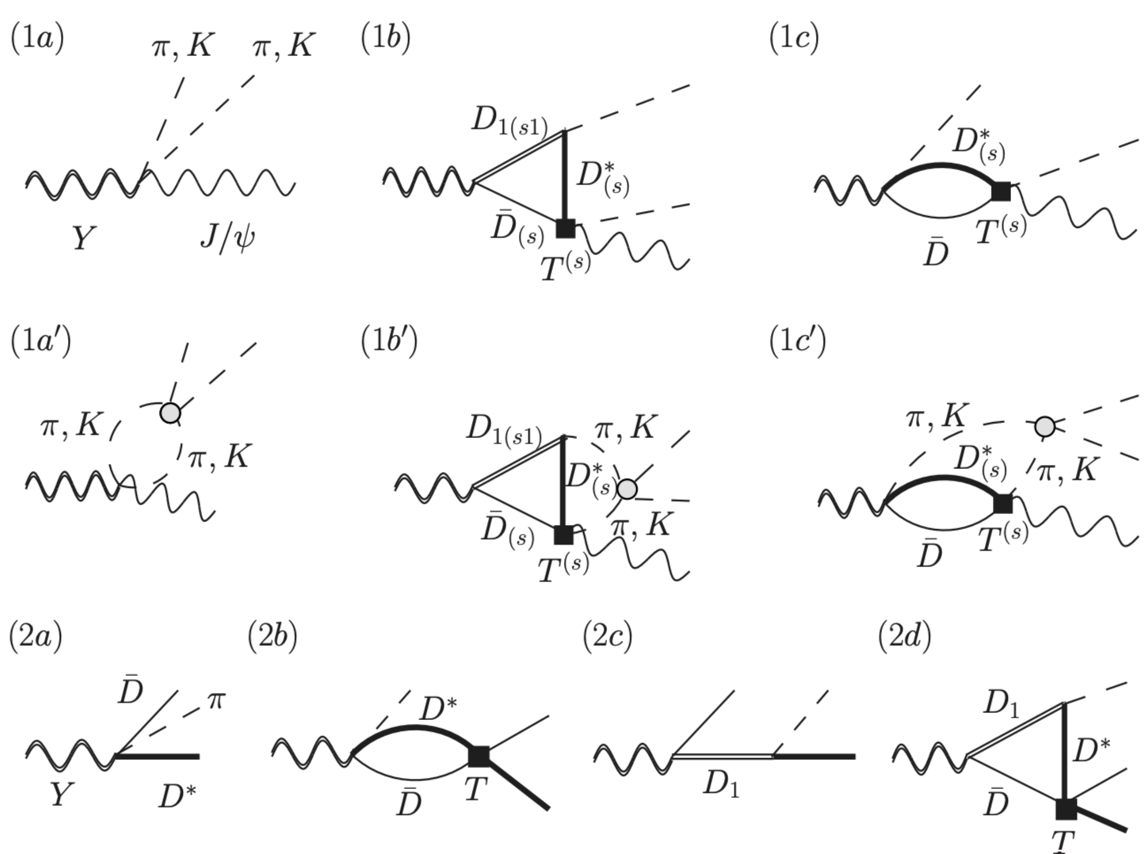


- A state does not necessary behave as a peak structure
- $J/\psi\rho^0 - D^0\bar{D}^{*0}$ two coupled channel in $e^+e^- \to J/\psi\pi^+\pi^-$ process
- $\chi_{c1}(3872)$ behaves as a dip, as well as its spin-2 partner in $e^+e^- \to J/\psi\pi^+\pi^-\pi^0$ process

Baru et al., PRD109(2024)L111501

Lineshapes and compositeness

- Global analysis with both exp. and lattice data
  - Complicated mechanisms, i.e. background, triangle singularity
  - Lattice QCD provides first-principles constraints
  - For instance, whether do we need a $Z_c(3900)$ pole? Or a purely tri. Singularity



Chen et al., arXiv:2604.25607[hep-ph]

$\Rightarrow$ $e^+e^- \to D\bar{D}^*\pi, J/\psi\pi\pi, J/\psi K\bar{K}$ @17 E_{cm}s

$\Rightarrow$ Both $Z_c(3900)$ and $Z_{cs}(3985)$

$\Rightarrow$ $\pi\pi, K\bar{K}$ FSI, three-body FSI via KT eq.

$\Rightarrow$ Lattice results from three groups

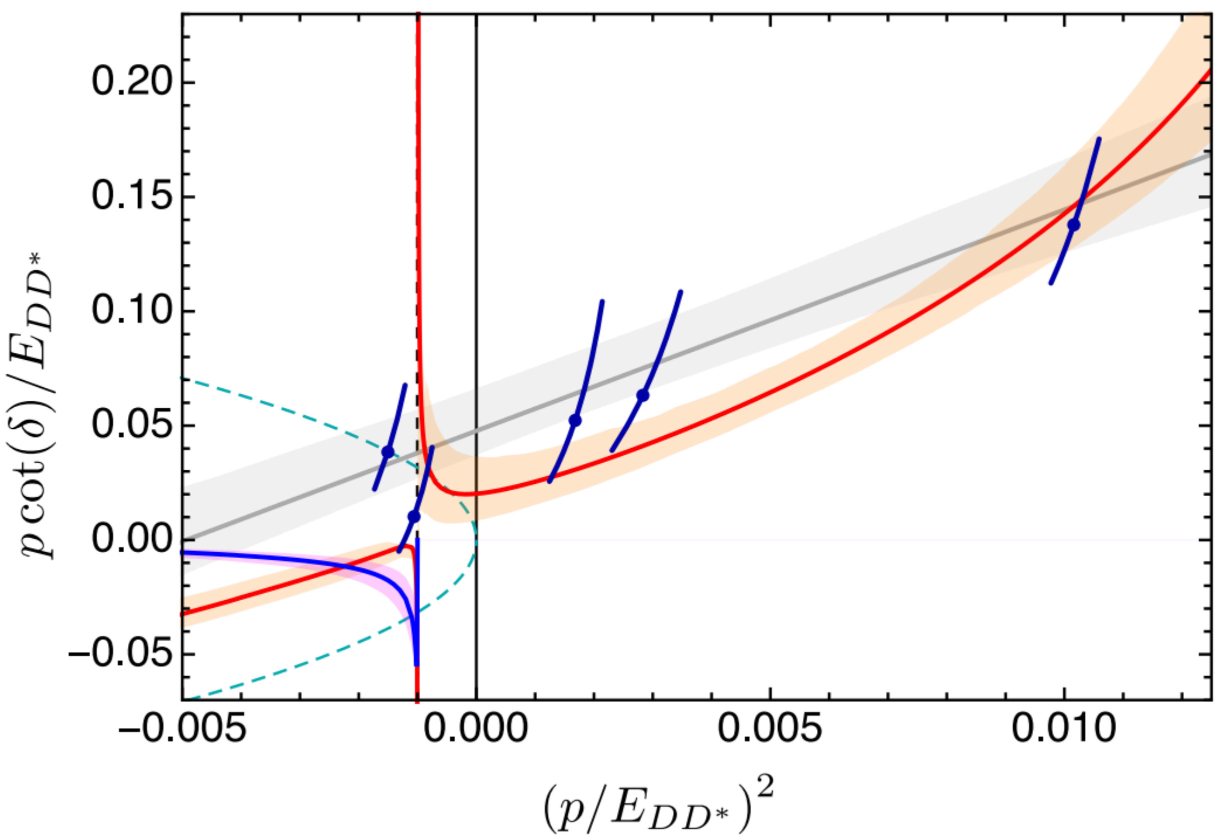
Chen et al., CPC43(2019)103103, Sadl et al., PRD111(2025)054513, Cheung et al., JHEP11(2017)033

$\Rightarrow$ Both TS and pole cannot neglected.

Lineshapes and compositeness

- The role of Left-hand cut

- The singularity in the partial wave amplitude from the crossed-channel
- LHC locate near threshold when $m_{\rm ex} > |m_1 - m_2|$ or $m_{\rm ex}$ sufficient small
- First noticed in the lattice results of T_{cc} with unphysical $D^{(*)}, \pi$ mass



Du et al., PRL131(2023)131903

- Plane wave basis to solve LHC problem

⇒ FV effect for long-range force

⇒ Partial wave mixing

Meng et al., PRD109(2024)L071506

- ERE with long-range force

⇒ A new parameterization with LHC

⇒ There parameters at LO

Du et al., PRL135(2025)011903

⇒ Higher order improvement

Wang et al., PRD114(2026)014003

Lineshapes and compositeness

- Compositeness analysis

- Weinberg compositeness works for bound state in the weak binding limit in 1960s
- Extend to virtual state — Matuschek et al., EPJA57(2021)101
- Compositeness from isospin breaking effect — Baru et al., PLB833(2022)137290

$$\bar{X}_A = \left(1 + 2\left|\frac{r_0'}{\mathrm{Re}a_0}\right|\right)^{-1/2}, \quad r_0' = r_0 - \Delta r_{\mathrm{IV}} \qquad \Delta r_{\mathrm{IV}} \equiv -\sqrt{\frac{1}{2\mu\Delta}}$$

- Once a bare state considered, a near-threshold state can be non-composite state

$$X = \left[1 + 2\pi \frac{g_0^2}{(B+E_0)^2} \frac{\kappa}{\mu(\mu+\kappa)}\right]^{-1}$$

Kinugawa et al., PRC109(2024)045205, EPJA61(2025)154

The compositeness can vary from 0 to 1 by fine tuning E_0

- Finite range correction to compositeness

$$-g_{\mathrm{eff}}^2 G_1^2 \frac{\partial V_{\mathrm{eff}}}{\partial E} - g_{\mathrm{eff}}^2 \frac{\partial G_1}{\partial E} = 1$$

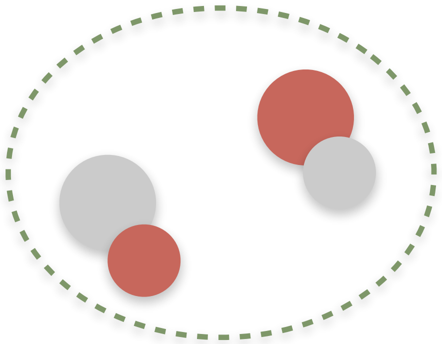
Li et al., PRD105(2022)071501,

Talk by Eulogio Oset on Mon.

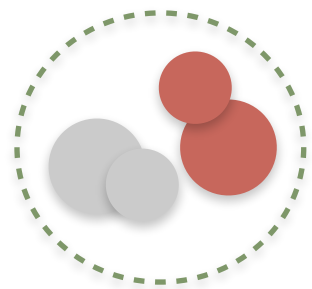
Song et al., EPJA58(2022)133, Albaladejo et al., EPJC82(2022)724, Kinugawa et al., PRC106(2022)015205, Yin et al., PRC110(2024)055202

Partners in various symmetries

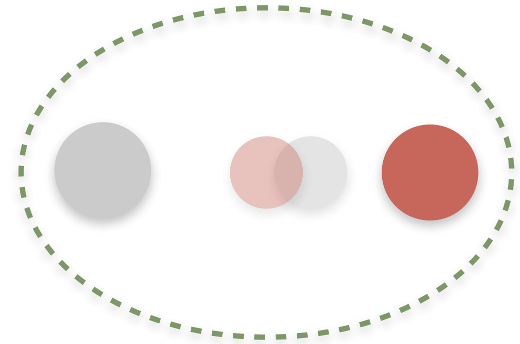
- Various scenarios



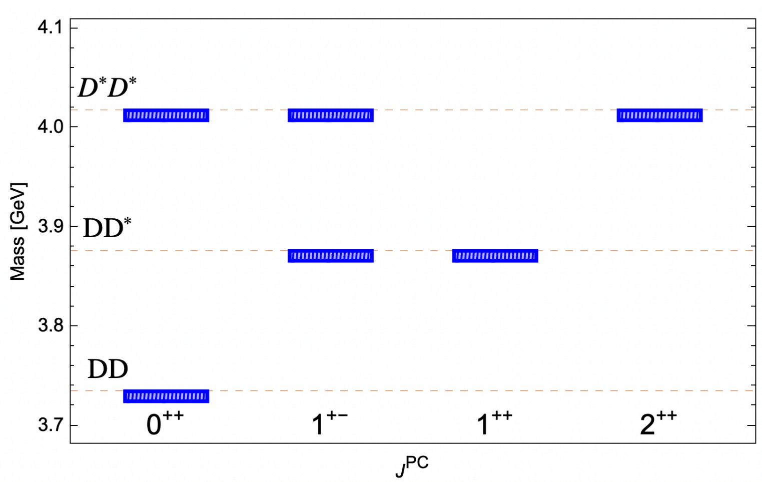
HM picture

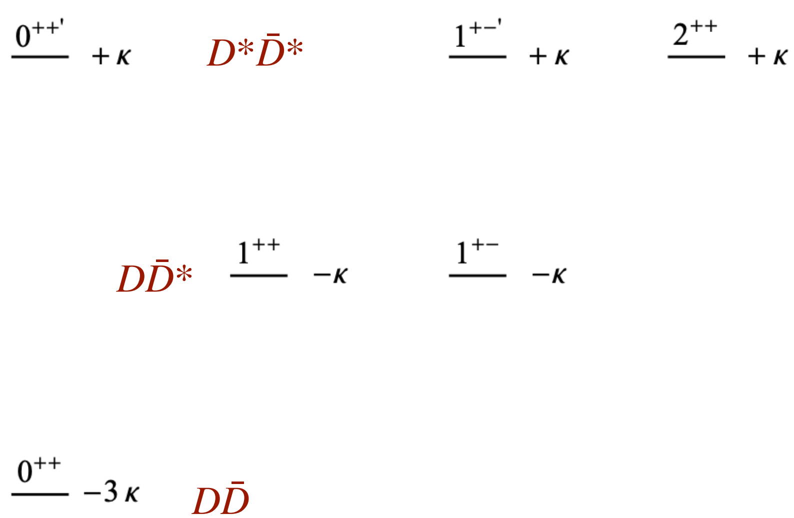


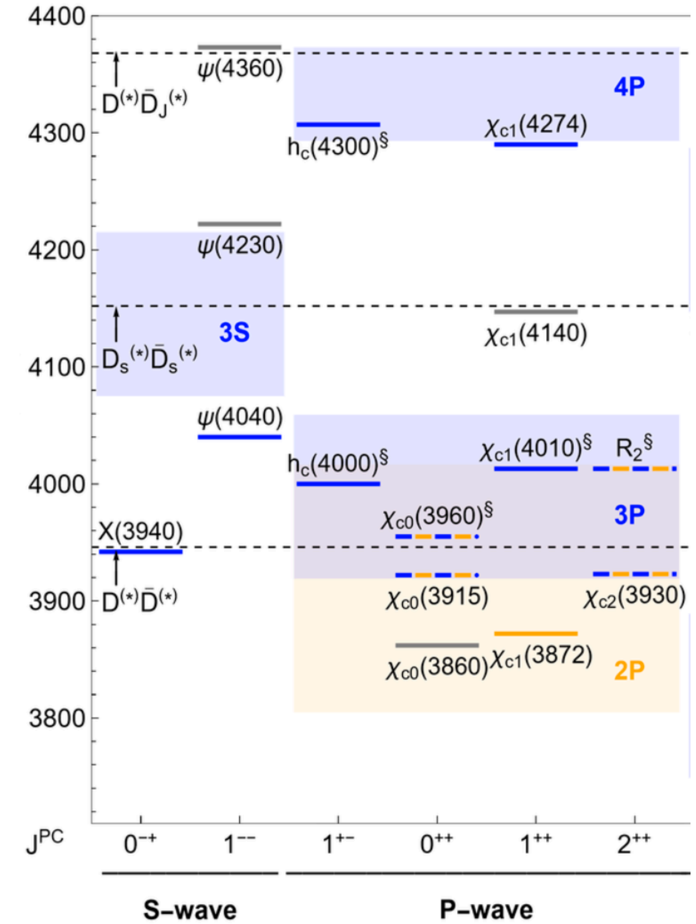
Compact tetra quark



BO-quarkoniumlike state







Appear around relevant thresholds

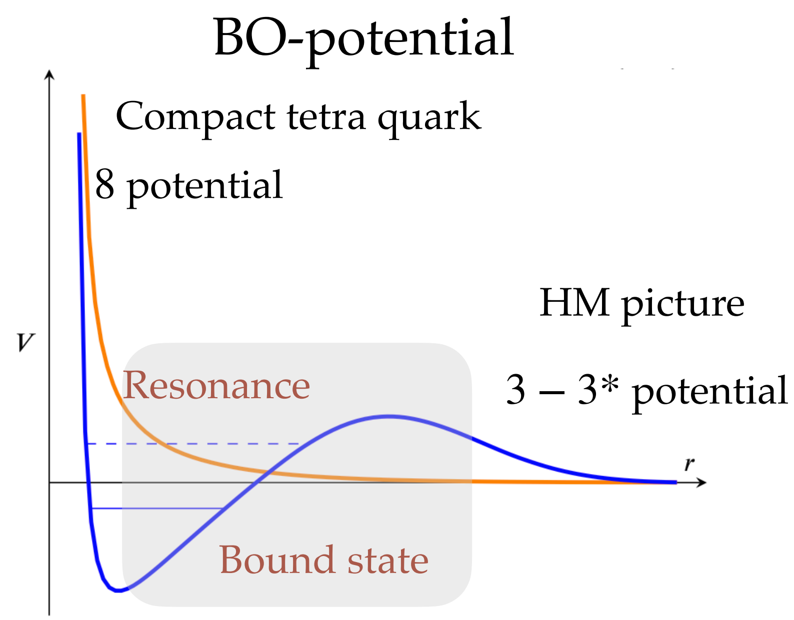
Guo et al., RMP90(2018)015004

Esposito et al., Phys.Rept.668(2017)1

Brambilla et al., arXiv:2608.04105[hep-ph]

Partners in various symmetries

- Consistent expression in BO potential



- Gay region unknown, but smooth
- Orange(1st one): no bound state
- Blue potential (3rd one): bound state or resonance, both of them close to open-flavor threshold
- $V_{SS}(S_1, S_2) = \Delta j_1 \cdot S_1 + \Delta j_2 \cdot S_2$

Braaten et al., PLB863(2025)139386

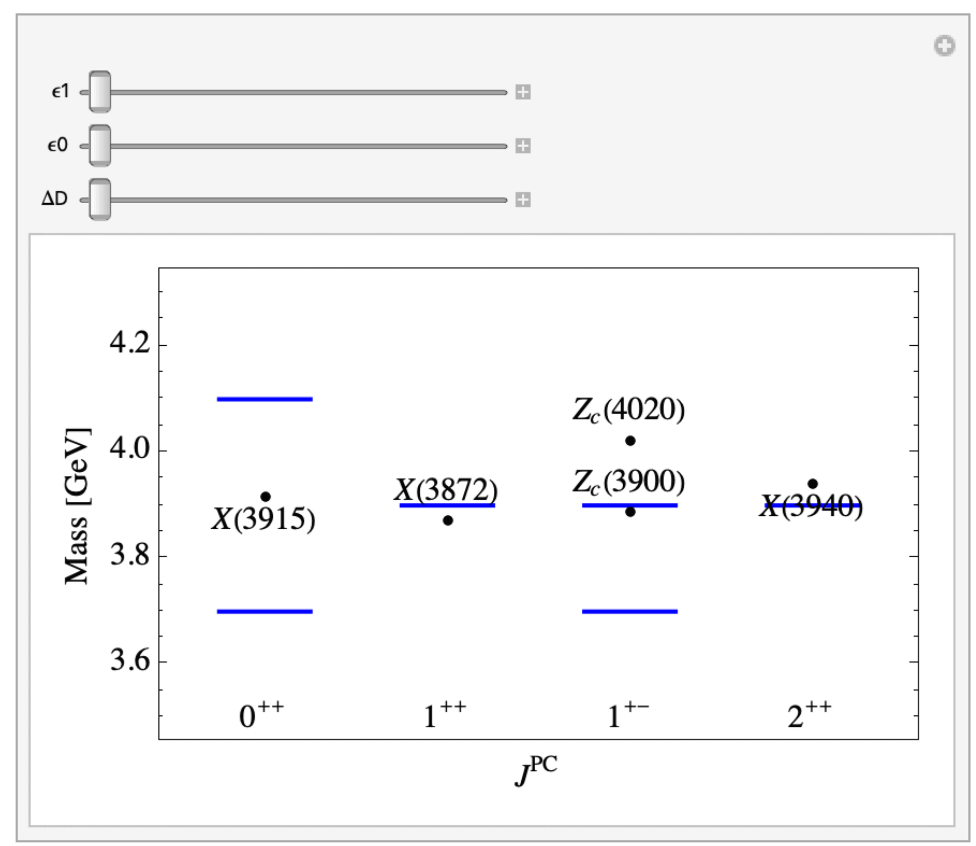
Gauge dependent

- ε_1 the energy of 1^{--} 8-meson
- ε_0 the energy of 0^{-+} 8-meson
- $\Delta = m_{D*} - m_D$

$$E_{2^{++}} = \varepsilon_1 + \frac{1}{2}\Delta \qquad E_{1^{++}} = \varepsilon_1 - \frac{1}{2}\Delta$$

$$E^{\pm}_{1^{+-}} = \frac{\varepsilon_1 + \varepsilon_0 \pm \sqrt{(\varepsilon_1 - \varepsilon_0)^2 + \Delta^2}}{2}$$

$$E^{\pm}_{0^{++}} = \frac{\varepsilon_1 + \varepsilon_0 - \Delta \pm \sqrt{(\varepsilon_1 - \varepsilon_0 - \Delta)^2 + 3\Delta^2}}{2}$$



Partners in various symmetries

- HQSS
  - $\chi_{c1}(3872) \to W_{c1}, X_0, X_2$ Zhang et al., JHEP08(2024)130,Ganbold et al., PRD111(2025)014014,Wu et al., EPJC84(2024)412,……
  - $T_{cc} \to T'_{cc}, T_{bb}, T_{bc}$ Jia et al., PRD107(2023)074029,Jia et al., PRD108(2023)074018,Sakai et al.,PRD112(2025)074036,……
  - $P_c \to$ the whole HQSS multiplet Talk by Vandan Patel on Mon.

    Li et al., PRD109(2024)054009, Wang et al., PRD108(2023)034022, Xu et al., PRD111(2025)034022,Chen et al., PRD110(2024)014033,……
- SU(3) flavor symmetry
  - $Z_c \to Z_{cs} \to Z_{css}$ Talk by Pan-Pan Shi on Mon. Tanaka et al., PRD110(2024)074015, Zhang et al., PRD113(2026)034029,……
  - $T_{cc} \to T_{ccs} \to T_{ccss}$ Yang et al., PRD110(2024)034022,Jafarzade et al., PRD112(2025)074040,……
  - $P_c \to P_{cs} \to P_{css}$ Mutuk et al., EPJC86(2026),Ulas Ozdem, PRD114(2026)014050,……

Talks by Eulogio Oset, Angel Ramos, Vandan Patel on Mon.

Talk by Hard Rathod on Tue. Talk by Chu-Wen Xiao on Wed.

- Methods
  - HHχPT/χEFT Meng et al., Phys.Rept.1019(2023)1
  - NREFT Soto et al., PRD102(2020)014005
  - BOEFT Brambilla et al., arXiv:2608.04105[hep-ph]
  - QM

Multi-hadron systems

- Three-hadron systems

Test the HM picture of two-hadron system

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ARTICLE

More Is Different: Broken symmetry and

P. W. ANDERSON Authors Info & Affiliations

SCIENCE • 4 Aug 1972 • Vol 177, Issue 4047 • pp. 393-396 • DOI: 10.1126/science.177.404

#52

Three ways to decipher the nature of exotic hadrons: Multiplets, three-body hadronic molecules, and correlation functions

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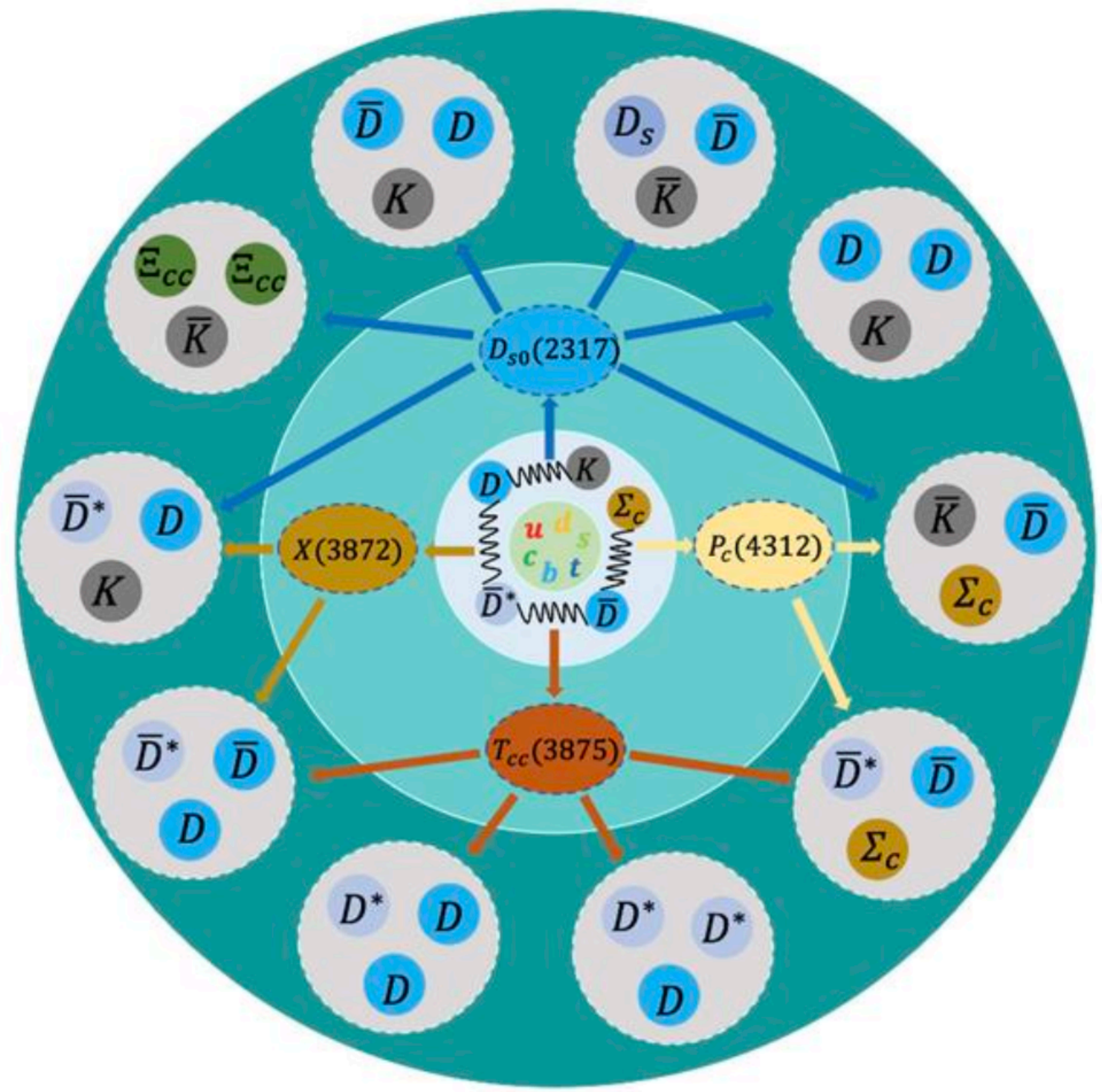


E. Oset, T. Hyodo, K.P. Khemchandani, A. Martinez Torres, L.S. Geng, C.W. Xiao, M.P. Valderramma, A. Hosaka, F.K. Guo……

Liu et al., Phys.Rept.1108(2025)1

Wu et al., Sci.Bull.67(2022)1735-1738

Multi-hadron systems

- Three-hadron systems

- $I = \dfrac{1}{2}$ DDD^* bound state when $Z_c(3900)$ is a virtual state with 15MeV below thr.

Zhu et al., PRD111(2025)094022

- $I(J^{PC}) = 0(0^{--})$ $\bar{D}_s DK$ and $I(J^{PC}) = 0(1^{-+})$ $\bar{D}^* D\eta$ bound states with exotic quantum numbers

Pan et al., PRL136(2026)151901, Wu et al., PRL135(2025)031902

⇒ A good system to determine the three-body force, due to the well-defined charge parity

Pan et al., PRL136(2026)151901

- Five $ND^*\bar{K}^*$ states with total spin 1/2,3/2,5/2 with binding energies 10 to 30 MeV in Fixed Center Approximation

Zhai et al., PRD111(2025)034039

- Efimov effect in $D^*D^*D^*$ system depends on the $I = 1$ interaction

Fu et al., JHEP07(2025)081

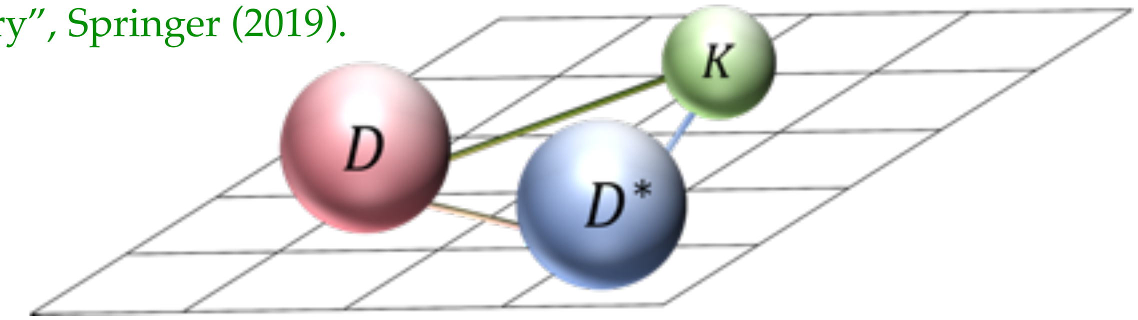
- Other systems $KD^{(*)}D^*$, $K^{*+}D^{*+}K^{*+}$, $B^*B^*K^*$, …

Ren et al., EPJC84(2024)1297, Jia et al., PLB875(2026)140320, Ikeno et al., Nuovon Cim. C47(2024)4,……

Multi-hadron systems

- Three-hadron systems

- Lattice EFT
  Dean Lee, Prog.Part.Nucl.Phys., 63(2009)117,
  Lähde, Meißner, “Nuclear Lattice Effective Field Theory”, Springer (2019).
- Advantages for many-body systems
- The DD^*K system on the lattice

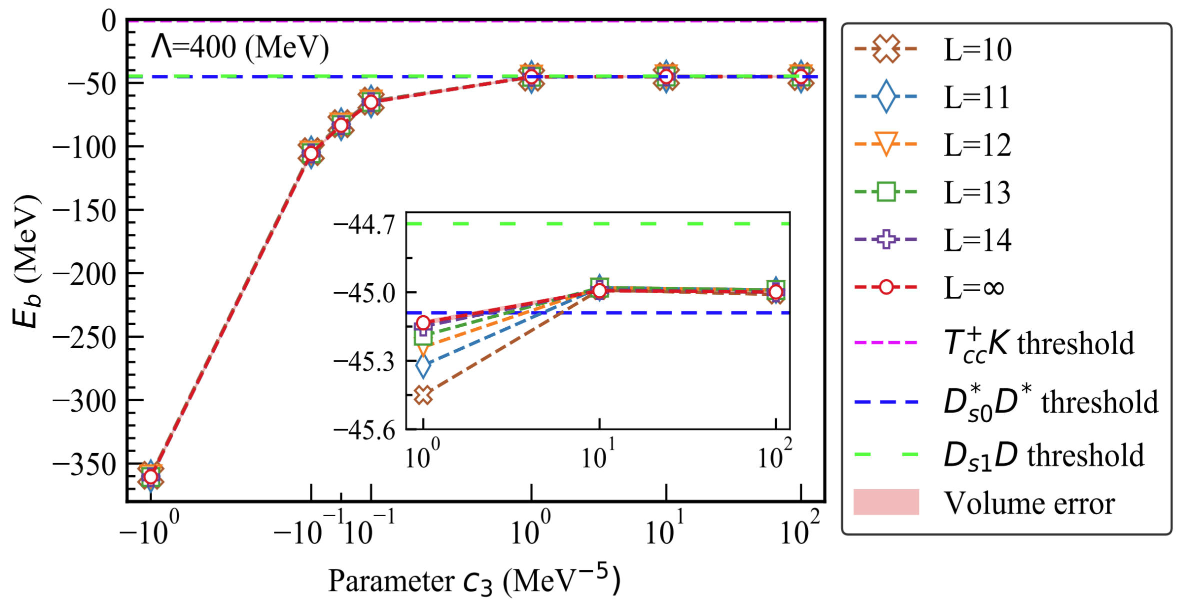


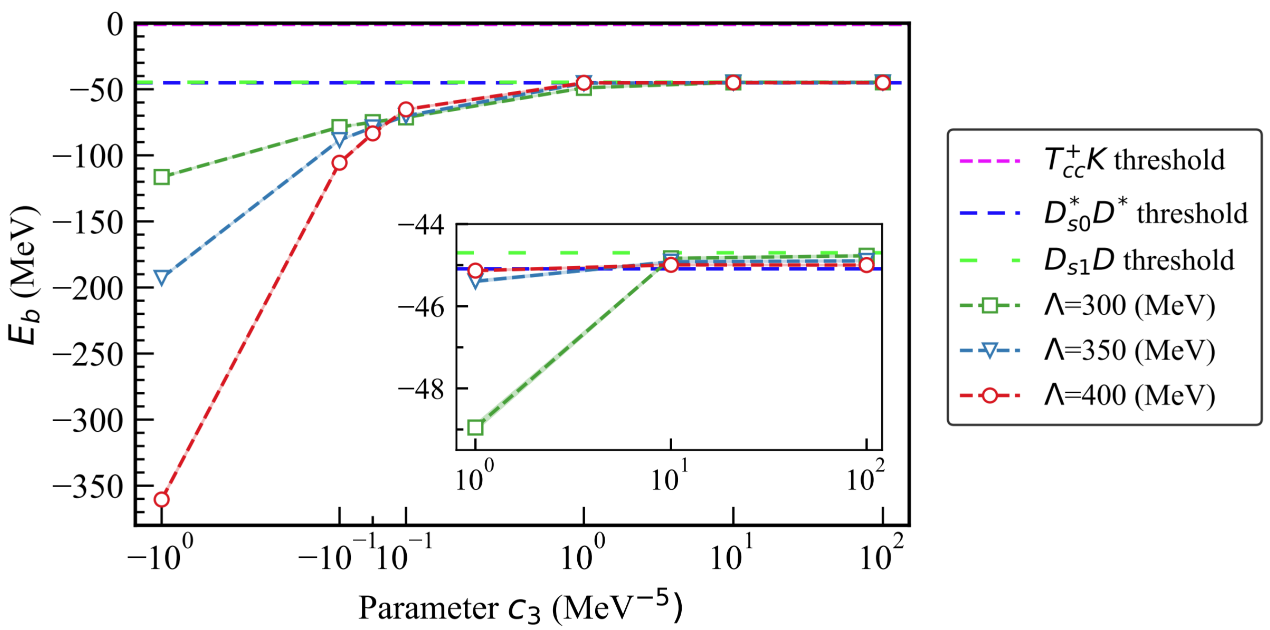
Disclaimer: particle number conservation

- The DD^*K binding energy with three-body force (1^- bound state)

Zhang et al., PRD111(2025)036002

$$\frac{\Delta E}{E_T} = -(\kappa L)^{-3/2} \sum_{i=1}^{3} C_i \exp\left(-\mu_i \kappa L\right)$$





Correlation function in HIC

- Two-body correlation function

  - Extract interaction between hadrons, especially unstable hadrons

    Fabbietti et al., Ann.Rev.Nucl.Part. Sci.71(2021)377, ALICE Nature 588(2020)232, Adam et al., PLB790(2019)490, Aboona et al., PLB864(2025)139412, Stefaniak, Nuovo Cim. C48(2024)4, Lednicky et al., Yad. Fiz., 35(1981)1316

  - Pin down the interaction between two components in a given exotic hadron

$D^0 D^{*+}, D^+ D^{*0}$ for T_{cc}^+ Albaladejo et al., PRD110(2024)114052, Ge et al., PRD114(2026)014054

$\bar{K}^0 p, \pi^+\Sigma^0, \pi^0\Sigma^+, \pi^+\Lambda, \eta\Sigma^+$ for $\Sigma^*(1430)$ Li et al., PRD110(2024)114018

Talk by Wei-Hong Liang on Mon.

$K^+\bar{K}^0$ for $a_0(980)$ Talk by Mikel F.Barbat on Tue. Molina et al., EPJC84(2024)3

$K^0\Sigma^+, K^+\Sigma^0, K^+\Lambda, \eta p$ for $\Sigma^*(1535)$ Molina et al., PRD109(2024)054002

$B^0 B^{*+}, B^+ B^{*0}$ for T_{bb}^+ Feijoo et al., PRD109(2024)016014

$J/\psi J/\psi$ for $X(6200)$ Liu et al., arXiv:2512.10459[hep-ph]

Talks by Juan M Nieves, Juan Torres-Rincon, Lisheng Geng on Tue.

$D_s^+ D_s^-$ for $X(3960)$ Liu et al., PRD113(2026)114005

…

Correlation function in HIC

- Debate in two-body correlation function

  - Two-body correlation function $C(\mathbf{k}) = \int d\mathbf{r} S_{12}(\mathbf{r}) |\Psi(\mathbf{r}, \mathbf{k})|^2$

    $S_{12}(\mathbf{r})$ source function, usually parameterized as Gaussian form $\dfrac{e^{-r^2/(4r_0^2)}}{(4\pi r_0^2)^{3/2}}$

    $\Psi(\mathbf{r}, \mathbf{k})$ relative wave function of out-going two-body system

  - Whether the source function is universal or not?

    The source function should not be universal. Epelbaum et al., PRL136(2026)21

    A physical observable does not depend on the choice of the Hilbert space

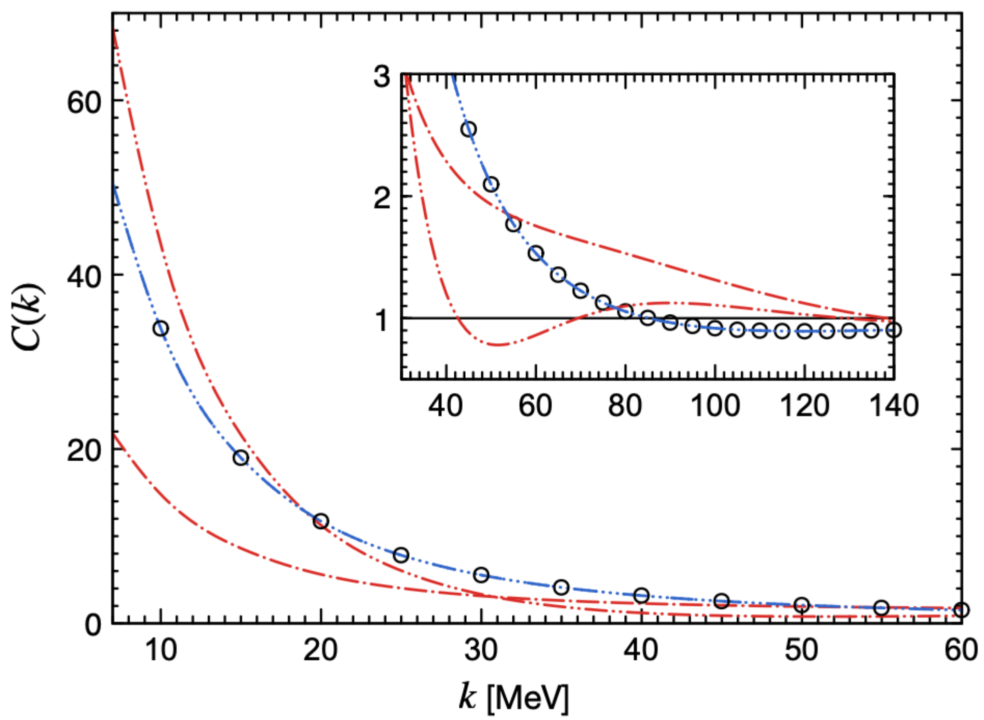
$$C(\mathbf{k}) = \left\langle \Psi^{(+)}_{-\mathbf{k}} \right| \hat{S}_{12} \left| \Psi^{(+)}_{-\mathbf{k}} \right\rangle$$

$$C(\mathbf{k}) = \left(\left\langle \Psi^{(+)}_{-\mathbf{k}} \right| \hat{U}^\dagger \right) \left(\hat{U} \hat{S}_{12} \hat{U}^\dagger \right) \left(\hat{U} \left| \Psi^{(+)}_{-\mathbf{k}} \right\rangle \right)$$
$$\equiv \left\langle \Psi'^{(+)}_{-\mathbf{k}} \right| \hat{S}'_{12} \left| \Psi'^{(+)}_{-\mathbf{k}} \right\rangle .$$

Assuming $\hat{S}'_{12} = \hat{S}_{12}$ makes a model-dependent correlation function, which stems from the off-shell interaction.

Correlation function in HIC

- Debate in two-body correlation function
  - Whether the source function is universal or not?



Epelbaum et al., PRL136(2026)21

① An example to illustrate model-dependence

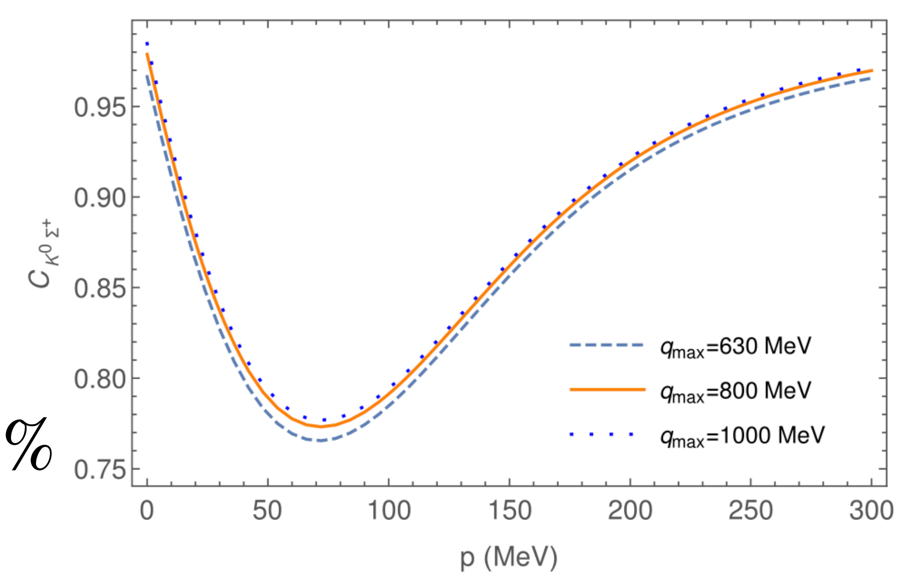
② Blue lines and red lines do not coincide

③ When $r_0 > r_{\rm range}$, it is not a serious problem, since the large-distance behavior of the wave function $\Psi(\mathbf{r}, \mathbf{k})$ is unambiguously determined by the S-matrix

① $K\Lambda, K\Sigma, \eta N$ coupled channels for $N^*(1535)$

② Realistic interactions based on χ dynamics

③ The uncertainty from off-shell ambiguity is $2 \sim 3$ %



Molina et al., PRD112(2025)096006

Summary and outlook

- The property of exotic hadrons is still challenging

①New computational methods — NNQS/DeepQuark and complex scaling — now allow us to solve multiquark systems accurately, and to treat bound states and resonances on the same footing.

②The first lattice results on the electromagnetic form factors of T_{bb} point to a compact structure, while magnetic moments remain a promising, though experimentally unexplored, discriminator.

③Symmetry-partner networks based on HQSS and SU(3) provide a unified framework, even though different scenarios lead to similar spectra — the real differences show up in the exact pole positions, couplings, and decay patterns.

④Combined analyses of lattice and experimental data have shown that both dynamical poles and kinematic effects, such as triangle singularities, are essential.

⑤Production in e^+e^- annihilation, hadron colliders, HIC, and photoproduction has become an independent and complementary probe of structure.

⑥New quantitative tools — compositeness, left-hand-cut parameterizations, and correlation functions with a basis-dependent source function — are sharpening our description of near-threshold states.

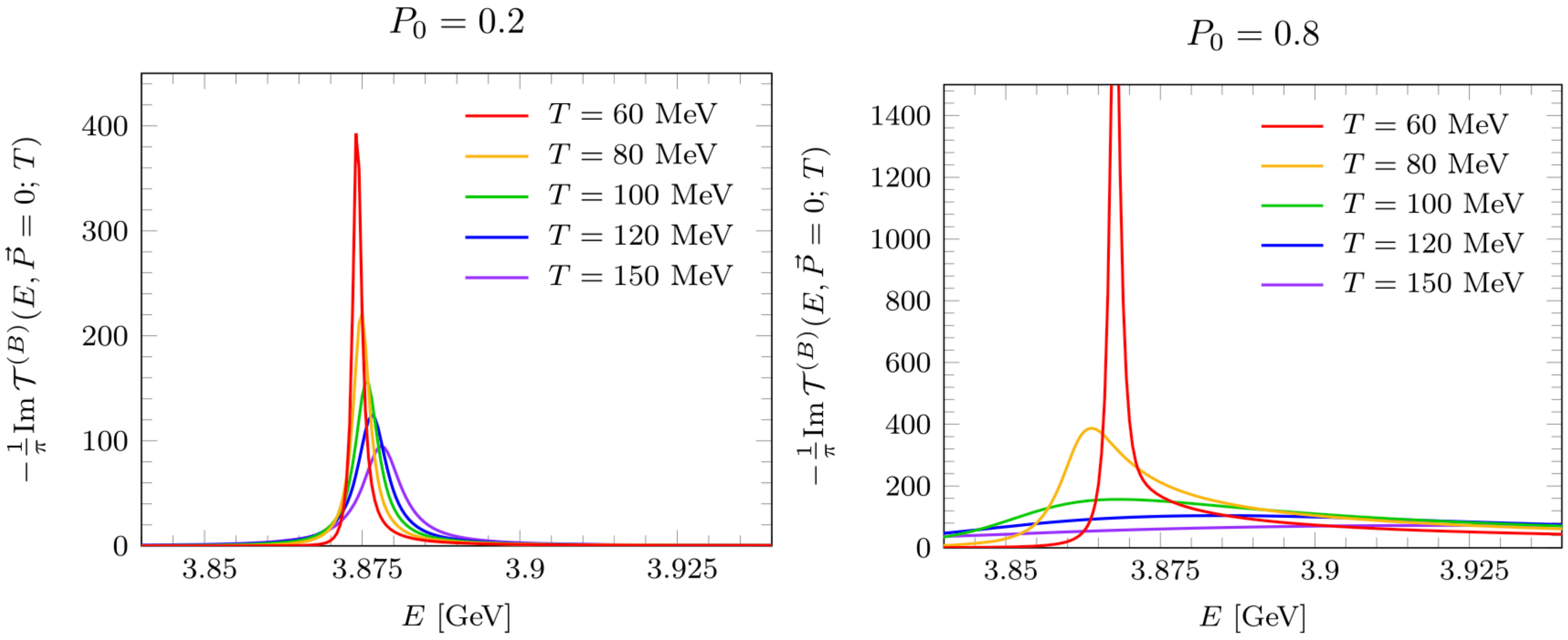
⑦Studies at finite temperature and density open yet another dimension for structure discrimination, with direct relevance to heavy-ion experiments.

⑧Three-hadron systems represent an exciting new frontier, including states with exotic quantum numbers.

A photon of NSTAR2009

Hadron properties at finite tem. and finite den.

- T_{cc} at finite temperature



Montesinos et al., PLB871(2025)140020

① The T_{cc} line shapes at various temperatures

② For small HM com., the peak shift to higher energy region with increasing T

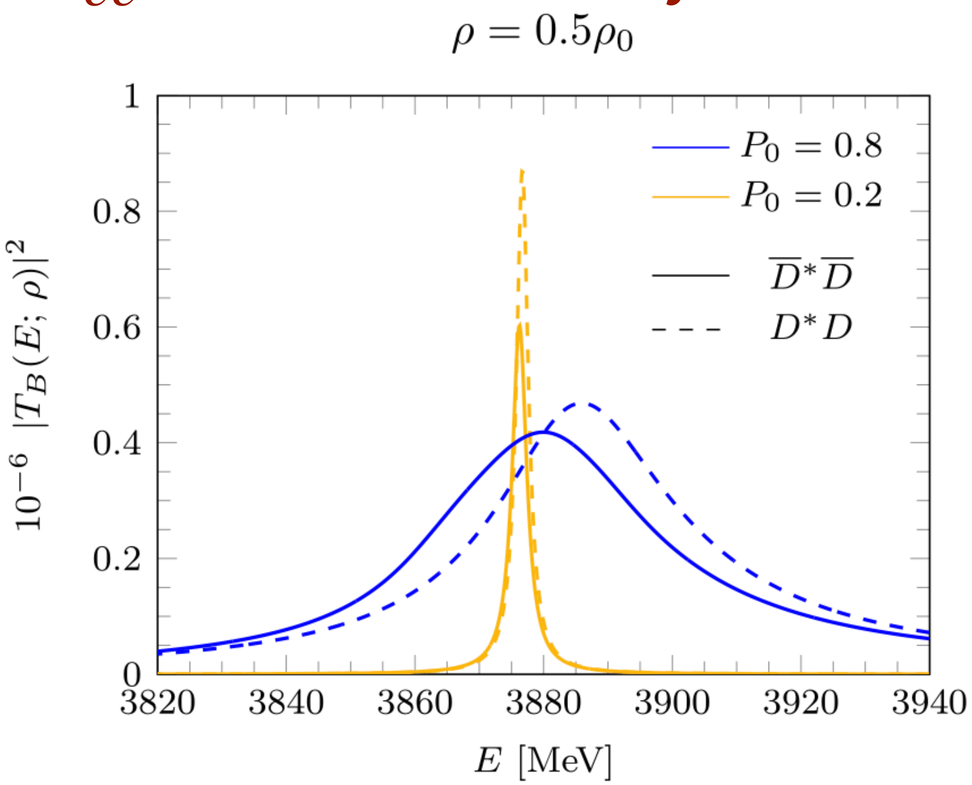
③ For large HM com., the peak shift to lower energy region with increasing T

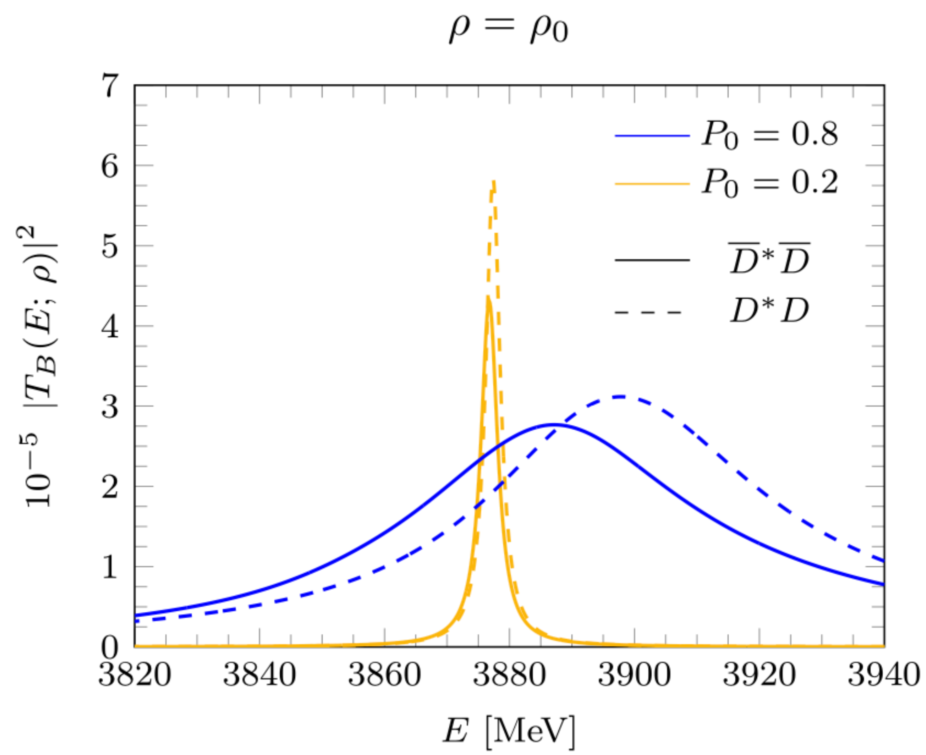
④ Width in both cases increase with increasing T

⑤ For a large HM com., T_{cc} melt down around 80 MeV temperature

Hadron properties at finite tem. and finite den.

- T_{cc} at finite density





Montesinos et al., PRC108(2023)035205

① The T_{cc} and its antiparticle line shapes at various densities

② The normal nuclear density $\rho_0 = 0.17\ \mathrm{fm}^{-3}$

③ Significant dif. between T_{cc} and its antiparticle due to different $D^{(*)}N, \bar{D}^{(*)}N$

④ For the large HM case, the changes are significant

⑤ For a large HM com., T_{cc} and $\bar{T}_{cc}$ peaks move to higher energy region with increasing density