中国物理学会高能物理分会第十二届全国会员代表大会暨学术年会 @广州

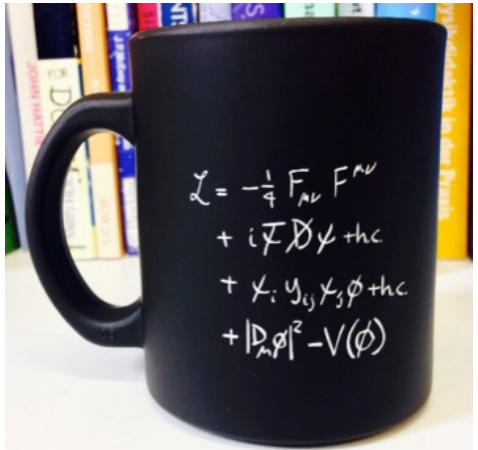
强子物理与味物理理论研究进展

孟 璐

东南大学

2026-7-18

The Standard Model



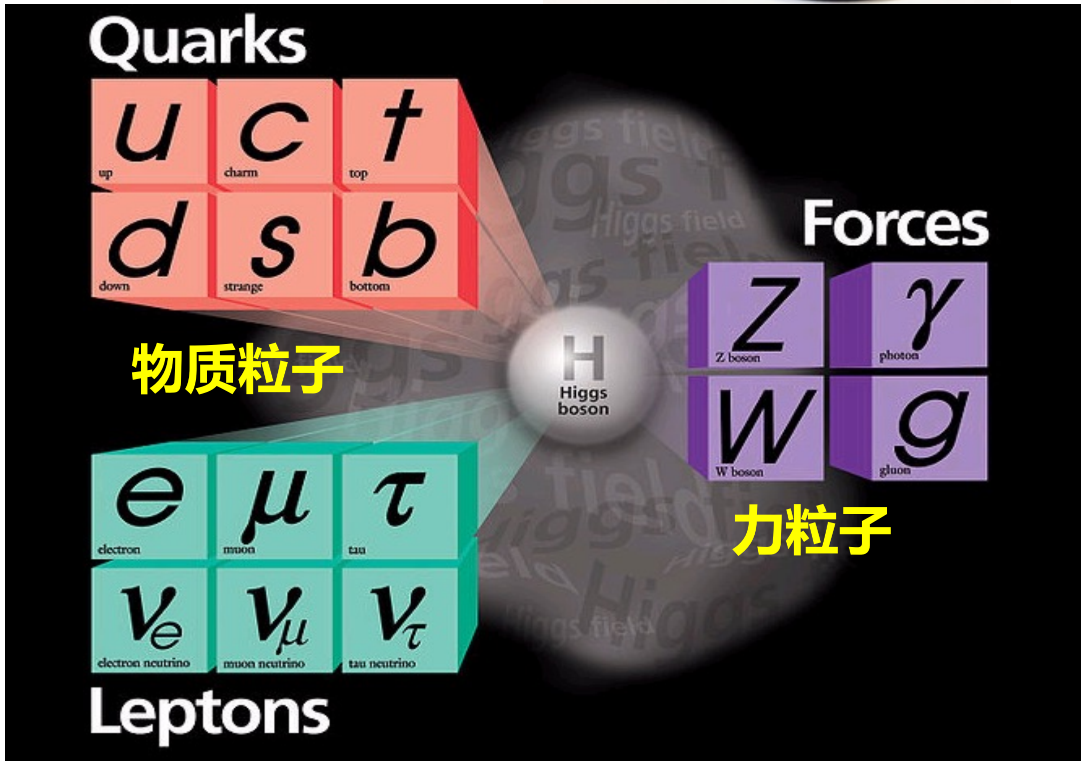
Remarkable successes

- All particles predicted by the SM have been observed
- Most experimental results agree remarkably well with SM

Meng Xiao's talk

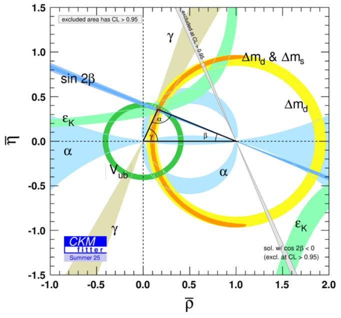
Open questions

- Dark matter
- Dark energy
- Neutrino masses
- More matter than antimatter in the Universe
- Color confinement
- …

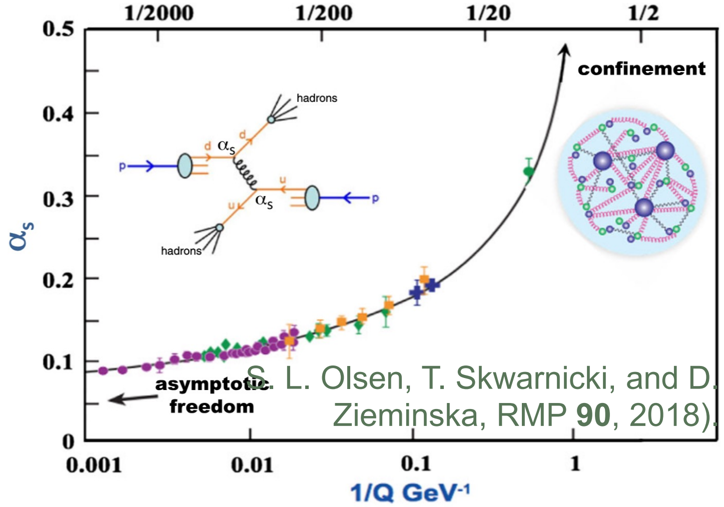


Flavor physics and hadron physics

- **Flavor physics**
  - ▶ Precisely determine CKM matrix elements, CP-violating phases, and the unitarity triangle
  - ▶ Search for BSM via CP violation and rare decays (FCNC)



- **Hadron physics**
  - ▶ Hadron spectrum/structure
  - ▶ Color confinement
  - ▶ Emergence of mass



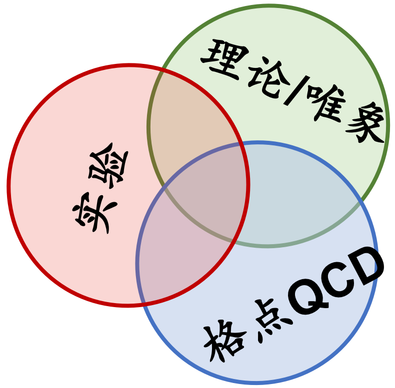
S. L. Olsen, T. Skwarnicki, and D. Zieminska, RMP **90**, 2018).

- **With different goals but closely connected**
  - ▶ Conduct in the same experiments, e.g. LHCb, Belle, BESIII,…
  - ▶ Flavor parameters <hadron process> Observations
  - ▶ Hadron structure: weak decay and productions (Flavor physics)

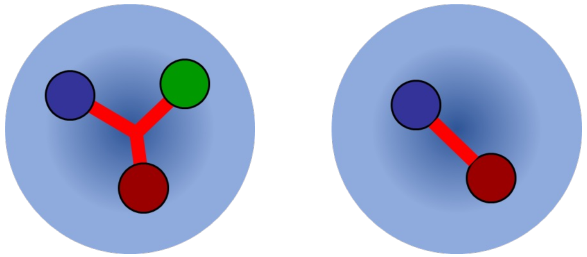
Ice cream has both color and flavor. So do quarks.

(RMP81.1887)

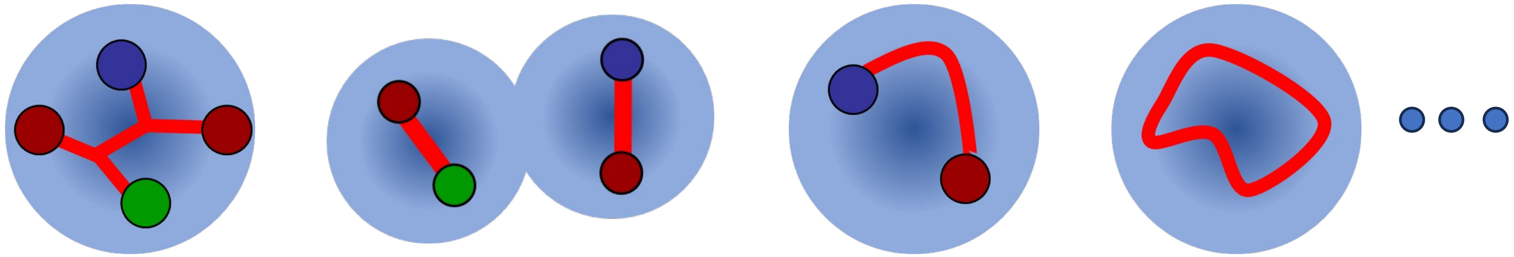
- Many notable advances in flavor & hadron physics theory
- A selective overview, not an exhaustive survey
- Developments since 2023
- Apologize for any omissions
- Focus on
  - ▶ **High precision** & New computational technologies
  - ▶ **Unified** phenomenological frameworks
  - ▶ **Model-independent/**systematic/data-driven approaches
  - ▶ Closer **connections** among Exp., Lattice and Th./Pheno.
  - ▶ **Interplay** between flavor and hadron physics



Exotic states



Conventional hadron



Compact multiquark

Hadronic molecule

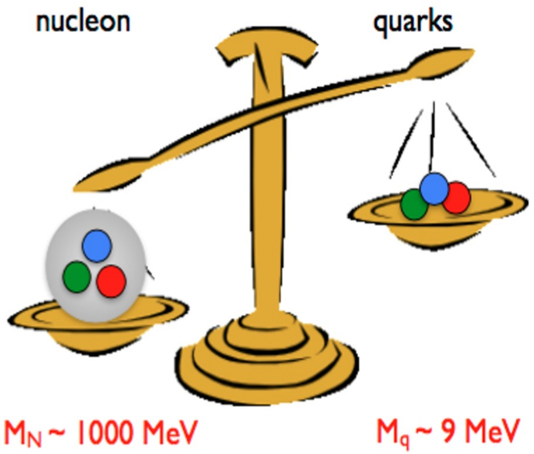
Hybrid state

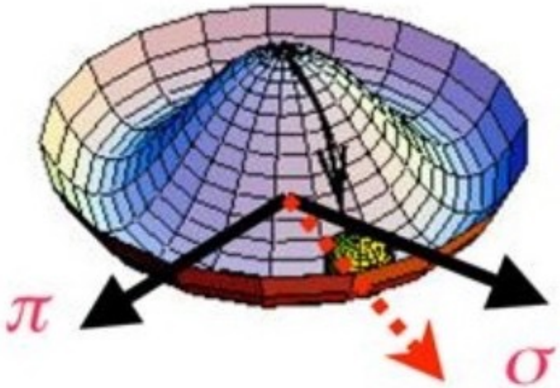
Glueball

Exotic, but allowed by QCD

Why Study Exotic States?

- Mass emergence in QCD
- Chiral dynamics
- Confinement：flux-tube of multiquarks
- **Few/Many-body physics**
  - Clustering? Molecule?



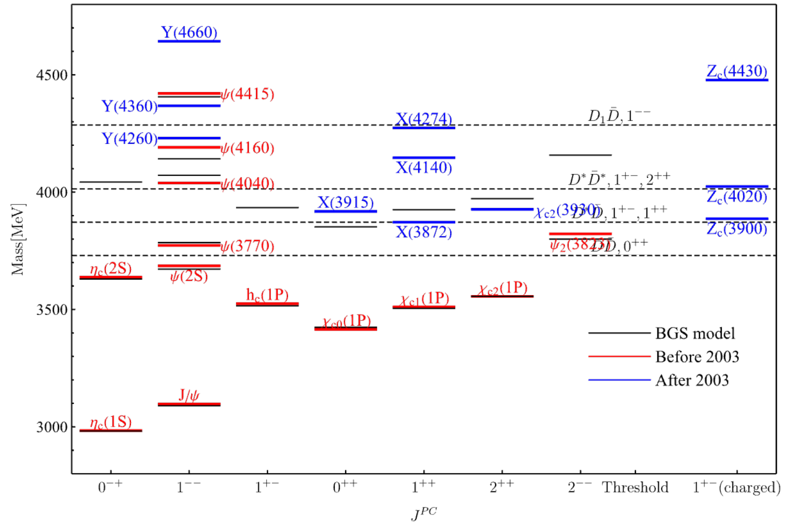


Multiquark states

- Heavy-quarkonium-like states: unquenched quark model

Z.-Y. Bai, D.-Y. Chen, Qi-Huang, X. Liu, S.-Q. Luo, and J.-Z. Wang, arXiv:2602.19887 【Review】
W. Hao, M. A. Sultan, and E. Wang, PRD**111**, 094024 (2025).
R.-H. Ni, J.-J. Wu, and X.-H. Zhong, PRD **109**, 116006 (2024).
Z.-L. Man, C.-R. Shu, Y.-R. Liu, and H. Chen, EPJC **84**, 810 (2024).
W. Hao and R. Zhu, CPC**48**, 123101 (2024).
…

B-S Zou's talks
https://indico.cern.ch/event/1457095/contributions/6563231/

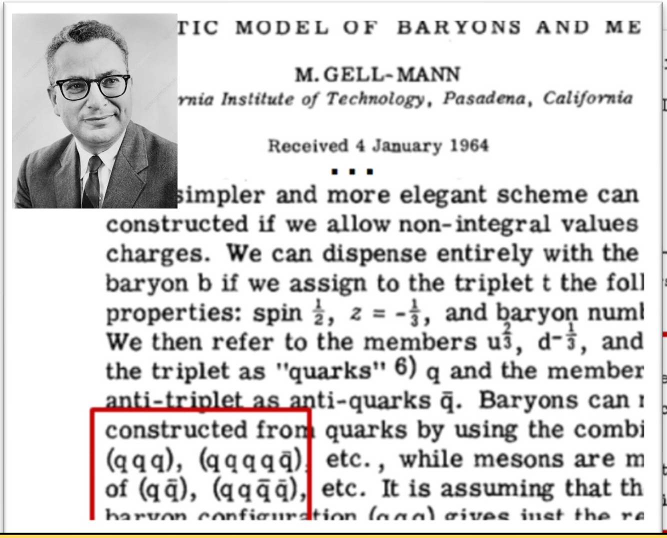


- **Multiquark systems**

$[c\bar{c}qqq]$ $P_{c\bar{c}}$	$[cc\bar{c}\,\bar{c}]$ $T_{cc\bar{c}\bar{c}}(6900)$ $T_{cc\bar{c}\bar{c}}(6600)$ $T_{cc\bar{c}\bar{c}}(7100)$	$[cs\bar{u}\,\bar{d}]$ $T^*_{cs1}(2900)$ $T^*_{cs0}(2870)$	$[c\bar{c}u\bar{s}]$ $T_{c\bar{c}s1}(3985)^+$ $T_{c\bar{c}s1}(4000)^+$ $T_{c\bar{c}s1}(4220)^+$	$[cc\bar{u}\,\bar{d}]$ $T_{cc}(3875)^+$	$[c\bar{s}u\bar{d}][c\bar{s}\bar{u}d]$ $T^*_{c\bar{s}0}(2900)^{++}$ $T_{c\bar{s}0}\,(2900)^0$	$[c\bar{c}qqq]$ $P_{c\bar{c}s}(4338)^0$ $P_{c\bar{c}s}(4459)$
LHCb	2006.16957 2306.07164 2304.08962 2506.07944 2602.02252 LHCb, CMS, ATLAS	2009.00025 2009.00026 LHCb	2011.07855 2103.01803 BESIII, LHCb	2109.01038 2109.01056 LHCb	2212.02716 2212.02717 2411.19781 LHCb	2210.10346 2012.10380 2502.09951 LHCb, Belle

Manifestly exotic and appearing as **Families**

Multiquarks in Quark model


TIC MODEL OF BARYONS AND ME

M. GELL-MANN

rnia Institute of Technology, Pasadena, California

Received 4 January 1964

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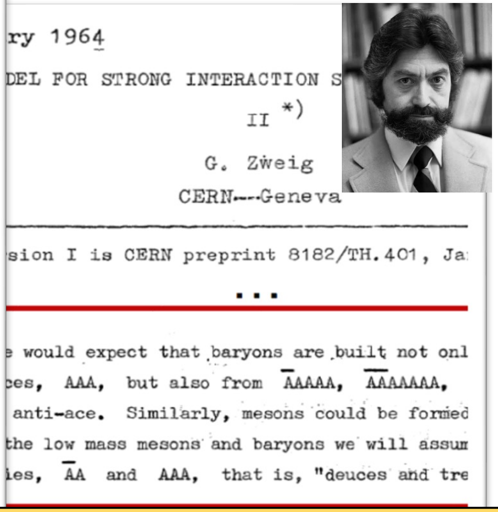
simpler and more elegant scheme can
constructed if we allow non-integral values
charges. We can dispense entirely with the
baryon b if we assign to the triplet t the foll
properties: spin $\frac{1}{2}$, $z = -\frac{1}{3}$, and baryon numl
We then refer to the members $u^{\frac{2}{3}}$, $d^{-\frac{1}{3}}$, and
the triplet as "quarks" 6) q and the member
anti-triplet as anti-quarks $\bar{q}$. Baryons can
constructed from quarks by using the combi
$(q q q)$, $(q q q q \bar{q})$, etc., while mesons are m
of $(q \bar{q})$, $(q q \bar{q} \bar{q})$, etc. It is assuming that th
baryon configuration $(q q q)$ gives just the r


ry 1964

DEL FOR STRONG INTERACTION S

II *)

G. Zweig

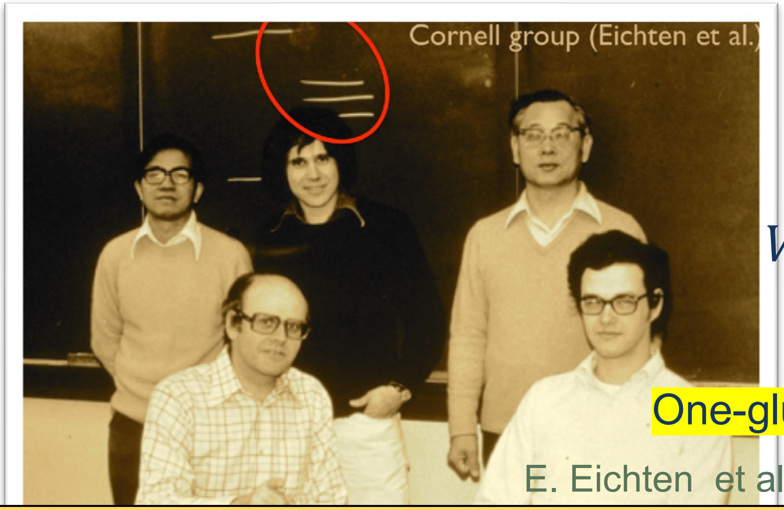
CERN---Geneva

sion I is CERN preprint 8182/TH.401, Ja

. . .

e would expect that baryons are built not onl
ces, AAA, but also from $\bar{A}AAAA$, $\bar{A}\bar{A}AAAAA$,
anti-ace. Similarly, mesons could be formed
the low mass mesons and baryons we will assum
ies, $\bar{A}A$ and AAA, that is, "deuces and tre

Multiquarks were predicted at the birth of quark model



$$V(r) = -\frac{\kappa}{r} + \frac{r}{a^2}$$

One-gluon-exchange

Confinement

E. Eichten et al., PRD 17, 3090 (1978).

Quark potential models work well for the conventional hadrons

Fully heavy/strange tetraquarks

Y. Wu, X. Liu, J. Ping, H. Huang, and Y. Tan, EPJC**85**, 147 (2025).
G. Yang, J. Ping, and J. Segovia, PRD **113**, 114001 (2026).
…

Doubly heavy tetraquarks

D. Wang, K.-R. Song, W.-L. Wang, and F. Huang, PRD**109**, 074026 (2024).
W.-C. Dong and Z.-G. Wang, NPB**1012**, 116828 (2025).
Q. Meng, G.-J. Wang, and M. Oka, PRD **111**, 014018 (2025)
…

Heavy tetraquarks with strangeness

F.-X. Liu, R.-H. Ni, X.-H. Zhong, and Q. Zhao, EPJC**85**, 1303 (2025).
…

Pentaquark

W. L. Wang, F. Huang, Z. Y. Zhang, and B. S. Zou, PRC84, 015203 (2011).
Y. Yan, Y. Wu, H. Huang, J. Ping, and X. Zhu, EPJC **83**, 610 (2023).
Z.-B. Liang, F.-X. Liu, and X.-H. Zhong, PRD **111**, 056013 (2025)
…

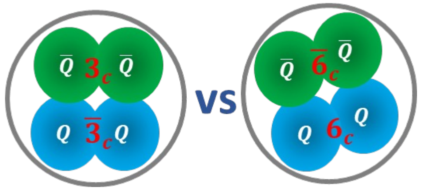
Dibaryon

C.-R. Deng, PRD **108**, 054037 (2023).
Y. Dong, P. Shen, and Z. Zhang, PPNP **131**, 104045 (2023).
…

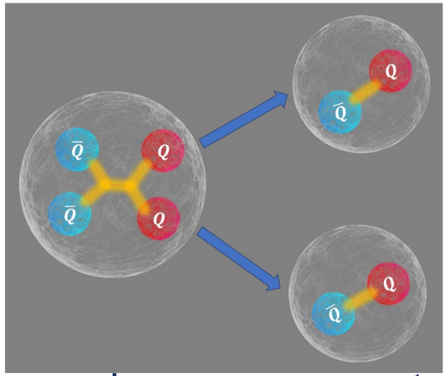
Multiquark potential models:
Extensive efforts, yet not well-established

Quark Models for Multiquarks: Challenging but Rewarding

- **Challenges**
  - ▶ Color structures: e.g. $3-\bar{3}$ and $6-\bar{6}$ tetraquark
  - ▶ Matrix element of double Y-type potential
  - ▶ Four/five body problem
  - ▶ Resonance above the di-hadron thresholds
  - ▶ ….

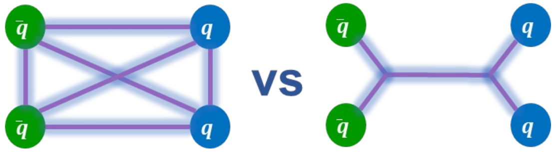


Color structures



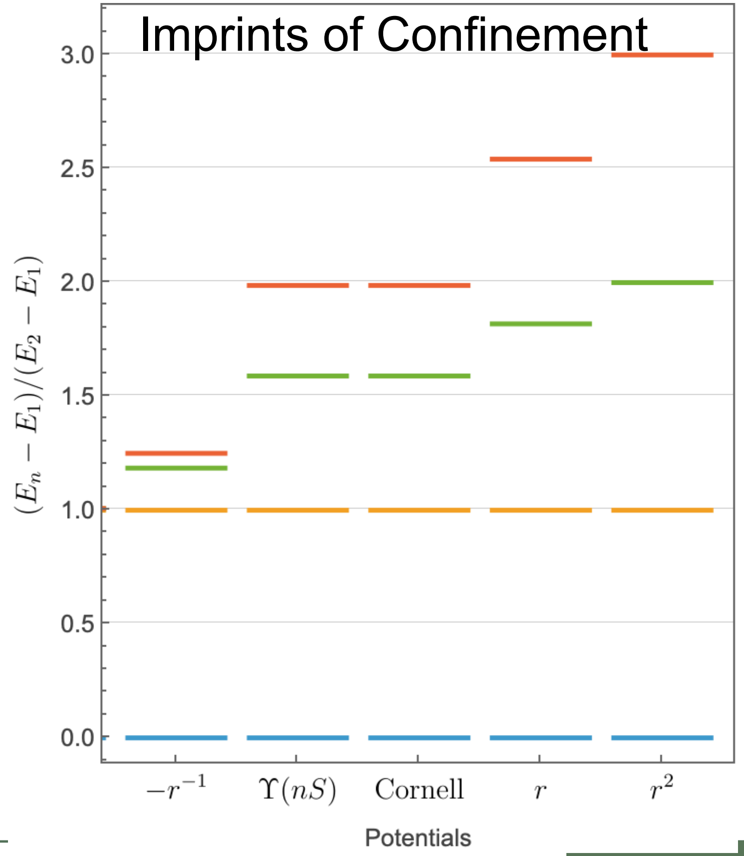
quark rearrangement

Interactions?
few-body (resonance) problem?



C. Alexandrou, PRD71 (2005) 014504; F.Okiharu, PRD72 (2005) 014505; P. Bicudo, PRD96 (2017) , 074508

- **Appealing features**
  - ▶ Unified framework to uncover patten of multiquark spectrum
  - ▶ Both molecule and compact states
  - ▶ Low cost with great prediction power
  - ▶ Masses and decays
  - ▶ Confinement

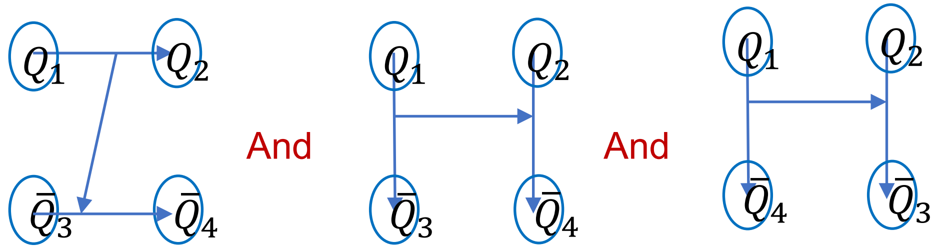


- **Opportunity**: All charmed tetraquark family

LHCb, CMS, ATLAS

Automatic and highly efficient package

Unified Model

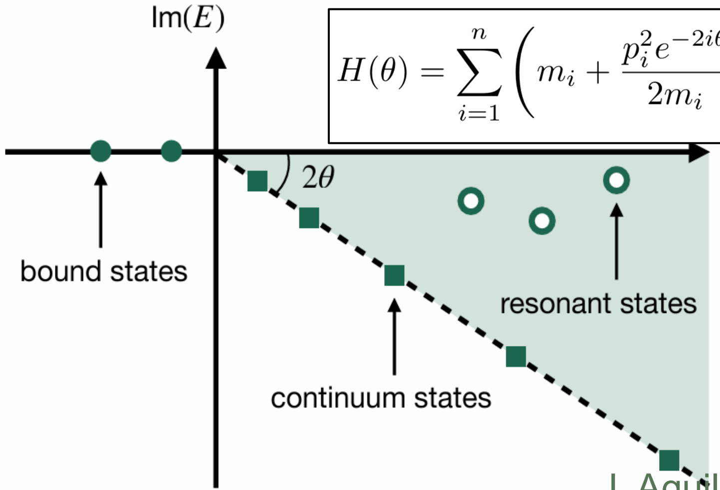


Diquark-antidiquark **Di-meson** **Di-meson**

E. Hiyama, Y. Kino and M. Kamimura, PPNP. 51 (2003) 223-307

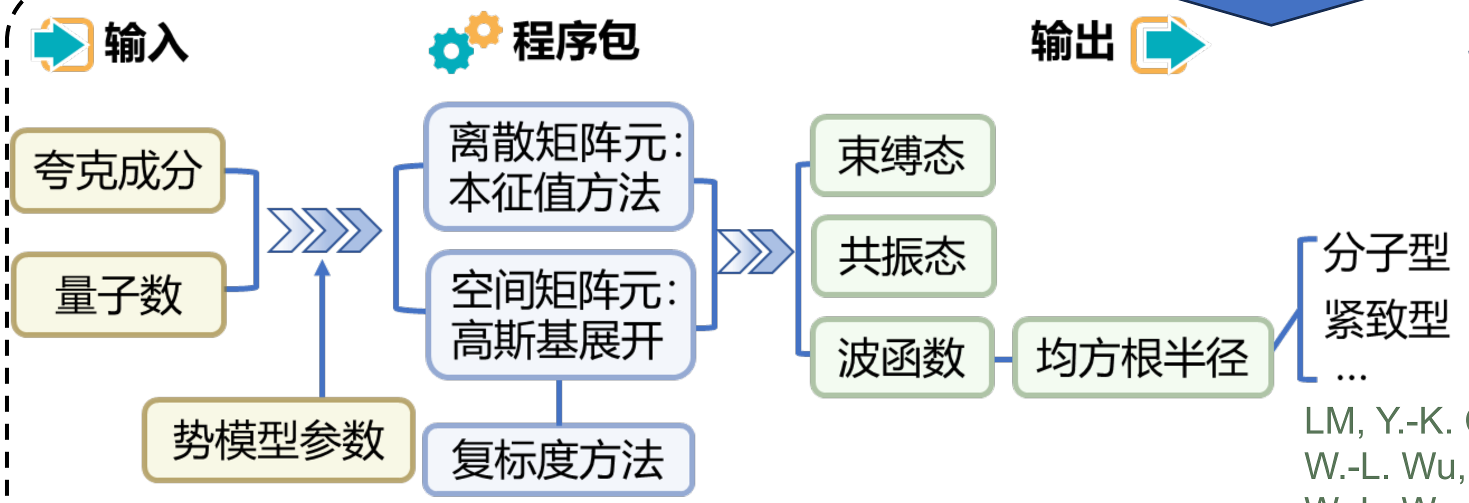
Gaussian expansion method:
compact and molecular configurations

$$H(\theta)=\sum_{i=1}^{n}\left(m_i+\frac{p_i^2 e^{-2i\theta}}{2m_i}\right)+\sum_{i<j=1}^{n}V_{ij}\left(r_{ij}e^{i\theta}\right).$$



J. Aguilar, E. Balslev, J.M. Combes, CMP. 22 (1971) 269-279 & 280-294

Complex scaling method
Bound states and resonances



Singly/doubly/triply/fully heavy tetraquarks

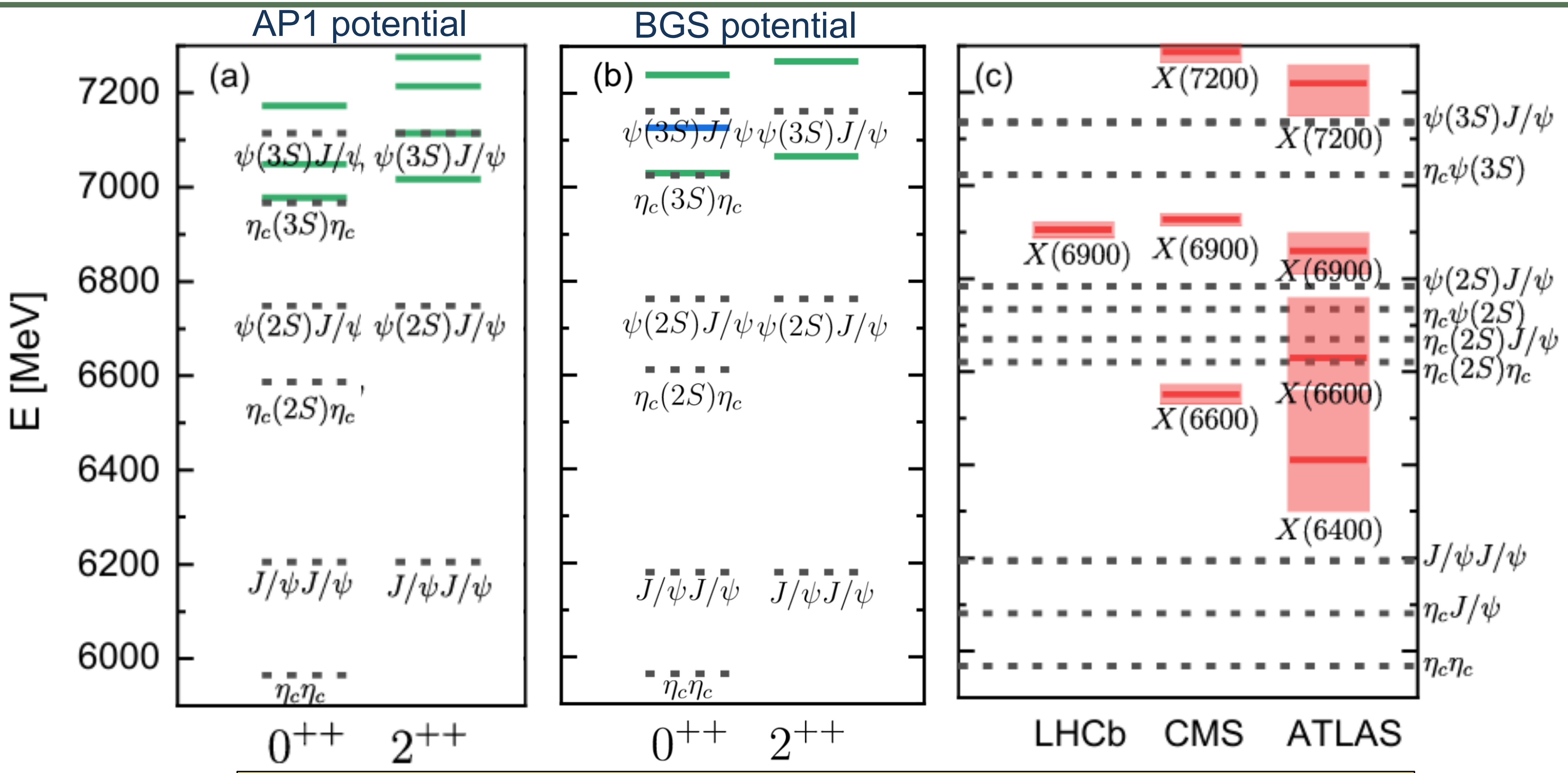
Few lepton systems, Few hadrons…

Efficiency: over 150 bound states taking **2.5h** on my laptop

LM, Y.-K. Chen, Y. Ma, and S.-L. Zhu, PRD **108**, 114016 (2023).
W.-L. Wu, Y.-K. Chen, LM, and S.-L. Zhu,PRD**109**, 054034 (2024).
W.-L. Wu, Y. Ma, Y.-K. Chen, LM, and S.-L. Zhu, PRD**110**, 094041 (2024).
Y.-K. Chen, W.-L. Wu, LM, and S.-L. Zhu, PRD**109**, 014010 (2024).

Automatic and highly efficient package

All-charm tetraquarks



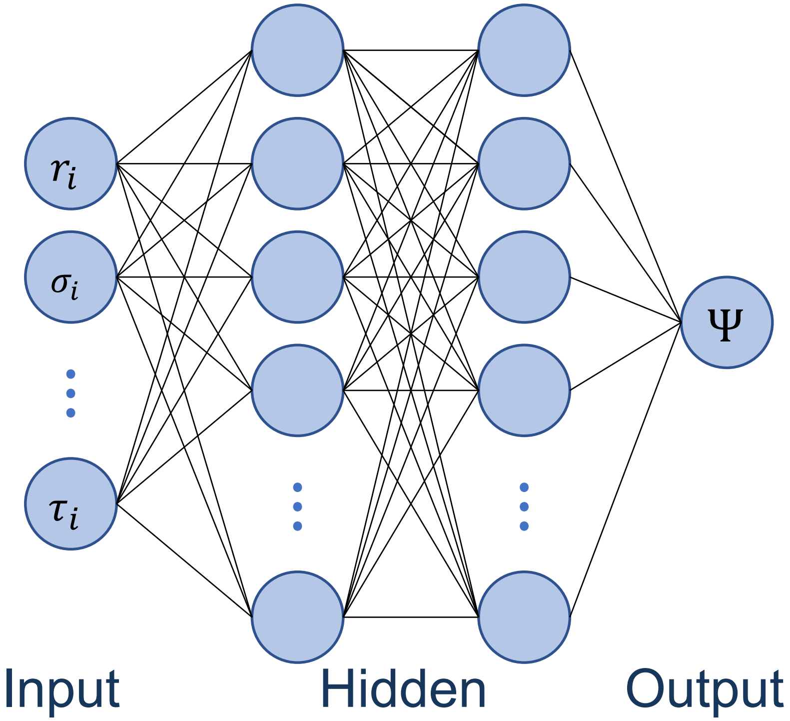
X(6600) is missing in pairwise confinement models

W.-L. Wu, Y.-K. Chen, LM, and S.-L. Zhu,PRD**109**, 054034 (2024).

Neural Network Quantum State Method

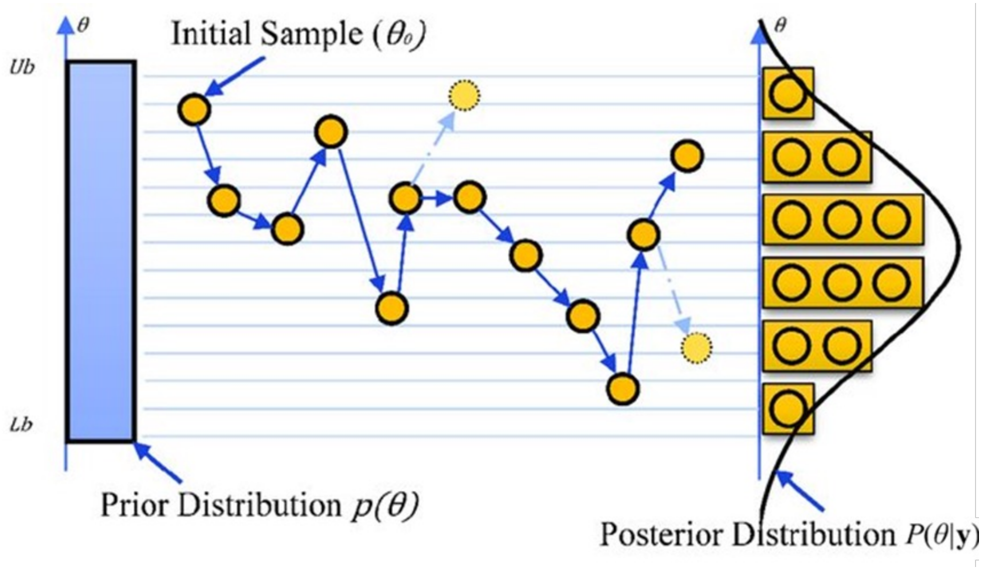
AI for Science

Neural Network Quantum States (NQSs):



Loss function: $E_{\boldsymbol{\theta}} = \dfrac{\langle \psi_{\boldsymbol{\theta}} | H | \psi_{\boldsymbol{\theta}} \rangle}{\langle \psi_{\boldsymbol{\theta}} | \psi_{\boldsymbol{\theta}} \rangle} \geq E_0$

Variational Monte Carlo (VMC)



Sample using Metropolis-Hasting algorithm

$$E_{\boldsymbol{\theta}} = \frac{\int |\psi_{\boldsymbol{\theta}}(r)|^2 \frac{H\psi(r)}{\psi(r)} dr}{\int |\psi_{\boldsymbol{\theta}}(r)|^2 dr}$$

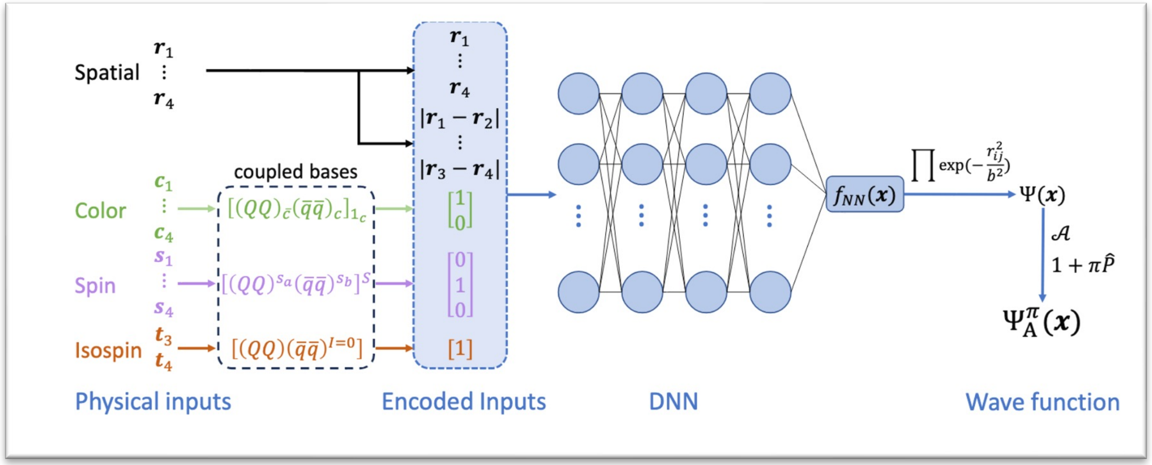
No training data required
Mitigates the curse of dimensionality and sign problem

Naturally incorporates few-body confinement

W.-L. Wu, L. Meng, and S.-L. Zhu, PRL**136**, 071901 (2026).

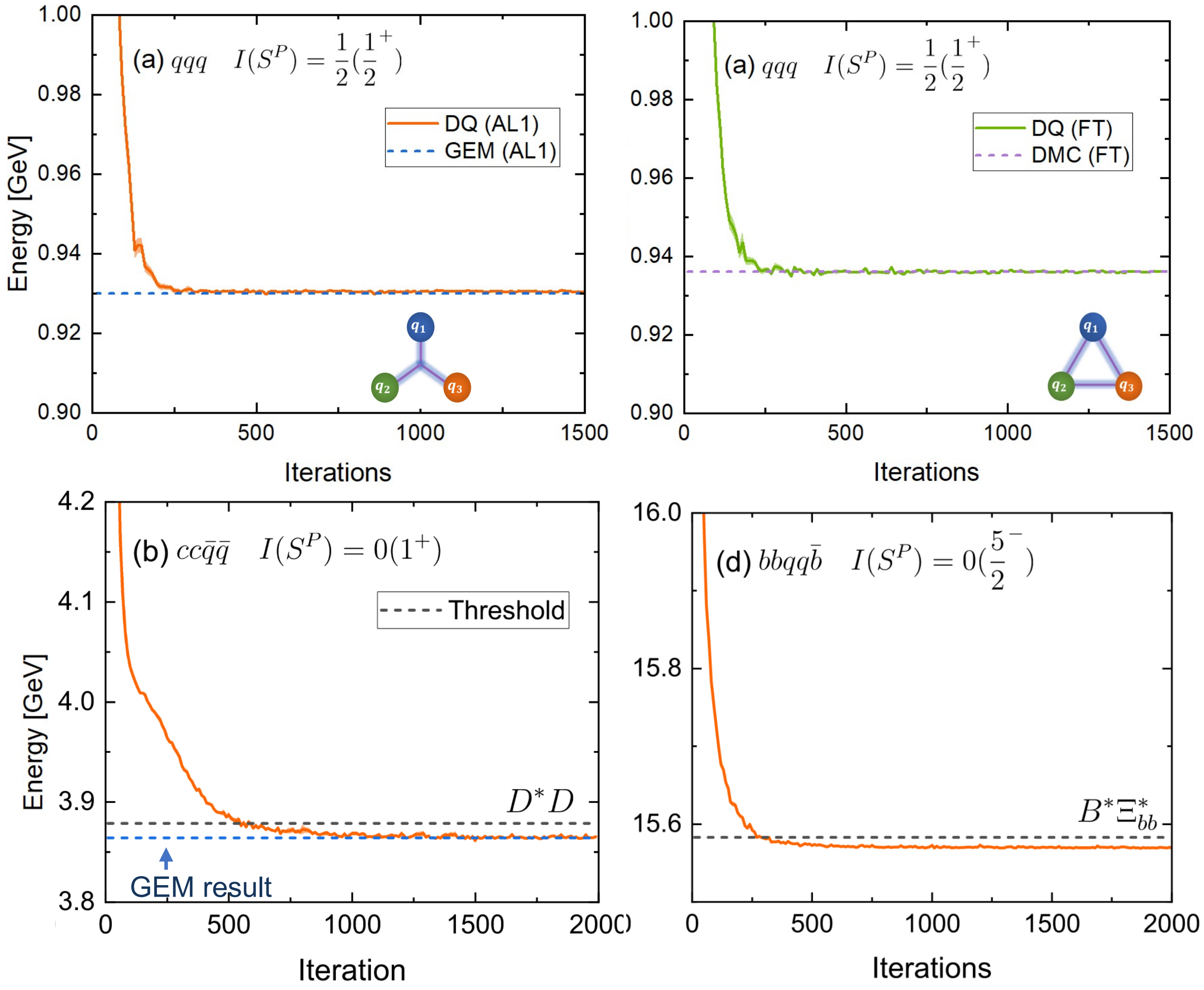
DeepQuark

DeepQuark



https://github.com/wlwuphy/DeepQuark

- $cc\bar{q}\bar{q}$: molecular state
- $bb\bar{q}\bar{q}$: compact heavy diquark
- $QQ\bar{Q}\bar{Q}$: no bound states
- Surpass traditional methods starting from pentaquark states
- Ready for flux-tube confinement



W.-L. Wu, L. Meng, and S.-L. Zhu, PRL**136**, 071901 (2026).

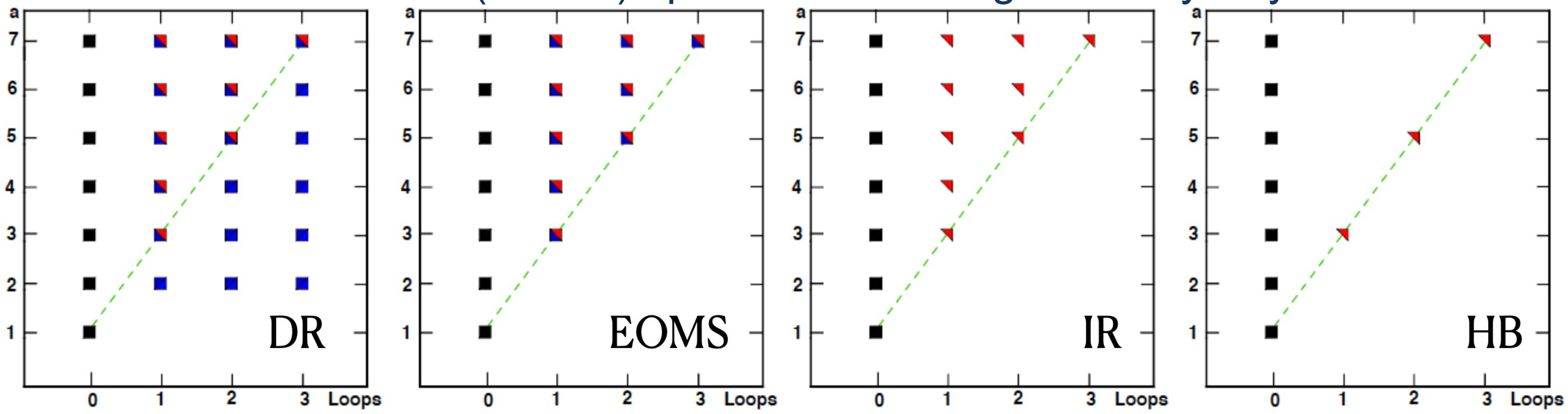
Baryon ChPT at 2-loop order

High precision

- Importance advance of QFT over NR-quantum mechanism:
  - ► Symmetric treatment fluctuations of virtual particles in loops
- Chiral perturbation theory (ChPT)
  - ► The loops diagram: new structure
  - ► E.g chiral logarithms, favored by about **5-8 $\boldsymbol{\sigma}$** for the chiral extrapolation of F_π
  - ► Pion: 3-loop J. Bijnens and N. Hermansson Truedsson, JHEP 11, 181 (2017).

BMW, PRD90 (2014) 11, 114504

- Baryon ChPT
  - ► Nucleon mass $\Longrightarrow$ extra renormalization schemes
  - ► Heavy baryon scheme, IR scheme: 2-loop J. A. McGovern and M. C. Birse, PLB446, 300 (1999). M. R. Schindler ,et al, PLB 649, 390 (2007).
  - ► Extended-on-Mass-shell (EOMS): preserves the original analyticity

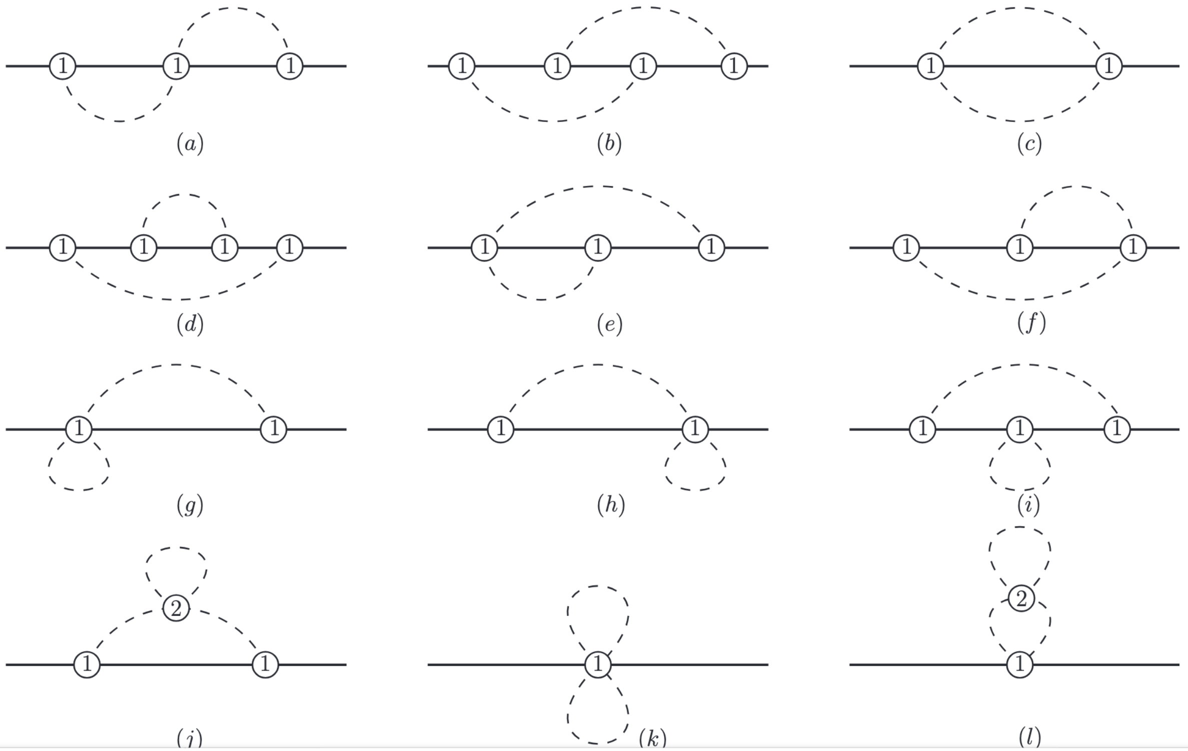


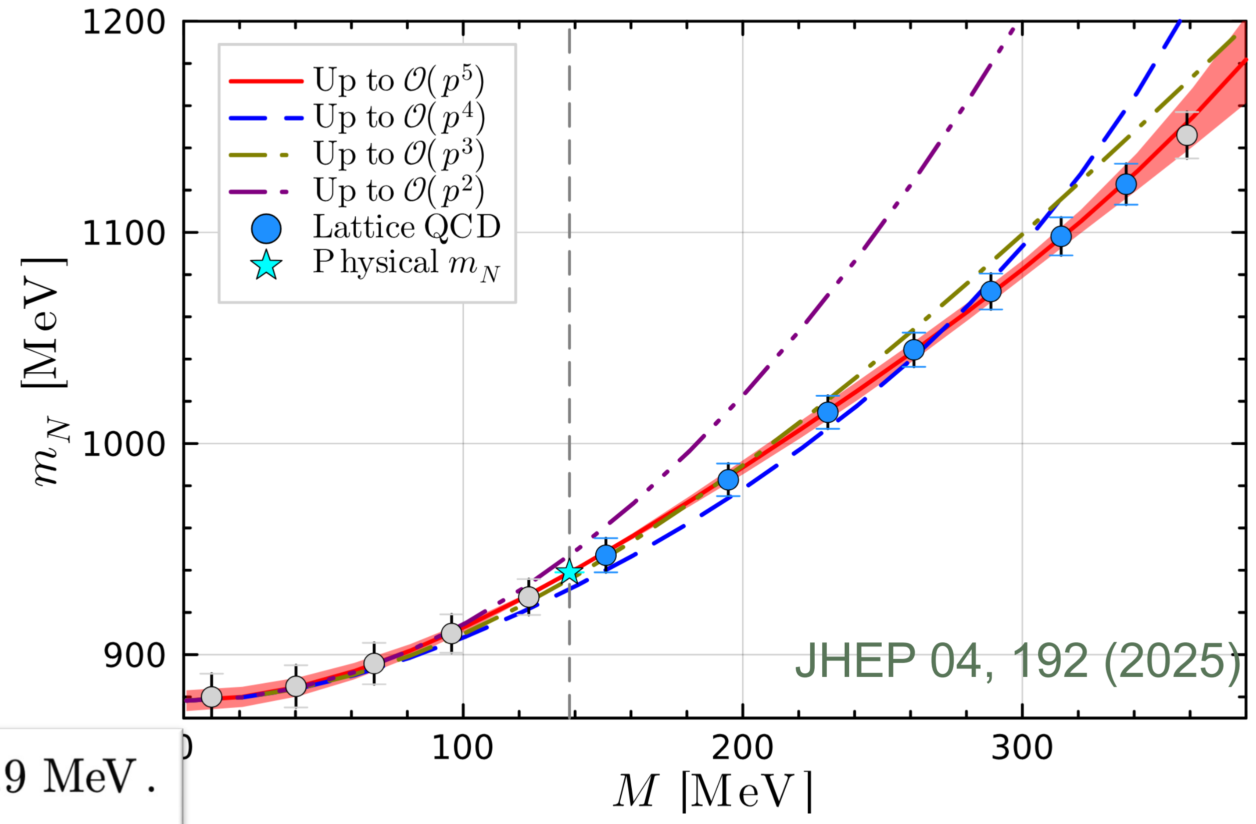
Nucleon mass in Baryon ChPT at 2-loop order

- Renormalizations of 2-loop in EOMS: nontrivial
  - ► Nonlocal UV divergences: e.g. $\frac{1}{\epsilon}\ln(M/\mu)$
  - ► Nonlocal power counting breaking terms

    e.g. $M^n \ln(M/m)$, $M^n \ln^2(M/m)$

N.D. Conrad, A. Gasparyan and E. Epelbaum, PoS CD2021 074 (2024)
L.-B. Chen, S. Hu, Y. Jia, and Z. Mo, arXiv:2406.04124 [hep-ph] (2024)
Z.-R. Liang, H.-X. Chen, F.-K. Guo, Z.-H. Guo, and D.-L. Yao, JHEP 04, 192 (2025)





$$m_N = \{878.2 + \underbrace{68.8}_{\mathcal{O}(p^2)} + \underbrace{[-11.4]}_{\mathcal{O}(p^3)} + \underbrace{[-4.6]}_{\mathcal{O}(p^4)} + \underbrace{7.9}_{\mathcal{O}(p^5)}\}\ \text{MeV} = 938.9\ \text{MeV}\,.$$

pion-nucleon sigma term

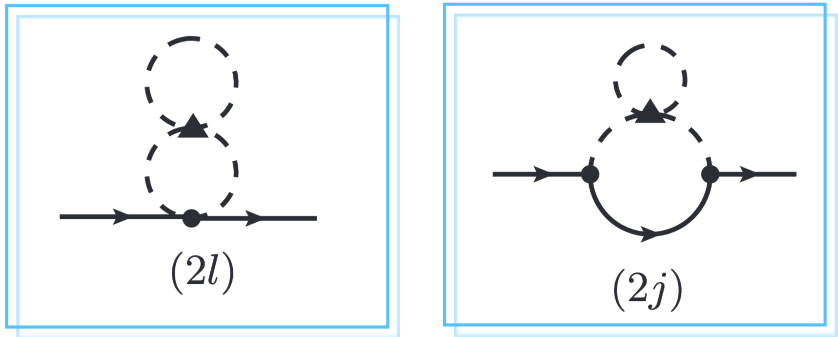
- Pion-nucleon sigma term: m_N due to m_u and m_d

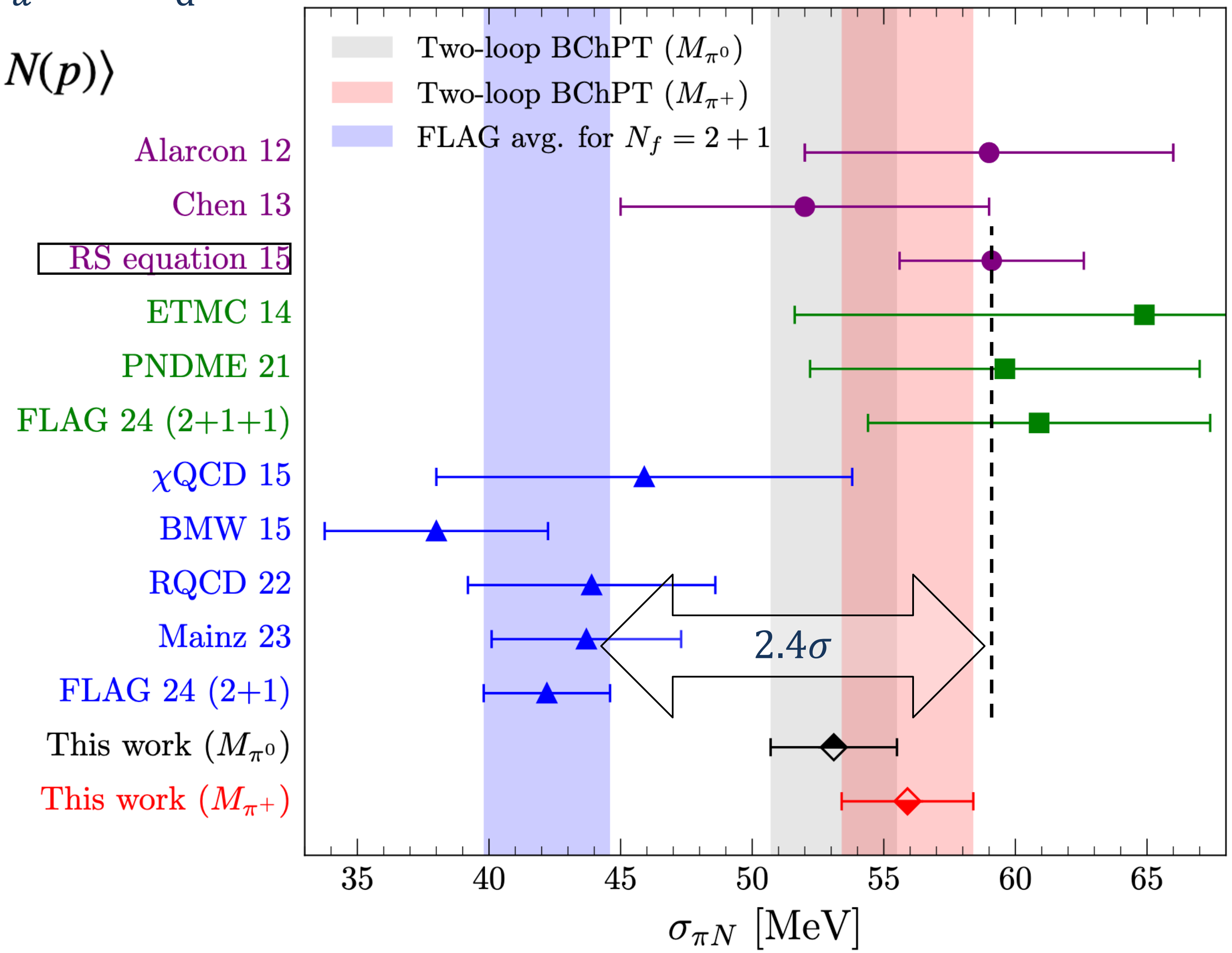
$$\sigma_{\pi N} = \sigma(t=0) = \frac{1}{2m_N}\langle N(p)|\hat{m}(\bar{u}u+\bar{d}d)|N(p)\rangle$$

- Lattice: Mainz group
  - ▶ Using $\mathcal{O}(p^3)$ chiral extrapolation
  - ▶ Tension with RS equation: 2.4σ

    Mainz Group, PRL 131, 261902 (2023).

- Reanalyze using **2-loop ChPT**
  - ▶ ChPT up to $\mathcal{O}(p^5)$
  - ▶ $\pi\pi$ rescattering effect is important
  - ▶ **Resolving the tension**





Z.-R. Liang, H.-X. Chen, F.-K. Guo, Z.-H. Guo, and D.-L. Yao, arXiv:2508.11435

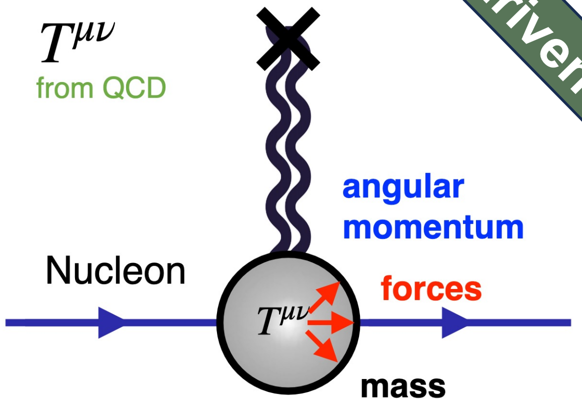
Nucleon Gravitational Form Factors

Data-driven

- Gravitational Form factors (GFF)
  - ▶ Matrix elements of energy-momentum tensor (EMT) current
  - ▶ gravitational forces within hadron 😭
  - ▶ mechanical properties of hadrons 😊

$$\langle N(p')|T^{\mu\nu}|N(p)\rangle = \frac{1}{4m_N}\bar{u}(p')\left[A(t)P^\mu P^\nu + J(t)\left(iP^{\{\mu}\sigma^{\nu\}\rho}\Delta_\rho\right) + D(t)(\Delta^\mu\Delta^\nu - g^{\mu\nu}\Delta^2)\right]u(p).$$

"last unknown global property"
Polyakov, and Schweitzer, (2018)



- ChPT

V. Belitsky and X. Ji, PLB538, 289 (2002)
…

- Lattice QCD

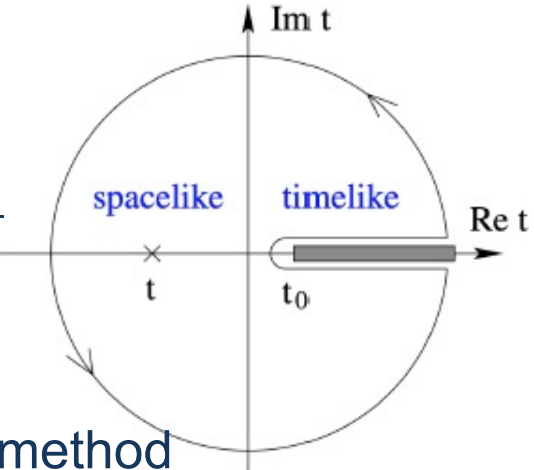
D. C. Hackett, D. A. Pefkou, and P. E. Shanahan, PRL**132**, 251904 (2024).
B. Wang, F. He, G. Wang, T. Draper, J. Liang, K.-F. Liu, Y.-B.Yang, PRD**109**, 094504 (2024).

- Other frameworks

S. Nair, C. Mondal, S. Xu, X. Zhao, A. Mukherjee, and J. P. Vary, PRD**110**, 056027 (2024).
X.-Y. Wang, F. Zeng, and J. Zhang, Chin. Phys. C **48**, 054102 (2024).
Y. Guo, F. Yuan, and W. Zhao, PRL**135**, 111902 (2025).
Y. Hagiwara, X.-B. Tong, and B.-W. Xiao, PRD**111**, L051503 (2025).
J. Wang, D. Fu, and Y. Dong, EPJC**85**, 1254 (2025).
Z.-Q. Yao, Y.-Z. Xu, D. Binosi, Z.-F. Cui, M. Ding, K. Raya, C. D. Roberts et al, EPJA **61**, 92 (2025).
M. Kawaguchi, M. Harada, and Y.-L. Ma, PLB **876**, 140400 (2026).
Z. Xing, K. Raya, Y. Liu, and L. Chang, PLB **878**, 140542 (2026).

GFFs in dispersion relation method

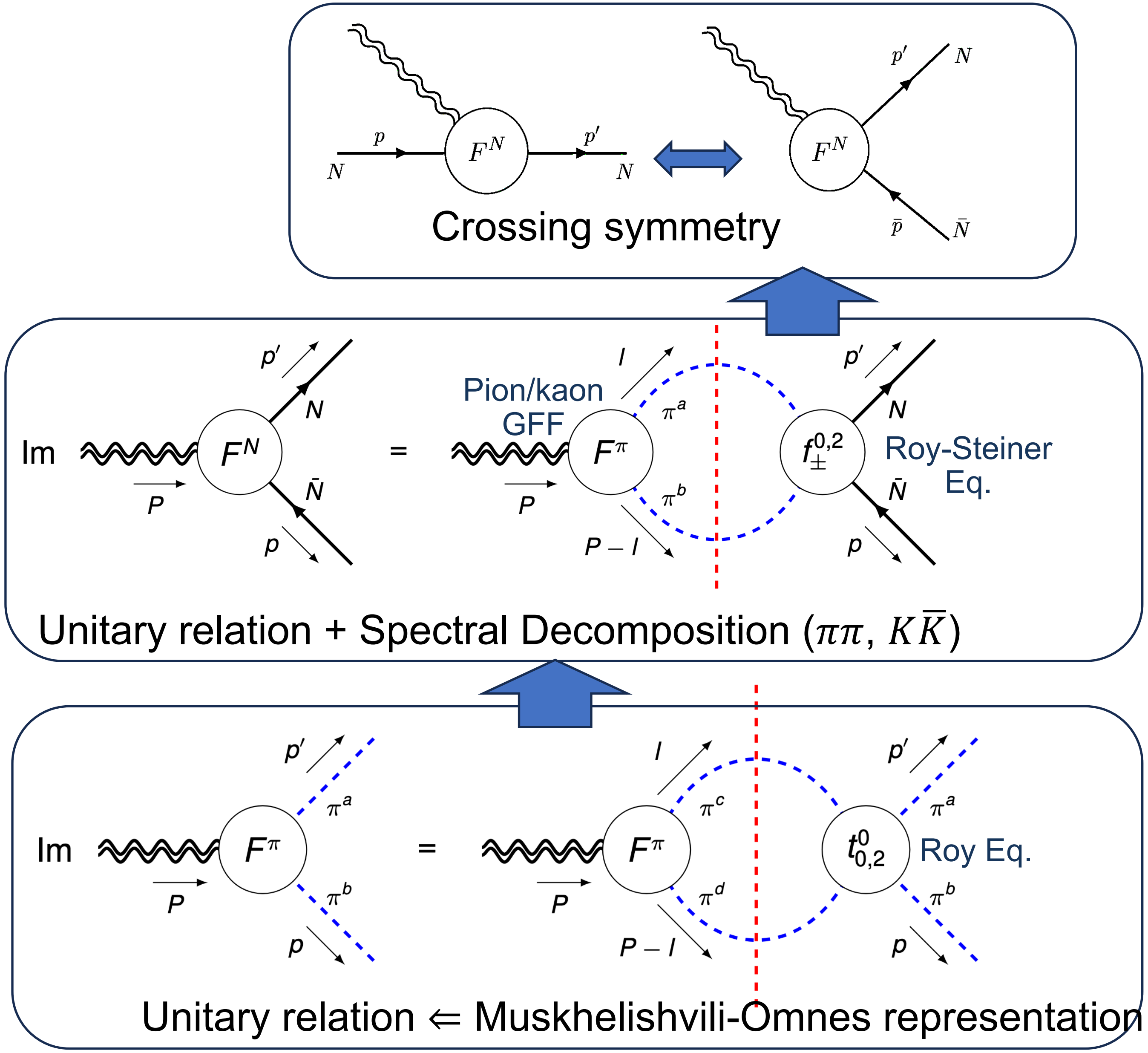
$$F(t) = \frac{1}{\pi}\int_{t_0}^{\infty} \frac{ImF(t')}{t'-t}$$



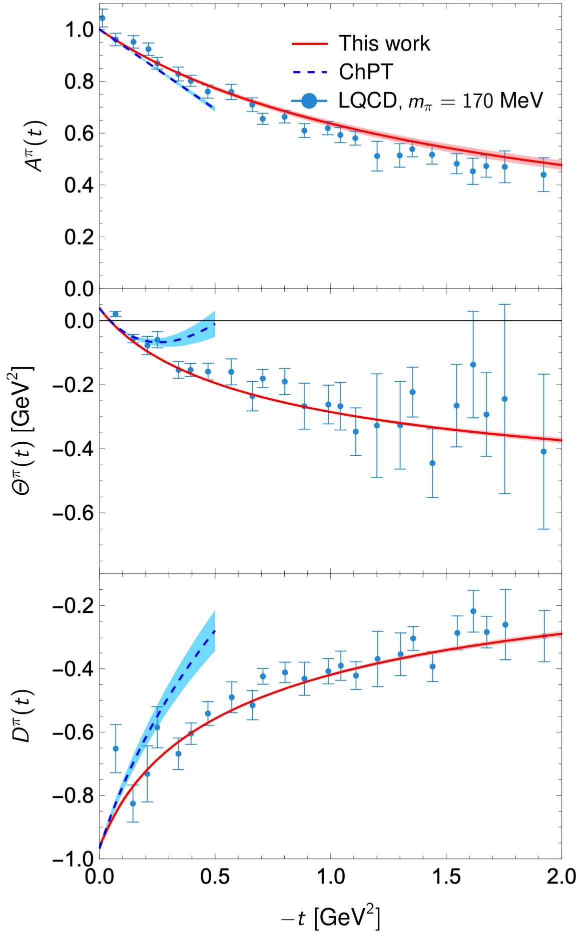
- Dispersion relations method
  - ▶ data-driven, less model-dependent
  - ▶ Based on: unitarity, analyticity and crossing symmetry
  - ▶ Connects timelike and spacelike data
- EM form factor:

  M. Hoferichter, et al, EPJA**52**, 331 (2016)
  M. A. Belushkin, et al. PRC **75**, 035202 (2007)
- Input of GFFs
  - ▶ GFFs of pion and kaon in NLO ChPT
  - ▶ $\pi\pi$, πN scattering data

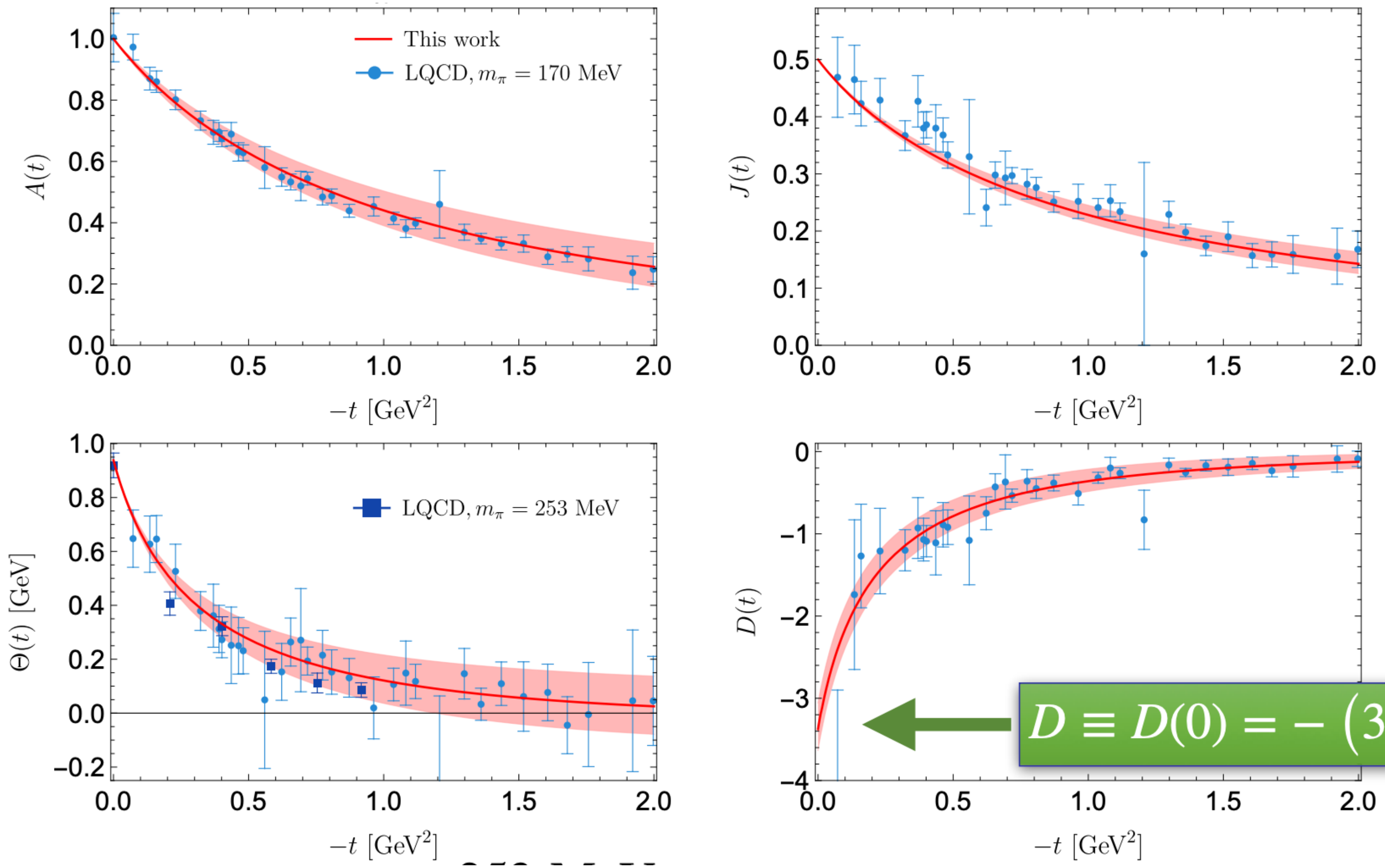
  X.-H. Cao, F.-K. Guo, Q.-Z. Li, and D.-L. Yao, Nature Commun. 16, 6979 (2025).



GFFs in dispersion relation method



Predictions: not a fit

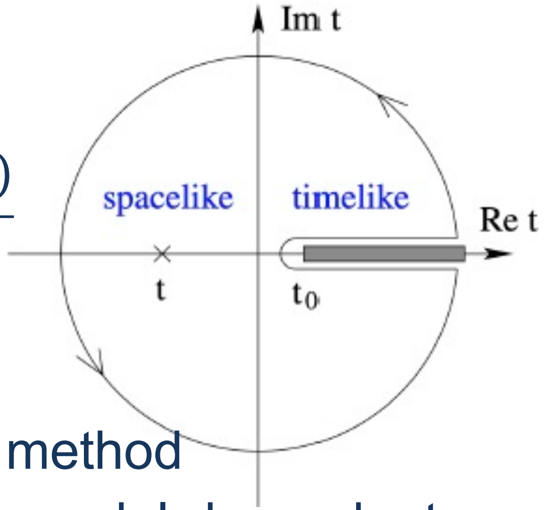


$$D \equiv D(0) = -\left(3.38^{+0.34}_{-0.35}\right)$$

X.-H. Cao, F.-K. Guo, Q.-Z. Li, and D.-L. Yao, Nature Commun. 16, 6979 (2025).

GFFs in dispersion relation method

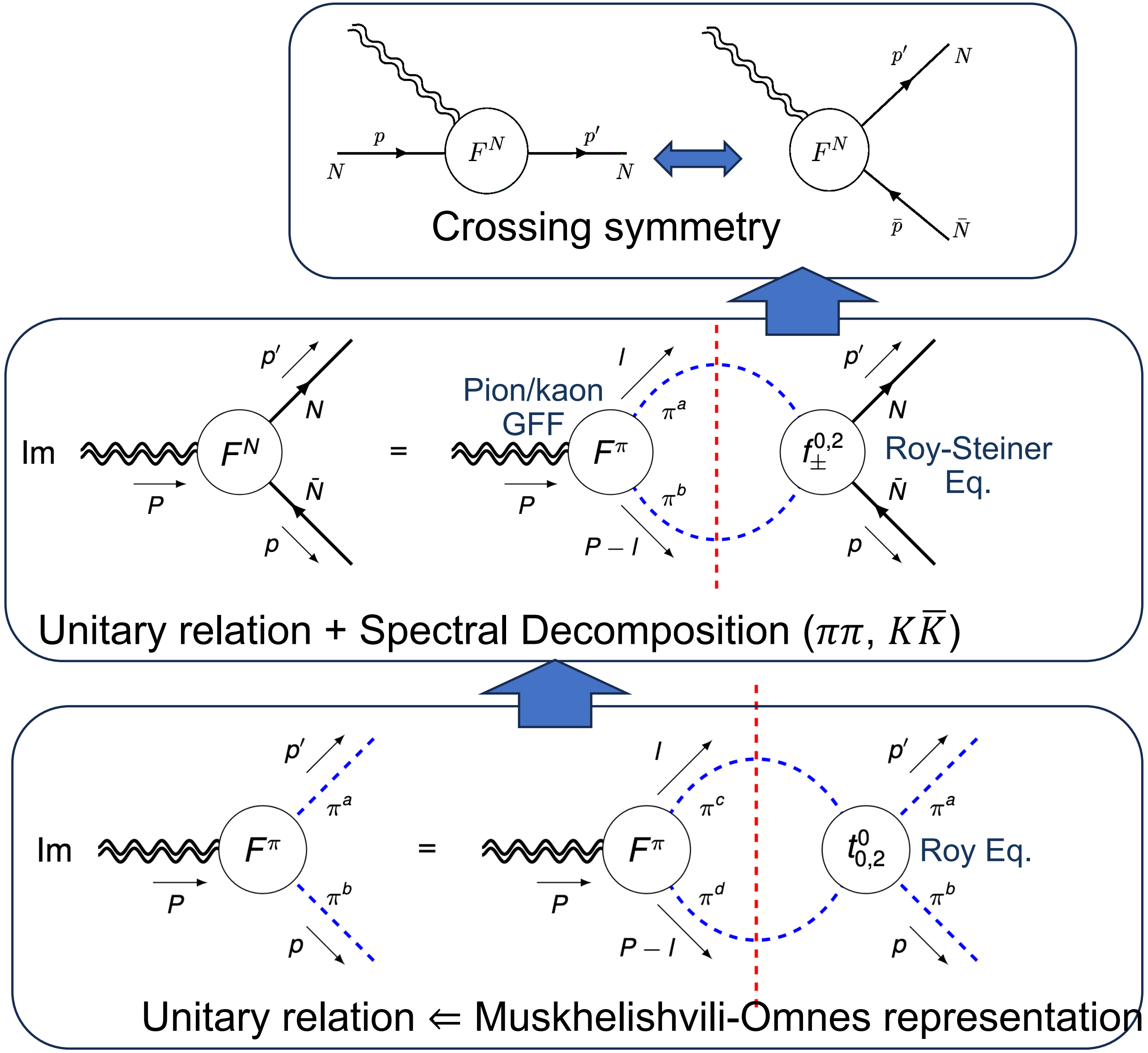
$$F(t) = \frac{1}{\pi}\int_{t_0}^{\infty} \frac{ImF(t')}{t'-t}$$



- Dispersion relations method
  - ▸ data-driven, less model-dependent
  - ▸ Based on: unitarity, analyticity and crossing symmetry
  - ▸ Connects timelike and spacelike data
- EM form factor:

  M. Hoferichter, et al, EPJA**52**, 331 (2016)
  M. A. Belushkin, et al. PRC **75**, 035202 (2007)
- Input of GFFs
  - ▸ GFFs of pion and kaon in NLO ChPT
  - ▸ $\pi\pi$, πN scattering data

  X.-H. Cao, F.-K. Guo, Q.-Z. Li, and D.-L. Yao, Nature Commun. 16, 6979 (2025).

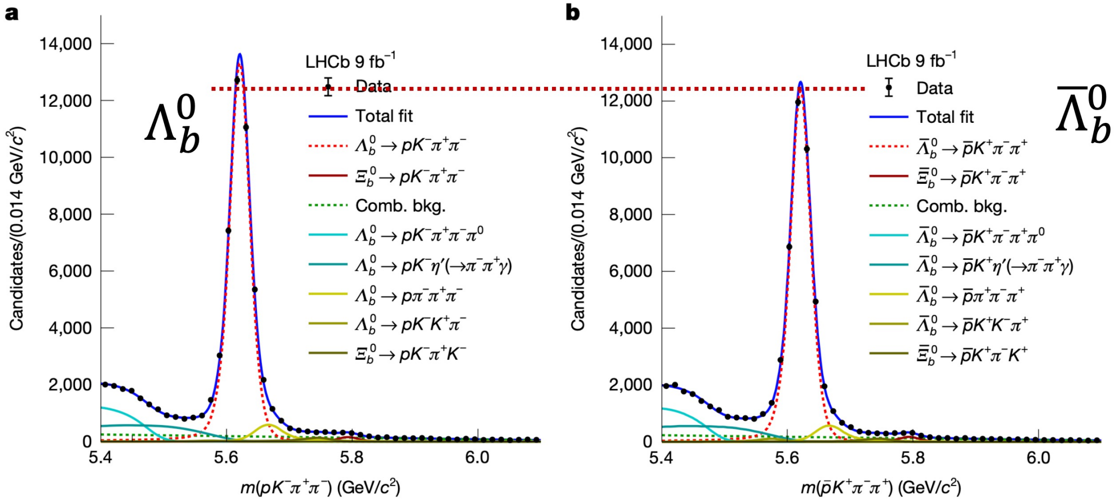


First observation of CP violation in baryons

- $\Lambda_b^0 \to pK^-\pi^+\pi^-$ decay: CP violations

LHCb, Nature 643, 1223 (2025).

$$A_{CP} = (2.45 \pm 0.46 \pm 0.10)\%, \ \ 5.2\sigma \text{ from zero}$$



Decay topology	Mass region (GeV/c^2)	$\mathcal{A}_{CP}$
$\Lambda_b^0 \to R(pK^-)R(\pi^+\pi^-)$	$m_{pK^-} < 2.2$ $m_{\pi^+\pi^-} < 1.1$	$(5.3 \pm 1.3 \pm 0.2)\%$
$\Lambda_b^0 \to R(p\pi^-)R(K^-\pi^+)$	$m_{p\pi^-} < 1.7$ $0.8 < m_{\pi^+K^-} < 1.0$ or $1.1 < m_{\pi^+K^-} < 1.6$	$(2.7 \pm 0.8 \pm 0.1)\%$
$\Lambda_b^0 \to R(p\pi^+\pi^-)K^-$	$m_{p\pi^+\pi^-} < 2.7$	$(5.4 \pm 0.9 \pm 0.1)\%$
$\Lambda_b^0 \to R(K^-\pi^+\pi^-)p$	$m_{K^-\pi^+\pi^-} < 2.0$	$(2.0 \pm 1.2 \pm 0.3)\%$

"Specific intermediate resonances play a key role"

- Theoretical works

S.-J. Wen, W.-C. Fu, and D. Wang, EPJC**86**, 338 (2026).
Y.-K. Hsiao, K.-L. Wang, and J. Wang, arXiv:2606.08248
Z.-D. Duan, T.-L. Feng, R.-H. Li, M.-Z. Liu, J.-P. Wang, and F.-S. Yu, arXiv:2602.03661
X.-G. He, C.-W. Liu, and J. Tandean, PRD **112**, L111302 (2025).
J.-J. Han, J.-X. Yu, Y. Li, H. Li, J.-P. Wang, Z.-J. Xiao, and F.-S. Yu, PRL**134**, 221801 (2025).
Z.-D. Duan, J.-P. Wang, R.-H. Li, C.-D. Lü, and F.-S. Yu, JHEP **09**, 160 (2025).
Q. Chen, X. Wu, Z.-P. Xing, and R. Zhu, PRD **112**, 033010 (2025).
J.-P. Wang, Q. Qin, and F.-S. Yu, arXiv:2411.18323 [hep-ph] (2024).
…

Final-state interaction in CPV

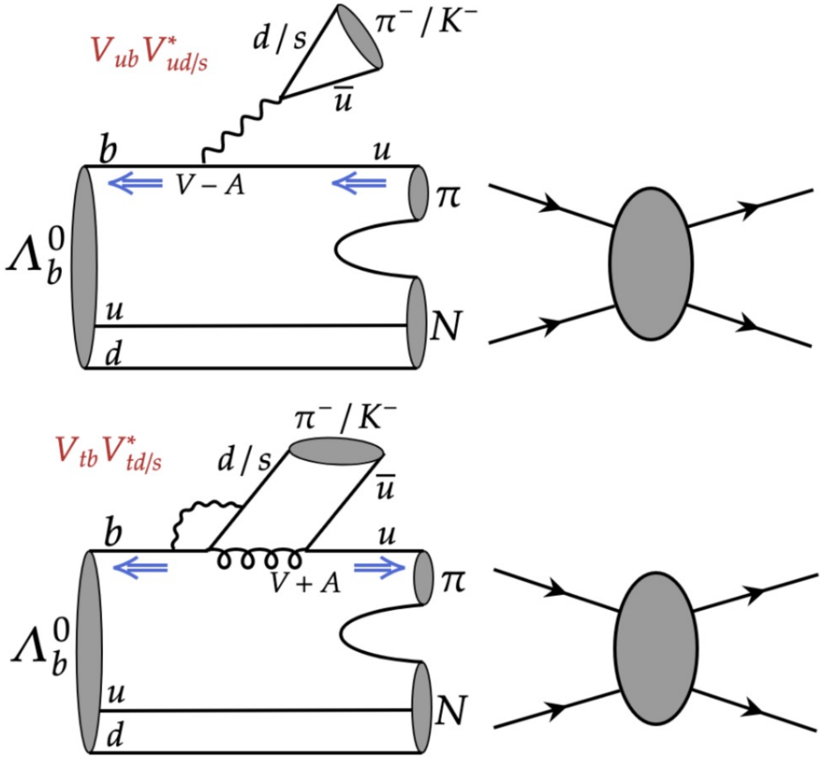
- CP violation $B \to K\pi^+\pi^-$: kaon-pion scattering
  - ► Muskhelishvili-Omnes Eq. with experimental pion-kion scattering data

B. El-Bennich, A. Furman, R. Kamiński, L. Leśniak, B. Loiseau, and B. Moussallam, PRD**79**, 094005 (2009).

- For baryon

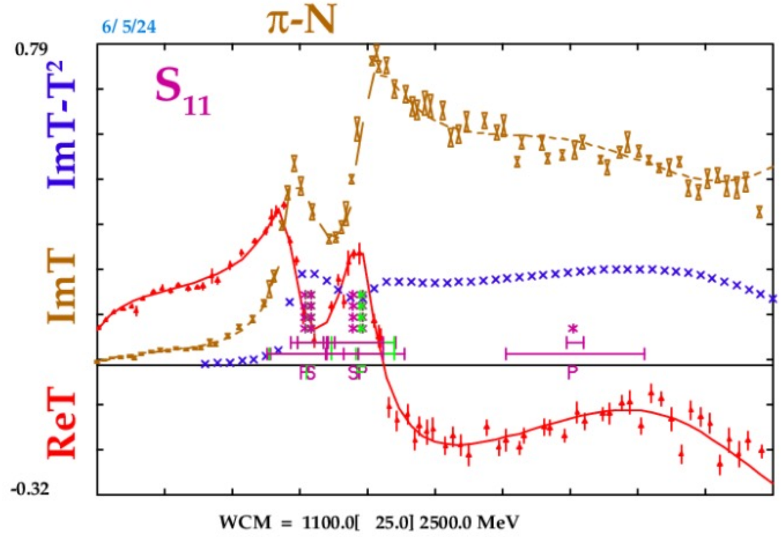
Tree

Penguin



Short distance week decays

Long distance $N\pi \to N\pi$ and $N\pi \to \Delta\pi$

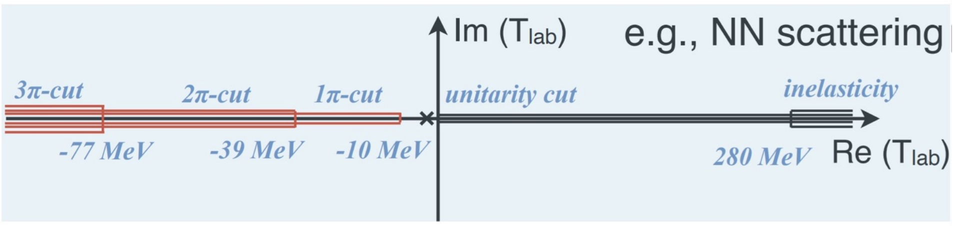


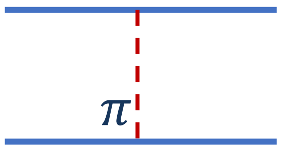
Partial wave amplitude from πN scattering data
https://gwdac.phys.gwu.edu/

J.-P. Wang and F.-S. Yu, CPC**48**, 101002 (2024)

Left-hand cut problems

- Left-hand cut (lhc): **long-range interactions**



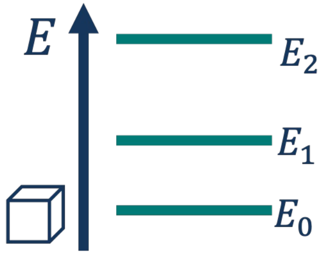


Left-hand cut
on-shell pion

- lhc problem in effective range expansion (ERE)

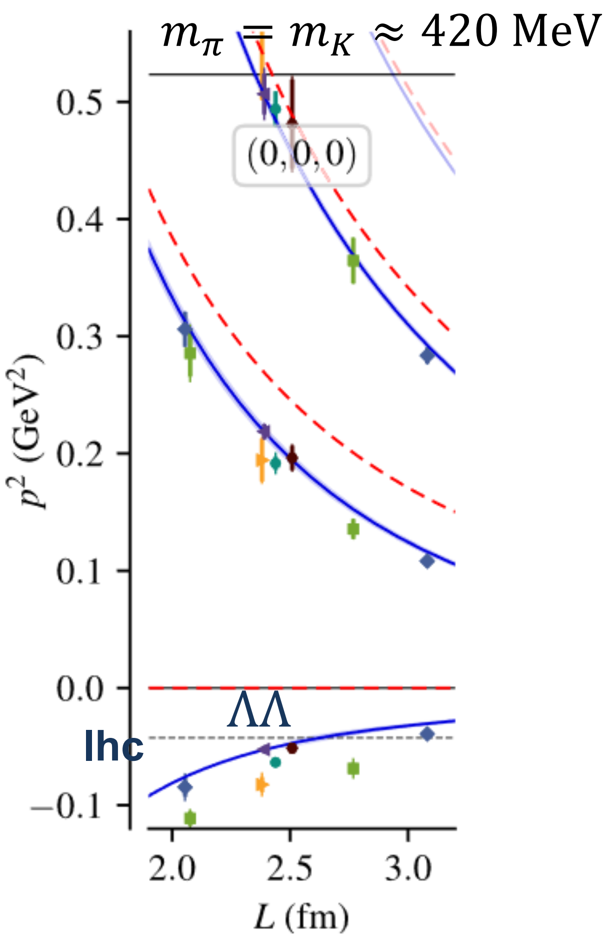
$$K^{-1}(p) = p\cot\delta(p) = \frac{1}{a} + \frac{1}{2} r p^2 + \cdots$$

- lhc problem in Lüscher formula

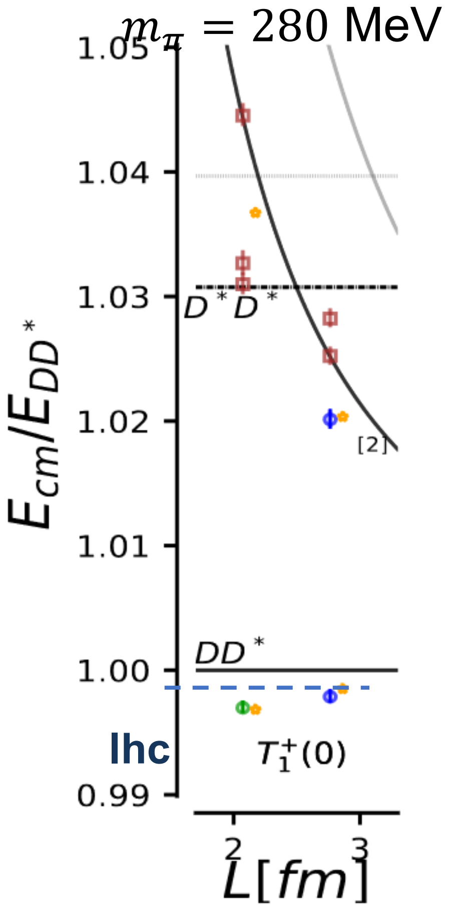


Lüscher 公式

H-dibaryons ($udsuds$)



DD^* (T_{cc})

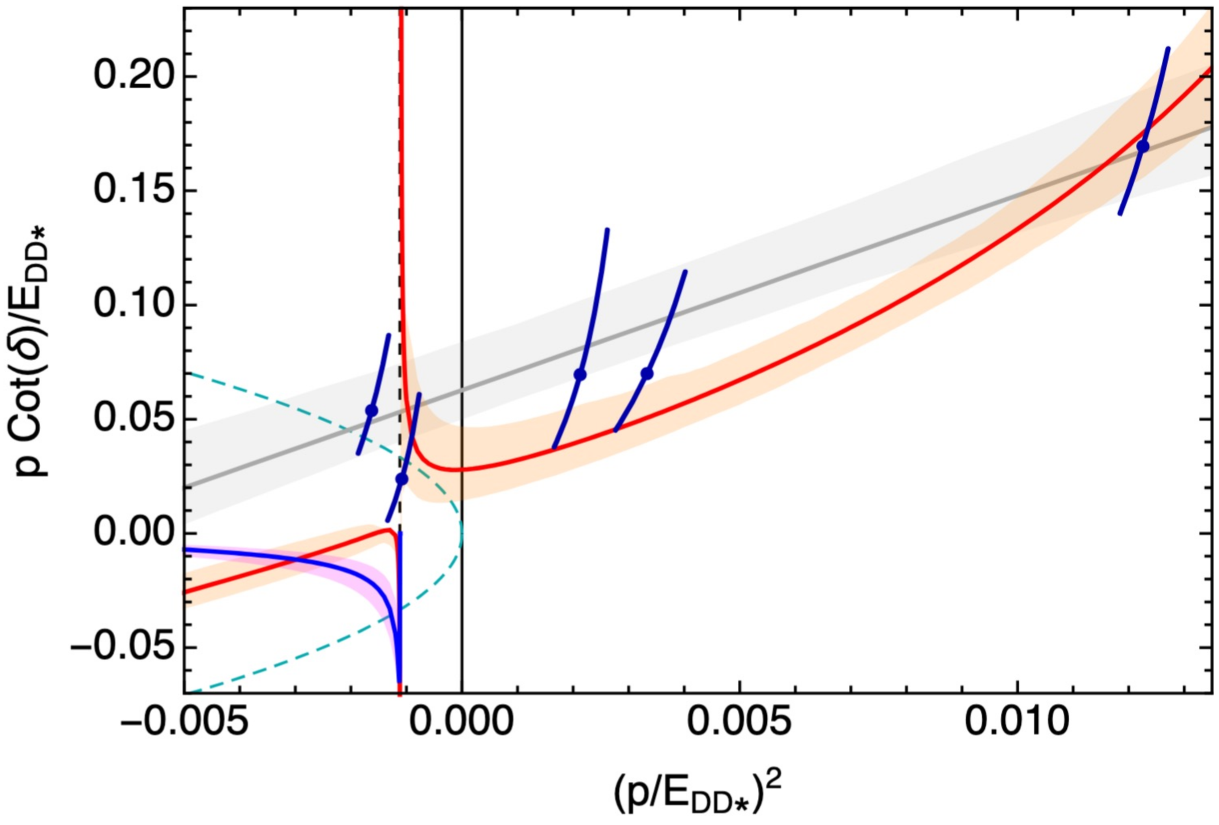


J.R. Green, PRL127 (2021) 24, 242003
M.Padmanath, PRL129 (2022) 3, 032002

lhc problem in ERE

- Point out their lhc problem in ERE
- Solve this problem in chiral EFT

M.-L. Du, A. Filin, V. Baru, X.-K. Dong, E. Epelbaum, F.-K. Guo, C. Hanhart, A. Nefediev, J. Nieves, and Q. Wang, PRL**131**, 131903 (2023)



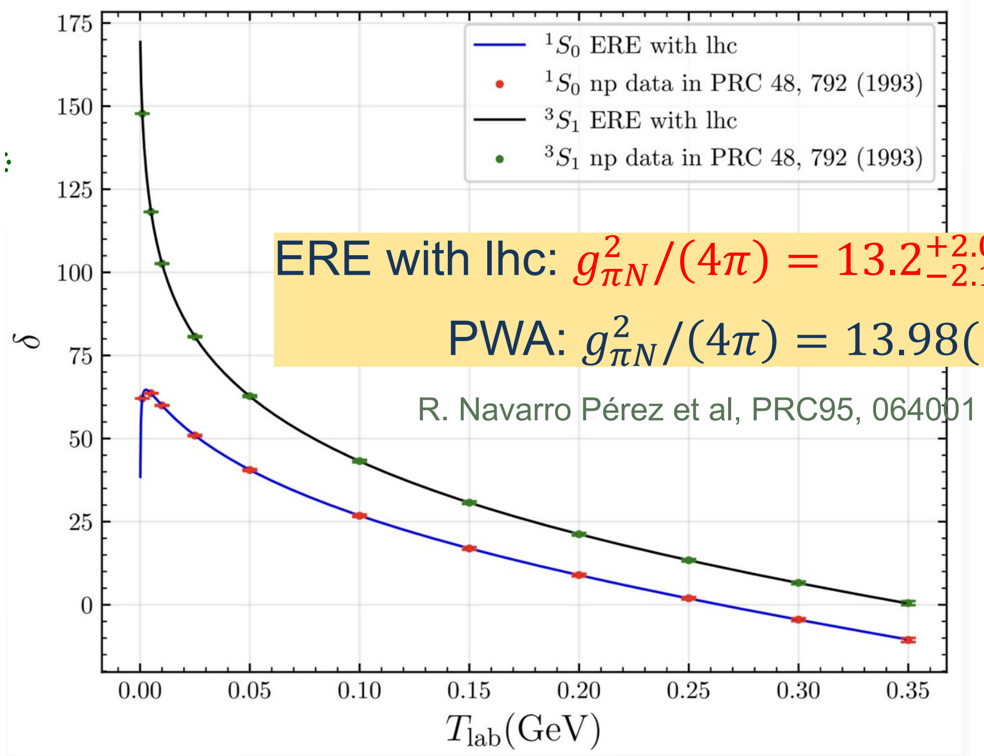
- Extend the ERE with left-hand cut

$$f_{[0,1]}(k^2) = \left[\frac{\tilde{d}_0 + \tilde{d}_1 k^2 - \tilde{g} d^{\mathrm{R}}(k^2)}{1 + \tilde{g}(L(k^2) - L_0)} - ik\right]^{-1}$$

M.-L. Du, F.-K. Guo, and B. Wu, PRL**135**, 011903 (2025).

- Application in NN system

B.-Y. Liu, B. Wu, J.-W. Fu, M.-L. Du, F.-K. Guo, and U.-G. Meißner, arXiv:2602.03115



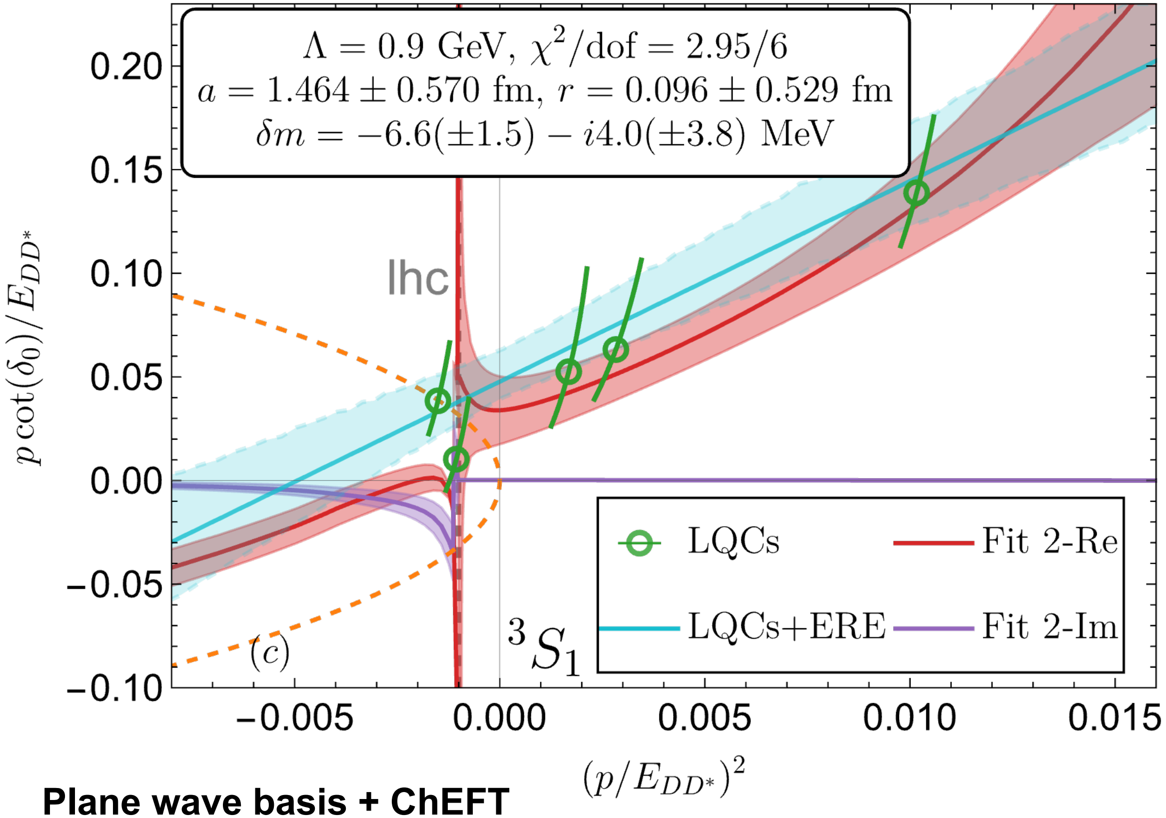
ERE with lhc: $g_{\pi N}^2/(4\pi) = 13.2^{+2.0}_{-2.1}$

PWA: $g_{\pi N}^2/(4\pi) = 13.98(11)$

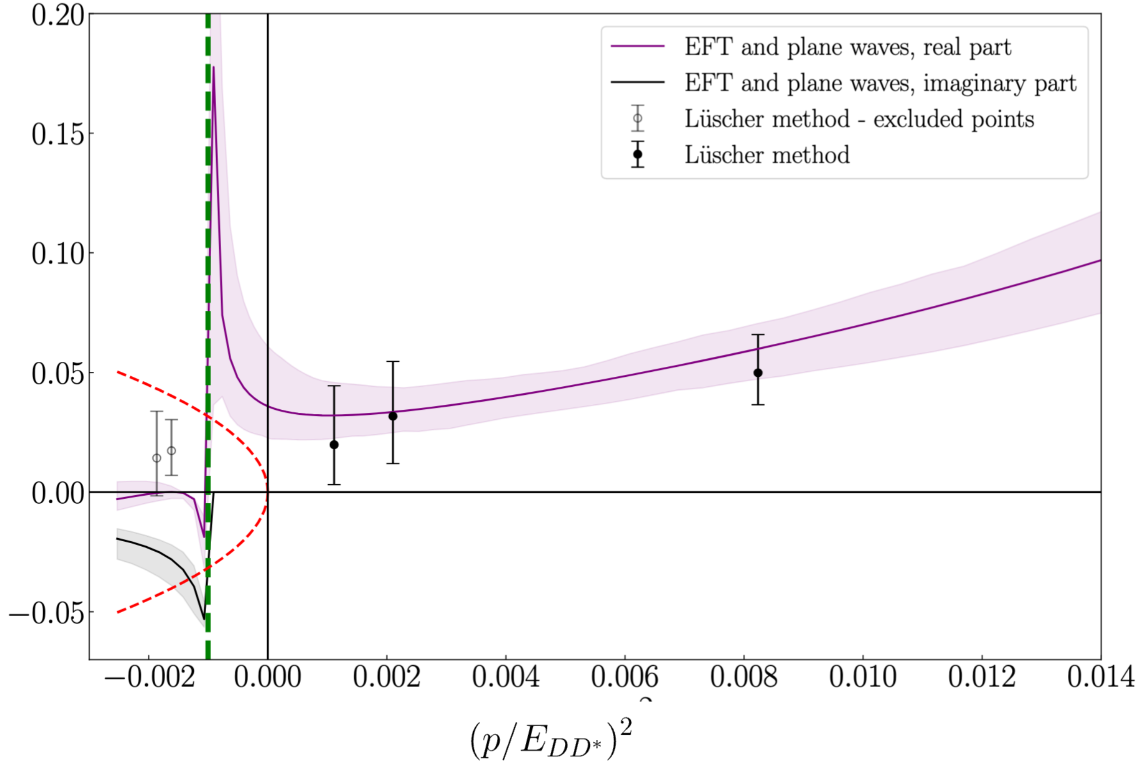
R. Navarro Pérez et al, PRC95, 064001 (2017)

lhc problem in Lüscher formula

L. Meng, V. Baru,et al, PRD**109**, L071506 (2024)



S. Prelovsek,et al, PRD**112**, 014507 (2025)



Plane wave basis + ChEFT

LM, V. Baru,et al, PRD**109**, L071506 (2024)
S. Prelovsek,et al, PRD**112**, 014507 (2025)
K. Yu, G.-J. Wang, J.-J. Wu, and Z. Yang, JHEP **04**, 108 (2025)

Modified ERE

R. Bubna, H.-W. Hammer, F. Müller, J.-Y. Pang, A. Rusetsky, and J.-J. Wu, JHEP **05**, 168 (2024)

Relativistic field theory & three-body formalism

M. T. Hansen, F. Romero-López, and S. R. Sharpe, JHEP **06**, 051 (2024)
B. Raposo and M. T. Hansen, JHEP **08**, 075 (2024)

N/D

S. M. Dawid, A. W. Jackura, and A. P. Szczepaniak, PLB **864**,

See Hao-Bo Yan’s talk for 3-body resonance

Talks and Posters in Flavor & Hadron Physics (th.)

- Talks: 22

杜勇	Flavor-Spin Entanglement and the Weak Phase Extraction in $\Lambda_b \to \Lambda D$	徐吉	Proposal for searching nucleon momentum distribution at electron-positron collider
柴健	Polarization fractions and helicity-dependent CP asymmetries in B(s)→ ρρ, ρK^* and K^*K^* decays	张文超	J/ψ and exotic hadron productions in high energy nuclear collisions with the parton and hadron cascade model PACIAE
张其安	核子自旋结构的第一性原理研究	白秋茹	J/ψ Production and Fragmentation Inside Jets in Proton-Proton Collisions
孙鹏	PDF @ lattice QCD	杨永亮	The single asymmetry $A_{UUT}^{\sin\phi_\Lambda}$at semi-inclusive DIS within collinear framework
王翔鹏	Gradient Flow in Heavy Flavor Physics	郑绪昌	Fragmentation functions for production of P-wave Bc mesons
杨科	Three-dimensional helicity distribution functions and EicC projections	肖楮文	Study of the Pc and Pcs states
刘明珠	三体强子分子态及三体力的研究	任修磊	基于时序微扰理论的手征介子-重子与重子-重子相互作用研究
姬尧	Recent theoretical progress in the study of Generalized Parton Distributions	黄卓然	Revising the mass of light hybrid mesons: NLO QCD sum rules point to ϕ(2170) as a prime candidate
张志清	Semi-leptonic B decays to tensor mesons	邵鼎煜	New Perspectives on Precision Nucleon Tomography
华俊	Toward a Unified Understanding of Hadron Light-Cone Distribution Amplitudes from Lattice QCD	燕浩波	Multi-Hadron Scattering in Lattice Quantum Chromodynamics
魏焰冰	B-meson LCDA and power corrections	刘晓辉	Spin Asymmetry from Charge and Angle Alone

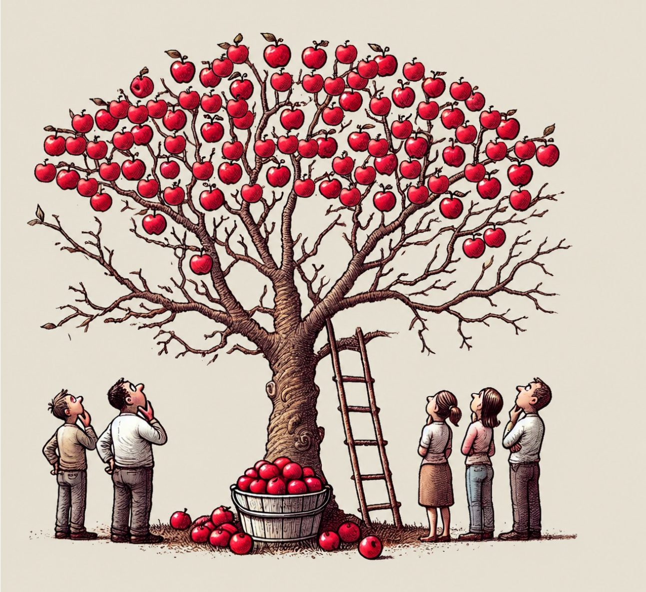
- 晨光杯: 5

曹雄辉	Dispersive determination of nucleon gravitational form factors
韩佳杰	Establishing CP violation in b-baryon decays
沈宏飞	Strong and Weak CP Tests in Sequential Decays of Polarized Σ^0 Hyperons
燕浩波	1. ω Meson from Lattice QCD 2. Emergence of the πð1300Þ Resonance from Lattice QCD
赵晓燕	Suppression of Spin Transfer to Λ Hyperon in Deep-Inelastic Scattering

- Posters： 14

Summary and Outlook

- Thanks to all the experimentalists
  - ▶ For interesting Exp. results
- Many notable advances in flavor & hadron physics theory
- Several long-standing questions remain unresolved and require further effort
- AI-assisted research will become more popular
  - ▶ How to use AI?
  - ▶ How will AI reshape the way we conduct research?
  - ▶ …
- More breakthroughs are anticipated in the coming years



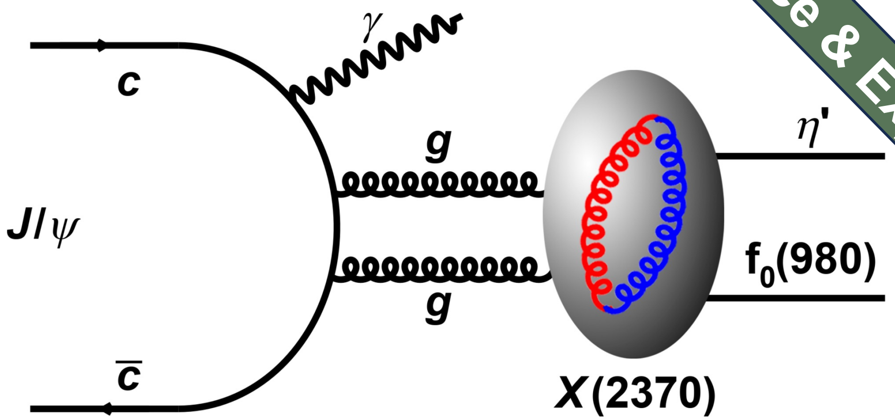
Low-hanging fruit

Thanks for your attentions!

Backup

Glueball-like state X(2370)

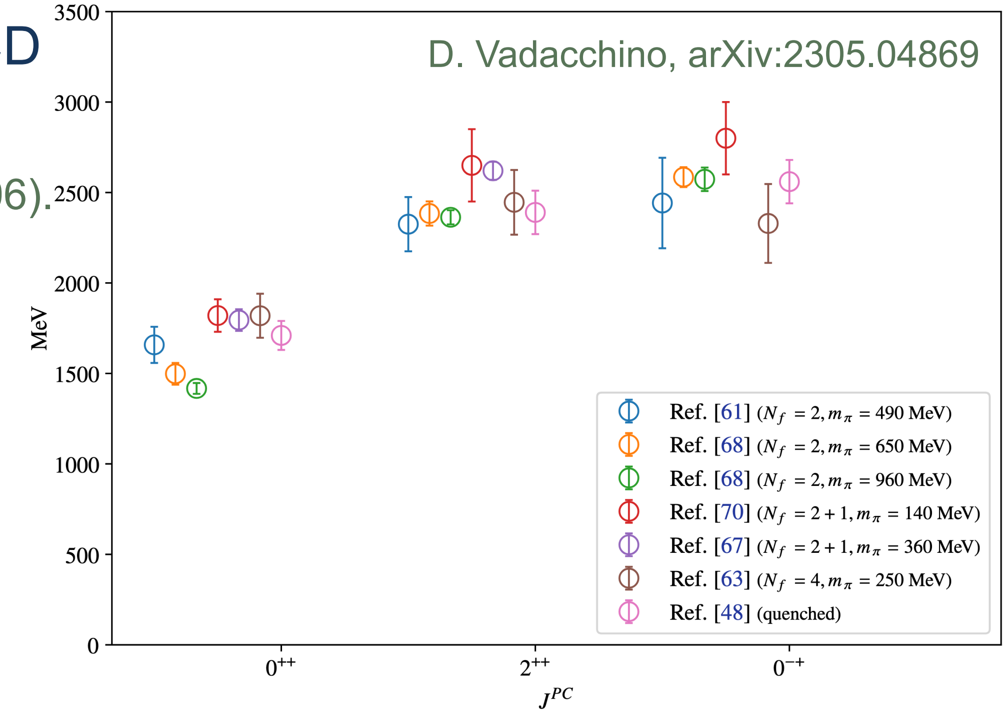
- X(2370): Determine $J^{PC} = 0^{-+}$ from $J/\psi \to \gamma K_S^0 K_S^0 \eta'$
  BESIII, PRL132, 181901 (2024)
- Earlier observation in $J/\psi \to \gamma \pi^0 \pi^0 \eta'$
  BESIII, PRL106, 072002 (2011)   see Y.-P Huang's talk
- Observations in $J/\psi \to \gamma K_S^0 K_S^0 \pi^0$ and $J/\psi \to \gamma \pi^0 \pi^0 \eta$
  - ▶ Similar decay modes with η_c
  BESIII, 2605.26495
- Gluon rich environment



Y.-P. Huang, S. Jin, and P. Zhang, Int.J.Mod.Phys.A 40 (2025) 19, 2530007

- Mass consistent with lightest 0^{-+} glueball from lattice QCD
  - ▶ Glueball spectrum: long history in lattice QCD

  Y. Chen, A. Alexandru, S. J. Dong, and others, PRD 73, 014516 (2006).
  C. Morningstar, Update on Glueballs, Lattice2024

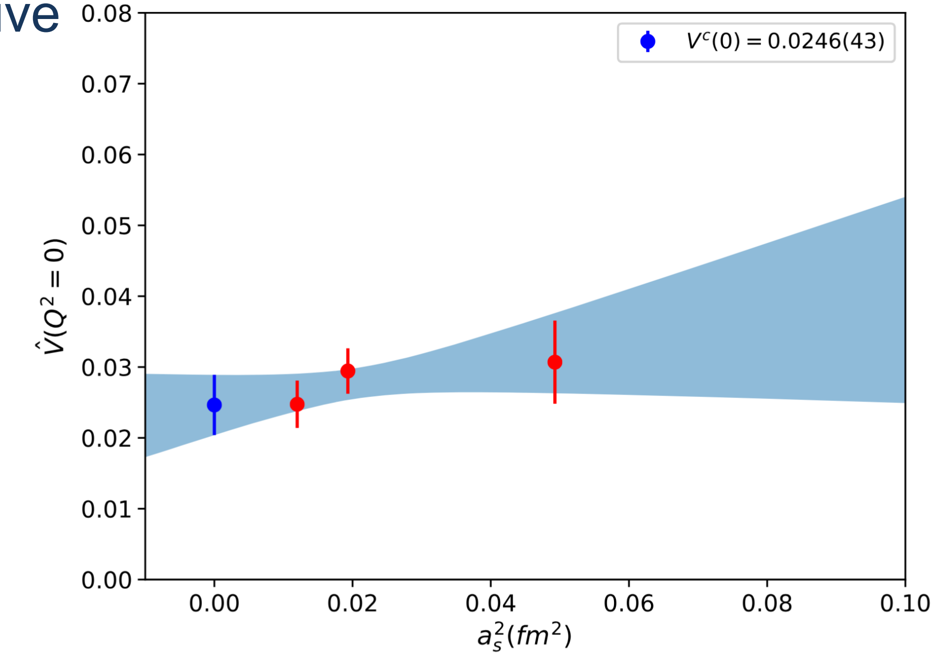


- Related theoretical works

  J. Cao, Z.-L. She, J.-P. Zhang, and others, PRD**110**, 054046 (2024).
  H. Li, CPL**41**, 101101 (2024).
  X.-T. Li, G.-Y. Wang, and Q.-A. Zhang, EPJC**85**, 365 (2025).
  Q.-N. Wang, D.-K. Lian, and W. Chen, PRD**112**, 034010 (2025).
  …

Glueball at lattice

- Comprehensive lattice calculations： challenging and expensive
  - ▶ Unquenched
  - ▶ Nearly physical pion mass
  - ▶ Operator basis: gluonic operator + $q\bar{q}$ + multi-hadron
  - ▶ Using Lüscher formula extract mass and width from finite volume energy levels
- Pseudoscalar glueball at lattice
  - ▶ quenched approximation
  - ▶ anisotropic lattices， $a_s \sim 0.11, 0.14, 0.22$ fm, continuum extrapolation
  - ▶ evaluate EM transition matrix element $\langle G_{0^{-+}} | J^{\mu}_{em} | J/\psi \rangle$, multipole expansion $V(Q^2)$
  - ▶ Evaluate $\Gamma_{J/\psi \to G\gamma}$



$$M_G = 2.395(14)\ \mathrm{GeV}$$

$$\Gamma(J/\psi \to \gamma\eta_c) = 2.47(11)\ \mathrm{keV}.$$

$$\Gamma(J/\psi \to \gamma G_{0^{-+}}) = 0.0215(74)\ \mathrm{keV}$$

$$\mathrm{Br}(J/\psi \to \gamma G_{0^{-+}}) = 2.31(80) \times 10^{-4}.$$

L.-C. Gui, J.-M. Dong, Y. Chen, and Y.-B. Yang, PRD**100**, 054511 (2019).

M = 2395 ±11$^{+26}_{-94}$ MeV

Γ = 188$^{+18}_{-17}$$^{+124}_{-33}$ MeV

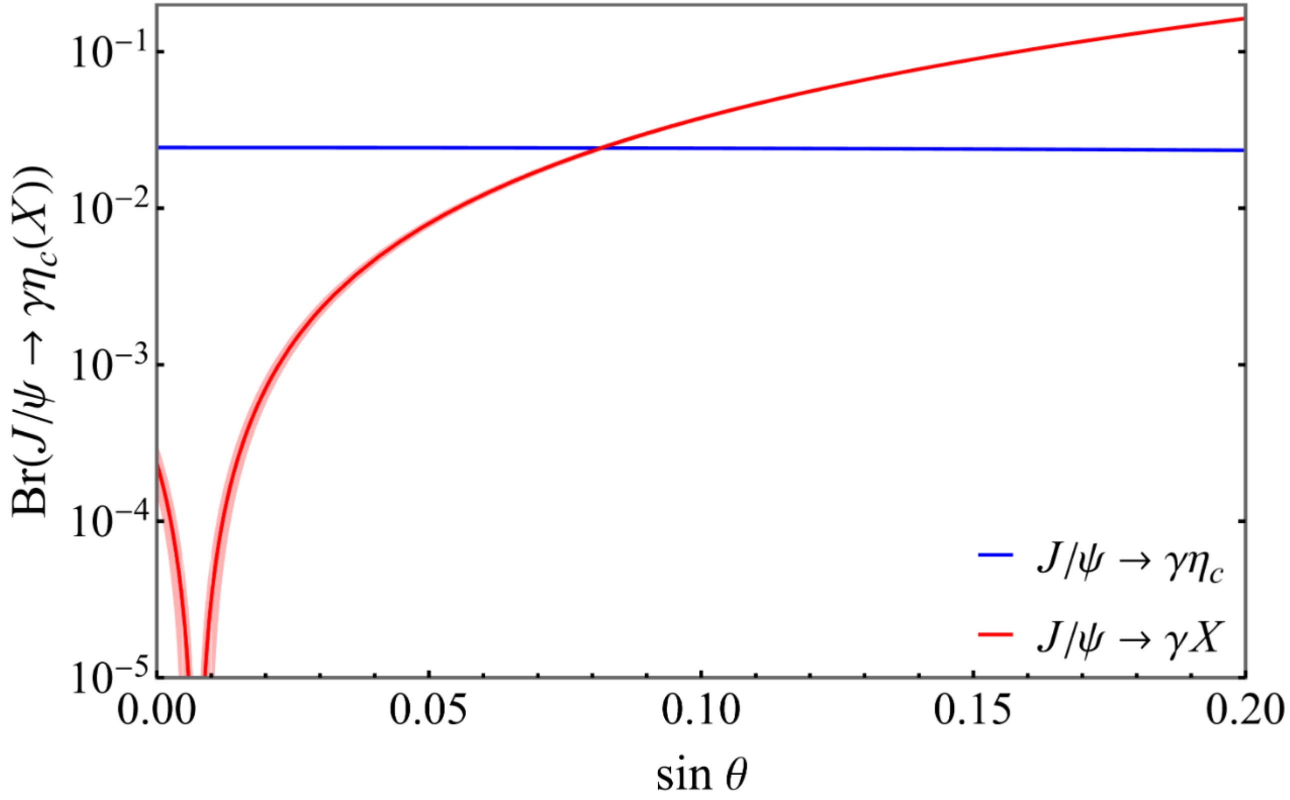
B(J/ψ→γX(2370))B(X(2370)→f_0(980)η')B(f_0(980)→$K^0_SK^0_S$)

= 1.31 ± 0.22$^{+2.85}_{-0.84}$ ×10^{-5}

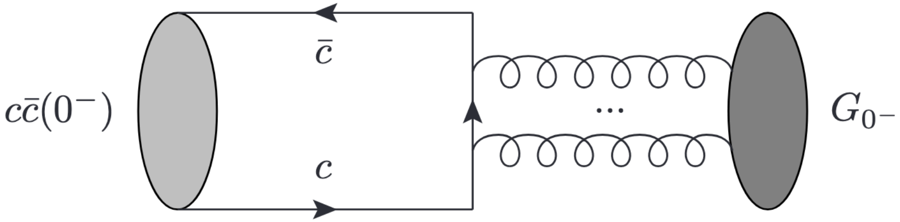
η_c and $G_{0^{-+}}$ **mixture**

- $\mathrm{X(2370)}$ as the mixture of η_c and $G_{0^{-+}}$
  - ▶ Lattice simulations
  - ▶ Pheno. researches

R. Zhang, W. Sun, Y. Chen, M. Gong, L.-C. Gui, and Z. Liu, PLB**827**, 136960 (2022)
Y. Chen, L.-C. Gui, G. Li, and W. Sun, arXiv:2605.01757



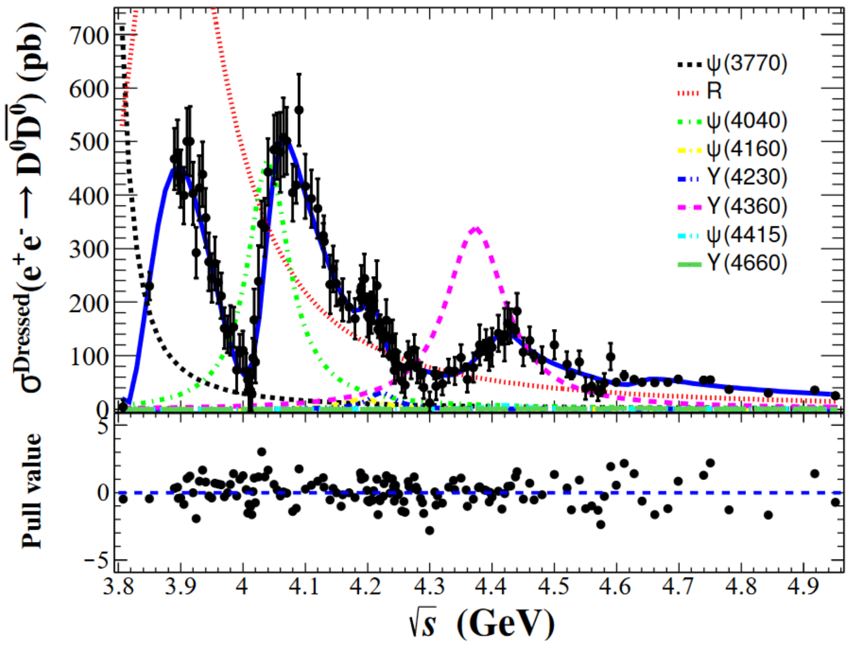
$$\Gamma(J/\psi \to \gamma\eta_c) = 2.47(11)\ \mathrm{keV}.$$
$$\Gamma(J/\psi \to \gamma G_{0^{-+}}) = 0.0215(74)\ \mathrm{keV}$$
$$\mathrm{Br}(J/\psi \to \gamma G_{0^{-+}}) = 2.31(80) \times 10^{-4}.$$

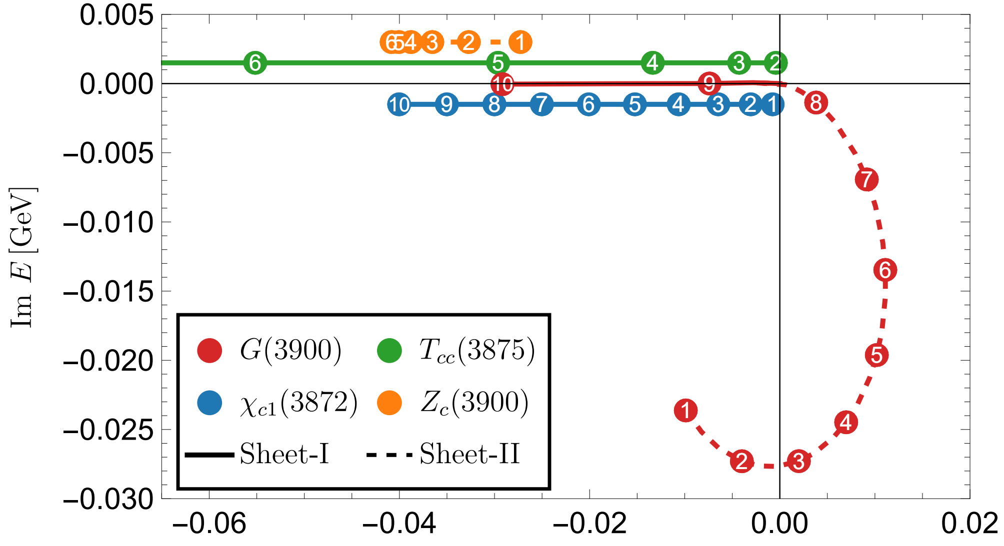


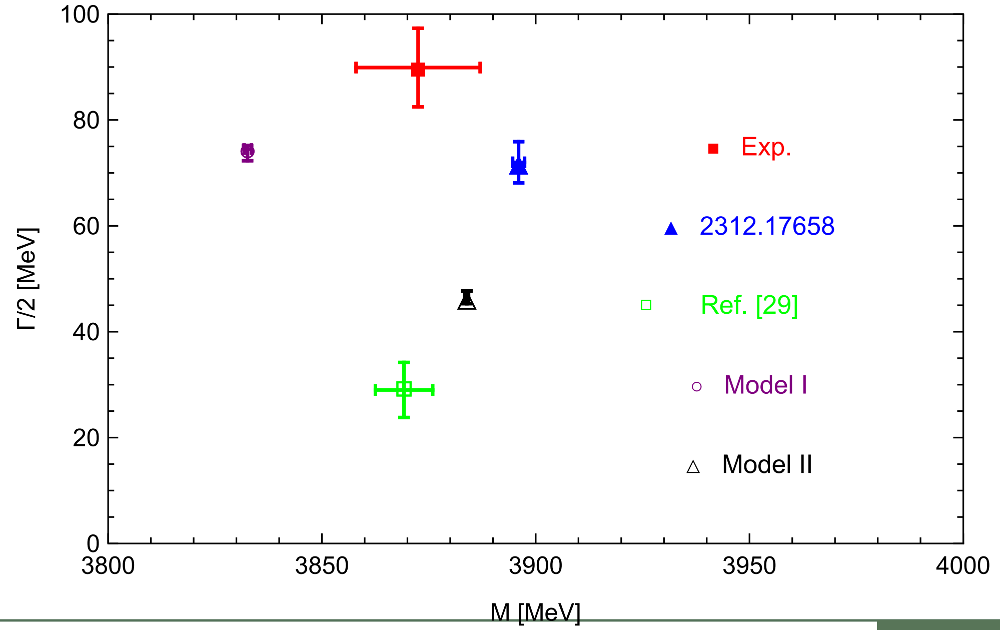
$$\begin{pmatrix} |X\rangle \\ |\eta_c\rangle \end{pmatrix} = \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} |G\rangle \\ |c\bar{c}\rangle \end{pmatrix}$$

- Other work

X. Sun, L.-Y. Dai, S.-Q. Kuang, W. Qin, and A. P. Szczepaniak, PRD**105**, 034010 (2022).
Y.-D. Tsai, H. Li, and Q. Zhao, PRD85, 034002 (2012),
W. Qin, Q. Zhao, and X.-H. Zhong, PRD **97**, 096002 (2018).


ψ(3770)
R
ψ(4040)
ψ(4160)
Y(4230)
Y(4360)
ψ(4415)
Y(4660)
Pull value
√s (GeV)


Im E [GeV]
G(3900)
Tcc(3875)
χc1(3872)
Zc(3900)
Sheet-I
Sheet-II


Exp.
2312.17658
Ref. [29]
Model I
Model II
Γ/2 [MeV]
M [MeV]

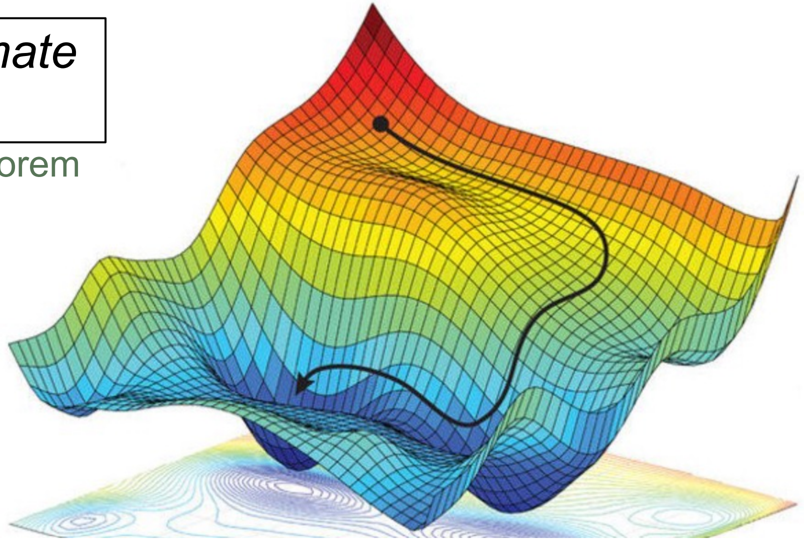
Advantages

- DNNs: approximate high-dimensional functions
  - ▶ **Universal approximation theorems**

sufficiently large or deep

Neural networks with a certain structure can, in principle, approximate ***any continuous function*** *to* ***any desired accuracy***

https://en.wikipedia.org/wiki/Universal_approximation_theorem



  - ▶ Variational principle: the more general the trial function, the more accurate the solution
  - ▶ Unbiasedly distinguish molecular and compact tetraquark states
- VMC: applicable for few-body potential
  - ▶ Flux-tube confinement potential
- Circumvents the sign problem in imaginary time evolution of DMC
- Fast optimization: AD+GPUs
- Easy-to-use open-source frameworks

TensorFlow PyTorch

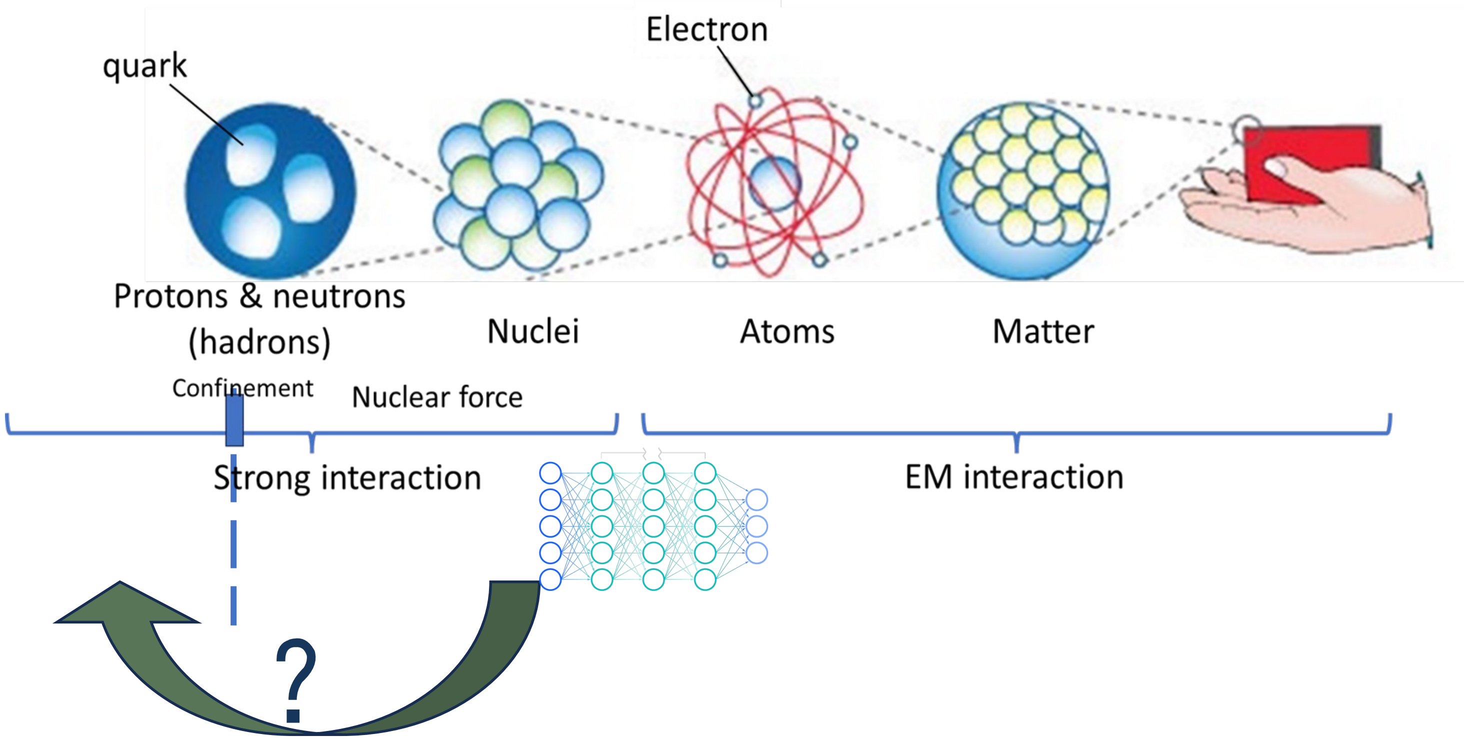
Quark potential models

$$V_{ij}(r) = V_{ij}^{OGE} + V_{ij}^{conf.}$$
$$= \left[\frac{\alpha_s}{r} - \frac{8\pi\alpha_s}{3m_Q^2}\,\tilde{\delta}(\sigma;r)\boldsymbol{S_i}\cdot\boldsymbol{S_j} - \frac{3}{4}br\right]\frac{\lambda_i\cdot\lambda_j}{4}$$

Quark potential model

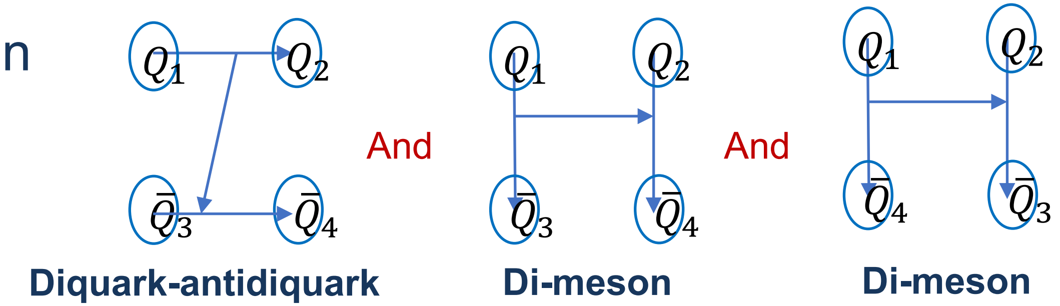
QCD-inspired model

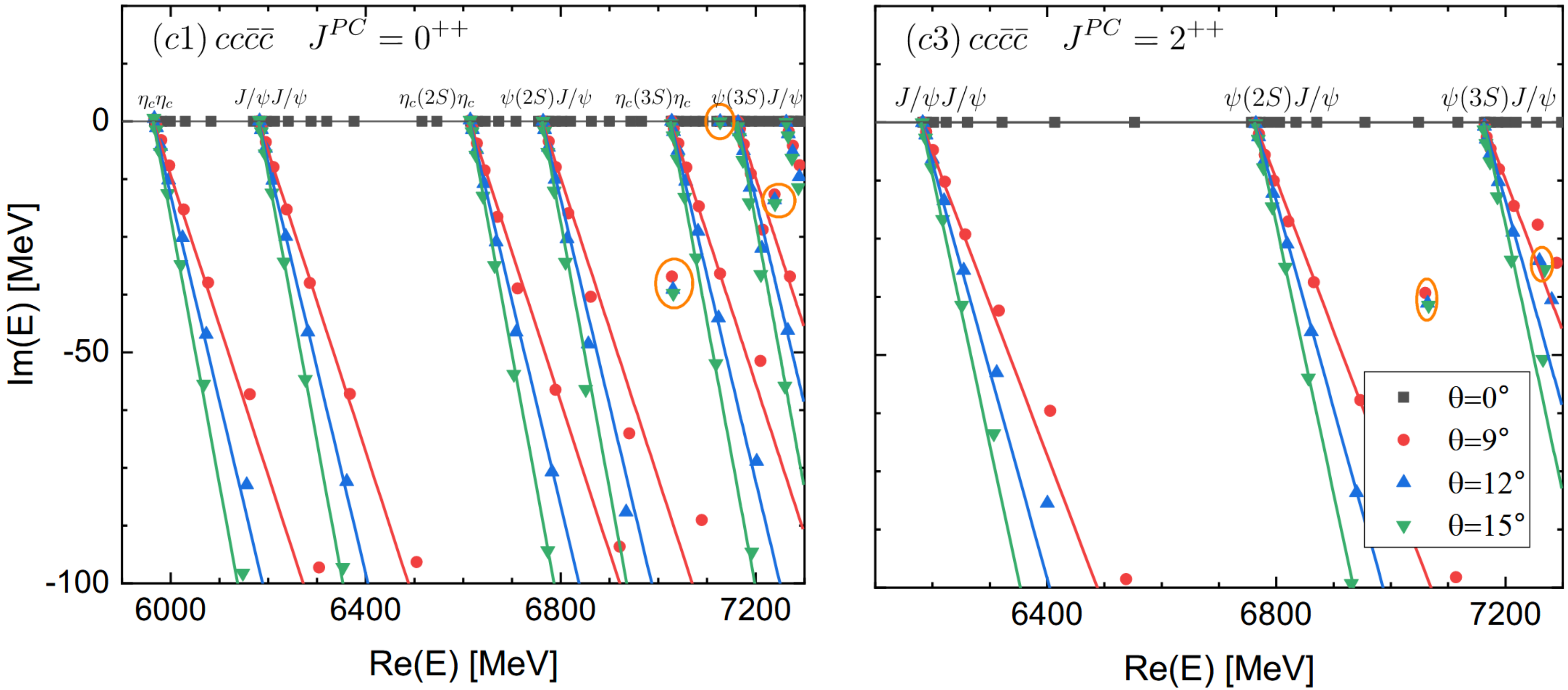
- $SU(3)_c$: color and spin projections
- Confinement
- Strong correlation
- ….



All-charm tetraquarks

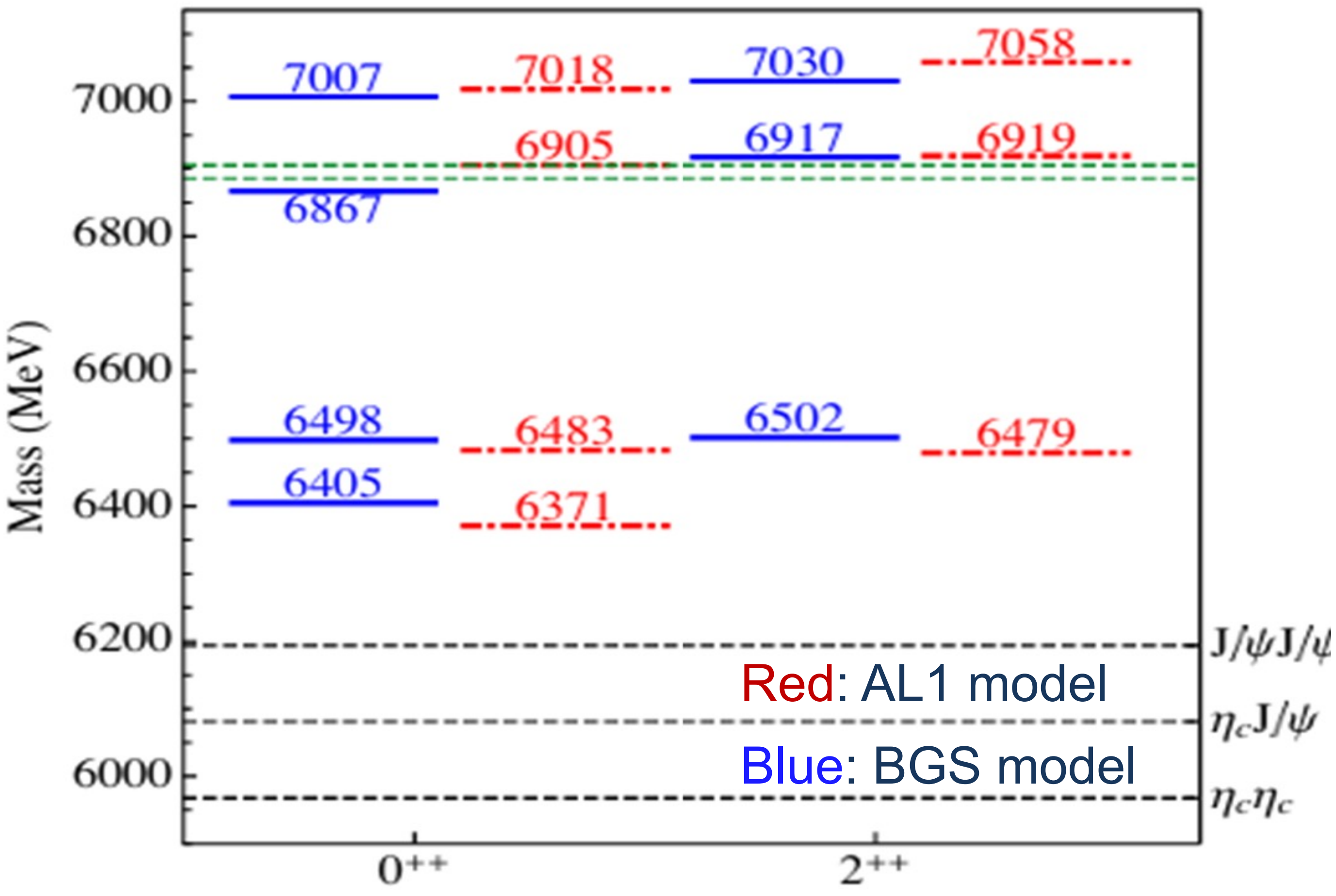
- BGS, AL1, AP1 models: **pairwise** confinement interaction
- Configurations: diquark-antidiquark, di-meson×2
- Tetraquark as resonances

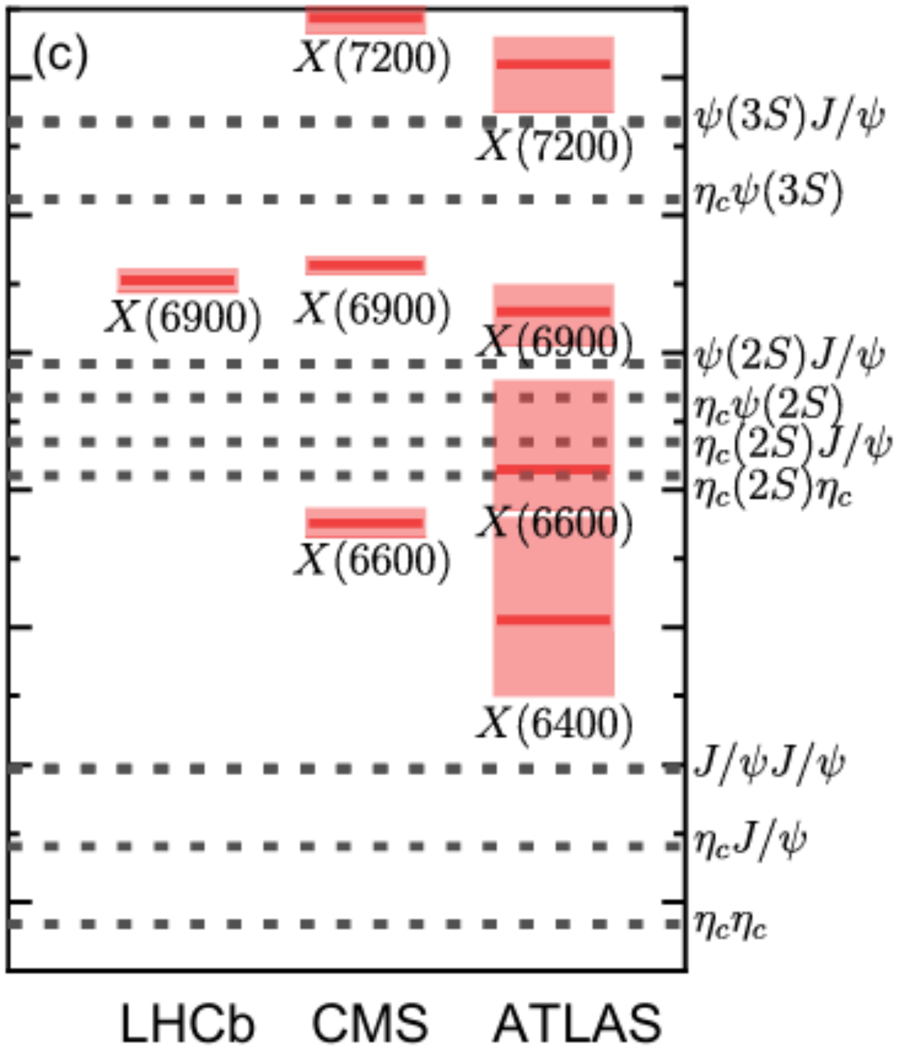




All-charm tetraquarks

- Earlier calculation neglecting di-meson configurations





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- Pairwise model: overestimate the transition between diquark-antidiquark and dimeson??