Recent Progress on Hadron exotics and the interplay with LQCD

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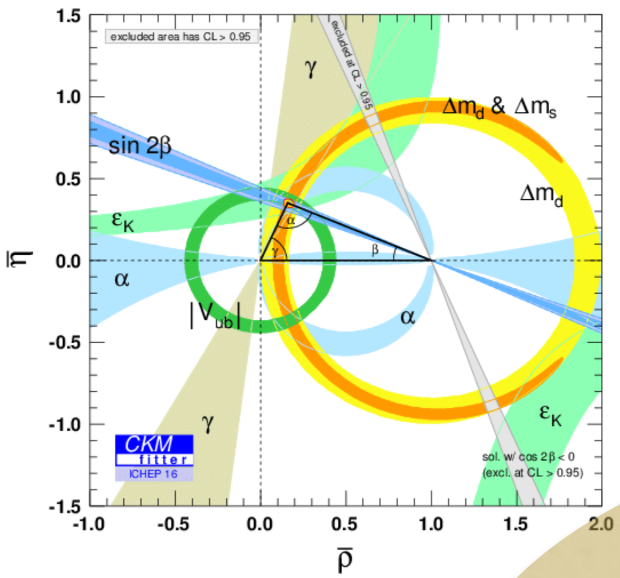
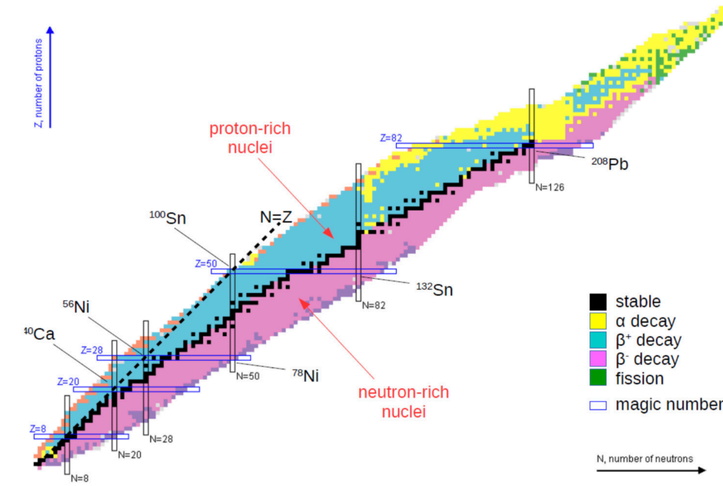
8th Oct. 2022

Hadron physics

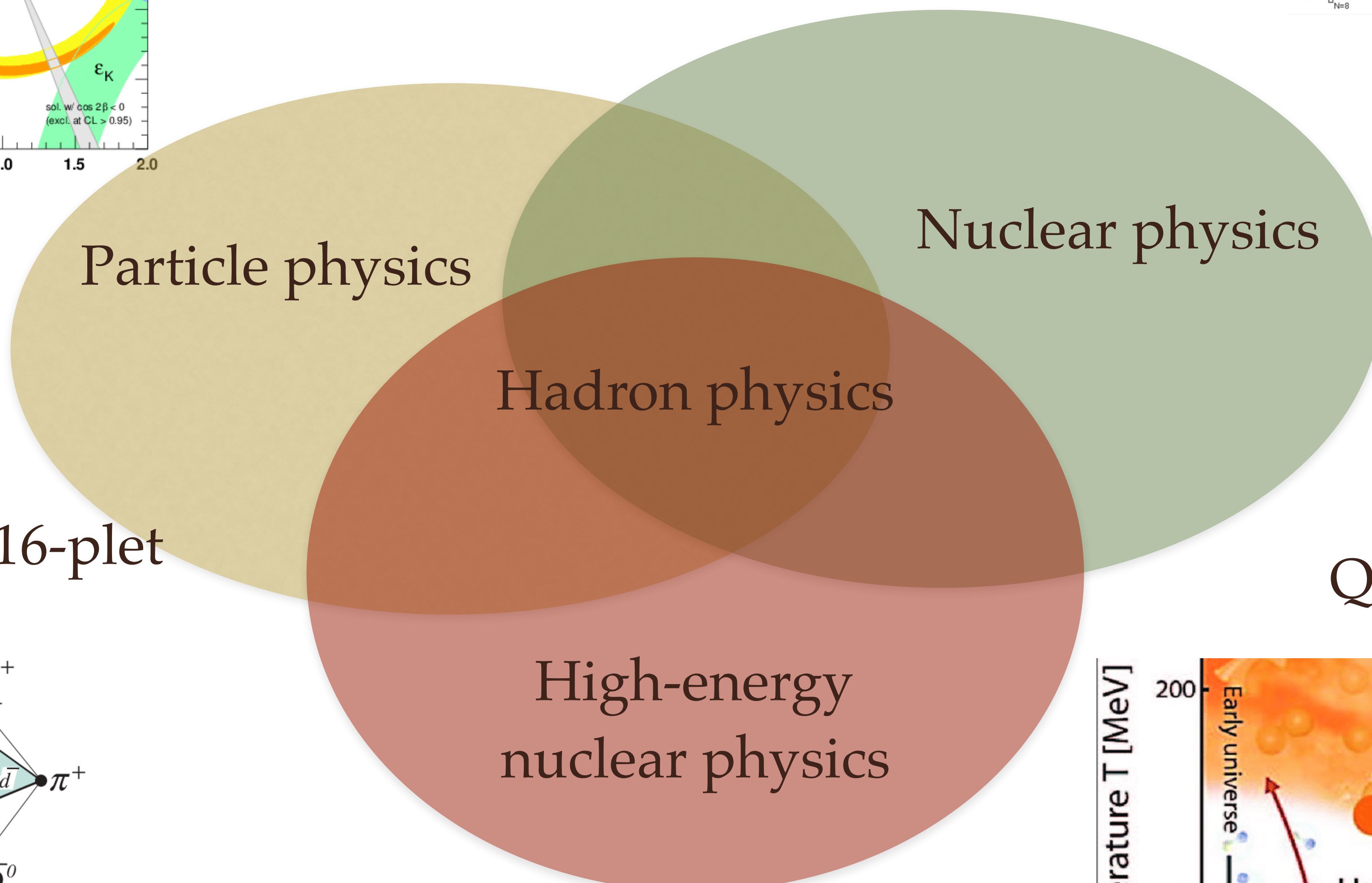
What is hadron physics?



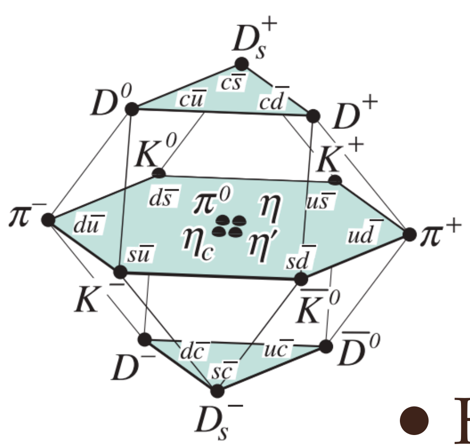
CKM matrix



Nuclide map

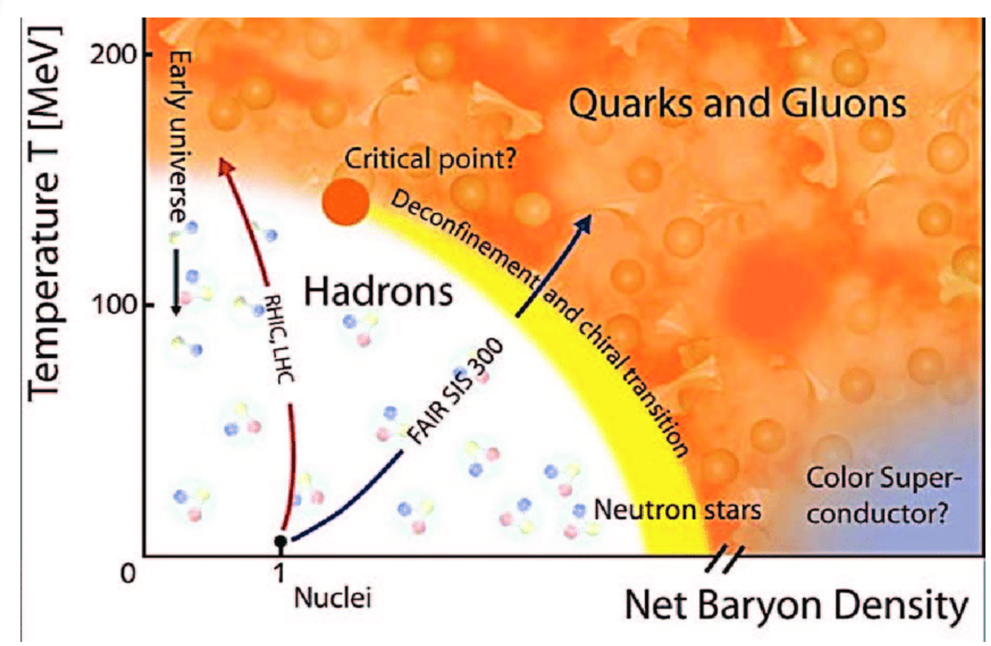


pseudo scalar 16-plet



- Hadron spectrum
- Production rate
- Quantum number
- ……

QCD phase diagram



Hadron physics

The topics

Hadron spectrum

- Search for missing states
- Precise calculation of life time, mass position, …..
- Exotic hadrons' spectrum
- ……

Internal Structure

- Normal hadrons
- Exotic hadrons

Hadron-hadron interaction

- Generated dynamic states
- Final / initial state interaction in hadron decay / production
- Evolution of hadrons in hadron gas
- ……

Hadron physics

The physics

- EM form factor of light hadrons
- PDF of light hadrons

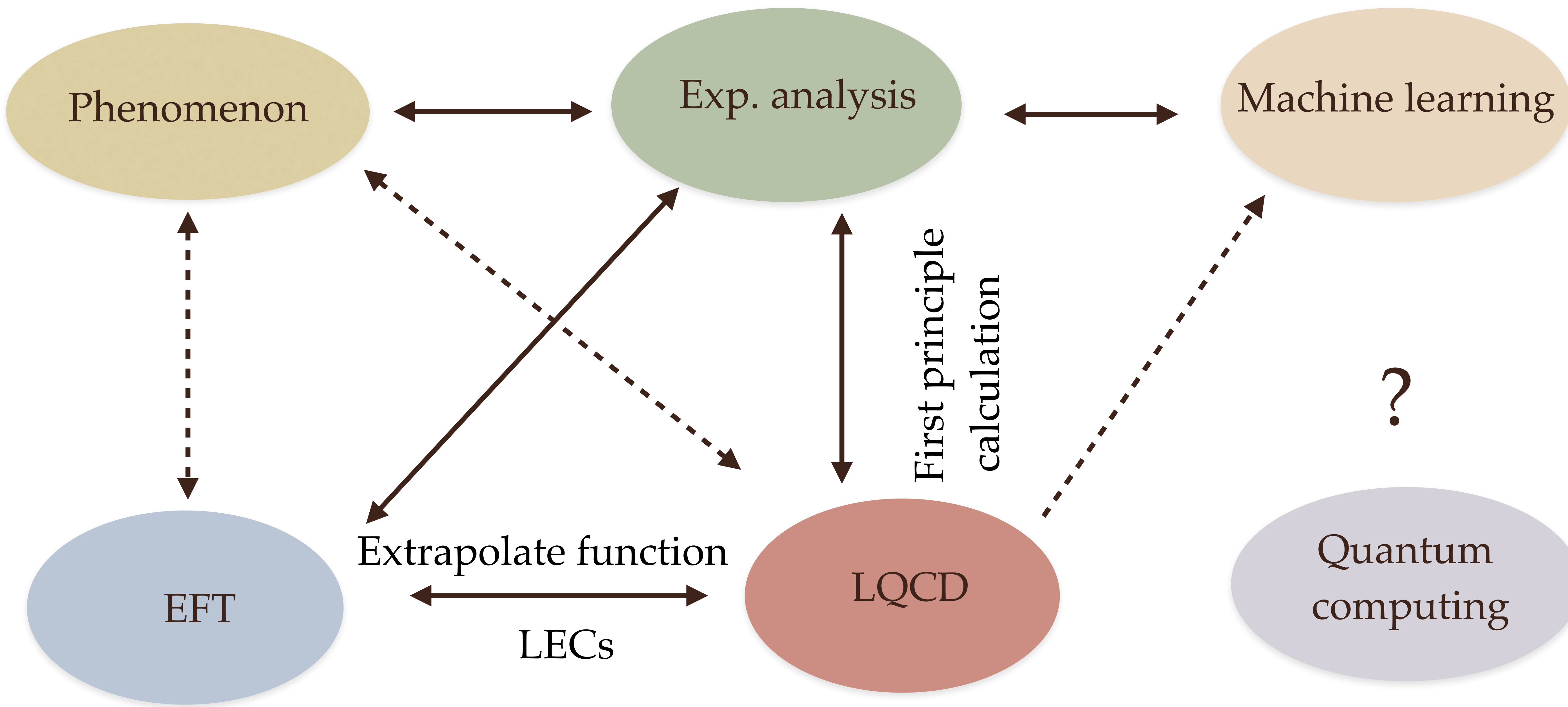
  Talk by Yong Zhao
- The calculation of Fundamental quantity
- Light hadron spectrum
- Electric weak decay of heavy hadrons
- Normal heavy hadrons mass positions and decay
- Glue ball
- Exotic hadrons
- Three-hadron system

  Talk by Jin-Yi Pang
- Double-baryon system
- ……

Hadron physics

The methods

Chen, et.al., 2205.03572,
Liu, et.al., PRD105(2022)076013
Zhang , et.al., CPL in press
Liu, et.al., JHEP08(2022)088
Lu et.al., 2210.02184



Talk by Xiang Dong Ji

路在脚下！

Progress Since 2nd Nov. 2021

Talk by Wen Bin Qian

Light hadron spectrum: $\eta_1(1855)$

BESIII, 2202.00621

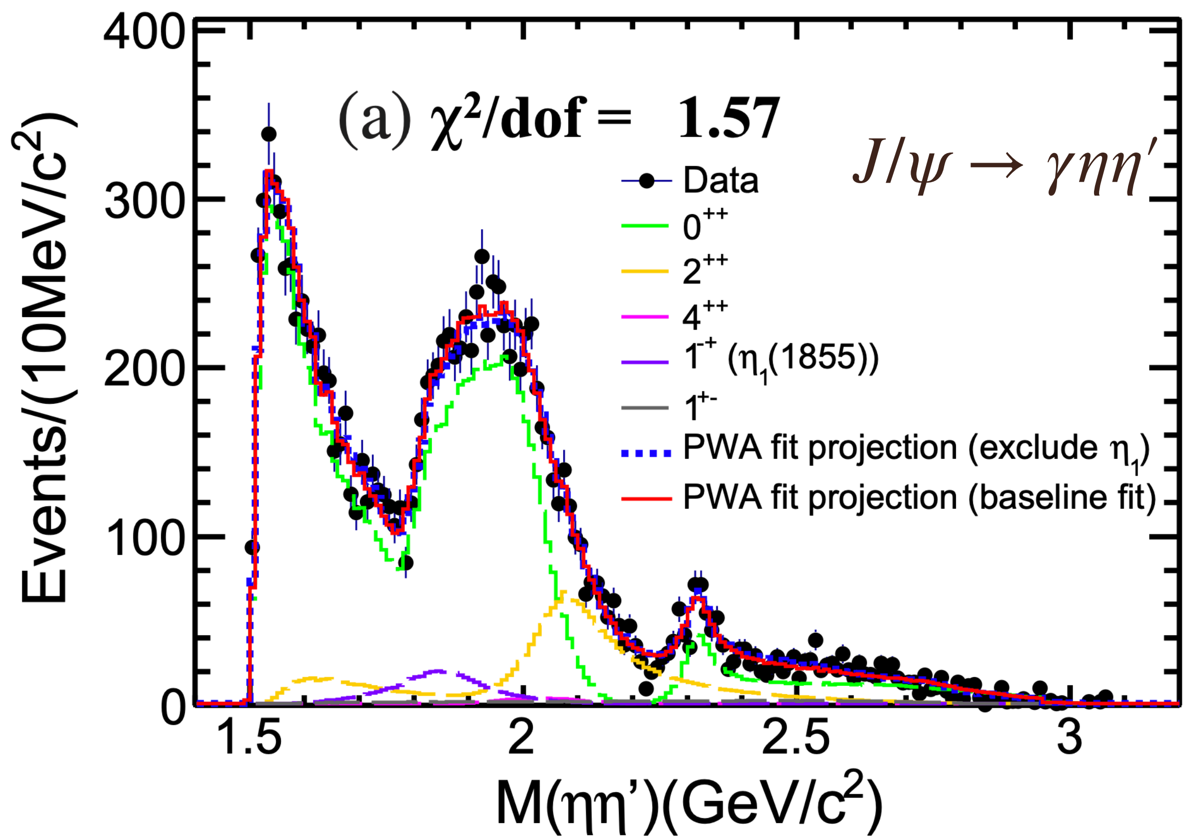
- Conventional meson $q\bar{q}$:

S-wave: $J^{PC} = 0^{-+}, 1^{--}$

P-wave: $J^{PC} = 0^{++}, 1^{++}, 2^{++}, 1^{+-}$

- Exotic J^{PC}: $0^{--}, 0^{+-}, 1^{-+}, 2^{+-}, \cdots$

- Interpretations:
  - Hybrid: $q\bar{q}g$, $s\bar{s}g$
  - Hadronic molecule: $K\bar{K}_1(1400)/K\bar{K}_1(1270)$
  - Compact tetraquark
  - Production in other reactions



- Exp:
  - $I^G(J^{PC}) = 0^+(1^{-+})$
  - $M_{\eta_1(1855)} = 1855 \pm 9^{+6}_{-1}$ MeV
  - $\Gamma_{\eta_1(1855)} = 188 \pm 18^{+3}_{-8}$ MeV
  - Stat. significance larger than 19 σ

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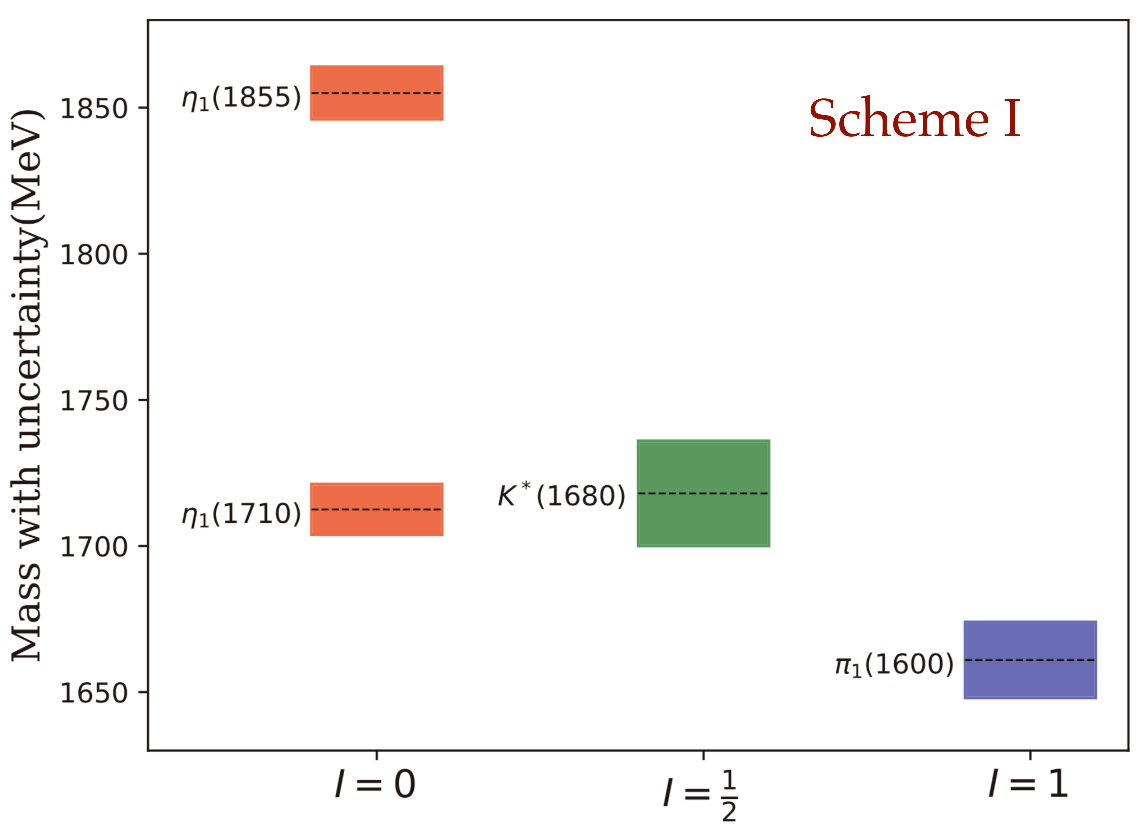
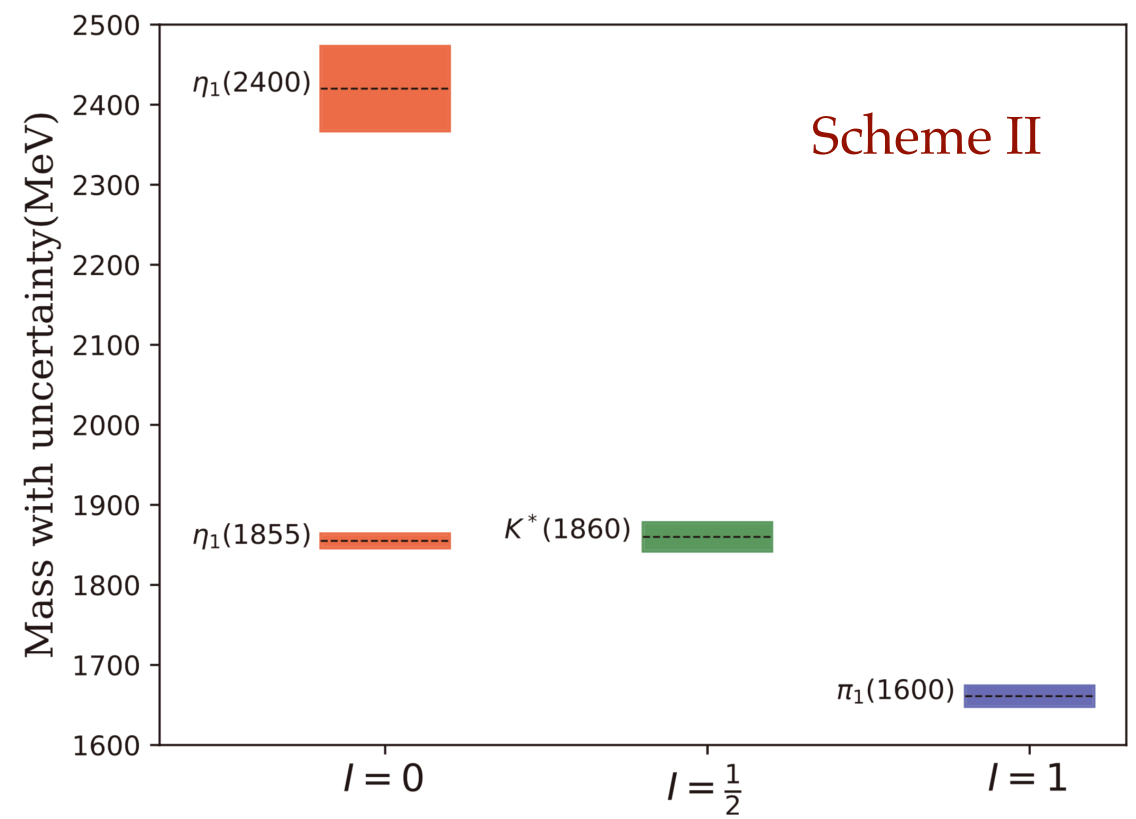
Light hadron spectrum: $\eta_1(1855)$

Qiu, Zhao, CPC46(2022)051001

- Hybrid: Flux tube model
  - static color source $q\bar{q}$ + a gluons lump with $J_g^{PC} = 1^{+-}$
  - S-wave $J_{q\bar{q}}^{PC} = 0^{-+}$, $J_g^{PC} = 1^{+-}$: $J^{PC} = 1^{--}$
  - S-wave $J_{q\bar{q}}^{PC} = 1^{--}$, $J_g^{PC} = 1^{+-}$: $J^{PC} = (0,\ 1,\ 2)^{-+}$
  - Establish a complete SU(3) flavor multiplet





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Light hadron spectrum: $\eta_1(1855)$

Qiu, Zhao, CPC46(2022)051001

- Hybrid: Flux tube model

- static color source $q\bar{q}$ + a gluons lump with $J_g^{PC} = 1^{+-}$
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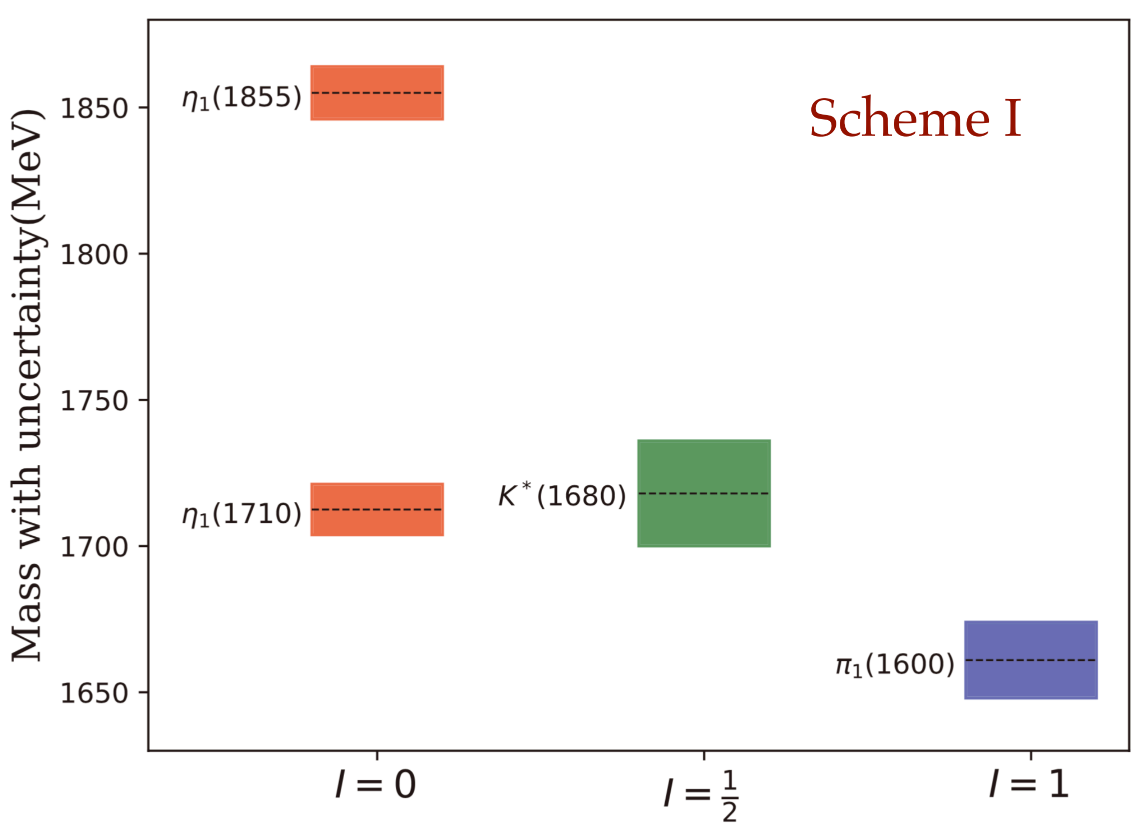
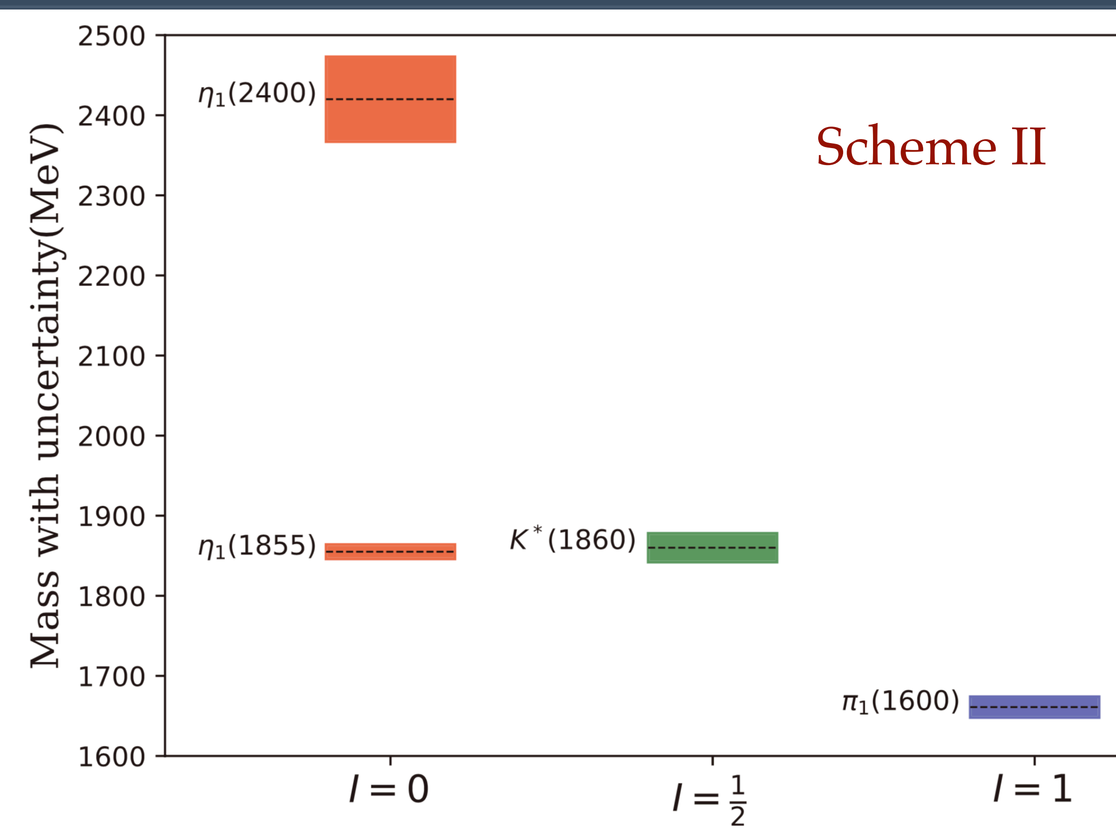
- Establish a complete SU(3)

- $K^*(1680)$ PDG $1/2(1^-)$





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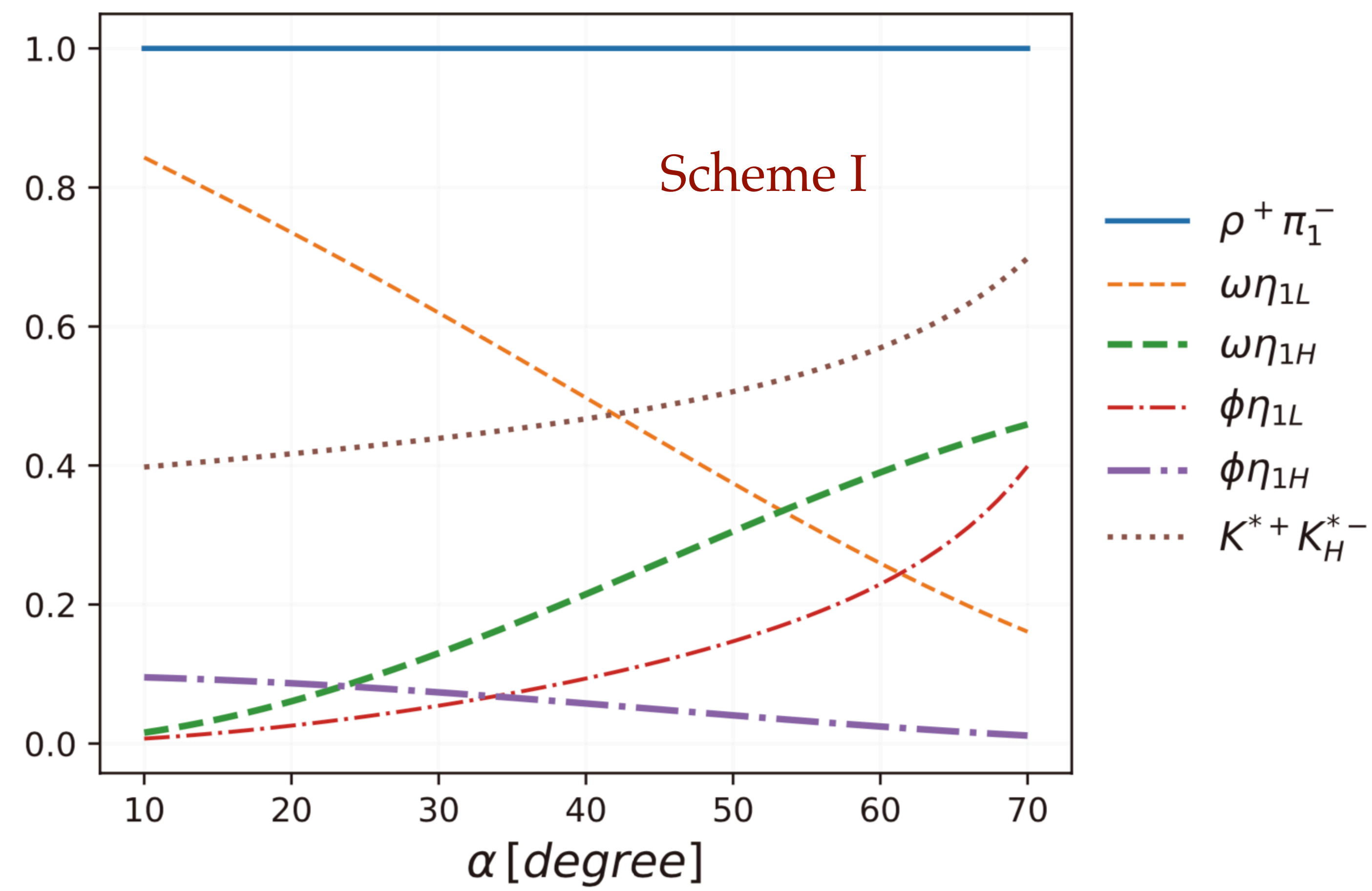
Light hadron spectrum: $\eta_1(1855)$

Qiu, Zhao, CPC46(2022)051001

- Hybrid: Flux tube model

  - The observed channel for other hybrids

$$\begin{pmatrix} \eta_{1\mathrm{L}} \\ \eta_{1\mathrm{H}} \end{pmatrix} = \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \eta_1^{(8)} \\ \eta_1^{(1)} \end{pmatrix} = \begin{pmatrix} \cos\alpha & -\sin\alpha \\ \sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} n\bar{n}\tilde{g} \\ s\bar{s}\tilde{g} \end{pmatrix},$$

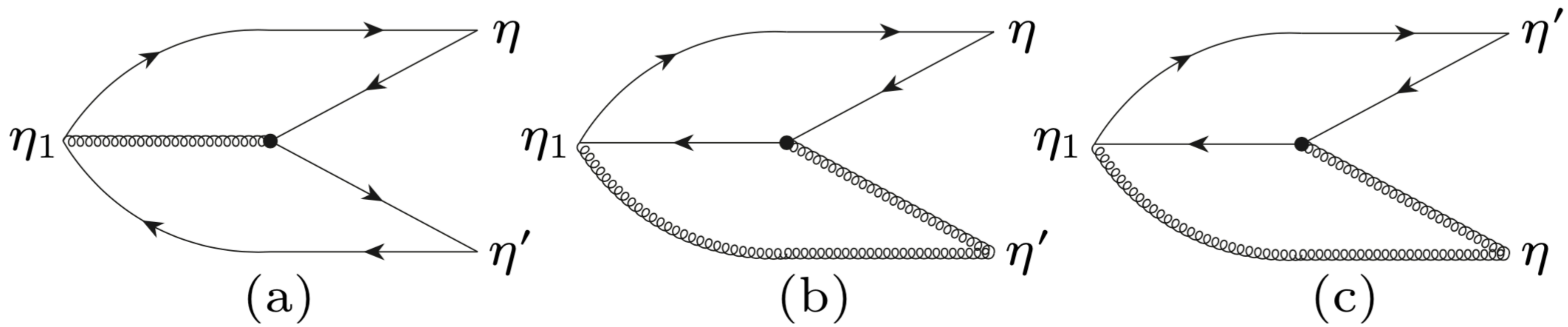


Progress   Since 2nd Nov. 2021

Light hadron spectrum: $\eta_1(1855)$

Chen, Su, Zhu, CPL39(2022)051201

- Hybrid:



QCD sum rule

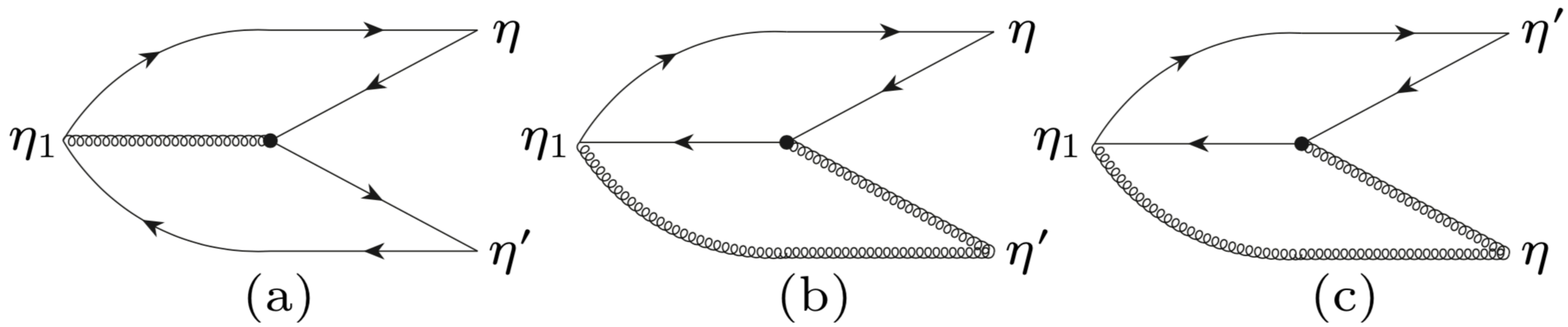
- $s\bar{s}g$ hybrid
- $\eta\eta'$ decay model enhanced by QCD axial anomaly, but suppressed by P-wave phase space
- Decay to $a_1(1260)\pi$, $f_1(1285)\eta$ in S-wave
- Decay to $K\bar{K}$, $\eta\eta'$ in P-wave
- The $\eta\eta$, $\eta'\eta'$ decay modes forbidden due to Bose-Einsterin statistics

Progress Since 2nd Nov. 2021

Light hadron spectrum: $\eta_1(1855)$

Chen, Su, Zhu, CPL39(2022)051201

- Hybrid:



$$\Gamma(\eta_1(1855) \xrightarrow{a} \eta\eta') = 0.7^{+2.3}_{-0.4}\,\mathrm{MeV},$$
$$\Gamma(\eta_1(1855) \xrightarrow{b} \eta\eta') = 1.8^{+0.7}_{-0.4}\,\mathrm{MeV},$$
$$\Gamma(\eta_1(1855) \xrightarrow{c} \eta\eta') = 0.7^{+0.4}_{-0.2}\,\mathrm{MeV},$$
$$\Gamma(\eta_1(1855) \to K^*(892)\overline{K} + c.c.) = 98.1^{+82.9}_{-60.4}\,\mathrm{MeV},$$
$$\Gamma(\eta_1(1855) \to K_1(1270)\overline{K} + c.c.) = 30.4^{+40.1}_{-19.3}\,\mathrm{MeV},$$

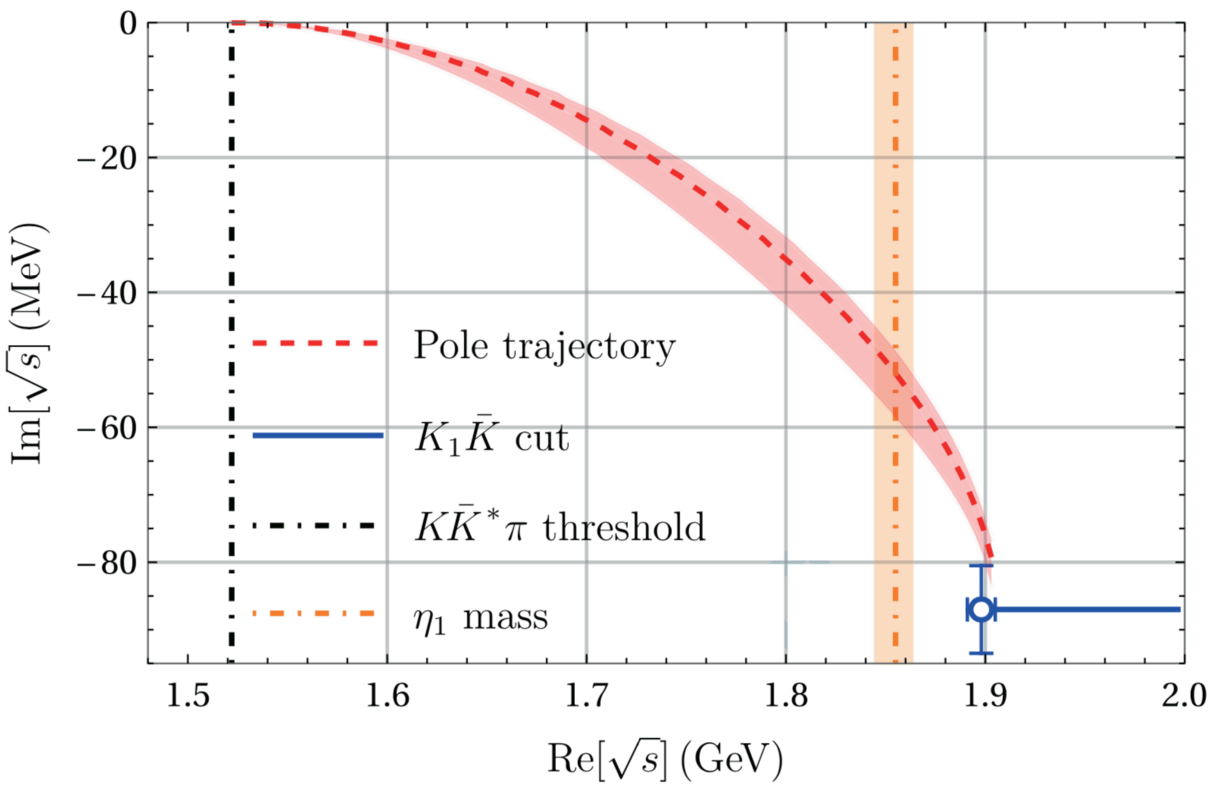
QCD sum rule

Progress Since 2nd Nov. 2021

Light hadron spectrum: $\eta_1(1855)$

Dong, Lin, Zou, Sci. China Pays. Mech. Astron. 65(2022)261011

- Hadronic molecular picture:



Mode	Widths (MeV)	
	1^{--} $E_B = 20$ MeV	1^{-+} $E_B = 40$ MeV
$K^*\bar{K}^*$	38.1	26.3
$K\bar{K}$	0.5	0
$K\bar{K}^*$	1.0	0.9
$a_1\pi$	0	9.2
$f_1\eta$	0	0.2
$\eta\eta'$	0	26.9
$\sigma\omega$	0.2	0
$\rho\rho$	0	0.04
$\pi\rho$	6.4	0
$\eta\omega$	0.4	0
$\omega\omega$	0	0.01
$\omega\phi$	0	0.4
$K\bar{K}^*\pi$	130.0	105.0
2-body	46.5	64.0
Total	176.5	169.0

5% D wave contribution

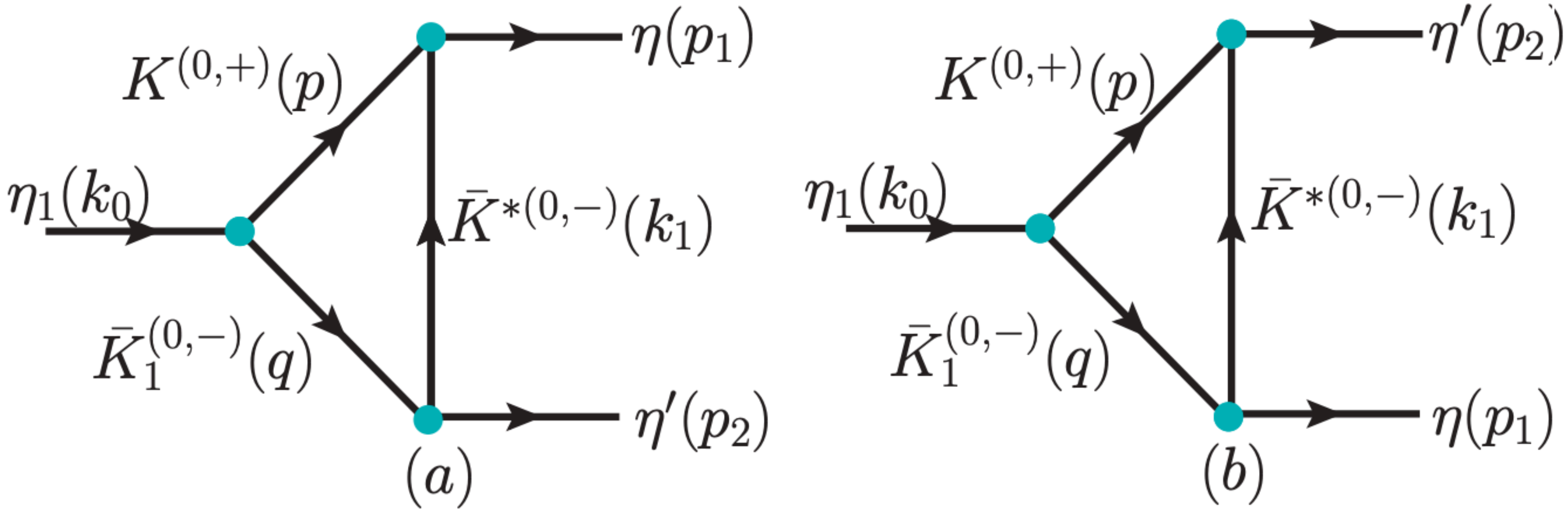
- One-boson exchange potential
- Attractive force for $J^{PC} = 1^{-+}$, $K\bar{K}_1(1400)$ with $\Lambda \simeq 2.5$ GeV, $E_B = 40$ MeV
- $J^{PC} = 1^{--}$, $K\bar{K}_1(1400)$ with $E_B = 10 \sim 30$ MeV
- Attractive/Repulsive force for $J^{PC} = 1^{--}/1^{-+}$, $K\bar{K}_1(1270)$
- Predict 2-body and 3-body decay width

Progress Since 2nd Nov. 2021

Light hadron spectrum: $\eta_1(1855)$

Yang, Huang, 2203.06934

- Hadronic molecular picture:



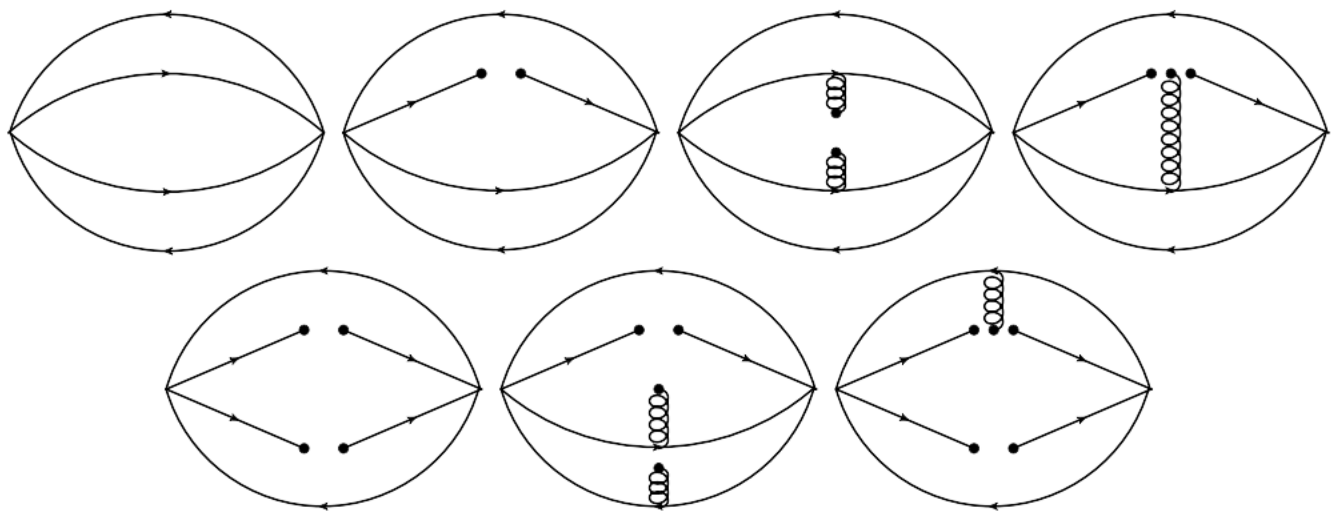
- $J^{PC} = 1^{-+}$, $K\bar{K}_1(1400)$ molecular picture
- Total width $197.27^{+1.64}_{-1.22}$ MeV
- $\Gamma(\eta_1(1855) \to K\bar{K}^*\pi) > \Gamma(\eta_1(1855) \to \eta\eta')$
- $\Gamma(\eta_1(1855) \to \gamma\phi) = 10.16^{+0.19}_{-0.35}$ keV

Progress   Since 2nd Nov. 2021

Light hadron spectrum: $\eta_1(1855)$

Wan, Zhang, Qiao, 2203.14014

- Compact tetra quark



QCD sum rule

- $J^{PC} = 1^{-+}$, $[1_c]_{s\bar{s}} \otimes [1_c]_{q\bar{q}}$, $[1_c]_{q\bar{s}} \otimes [1_c]_{s\bar{q}}$ configurations
- $\eta_1(1855)$ embedded into the $[1_c]_{s\bar{s}} \otimes [1_c]_{q\bar{q}}$ configuration
- Two $ss\bar{s}\bar{s}$ $J^{PC} = 1^{-+}$ ground states

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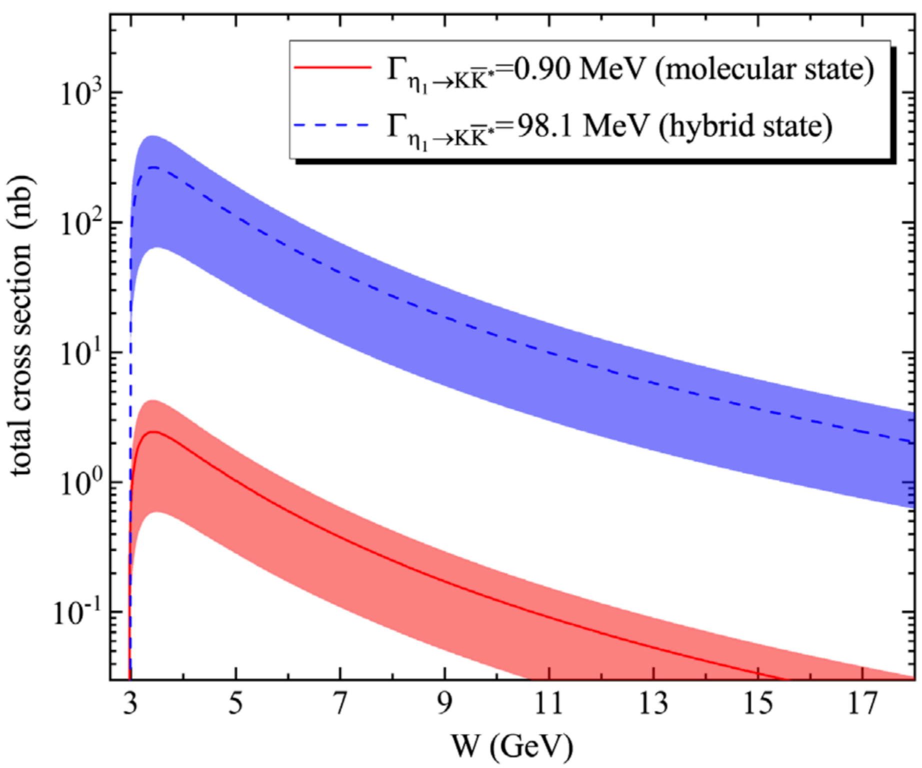
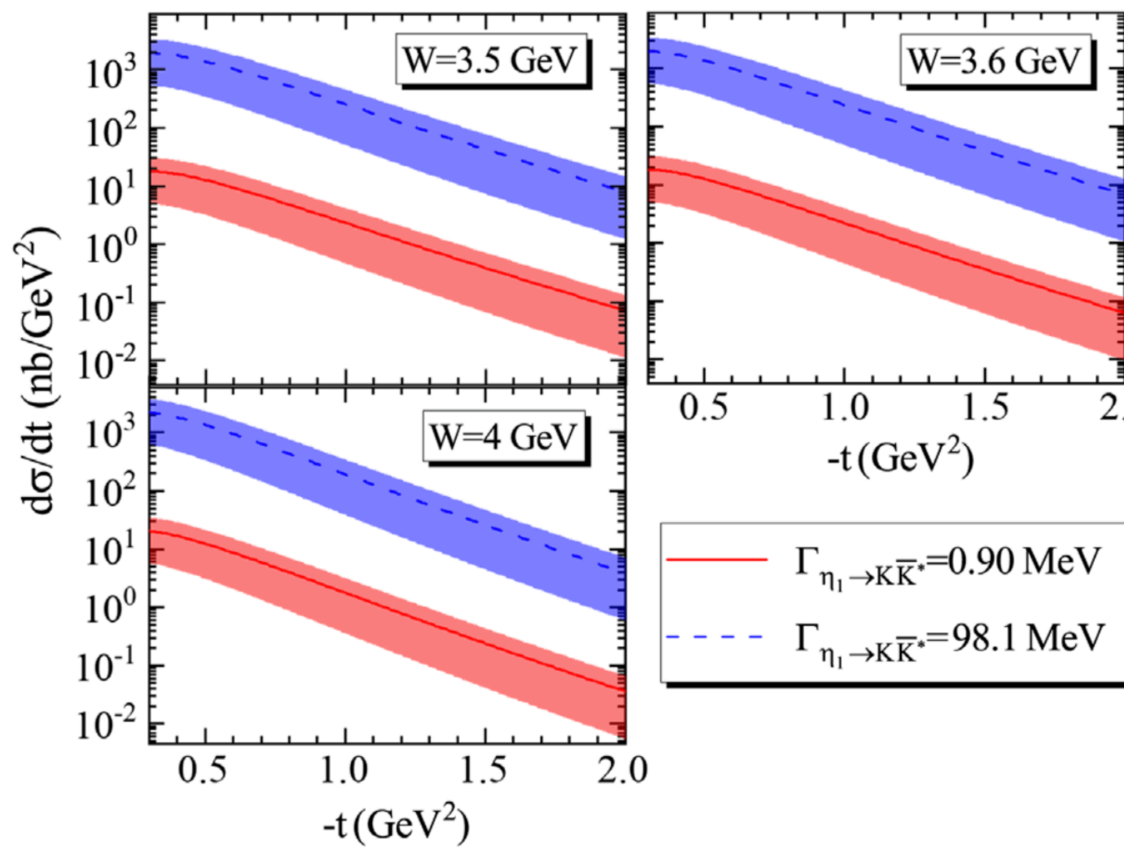
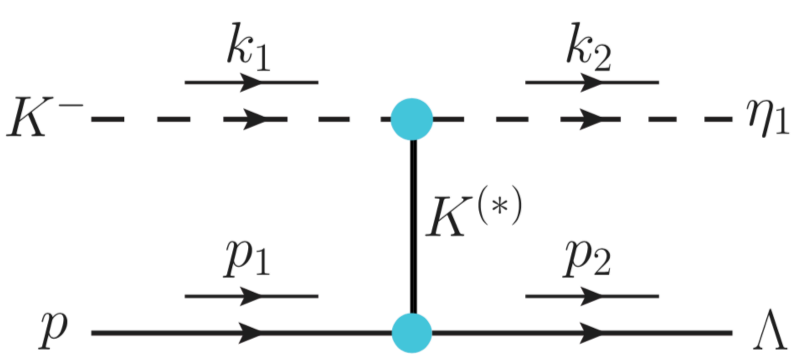
Light hadron spectrum: $\eta_1(1855)$

Wang, Zeng, Liu, PRD106(2022)036005

- Production in other reactions:







- Estimate the cross section of the $K^- p \to \eta_1 \Lambda$ process in hybrid and molecular picture
- σ(hybrid) > σ(molecule)
- Predict differential cross section distribution

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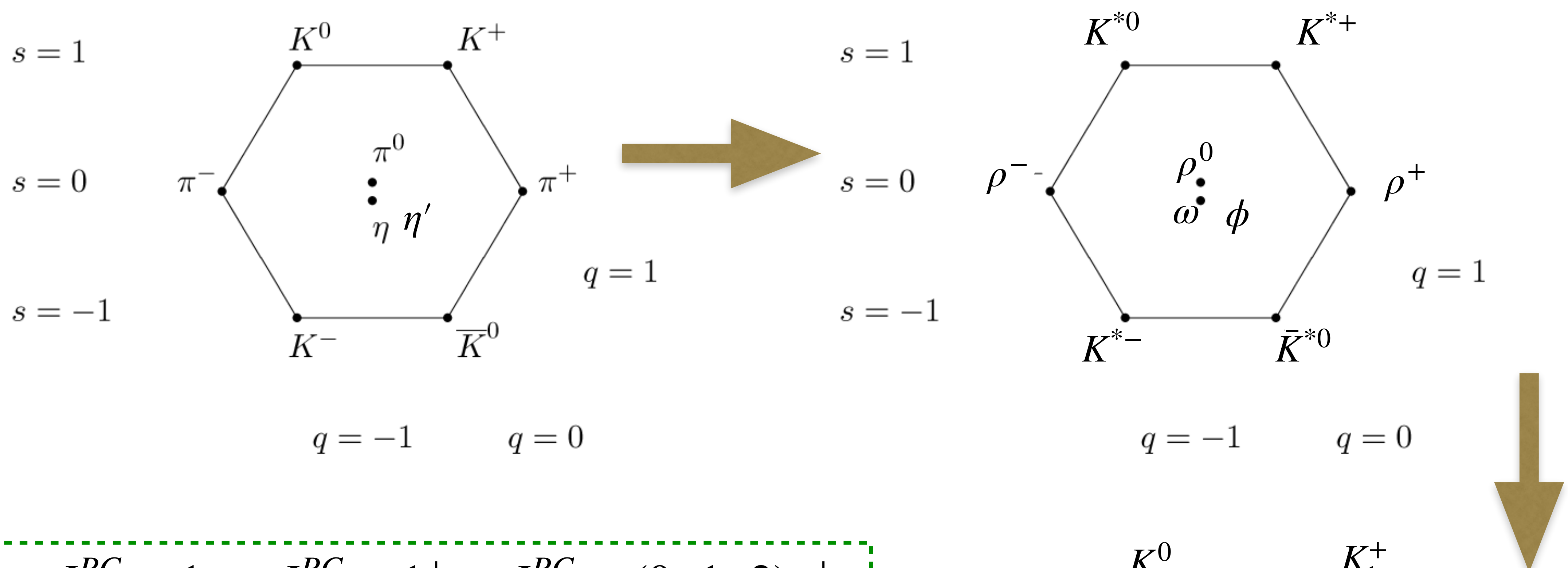
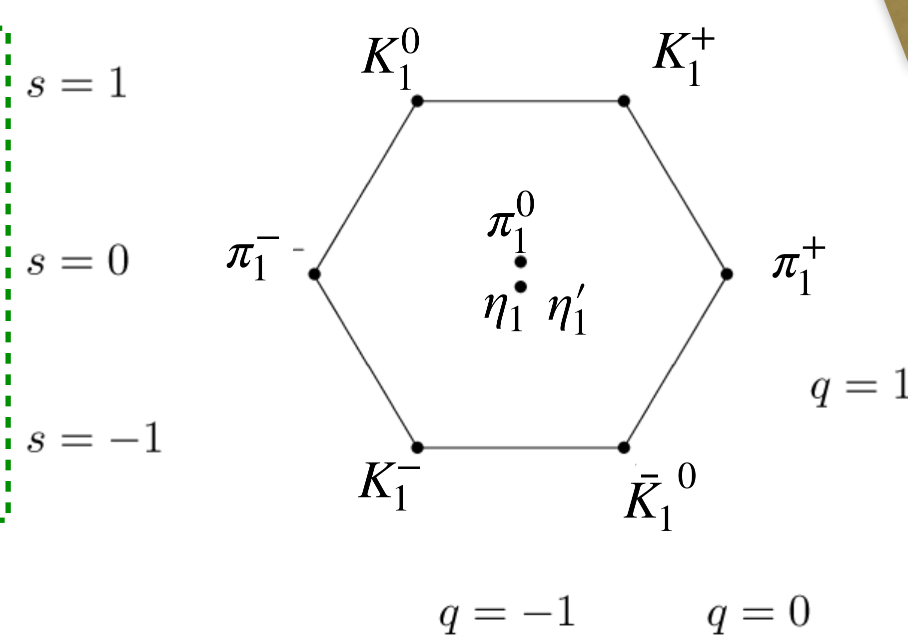
Light hadron spectrum: $\eta_1(1855)$

- the interplay with LQCD



- S-wave $J^{PC}_{q\bar{q}} = 1^{--}$, $J^{PC}_{g} = 1^{+-}$: $J^{PC} = (0,\ 1,\ 2)^{-+}$
- $\Delta m = m_{q\bar{q}g} - m_{q\bar{q}'}$, $m_{\pi_1} - m_\rho$, $m_{K_1} - m_{K^*}$, $m_{\eta_1} - m_\rho$, $m_{\eta_1'} - m_\phi$
- The mass positions of 0^{-+}, 2^{-+}



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Light hadron spectrum:

- $a_0(980)$, $f_0(980)$ Wang, et.al., EPJC82(2022)509,
- $a_0(1817)$ Guo, et.al., PRD105(2022), 114014,
- $\frac{1}{2}^-$ light baryon octet Chen, et.al., CPC46(2022), 081001,
- $K_0(1950/2130)$ Li, et.al., PRD106(2022), 034012,
- $\Omega(2012)$ Hu, et.al., PRD106(2022), 054028,
- $d(2380)$ Dong, et.al., CPC46(2022), 023105,
- $s = -2$ double baryon system Liu, et.al., 2201.04997
- The mixing angle for meson nonet Feng, et.al., 2205.05260
- Accurate relativistic chiral NN interaction up to NNLO Lu, et.al., PRL128(2022) 142002
- Two-photon-exchange effect in $ep \to en\pi^+$ at small $-t$ Guo, et.al., PRC106(2022) 015203

Progress Since 2nd Nov. 2021

Light hadron spectrum:

- Light baryonium Wan, et.al., PRD105(2022), 014016,
- Partial wave analysis for the in-hadron condensate Qin, et.al., PRD106(2022), 034006,
- γN reaction Wei, et.al., CPC46(2022), 053105, PRD105(2022)094017, Wang, et.al., PRD105(2022)034017
  Guo, et.al., PRD105(2022), 11
- Radiative Correction to Lepton Proton Scatterings in Manifestly Lorentz-Invariant Chiral Perturbation Theory Cao, et.al., PRD105(2022), 094008
- Vector meson production in e^+e^- annihilation Zhou, et.al., PRD105(2022), 074035
- Pion axioproduction: The Δ resonance contribution Vonk, et.al., PRD105(2022), 054029
- $N-\bar{N}, N-N$ scattering Zhou, et.al., PRC105(2022), 054005,
- Scrutinizing $\pi\pi$ scattering in light of recent lattice phase shifts
  Gao, et.al., PRD105(2022), 094002

Progress

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Exotic hadrons: T_{cc}

Breit-Wigner fit

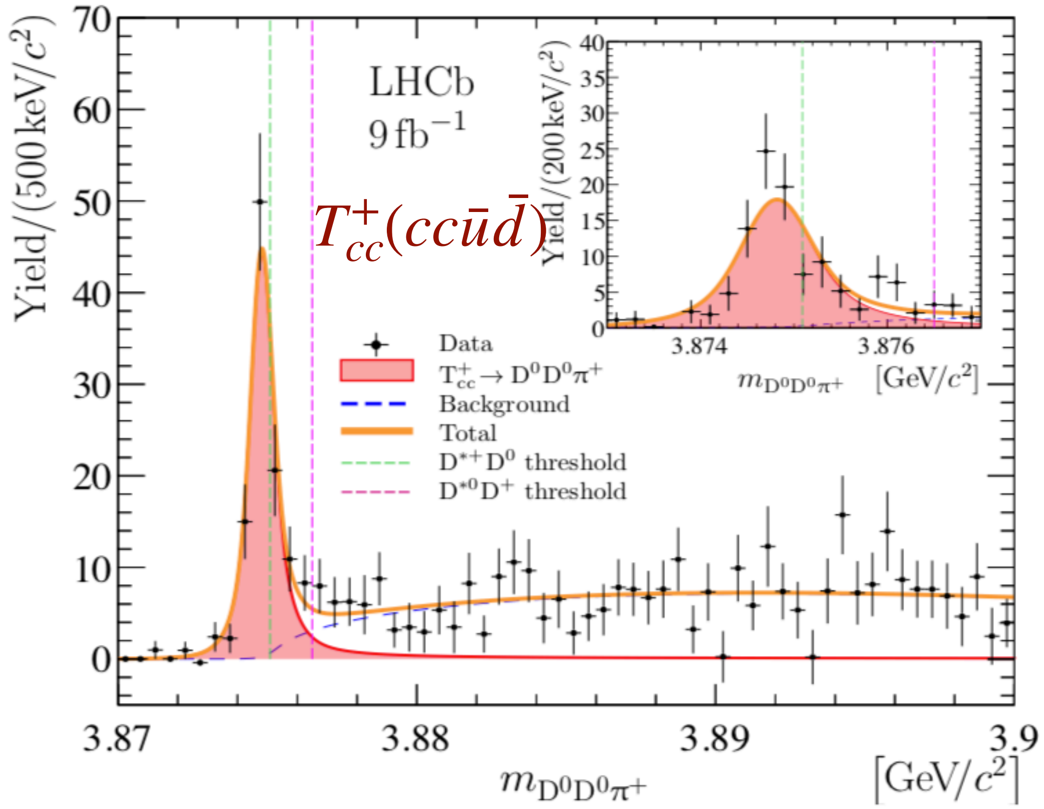
LHCb, arXiv:2109.01038

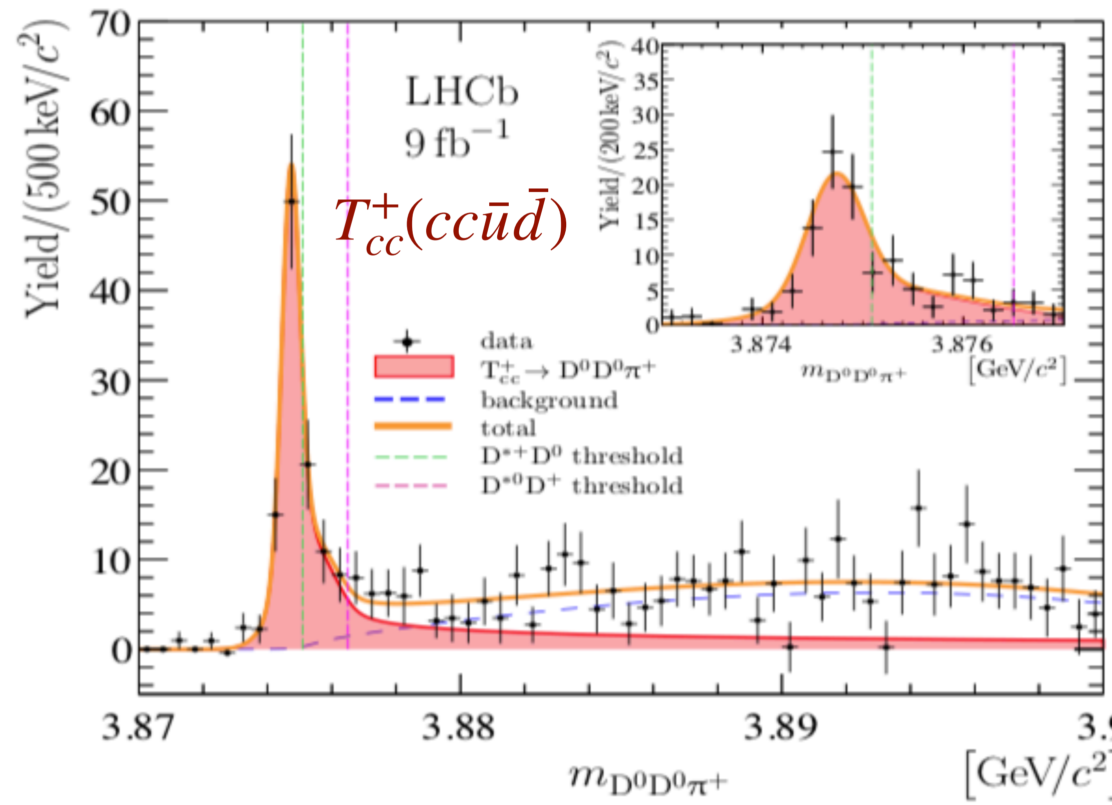
Nature Physics (2022)

Unitarized fit

LHCb, arXiv:2109.01056

Nature Commun. 13(2022)3351





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

$$\delta m_{\rm BW} = -273 \pm 61 \ \text{keV}$$

$$\Gamma_{\rm BW} = 410 \pm 165 \ \text{keV}$$

No signal in $D^+D^0\pi^+$, D^+D^+

$\to$ I=0 isoscalar

$$\delta m_{\rm pole} = -360 \pm 40^{+4}_{-0} \ \text{keV}$$

$$\Gamma_{\rm pole} = 48 \pm 2^{+0}_{-14} \ \text{keV}$$

$$a = \left[-(7.16 \pm 0.51) + i(1.85 \pm 0.28)\right] \ \text{fm}$$

$$-r < 11.9(16.9) \ \text{fm} \quad 90(95)\,\% \ \text{CL}\,.$$

Talk by Chun Jiang Shi from Lattice

Progress

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Exotic hadrons: T_{cc}

Before the observation

Bound or not?

- E. Braaten, et.al., PRD103(2021)016001, Not bound
- J. Chen et.al., CPC45(2021)043102, Not bound
- Faustov et. al., universe, not bound
- M.Z.Liu et. al., PRD102(2020)091502, OBE, loosely bound
- Q.Lv et.al., PRD102(2020)034012
- C. Deng, et.al., EPJA56(2020),9, deeply bound -150keV
- P. Junnarkar et.al., PRD99(2019)034057
- W. Park et.al., NPA983(2019)1
- Z.G. Wang ACTA Physica Polonica B(2018) bound
- E.J.Eichten et.al., PRL119(2017)202002, not bound
- M. Karliner et.al., PRL2017, 7MeV above D^0D^{*+} threshold
- Lattice QCD simulation, PLB729(2014)85, $j^P = 1^+$, $I = 0$ attractive
- G.Q. Feng, et.al., arXiv:1309.7813(2013), bound
- N.L., et al., PRD88(2013)114008, loosely bound
- ……

Progress Since 2nd Nov. 2021 Exotic hadrons: T_{cc}

After the observation

SU(3) flavor partners

- M.Karliner, et.al., PRD105(2022)034020
- H.W.Ke, et.al., PRD105(2022)114019
- L.R.Dai, et.al., PRD105(2022)074017
- K. Chen, et.al., PRD105(2022)096004
- G. Yang, et.al., PRD104(2021)094035
- ……

Other partners

- Z.Y. Yang, et.al., arXiv: 2206.06051
- S.Q. Luo, et.al., arXiv: 2206.04586
- S.Q.Luo, et.al., PRD105(2022)074033
- X.Z.Ling, et.al., EPJC81(2021)1090
- X.Z.Weng, et.al., PRD105(2022)034026
- F.L.Wang et.al., PRD104(2021)094030
- Y.W.Pan et.al., PRD105(2022)114048
- C.W.Shen et.al., PLB831(2022)137
- T.Guo et.al., PRD105(2022)014021
- Q.Qin et.al., PRD105(2022)L031902
- R.Chen et.al., PRD104(2021)114042
- ……

HQSS partners

- H.W.Ke, et.al., EPJC82(2022)144
- M.J.Zhao, et.al., PRD105(2022)096016
- C.R.Deng, et.al., PRD105(2022)054015
- ……

Dynamics

- S.Y. Chen, et.al., arXiv: 2206.06185
- Z.Y.Lin, et.al., arXiv: 2205.14628
- M.Albaladejo et.al., PLB829(2022)137052
- J.B. Cheng, et.al., arXiv: 2205.13354
- N.N.Achasov, et.al., PRD105(2022)096038
- J. He et.al., EPJC82(2022)387
- J.H.Liu et.al., PRD105(2022)076013
- L.Y.Dai et.al., PRD105(2022)L051507
- L. Meng et.al., PRD104(2021)051502
- X.Z.Ling et.al., PLB826(2022)136897
- M.Y. Yan et.al., PRD105(2022)014007
- A. Feijoo et.al., PRD104(2021)114015
- ……

Isospin property and other properties

- J.Shi, et.al., arXiv: 2205.05234
- ……

Progress

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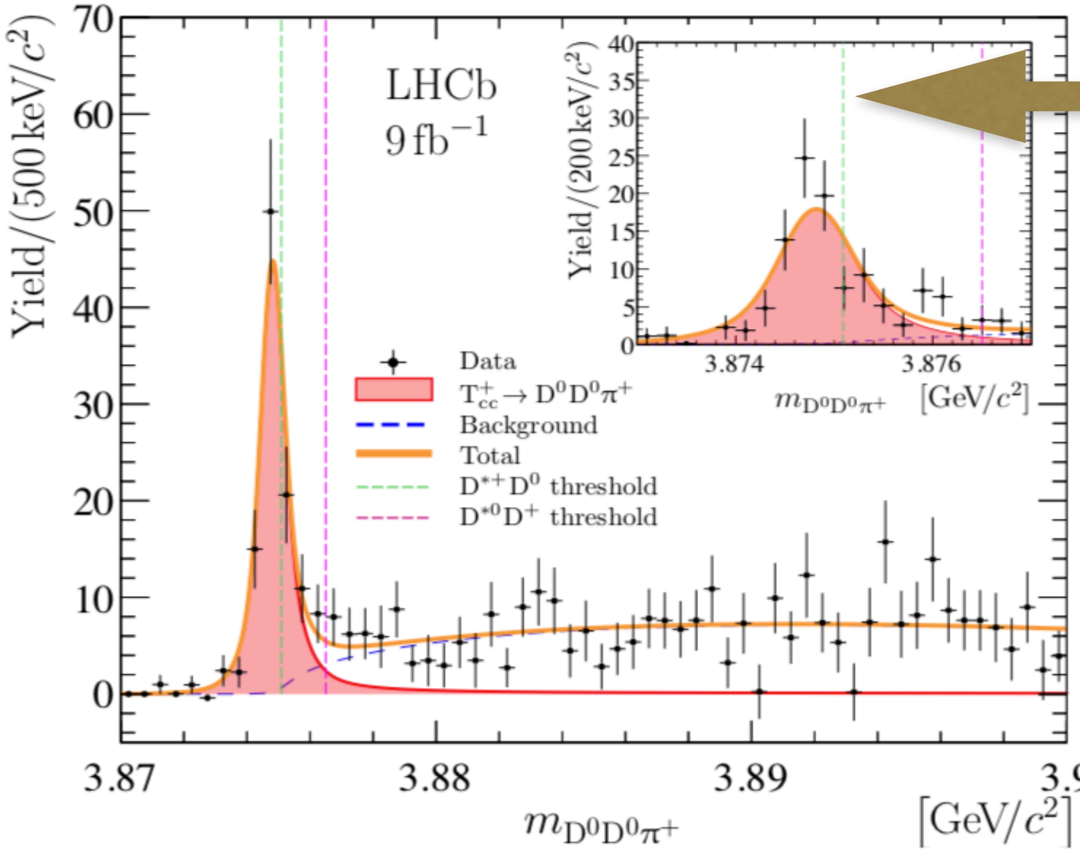
Exotic hadrons: T_{cc}



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

- Bound or not?
- a large negative effective range
- Isospin? Isospin breaking?

Meng et.al., 2017.14784

- Relation to the X(3872)

$$\tau_1 \cdot \tau_2^\star = -\frac{3}{4} \quad I = 0$$

$$\tau_1 \cdot \tau_2^\star = \frac{1}{4} \quad I = 1$$

D^*D?

$$\mathrm{thr}\,.\,[B + \bar{B} + \pi] > \mathrm{thr}\,.\,[B^* + \bar{B}^*]$$

$$> \mathrm{thr}\,.\,[B^* + \bar{B}]$$

$$\mathrm{thr}\,.\,[D + \bar{D} + \pi] < \mathrm{thr}\,.\,[D^* + \bar{D}]$$

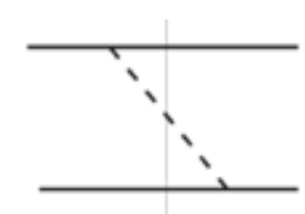
$$< \mathrm{thr}\,.\,[D^* + \bar{D}^*]$$

- Unexpected large width

$\Gamma(T_{cc}^{+}) \sim 400$ keV

273keV Meng et.al., 2017.14784

- Three-body effect



Progress

Since 2nd Nov. 2021

Exotic hadrons: T_{cc}

A large negative r?!

two-channel scattering amplitude

$$f_{ab}(E) = -\frac{g_a g_b}{2D(E)}$$

Denominator

$$D(E) = E - E_f + \frac{i}{2}\left(g_1^2 k_1 + g_2^2 k_2 + \sum_i \Gamma_i(E)\right)$$

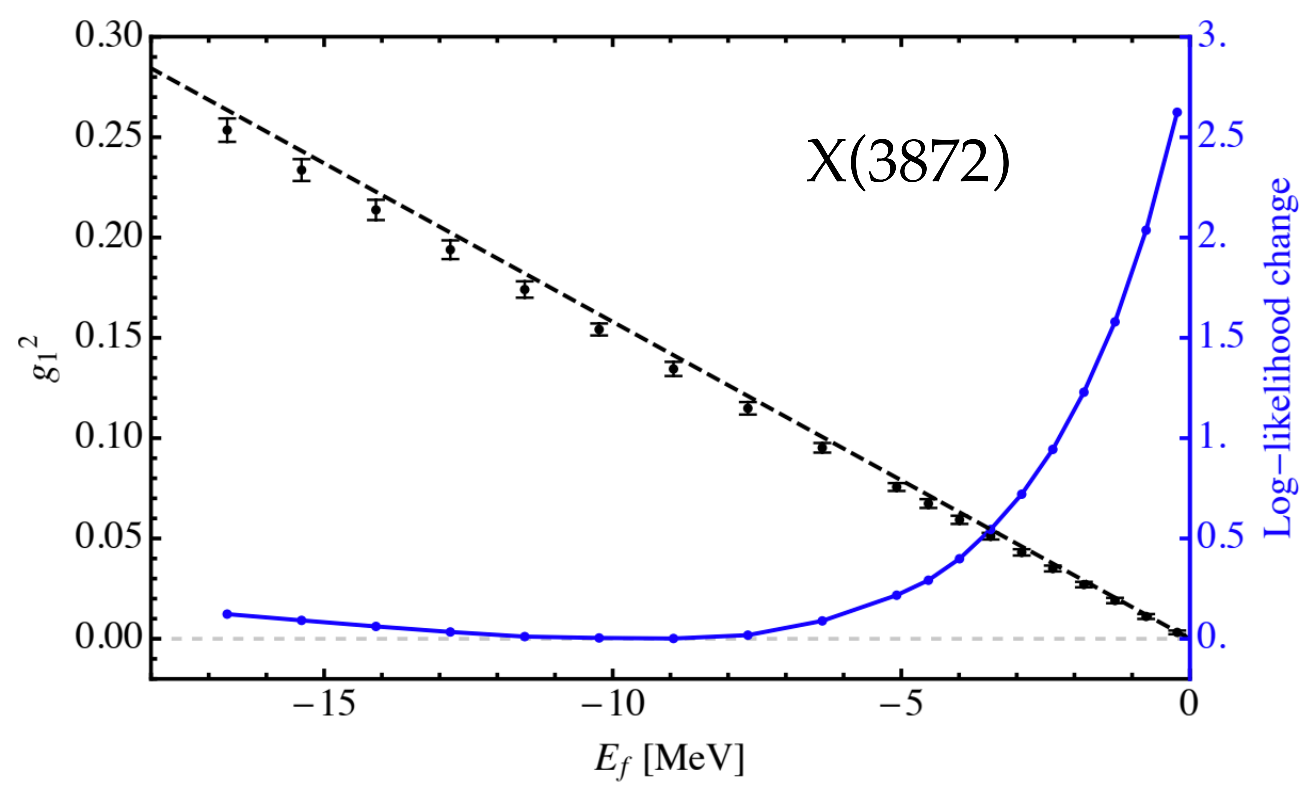
The three momentum

$$k_a = \sqrt{2\mu_a(E-\delta_a)}\Theta(E-\delta_a) + i\sqrt{2\mu_a(\delta_a - E)}\Theta(\delta_a - E)$$

The pole position on physical sheet

$$E_p = E_f + \frac{1}{2}(g_1^2\gamma_1 + g_2^2\gamma_2)$$

Large correlation



Baru, Dong, Du, Filin, Guo, Hanhart, Nefediev, Nieves, QW, PLB833(2022)137290

Progress

Since 2nd Nov. 2021

Exotic hadrons: T_{cc}

A large negative r?!

To remove correlation

$$D(E) = E - E_p + \frac{i}{2}\left(g_1^2(k_1 - i\gamma_1) + g_2^2(k_2 - i\gamma_2) + \sum_i \Gamma_i(E) \right)$$

Expand in terms of k_1

$$k_2 = i\sqrt{2\mu_2\left(\delta_2 - \frac{k_1^2}{2\mu_1}\right)} = i\sqrt{2\mu_2\delta_2} - \frac{i}{2}\sqrt{\frac{\mu_2}{2\mu_1^2\delta_2}}k_1^2 + \mathcal{O}\left(\frac{k_1^4}{\mu_1^2\delta_2^2}\right)$$

$$a = -\frac{g_1^2}{\gamma_1^2/\mu_1 + g_1^2/\gamma_1 + g_2^2(\gamma_2 - \sqrt{2\mu_2\delta_2}) + i\Gamma_{\text{inel}}}$$

$$r = -\frac{2}{\mu_1 g_1^2} - \frac{g_2^2}{g_1^2}\sqrt{\frac{\mu_2}{2\mu_1^2\delta_2}}$$

A large negative correction!

$$\bar{X}_A = \left(1 + 2\left|\frac{r}{a}\right|\right)^{-1/2}$$

Baru, Dong, Du, Filin, Guo, Hanhart, Nefediev, Nieves, QW, PLB833(2022)137290

Progress

Since 2nd Nov. 2021

Exotic hadrons: T_{cc}

3-body cut

Why the D^*D molecule?

- Close to the D^*D thresholds
- Approximate 90% of $D^0D^0\pi^+$ events contain a D^{*+}
- Z<0.52

Wave functions for isospin singlet and triplet

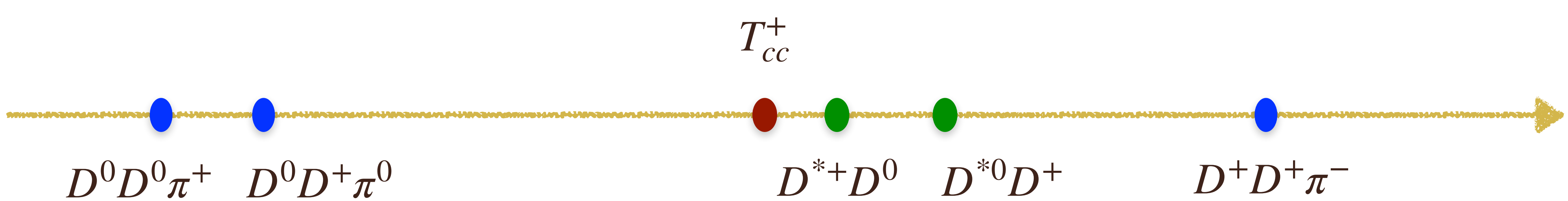
$$|D^*D,\, I=0\rangle = -\frac{1}{\sqrt{2}}\left(D^{*+}D^0 - D^{*0}D^+\right)$$

$$V_{\rm CT}^{I=0}(D^*D \to D^*D,\, J^P=1^+) = v_0$$

$$|D^*D,\, I=1\rangle = -\frac{1}{\sqrt{2}}\left(D^{*+}D^0 + D^{*0}D^+\right)$$

$$V_{\rm CT}^{I=1}(D^*D \to D^*D,\, J^P=1^+) = v_1$$

Three-body cut has to be considered

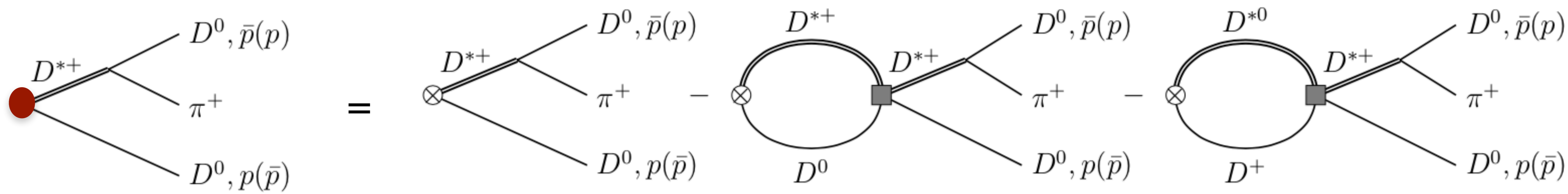


Progress

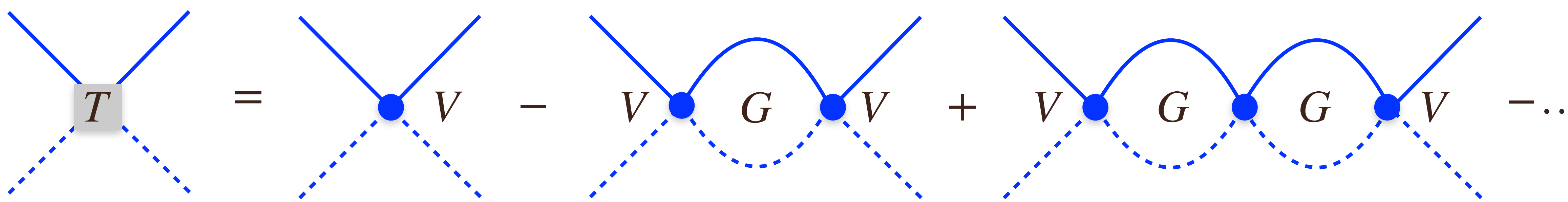
Since 2nd Nov. 2021

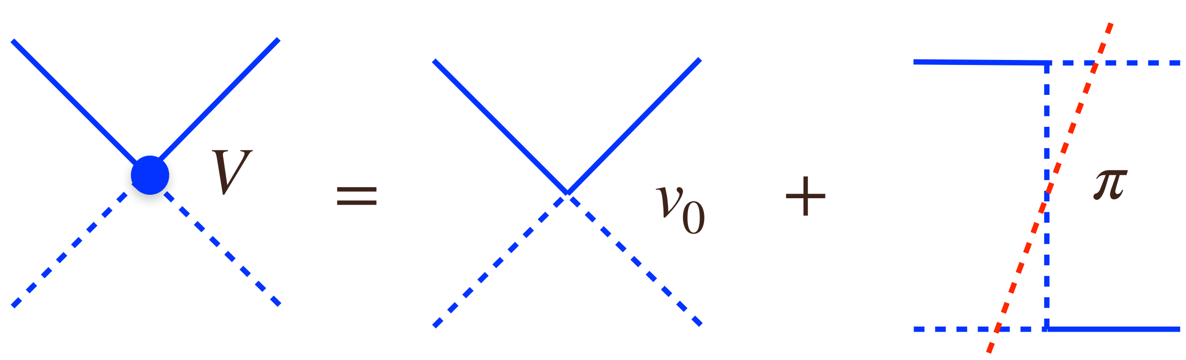
Exotic hadrons: T_{cc}

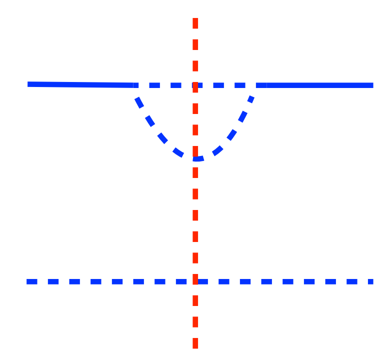
$D^0D^0\pi^+$ mass distribution



LSE







Du et al., PRD105(2022)014024

Progress

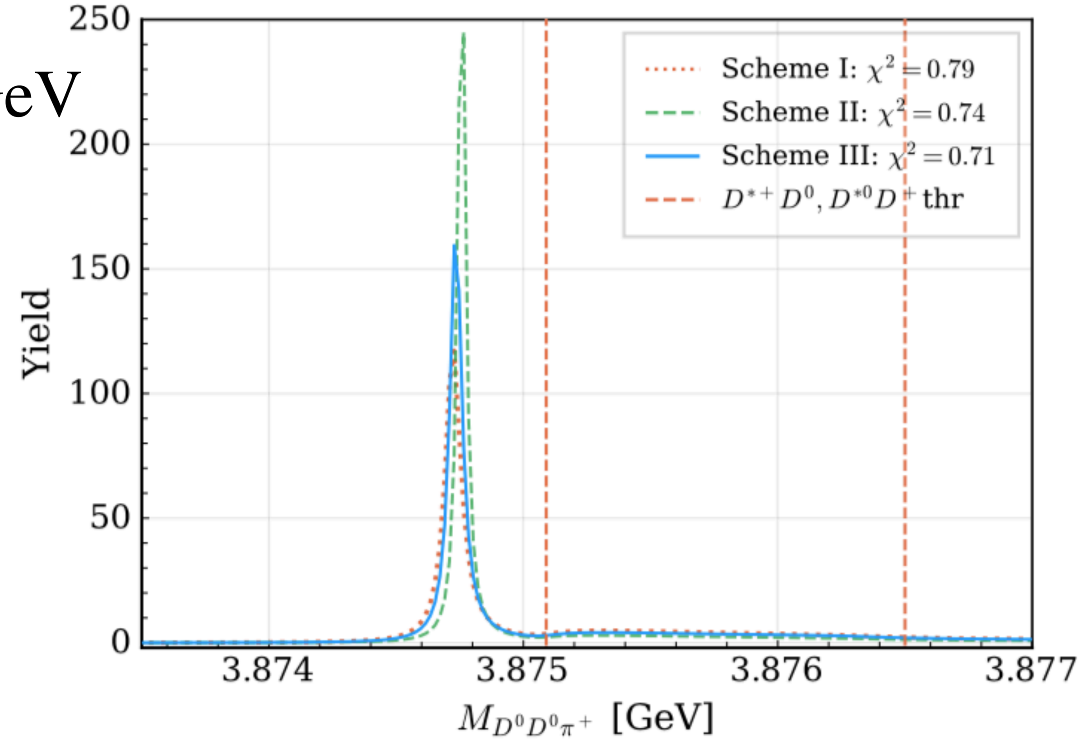
Since 2nd Nov. 2021

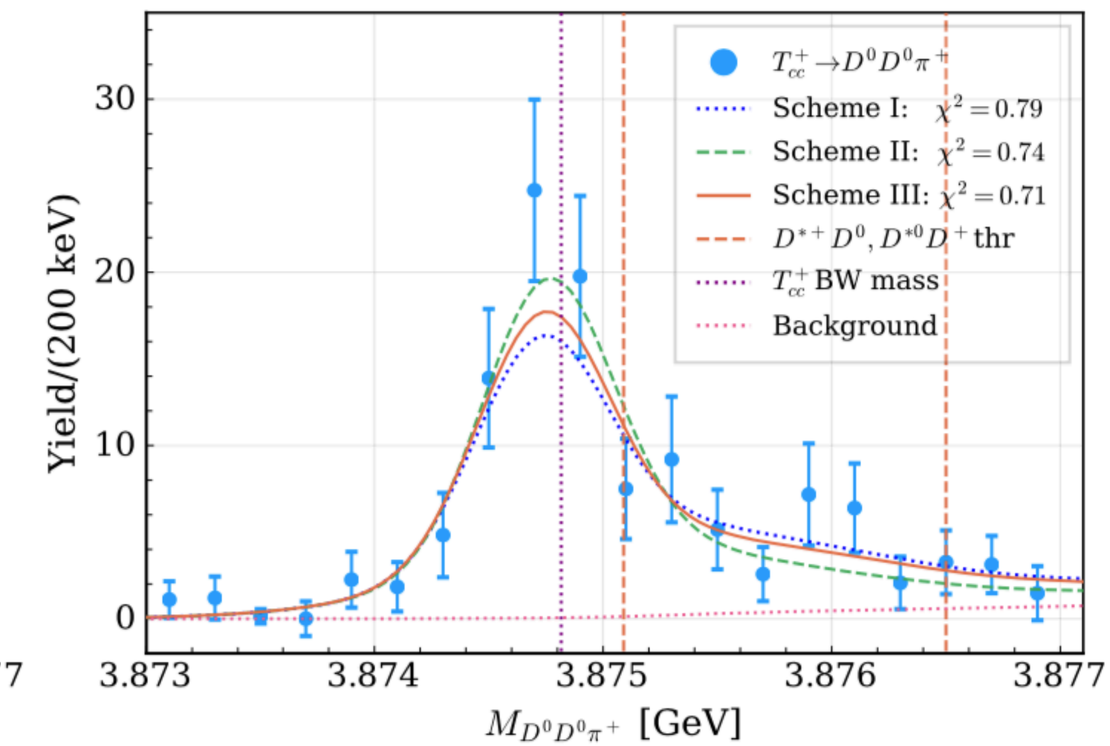
Exotic hadrons: T_{cc}

$D^0D^0\pi^+$ mass distribution

Cutoff independent for $\Lambda = [0.3 - 1.2]$ GeV

$\Lambda = 0.5$ GeV

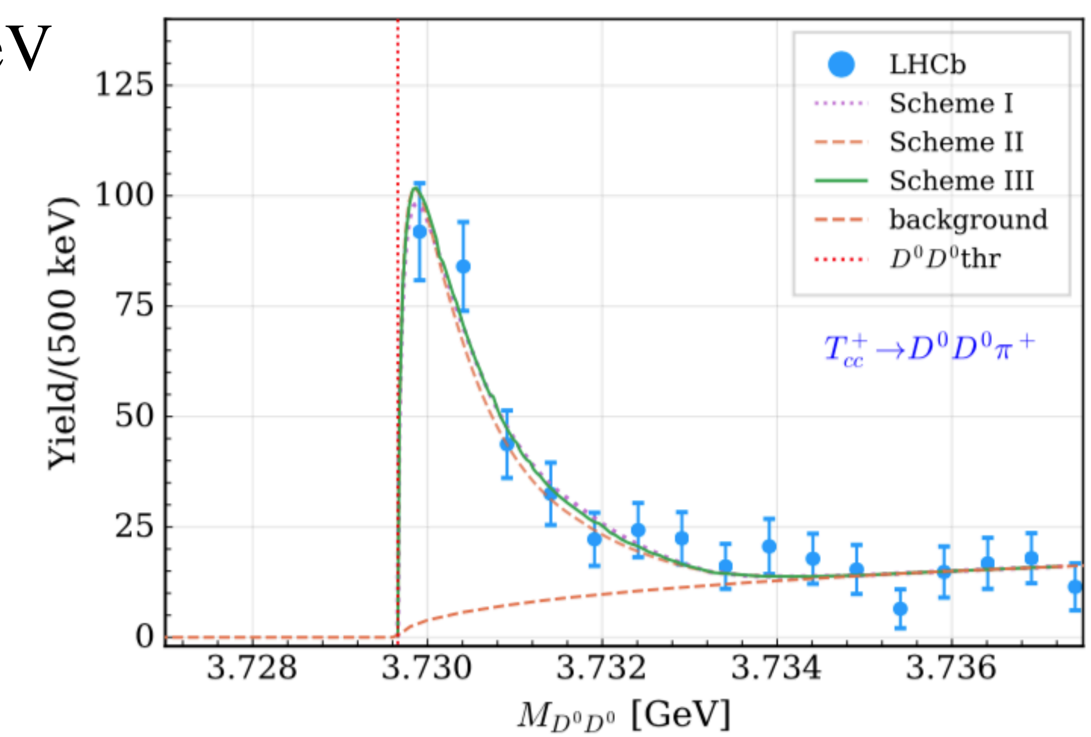


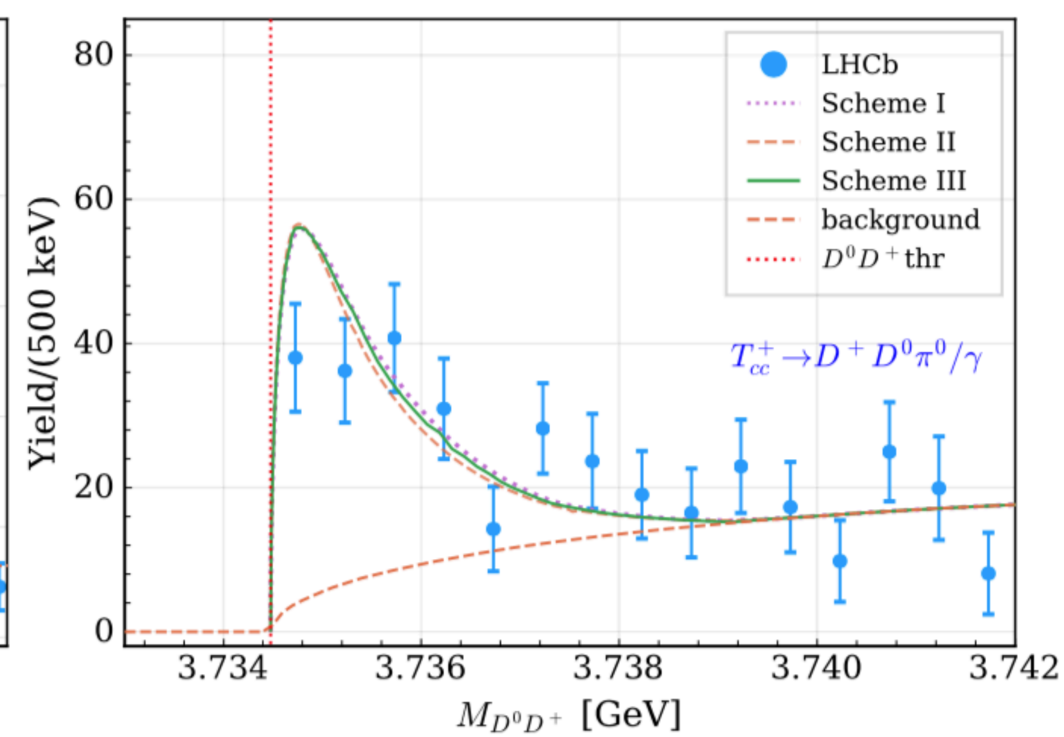


D^0D^0 and D^0D^+ mass distribution

Du et al., PRD105(2022)014024

$\Lambda = 0.5$ GeV





Progress

Since 2nd Nov. 2021

Exotic hadrons: T_{cc}

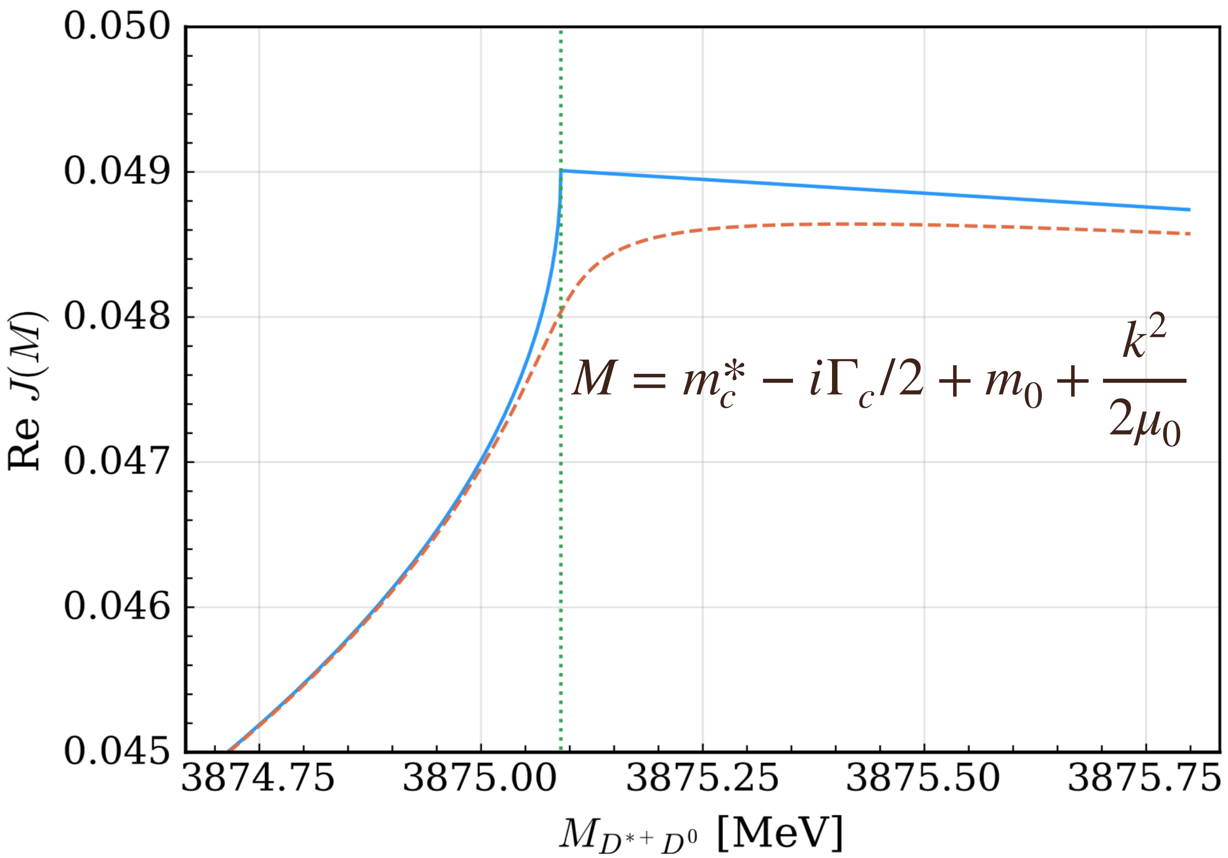
Du et al., PRD105(2022)014024

Low energy expansion of the scattering amplitude

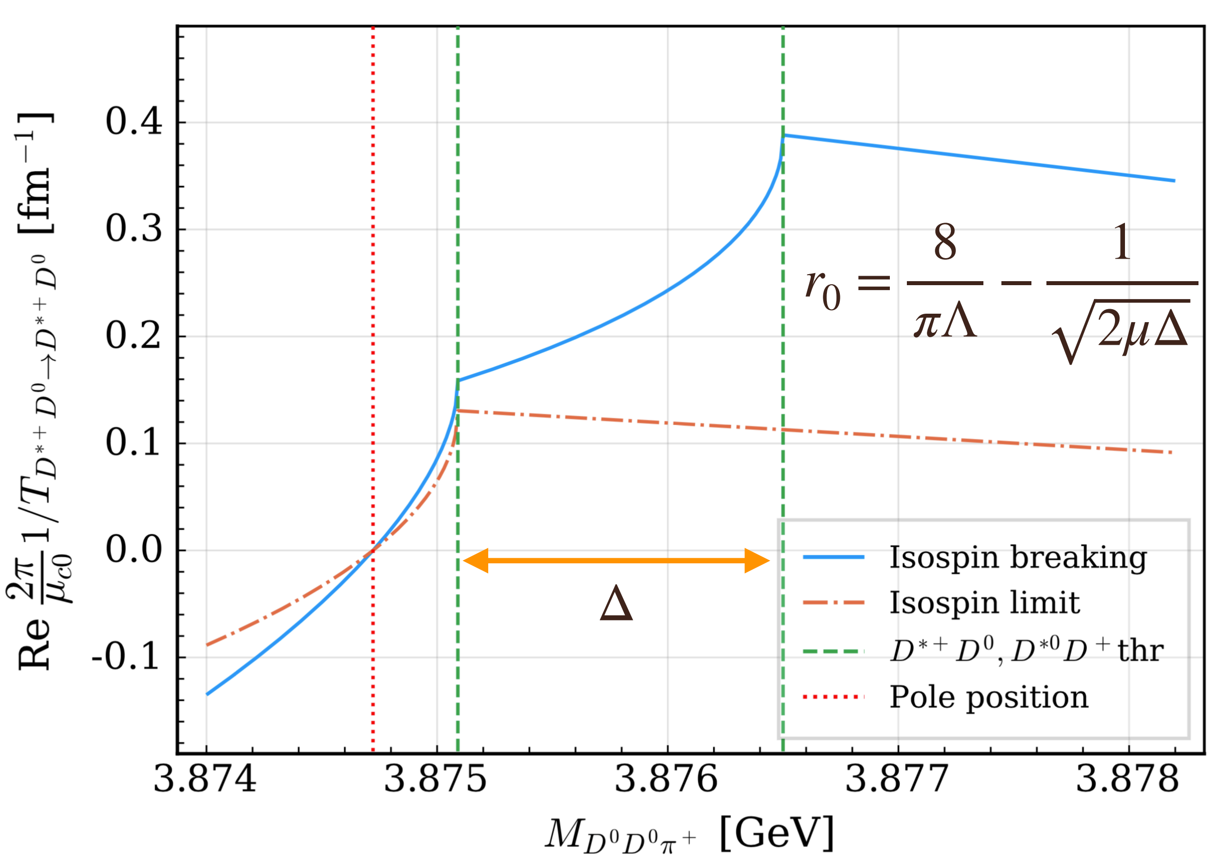
$$T_{D^{*+}D^0\to D^{*+}D^0}(k) = -\frac{2\pi}{\mu_{c0}}\left(\frac{1}{a_0}+\frac{1}{2}r_0k^2 - ik + \mathcal{O}(k^4)\right)$$

Effective range $\quad r_0 \propto -\,\mathrm{Re}\frac{dT^{-1}}{dM}\Big|_{M=M_{\rm thr}+0^+}$

Width effect



Isospin violation



Progress

Since 2nd Nov. 2021

Exotic hadrons: T_{cc}

Du et al., PRD105(2022)014024

Scheme I: Only contact potentials

$$T^{-1}_{D^{*+}D^0\to D^{*+}D^0}(M) = \frac{2}{v_0} + (J_1(M) + J_2(M)) \qquad E = M - M_{\text{thr.1}}$$

$$J_1(E) = \frac{\Lambda\mu}{\pi^2} - \frac{2\mu^2 E}{\pi^2\Lambda} + i\frac{\sqrt{2\mu E}\mu}{2\pi} + \mathcal{O}(E^2)$$

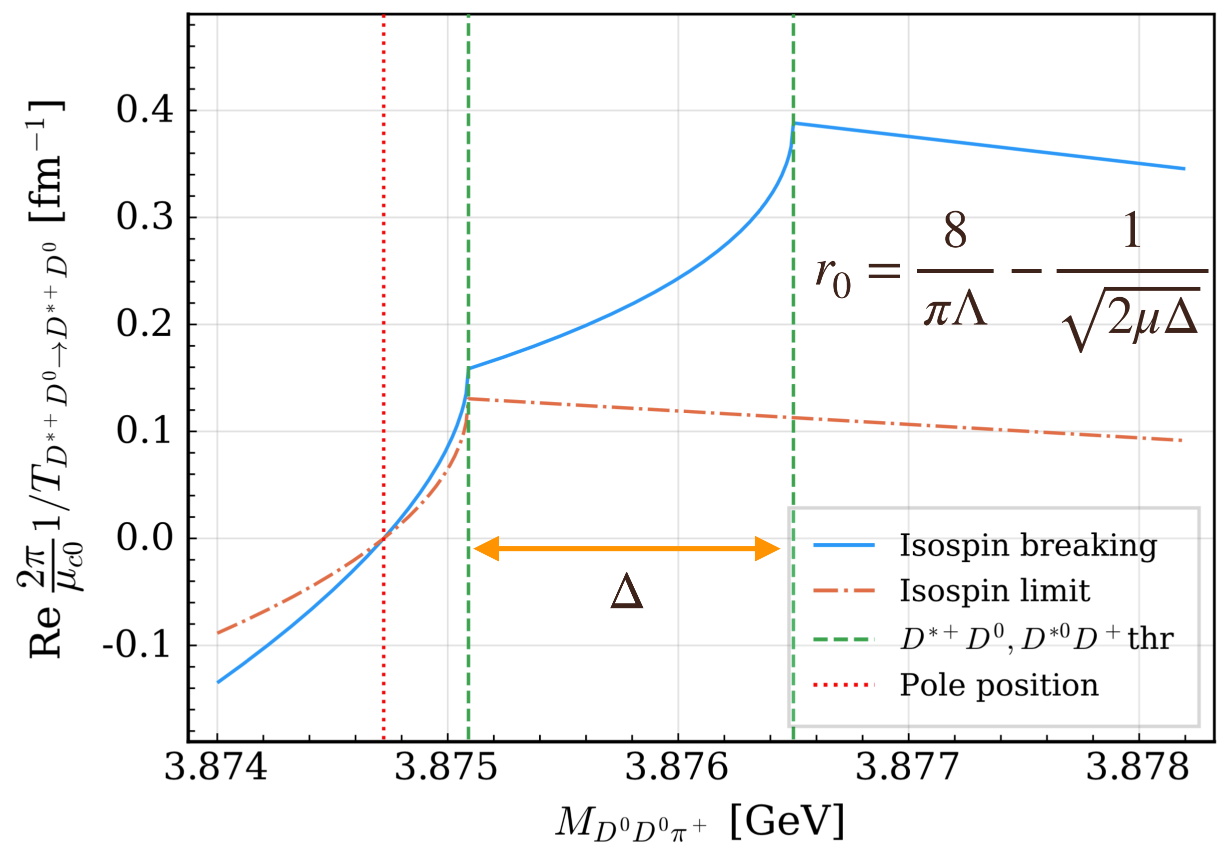
$$J_2(E) = \frac{\Lambda\mu}{\pi^2} - \frac{2\mu^2 E}{\pi^2\Lambda} + \frac{2\Delta\mu^2}{\pi^2\Lambda} - \frac{\mu\sqrt{2\mu\Delta}}{2\pi} + \frac{\mu E\sqrt{2\mu\Delta}}{4\pi\Delta} + \mathcal{O}(E^2)$$

Isospin violation

$$r_0 = -\frac{2\pi}{\mu^2}\frac{\mathrm{d}\left(J_1(M) + J_2(M)\right)}{\mathrm{d}M}\Big|_{M=M_{\text{thr.1}}+0^+}$$

$$= -\frac{8}{\pi\Lambda} - \frac{1}{\sqrt{2\mu\Delta}}$$

$$\Delta r_{\text{IV}} \equiv -\sqrt{\frac{1}{2\mu\Delta}} = -3.78\ \text{fm}$$



Progress

Since 2nd Nov. 2021

Exotic hadrons: T_{cc}

Compositeness

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

Du et al., PRD105(2022)014024

$$\Delta r_{\rm IV} \equiv -\sqrt{\frac{1}{2\mu\Delta}} = -\,3.78\ \mathrm{fm}$$

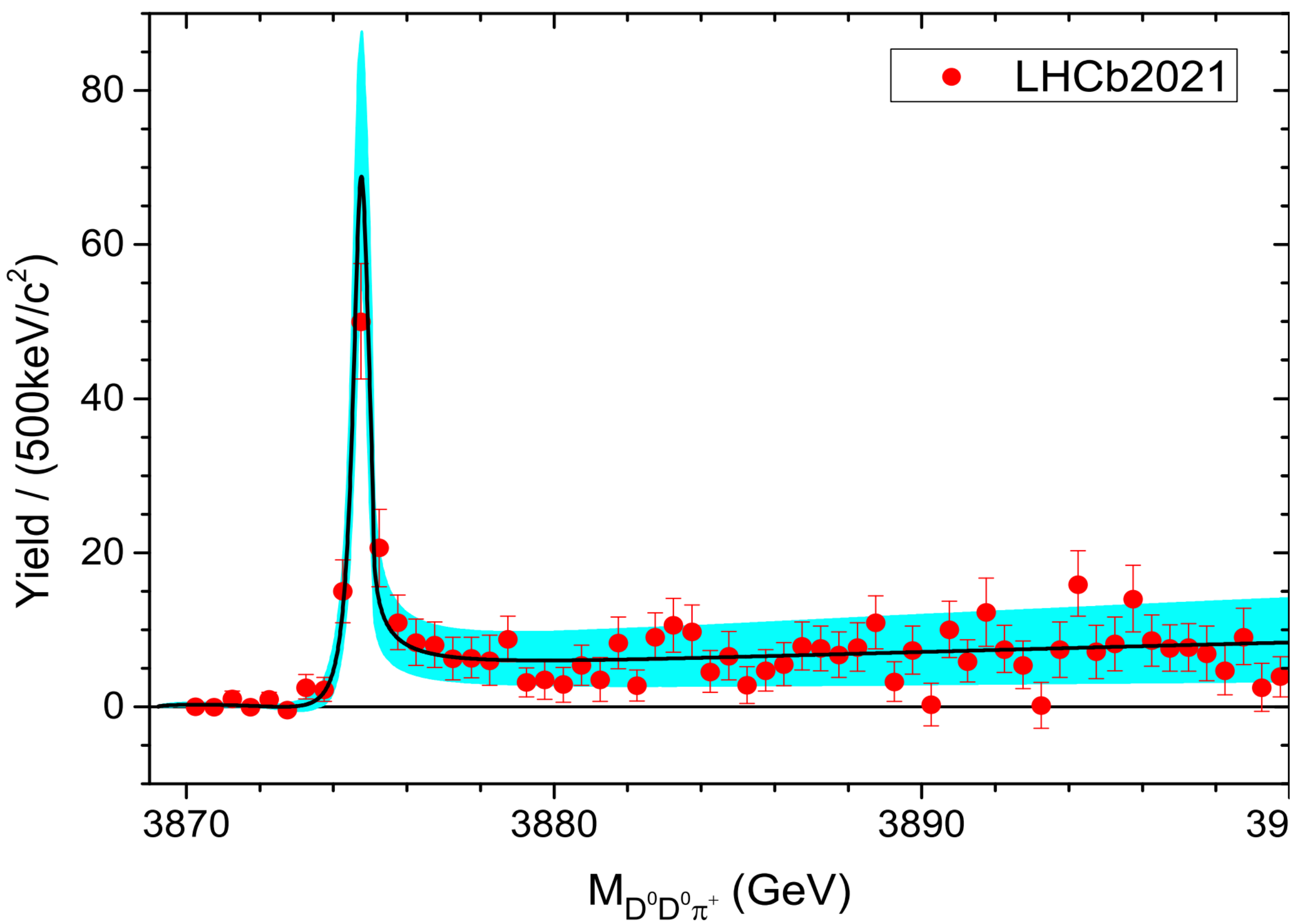
Scattering length and effective range

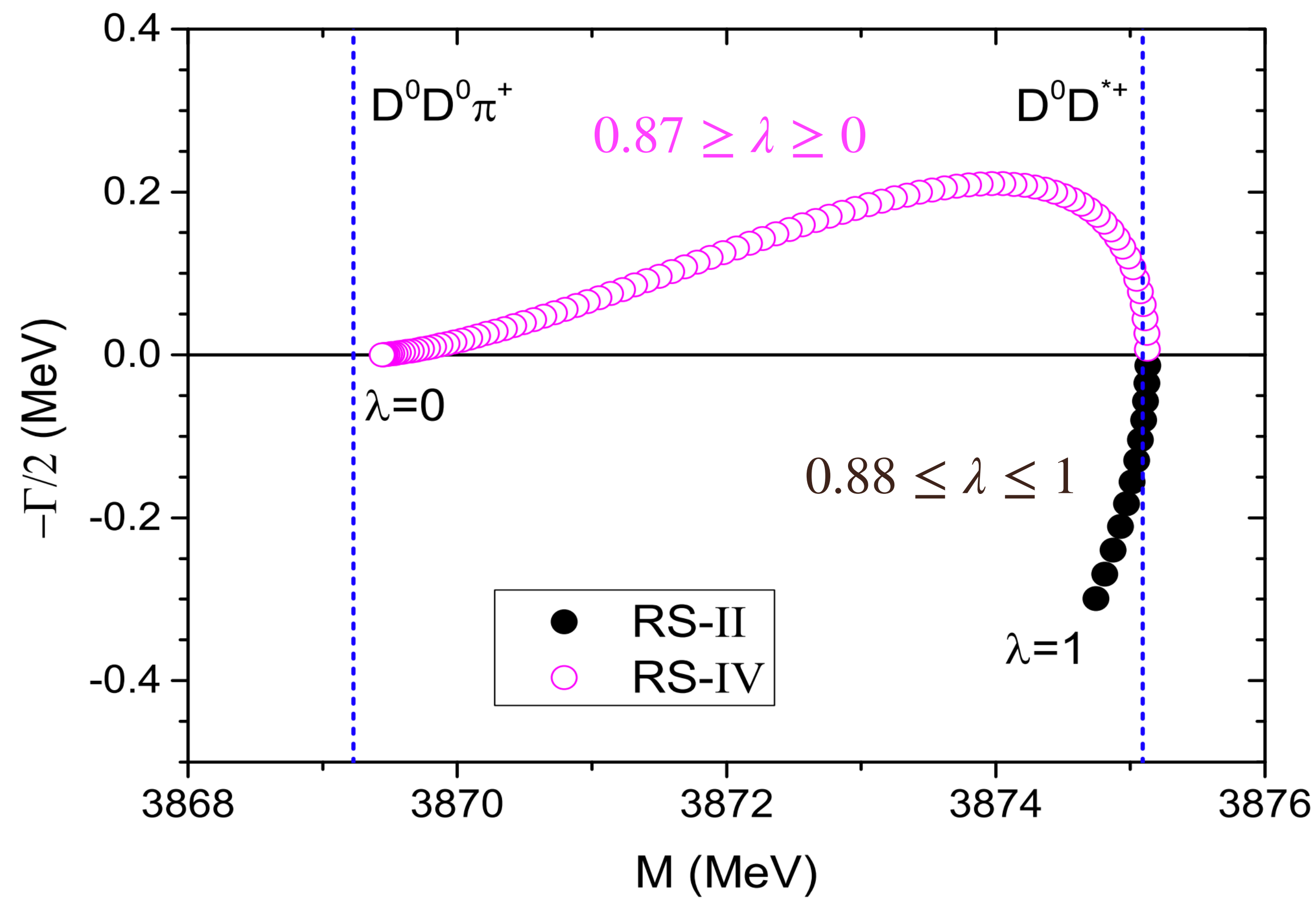
Schemes	a (fm)	r_0 (fm)	r_0' (fm)	$\bar{X}_A$
Scheme I	$\left(-6.31^{+0.36}_{-0.45}\right) + i\left(0.05^{+0.01}_{-0.01}\right)$	-2.78 ± 0.01	1.00 ± 0.01	0.87 ± 0.01
Scheme II	$\left(-6.64^{+0.36}_{0.50}\right) - i\left(0.10^{+0.01}_{-0.02}\right)$	-2.80 ± 0.01	0.98 ± 0.01	0.88 ± 0.01
Scheme III	$\left(-6.72^{+0.36}_{-0.45}\right) - i\left(0.10^{+0.03}_{-0.03}\right)$	-2.40 ± 0.01	1.38 ± 0.01	0.84 ± 0.01

OPE contribute 0.40

Progress
Since 2nd Nov. 2021

Exotic hadrons: T_{cc}





- $D^0D^0\pi^+ - D^{*+}D^0$ coupled channel
- K-matrix within the Chew-Mandelstam formalism
- T_{cc}^+ as a $D^{*+}D^0$ virtual state
- $K_{12}(s) \to \lambda K_{12}(s)$, pole trajectory
- Pole position $3874.74^{+0.11}_{-0.04} - i0.30^{+0.05}_{-0.09}$ MeV

Dai et.al., PRD105(2022)L051507

Progress

Since 2nd Nov. 2021

Exotic hadrons: T_{cc}

Zhao, et.al., PRD105(2022)096016

TABLE II: The numerical results for the $D\bar{D}^*$ and DD^* systems.

	$D\bar{D}^*$												DD^*					
	$G=1$						$G=-1$											
	$I=0$			$I=1$			$I=0$			$I=1$			$I=0$			$I=1$		
E_b	Λ_M	Λ_E	Λ_D	Λ_M	Λ_E	Λ_D	Λ_M	Λ_E	Λ_D	Λ_M	Λ_E	Λ_D	Λ_M	Λ_E	Λ_D	Λ_M	Λ_E	Λ_D
-5	1056	1013	1456	—-	—-	—-	1340	1250	1823	—-	—-	—-	1093	1097	1540	—-	—-	—-
-10	1117	1100	1562	—-	—-	—-	1402	1337	1928	—-	—-	—-	1146	1177	1635	—-	—-	—-
-15	1165	1166	1643	—-	—-	—-	1448	1401	2006	—-	—-	—-	1184	1234	1701	—-	—-	—-
-20	1208	1224	1714	—-	—-	—-	1488	1455	2072	—-	—-	—-	1214	1279	1755	—-	—-	—-
-25	1247	1276	1779	—-	—-	—-	1523	1502	2130	—-	—-	—-	1240	1318	1800	—-	—-	—-
-30	1284	1324	1839	—-	—-	—-	1555	1544	2182	—-	—-	—-	1264	1352	1840	—-	—-	—-

- Bethe-Salpeter equation
- $X(3872)$ as $I^G(J^{PC}) = 0^+(1^{++})$ $D\bar{D}^*$ hadronic molecule
- T_{cc}^+ as $I^G(J^P) = 0^+(1^+)$ DD^* hadronic molecule
- $Z_b(10610)$, $Z_c(3900)$ cannot be hadronic molecule

Progress

Since 2nd Nov. 2021

Exotic hadrons: T_{cc}

(a) (b)

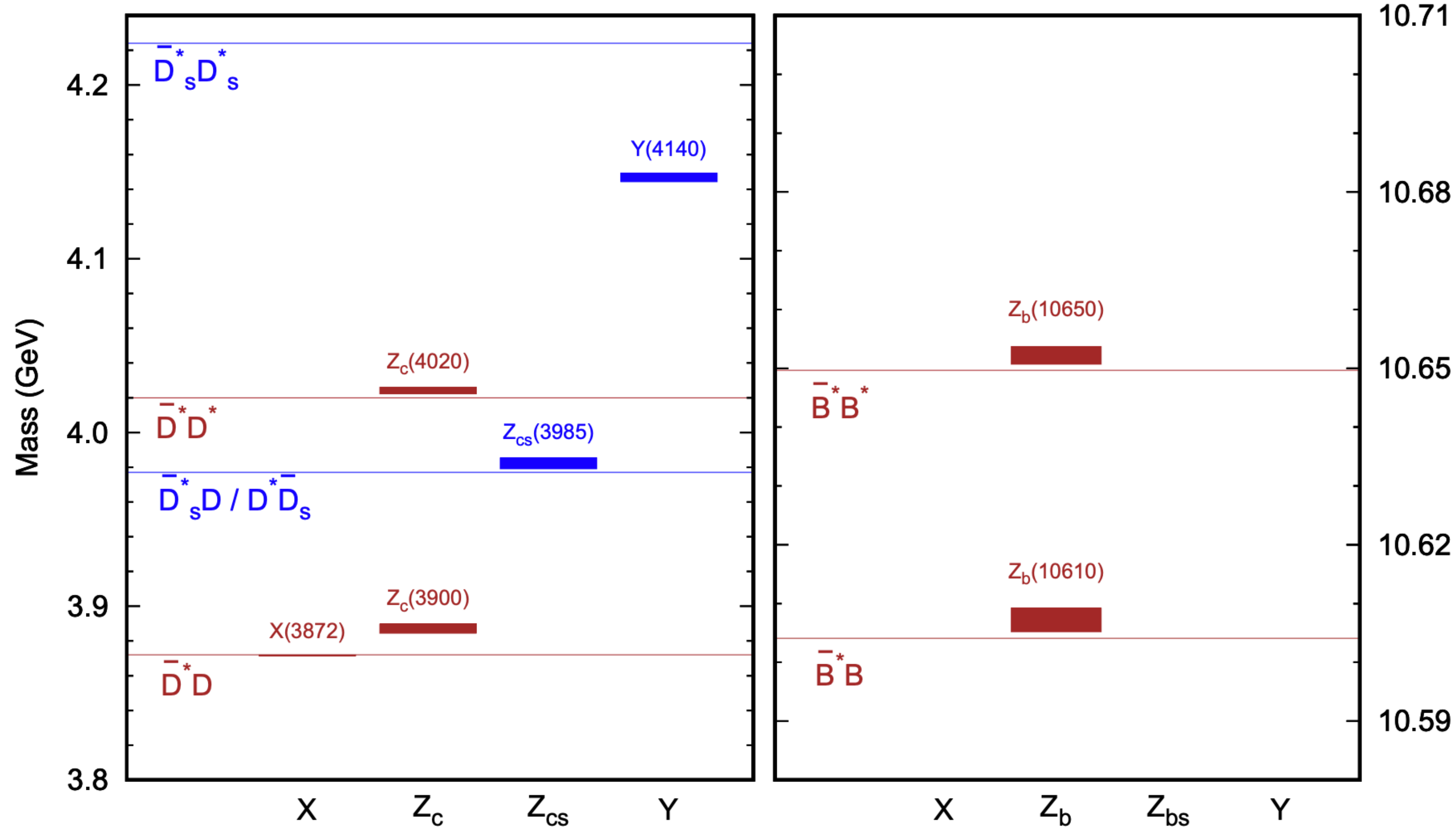
- Bethe-Salpeter equation with one-boson-exchange potential
- T_{cc} as an isospin singlet $J^P = 1^+$, DD^* hadronic molecule
- Isospin triplet $J^P = 0^+$, D^*D^* hadronic molecule exists
- the $B^{(*)}B^{(*)}$ counterparts are also analyzed

Ke, et.al., EPJC82(2022)144

Progress

Since 2nd Nov. 2021

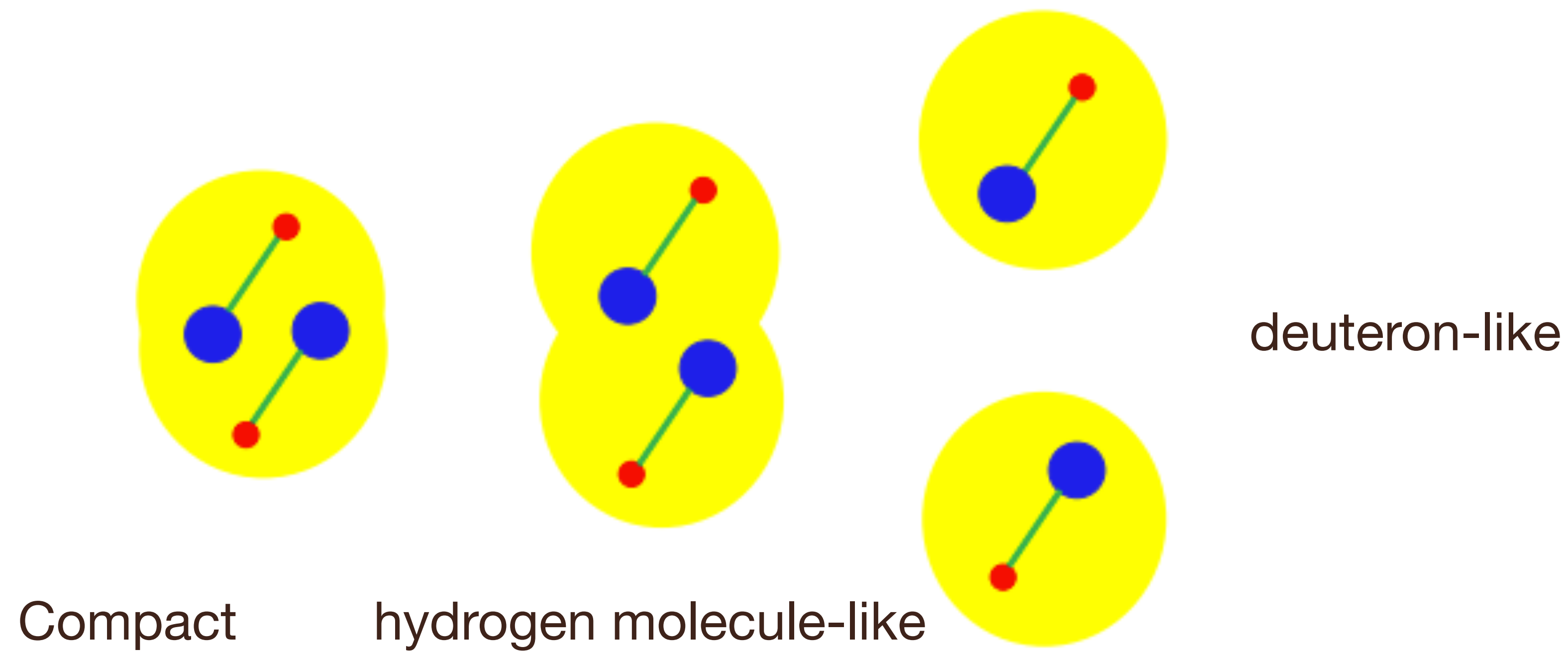
Exotic hadrons: T_{cc}



- Bethe-Salpeter equation with one-boson-exchange and J/ψ, Υ-exchange potential
- $Z_{cs}(3985)$, $Z_c(3900)$ hadronic molecule
- 0^+, $D_s\bar{D}_s$, 1^+ $D_s\bar{D}_s^*$, $(0,1,2)^+$, $D_s^*\bar{D}_s^*$ as well as their bottom partners
- $(1,2)^+$ $D^*D_s^*, D_s^*D_s^*$ as well as their bottom partners
- 1^+ $(D^*D_s + DD_s^*)$ as well as their bottom partners

Ding et.al., EPJC81(2021)732

Progress Since 2nd Nov. 2021 Exotic hadrons: T_{cc}



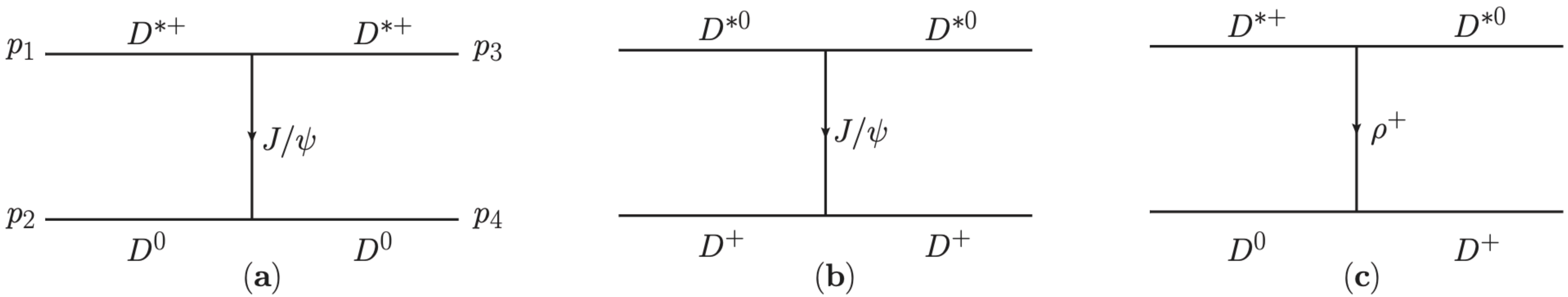
- $[Q_1\bar{q}_2]_{1_c}[Q_3\bar{q}_4]_{1_c}$ molecular configuration in a nonrelativistic quark model
- color screening confinement potential+meson exchange potential+one-gluon-exchange potential
- T_{cc}^+ is a $I(J^P) = 0(1^+)$ very loosely bound deuteron-like state with $E_B = 0.34$ MeV and size of 4.32 fm
- also investigate T_{bb}, T_{bc} system

Deng, et.al., PRD105(2022)054015

Progress

Since 2nd Nov. 2021

Exotic hadrons: T_{cc}



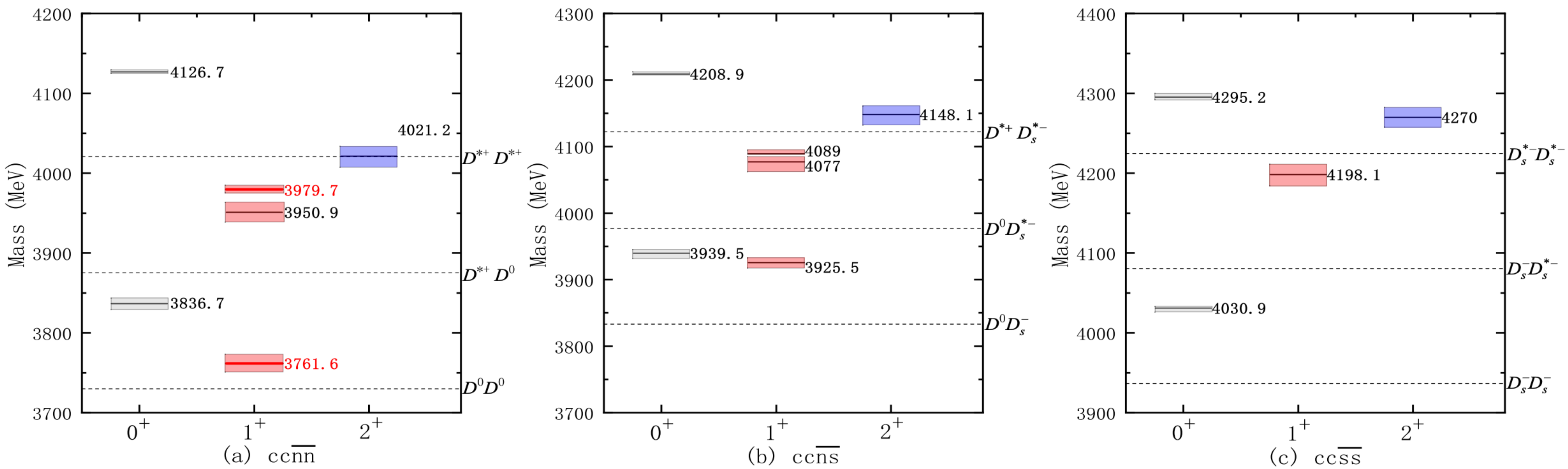
- unitary coupled channel study of the $D^{*+}D^0$, $D^{*0}D^+$ interaction
- the experimental $M_{T_{cc}^+}$ is the input
- The width is 80 keV/43 keV before and after the resolution
- Give the $D^0D^0\pi^+$ invariant mass distribution

Feijoo et.al., PRD104(2021)114015

Progress

Since 2nd Nov. 2021

Exotic hadrons: T_{cc}



- The improved chromomagnetic interaction (ICMI) model
- $J^P = 0^+,\ 1^+,\ 2^+$ double charm compact tetra quark
- $J^P = 0^+,\ 1^+,\ 2^+$ double bottom compact tetra quark

Guo et.al., PRD105(2022)014021

Progress

Since 2nd Nov. 2021

Exotic hadrons: T_{cc}

Wave function for both isospin singlet and isospin triplet

$$|T_{cc}^{+}\rangle = -\frac{1}{\sqrt{2}}(|D^{*+}\rangle|D^{0}\rangle - |D^{*0}\rangle|D^{+}\rangle), \quad I=0 \quad I_z = 0$$

$$|T_{cc}^{\prime ++}\rangle = |D^{*+}\rangle|D^{+}\rangle, \quad I=1 \quad I_z = +1$$

$$|T_{cc}^{\prime +}\rangle = -\frac{1}{\sqrt{2}}(|D^{*+}\rangle|D^{0}\rangle + |D^{*0}\rangle|D^{+}\rangle), \quad I=1 \quad I_z = 0$$

$$|T_{cc}^{\prime 0}\rangle = |D^{*0}\rangle|D^{0}\rangle, \quad I=1 \quad I_z = -1$$

Isospin property

$X(3872)[c\bar{c}q\bar{q}] \to J/\psi[c\bar{c}]3\pi$

Determine isospin from hidden charm channel

Decay amplitude

$$\mathcal{M} = \mathcal{M}_1 + \mathcal{M}_2 \equiv \frac{g_{D^{*+}D_0T_{cc}^+}}{\sqrt{1+r^2}}\left(\mathcal{M}'_1 + r\mathcal{M}'_2\right)$$

$$= \frac{1}{2\sqrt{1+r^2}}\left[(1+r)\mathcal{M}_{I=1} + (1-r)\mathcal{M}_{I=0}\right]$$

$\mathcal{M}'_1: \quad T_{cc}^{+} \to D^{*0}D^{+} \to D^{+}\pi^{0}D^{0}$

$\mathcal{M}'_2: \quad T_{cc}^{+} \to D^{*+}D^{0} \to D^{+}\pi^{0}D^{0}$

$r \equiv \dfrac{g_{D^{*0}D^{+}T_{cc}^{+}}}{g_{D^{*+}D^{0}T_{cc}^{+}}}$ $\qquad r = 1 \to I = 1 \qquad r = -1 \to I = 0$

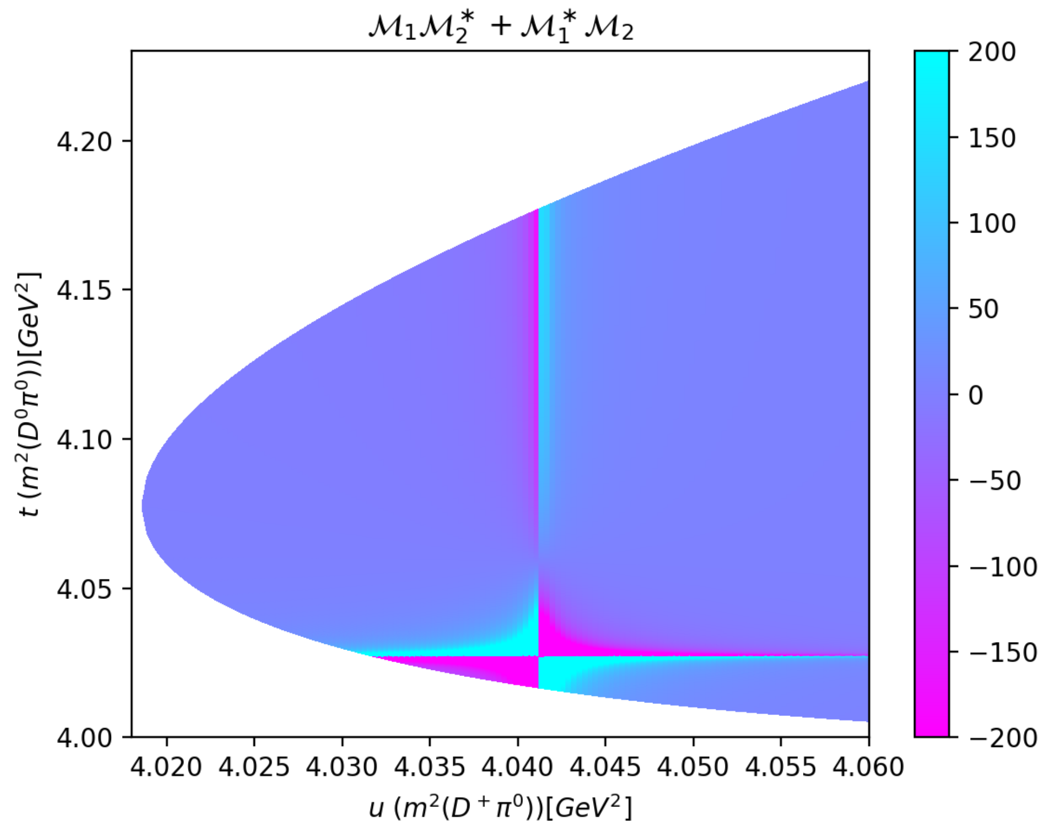
Shi, Wang, QW, hep-ph/2205.05234

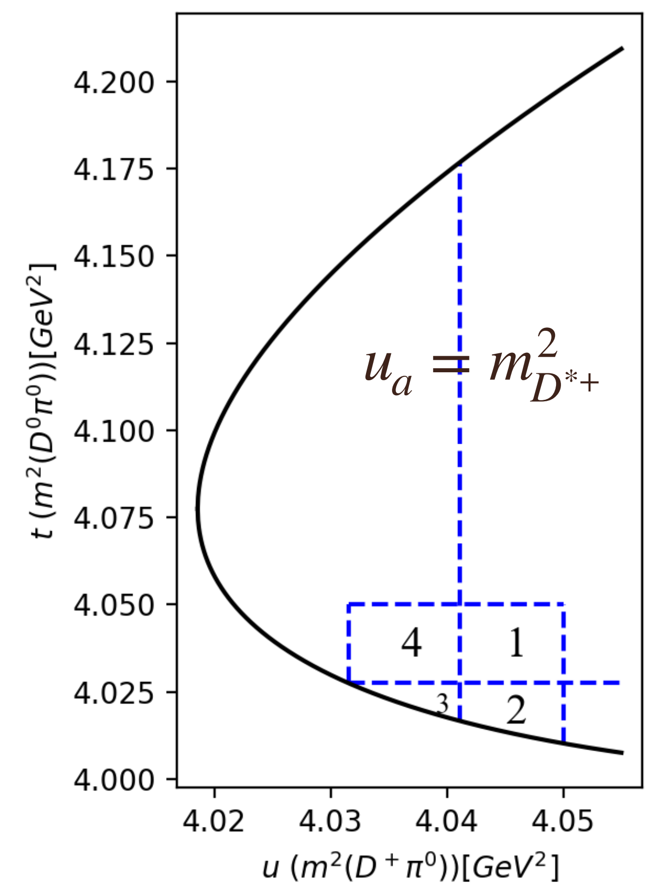
Progress

Since 2nd Nov. 2021

Exotic hadrons: T_{cc}

$$|\mathscr{M}|^2 = \frac{g^2_{D^{*+}D_0T^+_{cc}}}{1+r^2}\left[|\mathscr{M}'_1|^2 + r^2|\mathscr{M}'_2|^2 + r\left(\mathscr{M}'_1\mathscr{M}'^*_2 + \mathscr{M}'^*_1\mathscr{M}'_2\right)\right]$$





$t_b = 4.05\ \mathrm{GeV}^2$

$t_a = m^2_{D^{*0}}$

Remove quadratic term of r

$u_b = 4.03\ \mathrm{GeV}^2 \quad u_c = 4.05\ \mathrm{GeV}^2$

$$A \equiv \frac{N_1 + N_3 - N_2 - N_4}{N_1 + N_3 + N_2 + N_4} \qquad r \equiv \frac{g_{D^{*0}D^+T^+_{cc}}}{g_{D^{*+}D^0T^+_{cc}}}$$

$r = 1 \to I = 1 \qquad r = -1 \to I = 0$

$\mathscr{M}'_1: \quad T^+_{cc} \to D^{*0}D^+ \to D^+\pi^0D^0$

$\mathscr{M}'_2: \quad T^+_{cc} \to D^{*+}D^0 \to D^+\pi^0D^0$

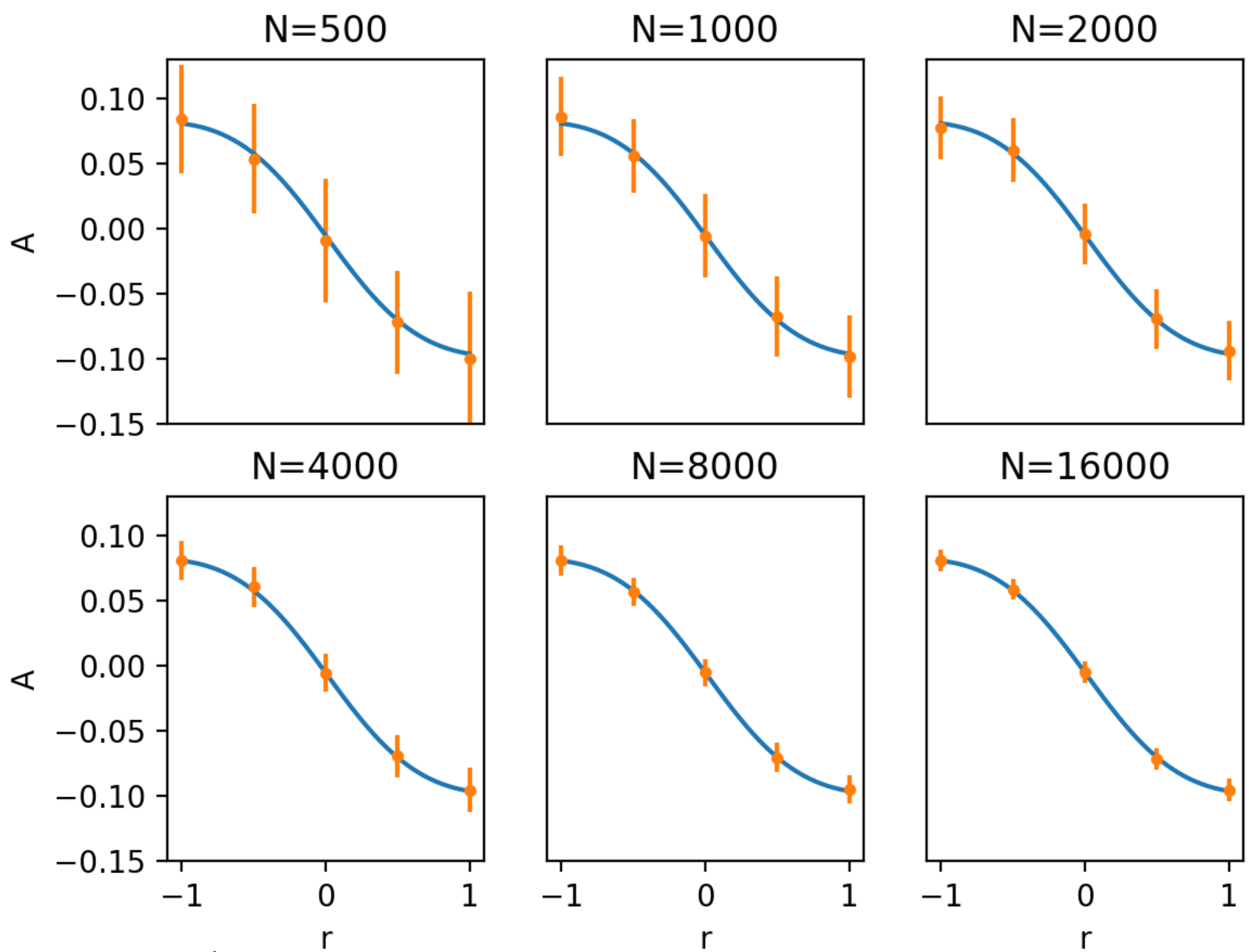
Shi, Wang, QW, hep-ph/2205.05234

Progress

Since 2nd Nov. 2021

Exotic hadrons: T_{cc}

A in terms of r



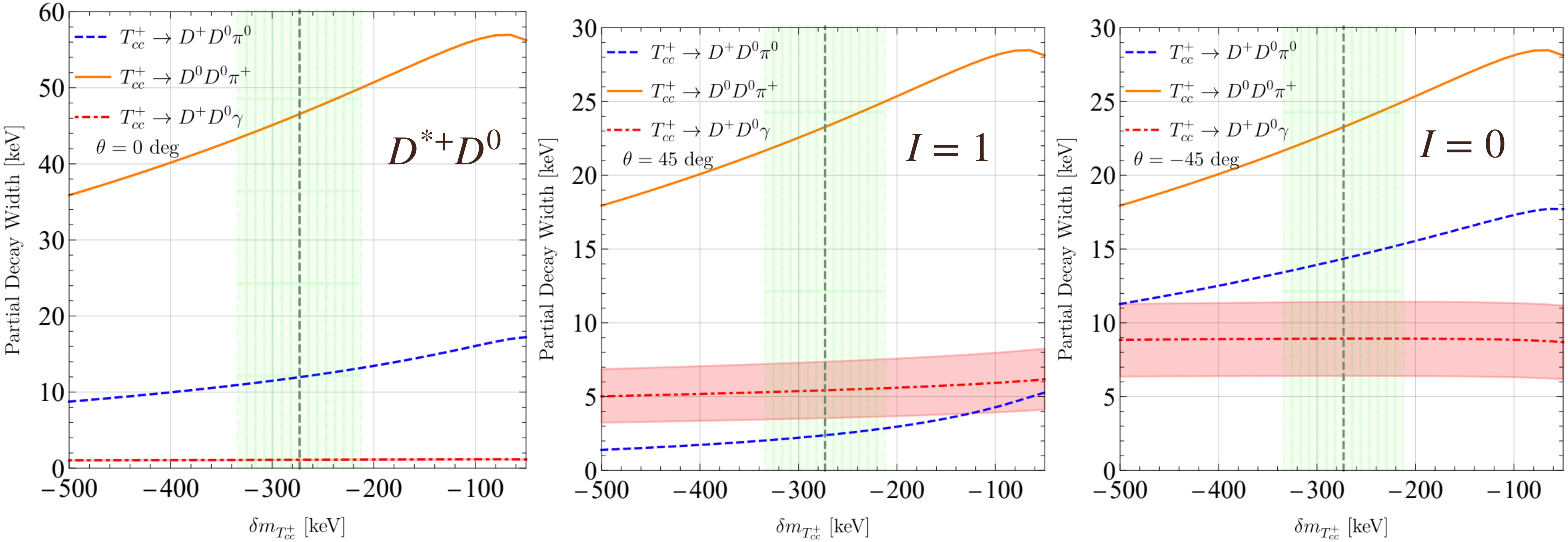
- N=1000 can determine the isospin property
- it also works for other open heavy flavor exotics
- The isospin property of hidden charm/bottom exotics can also be determined in hidden charm/bottom plus pion channels

Shi, Wang, QW, hep-ph/2205.05234

Progress

Since 2nd Nov. 2021

Exotic hadrons: T_{cc}



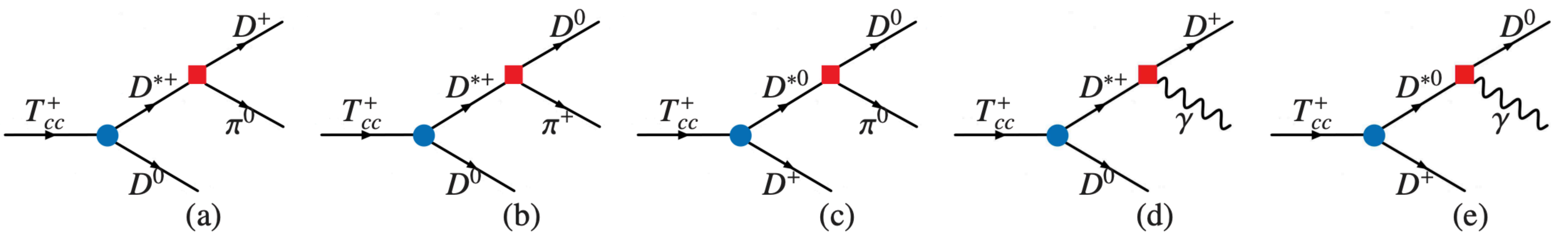
- $T_{cc}^{+} \to D^0 D^0 \pi^+$ is the largest one
- T_{cc}^{+} dominated by $D^{*+}D^0$ component
- $\Gamma(D^{*+}D^0) = 59.7^{+4.6}_{-4.4}$ keV, $\Gamma(I=0) = 46.7^{+2.7}_{-2.9}$ keV

Meng, et.al., PRD104(2021)051502

Progress Since 2nd Nov. 2021 Exotic hadrons: T_{cc}

Xin et.al., EPJA58(2022)110

- QCD sum rule
- $I = 0,\ J^P = 1^+,\ DD^*$ molecular assignment of the T_{cc}^+
- $I = 1,\ J^P = 1^+,\ DD^*$ molecule exist, but with higher mass



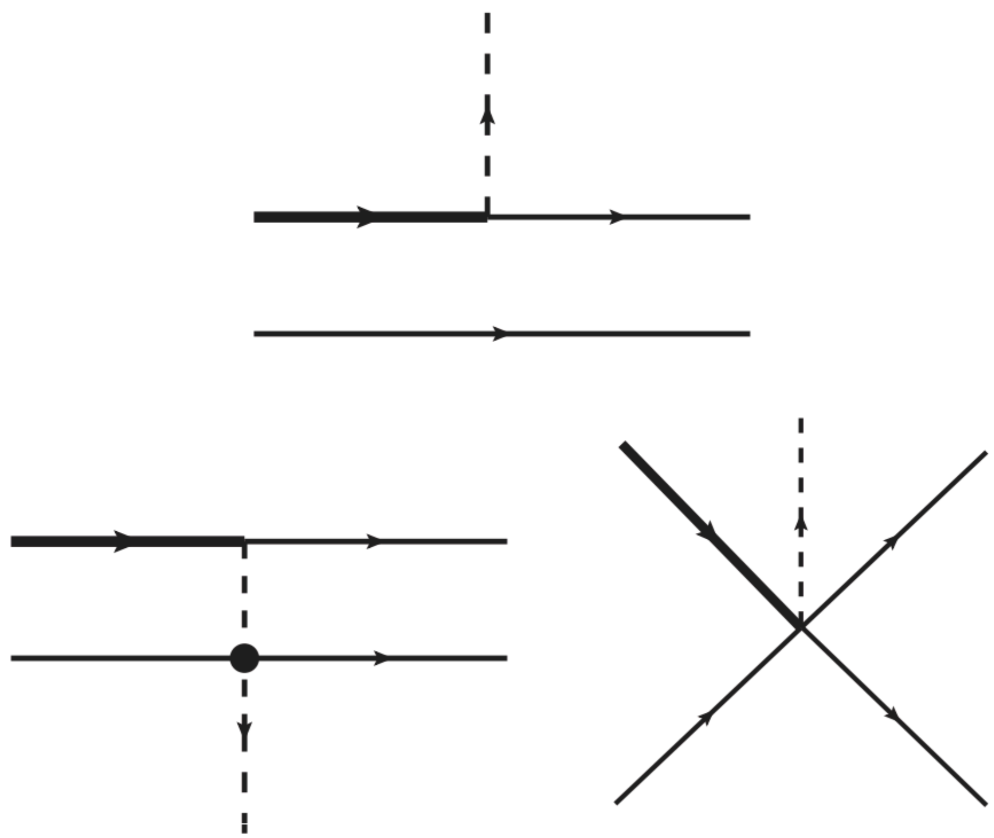
- Effective lagrangian approach
- $\Gamma = 63$ keV
- $\Gamma(DD\pi) > \Gamma(DD\gamma)$

Ling et.al., PLB826(2022)136897,

Progress

Since 2nd Nov. 2021

Exotic hadrons: T_{cc}



$$\Gamma^{\mathrm{NLO}(*)}\left(T_{cc}^{+} \to D^0 D^0 \pi^+\right) = 34.0 \pm 1.2^{+1.8+1.9}_{-1.7-1.0}\mathrm{keV}$$

$$\Gamma^{\mathrm{NLO}(*)}\left(T_{cc}^{+} \to D^+ D^0 \pi^0\right) = 16.4^{+0.6+0.6+1.2}_{-0.5-0.5-0.5}\mathrm{keV}$$

$$\Gamma^{\mathrm{NLO}(*)}\left(T_{cc}^{+} \to D^+ D^0 \gamma\right) = 7.5 \pm 0.6 \pm 0.2^{+0.9}_{-0.4}\mathrm{keV}$$

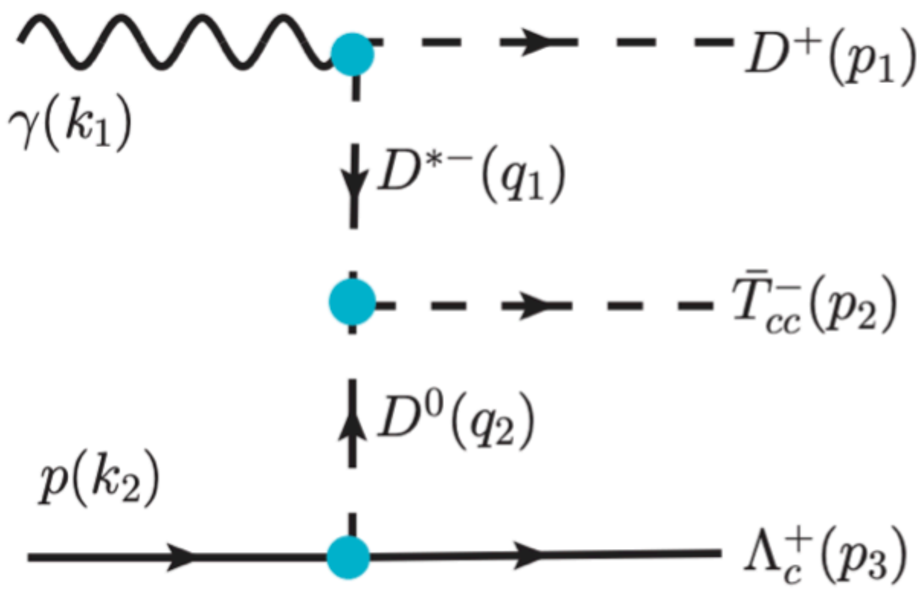
- Well scale separation where EFT can be applied
- $\Gamma^{\mathrm{LO}} = 49 \pm 16$ keV, $\Gamma^{\mathrm{NLO}} = 58^{+7}_{-6}$ keV
- Suggest the existence of a small non-molecular component

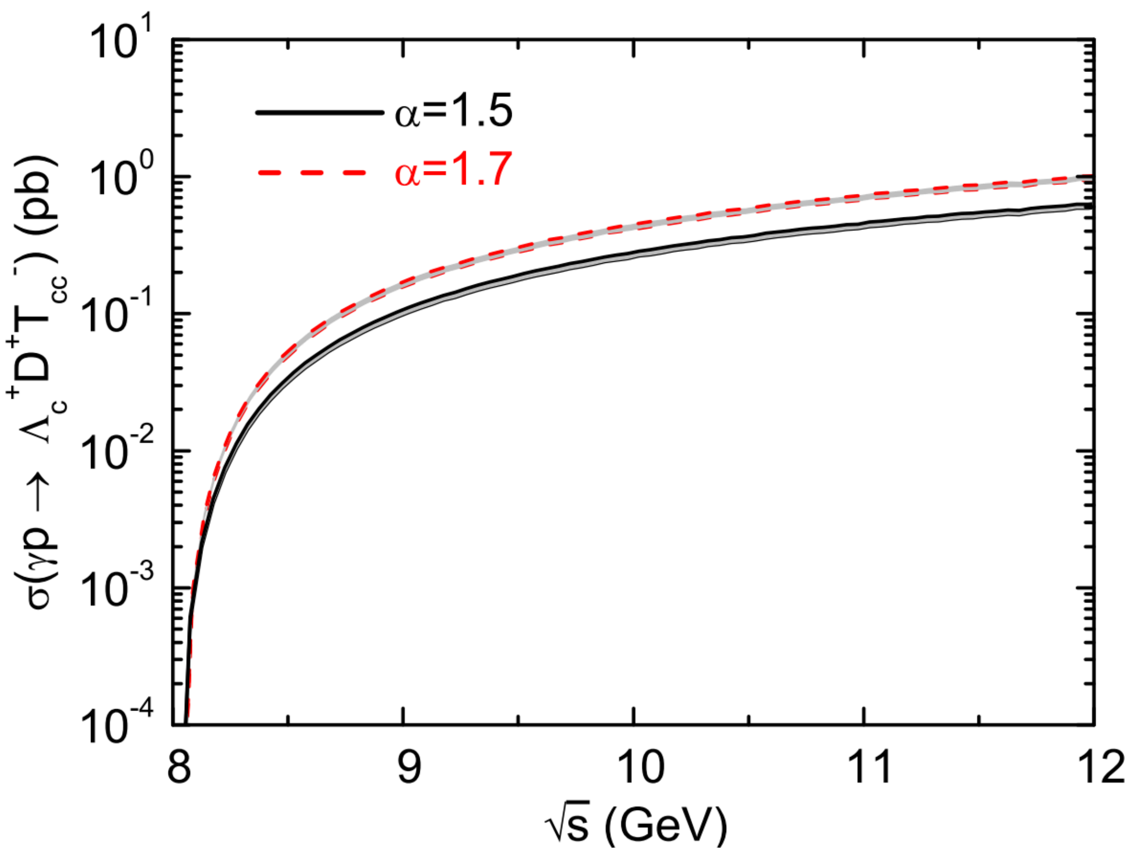
Yan et.al., PRD105(2022)014007

Progress

Since 2nd Nov. 2021

Exotic hadrons: T_{cc}





- Estimate $\gamma p \to D^+ \bar{T}_{cc}^- \Lambda_c^+$ cross section of the order of 1.0 pb
- $g_{T_{cc}D^*D}$ is from the theory
- $g_{\gamma DD^{(*)}}$ is from the experimental data
- $g_{\Lambda ND}$ is from light-cone sum rule
- accessible at the proposed EicC and the EIC

Huang, et.al., PRD104(2021)116008

Progress Since 2nd Nov. 2021

Exotic hadrons: T_{cc}

Production of T_{cc} in HIC

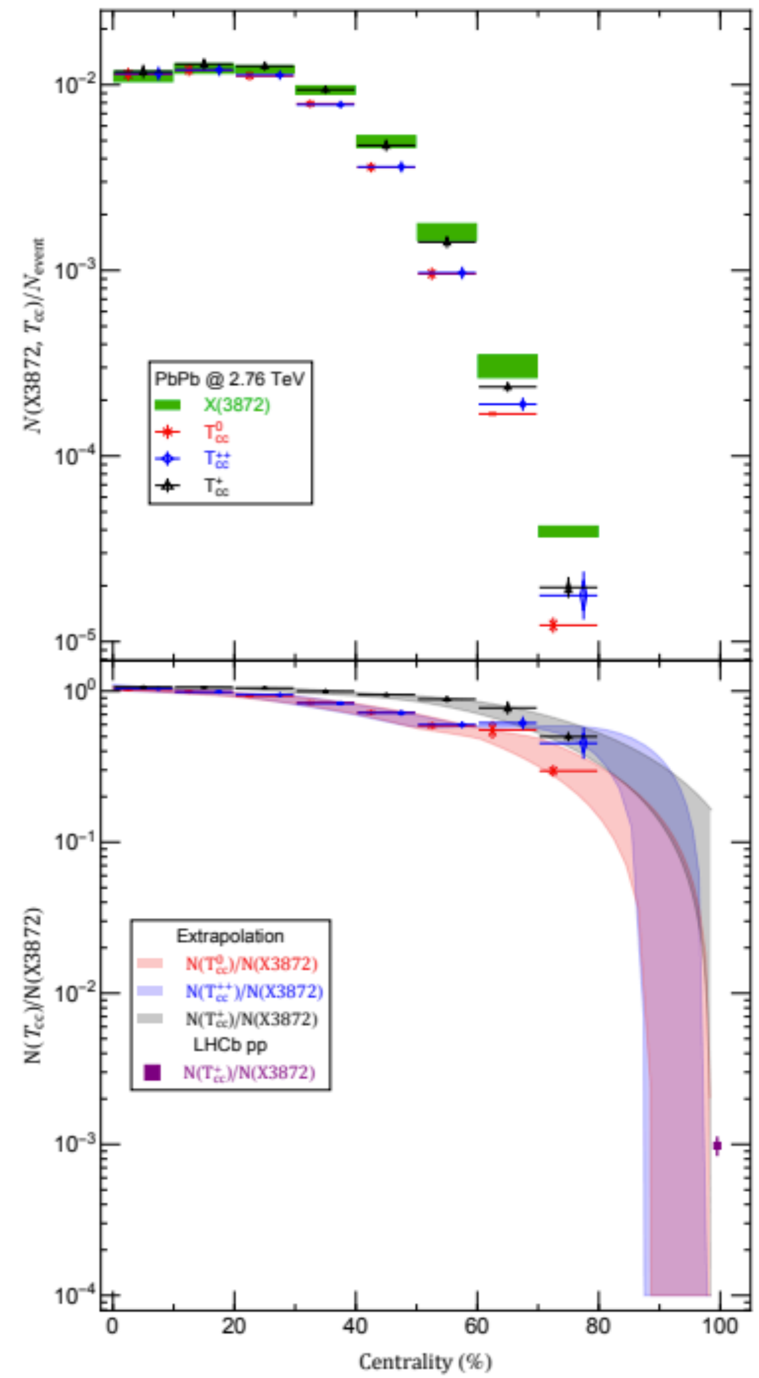
- $I = 1$: T'^0_{cc}, T'^+_{cc}, T'^{++}_{cc}

$I = 0$: T^+_{cc}

- $R(T^{0,+,++}_{cc}) \equiv N(T^{0,+,++}_{cc})/N(X(3872))$
- A third order polynomial function for
- the relative yield ratio
- T^+_{cc} is about 3 orders smaller at UPC
- Isotriplet partners is even smaller than

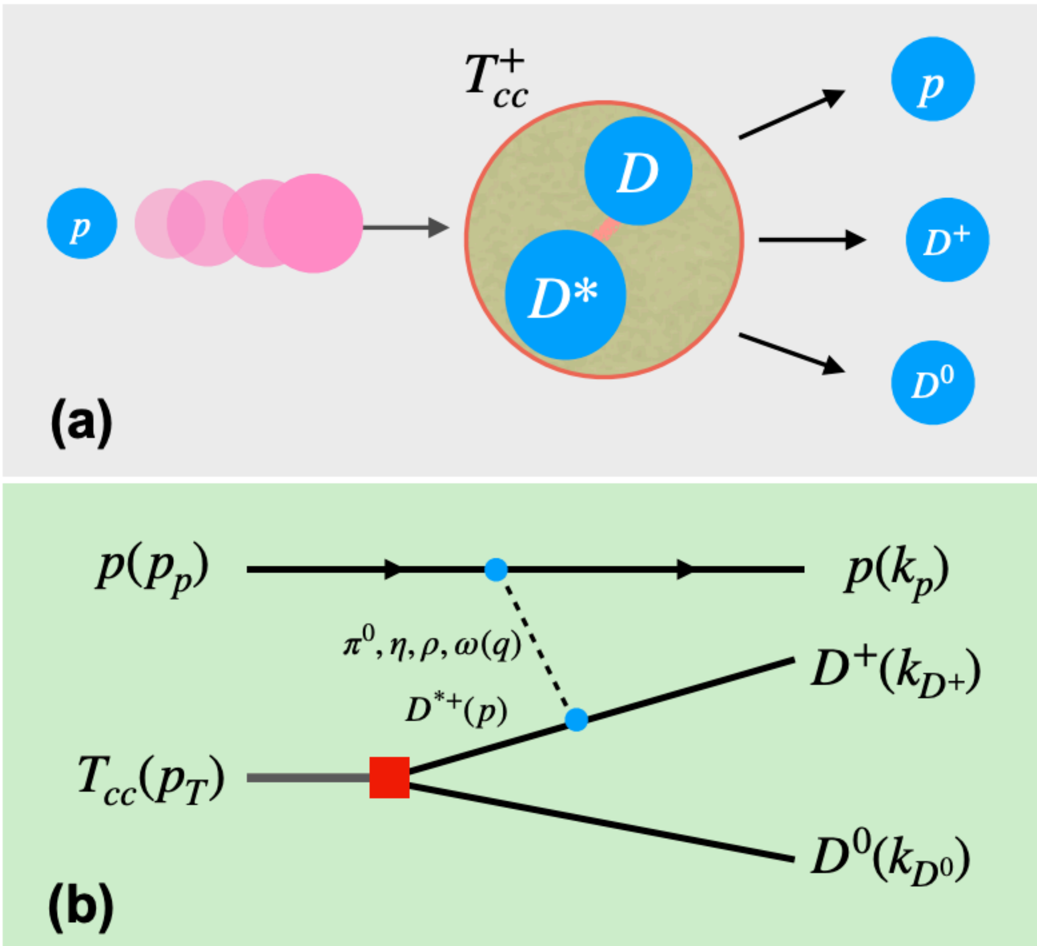
that of T^+_{cc}

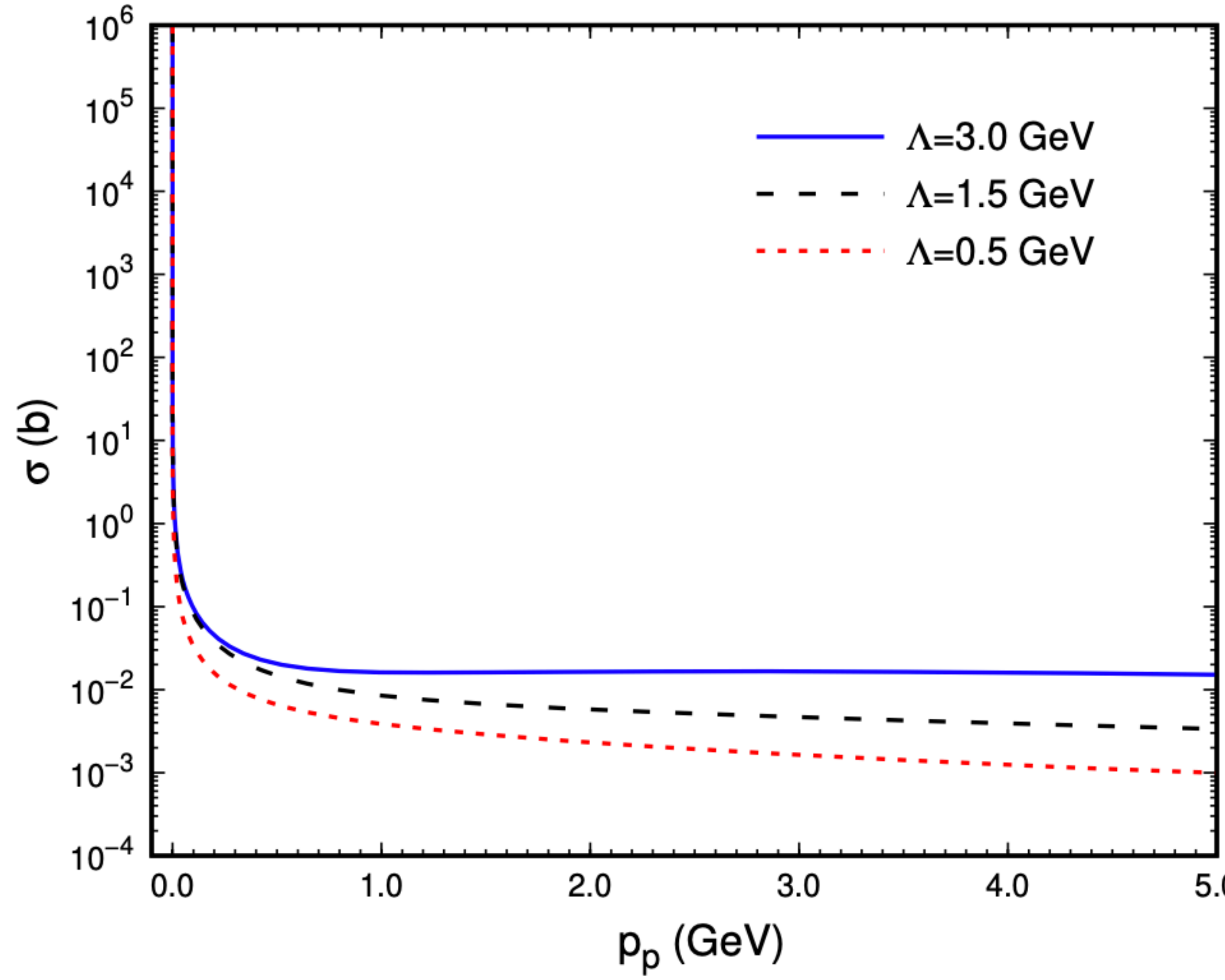
The centrality distribution



Hu et.al., PRD104(2021)L111502

Progress Since 2nd Nov. 2021 Exotic hadrons: T_{cc}





- $p + T^+_{cc} \to p + D^+ + D^0$ process, with 10 mb at p_p several GeV
- the guasi-fission phenomenon can be accessible at the forthcoming PANDA experiemnt

He, et.al., EPJC82(2022)387

Progress Since 2nd Nov. 2021

Exotic hadrons

- glueball and hybrid Jiang, et.al., 2205.12541, Chen, et.al., 2207.04694

- Double baryon system Liu, et.al., PRD105(2022)034006, Wang, 2201.02955, Chen et.al., 2204, 13316,

  Weng, et.al., 2207.05505, Liu, et.al., 2207.00183, Song, et.al., 2207.13957

- Pentaquark

  Chen, et.al., 2111.03241, Xie, et.al., 2204.12356, Wang et.al., Sci. China Phys. Mech. Astron 65(2022)291011

  Wang, et.al., 2207.10493, Xie, et.al., 2204.12356, Yang et.al., 2203.15616, Wang et.al., 2207.06060, 2205.02530,

  Yan, et.al., 2207.11144, Xie, et.al., 2204.12356, Zhu et.al., PRD105(2022)094036, Xing et.al., 2203.03248,

  Zhou et.al., PRD106(2022)034034, Xing et.al., 2203.03248, An et.al., 2207.02813, An et.al., PRD105(2022)7

  Yang et.al., PRD106(2022)014005, Chen et.al., PRD105(2022)014029, Wang et.al., EPJC82(2022)721

Progress Since 2nd Nov. 2021

Exotic hadrons

- Tetraquark

$X(2600, 2866)$ Zhang, et.al., 2206.13133 ,Dai, et.al., PRD105(2022)096022

Z_c Z_{cs} Chen, et.al., PRD105(2022)036002, Du, et.al., PRD105(2022)074018, Zhai et.al., PRD106(2022)034026

Liu, et.al., 2204.08104, Wu, et.al., EPJC82(2022)520, Wang, CPC46(2022)123106, CPC46(2022)103106,

Han, et.al., 2203.00168 Talk by Zhi Hui Guo

$QQ\bar{Q}\bar{Q}$ Chen, et.al., 2207.08593, Hu, et.al., 2202.10380, Zhou et.al., 2207.07537, Wang, 2207.08059,

Wang, et.al., PRD106(2022)054015, Zhuang, et.al., PRD105(2022)054026, BLFQ, PRD105(2022)094028

Liu et.al., PRD104(2022)116029, Dong, et.al., PRL126(2021)132001

$Q\bar{Q}s\bar{q}$ Ke, et.al., PRD105(2022)114019, Yang, et.al., 2206.06051, Yang et.al., PRD106(2022)014021,
Dai, et.al., PRD105(2022)074017, Wu, et.al., 2112.05967, Xie et.al., 2207.12178, Chen et.al., PRD105(2022)096004,

Ge et.al., 2207.09900,

Progress Since 2nd Nov. 2021

Exotic hadrons

- Tetraquark

$QQ\bar{q}\bar{q}$ Zhao, et.al., PRD105(2022)096016, Shi, et.al., 2205.05234,

Ke, et.al., EPJC82(2022)144, Du, et.al., PRD105(2022)014024, Ding et.al., EPJC81(2021)732, Guo et.al., PRD105(2022)014021, Dai et.al., PRD105(2022)016029, Dai et.al., PRD105(2022)L051507, Huang, et.al., PRD104(2021)116008, Feijoo et.al., PRD104(2021)114015, Wang, et.al., PRD104(2021)094030, He, et.al., EPJC82(2022)387, Chen et.al., 2206.10917, Xin et.al., EPJA58(2022)110, Ling et.al., PLB826(2022)136897, Yan et.al., PRD105(2022)014007, Ren et.al., Adv. High Energy Phys. 2022(2022)9103031,

X Ji, et.al., 2207.08563, Xin, et.al., 2207.09910, Wang et.al., NPB978(2022)115761,

Wang et.al., PRD in press

$QQ\bar{Q}\bar{q}$ Liu, et.al., 2205.08281

Talk by Zhi Yang

D_s Yang, et.al., PRL128(2022)11,2207.07320, Gao et.al., PRD105(2022)074037,

Du et.al., PRL126(2021)192001,

Progress Since 2nd Nov. 2021

Exotic hadrons

- Tetraquark

Y Qian, et.al., PLB833(2022)13792, Peng, et.al., 2205.13590

0^{--} Ji, et.al., PRL129(2022)102002

$D^{\pm}D^{*\mp}$ hadronic atom Zhang, et.al., PRL127(2022012002,

- Review Chen, et.al., 2204.02649, Meng, et.al., 2204.08716

Progress Since 2nd Nov. 2021

Exotic hadrons

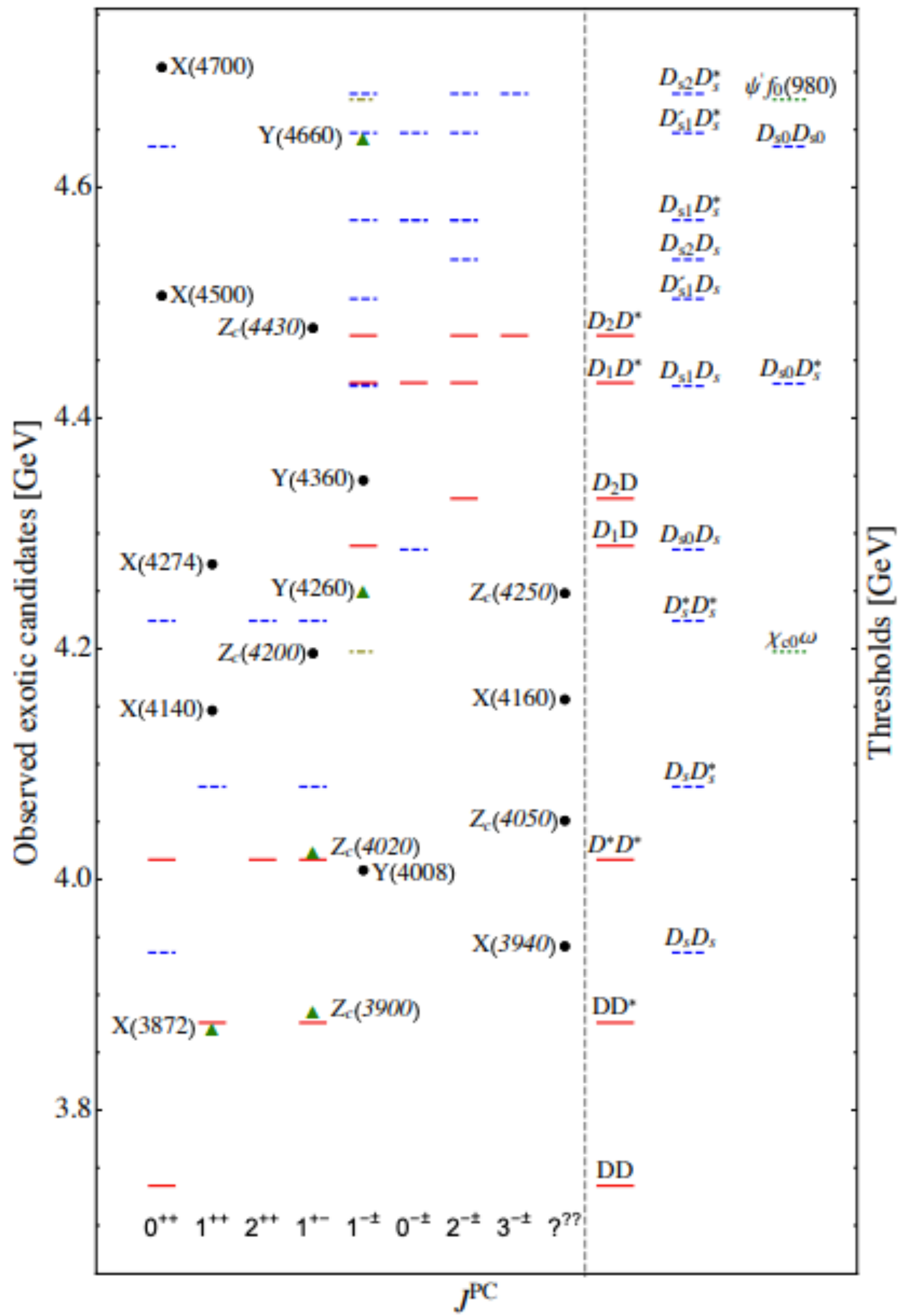
- Tetraquark

  Y Qian, et.al., PLB83

  0^{--} Ji, et.al., PRL129(2

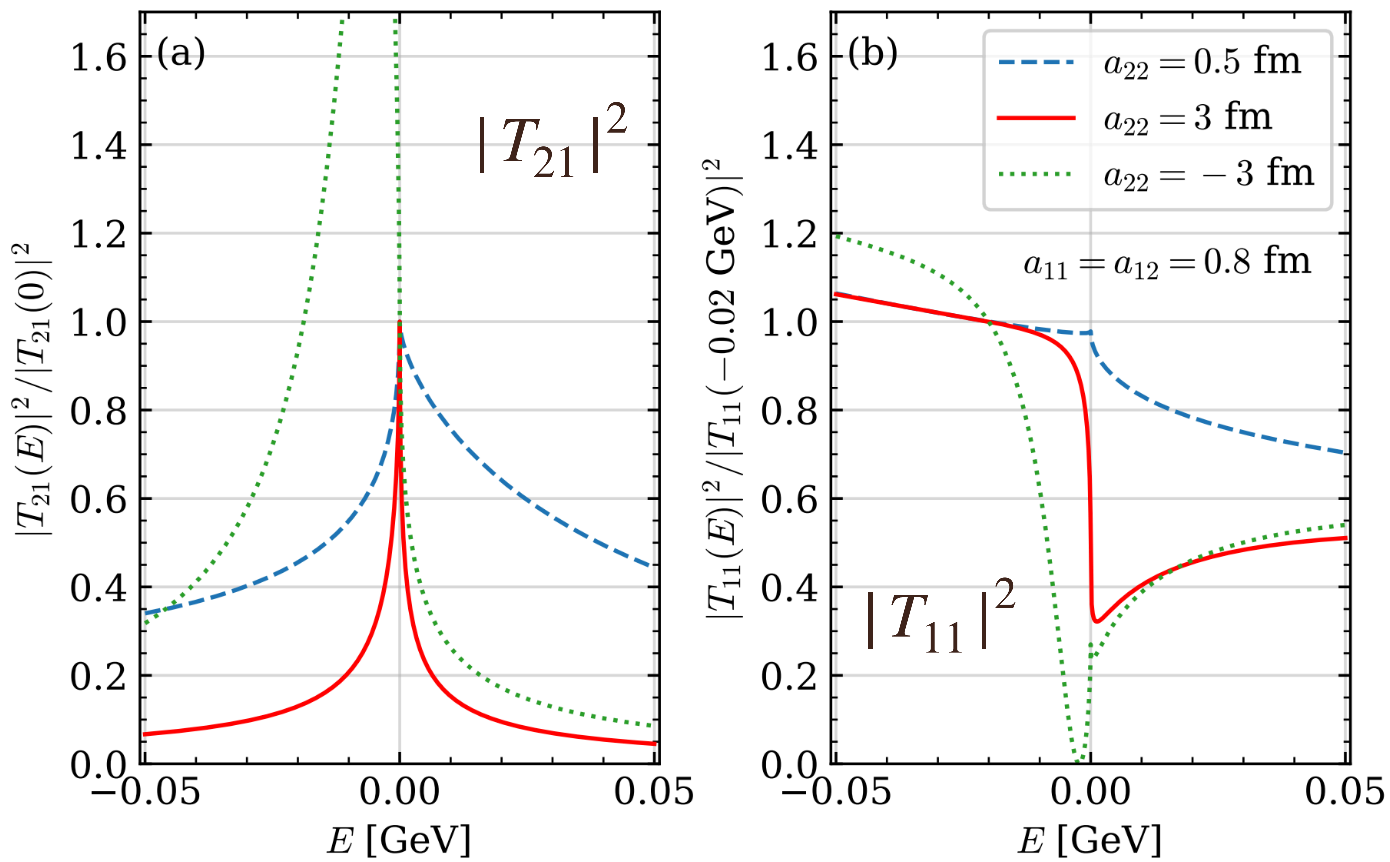
  $D^{\pm}D^{*\mp}$ hadronic atom Zha

- Review Chen, et.al., 2204



Progress Since 2nd Nov. 2021

Exotic hadrons



1 : $J/\psi\pi$

2 : $D\bar{D}^*$

- near-threshold peak for attractive force and $\Gamma \propto \dfrac{1}{\mu}$
- Always appear at any threshold of a pair of heavy-quark and heavy-antiquark hadrons, which have attractive interaction in the hidden charmonium/bottomonium plus light mesons

Dong et.al., PRL126(2021)152001

Progress   Since 2nd Nov. 2021

Exotic hadrons

TABLE I. Charm-anticharm hadron pairs that have attractive interaction at threshold from vector-meson exchanges (similar in the bottom sector). We use H, T and S to denote the ground state heavy mesons, SU(3) antitriplet and sextet heavy baryons, respectively. Isospin is labelled for each pair in square brackets. Those with † mean that the contribution from the light-vector exchanges vanishes, and the attraction is provided by sub-leading exchanges of vector charmonia [63].

$H\bar{H}$	$D^{(*)}\bar{D}^{(*)}[0,1^\dagger]$;	$D_s^{(*)}\bar{D}^{(*)}\ [\frac{1}{2}^\dagger]$;	$D_s^{(*)}\bar{D}_s^{(*)}\ [0]$
$\bar{H}T$	$\bar{D}^{(*)}\Xi_c\ [0]$;	$\bar{D}_s^{(*)}\Lambda_c\ [0^\dagger]$	
$\bar{H}S$	$\bar{D}^{(*)}\Sigma_c^{(*)}\ [\frac{1}{2}]$;	$\bar{D}_s^{(*)}\Sigma_c^{(*)}\ [1^\dagger]$;	$\bar{D}^{(*)}\Xi_c^{\prime(*)}\ [0]$;
	$\bar{D}^{(*)}\Omega_c^{(*)}\ [\frac{1}{2}^\dagger]$		
$T\bar{T}$	$\Lambda_c\bar{\Lambda}_c\ [0]$;	$\Lambda_c\bar{\Xi}_c\ [\frac{1}{2}]$;	$\Xi_c\bar{\Xi}_c\ [0,1]$
$T\bar{S}$	$\Lambda_c\bar{\Sigma}_c^{(*)}\ [1]$;	$\Lambda_c\bar{\Xi}_c^{\prime(*)}\ [\frac{1}{2}]$;	$\Lambda_c\bar{\Omega}_c^{(*)}\ [0^\dagger]$;
	$\Xi_c\bar{\Sigma}_c^{(*)}\ [\frac{3}{2}^\dagger, \frac{1}{2}]$;	$\Xi_c\bar{\Xi}_c^{\prime(*)}\ [1,0]$;	$\Xi_c\bar{\Omega}_c^{(*)}\ [\frac{1}{2}]$
$S\bar{S}$	$\Sigma_c^{(*)}\bar{\Sigma}_c^{(*)}\ [2^\dagger,1,0]$;	$\Sigma_c^{(*)}\bar{\Xi}_c^{\prime(*)}\ [\frac{3}{2}^\dagger, \frac{1}{2}]$;	$\Sigma_c^{(*)}\bar{\Omega}_c^{(*)}\ [0^\dagger]$;
	$\Xi_c^{\prime(*)}\bar{\Xi}_c^{\prime(*)}\ [1,0]$;	$\Xi_c^{\prime(*)}\bar{\Omega}_c^{(*)}\ [\frac{1}{2}]$;	$\Omega_c^{(*)}\bar{\Omega}_c^{(*)}\ [0]$

$1:\ J/\psi\pi$

$2:\ D\bar{D}^*$

- near-thresho
- Always appe ıvy-antiquark hadrons, whi ıium/ bottomonium plus light mesons

Dong et.al., PRL126(2021)152001

Summary and outlook

- Study normal hadrons is still interesting
- No consensus on any given exotic candidates
- We are on the right way
- Further inputs from experimental and lattice side

Thank you for your attention!