Double charm tetraquark in the molecular picture

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Outline

- A small review of exotic hadrons
- The observation of double charm tetraquark
- The line shape of double charm tetraquark
- The isospin property of charm tetraquark
- Summary and outlook

Du, Baru, Dong, Filin, Guo, Hanhart, Nefediev, Nieves, QW, PRD105(2022)014024

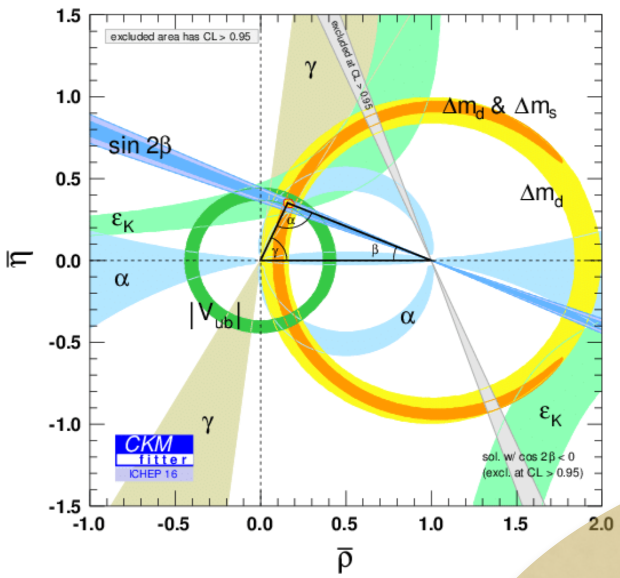
Baru, Dong, Du, Filin, Guo, Hanhart, Nefediev, Nieves, QW, hep-ph/2110.07484 (PLB in press)

Shi, Wang, QW, hep-ph/2205.05234

Hu, Liao, Wang, QW, Xing, PRD104(2021)L111502 张辉报告： 重离子对撞中奇特强子态的产生

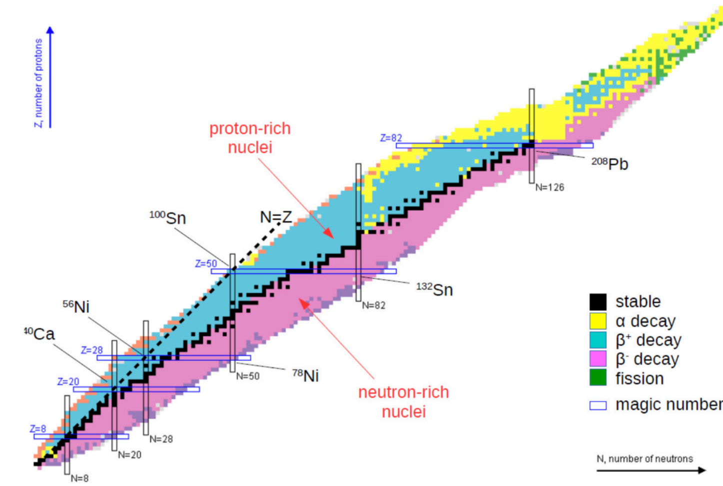
Liu, Zhang, Hu, QW, PRD105(2022)076013 张振宇报告：机器学习在强子物理中的应用

A small review of exotic hadrons

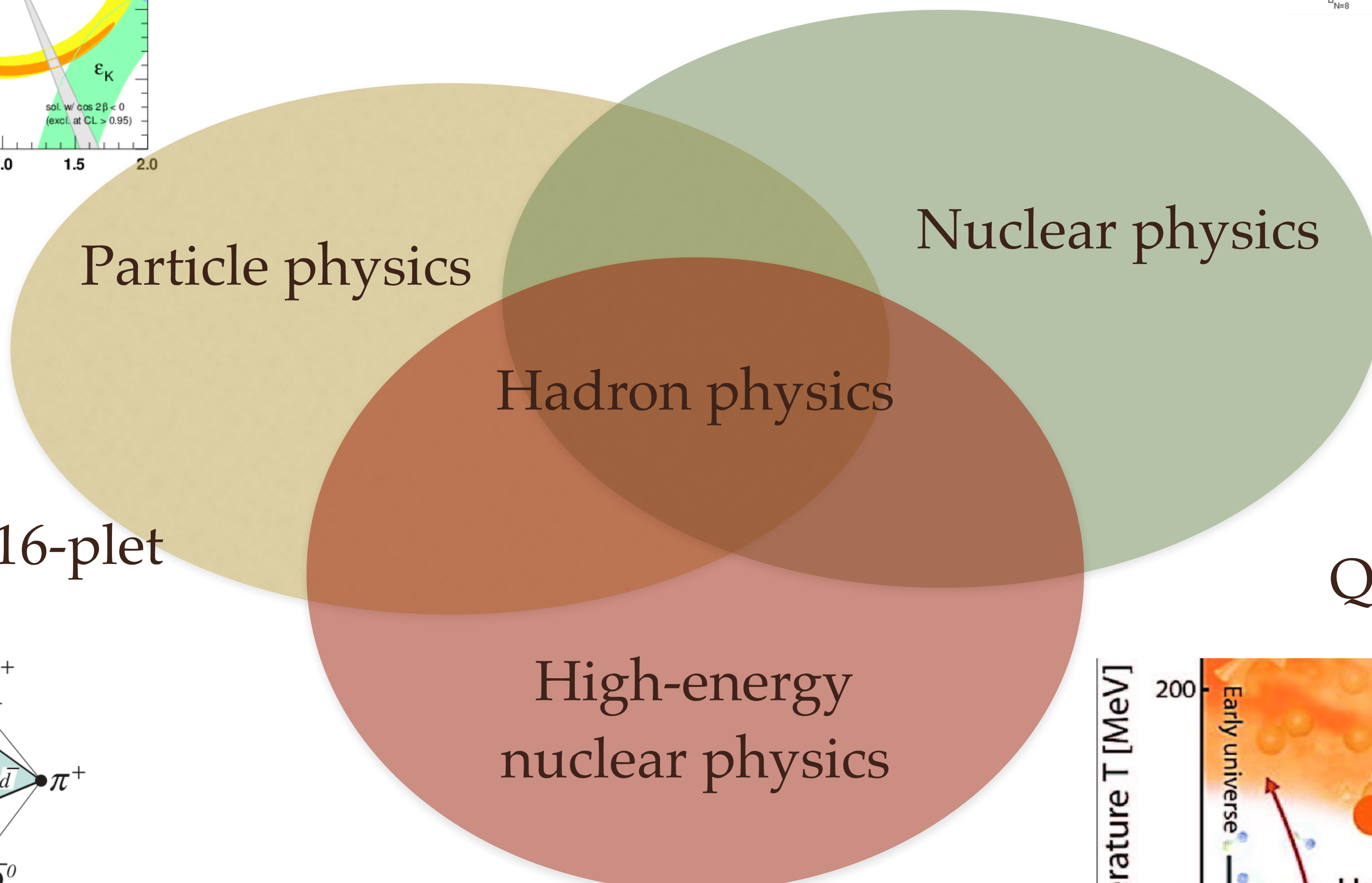


What is hadron physics?

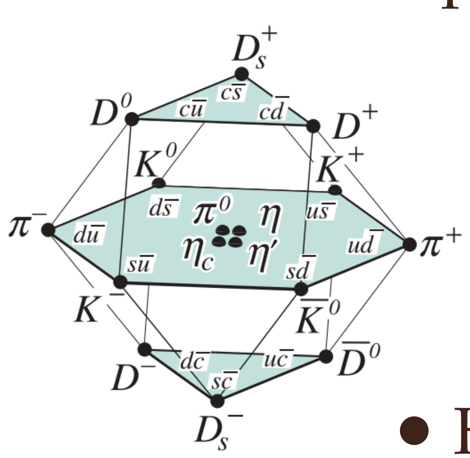
CKM matrix



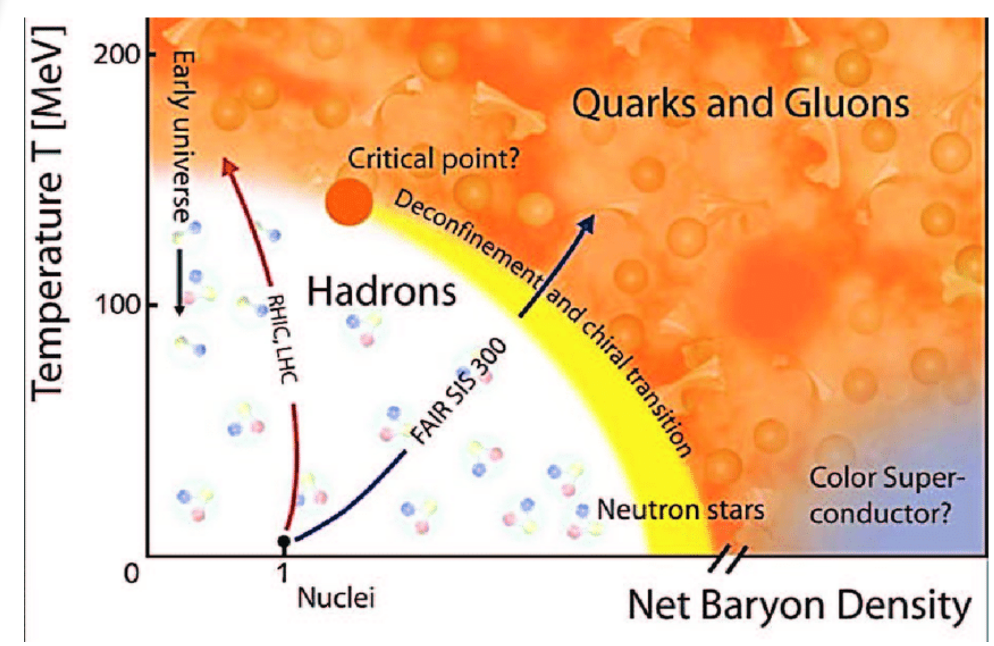
Nuclide map



pseudo scalar 16-plet



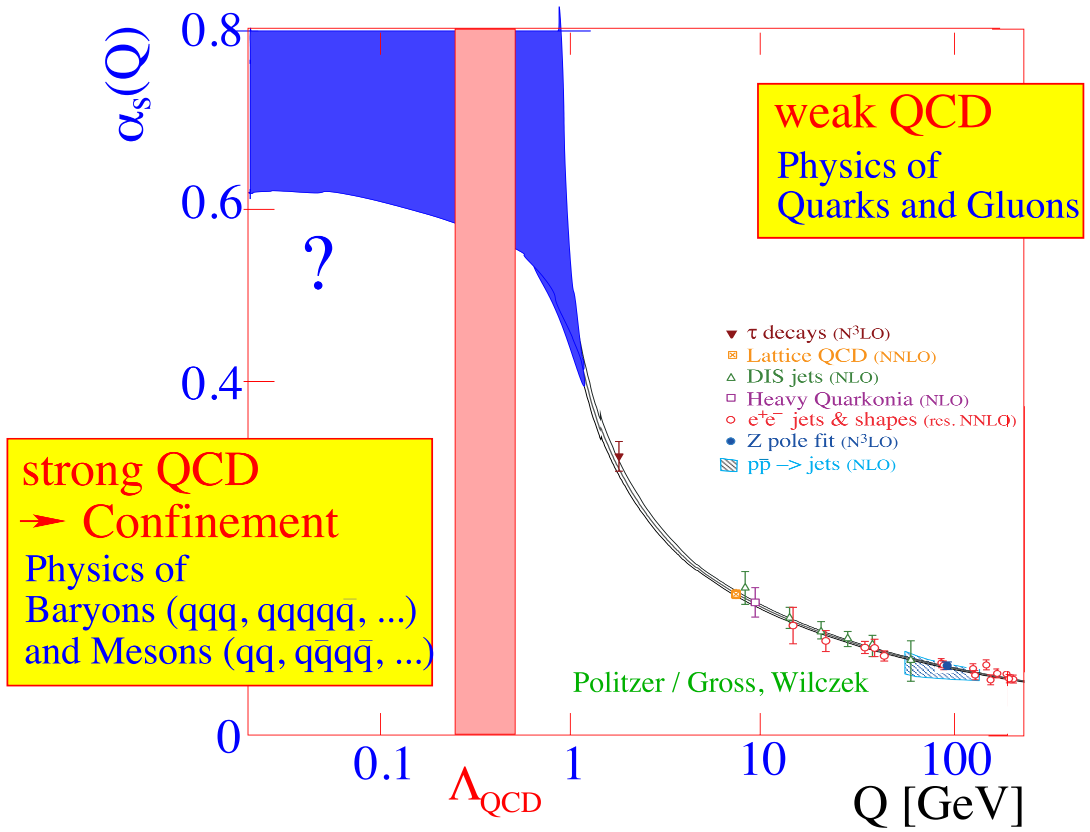
QCD phase diagram

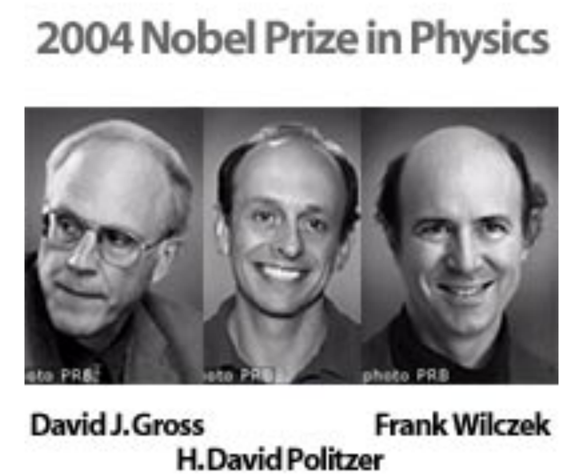


- Hadron spectrum
- Exotic hadrons
- Hadron-hadron interaction
- ……

A small review of exotic hadrons

Hadron physics ⟷ QCD





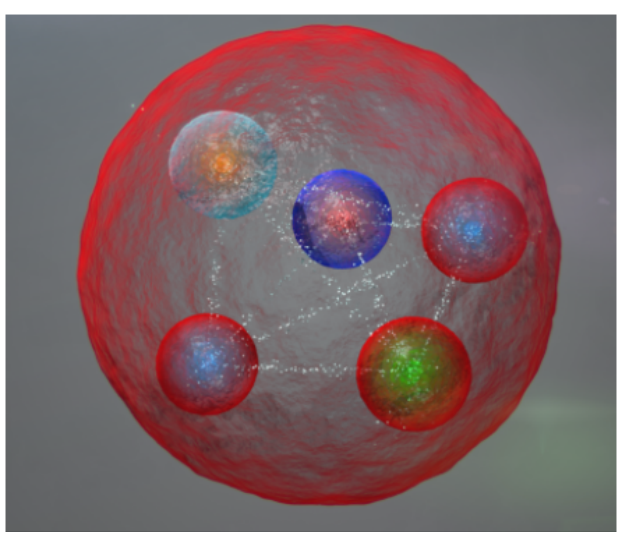
Color confinement

Non-perturbative

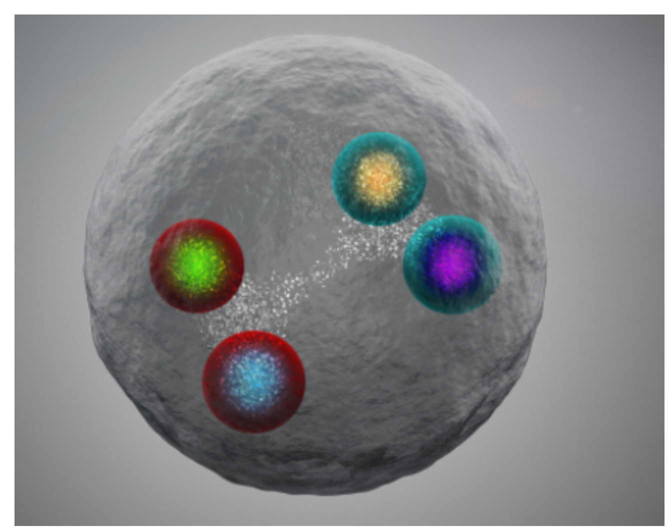
LHCb ↓

Asymptotic freedom

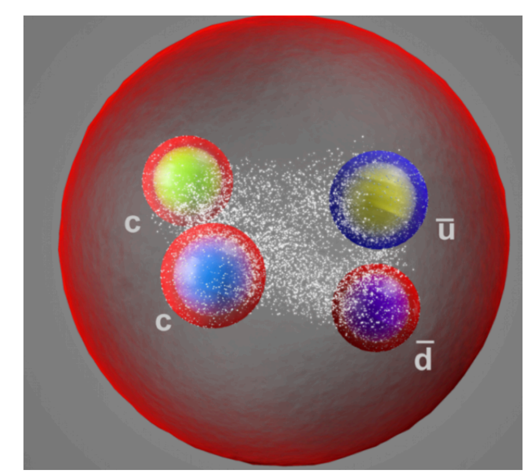
Perturbative



P_c@2019



X(2900)@2020



T_{cc}^+@2021

A small review of exotic hadrons

- H.X. Chen, W. Chen, X. Liu, S.L. Zhu, The hidden-charm pentaquark and tetraquark states, Phys. Rept. 639(2016)1-121
- H.X. Chen, W. Chen, X. Liu, Y.R. Liu, S.L. Zhu, A review of the open charm and bottom systems, Rept. Prog.Phys. 80(2017) 076201
- Y.B.Dong, A. Faessler, V.E. Lyubovitskij, Description of heavy exotic resonances as molecular states using phenomenological lagrangians, Prog.Part.Nucl.Phys.94(2017)282
- R.F.Lebed, R.E. Mitchell and E.S.Swanson, Prog.Part.Nucl.Phys.93(2017)143-194
- F.K. Guo, C.Hanhart, Ulf-G. Meissner, Q. Wang, Q. Zhao, B.S. Zou, Hadronic molecules, Rev.Mod.Phys.90(2018)015004
- Y.R.Liu, H.X.Chen, W. Chen, X.Liu, S.L. Zhu, Pentaquark and Tetraquark states, Prog.Part. Nucl. Phys, 107(2019)237
- R.M.Albuquerque, J.M.Diak, K.P.Khemchandani,A.Martinez Torres, F.S. Navarra, M.Nielsen and C.M. Zanetti, J.Phys.G46(2019)093002
- R.M.Yamaguchi, A.Hosaka,S.Takeuchi and M.Takizawa, J.Phys.G47(2020)053001
- F.K. Guo, X.H.Liu, S.Sakai, Threshold cusps and triangle singularities in hadronic reactions, Prog.Part.Nucl. Phys. 112(2020)103757
- N.Brambilla, S.Eldelman, C.Hanhart,A.Nefediev, C.P.Shen, C.E.Thomas,A.Vairo and C.Z. Yuan, Phys.Rept.873(2020)1-154

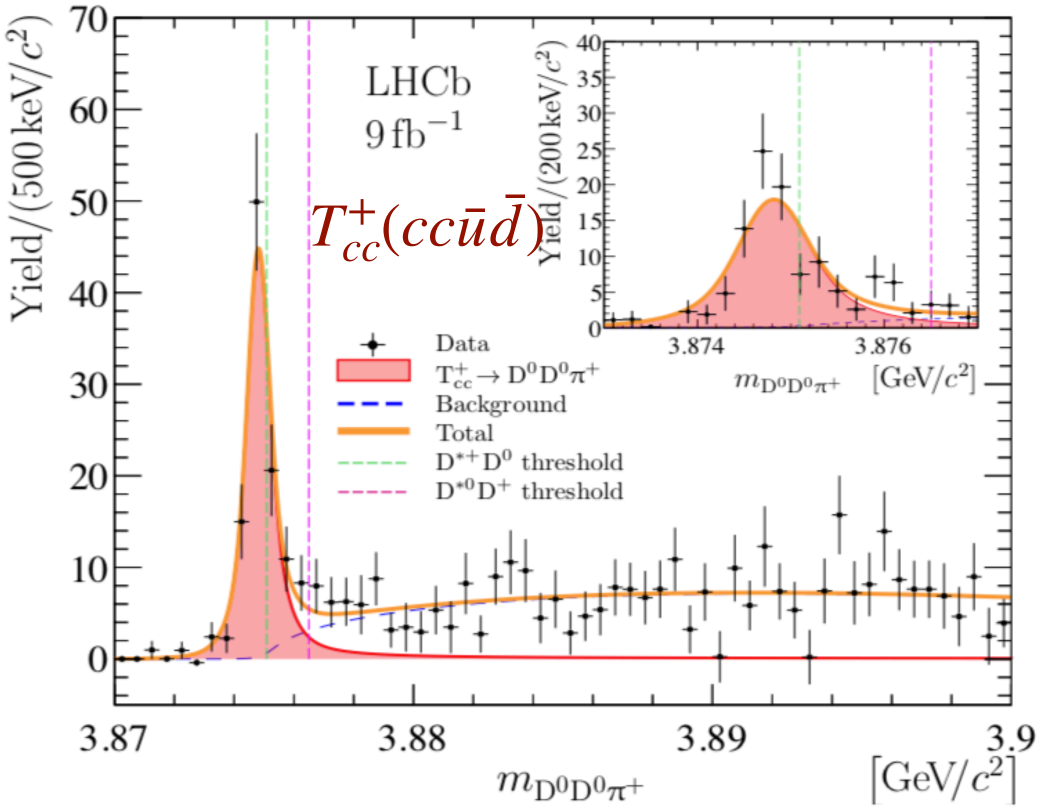
混杂态 胶球 多夸克态 强子分子态

The observation of double charm tetraquark

Breit-Wigner fit

LHCb, arXiv:2109.01038

Nature Physics (2022)



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

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

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

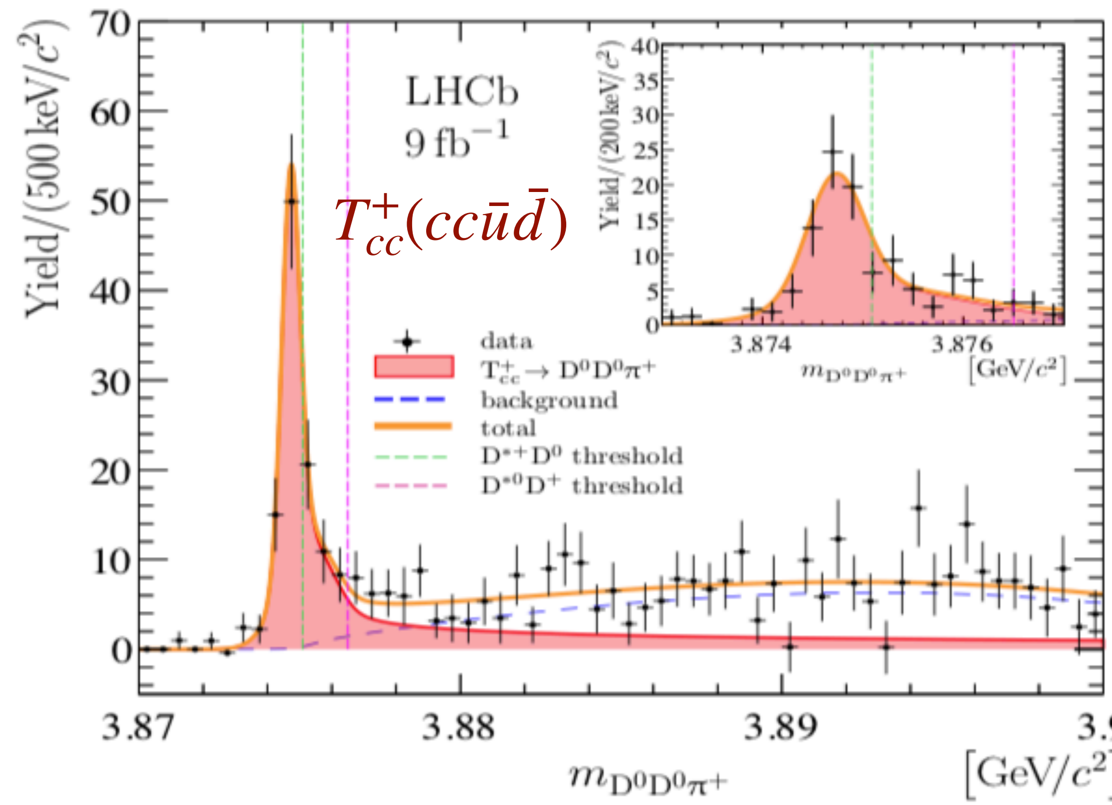
No signal in $D^+D^0\pi^+$, D^+D^+

→ I=0 isoscalar

Unitarized fit

LHCb, arXiv:2109.01056

Nature Commun. 13(2022)3351



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

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

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

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

The observation of double charm tetraquark

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
- ……

The observation of double charm tetraquark

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
- ……

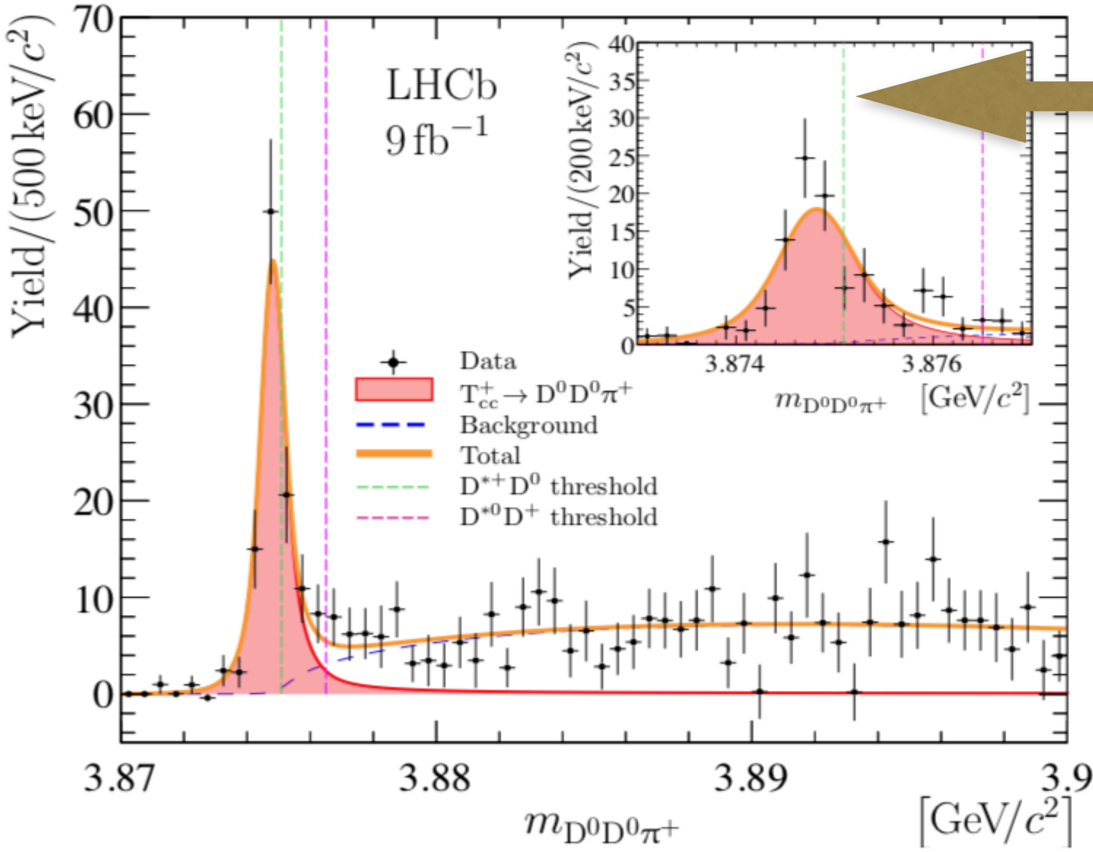
Dynamics

- 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
- ……

The observation of double charm tetraquark



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?

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

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

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

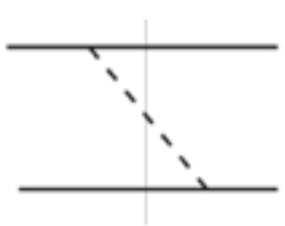
$$< \text{thr}\,.[D^* + \bar{D}^*]$$

- Unexpected large width

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

273keV Meng et.al., 2017.14784

- Three-body effect



The line shape of double charm tetraquark

One-channel Effective Range Expansion (ERE)

A large negative r?!

$$-\frac{2\pi}{\mu}\text{Re}[T(E)^{-1}] = k\cot\delta = \frac{1}{a} + \frac{1}{2}rk^2 + \mathcal{O}(k^4)$$

One channel

Regular potential

No CDD pole

Scattering length a: $a > 0$ mild attractive, $a < 0$ repulsive

Effective range r

$$a = -2\left(\frac{1-Z}{2-Z}\right)\frac{1}{\gamma} + \mathcal{O}\left(\frac{1}{\beta}\right) \qquad r = -\left(\frac{Z}{1-Z}\right)\frac{1}{\gamma} + \mathcal{O}\left(\frac{1}{\beta}\right)$$

Molecule: $a \to -\frac{1}{\gamma}$ & $r \to \frac{1}{\beta}$ $Z \to 0$

Compact: $a \to -\frac{1}{\beta}$ & $r \to -\infty$ $Z \to 1$

w.f. renormalization factor: Z

The probability to find HM in w.f.:

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

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

$$Z < 0.52(0.58)\ \text{fm} \quad 90(95)\,\%\ \text{CL}\,.$$

→ Compact tetraquark?!

Baru, Dong, Du, Filin, Guo, Hanhart, Nefediev, Nieves, QW, hep-ph/2110.07484 (PLB in press)

The line shape of double charm tetraquark

two-channel scattering amplitude

A large negative r?!

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

Denominator

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

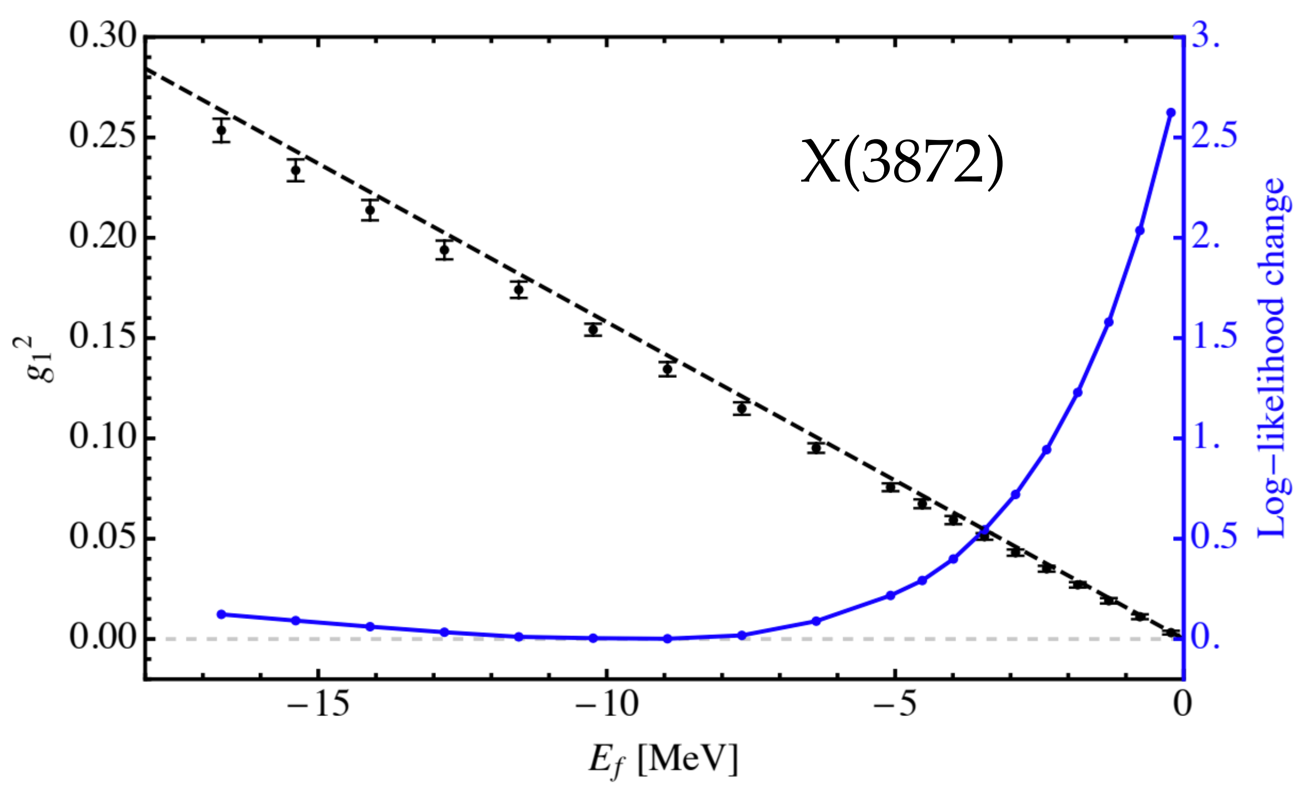
The three momentum

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

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, hep-ph/2110.07484 (PLB in press)

The line shape of double charm tetraquark

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

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

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

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

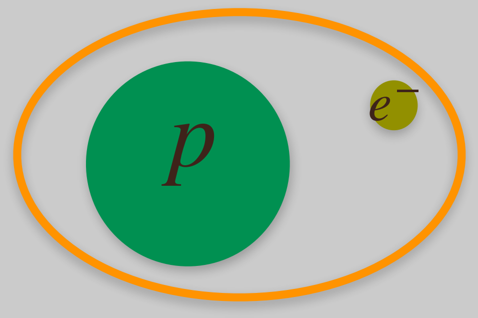
A large negative correction!

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

Baru, Dong, Du, Filin, Guo, Hanhart, Nefediev, Nieves, QW, hep-ph/2110.07484 (PLB in press)

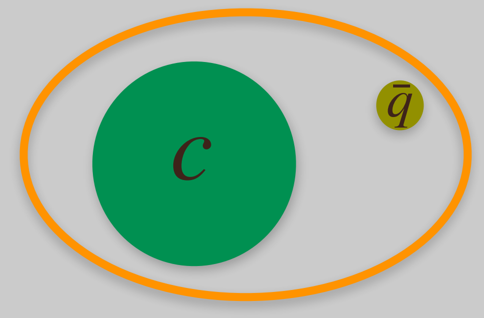
Heavy quark symmetry

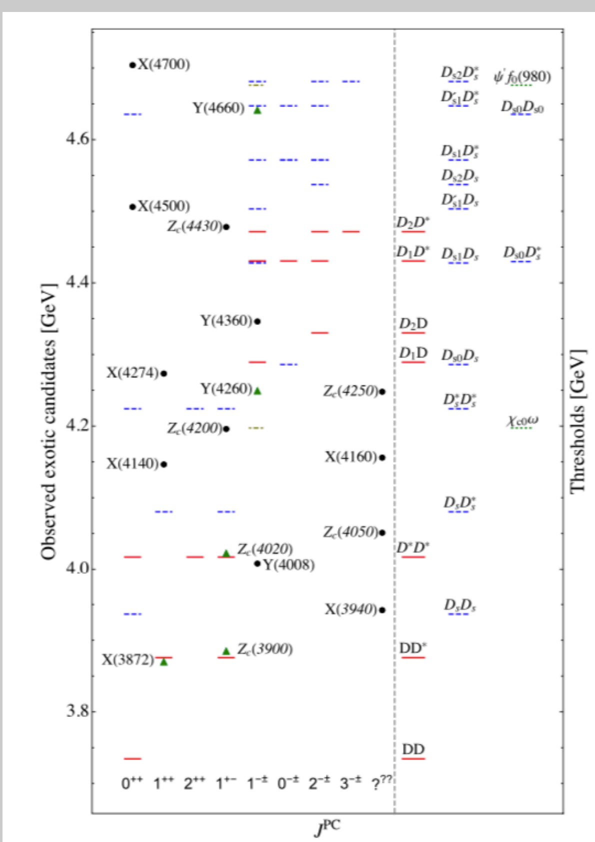
Hydrogen ⟷ Rydberg formula



$$\frac{1}{\lambda} = R\left(\frac{1}{n^2} - \frac{1}{m^2}\right)$$

Heavy-light meson



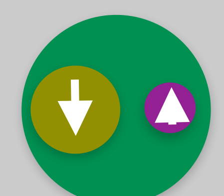


What can we learn for charmonium-like states?

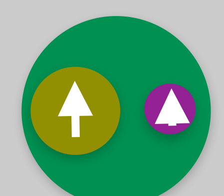
$$\frac{1}{2} \otimes \frac{1}{2} = 0 \oplus 1$$

$$\frac{1}{2} \otimes 1 = \frac{1}{2} \oplus \frac{3}{2}$$

HQSS, $s_l = \frac{1}{2}^-$ doublet



$$J = s_l - \frac{1}{2}$$



$$J = s_l + \frac{1}{2}$$

$$m_{D*} - m_D = 142 \text{ MeV}$$

$$m_{B*} - m_B = 46 \text{ MeV}$$

The line shape of double charm tetraquark

Why the D^*D molecule?

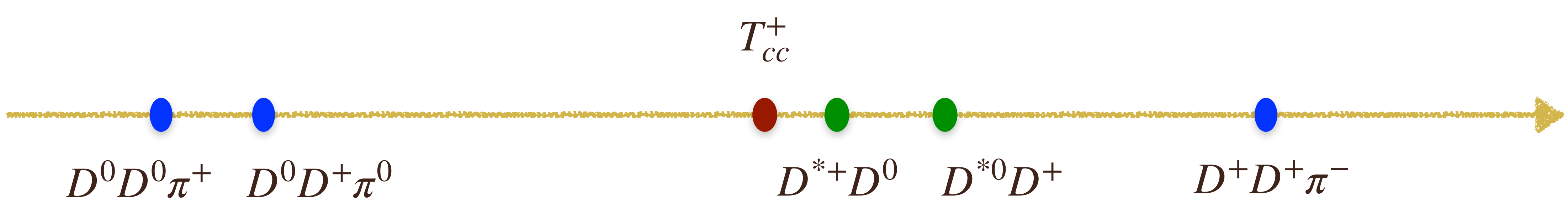
- Close to the D^*D thresholds
- Approximate 90% of $D^0D^0\pi^+$ events contain a D^{*+}
- Z<0.52

Wave functions for isospin singlet and triplet

$$|D^*D,\, I=0\rangle = -\frac{1}{\sqrt{2}}\left(D^{*+}D^0 - D^{*0}D^+\right) \qquad V_{\rm CT}^{I=0}(D^*D \to D^*D,\, J^P=1^+) = v_0$$

$$|D^*D,\, I=1\rangle = -\frac{1}{\sqrt{2}}\left(D^{*+}D^0 + D^{*0}D^+\right) \qquad V_{\rm CT}^{I=1}(D^*D \to D^*D,\, J^P=1^+) = v_1$$

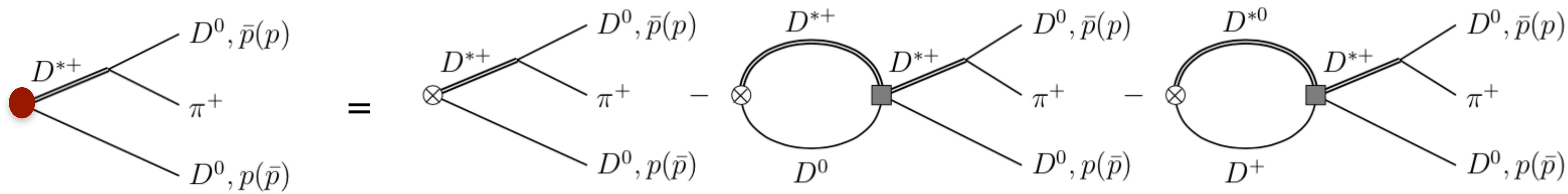
Three-body cut has to be considered



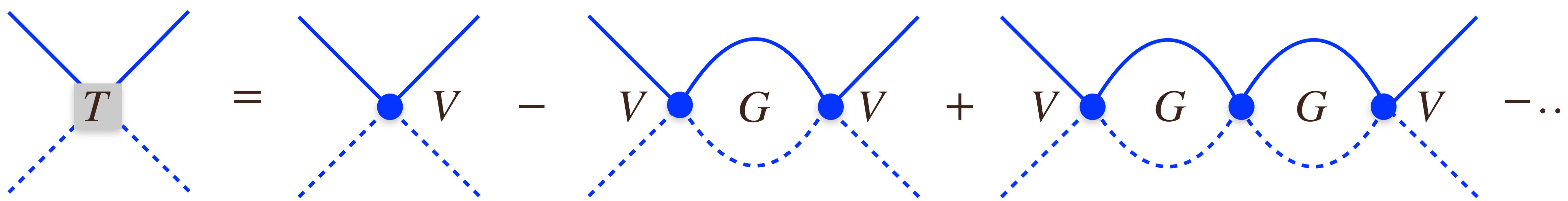
Double charm tetra quark in molecular picture

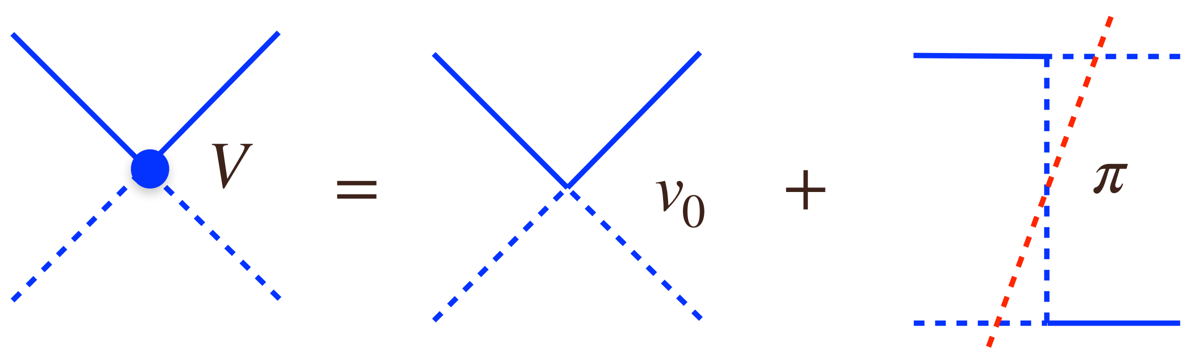
$D^0 D^0 \pi^+$ mass distribution

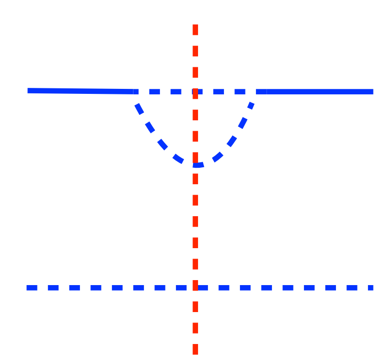
Du et al., PRD105(2022)014024



LSE





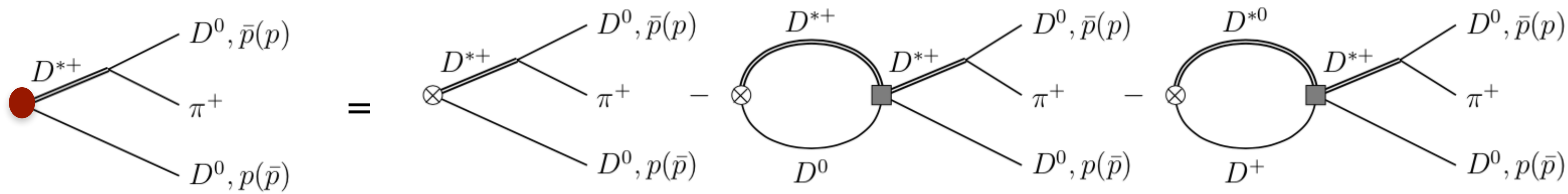


The only calculation with full 3-body cut up to now

Double charm tetra quark in molecular picture

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

Du et al., PRD105(2022)014024



Schemes	Potential	Pole (keV)	Width (keV)
Scheme I	No OPE $\Gamma_{D^{*+}} = 82.5$ keV $\Gamma_{D^{*0}} = 53.7$ keV	$-368^{+43}_{-42} - i(37 \pm 0)$	74
Scheme II	No OPE Dynamical widths of D^*	$-333^{+41}_{-36} - i(18 \pm 1)$	36
Scheme III	OPE Dynamical widths of D^*	$-356^{+39}_{-38} - i(28 \pm 1)$	56

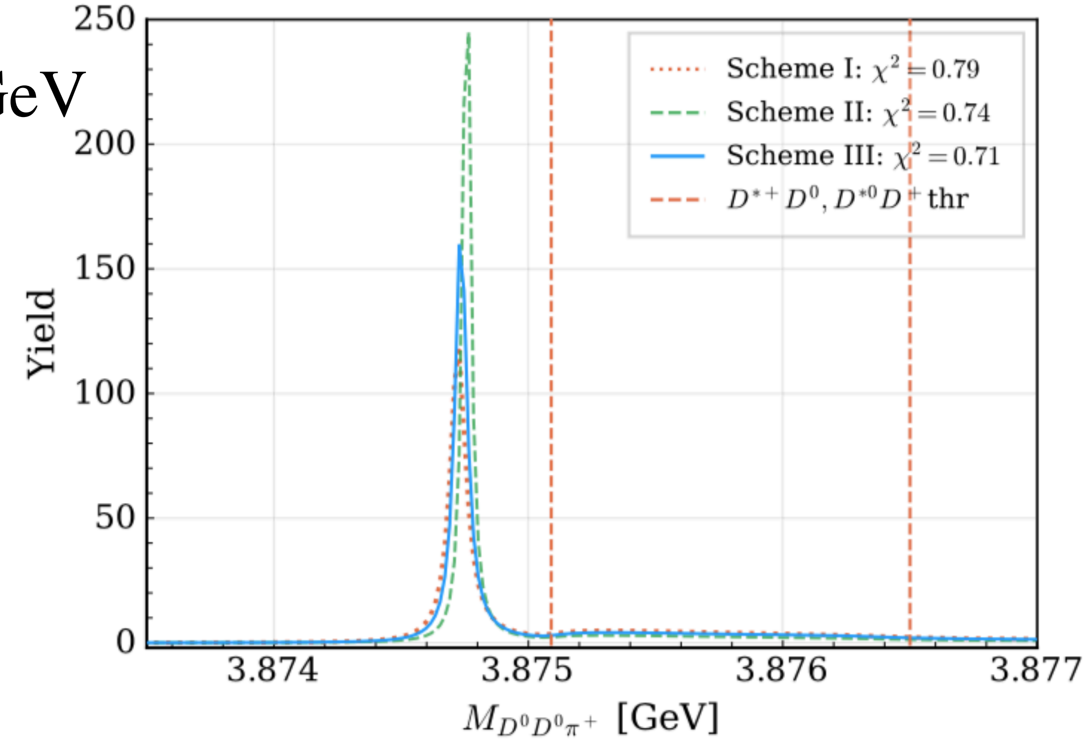
Width is not as large as 400keV.

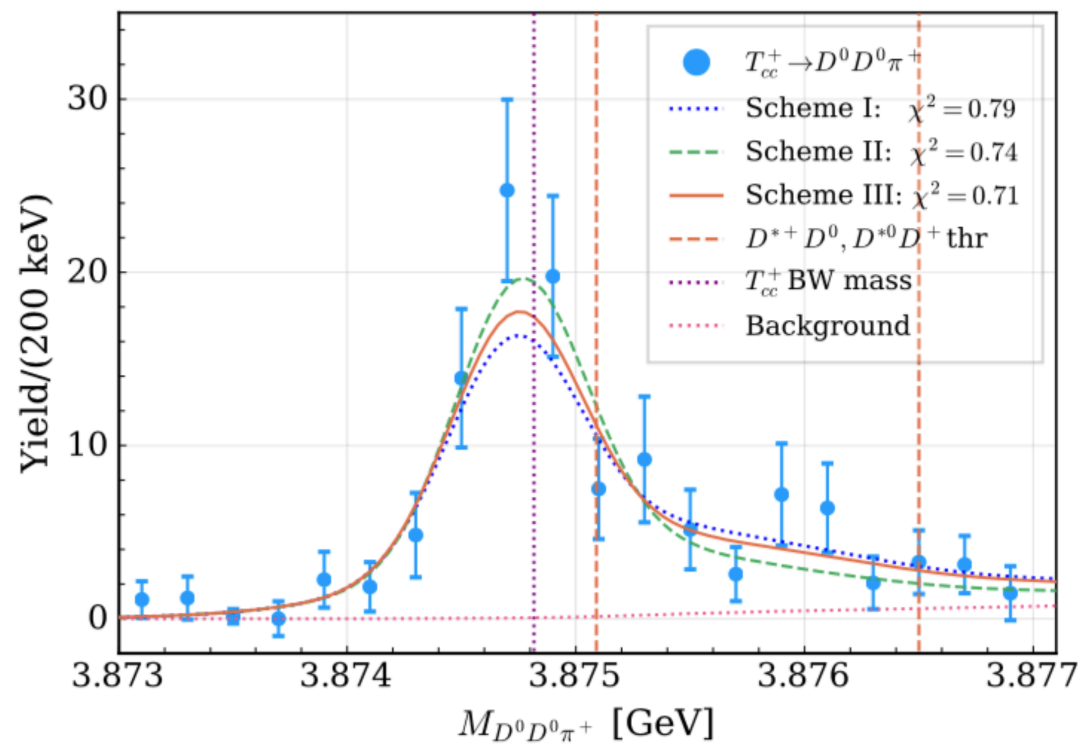
Isospin violation on effective range

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

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

$\Lambda = 0.5$ GeV

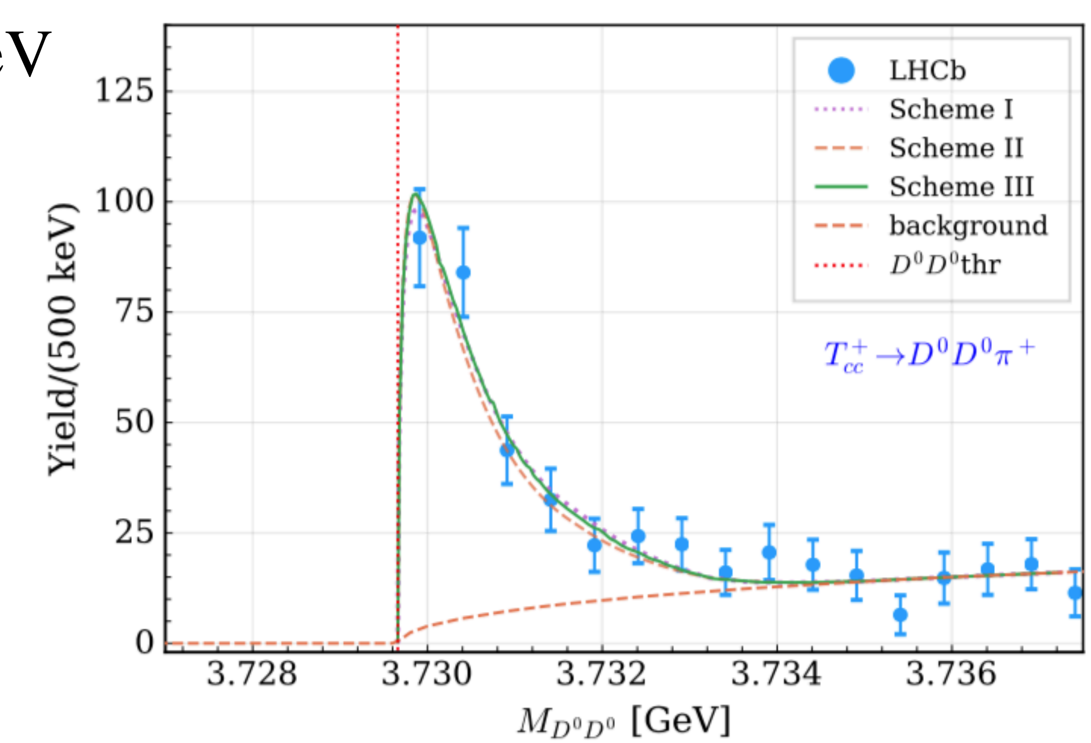


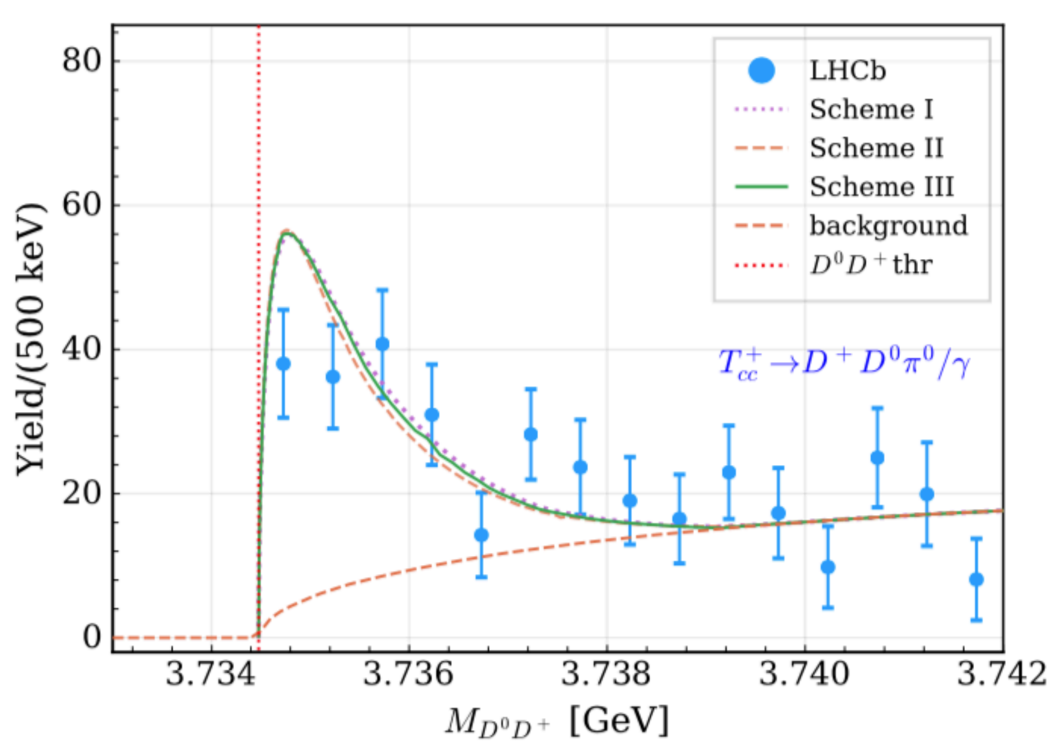


Du et al., PRD105(2022)014024

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

$\Lambda = 0.5$ GeV





Isospin violation on effective range

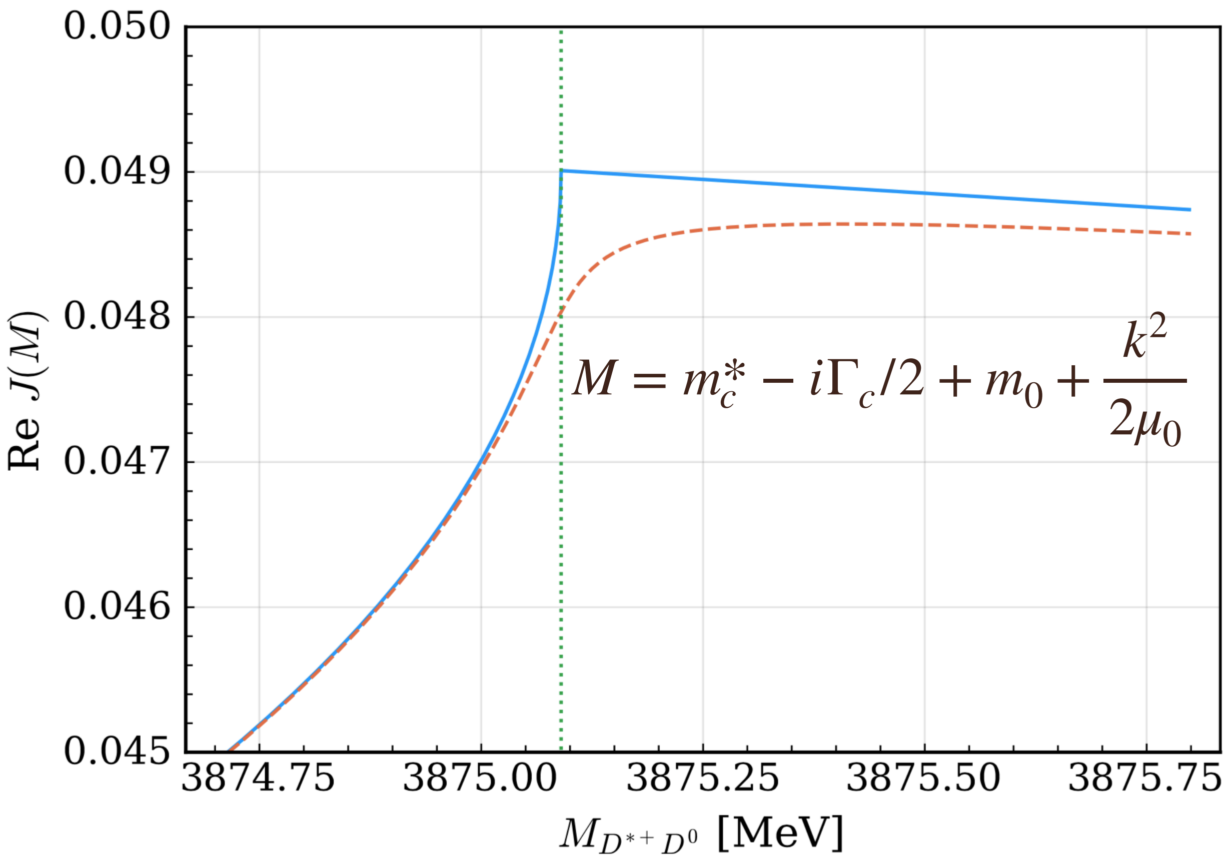
Du et al., PRD105(2022)014024

Low energy expansion of the scattering amplitude

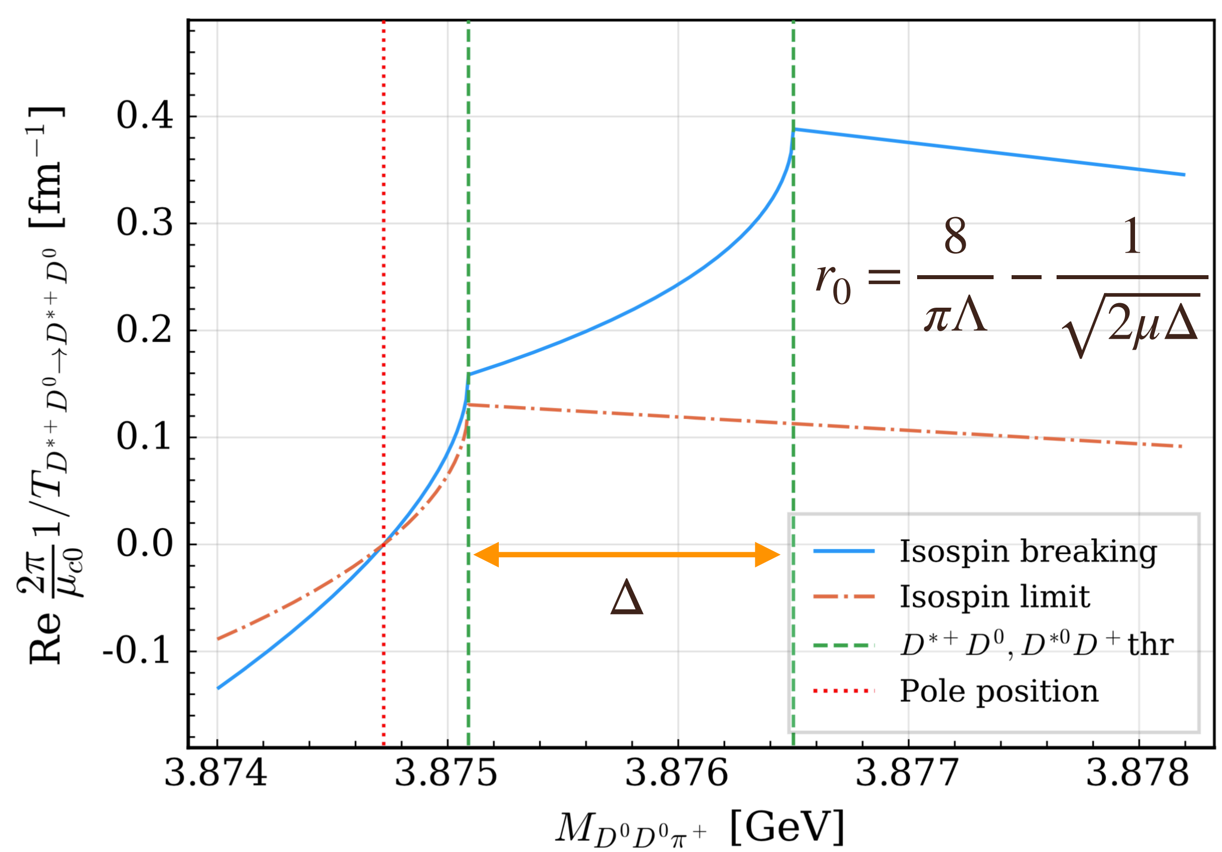
$$T_{D^{*+}D^0\to D^{*+}D^0}(k) = -\frac{2\pi}{\mu_{c0}}\left(\frac{1}{a_0}+\frac{1}{2}r_0k^2 - ik + \mathcal{O}(k^4)\right)$$

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

Width effect



Isospin violation



Isospin violation on effective range

Du et al., PRD105(2022)014024

Scheme I: Only contact potentials

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

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

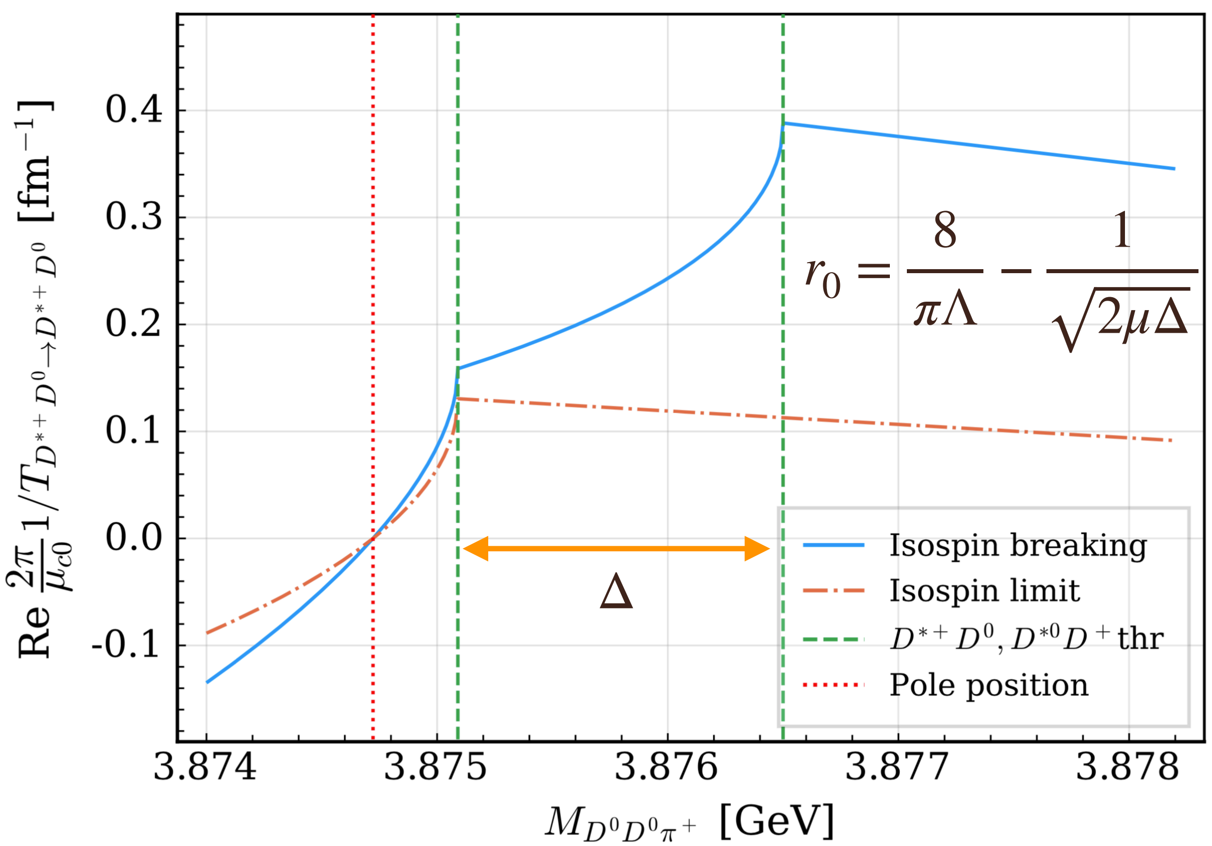
$$J_2(E) = \frac{\Lambda\mu}{\pi^2} - \frac{2\mu^2 E}{\pi^2\Lambda} + \frac{2\Delta\mu^2}{\pi^2\Lambda} - \frac{\mu\sqrt{2\mu\Delta}}{2\pi} + \frac{\mu E\sqrt{2\mu\Delta}}{4\pi\Delta} + \mathcal{O}(E^2)$$

Isospin violation

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

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

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



Isospin violation on effective range

Du et al., PRD105(2022)014024

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

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

Scattering length and effective range

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

OPE contribute 0.40

HQSS partner

Effective d.o.f. for (D, D^*) and (D, D^*) scattering

Du et al., PRD105(2022)014024

$$\frac{1}{2} \otimes \frac{1}{2} = 0 \oplus 1 \longrightarrow C_0, \quad C_1 \longrightarrow v_0 \equiv C_0 + C_1$$

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

Out of control from current Exp. data

$$V^{I=0}(D^*D^* \to D^*D,\ J^P = 1^+) = C_0 - C_1$$

Neglect $D^*D \to D^*D^*$ and widths of D^* ($\Lambda = 0.5$ GeV)

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

Scheme I $\quad \delta_{cc}^{*+} = -1444(61)$ keV

Scheme II $\quad \delta_{cc}^{*+} = -1138(50)$ keV

Scheme III $\quad \delta_{cc}^{*+} = -503(40)$ keV

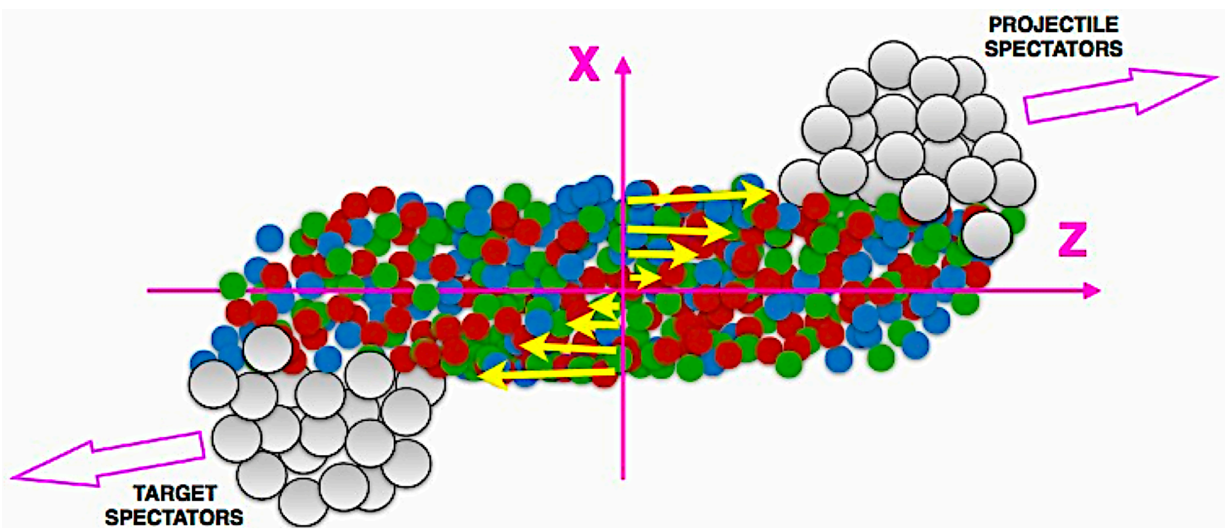
Two-body approx., two Λ, M.Albaladejo, PLB829(2022)137052

Width and strangeness, Dai, PRD105(2022)016029

The isospin property of double charm tetraquark

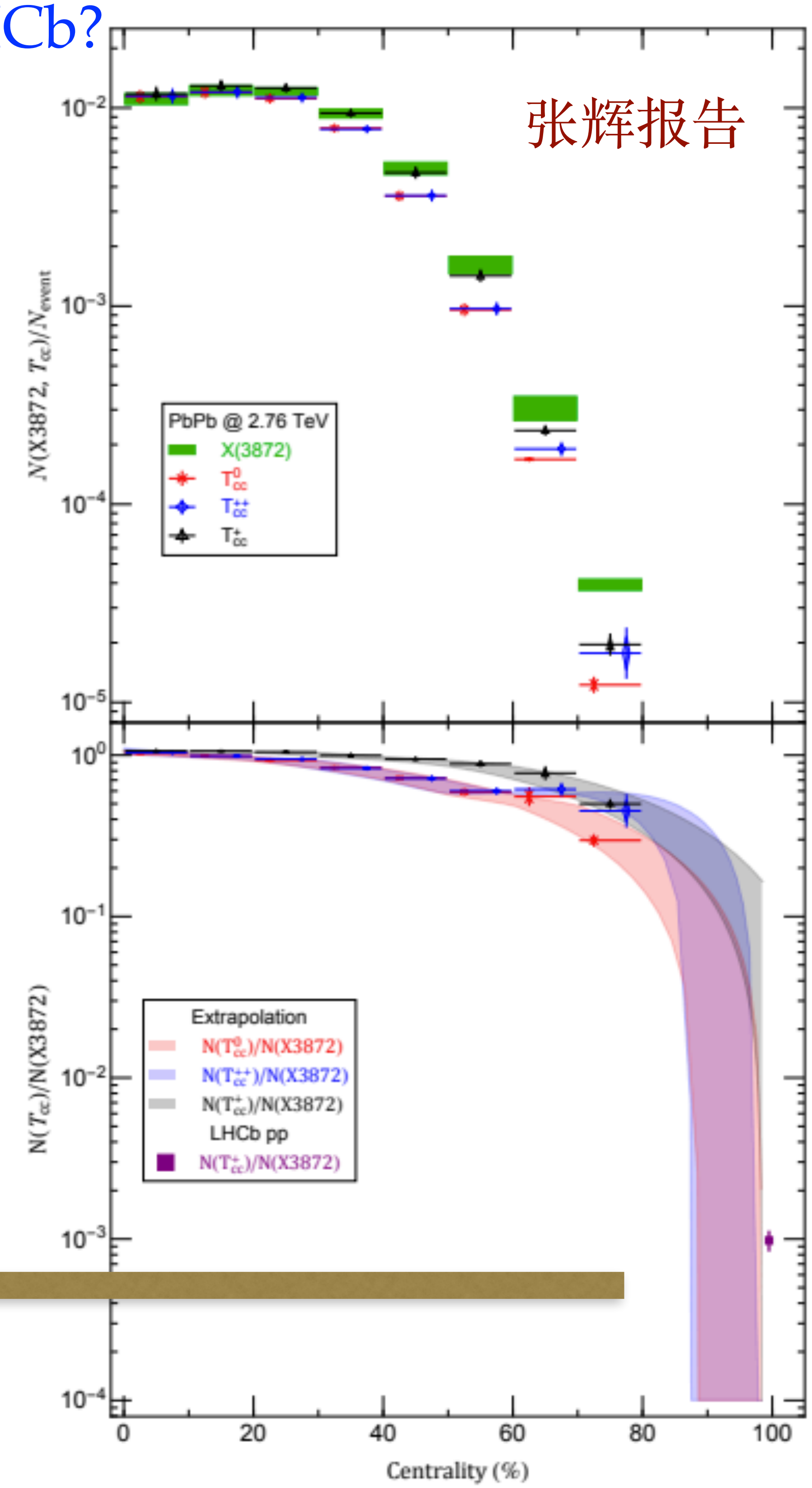
Why does the isospin triplet T_{cc} disappear in LHCb?

- Small production in pp collision
- Isotriplet DD^* state doesn't exist



$$\frac{\# T_{cc}^{+}}{\# X(3872)}_{\text{Exp.}} \simeq 10^{-3}$$

$$\frac{\# T_{cc}^{++}}{\# X(3872)}_{\text{Theory}} \simeq 10^{-4}$$



Hu, Liao, Wang, QW, Xing, PRD104(2021)L111502

The isospin property of double charm tetraquark

Wave function for both isospin singlet and isospin triplet

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

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

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

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

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

Determine isospin from hidden charm channel

Decay amplitude

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

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

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

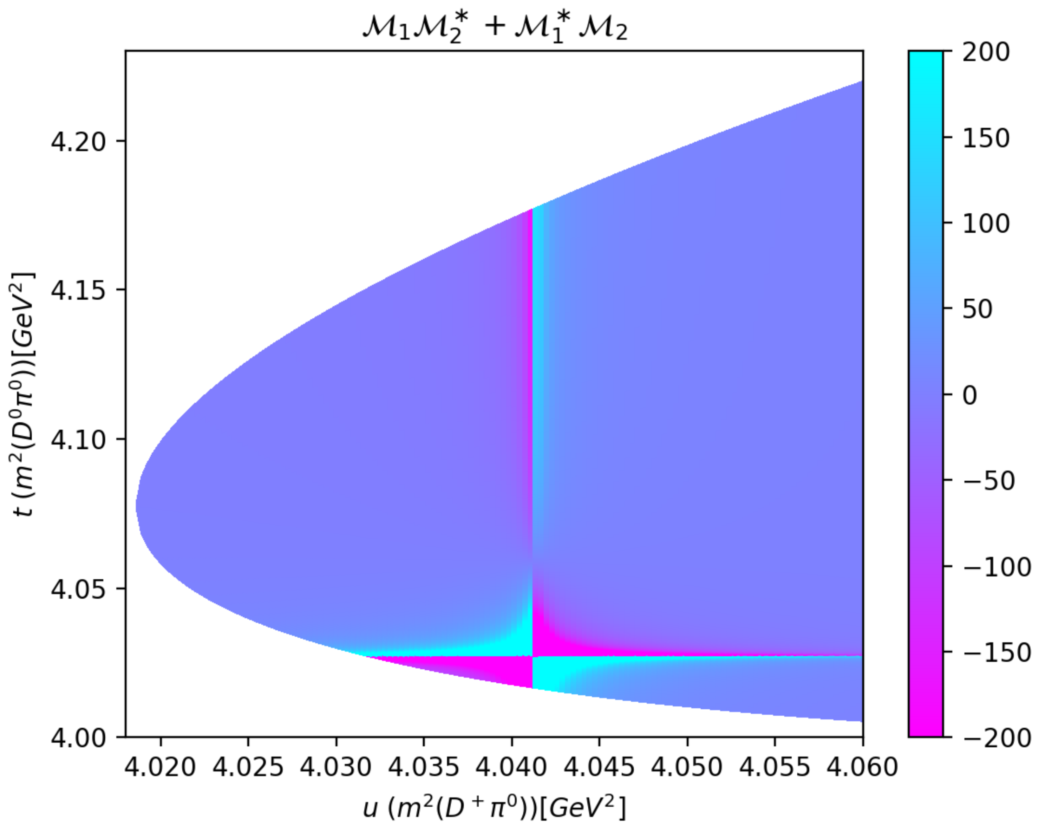
$\mathcal{M}'_2: \quad T_{cc}^{+} \to D^{*+}D^{0} \to D^{+}\pi^{0}D^{0}$

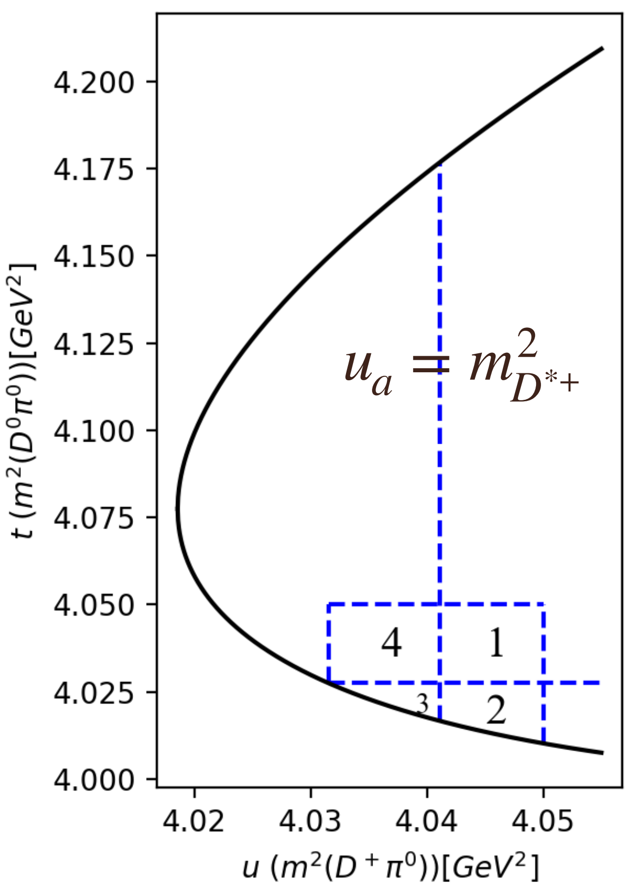
$r \equiv \frac{g_{D^{*0}D^{+}T_{cc}^{+}}}{g_{D^{*+}D^{0}T_{cc}^{+}}}$ $\qquad r=1 \to I=1$ $\qquad r=-1 \to I=0$

Shi, Wang, QW, hep-ph/2205.05234

The isospin property of double charm tetraquark

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





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

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

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

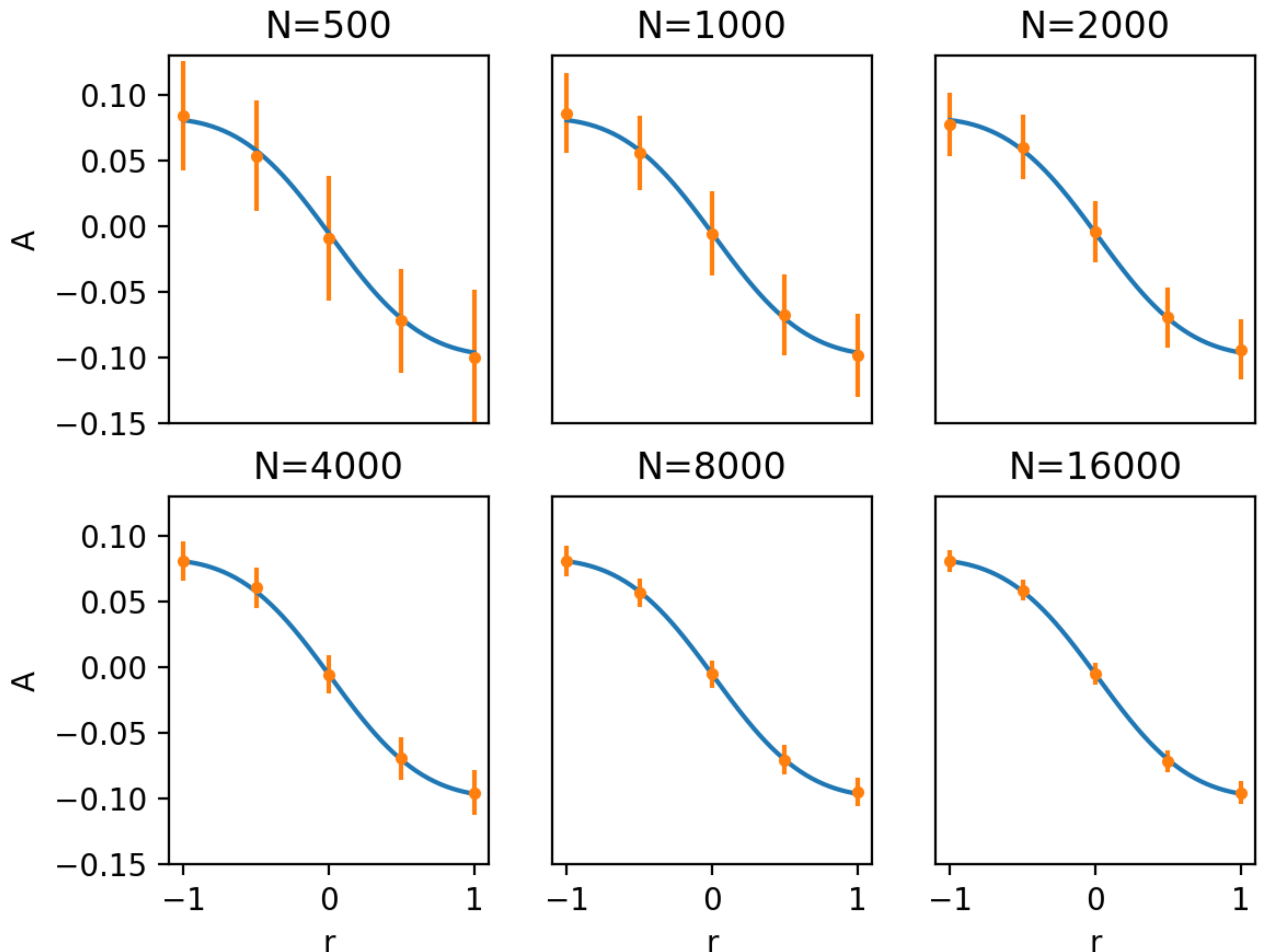
Remove quadratic term of r

$$A \equiv \frac{N_1 + N_3 - N_2 - N_4}{N_1 + N_3 + N_2 + N_4}$$

Shi, Wang, QW, hep-ph/2205.05234

The isospin property of double charm tetraquark

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

Summary and outlook

- T_{cc}^{+} exhibits as either a bound state or a virtual state
- A large negative effective range is from isospin violation
- Both isospin singlet and triplet double charm tetra quark could exist
- The width of T_{cc}^{+} is 56 keV
- The fully calculation of the three-body cut
- Predict the pole position of the HQSS partner T_{cc}^{*+}
- Provide a method to measure the isospin of the double charm tetra quark

Thank you for your attention!