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Fully charm tetraquark production and decay at LHC

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Heavy Flavor Physics

- **New physics**

  indirect detection

$$\mathcal{H}_{NP}^{\Delta C=2} = \frac{1}{\Lambda_{NP}^2} \sum_{i=1}^{8} z_i(\mu) Q_i'$$

- **CP violation**

  Understand its origin:
  Strong phase, new sources

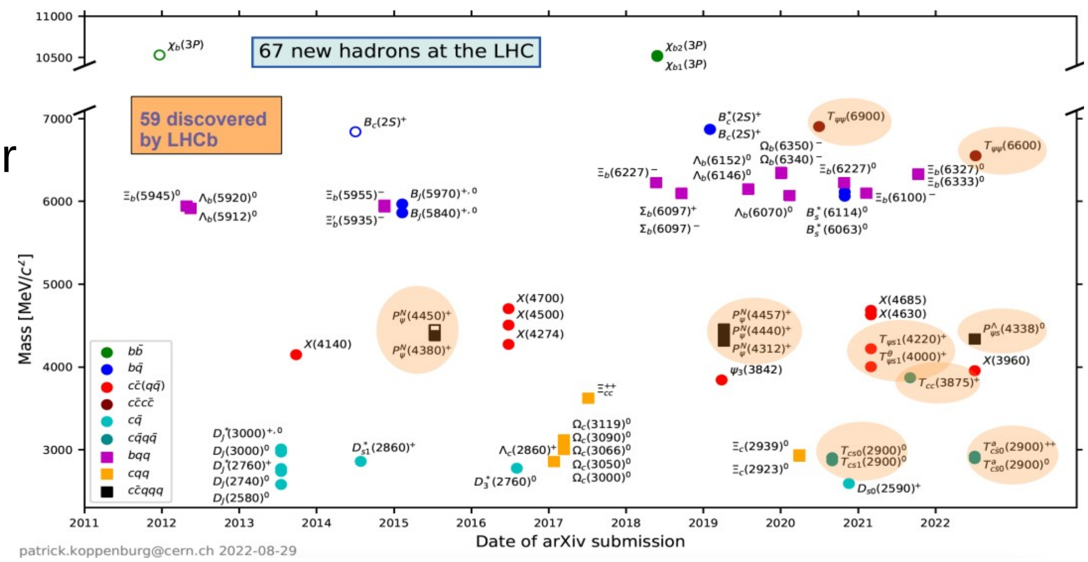
$$\Lambda_b^0 \rightarrow pK^-\pi^+\pi^-$$

[LHCb, Nature 2025]

$$\mathcal{A}_{CP} = (2.45 \pm 0.46 \pm 0.10)\% \quad 5.2\sigma$$

- **Exotic hadrons**

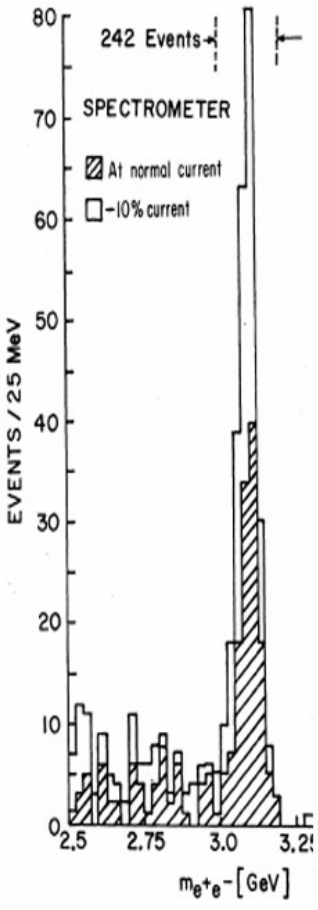
  Inner structure; Exploring Color confinement mechanism

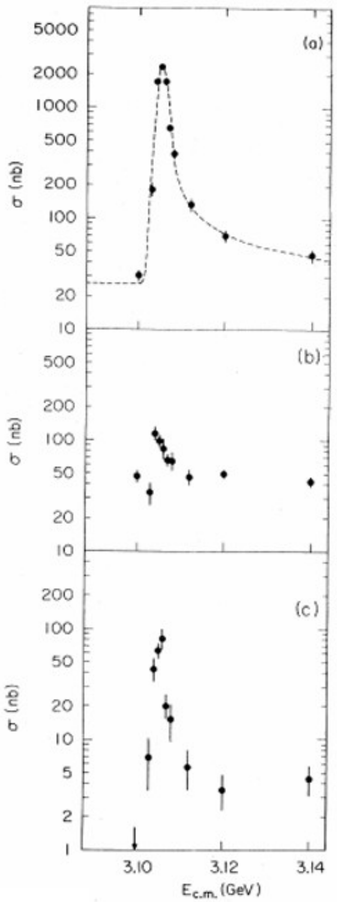


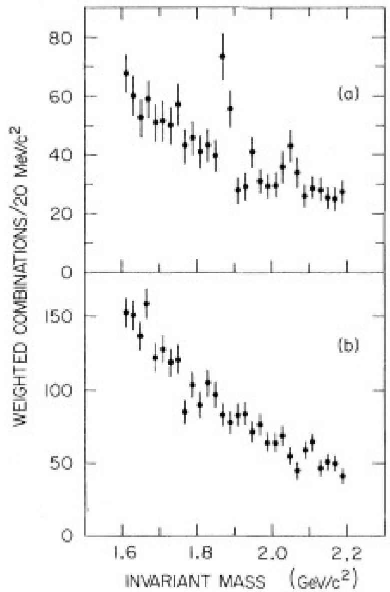
- **Heavy flavor theories**

  Heavy quark symmetry;
  nonrelativistic at Fermi-scale;
  test effective theory of QCD;

Charm family

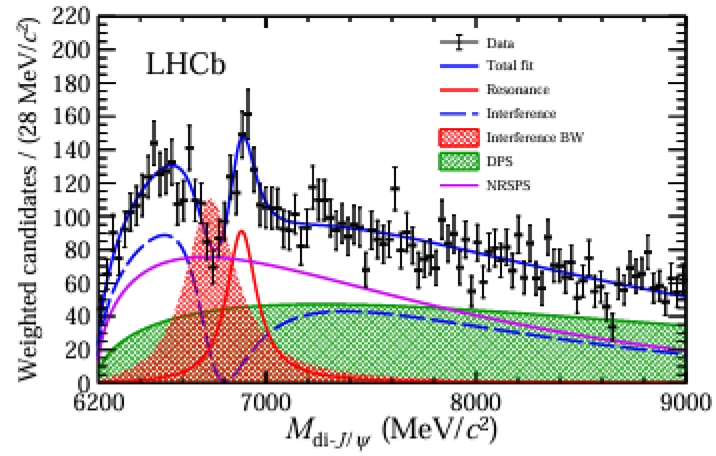






Ω_{ccc} (CCC)???

T_{3c} $(CC\bar{C}\bar{q})$???

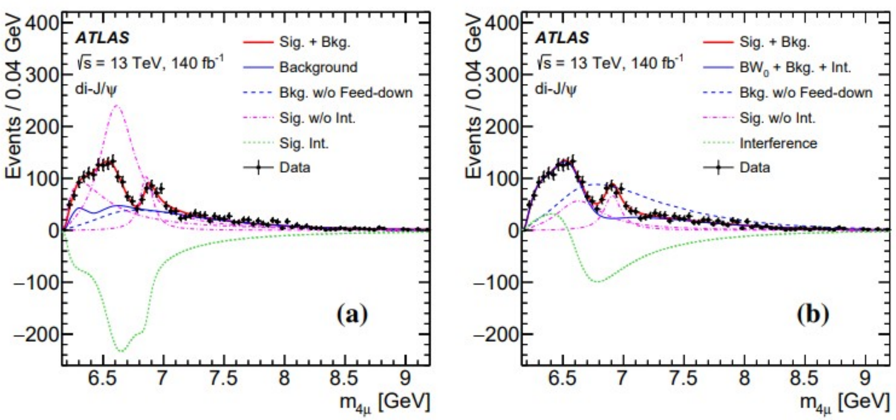


J/ψ $(C\bar{C})$  **(1976)** D $(C\bar{q})$ T_{4c} $(CC\bar{C}\bar{C})$

1974 by Ting and Richter 1976 at SLAC LHCb, 2006.16957

Latest data on fully charm tetraquarks

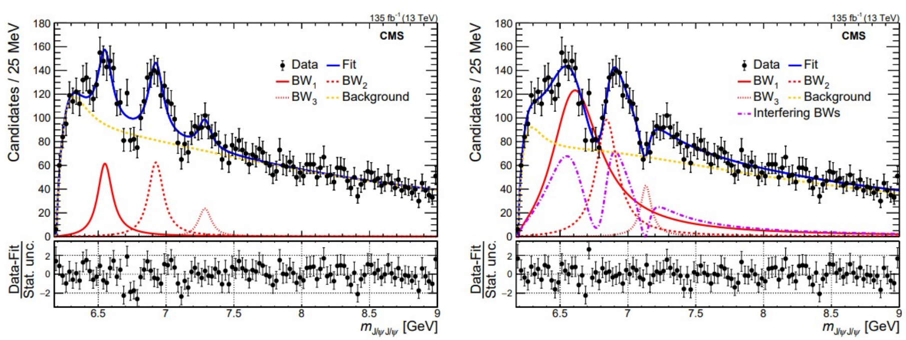
Exp.	Fit	M_{BW_1}	Γ_{BW_1}	$M_{X(6900)}$	$\Gamma_{X(6900)}$	M_{BW_3}	Γ_{BW_3}
LHCb	No interf.	–	–	$6905 \pm 11 \pm 7$	$80 \pm 19 \pm 33$	–	–
CMS	No interf.	$6552 \pm 10 \pm 12$	$124^{+32}_{-26} \pm 33$	$6927 \pm 9 \pm 4$	$122^{+24}_{-21} \pm 184$	$7287^{+20}_{-18} \pm 5$	$95^{+59}_{-40} \pm 19$
LHCb	Interf.	6741 ± 6	288 ± 16	$6886 \pm 11 \pm 11$	$168 \pm 33 \pm 69$	–	–
CMS	Interf.	6638^{+43+16}_{-38-31}	$440^{+230+110}_{-200-240}$	6847^{+44+48}_{-28-20}	191^{+66+25}_{-49-17}	7134^{+48+41}_{-25-15}	97^{+40+29}_{-29-26}
ATLAS	Fit-A	$6630 \pm 50^{+80}_{-10}$	$350 \pm 110^{+110}_{-40}$	$6860 \pm 30^{+10}_{-20}$	$110 \pm 50^{+20}_{-10}$	$7220 \pm 30^{+10}_{-40}$	$90 \pm 60^{+60}_{-50}$
ATLAS	Fit-B	$6650 \pm 20^{+30}_{-20}$	$440 \pm 50^{+60}_{-50}$	$6910 \pm 10 \pm 10$	$150 \pm 30 \pm 10$	–	–



ATLAS, 2304.08962; 140fb-1 data;

P_t(mu1,2,3,4)>4,4,3,3GeV; |eta(mu1,2,3,4)|<2.5;

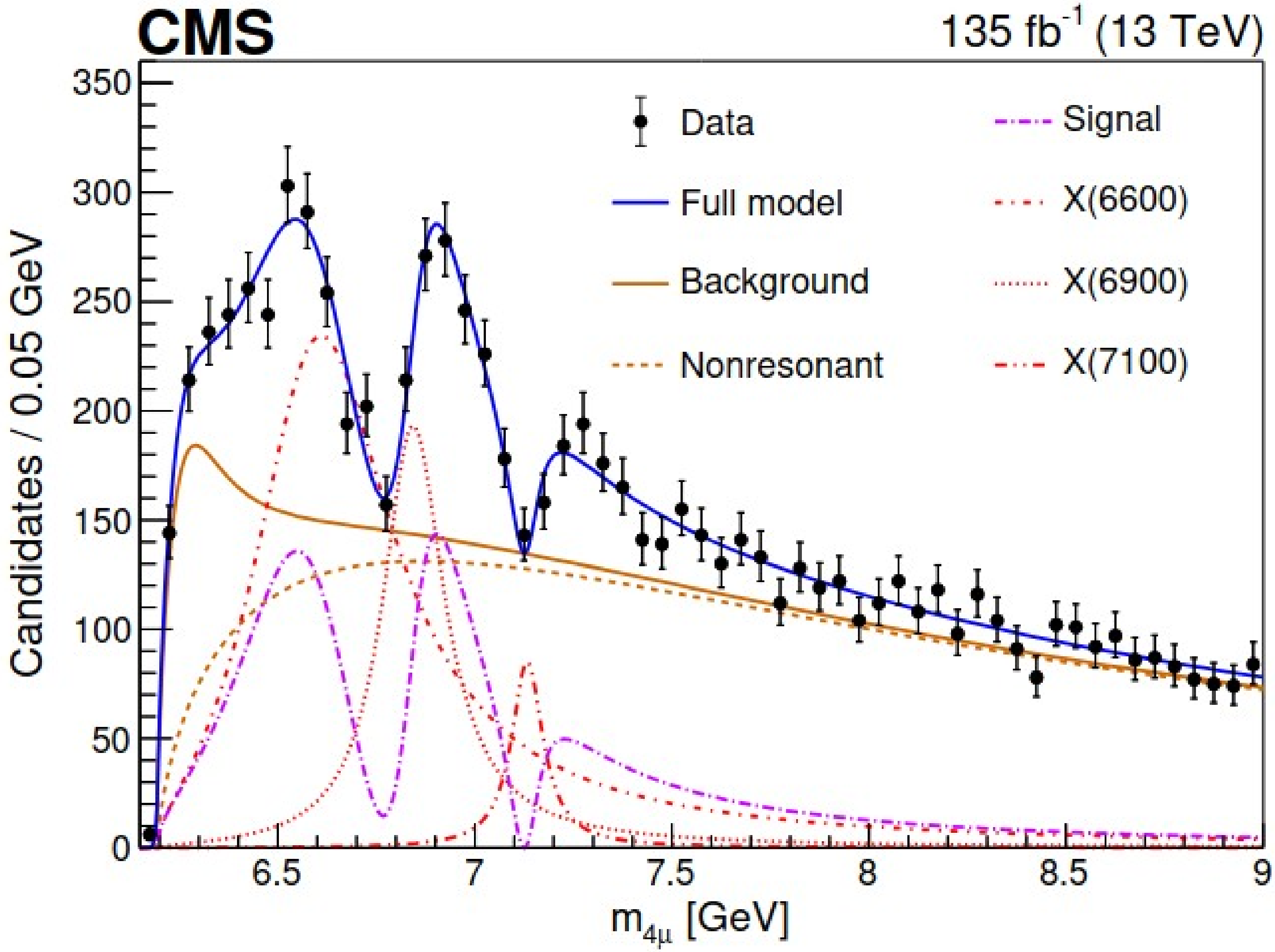
2.94(3.56)GeV<M(dimuon)<3.25(3.80)GeV



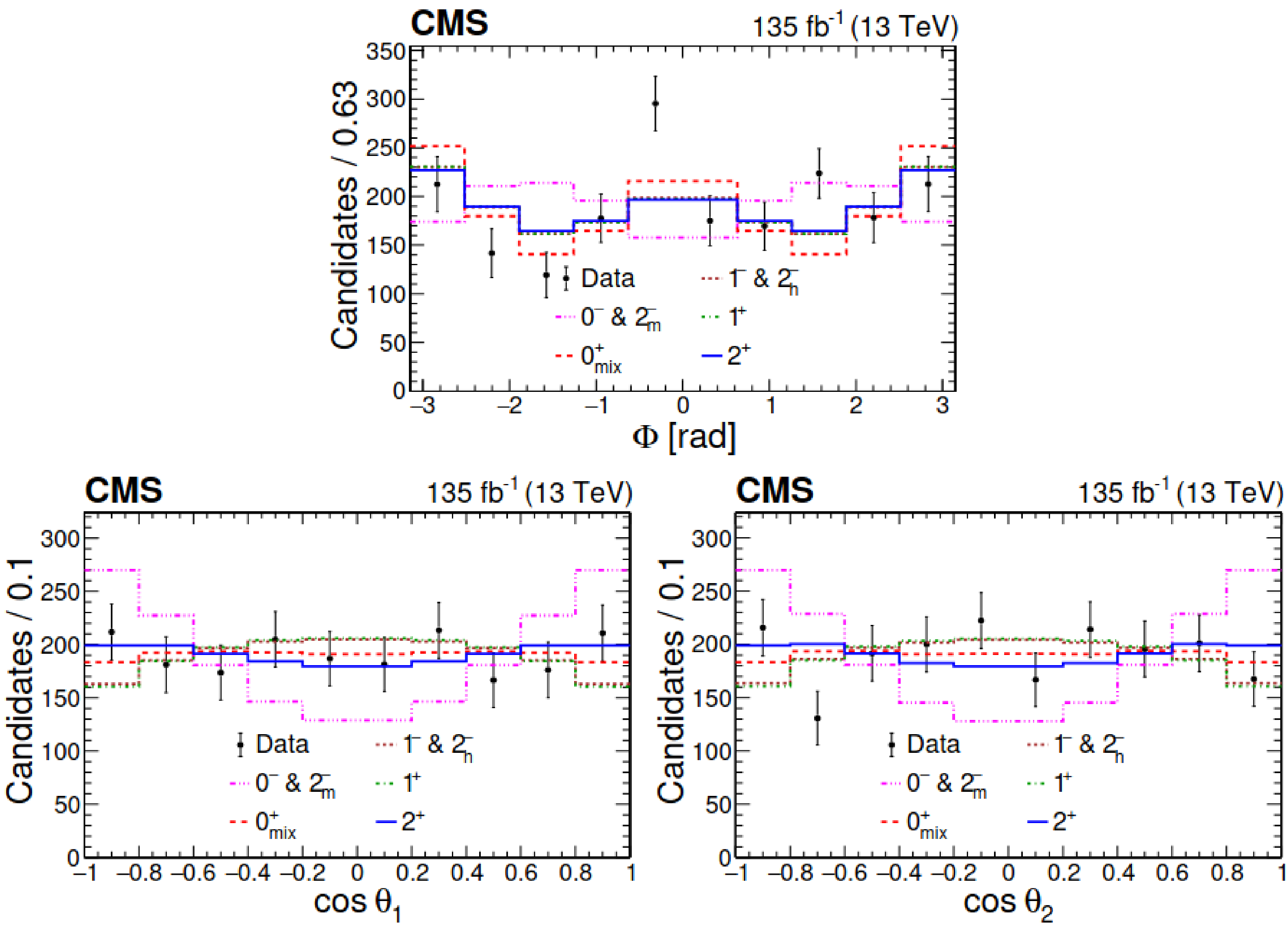
CMS, 2306.07164; 135fb-1 data;

P_t(muon)>2GeV;|eta(muon)|<2.4;

P_t(di muon)>3.5GeV;

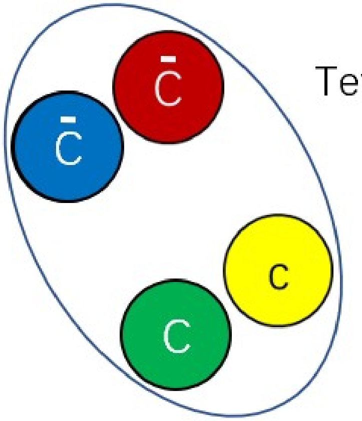


CMS,2506.07944 (submitted to Nature)

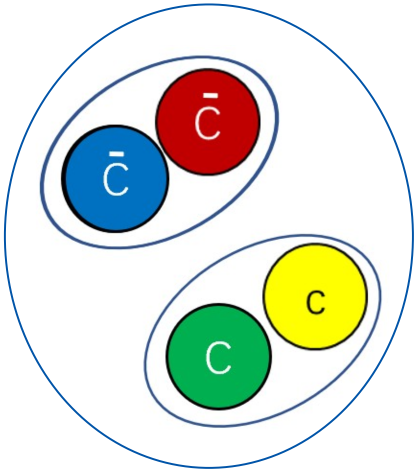


CMS data supports spin-parity 2^++

How to explain these exotic states?

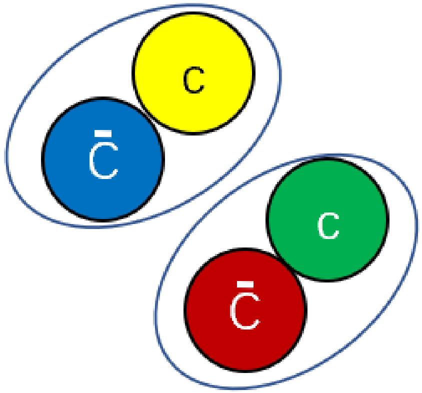


Tetraquark

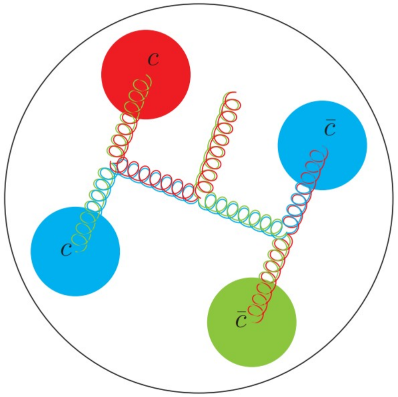


Diquark-antidiquark

Zhu, Bauer, Yi, 2410.11210



Charmonia Molecule



Gluonic Tetracharm Hybrid

Previous theoretical studies

Y. Iwasaki, Phys. Rev. Lett. 36, 1266 (1976)
K. T. Chao, Z. Phys. C 7, 317 (1981)
J. P. Ader, J. M. Richard and P. Taxil, Phys. Rev. D 25, 2370 (1982)
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W. Chen, H. X. Chen, X. Liu, T. G. Steele and S. L. Zhu, Phys. Lett. B 773, 247-251 (2017)
Z. G. Wang, Eur. Phys. J. C 77, no.7, 432 (2017)
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C. Deng, H. Chen and J. Ping, [arXiv:2003.05154]
F. Feng, Y. Huang, Y. Jia, W. L. Sang, X. Xiong and J. Y.Zhang, arXiv:2009.08450
Y.Q. Ma, H.F. Zhang, arXiv:2009.08376
……

Diquark-antidiquark or charmonium molecule?

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Fully-heavy tetraquark spectra and production at hadron colliders

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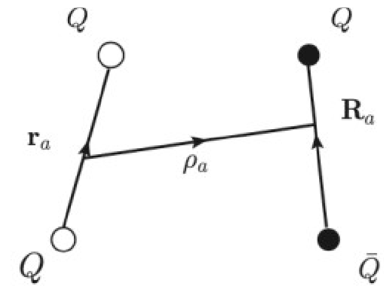
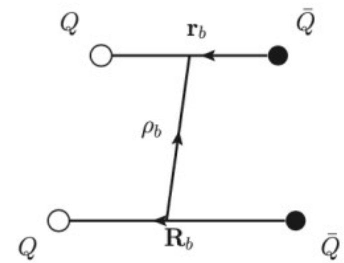
Abstract

Motivated by the observation of exotic structure around 6900 MeV in the J/ψ-pair mass spectrum using proton-proton collision data by the LHCb collaboration, we study the spectra of fully-heavy tetraquarks within Bethe-Salpeter equation and Regge trajectory relation. The $X(6900)$ may be explained as a radially excited state with quark content $cc\bar{c}\bar{c}$ and spin-parity $0^{++}(3S)$ or $2^{++}(3S)$ or an orbitally excited $2P$ state. New $cc\bar{c}\bar{c}$ structures around 6.0 GeV, 6.5 GeV, and 7.1 GeV are predicted together. Other $bb\bar{b}\bar{b}$ and $bc\bar{b}\bar{c}$ structures which may be experimentally prominent are discussed. On the other hand, the fully-heavy S-wave tetraquark production at hadron colliders is investigated and their cross sections are obtained.

$$\bar{3}_c \otimes 3_c = 1_c \text{ and } 6_c \otimes \bar{6}_c = 1_c.$$

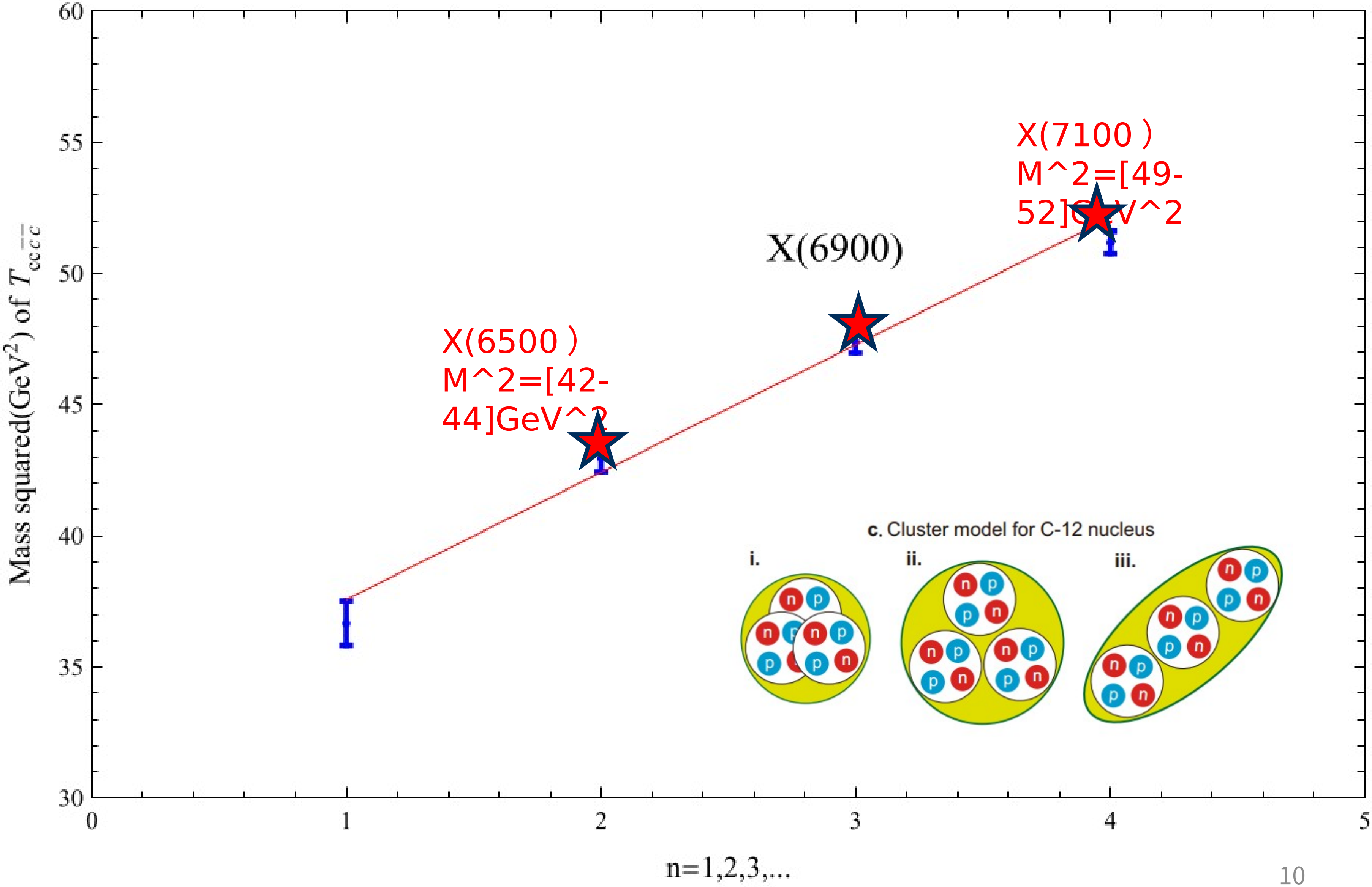


$$|\mathbf{1}\rangle \equiv |(Q_1\bar{Q}_3)_{\mathbf{1}}(Q_2\bar{Q}_4)_{\mathbf{1}}\rangle,$$
$$|\mathbf{8}\rangle \equiv |(Q_1\bar{Q}_3)_{\mathbf{8}}(Q_2\bar{Q}_4)_{\mathbf{8}}\rangle,$$



The masses (6.5GeV, 7.1GeV) are predicted previously and confirmed by CMS.

Fully charm tetraquark family: Linear Regge trajectories?



Outline

- Fully charm tetraquarks production properties
- Fully charm tetraquarks decay properties
- Summary and Outlook

- **Fully charm tetraquarks production properties**

Fully charm tetraquark production

QCD factorization:

$$\sigma\left(pp \to T_{4c} + X\right) = \sum_{i,j=q,g} \int_0^1 dx_1 dx_2 f_{i/p}\left(x_1, \mu_F\right) f_{j/p}\left(x_2, \mu_F\right) \hat{\sigma}(i + j \to T_{4c} + X)\left(\hat{s}, \mu_F\right)$$

Partonic processes:

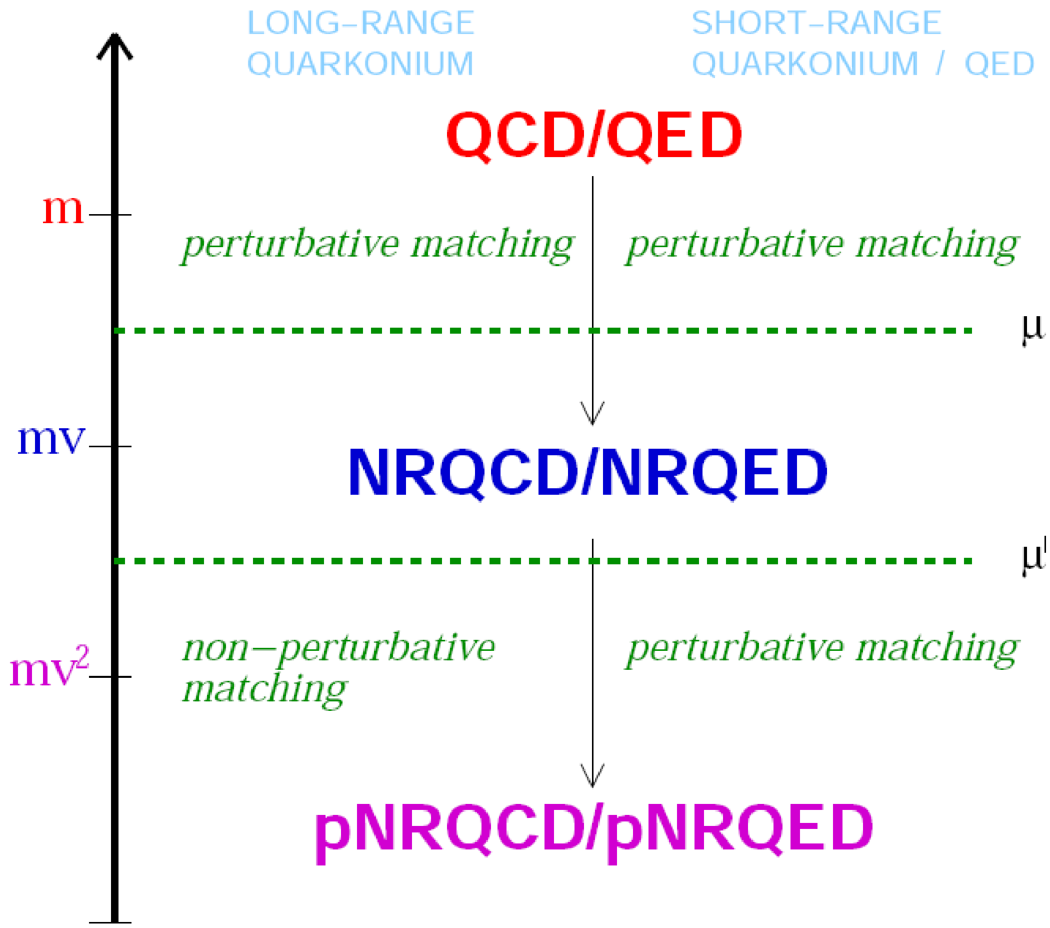
LO+NLO virtual: $g + g \to T_{4c}$ and $q + \bar{q} \to T_{4c}$.

NLO real:

$$g + g \to T_{4c} + g,\ q + \bar{q} \to T_{4c} + g$$

$$q + g \to T_{4c} + q,\ \bar{q} + g \to T_{4c} + \bar{q}$$

NRQCD/pNRQCD factorization



$$\alpha_s(mv) \sim v$$

$v^2 \approx 0.1$ for the Υ

Bodwin-Braaten-
Lapage
1995

Pineda-Soto-
Brambilla-Vairo
2000

NRQCD Lagrangian

- **QCD Lagrangian**

$$\mathcal{L}_{\rm QCD} = \sum_{q=u,d,s,\ldots} \overline{\psi}_{qi}(x)\left[(i\gamma_\mu D^\mu)_{ij} - m_q\delta_{ij}\right]\Psi_{qj}(x) - \frac{1}{4}F^a_{\mu\nu}(x)F^{\mu\nu\,a}(x)\ ,$$

- **Rewrite heavy quark field and do the NR expansion**

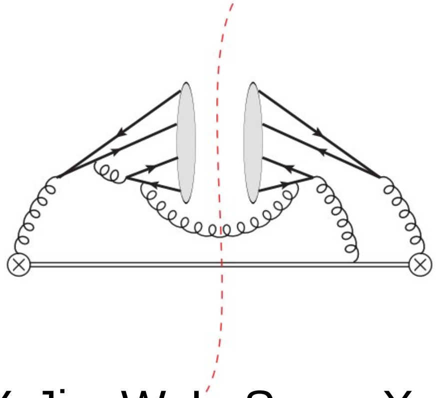
$$\Psi = e^{-iMt}\tilde{\Psi} = e^{-iMt}\begin{pmatrix}\psi\\ \chi\end{pmatrix}, \qquad \Psi' = e^{iM't}\tilde{\Psi} = e^{iM't}\begin{pmatrix}\psi'\\ \chi'\end{pmatrix},$$

- **Obtain NRQCD Lagrangian**

$$\begin{aligned}\mathcal{L}_{NRQCD} =& \psi^\dagger\left(iD_t - \frac{1}{2M}(i\mathbf{D})^2\right)\psi + \frac{c_F}{2M}\psi^\dagger\boldsymbol{\sigma}\cdot g\mathbf{B}\psi \\ &+ \frac{c_D}{8M^2}\psi^\dagger(\mathbf{D}\cdot g\mathbf{E} - g\mathbf{E}\cdot\mathbf{D})\psi^\dagger + \frac{c_S}{8M^2}\psi^\dagger(i\boldsymbol{\sigma}\cdot\mathbf{D}\times g\mathbf{E} - i\boldsymbol{\sigma}\cdot g\mathbf{E}\times\mathbf{D})\psi^\dagger \\ &+ \frac{c_4}{8M^3}\psi'^\dagger\left(\mathbf{D}^2\right)^2\psi' + \mathcal{O}\left(1/M^3\right) \\ &+ [\psi\to i\sigma^2\chi'*, A_\mu\to -A^T_\mu, M\to M'] + \mathcal{L}_{light}].\end{aligned}$$

Previous studies (selected)

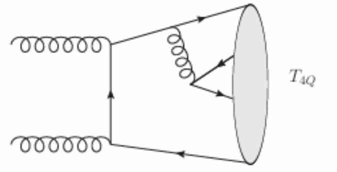
- **Fragmentation mechanism (based on NRQCD), equally considering the NLO real diagrams (valid for large Pt)**



F. Feng, Y. Huang, Y. Jia, W. L. Sang, X. Xiong and J. Y.Zhang, arXiv:2009.08450; F. Feng et al, 2304.11142
Y.Q. Ma, H.F. Zhang, arXiv:2009.08376
I. Belov, A. Giachino, and E. Santopinto, arXiv:2409.12070

- **NRQCD LO (Pt=0)**

R.L. Zhu, arXiv: 2010.09082



Differential cross section in NRQCD

$$\frac{\mathrm{d}\hat{\sigma}(T_{4c}^{(J)}+X)}{\mathrm{d}\hat{t}} = \frac{2M_{T_{4c}}}{m_c^{14}}\left[F_{3,3}^{(J)}\left\langle O_{3,3}^{(J)}\right\rangle + 2F_{3,6}^{(J)}\left\langle O_{3,6}^{(J)}\right\rangle + F_{6,6}^{(J)}\left\langle O_{6,6}^{(J)}\right\rangle\right],$$

$$O_{3,3}^{(J)} = \mathcal{O}_{\bar{\mathbf{3}}\otimes\mathbf{3}}^{(J)}\sum_X |T_{4c}^J + X\rangle\langle T_{4c}^J + X|\mathcal{O}_{\bar{\mathbf{3}}\otimes\mathbf{3}}^{(J)\dagger},$$

$$O_{6,6}^{(0)} = \mathcal{O}_{\mathbf{6}\otimes\bar{\mathbf{6}}}^{(0)}\sum_X |T_{4c}^0 + X\rangle\langle T_{4c}^0 + X|\mathcal{O}_{\mathbf{6}\otimes\bar{\mathbf{6}}}^{(0)\dagger},$$

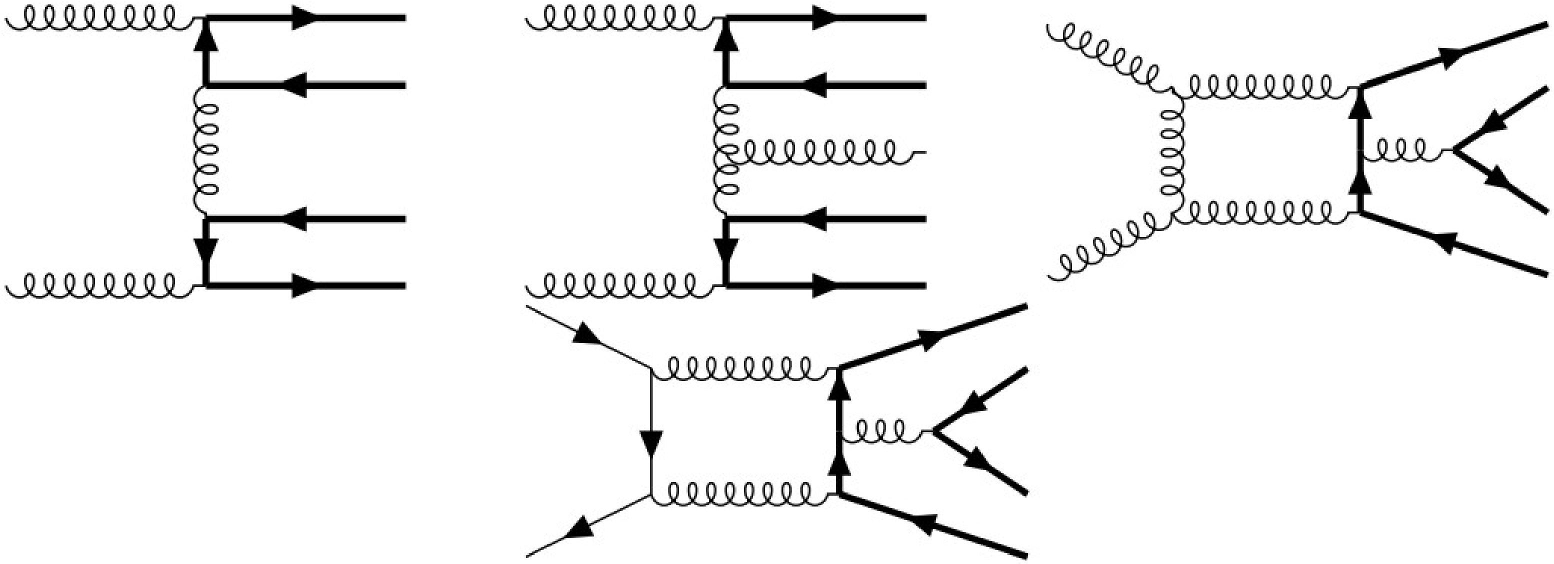
$$O_{3,6}^{(0)} = \mathcal{O}_{\bar{\mathbf{3}}\otimes\mathbf{3}}^{(0)}\sum_X |T_{4c}^0 + X\rangle\langle T_{4c}^0 + X|\mathcal{O}_{\mathbf{6}\otimes\bar{\mathbf{6}}}^{(0)\dagger},$$

$$\mathcal{O}_{\bar{\mathbf{3}}\otimes\mathbf{3}}^{(0)} = -\frac{1}{\sqrt{3}}[\psi_a^T(i\sigma^2)\sigma^i\psi_b][\chi_c^\dagger\sigma^i(i\sigma^2)\chi_d^*]\ \mathcal{C}_{\bar{\mathbf{3}}\otimes\mathbf{3}}^{ab;cd},$$

$$\mathcal{O}_{\bar{\mathbf{3}}\otimes\mathbf{3}}^{ij;(2)} = [\psi_a^T(i\sigma^2)\sigma^m\psi_b][\chi_c^\dagger\sigma^n(i\sigma^2)\chi_d^*]\ \Gamma^{ij;mn}\ \mathcal{C}_{\bar{\mathbf{3}}\otimes\mathbf{3}}^{ab;cd},$$

$$\mathcal{O}_{\mathbf{6}\otimes\bar{\mathbf{6}}}^{(0)} = [\psi_a^T(i\sigma^2)\psi_b][\chi_c^\dagger(i\sigma^2)\chi_d^*]\ \mathcal{C}_{\mathbf{6}\otimes\bar{\mathbf{6}}}^{ab;cd}.$$

Full NLO calculation in NRQCD



LO:64(gg)， 4(qqbar)

NLO Virtual:2008(gg)， 170(qqbar)

NLO Real: 618(gg)， 98(qqbar, qg)

Exact IR cancellation

$$K^{\rm LH3}_{\rm gg,virtual} = \frac{3}{\epsilon^2} - \frac{1}{\epsilon}\left(3\log\left(\frac{\mu}{4m_c}\right)^2 - \frac{n_l}{3} + \frac{11}{2}\right) - \frac{3}{2}\log^2\left(\frac{\mu}{4m_c}\right)^2$$
$$+ \left(\frac{11}{2} - \frac{2n_h + n_l}{3}\right)\log\left(\frac{\mu}{m_c}\right)^2 + \frac{4719}{256}\left(\mathrm{Li}_2\left(2\sqrt{2}-2\right) + \mathrm{Li}_2\left(-2\sqrt{2}-2\right)\right)$$
$$+ \cdots$$

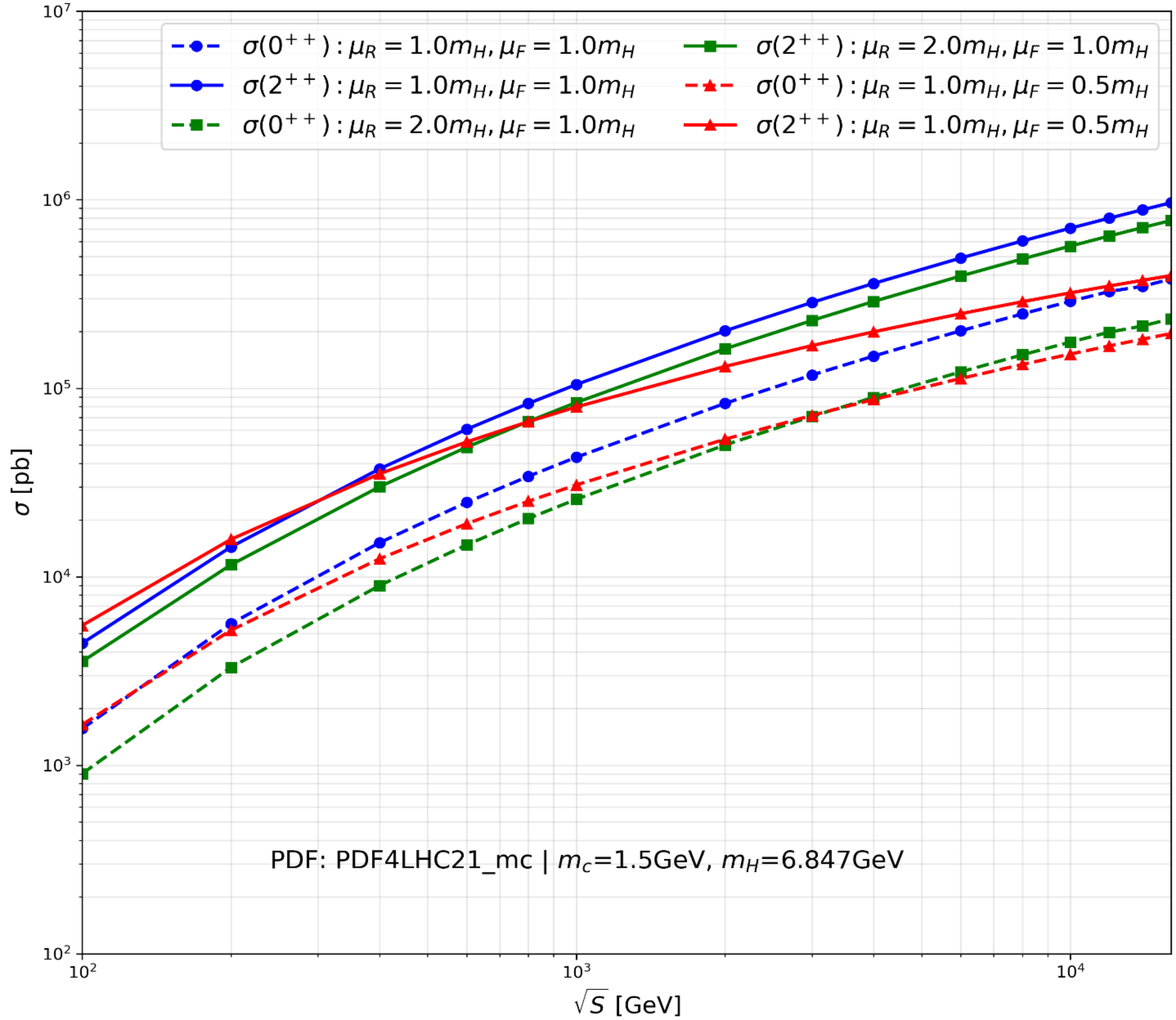
There are soft divergences when $k_g = 0$ or $z = 1$, and collinear divergences when $y_\theta = \cos\theta_{k_n k_g} = \pm 1$ with $k_n = k_1, k_2, k_T$.

$$\hat{\sigma}_{\rm soft}\ (i + j \to T_{4c} + k) = -C\frac{1}{2\epsilon_{\rm IR}}\delta(1-z)\frac{4^{-\epsilon}\Gamma(1-\epsilon)\Gamma(-\epsilon)}{\Gamma(1-2\epsilon)}\mathcal{B}_{ij}\left(z=1, y_\theta\right)$$
$$= \Gamma(1+\epsilon)\left(\frac{4\pi\mu_R^2}{\hat{s}}\right)^\epsilon \frac{\alpha_s}{\pi}\hat{\sigma}^{(0)}_{ij}\delta(1-z)\left(\frac{1}{\epsilon_{\rm IR}^2} - \frac{\pi^2}{3}\right)C_{ij}$$

$$\hat{\sigma}_{\text{hard col. } y_\theta=\pm1}\,(i + j \to T_{4c} + k)$$
$$= -C\frac{4^{-\epsilon}}{2\epsilon_{\rm IR}}\left[\left(\frac{1}{1-z}\right)_+ - 2\epsilon\left(\frac{\log(1-z)}{1-z}\right)_+\right]\mathcal{B}_{ij}\left(z, y_\theta = \pm 1\right)$$
$$= -C\frac{4^{-\epsilon}}{2\epsilon_{\rm IR}}\left[\left(\frac{1}{1-z}\right)_+ - 2\epsilon\left(\frac{\log(1-z)}{1-z}\right)_+\right]\mathcal{B}_{ij}\left(z=1, y_\theta\right)\frac{b^{\rm collinear}_{ij}}{z^3}$$
$$= \Gamma(1+\epsilon)\left(\frac{4\pi\mu_R^2}{\hat{s}}\right)^\epsilon \frac{\alpha_s}{\pi}\hat{\sigma}^{(0)}_{ij}\delta(1-z)\left[-2C_{ij}b^{\rm collinear}_{ij}\left(\left(\frac{1}{1-z}\right)_+\frac{1}{\epsilon_{\rm IR}} - 2\left(\frac{\log(1-z)}{1-z}\right)_+\right)\right]$$

$$\hat{\sigma}^{\rm AP-CT} = \frac{1}{\epsilon}\frac{\alpha_s}{2\pi}\left(\frac{4\pi\mu_R^2}{\mu_F^2}\right)^\epsilon\Gamma(1+\epsilon)\hat{\sigma}^{(0)}zP_{ij}(z),$$

Collider energy dependence for different spin and scales

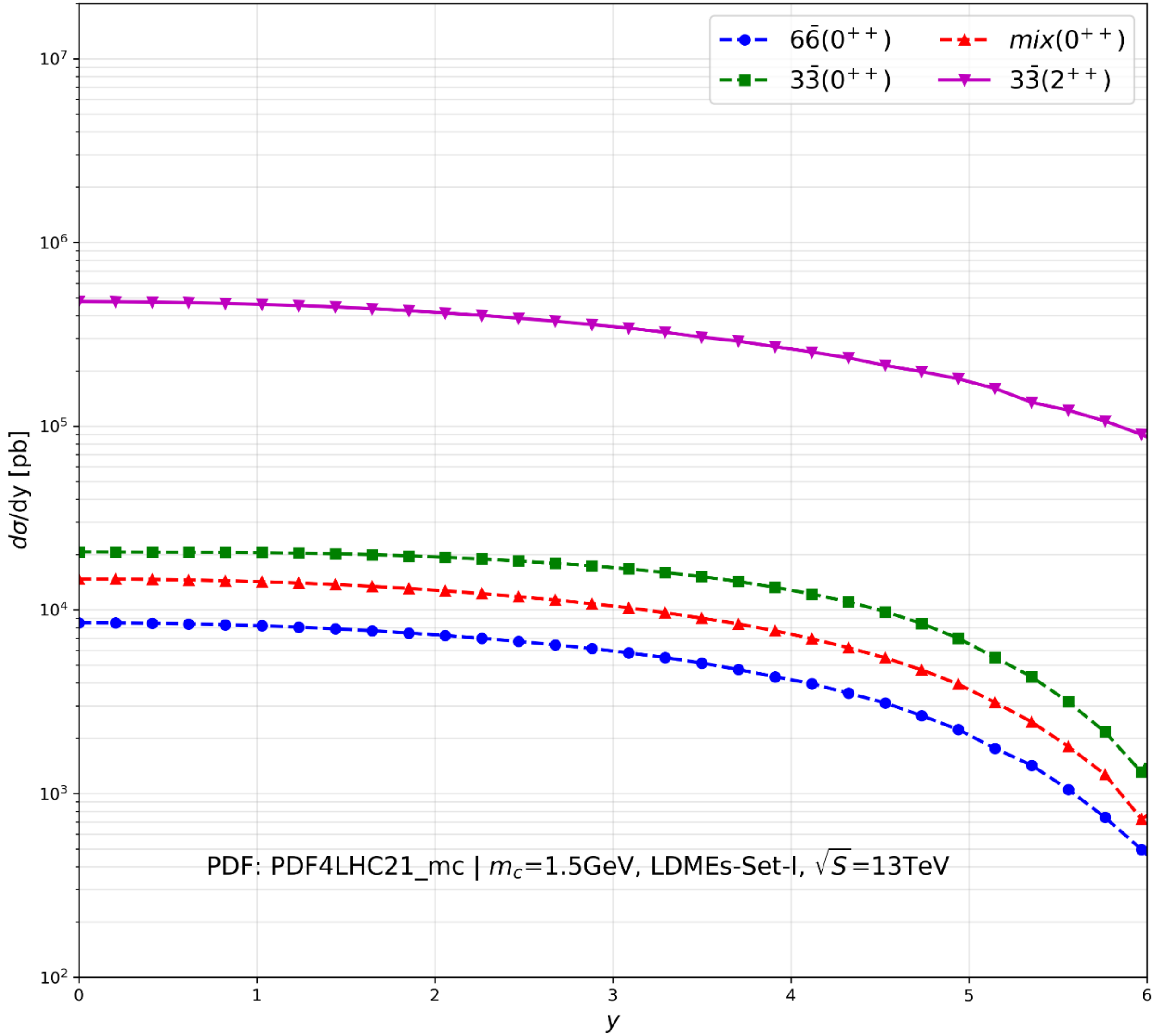


Reference at 7TeV:
σ(eta_c)~10^6nb

σ(2J/psi)~10nb

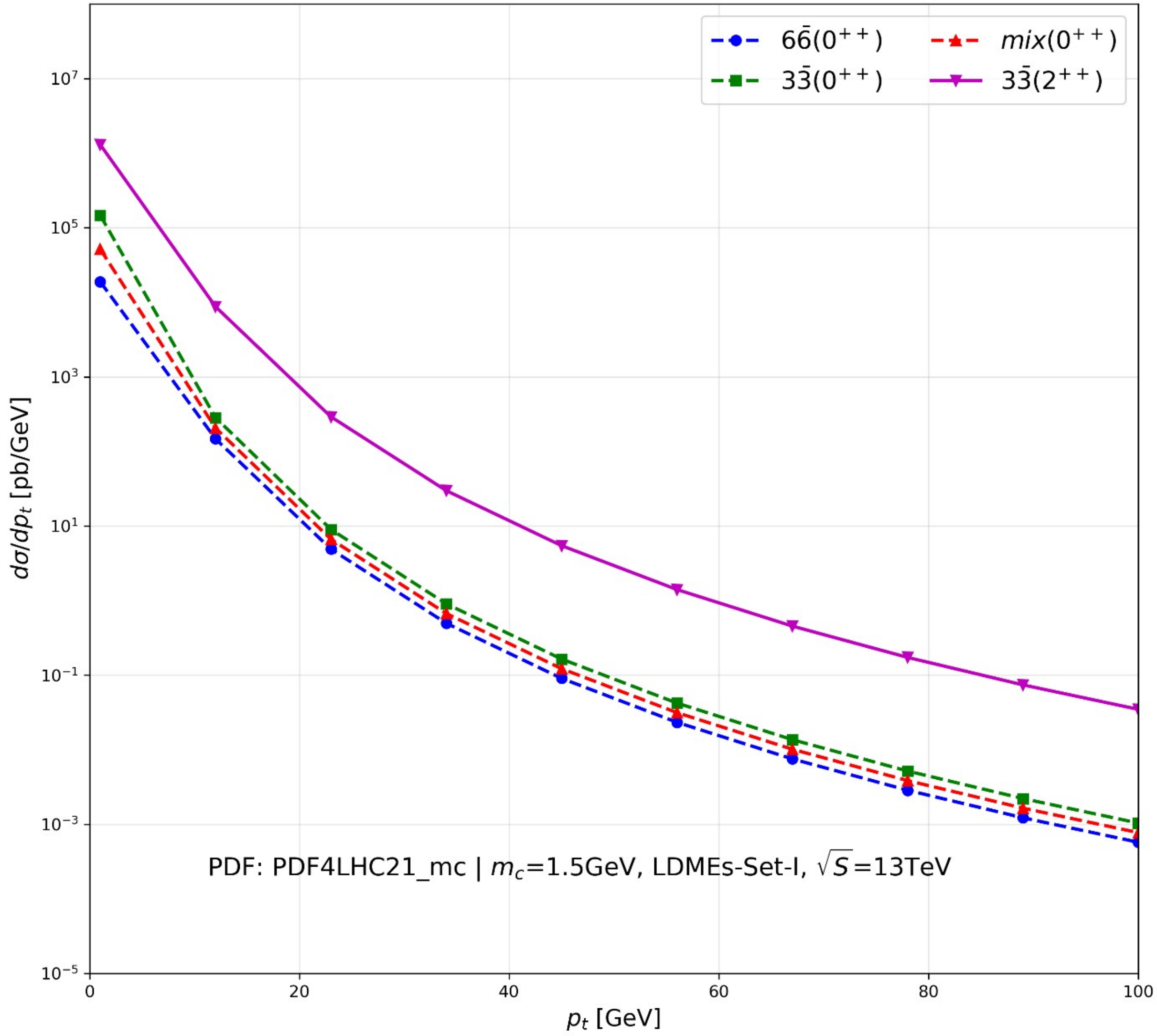
σ(T_4c)
~[10-100]nb

Rapidity dependence for different diquark configurations



[3 3_bar]
plays a major role

Transverse momentum distribution



Divergence when pt -> 0

Soft gluon radiation produces large logarithms

$$\frac{d\sigma}{dyd^2p_t}\Big|^{gg}_{p_t\ll M} = \sigma_0(T^{J,i}_{4c})\frac{\alpha_s C_A}{2\pi^2}\int f(x)dx f(x')dx'$$
$$\times \frac{1}{p_t^2}\left[\frac{2(1-\xi_1+\xi_1^2)^2}{(1-\xi_1)_+}\delta(1-\xi_2) + \frac{2(1-\xi_2+\xi_2^2)^2}{(1-\xi_2)_+}\delta(1-\xi_1)\right.$$
$$\left. + \left(2\ln\frac{M^2}{p_t^2}\right)\delta(1-\xi_2)\delta(1-\xi_1)\right],$$

At low P_perp, the soft gluon radiations generate the divergence, which should be resumed to obtain reliable predictions.

Collins-Soper-Sterman resummation

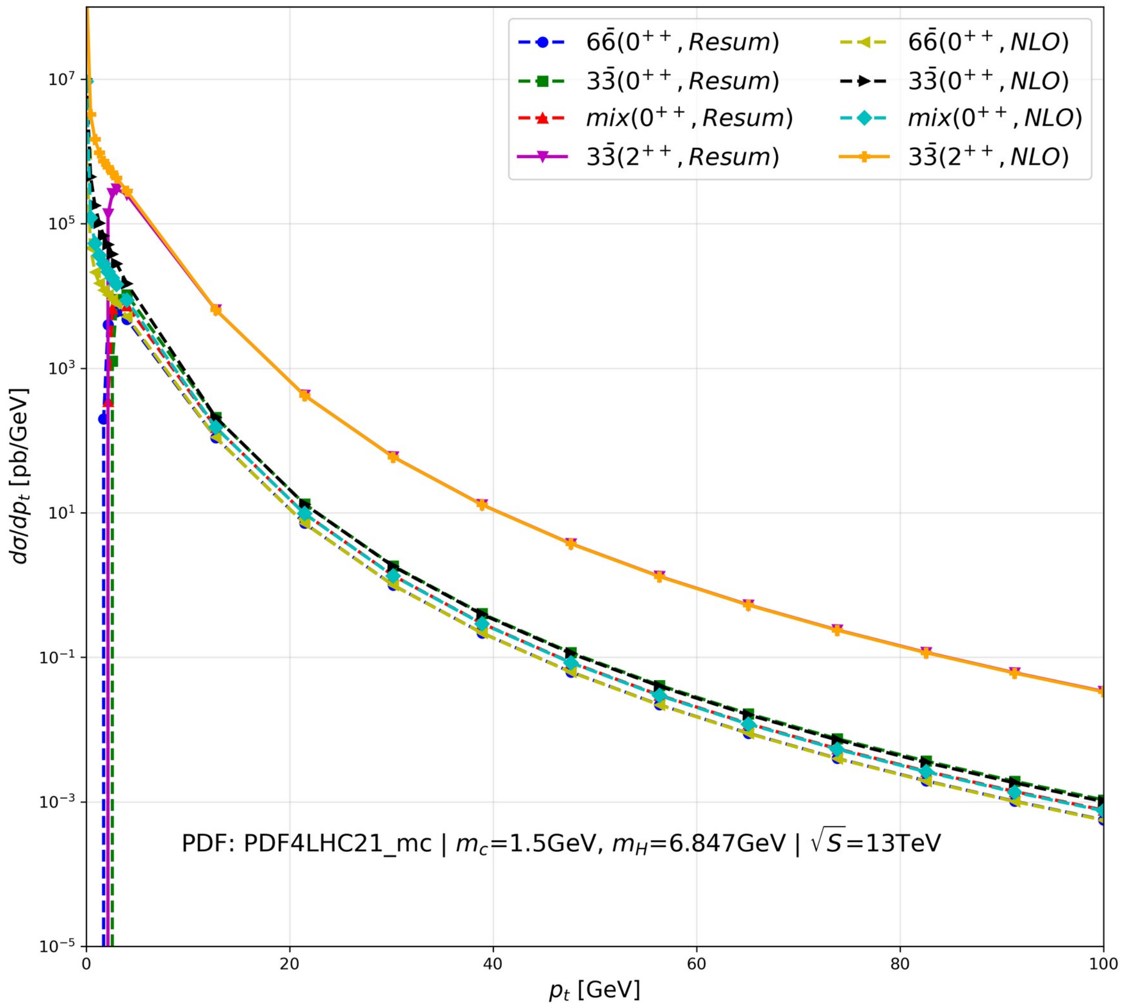
$$\frac{d\sigma}{dp_t^2} \sim \frac{(L+1)}{p_t^2}\Big\{\alpha_s + \alpha_s^2 L^2 + \alpha_s^3 L^4 + \alpha_s^4 L^6 \\ + \alpha_s^2 \quad + \alpha_s^3 L^2 + \alpha_s^4 L^4 \\ + \alpha_s^3 + \alpha_s^4 L^2 \cdots \Big\},$$

$$\frac{\partial W(b, M^2)}{\partial \ln M^2} = (K + G')W(b, M^2) \ ,$$

Collins, Soper 81
Collins, Soper, Sterman 85

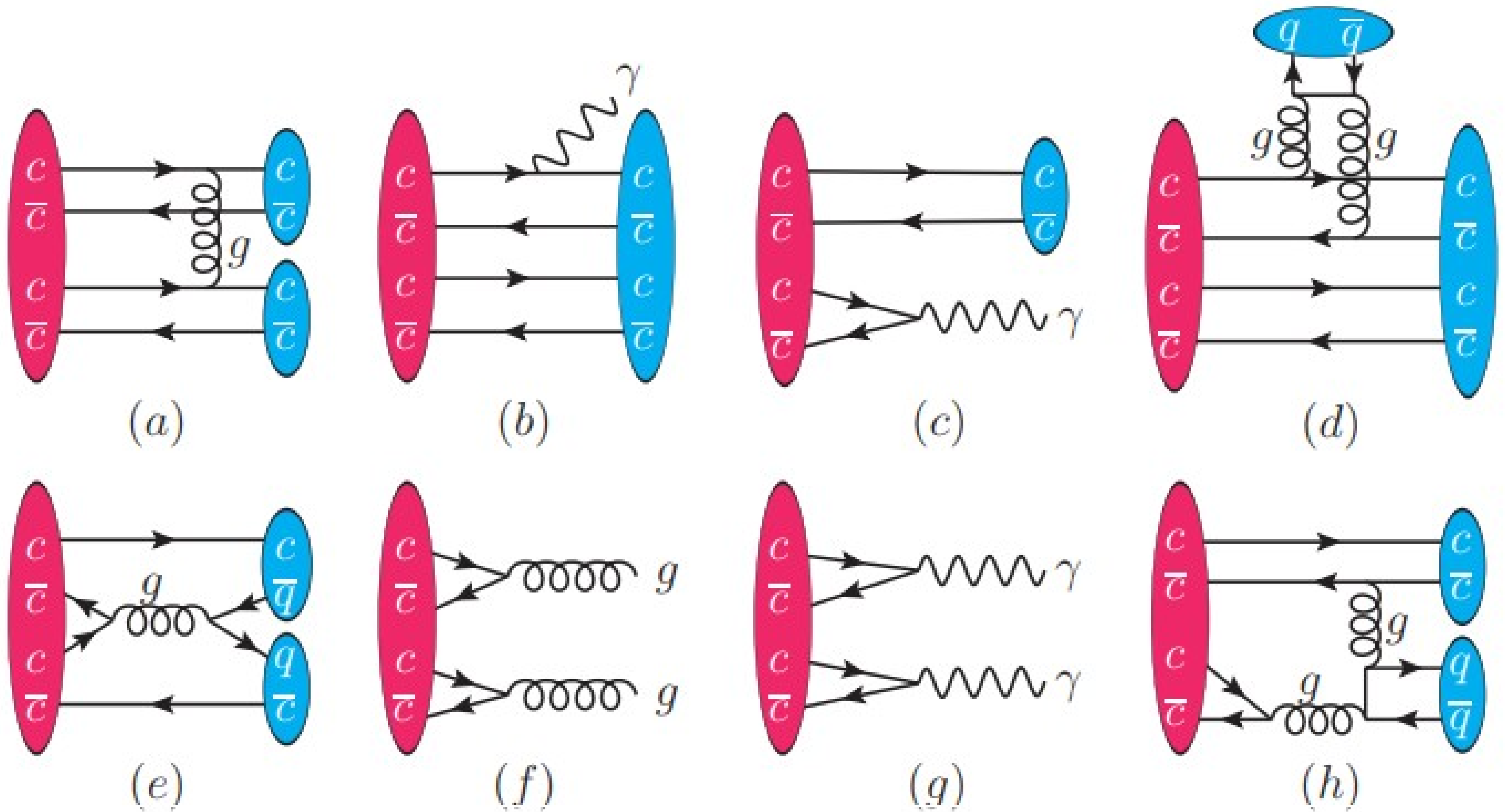
$$\frac{d\sigma}{dy dp_t^2} \sim \int d^2 b e^{ip_t \cdot b} \\ \times \sum_a \int_{x_A}^1 \frac{d\xi_A}{\xi_A} f_{a/A}(\xi_A; 1/b) \sum_b \int_{x_B}^1 \frac{d\xi_B}{\xi_B} f_{b/B}(\xi_B; 1/b) \\ \times \exp\left\{-\int_{1/b^2}^{Q^2} \frac{d\bar{\mu}^2}{\bar{\mu}^2}\left[\ln\left(\frac{Q^2}{\bar{\mu}^2}\right) A\left(g(\bar{\mu})\right) + B\left(g(\bar{\mu})\right)\right]\right\} \\ \times C_{ja}\left(\frac{x_A}{\xi_A}; g(1/b)\right) C_{jb}\left(\frac{x_B}{\xi_B}; g(1/b)\right) \\ + Y(p_t; Q, x_A, x_B).$$

NLL Resummation results

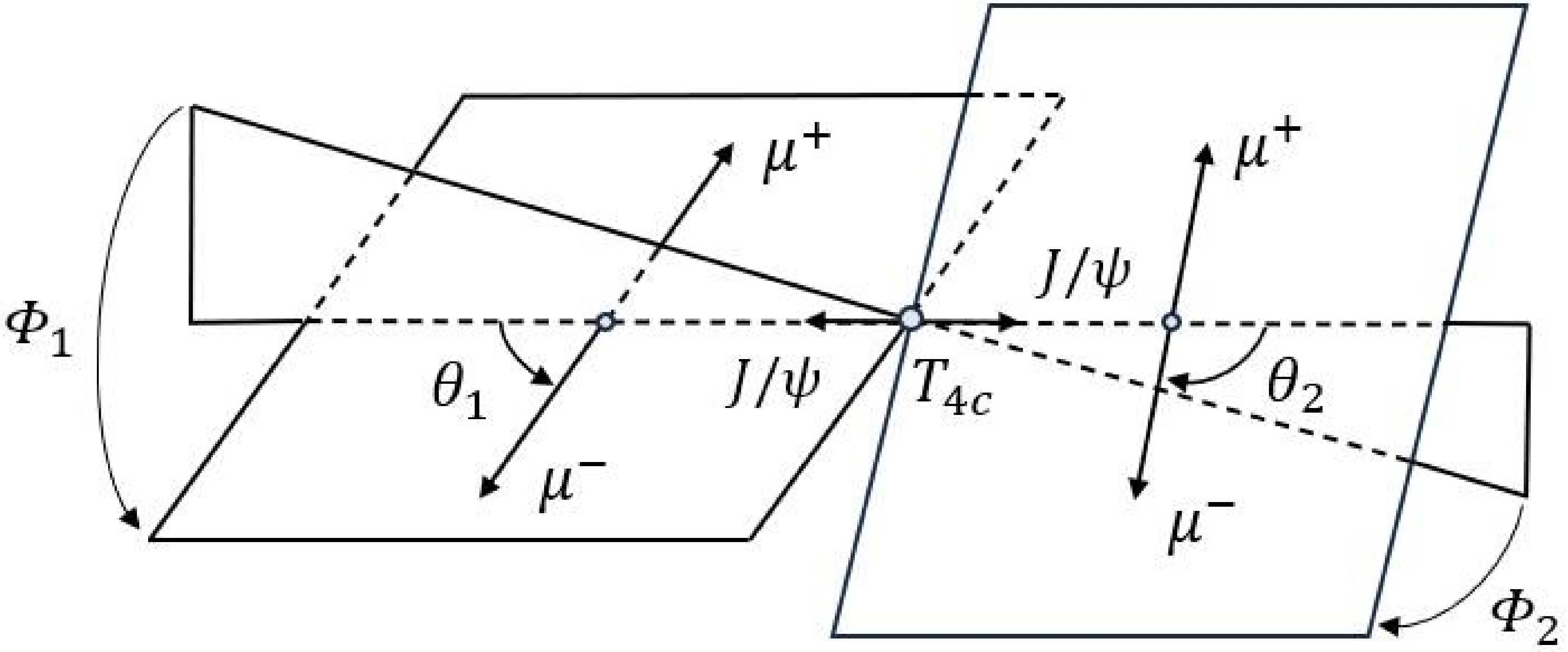


- **Fully charm tetraquarks decay properties**

Major decay modes



Cascade decay angles



Helicity amplitudes

$$\langle \vec{p}_1 \lambda_{a_1}, -\vec{p}_1 \lambda_{a_2} | H_1 | s_1 \lambda_1 \rangle = 4\pi \sqrt{\frac{\omega_1}{p_1}} \langle \Omega_1 \lambda_{a_1} \lambda_{a_2} | H_1 | s_1 \lambda_1 \rangle$$

$$= 4\pi \sqrt{\frac{\omega_1}{p_1}} \sum_{\lambda'_{a_1} \lambda'_{a_2}} \langle \Omega_1 \lambda_{a_1} \lambda_{a_2} | | s_1 \lambda_1 \lambda'_{a_1} \lambda'_{a_2} \rangle \langle s_1 \lambda_1 \lambda'_{a_1} \lambda'_{a_2} | H_1 | s_1 \lambda_1 \rangle$$

$$= 4\pi \sqrt{\frac{\omega_1}{p_1}} N_{s_1} D^{s_1 *}_{\lambda_1 \lambda_a}(-\Phi_1, \theta_1, \Phi_1) \langle s_1 \lambda_1 \lambda_{a_1} \lambda_{a_2} | H_1 | s_1 \lambda_1 \rangle$$

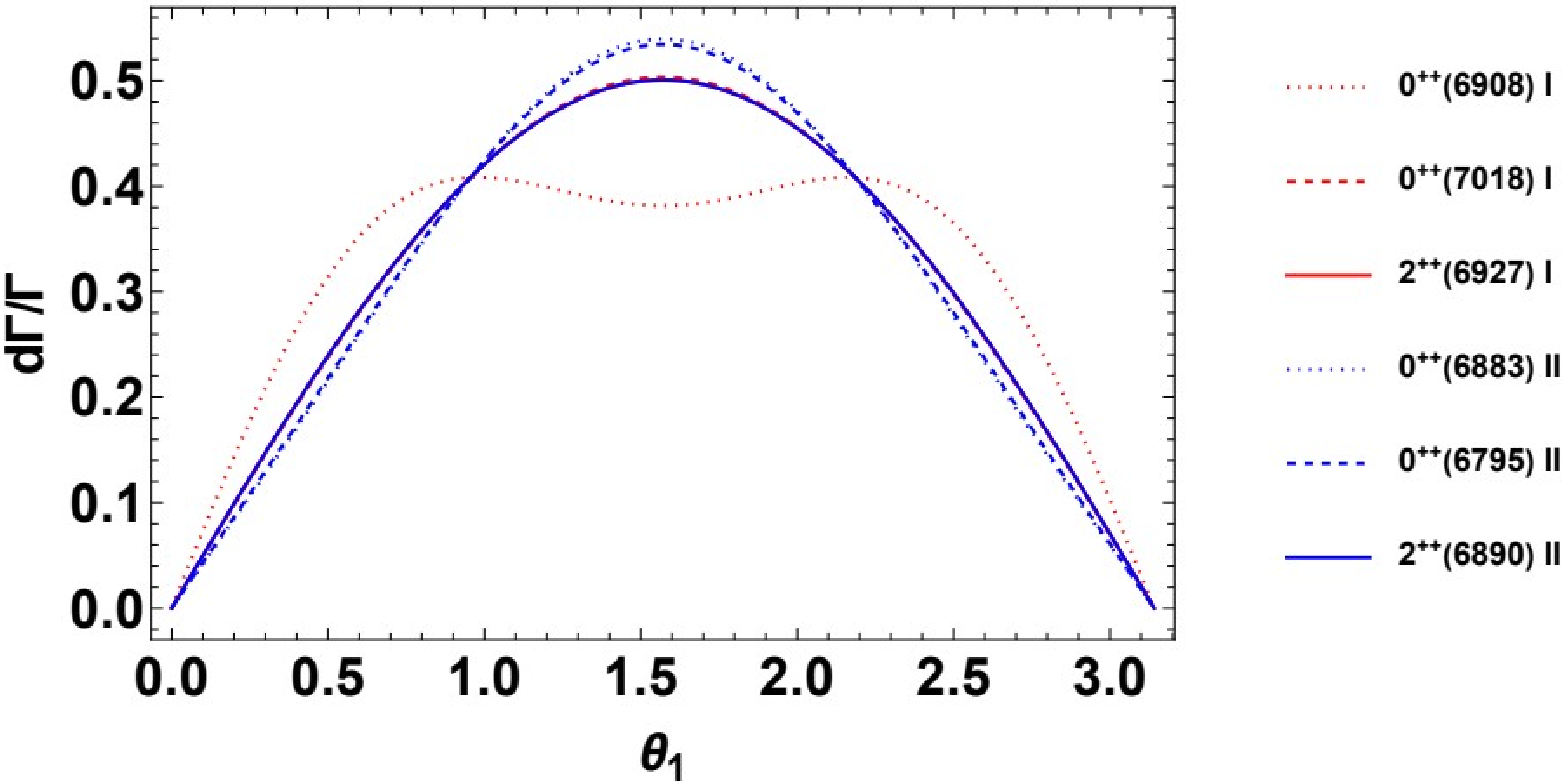
$$= N_{s_1} F^{s_1}_{\lambda_{a_1} \lambda_{a_2}} D^{s_1 *}_{\lambda_1 \lambda_a}$$

Symmetry constraint:
Parity conservation;
Identical particles

$$F^{s}_{\lambda_1 \lambda_2} = \eta \eta_1 \eta_2 (-1)^{s - s_1 - s_2} F^{s}_{-\lambda_1 - \lambda_2}$$

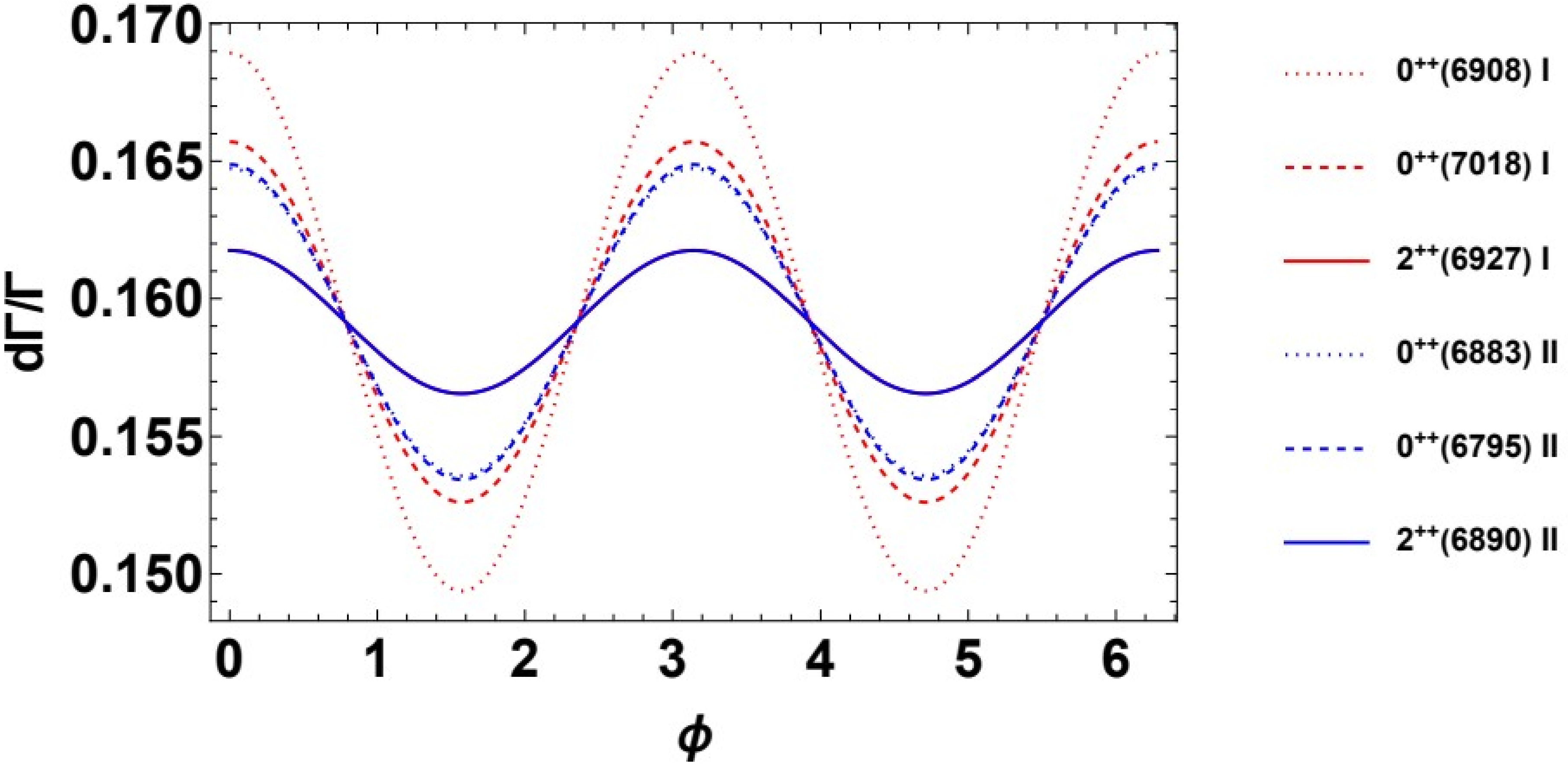
$$F^{s}_{\lambda_1 \lambda_2} = (-1)^{s} F^{s}_{\lambda_2 \lambda_1}$$

Polar angular distribution

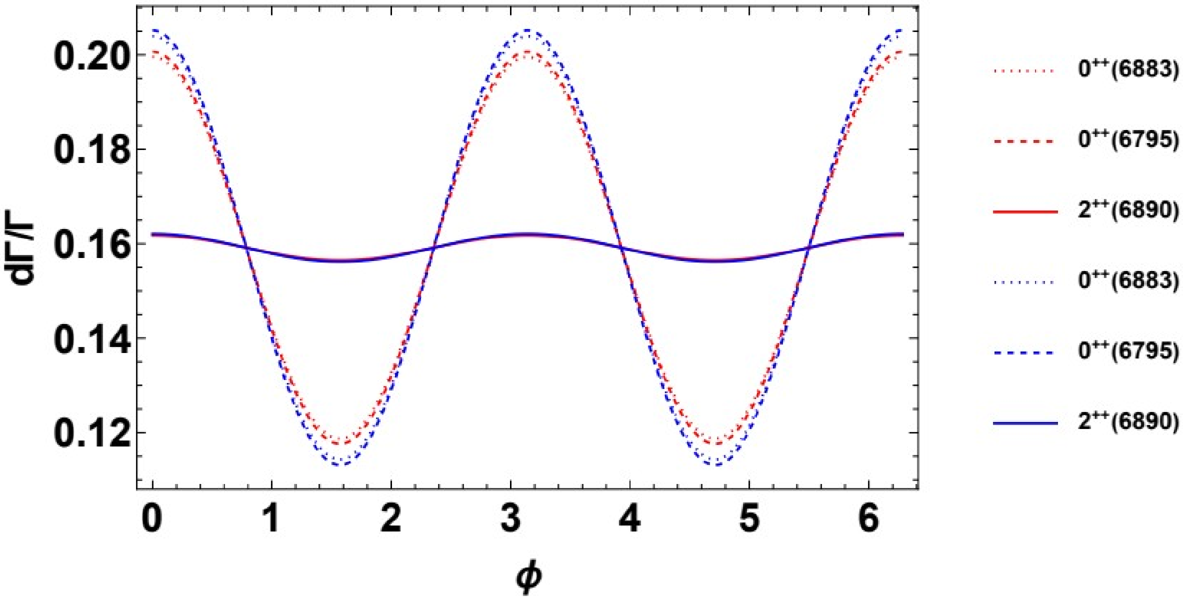


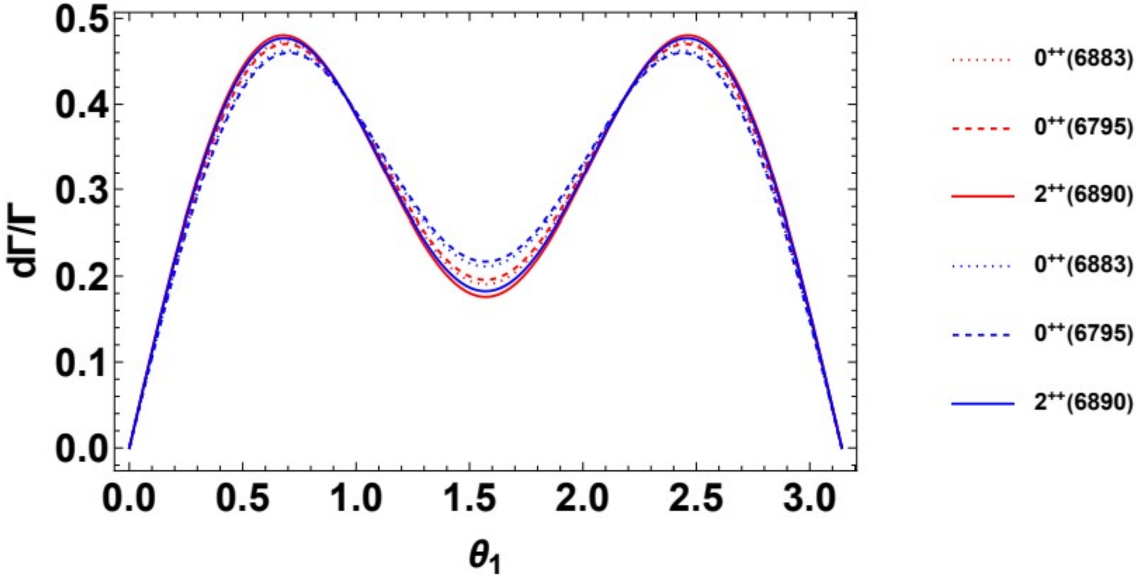
Model I: quark model (QM);
Model II: diquark model+heavy quark effective theory(HQET)

Plane angular distribution



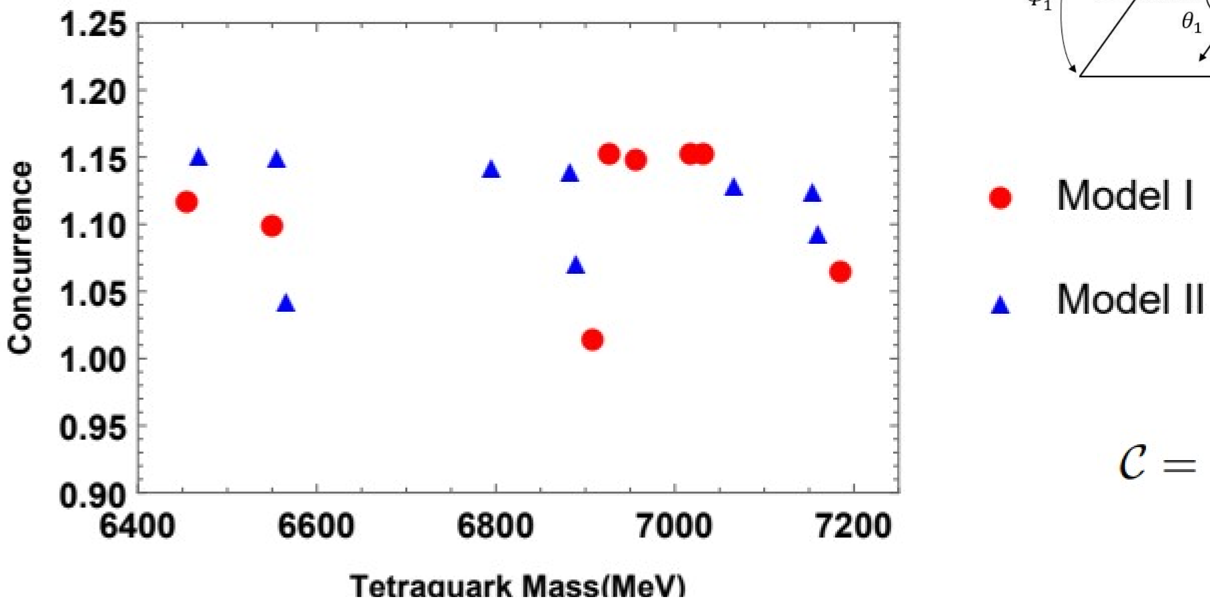
Charmed meson pair channel

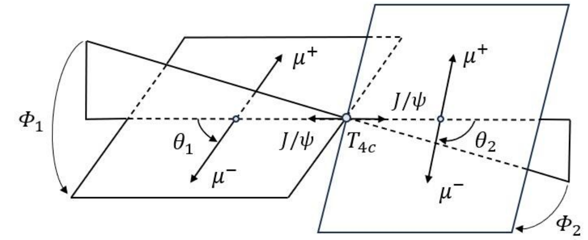




The θ_1 and Φ distributions for various tetraquarks near 6.9 GeV into $D^*(\to D\pi)$ and $\bar{D}^*(\to \bar{D}\pi)$ using Model II (HQET).

Quantum entanglement





$$\mathcal{C} = \sqrt{2(1 - \mathrm{Tr}\rho_A^2)},$$

$$max\left(0, \sqrt{\frac{1}{3}}\left[\frac{h_{00}^{00} + 2h_{01}^{01} + 4h_{11}^{00} + 2h_{11}^{11}}{N} - 1\right]\right) \leq \sqrt{2(1 - \frac{\left(h_{00}^{00}\right)^2 + 2\left(h_{11}^{11}\right)^2}{N^2})} \leq \frac{2}{\sqrt{3}}.$$

$$max\,(0, LB_2) \leq \sqrt{2(1 - \left(\frac{h_{00}^{00} + 2h_{10}^{10}}{N}\right)^2 - \left(\frac{h_{10}^{10} + h_{11}^{11} + h_{1-1}^{1-1}}{N}\right)^2 - \left(\frac{h_{10}^{10} + h_{1-1}^{1-1} + h_{11}^{11}}{N}\right)^2)} \leq \frac{2}{\sqrt{3}}.$$

If assume quantum entanglement as a basic principle, then a constraint formula for helicity amplitudes.

Summary and outlook

- ✓ The full NLO calculation for T4c production spectrum is given.
- ✓ The angular distribution and entanglement are studied in T4c decay processes

Outlook: measuring the (differential) cross section (or) and the decay angular distribution shall tell us the inner structure of fully charm tetraquarks; a lot of tasks in there

Thank you a lot!

Backup

	LDME	Model I [15]	Model II [16]
0^{++}	$\left\langle O_{3,3}^{(0)} \right\rangle$ [GeV^9]	0.0347	0.0187
	$\left\langle O_{3,6}^{(0)} \right\rangle$ [GeV^9]	0.0211	-0.0161
	$\left\langle O_{6,6}^{(0)} \right\rangle$ [GeV^9]	0.0128	0.0139
1^{+-}	$\left\langle O_{3,3}^{(1)} \right\rangle$ [GeV^9]	0.0780	0.0480
2^{++}	$\left\langle O_{3,3}^{(2)} \right\rangle$ [GeV^9]	0.072	0.0628

$$\mathcal{M}(0^{++}) = \epsilon^*_{1\mu}\epsilon^*_{2\nu}\left(a g^{\mu\nu} + \frac{b p_1^\mu p_2^\nu}{m_1 m_2} + \frac{ic\epsilon^{\mu\nu\alpha\beta}p_{1\alpha}p_\beta}{m_1 m_2}\right), \tag{A.29}$$

where m_i, p_i and ϵ_i are the mass, momentum and polarization vector for the two daughter particles, respectively. The relationship between the parameters a,b,c and the helicity amplitude can be expressed as

$$F^0_{11} = a + \sqrt{x^2-1}c, \quad F^0_{-1-1} = a - \sqrt{x^2-1}c,$$
$$F^0_{00} = -ax - b(x^2-1), \tag{A.30}$$

$$\mathcal{C} = \sqrt{2(1-\mathrm{Tr}\rho_A^2)},$$

where

$$x^2 = \frac{p_m^2 M_T^2}{m_1^2 m_2^2} + 1. \tag{A.31}$$

$$\varrho = \frac{1}{|H|^2}\begin{pmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & h_{+1}h^*_{+1} & 0 & h_{+1}h^*_0 & 0 & h_{+1}h^*_{-1} & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & h_0 h^*_{+1} & 0 & h_0 h^*_0 & 0 & h_0 h^*_{-1} & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & h_{-1}h^*_{+1} & 0 & h_{-}h^*_0 & 0 & h_{-1}h^*_{-1} & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{pmatrix}$$

$$|\Psi\rangle = \frac{1}{\sqrt{|H|^2}}\left[h_{+1}|J/\psi(+1)\rho(+1)\rangle + h_0|J/\psi(0)\rho(0)\rangle + h_{-1}|J/\psi(-1)\rho(-1)\rangle\right],$$

$$\mathcal{A}_{CP} \equiv \frac{\Gamma(\Lambda_b^0 \to pK^-\pi^+\pi^-) - \Gamma(\overline{\Lambda}_b^0 \to \overline{p}K^+\pi^-\pi^+)}{\Gamma(\Lambda_b^0 \to pK^-\pi^+\pi^-) + \Gamma(\overline{\Lambda}_b^0 \to \overline{p}K^+\pi^-\pi^+)}.$$

Table 1: Measurements of *CP* asymmetries in four phase-space regions.

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 $1.1 < m_{\pi^+K^-} < 1.6$	$(2.7 \pm 0.8 \pm 0.1)\%$
$\Lambda_b^0 \to R(p\pi^+\pi^-)K^-$	$m_{p\pi^+\pi^-} < 2.7$	$(5.4 \pm 0.9 \pm 0.1)\%$
$\Lambda_b^0 \to R(K^-\pi^+\pi^-)p$	$m_{K^-\pi^+\pi^-} < 2.0$	$(2.0 \pm 1.2 \pm 0.3)\%$

$$\mathcal{A}_{CP} \equiv \frac{\Gamma(\Lambda_b^0 \to pK^-\pi^+\pi^-) - \Gamma(\overline{\Lambda}_b^0 \to \overline{p}K^+\pi^-\pi^+)}{\Gamma(\Lambda_b^0 \to pK^-\pi^+\pi^-) + \Gamma(\overline{\Lambda}_b^0 \to \overline{p}K^+\pi^-\pi^+)} .$$

$$A(\Lambda_b^0) = |A_{\rm T}|\, e^{+i\phi_{\rm T}} e^{i\delta_{\rm T}} + |A_{\rm L}|\, e^{+i\phi_{\rm L}} e^{i\delta_{\rm L}}, \tag{3}$$

where $\phi_{\rm T}$ ($\delta_{\rm T}$) and $\phi_{\rm L}$ ($\delta_{\rm L}$) are the weak (strong) phases of the tree and loop processes, respectively, with $|A_{\rm T}|$ and $|A_{\rm L}|$ being their magnitudes. Similarly, the total amplitude for the $\overline{\Lambda}_b^0$ decay is given by

$$A(\overline{\Lambda}_b^0) = |A_{\rm T}|\, e^{-i\phi_{\rm T}} e^{i\delta_{\rm T}} + |A_{\rm L}|\, e^{-i\phi_{\rm L}} e^{i\delta_{\rm L}}. \tag{4}$$

Substituting into Eq. 1, where the decay rate Γ is proportional to the squared amplitude, the CP asymmetry is obtained as

$$\mathcal{A}_{CP} = \frac{|A(\Lambda_b^0)|^2 - |A(\overline{\Lambda}_b^0)|^2}{|A(\Lambda_b^0)|^2 + |A(\overline{\Lambda}_b^0)|^2} = \frac{2\sin\Delta\delta\sin\Delta\phi}{|A_{\rm T}/A_{\rm L}| + |A_{\rm L}/A_{\rm T}| + 2\cos\Delta\delta\cos\Delta\phi}. \tag{5}$$

A sizable $\mathcal{A}_{CP}$ requires $A_{\rm T}$ and $A_{\rm L}$ to have comparable magnitudes, along with notable differences in both the weak ($\Delta\phi$) and strong ($\Delta\delta$) phases.