Deciphering the nature of X(3872) in heavy ion collisions

Hongxi Xing

Based on collaboration with Hui Zhang, Jinfeng Liao, Enke Wang, Qian Wang
arXiv: 2004.00024, 2005.xxxxx

The 102nd HENPIC seminar, April 30th, 2020.

Outline

- ✦ **Introduction**

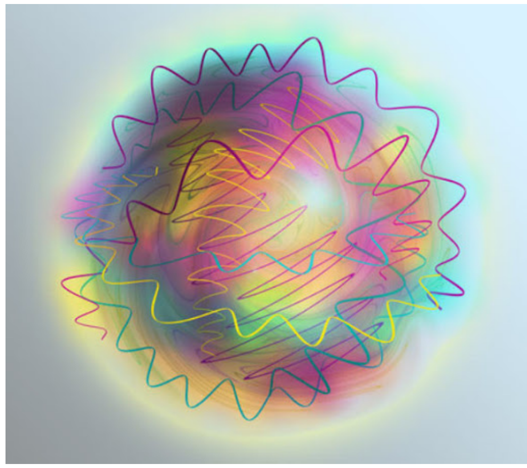
  What is X(3872)?

- ✦ **X(3872) in heavy ion collisions**
- ✦ **X(3872) in jet**
- ✦ **Summary**

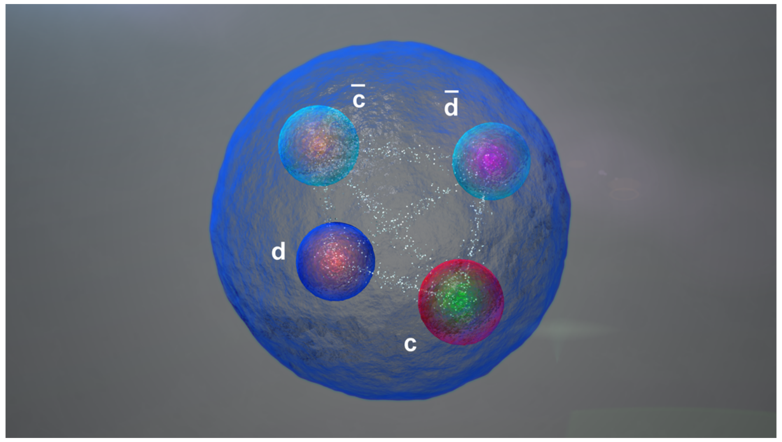
Exotic State XYZ

- **Particle physics textbooks tell us that hadrons appear in two modes:**
  - mesons ($q\bar{q}$)
  - baryons (qqq)

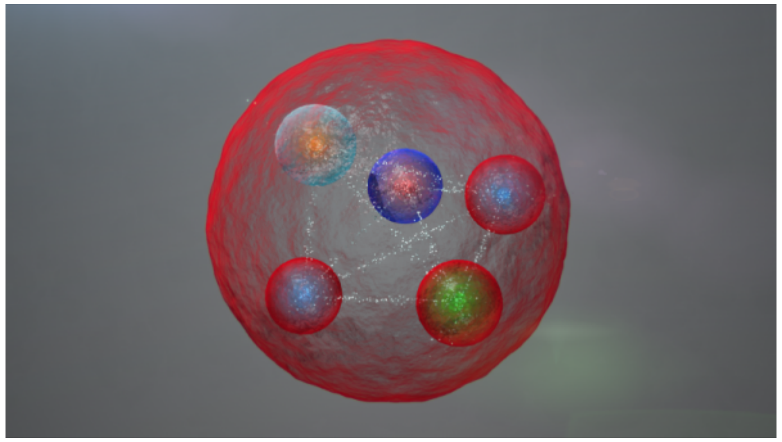
- **Many other types of color singlet compound hadrons, the so-called exotics, could exist**



Glueball



tetraquark



pentaquark

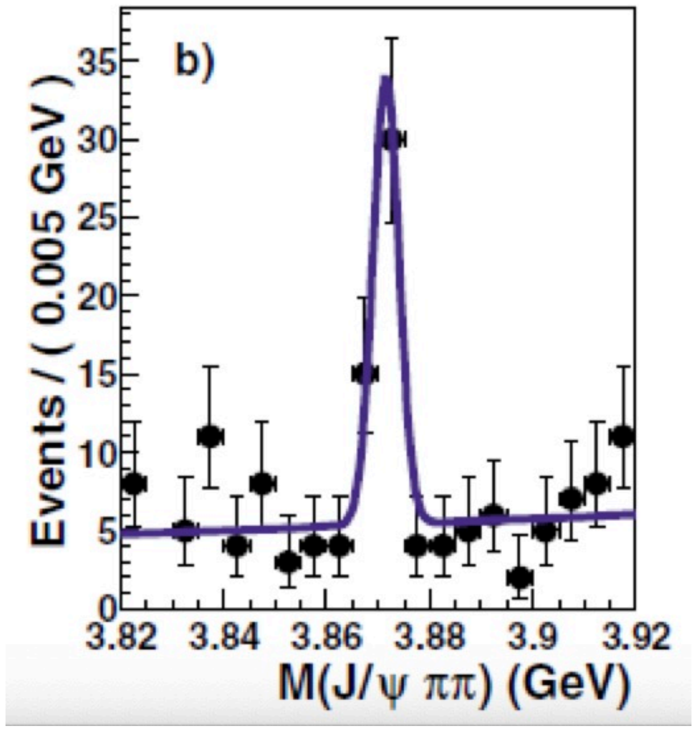
X - unknown
Y - the vector exotic states 1^{--}
Z - charged quarkoniumlike states

Exotic State X(3872)

- **First observed by Belle collaboration (2003)**

$$B \to J/\psi \pi^+ \pi^- K$$

Belle PRL 91, 262001(2003)



- **Mass** PDG 2012

$$m_X = 3871.68 \pm 0.17 MeV$$

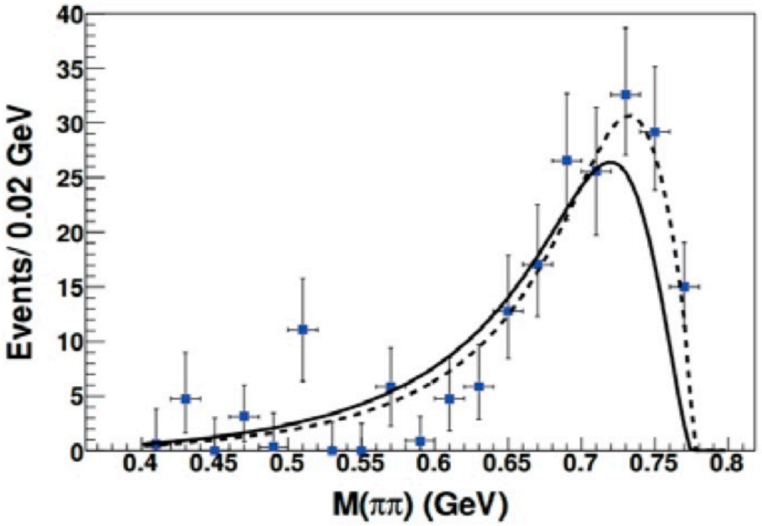
- **Quantum numbers** CDF PRL 98, 132002(2007) LHCb PRL 110, 222001 (2013)

$$J^{PC} = 1^{++}$$

- **Decay pattern** PDG 2012

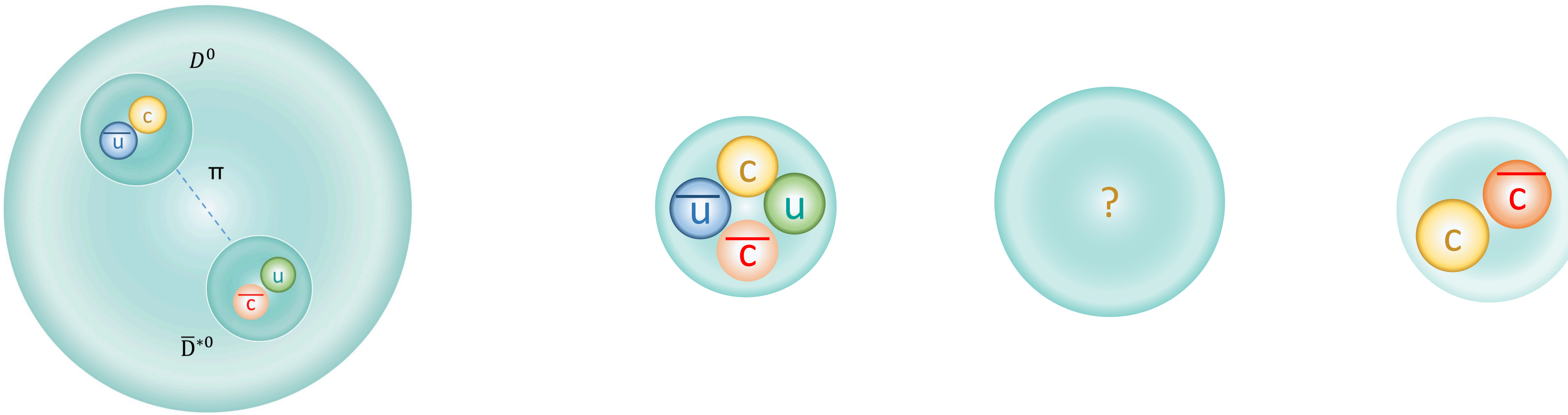
$$J/\psi\rho(\pi^+\pi^-),\ J/\psi\omega(\pi^+\pi^-\pi^0),\ D^0\bar{D}^{*0}/\bar{D}^0 D^{*0}/D\bar{D}\pi,\ J/\psi\gamma$$

Belle, Phys. Rev. D84(2011)052004



✦ The internal structure of X(3872)

Figs from Yen-Jie Lee

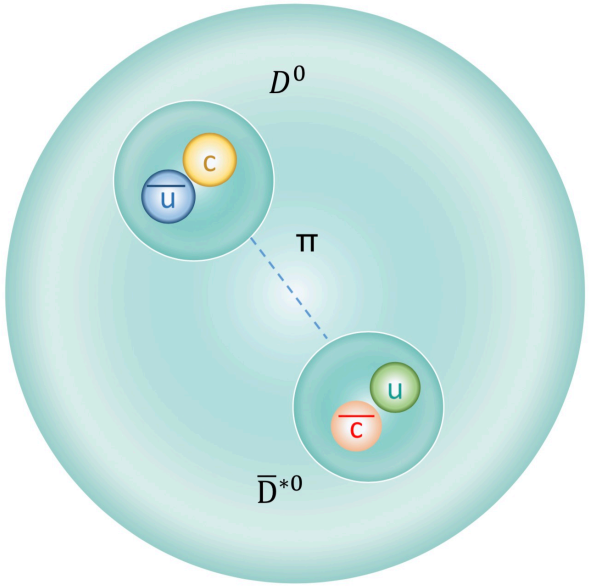


Hadronic molecule **Tetraquark** **Hybrid** **Charmonium**

No conclusive statement yet about the internal structure of X(3872).

The inner structure of X(3872)

✦ Loosely bound molecule state



- **X(3872) is a loosely bound state of** $D^0\bar{D}^{*0}/\bar{D}^0 D^{*0}$

- **The mass, quantum number and the large isospin violation can be understood naturally.**

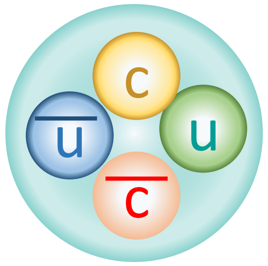
- **The large production rate seems to be questionable**
  Bignamini et al, PRL 09

$$\sigma^{th}_{CDF} < 0.085nb \qquad \sigma^{ex}_{CDF} = 3.1 \pm 0.7\ nb$$

- **Rescattering effects may enhance the rate, if the upper bound of the relative momentum of the molecule state is as large as 3m_pi**
  Artoisenet and Braaten, PRD 10

The inner structure of X(3872)

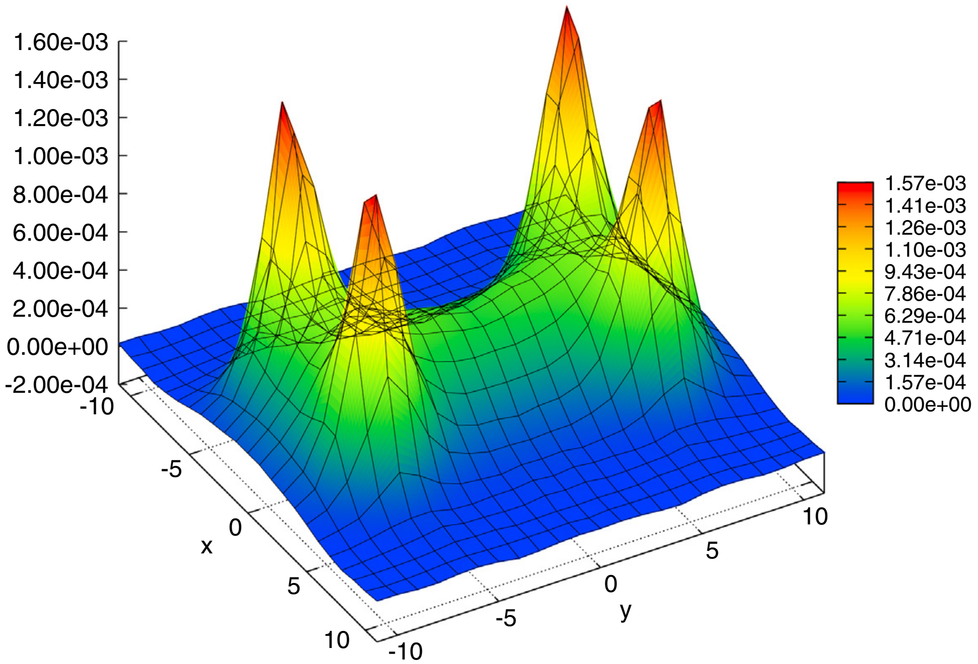
✦ Compact tetraquark state



- **X(3872) is a compact four quark state**
- **A tetraquark system with two quarks arrange their color in a diquark before interacting with the antiquarks**

- **The mass, quantum number and the large isospin violation can be understood naturally.**

- **Stimulated the discovery of charged exotic states, e.g., Zc(3900)**



H-shaped configuration from lattice simulation

Cardoso, Bicudo, PRD 84 (2011) 054508

The inner structure of X(3872)

✦ Quantum mixture of $\chi_{c1}(2p) - D^0\bar{D}^{*0}$

- **X(3872) is a mixed state of $\chi_{c1}(2p)$ and $D^0\bar{D}^{*0}/\bar{D}^0 D^{*0}$**

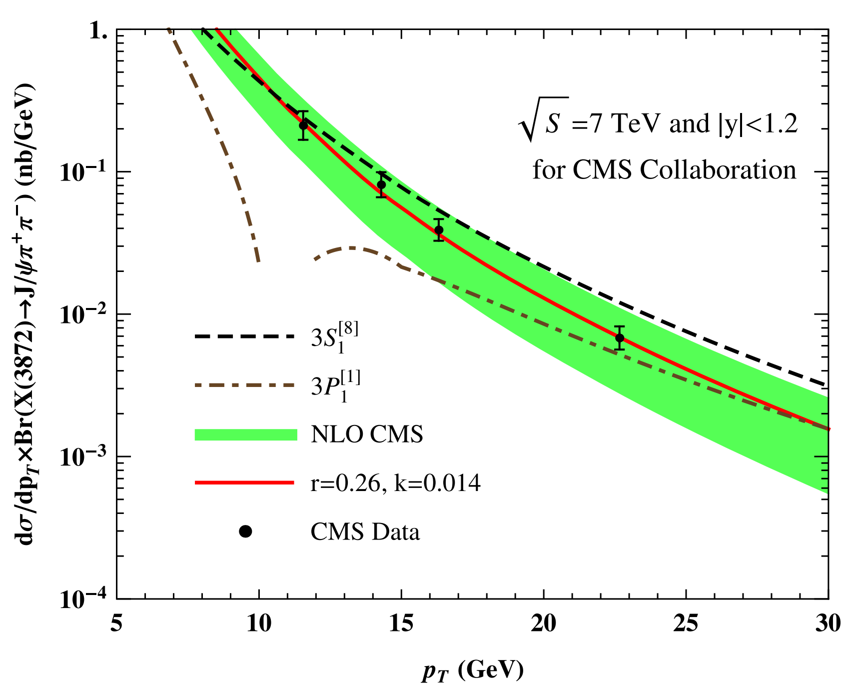
$$|X\rangle = \sqrt{Z_{c\bar{c}}}\,|\chi_{c1}(2p)\rangle + \sqrt{Z_{mol}}\,|D\bar{D}^*\rangle$$

Meng, Gao and Chao
PRD 87(2013)074035

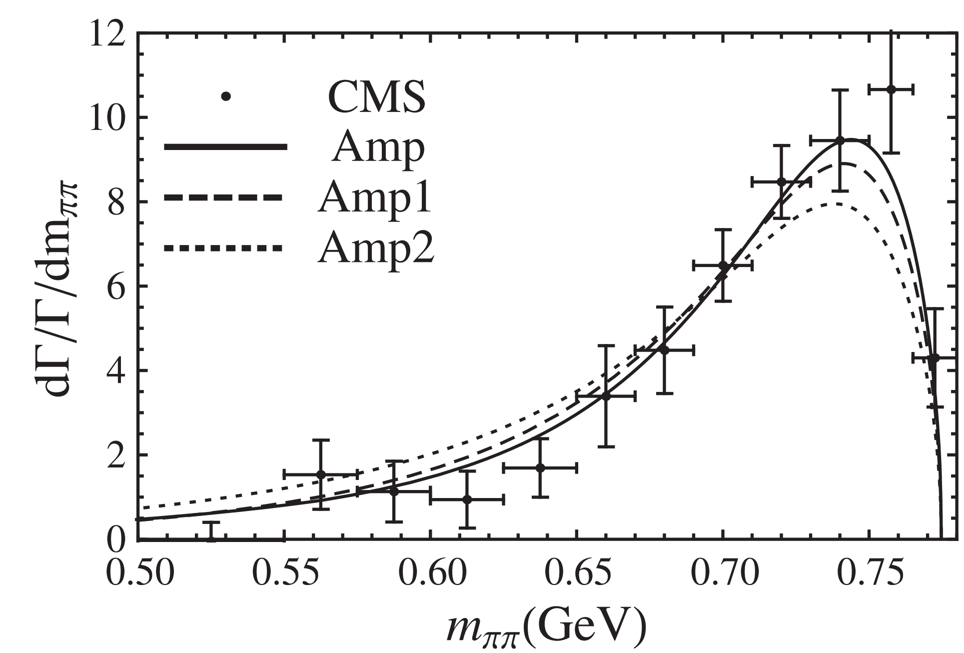
- **Different number of ‘valence’ quarks are superimposed**
- **Both the two components are substantial:**

✓ χ_{c1} component controls the short distance production

✓ $D\bar{D}^*$ components is mainly in charge of the hadronic decays



Meng, Han and Chao
PRD 96(2017)074014

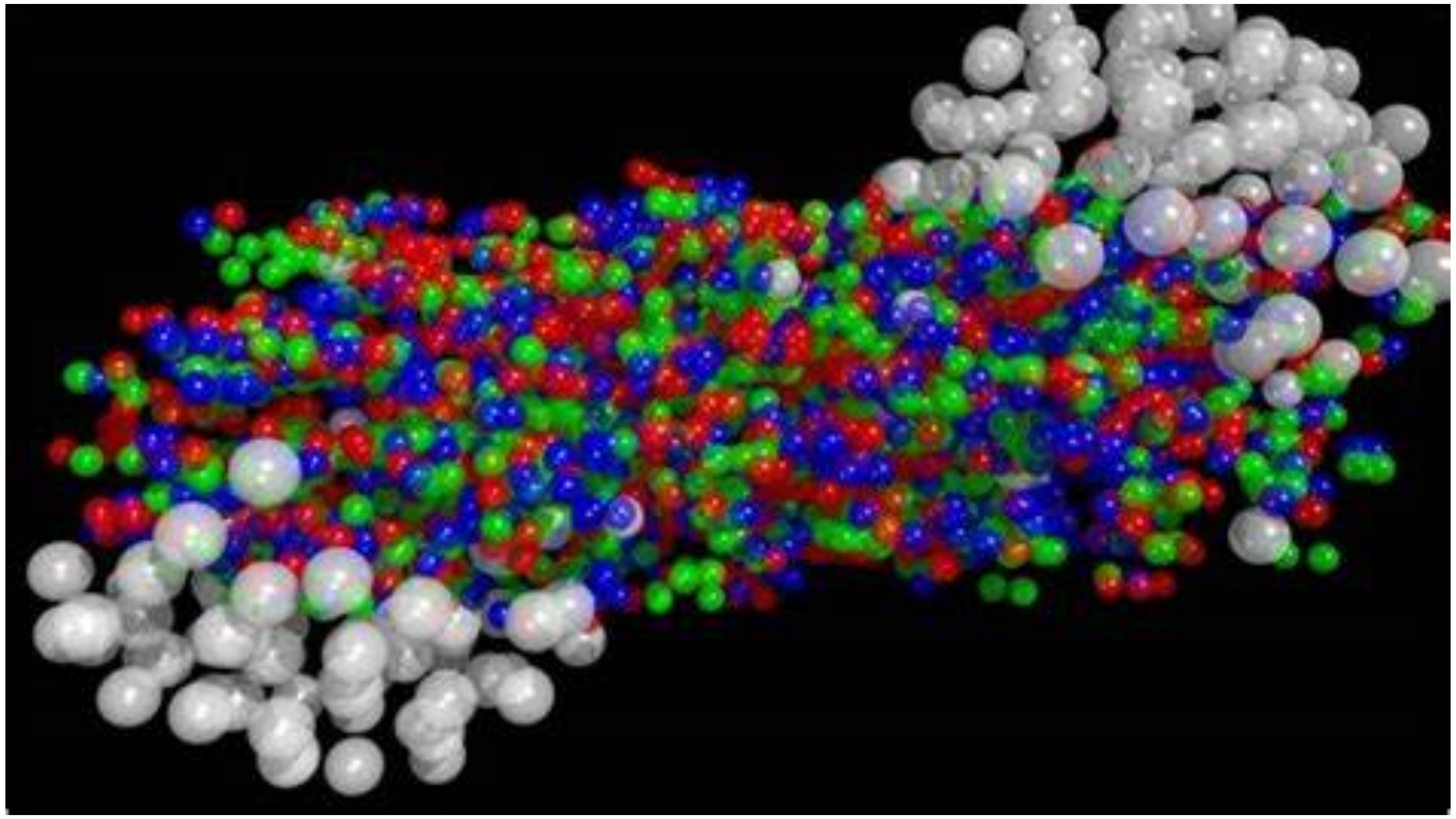


Butenschoen, He and Kniehl
PRL 123(2019)032001

X(3872) production in heavy ion collisions

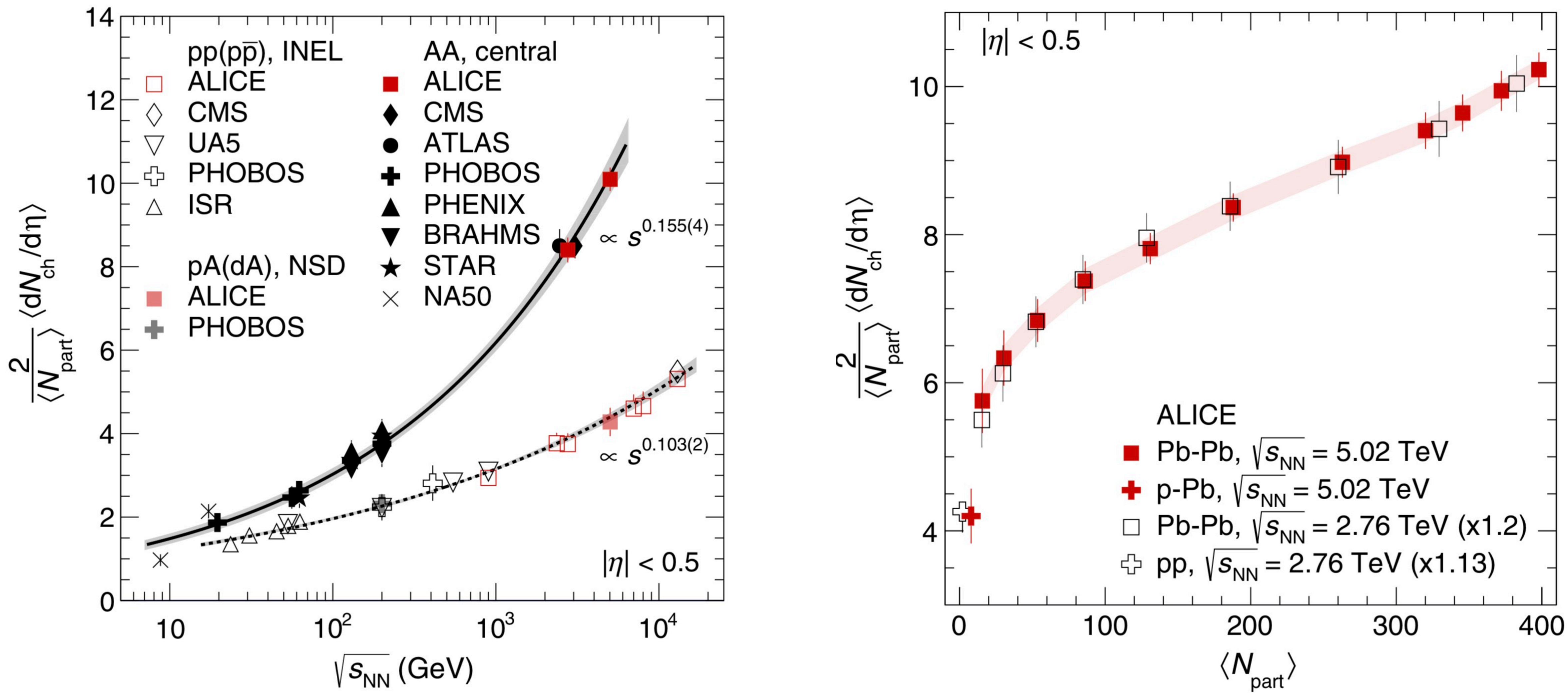
- ✦ **X(3872) is usually studied in leptonic or hadronic collisions**

- ✦ **HI is very different with pp, which could provide a unique opportunity to explore the nature of X(3872)**



X(3872) production in heavy ion collisions

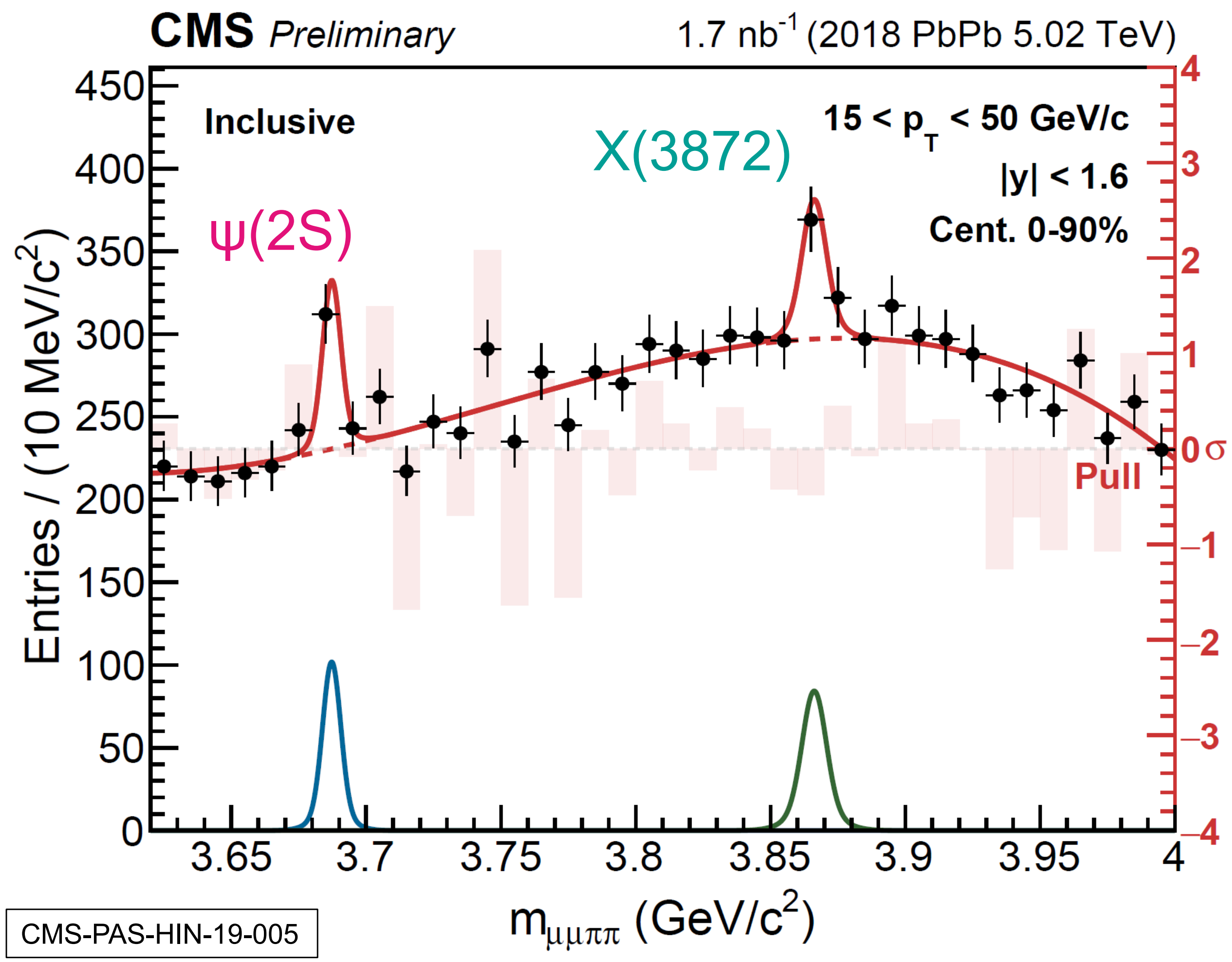
✦ Rich quark/gluon environment in HI

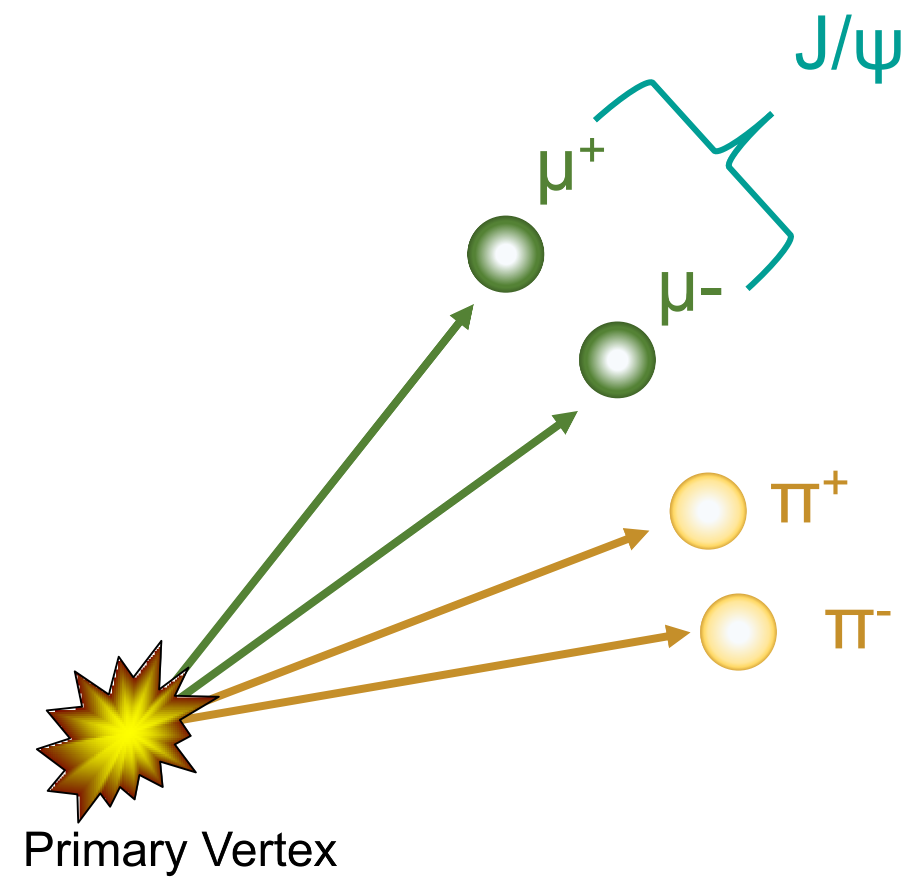


ALICE collaboration
PRL 116 (2016) 222302

X(3872) production in heavy ion collisions

✦ First experimental evidence of X(3872) in HI

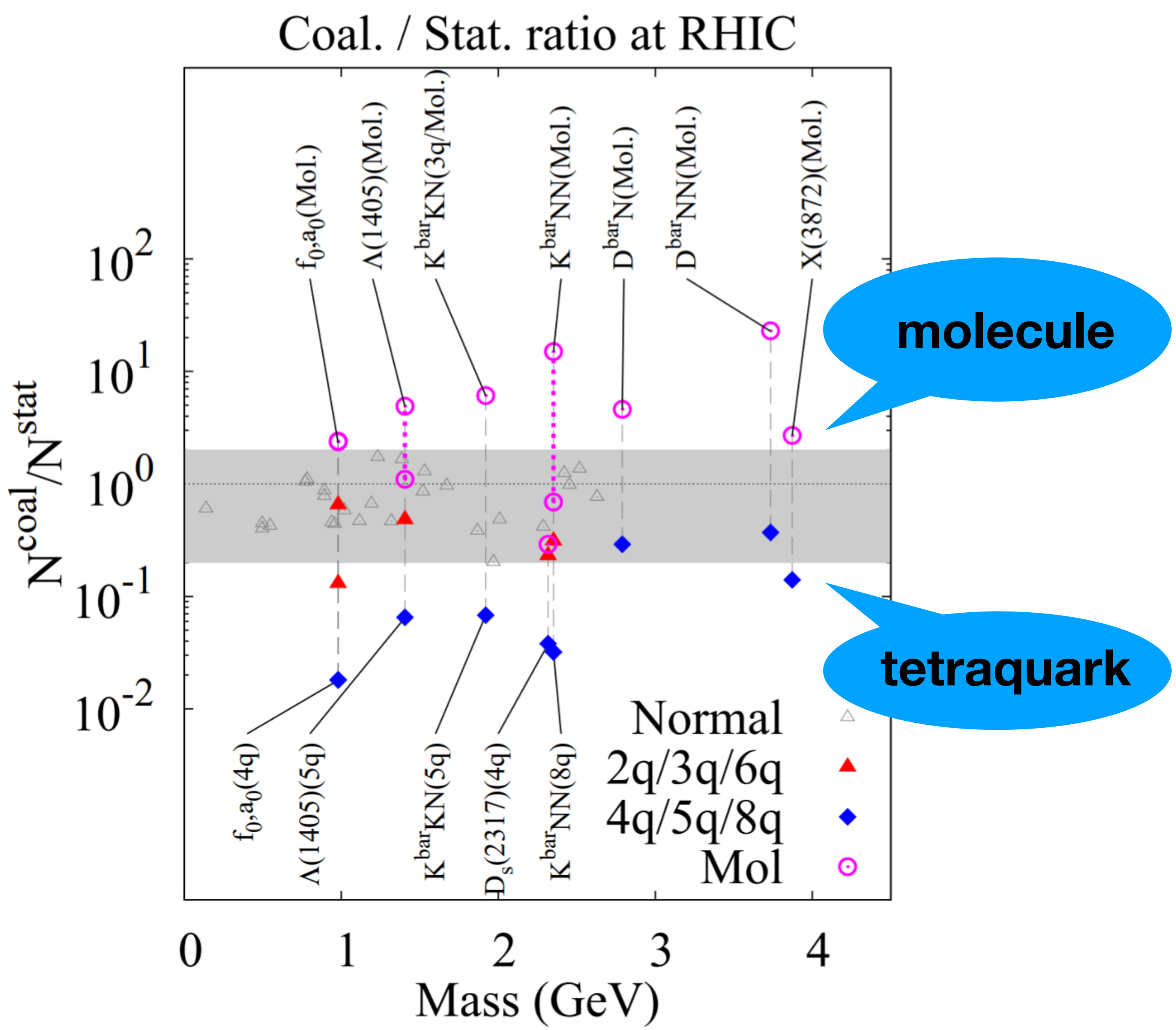




$X(3872) \to J/\psi\pi^+\pi^-$ **was used for reconstruction.**

X(3872) production in heavy ion collisions

✦ Theoretical estimation of X(3872) in HI



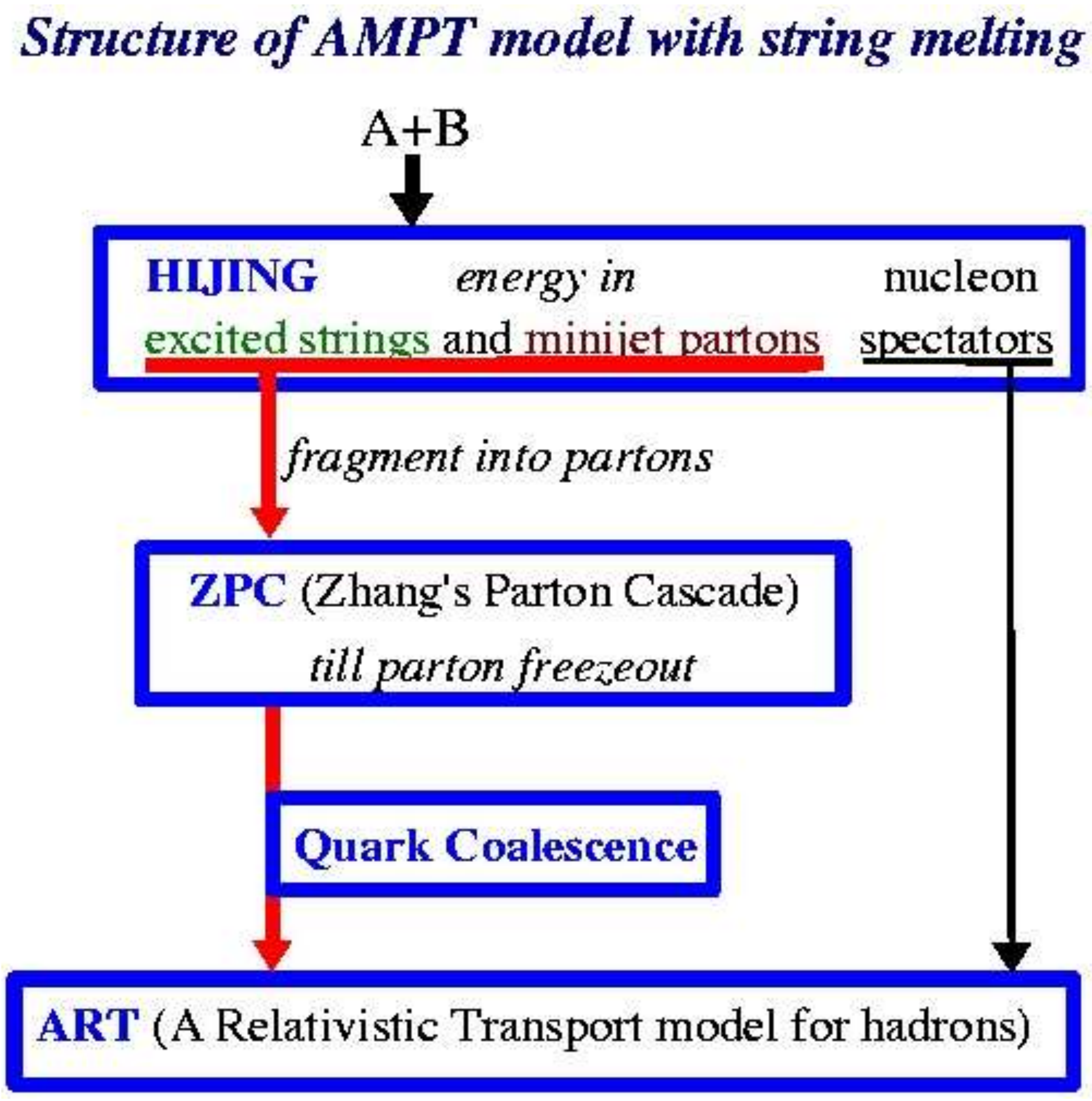
Orders of magnitude difference indicates the advantage of HI in identifying the inner structure of X(3872).

ExHIC collaboration
PRL 106 (2011) 212001

X(3872) production in heavy ion collisions

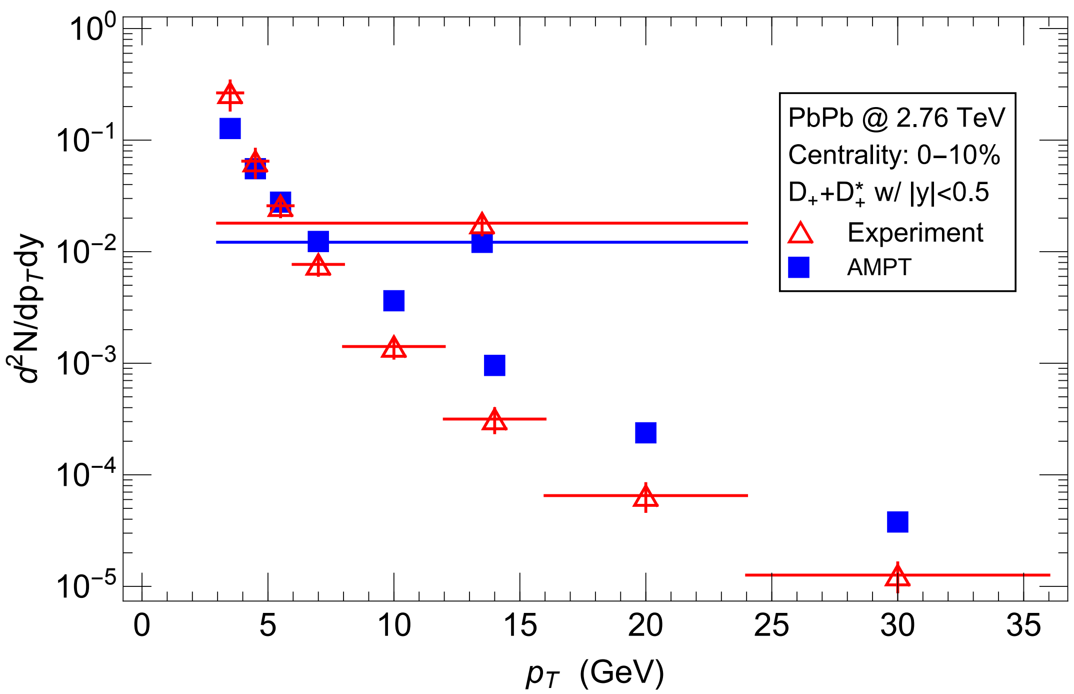
✦A "realistic" simulation by AMPT

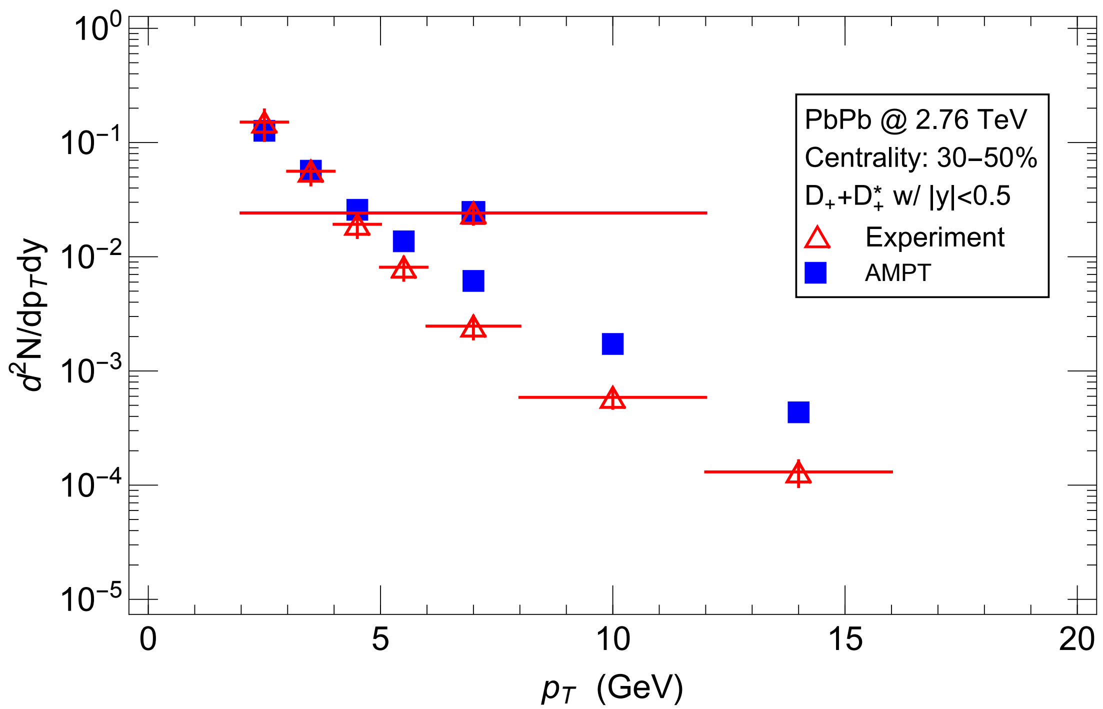
Z.-W. Lin et al, PRC 72 (2005) 064901



X(3872) simulation by AMPT

✦ Calibration of the baseline





- **AMPT does not have spin degrees of freedom, we distribute the yield into different spin state according to thermal model approximation**

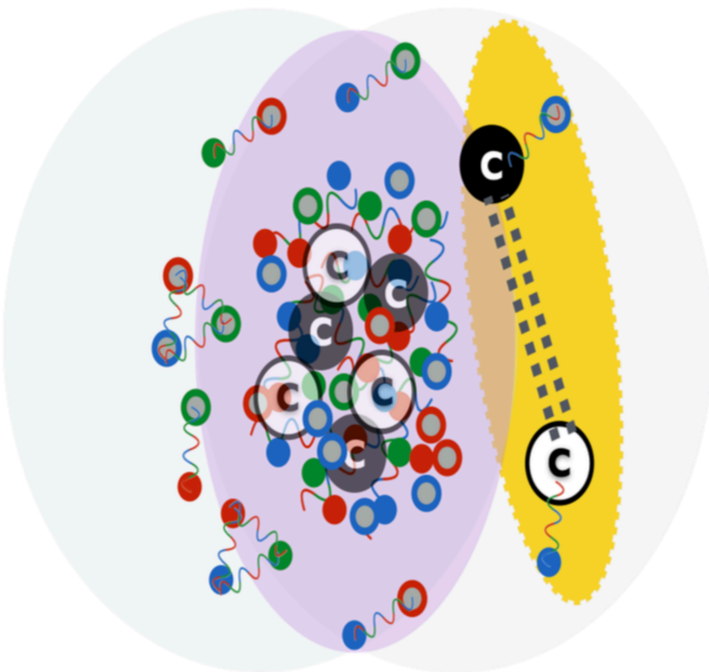
$$R \equiv \frac{\mathrm{Yield(A)}}{\mathrm{Yield(B)}} = \exp\left(\frac{M_B - M_A}{T}\right)$$

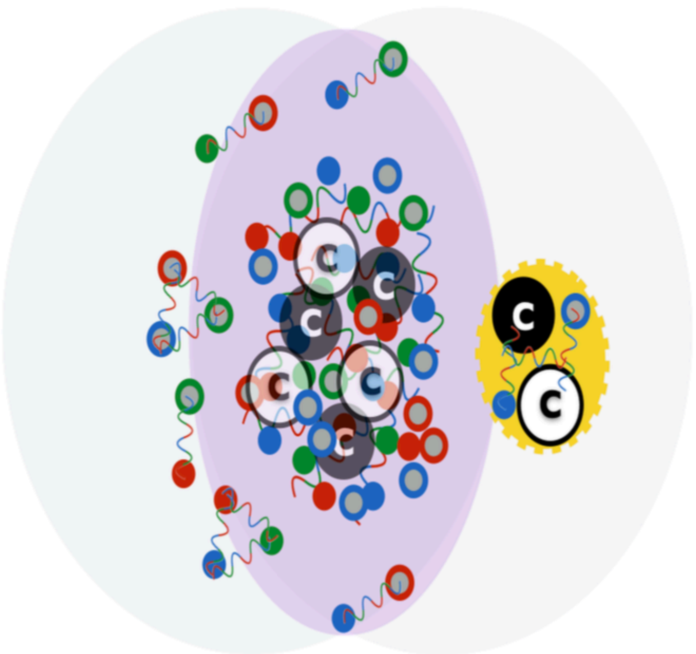
- **30% from D* and 70% from D**
- **35% for spin triplet, 65% from spin singlet diquark**

X(3872) simulation by AMPT

- **X(3872) coalescence**

Zhang, Liao, Wang, Wang, Xing
arXiv: 2004.00024





1. **Coalescence of D mesons**
2. **The average size:** $R_{D\bar{D}^*} \sim 5 - 7\ fm$
3. **mass:** $2M_D < M_X < 2M_{D^*}$

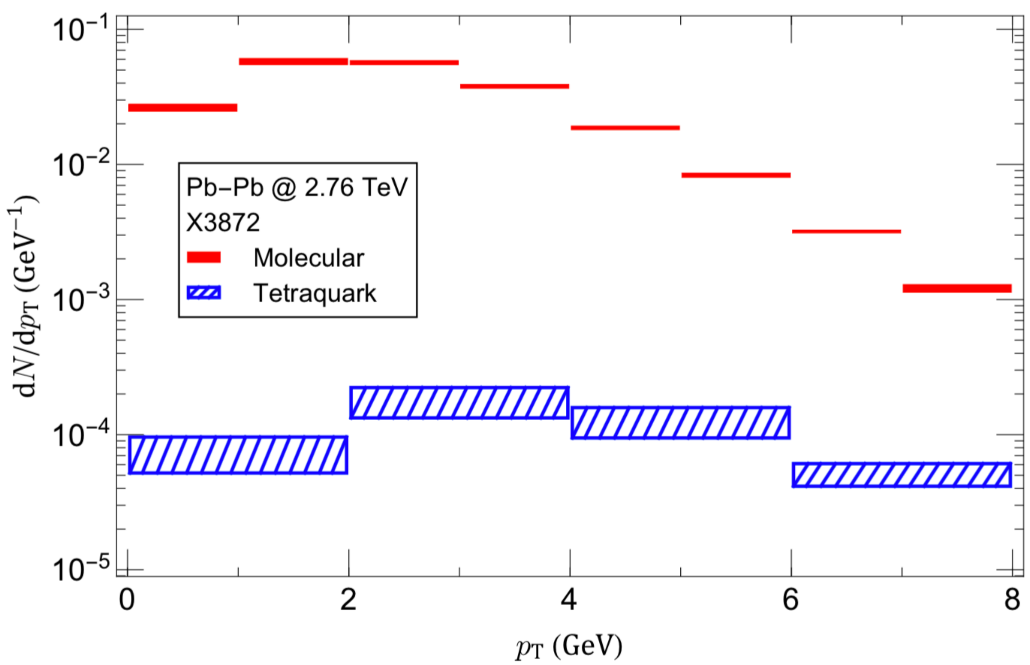
1. **Partonic coalescence of diquark and anti-diquark**
2. **The relative distance between diquark pairs** $R_{[cq][\bar{c}\bar{q}]} < 1\ fm$
3. **mass:** $2M_{|00\rangle_0} < M_X < 2M_{|11\rangle_0}$

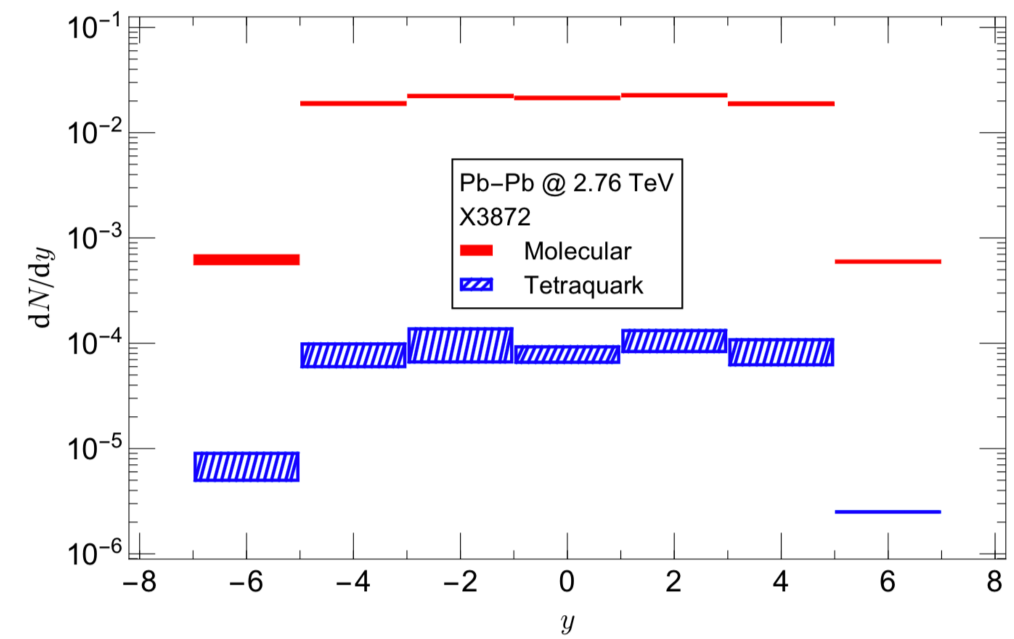
X(3872) production in heavy ion collisions

✦ Total yields in 1M events

220k for hadronic molecule and 880 for compact tetraquark state.

✦ p_T and rapidity dependence

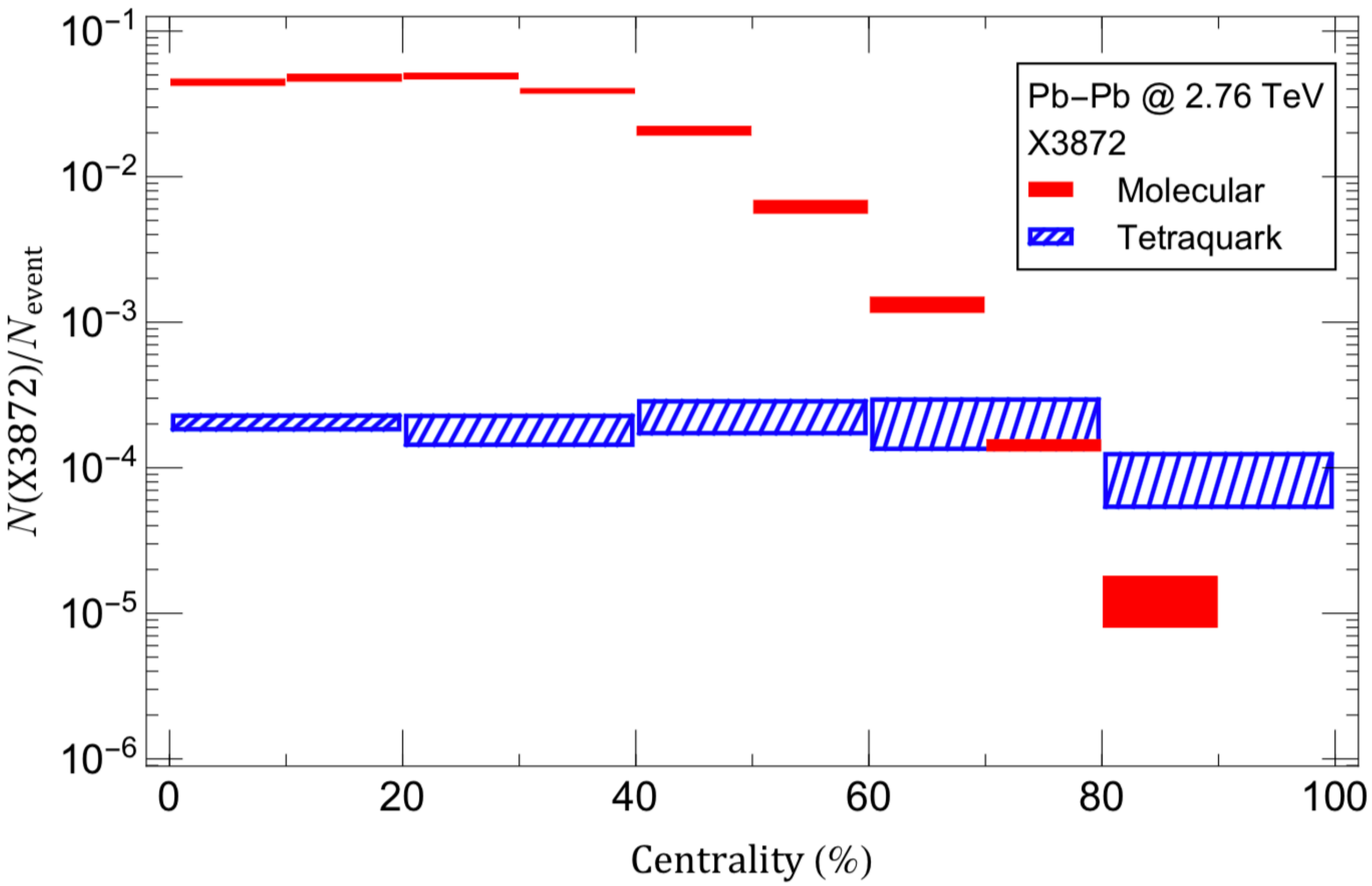


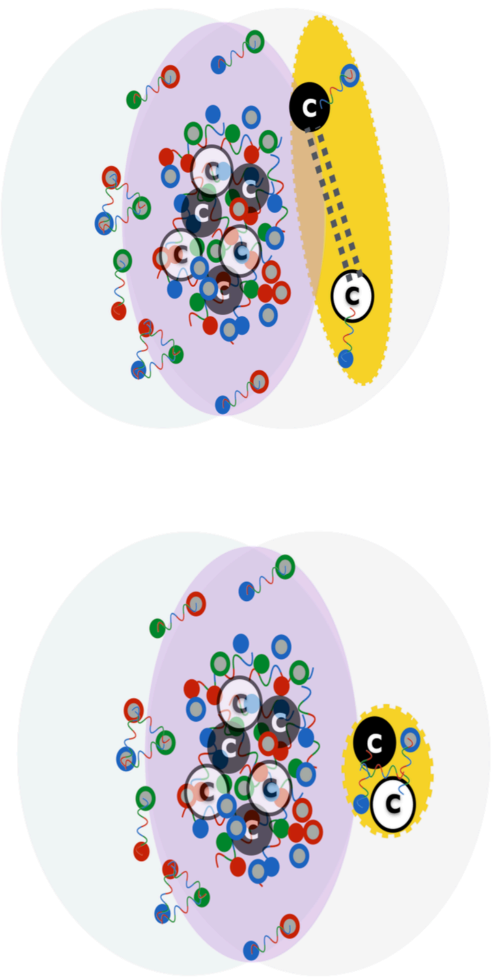


Orders of magnitude difference between hadronic molecule and compact tetraquark scenarios, an unique opportunity for HI collisions.

X(3872) production in heavy ion collisions

✦ Centrality dependence



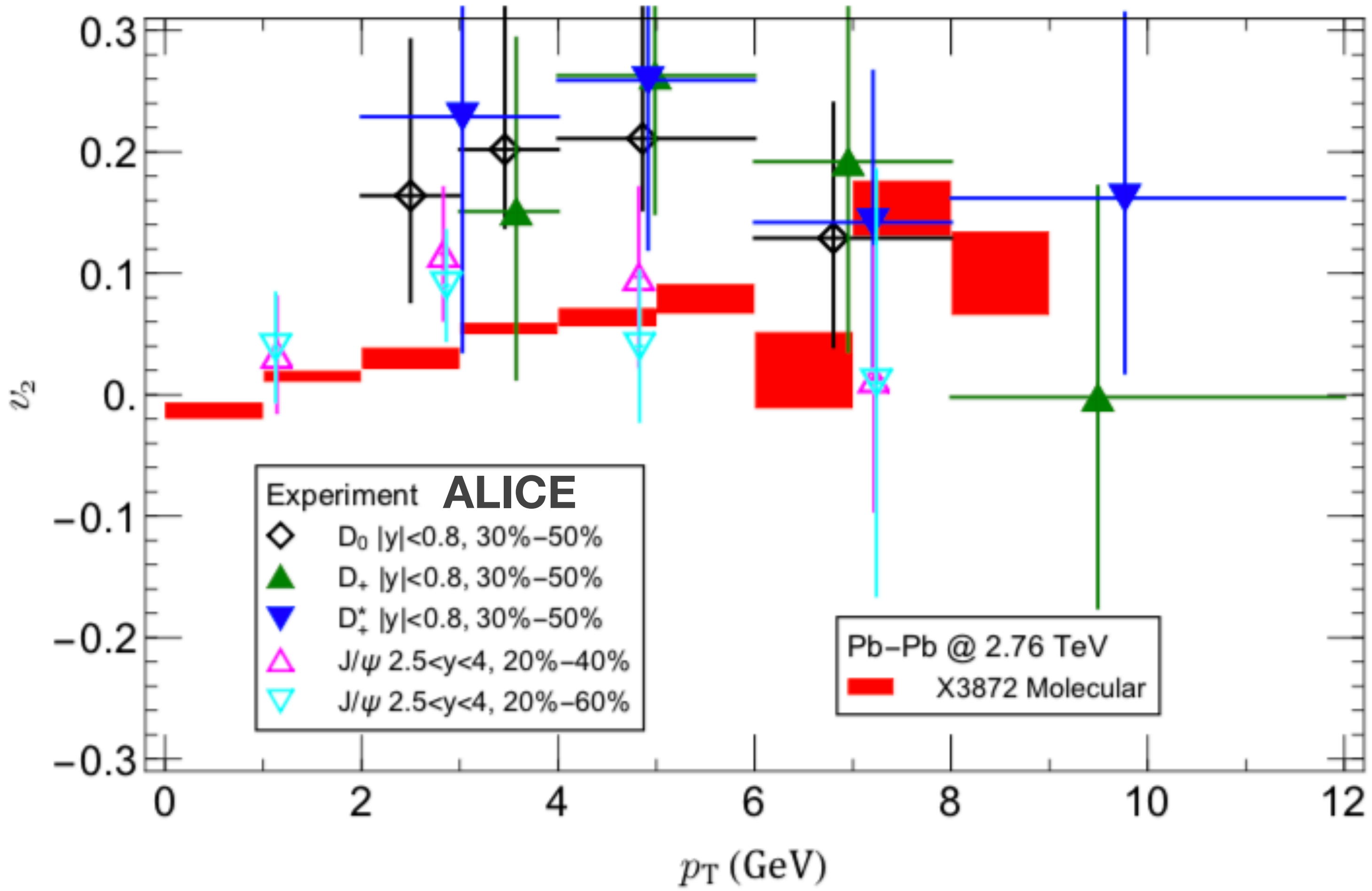


- Strongly decreasing for hadronic molecule
- Mild change for compact tetraquark
- System size dependence could be a good probe to X(3872) inner structure.

more differential = more power

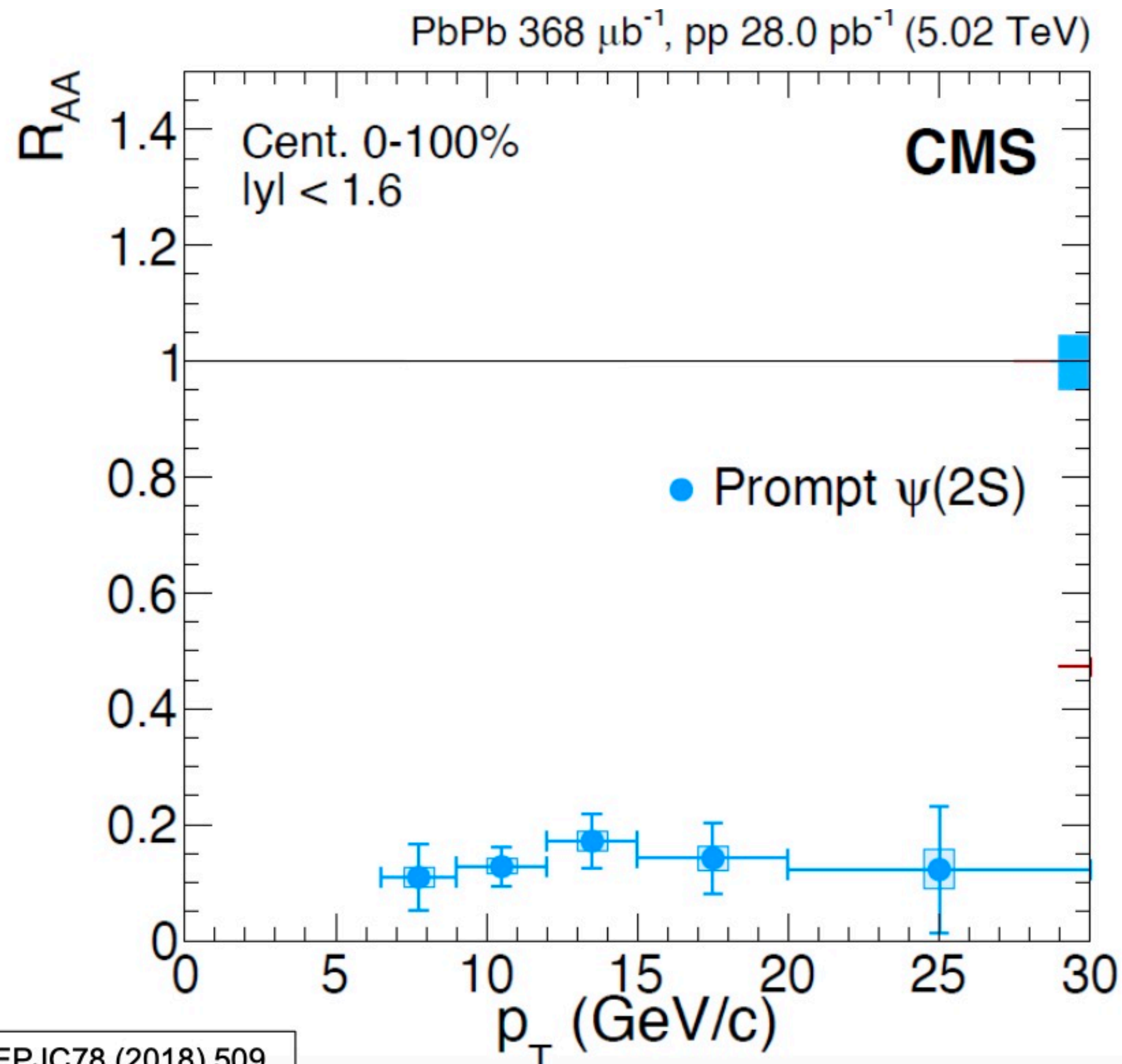
X(3872) production in heavy ion collisions

✦ Elliptic flow

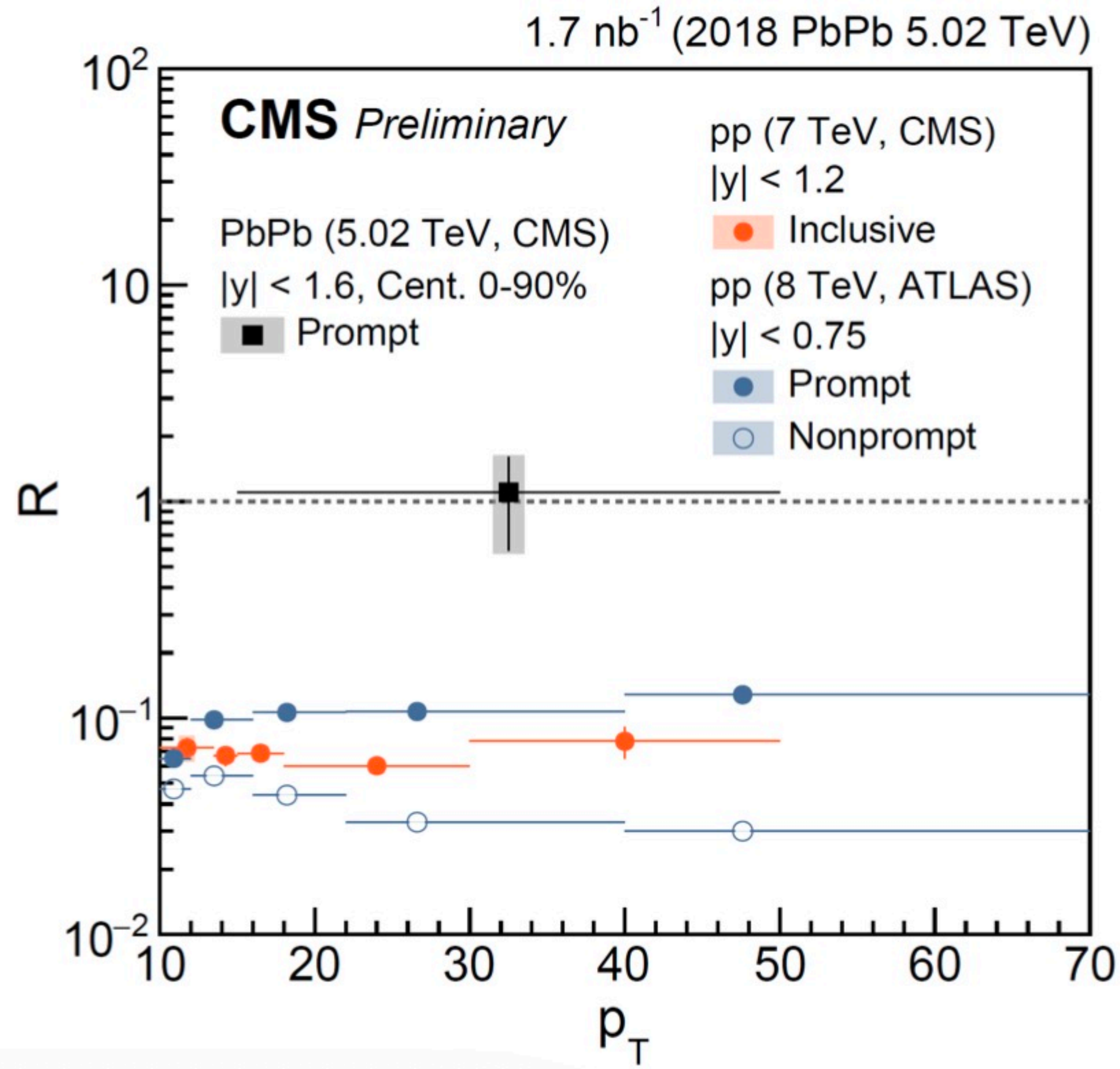


- **Elliptic flow is the key observable for collective property of bulk medium**
- **This is the first estimation of elliptic flow for exotic states**
- **Quark number scaling of tetraquark state?**

Puzzling result from CMS



EPJC78 (2018) 509



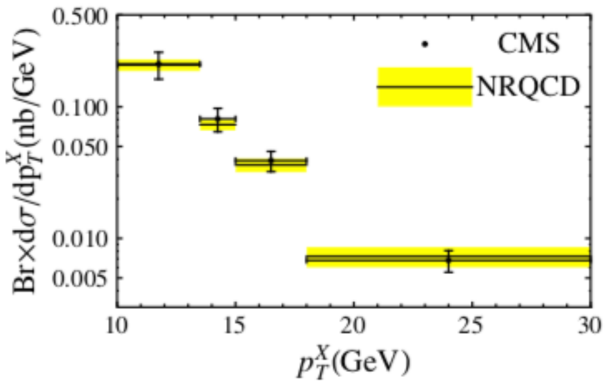
- **Energy loss leads to suppression in large pt**
- **Disassociation leads to suppression in large pt**
- **What caused enhancement in large pt? Strong coalescence/ regeneration?**

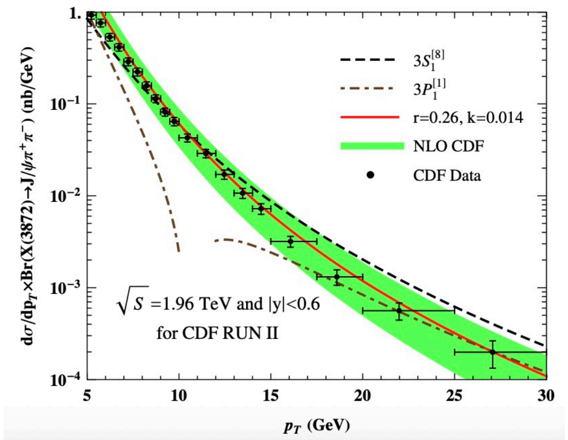
X(3872) in large pt

✦ Quantum mixture of $\chi_{c1}(2p) - D^0\bar{D}^{*0}$

Butenschoen, He and Kniehl
PRL 123(2019)032001

$$|X\rangle = \sqrt{Z_{c\bar{c}}}\,|\chi_{c1}(2p)\rangle + \sqrt{Z_{mol}}\,|D\bar{D}^*\rangle$$





Meng, Han and Chao
PRD 96(2017)074014

- **NRQCD**

$$d\sigma(pp\to\chi'_{c1}) = \sum_n d\hat{\sigma}((c\bar{c})_n)\frac{\langle\mathcal{O}_n^{\chi'_{c1}}\rangle}{m_c^{2L_n}} = \sum_{i,j,n}\int dx_1dx_2G_{i/p}G_{j/p}d\hat{\sigma}(ij\to(c\bar{c})_n)\langle\mathcal{O}_n^{\chi'_{c1}}\rangle$$

$$n = {}^3S_1^8,\ {}^3P_1^1$$

- **LDMEs**

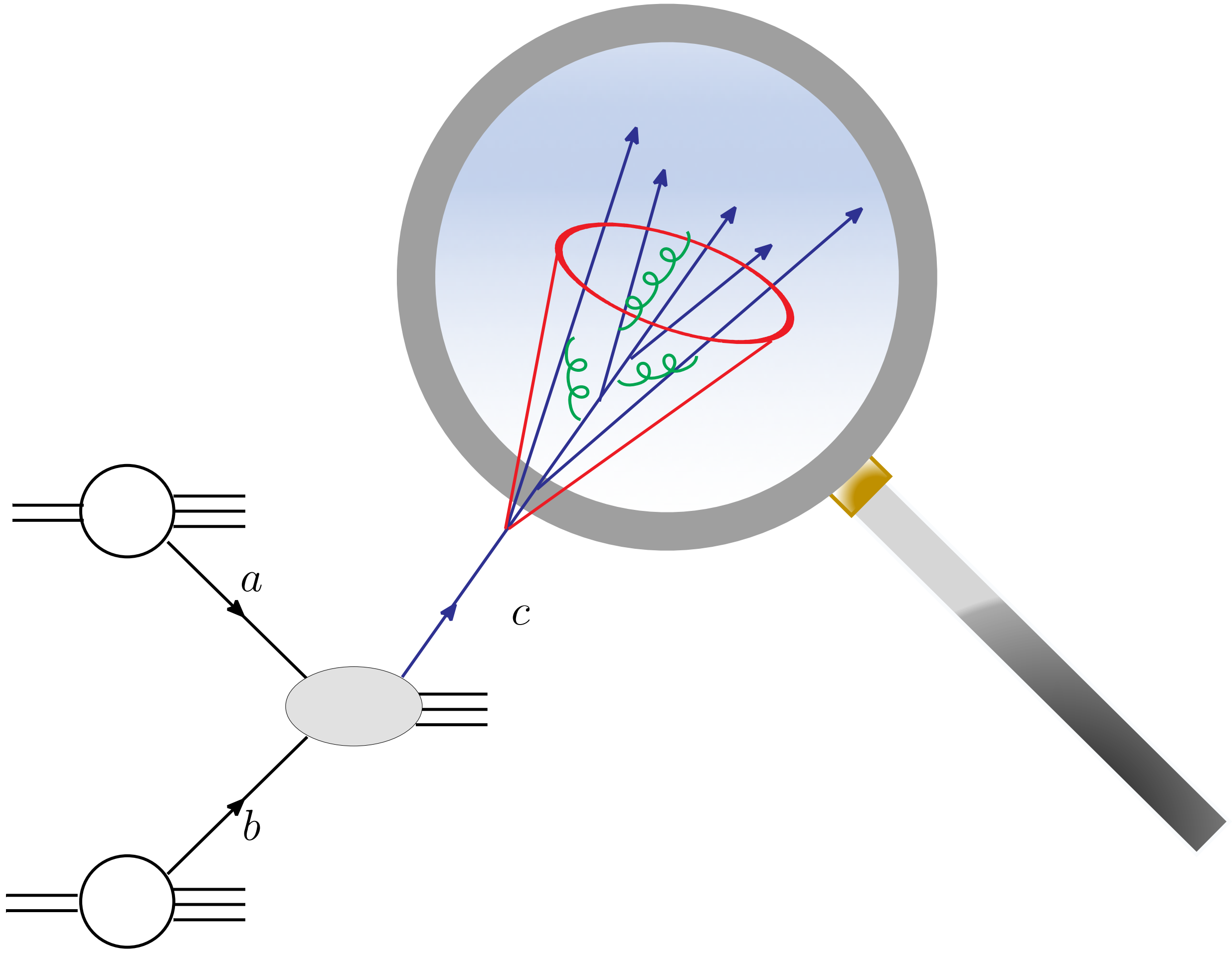
	$^3S_1^8\ (GeV^3)$	$^3P_1^1\ (GeV^5)$
Kniehl	$0.83^{+0.12}_{-0.16}\times10^{-4}$	$0.34^{+0.12}_{-0.15}\times10^{-2}$
Chao	$0.87^{+0.71}_{-0.51}\times10^{-4}$	$0.75^{+0.32}_{-0.32}\times10^{-3}$

- **Both loosely bound hadronic molecule and compact tetraquark state have problems to describe large p_T X(3872)**

- **Quantum mixture scenario is successful in large p_T region, confirmed by two groups from NLO NRQCD, but with different LDMEs.**

X(3872) production in jet

✦ Jet substructure

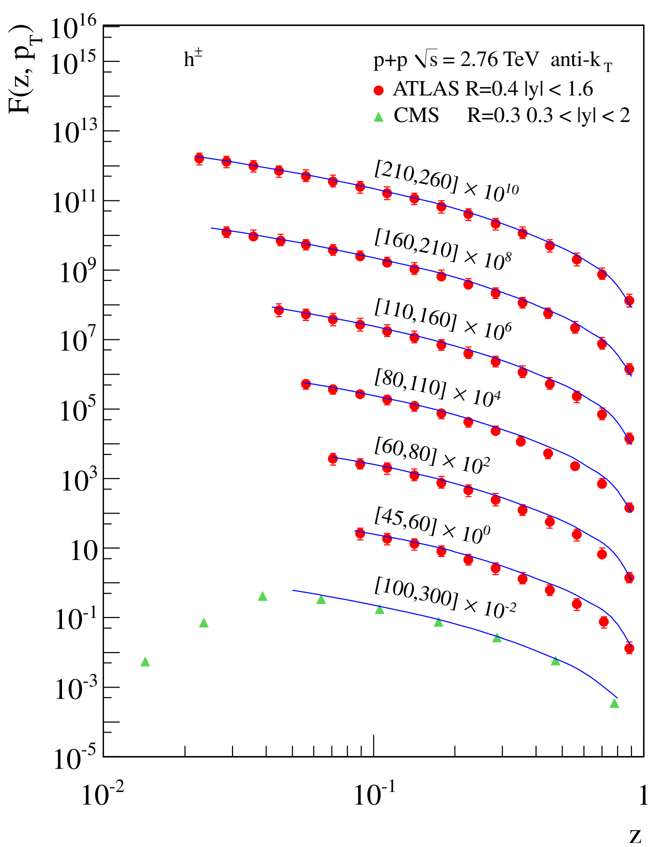


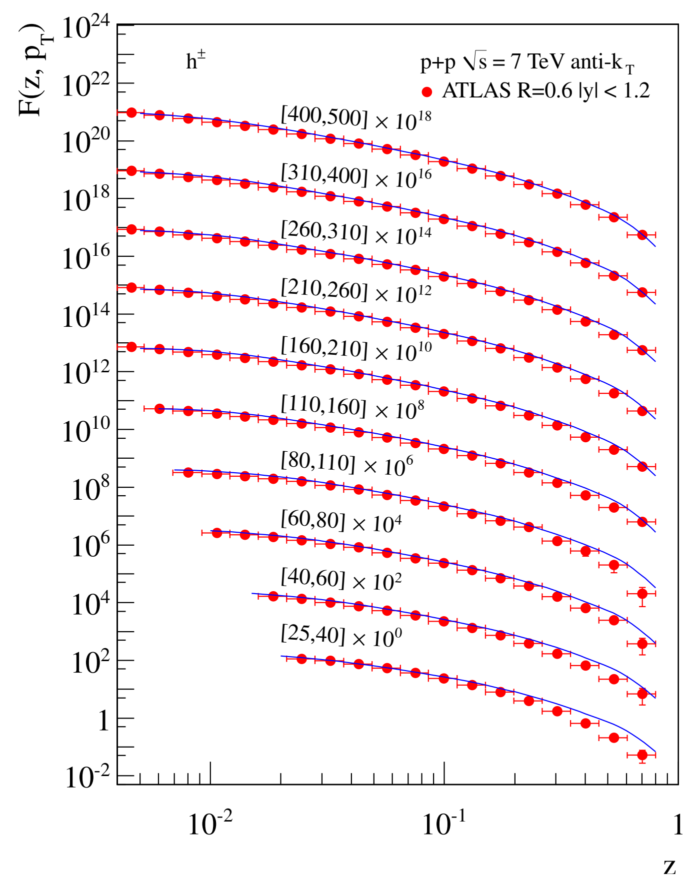
Jet substructure

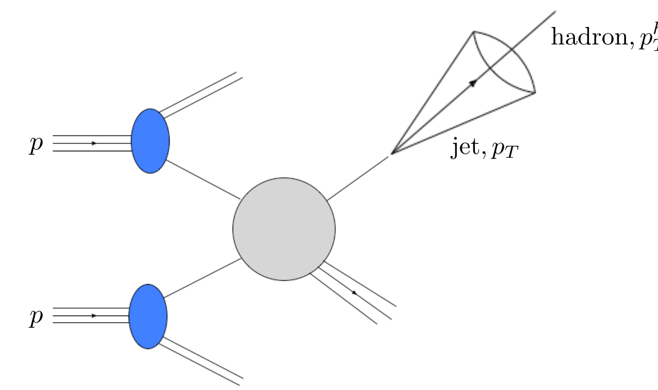
✦ Light hadron production in jet

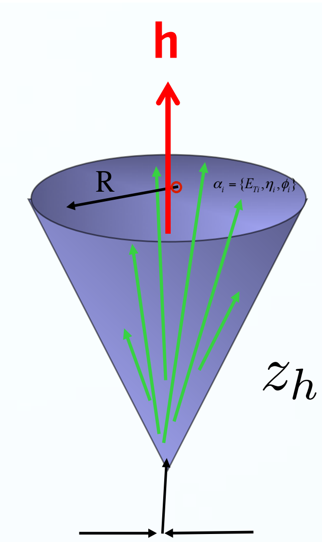
Xing et al., JHEP (2016)
Kang et al., JHEP

$$F(z_h, p_T) = \frac{d\sigma^h}{dp_T d\eta dz_h} \Big/ \frac{d\sigma^h}{dp_T d\eta}$$







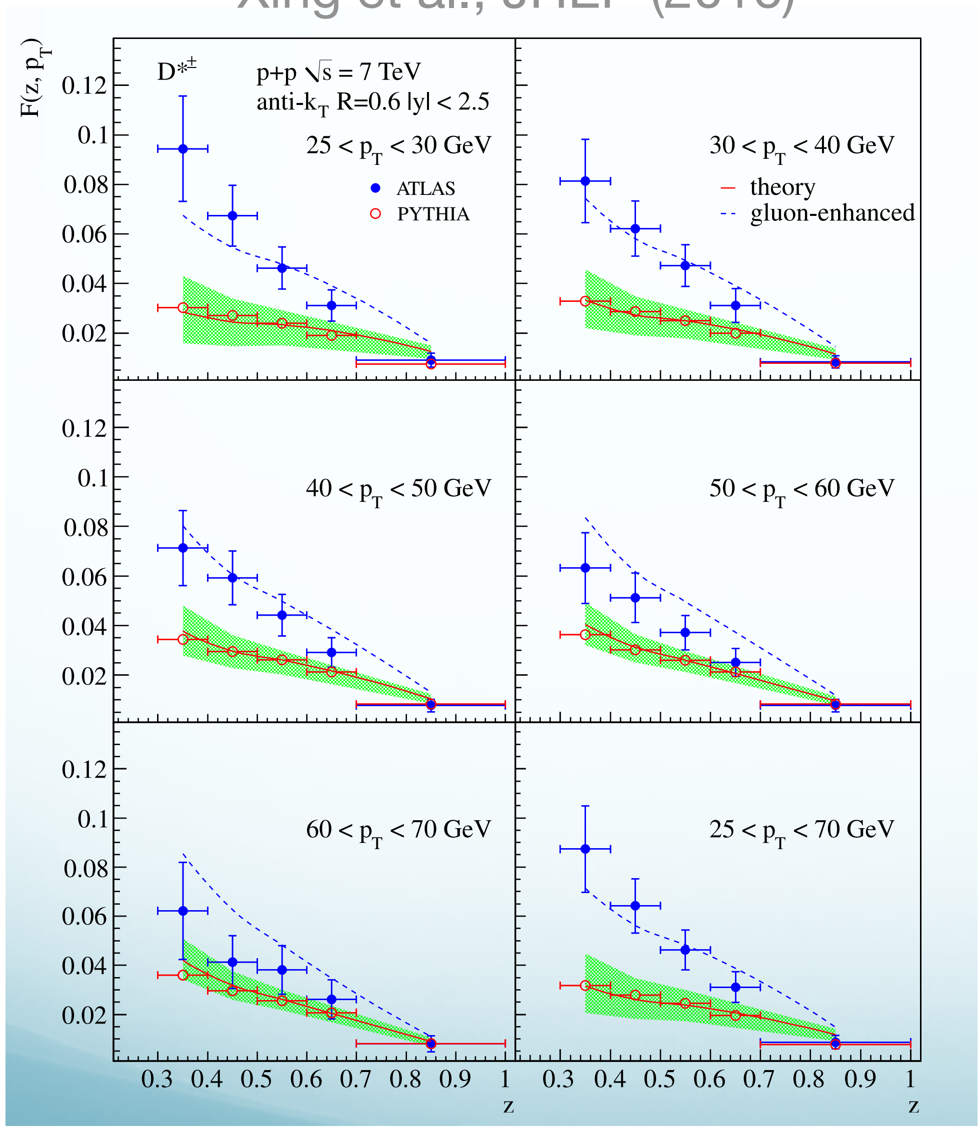


$$z_h = \frac{E_h}{E_{\text{jet}}}$$

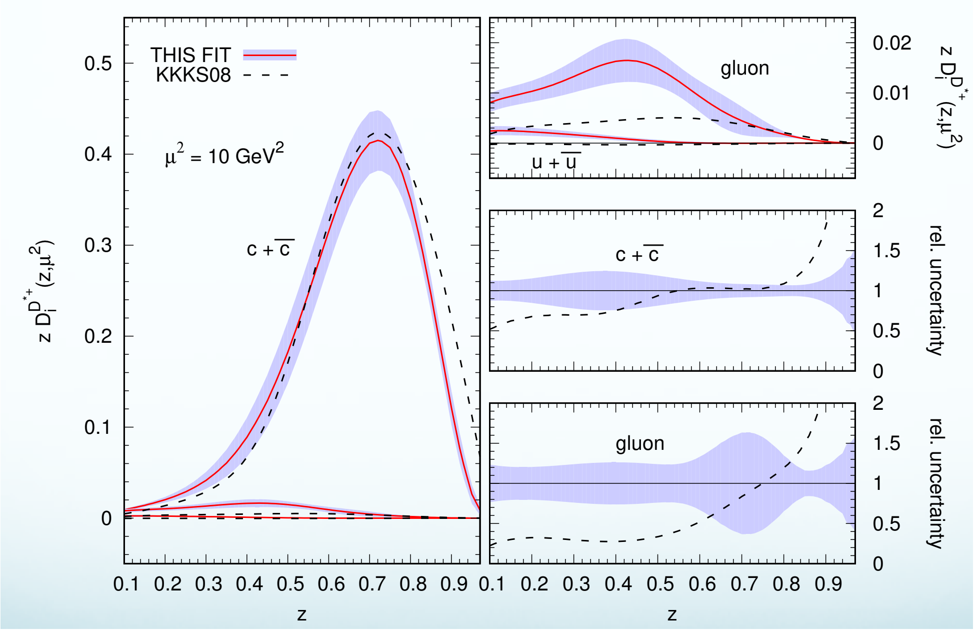
NLO + LL can describe the light hadron data very well.

✦ Open heavy flavor production in jet

Xing et al., JHEP (2016)



Anderle et al., PRD (2017)

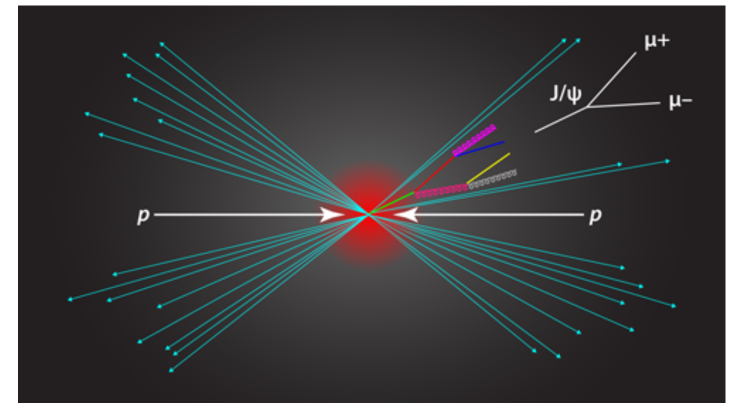


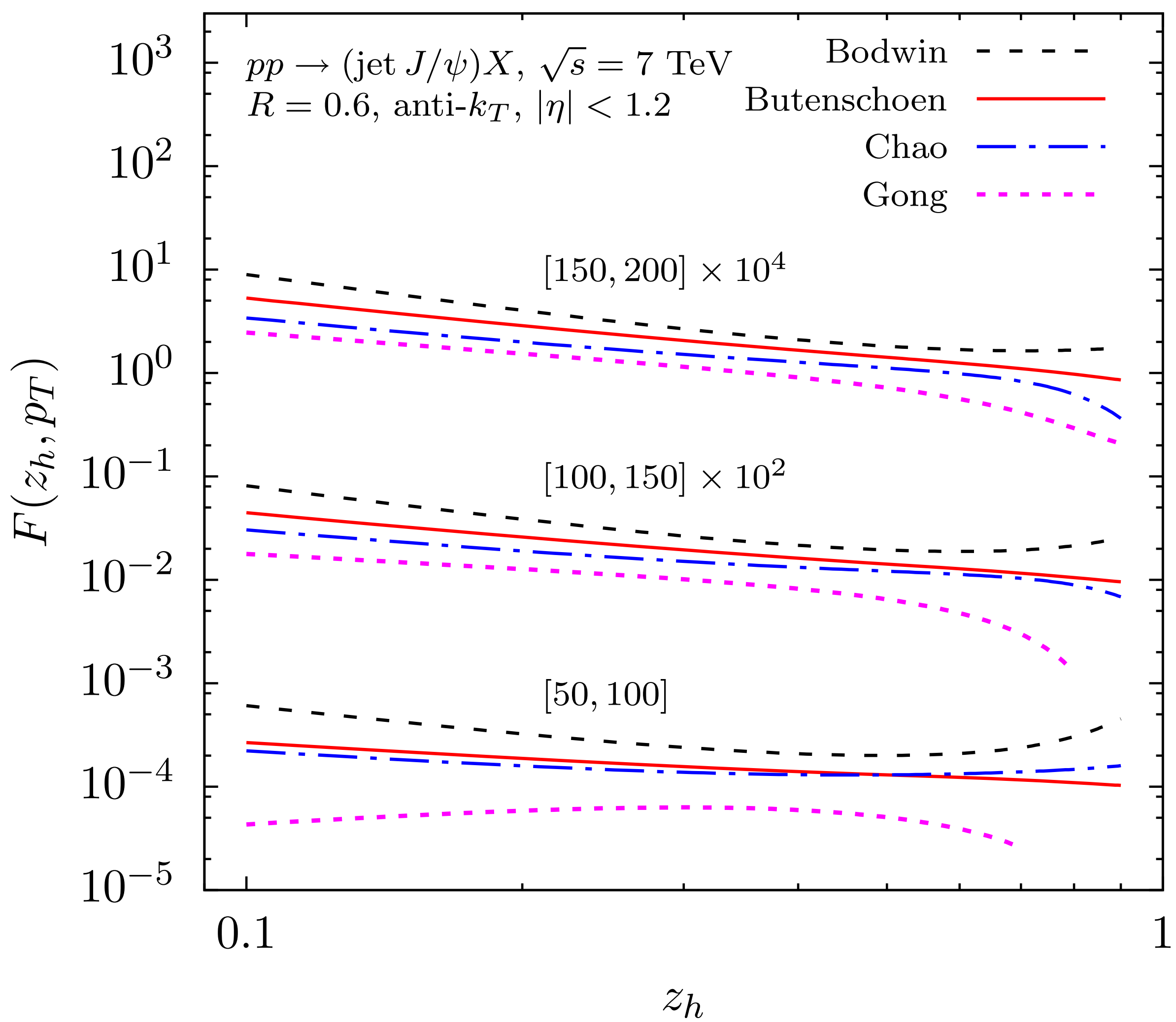
NLO + LL failed to describe the open heavy flavor data, eventually leads to new FFs global fit.

✦ Heavy quarkonium production in jet

TABLE I. J/ψ NRQCD LDMEs from four different groups.

	$\langle\mathcal{O}(^3S_1^{[1]})\rangle$ GeV^3	$\langle\mathcal{O}(^1S_0^{[8]})\rangle$ 10^{-2} GeV^3	$\langle\mathcal{O}(^3S_1^{[8]})\rangle$ 10^{-2} GeV^3	$\langle\mathcal{O}(^3P_0^{[8]})\rangle$ 10^{-2} GeV^5
Bodwin	0[a]	9.9	1.1	1.1
Butenschoen	1.32	3.04	0.16	−0.91
Chao	1.16	8.9	0.30	1.26
Gong	1.16	9.7	−0.46	−2.14



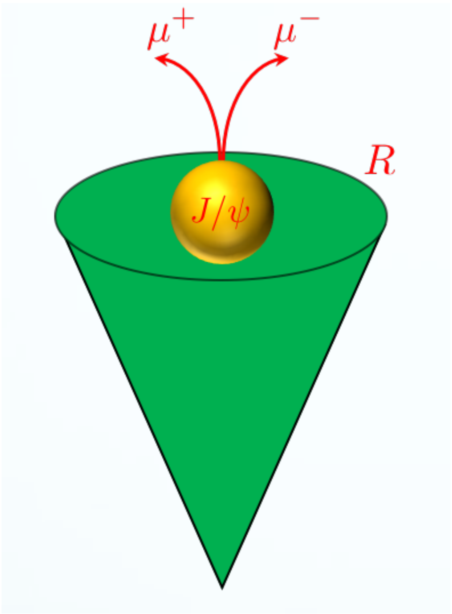


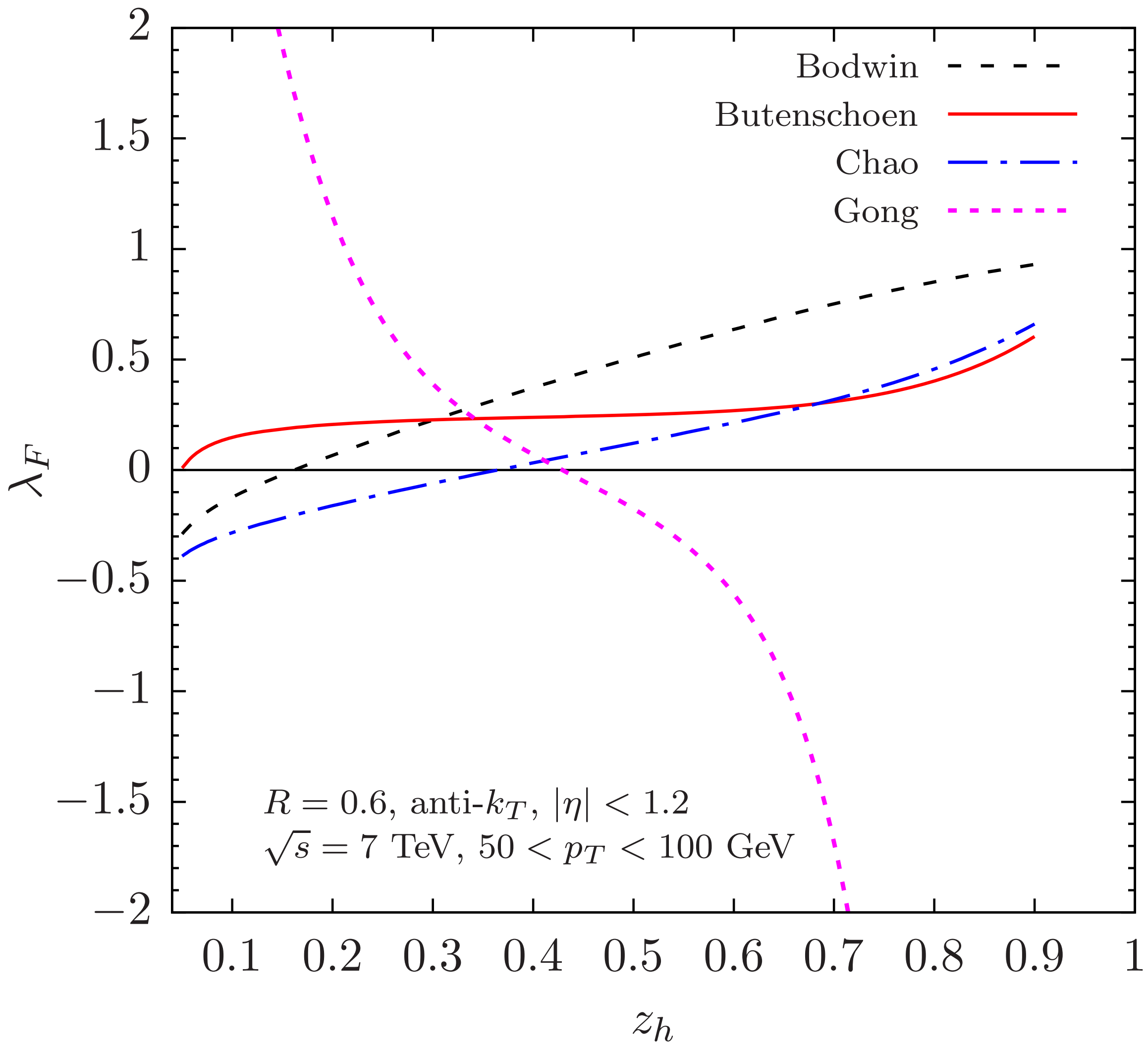
- **Both four sets of LDMEs can describe inclusive J/ψ production in pp at high p_T.**
- **Significant difference in the prediction for JFFs.**
- **J/ψ in jet is a sensitivity observable to probe the J/ψ production mechanism.**

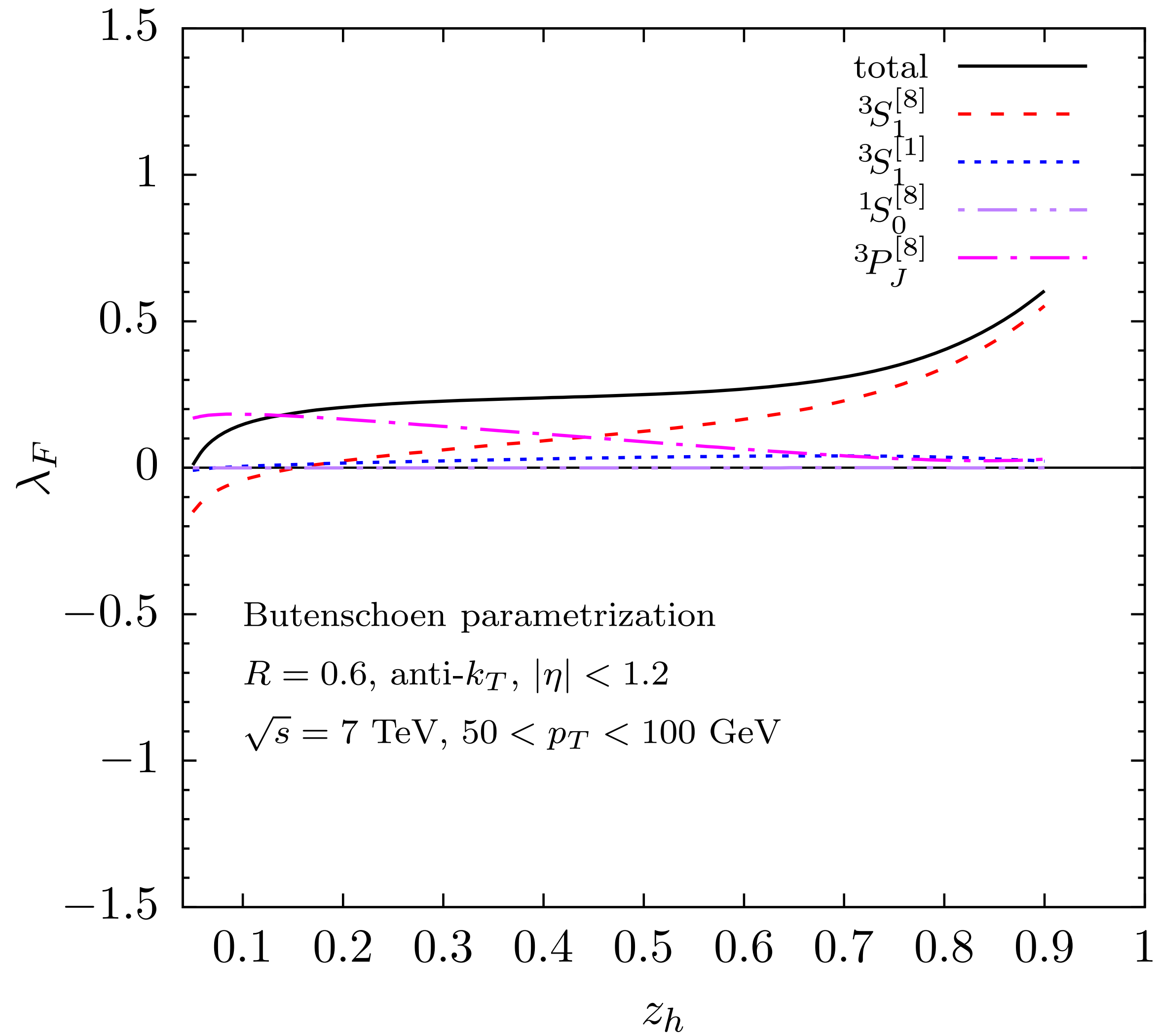
Jet substructure

✦ J/ψ polarization in jet

$$\lambda_F(z_h, p_T) = \frac{F_T^{J/\psi} - F_L^{J/\psi}}{F_T^{J/\psi} + F_L^{J/\psi}} = \begin{cases} +1, & \textbf{Transverse} \\ -1, & \textbf{Longitudinal} \end{cases}$$

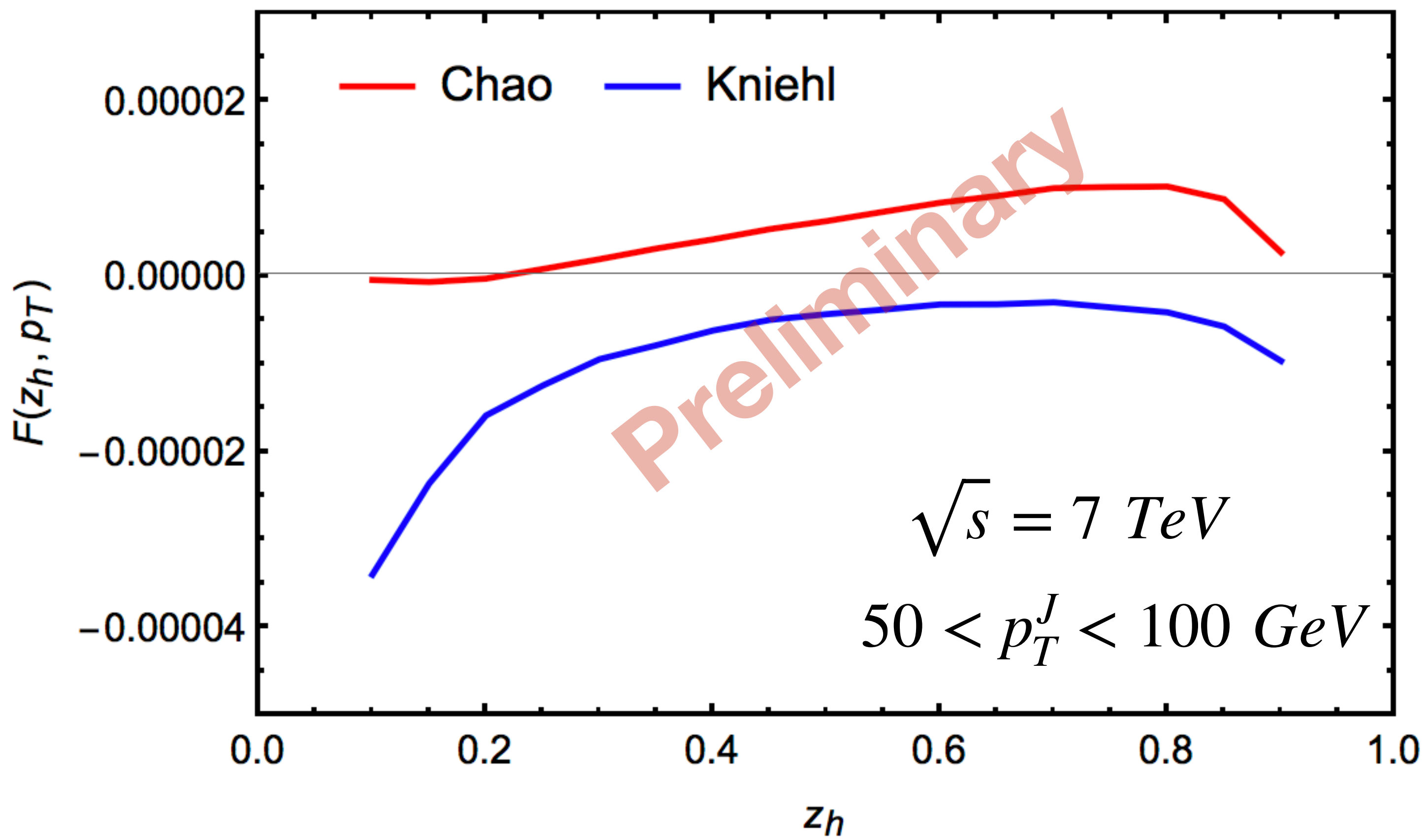


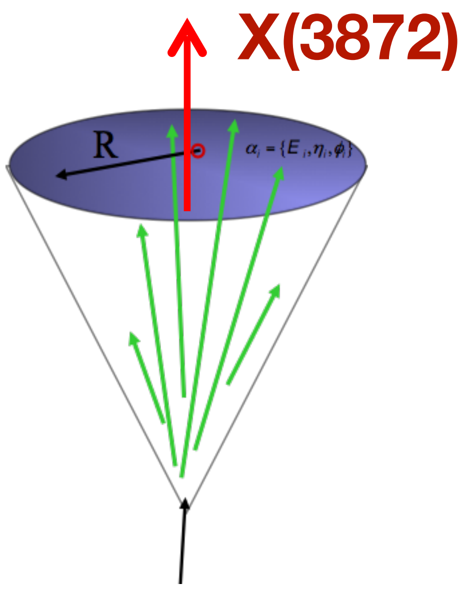




✦ X(3872) production in jet

H. Xing, 2005.xxxxx





JFFs for X(3872) is a powerful observable to test the quantum mixture scenario.

Summary

- ✦ HI collisions provide a unique opportunity to differentiate hadronic molecule and compact tetraquark scenarios for X(3872).

- ✦ X(3872) in jet is a rigorous observable to further test the picture of quantum mixture of $\chi_{c1}(2p) - D^0\bar{D}^{*0}$.

- ✦ Please stay tuned for further simulations in HI and precision pQCD (NRQCD) calculations for X(3872) in high p_T .

Thanks for your attention!