Deciphering the Nature of X(3872) in Heavy Ion Collisions

Qian Wang
South China Normal University, China

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The first exotic candidate X(3872)

- Quark Model: Meson ($q\bar{q}$) e.g. $\pi(0^-)$,$\rho(1^-)$

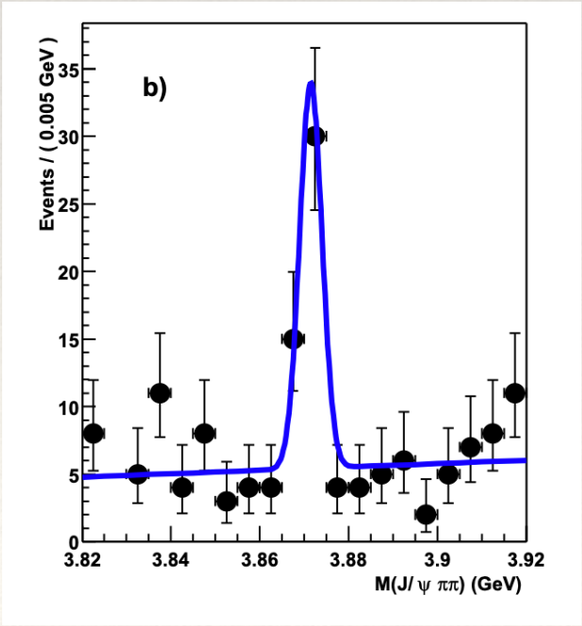
  Baryon(qqq) e.g. $p(1/2^+)$, $\Lambda(1/2^+)$

- Multiquarks: Meson ($qq\bar{q}\bar{q}$, $qqq\bar{q}\bar{q}\bar{q}$, $q\bar{q}g\ldots$)

  Baryon ($qqqq\bar{q}$, $qqqq\bar{q}q\bar{q}$, …)

Gell-Mann, PL8(1964)214, Jaffe, PRD15(1977)267

- The observation of the $X(3872)$ in 2003 Belle, PRL91(2003)262001



- $B^{\pm} \to K^{\pm}(J/\psi\pi^+\pi^-)$
- $3872.0 \pm 0.6(\text{stat}) \pm 0.5(\text{syst})$ MeV
- Near $D\bar{D}^*$ threshold

The first exotic candidate X(3872)

- The status of the *X*(3872)
- Theoretical side

HM@Tornqvist,…

2003 →

- Experimental side

→

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charmonium@Eichten,Lane,Quigg,Suzuki,Barnes, Godfrey,…

HM@Tornqvist,… hybrid@Li,…

2003 2005

Tetraquark@Close, Maiani, Piccinini, Polosa, Riquer,…

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2003 — 2005 — 2013 →

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2003 — 2005 — 2013 — 2021 →

Tetraquark@Close, Maiani, Piccinini, Polosa, Riquer,… unparticles@Braaten and Hammer

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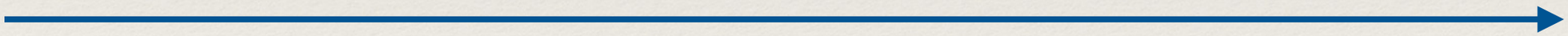

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$B^{\pm} \to J/\psi\pi^+\pi^- K^{\pm}$@Belle

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2003 — 2004 →

Confirm in $p\bar{p}$@CDF, D0

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$B^{\pm} \to J/\psi\pi^+\pi^- K^{\pm}$@Belle e^+e^-@BaBar

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$B^{\pm} \to J/\psi\pi^+\pi^- K^{\pm}$@Belle e^+e^-@BaBar $J^{PC} = 1^{++}$@LHCb

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$B^{\pm} \to J/\psi\pi^+\pi^-K^{\pm}$@Belle e^+e^-@BaBar $J^{PC} = 1^{++}$@LHCb Pb-Pb@CMS

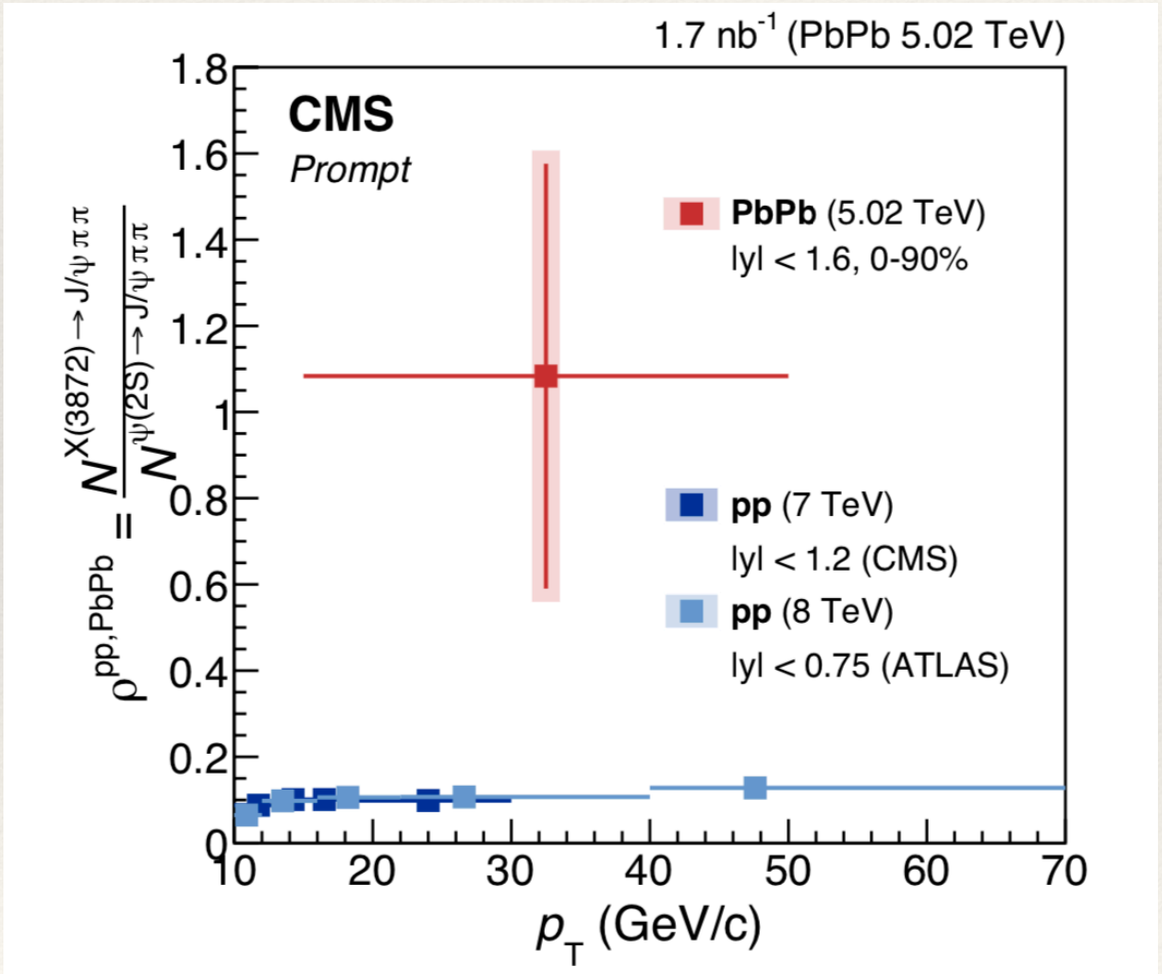
2003 — 2004 — 2005 — 2012 — 2019 →

Confirm in $p\bar{p}$@CDF, D0

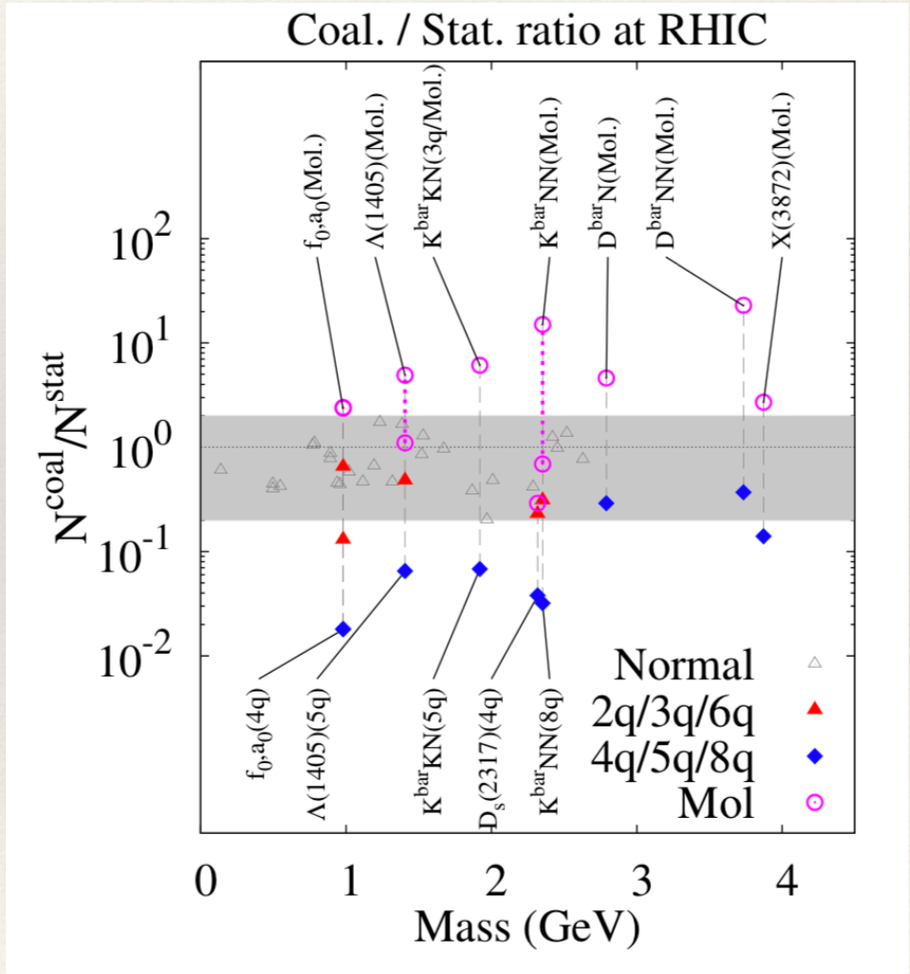
Multiplicity-dependence@LHCb

The X(3872) in Heavy Ion Collision

- Numerous heavy quarks v.s. $e^+e^-, pp, p\bar{p}$
- Order of magnitude difference for different scenarios
- Sensitive to the size of the hadrons



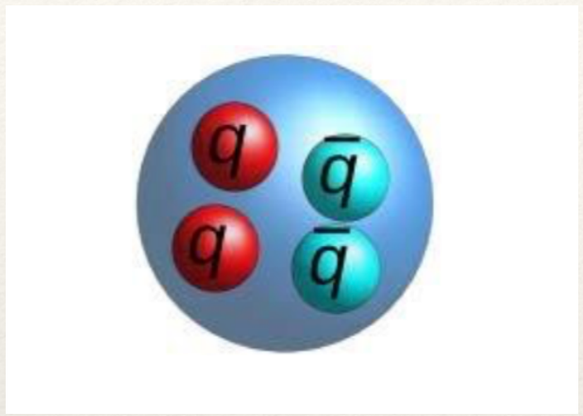
CMS, arXiv: 2102.13048



ExHIC, PRL106(2011)212001

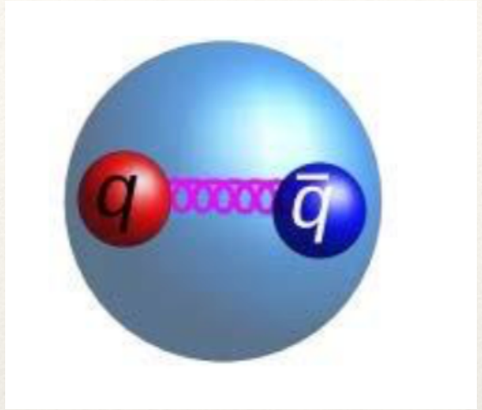
The Motivation

- Compact object ($r \sim 1$ fm)



Tetra quark

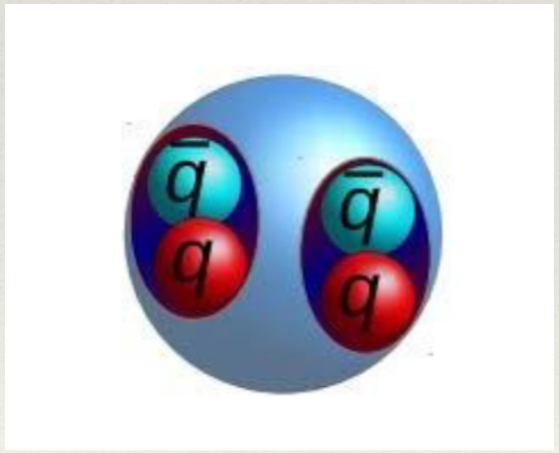
Charmonium



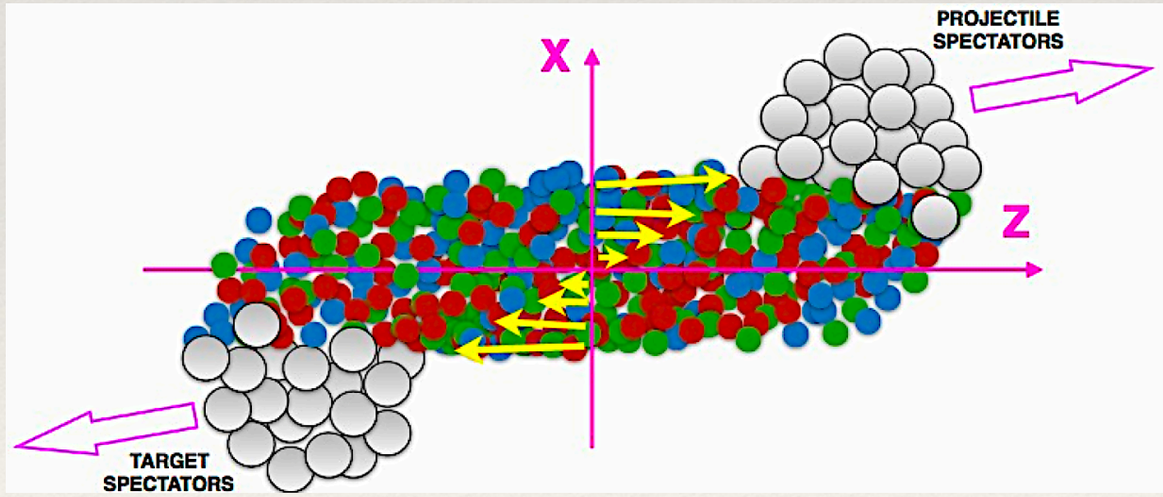
Hybrid

…

- Loose hadronic molecule ($r \sim 10$ fm)



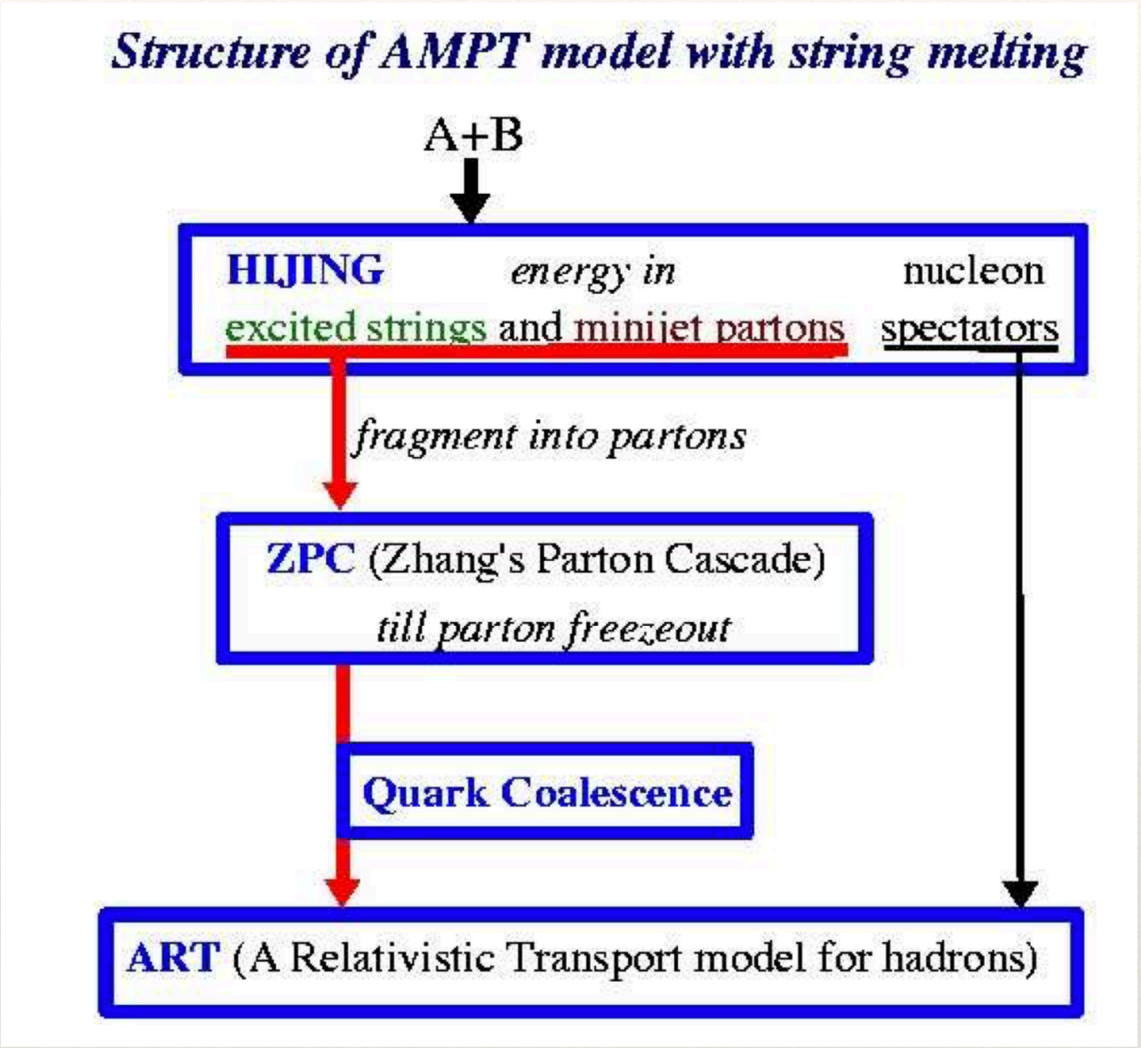
- Size effect



- Estimate the yield of X(3872) in HIC

Zhang, Liao, Wang, QW, Xing, PRL126(2021)012301

The multi-phase transport (AMPT) model



- Heavy Ion Jet Interaction Generator

Generate the initial conditions

- Zhang's Parton Cascade

Partonic scattering

- Diquark and antidiquark pairs in

"Quark Coalescence"

- $D^{(*)}$ and $\bar{D}^{(*)}$ in "ART"

Lin, et.al, PRC72(2005)064901

- The success of the AMPT model

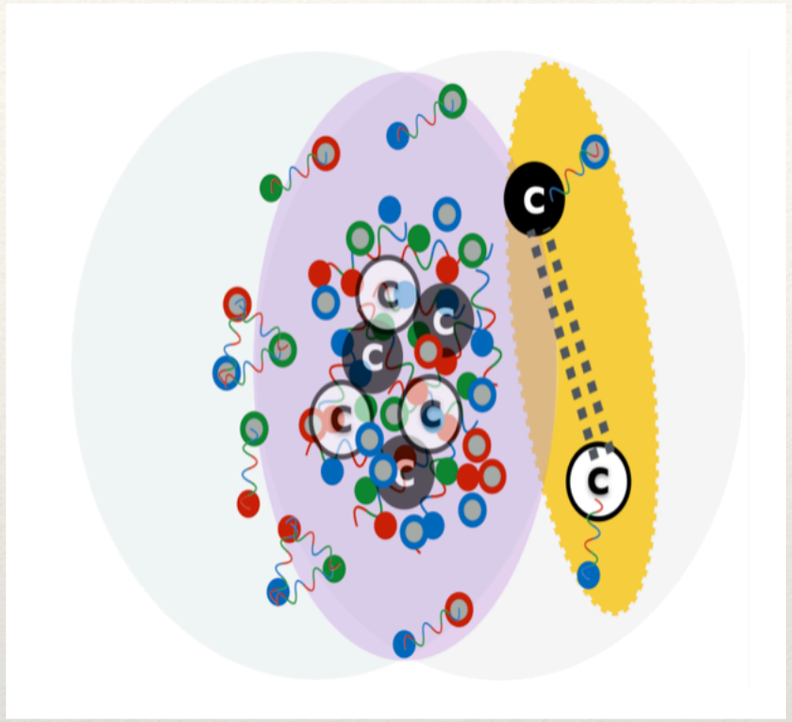
Lin, et.al, PRC90(2014)1403,6321

- Evolution of transverse flow and effective temperatures
- Pb+Pb Collisions@ 5.02 TeV Ma, Lin, PRC93(2016)054911
- Two-particle angular correlations in pp and p-Pb collisions Zhang, et.al., PRC98(2018)034912

Our framework

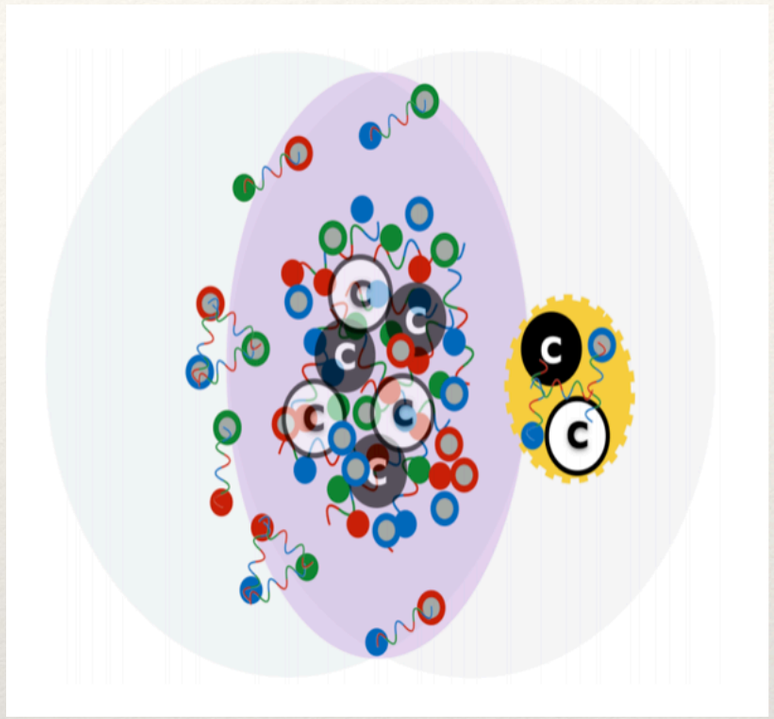
Zhang, Liao, Wang, QW, Xing, PRL126(2021)012301

- Molecular state



- $D^{(*)}$ and $\bar{D}^{(*)}$ in "ART"
- $5\ \text{fm} < r_{D\bar{D}^*} < 7\ \text{fm}$
- $2M_D < M_X < 2M_{D^*}$

- Tetraquark



- Diquark $[cq]$ and antidiquark $[\bar{c}\bar{q}]$ pairs in partonic coalescence
- $r_{[cq][\bar{c}\bar{q}]} < 1\ \text{fm}$
- $2M_{|00\rangle_0} < M_X < 2M_{|11\rangle_0}$

Maiani, et. al., PRD89(2014)114010

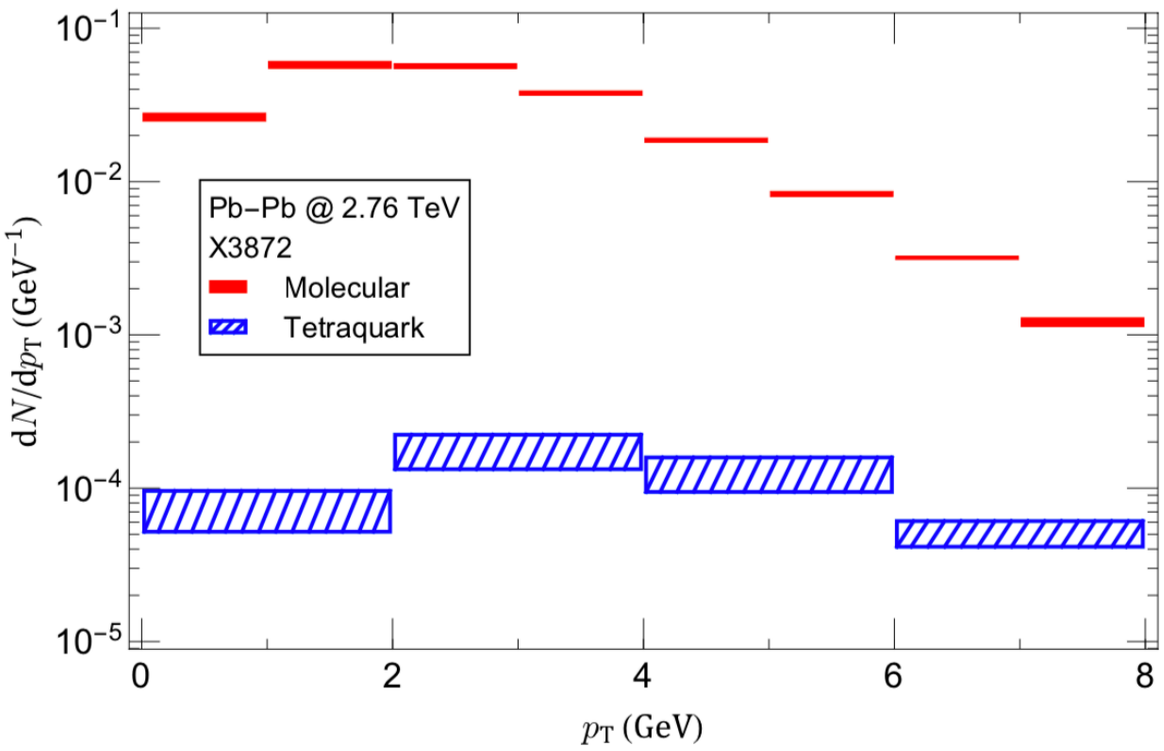
p_T and rapidity distributions

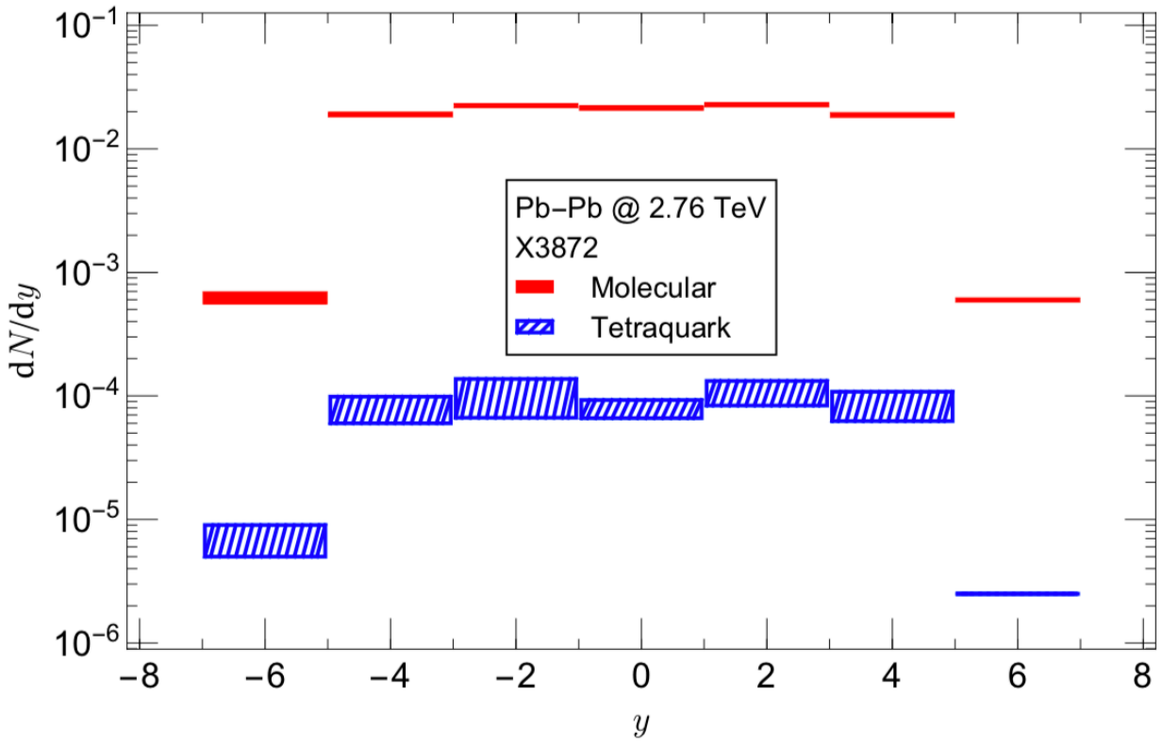
- Molecular state

  $2.2 \times 10^5/10^6$ yields

- Tetraquark

  $9 \times 10^2/10^6$ yields

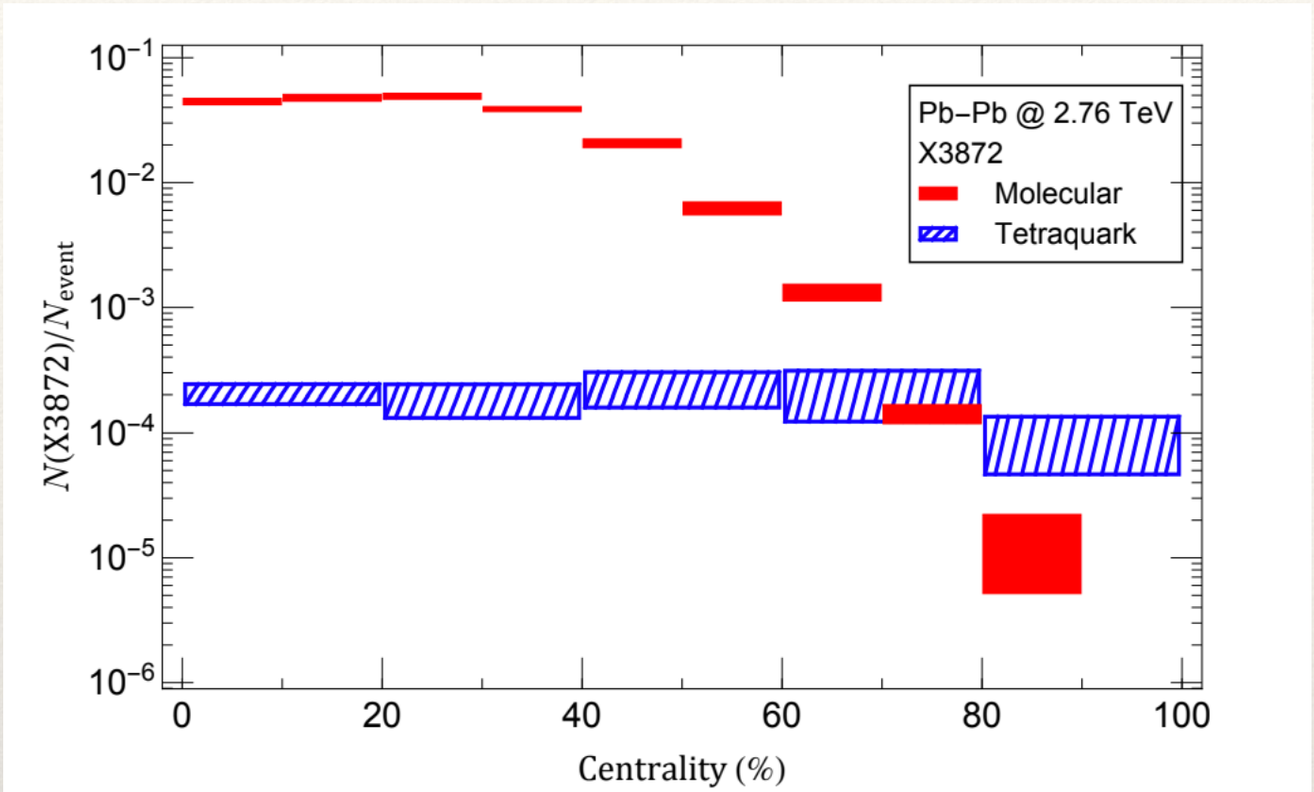


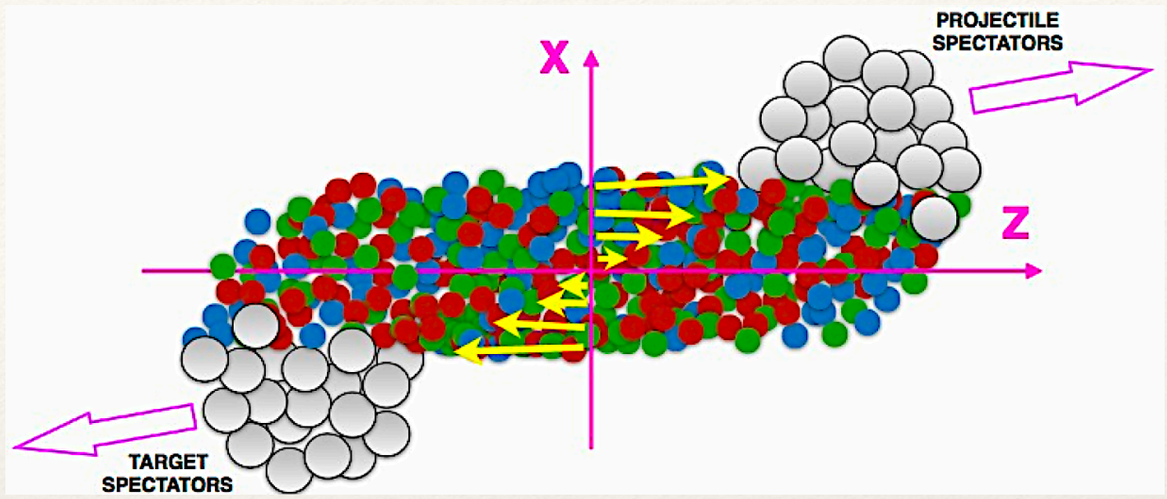


- HM is 2 times order larger
- Similar to the normal hadrons

Zhang, Liao, Wang, QW, Xing, PRL126(2021)012301

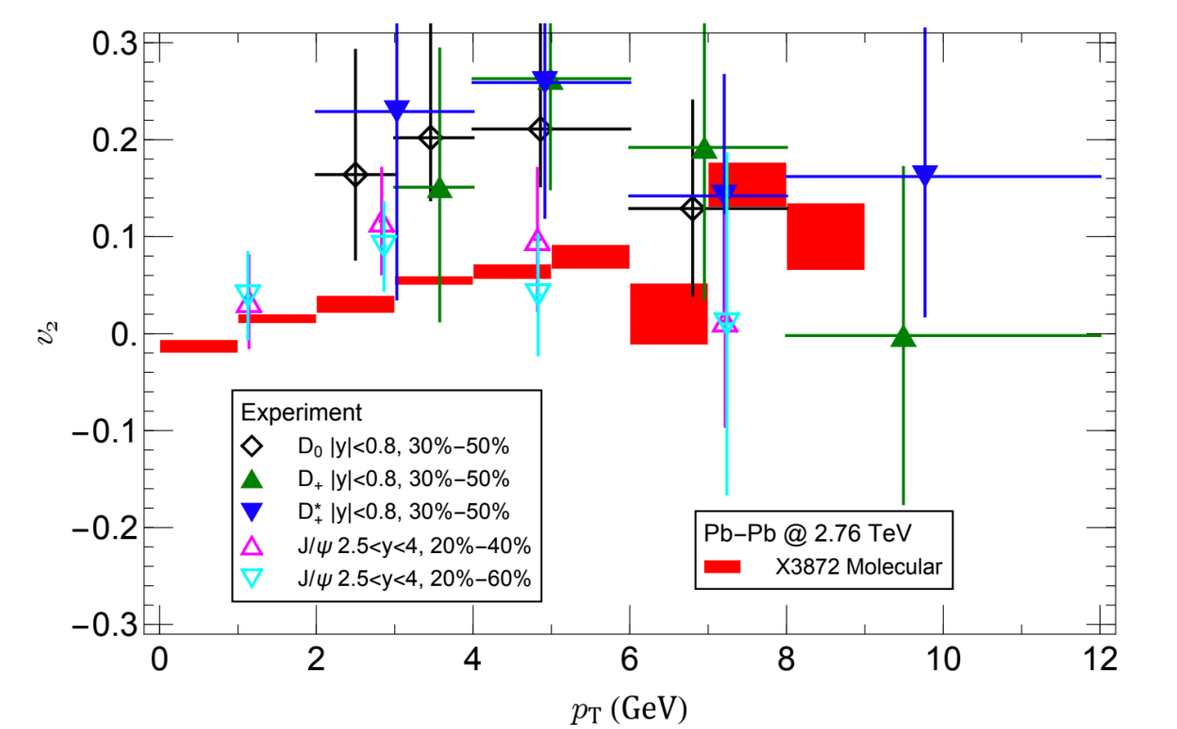
Centrality distribution





- Strongly decreasing for HM
- Mild change for compact tetra quark
- System size dependance could be a good probe to X(3872) inner structure
- The size dependance is universal for all the hadrons

Elliptic flow



- Elliptic flow $v_2 \equiv \dfrac{p_x^2 - p_y^2}{p_x^2 + p_y^2}$

p_x, p_y, p_z the three momentum of the produced hadron, with z-axis beam direction

CMS, PRL121(2018)082301

- The constituent quark scaling: v_2/n_q is within [0.5,1.5] GeV for normal light hadrons
- Elliptic flow is the key observable for collective property of bulk medium
- This study showed the first estimation of elliptic flow for exotic states
- The lower statistic for tetra quark do not allow for the v_2 plot

Summary

- First estimate the pT, rapidity, centrality dependence of the X(3872) in HM picture and tetra quark pictures in HIC
- The fireball volume plays a crucial role, leading to a two-order-of-magnitude and significant centrality dependence
- HIC provide a unique opportunity to differentiate hadronic molecule and compact tetra quark scenarios for X(3872)
- The elliptic flow is another key value to study the internal structure of the X(3872)

Outlook

- Further simulations/measurements in HIC:

Pb-Pb, Xe-Xe, Cu-Cu, O-O, d/p-Au, due to the system-size dependence of X(3872)

- Estimate the yields of other exotics in HIC

Thanks for your attention!