Exotic State in Heay Ion Collision
重离子碰撞中的奇特强子态

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Deciphering the nature of X(3872) in heavy ion collisions, **HZ**, Jinfeng Liao, Enke Wang, Qian Wang, Hongxi Xing, Phys. Rev. Lett. 126, 012301 (2021)
Production of doubly charmed exotic hadrons in heavy ion collisions, Yuanyuan Hu, Jinfeng Liao, Enke Wang, Qian Wang, Hongxi Xing, **HZ**, Phys.Rev.D 104 (2021) 11, L111502

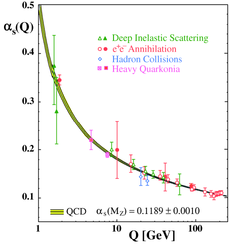
Introduction

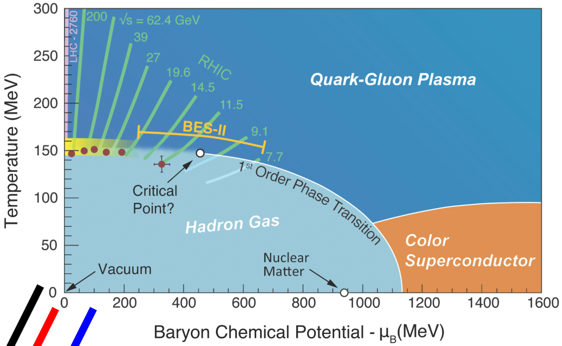
Charm-riched environment

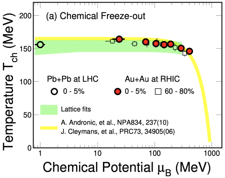
X(3872) in heavy ion collisions

doubly charmed exotic hadrons

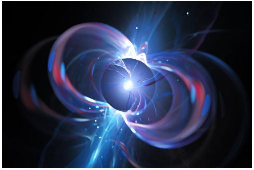
QCD Phase Diagram

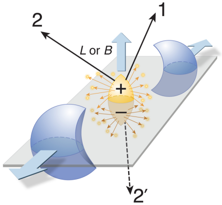






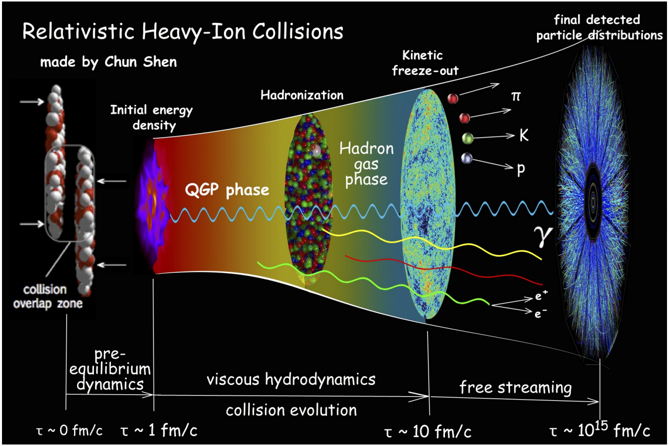
$\vec{B}$ $\vec{\omega}$ "C"





Opening up new dimensions:
Toward Hyper-Phase-Diagram!

Heavy Ion Collision



Quark-gluon plasma is created in such collisions!

The hottest matter!

The most perfect fluid!

Standard Model of Elementary Particles

粒子物理标准模型

三代物质粒子（费米子）

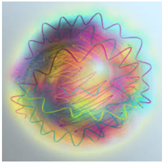
		I	II	III	规范玻色子	标量玻色子
夸克	质量 电荷 自旋	≃2.2 MeV/c^2 2/3 1/2 u 上	≃1.28 GeV/c^2 2/3 1/2 c 粲	≃173.1 GeV/c^2 2/3 1/2 t 顶	0 0 1 g 胶子	≈125.09 GeV/c^2 0 0 H 希格斯玻色子
夸克		≃4.7 MeV/c^2 -1/3 1/2 d 下	≃96 MeV/c^2 -1/3 1/2 s 奇	≈4.18 GeV/c^2 -1/3 1/2 b 底	0 0 1 γ 光子	
轻子		≈0.511 MeV/c^2 -1 1/2 e 电子	≃105.66 MeV/c^2 -1 1/2 μ μ子	≈1.7768 GeV/c^2 -1 1/2 τ τ子	≈91.19 GeV/c^2 0 1 Z Z玻色子	
轻子		<2.2 eV/c^2 0 1/2 ν_e 电中微子	<1.7 MeV/c^2 0 1/2 ν_μ μ中微子	<15.5 MeV/c^2 0 1/2 ν_τ τ中微子	≈80.39 GeV/c^2 ±1 1 W W玻色子	

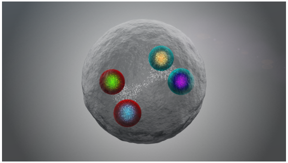
Exotic State XYZ

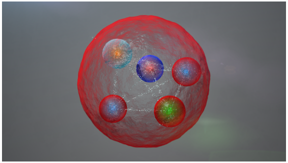
Hadrons are mostly found in two modes:

- Mesons ($q\bar{q}$)
- Baryons (qqq)

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


Glueball


tetraquark


pentaquark

X: unkown

Y: the vector exotic states 1^{--}

Z: charged quarkoniumlike states

Charmed hadrons

- Charmed mesons: D, D_s ...
- Singly charmed baryons: Λ_c, Σ_c, Ξ_c, Ω_c ...
- Doubly and triply charmed hardons: Ξ_{cc}, Ω_{ccc} ...

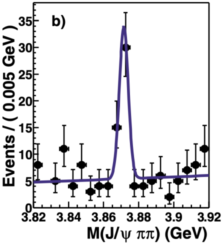
Multiquark state

Table: Tetra- & pentaquark candidates Nature Commun. 13 (2022) 1, 3351

States	Quark content
$X_0(2900)$, $X_1(2900)$	$\bar{c}du\bar{s}$
$\chi_{c1}(3872)$	$c\bar{c}q\bar{q}$
$Z_c(3900)$, $Z_c(4020)$, $Z_c(4050)$, $X(4100)$, $Z_c(4200)$, $Z_c(4430)$, $R_{c0}(4240)$	$c\bar{c}u\bar{d}$
$Z_{cs}(3985)$, $Z_{cs}(4000)$, $Z_{cs}(4220)$	$c\bar{c}u\bar{s}$
$\chi_{c1}(4140)$, $\chi_{c1}(4274)$, $\chi_{c0}(4500)$, $\chi_{c0}(4700)$, $X(4630)$, $X(4685)$, $X(4740)$	$c\bar{c}s\bar{s}$
$X(6900)$	$c\bar{c}c\bar{c}$
$Z_b(10610)$, $Z_b(10650)$	$b\bar{b}u\bar{d}$
$P_c(4312)$, $P_c(4380)$, $P_c(4440)$, $P_c(4457)$, $P_c(4357)$	$c\bar{c}uud$
$P_{cs}(4459)$	$c\bar{c}uds$

$X(3872) \quad J^{PC} = 1^{++} \quad (c\bar{c}q\bar{q})$

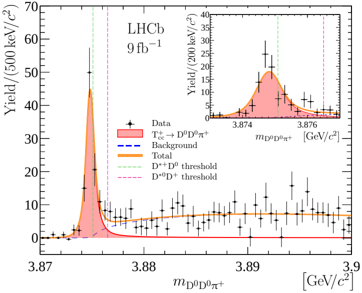
- Belle collaboration (2003) $B \to J/\psi\pi^+\pi^- K$
- $M_X = 3871.69 \pm 0.17 MeV$
- Decay pattern: $J/\psi\rho(\pi^+\pi^-),\ J/\psi\omega(\pi^+\pi^-\pi^0),$ $D^0\bar{D}^{*0}/\bar{D}^0 D^{*0}/D\bar{D}\pi,\ J/\psi\gamma$



Belle, PRL91(2003)262001

$T_{cc} \quad J^{PC} = 1^{+} \quad (cc\bar{q}\bar{q})$

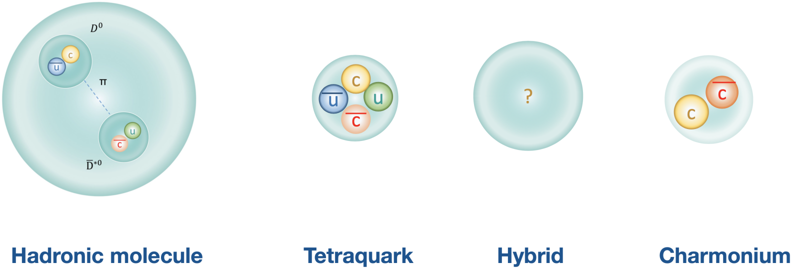
- LHCb collaboration (2019) $T_{cc}^+ \to D^0 D^0 \pi^+$
- $M_{T_{cc}^+} = 3875 \pm 0.41 MeV$



LHCb, Nature Commun. 13 (2022) 1, 3351; Nature Phys. (2022)

The internal structure of X(3872)

Figs from Yen-Jie Lee



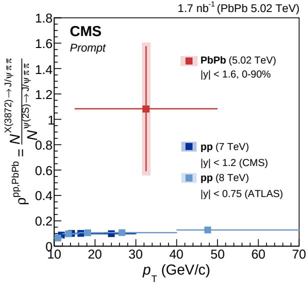
Estimated yields of $X(3872)$ and T_{cc}

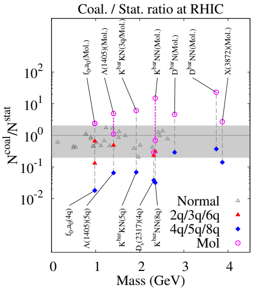
	RHIC				LHC			
	$2q/3q/6q$	$4q/5q/8q$	Mol.	Stat.	$2q/3q/6q$	$4q/5q/8q$	Mol.	Stat.
T_{cc}^{1}[a]	—	4.0×10^{-5}	2.4×10^{-5}	4.3×10^{-4}	—	6.6×10^{-4}	4.1×10^{-4}	7.1×10^{-3}
$X(3872)$	1.0×10^{-4}	4.0×10^{-5}	7.8×10^{-4}	2.9×10^{-4}	1.7×10^{-3}	6.6×10^{-4}	1.3×10^{-2}	4.7×10^{-3}

[a]Particles that are newly predicted by theoretical model.

S. Cho et al. (EXHIC Coll.), PRC84(2011)064910

Recent measurements

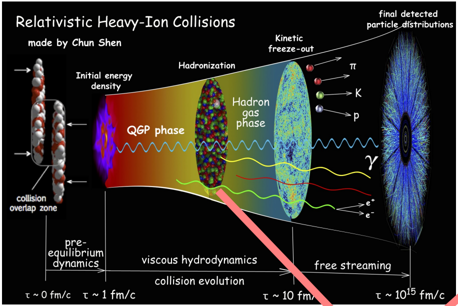


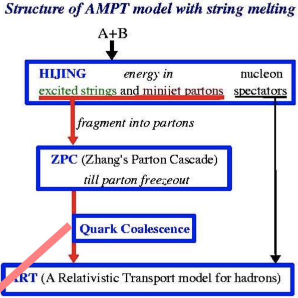


CMS, PRL128(2022)032001 ExHIC coll., PRL106(2011)212001

A "realistic" simulation by AMPT

U. W. Heinz, J.Phys.Conf.Ser455(2013)012044 Z. W. Lin .., PRC72(2005)064901





Coalescence

	$X(3872)$	T_{cc}
Molecule:	$D + \bar{D}^*$	$D + D^*$
Tetraquark:	$cq + \bar{c}\bar{q}$	

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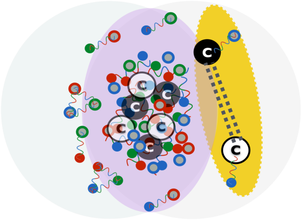
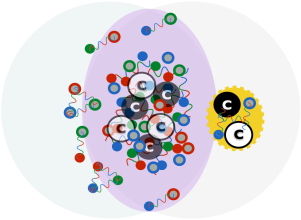
molecule state:



- Coalescence of D mesons
- The relative distance between D meson pairs: $R_{D\bar{D}^*} \sim 5 - 7fm$
- Mass: $2M_D < M_X < 2M_{\bar{D}^*}$

Tetraquark:



- Partonic coalescence of diquark and anti-diquark
- The relative distance between diquark pairs $R_{[cq]][\bar{c}\bar{q}]} < 1fm$
- 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 900 for compact tetraquark state.

p_T and rapidity dependence

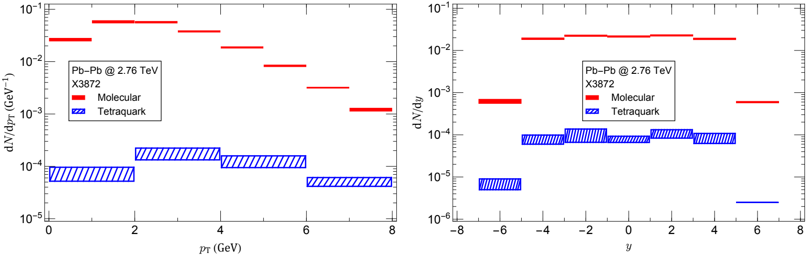
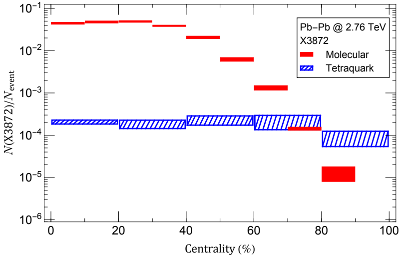
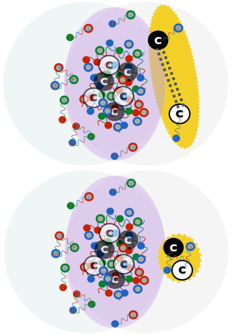


Figure: Orders of magnitude difference between hadronic molecule and compact tetraquark scenarios, an unique opportunity for HIC.

X(3872) in heavy ion collisions

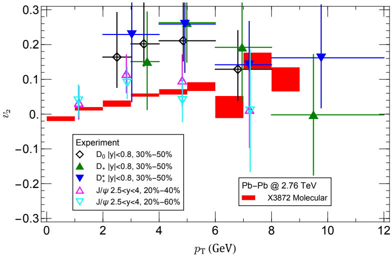
Centrality dependence





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

Elliptic flow



- Elliptic flow is the key observable for collective property of bulk medium
- This study showed the first estimation of elliptic flow for exotic states

Summary and Outlook

Summary

- HIC provide a unique opportunity to differentiate hadronic molecule and compact tetraquark scenarios for X(3872).
- A hot fireball with ample light as well as charm (anti-)quarks is available for producing the exotics.
- The fireball volume plays a crucial role, leading to a two-order-of-magnitude difference in the production of X(3872) between hadronic molecules and compact tetraquarks

Outlook

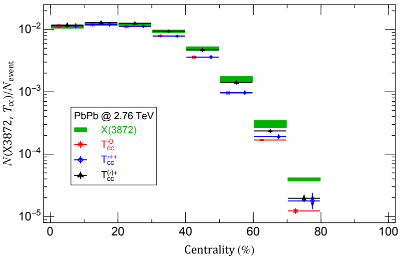
- further simulations in HIC: Pb-Pb, Xe-Xe, Cu-Cu, O-O, d/p-A, due to the system-size dependence of X(3872)
- Hadron Gas Phase: Interact with other hadrons: production + absorption

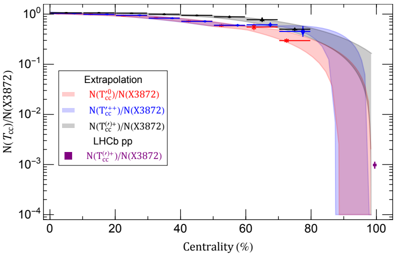
Introduction

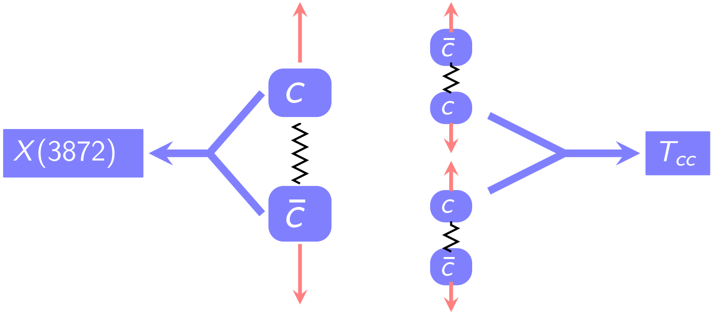
Charm-riched environment

X(3872) in heavy ion collisions

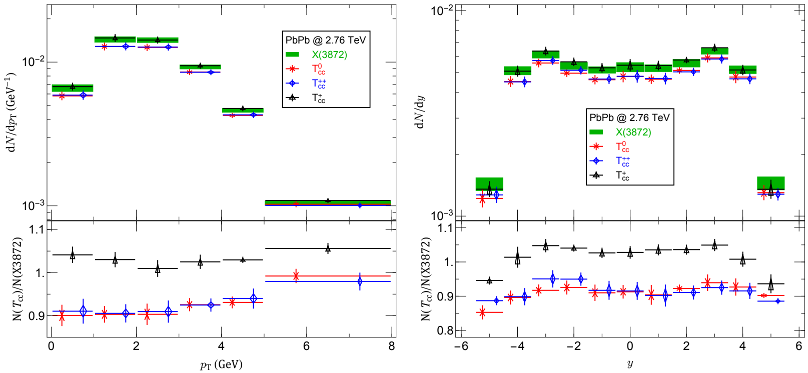
doubly charmed exotic hadrons


PbPb @ 2.76 TeV
X(3872)
Centrality (%)


Extrapolation
LHCb pp
Centrality (%)

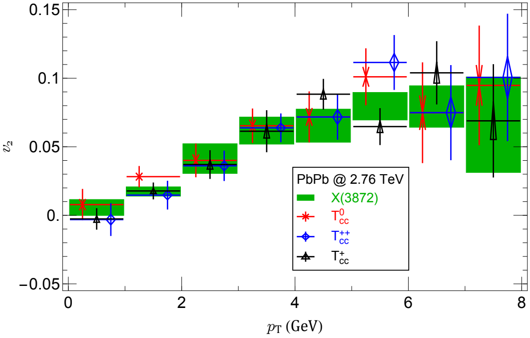

X(3872)
c
c̄
Tcc

p_T & y dependence



prediction of elliptic flow

Elliptic flow



- Elliptic flow is the key observable for collective property of bulk medium
- This study showed the first estimation of elliptic flow for exotic states

Summary

- HIC provides an extremely charm-rich enviroment.
- Yields of T_{cc}^{+} as well as its potential isospin partners are computed within the molecular picture for Pb-Pb collisions.
- We find three-order-of-magnitude enhancement in the production of T_{cc}^{+} in $Pb-Pb$ collisions as compared with the yield in $p-p$ collisions.

Outlook

- Compact state
- Hadron Gas Phase: Interact with other hadrons: production + absorption

Thank you for your attention!