Nuclear Physics across Energy Scales

-- Personal view from heavy ion collisions

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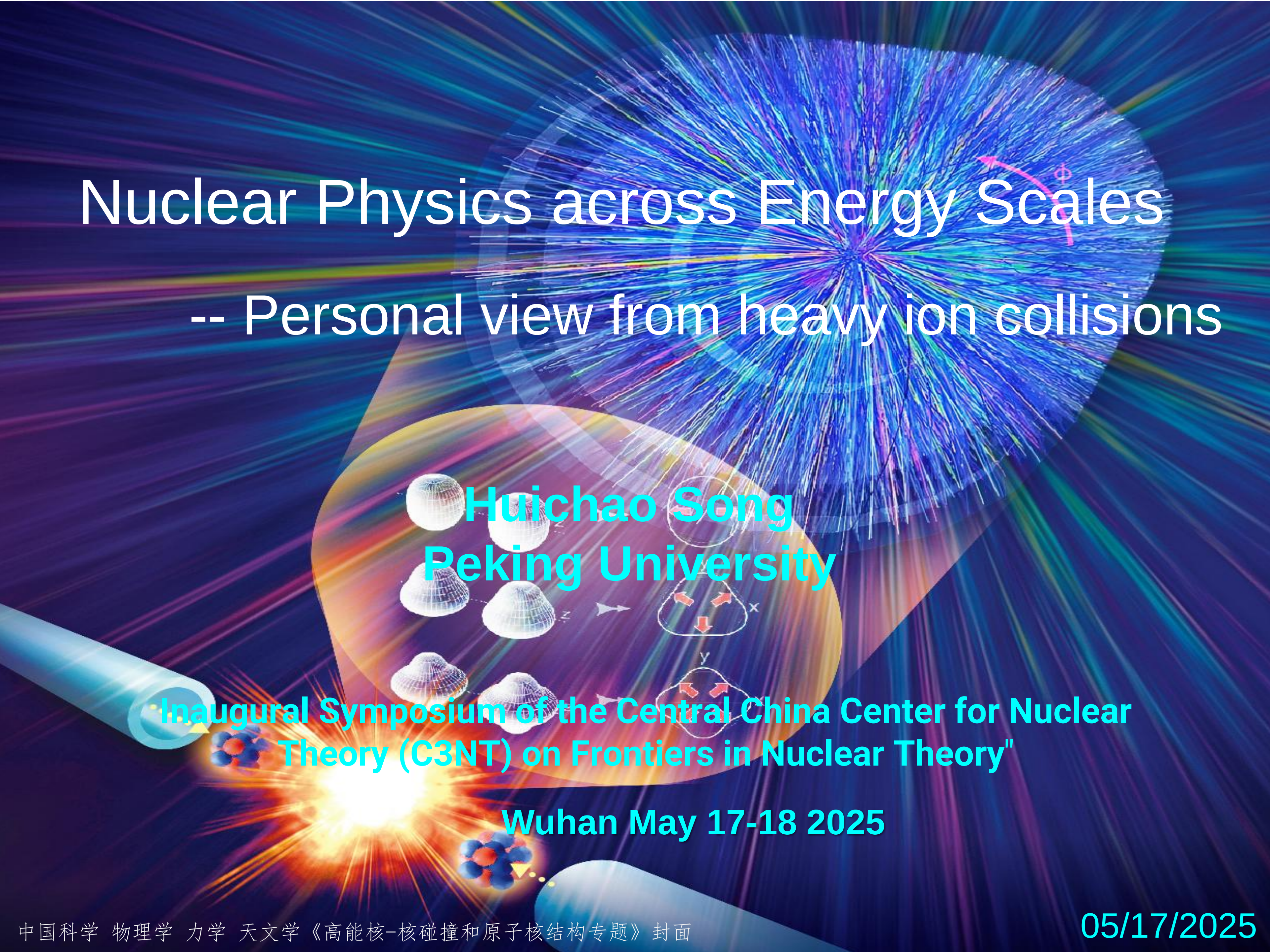
Peking University

Inaugural Symposium of the Central China Center for Nuclear Theory (C3NT) on Frontiers in Nuclear Theory"

Wuhan May 17-18 2025



中国科学 物理学 力学 天文学《高能核-核碰撞和原子核结构专题》封面

05/17/2025

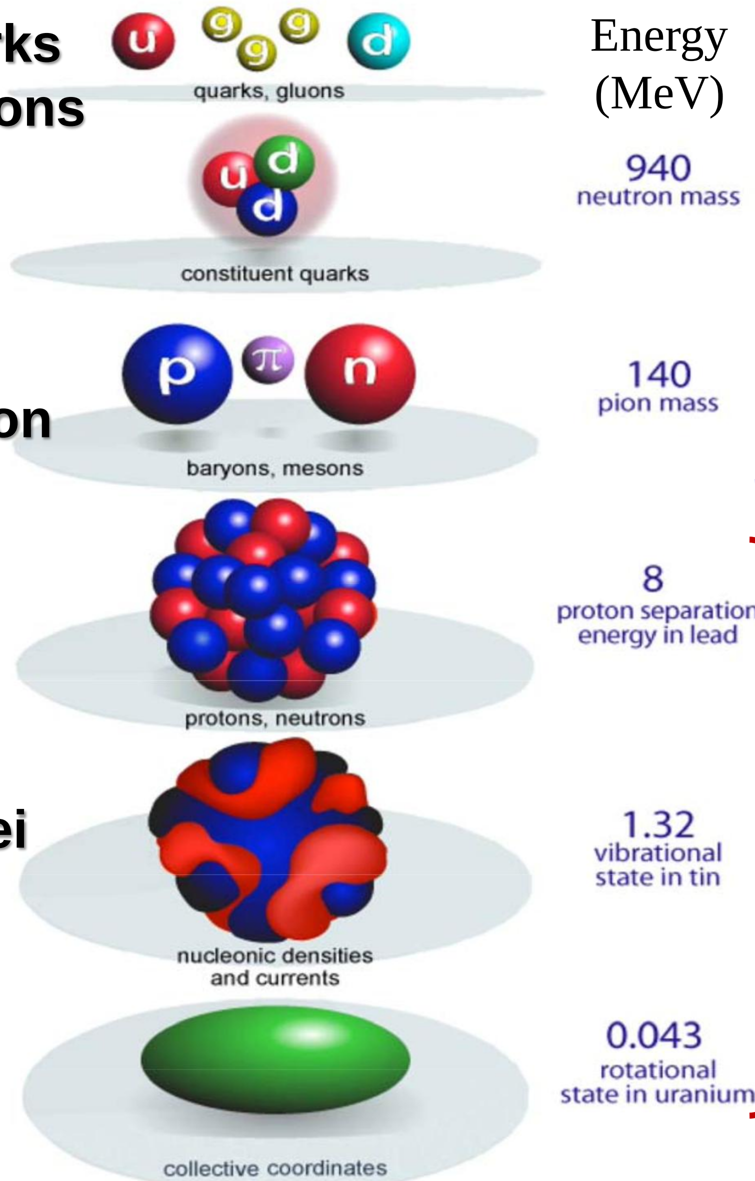
Landscape of nuclear physics

degrees of freedeom

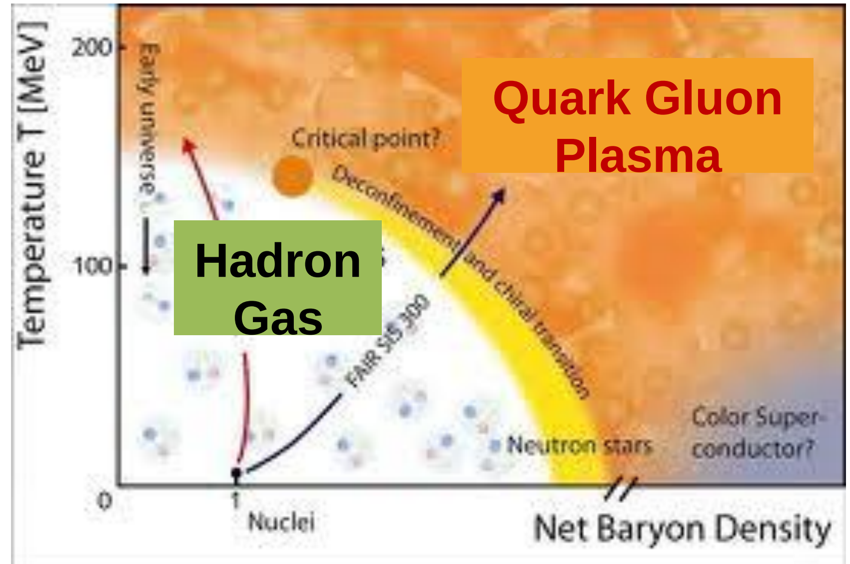
quarks & gluons

hadrons

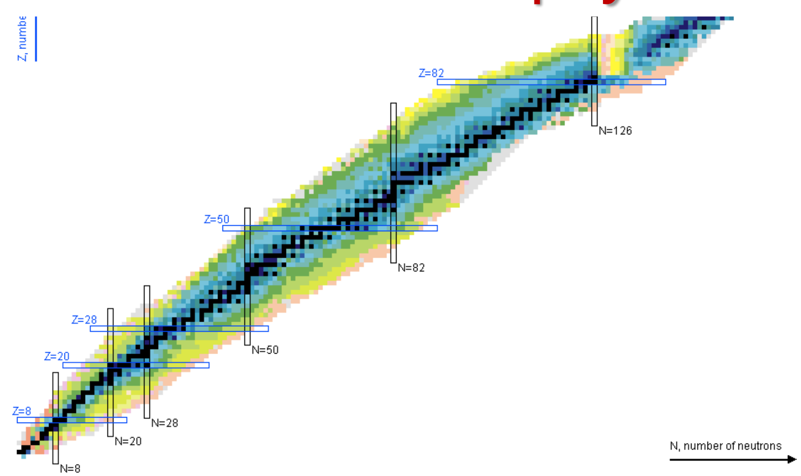
nuclei



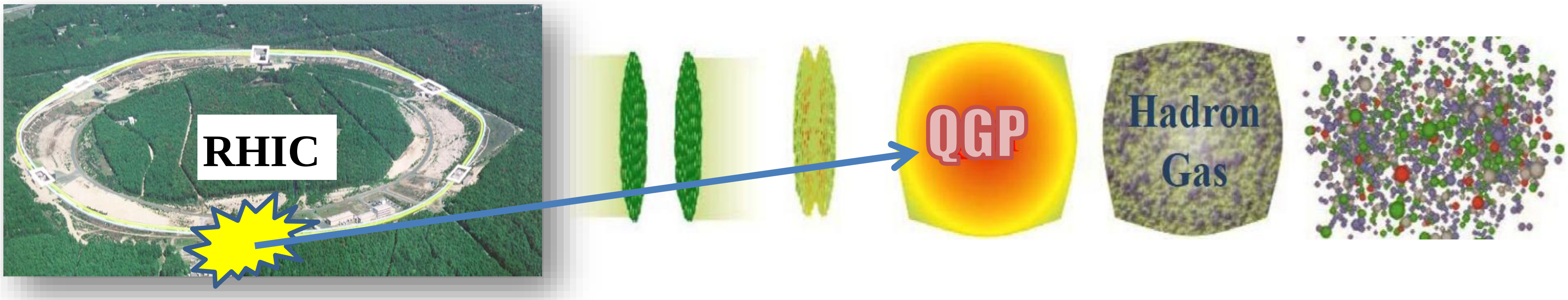
-intermediate and high energy nuclear physics



-nuclear structure physics

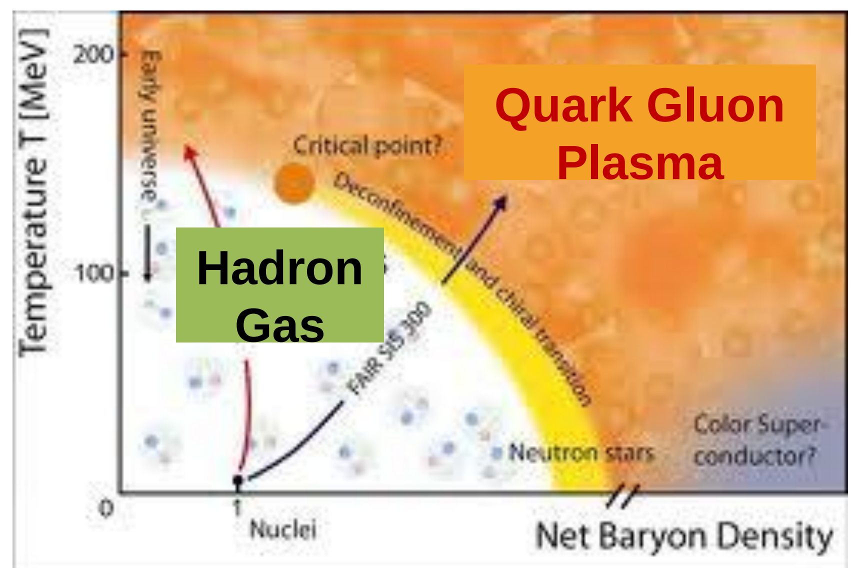


Relativistic heavy ion physics

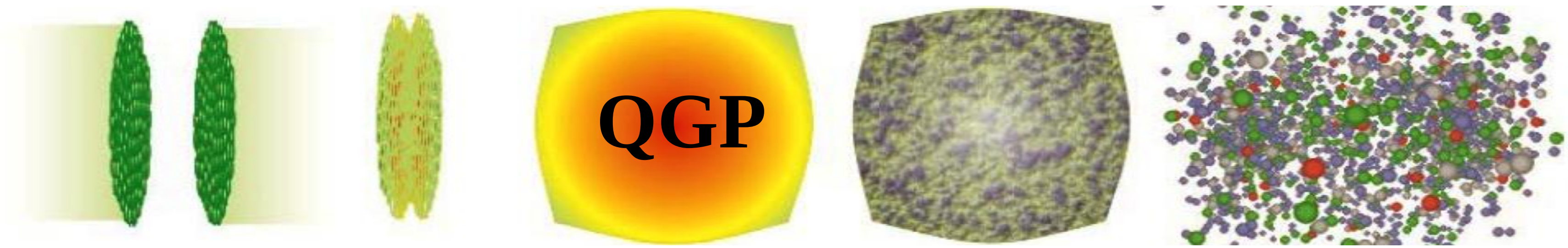


Relativistic heavy ion collisions

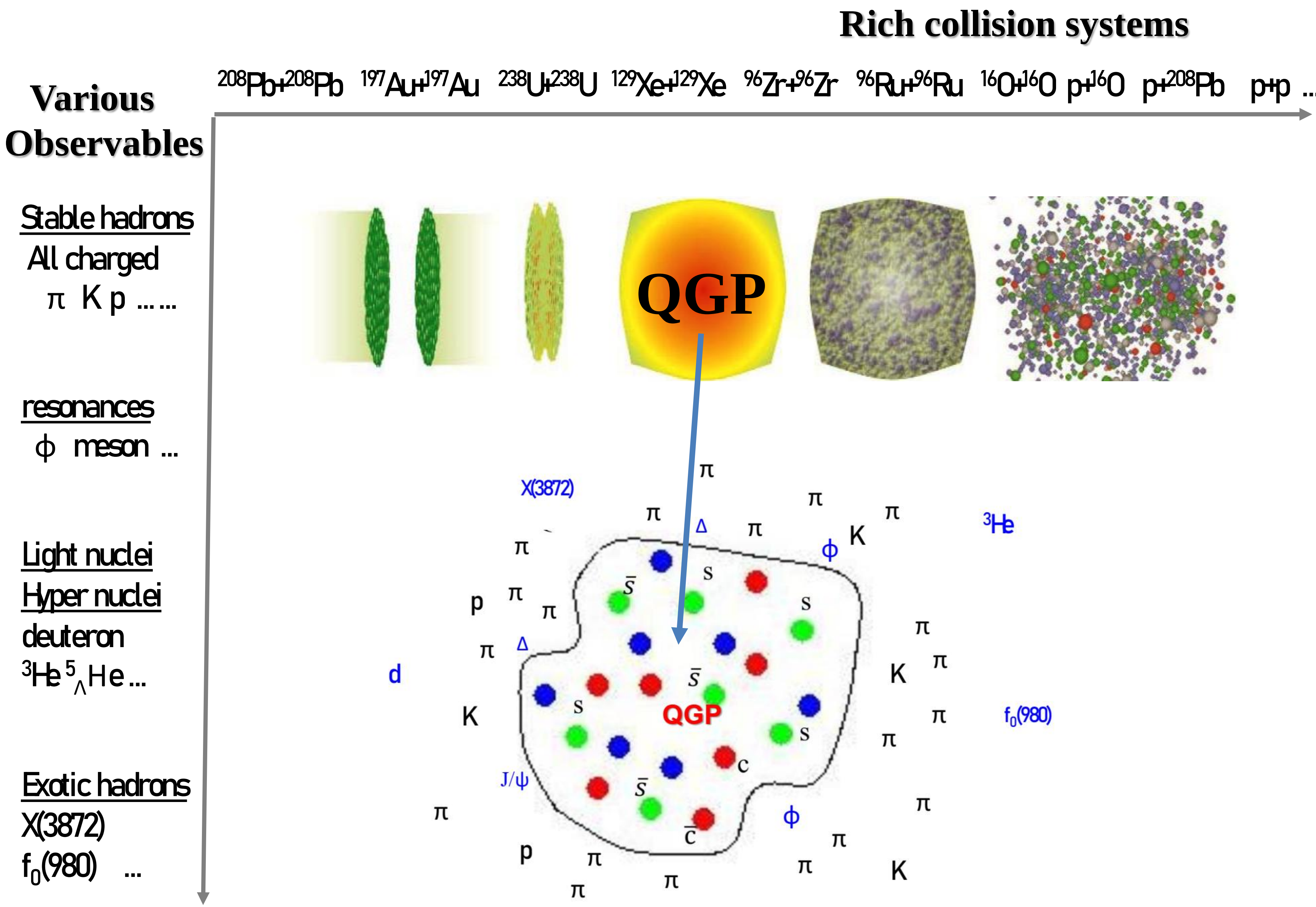
- create and study QGP
- the QCD phase diagram
- the deconfinement & chiral phase transition
- the QCD vacuum



The QGP has been created in relativistic heavy ion collisions

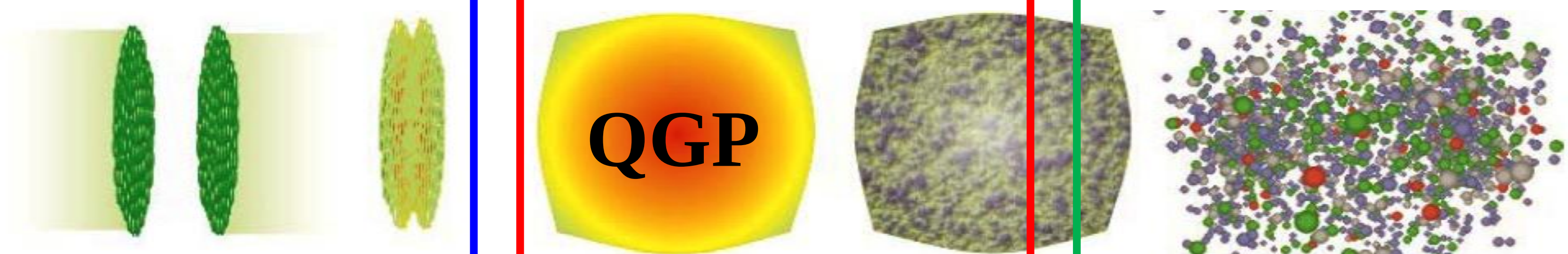


Hottest Matter on Earth


Rich collision systems
208Pb+208Pb 197Au+197Au 238U+238U 129Xe+129Xe 96Zr+96Zr 96Ru+96Ru 16O+16O p+16O p+208Pb p+p ...
Various Observables
Stable hadrons
All charged
π K p ......
resonances
ϕ meson ...
Light nuclei
Hyper nuclei
deuteron
3He 5ΛHe ...
Exotic hadrons
X(3872)
f0(980) ...
QGP
X(3872)
3He
d
f0(980)
J/ψ
Δ
ϕ
K
p
π
s
s̄
c
c̄
QGP

Exploring Nuclear Physics across Energy Scales

-- Personal view from heavy ion collisions



Initial conditions:

Intersection study with nuclear structure

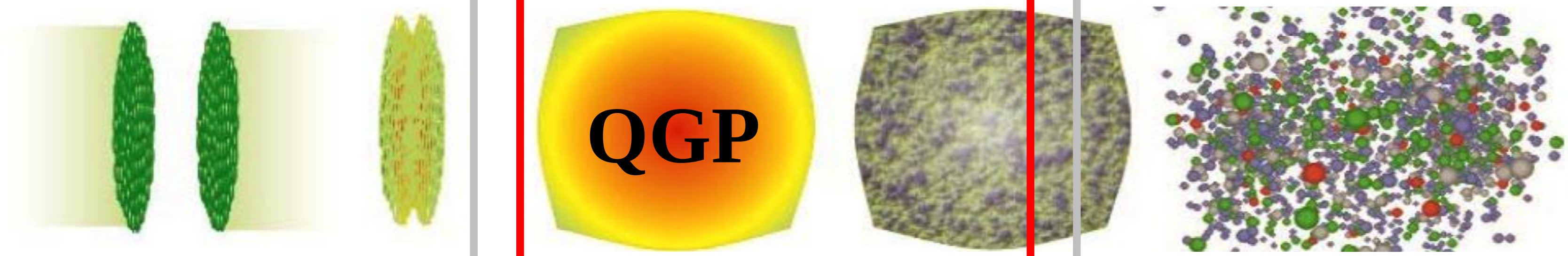
QGP evolution:

main goal: QGP & QCD phase diagram

Final Hadrons:

intersection study with hadron physics

Flow & QGP（signature） in large and small systems of heavy-ion / light-ion collisions



Initial conditions:

Intersection study with nuclear structure

QGP evolution:

main goal: QGP & QCD phase diagram

Final Hadrons:

intersection study with hadron physics

Viscous hydro & hybrid model

Conservation laws:

$$\partial_\mu T^{\mu\nu}(x) = 0 . \qquad \partial_\mu N_i^\mu(x) = 0 ,$$

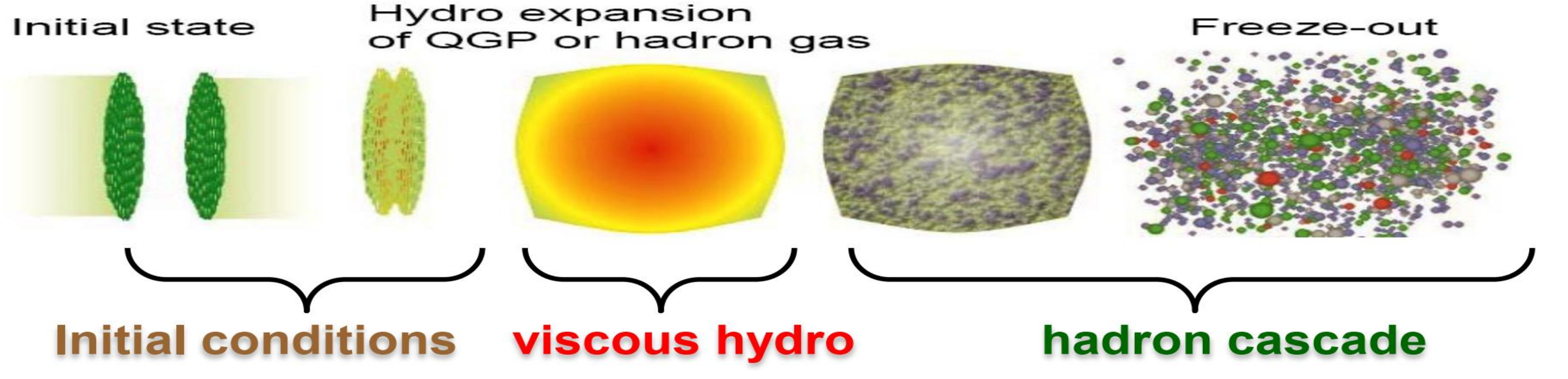
2nd order I-S equ:

$$\dot{\Pi} = -\frac{1}{\tau_\Pi}\left[\Pi + \zeta\theta - l_{\Pi q}\nabla_\mu q^\mu + \Pi\zeta T \partial_\mu\left(\frac{\tau_\Pi u^\mu}{2\zeta T}\right)\right],$$

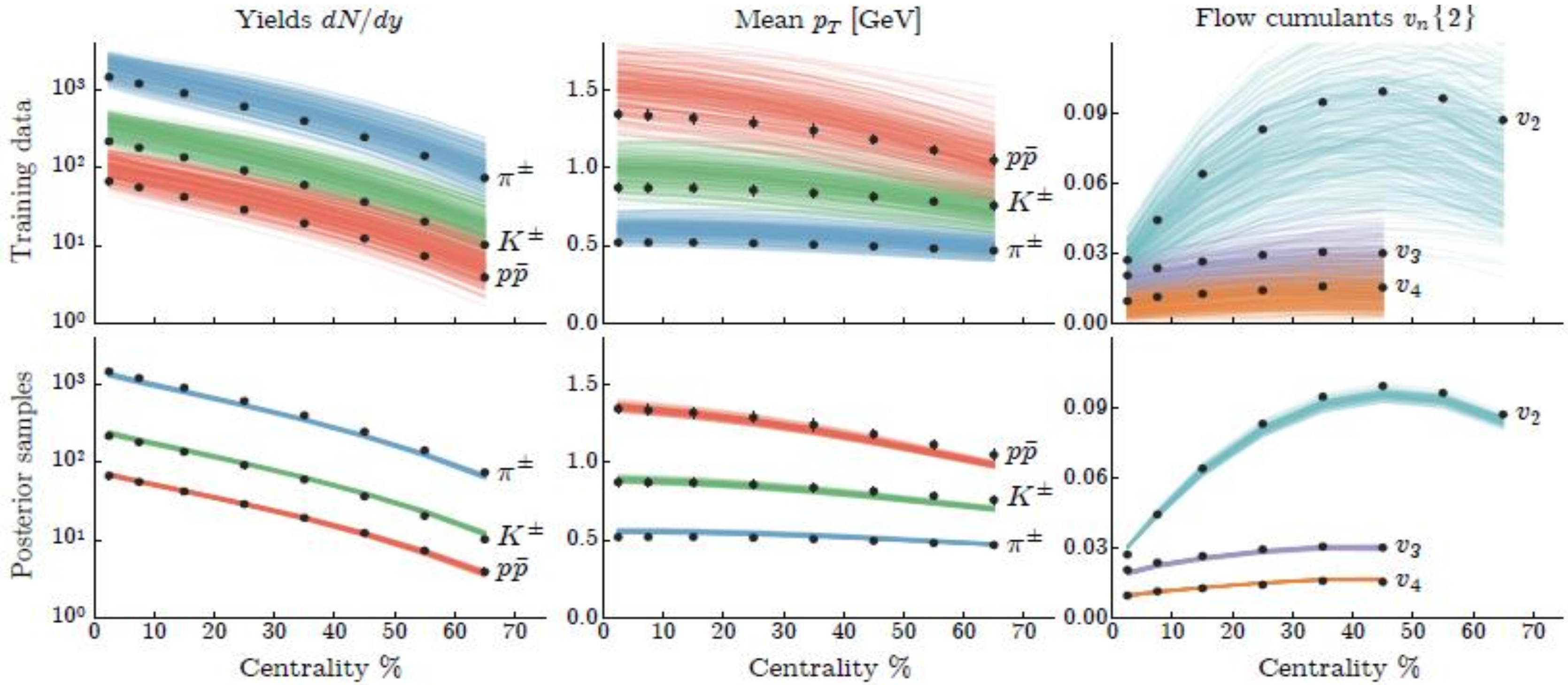
$$\Delta^\mu_\nu \dot{q}^\nu = -\frac{1}{\tau_q}\left[q_\mu + \lambda\frac{nT^2}{e+p}\nabla^\mu\frac{\nu}{T} + l_{q\pi}\nabla_\nu\pi^{\mu\nu} + l_{q\Pi}\nabla^\mu\Pi - \lambda T^2 q^\mu \partial_\mu\left(\frac{\tau_q u^\mu}{2\lambda T^2}\right)\right],$$

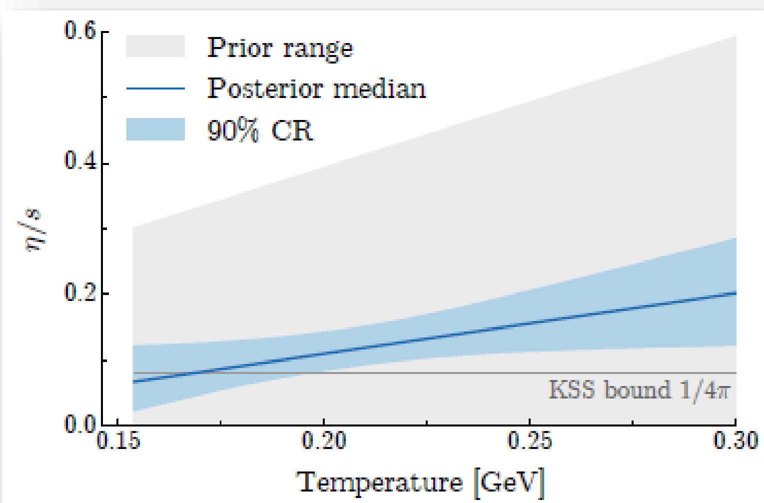
$$\Delta^{\mu\alpha}\Delta^{\nu\beta}\dot{\pi}_{\alpha\beta} = -\frac{1}{\tau_\pi}\left[\pi^{\mu\nu} - 2\eta\nabla^{\langle\mu}u^{\nu\rangle} - l_{\pi q}\nabla^{\langle\mu}q^{\nu\rangle} + \pi_{\mu\nu}\eta T\partial_\alpha\left(\frac{\tau_\pi u^\alpha}{2\eta T}\right)\right],$$

Input: "EOS" $\varepsilon = \varepsilon(p)$ initial and final conditions



Extract the QGP viscosity



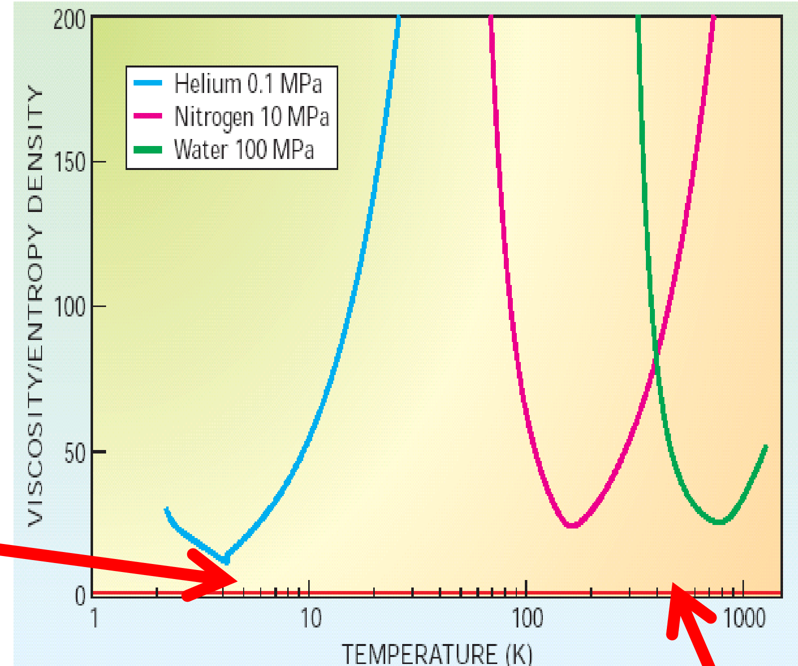


-An quantitatively extraction of the QGP viscosity with iEBE-VISHNU and the massive data evaluation

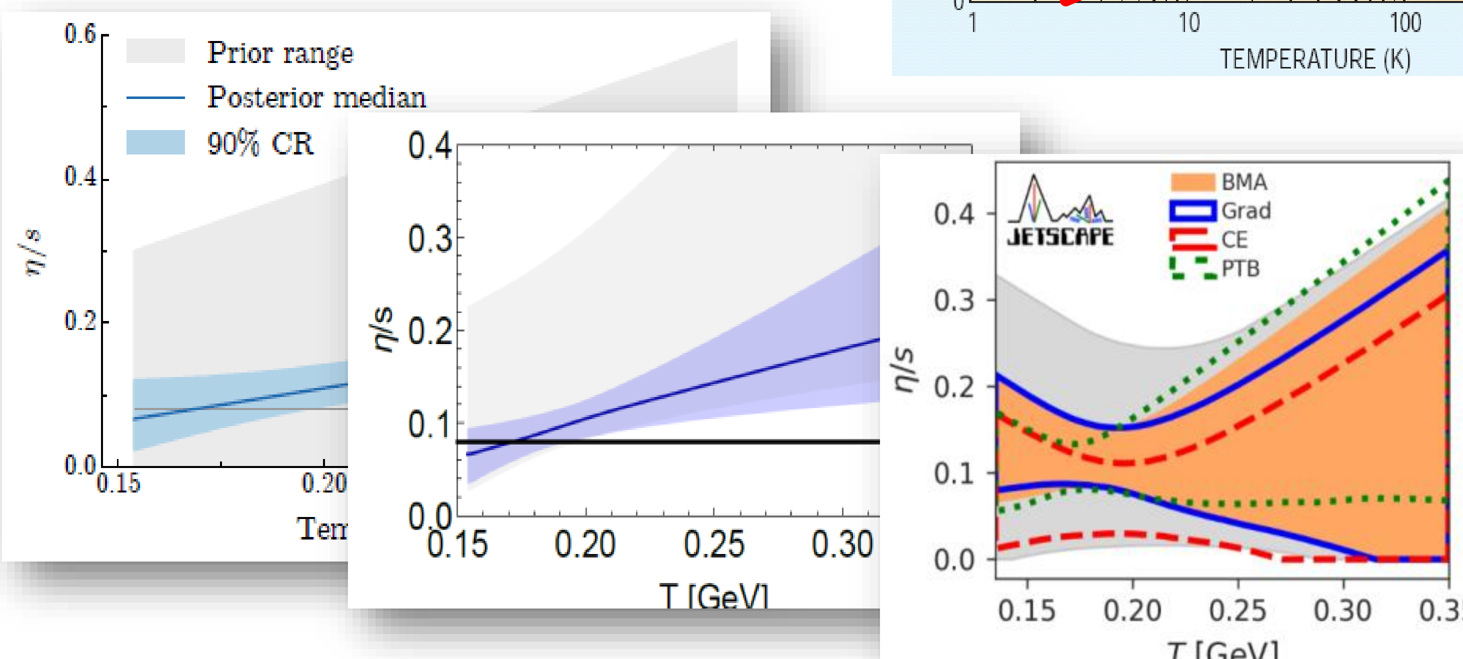
-η/s(T) is very close to the KSS bound of 1/4π

J. Bernhard, S. Moreland, S.A. Bass, J. Liu, U. Heinz, PRC 2015

QGP: most perfect liquid

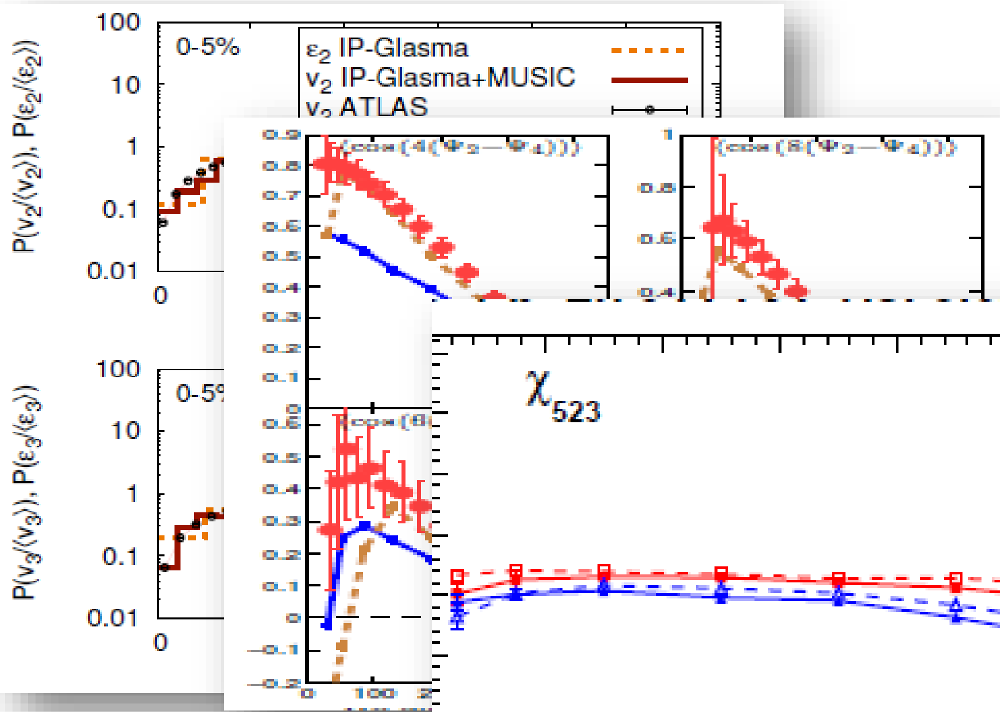


AdS/CFT $\frac{\eta}{s} \geq \frac{h}{k_B}$



QGP specific shear viscosity Extracted from exp data

Powerful predictions from hydrodynamics

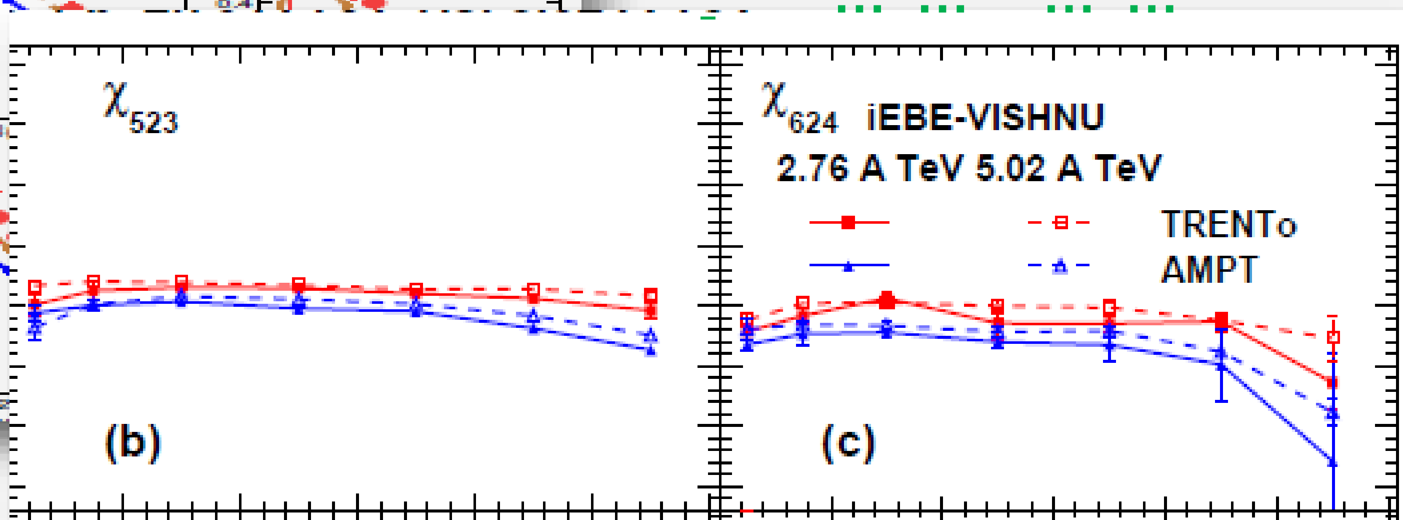


-V_n distributions

-non-linear response coeff.

-Correlations of Flow Harmonics

… … … …



-Hydrodynamics can quantitatively describe / predict various flow data
-perfect liquid for large systems

H. Xu, Z. Li and H. S*, Phys. Rev. C93, no. 6, 064905 (2016); W. Zhao, H. Xu and **H. S*,** Eur. Phys. J. C 77, no. 9, 645 (2017); X. Zhu, Y. Zhou, H. Xu and **H. S*,** Phys. Rev. C95, no. 4, 044902 (2017); W. Zhao, L. Zhu, H. Zheng, C. M. Ko and **H. S*.,** Phys. Rev. C 98, no. 5, 054905 (2018); Li, Zhao, Zhou, **H.S***, in preparation (2020) … … … …

-- How tiny the QGP droplet could be?

Small collisions systems at RHIC & LHC

System size scan:

Pb+Pb Xe+Xe O+O p-Pb p-p collisions …

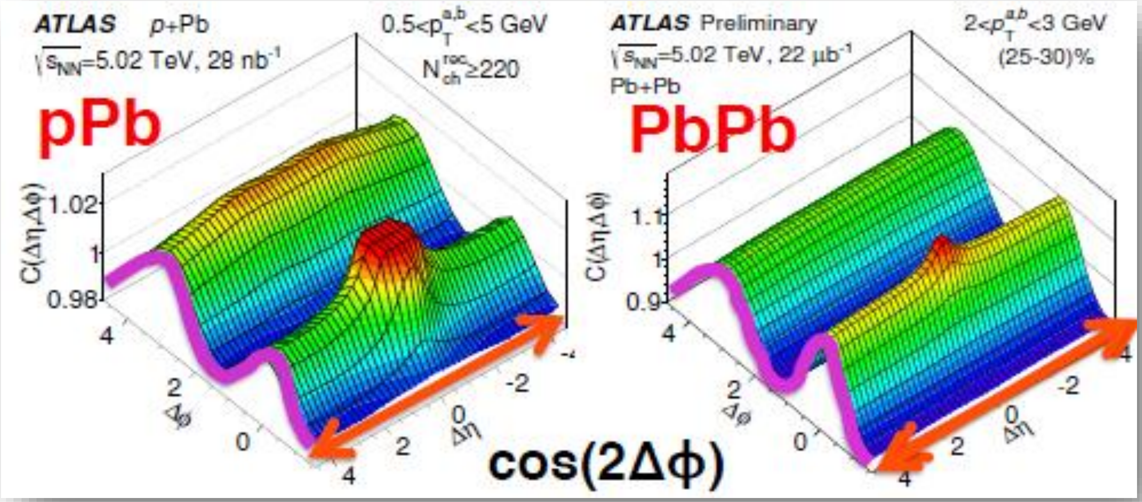
Geometry scan:

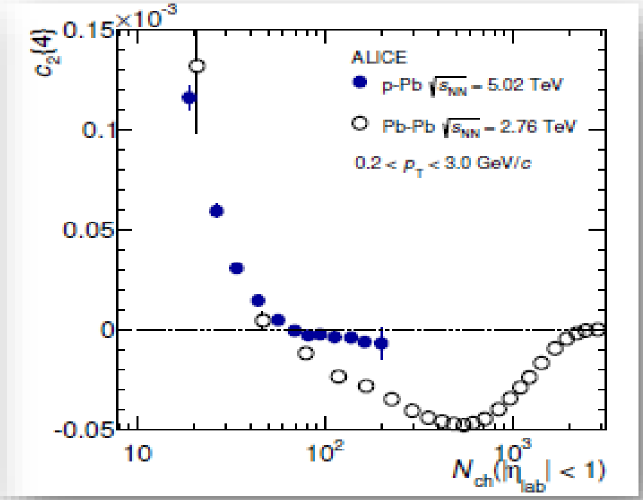
p-Au d+Au He-Au collisions …

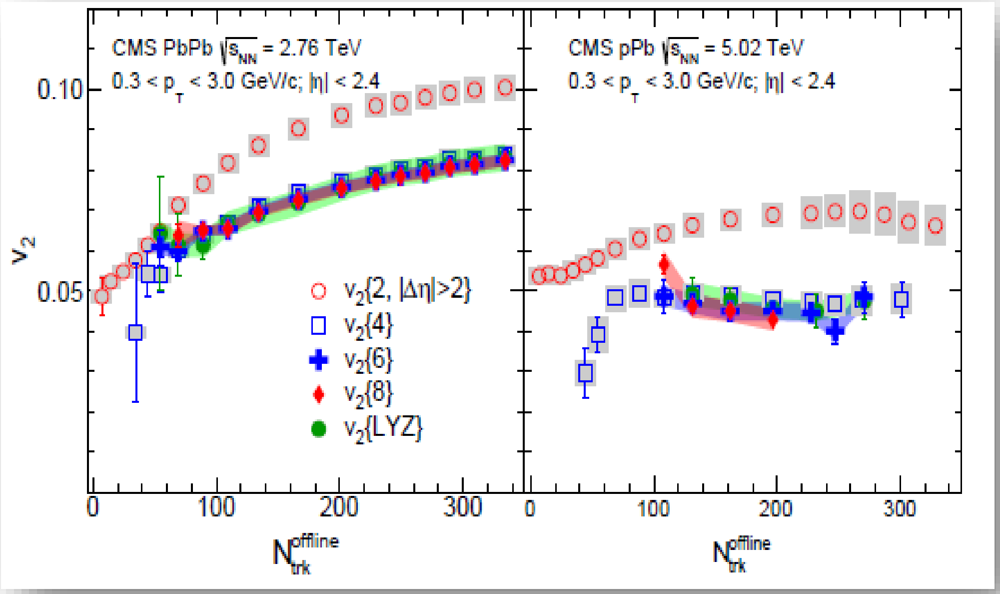
Other collision systems:

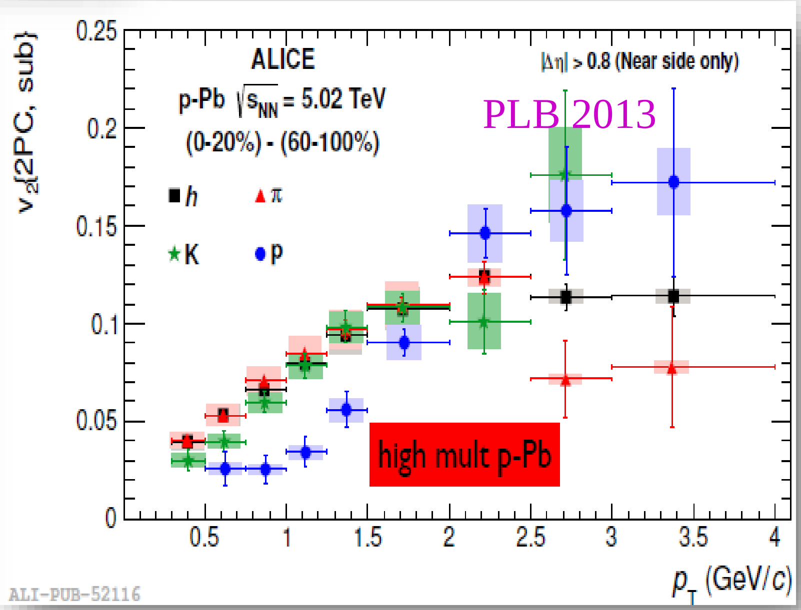
OBSERVABLES	A–A	p–A (high mult.)	pp (high mult.)	pp (low mult.)	UPC	ep	e^+e^- (high mult.)	e^+e^-
Near-side ridge yield	✓ [1,2]	✓ [30,32,33]	✓ [30,31]	✓ [34]	–	✗ [74,75]	✓ [77]	✗ [76]
Anisotropic flow	✓ [3,4]	✓ [36,37,38,39]	✓ [35,37]	✓ [30]	✓ [72,73]	✗ [74,75]	✓ [77]	–
Multiparticle cumulants	✓ [5]	✓ [40-45]	✓ [40,41,45]	–	–	–	–	–
Mass ordering	✓ [6]	✓ [47-49]	✓ [46,48]	–	–	–	–	–

Correlations & Flow in small systems





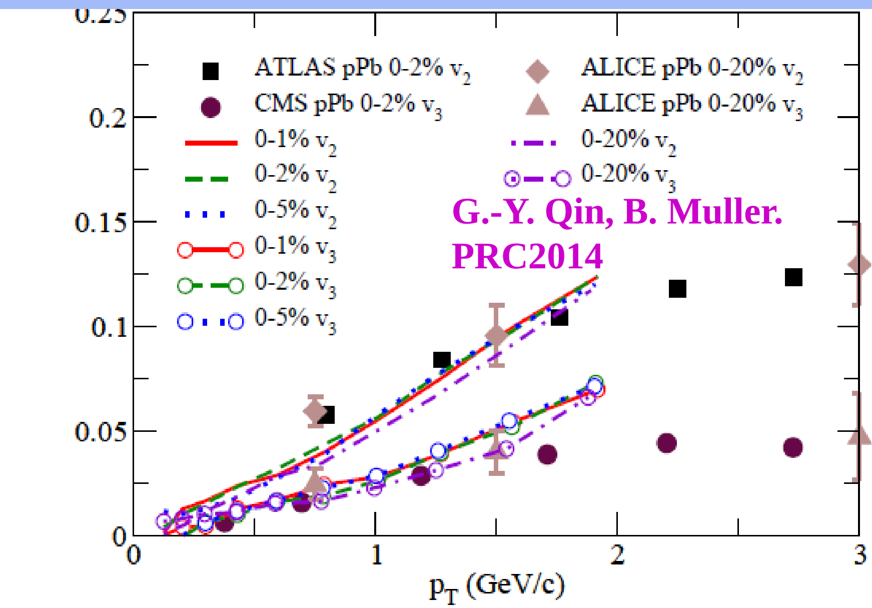


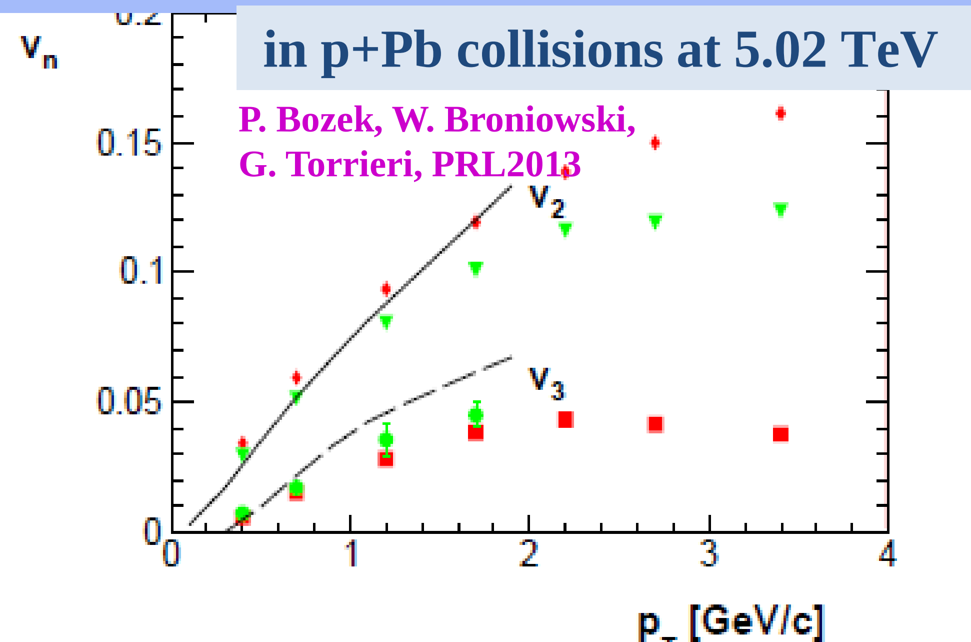


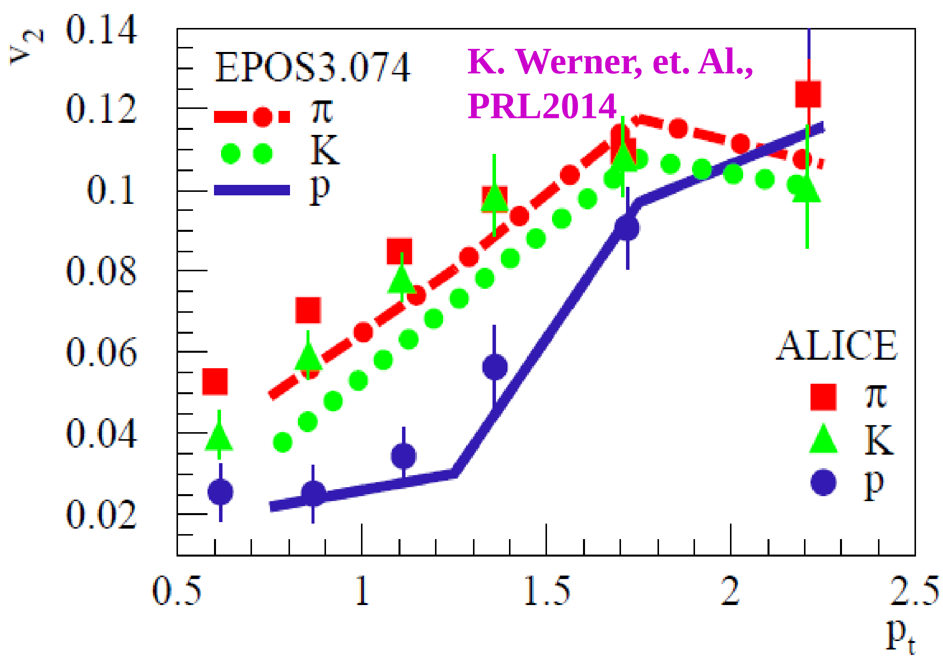
-Many flow-like signals have been observed in high multiplicity p-Pb collisions

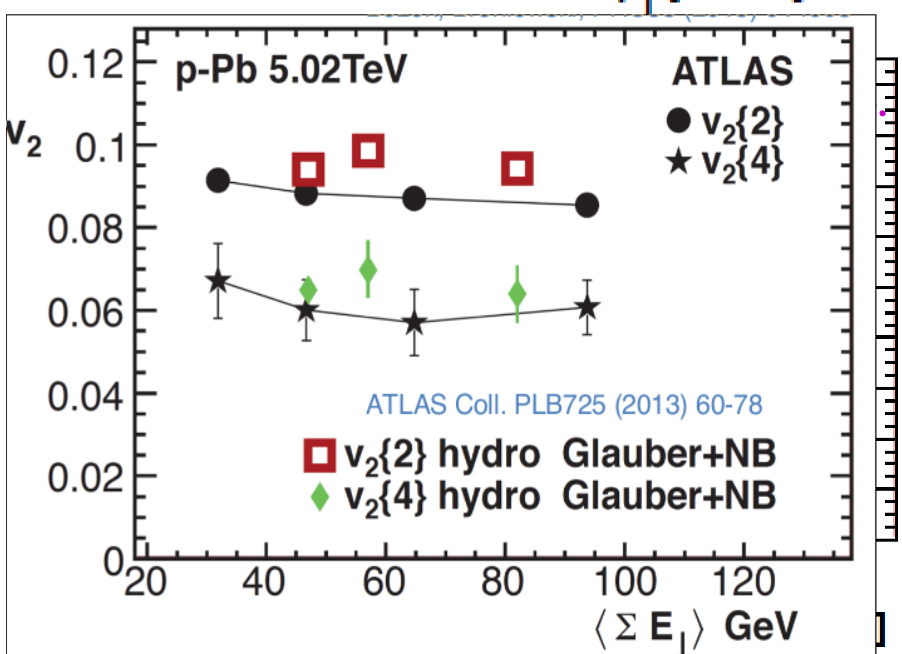
Hydrodynamic calculations for small systems

in p+Pb collisions at 5.02 TeV

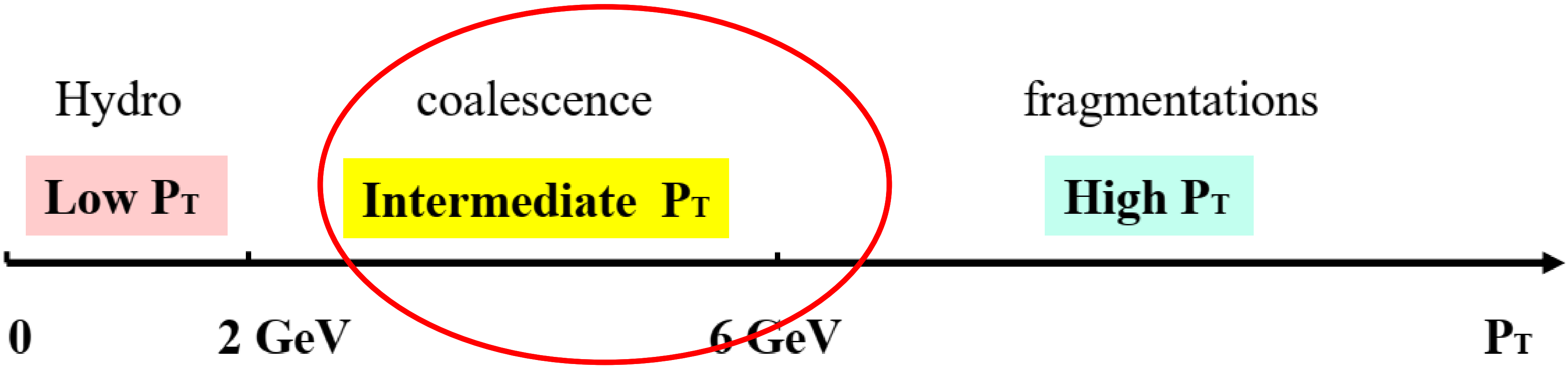


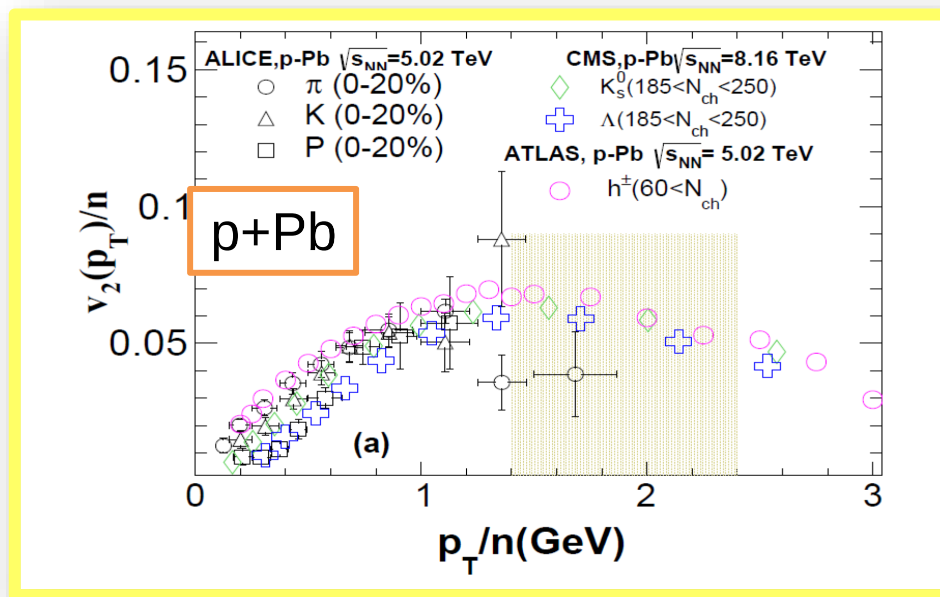






Partonic flow and QGP signals in small systems with VQS





Hydro-Coal-Frag Hybrid Model

Zhao, Ko, Liu, Qin & Song.
Phys. Rev. Lett. 125 7 072301(2020)in

Thermal hadrons (VISH2+1):

-generated by hydro.
with Cooper-Frye.
-Meson: $P_T < 2P_1$; baryon: $P_T < 3P_1$.

Coalescence hadrons (Coal Model):

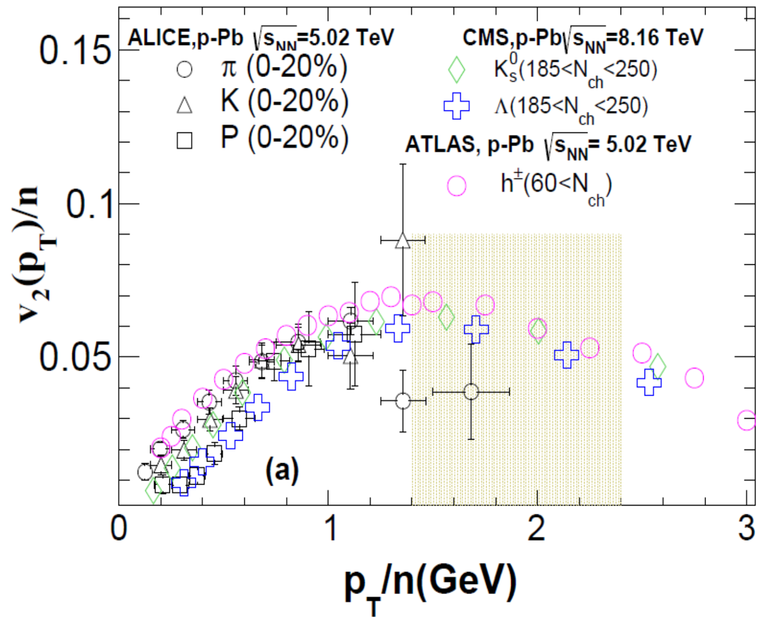
-generated by coalescences model including thermal-thermal, thermal-hard & hard-hard parton coalescence.

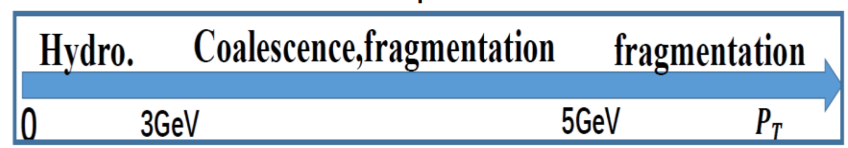
Fragmentation hadrons (LBT):

-*Hard partons* generated by PYTHIA8, then suffered energy loss by LBT

UrQMD afterburner:

-All hadrons are feed into UrQMD for hadronic evolution, scatterings and decays.





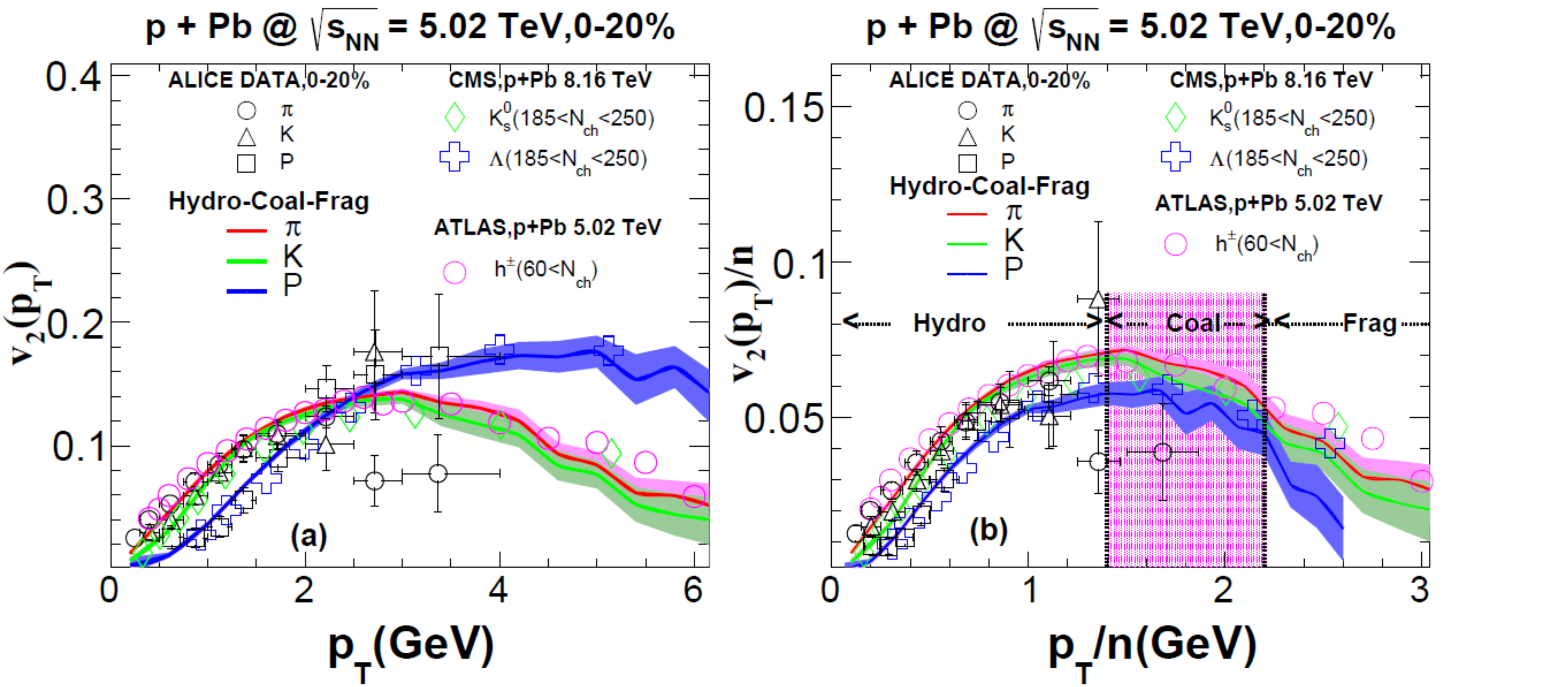
Main Parameters:

-*Thermal hadrons* from hydro with $P_T < P_1$.

-*Hard partons* from LBT with $P_T > P_2$.

Fixed by the p_T spectra
P_{T1} = 1.6GeV and P_{T2} = 2.6GeV

VCQ scaling of v_2 & partonic degree of freedom



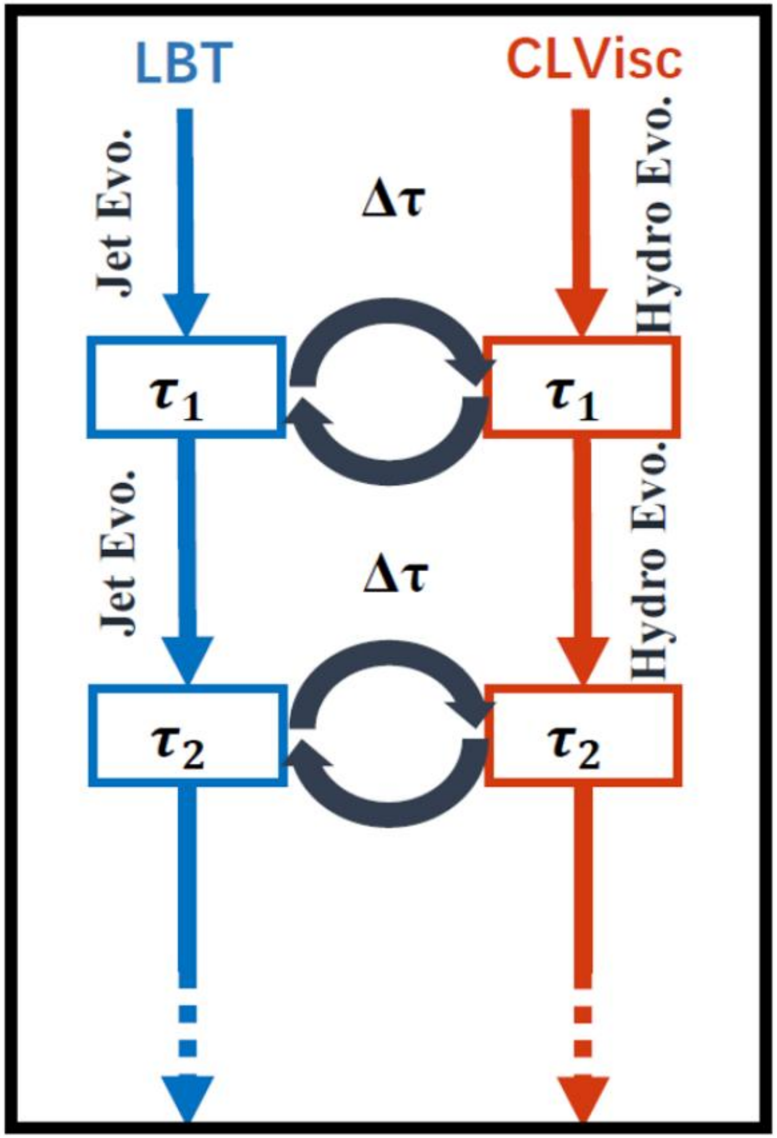
-Hydro-Coal-Frag model gives a nice description of $v_2(p_T)$ of pion, kaon and proton from 0 to 6 GeV.

-At intermediate p_T, Hydro-Coal-Frag model obtains an approximate NCQ scaling as shown by the data.

Zhao, Ko, Liu, Qin & Song. Phys. Rev. Lett. 125 7 072301(2020)

CoLBT-Hydro Model + Coal Model for Pb+Pb collisions

CoLBT-Hydro Model



Chen, Cao, Luo, Pang & Wang.
Phys. Lett. B 810, 135783 (2020).

Linear Boltzmann Transport Model
3+1D hydrodynamic model

LBT ⟷ CLVis

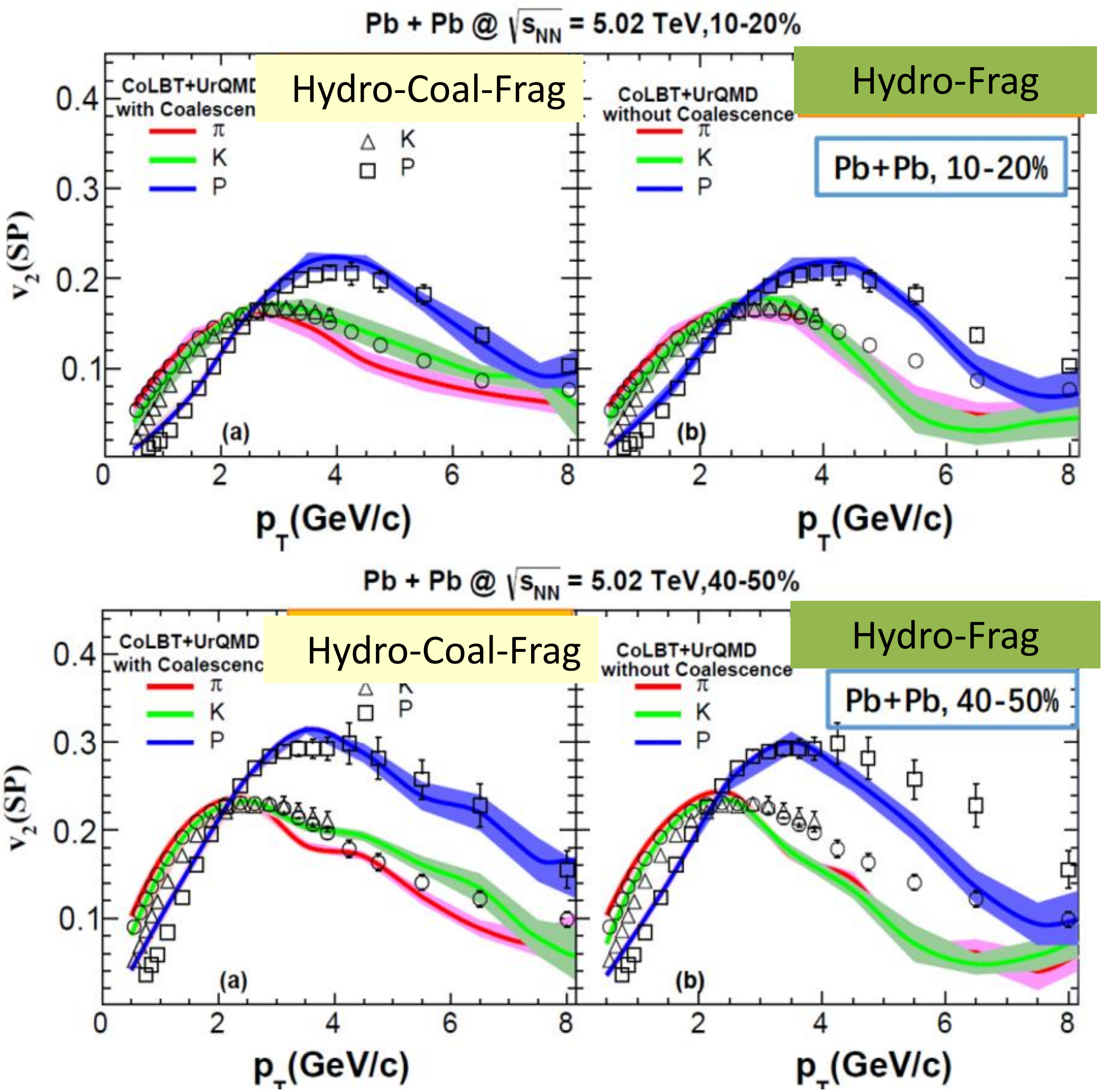
-Evolve the energetic partons and the bulk medium concurrently.

-Hadronization by Hydro-Coal-Frag followed by the UrQMD.

- thermal - thermal parton coal
- thermal - hard parton coalescence
- hard - hard parton coalescence

Zhao, Chen, Luo, Ke & Wang.
Phys. Rev. Lett. 128 2 022302(2022).

Quark coalescence for Pb+Pb collisions

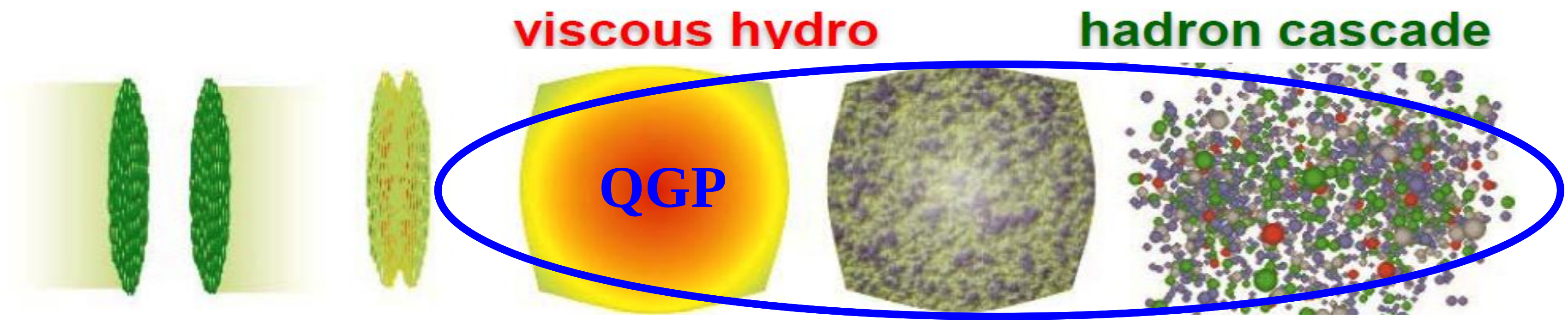


-CoLBT-hydro with coalescence works well for PID flow of Pb+Pb collisions from 0 to 8 GeV.

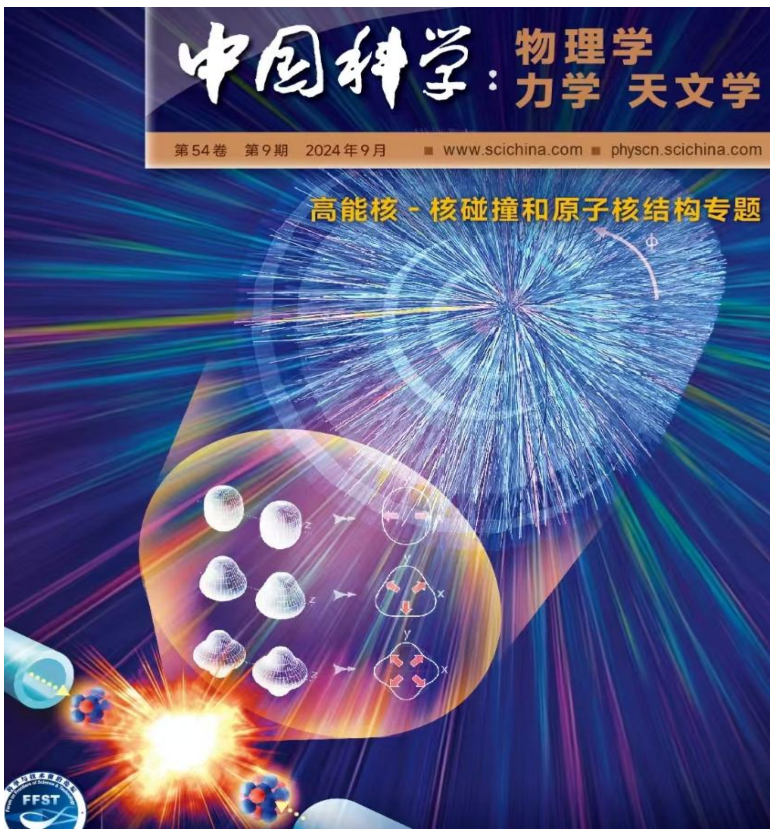
Quark coalescence is important at intermediate P_T

thermal-hard parton Coalescence & Fragmentation Breaks up the NCQ scaling of v2 in Pb+Pb collisions

Zhao, Chen, Luo, Ke & Wang. Phys. Rev. Lett. 128 2 022302(2022).



Theory: Hydrodynamics & hybrid approach are powerful tool to simulate the QGP fireball evolution and study its properties

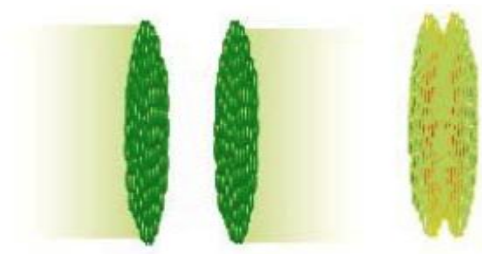


-We are ready to focus on the initial state of the QGP

nuclear structure of colliding nuclei

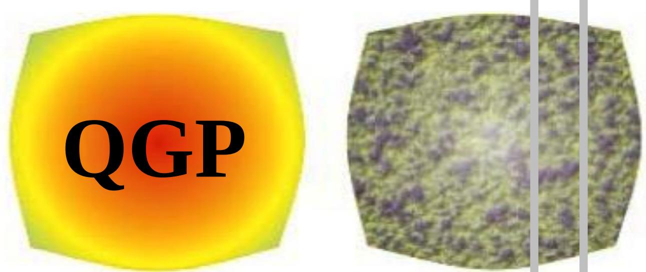
Exploring Nuclear Physics across Energy Scales

-- Personal view from heavy ion collisions



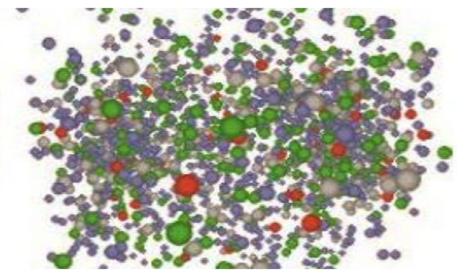
Initial conditions:

Intersection study with nuclear structure



QGP evolution:

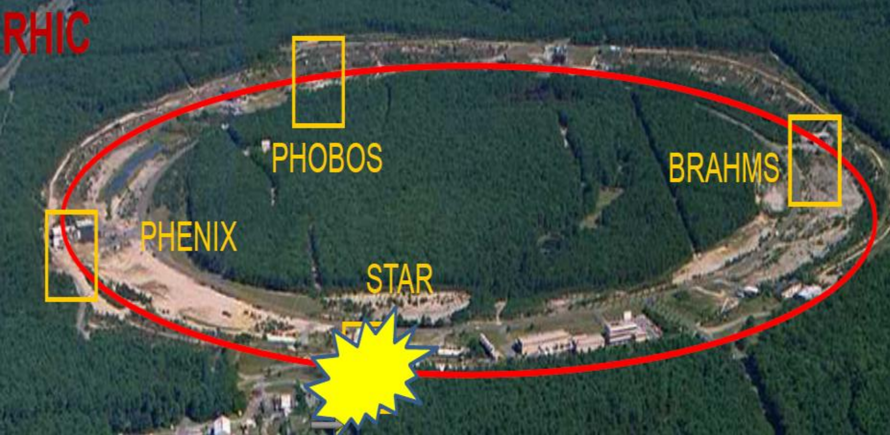
main goal: QGP & QCD phase diagram

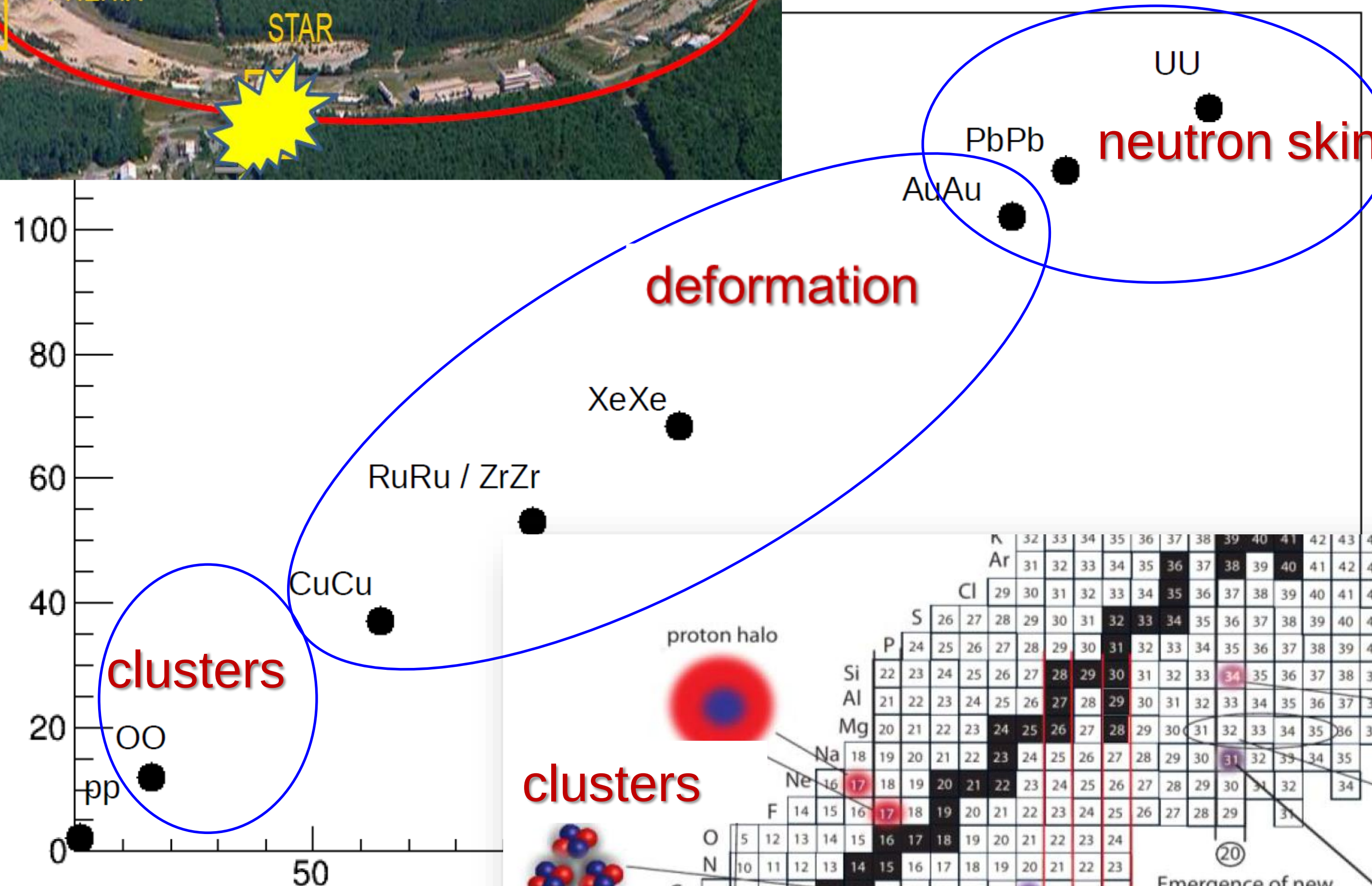


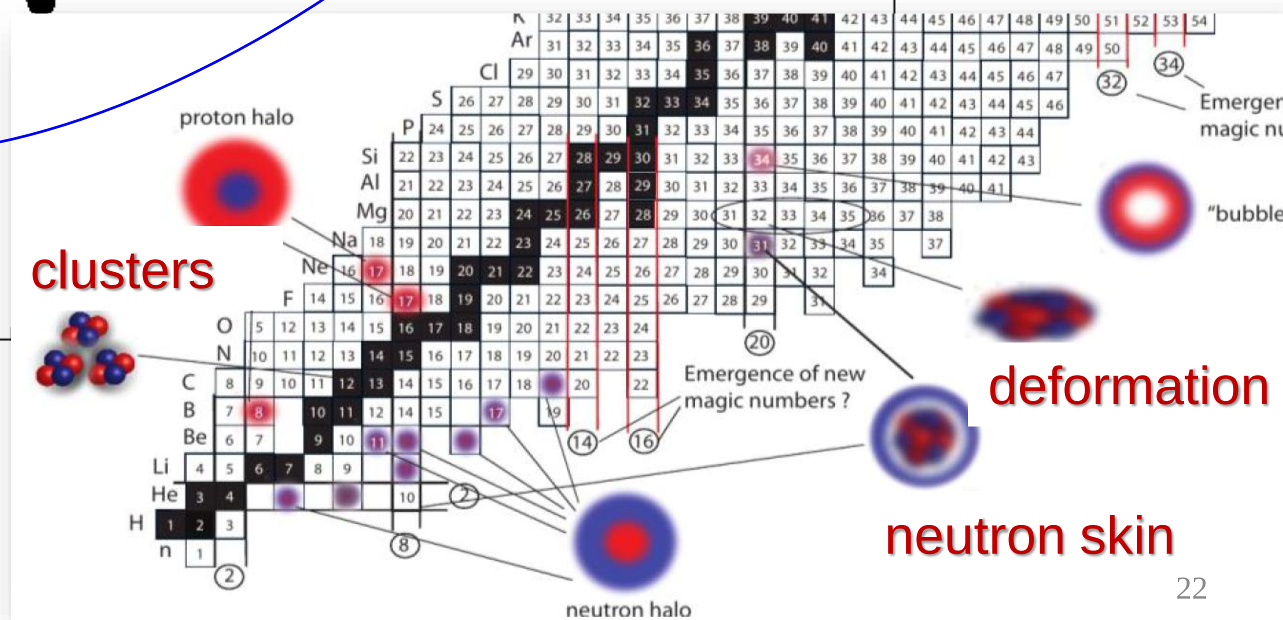
Final Hadrons:

intersection study with hadron physics

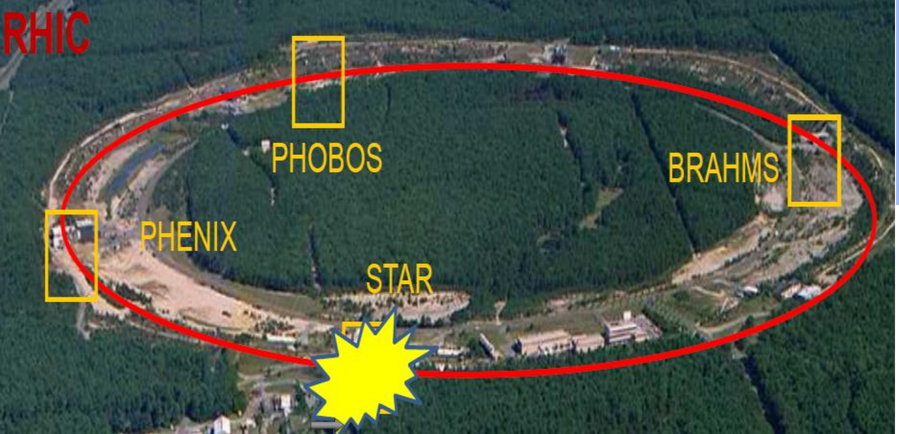
Rich collision systems at RHIC & the LHC







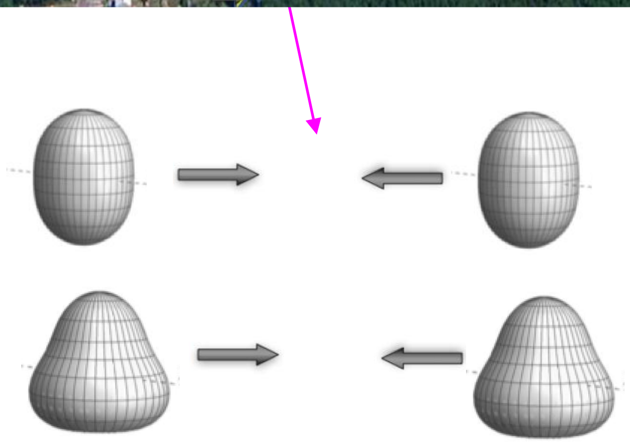
Probe nuclear structure with relativistic heavy ion collisions



- Relativistic heavy collisions
  start from nuclei

-Collision time < 10^{-24} s
  directly probe the ground state of nuclei

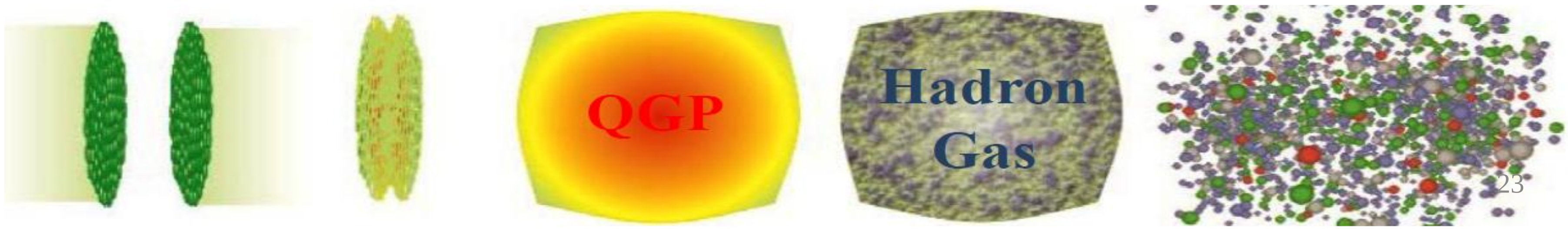
-Well calibrated calculations for QGP evolution; to focus on the initial state



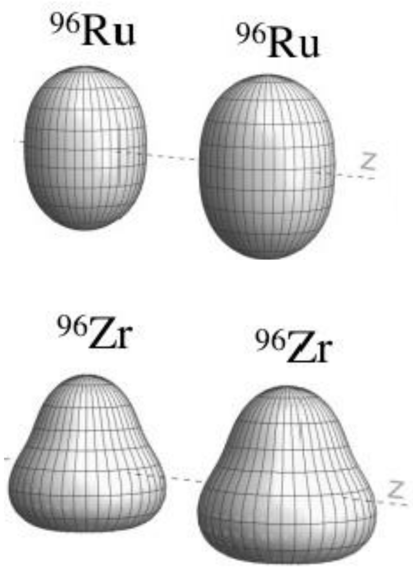
initial state with deformation

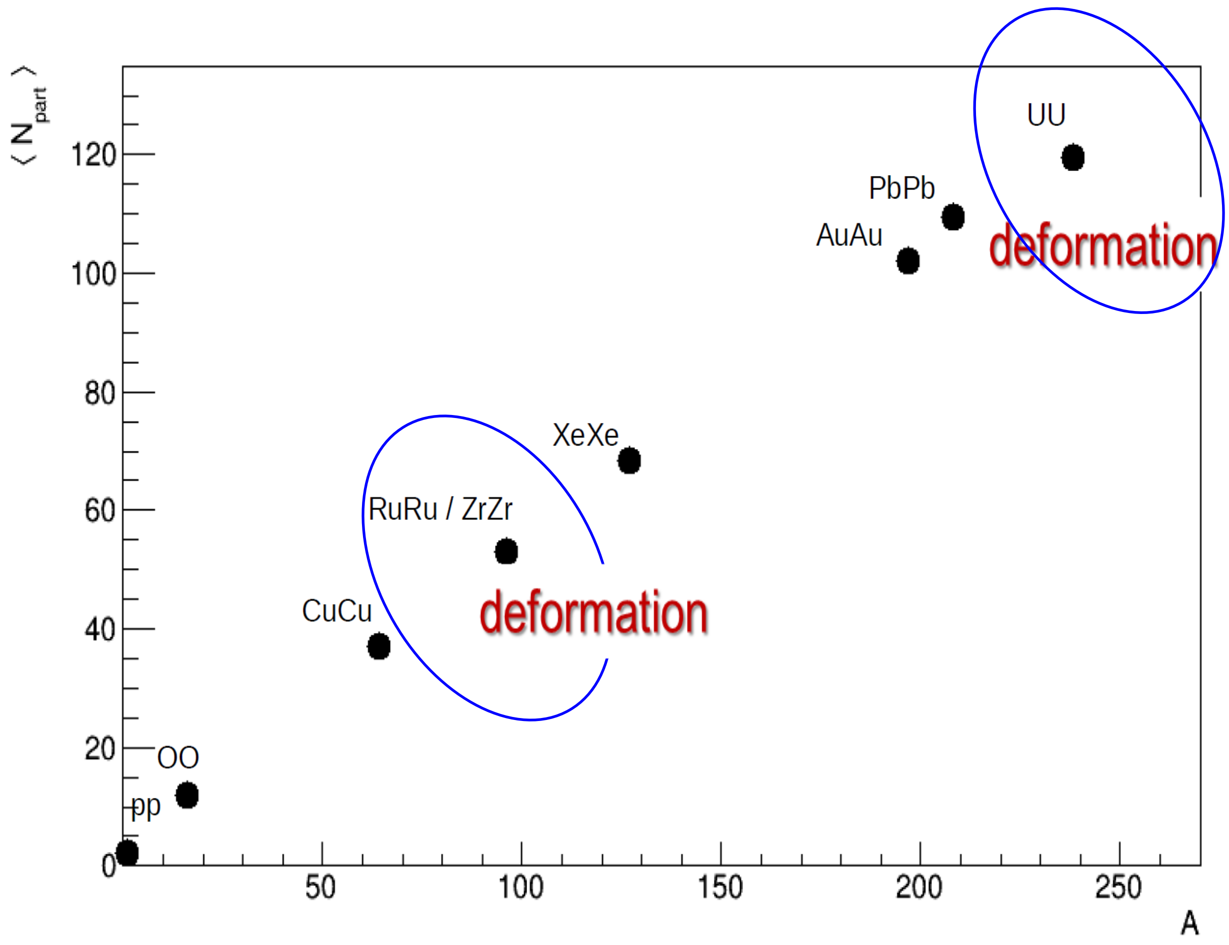
Well calibrated calculations

Initial conditions **viscous hydro** **hadron cascade**

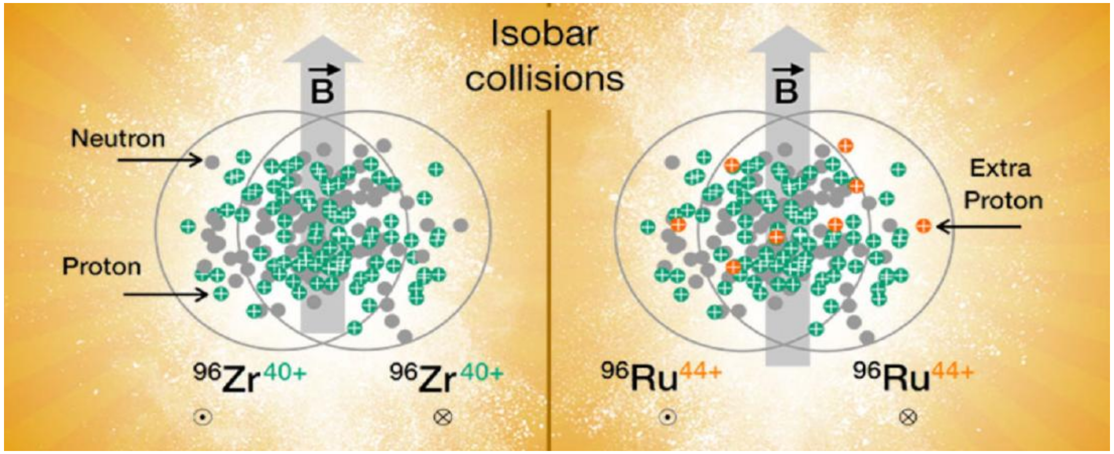


Study nuclear deformation with heavy ion collisions





^{96}Ru+^{96}Ru and ^{96}Zr+^{96}Zr Collisions @ RHIC isobar run



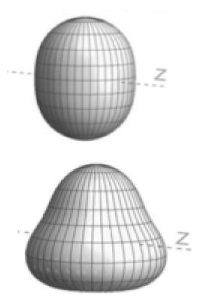
- To search the Chiral Magnetic Effect (CME)

- Obviously different early magnetic field for Ru+Ru and Zr+Zr collisions

Deformation of ^{96}Ru and ^{96}Zr

Conversion from B(En) to β_n via: $\beta_2 = \frac{4\pi}{3ZR_0^2}\sqrt{\frac{B(E2)\uparrow}{e^2}}$, $\beta_3 = \frac{4\pi}{3ZR_0^3}\sqrt{\frac{B(E3)\uparrow}{e^2}}$

	β_2	$E_{2_1^+}$ (MeV)	β_3	$E_{3_1^-}$ (MeV)
^{96}Ru	0.154	0.83	-	3.08
^{96}Zr	0.062	1.75	0.202,0.235,0.27	1.90

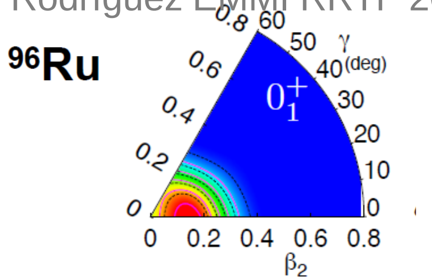


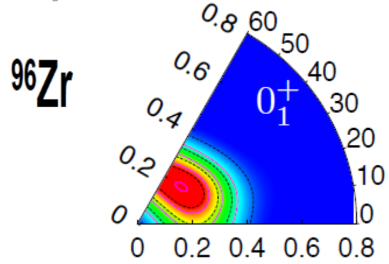
ADNDT107,1 (2016) ADNDT80,35(2002)

Deformation of ^{96}Ru & ^{96}Zr (nuclear structure)

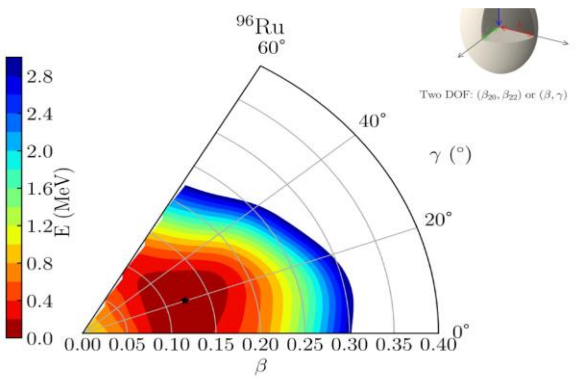
Gogny energy density functional |(Tiaxial)

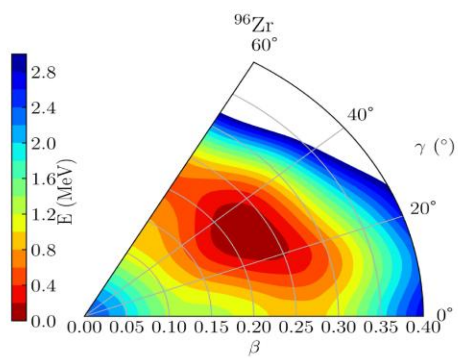
T R. Rodríguez EMMI RRTF 2022



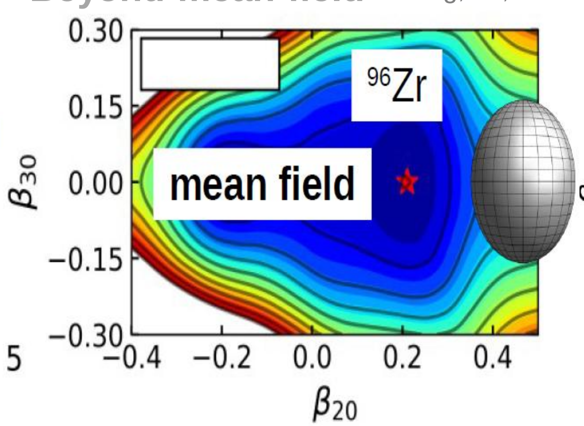


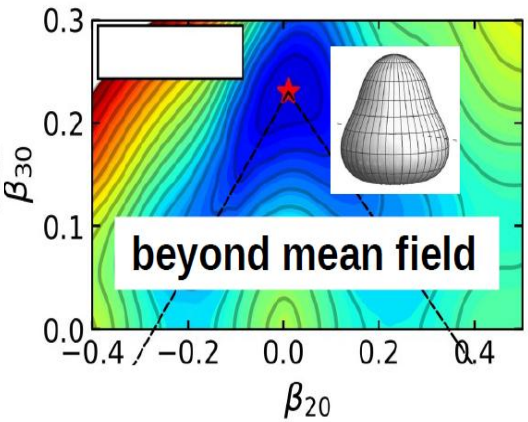
Skyrme EDF W Ryssens EMMI RRTF 2022

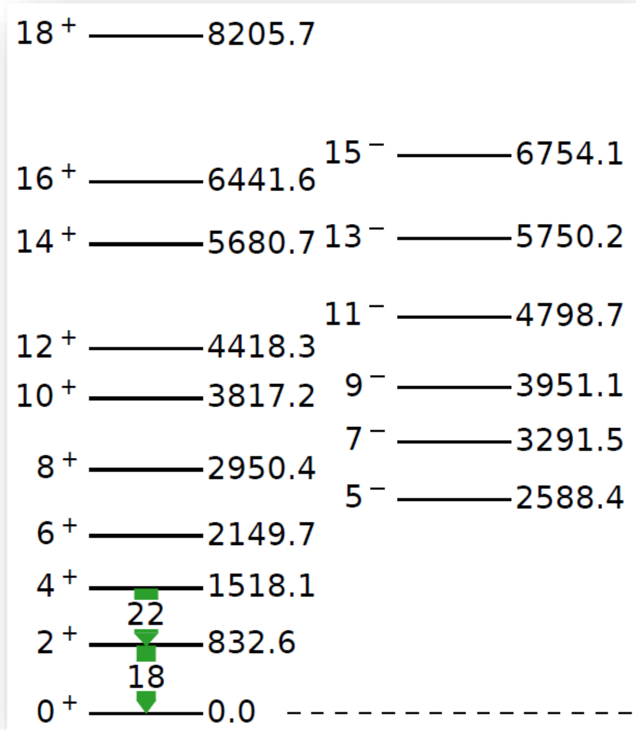




Beyond-mean-field Rong, Lu, arXiv:2201.02114



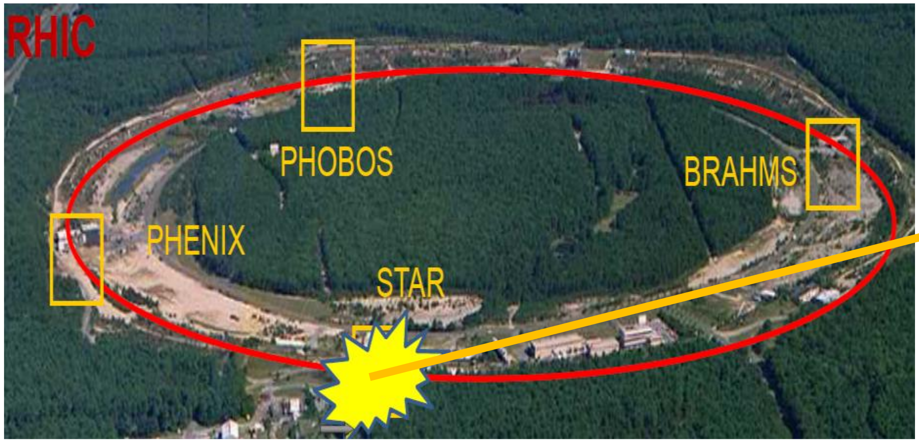


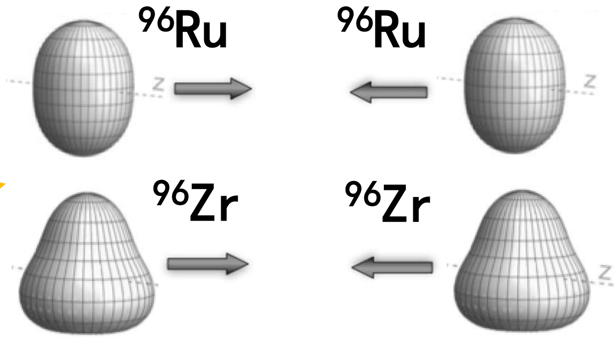


Nuclear structure physics obtain the deformation information from the spectrum with certain model calculations (not directly image the deformation in position space)

Probe the deformation (mass distributions) of ^{96}Ru & ^{96}Zr

Relativistic heavy ion collisions





initial conditions: (deformation / mass distributions)

Initial conditions (TRENTO)

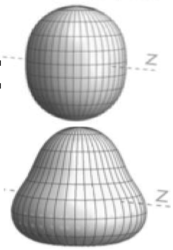
- Sample nucleon position in deformed nuclei with:

$$\rho(r,\theta,\phi) = \frac{\rho_0}{1+e^{(r-R(\theta,\phi))/a_0}}$$

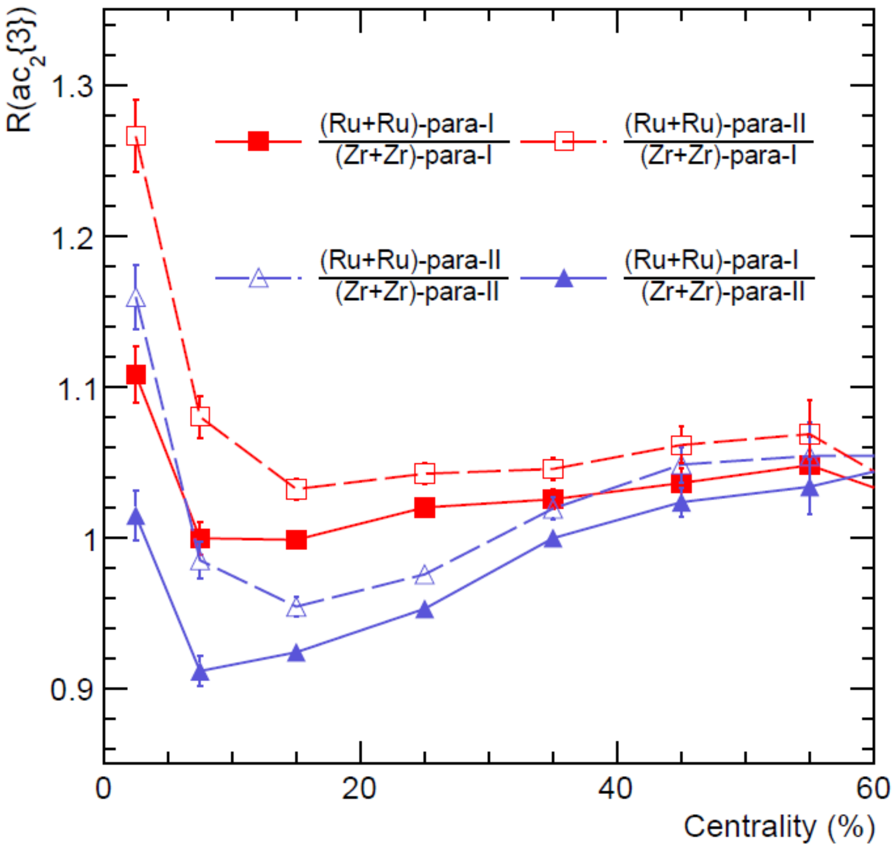
$$R(\theta,\phi) = R_0\Bigg(1+\beta_2[\cos\gamma Y_{2,0}+\sin\gamma Y_{2,2}] + \beta_3\sum_{m=-3}^{3}\alpha_{3,m}Y_{3,m}+\beta_4\sum_{m=-4}^{4}\alpha_{4,m}Y_{4,m}\Bigg)$$

Quadrupole:

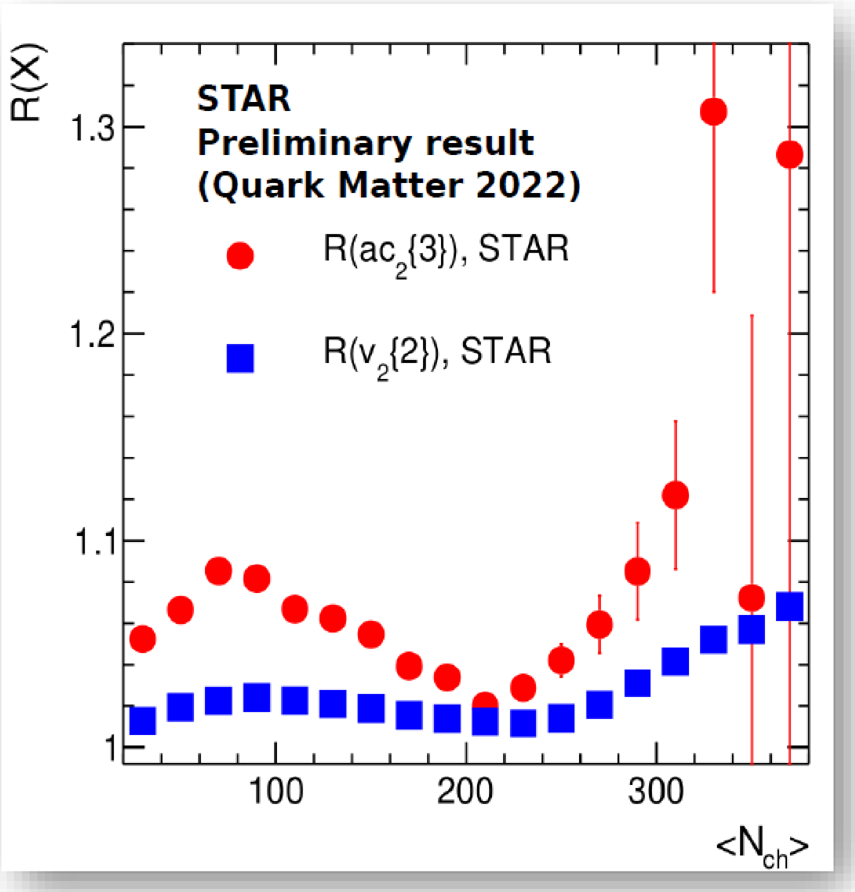
Octupole:



$ac_2\{3\}$ for Ru+Ru and Zr+Zr collisions



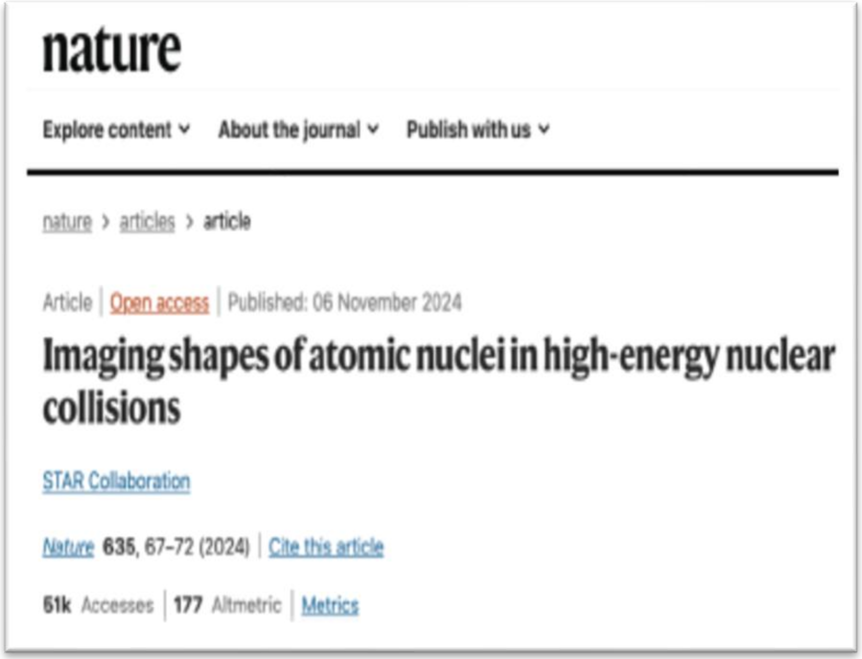
$$ac_2\{3\} = \langle v_2^2 v_4 \cos 4(\Phi_2 - \Phi_4)\rangle,$$



$ac_2\{3\}$ is sensitive to quadrupole and octupole deformations

S. Zhao, H. Xu, Y. Liu, H. Song. PLB2023, arXiv: 2204.02387

Imaging the deformation ^{238}U at RHIC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Article | Open access | Published: 06 November 2024

Imaging shapes of atomic nuclei in high-energy nuclear collisions

STAR Collaboration

Nature **635**, 67–72 (2024) | Cite this article

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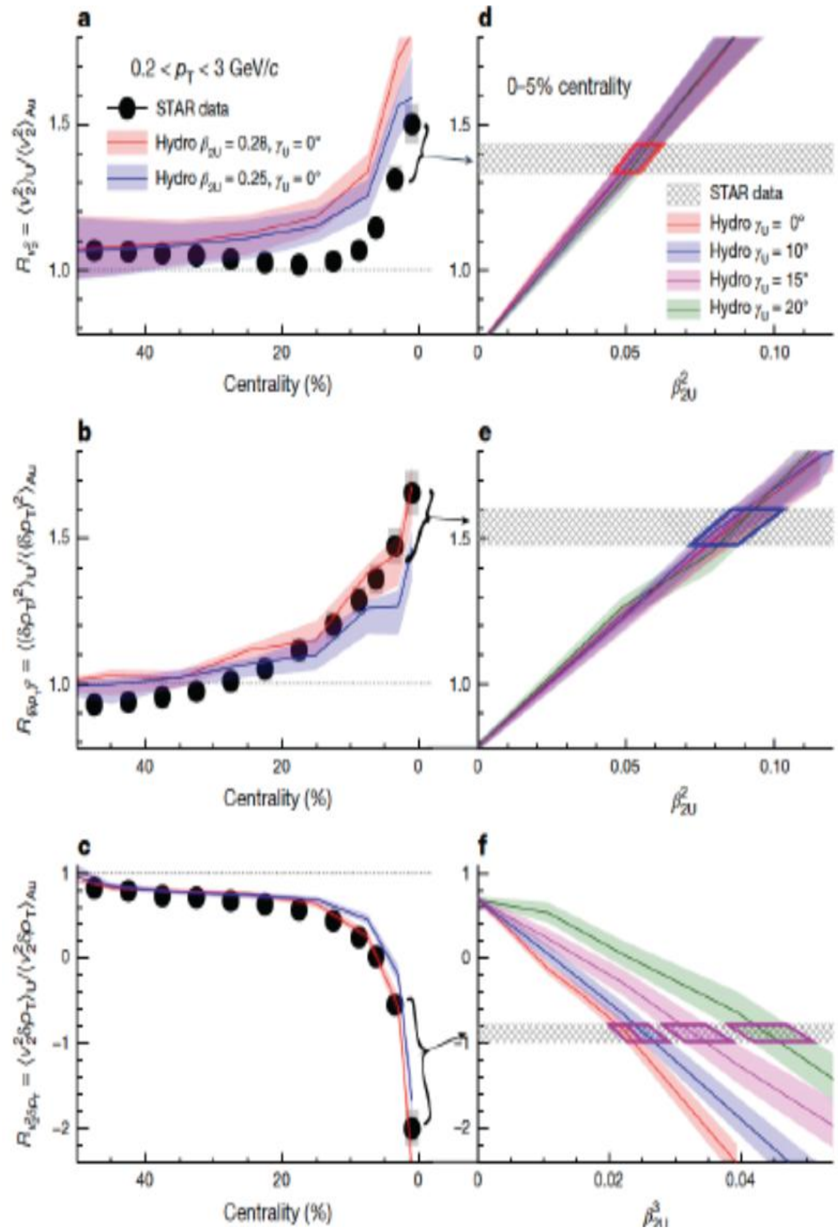
$$\langle v_2^2 \rangle = a_1 + b_1 \beta_2^2$$

$$\left\langle (\delta p_\mathrm{T})^2 \right\rangle = a_2 + b_2 \beta_2^2$$

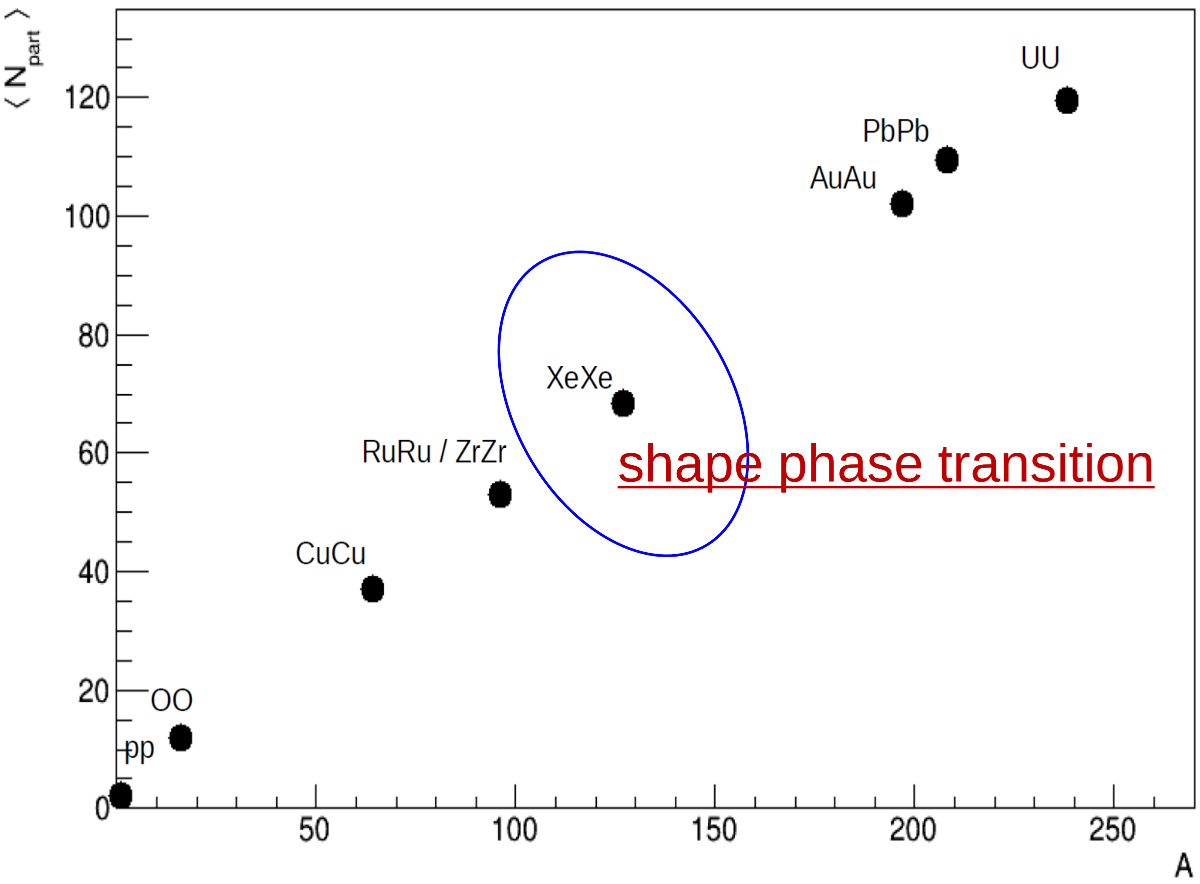
$$\langle v_2^2 \delta p_\mathrm{T} \rangle = a_3 - b_3 \beta_2^3 \cos(3\gamma)$$

$$\beta_{2\mathrm{U}} = 0.297 \pm 0.015$$

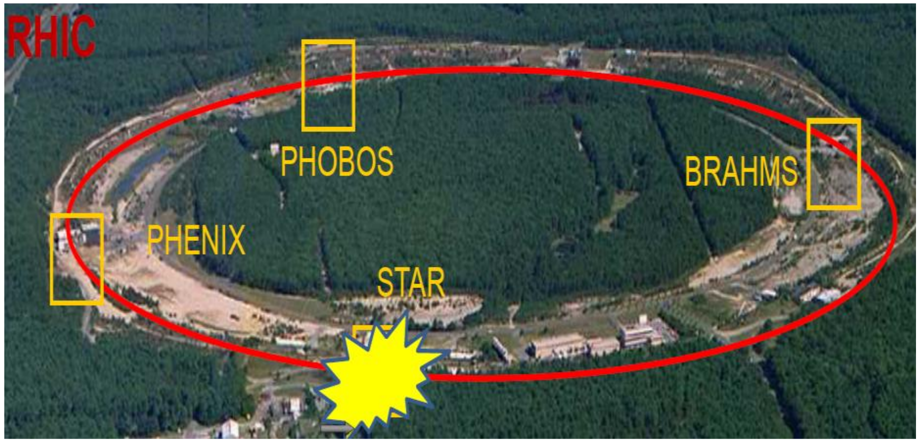
$$\gamma_U = 8.5^\circ \pm 4.8^\circ$$



Probe the shape phase transition with Xe +Xe collisions

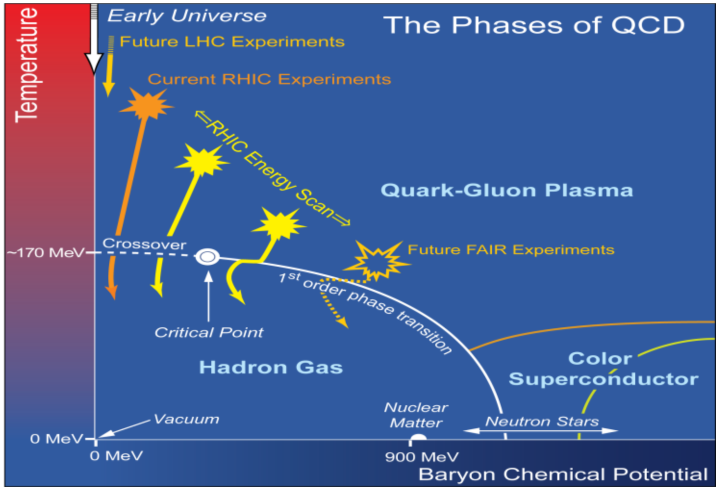


The Phase Transition



Relativistic heavy ion collisions

-mainly aim to explore QCD Phase Transition

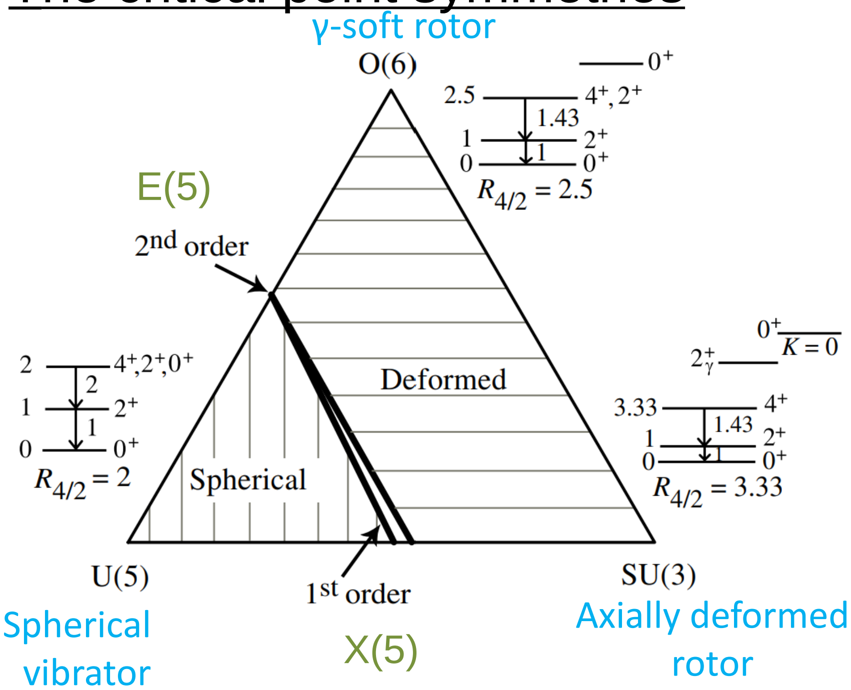


^{129}Xe+^{129} Xe collision

-explore the second-order shape phase transition occurring in the vicinity of $^{128\text{-}130}$Xe

S. Zhao, H. Xu, Y. Zhou, Y. Liu, H. Song, arXiv: 2403.07441 [nucl-th]

The critical point symmetries



Shape phase transition for Xe isotopes

The shape phase transition:

-rapid structural change along certain isotope or isotone chains
-the dynamic interplay between the spherical-driving pairing interaction and the deformation-driving proton-neutron interaction

The shape phase transition for the Xe isotopes:

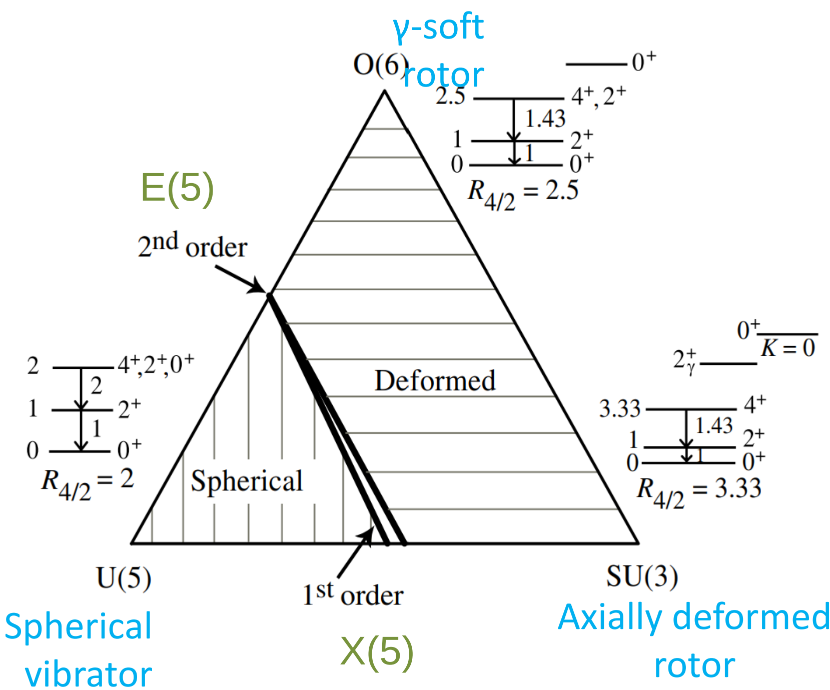
-Within the the framework of the interacting boson model (IBM), the Xe isotopes undergo a shape phase transition from a *γ*-soft rotor to a spherical vibrator

R. F. Casten, Nucl. Phys. A 439, 289 (1985). G. Puddu, O. Scholten, and T. Otsuka, Nucl. Phys. A 348, 109 (1980). R. F. Casten and P. Von Brentano, Phys. Lett. B 152, 22 (1985).

-Exp data and model calculations:
$^{128-130}$Xe: *E*(5) symmetry, associated with a 2nd order shape phase transition

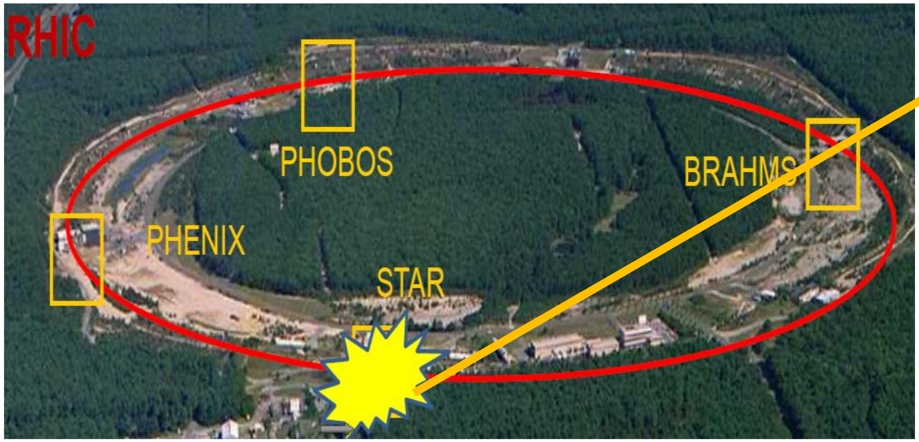
F. Iachello, Phys. Rev. Lett. 87, 052502 (2001);Phys. Rev. Lett. 85, 3580 (2000); R. M. Clark, et. al. Phys. Rev. C 69, 064322 (2004); R. Rodriguez-Guzman, et. al. Phys. Rev. C 76, 064303 (2007); L.M.Robledo, et. al. Phys. Rev.C 78 (2008) 034314

The critical point symmetries

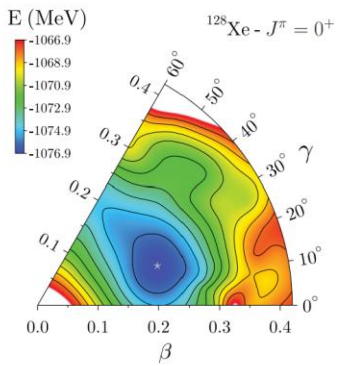


Probe the γ-soft deformation of ^{129}Xe

Relativistic heavy ion collisions



initial conditions:
(deformation / mass distributions)



Rigid triaxial deformation (γ=30º)

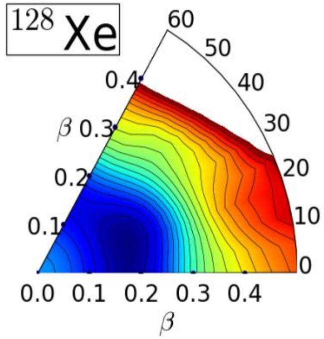
Bally et. al. Eur.Phys.J. A 58 (2022) 9, 187,

Initial conditions (TRENTO)

- Sample nucleon position in deformed nuclei with:

$$\rho(r,\theta,\phi) = \frac{\rho_0}{1 + e^{(r - R(\theta,\phi))/a_0}}$$

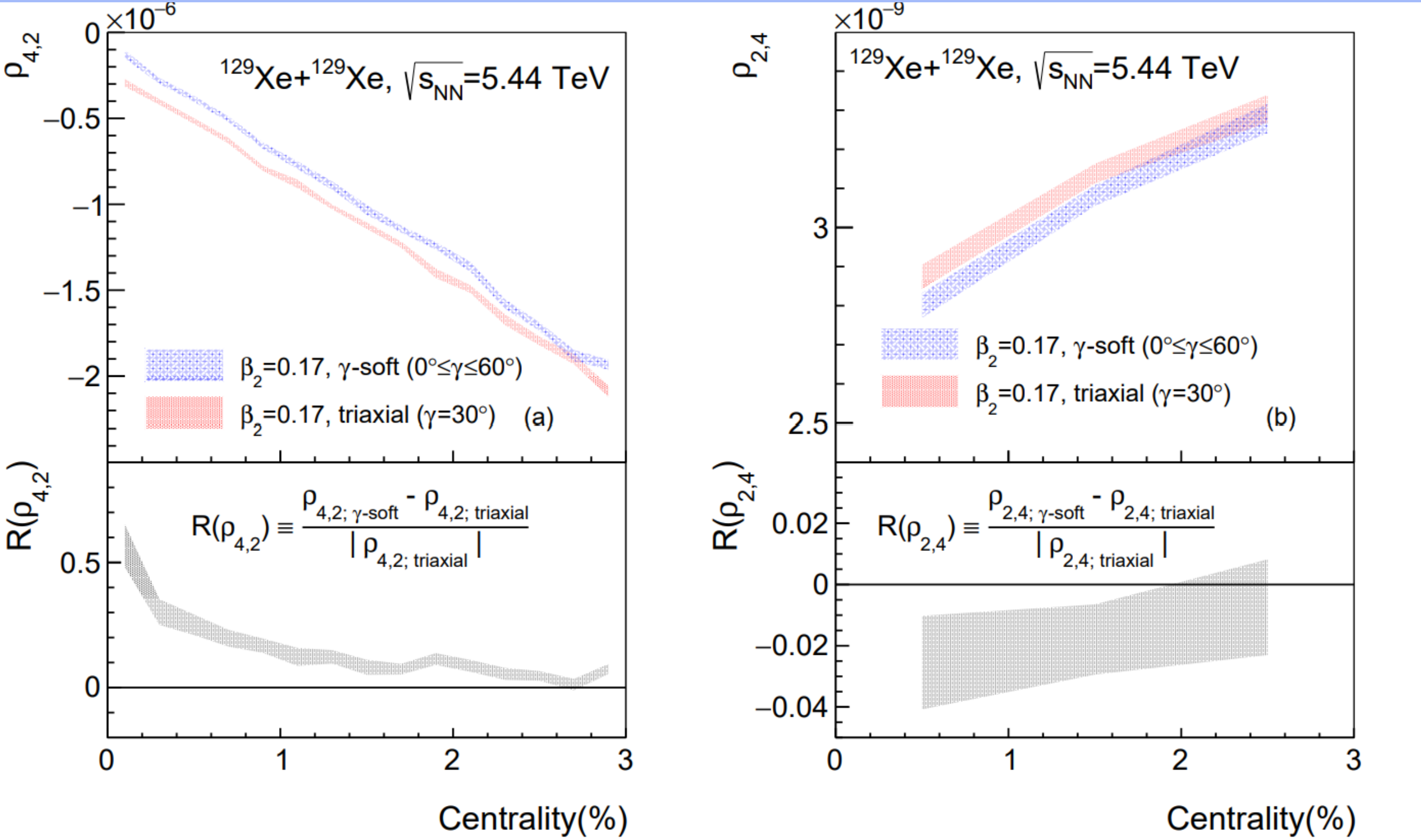
$$R(\theta,\phi) = R_0(1 + \beta_2[\cos\gamma Y_{2,0}(\theta,\phi) + \sin\gamma Y_{2,2}(\theta,\phi)]).$$



γ-soft (flat distribution in 0≤γ≤60º)

Z. P. Li, et. al. Phys. Rev. C 81, 034316 (2010),

6-particle correlations-Theoretical Predictions

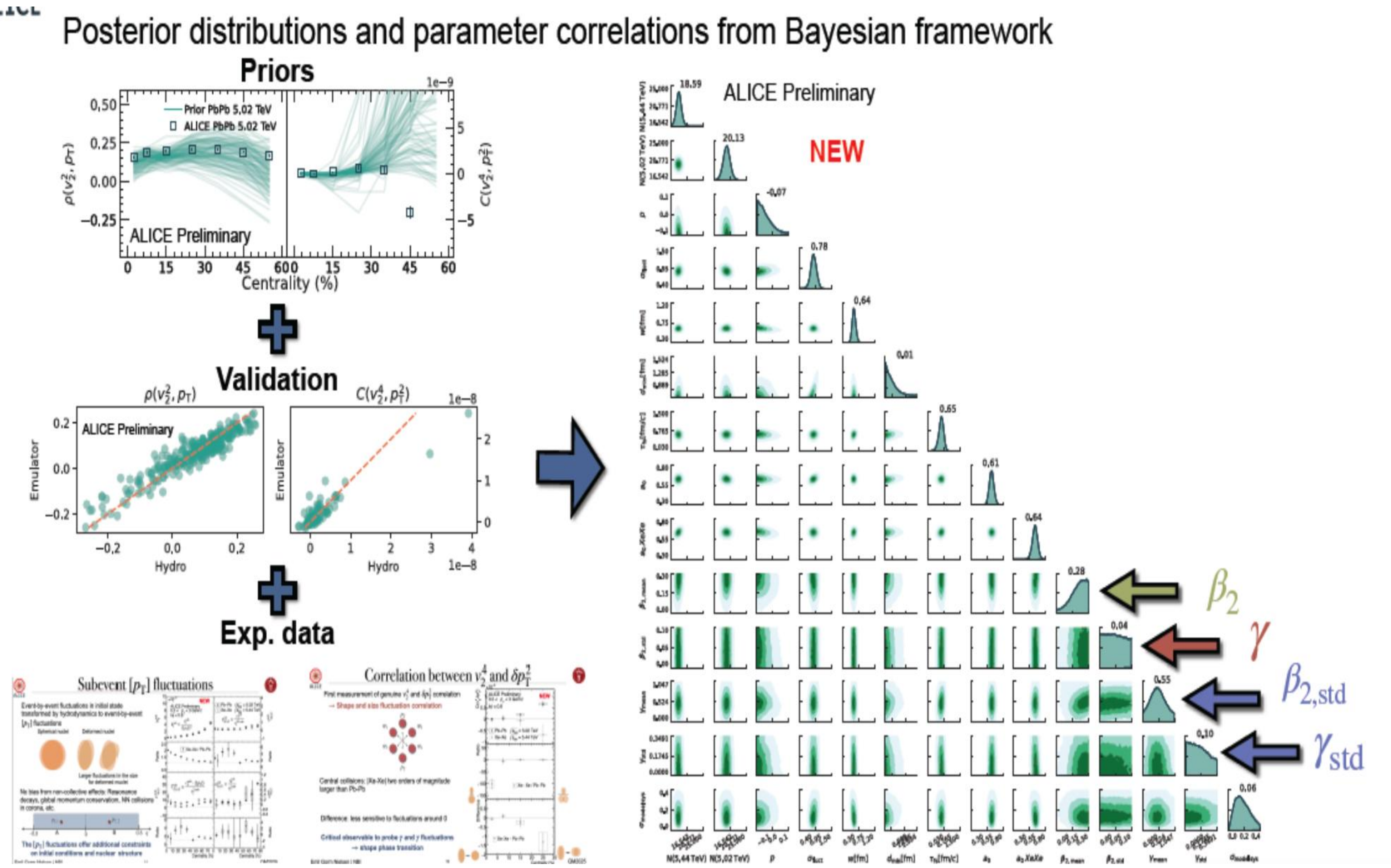


$$\rho_{4,2} \equiv \left(\frac{\langle \varepsilon_2^4 \delta d_\perp^2 \rangle}{\langle \varepsilon_2^4 \rangle \langle d_\perp \rangle^2} \right)_c \qquad \rho_{2,4} \equiv \left(\frac{\langle \varepsilon_2^2 \delta d_\perp^4 \rangle}{\langle \varepsilon_2^2 \rangle \langle d_\perp \rangle^4} \right)_c$$

The γ-soft deformation of ^{129}Xe lead to a clear enhancement of 6-particle correlations $\rho_{4,2}$ in ultra-central Xe+Xe collisions

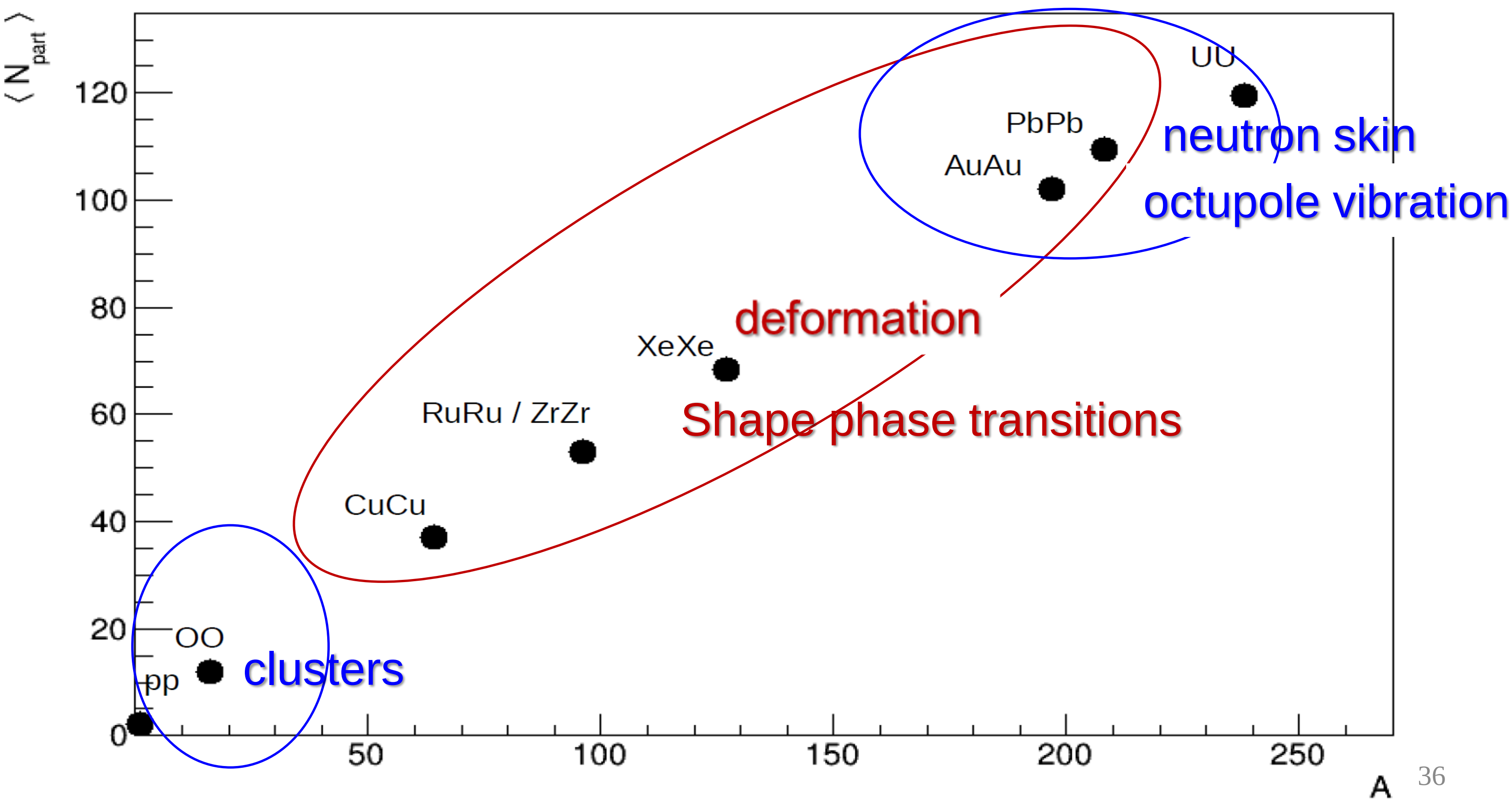
S. Zhao, H. Xu, Y. Zhou, Y. Liu, H. Song Phys. Rev. Lett. 133, 192301(2024)

ALCE Measurements & Bayesian Analysis

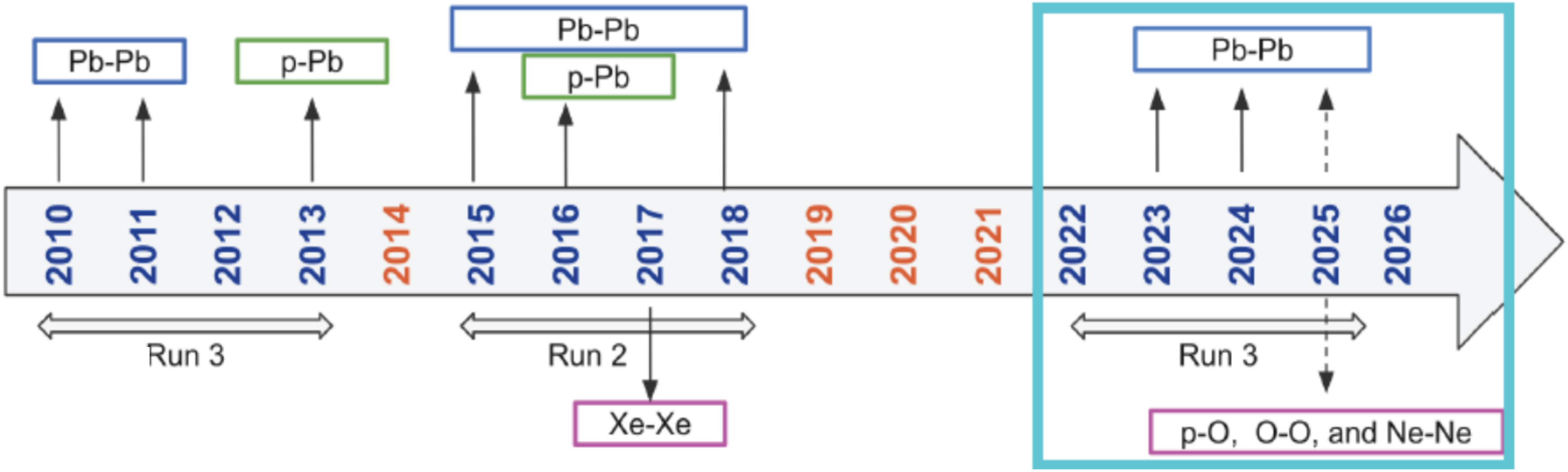


Y. Zhou, E.G. Nielsen QM 2025 talk

Probe nuclear structure with heavy ion collisions at RHIC & LHC



Physics opportunities from light ion collisions at the LHC



Also refer to the exp. talk of N. Triantafyllou (LHCP 2025)

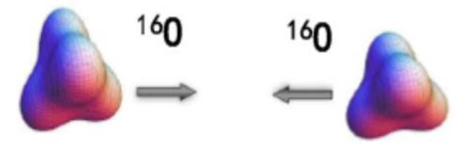
Probe cluster structure with light ion collisions

Probe the structure of ^{16}O with O+O collisions

Li, Zhang &Ma, Phys. Rev. C **102**,054907 (2020)

Wang, Zhao, Cao, Xu and Song. *Phys.Rev.C* 109 5, L051904 (2024)

… …   … …

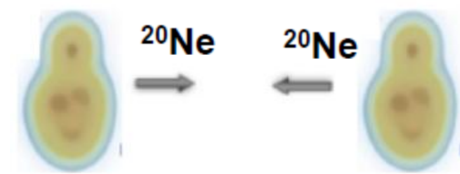


Probe the Bowling pin structure of ^{20}Ne with Ne+Ne collisions

Giaclaone,Bally, Nijs, Shen,et al, arXiv: 2402.05995

Li, Zhou and Ma,arXiv:2504.04688 [nucl-th].

… …   … …

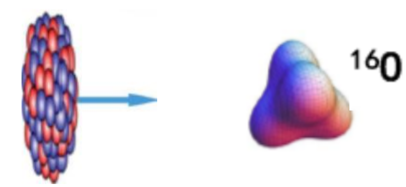


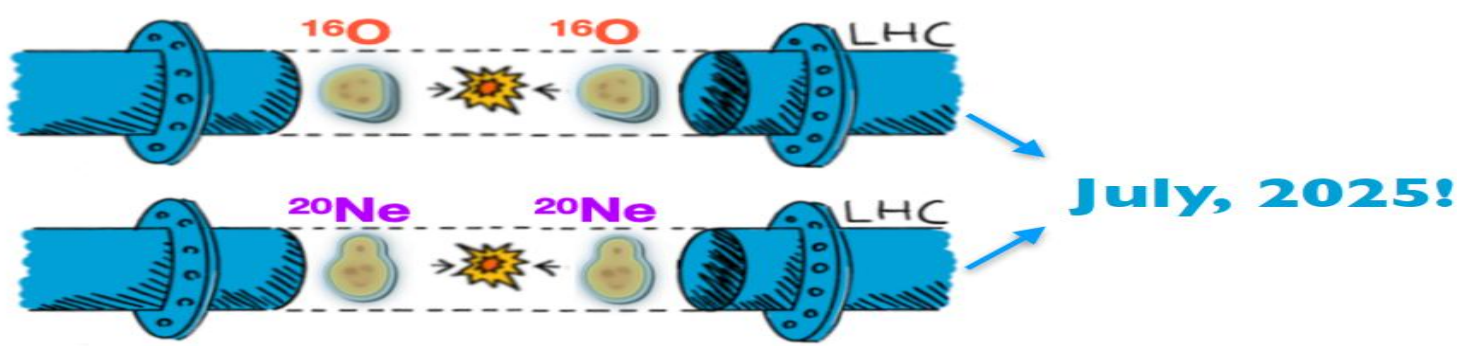
Probe the cluster structure Pb+Ne/Pb+O run at LHCb (SMOG)

Giaclaone,Zhao, et al, Phys. Rev. Lett.134 082301 (2025)

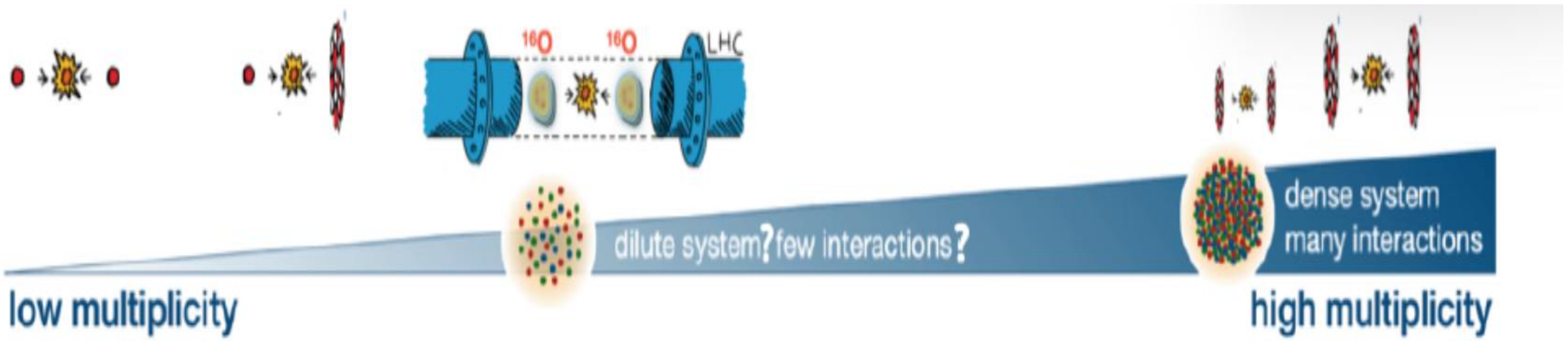
Lu, Zhao, Nielsen, Li and Zhou, arXiv:2501.14852 [nucl-th]

… …   … …





Collectivities in small systems with light ion collisions



Key questions: Origin of collective flow in small systems

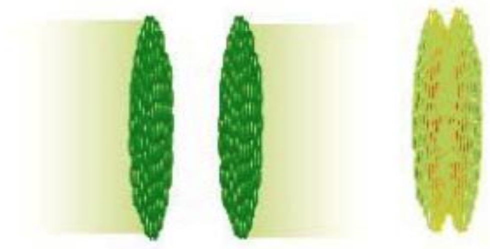
- ✳ Pb-Pb & Xe-Xe -> geometry
- ✳ pp & p-Pb -> fluctuation (challenging!)
- ✳ **Light-ions collisions** -> unique geometry & fluctuations

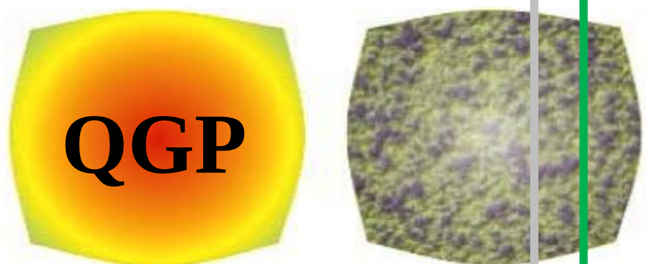
-"We strongly argue that short light ion runs should become part of the full exploitation of the scientific opportunities arising from HL-LHC"

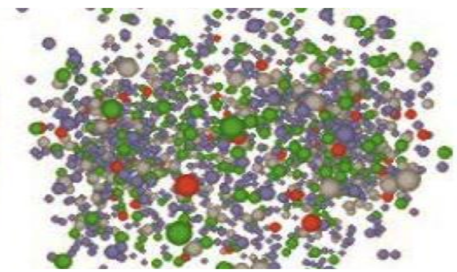
— Summary report for Light ion collisions at the LHC CERN Nov2024

Exploring Nuclear Physics across Energy Scales

-- Personal view from heavy ion collisions







Initial conditions:

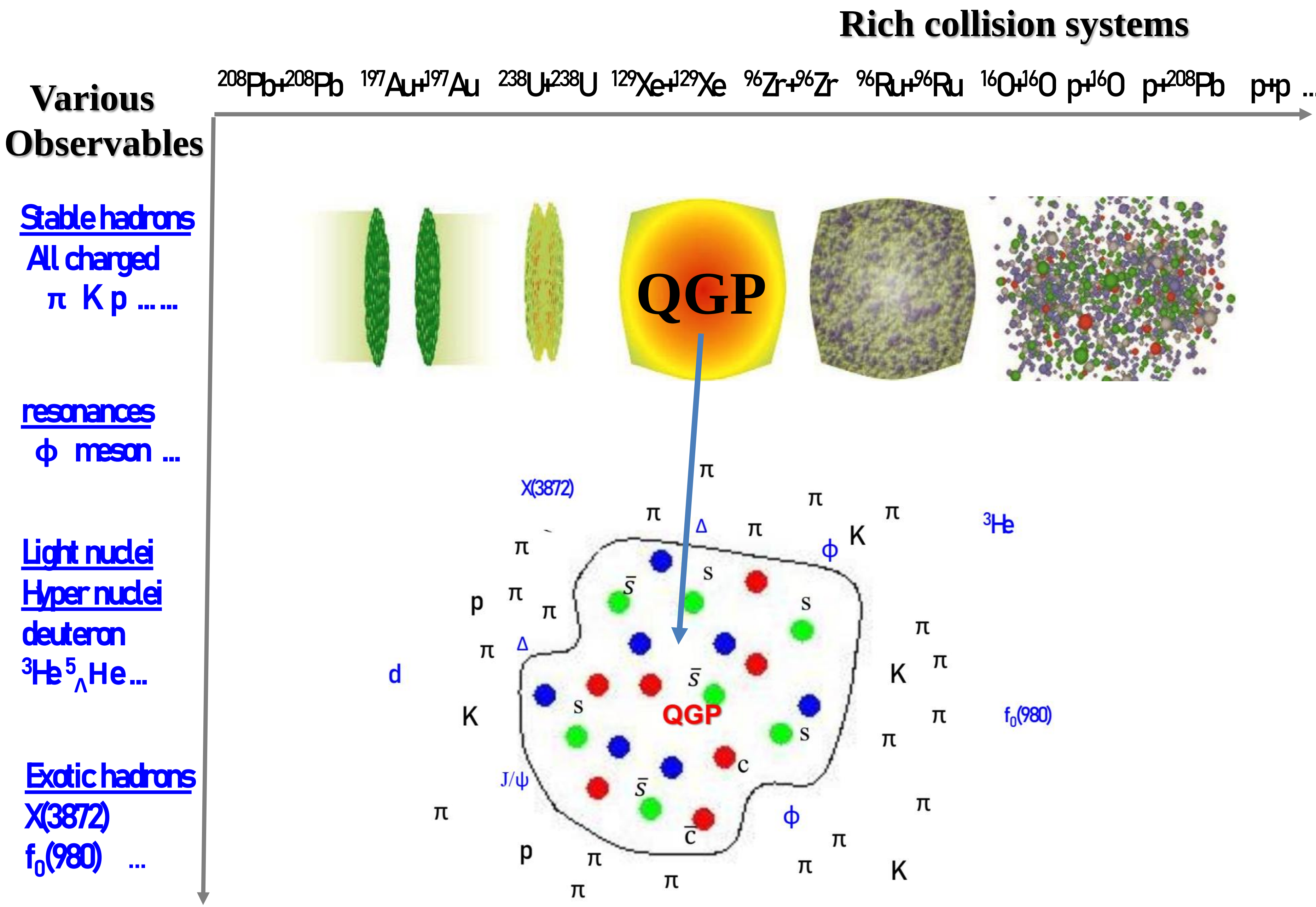
Intersection study with nuclear structure

QGP evolution:

main goal: QGP & QCD phase diagram

Final Hadrons:

intersection study with hadron physics



Rich collision systems
Various Observables
^{208}Pb+^{208}Pb ^{197}Au+^{197}Au ^{238}U+^{238}U ^{129}Xe+^{129}Xe ^{96}Zr+^{96}Zr ^{96}Ru+^{96}Ru ^{16}O+^{16}O p+^{16}O p+^{208}Pb p+p ...
Stable hadrons
All charged
π K p ... ...
resonances
ϕ meson ...
Light nuclei
Hyper nuclei
deuteron
^{3}He $^{5}_{\Lambda}$He ...
Exotic hadrons
X(3872)
f_0(980) ...
QGP
X(3872)
^{3}He
d
f_0(980)
J/ψ
Δ
ϕ
K
p
π
s
$\bar{s}$
c
$\bar{c}$
QGP

Light Nuclei

System sizes

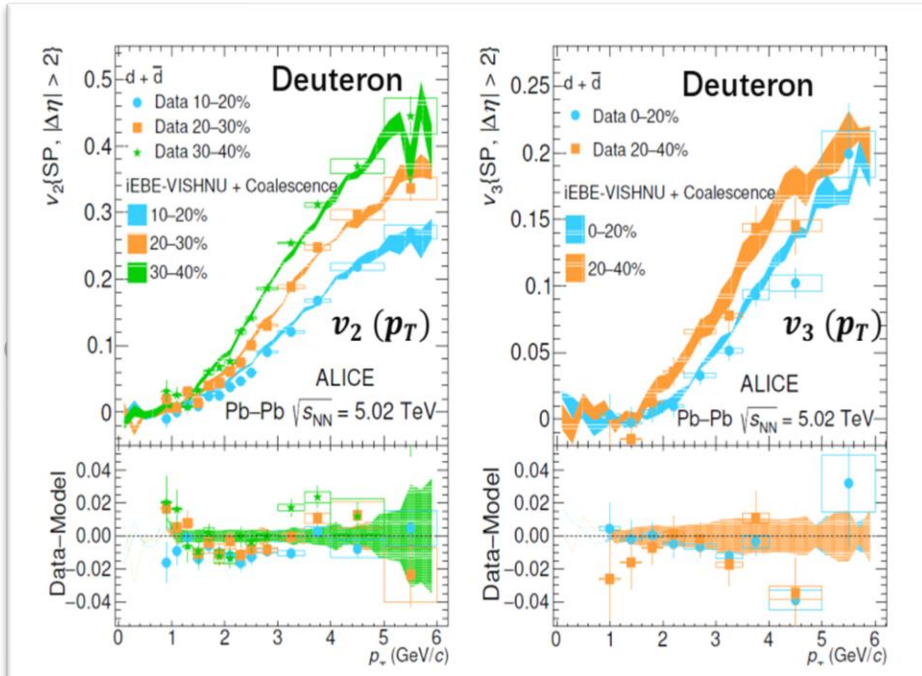
$^{208}Pb+^{208}Pb$ $^{197}Au+^{197}Au$ $^{238}U+^{238}U$ $^{129}Xe+^{129}Xe$ $^{96}Zr+^{96}Zr$ $^{96}Ru+^{96}Ru$ $^{16}O+^{16}O$ $p+^{208}Pb$ p+p ……

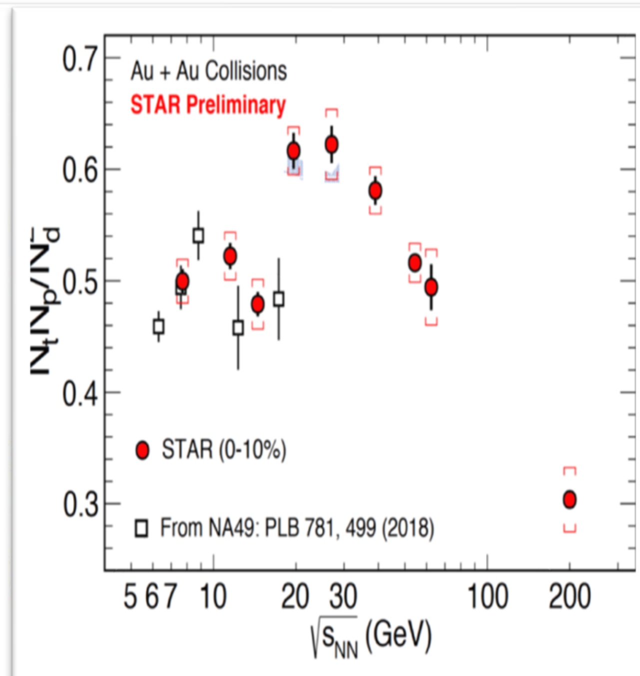
Observables

Stable hadrons
All charged h
π K p ……

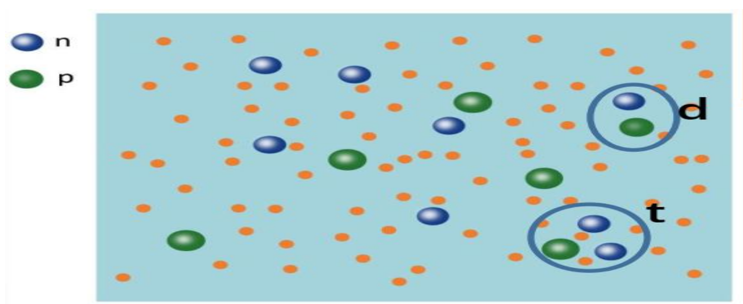
resonances
ϕ meson …

Light nuclei
Hyper nuclei
deuteron
^3He $^5_\Lambda He$ …





Light nuclei: produced by coalescence of n & p at kinetic freezeout
probe critical fluctuations & hadronic flow



Hyper Nuclei

System sizes

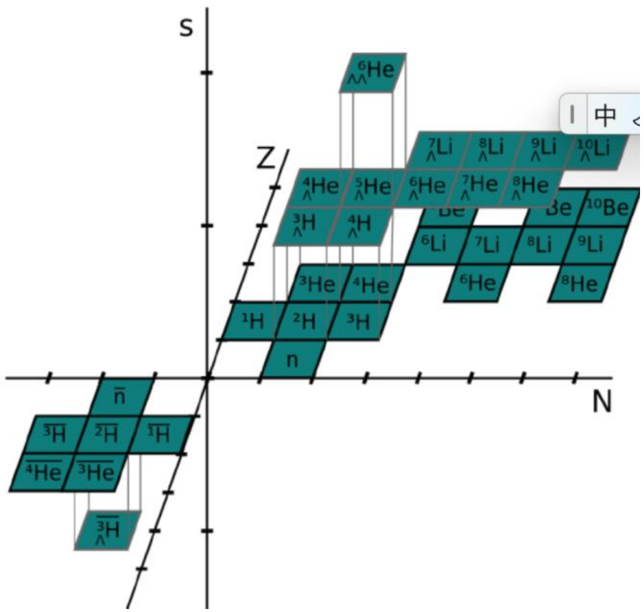
$^{208}Pb+^{208}Pb$ $^{197}Au+^{197}Au$ $^{238}U+^{238}U$ $^{129}Xe+^{129}Xe$ $^{96}Zr+^{96}Zr$ $^{96}Ru+^{96}Ru$ $^{16}O+^{16}O$ $p+^{208}Pb$ p+p ……

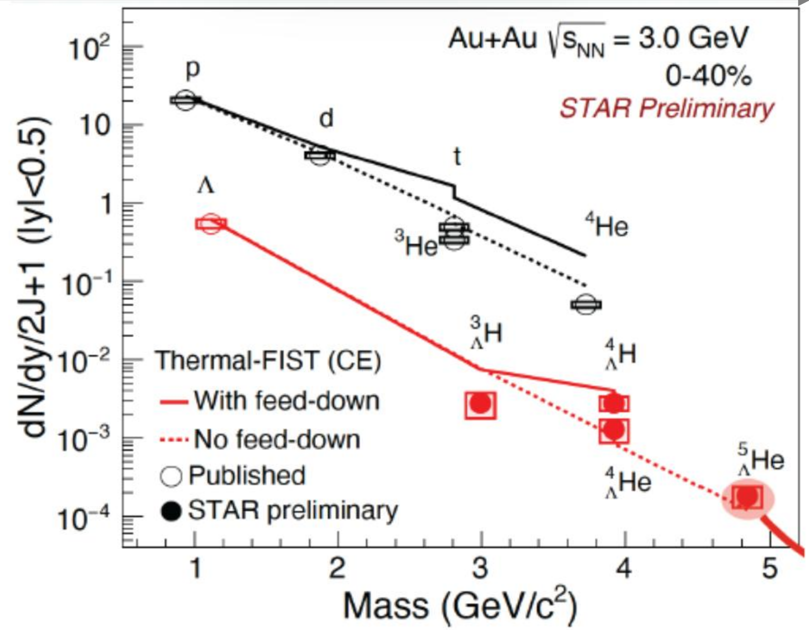
Observables

Stable hadrons
All charged h
π K p ……

resonances
ϕ meson …

Light nuclei
Hyper nuclei
deuteron
^3He $^5_\Lambda He$ …

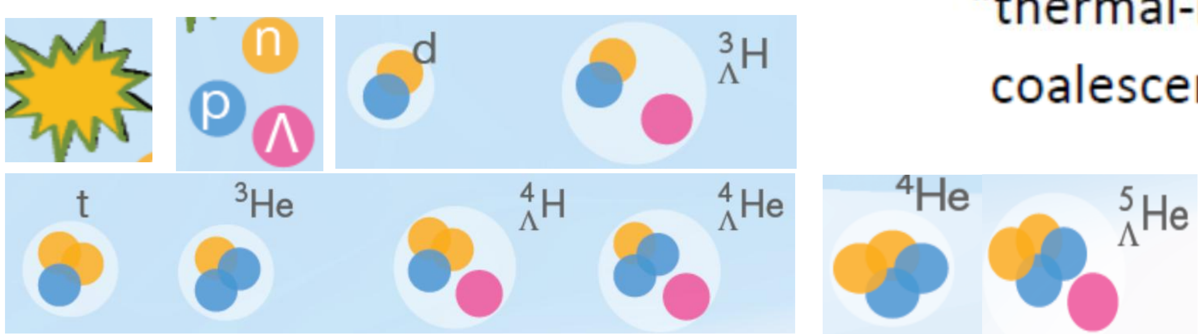




Hyper nuclei: production mechanism
in-medium Y-N interactions

“coalescence-like” and
“thermal-like” features

coalescence $d + \Lambda \rightarrow {}^3_\Lambda H$,
$t + \Lambda \rightarrow {}^4_\Lambda H$

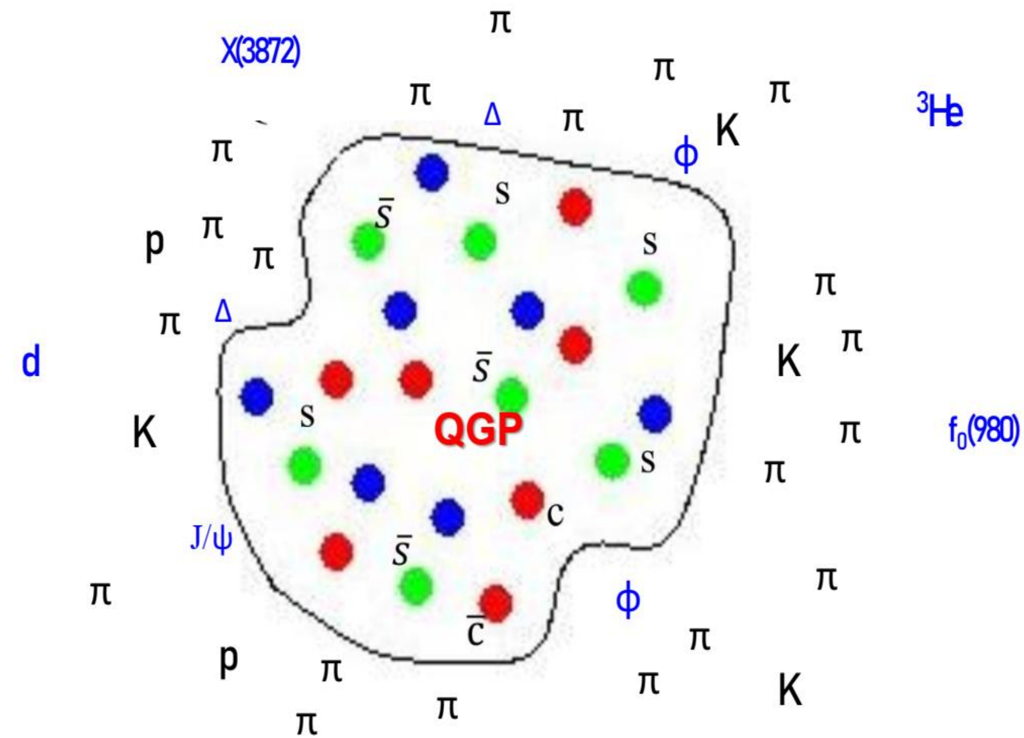


Exotic hadrons

System sizes

^{208}Pb+^{208}Pb ^{197}Au+^{197}Au ^{129}Xe+^{129}Xe ^{20}Ne+^{208}Pb ^{16}O+^{16}O p+^{16}O p+^{208}Pb p+p ……

Observables



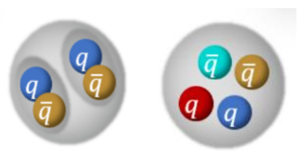
Stable hadrons
All charged
π K p ……

resonances
ϕ meson …

Light nuclei
Hyper nuclei
deuteron
^{3}He $^5_\Lambda$He …

Exotic hadrons
X(3872)
f_0(980) …

Exotic hadrons: easier to be produced with QGP formation;
less background contaminations in small systems



compact or molecular structure?

Probing exotic hadrons in relativistic heavy ion collisions

PRL **106,** 212001 (2011) PHYSICAL REVIEW LETTERS

Identifying Multiquark Hadrons from Heavy Ion Colli

Sungtae Cho,[1] Takenori Furumoto,[2,3] Tetsuo Hyodo,[4] Daisuke Jido,[2] Che Ming K
Marina Nielsen,[6] Akira Ohnishi,[2] Takayasu Sekihara,[2,7] Shigehiro Yasui,[8] and

PHYSICAL REVIEW LETTERS **126,** 012301 (2021)

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

Hui Zhang,[1,2,*] Jinfeng Liao,[3,†] Enke Wang,[1,2,‡] Qian Wang,[1,2,4,§] and Hongxi X

multiphase transport model (AMPT) for describing such collisions and
production mechanism of either molecule or tetraquark picture, we compute
servables for X(3872) in Pb-Pb collisions at the Large Hadron Collider. We find
crucial role, leading to a 2-order-of-magnitude difference in the X(3872) yield
entrality dependence between hadronic molecules and compact tetraquarks, thus

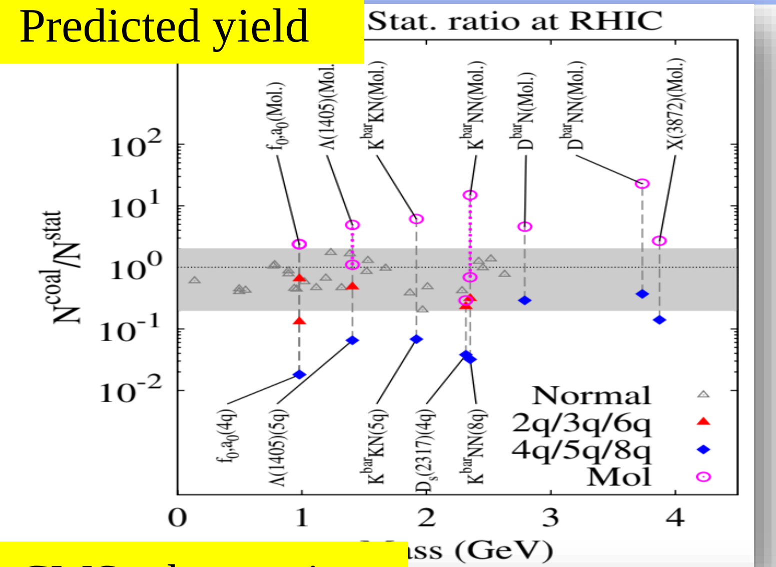
PHYSICAL REVIEW LETTERS **128,** 032001 (2022)

Evidence for X(3872) in Pb-Pb Collisions and Studies of its Prompt Production at $\sqrt{s_{NN}} = 5.02$ TeV

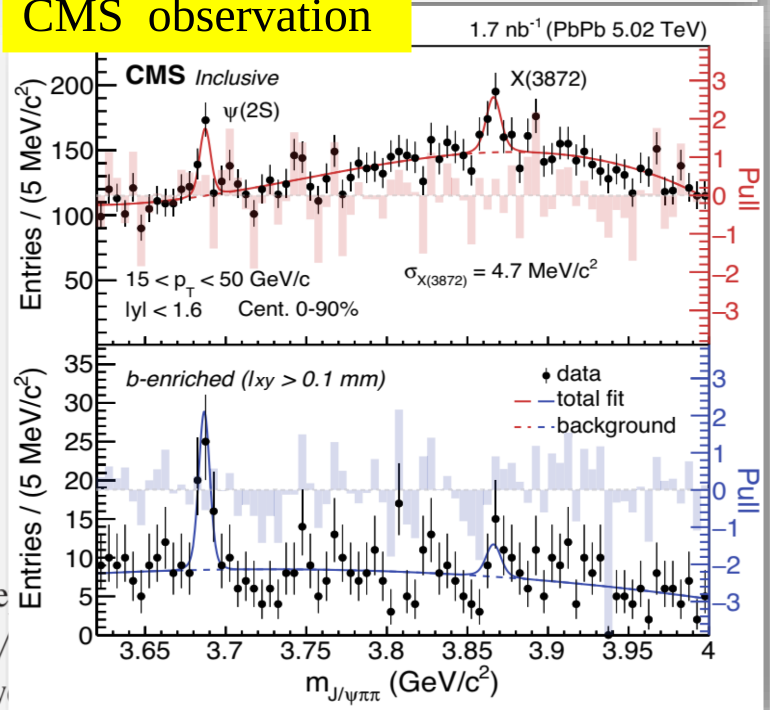
A. M. Sirunyan *et al.*[*]
CMS Collaboration

The first evidence for X(3872) production in relativistic heavy ion collisions is re
production is studied in lead-lead (Pb-Pb) collisions at a center-of-mass energy of $\sqrt{}$
nucleon pair, using the decay chain $X(3872) \rightarrow J/\psi\pi^+\pi^- \rightarrow \mu^+\mu^-\pi^+\pi^-$. The data w

Predicted yield

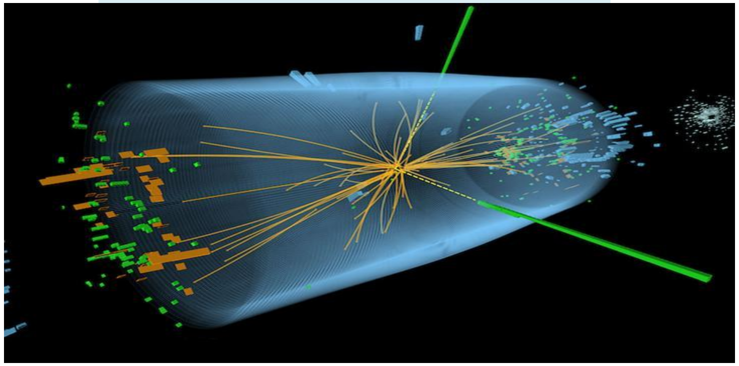


CMS observation



Advantage to study exotic hadrons in heavy ion collisions?

Particle physics



$f_0(980)$ $I^G(J^{PC}) = 0^+(0^{++})$

See the review on "Scalar Mesons below 1 GeV."

T-matrix pole $\sqrt{s} = (980\text{–}1010) - i\ (20\text{–}35)$ MeV [i]
Mass (Breit-Wigner) = 990 ± 20 MeV [i]
Full width (Breit-Wigner) = 10 to 100 MeV [i]

$f_0(980)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$\pi\pi$	seen	476
$K\overline{K}$	seen	36
$\gamma\gamma$	seen	495

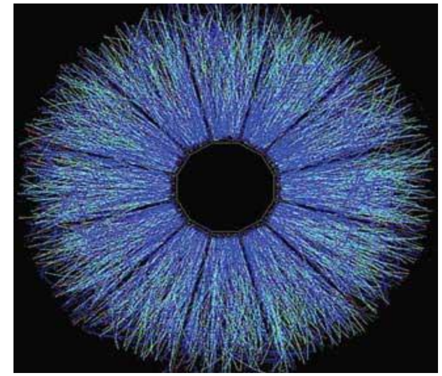
$a_0(980)$ $I^G(J^{PC}) = 1^-(0^{++})$

See the review on "Scalar Mesons below 1 GeV."

T-matrix pole $\sqrt{s} = (970\text{–}1020) - i\ (30\text{–}70)$ MeV [i]
Mass $m = 980 \pm 20$ MeV [i]
Full width $\Gamma = 50$ to 100 MeV [i]

$a_0(980)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$\eta\pi$	seen	319
$K\overline{K}$	seen	†

High energy nuclear physics



A large amount of particles produced
→ momentum distributions

-particle yield
→ - p_T spectra
- flow anisotropy

More info

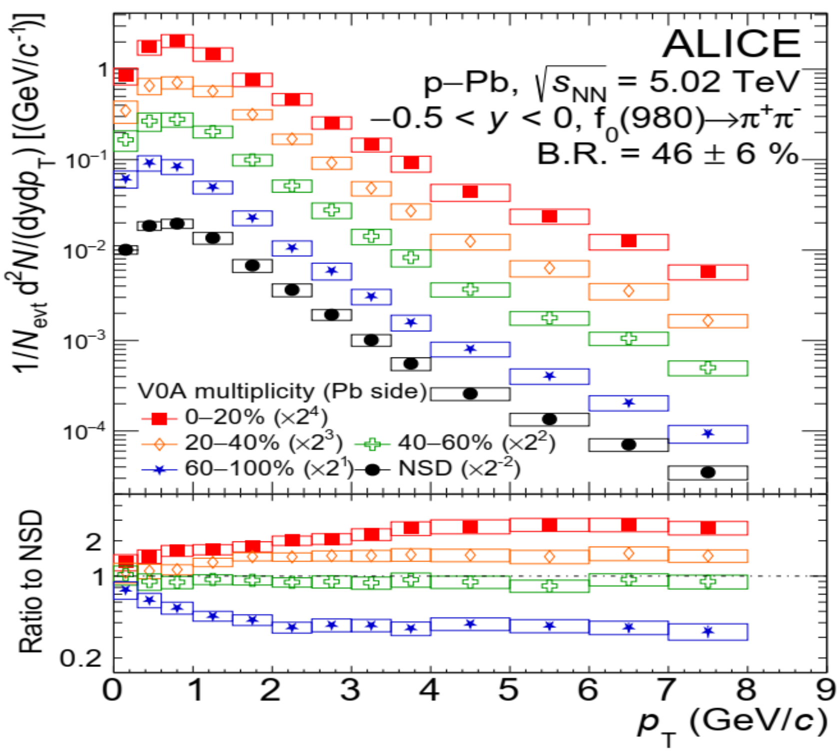
Advantage: provide complimentary information to constrain properties of hadrons
disadvantage: background is huge
→small systems

Probing the exotic hadron $f_0(980)$ in p-Pb collisions

particle yield

Multiplicity class (V0A)	d*N*/dy
0–20%	0.206±0.005±0.014
20–40%	0.153±0.004±0.010
40–60%	0.113±0.002±0.008
60–100%	0.064±0.001±0.005

p_T spectra



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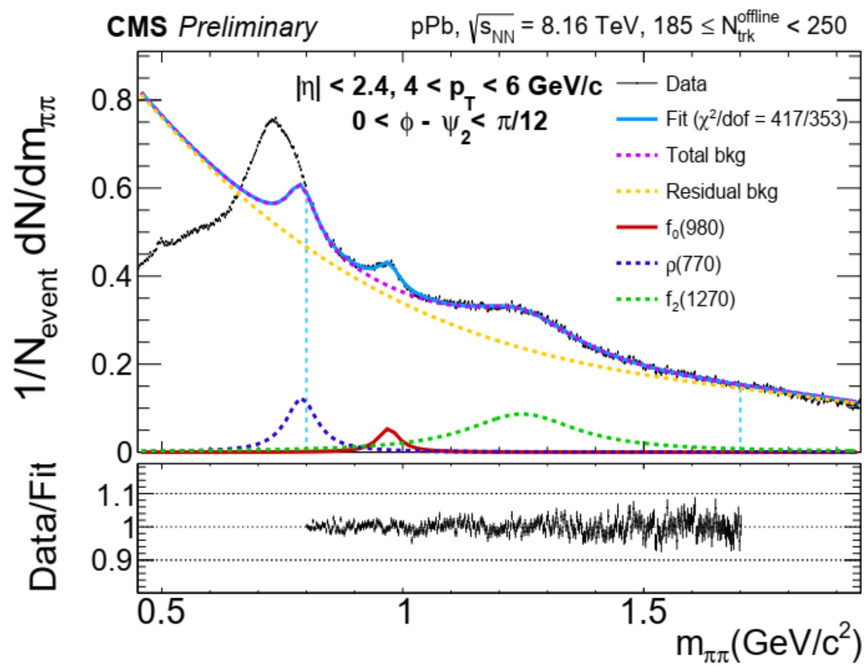
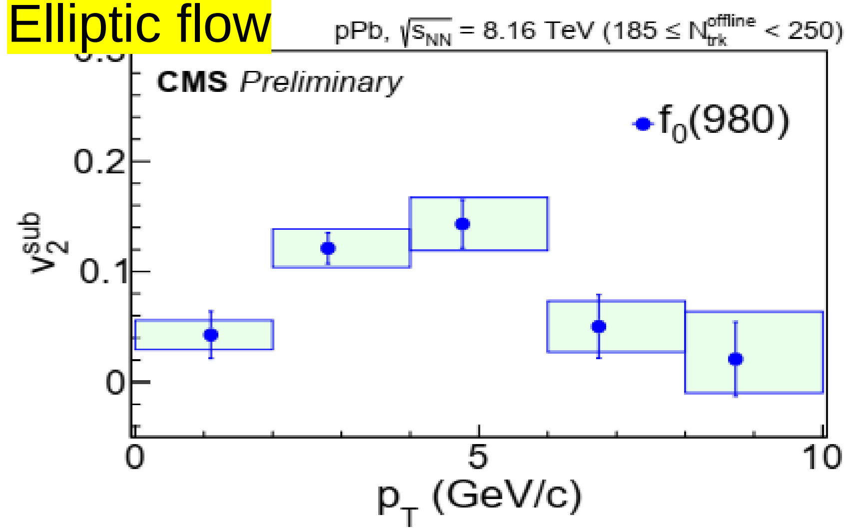
Reconstruction of $f_0(980)$

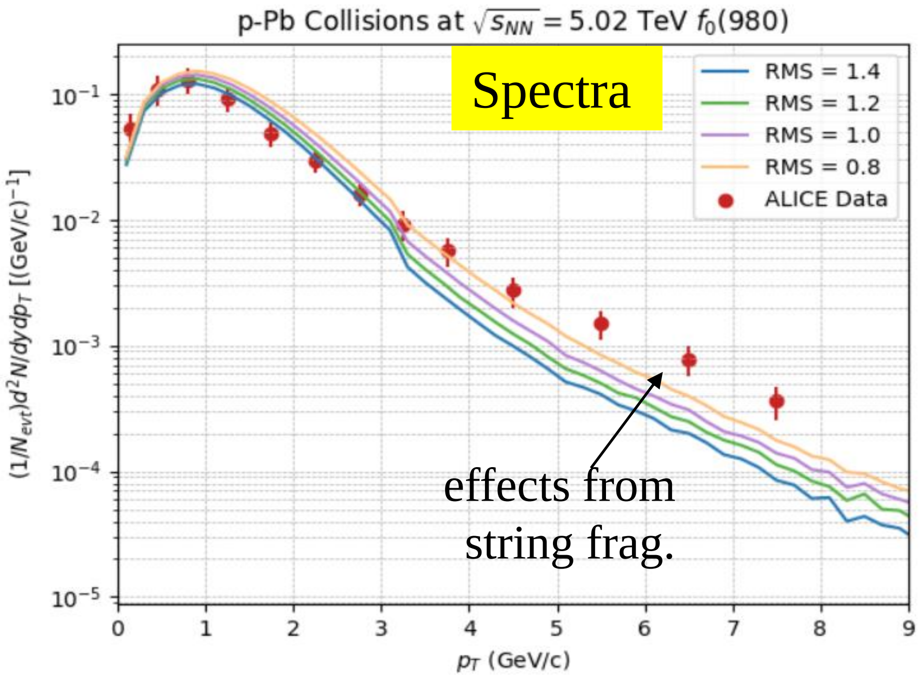
CMS 2312.17092

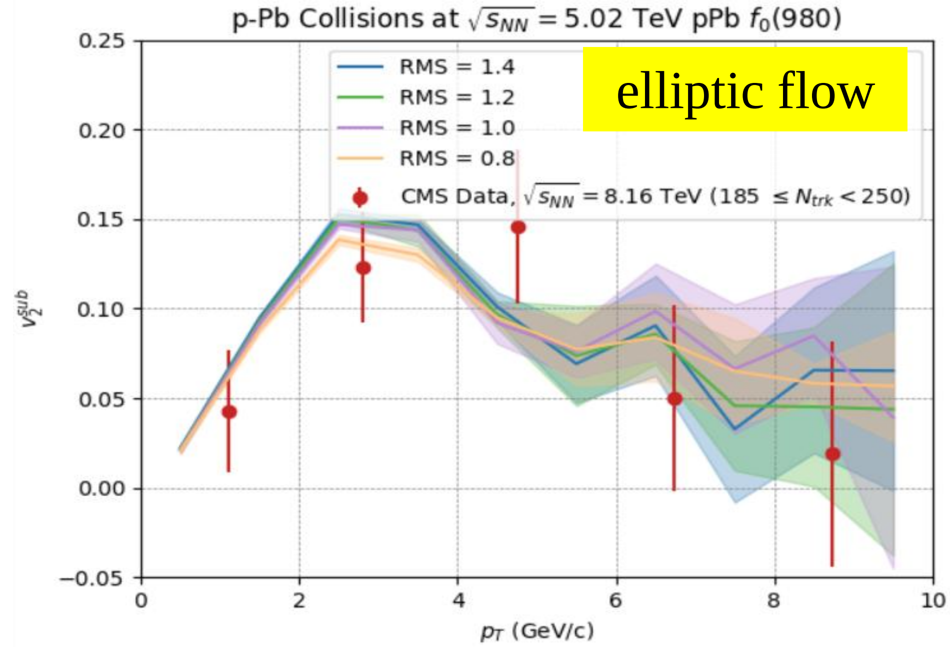


Elliptic flow



Coalescence calculations for $f_0(980)$ in p-Pb collisions





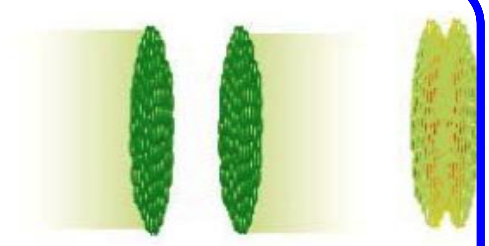
$f_0(980)$: ($K\overline{K}$ molecule) produced at kinetic freezeout by coalescence of K & $\overline{K}$
probe hadronic flow of kaons

$$\frac{d^3N_A}{d\mathbf{P}_A^3} = \frac{g_A}{Z! \cdot N!} \int \Pi_{i=1}^{A} p_i^{\mu} d^3\sigma_{i\mu} \frac{d^3\mathbf{p}_i}{E_i} f(\mathbf{x}_i, \mathbf{p}_i, t) \times f_A(\mathbf{x}_1', ..., \mathbf{x}_A'; \mathbf{p}_1', ..., \mathbf{p}_A'; t') \delta^{(3)} \left(\mathbf{P}_A - \sum_{i=1}^{A} \mathbf{p}_i \right),$$

$$f_2(\boldsymbol{\rho}, \mathbf{p}_\rho) = 8 g_2 \exp\left[-\frac{\rho^2}{\sigma_\rho^2} - \mathbf{p}_\rho^2 \sigma_\rho^2 \right] \qquad \boldsymbol{\rho} = \frac{1}{\sqrt{2}}(\mathbf{x}_1' - \mathbf{x}_2'), \quad \mathbf{p}_\rho = \sqrt{2}\, \frac{m_2 \mathbf{p}_1' - m_1 \mathbf{p}_2'}{m_1 + m_2},$$

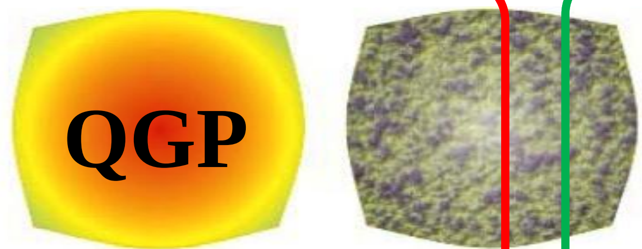
Nuclear Physics across Energy Scales

-- Personal view from heavy ion collisions



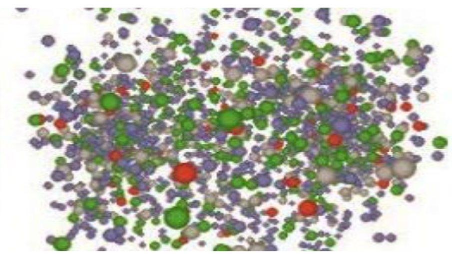
Initial conditions:

Intersection study with **nuclear structure**



QGP evolution:

main goal: QGP & QCD phase diagram



Final Hadrons:

intersection study with **hadron physics**

Happy 0th birthday C3NT

Central China Center for Nuclear Theory
华中核理论中心

- Nuclear structure
- Nuclear matter under extreme conditions
- Hadron physics
- Nuclear astrophysics and fundamental symmetry
- Quantum computing and AI in nuclear physics

Many Thanks