Soft Physics for high energy Nucleus-Nucleus Collisions

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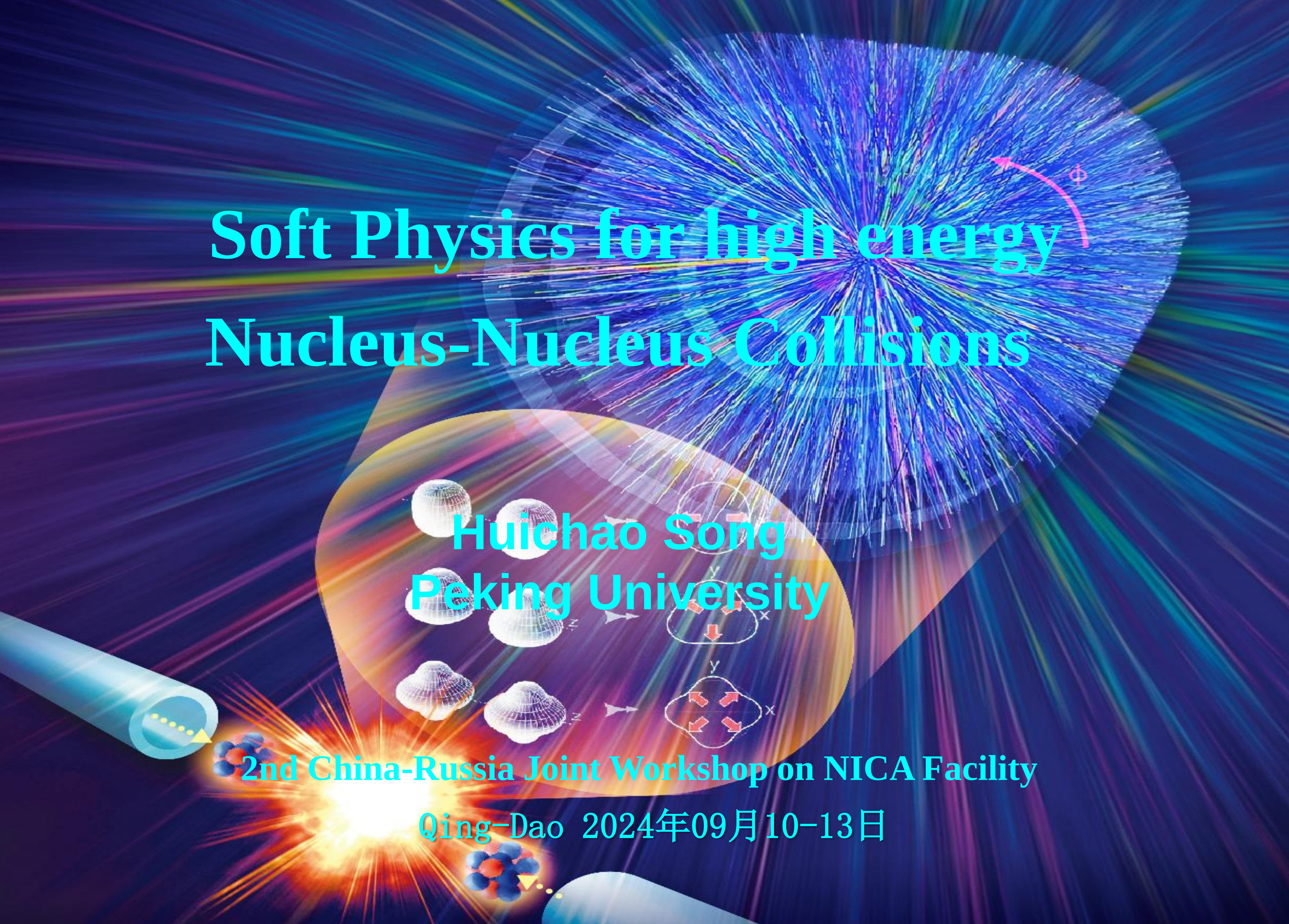
Peking University

2nd China-Russia Joint Workshop on NICA Facility

Qing-Dao 2024年09月10-13日



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

Landscape of nuclear physics

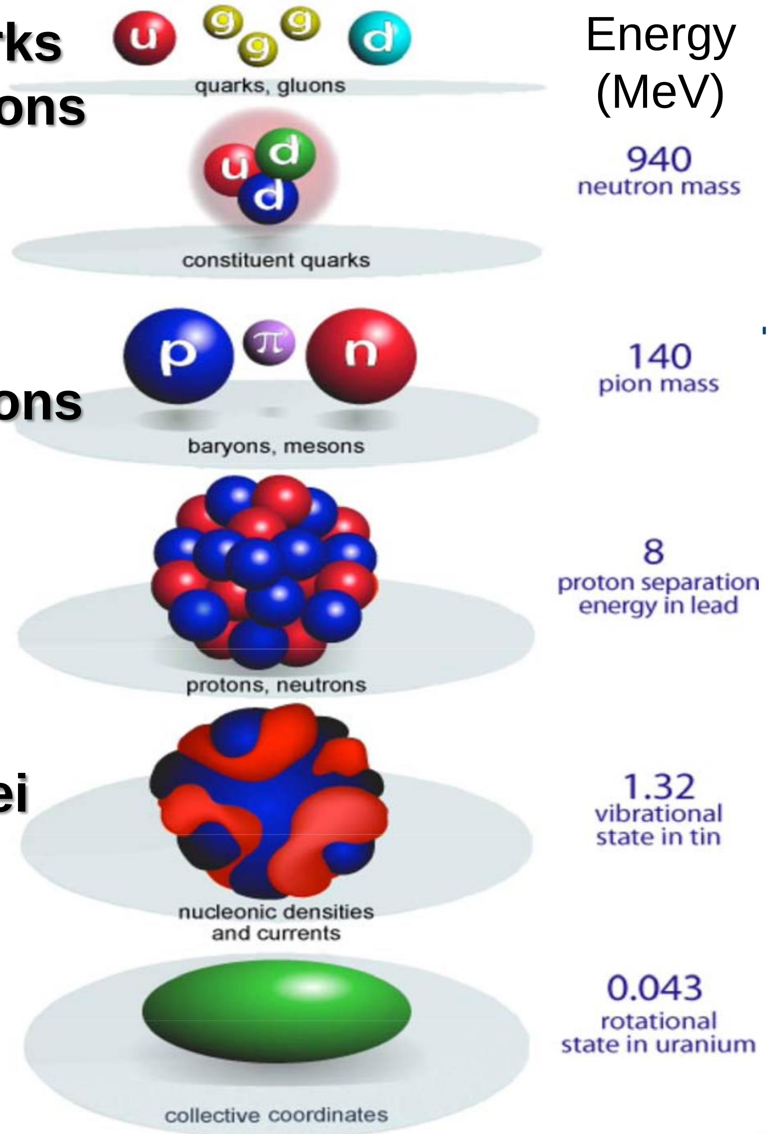
degrees of freedeom

quarks
& gluons

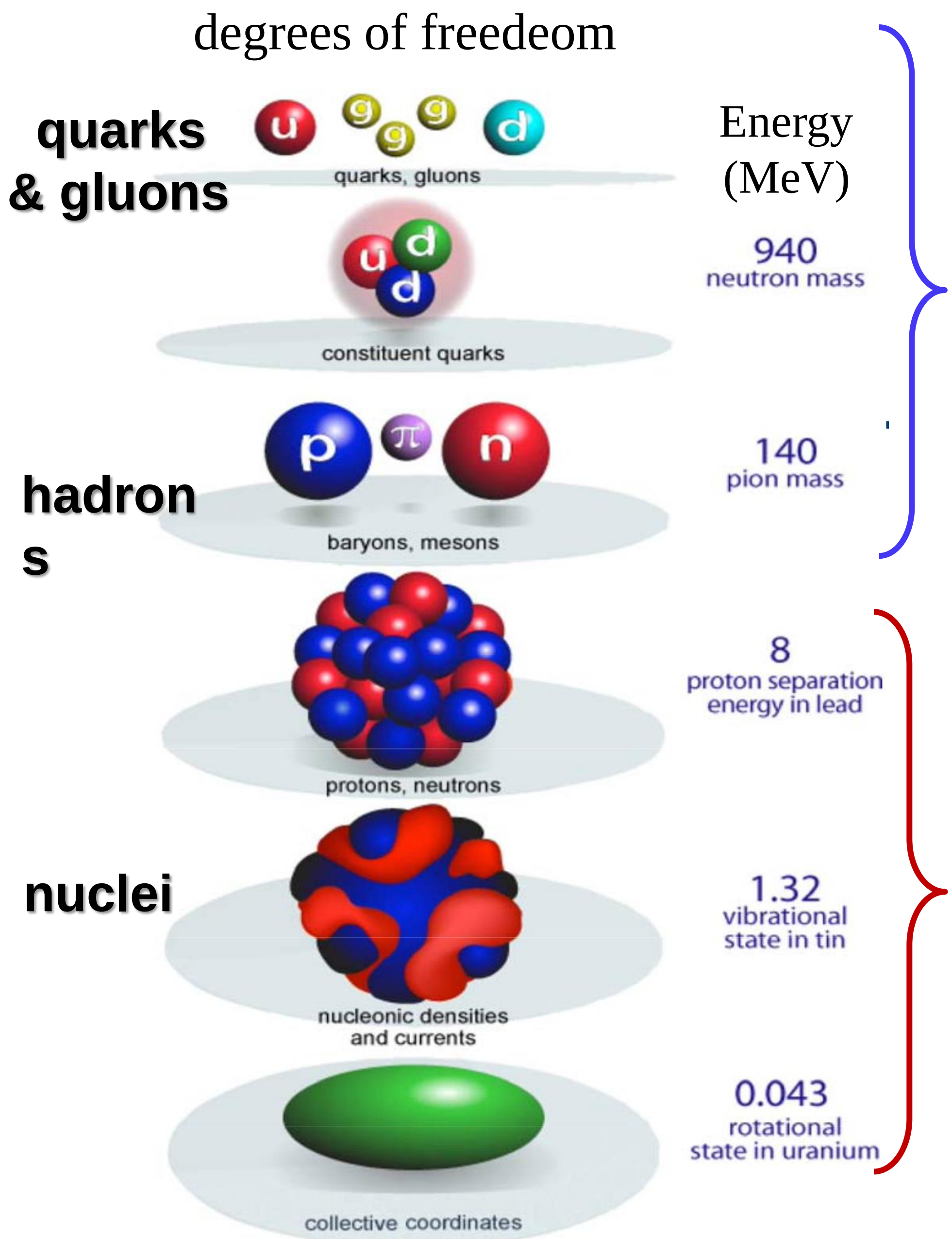
Energy
(MeV)

hadrons

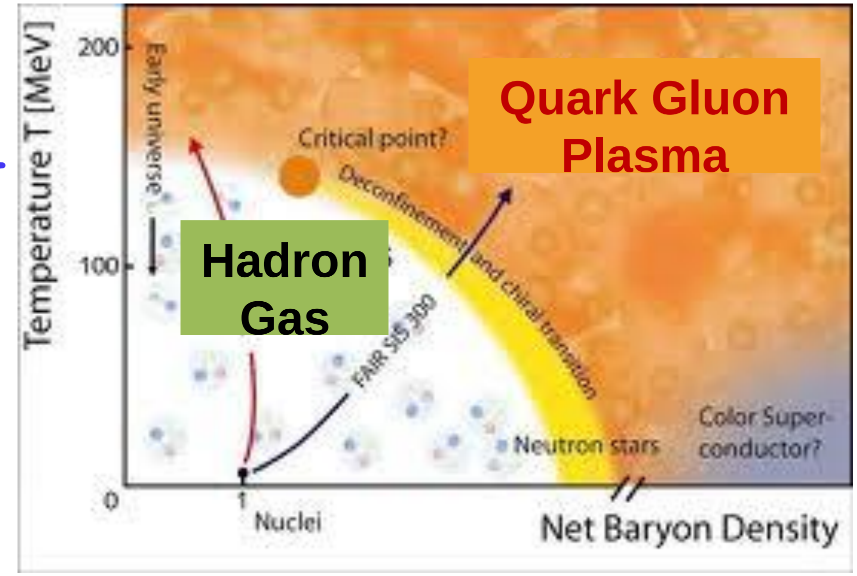
nuclei



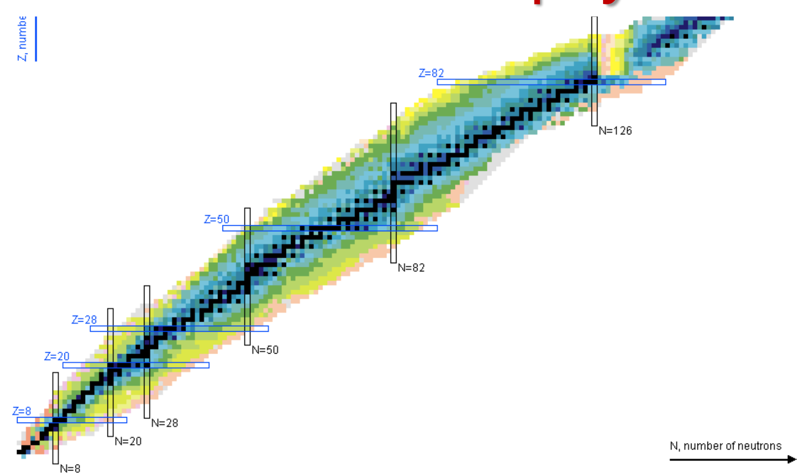
Landscape of nuclear physics



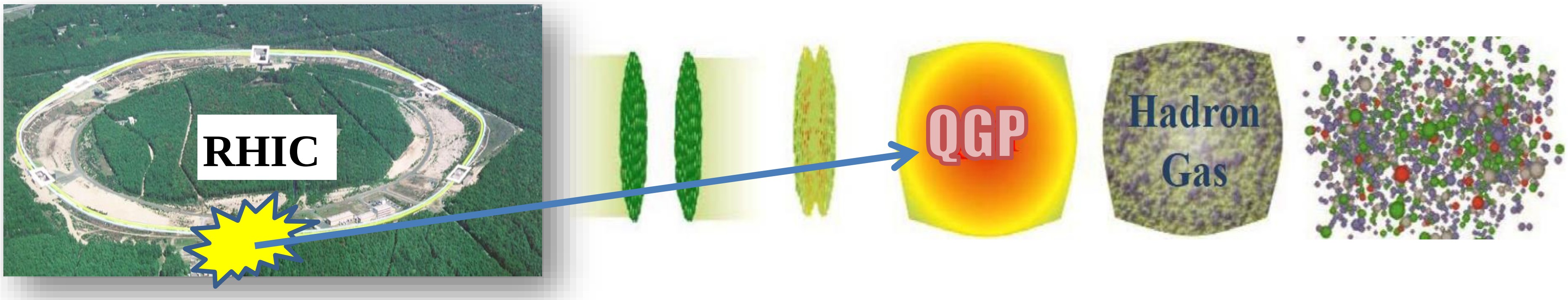
-intermediate and high energy nuclear physics

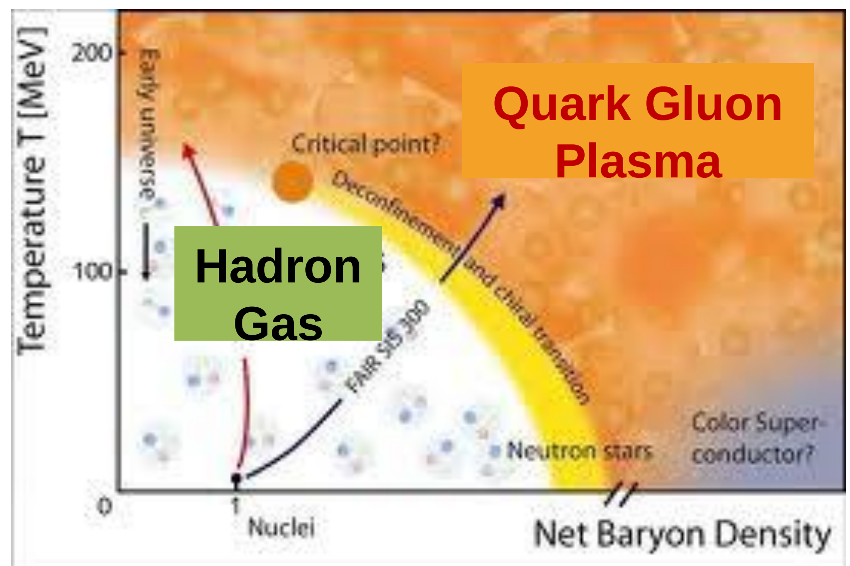


-nuclear structure physics



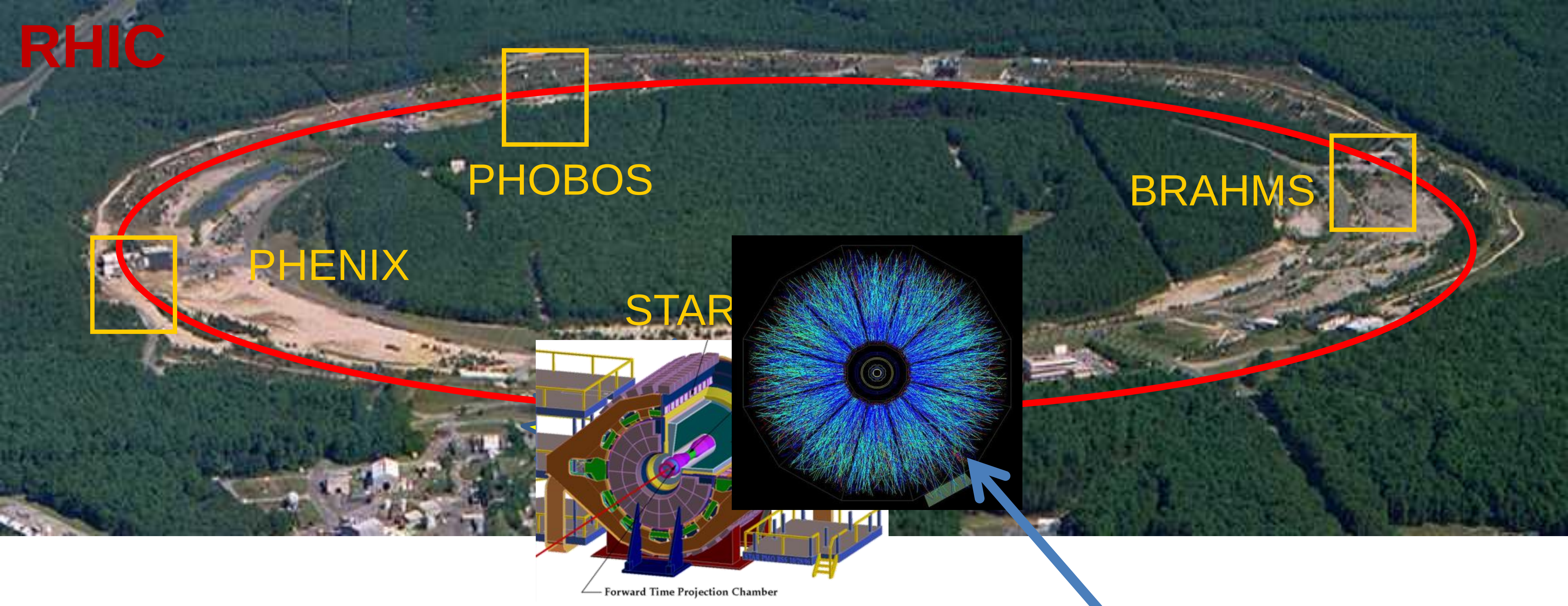
Relativistic heavy ion physics





Relativistic heavy ion collisions

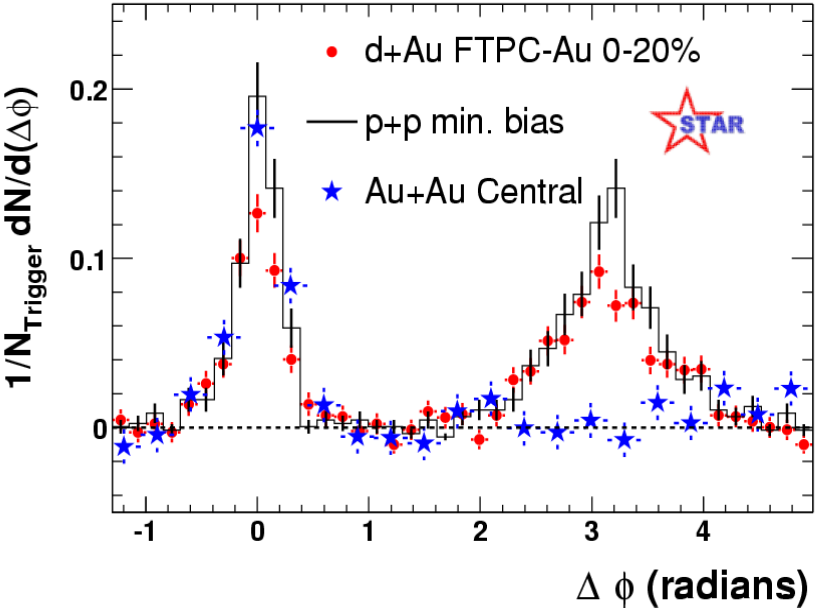
- create and study QGP
- the QCD phase diagram
- the deconfinement & chiral phase transition
- the QCD vacuum

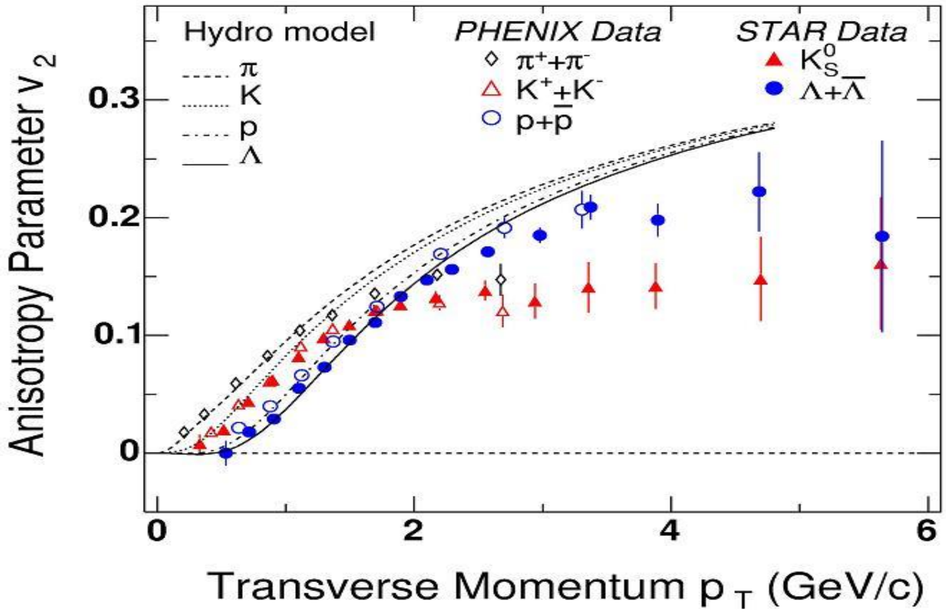


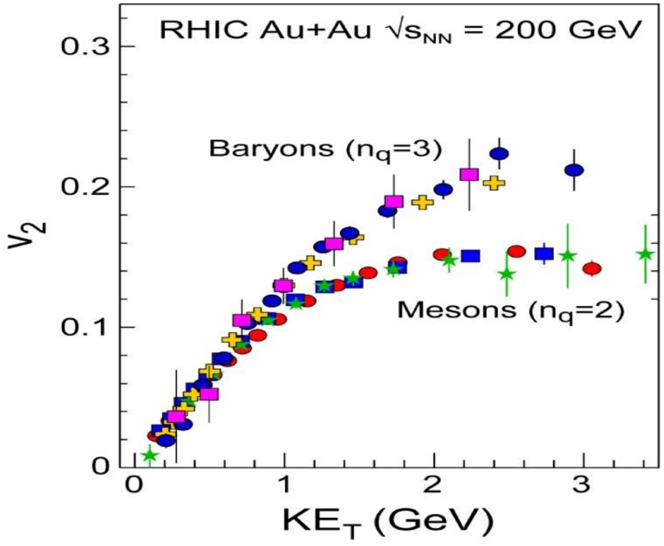
little bang: the different stage for a relativistic heavy ion collisions

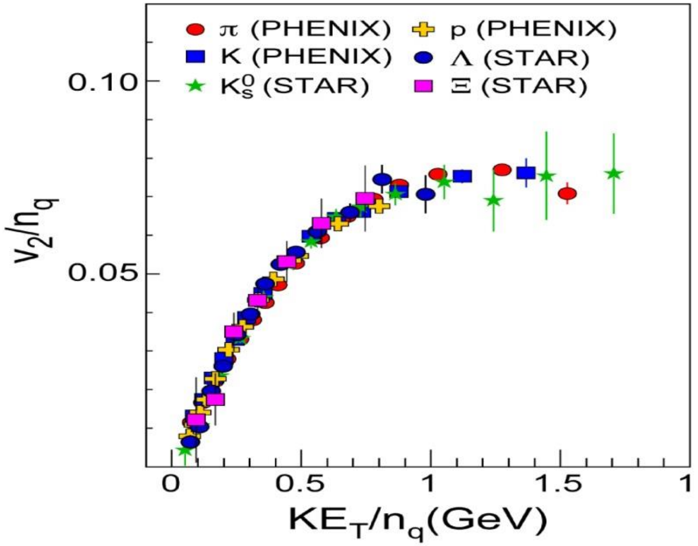
The QGP was discovered

RHIC (2000--)









QGP-the most perfect fluid in the world

BNL News, 2005

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:: Physics News

- LHC to Restart in 2009
- Disappearing Superconductivity Reappears -- in 2-D
- Electron Pairs Precede High-Temperature Superconductivity
- World's biggest computing grid launched
- First Beam for Large Hadron Collider

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RHIC Scientists Serve Up "Perfect" Liquid

New state of matter more remarkable than predicted -- raising many new questions

April 18, 2005

TAMPA, FL -- The four detector groups conducting research at the Relativistic Heavy Ion Collider (RHIC) -- a giant atom "smasher" located at the U.S. Department of Energy's Brookhaven National Laboratory -- say they've created a new state of hot, dense matter out of the quarks and gluons that are the basic particles of atomic nuclei, but it is a state quite different and even more remarkable than had been predicted. In peer-reviewed papers summarizing the first three years of RHIC findings, the scientists say that instead of behaving like a gas of free quarks and gluons, as was expected, the matter created in RHIC's heavy ion collisions appears to be more like a *liquid*.

"Once again, the physics research sponsored by the Department of Energy is producing historic results," said Secretary of Energy Samuel Bodman, a trained chemical engineer. "The DOE is the principal federal funder of basic research in the physical sciences, including nuclear and high-energy physics. With today's announcement we see that investment paying off."

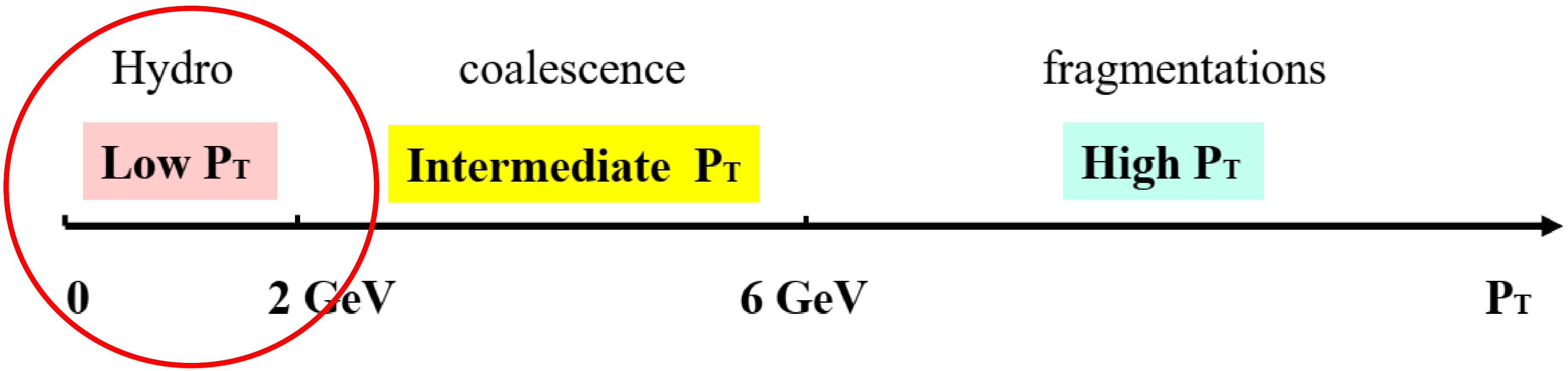
Secretary of Energy Samuel Bodman

"The truly stunning finding at RHIC that the new state of matter created in the collisions of gold ions is more like a liquid than a gas gives us a profound insight into the earliest moments of the universe," said Dr. Raymond L. Orbach, Director of the DOE Office of Science.

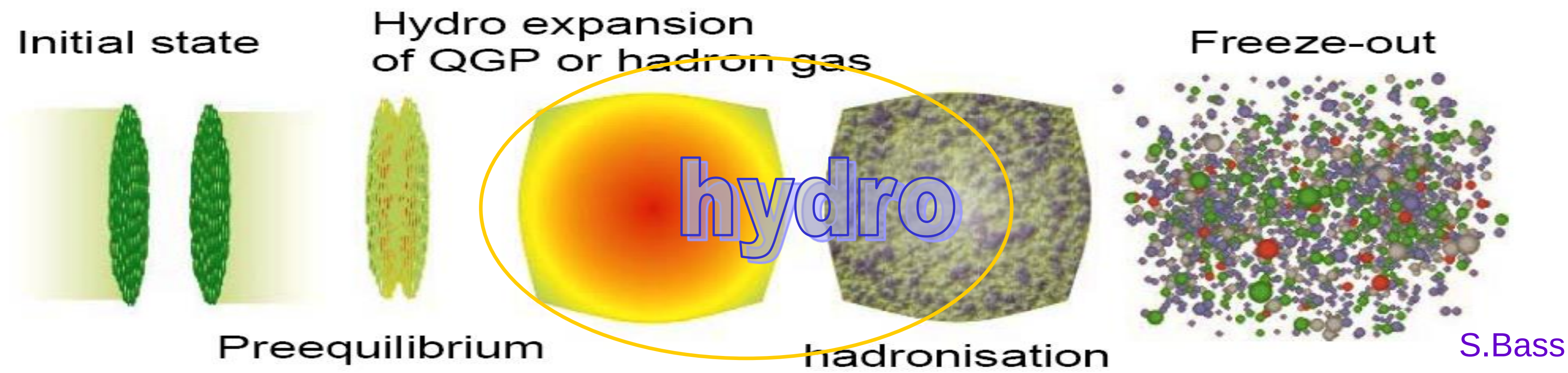
Also of great interest to many following progress at RHIC is the emerging connection between the collider's results and calculations using the methods of string theory, an approach that attempts to explain

Hydrodynamics & collective flow

in large systems (Au+Au & Pb+Pb collisions)



Viscous hydrodynamics



Conservation laws:

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

2nd order I-S equ:

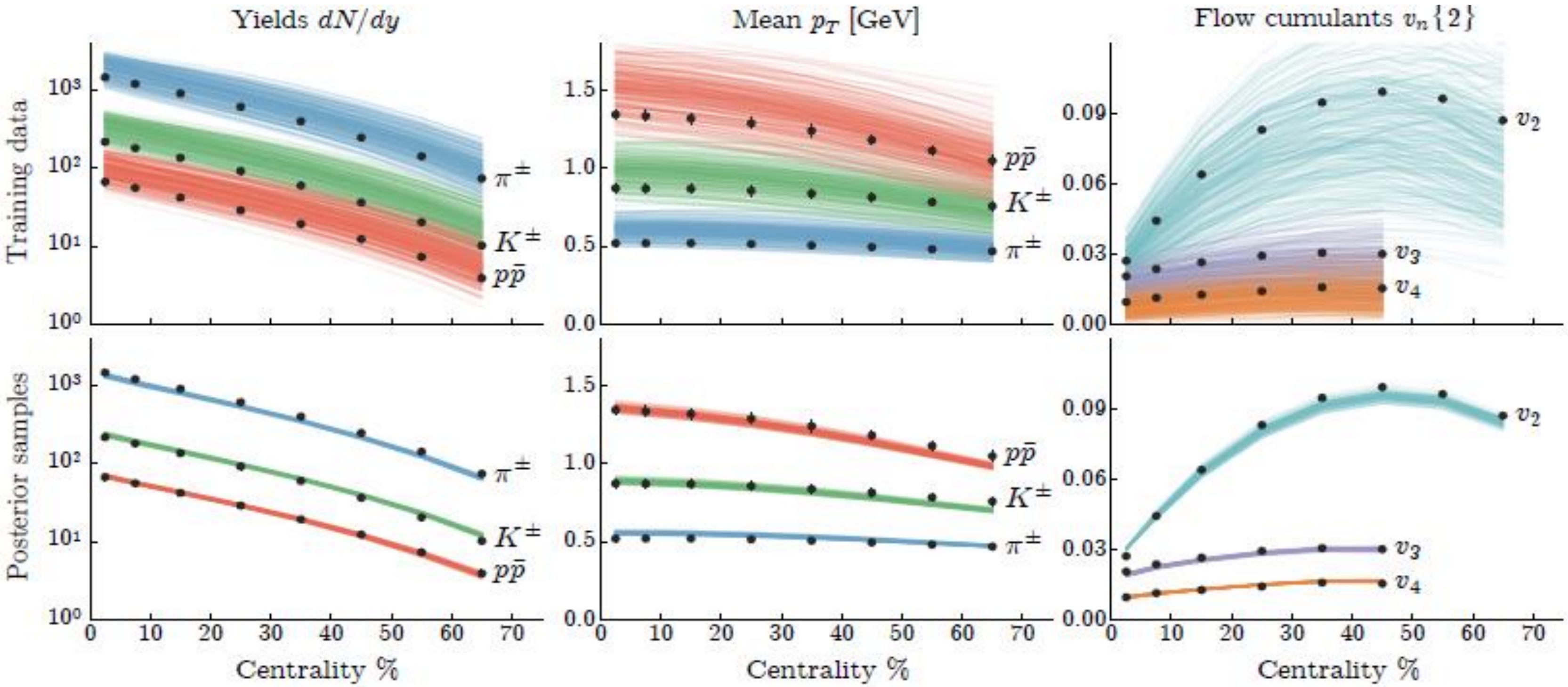
$$\dot{\Pi} = -\frac{1}{\tau_\Pi}\left[\Pi + \zeta\theta - l_{\Pi q}\nabla_\mu q^\mu + \Pi\zeta T\partial_\mu\left(\frac{\tau_\Pi u^\mu}{2\zeta T}\right)\right],$$

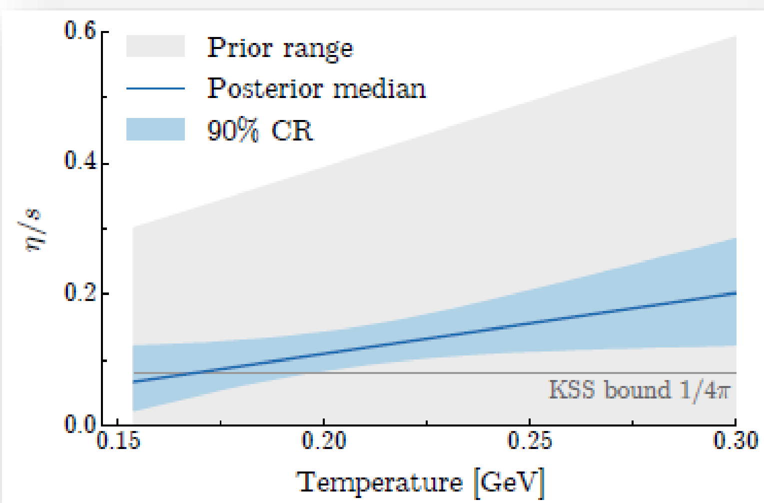
$$\Delta^\mu_\nu \dot{q}^\nu = -\frac{1}{\tau_q}\left[q_\mu + \lambda\frac{nT^2}{e+p}\nabla^\mu\frac{\nu}{T} + l_{q\pi}\nabla_\nu\pi^{\mu\nu} + l_{q\Pi}\nabla^\mu\Pi - \lambda T^2 q^\mu\partial_\mu\left(\frac{\tau_q u^\mu}{2\lambda T^2}\right)\right],$$

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

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

Extract QGP viscosity with hydrodynamics





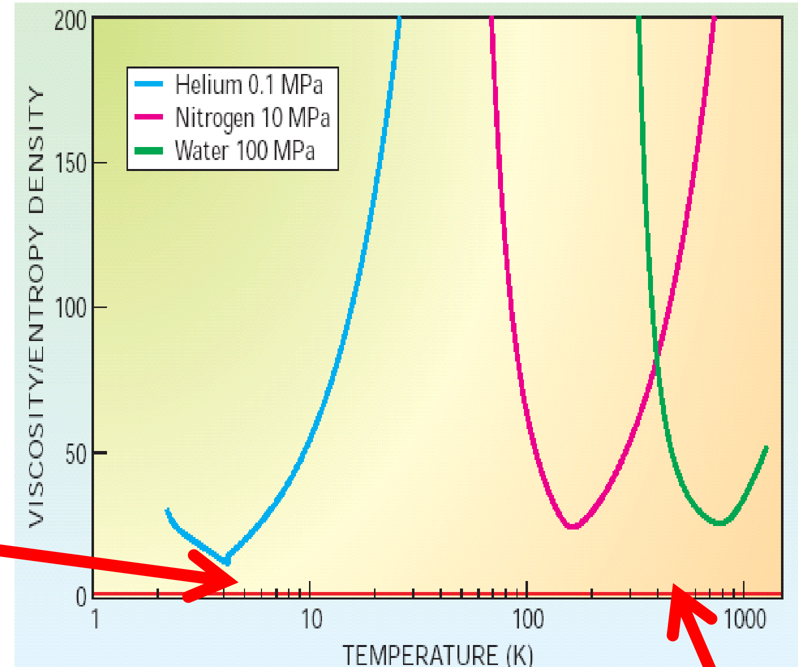
-An quantitatively extraction of the QGP viscosity with iEBE-VISHNU and the massive data evaluation

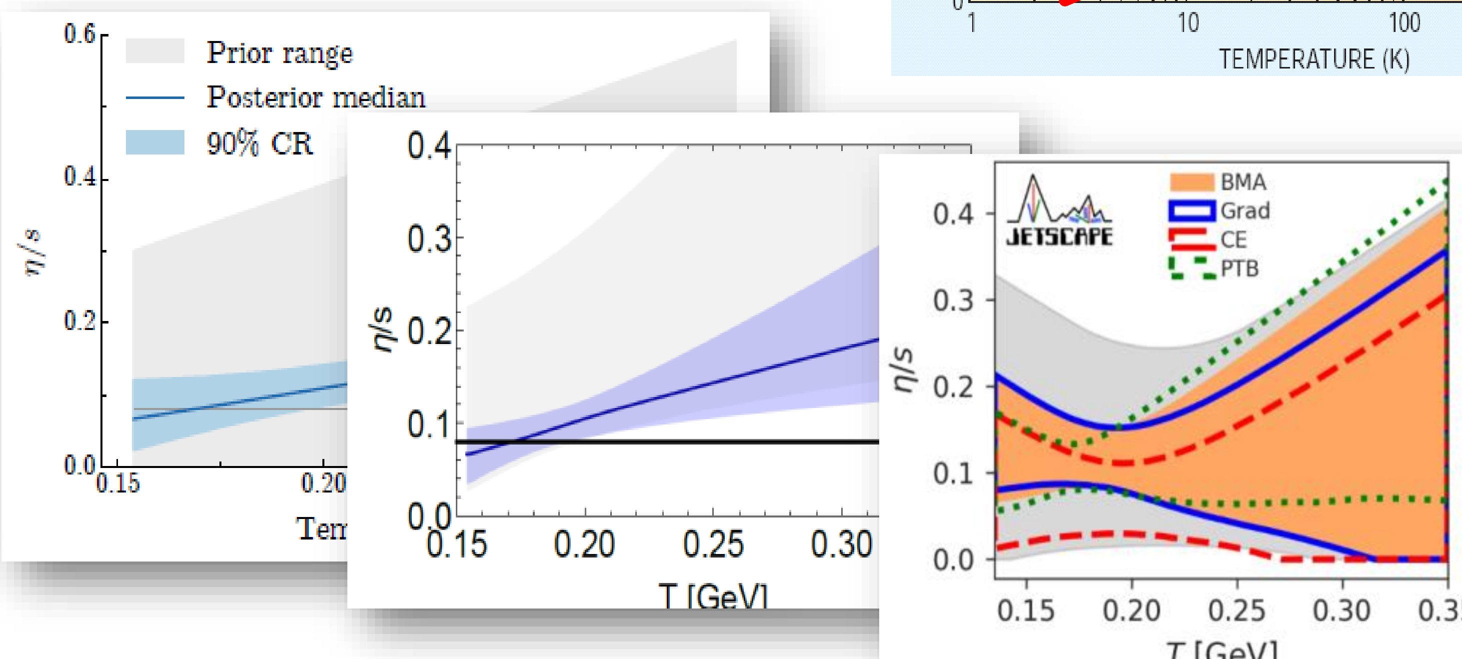
-η/s(T) is very close to the KSS bound of 1/4π

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

QGP: most perfect liquid

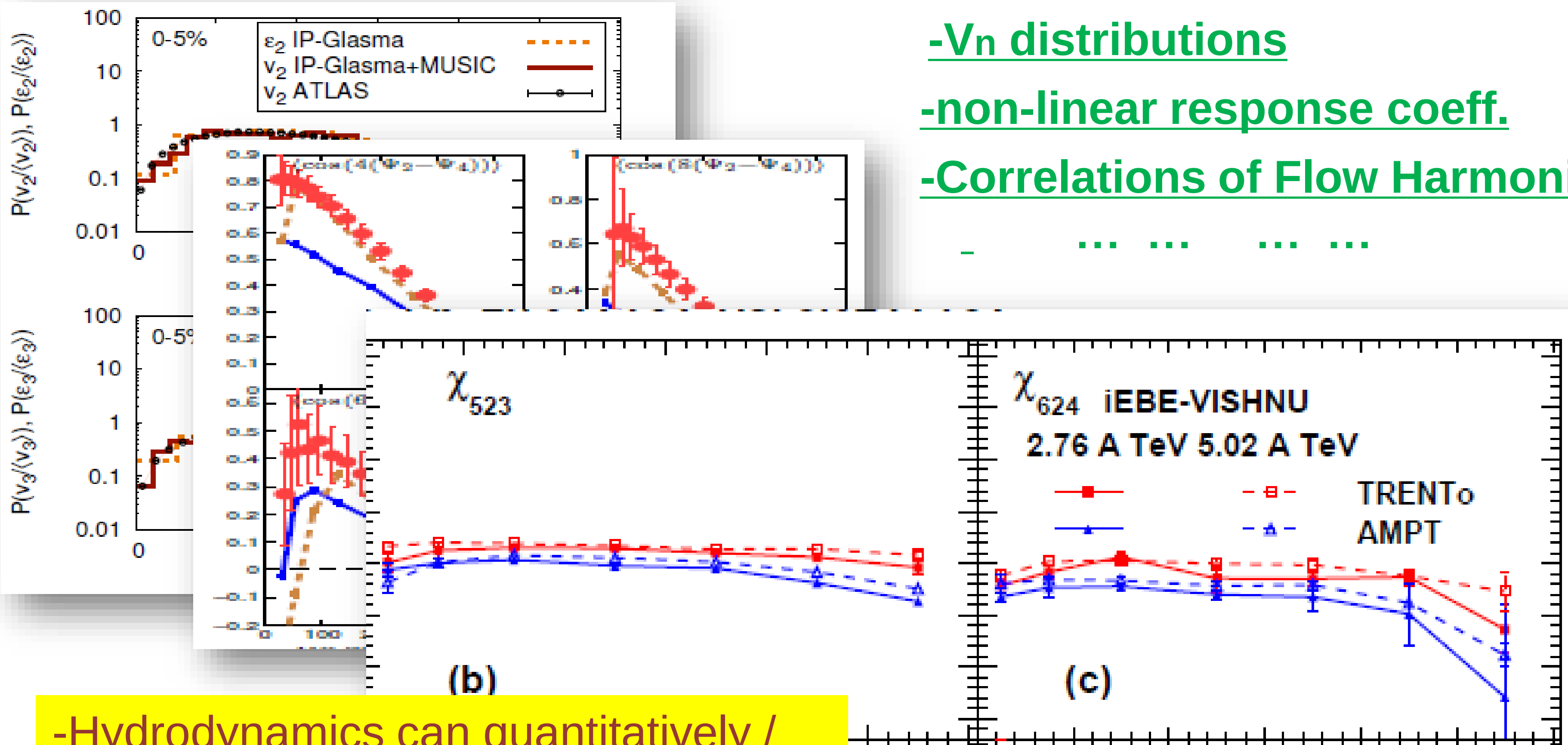
AdS/CFT $\frac{\eta}{s} \geq \frac{h}{k_B}$





QGP specific shear viscosity Extracted from exp data

Powerful predictions from hydrodynamics



-V_n distributions

-non-linear response coeff.

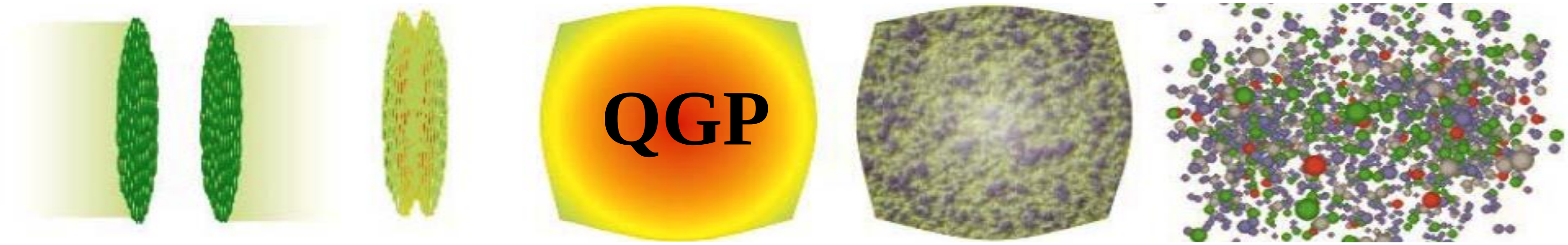
-Correlations of Flow Harmonics

- … … … …

-Hydrodynamics can quantitatively / qualitatively describe / predict various flow data

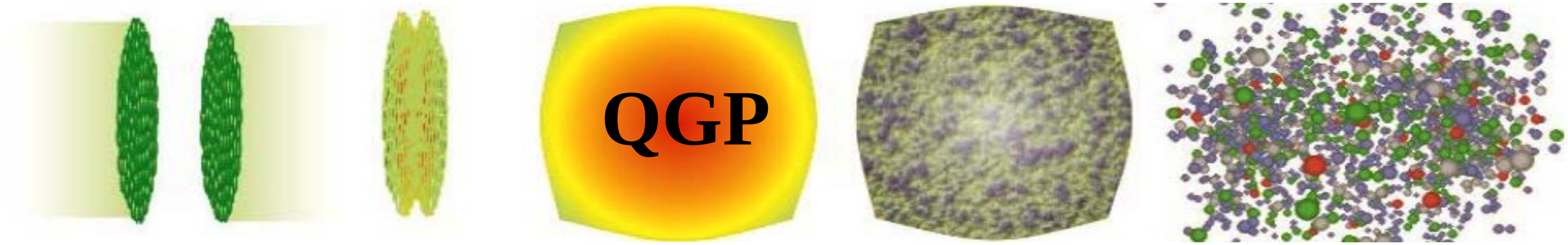
H. Xu, Z. Li and H. S*, Phys. Rev. C93, no. 6, 064905 (2016); W. Zhao, H. Xu and **H. S*,** Eur. Phys. J. C 77, no. 9, 645 (2017); X. Zhu, Y. Zhou, H. Xu and **H. S*,** Phys. Rev. C95, no. 4, 044902 (2017); W. Zhao, L. Zhu, H. Zheng, C. M. Ko and **H. S*.,** Phys. Rev. C 98, no. 5, 054905 (2018); Li,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

The QGP has been created in relativistic heavy ion collisions



Hottest Matter on Earth

The QGP has been created in relativistic heavy ion collisions



Hottest Matter on Earth

How tiny the QGP droplet could be?

Correlations & Flow in small systems

System size scan:

Pb+Pb Xe+Xe O+O p-p collisions …

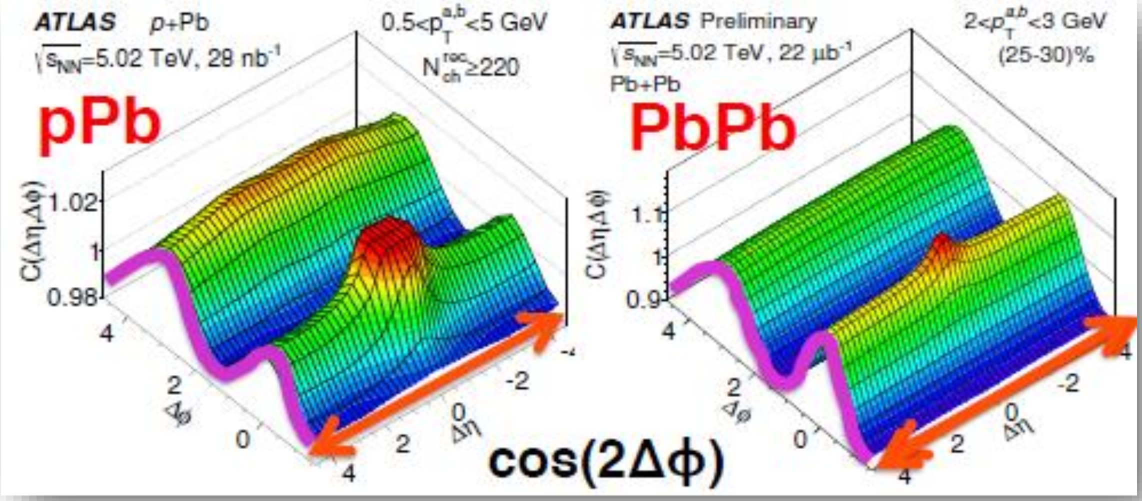
Geometry scan:

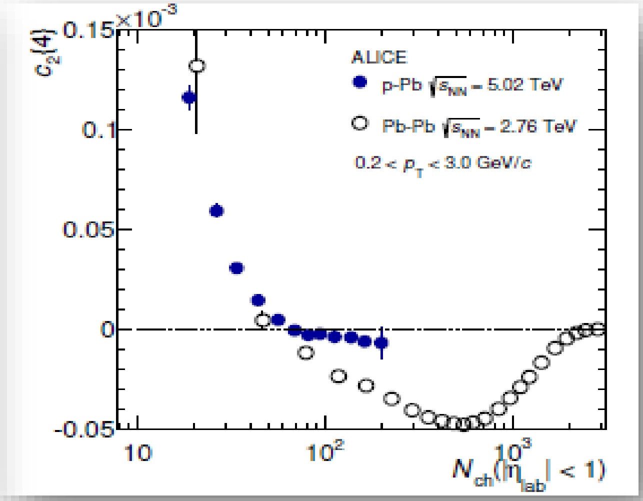
p-Au d+Au He-Au

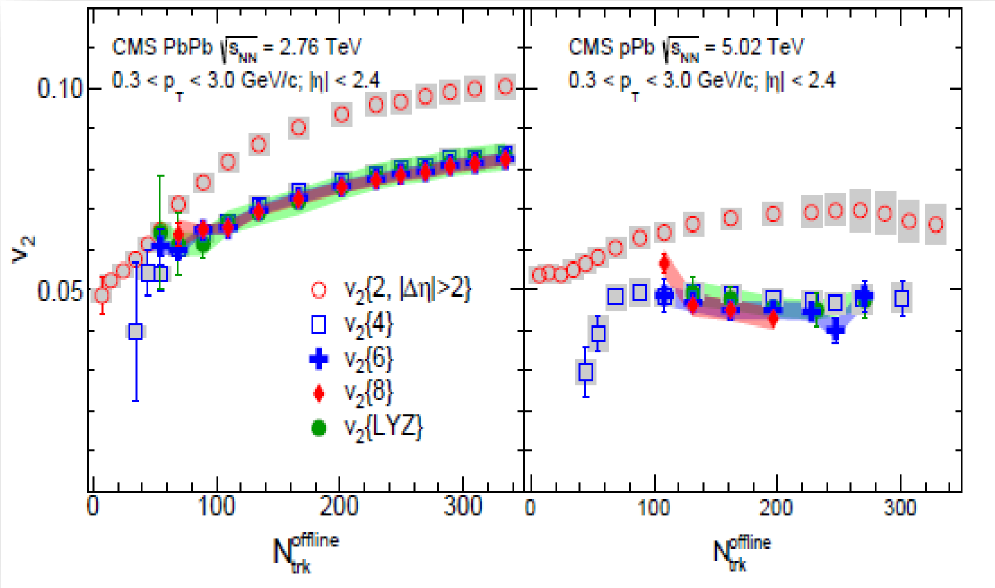
Other collision systems:

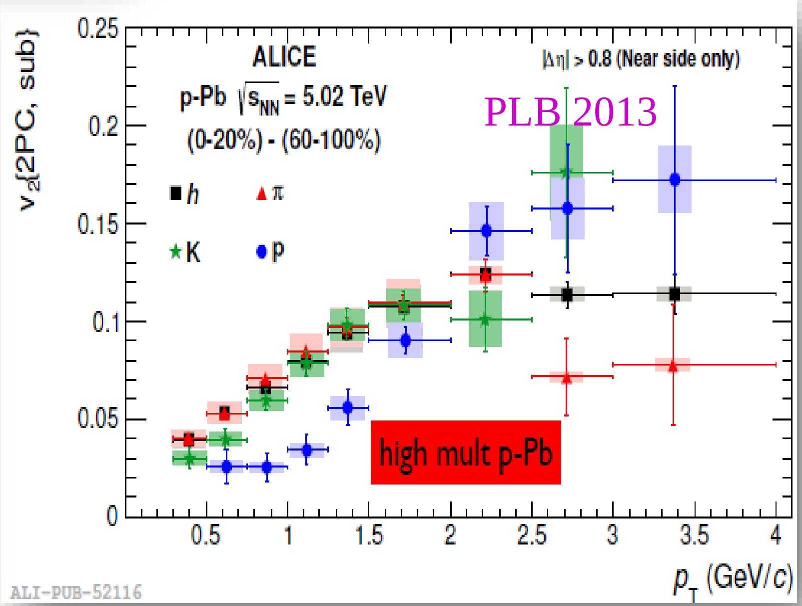
OBSERVABLES	A–A	p–A (high mult.)	pp (high mult.)	pp (low mult.)	UPC	ep	e^+e^- (high mult.)	e^+e^-
Near-side ridge yield	✓ [1,2]	✓ [30,32,33]	✓ [30,31]	✓ [34]	–	✗ [74,75]	✓ [77]	✗ [76]
Anisotropic flow	✓ [3,4]	✓ [36,37,38,39]	✓ [35,37]	✓ [30]	✓ [72,73]	✗ [74,75]	✓ [77]	–
Multiparticle cumulants	✓ [5]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

Correlations & Flow in p-Pb collisions



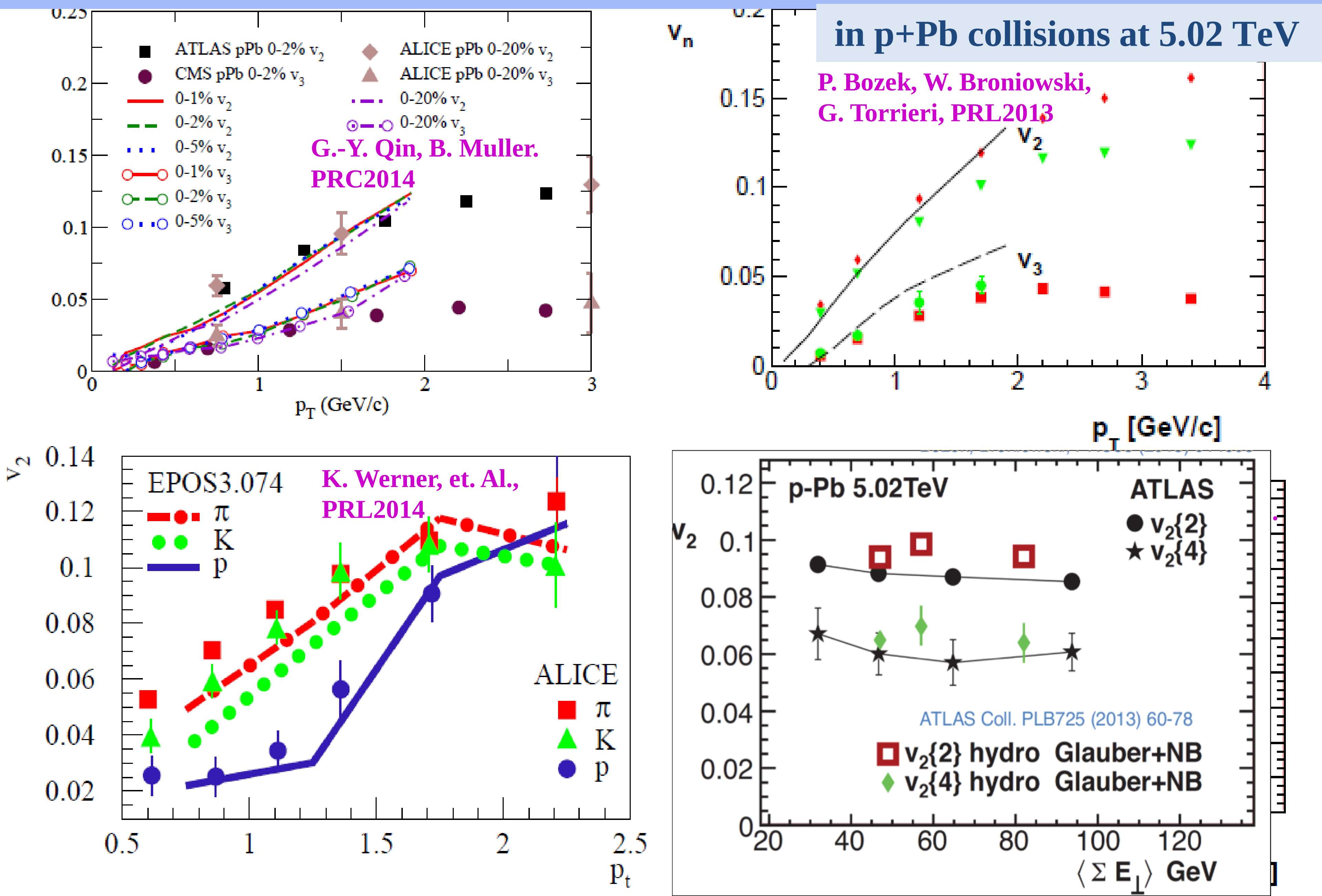






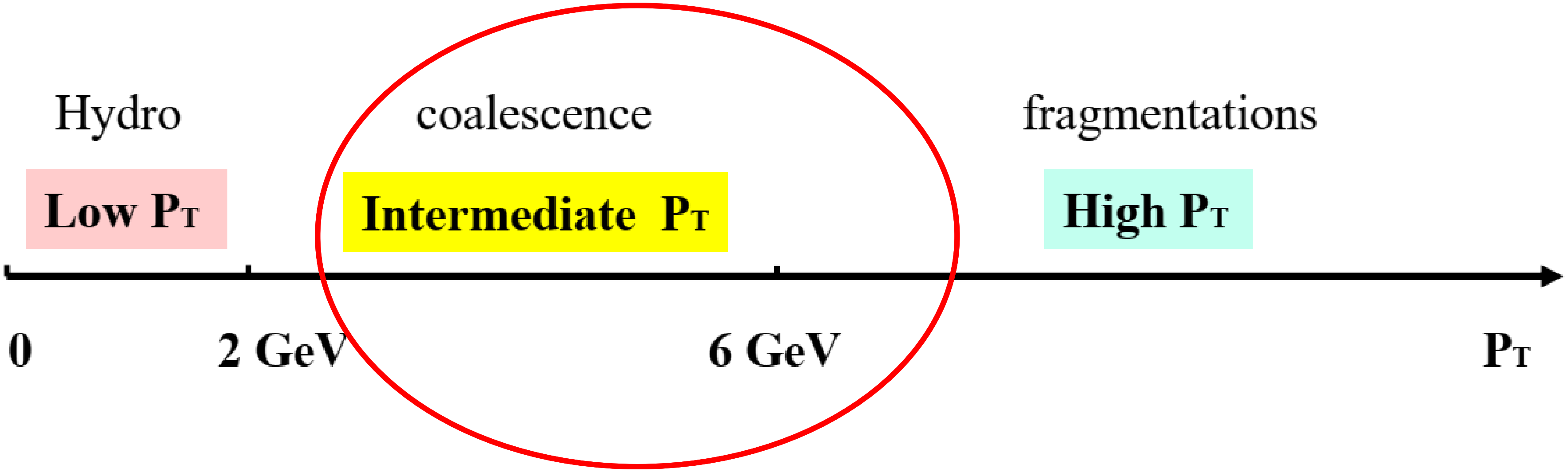
-Many flow-like signals have been observed in high multiplicity p-Pb collisions

Flow in p-Pb -- Hydrodynamics Simulations

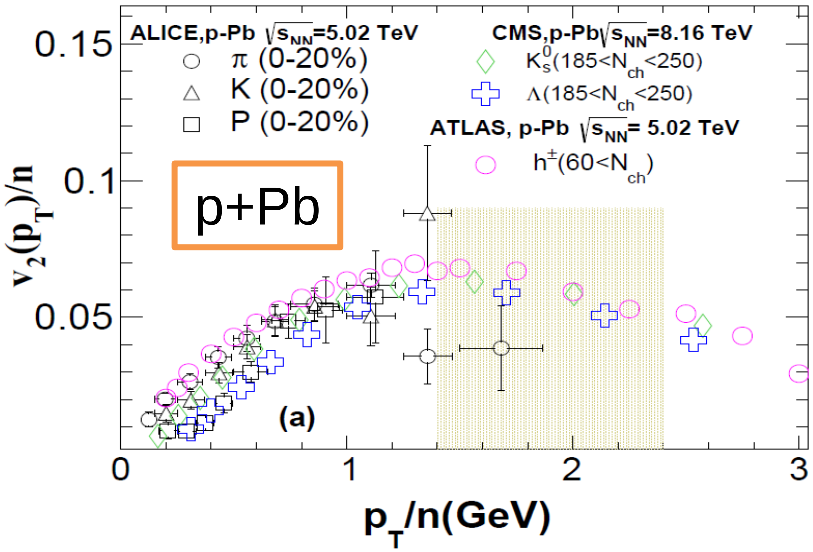


Partonic flow and QGP signals

in large & small systems



NCQ scaling of v_2 in p-Pb collisions



p+Pb collisions

-Where does such approximate NCQ scaling of v_2 come from?

-Is it an indication of partonic degree of freedom?

ALICE data: PLB,726,164 (2013).
CMS data: PRL, 121, 082301 (2018).
ATLAS data: PRC, 96, 024908 (2017).

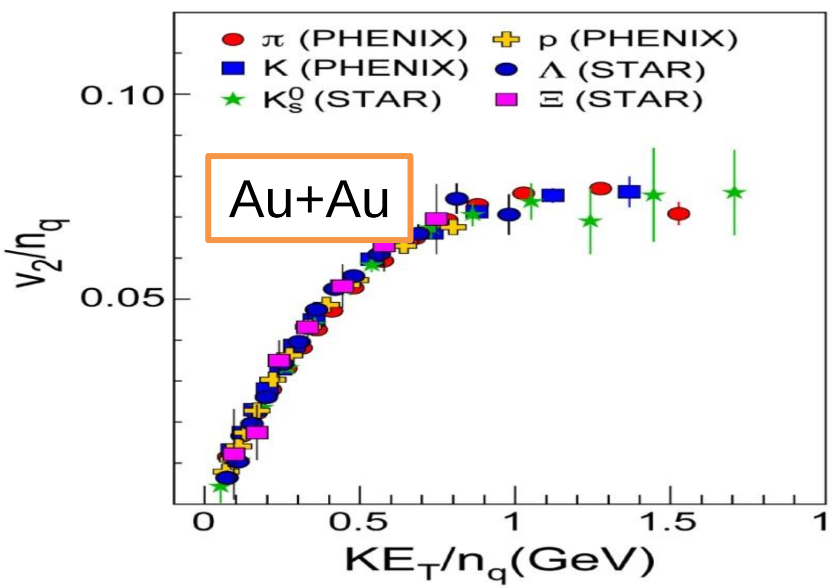
Au+Au collisions

<u>QGP was discovered @RHIC</u>

-strong elliptic flow

-jet quenching

-VCQ scaling of elliptic flow



Simple coalescence for large systems (Au+Au)

- thermal - thermal parton coalescence

$$\frac{dN_M}{d^3\mathbf{P}_M} = g_M \int d^3\mathbf{x}_1 d^3\mathbf{p}_1 d^3\mathbf{x}_2 d^3\mathbf{p}_2 f_q(\mathbf{x}_1,\mathbf{p}_1) f_{\bar{q}}(\mathbf{x}_2,\mathbf{p}_2) \times W_M(\mathbf{y},\mathbf{k}) \delta^{(3)}(\mathbf{P}_M - \mathbf{p}_1 - \mathbf{p}_2)$$

$$\frac{dN_B}{d^3\mathbf{P}_B} = g_B \int d^3\mathbf{x}_1 d^3\mathbf{p}_1 d^3\mathbf{x}_2 d^3\mathbf{p}_2 d^3\mathbf{x}_3 d^3\mathbf{p}_3 f_{q_1}(\mathbf{x}_1,\mathbf{p}_1) \times f_{q_2}(\mathbf{x}_2,\mathbf{p}_2) f_{q_3}(\mathbf{x}_3,\mathbf{p}_3) W_B(\mathbf{y}_1,\mathbf{k}_1;\mathbf{y}_2,\mathbf{k}_2) \times \delta^{(3)}(\mathbf{P}_B - \mathbf{p}_1 - \mathbf{p}_2 - \mathbf{p}_3)$$

Complicated coalescence for small systems (p+Pb,p+p)

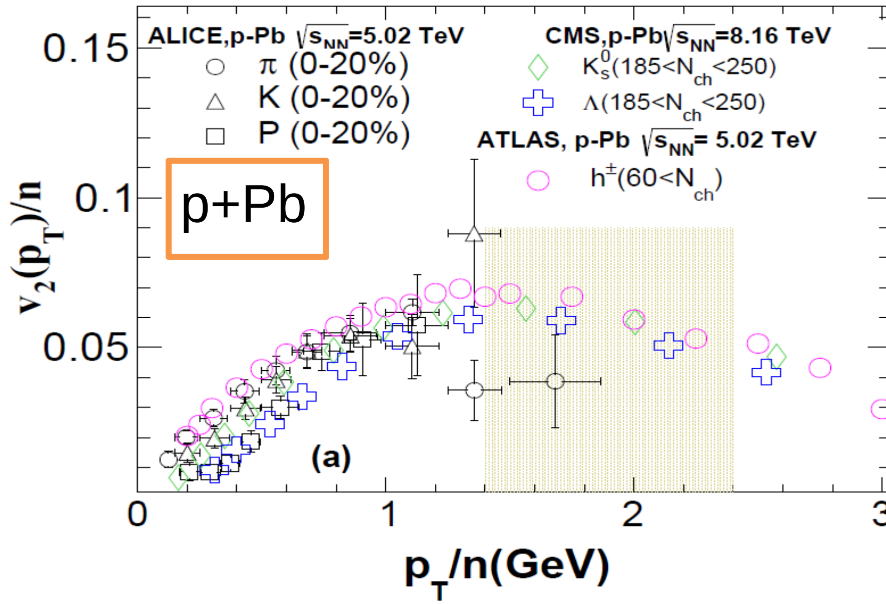
-the effects from jet/mini-jets

-fragmentations from high p_T become important

Complicated Coalescence processes:

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

Frag contributes more at intermediate p_T



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):

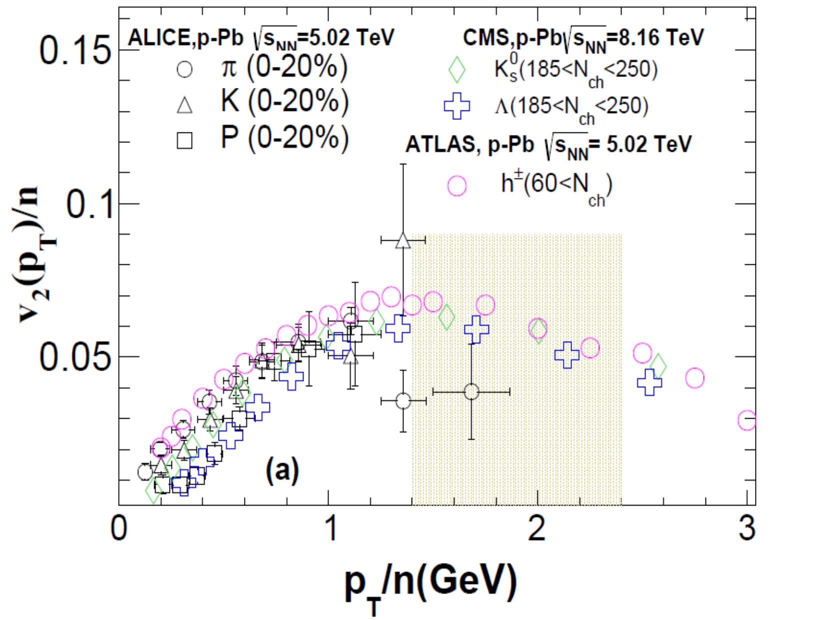
-generated by coalescences model including thermal-thermal, thermal-hard & hard-hard parton coalescence.

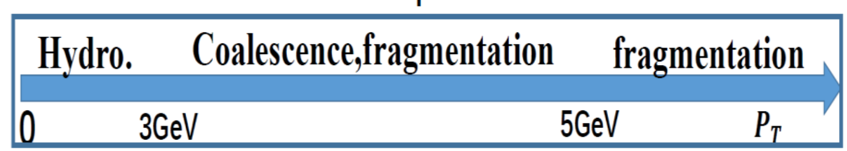
Fragmentation hadrons (LBT):

-*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:

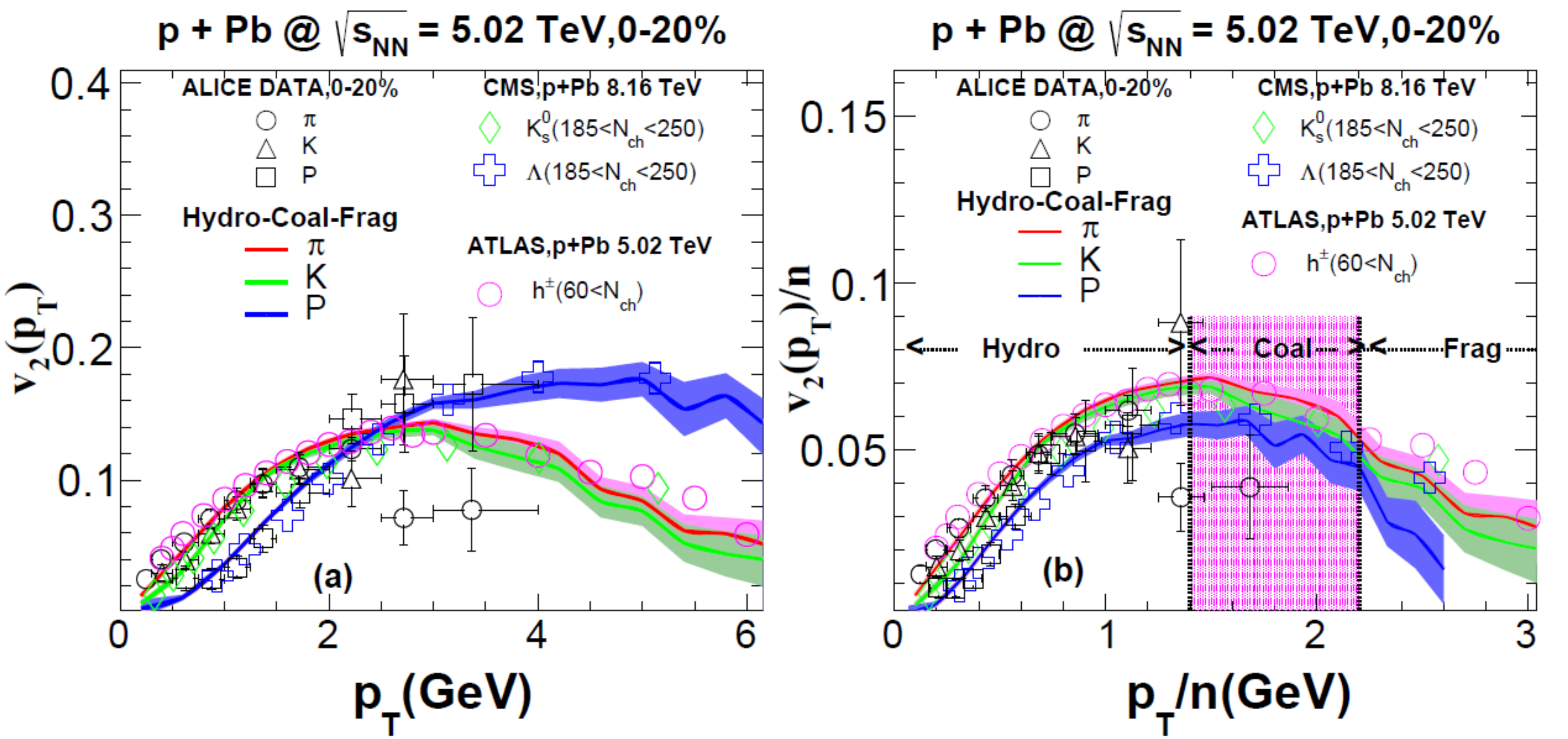
-*Thermal hadrons* from hydro with $P_T < P_1$.

-*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 & hint partonic degree of freedom

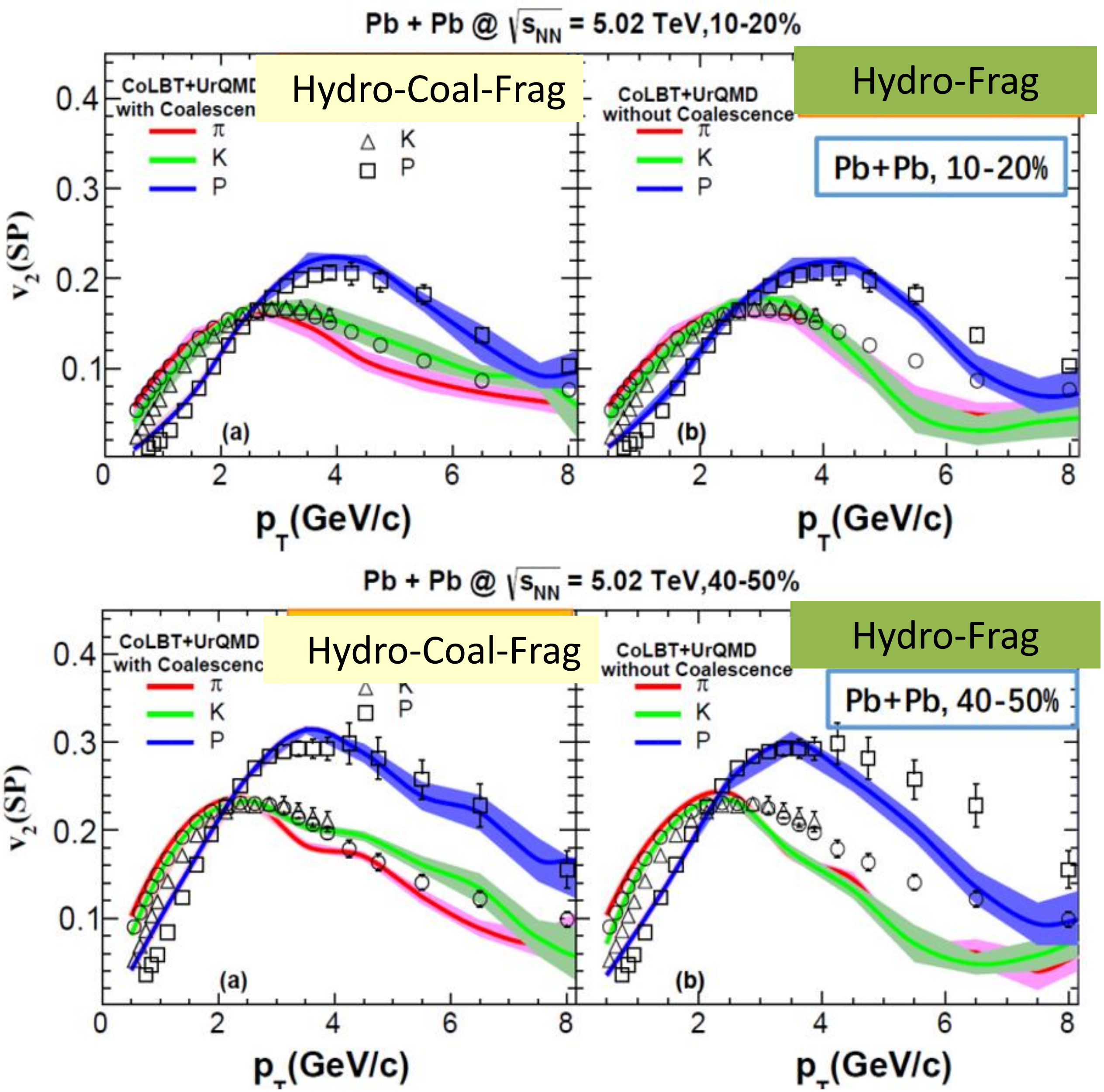


-At intermediate p_T, Hydro-Coal-Frag model obtains an approximate NCQ scaling as shown by the data.

Strongly indication of partonic degree of freedom in small system !

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

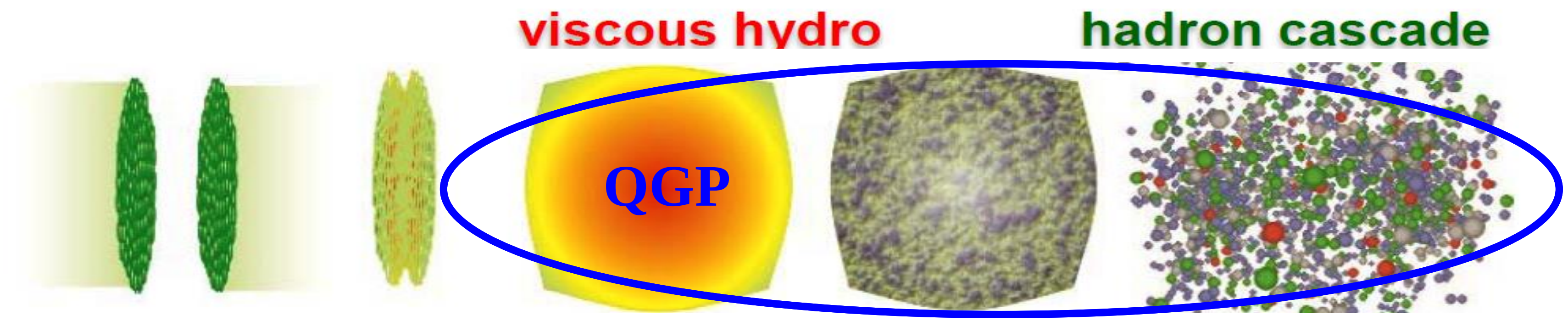
V_2 & the importance of quark coalescence



-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

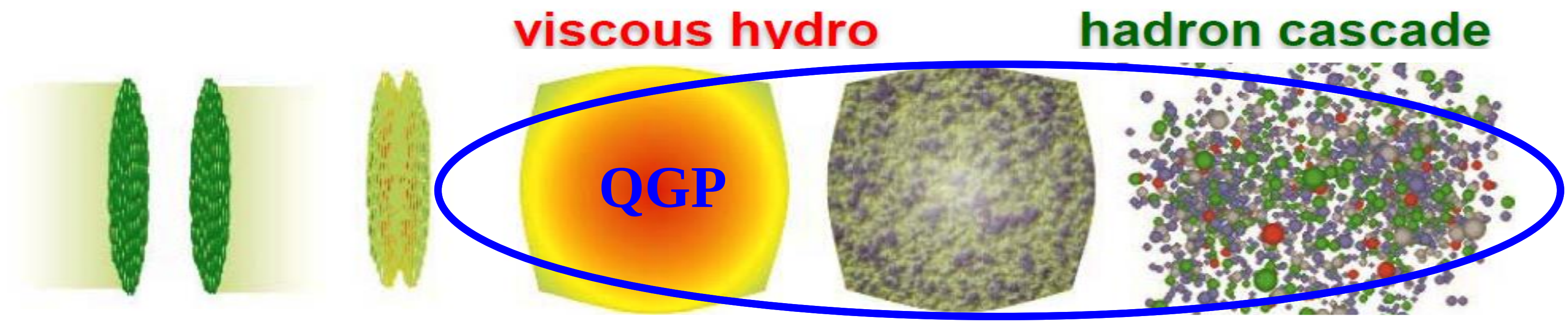
thermal-hard parton Coalescence & Fragmentation Breaks up the NCQ scaling of v2 in Pb+Pb collisions

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

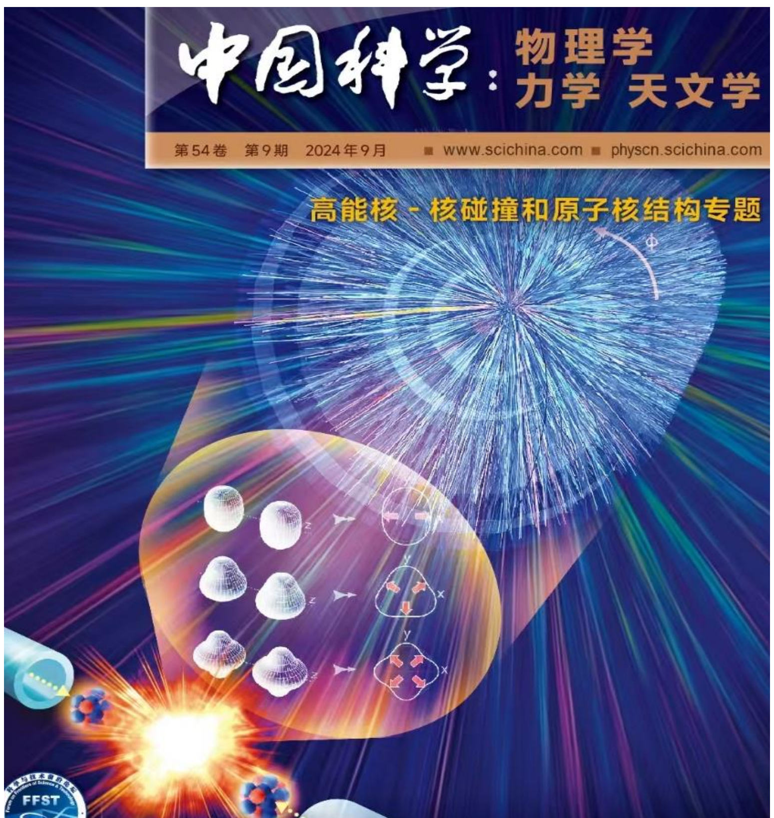


Theory: Hydrodynamics & hybrid approach are powerful tool to simulate the QGP fireball evolution and study its properties

Experiment: various flow observable have been measured quantitatively described/predicted by hydro



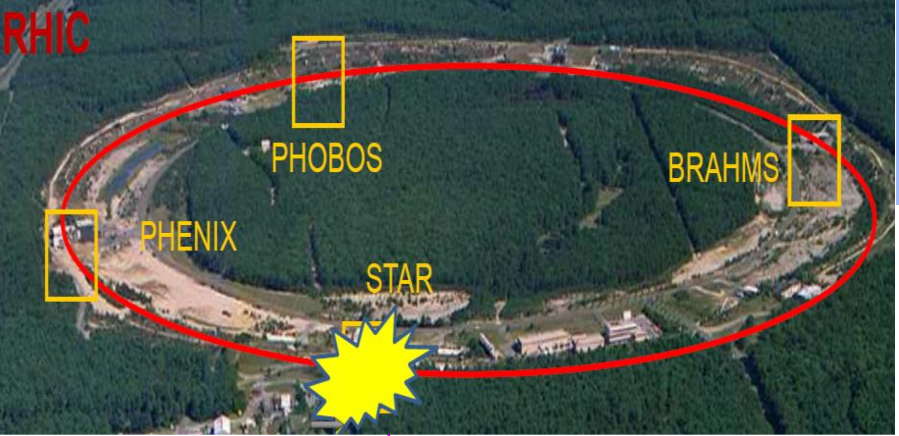
Theory: Hydrodynamics & hybrid approach are powerful tool to simulate the QGP fireball evolution and study its properties



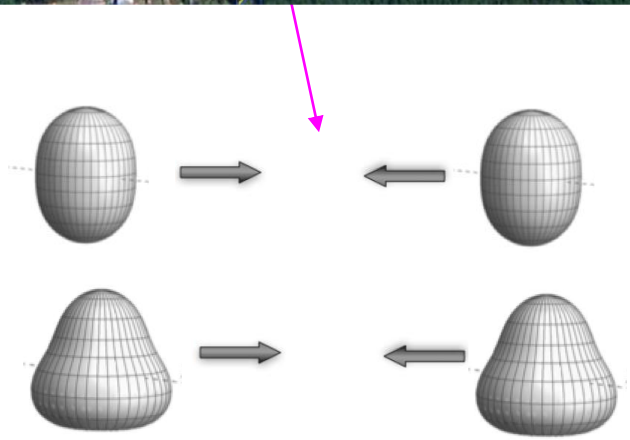
-We are ready to focus on the initial state of the QGP

nuclear structure of colliding nuclei

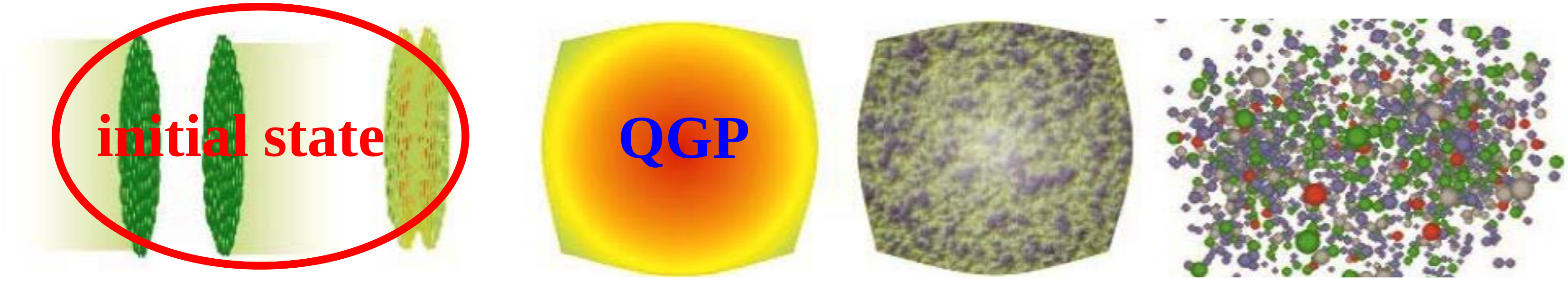
Probe nuclear structure with relativistic heavy ion collisions



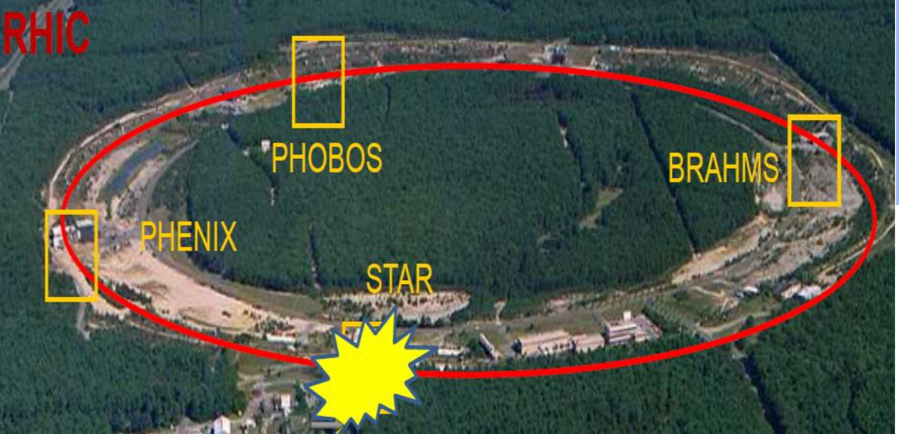
- Relativistic heavy collisions
  start from nuclei



initial state with deformation

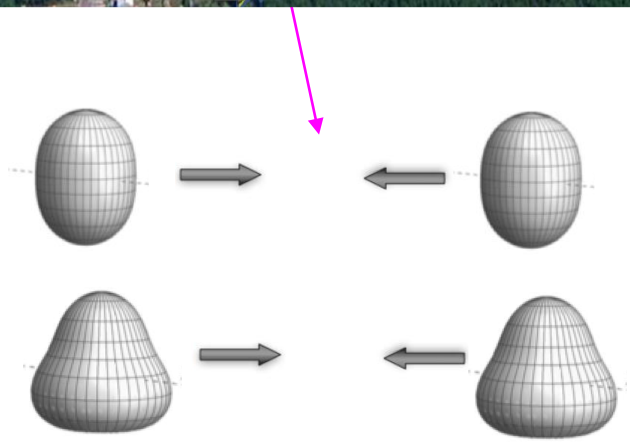


Probe nuclear structure with relativistic heavy ion collisions

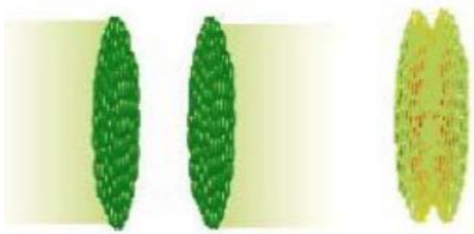


- Relativistic heavy collisions start from nuclei

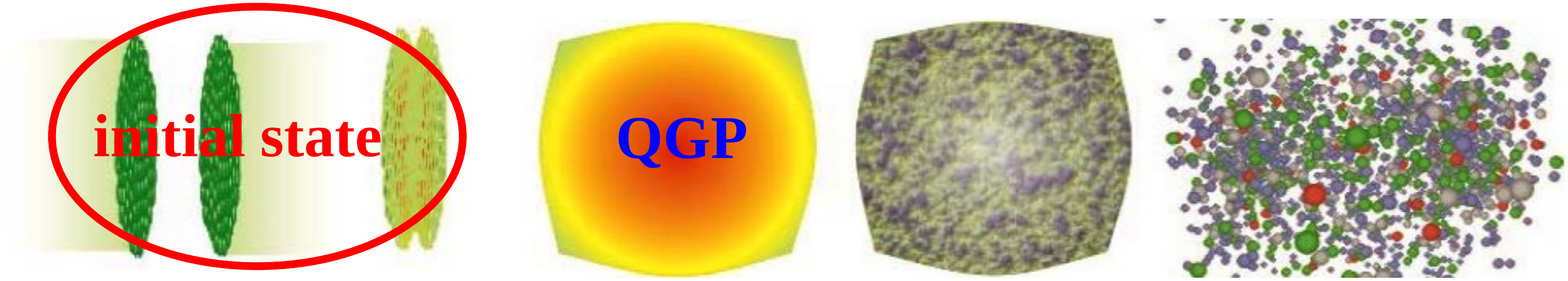
-Collision time < 10^{-24} s directly probe the ground state of nuclei



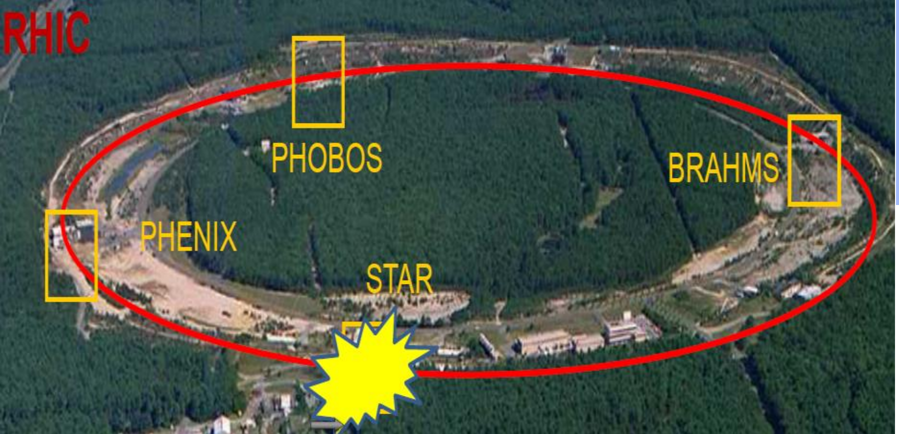
initial state with deformation

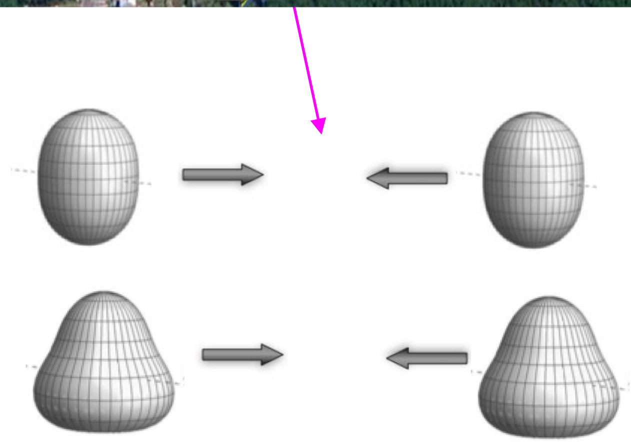


Collision time < 10^{-24} s



Probe nuclear structure with relativistic heavy ion collisions

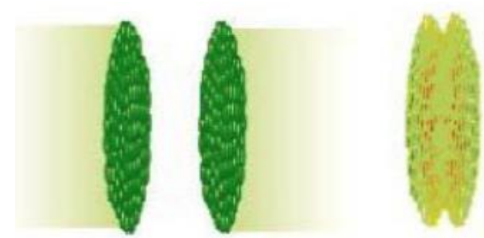




initial state with deformation

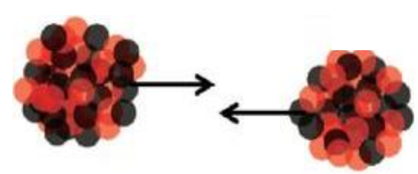
- Relativistic heavy collisions
  start from nuclei

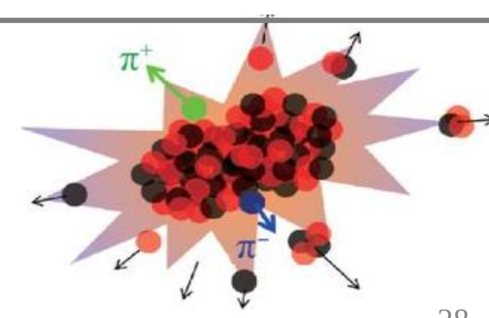
-Collision time < 10^{-24} s
  directly probe the ground state of nuclei

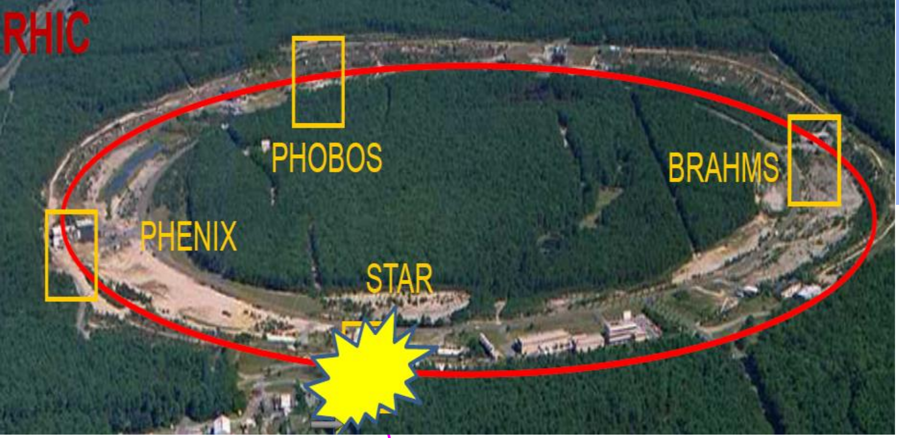


Collision time < 10^{-24} s

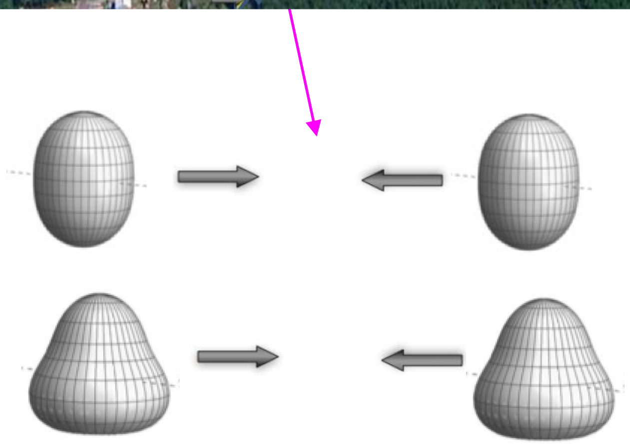
heavy ion collision at intermediate energies breaks up / excites nuclei during the collisions







Probe nuclear structure with relativistic heavy ion collisions



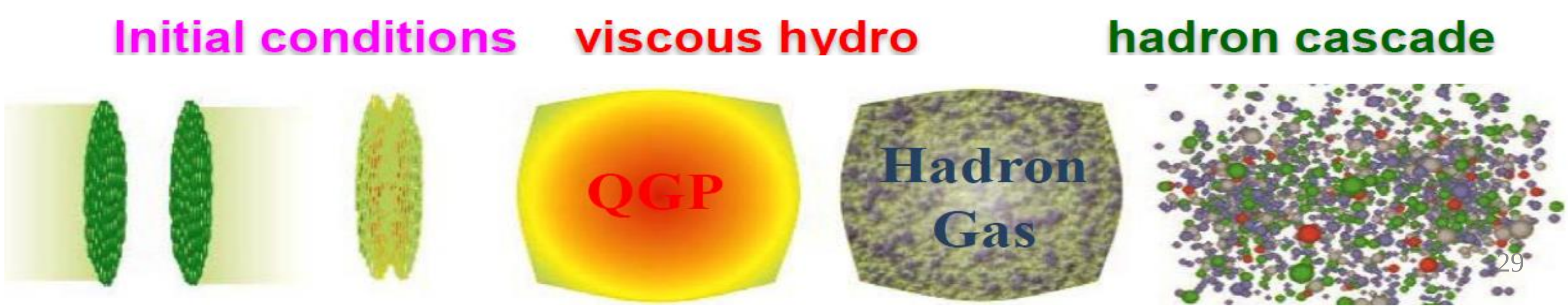
initial state with deformation

- Relativistic heavy collisions
  start from nuclei

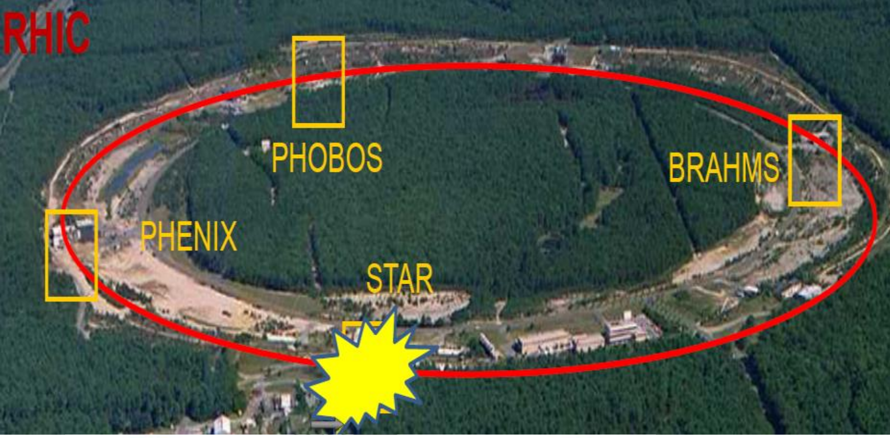
-Collision time < 10^{-24} s
  directly probe the ground state of nuclei

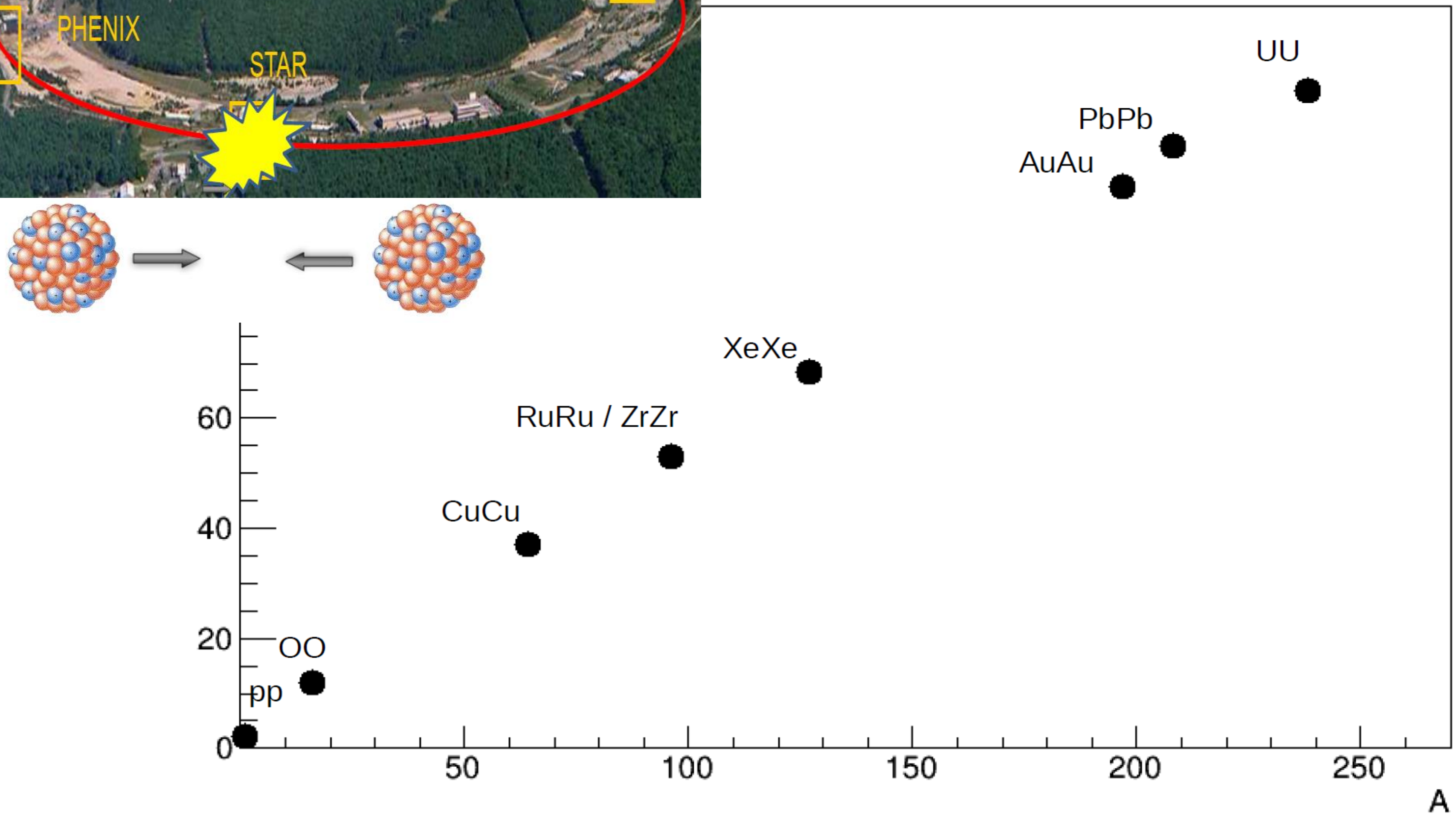
-Well calibrated calculations for QGP evolution; to focus on the initial state

Well calibrated calculations



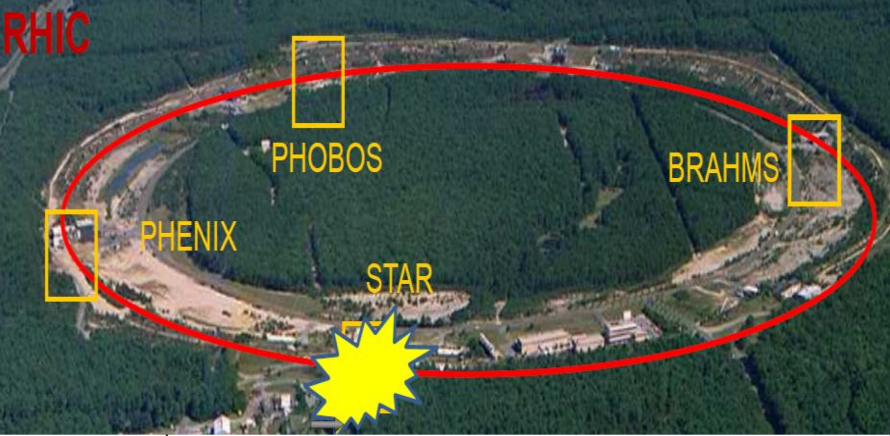
Rich collision systems at RHIC & the LHC

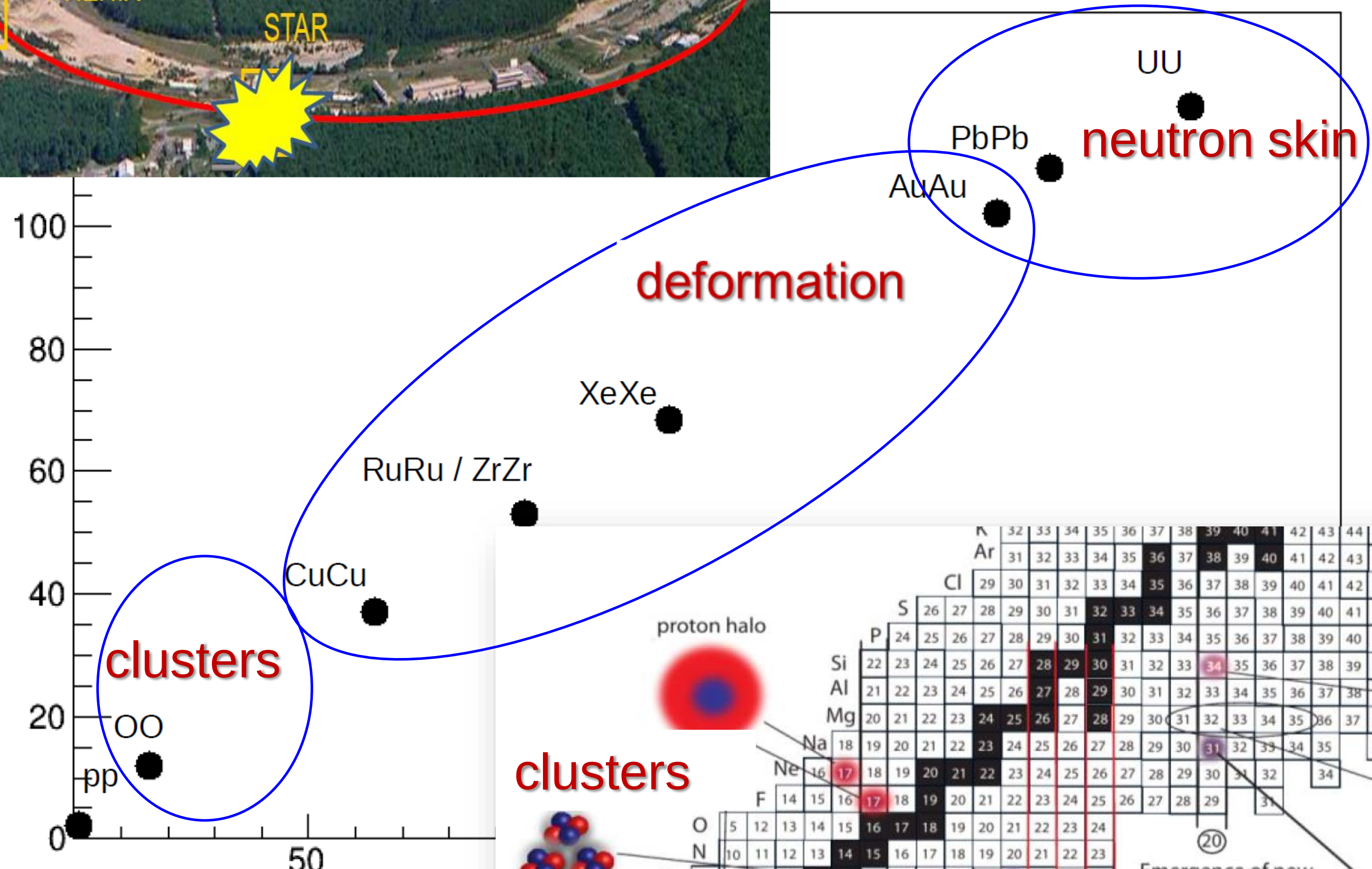


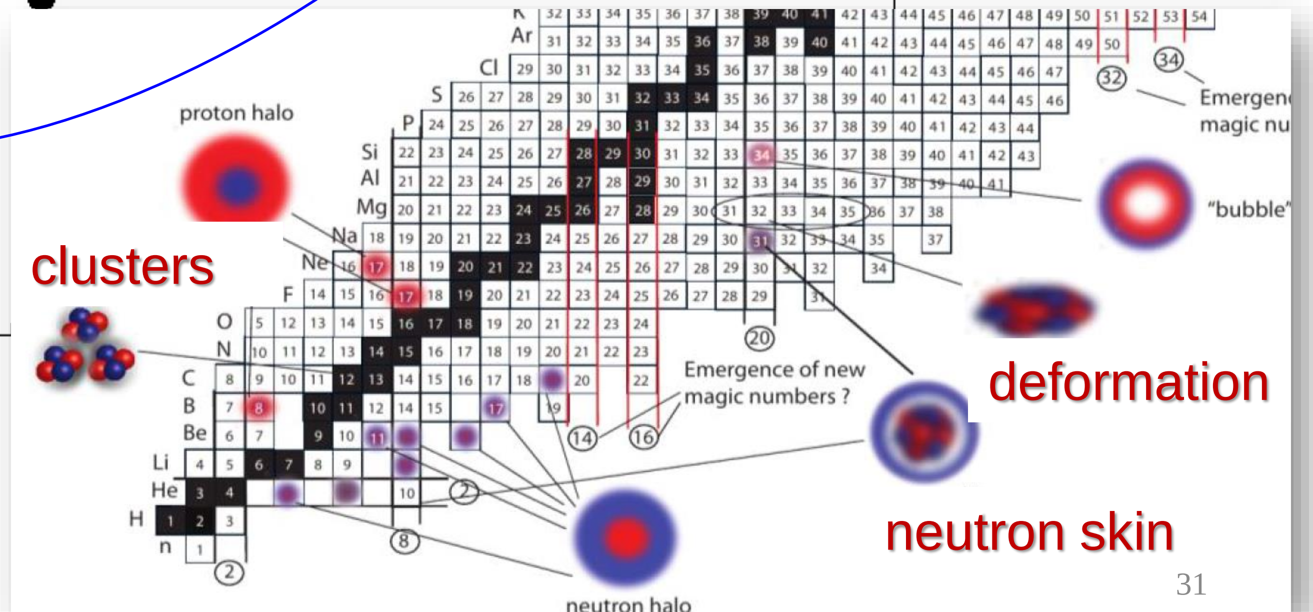


^{197}Au+^{197}Au、 ^{238}U+^{238}U、 ^{208}Pb+^{208}Pb、 ^{129}Xe+^{129}Xe、 ^{96}Zr+^{96}Zr、 ^{96}Ru+^{96}Ru、 ^{64}Cu+^{64}Cu 、 ^{16}O+^{16}O 、 p+^{208}Pb、 p+p … …

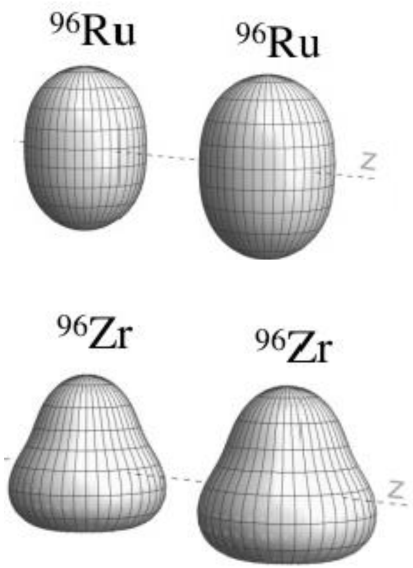
Rich collision systems at RHIC & the LHC

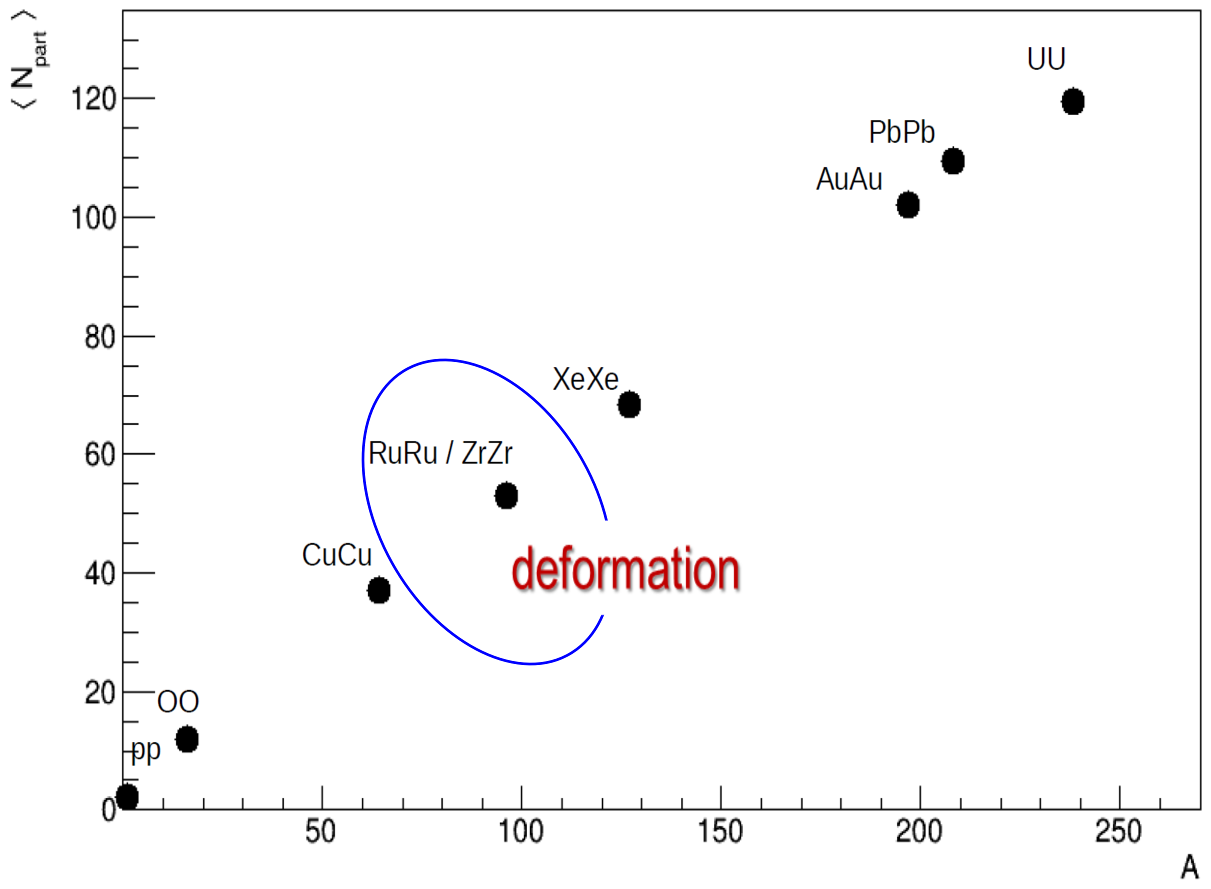




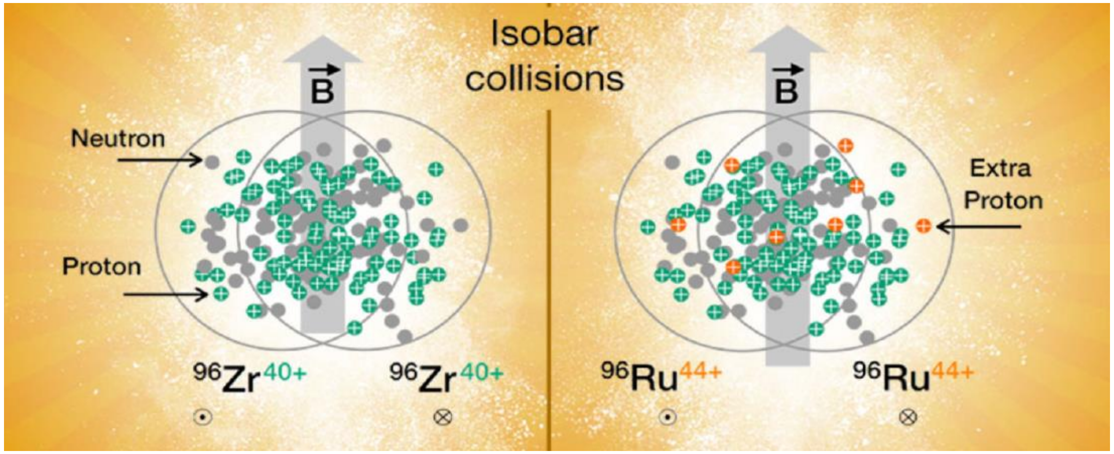


Study the deformation of ^{96}Ru and ^{96}Zr at RHIC isobar run





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



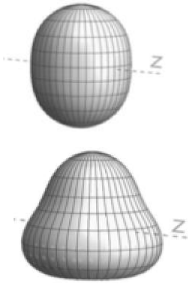
- To search the Chiral Magnetic Effect (CME)

- 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: $\beta_2 = \frac{4\pi}{3ZR_0^2}\sqrt{\frac{B(E2)\uparrow}{e^2}}$, $\beta_3 = \frac{4\pi}{3ZR_0^3}\sqrt{\frac{B(E3)\uparrow}{e^2}}$

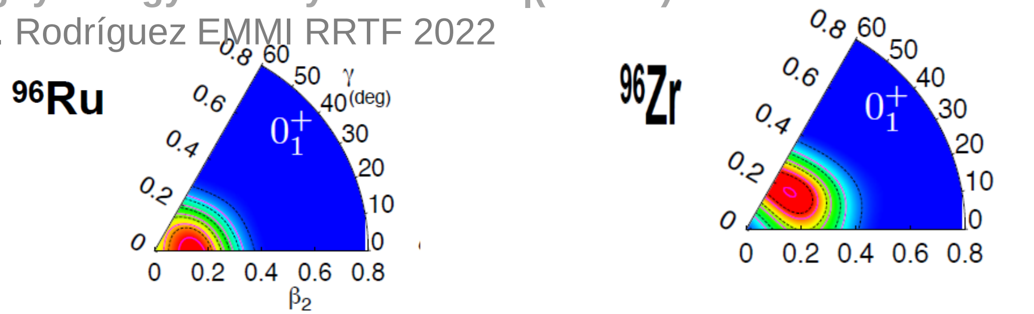
	β_2	$E_{2_1^+}$ (MeV)	β_3	$E_{3_1^-}$ (MeV)
^{96}Ru	0.154	0.83	-	3.08
^{96}Zr	0.062	1.75	0.202,0.235,0.27	1.90



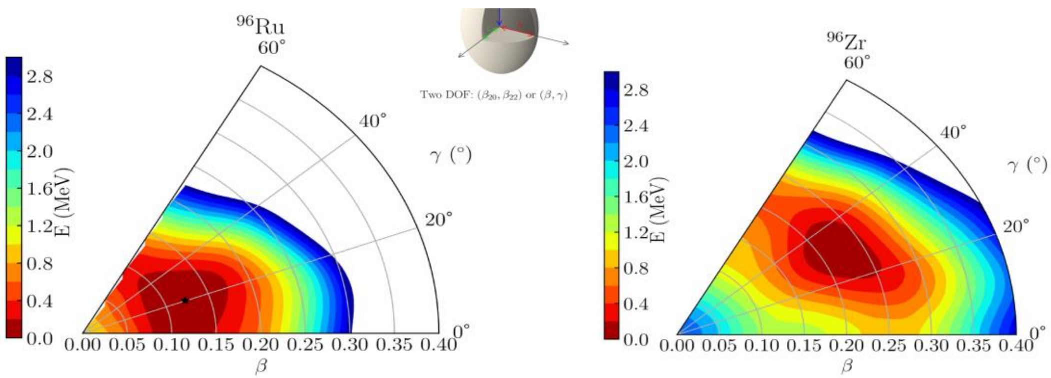
ADNDT107,1 (2016) ADNDT80,35(2002)

Deformation of ^{96}Ru & ^{96}Zr — personal comments

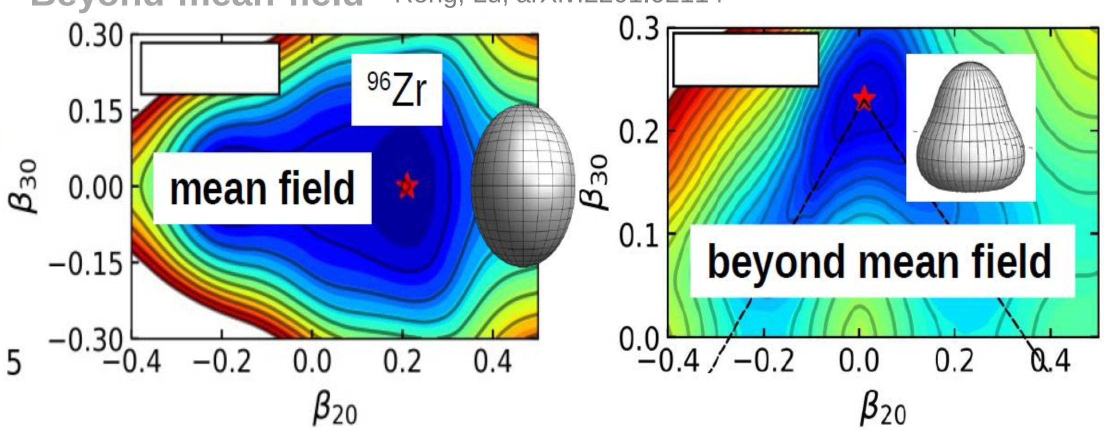
Gogny energy density functional |(Tiaxial)
T R. Rodríguez EMMI RRTF 2022

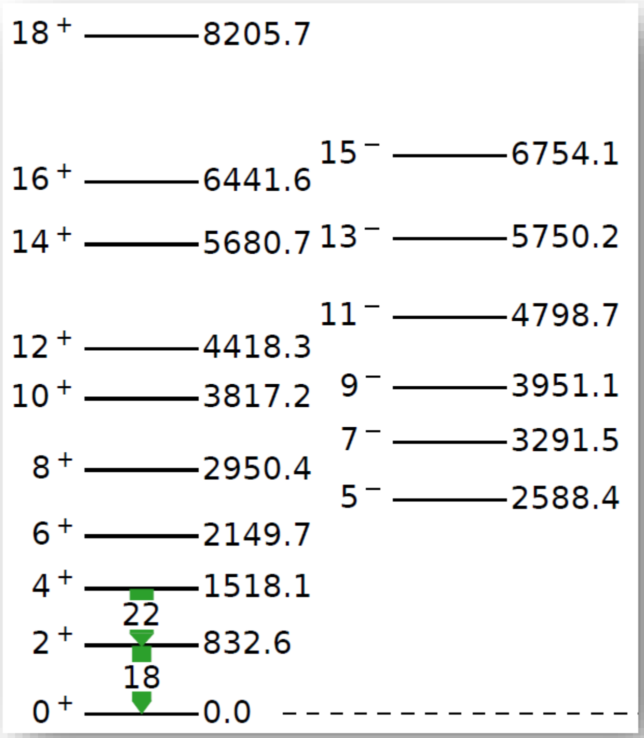


Skyrme EDF W Ryssens EMMI RRTF 2022



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

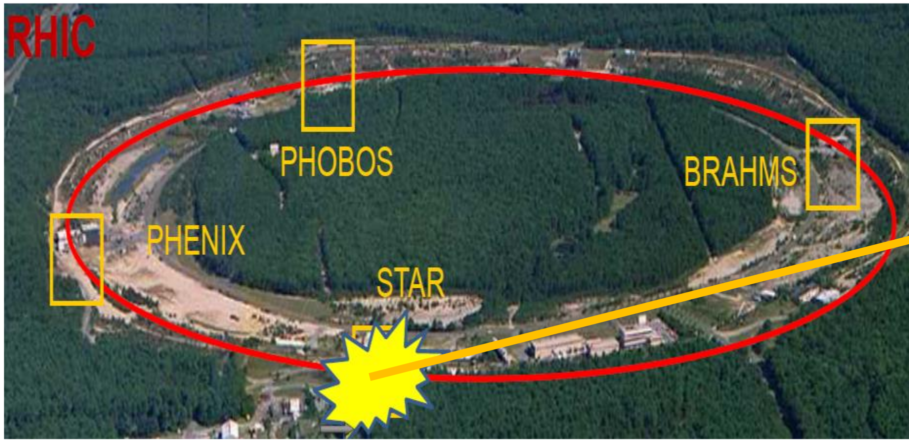


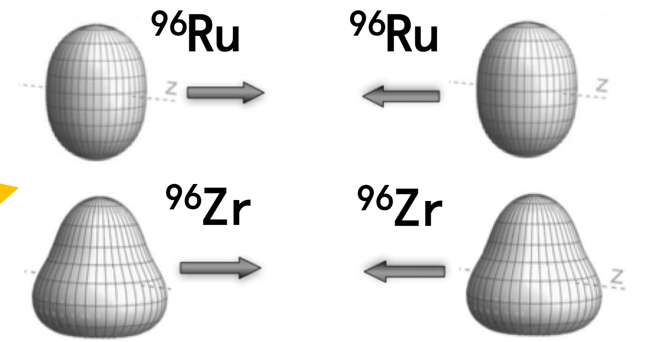


Nuclear structure physics obtain the deformation information from the spectrum with certain model calculations
(not directly image the deformation in position space)

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

Relativistic heavy ion collisions





initial conditions:
(deformation / mass distributions)

Initial conditions (TRENTO)

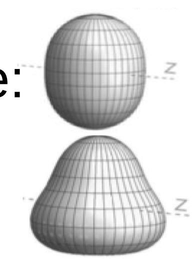
- Sample nucleon position in deformed nuclei with:

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

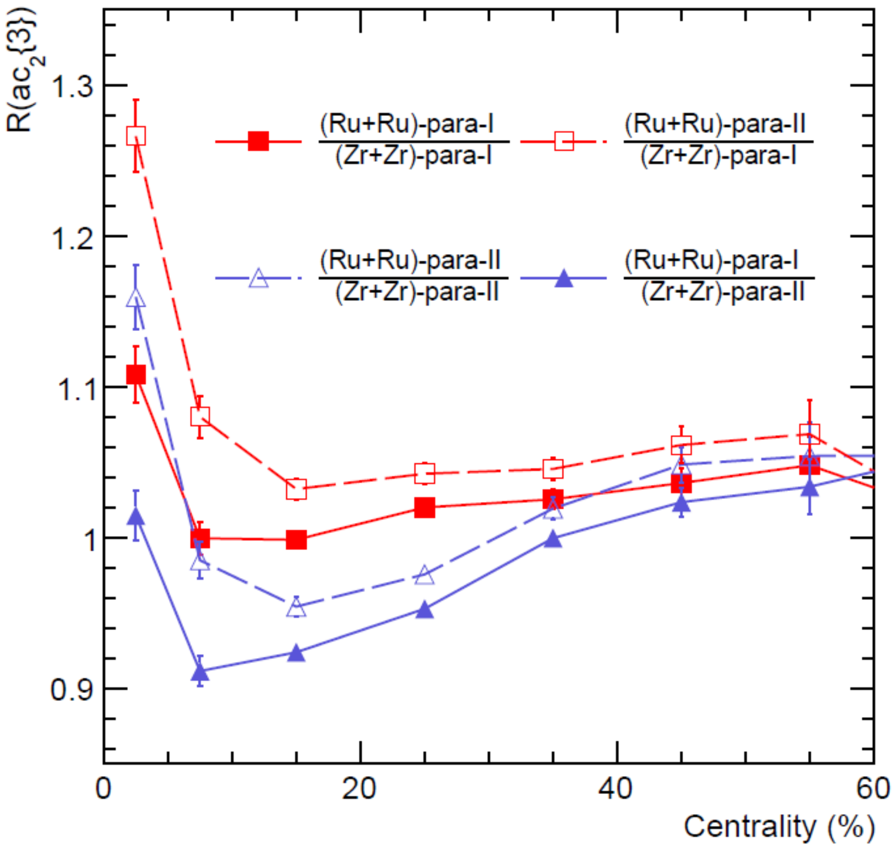
$$R(\theta,\phi) = R_0\left(1 + \beta_2[\cos\gamma Y_{2,0} + \sin\gamma Y_{2,2}] + \beta_3 \sum_{m=-3}^{3} \alpha_{3,m} Y_{3,m} + \beta_4 \sum_{m=-4}^{4} \alpha_{4,m} Y_{4,m}\right)$$

Quadrupole:

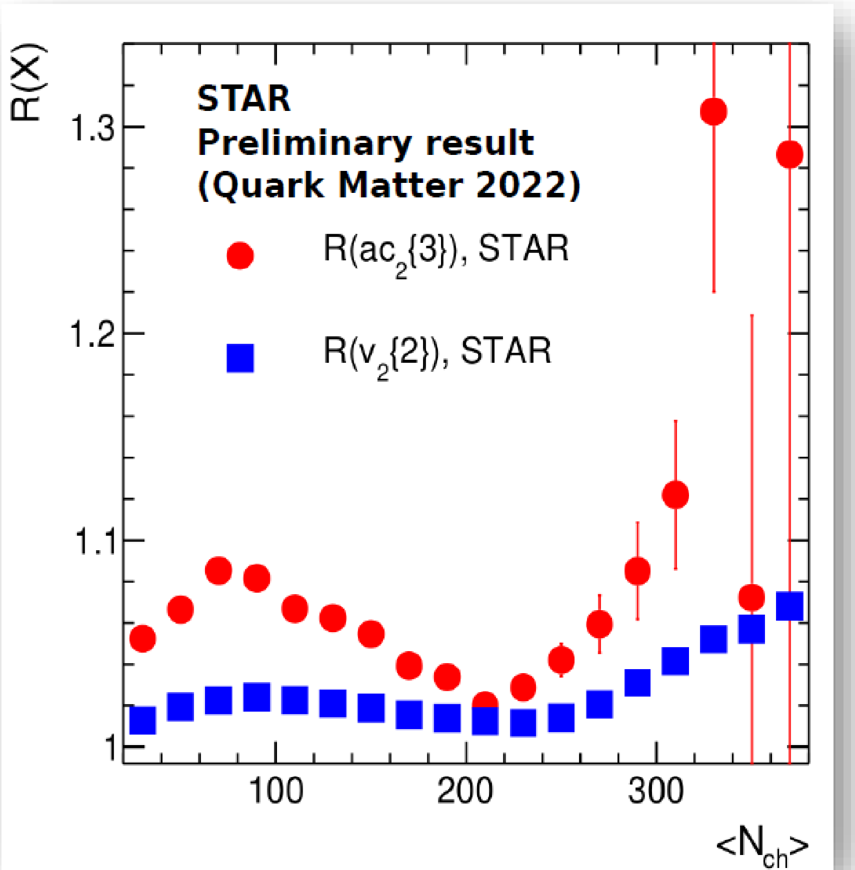
Octupole:



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



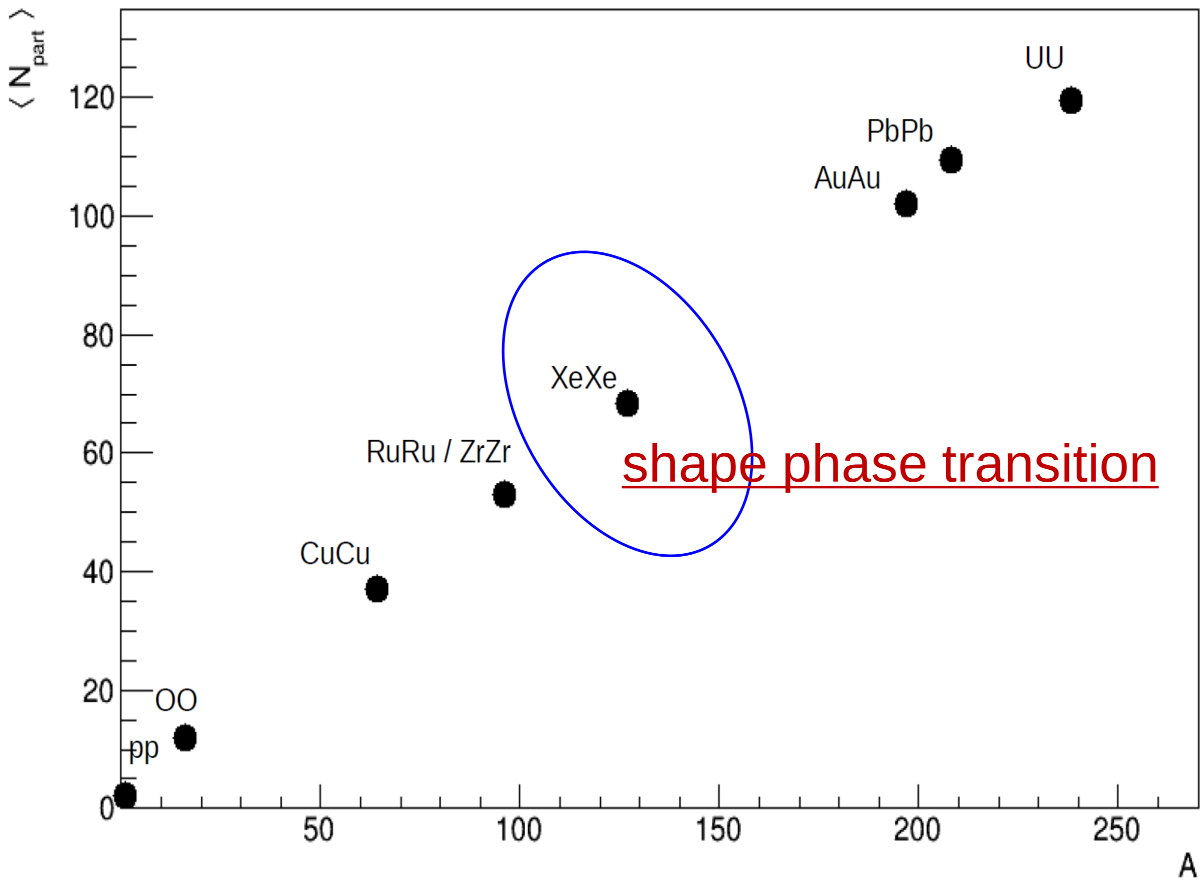
$$ac_2\{3\} = \langle v_2^2 v_4 \cos 4(\Phi_2 - \Phi_4)\rangle,$$



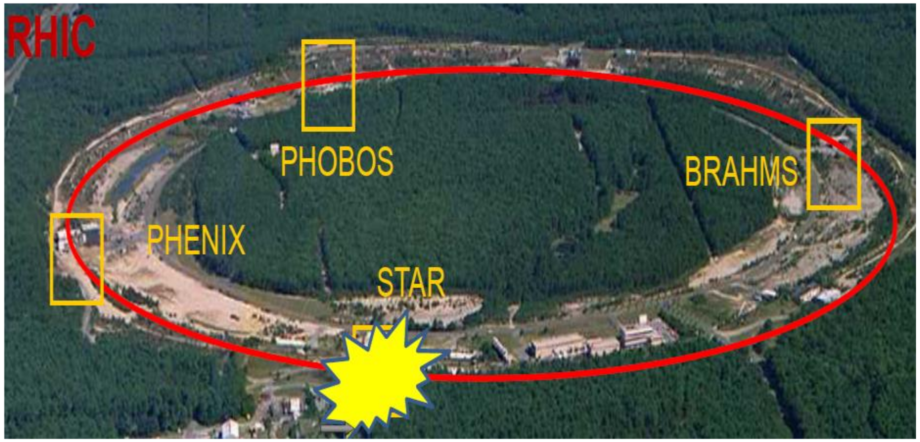
$ac_2\{3\}$ is sensitive to quadrupole and octupole deformations

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

Probe the shape phase transition with Xe +Xe collisions



The Phase Transition



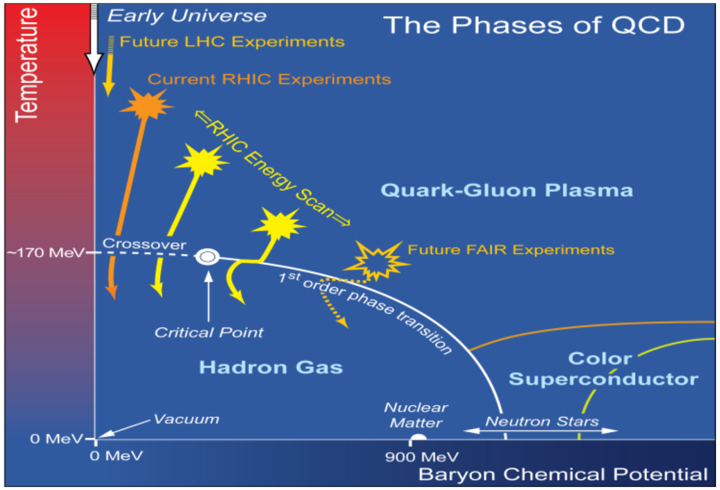
$^{129}Xe+^{129}Xe$ collision

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

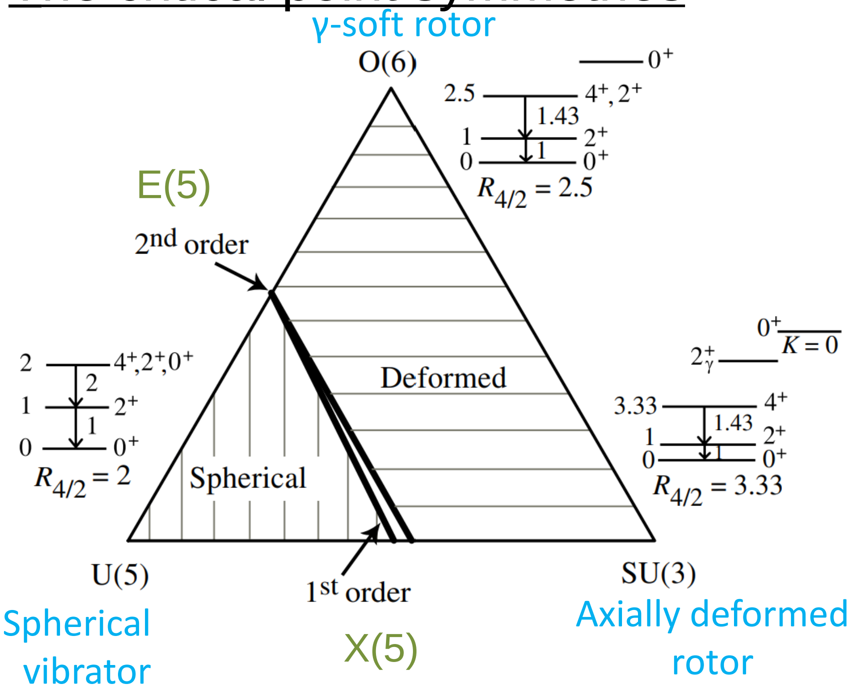
S. Zhao, H. Xu, Y. Zhou, Y. Liu, H. Song, arXiv: 2403.07441 [nucl-th]

Relativistic heavy ion collisions

-mainly aim to explore QCD Phase Transition



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:

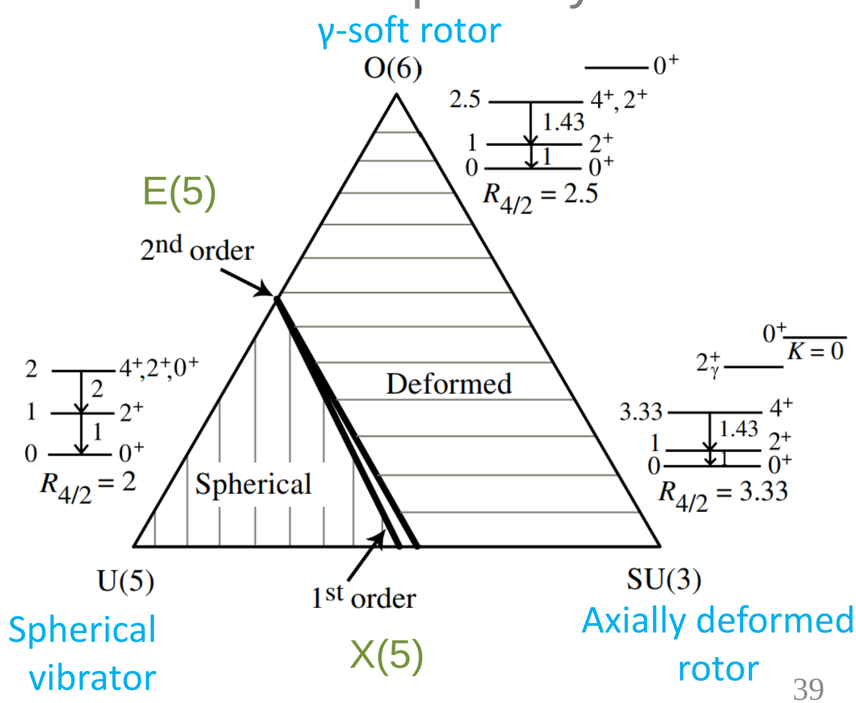
-Within the the framework of the interacting boson model (IBM), the Xe isotopes undergo a shape phase transition from a *γ*-soft rotor to a spherical vibrator

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).

-the critical point is described by the *E*(5) symmetry, associated with a 2nd order phase transition

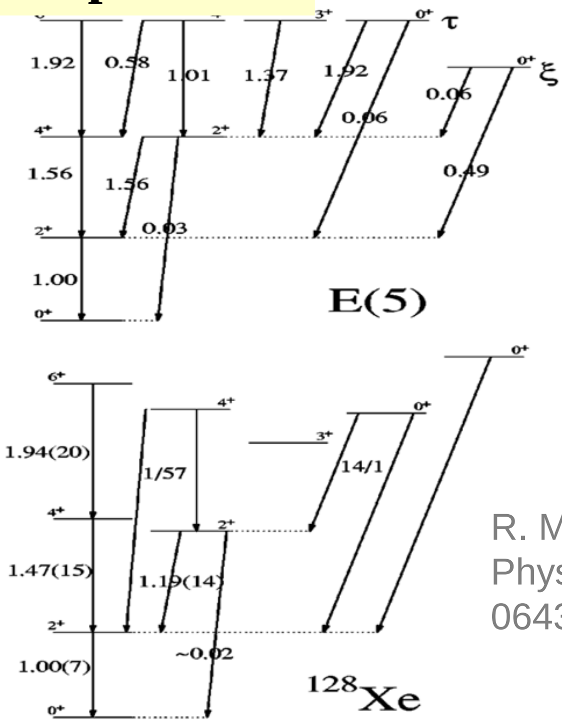
F. Iachello, Phys. Rev. Lett. 87, 052502 (2001).
F. Iachello, Phys. Rev. Lett. 85, 3580 (2000).

The critical point symmetries



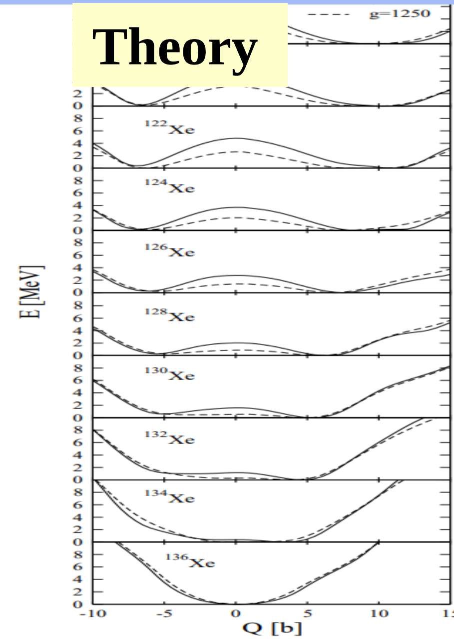
E(5) symmetry near $^{128-130}$Xe

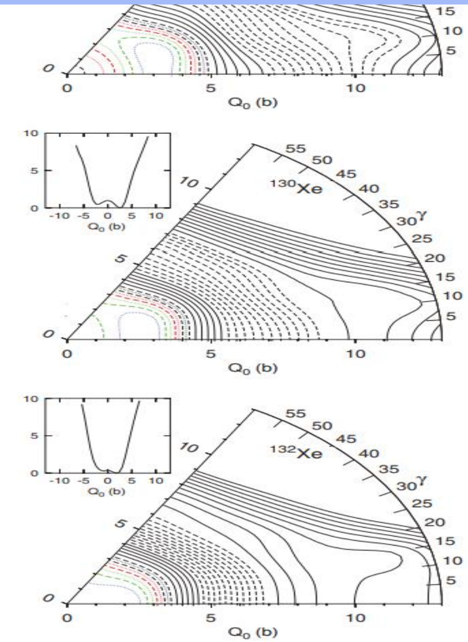
Experiment



R. M. Clark, et. al. Phys. Rev. C 69, 064322 (2004)

Theory





R. Rodriguez-Guzman, et. al. Phys. Rev. C 76, 064303 (2007)

L.M.Robledo, et. al. Phys. Rev.C 78 (2008) 034314

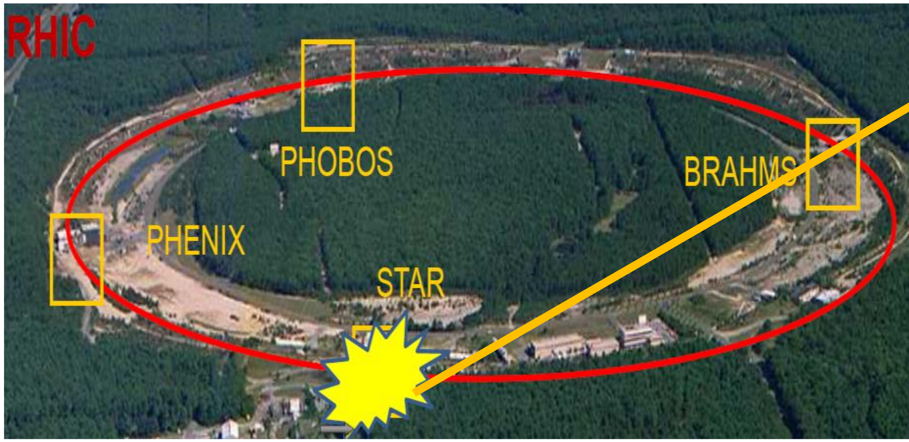
the measured energy spectroscopy of ^{128}Xe agrees well with the E(5) predic. (the normalized transition strengths, the branching ratios …)

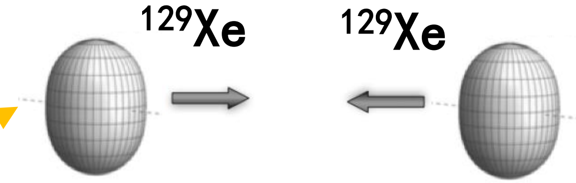
-Model calculations indicate a critical point of the second-order shape phase transition (E(5) symmetry) lies in the vicinity of $^{128-130}$Xe, associated with a γ-soft deformation

→Exploring the 2nd order shape transition of Xe isotope with Xe+Xe collisions at the LHC and **NICA**

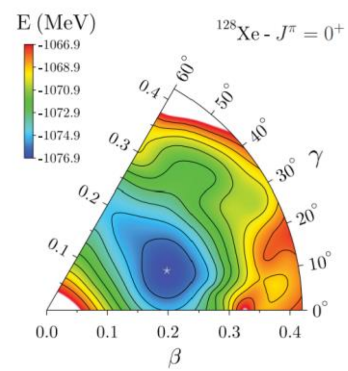
Probe the γ-soft deformation of ^{129}Xe

Relativistic heavy ion collisions



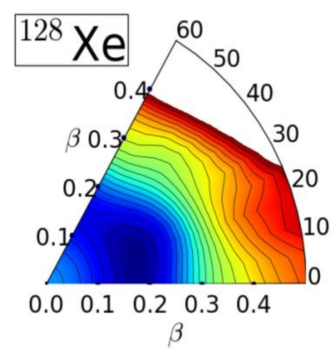


initial conditions:
(deformation / mass distributions)



Rigid triaxial deformation (γ=30º)

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



γ-soft (flat distribution in 0≤γ≤60º)

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

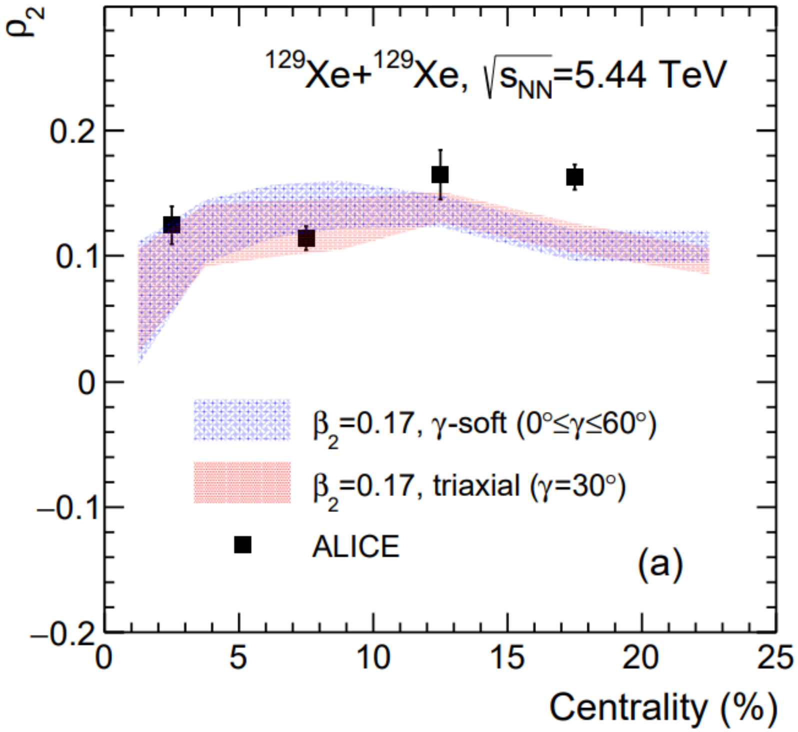
Initial conditions (TRENTO)

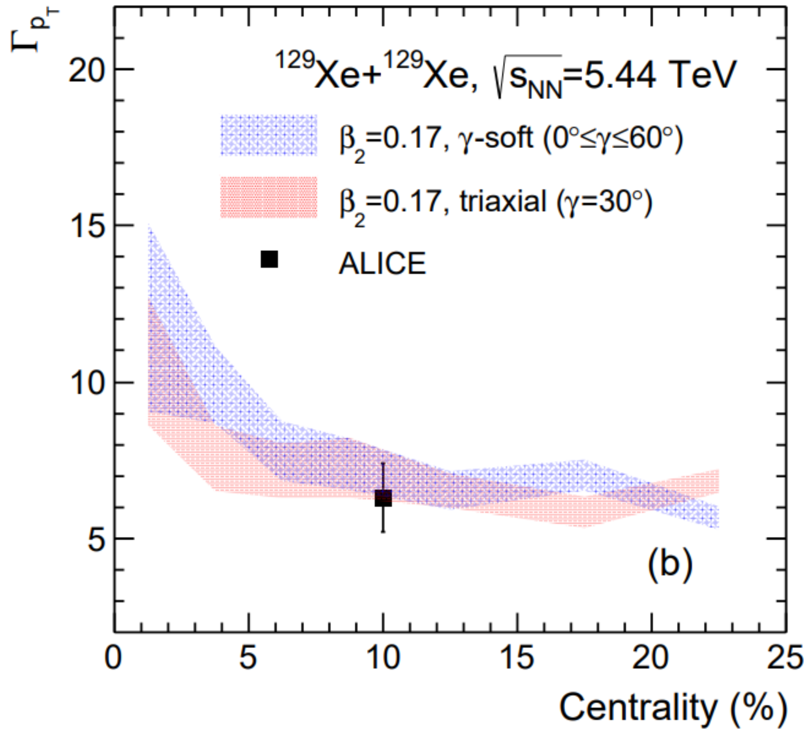
- Sample nucleon position in deformed nuclei with:

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

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

3-particle correlation





$$\rho_2 \equiv \frac{\mathrm{cov}(v_2\{2\}^2, [p_T])}{\sqrt{\mathrm{var}(v_2\{2\}^2)}\sqrt{\mathrm{var}([p_T])}}.$$

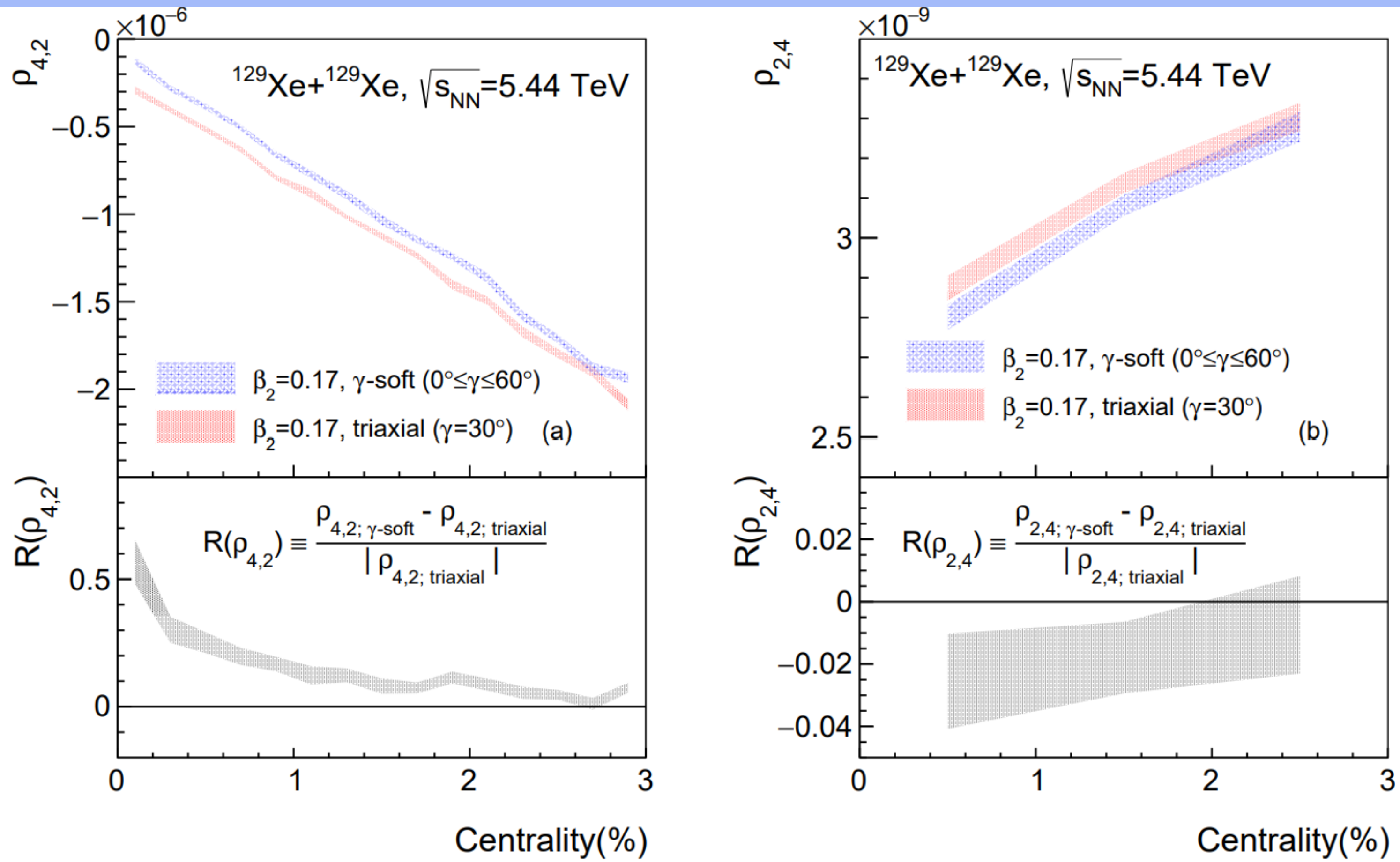
$$\Gamma_{p_T} = \frac{\langle \delta p_{T,i} \delta p_{T,j} \delta p_{T,k}\rangle \langle [p_T]\rangle}{\langle \delta p_{T,i} \delta p_{T,j}\rangle^2},$$

-Our calculations with rigid triaxial or γ-soft deformation of ^{129}Xe can describe the measured ρ_2 and Γ_{pT} equally well.

$\rho_2, \Gamma_{p_T} \propto \beta_2^3 \cos(3\gamma)$ insensitive to triaxial deformation γ=30º and γ-soft 0≤γ≤60º

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

6-particle correlations

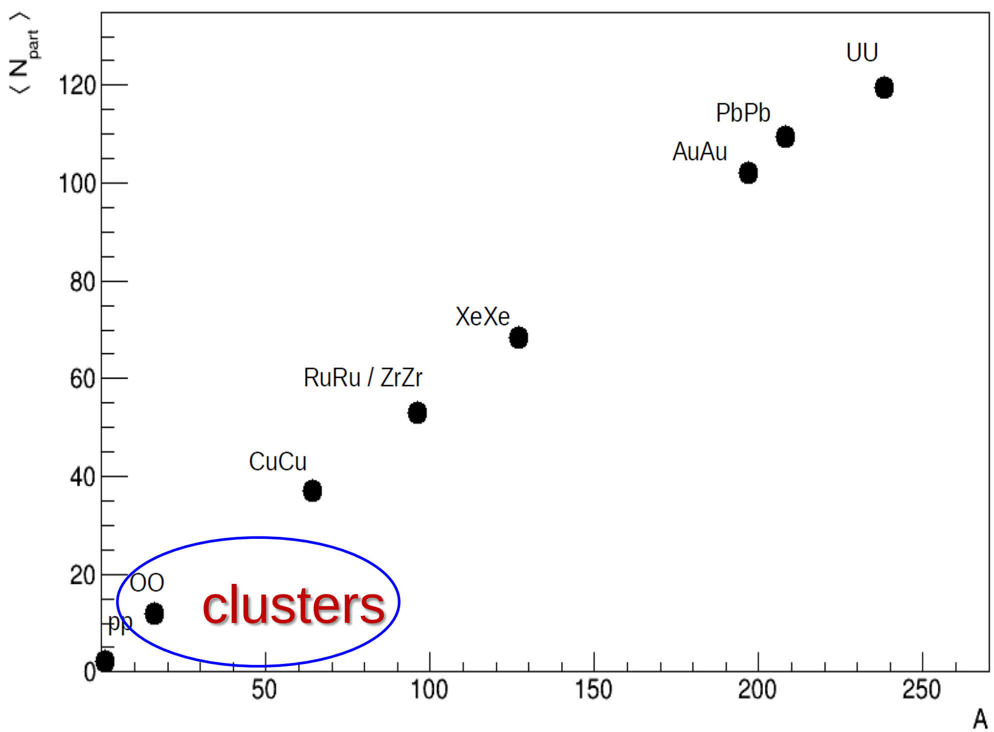


$$\rho_{4,2} \equiv \left(\frac{\langle \varepsilon_2^4 \delta d_\perp^2 \rangle}{\langle \varepsilon_2^4 \rangle \langle d_\perp \rangle^2} \right)_c \qquad \rho_{2,4} \equiv \left(\frac{\langle \varepsilon_2^2 \delta d_\perp^4 \rangle}{\langle \varepsilon_2^2 \rangle \langle d_\perp \rangle^4} \right)_c \qquad \langle \cos(6\gamma) \rangle$$

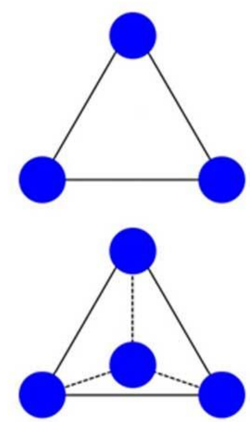
The γ-soft deformation of ^{129}Xe lead to a clear enhancement of 6-particle correlations $\rho_{4,2}$ in ultra-central Xe+Xe collisions

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

Probe the α-cluster of ^{16}O at RHIC and the LHC



^{8}Be

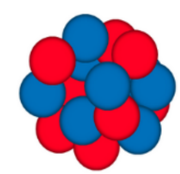


^{12}C

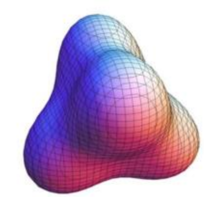
^{16}O

^{16}O+^{16}O collisions and p+^{16}O collisions originally aim to study the possible formation of the QGP in small systems

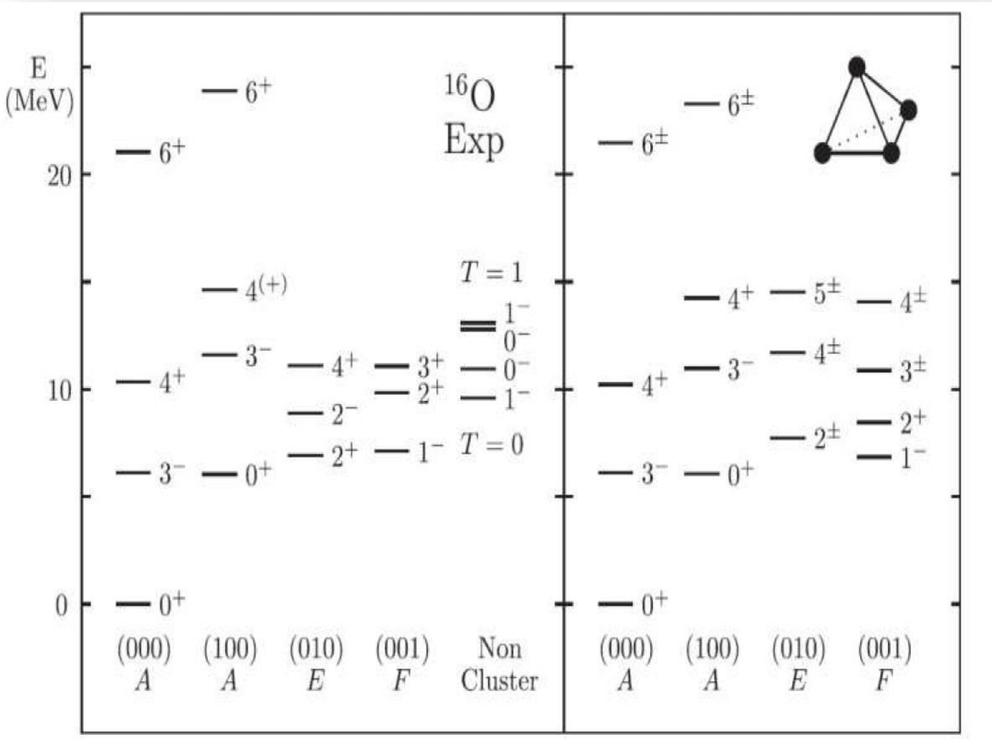
^{16}O



^{16}O



α-cluster of ^{16}O from nuclear structure

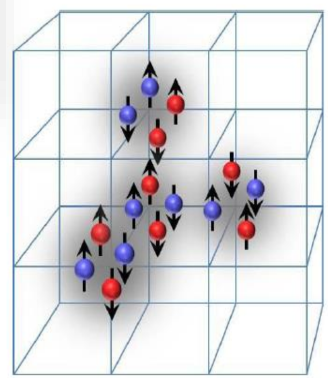


-ACM calculations show that the low-lying states of ^{16}O can be described as rotation-vibration of a 4α cluster with tetrahedral symmetry.

R.Bijker and F.Iachello, Phys. Rev. Lett. 112, no.15, 152501 (2014)

-ab initio lattice calculations demonstrate the nucleons are arranged in a tetrahedral alpha clusters in the ground state

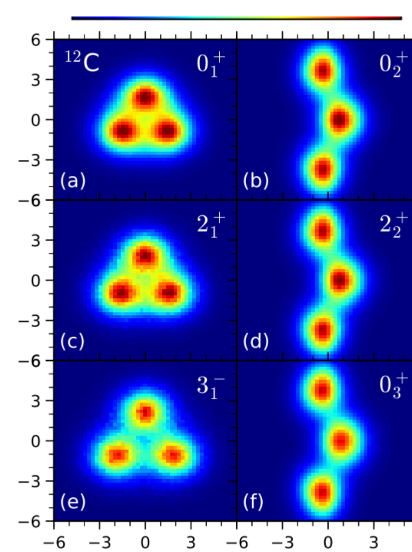
E. Epelbaum, et al Phys. Rev. Lett.112, no.10, 102501 (2014)



(a) Initial state "A", 8 equivalent orientations.

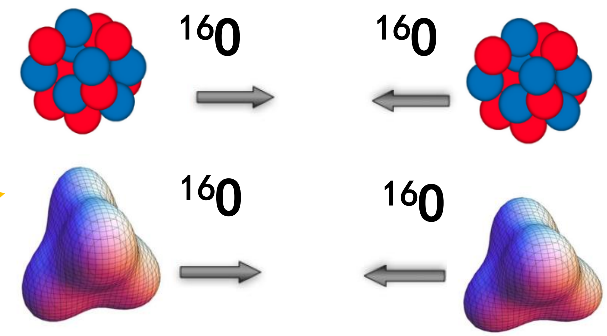
Recent NLEFT calculations for light nuclei: Intrinsic shape composed of alpha clusters

Shen, Elhatisari, Lahde, Lee, Lu, UGM, Nature Commun. **14** (2023) 2777
Dee Lee talk, today



Relativistic heavy ion collision to probe the structure of ^{16}O

Relativistic heavy ion collisions

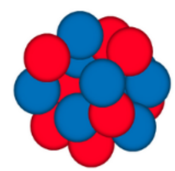


initial conditions:
(with or without α-cluster)

Initial conditions (TRENTO)

-Woods-Saxon:

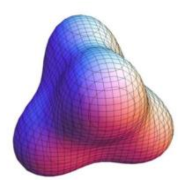
$$\rho(r,\theta,\phi) = \frac{\rho_0}{1 + e^{(r - R(\theta,\phi))/a_0}}$$



Spherical shape

-Alpha-Cluster:

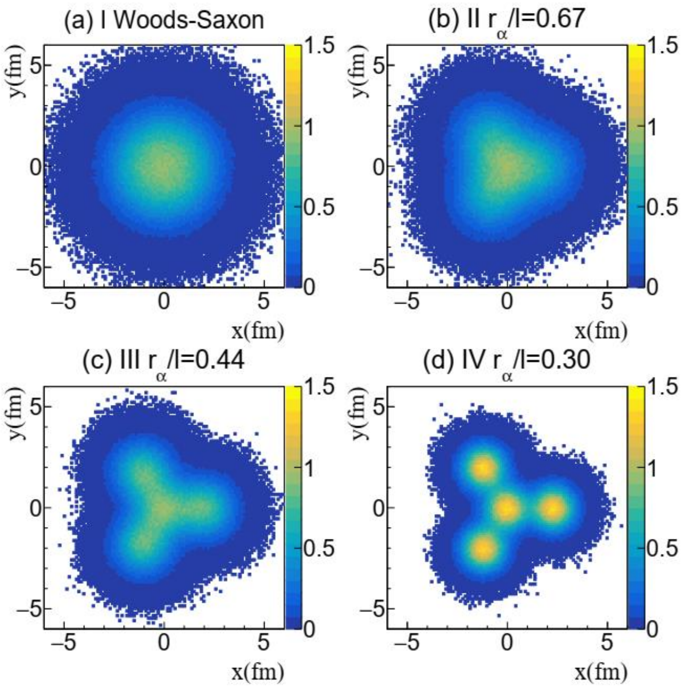
$$f_i(\mathbf{r}) = A\exp\left[-\frac{3(\mathbf{r}-\mathbf{r}_i)^2}{2{r_\alpha}^2}\right]$$

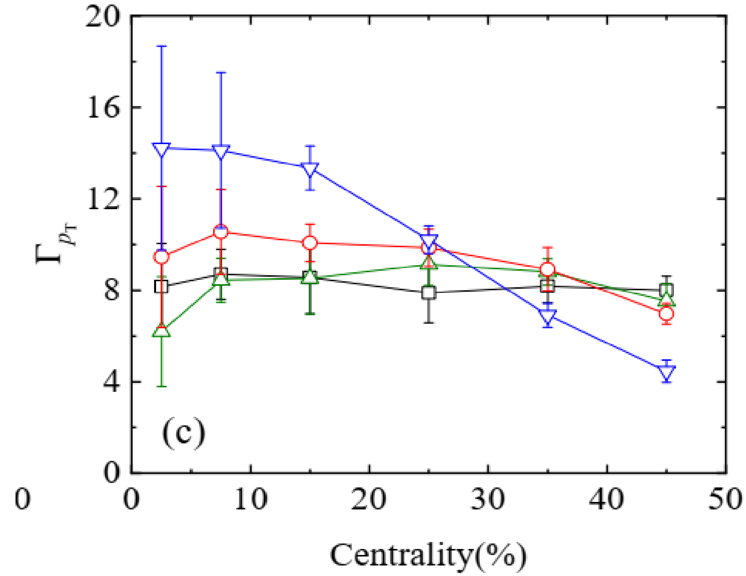


tetrahedral alpha clusters

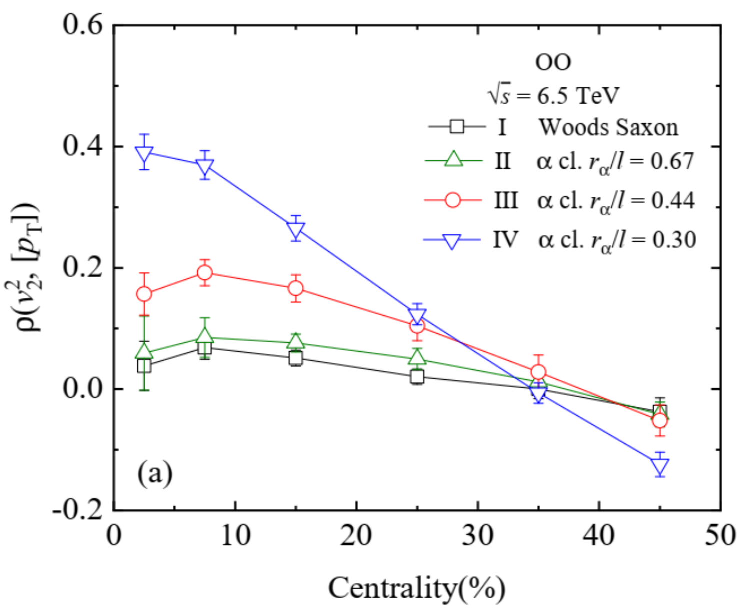
	distribution	l	r_α	r_α/l
I	Woods–Saxon			
II	α cluster	3.0	2.0	0.67
III	α cluster	3.6	1.6	0.44
IV	α cluster	4.0	1.2	0.30

Sensitive observables for α-clustering



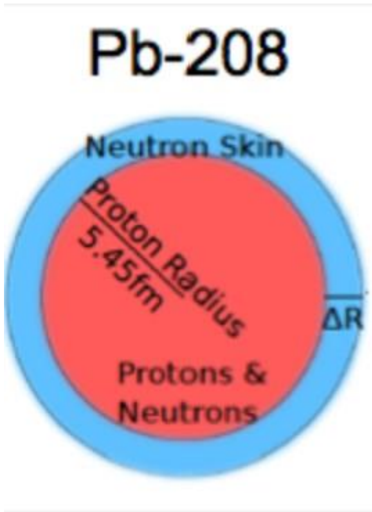


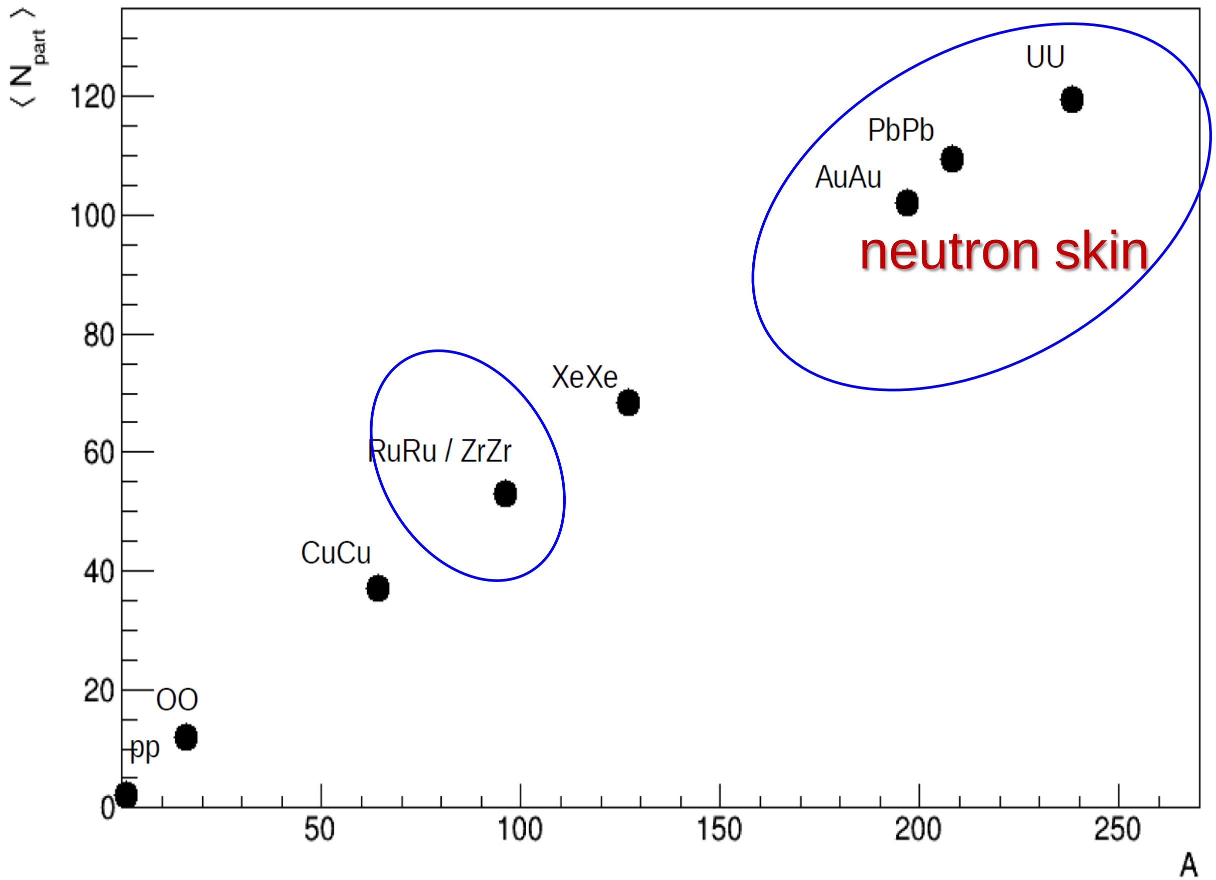
Several observables, such as the correlator Γ the $v_n - p_T$ correlations in $^{16}O+^{16}O$ collisions are sensitive to the compactness of the *α* cluster in the colliding nuclei, which can be used to constrain the detailed configurations of ^{16}O in the future.



Y. Wang, S. Zhao, B. Cao, H. Xu and H. Song. arXiv: 2401.15723 [nucl-th].

Probe neutron skin at RHIC and the LHC





Neutron skin & neutron star

EOS of nuclear matter

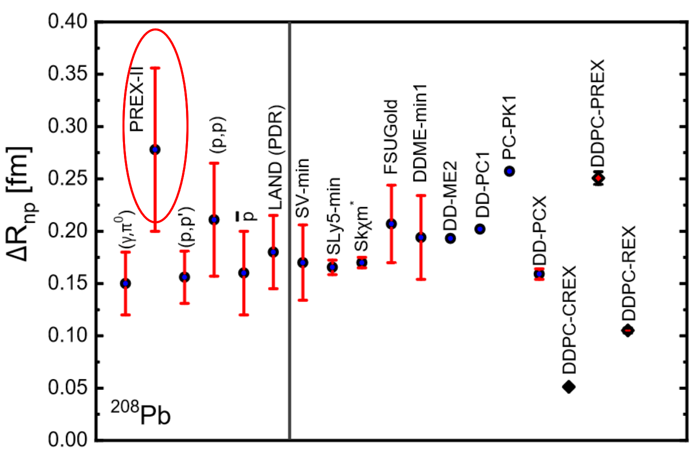
$$\epsilon(\rho,\alpha) = [\epsilon_{SNM}(\rho_0) + S(\rho_0)\alpha^2)] + \alpha^2 L \frac{\rho-\rho_0}{3\rho_0} + \frac{1}{2}(K_0 + \alpha^2 K_{sym})(\frac{\rho-\rho_0}{3\rho_0})^2$$

L: the first order term in EOS; symmetry energy; Large L thick neutron skin

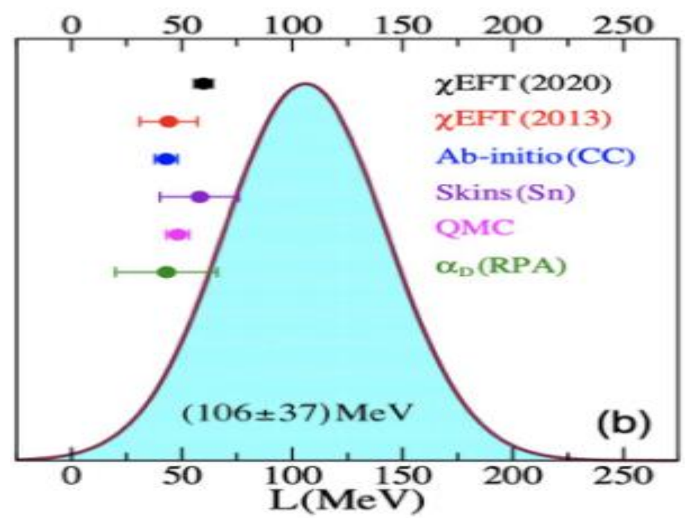
Probe the Neutron Skin at low energy nuclear physics

Parity-Violating Electron Scattering in Jefferson Lab

$R^{208}_{skin} = 0.278^{+0.078}_{-0.078} fm$ Phys. Rev. Lett. 126, 172502, (2021)



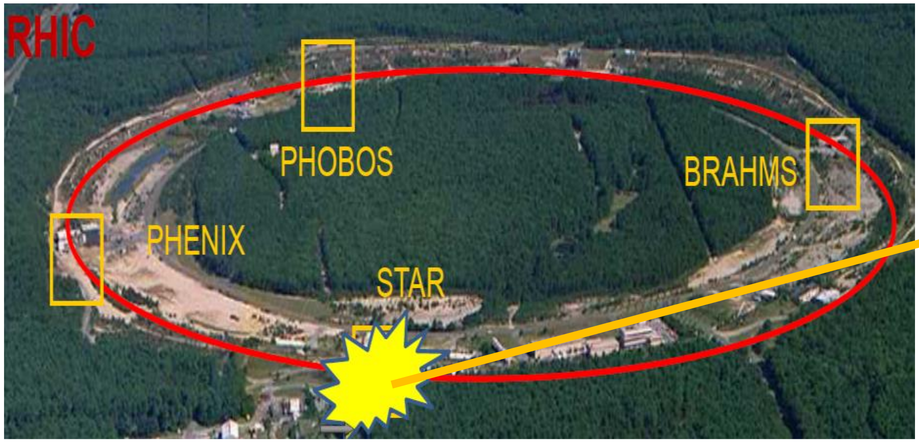
arXiv:2206.06527 Esra Yüksel and Nils Paar

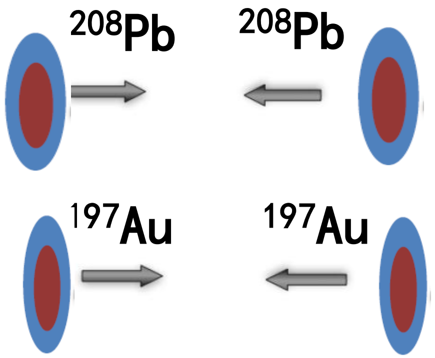


Phys. Rev. Lett. 126, 172502 D. Adhikari et al

Relativistic heavy ion collision to probe the neutron skin

Relativistic heavy ion collisions

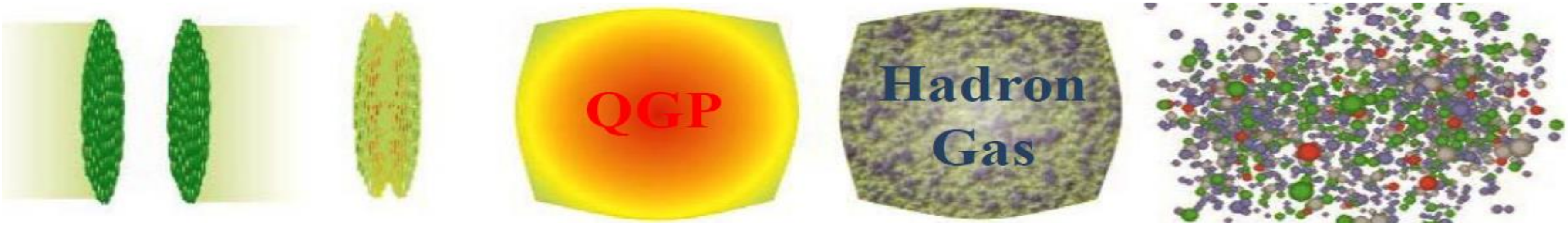




initial conditions:
(with neutron skin)

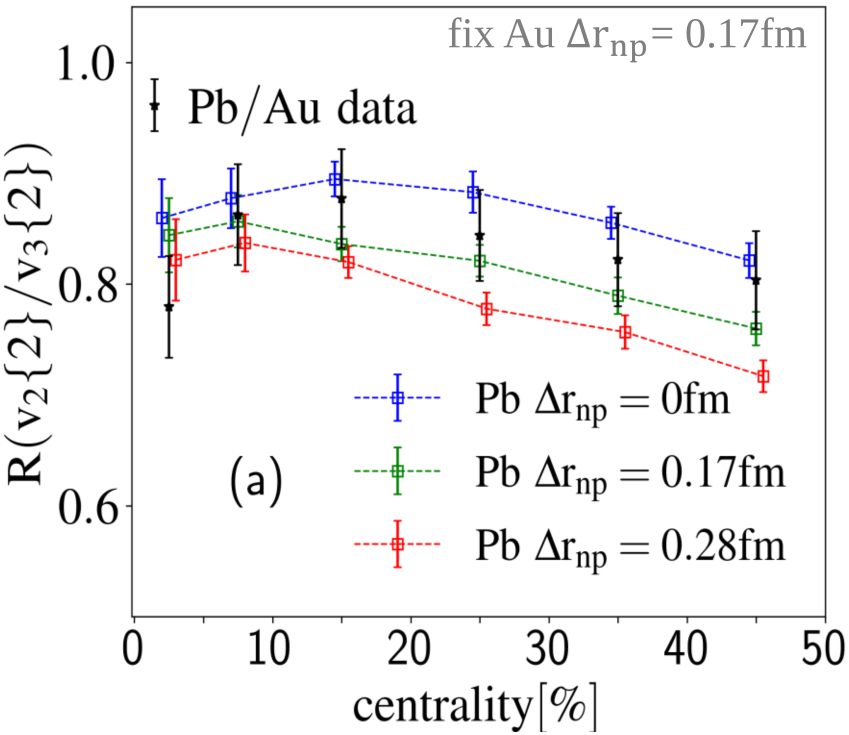
Well calibrated calculations

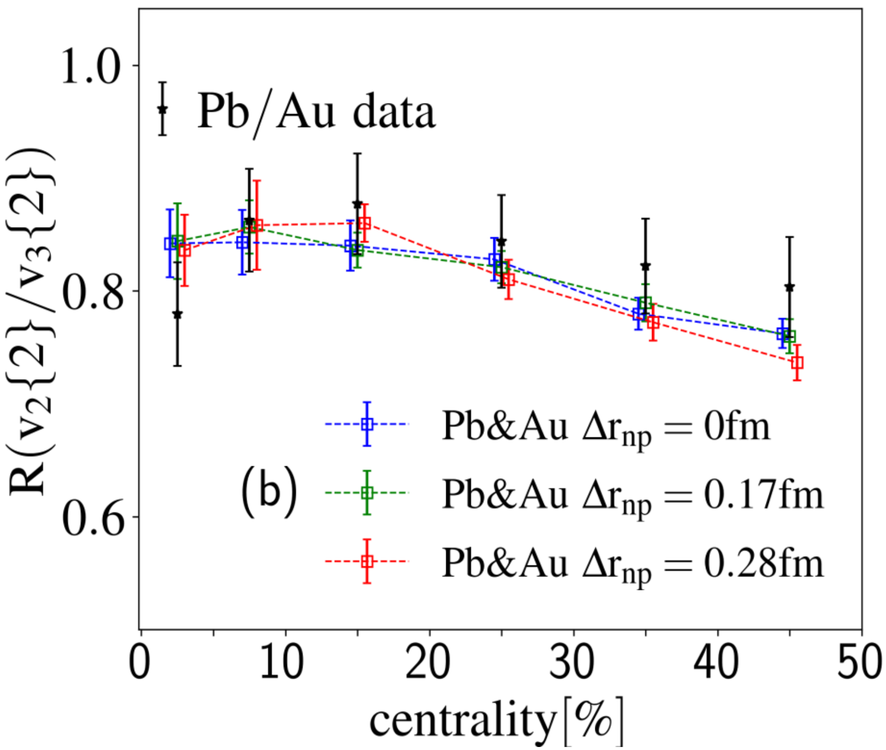
Initial conditions **viscous hydro** **hadron cascade**



Probing the neutron skin of ^{197}Au and ^{208}Pb

semi-isobaric double ratio





A scaling behavior was found in double ratio of $v_2\{2\}/v_3\{2\}$ when Au and Pb have the neutron skins of the same size,

The measured flow harmonics at various centrality suggest Au and Pb have similar neutron skin

Q. Liu, H. Xu and H. Song. Phys.Rev.C 109 (2024) 3, 034912.

Probing nuclear structure across energy scales

-Relativistic heavy ion collisions at RHIC and the LHC have provide rich collision systems to study various aspects in nuclear structure

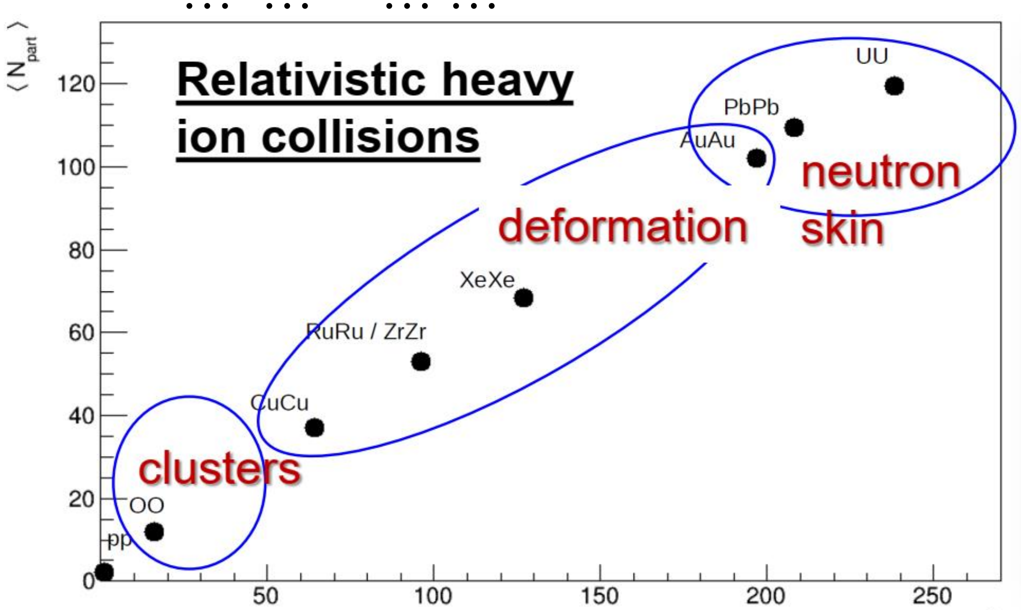
-Past & future workshop, program for such intersection study

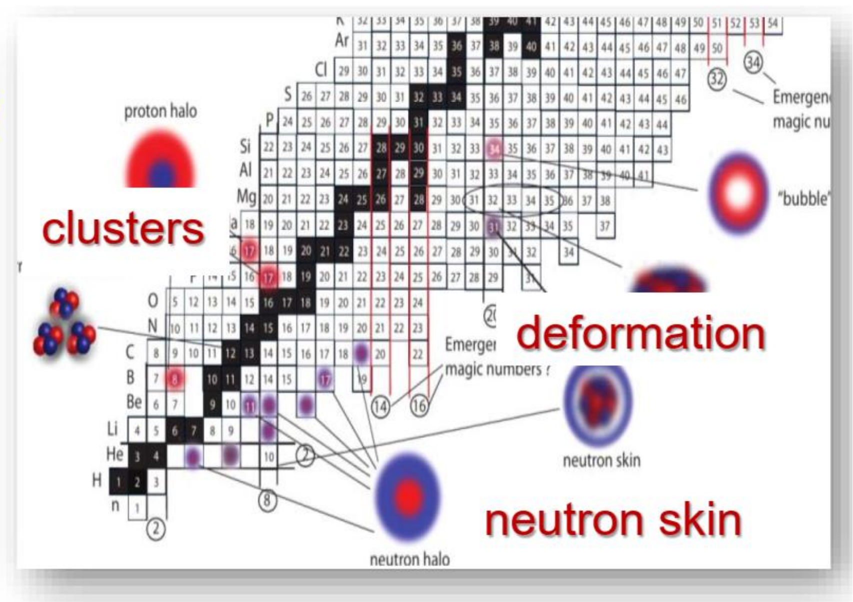
"Intersection of nuclear structure&high-energy nuclear collisions" INT, Jan.23-Feb.24 2023

"Exploring Nuclear Physics across Energy Scales", Beijing, April 15-17 2024

"Light ion collisions at the LHC" CERN, Oct 21-25 2024

… … … …





→ Probing nuclear structure at **NICA**,
exploring the 2nd order shape transition of Xe isotope with Xe+Xe collisions

Soft Physics for high energy Nucleons-Nucleons Collisions

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 …….

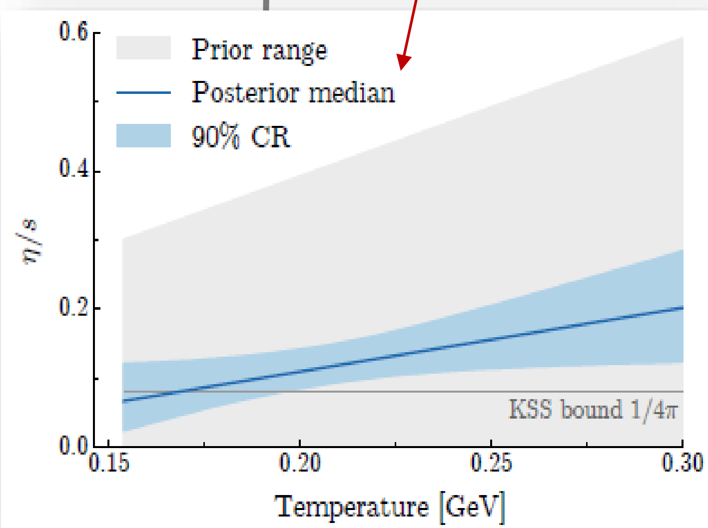
Observables

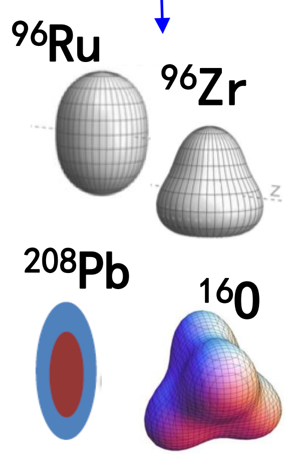
Stable hadrons
All charged h
π K p ……

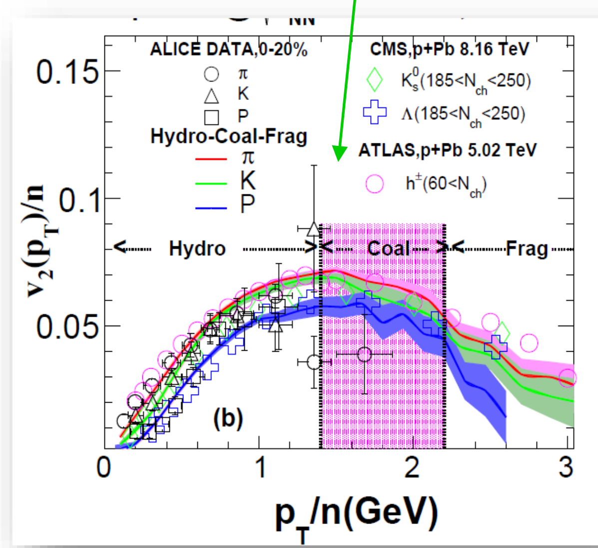
large systems
QGP properties
QCD phase diag
….

Initial condi.
nuclear structure of colliding nuclei
….

Small systems
Possible formation of QGP…







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Observables

Stable hadrons
All charged h
π K p …...

resonances
ϕ meson …

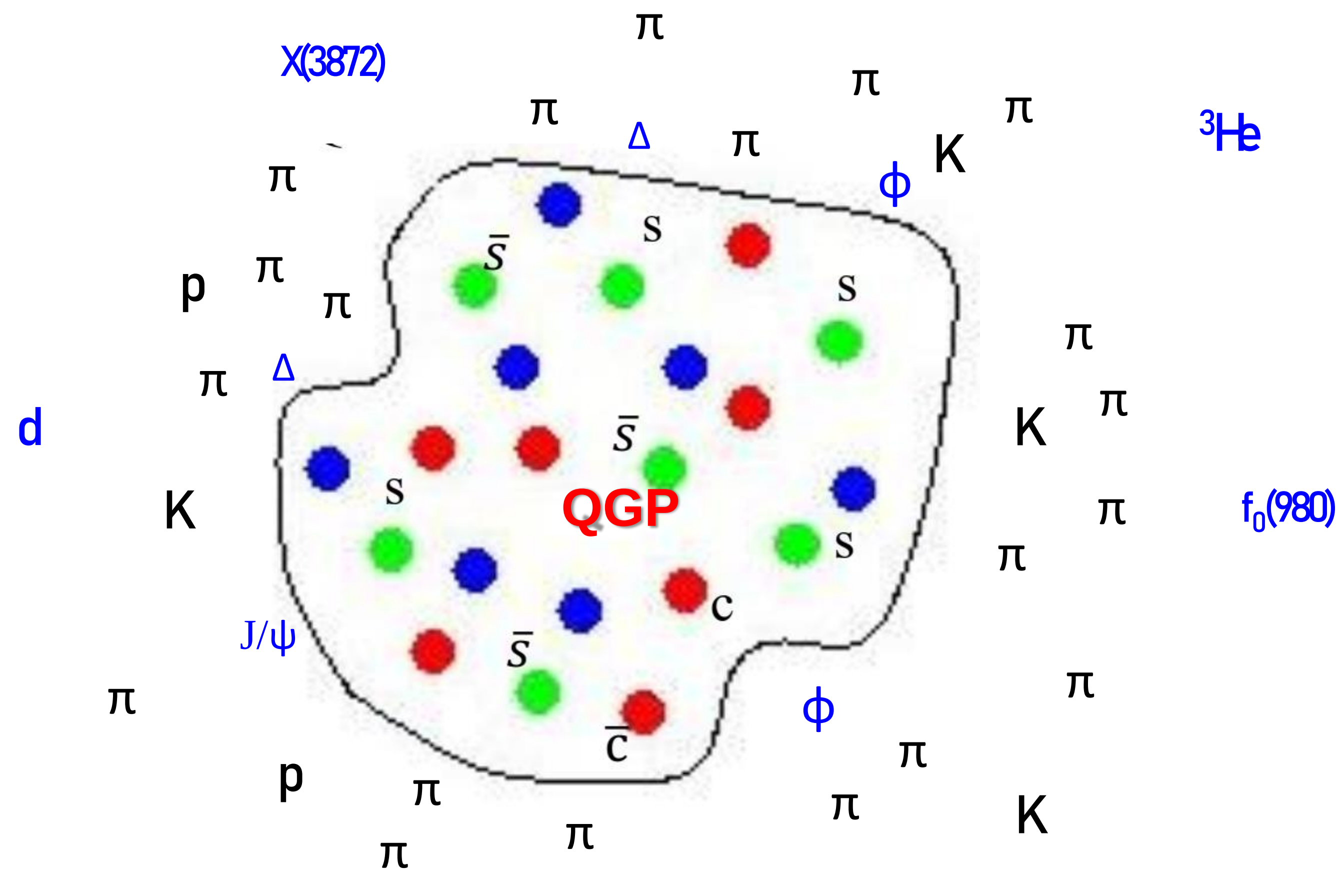
Light nuclei
deuteron
tritium ^{3}He …

Exotic hadrons
X(3872)
$f_0(980)$ …

large systems
QGP properties
QCD phase diag
….

Initial condi. (nuclear structure)
deformation shape phase transition
neutron skin α-cluster ….

Small systems
Possible formation
of QGP…



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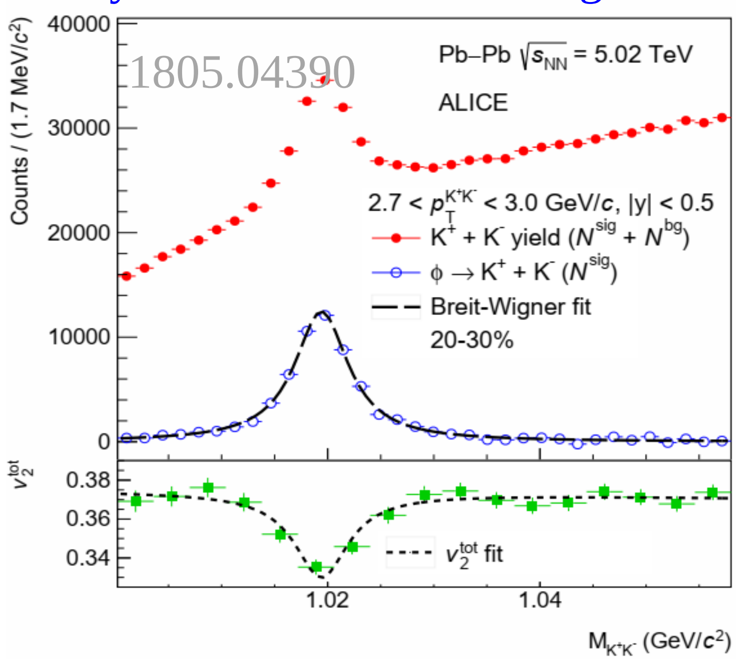
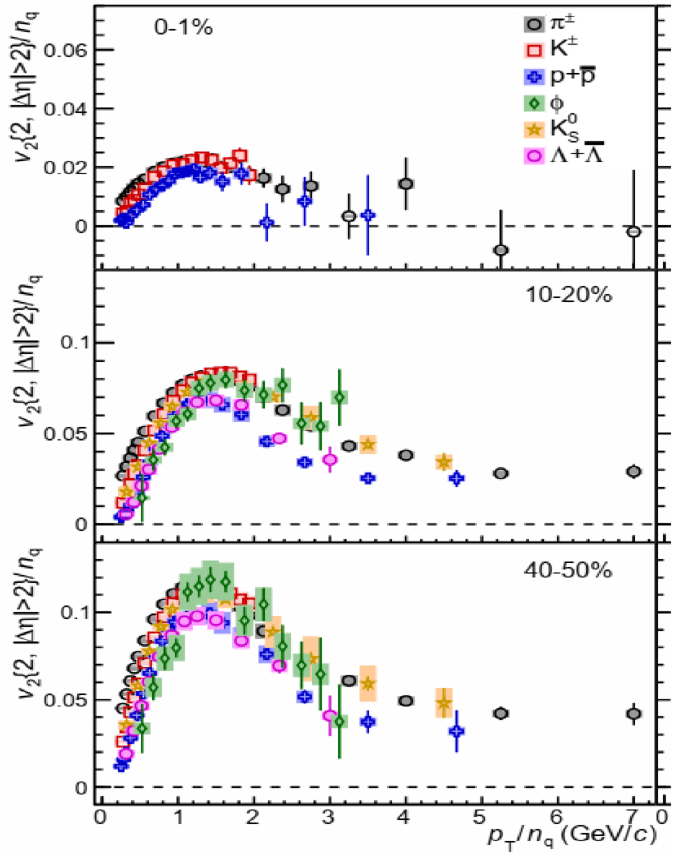
neutron skin α-cluster ….

Small systems
Possible formation of QGP…

resonances
ϕ meson …

φ meson: (nice probe for the QGP)
long life time (45fm/c),
weakly interact with hadronic gas





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. . . .

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deformation
neutron skin

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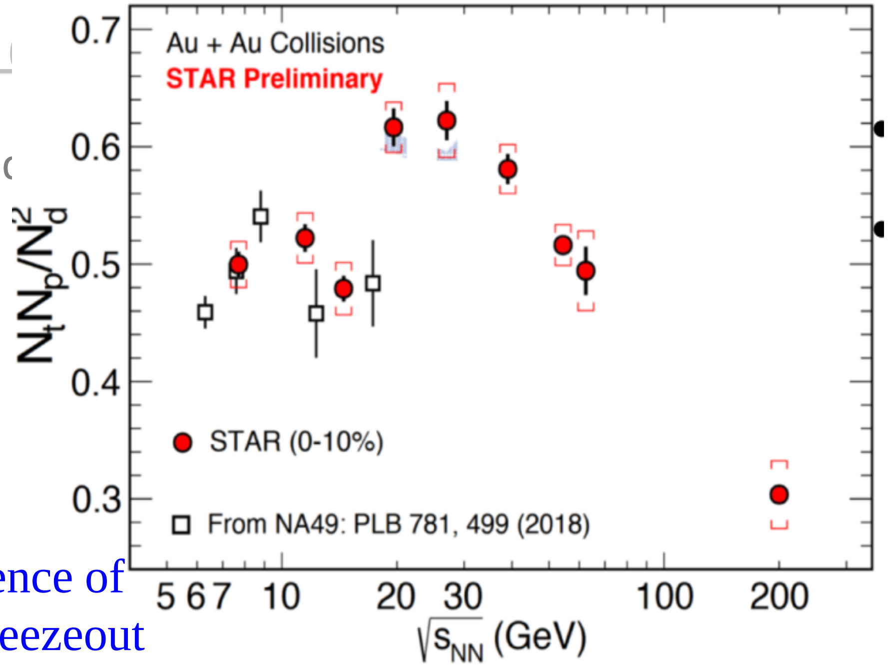
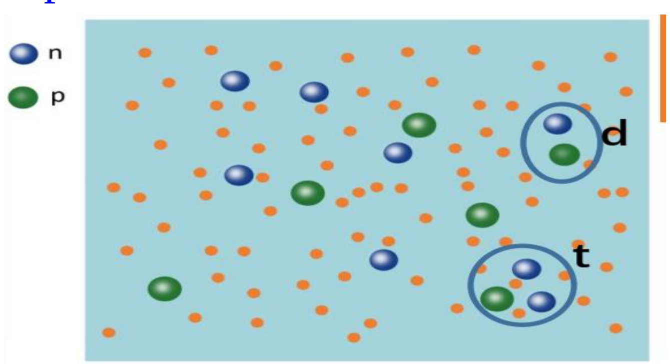
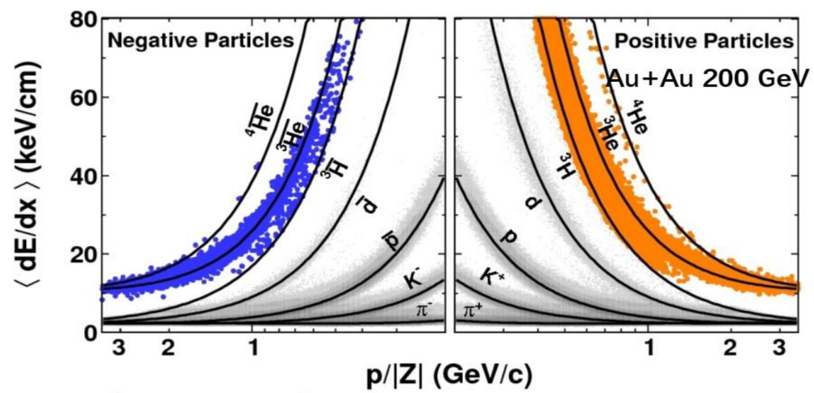
φ meson: nice probe for the QGP
long life time (45fm/c),
weakly interact with hadron gas
reconstruct with φ ---K^+K^-

Light nuclei
deuteron
tritium ^{3}He …

Light nuclei: produced by coalescence of neutrons & protons at kinetic freezeout
probe fluctuations & hadronic flow







STAR (Nature 473,353(2011))

Soft Physics for high energy Nucleons-Nucleons Collisions

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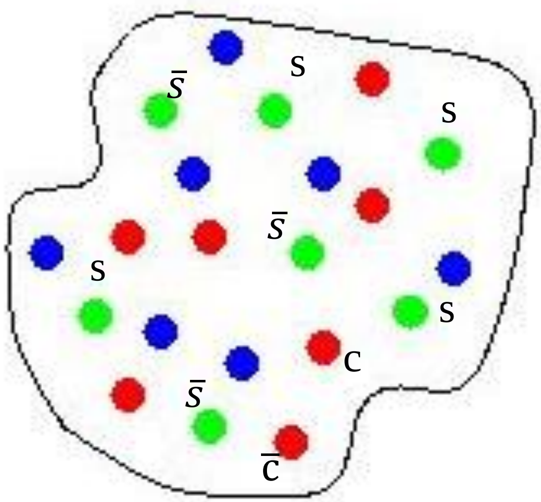
neutron skin α-cluster ….

Small systems
Possible formation
of QGP…

resonances
ϕ meson …

φ meson: nice probe for the QGP
long life time (45fm/c),
weakly interact with hadron gas
reconstruct with φ ---K^+K^-

Quark Gluon Plasma

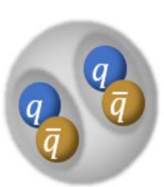


Light nuclei
deuteron
tritium ^3He …

Light nuclei: produced by coalescence of neutrons & protons at kinetic freezeout
probe fluctuations & hadronic flow

Exotic hadrons
X(3872)
$f_0(980)$ …

Exotic hadrons: easier to be produced with QGP formation; identify 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 ntrality dependence between hadronic molecules and compact tetraquarks, thus

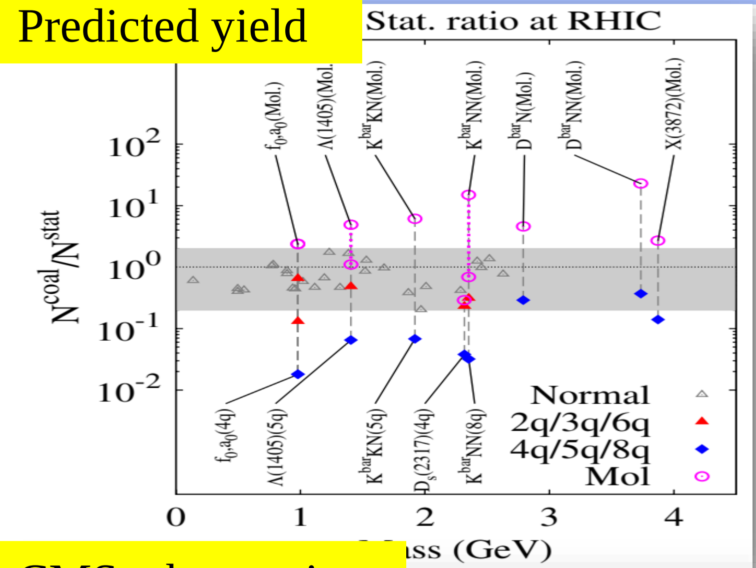
PHYSICAL REVIEW LETTERS **128,** 032001 (2022)

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

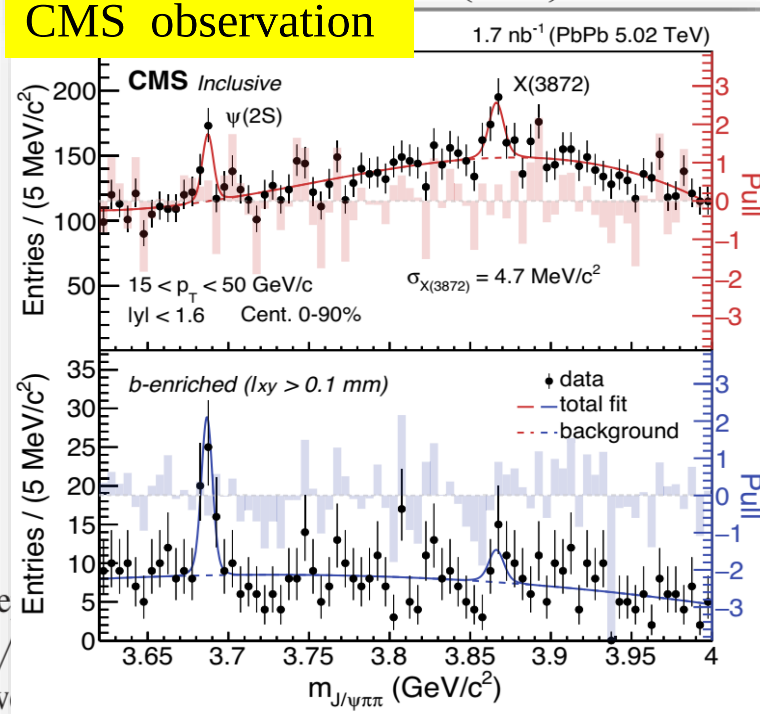
A. M. Sirunyan *et al.*[*]
CMS Collaboration

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 $X(3872) \to J/\psi\pi^+\pi^- \to \mu^+\mu^-\pi^+\pi^-$. The data w

Predicted yield

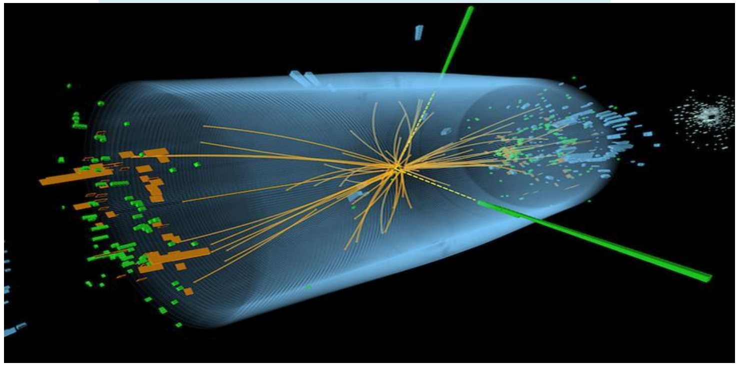


CMS observation



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) $= 990 \pm 20$ 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."

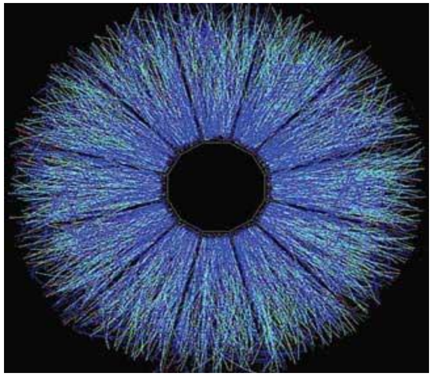
T-matrix pole $\sqrt{s} = (970\text{–}1020) - i\ (30\text{–}70)$ MeV [i]

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

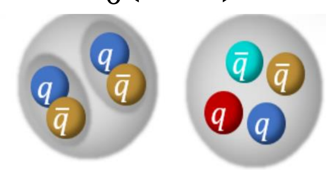
Advantage: provide complimentary information to constrain properties of hadrons

disadvantage: huge background

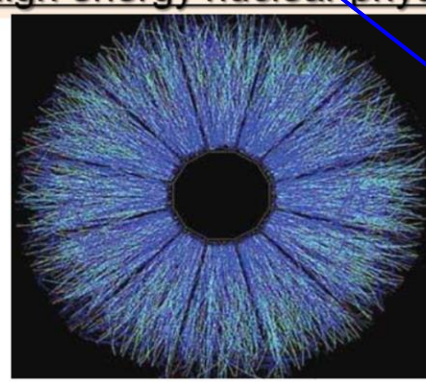
State	$I^G(J^{PC})$	M [MeV]	Γ[MeV]	S-wave threshold(s) [MeV]	Decay mode(s) [branching ratio(s)]
$f_0(500)$ (Peláez, 2016) [a]	$0^+(0^{++})$	449^{+22}_{-16}	550 ± 24	$\pi\pi(173^{+22}_{-16})$	$\pi\pi$ [dominant] $\gamma\gamma$
$\kappa(800)$	$\frac{1}{2}(0^+)$	682 ± 29	547 ± 24	$K\pi(48 \pm 29)$	πK
$f_0(980)$	$0^+(0^{++})$	990 ± 20	$10 \sim 100$	$K^+K^-(3 \pm 20)$ $K^0\bar{K}^0(-5 \pm 20)$	$\pi\pi$ [dominant] $K\bar{K}$ $\gamma\gamma$
$a_0(980)$	$1^-(0^{++})$	980 ± 20	$50 \sim 100$	$K\bar{K}(-11 \pm 20)$	$\eta\pi$ [dominant] $K\bar{K}$ $\gamma\gamma$
$f_1(1420)$	$0^+(1^{++})$	1426.4 ± 0.9	54.9 ± 2.6	$K\bar{K}^*(39.1 \pm 0.9)$	$K\bar{K}^*$(dominant) $\eta\pi\pi$ [possibly seen] $\phi\gamma$
$a_1(1420)$	$1^-(1^{++})$	1414^{+15}_{-13}	153^{+8}_{-23}	$K\bar{K}^*(27^{+15}_{-13})$	$f_0(980)\pi$ [seen]

State	$I^G(J^{PC})$	M [MeV]	Γ [MeV]	S-wave threshold(s) [MeV]	Observed mode(s) (branching ratios)
$X(3872)$	$0^+(1^{++})$	3871.69 ± 0.17	< 1.2	$D^{*+}D^- + c.c.(-8.15 \pm 0.20)$ $D^{*0}\bar{D}^0 + c.c.(0.00 \pm 0.18)$	$B \to K[\bar{D}^{*0}D^0](> 24\%)$ $B \to$ $B \to K$ B - $p\bar{p}$ pp $B \to K[J/\psi\omega](> 1.9\%)$ $B \to [J/\psi\gamma](> 6 \times 10^{-3})$ $B \to [\psi(2S)\gamma](> 3.0\%)$
$X(3940)$	$?^?(?^{??}$			$-75.1 \pm 9)$	$e^+e^- \to J/\psi[D\bar{D}^*]$
$X(4160)$	$?^?(?^{??}$			(139^{+29}_{-25})	$e^+e^- \to J/\psi[D^*\bar{D}^*]$
$Z_c(3900)$	$1^+(1^+$			$0.8 \pm 2.4)$	$e^+e^- \to \pi[D\bar{D}^* + c.c.]$

f$_0$(980)



High energy nuclear physics



A large amount of particles produced
→ momentum distributions

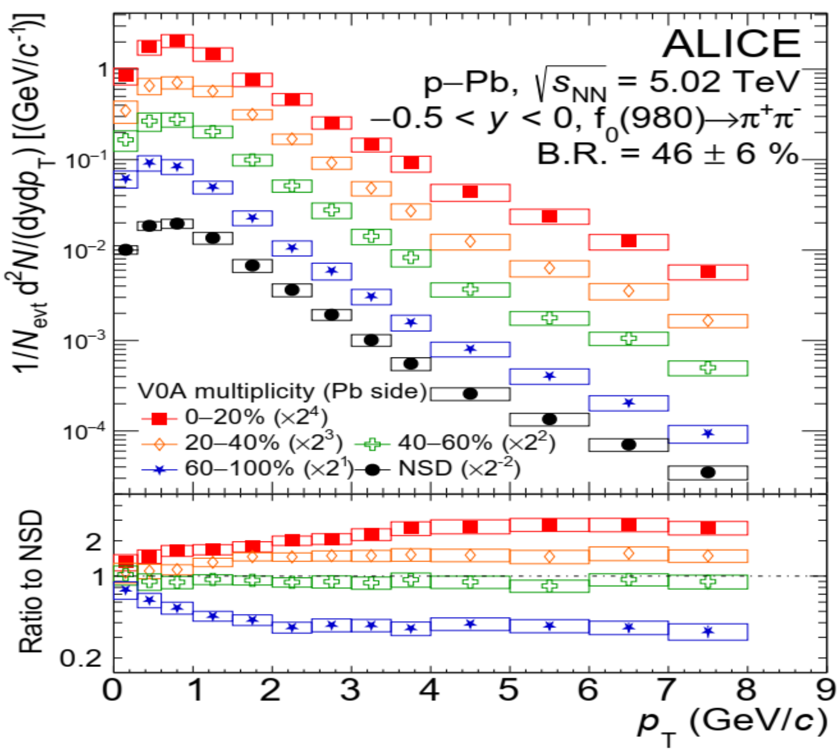
F.K.Guo, C.Hanhart, U.G…, Rev. Mod. Phys.90, no.1, 015004 (2018)

Probing $f_0(980)$ 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

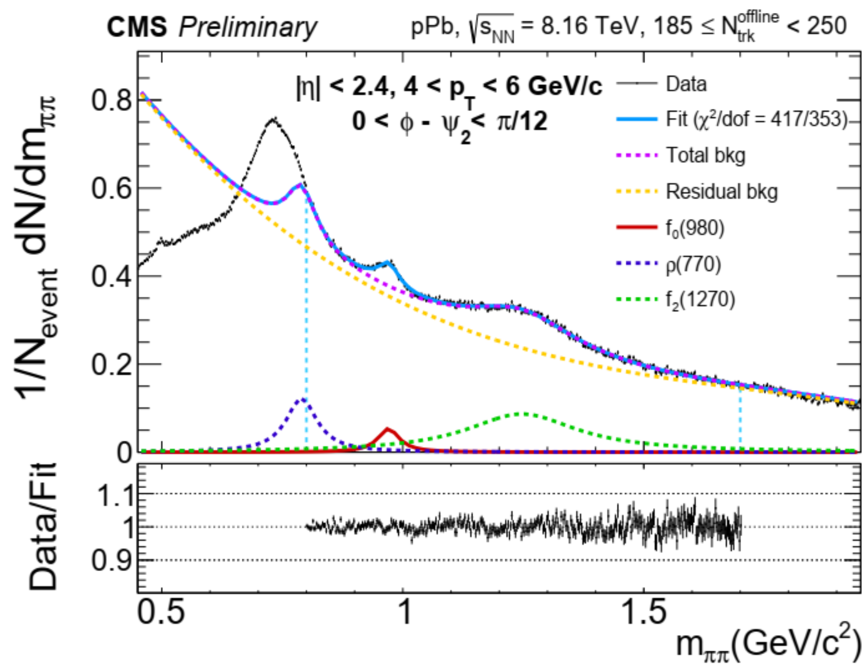
p_T spectra



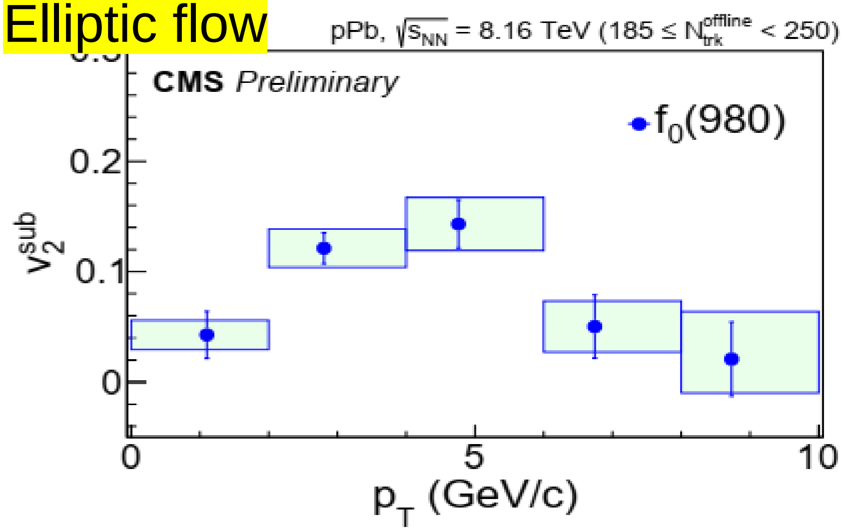
ALICE Phys.Lett.B 853 138665 (2024)

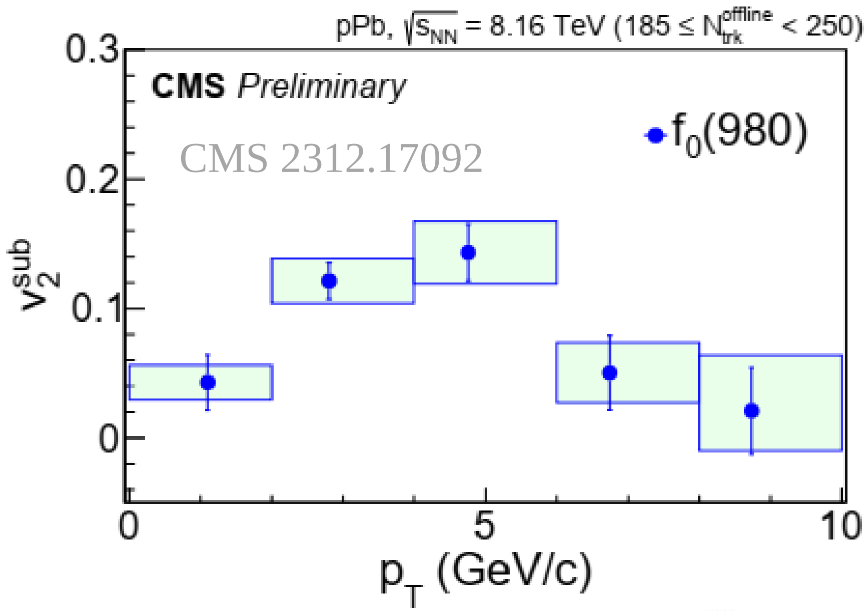
Reconstruction of $f_0(980)$

CMS 2312.17092



Elliptic flow

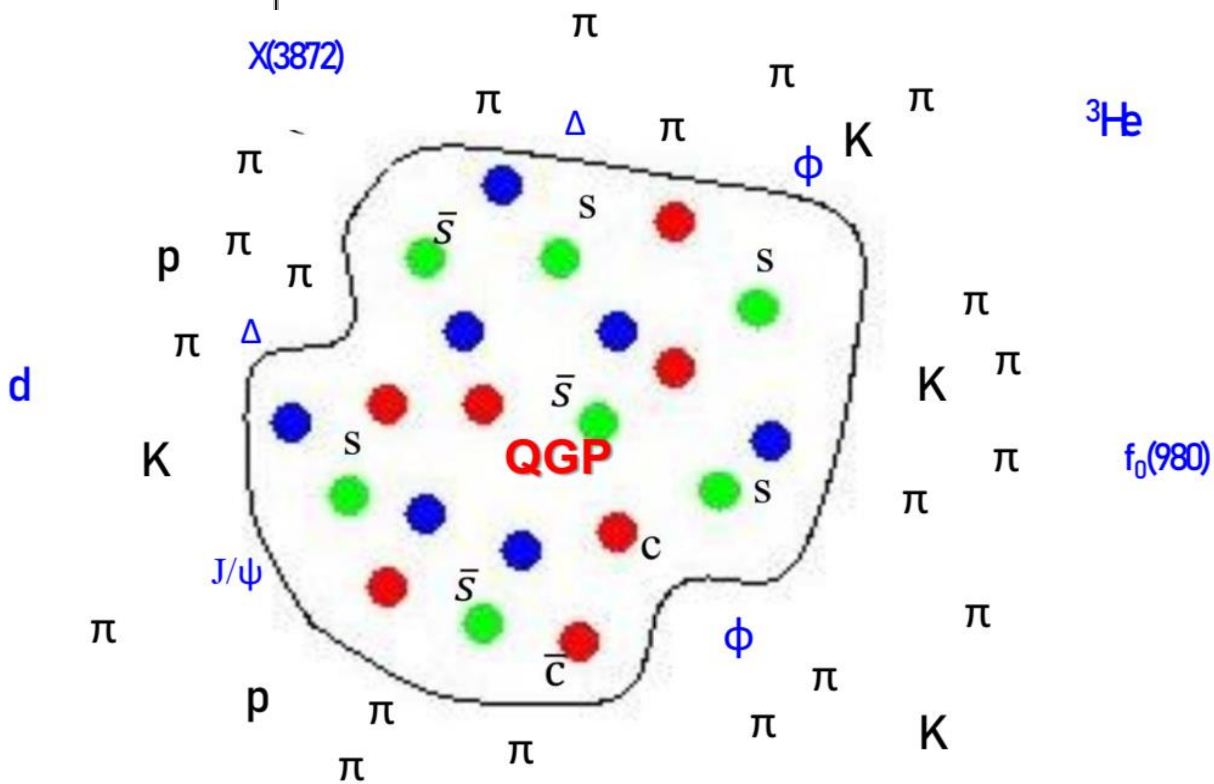




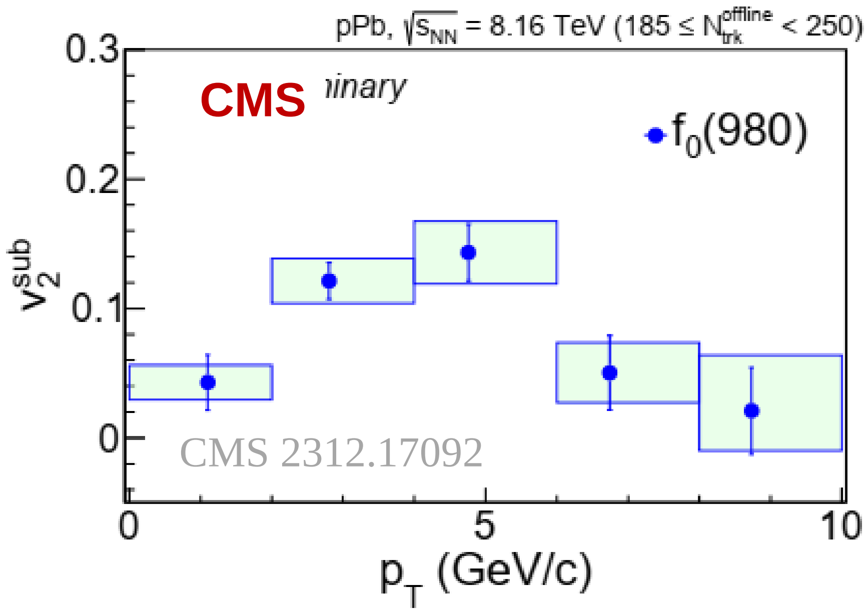
flow:

-- anisotropy for particle momentum distribution

-- contains rich information to constrain the formation /properties of an exotic hadron



Different flow behavior for hadrons produced near Tc or generated at kinetic freeze-out



flow:

-- anisotropy for particle momentum distribution
-- contains rich information to constrain the formation /properties of an exotic hadron

Comments:

-Dominant decay channel: $f_0(980) \to \pi^+\pi^-$; no PID in CMS, use all charged tracks

-**p-Pb collisions**, less background contamination for f_0(980) reconstruction

-flow is not easy to measure in small systems
-CMS: event plane method for flow measurement
-non flow subtraction
… … …

Flow for f_0(980): need efforts from ALICE, STAR collaboration
efforts from the theory community

TABLE I Mesons that contain at most one heavy quark that cannot be easily accommodated in the $q\bar{q}$ quark model. Their quantum numbers $I^G(J^{PC})$, masses, widths, the nearby S-wave thresholds, $m_{\text{threshold}}$, where we add in brackets $M - m_{\text{threshold}}$, and the observed decay modes are listed in order. The data without references are taken from the 2016 edition of the Review of Particle Physics (Patrignani *et al.*, 2016).

State	$I^G(J^{PC})$	M [MeV]	Γ[MeV]	S-wave threshold(s) [MeV]	Decay mode(s) [branching ratio(s)]
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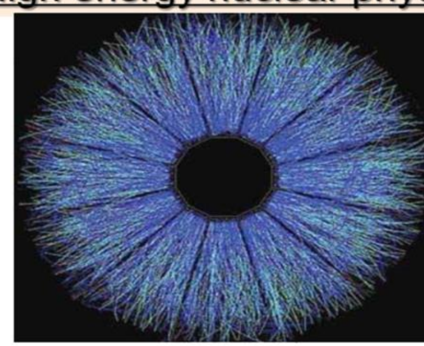
$a_1(1420)$	$1^-(1^{++})$	1414^{+15}_{-13}	153^{+8}_{-23}	$K\bar{K}^*(27^{+15}_{-13})$	$f_0(980)\pi$ [seen]
$X(1835)$	$?^?(0^{-+})$	$1835.8^{+4.0}_{-3.2}$	112 ± 40	$p\bar{p}(-40.7^{+4.0}_{-3.2})$	$p\bar{p}$ $\eta'\pi\pi$ $K^0_S K^0_S \eta$
$D^*_{s0}(2317)^+$	$0(0^+)$	2317.7 ± 0.6	$<$		$D_s^+\pi^0$
$D_{s1}(2460)^+$	$0(1^+)$	2459.5 ± 0.6	$<$		[(48 ± 11)%] [(18 ± 4)%] π^- [(4 ± 1)%] 7)$^+\gamma$ [(4^{+5}_{-2})%]
$D^*_{s1}(2860)^+$	$0(1^-)$	2859 ± 27	159		DK D^*K

→ With similar PID as STAR explore light exotic hadrons at **NICA**,

<u>High energy nuclear physics</u>



A large amount of particles producec
→ momentum distributions

→ -particle yield
- pT spectra
- flow anisotropy

F.K.Guo, C.Hanhart, U.G.Meissner, Q.Wang, ... , no.1, 015004 (2018)

Soft Physics for high energy Nucleons-Nucleons Collisions

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+^{16}O p+^{208}Pb p+p ...

Observables

Stable hadrons
All charged
π K p ......

large systems	Initial condi. (nuclear structure)	Small systems
QGP properties	deformation shape phase transition	Possible formation
QCD phase diag	neutron skin α-cluster ….	of QGP…
….		

resonances
ϕ meson ...

φ meson:
probe partonic flow

Light nuclei
deuteron
tritium ^{3}He ...

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

Exotic hadrons
X(3872)
f_0(980) ...

Exotic hadrons: easier to be produced with QGP formation; identify compact or molecular structure?

Soft Physics for high energy Nucleons-Nucleons Collisions

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+^{16}O p+^{208}Pb p+p ...

Observables

Stable hadrons
All charged
π K p ......

resonances
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Light nuclei
deuteron
tritium ^{3}He ...

Exotic hadrons
X(3872)
f_0(980) ...

large systems
QGP properties
QCD phase diag
....

Initial condi. (nuclear structure)
deformation shape phase transition
neutron skin α-cluster ....

Interdisciplinary study
with nuclear structure

Small systems
Possible formation
of QGP…

p-O for
cosmic rays

φ meson:
probe partonic flow

QGP & QCD phase diagram
at RHIC and LHC

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

Exotic hadrons: easier to be produced with QGP formation; identify compact or molecular structure?

Interdisciplinary study with hadron physics

→ More to explore at **NICA**,

Many Thanks

Soft Physics for high energy Nucleons-Nucleons Collisions

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 ……

large systems
QGP properties
QCD phase diag
….

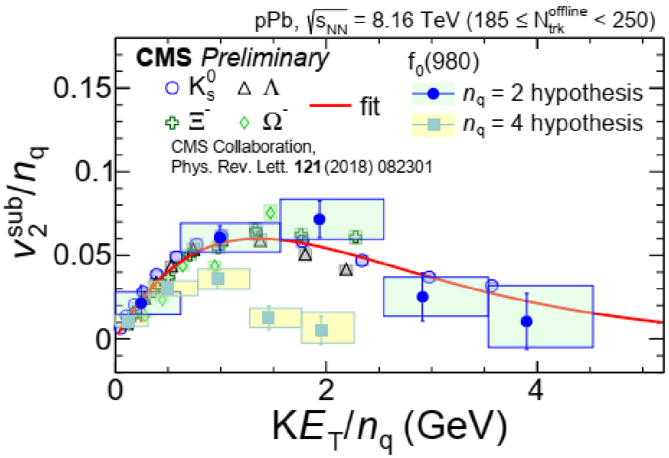
Initial condi. (nuclear structure)
deformation   shape phase transition
neutron skin α-cluster ….

Small systems
Possible formation
of QGP…

Probe nuclear structure

Study various hadrons

(Gu An for CMS)



- v_2 of $f_0(980)$ measured as a function of p_T up to 10 GeV/c
- Assuming NCQ scaling, n_q of $f_0(980)$ is consistent with 2.
- $n_q = 4$ (tetra-quark state or $K\bar{K}$ molecule) excluded with 7.7σ.
- $n_q = 3$ ($q\bar{q}g$ hybrid) excluded with 3.5σ.

- Our data favor $q\bar{q}$ normal meson state for $f_0(980)$.