Dynamical modeling of high-energy nuclear collisions

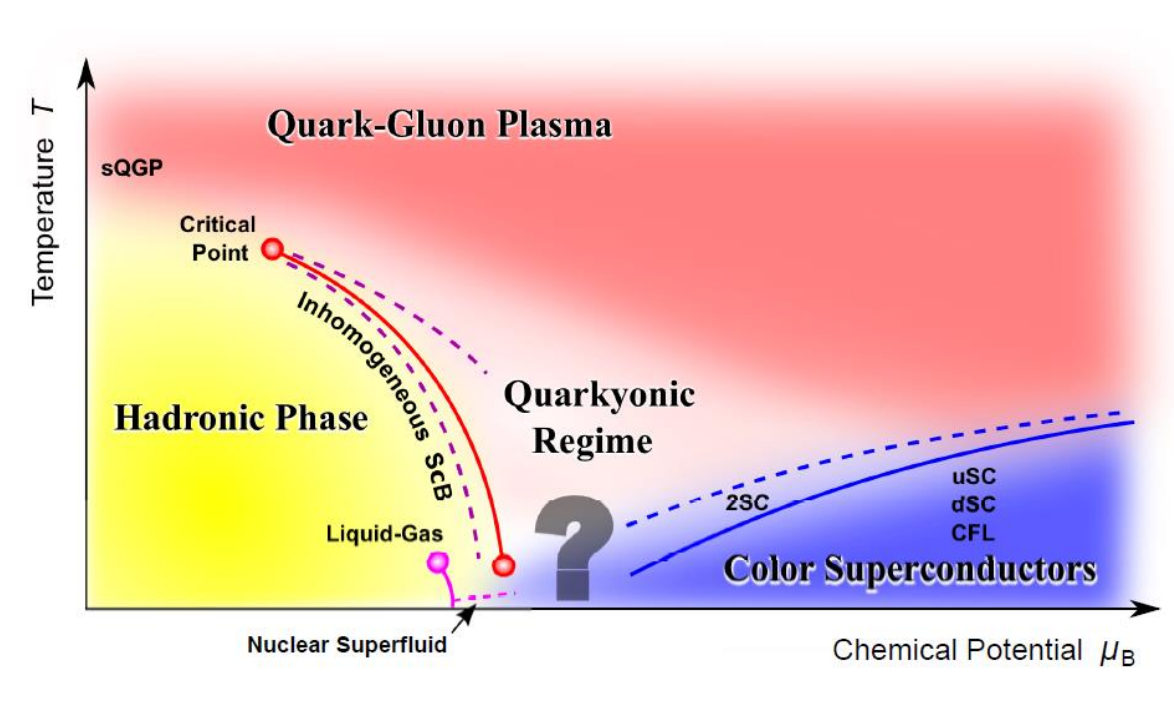
From small to large colliding systems

Tetsufumi Hirano (Sophia Univ.)

Contents

Physics of the QGP

Fukushima and Sasaki (2013)



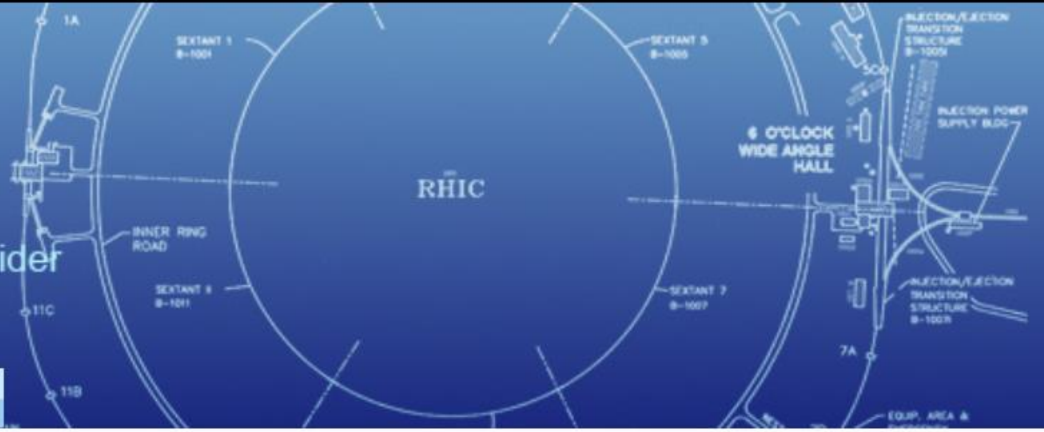
Investigation of properties of matter under extreme conditions

- Order of phase transition
- Location of critical point and 1st order phase transition line
- Equation of state
- Transport coefficients
- Structure of “vacuum”
- …

High-energy nuclear collisions: Unique approach to create matter under extreme conditions on the Earth

RHIC

Brookhaven National Laboratory's Relativistic Heavy Ion Collider



Contacts: Karen McNulty Walsh, (631) 344-8350 or Peter Genzer, (631) 344-3174

RHIC Scientists Serve Up 'Perfect' Liquid

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

Monday, 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

Other RHIC News

Using Supercomputers to Delve Ever Deeper into the Building Blocks of Matter

Summer Intern Jaime Avilés Acosta Studies Materials for Ultra-Fast Particle Detector

Successful Test of Small-Scale Accelerator with Big Potential Impacts for Science and Medicine

Trends in high energy nuclear collisions

Discovery stage

~2005

Precision study, new findings,…

Discovery of QGP at RHIC

Talks by H.Z.Huang, M.Stephanov, …

Energy frontier

QGP at the highest collision energy at LHC
→ Precision analyses of the QGP properties

Small colliding systems

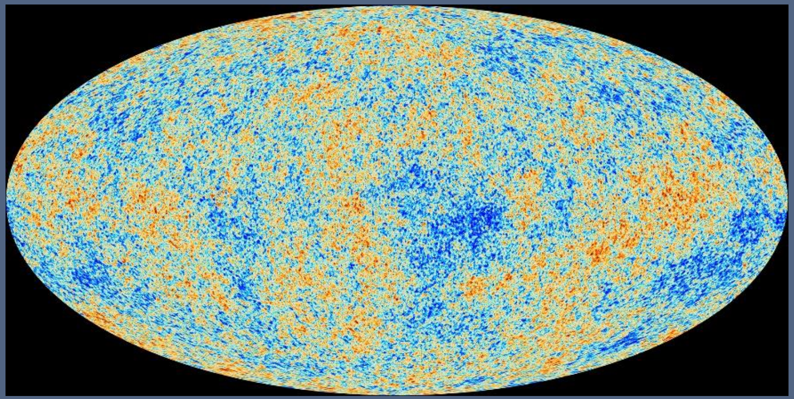
Collectivity in small colliding systems at RHIC and the LHC
→ How small could the QGP be?

Various collision energies

RHIC beam energy scan (BES) program
→ Onset of the QGP formation?
→ Investigation of super-dense matter

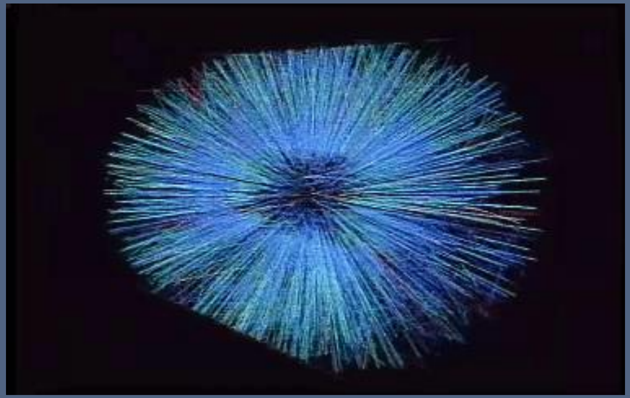
Bottom-up approach

http://www.esa.int/spaceinimages/Images
/2013/04/Planck_CMB_black_background

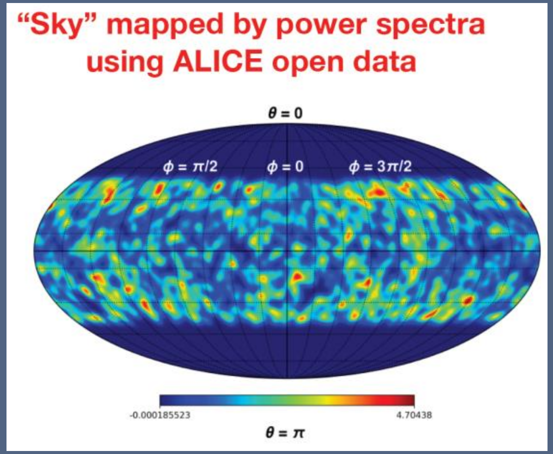


Cosmic Microwave Background
Fluctuations of temperature (Planck)

Cosmological parameters
- Energy budget
- Hubble constant (life time)
- …



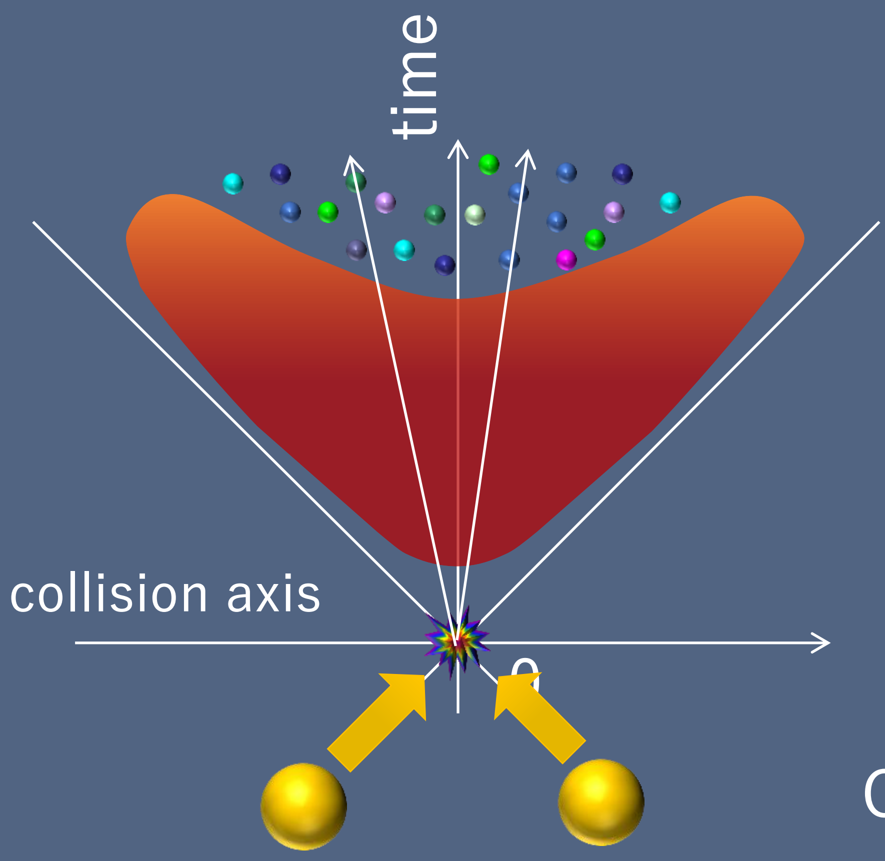
3-D event display(STAR)

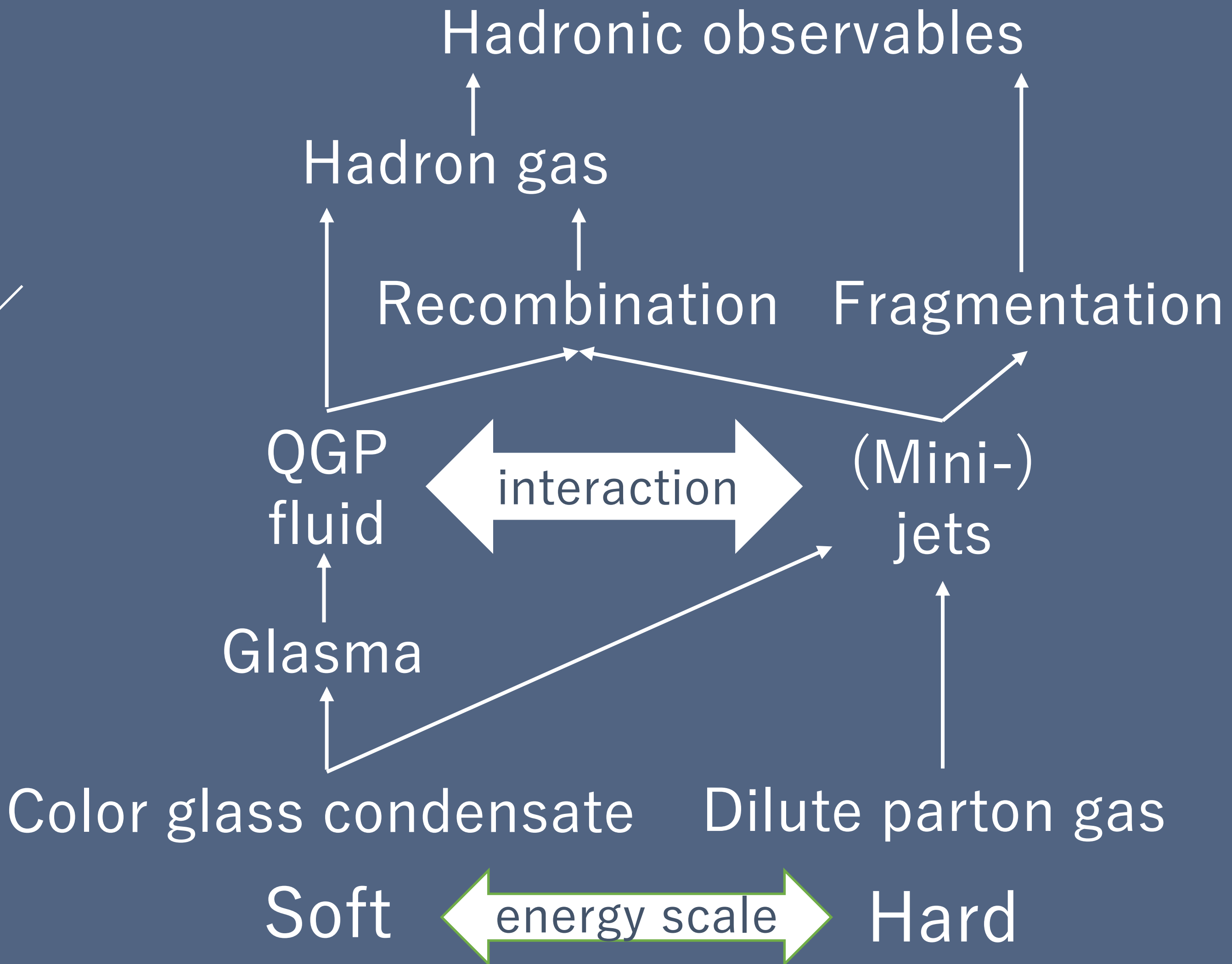


Y.Zhou, talk at QM2018

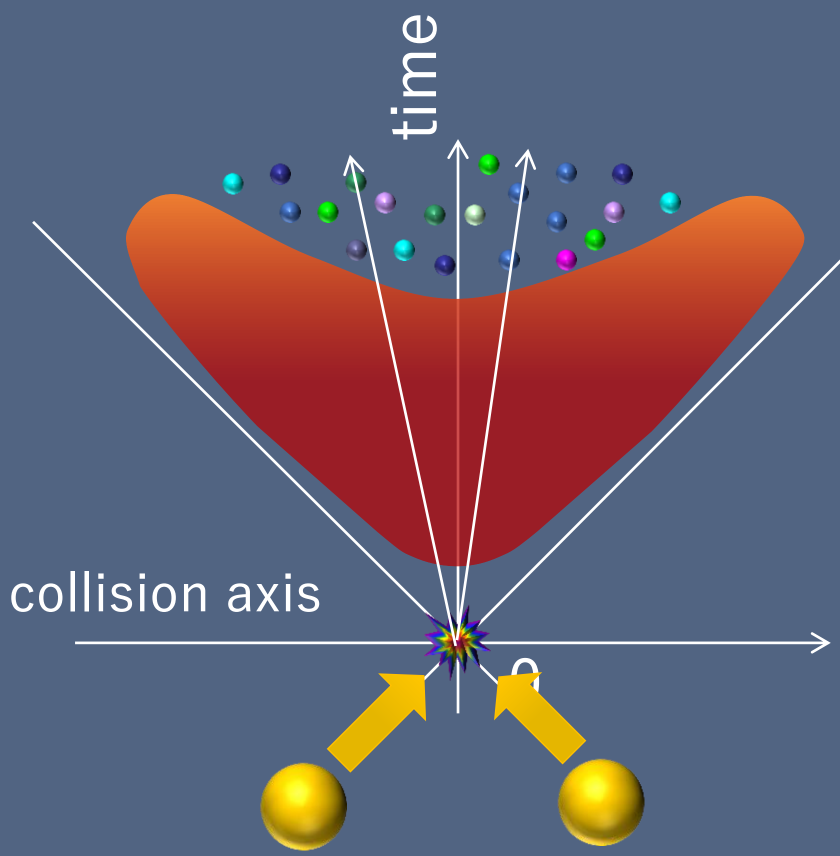
Physics properties of the QGP
- Equation of state
- Transport coefficients
- Stopping power
- …

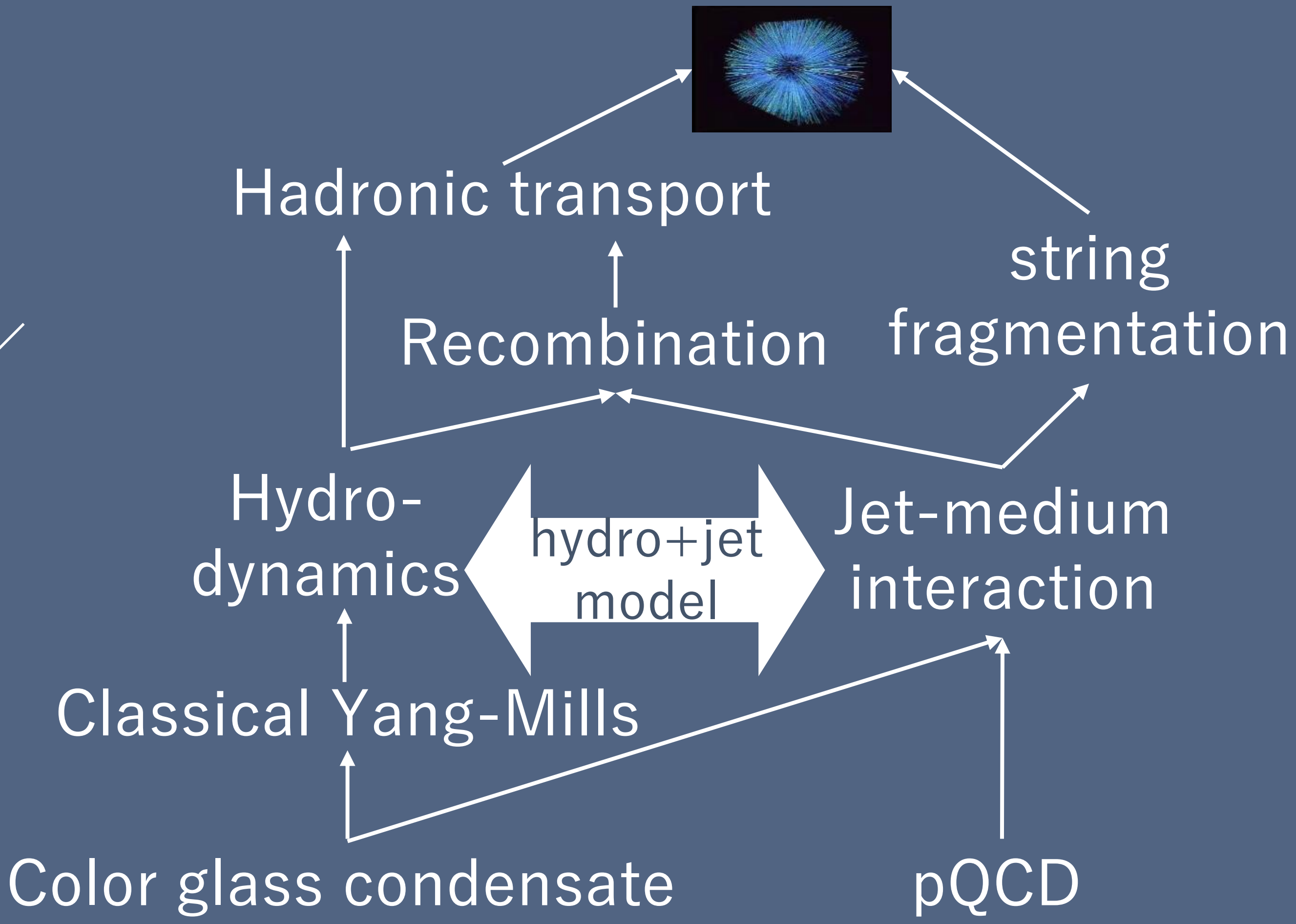
Standard picture of dynamics in high-energy nuclear collisions





Dynamical modeling in high-energy nuclear collisions





*Or put your favorite model here!

Many results shown in this talk
← Taken from presentation in QM2018

https://qm2018.infn.it/

https://indico.cern.ch/event/656452/

Energy frontier

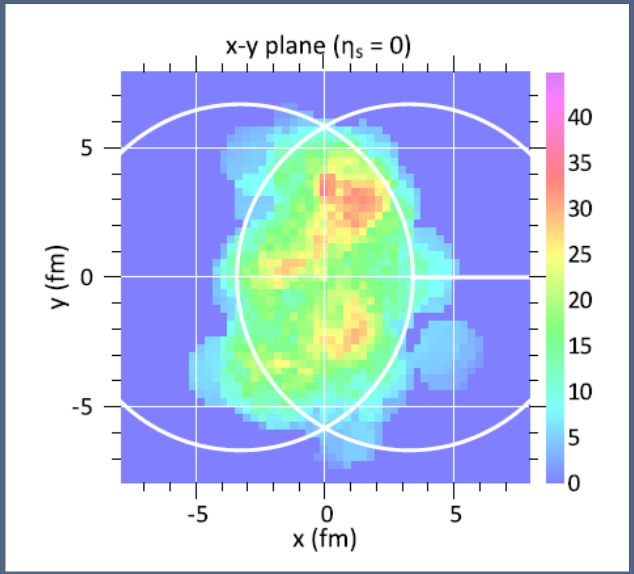
Anisotropic flow

Precision QGP physics

Hydrodynamic fluctuations

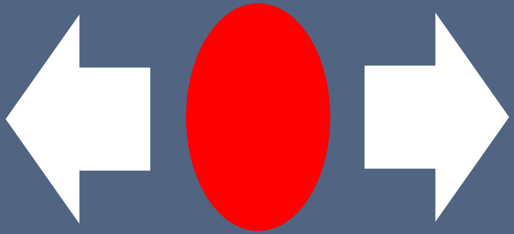
Response to initial fluctuations of geometry

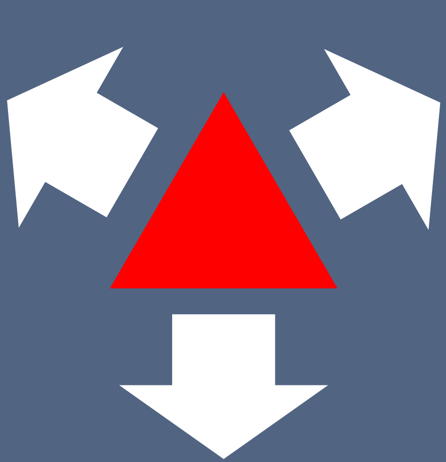
TH *et al.* (2013)



Entropy density distribution

Flow generated by anisotropic pressure gradient





$n = 2$ (quadrupole)
Elliptic flow

Ollitrault (1993)

$n = 3$ (hexapole)
Triangular flow

Alver, Roland (2010)

$n = 4$ (octapole)
Quadrangular flow

Kolb (2003)

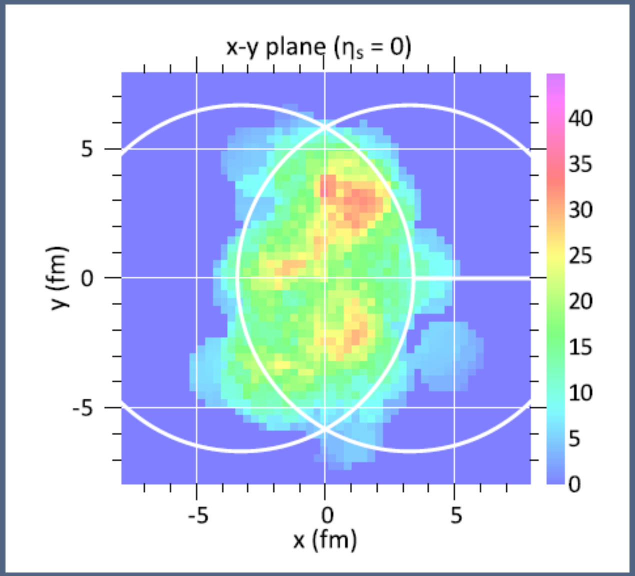
Fine structure of profile → Higher mode

Geometric anisotropy

$$\varepsilon_n = \frac{\langle r^n e^{in\phi} \rangle}{\langle r^n \rangle} = |\varepsilon_n| e^{in\Psi_n}$$

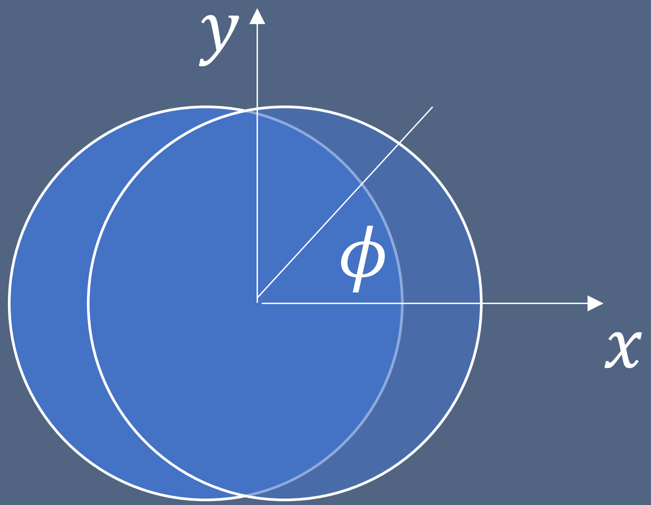
$$\langle \cdots \rangle = \int dxdy \cdots s(x,y)$$

TH *et al.* (2013)



Entropy density distribution

$s(x,y)$

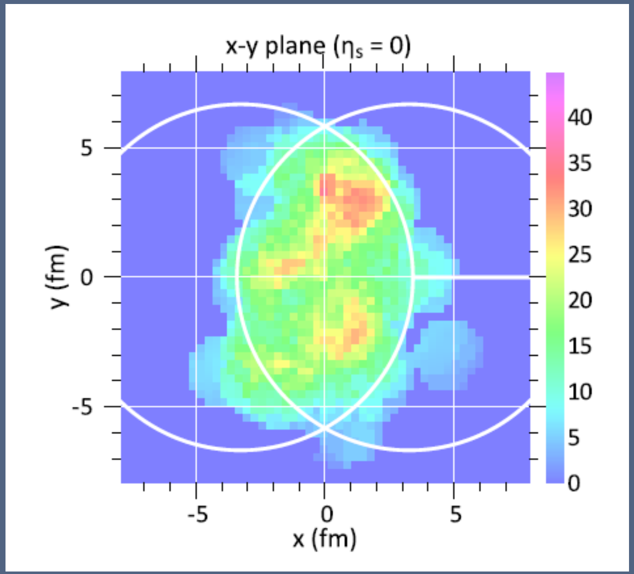


ex.)

Large ε_2 Small ε_2

Transport property through responses

TH *et al.* (2013)



ε_n — Response of the system → v_n

Geometric anisotropy

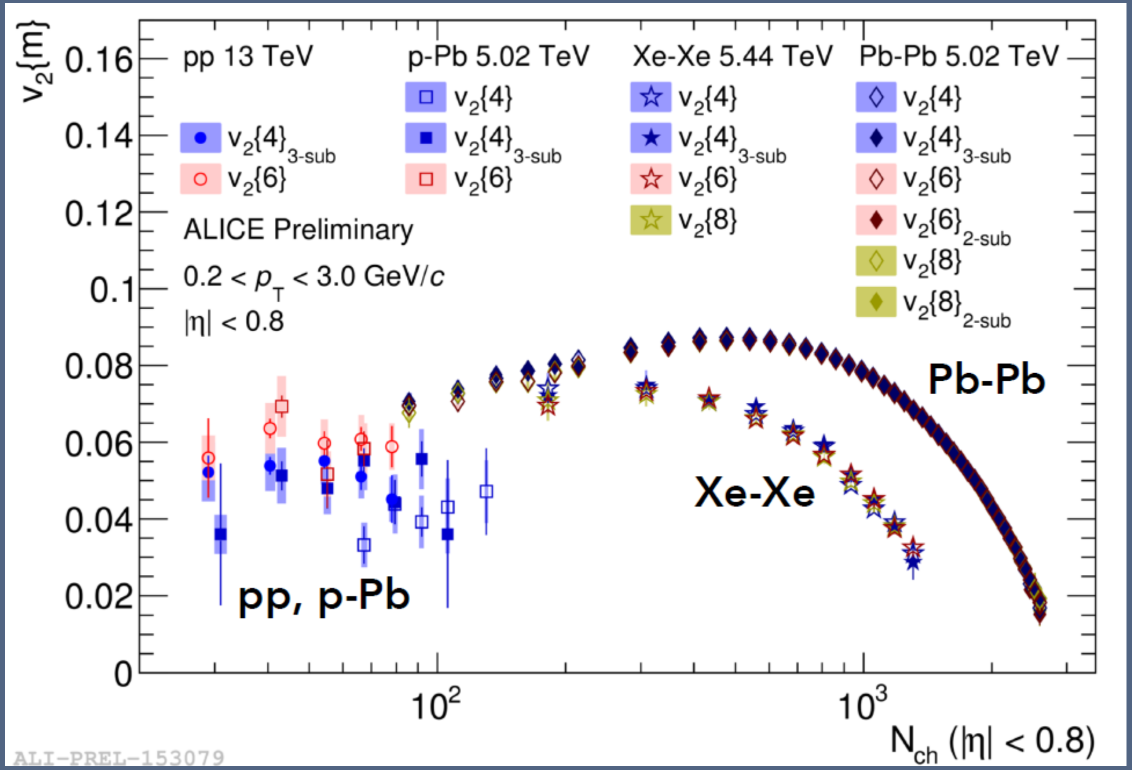
Momentum anisotropy

Competition between anisotropic pressure gradient and damping of shear flow

Small →Large shear viscosity ⟵ Response ⟶ Large →Small shear viscosity

Latest elliptic flow data at LHC

ALICE overview, talk at QM2018



Fluctuation dominance

Geometry dominance

Systematic behavior of elliptic flow in p+p, p+Pb, Xe+Xe and Pb+Pb collisions

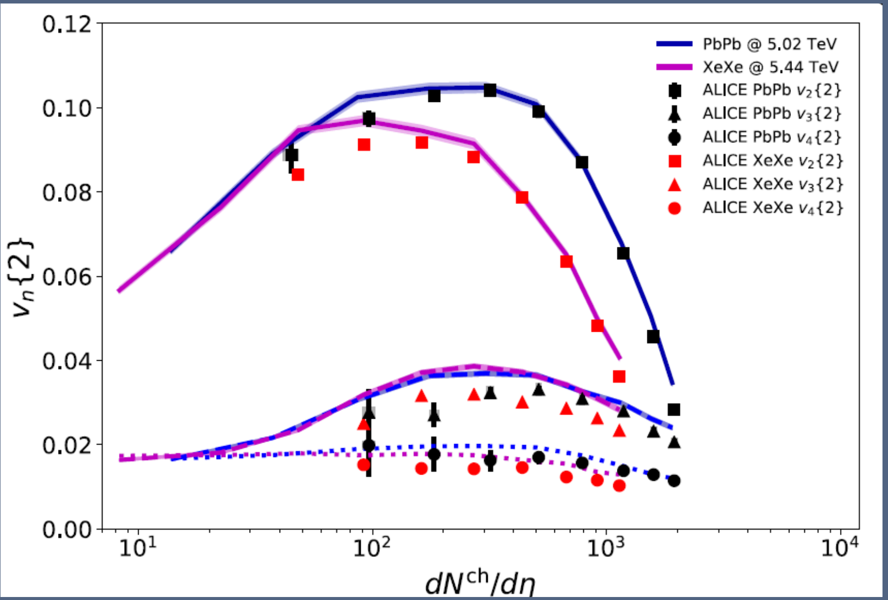
⇓

Challenges to theoretical modeling of high-energy nuclear collisions, in particular, in small colliding systems (See later slides)

See also talk by Nonaka

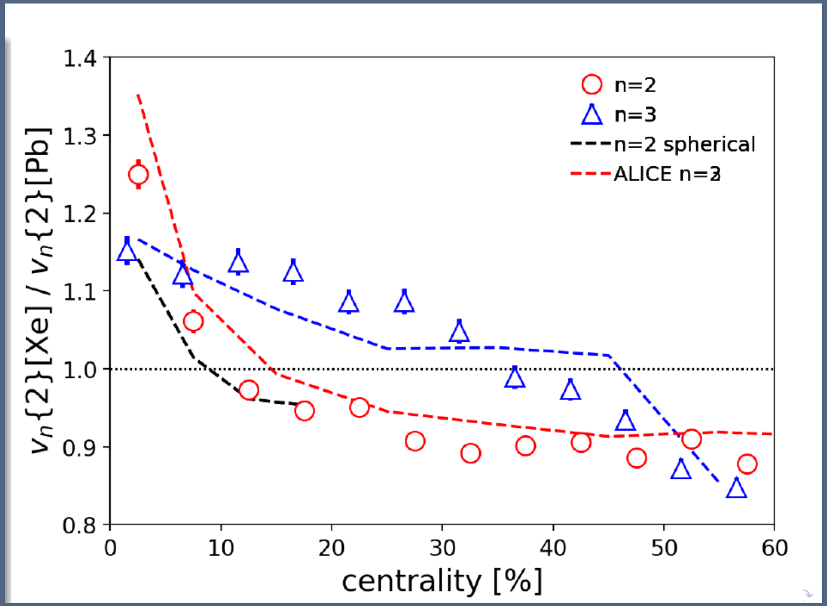
Recent hydrodynamic analysis

B.Schenke, talk at QM2018



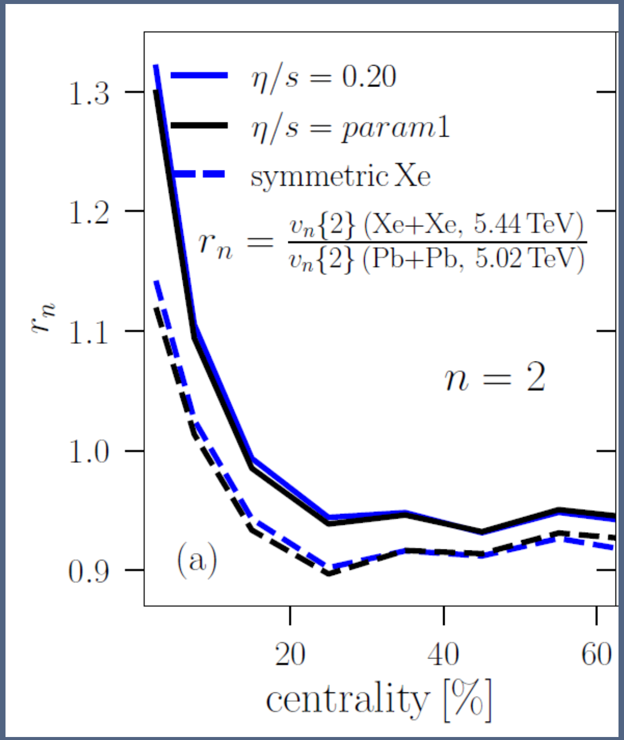
IP-Glasma
+3D hydro (shear+bulk)
+lattice EoS
+afterburner

M.Luzum, talk at QM2018



Trento
+2D hydro (shear)

H.Niemi, talk at QM2018



EKRT saturation
+2D hydro
(T-dep. shear)
+Lattice EoS

Energy frontier

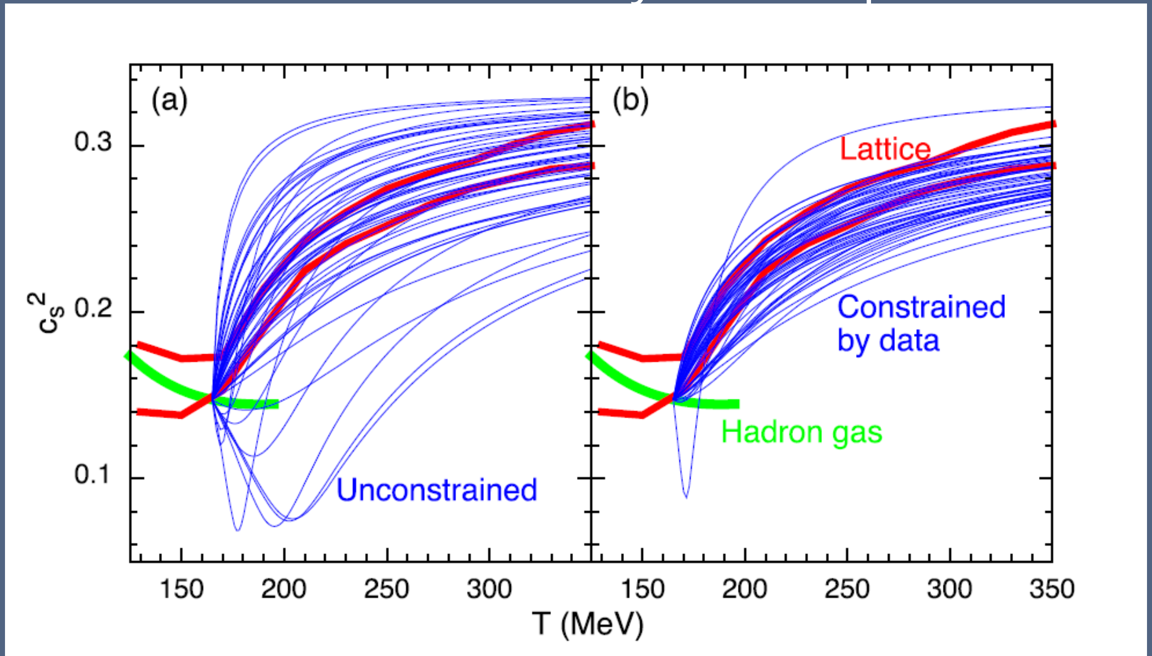
Anisotropic flow

Precision QGP physics

Hydrodynamic fluctuations

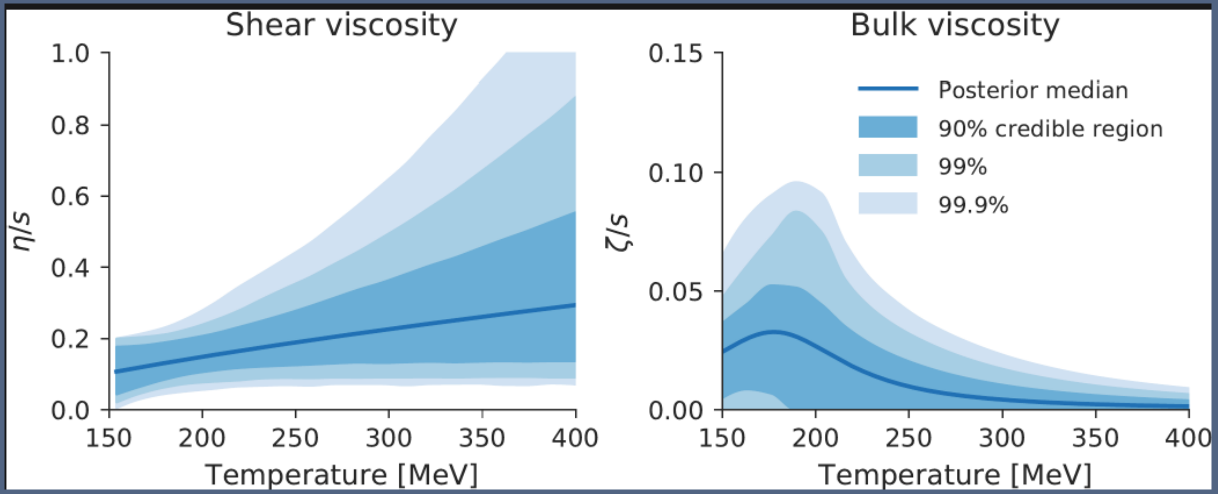
Precision QGP physics using Bayesian parameter estimation

Sound velocity vs. Temperature



Pratt *et al.*(2015)

(Shear viscosity)/(Entropy density)
&(Bulk viscosity)/(Entropy density)



Paquet, poster at QM2018

Experimental data → Posterior probability of parameter

Bayesian analysis

Energy frontier

Anisotropic flow

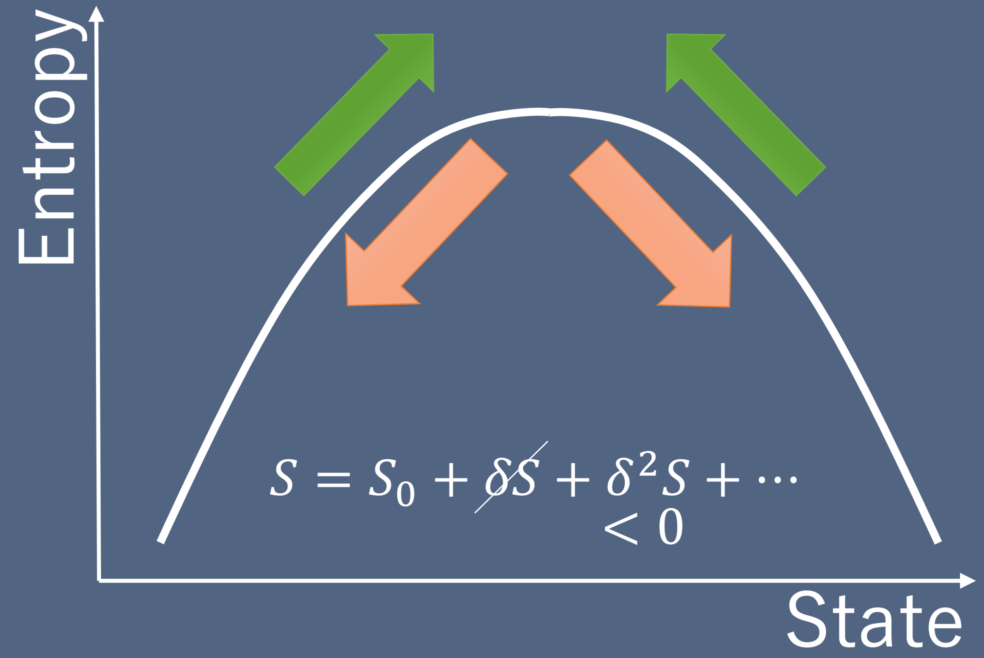
Precision QGP physics

Hydrodynamic fluctuations

PeraltaRamos, Calzetta(2011), Kapusta, Muller, Stephanov(2011), Moore, Kovtun, Romatschke(2011), Hirano, Murase(2013), Young(2014), Akamatsu, Mazeliauskas, Teaney (2017)…

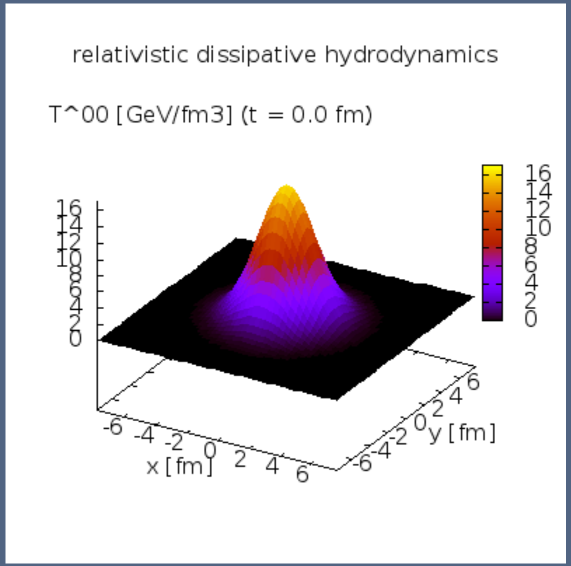
Hydrodynamic fluctuations

Fluctuation-Dissipation relations

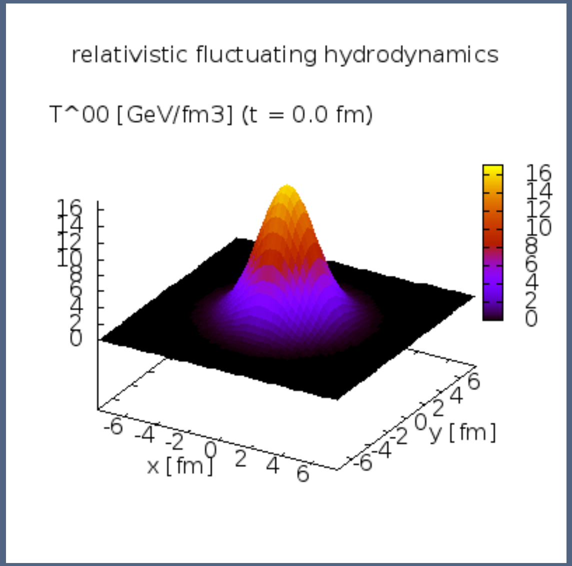


Fluctuating around maximum entropy state

QGP fluid simulations in a box



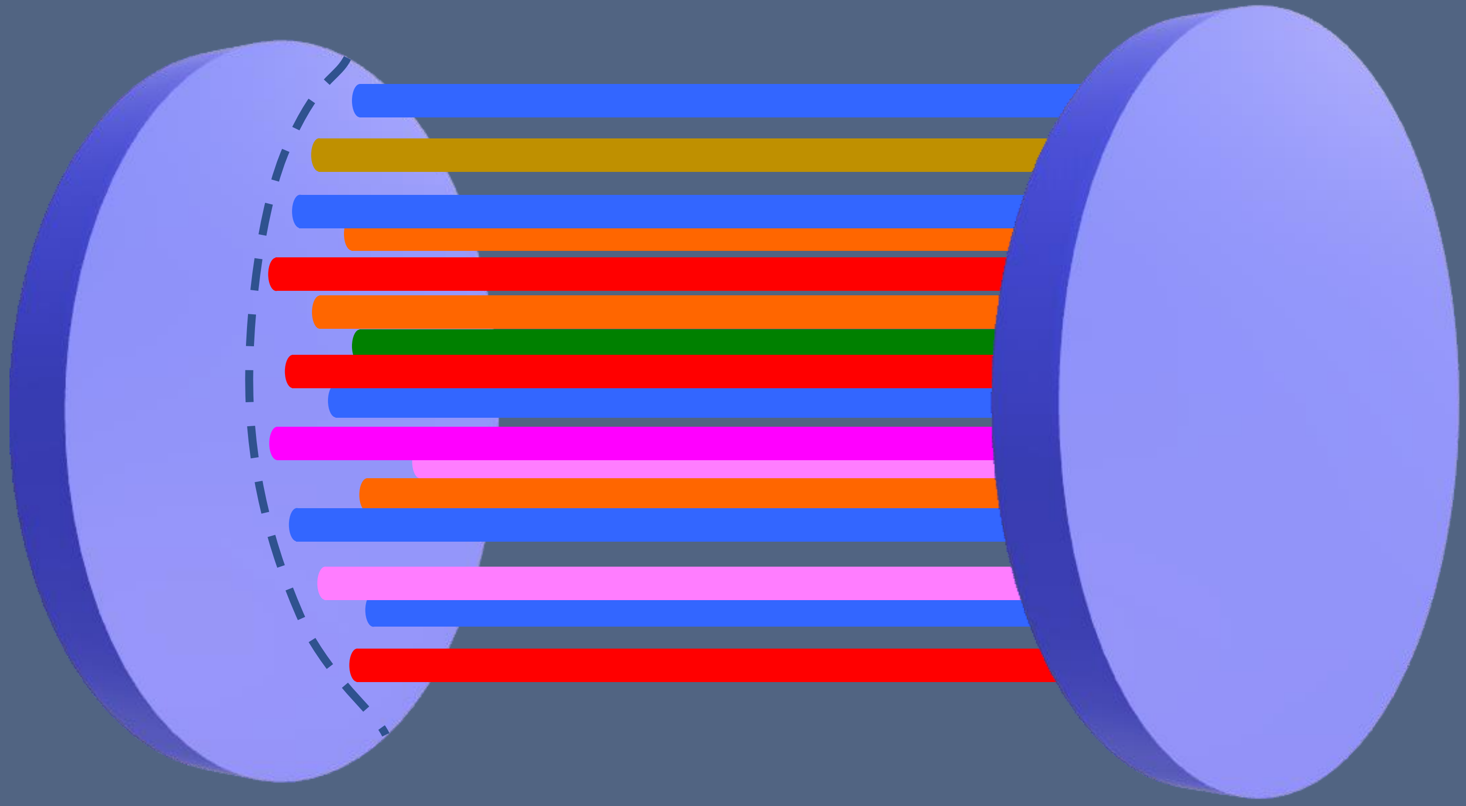
Dissipative hydro (2nd Generation)

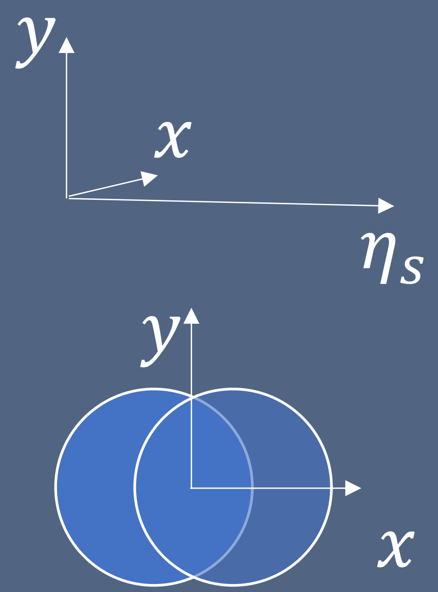


Fluctuating hydro (3rd Generation)

Courtesy of K.Murase

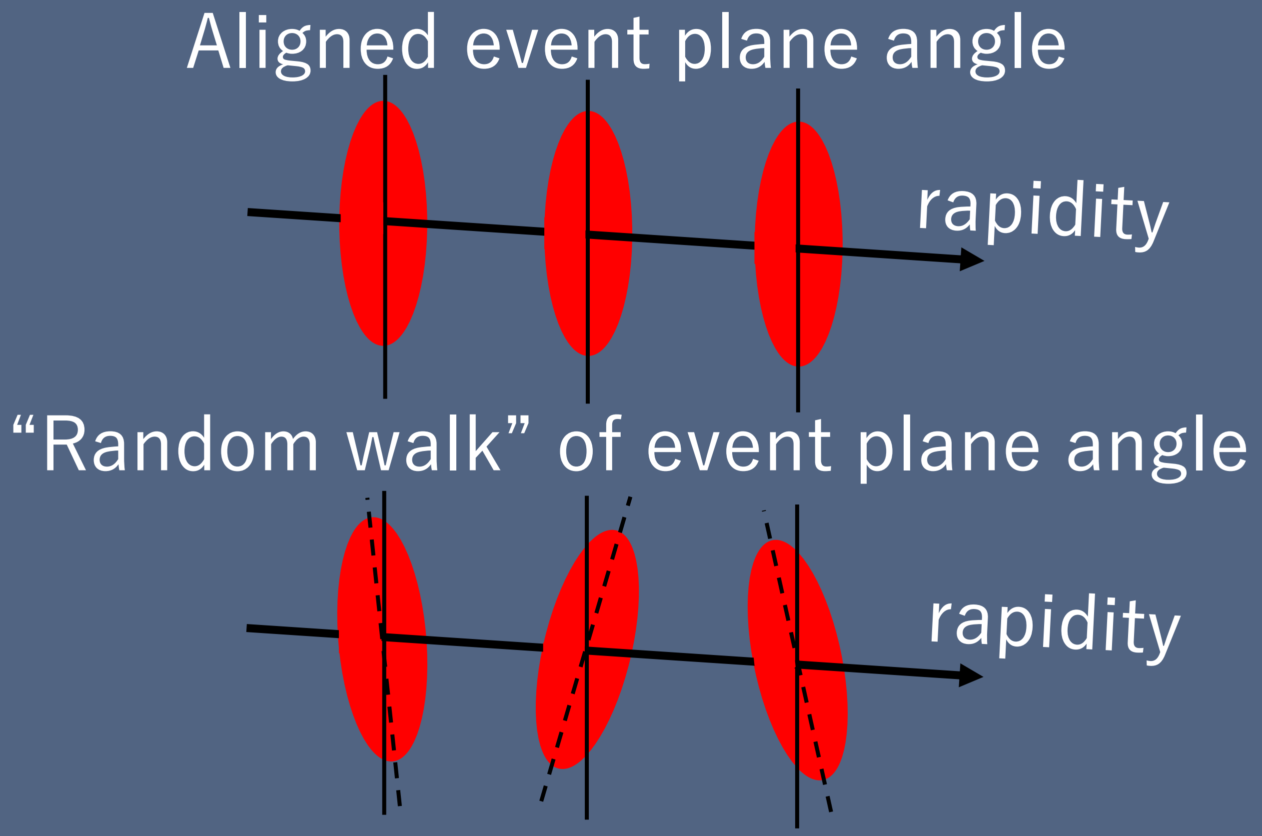
Correlation of initial conditions along collision axis

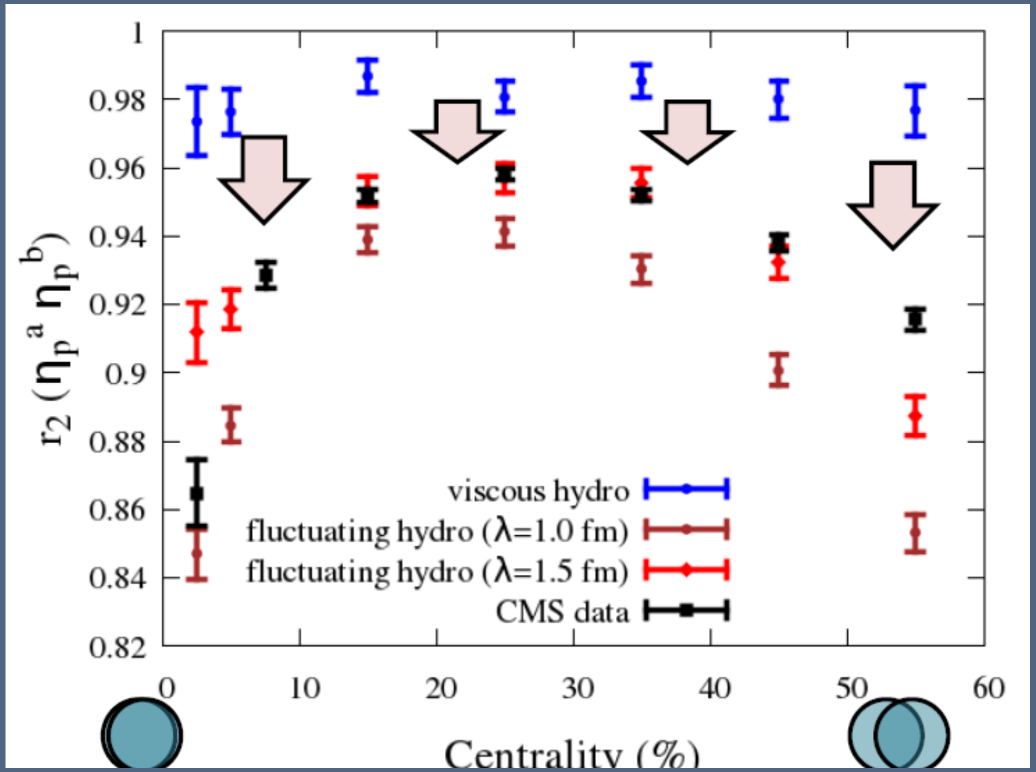




Heavy ion collision as a chromoelectric capacitor
→ Approximately boost-invariant formation of color flux tubes
→ Correlation of initial conditions in rapidity space

Event plane decorrelation from hydrodynamic fluctuations





Factorization ratio

A. Sakai, talk at QM2018

New opportunity to constrain transport coefficients
Genuine event-by-event hydrodynamic simulations

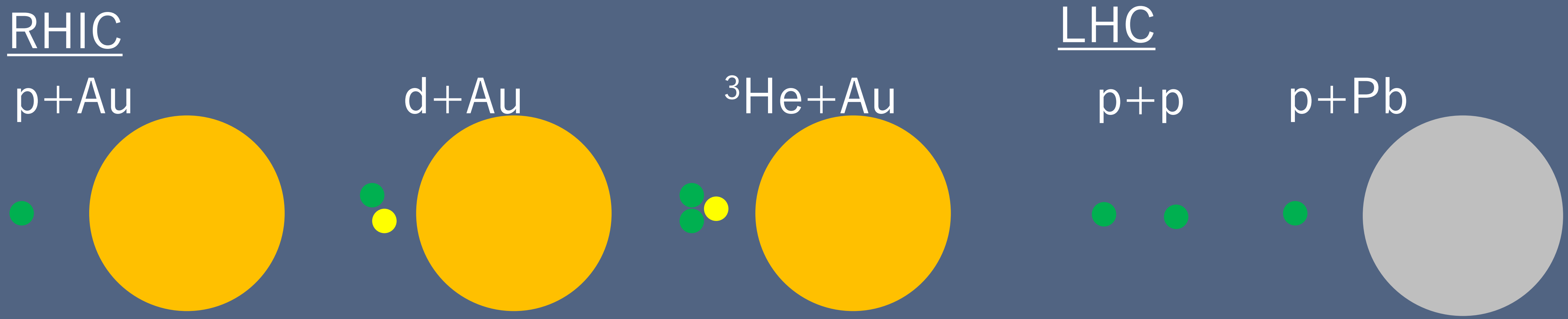
Small colliding systems

Collectivity

Strangeness enhancement

To be QGP or not to be?

That is THE question!



2003~2010: Control experiment

→ Understanding of initial state effects

2010: Discovery of “ridge” structure

2010~today: Discussion of possibility to create QGP

HEP vs HIC physicists' view

High multiplicity pp event

https://phys.org/news/2017-05-plasticsnot-simply-garbage.html

High Energy Physicist
→ Garbage dump for
Beyond Standard Model particle?
(Find a needle in a haystack?)

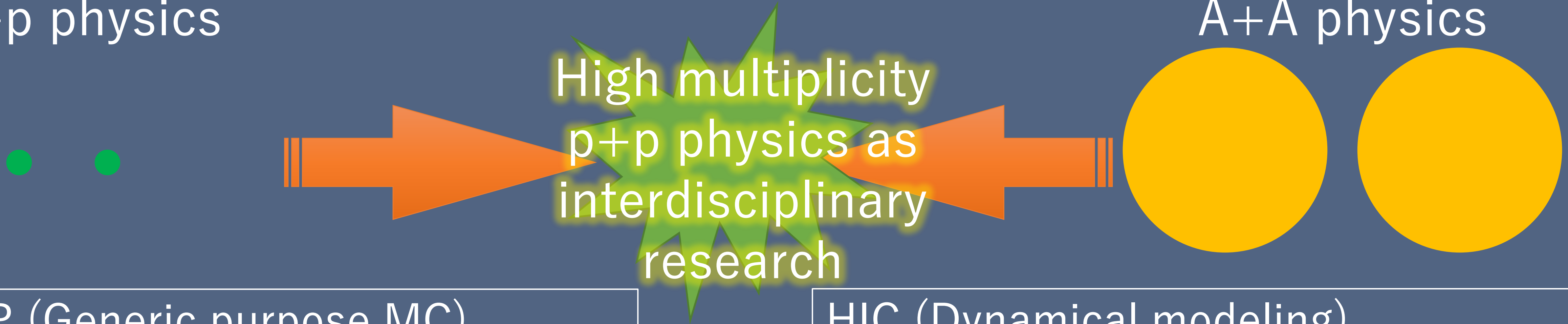
Heavy Ion Physicist
→ Treasure trove
"To be (QGP) or not to be?"

https://www.journalism.co.uk/news/why-openspending-data-is-a-treasure-trove-for-journalists/s2/a552805/

HEP vs HIC physicists' view (contd.)

p+p physics

A+A physics



HEP (Generic purpose MC)

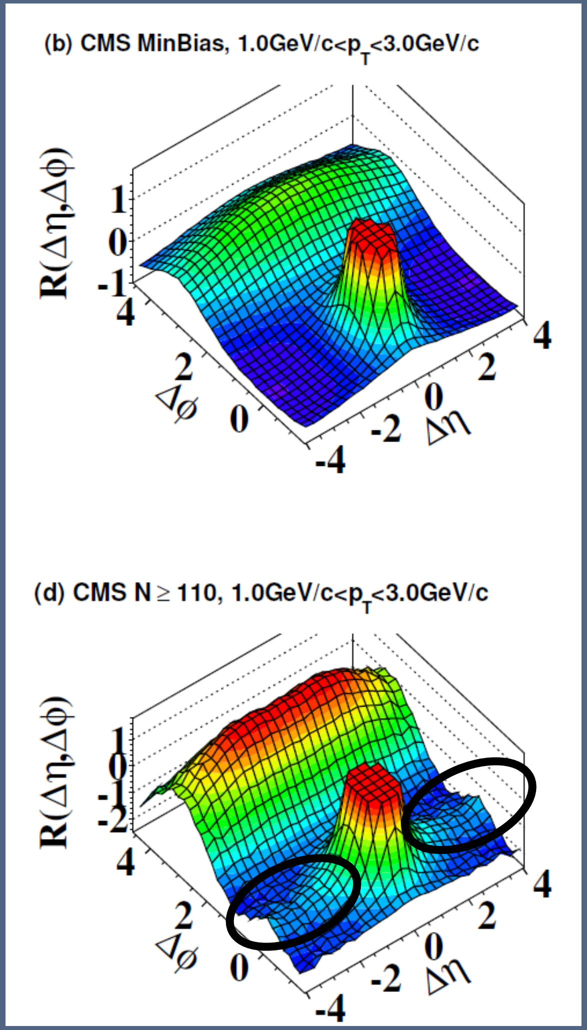
- Jet universality
  - Fragmentation from $e^+ + e^-$
    → Applied to p+p collisions
  - No multiplicity dependence of particle ratios
- Need non-perturbative, new mechanisms to interpret data

HIC (Dynamical modeling)

- Successful modeling in A+A collisions
  → Paradigm of QGP fluidity
- Testing understanding of the QGP in p+p collisions
- QGP-based modeling applicable in small colliding systems???

Everything starts from CMS findings

CMS Collabortion (2010)



What is "Ridge"?

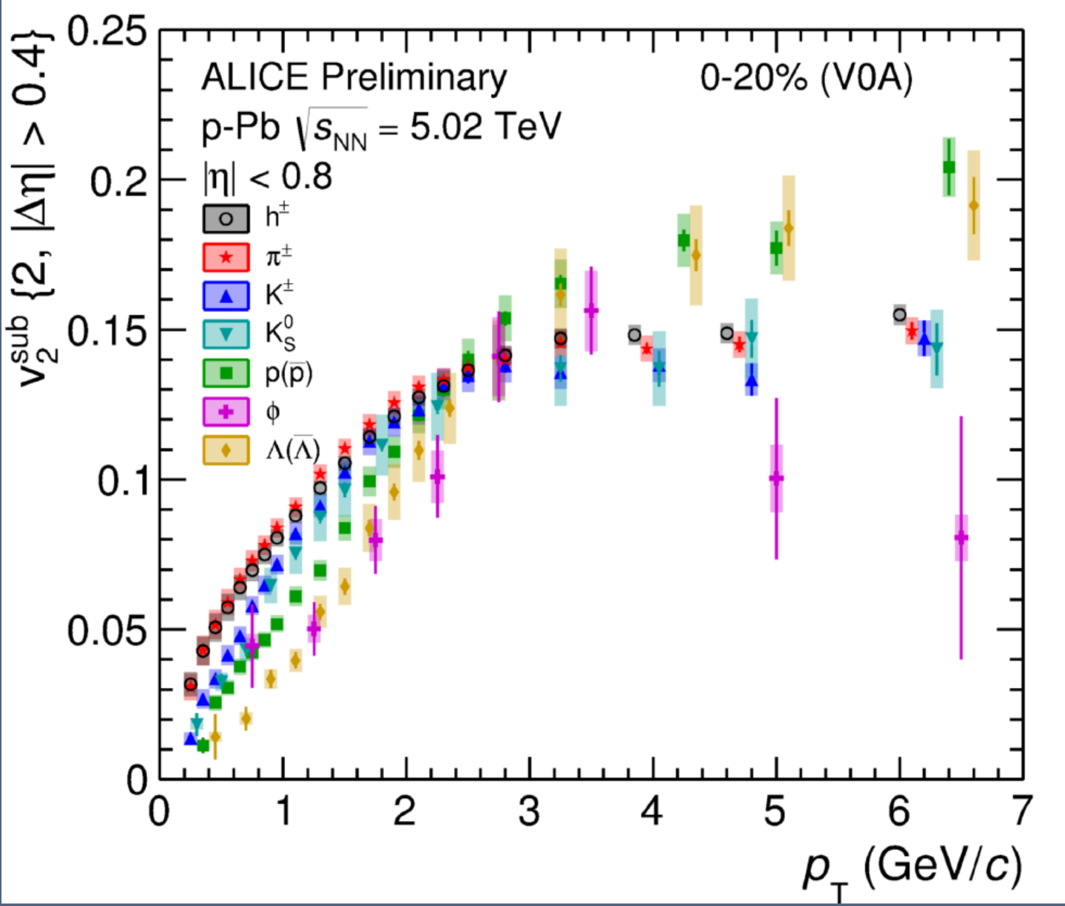
Correlation of two particle emission with the same azimuthal angle but large rapidity gap ($\Delta\eta$~2-4)←Need some correlation in the very early stage

Ridge in heavy ion collisions
← Correlated emission pattern along rapidity
← Interpreted as collective flow

First ridge observation in high-multiplicity pp collisions at $\sqrt{s} = 7$ TeV !

Mass Ordering in p+Pb at LHC

ALICE overview, talk at QM2018



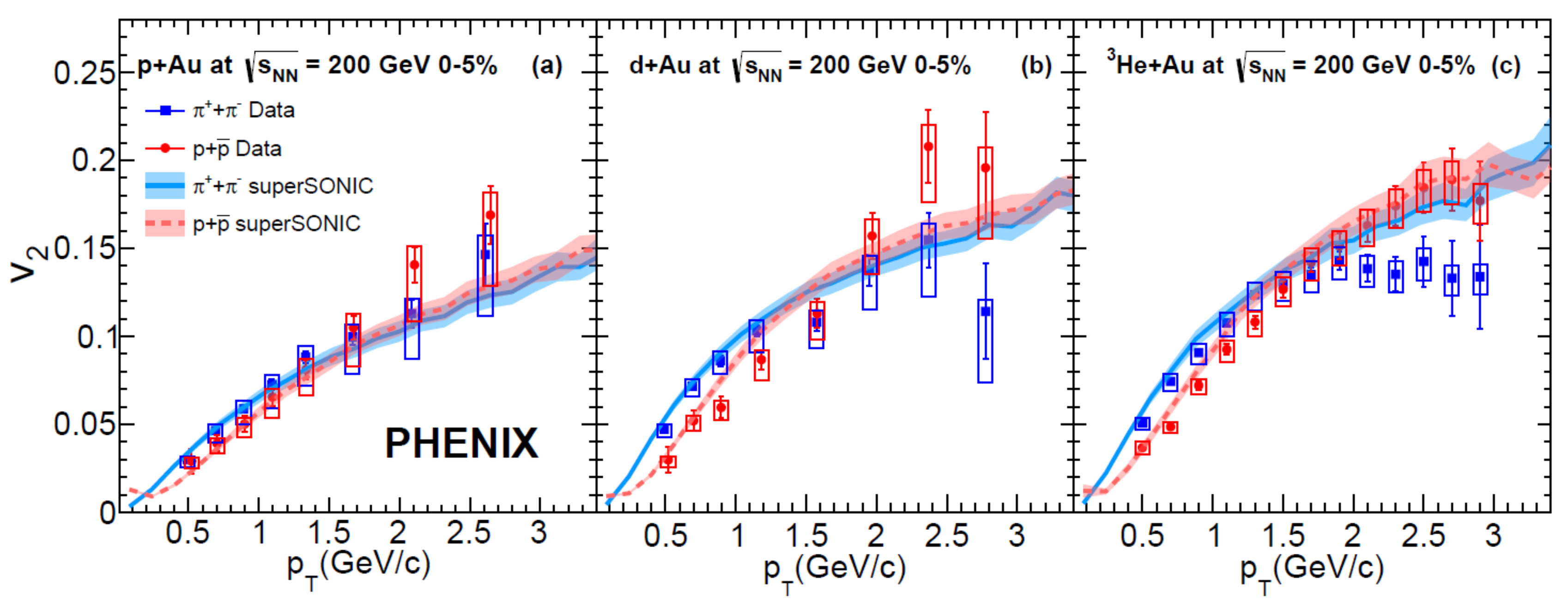
Mass ordering behavior among pi, K, p, and Lambda
← One of the typical results from hydrodynamic collectivity

(Selected) alternative interpretation:

- Hadronic cascade
  Y.Zhou, X.Zhu, P.Li, H.Song (2015)
- Parton transport
  P.Bozek, A. Bzdak, G.-L.Ma (2015)
- Parton escape mechanism
- L.He, T.Edmonds, Z.W.Lin, F.Liu, D.Molnar (2015)
- Free streaming + hadronization
  P.Romaschke (2015)
- Classical Yang-Mills + Lund fragmentaion
  B.Schenke, S.Schlichting, P.Tribedy, R.Venugopalan (2016)

Unified description from pp to AA?

Hydrodynamic analysis of elliptic flow in p,d,He+Au collisions at RHIC



PHENIX Collaboration(2017)

Large elliptic flow measured at RHIC

- Mass ordering
- Consistent with hydrodynamic calculations

$$\frac{\eta}{s} = 0.08$$

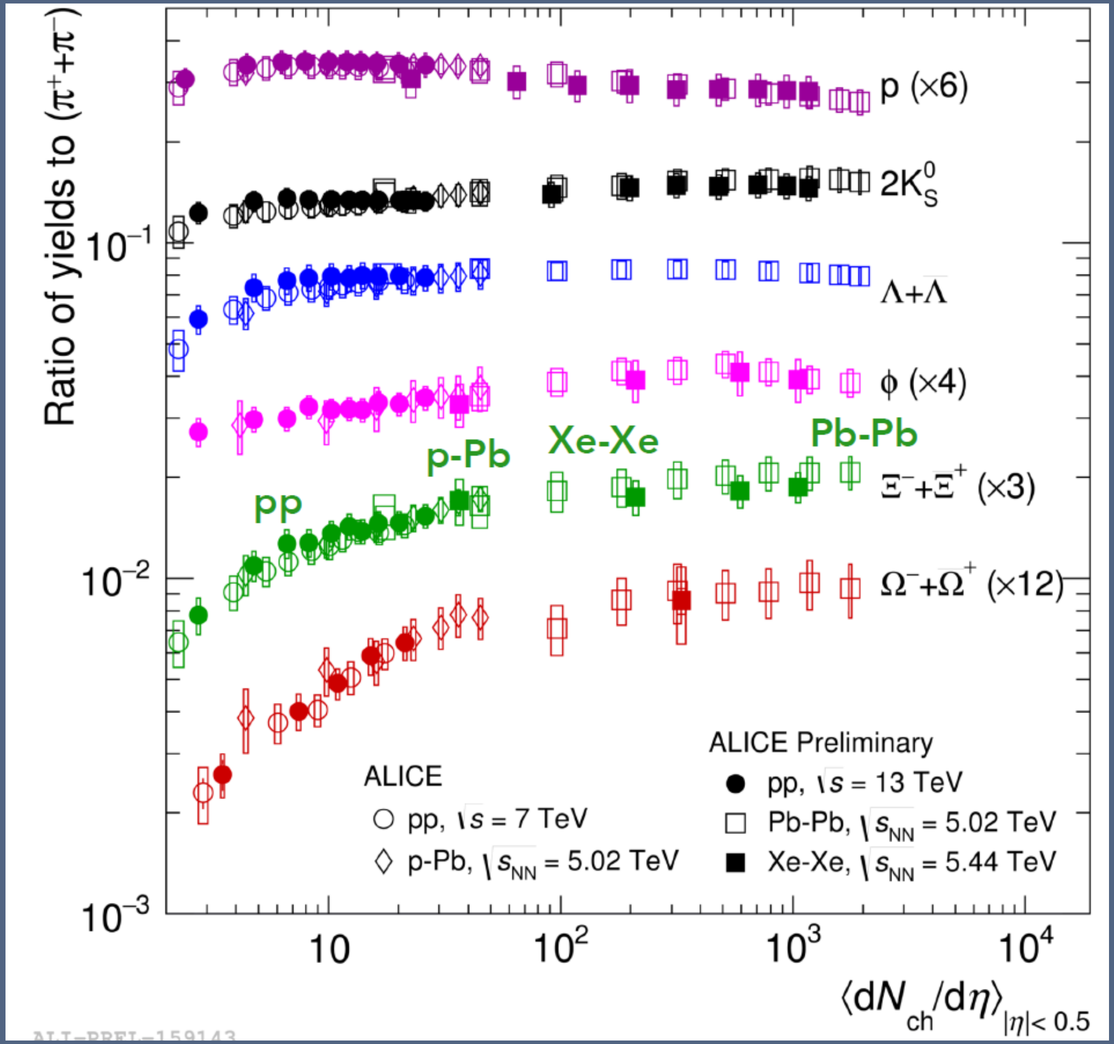
Reproduction of experimental results in both large and small systems at RHIC in a single hydro.

Small colliding systems

Collectivity

Strangeness enhancement

Strangeness enhancement



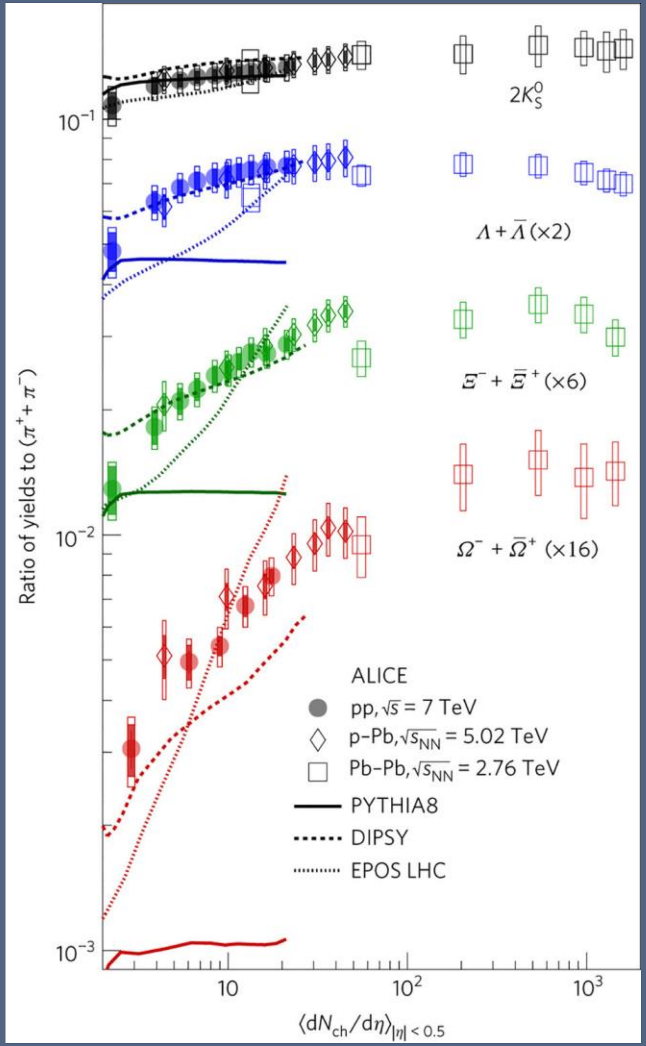
ALICE overview, talk at QM2018

Ratios of yields to pions in p+p, p+Pb, Xe+Xe and Pb+Pb collisions

→ All results for each hadron lie in a single curve

→ Scale with multiplicity, not N_{part} (geometry, system size) or collision energies

Violation of “jet universality”

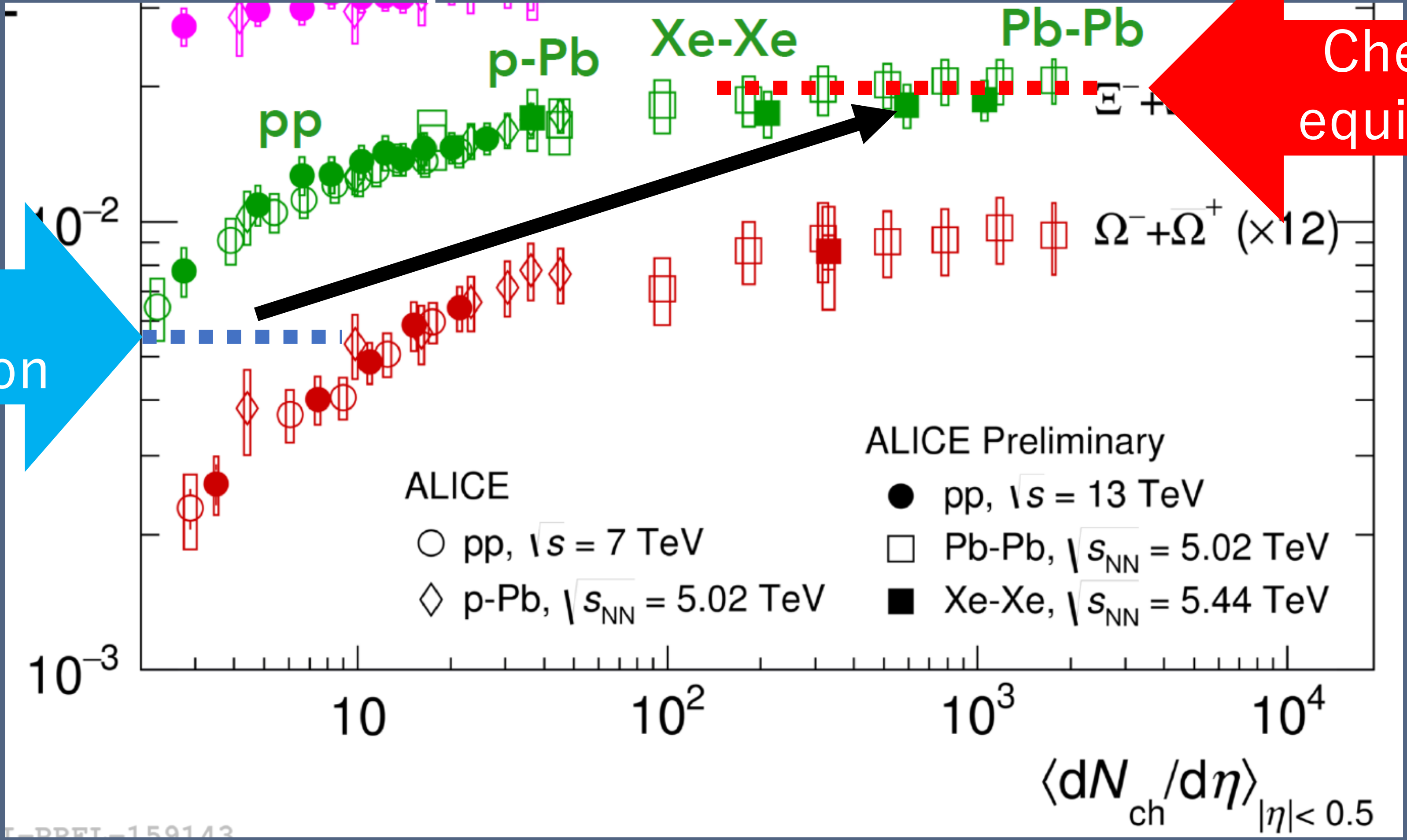


ALICE, Nature Physics (2017)

- Multi-strange hadrons increase more rapidly than charged pions
- Unable to reproduce from Lund string fragmentation
  ← Particle ratios controlled by a string tension
- Additional final state dynamics needed?

PYTHIA8: Lund string fragmentation
EPOS LHC: Core-corona QGP formation
DIPSY: Rope hadronization

Continuous change from fragmentation to chemical equilibrium?



String fragmentation

$$P \propto \exp\left(-\pi \frac{m_q{}^2}{\kappa}\right)$$

Chemical equilibrium

$$P \propto d_i \exp\left(-\frac{m_i}{T_{\mathrm{ch}}}\right)$$

How to deal with both string fragmentation and emission from chemically equilibrated matter at once?

Core-Corona Picture

Aichelin, Werner(2009), Becattini, Manninen (2009)
Pierog *et al.* (2015), Akamatsu *et al.*(2018)

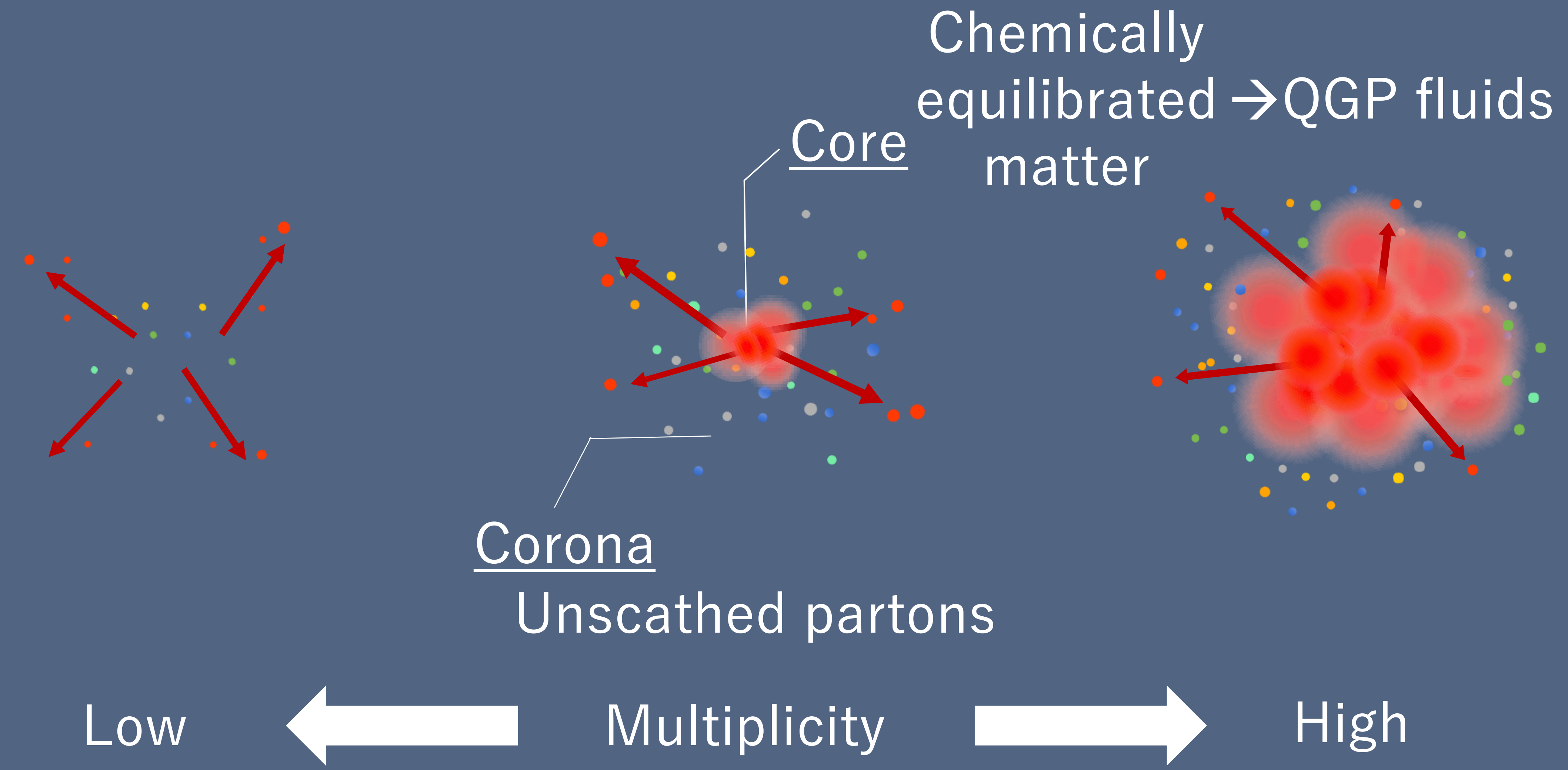
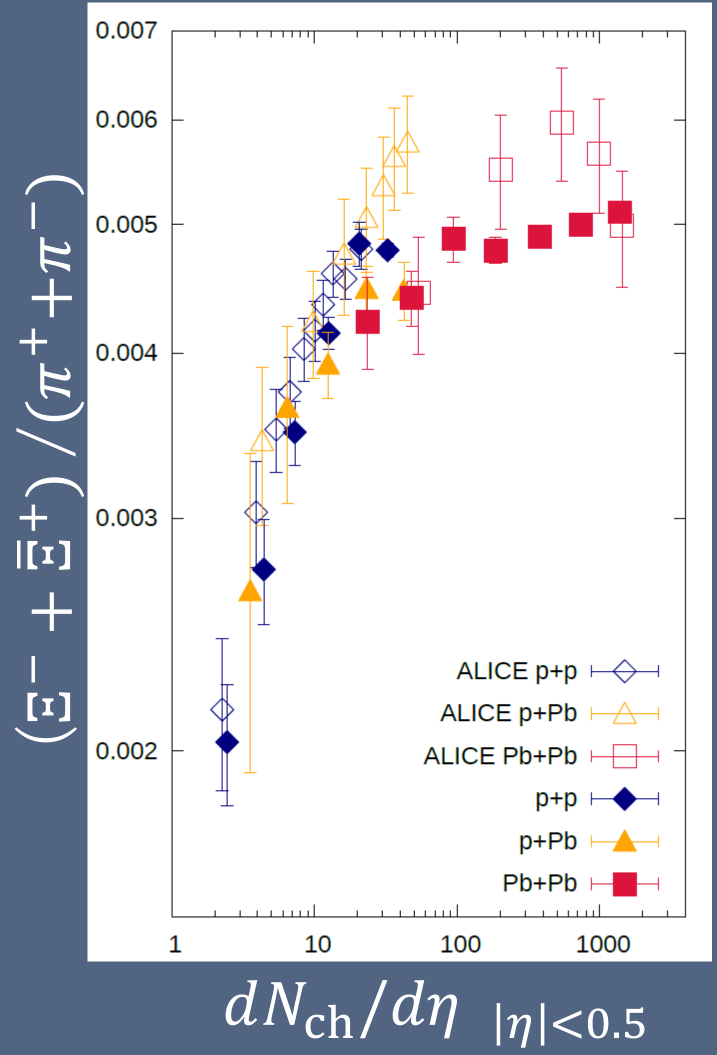
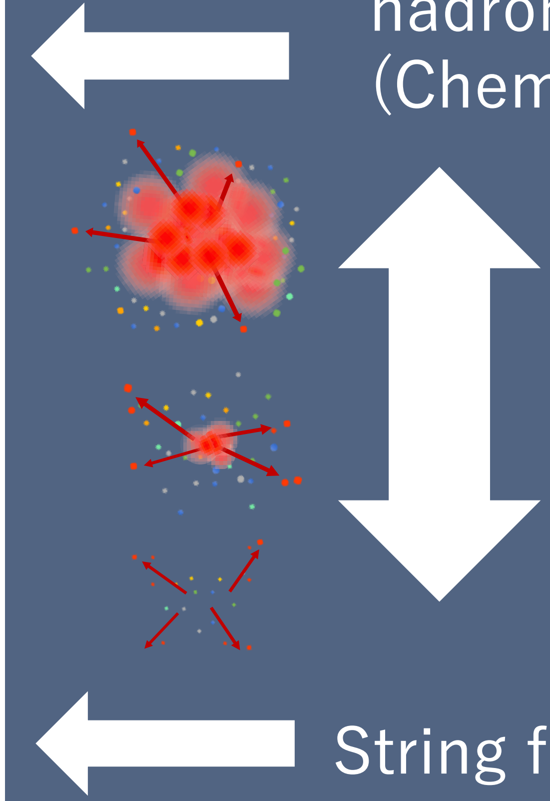


Figure: Courtesy of Y.Kanakubo

See also, K.Werner, talk at ISCHECRI2018

Core-corona effects on strangeness production





Hydro limit:
hadron production only from fluids
(Chemically equilibrated matter)

Continuous changes with multiplicity
← Dynamical initialization with core-corona picture

Y.Kanakubo, poster at QM2018

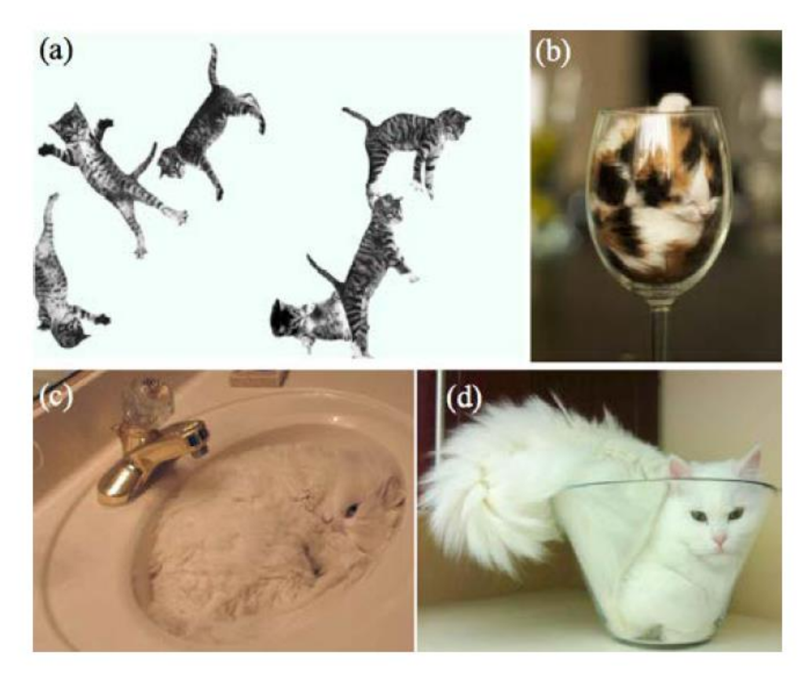
String fragmentation limit:
hadron production only from string fragmentation

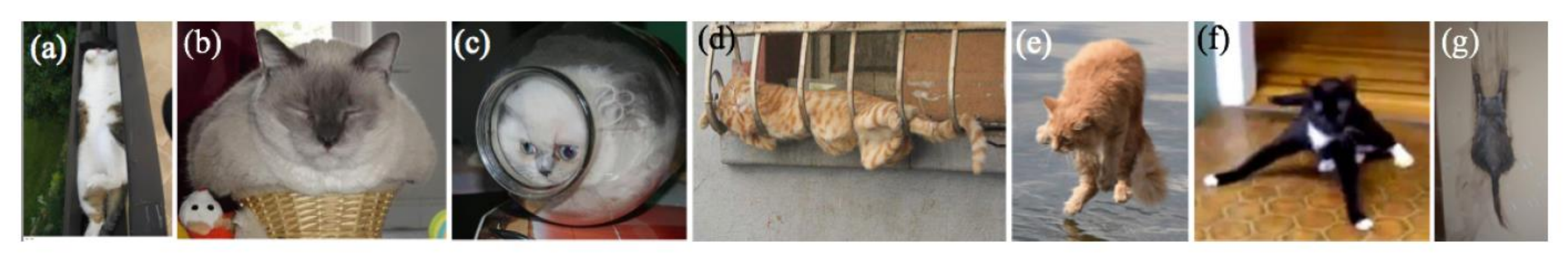
Summary and Outlook

- Construct robust models against precision data
  - “From soup to nuts”
  - Single framework from pp, pA to AA collisions
  - Not only single particle distribution but also two-particle correlations
- Need much more studies even in the “simplest” pp collisions!
  - How to model collectivity?
    - Initial or Initial + final?
    - Sensitive to thermalization process(?)

Final question: Everything flows?

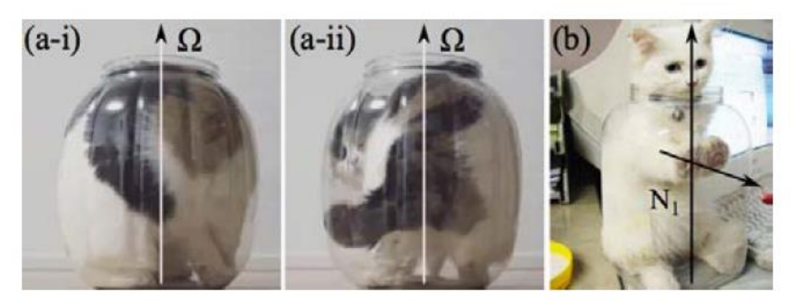
παντα ρει! Everything flows! 万物流転！





Even cats flow!

The 2017 Ig Nobel Prize in Physics: M.A. Fardin for using fluid dynamics to probe the question "Can a Cat Be Both a Solid and a Liquid?“ (https://www.improbable.com/ig)

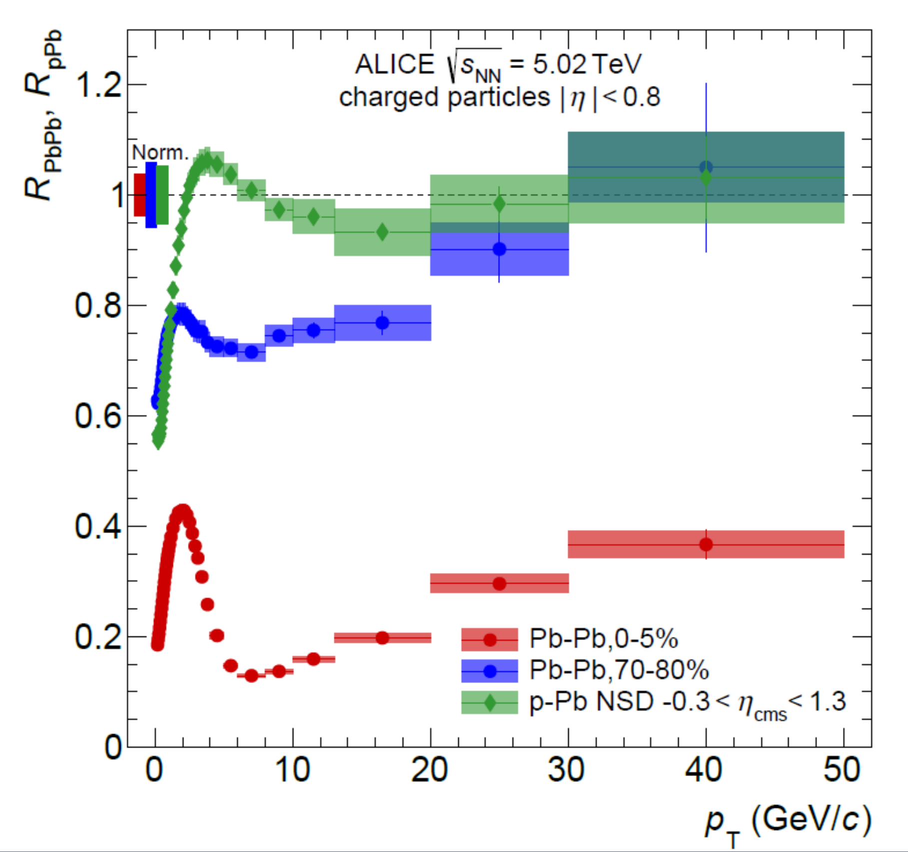


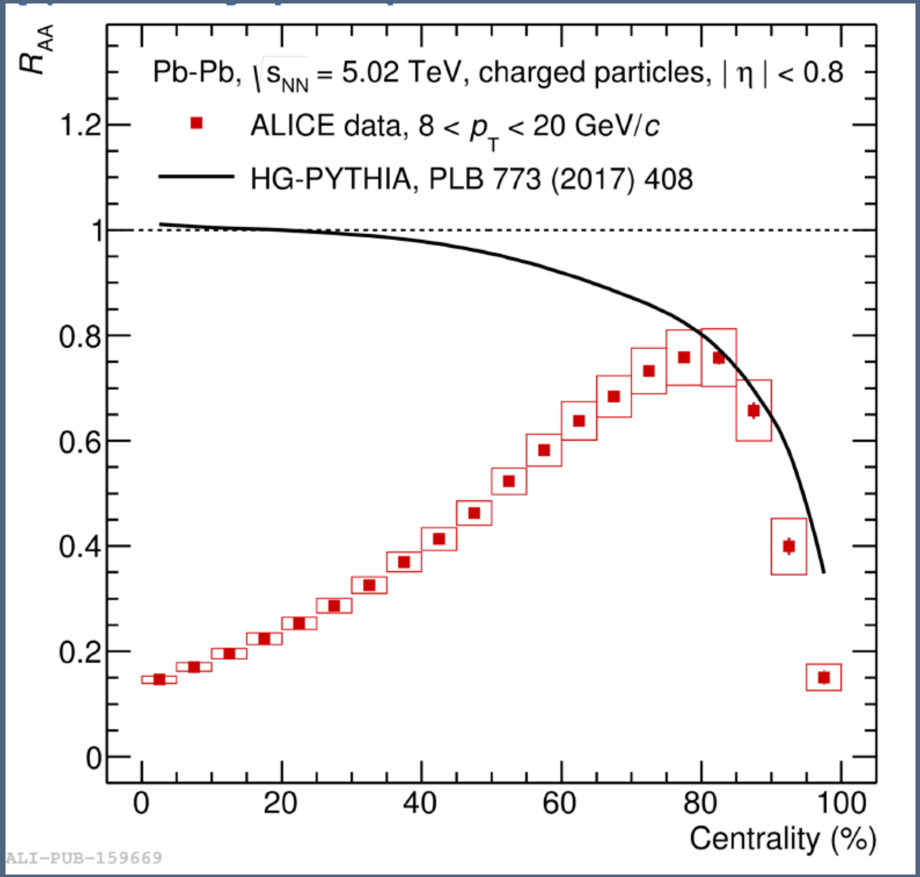
Spontaneous rotation

Figures taken from
M.A.Fardin, On the rheology of cats, Rheology Bulletin, 83(2) July 2014

No jet quenching in small colliding systems

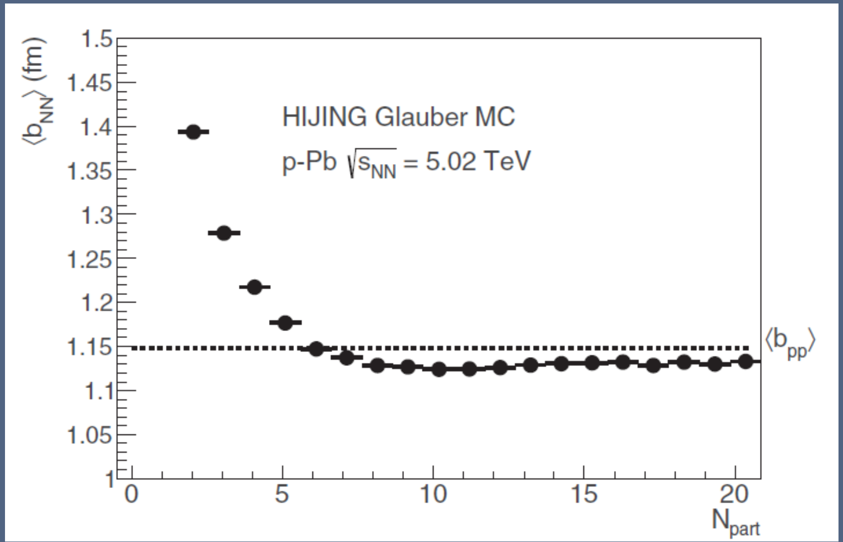
→Compatible with peripheral AA results?



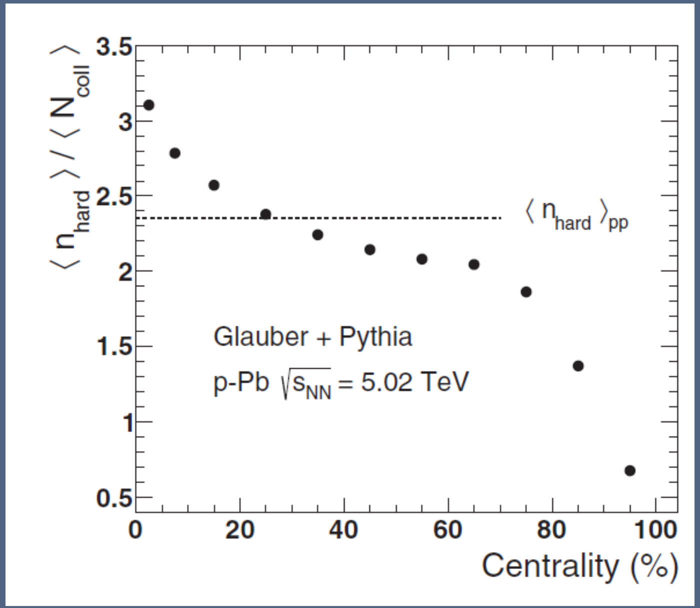


Peripheral $R_{AA} < 1$ ← Artifact of geometrical bias(?)

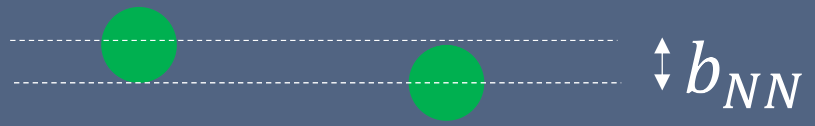
Why this happens?



Average of NN impact parameter vs N_{part}



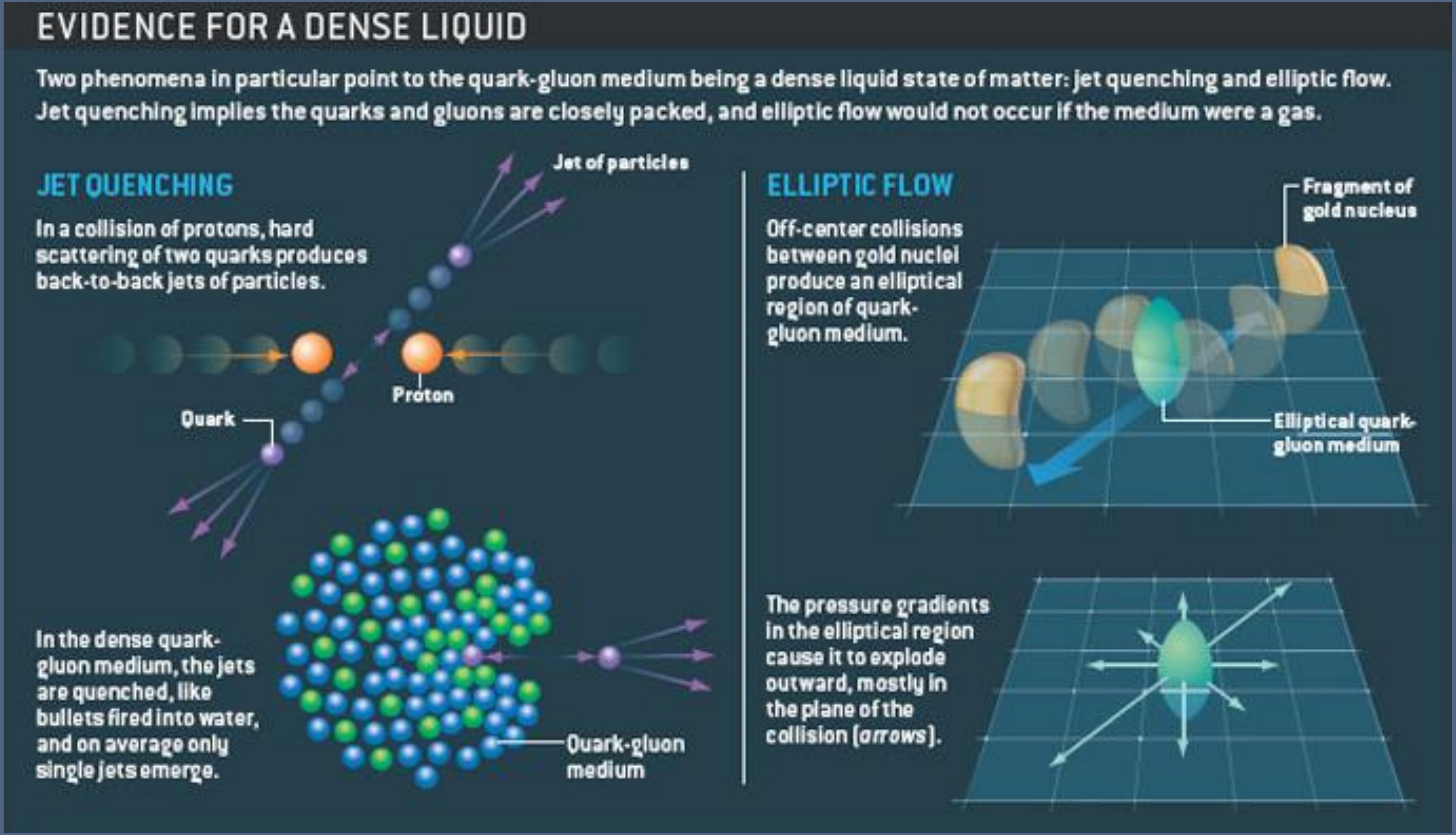
Number of hard scattering does NOT scale with N_{coll}.



The smaller b_{NN}, the more MPI.

ALICE, PRC91(2015)064905

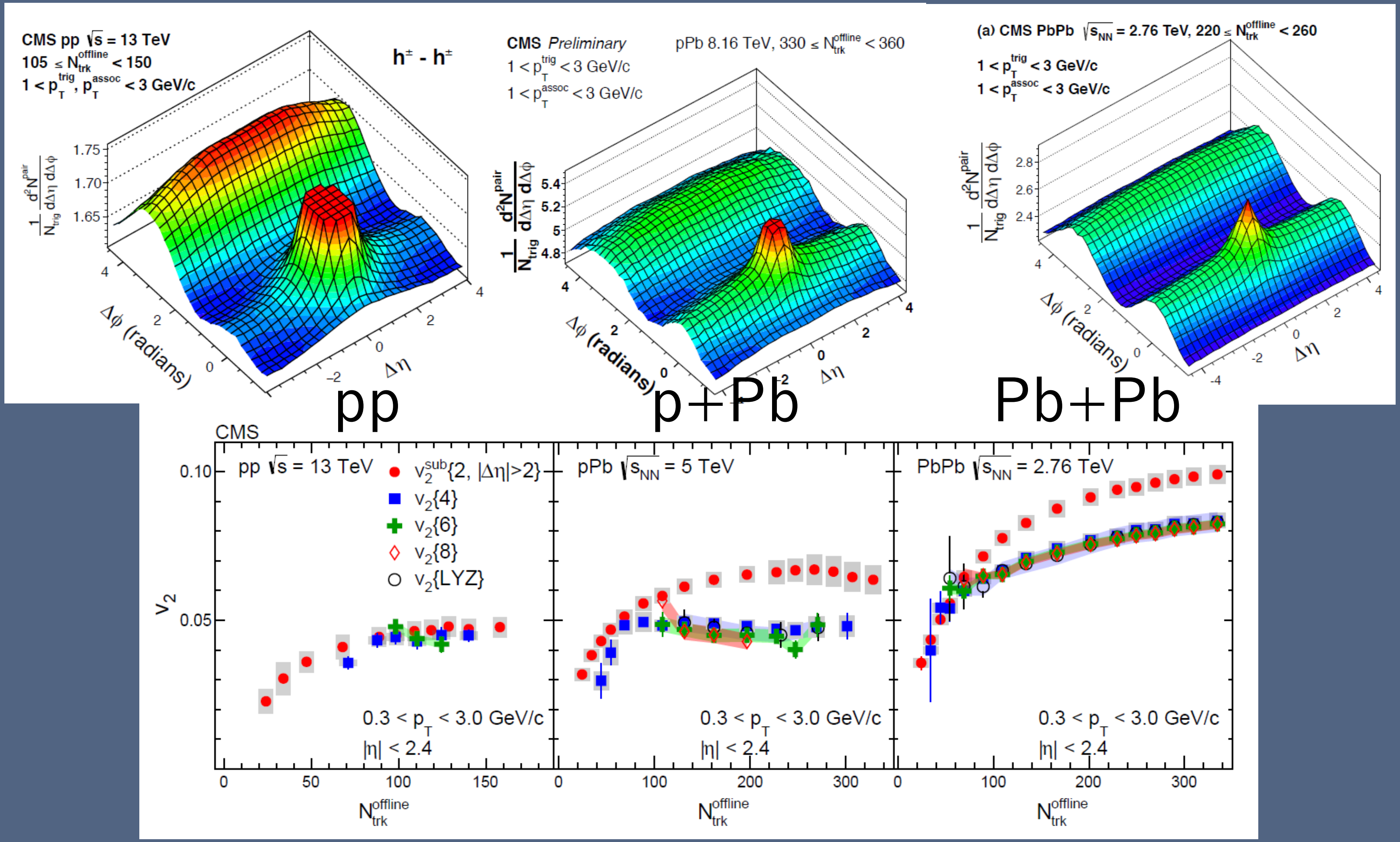
“Evidence for a dense liquid”



Michael Riordan and William A. Zajc
Scientific American 294, 34 - 41 (2006)

Two milestones in high-energy nuclear collisions at RHIC

Collectivity in pp and pPb collisions at LHC

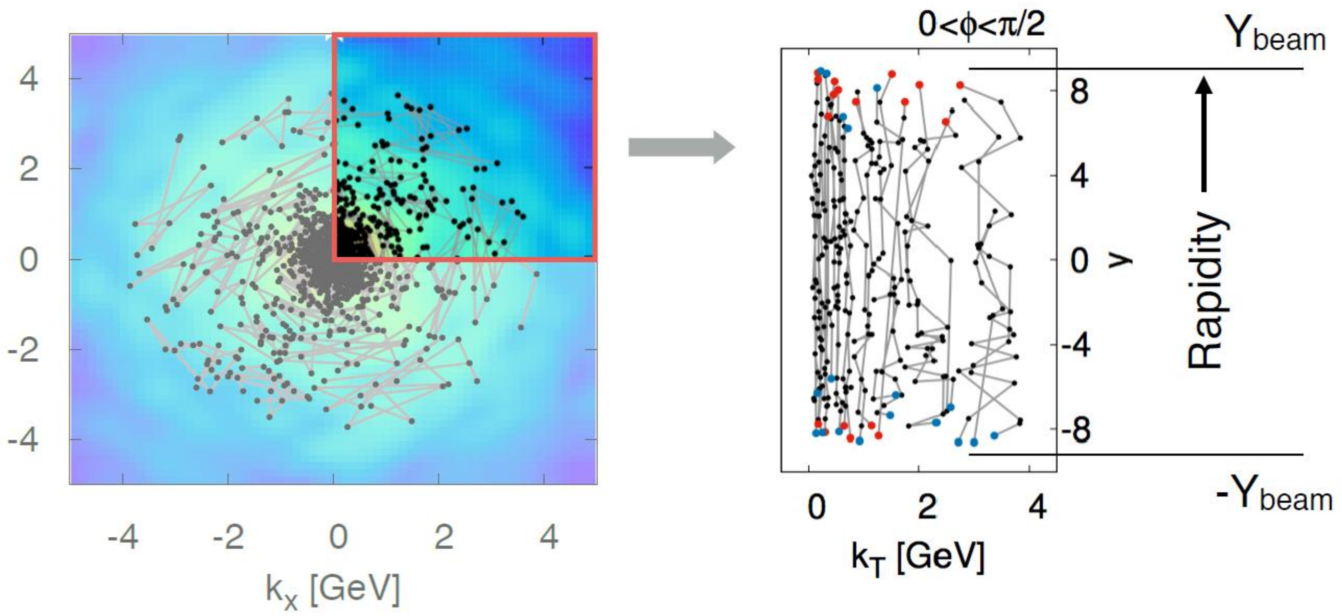


Guilbaud for CMS (2017)

Classical Yang-Mills + Lund fragmentation

P.Tribedy, talk at QM2018

PYTHIA strings stretch in the rapidity direction



Group gluons close in (k_x-k_y) into strings stretching mainly in the rapidity direction

Need to add a quark and an anti-quark at string ends for color neutrality

Classical Yang-Mills simulations of

Sampling gluons to form a string

Lund fragmentation

Grouping scheme:
Gluons close in momentum space
←Seed of collectivity?
←How to justify?

Rope + shove model

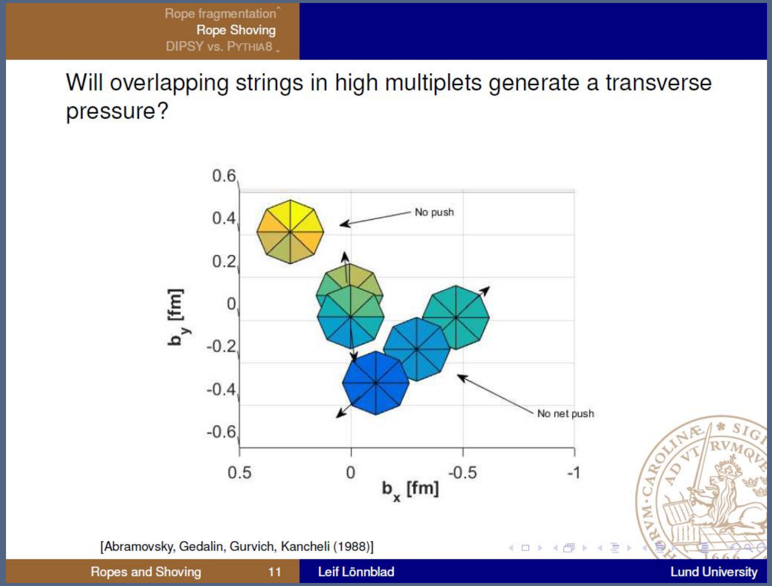
Bierlich *et al.*(2014, 2016)

Strings overlapping in transverse plane
→"Rope" formation (with larger string tension)

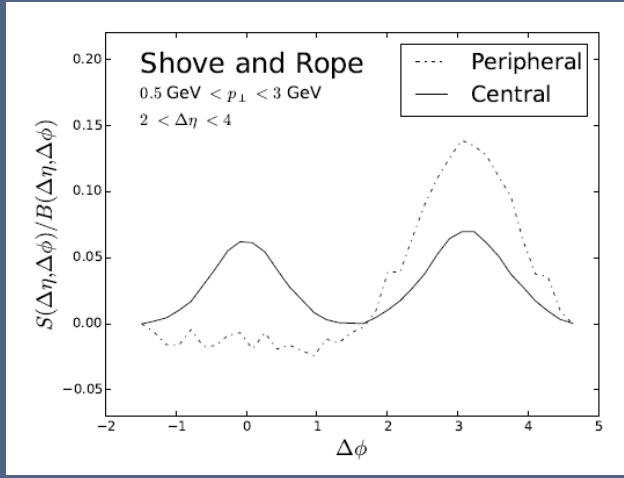
Schwinger mechanism

$$P \propto \exp\left(-\frac{\pi m_q^2}{\kappa}\right)$$

$\kappa \to \kappa'(> \kappa)$ expected to enhance yields of strange hadrons



Lönnblad (2017)



Ridge appears in central pp events
shoving model ~ hydro?

Short summary of small colliding systems

Experimental data in p+p and p+A:

- Collectivity (ridge, finite v_2, mass ordering of v_2, …)
- Strangeness enhancement

←How small could the QGP be?

←Collectivity or fluidity?

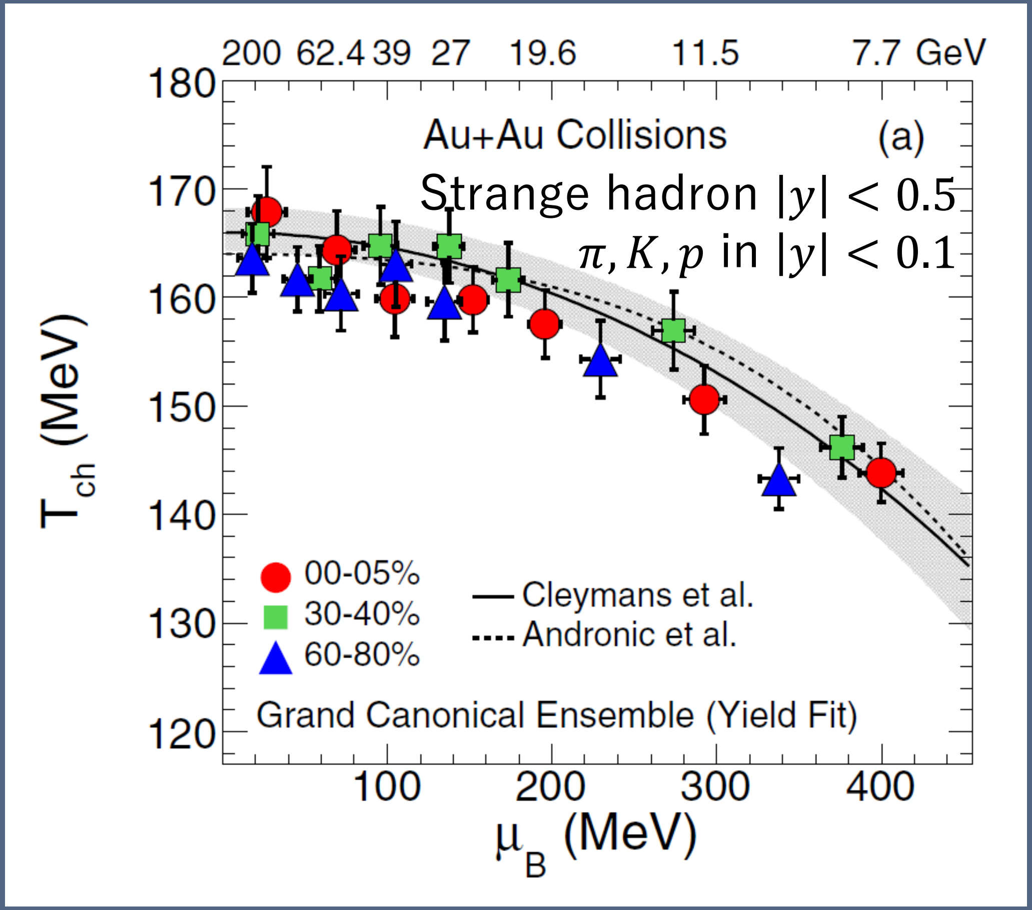
Interpretation not settled:

- Final state effects: QGP fluid, CYM+fragmentation, rope + shove,⋯
- Initial state effects: Color glass condensate

Various collision energies

RHIC-Beam Energy Scan program
and beyond

Scanning phase diagram

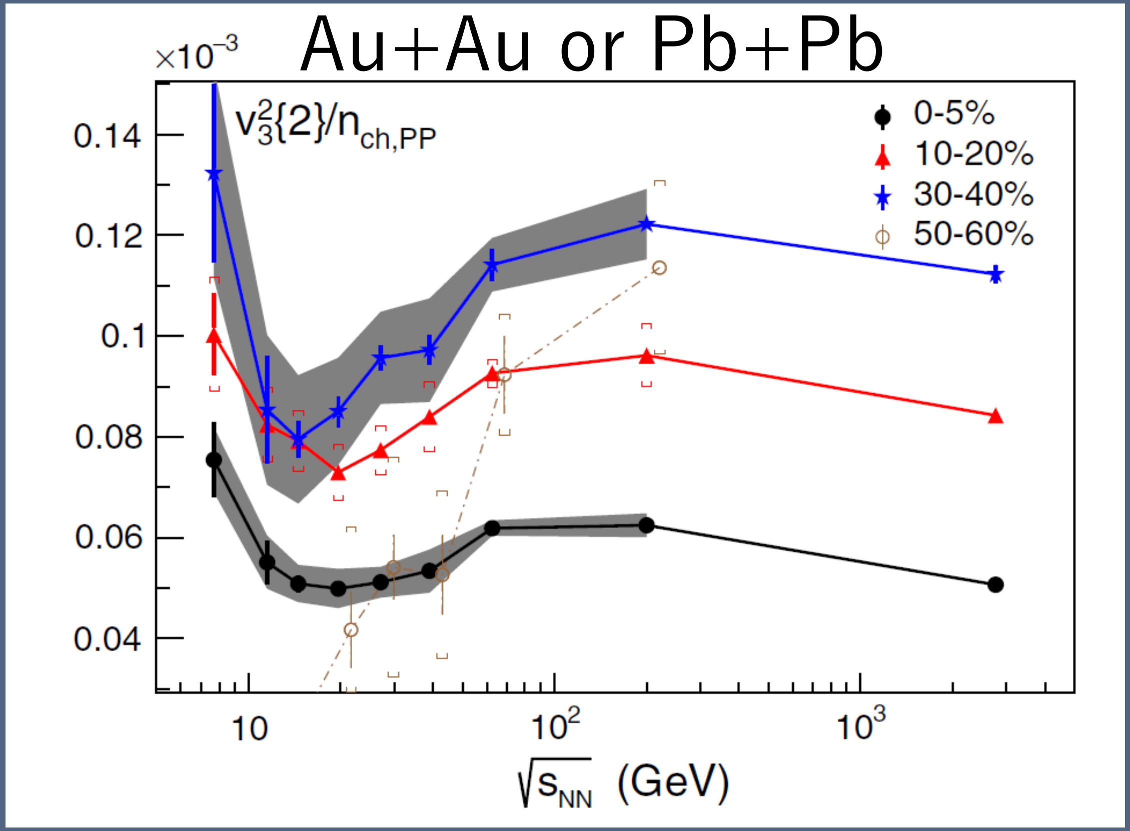


STAR Collaboration (2017)

Chemical freezeout parameters from particle yields in Au+Au collisions at various energies
Centrality dependence of μ_B at low energies ←Baryon stopping

Control baryon density and initial energy density
Scan broad regions of phase diagram

Collision energy evolution of third harmonics

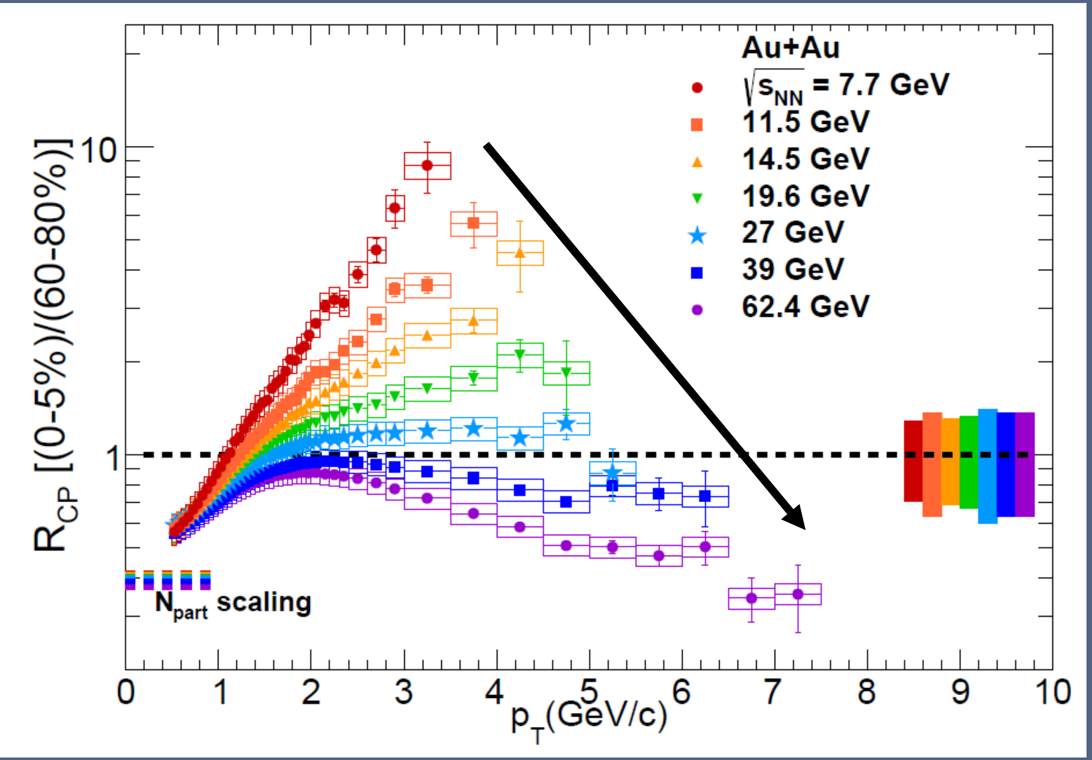


Response of the system
→ Minimum at $\sqrt{s_{NN}}$~20 GeV (mostly seen in semi-central collisions)
→ Indication of softest point (minimum sound velocity) in equation of state?

Small ← Initial energy density → Large

Collision energy evolution of jet quenching

Ratio of central to peripheral



STAR Collaboration (2017)

Yield at high p_T is suppressed at the top RHIC energy as an evidence for QGP formation

←Monotonic change with $\sqrt{s_{NN}}$

→ Null results on onset of QGP formation?

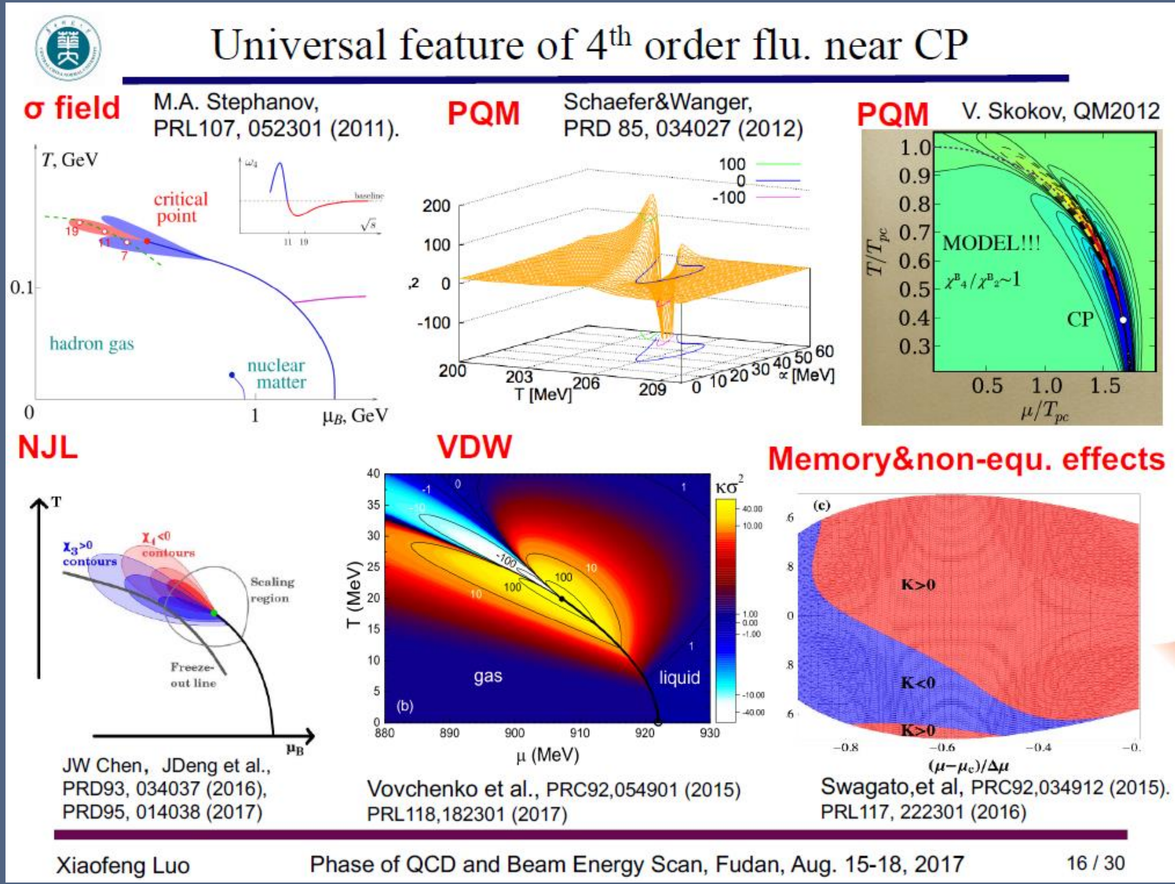
Hard to disentangle jet quenching from Cronin effect (random transverse kicks in the initial collision)

Higher order fluctuations of conserved quantity

Asakawa, Ejiri, Kitazawa (2009), Stephanov (2009, 2011), …

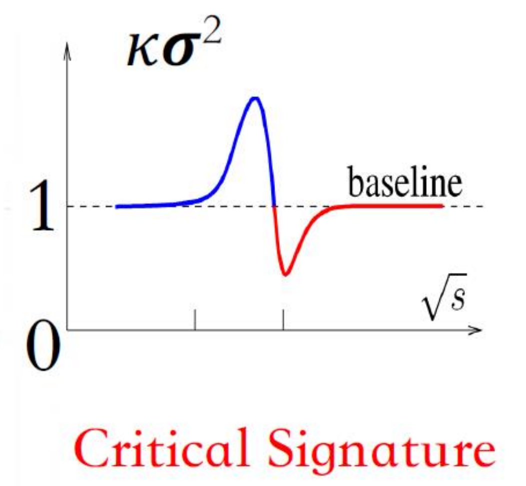
Non-monotonic behavior expected around critical point

X.F.Luo, talk at Fudan (2017)



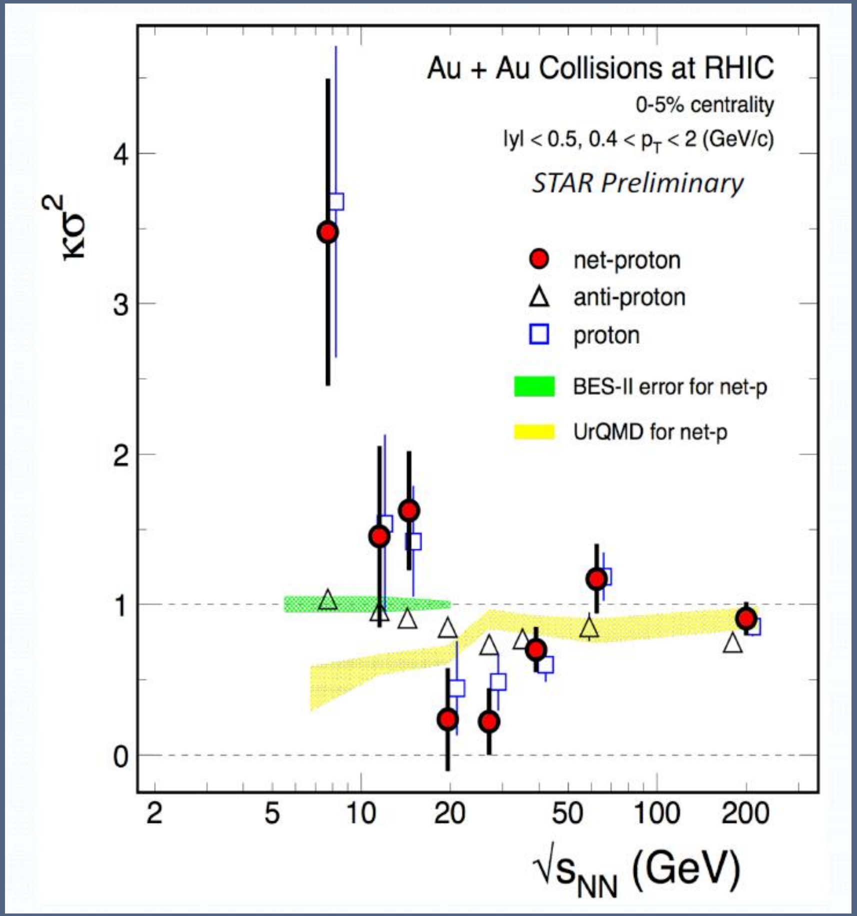
$$\kappa\sigma^2 = \frac{\chi_4}{\chi_2}$$

$$\chi_n = \frac{\partial^n \hat{p}}{\partial \hat{\mu}^n} \qquad \hat{p} = \frac{p}{T^4}, \hat{\mu} = \frac{\mu}{T}$$



Collision energy dependence of $\kappa\sigma^2$

Esha for STAR (2017)

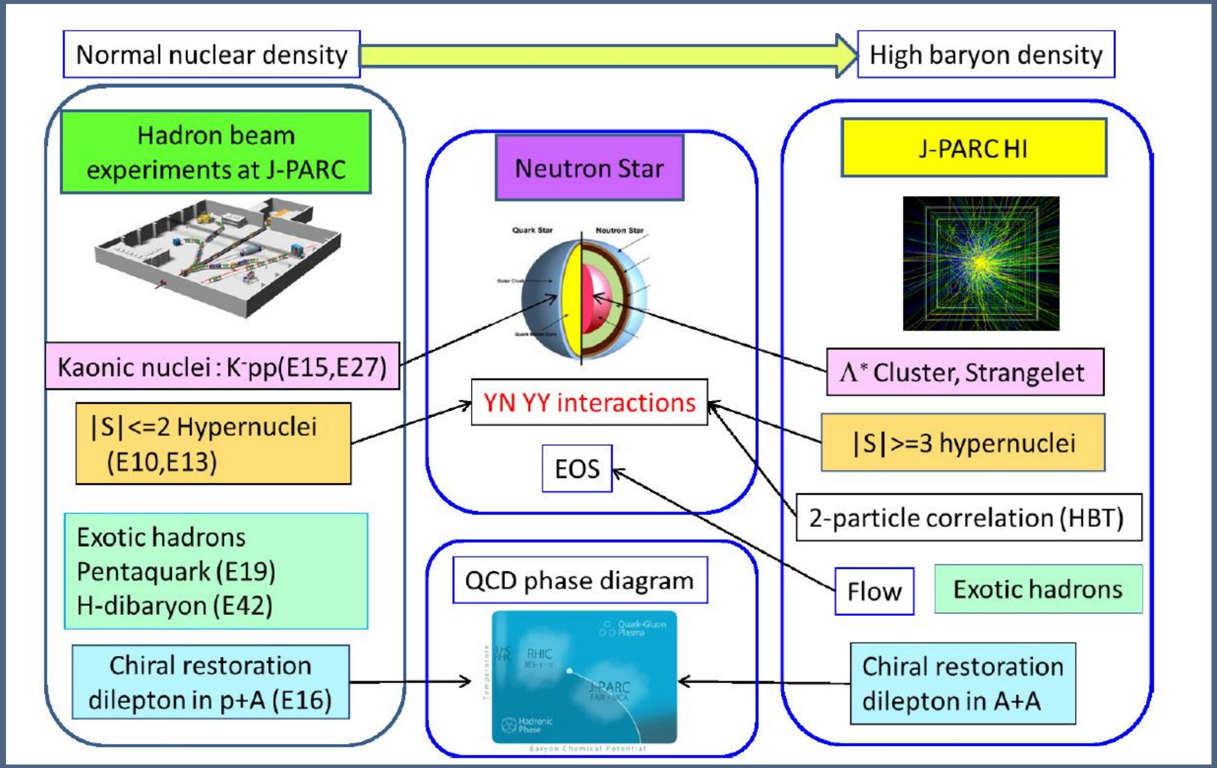


$$\kappa\sigma^2 = \frac{\langle(\delta N_B)^4\rangle}{\langle(\delta N_B)^2\rangle} = \frac{\chi_4}{\chi_2}$$

*In actual experimental data, not net baryon, but net proton

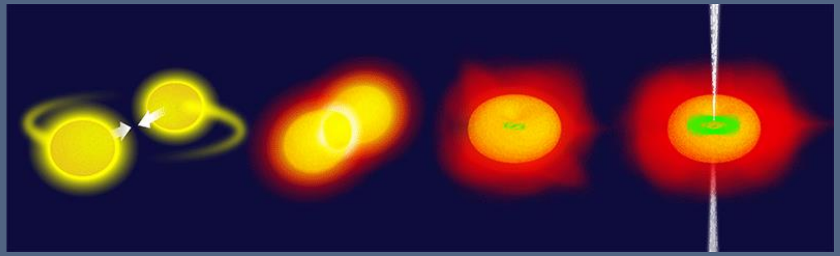
Expected non-monotonic behavior seen in experimental data
→Signature of critical point!?

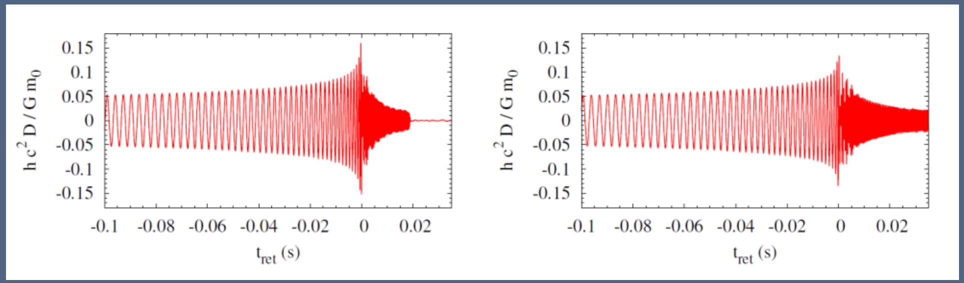
Future study of
Super-dense nuclear/quark matter



http://j-parc.jp/researcher/Hadron/en/pac_1607/pdf/LoI_2016-16.pdf

Binary neutron star merger

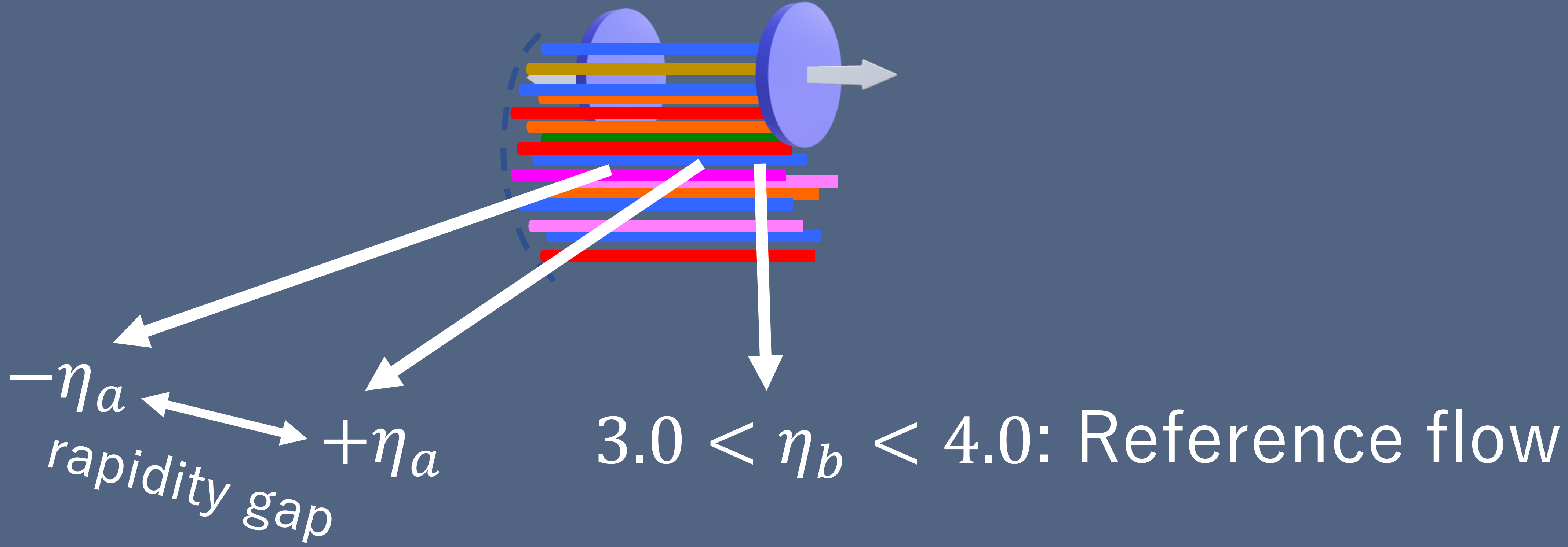




M. Shibata, talk at QM2015

https://physics.aps.org/articles/v10/114

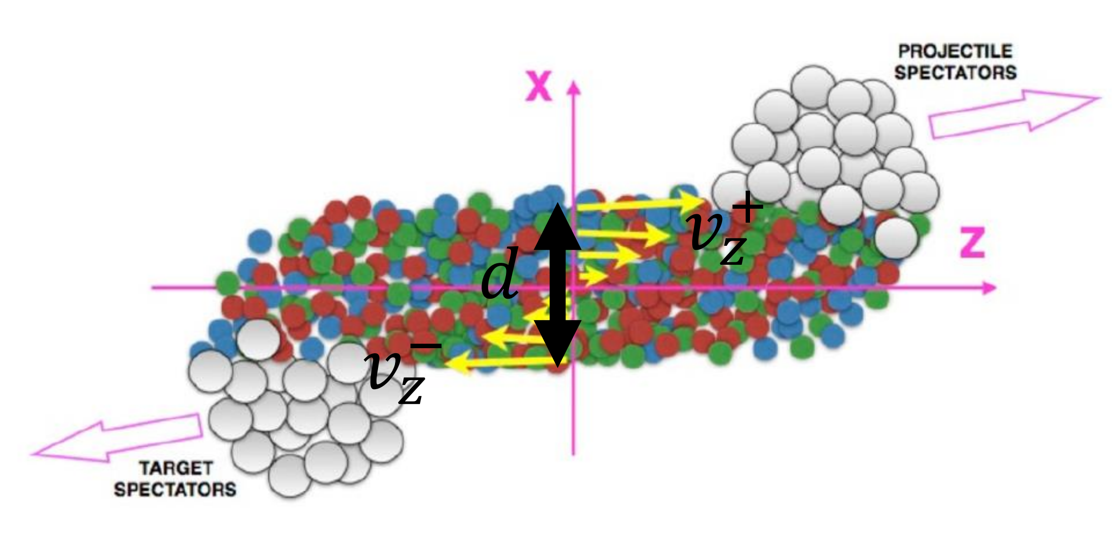
Correlation of elliptic flow parameter between different rapidity

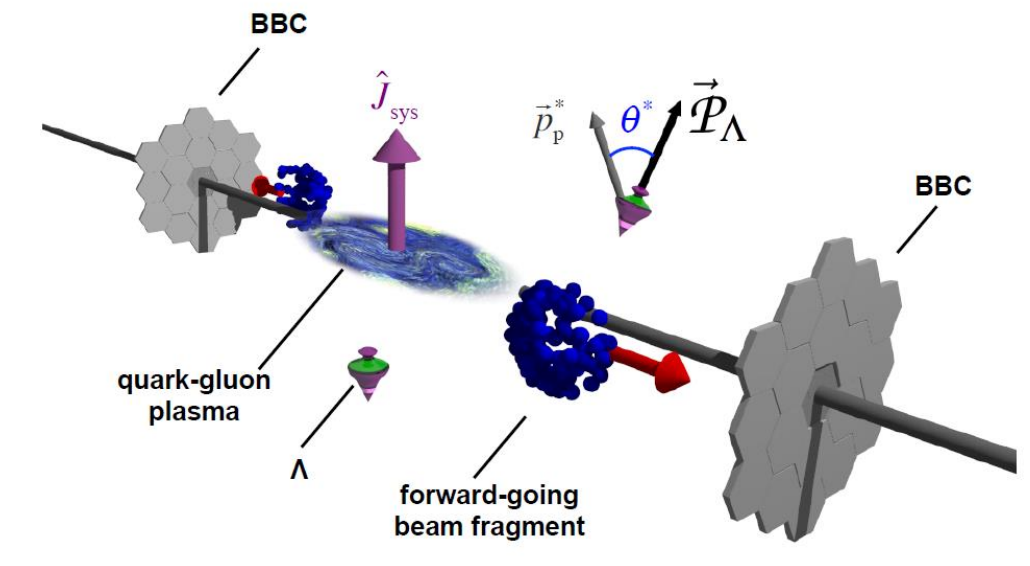


Same quadrupole emission pattern across rapidity?

QGP as the most vortical fluid

Z.T.Liang, X.N.Wang (2005), Voloshin (2004, unpublished),Betz, Gyulassy, Torrieri (2007)





$$\omega \sim \frac{1}{2} \nabla \times v$$
$$|v_z^+ - v_z^-| \sim 0.1c$$
$$d \sim 10\text{fm}$$

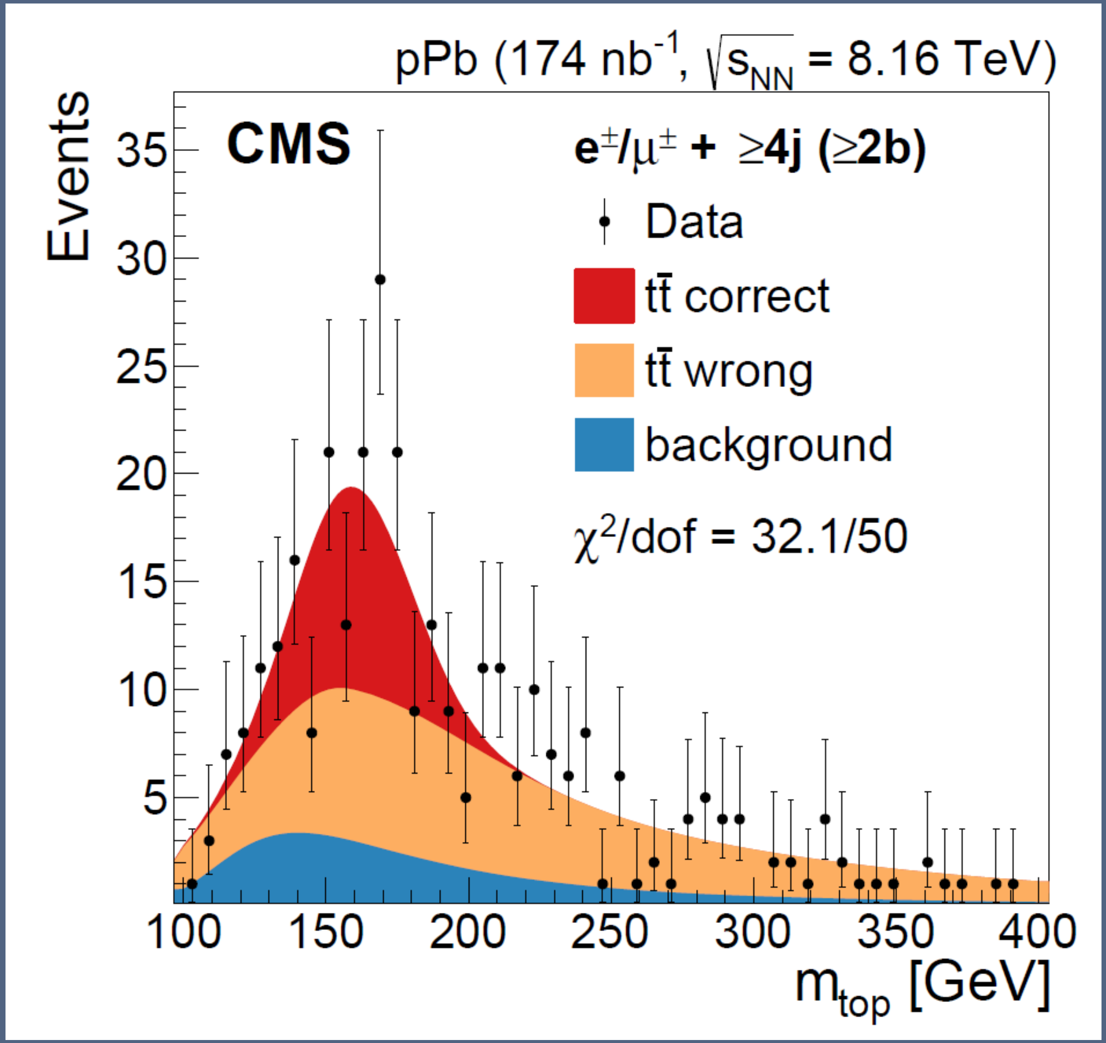
$$\Rightarrow |\omega| \sim 10^{22}\text{s}^{-1}$$

Protons from Λ carry information about polarization

$$P_\Lambda + P_{\bar{\Lambda}} = \frac{\hbar\omega}{k_B T} \Rightarrow \omega = (9 \pm 1) \times 10^{21} s^{-1}$$

Beccatini *et al.* (2017) STAR Collaboration (2017)

Discovery of top quarks in p+Pb collisions



CMS Collaboration (2017)

e.g.) $gg \rightarrow t\bar{t} \rightarrow W^{+}bW^{-}\bar{b}$

- Constraint on nPDFs

  $5 \cdot 10^{-3} < x < 0.05$

  $Q^2 \sim 3 \cdot 10^4\ \mathrm{GeV}^2$

- b-quark energy loss in heavy ion collision case

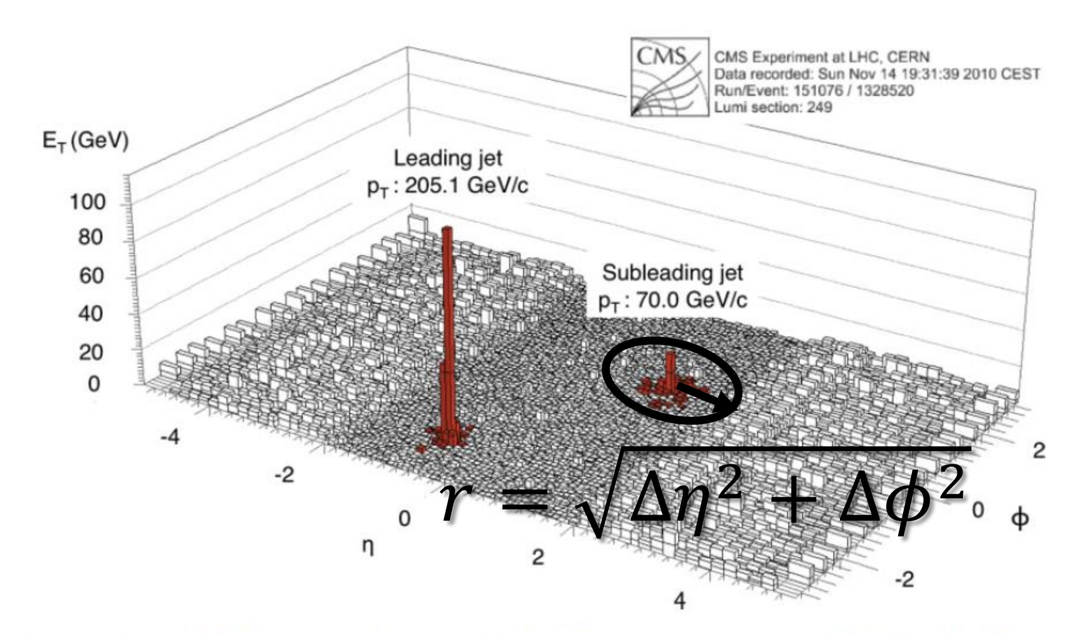
  $c\tau$ of top quarks$\sim 0.15\ \mathrm{fm}$

  << Dimension of the medium ~ several fm

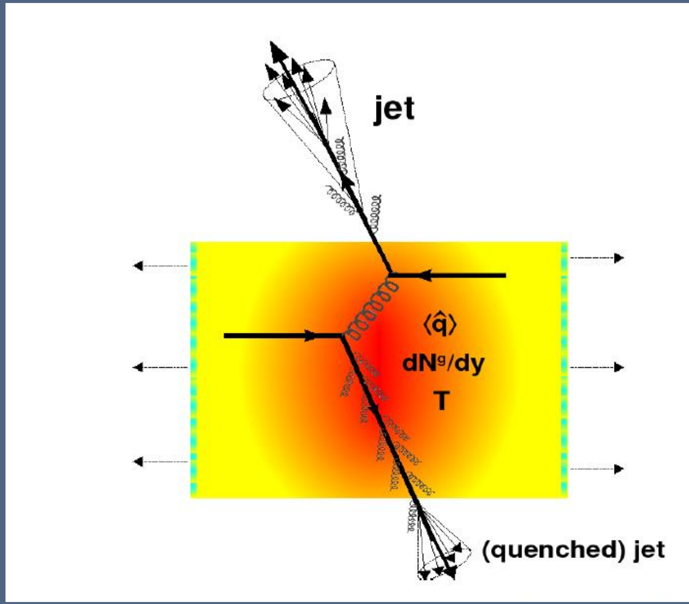
  → New channel to probe the QGP

d'Enterria *et al.* (2015)

Di-jet asymmetric event



CMS Collaboration (Quark Matter 2011)



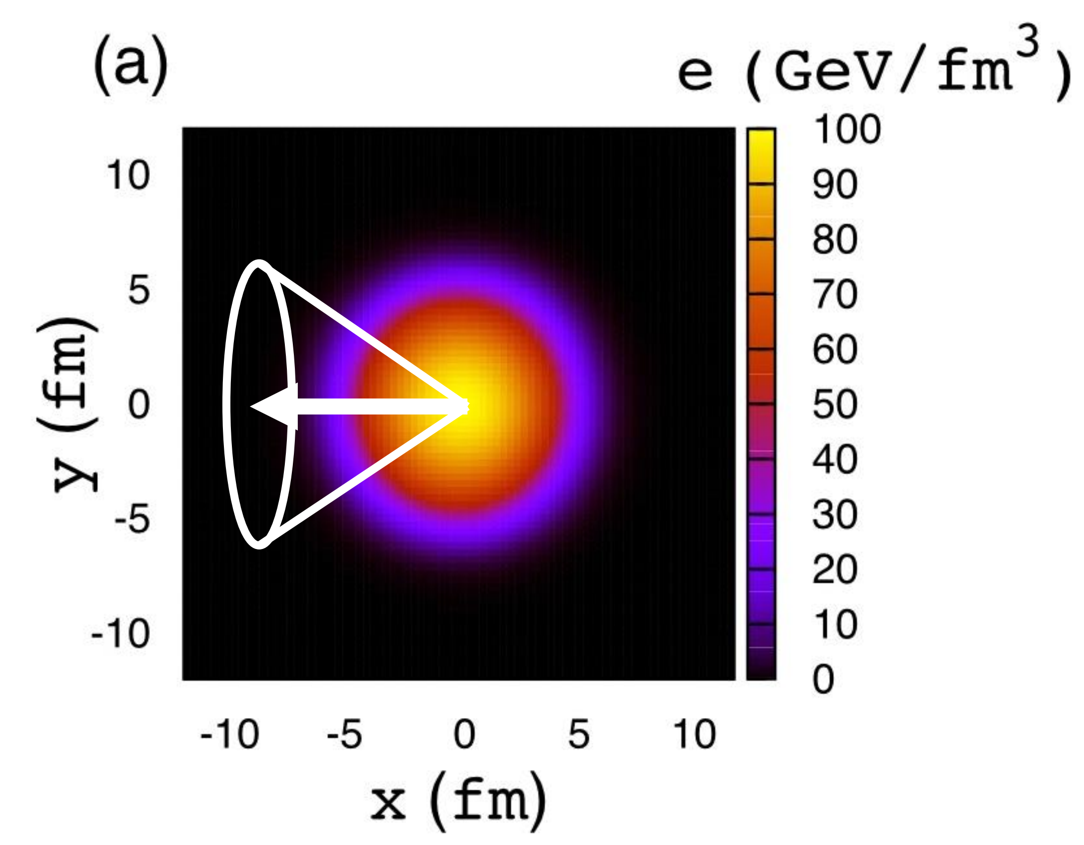
d'Enterria (2009)

$E \sim 200$ GeV jet dragged by medium with $T \sim 300$ MeV in a few femtometer

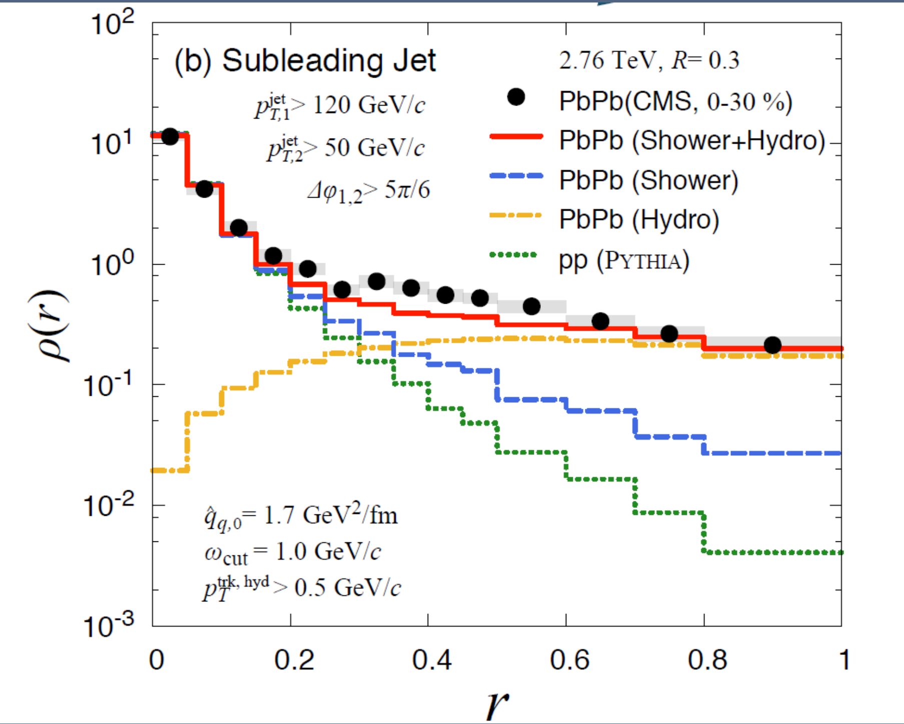
→Where the lost energy goes?

→Change of jet structure as a function of r?

Large angle emission of soft particles



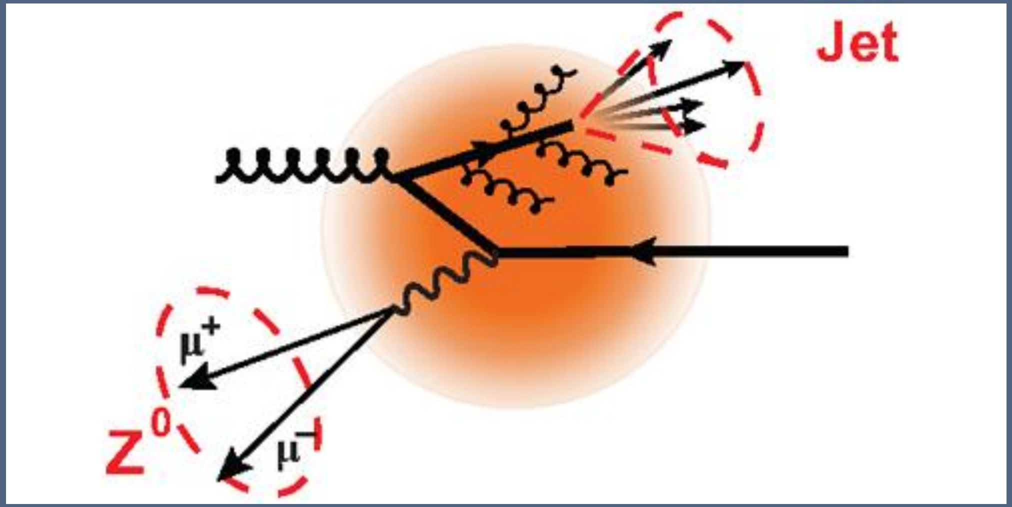
Mach-cone like medium response at large angle from jet axis



Y.Tachibana *et al.* (2017)

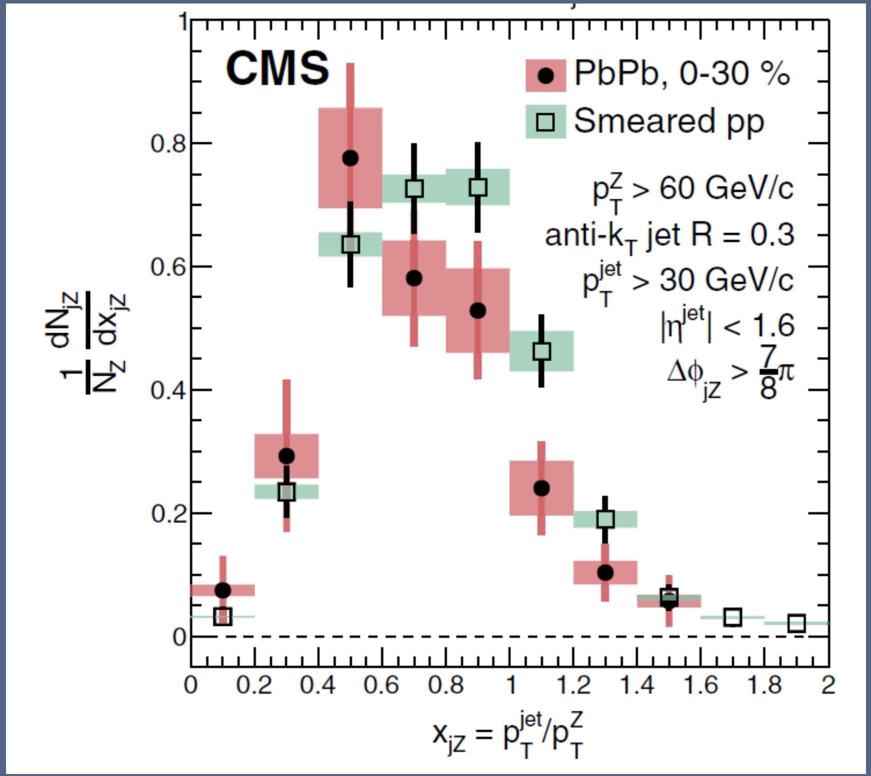
Jet structure at large r: A new channel to constrain transport properties of QGP?

Z^0-jet correlations as a new probe



$qg \to qZ$ and $\bar{q}g \to \bar{q}Z$
less background than
$qg \to q\gamma$ or $\bar{q}g \to \bar{q}\gamma$

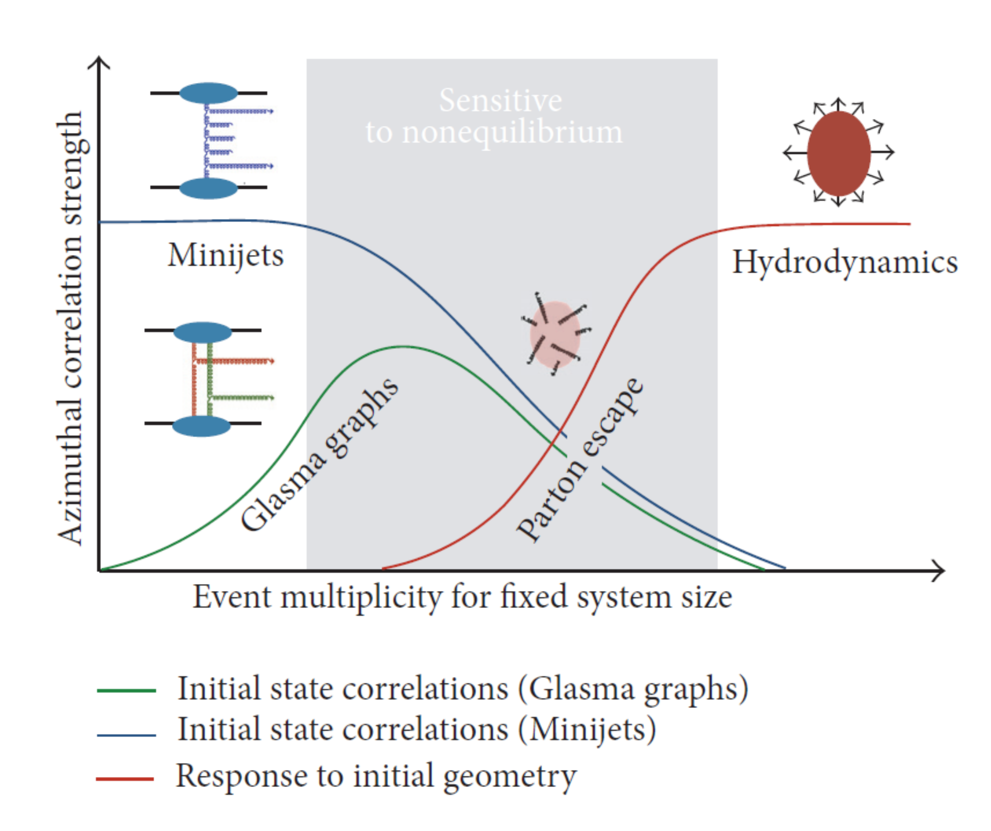
CMS Collaboration (2017)



$x_{jZ}{\sim}1$ → Balance btw. jet and Z
Peak shifted to lower x_{jZ}
→ New probe for jet tomography

Initial or Initial + Final?

Schlichting, Tribedy (2016)



Large system:

Final state effect

Small system:

Initial or Initial + Final state effect

→ Necessity for sophisticated modeling in small systems

→ Thermalization, hydrodynamization, …