臺灣大學
National Taiwan University

Workshop of Recent Developments in QCD and Quantum Field Theories

November 9-12, 2017
National Taiwan university, Taipei, Taiwan

Recent topics in relativistic heavy ion collisions and QGP

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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 matter created in RHIC's heavy ion collisions appears to be more like a *liquid*.

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

Energy frontier

QGP at the highest collision energy at LHC
→ Precision measurements and analyses

Small colliding systems

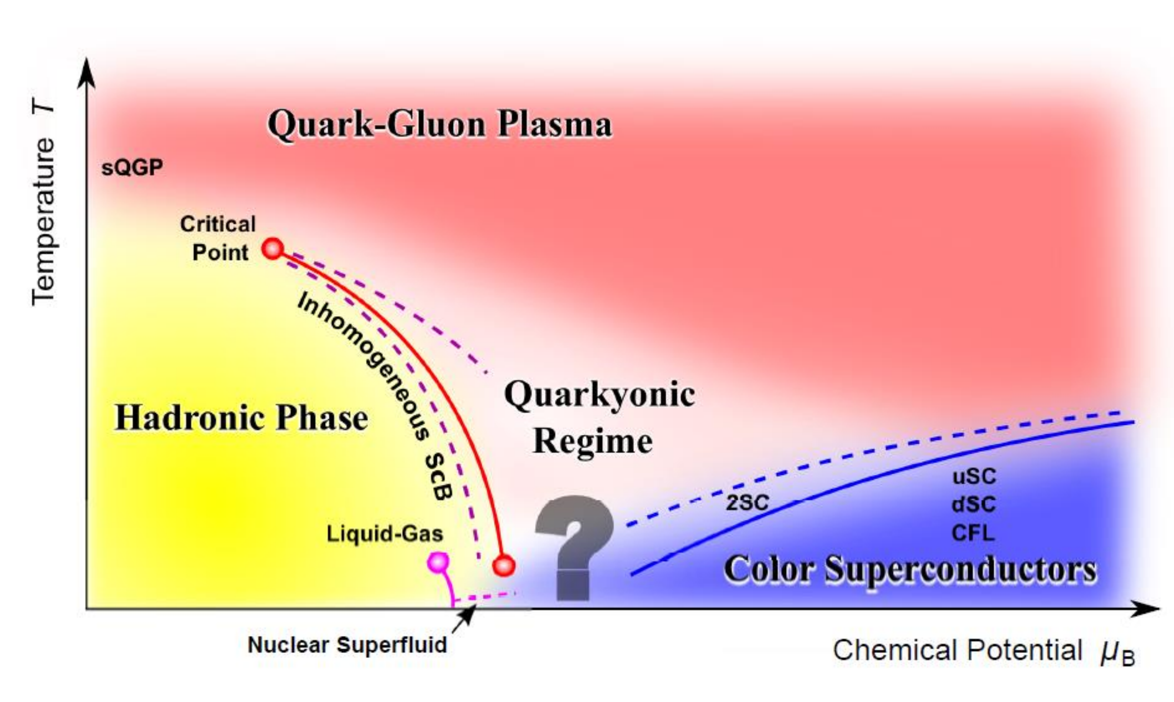
QGP created even in small size?
→ Collectivity in small colliding systems

Various collision energies

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

Physics of the QGP

Fukushima and Sasaki (2013)

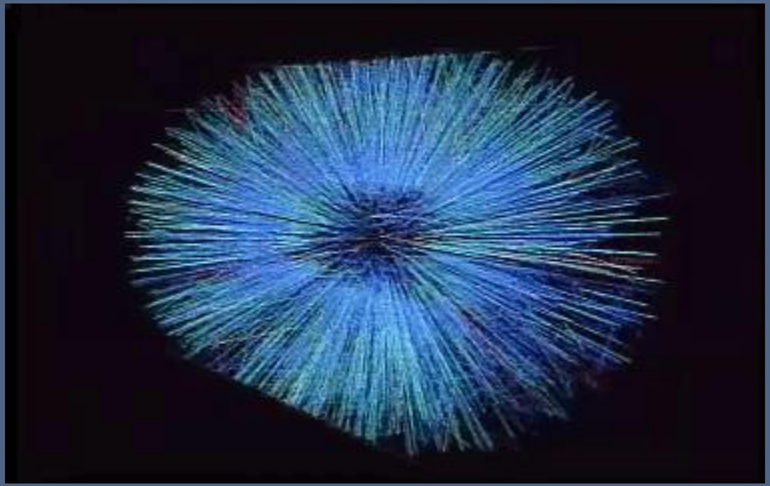


Investigation of matter under extreme conditions

- 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

Bottom-up approach



3-D event display from STAR
- Momentum distribution
- Particle species
- Correlation
- …

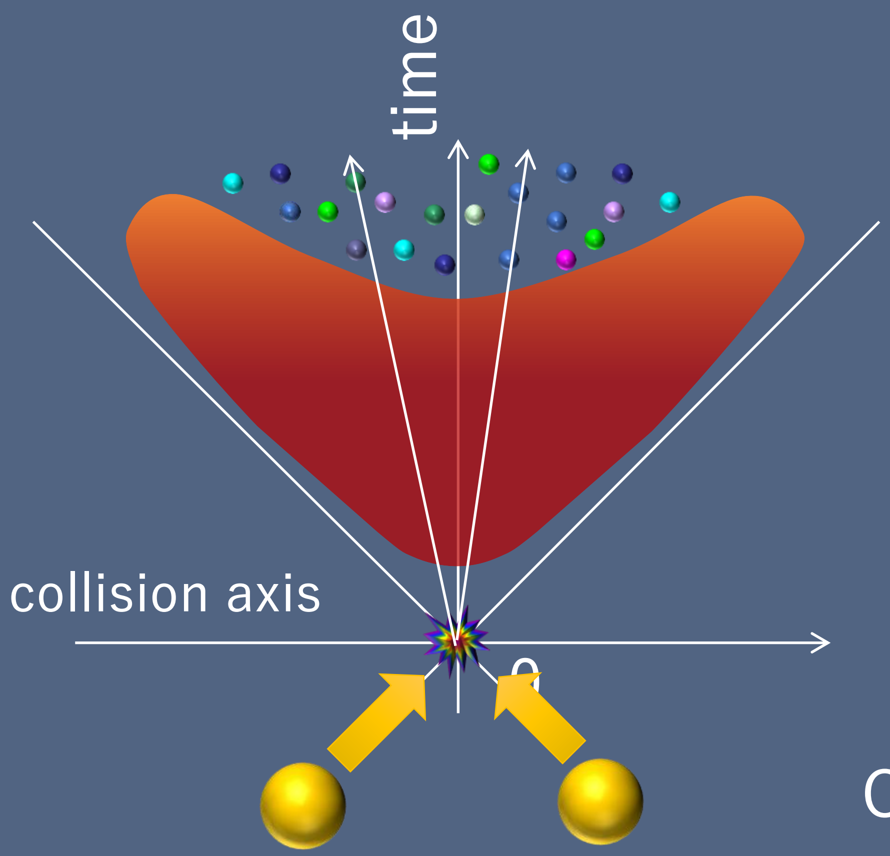
Physics properties of the QGP
- Equation of state
- Transport coefficients
- Stopping power
- Phase structure

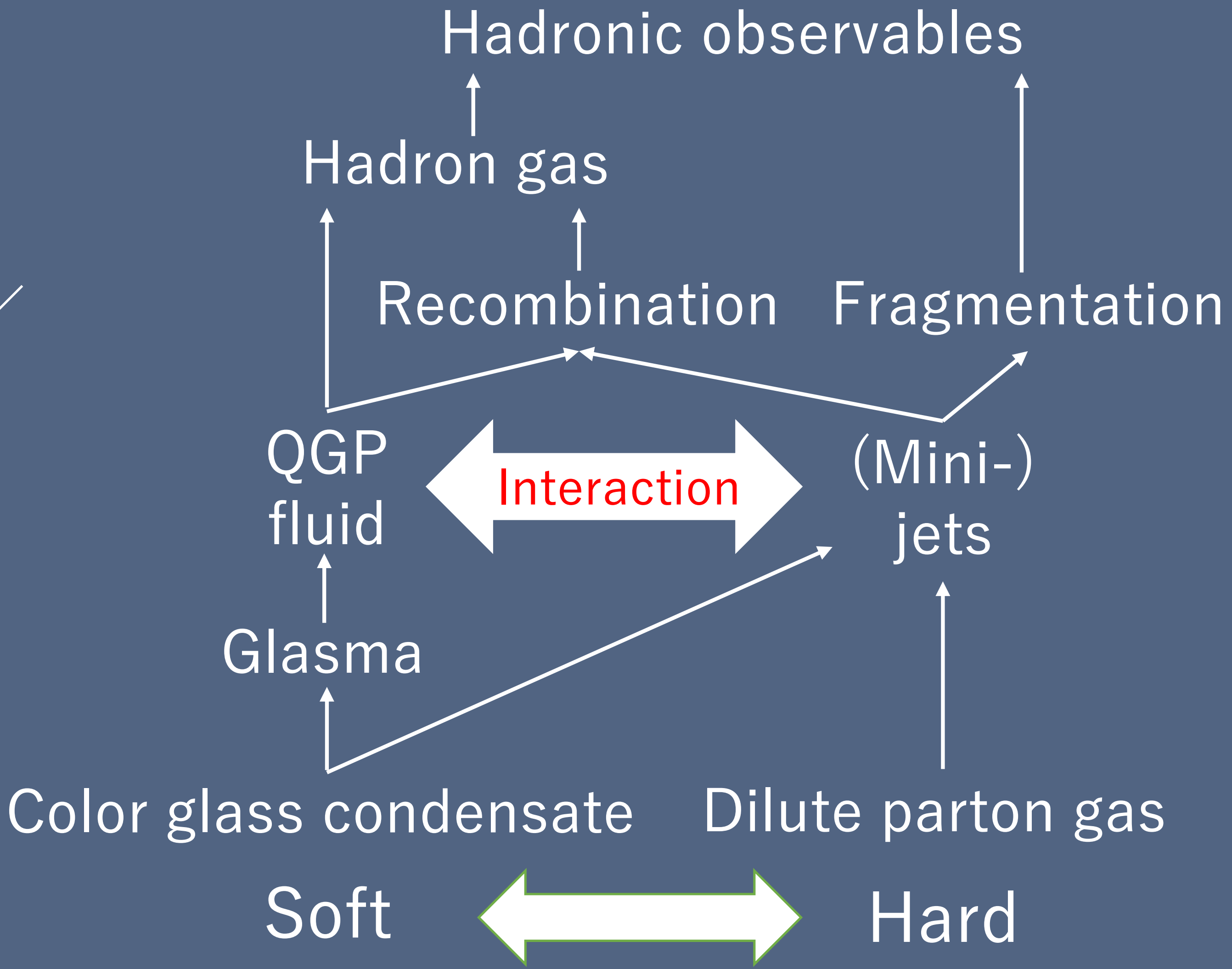
Phenomenological approach

<u>Top-down approach</u>

Results from lattice QCD, …

Standard picture of dynamics in high-energy nuclear collisions



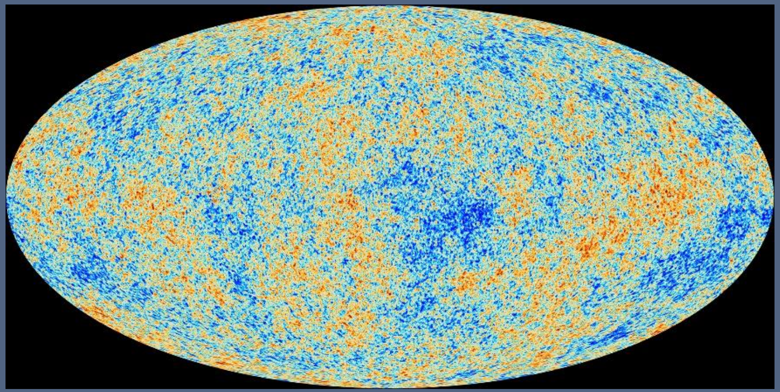


Energy frontier

Anisotropic flow and precision QGP physics

Lessons from observational cosmology

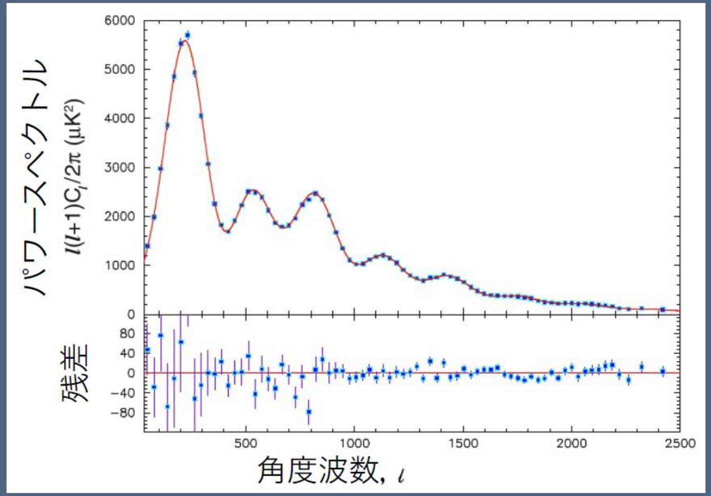
http://www.esa.int/spaceinimages/Images/2013/04/Planck_CMB_black_background



Cosmic Microwave Background
Fluctuations of temperature
(Planck)

power spectrum

E.Komatsu, talk at IPMU(2013)



$$l \approx 180°/\theta$$

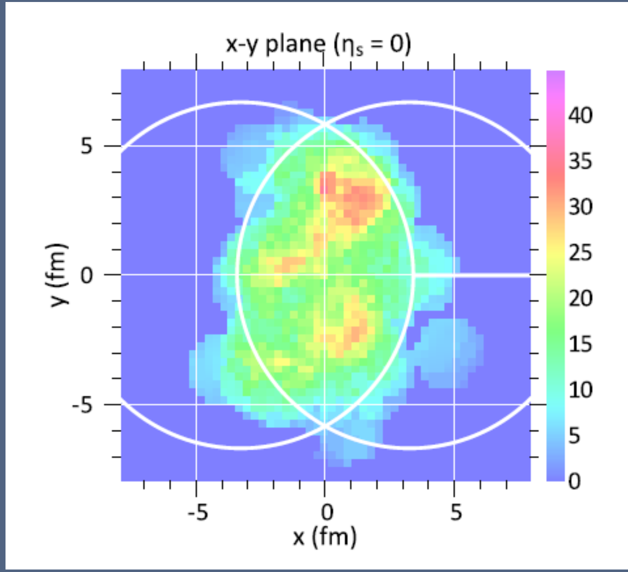
Precision measurements and analysis

Energy budget and lifetime of the Universe, inflation, …

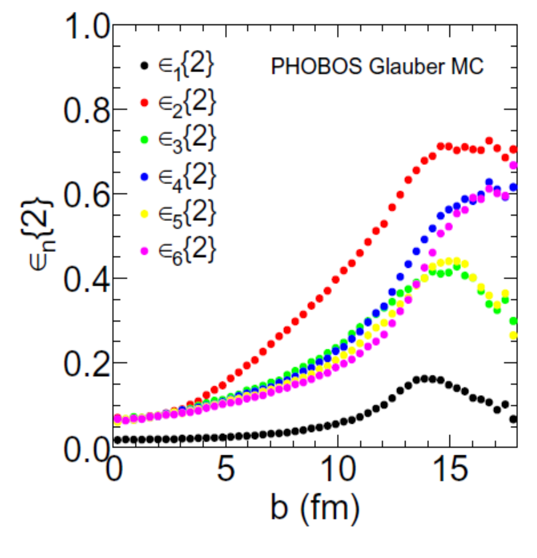
One can reach eras before decoupling through these analyses.

Response to initial fluctuations of geometry

TH *et al.* (2013)



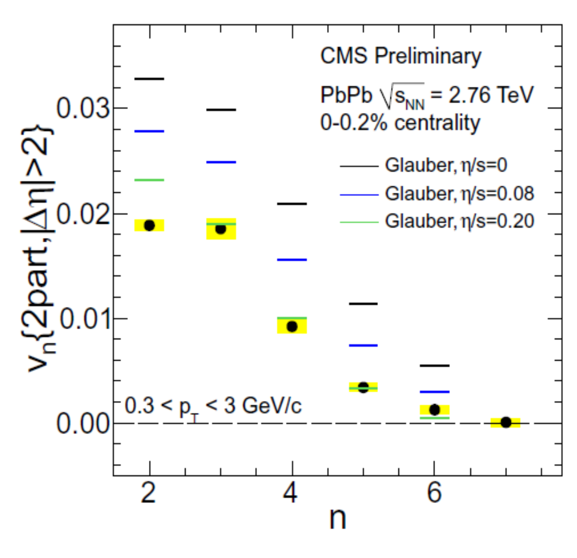
Entropy density distribution



Initial deformation

ε_n

CMS Collaboration (2013)



Response

v_n

$n = 2$ (quadrupole)
Elliptic flow
Ollitrault (1993)

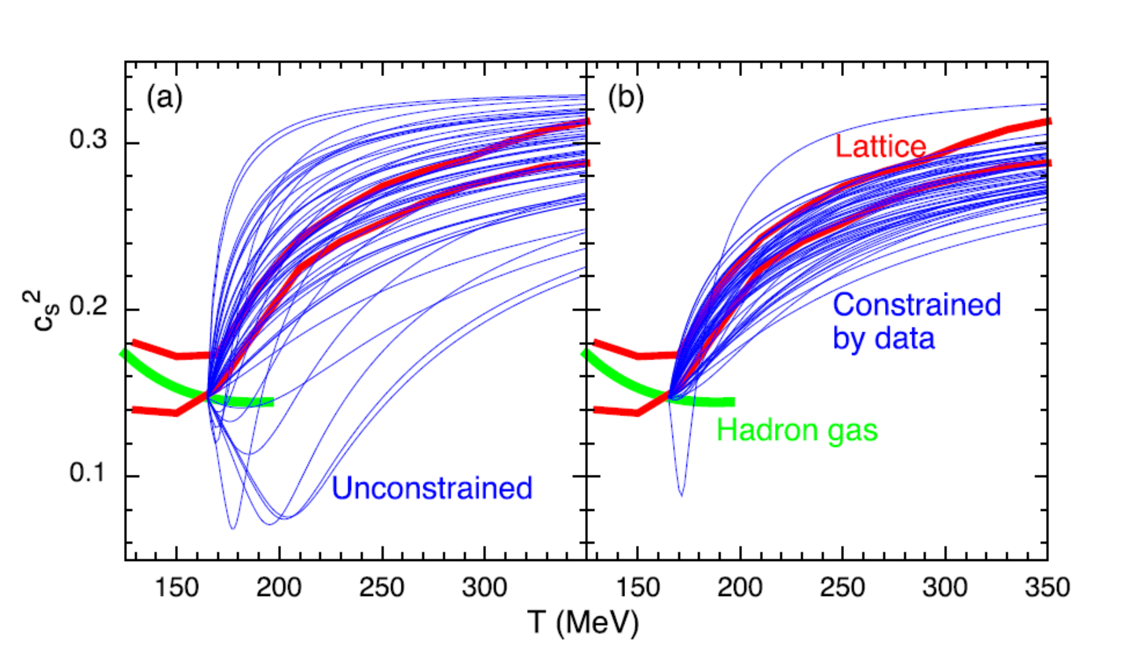
$n = 3$ (hexapole)
Triangular flow
Alver, Roland (2010)

$n = 4$ (octapole)
Quadrangular flow
Kolb (2003)

How does the system respond to initial deformation?
← Contain information about transport properties of the QGP

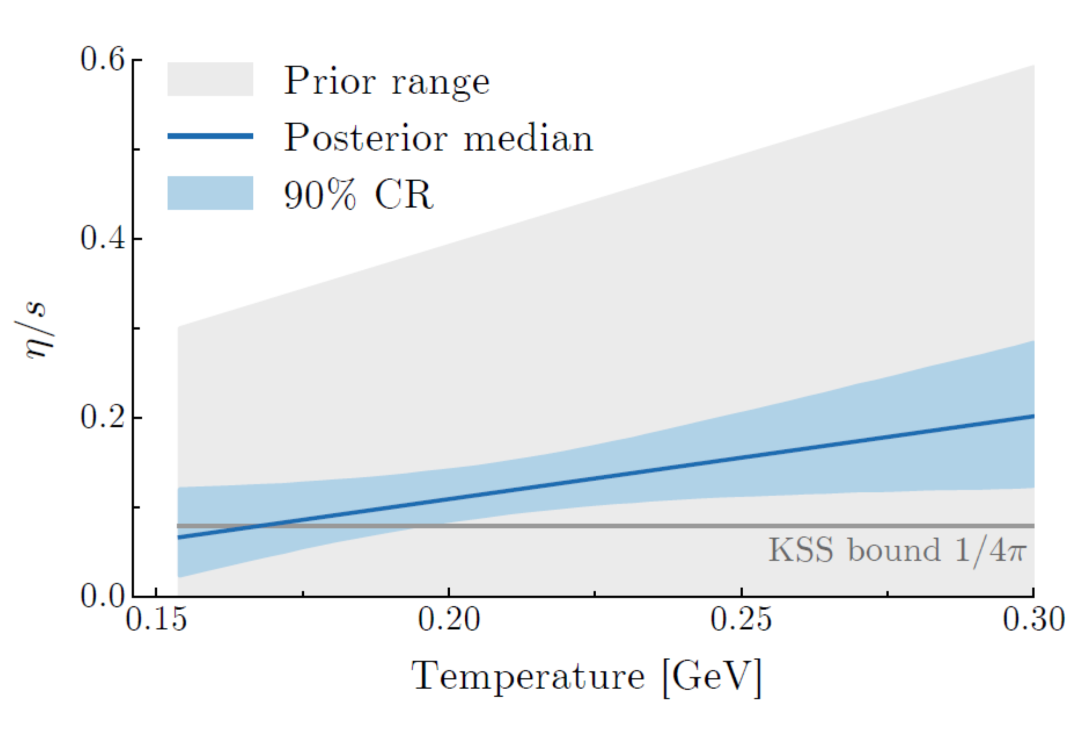
Precision QGP physics using Bayesian parameter estimation

Sound velocity vs. Temperature



Pratt *et al.*(2015)

(Shear viscosity)/(Entropy density)

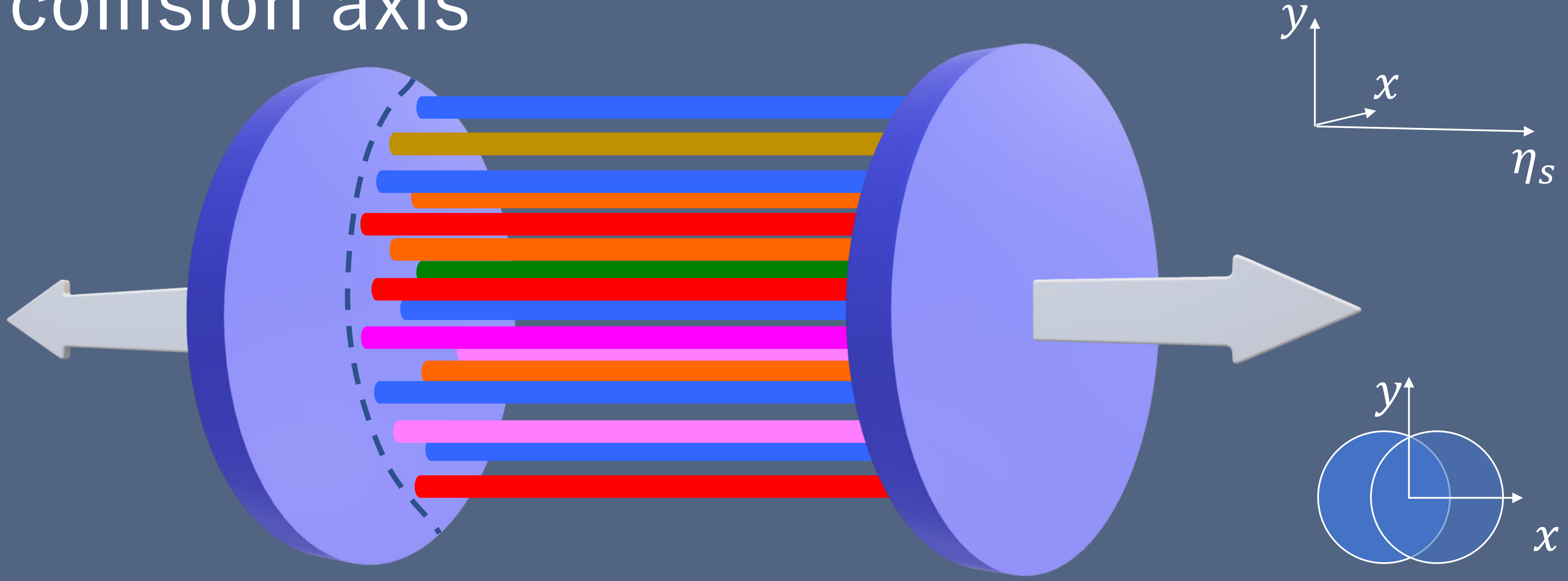


Bernhard *et al.* (2016)

Experimental data → Posterior probability of parameters

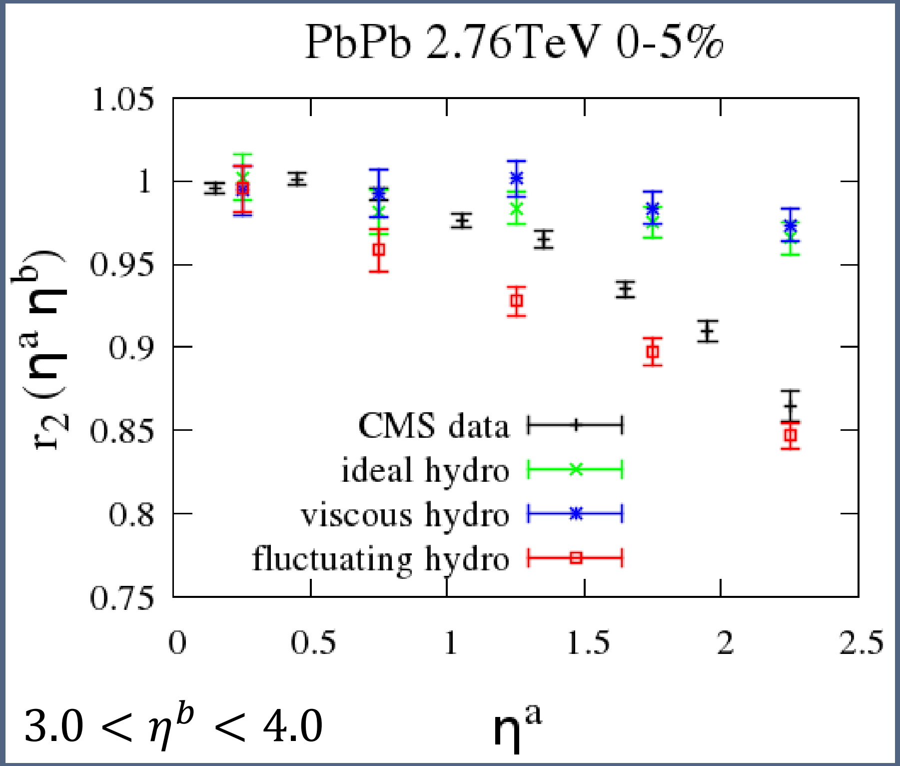
←→Comparison with results from lattice QCD

Correlation of initial conditions along collision axis



Heavy ion collision as a chromoelectric capacitor
→ Formation of color flux tubes ~Approximate boost invariance
→ Correlation of initial conditions in rapidity space

(De-)Correlation of elliptic flow along rapidity



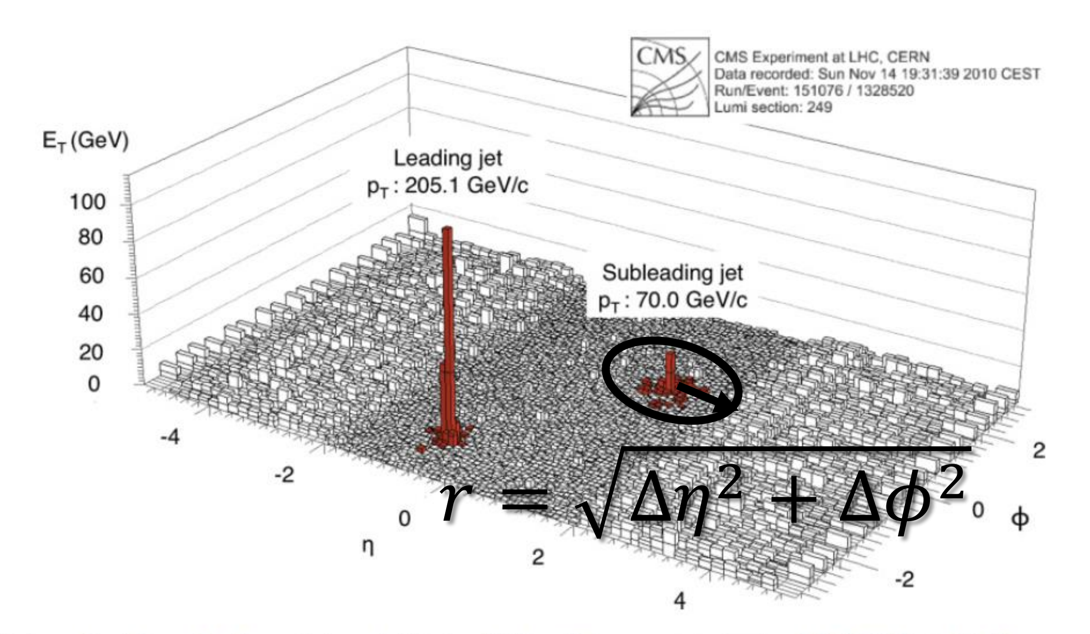
A. Sakai* (QM2017)
*Winner of Nuclear Physics A Young Scientist Awards

- Ideal and viscous hydro
  → Hard to break up correlations
- Random force from thermal (hydrodynamic) fluctuations in QGP
  → break up correlations
- New channel to constrain transport coefficients

Energy frontier

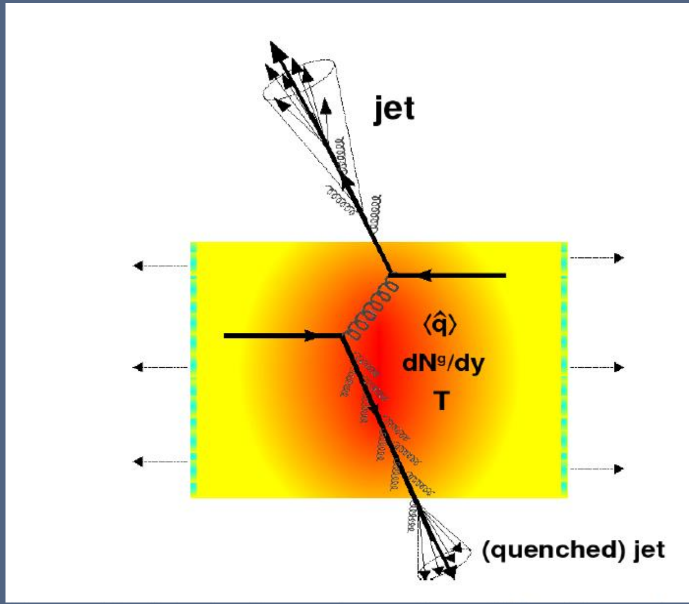
Medium response
and hard probes

Di-jet asymmetric event



$r = \sqrt{\Delta\eta^2 + \Delta\phi^2}$

CMS Collaboration (Quark Matter 2011)



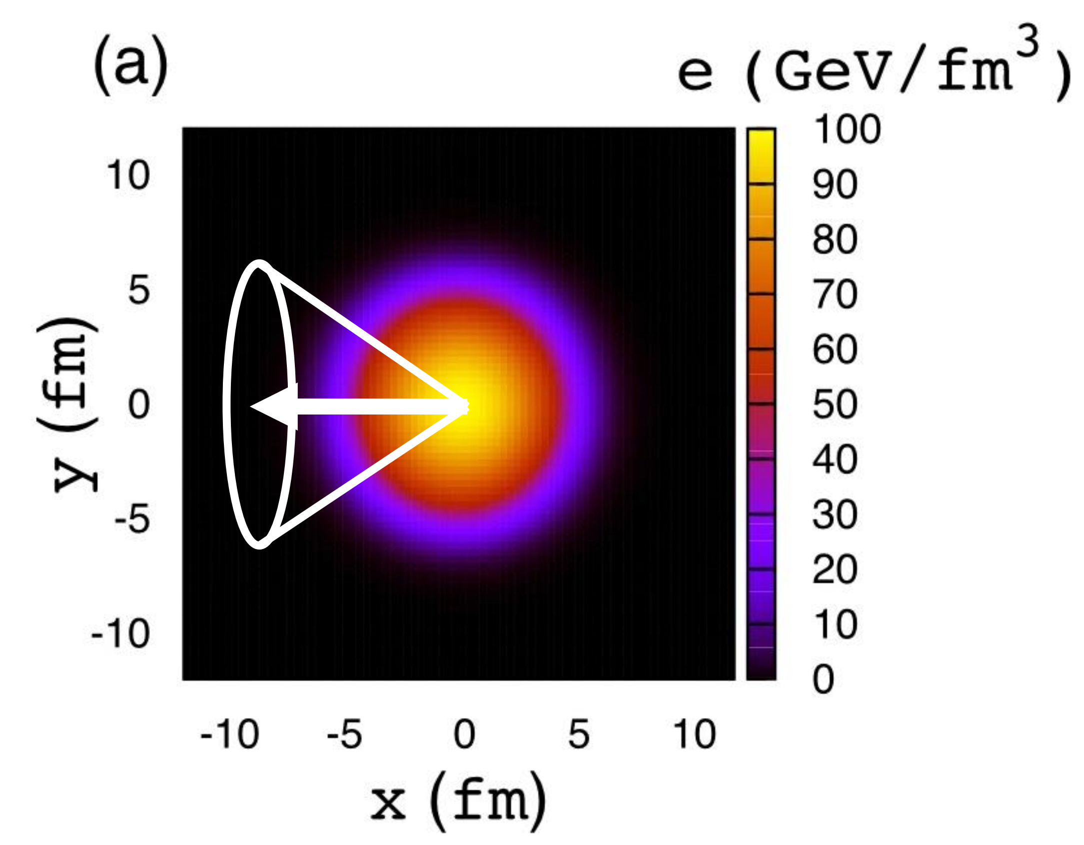
d'Enterria (2009)

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

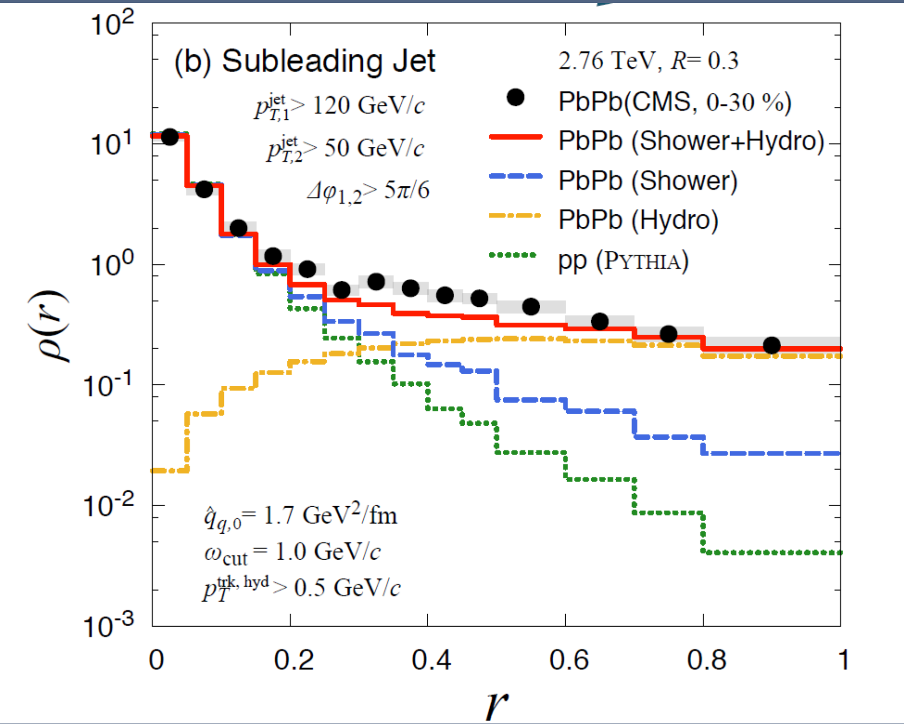
→Where the lost energy goes?

→Change of jet structure as a function of r?

Large angle emission of soft particles



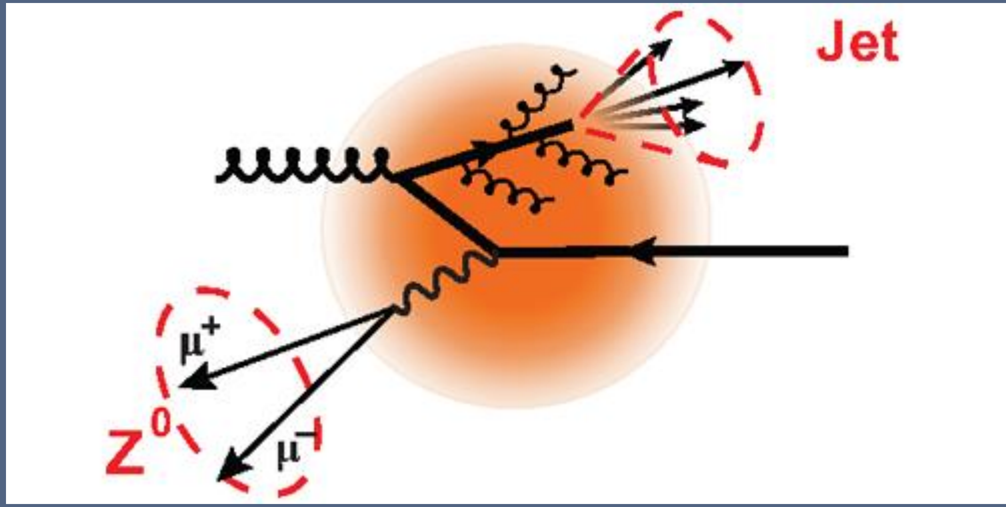
Mach-cone like medium response at large angle from jet axis



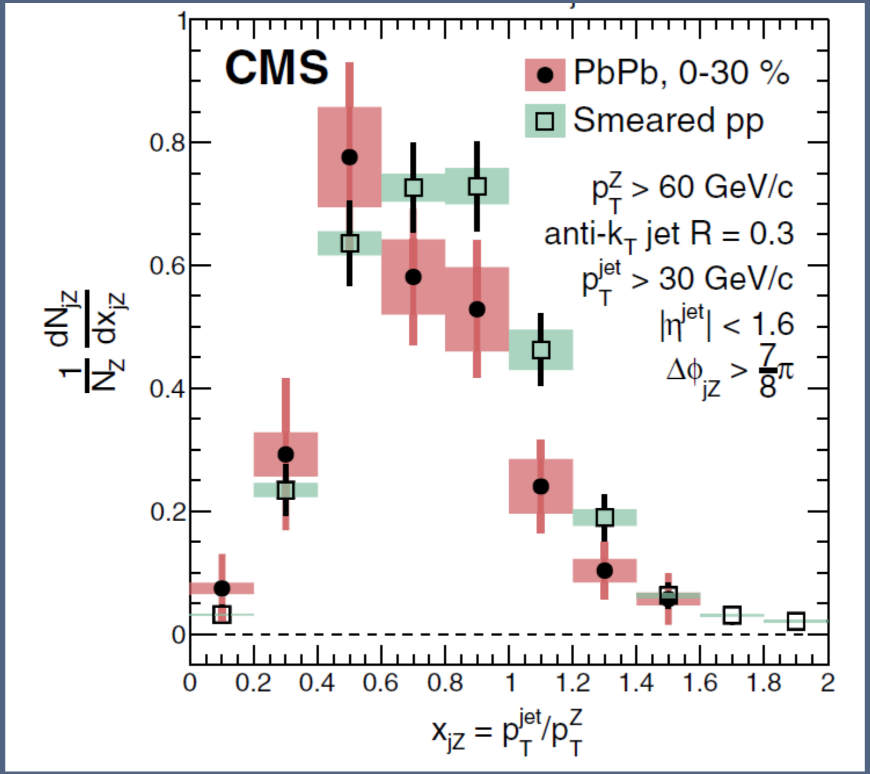
Y.Tachibana *et al.* (2017)

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

Z^0-jet correlations as a new probe



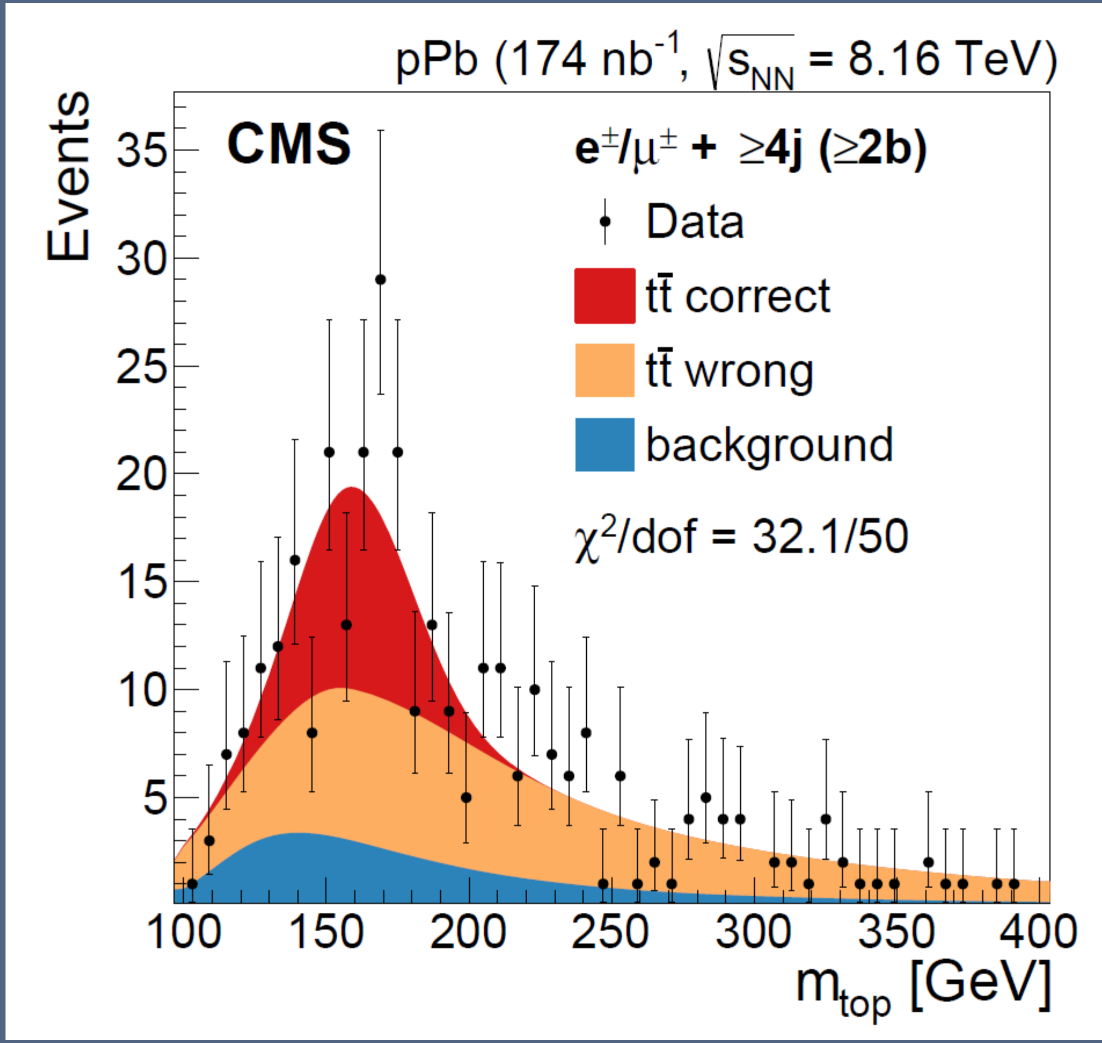
CMS Collaboration (2017)



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

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

Discovery of top quarks in p+Pb collisions



CMS Collaboration (2017)

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

- 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

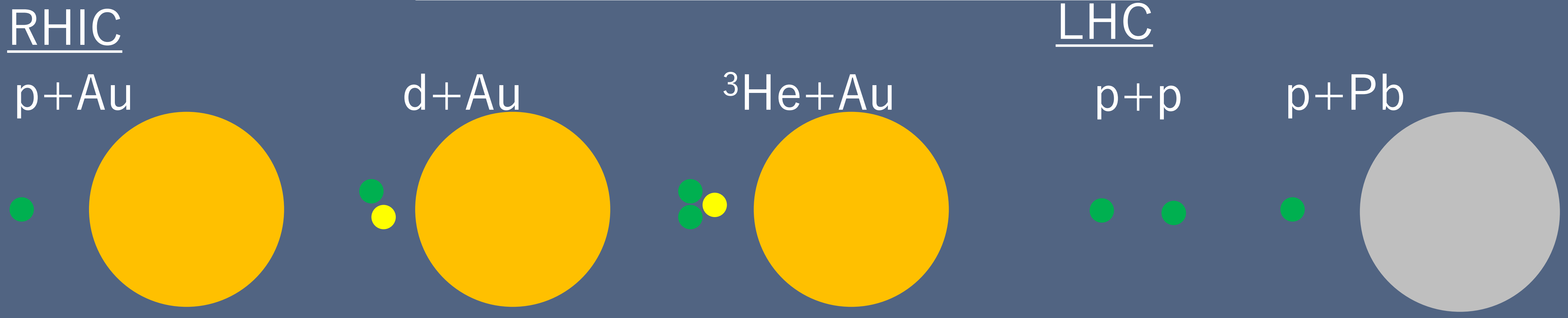
d'Enterria *et al.* (2015)

Small colliding systems

New challenge to models

To be QGP or not to be?

That is THE question!



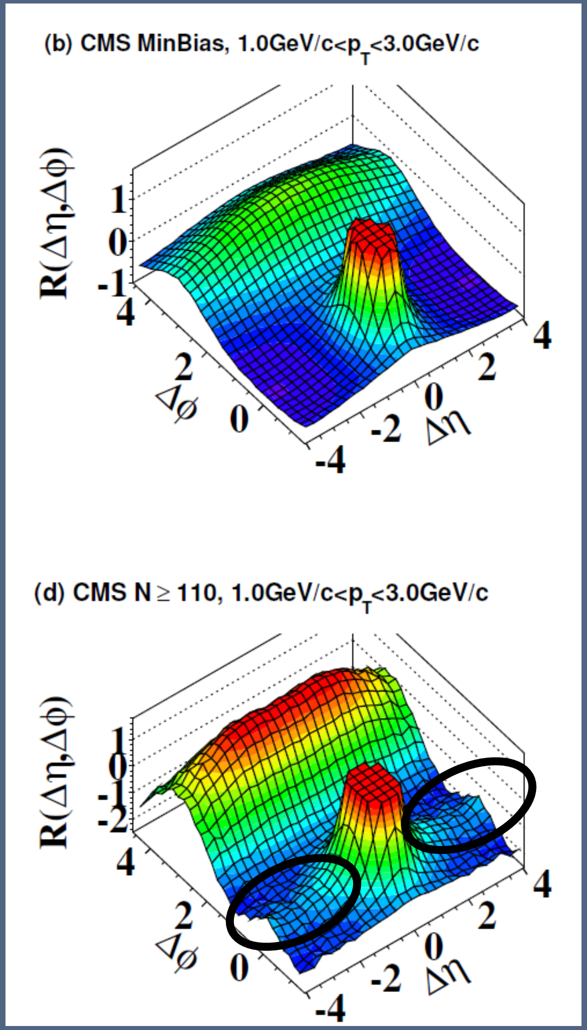
2003~2010: Control experiment → Initial state effects such as Cronin effect, (anti-)shadowing and saturation

2010~today: Discussion of possibility to create QGP in small colliding systems

* “Collectivity” = Correlated particle emission ≠ flow

Everything starts from CMS findings

CMS Collabortion (2010)



What is “Ridge”?

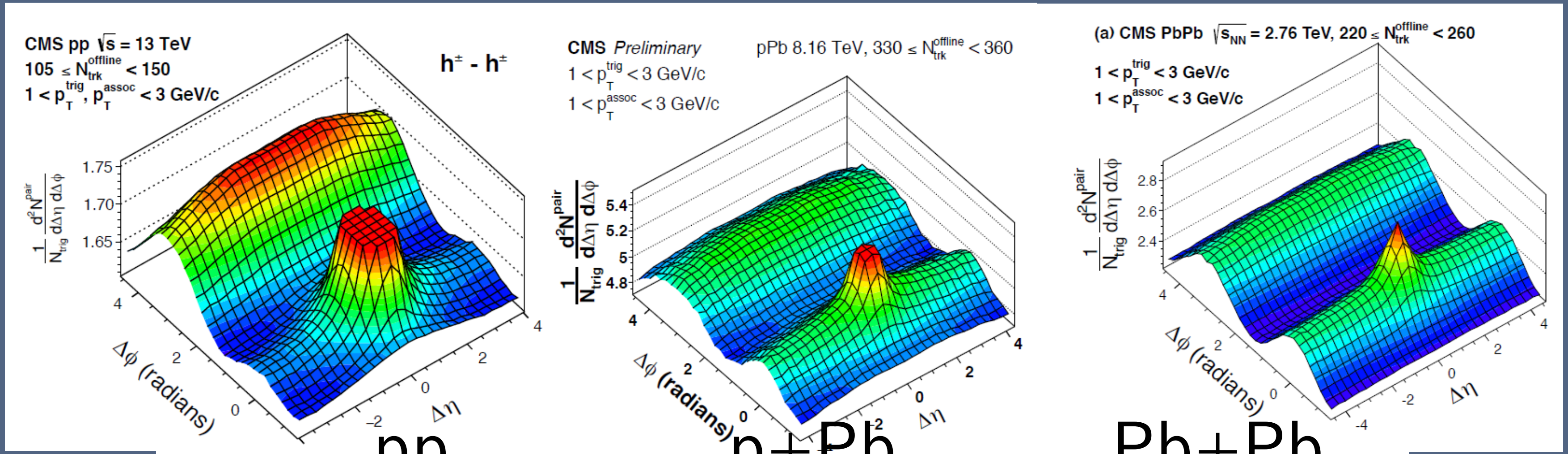
Correlation of two particle emission with the same azimuthal angle but large rapidity gap ($\Delta\eta \sim 2$-4)

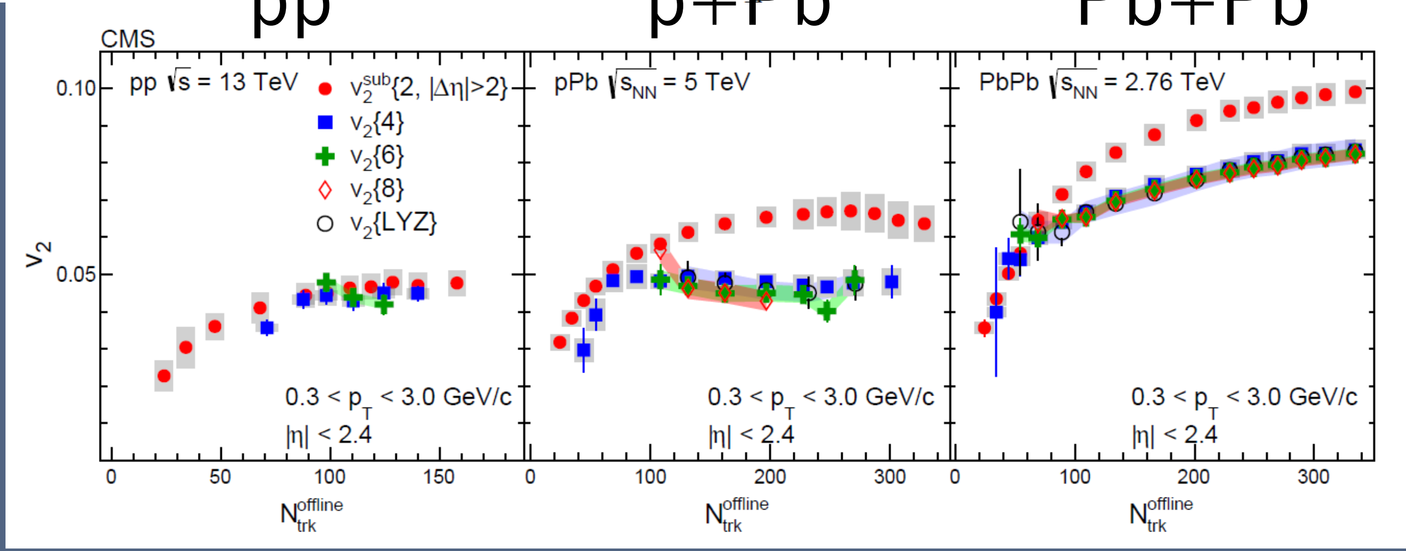
Ridge in heavy ion collisions

←Interpreted as collective flow

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

Collectivity in pp and pPb collisions at LHC

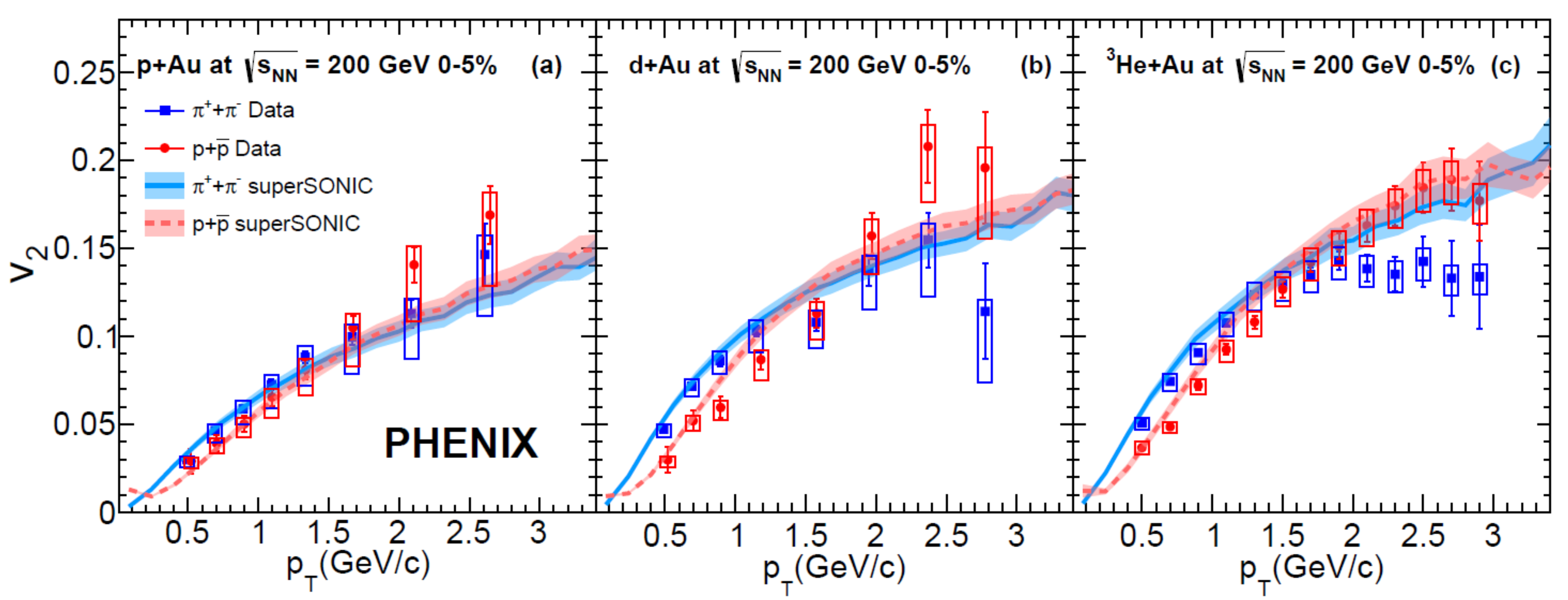




Guilbaud for CMS (2017)

Collectivity in p,d,He+Au collisions at RHIC

PHENIX Collaboration(2017)



Large elliptic flow measured at RHIC

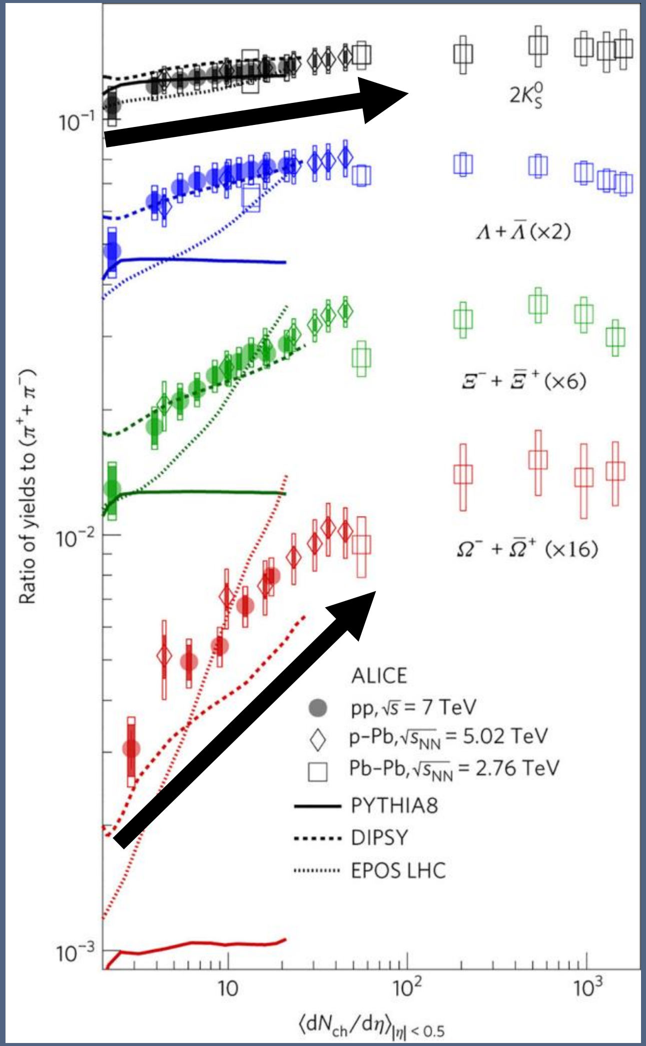
- Mass ordering
- Consistent with hydrodynamic calculations

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

The same hydro models reproduce experimental results in both large and small systems at RHIC.

Strangeness enhancement in pp

ALICE, Nature Physics (2017)



h_S/π increase with multiplicity

Multi-strange hadrons increase more rapidly

← Commonly seen in heavy ion data from SPS to LHC

Violation of "jet universality"?

QGP formation (EPOS, 2015)

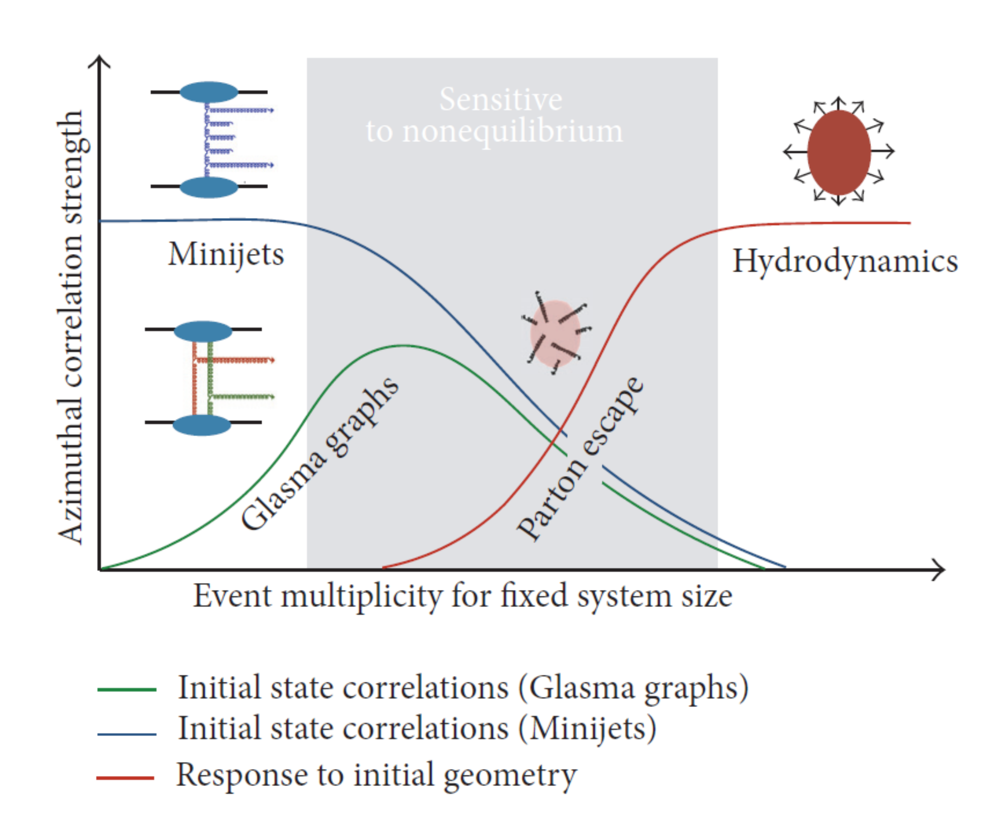
Rope hadronization (DIPSY, 2015, 2016)

Thermodynamical string model (Fischer,Sjöstrand, 2017)

→ Need more studies in final stage

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, …

Short summary of small colliding systems

Experimental data in pp and pA:

- Collectivity (ridge, finite $v_2,\cdots$)
- Strangeness enhancement

←How small can the QGP be?

←Collectivity or fluidity?

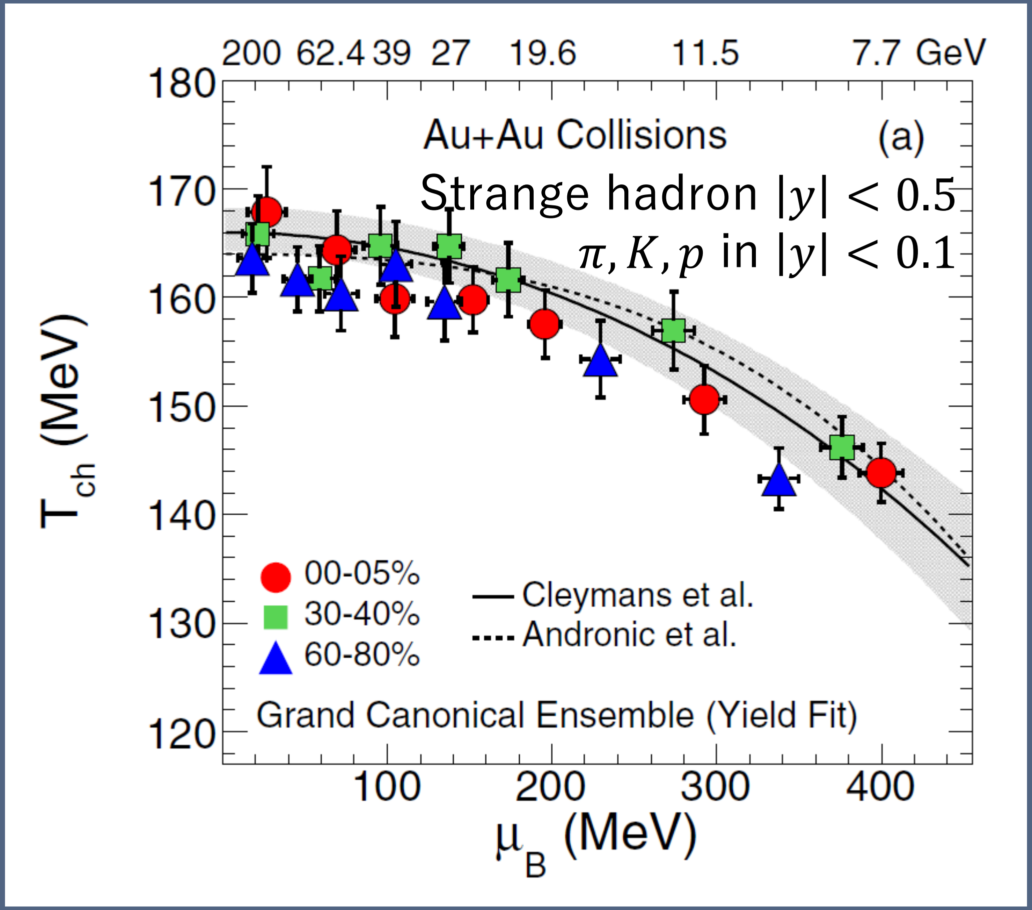
Interpretation not settled:

- Final state effects: QGP fluid, rope + shove, themodynamical string frag, color reconnection,⋯
- Initial state effects: Color glass condensate

Various collision energies

RHIC-Beam Energy Scan program
and beyond

Scanning phase diagram



STAR Collaboration (2017)

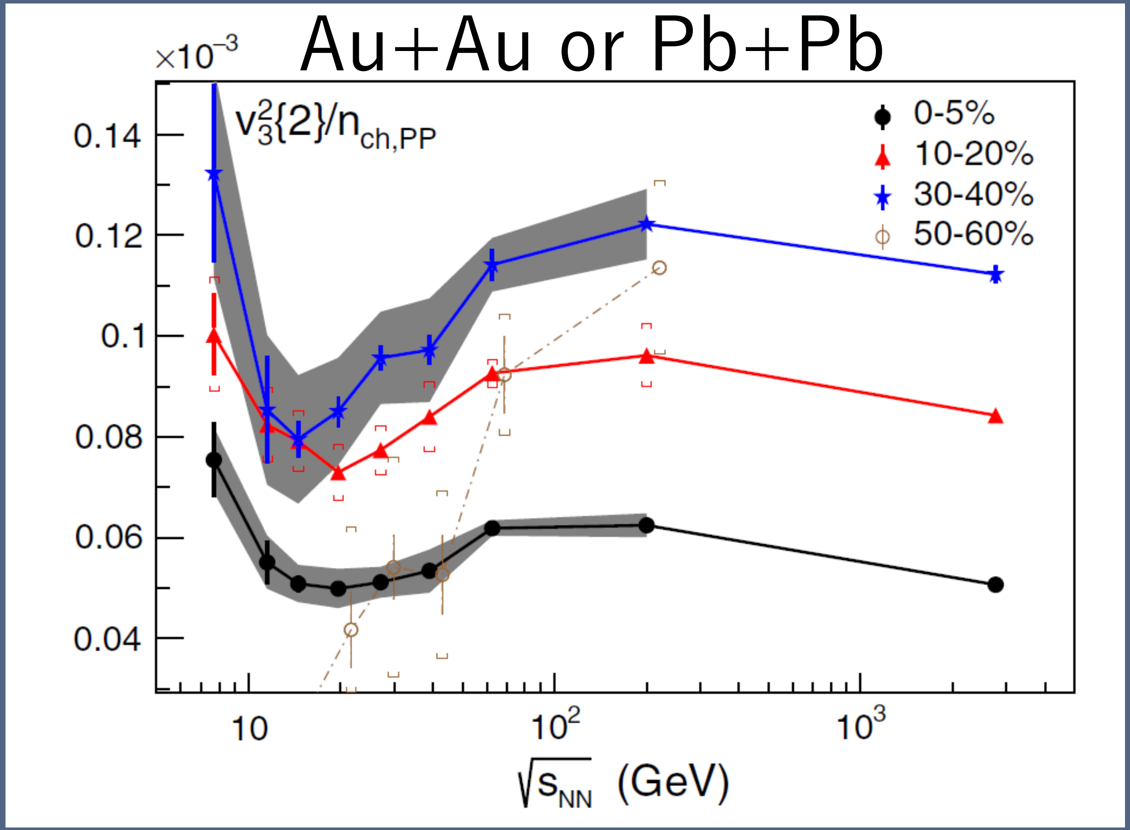
Chemical freezeout parameters from particle yields in Au+Au collisions at various energies

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

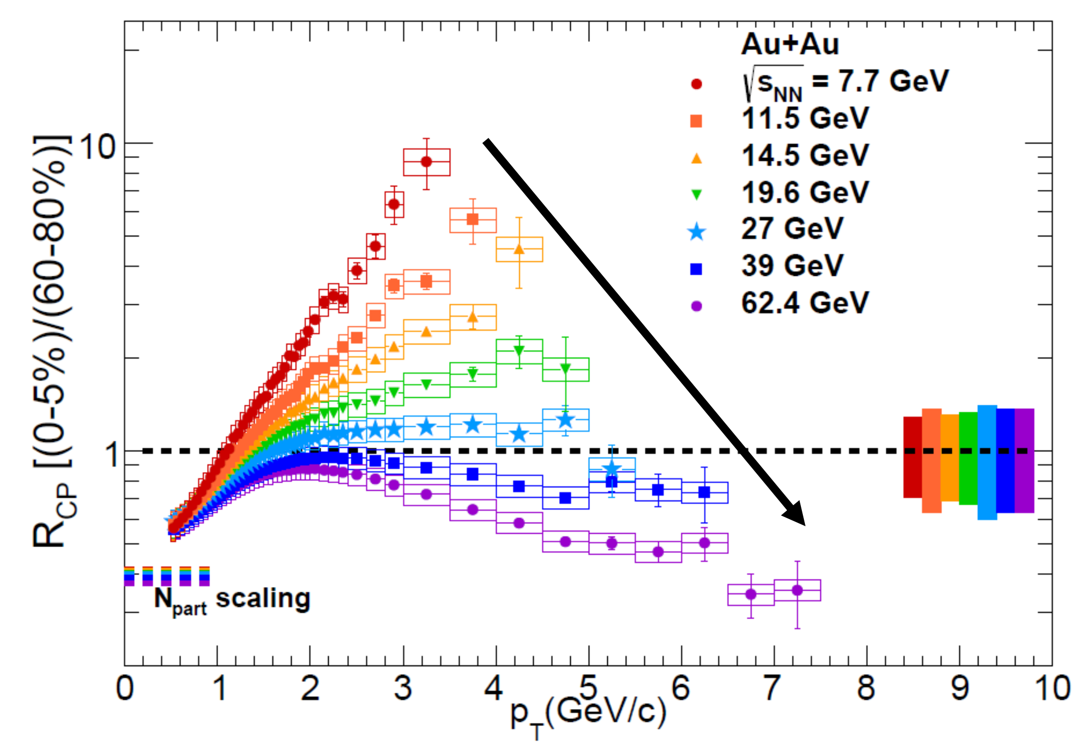
→ Minimum at $\sqrt{s_{NN}}$~20 GeV (mostly seen in semi-central collisions)

→ 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 <u>onset of QGP formation</u>?

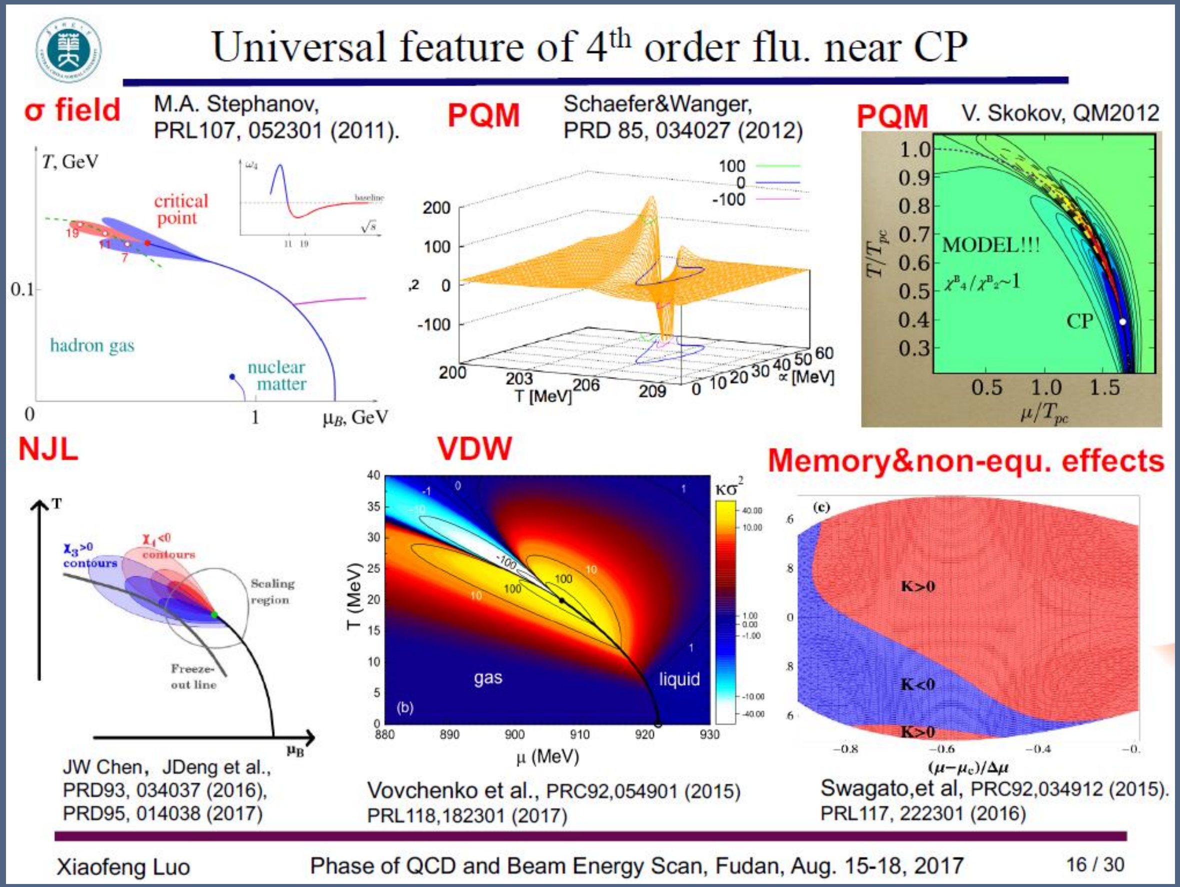
Hard to disentangle jet quenching from Cronin effect (random transverse kicks in the initial collision)

Higher order fluctuations of conserved quantity

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

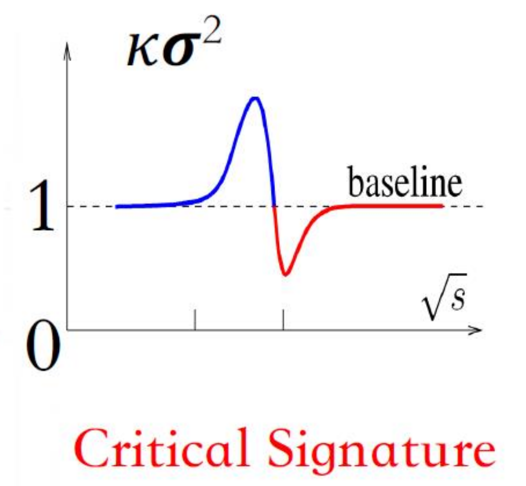
Non-monotonic behavior expected around critical point

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



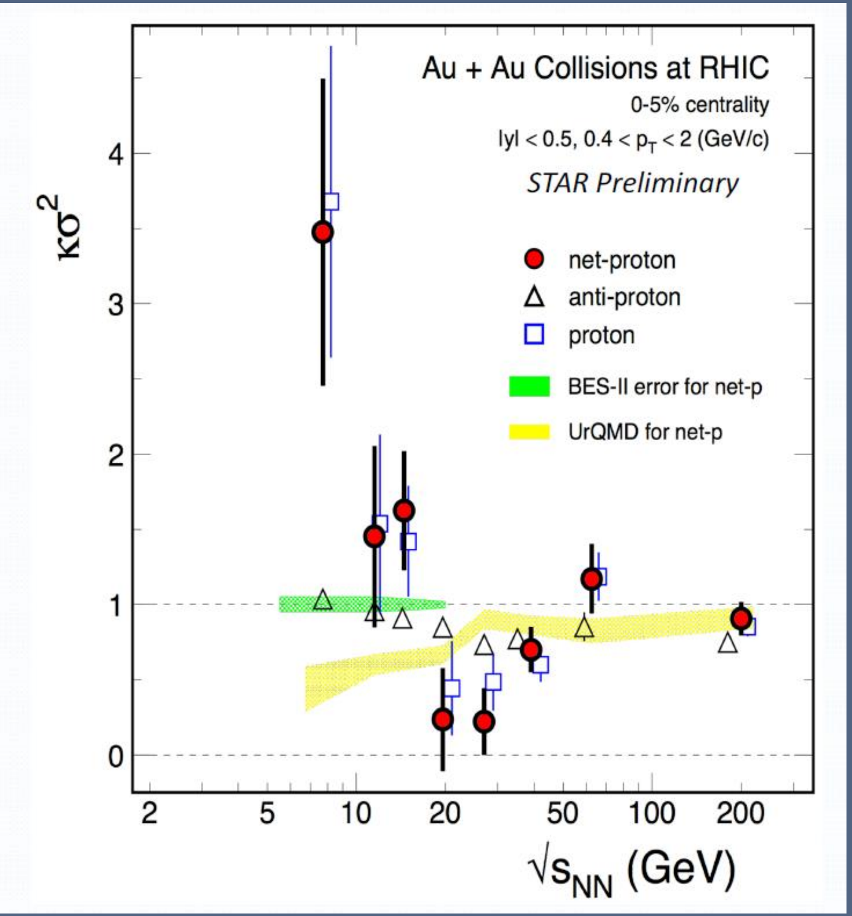
$$\kappa\sigma^2 = \frac{\chi_4}{\chi_2}$$

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



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

Esha for STAR (2017)

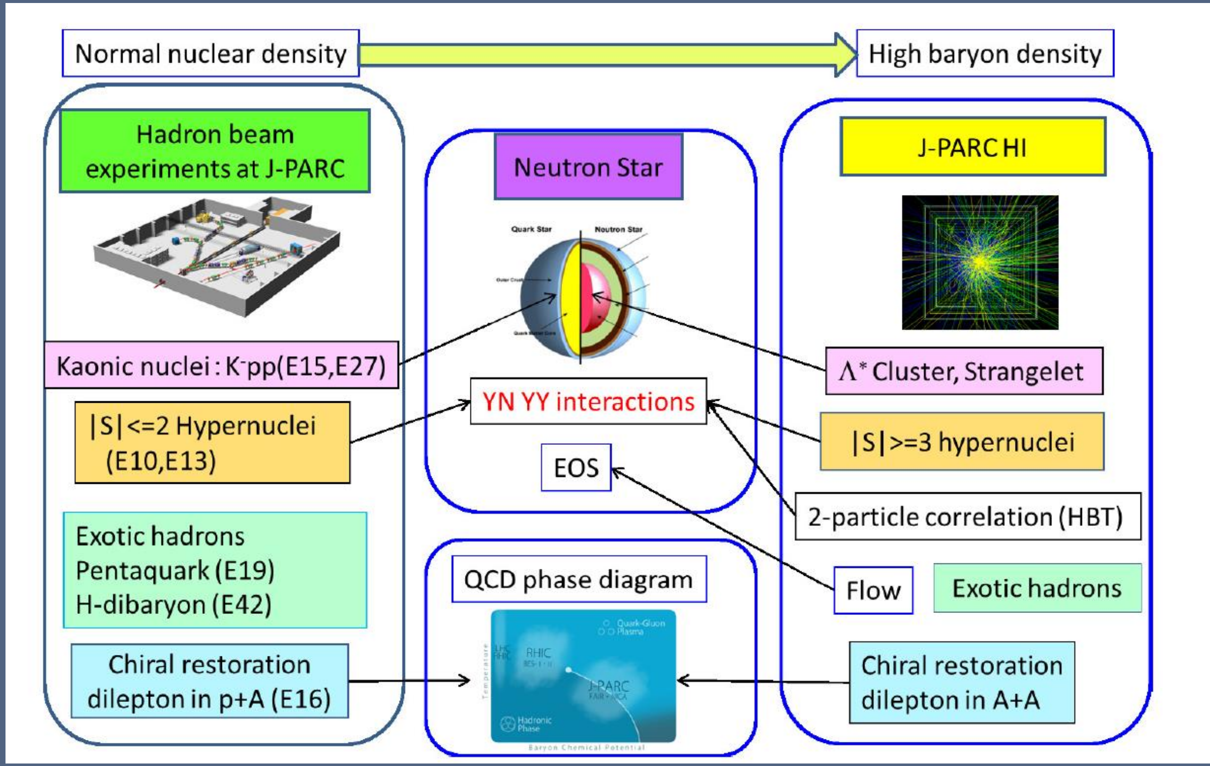


$$\kappa\sigma^2 = \frac{\langle(\delta N_B)^4\rangle}{\langle(\delta N_B)^2\rangle} = \frac{\chi_4}{\chi_2}$$

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

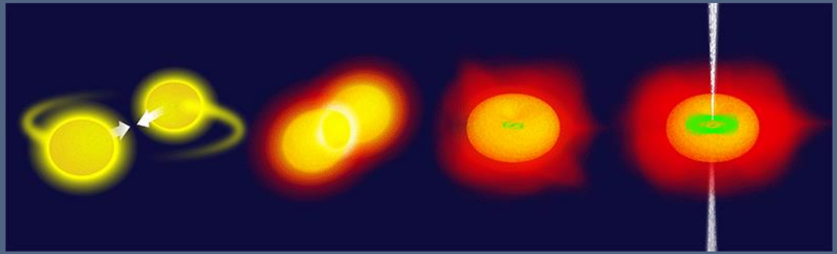
Expected non-monotonic behavior seen in experimental data
→Signature of critical point!?

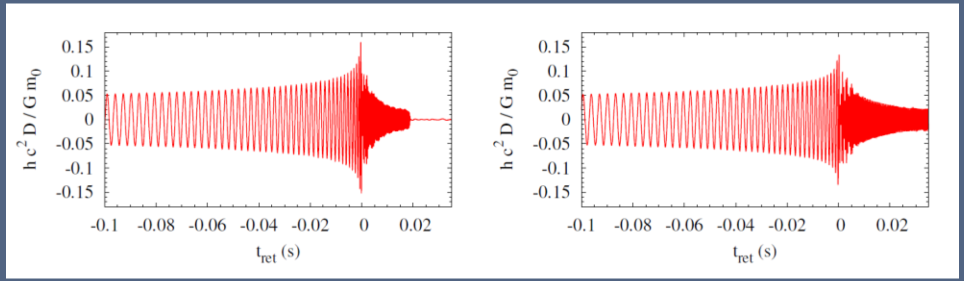
Future study of
Super-dense nuclear/quark matter



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

Binary neutron star merger





M. Shibata, talk at QM2015

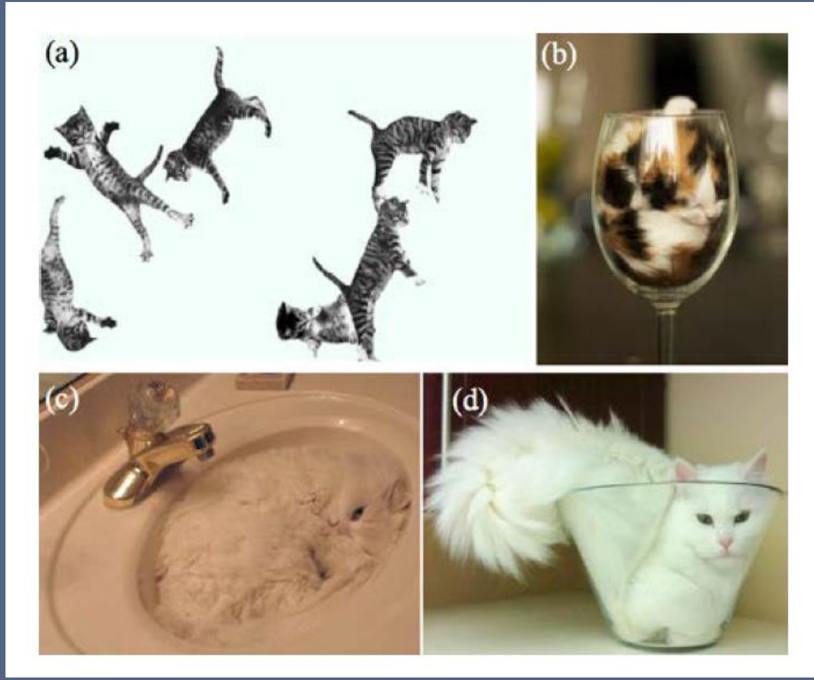
https://physics.aps.org/articles/v10/114

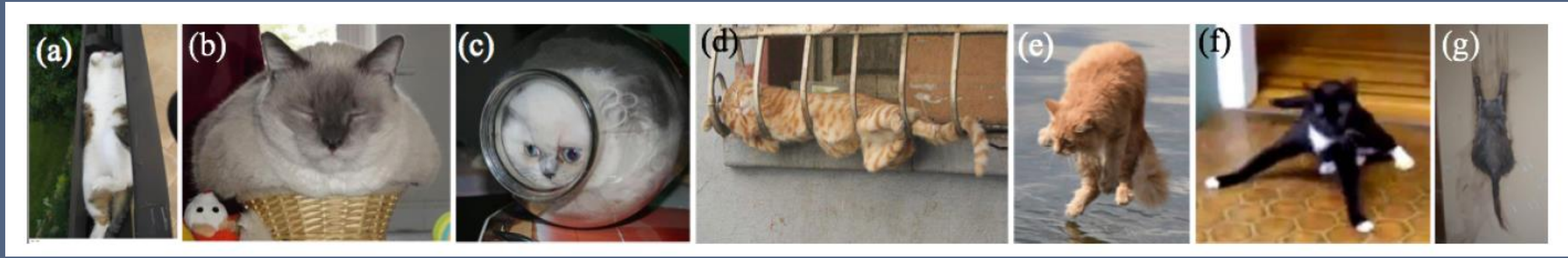
Outlook (instead of Summary)

- Construct robust models against precision data
  - Correlation measurement and its analysis
  - New (hard) probes
  - Interplay between soft and hard
- Need much more studies even in pp collisions!
  - Initial state: Particle production, thermalization?
  - Final state: hydro? Interacting color fields? Novel fragmentation?

Final question: Everything flows?

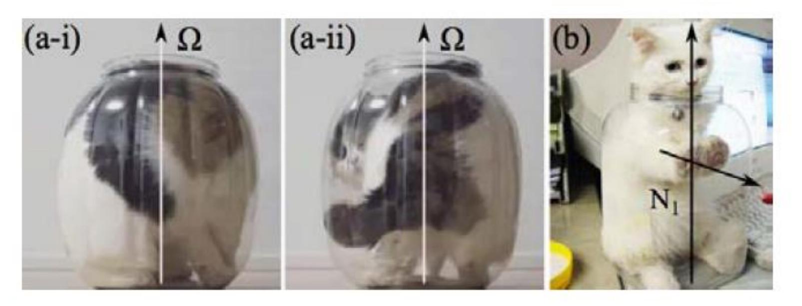
παντα ρει! Everything flows!





Even cats flow!

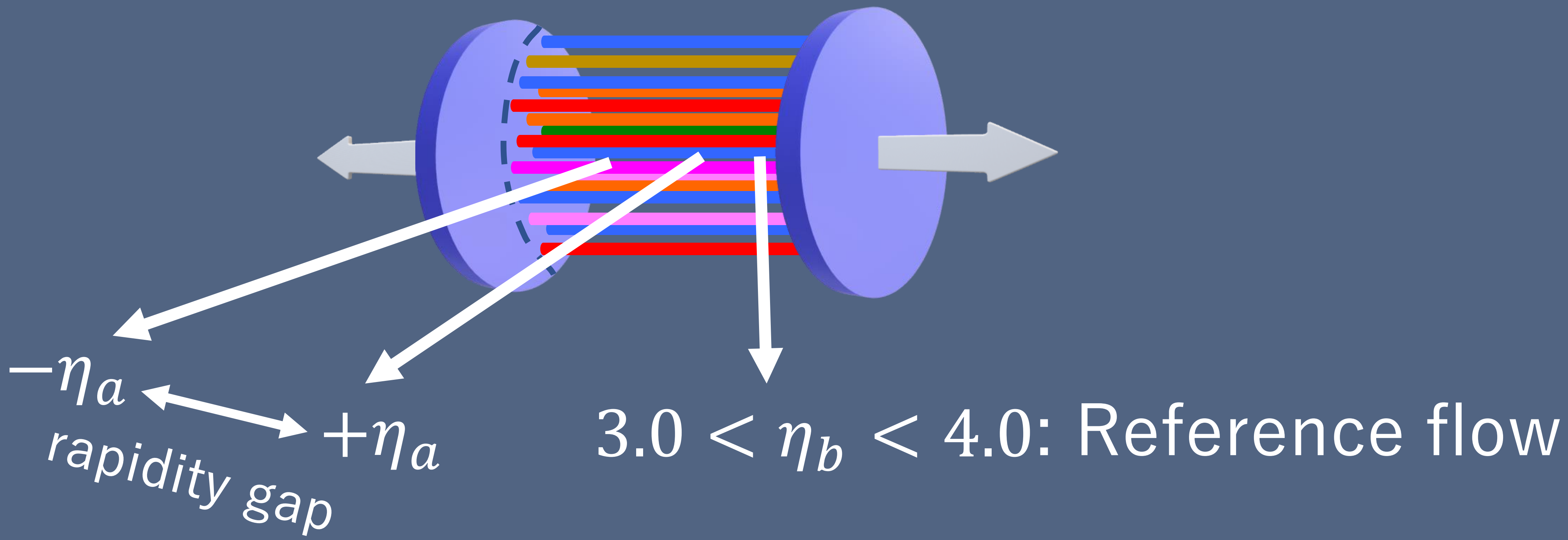
The 2017 Ig Nobel Prize in Physics: M.A. Fardin for using fluid dynamics to probe the question "Can a Cat Be Both a Solid and a Liquid?“ (https://www.improbable.com/ig)



Spontaneous rotation

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

Correlation of elliptic flow parameter between different rapidity



Same quadrupole emission pattern across rapidity?

Rope + shove model

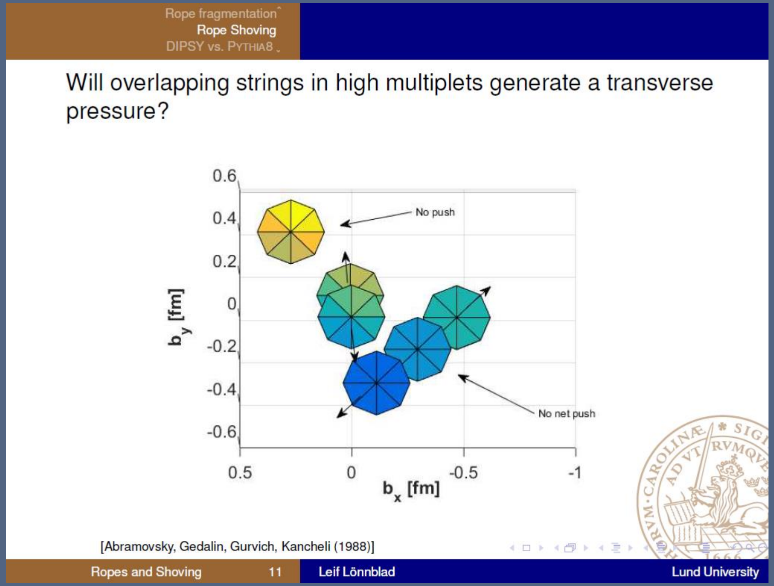
Bierlich *et al.*(2014, 2016)

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

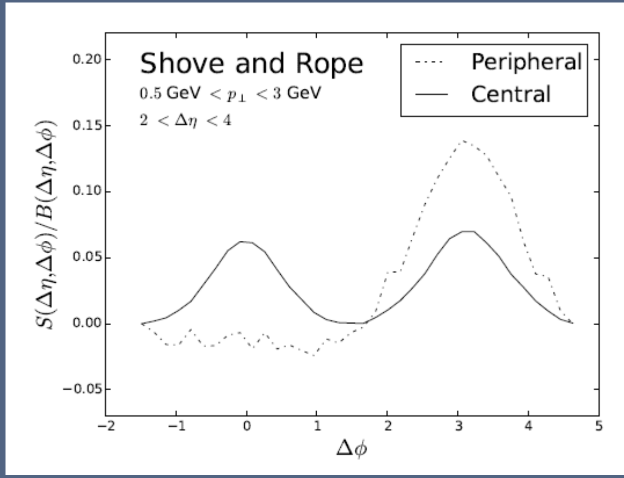
Schwinger mechanism

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

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



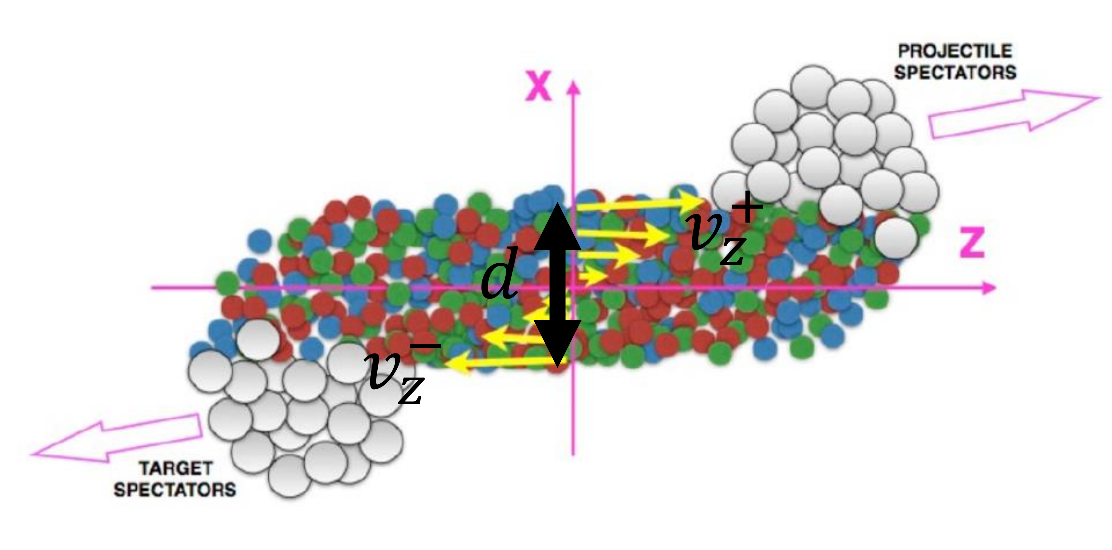
Lönnblad (2017)

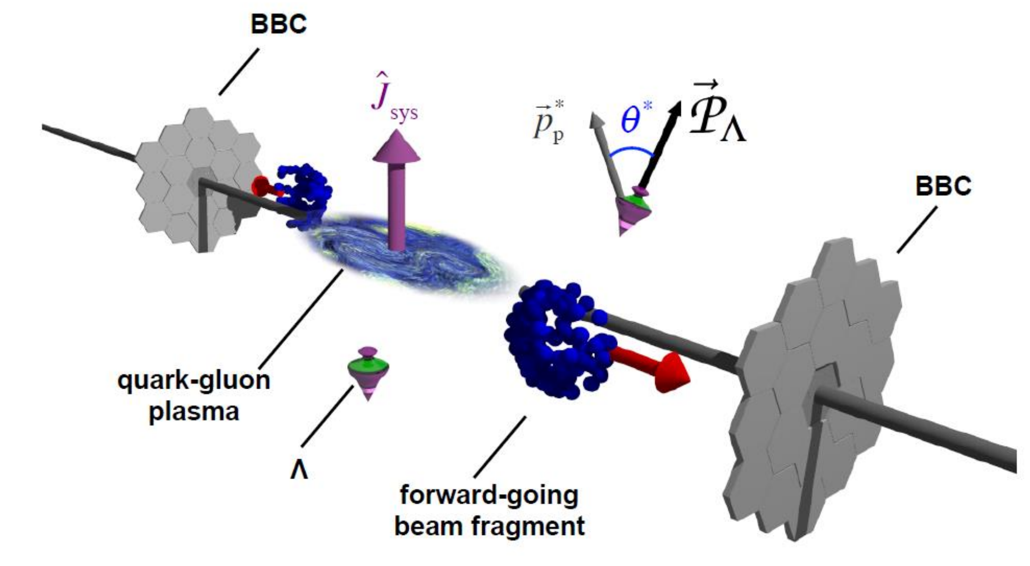


Ridge appears in central pp events shoving model ~ hydro?

QGP as the most vortical fluid

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





$$\left.\begin{array}{c} \boldsymbol{\omega} \sim \frac{1}{2} \nabla \times \boldsymbol{v} \\ |v_z^+ - v_z^-| \sim 0.1c \\ d \sim 10\mathrm{fm} \end{array}\right\} \Rightarrow |\boldsymbol{\omega}| \sim 10^{22}\mathrm{s}^{-1}$$

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)

Contents