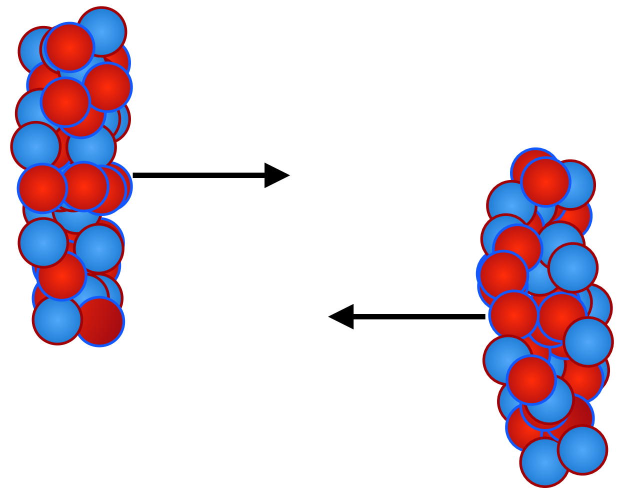
OVERVIEW OF HEAVY ION EXPERIMENT RESULTS AND PERSPECTIVES



Panos Christakoglou

Nikhef and Utrecht University

Nikhef

(SOME OF THE) SCIENTIFIC CHALLENGES (~2000)

What is dark matter?

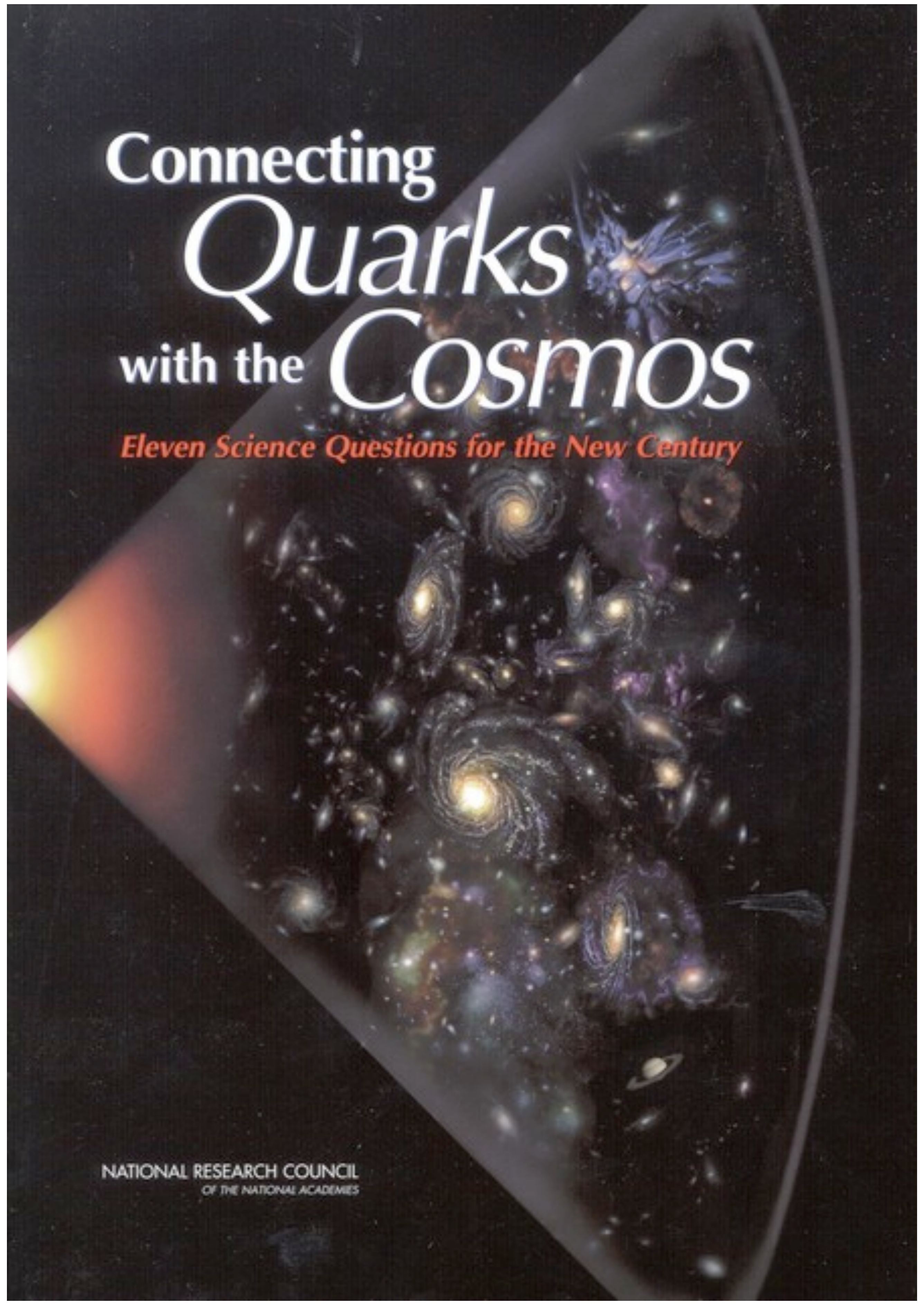
What is the nature of dark energy?

How did the universe begin and evolve?

Can we incorporate quantum effects in a general gravitational theory?

What are the neutrino masses and what is their role in the evolution of the universe?

How do Cosmic Accelerators work and what are they accelerating?



Are protons unstable?

What are the new states of matter at exceedingly high density and temperature?

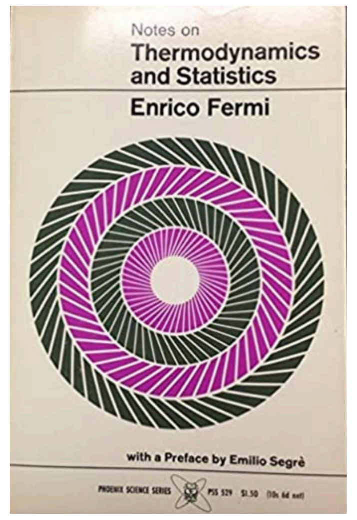
Are there additional space-time dimensions?

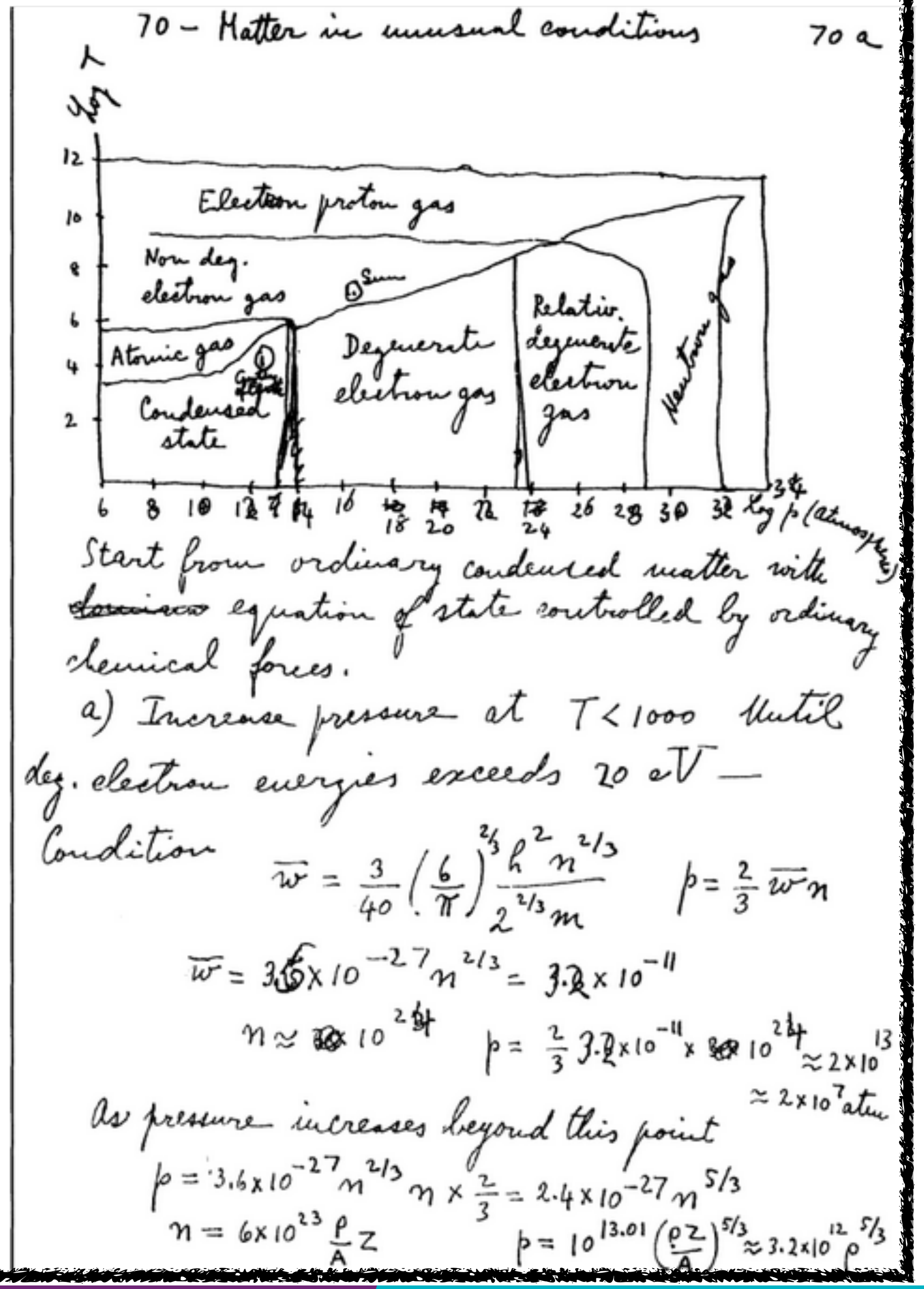
How were the elements from iron to uranium made?

Is a new theory of matter and light needed at the highest energies?

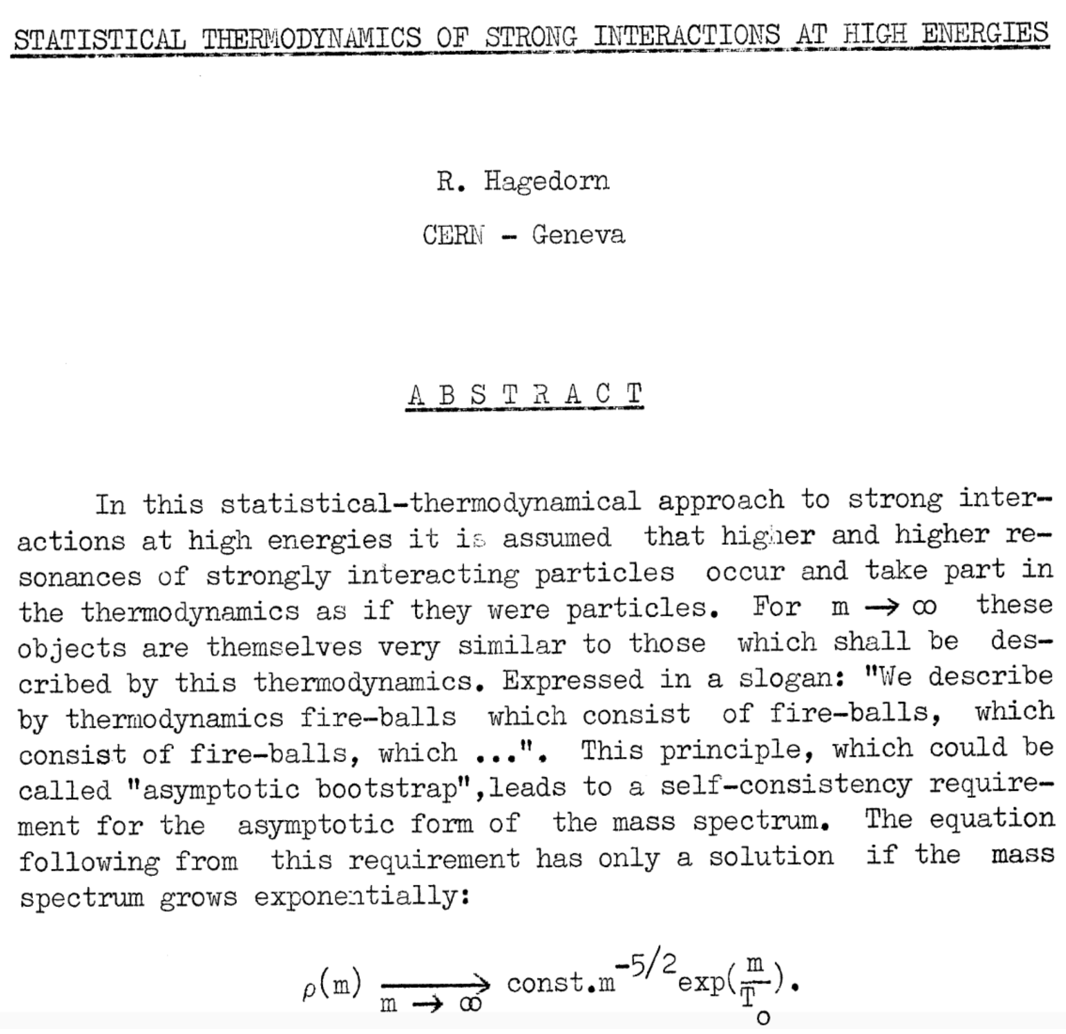
MATTER IN UNUSUAL CONDITIONS…

Fermi (~1953)





Hagedorn (~1965)



STATISTICAL THERMODYNAMICS OF STRONG INTERACTIONS AT HIGH ENERGIES

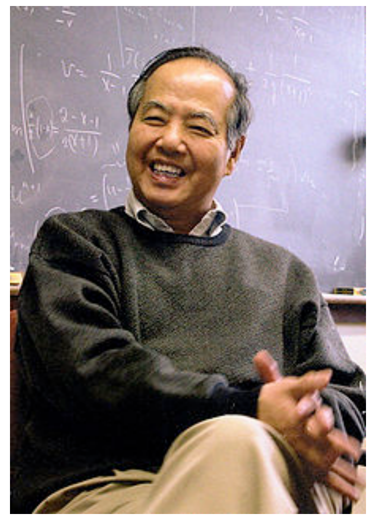
R. Hagedorn
CERN – Geneva

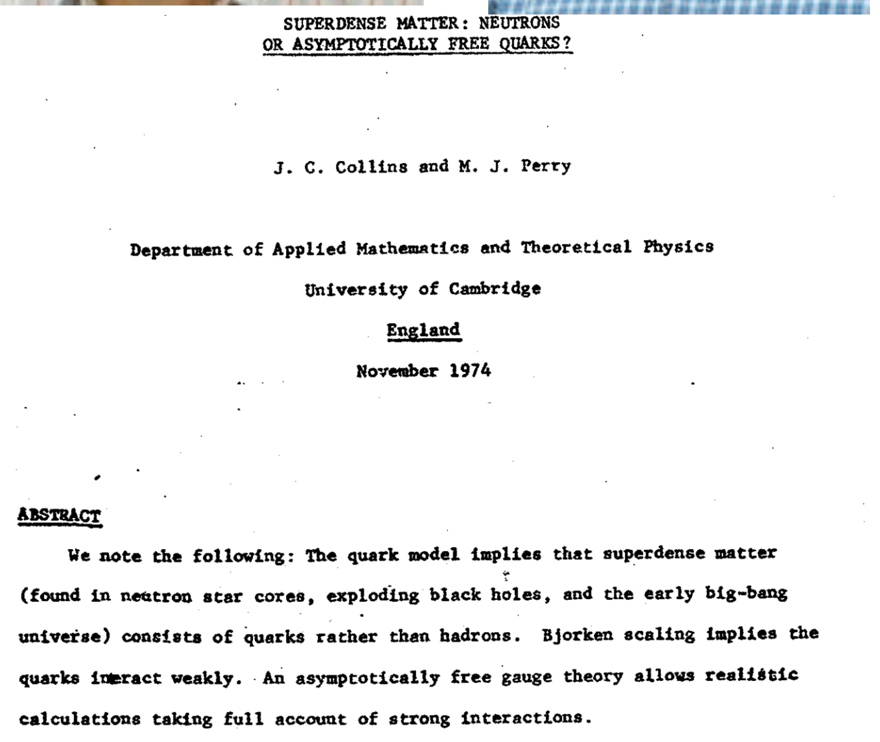
A B S T R A C T

In this statistical-thermodynamical approach to strong interactions at high energies it is assumed that higher and higher resonances of strongly interacting particles occur and take part in the thermodynamics as if they were particles. For $m \to \infty$ these objects are themselves very similar to those which shall be described by this thermodynamics. Expressed in a slogan: "We describe by thermodynamics fire-balls which consist of fire-balls, which consist of fire-balls, which ...". This principle, which could be called "asymptotic bootstrap", leads to a self-consistency requirement for the asymptotic form of the mass spectrum. The equation following from this requirement has only a solution if the mass spectrum grows exponentially:

$$\rho(m) \xrightarrow[m \to \infty]{} \text{const.}\, m^{-5/2} \exp\left(\frac{m}{T_0}\right).$$

Lee-Wick abnormal matter (~1974)





SUPERDENSE MATTER: NEUTRONS OR ASYMPTOTICALLY FREE QUARKS?

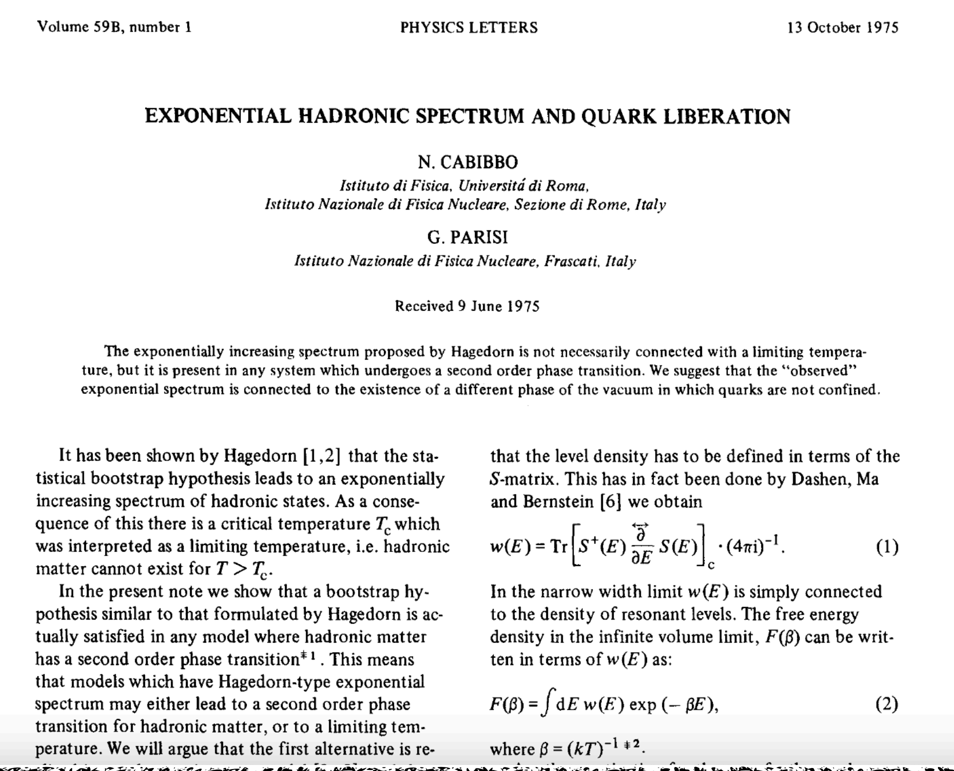
J. C. Collins and M. J. Perry

Department of Applied Mathematics and Theoretical Physics
University of Cambridge
England

November 1974

ABSTRACT

We note the following: The quark model implies that superdense matter (found in neutron star cores, exploding black holes, and the early big-bang universe) consists of quarks rather than hadrons. Bjorken scaling implies the quarks interact weakly. An asymptotically free gauge theory allows realistic calculations taking full account of strong interactions.



Volume 59B, number 1 PHYSICS LETTERS 13 October 1975

EXPONENTIAL HADRONIC SPECTRUM AND QUARK LIBERATION

N. CABIBBO
Istituto di Fisica, Universitá di Roma,
Istituto Nazionale di Fisica Nucleare, Sezione di Rome, Italy
G. PARISI
Istituto Nazionale di Fisica Nucleare, Frascati, Italy

Received 9 June 1975

The exponentially increasing spectrum proposed by Hagedorn is not necessarily connected with a limiting temperature, but it is present in any system which undergoes a second order phase transition. We suggest that the "observed" exponential spectrum is connected to the existence of a different phase of the vacuum in which quarks are not confined.

It has been shown by Hagedorn [1,2] that the statistical bootstrap hypothesis leads to an exponentially increasing spectrum of hadronic states. As a consequence of this there is a critical temperature T_c which was interpreted as a limiting temperature, i.e. hadronic matter cannot exist for $T > T_c$.

In the present note we show that a bootstrap hypothesis similar to that formulated by Hagedorn is actually satisfied in any model where hadronic matter has a second order phase transition[‡1]. This means that models which have Hagedorn-type exponential spectrum may either lead to a second order phase transition for hadronic matter, or to a limiting temperature. We will argue that the first alternative is re-

that the level density has to be defined in terms of the S-matrix. This has in fact been done by Dashen, Ma and Bernstein [6] we obtain

$$w(E) = \mathrm{Tr}\left[S^{+}(E)\,\frac{\overleftrightarrow{\partial}}{\partial E}\,S(E)\right]_c \cdot (4\pi i)^{-1}. \quad (1)$$

In the narrow width limit $w(E)$ is simply connected to the density of resonant levels. The free energy density in the infinite volume limit, $F(\beta)$ can be written in terms of $w(E)$ as:

$$F(\beta) = \int \mathrm{d}E\, w(E) \exp(-\beta E), \quad (2)$$

where $\beta = (kT)^{-1}$ [‡2].

Expectation for a weakly interacting quasi-particle gas

THE QUARK-GLUON PLASMA (QGP)

Shuryak

Quark Gluon Plasma - QGP (1978)

Volume 78B, number 1 PHYSICS LETTERS 11 Spetember 1797

QUARK–GLUON PLASMA AND HADRONIC PRODUCTION OF LEPTONS, PHOTONS AND PSIONS

E.V. SHURYAK
Institute of Nuclear Physics, Novosibirsk, USSR

Received 16 March 1978

QCD calculations of the production rate in a quark–gluon plasma and account of the space–time picture of hadronic collisions lead to estimates of the dilepton mass spectrum, $p_\perp$ distributions of $e^\pm$, $\mu^\pm$, γ, $\pi^\pm$, production cross sections of charm and psions.

Hadronic reactions, taking place at small and large distances, are treated on quite different theoretical grounds. While the former are well described by the parton model based on asymptotic freedom of QCD, the latter are still discussed in more phenomenological way. I should like to argue in this paper, that a very important intermediate region exists, namely reactions taking place far from the collision point and not obeying the parton model, but at the same time treatable by perturbative QCD methods. This region corresponds to production of particles with mass M or transverse momentum $p_\perp$ such that 1 GeV $\lesssim M, p_\perp \ll \sqrt{s}$ ($\lesssim$ 4–5 GeV at ISR energies).

The best known example is dilepton production ($\mu^+\mu^-$, e^+e^-), in which deviations from the Drell–Yan model [1] for dilepton mass $M \lesssim 5$ GeV reach a factor 10^1–10^2. Bjorken and Weisberg [2] proposed a qualitative explanation for it: such pairs are produced at later stages of the collision, when antiquarks are more numerous and can interact repeatedly. Much earlier, Feinberg [3] ascribed them to the charge-current fluctuations in the hydrodynamical model [4] and also stressed the importance of the space–time aspect of the problem.

We assume that in hadronic collisions after some time a *local* [7] *thermal equilibrium* is established in the sense that all properties are determined by a single parameter, the temperature T, depending on time and coordinates. The schematic space–time picture of the collisions is shown in fig. 1. We are interested in the final state interaction region, limited by two lines: $T(x, t) = T_i$, the initial temperature at which the thermodynamical description becomes reasonable, and $T(x, t) = T_f \sim m_\pi$, where the system breaks into secondaries [4,7]. The medium is assumed to be the quark–gluon

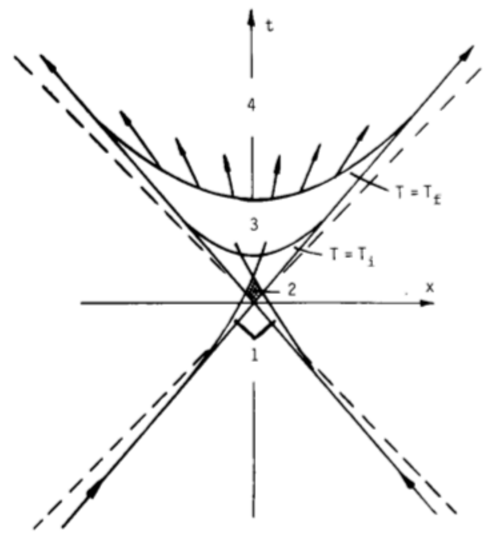
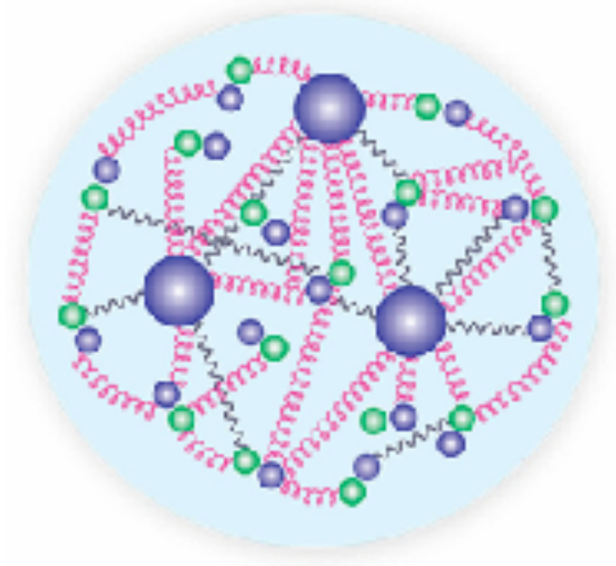
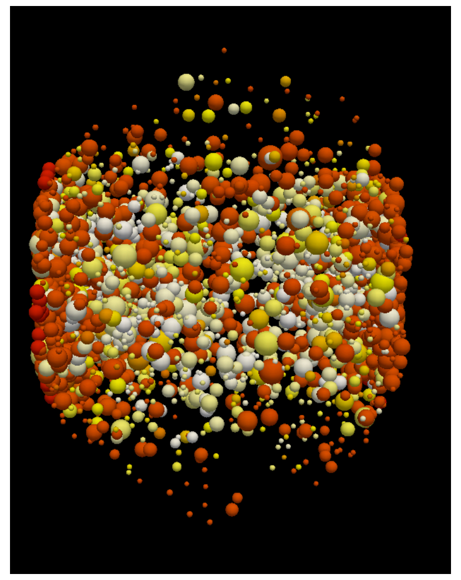


Fig. 1. The space–time picture of hadronic collisions, proceeding through the following stages: (1) structure function formation; (2) hard collisions; (3) final state interaction; (4) free secondaries.

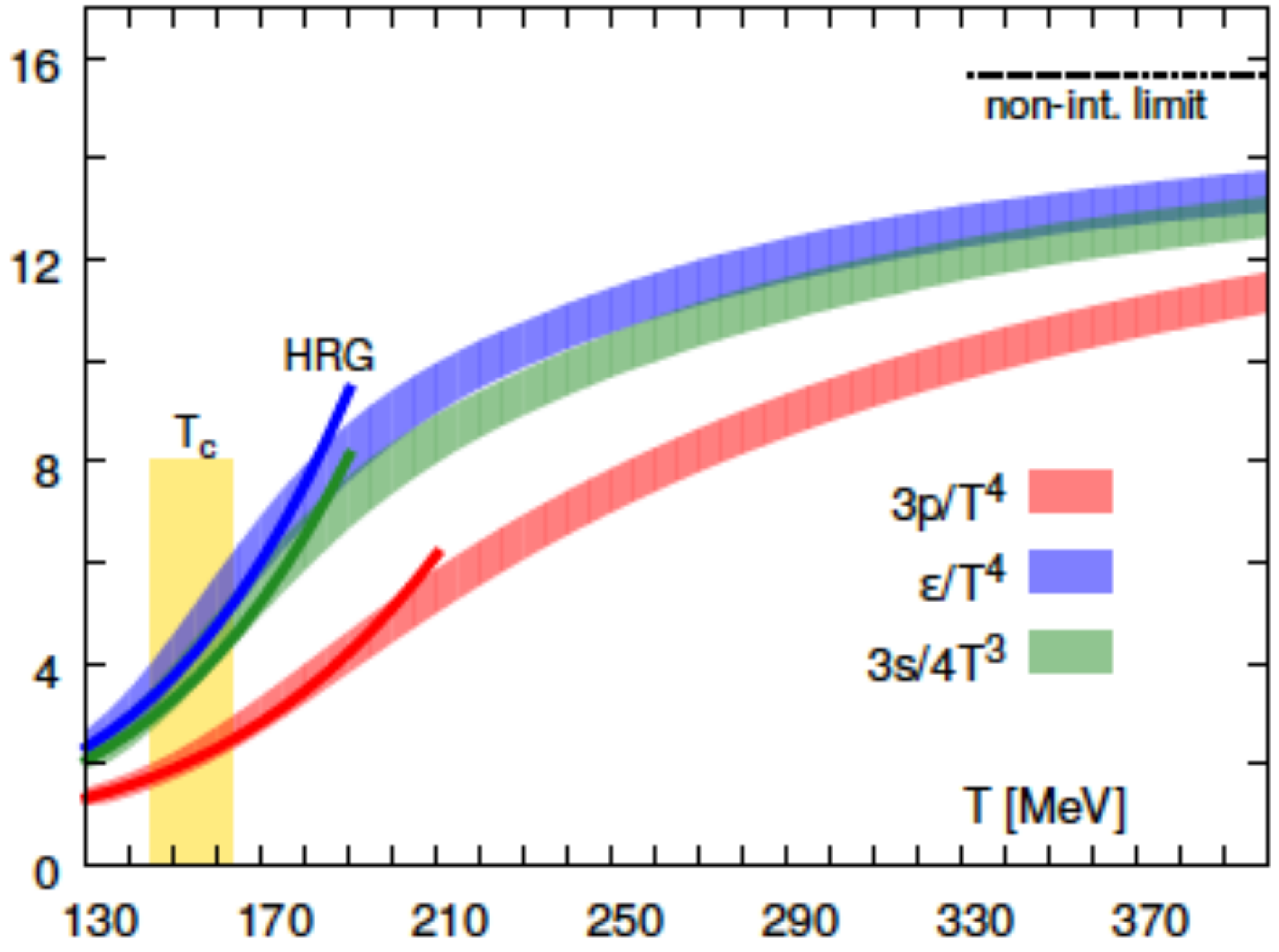
Nuclear matter



Quark Gluon Plasma



HotQCD Collaboration:
Phys.Rev. **D90**, (2014) 094503



Phase transition beyond a critical temperature (~155 MeV) and energy density (~0.5 GeV/fm^3)

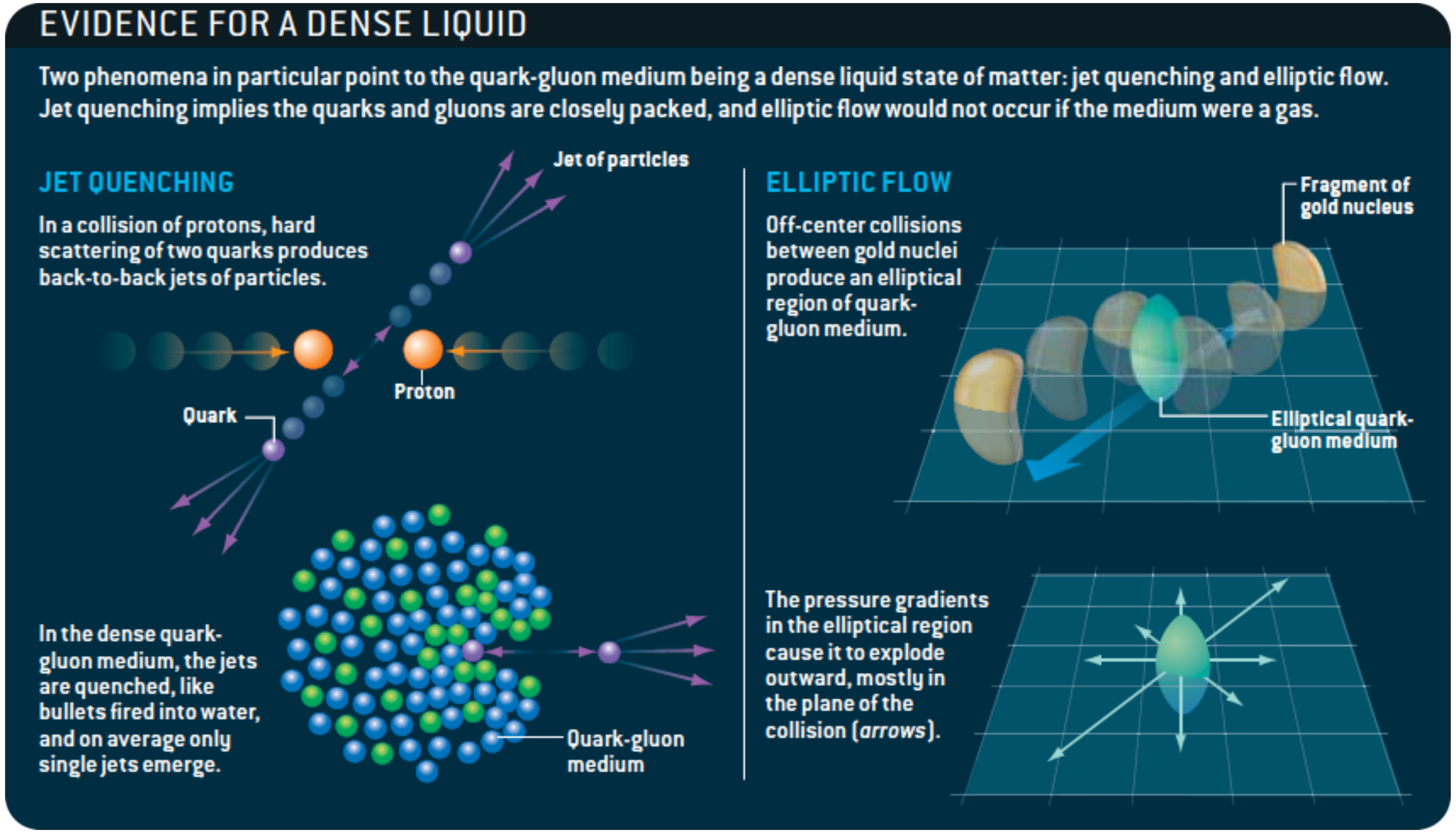
Nikhef

STUDYING QCD MATTER AT EXTREME CONDITIONS

Series of experiments at:

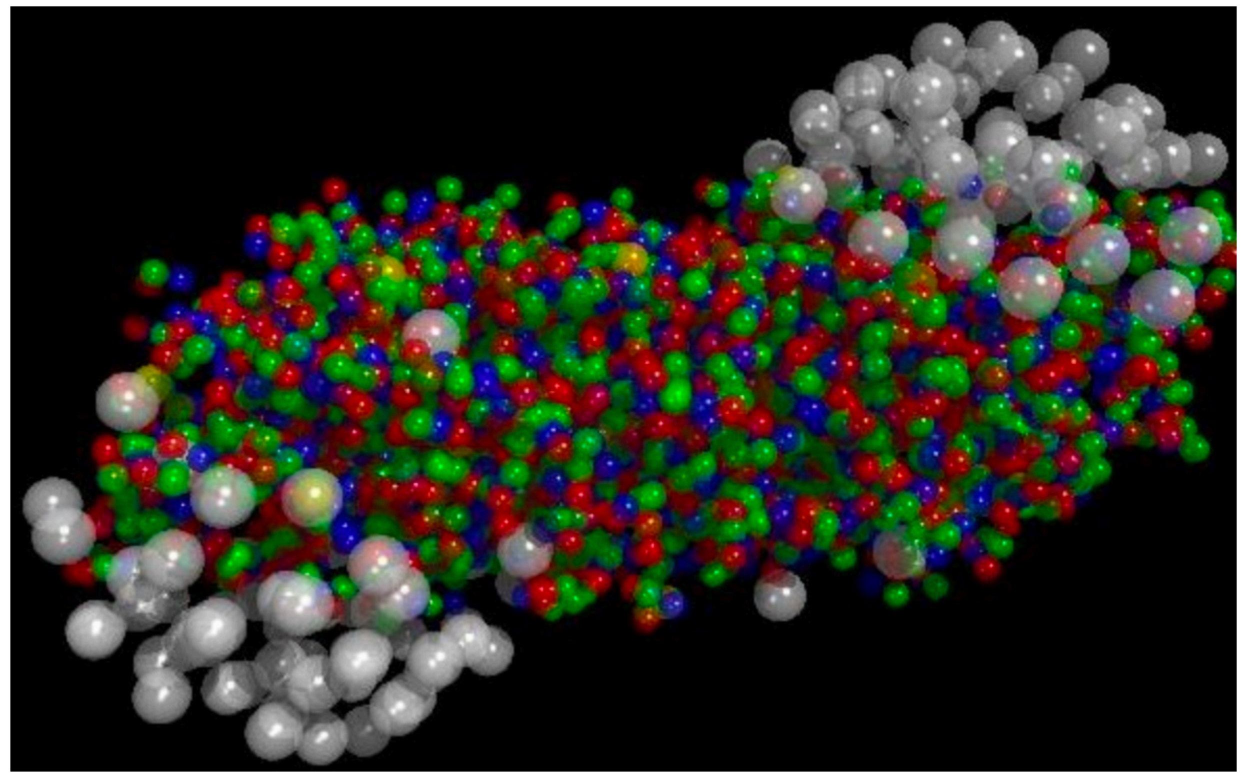
- Bevalac (HI between 1980-1993)
- AGS (Si/Au beams ~1986-1994)
- SPS (S/Pb beams ~1987-Today)
- RHIC (Au beams, 2000-Today)
- LHC (Pb beams, 2010-Today)

M. Roirdan and W. Zajc, Scientific American 34A May (2006)



New State of Matter created at CERN

10 Feb 2000



Geneva, 10 February 2000. At a special seminar on 10 February, spokespersons from the experiments on CERN[1]'s Heavy Ion programme presented compelling evidence for the existence of a new state of matter in which quarks, instead of being bound up into more complex particles such as protons and neutrons, are liberated to roam freely.

The birth of the perfect fluid paradigm

ANISOTROPIC FLOW

Anisotropies in coordinate space

- Initial geometry and its fluctuations

Transferred to anisotropies in momentum space

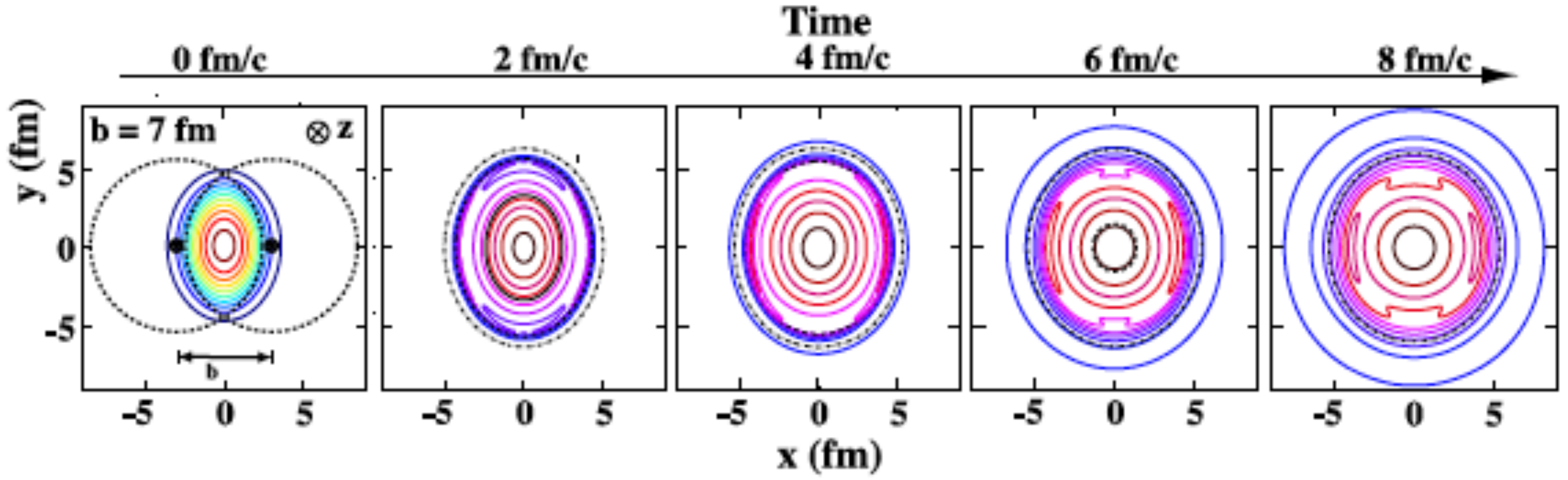
Quantified by Fourier coefficients v_n

$$E\frac{d^3}{dP^3} = \frac{1}{2\pi}\frac{d^2N}{p_T dp_T d\eta}\left[1 + 2\sum_{n=1}^{\infty} v_n(p_T,\eta)\cos[n(\varphi - \Psi_n)]\right]$$

$$v_n = \langle \cos[n(\varphi - \Psi_n)] \rangle$$

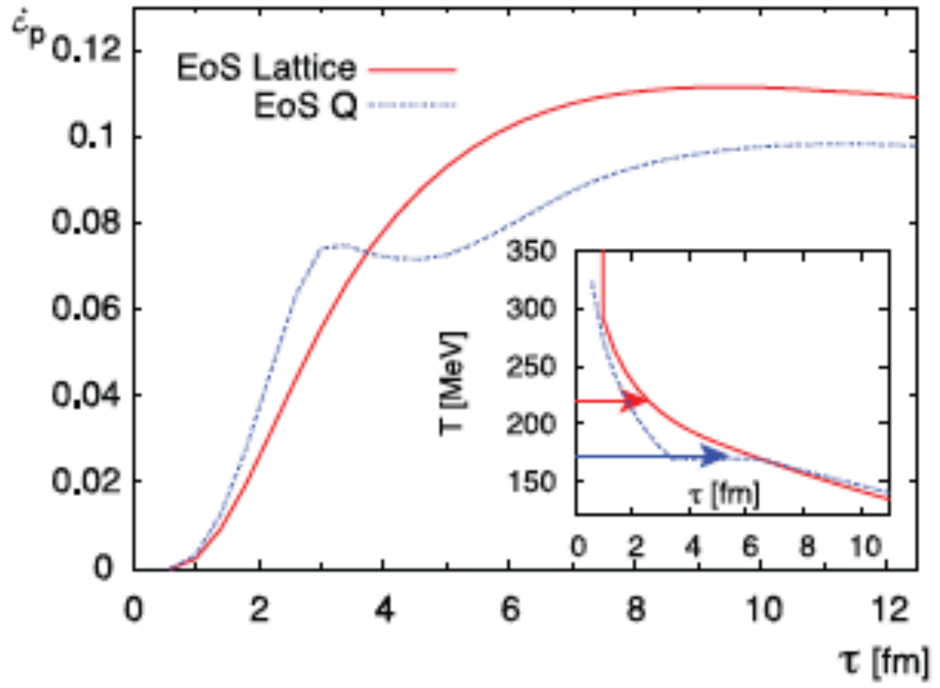
Voloshin and Zhang, Z. Phys. **C70** (1996) 665

Coordinate space: eccentricities

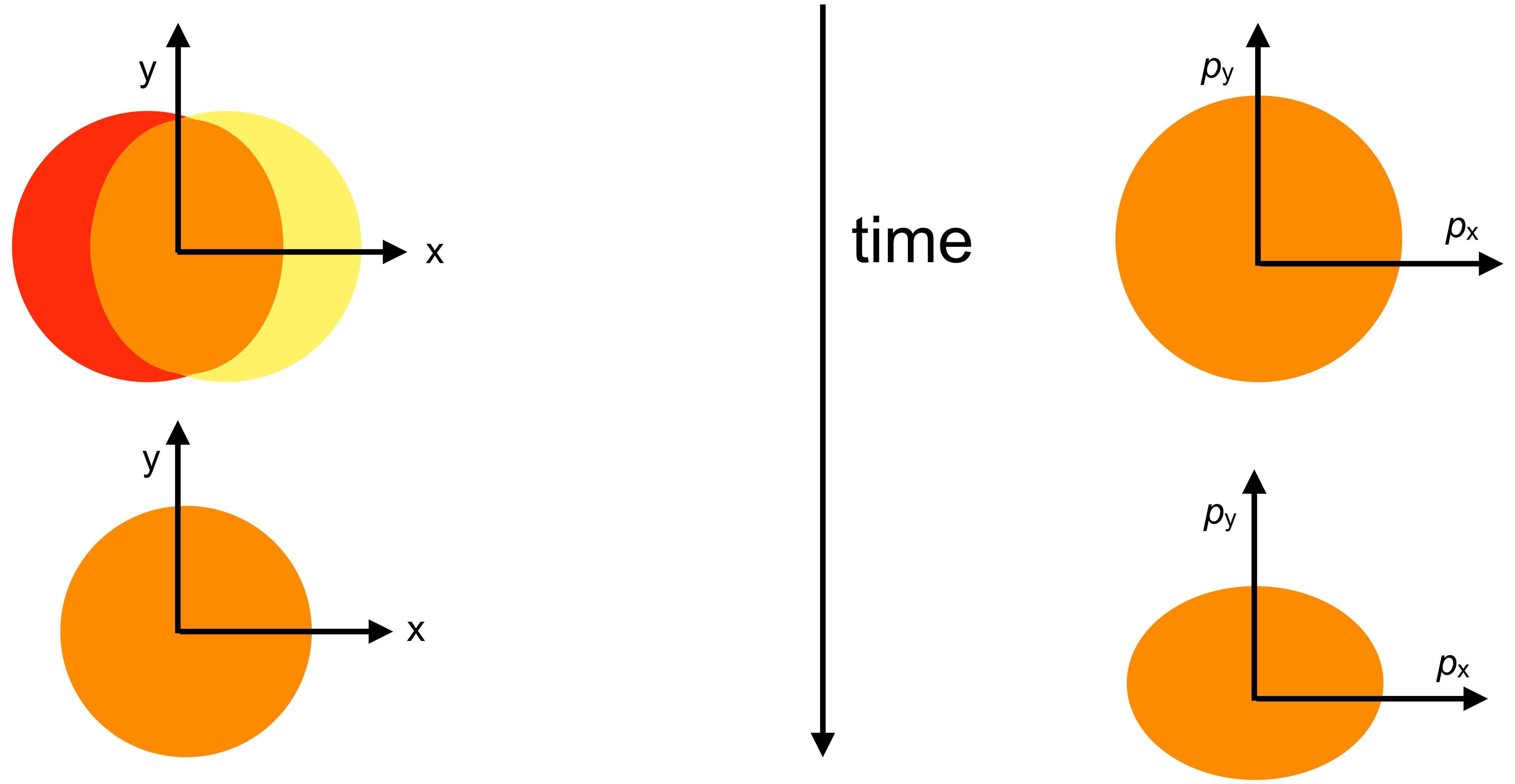


$$\epsilon = \frac{\langle y^2 - x^2 \rangle}{\langle y^2 + x^2 \rangle}$$

Momentum space: flow harmonics

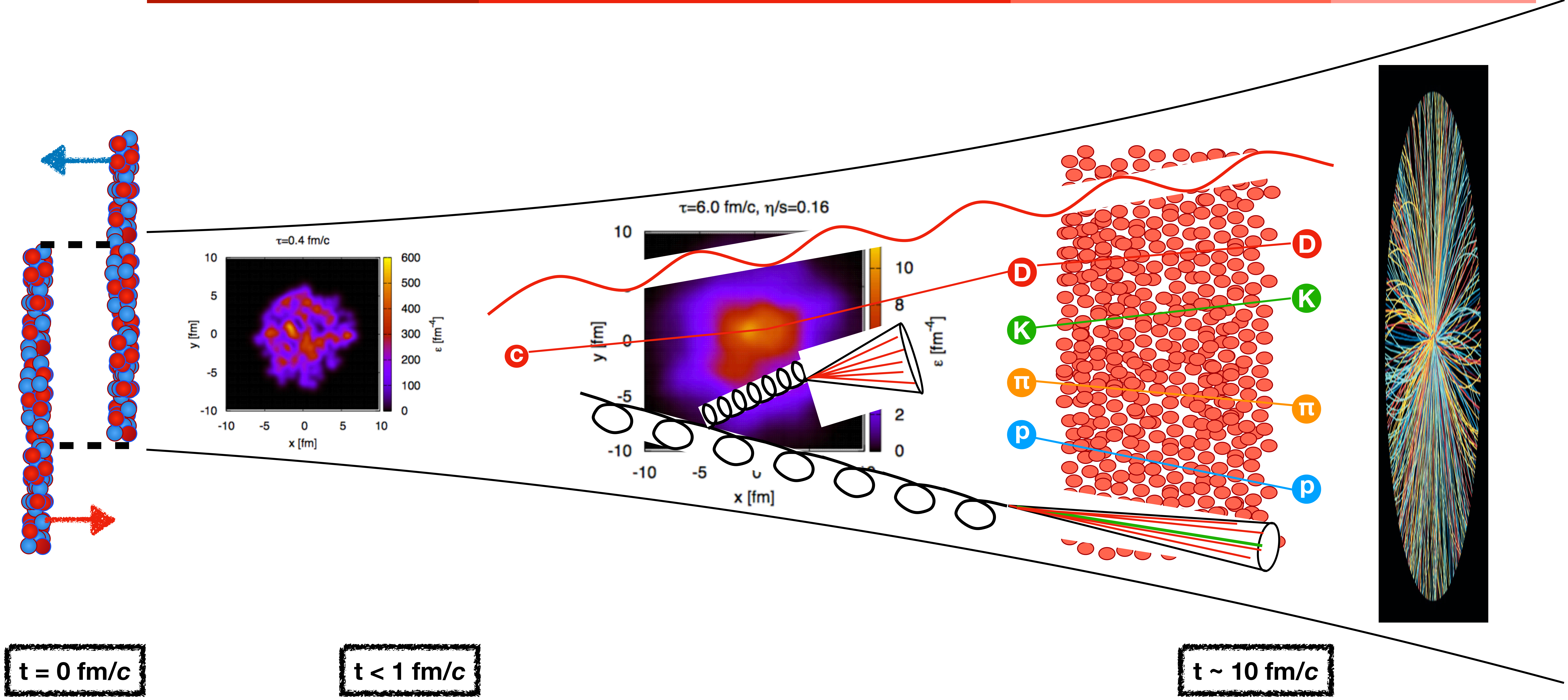


$$\epsilon_P = \frac{\langle T_{xx} - T_{yy} \rangle}{\langle T_{xx} + T_{yy} \rangle}$$



PROBING DIFFERENT STAGES OF THE EVOLUTION

Initial stage	QGP evolution	Hadronic gas	Detector



Pre-equilibrium	Viscous hydrodynamics	Hadronic rescattering	Free streaming

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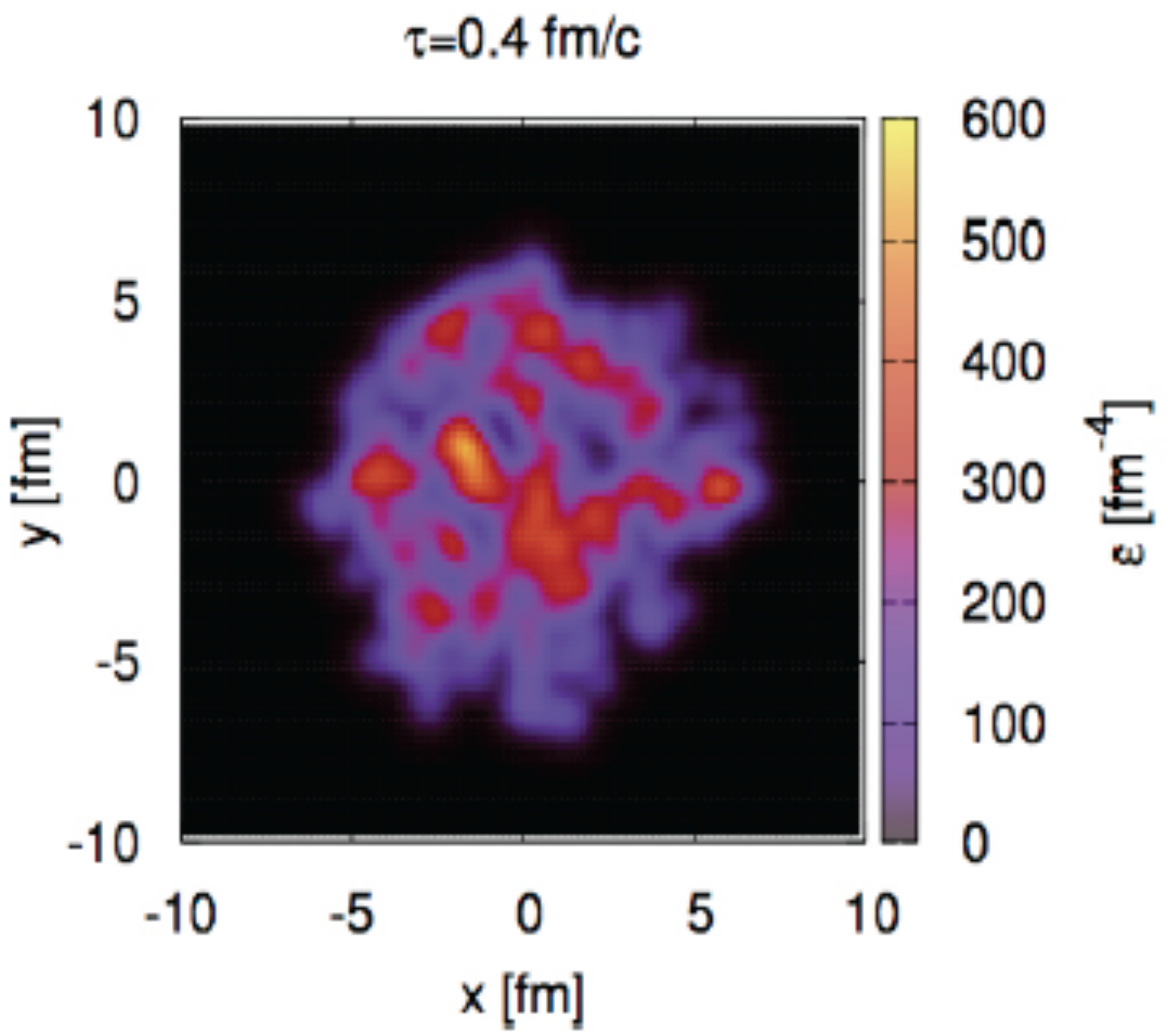
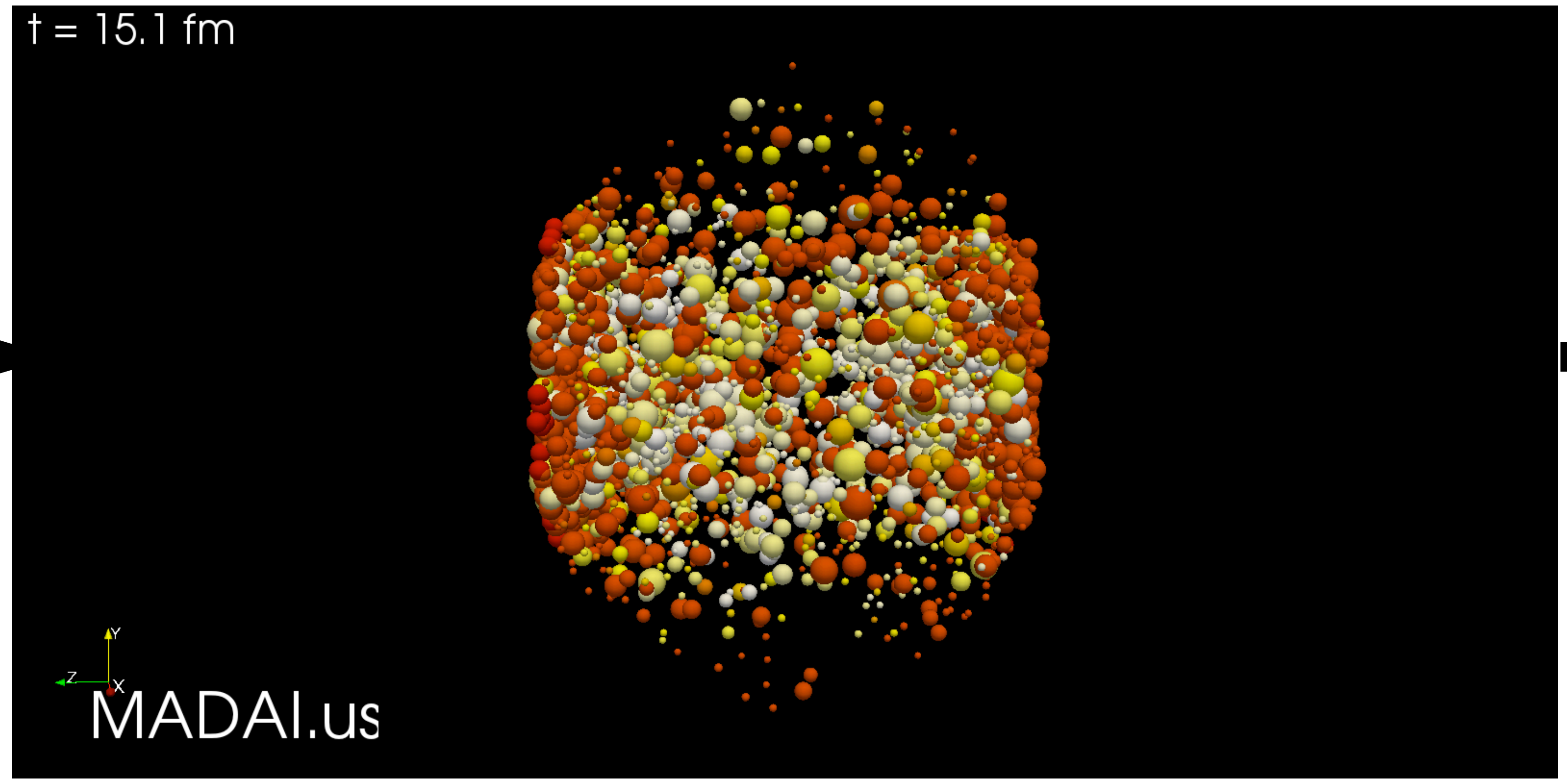
PROBING THE INITIAL STATE

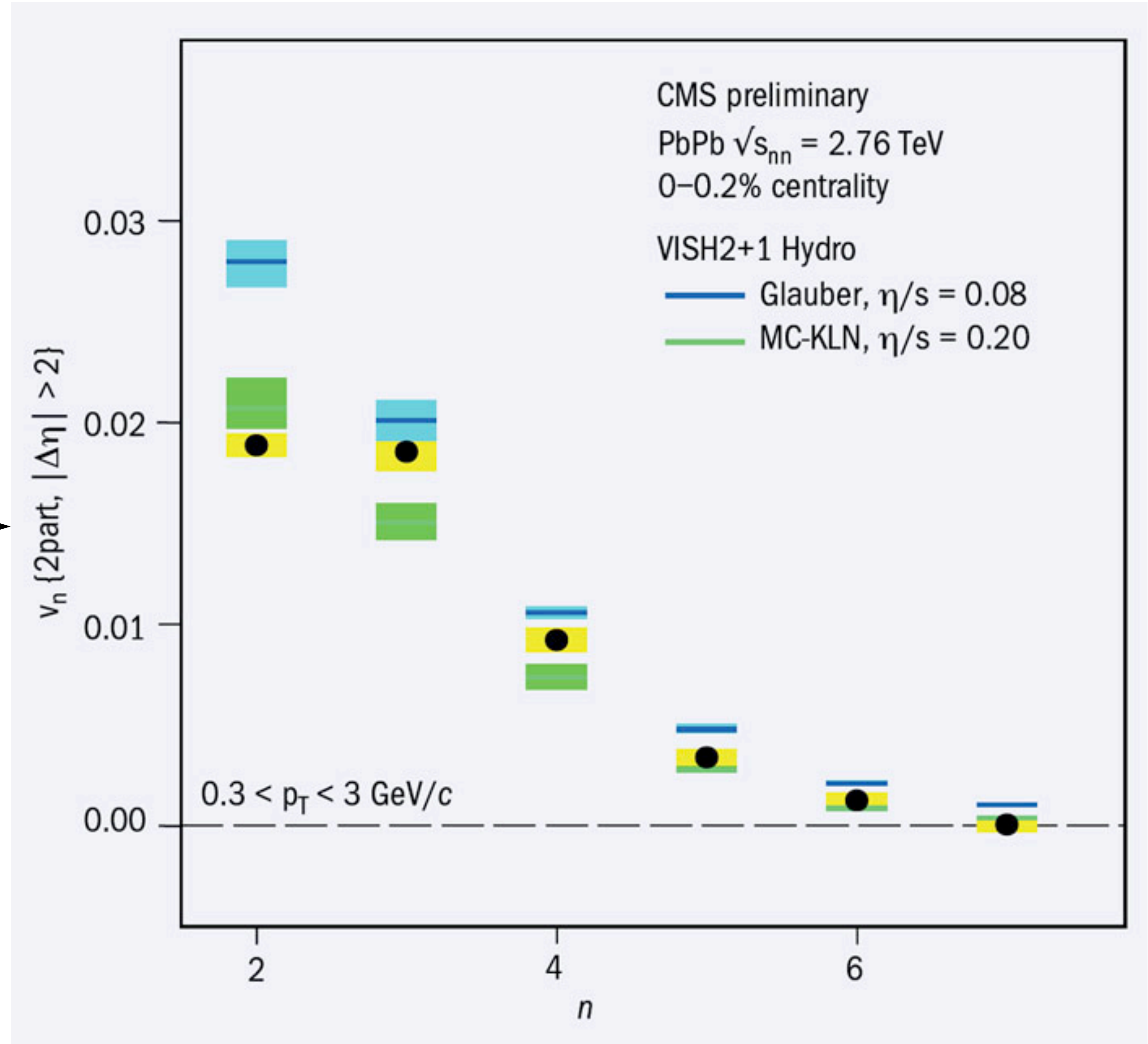
Initial state fluctuations

transferred via the low viscosity QGP

into final state correlations (higher, odd harmonics)





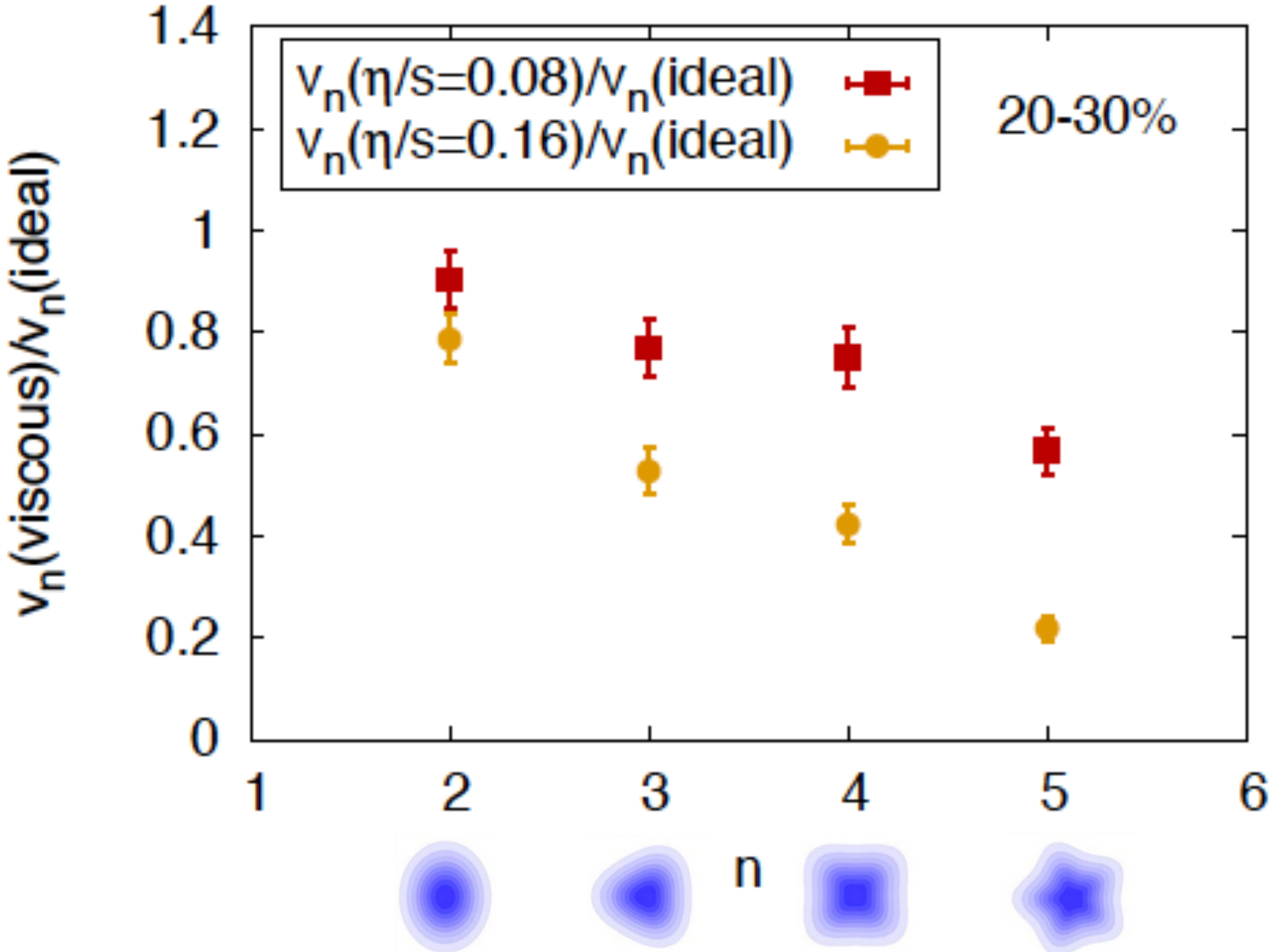


Higher anisotropic flow harmonics represent modulations in smaller spatial scales

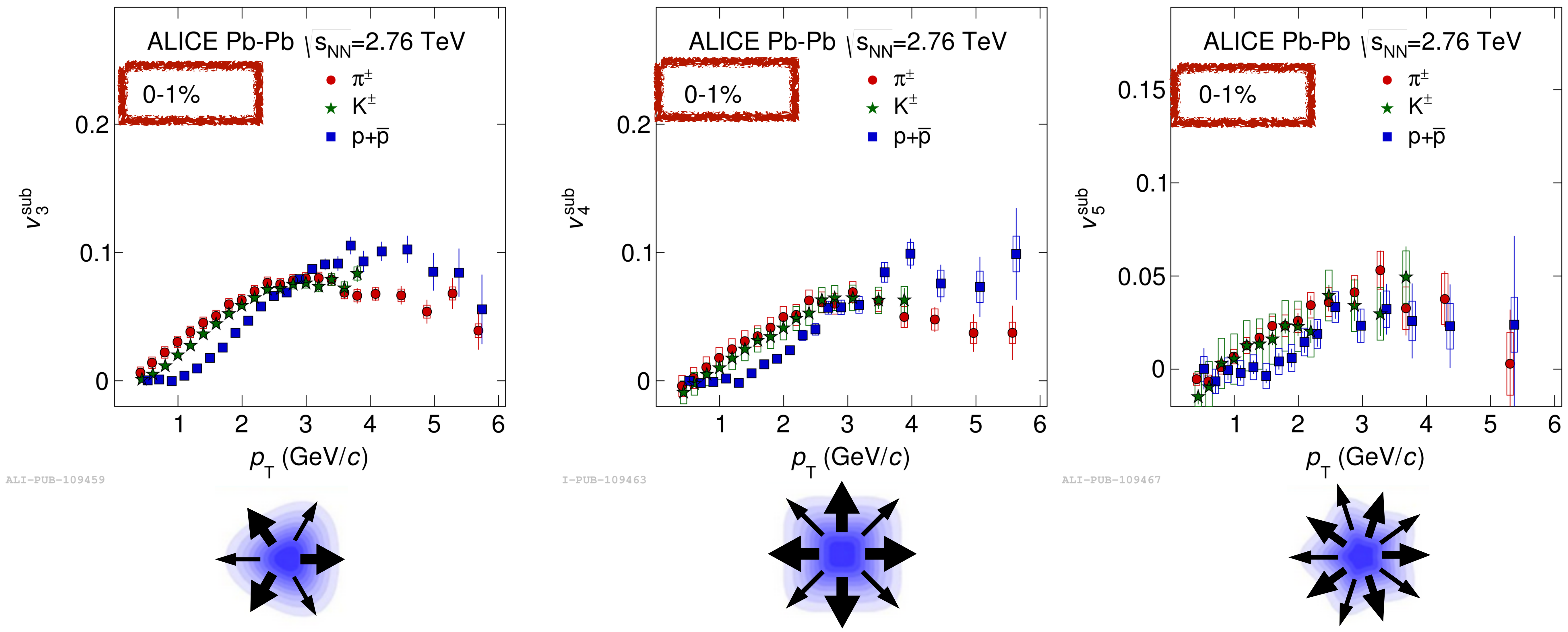
- Unique tool to constrain the IS

PROBING THE QGP TRANSPORT COEFFICIENTS

B. Schenke *et al.*, Phys.Rev. **C85** (2012) 024901



B. Abelev *et al.* (ALICE Collaboration), JHEP **09** (2016) 164

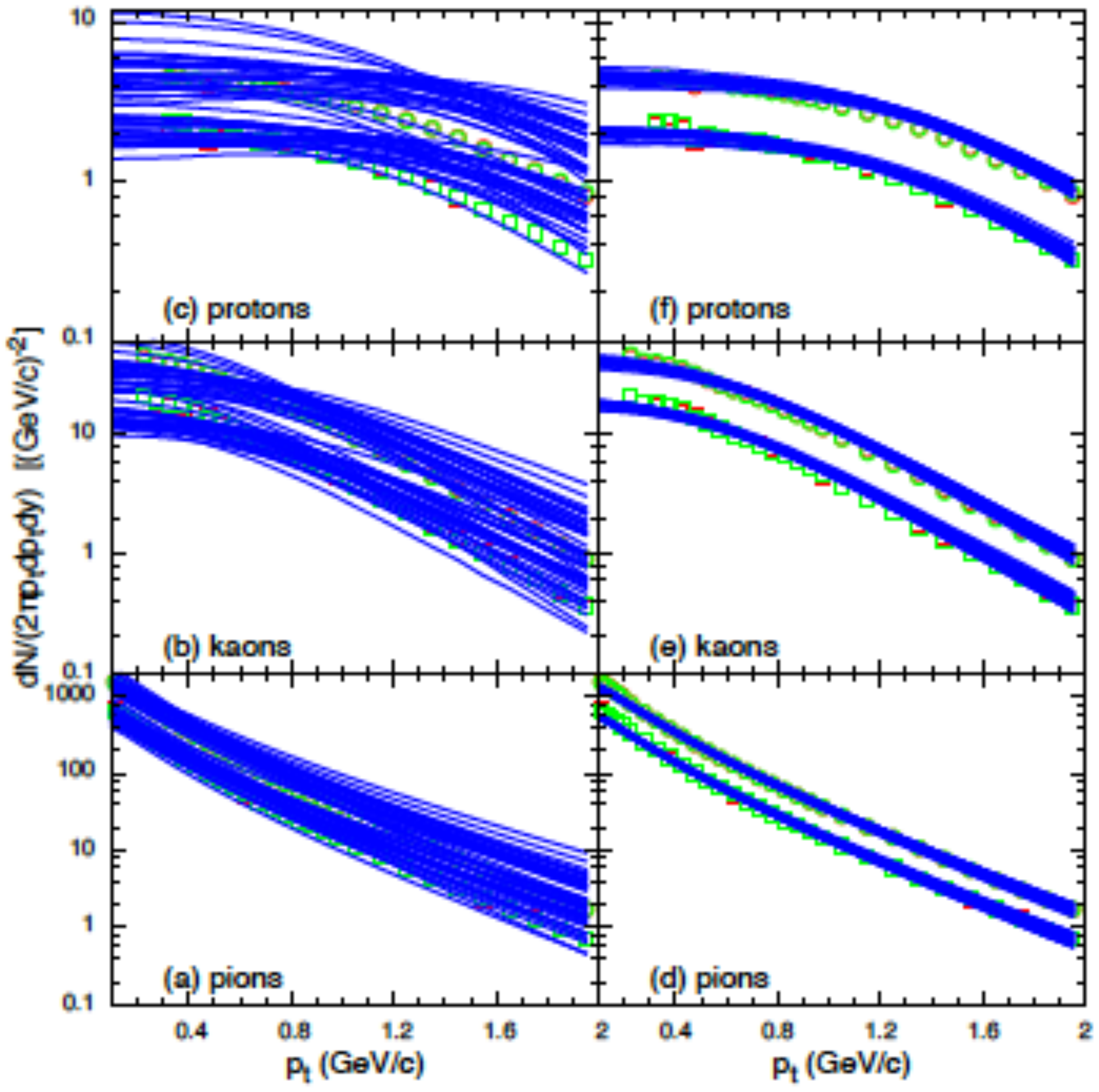


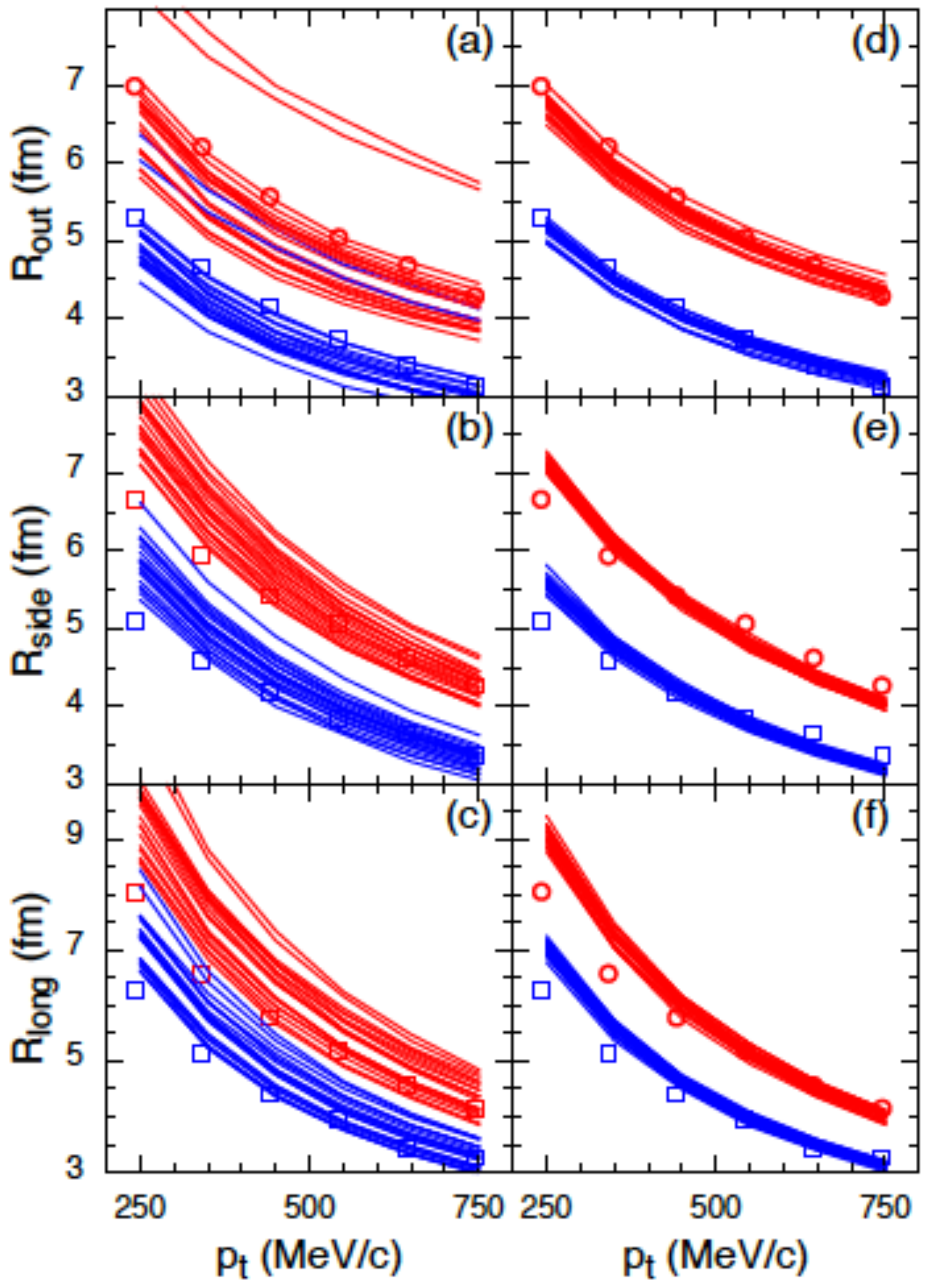
Higher anisotropic flow harmonics represent modulations in smaller spatial scales

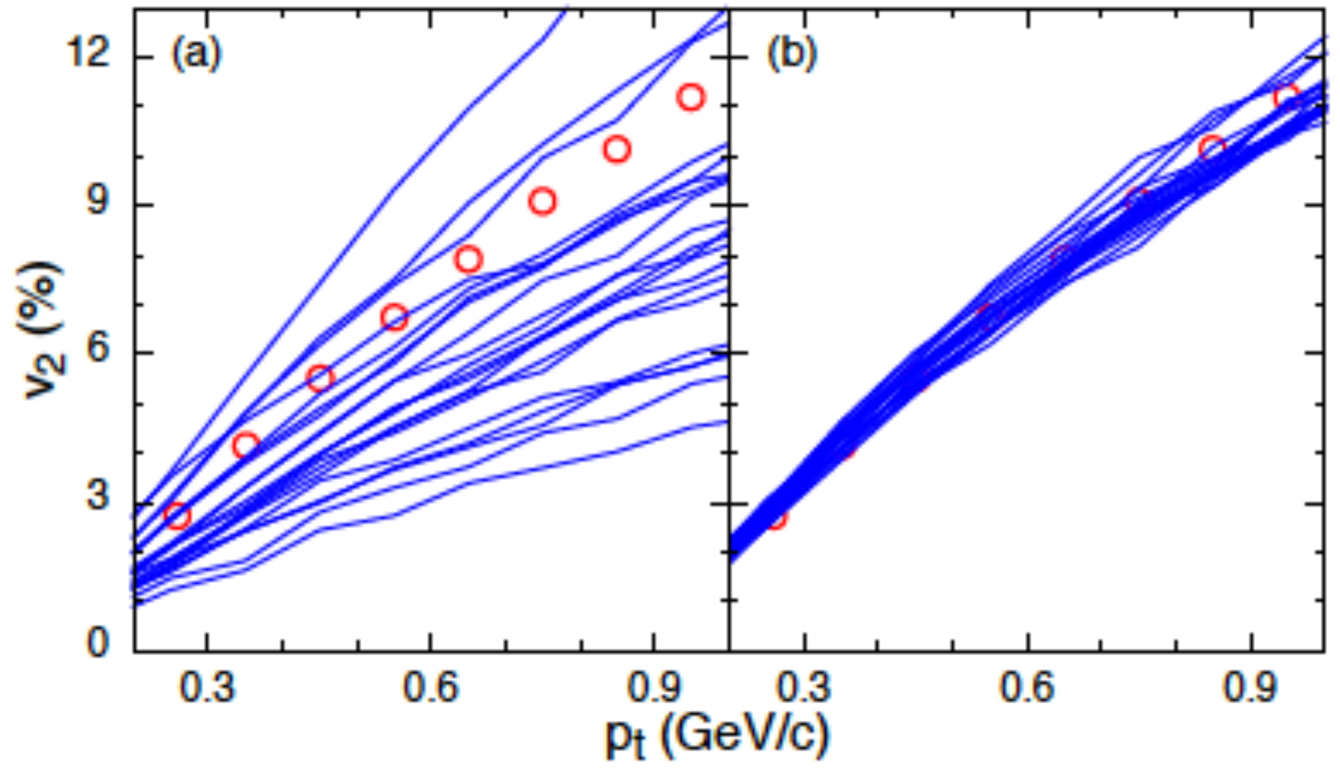
- Unique tool to constrain the IS
- More sensitive probes of the QGP transport properties

EOS CONSTRAINS

S.Pratt *et al.*, Phys. Rev. Lett. **114**, (2015) 202301







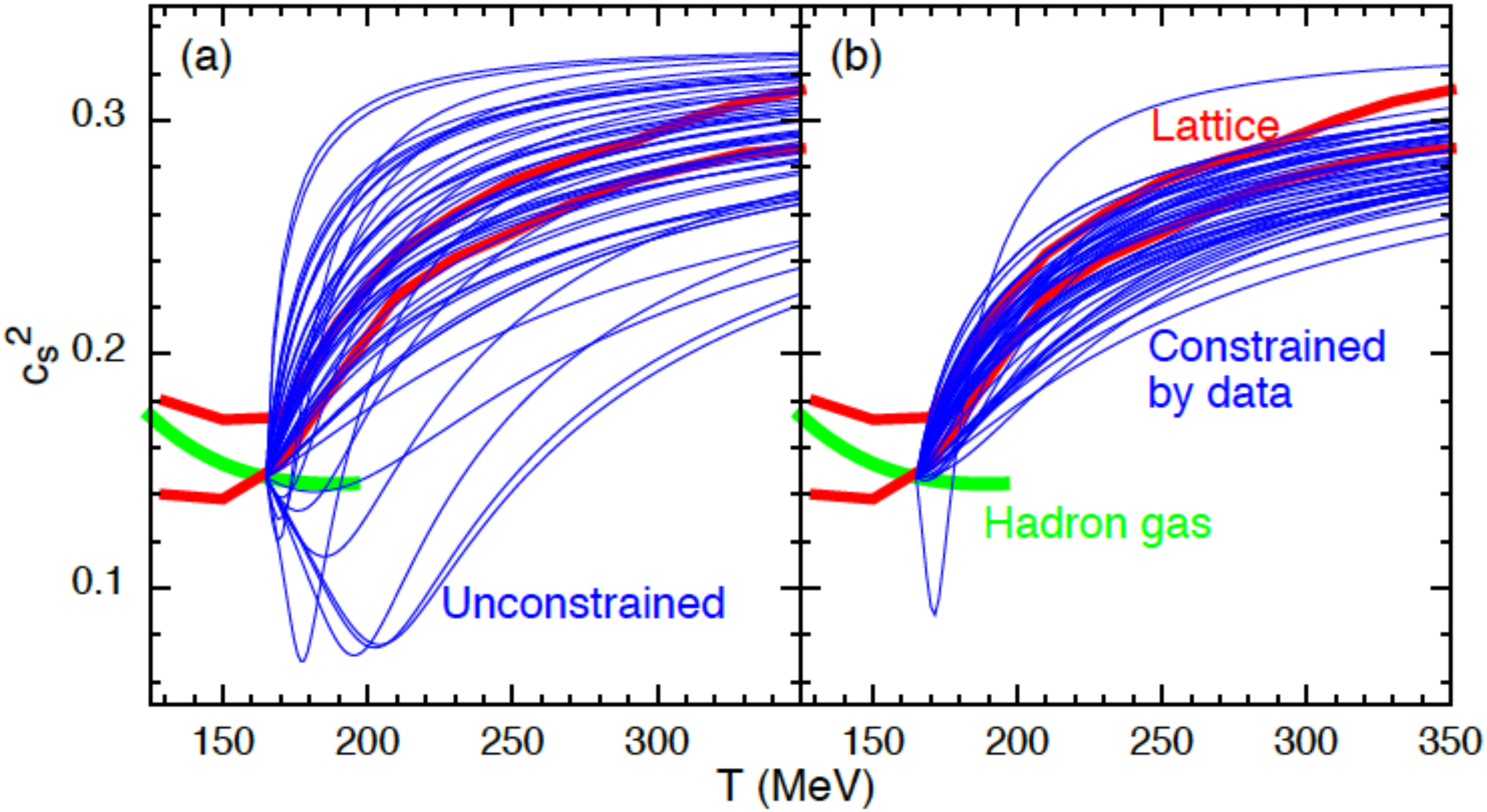
One of the first attempts for a global fit on data

- Spectra
- HBT radii
- $v_2(p_T)$

EOS CONSTRAINS

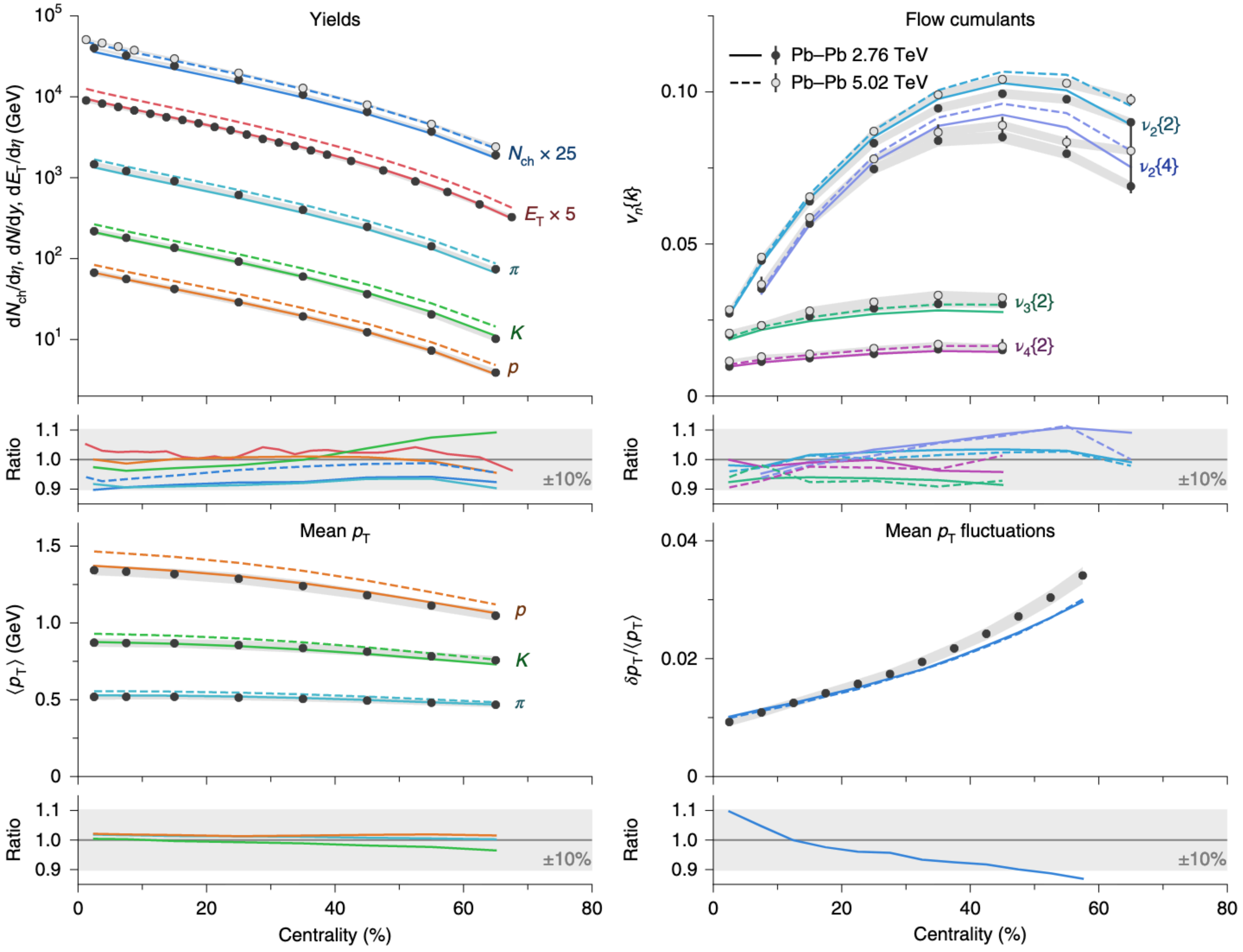
S.Pratt *et al.*, Phys. Rev. Lett. **114**, (2015) 202301

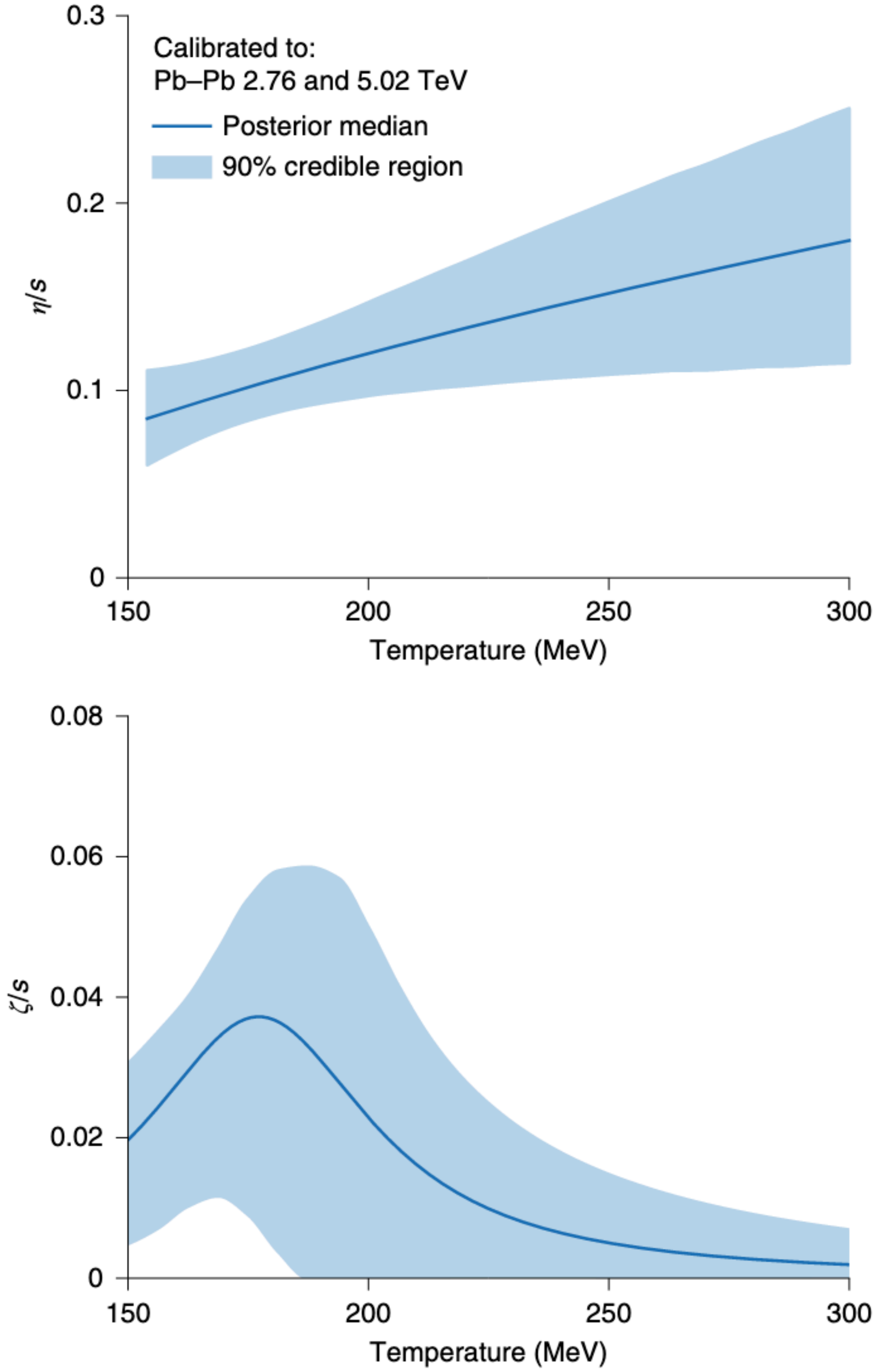
$$c_s^2 = \frac{\partial P}{\partial \epsilon}$$

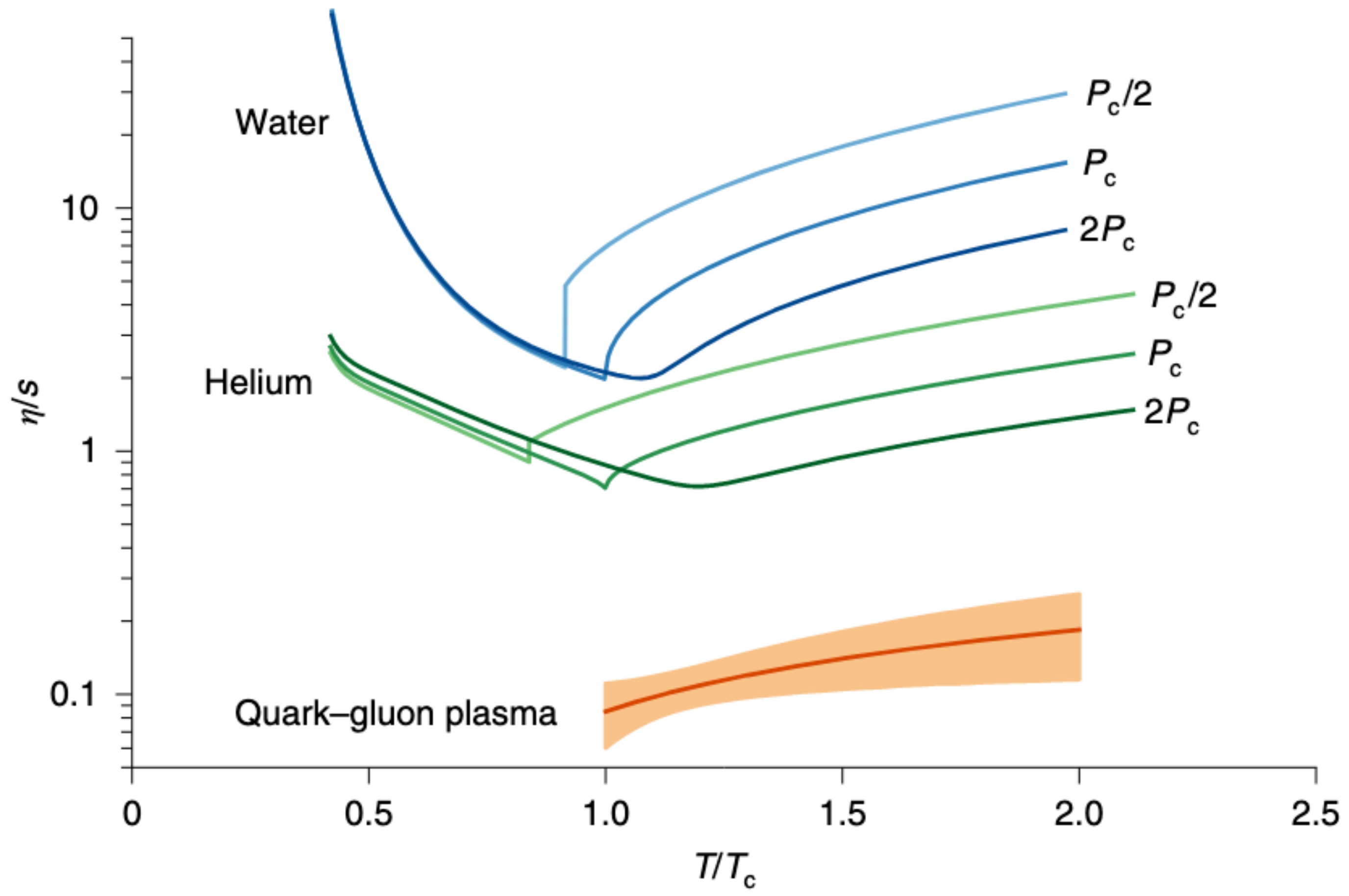


TRANSPORT PROPERTIES CONSTRAINS @ LHC

J. E. Bernhard *et al.*, Nature Phys. 15, 214 (2019)







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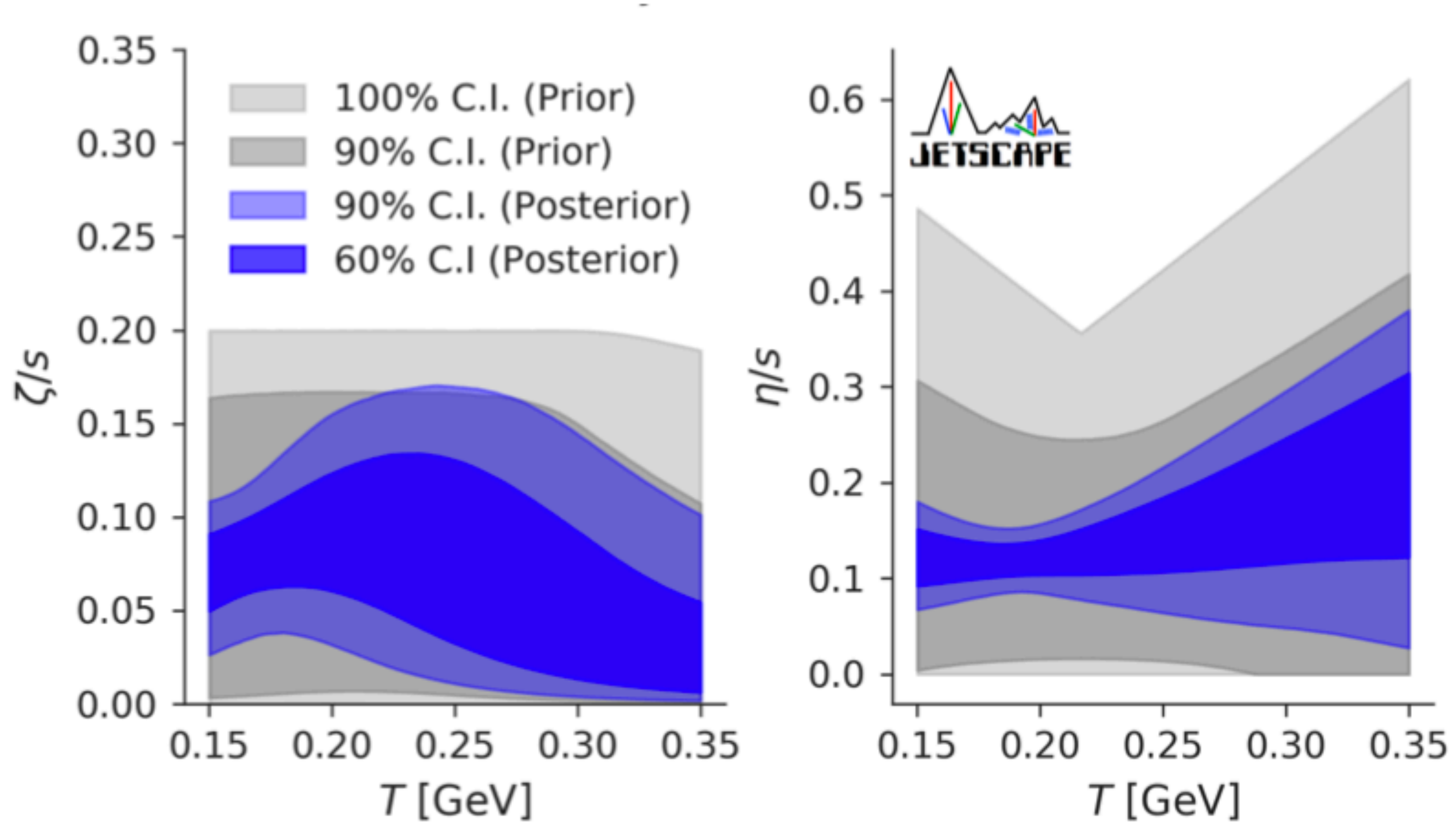
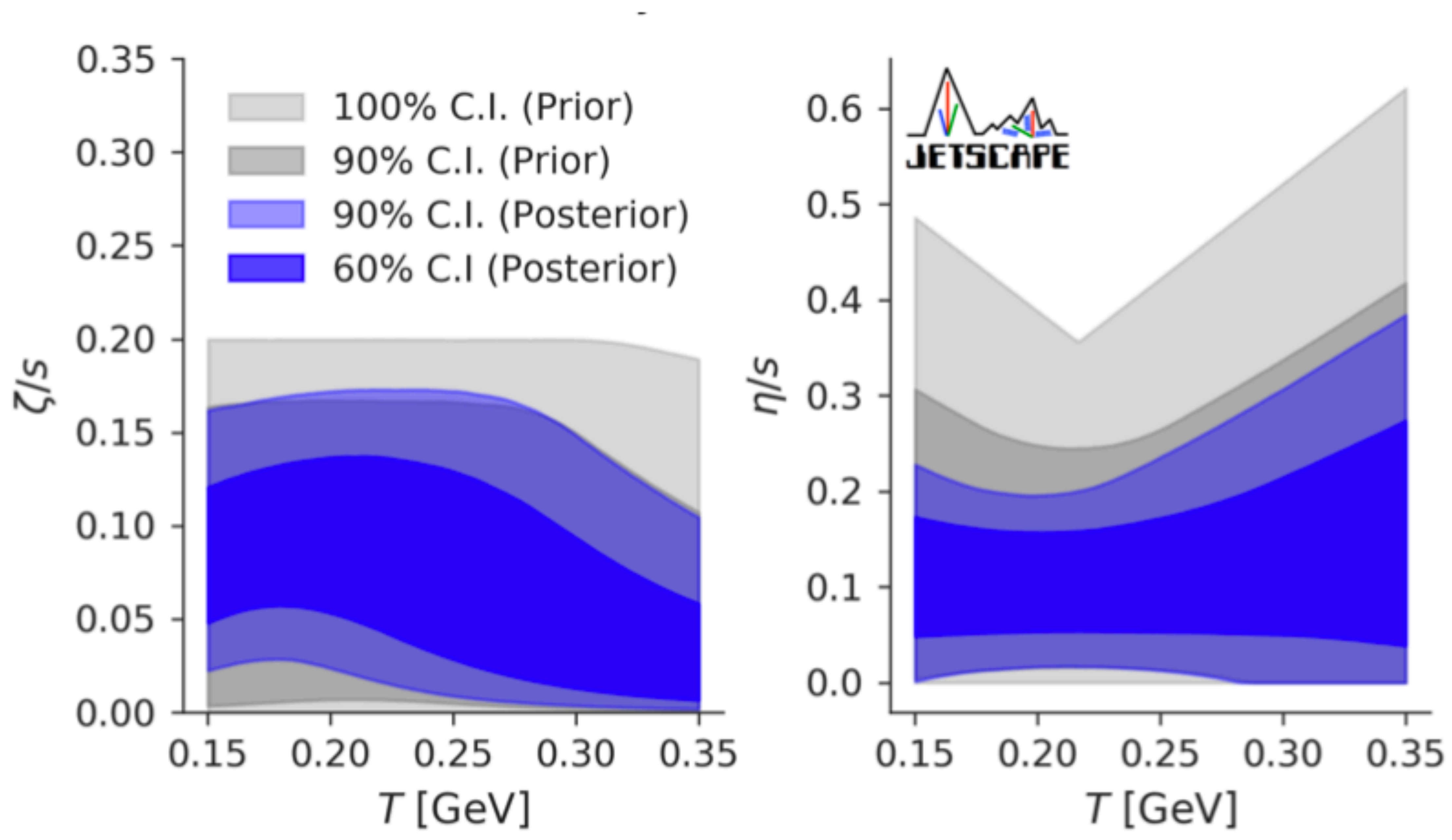
TRANSPORT PROPERTIES CONSTRAINS @ RHIC

(JETSCAPE Collaboration) Phys. Rev. C 103, 054904 (2021)

Posterior from LHC data



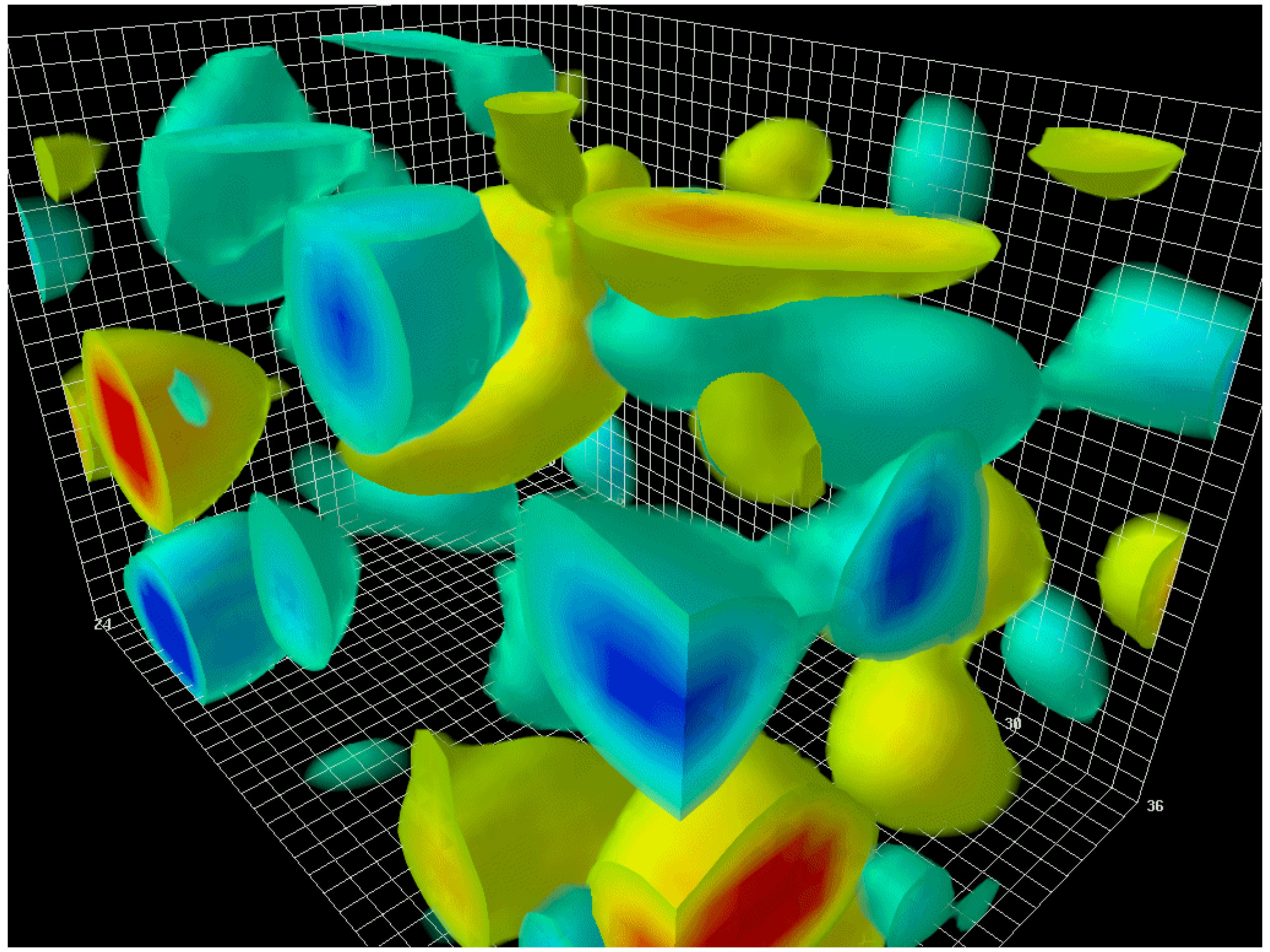
Posterior from RHIC data



Coherent physics description of experimental data at various energies from a single model with a common set of parameters (except the initial energy density)

SEARCH FOR NOVEL QCD PHENOMENA…

Animation @ http://www.physics.adelaide.edu.au/theory/staff/leinweber/VisualQCD/Nobel/



Ingredients

Strong magnetic field

Chirality imbalance

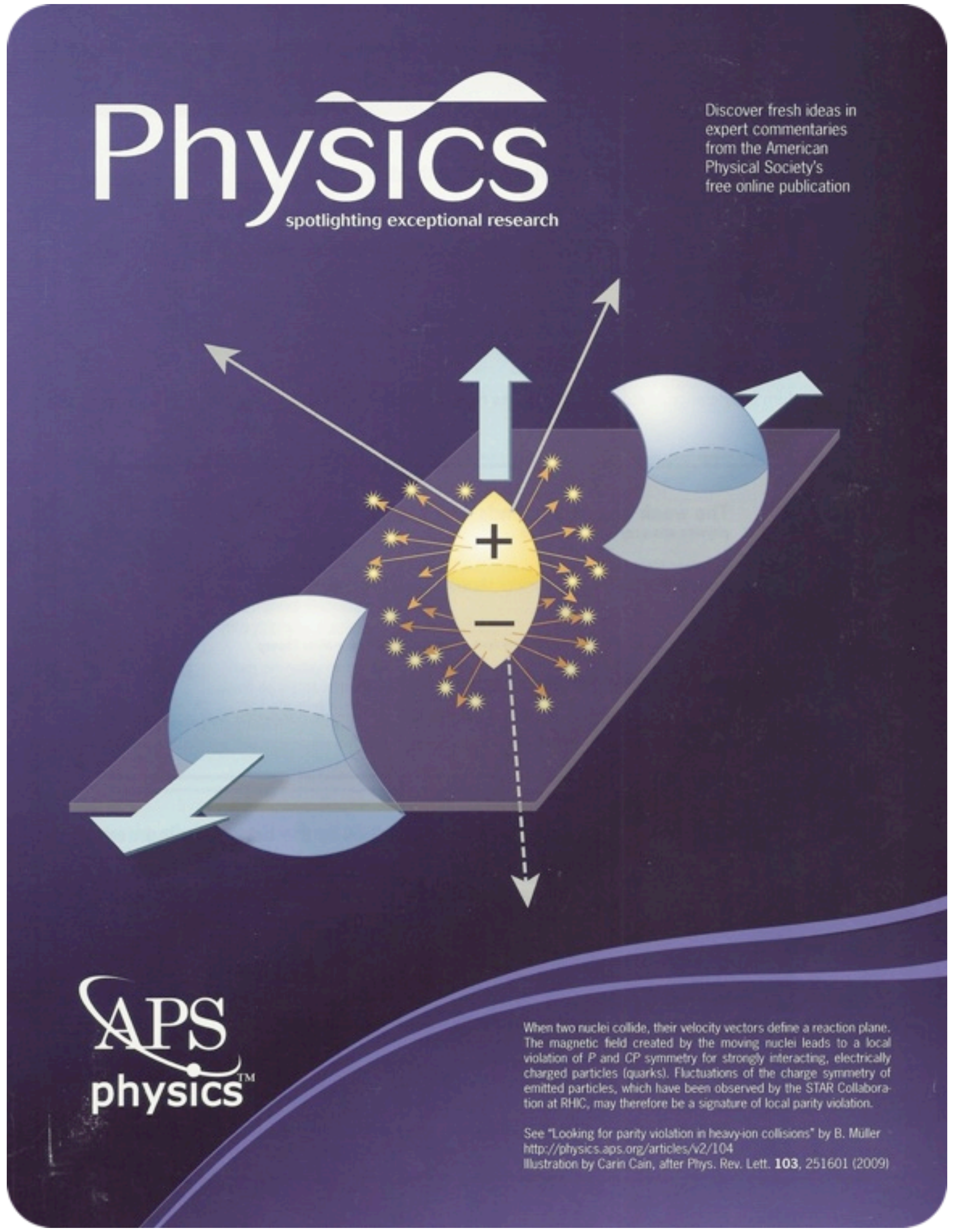
Chiral quarks

Collective flow

Hadronisation

↓

The Chiral Magnetic Effect (CME)



D. Kharzeev *et al.*, Phys. Rev. Lett. **81**, (1998) 512
D. Kharzeev, Prog. Part. Nucl. Phys. **75** (2014) 133

THE STRONGEST MAGNETIC FIELD IN NATURE…

$$\vec{B} = \frac{\mu_0}{4\pi}\int \frac{I d\vec{l} \times \hat{r}}{|\vec{r}|^2}$$

$$B \approx \gamma Z e \frac{b}{R^3}$$

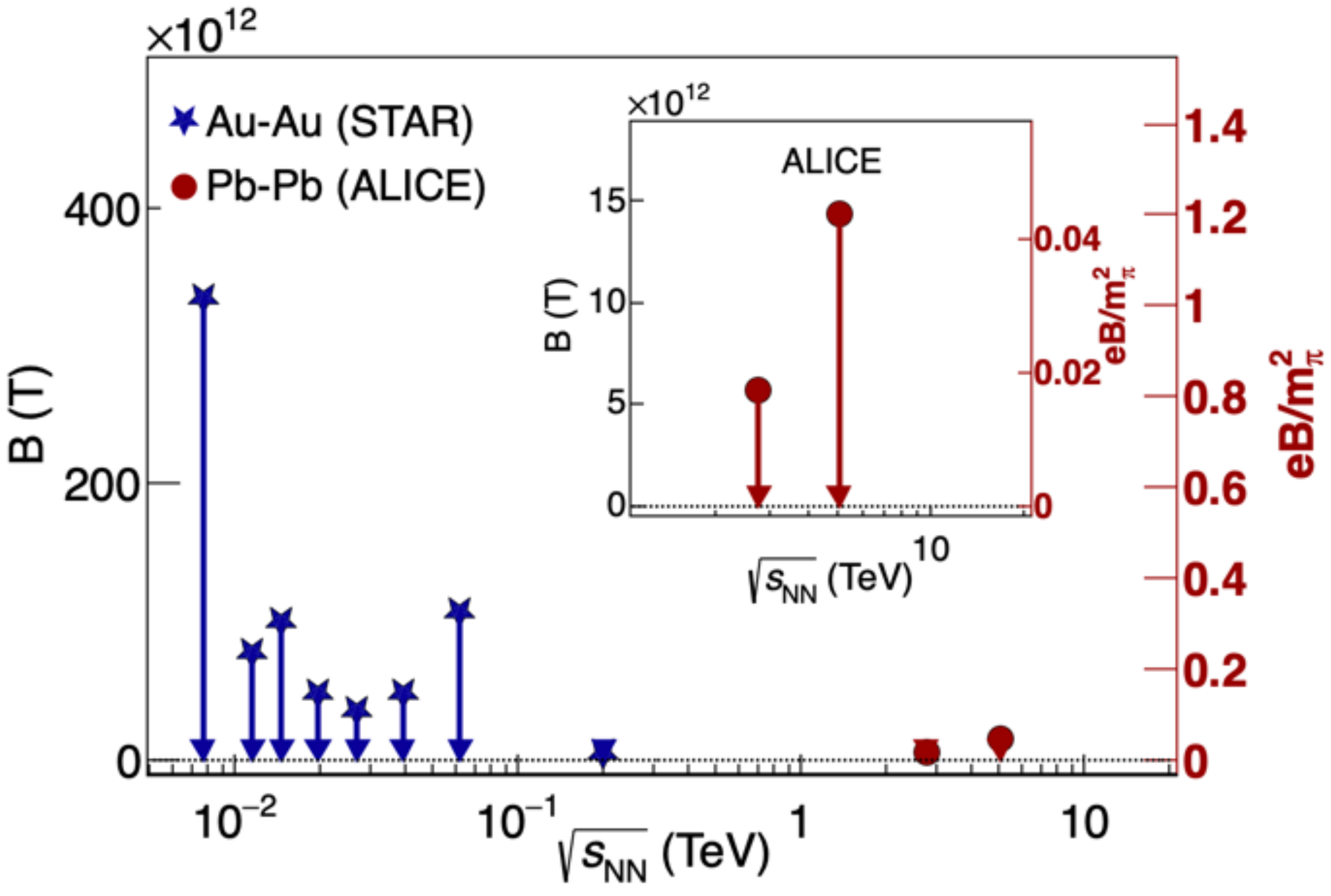
$$\gamma = \frac{\sqrt{s_{\mathrm{NN}}}}{2m_{\mathrm{p}}}$$

Au-Au collisions @ RHIC	Pb-Pb collisions @ LHC
$\sqrt{s_{NN}}$ = 200 GeV	$\sqrt{s_{NN}}$ = 2.76 GeV
γ = 100	γ = 1.38x10^3
Z = 79	Z = 82
b = R_{Au} ~ 7fm	b = R_{Au} ~ 7fm
eB ~ m_π^2	eB ~ $10m_\pi^2$

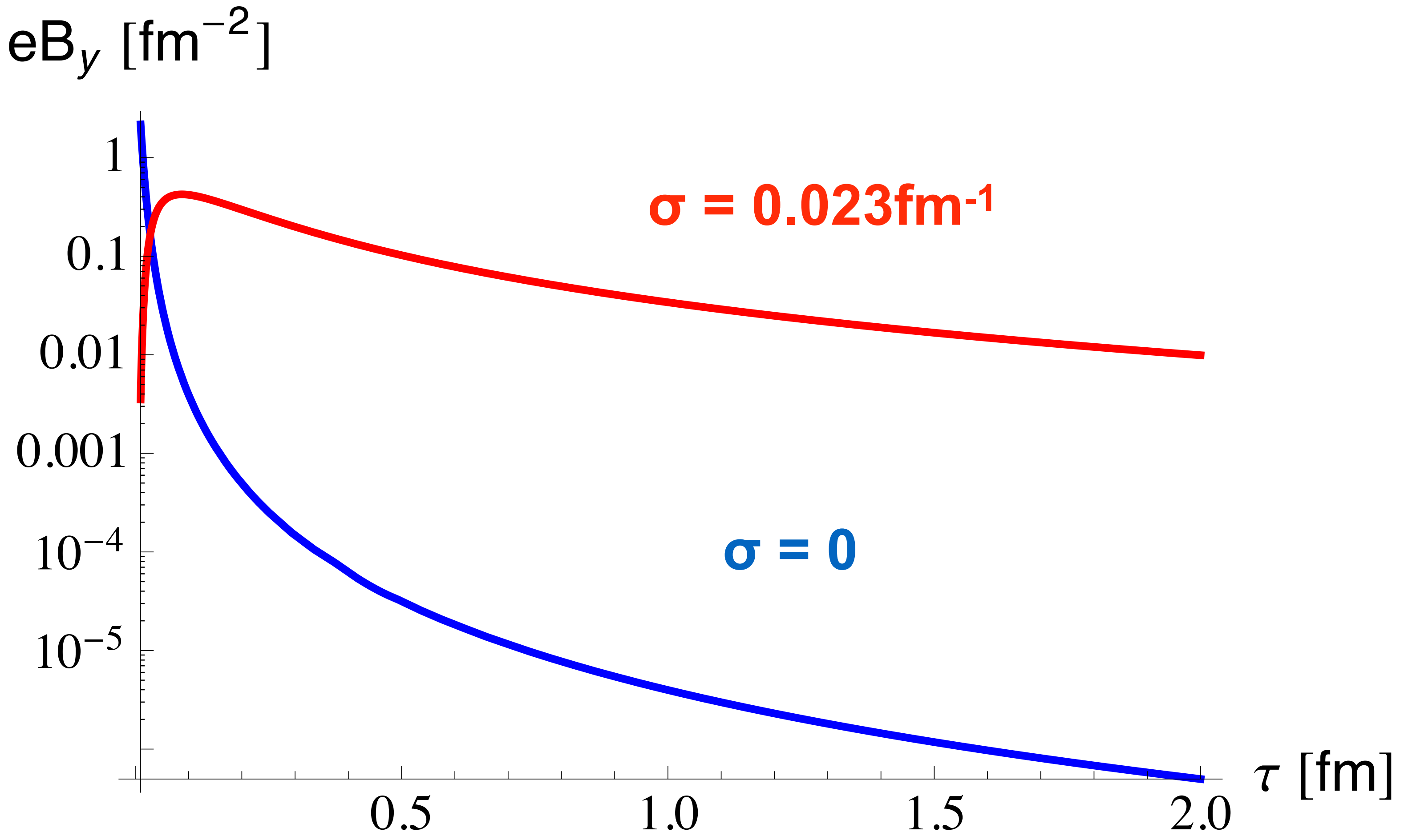
Heavy ion collisions: ~10^{19}-10^{20} G

U. Gürsoy *et al.*, Phys. Rev. **C89**, (2014) 054905

Limits for B @ freeze-out

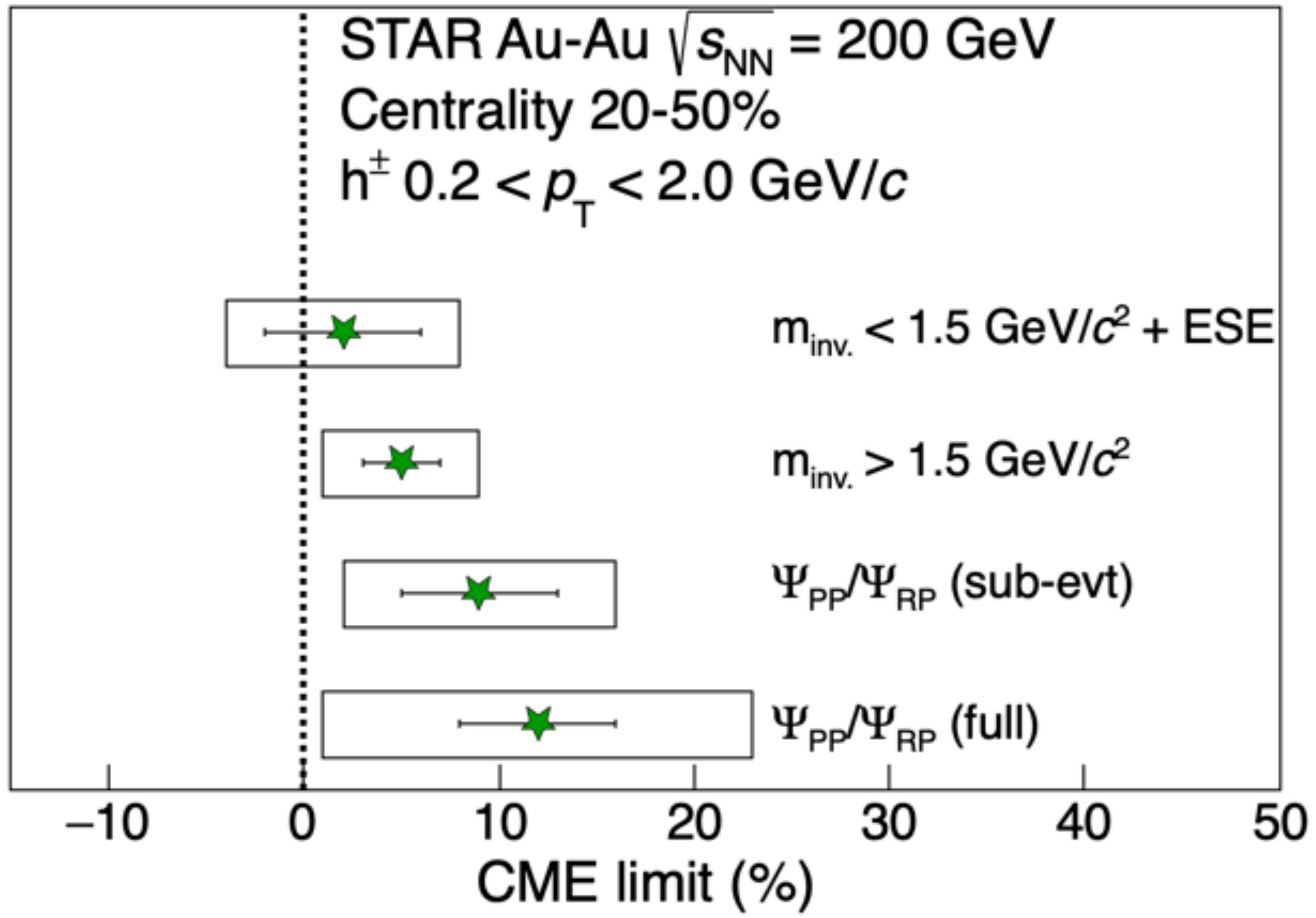


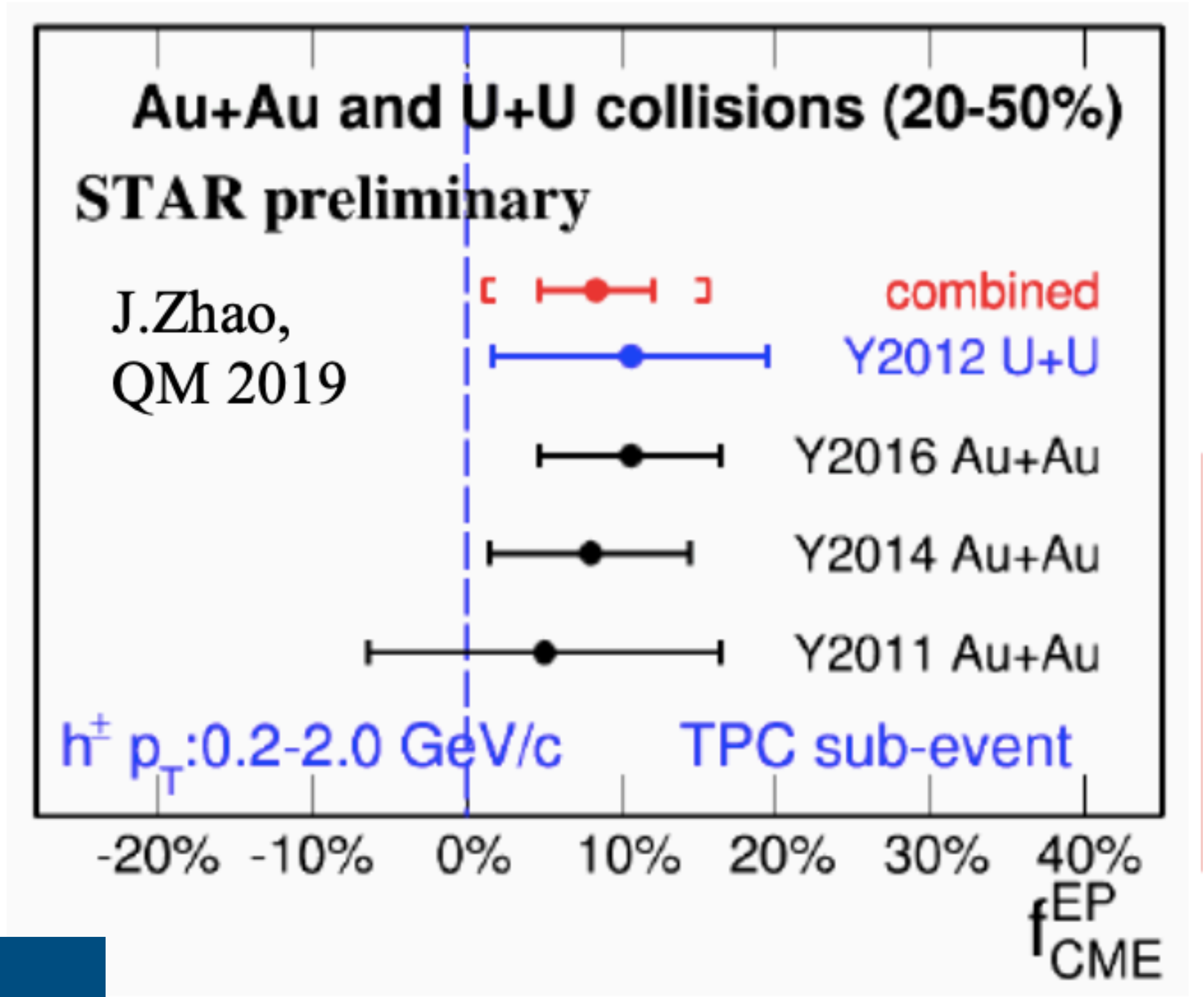
Magnetar's field: 10^{12} -10^{15} G



Decay rate depends on the electric conductivity of the medium → poorly constrained experimentally

CME FRACTION UPPER LIMITS



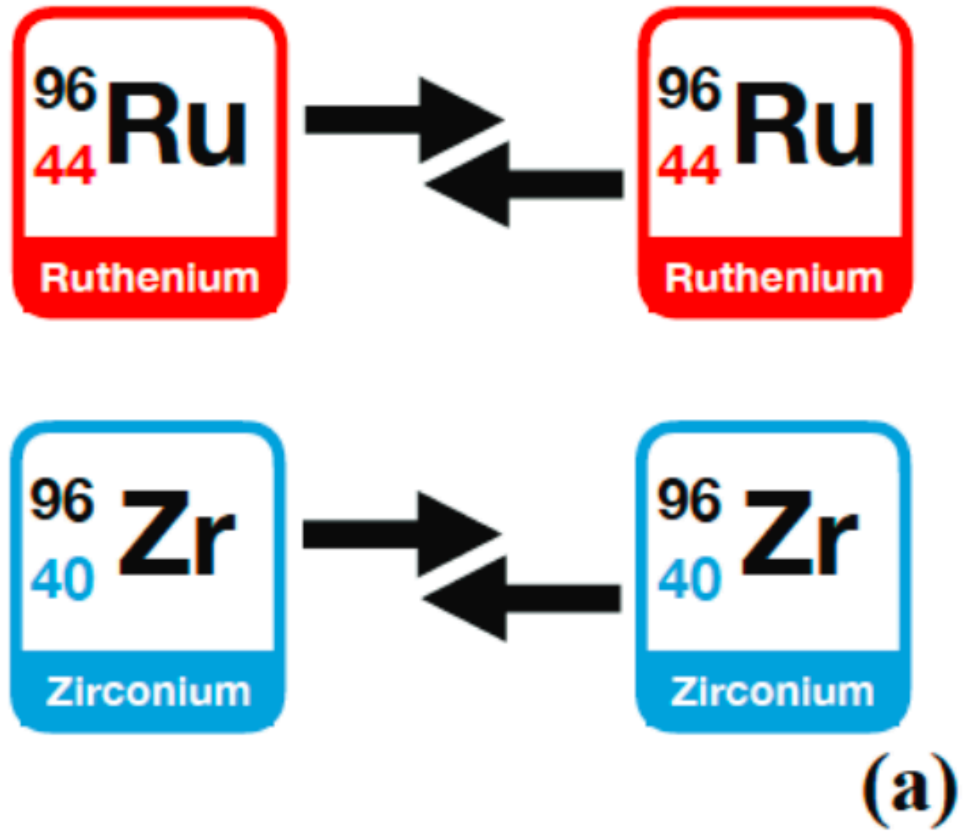


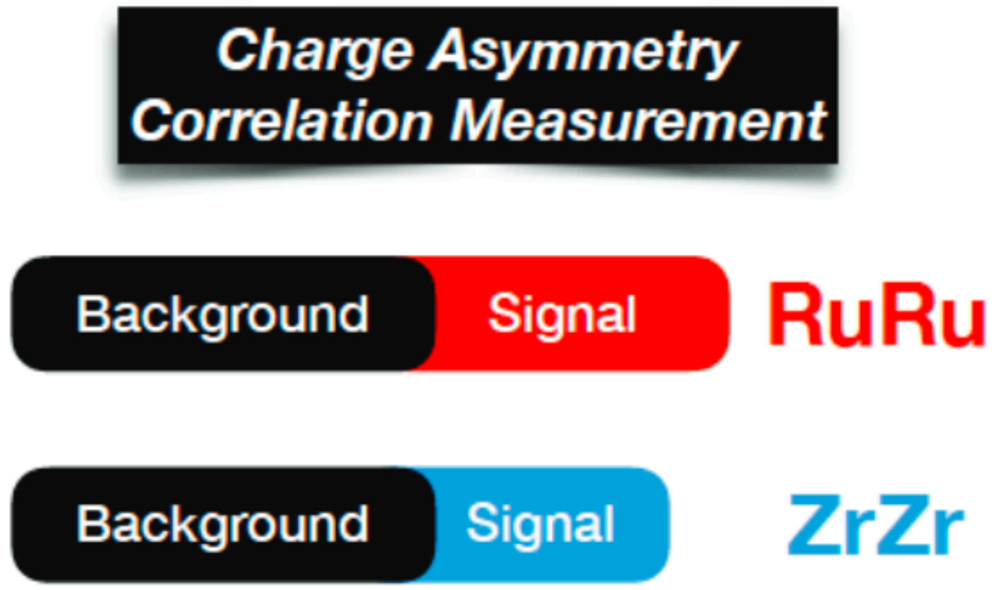
Summary of upper limits @ LHC (95% CL)		
ALICE	ESE in Pb-Pb collisions	26-33%
	Higher harmonics in Pb-Pb collisions	11-15%
CMS	p-Pb collisions	13%**
	ESE in Pb-Pb collisions	7%*

(ALICE Collaboration) Phys. Lett. **B777**, (2018) 151
(CMS Collaboration) Phys.Rev.C 97 (2018) 4, 044912
(ALICE Collaboration) JHEP 2020, (2020) 160

Current analyses provide stringent upper limits for the CME fraction at both RHIC and LHC energies → CME signal, if any, at the level of few %

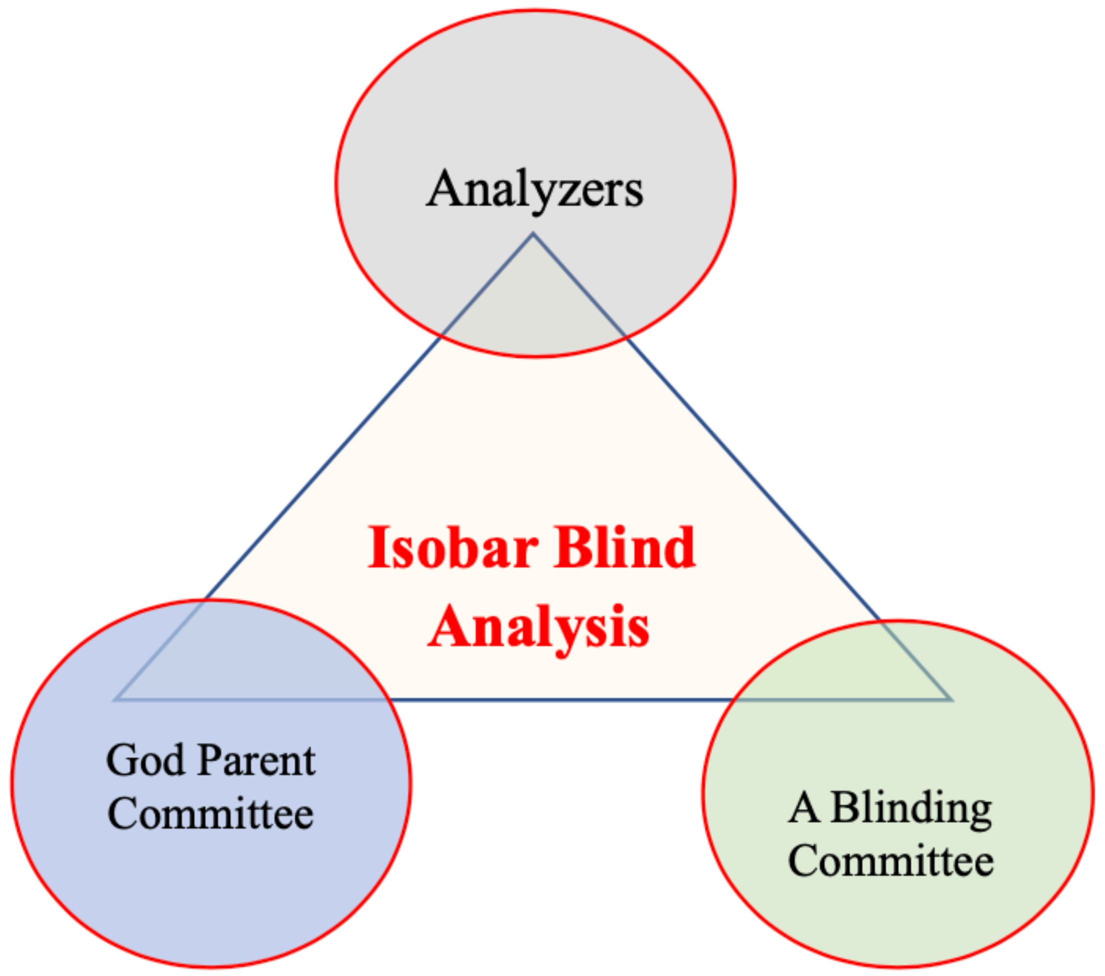
FUTURE PROSPECTS: ISOBAR ANALYSIS





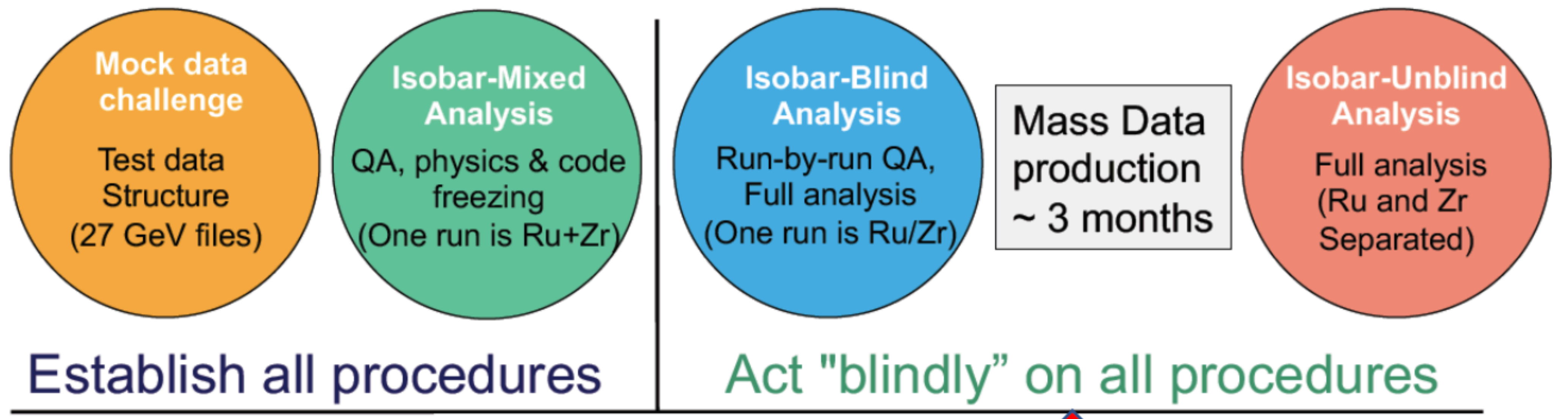
❖ Isobar Analysis:

A large, collective effort



P. Tribedy WWND 2020

A. Tang PAC meeting, Sept 2020



STAR, arXiv:1911.00596 (2019)

We are here

5-Isobar Blind Analyses

- $\Delta\gamma, \Delta\delta$ and κ
- $\Delta\gamma, \Delta\delta$ and $\Delta\gamma(\Delta\eta)$
- $\Delta\gamma$ in PP/SP and $\Delta\gamma(M_{inv})$
- $\Delta\gamma$ in PP/SP
- $R(\Delta S)$ Correlator.

1-Isobar Unblinded Analysis

- The signed balance function

Case for CME:

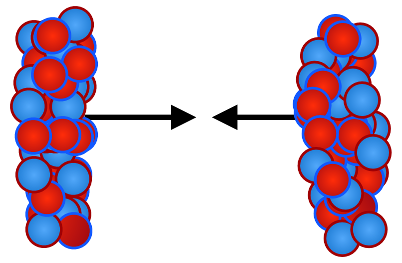
- $\Delta\gamma$ and its derivatives
  $\Delta\gamma/v_2$(Ru/Zr) > 1
  $\Delta\gamma_{112}/v_2$(Ru/Zr) $> \Delta\gamma_{123}/v_3$(Ru/Zr)
  κ(Ru/Zr) > 1
  $\Delta\gamma^{Ru} - a'r'\Delta\gamma^{Zr} > 0$
- $R(\Delta S)$ (Ru/Zr) show concave shape
- $f_{CME}^{Ru} > f_{CME}^{Zr} > 0$

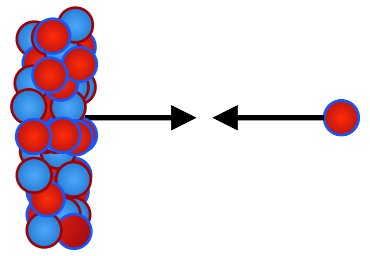
Slide "stolen" from talk of Niseem Magdy Abdelrahman @ RHIC & AGS Annual User's meeting

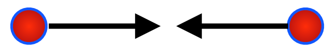
BNL, CCNU, Fudan, Huzhou, Purdue, SINAP, Stony Brook, Tsukuba, UCLA, UIC and Wayne State

19

FROM LARGE TO SMALL SYSTEMS

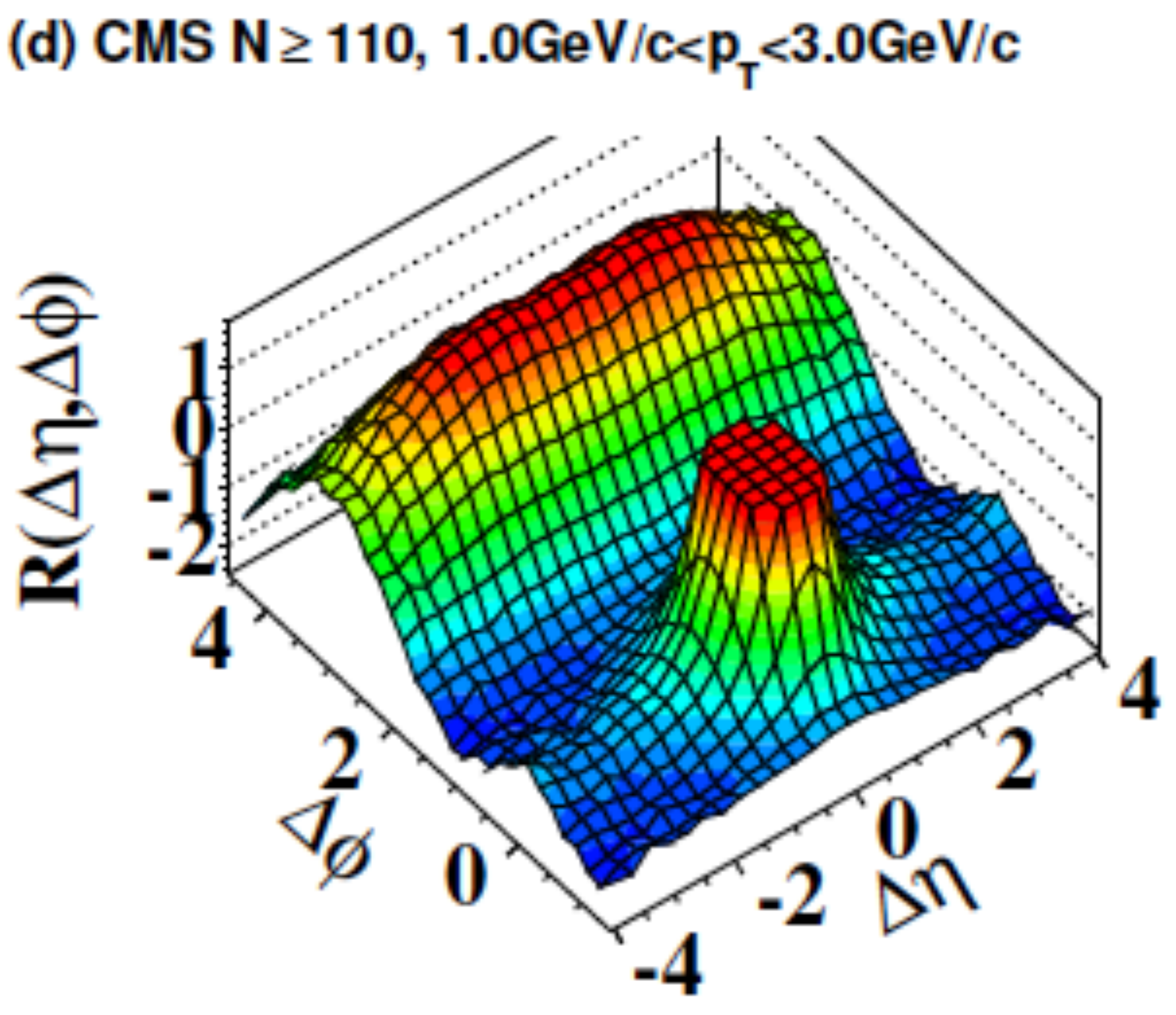






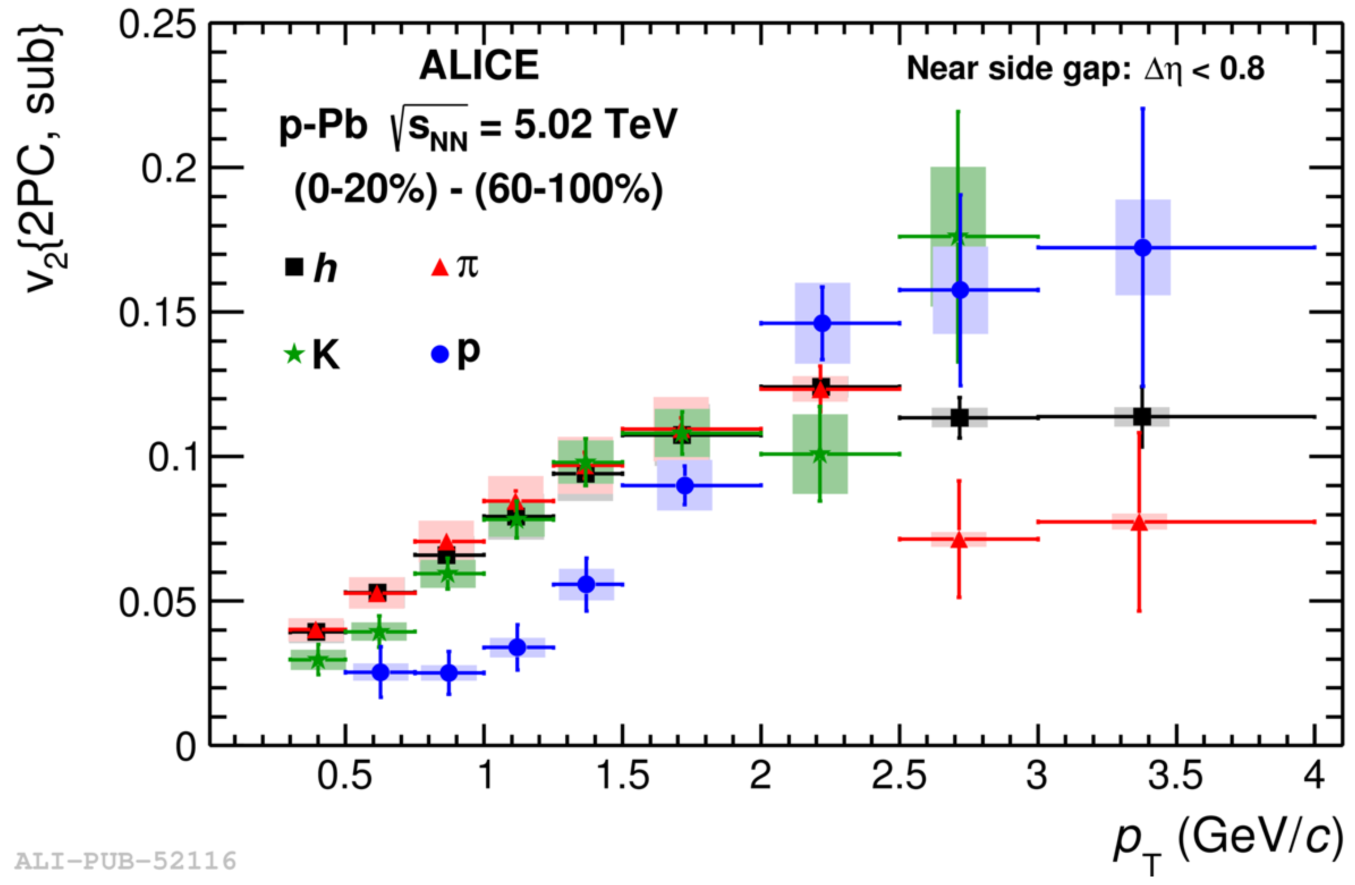
COLLECTIVITY IN SMALL COLLISION SYSTEMS

Ridges in pp collisions → pp collisions stopped being just a reference for the heavy-ion physics programs

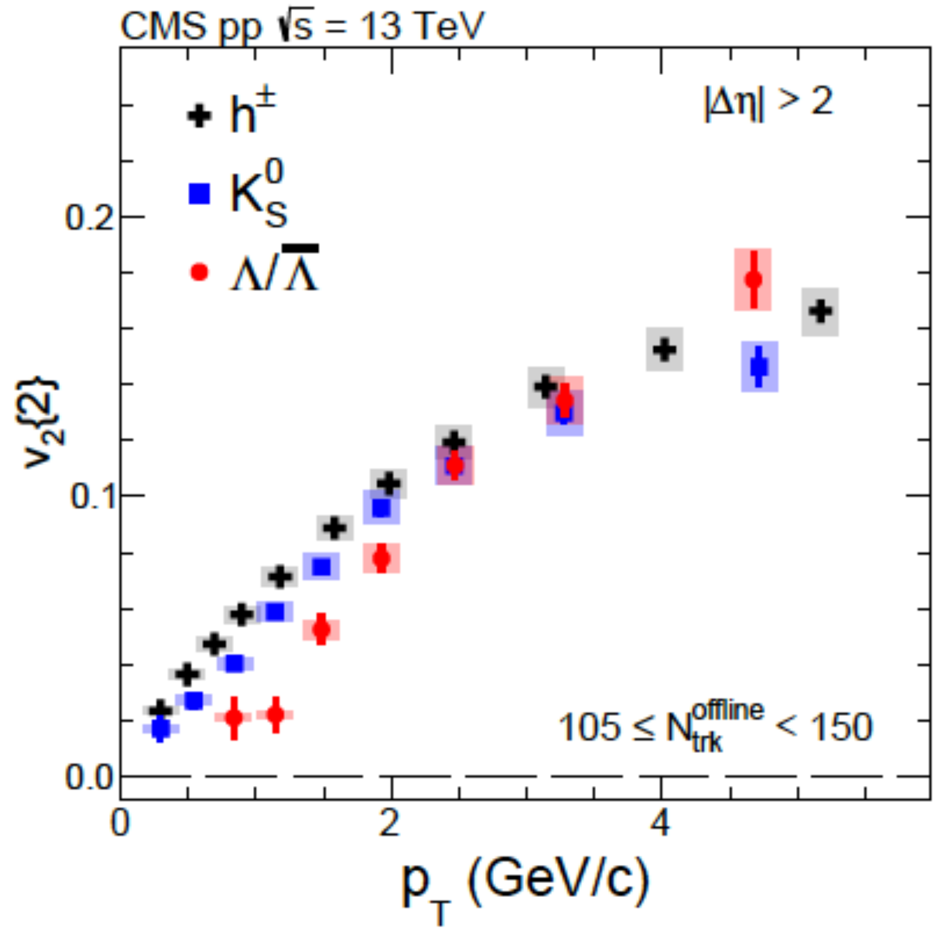


High event activity pp collisions @ √s = 7 TeV

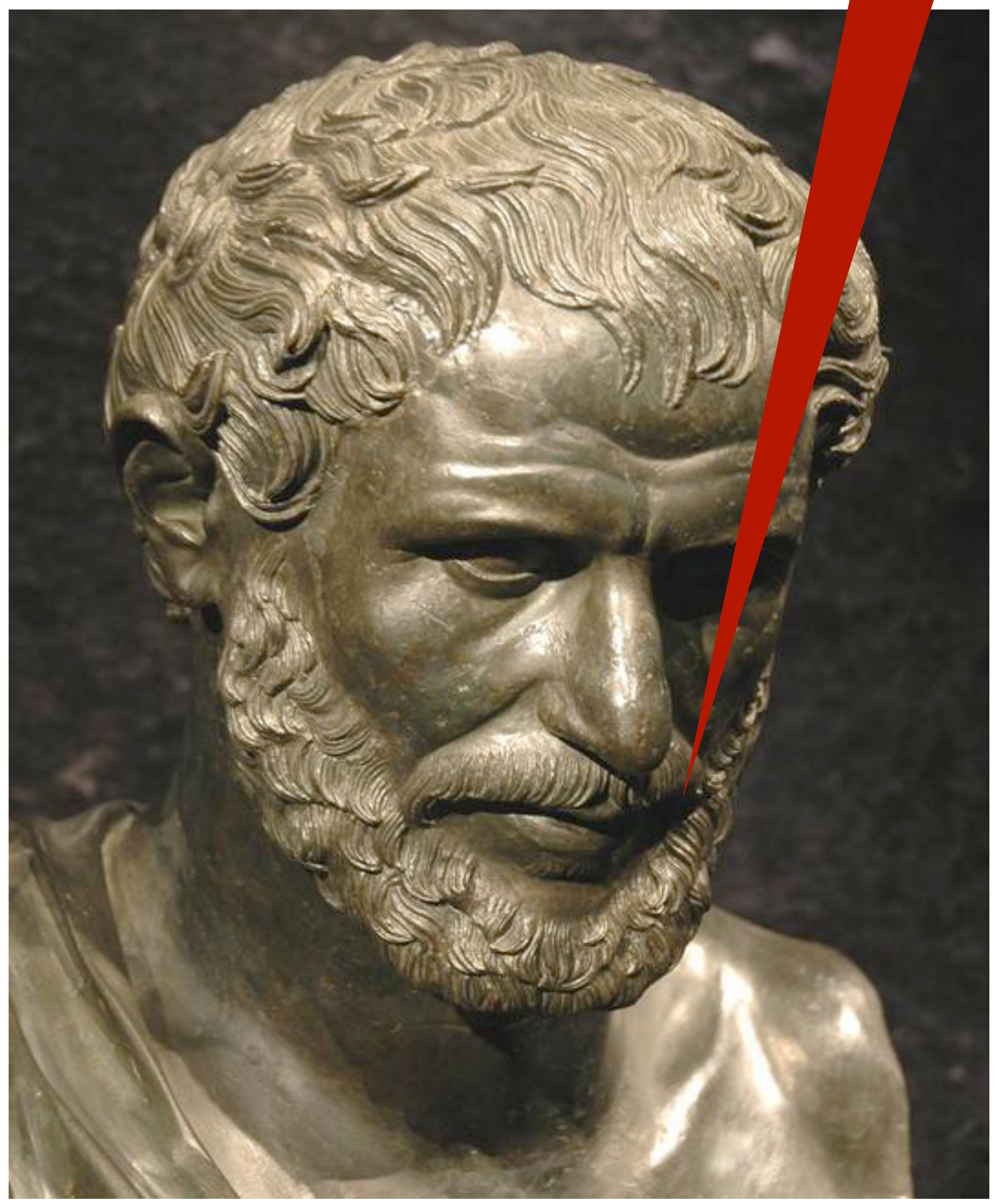
ALICE Collaboration, Phys. Lett. **B726**, (2013) 164



(CMS Collaboration) Phys. Lett. B 765 (2017) 193



Τα πάντα ρει…
(everything flows)



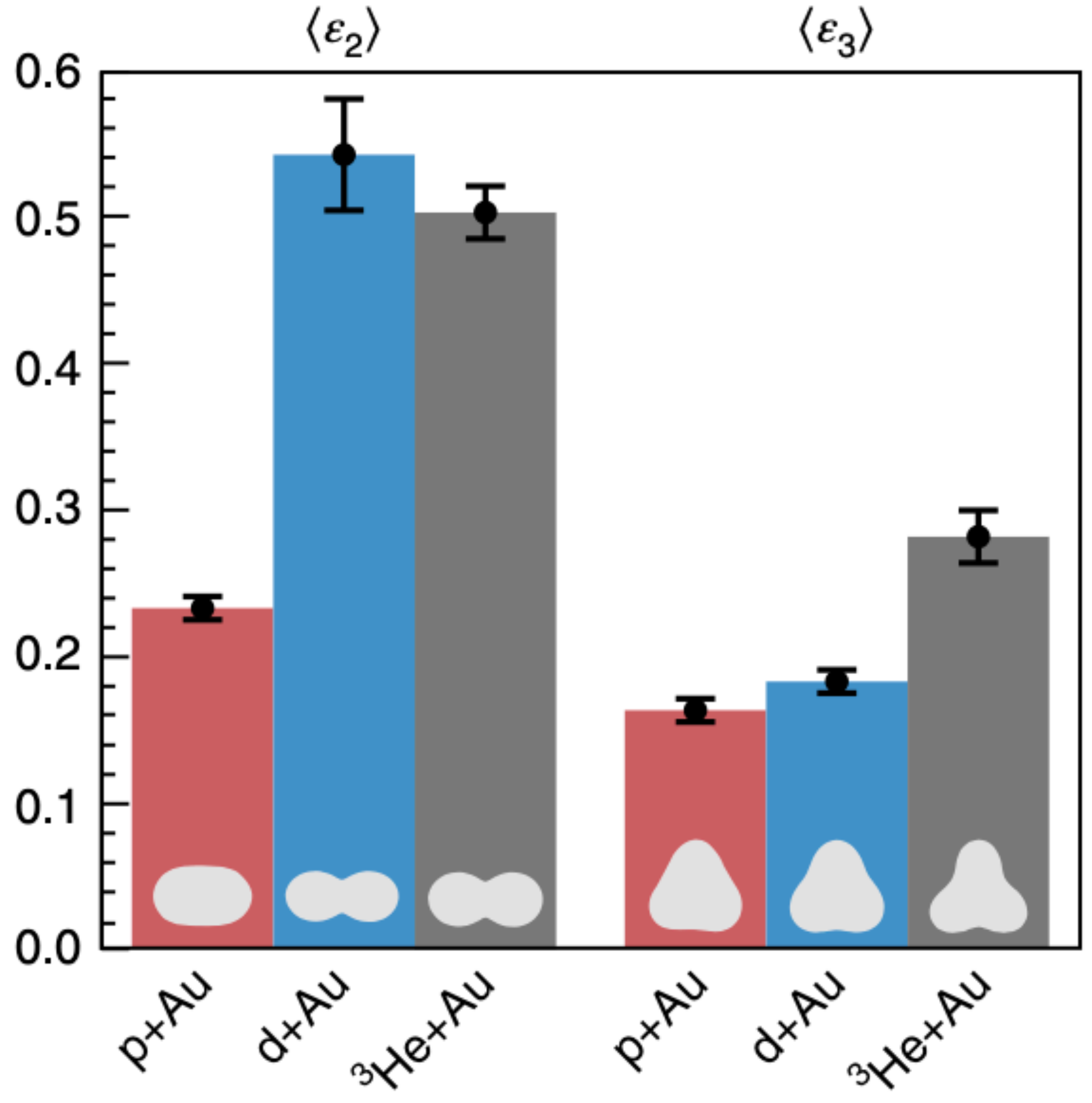
Ηράκλειτος (Heraclitus) ~535 - 475 BC

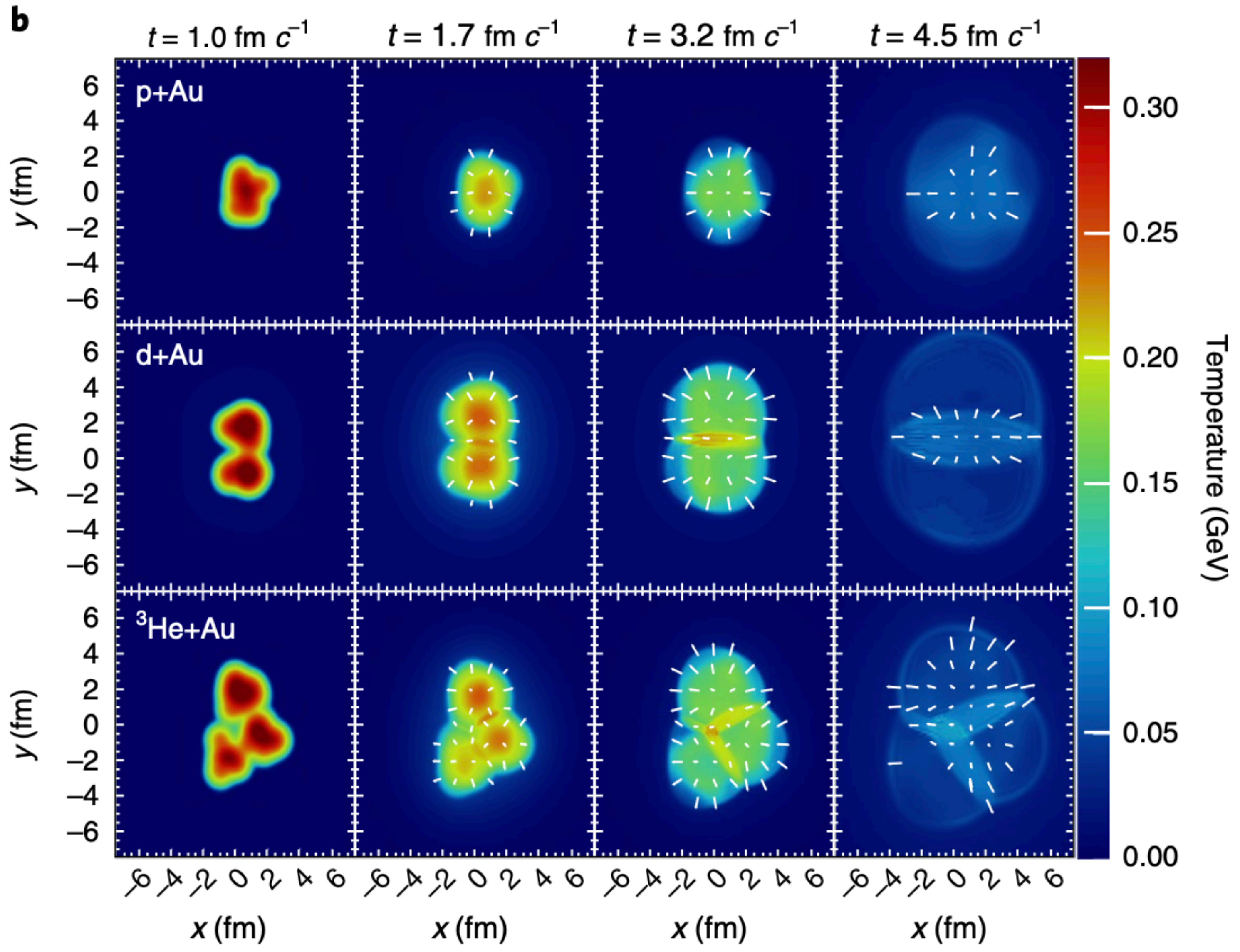
RHIC SYSTEM SCAN

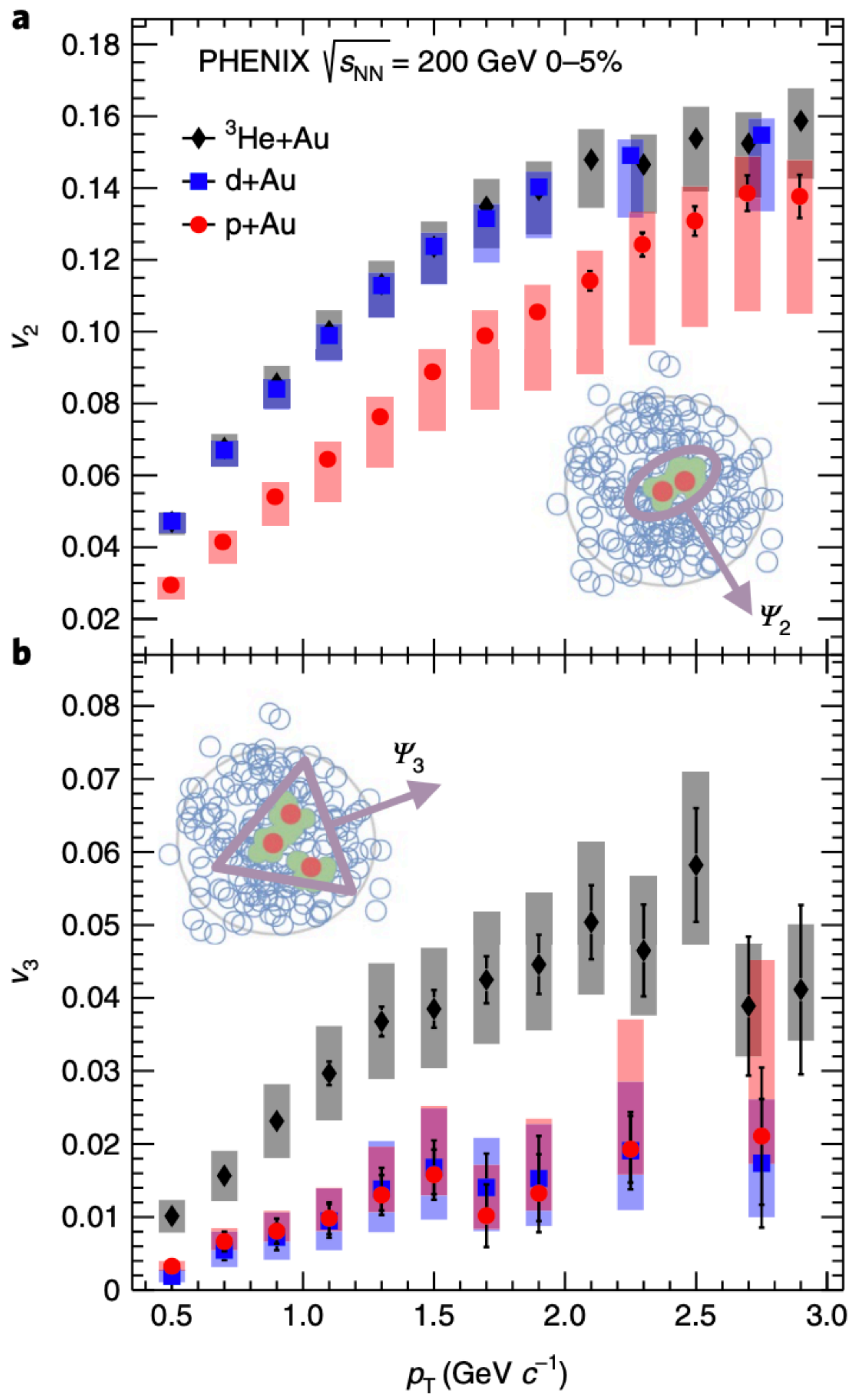
(PHENIX Collaboration), Nature Phys. 15, 214 (2019)

Hydrodynamical models → initial geometry vs IS momentum correlation models

Explore different initial collision geometry in p-Au, d-Au and He^3-Au





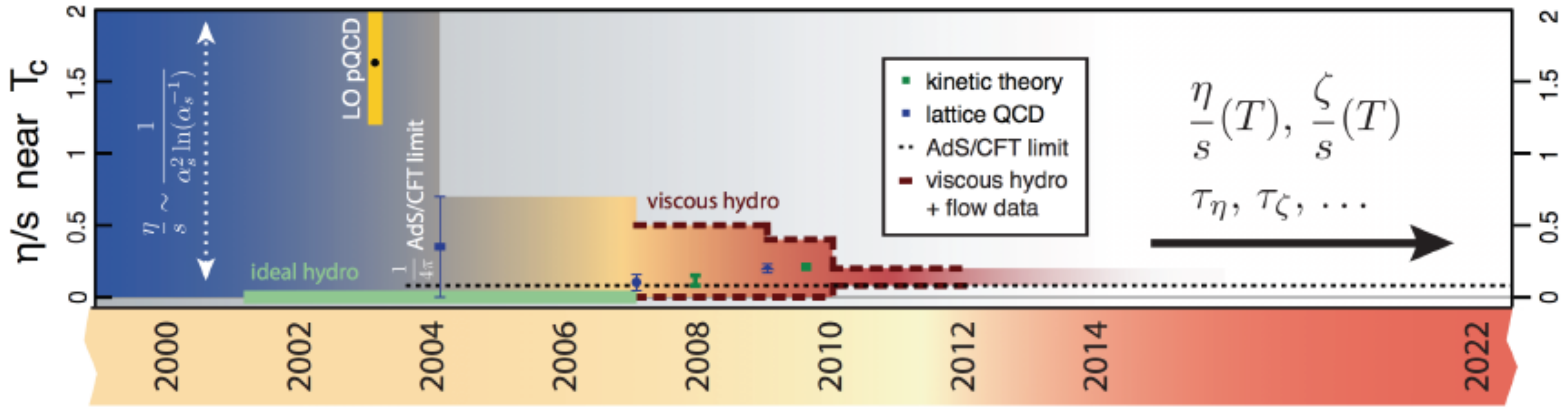


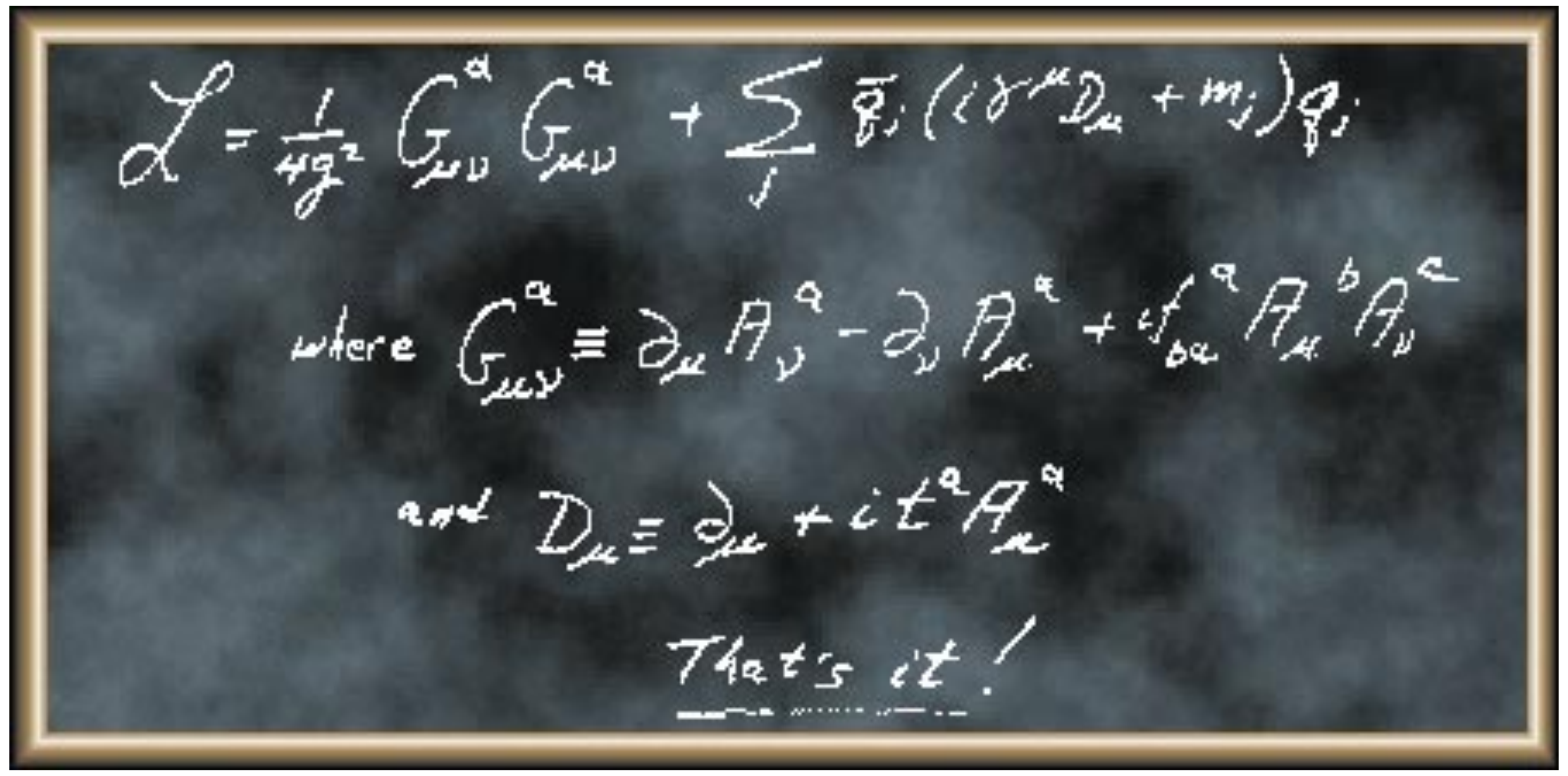
- Smaller ⟨ε_2⟩ in p-Au → smaller v_2
- Larger ⟨ε_3⟩ in He^3-Au → smaller v_3

Proof (?) of geometry + hydrodynamics
Reproduced only by hydroddynamical models

A LOT OF PROGRESS…

How does a strongly coupled QGP emerge from QCD?





- Additional precision measurements (e.g. heavy quarks, jets) → knowledge of poorly constrained parameters
- New phenomena (e.g. vorticity, magnetic fields, CME, CMW…)
- Origin of collectivity in small systems → can this lead to a unified picture of how QCD matter evolves as a function event activity?
- Critical point in QCD phase diagram?
- Connection with GW physics → how does QCD matter behave at large values of μ_B?

Discover the proper microscopic picture that describes the macroscopic behaviour of the QGP

LOOKING AT THE FUTURE: NICA - FAIR

MPD @ NICA

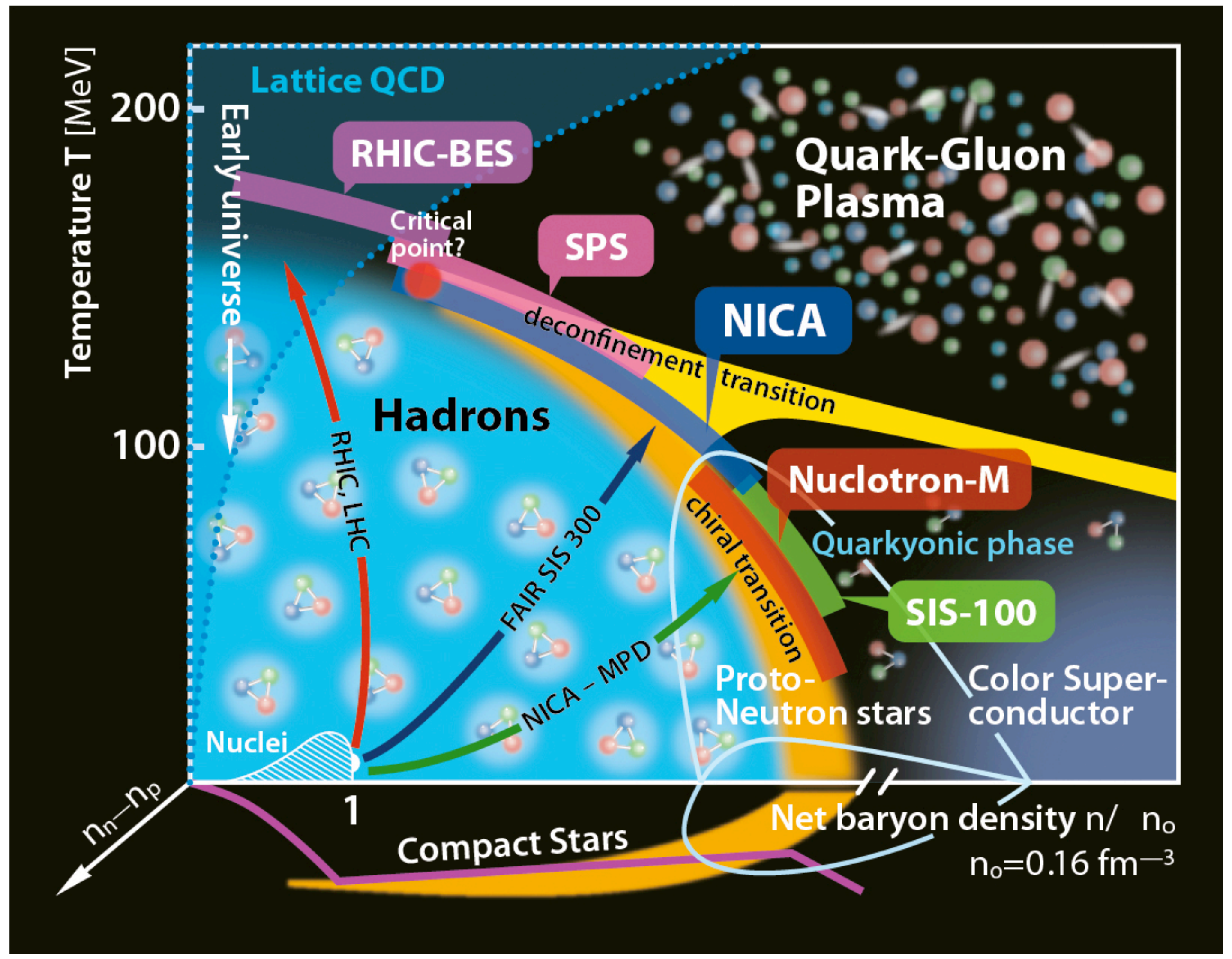
- TPC as central tracking detector
- MRPC Time-of-flight system
- Calorimetry

CBM @ FAIR

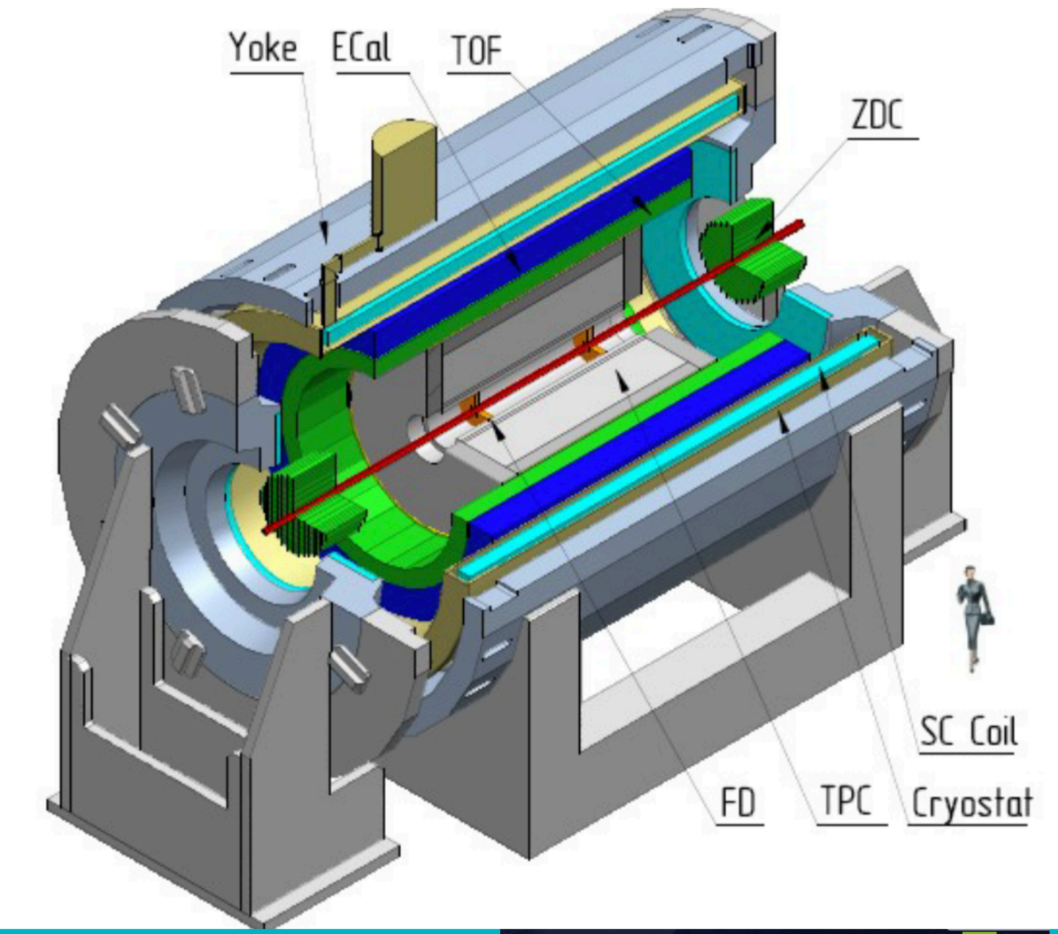
- Si-based vertexer
- TOF, TRD

EoS of QCD matter at high μ_B

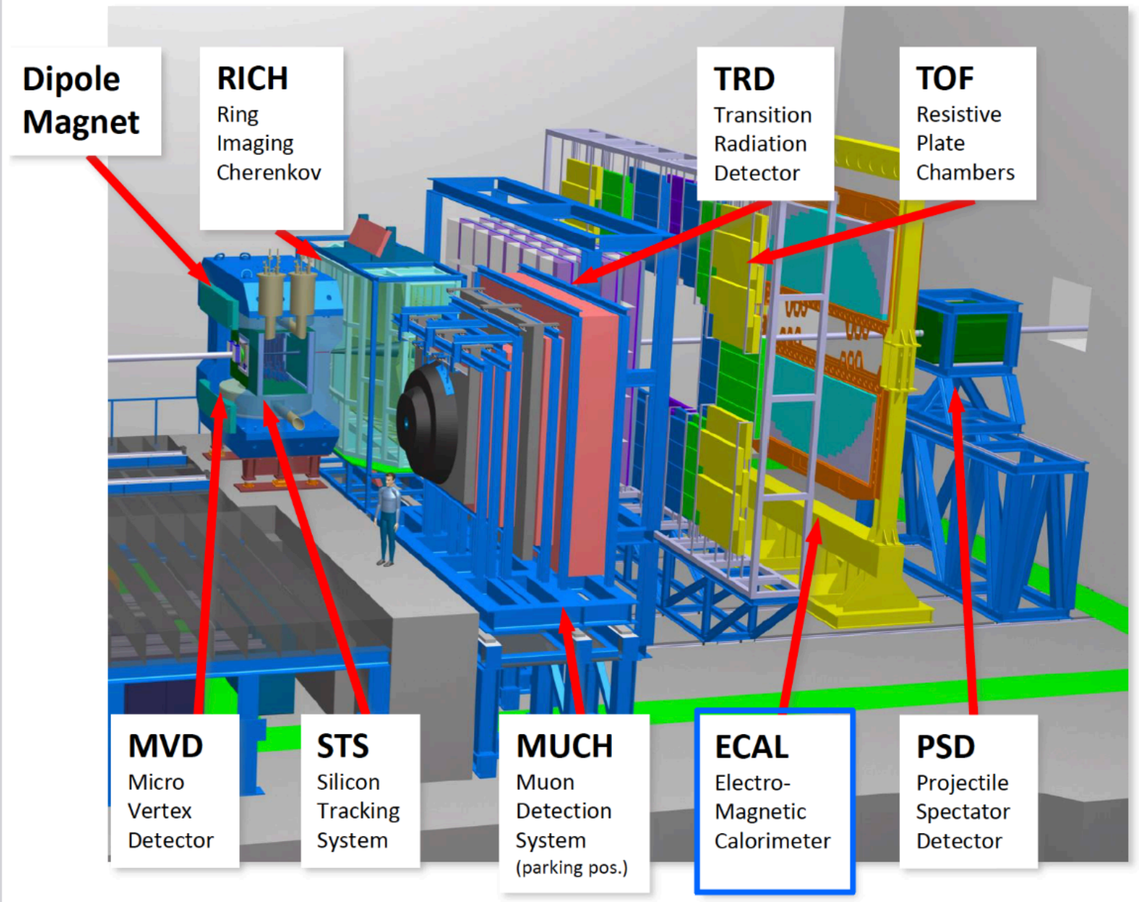
- Heavy flavour in cold and dense matter
- Strange matter



MPD @ NICA (2023 +)



CBM @ FAIR (2025 +)



Nikhef

LOOKING AT THE FUTURE: RHIC

Full azimuthal coverage with $|\eta| < 1.1$

Full ECAL+HCAL

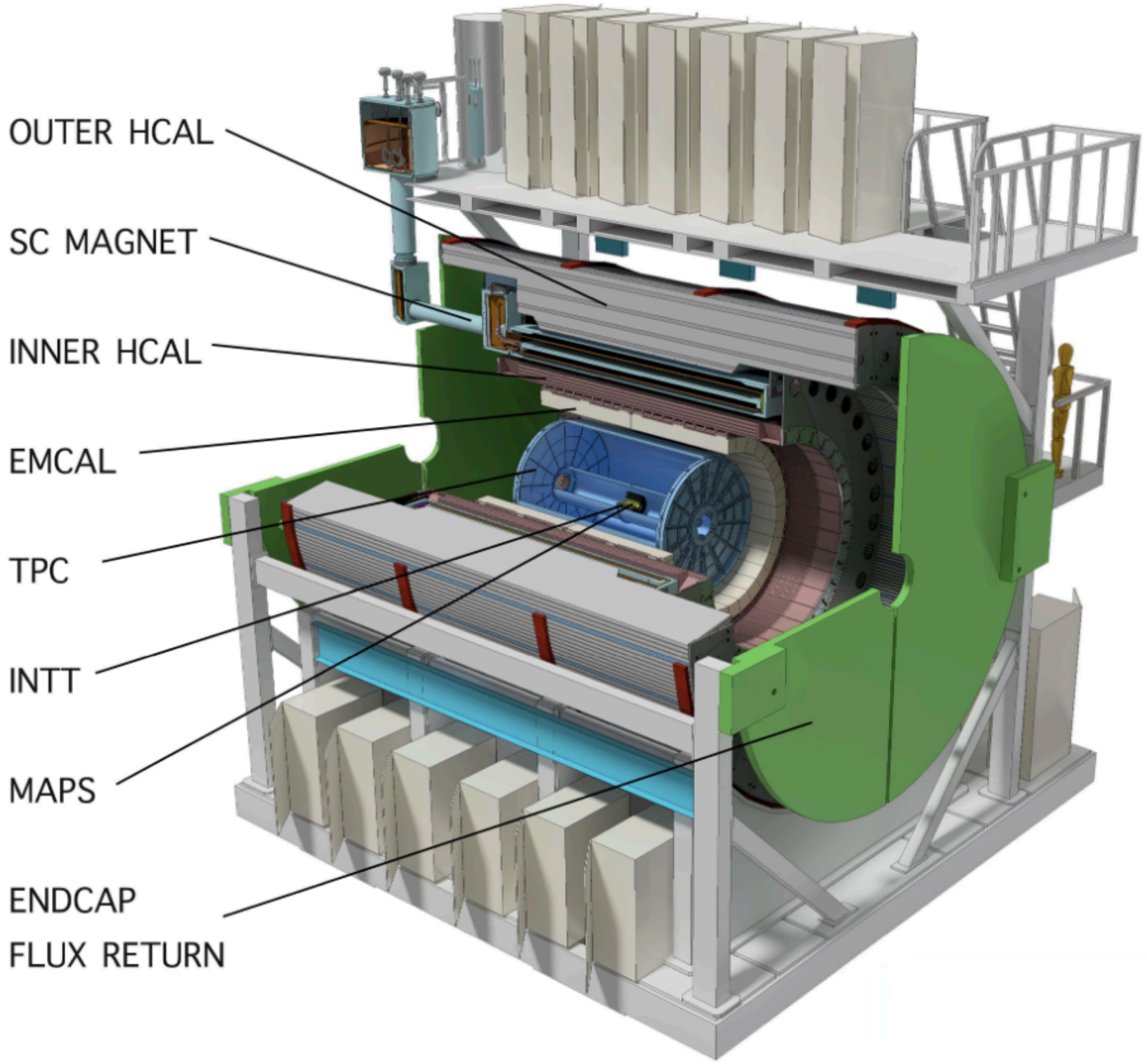
Vertexer based on MAPS

TPC based on GEM (continuous readout)

Physics focus

- Jets
- Open heavy flavour
- Quarkonia states
- Photons

sPHENIX (2023+)



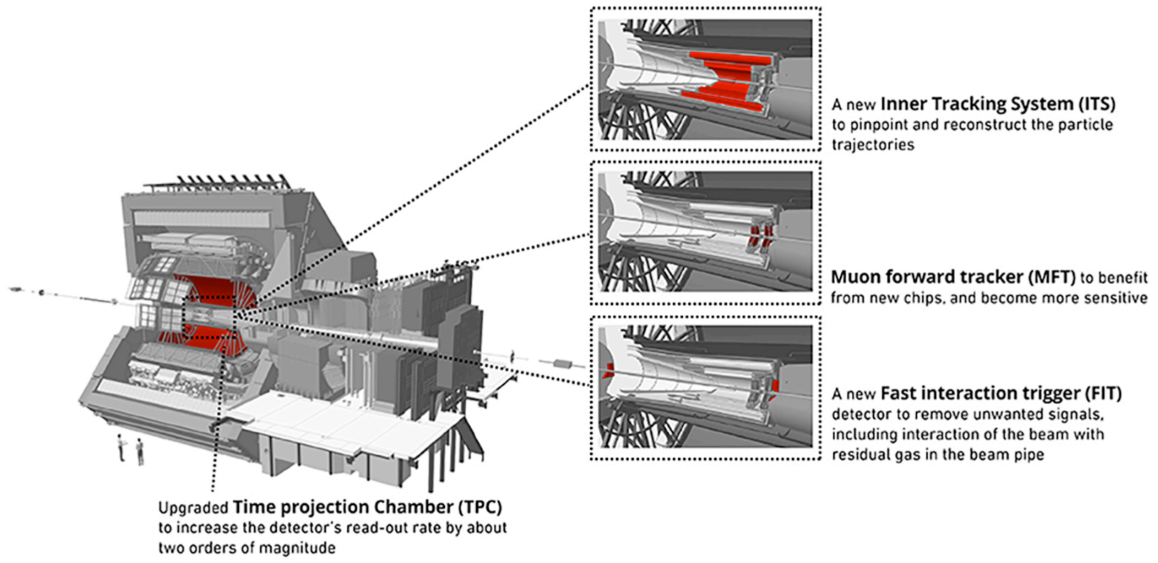
LOOKING AT THE FUTURE: HI@LHC 2022-2029

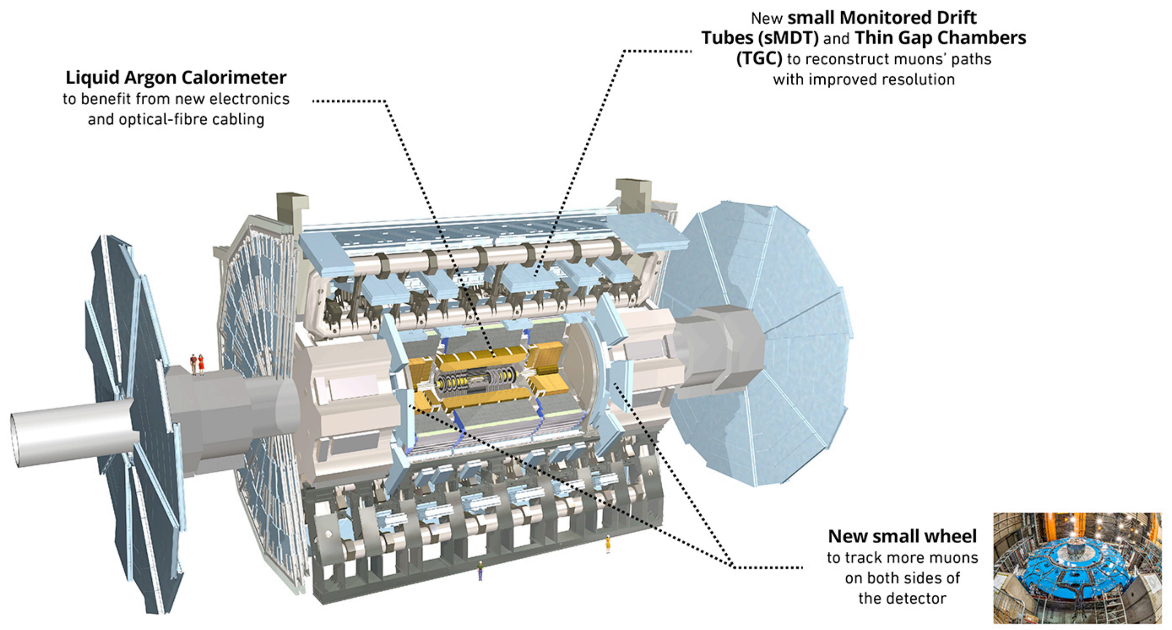
Physics focus

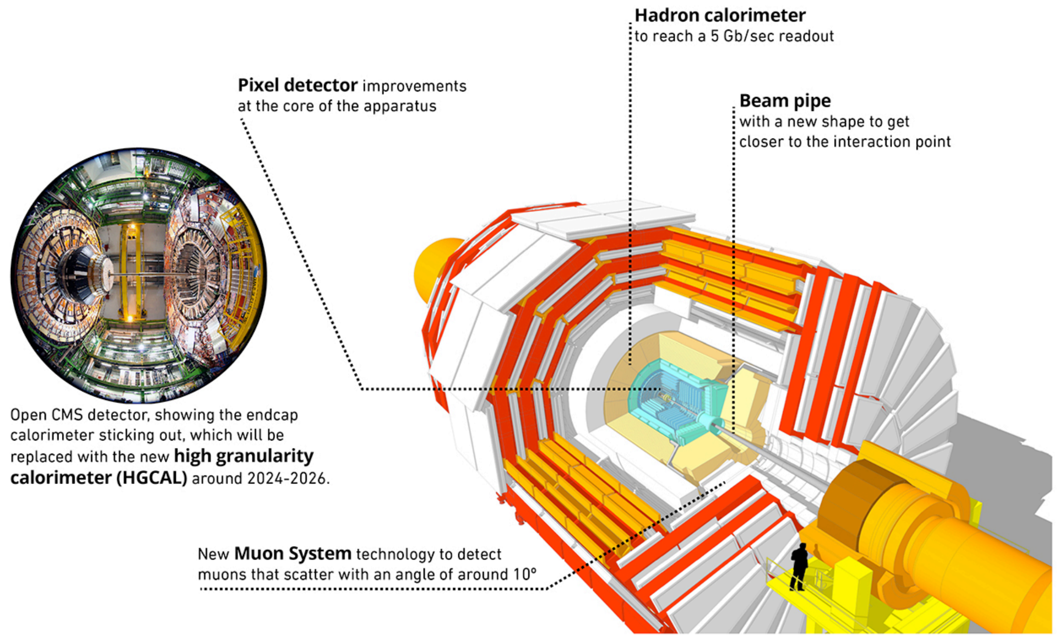
- Origin of collectivity in small systems
- Hard probes (Jets, Heavy flavour,…)
- Novel QCD phenomena, vorticity & magnetic fields

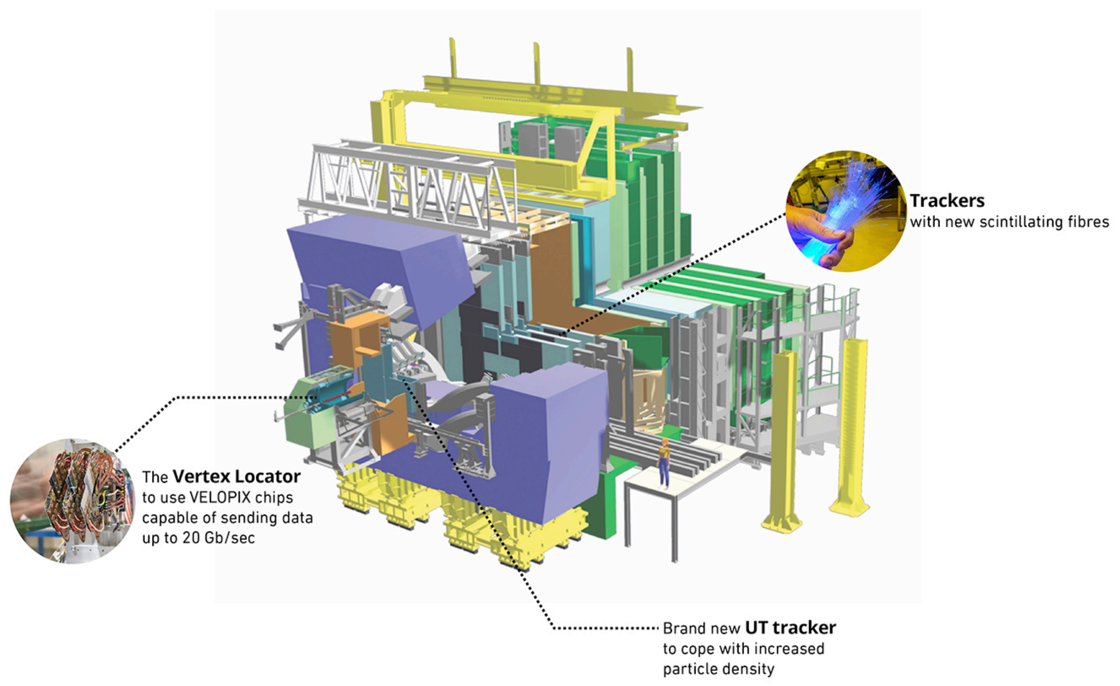
How does a strongly coupled QGP emerge from QCD

- Connection of the macroscopic QGP behaviour with the microscopic description of its degrees of freedom









LOOKING AT THE FUTURE: HI@LHC 2030+

Full azimuthal coverage with |η| < 4

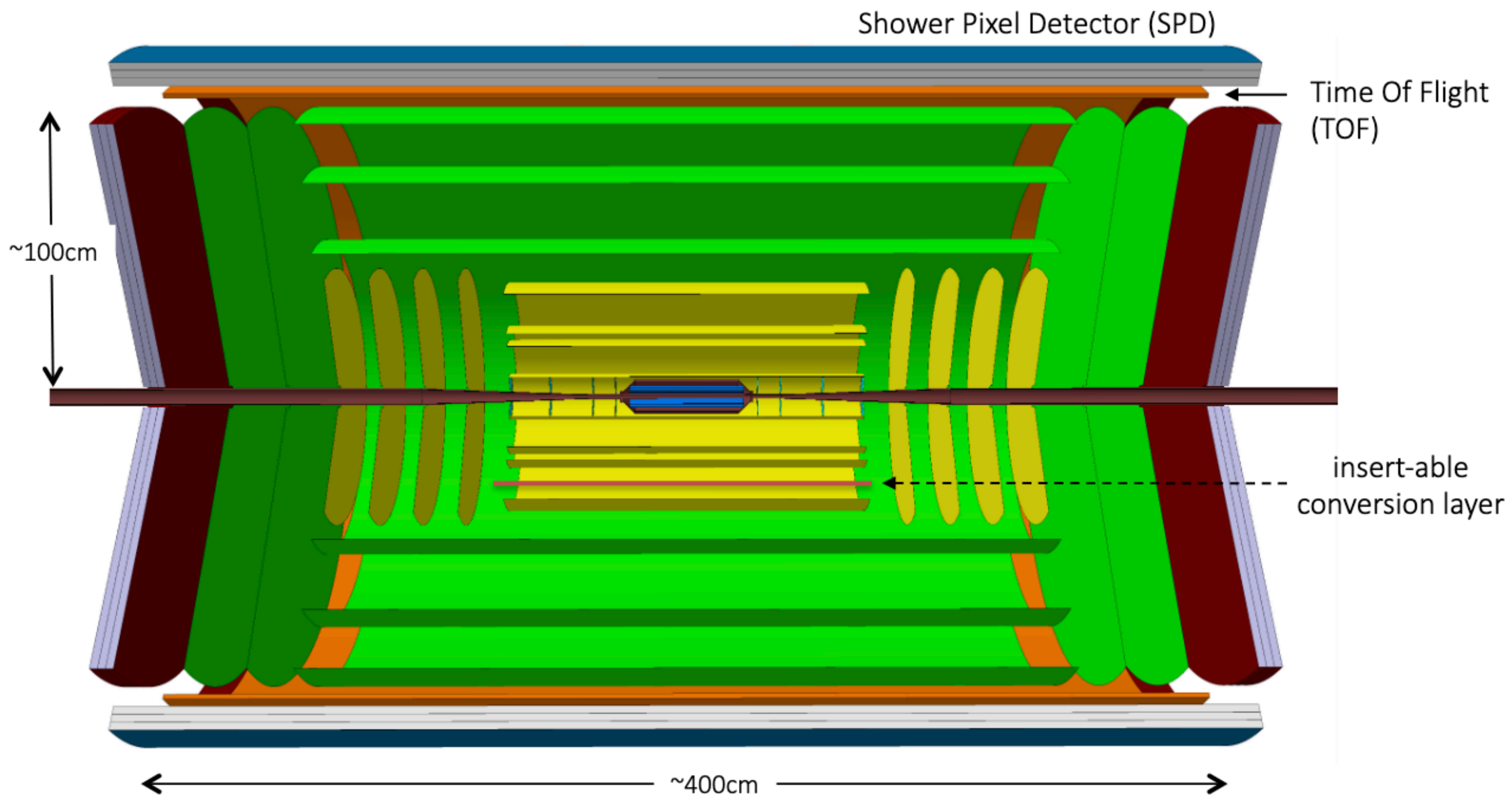
Retractable first layers inside the beam pipe

Fast timing silicon detectors, TOF, RICH, muon detector

Physics focus

- (Multi-)heavy flavour states
- Quarkonia states
- Soft photons
- Exotic states
- Chiral symmetry restoration

https://arxiv.org/abs/1902.01211



Thank you for your attention!

BACKUP


The XIVth Quark confinement and the Hadron spectrum conference