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INTRODUCTION TO HEAVY ION PHYSICS

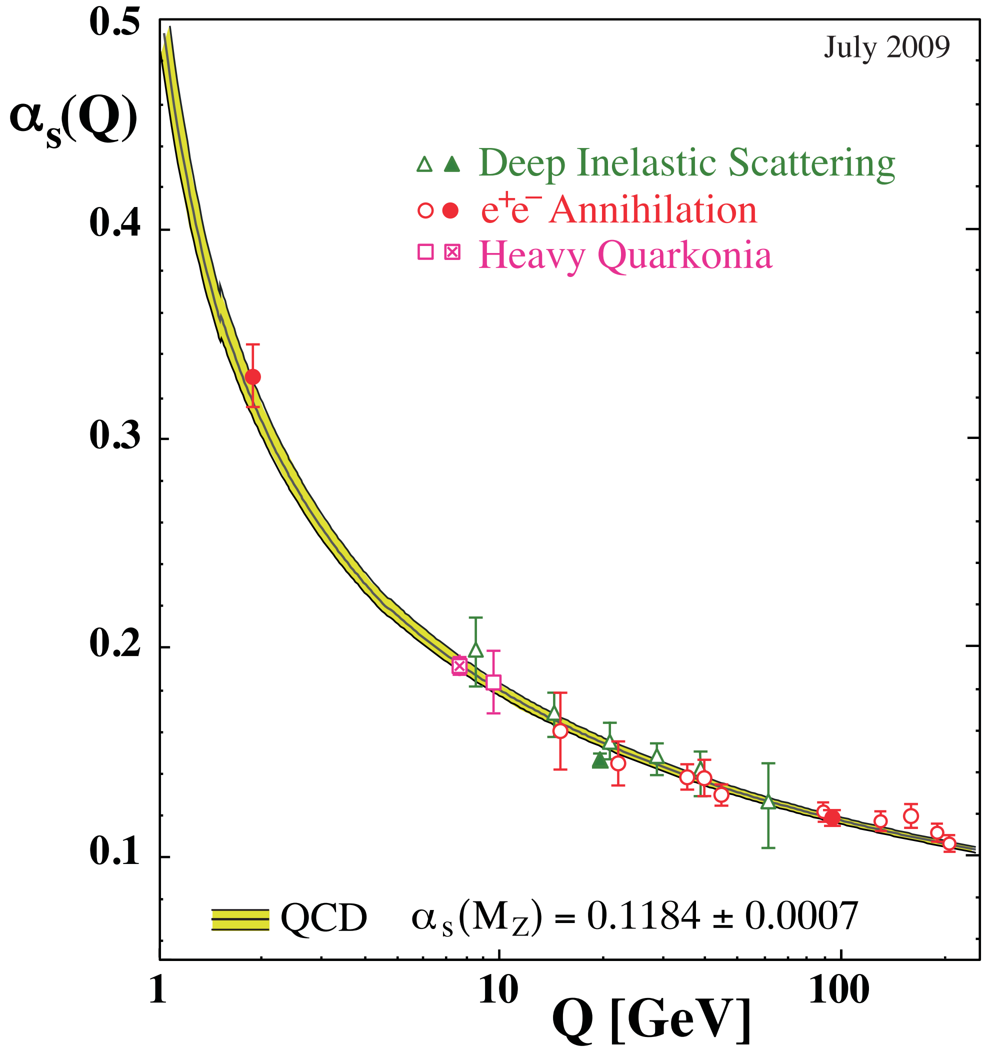
PARTICLE PHYSICS 2

Panos Christakoglou

SUMMARY

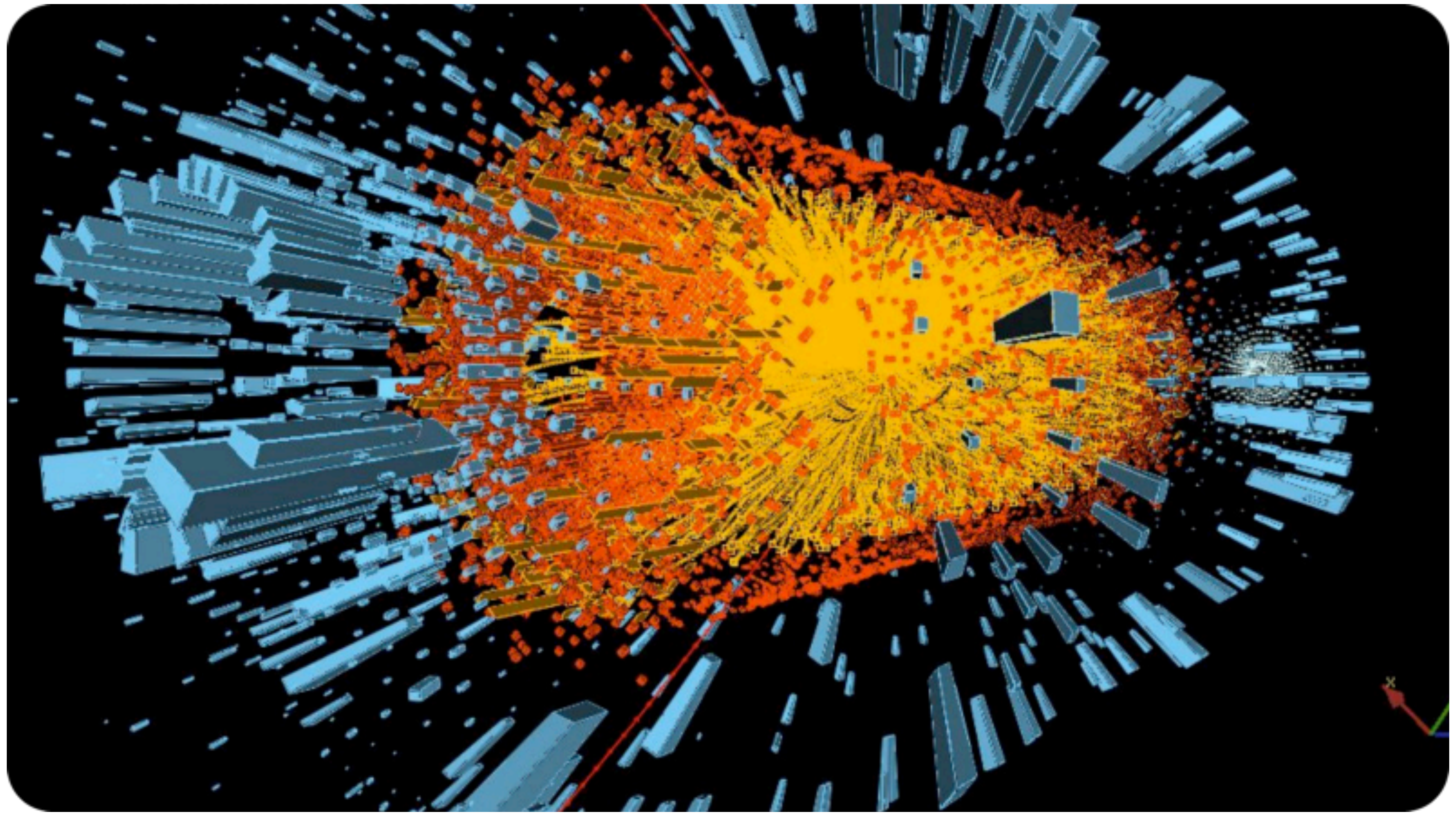
Last lecture

- Renormalisation
- The running of the coupling strength
  - Asymptotic freedom
- Confinement



Today's lecture

- Heavy ion physics



SCIENTIFIC QUESTION TO BE ANSWERED

…I collide two large objects that are accelerated at ultra-relativistic energies?

↓

Not an interesting question to answer!!!

SCIENTIFIC QUESTION TO BE ANSWERED

…I collide two large objects that are accelerated at ultra-relativistic energies?

Not an interesting question to answer!!!

Fundamental questions in physics

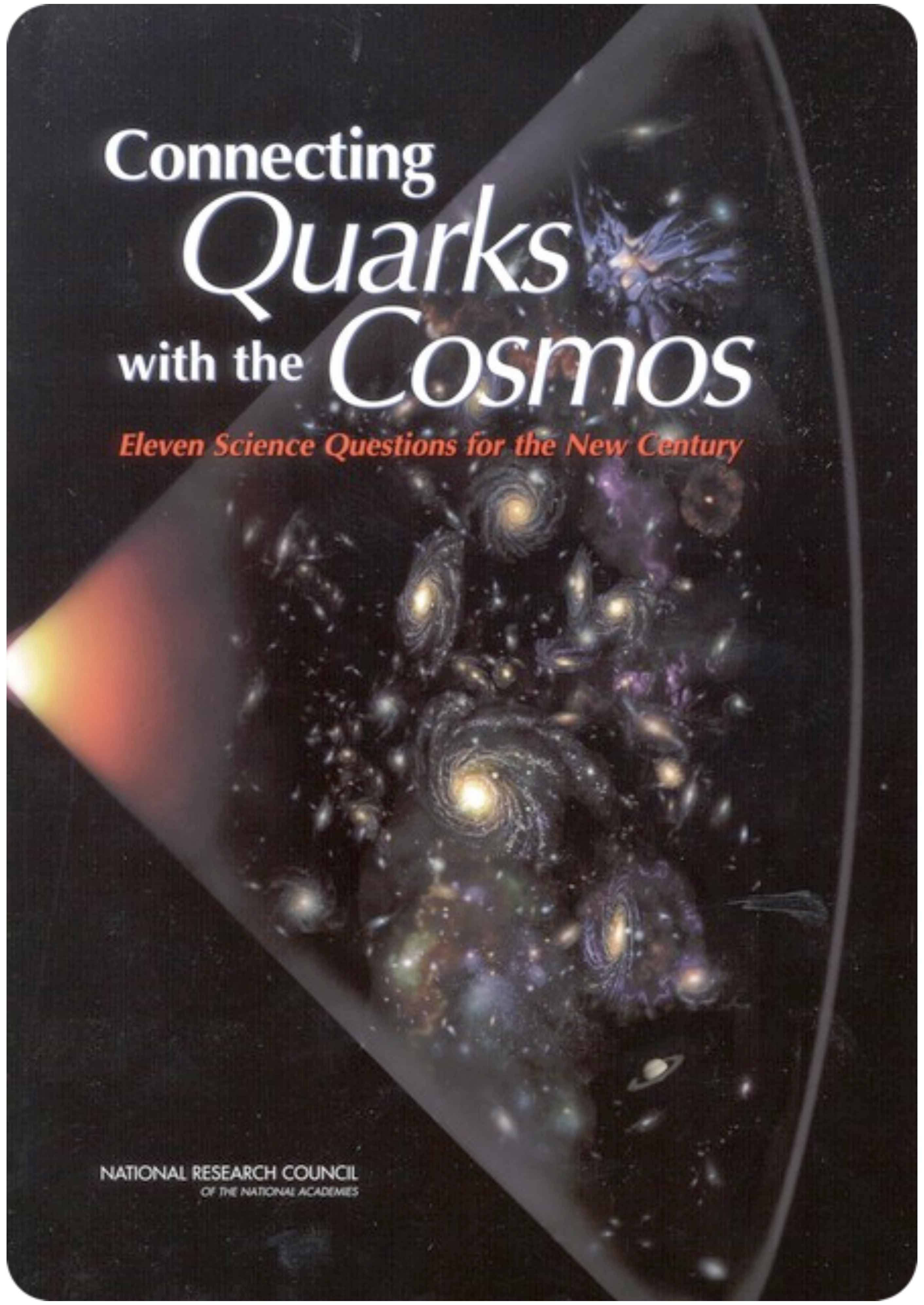
How did the universe evolve after the Big Bang?

Can we generate new states of matter at extreme temperatures and densities?

Interesting questions to answer!!!

11 UNANSWERED QUESTIONS FOR THIS CENTURY

- 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?



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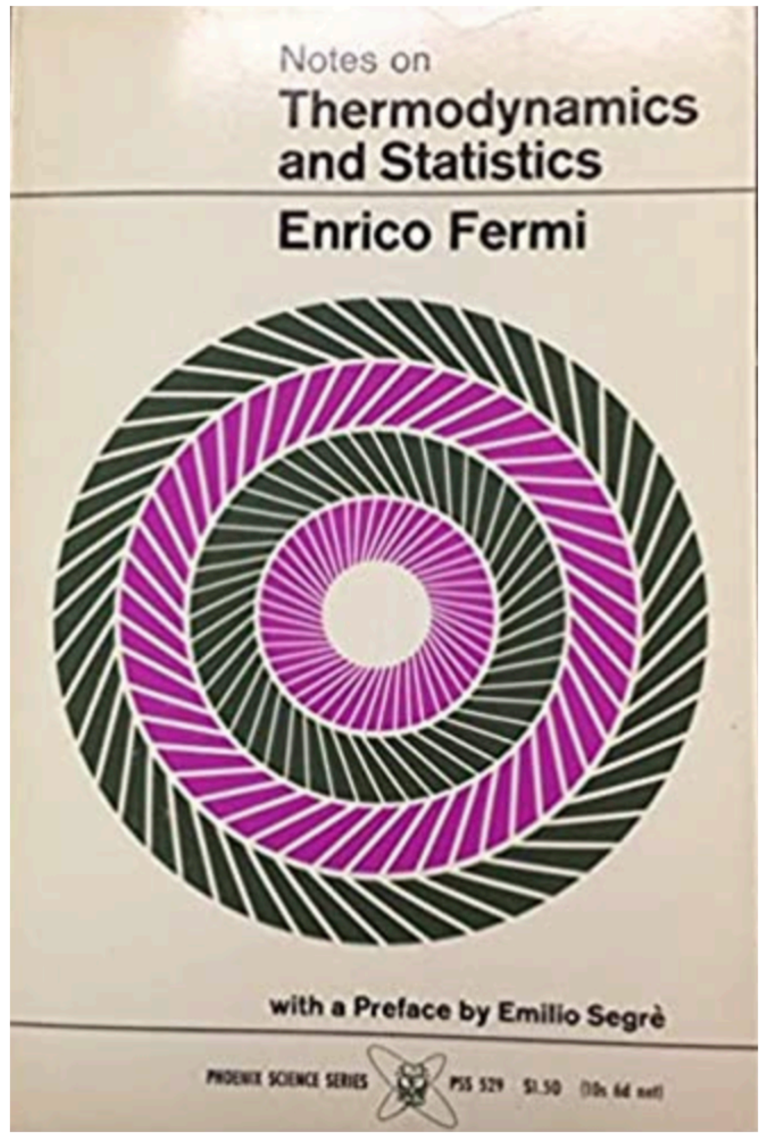
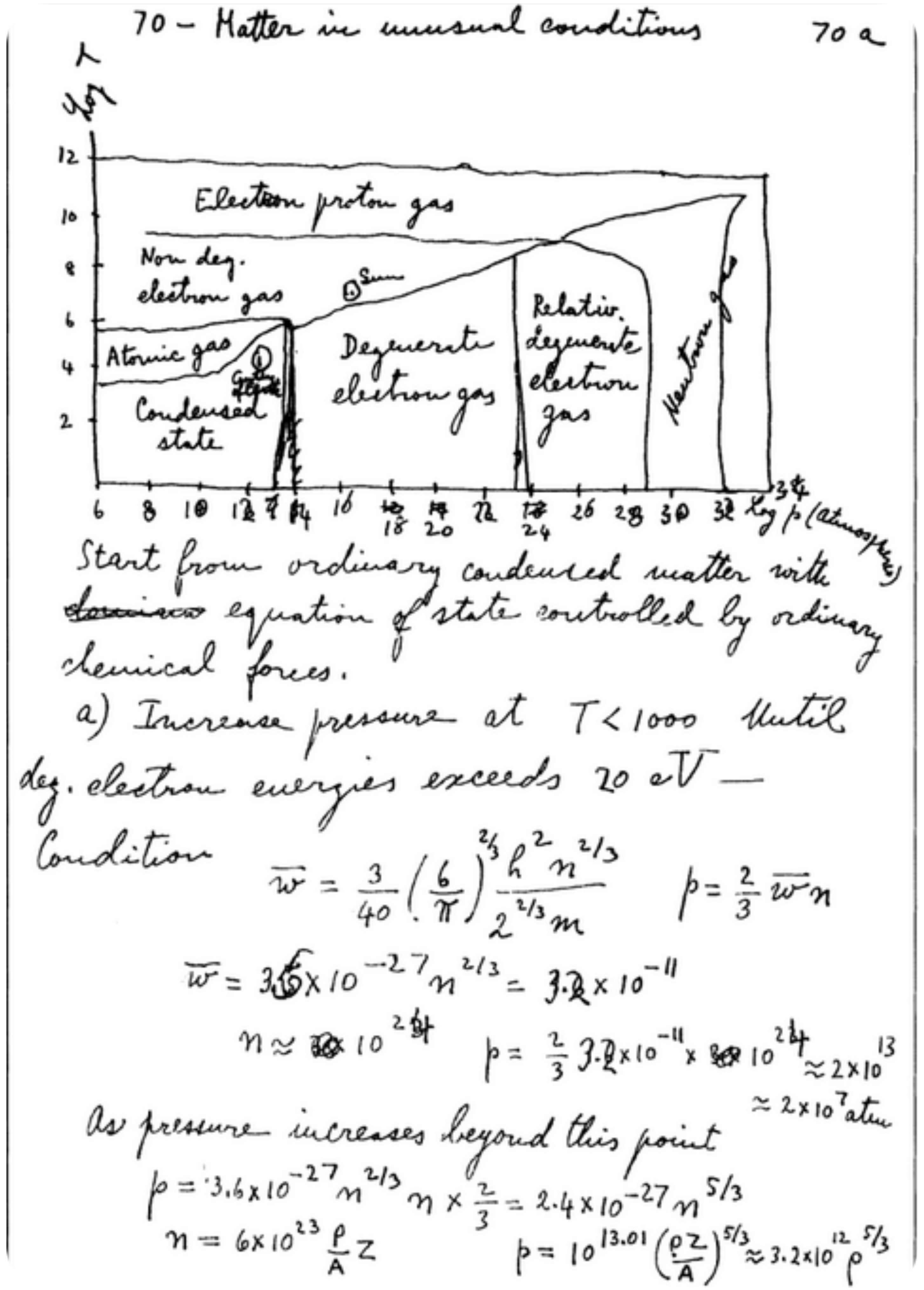
There is evidence that during its **earliest moments the universe** underwent a tremendous burst of expansion, known as **inflation**, so that the largest objects in the universe had their origins in subatomic quantum fuzz. The underlying physical cause of this inflation is a mystery. In addition, **the universe evolved passing through the EW and the strong phase transition**, through **a state of extreme conditions** which are too of a complete mystery.

The theory of how protons and neutrons form the atomic nuclei of the chemical elements is well developed. At **higher densities**, **neutrons and protons** may **dissolve** into an undifferentiated “**soup of quarks and gluons**", which can be probed in **heavy-ion accelerators**. Densities beyond nuclear densities occur and can be probed in **neutron stars**, and still higher densities and temperatures **existed in the early universe**.

FERMI'S NOTES

Fermi (~1953)




70 – Matter in unusual conditions 70 a

Start from ordinary condensed matter with ~~[illegible]~~ equation of state controlled by ordinary chemical forces.

a) Increase pressure at $T < 1000$ until deg. electron energies exceeds 20 eV —

Condition

$$\overline{w} = \frac{3}{40}\left(\frac{6}{\pi}\right)^{2/3} \frac{h^2 n^{2/3}}{2^{2/3} m} \qquad p = \frac{2}{3}\overline{w} n$$

$$\overline{w} = 3.6 \times 10^{-27} n^{2/3} = 3.2 \times 10^{-11}$$

$$n \approx 10^{24} \qquad p = \frac{2}{3} 3.2 \times 10^{-11} \times 10^{24} \approx 2 \times 10^{13} \approx 2 \times 10^{7}\,\text{atm}$$

As pressure increases beyond this point

$$p = 3.6 \times 10^{-27} n^{2/3}\, n \times \frac{2}{3} = 2.4 \times 10^{-27} n^{5/3}$$

$$n = 6 \times 10^{23} \frac{\rho}{A} Z \qquad p = 10^{13.01} \left(\frac{\rho Z}{A}\right)^{5/3} \approx 3.2 \times 10^{12} \rho^{5/3}$$

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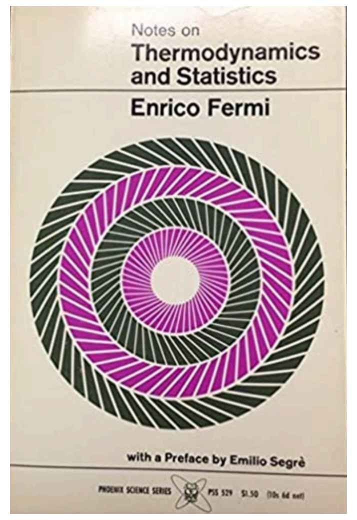
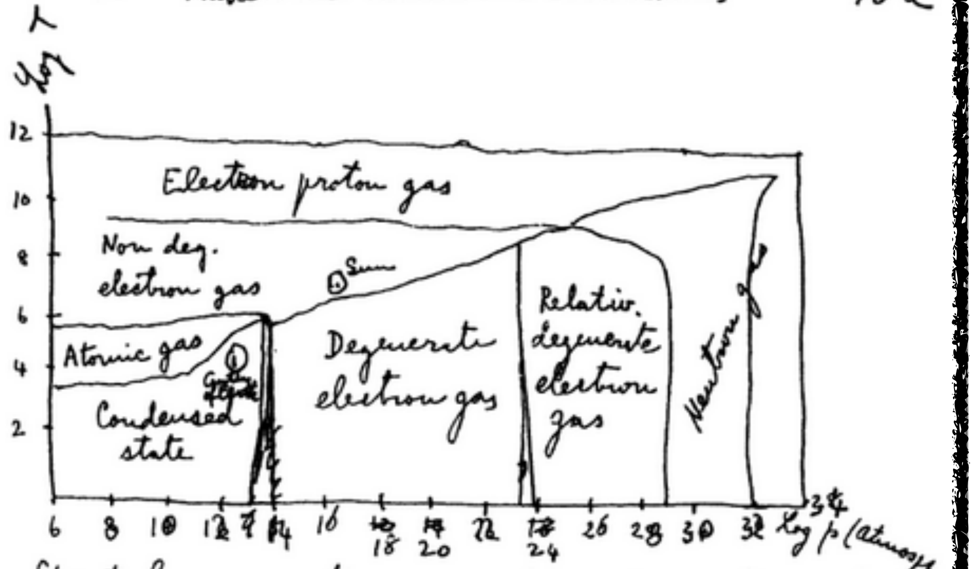
MATTER IN UNUSUAL CONDITIONS…

Fermi (~1953)



70 – Matter in unusual conditions 70 a



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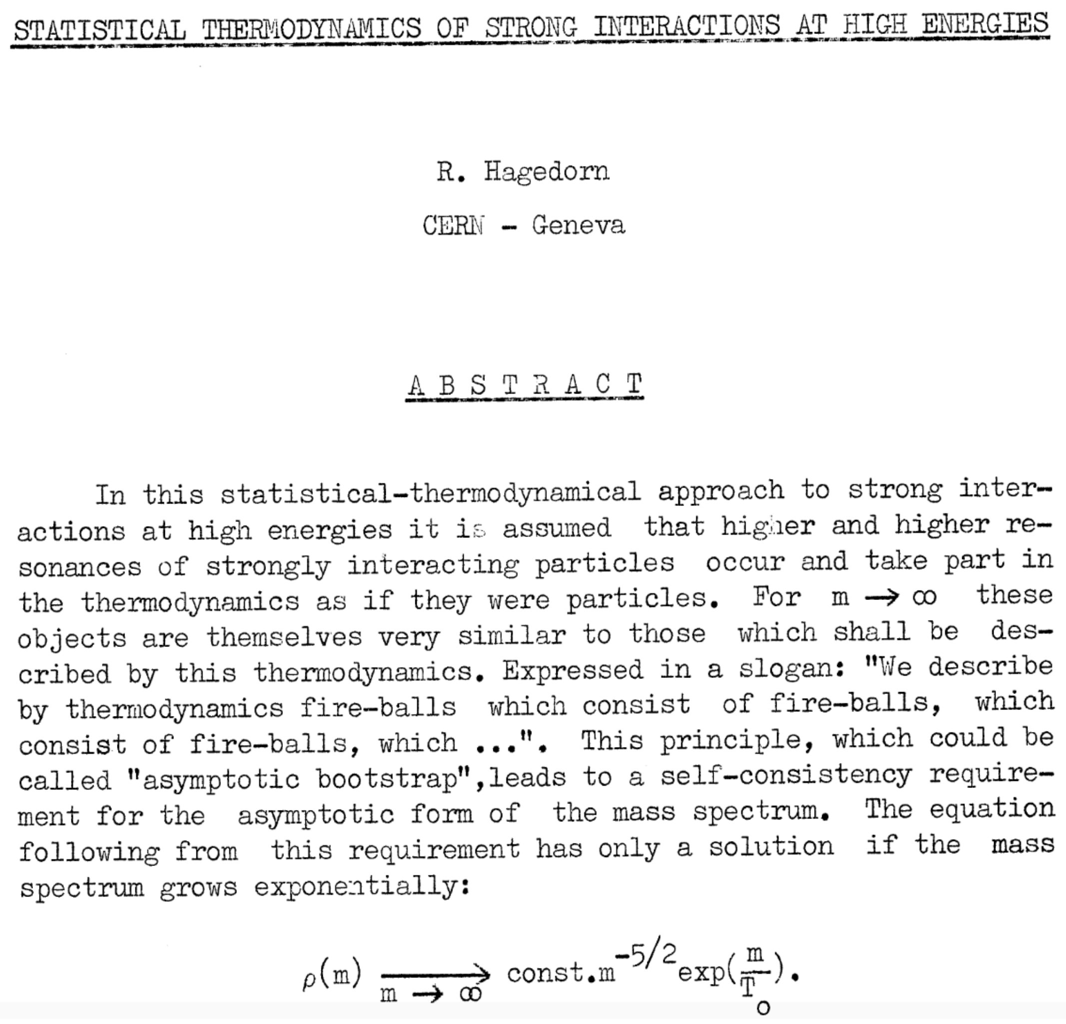
Hagedorn (~1965)



STATISTICAL THERMODYNAMICS OF STRONG INTERACTIONS AT HIGH ENERGIES

R. Hagedorn

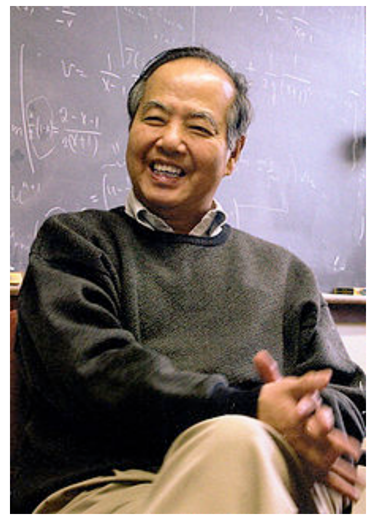
CERN – Geneva

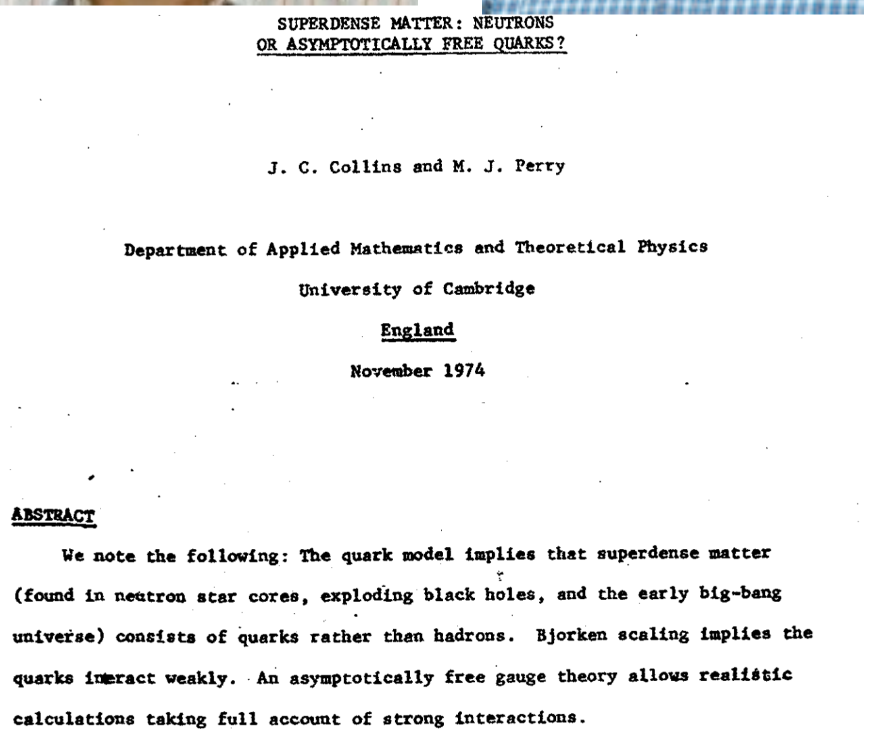
ABSTRACT

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

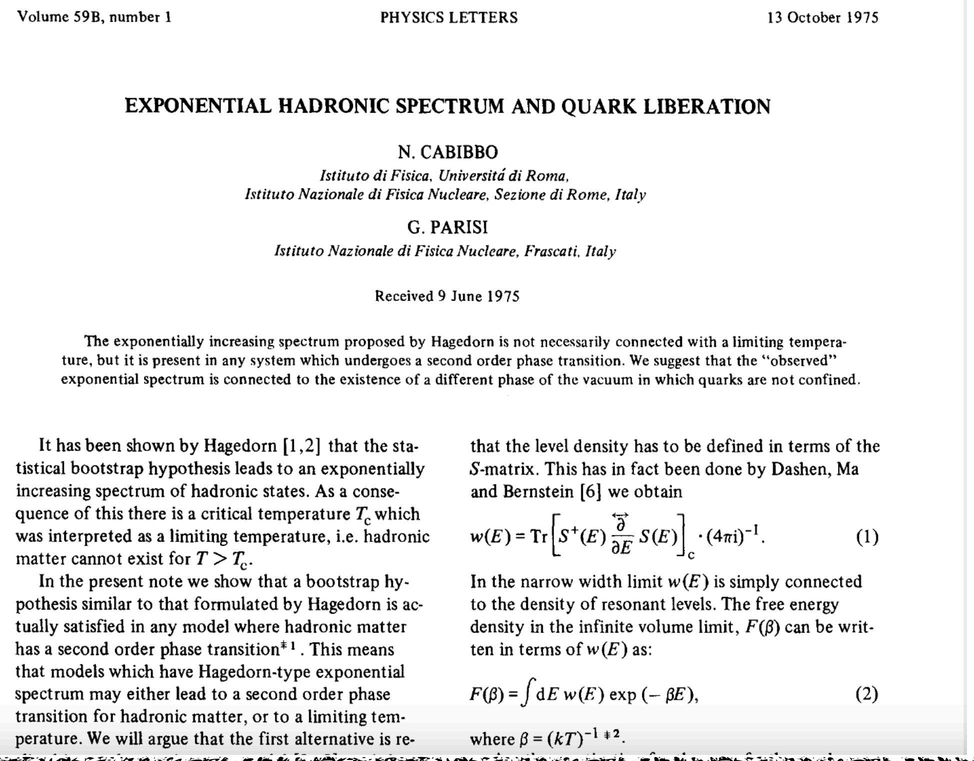
University of Cambridge

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:

$$F(\beta) = \int dE\, w(E) \exp(-\beta E), \quad (2)$$

where $\beta = (kT)^{-1}$ [‡2].

Expectation for a weakly interacting quasi-particle gas

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THE BIRTH OF QCD

VOLUME 30, NUMBER 26 PHYSICAL REVIEW LETTERS 25 JUNE 1973

Ultraviolet Behavior of Non-Abelian Gauge Theories*

David J. Gross† and Frank Wilczek
Joseph Henry Laboratories, Princeton University, Princeton, New Jersey 08540
(Received 27 April 1973)

It is shown that a wide class of non-Abelian gauge theories have, up to calculable logarithmic corrections, free-field-theory asymptotic behavior. It is suggested that Bjorken scaling may be obtained from strong-interaction dynamics based on non-Abelian gauge symmetry.

Non-Abelian gauge theories have received much attention recently as a means of constructing unified and renormalizable theories of the weak and electromagnetic interactions.[1] In this note we report on an investigation of the ultraviolet (UV) asymptotic behavior of such theories. We have found that they possess the remarkable feature, perhaps unique among renormalizable theories, of asymptotically approaching free-field theory. Such asymptotically free theories will exhibit, for matrix elements of currents between on-mass-shell states, Bjorken scaling. We therefore suggest that one should look to a non-Abelian gauge theory of the strong interactions to provide the explanation for Bjorken scaling, which has so far eluded field-theoretic understanding.

The UV behavior of renormalizable field theories can be discussed using the renormalization-group equations,[2,3] which for a theory involving one field (say $g\varphi^4$) are

$$[m\partial/\partial m + \beta(g)\partial/\partial g - n\gamma(g)]\Gamma_{asy}^{(n)}(g; P_1, \ldots, P_n) = 0. \quad (1)$$

VOLUME 30, NUMBER 26 PHYSICAL REVIEW LETTERS 25 JUNE 1973

[14] Y. Nambu and G. Jona-Lasino, Phys. Rev. 122, 345 (1961); S. Coleman and E. Weinberg, Phys. Rev. D 7, 1888 (1973).
[15] K. Symanzik (to be published) has recently suggested that one consider a $\lambda\varphi^4$ theory with a negative λ to achieve UV stability at $\lambda = 0$. However, one can show, using the renormalization-group equations, that in such theory the ground-state energy is unbounded from below (S. Coleman, private communication).
[16] W. A. Bardeen, H. Fritzsch, and M. Gell-Mann, CERN Report No. CERN-TH-1538, 1972 (to be published).
[17] H. Georgi and S. L. Glashow, Phys. Rev. Lett. 28, 1494 (1972); S. Weinberg, Phys. Rev. D 5, 1962 (1972).
[18] For a review of this program, see S. L. Adler, in Proceedings of the Sixteenth International Conference on High Energy Physics, National Accelerator Laboratory, Batavia, Illinois, 1972 (to be published).

Reliable Perturbative Results for Strong Interactions?*

H. David Politzer
Jefferson Physical Laboratories, Harvard University, Cambridge, Massachusetts 02138
(Received 3 May 1973)

An explicit calculation shows perturbation theory to be arbitrarily good for the deep Euclidean Green's functions of any Yang-Mills theory and of many Yang-Mills theories with fermions. Under the hypothesis that spontaneous symmetry breakdown is of dynamical origin, these symmetric Green's functions are the asymptotic forms of the physically significant spontaneously broken solution, whose coupling could be strong.

The Nobel Prize in Physics 2004
David J. Gross, H. David Politzer, Frank Wilczek

The Nobel Prize in Physics 2004

David J. Gross

H. David Politzer

Frank Wilczek

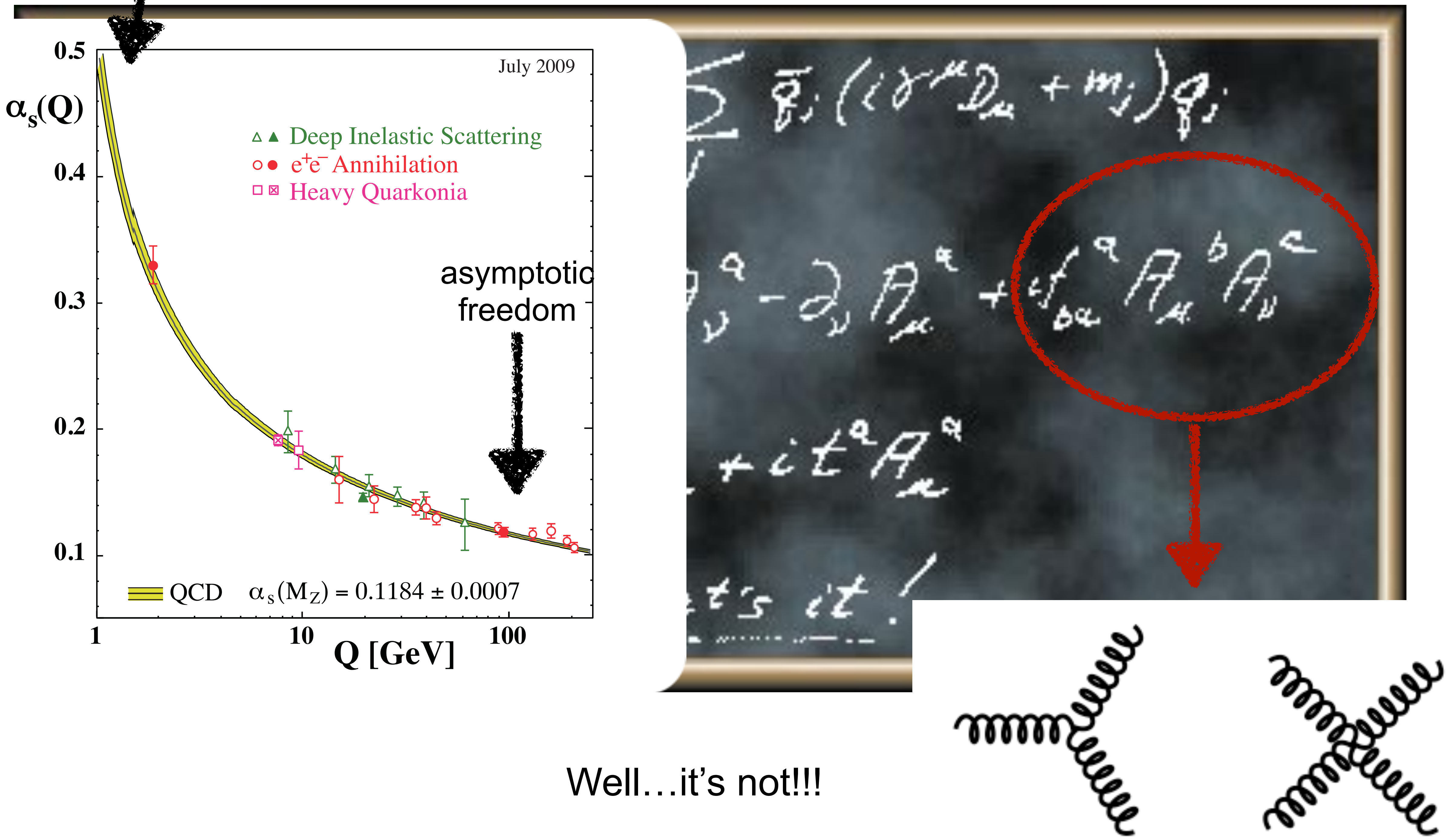
The Nobel Prize in Physics 2004 was awarded jointly to David J. Gross, H. David Politzer and Frank Wilczek *"for the discovery of asymptotic freedom in the theory of the strong interaction"*.

1973: QCD

QCD

infrared slavery
(confinement)

It looks like QED, no?

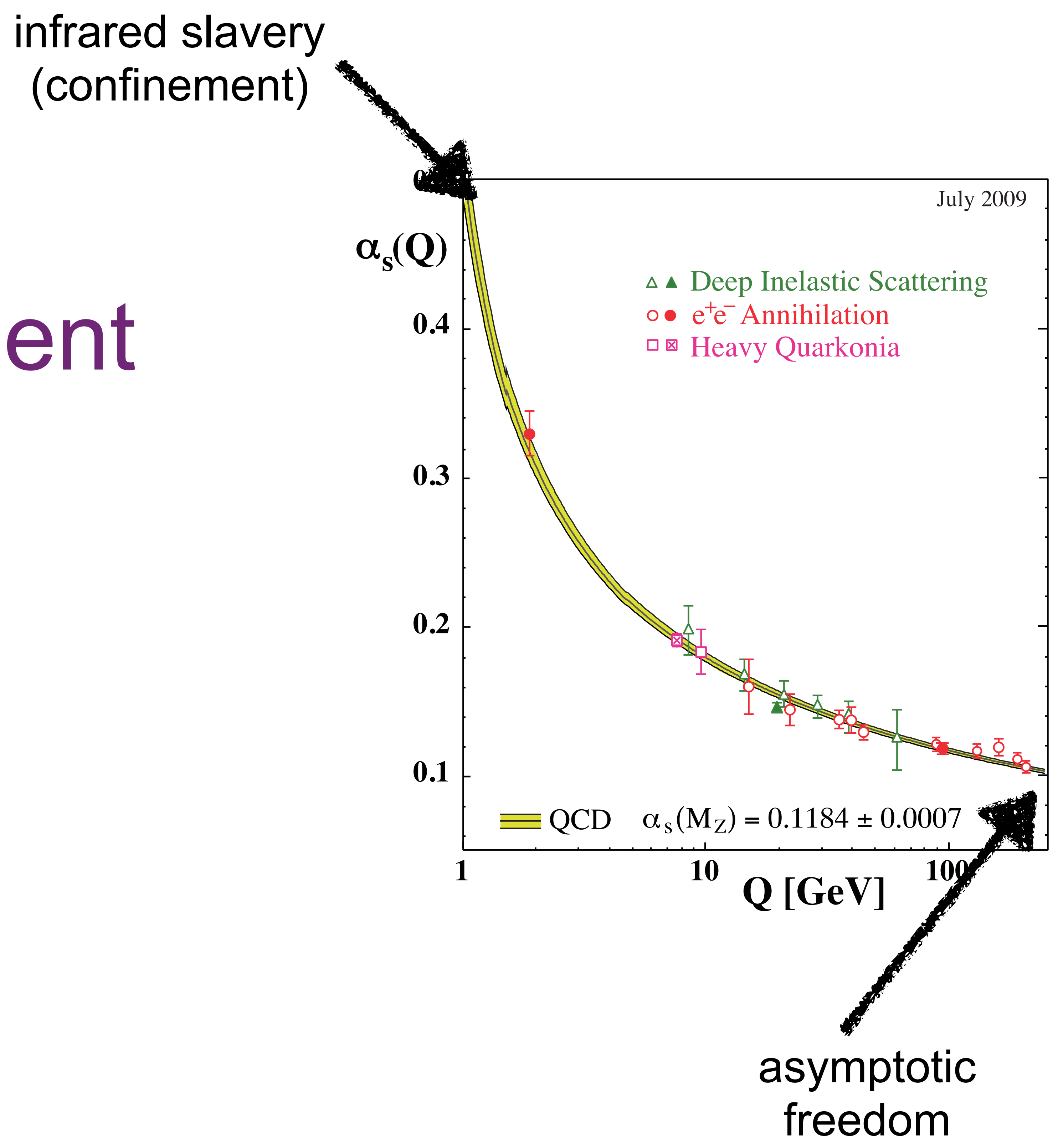


Well…it’s not!!!

QCD DISTINCT FEATURES

Typical hadron size: ~10^{-15}m = 1fm

- Planck's constant: hbar c ~ 0.2GeV.fm
- 200 MeV is the characteristic scale of confinement
- the Λ_{QCD} scale



STRONG PHASE TRANSITION

The running coupling constant suggests the possibility of creating a new state of QCD matter where quarks and gluons are “free” ➡ the **strong phase transition**

This transition can happen at sufficiently large:

- temperature T & energy density ε

Which T and ε?

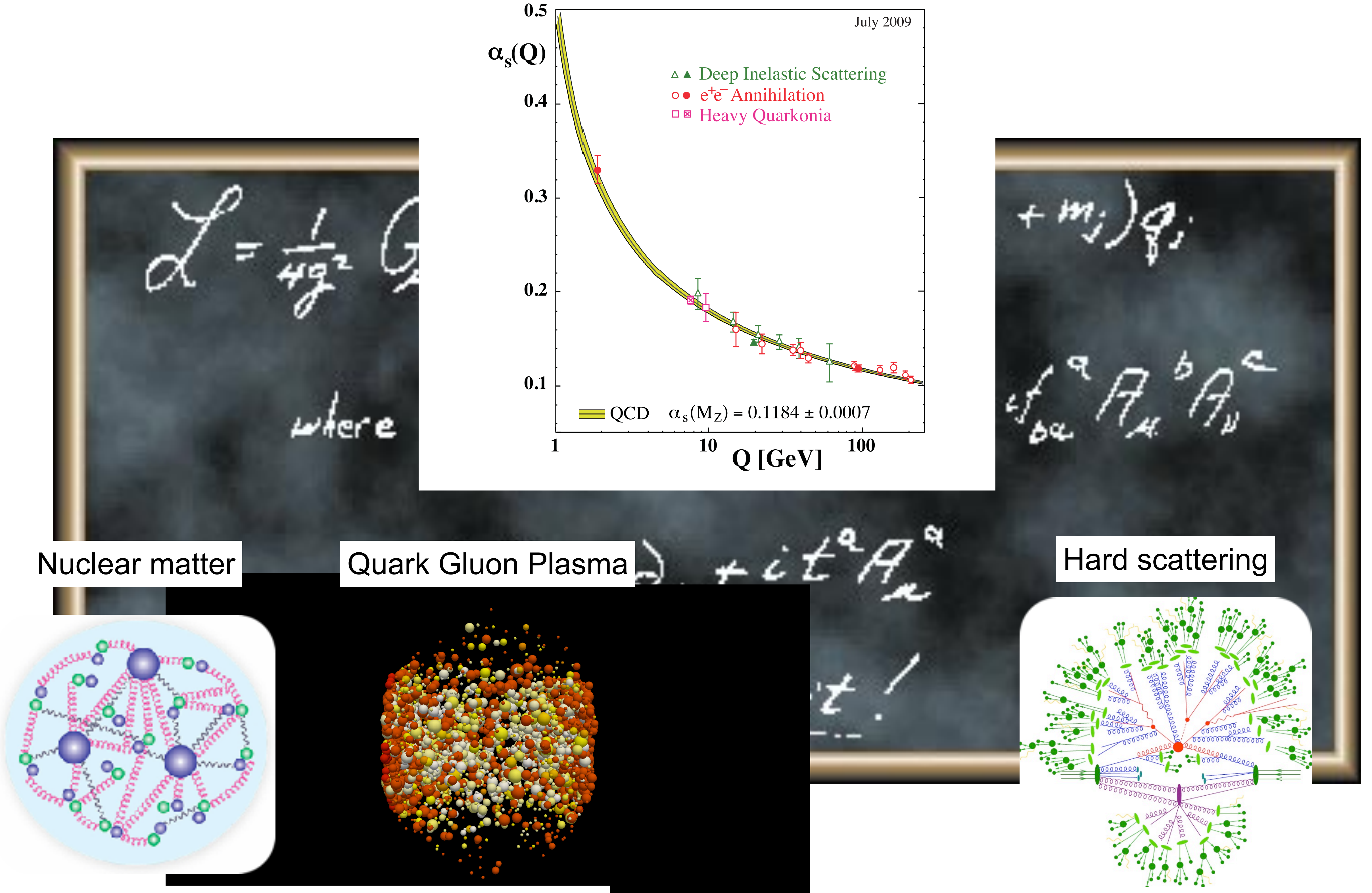
- for massless quarks and gluons the only physical scale in QCD is the confinement scale ~1 fm
  - T ~ 200 MeV
  - ε ~ 1 GeV/fm^3

At these scales the strong coupling constant becomes large

- Perturbation theory can not be applied and analytical calculations are notoriously difficult to be made
- Confinement is still poorly understood from first principles!

Better understanding of this non-perturbative domain comes from lattice QCD calculations

STUDYING QCD MATTER



Large α_s: calculations with Lattice QCD

Small α_s: calculations with perturbative QCD

LATTICE QCD CALCULATIONS

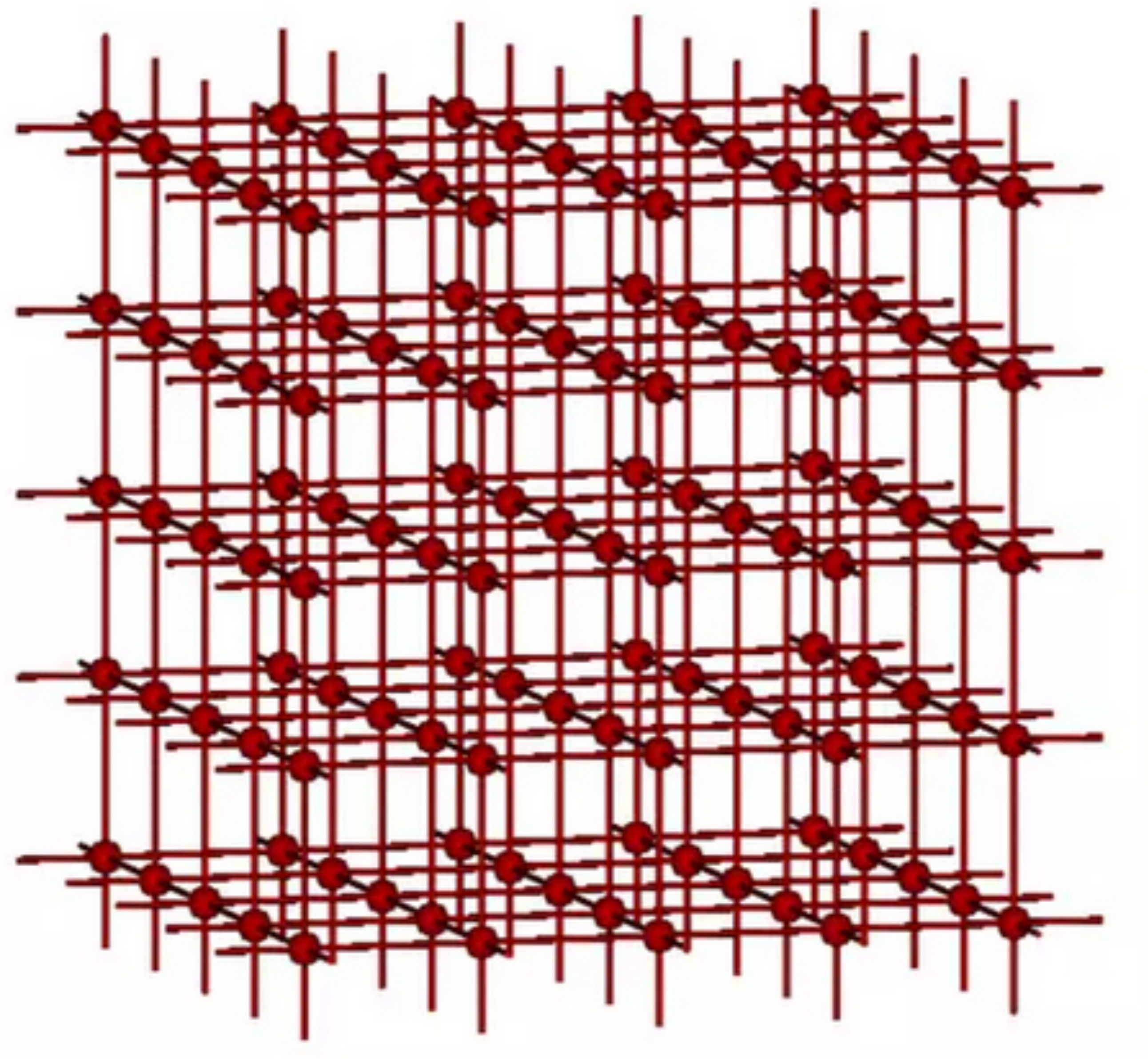
Embed a discrete space-time grid over the QCD continuum

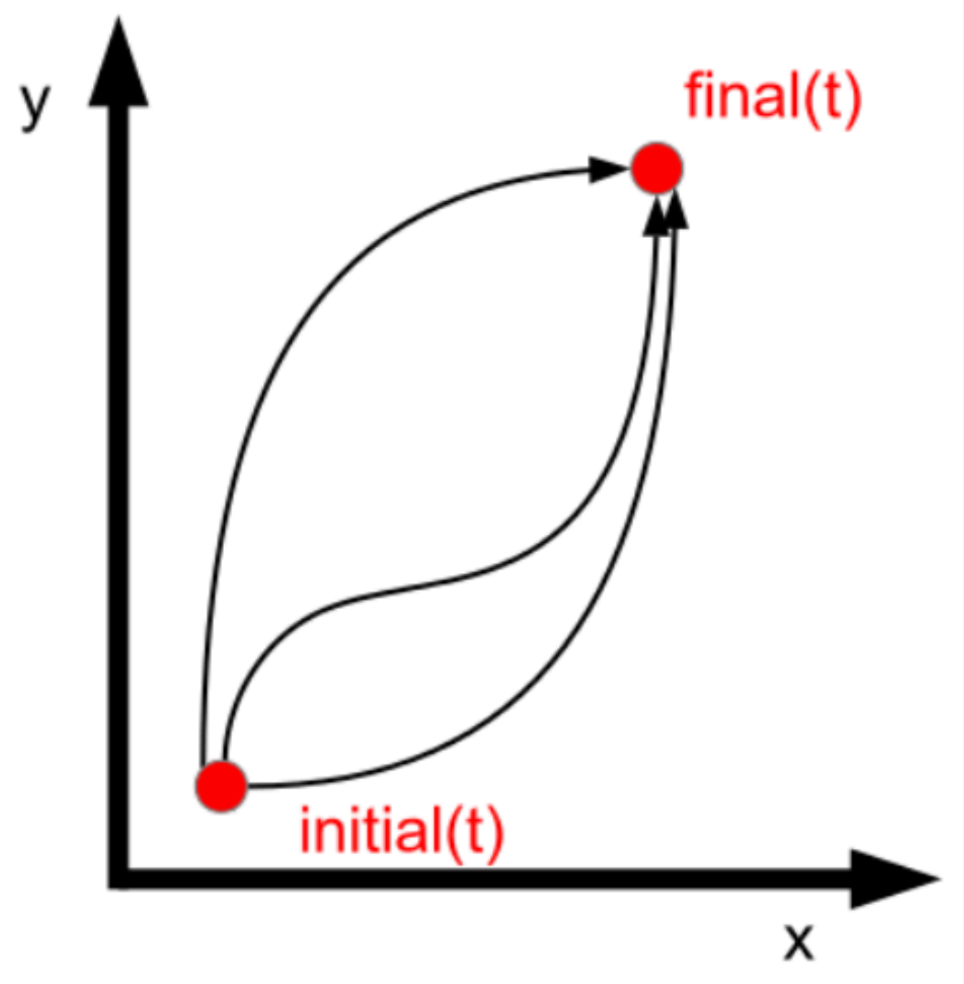
Solve QCD numerically, and enable direct comparison to experimental results

Perform Feynman's Path Integral to compute quantum expectation value of an observable O

$$\langle \mathcal{O} \rangle = \frac{1}{Z} \int \mathcal{D}U_\mu(x)\mathcal{D}\psi(x)\mathcal{D}\bar{\psi}(x) e^{-S_G + \bar{\psi}(\not{D}+m)\psi} O[\psi, \bar{\psi}, U_\mu]$$

Lattice spacing ~0.1 fm



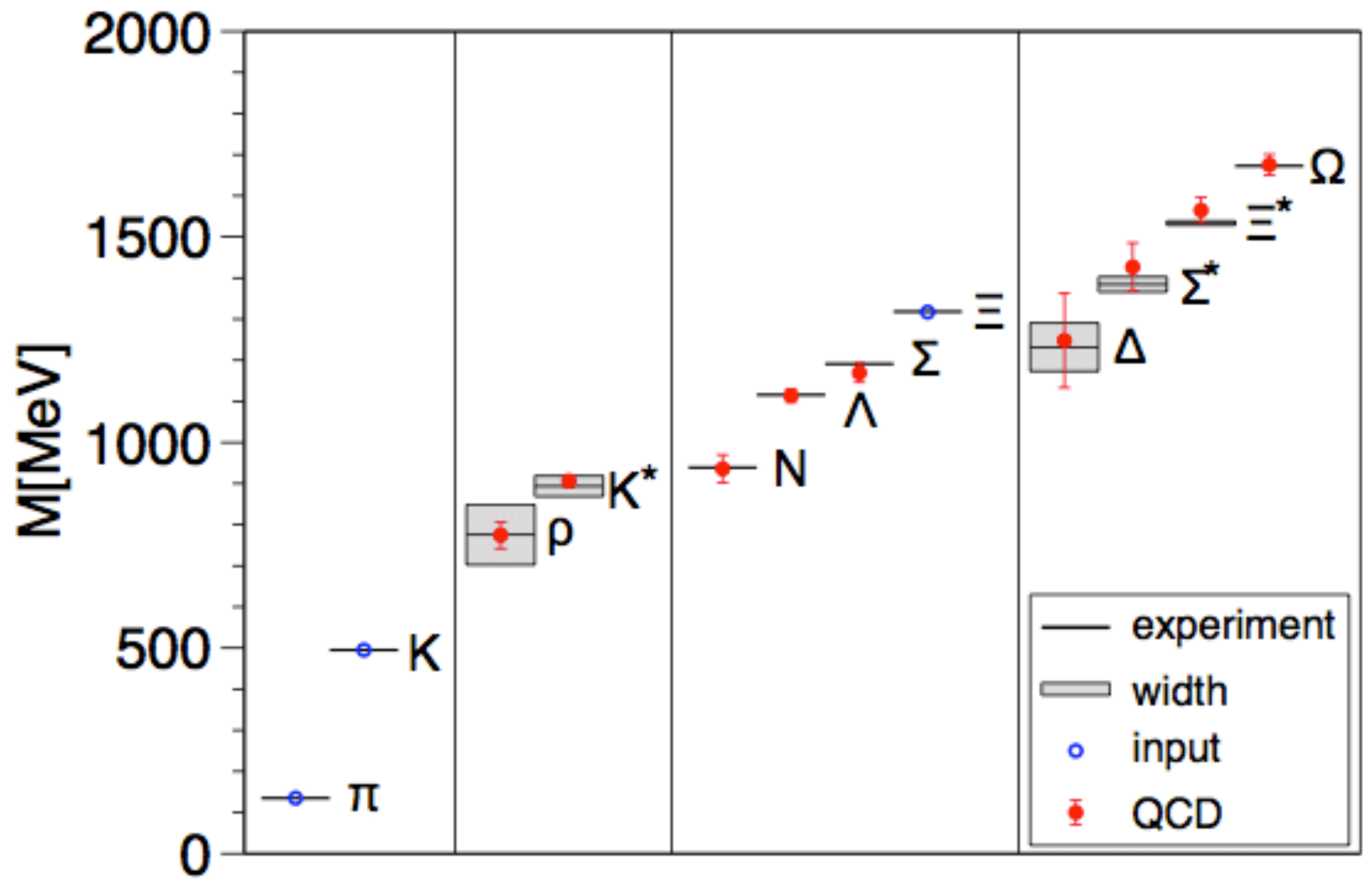


LATTICE QCD CALCULATIONS

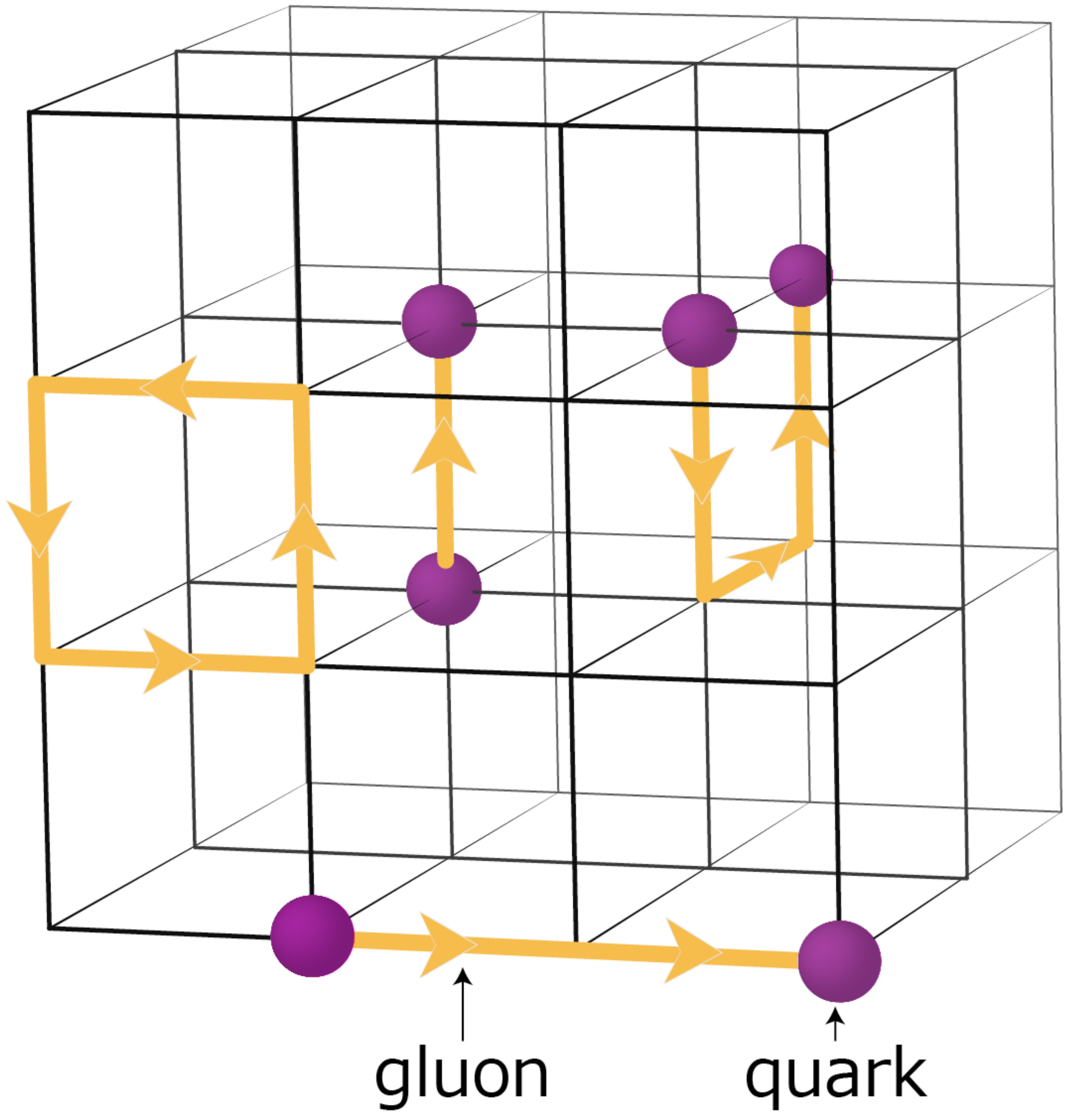
As an example ➡ calculating the proton mass on the lattice

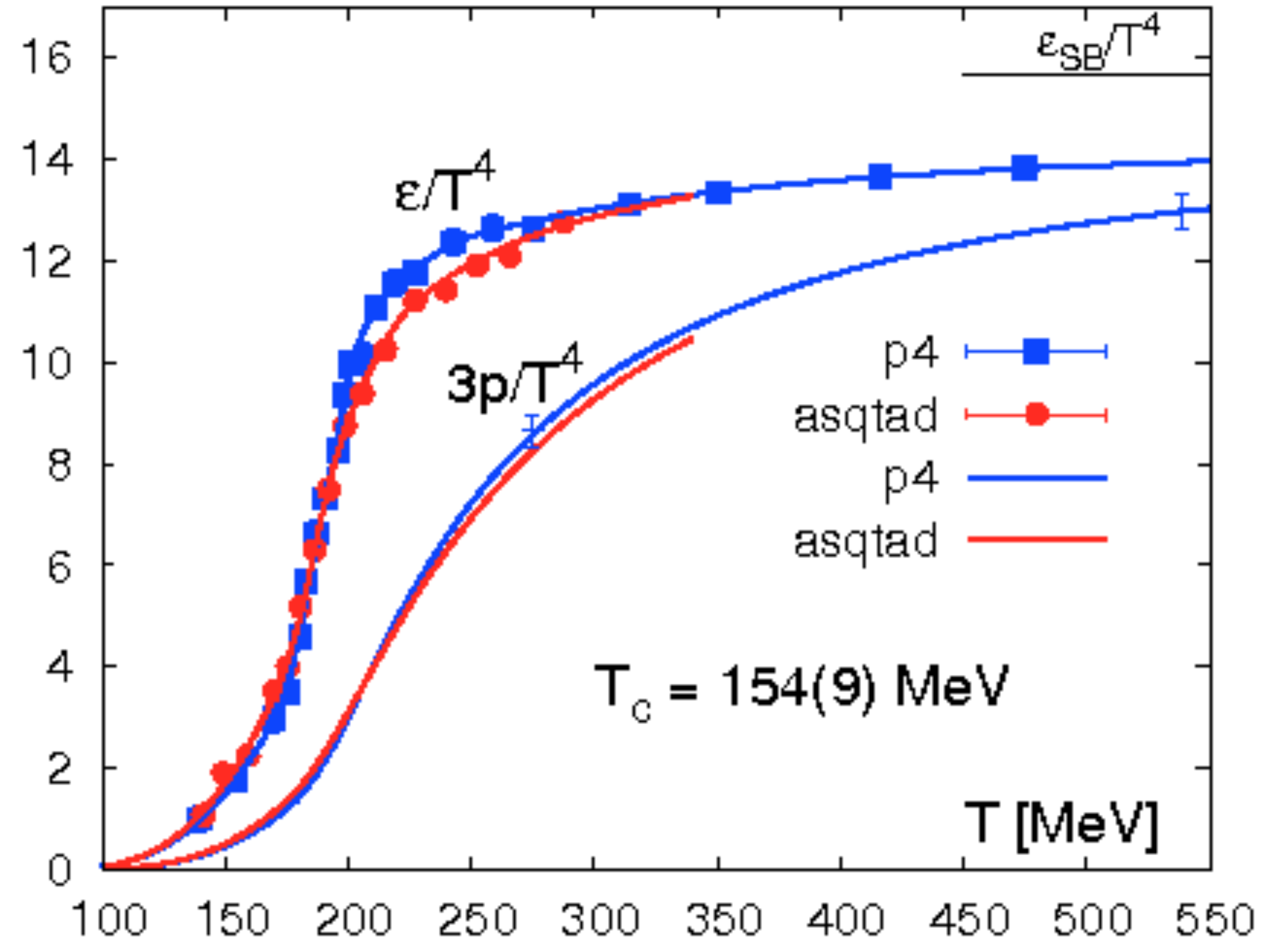
- 100-1,000 Exa floating point operations (aka flops)

  - 1020- 1021 floating operations
  - 100 days on one rack of Blue Gene / Q
  - 100-1000 years on one desktop



LATTICE QCD CALCULATIONS



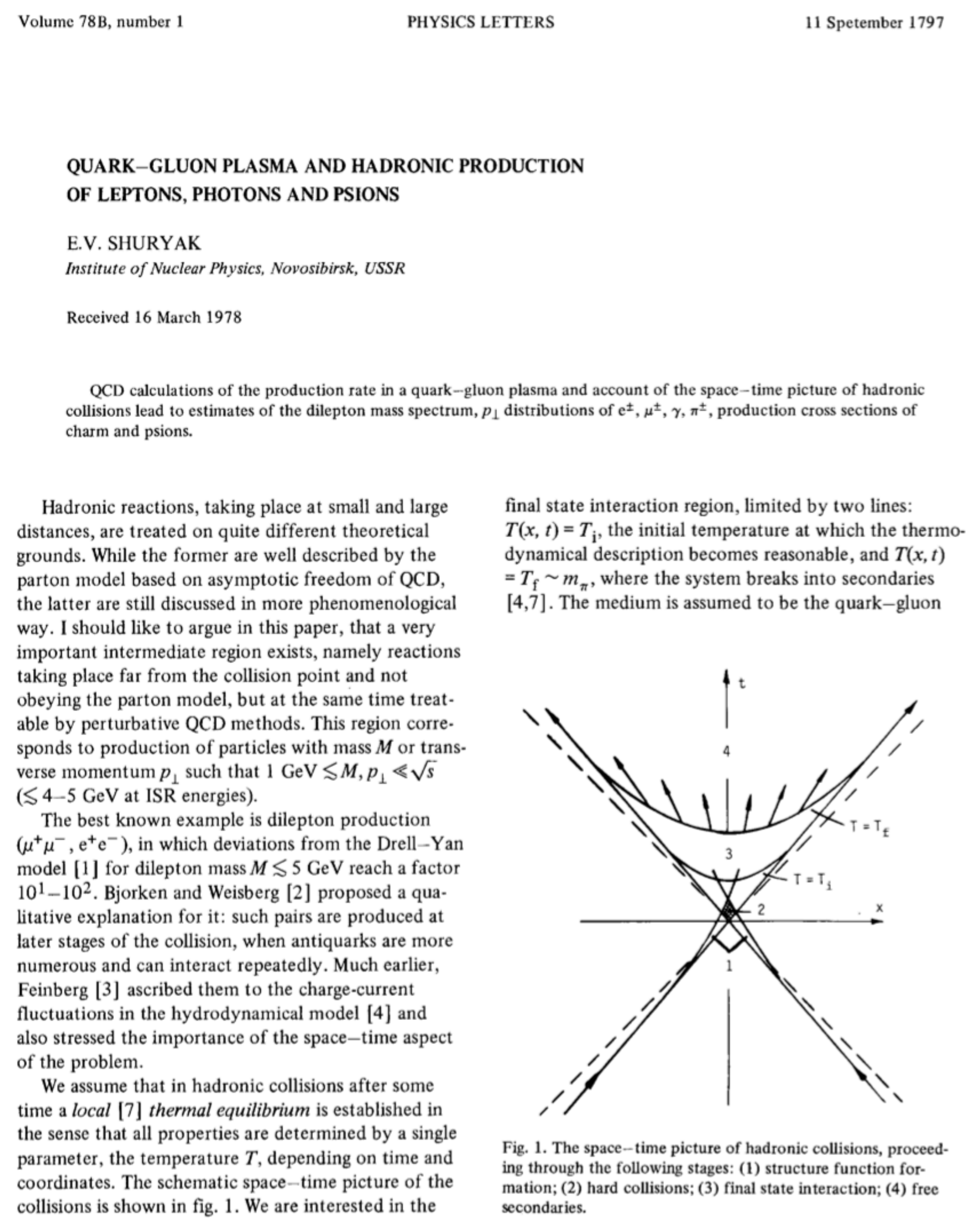


Lattice QCD: beyond a critical temperature there is a rapid rise in the number of degrees of freedom ➡ phase transition to a deconfined state of quarks and gluons!!!

Quark-Gluon Plasma (QGP)

THE 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.

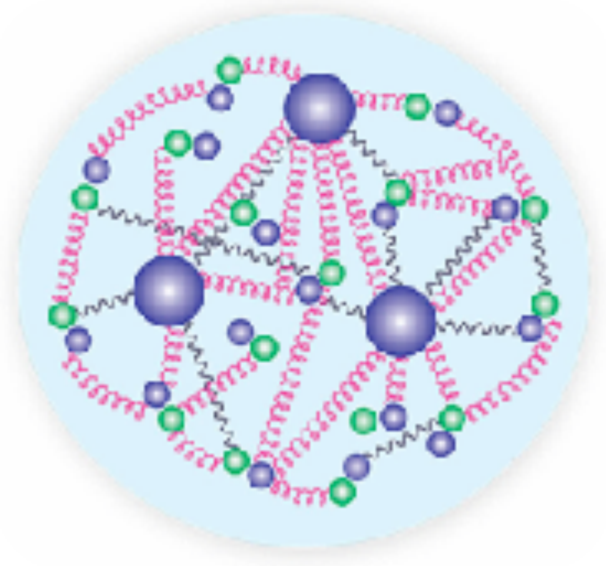
Hadronic reactions, taking place at small and large distances, are treated on quite different theoretical grounds. While the former are well described by the parton model based on asymptotic freedom of QCD, the latter are still discussed in more phenomenological way. I should like to argue in this paper, 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.

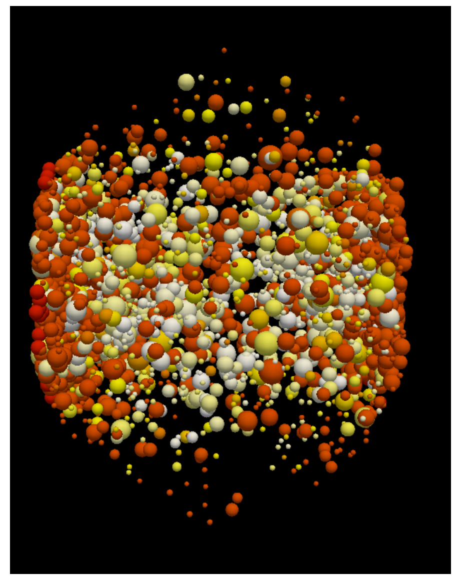
We assume that in hadronic collisions after some time a *local* [7] *thermal equilibrium* is established in the sense that all properties are determined by a single parameter, the temperature T, depending on time and coordinates. The schematic space–time picture of the collisions is shown in fig. 1. 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.

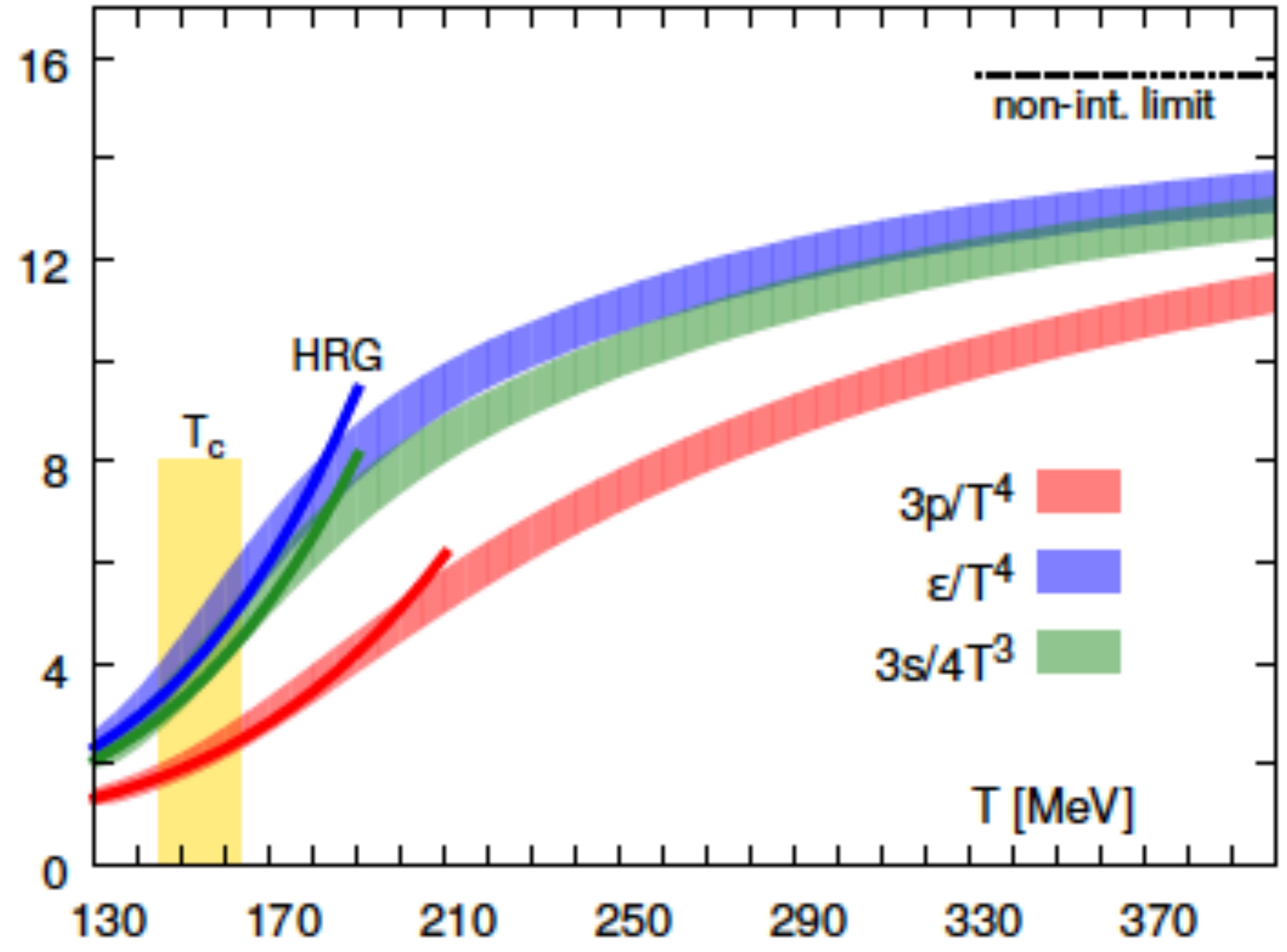
Nuclear matter



Quark Gluon Plasma

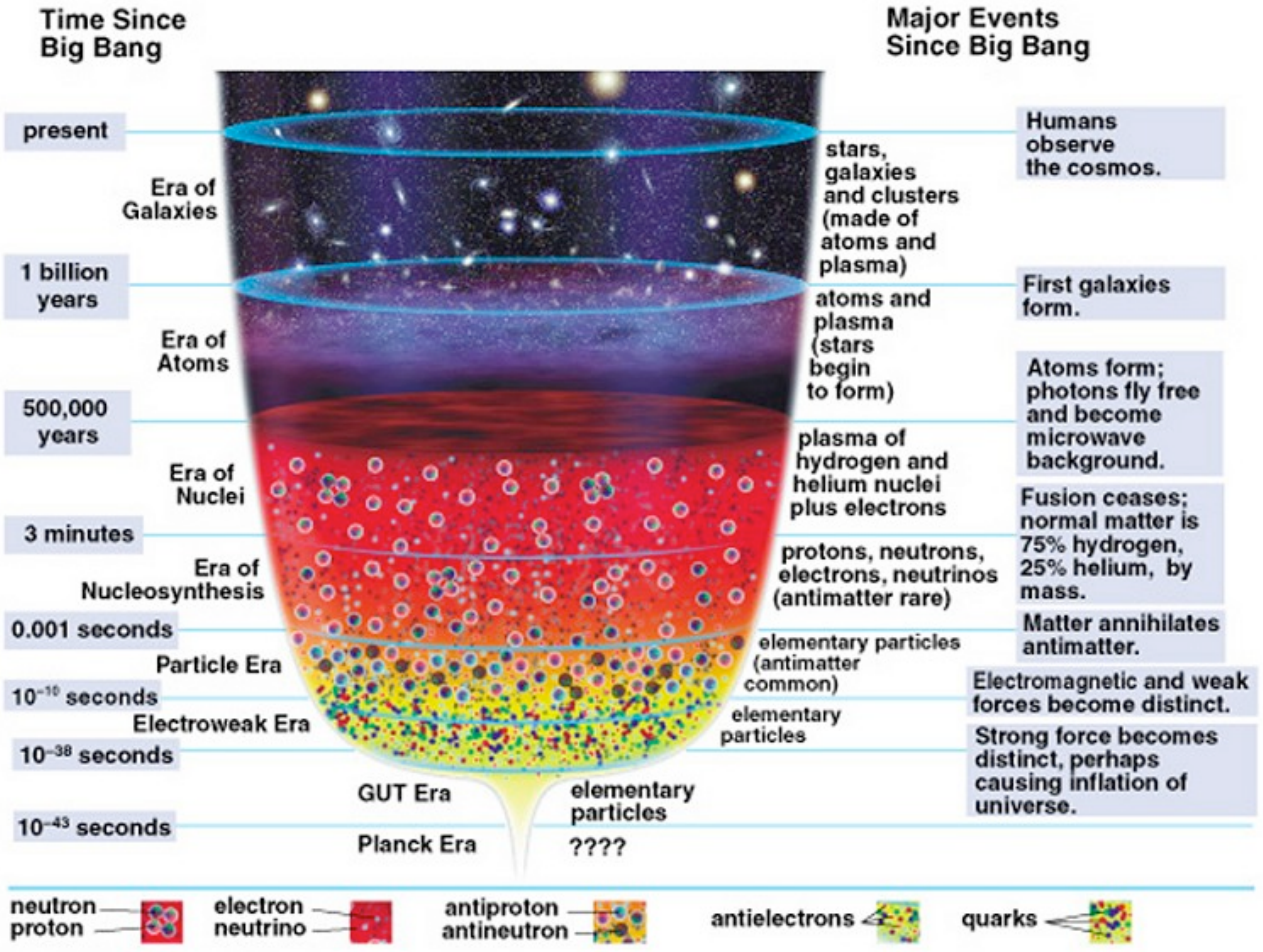


HotQCD Collaboration:
Phys.Rev. **D90**, (2014) 094503

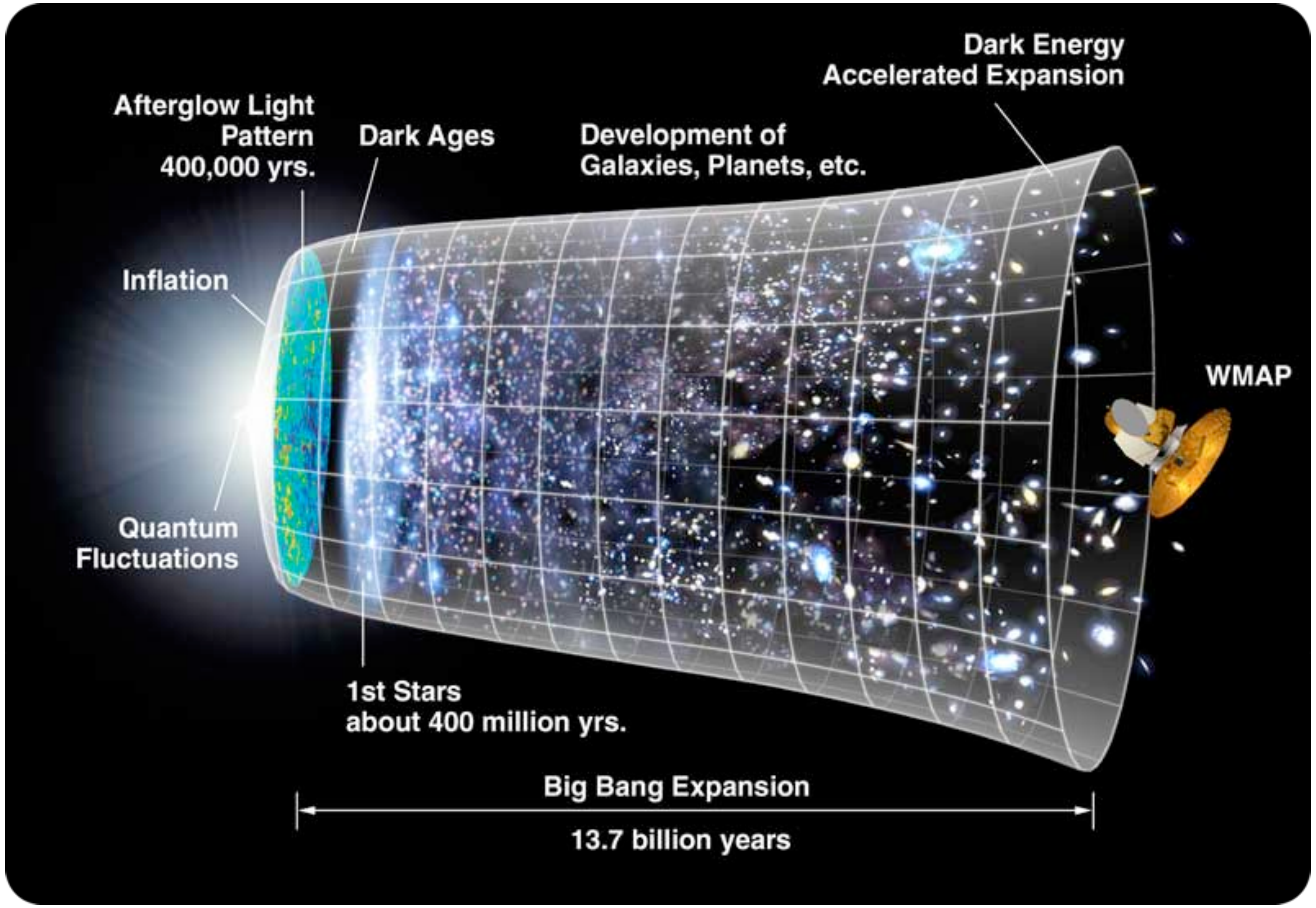


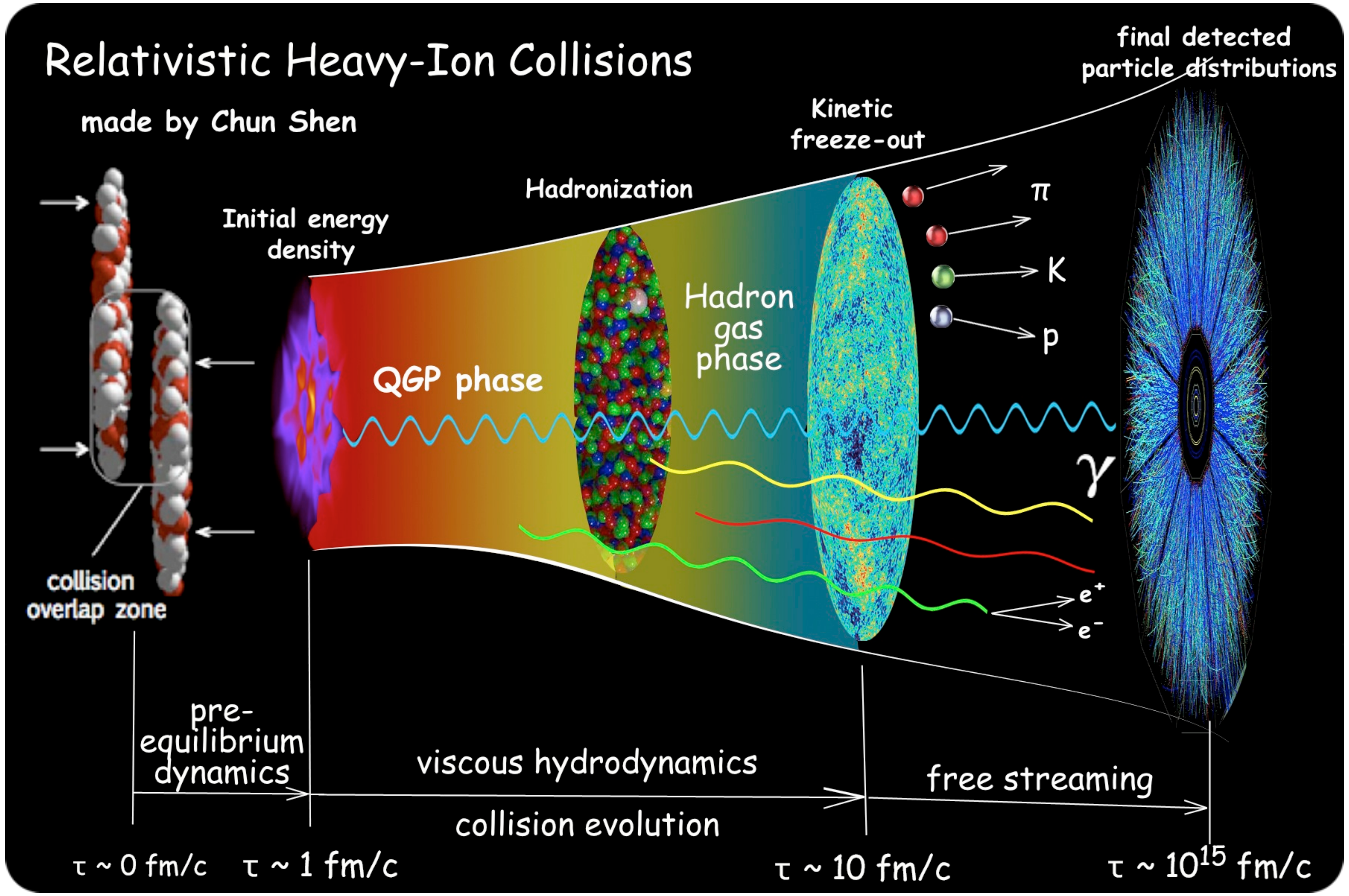
Phase transition beyond a critical temperature (~155 MeV) and energy density (~0.5 GeV/fm^3)

QGP: PRIMORDIAL MATTER



STRONG PHASE TRANSITION IN THE LAB





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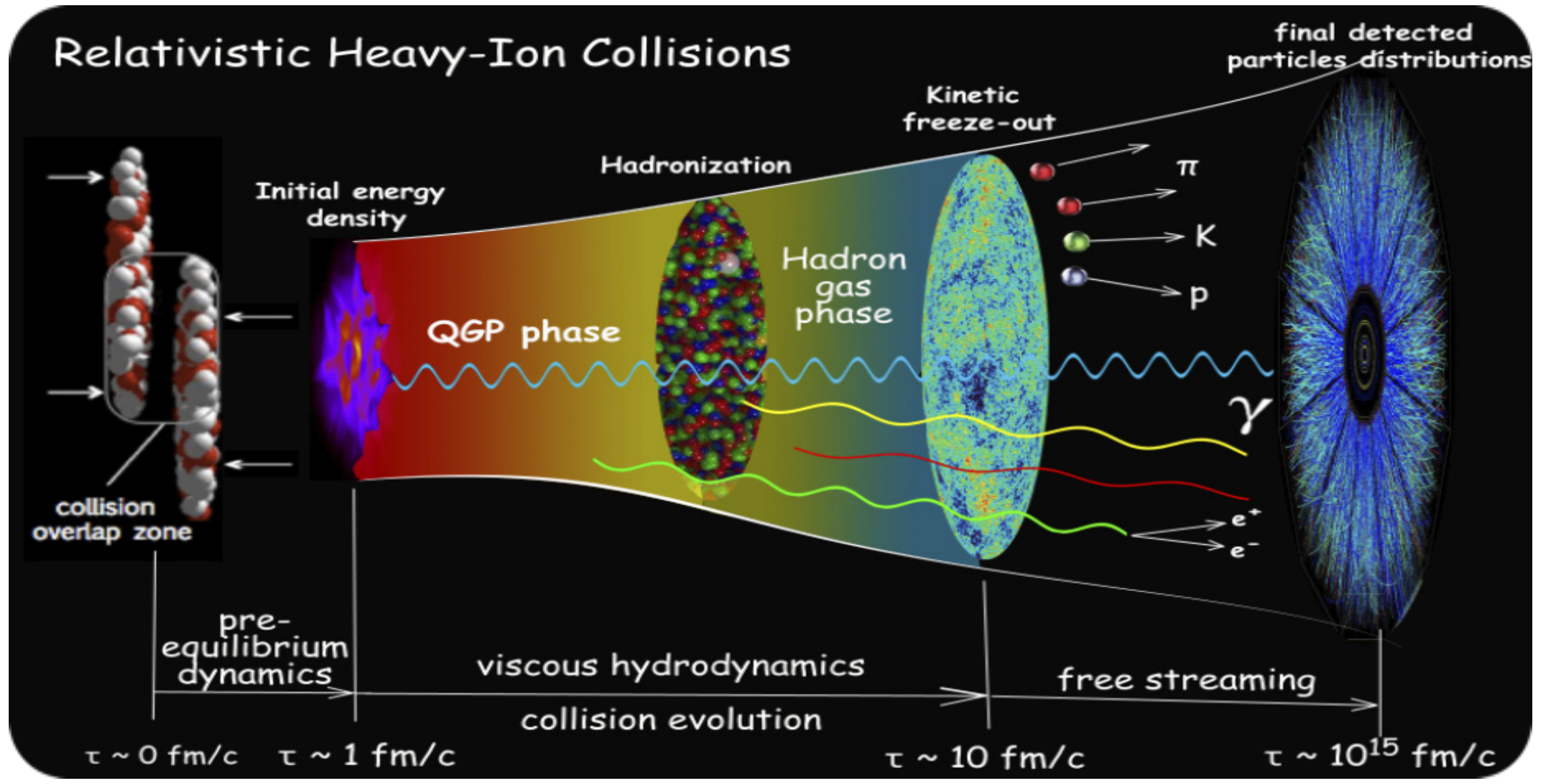
STRONG PHASE TRANSITION IN THE LAB



$T_{(QGP\text{-}transition)}$~170MeV → 10^{12} degrees

$T_{(Sun's\ core)}$~10^7 degrees

↓

$T_{(QGP\text{-}transition)}$ 10^5x$T_{(Sun's\ core)}$

The Quark-Gluon Plasma (QGP):

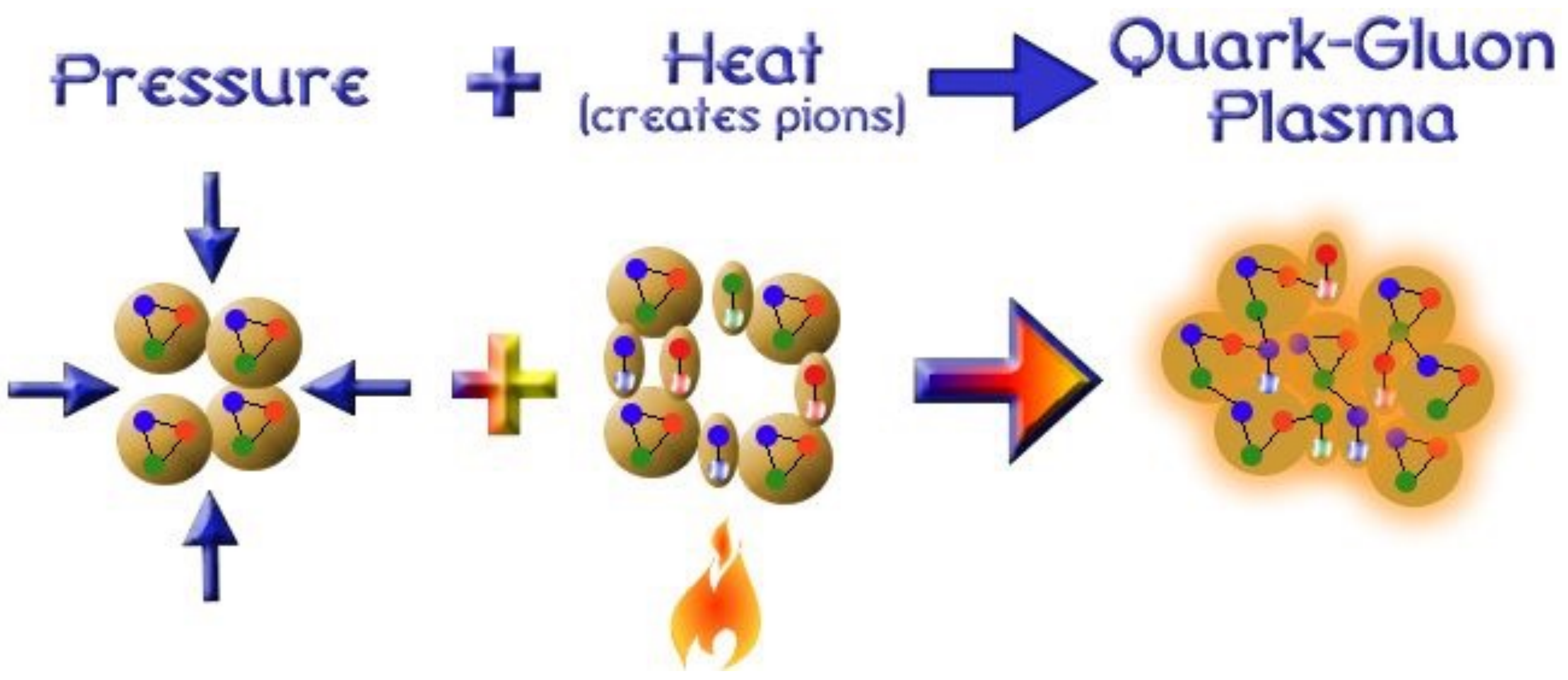
- a state of matter where the quarks and gluons should eventually be the relevant degrees of freedom
- existed few μs after the Big-Bang (the universe crossed this phase after expanding and cooling down): Studying the strong phase transition → study primordial matter
- QCD: Phase transition beyond a critical temperature (~170 MeV) and energy density (~0.5 GeV/fm^3) → accessible in the laboratory → heavy-ion collisions

Can we constrain the equation of state and the transport properties of QGP?

STRONG PHASE TRANSITION IN THE LAB

How can we recreate in the laboratory the necessary conditions for the phase transition to occur?

- “Smash” large objects, accelerated at almost the speed of light to each other
  - Concentrate large amount of energy in a small volume
  - Create high pressure
  - Create high temperatures



Heavy-ion collisions!!!

HEAVY ION PHYSICS PROGRAM

Some of the topics could have (direct) connections to GW physics

Thermodynamics description of the medium, using macroscopic quantities

- EoS, V, T, ε, η/s, …

Understand the microscopic details of the matter formed

- Can we resolve quarks and gluons as the degrees of freedom?

(non-QGP focused) QCD studies

- Parity violation in strong interactions
- Strong interaction potentials

Full Application - NWO Open Competition Domain Science - XL, 2021-2022

NWO Open Competition Domain Science - XL Round 2021-2022

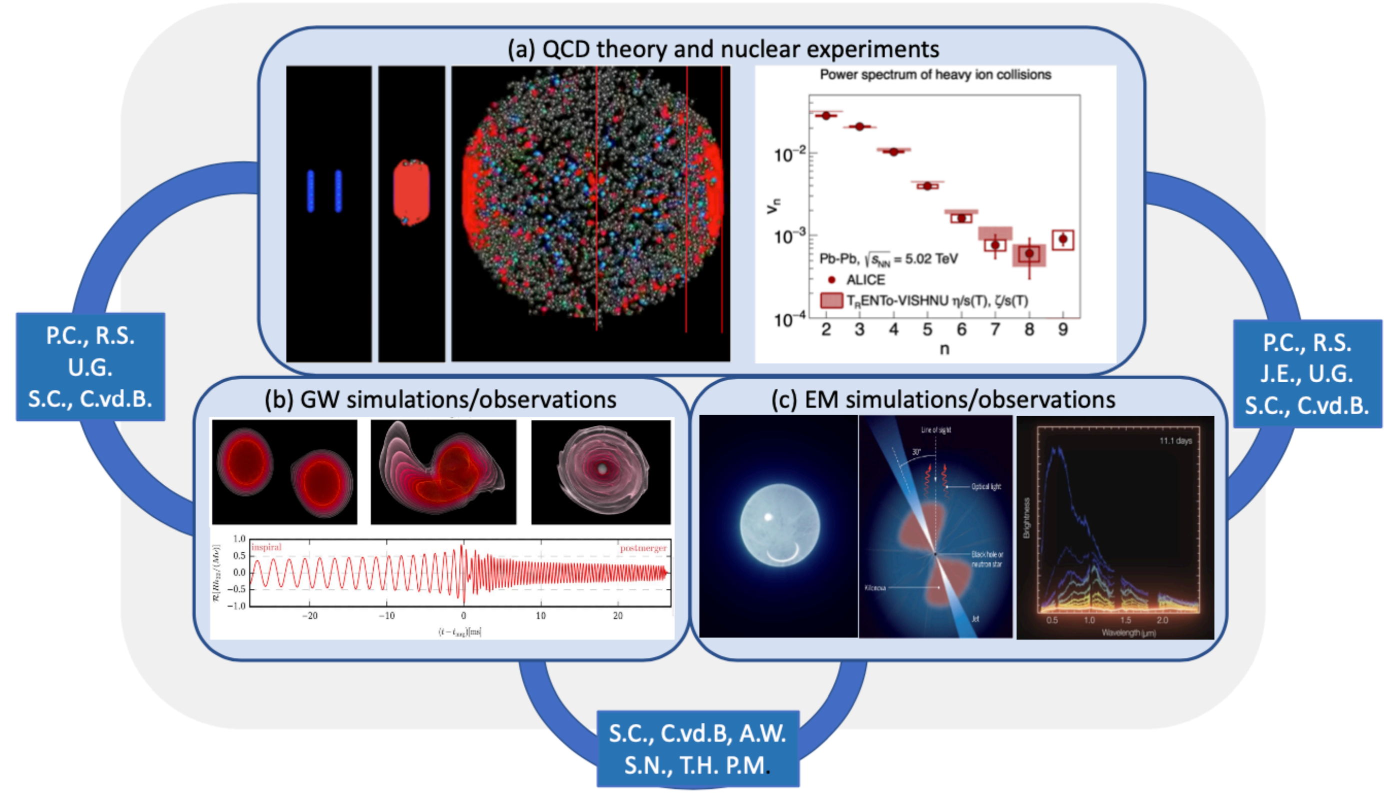
Grant application form

PART A: Scientific proposal

A.1 General information

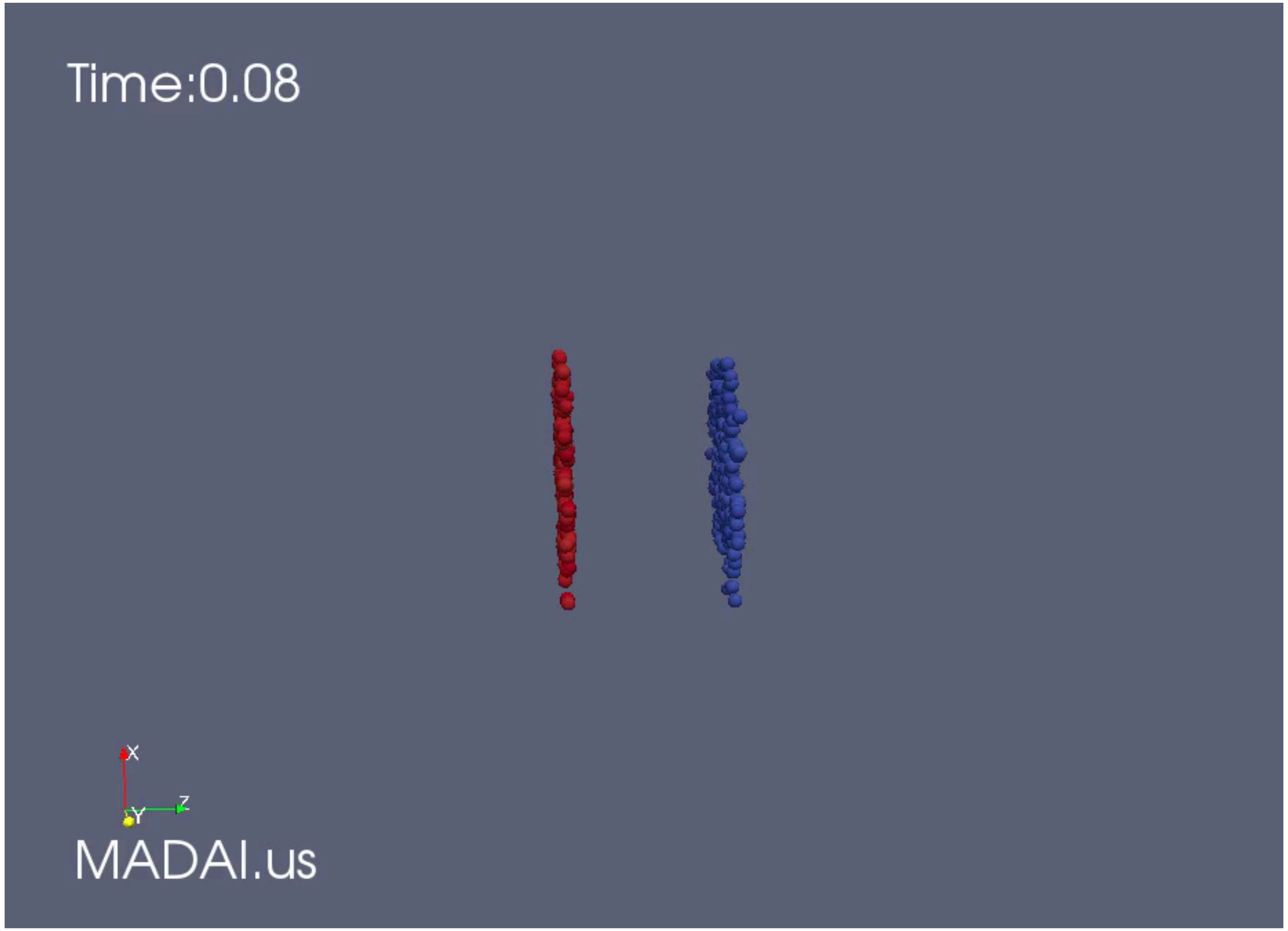
A.1.1 Grant application title

Probing the phase diagram of quantum chromodynamics

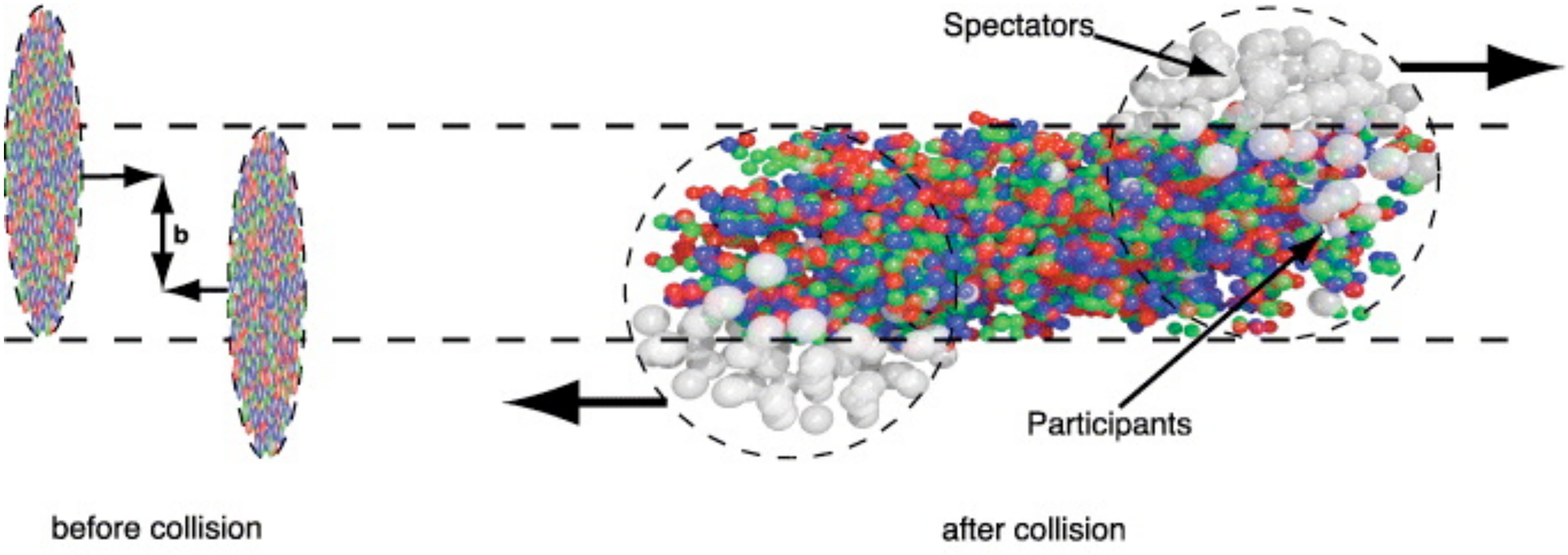


Need to study as many observables as possible as a function of centrality

SIMULATION



CENTRALITY IN HEAVY ION COLLISIONS

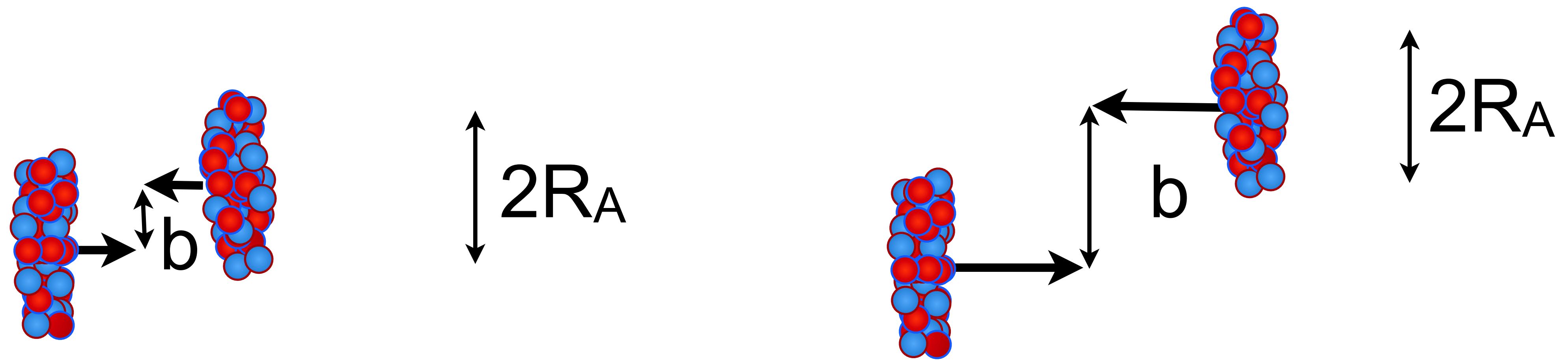


DEFINING CENTRALITY: IMPACT PARAMETER

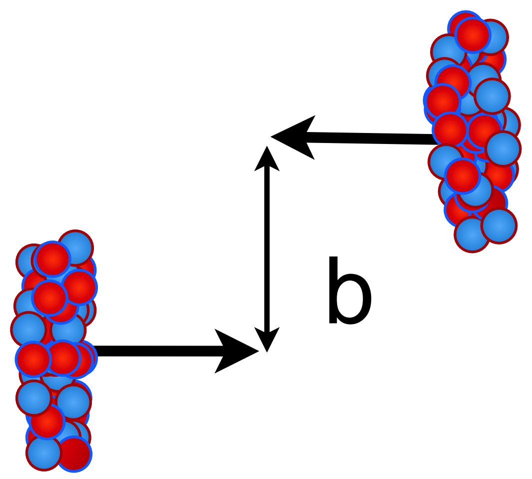
Heavy ions are not point-like objects

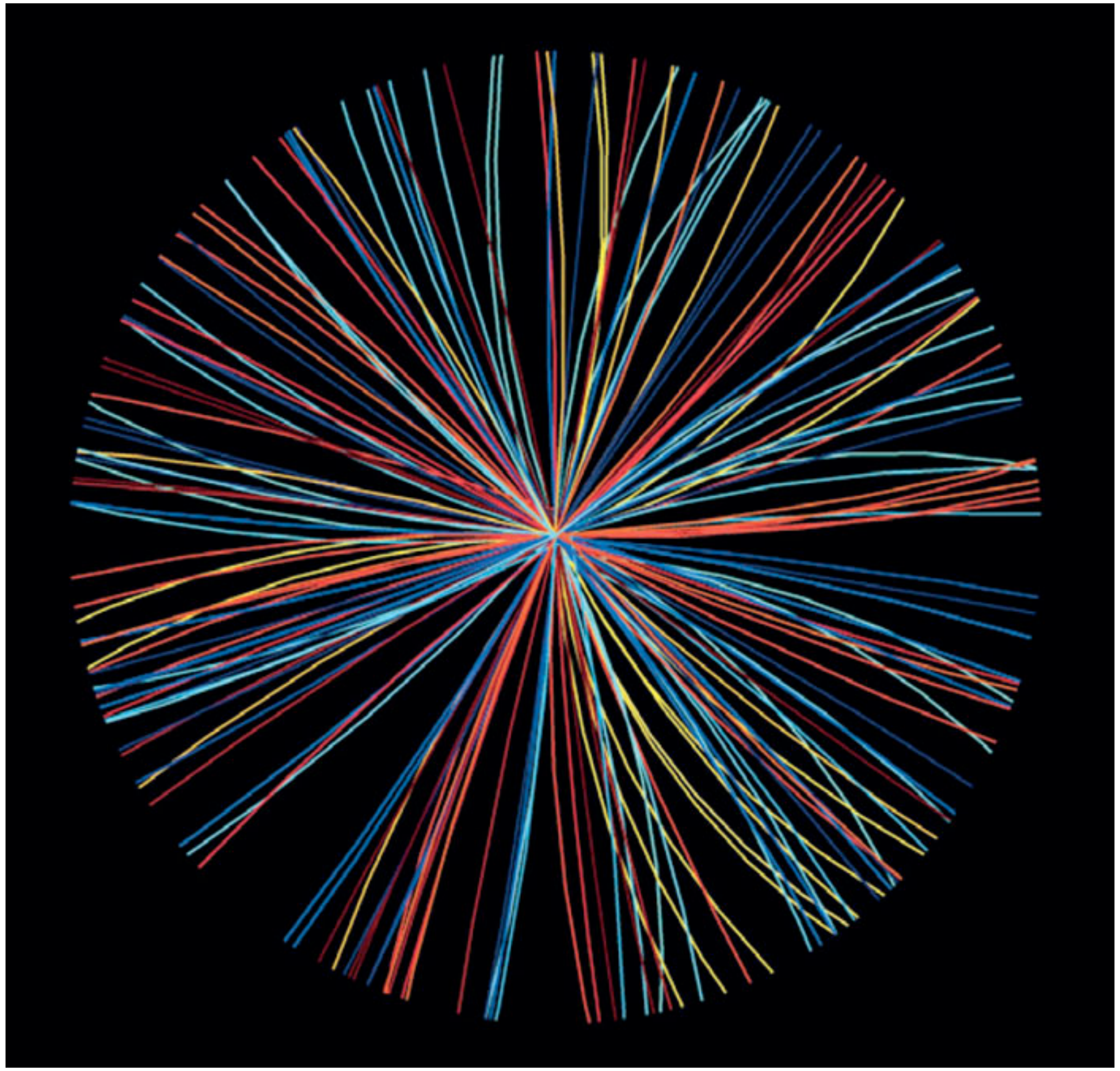
- Collisions can create systems with different properties depending on whether they are head-on (i.e. large overlap region) or if the nuclei graze each other (i.e. small overlap region)
- Centrality defined geometrically by the impact parameter b
  - Distance between the centres of the two nuclei
  - Perpendicular to the beam axis
- Centrality related to the fraction of the geometrical cross-section that overlaps
  - proportional to $\pi b^2/\pi(2R_A)^2$

Experimentally centrality defined from particle multiplicity or energy deposited in (forward) detectors

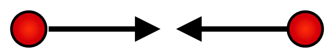


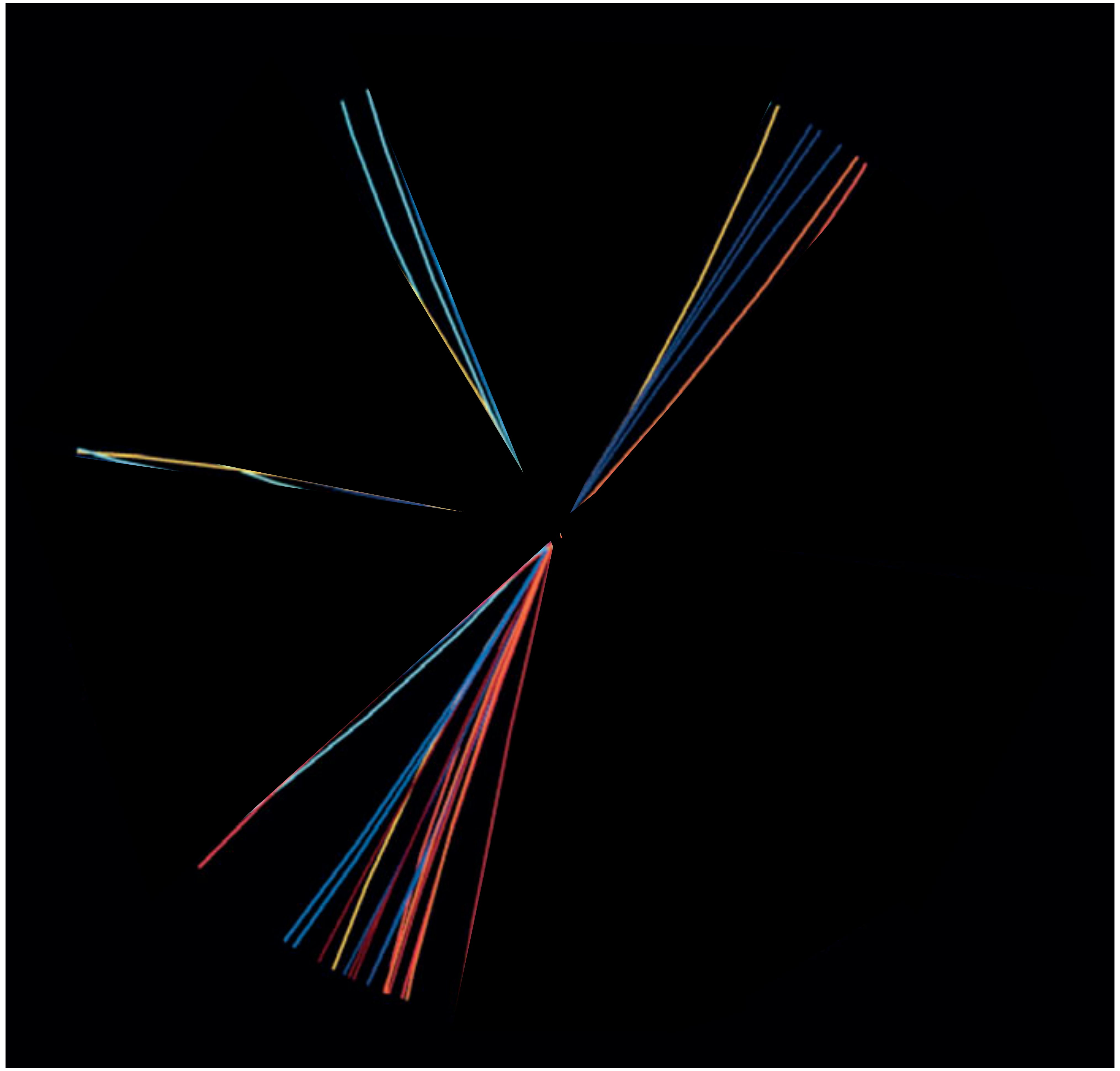
PERIPHERAL COLLISIONS: FEW PARTICLES



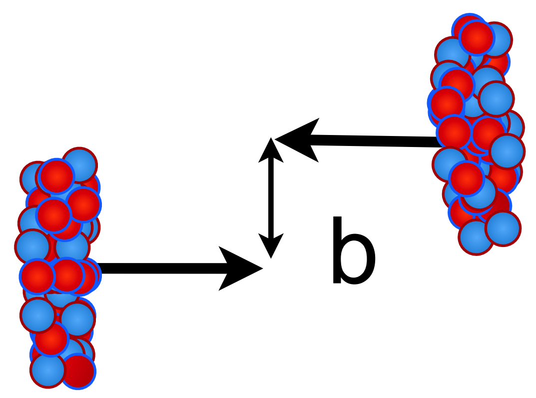


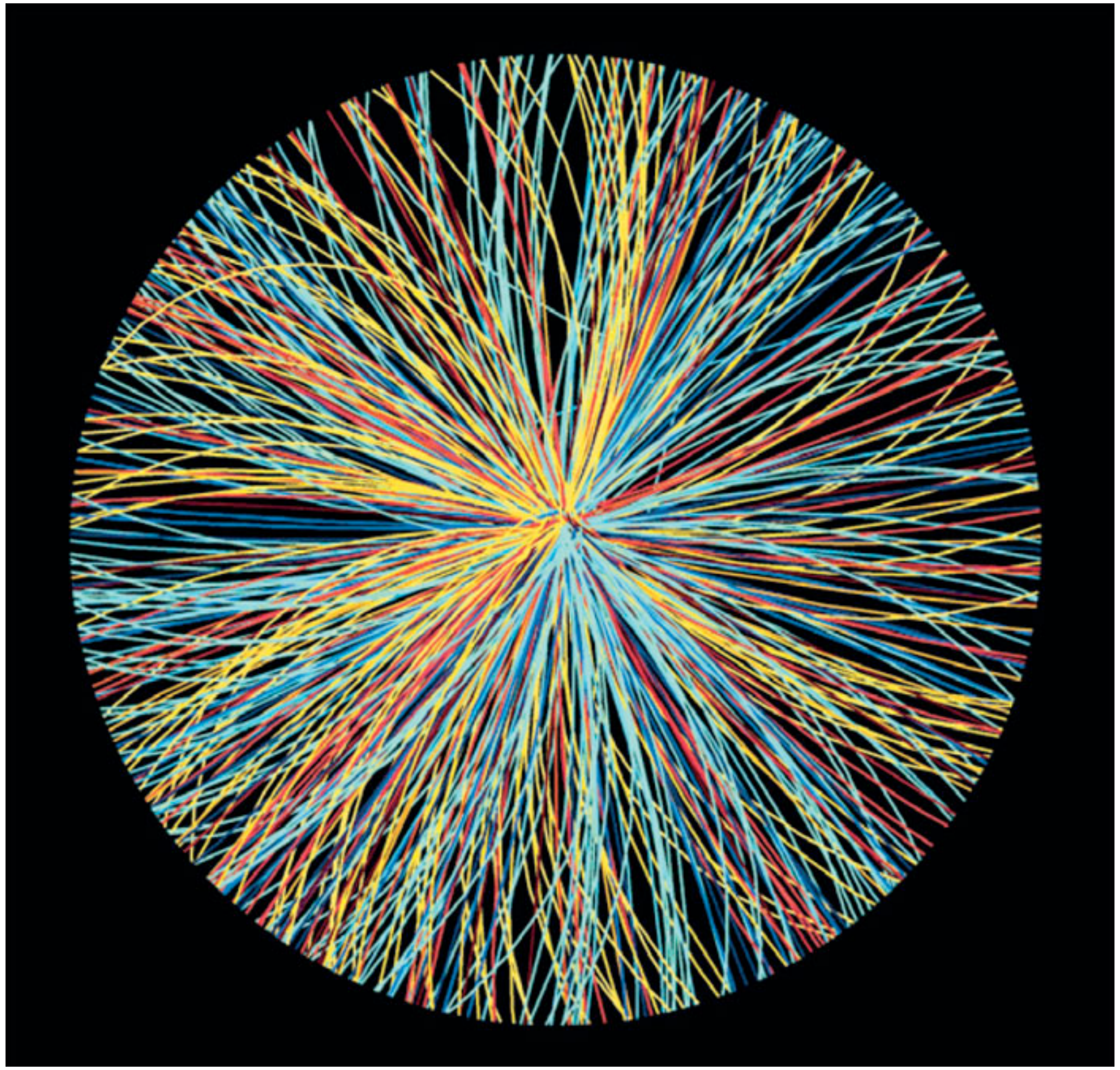
PROTON-PROTON: VERY FEW PARTICLES



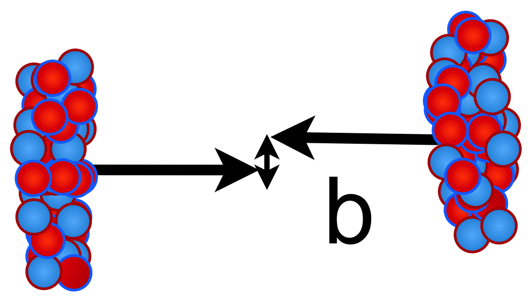


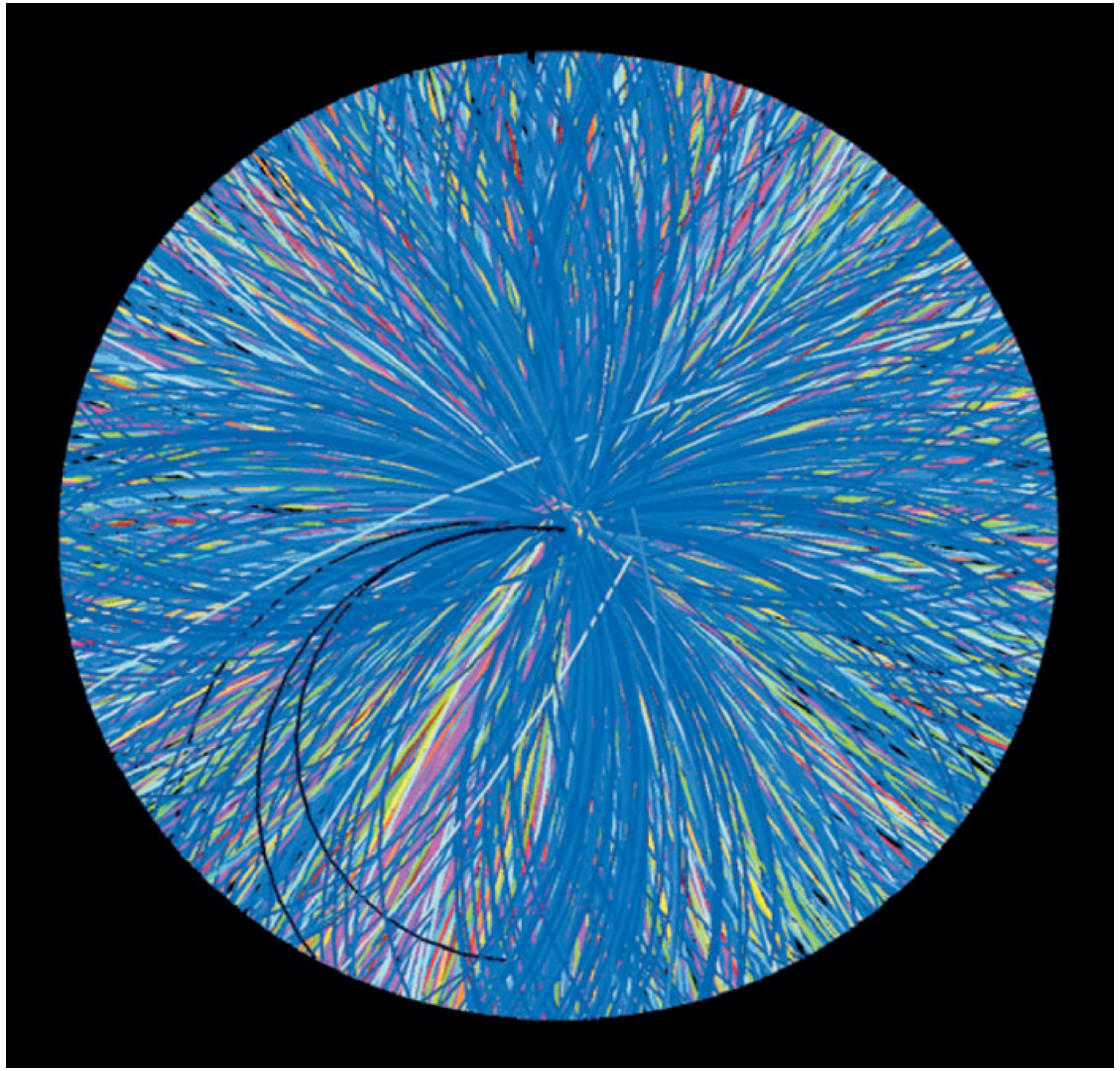
MID-CENTRAL COLLISIONS: MORE PARTICLES



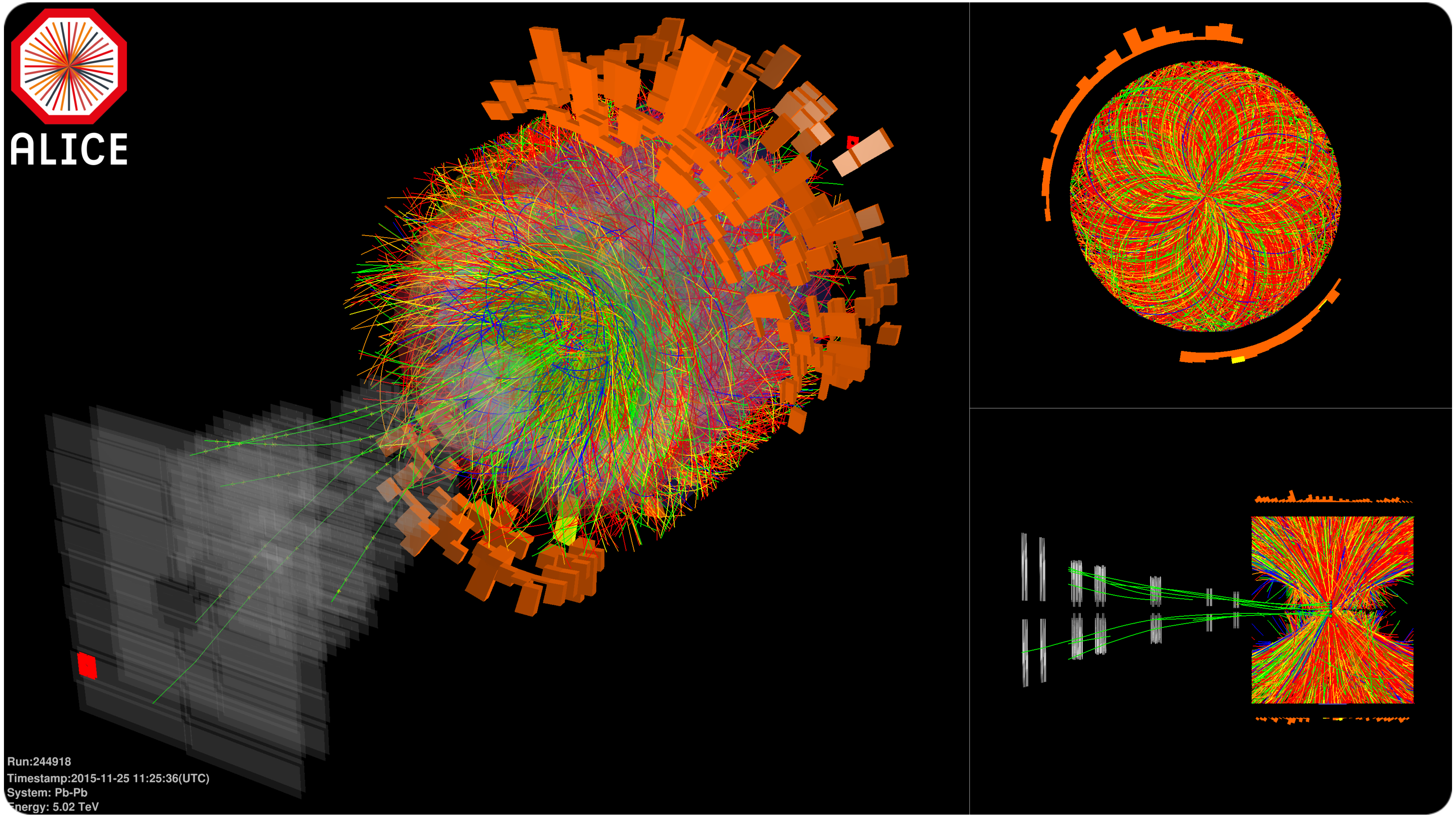


CENTRAL COLLISIONS: EVEN MORE PARTICLES

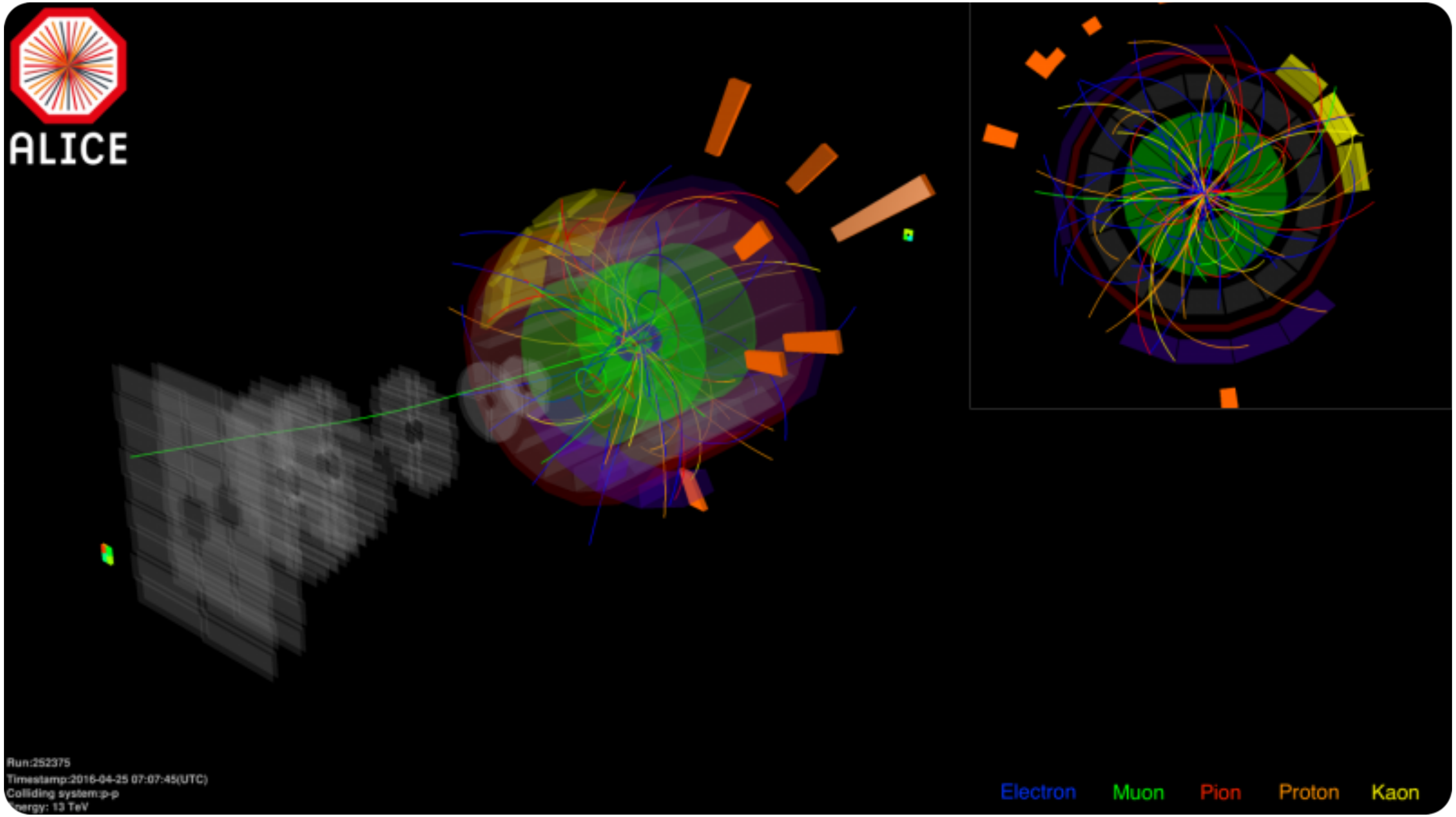




MULTIPLICITY IN CENTRAL COLLISIONS

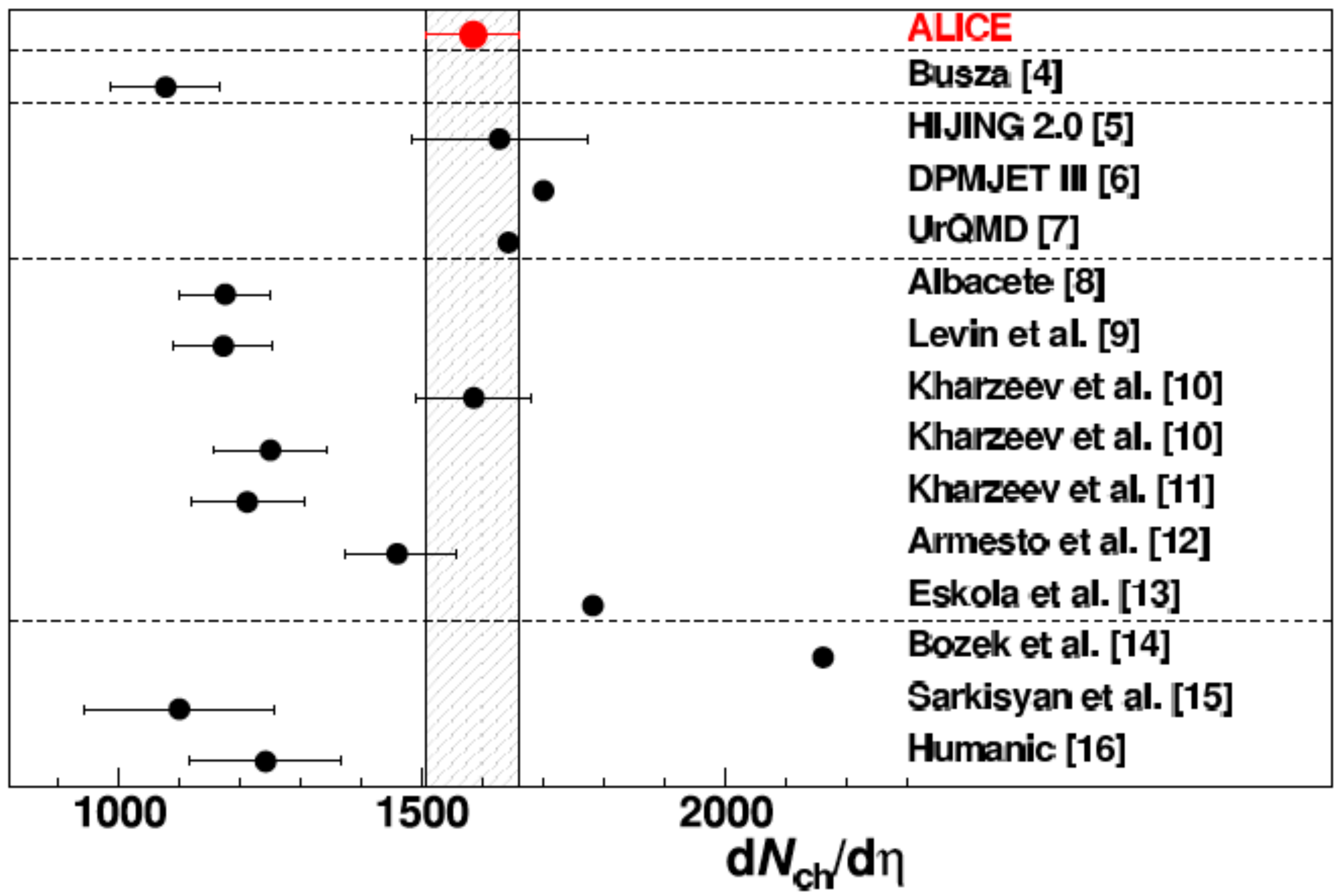


MULTIPLICITY IN PROTON-PROTON COLLISIONS



MEASURED MULTIPLICITY IN CENTRAL COLLISIONS

ALICE Collaboration, Phys. Rev. Lett. **105**, 252301 (2010)



~1600 particles in the central region (not the whole phase space) in central Pb-Pb collisions!!!

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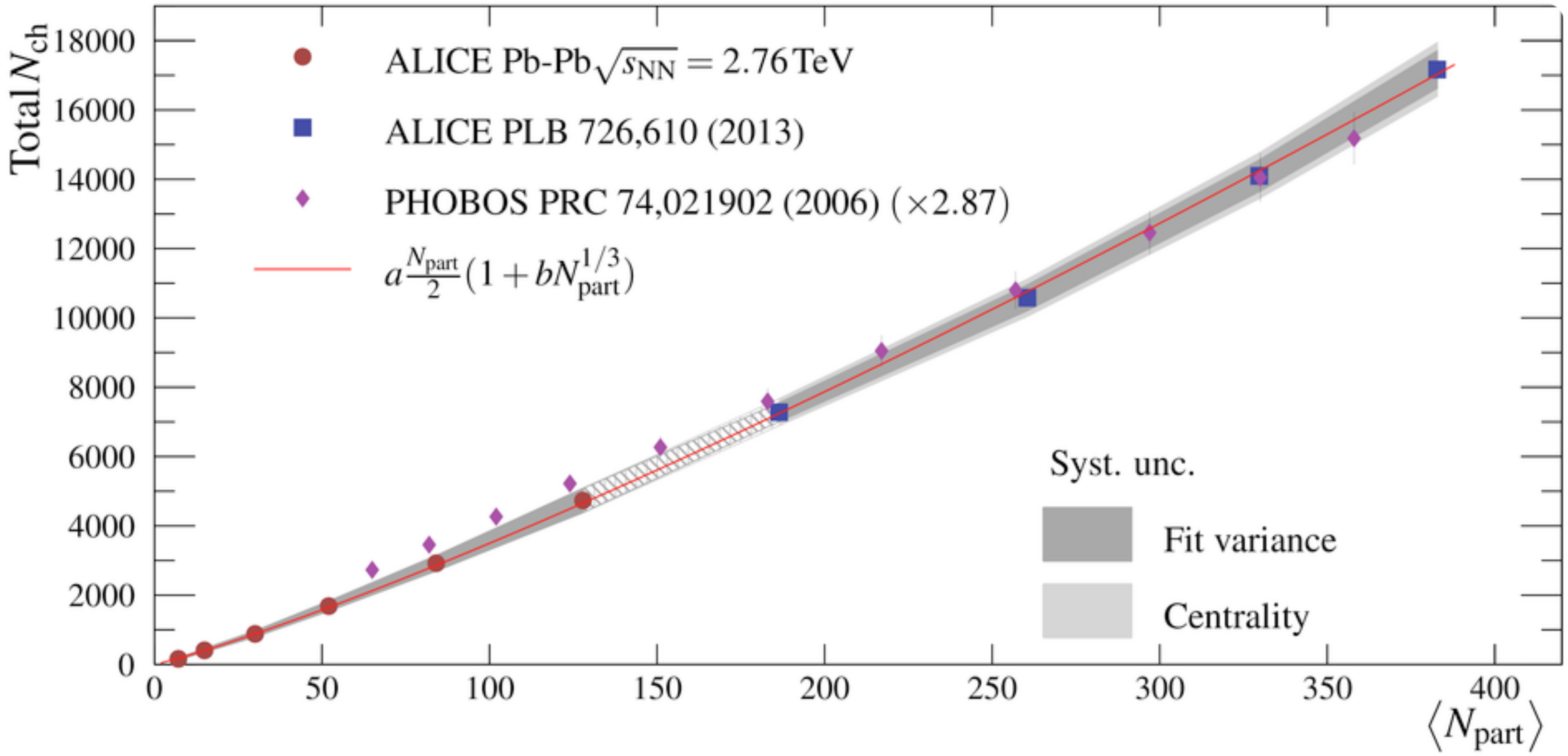
TOTAL PARTICLE MULTIPLICITY

ALICE Collaboration, Phys. Lett. **B754** (2016) 373



NUMBER OF PARTICIPANTS, SPECTATORS

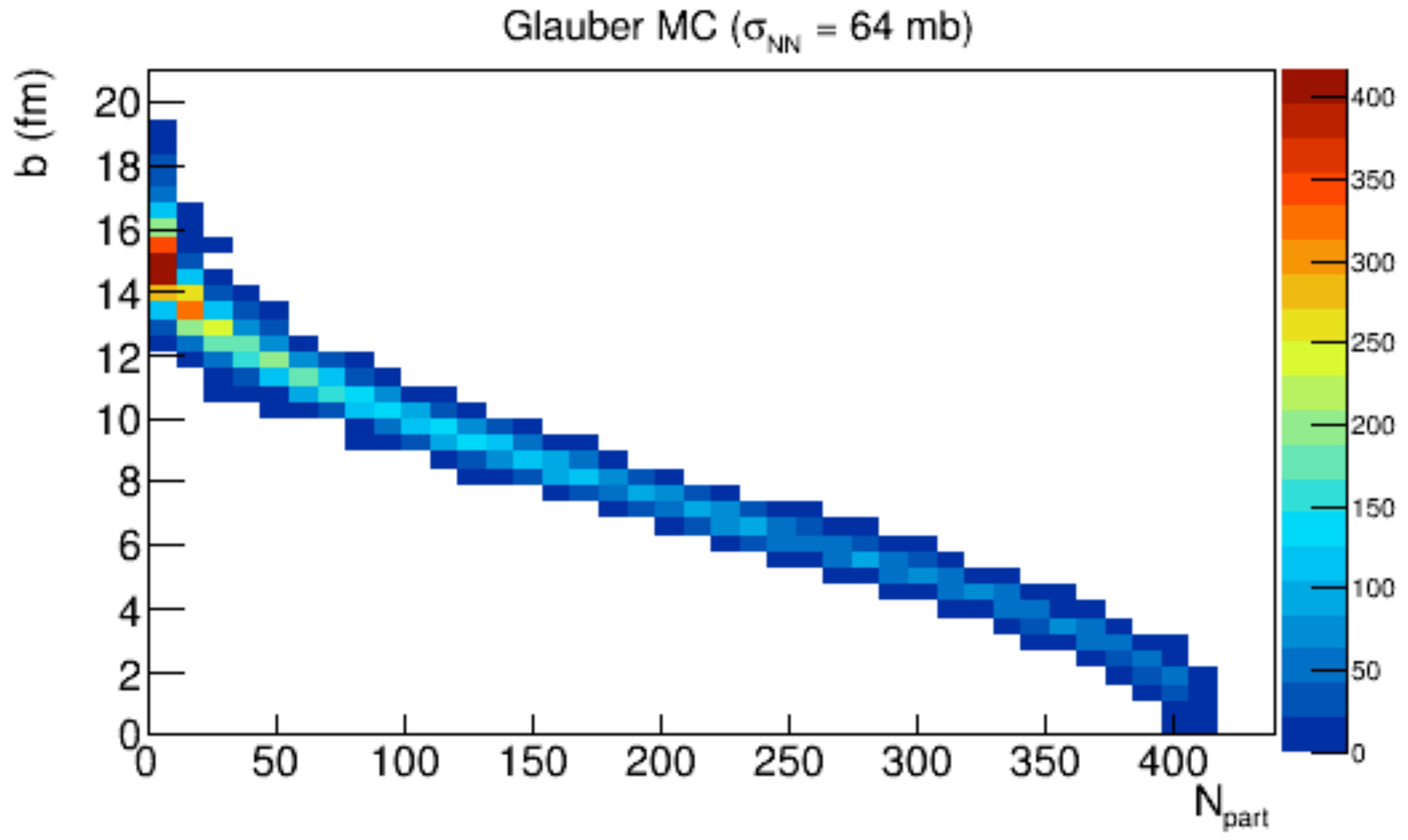
Number of participants (N_{part}): nucleons undergoing at least one collision

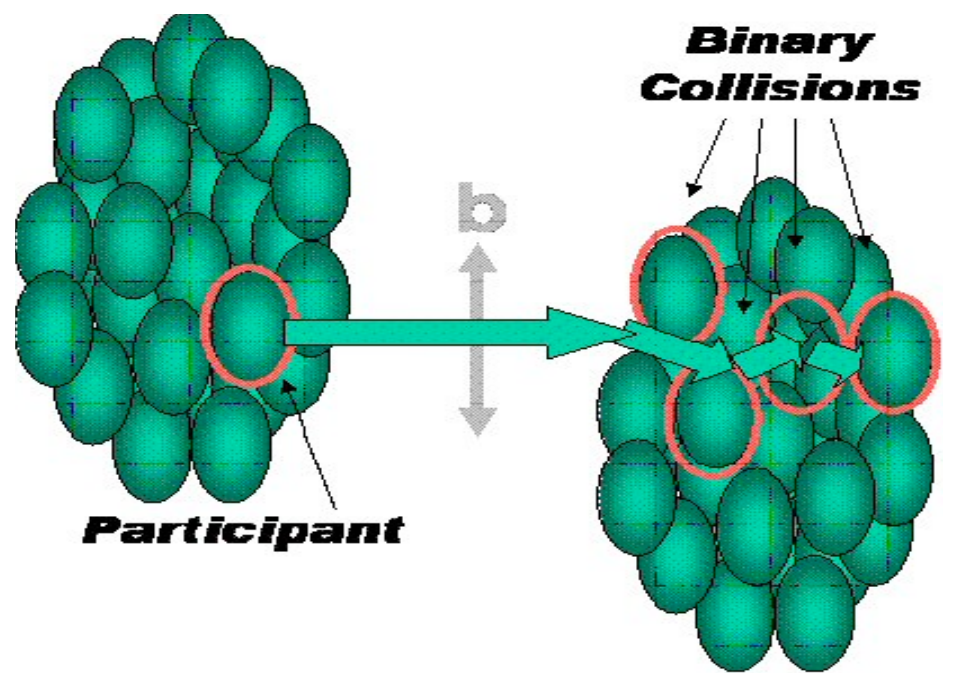
- Scale with volume ~2A

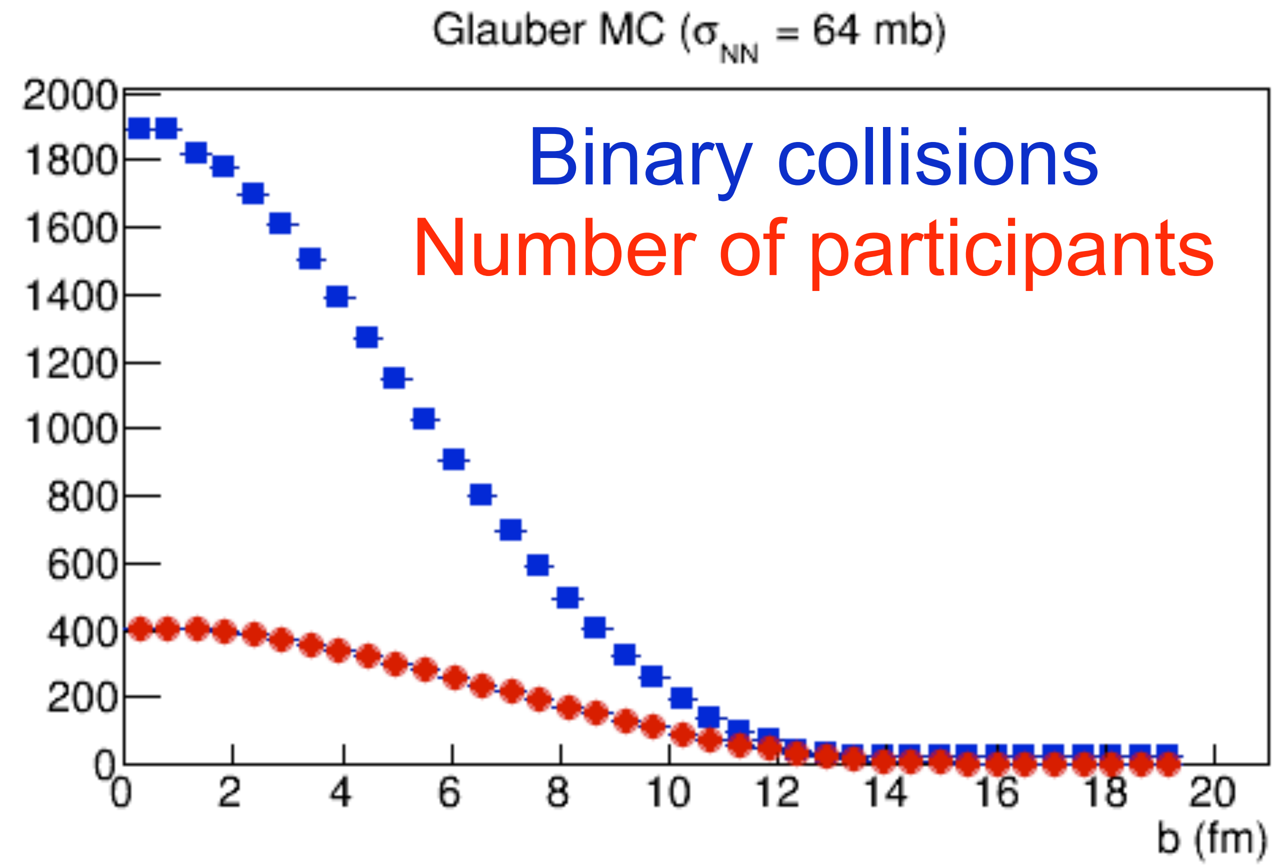
Number of binary collisions (N_{coll}): inelastic collisions between a nucleon of one nucleus and at least one nucleon of the other nucleus

- Scale with $AxA^{1/3}=A^{4/3}$

Number of spectators (N_{spec}): nucleons that do not lie in the overlap region and thus fly away without interacting







Ann.Rev.Nucl.Part.Sci.57,2007

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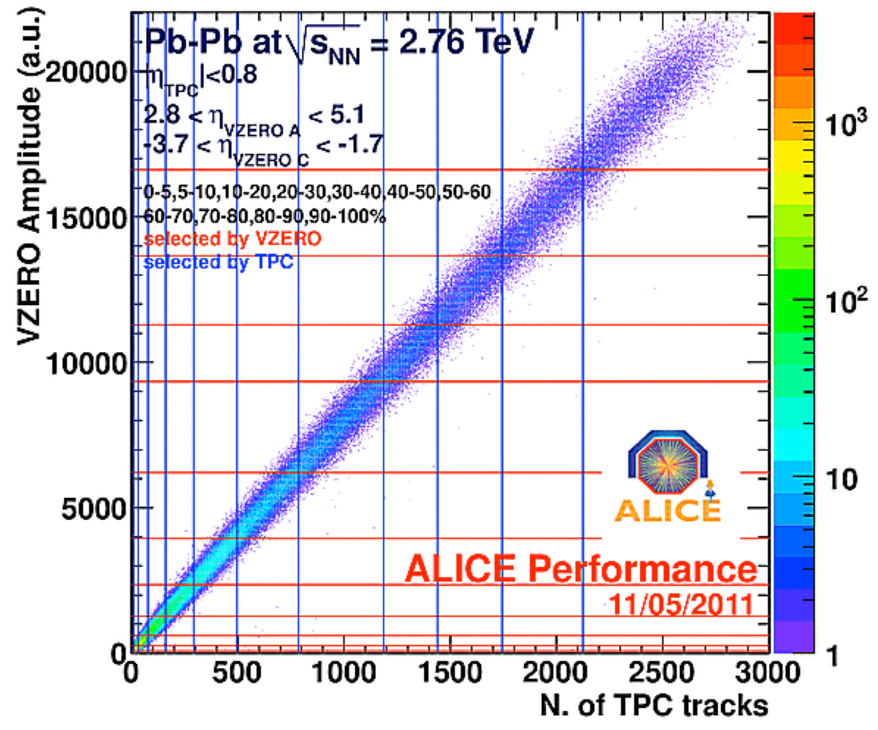
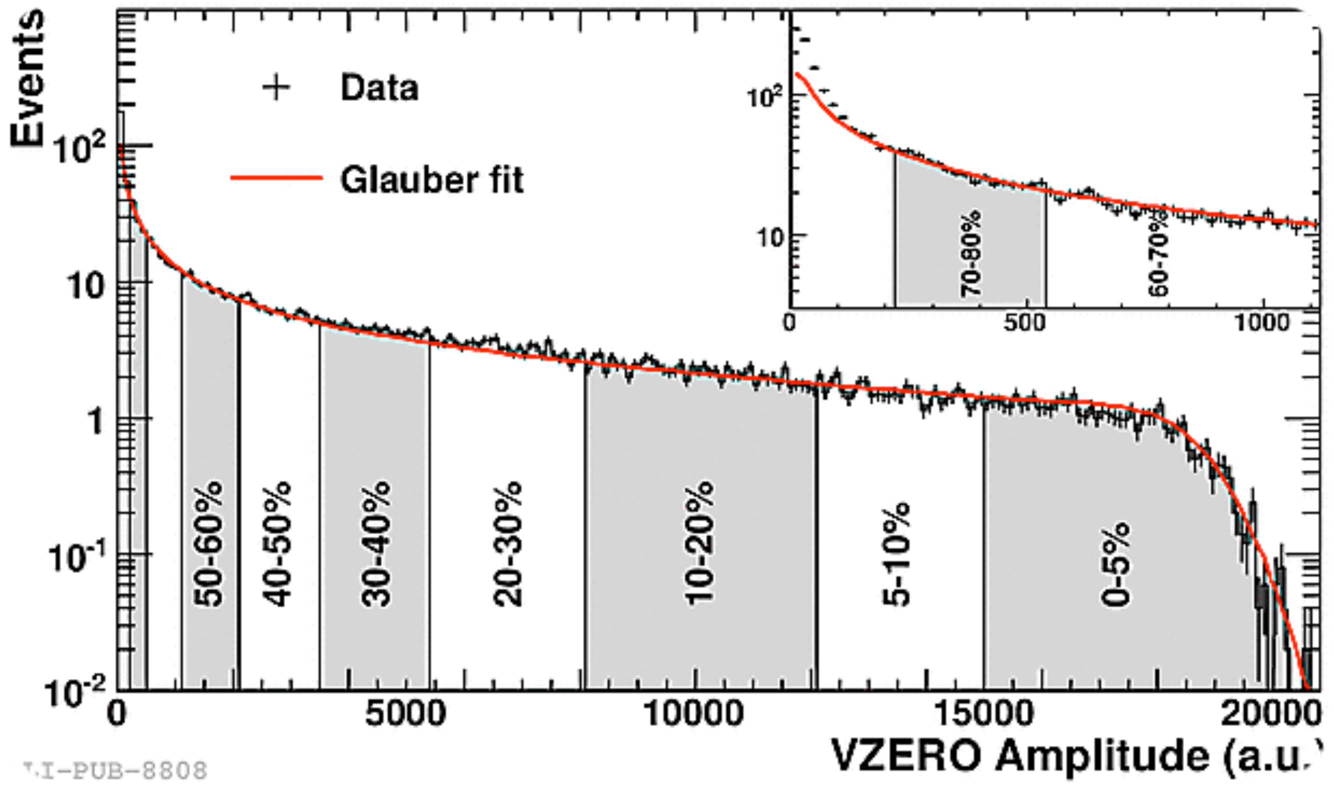
CENTRALITY IN EXPERIMENTS

Experimentally neither the impact parameter nor the N_{part}/N_{spec} can be measured

- Have to rely on experimental measurements:
  - Multiplicity (central or/and forward regions)
    - Large (small) for central (peripheral) collisions
  - Zero degree calorimeters (energy deposited by spectator nucleons)
    - E_{ZDC} small (large) for central (peripheral) collisions
- Expressed as the percentage of the total nuclear interaction cross section
  - e.g. 5% most central Pb-Pb (or Au-Au) collisions are the 5% with the highest multiplicity





(ALICE Collaboration)
Phys. Rev. C88 (2013) 044909

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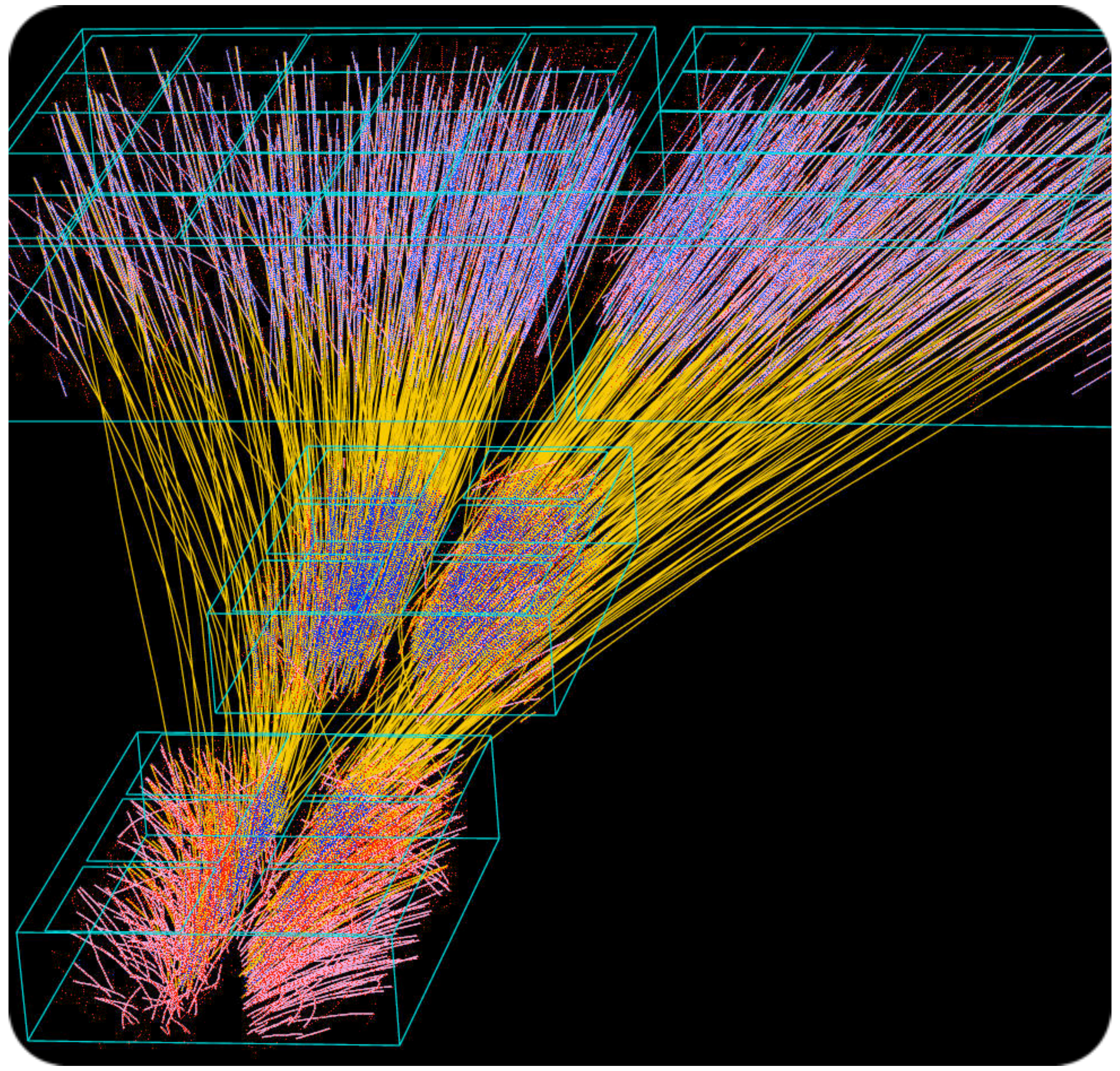
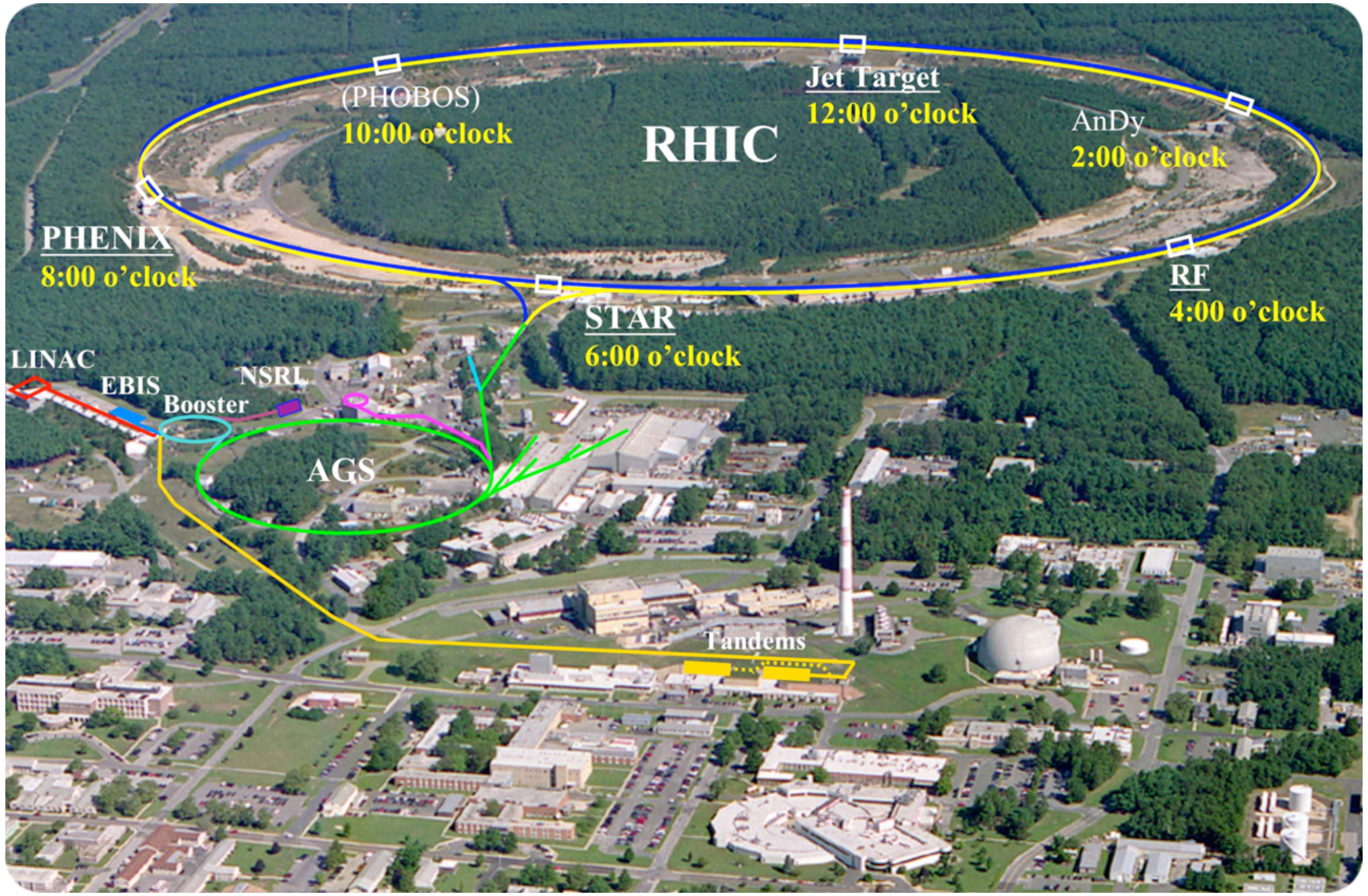
HEAVY ION PHYSICS @ CERN-SPS

(Mainly) Pb beams $\sqrt{s_{NN}}$ = 6.3 - 17.3 GeV

Fixed target experiments
(event display courtesy of NA49)



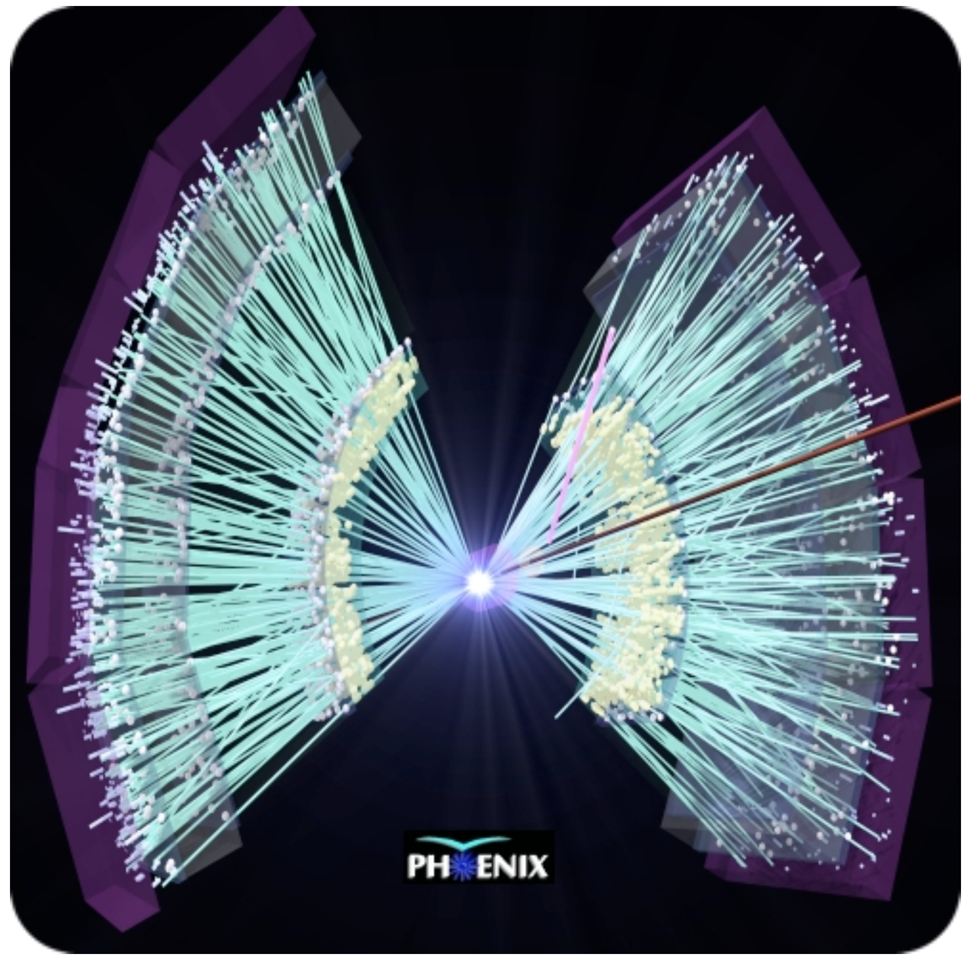
HEAVY ION PHYSICS @ BNL-RHIC

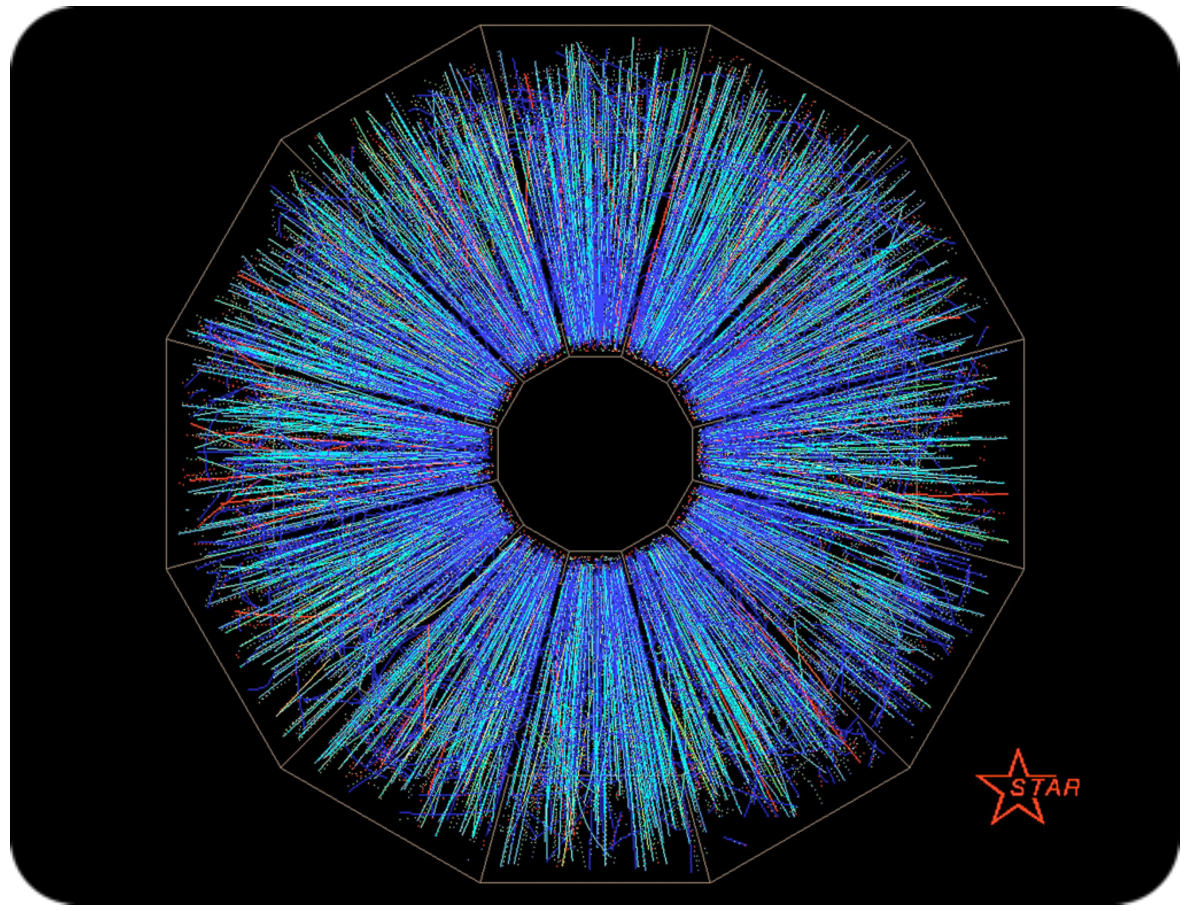


(Mainly) Au beams $\sqrt{s_{NN}}$ = 200 GeV

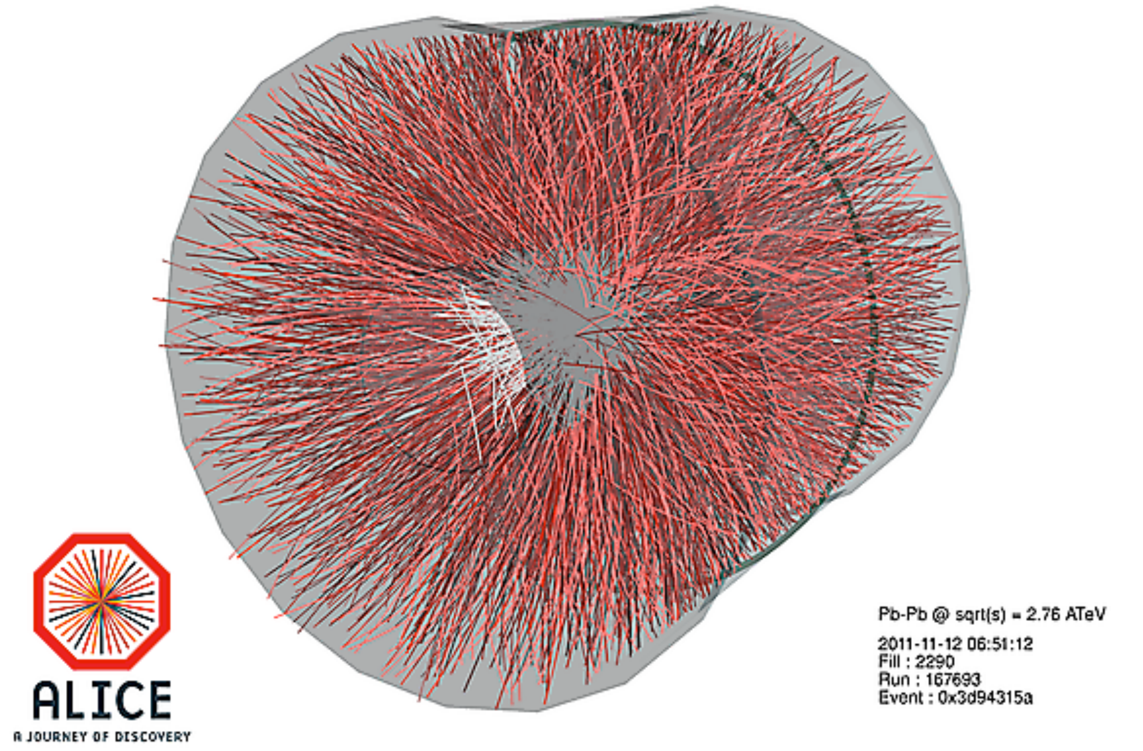
BES: $\sqrt{s_{NN}}$ = 7.7 - 62.4 GeV

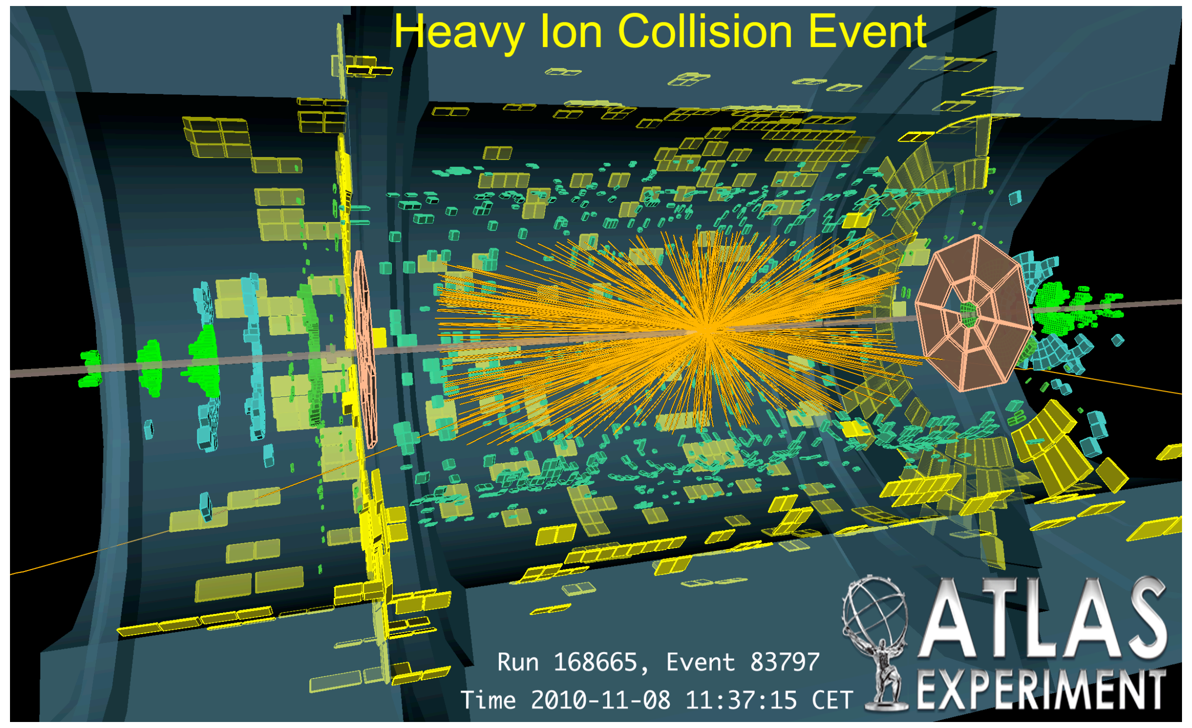
Collider experiments (event displays courtesy of PHENIX and STAR)

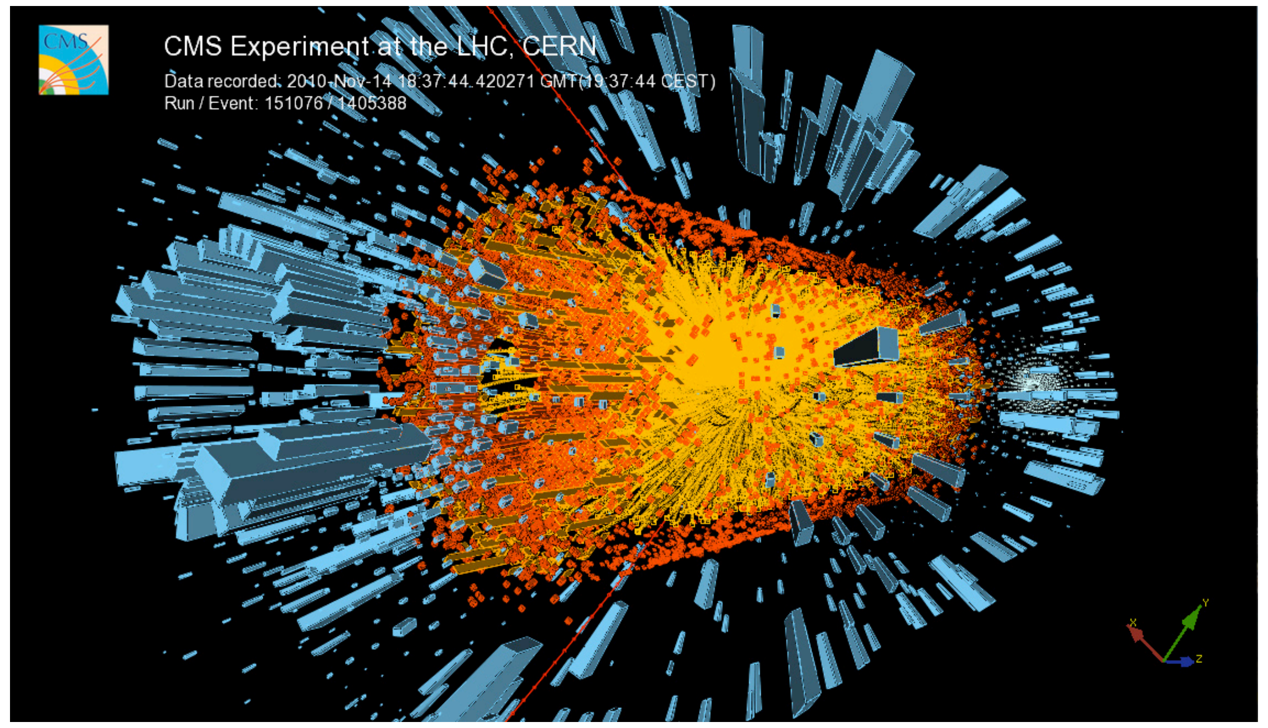


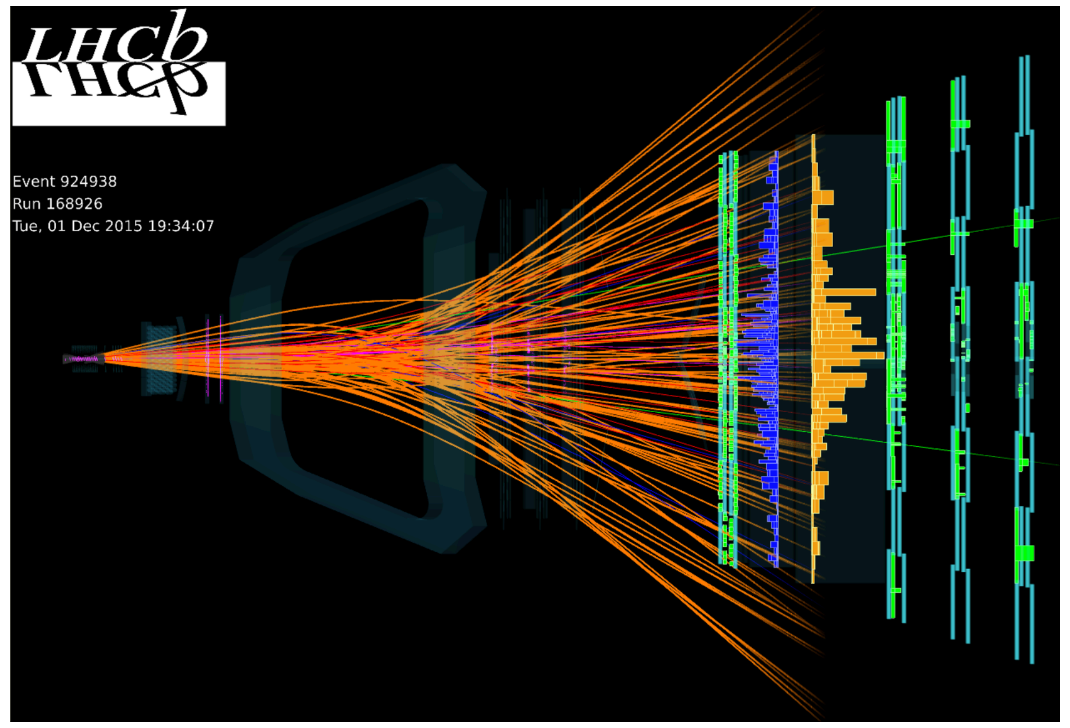


HEAVY ION PHYSICS @ CERN-LHC



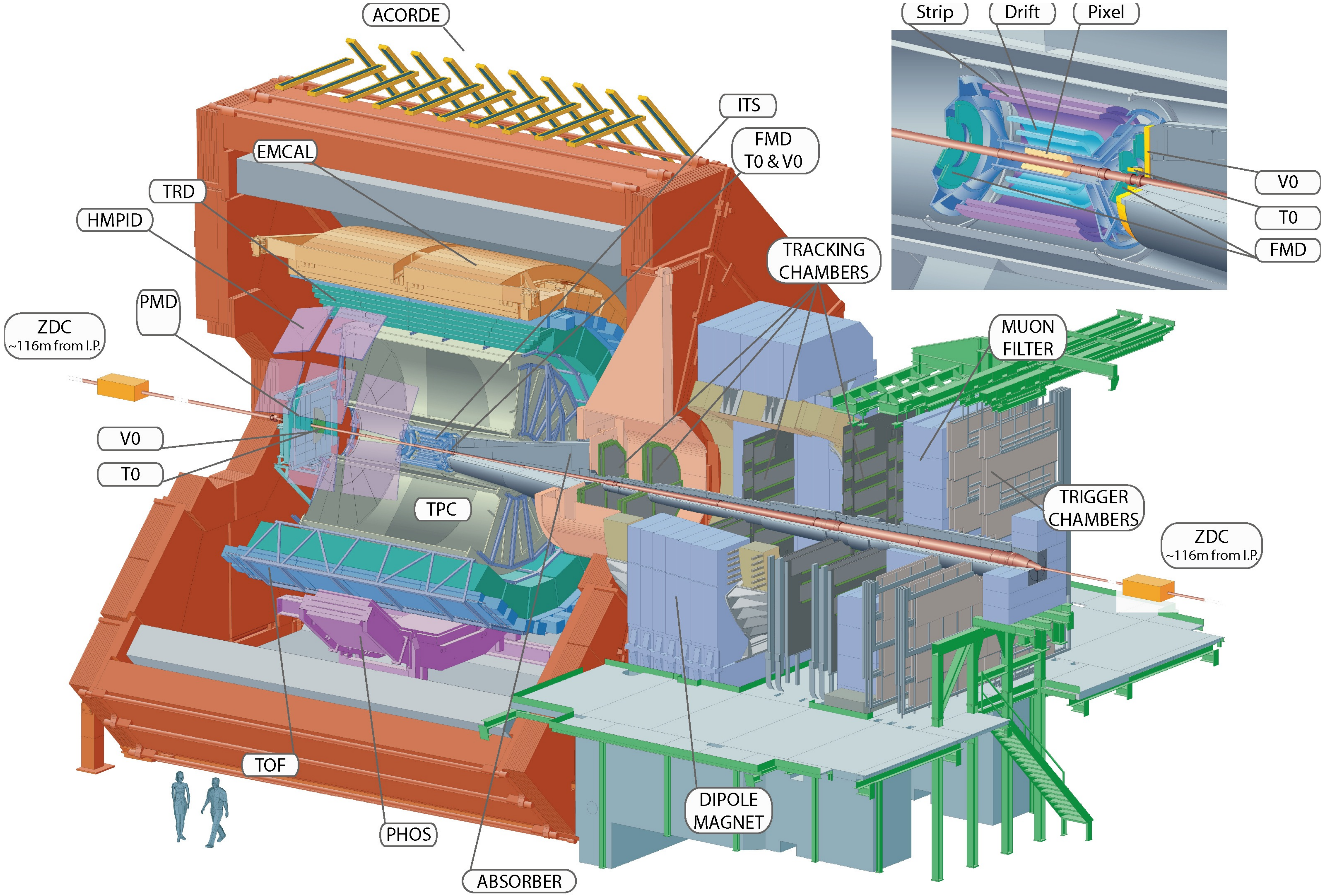






Pb beams $\sqrt{s_{NN}}$ = 2.76 & 5.02 TeV

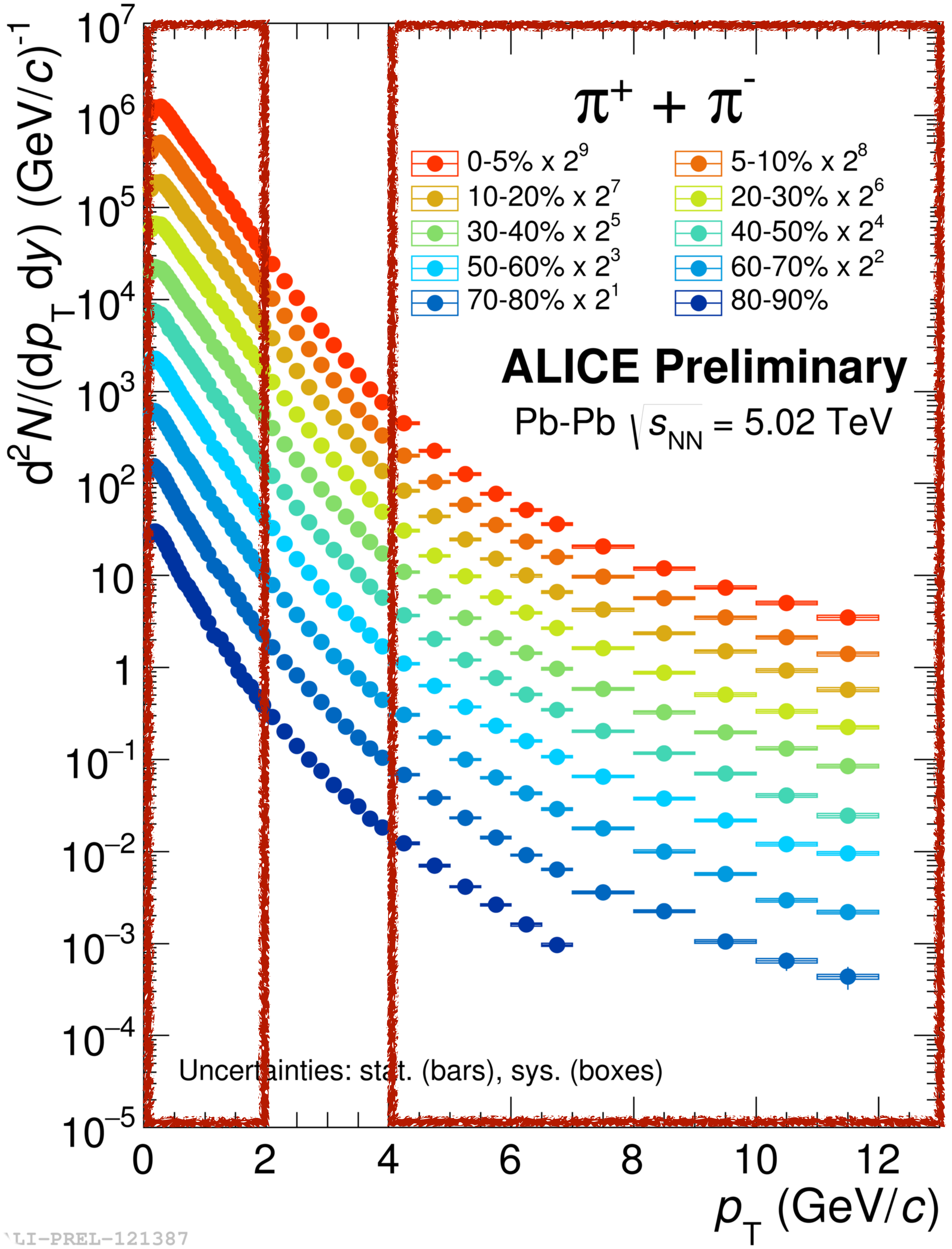
EXPERIMENTAL SETUP



STUDYING THE QGP PROPERTIES

Two main ways to probe the QGP properties:

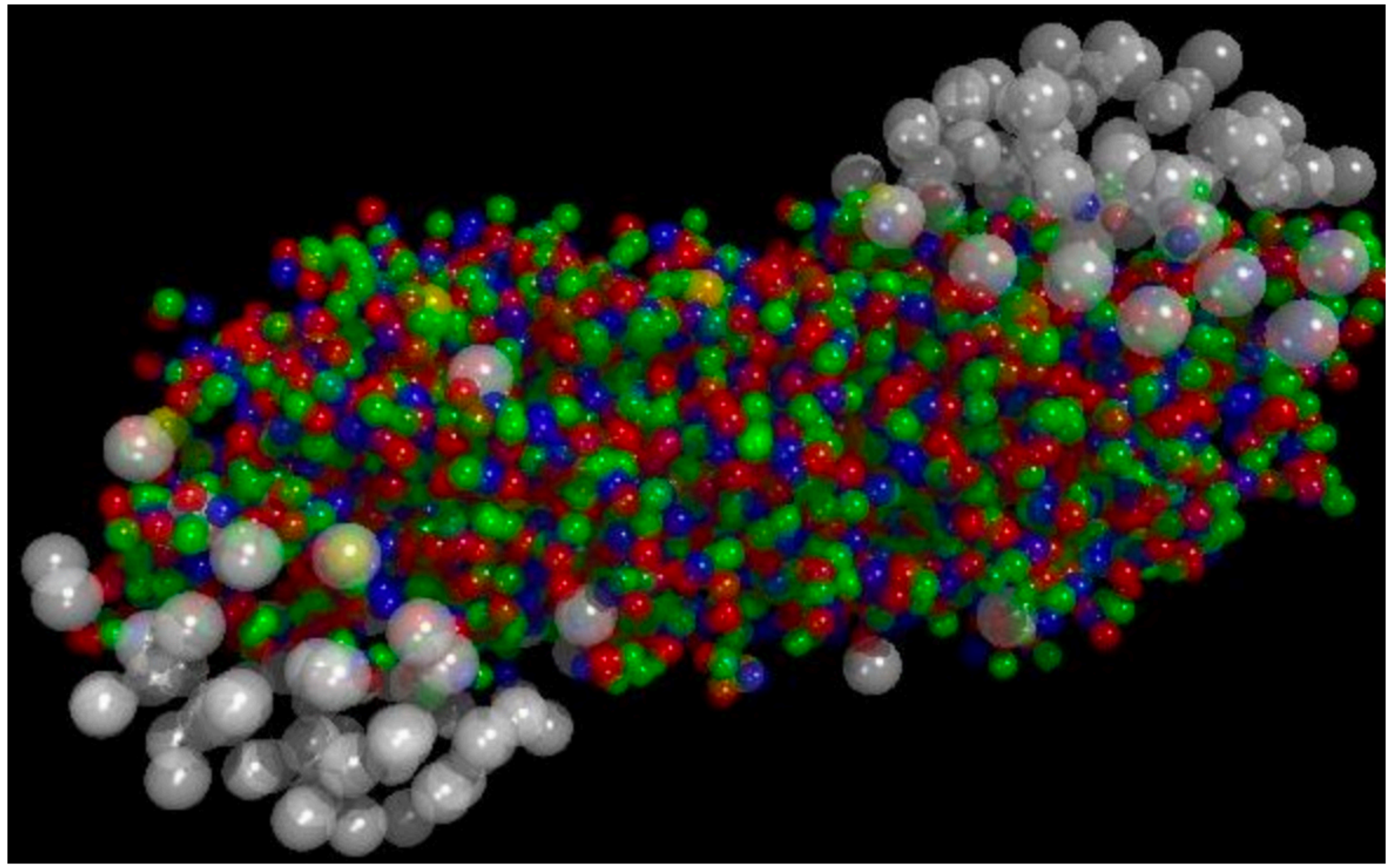
- Through bulk observables
  - The vast majority of particles are produced with $p_T < 2$ GeV/*c*
- Hard (rare) probes with $p_T > 6$ GeV/*c*
  - High p_T hadrons
  - Jets
  - Heavy flavour (e.g. charm-mesons)



THE QGP @ CERN-SPS

New State of Matter created at CERN

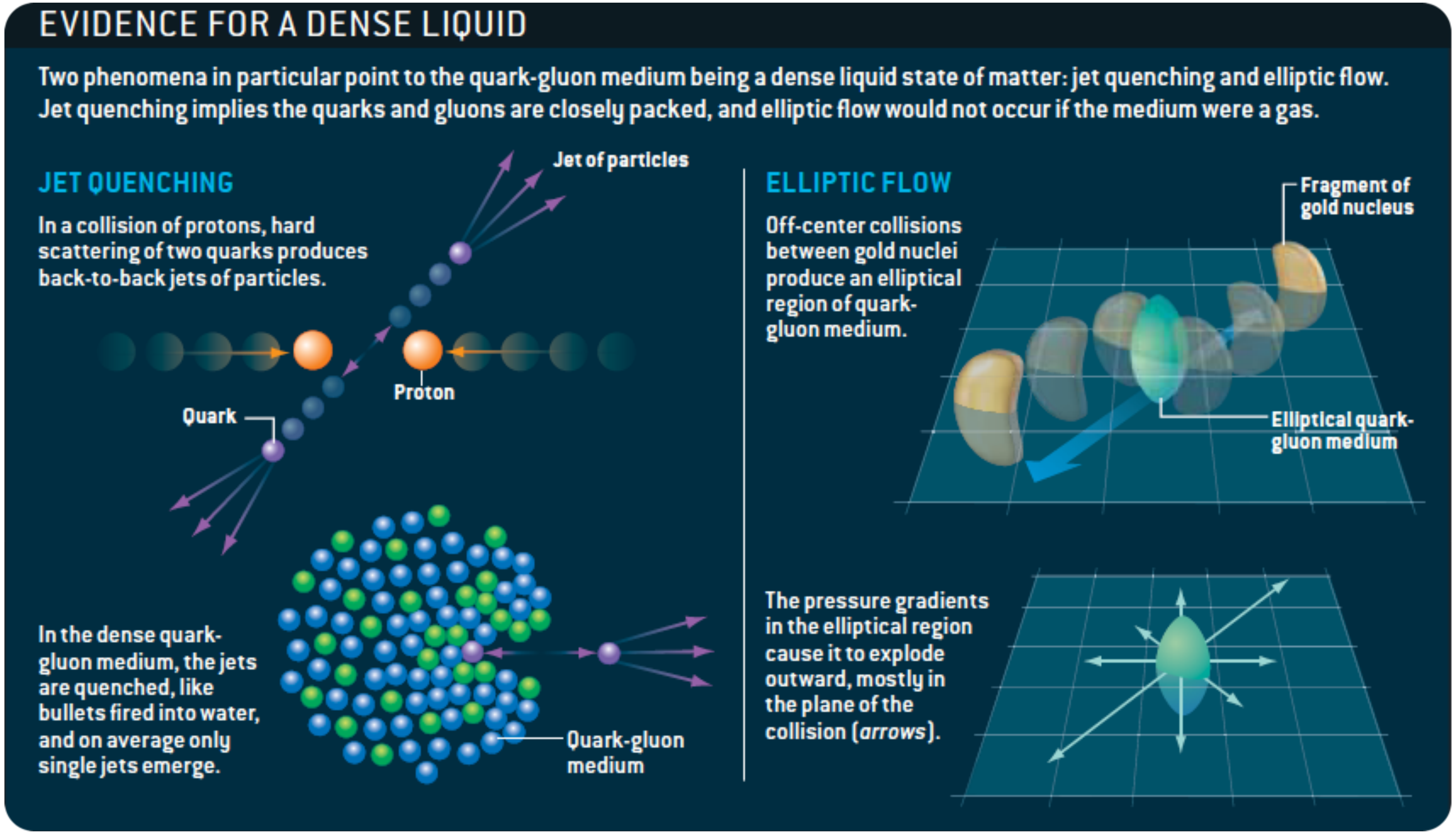
10 Feb 2000



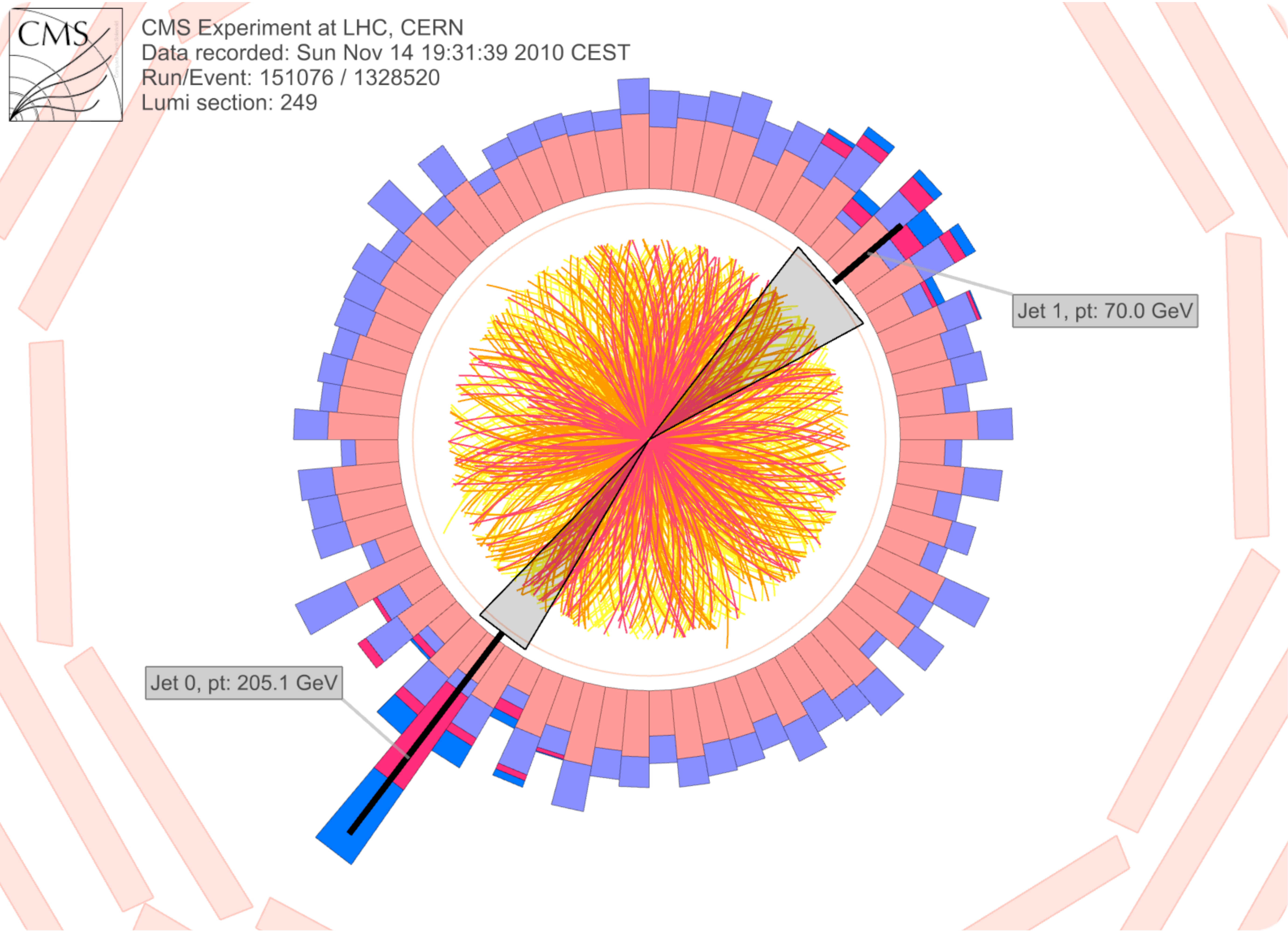
Geneva, 10 February 2000. At a special seminar on 10 February, spokespersons from the experiments on CERN[1]'s Heavy Ion programme presented compelling evidence for the existence of a new state of matter in which quarks, instead of being bound up into more complex particles such as protons and neutrons,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

WHAT IS THE QGP?

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



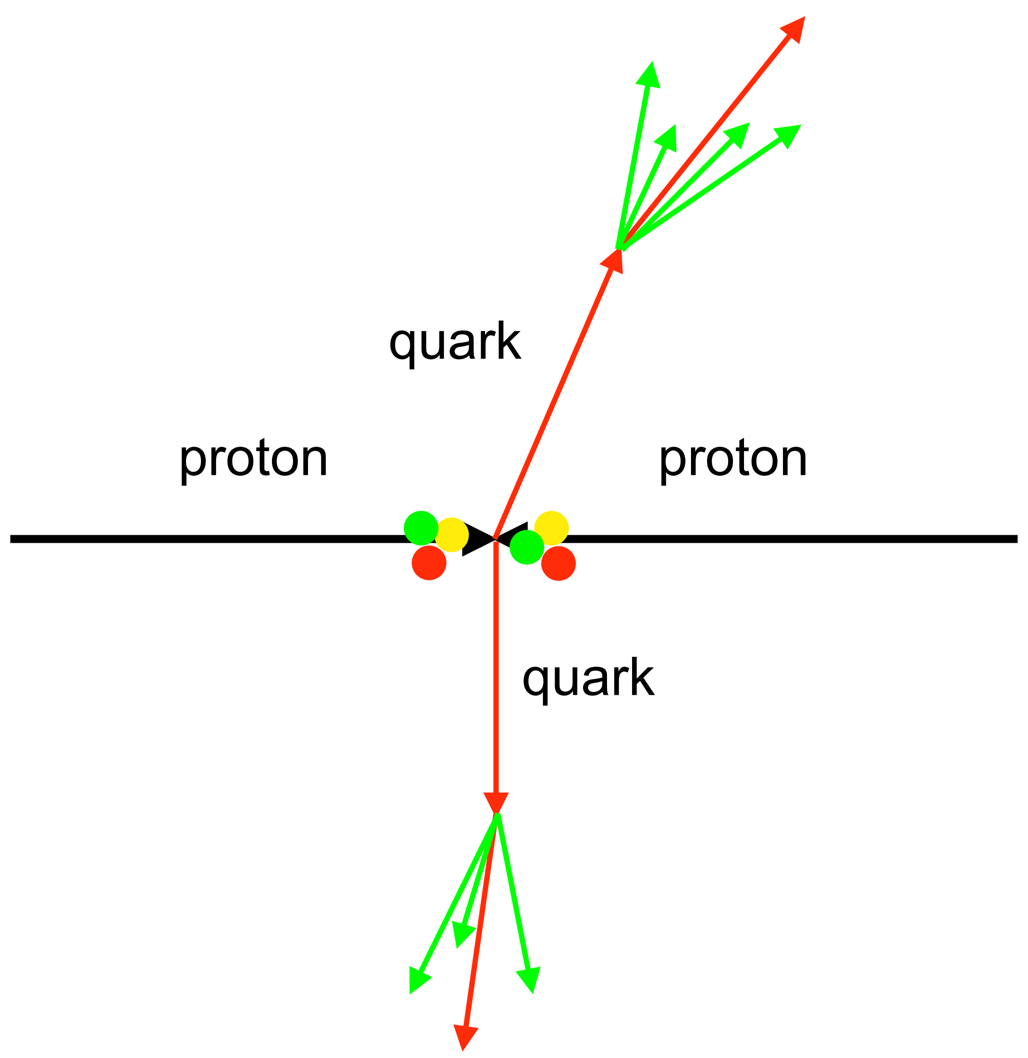
HARD PROBES

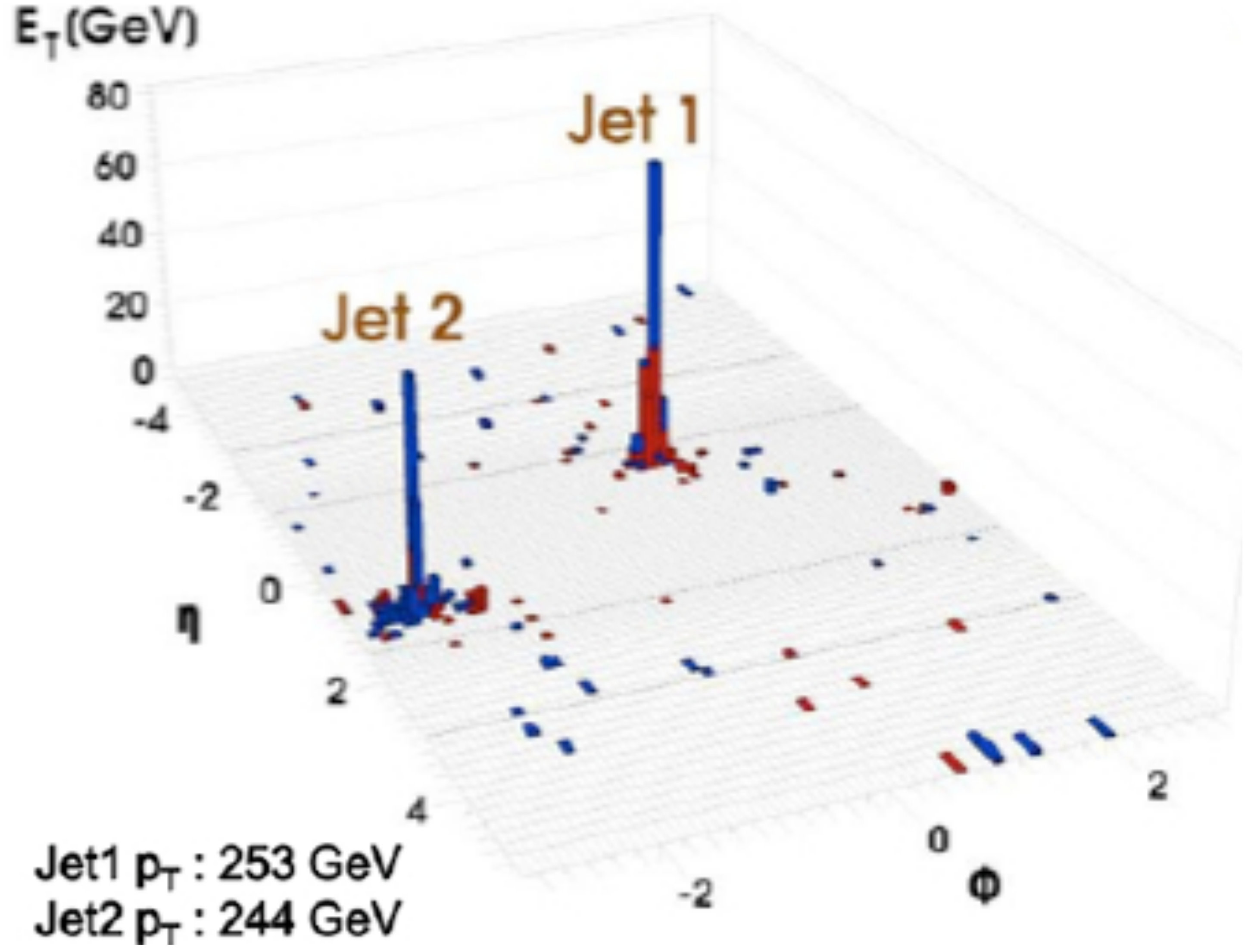

CMS
CMS Experiment at LHC, CERN
Data recorded: Sun Nov 14 19:31:39 2010 CEST
Run/Event: 151076 / 1328520
Lumi section: 249
Jet 1, pt: 70.0 GeV
Jet 0, pt: 205.1 GeV

JET QUENCHING IN A NUTSHELL

Hard process scale: Q >> Λ_{QCD} (~200 MeV)

- High p_T parton with Q ~ p_T
- These partons are formed early during the evolution of the system
  - They fragment and create jets and high transverse momentum hadrons
  - These processes can be calculated in perturbative QCD





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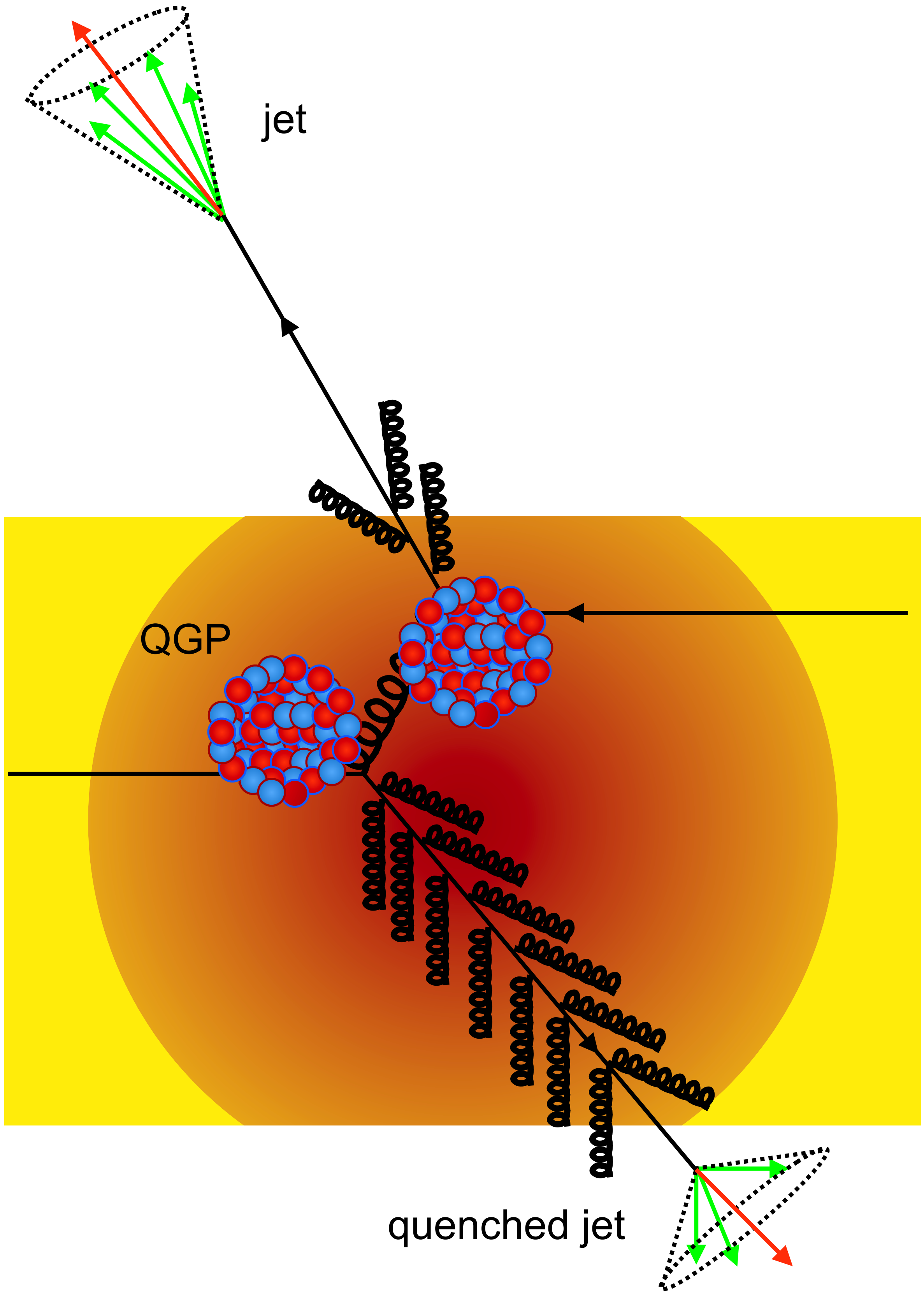
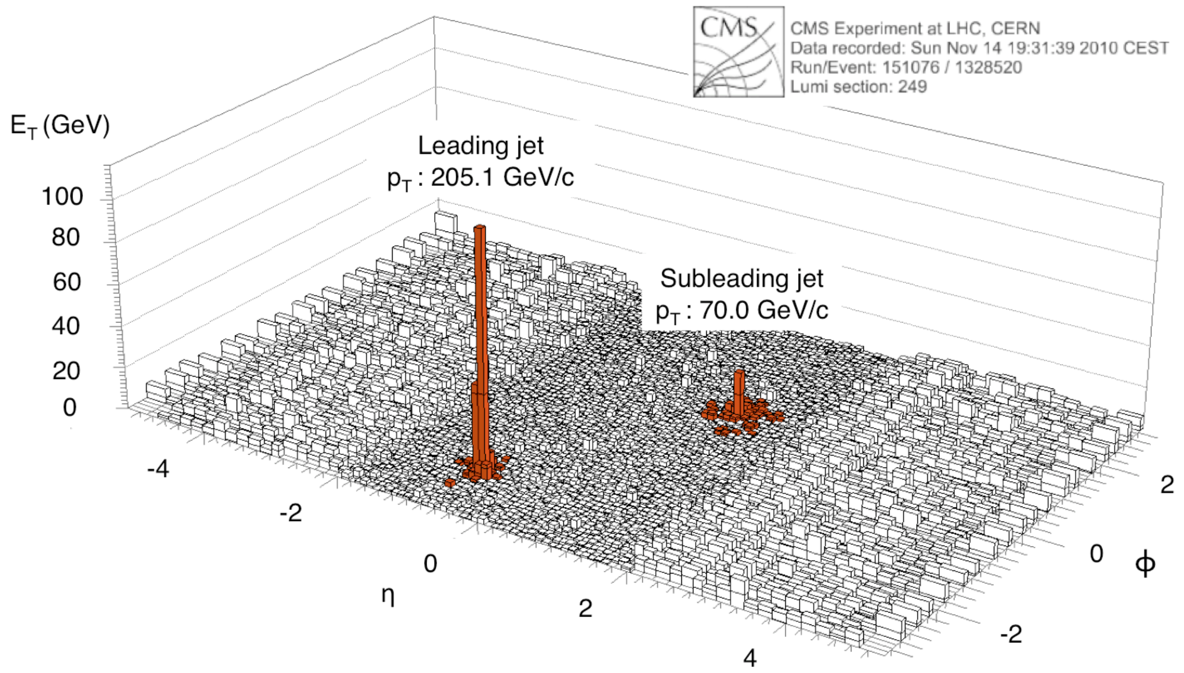
JET QUENCHING IN A NUTSHELL

In heavy ion collisions, in the presence of a hot and dense medium (QGP), during the propagation through the QGP, these objects interact with the medium and lose energy either via collisional or radiative energy loss

- Experimental consequence:
  - Suppression of high transverse momentum particles
  - Attenuation of energy of jets
  - Modification of soft particle production





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A WAY OF VISUALISING THE QUENCHING

PHENIX Collaboration Phys.Rev.Lett. 91 (2003) 072301

We need to compare particle production

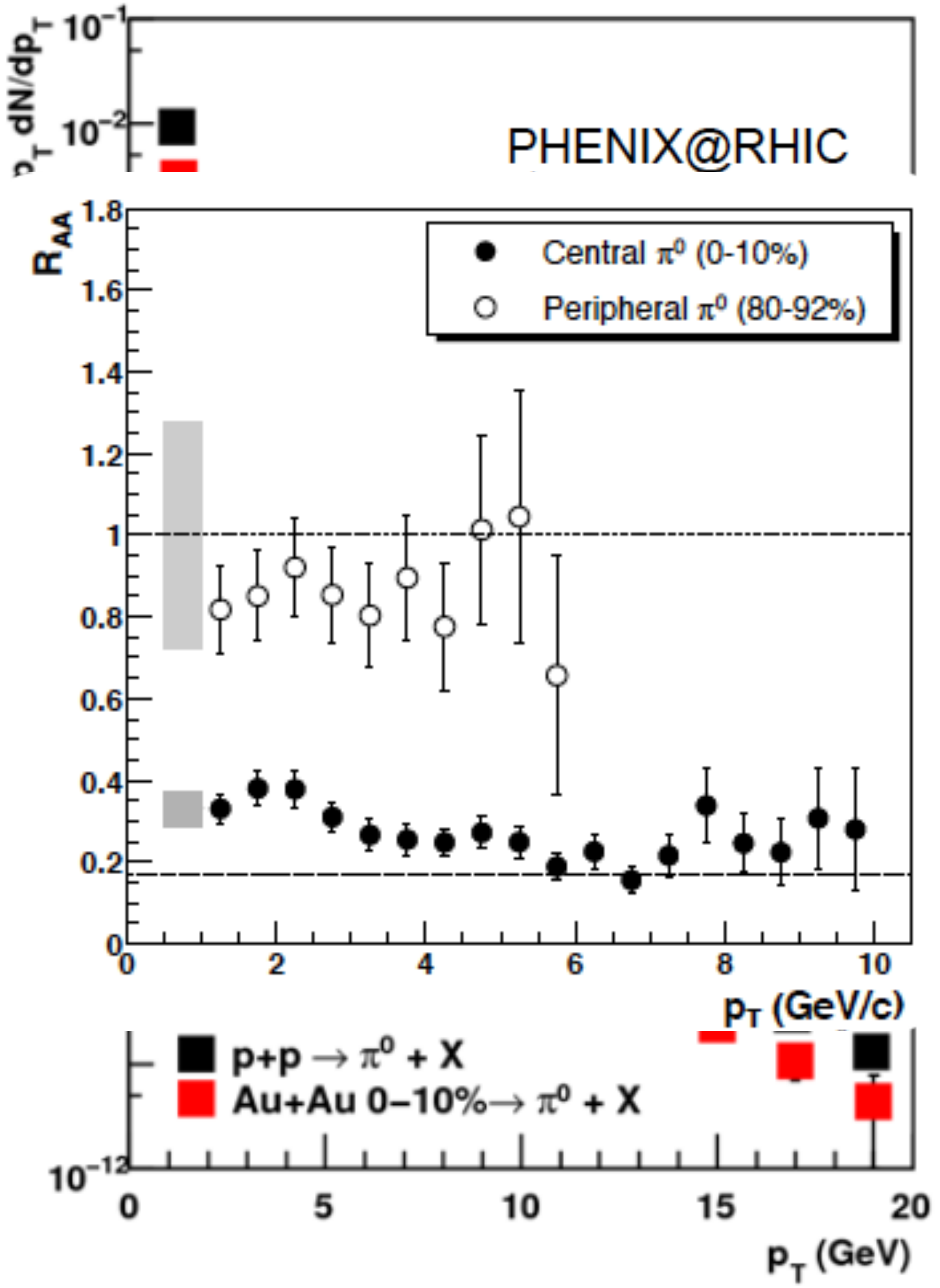
- In the QGP medium (heavy-ion collisions)
- In the vacuum (pp collisions) scaled
    - Assumes that a heavy-ion collision can be considered as a superposition of independent pp collisions

$$R_{AA} = \frac{\text{QCD medium}}{\text{QCD vacuum}} = \frac{\left(\frac{d^2N}{dp_T d\eta}\right)_{AA}}{N_{coll}\left(\frac{d^2N}{dp_T d\eta}\right)_{pp}}$$

$$R_{AA} \rightarrow \begin{cases} < 1 \\ \approx 1 \end{cases}$$

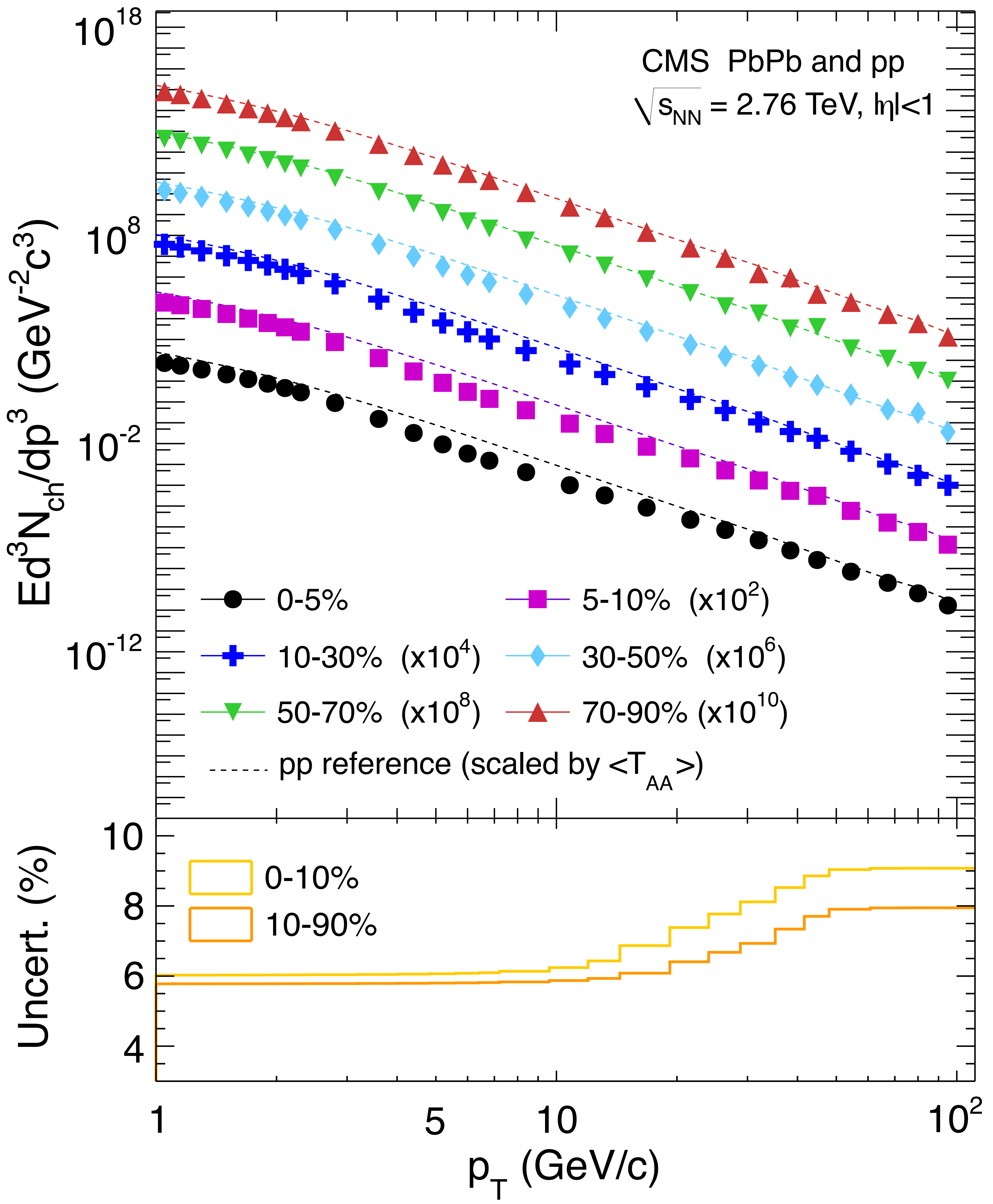
< 1: in-medium effects

≈ 1: no in-medium effects



JET QUENCHING @ LHC

CMS Collaboration, EPJC **72** (2012) 1945



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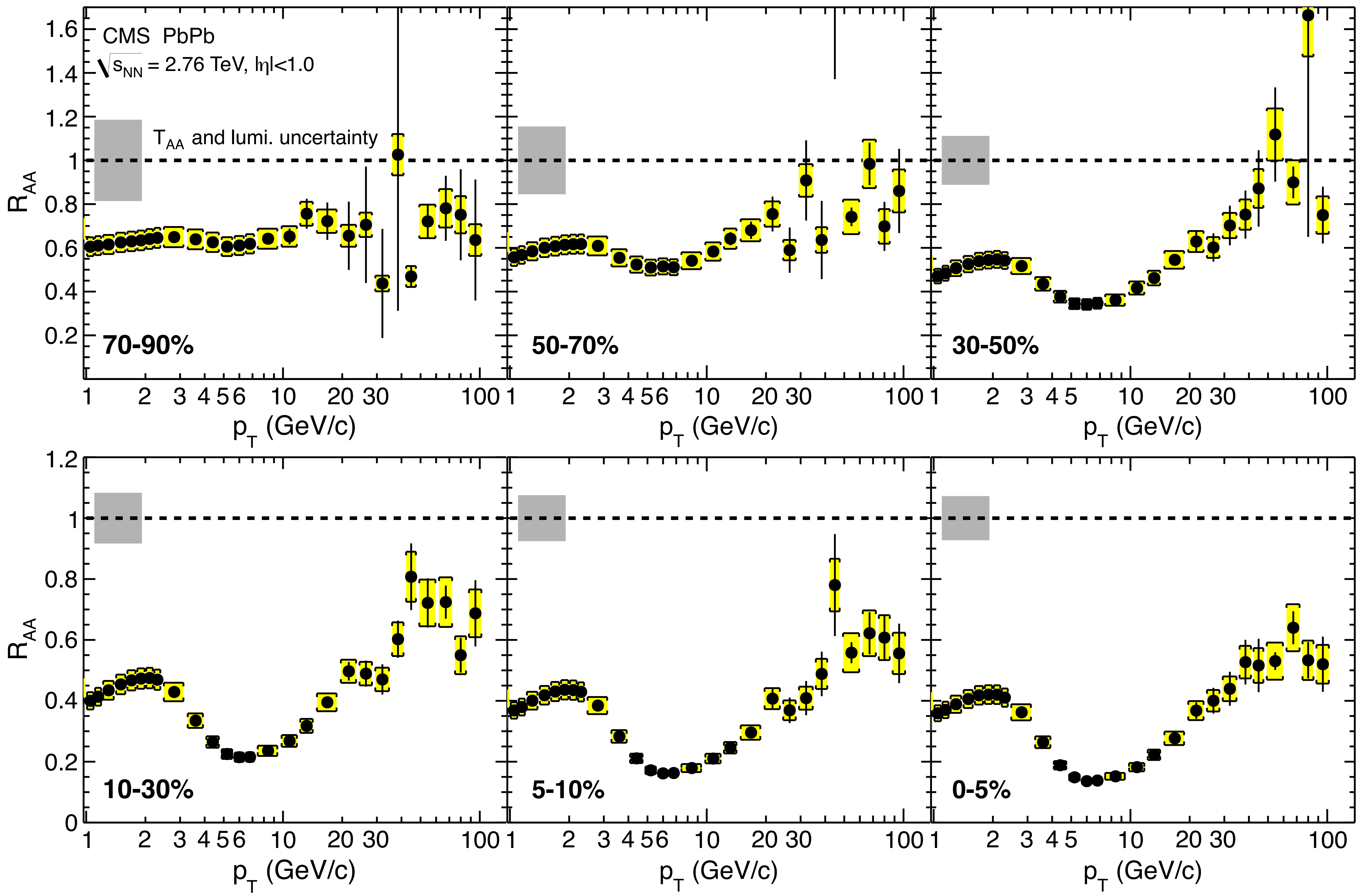
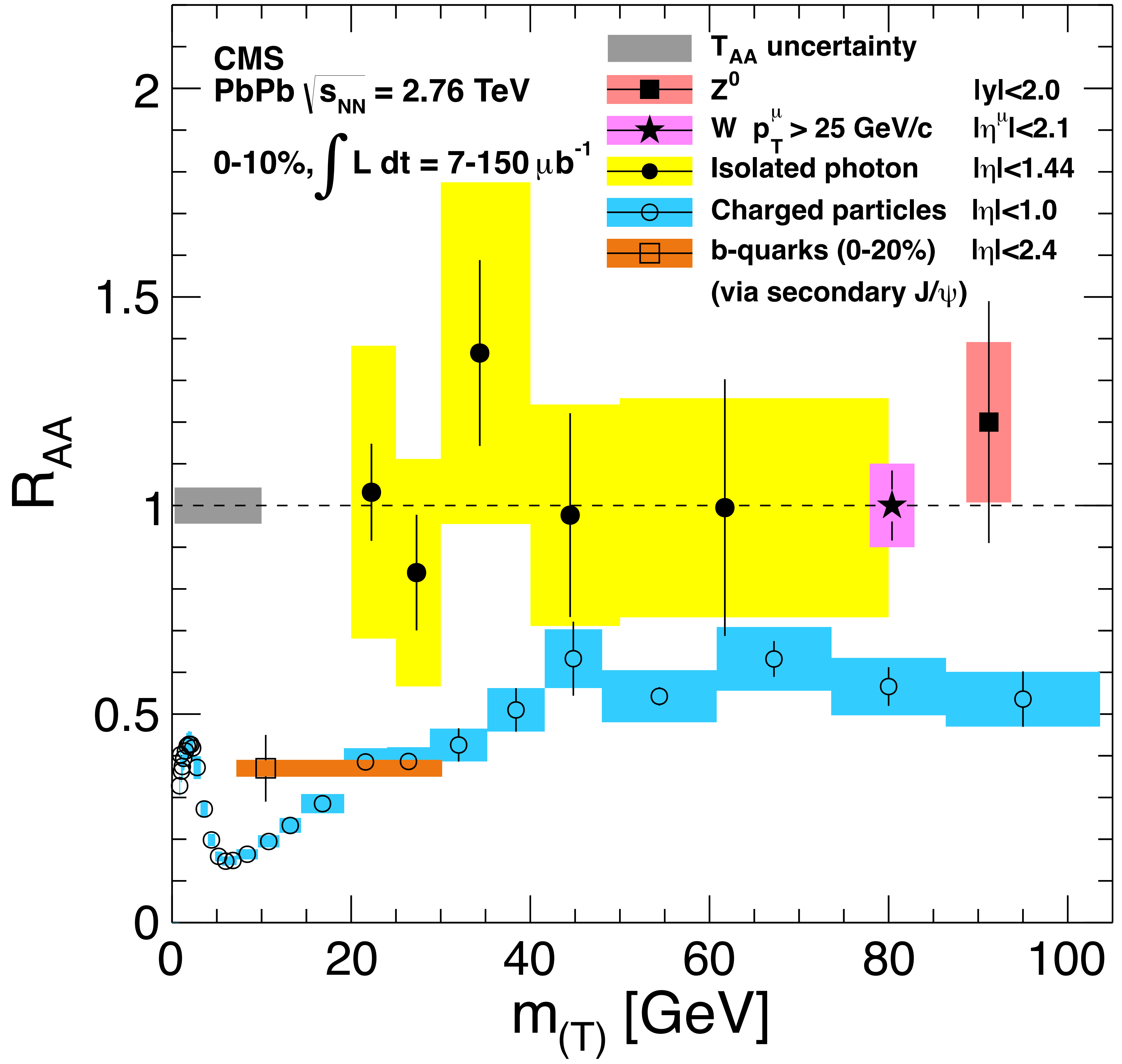
JET QUENCHING @ LHC

CMS Collaboration, EPJC **72** (2012) 1945



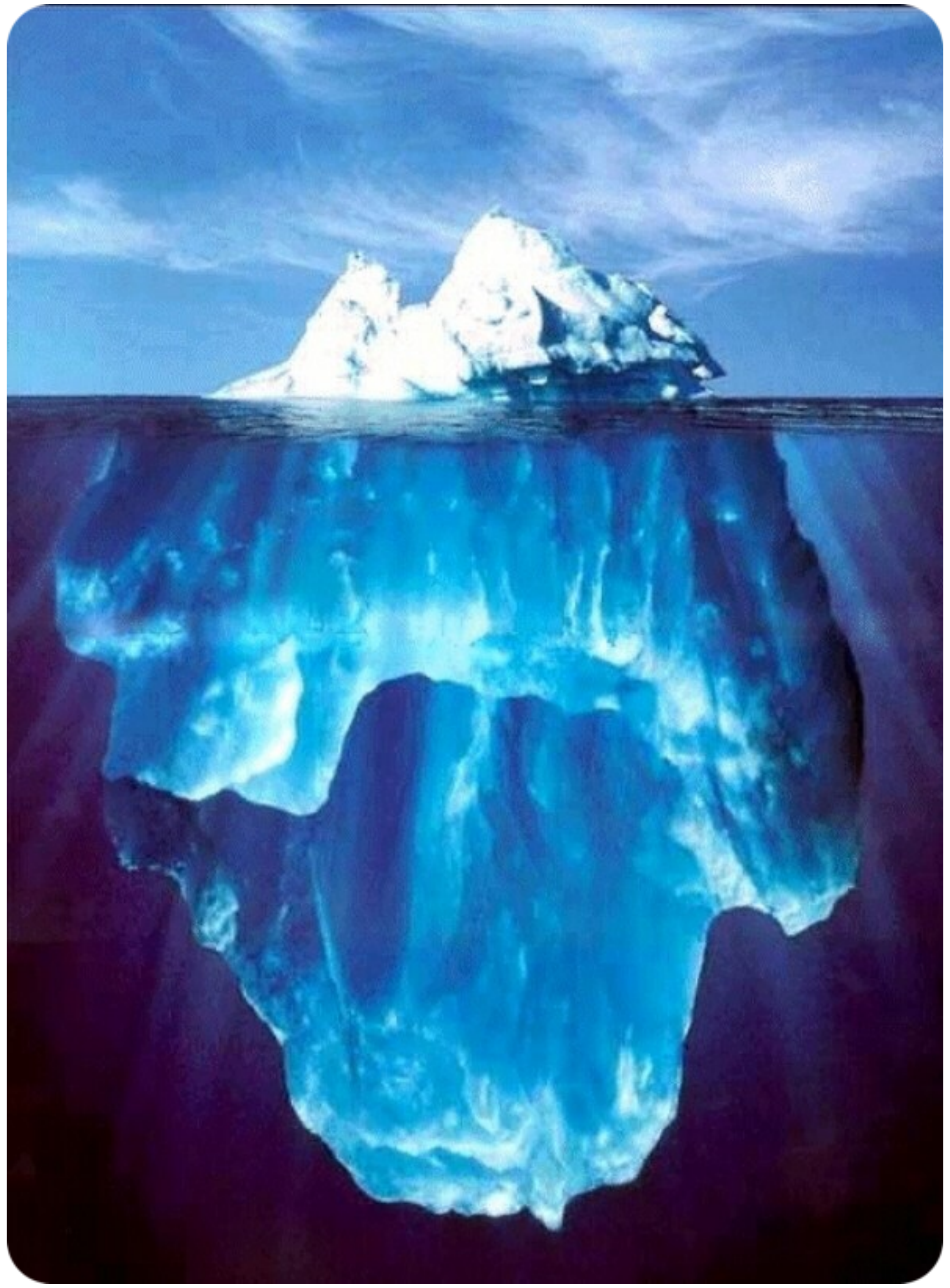
REFERENCE PROBES

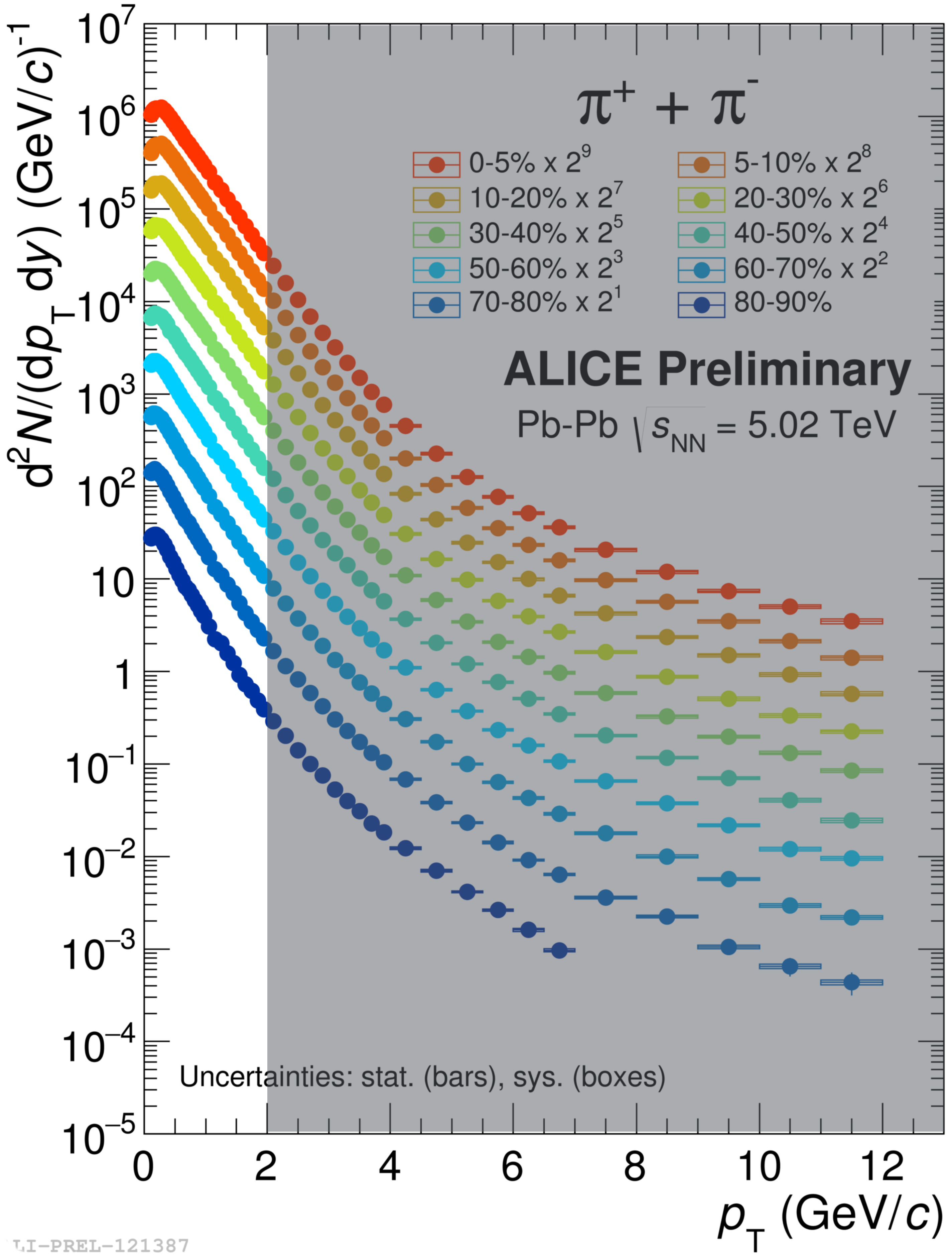
CMS Collaboration, EPJC **72** (2012) 1945



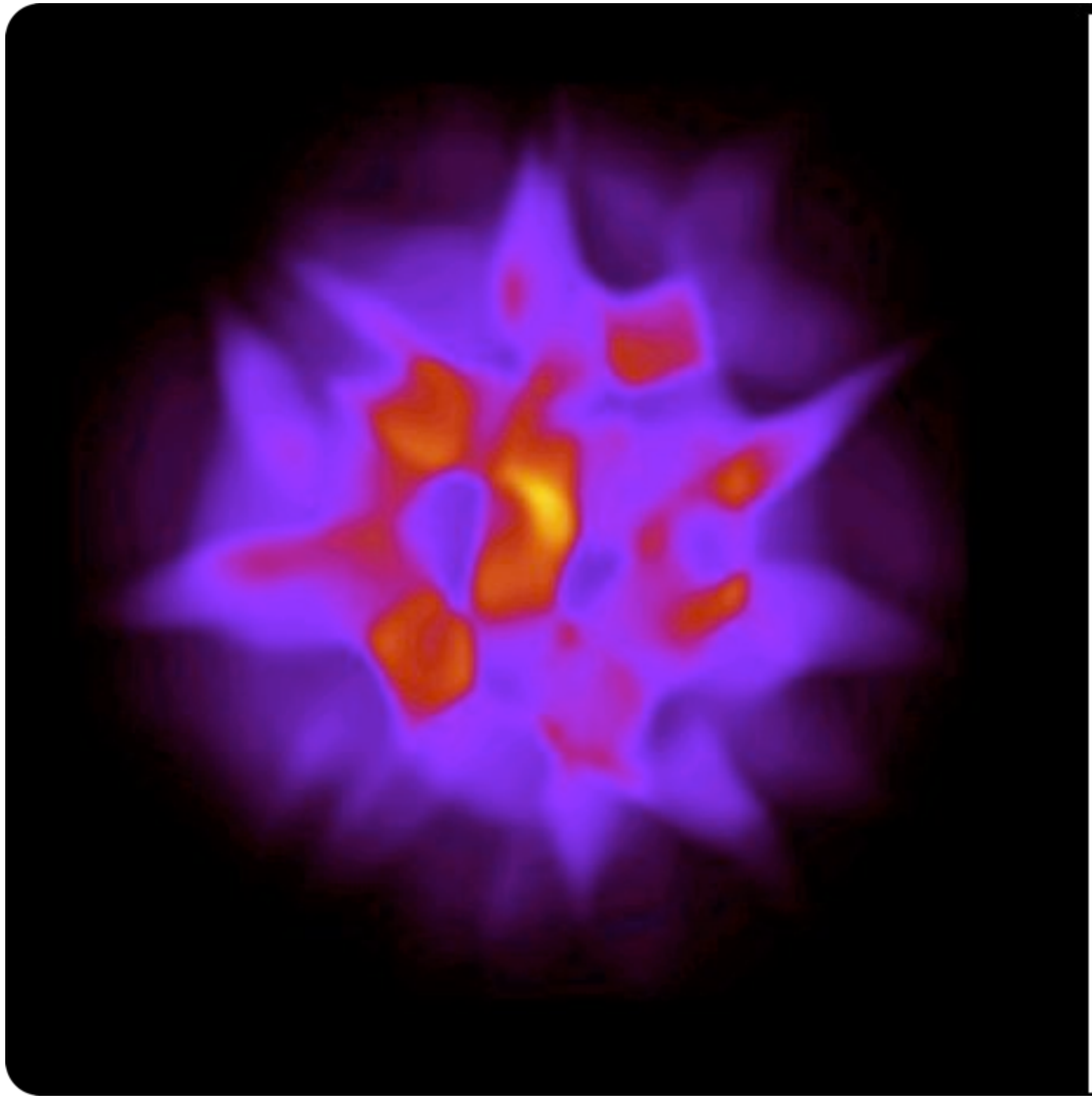
Particles not interacting with the medium (e.g. γ, Z^0, W) do not show any in medium effects

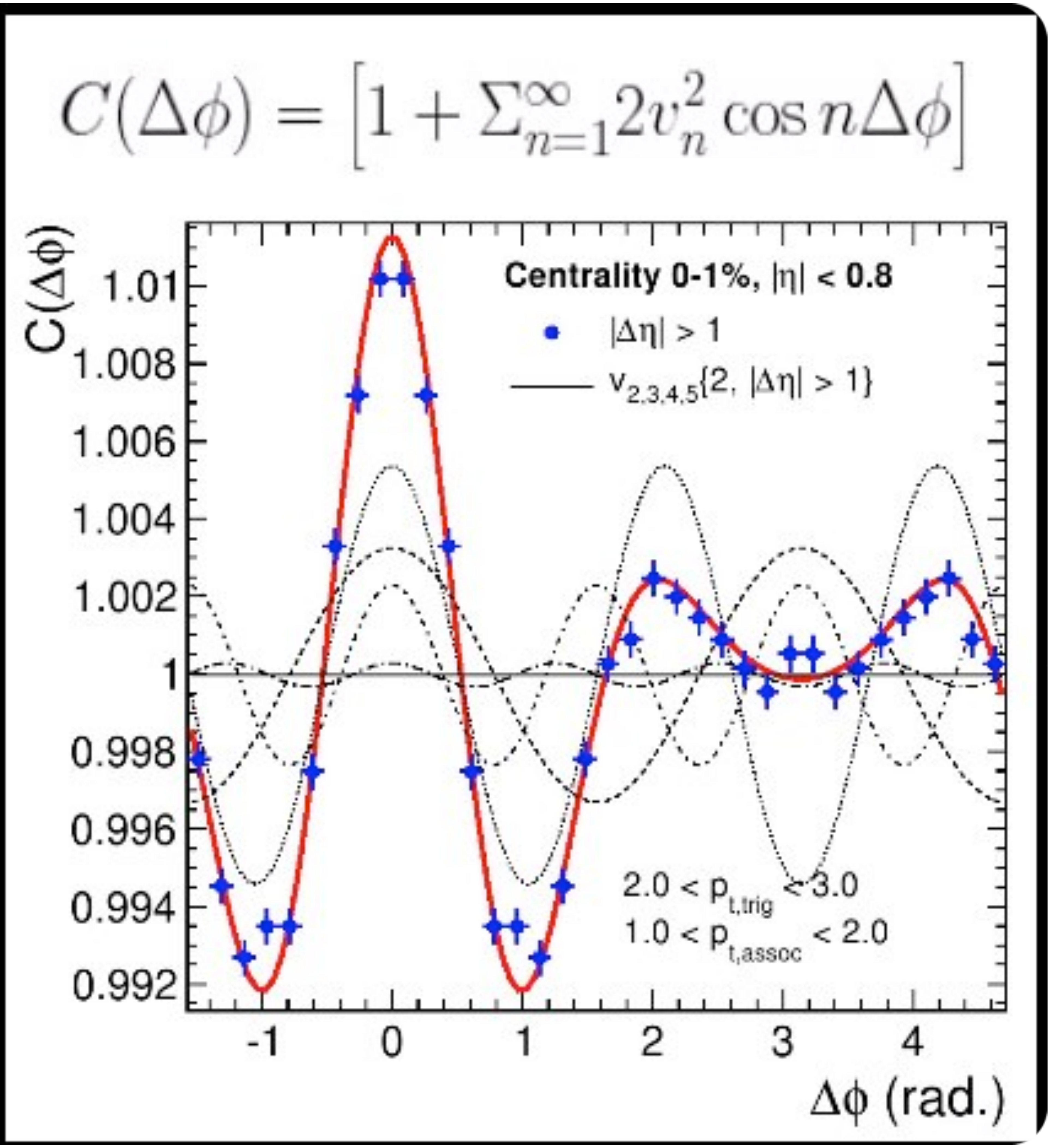
THE OTHER 99%…BULK OF PARTICLE PRODUCTION





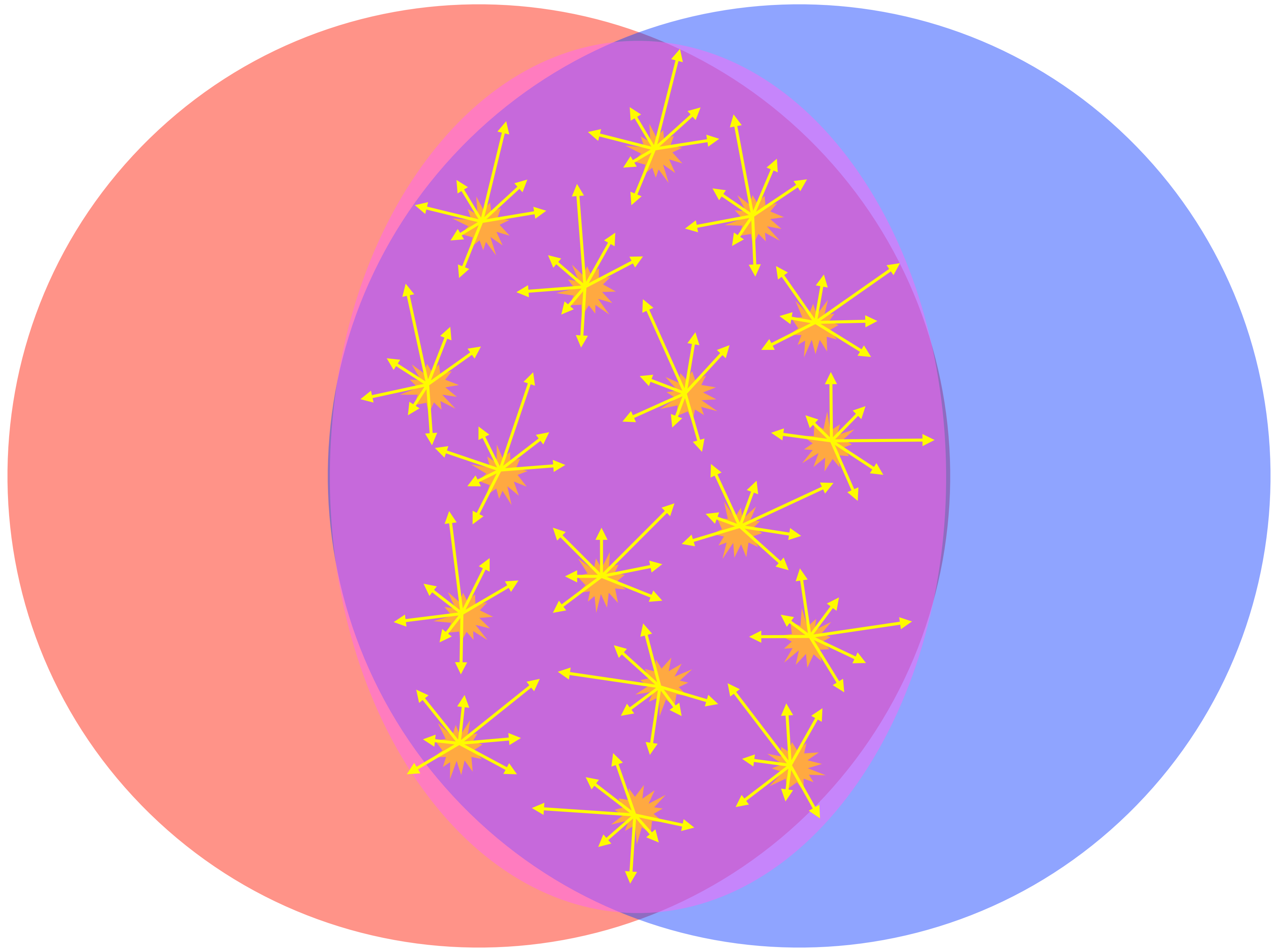
ANISOTROPIC FLOW



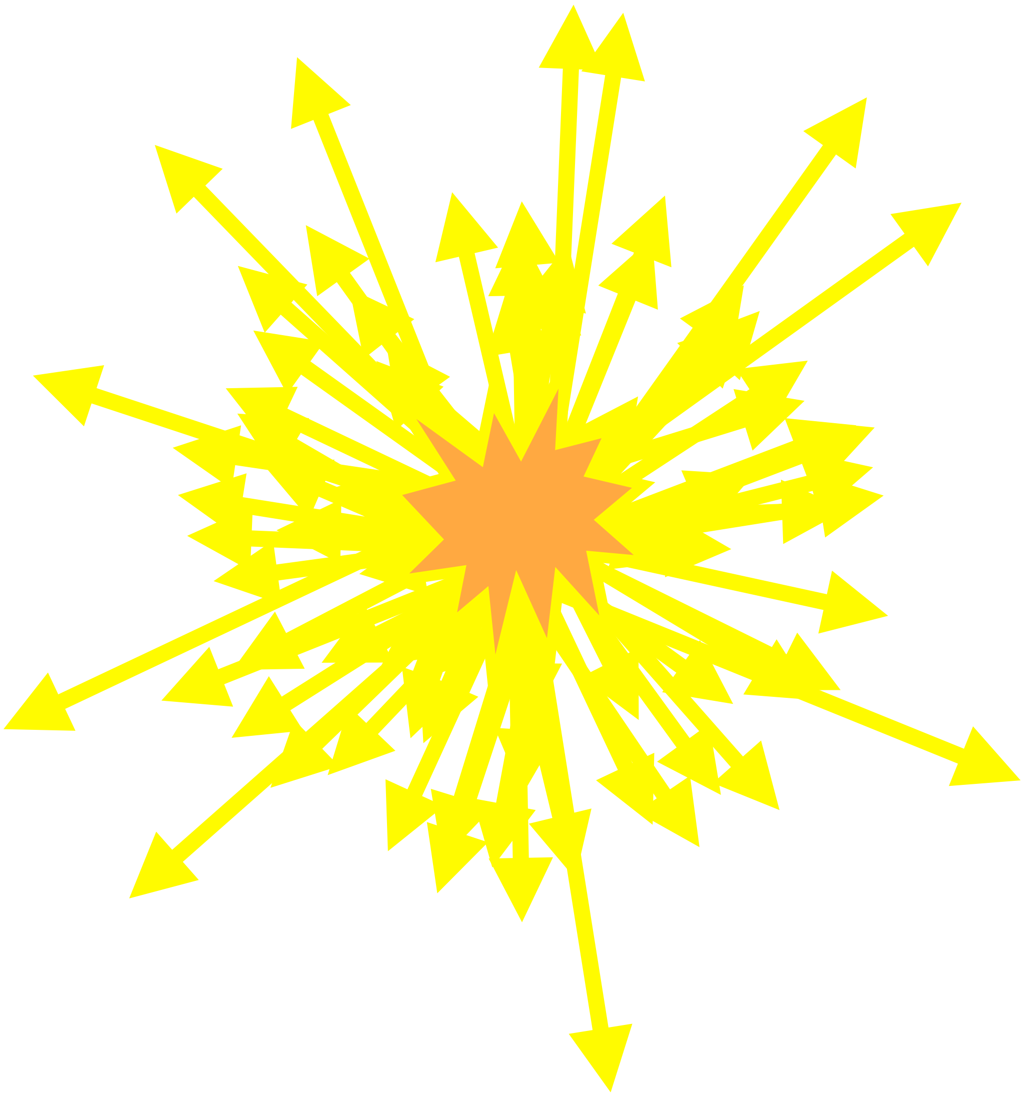


TO FLOW OR NOT TO FLOW?

Superposition of independent pp collisions



Momenta pointing at random directions relative to the reaction plane



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

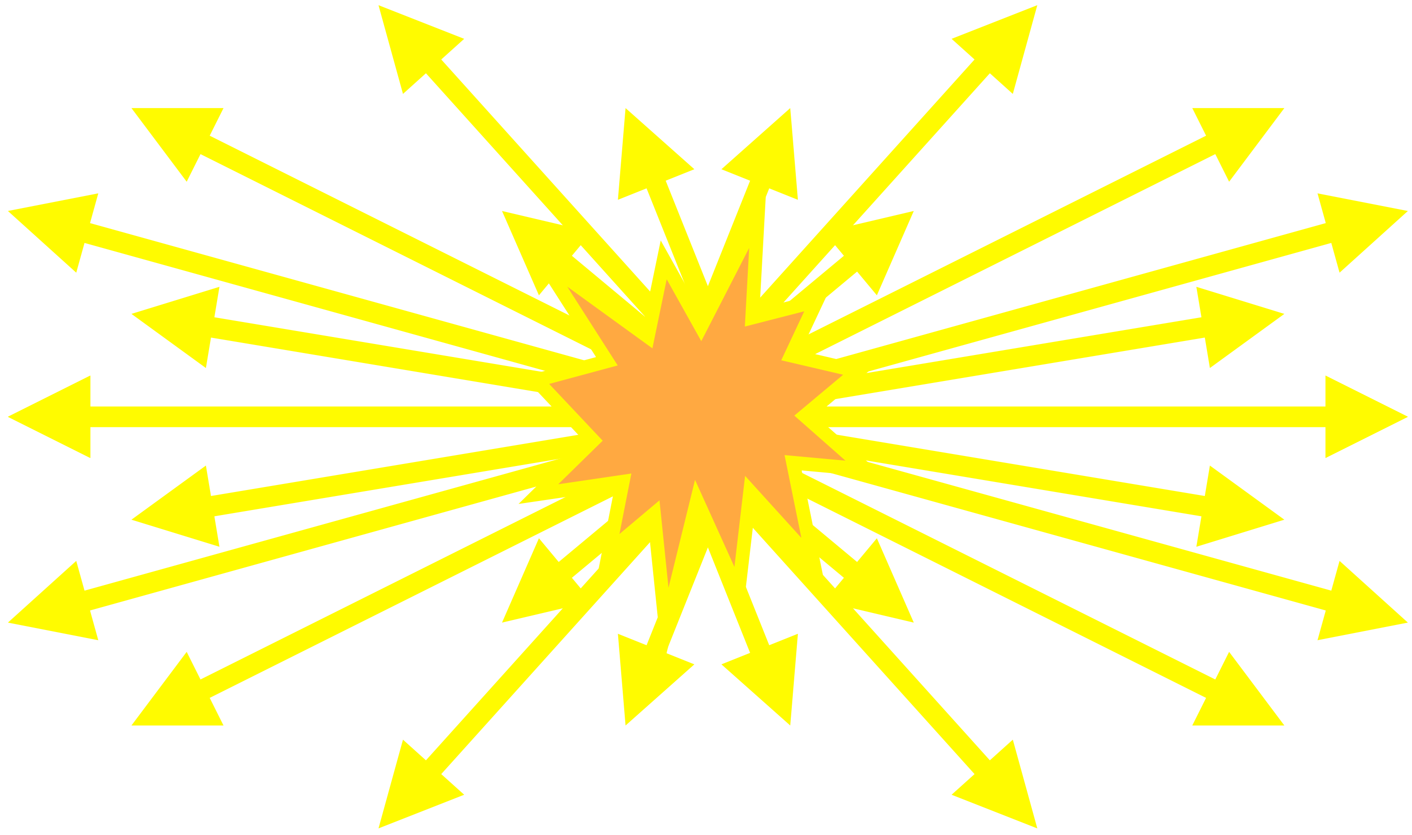
TO FLOW OR NOT TO FLOW?

Evolution as a bulk system

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

Pressure gradient higher in-plane i.e. pushes bulk out: flow

More and faster particles in-plane than out-of-plane



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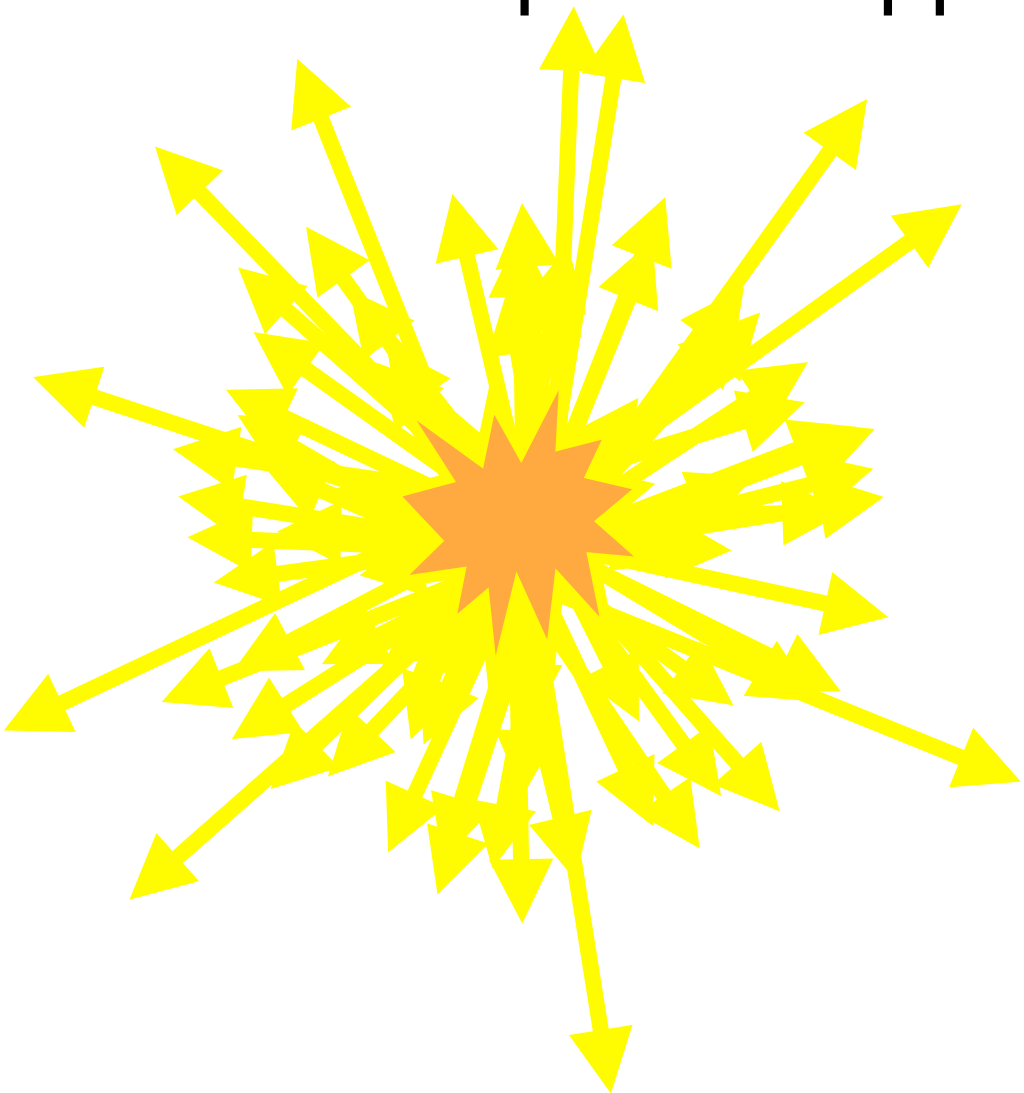
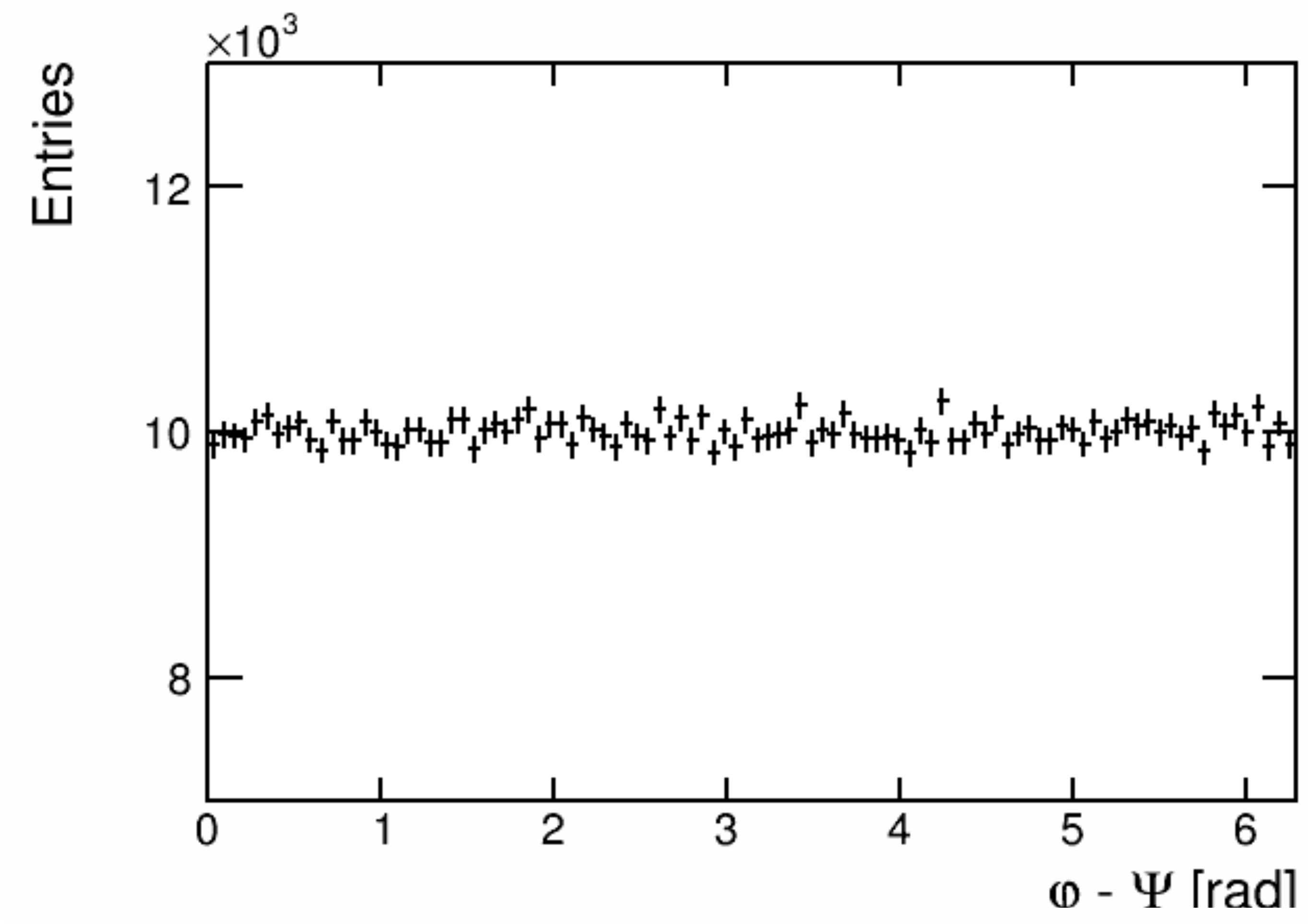
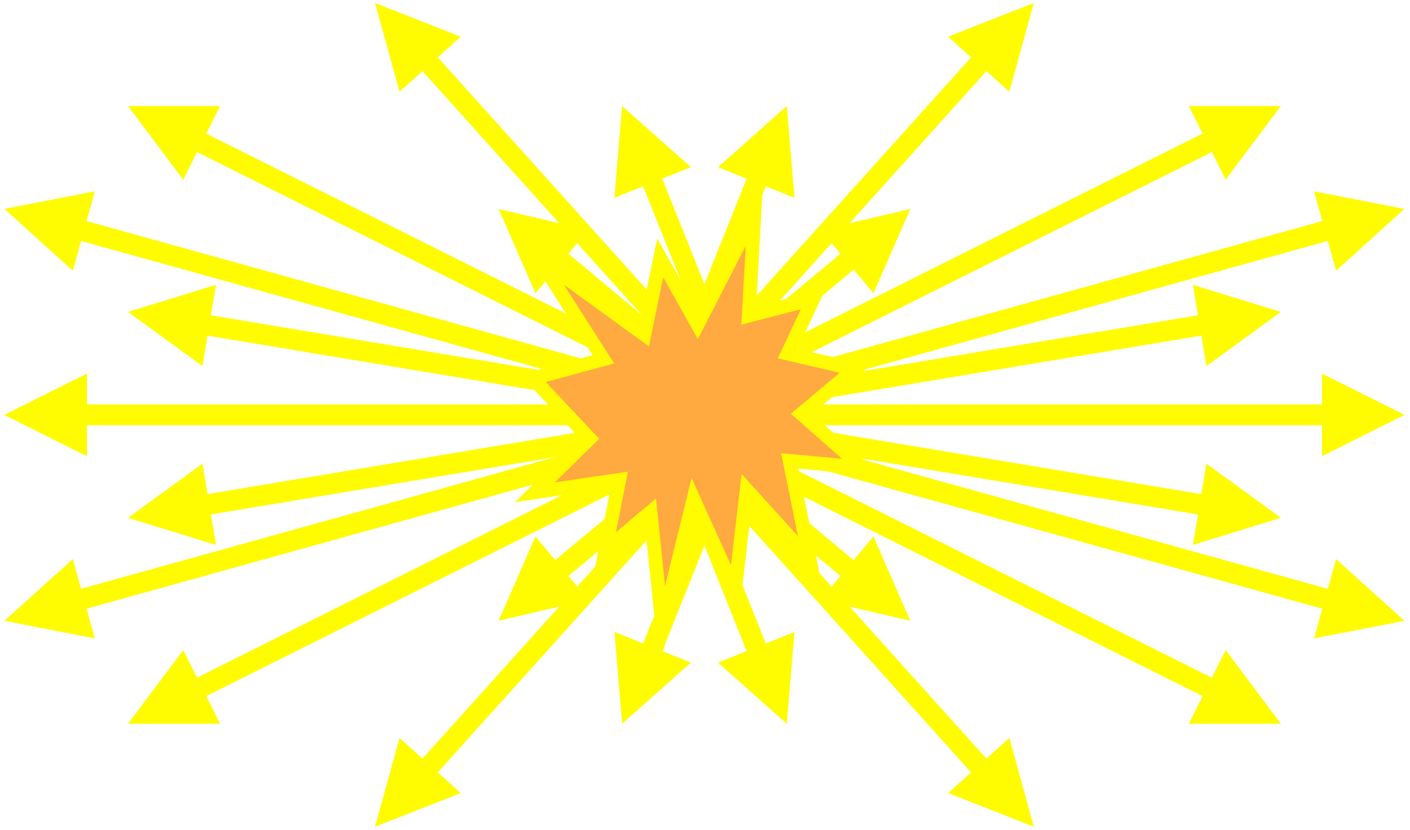
ELLIPTIC FLOW

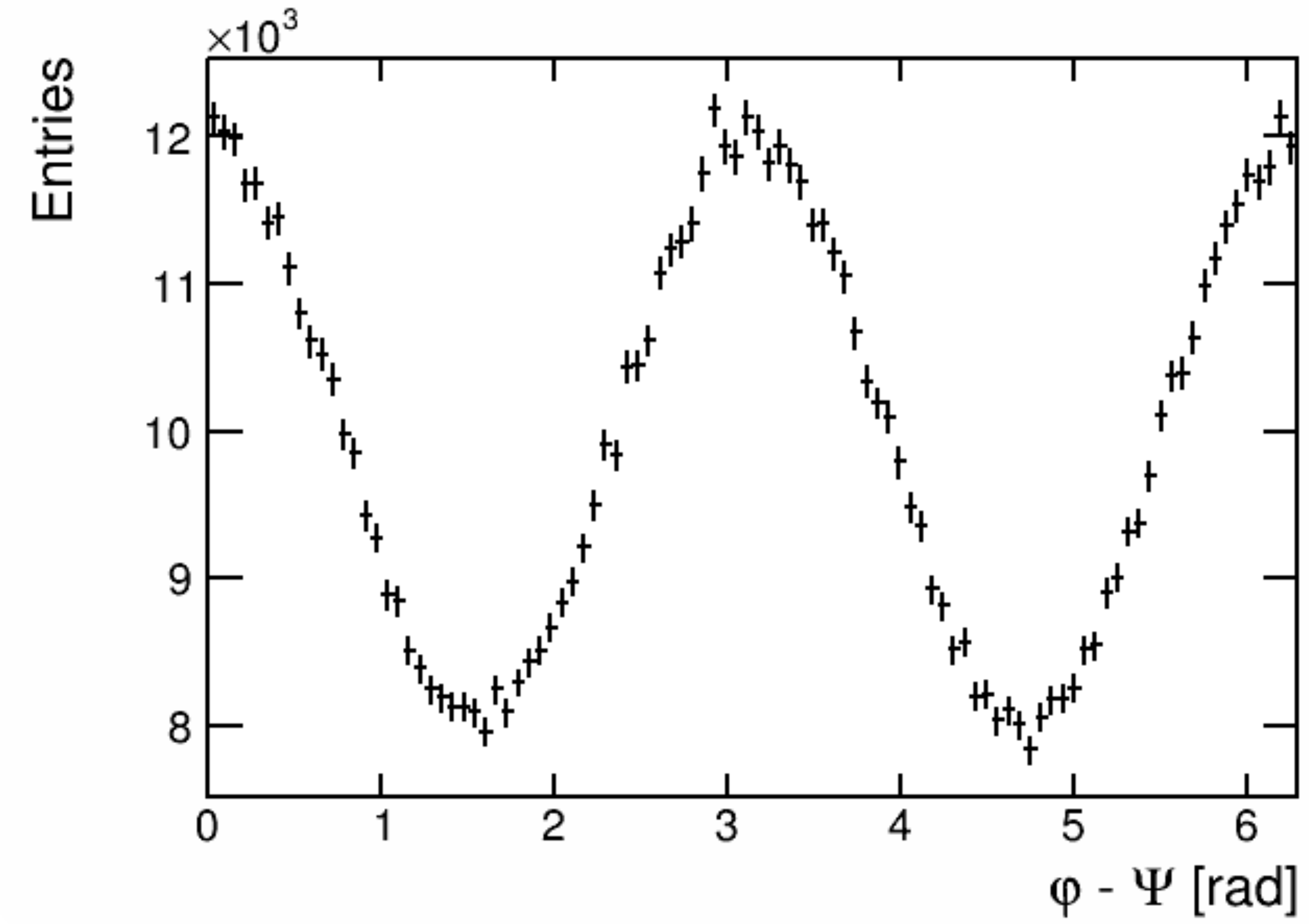
Superposition of independent pp collisions



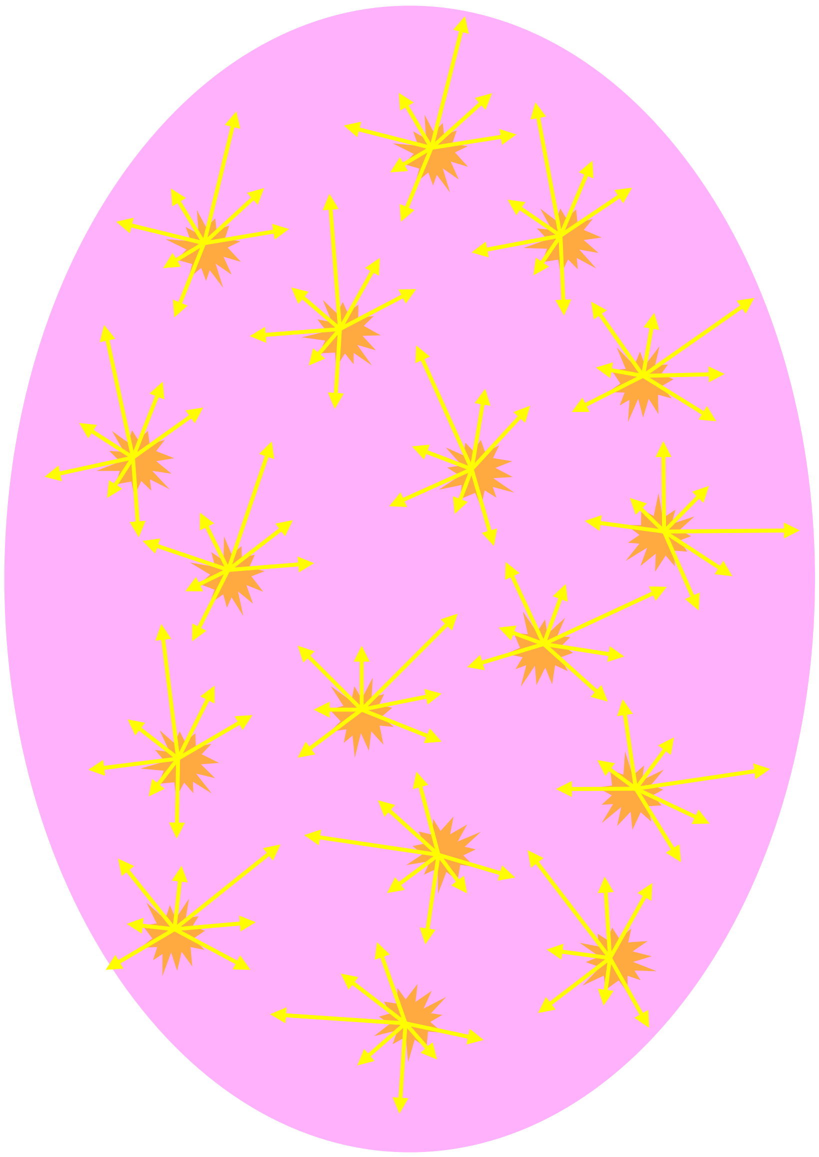


Evolution as a bulk system

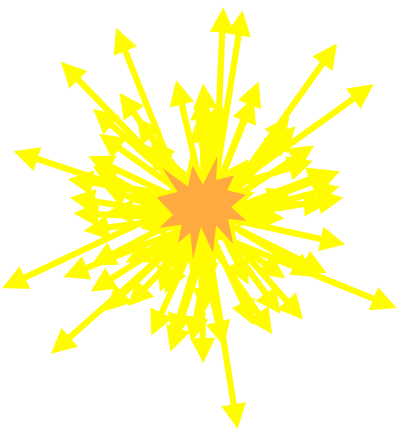




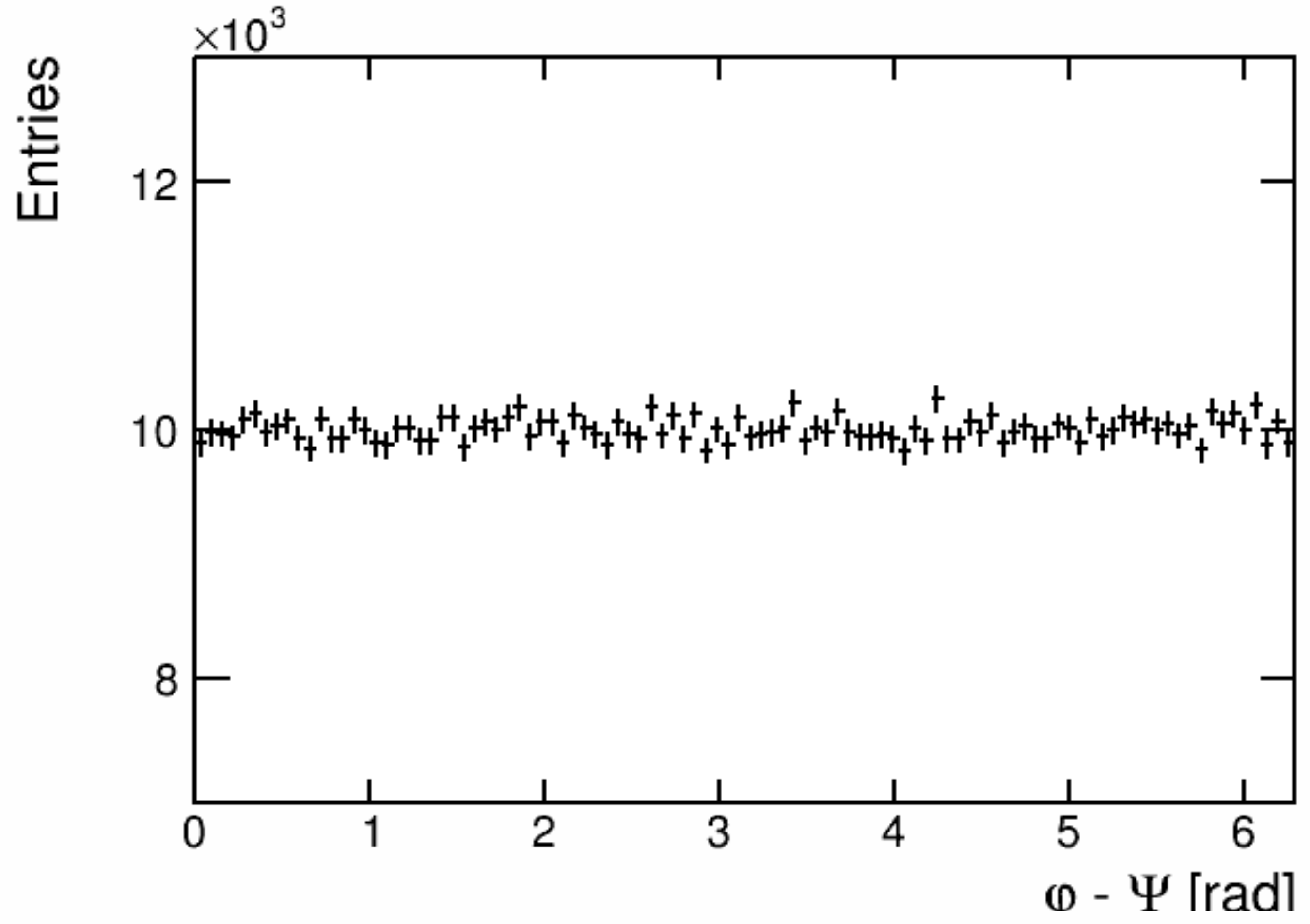
BULK OBSERVABLES: ANISOTROPIC FLOW

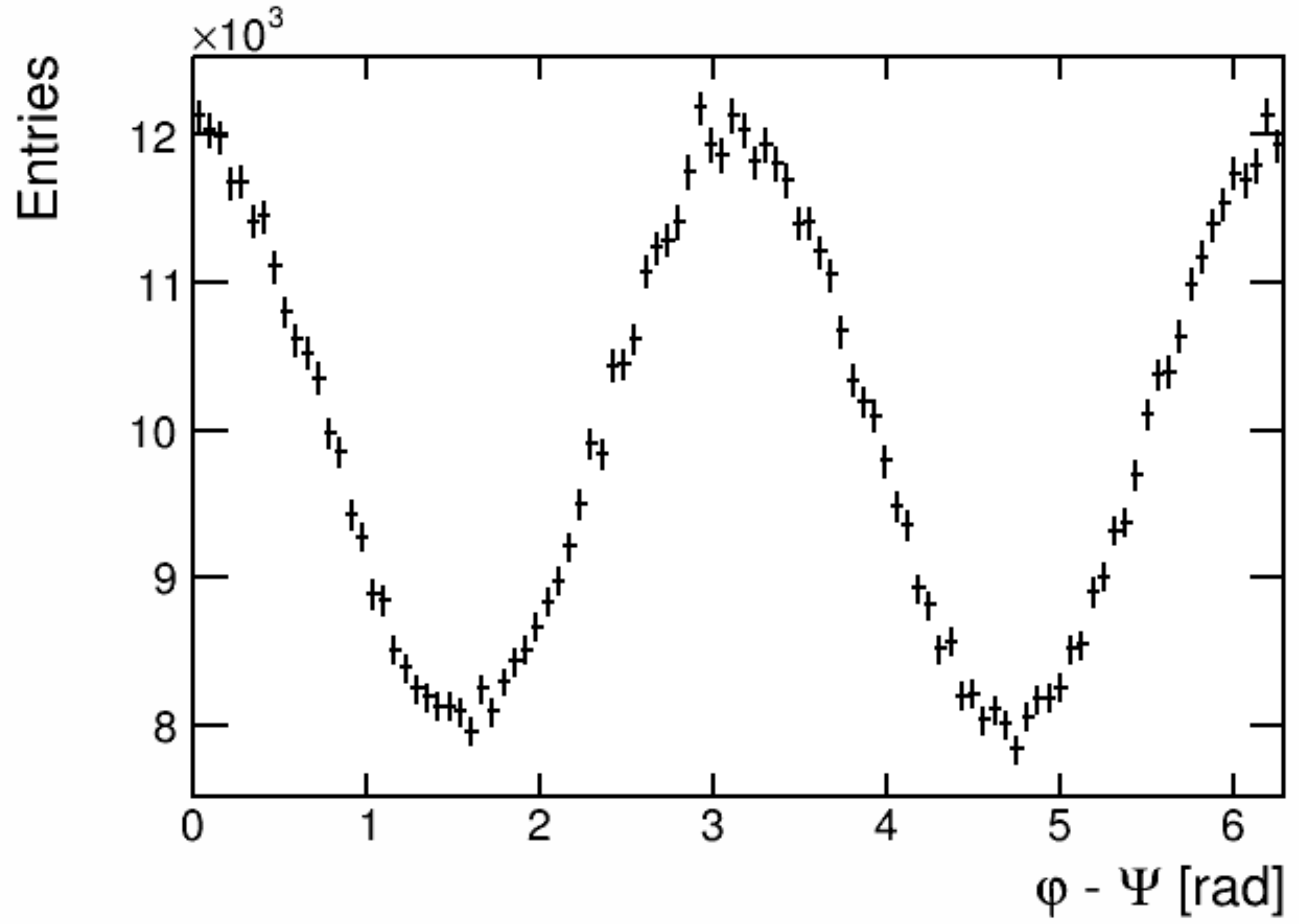


Superposition of independent pp collisions



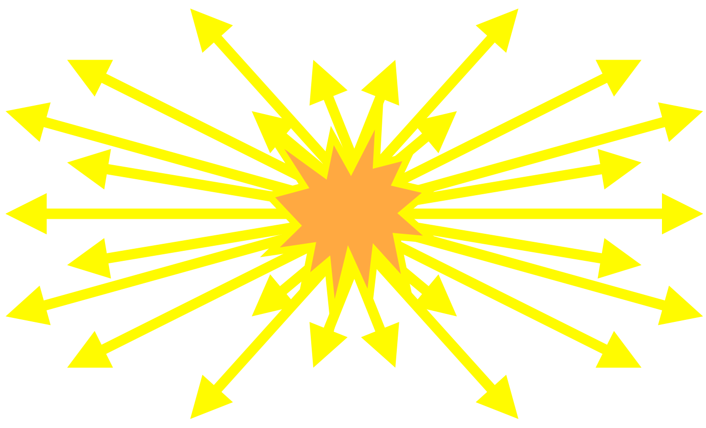
Momenta pointing at random directions





Development as a bulk system: high density and pressure at the centre of the fireball

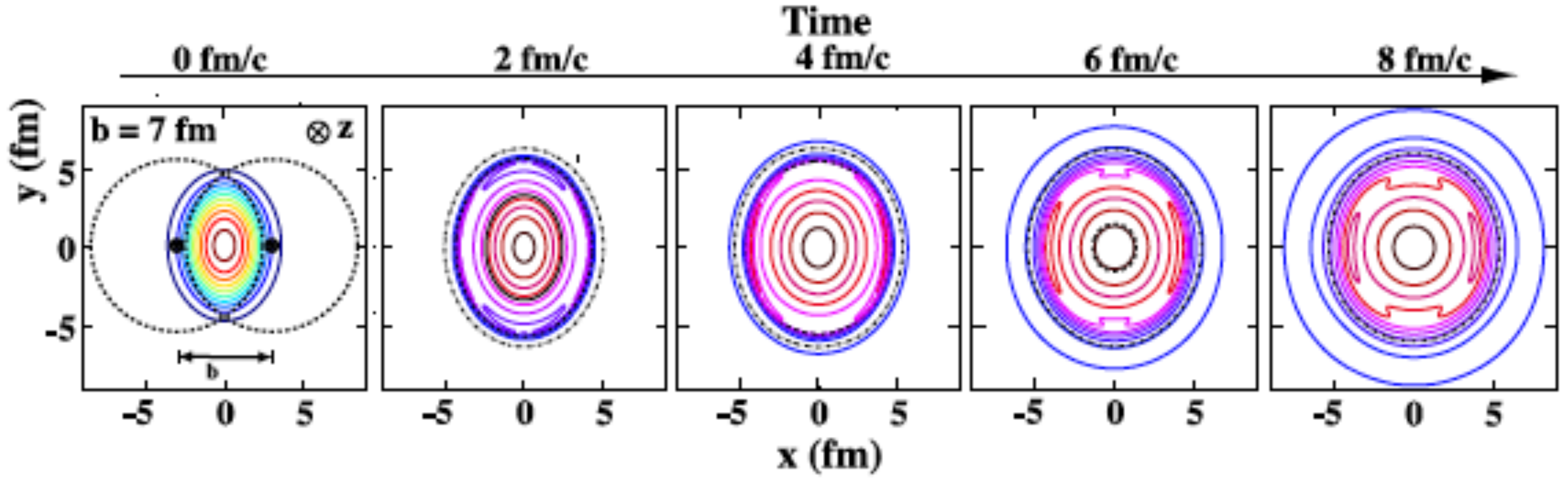
Asymmetric pressure gradients (larger in-plane than out-of-plane) push bulk out → flow



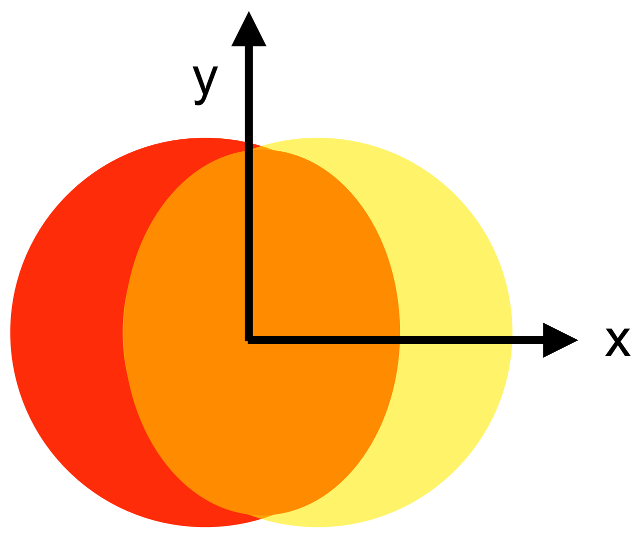
More and faster particles in-plane than out-of-plane

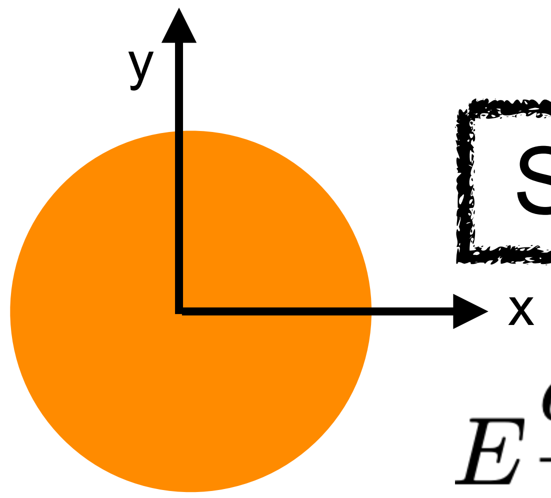
COORDINATE SPACE VS MOMENTUM ANISOTROPIES

Coordinate space: eccentricities

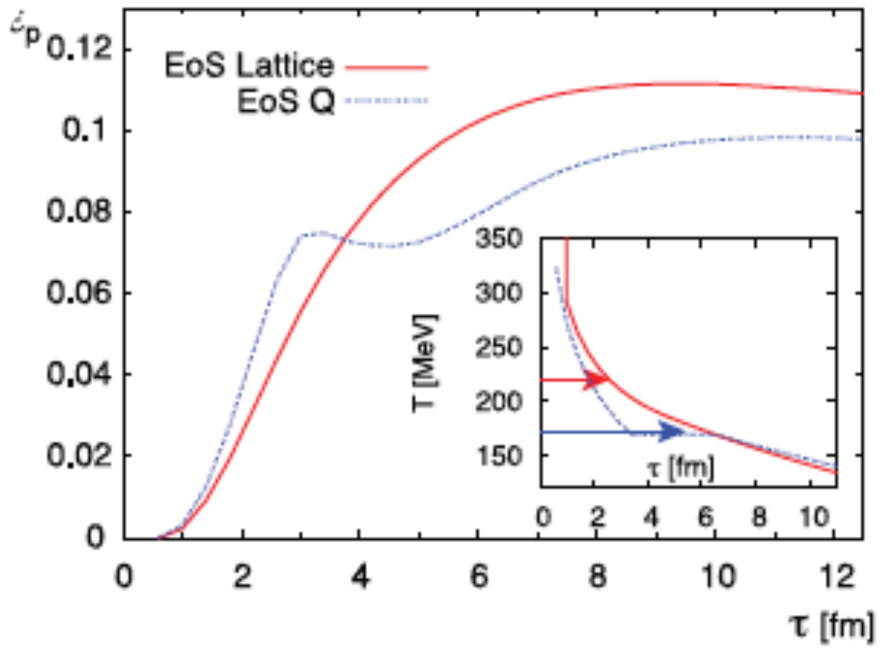


$$\epsilon = \frac{\langle y^2 - x^2 \rangle}{\langle y^2 + x^2 \rangle}$$

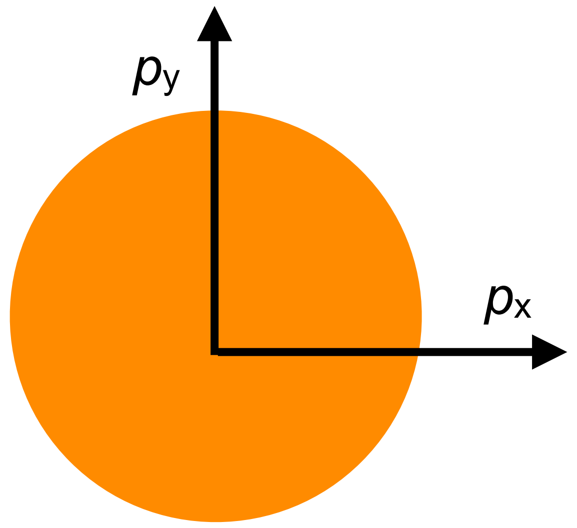




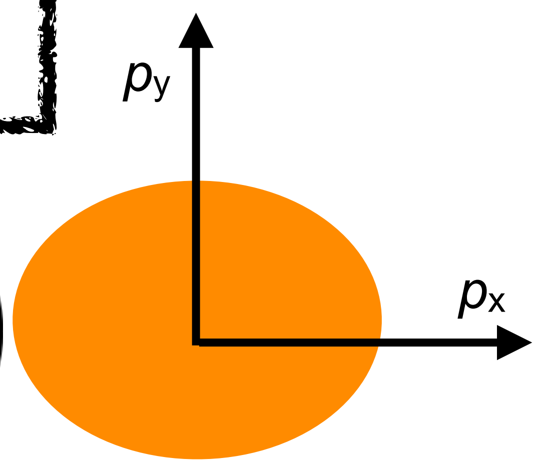
Momentum space: flow harmonics



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



time



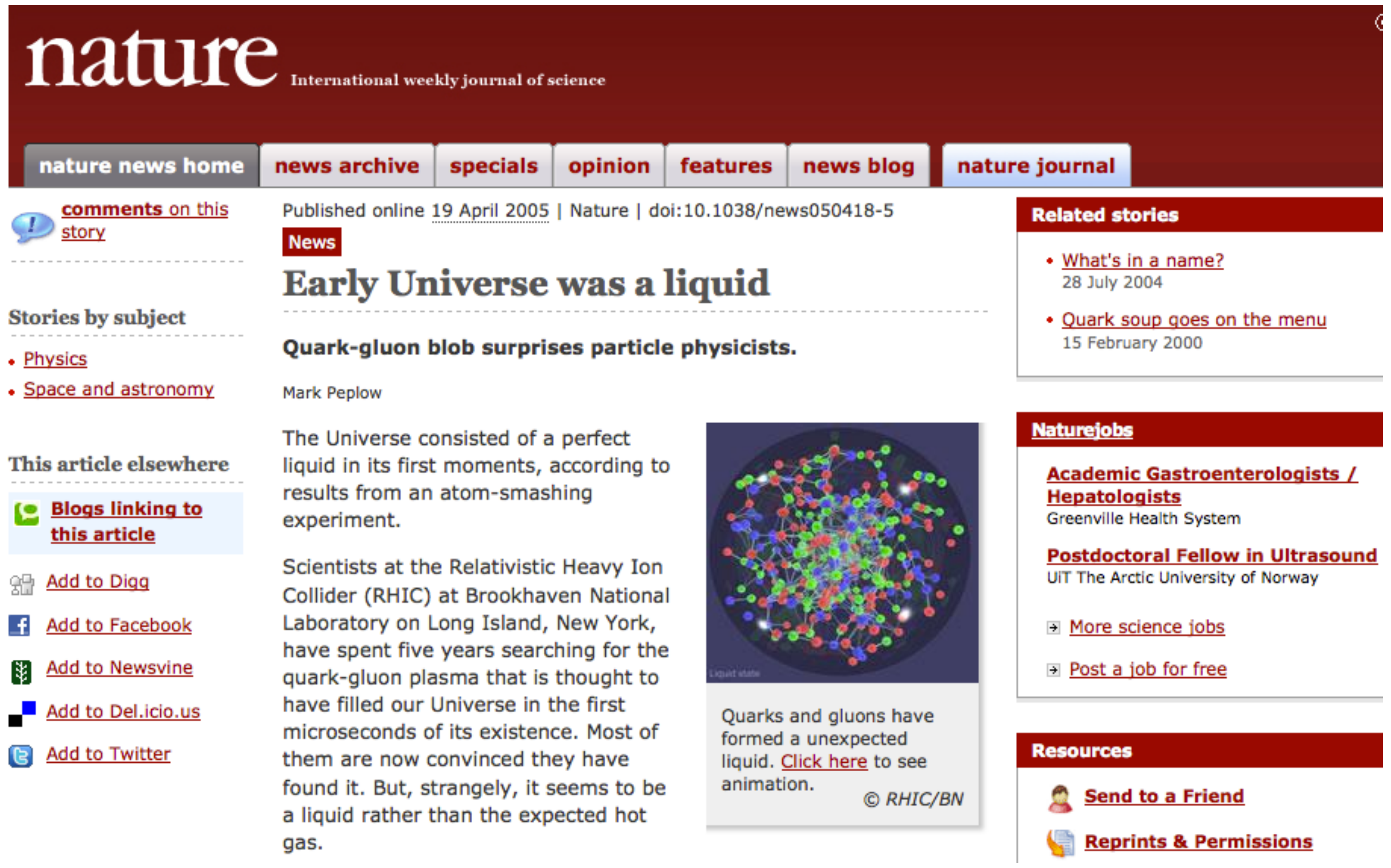
S. Voloshin and Y. Zhang, Z. Phys. **C70**, 665 (1996)

$$E\frac{d^3N}{d^3\vec{P}} = \frac{1}{2\pi}\frac{d^2N}{p_T dp_T dy}\left(1 + \sum_{n=1}^{\infty} 2v_n \cos[n(\varphi - \Psi_{RP})]\right)$$

$$v_n = \langle \cos[n(\varphi - \Psi_{RP})] \rangle$$

Connection to equation of state and to the system's transport properties (e.g. η/s, ζ/s)

THE PERFECT LIQUID AT RHIC AND LHC



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News

Early Universe was a liquid

Quark-gluon blob surprises particle physicists.

Mark Peplow

The Universe consisted of a perfect liquid in its first moments, according to results from an atom-smashing experiment.

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Quarks and gluons have formed a unexpected liquid. Click here to see animation. © RHIC/BN

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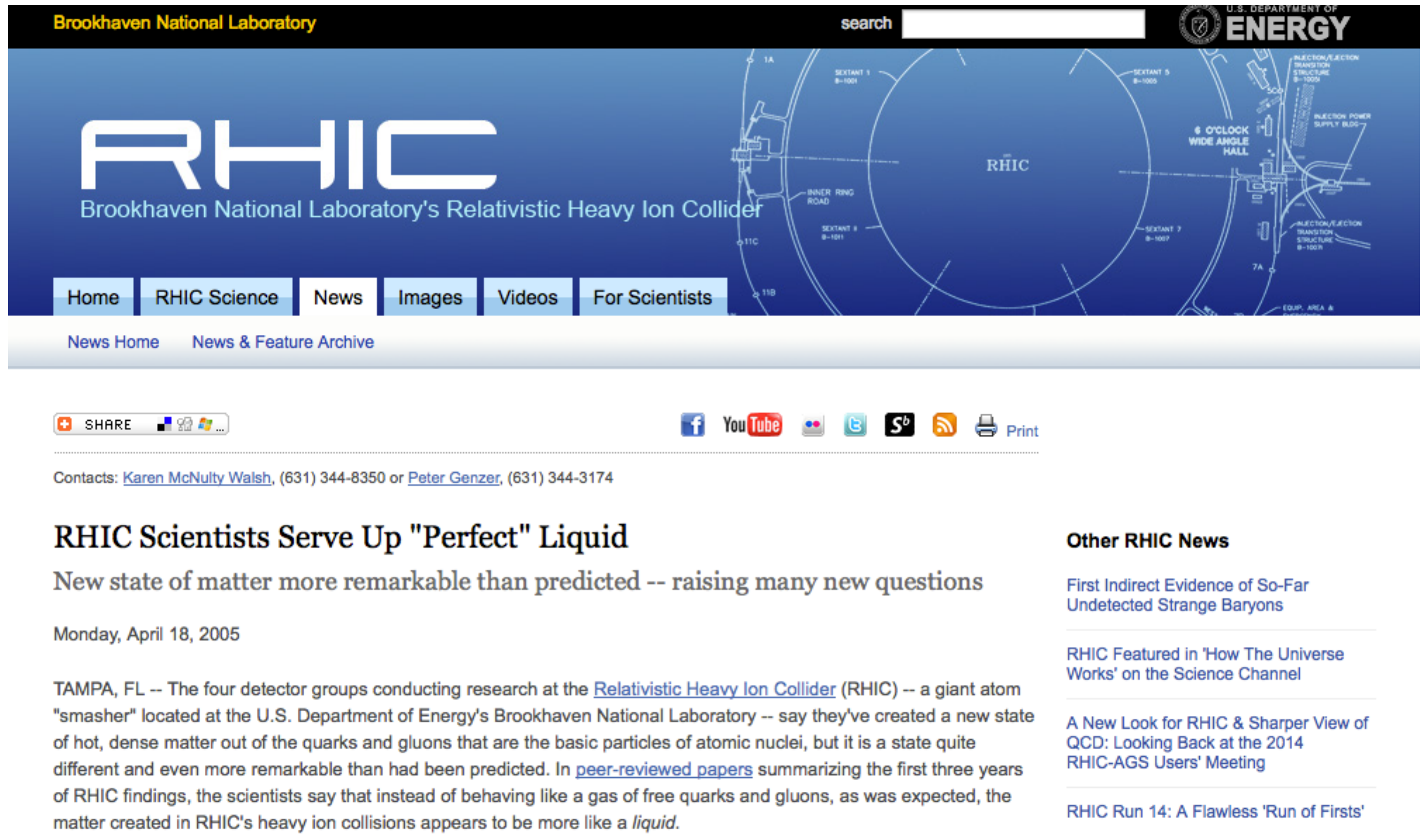

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Contacts: Karen McNulty Walsh, (631) 344-8350 or Peter Genzer, (631) 344-3174

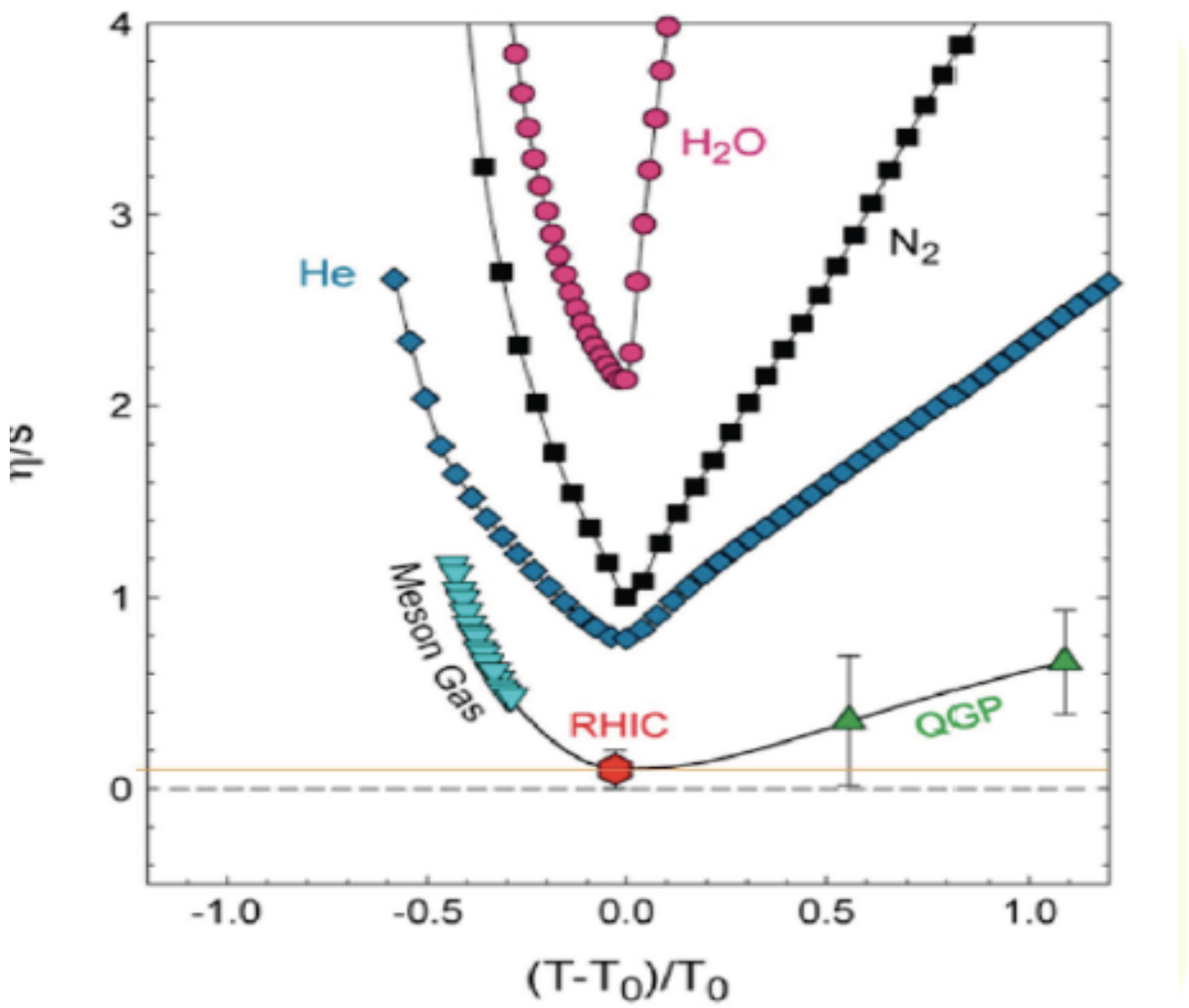
RHIC Scientists Serve Up "Perfect" Liquid

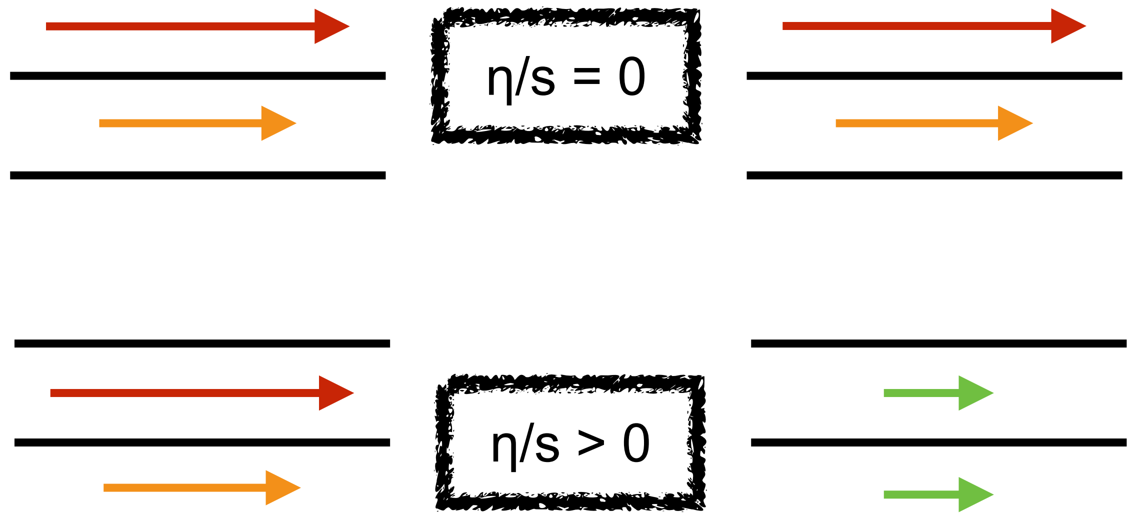
New state of matter more remarkable than predicted -- raising many new questions

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

Other RHIC News
- First Indirect Evidence of So-Far Undetected Strange Baryons
- RHIC Featured in 'How The Universe Works' on the Science Channel
- A New Look for RHIC & Sharper View of QCD: Looking Back at the 2014 RHIC-AGS Users' Meeting
- RHIC Run 14: A Flawless 'Run of Firsts'





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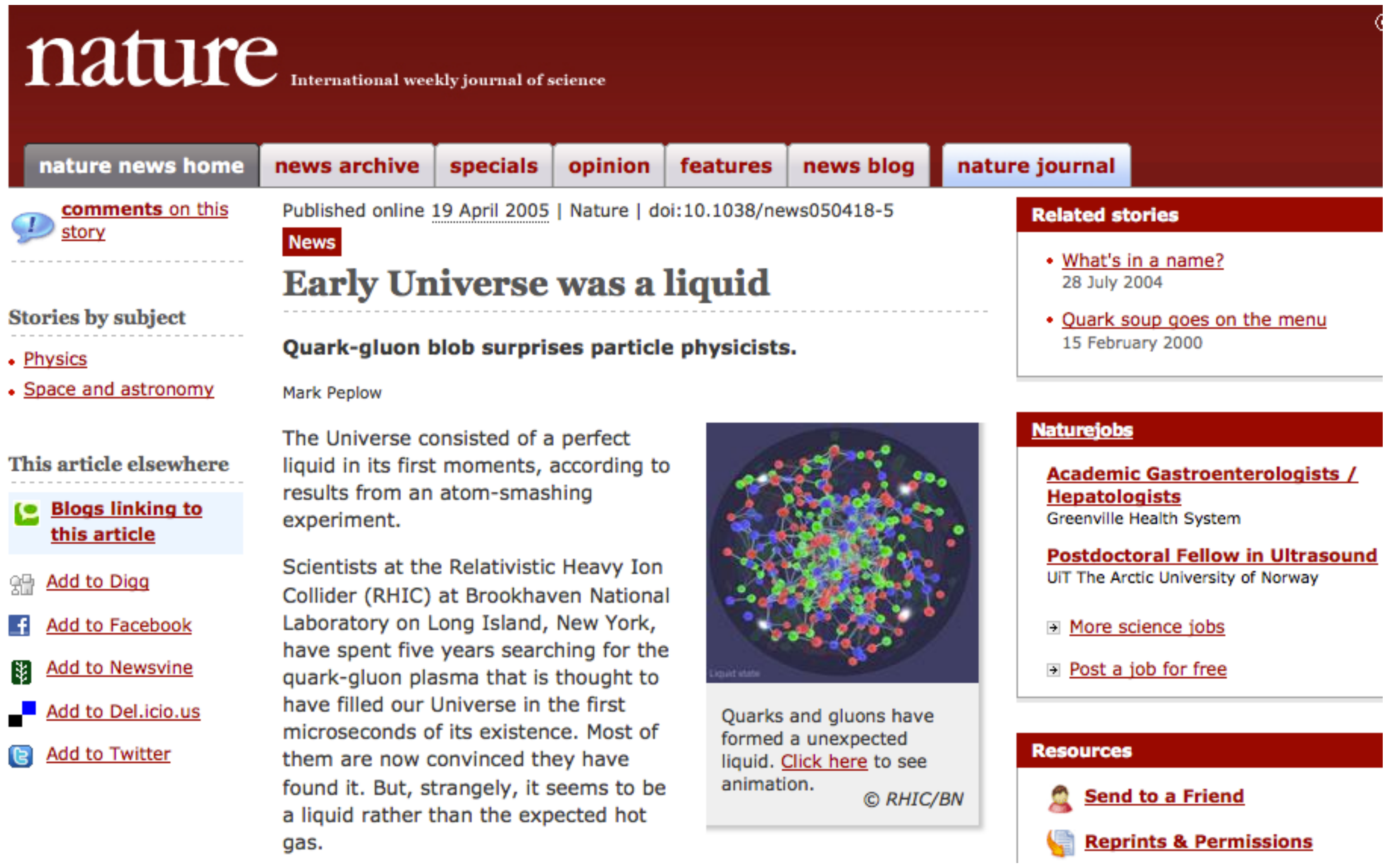

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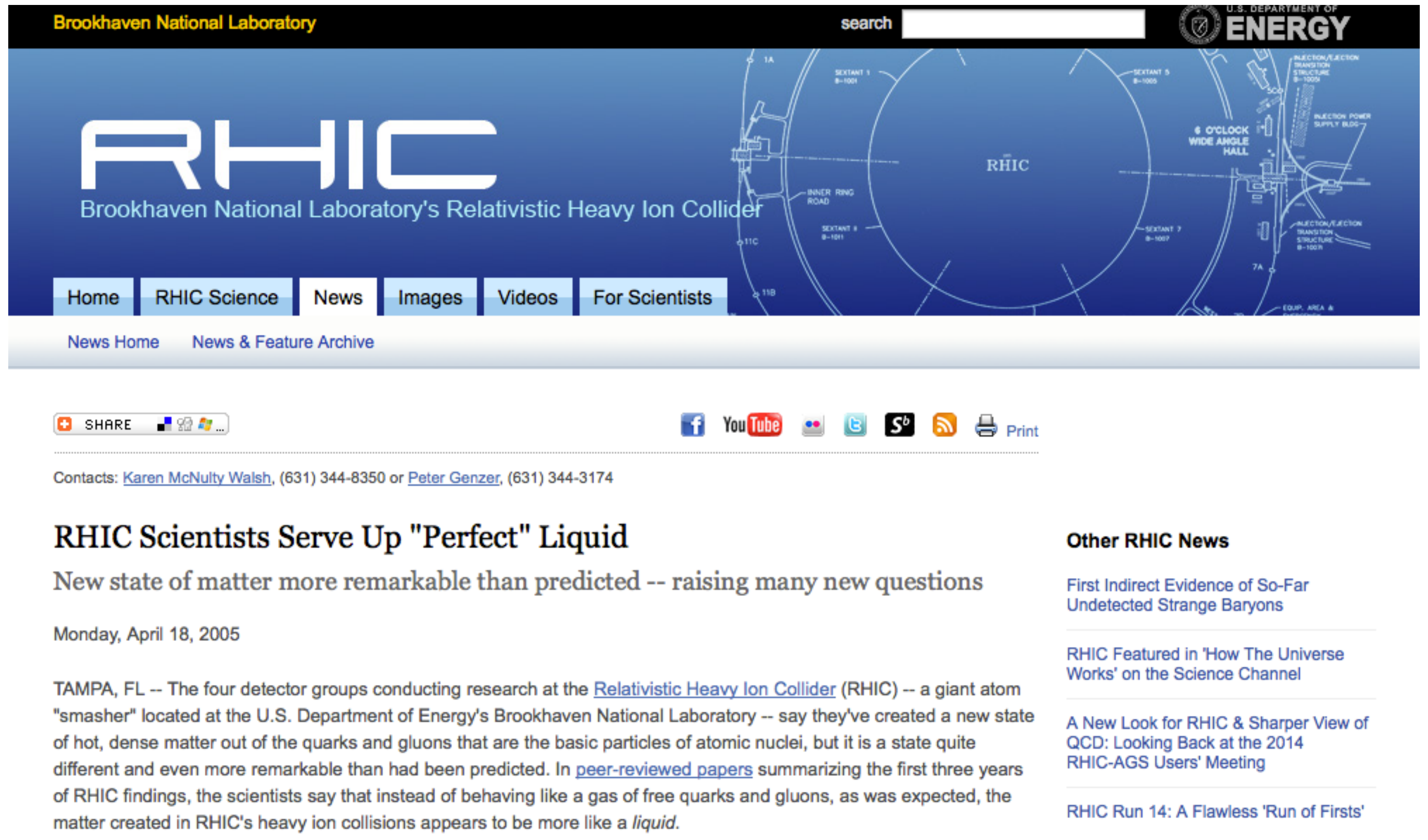

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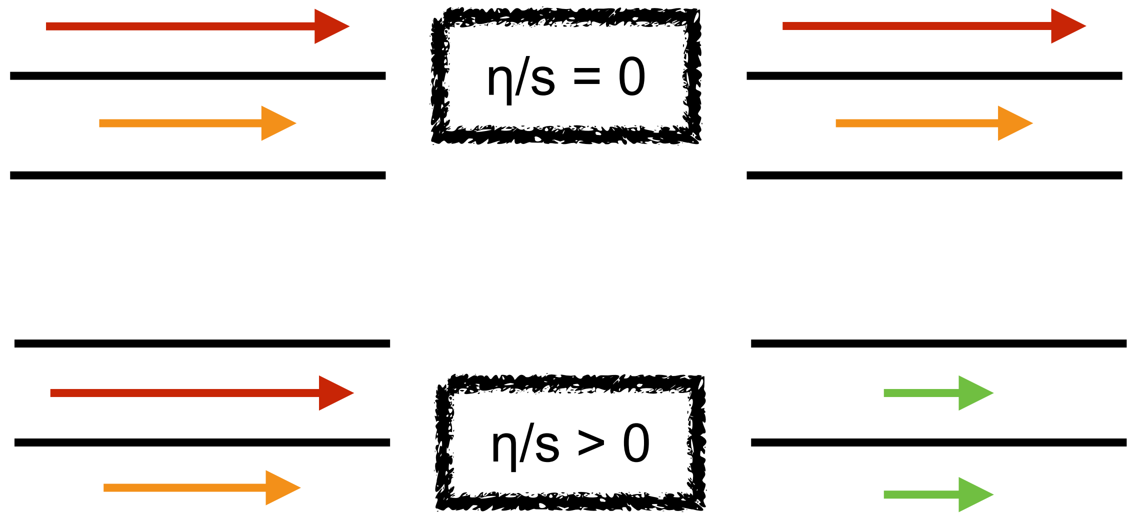
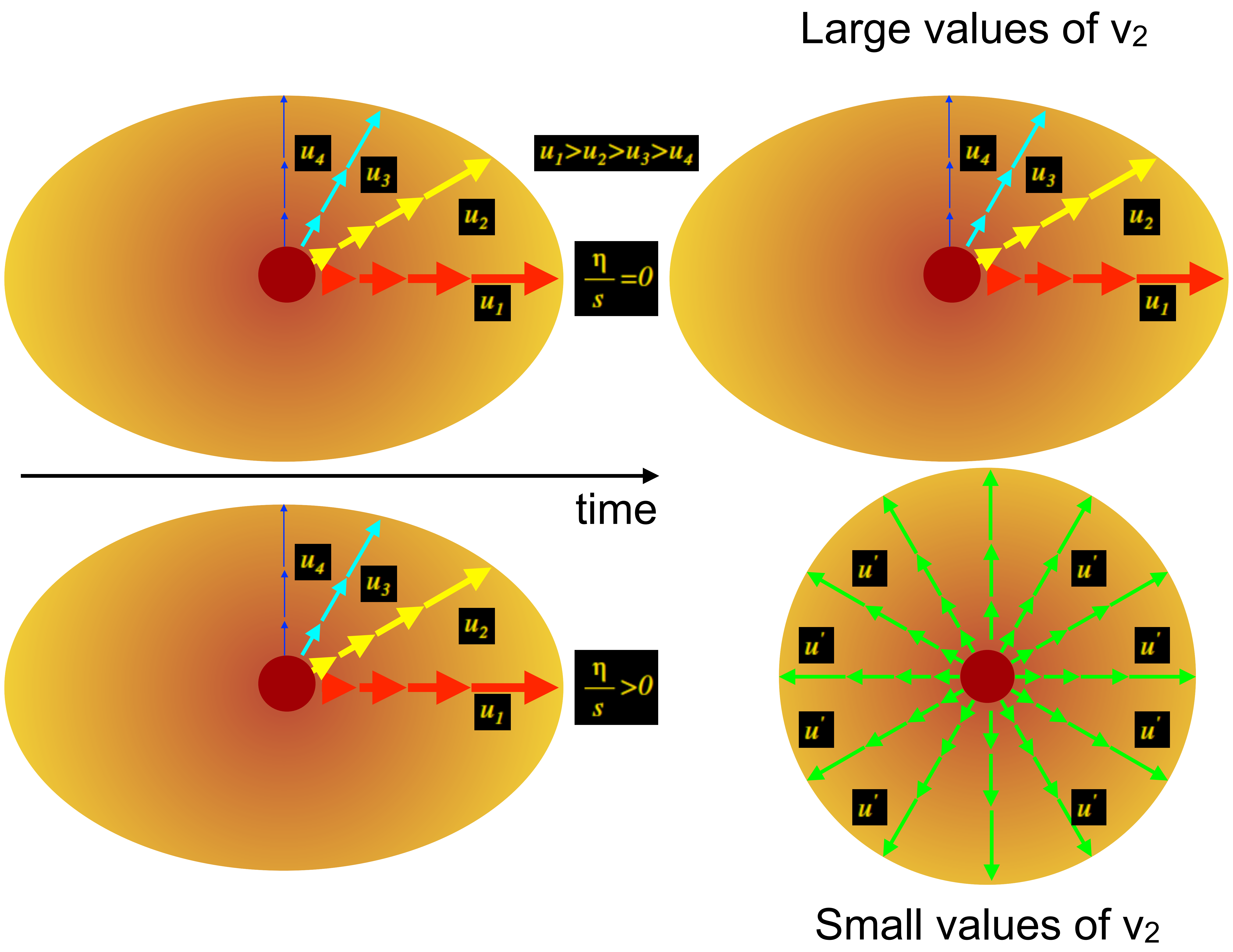
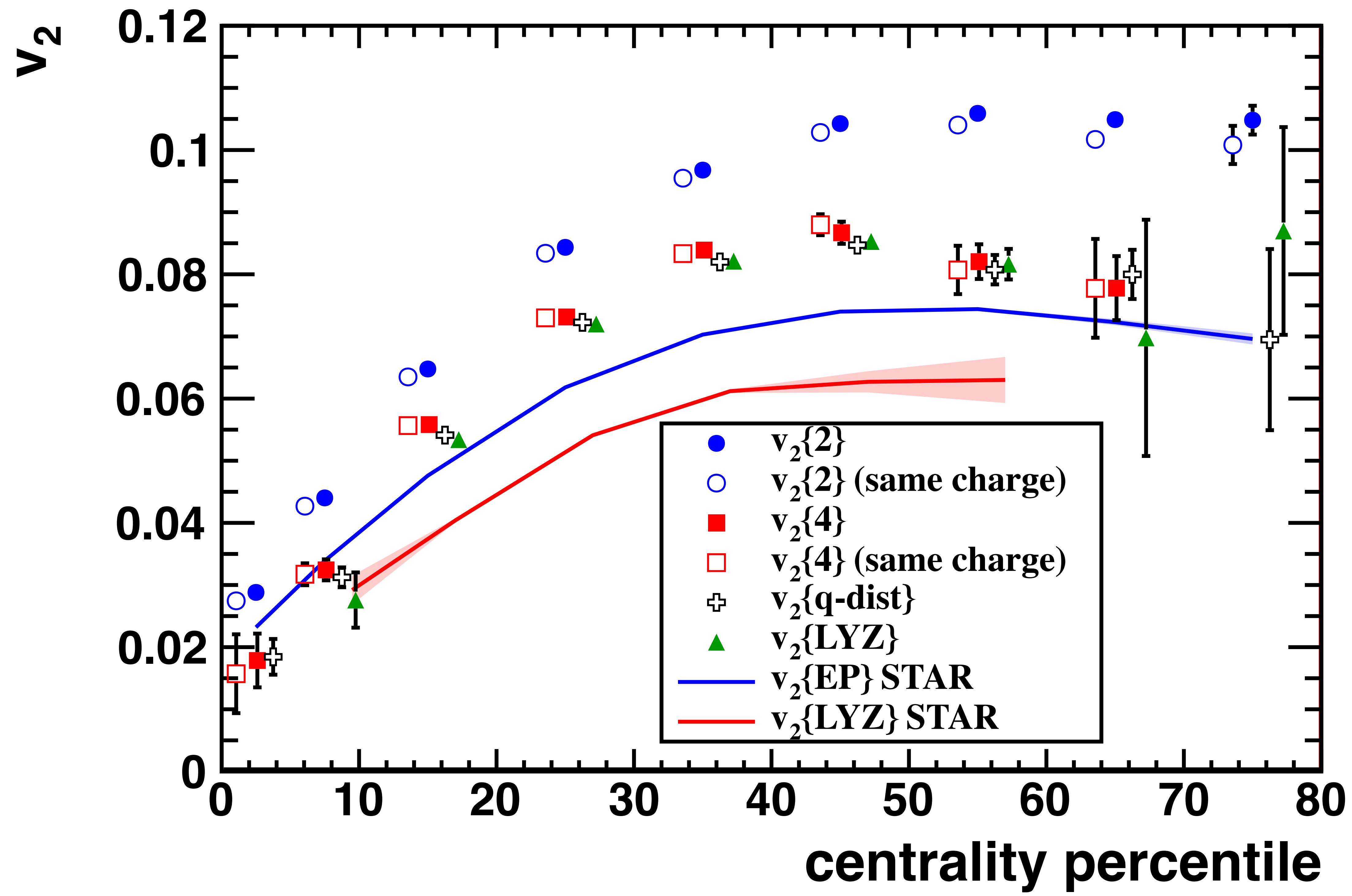
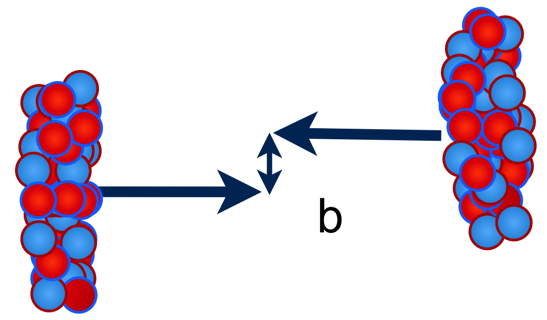


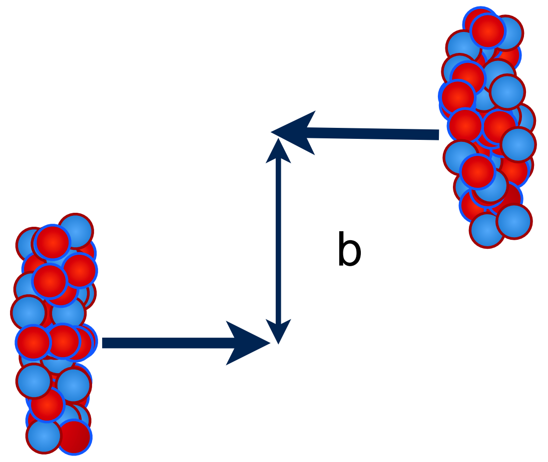
SPECIFIC SHEAR VISCOSITY



ELLIPTIC FLOW @ LHC







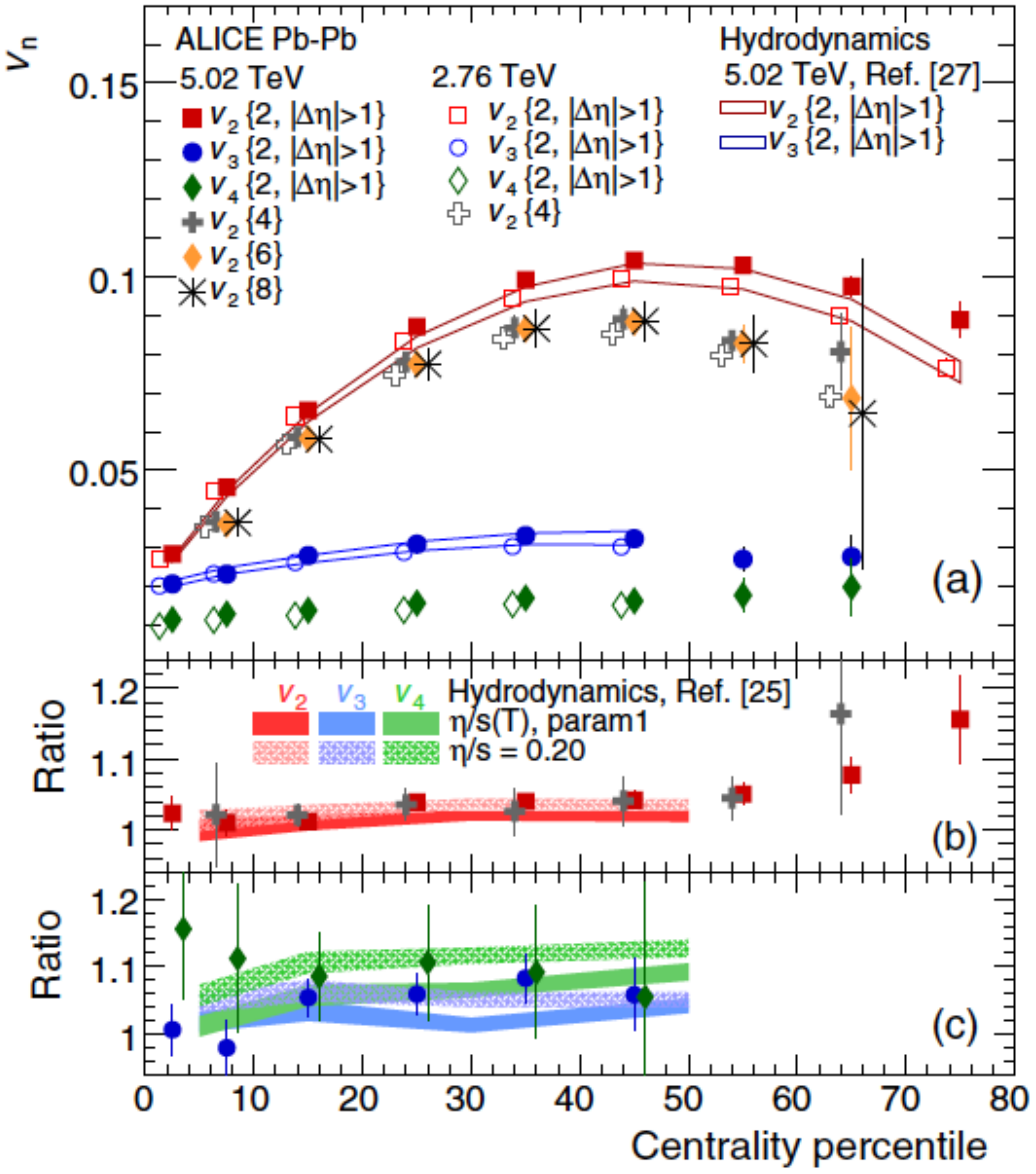
ANISOTROPIC FLOW @ LHC

Study the QGP properties in more detail

- Allows for the first time to probe the temperature dependence of η/S
- Connection to EoS

Looking at the details

- Initial state
- η/S(T), ζ/S(T)
- EoS
- Hadronic phase
- Surprises?



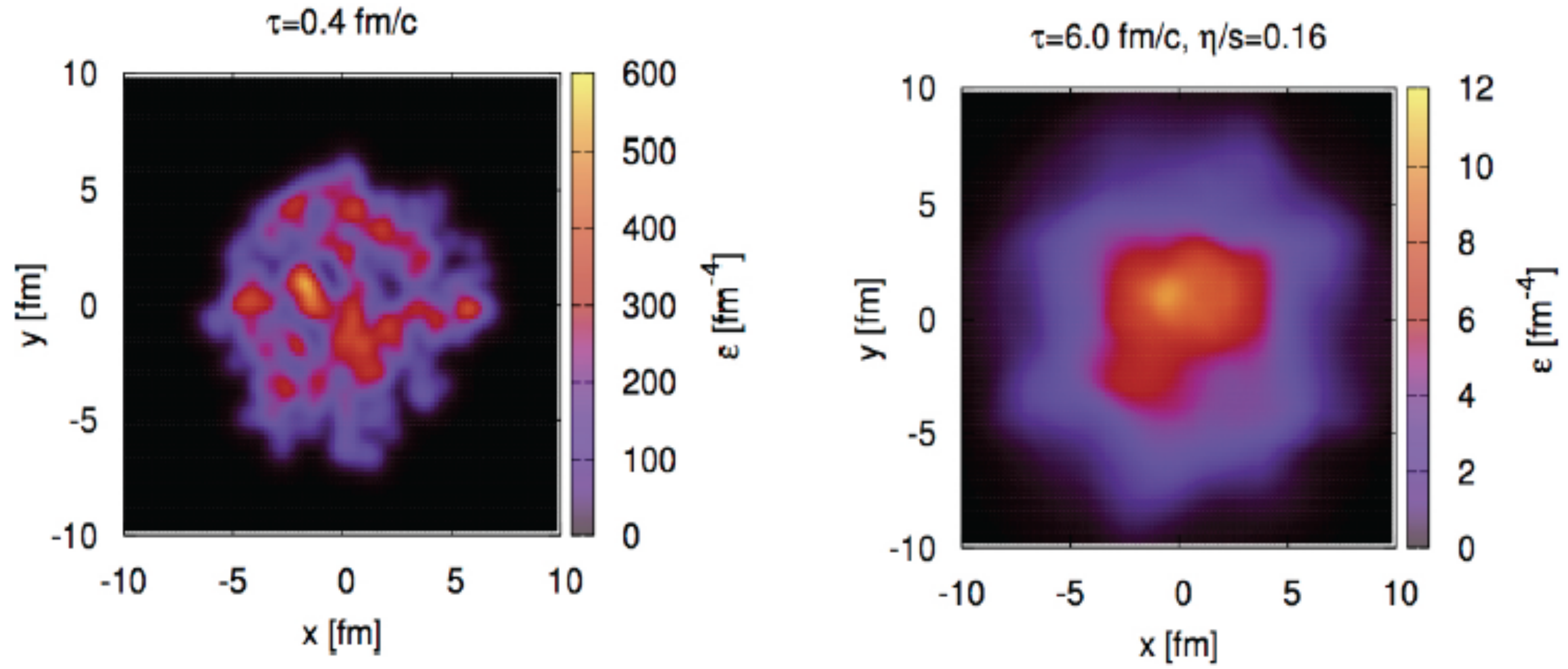
The medium behaves as an almost perfect liquid!!!

Nikhef

THERE ARE ALSO FLUCTUATIONS…

Initial geometry not described by the (ideal) almond shape

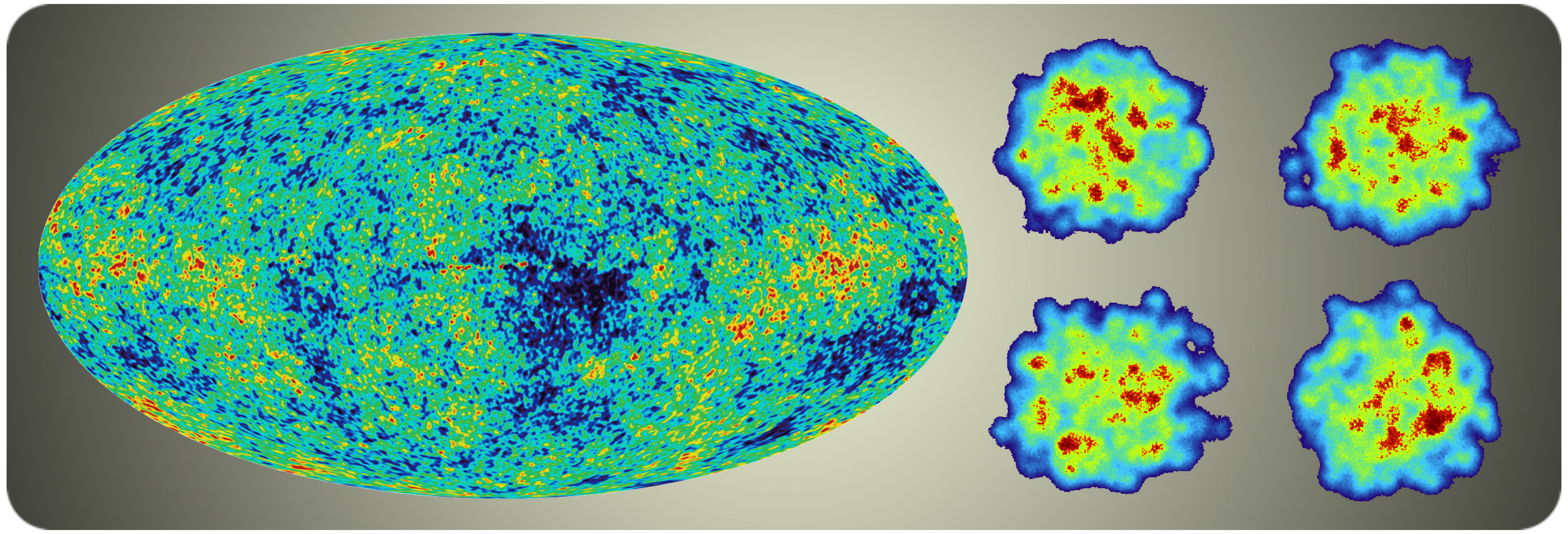
- Fluctuations of the initial energy/pressure distributions lead to “irregular” shapes that fluctuate from one event to the other
- Higher order (odd) harmonics develop, each one having its own symmetry plane
  - Higher order harmonics more sensitive to the value of η/S



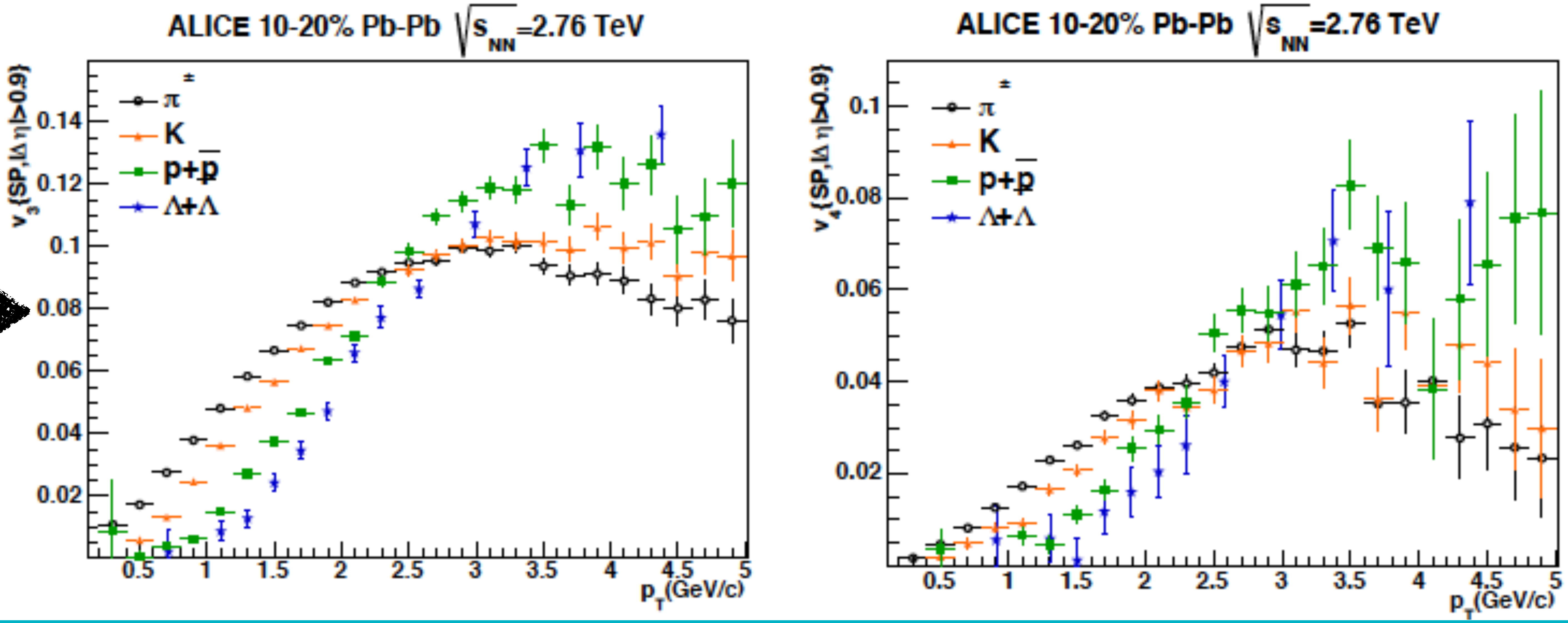
But initial conditions not known precisely enough (model dependent)

- Data can be described by different combinations of initial conditions and η/S

HIGHER HARMONICS



Due to the low value of η/s, higher harmonics survive at the final state
Allow the study of initial conditions of heavy-ion collisions for the first time!



Part of a MSc thesis!!!

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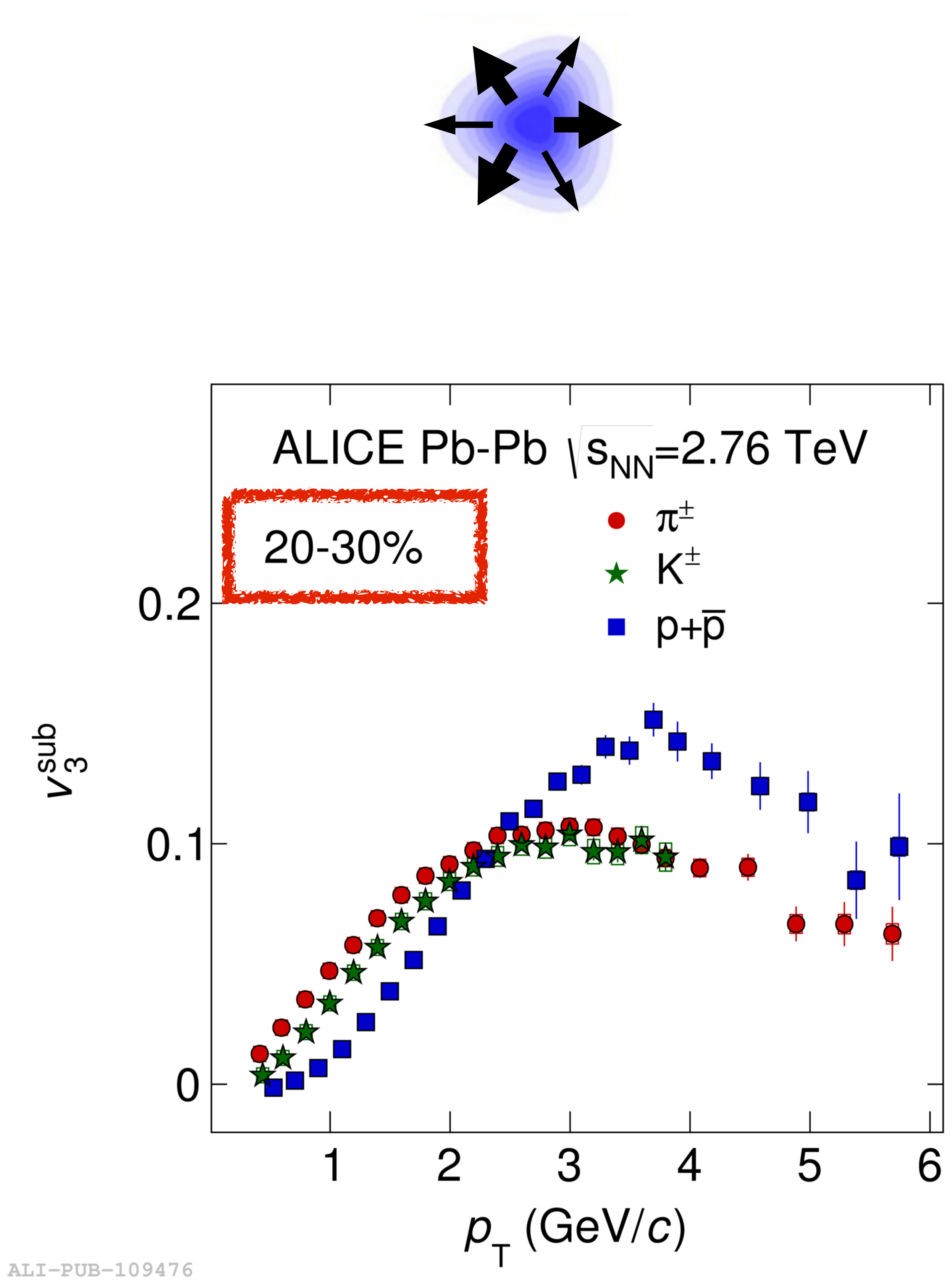
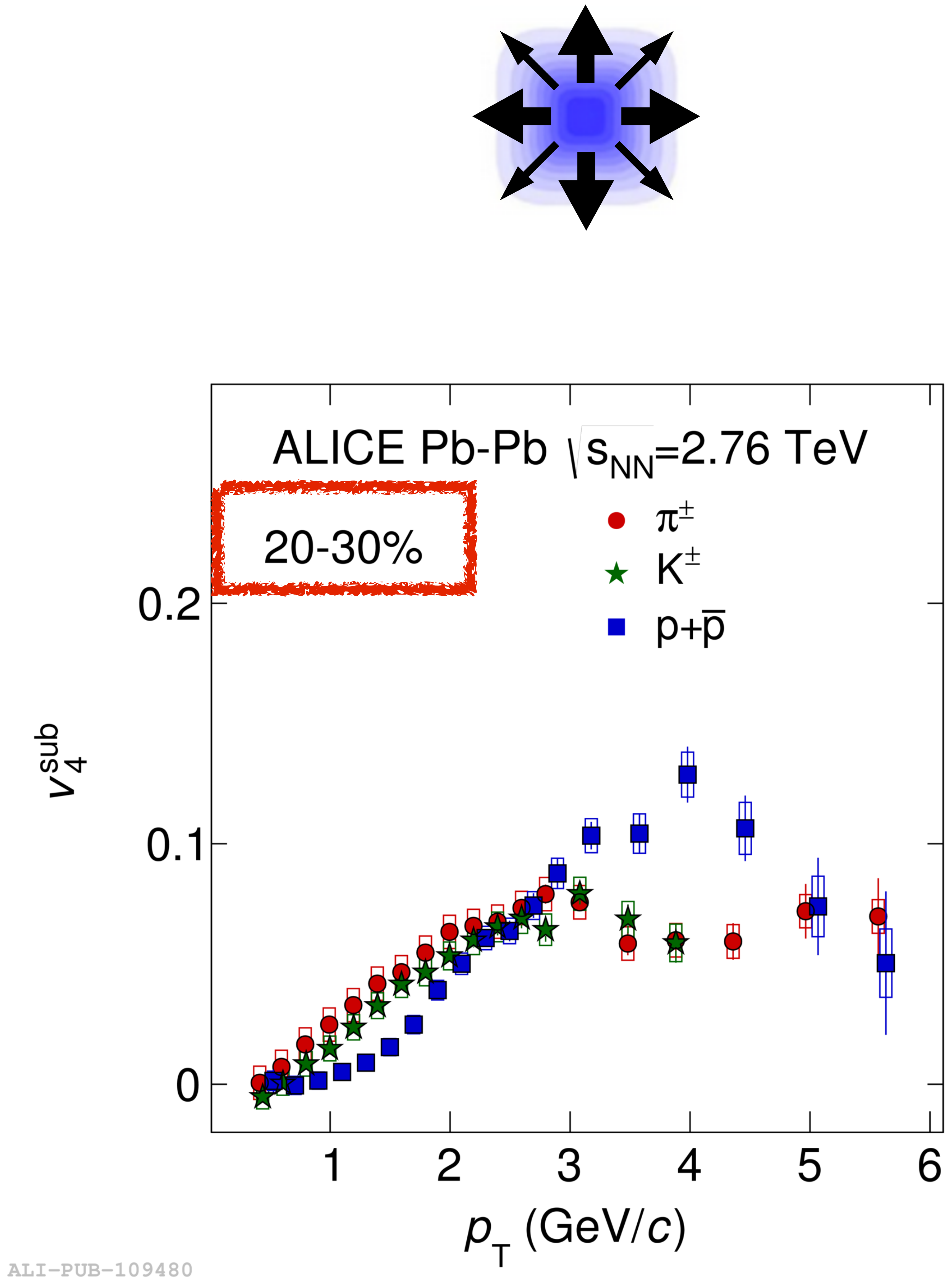
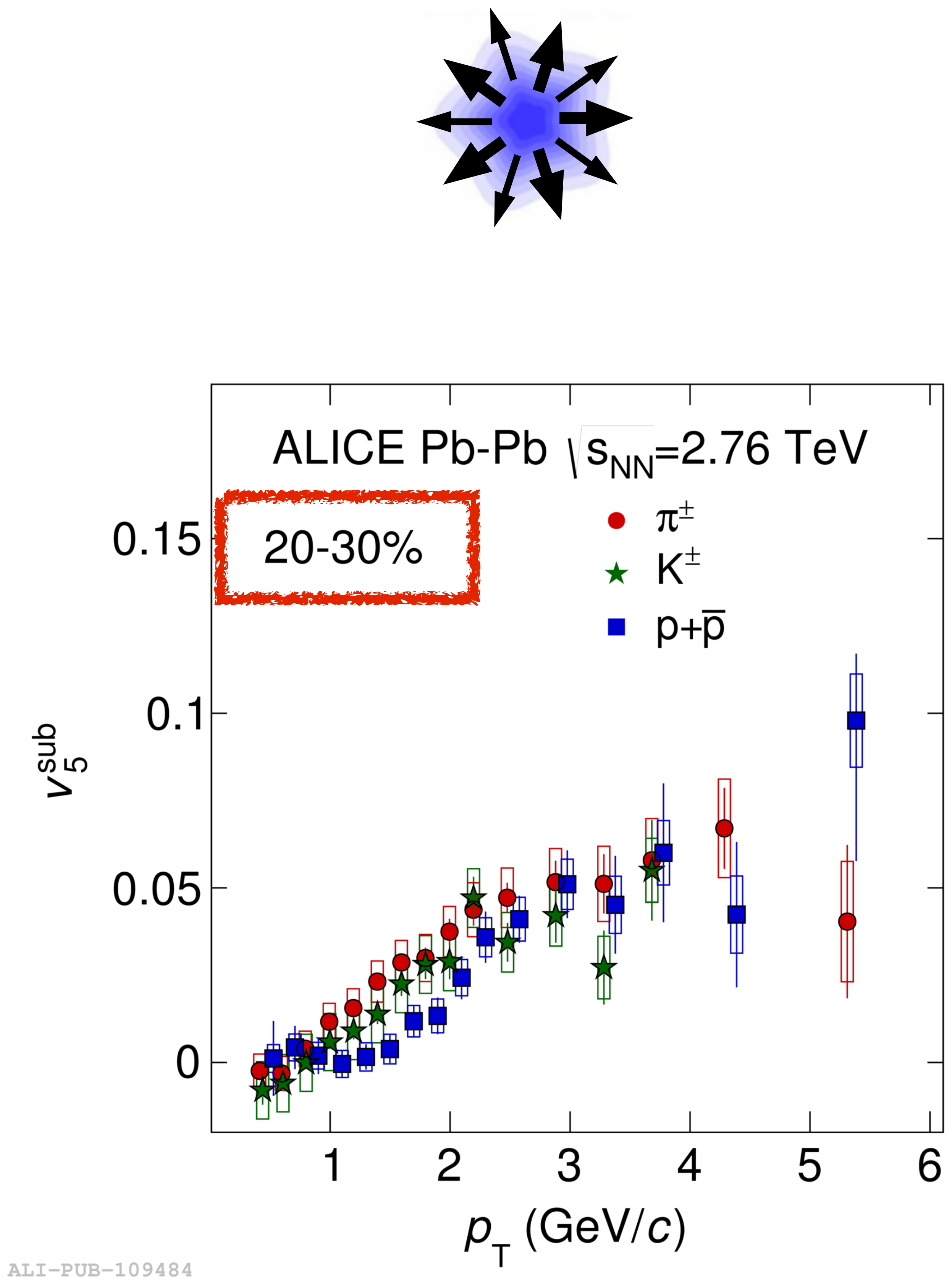
HIGHER HARMONICS @ LHC (RUN 1)







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

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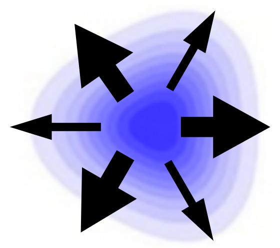
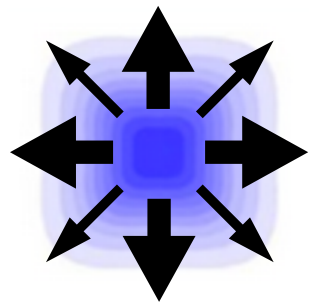
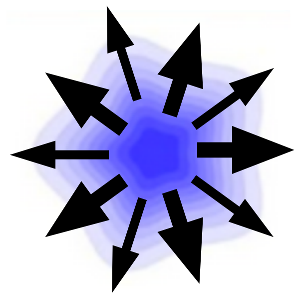
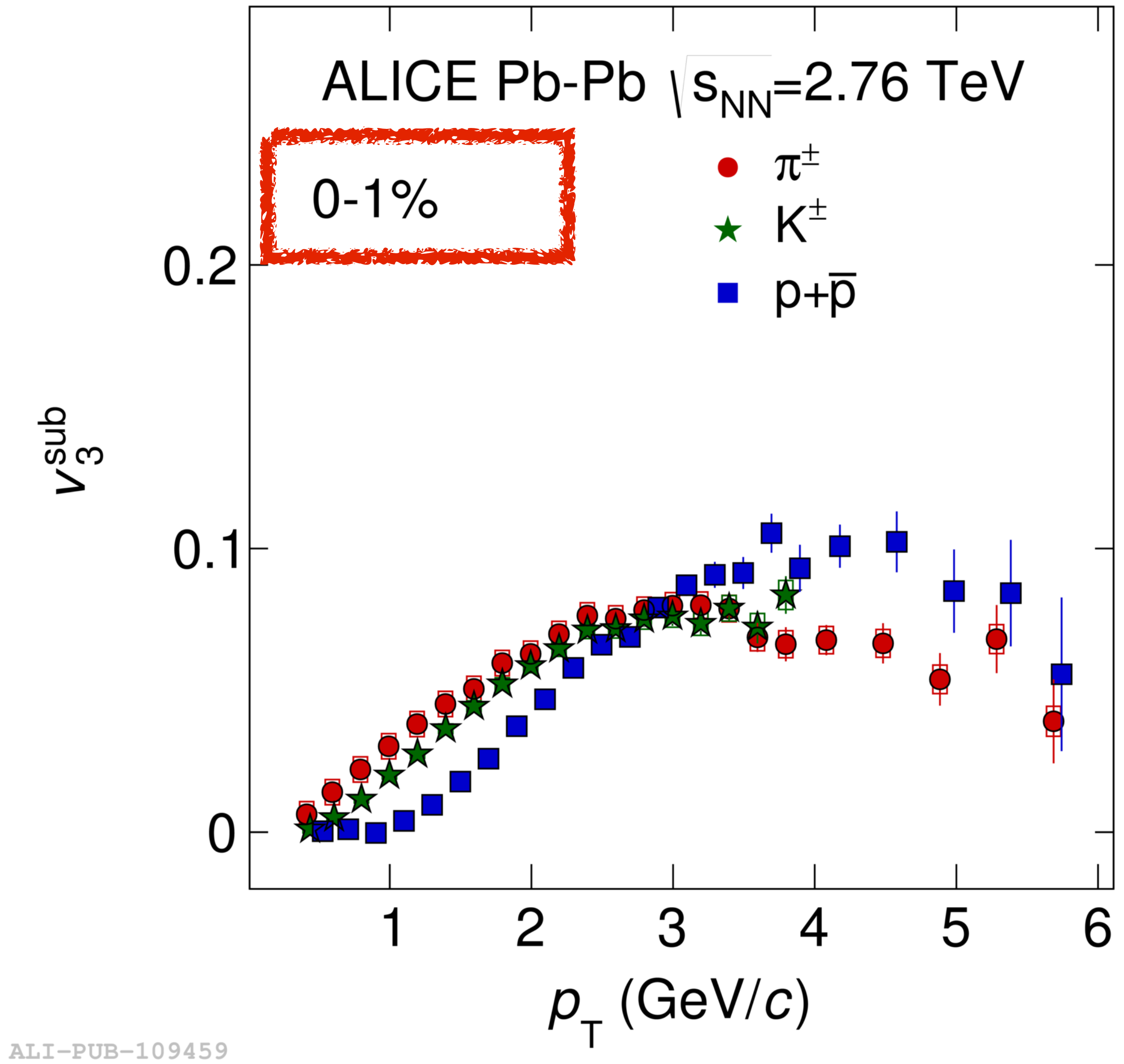
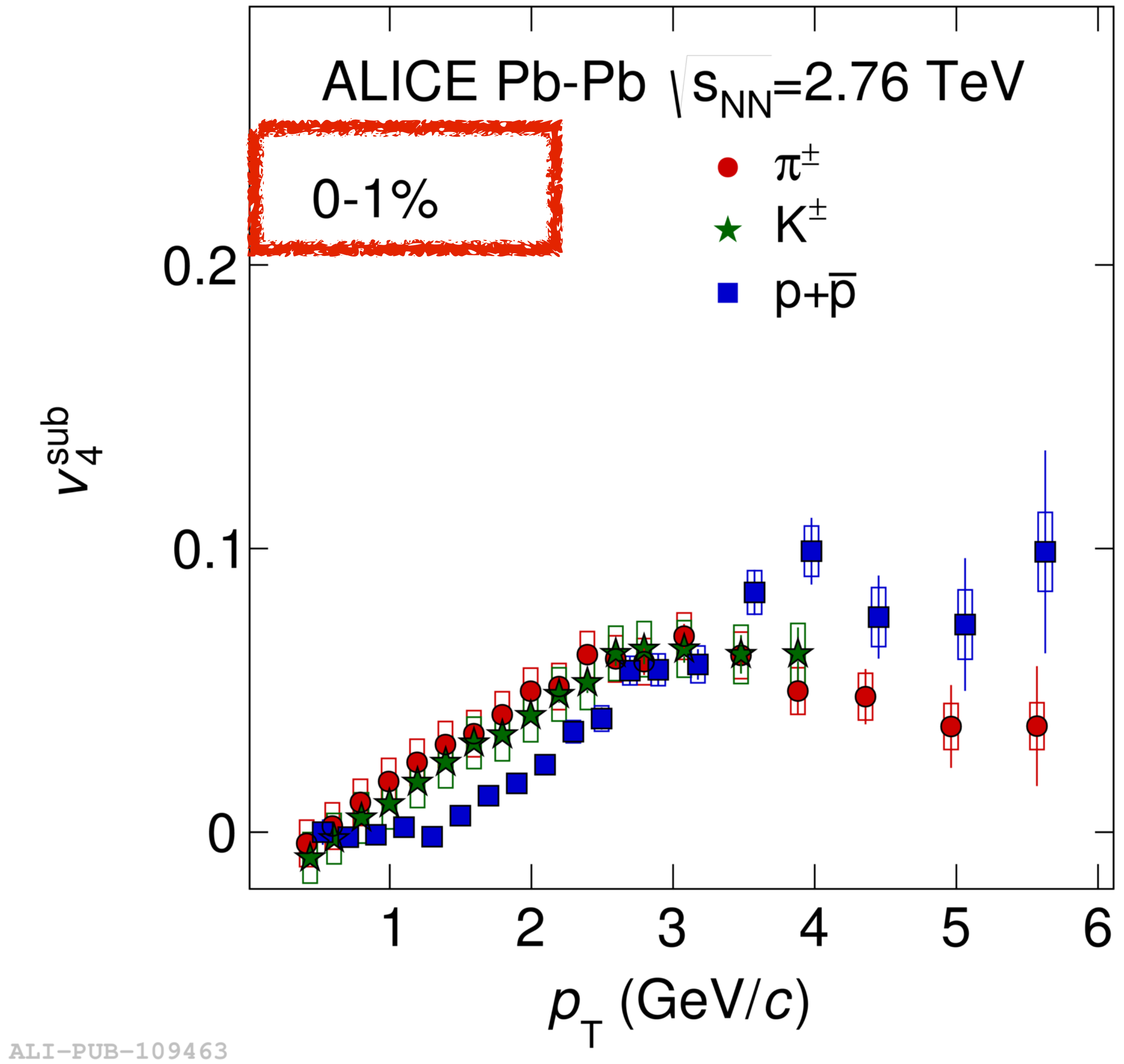
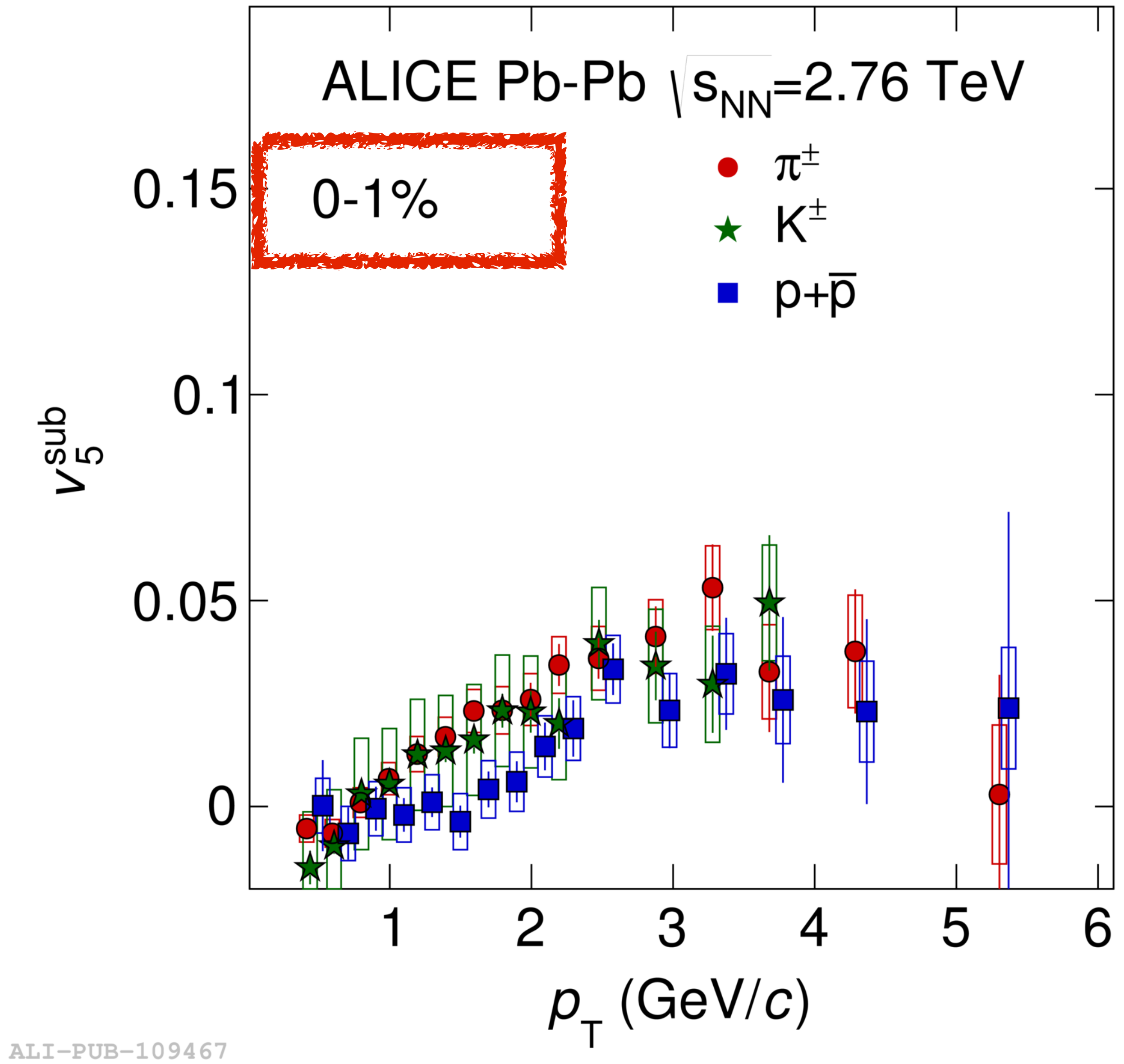






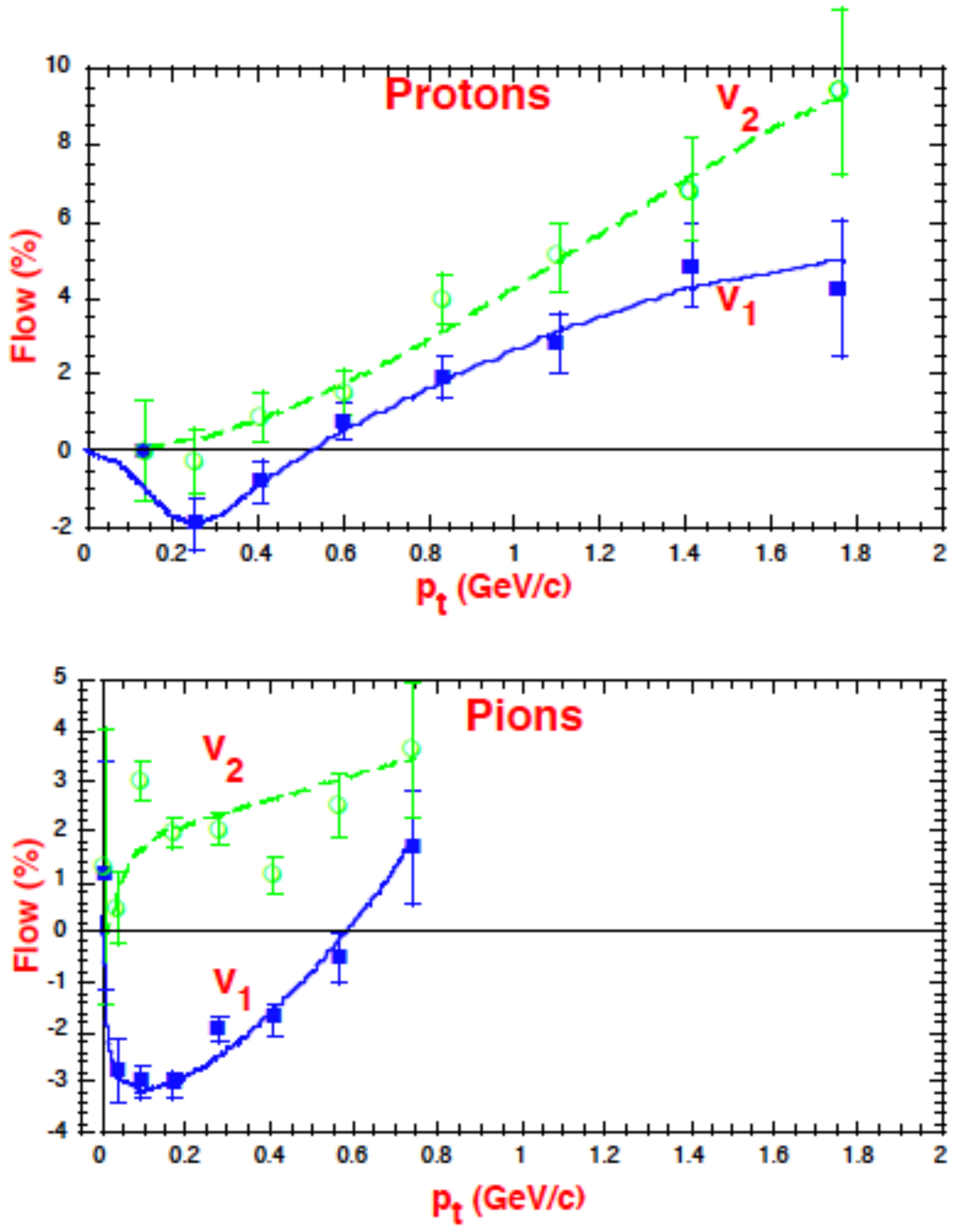




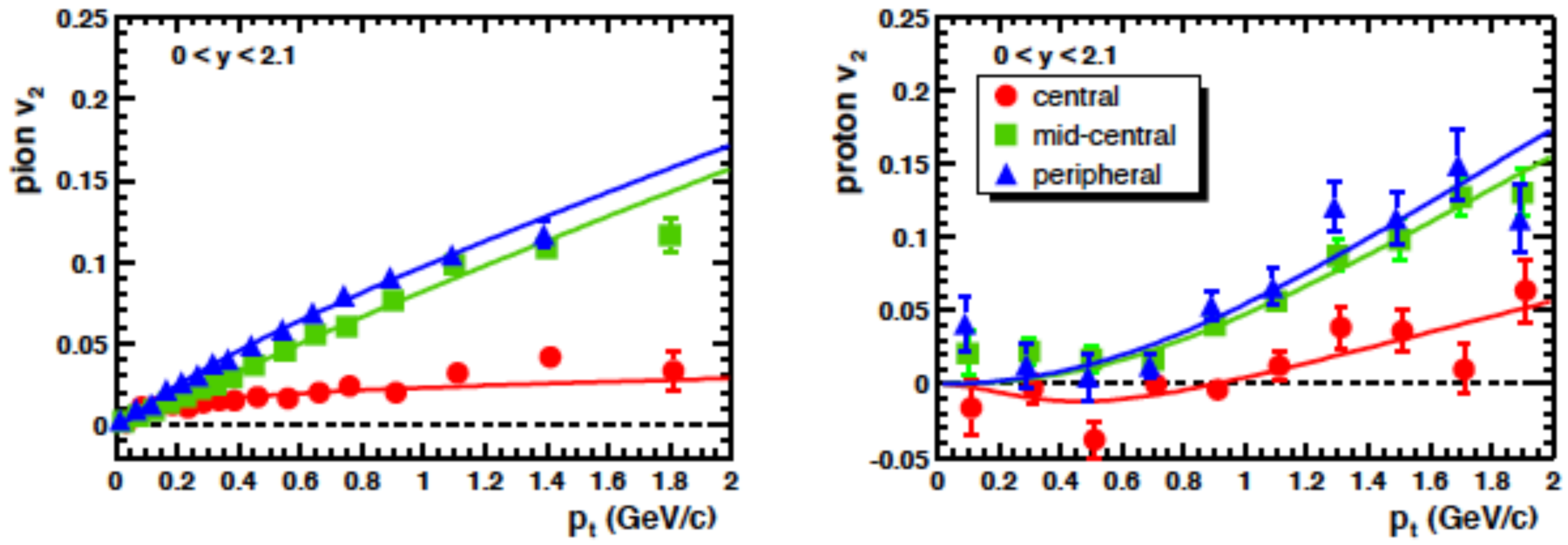
B. Abelev *et al.* (ALICE Collaboration), JHEP **09** (2016) 164

A LOT OF PROGRESS…FROM THIS

(NA49 Collaboration) Phys.Rev.Lett. 80 (1998) 4136



(NA49 Collaboration) Phys.Rev. C68 (2003) 034903



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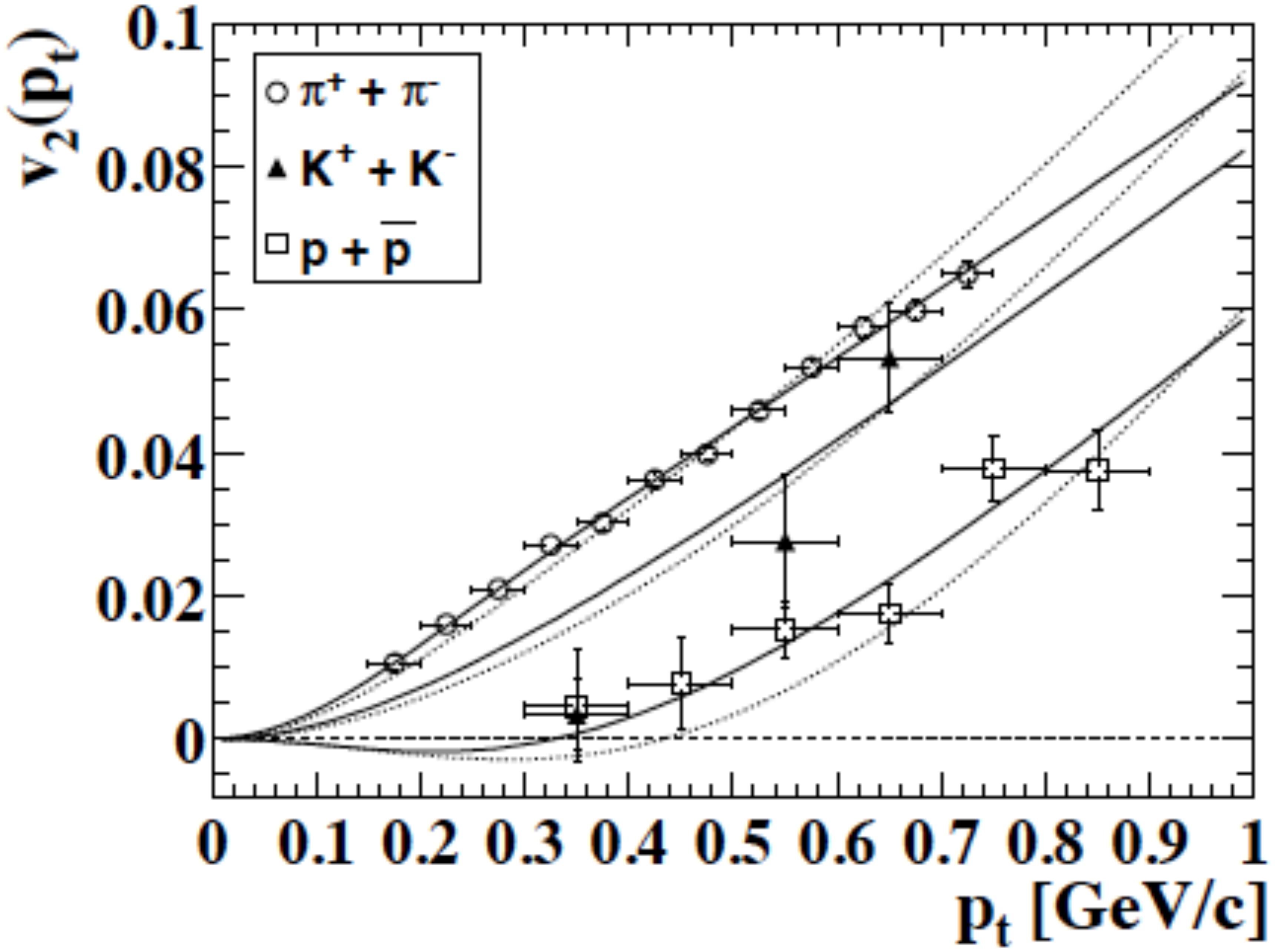
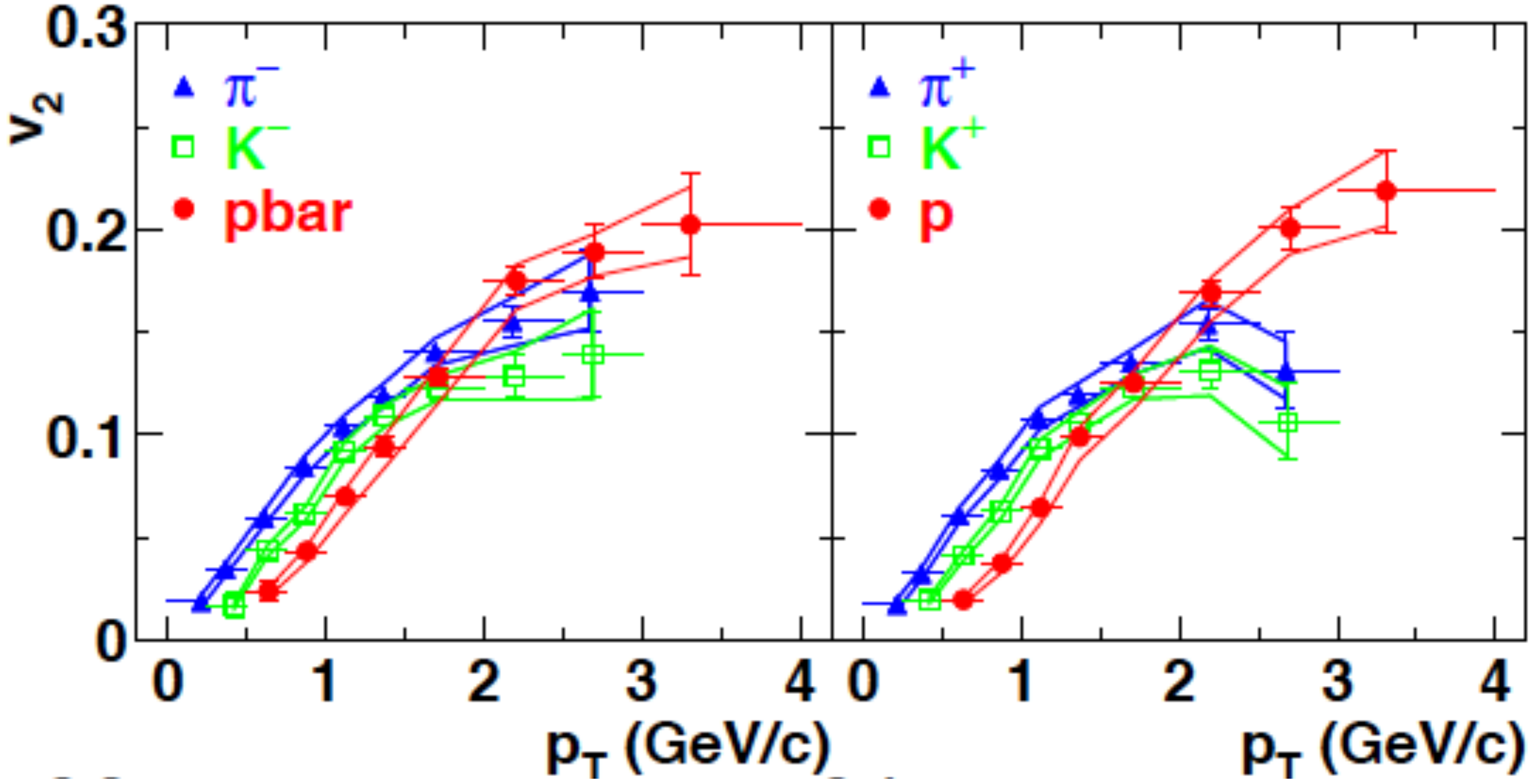
(STAR Collaboration): Phys. Rev. Lett. 87 (2001) 182301



(PHENIX Collaboration): Phys. Rev. Lett.91, 182301,2003



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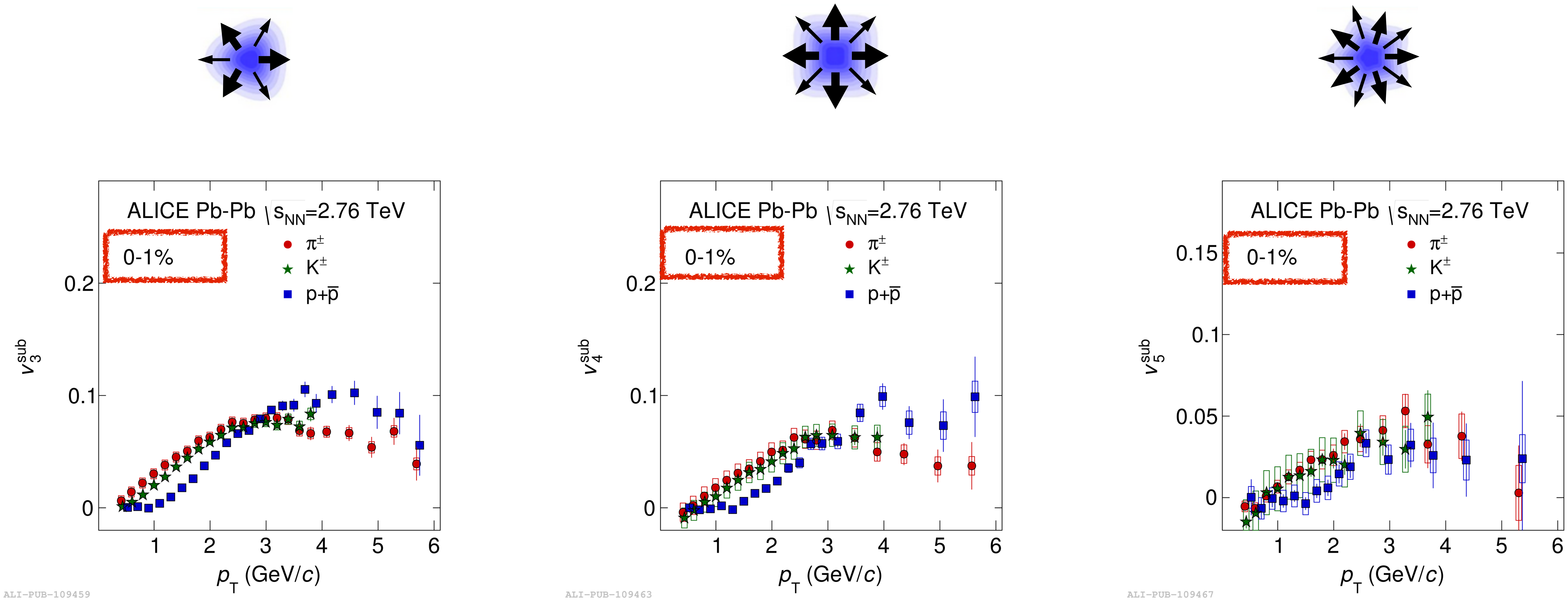

B. Abelev *et al.* (ALICE Collaboration), JHEP **09** (2016) 164

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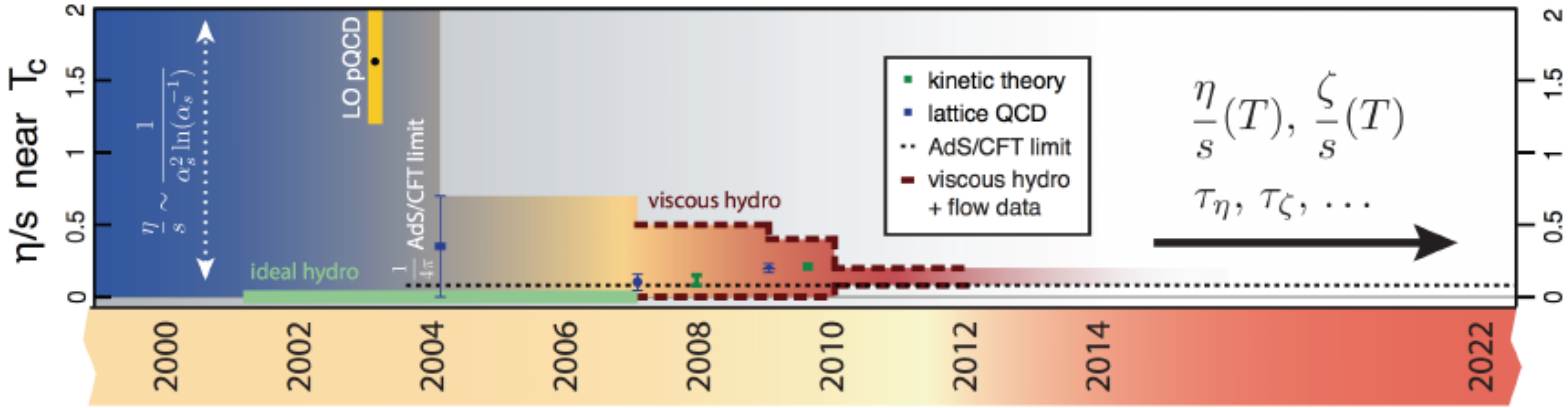

Time evolution of constrains on η/s

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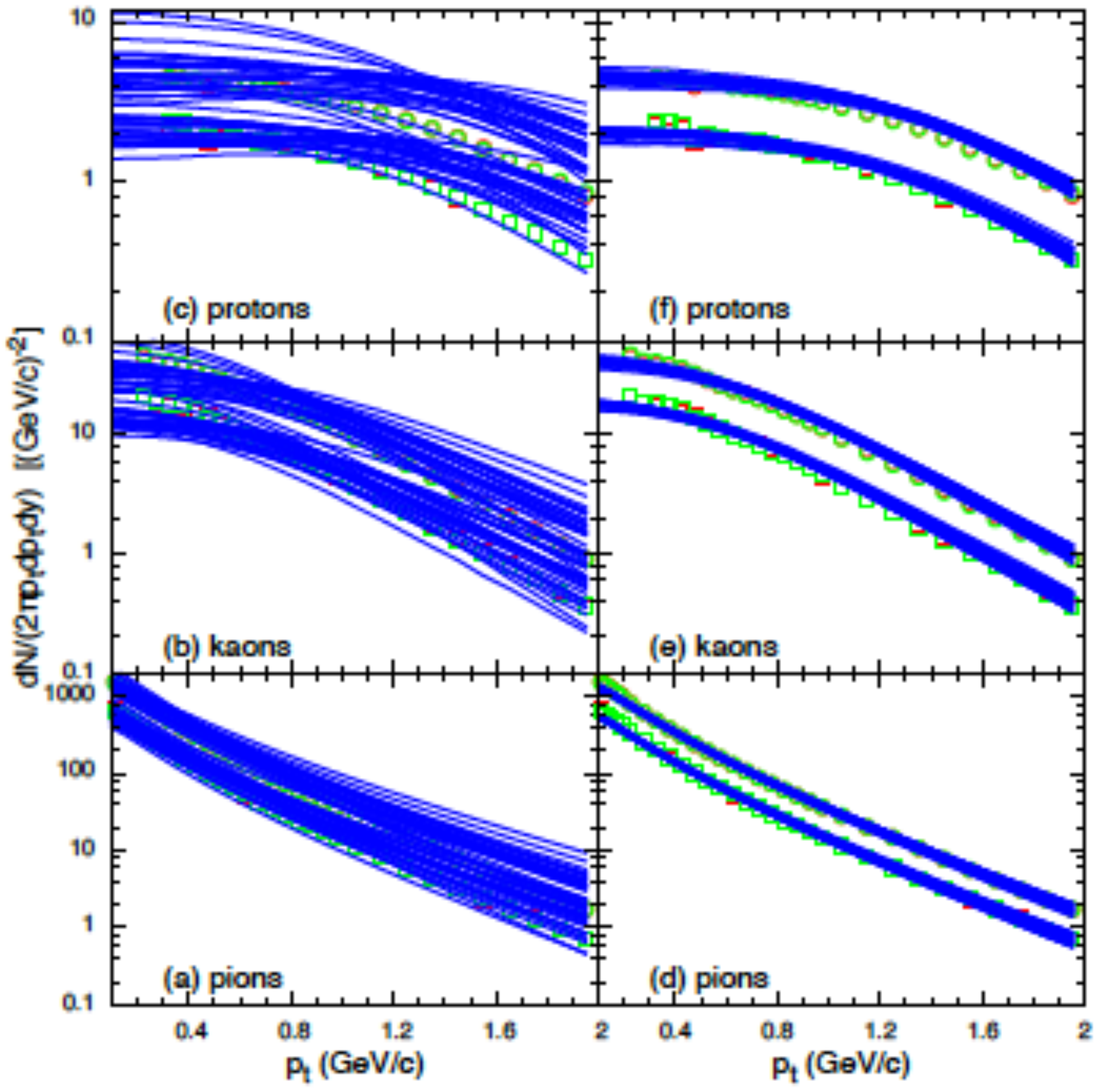
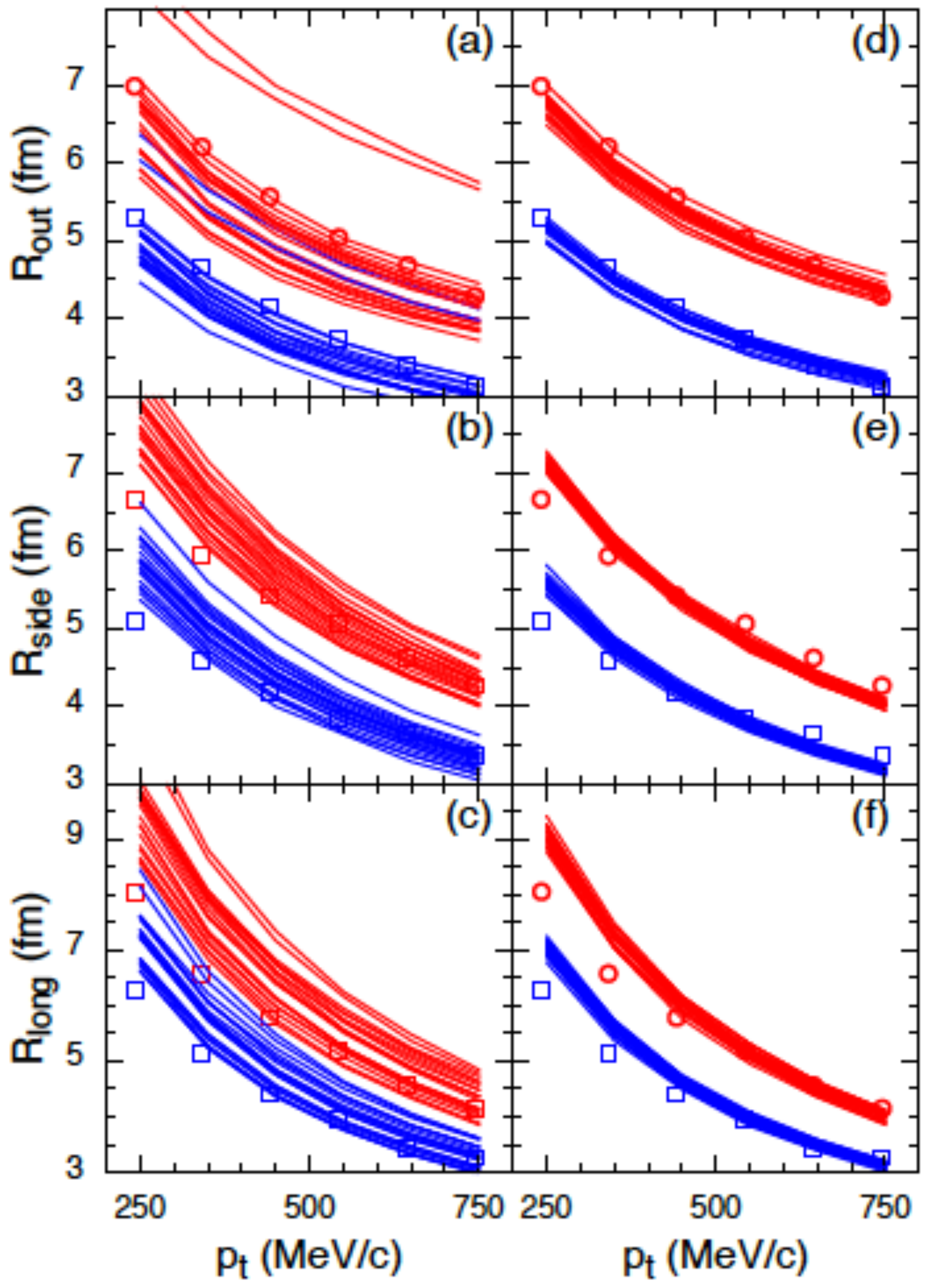
FROM QUALITATIVE TO QUANTITATIVE

EOS CONSTRAINS

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





Model parameters

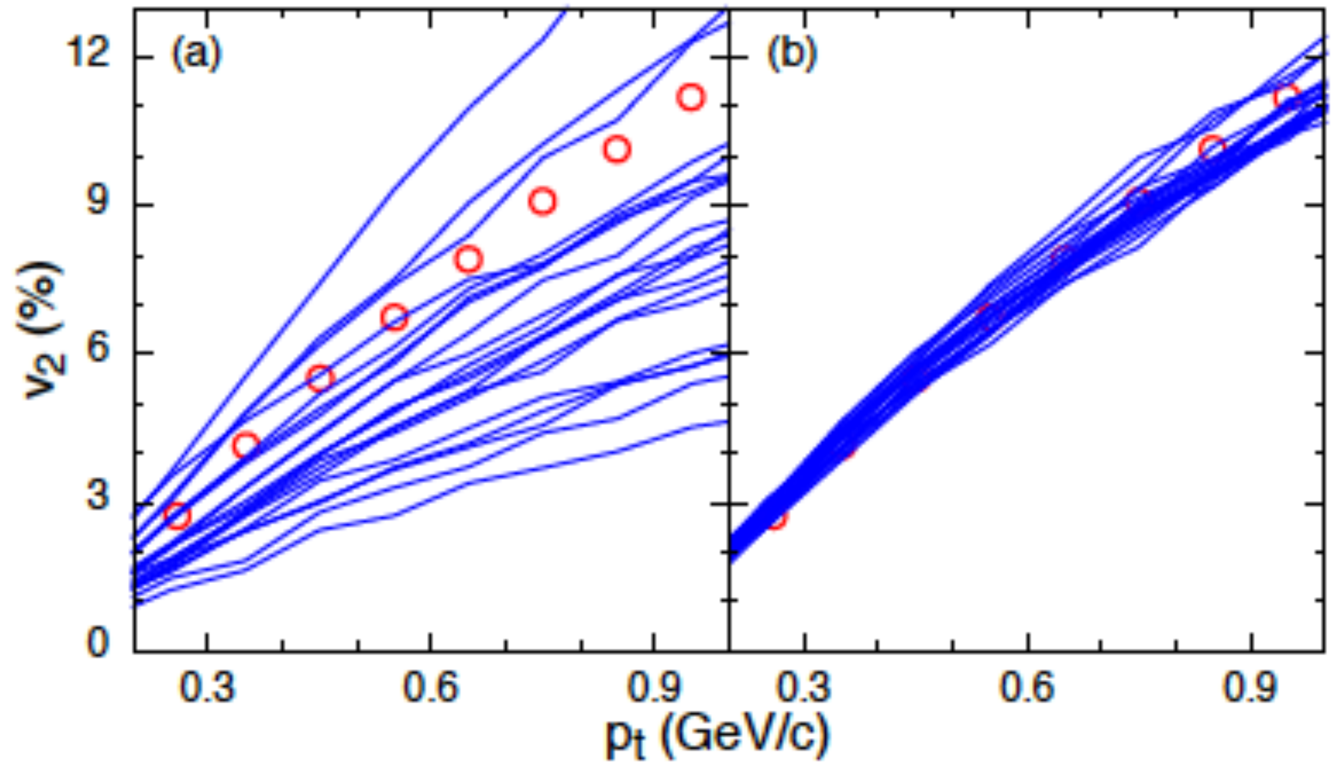
Experimental data

Priors

$$P(\mathbf{x}|\mathbf{y}_{\mathrm{exp.}}) = \frac{P(\mathbf{y}_{\mathrm{exp.}}|\mathbf{x})P(\mathbf{x})}{P(\mathbf{y}_{\mathrm{exp.}})}$$

Posterior distribution

Normalisation
("Bayesian evidence")



One of the first attempts for a global fit on data

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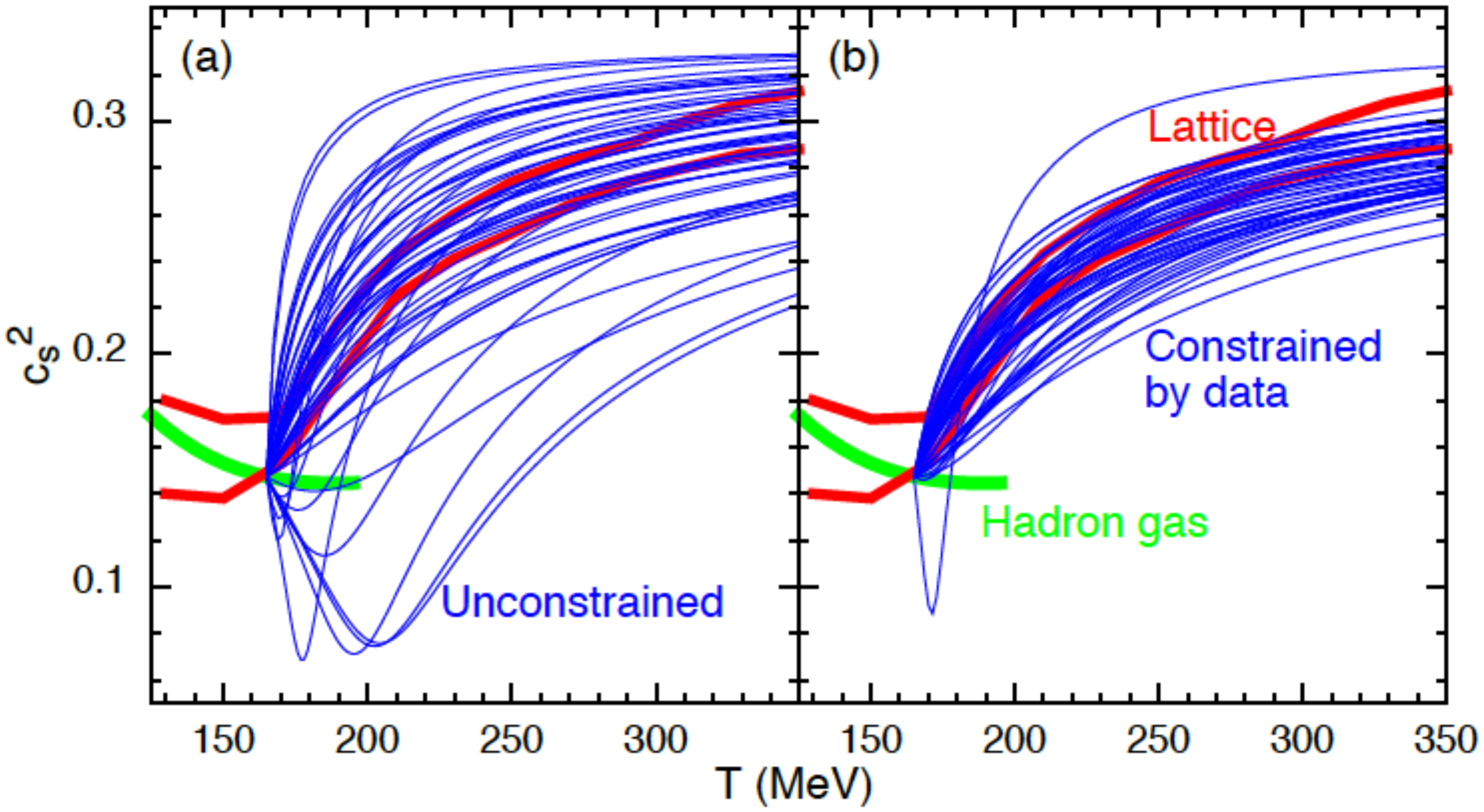
A LOT OF PROGRESS…AND NOW TO THIS

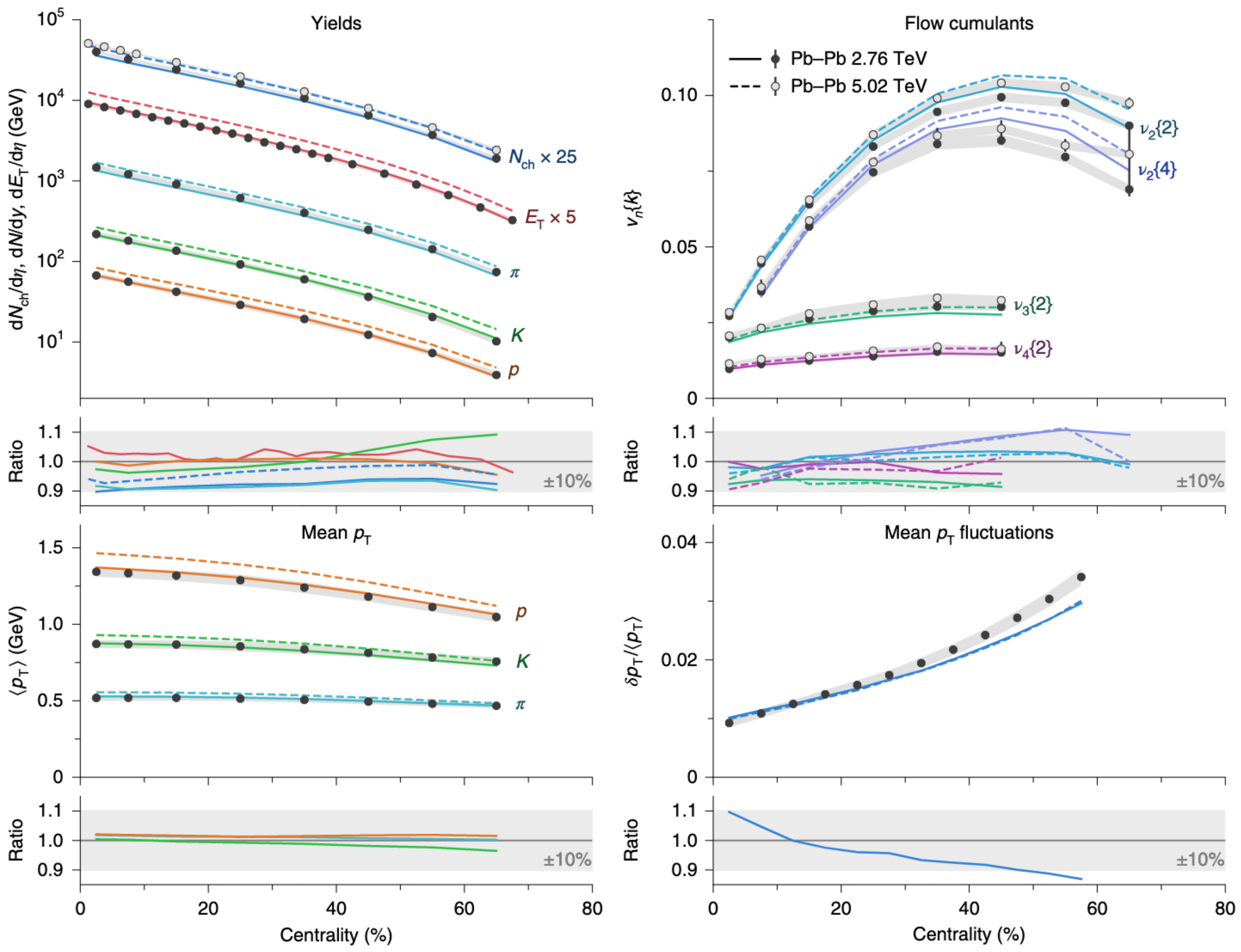
S.Pratt *et al.*, Phys. Rev. Lett. **114**, (2015) 202301

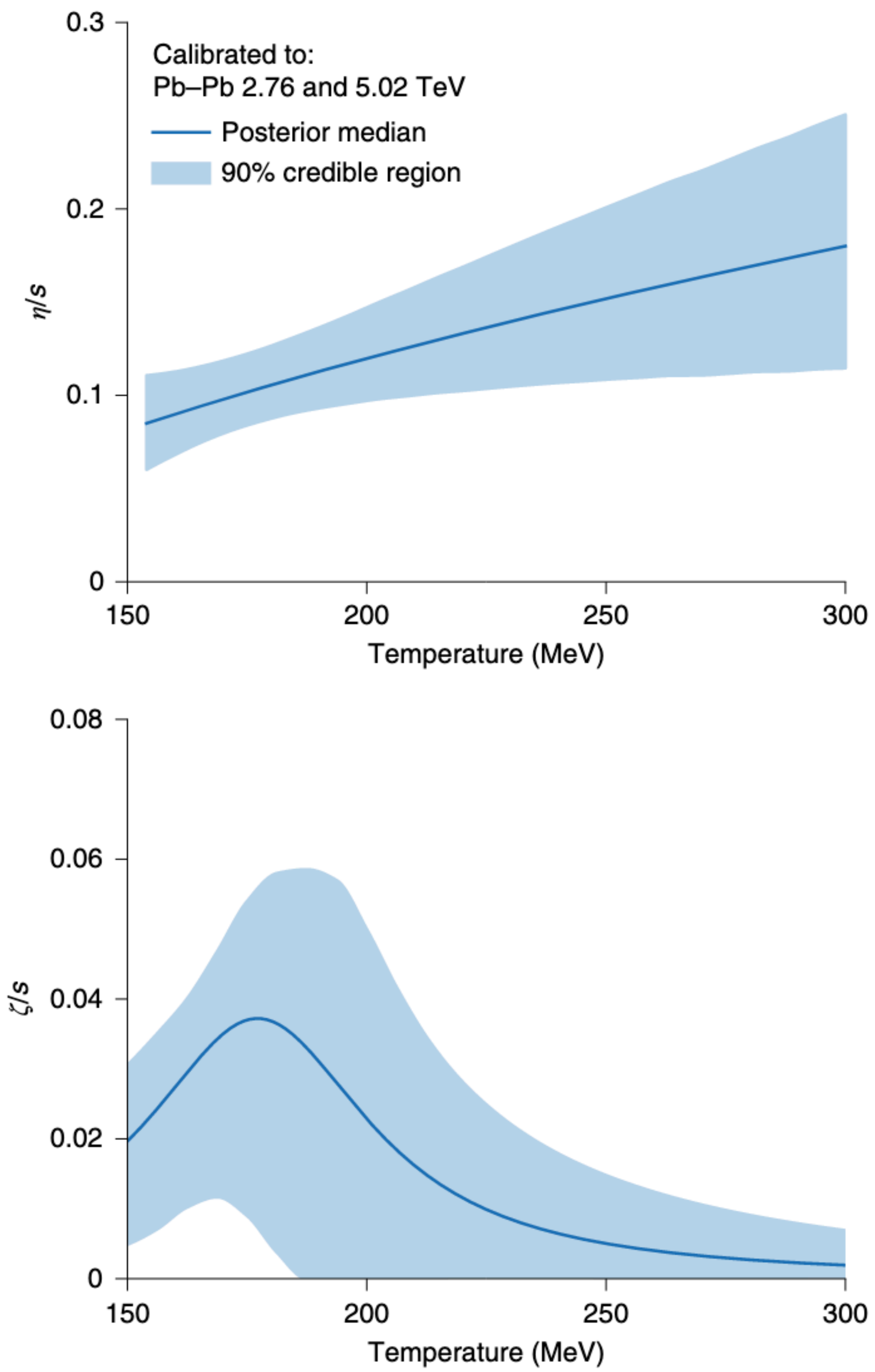


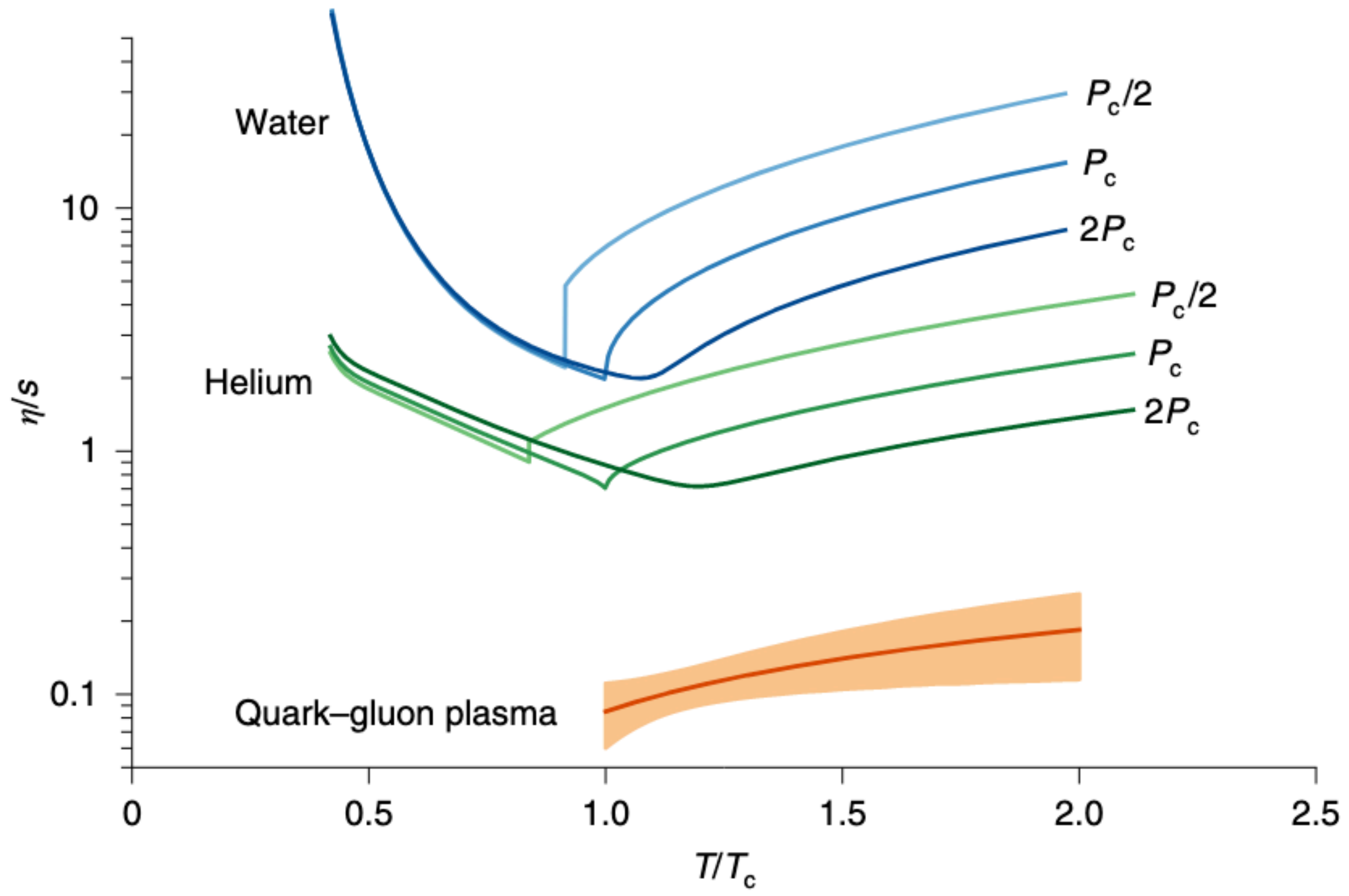
Constraining the EoS

TRANSPORT PROPERTIES CONSTRAINS @ LHC

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







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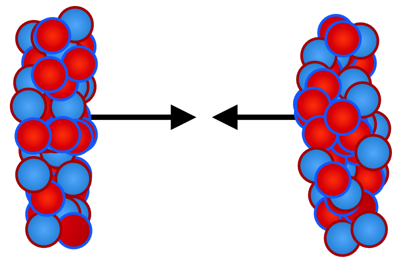
FROM LARGE TO SMALL COLLIDING SYSTEMS

Pb-Pb
$\sqrt{s_{NN}}$ = 2.76 TeV
$\sqrt{s_{NN}}$ = 5.02 TeV

Xe-Xe
$\sqrt{s_{NN}}$ = 5.44 TeV

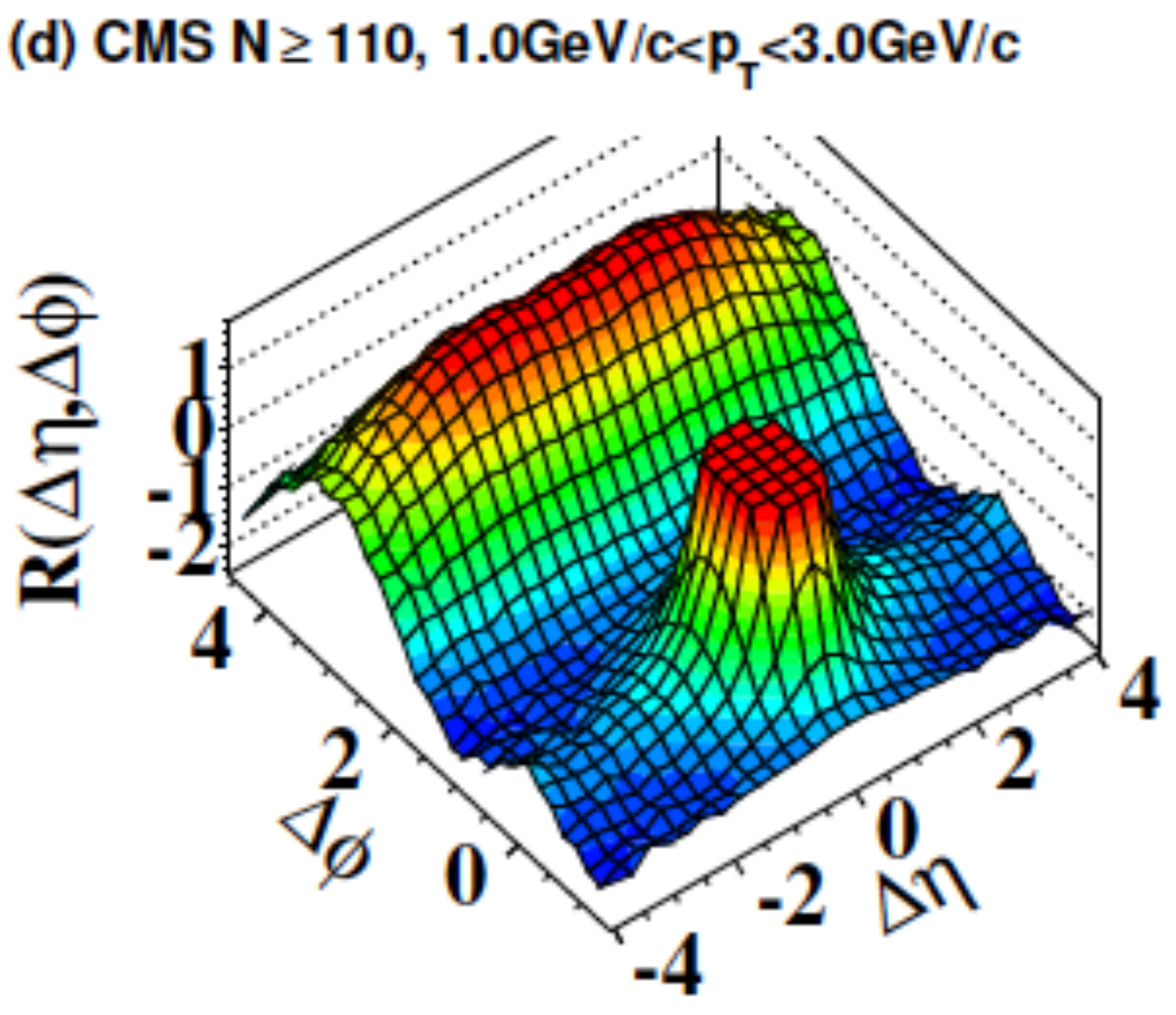


p-Pb
$\sqrt{s_{NN}}$ = 5.02 TeV
$\sqrt{s_{NN}}$ = 8 TeV
p-Au, d-Au, He[3]-Au
$\sqrt{s_{NN}}$ = 0.2 TeV

pp
$\sqrt{s}$ = 2.76 TeV
$\sqrt{s}$ = 5.02 TeV
$\sqrt{s}$ = 7 TeV
$\sqrt{s}$ = 8 TeV
$\sqrt{s}$ = 13 TeV

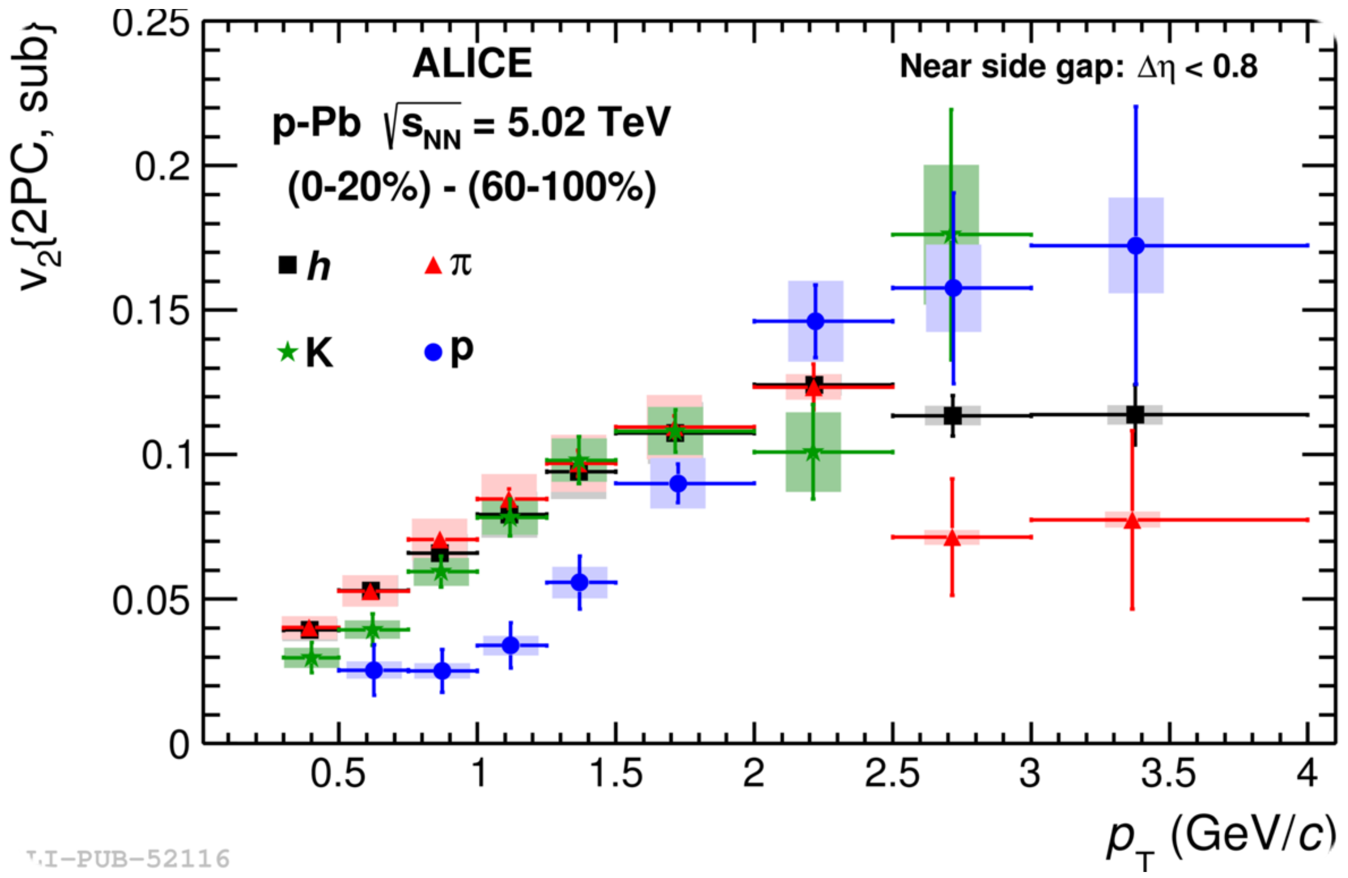
QGP IN SMALL SYSTEMS?

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

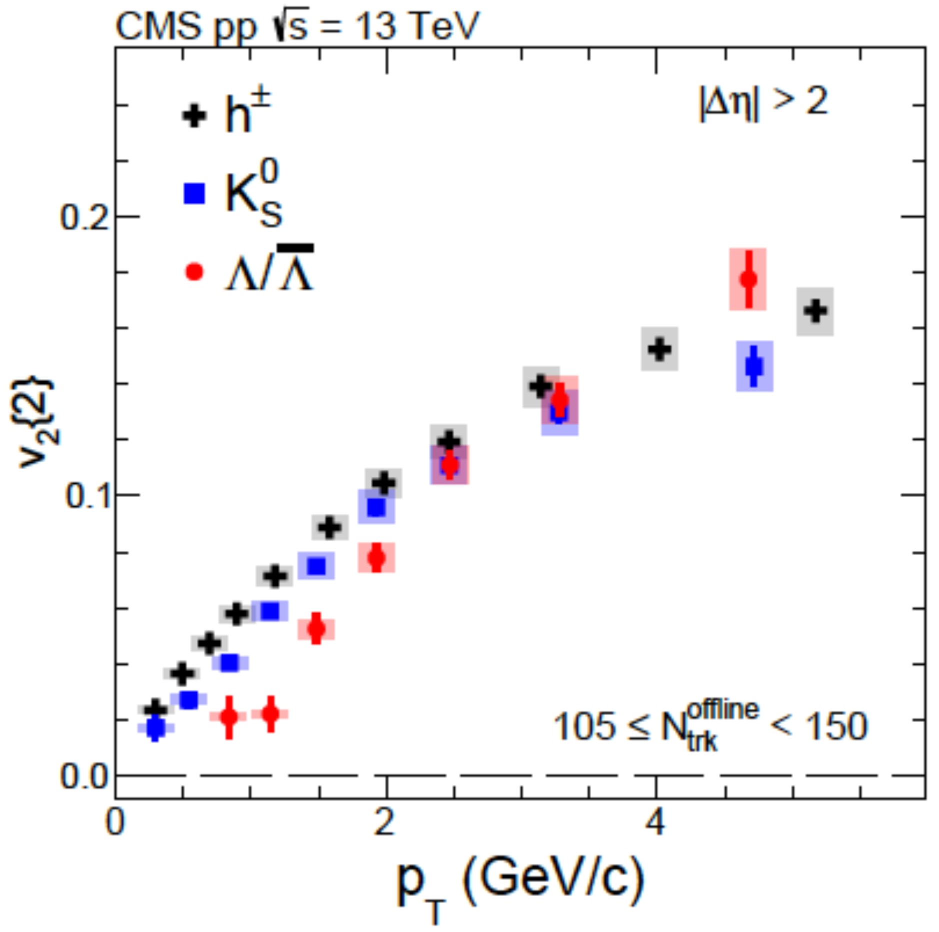


High event activity pp collisions @ √s = 7 TeV

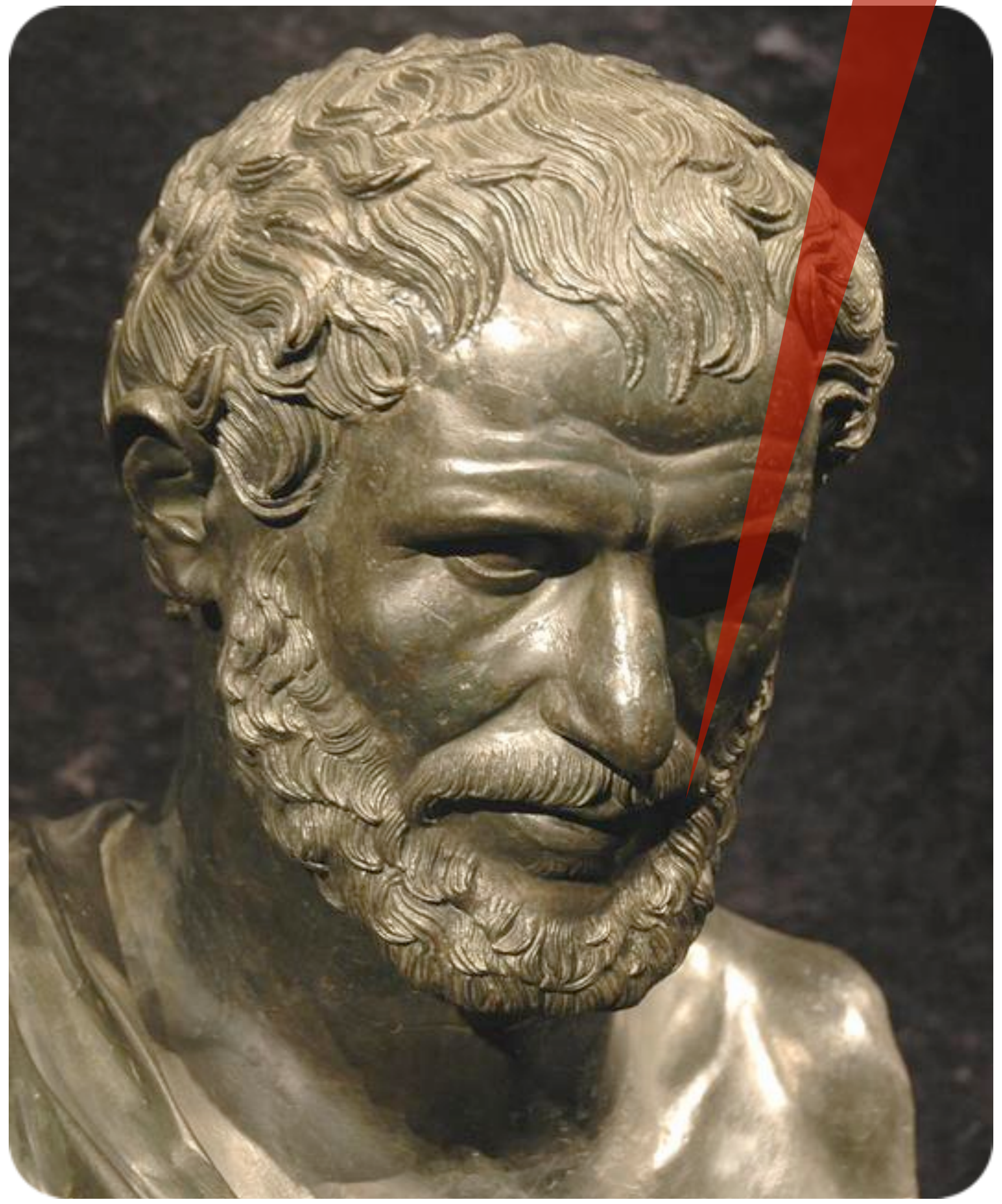
(ALICE Collaboration) Phys. Lett. **B726**, (2013) 164



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



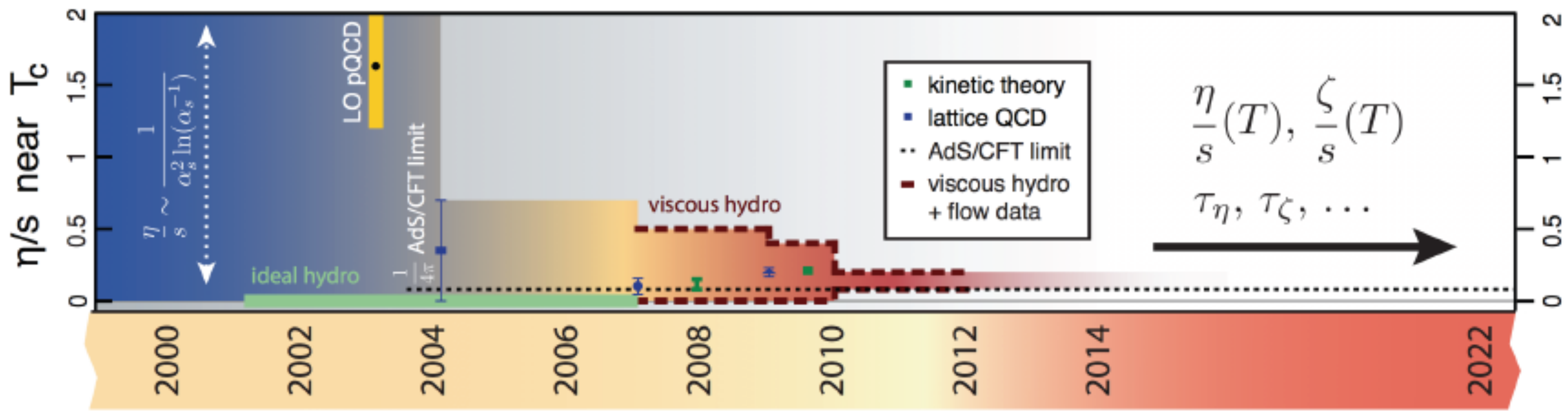
Τα πάντα ρει…
(everything flows)

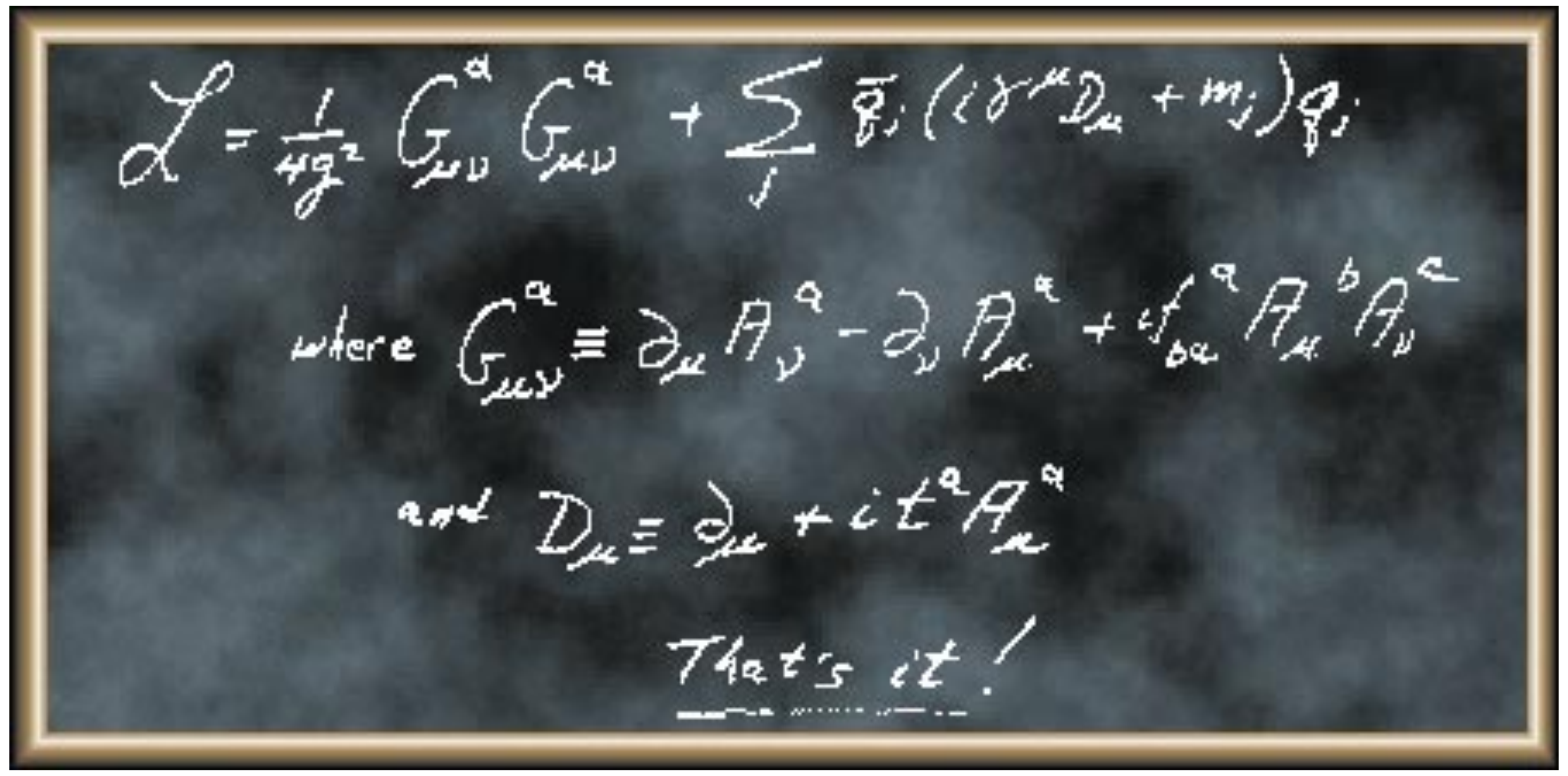


Ηράκλειτος (Heraclitus) ~535 - 475 BC

A LOT OF PROGRESS…BUT STILL PLENTY OF UNANSWERED QUESTIONS

How does a strongly coupled QGP emerge from QCD?



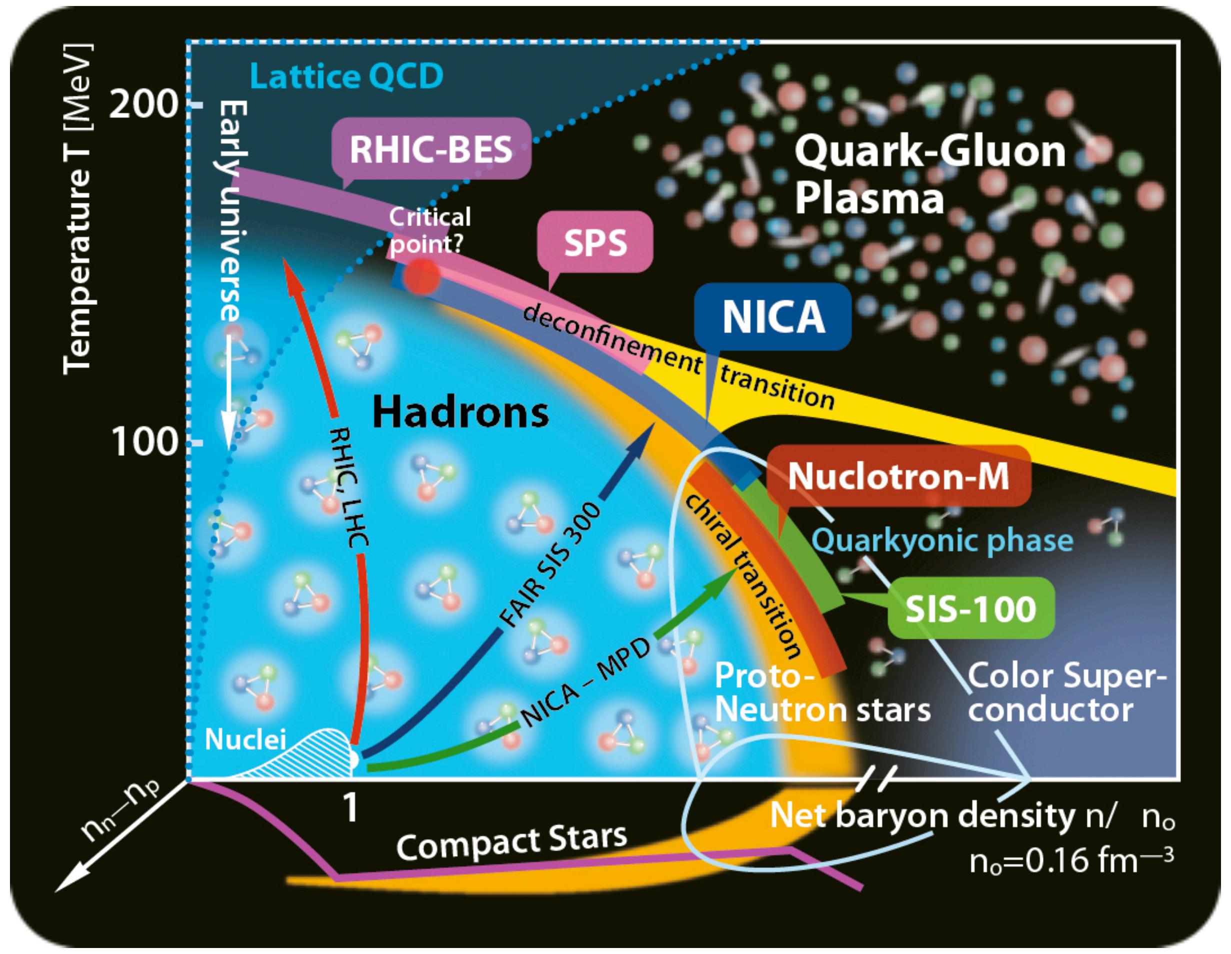


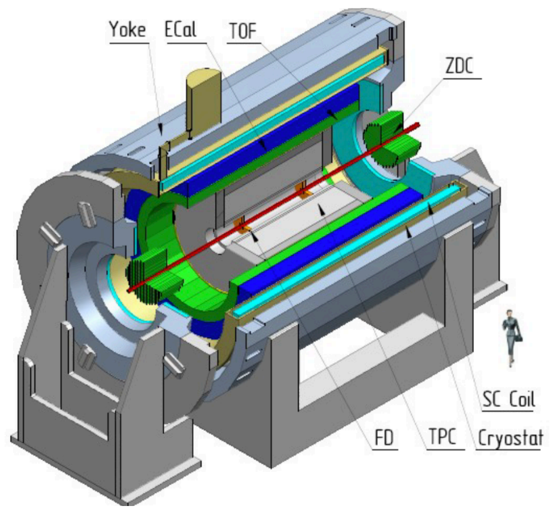
- Additional precision measurements (e.g. heavy quarks, jets) → knowledge of poorly constrained parameters
- New phenomena (e.g. vorticity, magnetic fields, CME, CMW…)
- Origin of collectivity in small systems → can this lead to a unified picture of how QCD matter evolves as a function event activity?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

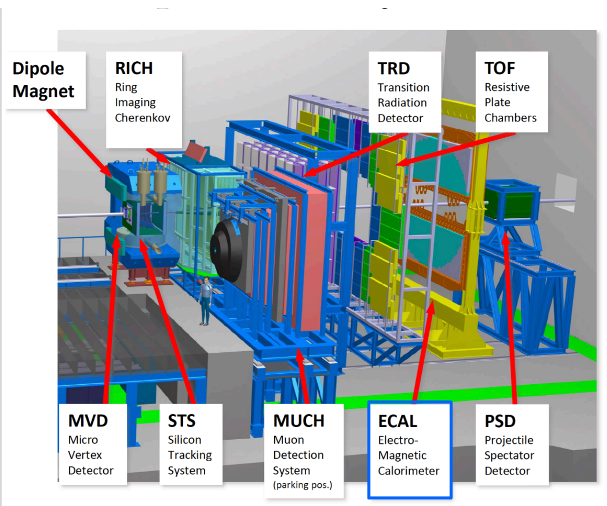
Discover the proper microscopic picture that describes the macroscopic behaviour of the QGP

LOOKING AT THE FUTURE

Low energies

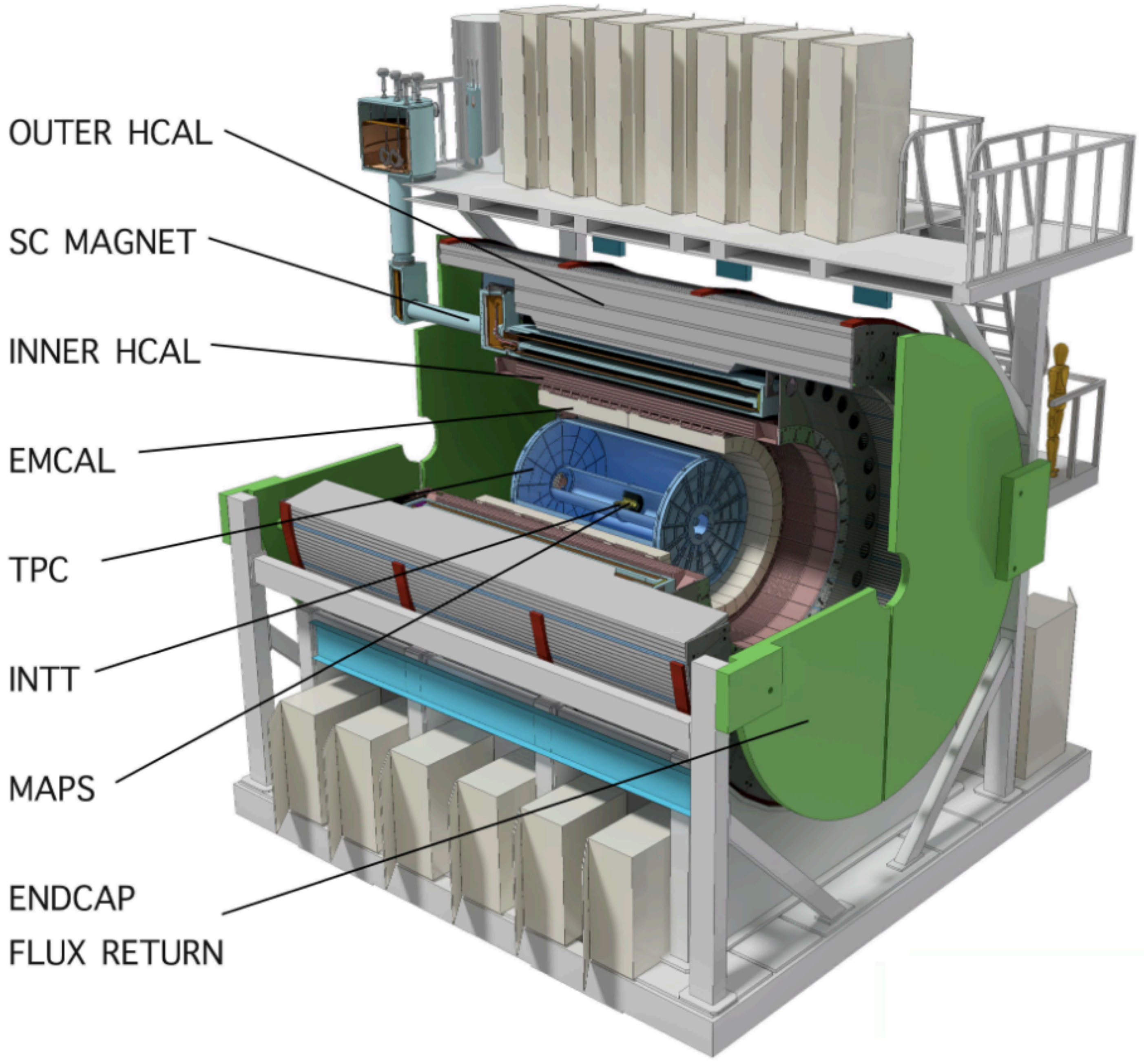






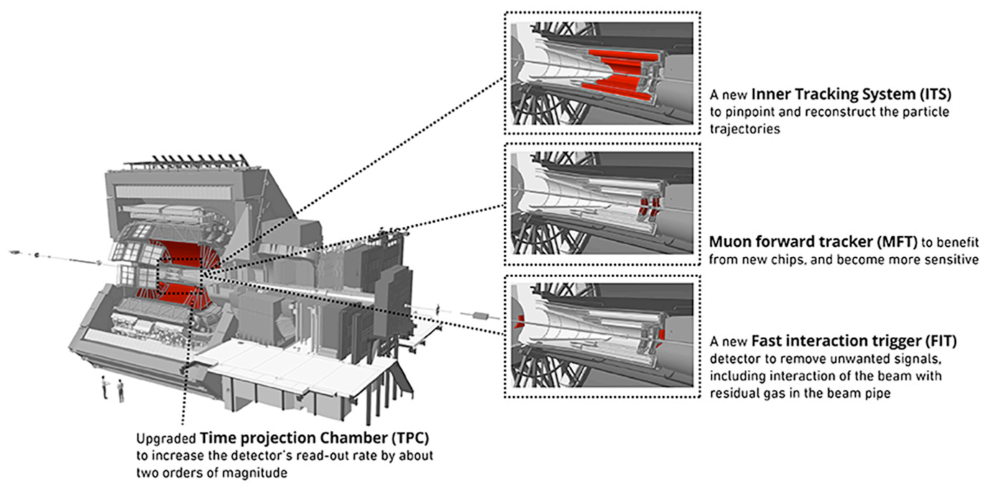
MPD @ NICA (2023+)   CBM @ FAIR (2025+)

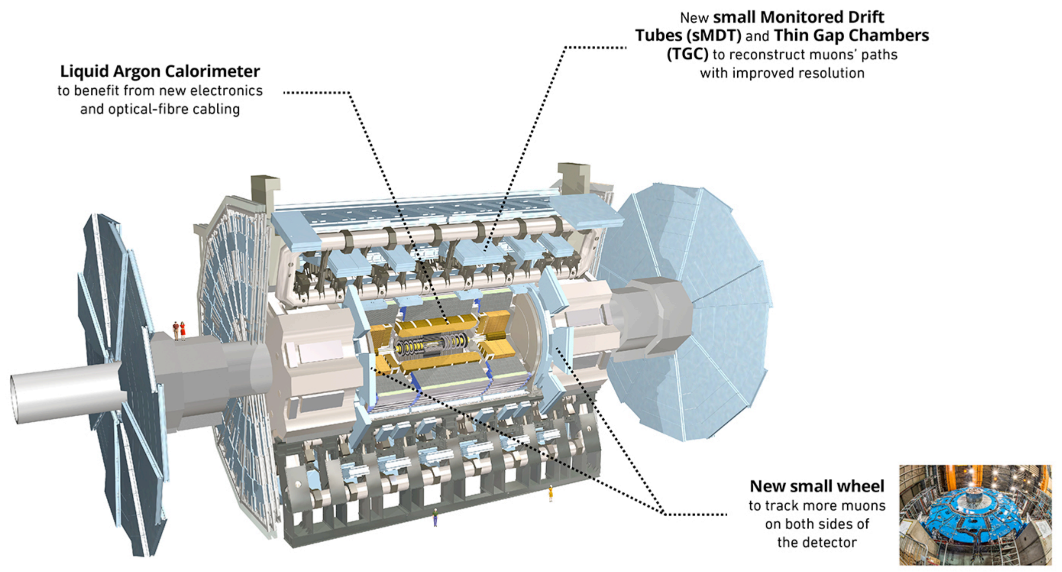
Intermediate energies

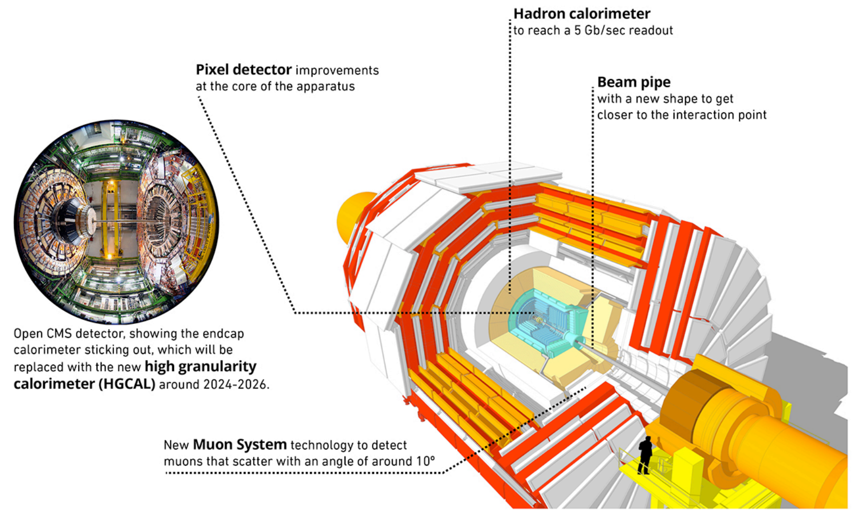


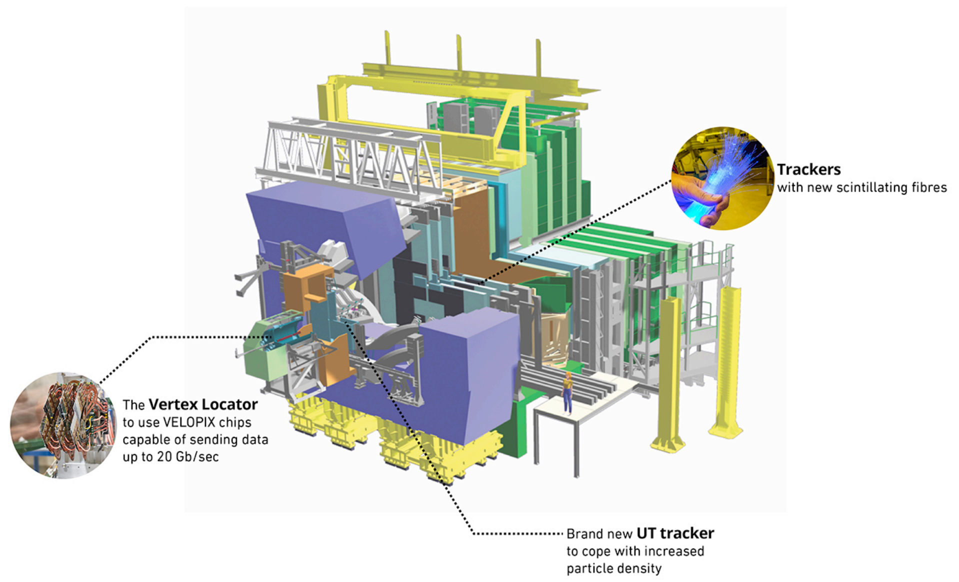
sPHENIX (2023+)

High energies









LHC experiments (2022-2030)

LOOKING AT THE FUTURE: HI@LHC 2032+

Full azimuthal coverage with |η| < 4

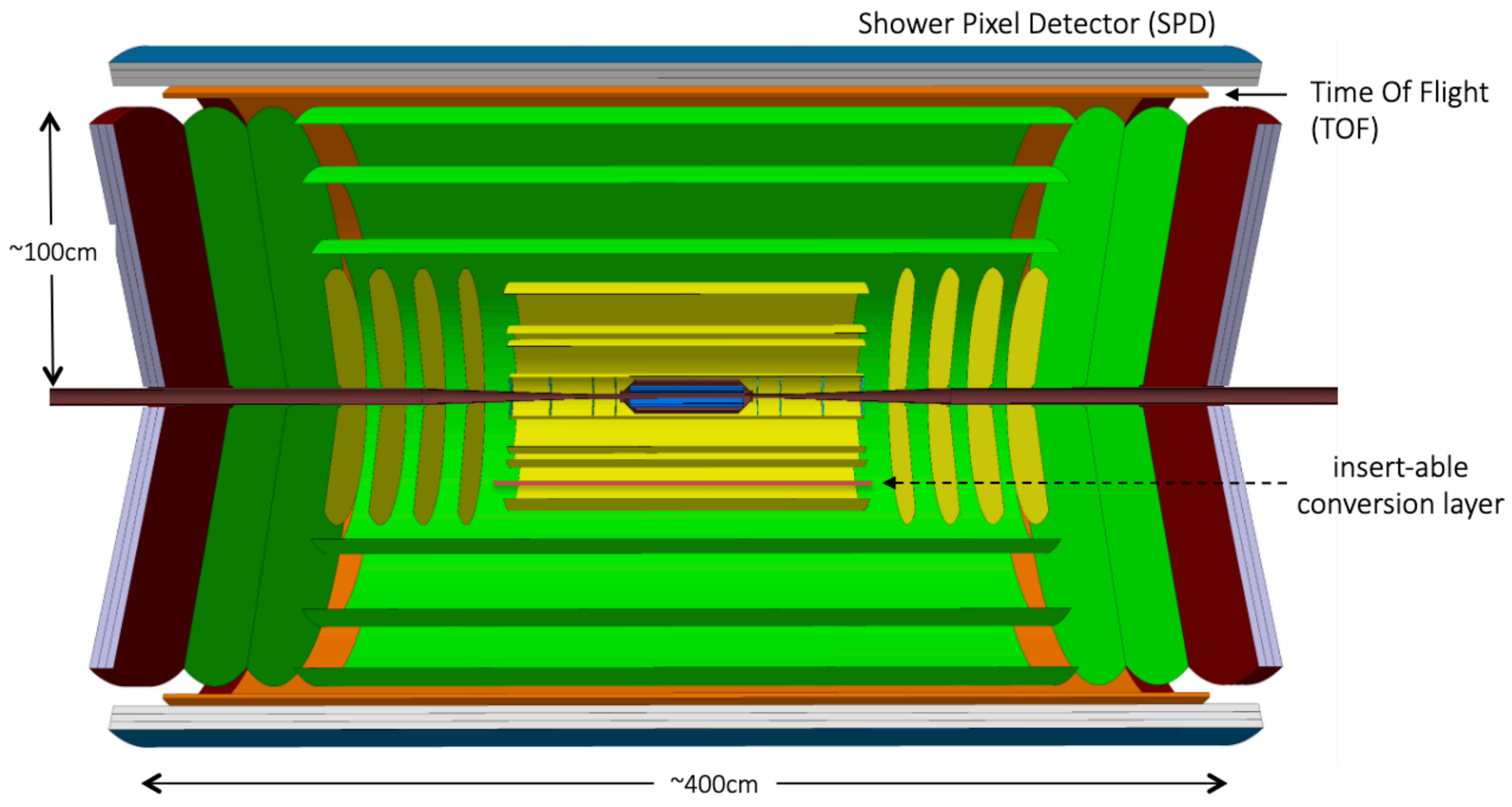
Retractable first layers inside the beam pipe

Fast timing silicon detectors, TOF, RICH, muon detector

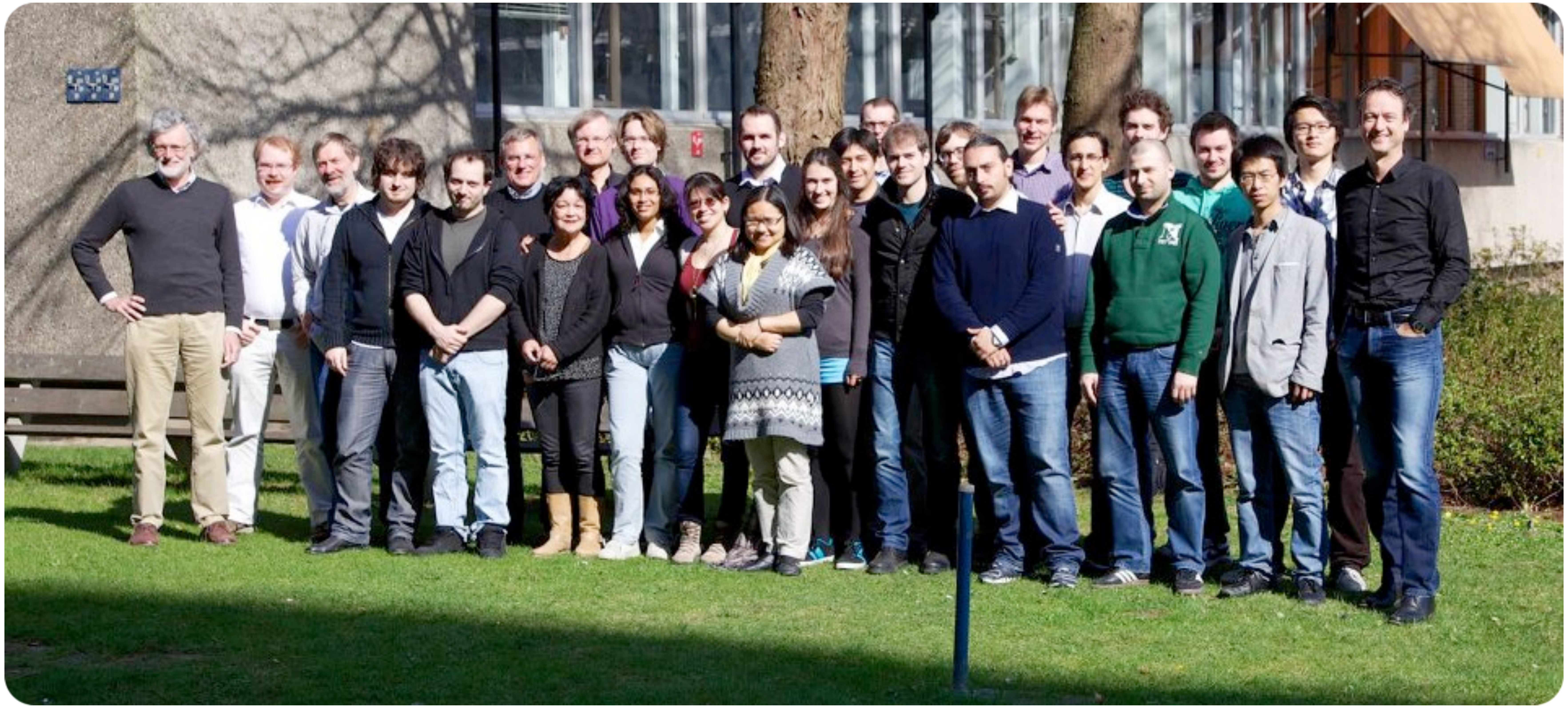
Physics focus

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

https://arxiv.org/abs/1902.01211



(PART OF) THE NIKHEF/UU ALICE GROUP



We are leading the field with a number of interesting physics projects that could easily lead to an advanced stage (e.g. publication)

Feel free to pass by my office @ Nikhef (N325) or drop me a mail if you are interested!!!

Thank you for your attention!

LATEX

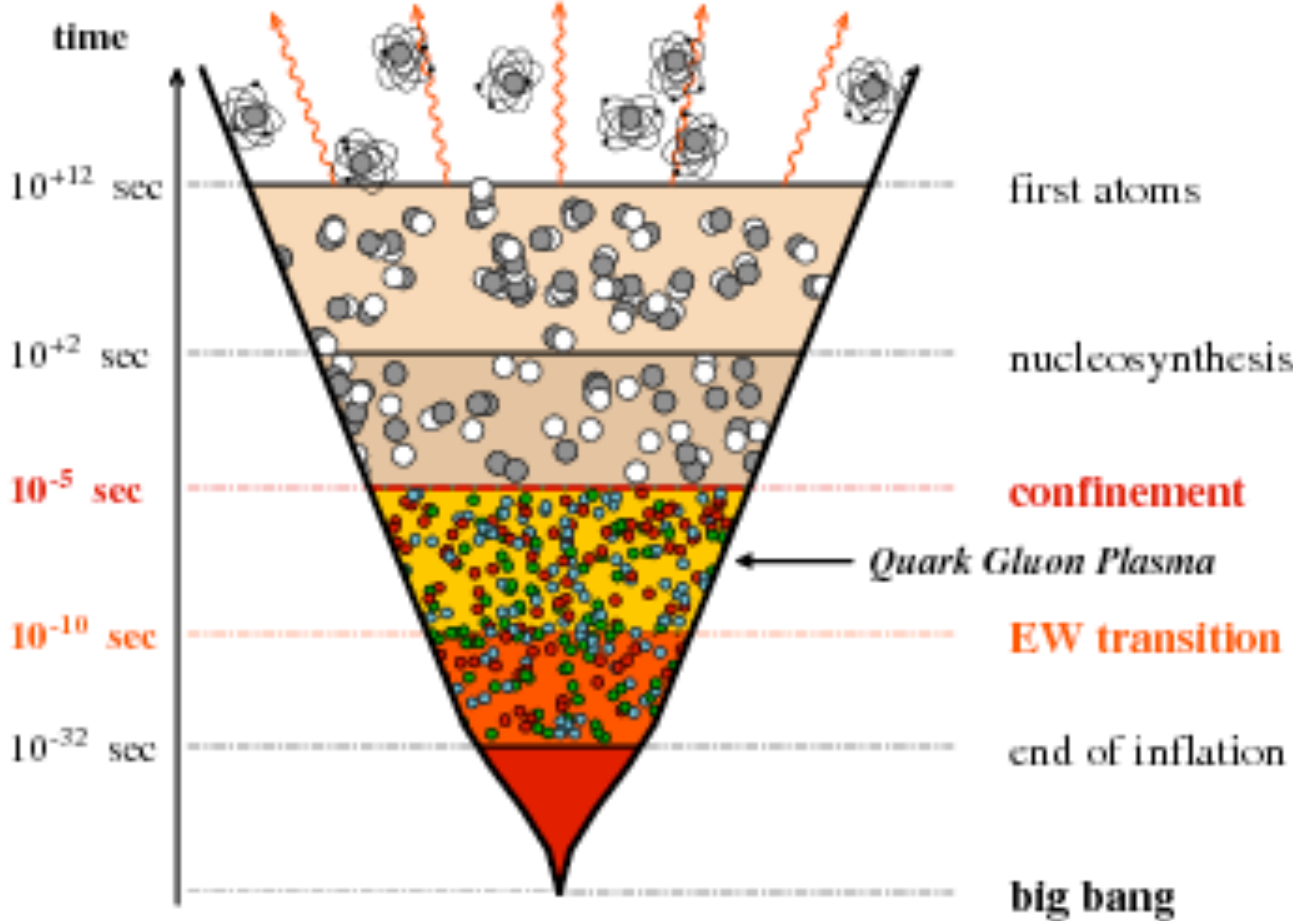
```
R_{AA} \rightarrow \Big\{ \begin{matrix} < 1  \\ \approx 1 \end{matrix}

R_{AA} = \frac{\mathrm{QCD~medium}}{\mathrm{QCD~vacuum}} = \frac{\Big(\frac{d^2N}{dp_{T}d\eta}\Big)_{AA}}{N_{coll}\Big(\frac{d^2N}{dp_{T}d\eta}\Big)_{pp}}
\epsilon = \frac{\langle y^2 - x^2\rangle}{\langle y^2 + x^2\rangle}

\epsilon_P = \frac{\langle T_{xx} - T_{yy}\rangle}{\langle T_{xx} + T_{yy}\rangle}
E\frac{d^3 N}{d^3\vec{P}} = \frac{1}{2\pi}\frac{d^2N}{p_Tdp_Tdy}\Big(1 + \sum_{n=1}^{\infty}2v_n\cos[n(\varphi - \Psi_{RP})]\Big)

v_n = \langle \cos[n(\varphi - \Psi_{RP})] \rangle
```

QGP: PRIMORDIAL MATTER



QUANTIFYING THE AZIMUTHAL ANISOTROPY

In non-central collisions the coordinate space configuration is anisotropic (e.g. almond shape)

- The initial momentum distribution is isotropic (spherically symmetric)

The interactions among constituents generate a pressure gradient that transforms the initial coordinate space anisotropy into the observed momentum space anisotropy

- Azimuthal anisotropy quantified by a Fourier expansion
    - v_1: directed flow, v_2: elliptic flow, v_3: triangular flow, v_4: quadrangular flow,…

Connection to equation of state and to the system's transport properties (e.g. η/S)

$$E\frac{d^3N}{d^3\vec{P}} = \frac{1}{2\pi}\frac{d^2N}{p_T dp_T dy}\left(1 + \sum_{n=1}^{\infty} 2v_n \cos[n(\varphi - \Psi_{RP})]\right)$$

$$v_n = \langle \cos[n(\varphi - \Psi_{RP})] \rangle$$

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