Lecture 8:

Heavy Ion Physics

Panos Christakoglou

Nikhef

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 to ultra-relativistic energies?

Not an interesting question to answer!!!

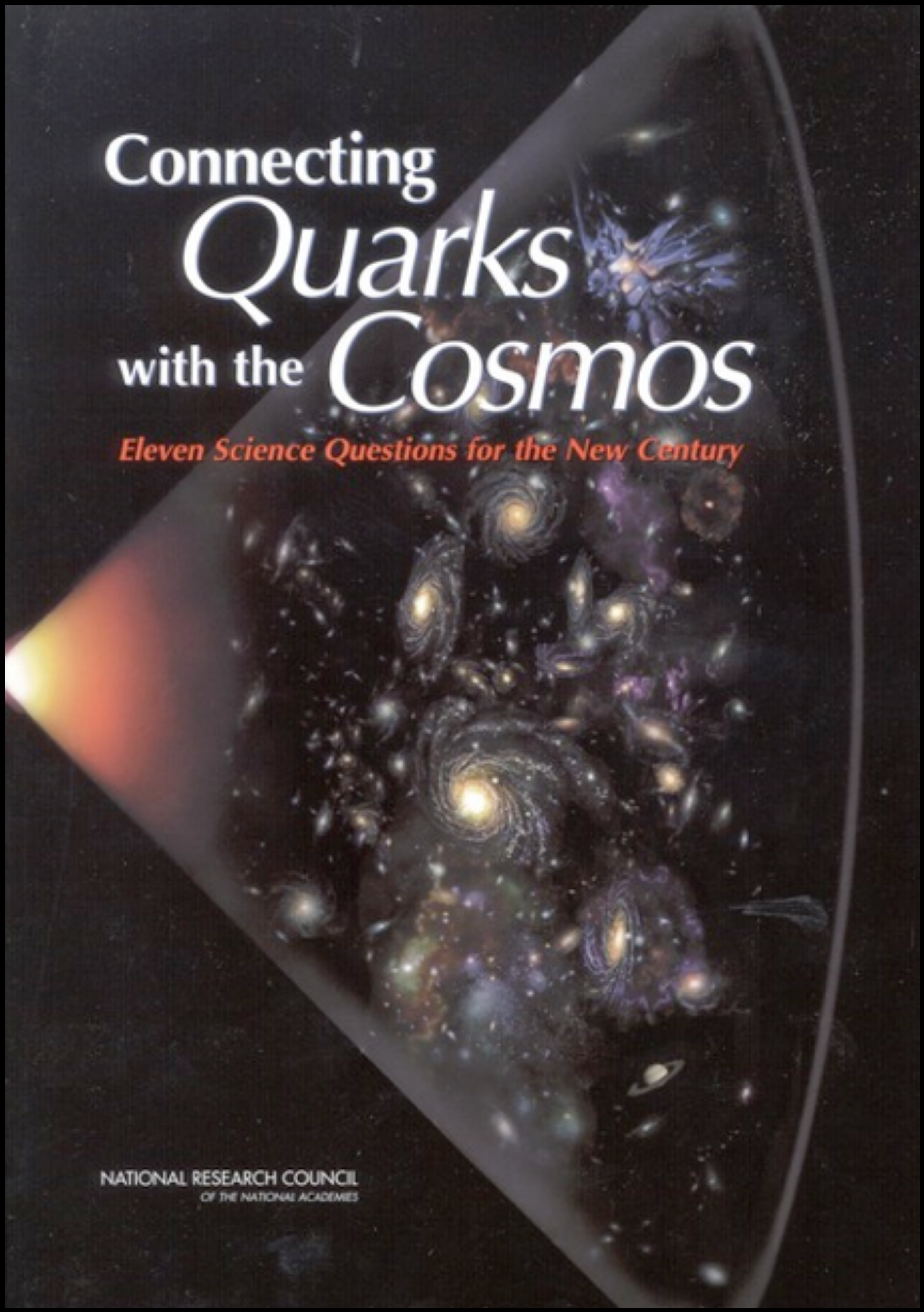
- How did the universe evolve after the Big Bang?
- Can we generate new states of matter at extreme temperatures and densities?

Interesting questions to answer!!!

Fundamental questions in physics

Eleven unanswered science 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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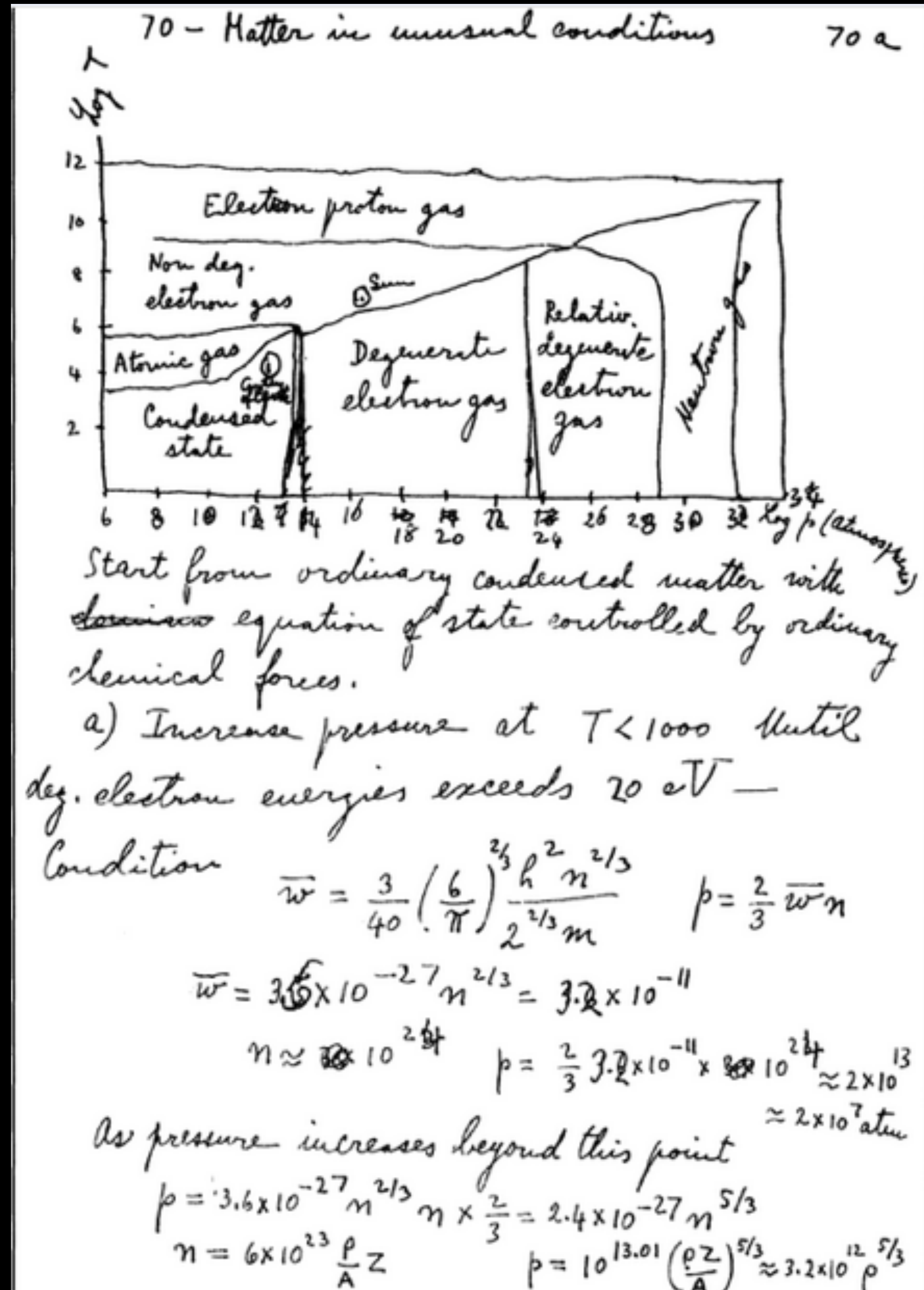
There is evidence that during its earliest moments the universe underwent a tremendous burst of expansion, known as inflation, so that the largest objects in the universe had their origins in subatomic quantum fuzz. The underlying physical cause of this inflation is a mystery. In addition, the universe 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: 2010 physics discussed in ~1950



70 – Matter in unusual conditions 70 a

Start from ordinary condensed matter with ~~dominan~~ equation of state controlled by ordinary chemical forces.

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

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

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

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

As pressure increases beyond this point

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

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

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

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

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

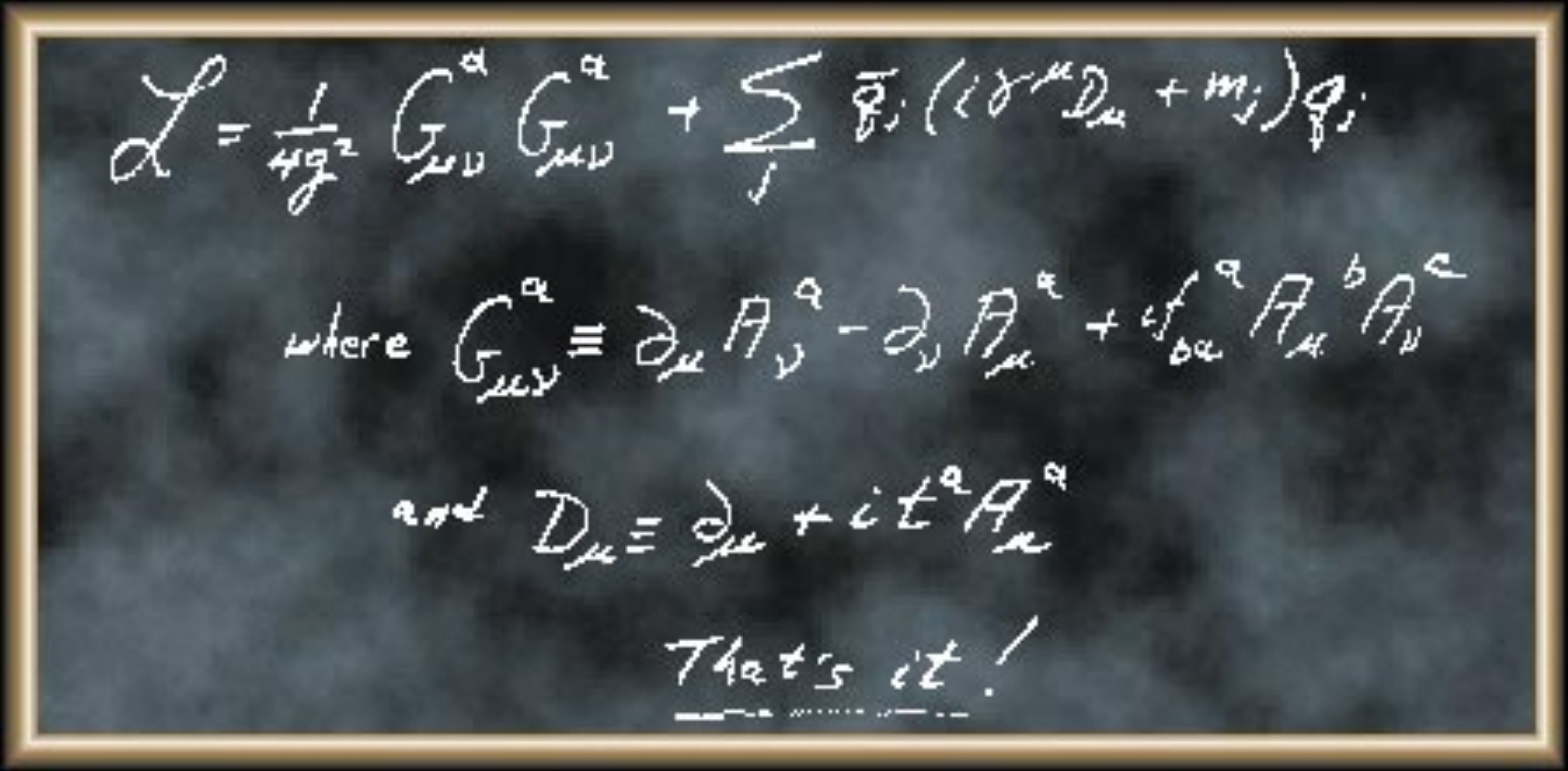

Frank Wilczek

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

Quantum Chromodynamics

It looks like QED, no?



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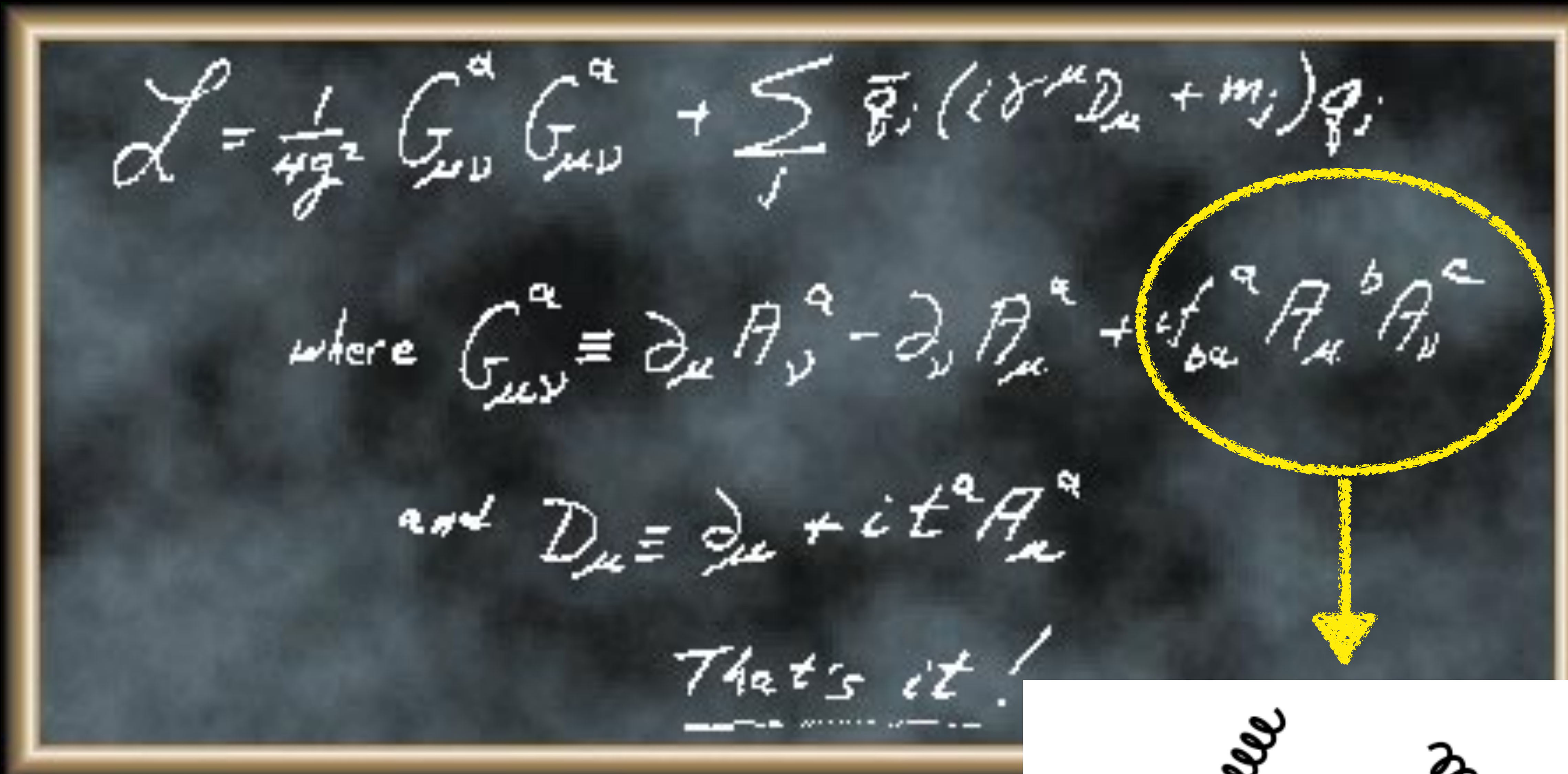
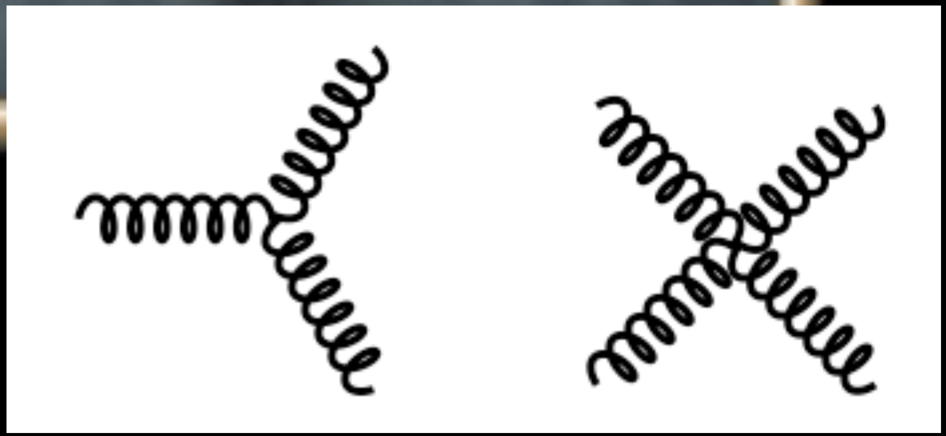
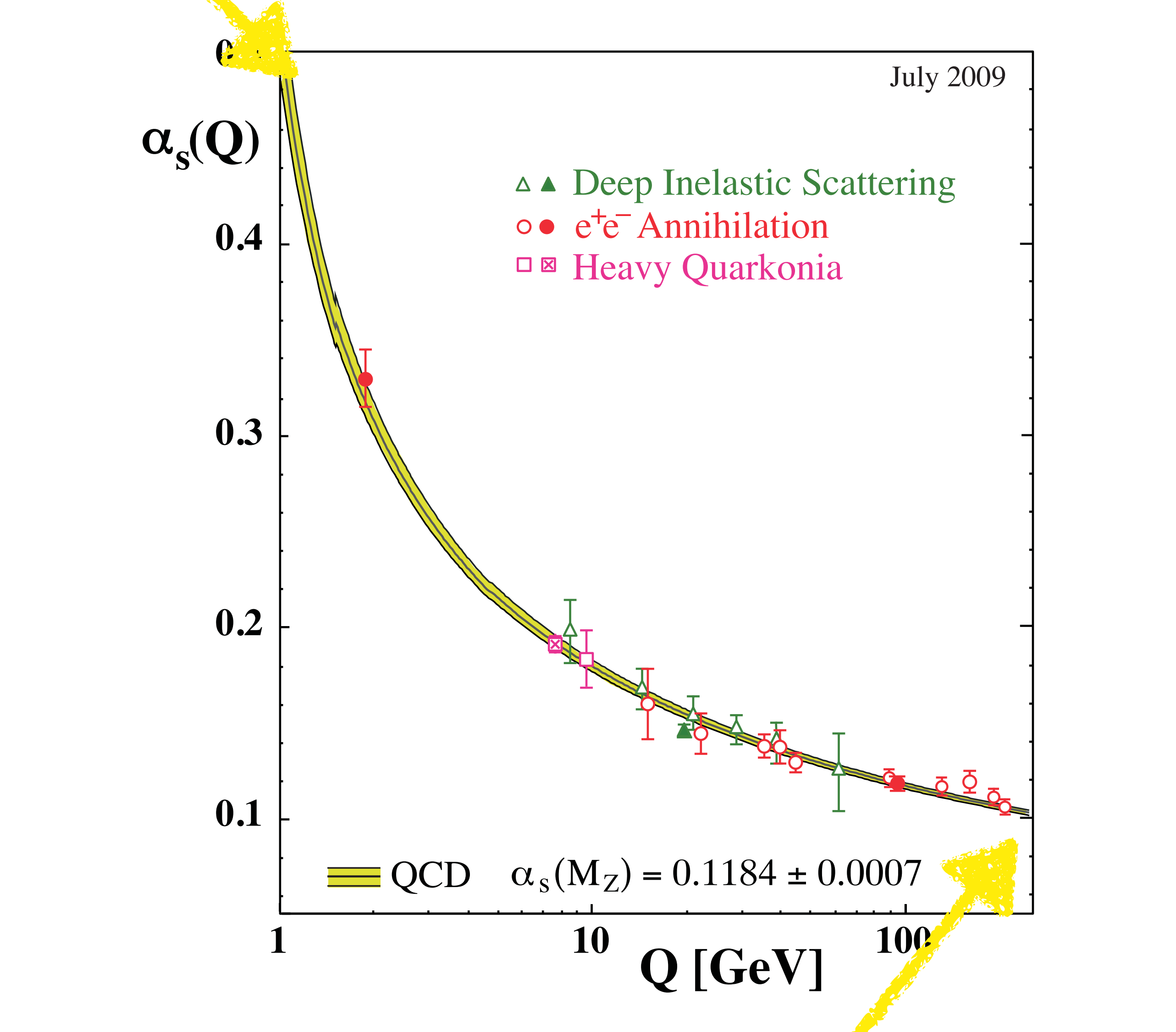




Well…it's not!!!

QCD distinct features

infrared slavery (confinement)



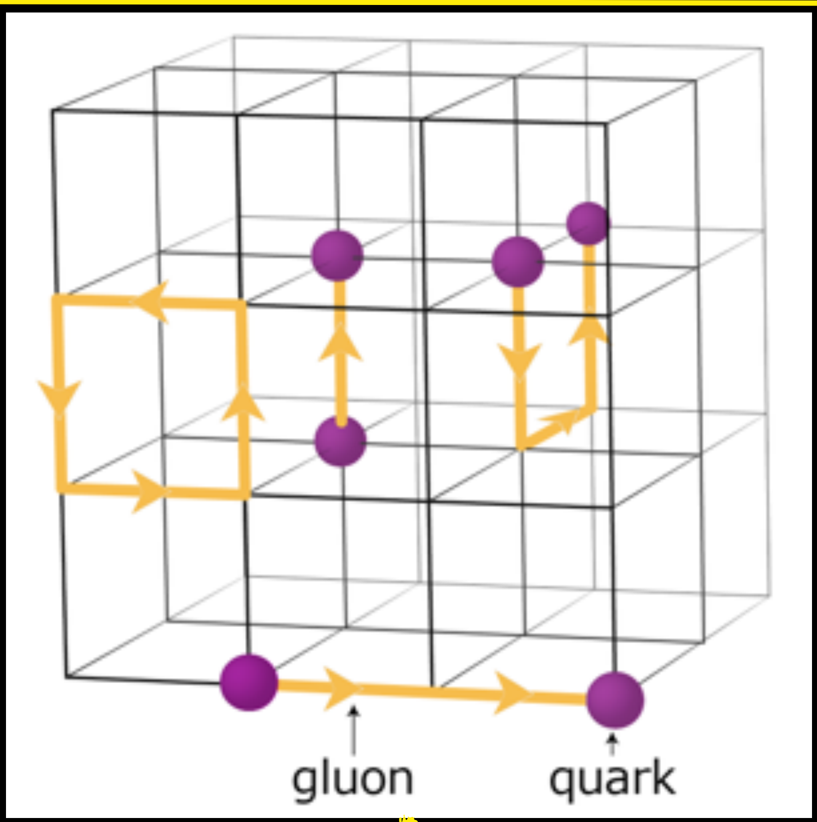
asymptotic freedom

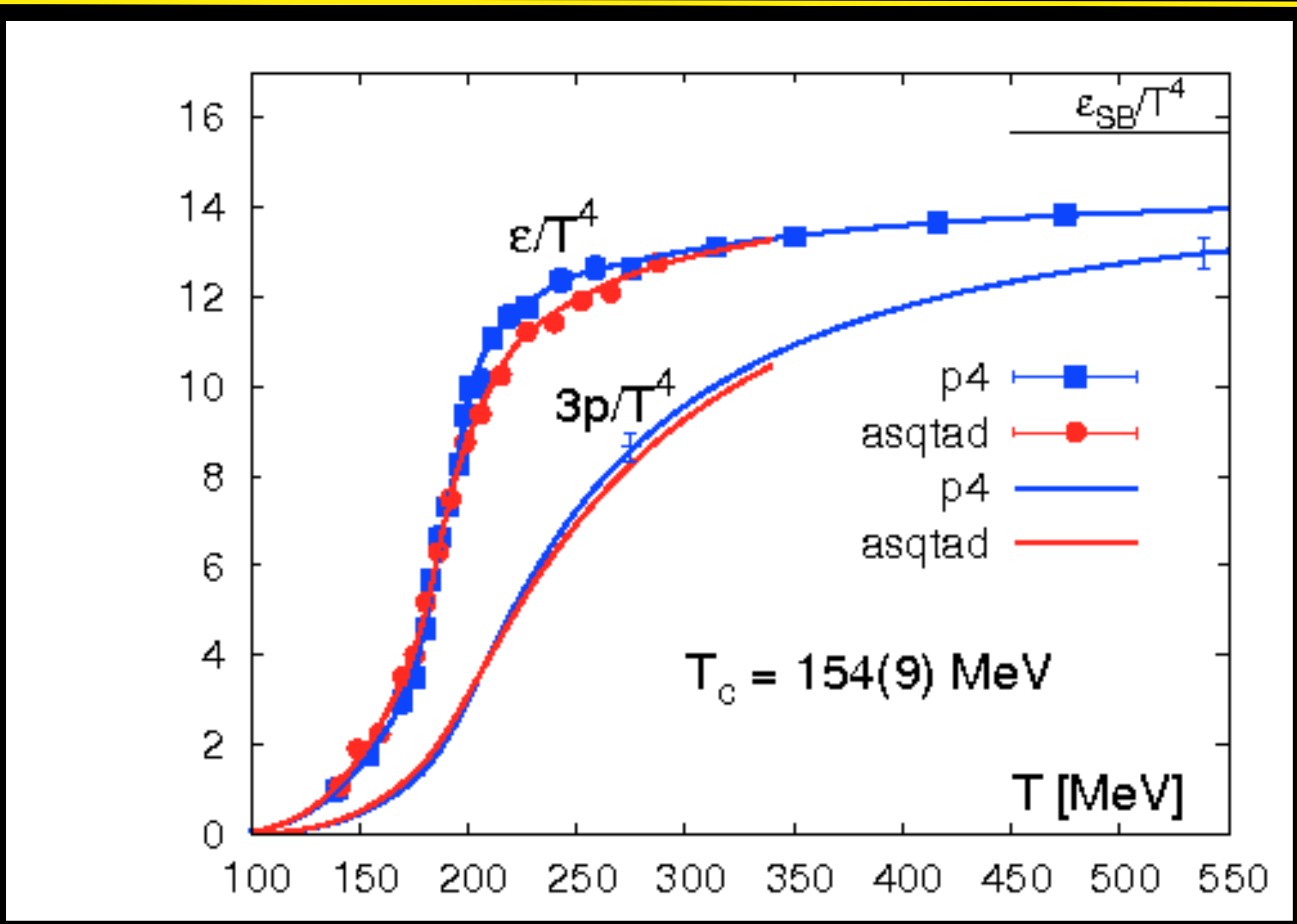
- Typical hadron size: $\sim 10^{-15}$m = 1fm
- Planck's constant: hbar c ~ 0.2GeV·fm
    - 200 MeV is the characteristic scale of confinement
    - the Λ_{QCD} scale

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

Lattice QCD calculations

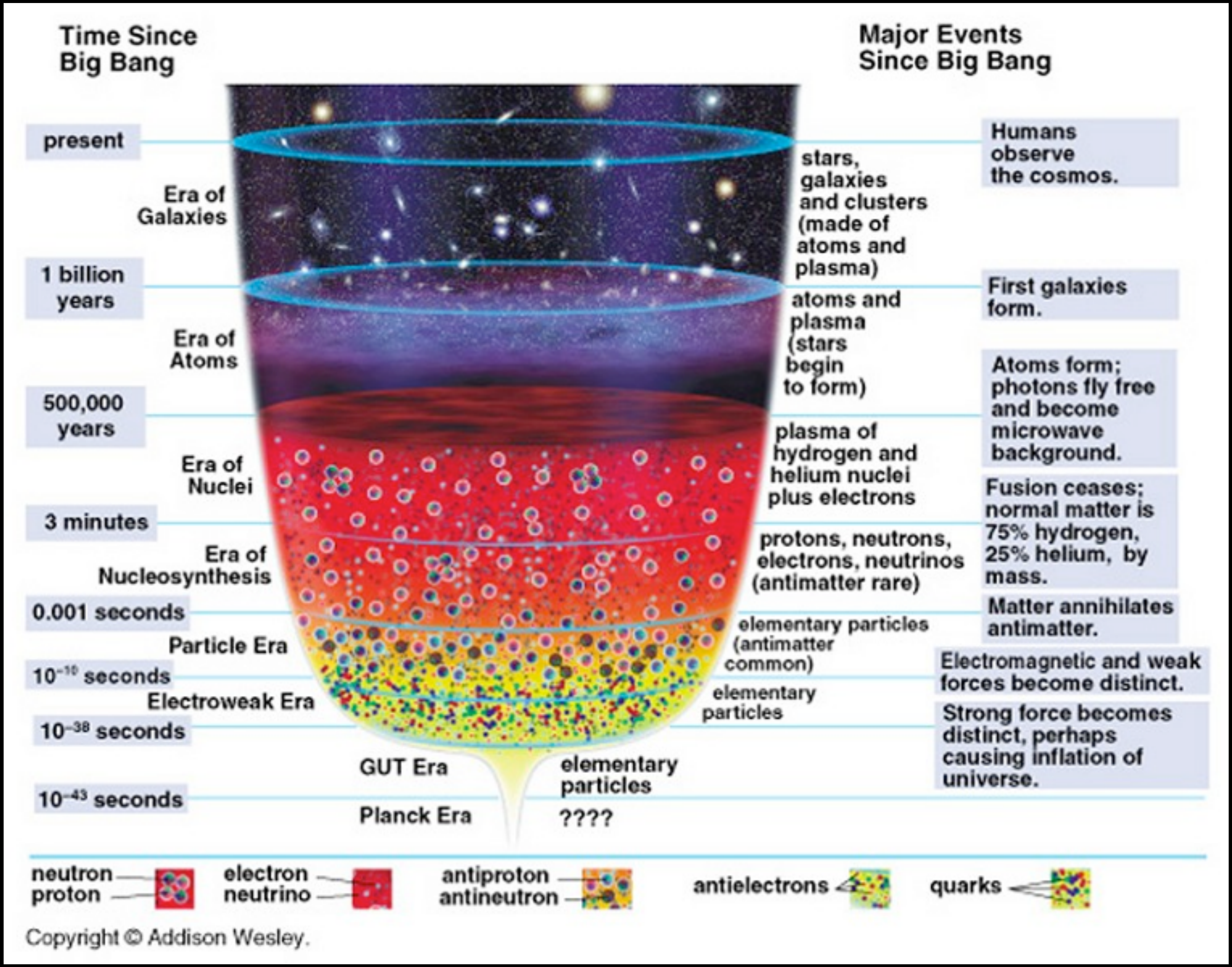




Lattice QCD: beyond a critical temperature there is a rapid rise in the number of degrees of freedom ➡ phase transition to a deconfined state of quarks and gluons!!!

Quark-Gluon Plasma (QGP)

Going back in time: few μsec after the Big-Bang



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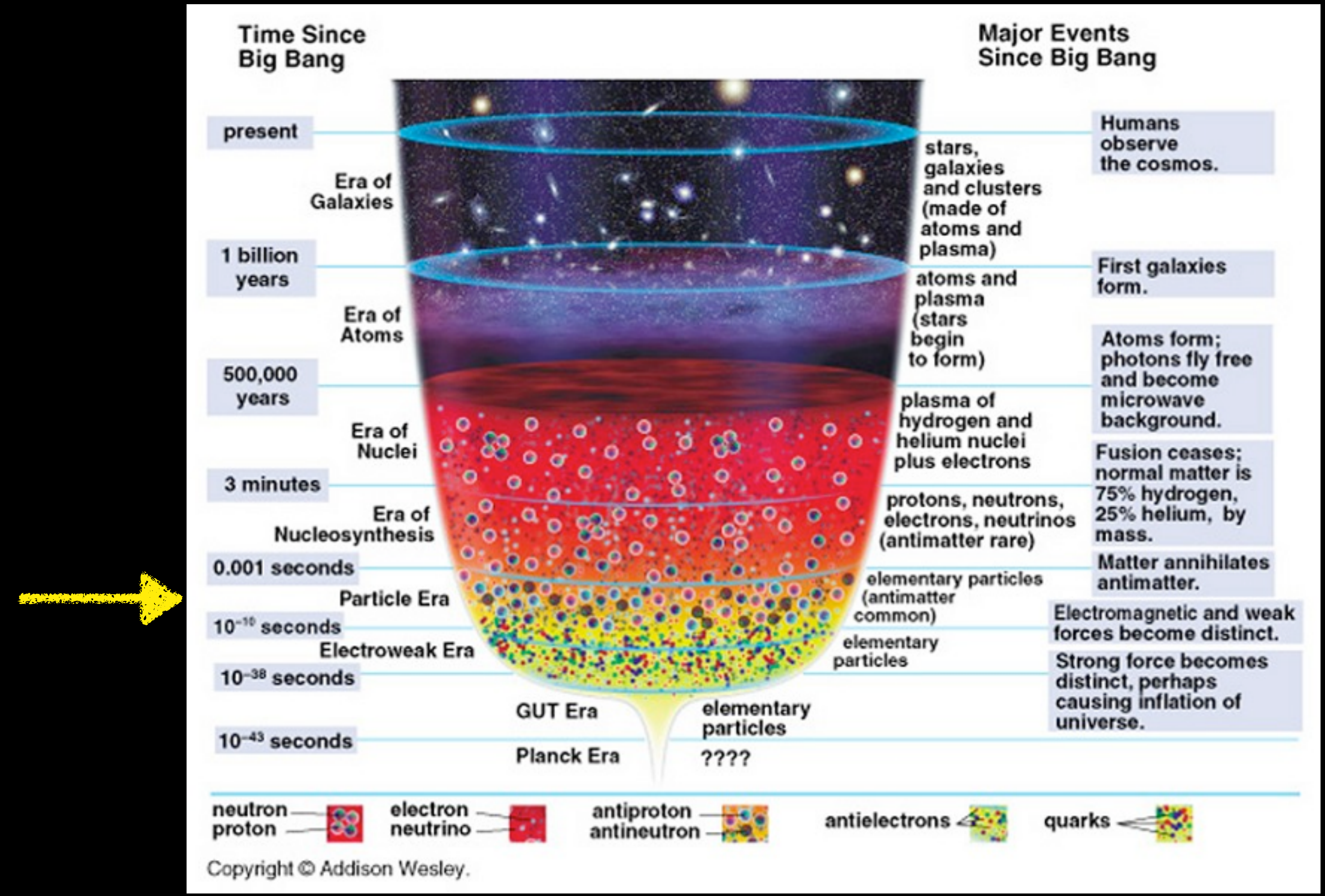

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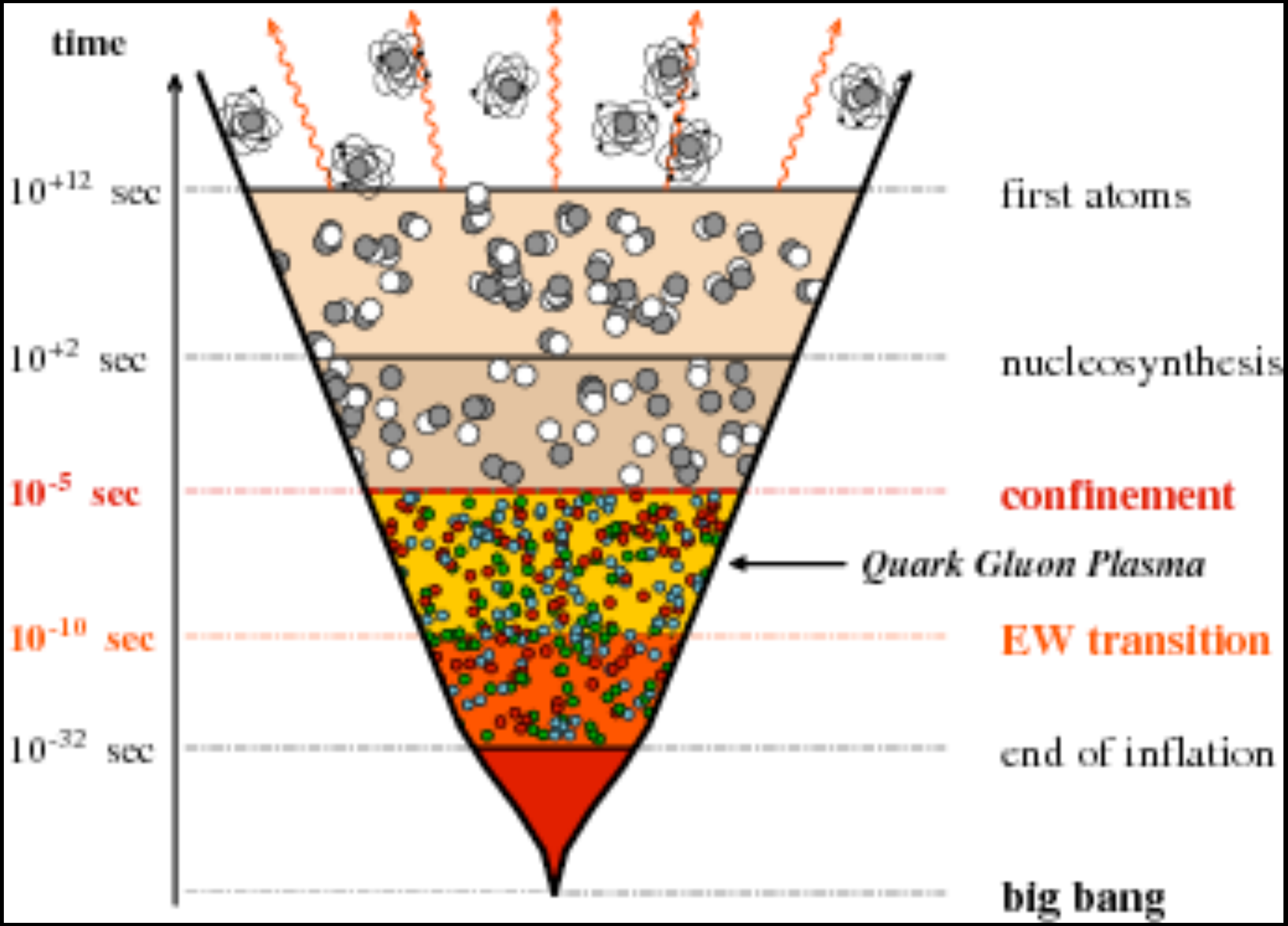
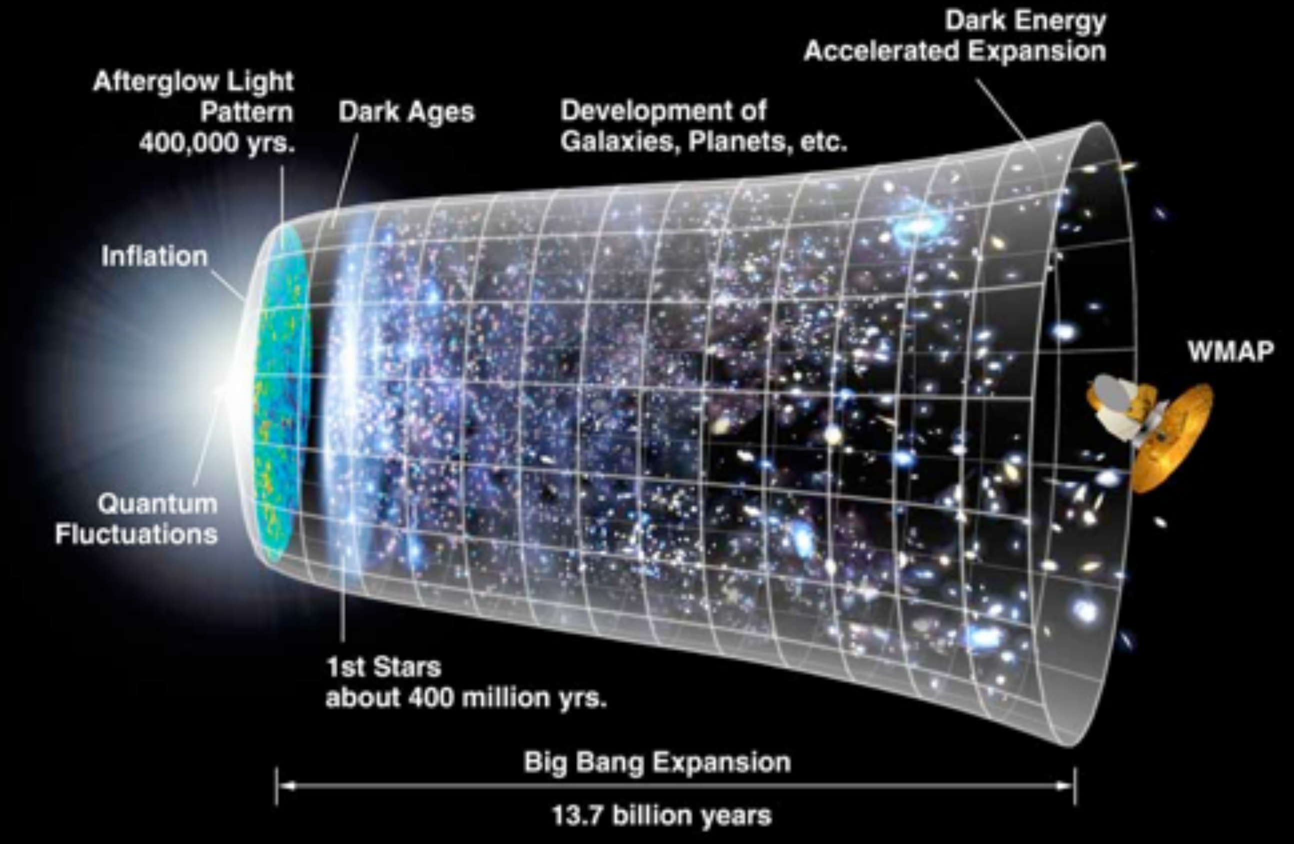
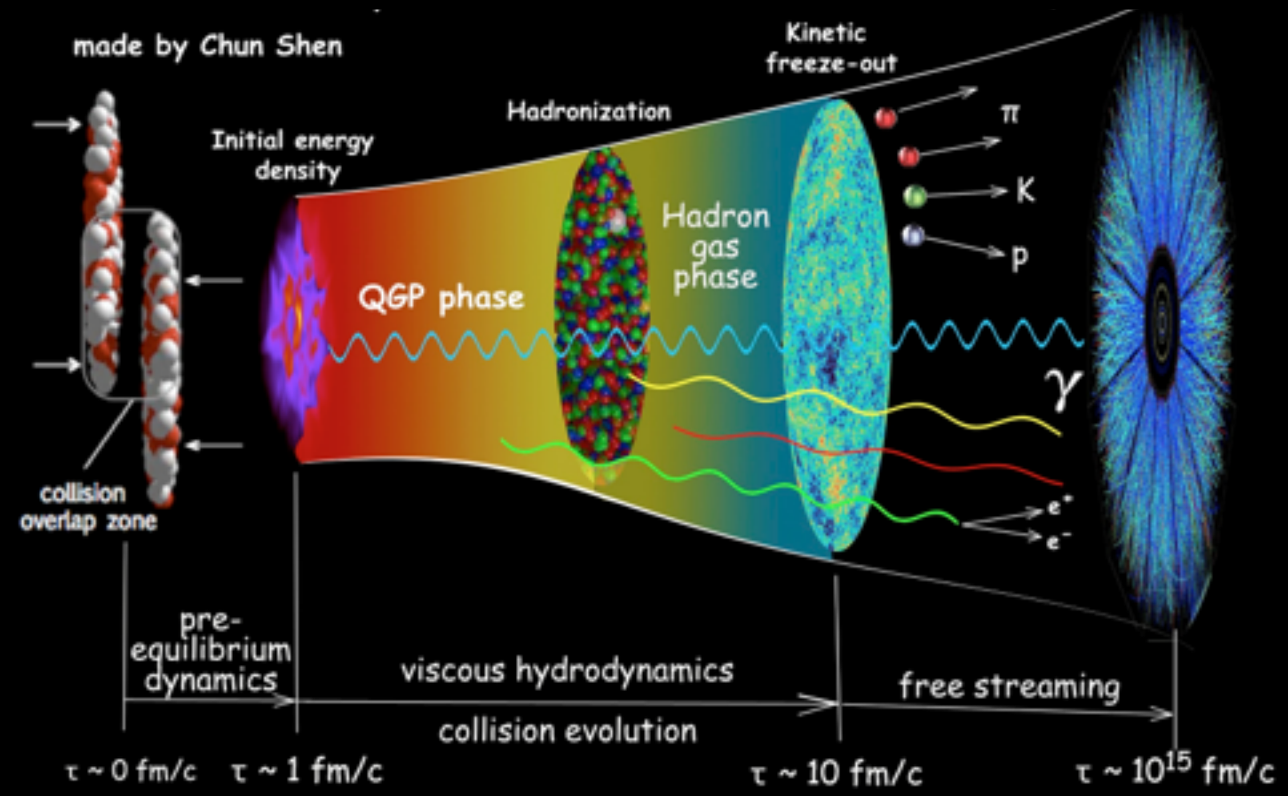
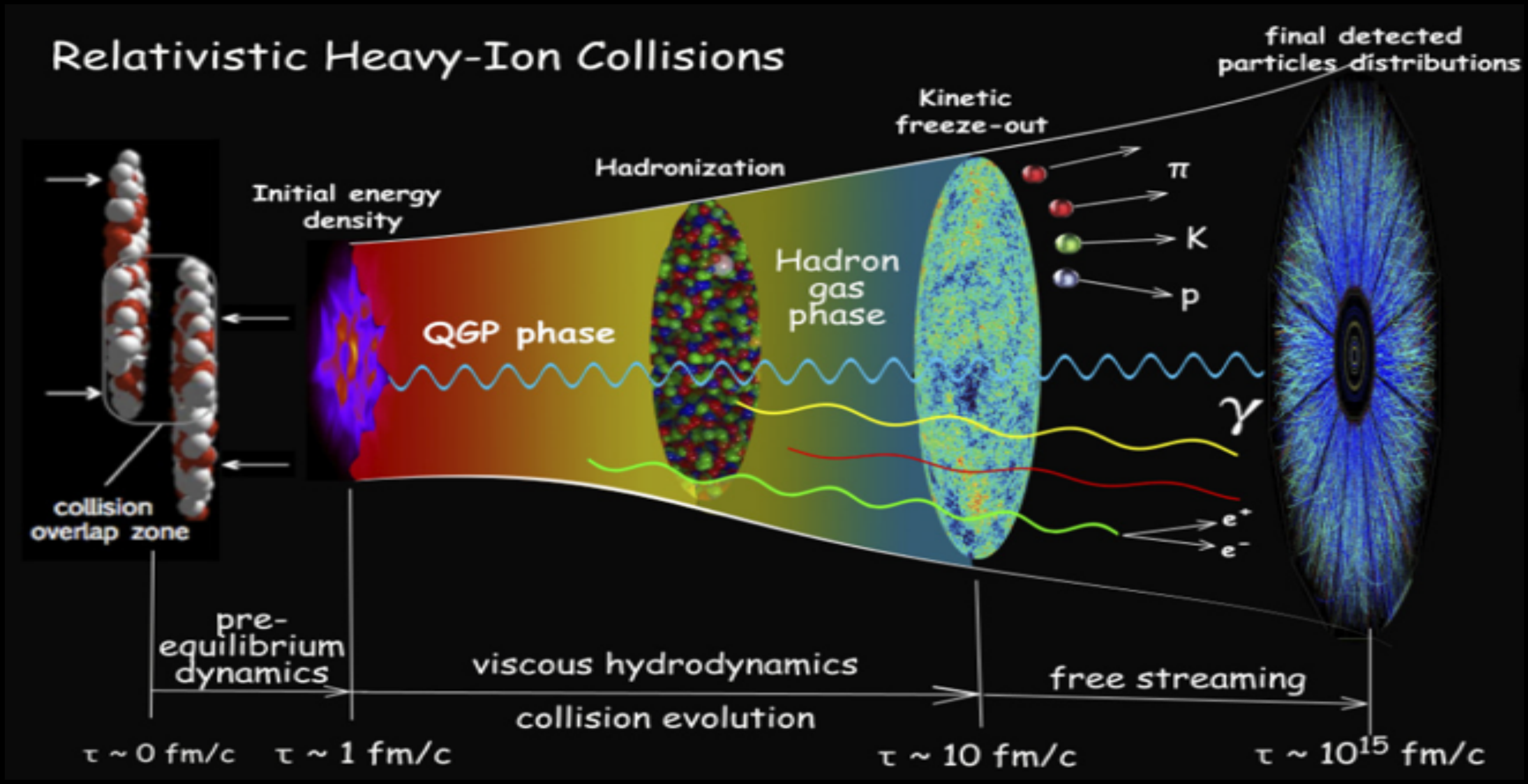


The strong phase transition can be studied in the lab!!!





From the Big-Bang to the Little-Bangs…



- The Quark-Gluon Plasma (QGP):
  - ★ a state of matter where the quarks and gluons are 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

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

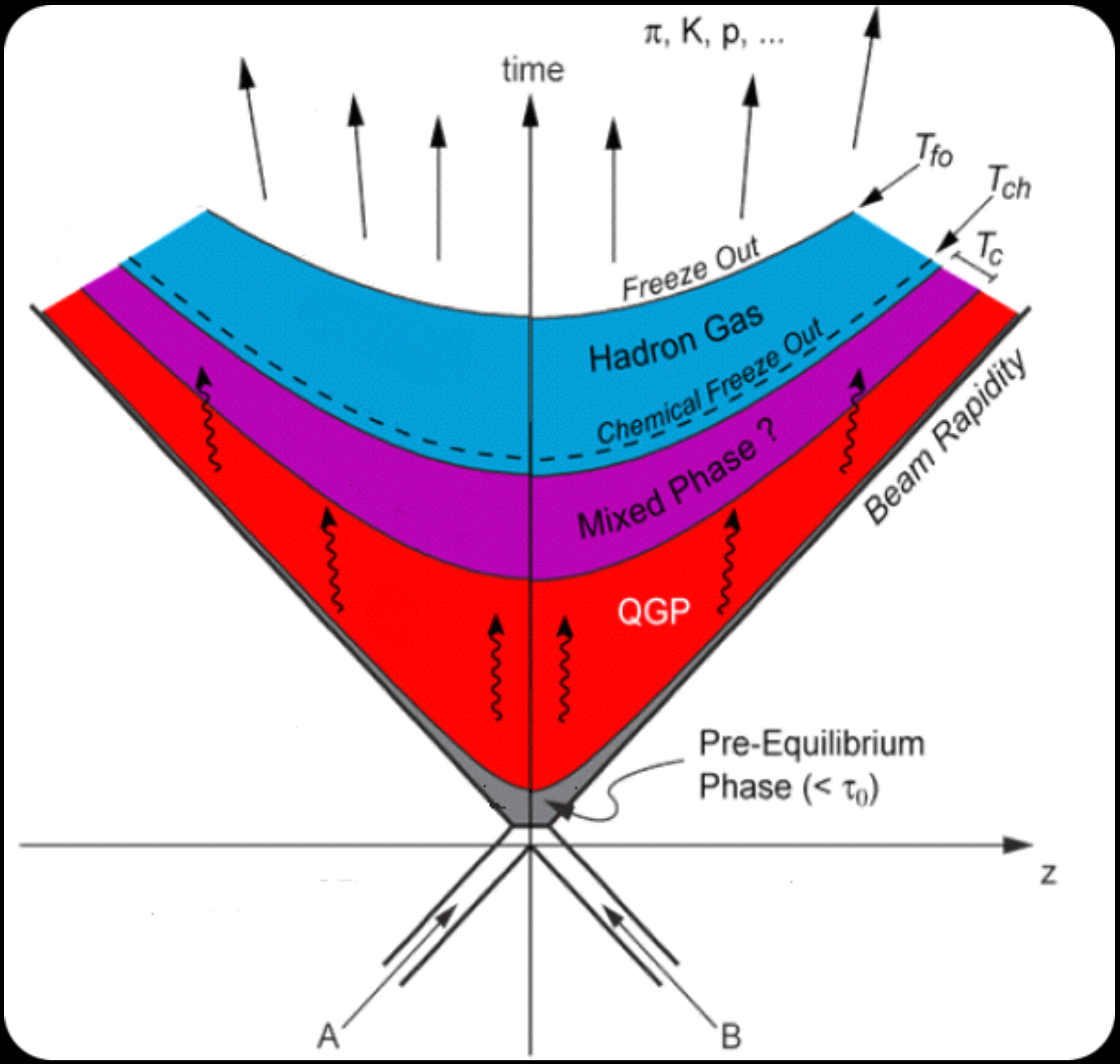
$T_{(Sun's\ core)}$~10^7 degrees

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

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

Heavy-ion physics program: scientific goal

What are the properties of the QGP? EoS, transport properties (density, viscosity…)



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

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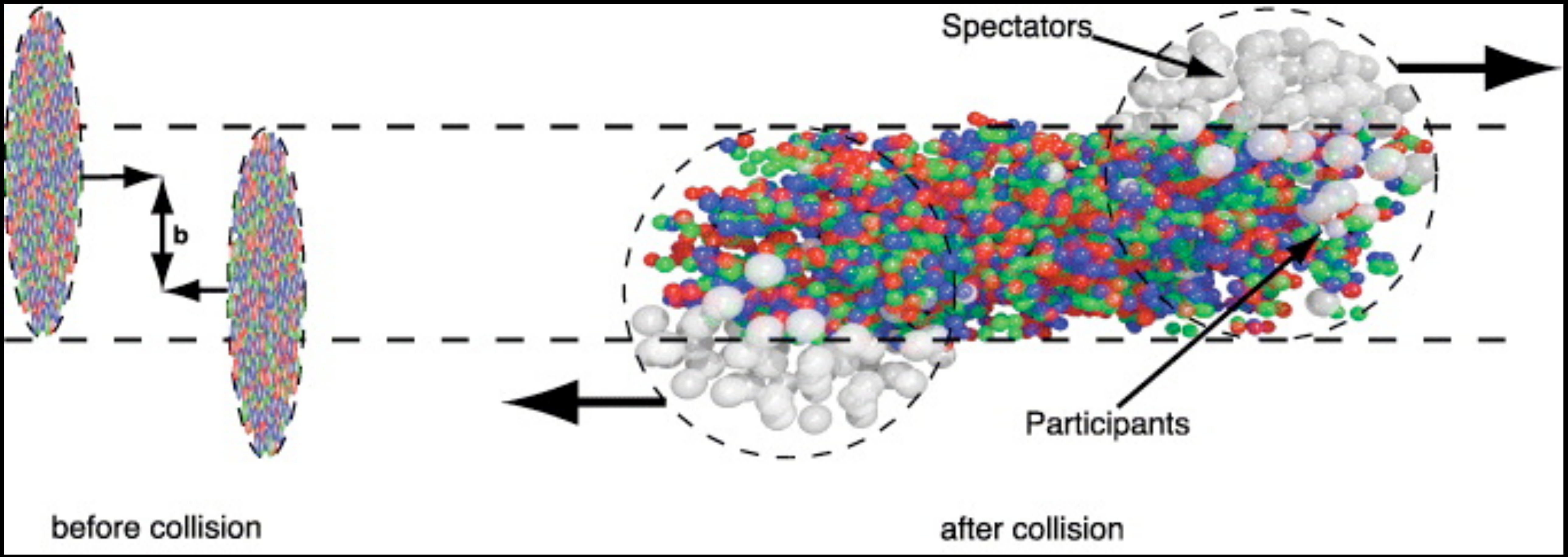
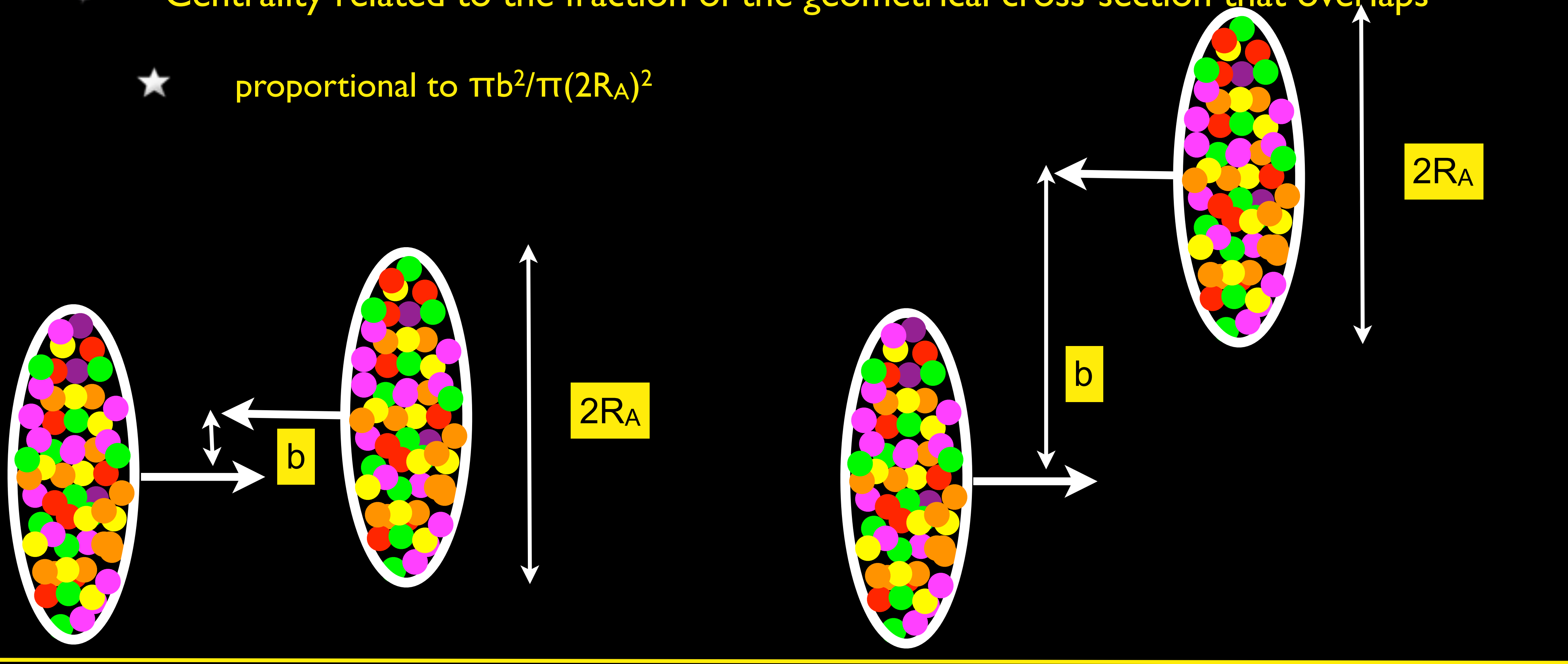
Centrality in heavy-ion collisions



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 centers of the two nuclei
  - ★ Perpendicular to the beam axis
- Centrality related to the fraction of the geometrical cross-section that overlaps
  - ★ proportional to $\pi b^2/\pi(2R_A)^2$



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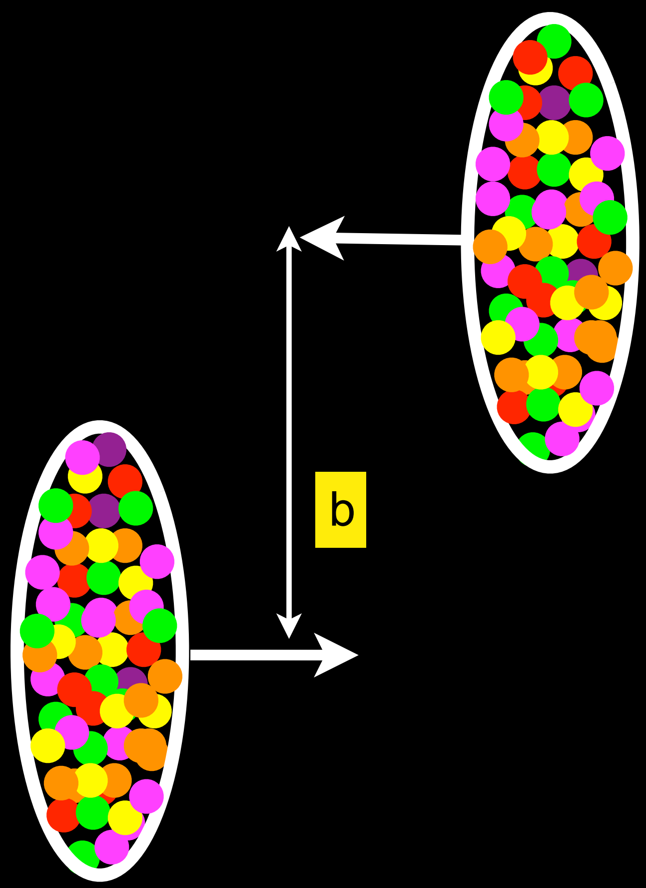
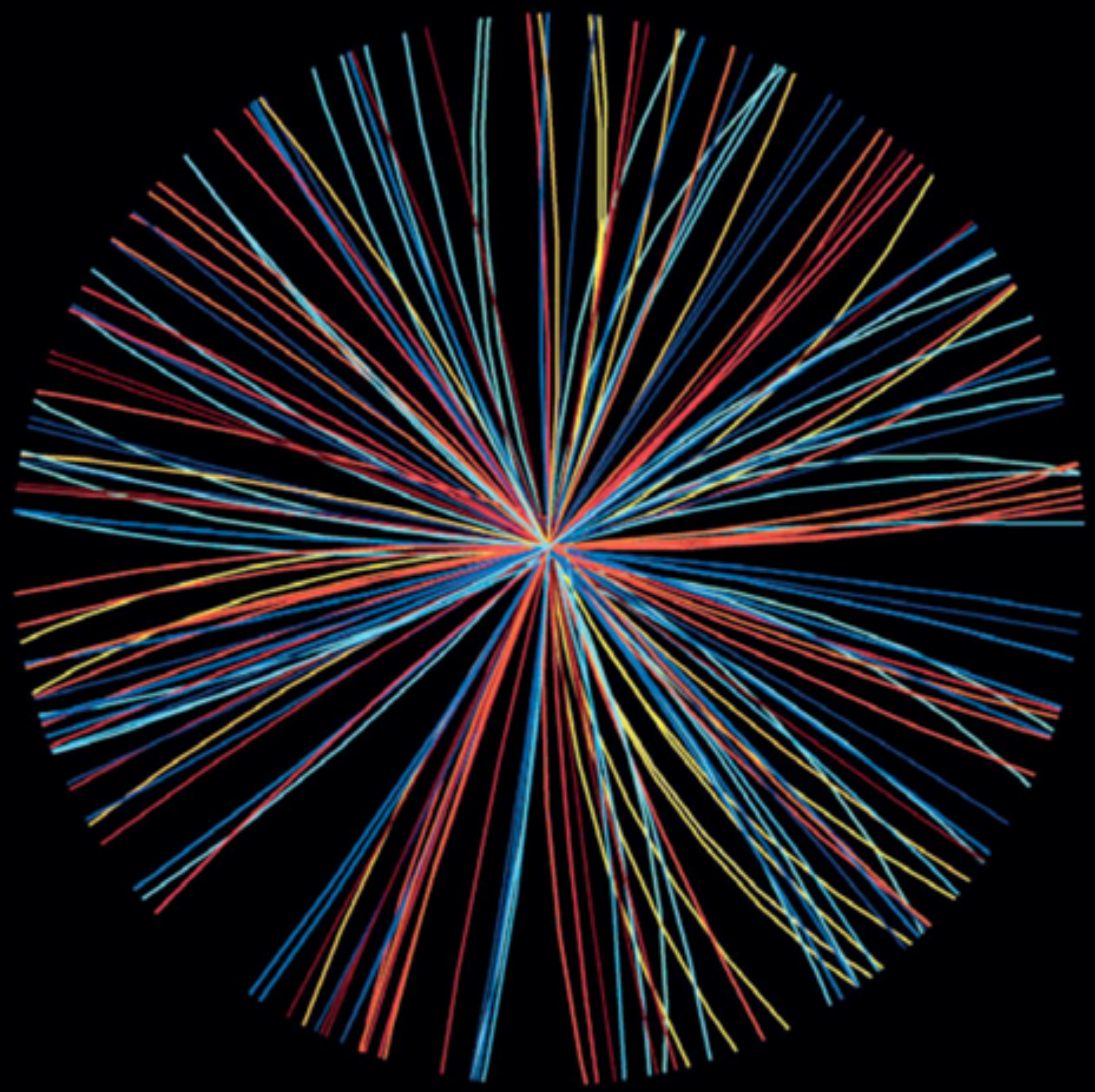
Peripheral collisions: few particles





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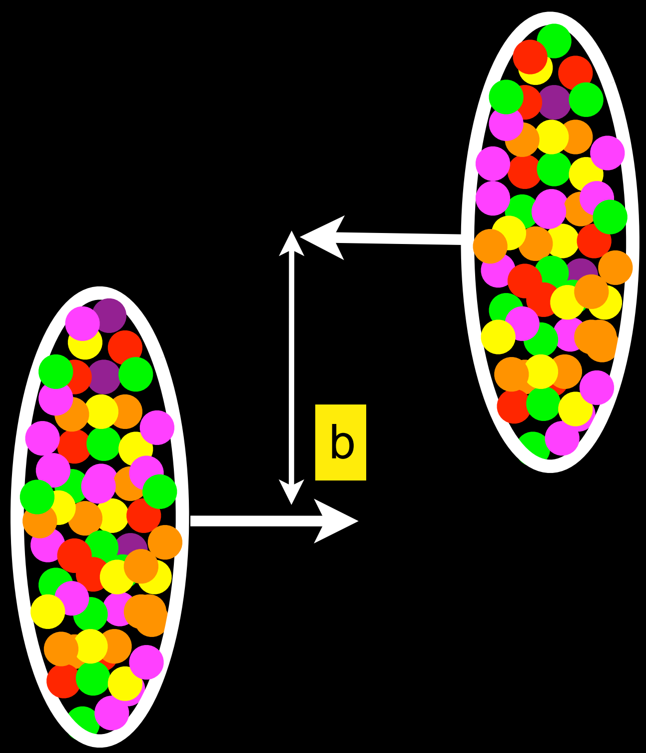
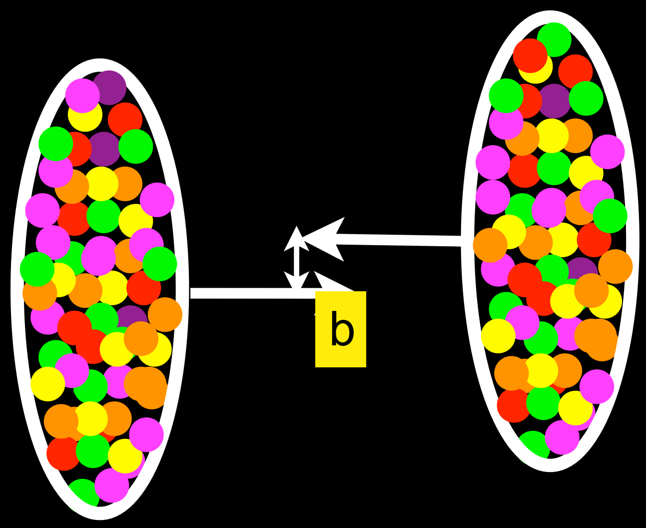
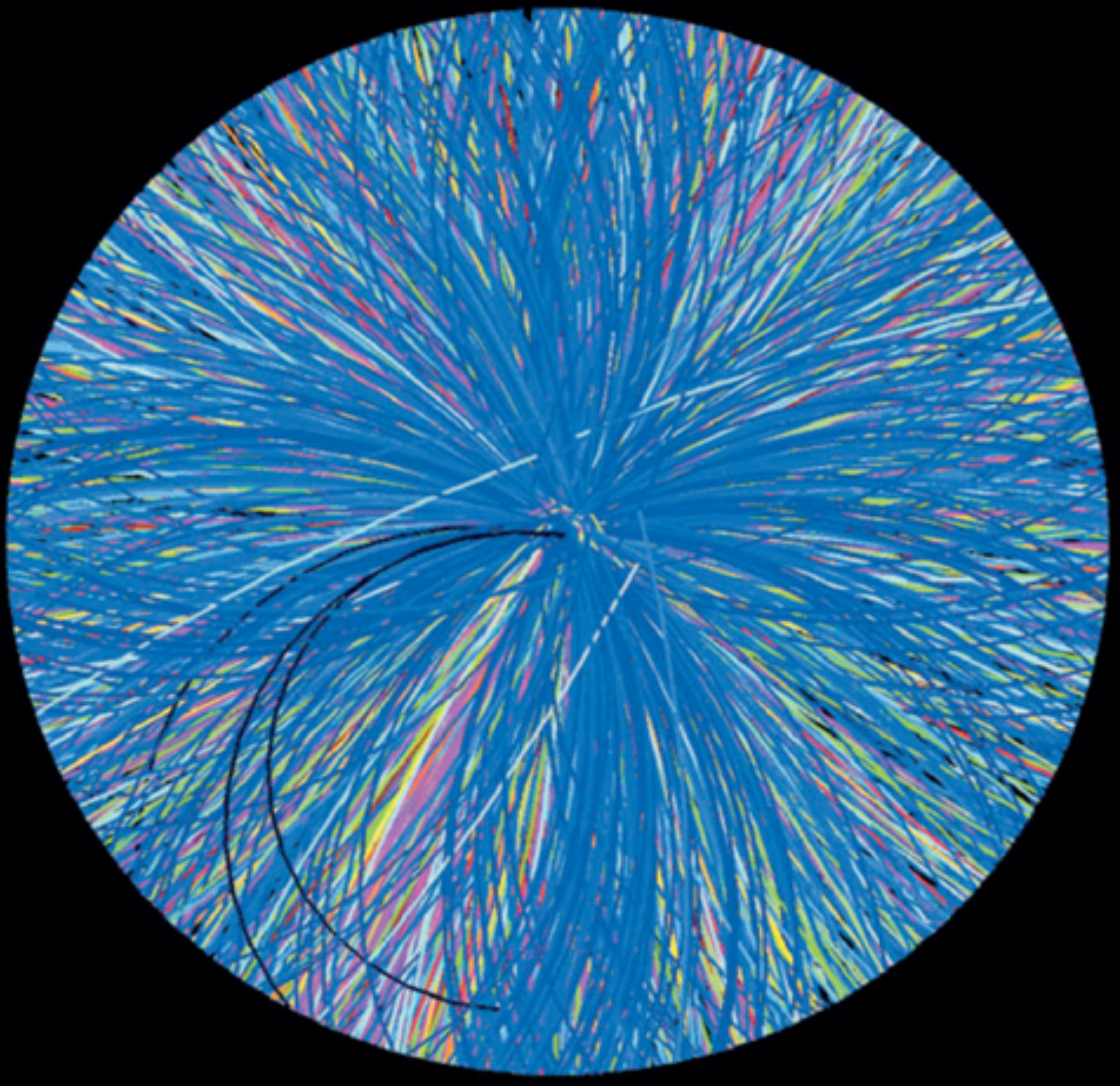
Mid-central collisions: more particles



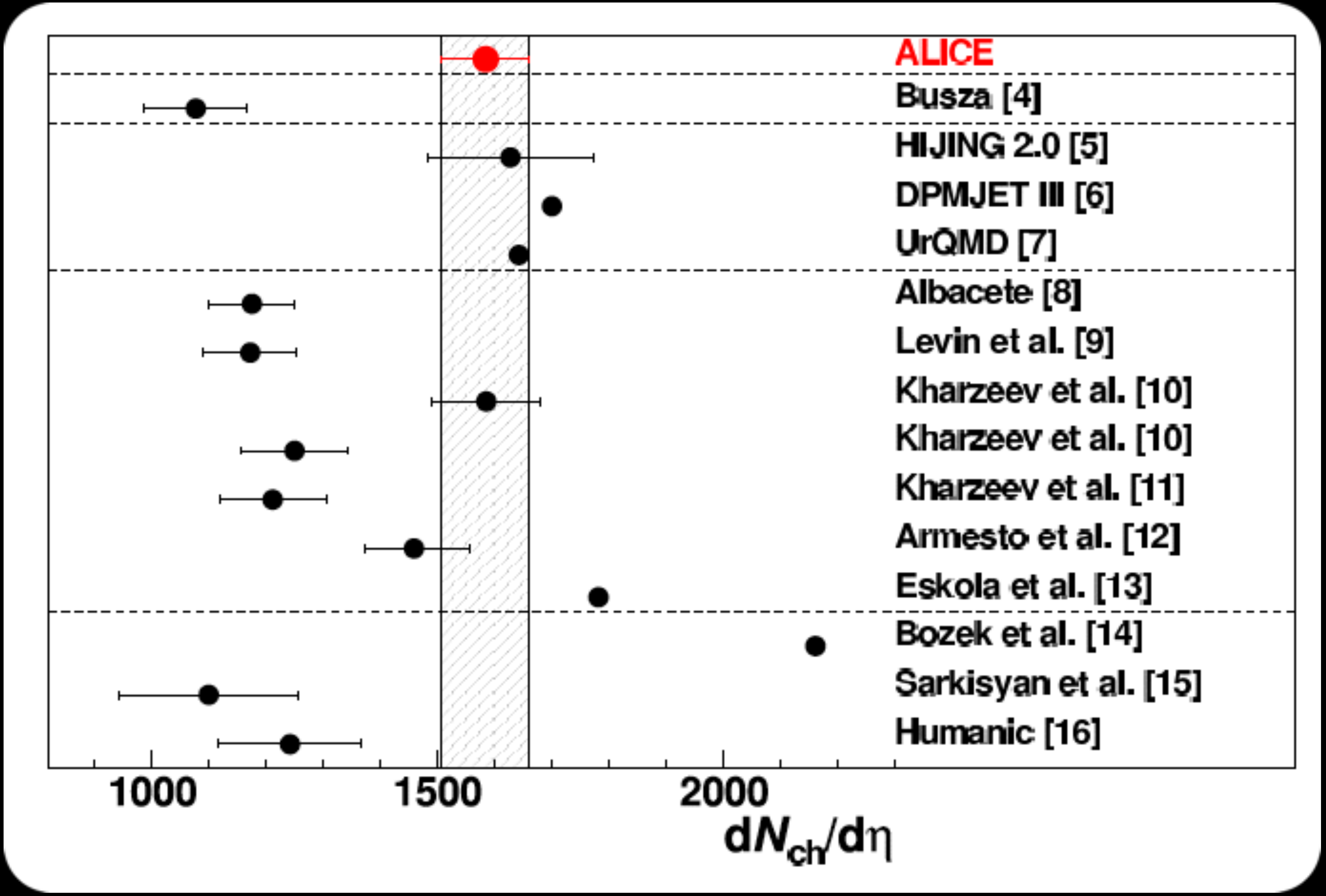
Central collisions: even more particles





Measured particle multiplicity in central collisions

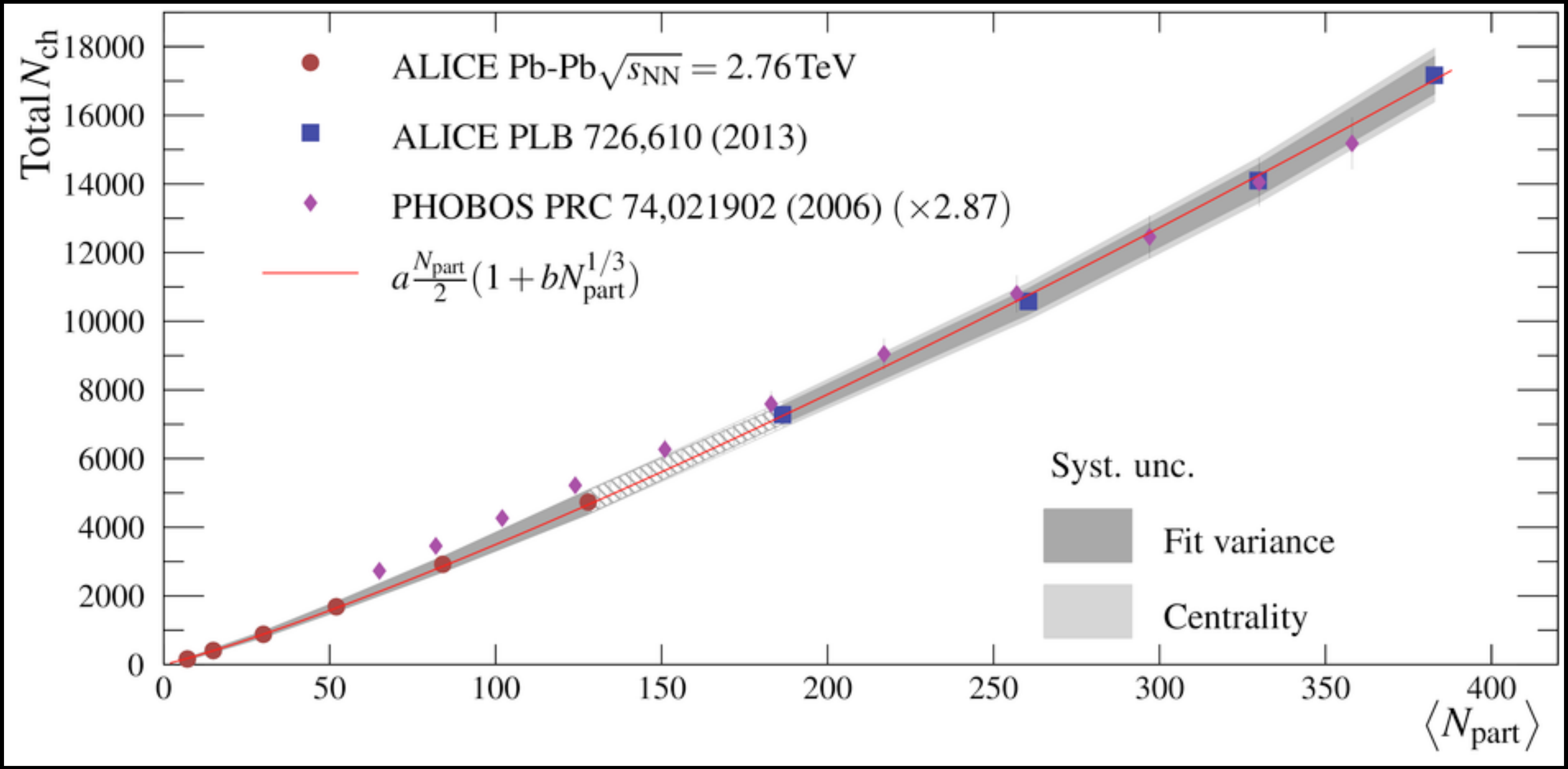
ALICE Collaboration, Phys. Rev. Lett. **105**, 252301 (2010)



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

Particle multiplicity in ALICE @ the LHC

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



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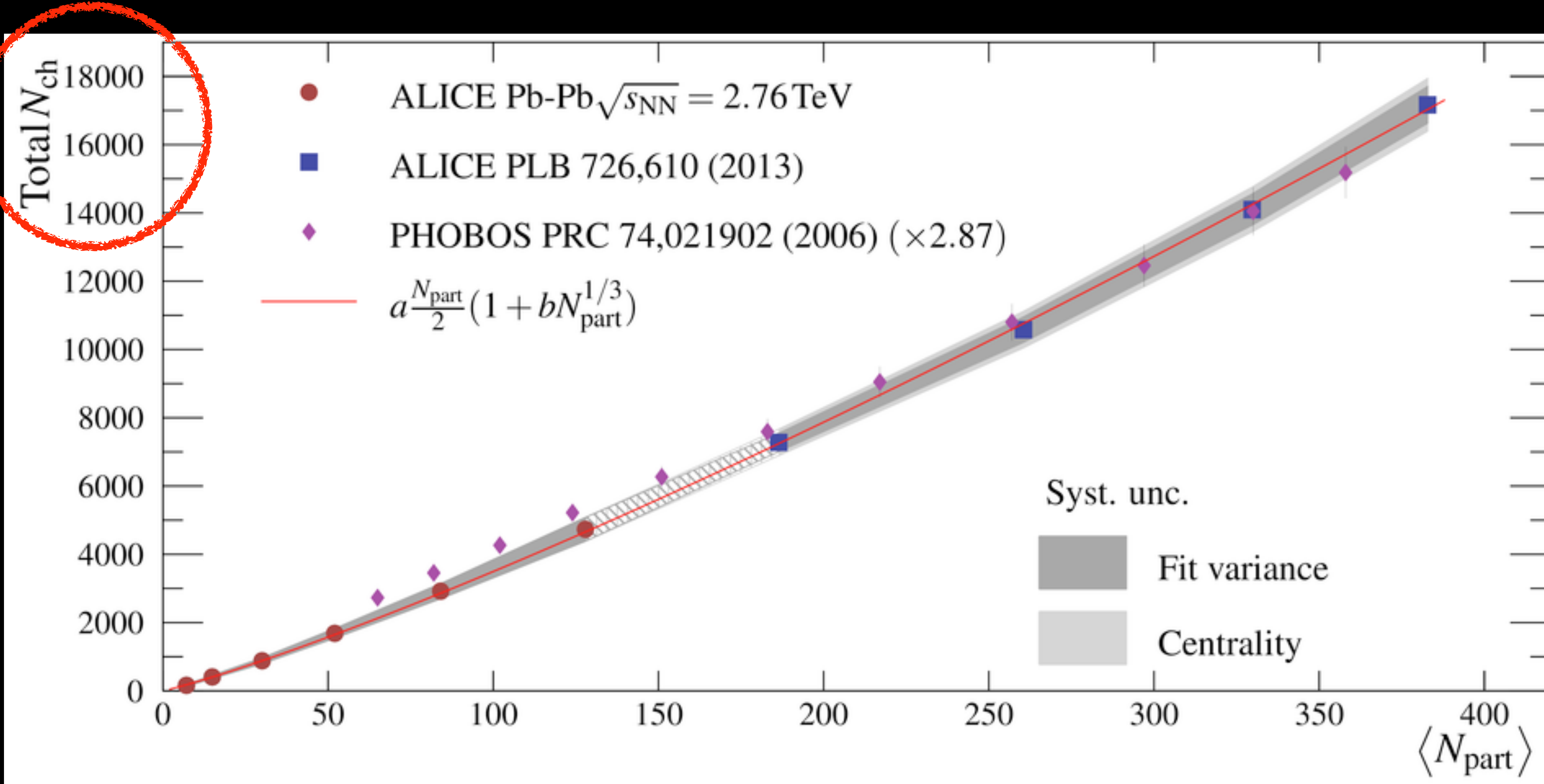
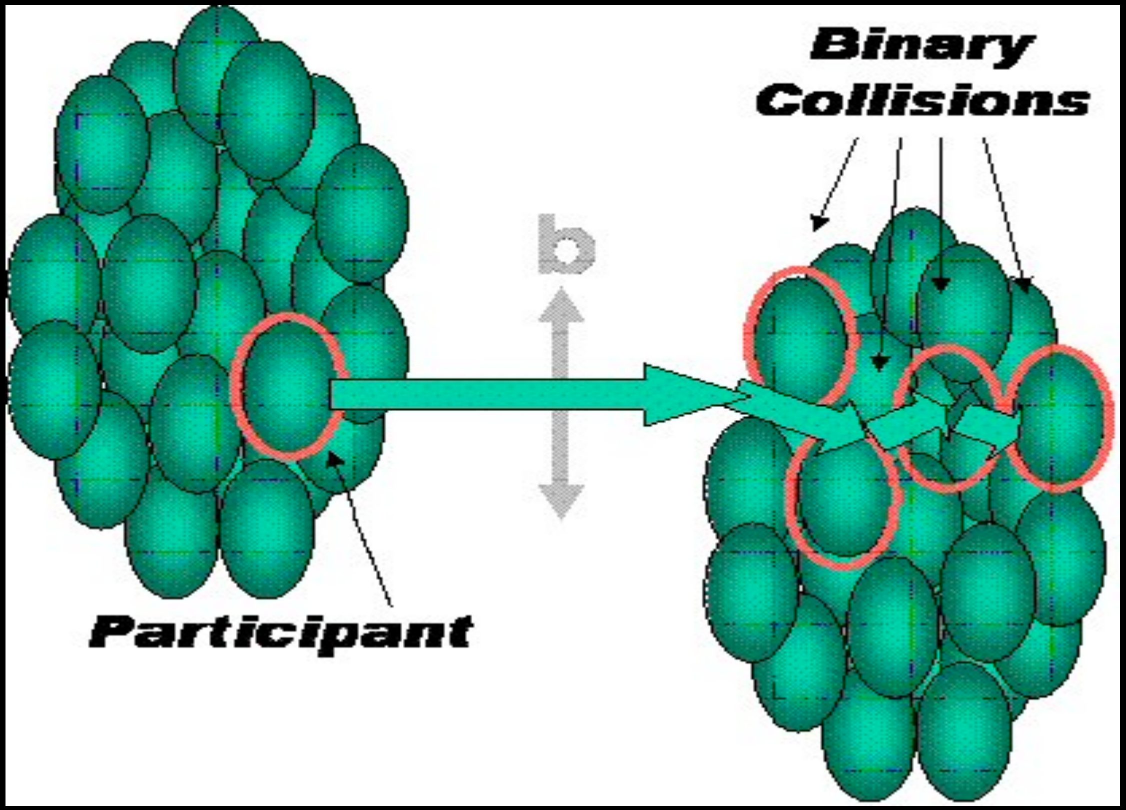
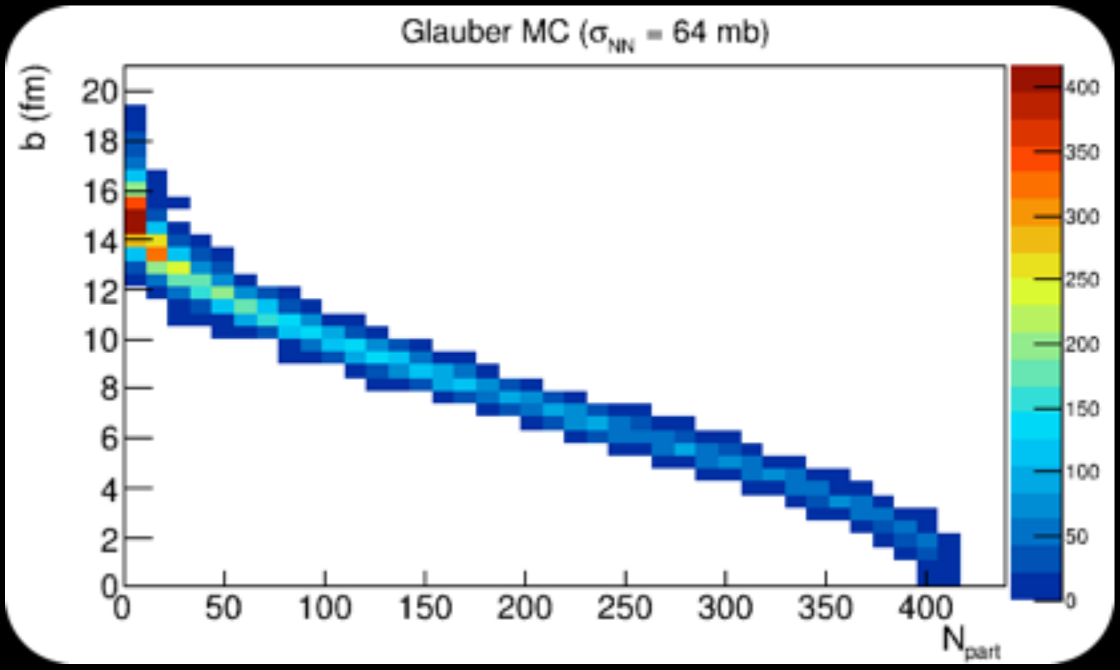
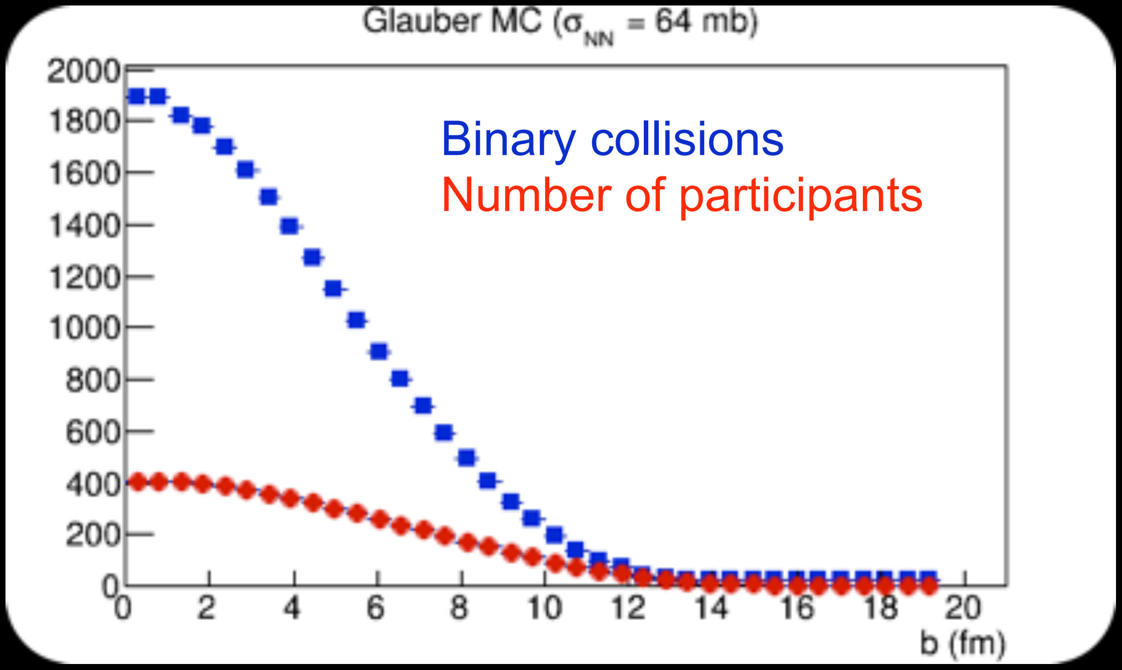


Number of participants, spectators, binary collisions

- 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

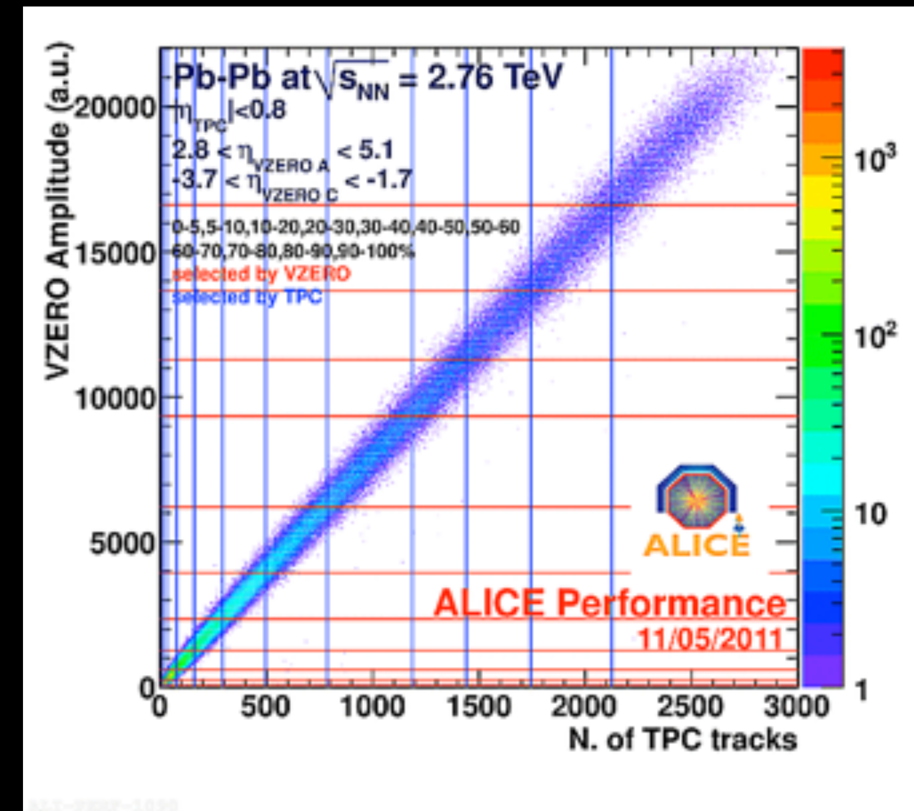


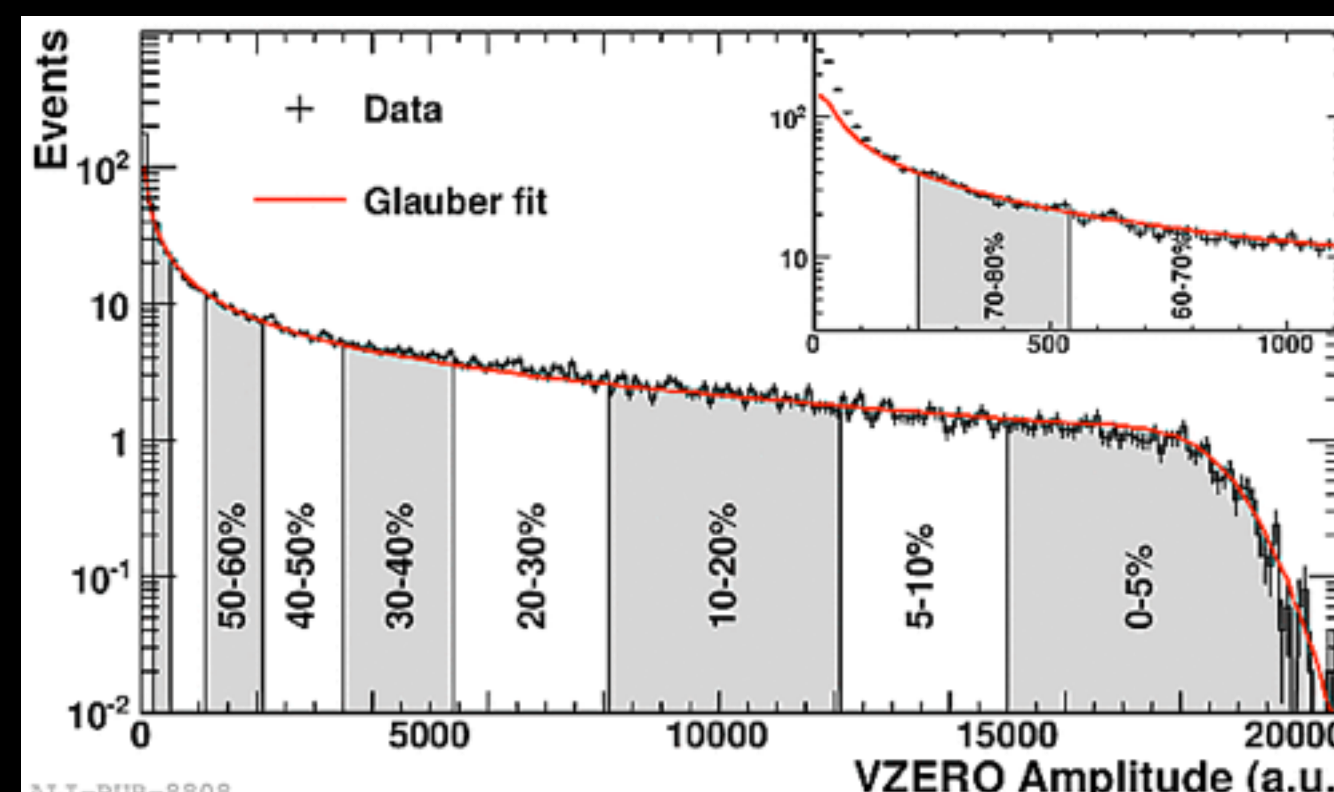




Centrality in the experiment

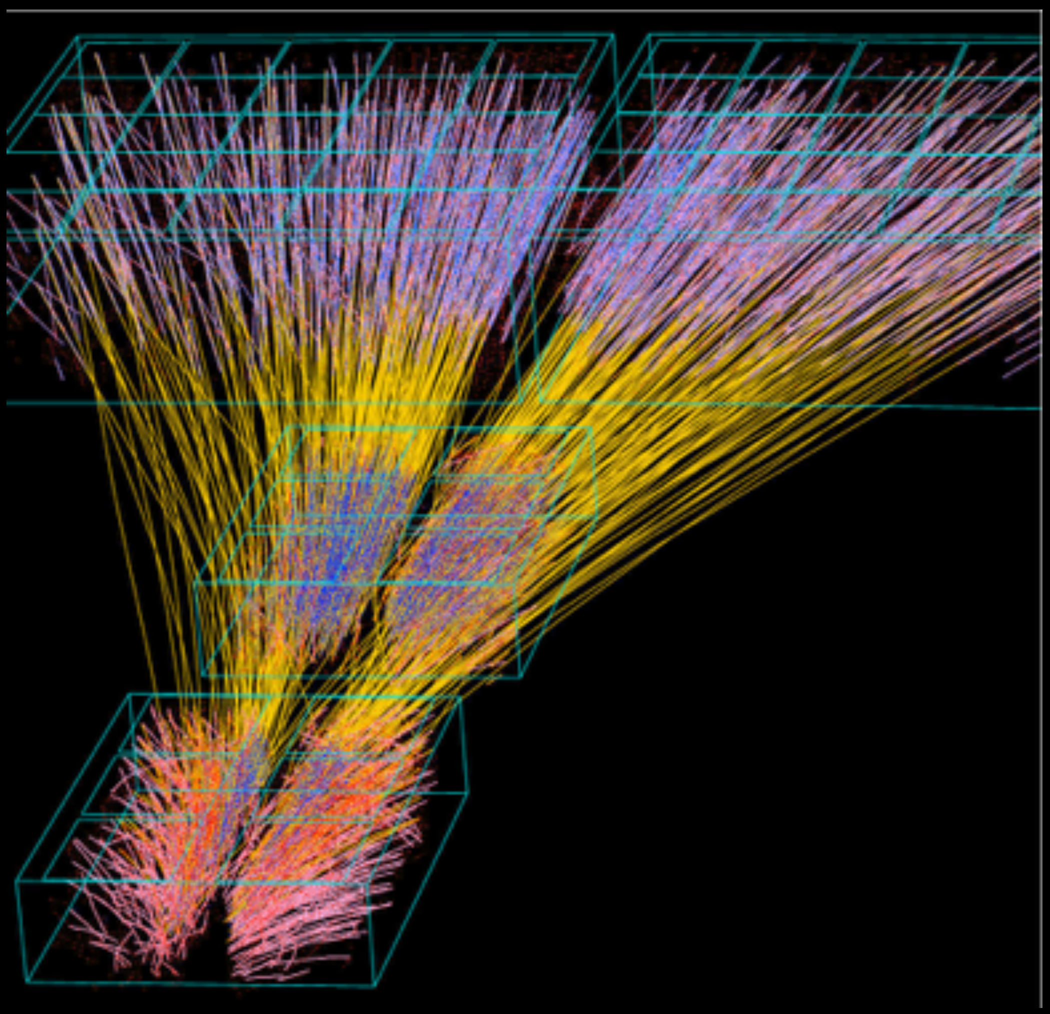
- Experimentally neither the impact parameter nor the N_{part}/N_{spec} can be measured
- Have to rely on experimental measurements:
  - Multiplicity (central or/and forward regions)
    - Large (small) for central (peripheral) collisions
  - Zero degree calorimeters (energy deposited by spectator nucleons)
    - 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



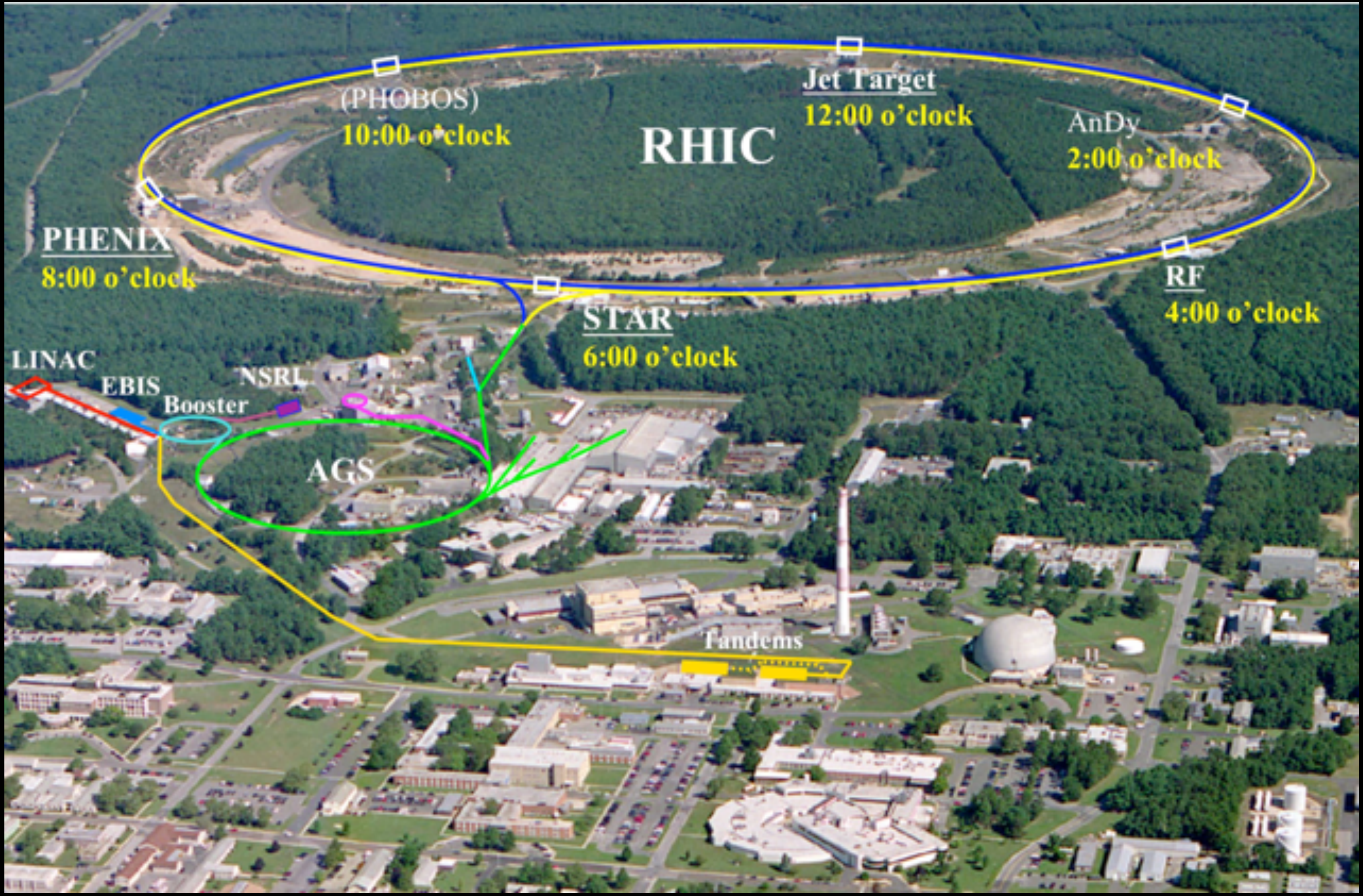


Heavy-ion physics: SPS (CERN) (~1990)

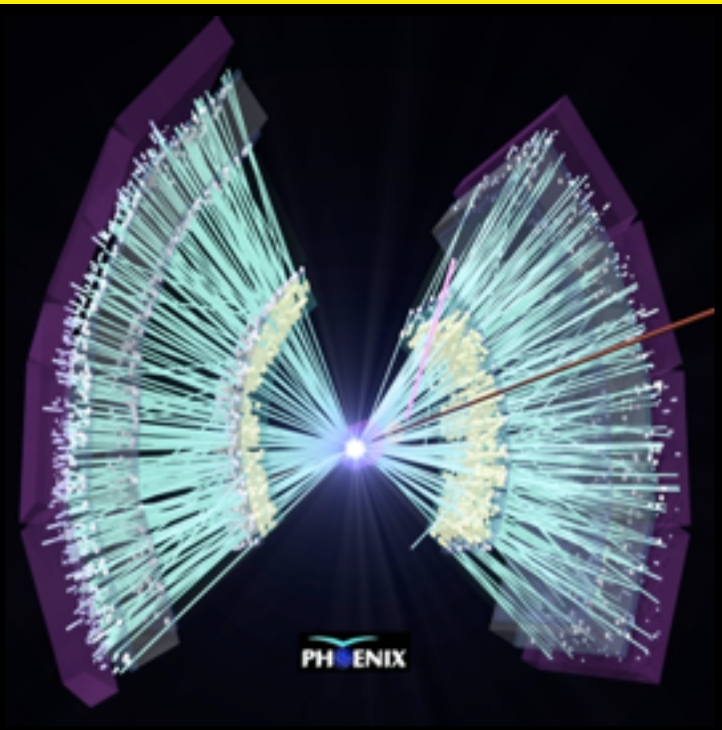
Fixed target experiments
(event display courtesy of NA49)

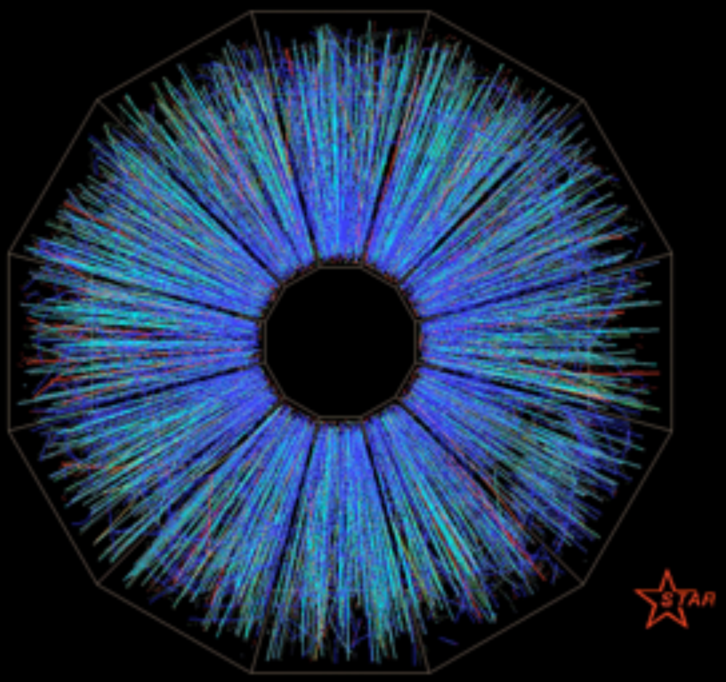


Heavy-ion physics: RHIC (BNL) (~2000)

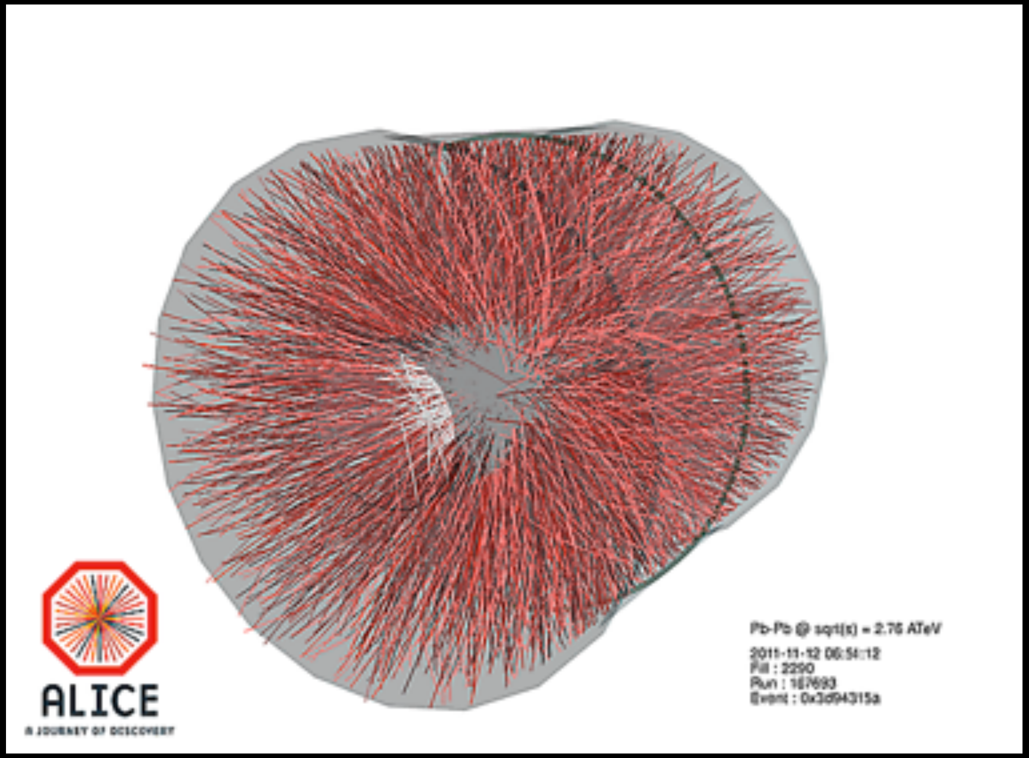


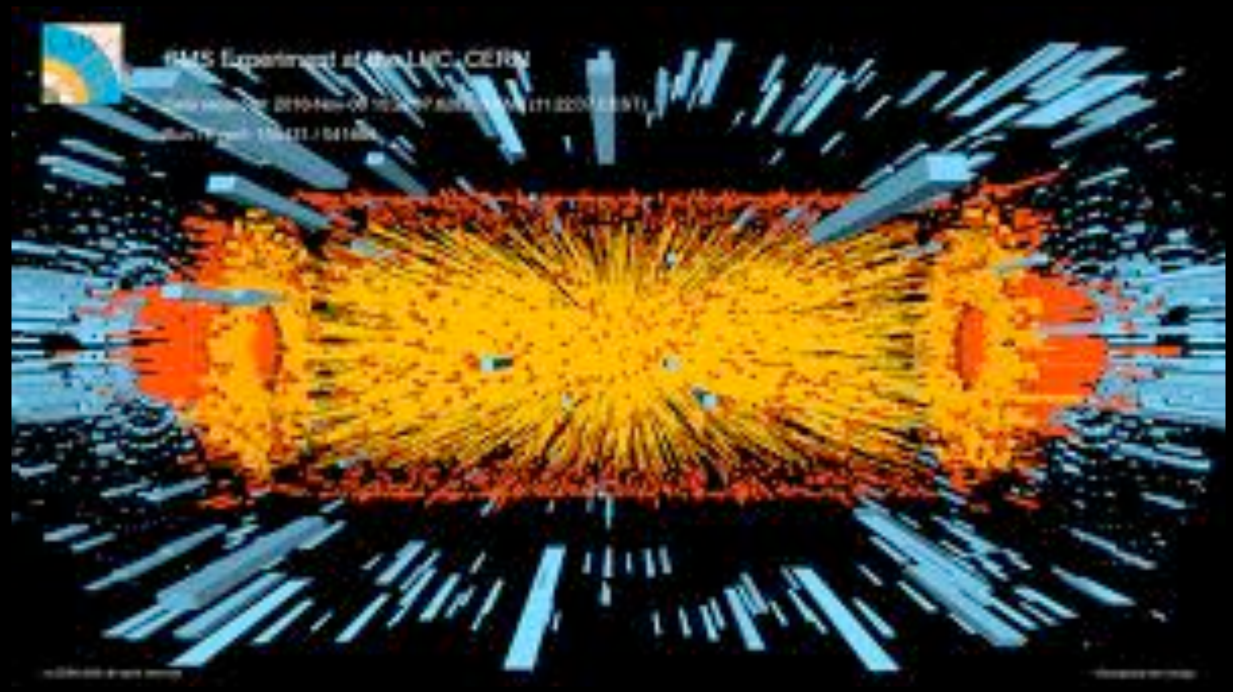
Collider experiments
(event displays courtesy of
PHENIX and STAR)





Heavy-ion physics: LHC (CERN) (2010)





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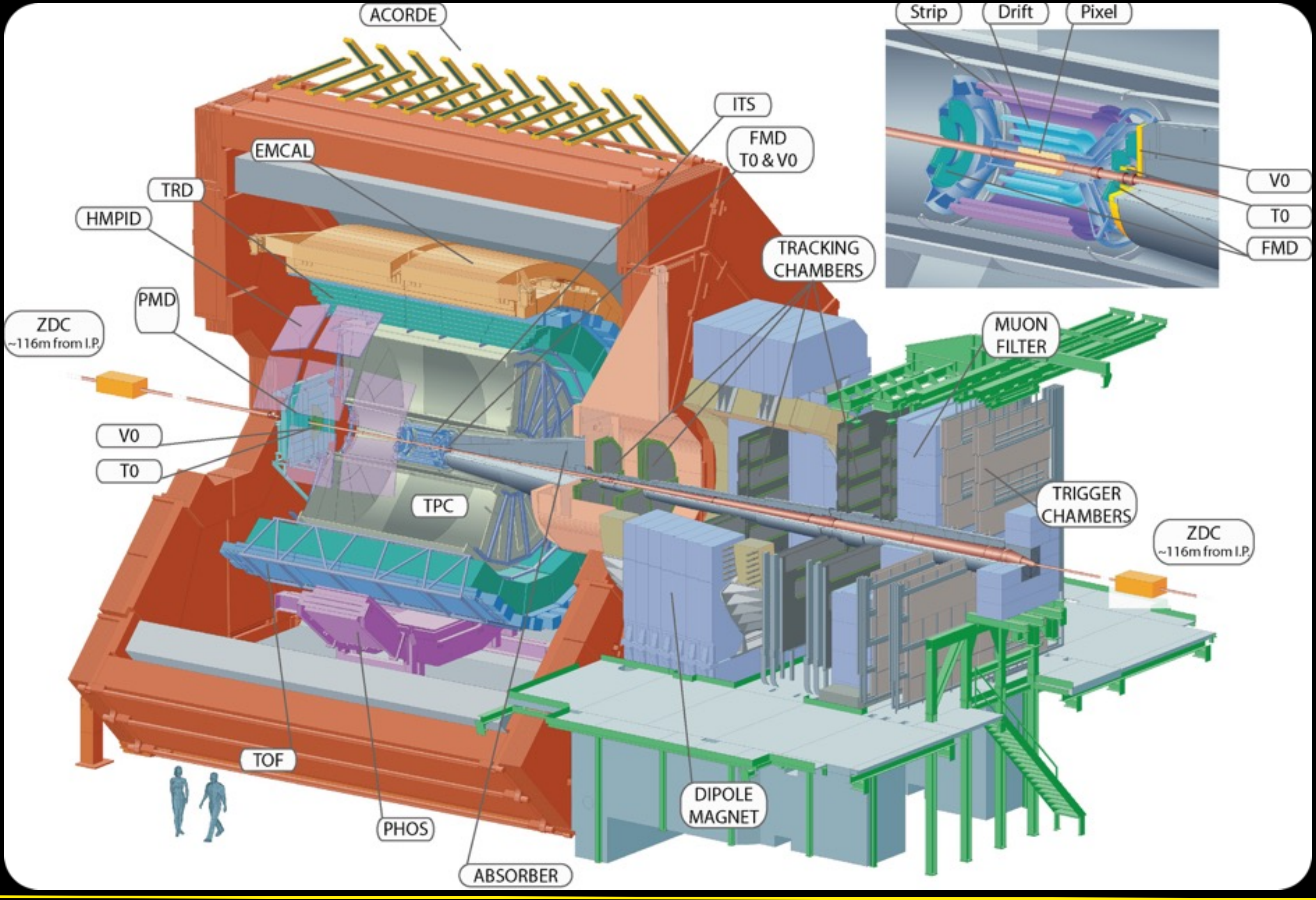
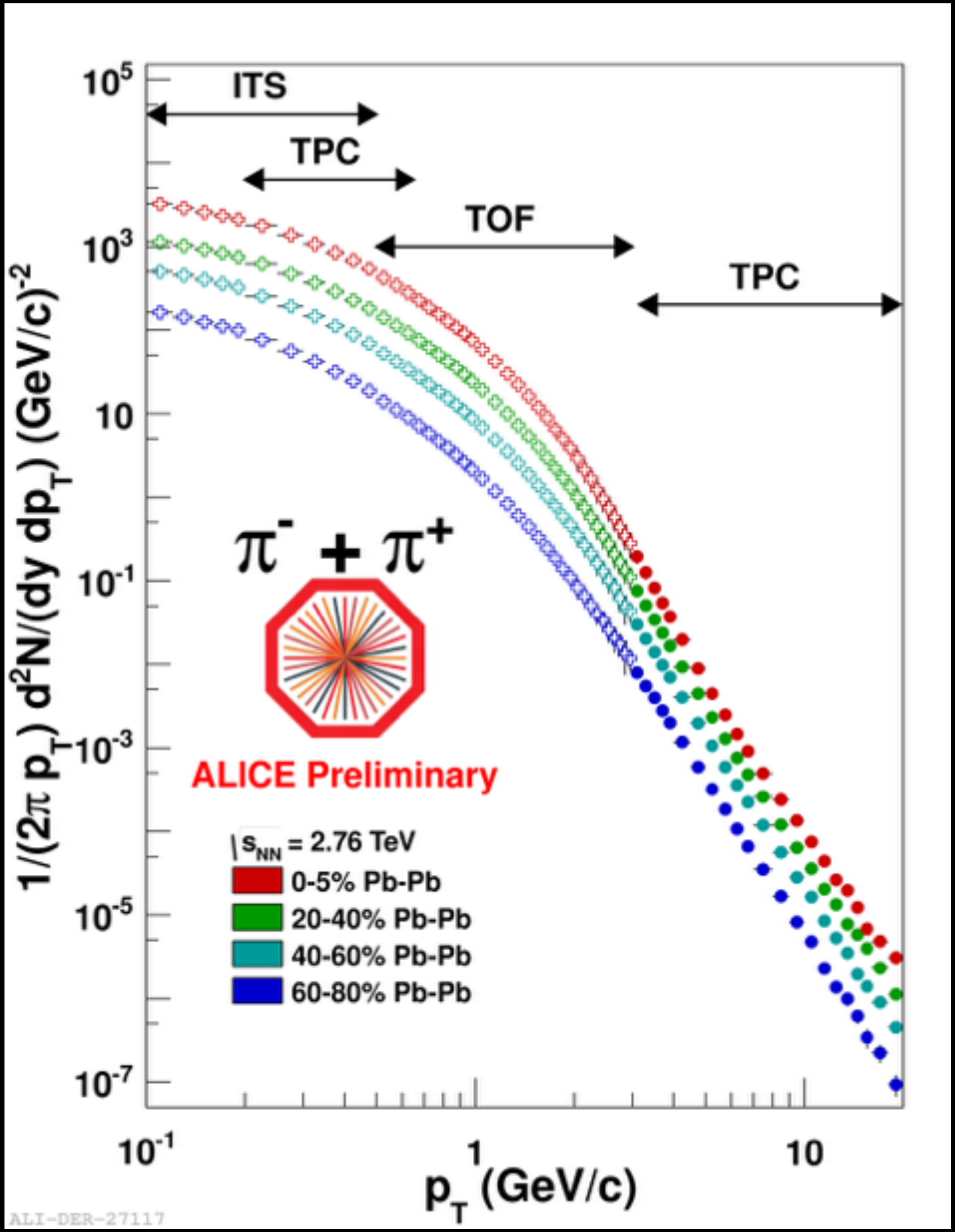
Experimental setup



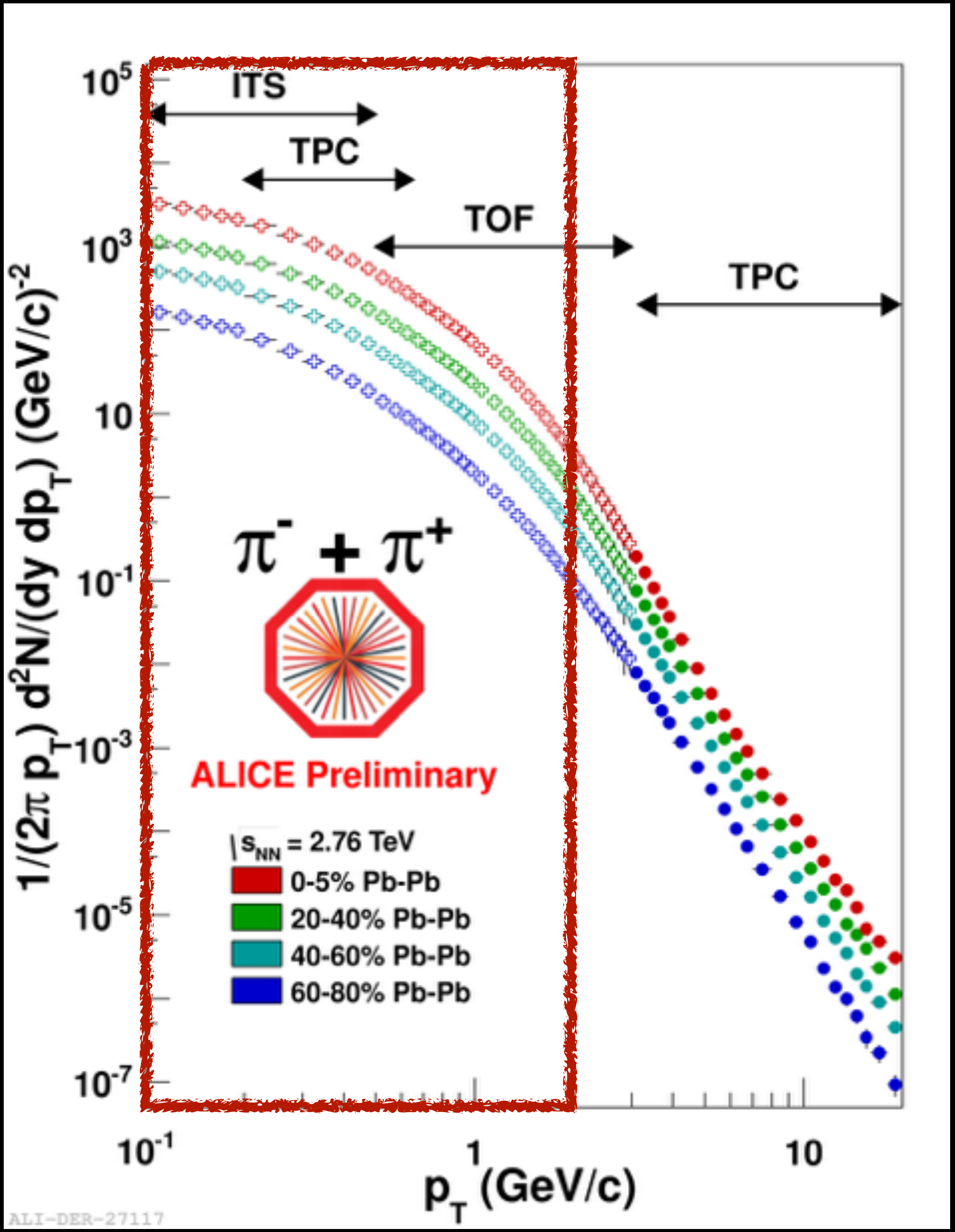
Studying the properties of the QGP

- Two main ways to probe the QGP properties:



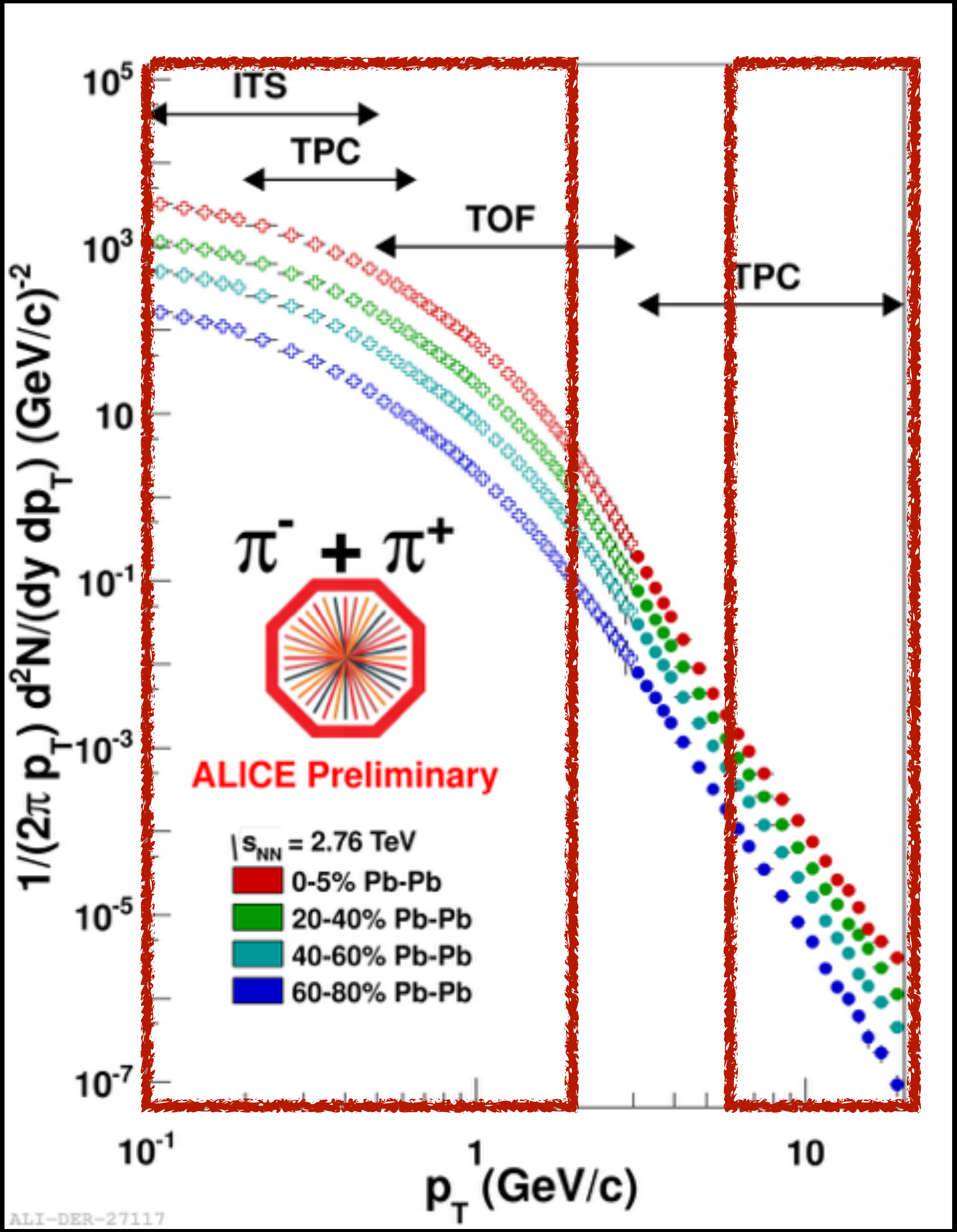
Studying the properties of the QGP

- Two main ways to probe the QGP properties:
  - Through bulk observables
    - The vast majority of particles are produced with $p_T < 2$ GeV/*c*



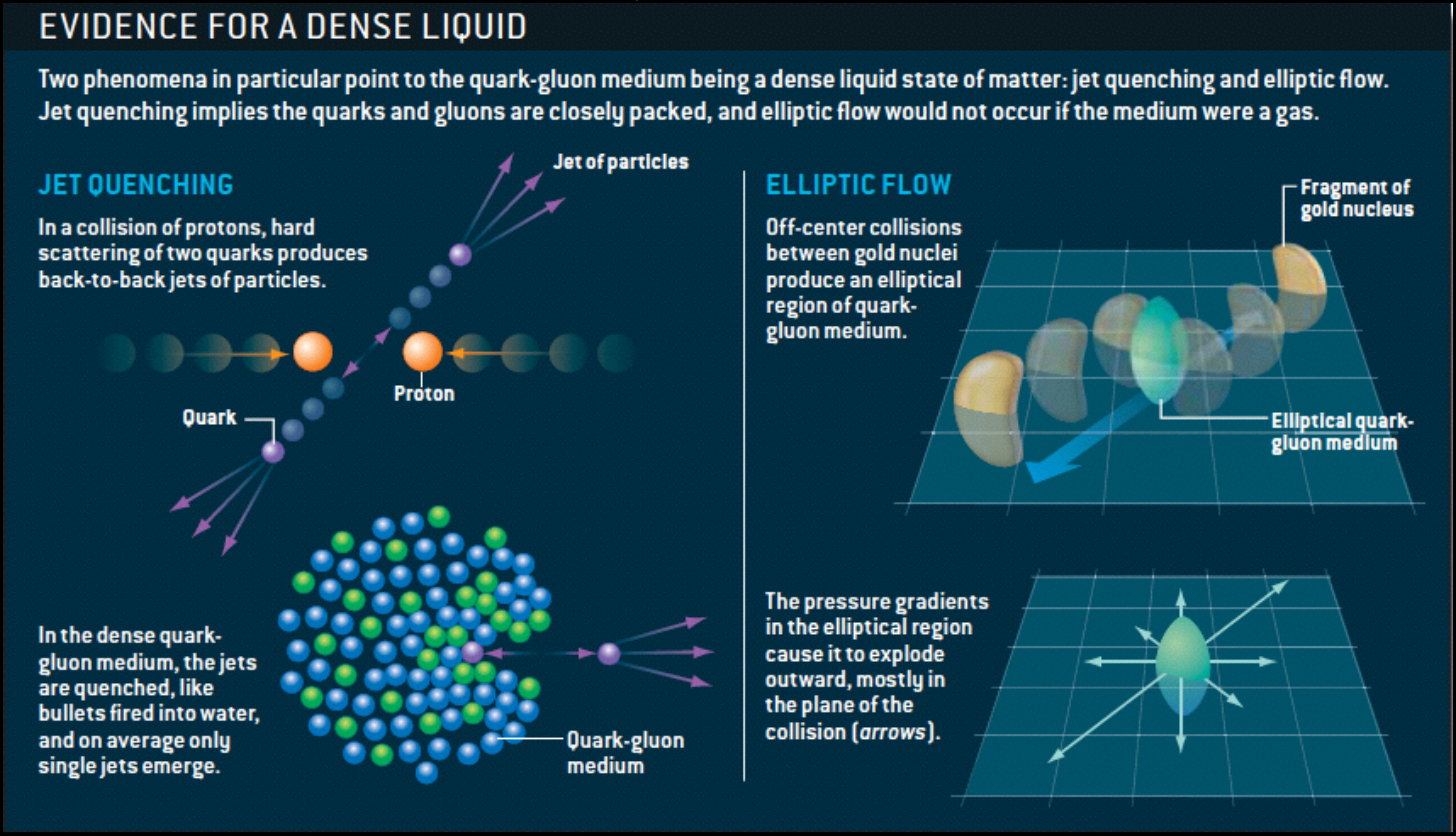
Studying the properties of the QGP

- 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)

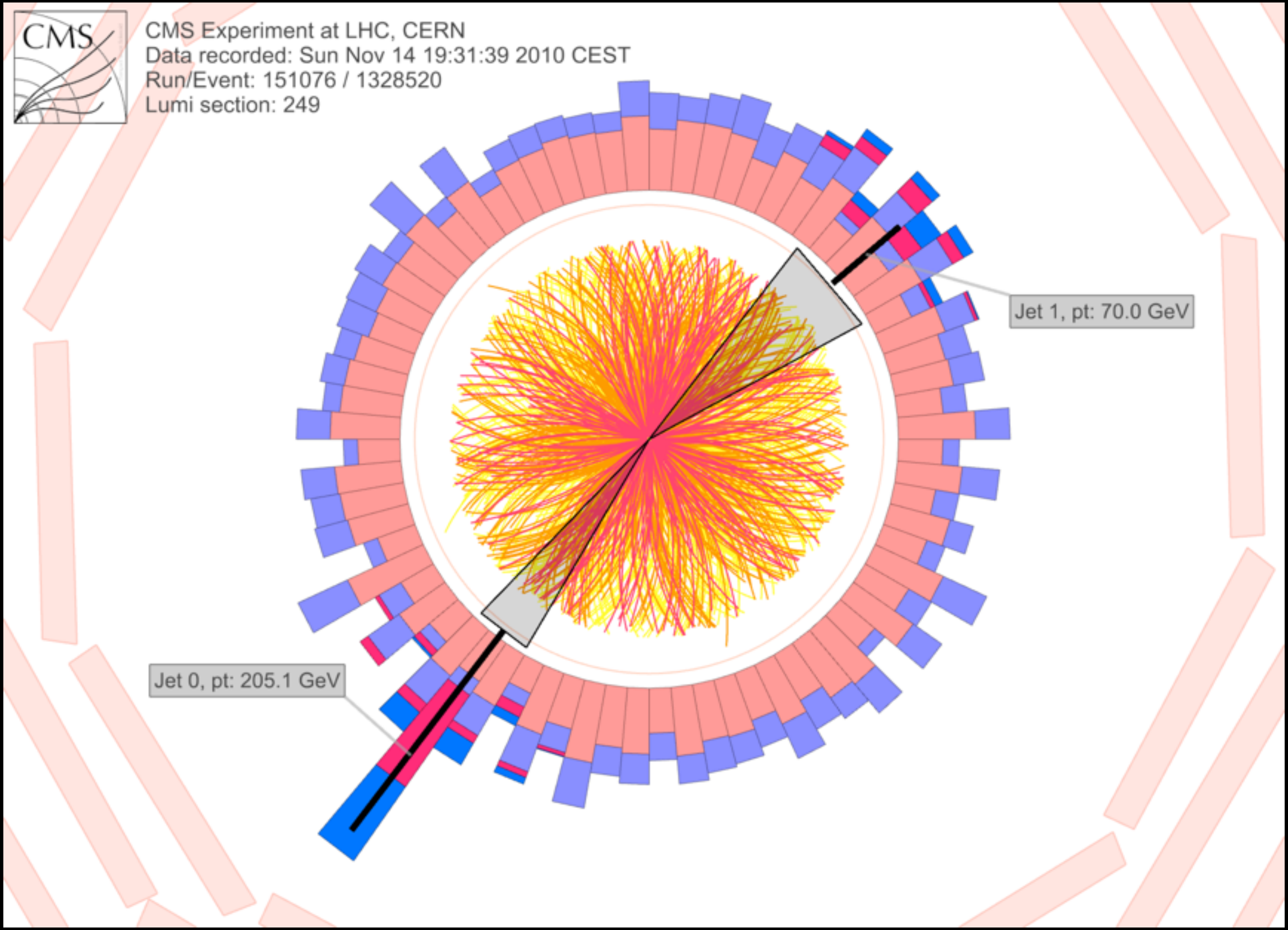


Studying the properties of the QGP

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



Hard probes: Jet quenching



Jet quenching in a nutshell

- Hard process scale: $Q >> \Lambda_{QCD}$
- High p_T parton with $Q \sim p_T$
- 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
- During the propagation through the medium, 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

Jet quenching in a nutshell

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- High p_T parton with $Q \sim p_T$
- These partons are formed early during the evolution of the system
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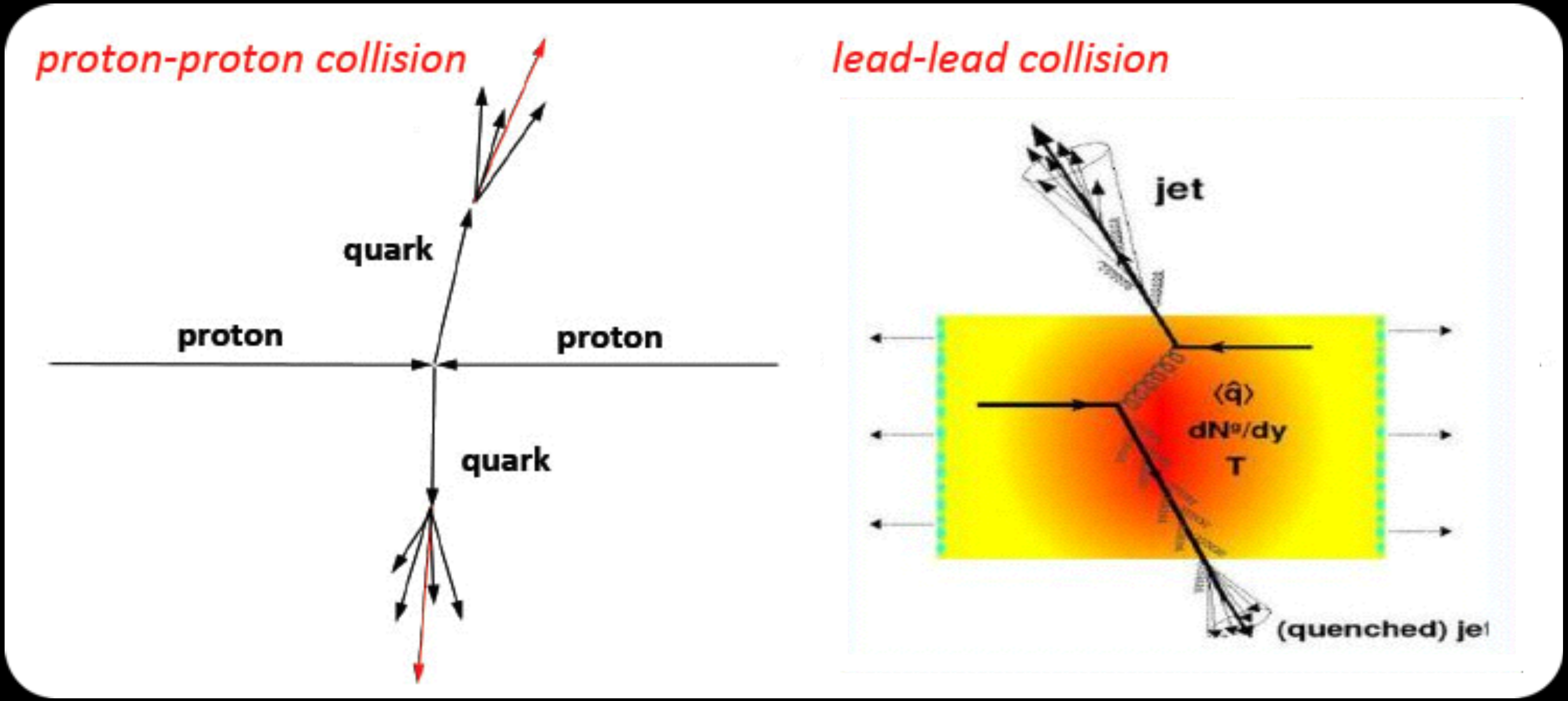


A way of quantifying jet quenching

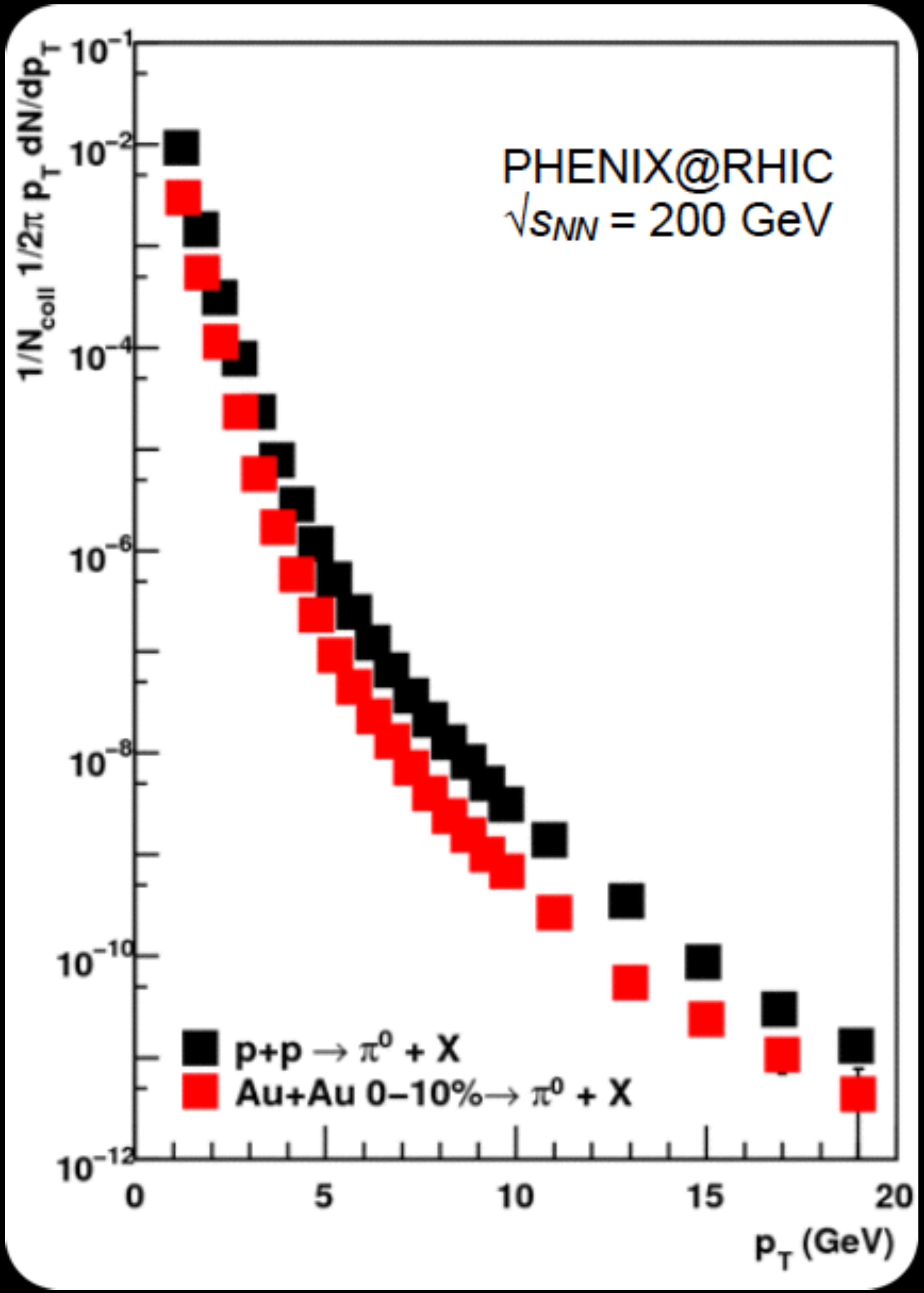
- We need to compare particle production
  - ★ In the vacuum (pp collisions)
  - ★ In the QGP medium (heavy-ion collisions)

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

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

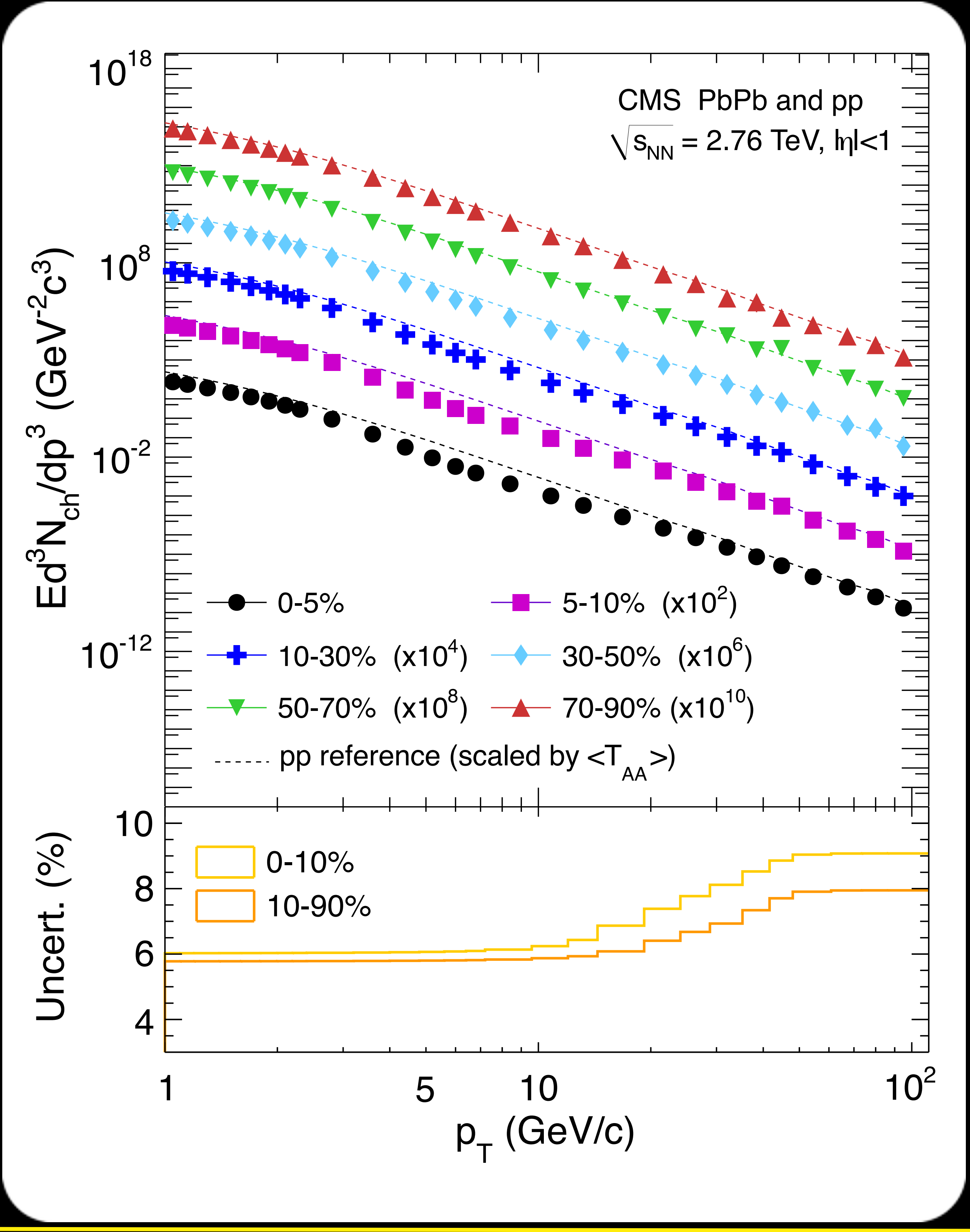
<1 → in-medium effects

$\simeq 1$ → no in-medium effects



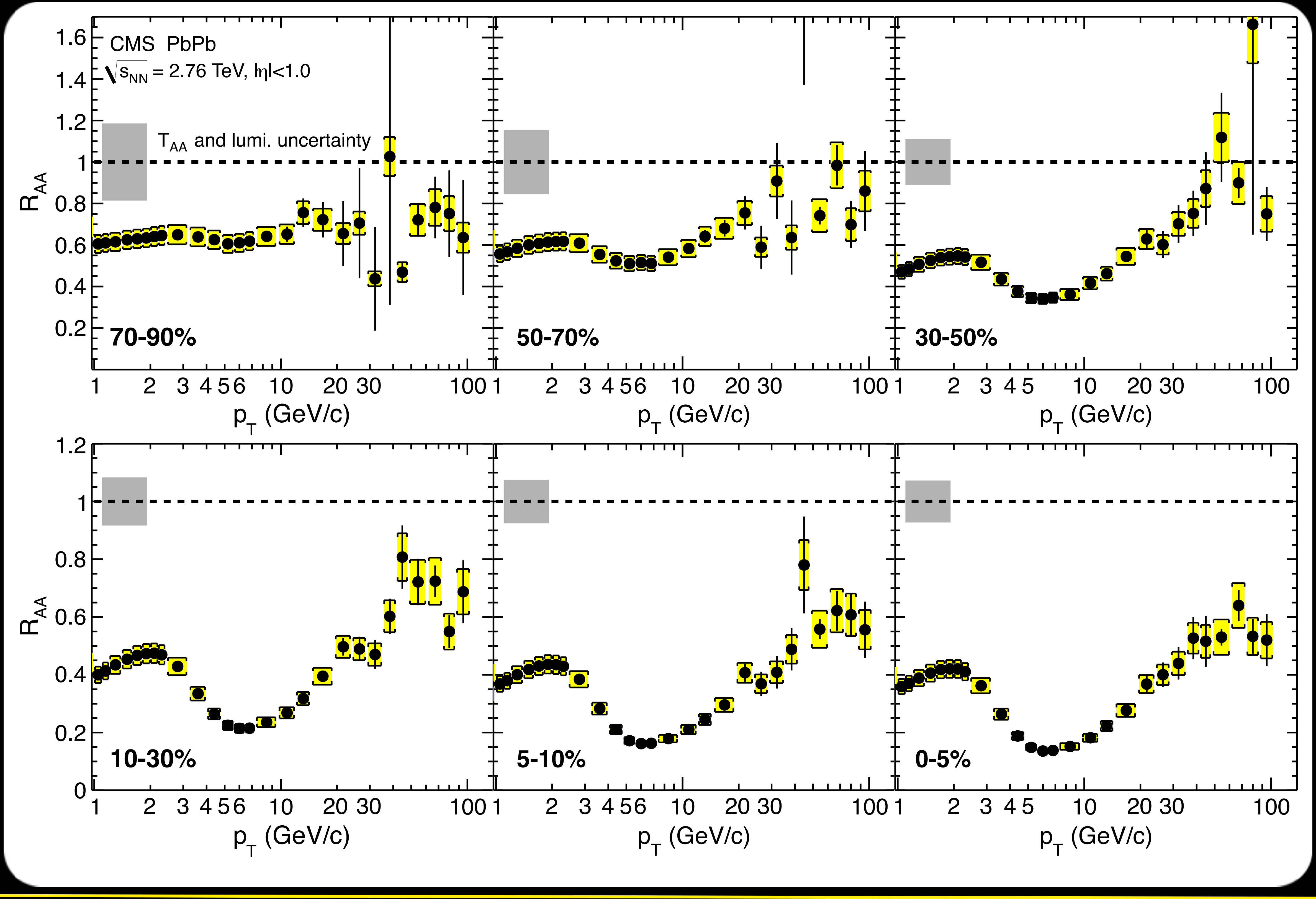
Jet quenching at the LHC: Pb-Pb and pp spectra

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



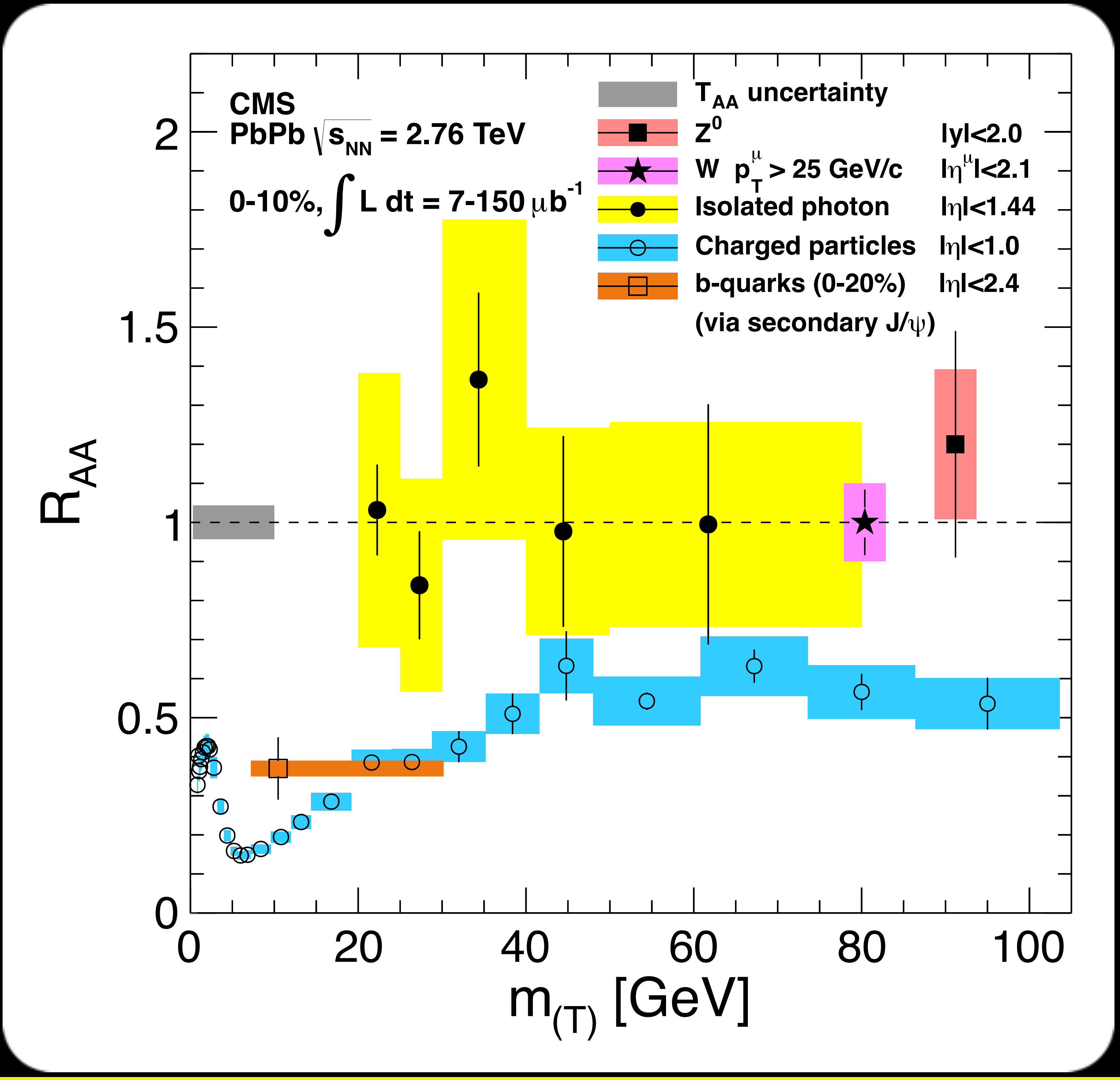
Jet quenching at the LHC: R_{AA}

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



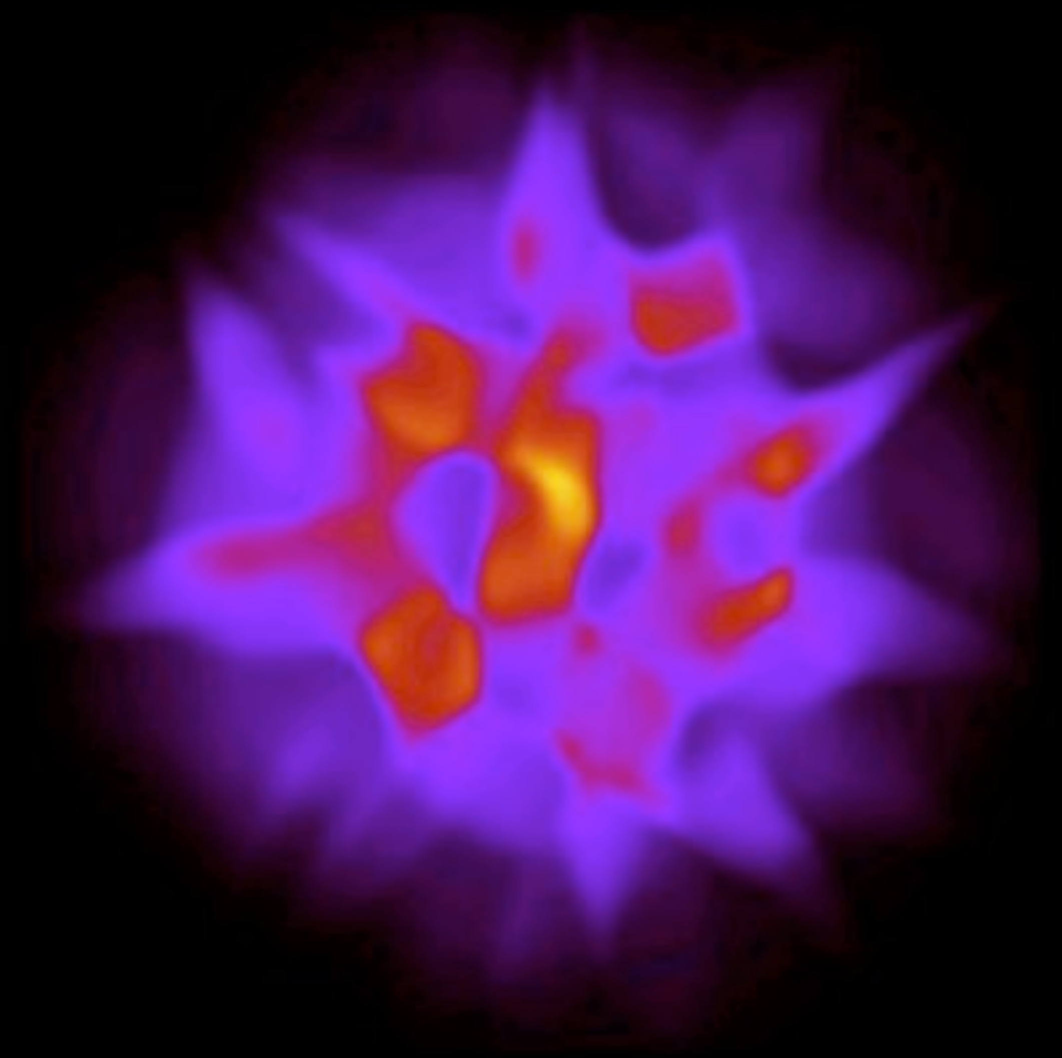
Jet quenching at the LHC: R_{AA} for reference probes

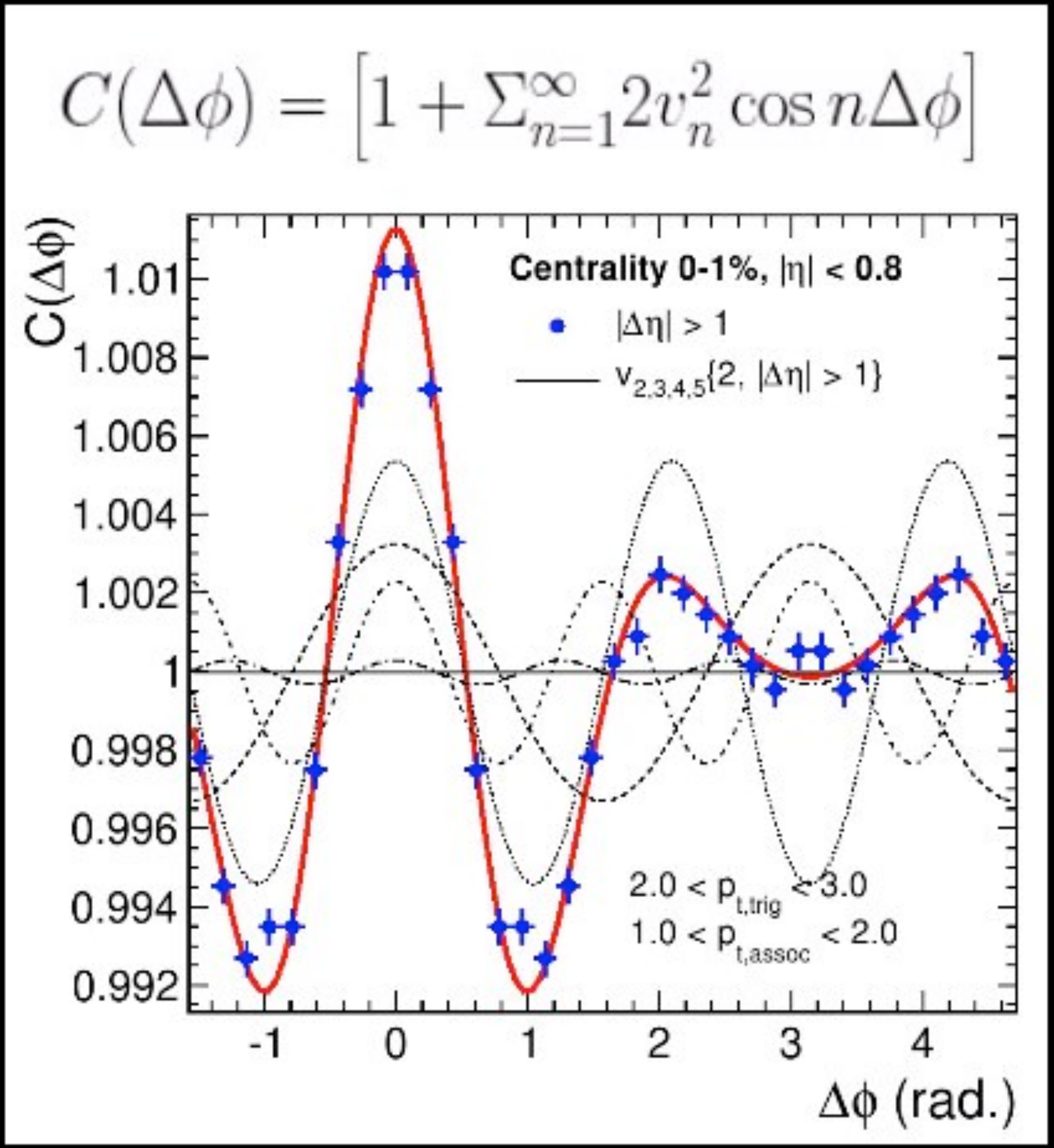
CMS Collaboration, EPJC **72** (2012) 1945



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

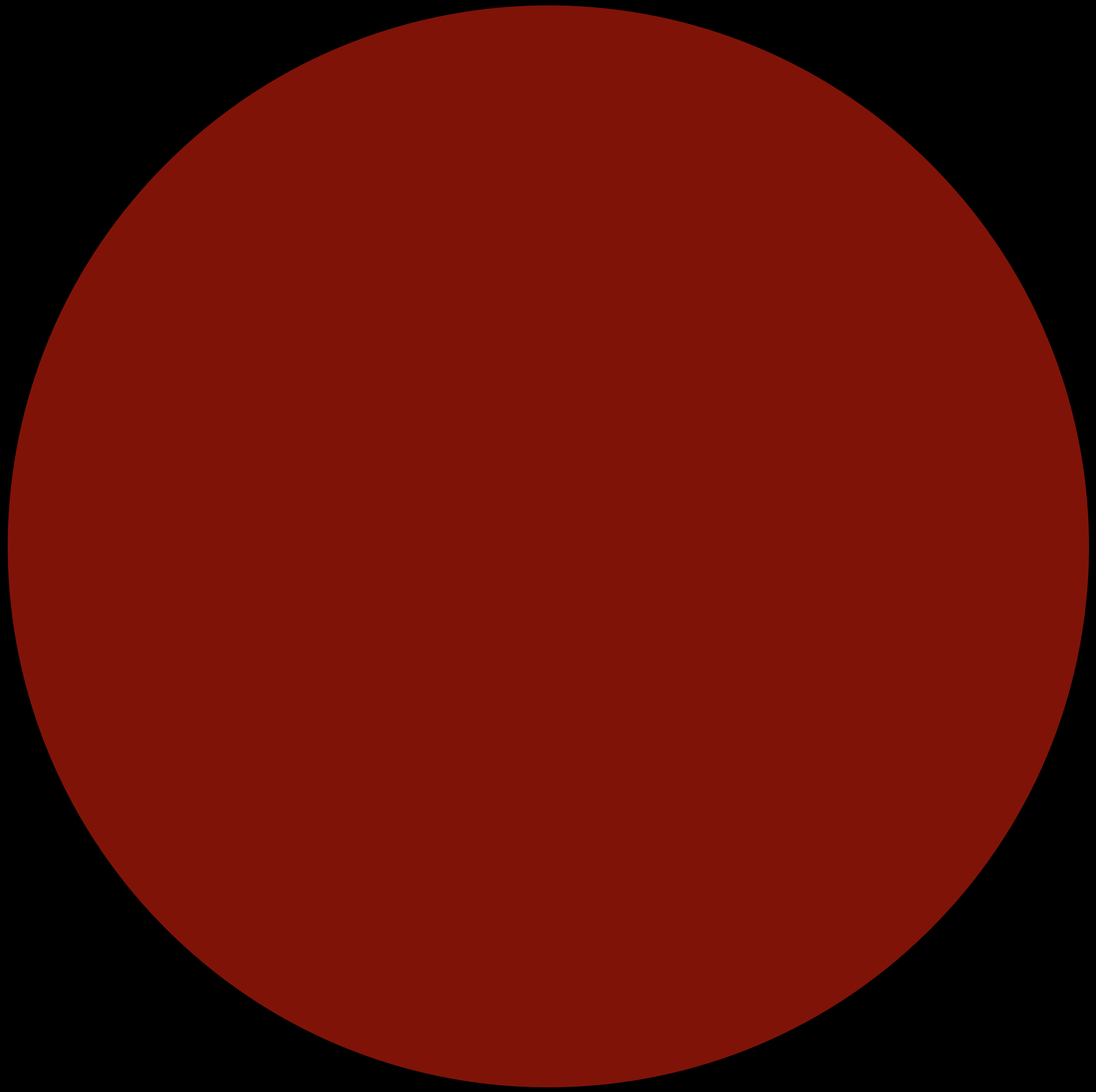
Bulk observables: Anisotropic flow





To flow or not to flow?

Courtesy of Mike Lisa



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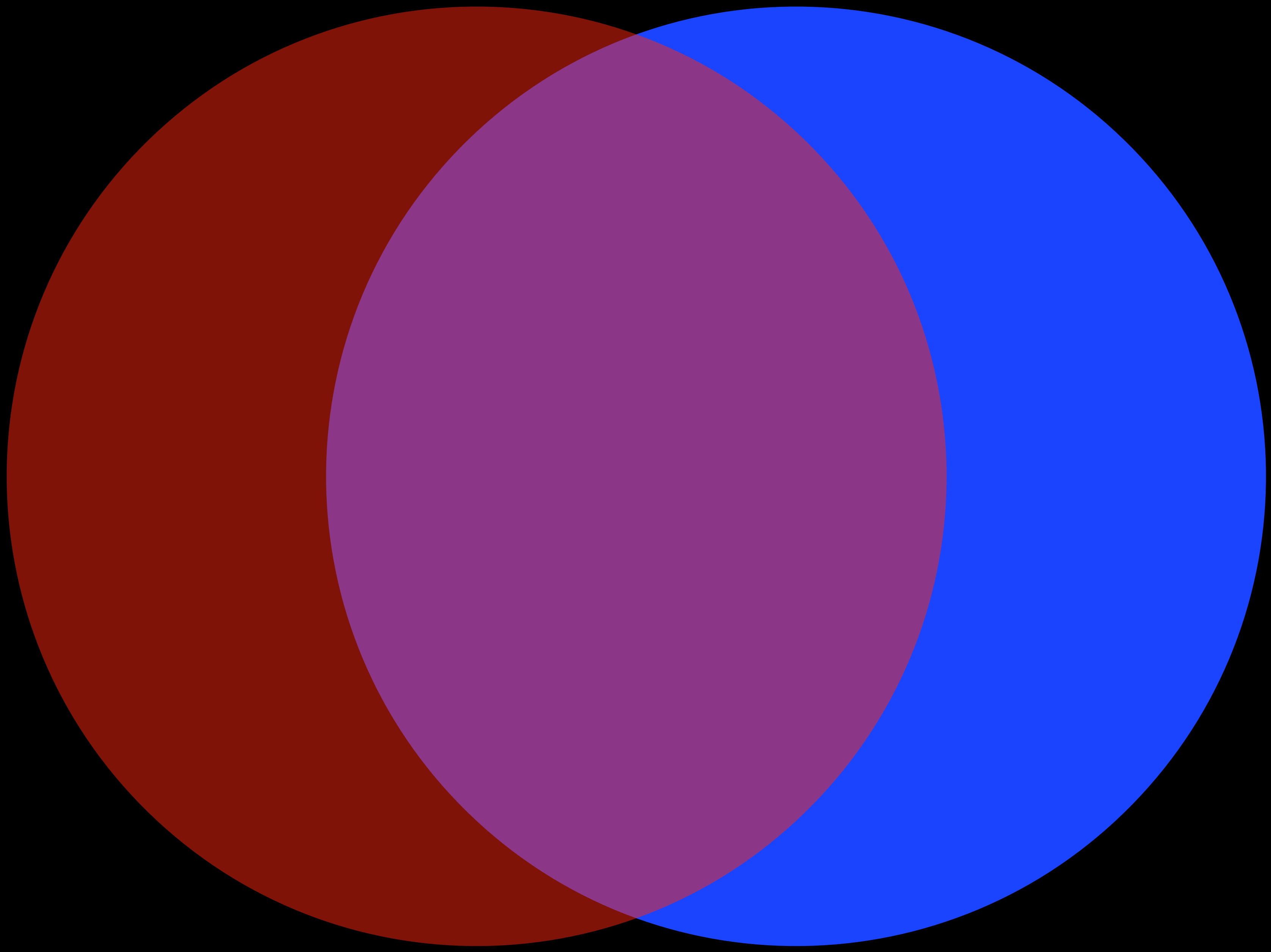

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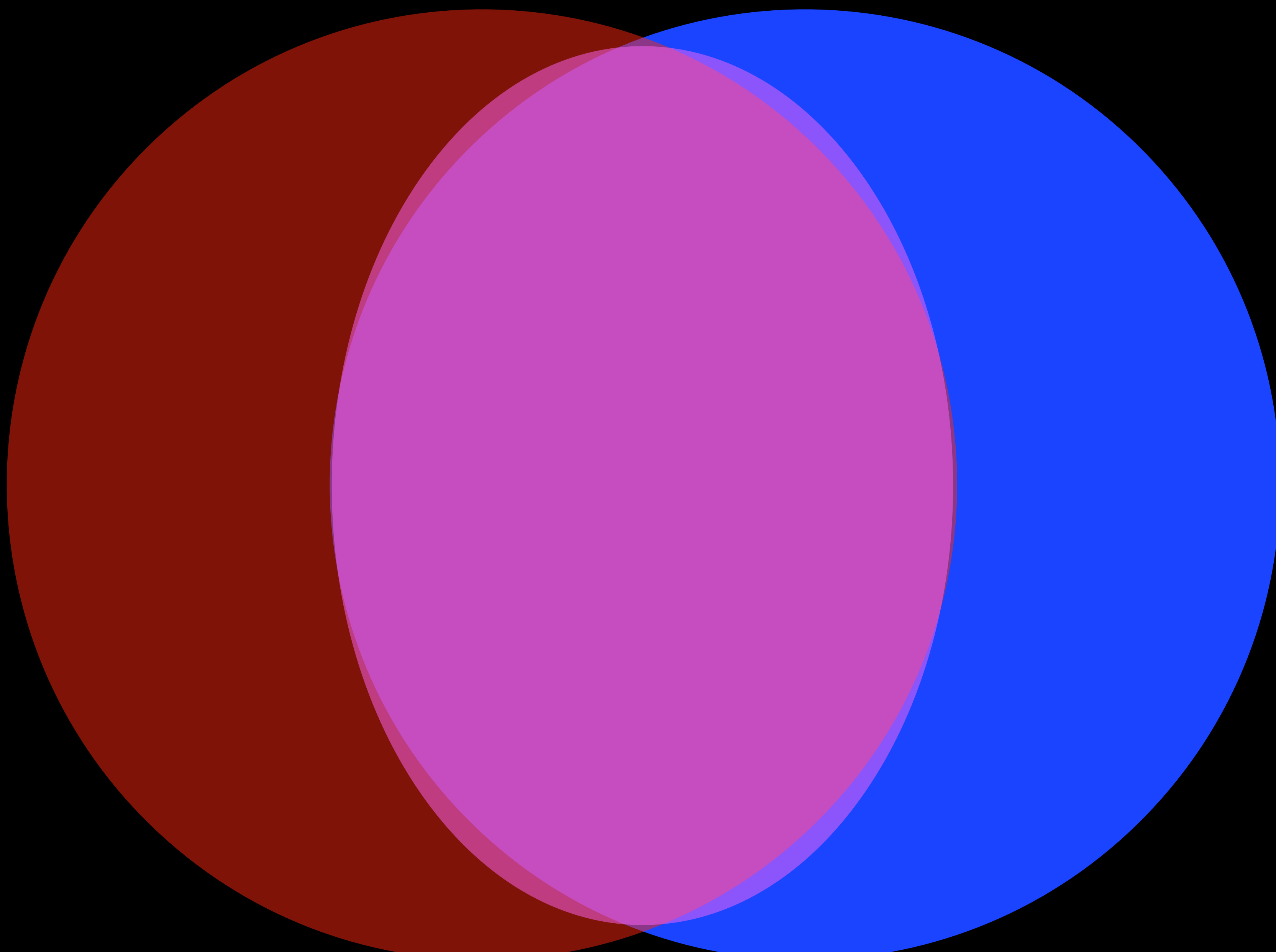
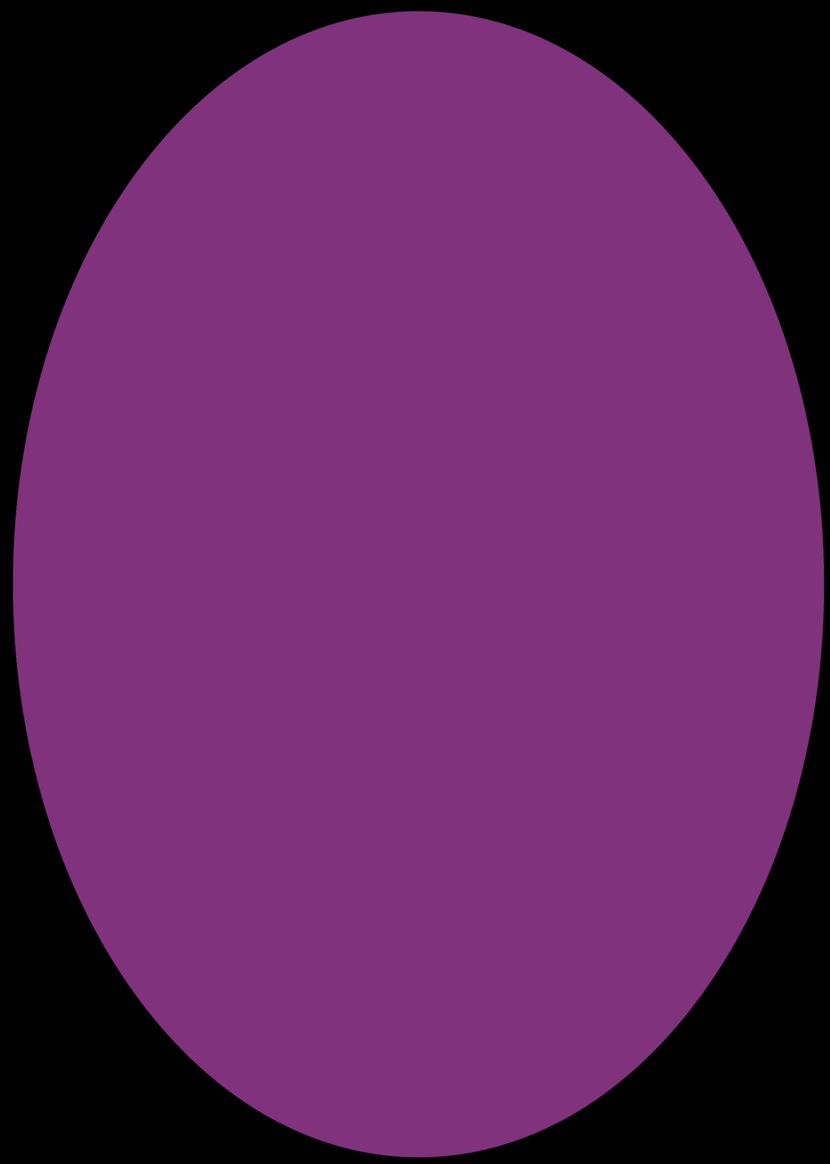


Independent pp collisions

Courtesy of Mike Lisa

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



Independent pp collisions

Courtesy of Mike Lisa

Superposition of independent pp collisions

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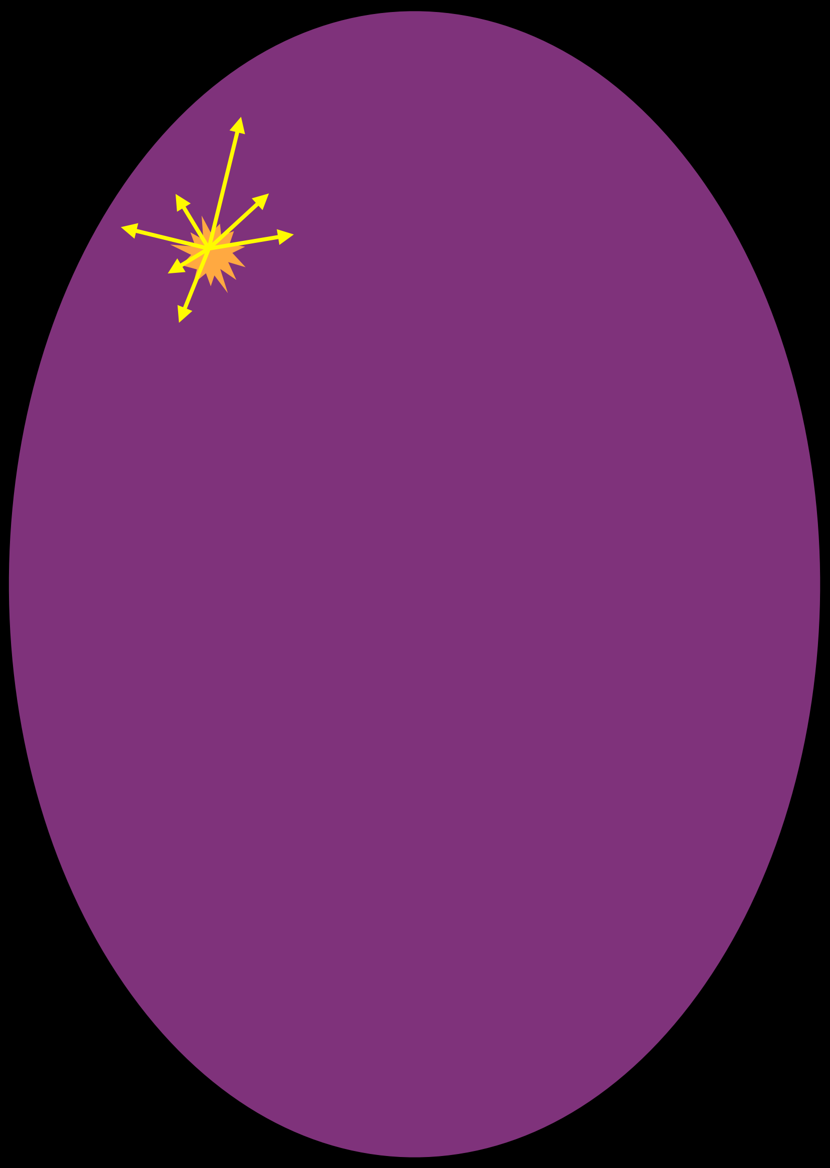

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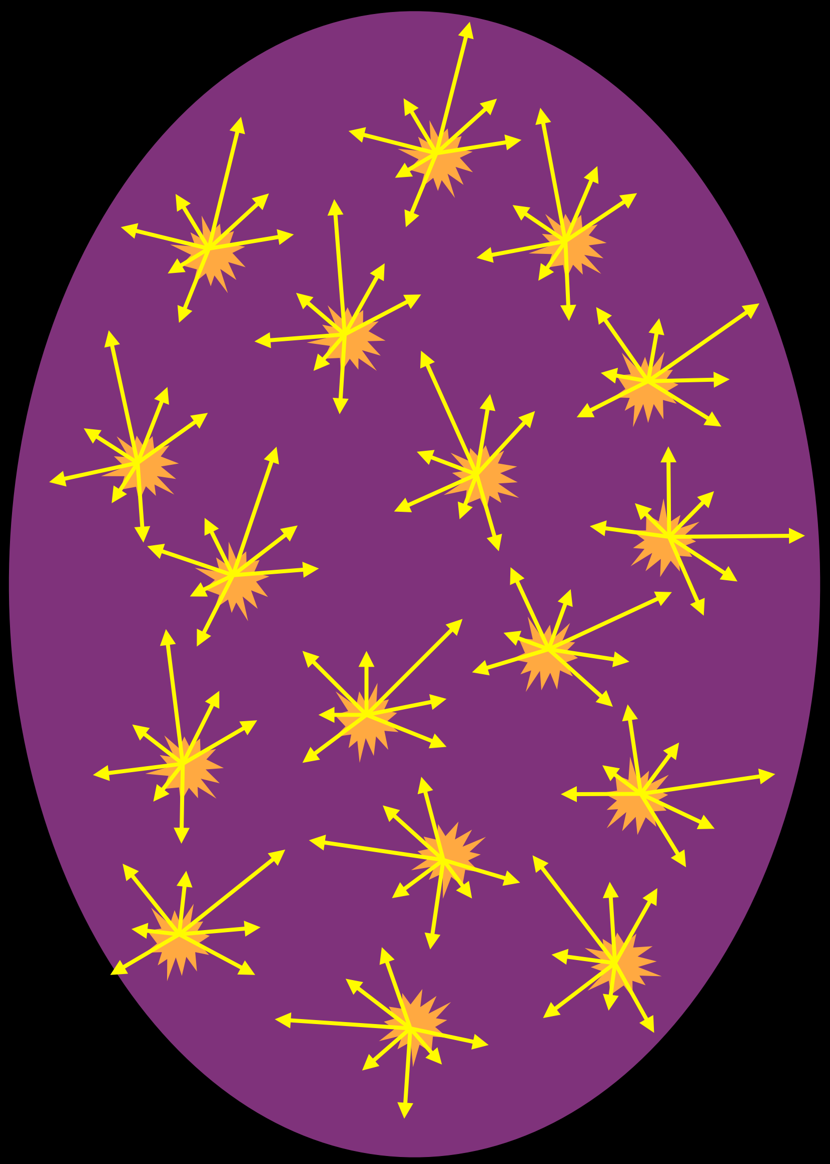


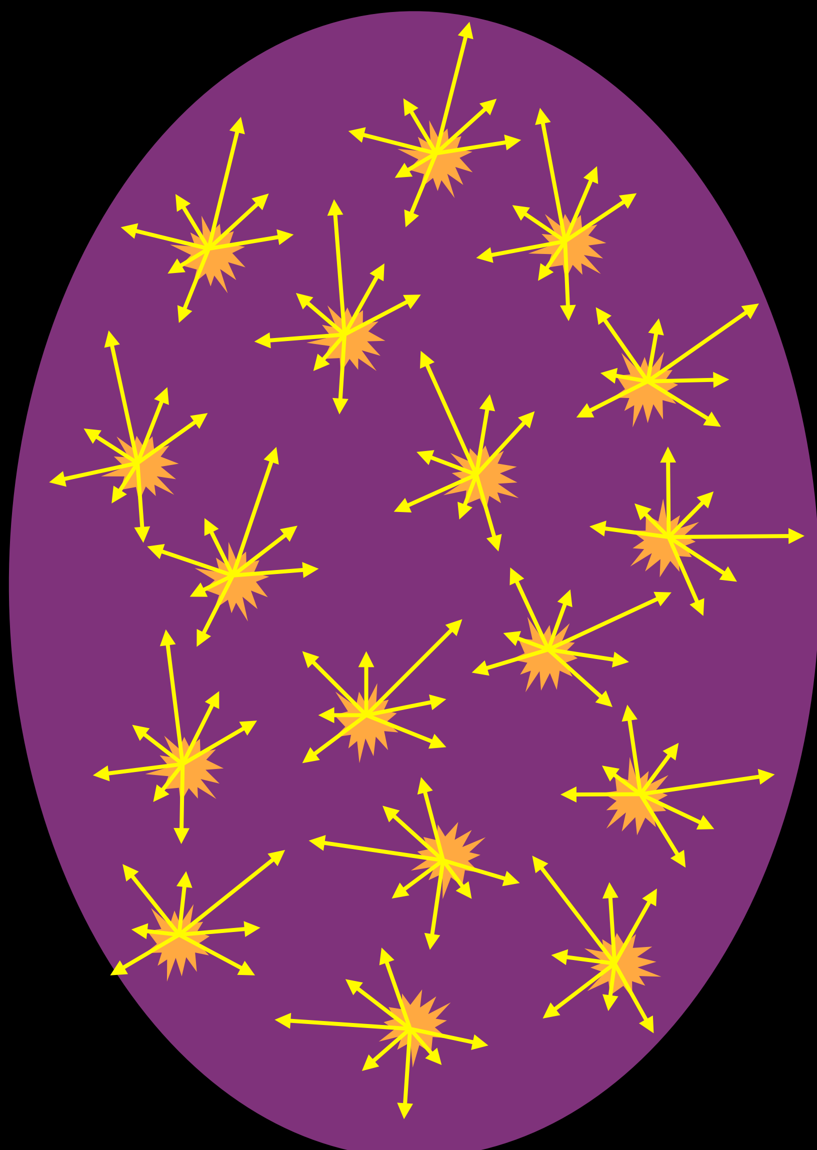
Independent pp collisions

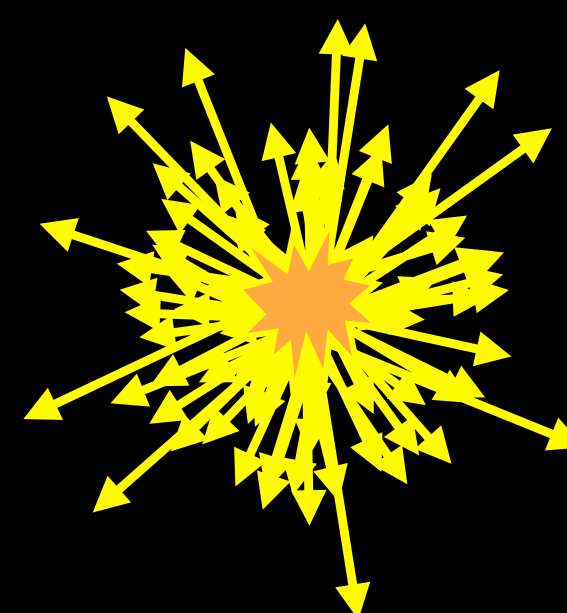
Courtesy of Mike Lisa

Superposition of independent pp collisions

Momenta pointing at random directions relative to the reaction plane

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





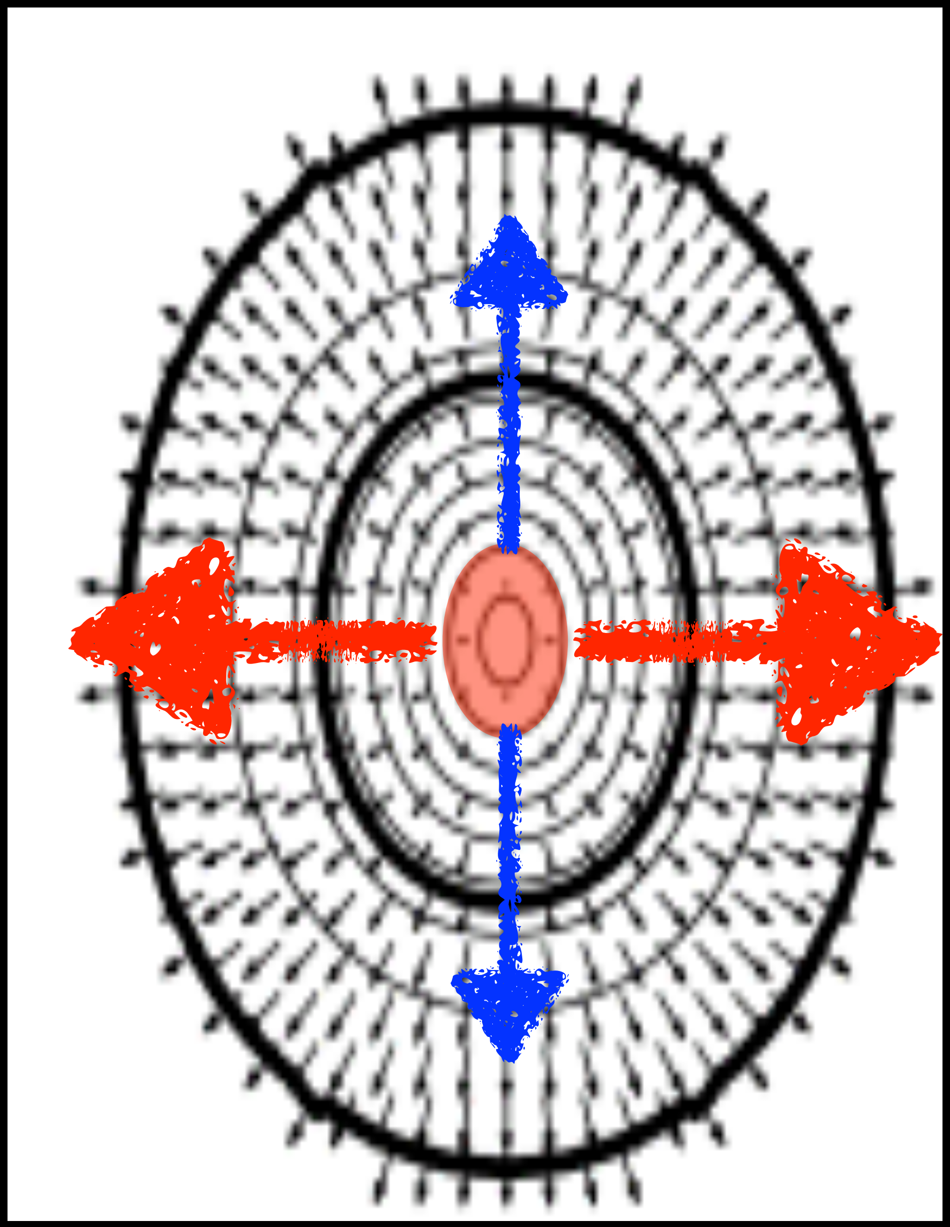
Panos.Christakoglou@nikhef.nl

Collectivity

Courtesy of Mike Lisa

Evolution as a bulk system

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



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

Collectivity

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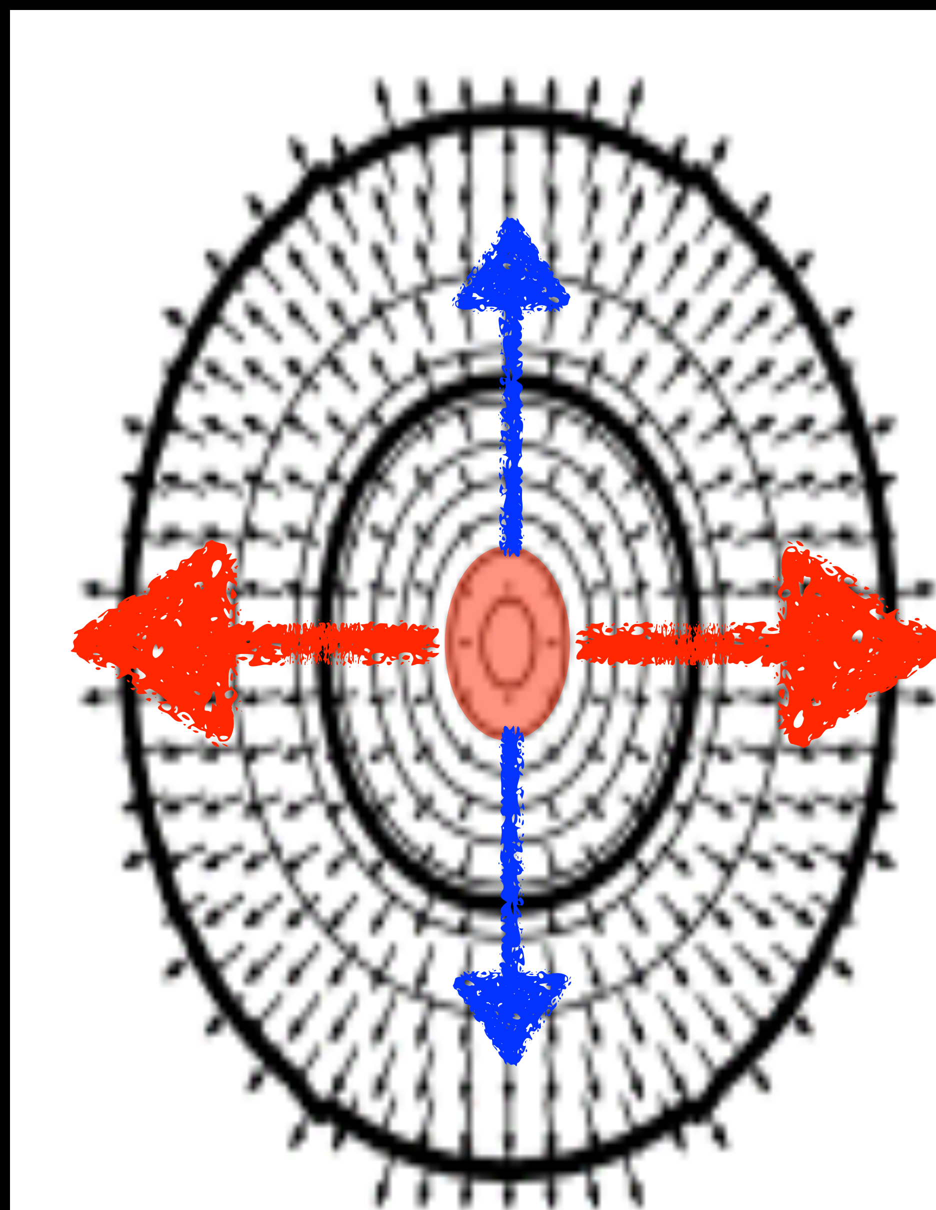
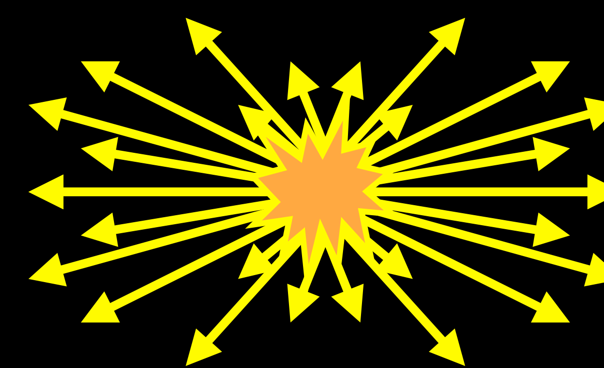


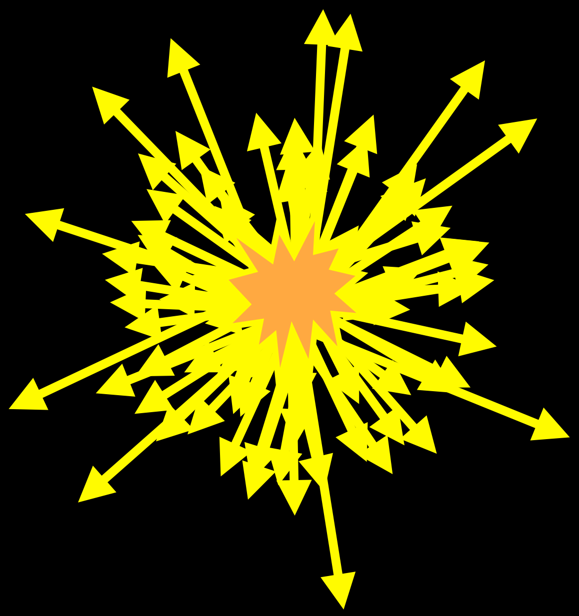
Pressure gradient higher in-plane i.e. pushes bulk out: flow

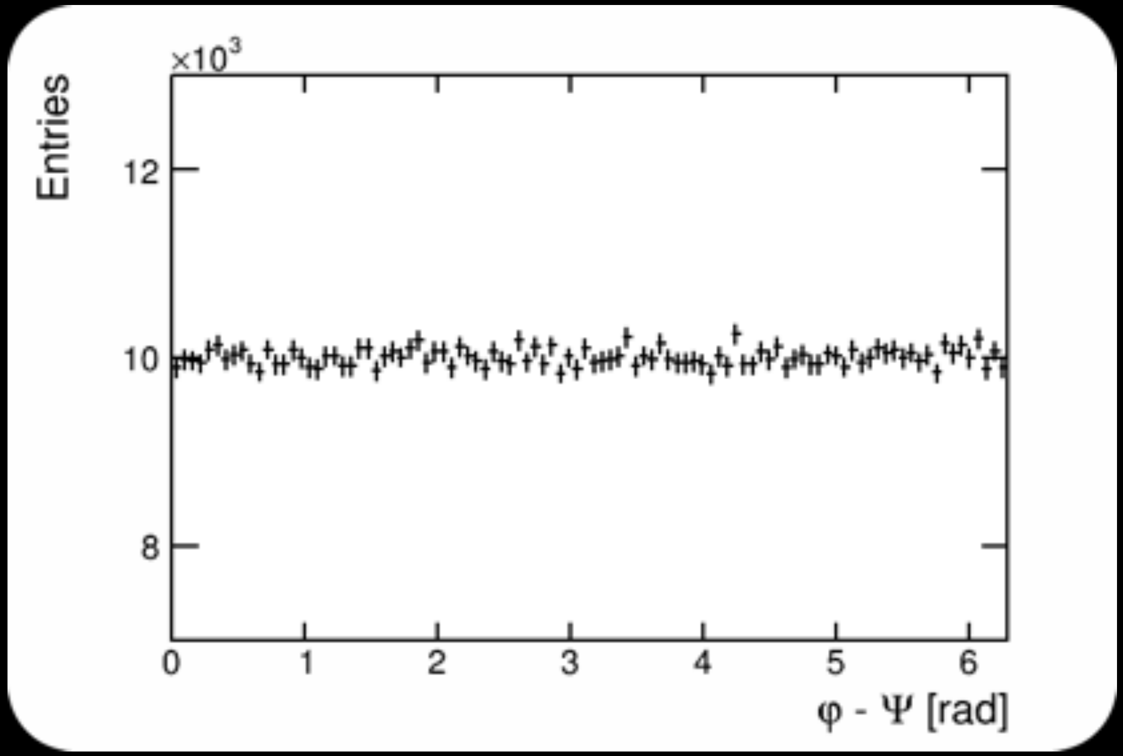
More and faster particles in-plane than out-of-plane



Elliptic flow

Superposition of independent pp collisions





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Elliptic flow

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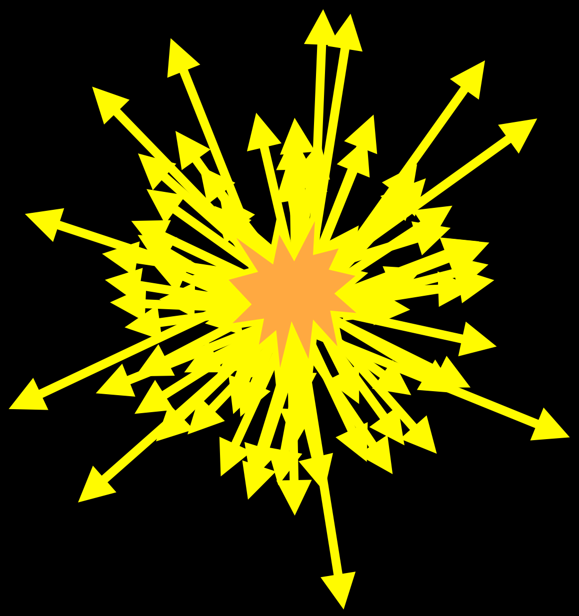

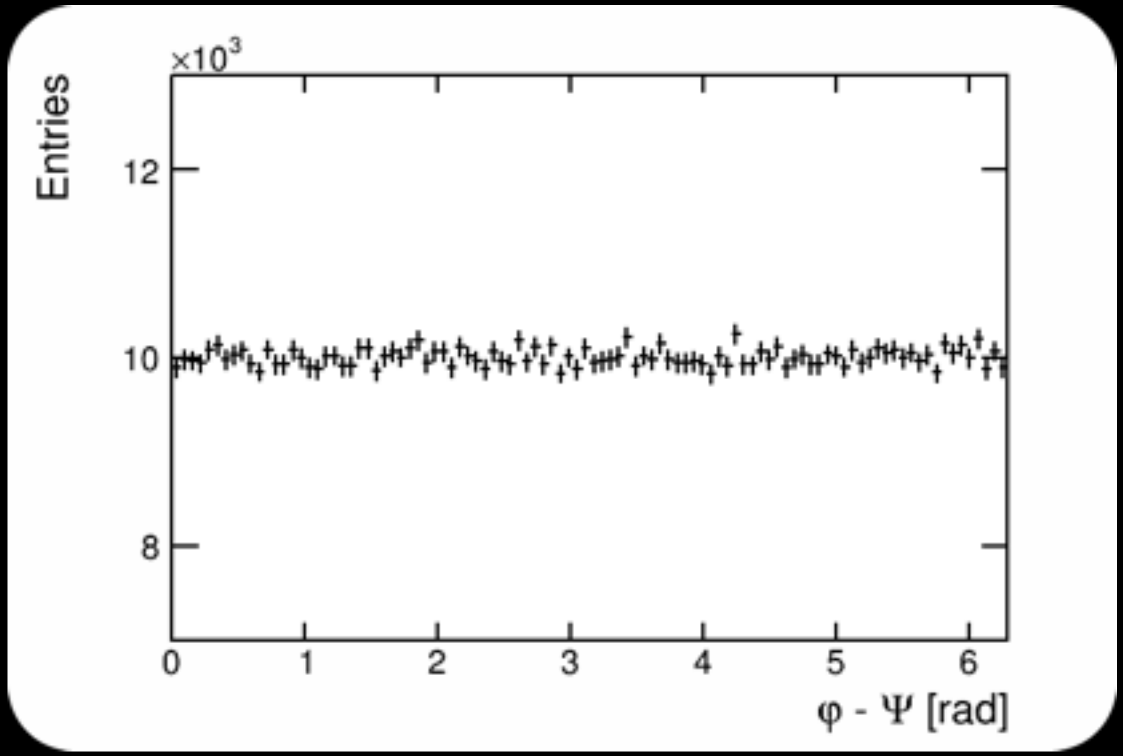

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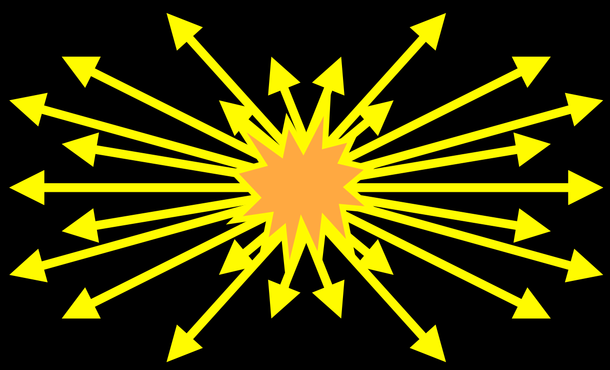

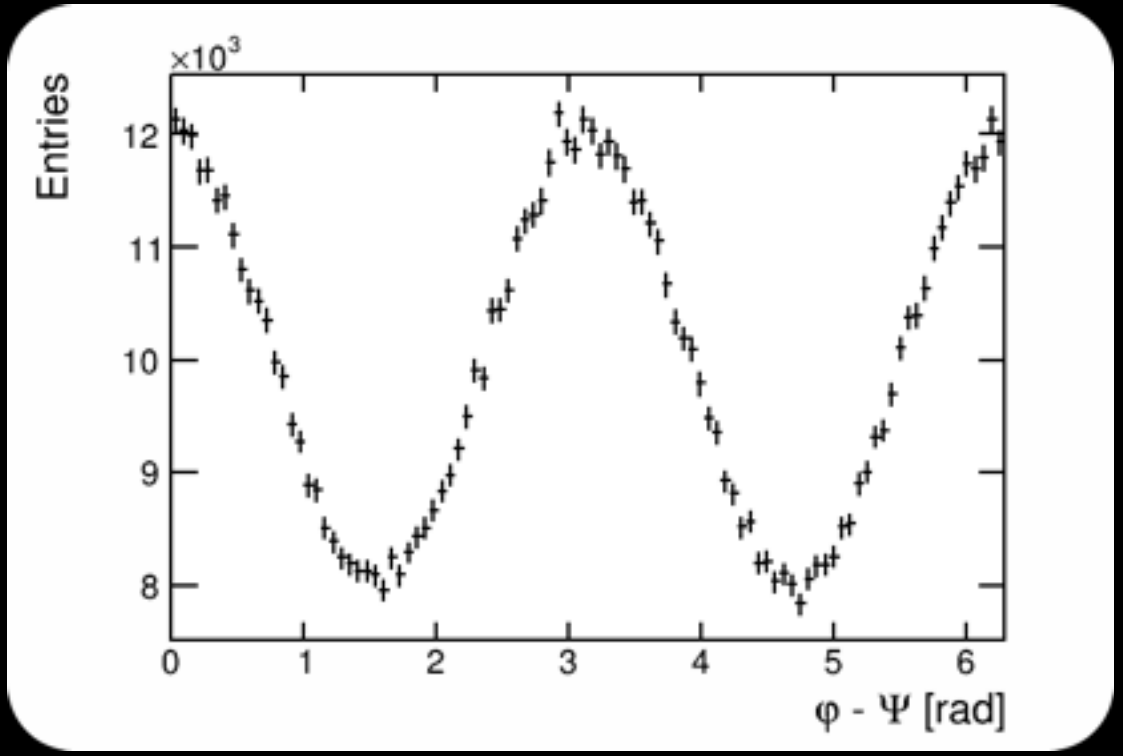

Quantifying the azimuthal anisotropy

- 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)

The “perfect liquid” at RHIC and LHC

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Published online 19 April 2005 | Nature | doi:10.1038/news050418-5

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Early Universe was a liquid

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Mark Peplow

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

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

Monday, April 18, 2005

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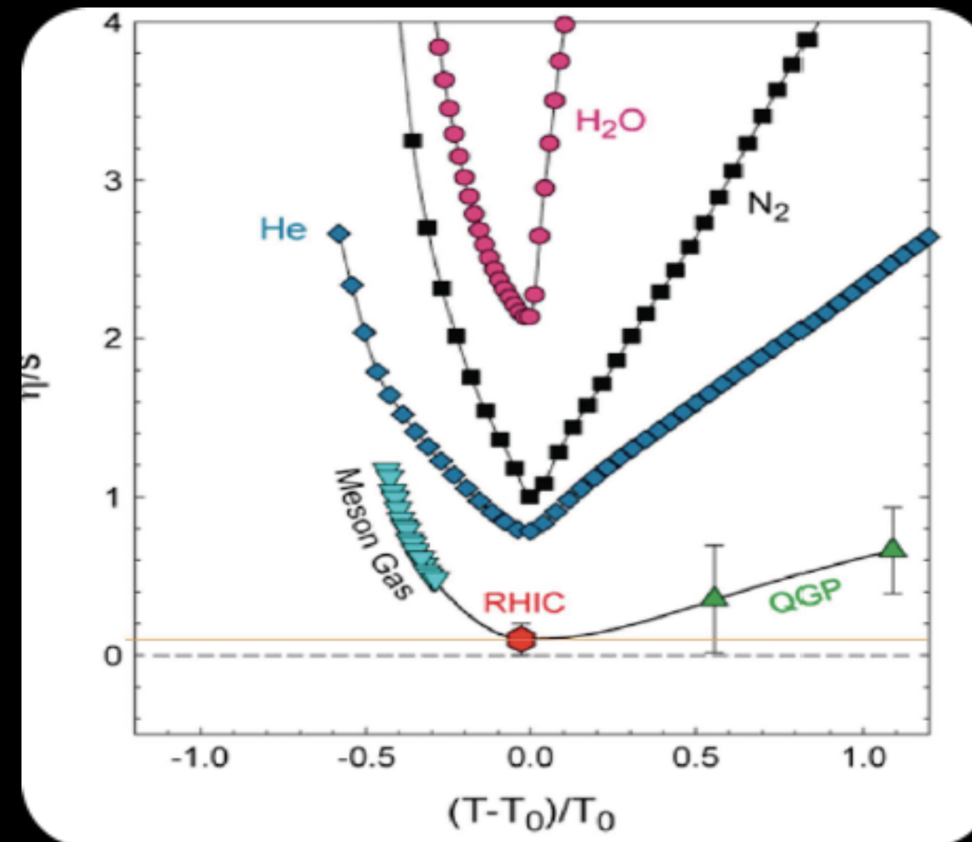


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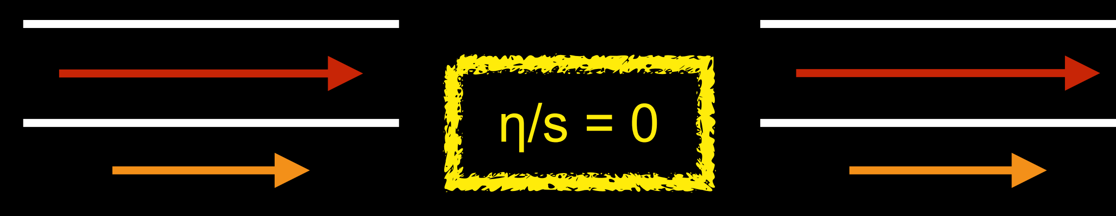

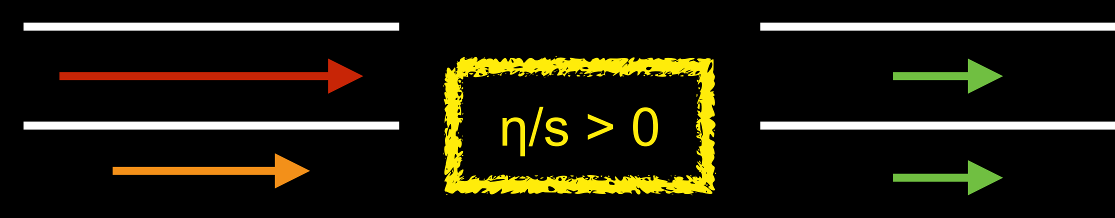

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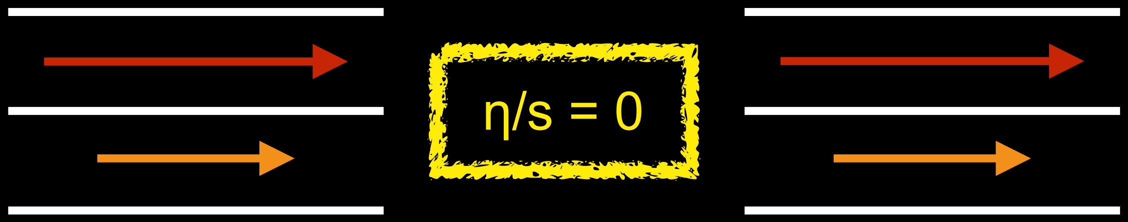
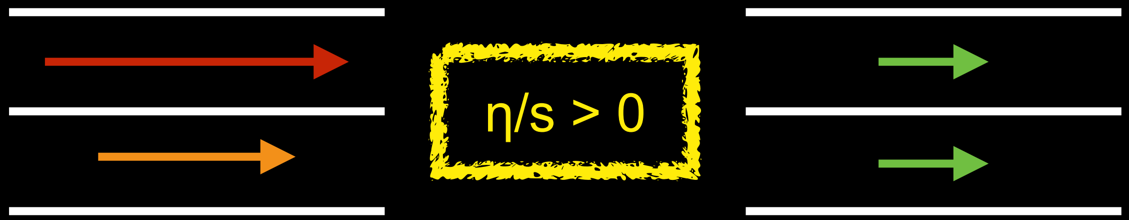
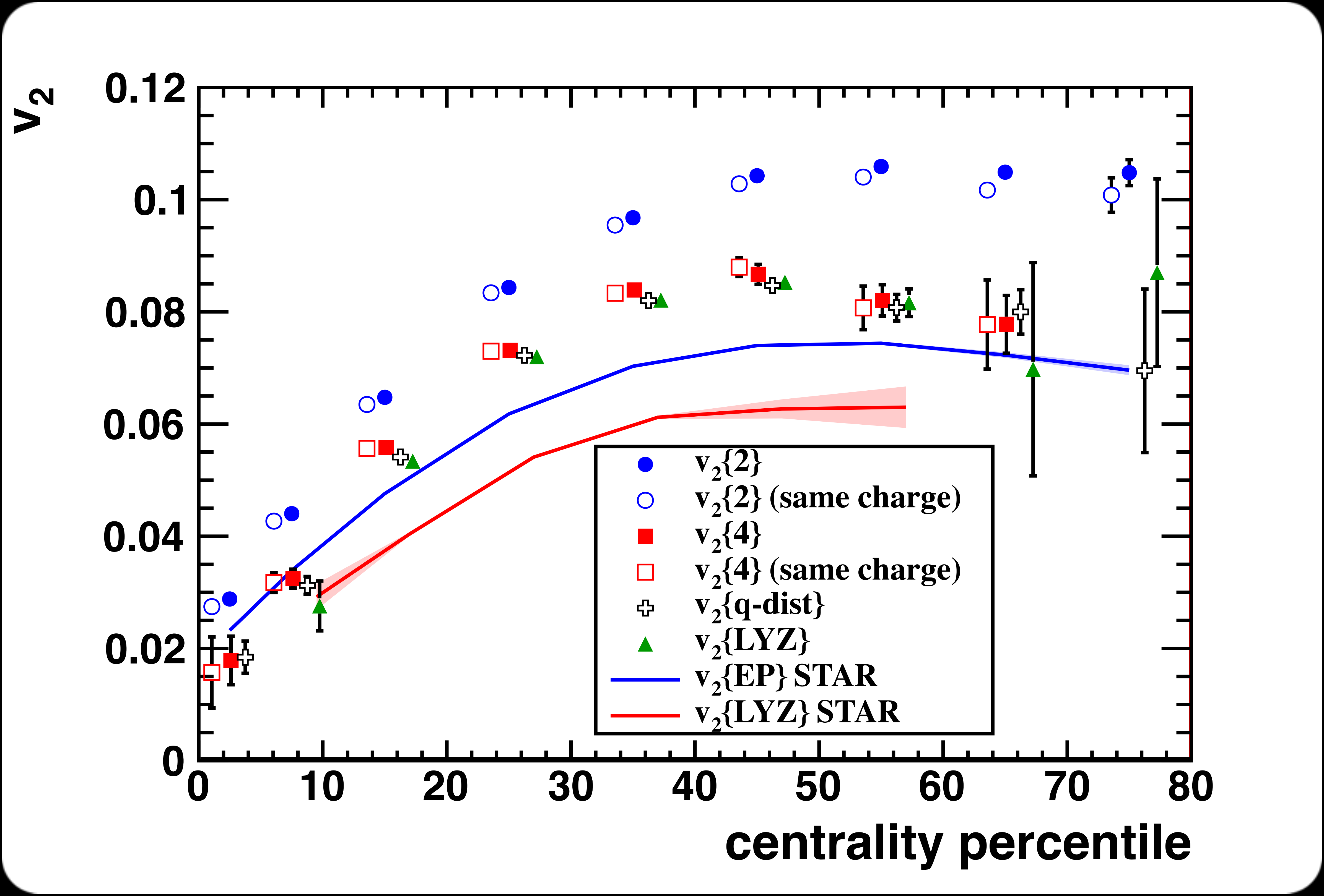


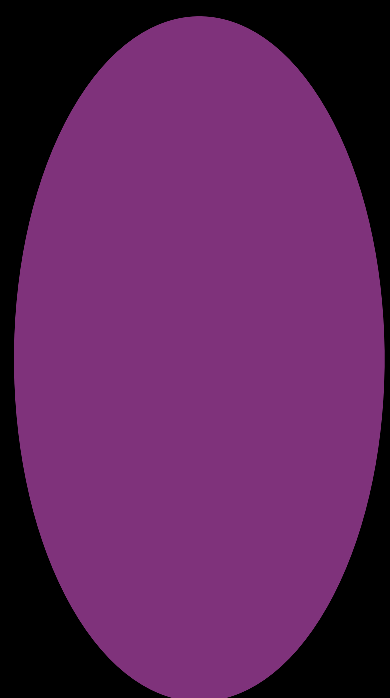


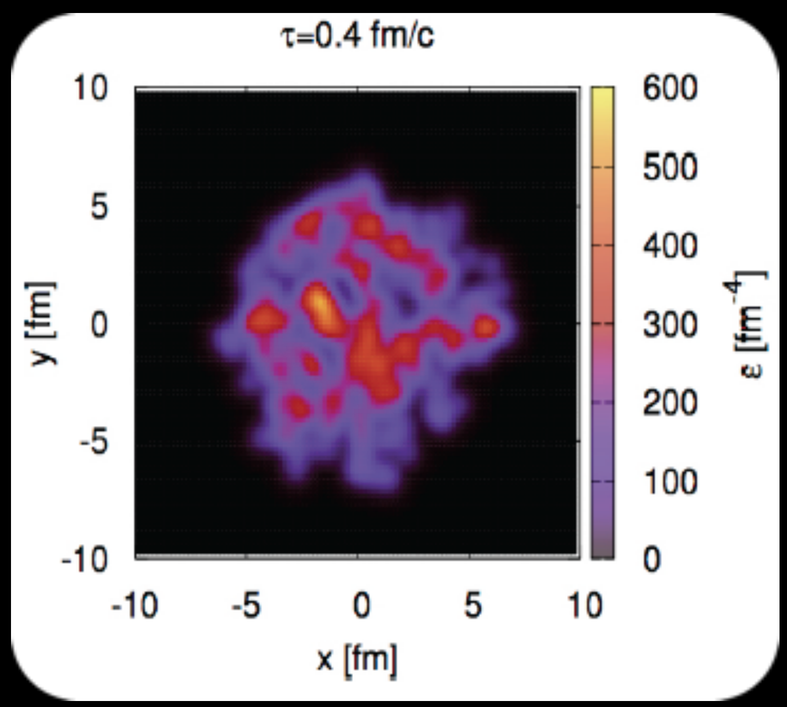
Elliptic flow @ the LHC

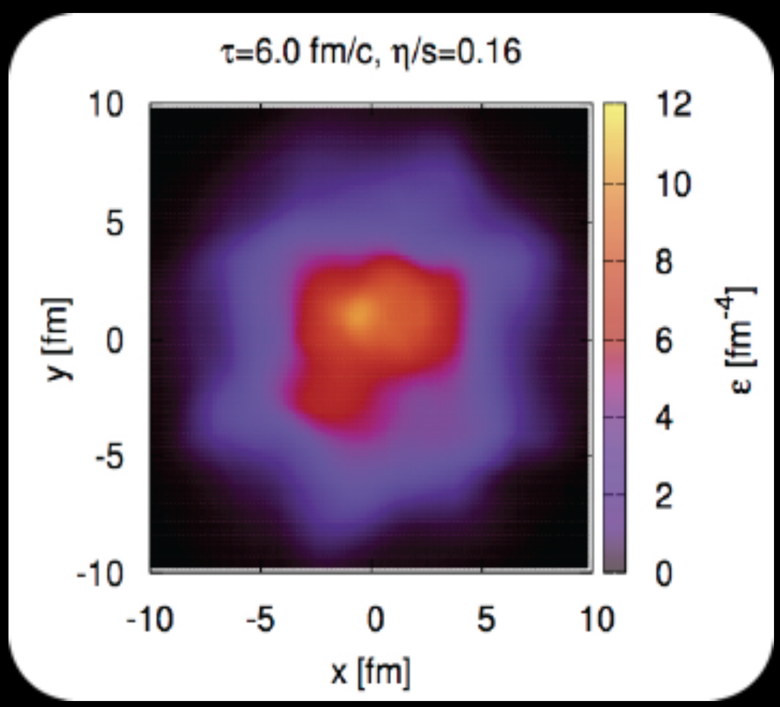


There are also fluctuations...

- 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



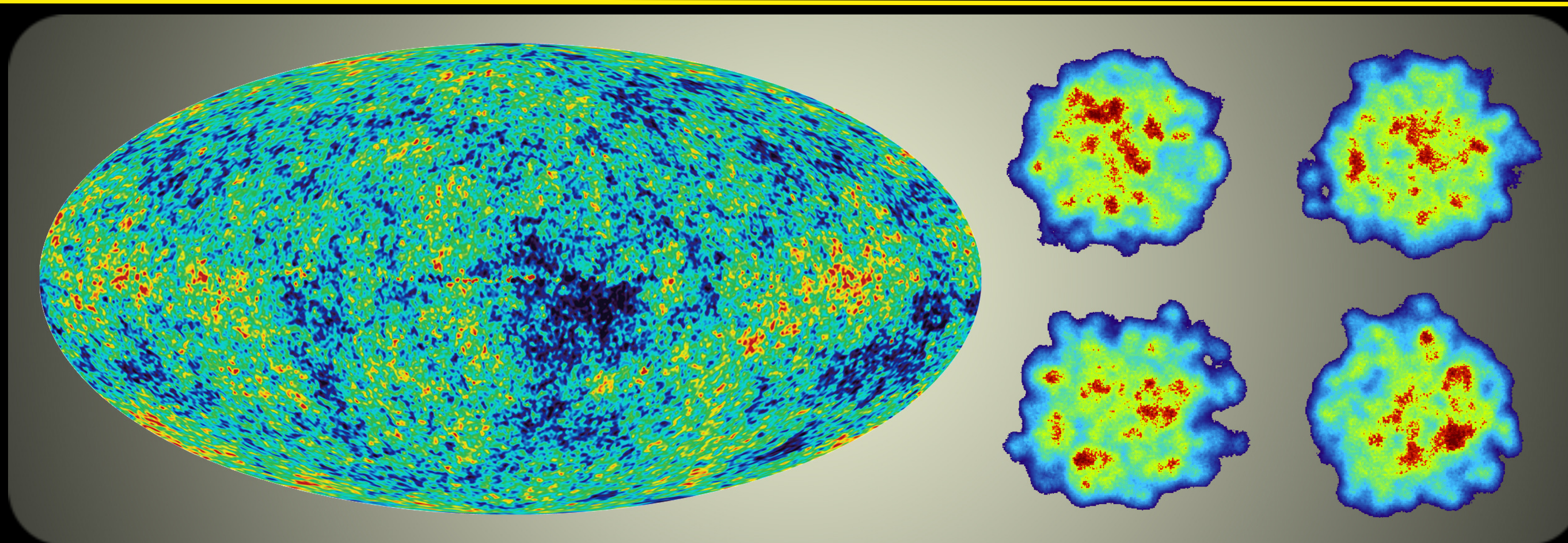




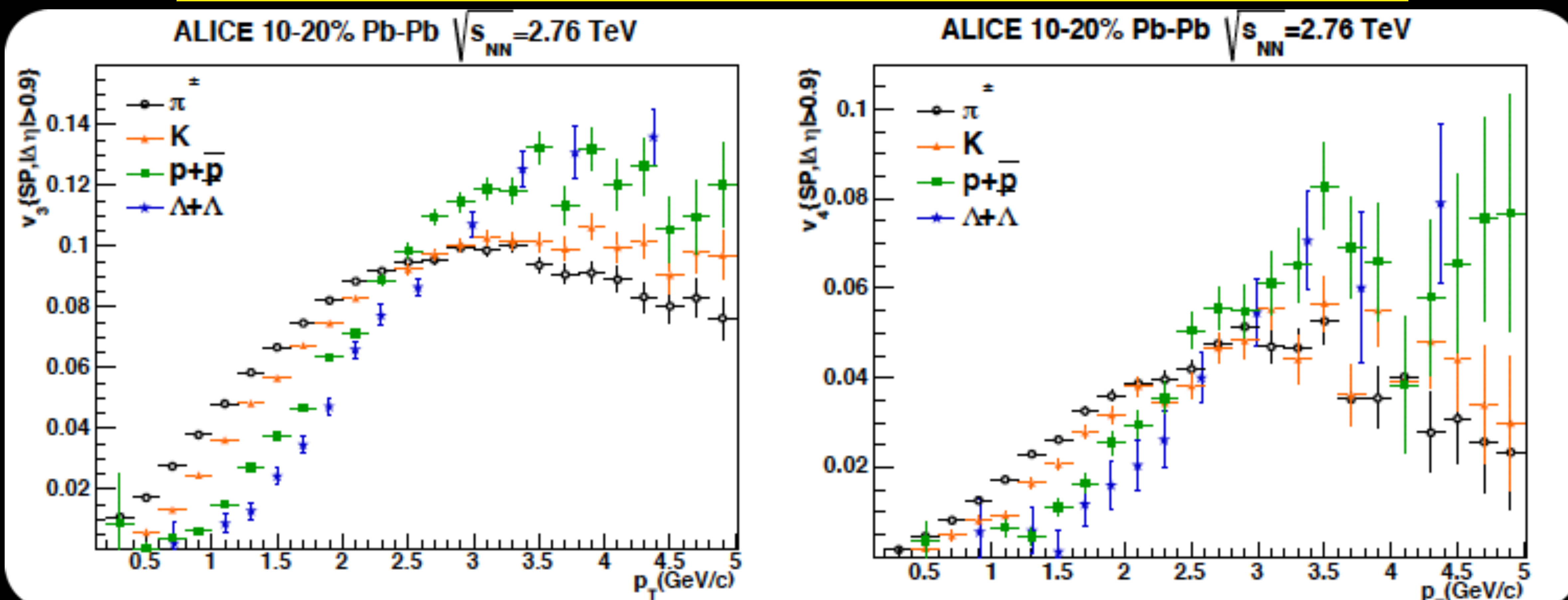
- But initial conditions not known precisely enough (model dependent)
  - ★ Data can be described by different combinations of initial conditions and η/S

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

And there is even more…: 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!



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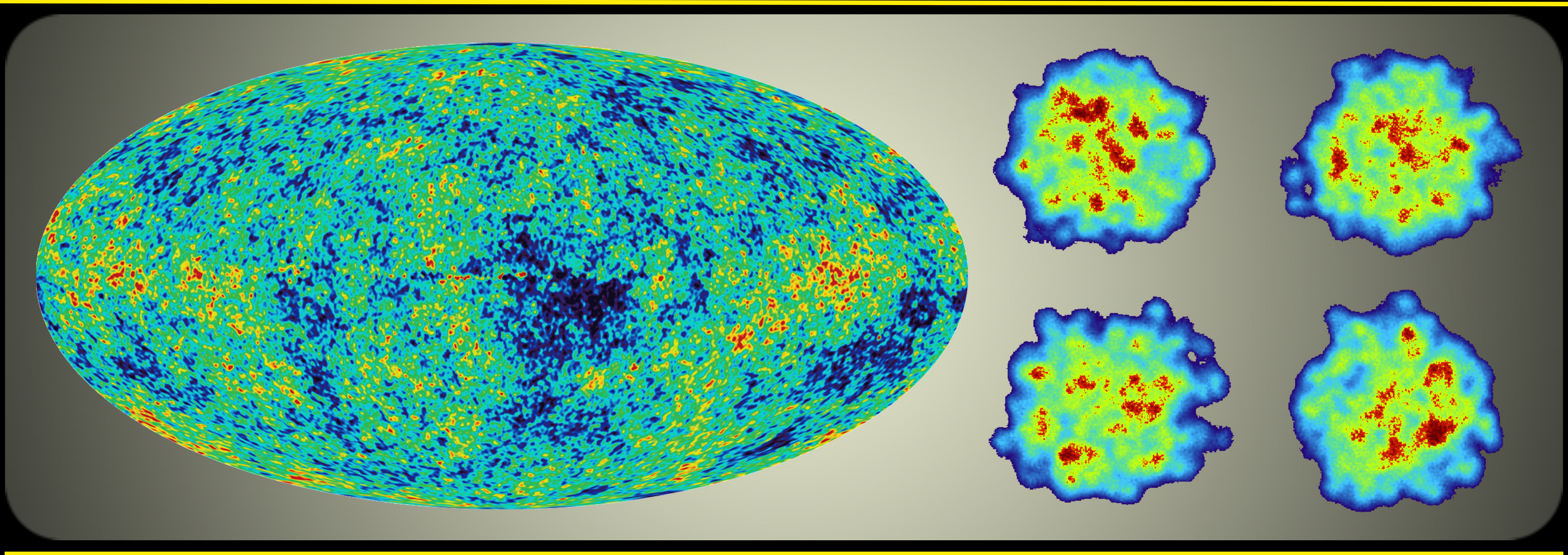

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Naghmeh Mohammadi

You knew this was coming…

Higher harmonic flow: towards the publication

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CERN-PH-EP-2015-XXX
Day Month 2015

Higher harmonic flow coefficients of identified hadrons in Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV

ALICE Collaboration*

Abstract

The anisotropic flow coefficients, v_2, v_3, v_4 and v_5, of $\pi^{\pm}$, $K^{\pm}$ and $p+\overline{p}$ in Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV were measured with the ALICE detector at the Large Hadron Collider (LHC). The results were obtained with the Scalar Product method using a pseudo-rapidity gap of $|\Delta\eta| > 0.0$ between the identified hadron under study and the reference particles. Correlations not related to the common symmetry plane, known also as non-flow, were estimated and subtracted from the measurement using the measured correlations in pp collisions. The values of these flow coefficients exhibit a clear mass ordering for $p_T < 3$ GeV/c for all harmonics. For transverse momentum values larger than about 3 GeV/c, particles tend to group at an approximate level according to their type, suggesting that coalescence might be the relevant particle production mechanism in this region. The experimental data are described fairly well by a model that describes the hydrodynamical expansion of the fireball using a given set of initial conditions and a value of $\eta/S = 0.08$, close to the lower bound, coupled to a hadronic cascade model. Finally, the comparison of the measurements with A Multi Phase Transport model (AMPT) illustrates the significance of this late hadronic rescattering stage to the development of the observed mass ordering at low values of p_T and of coalesence as a particle production mechanism for the particle type grouping at intermediate values of p_T for all harmonics.

*See Appendix A for the list of collaboration members

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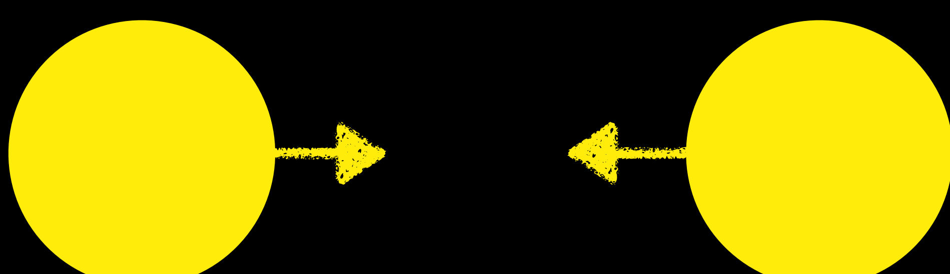
ALICE physics program extends to smaller systems!!!

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



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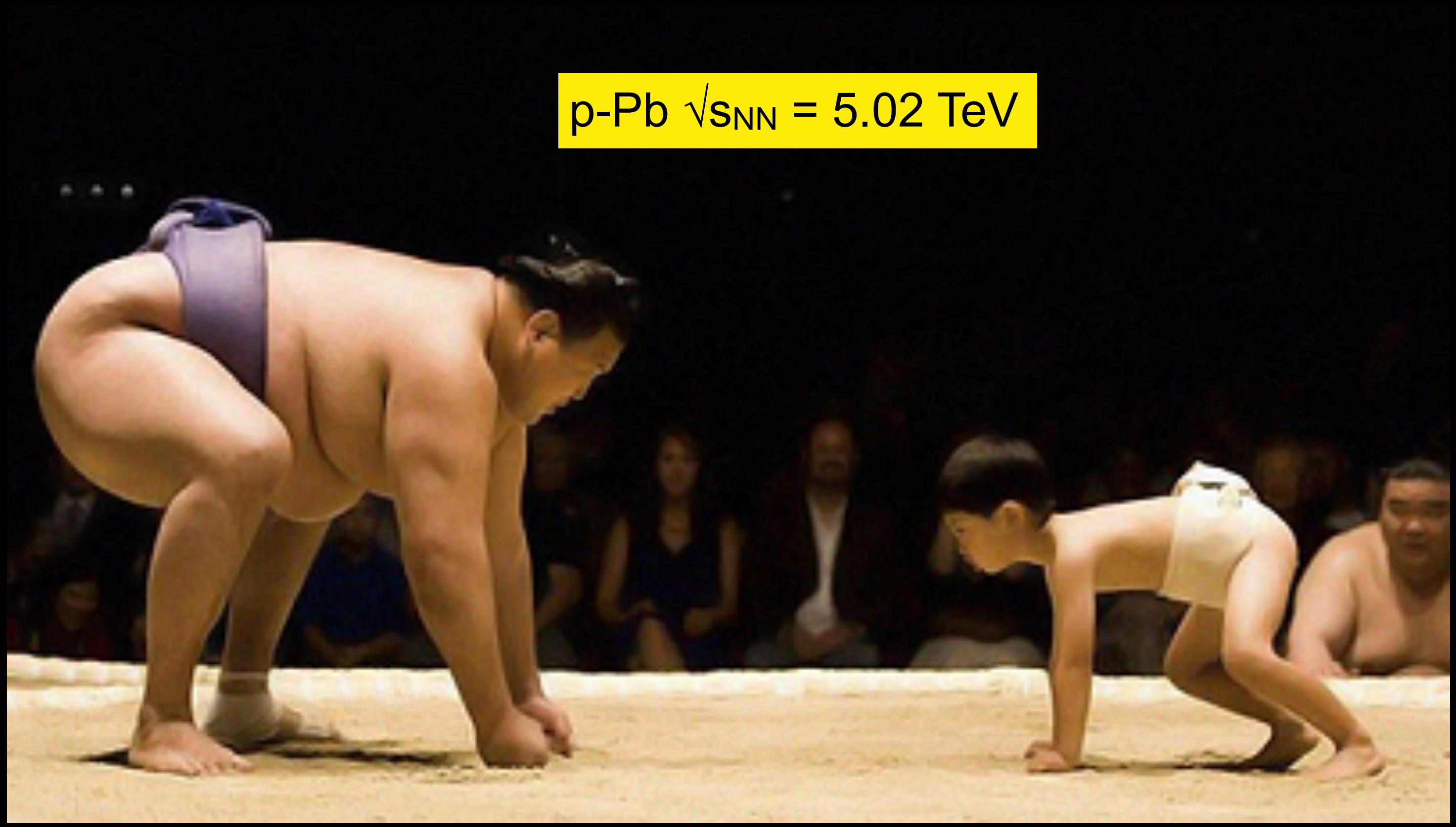

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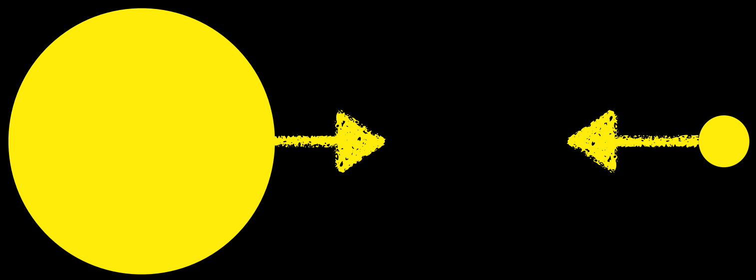
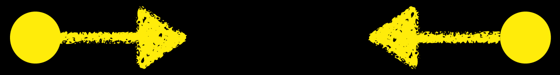


ALICE physics program extends to smaller systems!!!

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

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

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



(part of) the Nikhef-Utrecht 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 (N328) if you are interested!!!

Thank you for your attention!

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Backup

Elliptic flow and how to measure it

Event plane method

$$v_n = \frac{v_n^{obs}}{R_n}$$

Scalar product method

$$v_n = \left(\frac{\sqrt{\langle M_a M_b \rangle}}{\langle M \rangle - 1} \right) \frac{\langle Q_n u_{n,i}(p_T, \eta) \rangle}{\sqrt{\langle Q_n^a Q_n^b \rangle}}$$

- Uses the length of the Q-vector as a weight
- u: unitary vector of the ith particle which is excluded from the Q-vector calculation

Q-cumulants: 2 and multi-particle correlations

$$C_n\{2\} = \langle\langle e^{in(\varphi_1 - \varphi_2)} \rangle\rangle = \langle v_n^2 \rangle$$

$$C_n\{4\} = \langle\langle e^{in(\varphi_1 + \varphi_2 - \varphi_3 - \varphi_4)} \rangle\rangle - 2 \langle\langle e^{in(\varphi_1 - \varphi_2)} \rangle\rangle^2 = -\langle v_n^4 \rangle$$

In the absence of non-flow and flow fluctuations!!!

A. Bilandzic, R. Snellings, S. Voloshin, Phys. Rev. **C83**, 044913 (2011)

Non-flow effects

- Correlations not connected to the common symmetry plane
  - resonances, jets, femtoscopic correlations,...
- Suppressed utilizing multi-particle techniques, η-gap analysis (e.g. event plane or SP methods with forward detectors), different charge combinations,...

$$C_n\{2\} = \langle\langle e^{in(\varphi_1-\varphi_2)}\rangle\rangle = \langle v_n^2\rangle + \delta_2$$

$$C_n\{4\} = \langle\langle e^{in(\varphi_1+\varphi_2-\varphi_3-\varphi_4)}\rangle\rangle - 2\langle\langle e^{in(\varphi_1-\varphi_2)}\rangle\rangle^2 =$$
$$= \langle v_n^4\rangle + 4\langle v_n^2\rangle\delta_2 + 2\delta_2^2 - 2(\langle v_n^2\rangle + \delta_2)^2 + \delta_4$$
$$= -\langle v_n^4\rangle + \delta_4$$

$$\delta_2 \sim \frac{1}{M} \Rightarrow v_n \gg \frac{1}{\sqrt{M}}$$

$$\delta_4 \sim \frac{1}{(M-3)(M-2)(M-1)} \sim \frac{1}{M^3} \Rightarrow v_n \gg \frac{1}{\sqrt[4]{M^3}}$$

- For a typical Pb-Pb LHC collision at 2.76 TeV, M~400-500 for 30-40% centrality
  - v_n >> 5% for the 2-particle correlation technique
  - v_n >> 1% for the 4-particle correlation technique

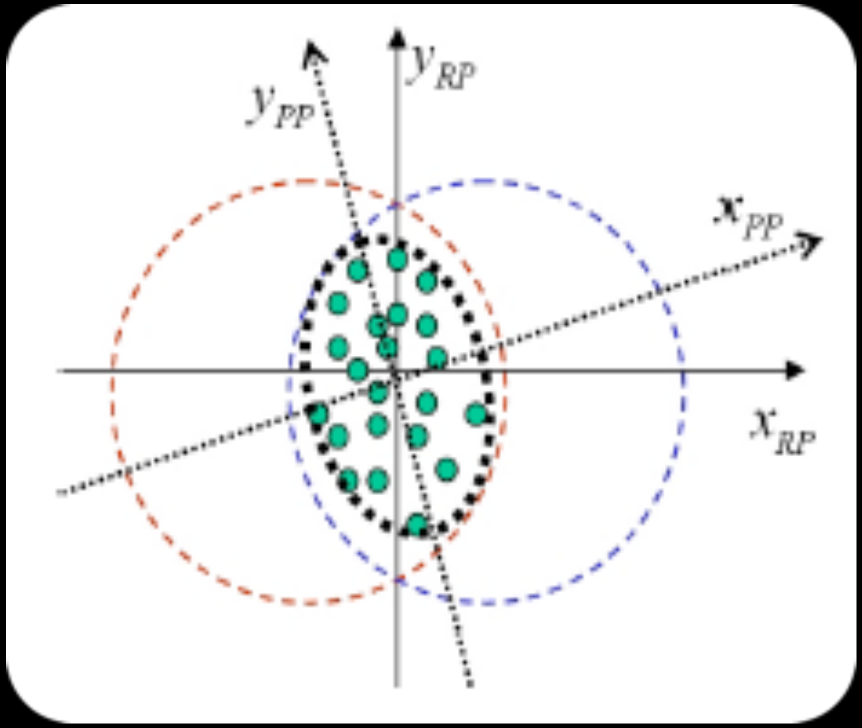
$$\langle v_n^2\rangle \neq \langle v_n\rangle^2$$

$$\langle v_n^2\rangle = \langle v_n\rangle^2 + \sigma_v^2$$

$$\langle v_n^4\rangle = \langle v_n\rangle^4 + 6\sigma_v^2\langle v_n\rangle^2$$

$$\langle v_n^6\rangle = \langle v_n\rangle^6 + 15\sigma_v^2\langle v_n\rangle^4$$

$$\langle v_n^8\rangle = \langle v_n\rangle^8 + 28\sigma_v^2\langle v_n\rangle^6$$



$$v_2\{2\} = \sqrt{\langle v_2^2\rangle} = \ldots = \langle v_2\rangle + \frac{1}{2}\frac{\sigma_v^2}{\langle v_2\rangle}$$

$$v_2\{4\} = \sqrt[4]{2\langle v_2^2\rangle^2 - \langle v_2^4\rangle} = \ldots = \langle v_2\rangle - \frac{1}{2}\frac{\sigma_v^2}{\langle v_2\rangle}$$

$$v_2\{6\} = \sqrt[6]{\frac{1}{4}\left(\langle v_2^6\rangle - 9\langle v_2^2\rangle\langle v_2^4\rangle + 12\langle v_2^2\rangle^3\right)} = \ldots = \langle v_2\rangle - \frac{1}{2}\frac{\sigma_v^2}{\langle v_2\rangle}$$