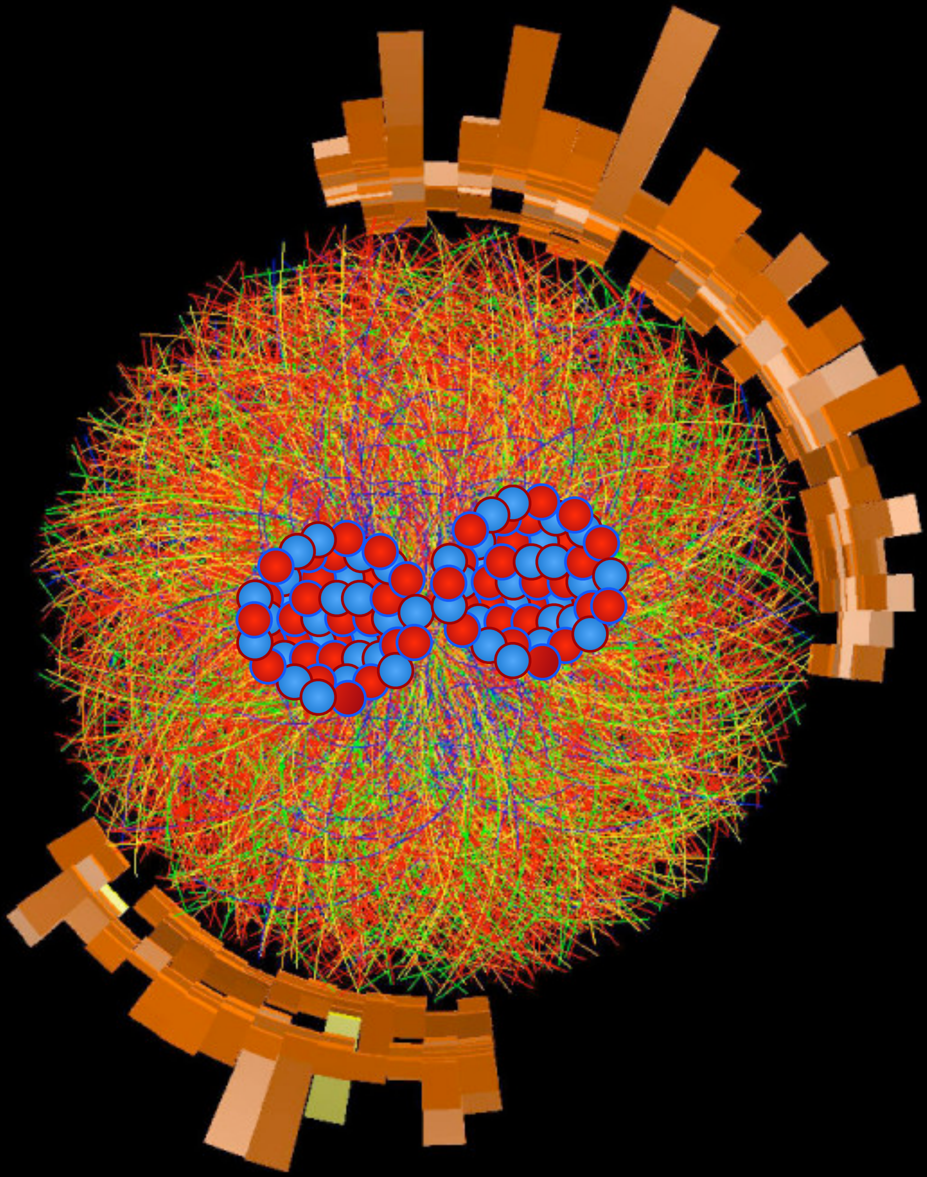
Heavy-ion collisions at the LHC with ALICE



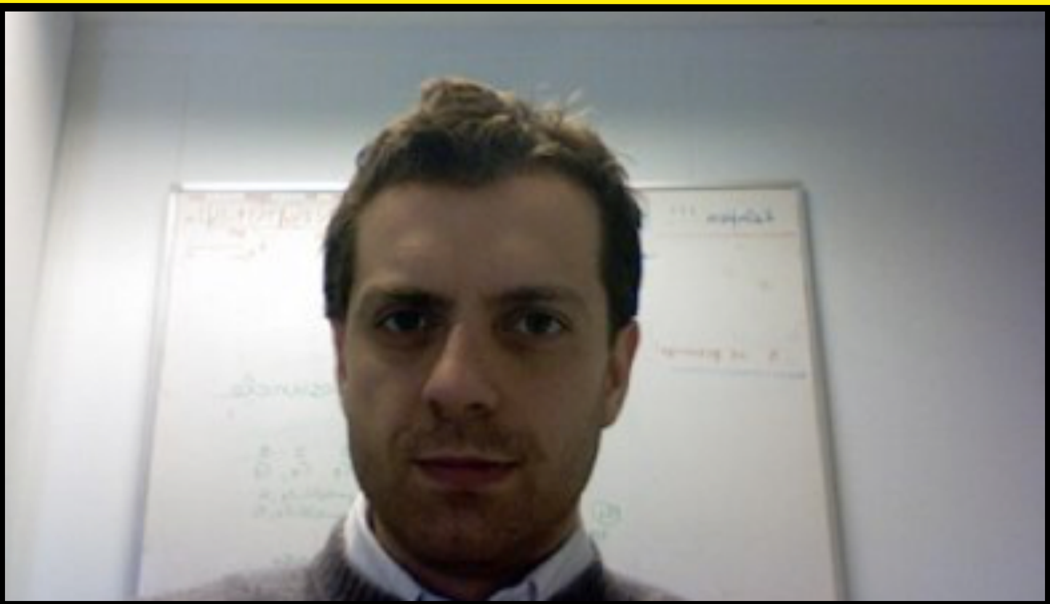
Panos Christakoglou

Nikhef and Utrecht University

Panos.Christakoglou@nikhef.nl

Briefly about me…

- ✓ Working at CERN from 2003 until 2010
- ✓ Senior scientist at Nikhef, Amsterdam,
- ✓ Assistant professor at UU, subatomic physics institute



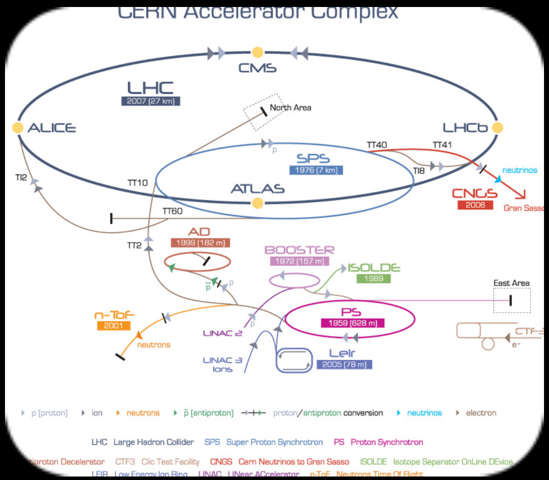
- ✓ E-mail addresses
  - Panos.Christakoglou@nikhef.nl
  - Panos.Christakoglou@cern.ch
  - p.christakoglou@uu.nl

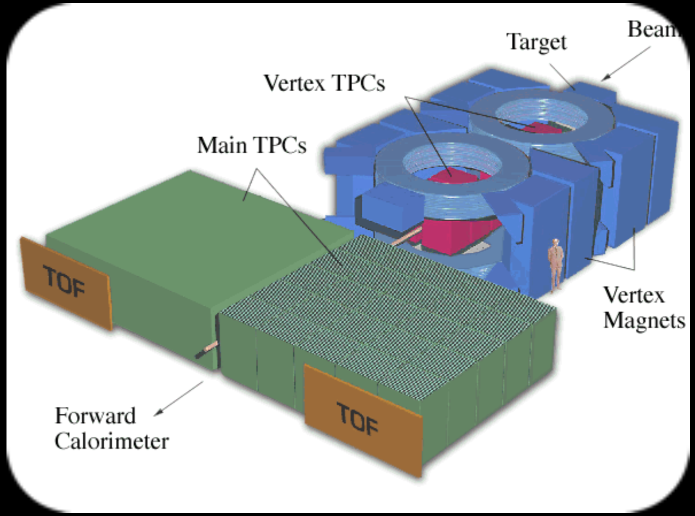
- ✓ Where can you find me?
  - Nikhef, Room N327, Science Park 105 Amsterdam
  - S. Ornsteinlaboratorium Princetonplein 1, Room 215, 3584 CC Utrecht

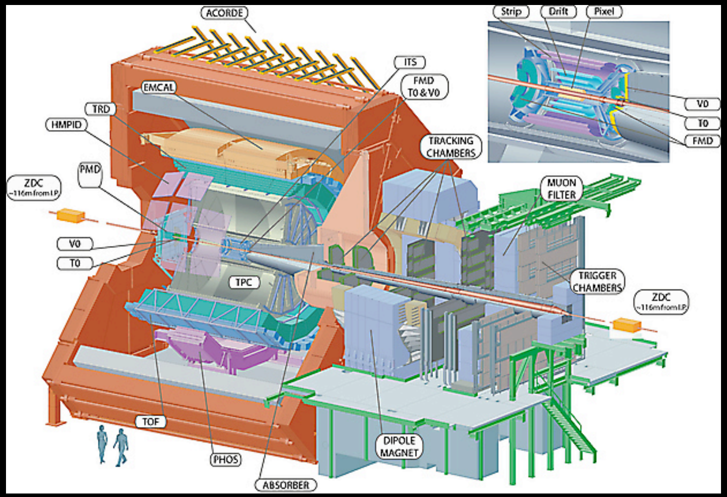
Briefly about me…

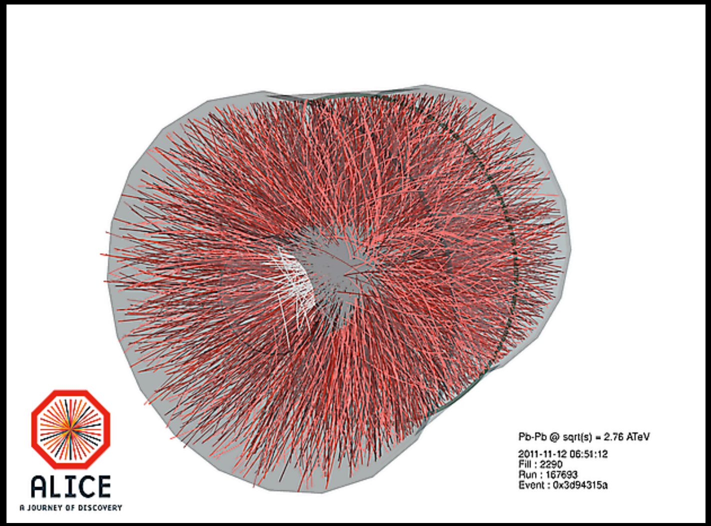
✓ Research interests

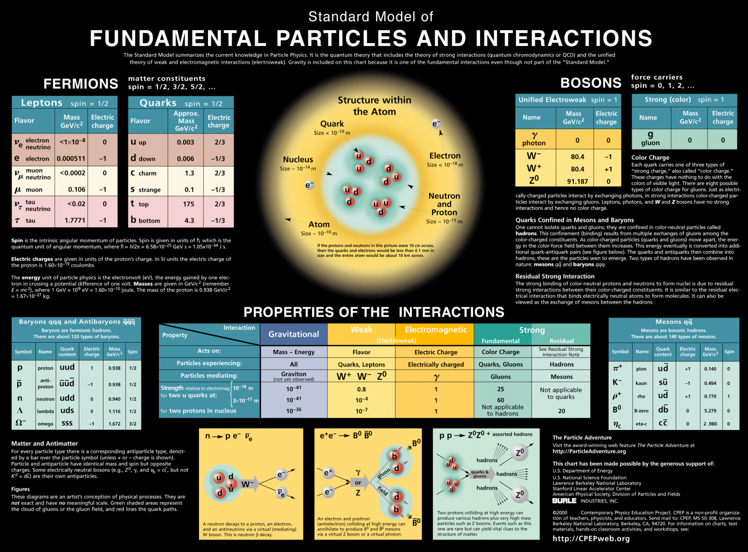
- Quantum chromodynamics
- Heavy-ion physics
- Alice @ LHC











Standard Model of

FUNDAMENTAL PARTICLES AND INTERACTIONS

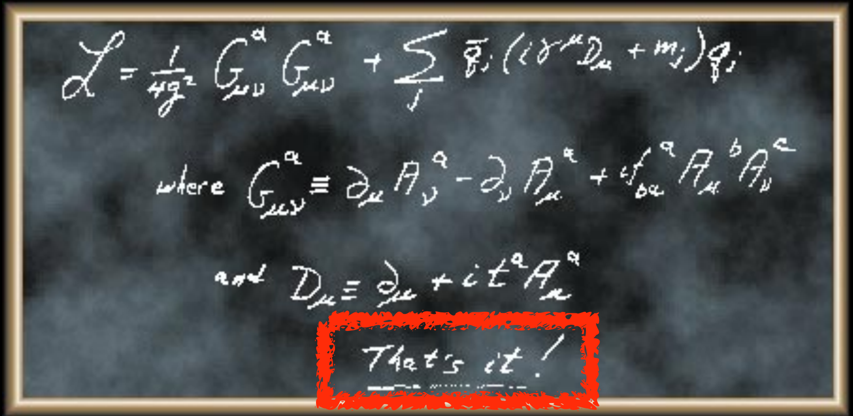
FERMIONS matter constituents spin = 1/2, 3/2, 5/2, ...

BOSONS force carriers spin = 0, 1, 2, ...

PROPERTIES OF THE INTERACTIONS

✓ Teaching

- Subatomic physics (3rd year bachelor)
- Particle physics 2: QCD (MSc)



$$\mathcal{L} = \frac{1}{4g^2} G^a_{\mu\nu} G^a_{\mu\nu} + \sum_f \bar{q}_f (i\gamma^\mu D_\mu + m_f) q_f$$

where $G^a_{\mu\nu} \equiv \partial_\mu A^a_\nu - \partial_\nu A^a_\mu + f^a_{bc} A^b_\mu A^c_\nu$

and $D_\mu \equiv \partial_\mu + i t^a A^a_\mu$

That's it!

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Scientific question to be answered:

- ✓ …I collide two large objects that are accelerated at 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?

↓

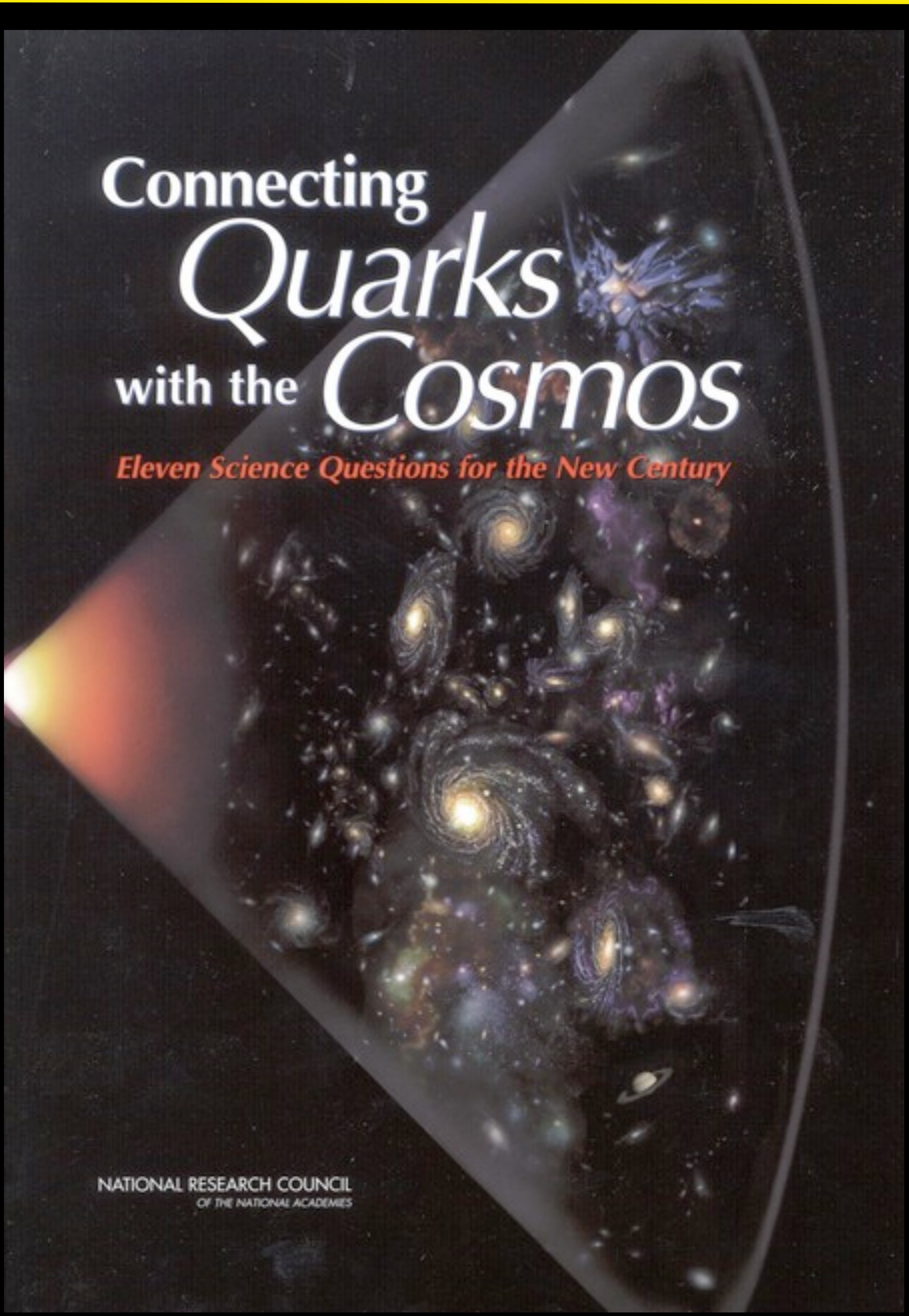
Interesting questions to answer!!!

Fundamental questions in physics

Panos.Christakoglou@nikhef.nl

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?



Connecting Quarks with the Cosmos

Eleven Science Questions for the New Century

NATIONAL RESEARCH COUNCIL
OF THE NATIONAL ACADEMIES

Panos.Christakoglou@nikhef.nl

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?

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**.

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The Standard Model of particle physics

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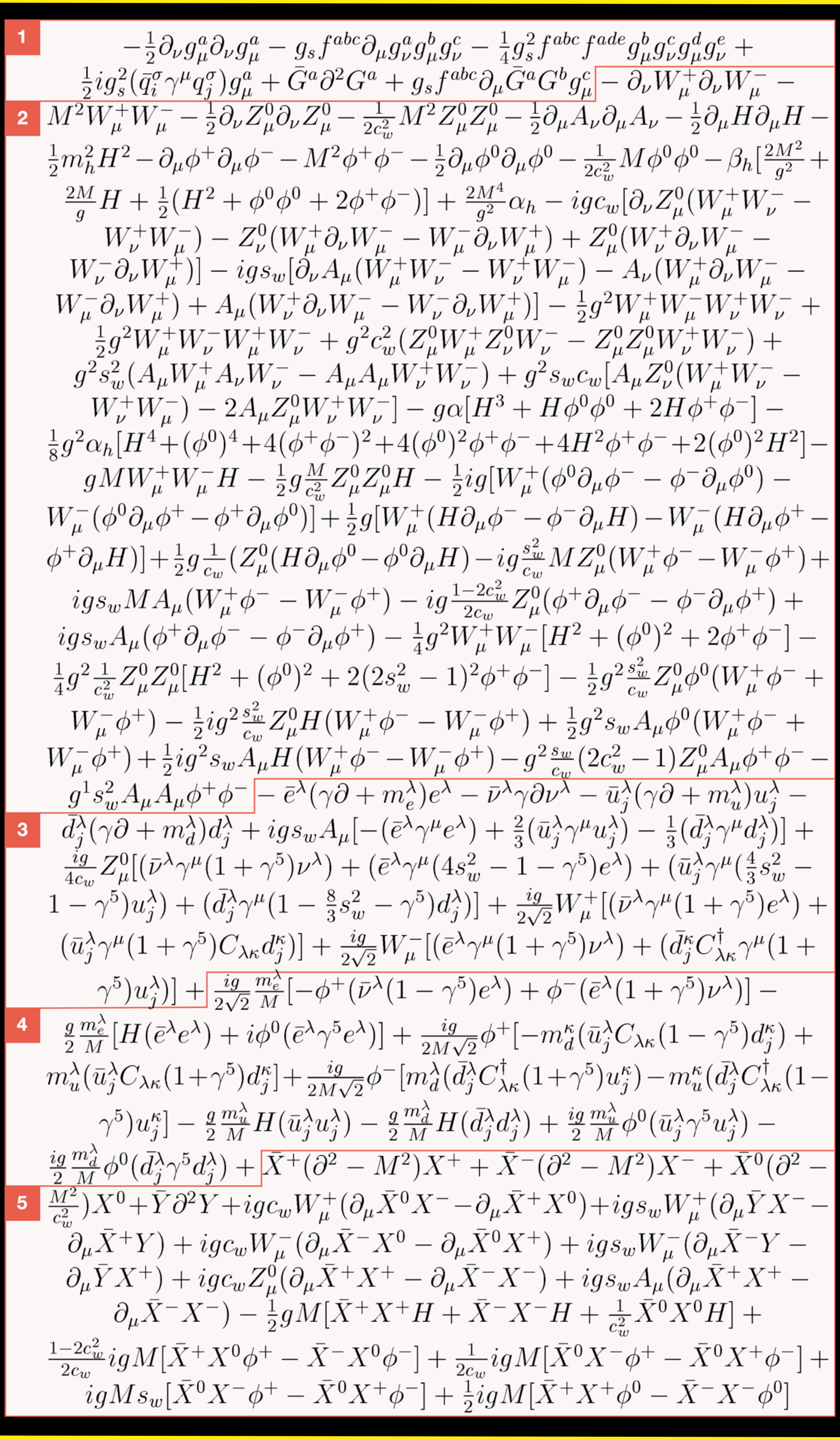
The (complete?) Standard Model Lagrangian



$$
\begin{gathered}
-\tfrac{1}{2}\partial_\nu g^a_\mu \partial_\nu g^a_\mu - g_s f^{abc}\partial_\mu g^a_\nu g^b_\mu g^c_\nu - \tfrac{1}{4}g_s^2 f^{abc} f^{ade} g^b_\mu g^c_\nu g^d_\mu g^e_\nu + \\
\tfrac{1}{2} i g_s^2 (\bar{q}^\sigma_i \gamma^\mu q^\sigma_j) g^a_\mu + \bar{G}^a \partial^2 G^a + g_s f^{abc} \partial_\mu \bar{G}^a G^b g^c_\mu - \partial_\nu W^+_\mu \partial_\nu W^-_\mu - \\
M^2 W^+_\mu W^-_\mu - \tfrac{1}{2}\partial_\nu Z^0_\mu \partial_\nu Z^0_\mu - \tfrac{1}{2c_w^2} M^2 Z^0_\mu Z^0_\mu - \tfrac{1}{2}\partial_\mu A_\nu \partial_\mu A_\nu - \tfrac{1}{2}\partial_\mu H \partial_\mu H - \\
\tfrac{1}{2} m_h^2 H^2 - \partial_\mu \phi^+ \partial_\mu \phi^- - M^2 \phi^+ \phi^- - \tfrac{1}{2}\partial_\mu \phi^0 \partial_\mu \phi^0 - \tfrac{1}{2c_w^2} M \phi^0 \phi^0 - \beta_h [\tfrac{2M^2}{g^2} + \\
\tfrac{2M}{g} H + \tfrac{1}{2}(H^2 + \phi^0\phi^0 + 2\phi^+\phi^-)] + \tfrac{2M^4}{g^2}\alpha_h - igc_w[\partial_\nu Z^0_\mu (W^+_\mu W^-_\nu - \\
W^+_\nu W^-_\mu) - Z^0_\nu (W^+_\mu \partial_\nu W^-_\mu - W^-_\mu \partial_\nu W^+_\mu) + Z^0_\mu (W^+_\nu \partial_\nu W^-_\mu - \\
W^-_\nu \partial_\nu W^+_\mu)] - igs_w[\partial_\nu A_\mu (W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - A_\nu (W^+_\mu \partial_\nu W^-_\mu - \\
W^-_\mu \partial_\nu W^+_\mu) + A_\mu (W^+_\nu \partial_\nu W^-_\mu - W^-_\nu \partial_\nu W^+_\mu)] - \tfrac{1}{2} g^2 W^+_\mu W^-_\mu W^+_\nu W^-_\nu + \\
\tfrac{1}{2} g^2 W^+_\mu W^-_\nu W^+_\mu W^-_\nu + g^2 c_w^2 (Z^0_\mu W^+_\mu Z^0_\nu W^-_\nu - Z^0_\mu Z^0_\mu W^+_\nu W^-_\nu) + \\
g^2 s_w^2 (A_\mu W^+_\mu A_\nu W^-_\nu - A_\mu A_\mu W^+_\nu W^-_\nu) + g^2 s_w c_w [A_\mu Z^0_\nu (W^+_\mu W^-_\nu - \\
W^+_\nu W^-_\mu) - 2A_\mu Z^0_\mu W^+_\nu W^-_\nu] - g\alpha[H^3 + H\phi^0\phi^0 + 2H\phi^+\phi^-] - \\
\tfrac{1}{8} g^2 \alpha_h [H^4 + (\phi^0)^4 + 4(\phi^+\phi^-)^2 + 4(\phi^0)^2\phi^+\phi^- + 4H^2\phi^+\phi^- + 2(\phi^0)^2 H^2] - \\
gMW^+_\mu W^-_\mu H - \tfrac{1}{2} g \tfrac{M}{c_w^2} Z^0_\mu Z^0_\mu H - \tfrac{1}{2} ig [W^+_\mu (\phi^0 \partial_\mu \phi^- - \phi^- \partial_\mu \phi^0) - \\
W^-_\mu (\phi^0 \partial_\mu \phi^+ - \phi^+ \partial_\mu \phi^0)] + \tfrac{1}{2} g [W^+_\mu (H \partial_\mu \phi^- - \phi^- \partial_\mu H) - W^-_\mu (H \partial_\mu \phi^+ - \\
\phi^+ \partial_\mu H)] + \tfrac{1}{2} g \tfrac{1}{c_w} (Z^0_\mu (H \partial_\mu \phi^0 - \phi^0 \partial_\mu H) - ig \tfrac{s_w^2}{c_w} M Z^0_\mu (W^+_\mu \phi^- - W^-_\mu \phi^+) + \\
igs_w M A_\mu (W^+_\mu \phi^- - W^-_\mu \phi^+) - ig \tfrac{1-2c_w^2}{2c_w} Z^0_\mu (\phi^+ \partial_\mu \phi^- - \phi^- \partial_\mu \phi^+) + \\
igs_w A_\mu (\phi^+ \partial_\mu \phi^- - \phi^- \partial_\mu \phi^+) - \tfrac{1}{4} g^2 W^+_\mu W^-_\mu [H^2 + (\phi^0)^2 + 2\phi^+\phi^-] - \\
\tfrac{1}{4} g^2 \tfrac{1}{c_w^2} Z^0_\mu Z^0_\mu [H^2 + (\phi^0)^2 + 2(2s_w^2 - 1)^2 \phi^+\phi^-] - \tfrac{1}{2} g^2 \tfrac{s_w^2}{c_w} Z^0_\mu \phi^0 (W^+_\mu \phi^- + \\
W^-_\mu \phi^+) - \tfrac{1}{2} i g^2 \tfrac{s_w^2}{c_w} Z^0_\mu H (W^+_\mu \phi^- - W^-_\mu \phi^+) + \tfrac{1}{2} g^2 s_w A_\mu \phi^0 (W^+_\mu \phi^- + \\
W^-_\mu \phi^+) + \tfrac{1}{2} i g^2 s_w A_\mu H (W^+_\mu \phi^- - W^-_\mu \phi^+) - g^2 \tfrac{s_w}{c_w} (2c_w^2 - 1) Z^0_\mu A_\mu \phi^+ \phi^- - \\
g^1 s_w^2 A_\mu A_\mu \phi^+ \phi^- - \bar{e}^\lambda (\gamma\partial + m_e^\lambda) e^\lambda - \bar{\nu}^\lambda \gamma\partial \nu^\lambda - \bar{u}^\lambda_j (\gamma\partial + m_u^\lambda) u^\lambda_j - \\
\bar{d}^\lambda_j (\gamma\partial + m_d^\lambda) d^\lambda_j + igs_w A_\mu [-(\bar{e}^\lambda \gamma^\mu e^\lambda) + \tfrac{2}{3}(\bar{u}^\lambda_j \gamma^\mu u^\lambda_j) - \tfrac{1}{3}(\bar{d}^\lambda_j \gamma^\mu d^\lambda_j)] + \\
\tfrac{ig}{4c_w} Z^0_\mu [(\bar{\nu}^\lambda \gamma^\mu (1 + \gamma^5) \nu^\lambda) + (\bar{e}^\lambda \gamma^\mu (4s_w^2 - 1 - \gamma^5) e^\lambda) + (\bar{u}^\lambda_j \gamma^\mu (\tfrac{4}{3} s_w^2 - \\
1 - \gamma^5) u^\lambda_j) + (\bar{d}^\lambda_j \gamma^\mu (1 - \tfrac{8}{3} s_w^2 - \gamma^5) d^\lambda_j)] + \tfrac{ig}{2\sqrt{2}} W^+_\mu [(\bar{\nu}^\lambda \gamma^\mu (1 + \gamma^5) e^\lambda) + \\
(\bar{u}^\lambda_j \gamma^\mu (1 + \gamma^5) C_{\lambda\kappa} d^\kappa_j)] + \tfrac{ig}{2\sqrt{2}} W^-_\mu [(\bar{e}^\lambda \gamma^\mu (1 + \gamma^5) \nu^\lambda) + (\bar{d}^\kappa_j C^\dagger_{\lambda\kappa} \gamma^\mu (1 + \\
\gamma^5) u^\lambda_j)] + \tfrac{ig}{2\sqrt{2}} \tfrac{m_e^\lambda}{M} [-\phi^+ (\bar{\nu}^\lambda (1 - \gamma^5) e^\lambda) + \phi^- (\bar{e}^\lambda (1 + \gamma^5) \nu^\lambda)] - \\
\tfrac{g}{2} \tfrac{m_e^\lambda}{M} [H (\bar{e}^\lambda e^\lambda) + i\phi^0 (\bar{e}^\lambda \gamma^5 e^\lambda)] + \tfrac{ig}{2M\sqrt{2}} \phi^+ [-m_d^\kappa (\bar{u}^\lambda_j C_{\lambda\kappa} (1 - \gamma^5) d^\kappa_j) + \\
m_u^\lambda (\bar{u}^\lambda_j C_{\lambda\kappa} (1 + \gamma^5) d^\kappa_j] + \tfrac{ig}{2M\sqrt{2}} \phi^- [m_d^\lambda (\bar{d}^\lambda_j C^\dagger_{\lambda\kappa} (1 + \gamma^5) u^\kappa_j) - m_u^\kappa (\bar{d}^\lambda_j C^\dagger_{\lambda\kappa} (1 - \\
\gamma^5) u^\kappa_j] - \tfrac{g}{2} \tfrac{m_u^\lambda}{M} H (\bar{u}^\lambda_j u^\lambda_j) - \tfrac{g}{2} \tfrac{m_d^\lambda}{M} H (\bar{d}^\lambda_j d^\lambda_j) + \tfrac{ig}{2} \tfrac{m_u^\lambda}{M} \phi^0 (\bar{u}^\lambda_j \gamma^5 u^\lambda_j) - \\
\tfrac{ig}{2} \tfrac{m_d^\lambda}{M} \phi^0 (\bar{d}^\lambda_j \gamma^5 d^\lambda_j) + \bar{X}^+ (\partial^2 - M^2) X^+ + \bar{X}^- (\partial^2 - M^2) X^- + \bar{X}^0 (\partial^2 - \\
\tfrac{M^2}{c_w^2}) X^0 + \bar{Y} \partial^2 Y + igc_w W^+_\mu (\partial_\mu \bar{X}^0 X^- - \partial_\mu \bar{X}^+ X^0) + igs_w W^+_\mu (\partial_\mu \bar{Y} X^- - \\
\partial_\mu \bar{X}^+ Y) + igc_w W^-_\mu (\partial_\mu \bar{X}^- X^0 - \partial_\mu \bar{X}^0 X^+) + igs_w W^-_\mu (\partial_\mu \bar{X}^- Y - \\
\partial_\mu \bar{Y} X^+) + igc_w Z^0_\mu (\partial_\mu \bar{X}^+ X^+ - \partial_\mu \bar{X}^- X^-) + igs_w A_\mu (\partial_\mu \bar{X}^+ X^+ - \\
\partial_\mu \bar{X}^- X^-) - \tfrac{1}{2} gM [\bar{X}^+ X^+ H + \bar{X}^- X^- H + \tfrac{1}{c_w^2} \bar{X}^0 X^0 H] + \\
\tfrac{1-2c_w^2}{2c_w} igM [\bar{X}^+ X^0 \phi^+ - \bar{X}^- X^0 \phi^-] + \tfrac{1}{2c_w} igM [\bar{X}^0 X^- \phi^+ - \bar{X}^0 X^+ \phi^-] + \\
igMs_w [\bar{X}^0 X^- \phi^+ - \bar{X}^0 X^+ \phi^-] + \tfrac{1}{2} igM [\bar{X}^+ X^+ \phi^0 - \bar{X}^- X^- \phi^0]
\end{gathered}
$$

Source: Symmetry magazine

Fun fact

- ✓ Written by Thomas Gutierrez (assistant professor of Physics at CalPoly (California Polytechnic State University)
- ✓ He derived it from Diagrammatica, a theoretical physics reference written by Nobel Laureate **Martinus Veltman**
- ✓ In Gutierrez's dissemination of the transcript, **he noted a sign error he made somewhere in the equation**

Good luck finding it!

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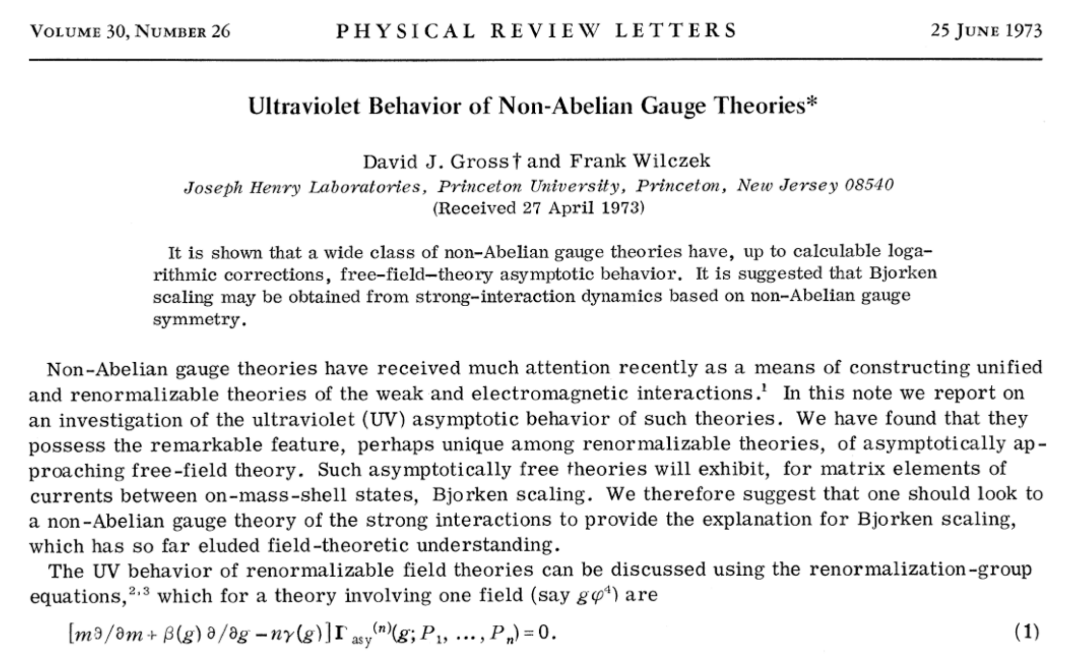
Focus on strong interactions…

The birth of QCD



VOLUME 30, NUMBER 26 PHYSICAL REVIEW LETTERS 25 JUNE 1973

Ultraviolet Behavior of Non-Abelian Gauge Theories*

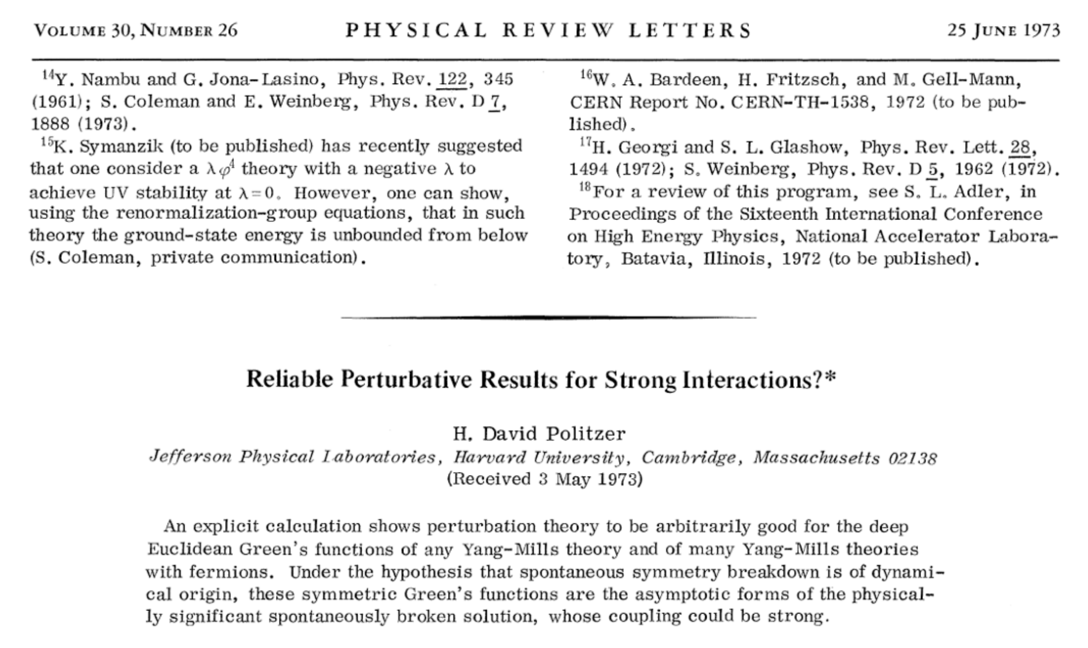
David J. Gross† and Frank Wilczek
Joseph Henry Laboratories, Princeton University, Princeton, New Jersey 08540
(Received 27 April 1973)

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

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



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).

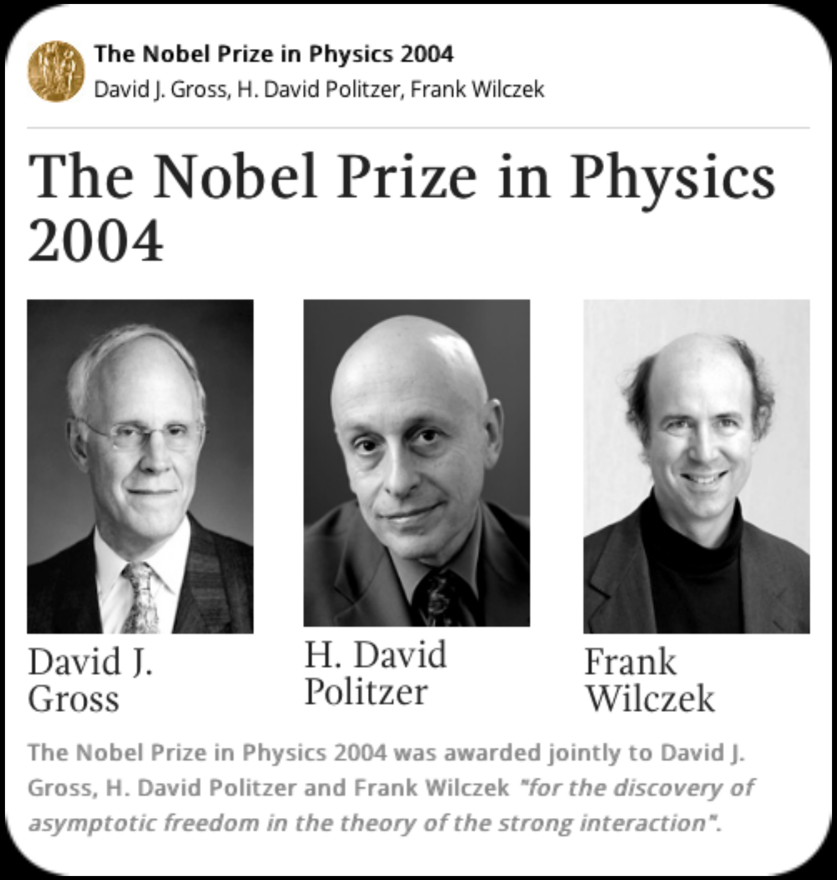
[17] H. Georgi and S. L. Glashow, Phys. Rev. Lett. 28, 1494 (1972); S. Weinberg, Phys. Rev. D 5, 1962 (1972).

[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

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

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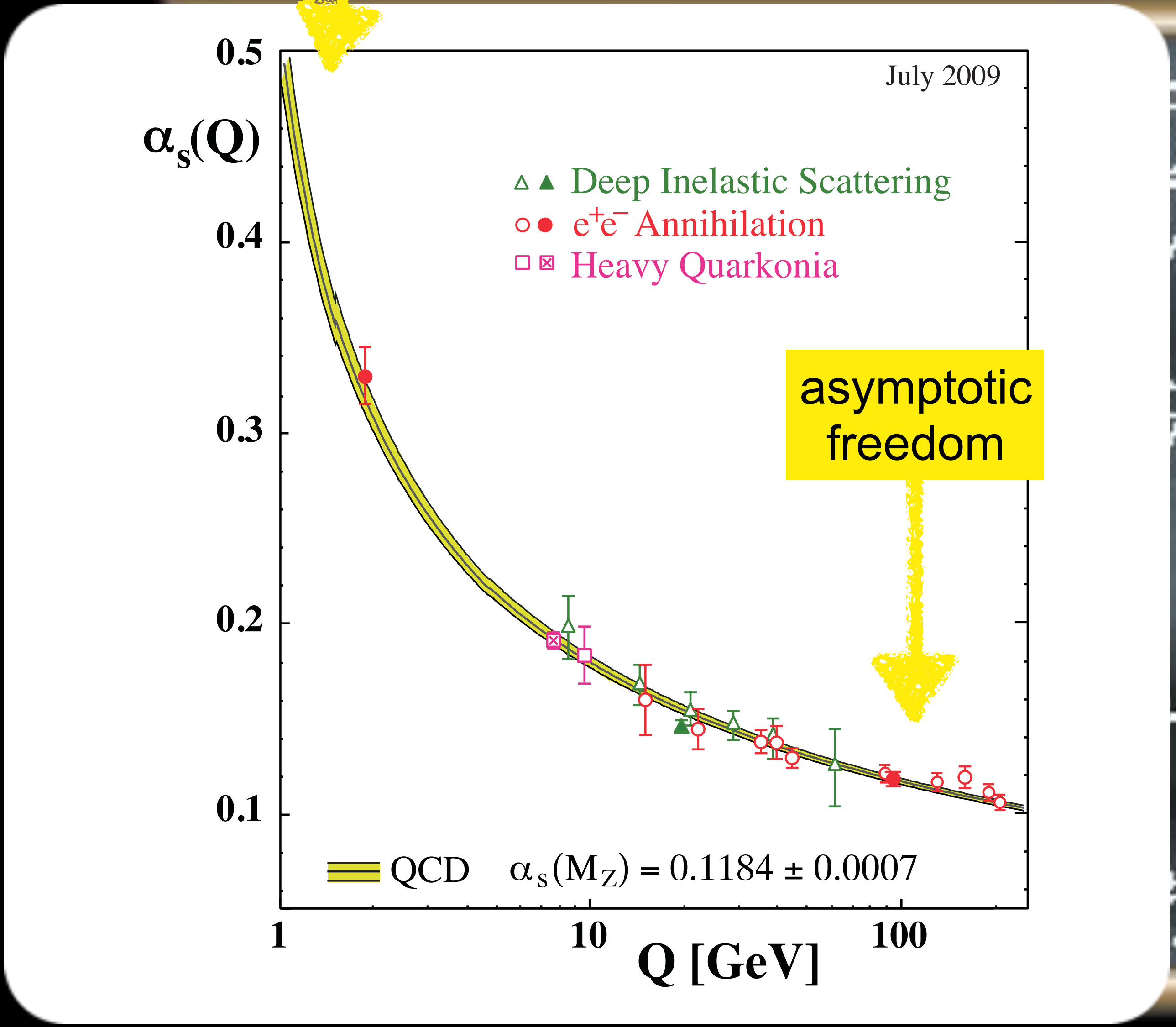
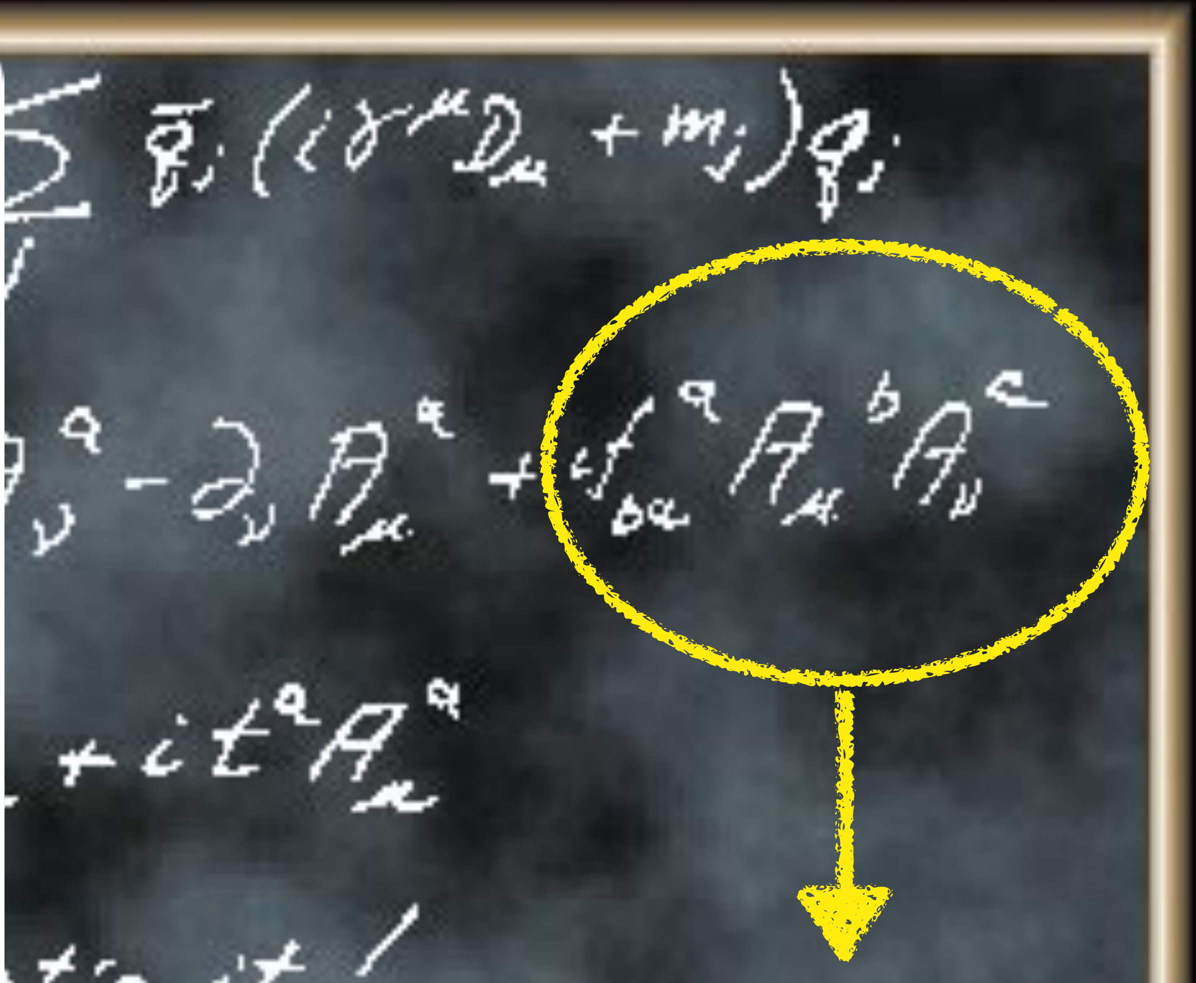
Quantum Chromodynamics

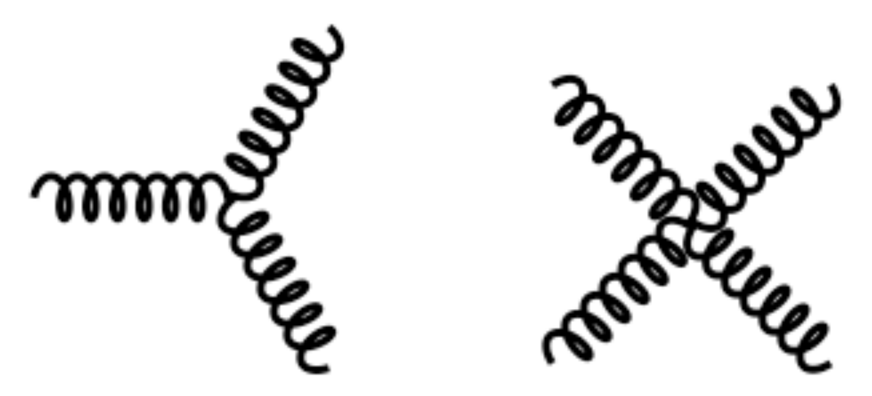
infrared slavery
(confinement)

It looks like QED, no?



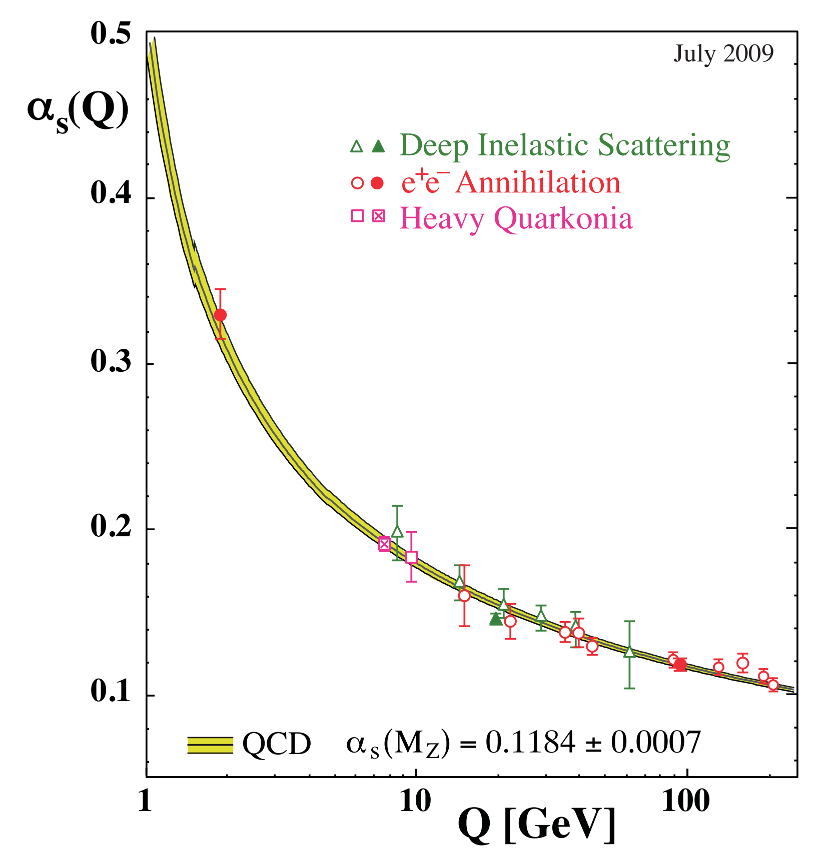
asymptotic
freedom



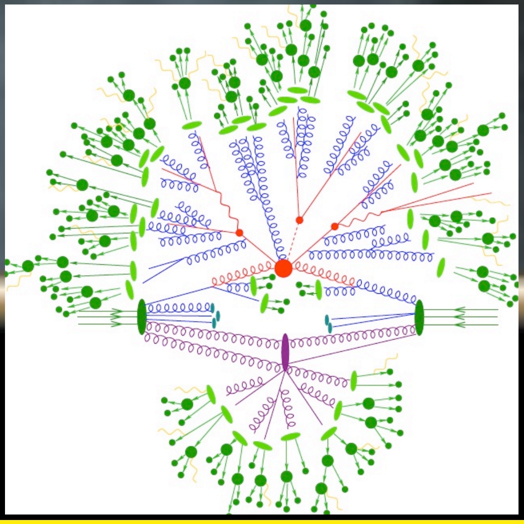


Well…it’s not!!!

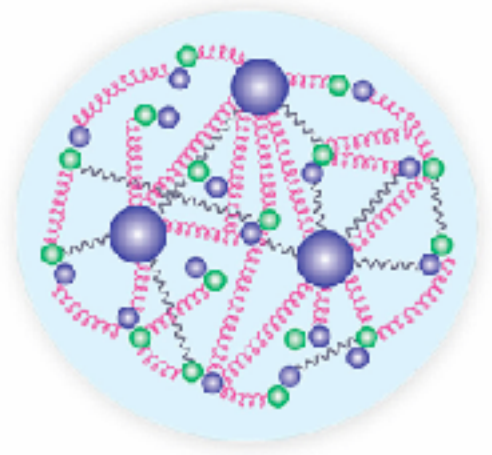
Studying QCD matter



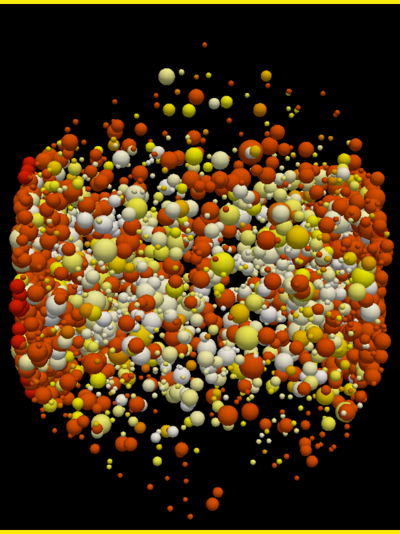
Hard scattering



Nuclear matter



Quark Gluon Plasma



Small α_s: calculations with perturbative QCD

Large α_s: calculations with Lattice QCD

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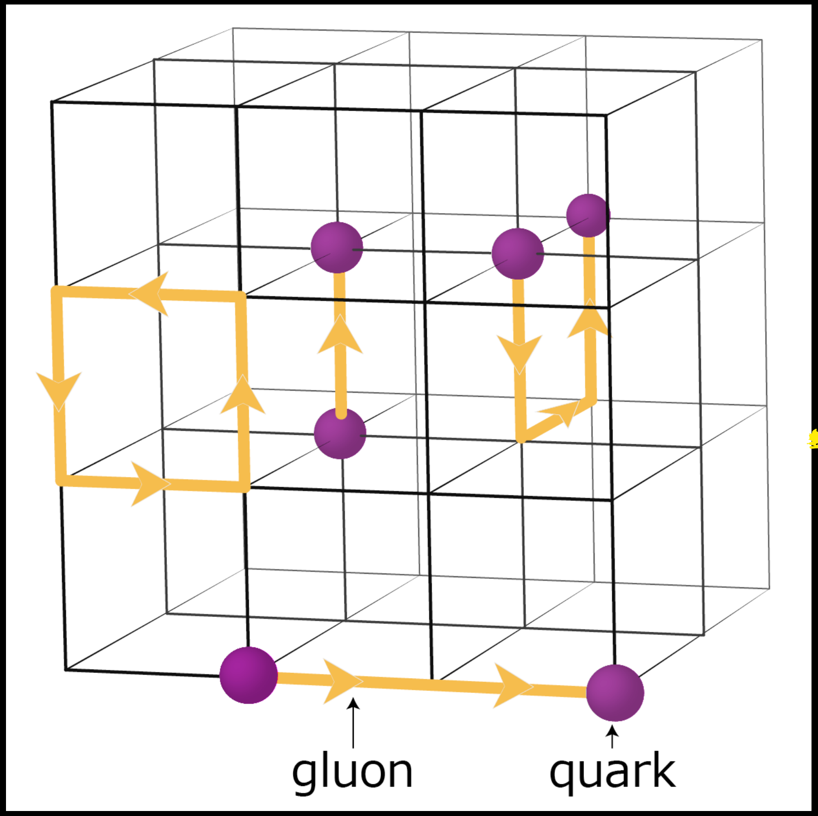
Strong phase transition: guidance from lattice calculations



- ✓ The Quark-Gluon Plasma (QGP):
  - a state of matter where the quarks and gluons behave as quasi free particles
  - 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 (~155 MeV) and energy density (~0.5 GeV/fm^3) ➞ accessible in the laboratory ➞ heavy-ion collisions

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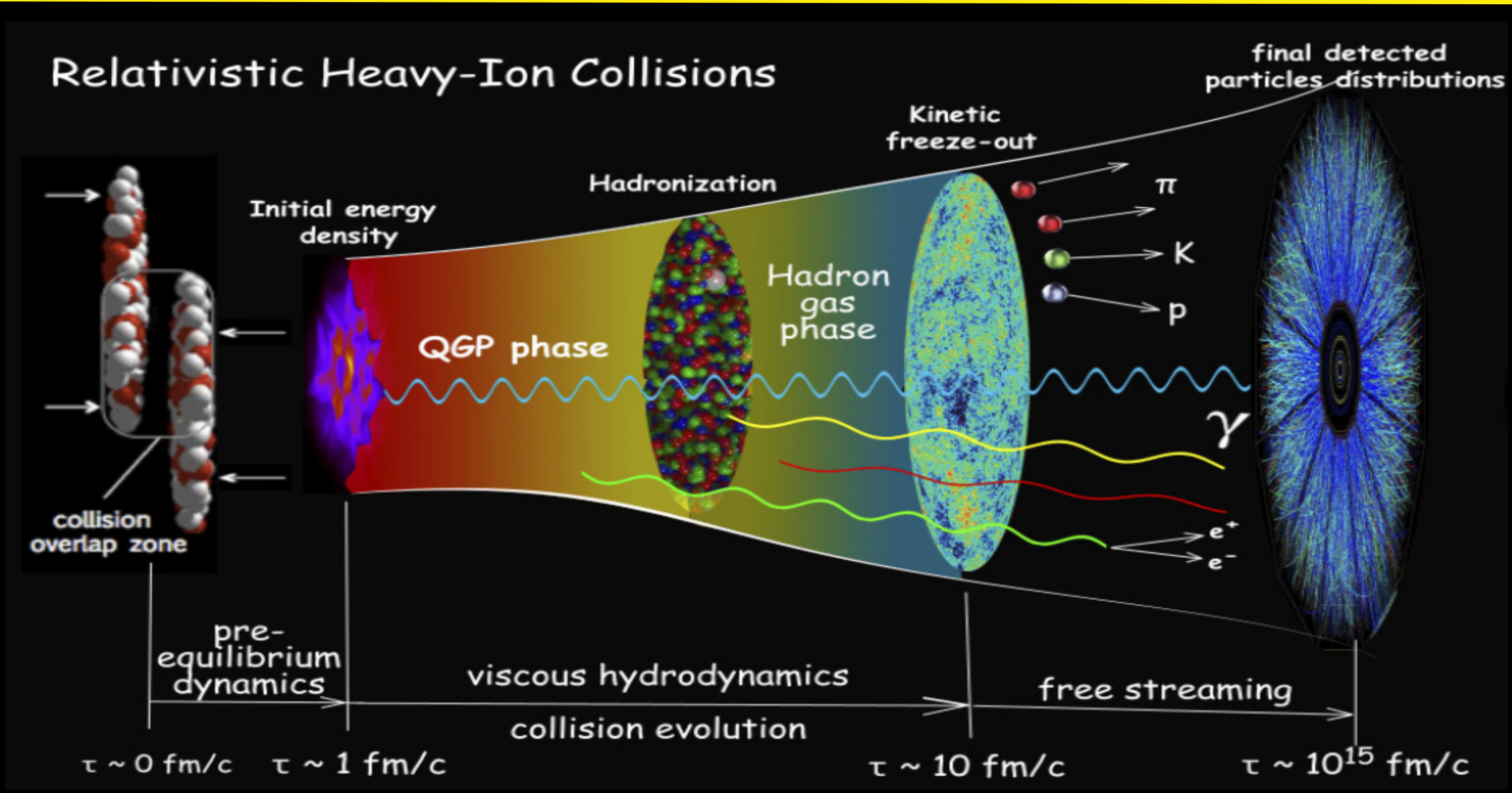
From the Big-Bang to the Little-Bangs…



$T_{\text{(QGP-transition)}}$~155 MeV
→ 10^{12} degrees

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

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

What are the degrees of freedom?
Can we constrain the equation of state and the transport properties of QGP?

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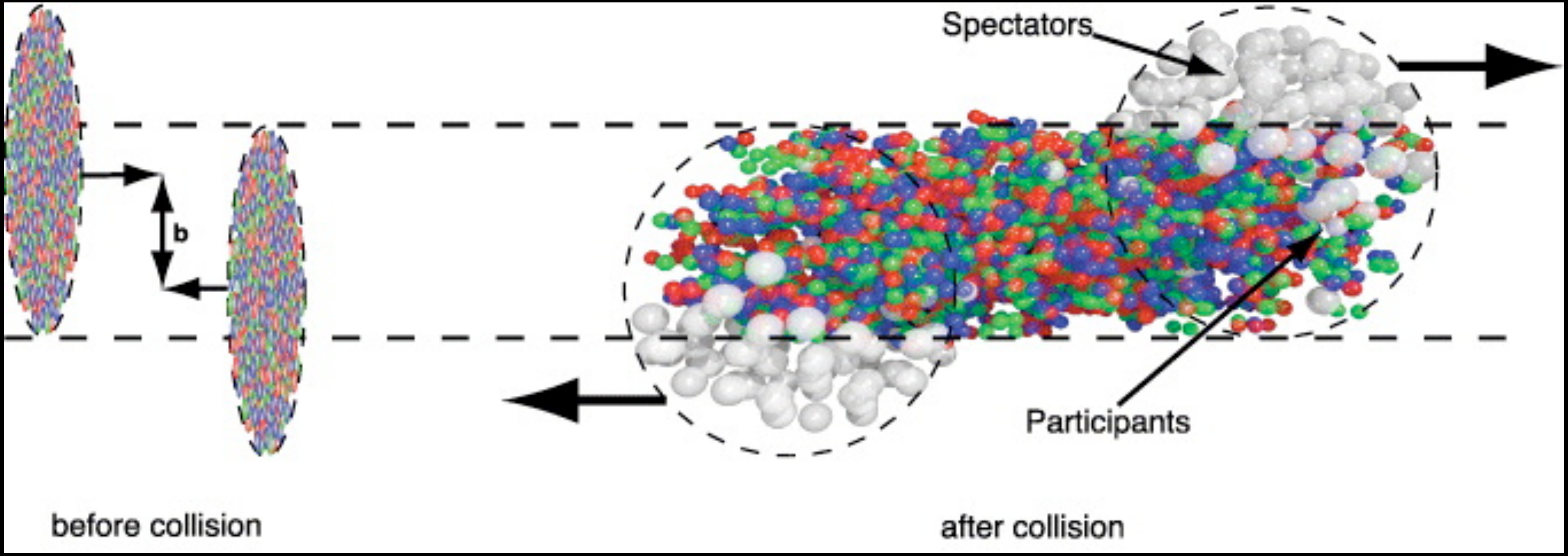
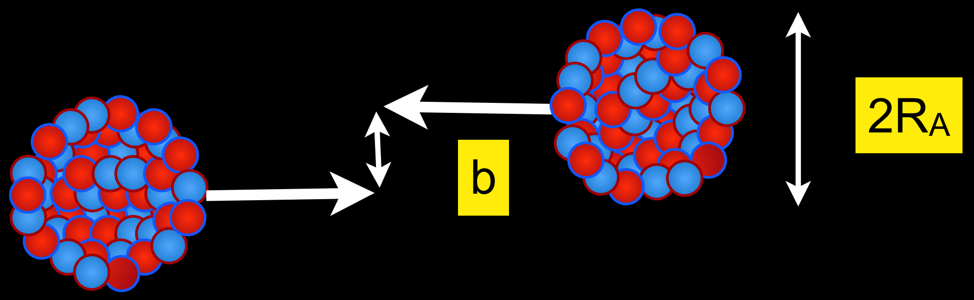
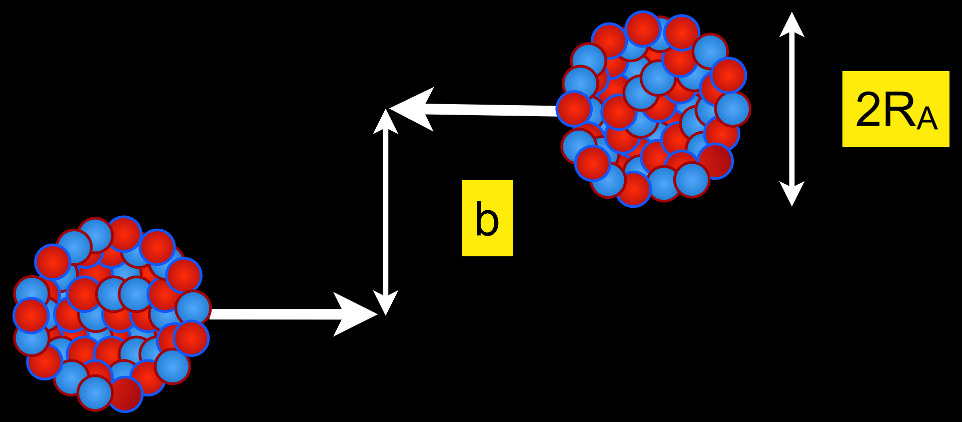
Centrality in heavy-ion collisions



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 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





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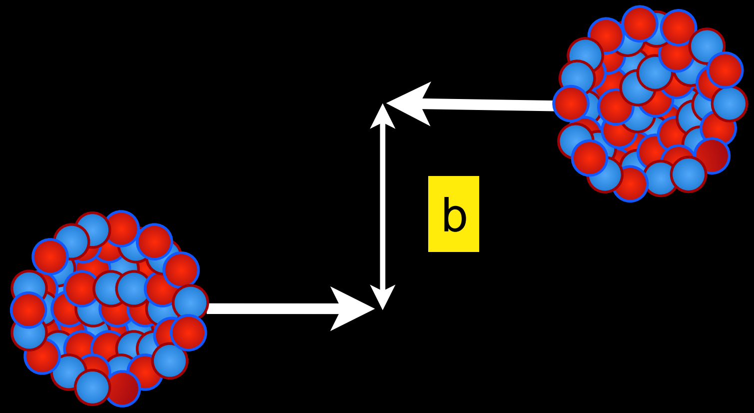
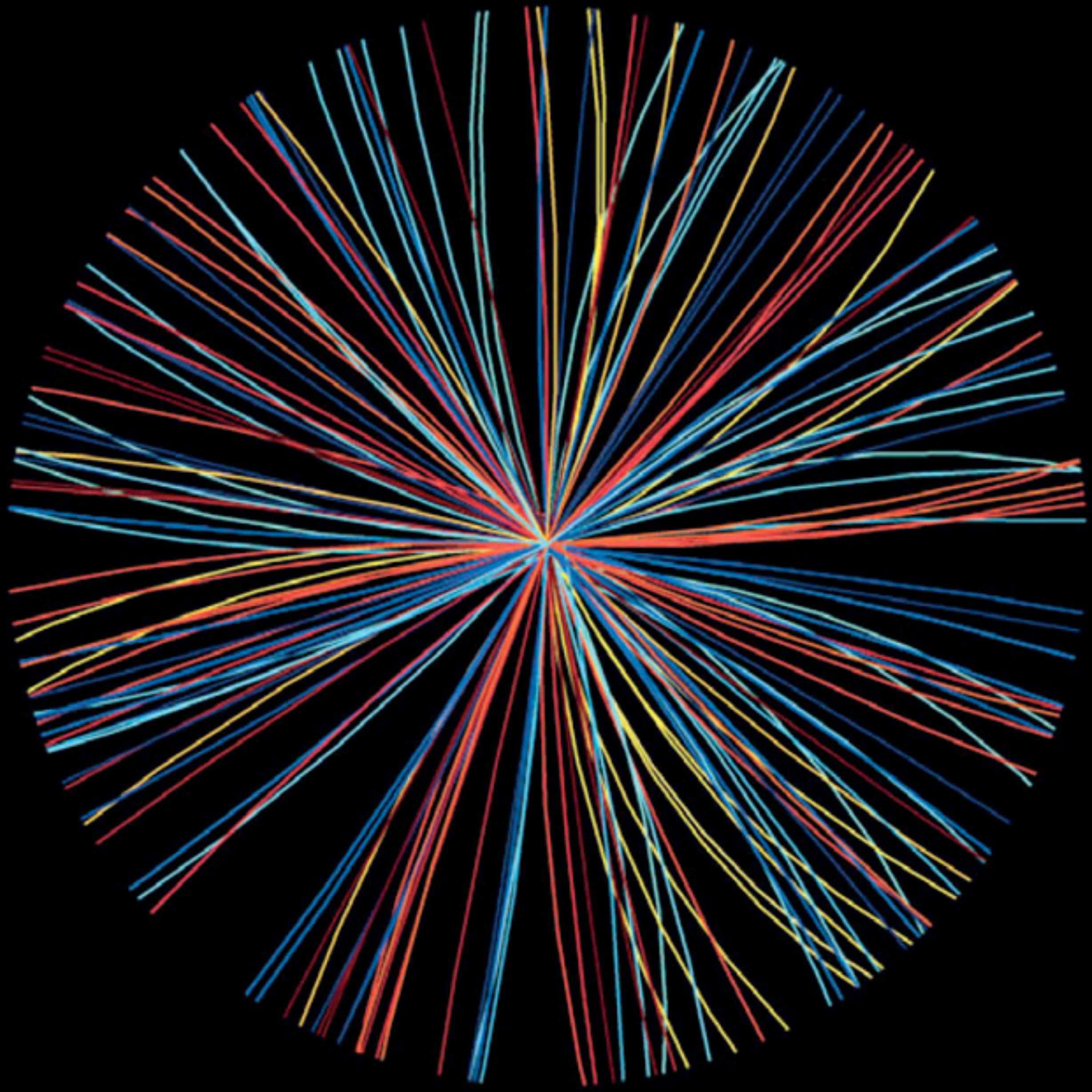
Peripheral collisions: few particles





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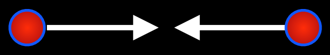
pp collisions: (really) few particles



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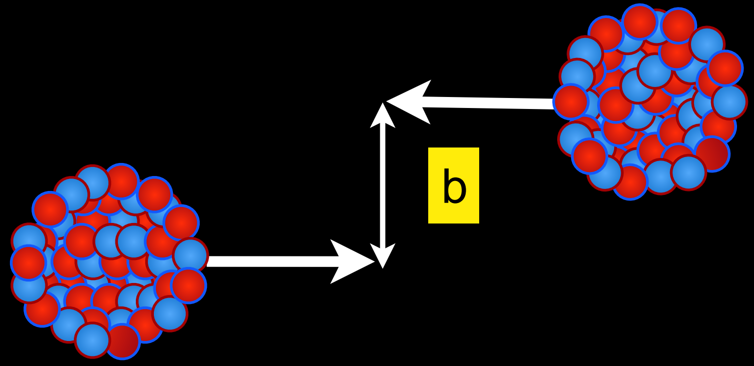
Mid-central collisions: more particles



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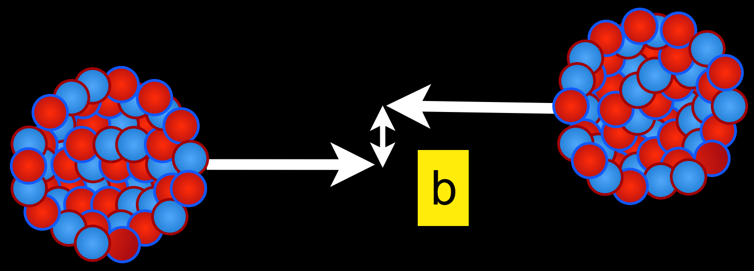
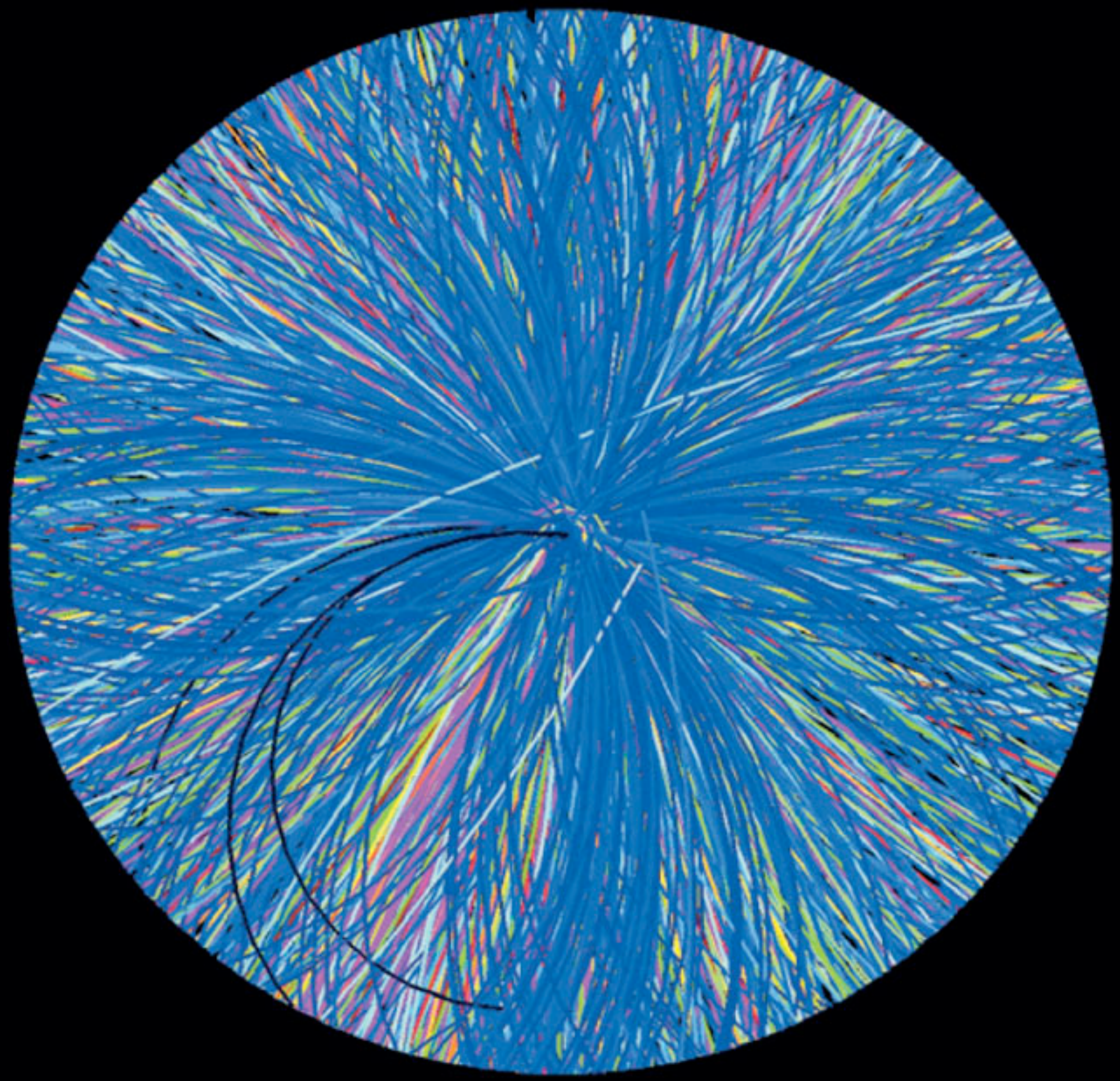
Central collisions: even more particles





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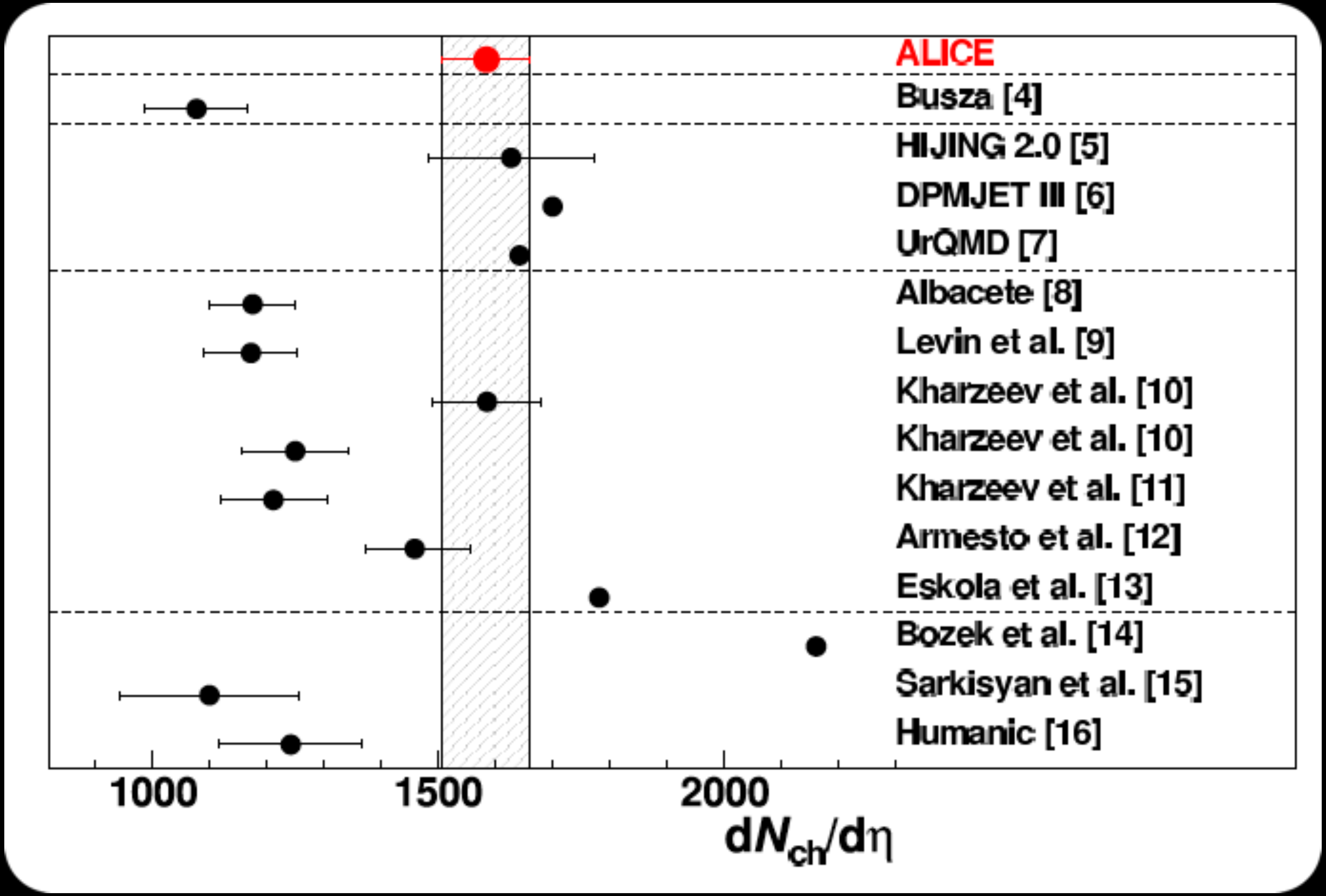
Measured particle multiplicity in central collisions

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



~1600 (~2000 at 5 TeV) particles in the central region (not the whole phase space) in central Pb-Pb collisions at 2.76 TeV!!!

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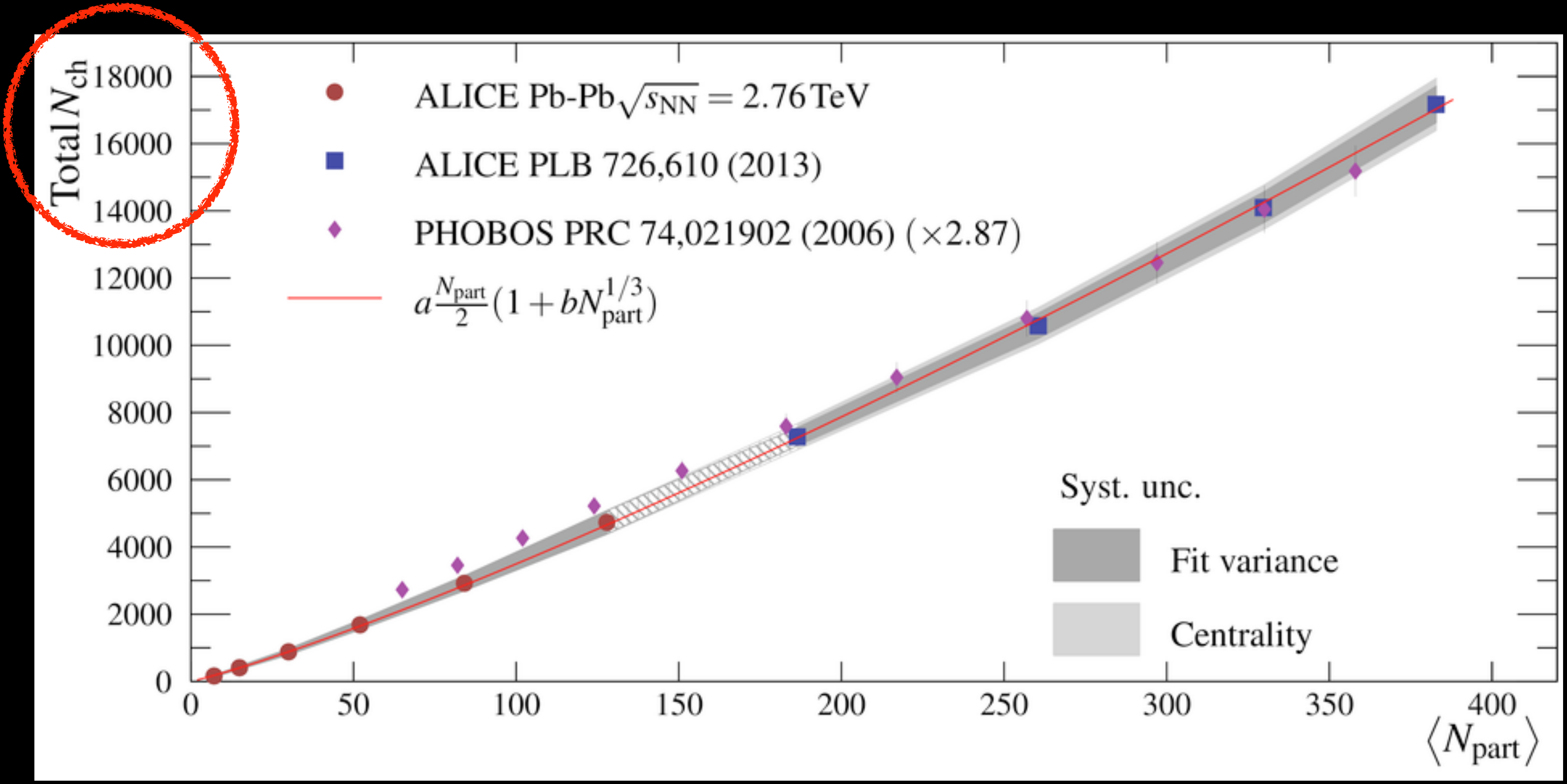
Particle multiplicity in ALICE @ the LHC

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



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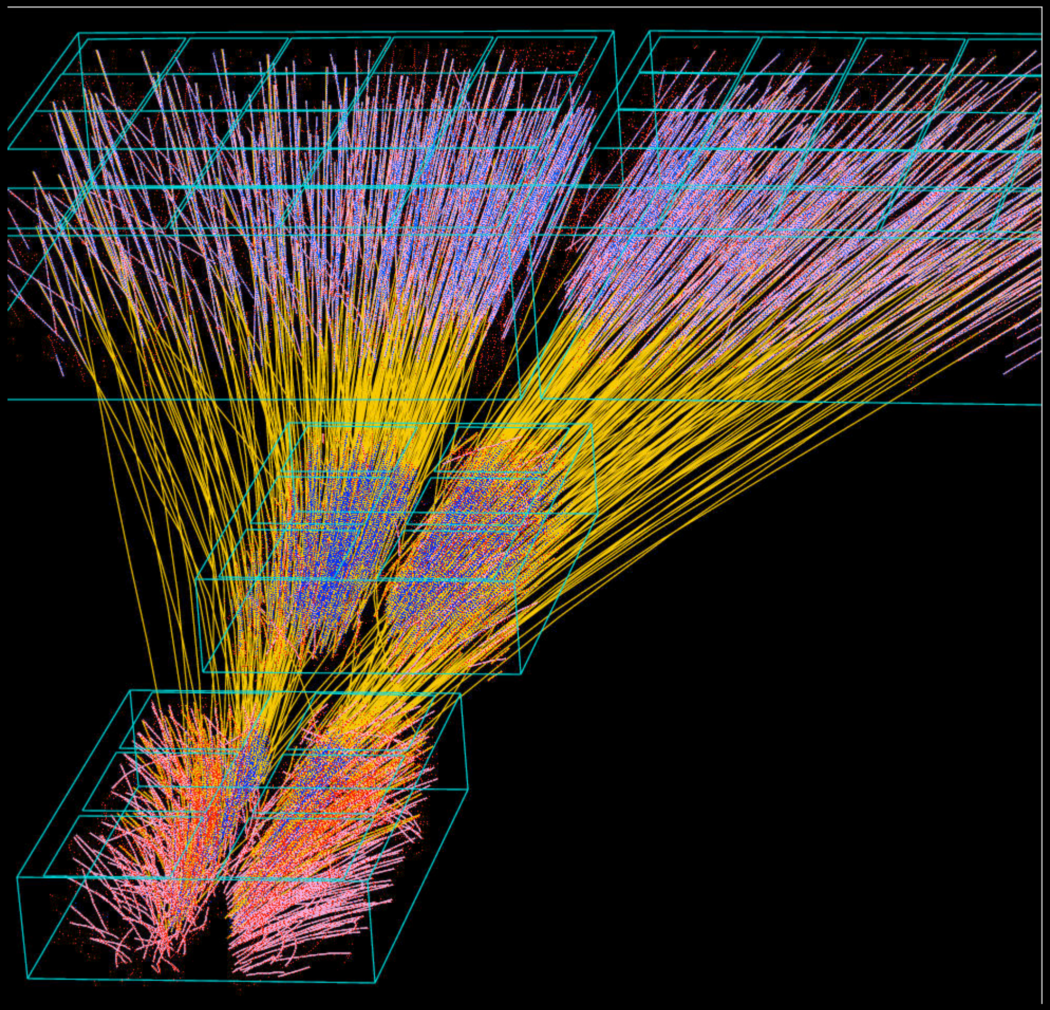
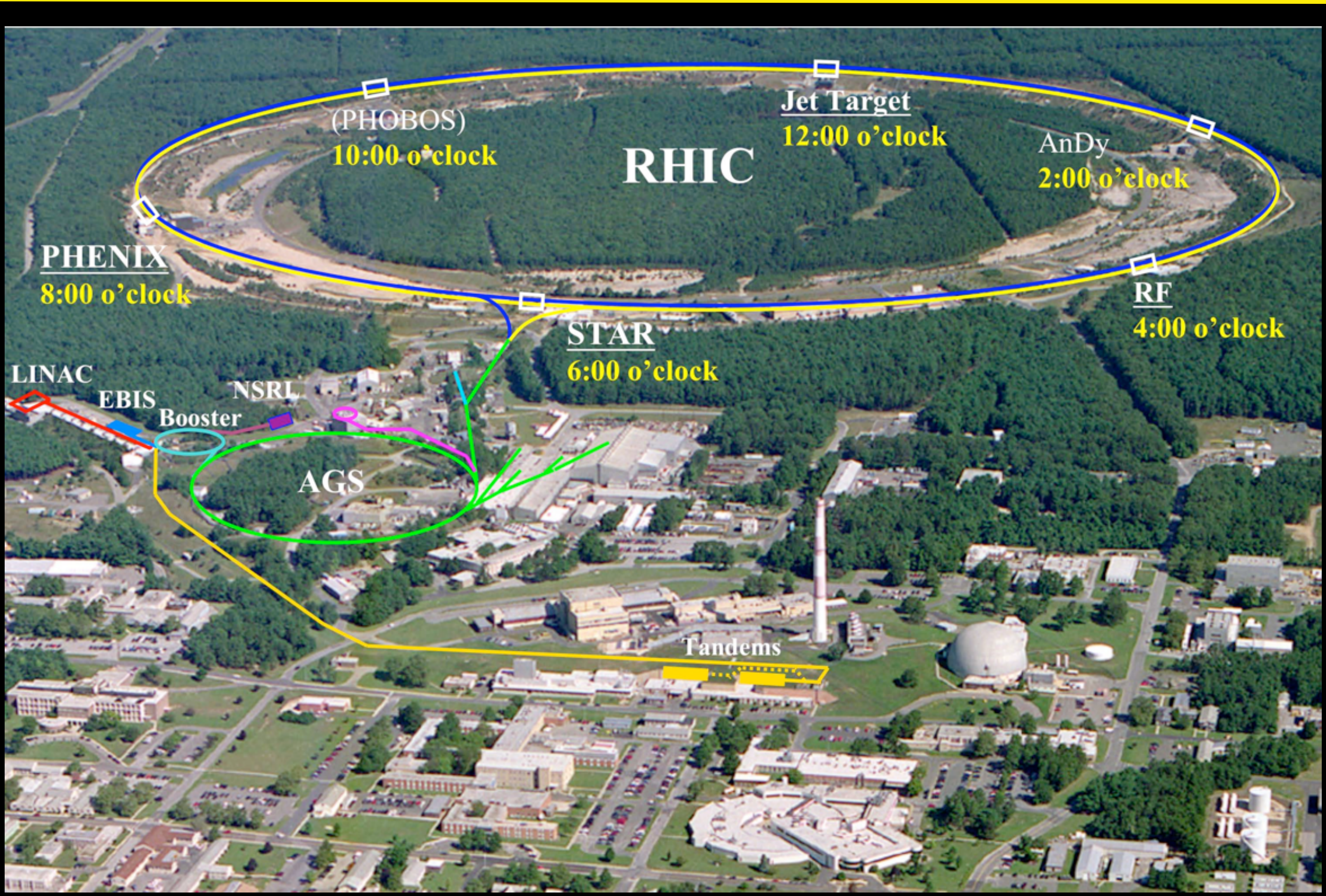
Heavy-ion physics: SPS (CERN) (~1990)

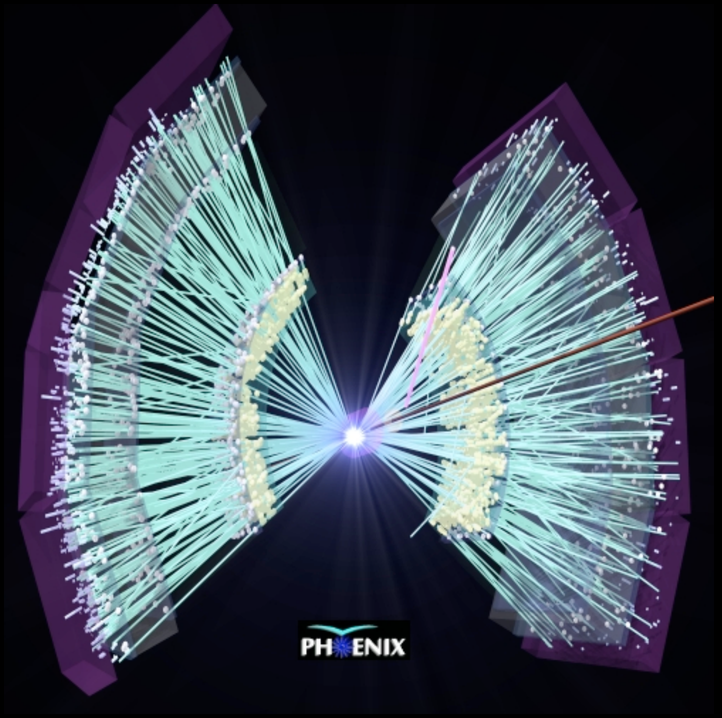
Fixed target experiments
(event display courtesy of NA49)

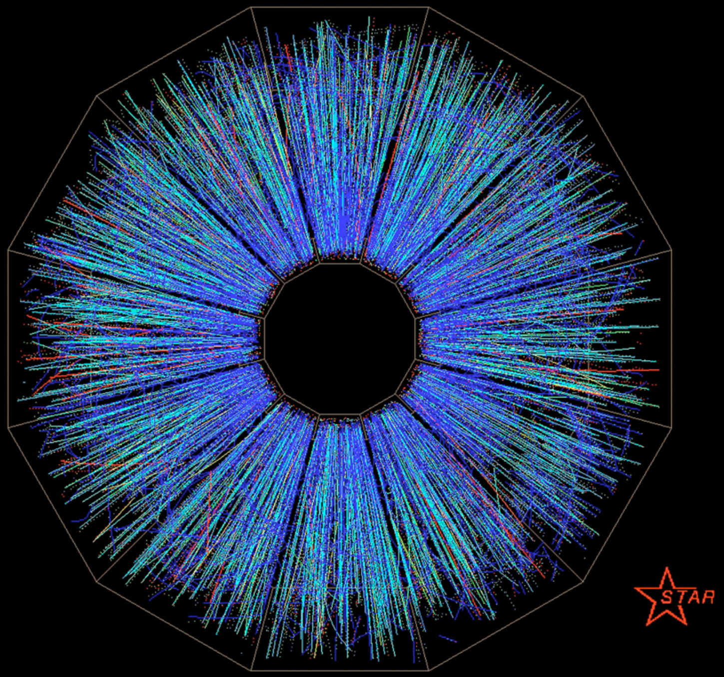


Heavy-ion physics: RHIC (BNL) (~2000)



Collider experiments (event displays courtesy of PHENIX and STAR)





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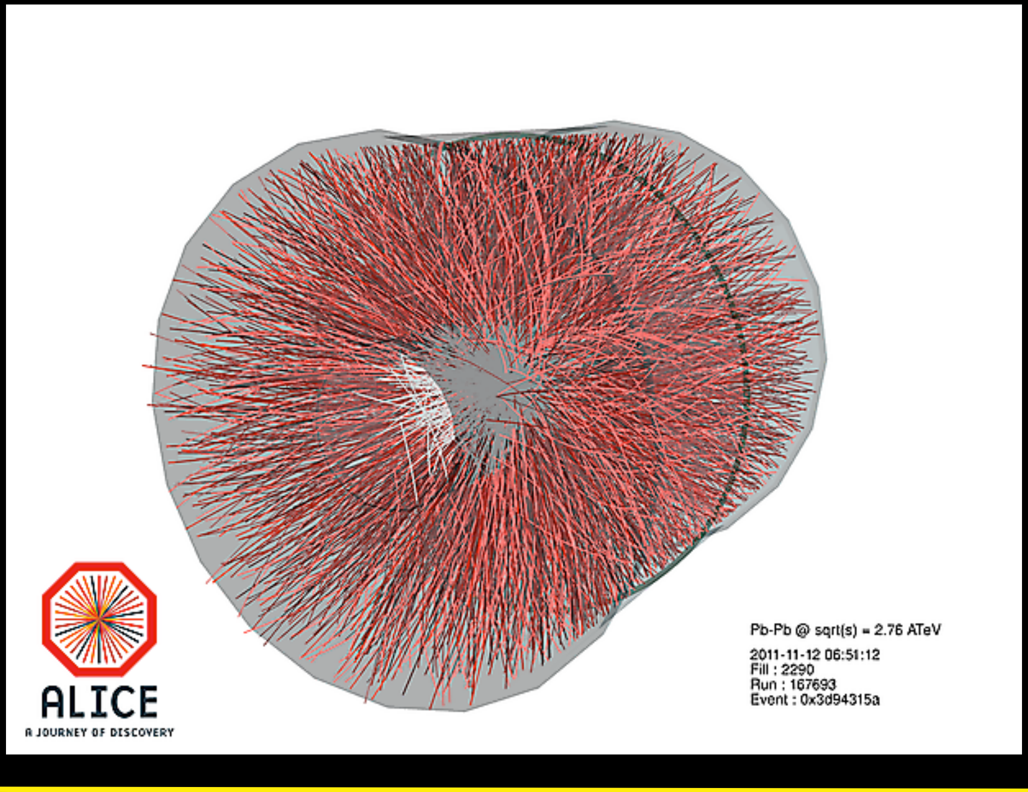
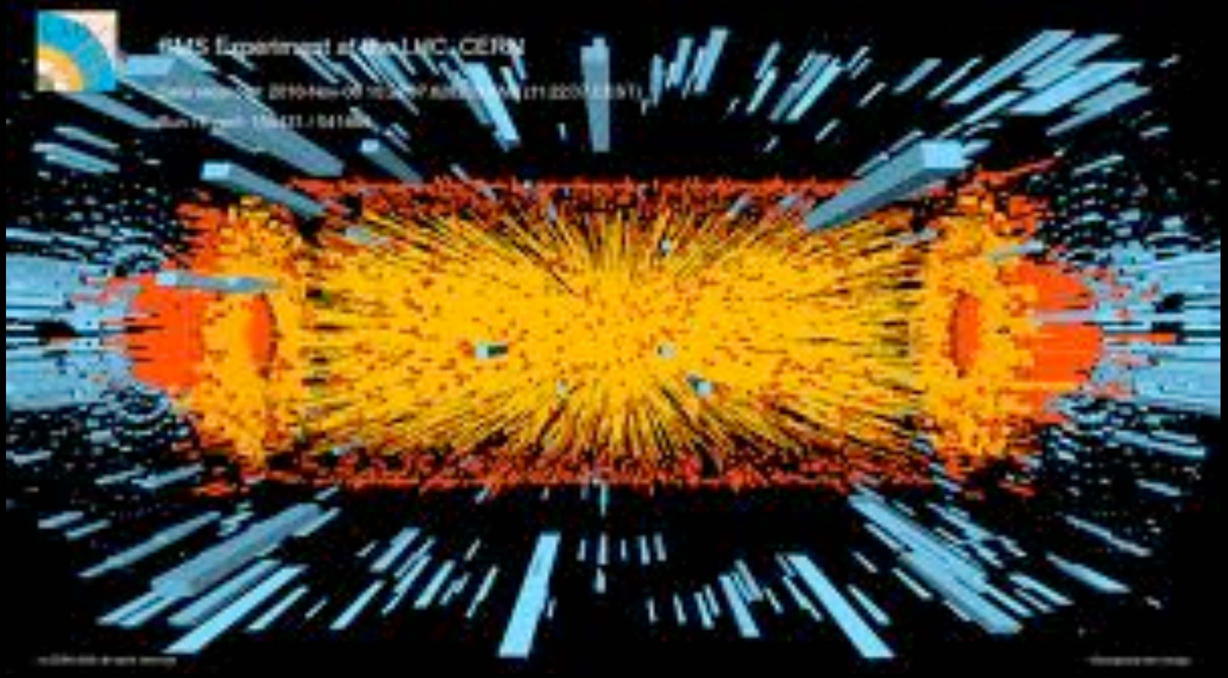
Heavy-ion physics: LHC (CERN) (2010)





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The heavy-ion guys…

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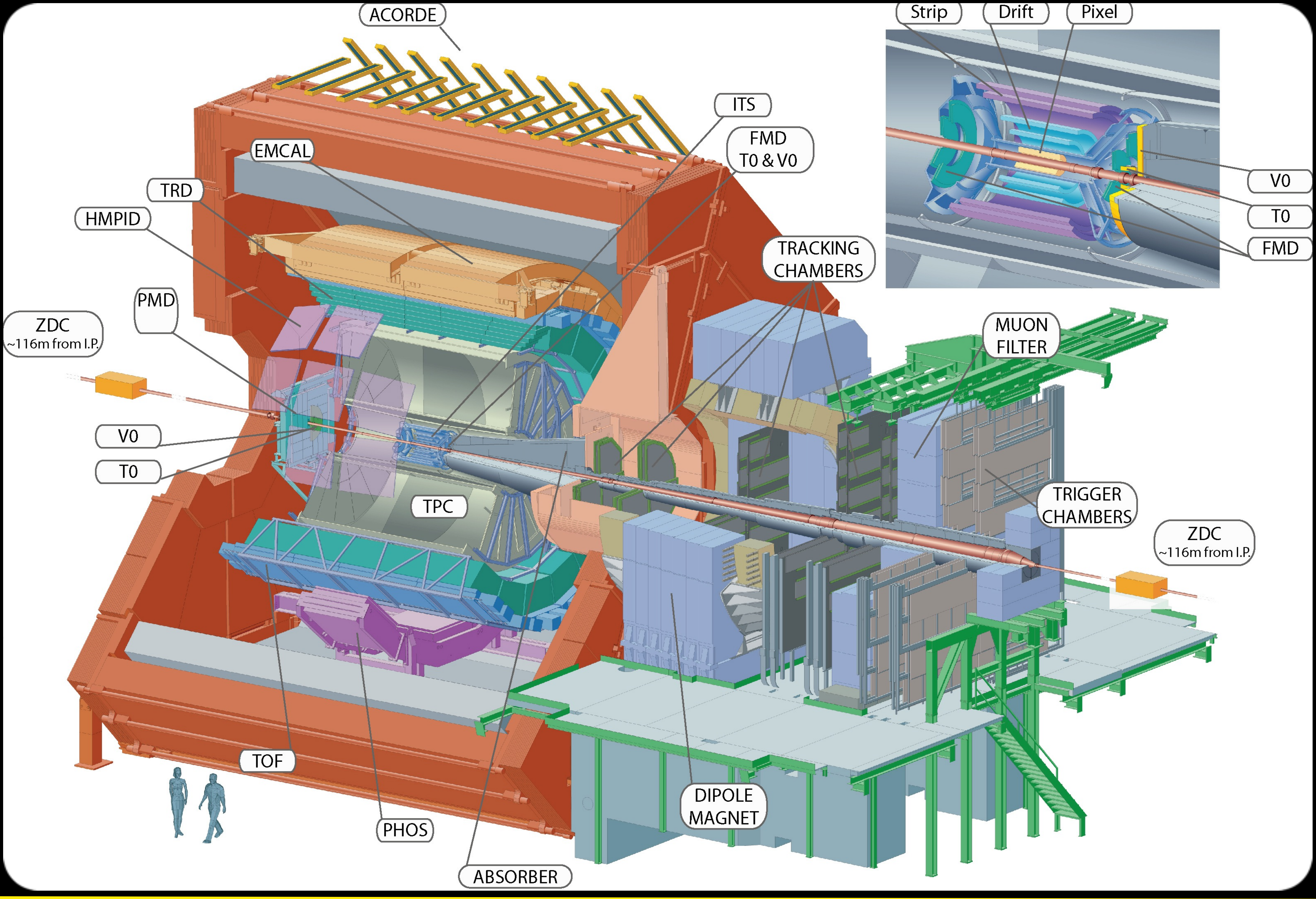
Experimental setup



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Revealing the nature of the QGP

- ✓ Heavy-ion physics is an experimentally driven field
- ✓ Strong guidance from theory (lQCD, pQCD) but…
  - No smoking gun signature e.g. invariant mass peak (Higgs discovery)
- ✓ Need for new, creative ideas with robust and as less biased as possible observables

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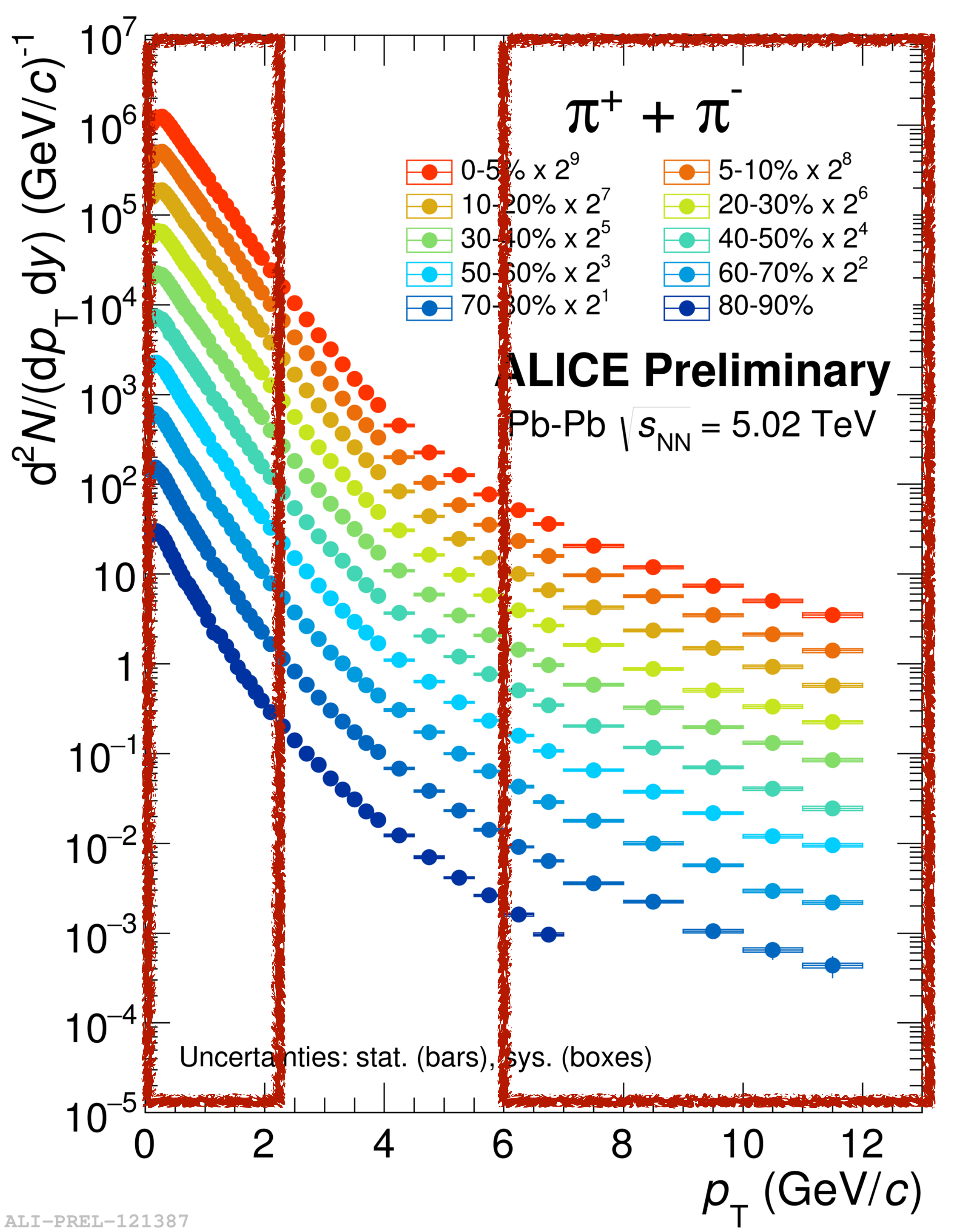
Probing the properties of the QGP

- ✓ Two main ways to probe the QGP properties:



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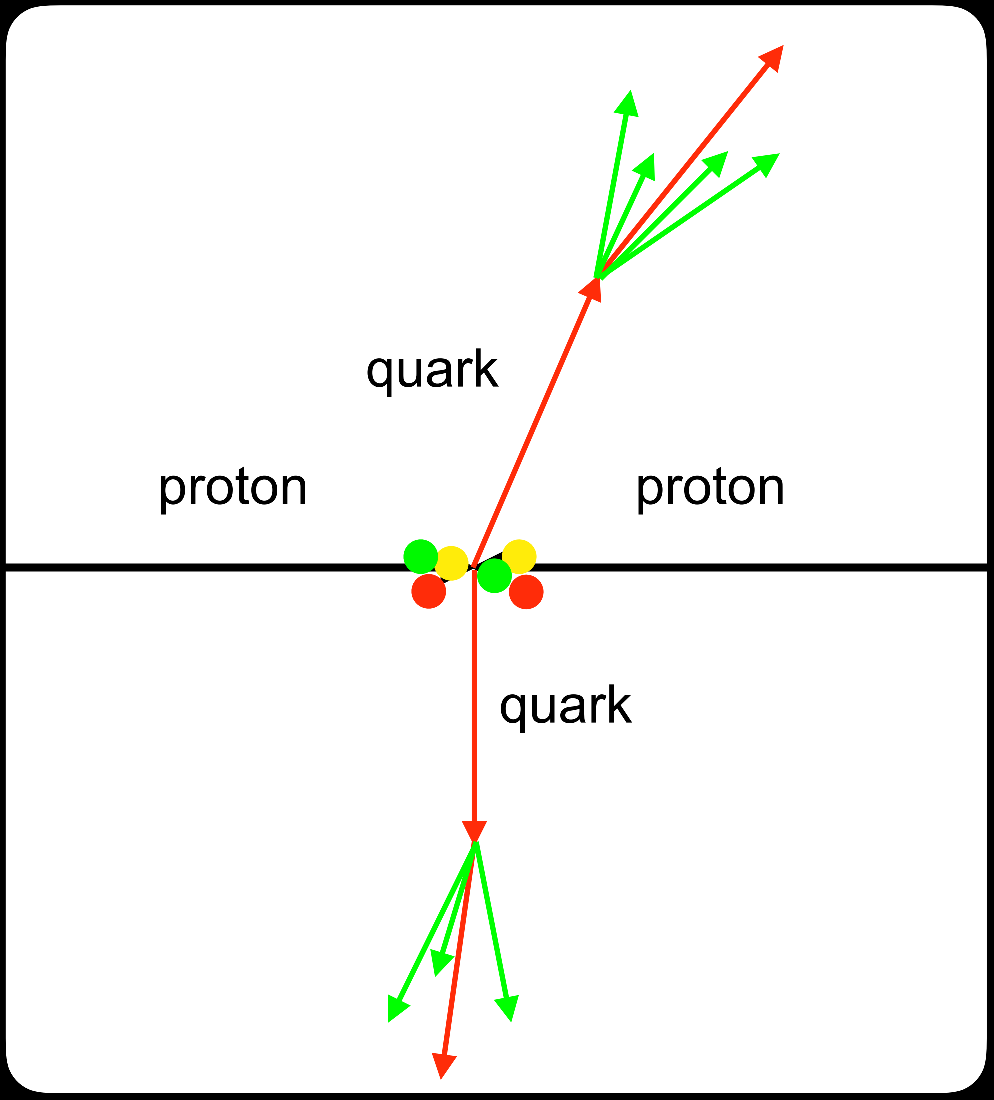
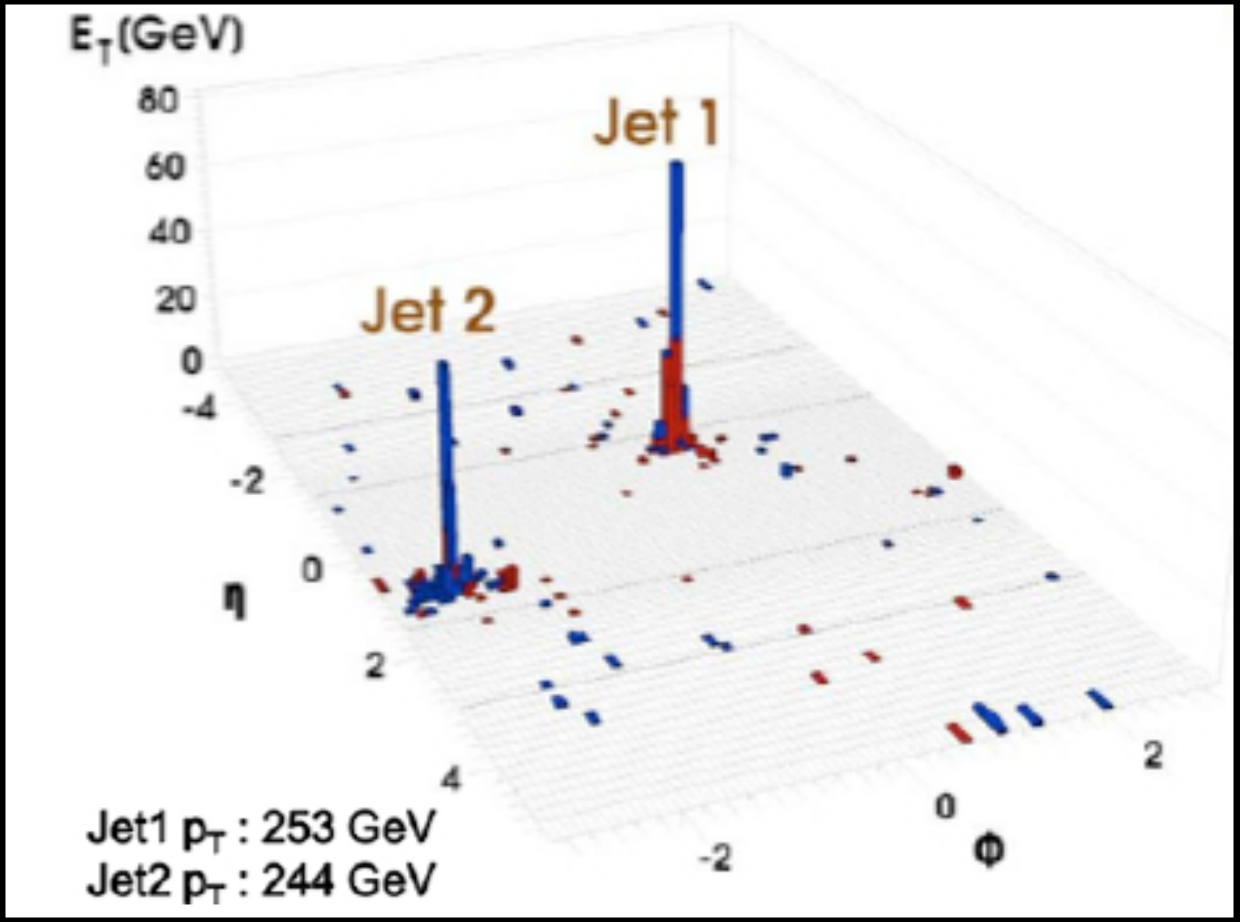
QGP imaging through hard probes: control experiment



- ✓ 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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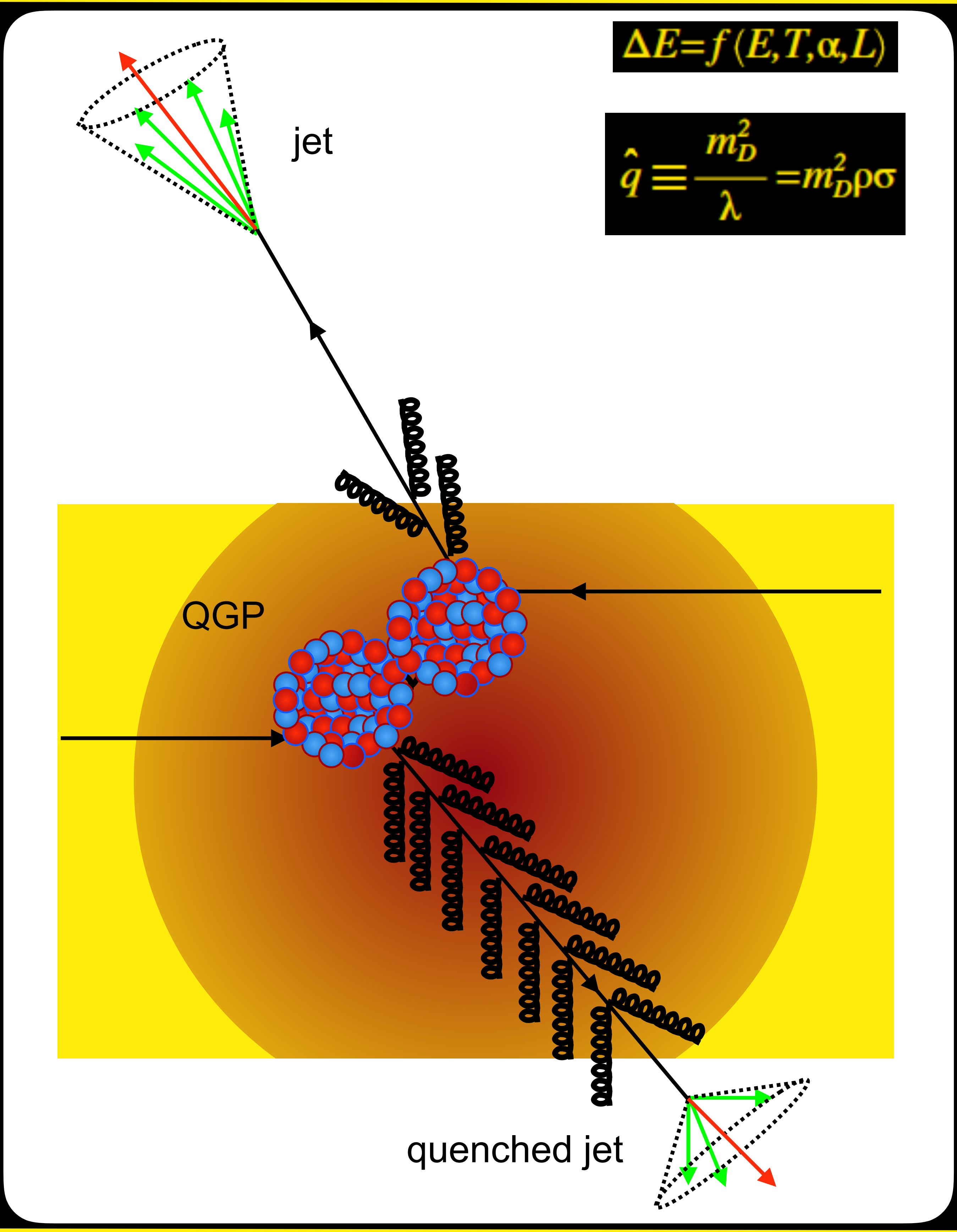
QGP imaging through hard probes: jet quenching

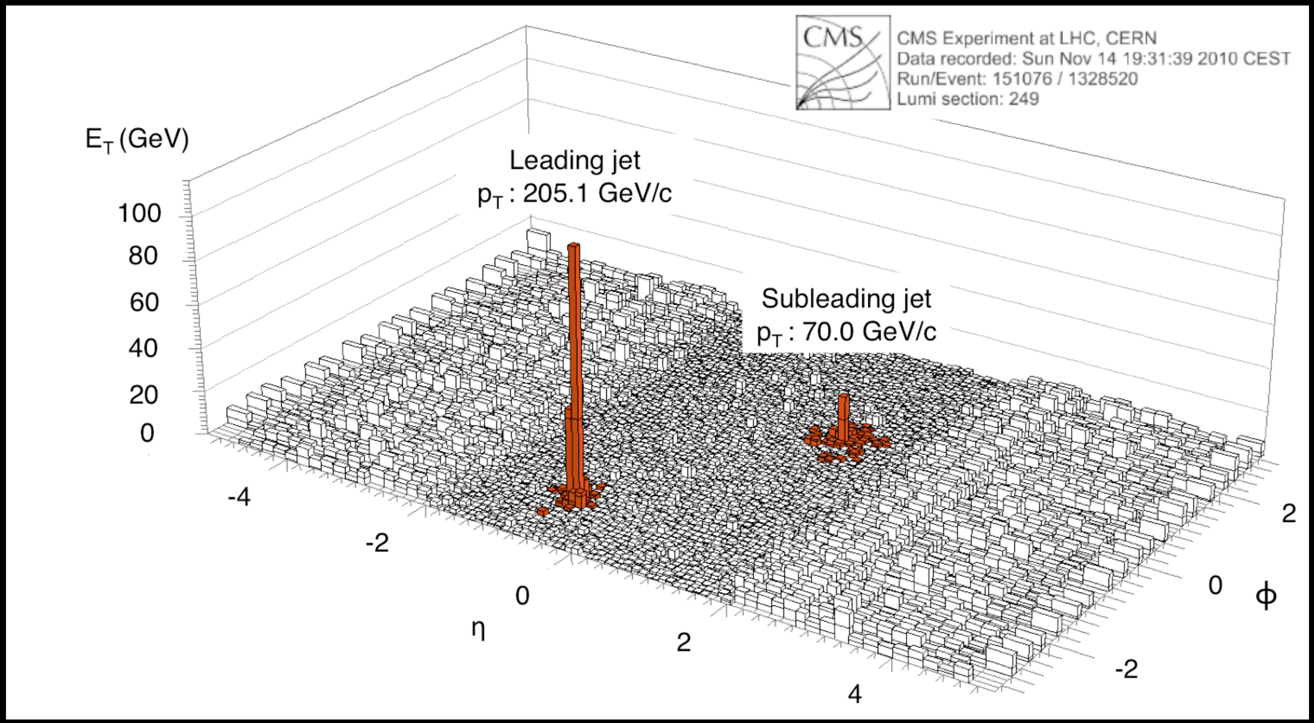


$$\Delta E = f(E, T, \alpha, L)$$

$$\hat{q} \equiv \frac{m_D^2}{\lambda} = m_D^2 \rho \sigma$$

- ✓ 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

The medium is very dense!!!



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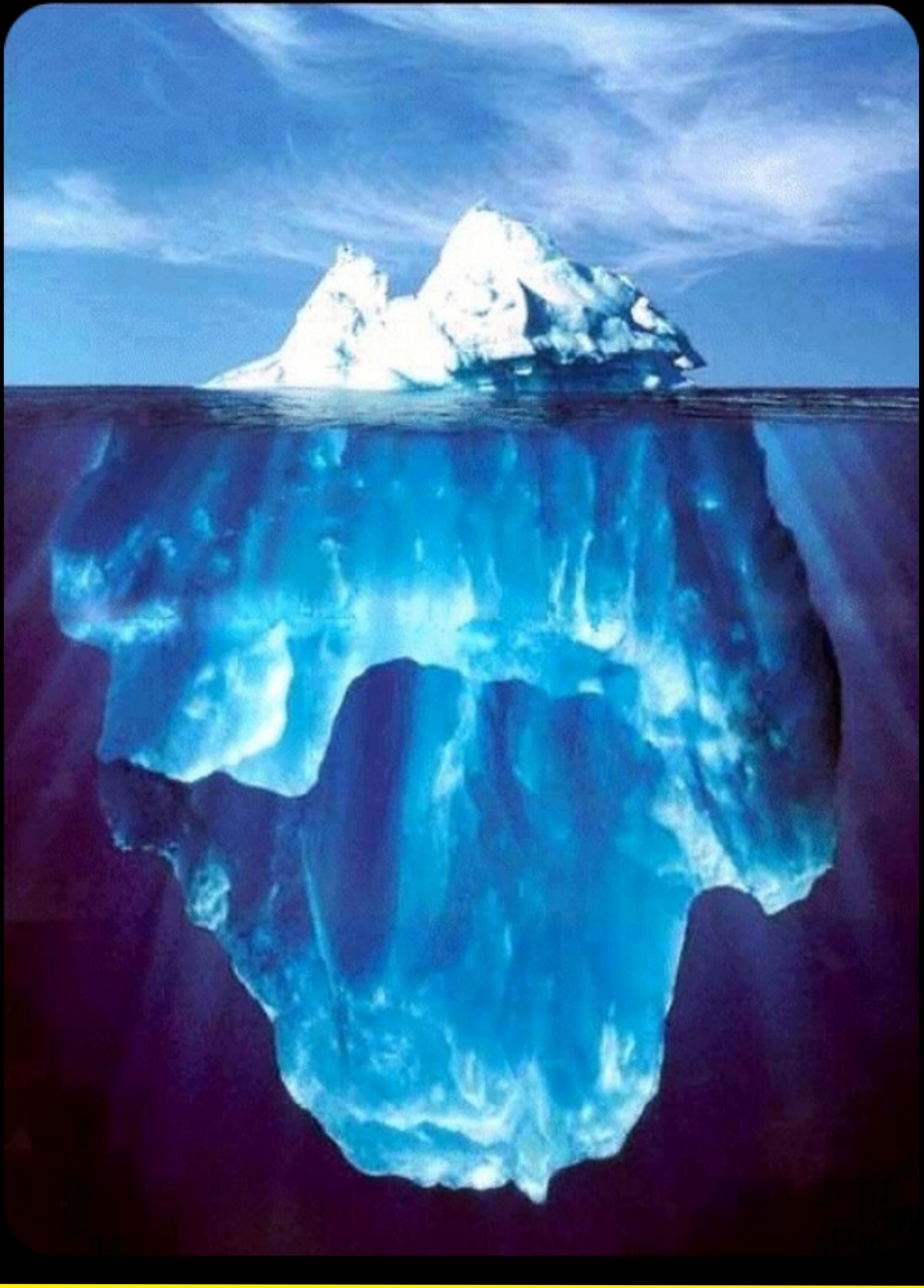
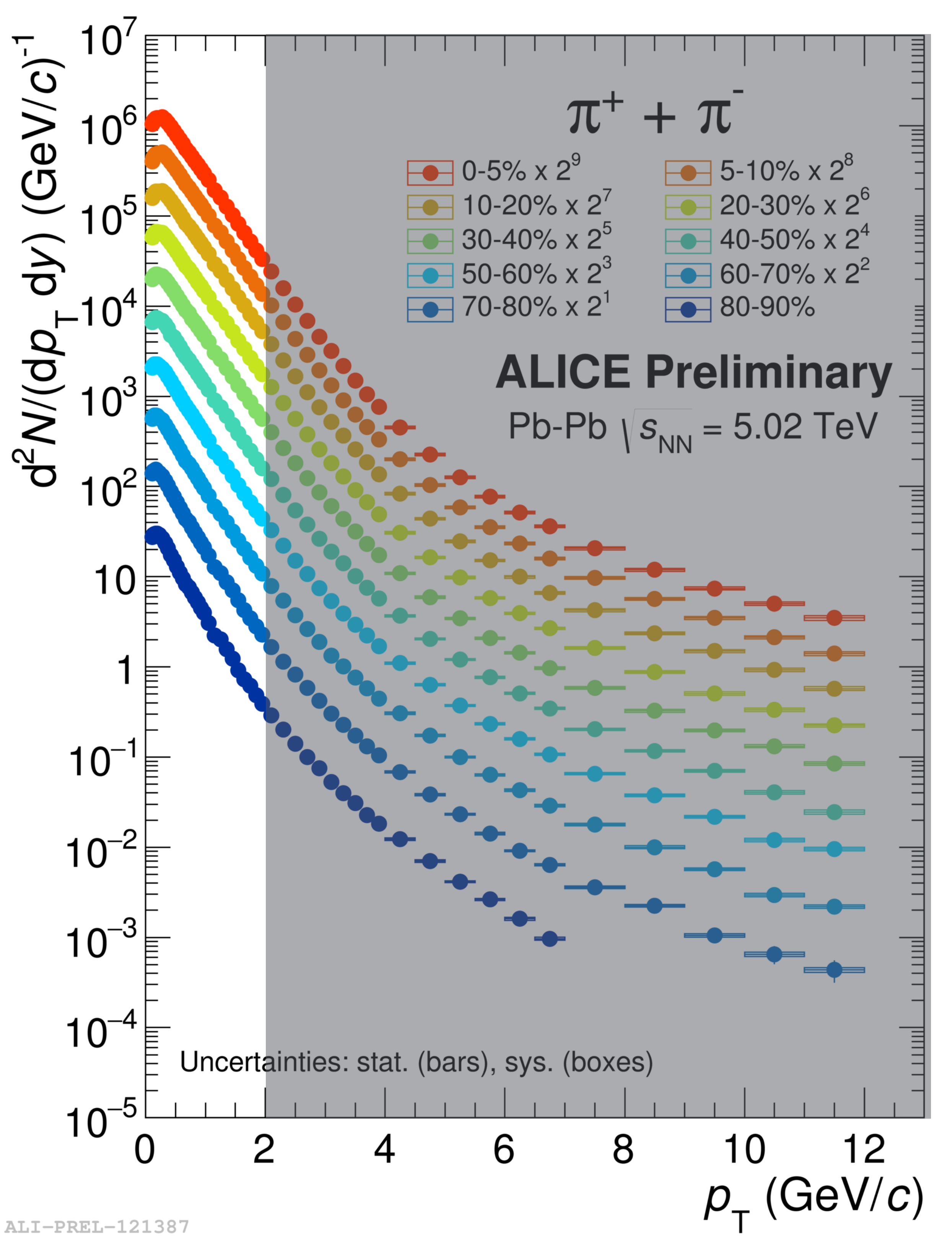
The other 99.9%…aka bulk particle production (and observables)





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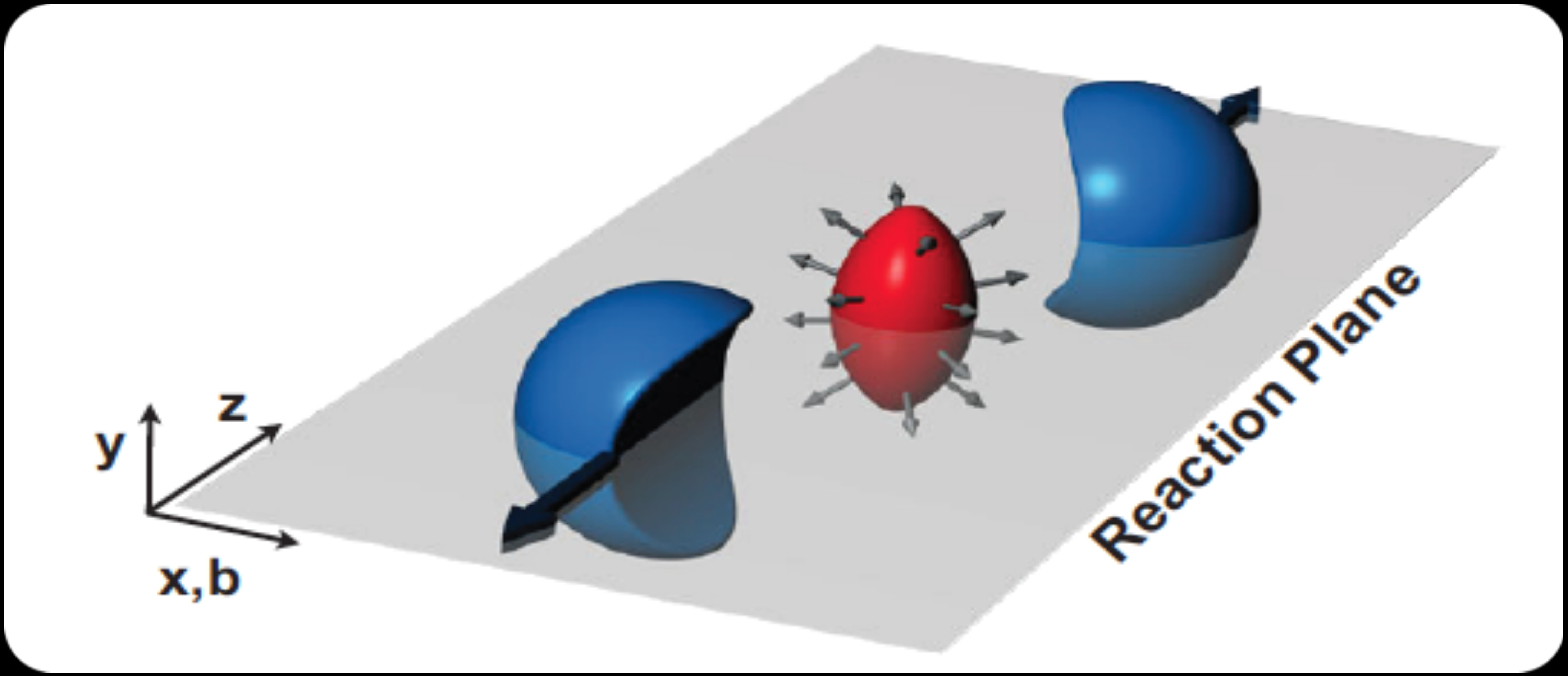
Bulk observables: Anisotropic flow



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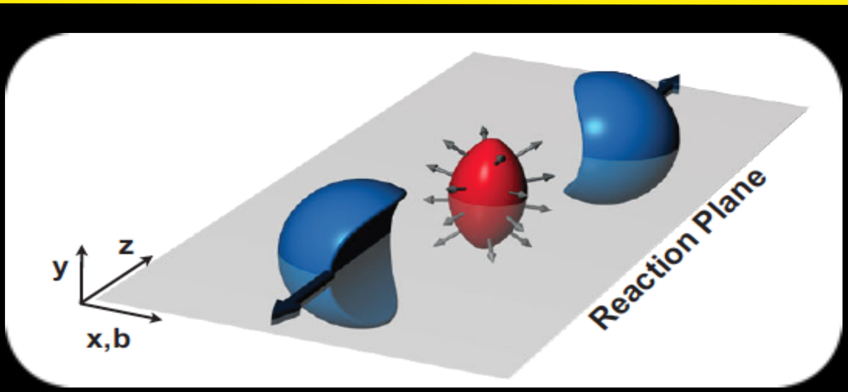
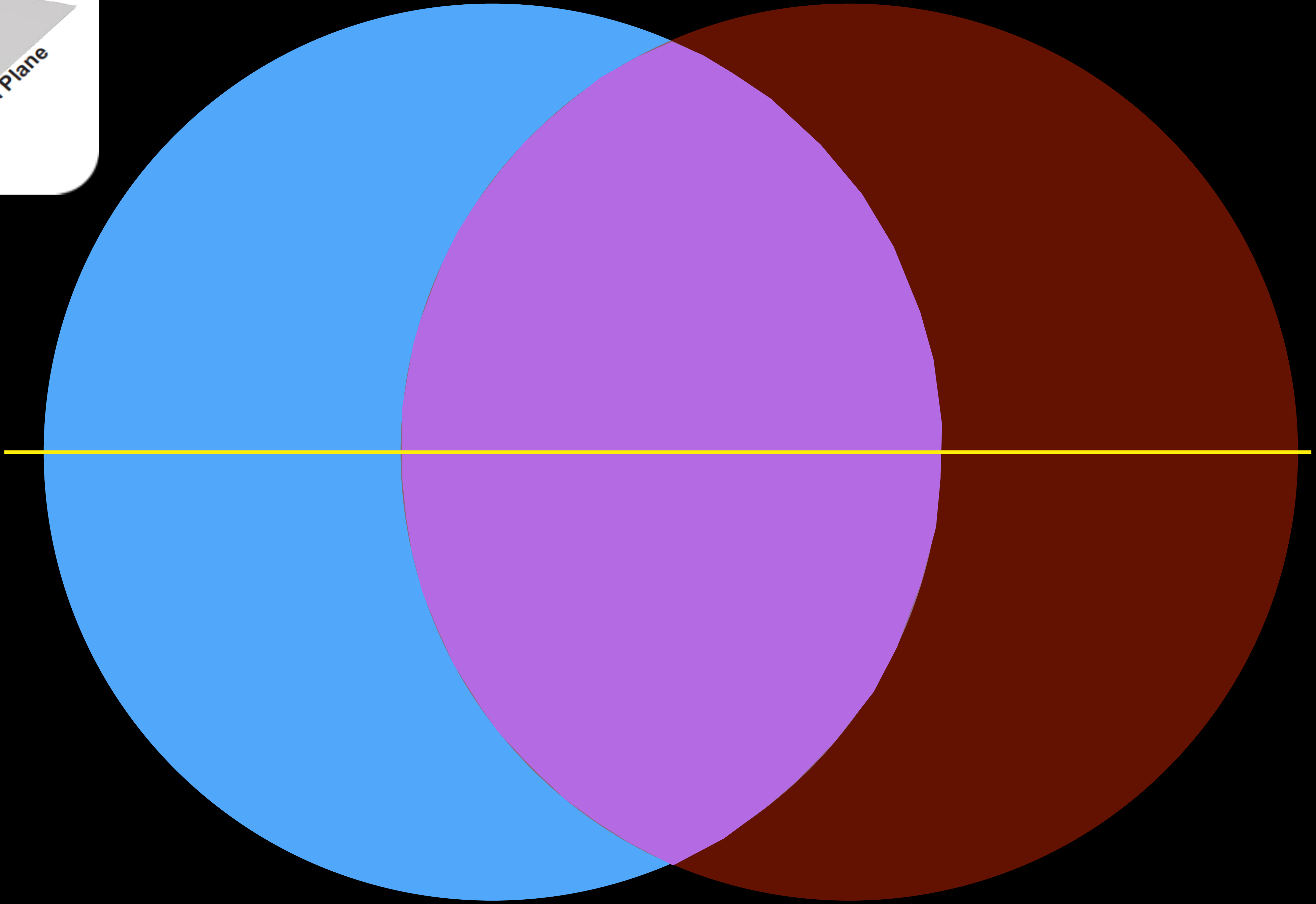
Bulk observables: Anisotropic flow





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

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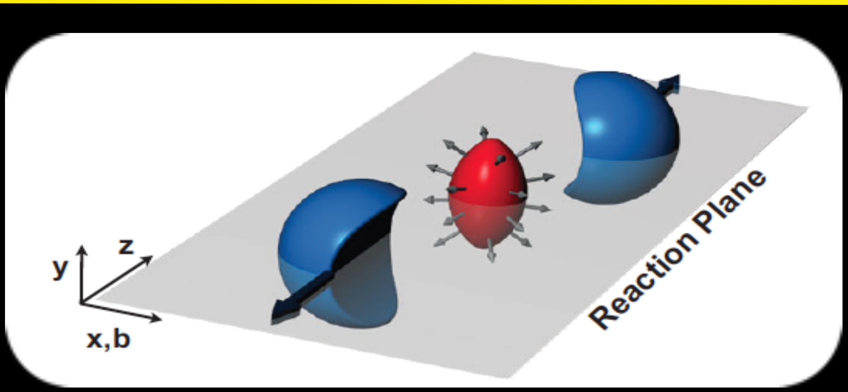
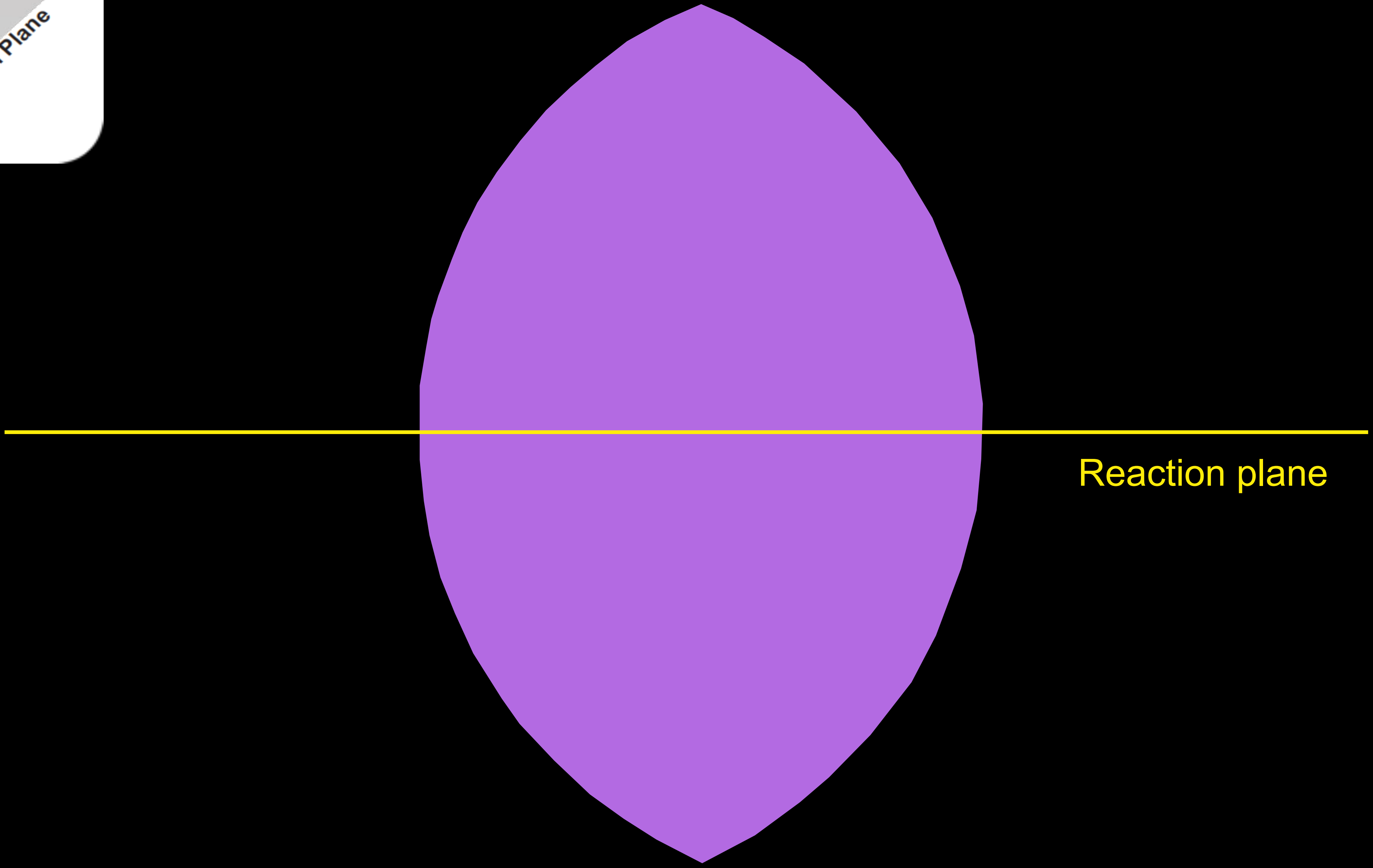
Bulk observables: Anisotropic flow




Reaction plane

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

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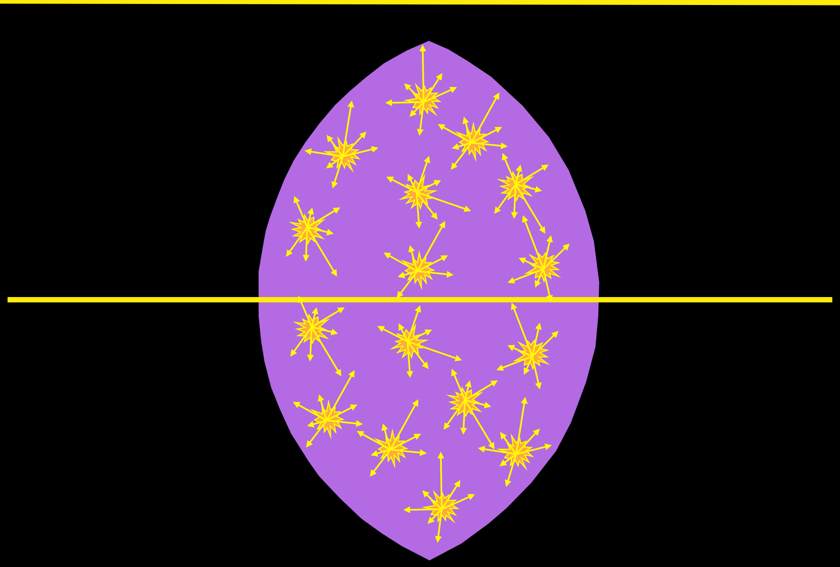
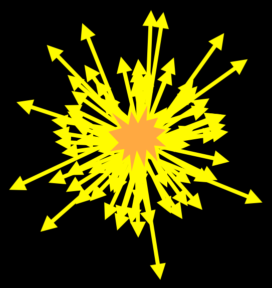
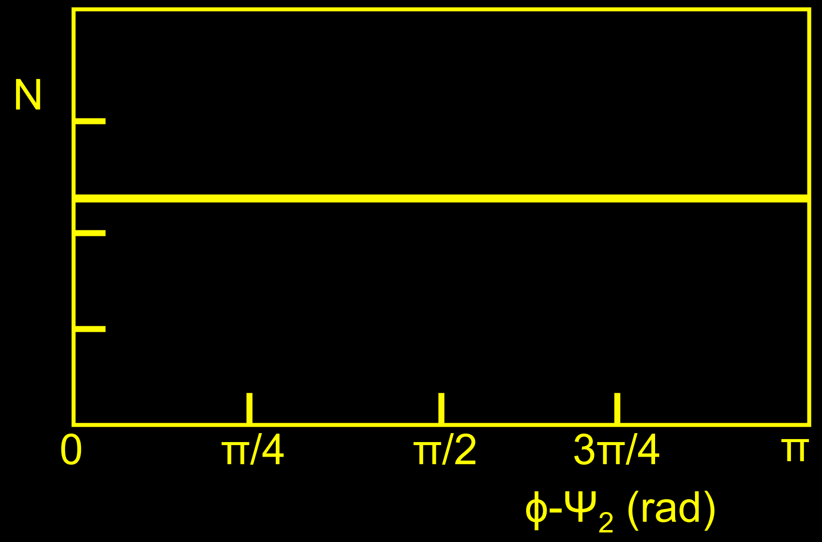
Bulk observables: Anisotropic flow



Superposition of independent pp collisions

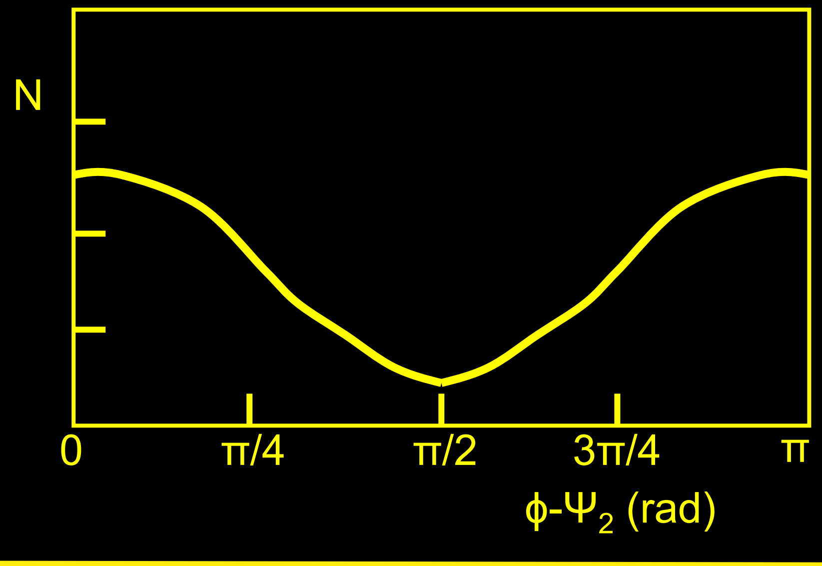


Momenta pointing at random directions



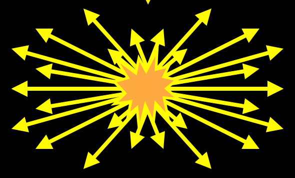
$$\frac{dN}{d\Delta\varphi} \propto \sum_{n=1}^{\infty} 2v_n \cos(n\Delta\varphi)$$

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



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

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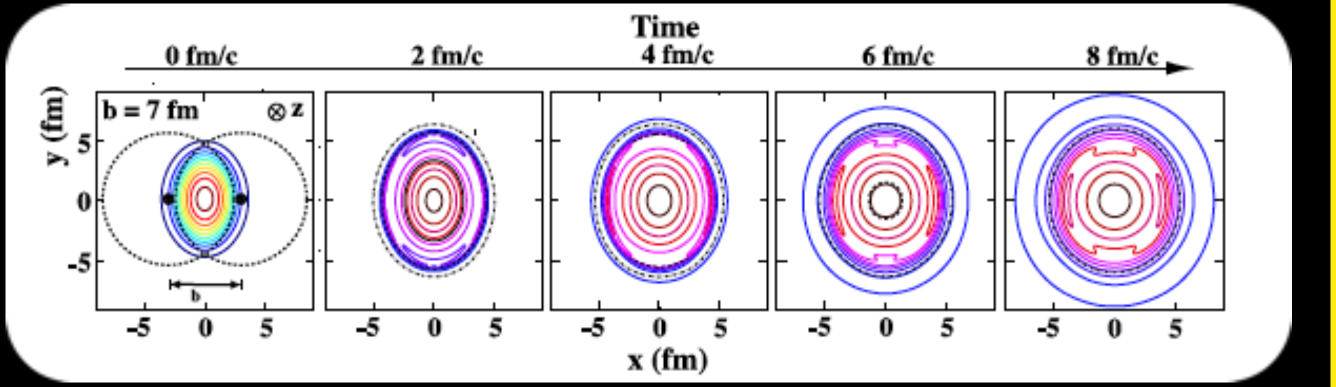
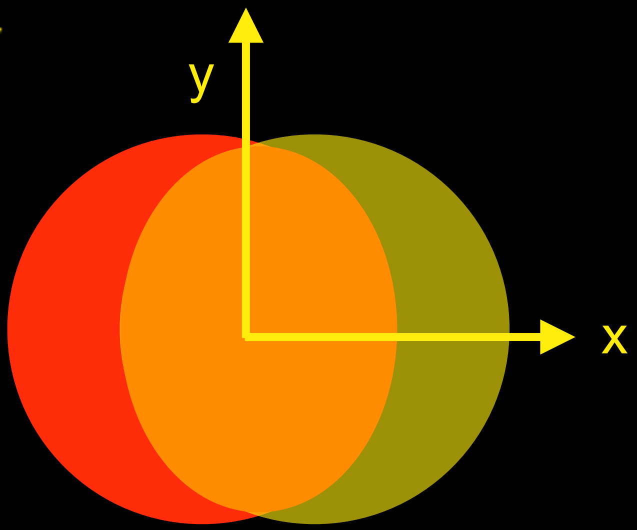
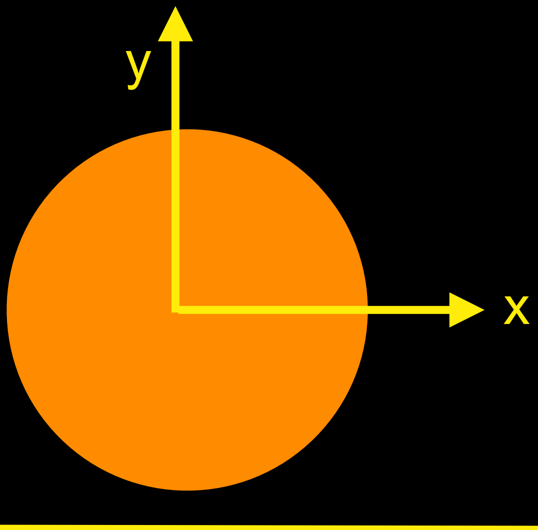
Coordinate vs momentum anisotropies

Coordinate space: eccentricities



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

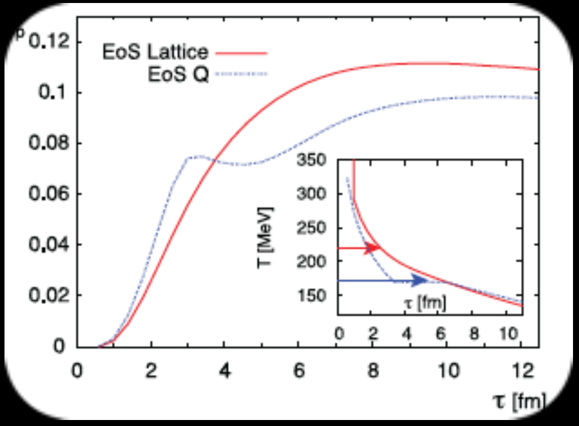


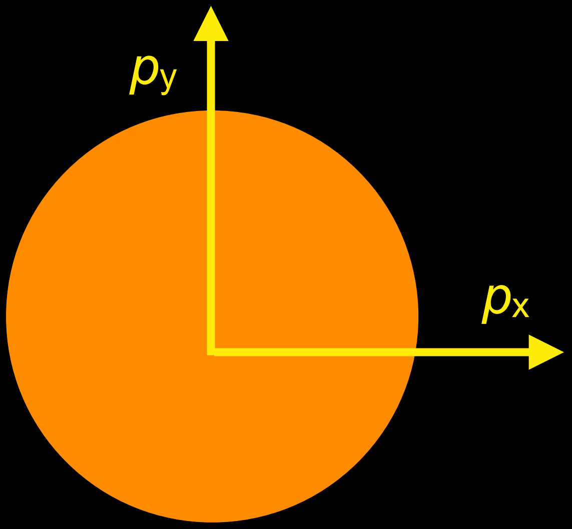


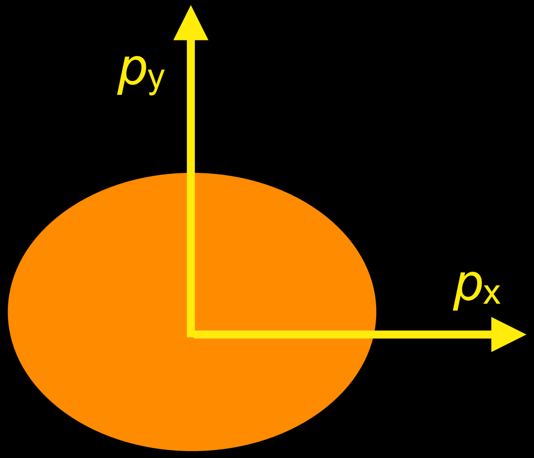
time

Momentum space: flow harmonics

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







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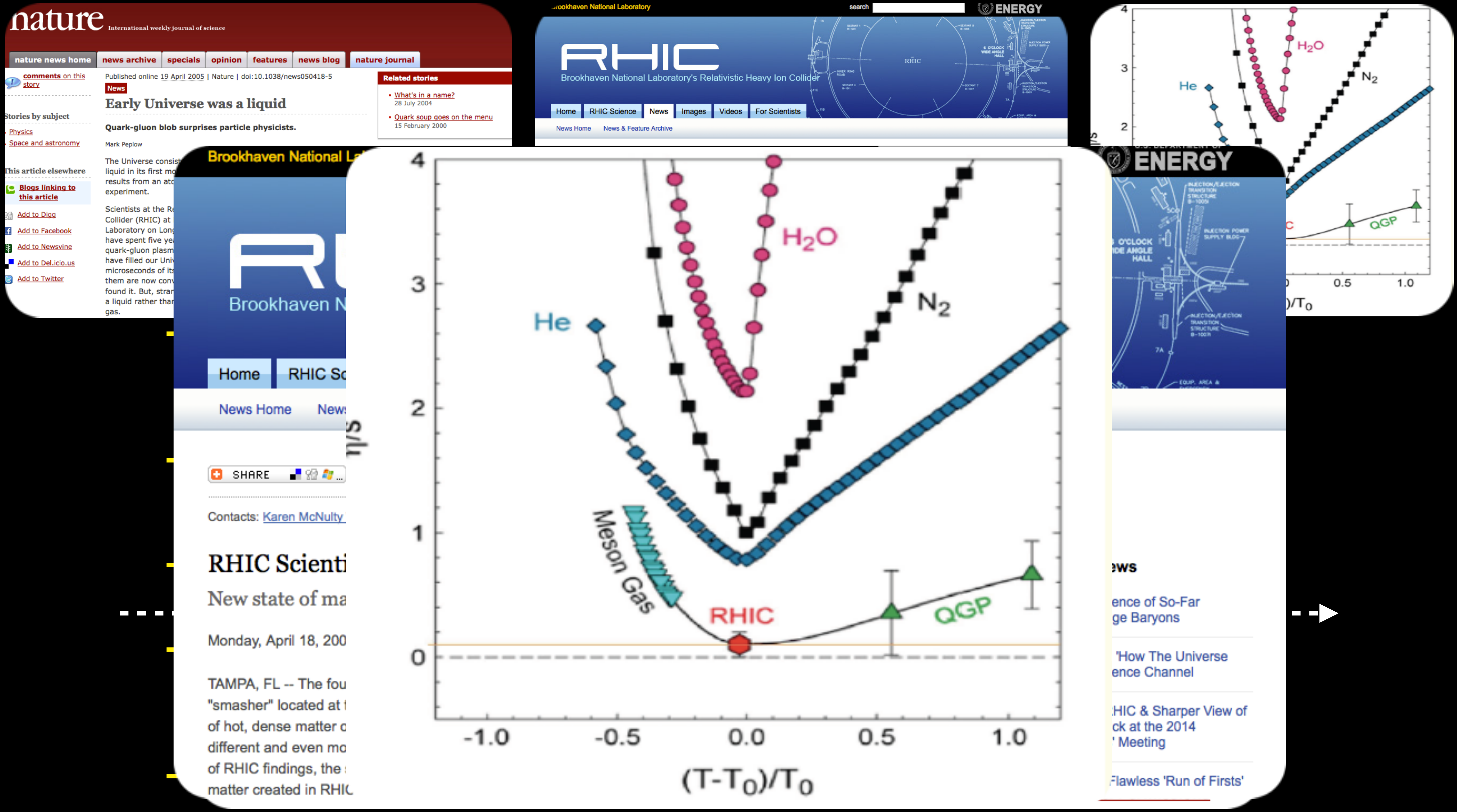
The “perfect liquid” @ RHIC



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

News

Early Universe was a liquid

Quark-gluon blob surprises particle physicists.

Mark Peplow

The Universe consist
liquid in its first mo
results from an ato
experiment.

Scientists at the Re
Collider (RHIC) at
Laboratory on Long
have spent five yea
quark-gluon plasm
have filled our Univ
microseconds of its
them are now conv
found it. But, stran
a liquid rather than
gas.

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Brookhaven National Laboratory search ENERGY

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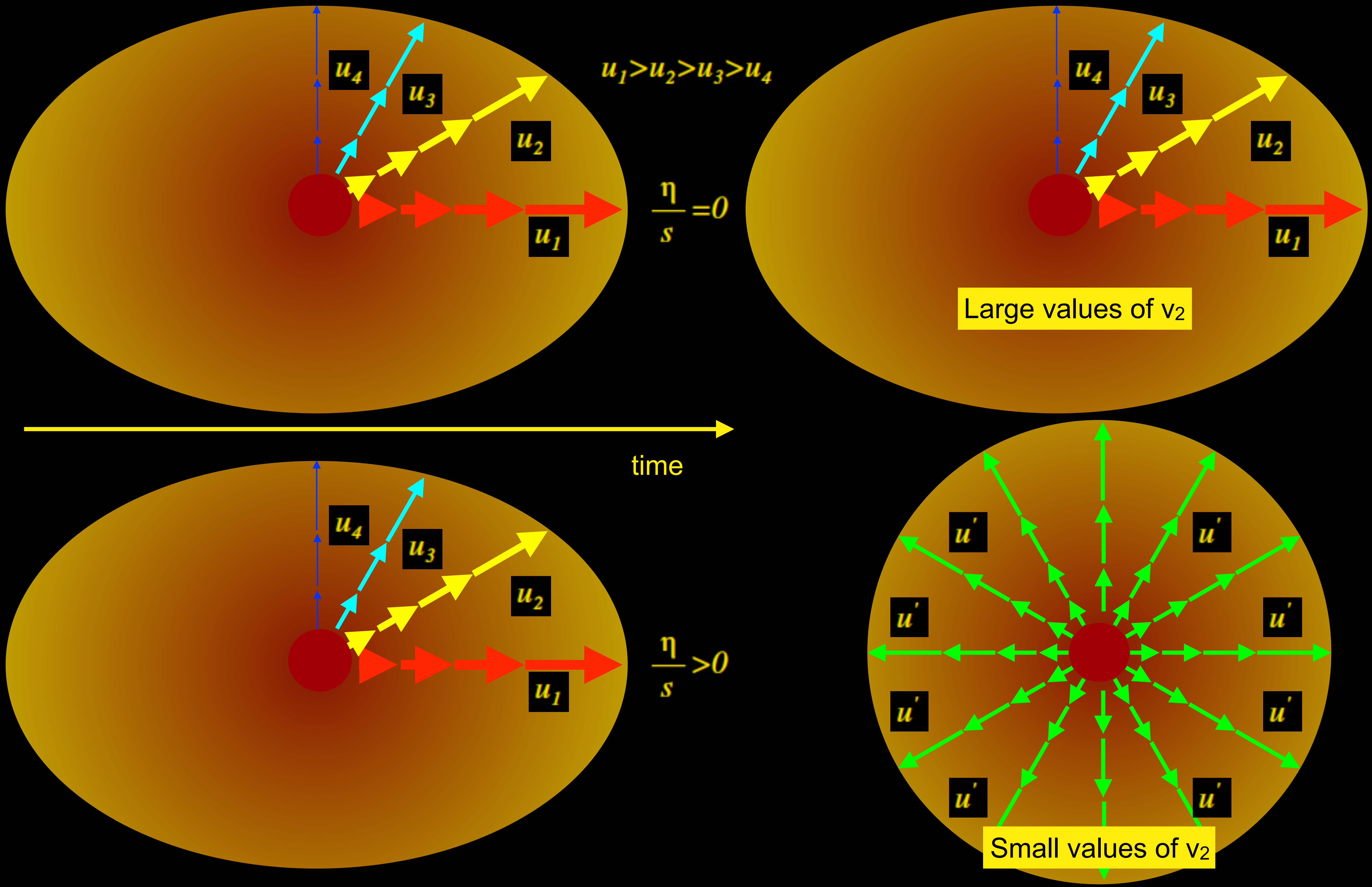
Shear viscosity acting in momentum space



Large values of v_2

Small values of v_2

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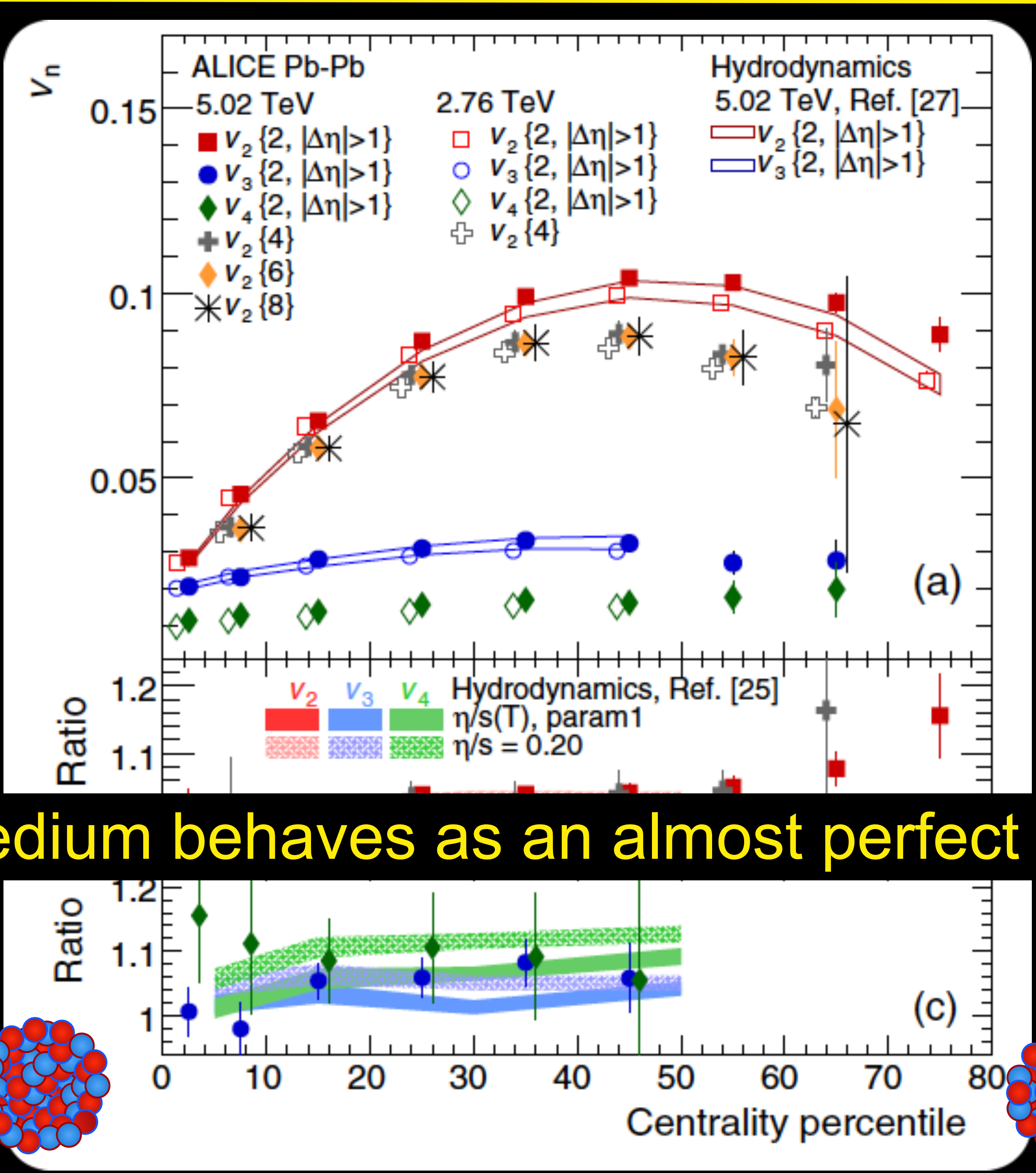
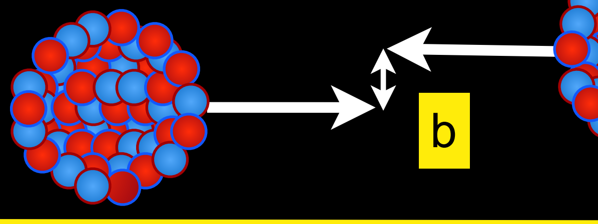
Large v_n values at the LHC

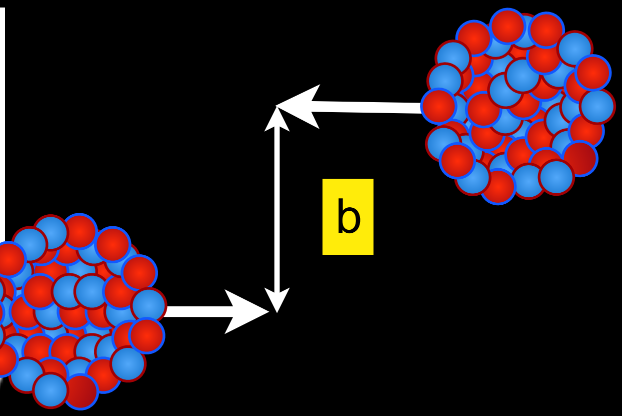
- ☑ Study the QGP properties in more detail
  - Allows for the first time to probe the temperature dependence of η/S
- ☑ Connection to EoS



Looking at the details
- ☑ Initial state
- ☑ η/S(T)
- ☑ ζ/S, ζ/S(T)
- ☑ EoS
- ☑ Hadronic phase
- ☑ …

The medium behaves as an almost perfect liquid!!!





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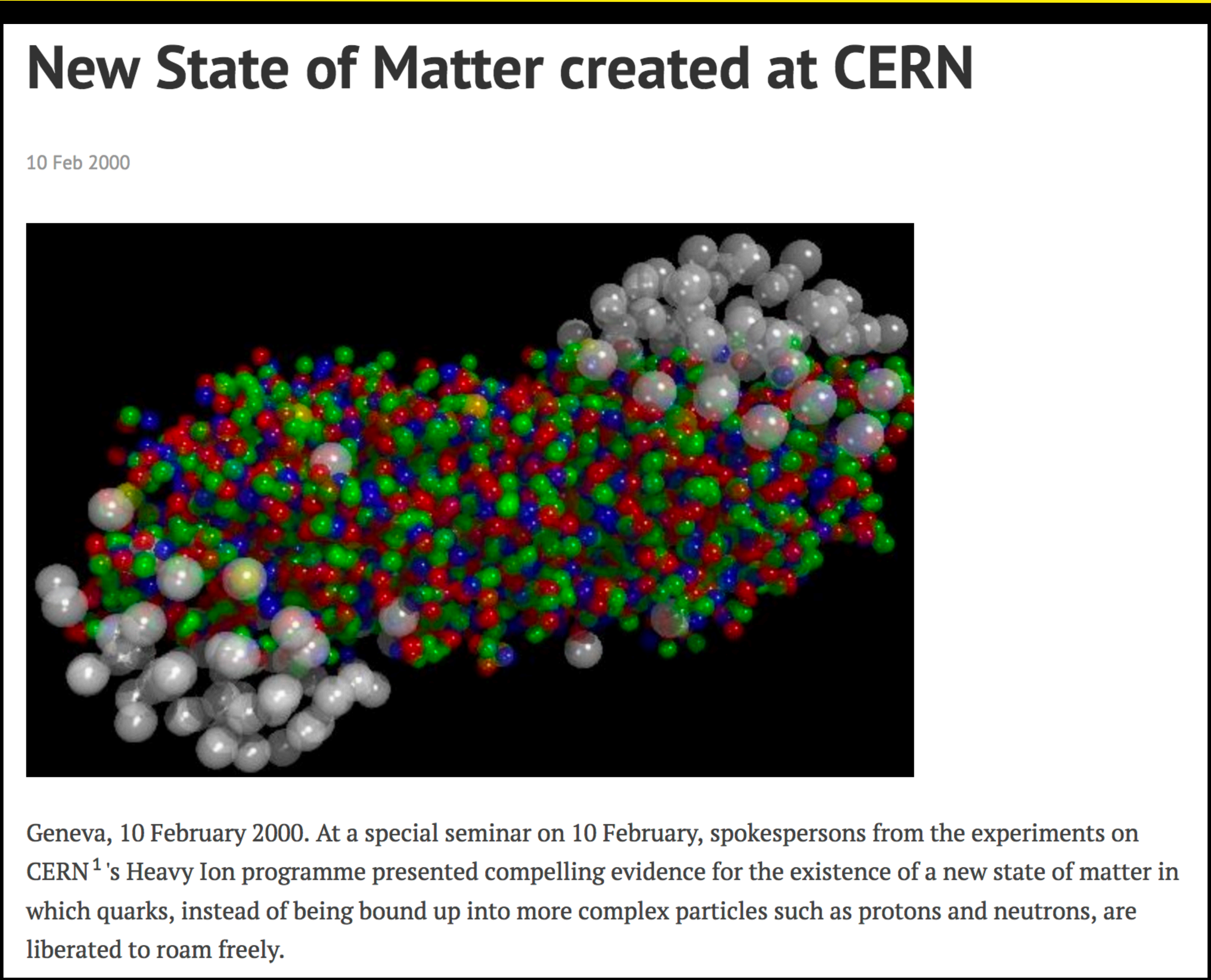
We’ve come a long way…from the QGP @ CERN-SPS



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.

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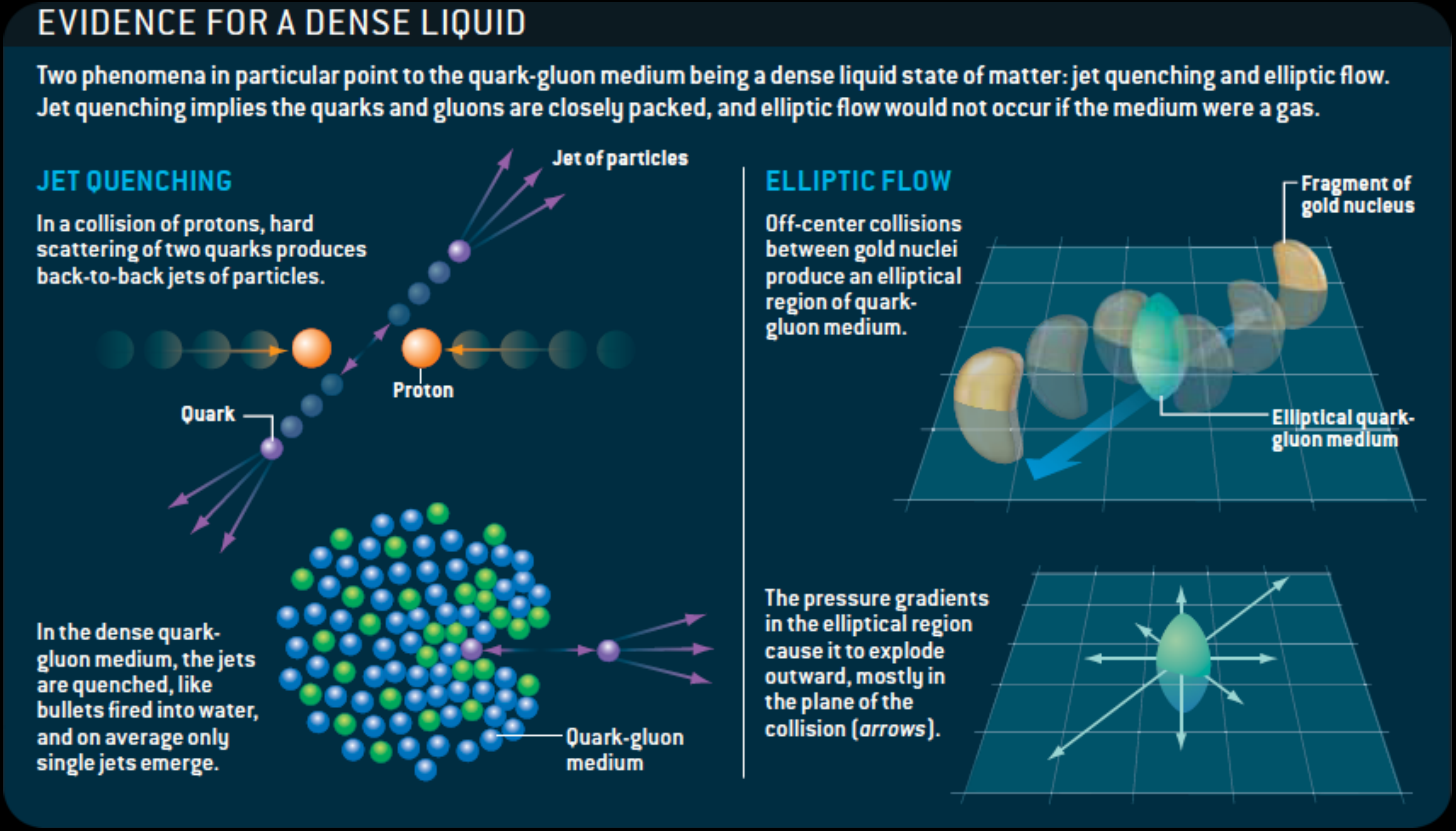
We’ve come a long way…to the QGP @ BNL-RHIC

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



EVIDENCE FOR A DENSE LIQUID

Two phenomena in particular point to the quark-gluon medium being a dense liquid state of matter: jet quenching and elliptic flow. Jet quenching implies the quarks and gluons are closely packed, and elliptic flow would not occur if the medium were a gas.

JET QUENCHING

In a collision of protons, hard scattering of two quarks produces back-to-back jets of particles.

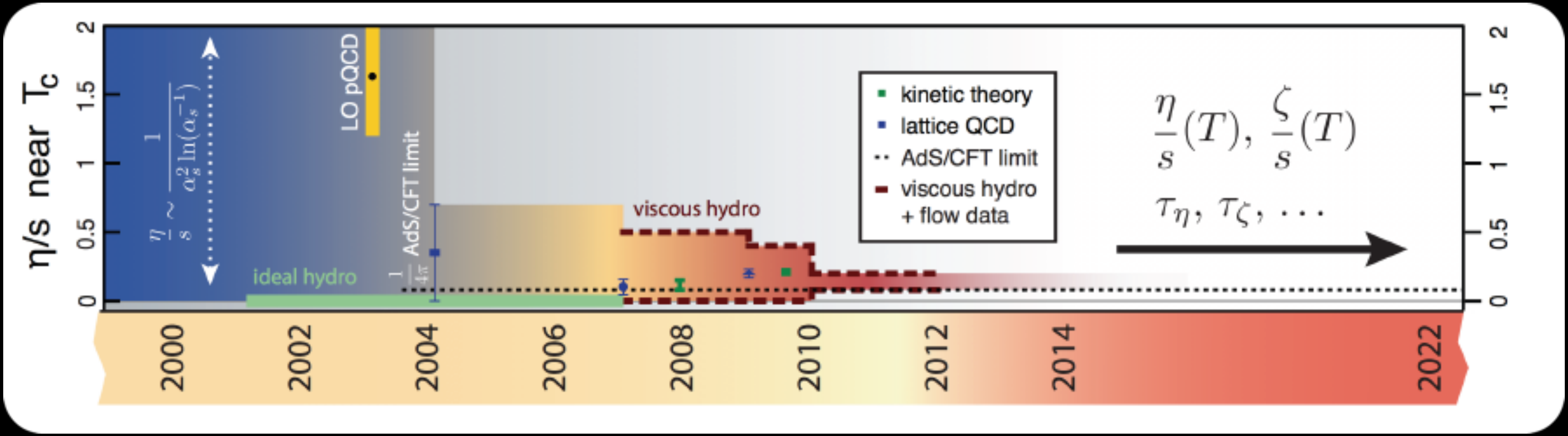
In the dense quark-gluon medium, the jets are quenched, like bullets fired into water, and on average only single jets emerge.

ELLIPTIC FLOW

Off-center collisions between gold nuclei produce an elliptical region of quark-gluon medium.

The pressure gradients in the elliptical region cause it to explode outward, mostly in the plane of the collision (*arrows*).

We’ve come a long way…and now to this @ LHC



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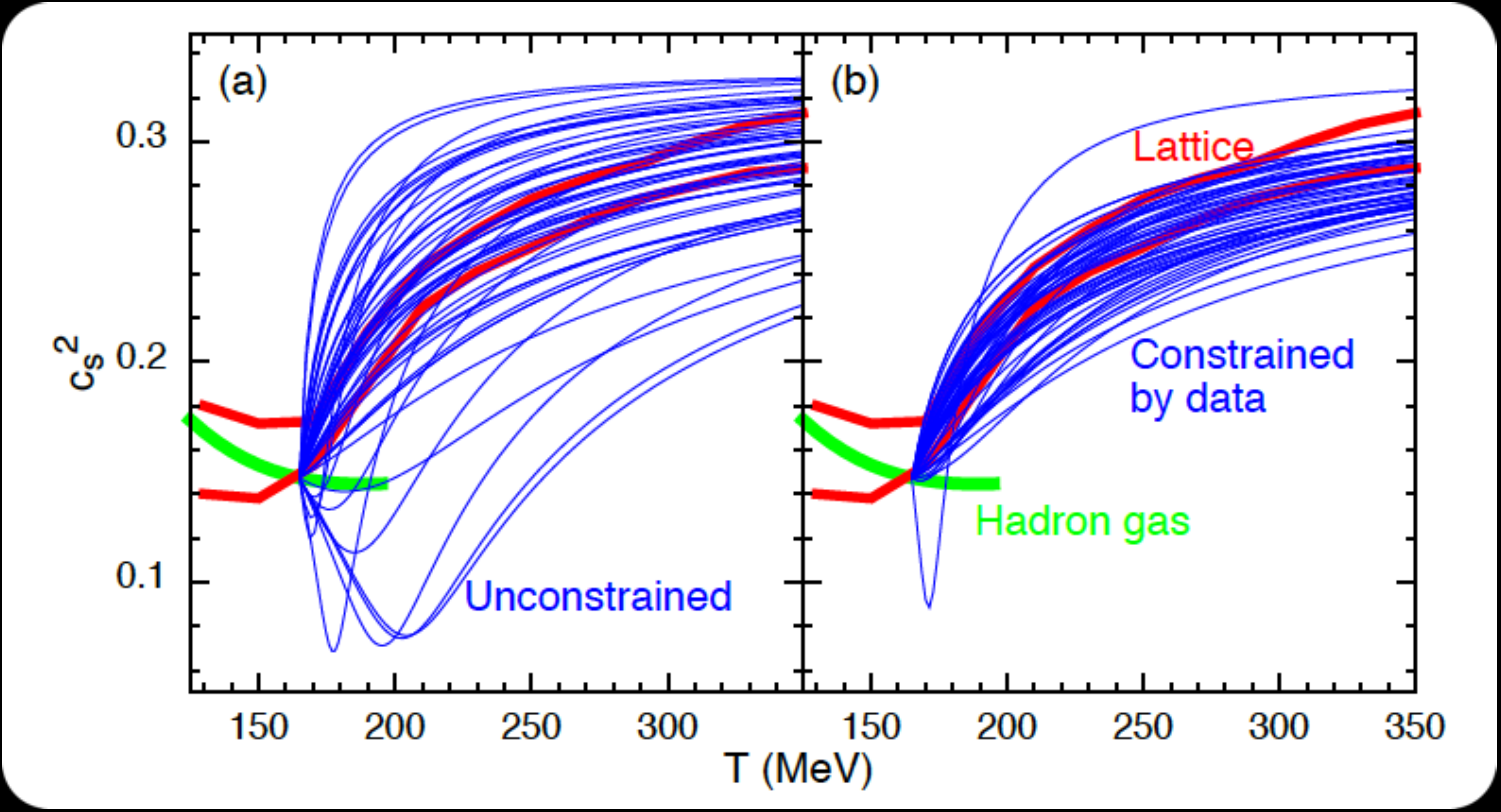
We’ve come a long way…and now to this @ LHC

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



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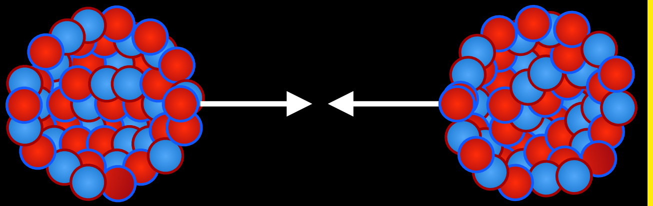
ALICE physics program covers all systems!!!

p-Pb
$\sqrt{s_{NN}}$ = 5.02 TeV
$\sqrt{s_{NN}}$ = 8 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

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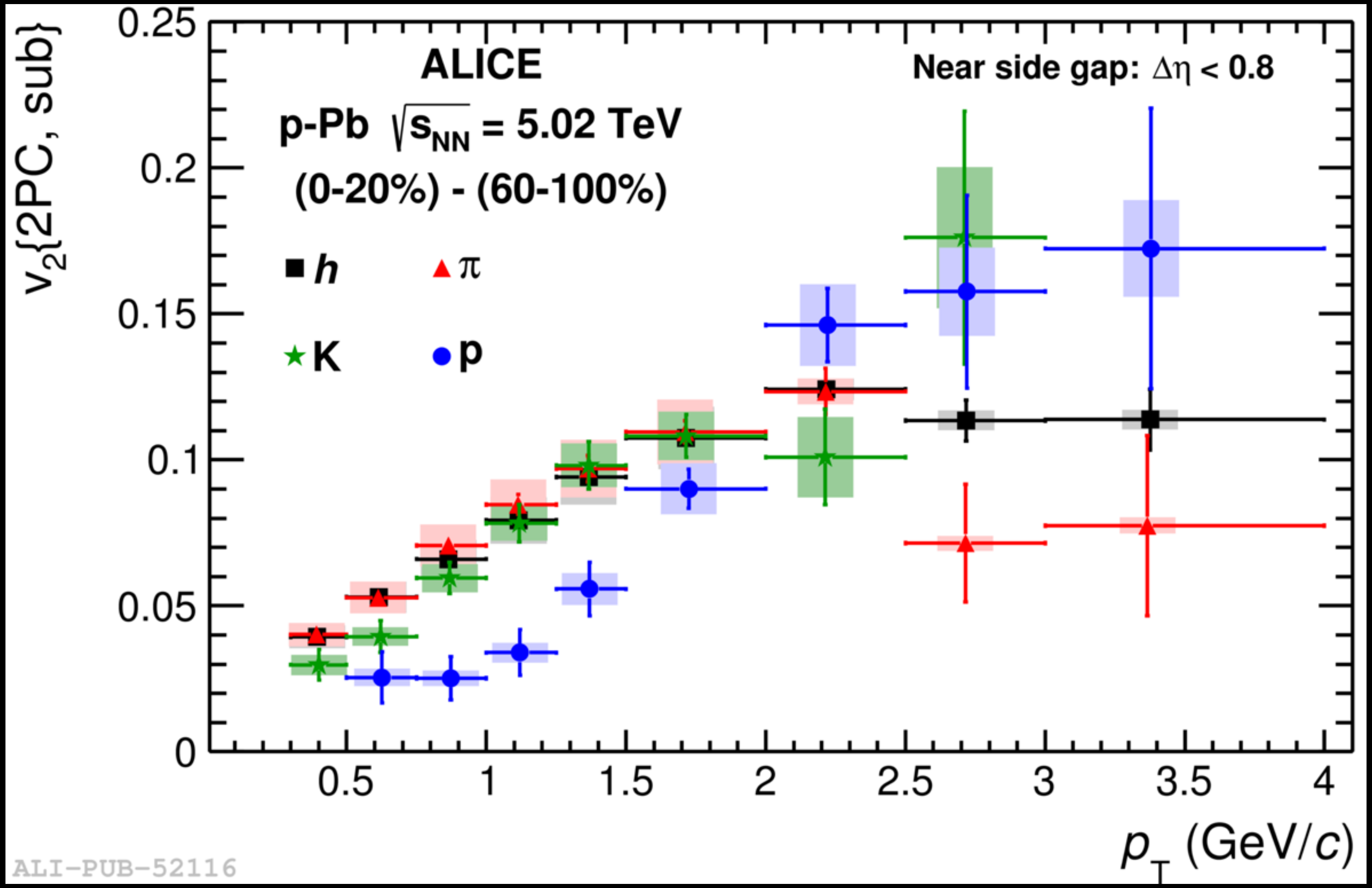
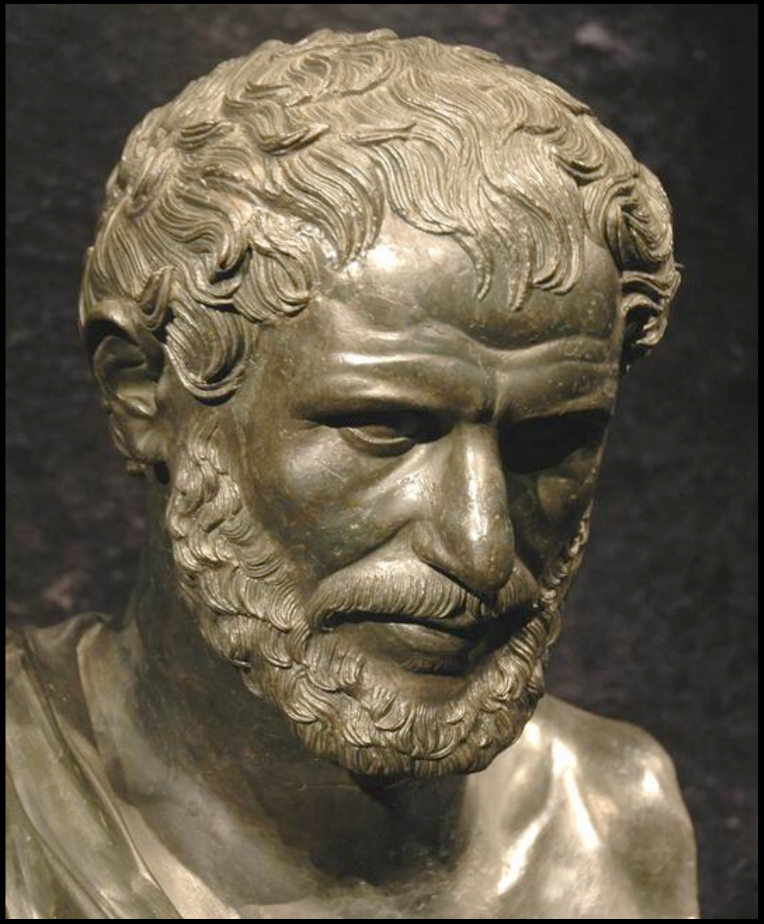
Τα πάντα ρει…(everything flows)

Ηράκλειτος (Heraclitus) ~535 - 475 BC





Not only in A-A it seems but also for smaller systems!

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(part of) the Nikhef-Utrecht ALICE group

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

Feel free to pass by my office @ **Nikhef (room N327)** or @ **Ornsteinlaboratorium (room 259)** if you are interested to learn more!!!

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Thank you for your attention!

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Backup

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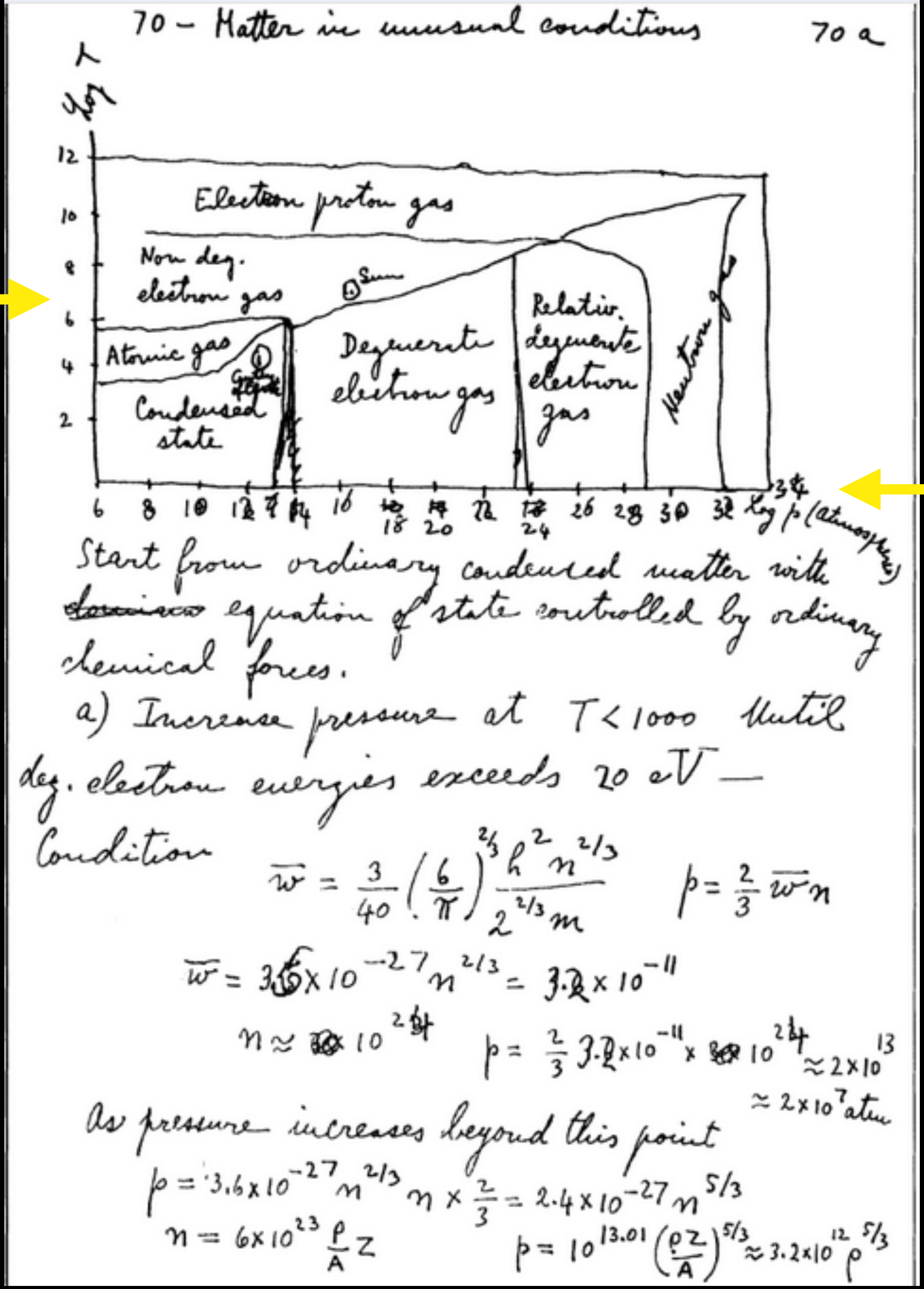
Fermi's notes: 2000+ physics discussed in ~1950

Temperature

Pressure



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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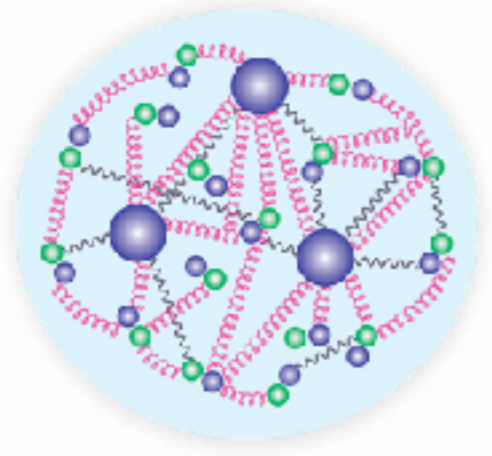
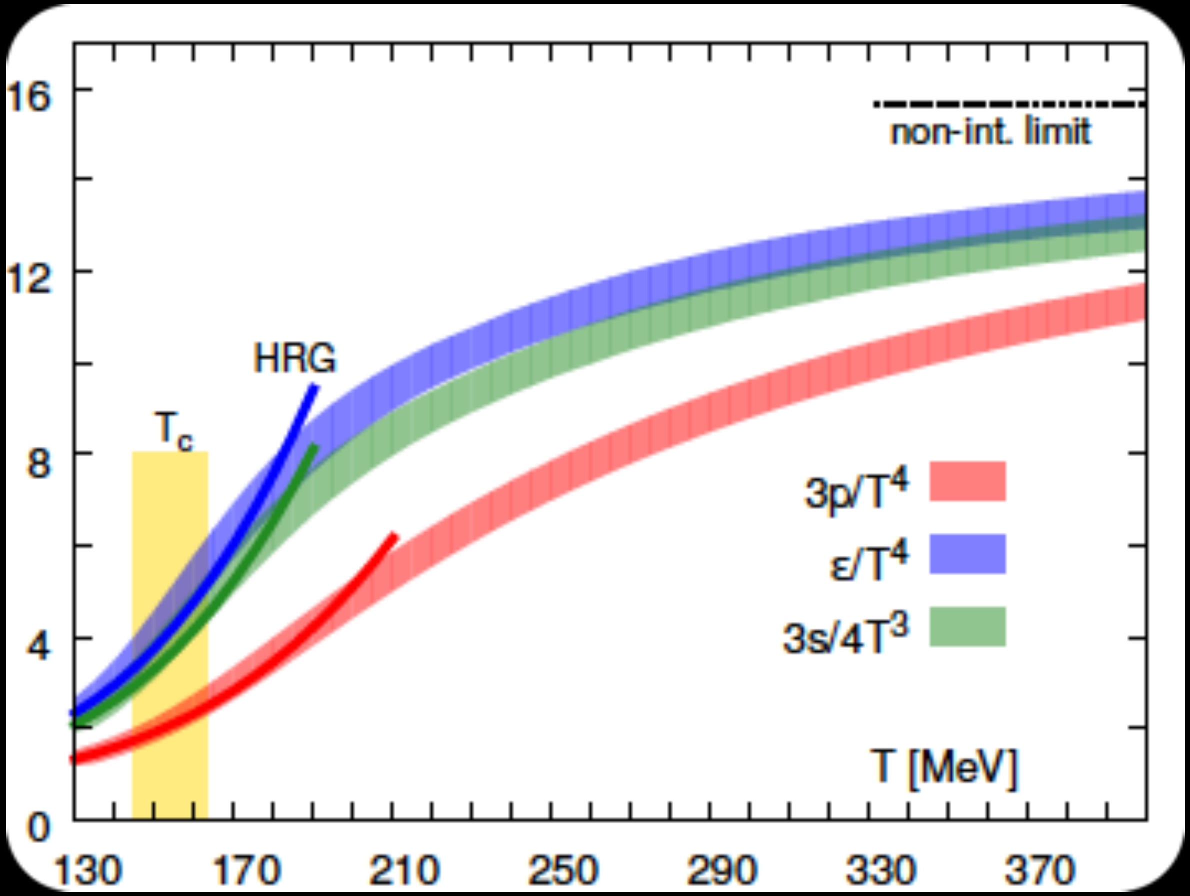
Strong phase transition: guidance from lattice calculations

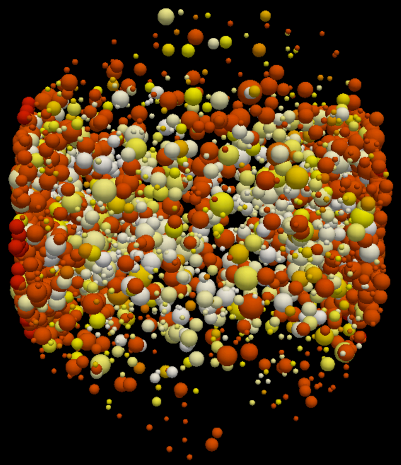
HotQCD Collaboration: Phys.Rev. **D90**, (2014) 094503

Nuclear matter





Quark Gluon Plasma



- ✓ The Quark-Gluon Plasma (QGP):
  - a state of matter where the quarks and gluons behave as quasi free particles
  - 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 (~155 MeV) and energy density (~0.5 GeV/fm^3) ➞ accessible in the laboratory ➞ heavy-ion collisions

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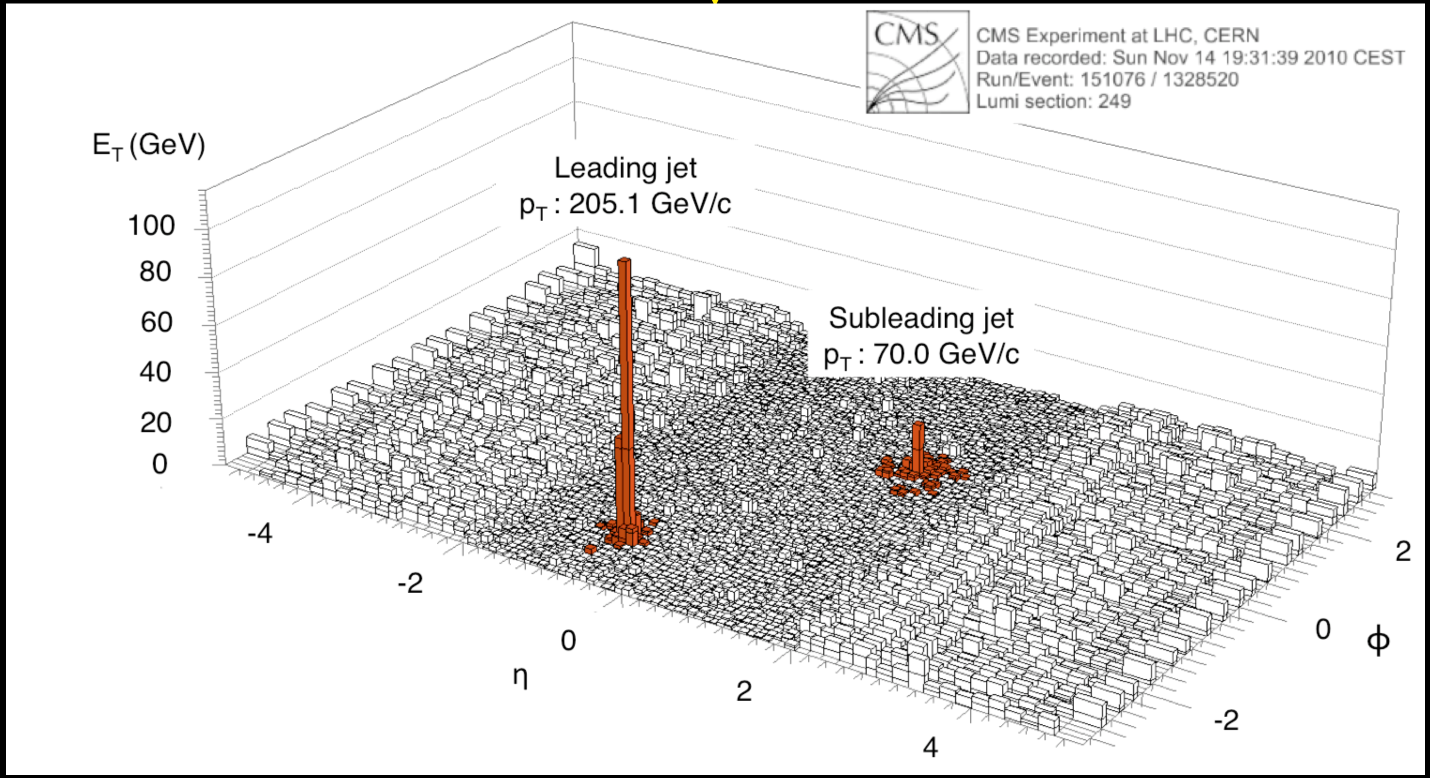
Focus on…

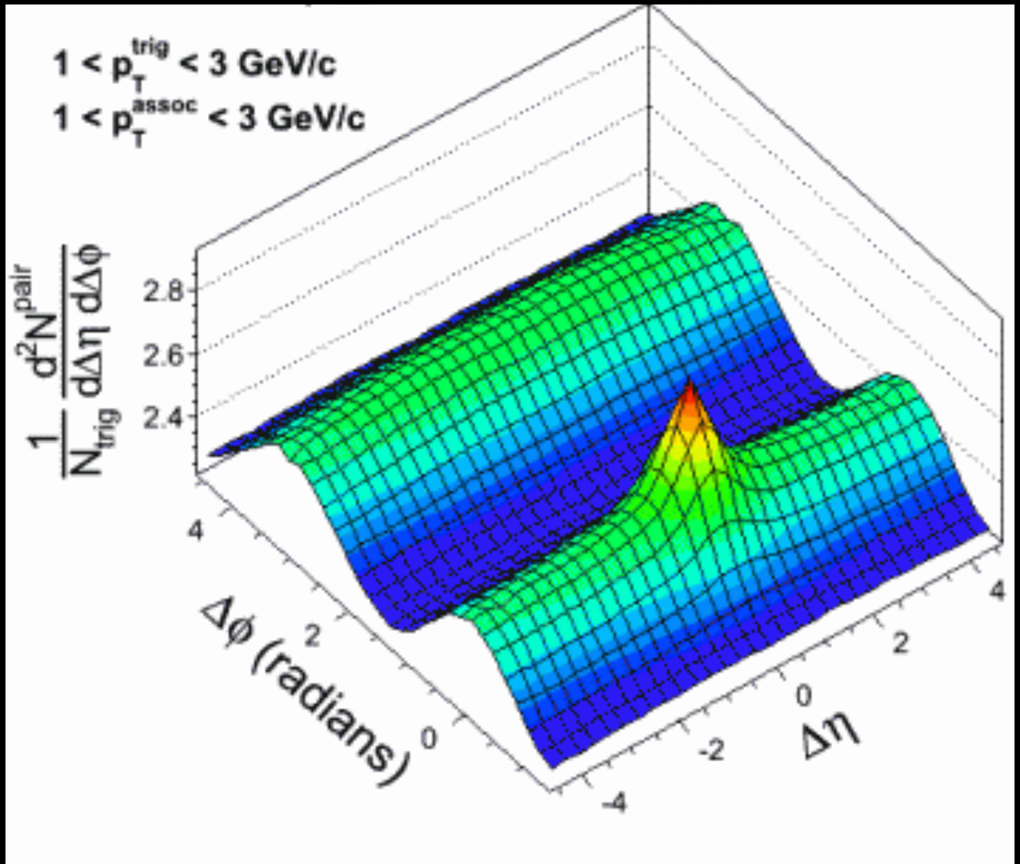
Jet quenching

Probe: Suppression/modification of jets



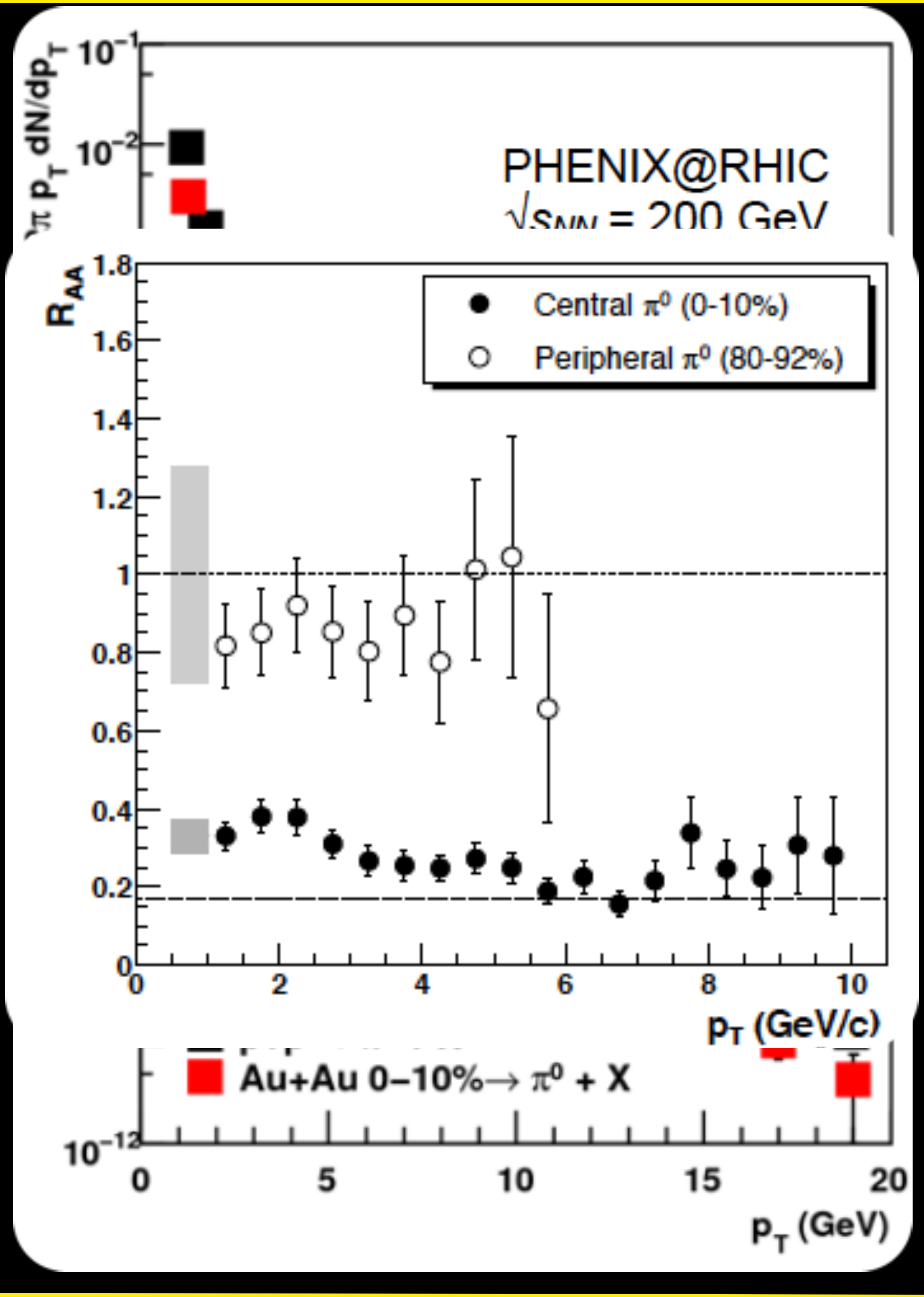
Collective (anisotropic) flow

Probe: correlation functions and flow harmonics (elliptic, triangular, quantrangular, pentagonal,…



A way of quantifying jet 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

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

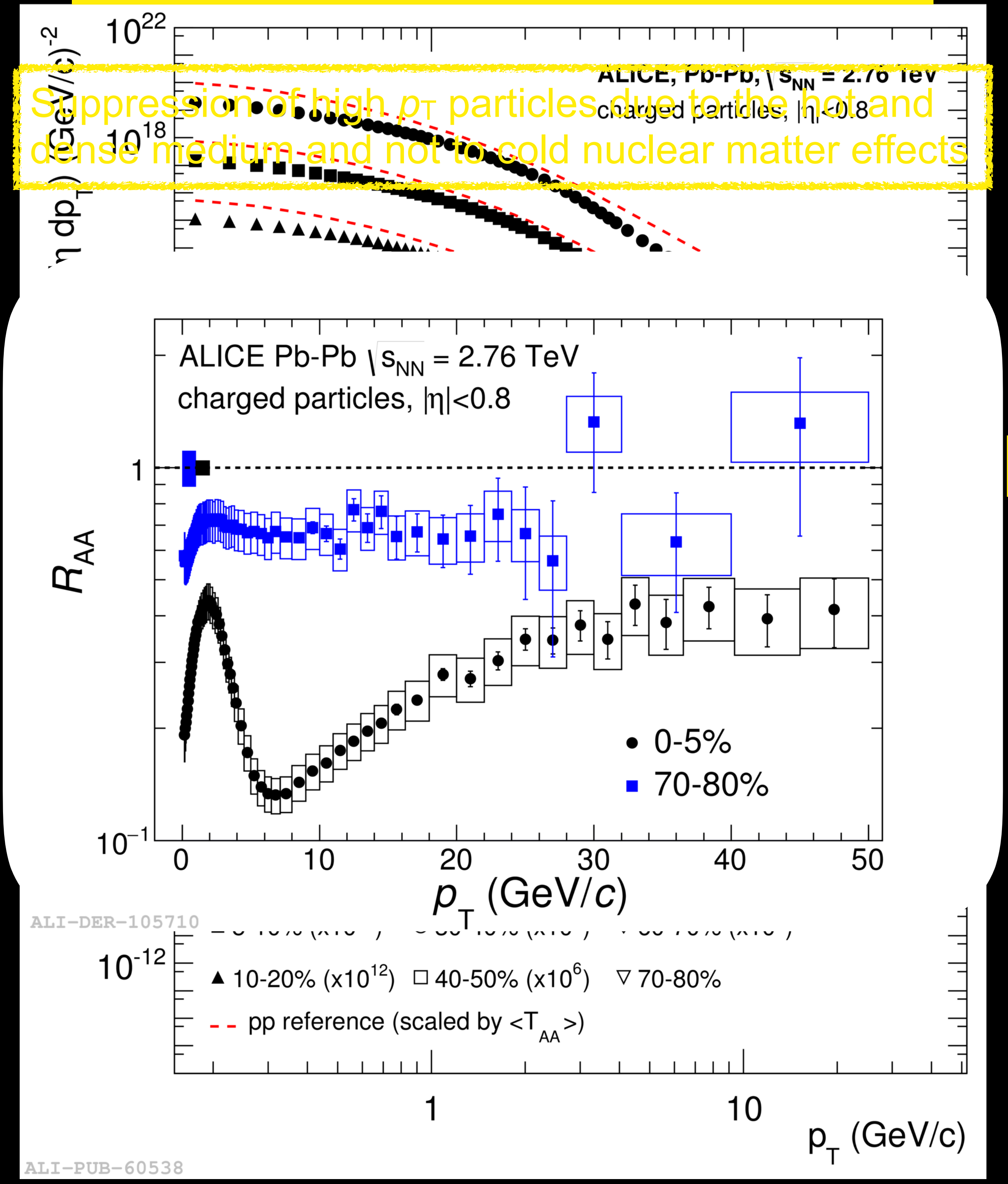
$$R_{AA}\rightarrow\begin{cases}<1\\ \simeq 1\end{cases}$$

in-medium effects

no in-medium effects

Hard probes @ the LHC

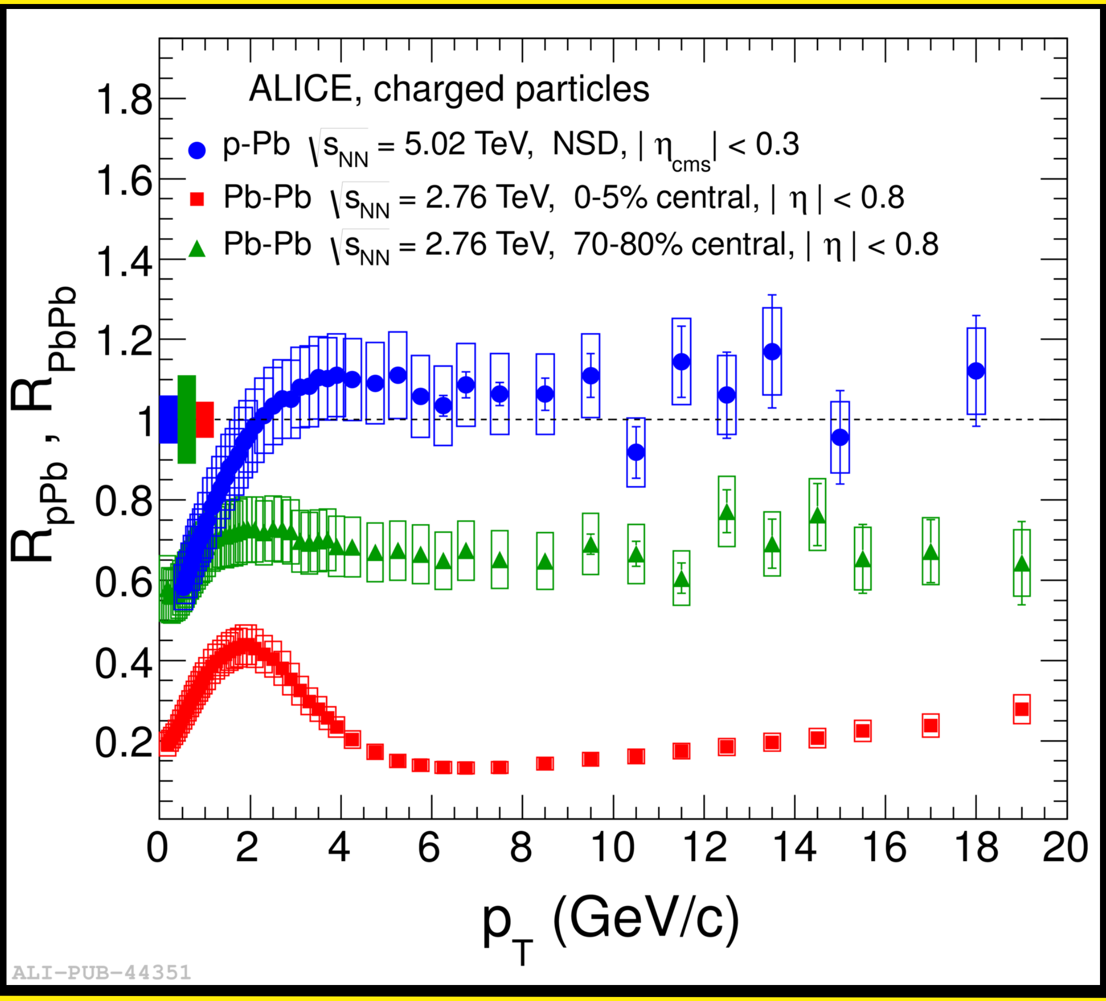
(Alice Collaboration) Phys.Lett. B720 (2013) 52



Suppression of high p_T particles due to the hot and dense medium and not to cold nuclear matter effects

System	Year	$\sqrt{s_{NN}}$ (TeV)	L_{int}
pp	2009-2010	0.9	~0.15 nb^{-1}
pp	2010-2011	7	~4.8 pb^{-1}
pp	2011	2.76	~1.1 pb^{-1}
pp	2012	8	~9.7 pb^{-1}
p-Pb	2013	5.02	~30 nb^{-1}
Pb-Pb	2010-2011	2.76	~0.1 nb^{-1}

(Alice Collaboration) Phys. Rev. Lett. 110 (2013) 082302



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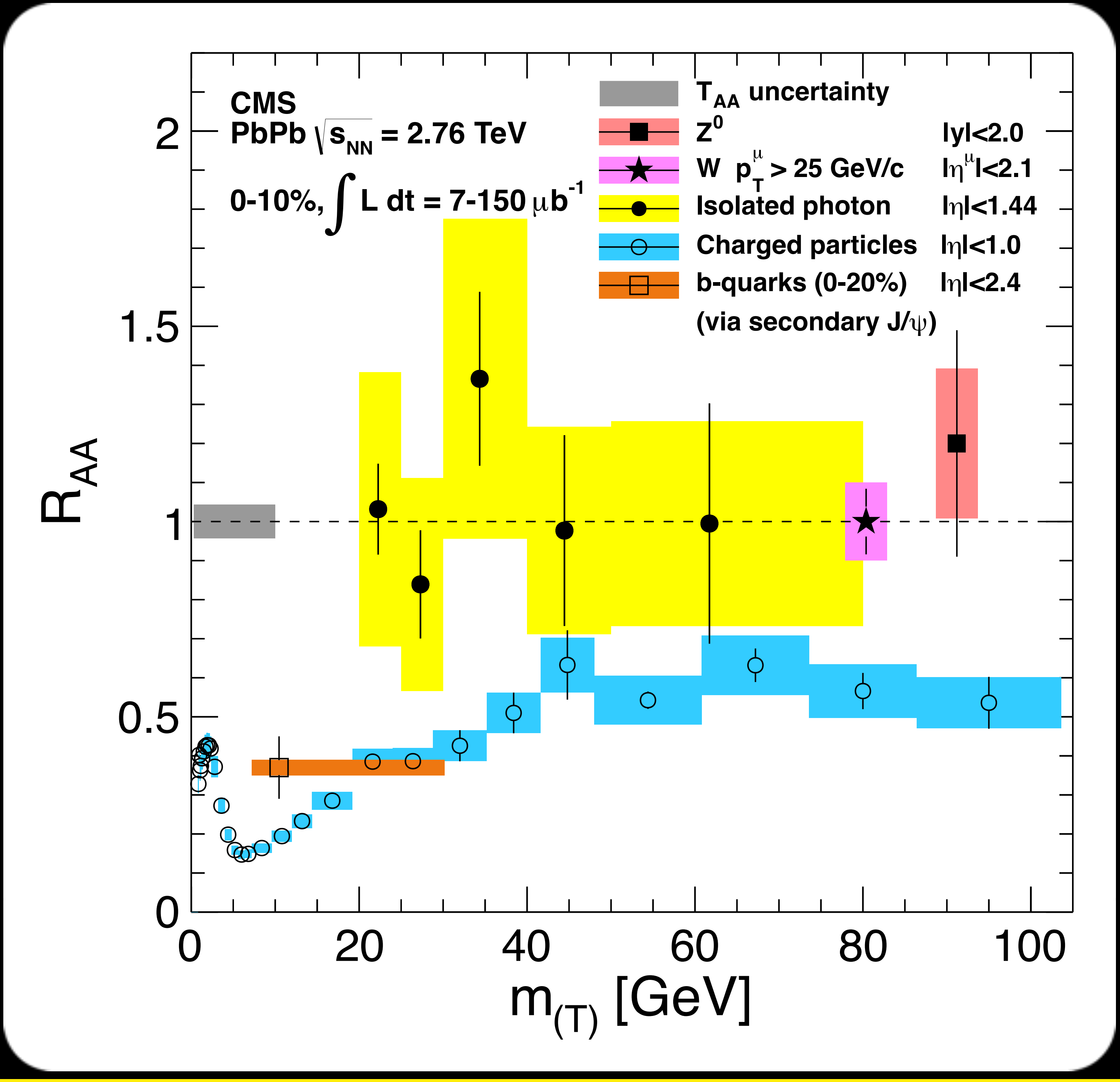
Jet quenching at the LHC: R_{AA} for reference probes

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



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

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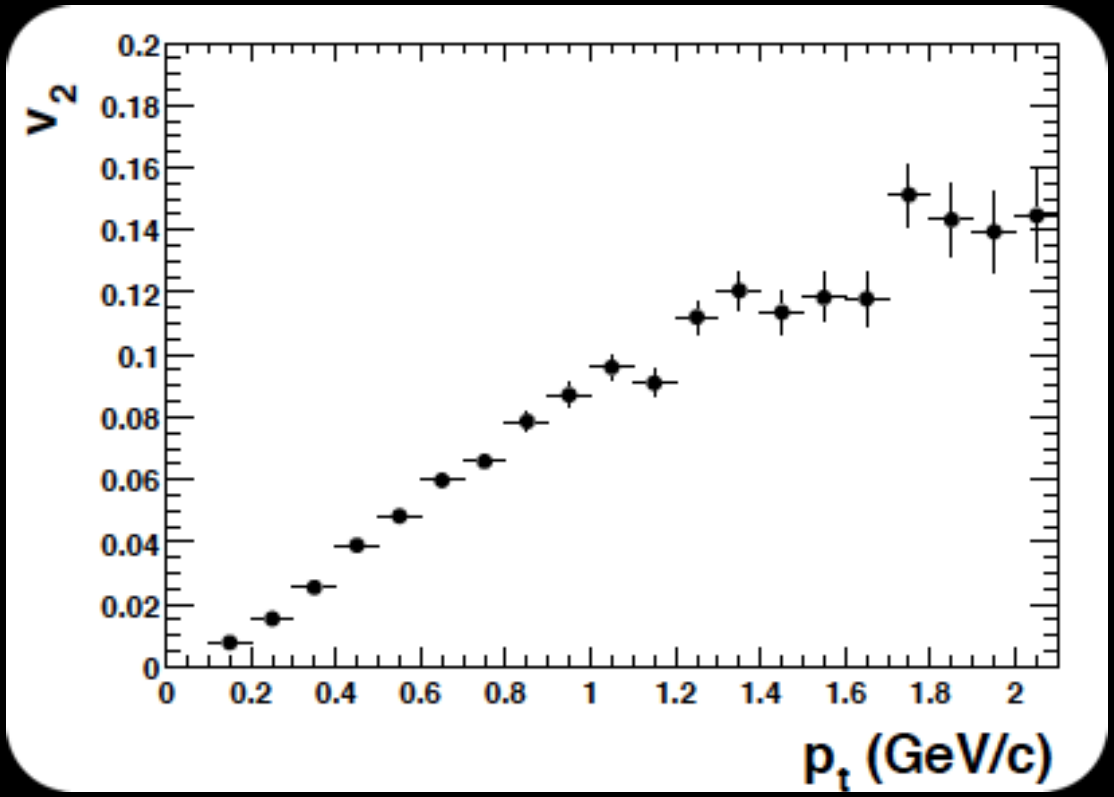
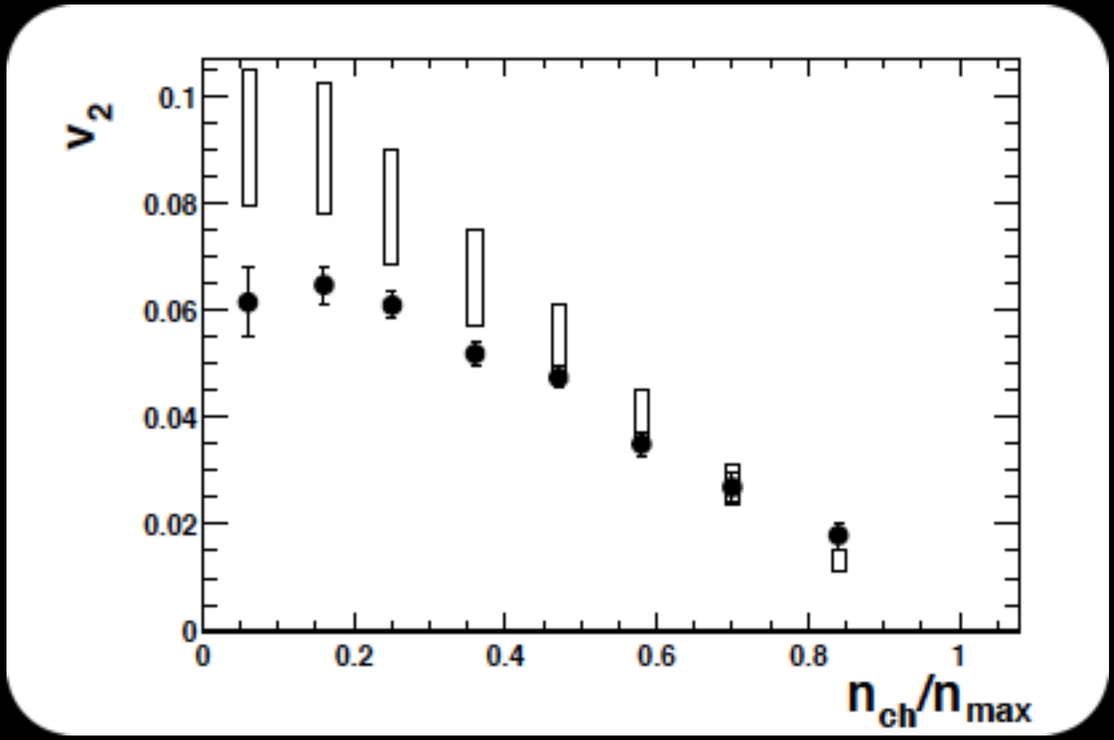
The birth of the sQGP paradigm…

(STAR Collaboration) Phys. Rev. Lett. 86 (2001) 402





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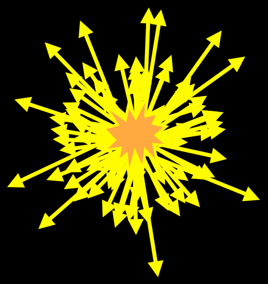
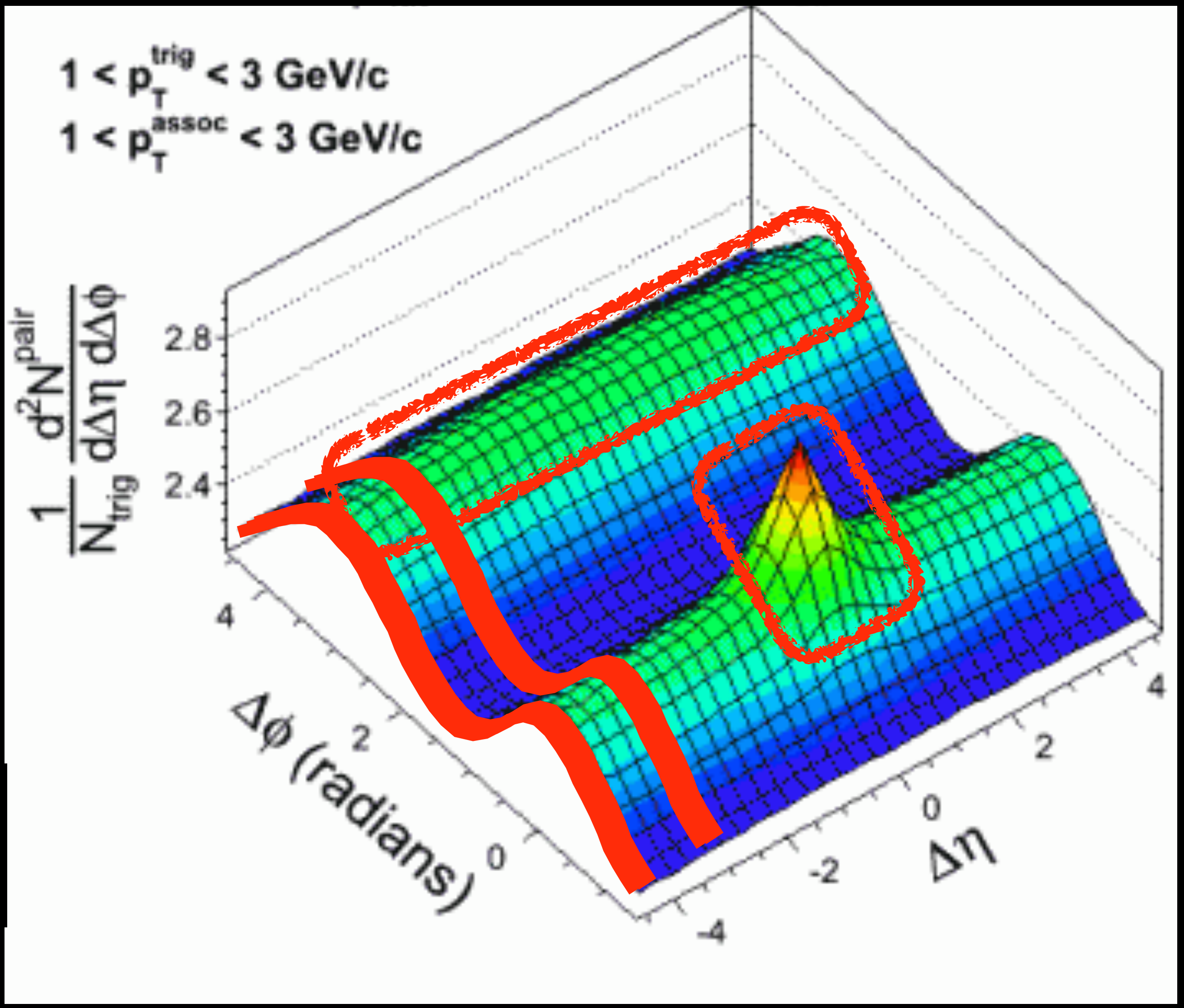
Collective effects as seen in correlation functions

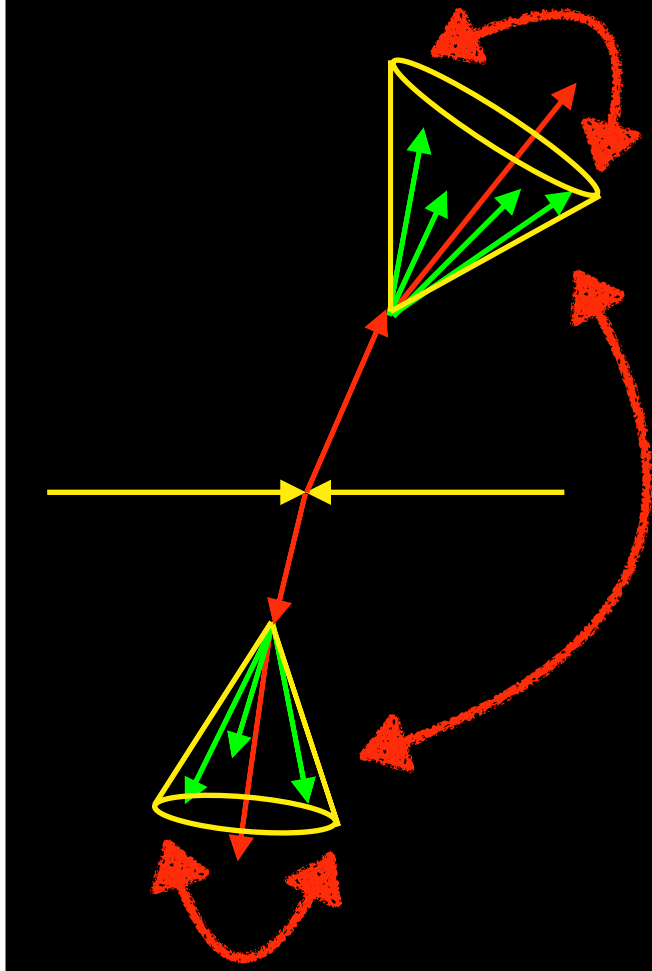
Collective effects
Near and away side ridge

$$C(\Delta\eta,\Delta\varphi)=\frac{1}{N_{trig.}}\frac{d^2N_{assoc.}}{d(\Delta\eta)d(\Delta\varphi)}=\frac{S(\Delta\eta,\Delta\varphi)}{f(\Delta\eta,\Delta\varphi)}$$

Jet correlations
Near side jet peak
+
away side ridge







$$\frac{dN}{d\Delta\varphi}\propto\sum_{n=1}^{\infty}2v_n\cos(n\Delta\varphi)$$

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

$$S(\Delta\eta,\Delta\varphi)=\frac{1}{N_{trig.}}\frac{d^2N_{assoc.}(same)}{d(\Delta\eta)d(\Delta\varphi)}$$

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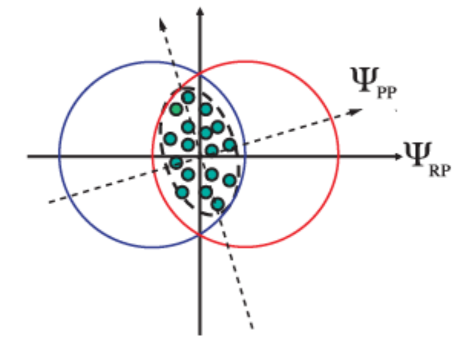
And there is more…: higher (odd) harmonics!

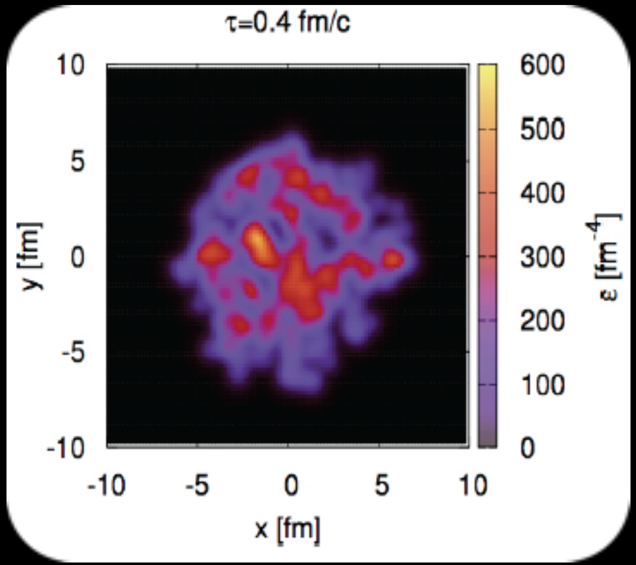


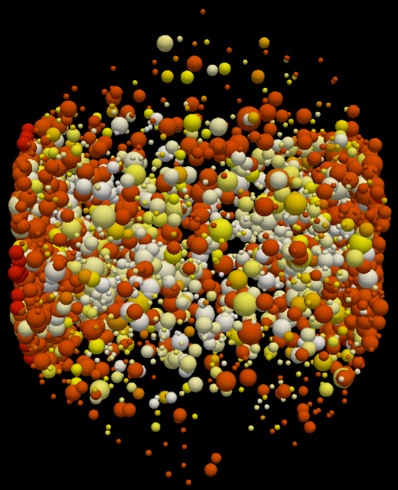
Initial state fluctuations

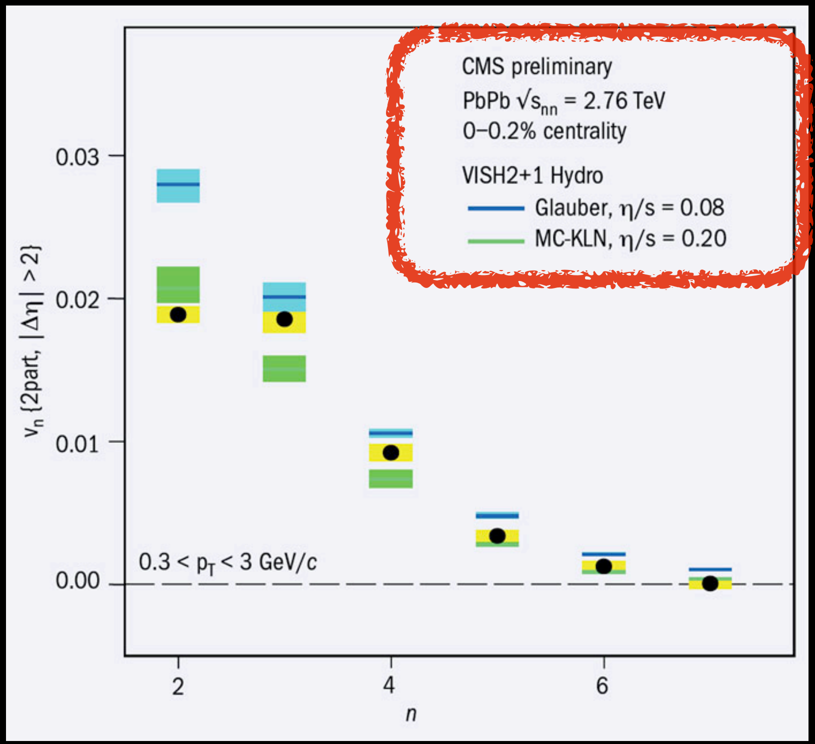
Reaction plane (Ψ_{RP}) → Participant (symmetry) plane Ψ_n

transferred via the low viscosity QGP

into final state correlations (higher, odd harmonics)







✓ Higher harmonics represent modulations in smaller spatial scales

  - More sensitive probes of the QGP transport properties
  - Unique tool to constrain initial state fluctuations

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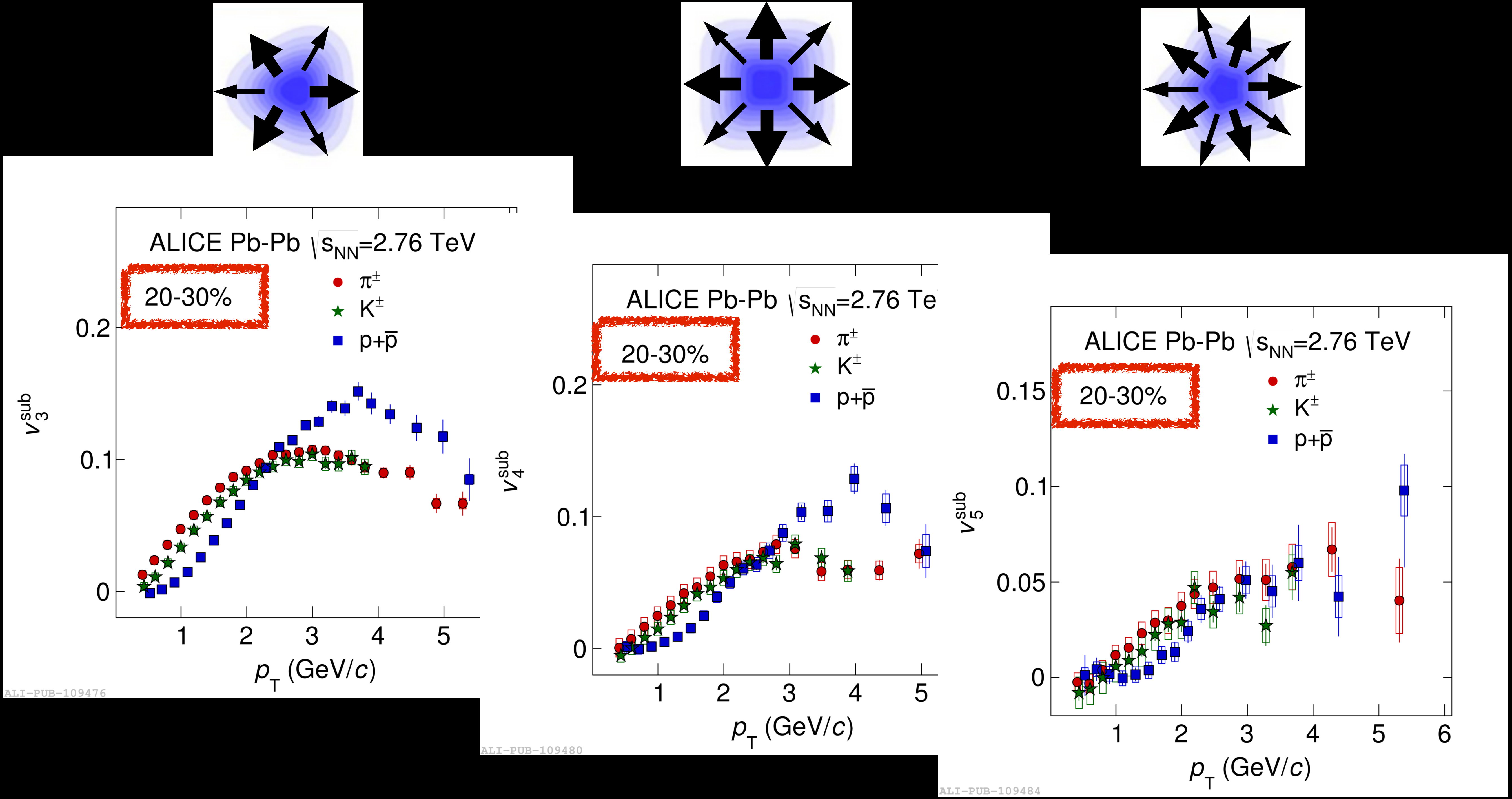
Higher harmonics @ LHC



ALICE-NL contribution

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

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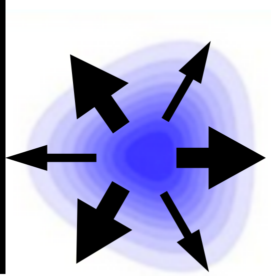
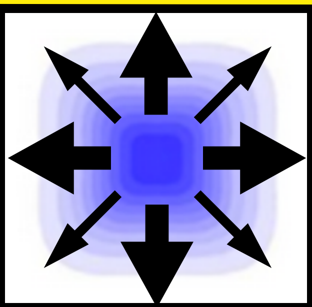
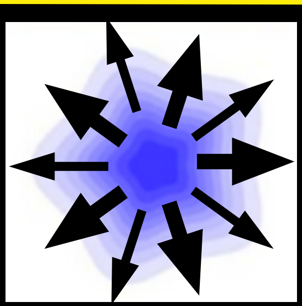
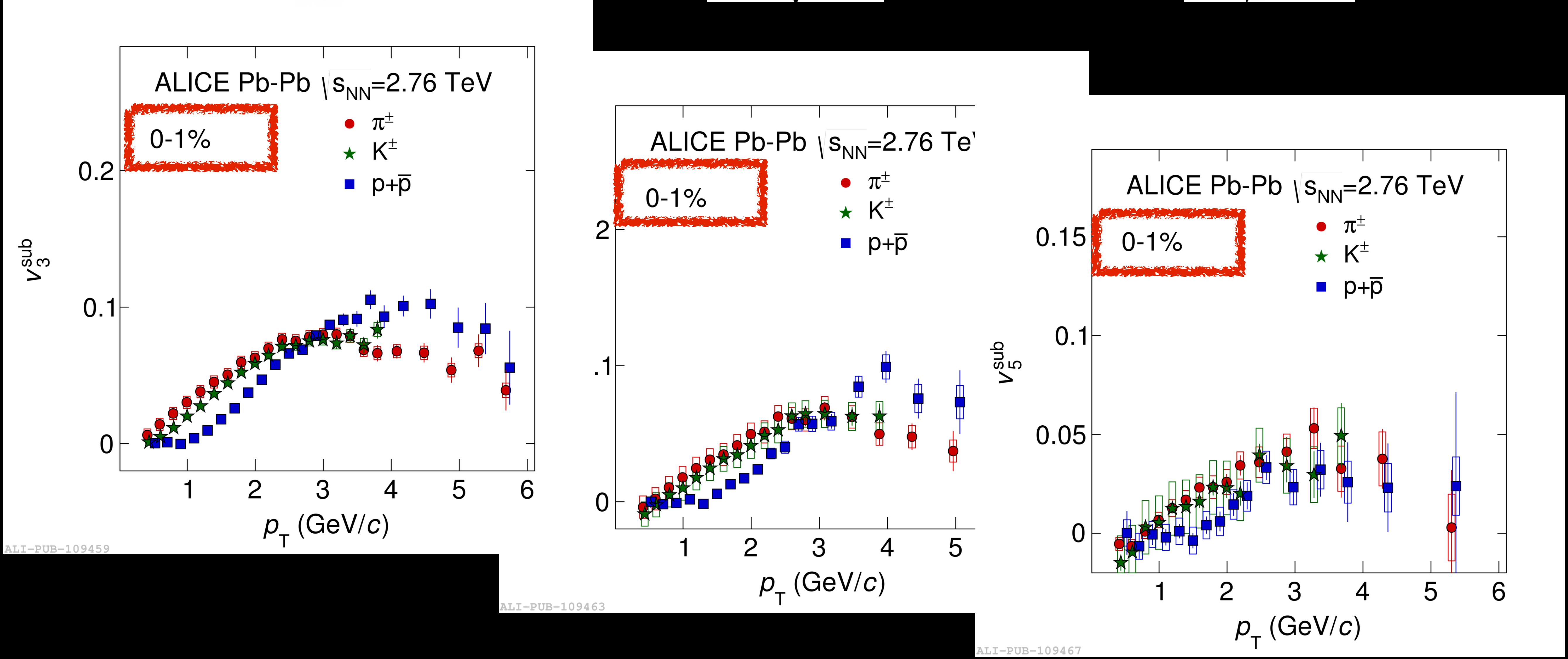
Higher harmonics @ LHC (ultra-central events)









ALICE-NL contribution

Same features for different v_n (up to v_5!) even for ultra-central collisions

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