Journées de Rencontre des Jeunes Chercheurs 2015

La Saulaie

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Société Française de Physique

(an) INTRODUCTION to HEAVY-ION PHYSICS

Antonio Uras - IPNL

Outline

- **From the QCD to the Quark-Gluon Plasma**
  - The strong interaction and its properties
  - The QCD phase diagram
  - The QGP recipe

- **Observations:**
  - Facilities
  - Global observables
  - Electroweak and electromagnetic probes
  - Heavy flavors and Quarkonia

Part I: From the QCD to the QGP

- QCD matter under extreme conditions
- QCD as a multi-particle theory?
- A small Heavy-Ion vocabulary

Elementary Particles: Matter Bricks & Force Carriers

Relatively few truly elementary particles in the Standard Model...

... compared to the **wealth of subnuclear particles discovered until now!**

- **A fact:** all the subnuclear particles we list in our PDG booklet is made out of quarks, either in the “meson” or “baryon” format (even if pentaquarks seem now to be a real option in Nature)
- **A question:** what is responsible for the existence and the properties of the 99.9...% of the particles we know?

FERMIONS

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

Leptons spin = 1/2

Flavor	Mass GeV/c^2	Electric charge
ν_e electron neutrino	$<1\times10^{-8}$	0
e electron	0.000511	–1
ν_μ muon neutrino	<0.0002	0
μ muon	0.106	–1
ν_τ tau neutrino	<0.02	0
τ tau	1.7771	–1

Quarks spin = 1/2

Flavor	Approx. Mass GeV/c^2	Electric charge
u up	0.003	2/3
d down	0.006	–1/3
c charm	1.3	2/3
s strange	0.1	–1/3
t top	175	2/3
b bottom	4.3	–1/3

BOSONS

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

Unified Electroweak spin = 1

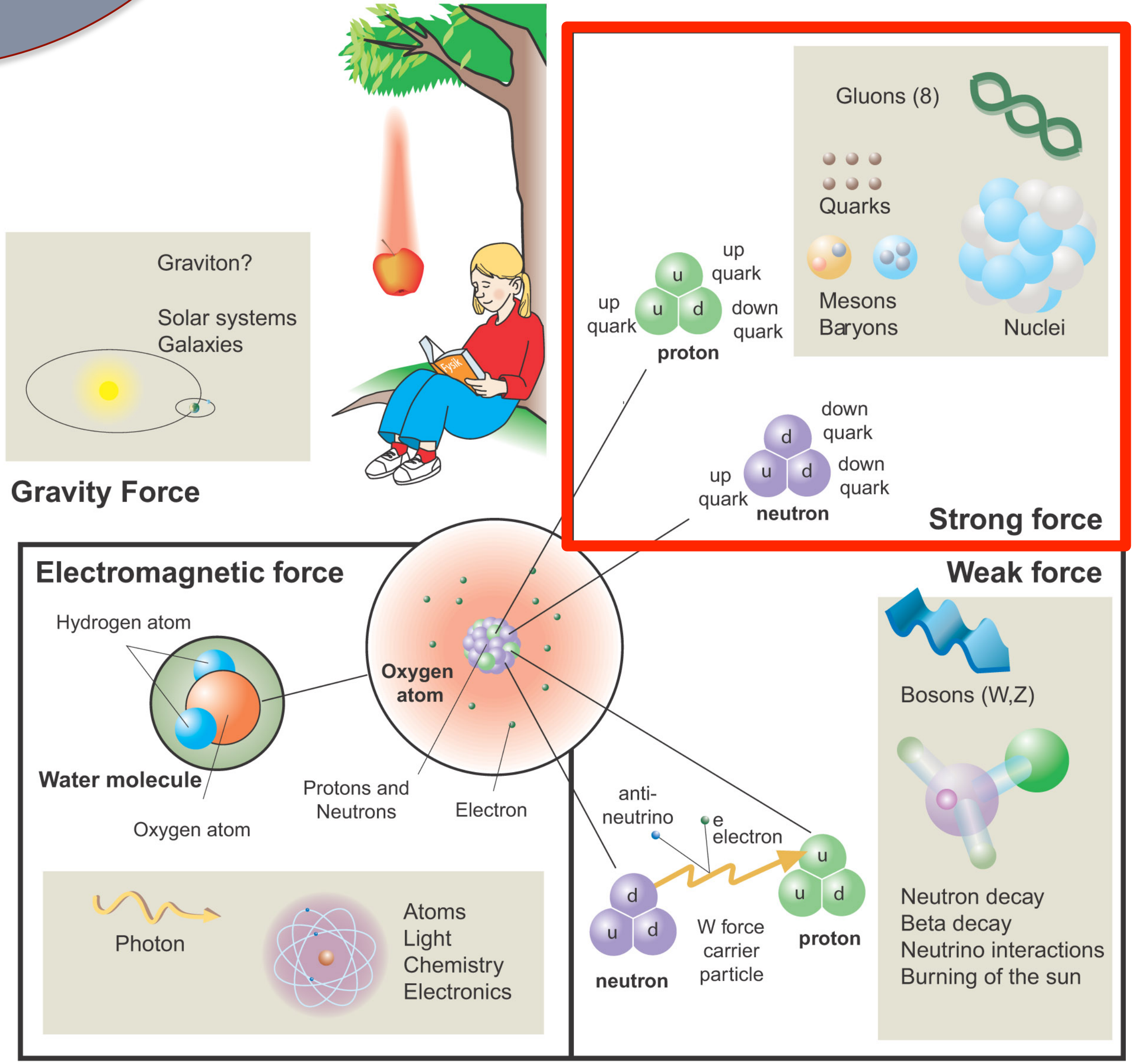
Name	Mass GeV/c^2	Electric charge
γ photon	0	0
W^-	80.4	–1
W^+	80.4	+1
Z^0	91.187	0

Strong (color) spin = 1

Name	Mass GeV/c^2	Electric charge
g gluon	0	0

+ the Higgs!

The Fundamental Interactions



Nuclei are held together by exchanging mesons (but deuterons are easy to break apart)

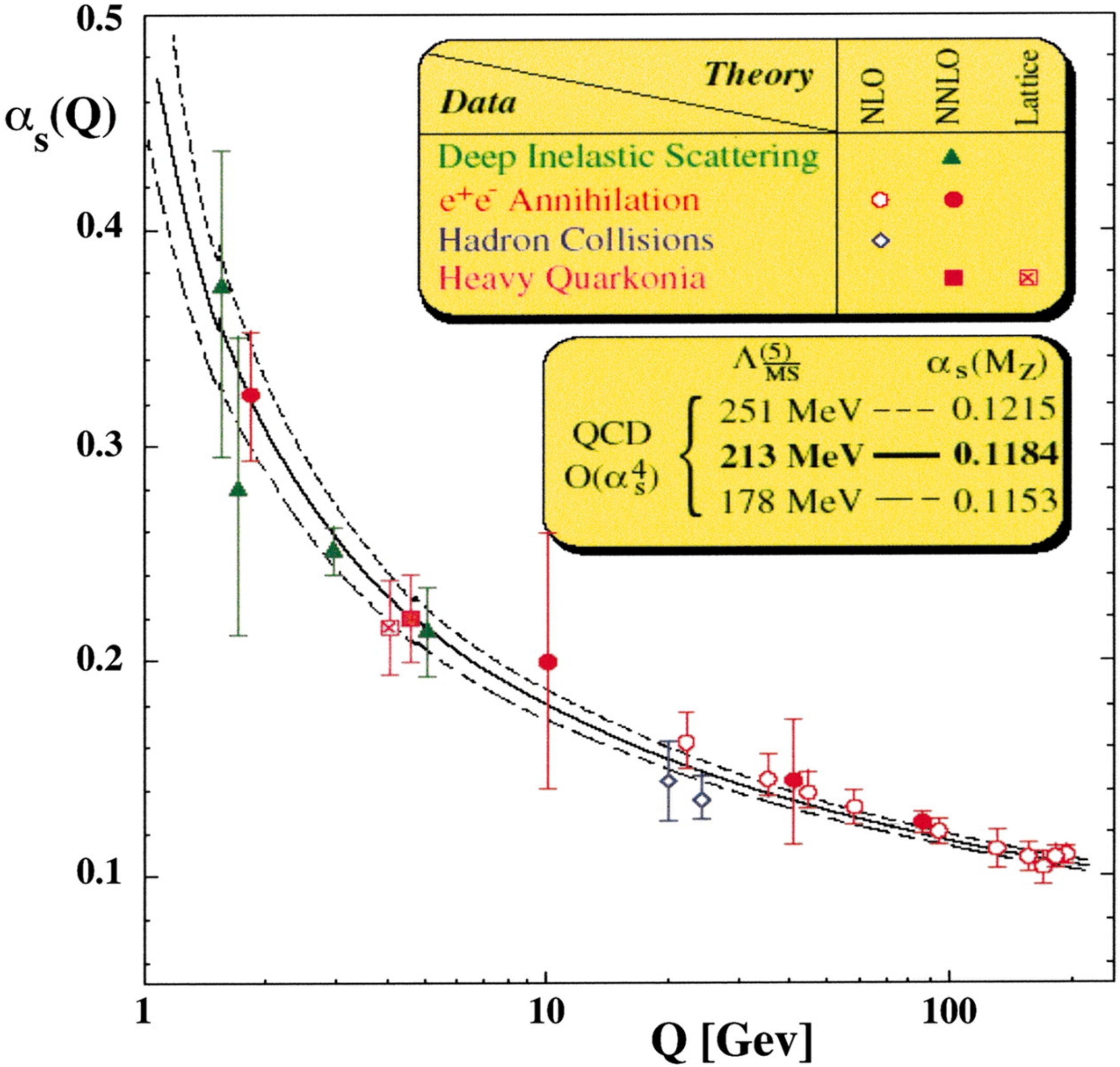
Nucleons (and hadrons in general) are held together by exchanging gluons

- **To which extent do we understand QCD properties?**
- Do we understand QCD multi-particle properties in an **extended medium dominated by the strong interaction?**

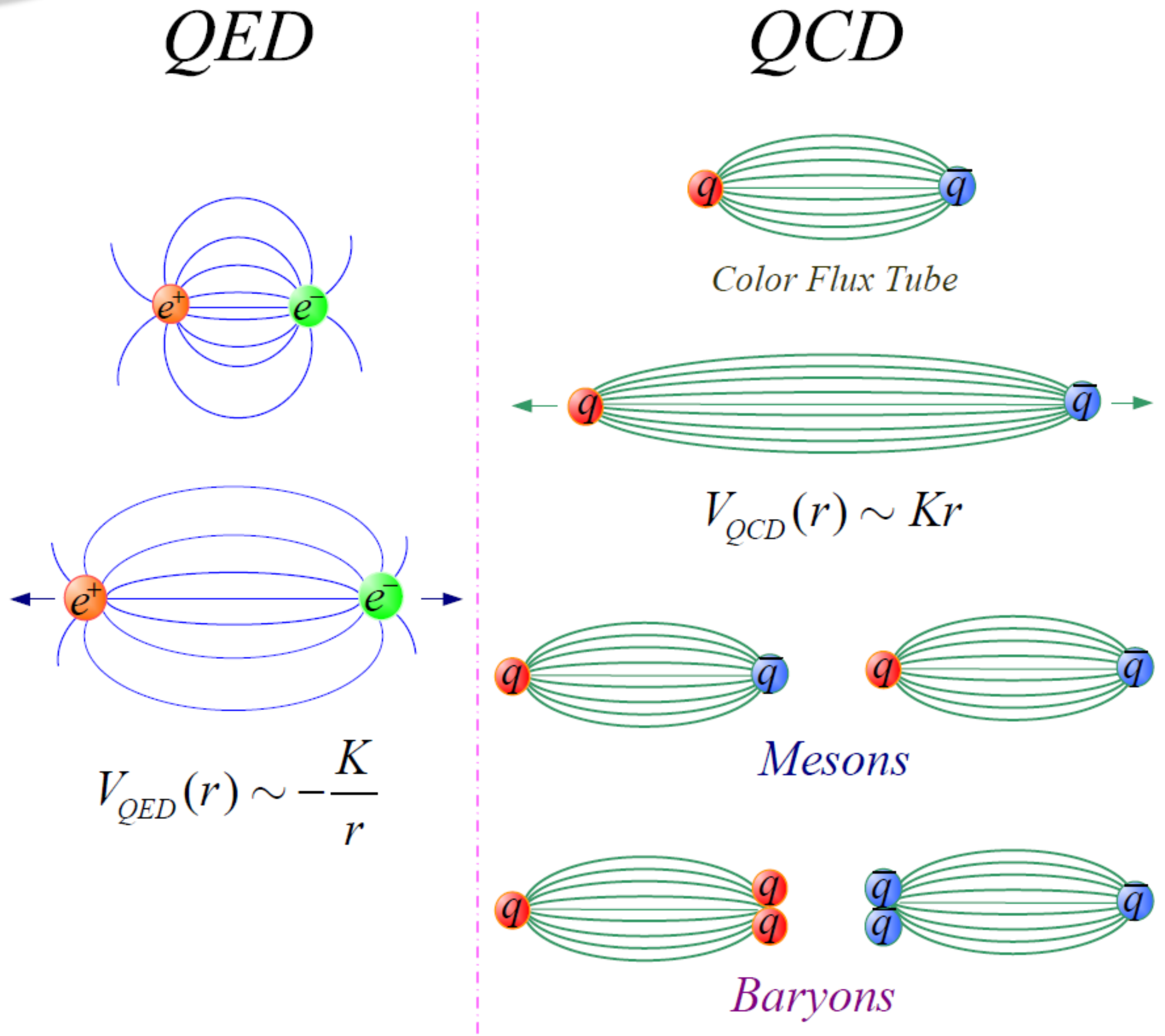
Strong Interaction: Asymptotic Freedom…

The QCD “running” coupling “constant”

- Gross, Politzer, Wilczek 1973: Strong interactions are weak at short distances (high momentum transfers)…
- … but at large distance the strong interaction is **really** strong!



… and Color Confinement



- **The energy in the color flux tube connecting two partons grows with the distance**

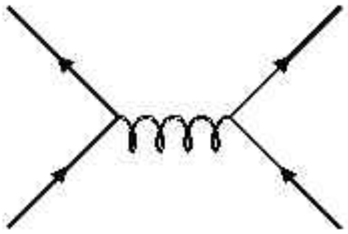
- At large distances (of the order of fm) quark-antiquark pairs pop out from the "vacuum" (it is energetically favorable to do so)

⇒ Pulling apart partons only leads to more hadrons!

Two Regimes of QCD

Perturbative QCD (pQCD) means that rigorous (converging) calculations can be done with Feynman integrals

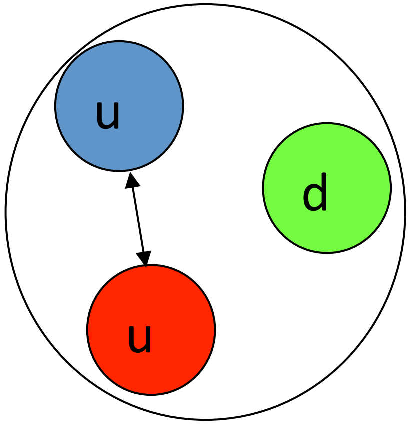
- Well defined for interactions between quarks and gluons with large momentum exchange ($Q^2 > 1$ GeV)



$Q^2 > 1$ GeV

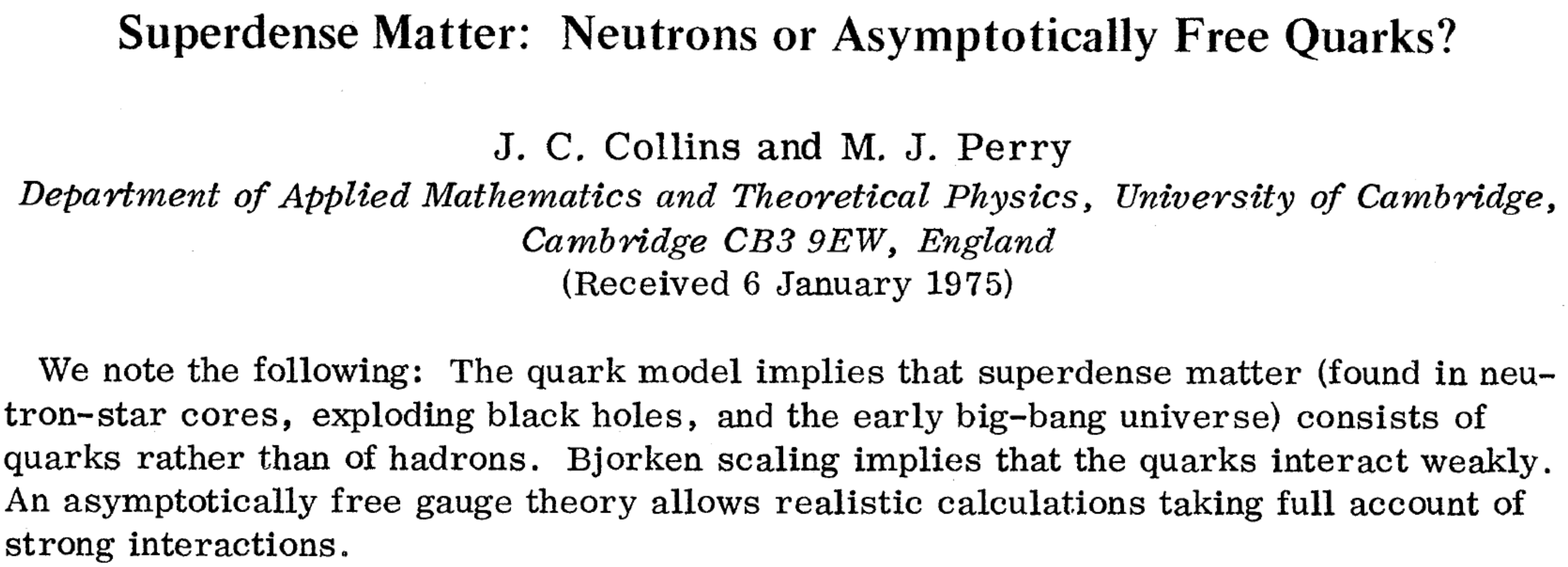
However, at large distances (r ≈ 1 fm) one can no longer write down Feynman diagrams and compute amplitudes, because of the too large values of the α_S.

- The particles we observe in nature are in the regime of **non-perturbative QCD**
- Small momentum exchange ($Q^2 << 1$ GeV) is implied in this regime. Typical example: interaction between the partons composing baryons & mesons



$Q^2 << 1$ GeV

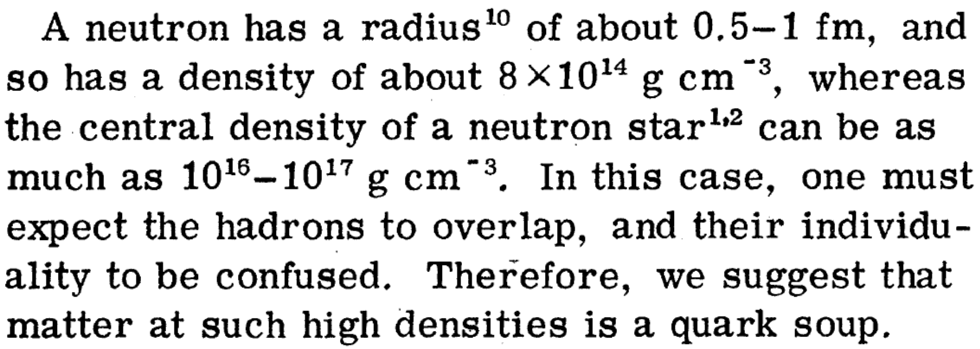
Hadronic Matter under Extreme Conditions



Superdense Matter: Neutrons or Asymptotically Free Quarks?

J. C. Collins and M. J. Perry
Department of Applied Mathematics and Theoretical Physics, University of Cambridge,
Cambridge CB3 9EW, England
(Received 6 January 1975)

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 of hadrons. Bjorken scaling implies that the quarks interact weakly. An asymptotically free gauge theory allows realistic calculations taking full account of strong interactions.



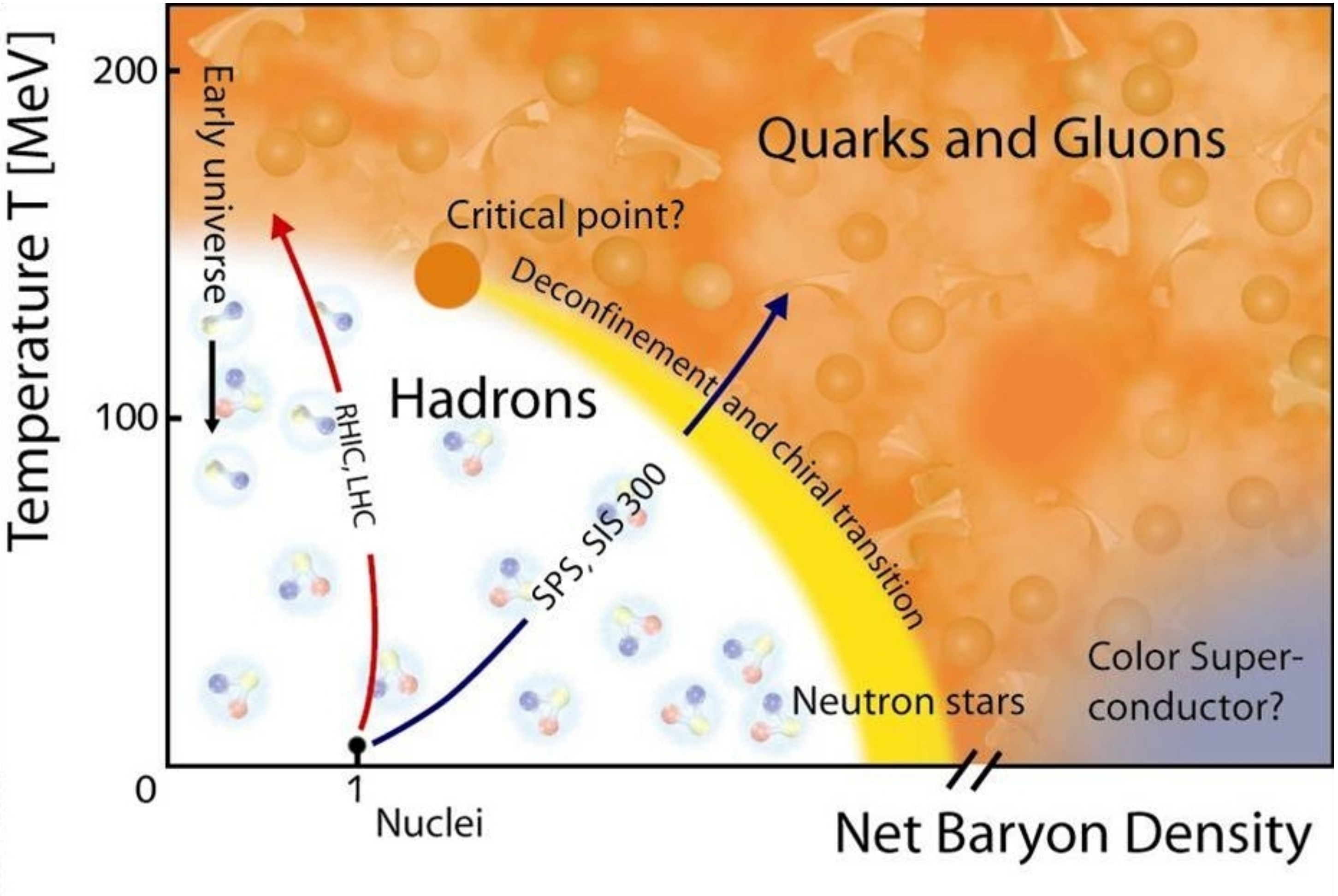
A neutron has a radius[10] of about 0.5–1 fm, and so has a density of about 8×10^{14} g cm^{-3}, whereas the central density of a neutron star[1,2] can be as much as 10^{16}–10^{17} g cm^{-3}. In this case, one must expect the hadrons to overlap, and their individuality to be confused. Therefore, we suggest that matter at such high densities is a quark soup.

How does QCD matter behave under extreme conditions of temperature and energy density?

- **A question rooted in the QCD, with cosmological and astrophysical implications**

Phase Diagram of the QCD Matter…

- **What is the state of QCD matter under specific conditions of temperature and baryon density?**



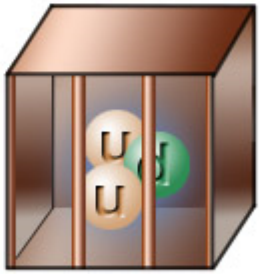
- Challenging task for the **lattice QCD**, experimental **observations are needed!**

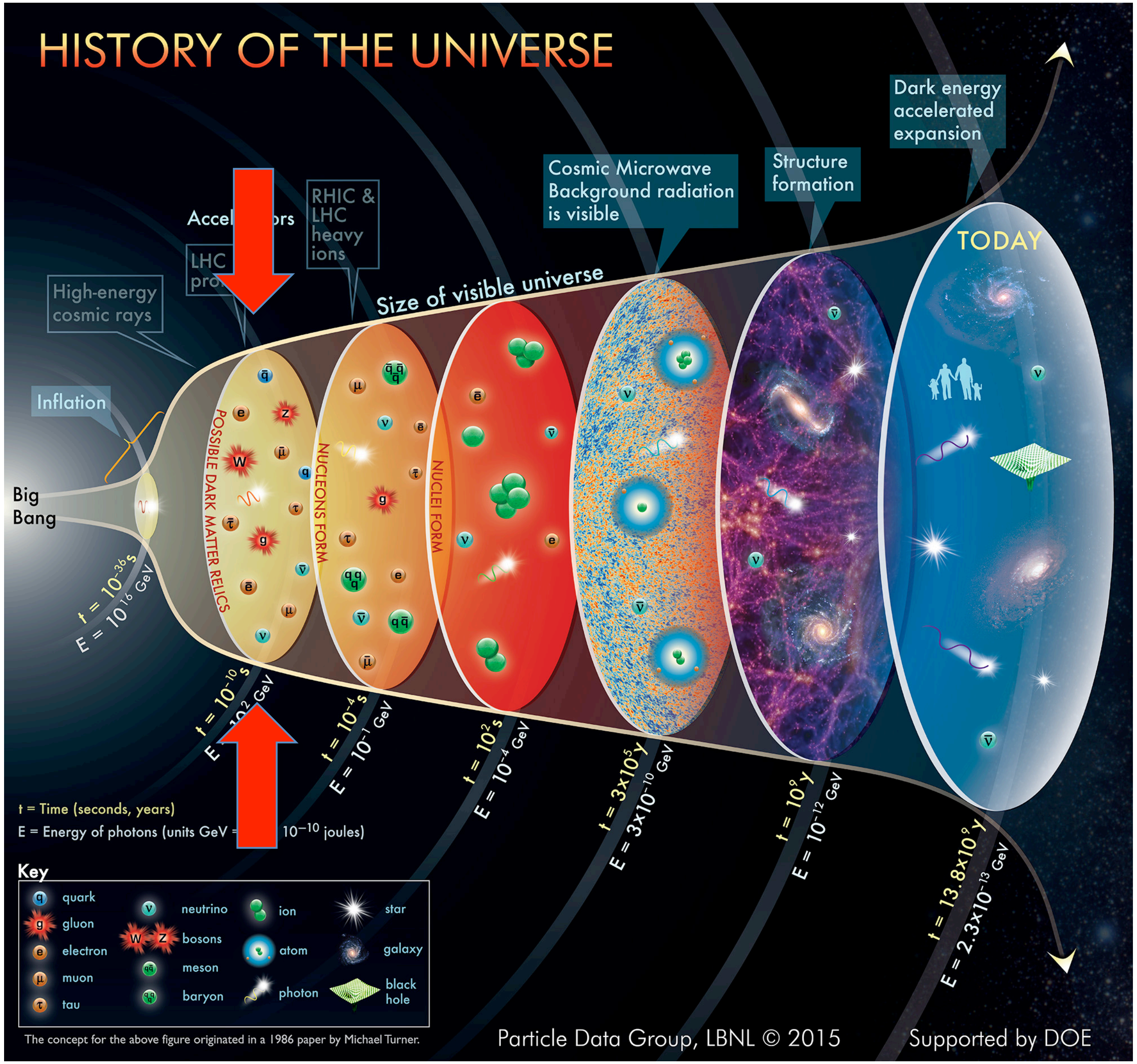
- Which is the nature of the phase transition at large net baryon density?
- Is there a critical point?

… and its Cosmological Context

- **In the early stages of the Universe, quarks and gluons were reaming freely** due to the large temperature and energy density

- As the universe cooled down, they got confined and have remained imprisoned ever since…





The concept for the above figure originated in a 1986 paper by Michael Turner.

Particle Data Group, LBNL © 2015

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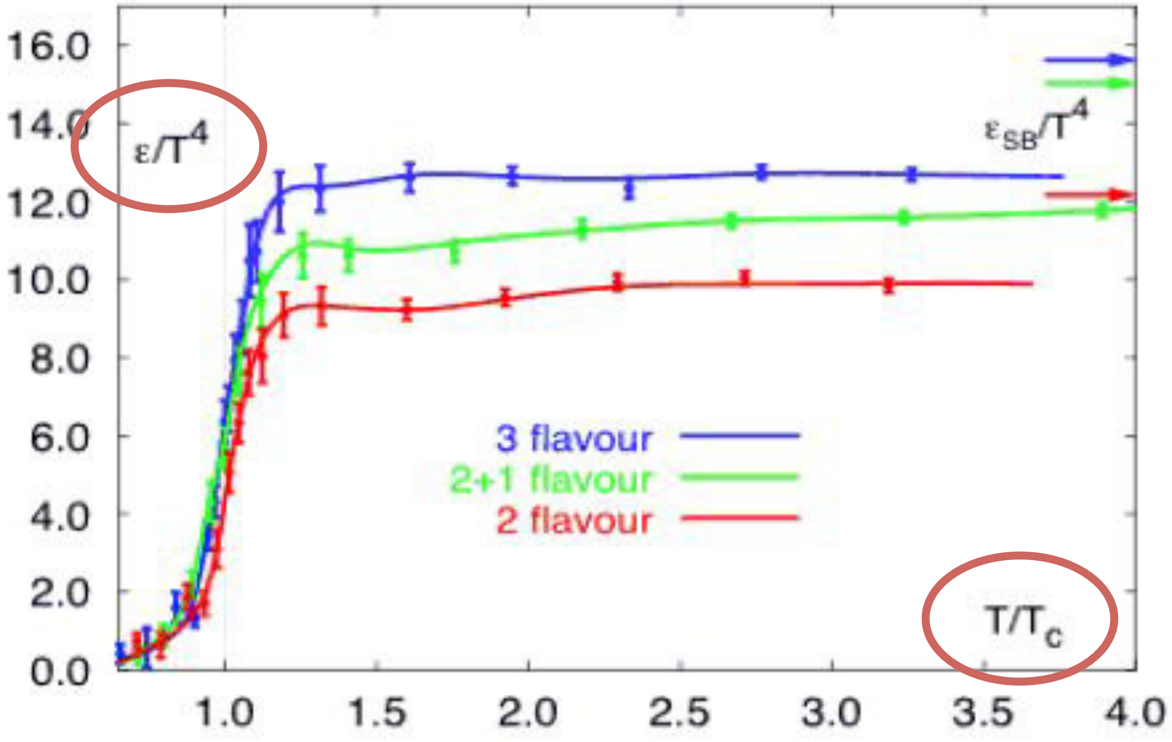
Lattice QCD Predictions

Understanding the strong force and the phenomenon of **confinement**:

- We must create and study a system of **deconfined** quarks and gluons
- **But… how about the theory?**



Lattice QCD is the only 1st principle calculation of non-perturbative QCD (large α_s)
⇛ hadron properties (e.g. masses), phase transition and QGP properties. **QGP onset:**

- $T_C \approx 170$ MeV (approx. $2 \cdot 10^{12}$ K, 100.000 times the temperature at the center of the Sun)
- $\varepsilon_C \approx 1$ GeV/fm^3 (approximately 5 times the density of ordinary nuclear matter)

Resuming…

Can we explore the phase diagram of hadronic matter? We think so!

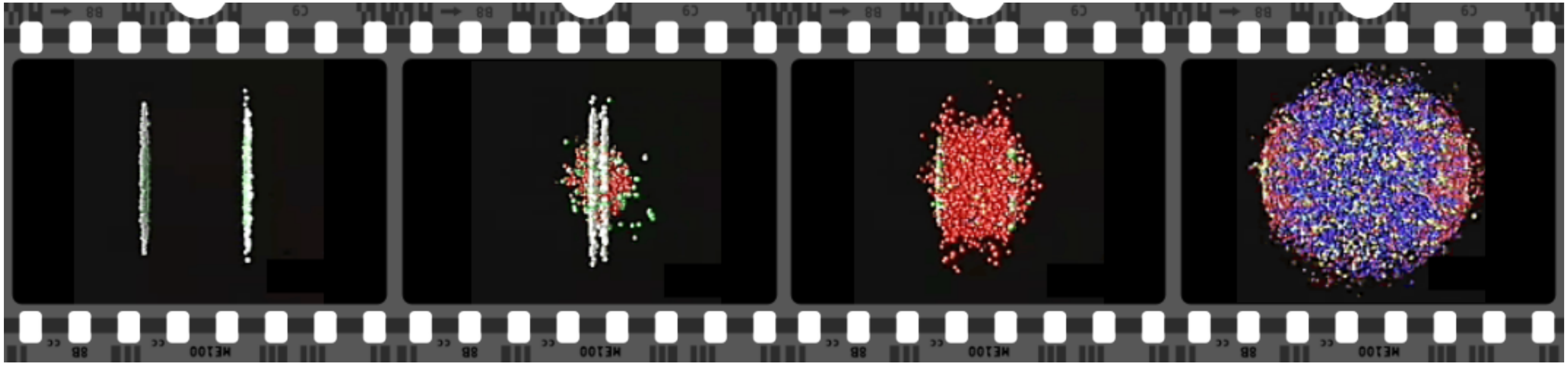
- By colliding nuclei in the laboratory
- By varying the nuclei size (A) and colliding energy (net baryon density)
- By studying spectra and correlations of the produced particles
- **But… the system must be at equilibrium**, so dense and large (even for a very short time) to study the multi-particle aspects of the QCD

Can we create and characterize the Quark-Gluon Plasma? We hope so!

- By colliding large nuclei at large energies
- Which conditions at the phase transition? Lattice QCD predicts:
  - Critical temperature $T_c \approx 170$ MeV
  - Critical energy density ≈ 5 × ordinary nuclear matter

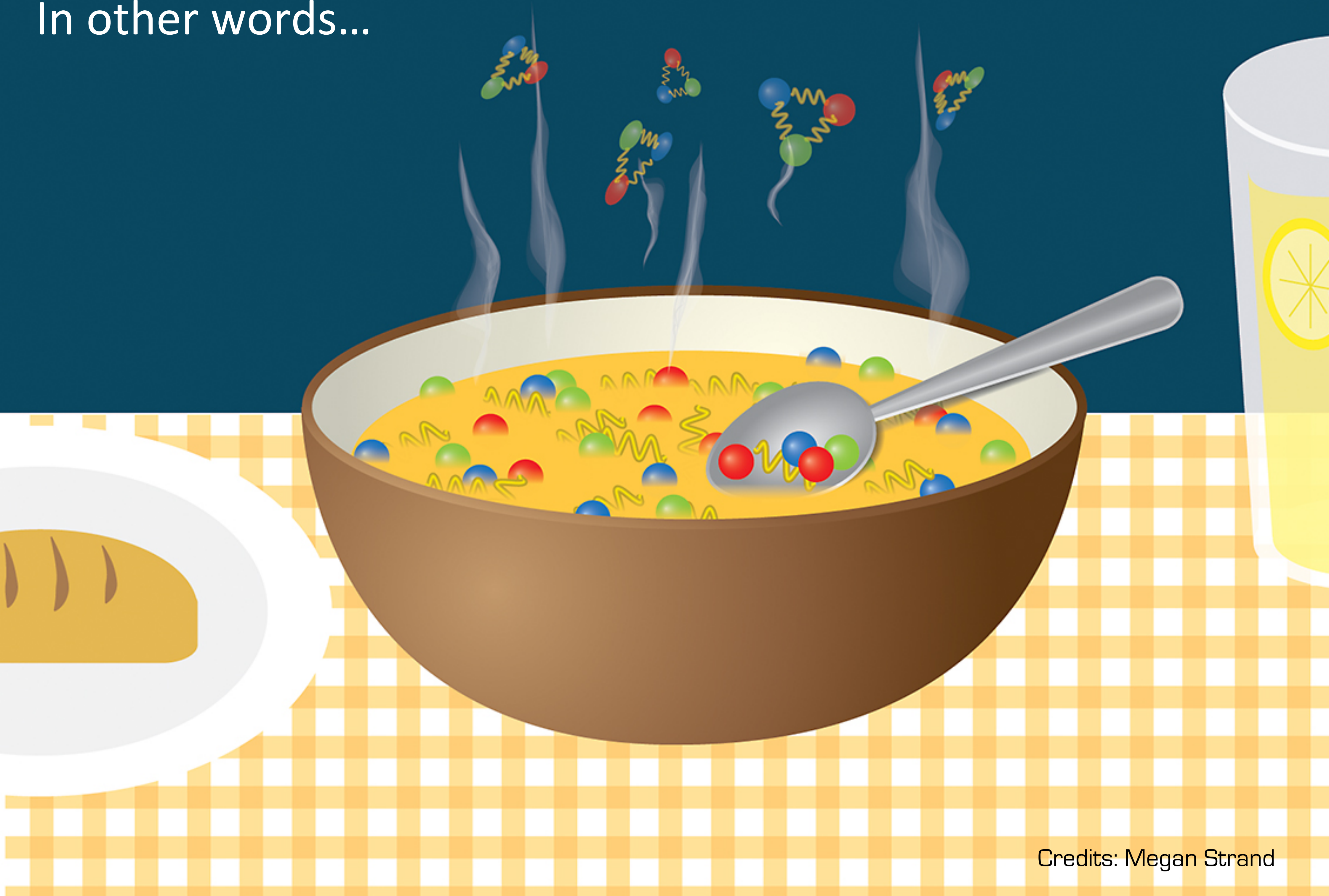
QGP in Lab: Heavy-Ion Collisions or the "Little Bang"

- **Initial conditions.** Large Lorentz contraction. Nucleus wave function is mostly given by gluon contributions
- **Particle (entropy) production.** Involves mostly "small-*x*" partons. One characteristic scale: saturation momentum Q_s. Large initial fluctuations
- **Thermalization of produced partons.** QGP phase. Hydrodynamical expansion
- **Hadronization** (boundary between QGP and hadronic matter) and **chemical freeze-out**. Elastic interactions until thermal freeze-out. Measurements



t = 0 t ≈ 0.3 fm/c t ≈ 3 fm/c

In other words…



Credits: Megan Strand

Challenge: Creating and Calibrating the Probes

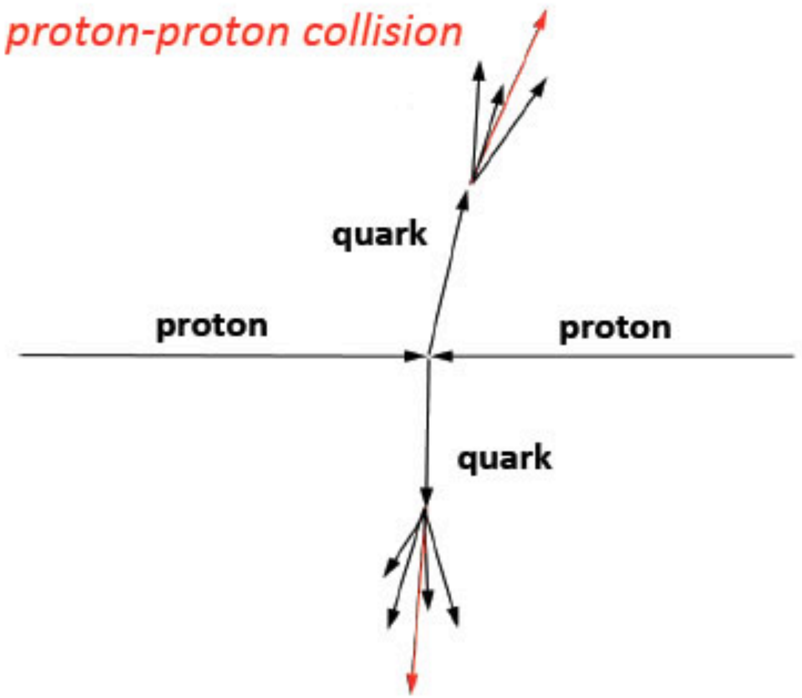
- **The “probes” must be *produced* together with the system they probe!**

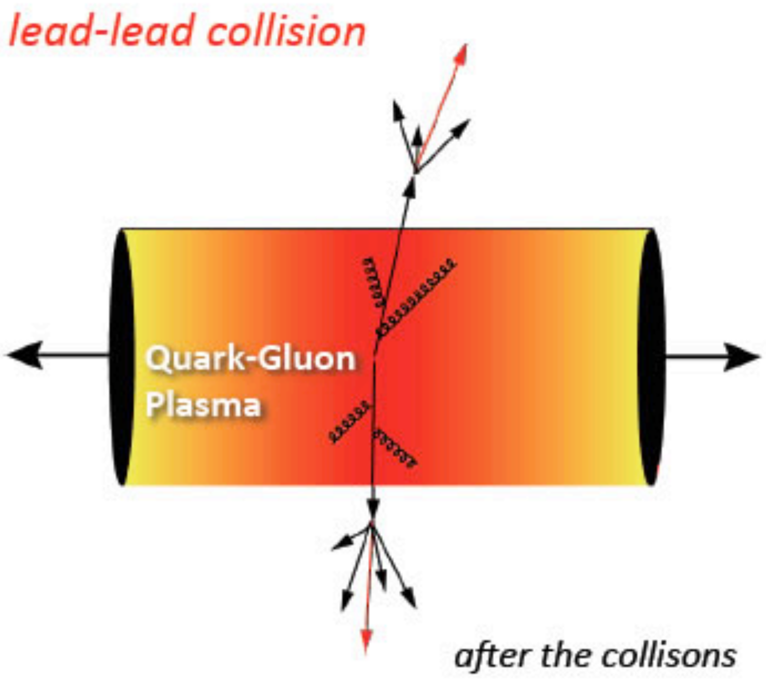
- In particular: we look for probes which are created **very early in the collision evolution**, so that they are there before the matter to be probed (the QGP) is formed: hard probes (jets, quarkonia, high-p_T particles, ...)

- **We must have “trivial” probes**, *not affected* by the dense QCD matter, to serve as baseline reference for the interesting probes: photons, Z and W bosons, Drell-Yan dileptons

- **We must have “trivial” collision systems**, to understand how the probes are affected in the *absence* of “new physics”: pp, p-A, d-A, light ions

Challenge: Creating and Calibrating the Probes





The “reference”

The “QGP physics”

From the Heavy-Ion Physics Vocabulary: R_{AA}

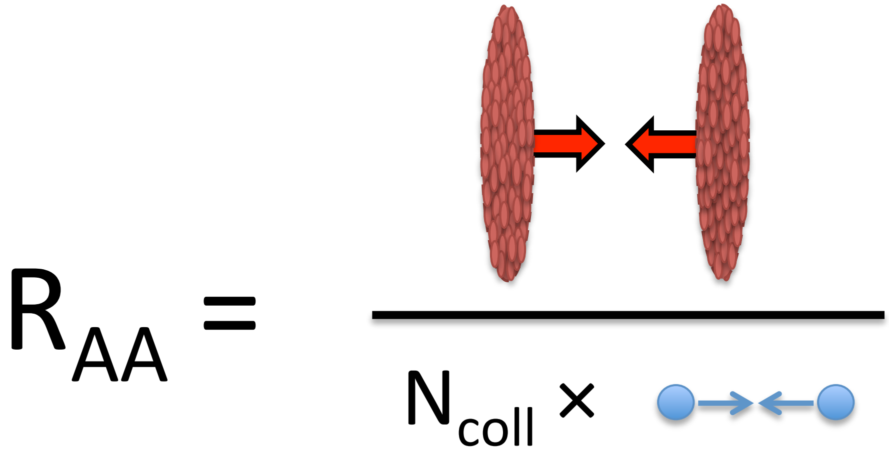
R_{AA} = nuclear modification factor (in A-A collisions w.r.t. pp collisions)

How is it built?

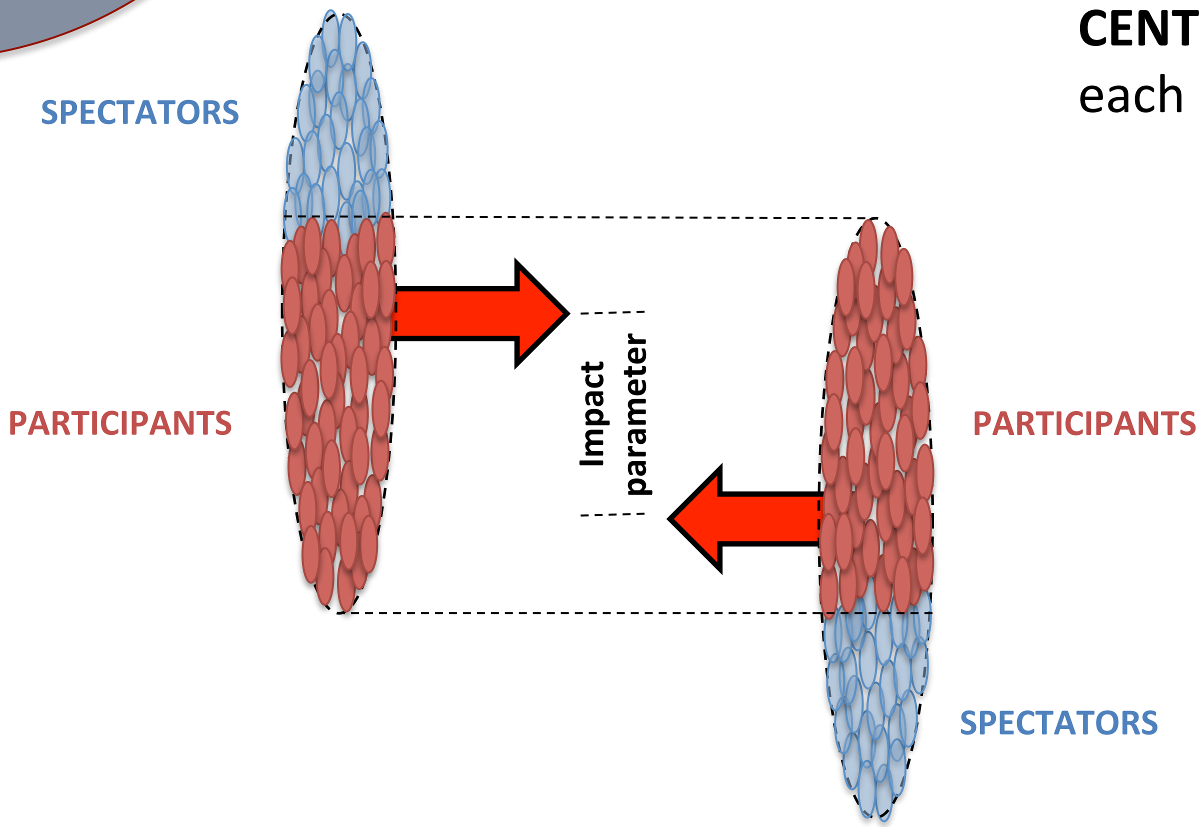
- Take the outcome of a measurement in pp (e.g. J/ψ yield)
- Evaluate the expected outcome of the same measurement in A-A in the hypothesis that A-A is a simple superposition of N_{coll} nucleon-nucleon collisions
- Take the ratio between the real and the expected outcomes of the measurement in A-A, and you have the R_{AA}

What does it mean?

- The R_{AA} quantifies the influence of the hot medium on the “vacuum” physics



From the Heavy-Ion Physics Vocabulary: Centrality



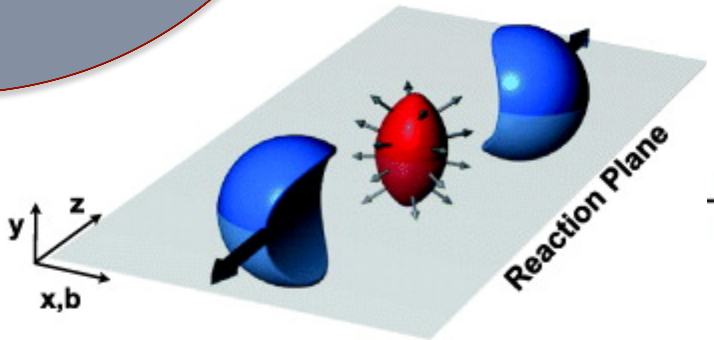
CENTRALITY: parameter characterizing each nucleus-nucleus collision

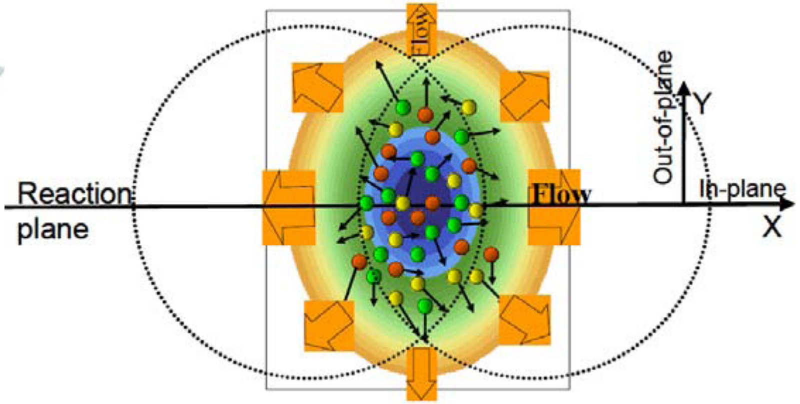
Linked to the collision geometry via the impact parameter (transverse distance between the nuclei centers)

Collision geometry implies collision dynamics: the smaller the impact parameter, the larger the number of nucleons participating to the collision

- Small impact parameter, large number of participating nucleons: **"central" collision, largest hot-medium effects**
- Large impact parameter, small number of participating nucleons: **"peripheral" collision, smallest hot-medium effects (possibly no hot-medium effect at all)**

From the Heavy-Ion Physics Vocabulary: v_2





Initial spatial anisotropy of
the overlap region of
colliding nuclei

⬇⬇⬇

Anisotropy in momentum
space through interactions of
produced particles

- **Elliptic flow:** measured by the v_2 parameter extracted from the Fourier decomposition of particle azimuthal distributions relative to the reaction plane Ψ_{RP}

$$\frac{\mathrm{d}N}{\mathrm{d}\phi} \propto 1 + 2v_2\cos(2(\phi - \Psi_{\mathrm{RP}})) + \mathrm{higher\ harmonics}\ (v_3,\ v_4,\ \ldots)$$

v_2 provides a measurement of collectivity: constraints the properties of hot medium

Large mean free path ⇛ particles stream out isotropically, no memory of initial asymmetry **(ideal gas)**

Small mean free path ⇛ large density and pressure gradients, larger mom. anisotropy **(ideal liquid)**

Part II: Observables

- Non-exhaustive list of possible measurements in a heavy-ion experiment
- **Focus on the available probes/methods** more than on the specific results (which varies according to the energies, and whose interpretation often still waits for a common theoretical framework)

Two Laboratories to Study the QGP

- **AGS**: 1986 – 2000
  - Si and Au beams, up to 14.6 AGeV
  - Only hadronic variables

- **SPS**: 1986 – 2003; 2009 ⟶
  - Various beams up to Pb, 200 AGeV
  - Beam energy scan
  - Hadrons, photons and dileptons

- **RHIC**: 2000 ⟶
  - Various beams up to U, up to sqrt(s) = 200 GeV
  - Beam energy scan
  - STAR, PHENIX, BRAHMS, PHOBOS experiments

- **LHC**: 2009 ⟶
  - Pb beams up to sqrt(s) = 5.5 TeV
  - ALICE, CMS, ATLAS (maybe LHCb?) experiments

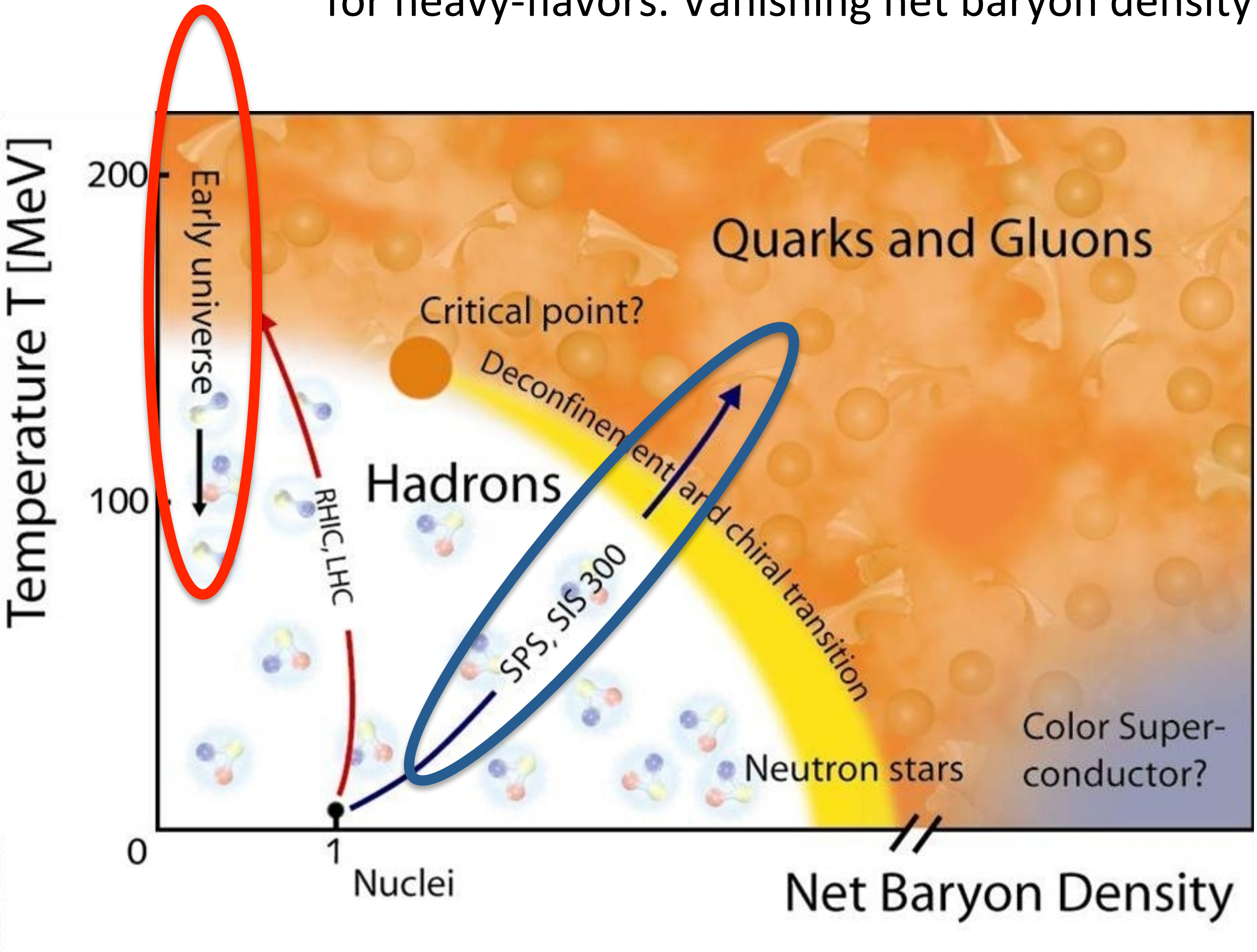
AGS + RHIC @ BNL

© Brookhaven National Laboratory

SPS + LHC @ CERN

High- and Low-Energy Frontiers

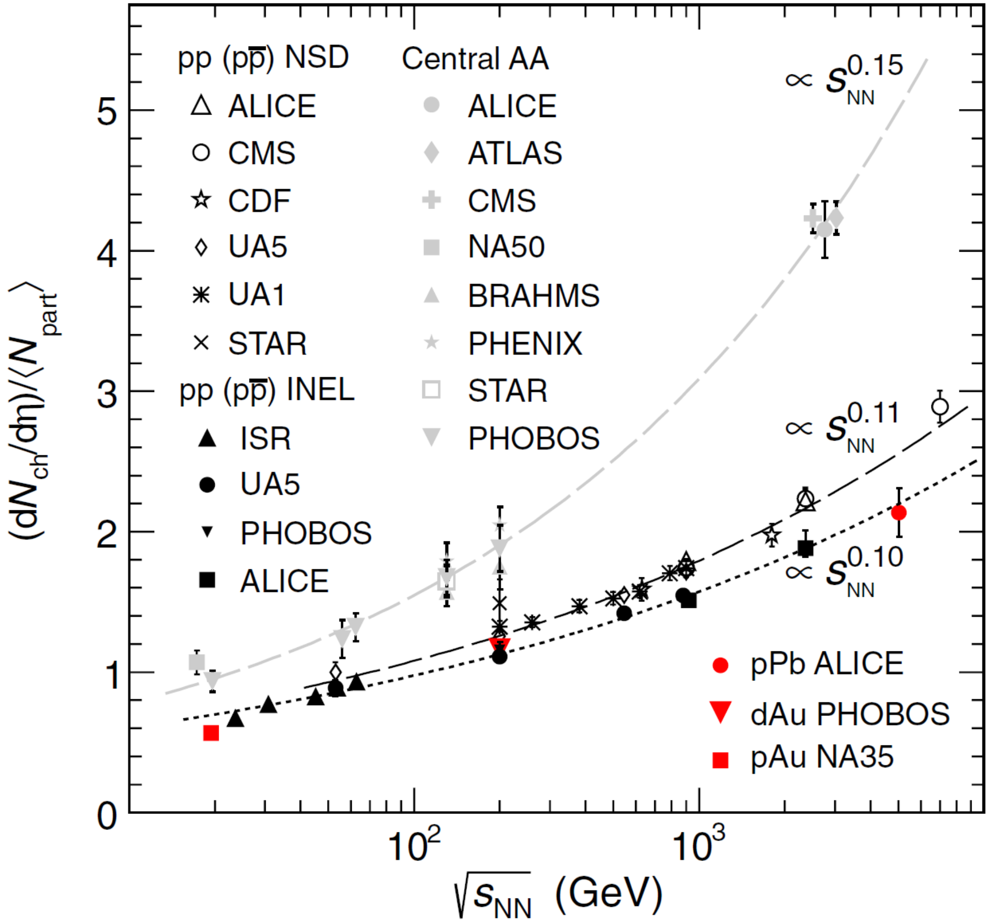
- **The high-energy frontier:** large and long-living QGP, large cross-sections for heavy-flavors. Vanishing net baryon density: Early Universe conditions



- **The low-energy frontier:** focus on light-flavor observables. **Energy scan:** search of the critical point and characterization of the phase transition

Counting Particles

First challenge to models: how many particles are produced in central A-A collisions?



- Particle multiplicity in pp, p-A and AA: well described by **power-laws of the center-of-mass energy**
- Dependence on sqrt(s) is **stronger for AA collisions** then for non-single-diffractive (NSD) pp
- sqrt(s) dependence is compatible for inelastic pp and p-A

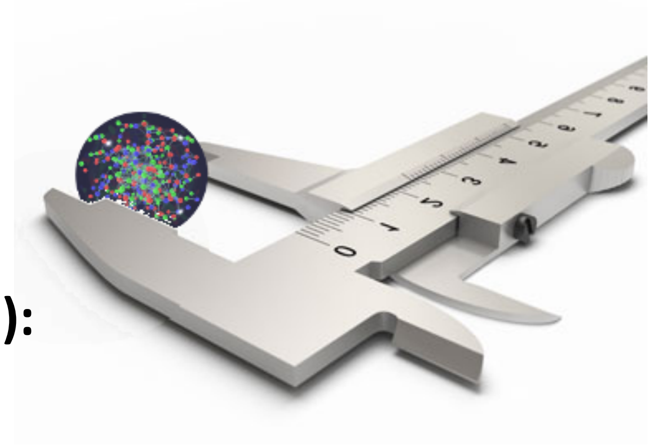
QGP Size and Temperature

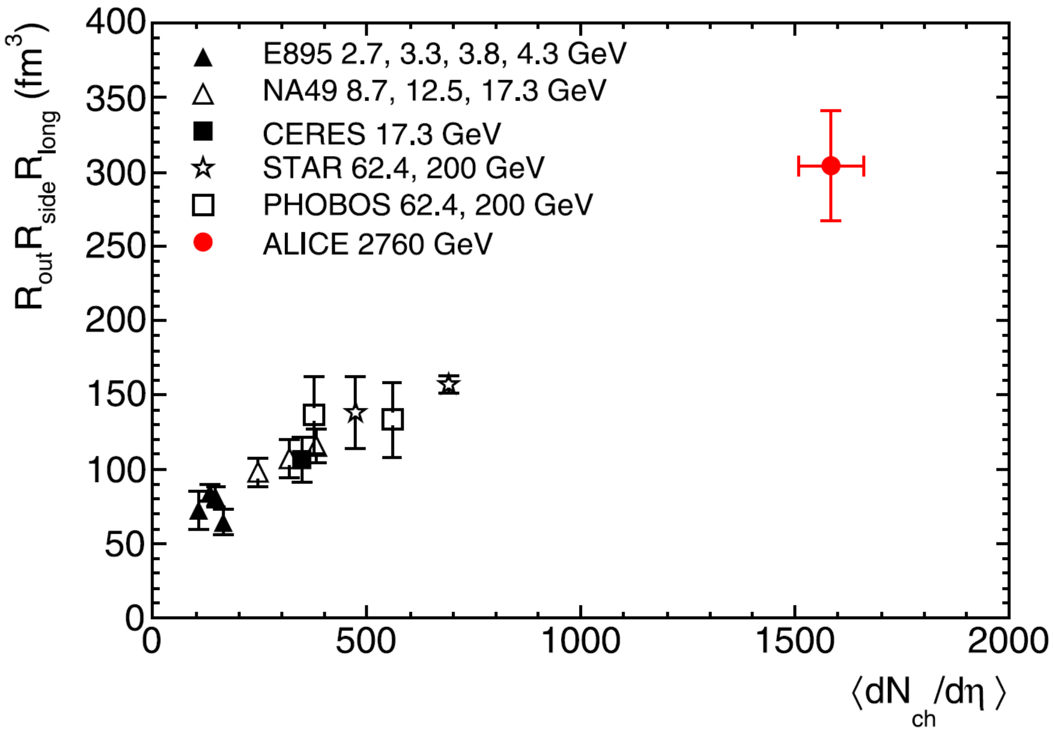
From identical boson interferometry:

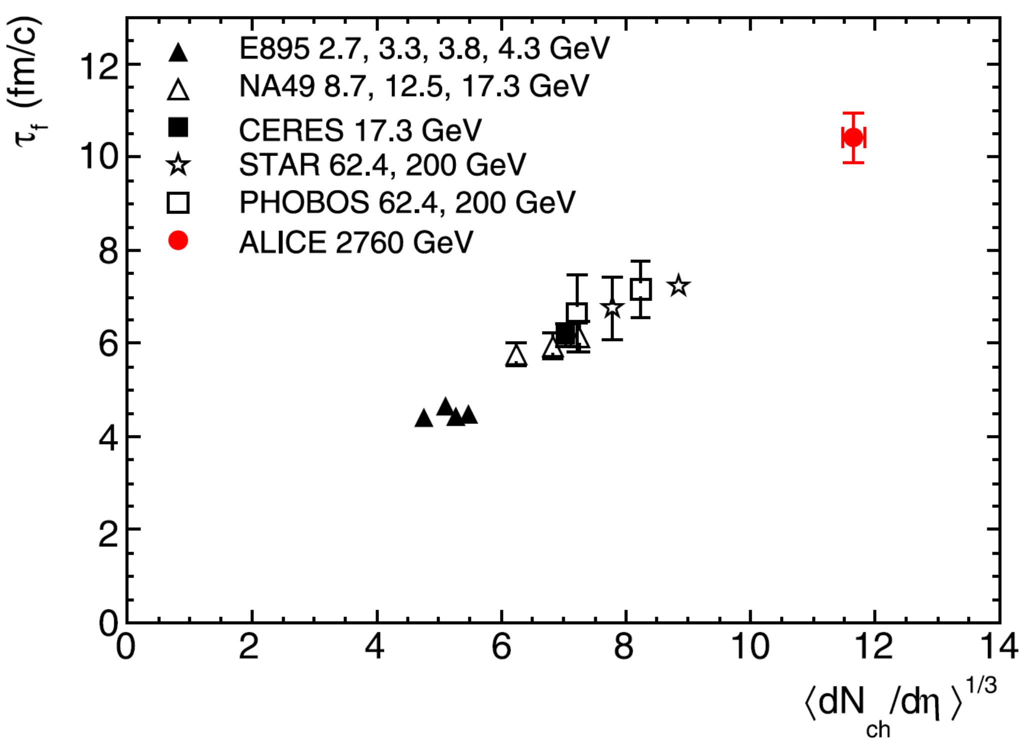
- Freeze-out volume: LHC = RHIC × 2
- Lifetime (decoupling time): LHC = 40 % larger than RHIC

From direct photon measurements (not shown here):

- T = 304 ± 51 MeV: LHC = RHIC × 1.4



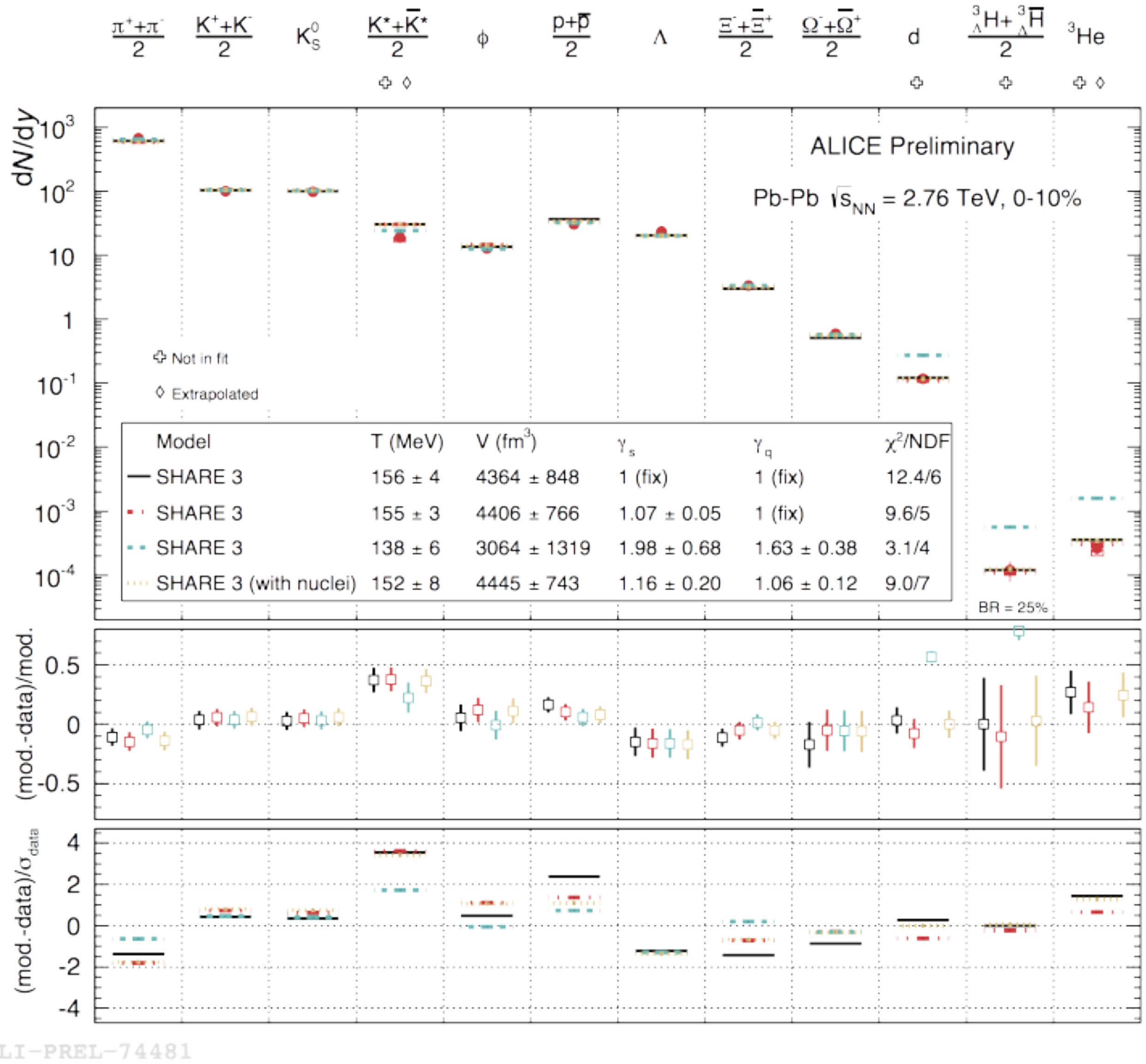




Hadron Yields: a Thermalized QGP?

- **Central heavy ion collisions** are commonly regarded as the ideal system for the **applicability of the thermal model**

- Fit of the ALICE data with an **equilibrium model** (SHARE) ⇛ χ^2/ndf ≈ 2. Better than any other colliding system at the LHC, but still some tension with the data

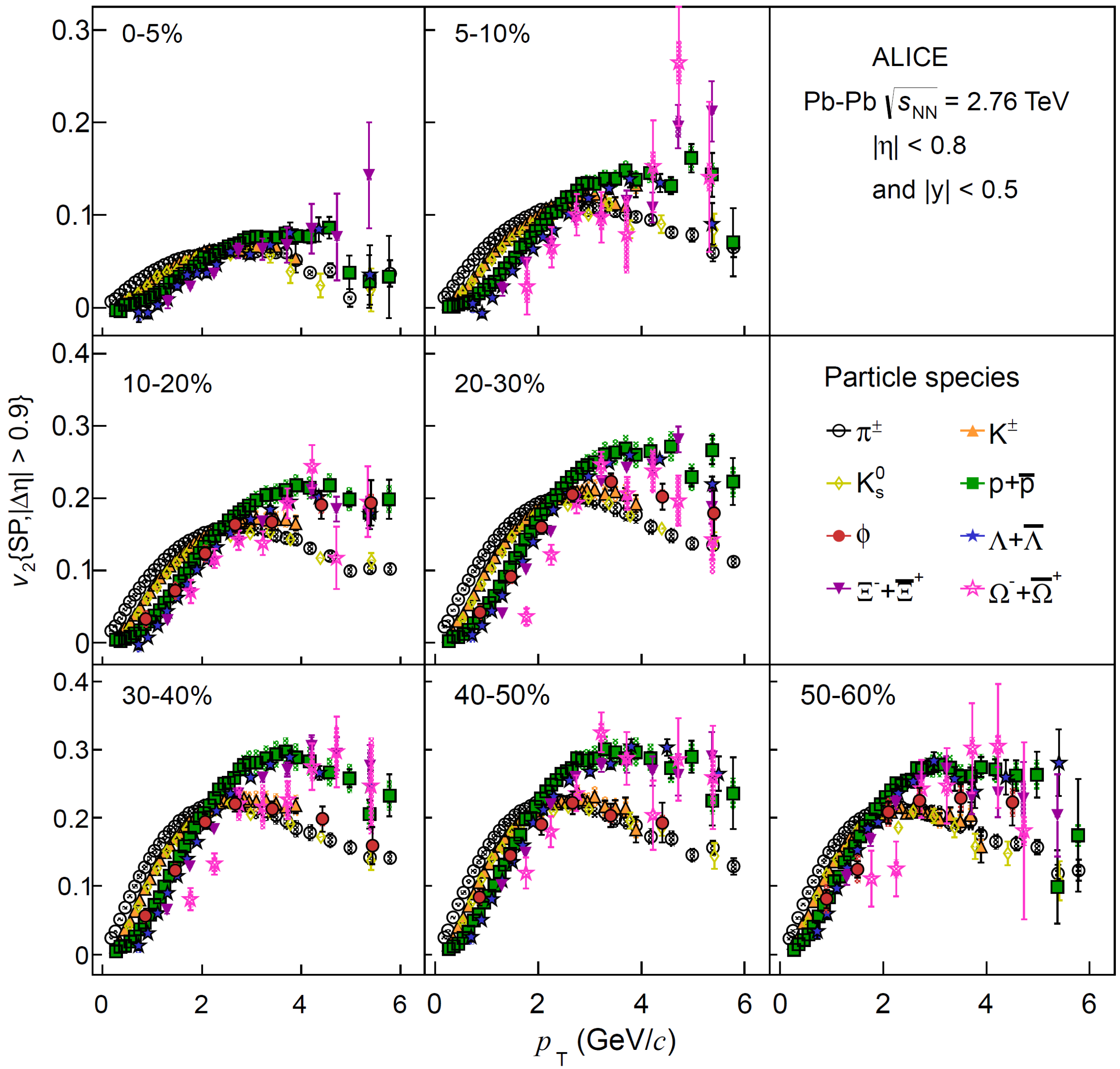


	Model	T (MeV)	V (fm^3)	γ_s	γ_q	χ^2/NDF
—	SHARE 3	156 ± 4	4364 ± 848	1 (fix)	1 (fix)	12.4/6
- ·	SHARE 3	155 ± 3	4406 ± 766	1.07 ± 0.05	1 (fix)	9.6/5
- -	SHARE 3	138 ± 6	3064 ± 1319	1.98 ± 0.68	1.63 ± 0.38	3.1/4
····	SHARE 3 (with nuclei)	152 ± 8	4445 ± 743	1.16 ± 0.20	1.06 ± 0.12	9.0/7

Collective Phenomena: a Strongly-Coupled QGP?

- The value of v_2 **progressively increases** from central to peripheral collisions up to the 40-50% centrality interval for all particle species

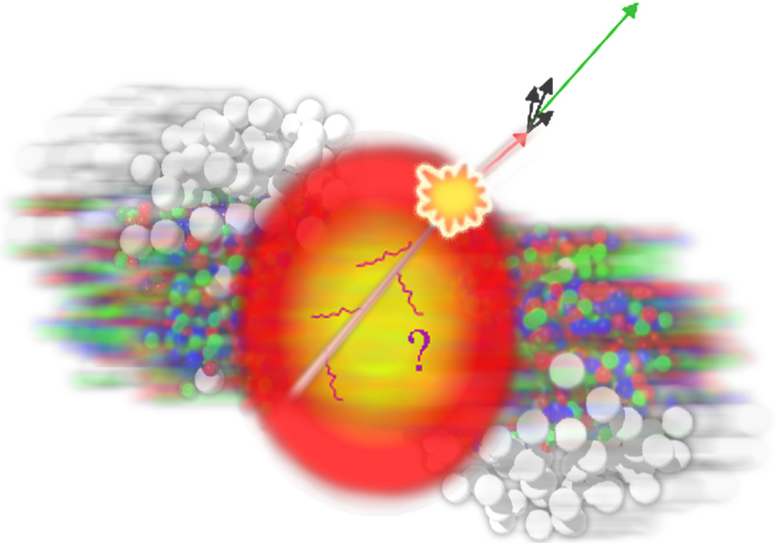
- This is consistent with the picture of the **final state anisotropy driven by the geometry of the collision,** as represented by the initial state eccentricity which increases for peripheral collisions

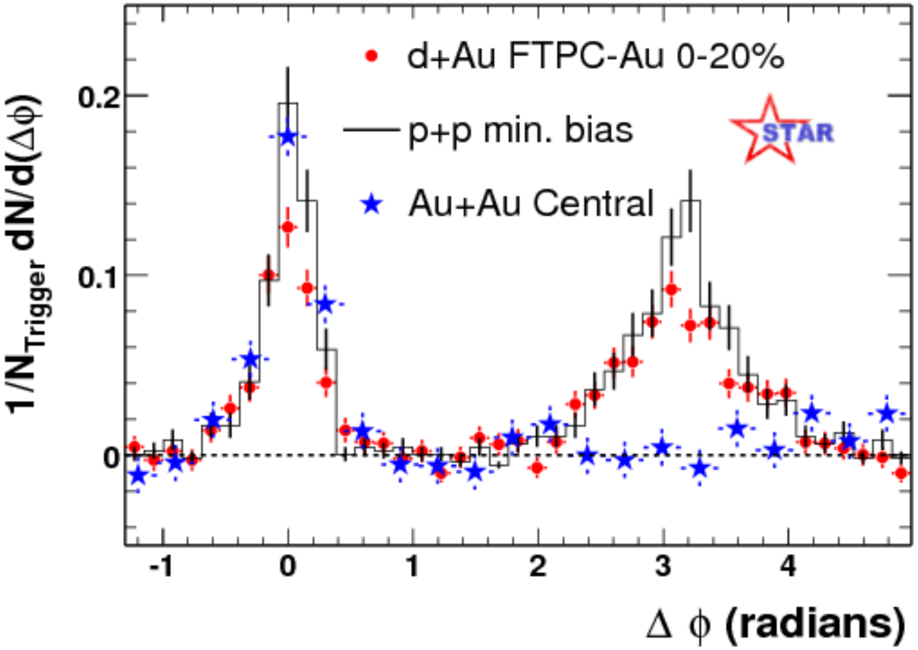


Jet Quenching: an Opaque QGP?

- **When back-to-back jets of particles are produced inside the hot, dense medium** produced by colliding heavy nuclei, one jet may be unable to escape the fireball

- How the jets propagate through the fireball, and how much quenching occurs, tells us a lot about the **properties of the hot matter generated in the collision**. Theory is challenged to understand this phenomenon quantitatively, using the tools of QCD



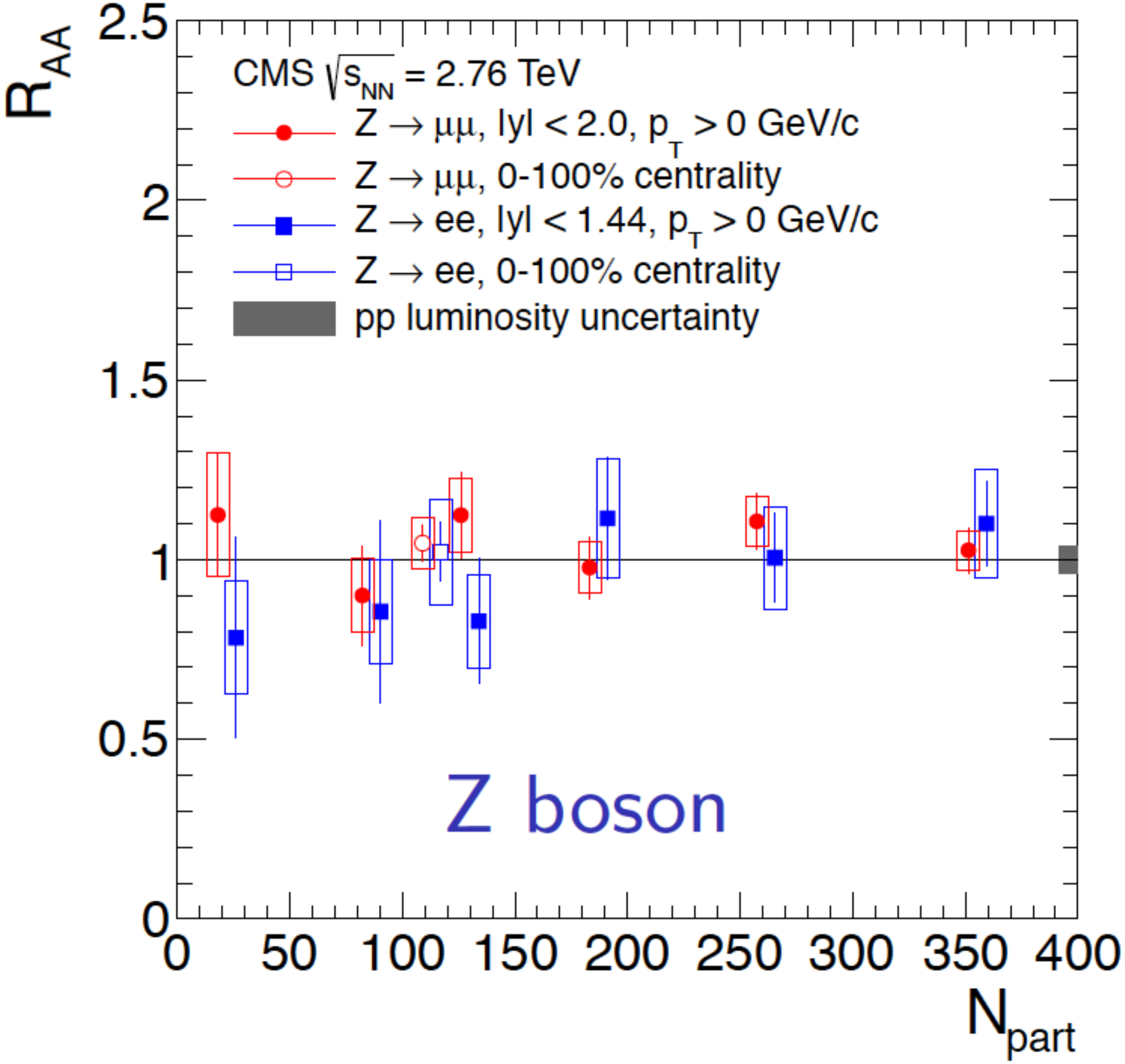


Electroweak Probes

- **Reference (control) probe:** electroweak bosons are not affected by the strong color field dominating the deconfined medium

- **Z bosons from CMS: no modification in the yield in Pb-Pb compared to pp, as expected**

- No dependence on collision centrality

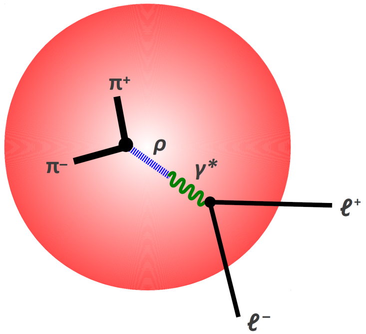


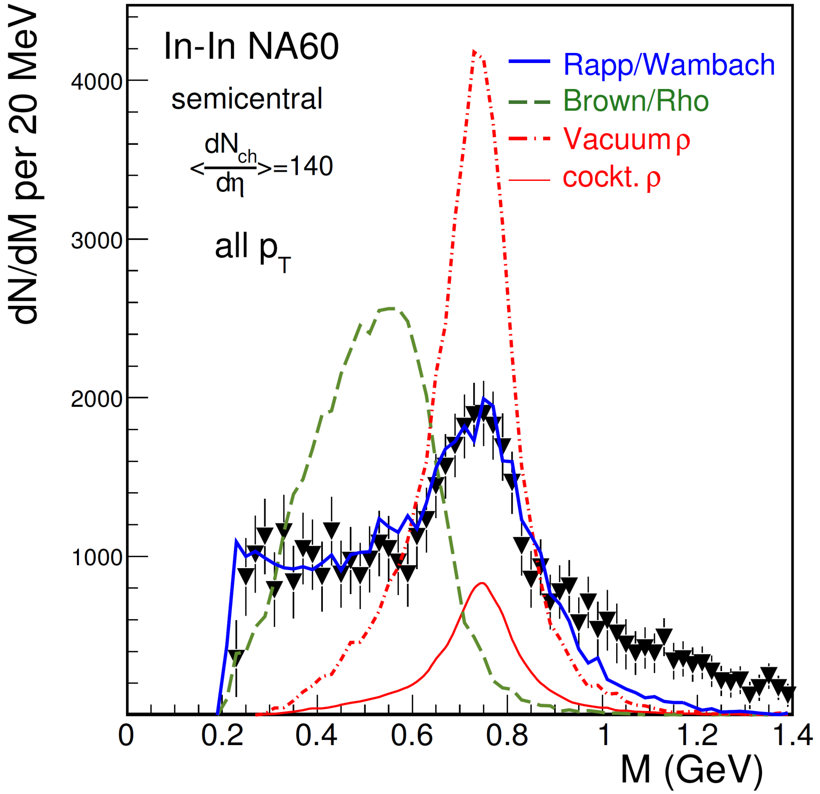
Electromagnetic Probes

- **Golden probes to** study the QCD phase transition (low-energy frontier) and its relations with the chiral symmetry restoration in the deconfined medium

- Dileptons (virtual photons) ⇛ no interactions with the hot medium, coupling with the light vector mesons

- **Two more imminent (and relatively easier) objectives:**
  - Describing medium modifications of the vector mesons spectral functions
  - Measure the dilepton radiation from the partonic phase (QGP) exploiting the double degree of freedom given by the mass and the p_T





Quarkonium Suppression…

Heavy quark-antiquark bound states are called quarkonium

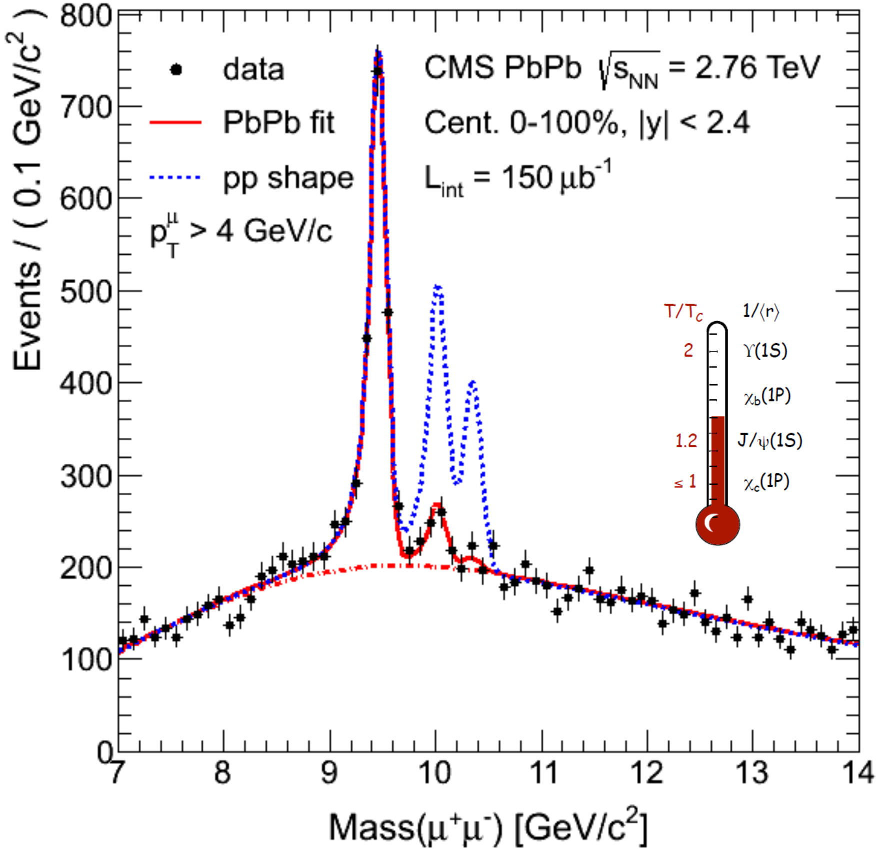
- The (meta-) stability of a quarkonium state in the vacuum is given by the specific **quark-antiquark potential**, shaped by the strong interaction

- But… the QGP is filled with free color charges (quarks and gluons)

  In the QGP, the quarkonium potential is screened (equivalent to Debye screening for e.m. plasmas)

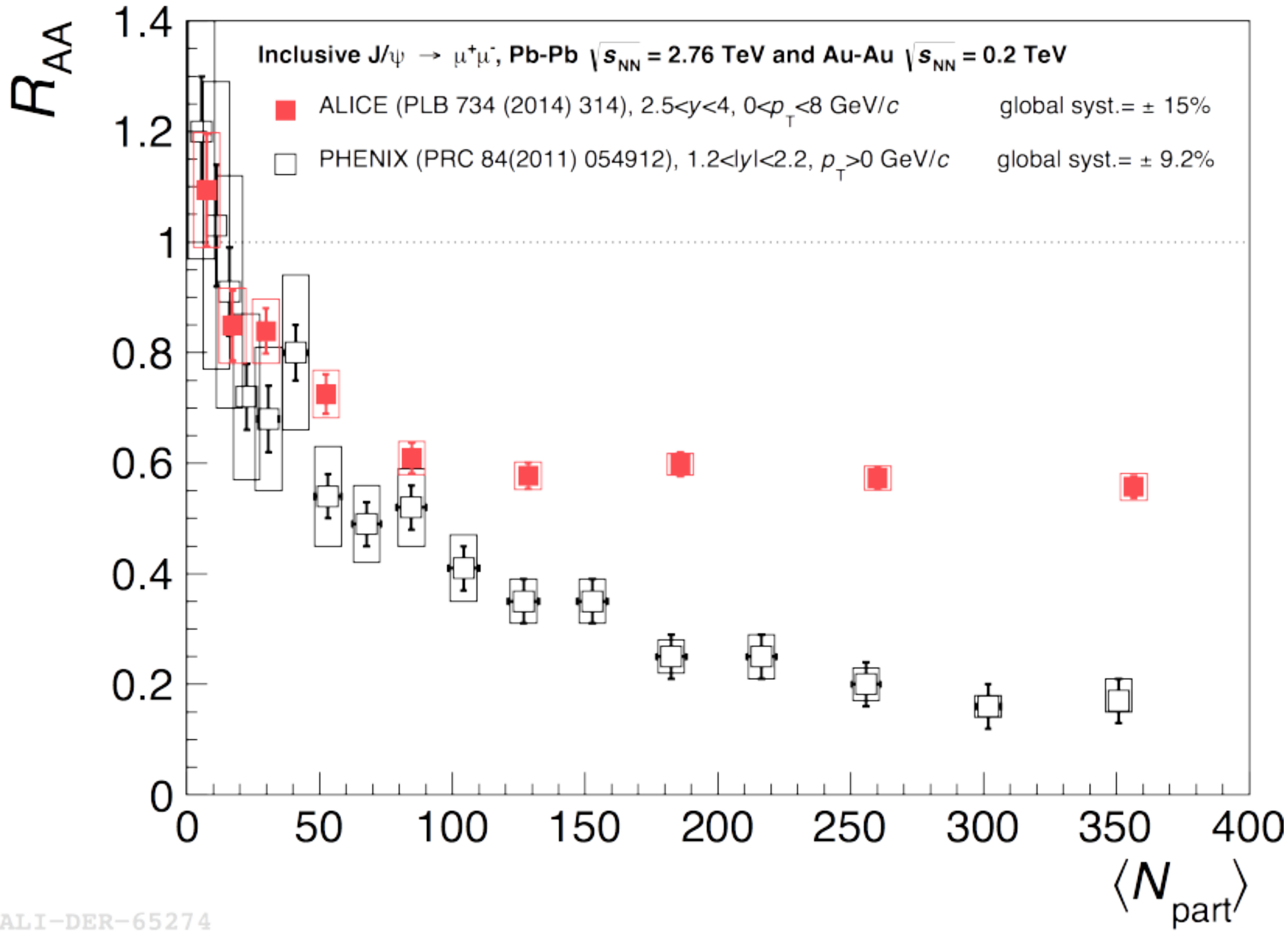
- If the screening radius drops below the quarkonium binding radius, the **quarkonium should melt**

- Screening radius decreases with temperature, therefore suppression of quarkonia in A-A w.r.t. p-p acts as **a thermometer of QGP**



.. and Recombination?

- The higher the energy, the larger the charm production cross-section. **Can we have recombination of dissociated cc pairs, at sufficiently large energies?**



- PHENIX (RHIC top energy): vs ALICE (LHC Run1) ⇛ weaker centrality dependence and **smaller suppression for central events**

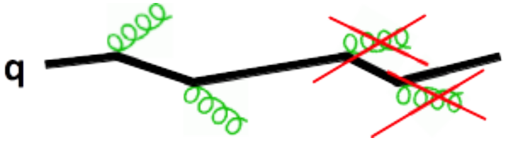
Is this the expected signature for (re)combination? LHC Run 2 needed!

Heavy Flavors

- **Large mass** ($m_c \approx 1.5$ GeV, $m_b \approx 5$ GeV) ⇛ produced in large virtuality Q^2 processes at the initial stage of the collision with **short formation time** $\Delta t > 1/2m \approx 0.1$ fm << τ(QGP) ≈ 5-10 fm/c. Insight on the short time scale of the collision

- **Charmed and beauty hadrons have a long life time** ($c\tau \approx$ 150-300 μm and $c\tau \approx$ 500 μm): information on the evolution of the deconfined medium

- **Sensitivity to the density of the medium** is provided by in-medium energy loss of heavy quarks (“**Dead-cone” effect**)



- **Possible charm thermal production?** ⇛ May increase the yield of charm hadrons at low p_T by up to 50-100%. Need to measure charm production **down to $p_T = 0$**

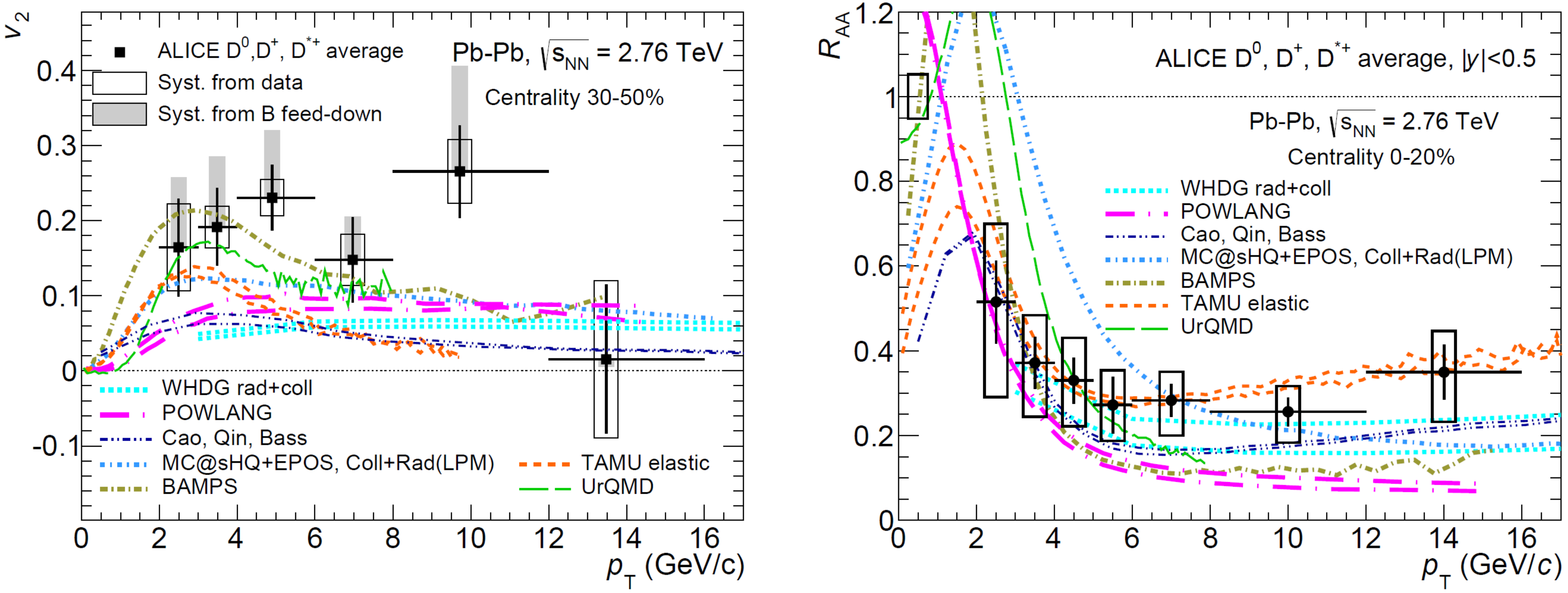
- **Measuring total charm and beauty cross section:** natural normalization for quarkonia production (main uncertainty for J/ψ regeneration models)

Heavy Flavors

- **Simultaneous description of open charm R_{AA} and v_2 is a challenge for the models**

- In general, the models that are best in describing R_{AA} tend to underestimate v_2 and the models that describe v_2 tend to underestimate the measured R_{AA} at high p_T

Anisotropy description: charm quark energy loss in a geometrically anisotropic medium (+) mechanisms that transfer to charm quarks the elliptic flow induced during the system expansion



Conclusions

- Our understanding of the QCD phase diagram is extremely limited, but lattice QCD suggests a phase transition to a QGP

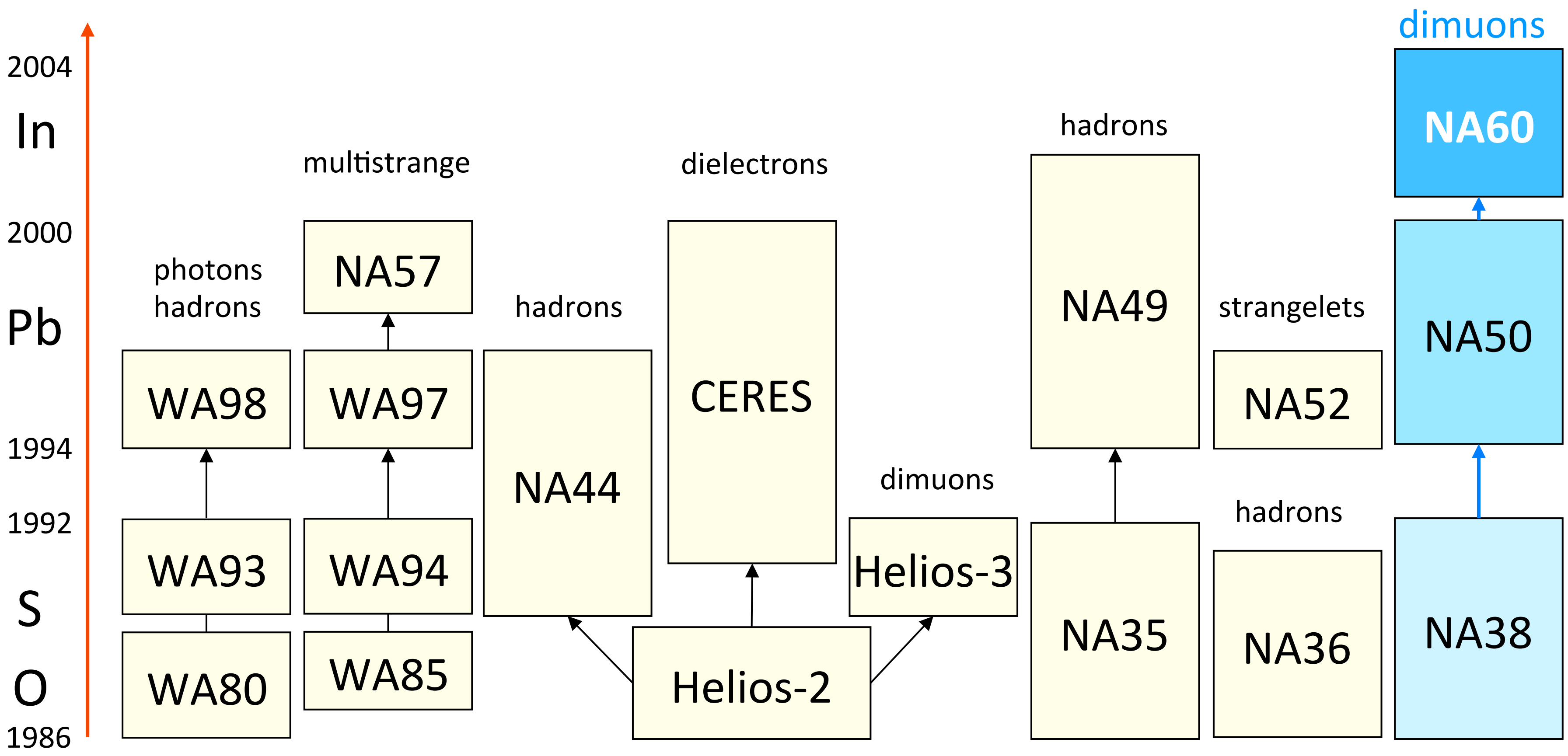
- **Three experimental energy regimes:** SPS, RHIC, LHC. **A wealth of observables:** bulk properties, light flavors, electroweak probes, heavy flavors, quarkonia, . . .

- **No serious doubts that QGP with perfect liquid properties is created at RHIC energies** and above without phase transition (crossover between partonic and hadronic phases)
  - The high-energy frontier is the best way to study the properties of the QGP (larger volumes, longer life, larger cross section for heavy-flavor probes).
  - LHC is the most advanced effort at this frontier. The future is probably the FCC

- **Which is the minimum collision energy at which QGP can be created?** Which is the nature of the phase transition? Is there a critical point?
  - At the low-energy frontier we can address these fundamental questions
  - The SPS is the only current effort at this frontier. At least four alternative projects are proposed (Germany, Russia, Japon, FixedTarget@LHC)

Backup Slides

The SPS Heavy-Ion Program



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