La physique des ions lourds, état de l'art et prochains défis

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Paris, 6 février 2023

Disclaimer

- Limited time = selected topics
- I'm associate theorist in CMS. . . hopefully not too biased
- Will try to highlight exciting developments in the field, and what to expect in the years to come

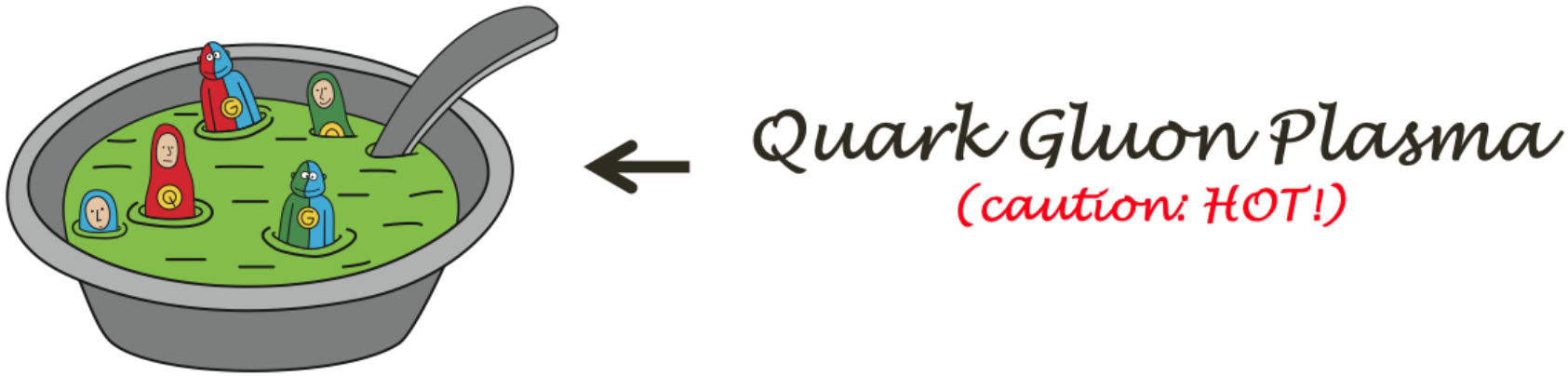
Thanks to many colleagues for discussions while preparing the talk !

Outline

Heavy ion collisions and the quark-gluon plasma

What we look after

QUARK-GLUON PLASMA noun – 1975 ▪ Deconfined state of matter made of quarks and gluons in thermal equilibrium. Existed in the early Universe (ca. 1 μs after Big Bang), produced in the early stage of high-energy heavy ion collisions and possibly in the core of massive neutron stars ▪ *nick: cosmic soup*.



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Idea of QGP existence almost as old as QCD

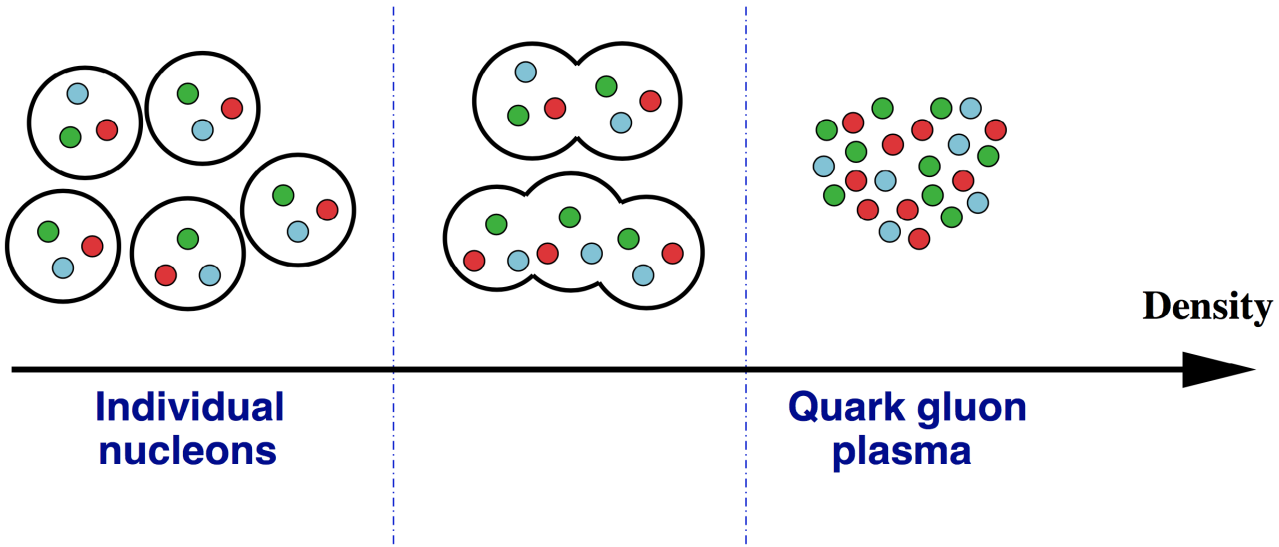
- Follows directly from the **parton model**
- Weakly coupled system at large T and/or μ due to **asymptotic freedom**
- Addresses the origin of **QCD confinement**

From QCD to QGP

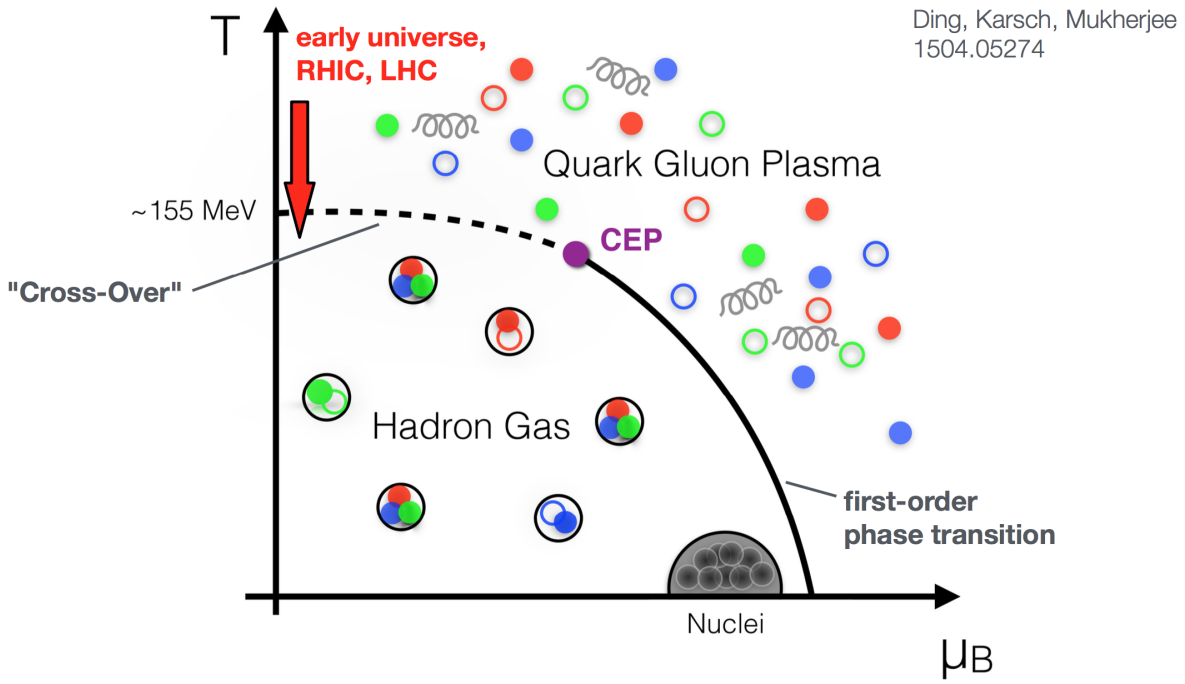
Superdense Matter: Neutrons or Asymptotically Free Quarks?

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.

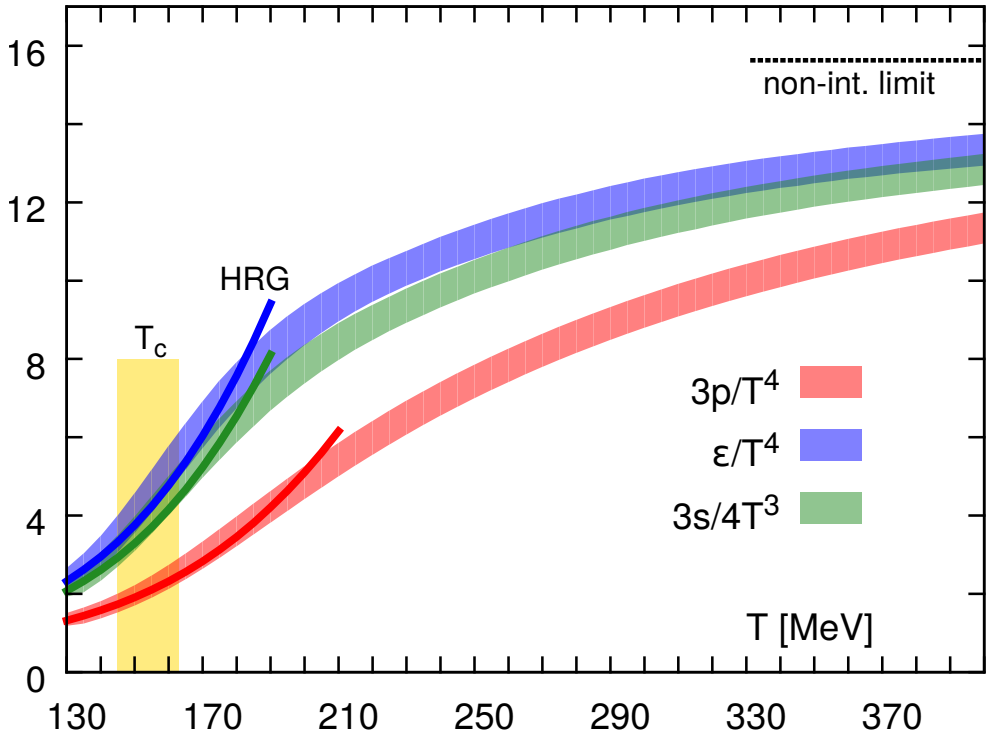


QCD phase diagram: a rich structure



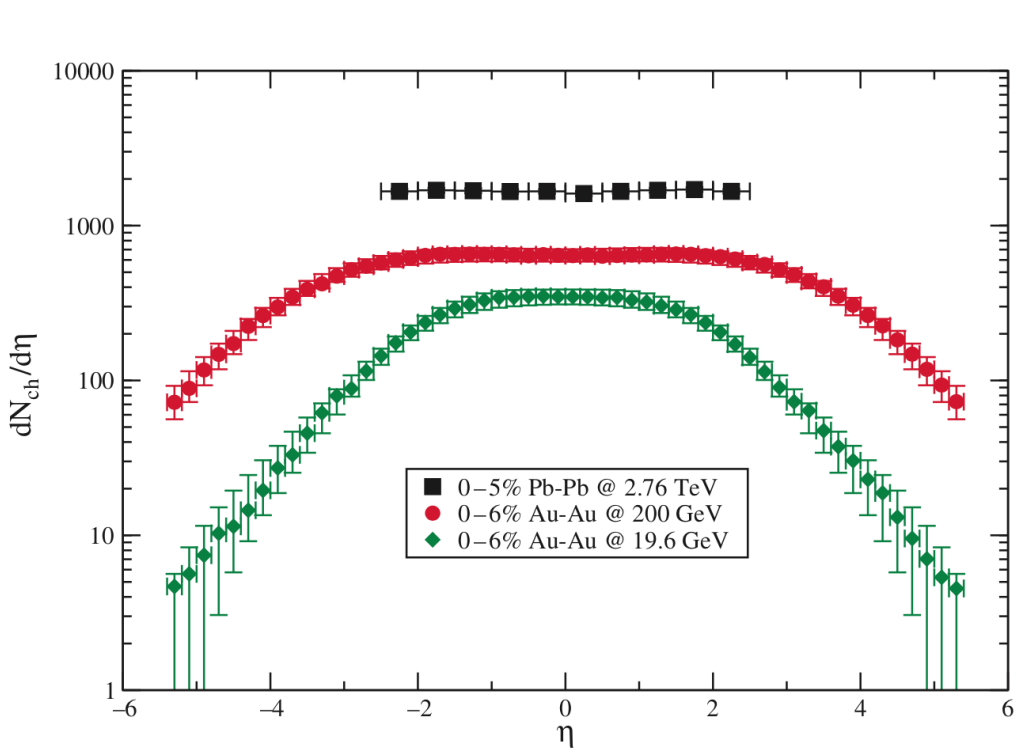
- High T, small μ_B — RHIC, LHC
- High T, high μ_B (near CEP) — RHIC beam energy scan, FAIR
- Small T, high μ_B — FAIR (?), neutron stars

Equation of state

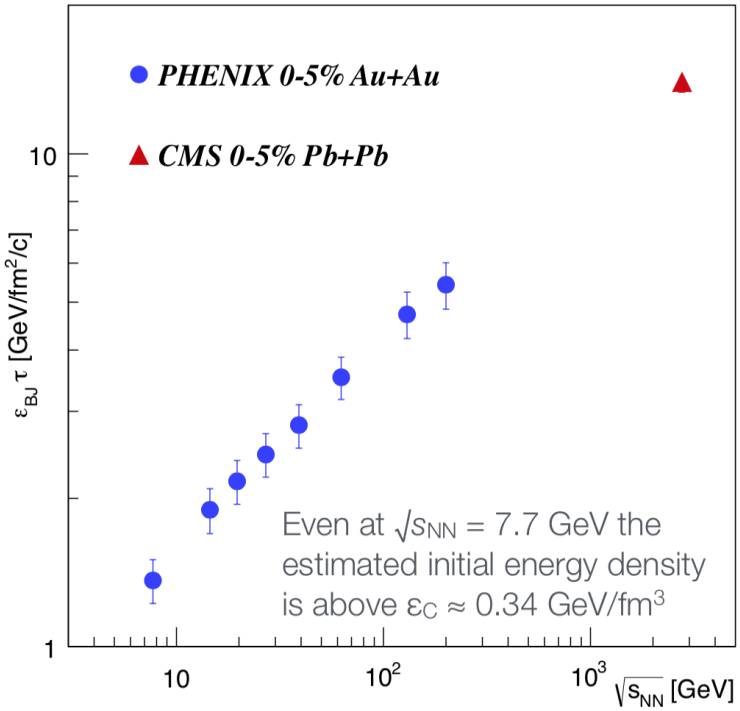


- Jump in energy density from pion gas to QGP ($T_c = 155$ MeV)
  - No real phase transition at $\mu_B = 0$
  - Possible 1st-order phase transition at finite μ_B ($\rightarrow$ critical endpoint)
- Still far away from Stefan-Boltzmann (weakly coupled) limit !
  - Strongly interacting system due to large occupation number

Rapidity plateau and energy density



PHENIX, arXiv:1509.06727



- Rapidity plateau expected from Bjorken longitudinal expansion
- Allows for computing the initial energy density of the medium
  - $\varepsilon_{\mathrm{LHC}} = 14\,\mathrm{GeV/fm} \approx 2.6 \times \varepsilon_{\mathrm{RHIC}}\ (\tau_0 = 1\,\mathrm{fm}) > \varepsilon_{\mathrm{C}}$
- QGP properties do not change significantly with collision energy
  - . . . but the rates of hard probes increase dramatically with $\sqrt{s}$

Strategies to study QGP

Measuring QGP (remnants) through soft particle production ($p_\perp \lesssim$ GeV)

- Single particle distribution and 2-particle correlations
- Electromagnetic thermal radiation
- Azimuthal anisotropies

☞ Relativistic fluid dynamics, assuming local thermodynamic equilibrium

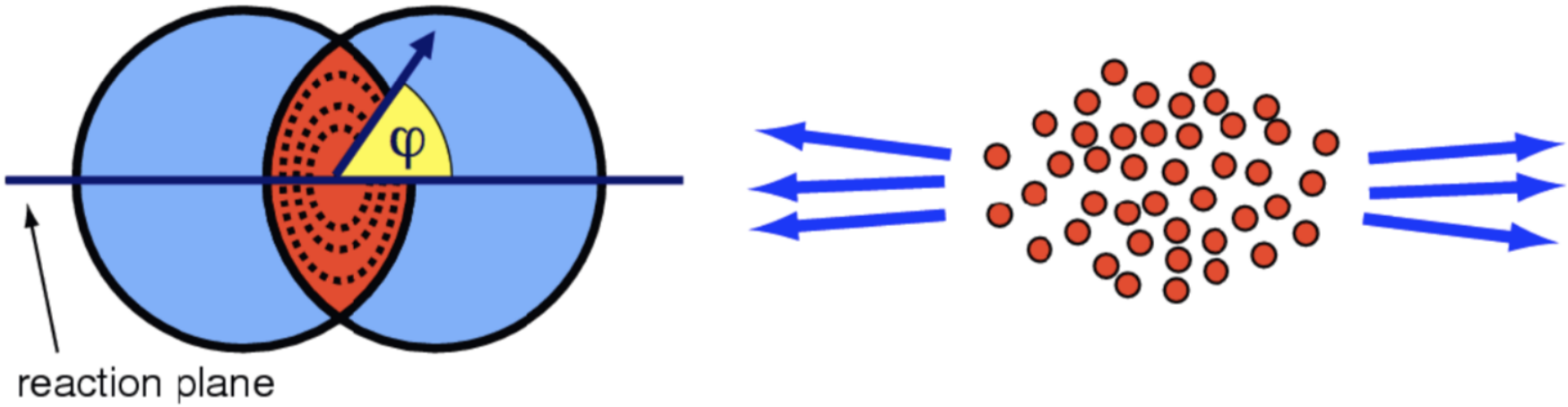
Probing QGP through hard 'external' probes ($M, p_\perp \gg$ GeV)

- Heavy quarks and quarkonia
- Jets and large $p_\perp$ hadrons

☞ Perturbative techniques (possibly embedded into soft hydro medium)

Elliptic flow

Consider non-central collisions: overlap region has an almond shape

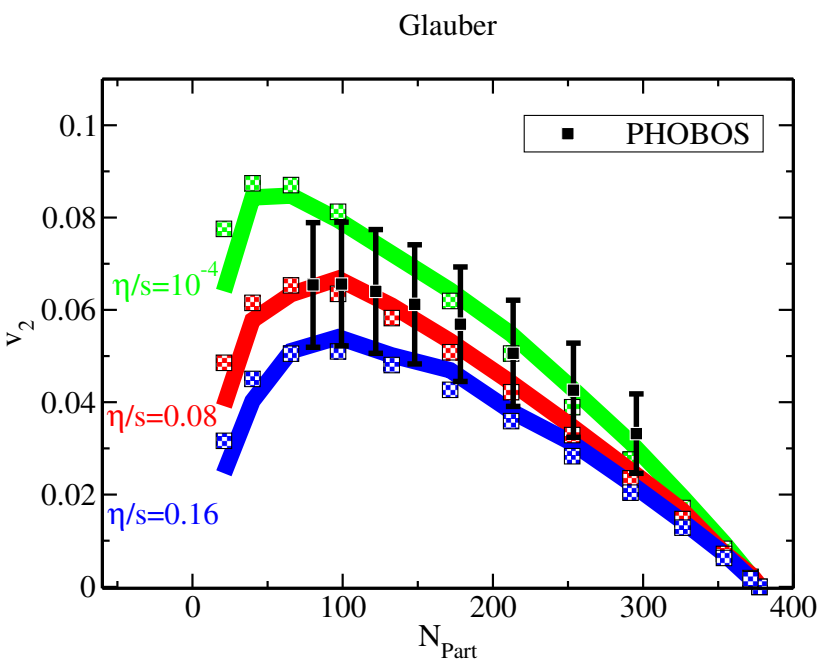


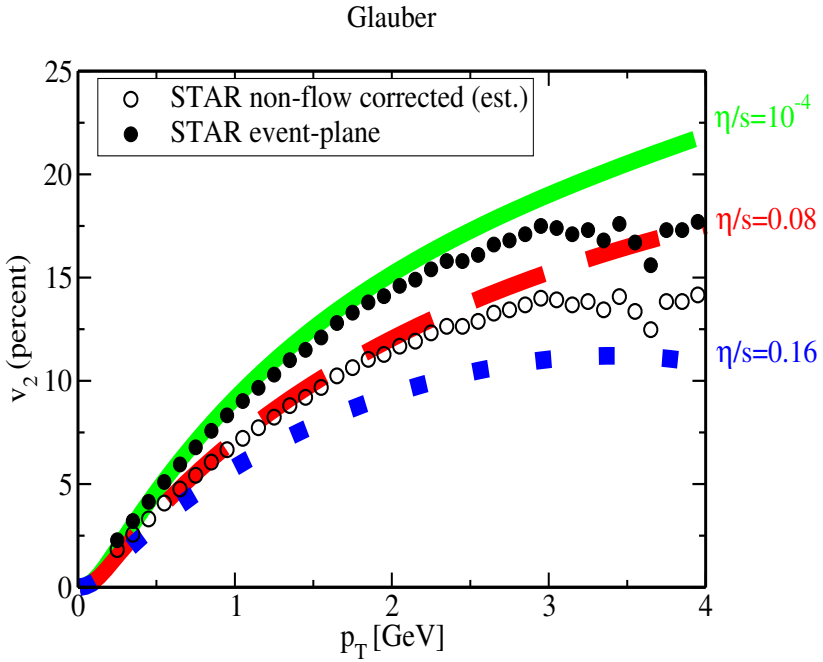
Collectivity transforms spatial anisotropies into momentum anisotropies

Ollitrault 1992

- Strong pressure gradient in the reaction plane
- Weaker pressure at $\varphi = \pm \pi/2$
- Anisotropies measured by Fourier coefficients $v_n = \langle \cos(n\varphi) \rangle$

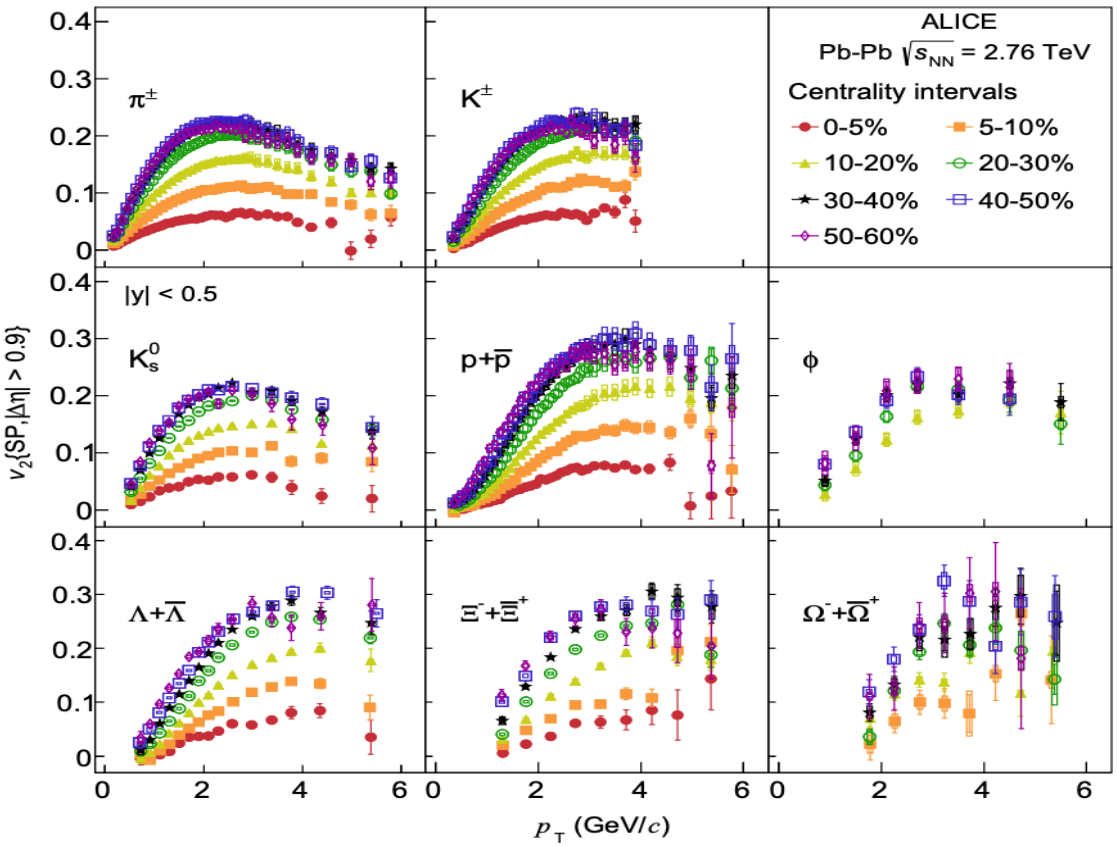
Elliptic flow at RHIC/LHC





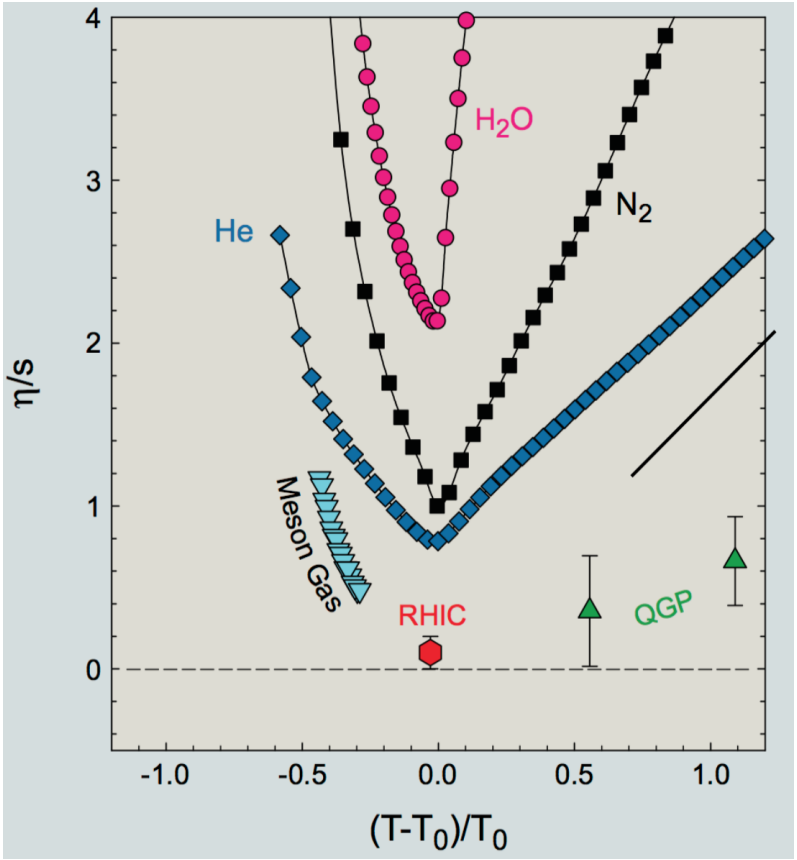
- Strong flow measured at RHIC
- Data best described with hydro, with small viscosity: $\eta/s = 0.2 \pm 0.1$
- Challenging extraction of η/s from data
  - Sensitive to initial conditions, non-flow effects...

Elliptic flow at RHIC/LHC



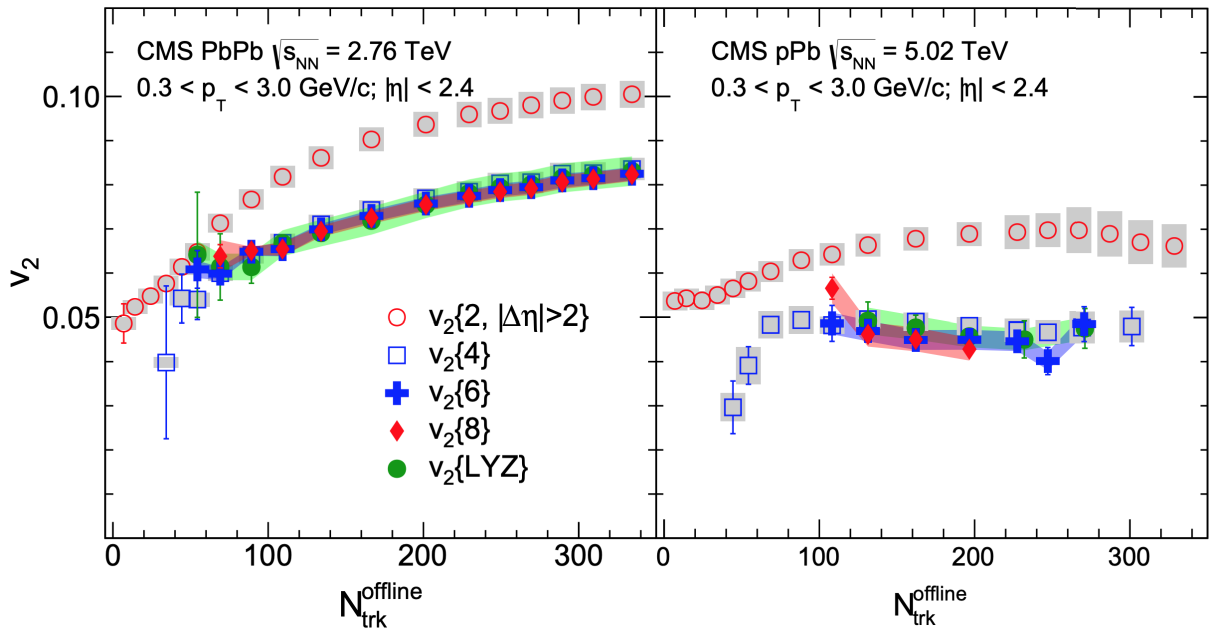
- Impressive systematics on hadron species and collision centralities
- Now extracting higher harmonics
- Flow at LHC also compatible with very low ratio $\eta/s \simeq 0.2$

Most perfect fluid ever ?



- QGP five times less viscous than superfluid He-4
- Conjectured lower bound from string theory **Kovtun Son Starinets 2003**
- Paradigm of the (almost) perfect fluid discovered

A surprise: flow in small systems



Elliptic flow also reported in proton-nucleus collisions ! $v_2|_{pPb} \lesssim v_2|_{PbPb}$

- Is a fluid also produced in proton-nucleus collisions ?
- Similar observations in pp collision with high multiplicity

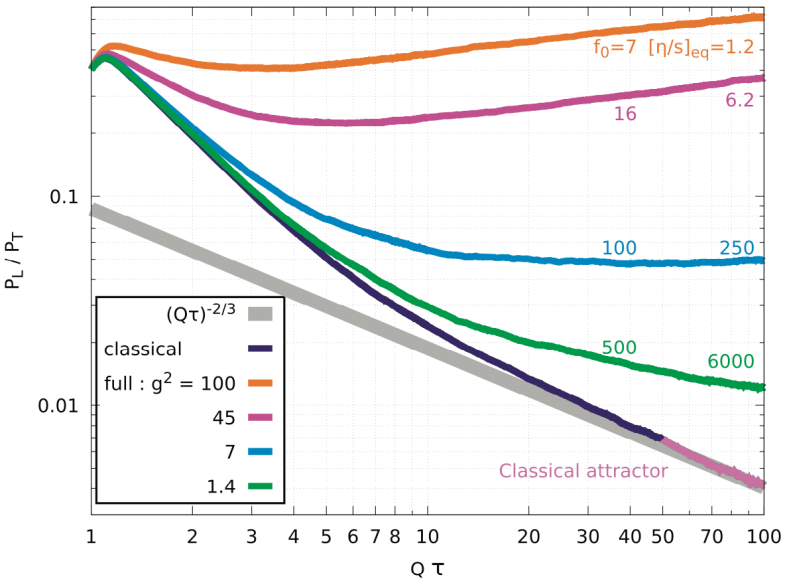
☞ Origin still to be clarified

Thermalization

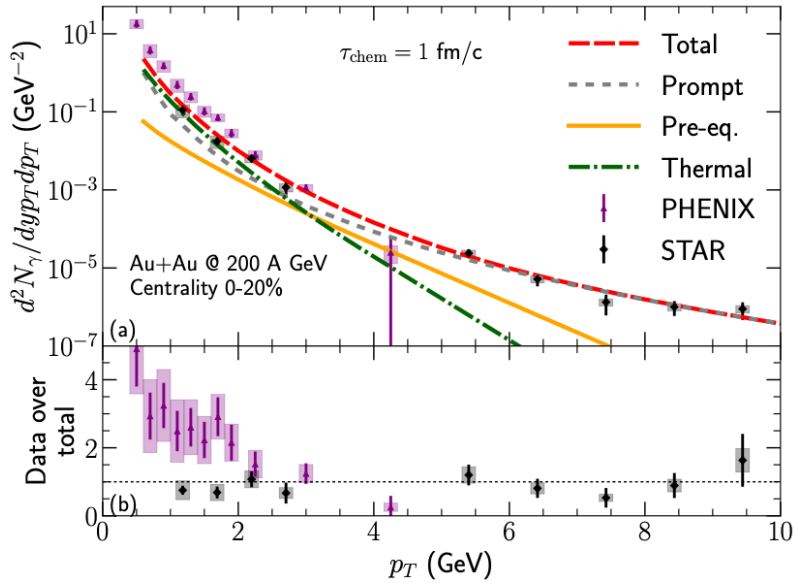
QGP appears in local thermal equilibrium : what drives thermalization ?

Understanding the transition from far-off equilibrium gluonic state at initial times towards QGP is a theoretical challenge

- Role of quantum fluctuations, non-perturbative effects. . .
- Natural signature is electromagnetic radiation (γ, $\ell^+\ell^-$)
  - However EM emission at all stages, not just early times



Epelbaum, Gelis et al.

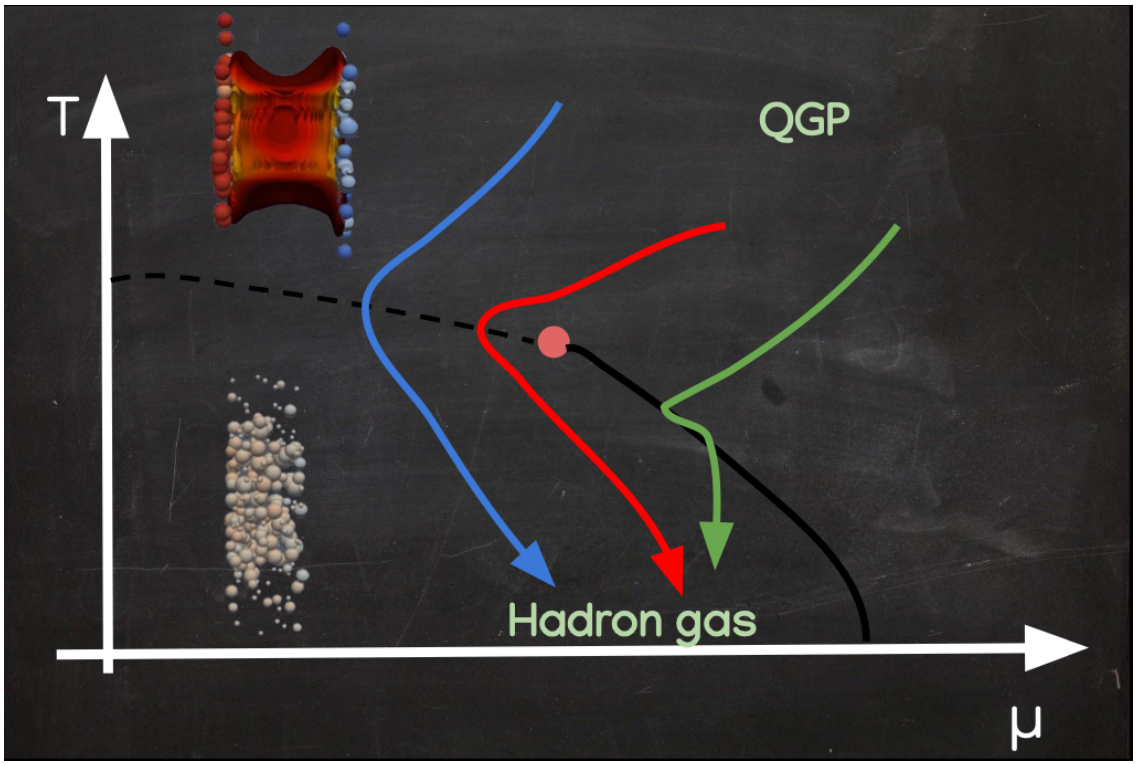


Gale et al.

Finite density: looking for the critical end point

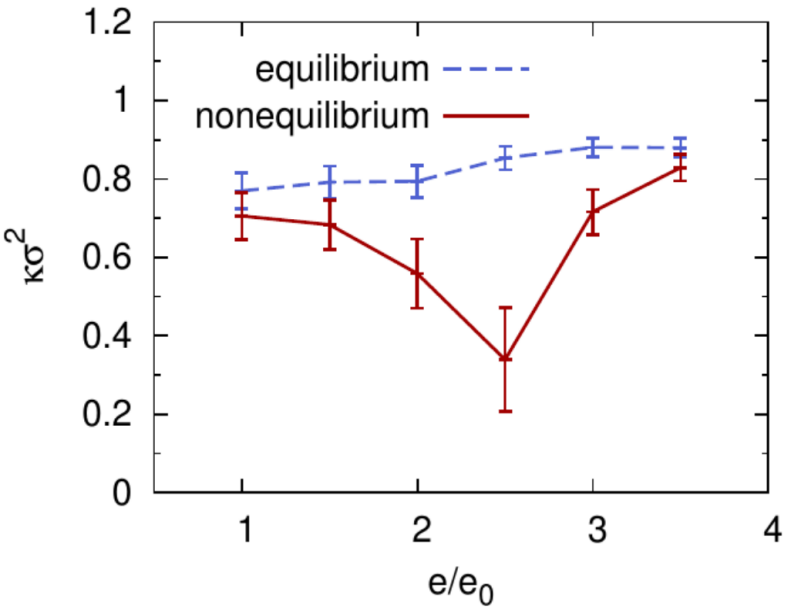
Which observables might be sensitive to the presence of the CEP ?

☞ Event-by-event fluctuations of multiplicity distributions

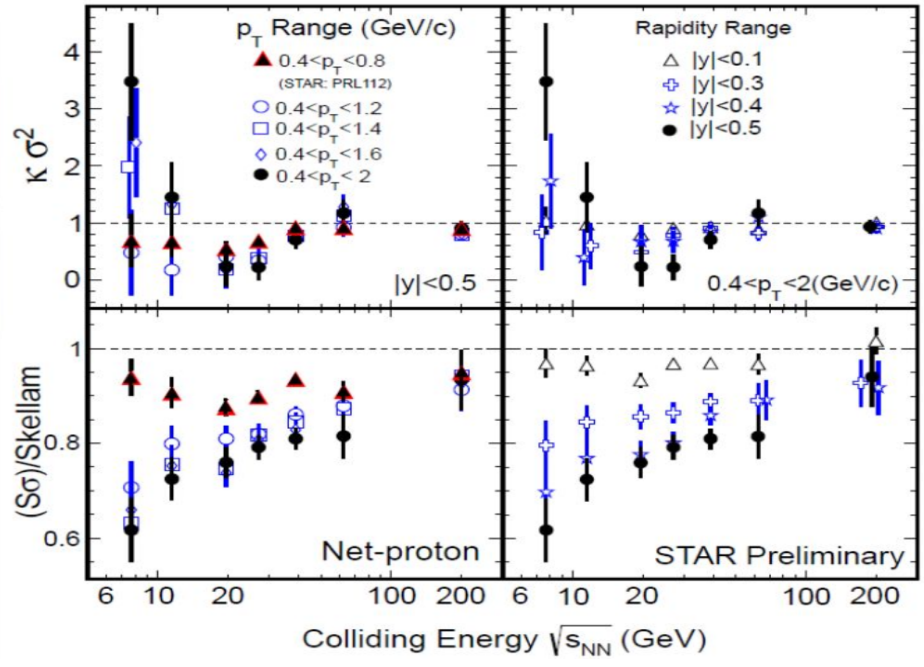


Finite density: looking for the critical end point

- Supplement standard hydro by embedding dynamics of fluctuations
- Best studied at the RHIC beam energy scan and FAIR
- Challenging numerical implementation

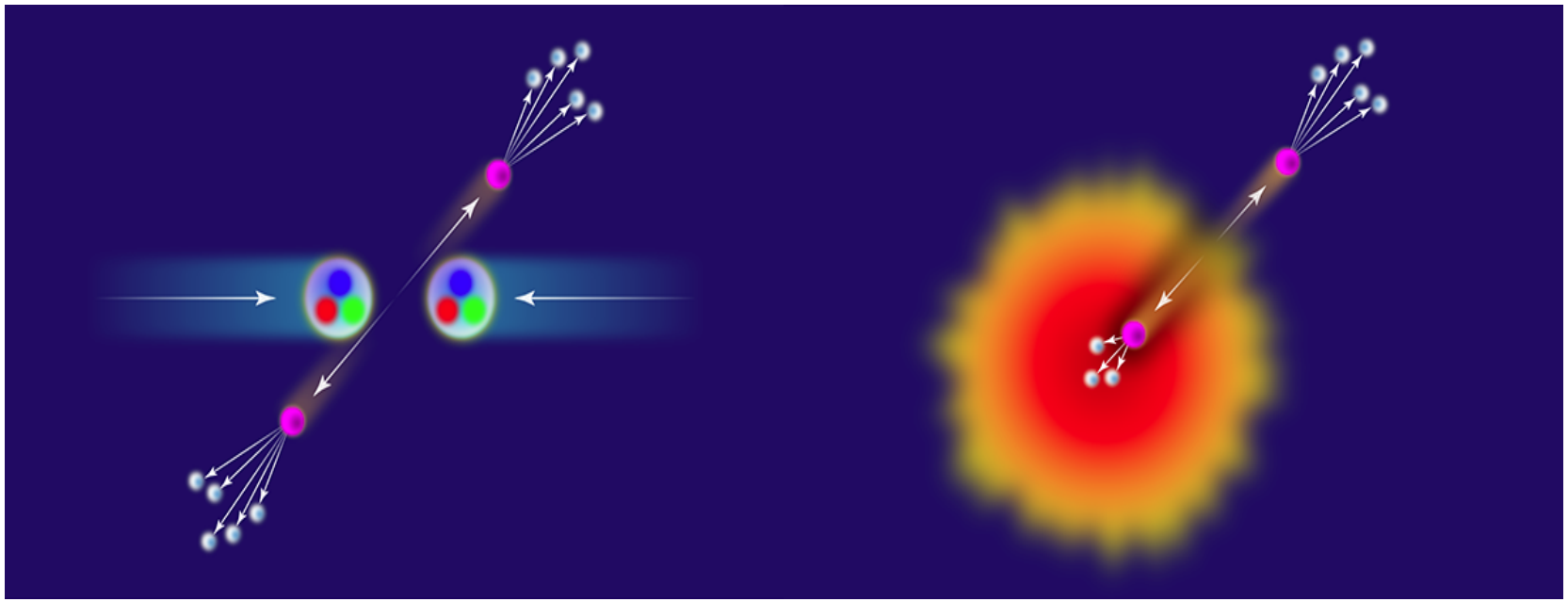


Bluhm, Nahrgang, Sami et al.



Jet quenching

Relative suppression of high $p_\perp$ jets in AA collisions, with respect to pp collisions, due to **parton energy loss in QGP**



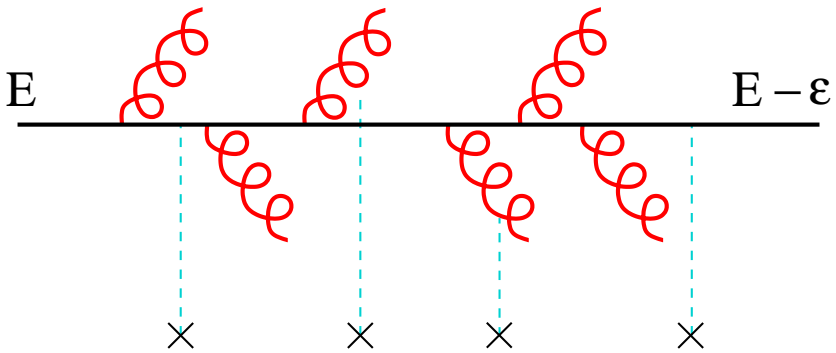
proton-proton **nucleus-nucleus**

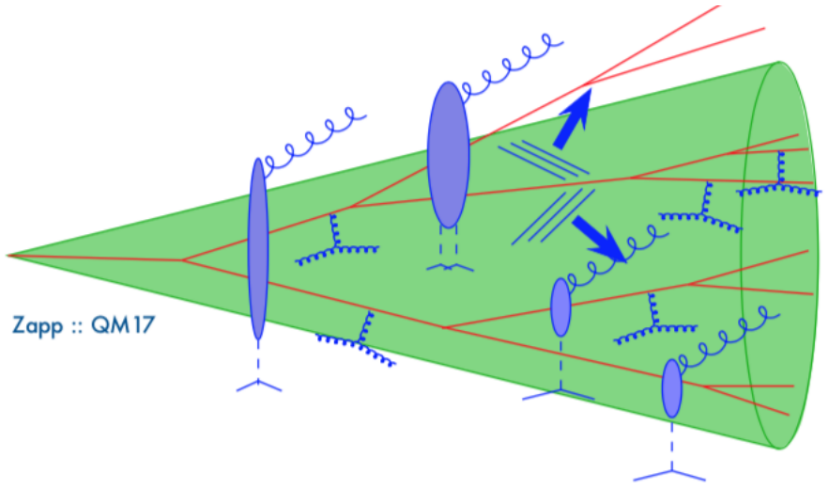
☞ Spectacular observation at LHC

A very active field

Theory

- 90-00s: Energy loss of a single hard parton in QGP
  - Many theoretical perturbative formalisms
  - Can naturally be studied from high $p_\perp$ hadron production
- 10-20s: Energy loss of a multiparticle final state
  - Attempts to model the full partonic shower in QGP
  - Advanced techniques for jet reconstruction in a dense environment





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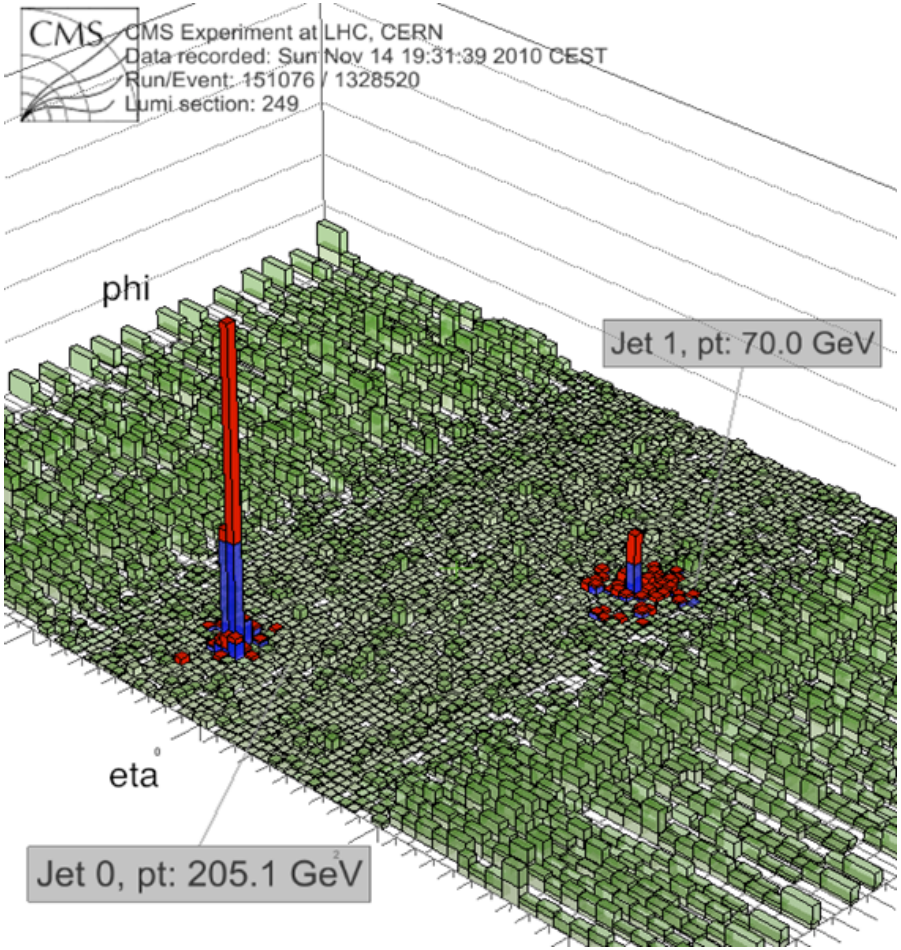
Experiment

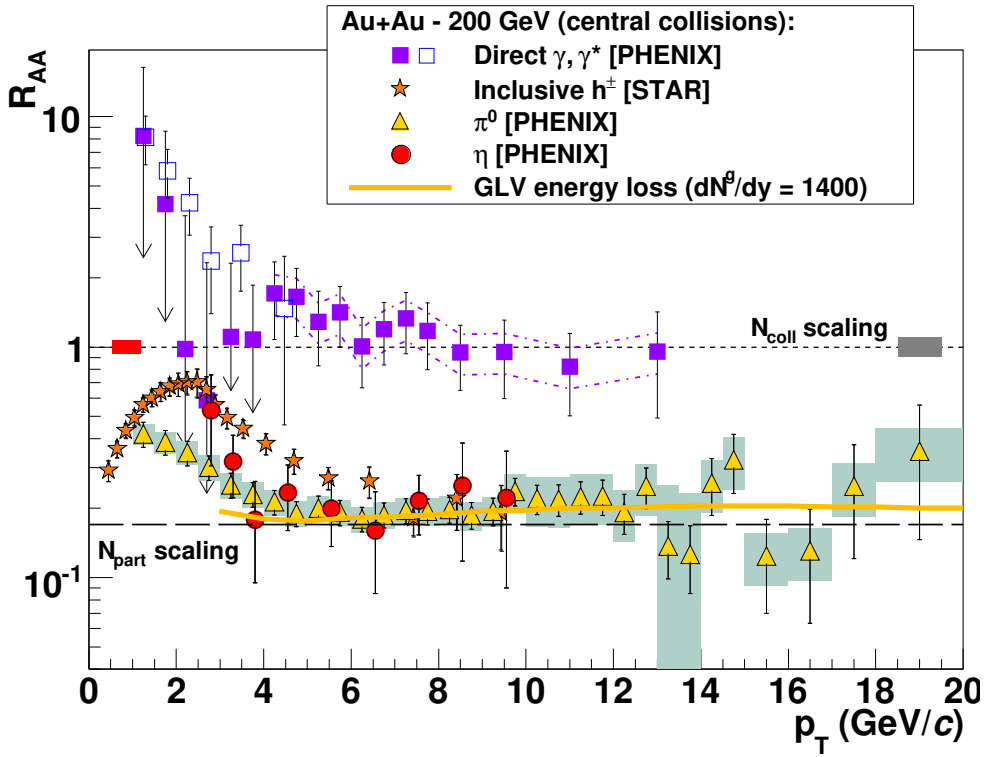
- 2001: Discovery of 'jet' quenching at RHIC ($p_\perp \lesssim 10$ GeV hadrons)
- 2010: First measurements of jets in HIC at LHC
- 2017: Measurement of jet substructure in HIC

☞ Access to medium-induced intrajet radiation

A very active field



Discovery of ~~jet~~ hadron quenching at RHIC



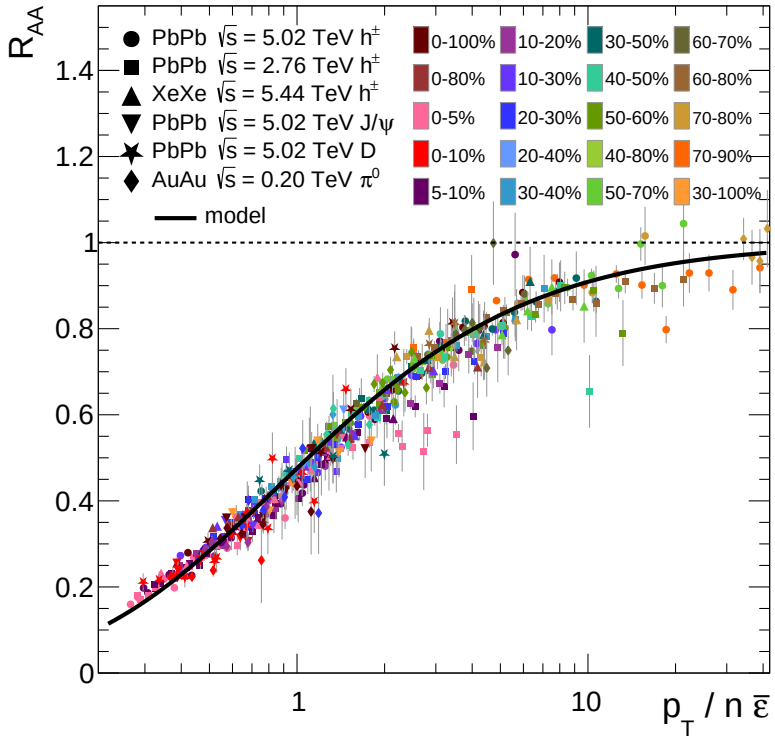
- Hadrons are suppressed by a factor of ~ 5, almost independent of $p_\perp$
- No suppression for prompt photons nor in dAu collisions

☞ Evidence for parton energy loss in a dense QCD medium

Hadron quenching at LHC

Wealth of measurements up to very large $p_\perp \lesssim 300\,\text{GeV}$

- light and heavy hadron species and different collision energies



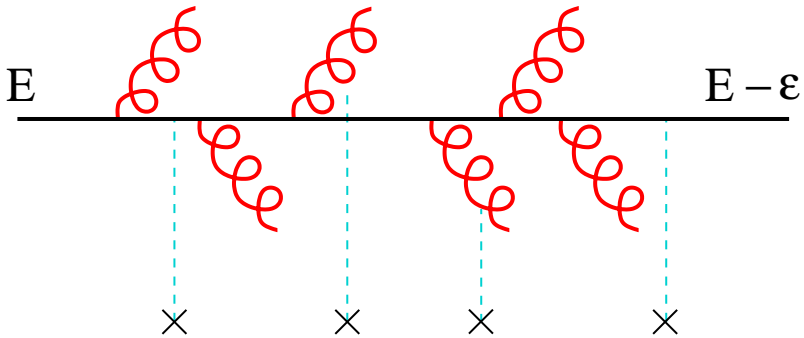
FA, Falmagne

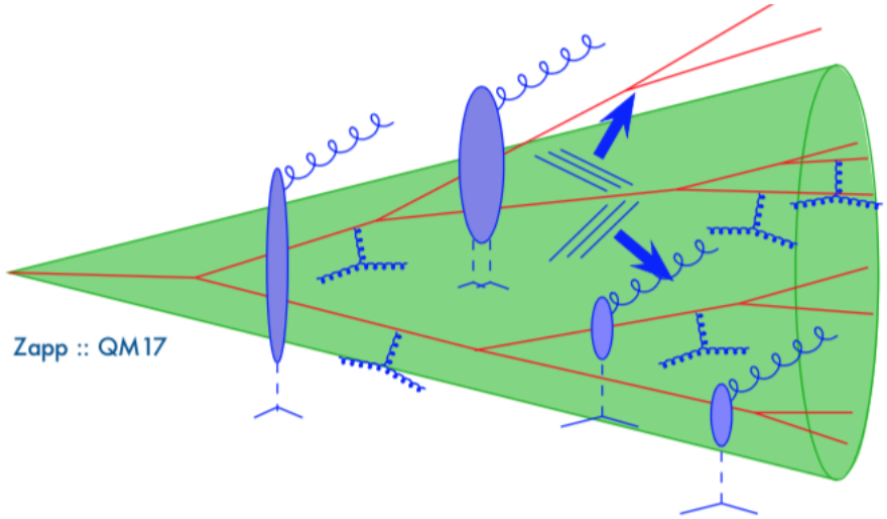
- Simple scaling behavior at $p_\perp \gtrsim 10$ GeV observed in data
- Nicely compatible with single parton energy loss in QGP

Most recent developments on jets

- Emergence of Monte Carlo generators for heavy ion collisions
  - JEWEL, Q-PYTHIA, SCET$_G$...
- Analytic (perturbative) results in simplified cases
  - Gluon radiation off an evolved jet, beyond single parton energy loss

Blaizot, Caucal, Iancu, Soyez...





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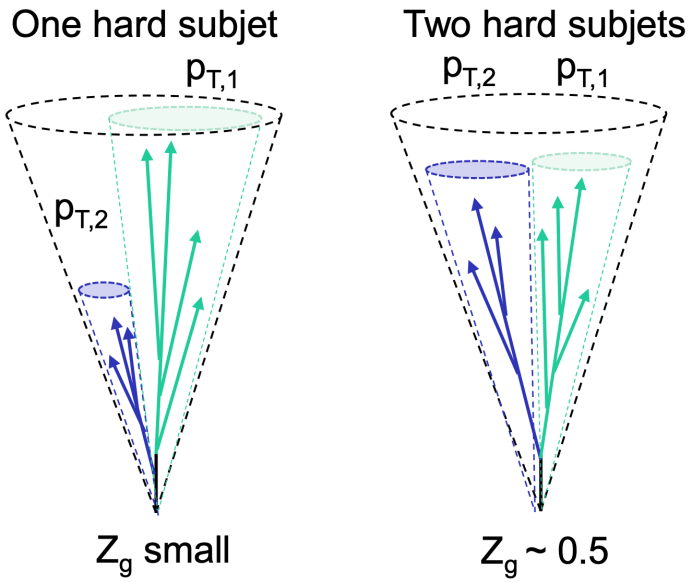
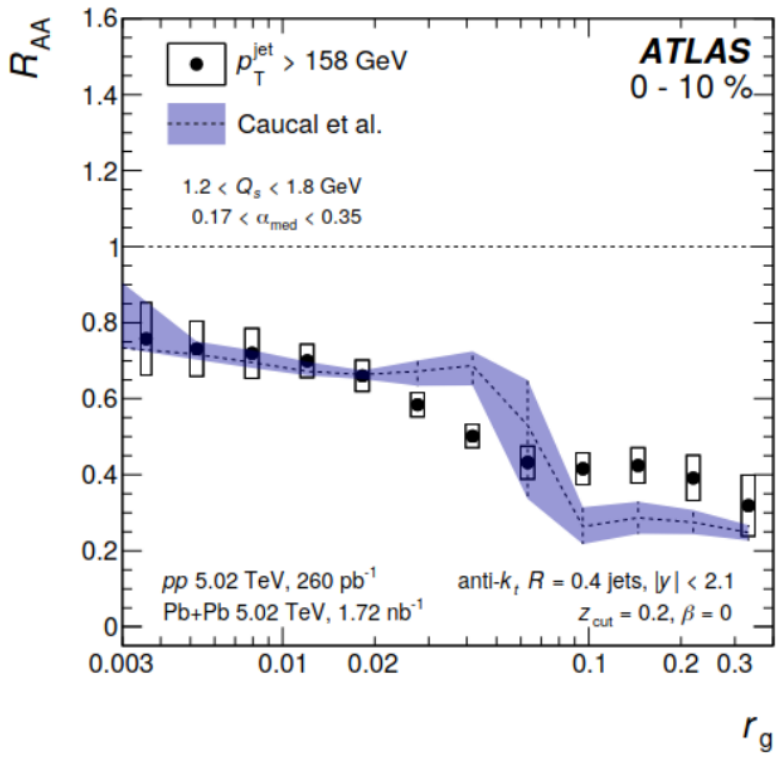
  - JEWEL, Q-PYTHIA, SCET$_G$...
- Analytic (perturbative) results in simplified cases
  - Gluon radiation off an evolved jet, beyond single parton energy loss
- New measurements becoming accessible
  - fragmentation functions
  - jet substructure...
  - boson+jet, b-jets, top quarks





Cooking quarkonia

40 years ago

- One hot matter effect: Debye screening
- Iconic signature for QGP formation

J/ψ SUPPRESSION BY QUARK–GLUON PLASMA FORMATION ☆

T. MATSUI
Center for Theoretical Physics, Laboratory for Nuclear Science, Massachusetts Institute of Technology, Cambridge, MA 02139, USA

and

H. SATZ
Fakultät für Physik, Universität Bielefeld, D-4800 Bielefeld, Fed. Rep. Germany and Physics Department, Brookhaven National Laboratory, Upton, NY 11973, USA

Received 17 July 1986

Cooking quarkonia

40 years ago

- One hot matter effect: Debye screening
- Iconic signature for QGP formation

Now

- Debye screening
- Recombination
- Gluon dissociation, Landau damping, Comovers...

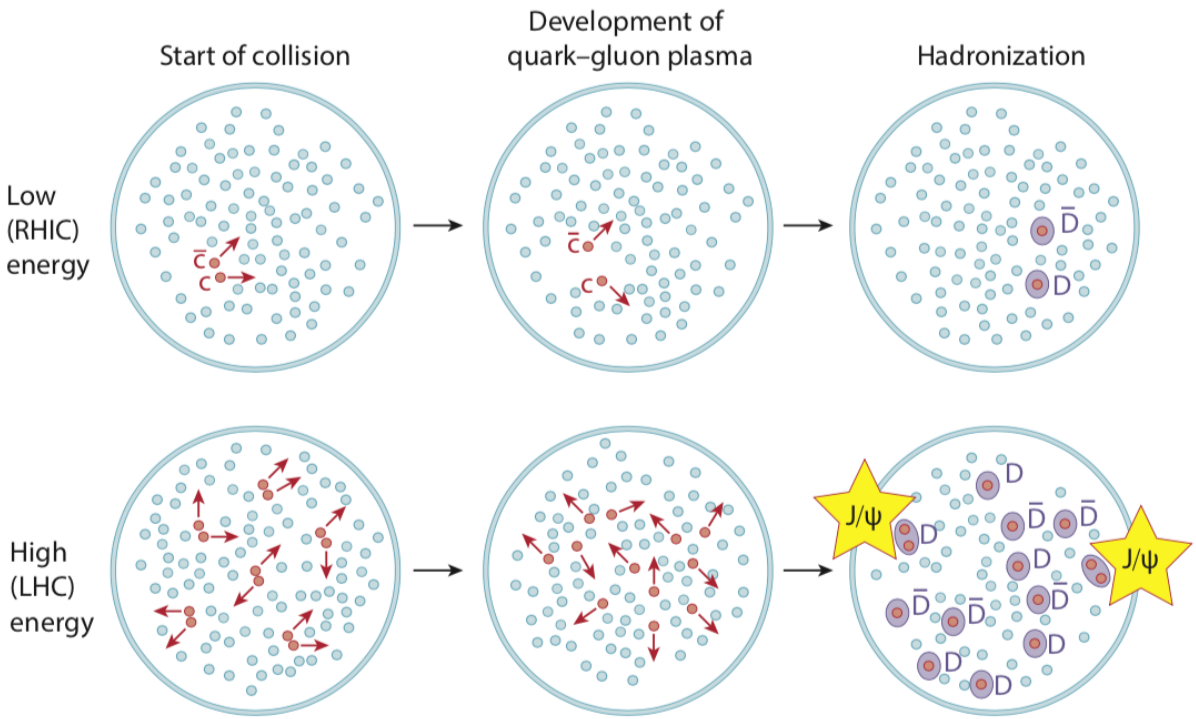
Exciting phenomena to investigate but a real challenge for phenomenology!

Charmonium in heavy-ion collisions

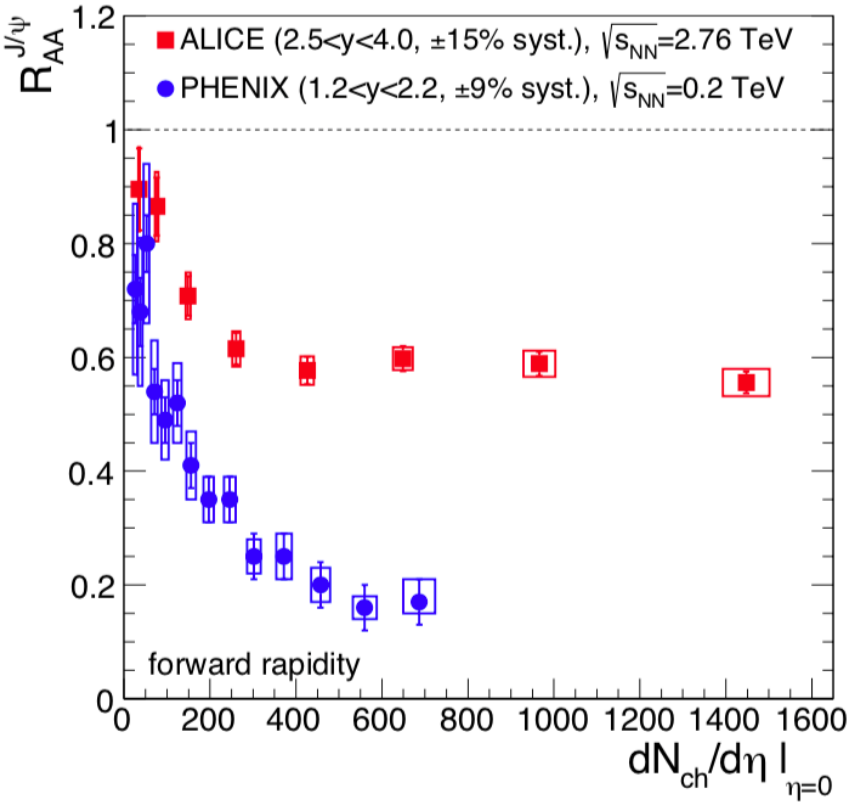
At LHC the number of produced charm quarks in a single PbPb collision exceeds 1 $\Rightarrow$ possible coalescence of charm quarks in QGP

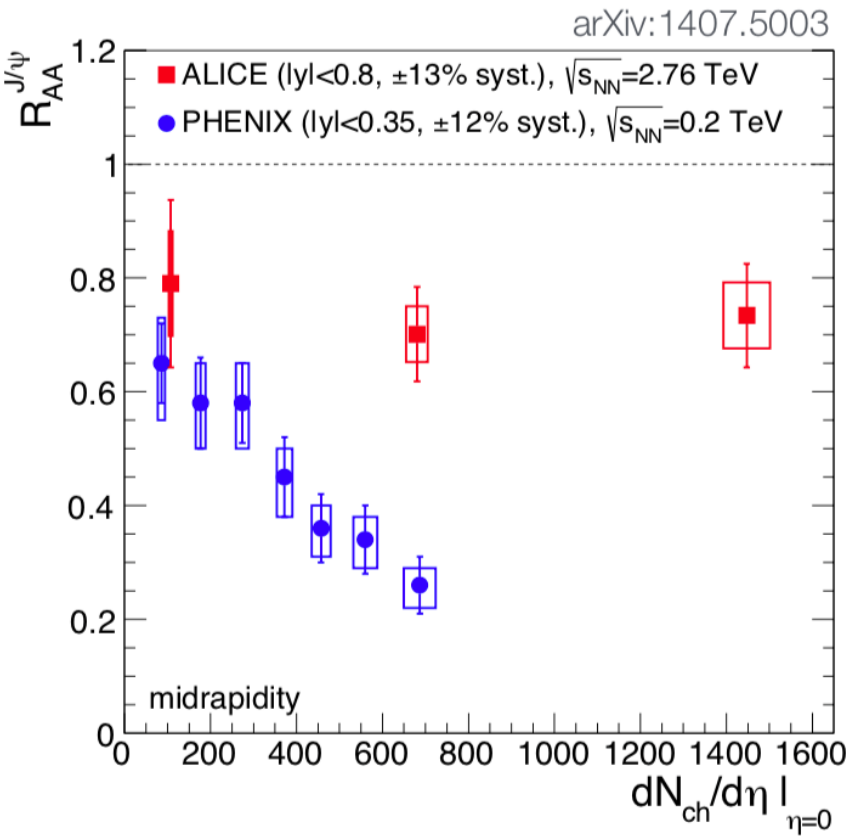
$$c + \bar{c} \rightarrow J/\psi + \mathrm{X}$$

New production mechanism in QGP known as regeneration



Comparing RHIC vs. LHC: The Surprise

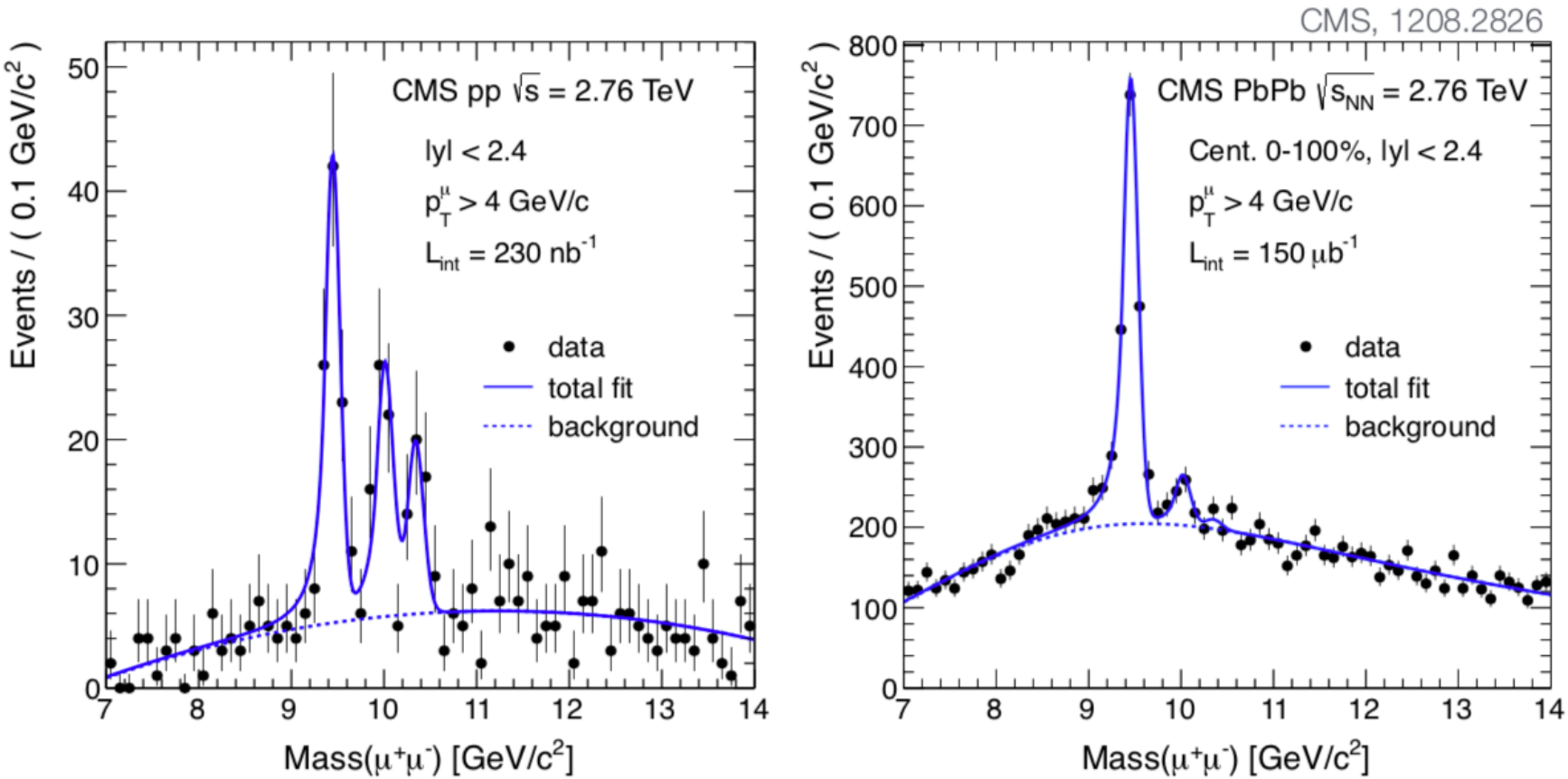




- J/ψ less suppressed at LHC than at RHIC
- J/ψ are less suppressed than Υ at LHC

☞ Hint of recombination ?

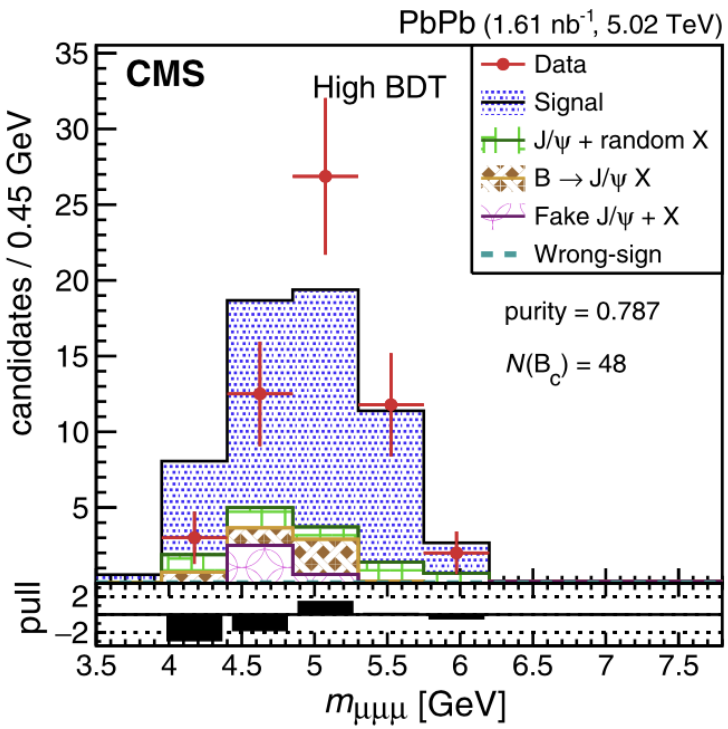
Υ suppression in heavy ion collisions

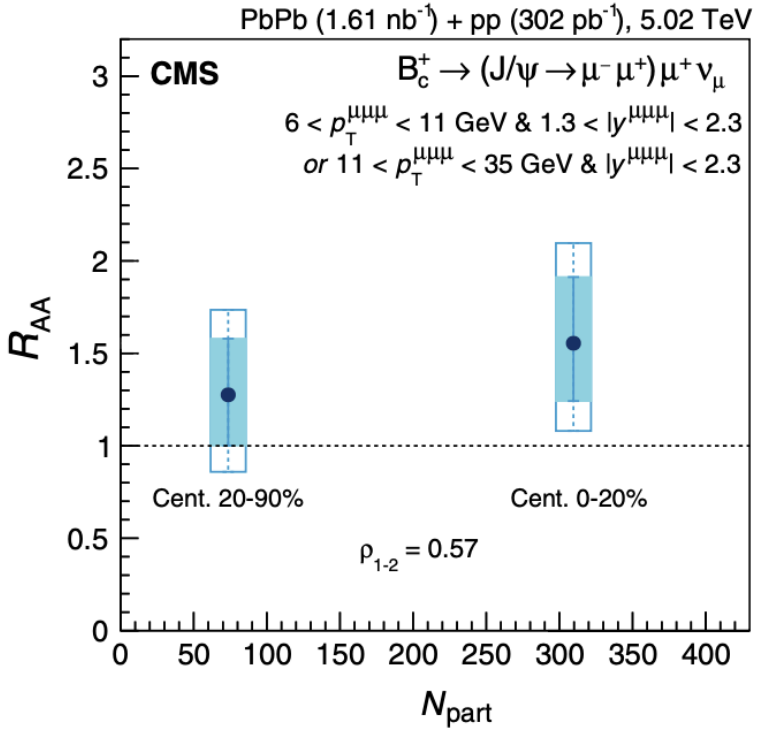


- Excited states more suppressed, consistent with sequential suppression
- No recombination expected ☞ Υ ideal probe of Debye screening

What next

- Important theoretical developments on open quantum systems to treat $Q\bar{Q}$ pairs in QGP **Blaizot et al, Gossiaux et al**
  - Connection with lattice QCD and towards phenomenology
- Multi heavy-quark hadrons appear very promising !
  - First measurement of B_c mesons in heavy ion collisions by CMS
  - Double charm Ξ_{cc} ideal to probe recombination/hadronization



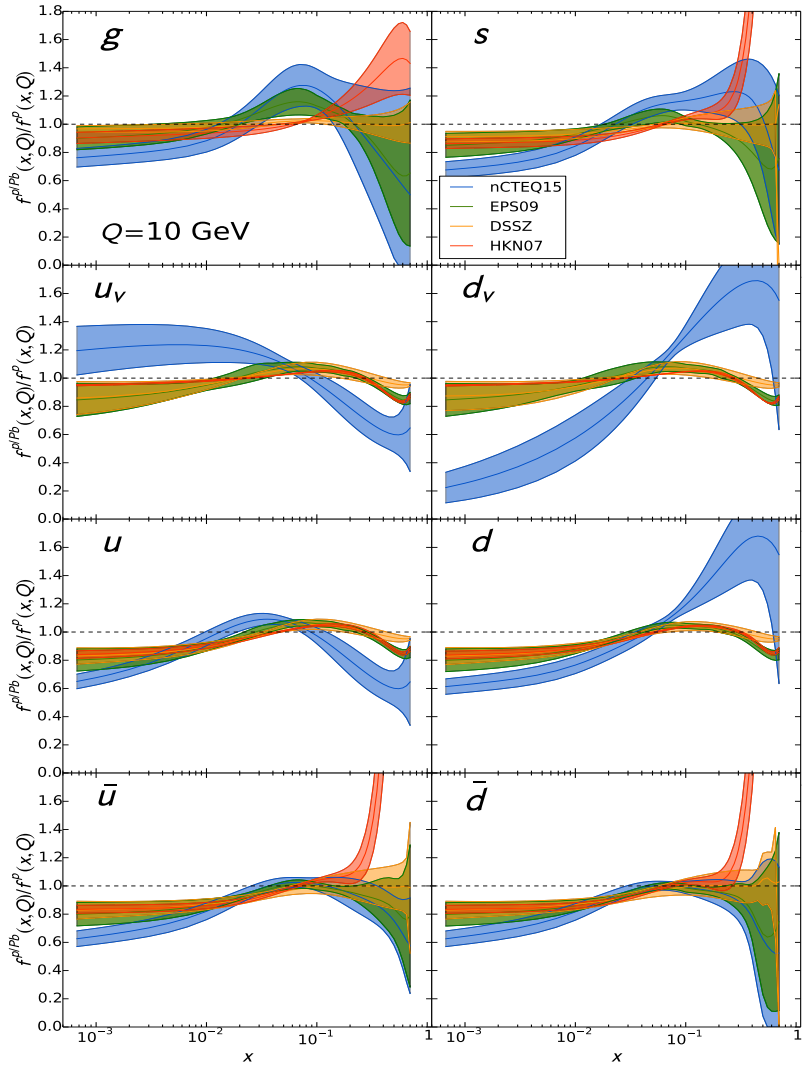


Probing QCD with nuclei

Nuclear Parton Distribution Functions (nPDF)

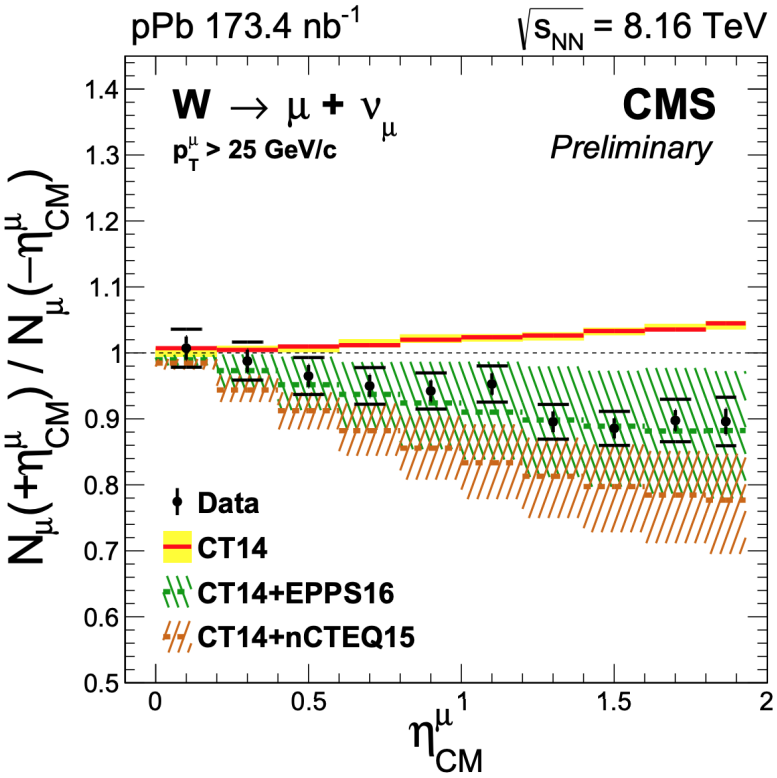
Parton densities are modified in nuclei

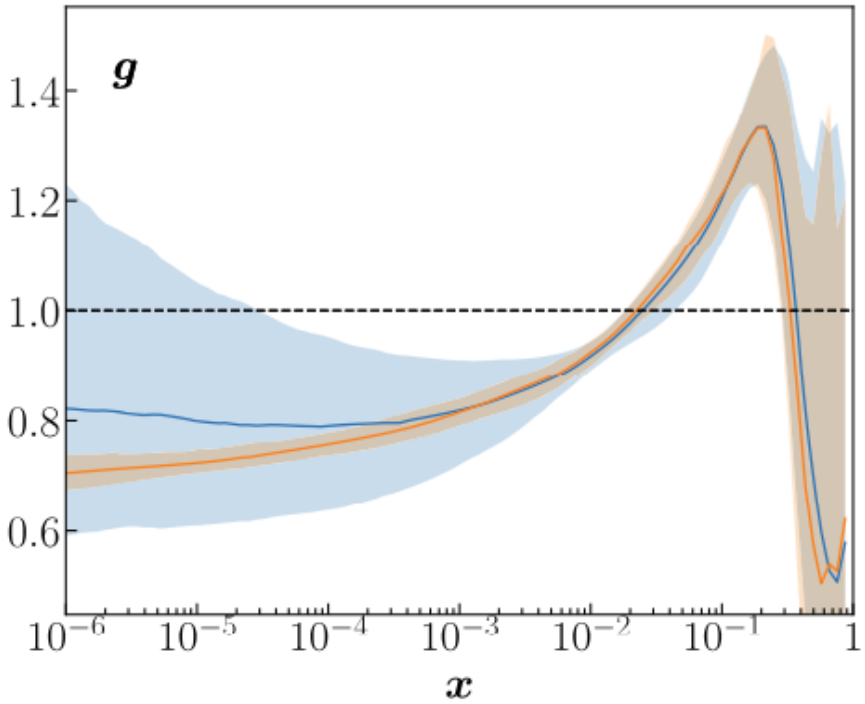
- Obtained from global fits
- Poor constraints, especially at small-x and in the gluon channel
- Crucial need to use LHC pPb data



Schienbein et al, nCTEQ15, 1509.00792

Constraints from LHC data

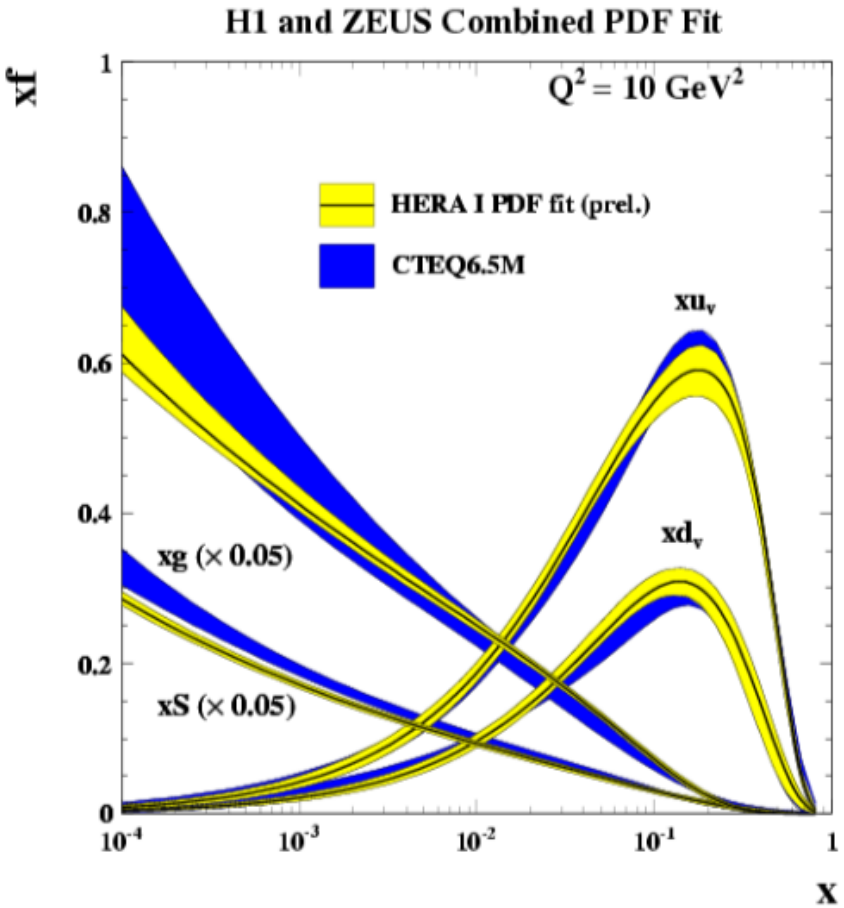


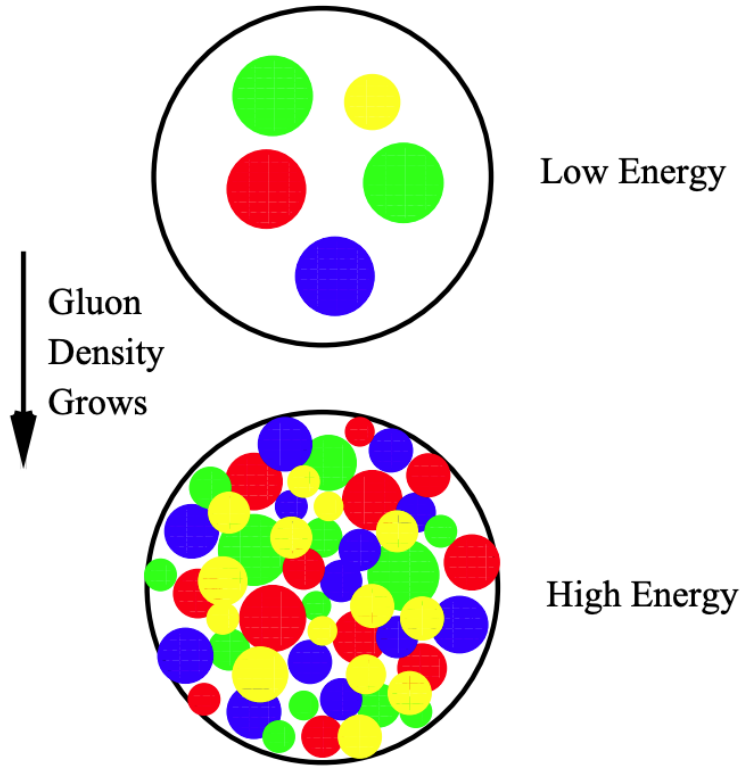


- Significant constraints from LHC
  - W/Z (ATLAS/CMS), D mesons (LHCb), dijets (CMS)...
- Expecting strong constraints from forward Drell-Yan by ALICE/LHCb

QCD saturation

Shadowing is related to the **saturation of the gluon density** in a nucleus



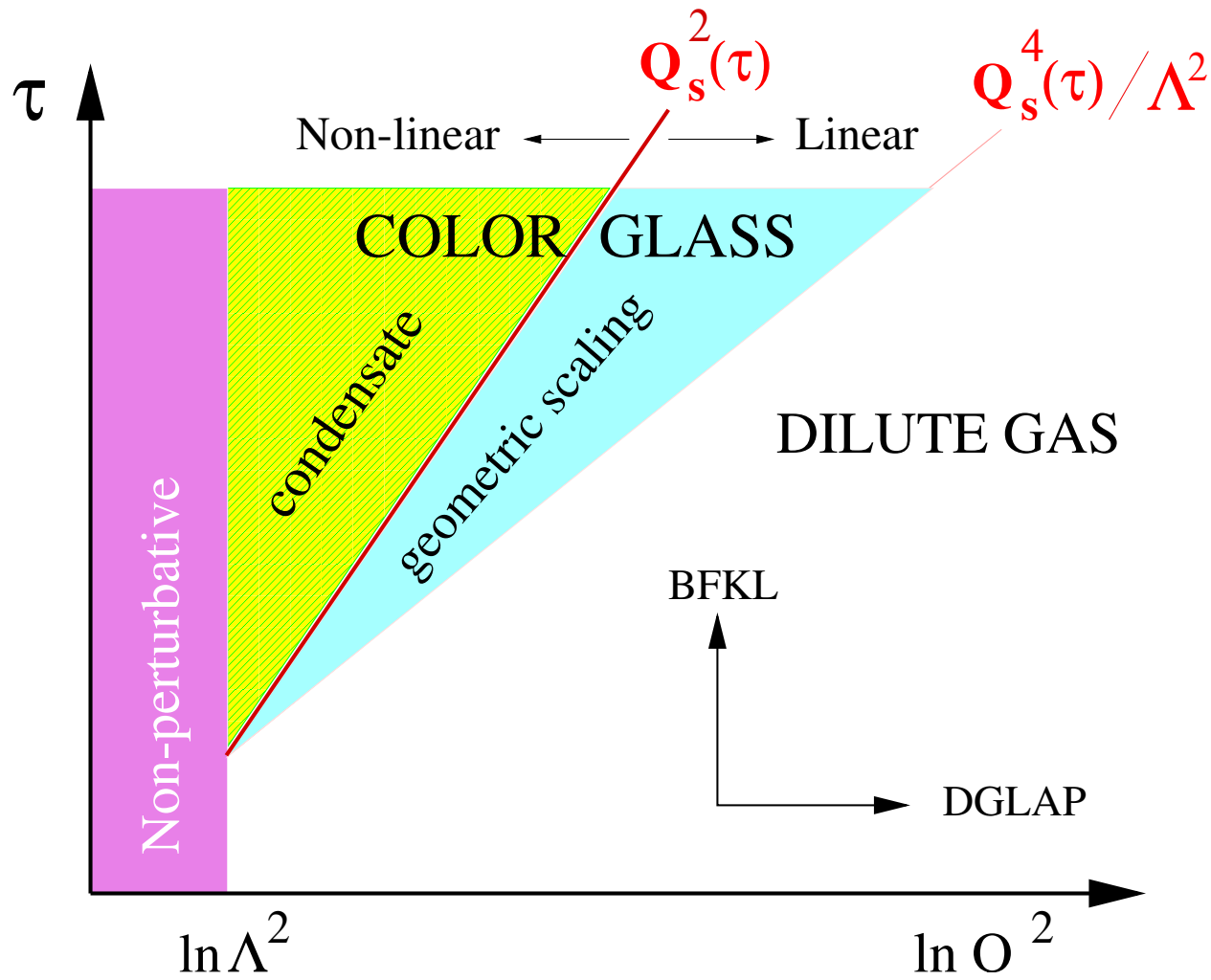


☞ What happens when the gluon density gets large, $xG(x) \sim \frac{1}{\alpha_s}$?

Non-linear evolution

At small x, non-linear evolution comes into play and cannot be neglected

$$\tau \equiv \ln\left(\frac{1}{x}\right)$$

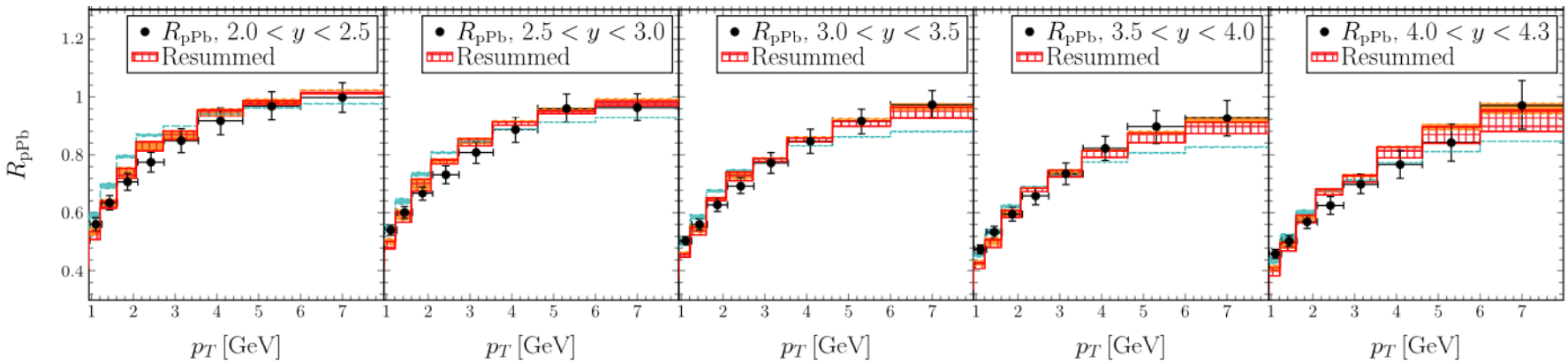


Non-linear evolution

- Tremendous theoretical effort over the last 2 decades to derive/solve **non-linear evolution equations** (BK and JIMWLK)

Gelis, Iancu, Marquet, Munier, Wallon...

- Several processes investigated
  - light hadrons, open heavy-flavour hadrons, quarkonia, photons...
- Ideal region is forward ($x \propto e^{-y} \ll 1$) eg. ALICE, LHCb

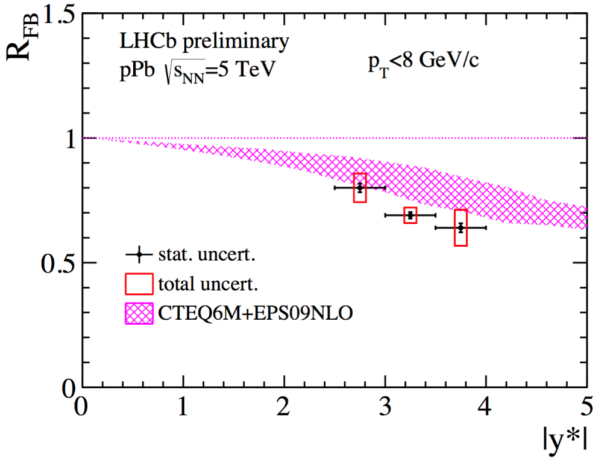


Shi et al.

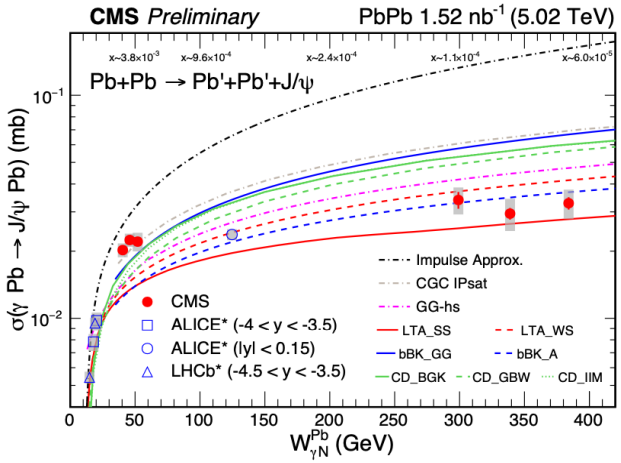
Probing high-energy QCD

Heavy ion collisions versatile tools to probe high-energy QCD :

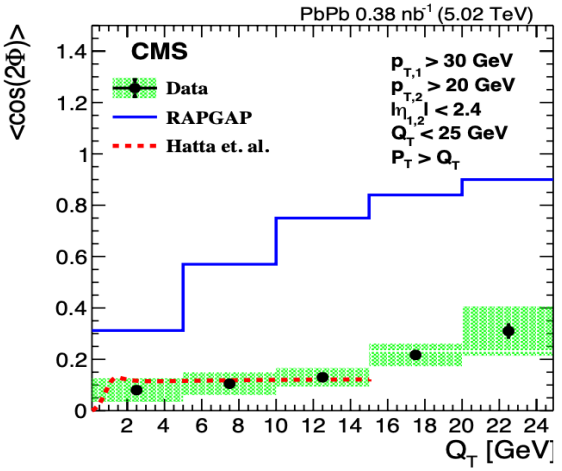
- Proton-nucleus collisions at LHC
  - Inclusive measurements of particle production in pPb, pO, ...
- Photon-nucleus reactions via ultra-peripheral heavy ion collisions
  - Exclusive measurements, eg. J/ψ and dijets
- Deep inelastic scattering on nuclei
  - Future measurements at the EIC



Inclusive D



Exclusive J/ψ



Exclusive dijets

Probing high-energy QCD

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☞ Crucial to compare the different systems: pA, AA, eA

- Which processes are universal (eg. nPDF), which are not (eg. radiative energy loss) ?
- Addresses the validity of QCD factorization in nuclear collisions

Heavy ion collisions and related fields

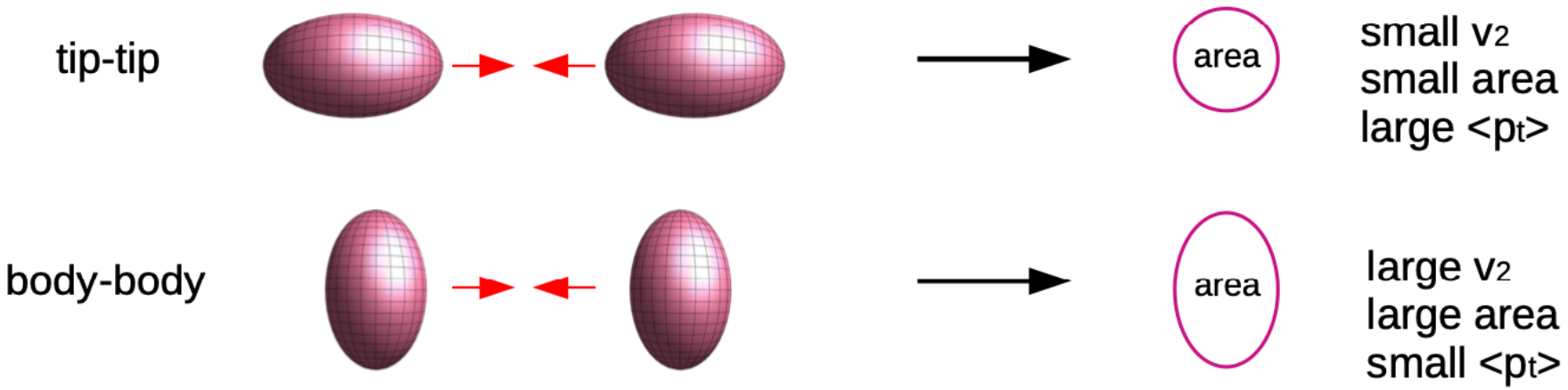
From nuclear physics to BSM and astrophysics

Towards a new method to image nuclei

Particle anisotropy reflects the spatial distribution of incoming nucleons

- Flow harmonics different in spherical vs. deformed nuclei

Giacalone Ollitrault 2021



- Can be tested using different nuclei at RHIC/LHC (FAIR)
  - Ru, Zr, Cu (RHIC), Xe, Pb, Ar, Kr, In, Ca...(LHC)

Towards a new method to image nuclei

Particle anisotropy reflects the spatial distribution of incoming nucleons

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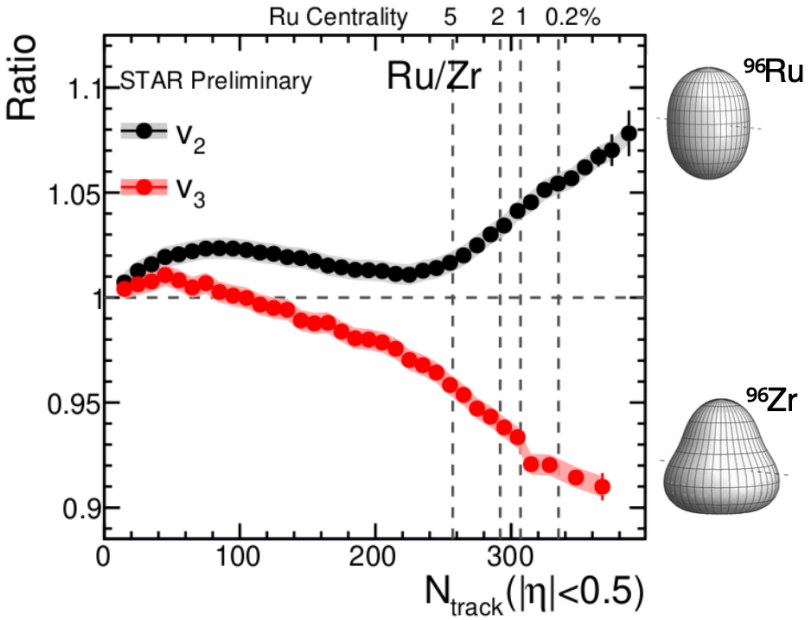
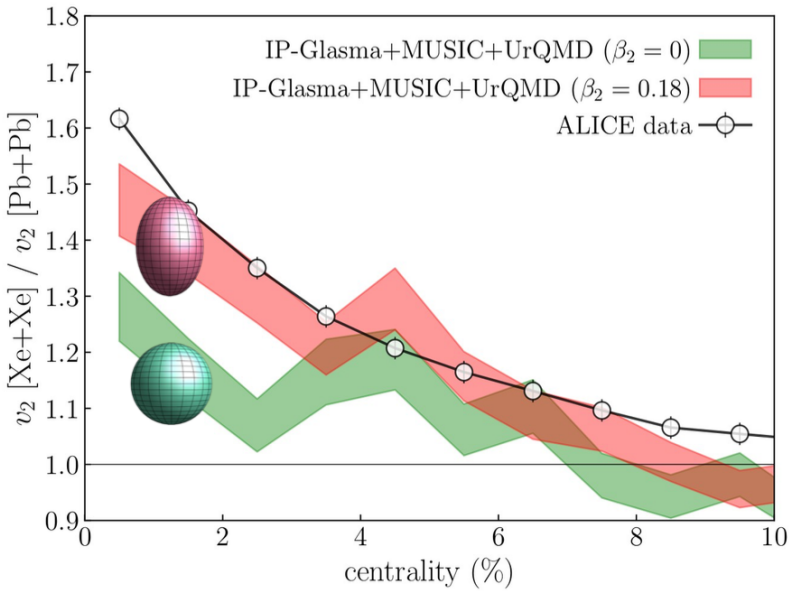
Giacalone Ollitrault 2021





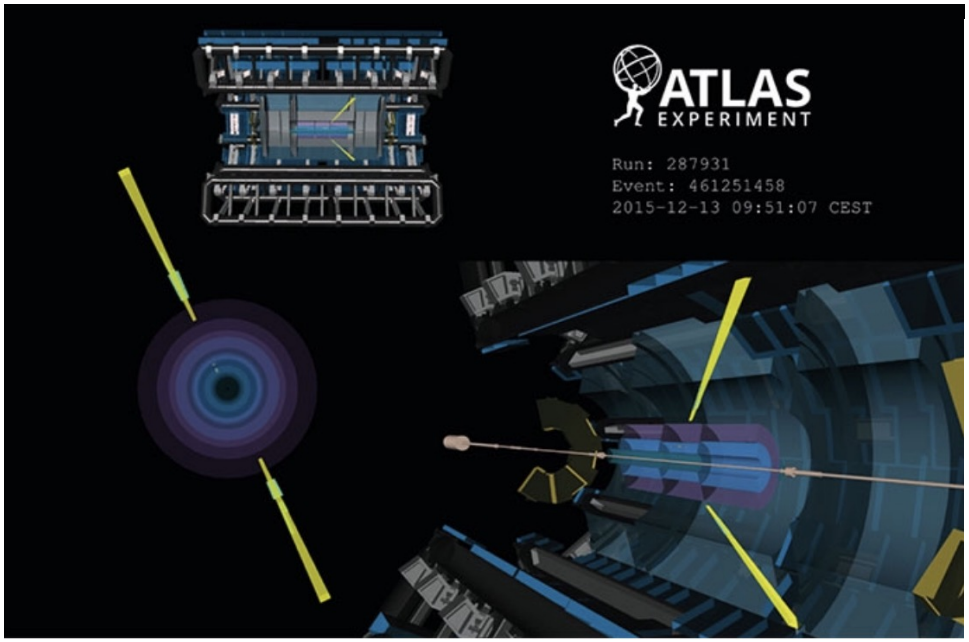
☞ Has now become a very active field

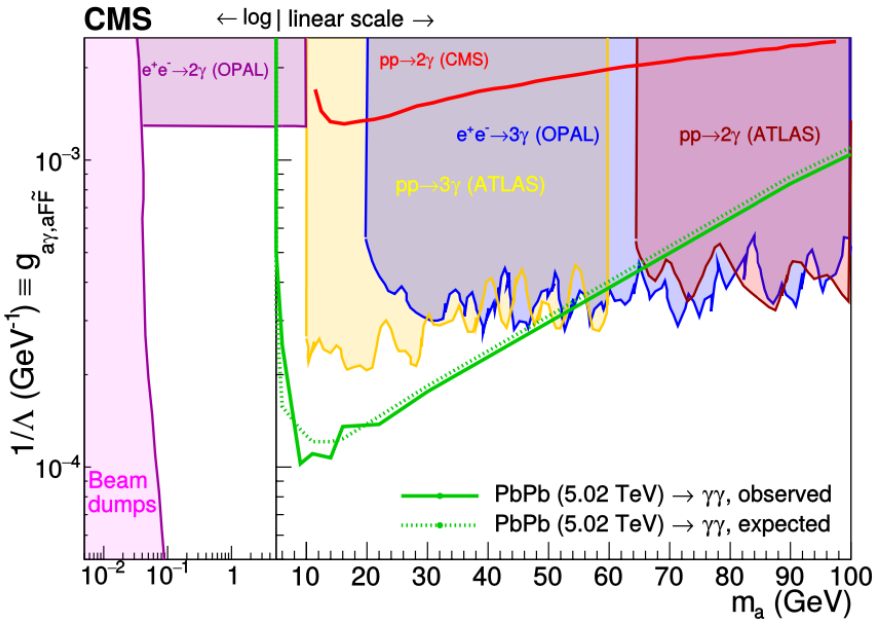
☞ Link between high-energy heavy ion collisions and nuclear physics

Probing QED. . . and BSM

Evidence for light-by-light scattering $\gamma\gamma \rightarrow \gamma\gamma$ in PbPb collisions

ATLAS, CMS



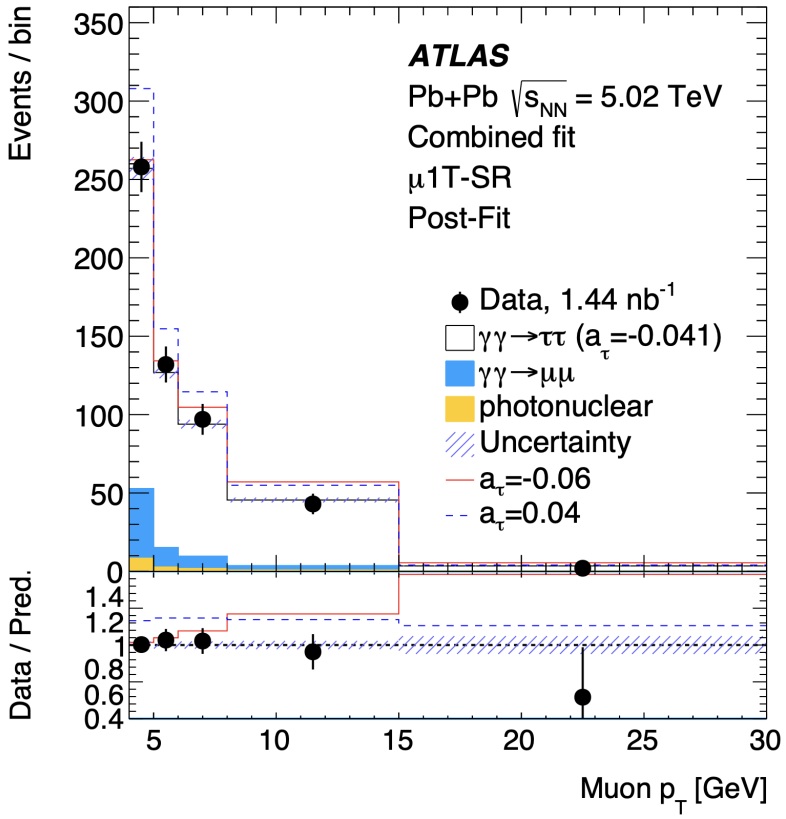


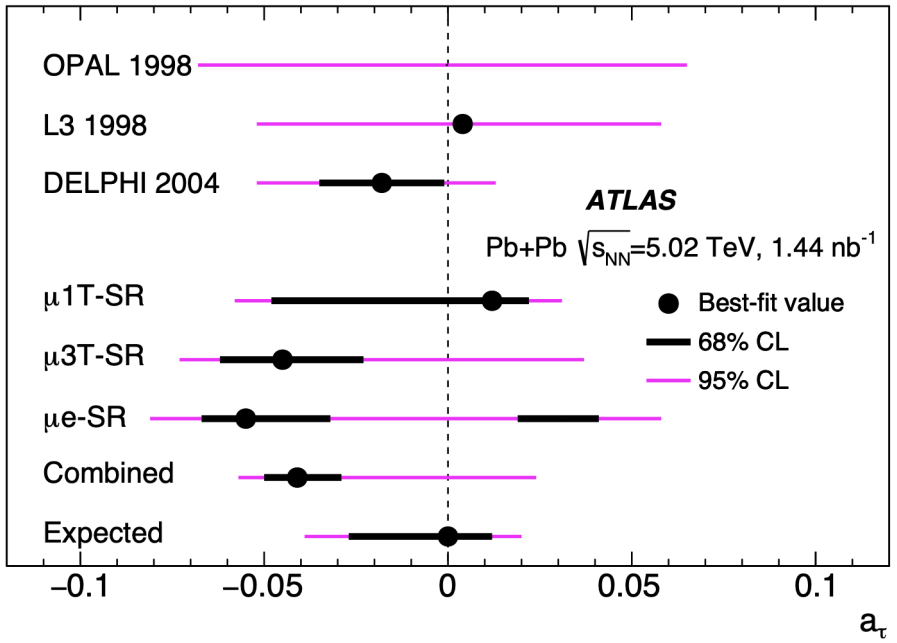
- Sensitive test of QED. . . setting upper limits on Axion searches

Probing QED. . . and BSM

Observation of $\gamma\gamma \to \tau\tau$

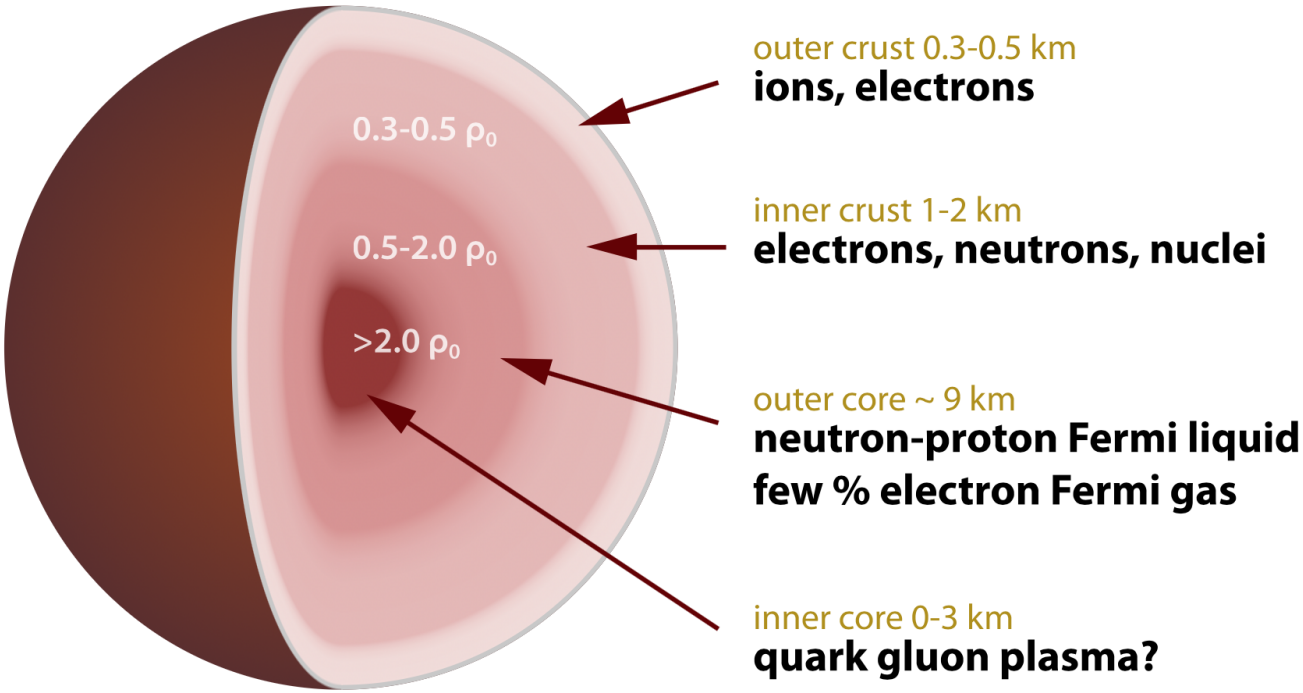
ATLAS, CMS 2022





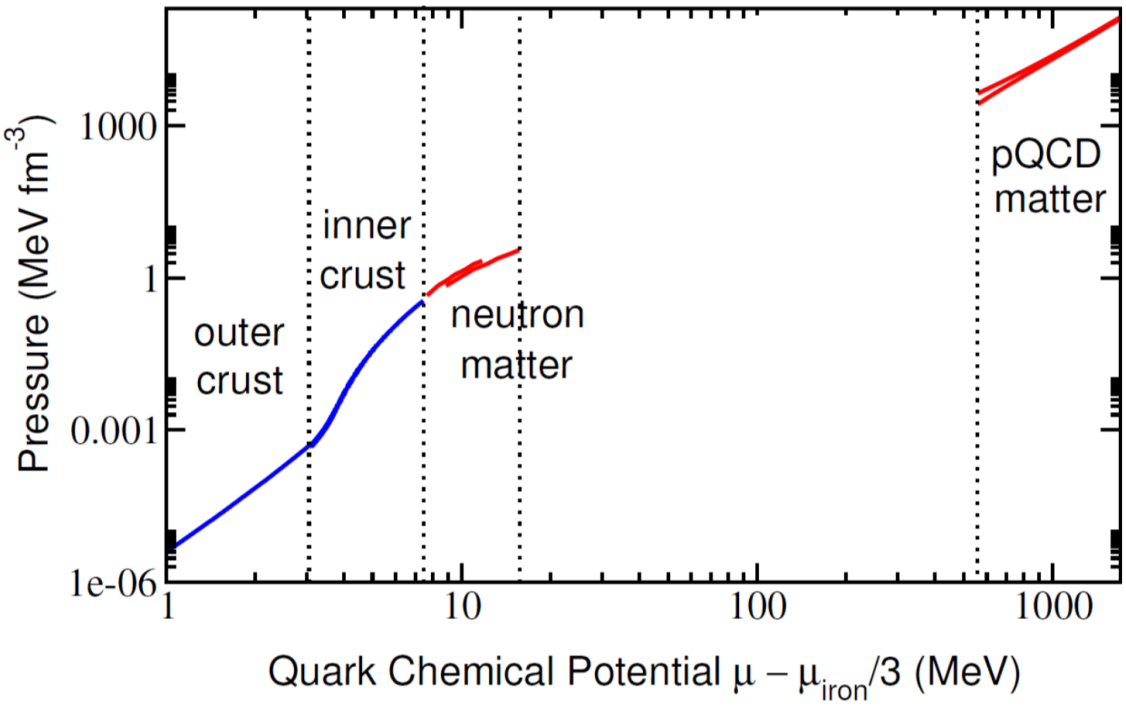
- Sensitivity similar to LEP experiments. . . and expected to improve !

Probing neutron stars



- Baryon density increase from 0 up to beyond $\rho_0 = 0.16$ fm^{-3}
- Can we infer the QCD matter EoS from observations ?
- Can deconfined matter be found inside the stars ?
- Competition between gravity and QCD pressure: $\epsilon(p)$ to $M(R)$

Equation of state of neutron stars



Known limits of the equation of state

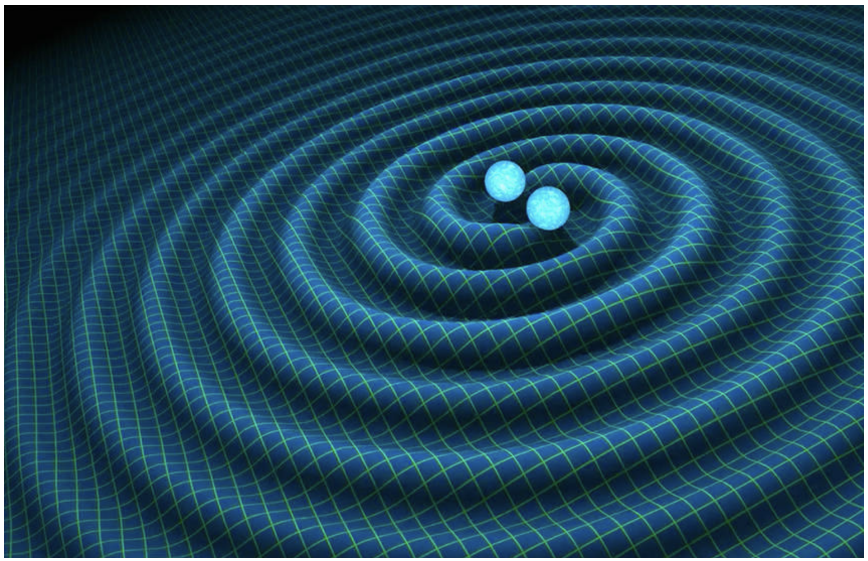
- Low density up to $\rho \simeq \rho_0$: phenomenological nuclear theory
- Perturbative QCD offers limiting behavior at very large densities
- Not clear how to bridge the gap
  - Neither pQCD nor lattice may be reliable

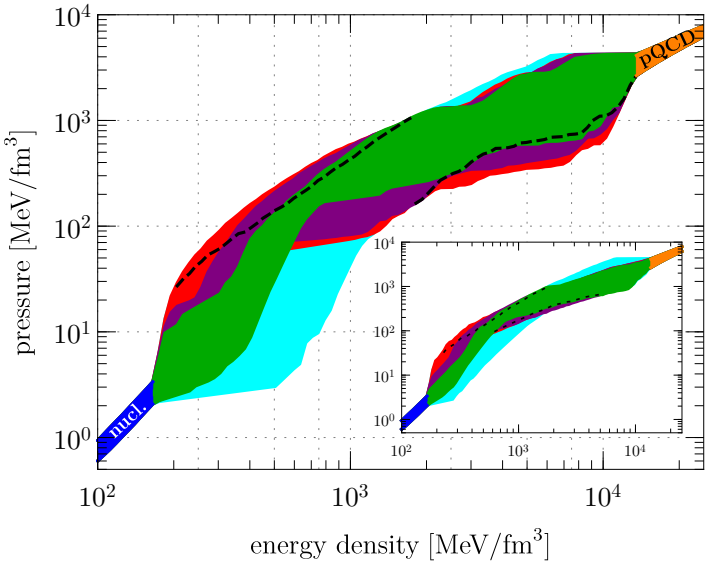
Help from astrophysical observations

- Existence of neutron stars with mass $M > 2M_\odot$
- Observation of gravitational waves from a binary neutron star inspiral

LIGO/VIRGO GW170817

☞ Restricts the class of possible equations of state





Annala Gorda Kurkela Vuorinen 2018

- Astrophysical measurements start setting stringent bounds on the collective properties of dense QCD matter

Summary

Heavy ion collisions = versatile QCD lab

- Discovery and study of QGP
  - EOS, transport coefficients. . . even more quantitative with Run 3 & 4
  - Still many puzzles to solve (= fun)
- Probing perturbative QCD, differently
  - Gluon radiation off a complex system in a dense environment
  - New QCD evolution in nuclei, beyond DGLAP
  - Testing limits of QCD factorization in pA collisions
  - Obvious links with electron ion collider
- Nascent links with other branches of physics
  - Nuclear physics, BSM physics, astrophysics
- Crucial / complimentary measurements expected from LHC expts
  - High precision
  - New particles & new final states
  - Testing phase space boundaries (where unexpected might happen)

Heavy ion physicists tasting homemade QGP

Thanks for your attention !