Heavy-ion experimental results at the LHC

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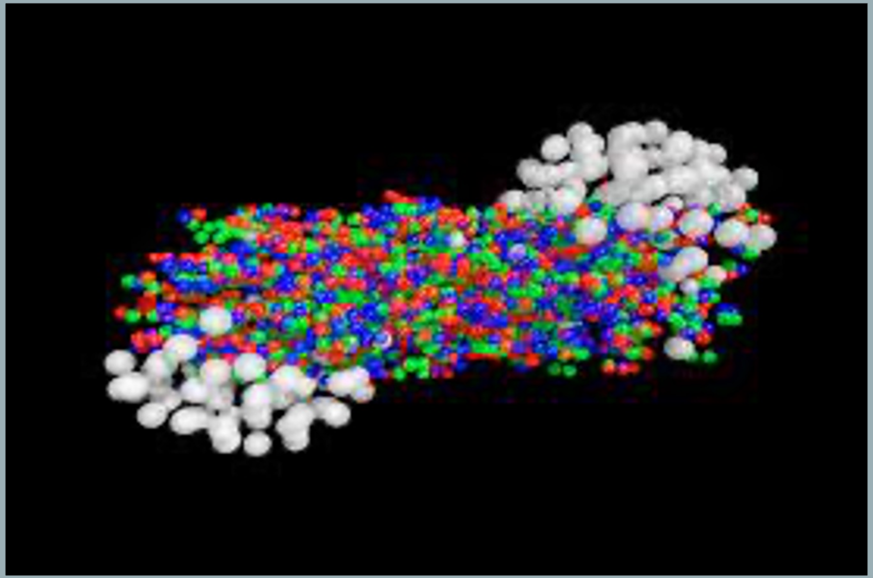
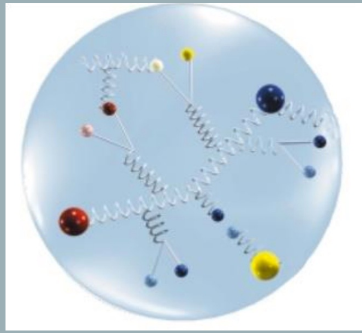


34th Rencontres de Blois – 14-19 May 2023 – Blois, France

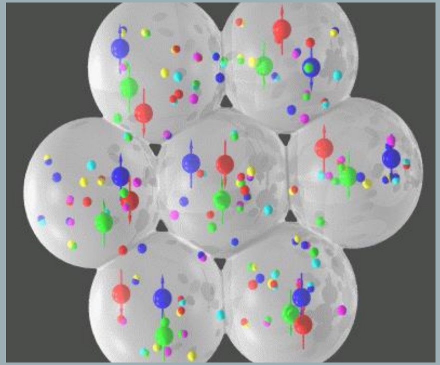
Scientific context : Quantum Chromodynamics (QCD)

Theory of strong interaction with rich variety of features : asymptotic freedom, confinement, chiral symmetry…



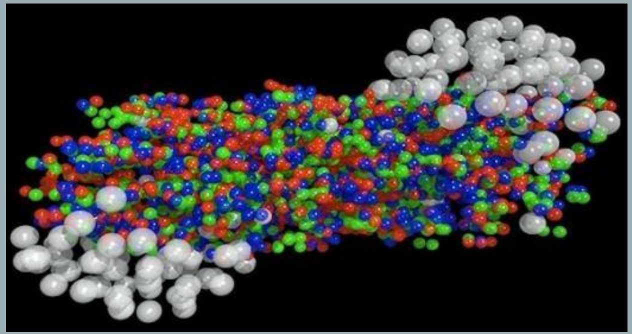
Nucleon and hadron structure

How do the mass and spin of the nucleon arise from its constituents? What are the static and dynamical properties of hadrons?



Medium effects

What are the modification of the quark and gluon structure of a nucleon when it is immersed in a nuclear medium?



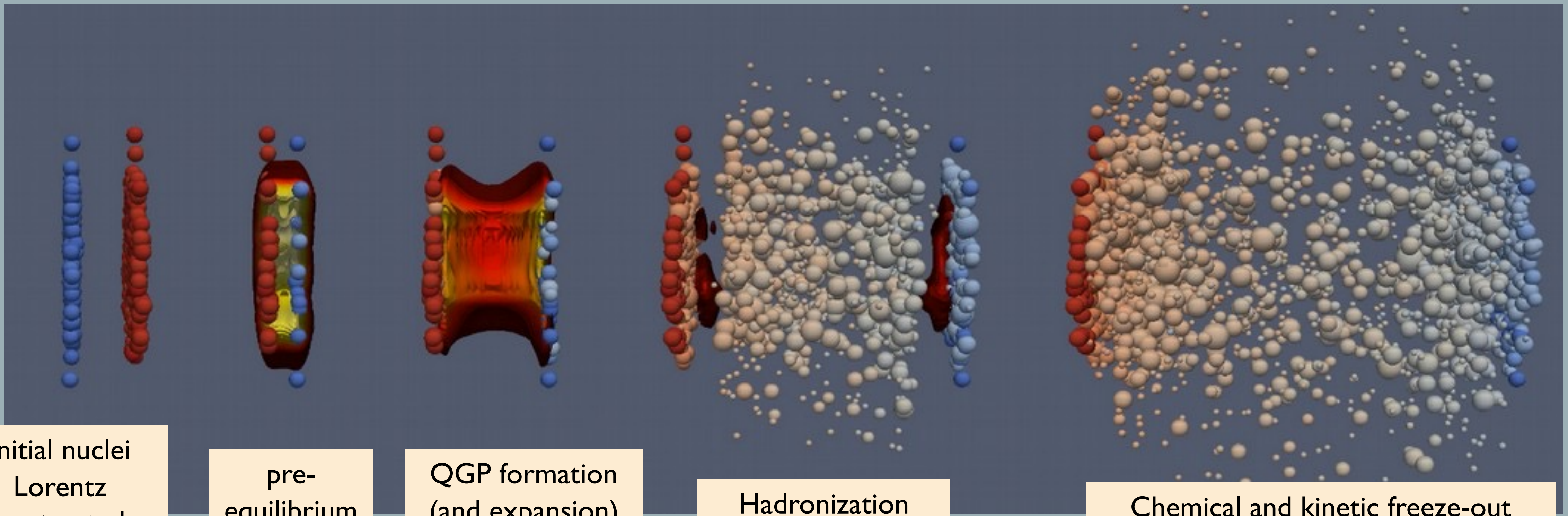
Quark Gluon Plasma

What are the properties of nuclei and strongly-interacting matter as encountered shortly after the Big Bang, in catastrophic cosmic events and in compact stellar objects?

from QCD in vacuum to QCD under extreme conditions

Space-time evolution of a heavy-ion collision at LHC energies

MADAI Collaboration, https://madai.phy.duke.edu/indexaae2.html?page_id=503



Initial nuclei Lorentz contracted

pre-equilibrium

QGP formation (and expansion)

Hadronization

Chemical and kinetic freeze-out

0 fm/c ~ 1 fm/c ~ 10 fm/c time

MC-Glauber, CGC

pQCD

Viscous hydrodynamics

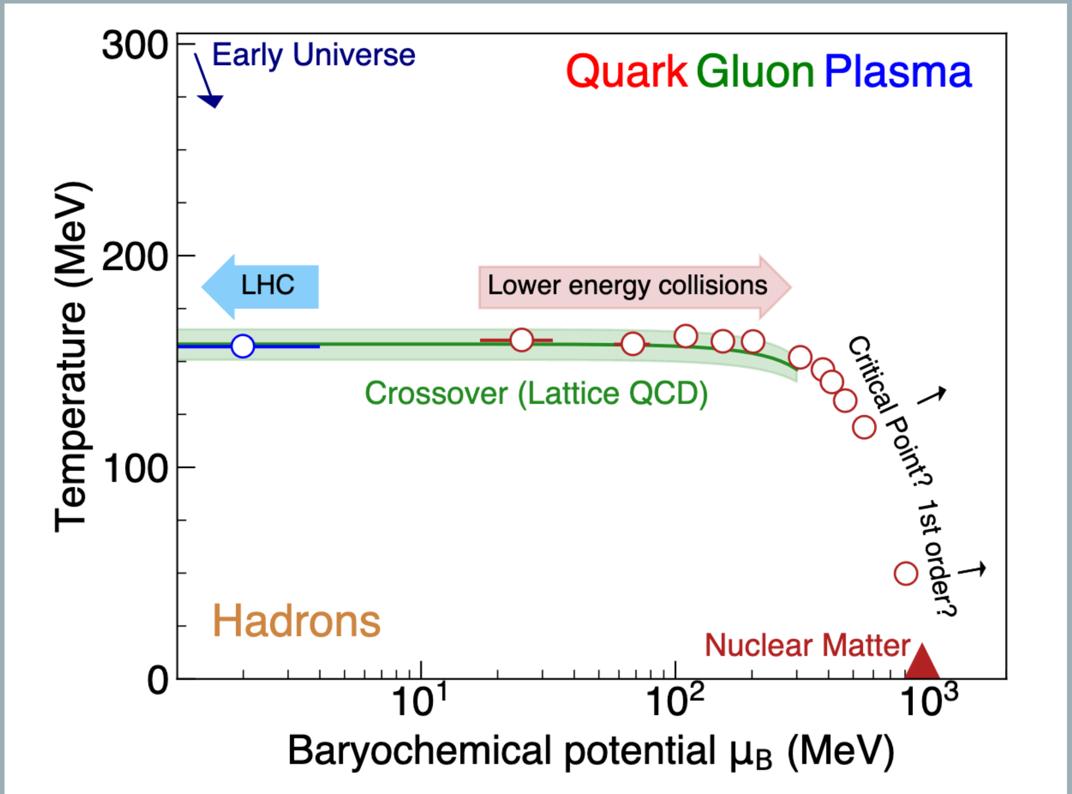
Hadronic transport and statistical models

Lattice QCD

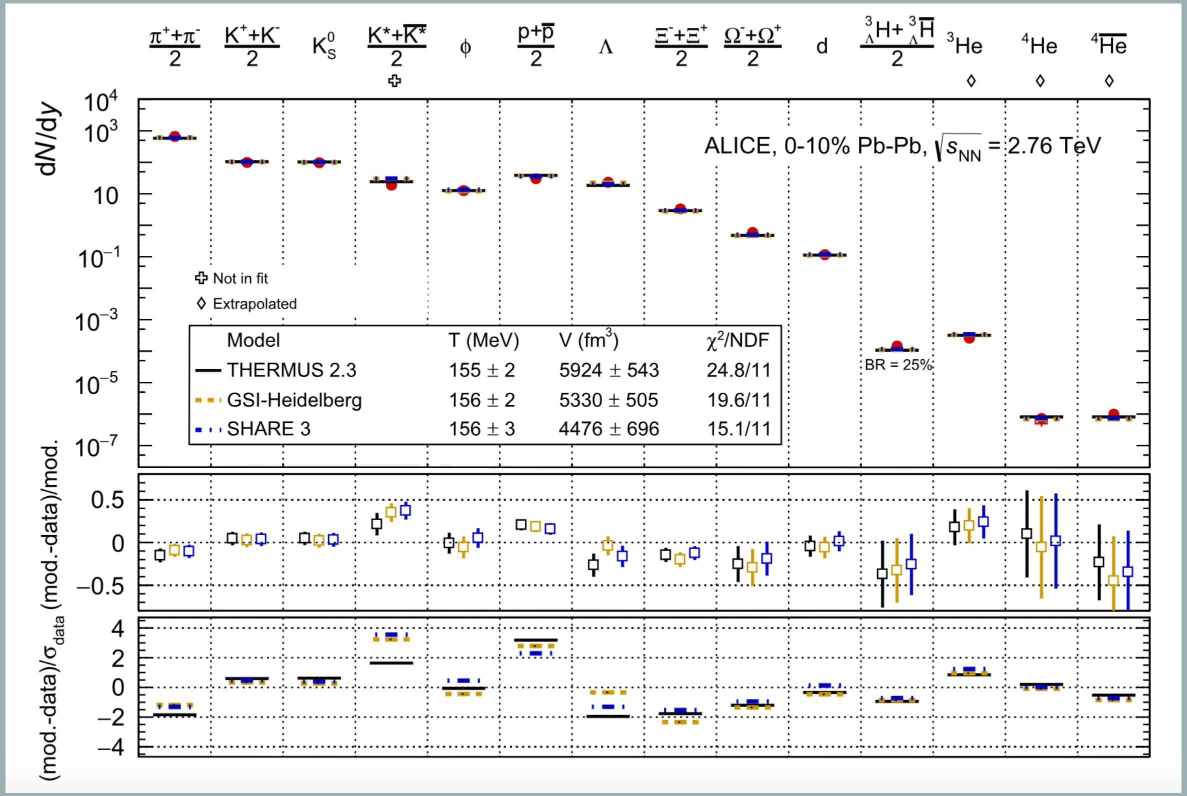
Theoretical tools

QCD phase diagram and QGP properties

- QCD phase diagram : T_{chem} and μ_B at chemical freeze-out in agreement with LQCD at LHC → chemical equilibration of the system at, or shortly after hadronization
- At LHC, bulk chemistry of QGP freeze out described by statistical model of particle production, in thermal equilibrium, with common temperature (T~155 MeV) and volume (5000 fm^3)



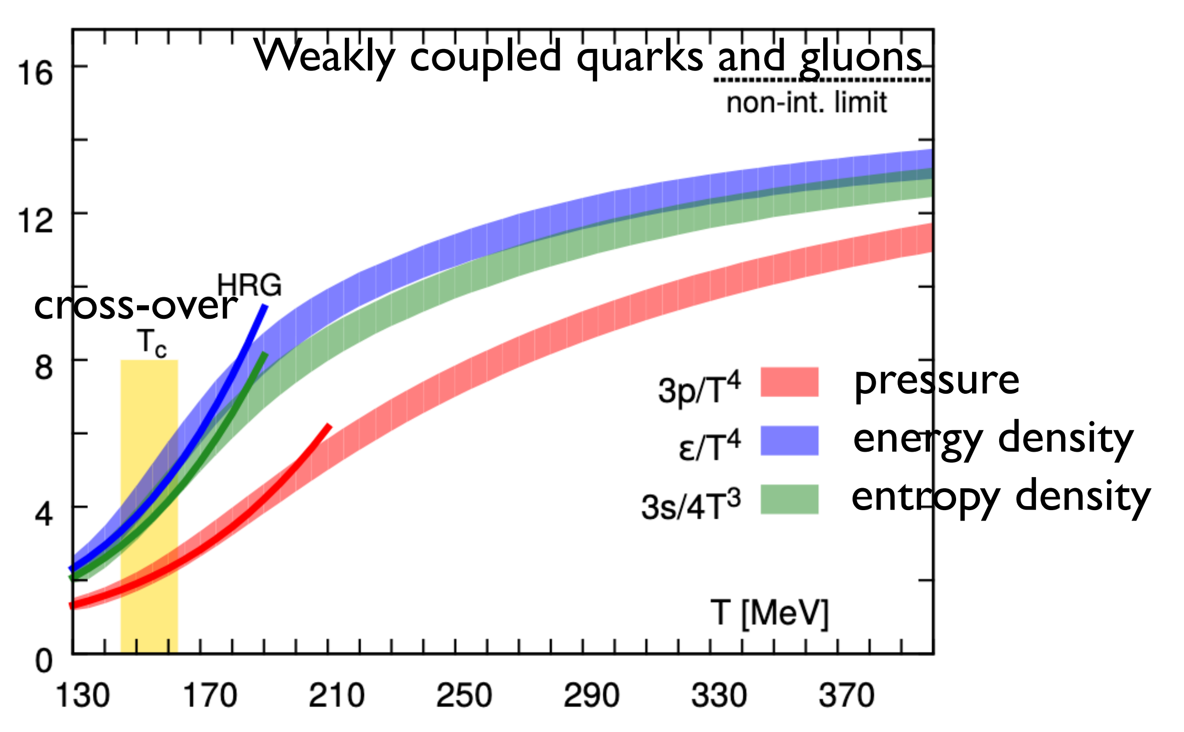
ALICE Collaboration, arXiv:2211.04384v1



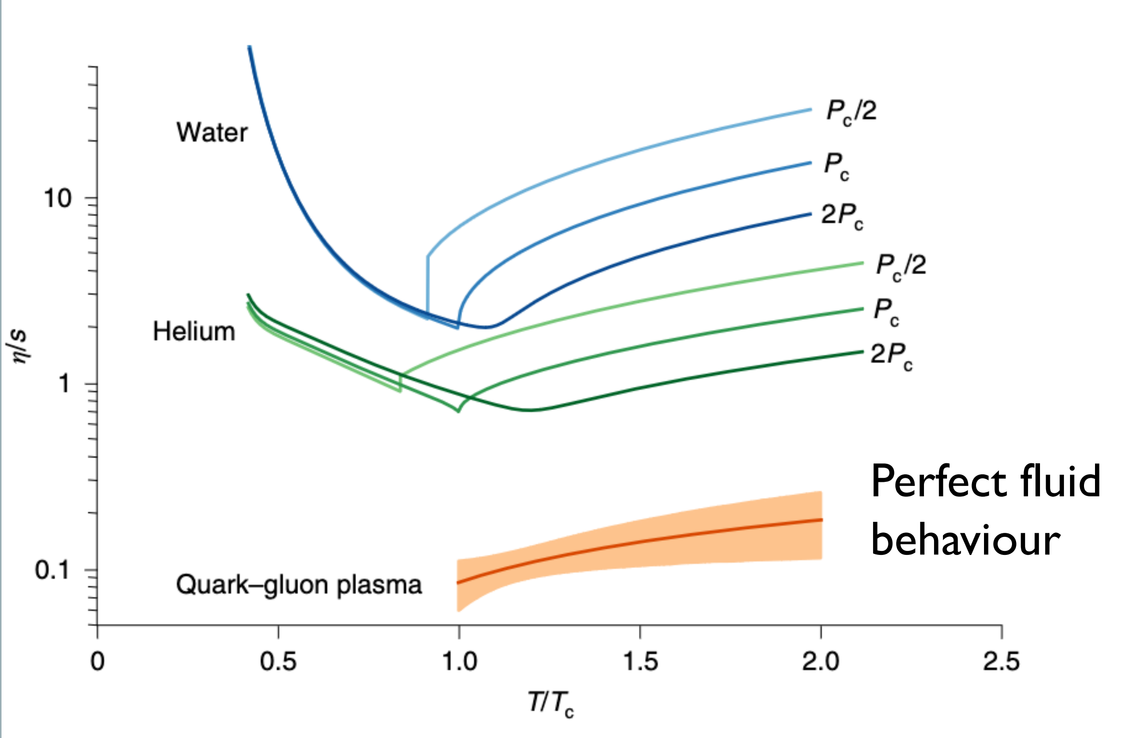
ALICE Collaboration, Nucl. Phys. A. 971 (2018) 1-20,

Thermodynamics of the QGP

- Lattice QCD calculation of pressure, energy density, entropy density of hot QCD matter in thermal equilibrium shows a continuous crossover around T_c ~ 150 MeV from a hadron resonance gas to a QGP
- QGP properties can be derived from Bayesian fit to data (eg. fit of flow coefficients v_n and estimation of T dependence of shear viscosity to entropy density ratio) → QGP η/s one order of magnitude smaller than other common fluids.

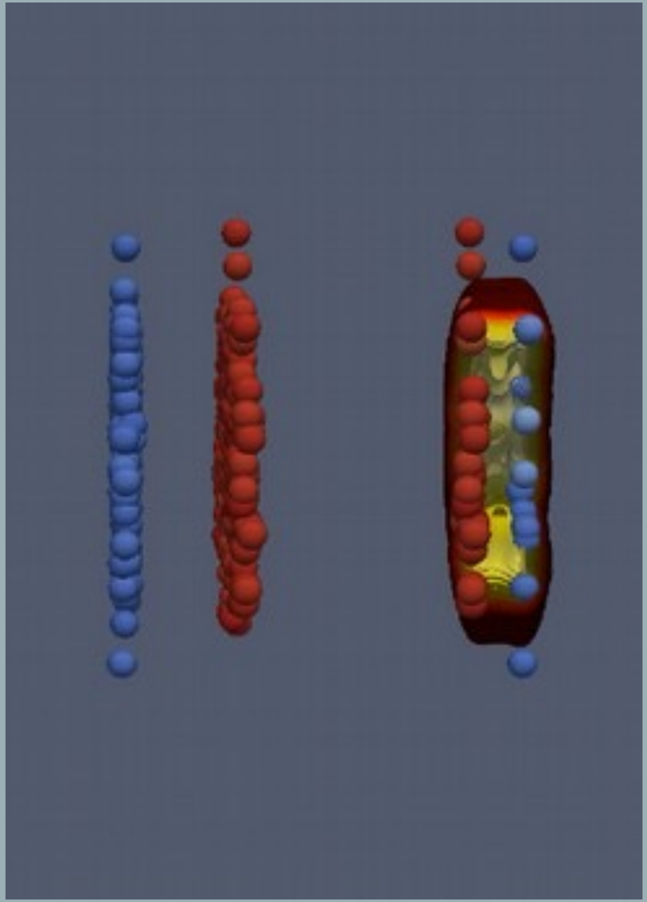


Hot QCD Collaboration, Phys. Rev. D. 90, 094503 (2014)

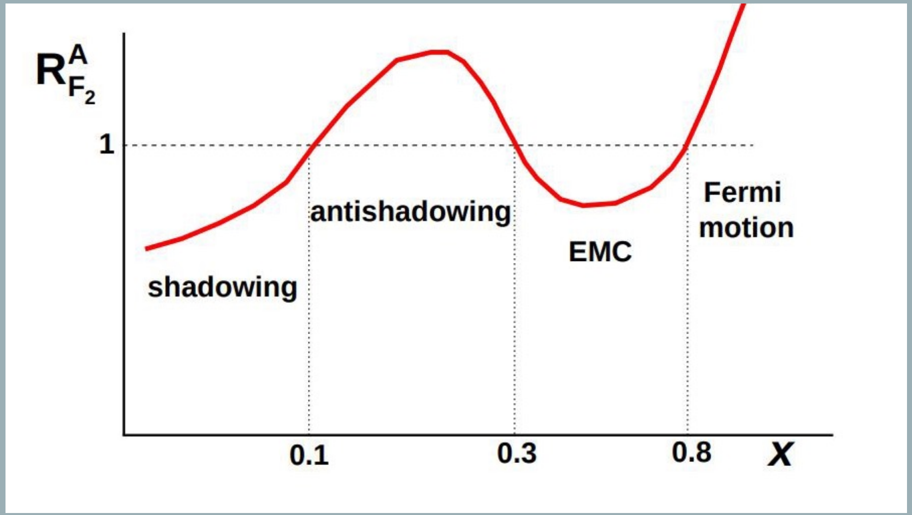


J. Bernhard et al., Nat. Phys. 15, 1113-1117 (2019)

Initial stages of the heavy-ion collision



- Characterization of the initial stages of the collision (nPDFs, gluon saturation, collision geometry….)
- Tools : reference p-Pb collisions, ultra-peripheral Pb-Pb collisions
- Main Observables : cross sections, R_{pPb}, R_{FB}
- Creation of hard probes



$$R_{pPb}(p_T, y^*) \equiv \frac{1}{A} \frac{d^2\sigma_{pPb}(p_T, y^*)/(dp_T dy^*)}{d^2\sigma_{pp}(p_T, y^*)/(dp_T dy^*)}$$

$$R_{FB} = \frac{Y^{pPb}_{forward}}{Y^{pPb}_{backward}}$$

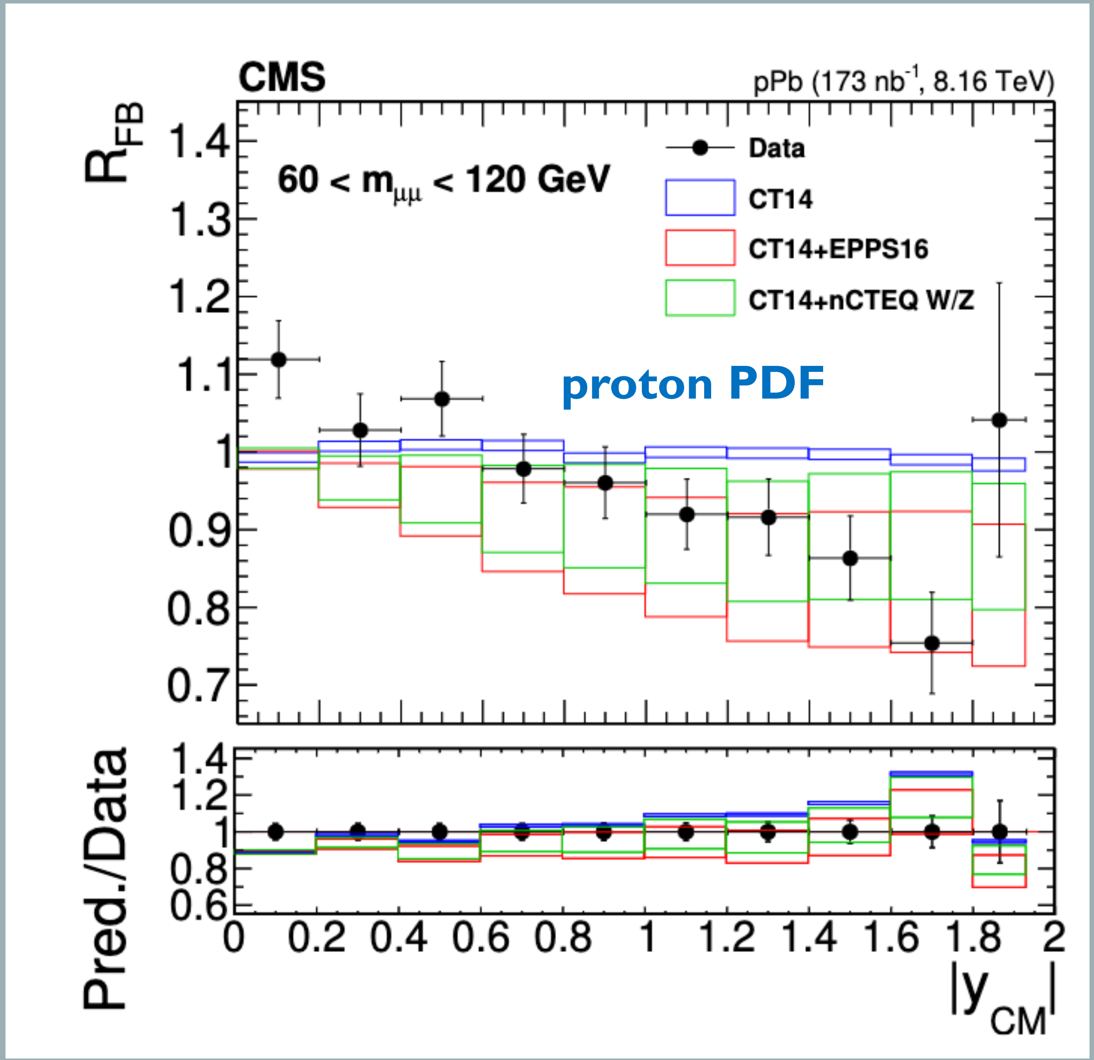
In a common $|y_{c.m.s}|$ window

p-Pb data as a tool to constrain quark nPDFs

CMS Collaboration, JHEP 05 (2021) 182

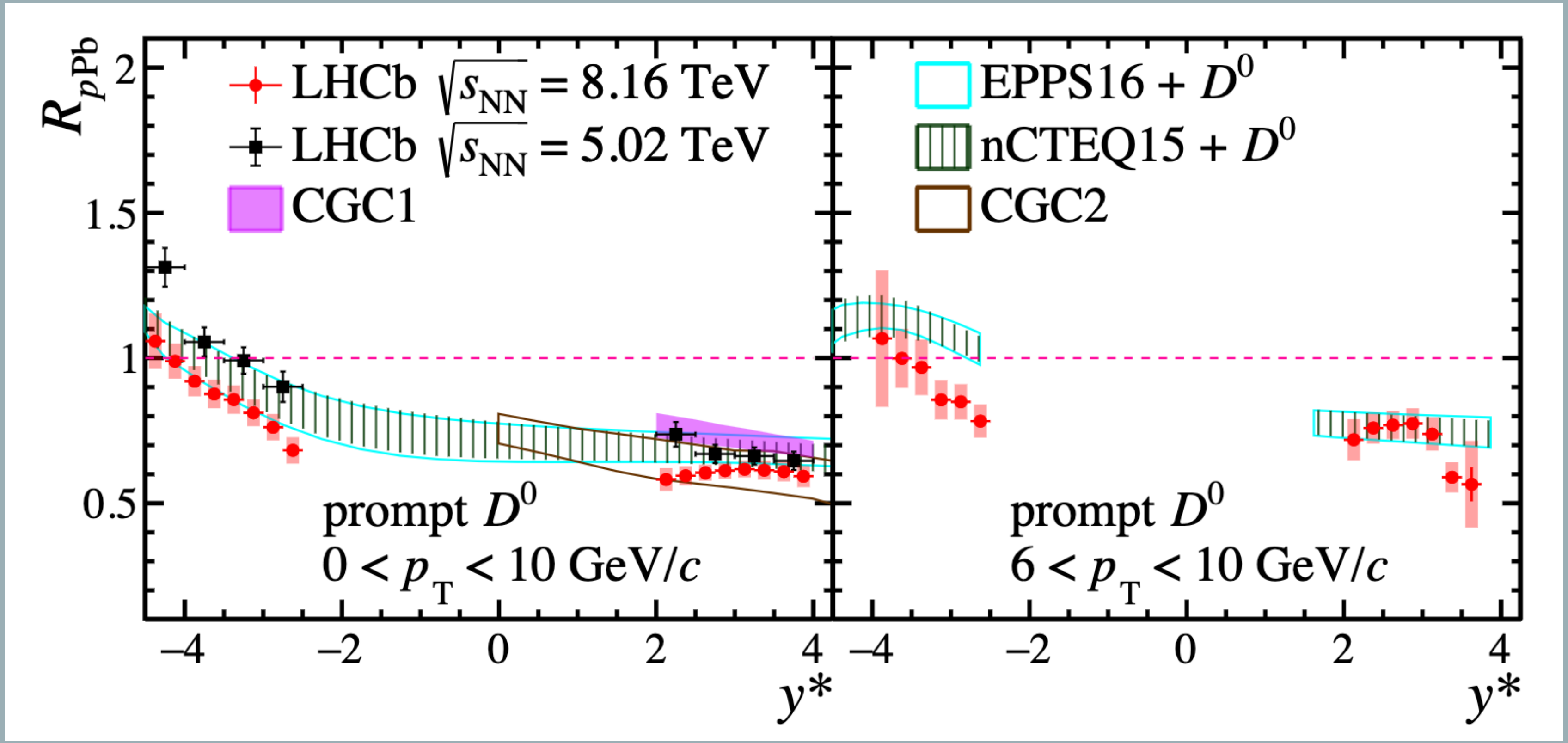
- ❑ Drell –Yan (Z/γ*) in pPb
  - ➢ In absence of nuclear effects R_{FB} = 1 (CT14, proton PDF)
  - ➢ Decrease of R_{FB} with $|y_{CM}|$ for CT14+EPPS16 nPDFs and CT14+nCTEQ nPDFS
  - ➢ Evidence for nuclear effects in CMS data (as expected from combination of shadowing and antishadowing in nPDFs)

- ❑ Experimental uncertainties smaller than nPDF ones → can provide novel constraints on quark/antiquark nPDFs



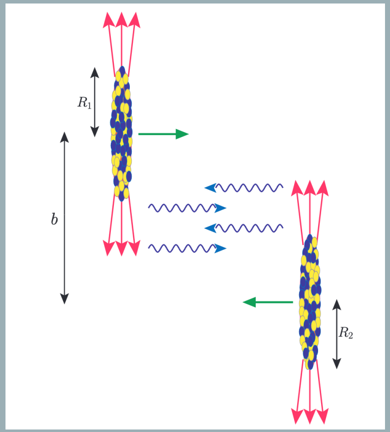
p-Pb data as a tool to constrain gluon nPDFs

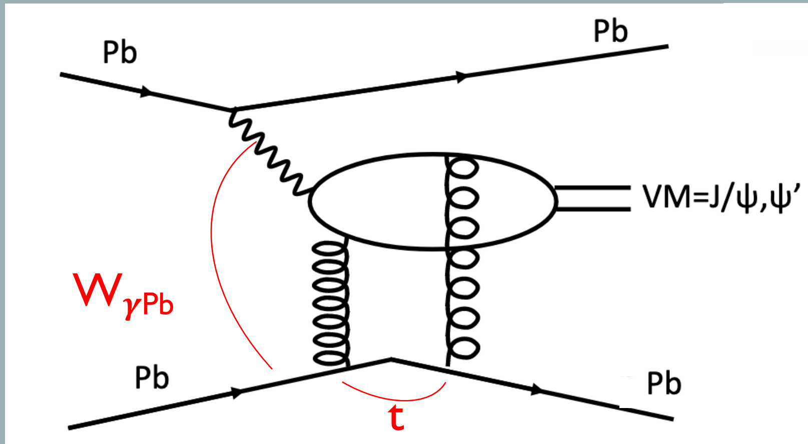
- Prompt D^0 in pPb
  - Stronger suppression in p-Pb (w.r.t scaled pp) at forward rapidity (lower Bjorken-x) w.r.t backward rapidity. Well described by nPDFs and CGC (saturation effects) calculations
  - High p_T and backward rapidity : room for additional Cold Nuclear Matter effects (eg. final state energy loss)



LHCb Collaboration, arXiv:2205.03936

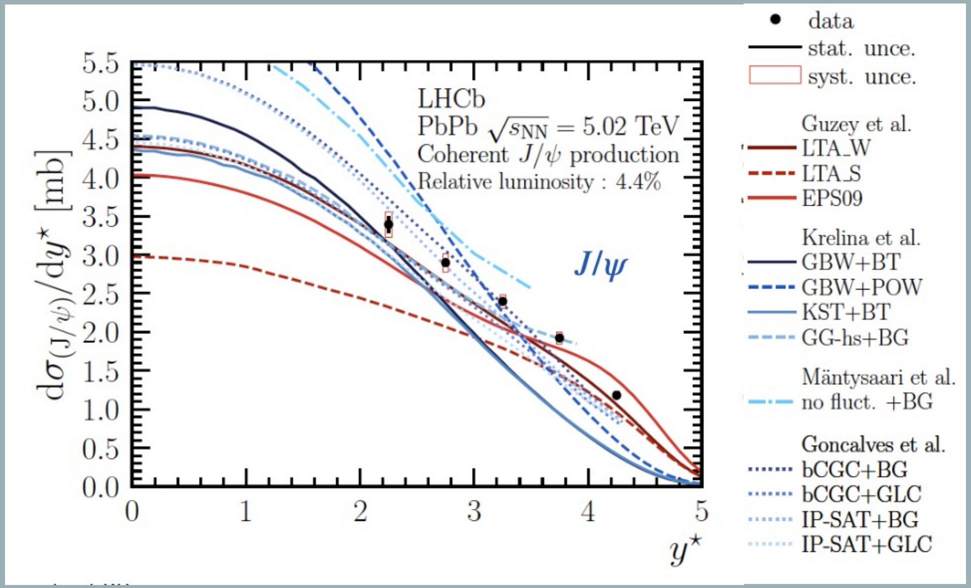
Vector meson photoproduction in Pb-Pb UltraPeripheral Collisions



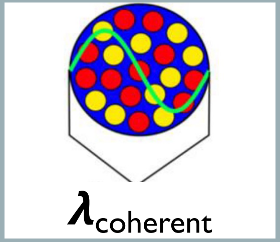


- ❑ The EM field of Pb nuclei → beam of quasi-real **γ**
- ❑ UPC: interactions with b > 2R. Involve at least one **γ**
- ❑ Gives access to gluon distributions in nuclei at low Bjorken-x ($10^{-5} < x < 10^{-2}$ at LHC energies)
- ❑ LHCb coherent J/**ψ** described by nPDFs/CGC models. Exp. unc. Smaller than spread of theory curves
- ❑ ALICE incoherent J/**ψ** : need for inclusion of sub-nucleon fluctuations to describe data

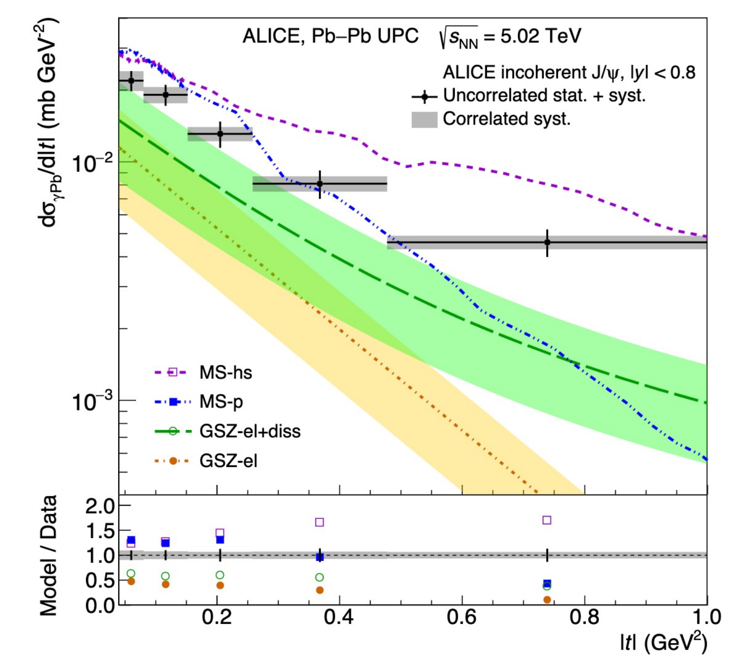
❑ Coherent J/ψ in Pb-Pb

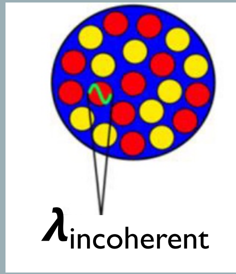


LHCb Collaboration, arXiv:2206.08221



❑ Incoherent J/ψ in Pb-Pb

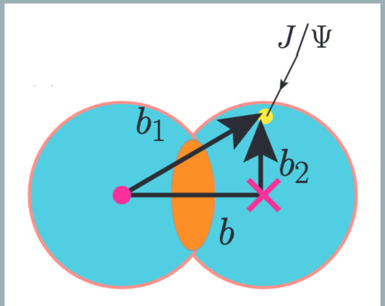




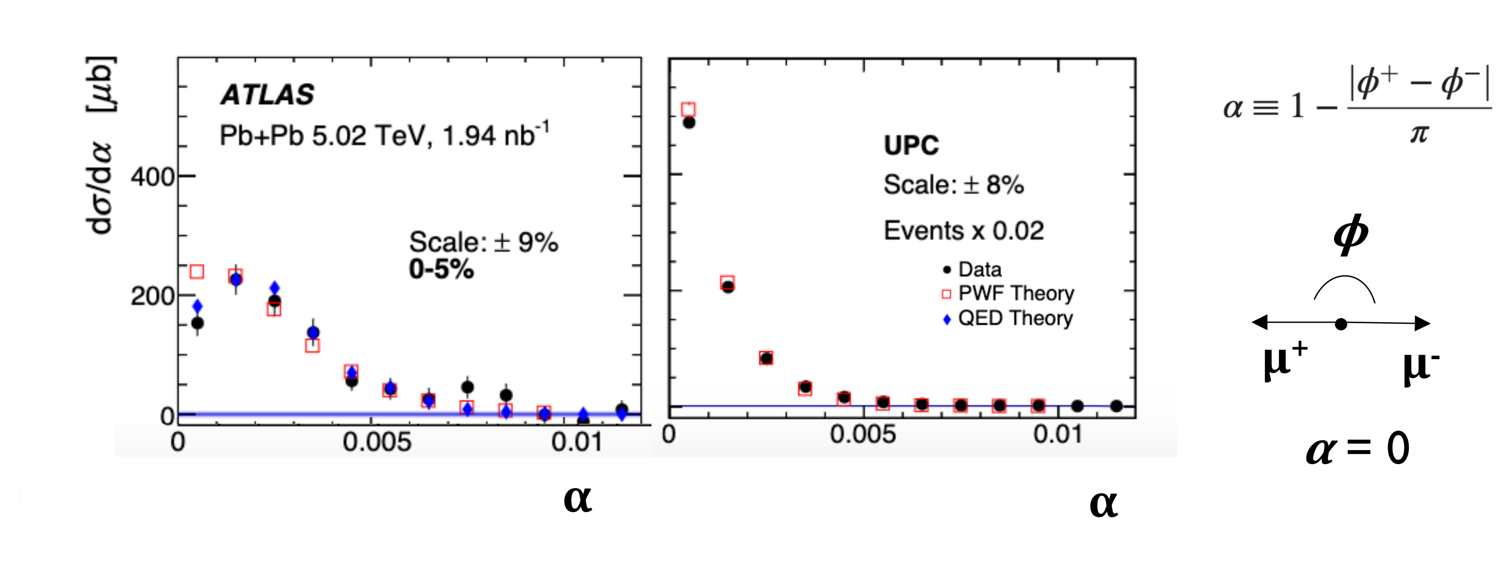
ALICE Collaboration, arXiv:2305.06169

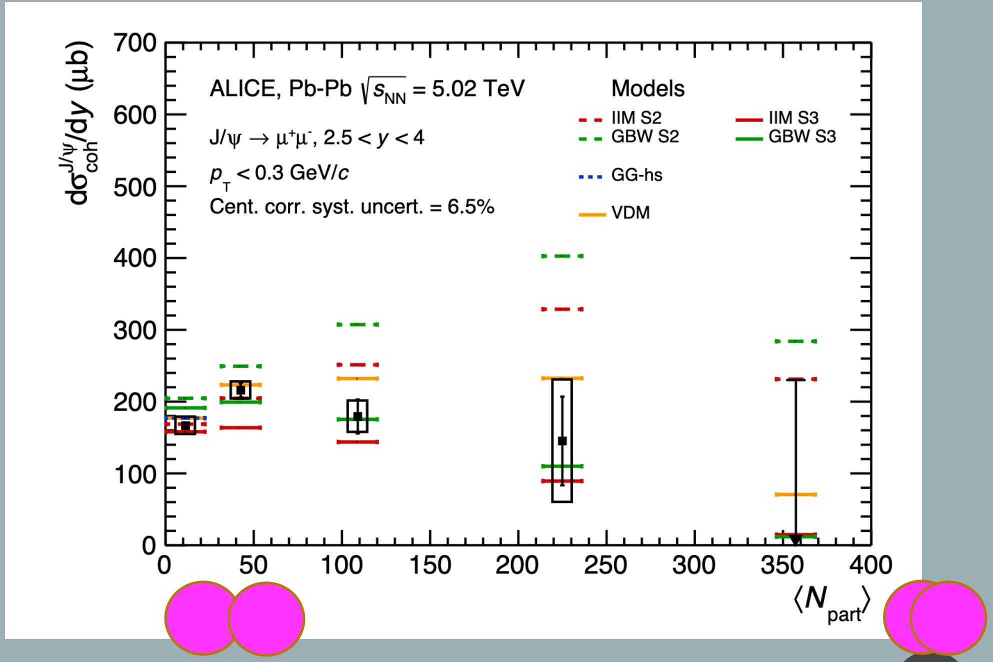
Photon-induced processes in Pb-Pb collisions with nuclear overlap

- ❑ Photon-induced processes observed for the first time at LHC in Pb-Pb collisions with nuclear overlap (interplay between hadronic interaction and photon-induced processes)
- ❑ Required new theoretical developments (eg. coherent VM photoproduction while nuclei broken by hadronic interaction, interaction of the probe with QGP?)
- ❑ ATLAS ($\gamma\gamma \rightarrow \mu^+\mu^-$) : centrality-dependent broadening of α distribution well reproduced by QED (without need for QGP effects)
- ❑ ALICE (γPb $\rightarrow$J/ψ): centrality dependence of coherent cross section reproduced by models accounting for nuclear overlap in photon flux and/or photonuclear σ computations



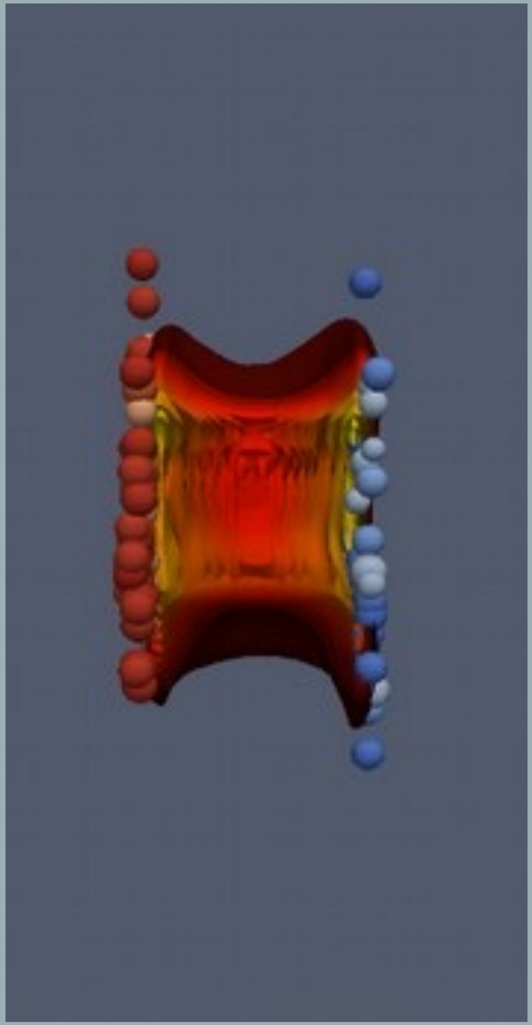
ATLAS Collaboration, arXiv:2206.12594

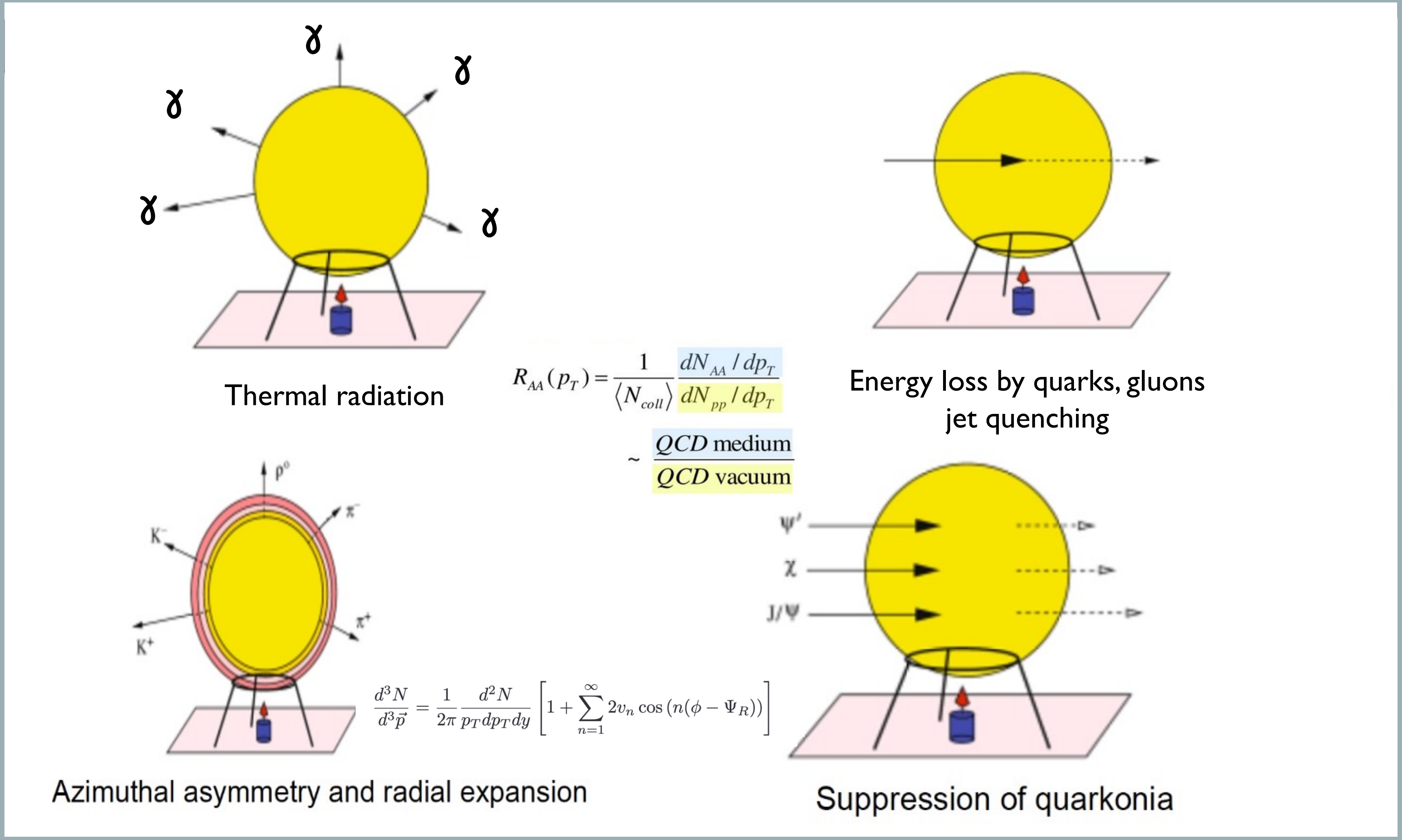




ALICE Collaboration, arXiv:2204.10684

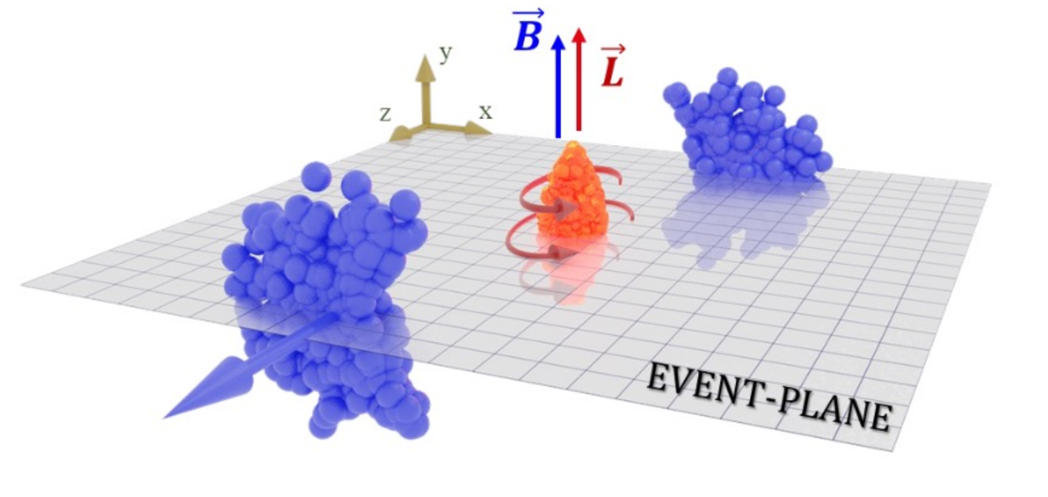
Medium modifications





Properties of the early dynamics of the collision

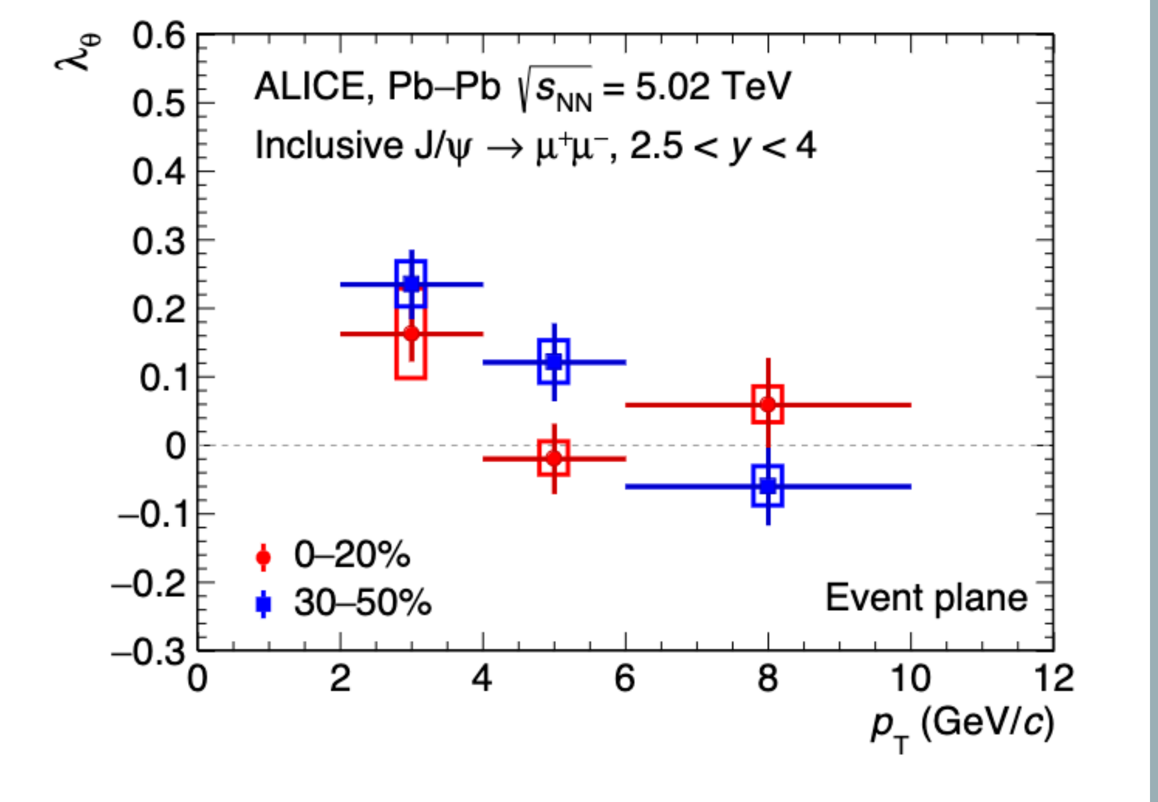
Event plane based frame : normal to $\vec{B}$ and $\vec{L}$



$$W(\cos\theta,\phi) \propto \frac{1}{3+\lambda_\theta} \cdot (1 + \lambda_\theta \cos^2\theta + \lambda_\phi \sin^2\theta \cos 2\phi + \lambda_{\theta\phi} \sin 2\theta \cos\phi)$$

λ_θ = 0 (no polarization); +1 (transverse polarization), -1 (longitudinal polarization)

- Heavy quark pair production occurs early in the collision and can experience both the short living $\vec{B}$ (10^{14}T) and $\vec{L}$ of the rotating medium
- Evidence for non-zero J/ψ polarization w.r.t event plane → need theoretical guidance to understand which contribution is dominant (vorticity and/or magnetic field)
- Spin alignment also observed for light vector mesons (K^{*0},ϕ)



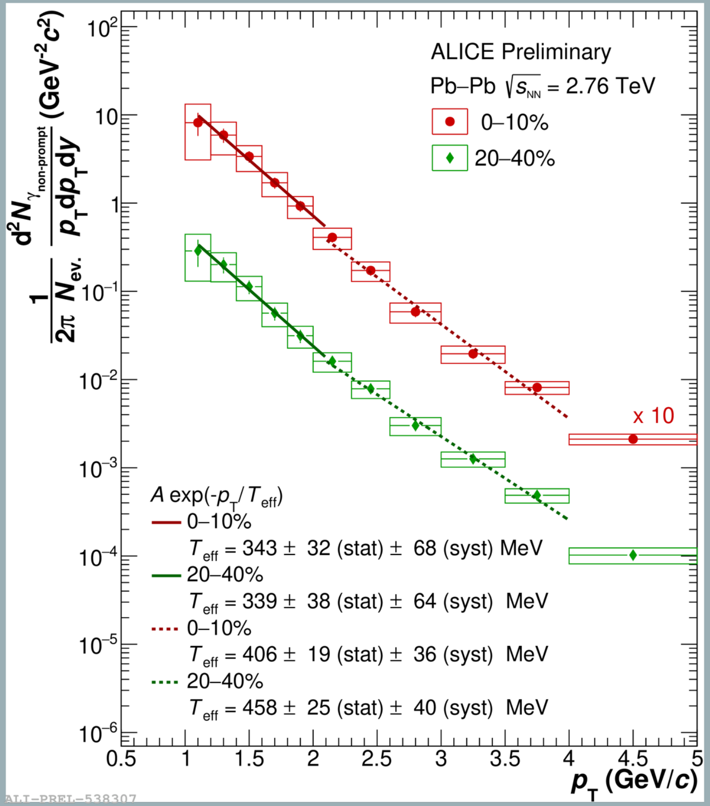
ALICE Collaboration, PRL 125 (2020) 012301

ALICE Collaboration, 2204.10171

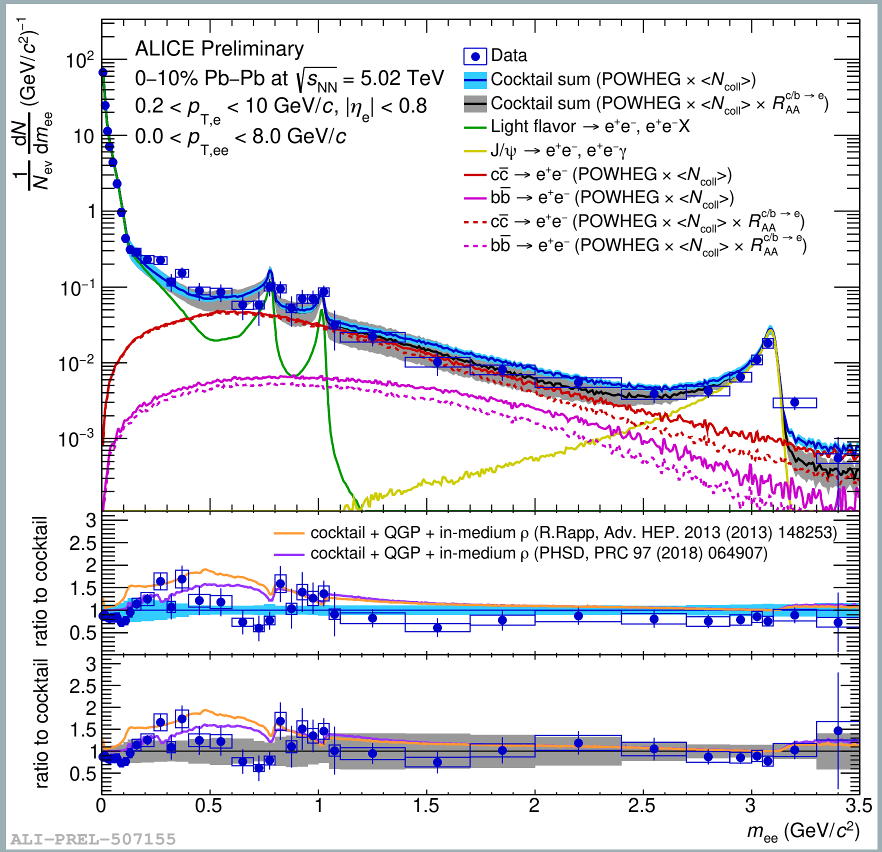
Bulk properties of the QGP : thermal photons and dileptons

- ❑ Electromagnetic radiation are sensitive to the QGP temperature
- ❑ Direct photons : prompt photons (pQCD) dominant at high-p_T + thermal photons (direct measurement of medium T) dominant at low-p_T + (pre-equilibirum photons)

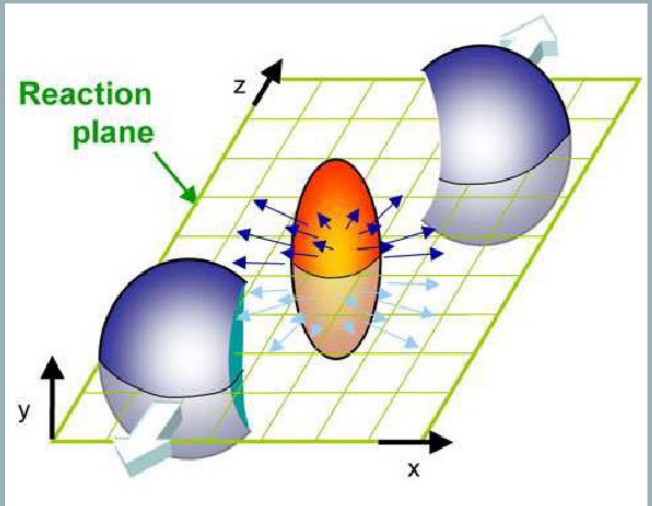
Direct photon – prompt photon (T_{AA} . pQCD)
Teff ~ 340 MeV (exp fit to low-p_T part of spectrum)



Hint for thermal excess in low mass dielectron spectrum



Bulk properties of the QGP : azimuthal anisotropies

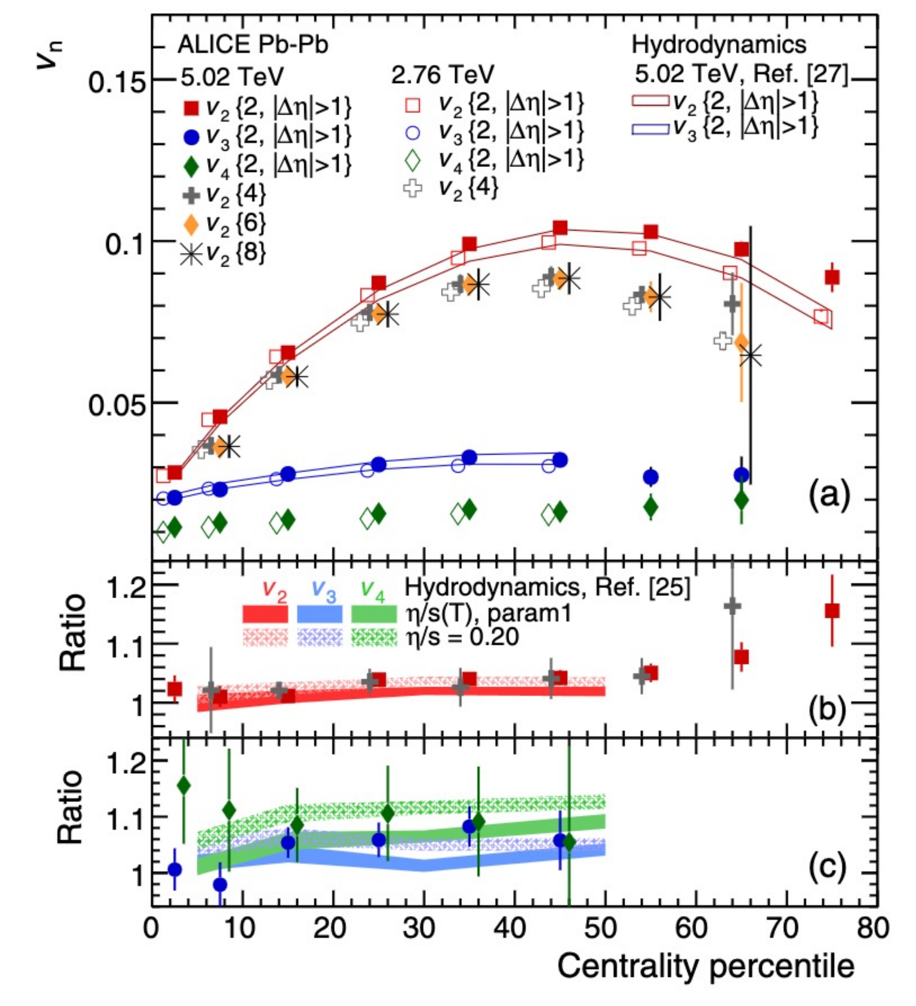


$$\frac{d^3N}{d^3\vec{p}} = \frac{1}{2\pi}\frac{d^2N}{p_T dp_T dy}\left[1 + \sum_{n=1}^{\infty} 2v_n \cos\left(n(\phi - \Psi_R)\right)\right]$$

In non-central collisions → initial spatial anysotropy

If particle strongly interact → different pressure gradients → final state particle momentum distribution is anisotropic

ALICE Collaboration, PRL 116, 132302 (2016)

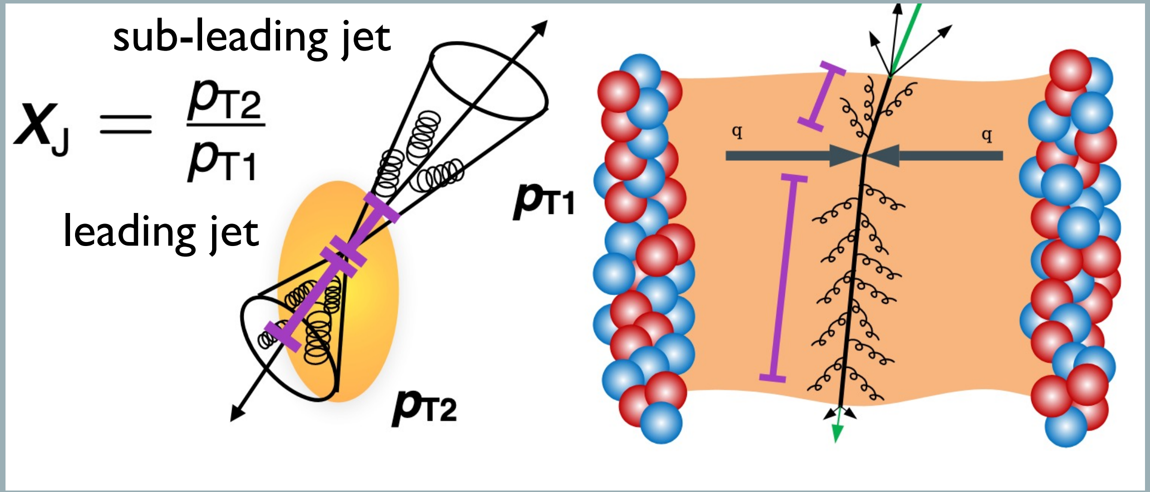


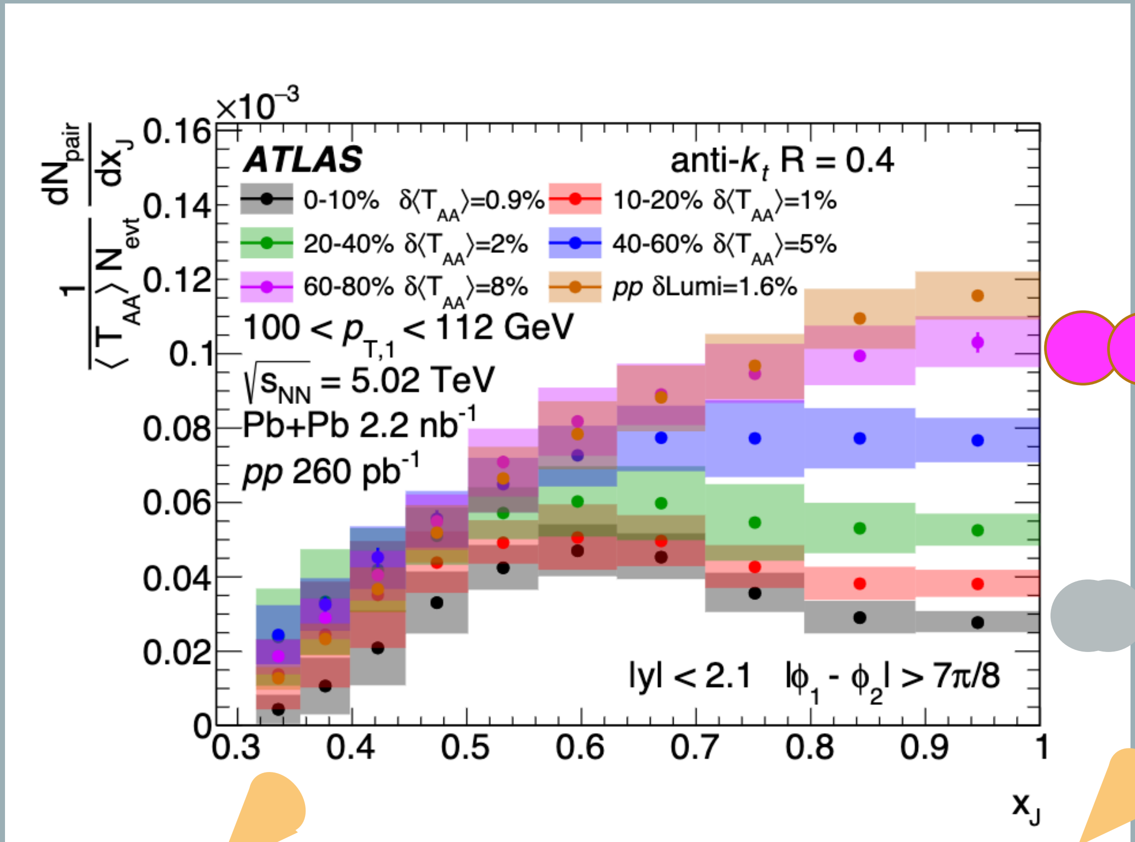
- ❑ Provide information on degree of thermalization in medium
- ❑ Large v_2 of charged particles in Pb-Pb collisions → measurement described by viscous hydrodynamics model considering low viscosity

Hard probes of the QGP: di-jet imbalance

- Jet energy loss depends on the path traveled in the medium

ATLAS Collaboration, arXiv:2205.00682





Suppression of balanced dijets

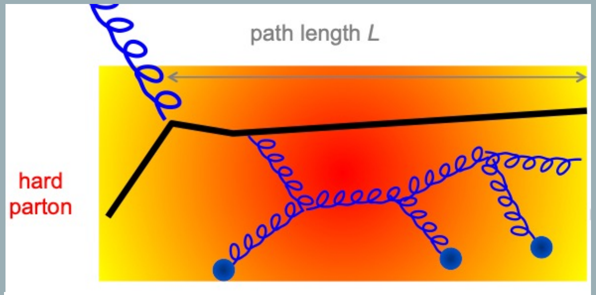
Dijet asymmetry due to different path lenght and energy loss

Shift of the peak in central collisions : most probable configuration for dijet is highly imbalanced in p_T

Hard probes of the QGP : heavy quark energy loss

- Interaction of heavy quarks with the QCD medium constituents, eloss via:
  - Elastic collisions with the medium constituent (→ collisional energy loss)
  - Gluon radiation (radiative energy loss)

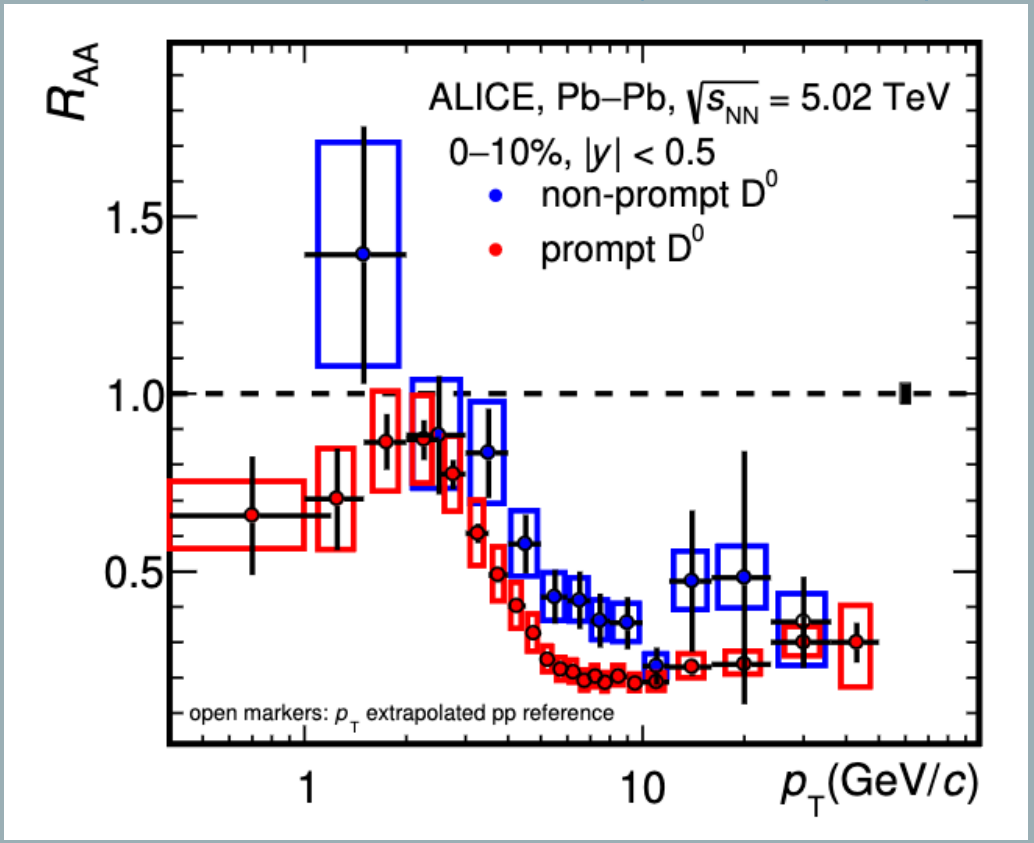
ALICE Collaboration, JHEP 12 (2022) 126



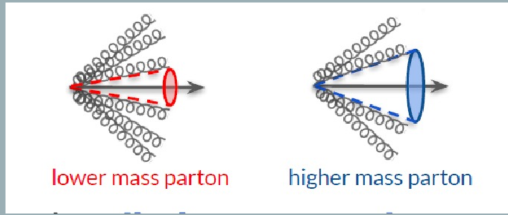
$$\langle \Delta E \rangle \propto \alpha_s C_R \hat{q} L^2$$

Cassimir factor, transport coefficient

Depends on path length, colour charge and mass of partons
Related to the medium properties (transport coefficients)



- Dead cone effect : gluon radiation suppressed for $\theta \leq m_q/E_q$



→ Smaller radiative energy loss expected for beauty quarks w.r.t charm quark : $\Delta E_c > \Delta E_b$ → $R_{AA}(D) < R_{AA}(B)$

- R_{AA} (c→D^0) < R_{AA} (b→D^0) at intermediate p_T → consistent with in-medium energy loss mass dependence

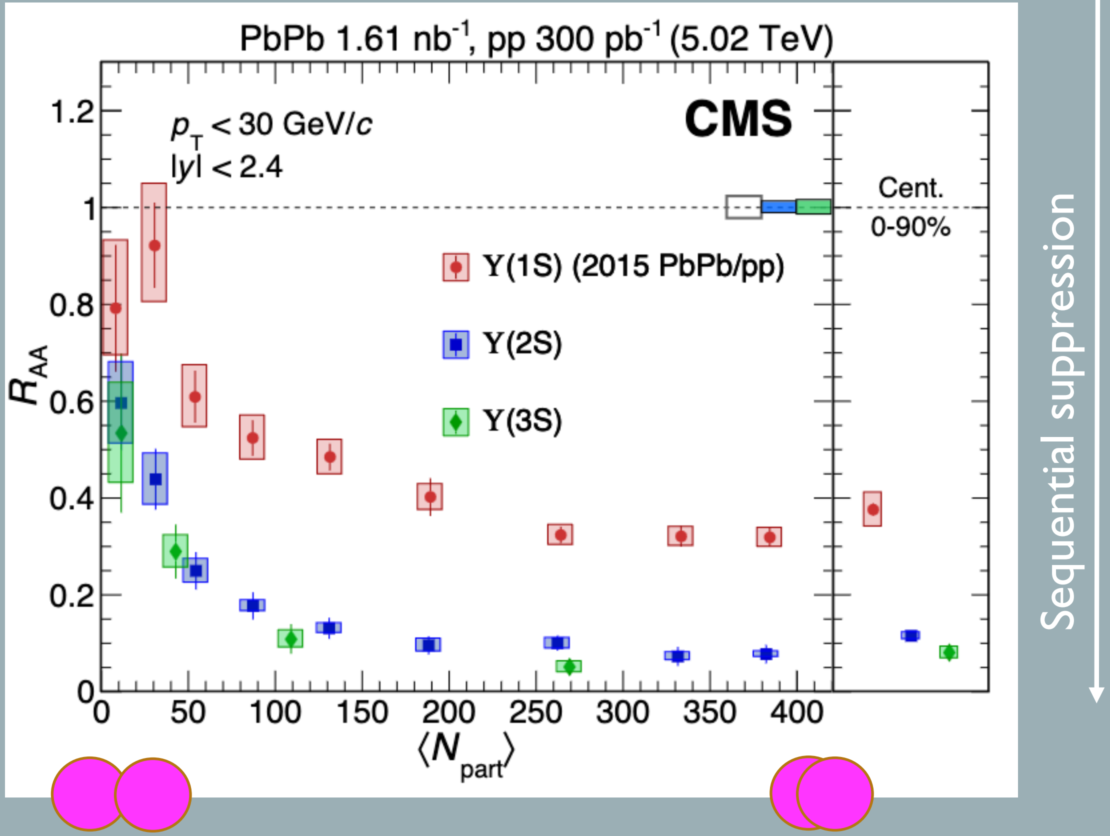
Hard probes of the QGP : bottomonium suppression

- ❑ Quarkonium dissociated due to the high density of colour charges in medium ($T > T_D$)
- ❑ Sequential suppression due to the different binding energies of the quarkonium states
- ❑ Quarkonium dissociation as a QGP thermometer

CMS Collaboration, arXiv:2303.17026

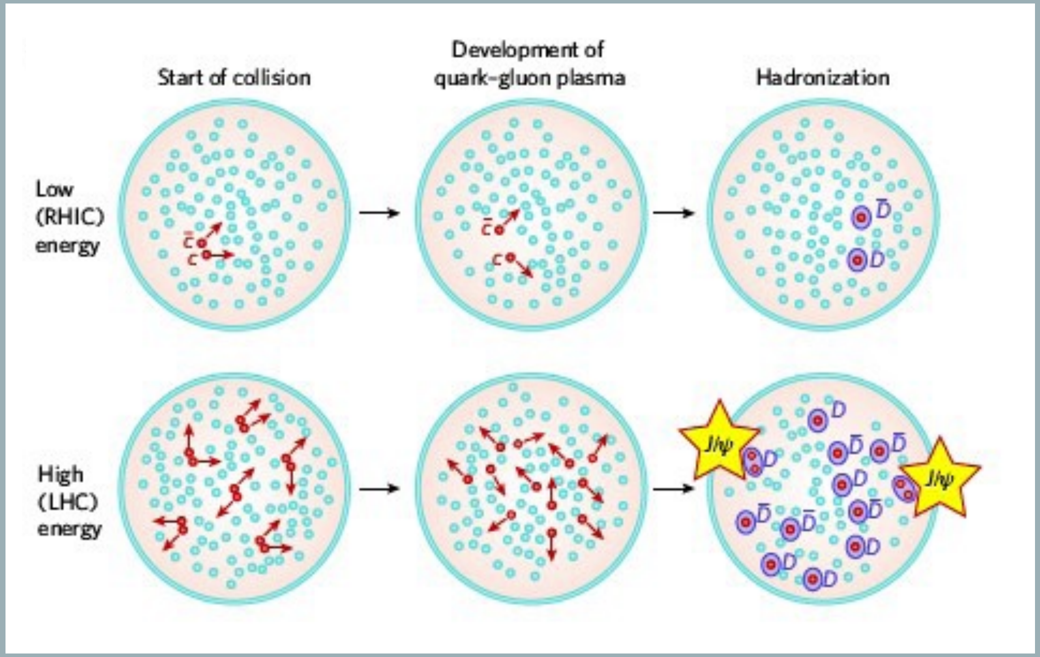
Bound state	χ_c	Ψ'	J/ψ	Υ(2S)	Υ(1S)
T_D/T_c	≤ 1	≤ 1	1.2	1.2	2
ΔE [GeV]	0.32	0.05	0.64	0.53	1.10

Conservative upper limits on the dissociation temperature obtained from a full QCD calculation, N. Brambilla et al., Eur. Phys. J. C71:1534,2011

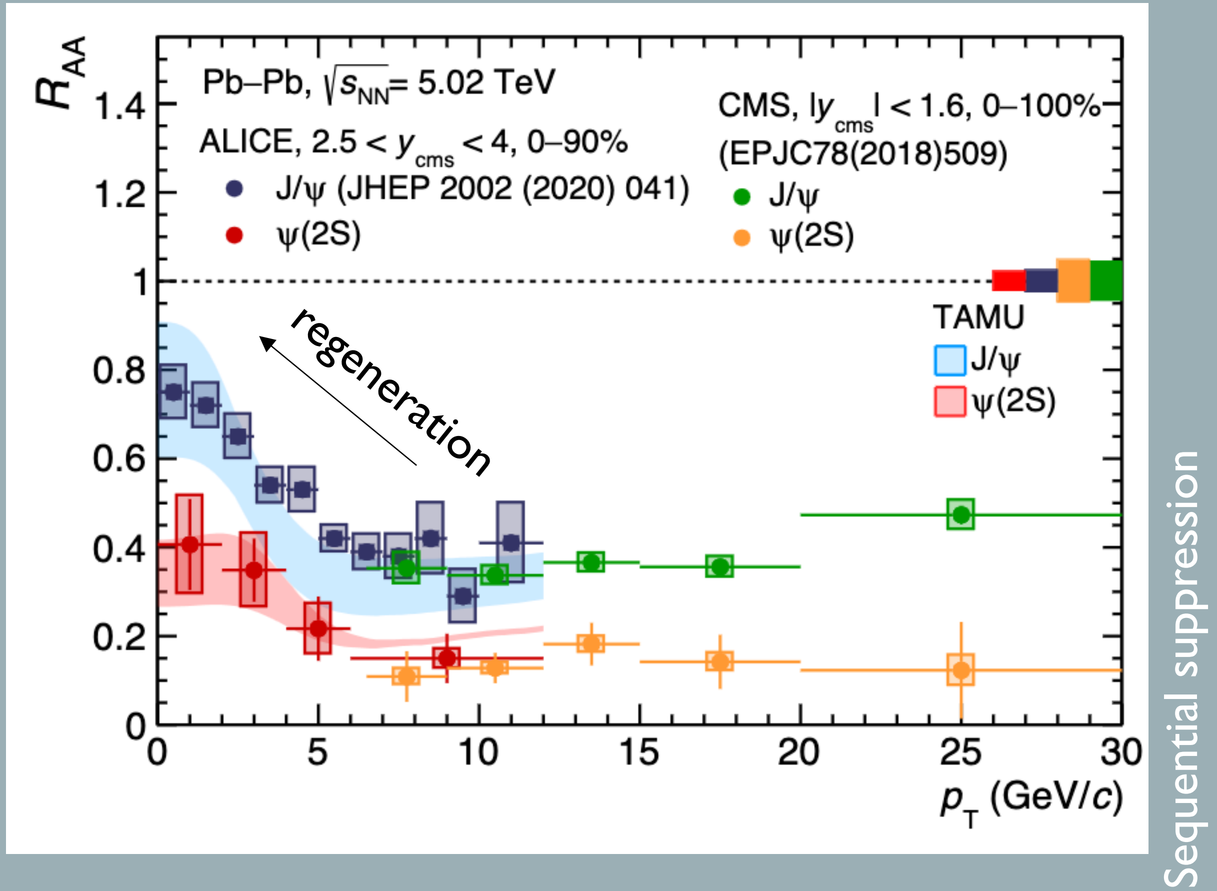


- ❑ First observation of Υ(3S) in PbPb collisions
- ❑ Indication of sequential suppression of Υ(3S), Υ(2S) and Υ(1S)

Hard probes of the QGP : charmonium suppression and regeneration

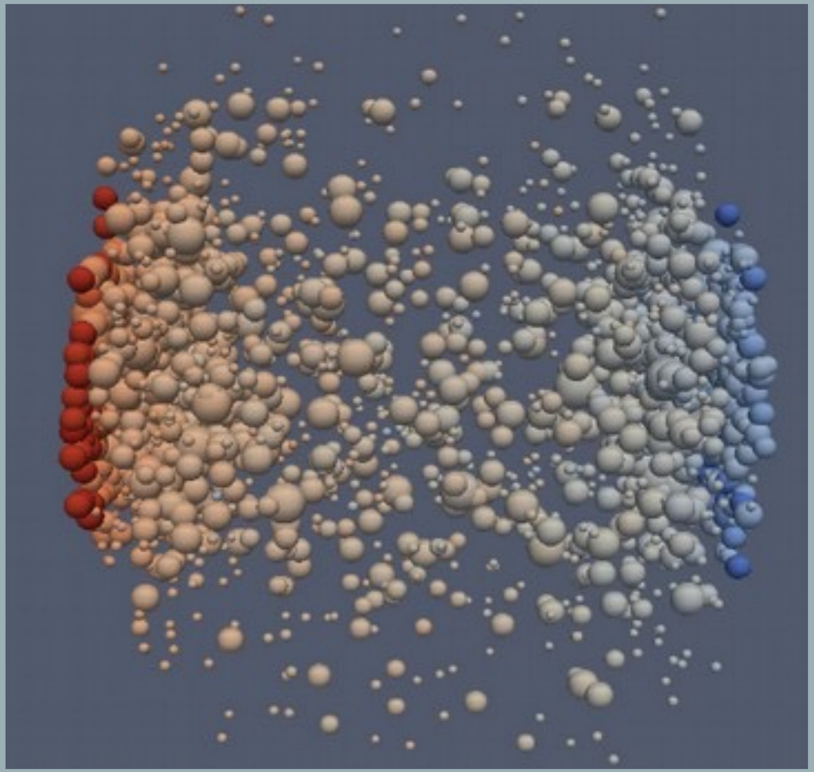


ALICE Collaboration, arXiv:2210.08893
CMS Collaboration, EPJC78 (2018) 509

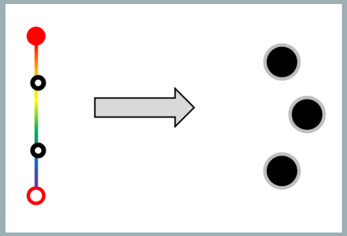


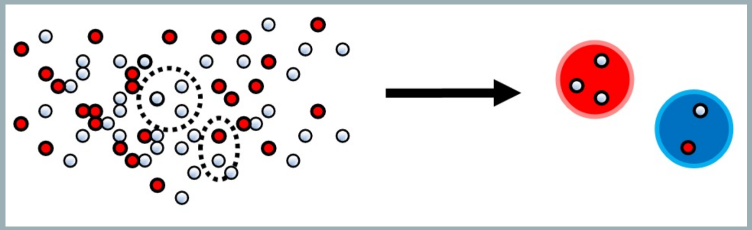
- Large $c\bar{c}$ cross section at LHC energies
- Increased probability for c and $\bar{c}$ (re)combination in medium or at phase boundary → enhancement of charmonia, evidence for thermalization of charm quarks
- First indication for ψ(2S) recombination → can occur later in the evolution of the system, because of its larger size w.r.t J/ ψ

Hadronization



- How does the hadron form?
  - Fragmentation versus coalescence/recombination





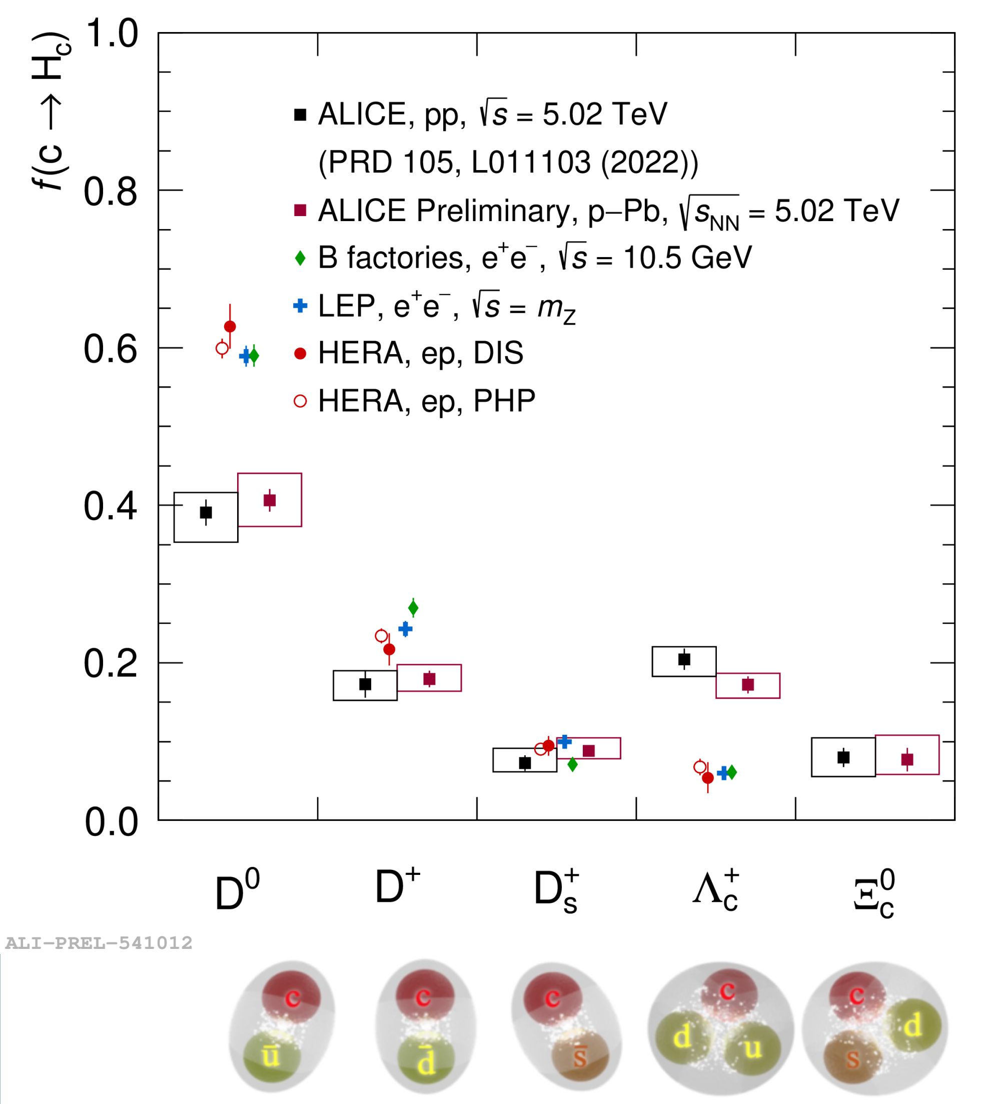
- When does the hadron form?
  - Inside the deconfined medium versus in vacuum

→ Requires a good understanding of hadronisation in vacuum with studies in pp collisions

Charm fragmentation fraction in pp/pPb

- Charm fragmentation fractions measured including charm baryons (Λ_c, Ξ_c) at the LHC in pp and pPb

- Charm fragmentation fractions in pp/pPb at the LHC differ significantly from those of e^+e^- and ep collisions → non-universality of charm fragmentation fraction among colliding systems. Constrains for hadronization models

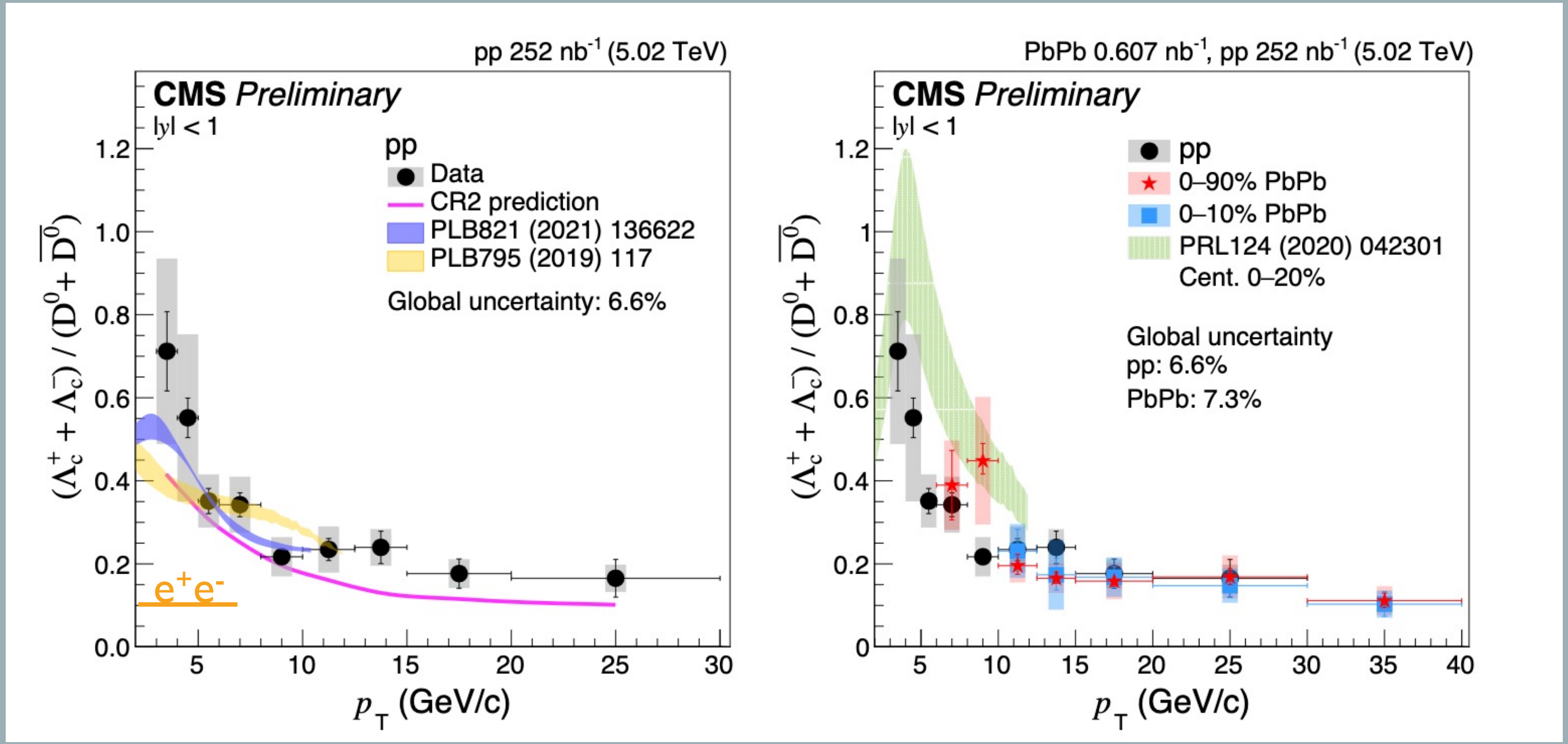


Charm baryon to meson ratio in pp and Pb-Pb

CMS Collaboration, CMS-PAS-HIN-21-004

- Λ_c/D_0 ratio in pp collisions described by several models:
  - PYTHIA8 with color reconnection
  - Model with fragmentation + coalescence process
  - Statistical hadronization approach (incl Λ_c from decay of excited charm baryon states)

- Λ_c/D_0 ratio in PbPb collisions compatible with pp collisions for p_T > 10 GeV/c
  - No significant contribution from coalescence in this p_T region

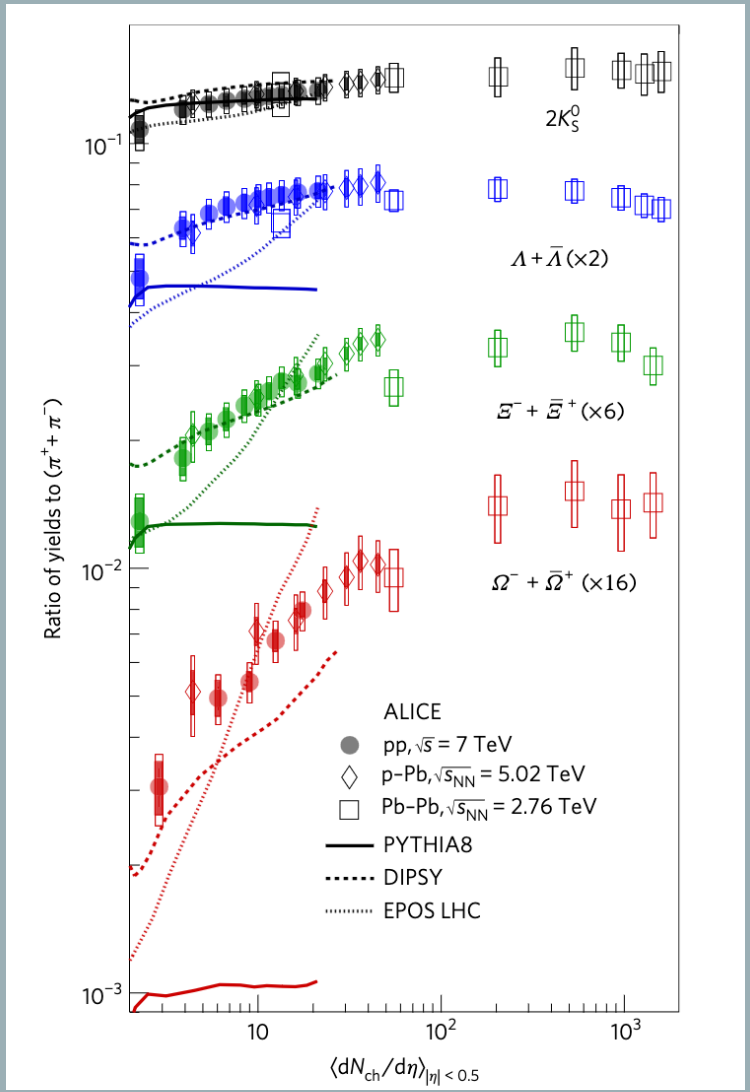


Surprising small systems at the LHC

ALICE Collaboration, Nat. Phys. 13, 535-539 (2017)

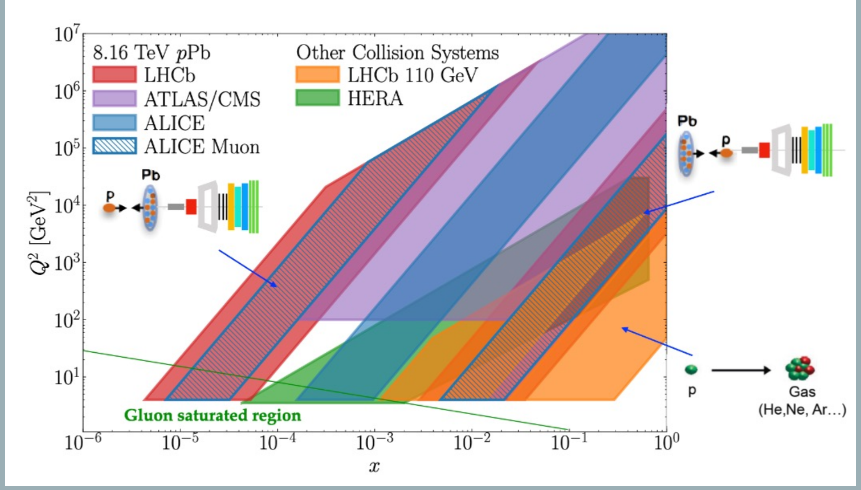
- Several effects usually tipically attributed to the formation of a QGP also observed in high multiplicity pp/p-Pb collisions
  - Near side long range angular correlations, anisotropic flow → sign of collectivity in high multiplicity pp collisions
  - Strangeness enhancement
  - Suppression of ψ(2S) in backward pPb collisions
  - …

- Progressive onset of a QGP medium already starting to develop in small systems?

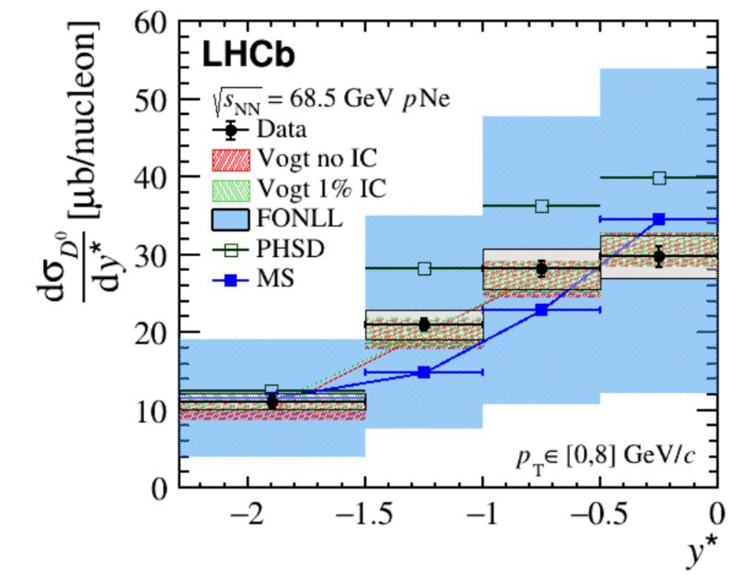


Heavy ion physics in fixed-target collisions at the LHC

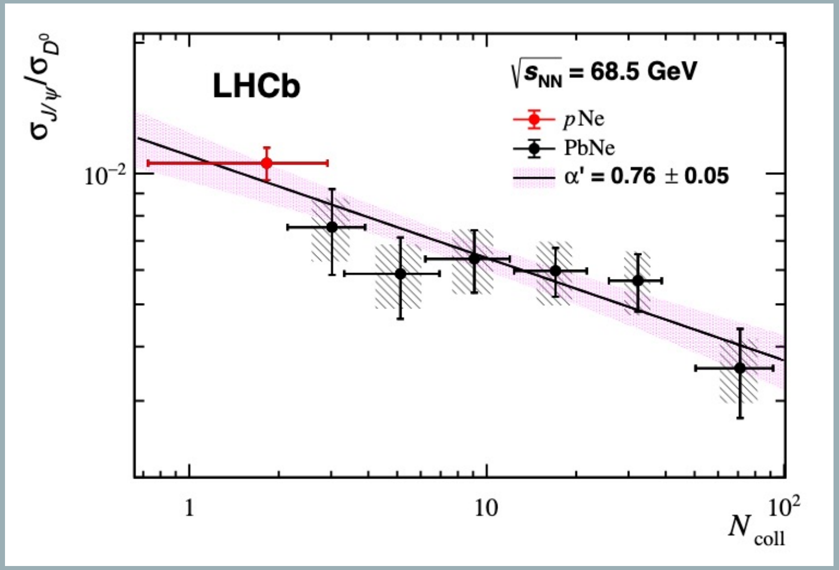
- Unique capabilility of LHCb to perform fixed target collisions at the LHC, with the SMOG system (gas injection)
- Unique access to high Bjorken-x and low Q^2 (nPDFs, intrinsic charm content of the proton…)
- Energy range in between SPS and RHIC top energies for HI (look for onset of deconfinement via rapidity scan)
- Large variety of nuclear target (constrain to nPDFs, nuclear absorption…)
- Benefiting for high luminosity LHC beam and dense target (revisit low energy measurements with rare probes, high multiplicity reach in small systems)



LHCb Collaboration, arXiv:1810.07907



LHCb Collaboration, arXiv:2211.11652



Conclusion

- Heavy ions collisions at LHC are interesting tools to :
  - Characterize the initial state of the collision (nuclear PDFs, saturation)
  - Study macroscopic and microscopic properties of the QGP
  - Study hadronization mechanisms
  - And can also bring contributions for other fields of physics (astroparticle, neutrino, BSM)

- QCD measurements in all systems are interesting in themselves and mandatory to get a complete understanding of AA collisions

- The understanding of QGP-like effects in high multiplicity small systems is currently a hot topic in the field

- Looking forward to the new LHC Run 3 Pb-Pb run end of this year!

Back up

Table prepared by the WG small systems from the HL/E-LHC working group
See the yellow report, in preparation, for references (140)

Observable of effect	Pb-Pb	pPb (high mult)	pp (high mult)
SOFT Probes			
low p_T spectra ("radial flow")	yes	yes	yes
Intermediate p_T ("recombination")	yes	yes	yes
HBT radii	R_{out}/R_{side}~1	$R_{out}/R_{side} \leq 1$	$R_{out}/R_{side} \leq 1$
Azimuthal anisotropy (v_n) (2 prt. correlations)	v_1-v_7	v_1-v_5	v_2-v_4
Characteristic mass dependence	v_2-v_5	v_2-v_3	v_2
Higher order cumulants	"4~6~8 " + higher harmonics	"4~6~8 " + higher harmonics	"4~6 "+ higher harmonics
Event by event v_n distributions	n=2-4	Not measured	Not measured
Event plane and v_n correlations	yes	yes	yes
HARD Probes			
Direct photons at low-p_T	yes	Not measured	yes
Jet Quenching	yes	Not observed	Not observed
Quarkonia	J/Ψ regeneration / Υ supression	suppressed	Not measured
Heavy-flavor anisotropy	yes	yes	Not measured