High-Energy QCD Matter Theory

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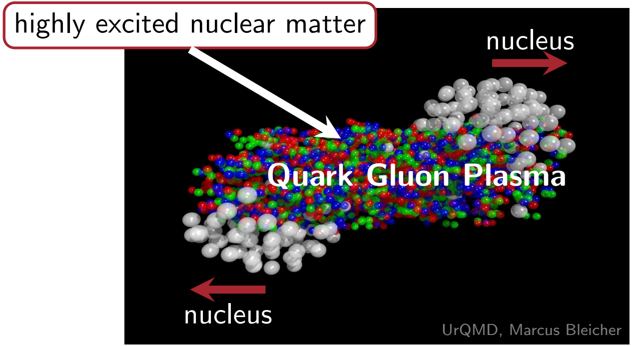
High-energy nuclear collisions — a new direction to study QCD

High-energy physics concentrate higher energy in smaller and smaller volume.
Turn to a different direction and study new phenomena *"by distributing high energy or high nucleon density over a relatively large volume."* – T.D. Lee, 1974



$T \sim 1$ GeV

~ 10 fm

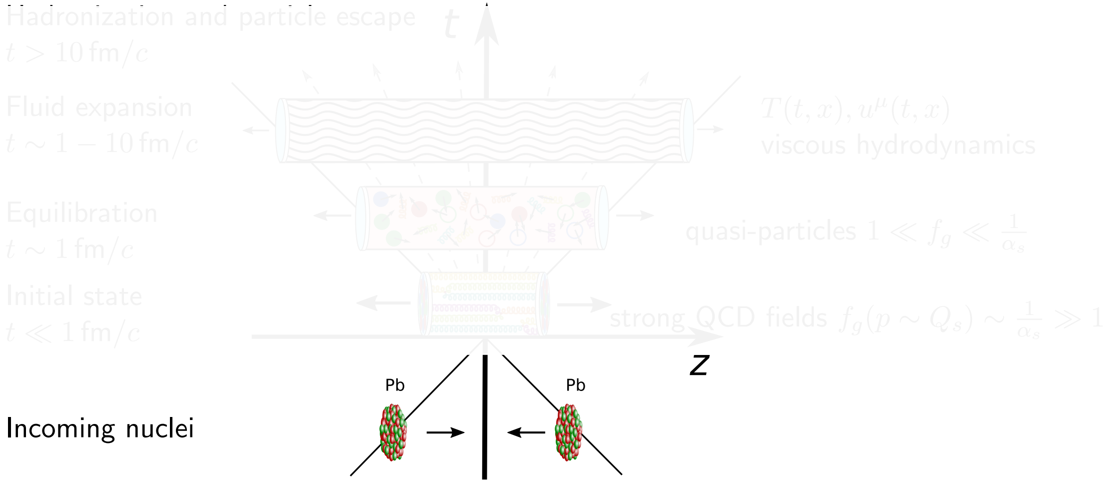
Unique chance to study the many-body dynamics of non-abelian gauge theory:
thermalisation, transport properties, phase diagram, hadron production,. . .

QCD thermalisation in high-energy nuclear collisions

Thermalisation in QCD at weak couplings $\alpha_s \ll 1$

Berges, Heller, AM, Venugopalan (2020) [1]

At the high-energy limit can use first-principles effective descriptions of QCD.



Formation of thermalised QCD matter is a natural limit of high-energy collisions.

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Hadronization and particle escape
$t > 10\,\mathrm{fm}/c$

Fluid expansion
$t \sim 1 - 10\,\mathrm{fm}/c$

$T(t,x), u^\mu(t,x)$
viscous hydrodynamics

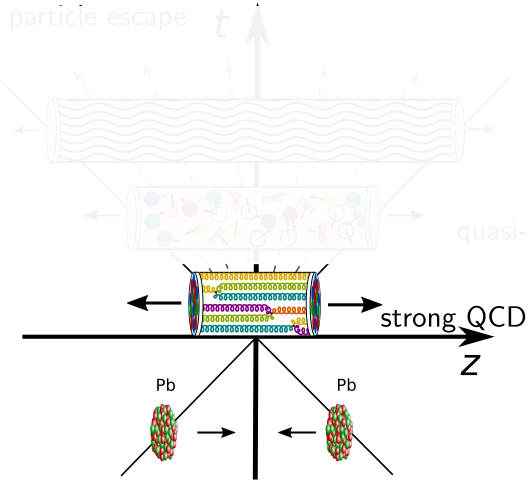
Equilibration
$t \sim 1\,\mathrm{fm}/c$

quasi-particles $1 \ll f_g \ll \frac{1}{\alpha_s}$

Initial state
$t \ll 1\,\mathrm{fm}/c$

strong QCD fields $f_g(p \sim Q_s) \sim \frac{1}{\alpha_s} \gg 1$

Incoming nuclei



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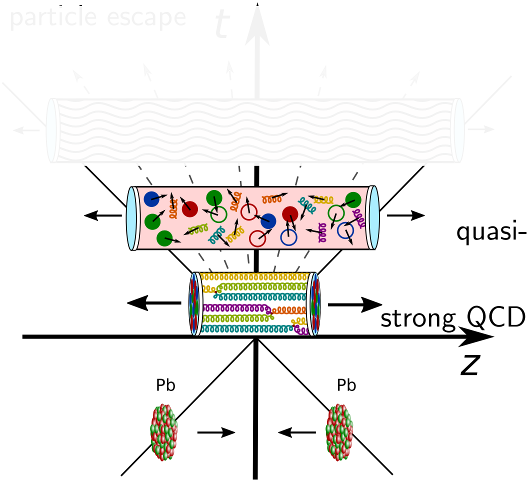

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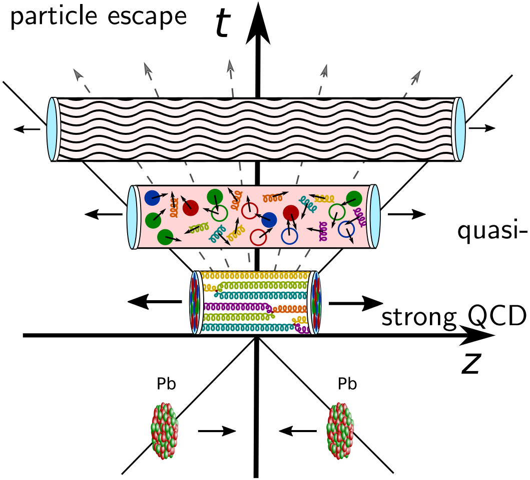

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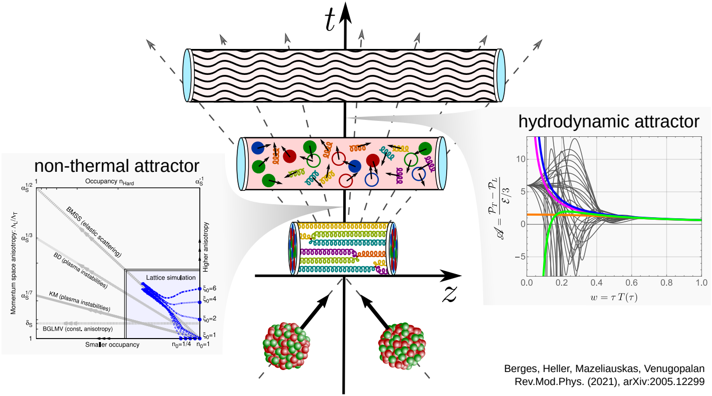
Formation of thermalised QCD matter is a natural limit of high-energy collisions.

Non-thermal and hydrodynamic attractors in QCD thermalisation

- Remarkable simplification of nonequilibrium QCD evolution.
- *Emergence of fluid dynamics behaviour at timescales of* $\tau \sim 1/T \sim 1\,\mathrm{fm}/c$.
- Supported by QCD kinetic theory, QFTs with gravity duals.
- Rethinking applicability of hydrodynamics.



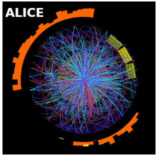
Berges, Heller, Mazeliauskas, Venugopalan
Rev.Mod.Phys. (2021), arXiv:2005.12299

See also reviews by Florkowski, Heller and Spalinksi (2017)[2], Romatschke and Romatschke (2017) [3]

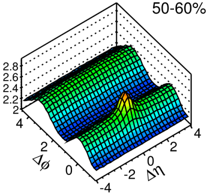
Collective behaviour of QCD matter

Multiparticle collective flows

Produced particles show significant angular modulations v_n



$$\frac{dN}{d\phi} = \frac{N}{2\pi}\left(1 + 2v_2\cos(2\phi) + 2v_3\cos(3\phi)\ldots\right)$$



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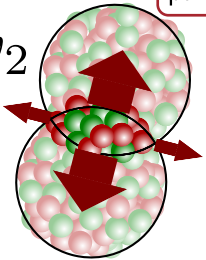
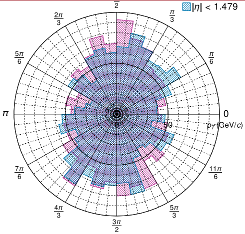
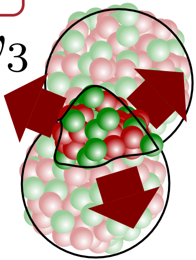
particle momentum deposition

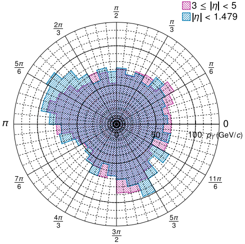
v_2





v_3





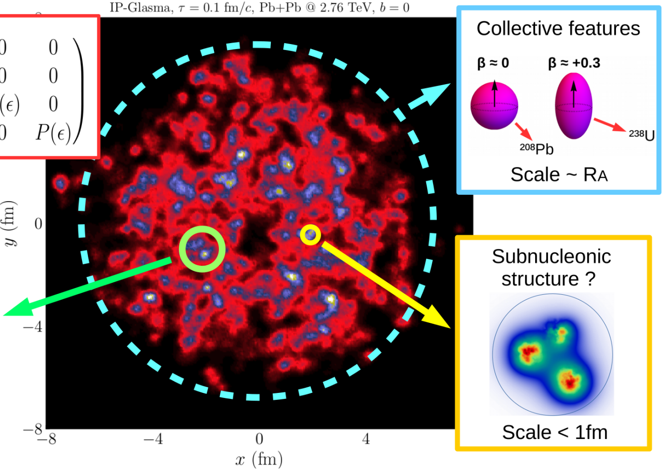
CMS Detector Performance Plots [4]

Collective particle flow is explained by pressure gradient driven QGP expansion.

Initial conditions in nuclear collisions: sources of fluctuations

Structure of nuclei across length scales → primordial anisotropy → observed anisotropy

$$T^{\mu\nu}(\tau_0) \approx \begin{pmatrix} \epsilon & 0 & 0 & 0 \\ 0 & P(\epsilon) & 0 & 0 \\ 0 & 0 & P(\epsilon) & 0 \\ 0 & 0 & 0 & P(\epsilon) \end{pmatrix}$$



from Giacalone, SEWM 2021 [indico]

Experimental sensitivity allows to test both large and small scale nuclear structure.

Hydrodynamic modelling of nuclear collisions in a nutshell

initial conditions → viscous hydrodynamics → hadron cascade

Numerically solve 2D or 3D relativistic fluid equations of motion

$$\partial_\mu T^{\mu\nu} = 0, \quad T^{\mu\nu} = e u^\mu u^\nu + (p + \underbrace{\Pi}_{-\zeta \partial_\mu u^\mu})\Delta^{\mu\nu} + \underbrace{\pi^{\mu\nu}}_{-\eta \partial^{(\mu} u^{\nu)}} + \ldots .$$

$p\,(e)$ – equation of state, obtained from lattice QCD.

η, ζ – shear and bulk viscosity – fundamental transport properties of QGP.

- difficult to extract from lattice QCD, because of sign problem.
- perturbatively calculable only at very small couplings.

  NLO computations by Ghiglieri, Moore and Teaney (2018) [5, 6]

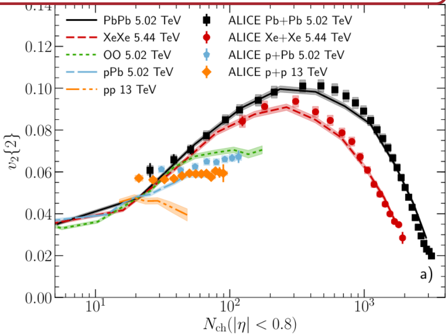
- excellent experimental data $\Longrightarrow$ can extract $\eta/s, \zeta/s$ and higher transport coefficients from particle spectra and collective flow data.

For QGP $\eta/s \sim 0.1$ (in natural units)— smallest of all known fluids!

Multi-parameter model fits to multi-observable multi-system data

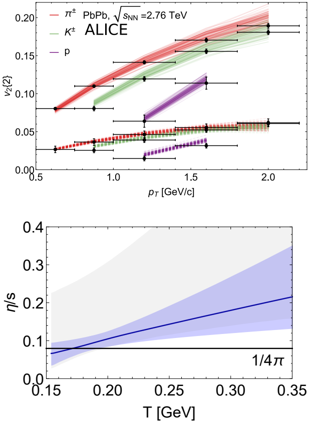
Many comprehensive analyses: Novak, Novak, Pratt, Vredevoogd, Coleman-Smith, Wolpert (2013) [7], Niemi, Eskola, Paatelainen (2015) [8]
Bernhard, Moreland, Bass, Liu, Heinz (2016) [9],Devetak, Dubla, Floerchinger, Grossi, Massiocchi, AM, Selyuzhenkov (2019) [10],. . .

simultaneous multi-system predictions



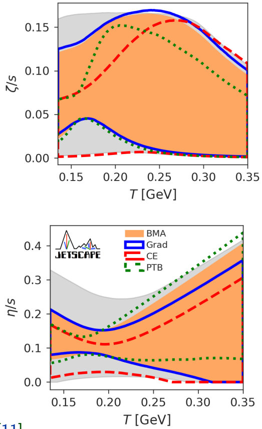
MUSIC: Schenke, Shen and Tribedy (2020) [12]

Bayesian $\eta/s, \zeta/s$ analysis



TRAJECTUM: Nijs, van der Schee, Gürsoy, Snellings (2020) [11]

model averaging



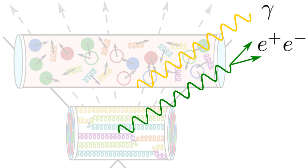
JETSCAPE (2020) [13, 14]

Current focus—increasing precision, reducing systematics, accessing new properties.

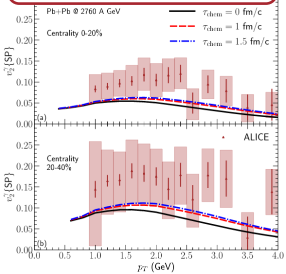
Multi-messenger (QCD+QED) study of high-energy nuclear matter

Photon and dilepton production is sensitive to

- Chemical equilibration
- QGP properties and temperature
- Early-time expansion

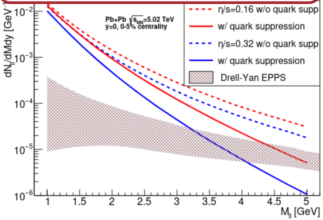


photon v_2 and τ_{chem}



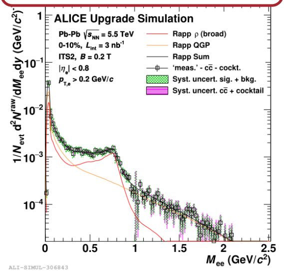
Gale, Paquet, Schenke, Shen (2021) [15]

dilepton spectra and η/s



Coquet, Du, Ollitrault, Schlichting, Winn (2021) [16]

dileptons in runs 3+4



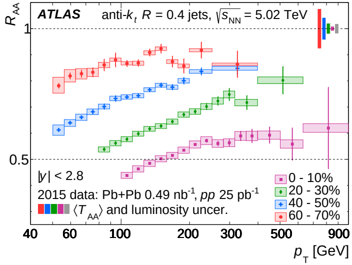
Yellow report (2018) [17]

Penetrating electromagnetic probes give unique window into QCD thermalisation.

High momentum transfer processes in QCD matter

High p_T parton energy loss — jet quenching

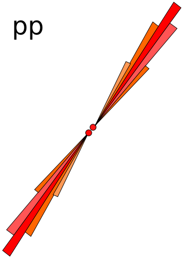
ATLAS (2018) [18]

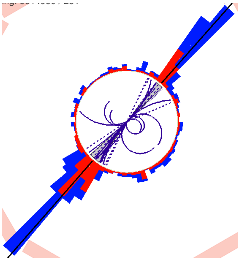


High-energy jets are suppressed in nuclear collisions compared to proton-proton

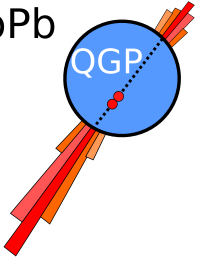
$$R_{AA} = \frac{dN^j_{AA}/dp_T}{N_{\text{coll}} dN^j_{pp}/dp_T} < 1$$

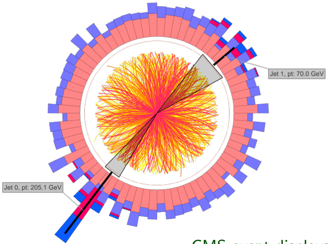
pp





PbPb





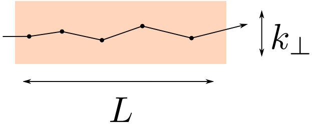
CMS event displays

Jet quenching is explained by energy loss in strongly interacting plasma.

Medium induced gluon radiation

Baier, Dokshitzer, Mueller, Peigne, Schiff (1996) [19], Zakharov (1996) [20] and others

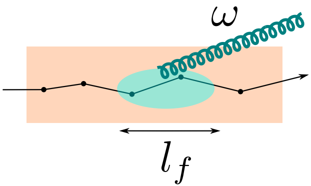
Partons suffers multiple soft scatterings in the medium $\Longrightarrow$ momentum diffusion



$$\langle k_\perp^2 \rangle = \hat{q} L$$

$\hat{q}$ – quenching parameter, property of the medium.

Finite emission formation time and interference $\Longrightarrow$ LPM suppression



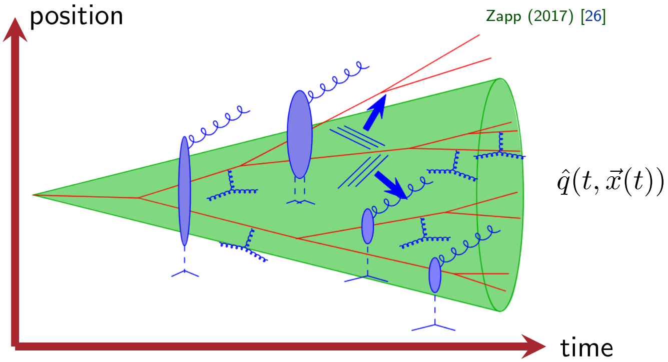
$$l_f \propto \frac{\omega}{k_\perp^2} \Longrightarrow l_f \propto \sqrt{\frac{\omega}{\hat{q}}}$$

Gluon radiation induces energy loss of parent parton.

For progress on double emission see Arnold, Gorda, Iqbal (2020) [21], improved opacity expansion Barata, Mehtar-Tani (2020)[22] full resummation Andres, Apolinário, Dominguez (2020) [23], non-perturbative broadening Moore, Schlichting, Schlusser, Soudi (2021) [24], vacuum and in-medium factorization Caucal, Iancu, Soyez (2020) [25], . . .

Jets in high-energy QCD matter

Different from vacuum – need to know the space-time structure of parton shower.



There are ongoing community efforts to improve all aspects of the modelling:

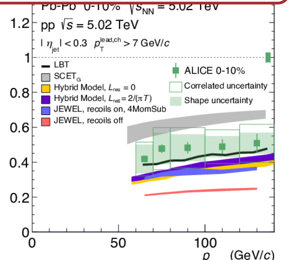
- Jet-medium interactions, e.g., onset of jet-quenching
- Background medium evolution, e.g., hydrodynamics tuned to soft observables.

Casalderrey-Solana, Hulcher, Milhano, Pablos, Rajagopal (2018) [27], Andres, Néstor, Niemi, Paatelainen, Salgado (2019) [28]
Zigic, Ilic, Djordjevic, Djordjevic (2019) [29], Huss, Kurkela, AM, Paatelainen, van der Schee, Wiedemann (2020) [30], JETSCAPE (2021) [31]

Energy loss observables

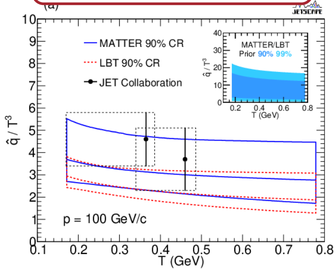
- Inclusive jet, hadron suppression – nuclear modification factor R_{AA}.
- Coincidence measurements, e.g., Z or γ tagged hadron or jet spectra I_{AA}.

Jet suppresion in PbPb



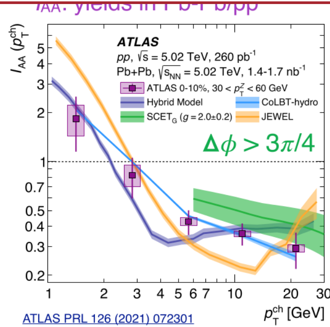
ALICE 2019 [32]

Bayesian $\hat{q}$ extraction



JETSCAPE (2021) [31]

Z-tagged hadron suppression



ATLAS PRL 126 (2021) 072301

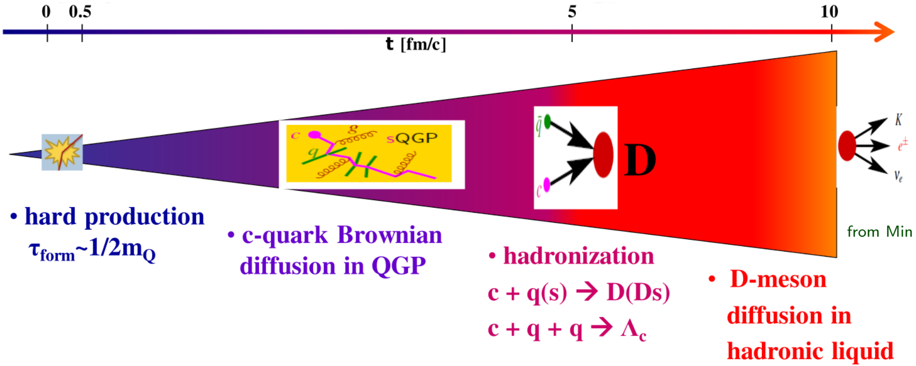
Broad agreement among different models for basic observables $\Longrightarrow$ focus on controlling model systematics and more differential observables

Heavy quarks in QCD matter

Heavy quarks evolution in QGP

Charm and beauty quarks make excellent probes of QGP evolution

- Produced perturbatively ($m_Q \gg T$) and at early times $t_f \sim (2m_Q)^{-1}$
- Interacts strongly with QGP during evolution: D_s – diffusion coefficient.
- Quark flavour preserved – can be tagged.



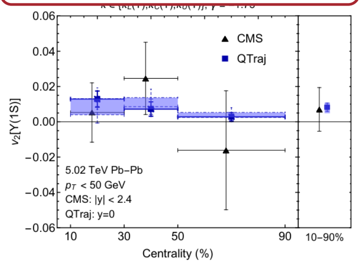
from Min He [indico]

Focus on understanding heavy quark co-flow with the medium.

Hidden and open heavy quark dynamics

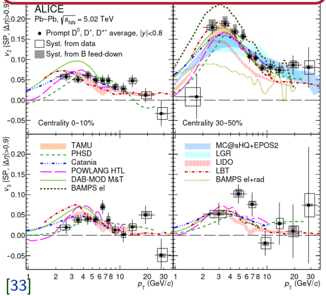
- Bound state $q\bar{q}$ dissociation and recombination – open quantum system.
  Lindblad equation for density matrix ρ Brambilla, Escobedo, Strickland, Vairo, Griend, Weber (2021) [33]
  Coupled Boltzmann Transport Equations, Yao, Ke, Xu, Bass, Müller (2020) [34]
- Open heavy quark evolution – several approaches: Langevin diffusion, Boltzmann transport, energy loss, etc. see Heavy-Flavor Transport in QCD Matter [indico]

Elliptic flow of botomonium



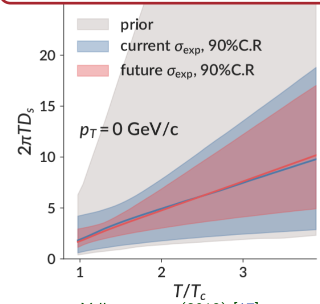
Brambilla, Escobedo, Strickland, Vairo, Griend, Weber (2021) [33]

Elliptic flow of D mesons



ALICE (2020) [35]

Diffusion coefficient run 3+4



Yellow report (2018) [17]

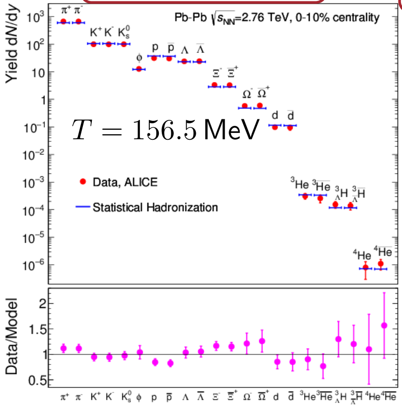
Future runs will extend low p_T reach and pin down bottom quark flow $\Longrightarrow$ better contraints on heavy quark transport and thermalisation in QCD matter.

Charm thermalisation in Statistical Hadronization Model (SHM)

Observed *thermal particle yields* with $T \approx 156.5\,\text{MeV}$ from pions to ^{4}He.

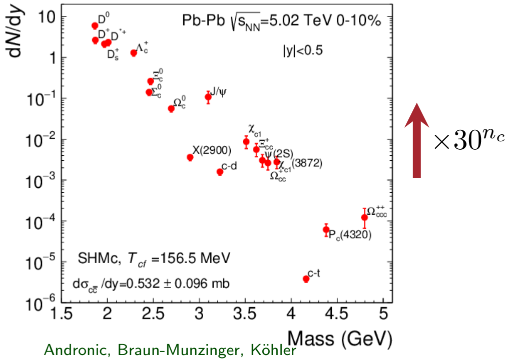
Multicharm hadron production is greatly enhanced, e.g., $\sim 2.7 \cdot 10^4$ times for Ω_{ccc}

thermal fit to data



Andronic, Braun-Munzinger, Redlich, Stachel (2018) [36]

thermal predictions for charmed hadrons



Andronic, Braun-Munzinger, Köhler

AM, Redlich, Stachel, Vislavicius (2021) [36]

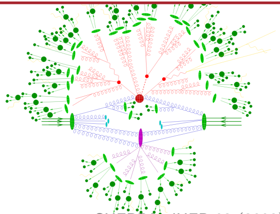
ALICE 3 is ideally suited to measure multicharm baryon hierarchy.

see EOI [37].

QCD matter in pp and pPb and other small systems

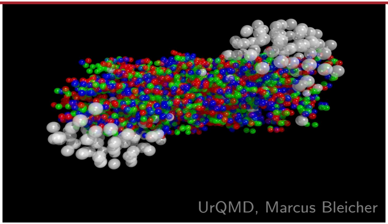
Two successful paradigms of hadron collisions

free-streaming final state in pp



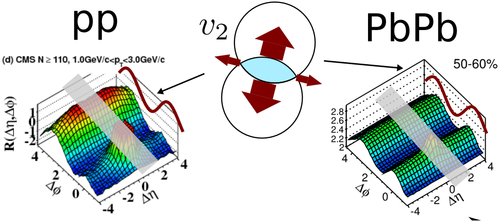
SHERPA, JHEP 02 (2009)

abundant parton re-scatterings in AA



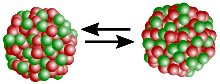
Arguably the first discovery at LHC:
long-range 2-particle correlations in pp
CMS (2010) [38]

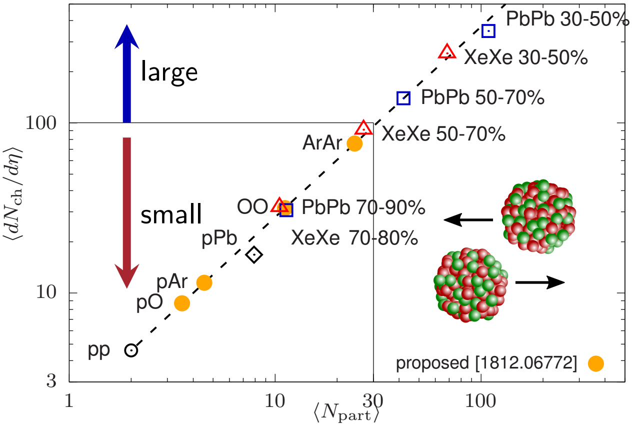
Now supported by *multi-particle correlations* and *strangeness enhancement* in pp and pPb.

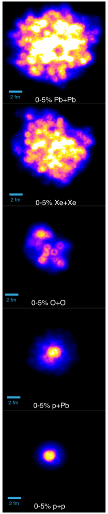


Multiplicity as a measure of the system size

LHC: pp, pPb, XeXe, PbPb (OO, ArAr)





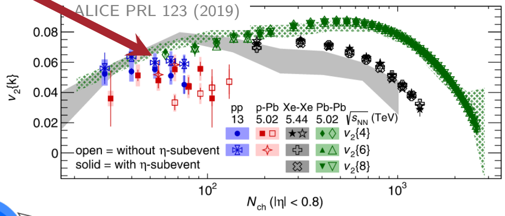


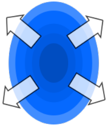
Do all small systems exhibit the same collective phenomena?

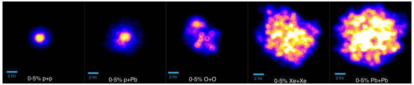
Challenges to partonic rescattering paradigm in small systems

Different system size dependence of parton rescattering for soft and hard probes.

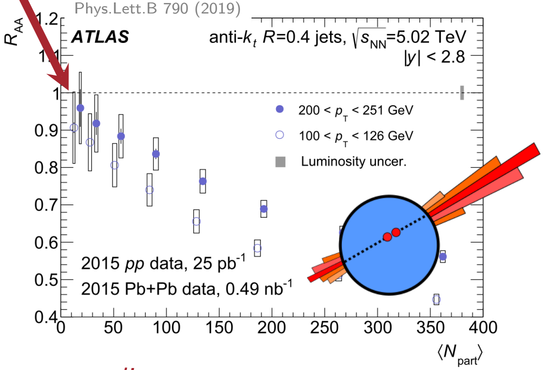
collective $p_T \sim 1$ GeV particle flow







no suppression of $p_T \sim 100$ GeV jets in peripheral PbPb or pPb



Absence of jet quenching contradicts the current paradigm:
collective flow $\Longleftrightarrow$ high-p_T energy loss.

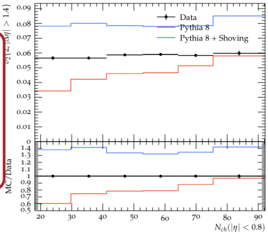
What is the microscopic origin of collectivity in small systems?

Competing approaches in small systems:

- From small to large: extending HEP event generators
- From large to small: pushing macroscopic descriptions to small size limits
- Intermediate descriptions: QCD kinetic theory in small systems.

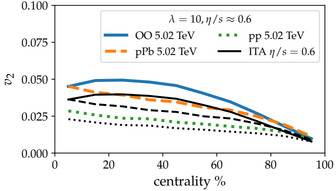
string fragmentation

elliptic flow



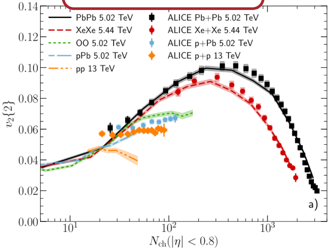
Bierlich, Chakraborty, Gustafson, Lönnblad (2020) [39]

kinetic theory



Kurkela, AM, Törnkvist (2021) [40]

hydrodynamics



Schenke, Shen, Prithwish (2020) [12]

Collectivity in small systems $\Longrightarrow$ window to microscopic dynamics of QCD.

Light-ions at the LHC

Light-ions (e.g. O, Ar, Kr) Yellow report (2018) [17]:

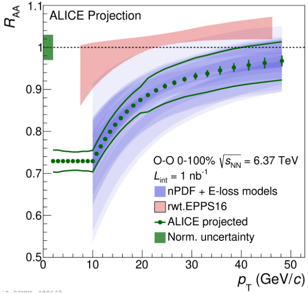
- High achievable luminosity.
- Short oxygen run planned in LHC Run 3.
- pO: strong interest from cosmic ray physics.
- OO comparable to pPb, but better geometry control.
- Many physics opportunities see OppOatLHC [indico]

Experimental projections and theory calculations show measurable energy loss signal in $10\,\mathrm{GeV} < p_T < 50\,\mathrm{GeV}$.

Huss, Kurkela, AM, Paatelainen, van der Schee, Wiedemann (2020) [41]

Opportunity to discover jet quenching in small systems.

Brewer, AM, van der Schee (2021) [42]



ALICE (2021) [43]

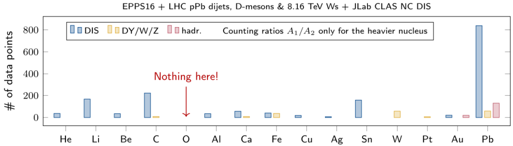
Nuclear parton distribution functions from pA

nPDFs are crucial ingredients in perturbative of QCD matter probes:

- jets, high-p_T hadrons
- heavy quark production

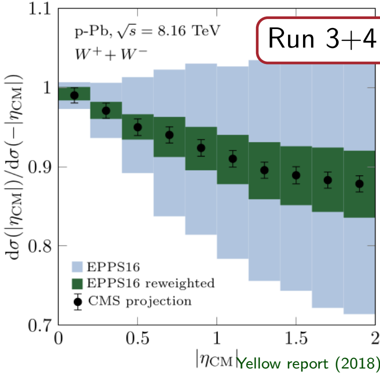
Precision determination of hard probes modification requires precise null baselines.

Global nPDF fits to nuclear data



Paakkinen [indico]

Run 3+4 projection



Yellow report (2018) [17]

High statistics $pPb \Rightarrow$ smaller nPDF uncertainties, $pO \Rightarrow$ mass number dependence.

Summary

Experiments with nuclear collisions have revealed many new phenomena of high-energy QCD matter.

- Detailed theoretical picture of QCD thermalisation.
- Successful extraction of QGP properties from precise data.
- Strong high-p_T and heavy quark interaction with QCD matter.

Outlook:

- LHC run 3 and 4 will deliver high-statics pp, pPb and PbPb data
  access to rare observables, e.g., Z-tagging, bottom quark flow
- Advanced models and statistical analysis of extensive datasets
  the field is ready for precision era
- Small system scan: high-multiplicity pp, peripheral PbPb, pPb and light-ions.
  time for a unified picture of collectivity in all hadronic collisions

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