High-Density QCD with Proton and Ion Beams

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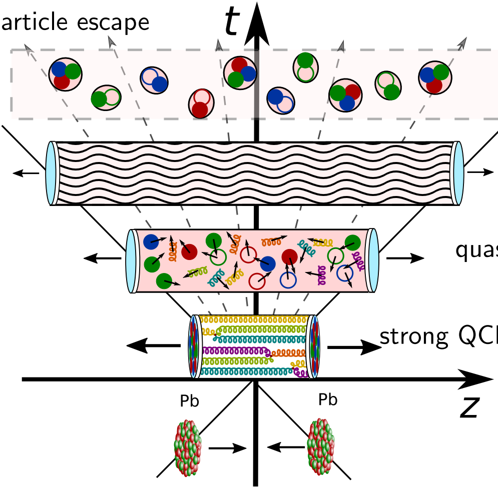
Recap of the first lecture

Different stages of heavy-ion collisions (high-energy/weak-coupling picture)



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

Hadron gas

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

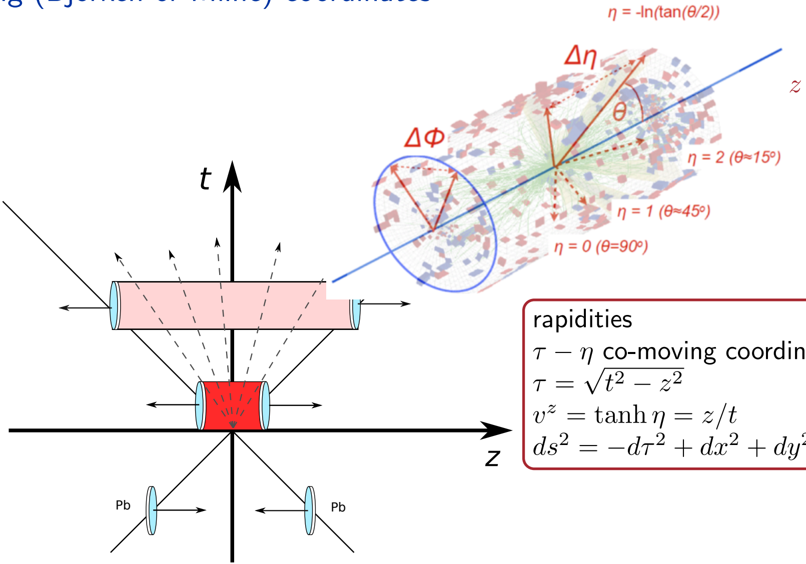
strong QCD fields $f_g(p \sim Q_s) \sim \frac{1}{\alpha_s} \gg 1$

Incoming nuclei

- HI collisions create high-density deconfined state of matter $\Longrightarrow$ Quark-Gluon Plasma.
- Rapid QCD thermalisation $\Longrightarrow$ applicability of fluid dynamic picture

Relativistic viscous hydrodynamics

Co-moving (Bjorken or Milne) coordinates



rapidities

$\tau - \eta$ co-moving coordinates

$\tau = \sqrt{t^2 - z^2}$

$v^z = \tanh \eta = z/t$

$ds^2 = -d\tau^2 + dx^2 + dy^2 + \tau^2 d\eta^2$

We will discuss mid-rapidity region $\eta \approx 0$.

Ideal hydrodynamics

- Energy-momentum tensor for ideal fluid at rest:

$$T^{\mu\nu}_{\text{rest}} = \begin{pmatrix} e & 0 & 0 & 0 \\ 0 & p & 0 & 0 \\ 0 & 0 & p & 0 \\ 0 & 0 & 0 & p \end{pmatrix} \quad \Longrightarrow \quad \Lambda^{\mu}_{\rho}(u)\Lambda^{\nu}_{\sigma}(u)T^{\rho\sigma}_{\text{rest}} = eu^{\mu}u^{\nu} + p(g^{\mu\nu} + u^{\mu}u^{\nu})$$

- e is relativistic energy density, equation of state $p(e)$, u^{μ} fluid 4-velocity, $u^{\mu}u_{\mu} = -1$.
- The energy-momentum conservation is written

$$\partial_{\mu}T^{\mu\nu} = 0$$

- Ideal equations of motion in a fluid rest-frame

$$\partial_t e = -(e+p)\vec{\nabla}\vec{v}$$

$$\partial_t \vec{v} = -\frac{\vec{\nabla}p}{e+p}$$

- *Change in energy is driven by expansion* $\theta = \partial_{\mu}u^{\mu} = \vec{\nabla}\vec{v}$*!*
- *Change in velocity driven by gradients in pressure* $\vec{\nabla}p$*!*

Bjorken solution

- Let's find a hydro solution in Bjorken coordinates
- Fluid velocity $u^\mu = (1,0,0,0)$, $\theta = \partial_\mu u^\mu = \frac{1}{\tau}$
- Energy density evolution

$$\frac{\partial e}{\partial \tau} = -\frac{e+p}{\tau}.$$

- For pressureless (free-streaming) expansion $p = 0$

$$e = e_0 \left(\frac{\tau_0}{\tau}\right).$$

- For ideal (conformal) QGP $p = \frac{1}{3}e$

$$e = e_0 \left(\frac{\tau_0}{\tau}\right)^{4/3}.$$

Faster decrease due to longitudinal work

$$ds^2 = -d\tau^2 + dx^2 + dy^2 + \tau^2 d\eta^2.$$

$$v^z = \frac{z}{t} = \tanh \eta.$$

$$\tau = t \quad \text{at} \quad \eta = 0.$$

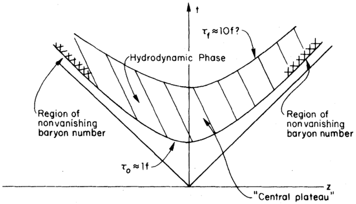


FIG. 3. Space-time diagram of longitudinal evolution of the quark-gluon plasma.

Bjorken (1982) [1]

Relativistic viscous hydrodynamics

- Gradient corrections to the energy momentum tensor

$$T^{\mu\nu}_{1st} = T^{\mu\nu}_{\text{ideal}} + \Pi(g^{\mu\nu} + u^\mu u^\nu) + \pi^{\mu\nu}$$

- Viscous corrections: allowed gradients in fluid field

$$\text{shear tensor} \quad \pi^{\mu\nu} = -\eta \partial^{(\mu} u^{\nu)}$$

$$\text{bulk pressure} \quad \Pi = -\zeta \partial_\mu u^\mu$$

- *η – shear viscosity, ζ bulk viscosity*, positive quantities, properties of the medium.
- Effect of viscous corrections for 1D boost-invariant expansion ($e + p = sT$)

$$\frac{\partial e}{\partial \tau} = -\frac{e + p - \frac{4}{3}\frac{\eta}{\tau} - \frac{\zeta}{\tau}}{\tau} = -\frac{e+p}{\tau}\left(1 - \frac{4}{3}\frac{\eta/s}{T\tau} - \frac{\zeta/s}{T\tau}\right).$$

  Energy drops slower in viscous fluid (entropy production).
- At high temperature QCD ($g \ll 1$): $\eta/s \approx 5.11/(g^4 \log \frac{2.4}{g})$
- For infinitely strongly coupled supersymmetric theories: $\eta/s = \frac{1}{4\pi} \approx 0.08$

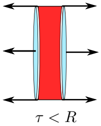
Viscosity per entropy $\eta/s, \zeta/s$ are key transport properties of QGP.

Beyond conventional gradient expansion: hydrodynamic attractors

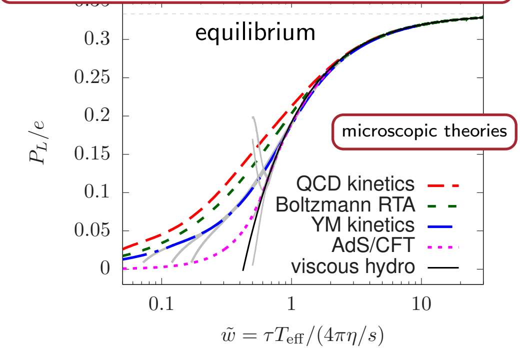
Pressure anisotropy collapse to a *hydrodynamic attractor*

Heller, Janik, Witaszczyk (2011)

$$\frac{\tau\partial_\tau e}{e} = -\frac{4}{3} + \underbrace{\frac{16}{9}\frac{\eta/s}{\tau T}}_{\text{1st gradient}} \ldots = -1 - \frac{P_L}{e}\left[\tilde{w} = \frac{\tau T}{4\pi\eta/s}\right]$$



pressure anisotropy in longitudinal expansion



microscopic theories

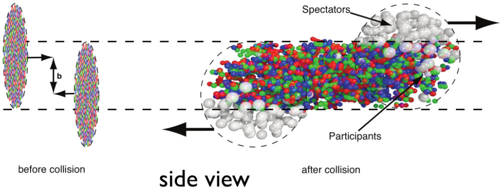
Giacalone, AM, Schlichting, (2019)

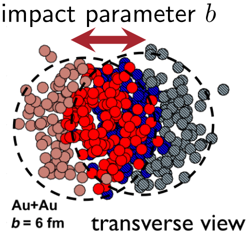
Hydrodynamic attractor $\Longrightarrow$ *the universality and simplification of non-equilibrium evolution.*

Experimental signals of QGP formation: collective flow

Transverse geometry and centrality

see Miller, Reygers, Sanders and Steinberg (2007) [2]

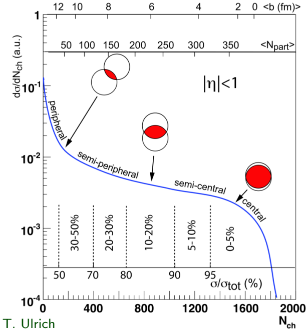




Not all nucleons participate in a collision.

- Monte-Carlo Glauber model of nucleons inside nuclei
- More colliding nucleons N_{part} if b is small.
- Larger $N_{\text{part}} \implies$ more produced particles.
- Order events in multiplicity (centrality) classes
- 0-5% centrality $\implies$ most head on collisions.

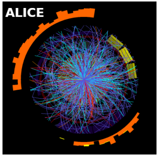
Strong correlation between initial geometry and particle multiplicity $\implies$ select events with different geometry/size.



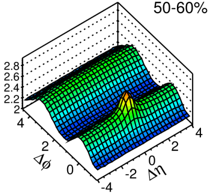
T. Ulrich

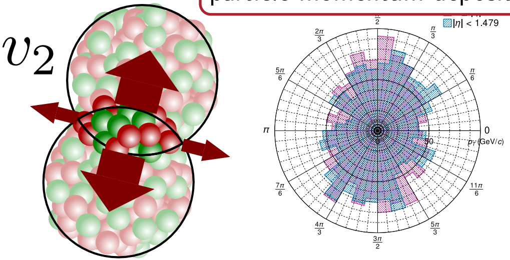
Multiparticle collective flows

Produced particles show significant angular modulations v_n in the azimuthal angle ϕ

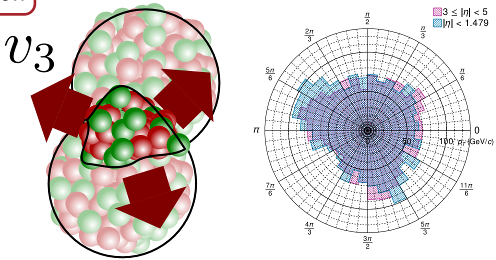


$$\frac{dN}{d\phi} = \frac{N}{2\pi}\left(1 + 2v_2\cos(2\phi) + 2v_3\cos(3\phi)\ldots\right).$$





particle momentum deposition



CMS Detector Performance Plots [3]

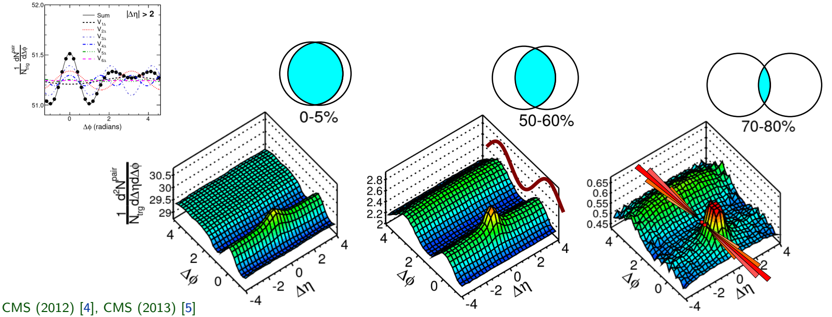
Collective particle flow is explained by pressure gradient driven transverse QGP expansion.

Two-particle correlations — near-side and away-side ridges

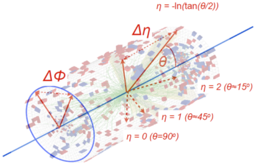
Practical way of quantifying collective flows – two-particle correlation function

$$\left\langle \frac{dN}{d\phi_1}\frac{dN}{d\phi_2} \right\rangle \propto 1 + 2\sum_n v_n^2 \cos(n\Delta\phi).$$

Also generalizes to multi-particle correlations (8-particle v_n's measured).



CMS (2012) [4], CMS (2013) [5]



elliptic+triangular flow

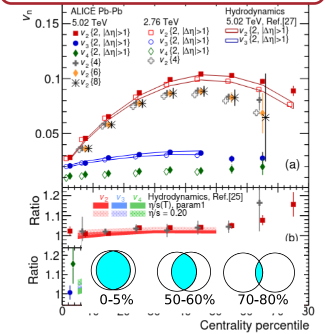
strong elliptic flow

dominance of jet fragmentation

Collective flow correlations are long-ranged $|\Delta\eta| > 1$ – must be sourced by initial state.

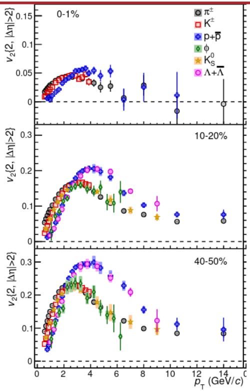
Centrality and momentum dependence of flow coefficients

centrality dependence of v_n

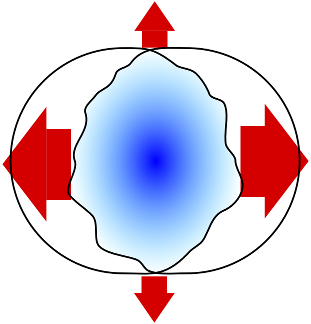


ALICE (2016) [6]

p_T and particle species dependence



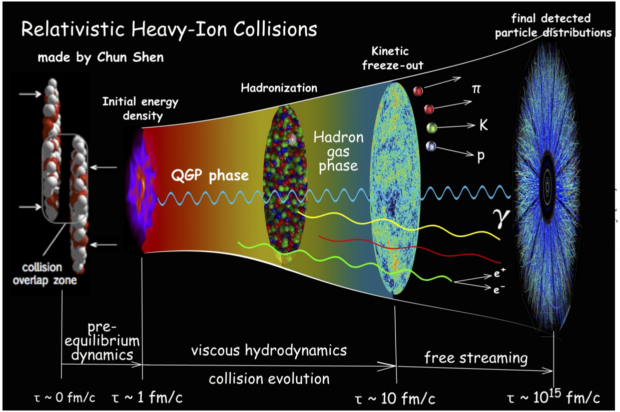
ALICE (2018) [7]

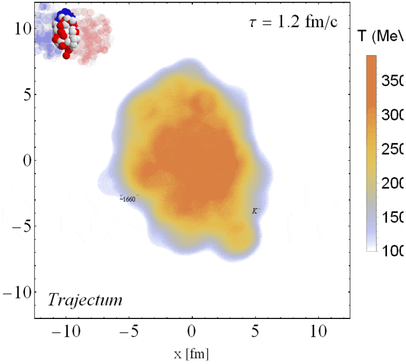


- Strong elliptic flow in mid-central events $\Longrightarrow$ overlap geometry
- v_3, v_4 with weak centrality dependence $\Longrightarrow$ fluctuations in geometry
- Mass ordering of $v_n(p_T)$ $\Longrightarrow$ radial flow velocity $p_T \sim m v_T$

Standard hydrodynamic model of little Big Bang

- Multi-stage 2D/3D viscous hydrodynamic codes are widely available.
- Initial conditions and transport properties have to be constrained by data.



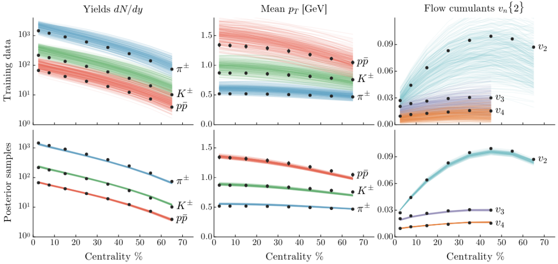


QGP properties from Bayesian parameter estimation

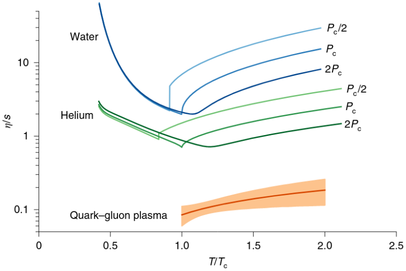
- Thousands of sample points in parameter space × thousands of events
- Construct the posterior distributions for model parameters

$$\underbrace{P(\text{parm}_i|\text{data})}_{\text{posterior}} \sim \underbrace{P(\text{data}|\text{parm}_i)}_{\text{likelihood}}\,\underbrace{P(\text{parm}_i)}_{\text{prior}}.$$

$$P(\text{data}|\text{parm}_i) \sim \exp\left[-\Delta_i(\Sigma^{-1})_{ij}\Delta_j\right],\ \Delta = \text{data} - \text{model}$$



Bernhard et al. (2016) [8]

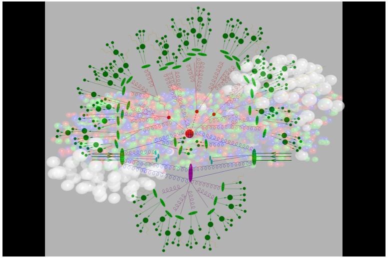


Bernhard, Moreland, Bass (2019) [9]

Extracted physical parameters of QGP, e.g. $\eta/s \sim 0.08 - 0.2$ – smallest of all fluids.

Experimental signals of QGP formation: modification of hard probes

Hard Standard Model processes embedded in nuclear environment



Self-generated probes of QGP

- Examples: high-p_T jets or hadrons, heavy quarks, W, Z, γ
- Characteristic timescale $\Delta t \sim 1/Q \ll 1\text{fm}$ for $Q \gg T \sim 1\,\text{GeV}$
- Hard probe are produced before the formation of the medium.

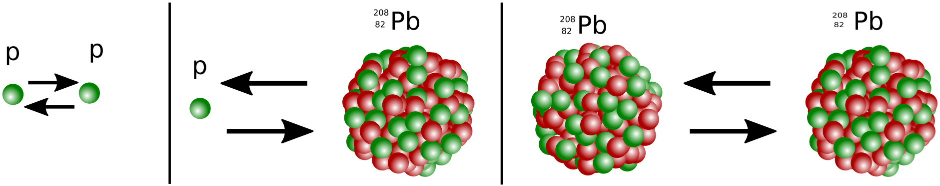
We use the modification of hard probes to understand high-density QCD.

QCD factorisation in nuclear collisions

In the absence of medium, hard cross-sections can be calculated order by order:

$$\sigma\left(P_1, P_2\right) = \sum_{i,j} \int_0^1 dx_1 dx_2 \underbrace{f_i(x_1, Q^2) f_j(x_2, Q^2)}_{\text{long distance}} \underbrace{\hat{\sigma}_{ij}\left(x_1 P_1, x_2 P_2, Q^2\right)}_{\text{short distance}} .$$

- $\hat{\sigma}_{ij}$ – hard partonic cross-section, universal, systematically improvable
- $f_i\left(x, Q^2\right)$ – parton distribution functions (PDFs), process-independent, non-perturbative, extracted by global fits to various cross-sections.



- *Nuclear PDFs are different from proton PDF — need separate extraction.*

Nuclear modification factor R_{AA}

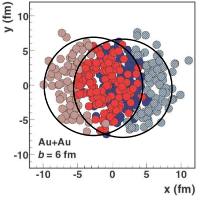
- Quantify nuclear effects by normalizing hard spectra in heavy-ions (AA) to pp

$$R_{\mathsf{AA}} = \frac{dN_{AA}/dp_T}{\langle N_{\mathsf{coll}}\rangle\, dN_{pp}/dp_T}.$$

- $\langle N_{\mathsf{coll}}\rangle$ – number of binary nucleon-nucleon collisions. Hard partonic luminosity $\propto N_{\mathsf{coll}}$

$N_{\text{part}} = 4 \;\; N_{\text{coll}} = 3$ $\qquad$ $N_{\text{part}} = 4 \;\; N_{\text{coll}} = 4$

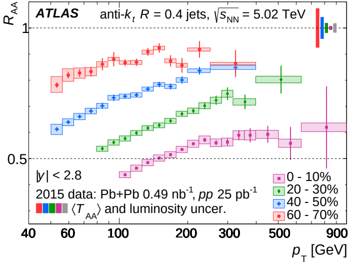
$\langle N_{\mathsf{coll}}\rangle$ estimated by Monte-Carlo Glauber models.



- In the absence of medium effects expect $R_{\mathsf{AA}} \approx 1$ (up to nPDF and isospin corrections).

High-p_T parton energy loss — jet quenching

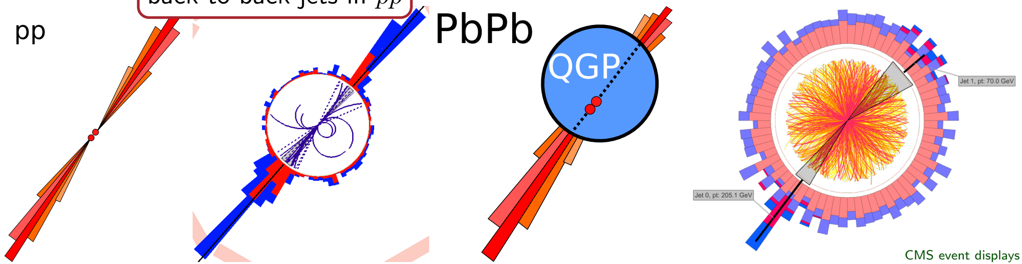
ATLAS (2018) [12]



Jet spectrum is suppressed in nuclear collisions compared to proton-proton collisions

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

back-to-back jets in pp



CMS event displays

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

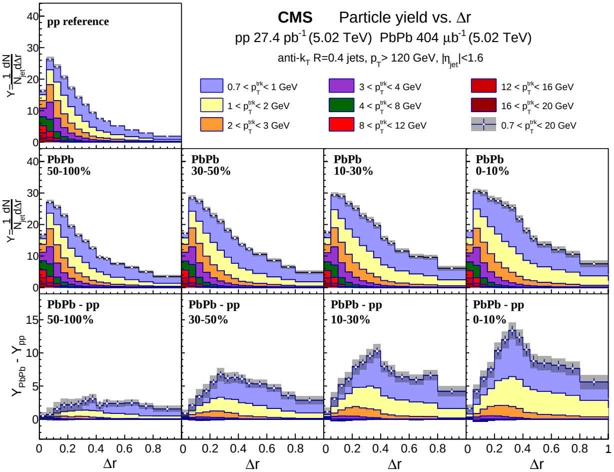
Soft particle production around the jet cone

Compare soft ($p_T < 5\,\mathrm{GeV}$) particles around $p_T > 120\,\mathrm{GeV}$ jet

pp

PbPb

PbPb-*pp*



distance from jet axis

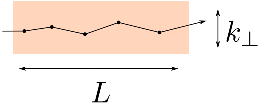
Energy loss ⟹ enhanced soft particle production at large angles from jet axis.

Medium induced gluon radiation

(BDMPS-Z) Baier, Dokshitzer, Mueller, Peigne, Schiff (1996) [14], Zakharov (1996) [15] and others

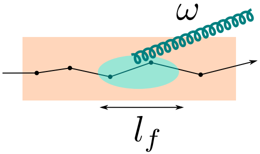
Energy loss at strong coupling: infall of a classical string in a black hole, see Casalderrey-Solana, Liu, Mateos, Rajagopal, Wiedemann (2014) [13]

Multiple soft scatterings of a hard parton $\Longrightarrow$ transverse momentum diffusion



$\langle k_\perp^2 \rangle = \hat{q} L$ $\quad \hat{q} \propto T^3$ – *quenching parameter (medium property).*

Medium induced gluon radiation – interference of multiple scatterings (LPM suppression)



$$l_f \propto \frac{\omega}{k_\perp^2} \Longrightarrow \underbrace{l_f \propto \sqrt{\frac{\omega}{\hat{q}}}}_{\text{gluon formation time}} < L \Longrightarrow \omega < \omega_c \sim \hat{q} L^2$$

Gluon radiation causes the energy loss of parent parton.

$$\omega \frac{dI}{d\omega dz} \approx \underbrace{\frac{L}{l_f}}_{\#\text{ incoh. scat. centers}} \times \underbrace{\frac{\alpha_s}{L}}_{\text{scatterings probability/distance}} = \alpha_s \sqrt{\frac{\hat{q}}{\omega}}.$$

Medium modified spectra for a single parton (a quark or a gluon)

Energy loss for a parton moving distance L in a medium

$$\epsilon = \int_0^L dz \int_0^{\omega_c} d\omega \omega \frac{dI}{d\omega dz} = \int_0^L dz \int_0^{\omega_c} d\omega \alpha_s \sqrt{\frac{\hat{q}}{\omega}} \propto \alpha_S \hat{q} L^2.$$

Sensitivity to the path-length L.

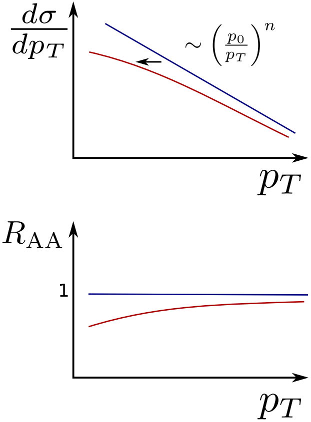
Steeply falling vacuum spectra

$$\frac{d\sigma_{\text{vac}}}{dp_T} = \sigma_0 \left(\frac{p_0}{p_T}\right)^n, \quad n \approx 5 - 7$$

For average $\langle \epsilon \rangle$ energy loss, the modification is

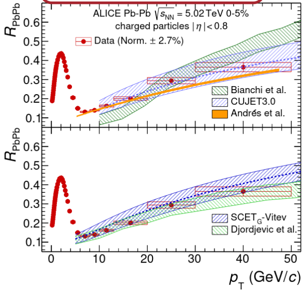
$$R_{\text{AA}} \propto \exp\left(-\frac{n \langle \epsilon \rangle}{p_T}\right)$$

Relative suppression becomes less at larger momentum.



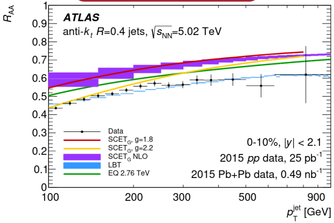
Energy loss model comparisons to data

Hadron suppression



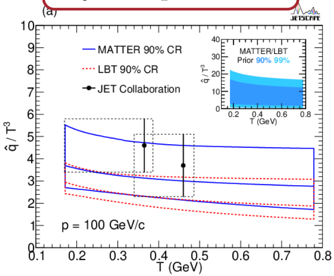
ALICE (2018) [19]

Jet suppression



ATLAS (2018) [12]

Bayesian $\hat{q}$ extraction



JETSCAPE (2021) [20]

- Broad agreement among different models for basic observables like R_{AA}
- Use data-to-model comparisons to determined medium properties, e.g. $\hat{q}$.

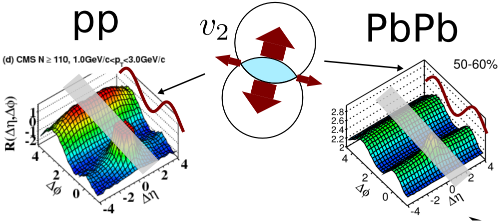
Jet evolution in medium is an active field of theoretical development.

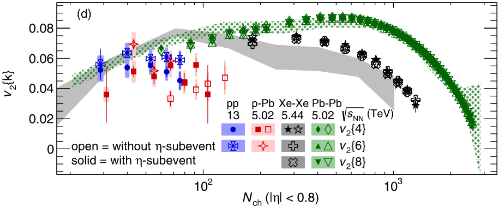
“Heavy-ion” phenomena in pp and pPb and other small systems

Surprising macroscopic physics in small collision systems

Arguably the first discovery at LHC: long-range 2-particle correlations in high-multiplicity pp collisions

CMS (2010) [29]





ALICE (2019) [30]

- Collective flow signals in pp and pPb collisions, where QGP was not expected.

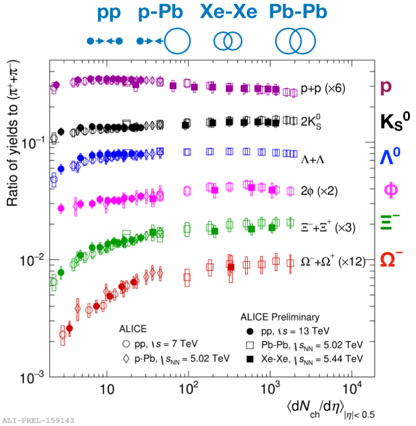
$$L_p \sim 1\,\text{fm} \ll L_{\text{Pb}} \sim 10\,\text{fm}.$$

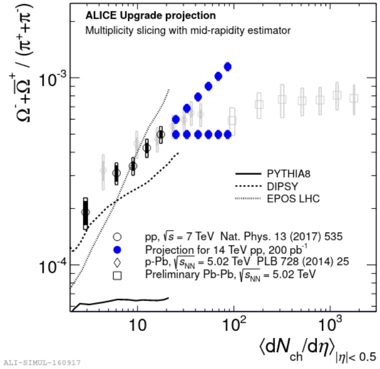
- Not a jet effect: persists for 4-, 6- particle correlations and with rapidity cuts.
- Not reproduced by standard pp event generators, e.g., PYTHIA.

Fluid expansion in a system with $N_{ch} < 100$? Is there QGP in pp, pPb?

Enhanced production of strange hadrons

- Thermal abundances of strange hadrons $\Longrightarrow$ sign of chemical equilibration.
- Continuous increase of strangeness with multiplicity *across all systems*.





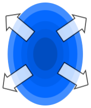
Yellow report (2018) [31]

- What drives strangeness enchancement? QGP thermalization?
- *Will strangeness saturate in ultra high-multiplicity pp collisions?*

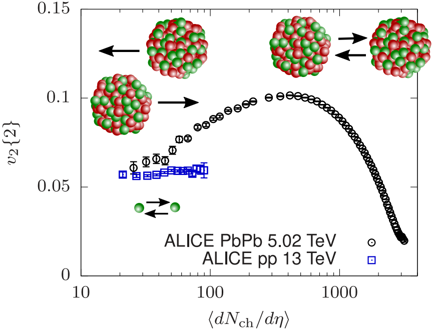
Outstanding problem: origin of collective behaviour in small systems

Collective flow seen in all hadron collisions, but not parton energy loss.

$\pi T \sim 1\mathrm{GeV}$

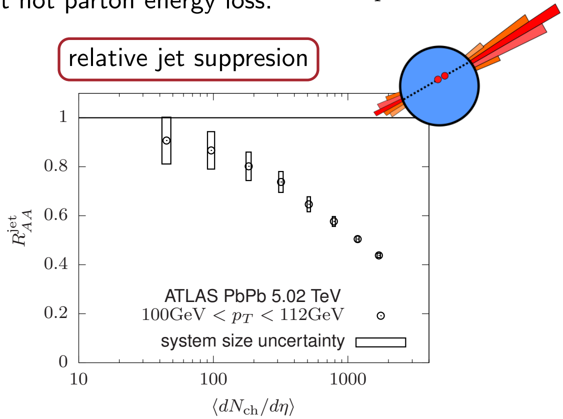


elliptic flow



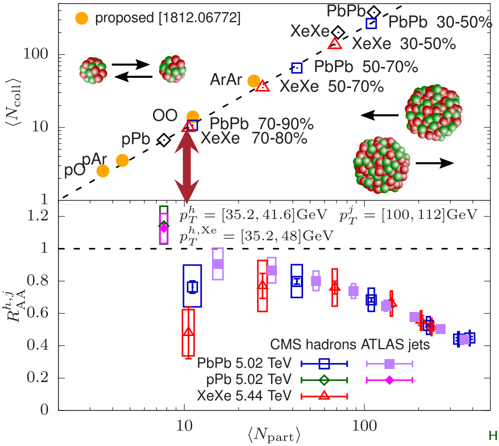
$p_T \sim 100\mathrm{GeV}$

relative jet suppresion



Big question: Is Quark Gluon Plasma created in small systems?

New opportunities with light ions



$\sqrt{s_{NN}} \sim 7\,\text{TeV}$ OO at LHC in 2024
STAR collected $\mathcal{L}_{\text{OO}} = 32\,\text{nb}^{-1}$

Brewer, AM, van der Schee (2021), 2103.01939

Huss, Kurkela, AM, Paatelainen, van der Schee, Wiedemann *PRL,PRC* (2020)

- No jet quenching signals in peripheral PbPb and pPb collisions seen
- *Minimum bias oxygen-oxygen collisions probe the relevant size regime!*

Summary

High-density QCD physics with nucleus-nucleus collisions

- Large volumes of high-density deconfined nuclear matter – QGP.
- Abundant medium signals: collective flows, jet quenching, EM radiation, etc.
- Rapid QCD thermalisation, QGP behaves like nearly perfect fluid.

"Heavy-ion"-like phenomena with proton-nucleus and proton-proton collisions

- Surprising signals of collective flows and strangeness enhancement.
- Missing suppression of high-p_T hadrons and jets
- Several competing interpretations $\Longrightarrow$ open space for new ideas.

Outlook:

- Rich experimental program with heavy and light ions at LHC in Run 3 and 4
- Complementary studies of baryon rich QCD matter at RHIC and other colliders.
- New generation heavy-ion detector ALICE 3 for low-p_T and heavy quark studies.

Many-body QCD phenomena are universal and widespread in all hadronic collisions
$\Longrightarrow$ *increasing synergy of HEP and HIP fields.*

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Backup

Hard partonic luminosities in nuclear collisions (no medium)

Nuclear parton distribution functions

- Bound proton PDF as modification of free proton

$$f_i^{p/A}\left(x, Q^2\right) = R_i^A\left(x, Q^2\right) f_i^p\left(x, Q^2\right).$$

  at initial scale $Q \sim 1\,\text{GeV}$. Isospin symmetry $\Longrightarrow$ neutrons.
- Modification depends on mass number A (parametrized)
- Q^2 evolution described by DGLAP
- Global fit to fixed target DIS, DY and selected collider data.

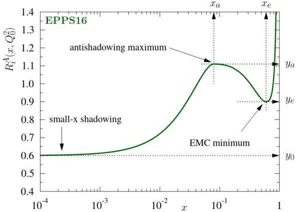
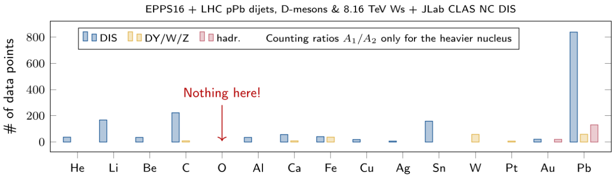


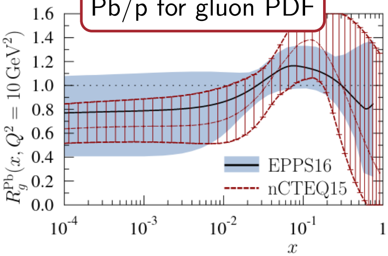
Fig. 1 Illustration of the EPPS16 fit function $R_i^A(x, Q_0^2)$.

Gloabal nPDF fits to nuclear data



Paakkinen [indico]

Pb/p for gluon PDF

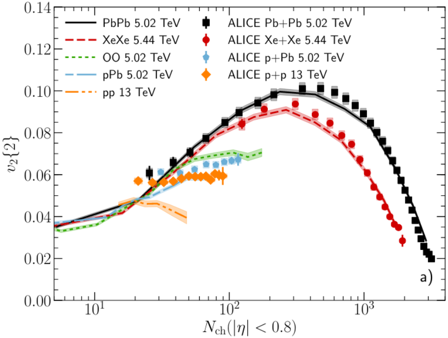


Eskola et al. (2016)[32]

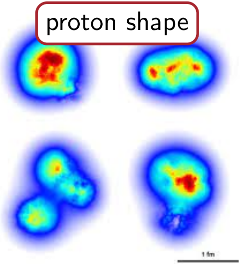
Different collaborations (nCTEQ, nNNPDF, EPPS) improving nPDFs with LHC data.

Scenario I: hydrodynamic in small systems

Assume small droplets of QGP in pp and pPb collisions.



Schenke, Shen, Tribedy (2020) [33]

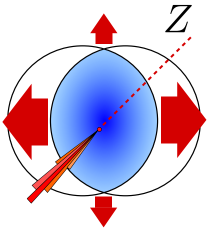


proton shape

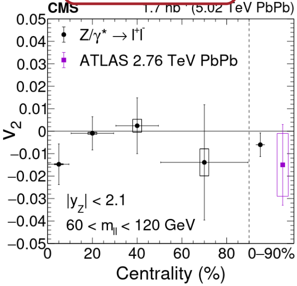
Mäntysaari, Schenke (2016) [34]

- v_n in $pp \implies$ what is the shape of a proton?
- Qualitative description of data, but questions remain about model validity.
- Applicability of hydrodynamics even far-from-equilibrium?

W and Z in PbPb collisions

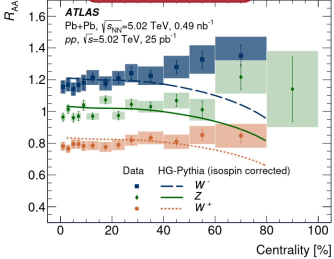


Z elliptic flow



CMS (2021) [11]

R_{AA} for W, Z



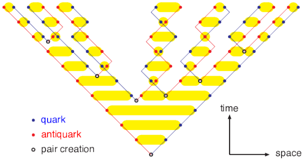
ATLAS (2019) [10]

- No Z-boson elliptic flow $\Longrightarrow$ not interacting with medium.
- Flat R_{AA} in central collisions consistent with N_{coll} scaling.
- Deviation in peripheral events $\Longrightarrow$ potential selection bias.
- W and Z are important calibrating probes, e.g. initial momentum in Z+jet or Z+hadron events.

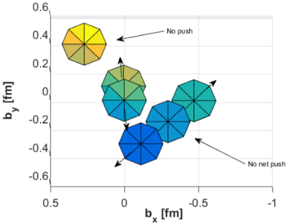
Scenario II: collectivity in HEP event generators

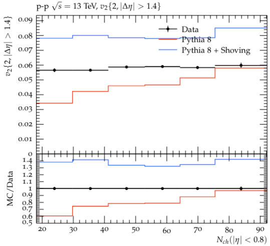
Hadron production from string breaking in PYTHIA: Lund string model.

- Color ropes – increase in string tension $\Longrightarrow$ more strange hadrons
- String shoving – repulsions of closely packed string $\Longrightarrow$ flow.
- Hadron rescattering after hadronization $\Longrightarrow$ more collective flow.



Sjöstrand, Utheim (2020) [35]





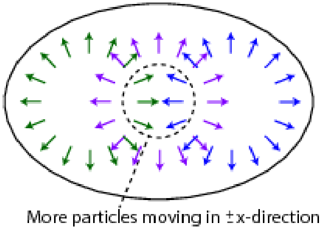
Bierlich, Chakraborty, Gustafson, Lönnblad (2020) [36]

- Challenge to quantitatively describe multi-particle correlations.
- Gradient driven expansion in QGP and between strings $\Longrightarrow$ how to tell apart?

Other theory approaches

Kinetic theory in dilute systems:

- Interpolate from free-streaming to hydrodynamic limits.
- Can generate collective flow from just few scatterings.
- Elucidate the limits of hydrodynamics.
- Currently limited to simplified theories/scenarios.

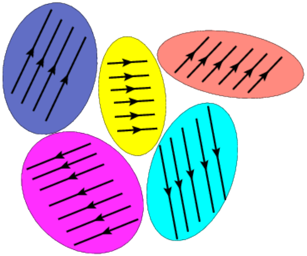


Kurkela, Wiedemann, Wu (2018) [37]

Scattering of colour domains in CGC

- Anisotropic scatterings in momentum space
- Not related to system geometry
- Small signal, often washed out by final-state scatterings.
- Proposed signatures in small systems, e.g. v_2 and $\langle p_T \rangle$ correlations.

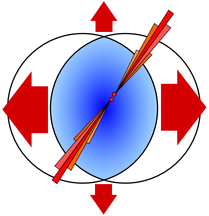
Many ideas about collectivity in small systems $\Longrightarrow$ opportunity/challenge to discover the right QCD degrees of freedom.

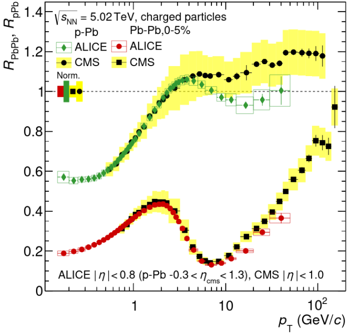


Lappi, Schenke, Schlichting, Venugopalan (2015) [38]

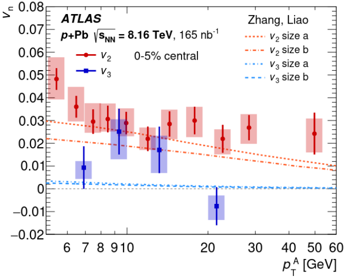
Puzzle of missing high-momentum energy loss in small systems

- No evidence of hadron/jet suppression in pPb, i.e. $R_{p\mathrm{A}} \approx 1$
- Clear azimuthal modulations of high p_T hadrons.
- *Contradicts the current paradigm: collective flow* $\Longleftrightarrow$ *suppression of high-*p_T *spectra.*





ALICE (2018) [19]



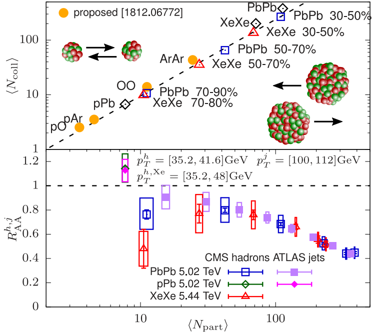
ATLAS (2019) [39]

Intensive searches for subtle energy loss signals (new observables, new systems).

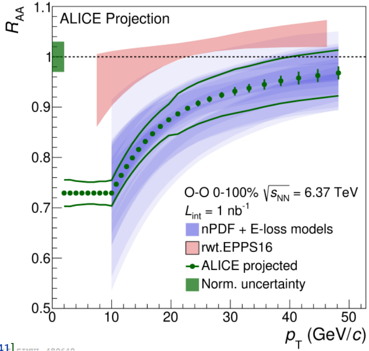
Oxygen run at LHC in Run 3 (also at RHIC)

Many physics opportunities with OO and pO see Yellow report (2018) [31], OppOatLHC workshop [indico]

- pO: interest from cosmic ray physics.
- OO comparable size to pPb, but better geometry control.
- Minimum-bias R_{AA} free of geometry uncertainties $\Longrightarrow$ precise energy loss measurement



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



ALICE (2021) [40]

baseline

medium effect

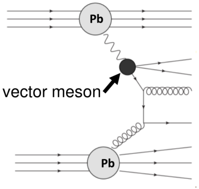
exp. projection

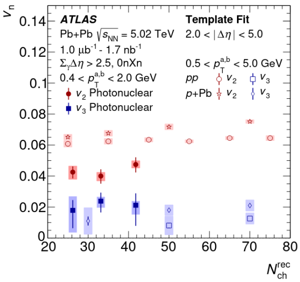
Potential for discovering energy loss in $N_{part} \approx 10$ system

Smaller than pp

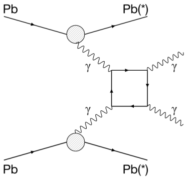
Ultra-peripheral collisions (= at least one nucleus intact)

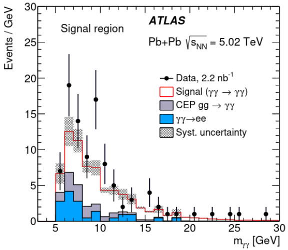
- Ultrarelativistic ions $\Longrightarrow$ large photon flux $\propto Z^2$
- Can study photon-nucleus and photon-photon collisions





ATLAS (2021) [43]



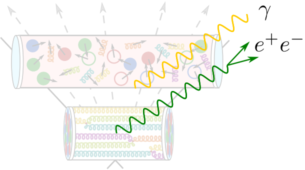


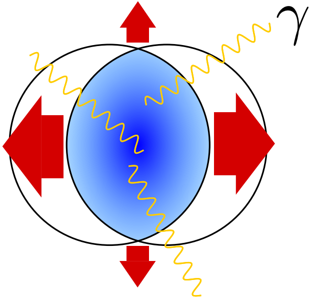
ATLAS (2020) [42]

- Anisotropic flow signal in γA (photon fluctuates into ρ, ω)
- Verification of QED prediction, constraints on axion like particle production.

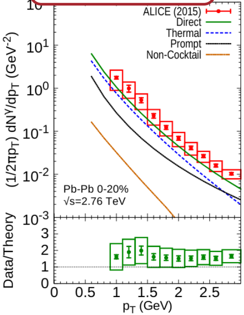
Photon and di-leptons — penetrating probes of QGP

- Produced perturbatively at initial stages (prompt)
- Radiated thermally by QGP (rate depends on temperature, quark content).
- Do not reinteract with the medium once produced (but can be boosted at emission point)

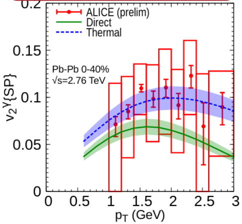




photon spectra



photon elliptic flow



Paquet et al. (2015) [21]

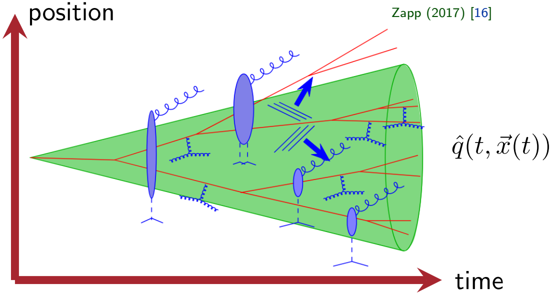
Excess of thermal photon production and collective flow ⟹ signature of hot flowing QGP.

Can use EM radiation to study the early time quark production in QGP.

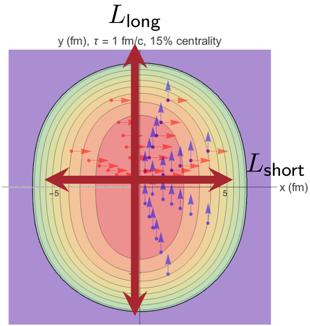
Jets in high-energy QCD matter

In-medium Monte-Carlo jet implementations (Jewel, Martini, LBT, Hybrid, Jetscape. . .)

- Space-time structure of vacuum parton shower via formation time $\Delta t \sim E/Q^2$.
- Quenching parameter $\hat{q}\,(t, \vec{x}\,(t))$ from hydrodynamic background.
- $L_{\text{long}} > L_{\text{short}} \implies$ anisotropic energy loss.



Zapp (2017) [16]

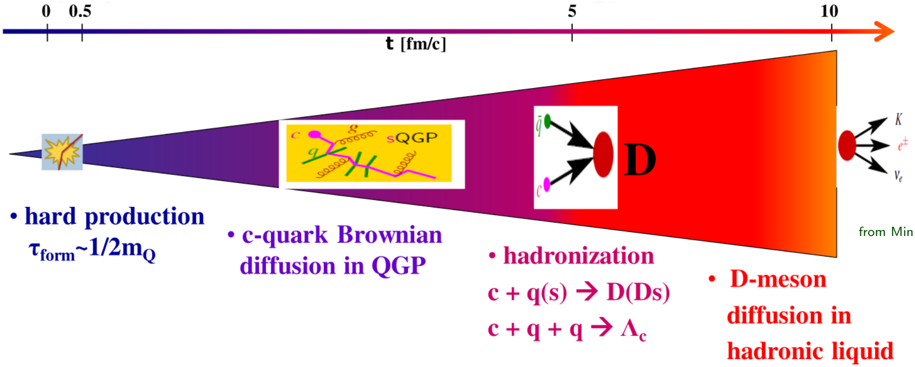


Heavy quarks in QCD matter

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 in final state.



from Min He [indico]

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

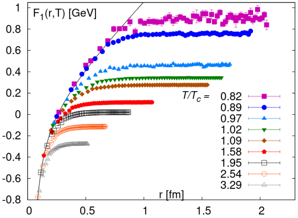
Quarkonium $Q\bar{Q}$ states in heavy-ion collision

- In vacuum: confining potential between Q and $\bar{Q}$

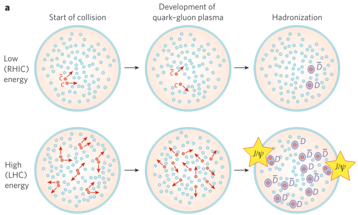
$$F_{Q\bar{Q}}(r) = -\frac{\alpha}{r} + \underbrace{\sigma}_{\text{string tension}} r.$$

- Colour screening in QGP $\Longrightarrow$ dissociation of quarkonium, sensitive to QGP temperature.

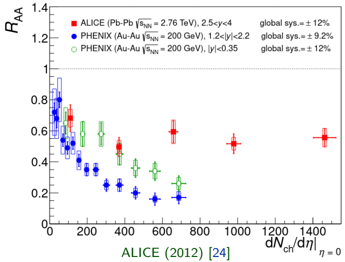
static quark free energy



RBC-Bielefeld [22]



Braun-Munzinger and Stachel (2007) [23]



ALICE (2012) [24]

$J/\psi = c\bar{c}$ suppression at RHIC and LHC

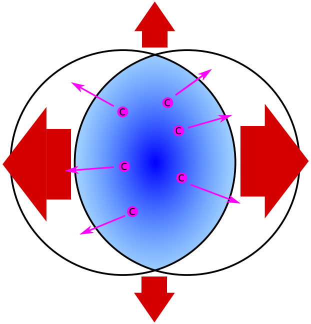
- Observed significant suppression of J/ψ, but less at higher collision energies.
- Dissociated charm quarks in QGP recombine at phase transition $\Longrightarrow$ J/ψ regeneration.

Full story more complicated: Lindblad equation for density matrix ρ Brambilla, Escobedo, Strickland, Vairo, Griend, Weber (2021) [25]
Coupled Boltzmann Transport Equations, Yao, Ke, Xu, Bass, Müller (2020) [26]

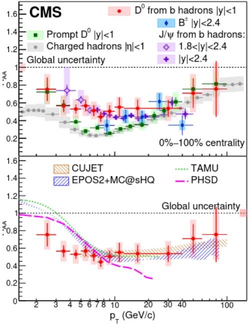
Suppression and flow of heavy quarks in medium

for different theoretical approaches see Heavy-Flavor Transport in QCD Matter [indico]

- At high p_T: partonic energy loss $\Longrightarrow$ same suppression as light hadrons.
- At low p_T: Brownian motion of massive quarks in flowing background
  $\Longrightarrow$ *heavy quarks are boosted by the medium generating momentum anisotropy.*

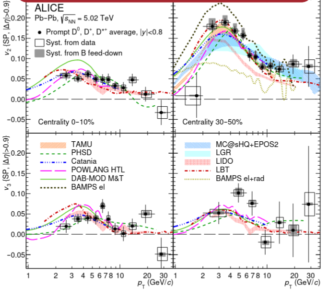


R_{AA} of heavy flavour



CMS (2019) [28]

Elliptic flow of D mesons

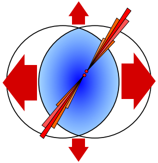


ALICE (2020) [27]

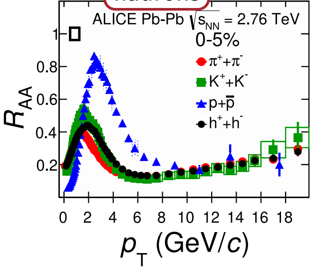
- Significant collective flow of heavy-flavour $\Longrightarrow$ determine diffusion coefficient.
- Strong indication of kinetic charm equilibration $\Longrightarrow$ studies of beauty thermalisation.

Hadron and jet R_{AA} and azimuthal harmonics

$$R_{AA} = \frac{dN_{AA}/dp_T}{N_{\text{coll}}\, dN_{pp}/dp_T}, \qquad \frac{dN}{d\phi_{\text{jet}}} \sim 1 + \sum_m 2 v_n^{\text{jet}} \cos \underbrace{\left[n\left(\phi_{\text{jet}} - \Phi_n^{\text{bulk}}\right)\right]}_{\text{correlation to soft particles}}$$

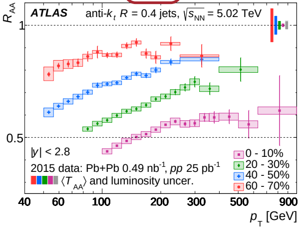


hadrons



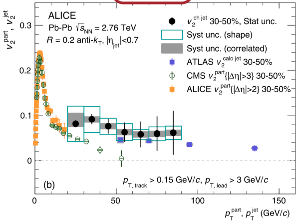
ALICE (2015) [17]

jets



ALICE (2015) [18]

jet v_2



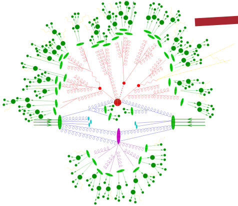
ATLAS (2018) [12]

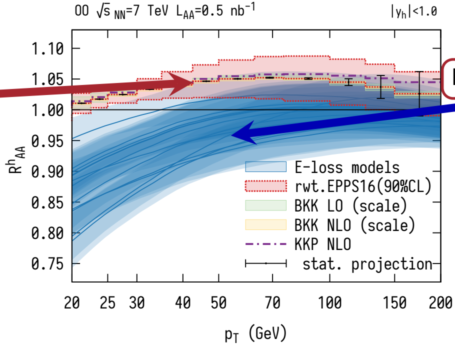
- Flavour independent suppression of hardons $p_T > 10\,\text{GeV}$
  $\implies$ support for partonic energy loss picture
- Significant jet suppression (centrality dependent) and azimuthal modulation
  $\implies$ support for path-length dependent energy loss.

Oxygen-oxygen collisions — unique opportunity to discover energy loss

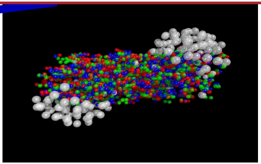
- Discovery of small energy loss ⇒ *important to quantify uncertainties in the baseline*
- We performed next-to-leading order computations of perturbative baseline.
- Extrapolated energy loss models down to oxygen-oxygen collisions.

HEP: no-rescattering





HIP: prediction for energy loss



Measurable difference between the baseline and modelled medium effect!

Huss, Kurkela, AM, Paatelainen, van der Schee, Wiedemann, *PRC,PRL* (2021)