# High-Density QCD with Proton and Ion Beams

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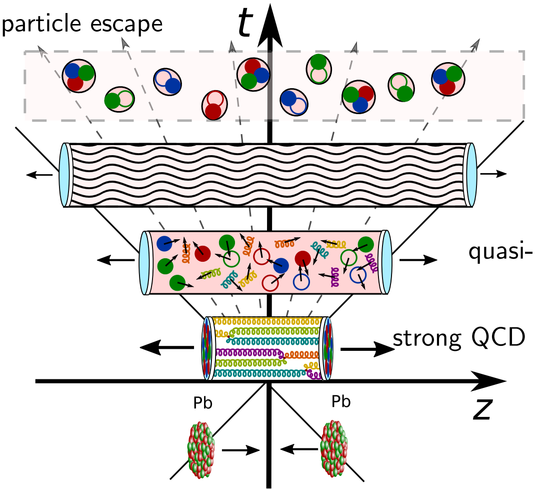
# Recap of the first lecture

# 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

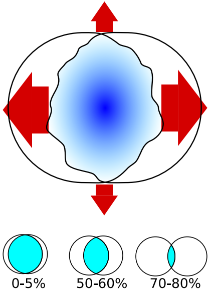
Equilibration
$t \sim 1\,\mathrm{fm}/c$ — quasi-particles $1 \ll f_g \ll \frac{1}{\alpha_s}$

Initial state
$t \ll 1\,\mathrm{fm}/c$ — strong QCD fields $f_g(p \sim Q_s) \sim \frac{1}{\alpha_s} \gg 1$

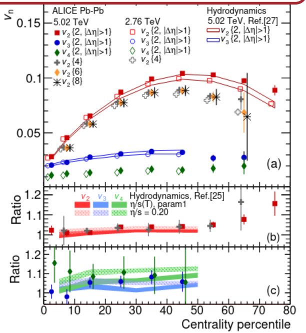
Incoming nuclei

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

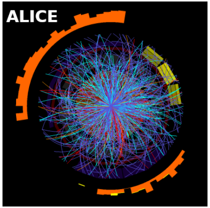
# Hydrodynamic expansion and collective flows




centrality dependence of $v_n$




ALICE (2016) [1]

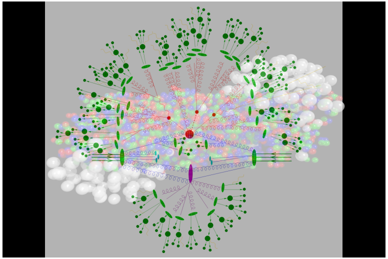



$$\frac{dN}{d\phi} \propto 1 + \sum_n 2v_n \cos(n\phi)$$

- Strong correlation between particle production and nuclear overlap $\Longrightarrow$ centrality.
- Azimuthal anisotropy of particle production $\Longrightarrow$ collective flows.
- Hydrodynamic expansion converts geometry deformation to momentum anisotropies.
- Model comparisons reveal QGP properties: $\eta/s \sim 0.08 - 0.2$.

# Hard probes of high-density QCD matter

# Hard QCD processes embedded in nuclear environment



Self-generated probes of QGP

- Examples: high-$p_T$ jets or hadrons, heavy quarks, $W, Z, \gamma$
- 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.

*Use the modification of hard probes to understand high-density QCD.*

- Initial production rate is different (colliding different quark and gluon distributions)
- Medium induced modification (energy loss of jets, heavy-quark diffusion).

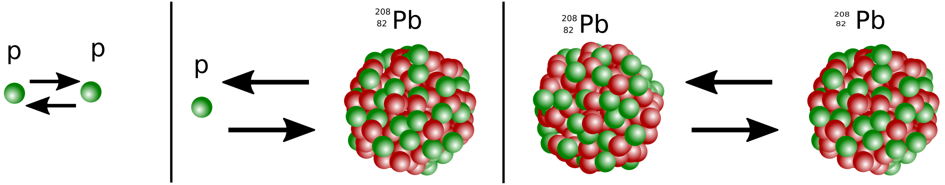
# Hard partonic luminosities in nuclear collisions (no medium)

# QCD factorisation in nuclear collisions

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

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

- $\hat{\sigma}_{ij}$ – hard partonic cross-section, universal, systematically improvable
- $f_i(x, Q^2)$ – 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.*
- To avoid contamination with QGP effects in fits, use EW cross-sections (no QCD interaction) or small systems, e.g., $p$Pb.

# 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.

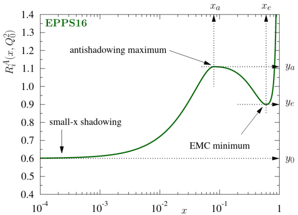
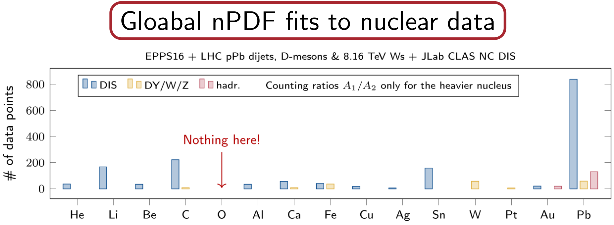
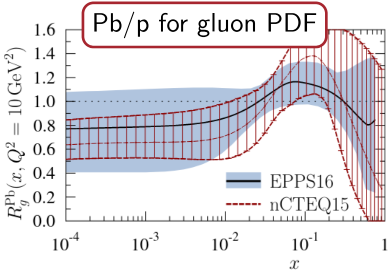



**Fig. 1** Illustration of the EPPS16 fit function $R_i^A(x, Q_0^2)$.




Paakkinen [indico]




Eskola et al. (2016)[2]

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

# Comparing hard probes in heavy-ion (AA) and $pp$ collisions

# Nuclear modification factor $R_{\mathrm{AA}}$

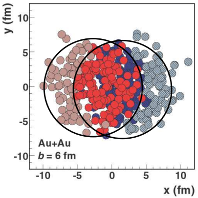
- Quantify nuclear effects by normalizing hard spectra in heavy-ions (AA) to $pp$

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

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

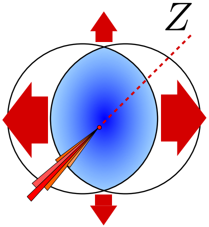
$N_{\mathrm{part}} = 4 \; N_{\mathrm{coll}} = 3$ $\qquad$ $N_{\mathrm{part}} = 4 \; N_{\mathrm{coll}} = 4$

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

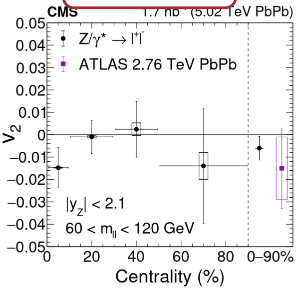



- In the absence of medium effects expect $R_{\mathrm{AA}} \approx 1$ (up to nPDF and isospin corrections).

# $W$ and $Z$ in PbPb collisions

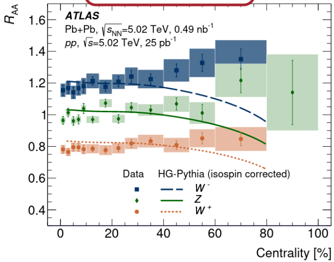



$Z$ elliptic flow




CMS (2021) [4]

$R_{AA}$ for $W, Z$



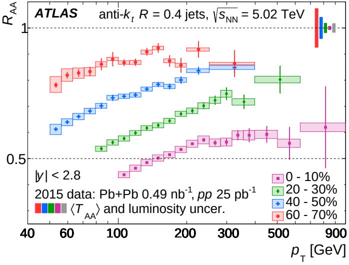

ATLAS (2019) [3]

- No $Z$-boson elliptic flow $\Longrightarrow$ not interacting with medium.
- Flat $R_{\mathrm{AA}}$ in central collisions consistent with $N_{\mathrm{coll}}$ 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.

# Jets and hadron production in high-density QCD medium

# High-$p_T$ parton energy loss — jet quenching

ATLAS (2018) [5]

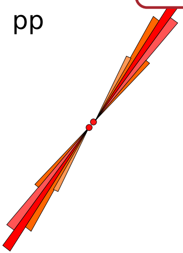


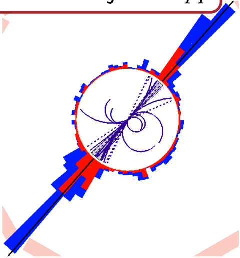

Jet spectrum is suppressed in nuclear collisions compared to proton-proton collisions

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

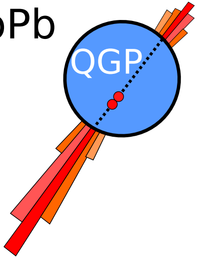
back-to-back jets in $pp$

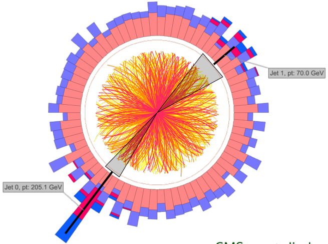
pp





PbPb

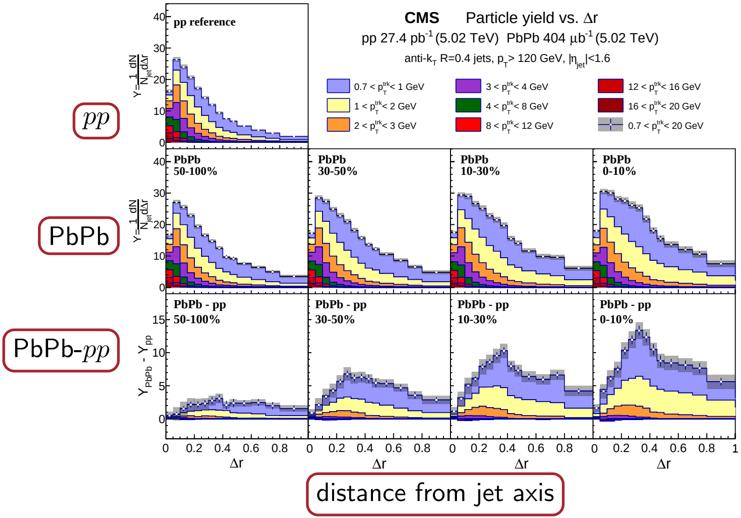



CMS event displays

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

# Particle production around the jet cone

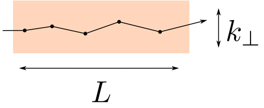



*Energy loss $\Longrightarrow$ enhanced soft particle production at large angles from jet axis.*

# Medium induced gluon radiation (BDMPS-Z) Baier, Dokshitzer, Mueller, Peigne, Schiff (1996) [7], Zakharov (1996) [8] and others

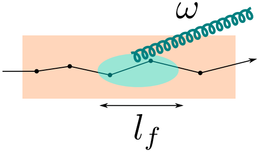
Energy loss at strong coupling: infall of a classical string in a black hole, see Casalderrey-Solana, Liu, Mateos, Rajagopal, Wiedemann (2014) [6]

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 $L$.

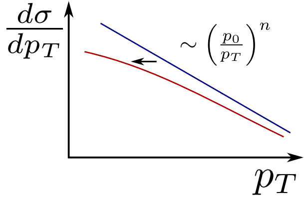
Modification of steeply falling vacuum spectra

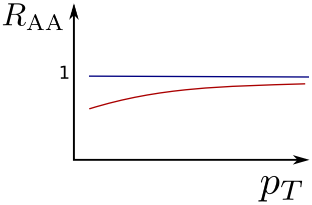
$d\sigma_{\text{vac}}/dp_T = \sigma_0 (p_0/p_T)^n$

$$\frac{d\sigma_{\text{med}}}{dp_T} = \int_0^\infty d\epsilon P(\epsilon) \frac{\sigma_0 p_0^n}{(p_T+\epsilon)^n} \approx \frac{d\sigma_{\text{vac}}}{dp_T} \exp\left(-\frac{n\langle\epsilon\rangle}{p_T}\right).$$

$P(\epsilon)$ – probability for multiple independent emissions $\epsilon = \sum_n \omega_i$

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



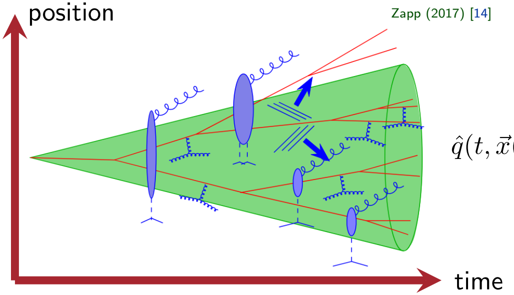

- hadrons: convolve parton spectra with vacuum fragmentation functions.
- jets: model energy transport outside the jet cone (out-of-cone radiation and thermalization).

For progress on double emission see Arnold, Gorda, Iqbal (2020) [9], improved opacity expansion Barata, Mehtar-Tani (2020)[10] full resummation Andres, Apolinário, Dominguez (2020) [11], non-perturbative broadening Moore, Schlichting, Schlusser, Soudi (2021) [12], vacuum and in-medium factorization Caucal, Iancu, Soyez (2020) [13], . . .

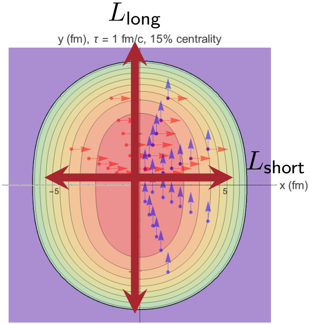
# Jets in high-energy QCD matter

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 $\hat{q}\left(t, \vec{x}\left(t\right)\right)$ from hydrodynamic background.
- $L_{\text{long}} > L_{\text{short}} \implies$ anisotropic energy loss.



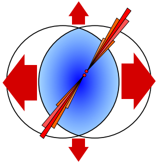

$\hat{q}(t, \vec{x}(t))$



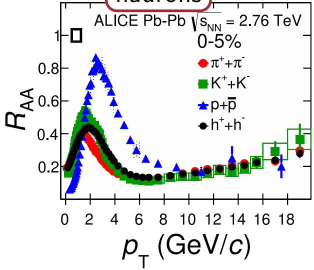

Casalderrey-Solana, Hulcher, Milhano, Pablos, Rajagopal (2018) [15], Andres, Néstor, Niemi, Paatelainen, Salgado (2019) [16]
Zigic, Ilic, Djordjevic, Djordjevic (2019) [17], Huss, Kurkela, AM, Paatelainen, van der Schee, Wiedemann (2020) [18], JETSCAPE (2021) [19]

# Hadron and jet $R_{AA}$ and azimuthal harmonics

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

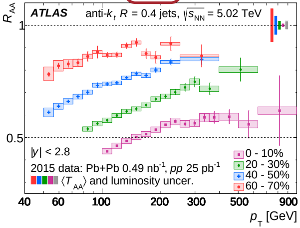


hadrons



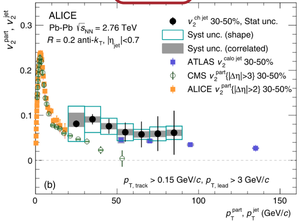

ALICE (2015) [20]

jets




ALICE (2015) [21]

jet $v_2$

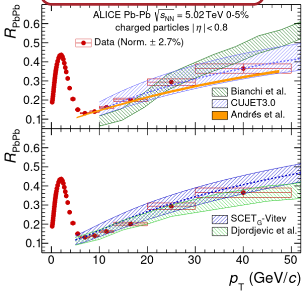



ATLAS (2018) [5]

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

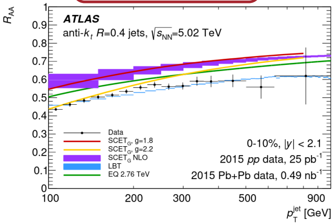
# Energy loss model comparisons to data

Hadron suppression



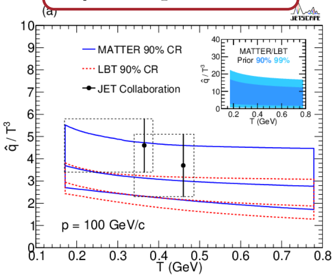

ALICE (2018) [22]

Jet suppression




ATLAS (2018) [5]

Bayesian $\hat{q}$ extraction




JETSCAPE (2021) [19]

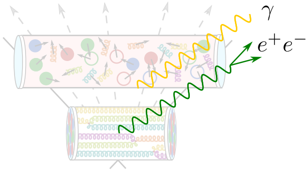
- Broad agreement among different models for basic observables like $R_{\mathrm{AA}}$
- Use data-to-model comparisons to determined medium properties, e.g. $\hat{q}$.
- More differential observables, e.g. jet substructure $\Longrightarrow$ differentiate energy loss models.

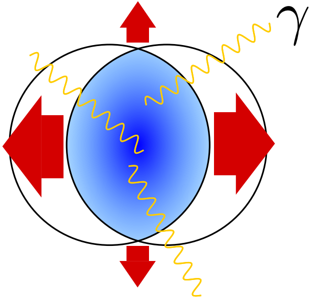
*Jet evolution in medium is an active field of theoretical development.*

# Electromagnetic radiation in QGP

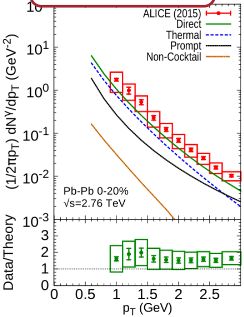
# Photon and di-leptons — penetrating probes of QGP

- 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)

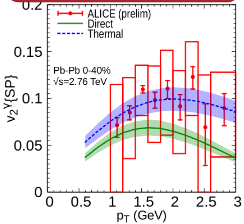



photon spectra




photon elliptic flow




Paquet et al. (2015) [23]

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

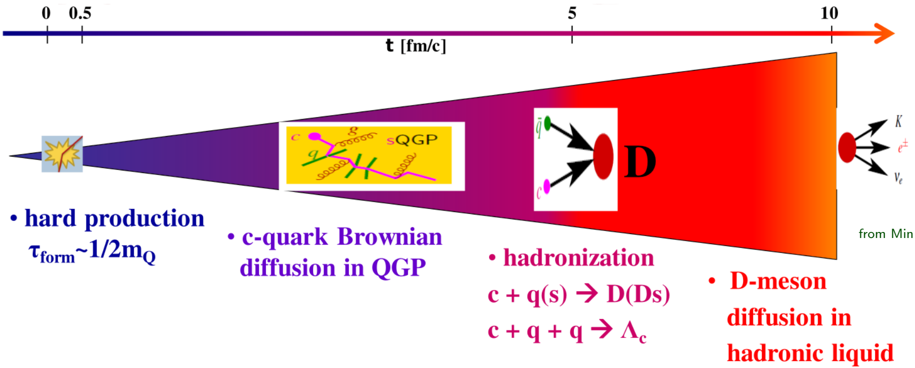
Can use EM radiation to study the early time quark production in QGP.

# 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.

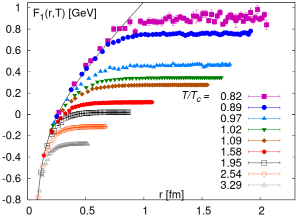



from Min He [indico]

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

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

static quark free energy

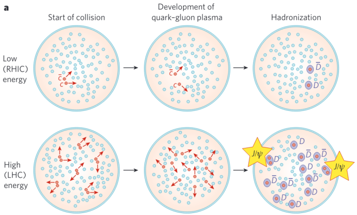



RBC-Bielefeld [24]

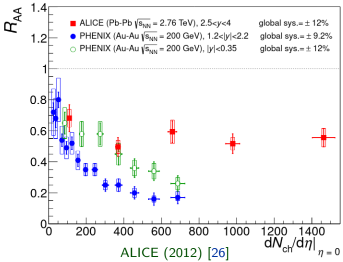
- In vacuum: confining potential between $Q$ and $\bar{Q}$

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

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




Braun-Munzinger and Stachel (2007) [25]




ALICE (2012) [26]

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

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

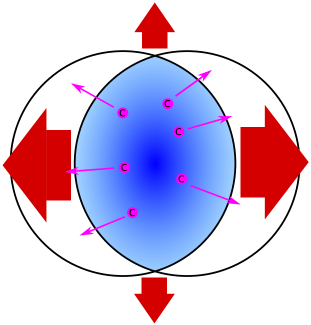
Full story more complicated: Lindblad equation for density matrix $\rho$ Brambilla, Escobedo, Strickland, Vairo, Griend, Weber (2021) [27]

Coupled Boltzmann Transport Equations, Yao, Ke, Xu, Bass, Müller (2020) [28]

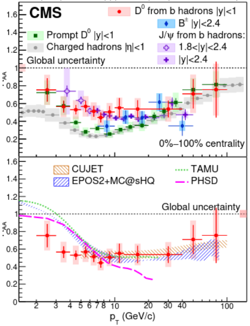
# Suppression and flow of heavy quarks in medium

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.*

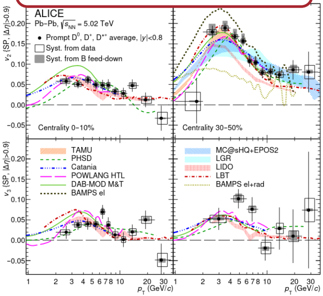


$R_{\mathrm{AA}}$ of heavy flavour




CMS (2019) [30]

Elliptic flow of D mesons




ALICE (2020) [29]

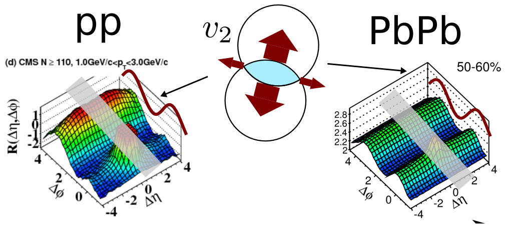
- Significant collective flow of heavy-flavour $\Longrightarrow$ determine diffusion coefficient.
- Strong indication of kinetic charm equilibration $\Longrightarrow$ studies of beauty thermalisation.

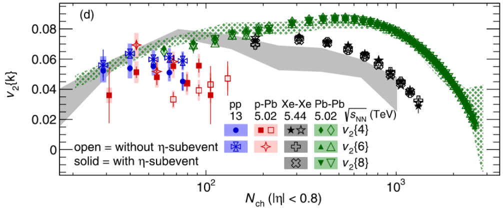
# "Heavy-ion" phenomena in $pp$ and $p$Pb and other small systems

# 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) [31]




ALICE (2019) [32]

- Collective flow signals in $pp$ and $p$Pb collisions, where QGP was not expected.

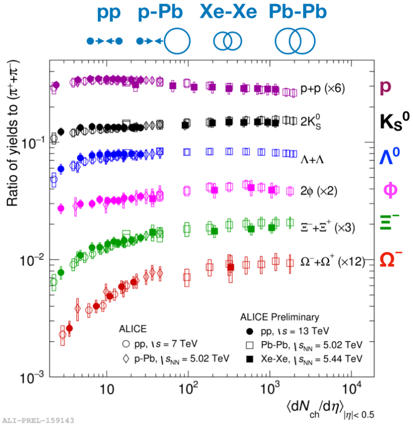
$$L_p \sim 1\,\text{fm} \ll L_{\text{Pb}} \sim 10\,\text{fm}.$$

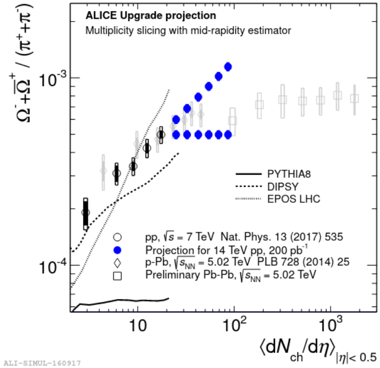
- Not a jet effect: persists for 4-, 6- particle correlations and with rapidity cuts.
- Not reproduced by standard $pp$ event generators, e.g., PYTHIA.

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

# Enhanced production of strange hadrons

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



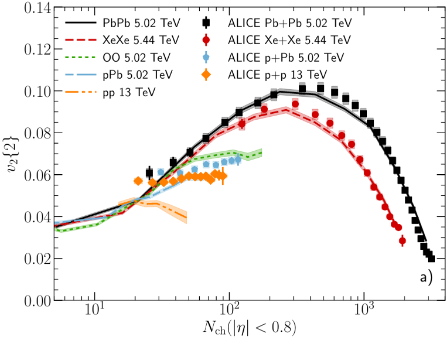




Yellow report (2018) [33]

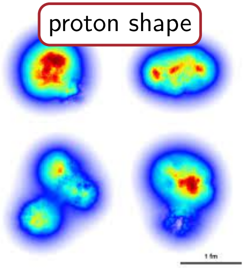
- What drives strangeness enchancement? QGP thermalization?
- *Will strangeness saturate in ultra high-multiplicity $pp$ collisions?*

# Scenario I: hydrodynamic in small systems

Assume small droplets of QGP in $pp$ and $p$Pb collisions.




Schenke, Shen, Tribedy (2020) [34]



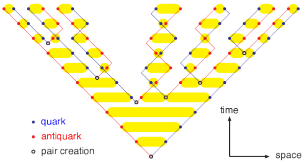

Mäntysaari, Schenke (2016) [35]

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

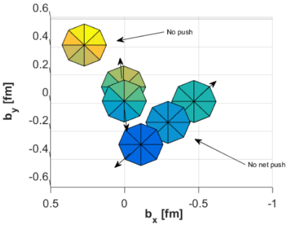
# Scenario II: collectivity in HEP event generators

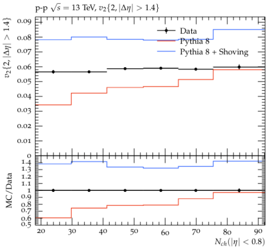
Hadron production from string breaking in PYTHIA: Lund string model.

- 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) [36]



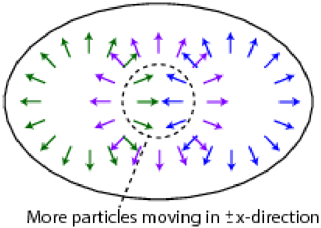

Bierlich, Chakraborty, Gustafson, Lönnblad (2020) [37]

- 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:

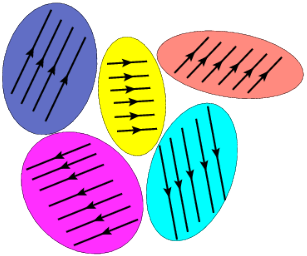
- Interpolate from free-streaming to hydrodynamic limits.
- Can generate collective flow from just few scatterings.
- Elucidate the limits of hydrodynamics.
- Currently limited to simplified theories/scenarios.




Kurkela, Wiedemann, Wu (2018) [38]

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.

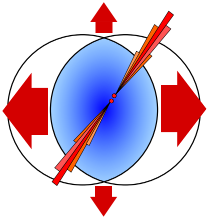


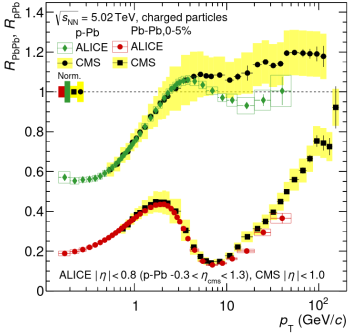
Lappi, Schenke, Schlichting, Venugopalan (2015) [39]

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

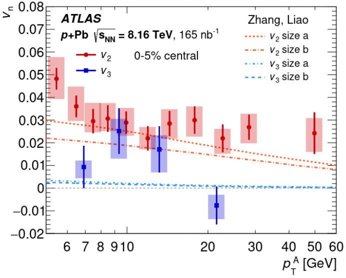
# Puzzle of missing high-momentum energy loss in small systems

- No evidence of hadron/jet suppression in $p$Pb, 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) [22]



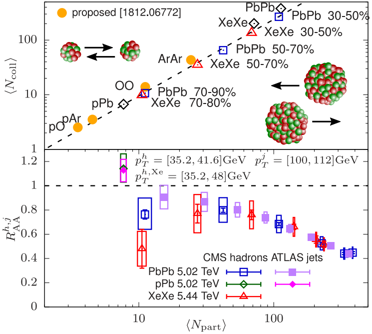
ATLAS (2019) [40]

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

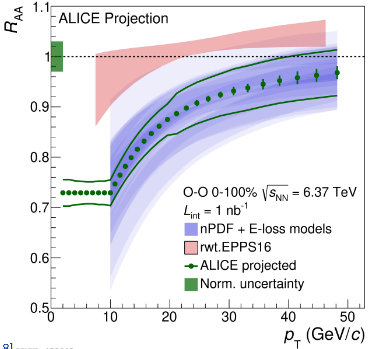
# Oxygen run at LHC in Run 3 (also at RHIC)

Many physics opportunities with OO and $p$O see Yellow report (2018) [33], OppOatLHC workshop [indico]

- $p$O: interest from cosmic ray physics.
- OO comparable size to $p$Pb, 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) [18]




ALICE (2021) [41]

baseline

medium effect

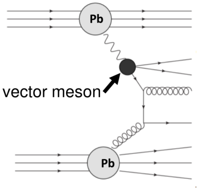
exp. projection

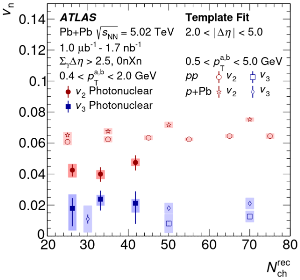
*Potential for discovering energy loss in $N_{part} \approx 10$ system*

# Smaller than $pp$

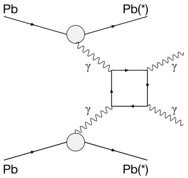
# Ultra-peripheral collisions (= at least one nucleus intact)

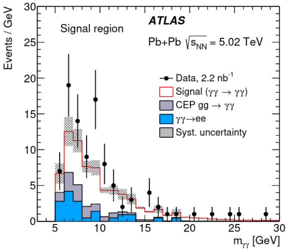
- Ultrarelativistic ions $\Longrightarrow$ large photon flux $\propto Z^2$
- Can study photon-nucleus and photon-photon collisions




ATLAS (2021) [43]




ATLAS (2020) [42]

- Anisotropic flow signal in $\gamma A$ (photon fluctuates into $\rho, \omega$)
- Verification of QED prediction, constraints on axion like particle production.

# 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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