Theory Overview of Heavy-Ion Collisions

The 9th China LHC Physics Workshop (CLHCP2023), Shanghai, Nov 19, 2023

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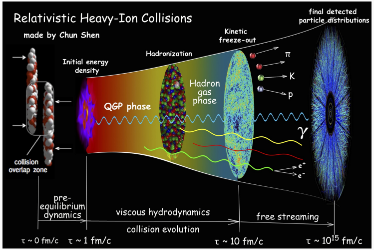
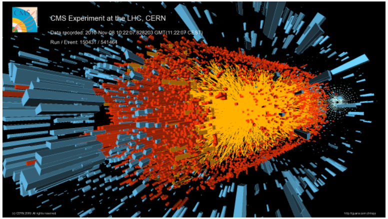
Introduction

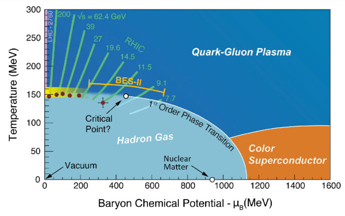
Heavy-ion collisions at the LHC



$L \sim 10$ fm, $\tau \sim 10$fm$/c$

A finite-temperature ($T_i = 500$ MeV) QCD system is created by colliding two relativistic nuclei. Producing $\mathcal{O}(10^4)$ final particles.

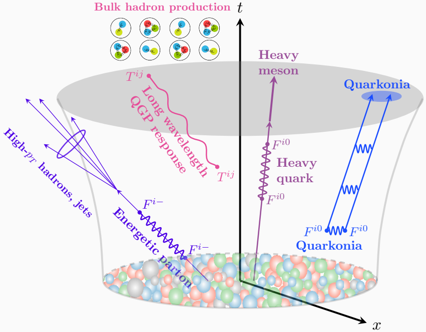




- Study the deconfined state of matter quark-gluon plasma (QGP).
- The phase transition from partonic matter to hadronic matter.

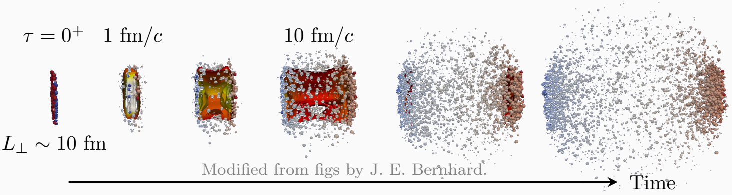
A key question for the heavy-ion theory: how to connect the observations to well-defined properties of the QCD matter?

Probes of the highly-dynamical medium



- Collective dynamics of fireball
  $\Longrightarrow$ static and long-wavelength properties.
- Penetrating probes (jets and high-p_T hadrons)
  $\Longrightarrow$ multi-scale probes, from medium length scale to the partonic structure of QGP.
- Heavy quarks (b, c, $M \gg T$) and quarkonia
  $\Longrightarrow$ charge diffusion, plasma screening, and hadronization in a finite-temperature environment.
- $\cdots$.

Hydrodynamic-based models for a strongly-coupled plasma



Potential/kinetic term

$g_s \sim \mathcal{O}(1) \Rightarrow$ **fluid-like**

Initial condition **models**

QCD equation of state $P = P(e)$

QGP viscosity η, ζ

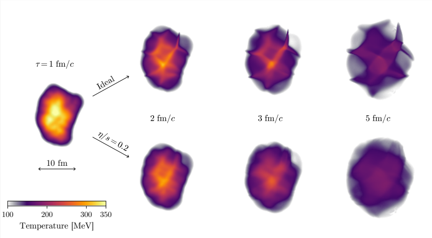
Higher-order transport pararmeters

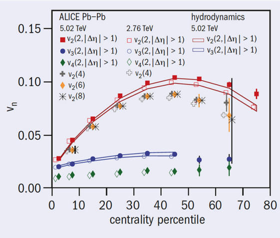
- $\partial_\mu T^{\mu\nu} = 0$, energy-momentum continuity.
- Gradient expansion from local equilibirum $T^{\mu\nu} = e u^\mu u^\nu + (u^\mu u^\nu - g^{\mu\nu})(P + \Pi) + \pi^{\mu\nu}$
- Relaxization of off-equilibirum effects: $\dot{\pi}^{\mu\nu} = -\frac{\pi^{\mu\nu} + 2\eta\partial^{\langle\mu}u^{\nu\rangle}}{\tau_\pi} \cdots, \dot{\Pi} = -\frac{\Pi + 2\zeta\nabla\cdot u}{\tau_\Pi} \cdots$

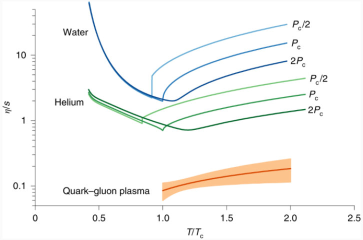
Reverse engineer $P(e)$, η/s, and ζ/s using the system's response to (anisotropic) expansion.

Hadronic afterburner till freezeout $\Longrightarrow$ data

Applications and developments of the relativistic hydrodynamics







Sensitivity of flow development to viscosity.

$\frac{dN}{d\phi} = N_0[1+\sum_n 2v_n \cos(n(\phi-\Psi_n))]$

The near perfect liquid

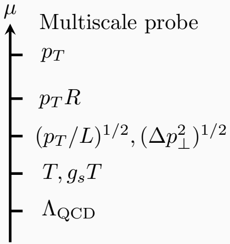
Nat.Phys.15(2019)1113 .

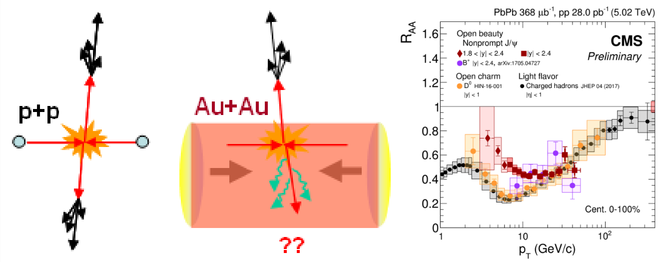
- Bayesian analysis of soft particle production (flow, fluctuations, correlations, hadron chemistry) $\Rightarrow$ QGP is a near-perfect fluid with the tiniest specific viscosity.
- A rapidity development of relativistic hydrodynamic theory:
    - Hydrodynamics with large gradients/fluctuations/phase transitions, etc.
    - Hydrodynamics response to the passage of energetic partons.
    - Incorporate the spin degree of freedom: beyond just energy-momentum response.

High-p_T probes of QCD medium

Jet tomography in high-energy nuclear collisions

Reverse engineer the structure of the medium by modifications of the probe.





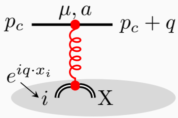
$$\frac{d\sigma_{pp\to j}}{dp_T} = \sum_{ijkX} f_{i/p}(x_1, p_T) f_{j/p}(x_2, p_T) \otimes H_{ij\to kX}(p_T) \otimes \mathcal{J}_k(z, p_T, p_T R)$$

$$\frac{d\sigma_{AA\to j}}{dp_T} = \sum_{ijkX} f_{i/A}(x_1, p_T) f_{j/A}(x_2, p_T) \otimes H_{ij\to kX}(p_T) \otimes \left(\mathcal{J}_k(z, p_T, p_T R) + \Delta\mathcal{J}_k\right)$$

Partonic dynamics in a thermal plasma

- **Jet-medium collisions:** a screened Coulomb type forward scattering

$$\frac{d\sigma}{d^2\mathbf{q}} \sim \frac{\alpha_s^2 C_R C_T}{(\mathbf{q}^2 + (gT)^2)^2}$$



Multiple collisions

Mean-free-path: $\lambda_g \sim \frac{1}{n\sigma} \sim \frac{1}{g^2 T}$.

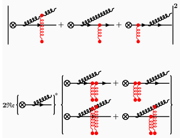
Collisional broadening: $\frac{d\langle p_\perp^2 \rangle}{dL} \sim \frac{g^2 T^2}{\lambda_g} \sim g^4 T^3$.

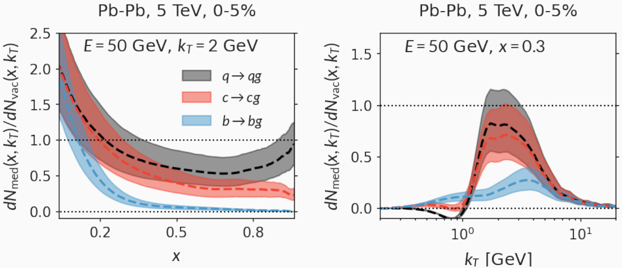
Collisional energy loss: $\frac{d\langle p^+ \rangle}{dL} \sim \frac{g^2 T}{\lambda_g} \sim g^4 T^2$.

- **Medium-induced QCD splittings**:.

▽ An opacity-one calculation of $\frac{dN_{ji}^{\rm med}}{dxd^2\mathbf{k}}$ Kang, Ringer, Vitev, JHEP03(2017)146 , averaged in medium

$$\left(\frac{dN^{\rm med}}{dxd^2\boldsymbol{k}_\perp}\right)_{Q\to Qg} = \frac{\alpha_s}{2\pi^2}C_F \int \frac{d\Delta z}{\lambda_g(z)} \int d^2\boldsymbol{q}_\perp \frac{1}{\sigma_{el}} \frac{d\sigma_{el}^{\rm med}}{d^2\boldsymbol{q}_\perp} \left\{ \left(\frac{1+(1-x)^2}{x}\right) \left[\frac{\boldsymbol{B}_\perp}{\boldsymbol{B}_\perp^2+\nu^2} \right.\right.$$
$$\times \left(\frac{\boldsymbol{B}_\perp}{\boldsymbol{B}_\perp^2+\nu^2} - \frac{\boldsymbol{C}_\perp}{\boldsymbol{C}_\perp^2+\nu^2}\right)(1-\cos[(\Omega_1-\Omega_2)\Delta z]) + \frac{\boldsymbol{C}_\perp}{\boldsymbol{C}_\perp^2+\nu^2}\cdot\left(2\frac{\boldsymbol{C}_\perp}{\boldsymbol{C}_\perp^2+\nu^2} - \frac{\boldsymbol{A}_\perp}{\boldsymbol{A}_\perp^2+\nu^2}\right.$$
$$\left. - \frac{\boldsymbol{B}_\perp}{\boldsymbol{B}_\perp^2+\nu^2}\right)(1-\cos[(\Omega_1-\Omega_3)\Delta z]) + \frac{\boldsymbol{B}_\perp}{\boldsymbol{B}_\perp^2+\nu^2}\cdot\frac{\boldsymbol{C}_\perp}{\boldsymbol{C}_\perp^2+\nu^2}(1-\cos[(\Omega_2-\Omega_3)\Delta z])$$
$$+ \frac{\boldsymbol{A}_\perp}{\boldsymbol{A}_\perp^2+\nu^2}\cdot\left(\frac{\boldsymbol{D}_\perp}{\boldsymbol{D}_\perp^2+\nu^2} - \frac{\boldsymbol{A}_\perp}{\boldsymbol{A}_\perp^2+\nu^2}\right)(1-\cos[\Omega_4\Delta z]) - \frac{\boldsymbol{A}_\perp}{\boldsymbol{A}_\perp^2+\nu^2}\cdot\frac{\boldsymbol{D}_\perp}{\boldsymbol{D}_\perp^2+\nu^2}(1-\cos[\Omega_5\Delta z])$$
$$\left. + \frac{1}{N_c^2}\frac{\boldsymbol{B}_\perp}{\boldsymbol{B}_\perp^2+\nu^2}\cdot\left(\frac{\boldsymbol{A}_\perp}{\boldsymbol{A}_\perp^2+\nu^2} - \frac{\boldsymbol{B}_\perp}{\boldsymbol{B}_\perp^2+\nu^2}\right)(1-\cos[(\Omega_1-\Omega_2)\Delta z])\right]$$
$$\left. + x^3 m^2 \left[\frac{1}{\boldsymbol{B}_\perp^2+\nu^2}\cdot\left(\frac{1}{\boldsymbol{B}_\perp^2+\nu^2} - \frac{1}{\boldsymbol{C}_\perp^2+\nu^2}\right)(1-\cos[(\Omega_1-\Omega_2)\Delta z]) + \ldots\right]\right\} \qquad (2.51)$$





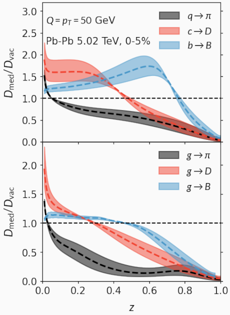
Induced emissions are softer. Clear mass dependence. Dynamically generated energy scale appear. Further factorization is possible.

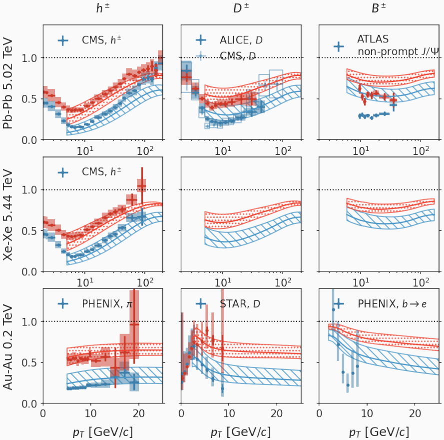
Fragmentation functions from the modified DGLAP evolution

A common practice for very energetic partons: collisional energy loss + numerically solving a medium-modified DGLAP evolution

$$\partial D_{h/i}(z,\mu^2;E')/\partial \ln \mu^2 = [P_{ji}^{\mathrm{vac}} + \Delta P_{ji}^{\mathrm{med}}(x,E')] \otimes D_{h/j}(z,\mu^2;E'), \quad E' = E + \Delta E_{\mathrm{coll}}$$

Medium modified $D(z)$





Reasonable understanding at high-p_T with jet-medium coupling $g_{\mathrm{med}} \sim 1.6$–$2.0$.

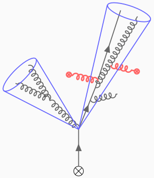
Deviations at low p_T for heavy mesons: low p_T heavy flavor dynamics is qualitatively different!

Most modifications come from $D(z)$ near $z \to 1$, threshold effects?

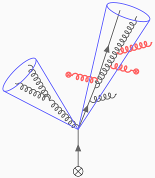
Ke, Vitev PRC107(2023)064903

Dynamics of full jet in medium

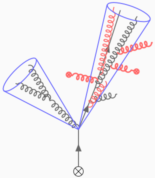
Collision broadening and energy loss



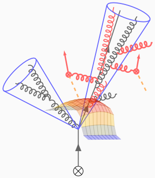
Induced radiation out of the cone



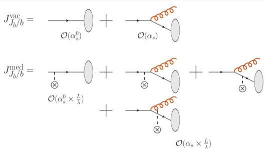
Induced radiation inside the cone

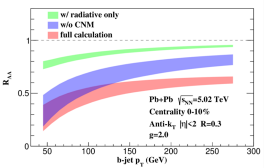


Medium recoil, collective response



Jet function approach: requires a clear separation of scales. The challenge is to consistently incorporate collisional energy loss.





Monte-Carlo coupled to hydro: comprehensive modeling of all effects, computationally intensive to concurrently treat medium response.

$$\partial f_i(z,\mu^2)/\partial \ln \mu^2 = [P_{ij}^{\rm vac} + \Delta P_{ij}^{\rm med}] \otimes f_j(z,\mu^2)$$

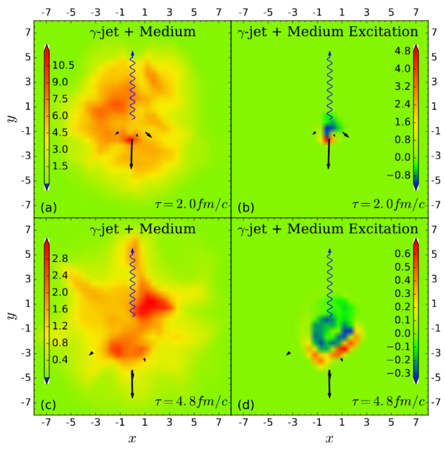
$$p \cdot \partial_x f_i(t,x,p) = \sum \mathcal{C}_{ijX}[f_j, T(x), u^\mu(x)]$$

$$\partial_\mu T^{\mu\nu} = -\sum_i \int d^3p \Theta(p \cdot u - E_{\rm cut}) p^\nu \frac{1}{p^0} p \cdot \partial_x f_i(t,x,p)$$

HT Li, I Vitev JHEP07(2019)148

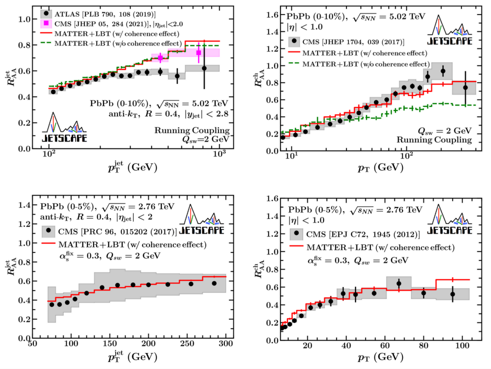
The CoLBT/LBT model:

PLB12(2017)015 transport model with twist-4 splitting function coupled to hydrodynamic evolution

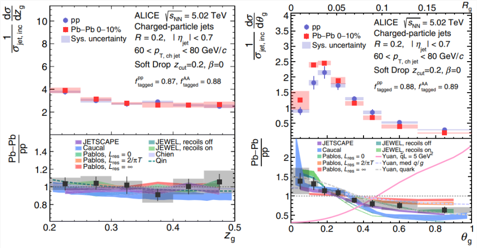


JETSCAPE modular framework: https://jetscape.org/

A multi-stage bulk medium simulation + high-virtual medium-modified shower + parton transport + hadronization + jet-medium coupling.



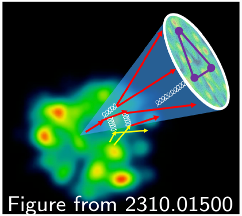
Groomed jets θ_g and z_g distribution

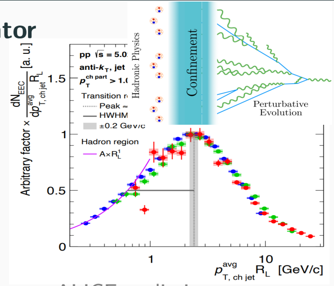


ALICE PRL128(2022)102001

- Use the soft drop grooming to access harder splitting ⇔ perturbative region of medium induced emissions.
- A more differential test of theory.

Energy-energy correlator



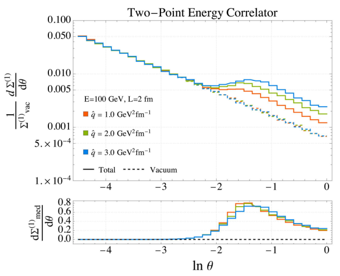


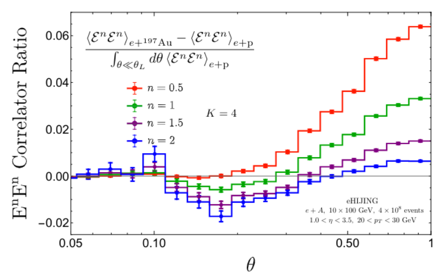
ALICE preliminary
W. Fan's talk at QM23

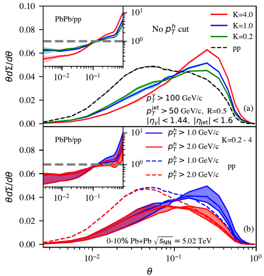
$$\mathrm{EEC}(\theta) = \sum_{ij,X} \int \delta(\theta - \theta_{ij}) \left(\frac{E_i}{Q}\right)^n \left(\frac{E_j}{Q}\right)^n d\sigma_{ij+X}$$

- A very "intuitive" way to analyze correlations of a multi-particle system with "freeze out".
- Scale (θQ) scans from perturbative to NP.

Scan *AA* collisions using jet EEC







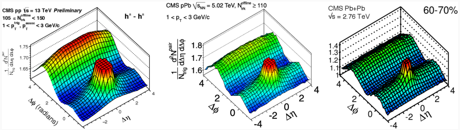
Andres, Dominguez, Holguin, Marquet, Moult 2303.03413

Kyle, Fan, Ke, Kyle, Moult 2303.08143

Yang, He, Moult, Wang 2310.01500

- Dynamical scales from medium-induced emissions on the EEC signal.
- Tuning *n*: flexible to dial down/up medium-induced effects (usually softer).
- A coupled simulation of jet+medium reveals a complicated interplay of broadening, induced radiation, screening, and medium response.
- **Theoretical exploration of the full capacity of the EEC is underway.**

The big puzzle: quenching in small collision systems

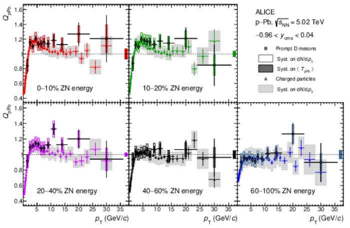


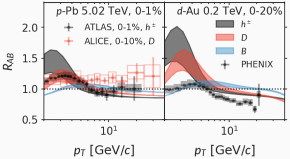
Two-particle correlation in p-p, p-Pb, Pb-Pb, CMS

• Similarity among p-Pb and Pb-Pb may suggest final-state effects in small systems.

T_{max} [GeV] achieved in hydro simulation			
p-Pb 5 TeV		O-O 7 TeV	
0-1%	60-90%	0-10%	30-50%
0.315	0.174	0.325	0.263

• But absence of quenching of high-p_T particles and jets?



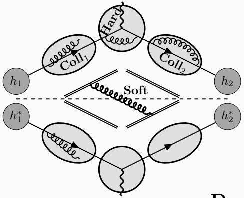


ALICE JHEP12(2019)092.

• The cold nuclear matter effects alone already provide a qualitative understanding.

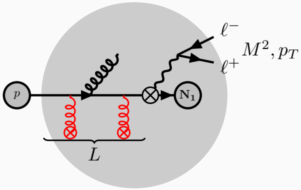
• Need a better control of uncertainty in the cold nuclear matter calculations.

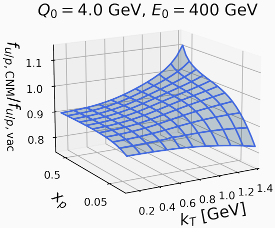
Improve cold nuclear matter calculations using Drell Yan

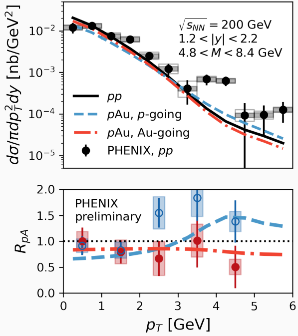


TMD factorization in pp, Boussarie et al. arXiv:2304.03302: $\Lambda^2 \ll \mathbf{p}_T^2 \ll M^2$

$$\frac{d\sigma}{dY dM^2 p_T dp_T} = \sum_{ijq} H_{q\bar{q}}(M,\mu) \int_0^\infty b db J_0(p_T b)[C_{qi} \otimes f_{i/h_1} e^{-S}][C_{\bar{q}j} \otimes f_{j/h_2} e^{-S}] + [q \leftrightarrow \bar{q}]$$







PHENIX PRD99(2019)072003, Leung PoS(HP2018)160.

With TMD parton density evolved in cold nucleat matter, one can use DY data to test the CNM calculation and constrain the parameters Ke, Vitev, in preparation . + **many more we can borrow from the HE/EFT community.**

Heavy flavors: diffusion and hadronization

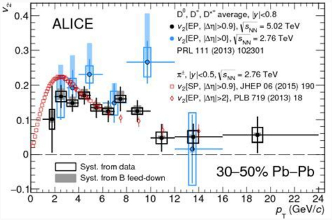
Heavy quark dynamics and hadronization

- Low $p_T \lesssim M$ HQ, radiation suppressed by phase space. Frequent, random interactions with thermal excitations $\Longrightarrow$ Brownian motion described by Langevin equations:

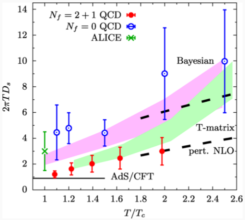
$$\frac{\Delta\vec{x}}{\Delta t} = \frac{\vec{p}}{E}, \quad \frac{\Delta\vec{p}}{\Delta t} = -\Gamma\vec{p} + \delta\vec{F} \Longrightarrow \text{Drag} + \text{random force}$$

$$\langle\delta F_i \delta F_j\rangle = \delta_{ij}\frac{1}{\Delta t}\kappa, \quad \Gamma = \frac{\kappa}{2MT}, \quad \langle\delta x_i \delta x_j\rangle = \delta_{ij} D_s \Delta t \Longrightarrow \text{Spatial diffusion parameter, } D_s = \frac{2T^3}{\kappa}$$

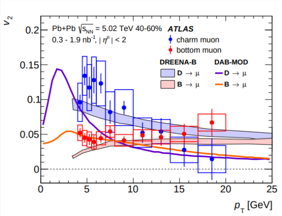
- Phenomenological extracted D_s is found to be consistent with recent lattice calculations, charm quark is strongly coupled with QGP at low p_T.



Low-p_T D-meson flow with the QGP.



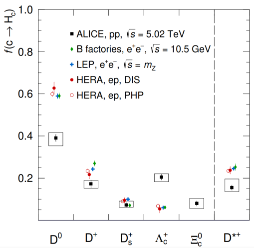
Lattice calculation HotQCD Collaboration, PRL130(2023)231902



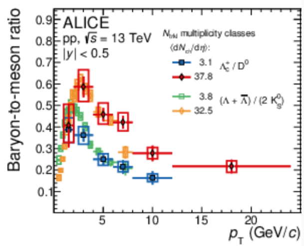
ATLAS PLB807(2020)135595 Bottom quark is too heavy to catch the QGP flow, $\tau_R \sim \frac{T^2/D_s}{M}$. $D_s = A + \frac{??}{M}$.

The hadronization mechanism of heavy flavor

- In e^+e^-, the heavy quark turns into a heavy hadron primarily through the universal fragmentation mechanism.
  - Chance that heavy quark recombines with another parton is power suppressed.
- In pp, AA, low p_T heavy baryon/meson ratio is found to significantly deviate from e^+e^-.
  - Explained by recombination (easier to form baryon) in a parton-rich environment.



Strong enhancement of Λ_c fraction.



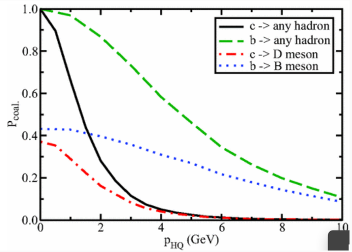
Clear multiplicity dependence at low and intermediate p_T

⋆ Power-suppressed contribution is enhanced by environments.

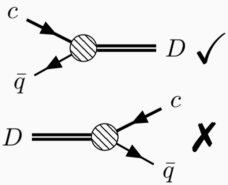
⋆ Fragmentation mechanism is still universal $\Rightarrow$ a two-component model.

⋆ How to match the two? May require EFT analysis.

The instantaneous approach for recombination



Cao, Qin, Bass PRC88(2013)044907



Instantaneous recombination model Oh, Ko, Lee, Yasui, PRC79(2009)044905

- Recombination probability given by **wave function** overlap $|\langle f|i\rangle|^2$.

$$\frac{dP_M}{d^3\vec{P}} = g_M \int_{\vec{r},\vec{p}_2} f_{\bar{q}}(\vec{p}_2) W_M(\vec{r},\vec{q})\delta^{(3)}(\vec{P} - \sum_{i=1}^{2} \vec{p}_i)$$

$$\frac{dP_B}{d^3\vec{P}} = g_B \int_{\vec{r}_{12},\vec{r}_{123},\vec{p}_2,\vec{p}_3} f_{\bar{q}}(\vec{p}_2) f_{\bar{q}'}(\vec{p}_3) W_B(\vec{r}_{12},\vec{r}_{123},\vec{q}_{12},\vec{q}_{123})\delta^{(3)}(\vec{P} - \sum_{i=1}^{3} \vec{p}_i)$$

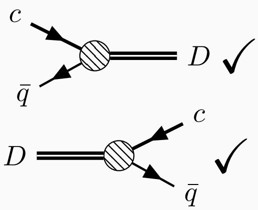
f^W: the Wigner function of the bound state.

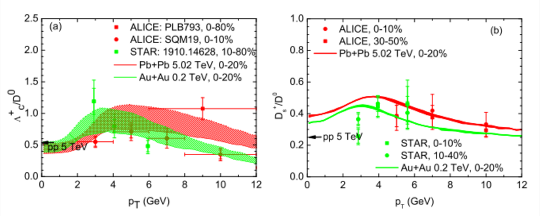
f_q: light quark distribution at the instant of hadronization.

- Neglects the detailed balance contribution. A highly non-equilibrium procedure: f_q thermal, $\frac{dP_M}{d^3\vec{P}}$ non-thermal.

The resonance recombination model

- Treat the recombined meson as resonance Ravagli, Rapp PLB655(2007)126–131, He, Rapp
- The instantaneous approach violates energy conservation. This can be fixed by the finite resonance width.
- Detailed balance can be restored, and the correct equilibrium limit is restored in the model.





He, Rapp PRL124(2020)042301

Summary

- Heavy-ion collisions at the LHC are excellent for the study of QCD matter at finite temperature: "perturb" the medium and study the "response".
- Long-wave length response $\Rightarrow$ hydrodynamic energy-momentum transport.
- Jets are multiscale probles. Contain the information from the basic interaction strength between jet and QGP to medium energy/length scales.
    - Require both event generator and EFT studies.
    - Explore the full potential of novel observables: jet substructures, EEC.
- Heavy flavor production in AA, pA, pp calls for new understanding of hadronization in environment.
- Many topics not covered: quarkonia, polarization, magnetic field, CME, small-x, UPC, etc.

Questions