Energy loss and transport in the medium and in small systems

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Large systems: experimental status, charm

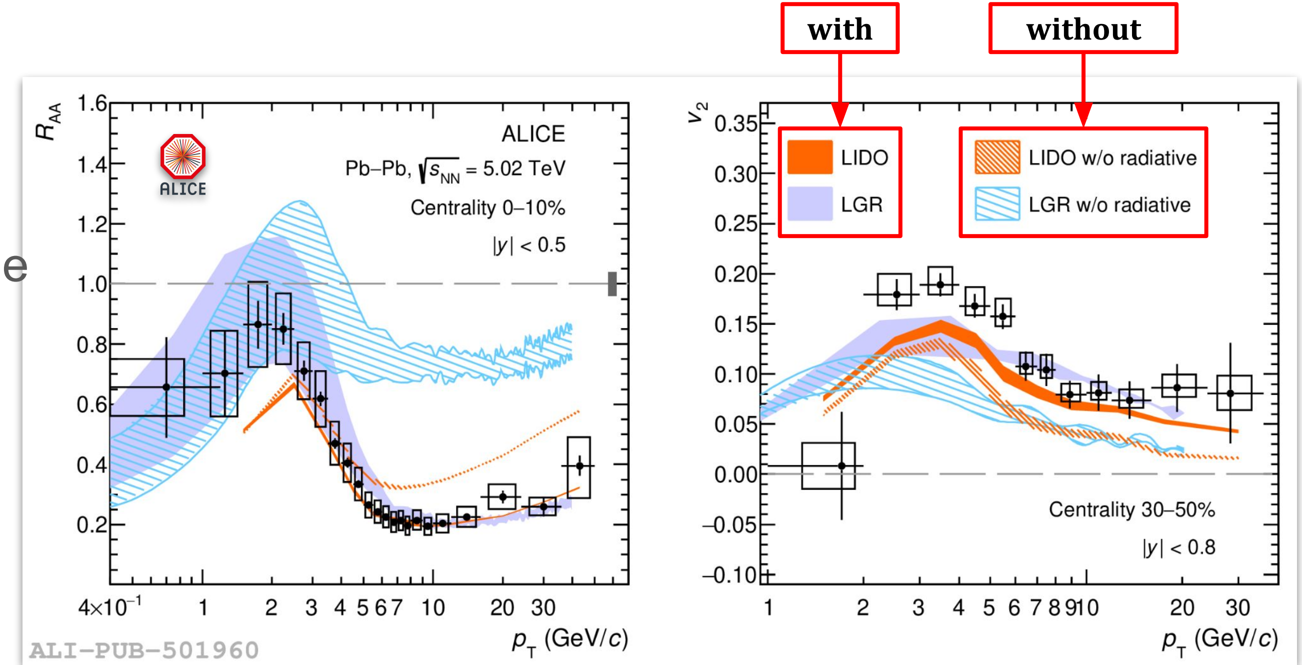
Non-strange prompt D mesons R_{AA}, v_2, v_3 measured with good precision

High p_T: role of radiative processes clearly evidenced (well understood?), data precision comparable or better than theoretical uncertainties.

New measurements in peripheral collisions?

may allow constraining the system-size dependence of energy loss

+bridge to small systems including O-O



with

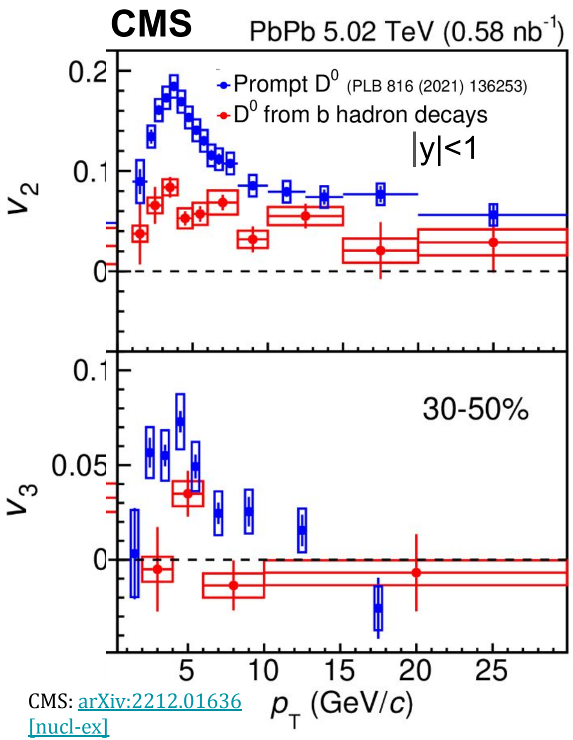
without

ALICE: JHEP 01 (2022) 174 LIDO: PRC 98, 064901 (2018) LGR: EPJC 80 (2020) 7, 671

Large systems: experimental status, charm

Non-strange prompt D mesons R_{AA}, v_2, v_3 measured with good precision

Low p_T: constrain transport models and transport coefficient Ds but hadronization…



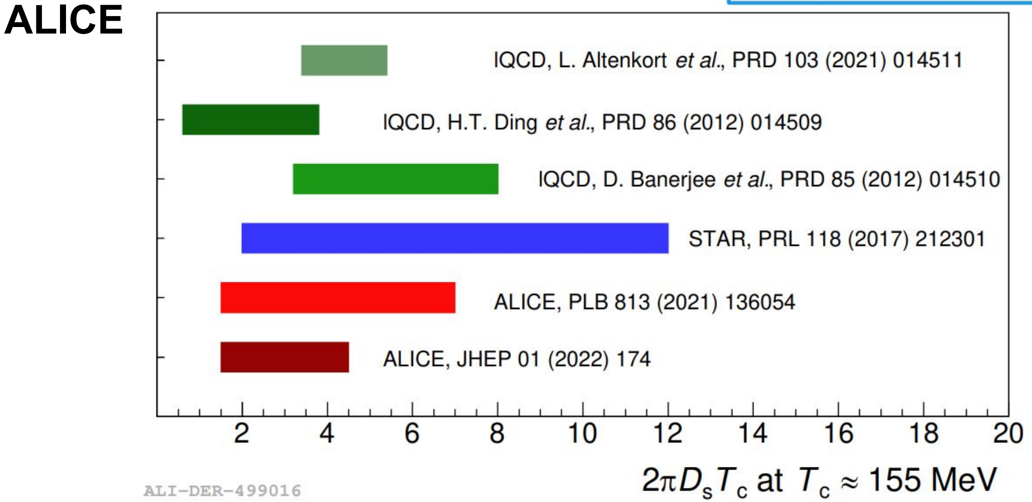
CMS: arXiv:2212.01636 [nucl-ex]

Constraining the spatial diffusion coefficient via the **data-to-model agreement**

→ Using R_{AA} (with $\chi^2/\mathrm{ndf} < 5$) and v_2 (with $\chi^2/\mathrm{ndf} < 2$) non-strange D measurements

→ TAMU, MC@sHQ, LIDO, LGR, and Catania "selected"

→ $1.5 < 2\pi D_s T_c < 4.5$
→ $\tau_{\mathrm{charm}} \simeq$ 3–8 fm/c



Remarks from the WS: better discuss **κ**, not Ds
Remember **κ** depends on momentum!

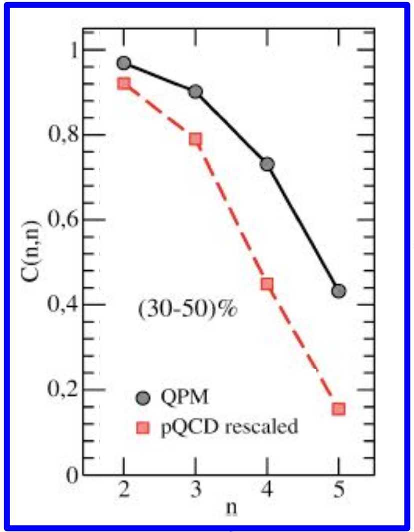
Charm: further, more “differential” view?

Discussion on new observables possibly in reach in the future

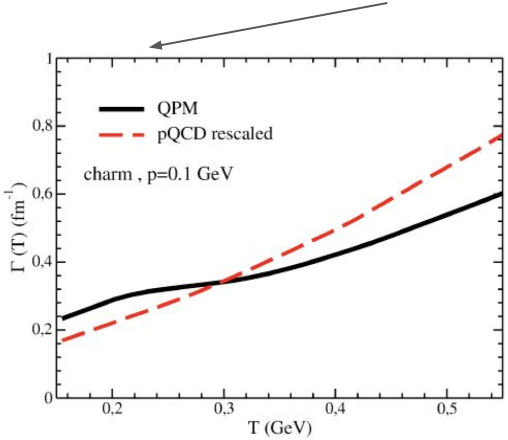
Light-heavy v_n-fluctuation correlations

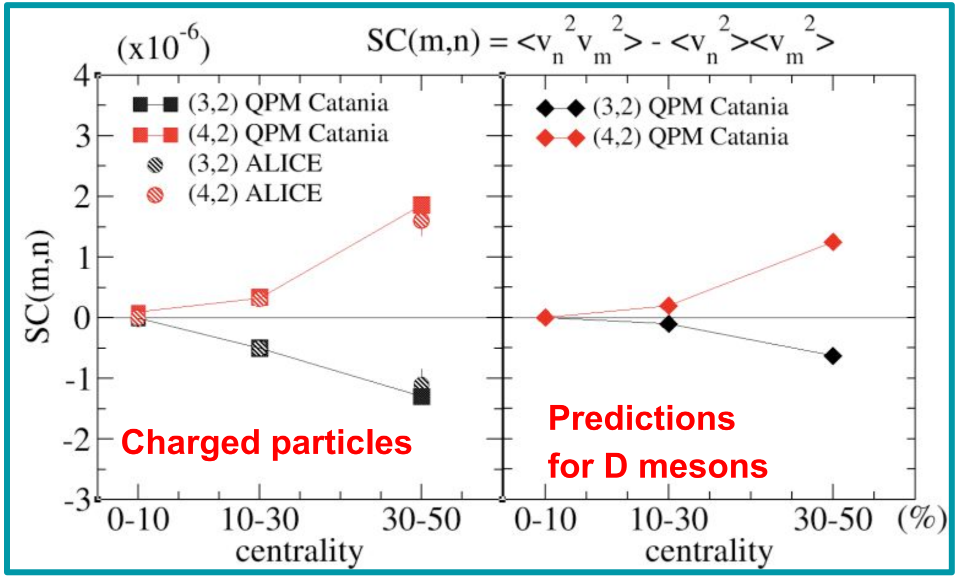
v_n- v_m correlations

gain sensitivity to temperature (and momentum?) dependence of drag coeff.?



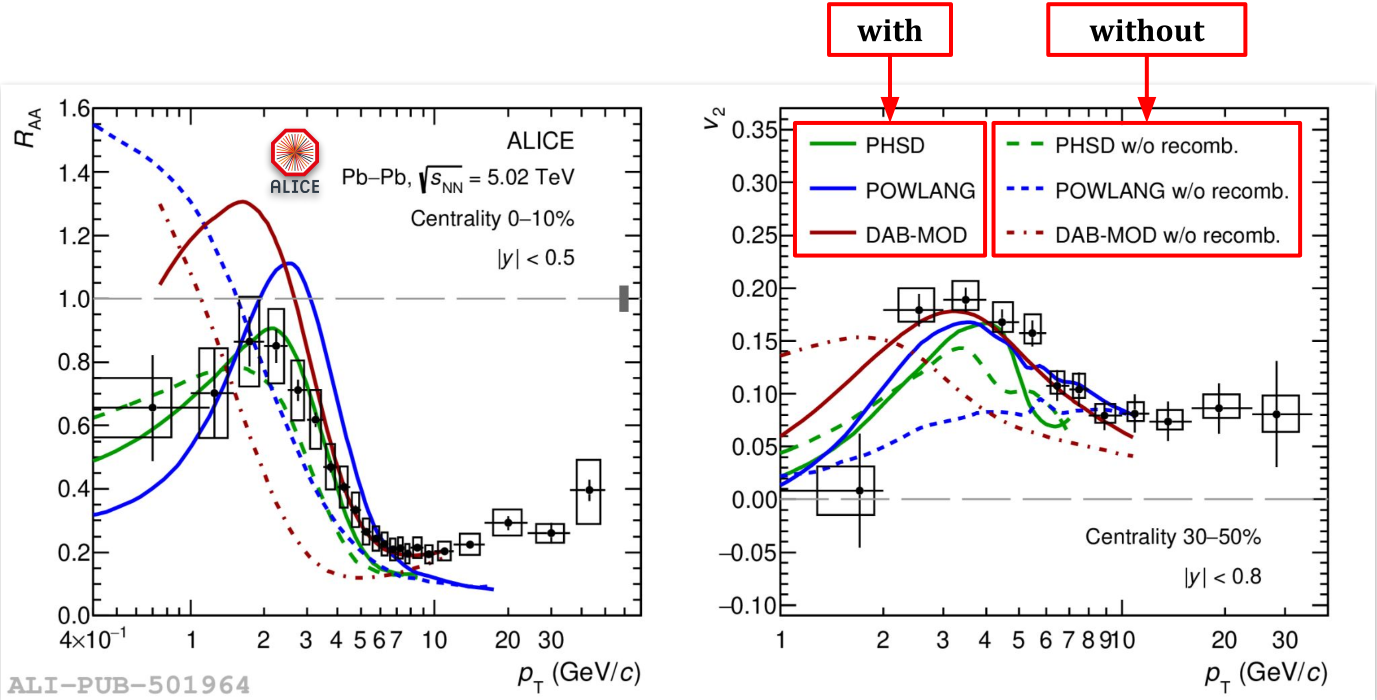
$$C\left(v_n^{light}, v_m^{heavy}\right)=\left\langle \frac{\left(v_n^{light}-\langle v_n^{light}\rangle\right)\left(v_m^{heavy}-\langle v_m^{heavy}\rangle\right)}{\sigma_{v_n^{light}}\,\sigma_{v_m^{heavy}}} \right\rangle$$





Plumari et al, Phys.Lett.B 805 (2020) 135460 M.L. Sambataro, et al., *Eur.Phys.J.C*82 (2022)

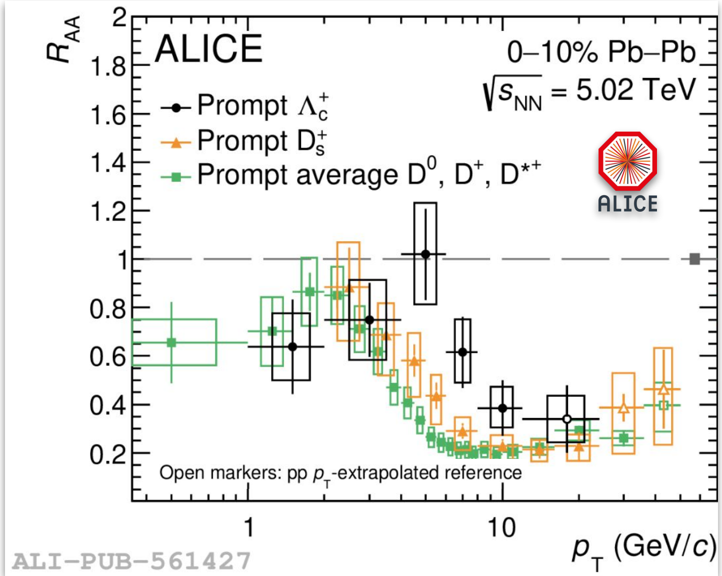
Charm hadronization



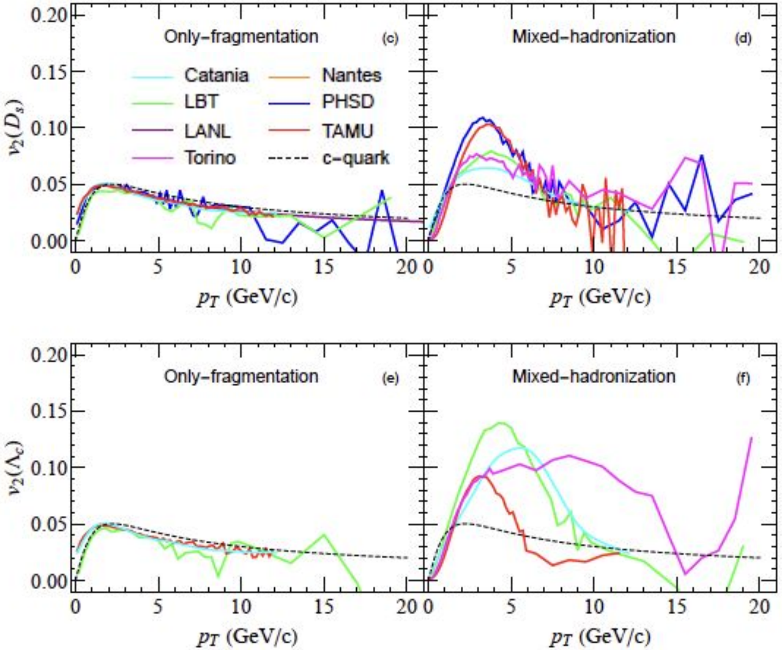
ALICE: JHEP 01 (2022) 174

Modelling of hadronization crucial for reproducing data → confounding effect for the goal of understanding partonic dynamics and extracting transport coefficients

Charm hadronization



ALICE: PLB 839 (2023) 137796



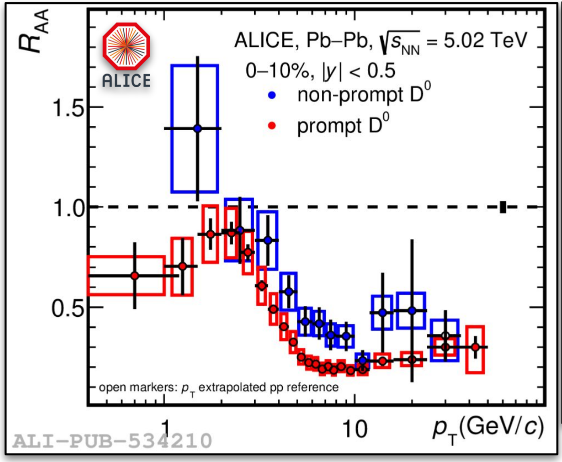
J. Zhao et al., Phys.Rev.C 109 (2024) 5, 054912

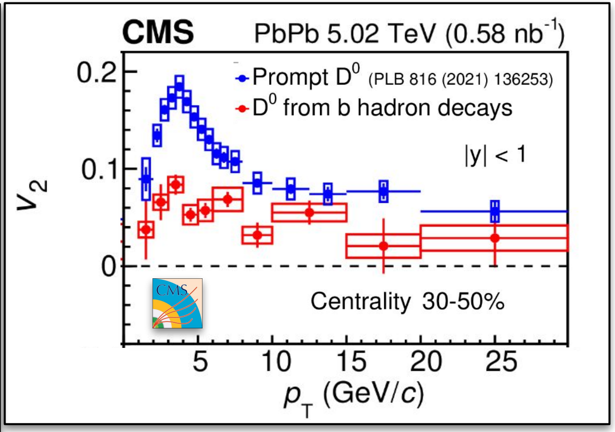
Effort on both experimental and theoretical sides ongoing

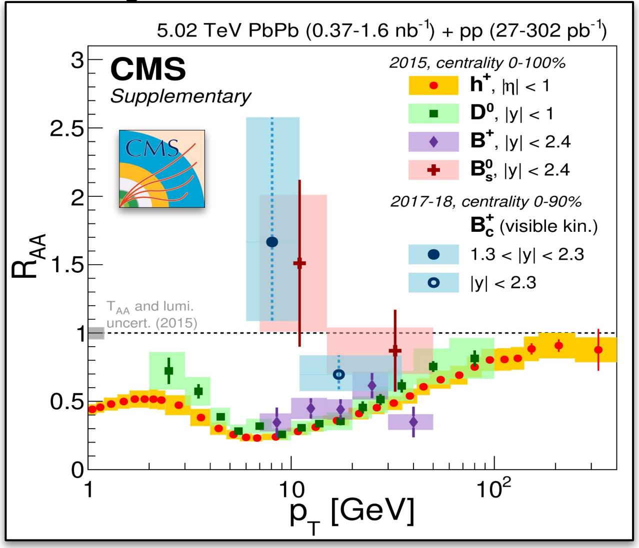
Measurements of different hadron species needed

- baryons in Pb-Pb: run 2 measurements of Λ_c limited precision. Other missing: Ξ_c, …
- D_s vs. D also require better precision

Large systems: experimental status, beauty







LHC run 2 measurements provided important indications but still limited

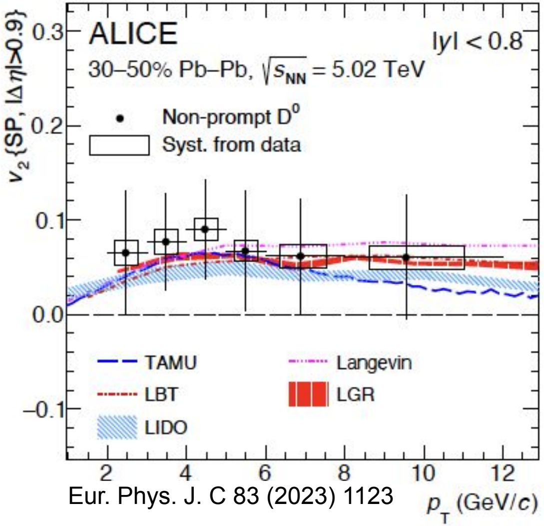
- precision
- p_T reach
- “smearing” of physical effects due to decay kinematics

Run 3,4 at LHC: era of precise beauty measurements?

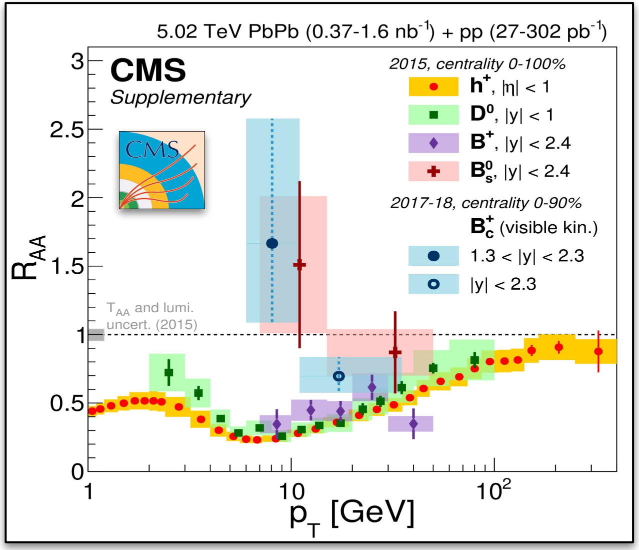
Beauty more “ideal” than charm for transport models. But precise measurement of fully reconstructed B mesons or Λ_b down to low pt remains very challenging.

CMS: PRL 128 (2022) 252301
CMS: PRL 123, 022001 (2019)
ALICE: JHEP 12 (2022) 126

Full b-hadrons and non-prompt signals



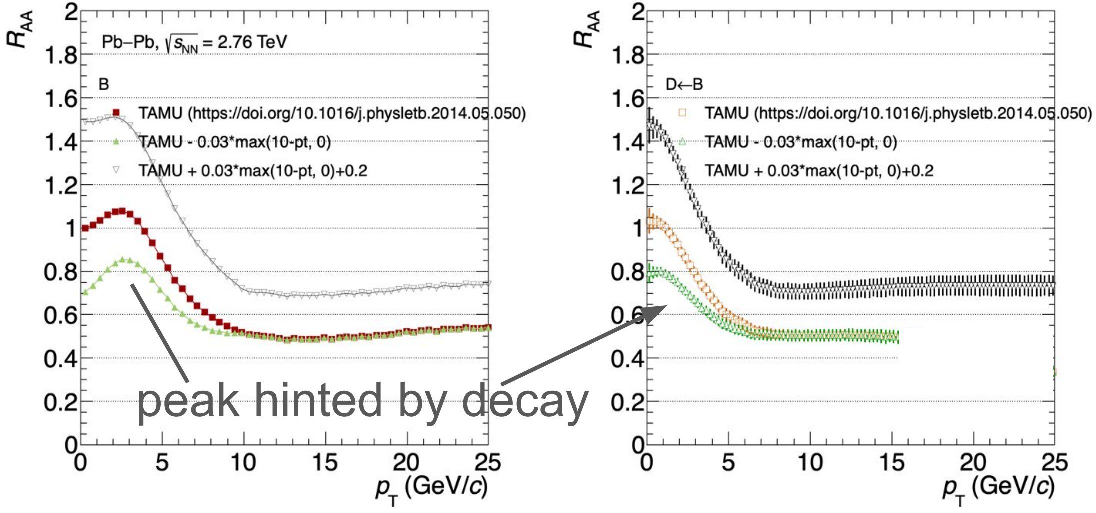
Eur. Phys. J. C 83 (2023) 1123



Measurements of b-hadron in exclusive decay require a lot of statistics

1) Up to what extent we lose information by measuring instead non-prompt signals (e.g. non-prompt $D^{0,+}$, D_s^+, J/ψ, Λ_c^+) with high-precision over a wide pt range ?
   a) what is the precision needed on B, Λ_b measurements to really carry superious information than non-prompt signals?
   b) How much do beauty R_{AA} and v_2 depend on p_T?
2) what is the uncertainty from the decay kinematics on non-prompt signals?
   a) proposal: all theorists try with same decayer or share the decayers

Full b-hadrons and non-prompt signals



peak hinted by decay

Quick toy test done at the WS.
Input: FONLL B mesons + RAA model + PYTHIA decayer
Could be repeated for different R_{AA} predictions and decayers
Also for v_2

Measurements of b-hadron in exclusive decay require a lot of statistics

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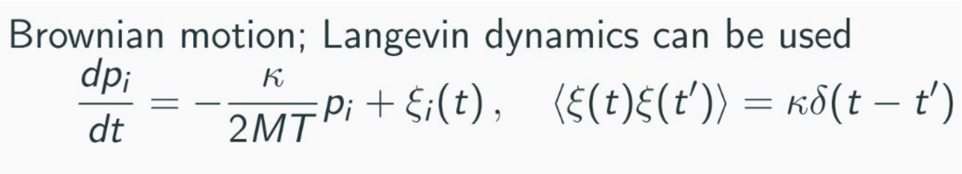
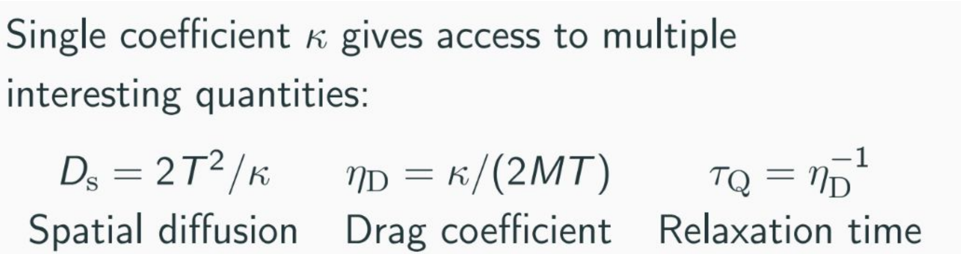
Traditional theoretical framework



Brownian motion; Langevin dynamics can be used

$$\frac{dp_i}{dt} = -\frac{\kappa}{2MT} p_i + \xi_i(t)\,, \quad \langle \xi(t)\xi(t') \rangle = \kappa\delta(t-t')$$



Single coefficient κ gives access to multiple interesting quantities:

$D_\mathrm{s} = 2T^2/\kappa$	$\eta_\mathrm{D} = \kappa/(2MT)$	$\tau_\mathrm{Q} = \eta_\mathrm{D}^{-1}$
Spatial diffusion	Drag coefficient	Relaxation time

$$P(\Delta x, t) = \frac{1}{(2\pi\sigma^2)^{d/2}} e^{-\frac{1}{2}\frac{(\Delta x)^2}{\sigma^2}} \qquad \sigma^2(t) = 2Dt - \frac{2D}{\eta}(1 - e^{-\eta t})\,.$$

NB kappa is the quantity with a well-defined QFT meaning: please, use it rather then Ds!

kappa from lattice-QCD: the basis

kappa arises from force-force correlator:

$$\langle \xi(t)\xi(t')\rangle = \kappa\delta(t-t') \qquad F(t) = \dot{p} = q\,(E + v \times B))\,(t)$$

Both electric and *magnetic field* (new!) fluctuations contribute:

$$\kappa_{\mathrm{tot}} \simeq \kappa_{\mathrm{E}} + \frac{2}{3}\langle v^2\rangle \kappa_{\mathrm{B}}$$

Only Euclidean correlators

accessible on the lattice!

kappa to be extracted

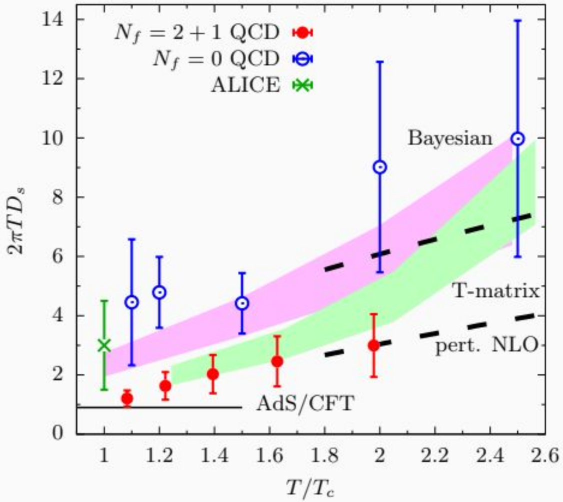
from the spectral function!

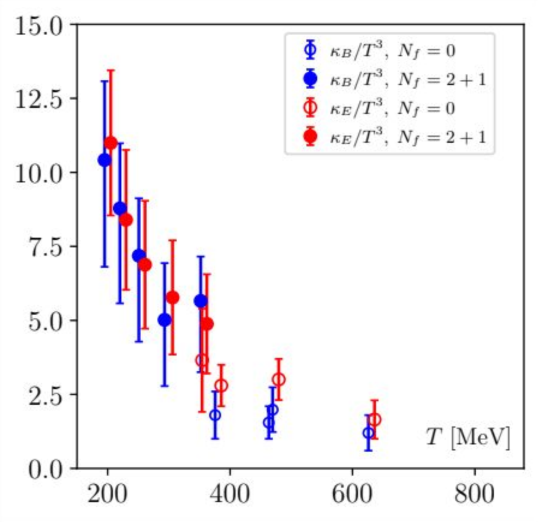
$$G_{\mathrm{E}}(\tau) = -\frac{1}{3}\sum_{i=1}^{3}\frac{\langle \mathrm{Re\,Tr}\,[U(\beta,\tau)gE_i(\tau,0)U(\tau,0)gE_i(0,0)]\rangle}{\langle \mathrm{Re\,Tr}\,[U(\beta,0)]\rangle},$$

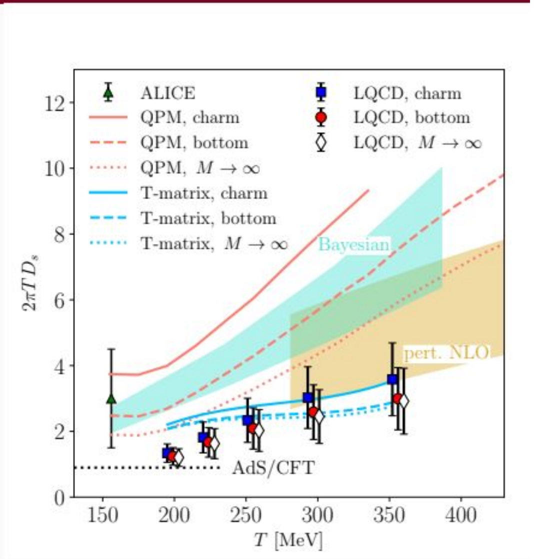
$$G_{\mathrm{B}}(\tau) = \sum_{i=1}^{3}\frac{\langle \mathrm{Re\,Tr}\,[U(1/T,\tau)B_i(\tau,0)U(\tau,0)B_i(0,0)]\rangle}{3\,\langle \mathrm{Re\,Tr}\,U(1/T,0)\rangle}$$

$$\kappa_{\mathrm{E,B}} = \lim_{\omega\to 0}\frac{2T}{\omega}\rho(\omega) \qquad G_{\mathrm{E,B}}(\tau) = \int_0^\infty \frac{\mathrm{d}\omega}{\pi}\rho(\omega)\frac{\cosh\left(\frac{\omega}{T}[\tau T - \frac{1}{2}]\right)}{\sinh\frac{\omega}{2T}}$$

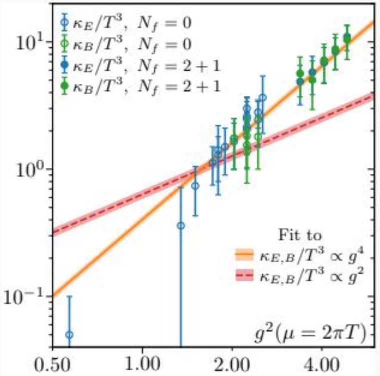
κ_{E} dependence on dynamical fermions







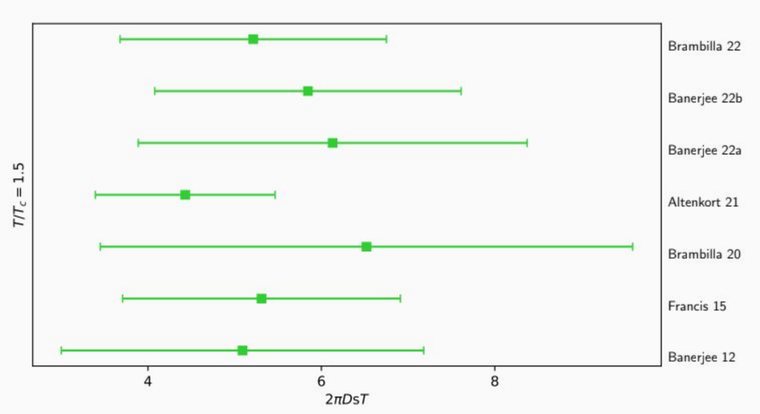
- Most studies have been in pure gauge
- Recent results from HOTQCD
- Main difference to pure gauge is different T_c

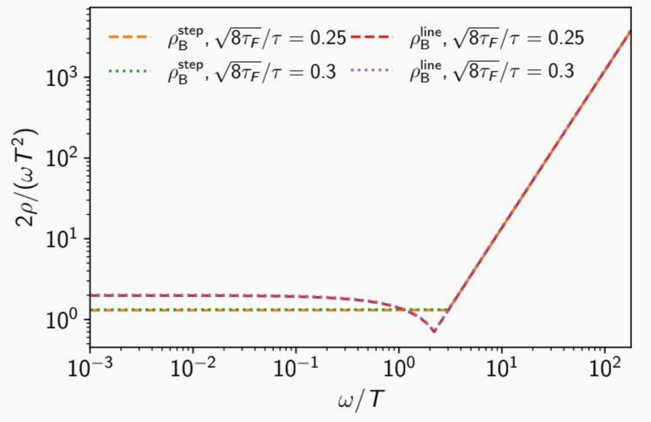


HOTQCD: Phys.Rev.Lett. 130 (2023), Phys.Rev.Lett. 132 (2024), Phys.Rev.D 109 (2024)

kappa from lattice-QCD: limitations

Huge systematic uncertainties from spectral-function extraction

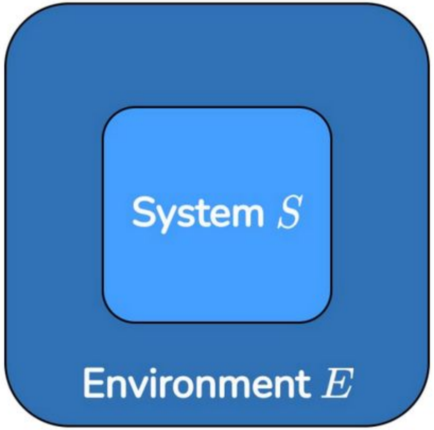




Most experimental data referring to a relativistic kinematics, where momentum dependence of transport coefficients, not accessible on the lattice, can play important role!

Open Quantum Systems:
a unified picture of HQ and quarkonia

Open Quantum Systems



- Time evolution by Von-Neumann Equation

$$\frac{d}{dt}\rho = -i[H,\rho]$$

- Environmental d.o.f. not needed Trace out!

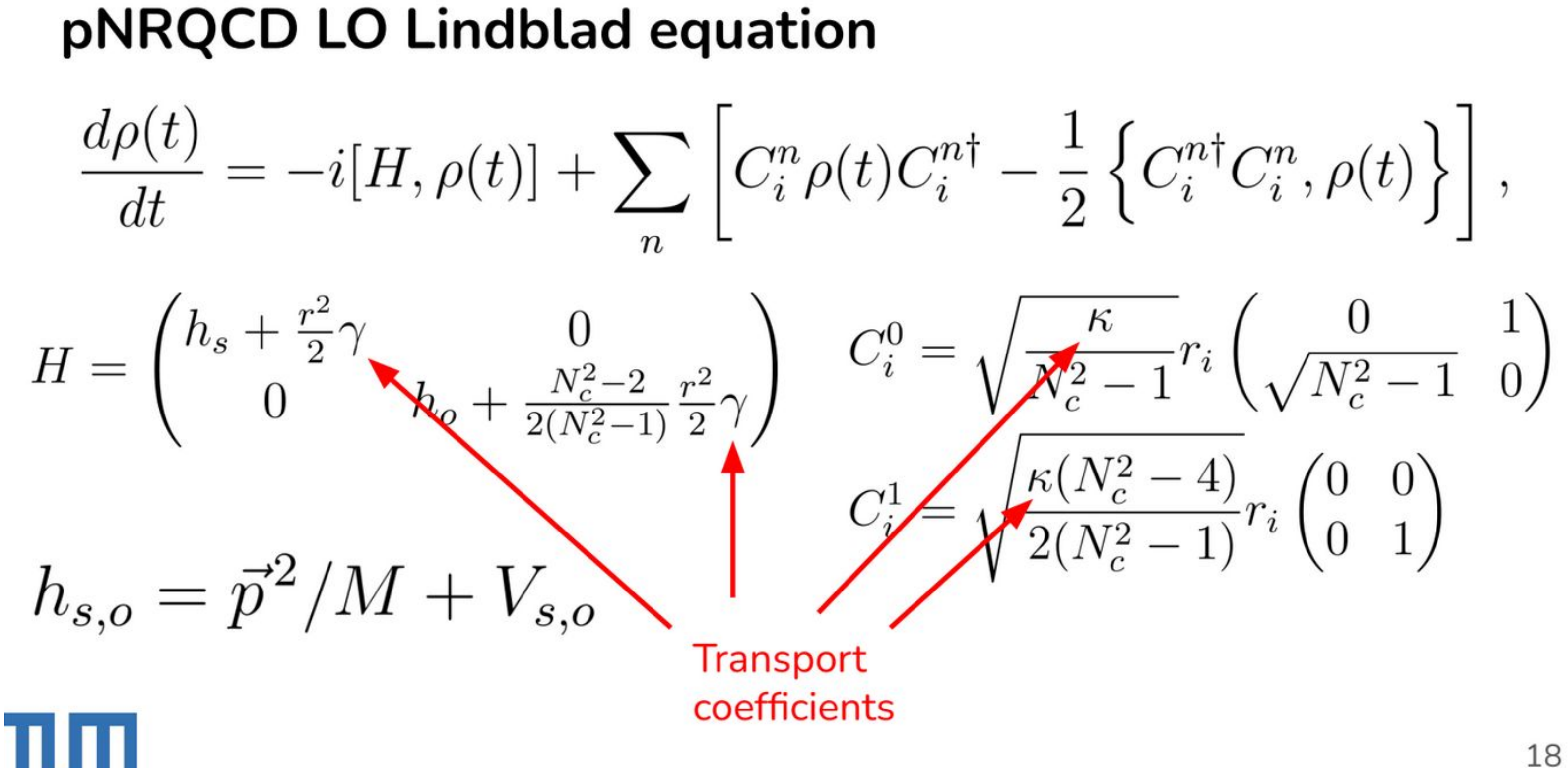
$$\rho_S = \mathrm{Tr}_E[\rho]$$

- “Master equation” for the System: **Lindblad Equation**

non-unitary

$$\frac{d\rho_S}{dt} = -i[H_S,\rho_S] + \sum_n \left(C_n \rho_S C_n^\dagger - \frac{1}{2}\{C_n^\dagger C_n, \rho_S\} \right)$$

Open Quantum Systems: transport coefficients



pNRQCD LO Lindblad equation

$$\frac{d\rho(t)}{dt} = -i[H,\rho(t)] + \sum_n \left[C_i^n \rho(t) C_i^{n\dagger} - \frac{1}{2}\left\{C_i^{n\dagger} C_i^n, \rho(t)\right\}\right],$$

$$H = \begin{pmatrix} h_s + \frac{r^2}{2}\gamma & 0 \\ 0 & h_o + \frac{N_c^2-2}{2(N_c^2-1)}\frac{r^2}{2}\gamma \end{pmatrix}$$

$$C_i^0 = \sqrt{\frac{\kappa}{N_c^2-1}}\, r_i \begin{pmatrix} 0 & 1 \\ \sqrt{N_c^2-1} & 0 \end{pmatrix}$$

$$C_i^1 = \sqrt{\frac{\kappa(N_c^2-4)}{2(N_c^2-1)}}\, r_i \begin{pmatrix} 0 & 0 \\ 0 & 1 \end{pmatrix}$$

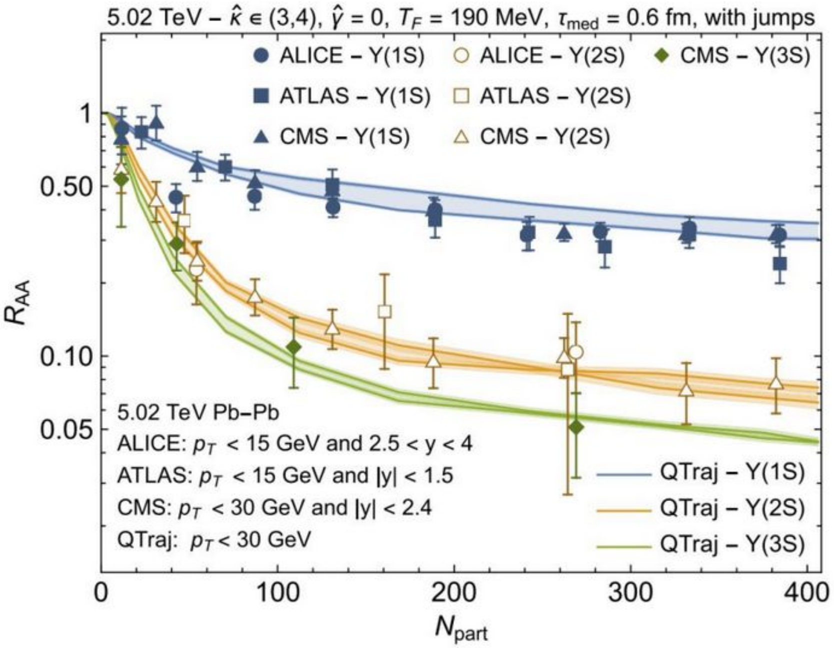
$$h_{s,o} = \vec{p}^{\,2}/M + V_{s,o}$$

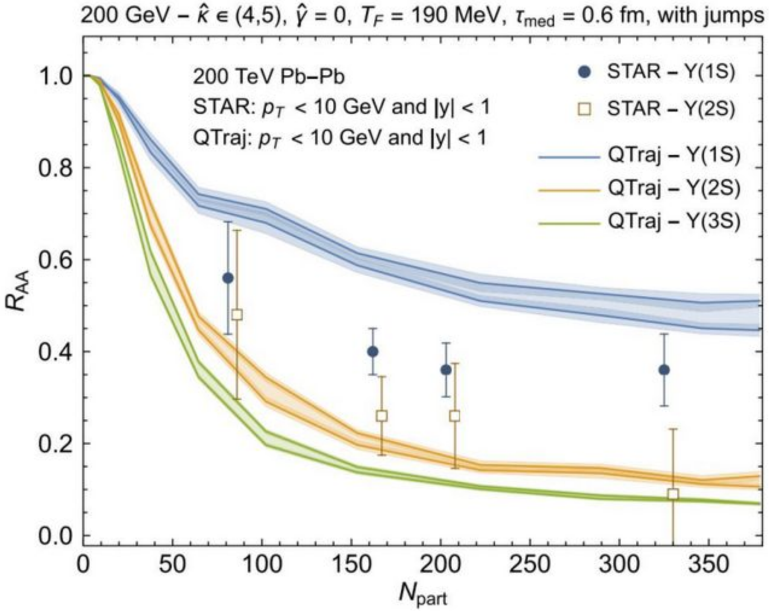
Transport coefficients

Open Quantum Systems for Upsilon: results

NLO results

Michael Strickland, Sabin Thapa, PHYSICAL REVIEW D 108, 014031 (2023)

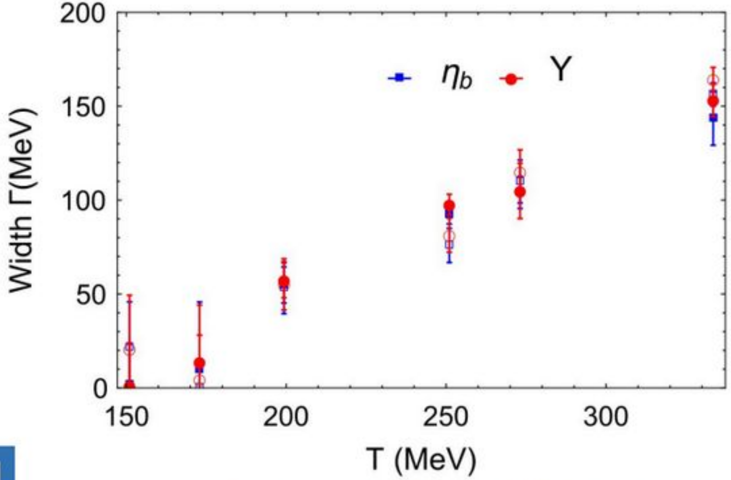




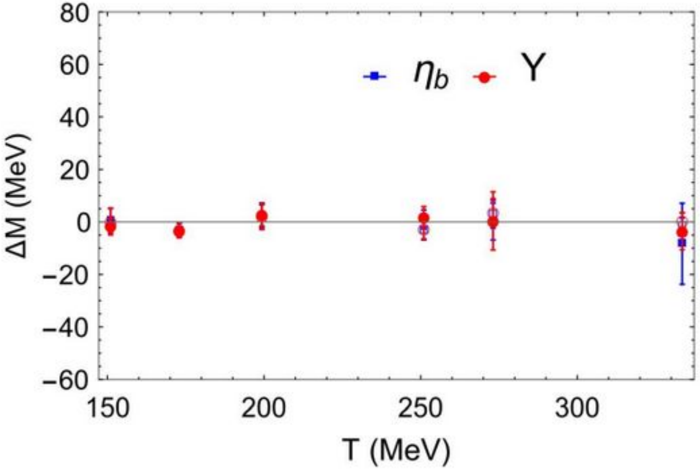
HF transport coefficients and OQS

- Indirectly determine $\hat{\kappa}$ and $\hat{\gamma}$ from lattice measurements of the **in medium width** Γ and **mass shift** δm

$$\Gamma \propto \hat{\kappa}$$



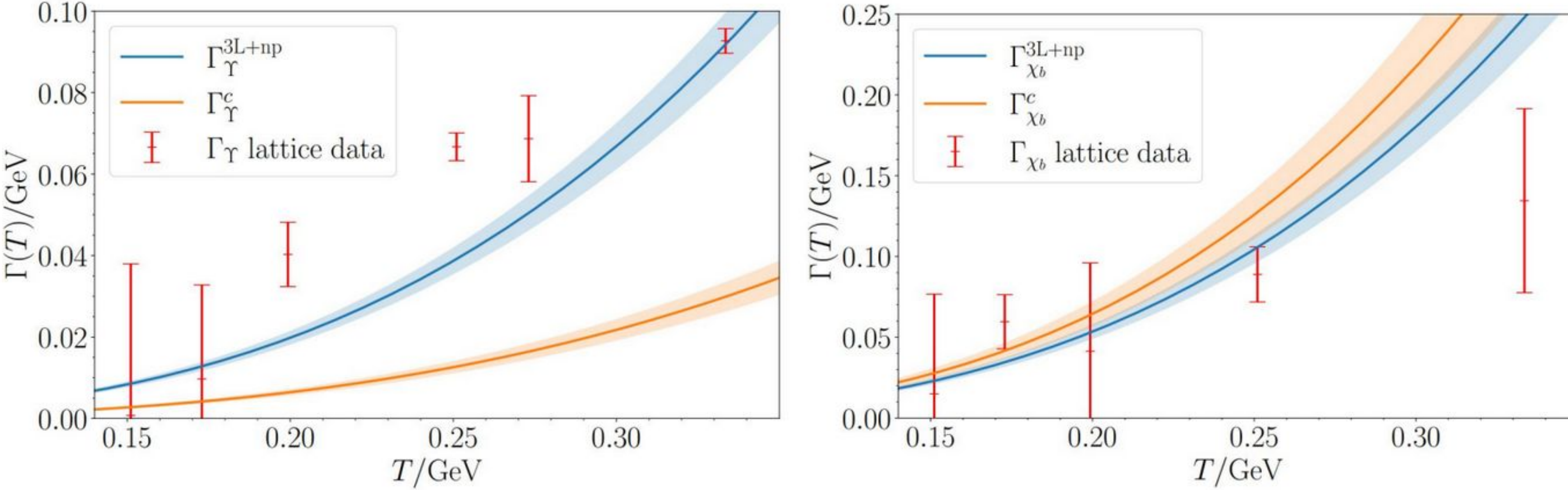
$$\delta m \propto \hat{\gamma} \;\Rightarrow \hat{\gamma} = 0$$



R. Larsen, S. Meinel, S. Mukherjee, and P. Petreczky, Physical Review D 100 (2019)

Determination of transport coefficients

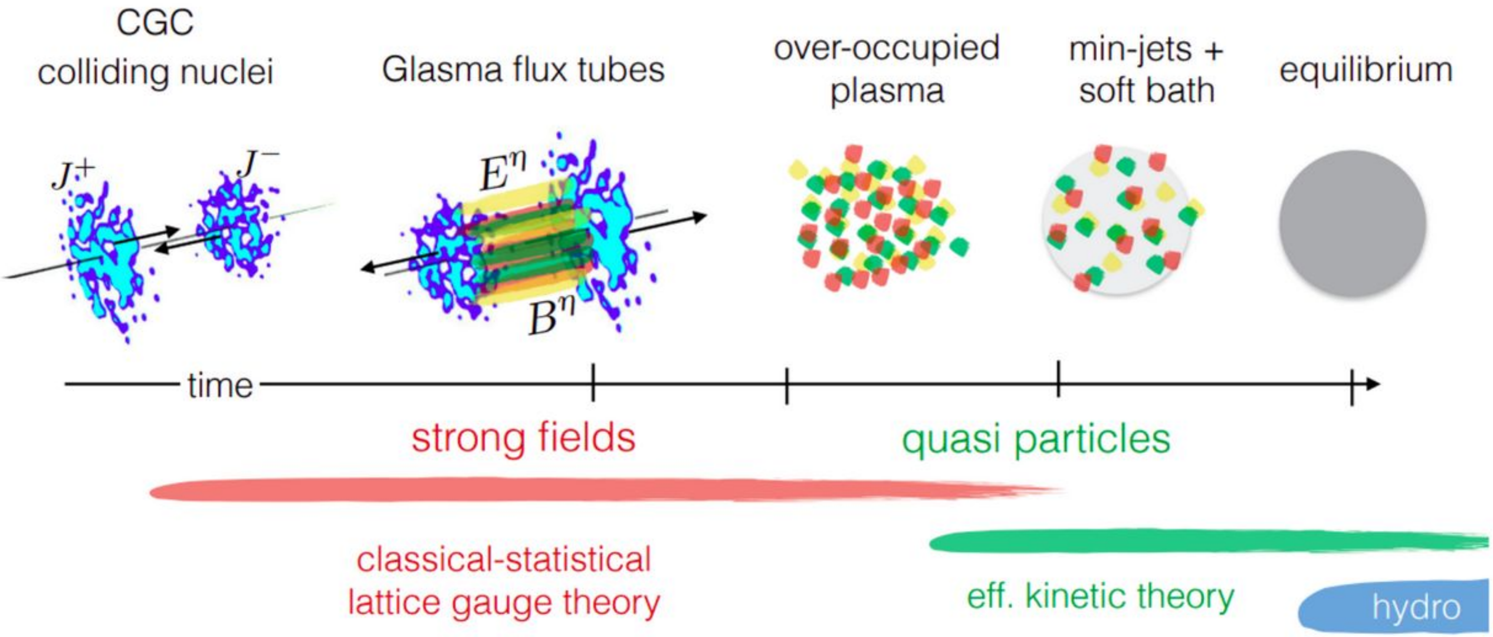
- Obtain $\hat{\kappa}$ from fits to $1S$ and $1P$ data and average



Coulomb: $\hat{\kappa} = 0.33 \pm 0.04$

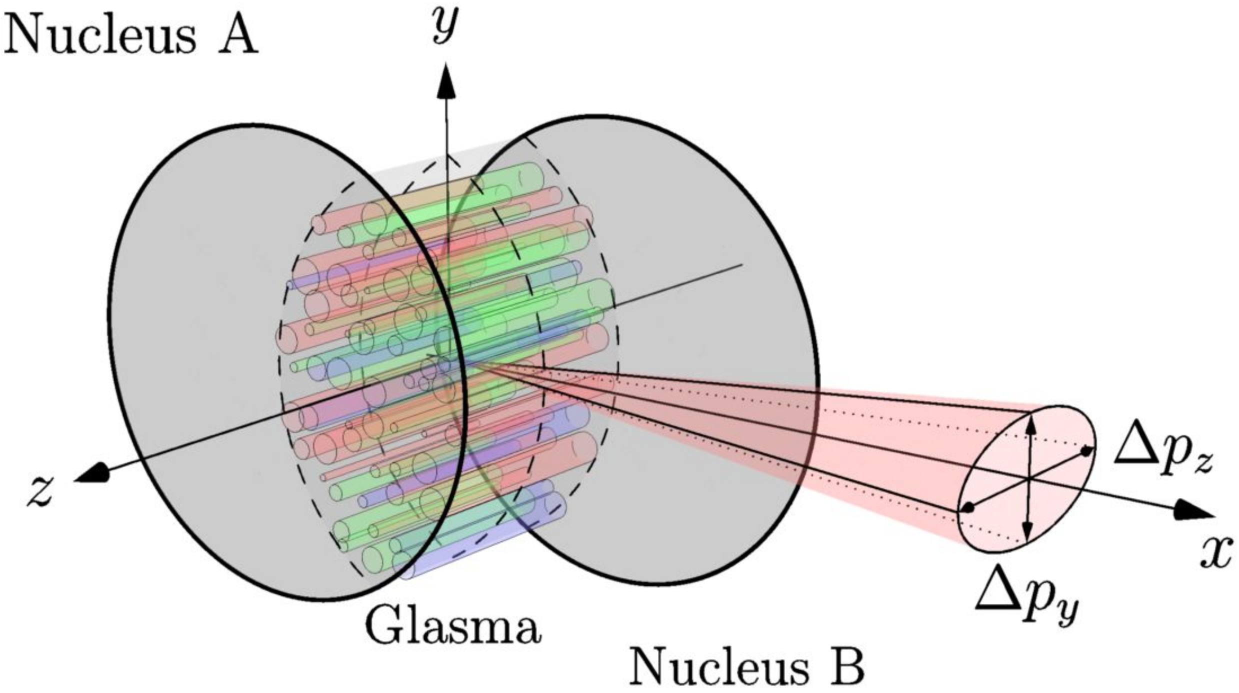
New potential: $\hat{\kappa} = 1.88 \pm 0.16$

(HQ-)Transport in the pre-equilibrium stage



Schlichting [Initial Stages (2016)]

HQ transport in the Glasma



Ipp, Müller, Schuh [Phys.Lett.B810(2020)]

Wong's equations

coordinate

$$\frac{\mathrm{d}}{\mathrm{d}\boldsymbol{\tau}}x^{\mu} = \frac{p^{\mu}}{m},$$

mass

proper time

momentum

gauge field

$$\frac{\mathrm{D}}{\mathrm{d}\boldsymbol{\tau}}p^{\mu} = 2g\mathrm{Tr}\left\{QF^{\mu\nu}[A^{\mu}]\right\}\frac{p_{\nu}}{m},$$

coupling constant

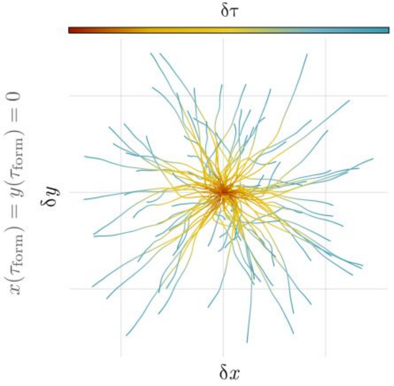
covariant derivative

color charge

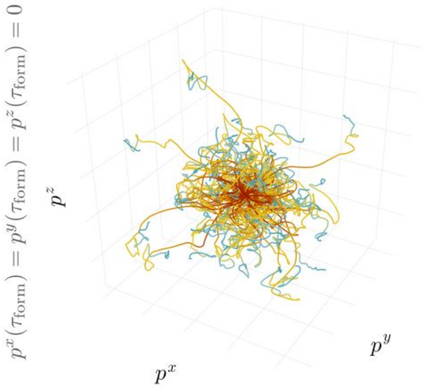
$$\underbrace{\frac{\mathrm{d}}{\mathrm{d}\boldsymbol{\tau}}Q = -\mathrm{i}g[A_{\mu}, Q]\frac{p^{\mu}}{m}}_{\text{color rotation} \to \mathcal{U} \in \mathrm{SU}(3)}$$

$$Q(\boldsymbol{\tau}) = \mathcal{U}(\boldsymbol{\tau},\boldsymbol{\tau}')Q(\boldsymbol{\tau}')\mathcal{U}^{\dagger}(\boldsymbol{\tau},\boldsymbol{\tau}')$$

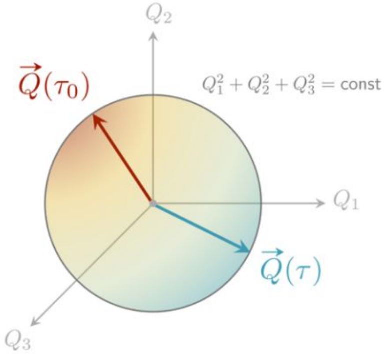
Change of coordinates



Color Lorentz force



Color rotation



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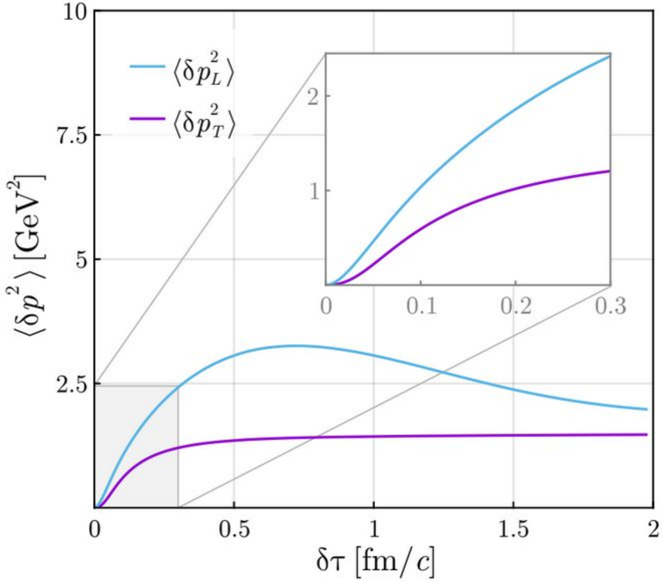
*Avramescu, Băran, Greco, Ipp, Müller, Ruggieri [Phys.Rev.D107(2023)]

HQ in the Glasma: results

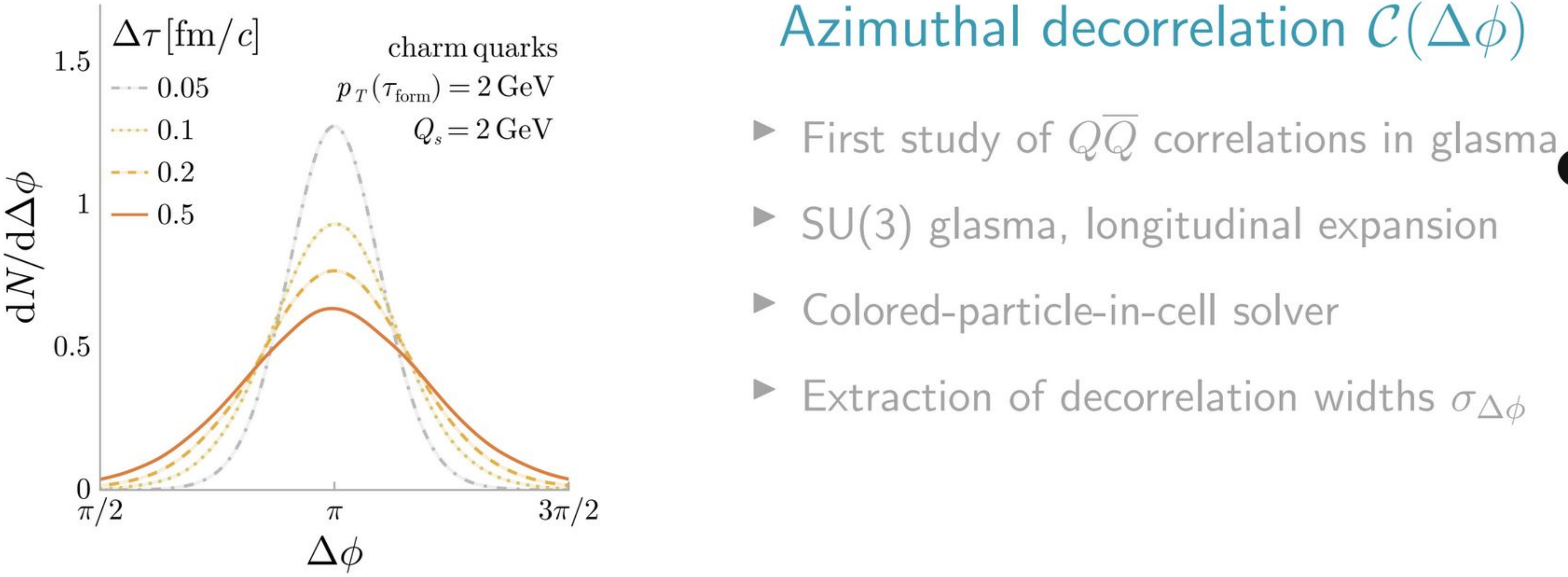


Momentum broadening $\langle \delta p^2 \rangle$
Transport coefficient κ

- SU(3) glasma, longitudinal expansion
- Colored-particle-in-cell solver
- Compared with correlator method

Avramescu, Băran, Greco, Ipp, Müller, Ruggieri [Phys.Rev.D107(2023)]

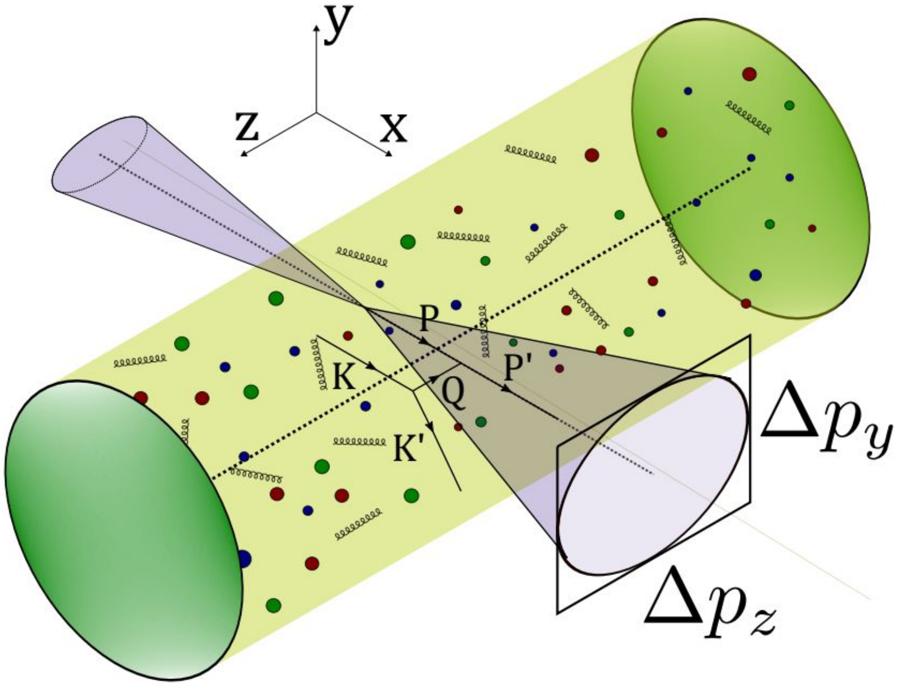
HQ in the Glasma: results



Azimuthal decorrelation $\mathcal{C}(\Delta\phi)$

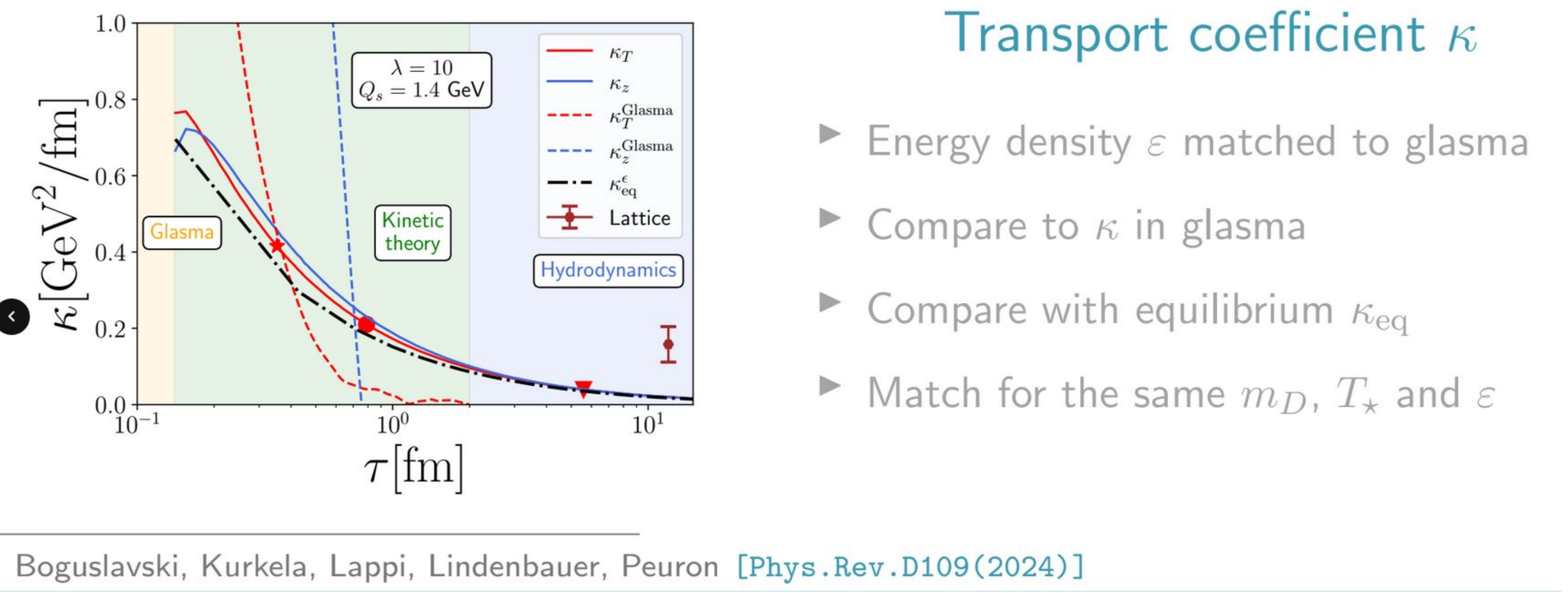
- First study of $Q\overline{Q}$ correlations in glasma
- SU(3) glasma, longitudinal expansion
- Colored-particle-in-cell solver
- Extraction of decorrelation widths $\sigma_{\Delta\phi}$

Pre-equilibrium HQ transport in EKT



Boguslavski, Kurkela, Lappi, Lindenbauer, Peuron [Phys.Rev.D110(2024)]

Problems: Glasma-EKT matching



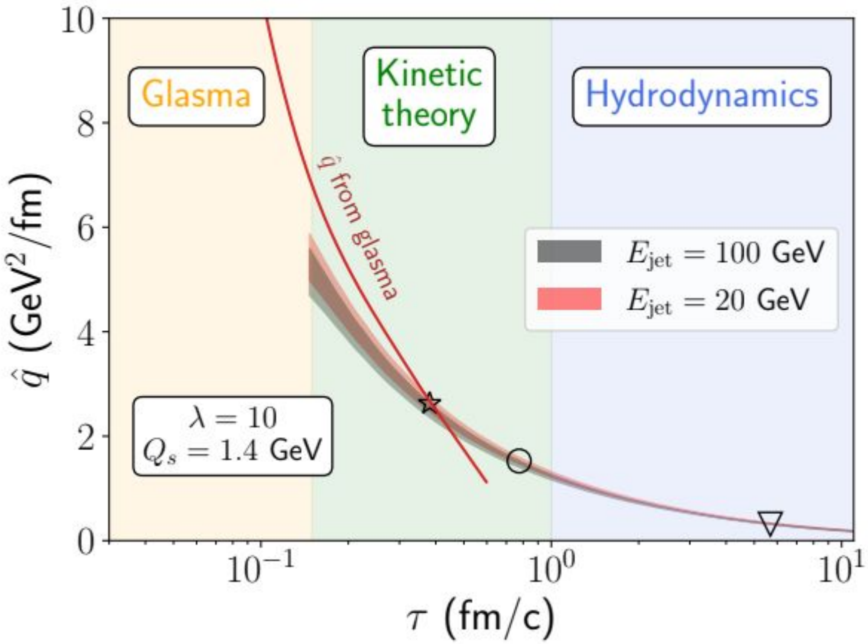
Transport coefficient κ

- Energy density ε matched to glasma
- Compare to κ in glasma
- Compare with equilibrium κ_{eq}
- Match for the same m_D, $T_\star$ and ε

Boguslavski, Kurkela, Lappi, Lindenbauer, Peuron [Phys.Rev.D109(2024)]

Not the same problem for qhat: why?

Kinetic theory* connects the large $\hat{q}$ in Glasma
to subsequent hydrodynamics



HQ transport near-equilibrium: QPM model

Relativistic Boltzmann equation at finite η/s

Bulk evolution

$$p^{\mu}\partial_{\mu}f_q(x,p)+m(x)\partial^{x}_{\mu}m(x)\partial^{\mu}_{p}f_q(x,p)=C[f_q,f_g]$$

$$\underbrace{p^{\mu}\partial_{\mu}f_g(x,p)}_{\text{Free-streaming}}+\underbrace{m(x)\partial^{x}_{\mu}m(x)\partial^{\mu}_{p}f_g(x,p)}_{\substack{\text{field interaction}\\ \varepsilon\,-3p\,\neq\,0}}=\underbrace{C[f_q,f_g]}_{\substack{\text{Collision term}\\ \text{gauged to some }\eta/s\neq 0}}$$

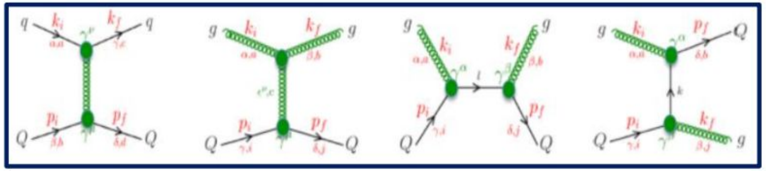
Equivalent to viscous hydro at η/s ≈ 0.1

HQ evolution

$$p^{\mu}\partial_{\mu}f_Q(x,p)=C[f_q,f_g,f_Q]$$

$$C[f_q,f_g,f_Q]=\frac{1}{2E_1}\int\frac{d^3p_2}{2E_2(2\pi)^3}\int\frac{d^3p_1'}{2E_1'(2\pi)^3}$$
$$\times[f_Q(p_1')f_{q,g}(p_2')-f_Q(p_1)f_{q,g}(p_2)]$$
$$\times|M_{(q,g)\to Q}(p_1p_2\to p_1'p_2')|$$
$$\times(2\pi)^4\delta^4(p_1+p_2-p_1'-p_2')$$

Feynman diagrams at first order pQCD for HQs-bulk interaction:



Scattering matrices $M_{g,q}$ by QPM fit to lQCD thermodynamics

HADRONIZATION: hybrid Coalescence + fragmentation

QPM extension: QPMp(N_f=2+1+1) and m_c (T)

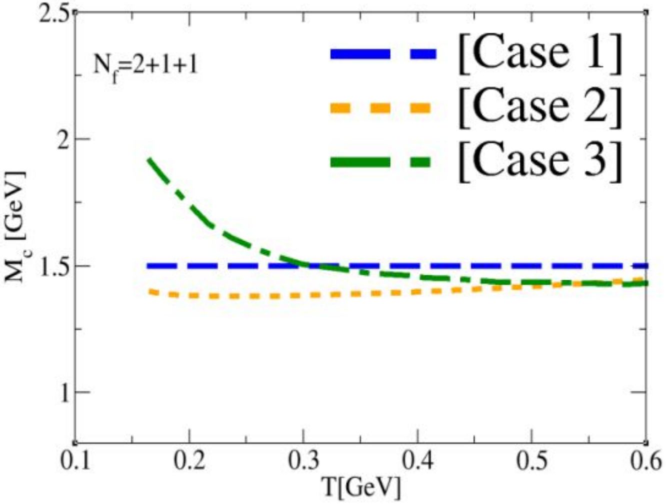
we have also extended our quasi-particle model approach for **Nf = 2+1** to **Nf = 2 + 1 + 1** where the **charm quark is included**

Temperature parametrization for charm mass:

Case 1: $m_c = 1.5\ GeV$

Case 2: $m_c^2 = m_{c0}^2 + \frac{N_c^2-1}{8N_c} g^2 [T^2 + \frac{\mu_c^2}{\pi^2}]$ with $m_{c0} = 1.3\ GeV$

Case 3: m_c fixed by charm fluctuation $\chi_2^c = \frac{T}{V} \frac{\partial^2 \ln Z}{\partial \mu_i^2}$



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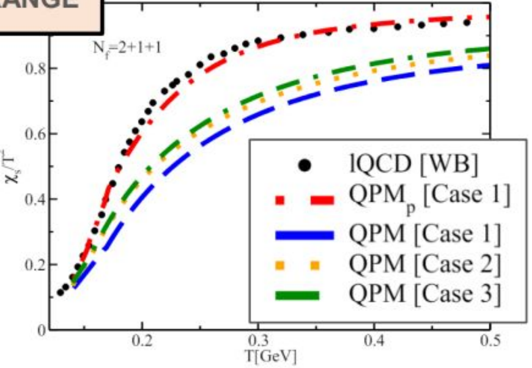
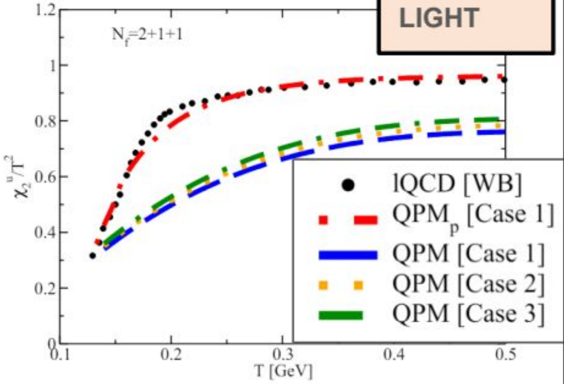
QUARK SUSCEPTIBILITIES

$$\chi_{u,s,c} = \frac{T}{V} \frac{\partial^2 \ln Z}{\partial \mu_{u,s,c}^2}$$

STRANGE

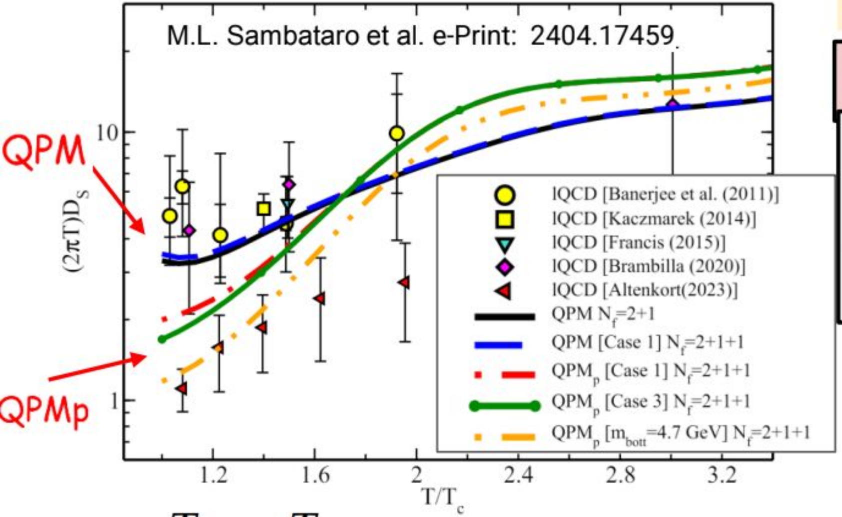


LIGHT



QPM understimates the lQCD data;
QPMp -> smaller 'thermal average mass' -> extra contribution in susceptibility

QPMp – spatial diffusion coefficient D_S



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Spatial diffusion coefficient D_s → standard QPM

standard QPM including charm

extended QPM

QPMp

- $T/T_c < 1.6$ -> strong non-perturbative behaviour of D_S.
- high T region -> D_S grows toward the pQCD estimate faster than QPM

QPMp for charm Case 3 and bottom (M=4.7 GeV): closer to D_S lQCD which include dynamical fermions

$$D_s = \frac{T}{M\,\gamma} = \frac{T}{M}\,\tau_{th}$$

in the p → 0 limit

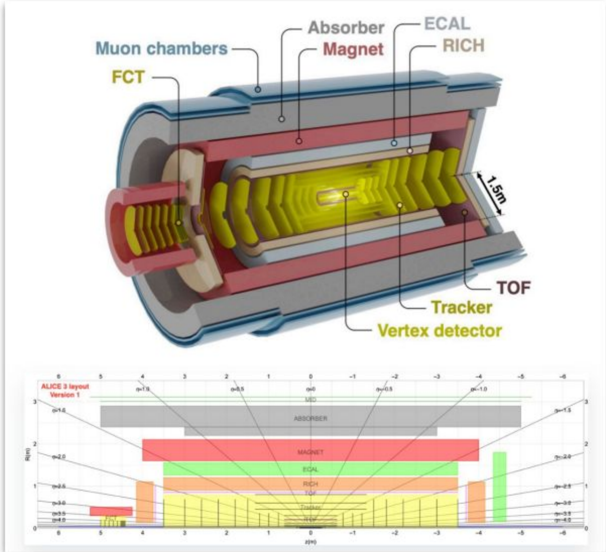
From D_s we obtain at T_c :

- τ_{th}(c , p=0) ~ 6 fm/c (QPM) -> 4 fm/c (QPMp)
- τ_{th}(b , p=0) ~ 13 fm/c (QPM) -> 7 fm/c (QPMp)

Which opportunities for ALICE 3?

… actually, just an unsatisfactory appetizer …

ALICE 3 LOI: CERN-LHCC-2022-009



Experiment vs. theory

①

- **Direct beauty** measurement **more challenging** that **non-prompt charm** (at least fro ALICE)
- **Do we really gain** in physics knowledge by measuring beauty hadrons rather than non-prompt charm?
  - decay kinematics non trivial? (e.g. polarization)

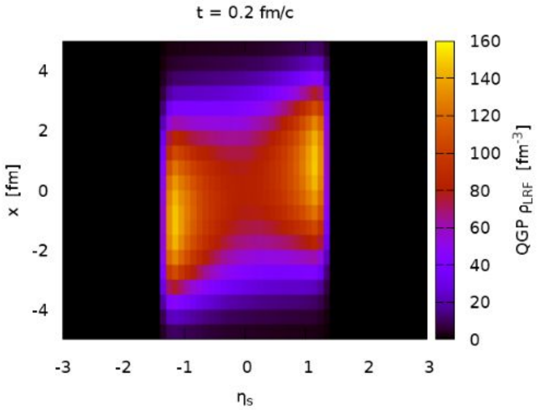
Future experiments

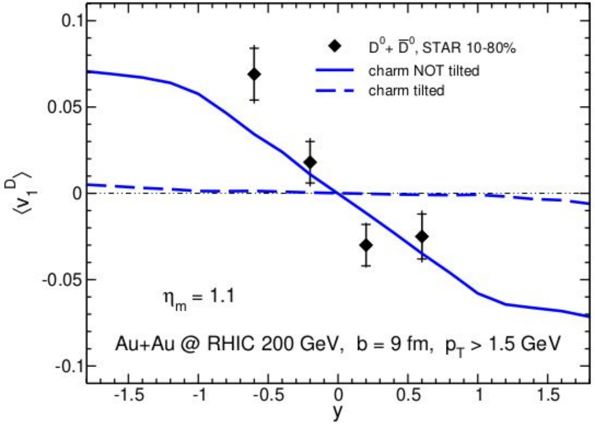
②

- Increase of statistics and acceptance (e.g. ALICE 3 up to $|\eta| < 4$)
- Possible measurements: $D\bar{D}$ correlation, … what else?!
- Can larger acceptance detectors be useful for other observables (e.g. hadronization vs. rapidity)?

② ③ ④ …

Directed flow v1: a window on spatial diffusion



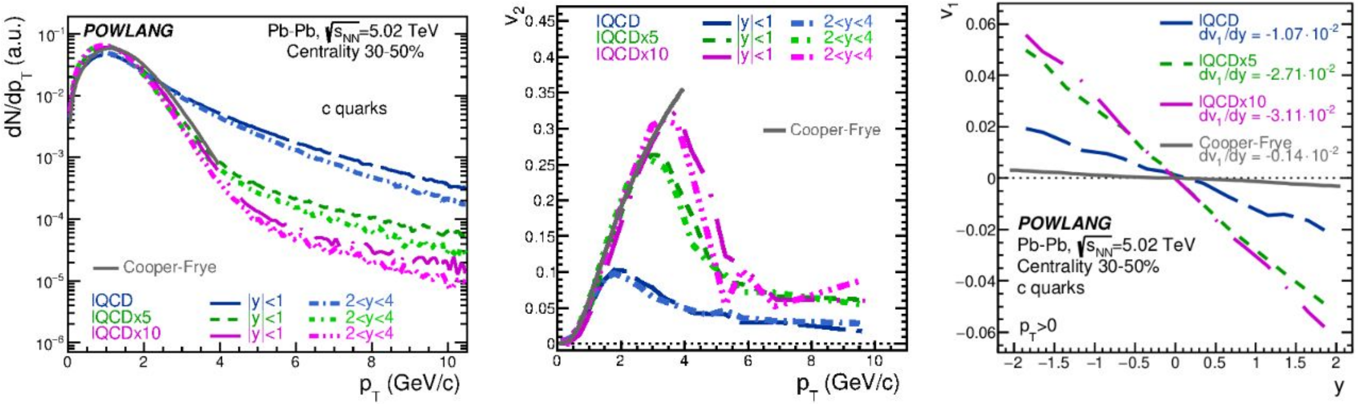


Initial off-equilibrium HQ distribution

- in momentum space: $d\sigma/d\vec{p}_T dy \neq e^{-p\cdot u/T}$
- in coordinate space: $n_{\rm coll}(\vec{x}_\perp) \neq s_0(\vec{x}_\perp, \eta_s)$

Most studies focused only on approach to *kinetic* equilibrium. However, observables sensitive to spatial inhomogeneity of HQ distribution, like the directed flow v_1, can provide a richer information on HF transport coefficients (S. Chatterjee and P. Bozez, PRL 120 (2018) 19, 192301, A.B. et al., JHEP 05 (2021) 279, L. Oliva et al., JHEP 05 (2021) 034)

Stronger sensitivity to kappa



Initial off-equilibrium HQ distribution

- in momentum space: $d\sigma/d\vec{p}_T dy \neq e^{-p\cdot u/T}$
- in coordinate space: $n_{\mathrm{coll}}(\vec{x}_\perp) \neq s_0(\vec{x}_\perp, \eta_s)$

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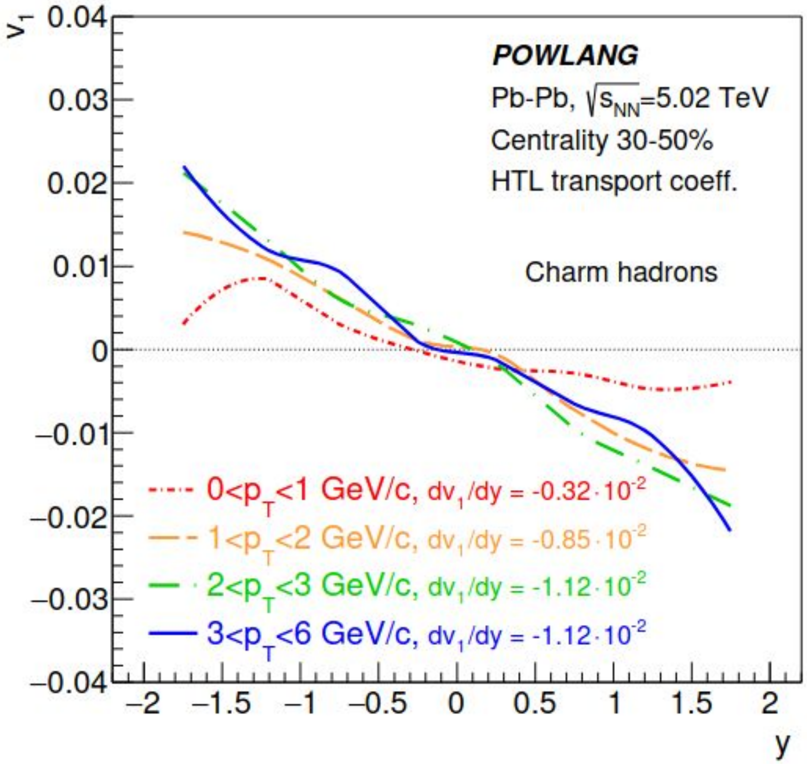
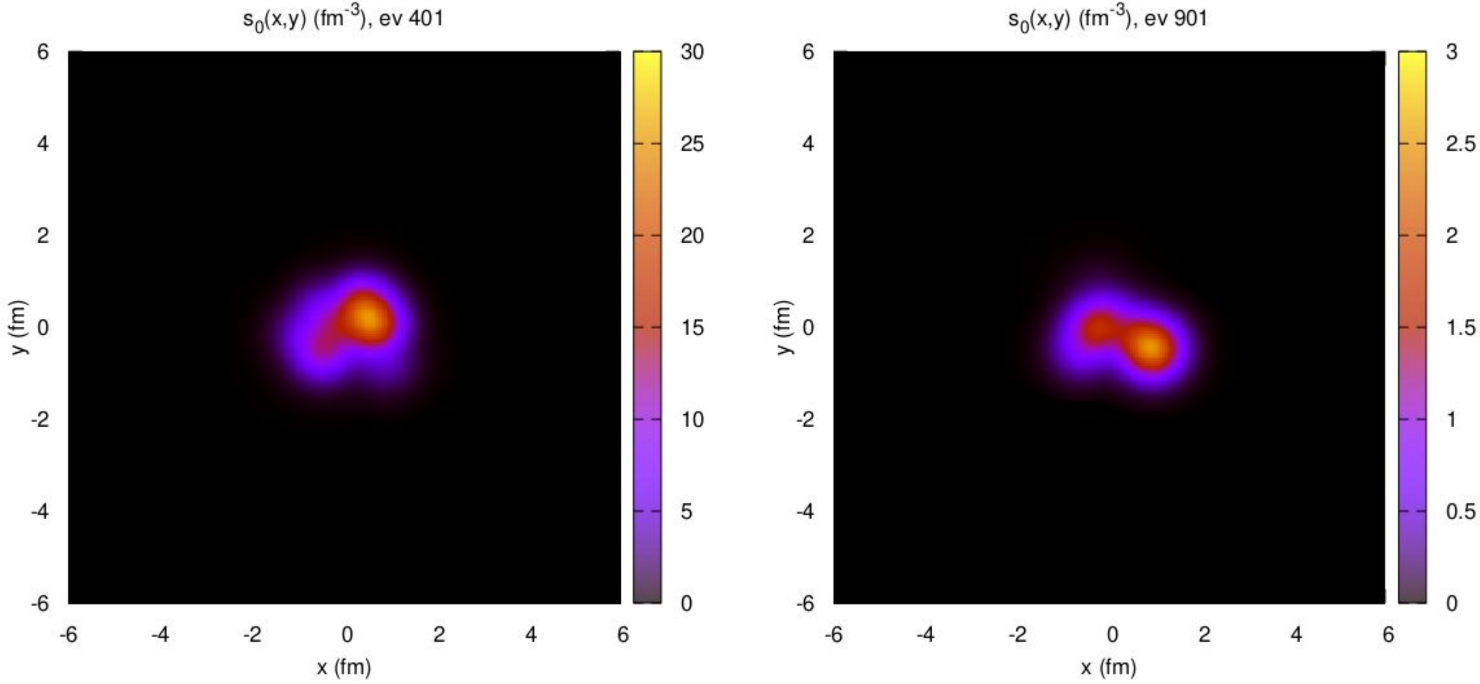


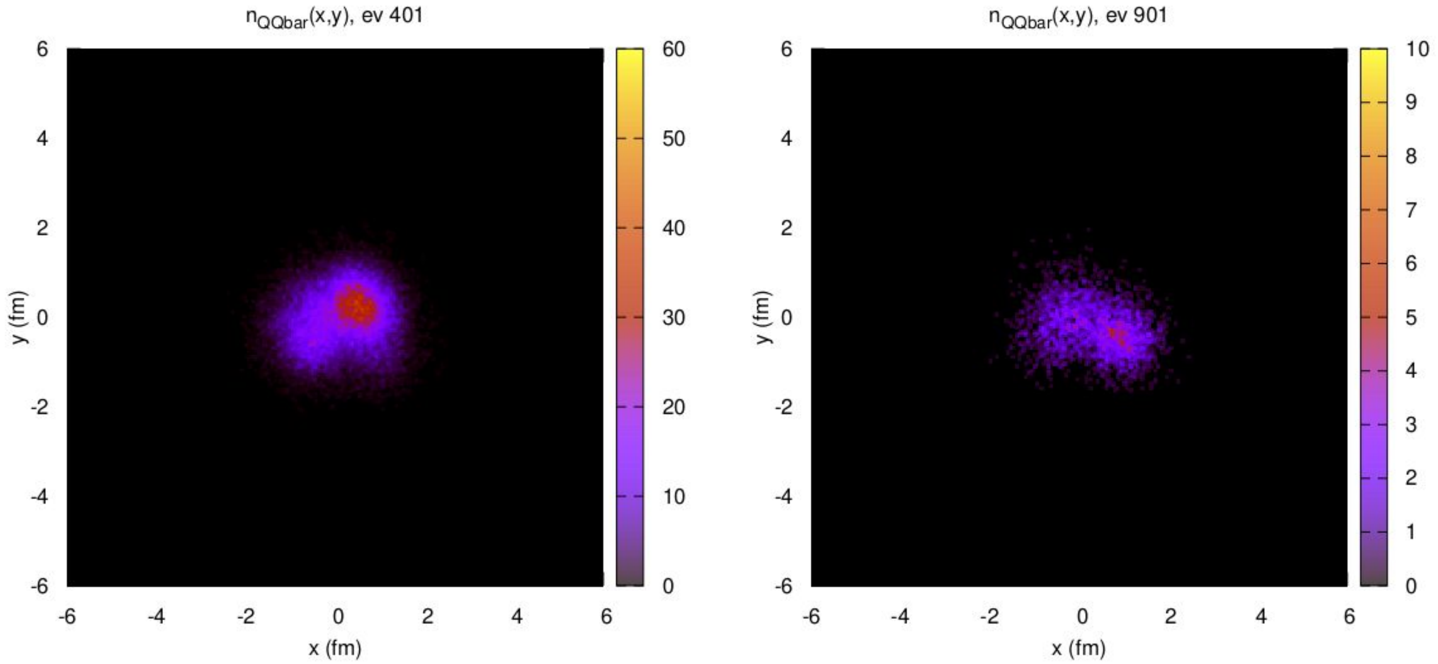
Signal dominated by particles with *mildly relativistic momenta*: Langevin approach and evaluation of transport coefficients under better control (kappa(p=0) may be enough to quantify medium effects). See A.B. et al., JHEP 05 (2021), 279

Towards the solution of the small-system puzzle



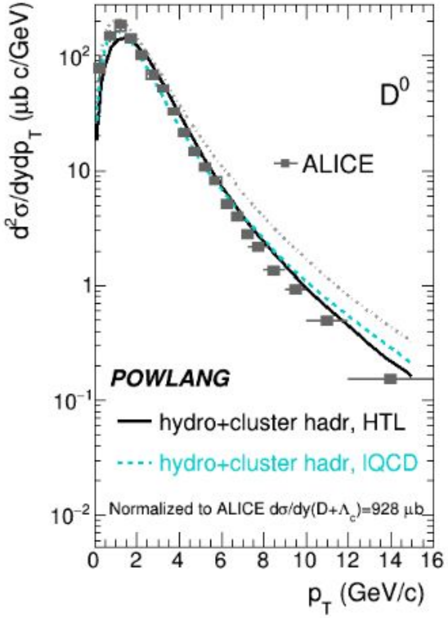
A small fireball produced also in minum-bias pp collisions!

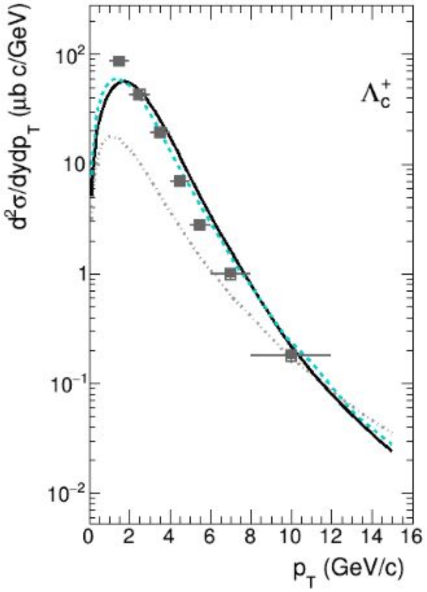
Towards the solution of the small-system puzzle

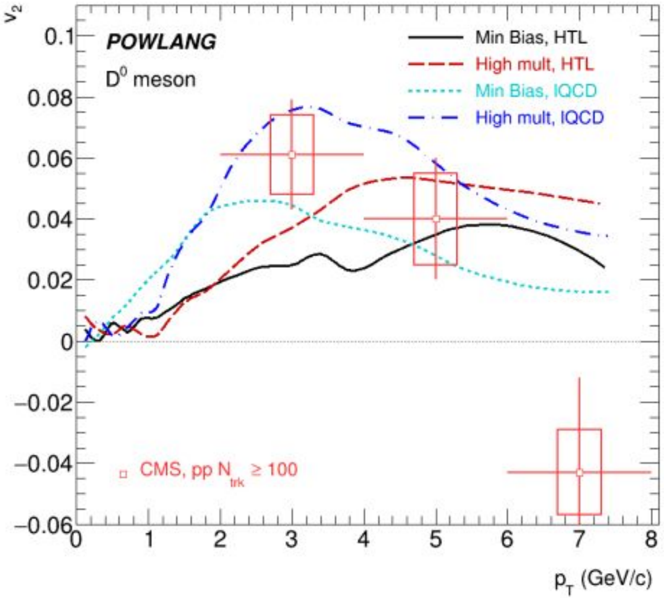


QQbar production biased towards hot spots of highest-multiplicity events!

Towards the solution of the small-system puzzle







In-medium transport+hadronization fundamental to describe pT-distribution, hadrochemistry and v2. See A.B. et al, PRD 109 (2024), 5 054912

Summary

Nucleus-nucleus: time is of understanding hadronisation for charm and beauty and of (precise) beauty measurements.
More suited kinematics to a data-to-theory comparison.

Discussion of transport cannot be decoupled from the one on in-medium hadronization.

Further independent evidence (Catania, Torino, Nantes…), from a hard observable, that a small fireball is formed also in pp collisions.

Interesting opportunities from future upgrades and detectors, like ALICE 3

Can Catania group tell us what are the most sensitive observables to constrain various effects / various parts of the theoretical models ?

Can we make a dynamical repository of theory predictions and ingredients (like the Ds(T), κ(v), …+ version, references) + associated engine to build compilation plots?

EXTRA

Two challenges (P. Gossiaux)

Can we ask ML to tell us what are the most sensitive observables to constrain various effects / various parts of the theoretical models ?
This could be achieved by requiring from the theory community to come with a “generic” model containing perturbative part dependent on the momentum exchange + NP + radiative component with non 0 gluon mass and extracting the most pertinent correlations between these various ingredients and the present and upcoming experiment. This should be made a tool open to the full community

Can we make a dynamical repository of theory predictions and theory ingredients (like the Ds(T), kappa(p), …) that would be fed by the various groups (+ version, ref to a publication) + associated engine to build compilation plots?