Recent Developments in Charm Phenomenology

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THIC 2025

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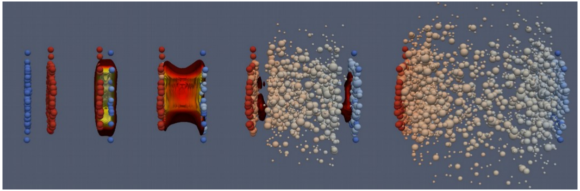
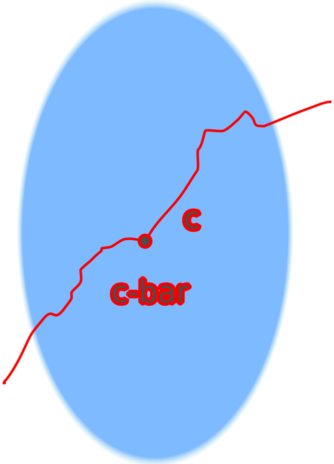
Heavy flavor in heavy-ion collisions

- Heavy-flavor quarks are mostly produced at the very early stage of the collision
- They traverse the medium while interacting with it
- They explore every stage of the medium evolution



MADAI Collaboration, H Petersen, J Bernhard



The random walk of charm

- The propagation of charm quarks can be considered a random walk
- In the hydrodynamic phase, it can be described in a Fokker Planck or Langevin approach

$$dp_i = -Ap_i dt + \xi_i(\mathbf{p})dt$$

- The physical parameters are the drag and diffusion coefficients
- The diffusion coefficient is related to fluctuation by the fluctuation-dissipation theorem,

$$\langle \xi_i(t)\xi_j(t')\rangle = B\delta_{ij}\delta(t-t')$$

Target areas in charm phenomenology

- I find the EMMI task force report from 2018 a good guide for next steps

Extraction of Heavy-Flavor Transport Coefficients in QCD Matter

R. Rapp[*1], P.B. Gossiaux[*2], A. Andronic[*3,4], R. Averbeck[*3], S. Masciocchi[*3], A. Beraudo[5], E. Bratkovskaya[3,6], P. Braun-Munzinger[3,7], S. Cao[8], A. Dainese[9], S.K. Das[10,11], M. Djordjevic[12], V. Greco[11,13], M. He[14], H. van Hees[6], G. Inghirami[3,6,15,16], O. Kaczmarek[17,18], Y.-J. Lee[19], J. Liao[20], S.Y.F. Liu[1], G. Moore[21], M. Nahrgang[2], J. Pawlowski[22], P. Petreczky[23], S. Plumari[11], F. Prino[5], S. Shi[20], T. Song[24], J. Stachel[7], I. Vitev[25], and X.-N. Wang[26,18]

Nucl. Phys. A 979 (2018)

Target areas in charm phenomenology

- The task-force made clear recommendations for modeling

1. Adopt FONLL baseline HQ spectra with EPS09 shadowing for the initial conditions in transport simulations.
2. Employ publicly available hydrodynamic or transport evolution models which have been tuned to data, with a maximal range of viable initial conditions and model parameters; or even a single one with a pre-specified tune as a single point of contact of all approaches.
3. Use recombination schemes of heavy quarks with light medium partons which satisfy 4-momentum conservation and recover equilibrium distributions in the long-time limit for the resulting hadron distributions.
4. Incorporate nonperturbative interactions in the modeling of heavy-flavor transport in a QGP at moderate temperatures as established and constrained by information from lattice QCD; utilize resummed interactions leading to bound-state formation near T_c to facilitate a seamless transition into coalescence processes.
5. Include diffusion through the hadronic phase of heavy-ion collisions.

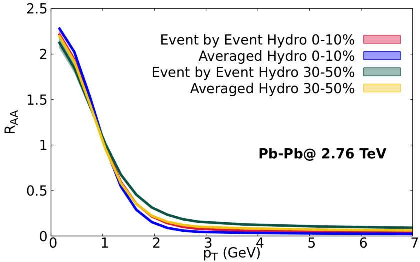
Hydrodynamic background

2. Employ publicly available hydrodynamic or transport evolution models which have been tuned to data, with a maximal range of viable initial conditions and model parameters; or even a single one with a pre-specified tune as a single point of contact of all approaches.

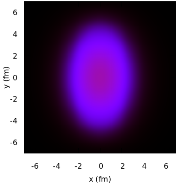
- Important to have realistic background tuned to soft data
- Helps mimic experimental procedure of taking correlations with charged hadrons
- Hydro codes in public domain, not expensive
- Modular frameworks like JETSCAPE/X-SCAPE make it easier to adapt
- Push towards publicly available emulators

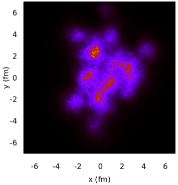
Importance of using realistic backgrounds

- Background space-time profile is sensitive to initial conditions
- Hotspots where more binary collisions took place forming HF quarks are distributed differently
- Experiments correlate HF event-plane with charged hadron event-plane



M. Singh, M. Kurian, S. Jeon, C. Gale, Phys.Rev.C 2023





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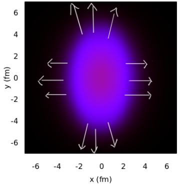

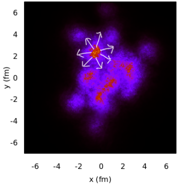

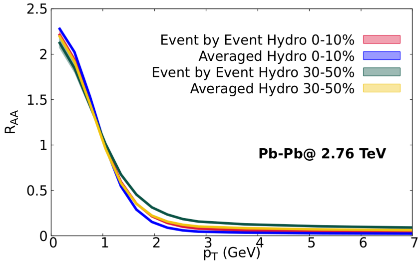

M. Singh, M. Kurian, S. Jeon, C. Gale, Phys.Rev.C 2023

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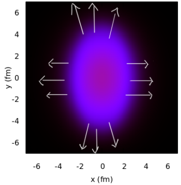
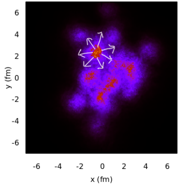
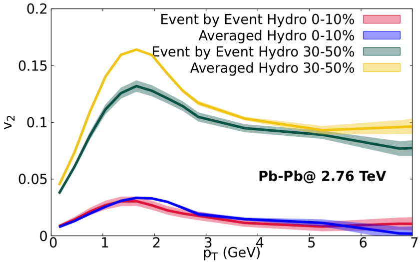


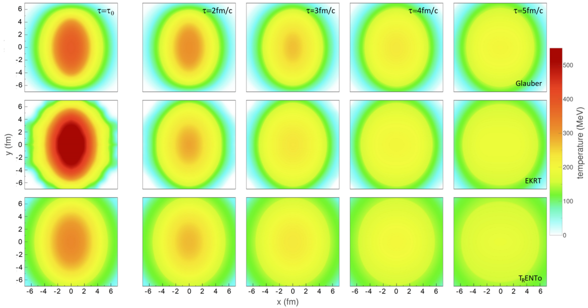




M. Singh, M. Kurian, S. Jeon, C. Gale, Phys.Rev.C 2023

Mapping spatial QGP profile

- Degeneracy in charged hadron data, cannot resolve space-time evolution
- With realistic background models, HF observables can help constrain **both** HF and LF evolution

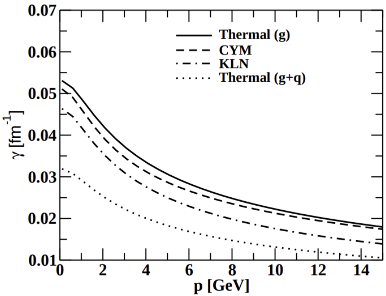


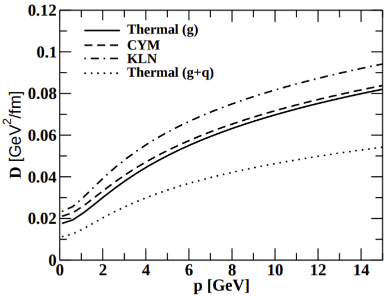
D. Zigic, I. Salom, J. Auvinen, P. Huovinen, M. Djordjevic, Front.Phys. 2022

Talk by Bithika Karmakar, Wed

Pre-hydro evolution

- Pre-hydro interactions of heavy-flavor quarks were initially neglected
- Short pre-hydro time (0.5∼1 fm) compared to hydro time (10 fm)
- However, interaction strength is much larger for gluons than for QGP

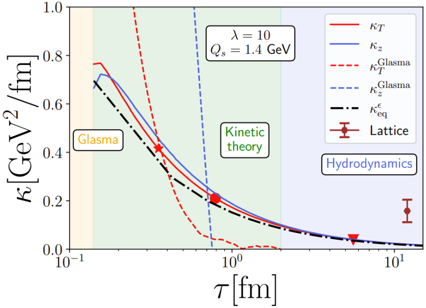




S. K. Das, M. Ruggieri, S. Mazumder, V. Greco, and J.-e Alam, J.Phys.G (2015)

Glasma vs Kinetic theory approaches

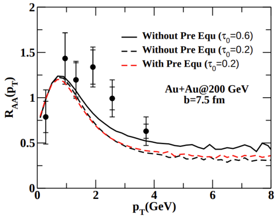
- The charm energy loss in pre-hydro phase can be described in glasma or in QCD kinetic theory approaches
- For smooth matching of different regimes in soft sector, we often do Glasma $\rightarrow$ KT $\rightarrow$ Hydro



K. Boguslavski, A. Kurkela, T. Lappi, F. Lindenbauer, J. Peuron, PRD 2024

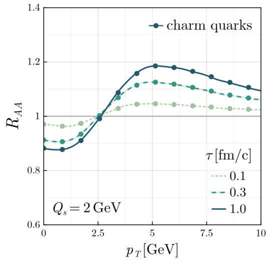
Does pre-hydro phase matter for charm observables?

Suppression in R_{AA}



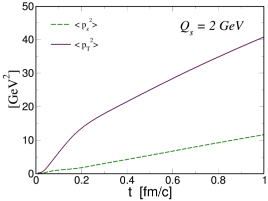
S. K. Das, M. Ruggieri, F. Scardina, S. Plumari and V. Greco, J.Phys.G 2017

Momentum broadening by Wong's equation in infinitely large expanding Glasma



D. Avramescu, V. Greco, T. Lappi, H. Mäntysaari, D. Müller, arXiv:2409.10564

Momentum broadening in static plasma with NR Dirac equations



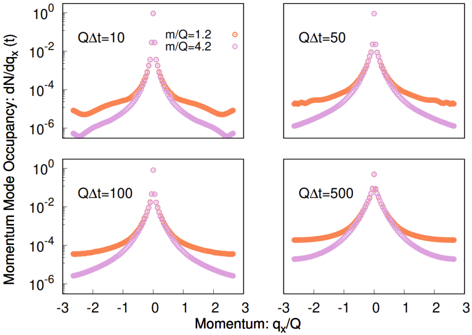
Pooja, S. K. Das, M. Ruggieri, V. Greco, Eur.Phys.J.Plus, 2023

Talk by Pooja, Wed

Does pre-hydro phase matter for charm observables?

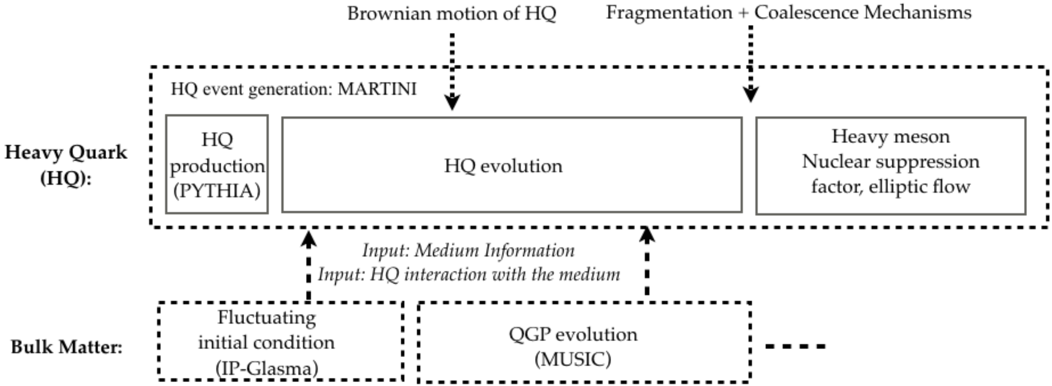
- Broadening also observed from ab-initio calculations studying interactions of relativistic heavy-quarks with overpopulated non-Abelian plasma

Talk by Harshit Pandey, Wed



H. Pandey, S. Schlichting, S. Sharma, Phys.Rev.Lett. 2024

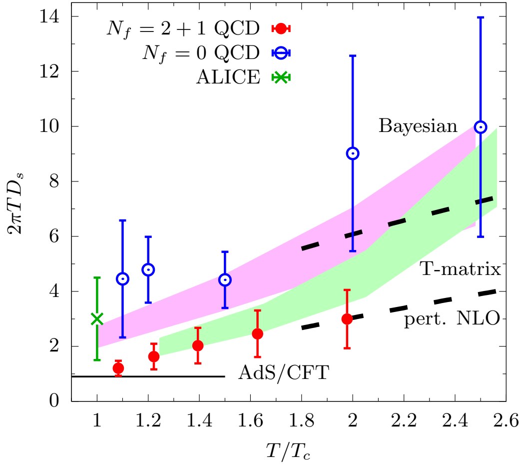
Consistent IP-Glasma + Hydro framework for charm



M. Singh, M. Kurian, B. Schenke, S. Jeon, C. Gale, In preparation

Diffusion rates from lattice

- Recent lattice results provide spatial diffusion coefficient in 2+1 flavor QCD
  HotQCD, PRL (2023)
- We used 0 flavor results in the Glasma phase N. Brambilla, V. Leino, P. Petreczky, A. Vairo, Phys.Rev.D 2023; L. Altenkort, A. M. Eller, O. Kaczmarek, L. Mazur, G. D. Moore, H.-T. Shu, Phys.Rev.D 2021; D. Banerjee, R. Gavai, S. Datta, P. Majumdar, Nucl.Phys.A 2023
- Interaction strength larger than previously thought
- Momentum dependence inspired by pQCD calculations

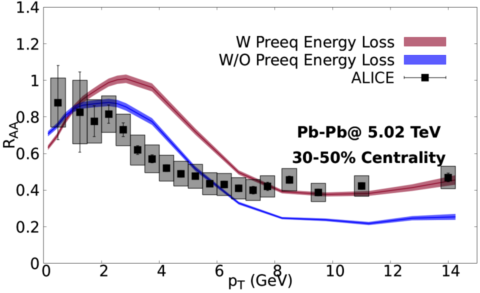


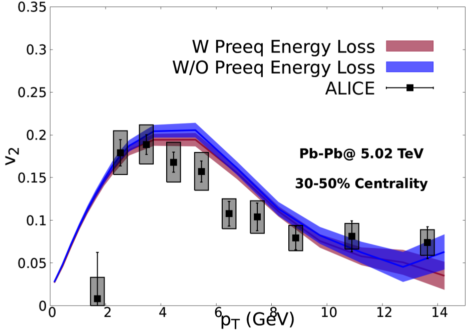
HotQCD, PRL (2023)

Consistent IP-Glasma + Hydro framework for charm

- Pre-hydro diffusion can significantly enhance p_T leading to a larger R_{AA}
- Not tuned to data

Preliminary





M. Singh, M. Kurian, B. Schenke, S. Jeon, C. Gale, In preparation

Hydrodynamized quarks

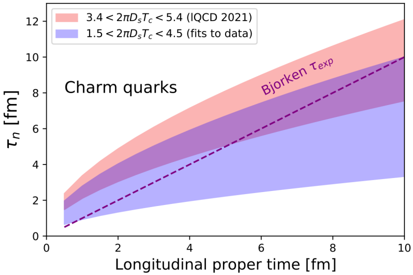
F. Capellino, A. Beraudo, A. Dubla, S. Floerchinger, S. Masciocchi, J. Pawlowski, I. Selyuzhenkov, Phys. Rev. D, 2023

- An interesting new idea to treat charm as a conserved current
- Formed initially, low in-medium annihilation rates
- Heavy quark and anti-quark currents are conserved independently

- Conservation equation

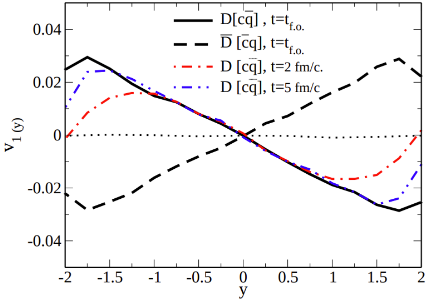
$$N^{\mu}_{Q/\bar{Q}} = n_{Q/\bar{Q}} u^{\mu} + \nu^{\mu}_{Q/\bar{Q}}$$
$$\partial_{\mu} N^{\mu}_{Q/\bar{Q}} = 0.$$

- Thermalization is assumed
- Transverse expansion dominates late times



Effect of magnetic fields

- Heavy-flavor directed flow can be used to extract magnetic field at early times
- Transport coefficients in presence of magnetic field Talk by Debarshi Dey, Wed
- Recent progress made in MHD Talks by Chiho Nonaka, Ashutosh Dash, Mon

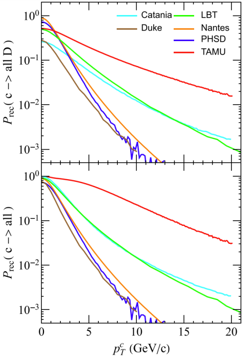


S. K. Das, S. Plumari, S. Chatterjee, J.-e Alam, F. Scardina, V. Greco, Phys.Lett.B 2017

Recombination models

3. Use recombination schemes of heavy quarks with light medium partons which satisfy 4-momentum conservation and recover equilibrium distributions in the long-time limit for the resulting hadron distributions.

- Hadronization by fragmentation + recombination
- Models differ in details



PHYSICAL REVIEW C **109**, 054912 (2024)

Hadronization of heavy quarks

Jiaxing Zhao,[1] Jörg Aichelin,[1] Pol Bernard Gossiaux,[1] Andrea Beraudo,[2] Shanshan Cao,[3] Wenkai Fan,[4] Min He,[5] Vincenzo Minissale,[6,7] Taesoo Song,[8] Ivan Vitev,[9] Ralf Rapp,[10] Steffen Bass,[4] Elena Bratkovskaya,[8,11,12] Vincenzo Greco,[6,7] and Salvatore Plumari[6,7]

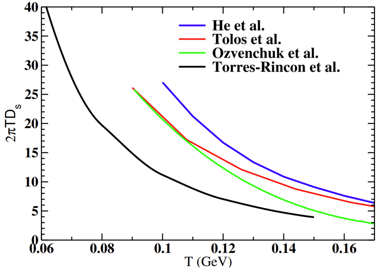
	D	D_s	Λ_c
Catania	D^0, D^+, D^{*0}, D^{*+}	D_s, D_s^{*+}	Λ_c, $\Lambda_c(2595)$, $\Lambda_c(2625)$, $\Sigma_c(2455)$, $\Sigma_c(2520)$
Duke	D^0, D^+, D^{*0}, D^{*+}		
LBT	All S- and P-wave D^0 and D^+	All S- and P-wave D_s	All S- and P-wave Λ_c and Σ_c
Nantes	D^0		
PHSD	Most S- and P-wave D^0	Most S- and P-wave D_s	
TAMU	PDG	PDG	RQM
Torino	D^0	D_s	Λ_c
LANL	D^0, D^+, D^{*0}, D^{*+}		

Hadronic diffusion

5. Include diffusion through the hadronic phase of heavy-ion collisions.

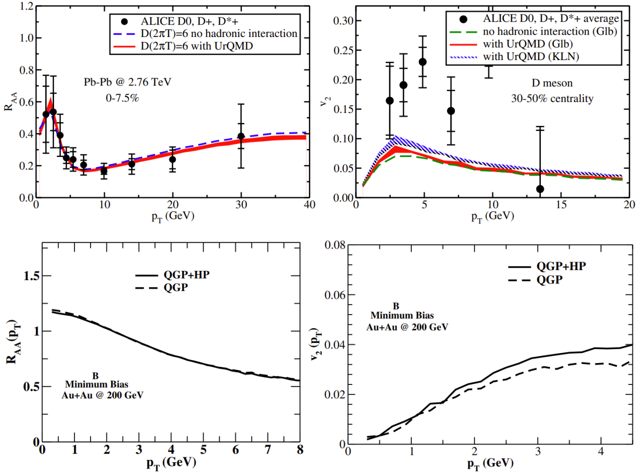
- HF flavor hadrons do not cease interactions in hadronic phase
- While medium density is lower, flow is high
- Hadronic interactions expected to enhance v_2
- R_{AA} is not significantly affected
- HF interaction strength with hadronic gas evaluated using EFTs

Talk by Kangkan Goswami, Wed



S. K. Das, J. M. Torres-Rincon, R. Rapp, arxiv:2406.13286

Hadronic diffusion



S. Cao, G.-Y. Qin, and S. A. Bass, Phys.Rev.C 2015

S. K. Das, J. M. Torres-Rincon, L. Tolos, V. Minissale, F. Scardina, and V. Greco, Phys.Rev.D 2016

Figures from S. K. Das, J. M. Torres-Rincon, R. Rapp, arxiv:2406.13286

Outlook

- Exciting developments being made in heavy flavor phenomenology
- Pre-hydro regime seems to have significant effect on R_{AA}
- Hadronic interactions enhance v_2
- We are entering era of simultaneous description of soft+hard observables
- Bayesian techniques can be leveraged to isolate tension between data and models and to identify areas where we need to improve our understanding

THANK YOU!