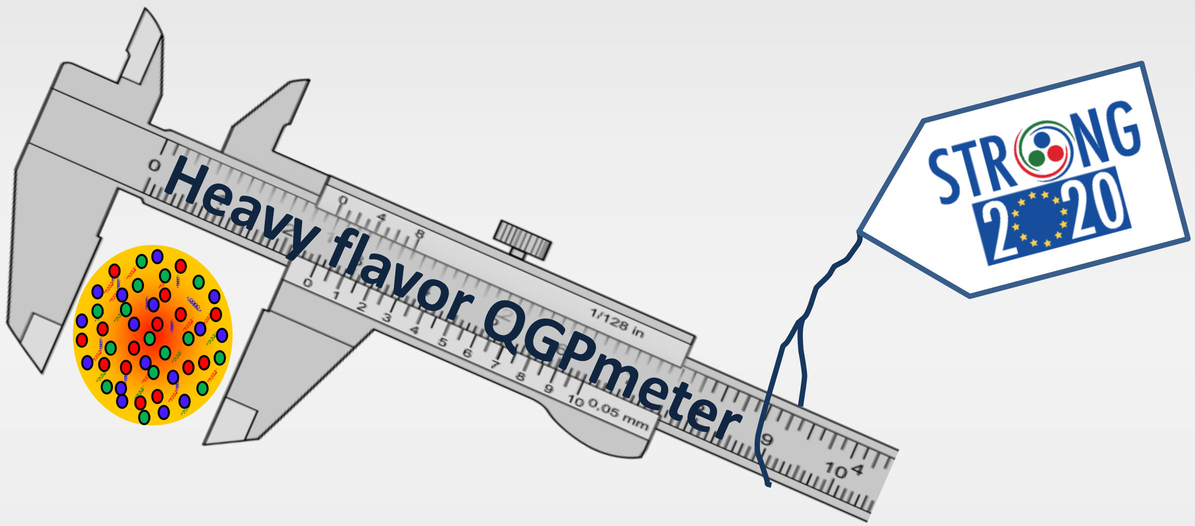
Heavy flavor transport with DAB-MOD



Roland Katz (SUBATECH, France)
Project developed at the University of São Paulo (Brazil)
with C. Prado, J. Noronha-Hostler, J. Noronha, M. Munhoz, A. Suaide

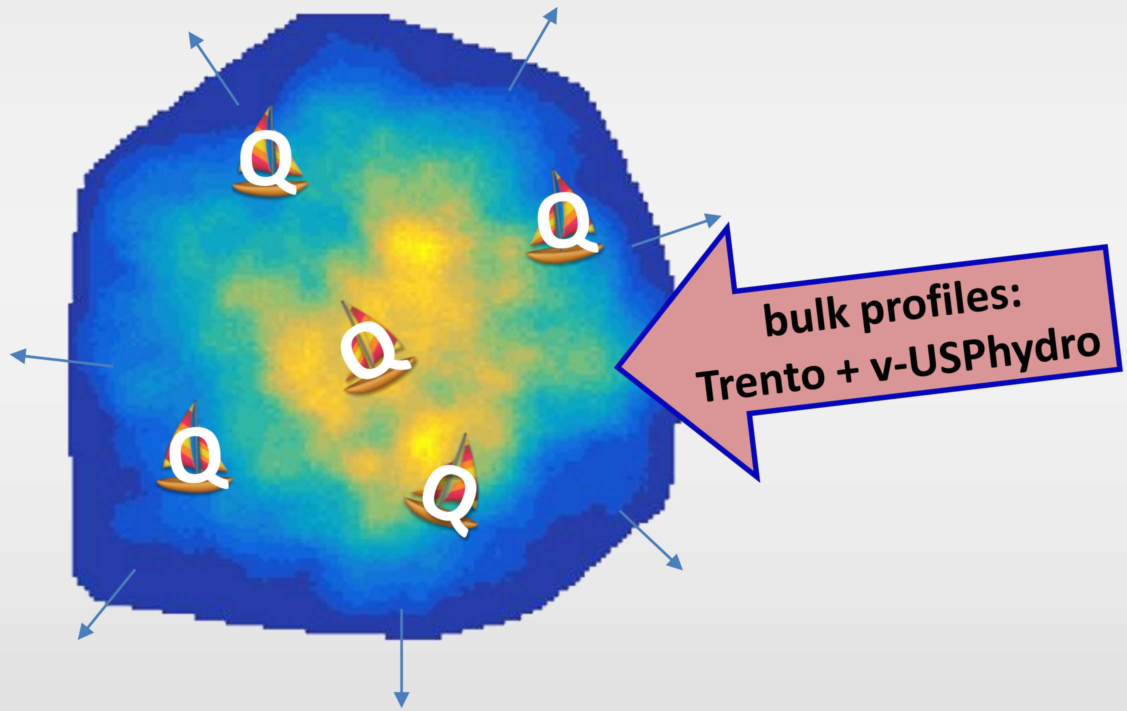
DAB-MOD: basics

"D and B mesons - modular code"

Heavy quarks evolve on the top of 2d+1 bulk profiles

Transport:
- parametric energy loss
- relativistic Langevin

Hadronization:
- fragmentation
- coalescence



***Analyses:* -- R_{AA} vs. v_2 -- anisotropies with cumulants -- system size scan --**

Phys. Rev. C 96, 064903 (2017) [1611.02965], Phys. Rev. C 102, 024906 (2020) [1906.10768], Phys. Rev. C 102, 041901 (2020) [1907.03308]

Energy loss

Simple parametric energy loss from jet physics

Inspired by Betz & Gyulassy, JHEP 08, 090 (2014) and Horowitz & Gyulassy, Nucl. Phys. A872, 265 (2011)

Local medium temperature

Heavy quark velocity in lab frame

« Boosts »

$$\frac{\mathrm{d}E}{\mathrm{d}x}(T, v_{\mathrm{Q}}) = -f(T, v_{\mathrm{Q}})\,\zeta\,\Gamma_{\mathrm{flow}},$$

Parametrization

Energy loss fluctuations

Pros
- Allows to easily test different parameter dependences
- Keep it simple

Cons
- No direct connection to microscopic processes
- Mix of radiative and collisional energy losses ?

Energy loss

Simple parametric energy loss from jet physics

$$\frac{\mathrm{d}E}{\mathrm{d}x}(T, v_{\mathrm{Q}}) = -f(T, v_{\mathrm{Q}})\,\zeta\,\Gamma_{\mathrm{flow}},$$

takes into account
the *boost* from the medium cell frame to the global lab frame

- Jet formulation (p>>m): $\Gamma_{\mathrm{flow}} = \gamma\left[1 - v_{\mathrm{flow}}\cos(\varphi_{\mathrm{Q}} - \varphi_{\mathrm{flow}})\right],$

Baier, Mueller & Schiff,
Phys. Lett. B649, 147 (2007)

with $\gamma = 1\Big/\sqrt{1 - v_{\mathrm{flow}}^2},$

local medium velocity

azimuthal angle between heavy quark and medium velocities

- Any momentum formulation:

$$\Gamma_{\mathrm{flow}}^{\mathrm{exact}} = \gamma\sqrt{1 - 2\frac{v_{\mathrm{flow}}}{v_{\mathrm{Q}}}\cos(\varphi_{\mathrm{Q}} - \varphi_{\mathrm{flow}}) + \frac{v_{\mathrm{flow}}^2}{v_{\mathrm{Q}}^2} - v_{\mathrm{flow}}^2\sin^2(\varphi_{\mathrm{Q}} - \varphi_{\mathrm{flow}})},$$

Same derivation as in the original paper but without assuming p>>m

Energy loss

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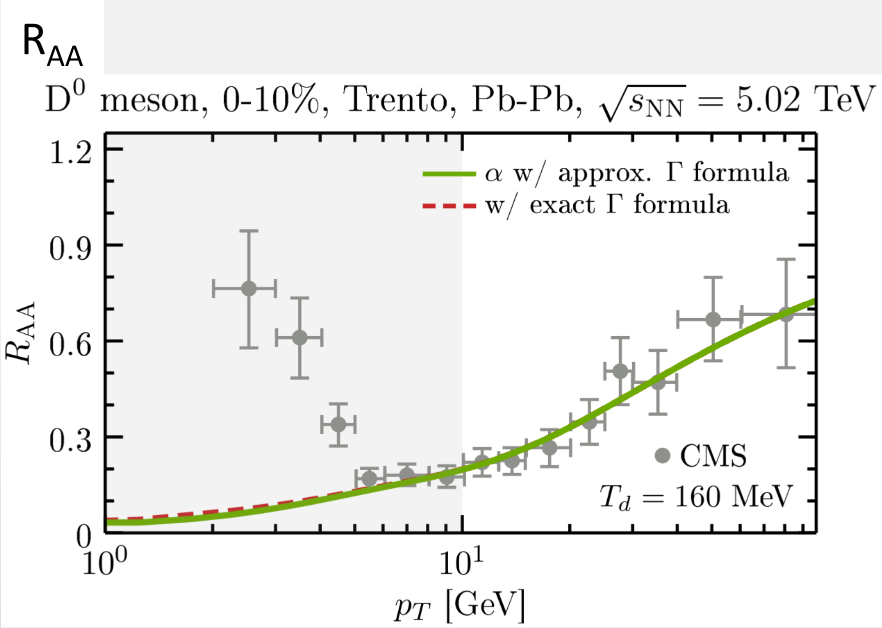
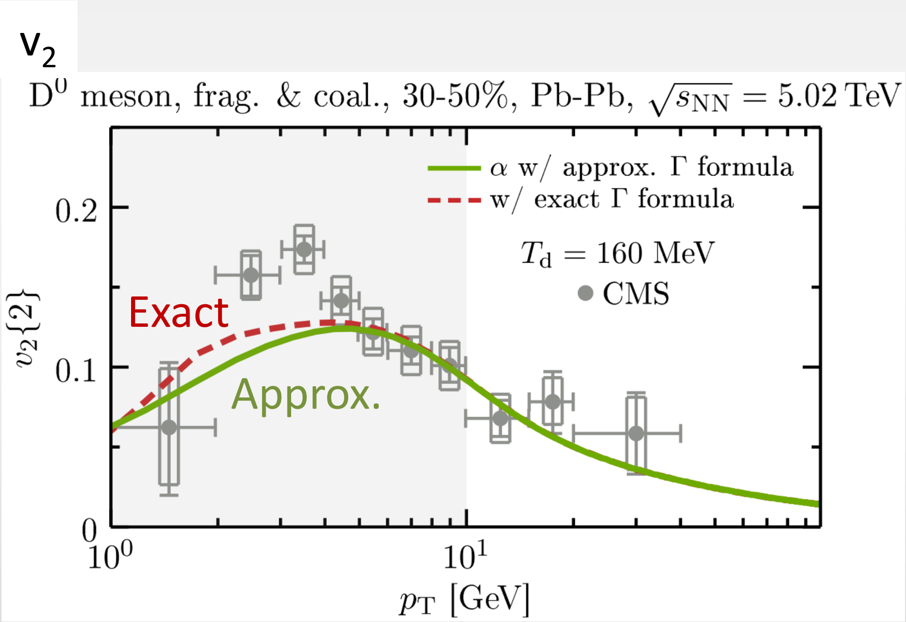




Discrepancies between the two expressions: when $p_Q \leq 3m_Q$

Energy loss

Simple parametric energy loss from jet physics

$$\frac{\mathrm{d}E}{\mathrm{d}x}(T, v_\mathrm{Q}) = -f(T, v_\mathrm{Q})\,\zeta\,\Gamma_\mathrm{flow},$$

Function encoding the *energy loss parametrization*

5 different parametrizations tested:

- $f = \xi T^2$
- $f = \delta \gamma_\mathrm{Q} v_\mathrm{Q} T^2$

inspired by conformal AdS/CFT calculations
Gubser, Phys. Rev. D74, 126005 (2006)

with $\gamma_\mathrm{Q} = 1/\sqrt{1 - v_\mathrm{Q}^2}$

- $f = \alpha$
- $f = \beta \gamma_\mathrm{Q} v_\mathrm{Q}$

inspired by R_{AA} vs. v_2 analysis
Das et al., Phys. Lett. B747, 260 (2015)
-> nearly T-independent coefficients favored

- $f = \lambda T^2 F_\mathrm{drag}$

F_{drag} from holographic model that describes lQCD thermodynamics
Rougemont, Ficnar, Finazzo, and Noronha, JHEP 04, 102 (2016)

Energy loss

Simple parametric energy loss from jet physics

$$\frac{\mathrm{d}E}{\mathrm{d}x}(T, v_{\mathrm{Q}}) = -f(T, v_{\mathrm{Q}})\zeta\, \Gamma_{\mathrm{flow}},$$

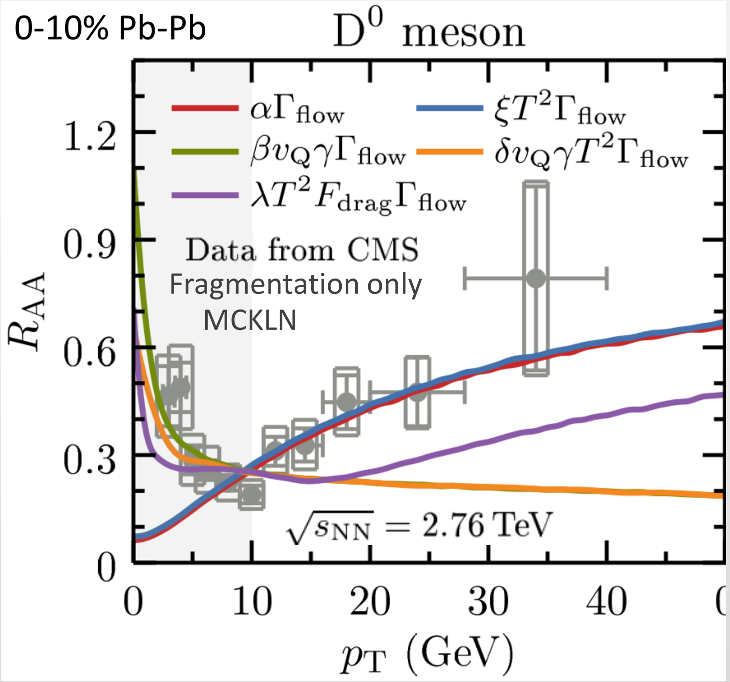
Function encoding the *energy loss parametrization*

We have tested 5 different parametrizations:

α, β, δ, λ and ξ :
proportionality coefficients
fixed here to get the same
R_{AA} at p_T=10 GeV

- Best models: v_Q independent
- T dependence does not play a role for R_{AA} (but does for v_2)

=> We only kept $f = \alpha$ **and** $f = \xi T^2$



Energy loss

Simple parametric energy loss from jet physics

$$\frac{\mathrm{d}E}{\mathrm{d}x}(T, v_Q) = -f(T, v_Q)\,\zeta\,\Gamma_{\mathrm{flow}},$$

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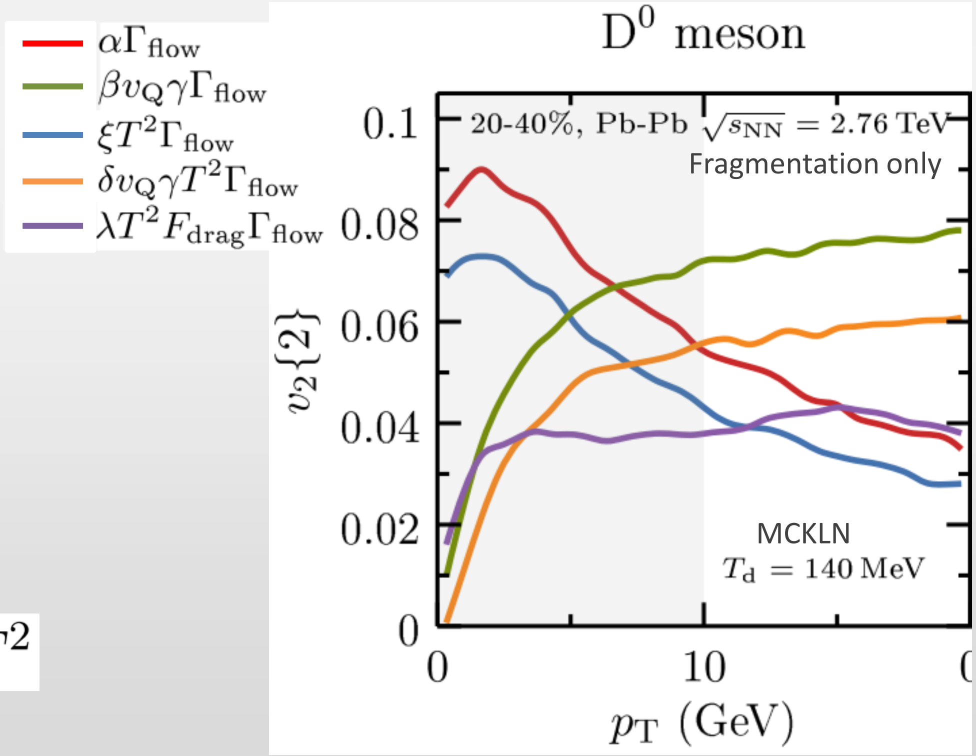


Energy loss

Simple parametric energy loss from jet physics

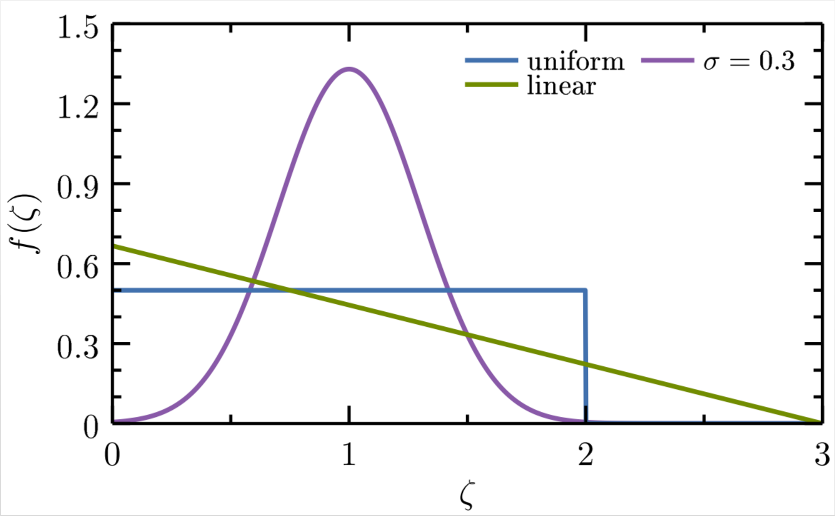
$$\frac{\mathrm{d}E}{\mathrm{d}x}(T, v_{\mathrm{Q}}) = -f(T, v_{\mathrm{Q}})\,\zeta\,\Gamma_{\mathrm{flow}},$$

A random variable to tackle *energy loss fluctuations*

Takes one value for each heavy quark

Inspired by B. Betz and M. Gyulassy, JHEP 08, 090 (2014)

We tested 3 different probability distributions:

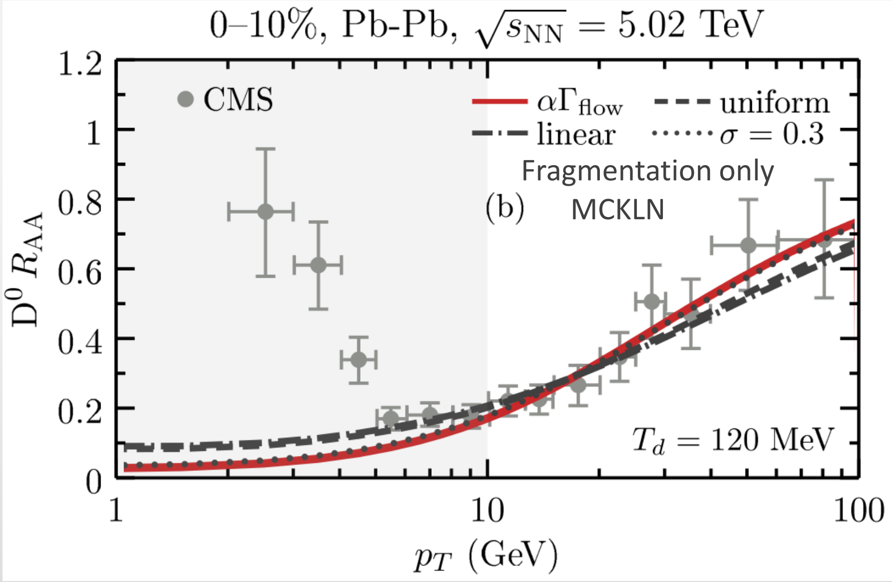


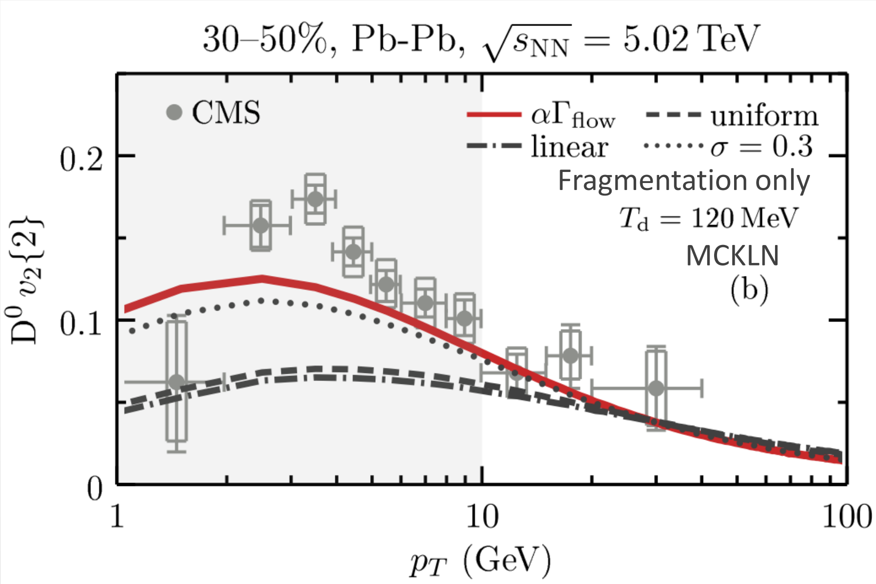
Energy loss

Simple parametric energy loss from jet physics

$$\frac{\mathrm{d}E}{\mathrm{d}x}(T, v_{\mathrm{Q}}) = -f(T, v_{\mathrm{Q}})\,\zeta\,\Gamma_{\mathrm{flow}},$$

A random variable to tackle *energy loss fluctuations*
Takes one value for each heavy quark





Small impact on R_{AA}

Large impact on v_n

Comparison to data: not relevent here

Langevin dynamics

Relativistic Langevin equation

$$\mathrm{d}x_i = \frac{p_i}{E}\,\mathrm{d}t,$$
$$\mathrm{d}p_i = -\Gamma(\boldsymbol{p})p_i\,\mathrm{d}t + \sqrt{\mathrm{d}t}\sqrt{\kappa}\rho_i,$$

With all the necessary boosts between the medium cell and lab frame

Relativistic Einstein fluctuation-dissipation relation: $\kappa = 2E\Gamma T = 2T^2/D,$

<u>Two different parametrizations:</u>

- "**M&T**": from Moore and Teaney, QCD+HTL model

Moore and Teaney, Phys. Rev. C71, 064904 (2005)

$$D_{\mathrm{M\&T}} = k_{\mathrm{M\&T}}/(2\pi T),$$

- "**G&A**" : from Gossiaux and Aichelin, QCD+HTL collisional model with running coupling and optimized propagator.

Gossiaux and Aichelin, Nucl. Phys. A830, 203C (2009)

$$\Gamma_{\mathrm{G\&A}} = k_{\mathrm{G\&A}}\;A_{\mathrm{G\&A}}(T,p)$$

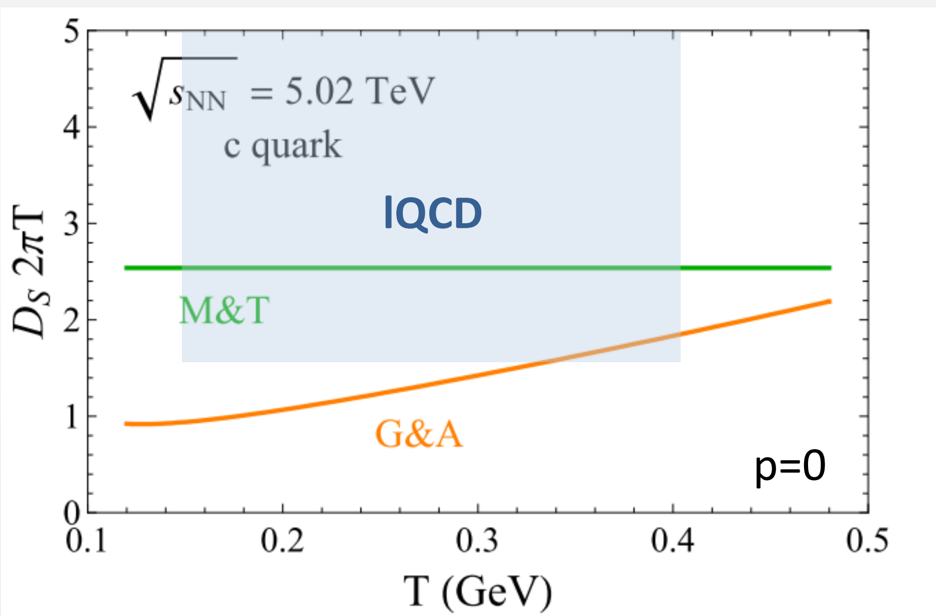
Langevin dynamics

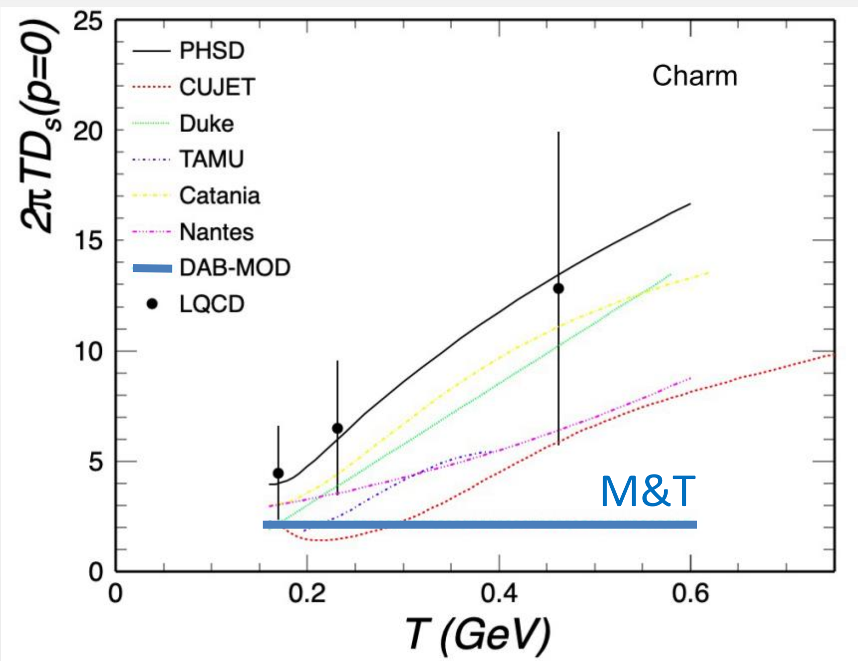
Relativistic Langevin equation

$$\mathrm{d}x_i = \frac{p_i}{E}\,\mathrm{d}t,$$
$$\mathrm{d}p_i = -\Gamma(\boldsymbol{p})p_i\,\mathrm{d}t + \sqrt{\mathrm{d}t}\sqrt{\kappa}\rho_i,$$

With all the necessary boosts between the medium cell and lab frame

Relativistic Einstein fluctuation-dissipation relation: $\kappa = 2E\Gamma T = 2T^2/D,$





Here with $k_{\rm M\&T} = 0.5$ and $k_{\rm G\&A} = 0.62$

Calibration

For each transport model -> one free parameter

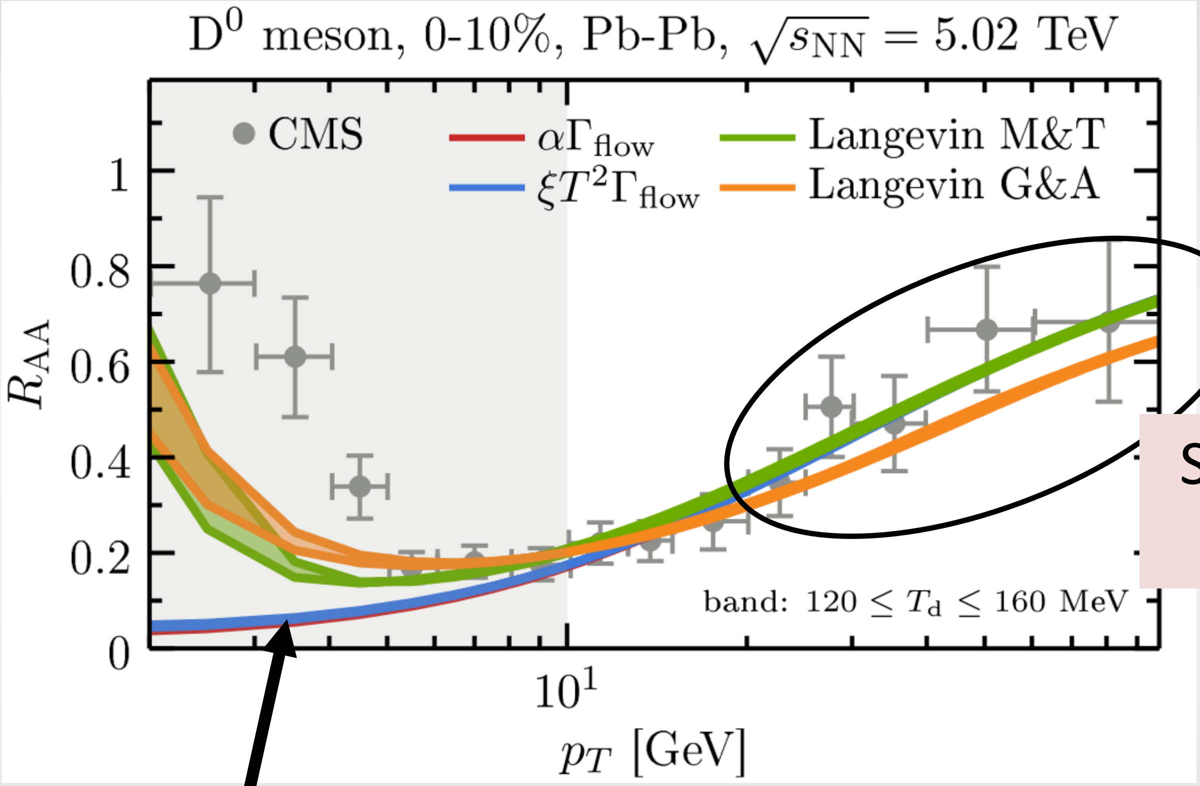
(α and ξ for energy losses -- $k_{M\&T}$ and $k_{G\&A}$ for Langevin)

fixed with 0-10% R_{AA} data at high-p_T (energy loss) or intermediate-p_T (Langevin)

(D^0 data for c quarks, electron from HF data for b quarks)

R_{AA}

MCKLN, fragmentation only



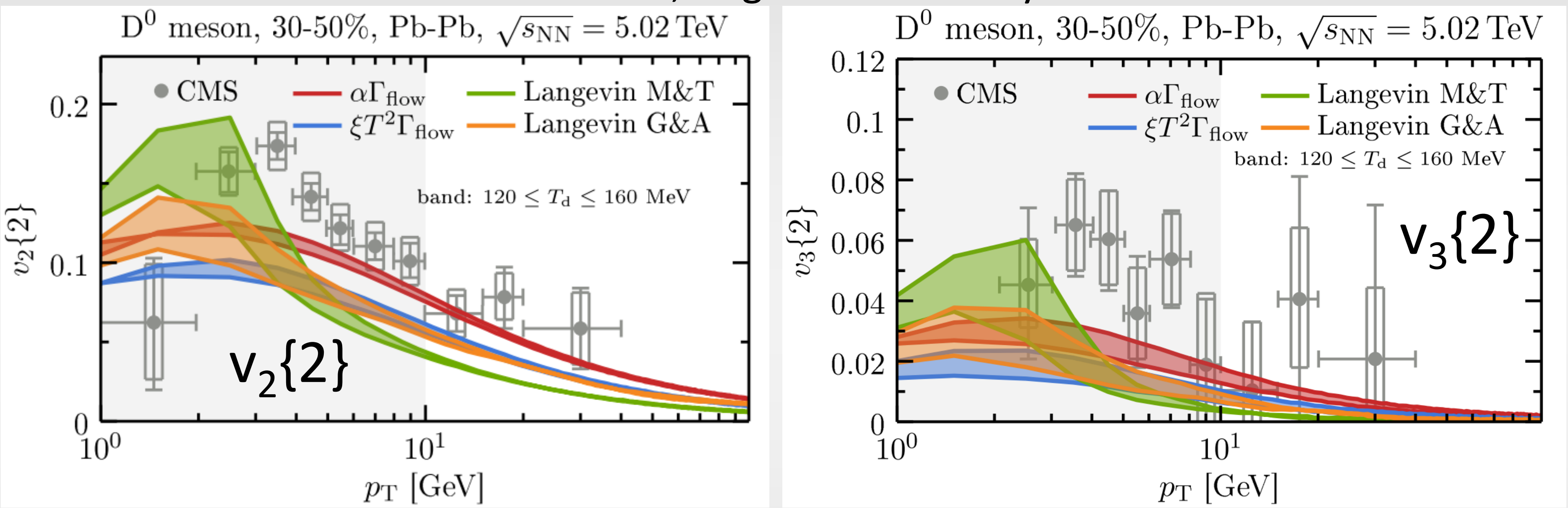
Similar trends at high p_T

Energy loss:
very wrong at low p_T

Ref data: arXiv:1708.04962

Azimuthal anisotropies

MCKLN, fragmentation only



Langevin M&T: best at low-p_T $\neq$ const Energy loss: best at high-p_T

Underestimate the v_n at high-p_T

Ref data: arXiv:1708.03497

Conclusion

- « Multi-scale » behaviour:
  Langevin better at low-p_T, energy loss at high-p_T

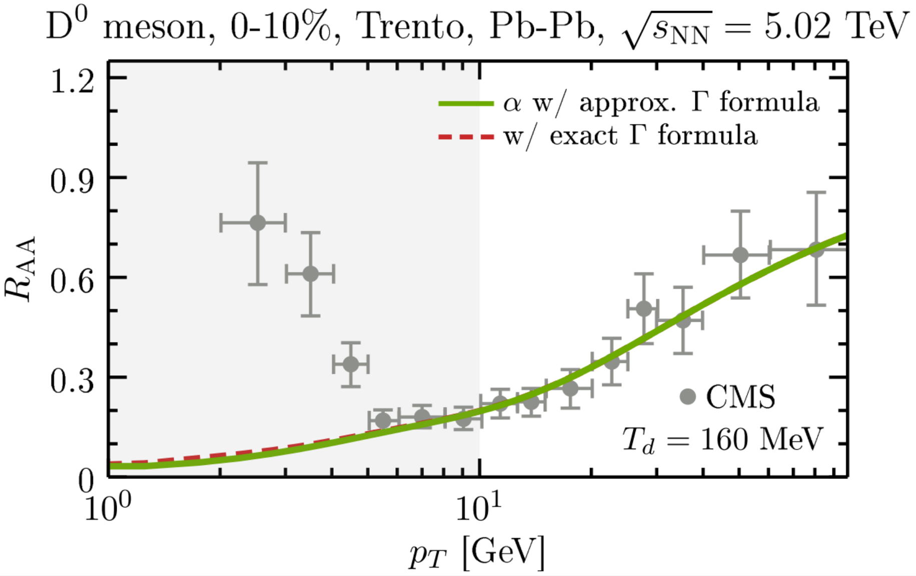
- T & v_Q independent energy loss
  « Moore and Teaney » diffusion coeff.

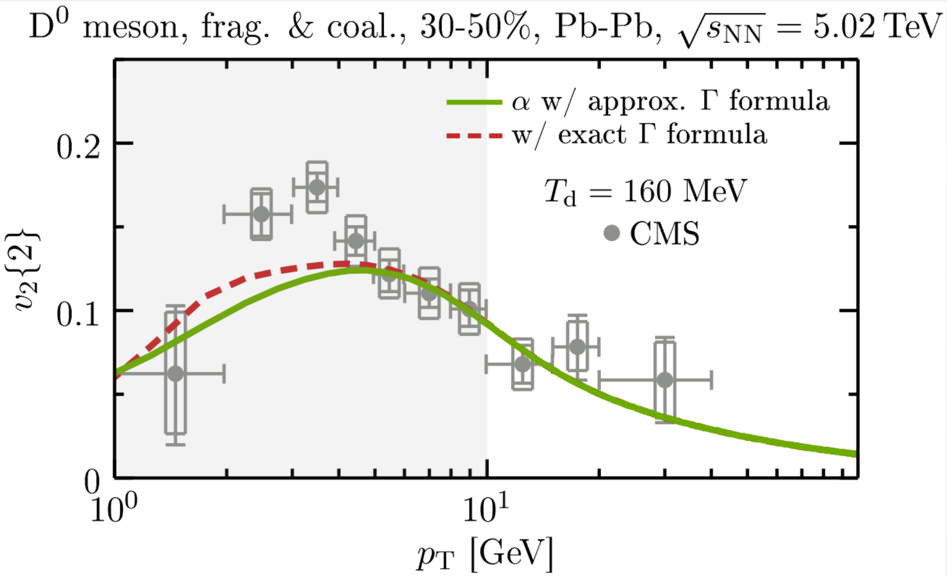
  favored within DAB-MOD

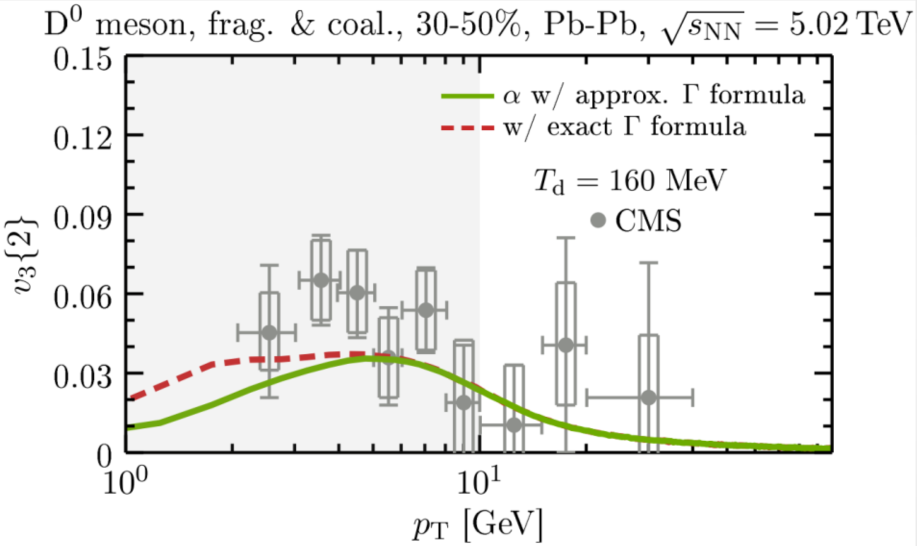
Thank you !

Back up

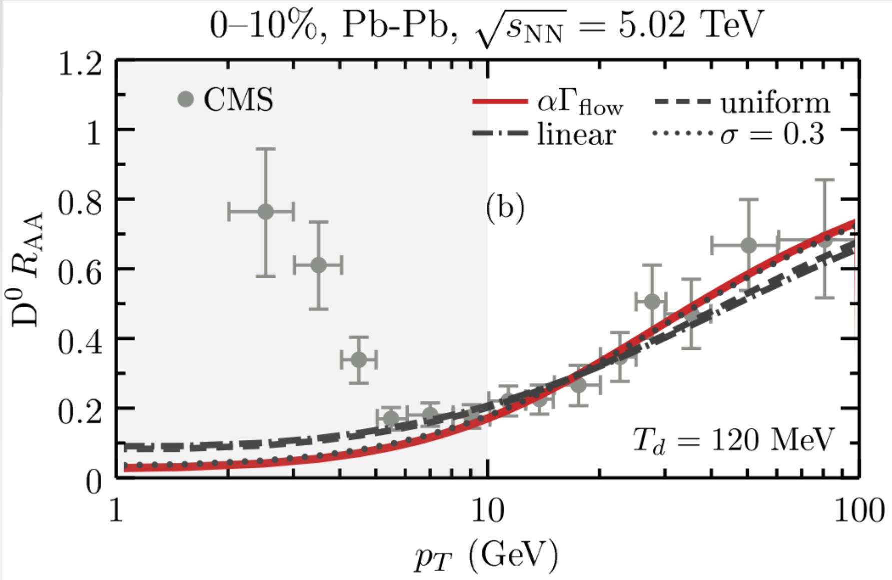
Jet Γ_{flow} vs. Exact Γ_{flow}

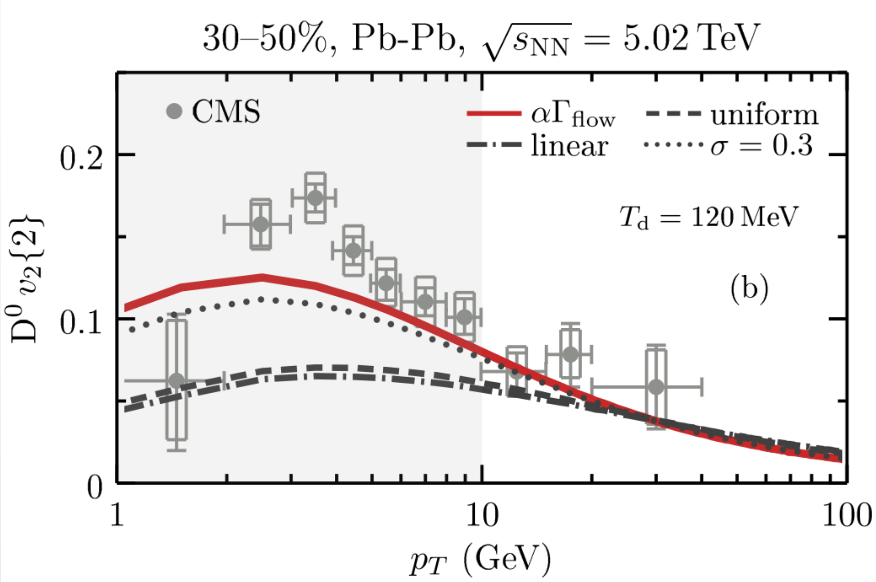


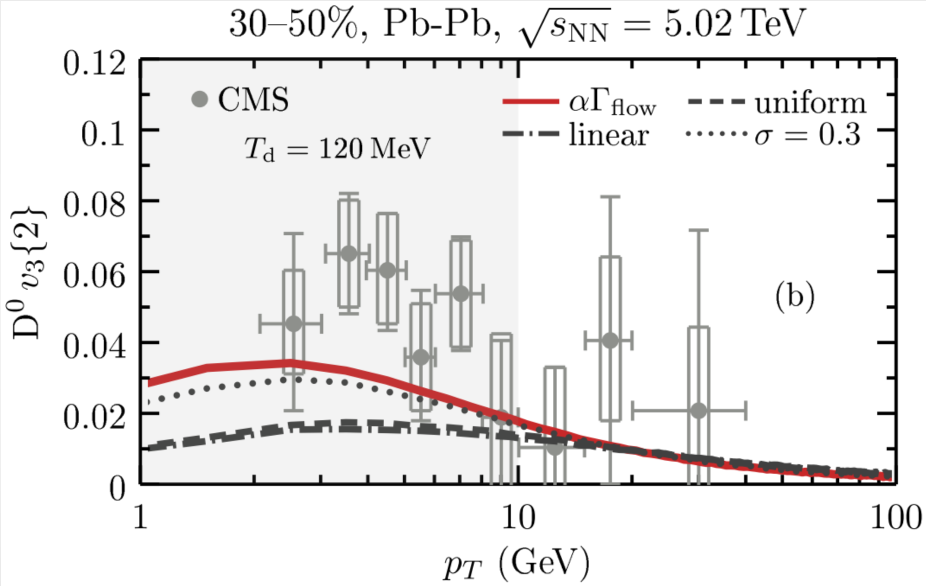




Energy loss fluctuations







Coupling factors

Coupling factors for charm quarks at $T_d = 120 \setminus 160$ MeV	RHIC AuAu $\sqrt{s_{NN}} = 200$ GeV	LHC PbPb $\sqrt{s_{NN}} = 2.76$ TeV	LHC PbPb $\sqrt{s_{NN}} = 5.02$ TeV
α without fluctuations	0.393 \ 0.623	1.0 \ 1.624	0.708 \ 1.011
α with uniform fluct.	0.649 \ none	1.7 \ none	0.993 \ none
α with linear fluct.	0.77 \ none	2.024 \ none	1.130 \ none
α with gaussian fluct.	0.43 \ none	1.1 \ none	0.751 \ none
ξ	11.57 \ 15.16	30.28 \ 40.05	14.76 \ 17.16
$k_{M\&T}$	0.48 \ 0.34	0.227 \ 0.169	0.5 \ 0.41
$k_{G\&A}$	0.639 \ 0.921	1.039 \ 1.577	0.622 \ 0.828

TABLE I. Values of the coupling factors for charm quarks determined for each transport model, collision energy, and decoupling temperature. These values are obtained using MCKLN initial conditions.

Coupling factors for bottom quarks at $T_d = 120 \setminus 160$ MeV	RHIC AuAu $\sqrt{s_{NN}} = 200$ GeV	LHC PbPb $\sqrt{s_{NN}} = 2.76$ TeV	LHC PbPb $\sqrt{s_{NN}} = 5.02$ TeV
α without fluctuations	0.264 \ 0.4	0.72 \ 1.12	0.667 \ 0.823
α with uniform fluct.	0.316 \ none	0.857 \ none	0.824 \ none
α with linear fluct.	0.339 \ none	0.921 \ none	0.913 \ none
α with gaussian fluct.	0.265 \ none	0.76 \ none	0.624 \ none
ξ	7.6 \ 10	21.52 \ 27.06	none \ none
$k_{M\&T}$	0.648 \ 0.486	0.32 \ 0.226	0.516 \ 0.411
$k_{G\&A}$	0.606 \ 0.808	3.21 \ 2.26	0.681 \ 0.884

TABLE II. Values of the coupling factors for bottom quarks determined for each transport model, collision energy, and decoupling temperature. These values are obtained using MCKLN initial conditions.

DAB-MOD: bulk profiles

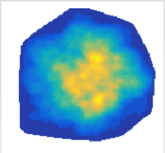
Initial fluctuations

- "**MCKLN**": implementation of a Color Glass Condensate k_T-factorization model

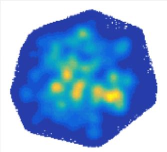
or

- **Trento**: tuned to IP-Glasma. Has larger initial T.
  At LHC run 2 Trento generally works best

MCKLN



TRENTO



Expansion

- Using **v-USPhydro**: a **2d+1 event-by-event relativistic viscous hydro**
  Viscosity set to $\eta/s = 0.05$
- With MCKLN: Equation of state S95n-v1 ≠ Trento: EOS2+1 from lQCD

Final stages

- **Cooper-Frye** freeze-out with viscous corrections

t

~1000 profiles per 10% centrality range

Describes data in the soft sector => hydro parameters are fixed

Refs: IC: arXiv:0707.0249, arXiv:1412.4708, arXiv:1711.08499; hydro: arXiv:1305.1981, arXiv:1508.02455, arXiv:1307.6130, arXiv:0707.0249

DAB-MOD: heavy quarks

Initial conditions

- **Large oversampling** of the HQs (statistics)
- Spatial -> following initial bulk densities; p_T -> **FONLL spectra**
- **No shadowing or cold nuclear matter** effects

Transport

- **Parametric Energy loss models** $\frac{dE}{dx} = -f(T, p, x)\,\Gamma_{\text{flow}}$

  Where Γ_{flow} : takes into account the boosts

  Parametrizations $f(T, p, x) = \alpha$ or $f(T, p, x) = \xi T^2$ -> R_{AA} trends ok

or

- **Relativistic Langevin models** $dp_i = -\Gamma(\vec{p})p_i dt + \sqrt{dt}\sqrt{\kappa}\rho_i$

  Two different parametrizations:
  - "**M&T**": from Moore and Teaney, QCD+HTL model $D \propto 1/(2\pi T)$
  - "**G&A**" : from Gossiaux and Aichelin, QCD+HTL model with running coupling and optimized propagator.

Refs: arXiv:1404.6378, arXiv:1609.05171, arXiv:0412346, arXiv:0802.2525

DAB-MOD: heavy quarks

Hadronization

- **Decoupling T_d**: 120 < T_d < 160 MeV -> hadronization uncertainties
- **Fragmentation**: Peterson function $f(z) \propto [z(1 - 1/z - \epsilon_Q/(1-z))]^{-1}$ to obtain the fraction z of the HQ E_Q+p_Q taken by the hadron E_H+p_H

with or without

- **Light-heavy quark coalescence**
  - Inspired by Dover et al.: instantaneous projection of states
  - Coalescence proba. function of $\vec{p}_Q$, $\overrightarrow{\text{local flow}}$ & angle between
  - To better fit the observed heavy hadron ratios, we included: thermal factors "$\exp[-(m_{excited}-m_{ground})/T_d]$" between energy states of equal quark content => not only spin but also mass hierarchy between energy states of a hadron type

Final stages

- **No final hadronic re-scattering**

t

Details in: arXiv:1906.10768

Refs: arXiv:1804.09083v1, L. Vermunt SQM 2019 poster, arXiv:1505.01413

Conclusion

- « Multi-scale » behaviour:
  Langevin better at low-p_T, energy loss at high-p_T

- T & v_Q independent energy loss
  « Moore and Teaney » diffusion coeff.

  } favored within DAB-MOD

Possible ideas for DAB-MOD transport

- Implement a more refined microscopic energy loss model ?
- Explore coupled Langevin equations in phase space and color space ?
  Akamatsu, Phys. Rev. C92, 044911 (2015)
- Implement radiative component in Langevin (through Drag or additional force term) ?
  Cao, Qin and Bass, Phys. Rev. C 92, 024907 (2015)

Thank you !