# Energy loss and transport from small to large systems

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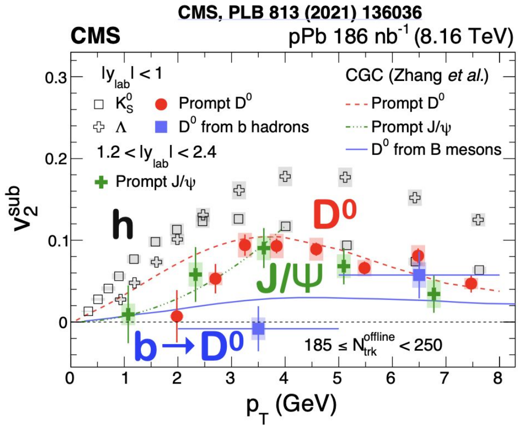
# Main Topics we discussed ...

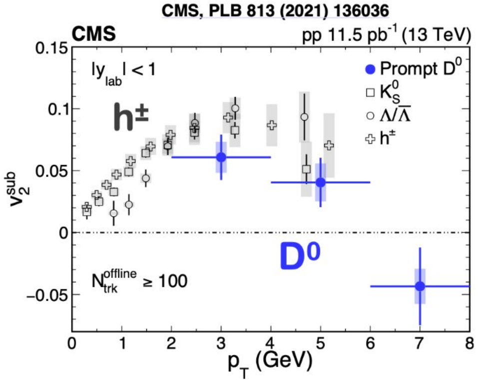
... not a systematic review of open questions, but rather driven by the interests of the participants and result of brainstorming

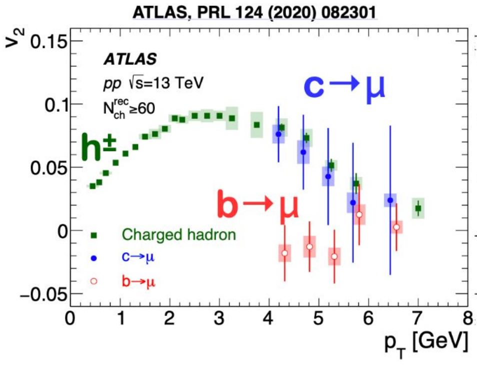
- Signals for energy loss in small systems
- Role of the pre-equilibrium stage
- Energy dependence of q-hat
- Energy loss in quarkonia production
- Better constraints on Heavy Flavor Diffusion
- Signals for Heavy Flavor Thermalisation
- Challenges from future high precision measurements

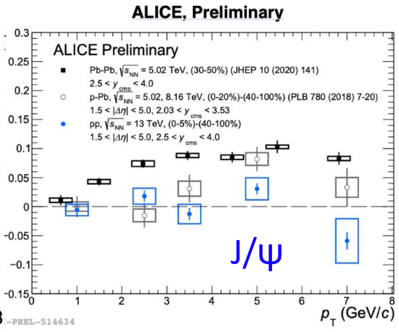
# Energy loss in small systems ?

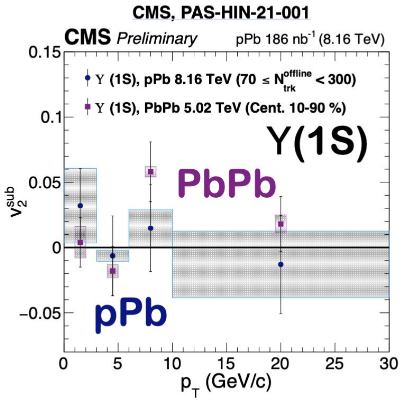
- $v_2$ - $R_{pA}$ puzzle: $v_2$>0 and $R_{pA}$~1 including charm and jets ...
- Described by CGC but would also expect $v_2(\Upsilon)$ > 0 (not observed)
    - However, open b-hadrons and Υ have $v_2$ compatible with 0
- HF $v_2$>0 also observed in pp



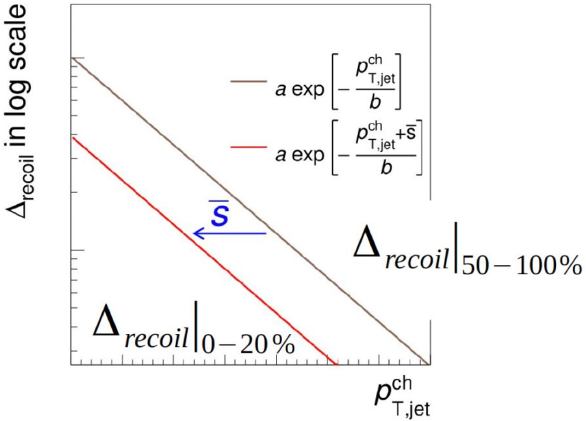



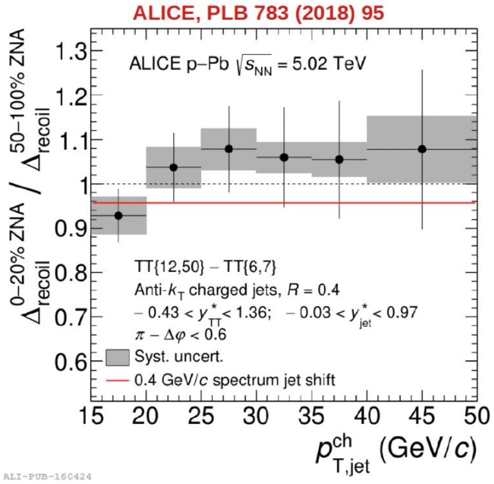



# Energy loss in small systems ?

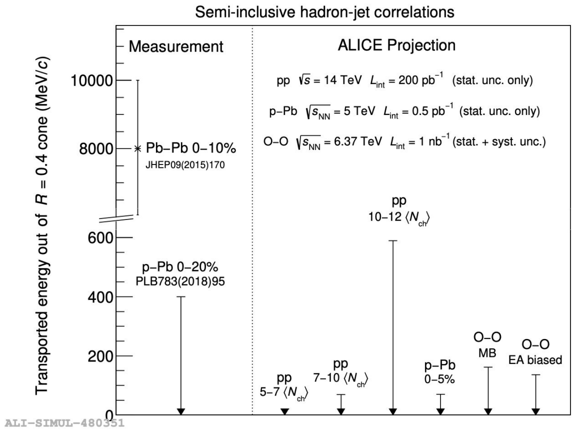
- Energy loss effects have not been observed in pp and p-Pb …
    - … within current experimental uncertainties.
    - Limits on energy loss outside jet cone have been put using h-Jet correlations.




$$\frac{\Delta_{\mathrm{recoil}}|_{0-20\,\%}}{\Delta_{\mathrm{recoil}}|_{50-100\,\%}} = \exp\left(-\frac{\bar{s}}{b}\right)$$



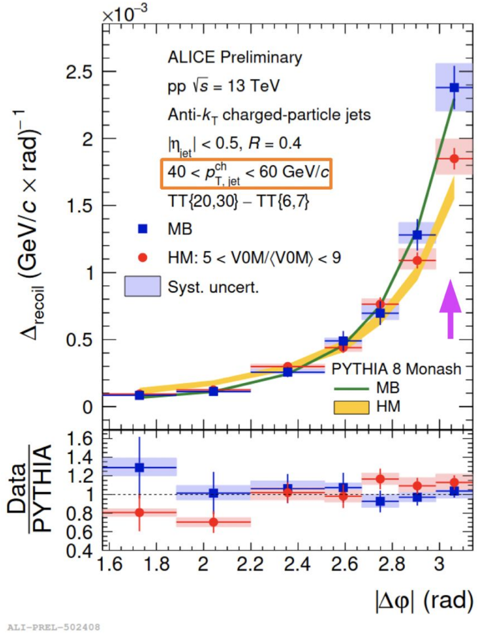

**Medium-induced charged energy transport out of $R$ = 0.4 cone is less than 0.4 GeV/c (90% CL)**




Projections for Run 3:
pp p-Pb, O-O
(caveat: nPDFs may play a role)
https://cds.cern.ch/record/2765973

# Energy loss in small systems ?

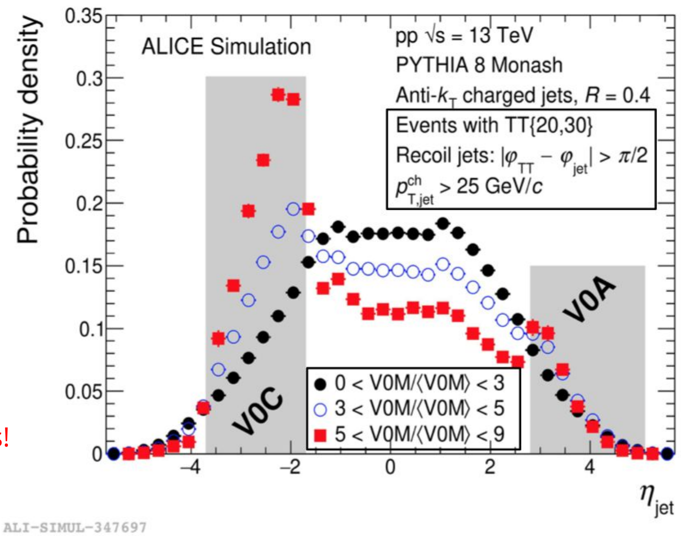
- Energy loss effects are expected to be larger in High Multiplicity (HM) events
- Exp. search in these events is complicated by selection biases (interplay of jets and HM)
  - New directions:
    - Control $N_{ch}$ dispersion on wide acceptance?
    - Redistribution of lost energy in the UE as possible signal?




- PYTHIA 8 Monash shows similar suppression pattern
- Need to understand this bias for jet quenching effect

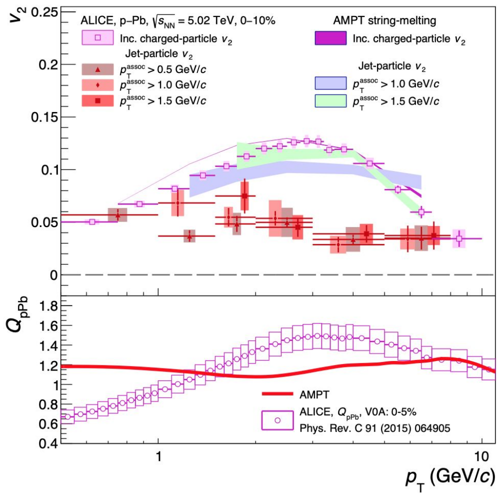
Warning: Pythia not reproducing an effect does not necessarily mean there is no bias!

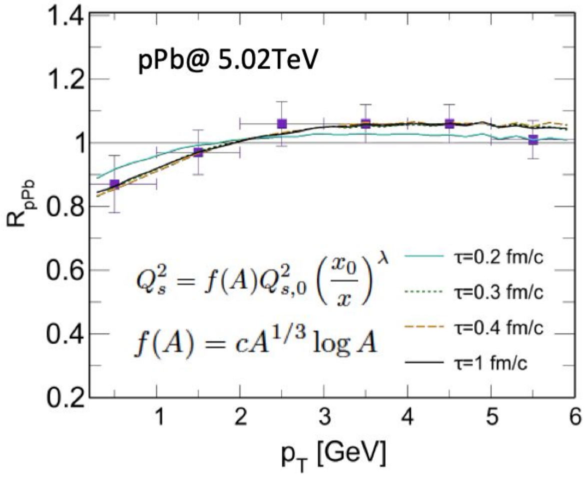
**Recoil jet pseudorapidity distribution vs. event activity**



# Energy loss in small systems ?

- Theory: connect $v_2$ to expected $R_{pA}$
  - Each model that describes $v_2$>0 should provide estimation of minimum necessary energy loss effect on $R_{pA}$ or other observables



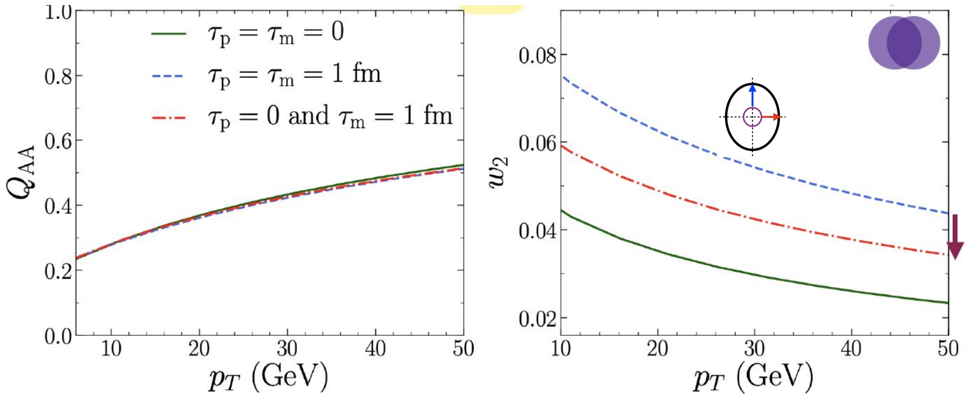

J.H.Liu et al., arXiv:1911.02480

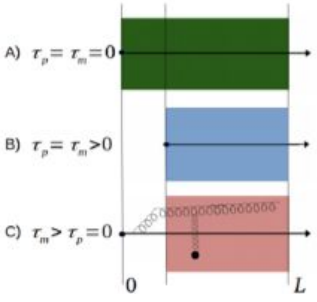
## Examples for possible “solutions” of the puzzle

- AMPT $v_2$ > 0, $Q_{pPb}$~1 from parton escape mechanism (see: ALICE, arXiv:2212.12609)
- Glasma phase alone could give “diffusion” and no energy loss resulting in $R_{pPb}$ > 1 which moves back to 1 through energy loss in a medium.

# Role of the pre-equilibrium stage in AA

- Most model calculations assume no interactions in the first ~1 fm/c (before QGP formation)
- However, this phase could play a role in gluon radiation
    - Increase radiation in later QGP phase
- Could lead to large effect in estimation of q-hat and understanding of QGP interactions




$\tau_p$: production time of parton
$\tau_m$: production time of medium

| Case | $C_1$ |
|---|---|
| A) $\tau_p = \tau_m = 0\,\text{fm}$ | 2.2 |
| B) $\tau_p = \tau_m = 1\,\text{fm}$ | 4.5 |
| C) $\tau_p = 0$ and $\tau_m = 1\,\text{fm}$ | 2.5 |

$n(t) = C_1 T(t)$ $\quad \mu^2(t) = 6\pi\alpha_s T^2(t)/e$

Using the *Full* formalism yields to more robust results

CA, Apolinário, Dominguez, **M. G. Martinez**, Salgado
arXiv: 2211.10161

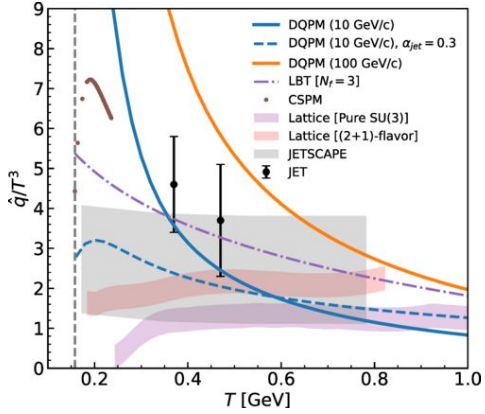
# Role of the pre-equilibrium stage in AA

- So far no interactions in the pre-equilibrium phase, however …
- Glasma predicts large and anisotropic q-hat in 0-1 fm/*c*
- Needs effort from the theory community to understand consequences for $v_2$ and energy loss
- Are small systems a proxy for pre-equilibrium effects (since this phase dominates) ?

# Energy dependence of q-hat

- q-hat calculations from first principles (2→2 and 2→3 partonic scatterings in PHSD (**D**ynamical **Q**uasi**P**article **M**odel - QGP phase) show significant jet-energy dependence
- Most energy loss implementations don't take this dependence into account
- What are the consequences for parton shower / jet shape?
- Can it be constrained from experimental data?
    - Bayesian analysis with constant relative / absolute energy loss from $R_{\mathrm{AA}}$

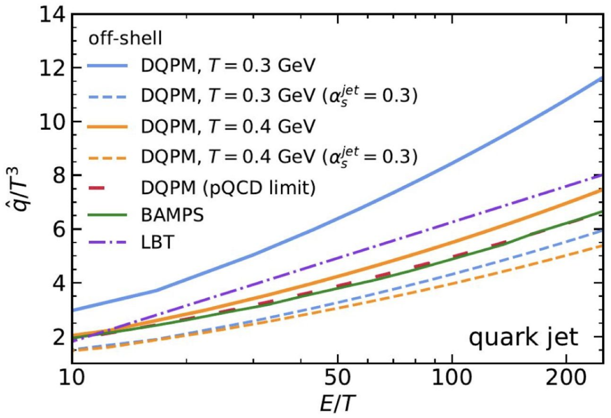
quark jet q-hat (2→2)
I Grismanovskii, O Soloveva, … PRC 106, 014903




$E_{\mathrm{jet}}$=10 GeV, 100 GeV

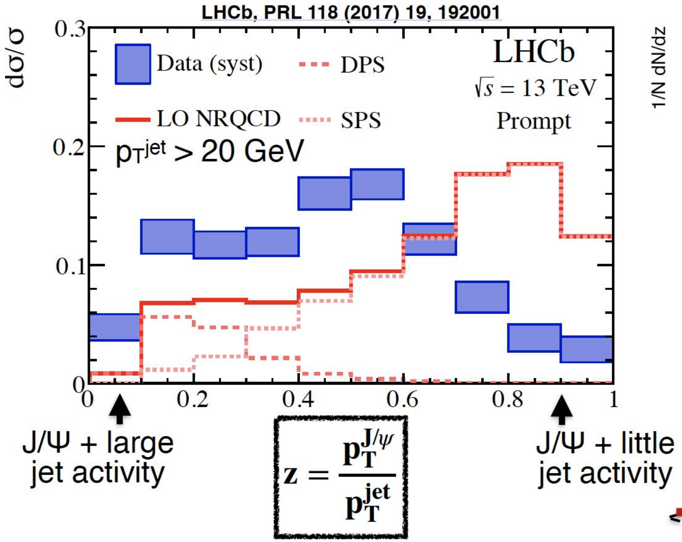
**JET:** K. M. Burke et al., *PRC 90, 014909 (2014)*
**lQCD:** A. Kumar et al., *arxiv:2010.14463*
**LBT:** Y. He et al., *PRC 91 (2015)*
**JETSCAPE:** S. Cao *et al. PRC 104, 024905 (2021)*

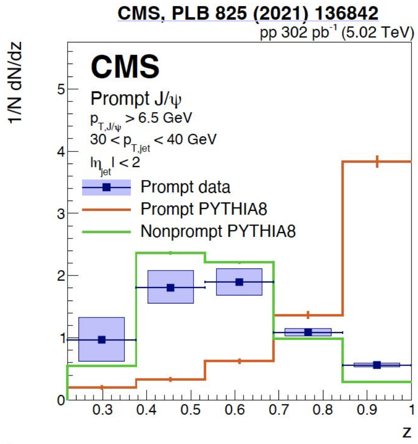
**jet-energy dependence**

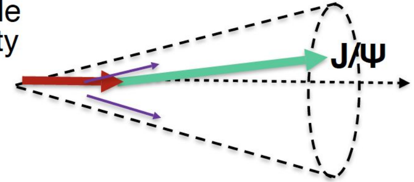


# Energy Loss in Quarkonia Production

- Non-isolated direct J/ψ production
  - Possible explanation: Color octet radiates gluons becoming a singlet
  - Characterize correlated particles (in pp) to constrain the production mechanism
    - Expect soft gluon radiation ?

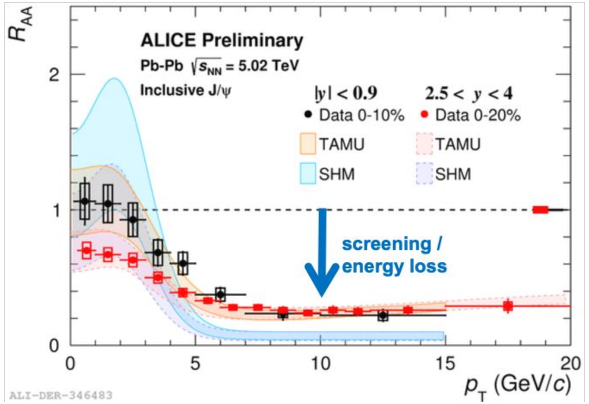


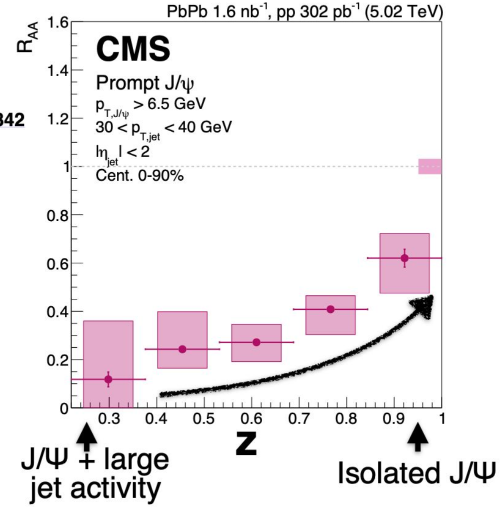
# Energy Loss in Quarkonia Production

- Energy loss of color-octet in the medium?
- Explanation for J/ψ suppression at high $p_T$ ?
  - CMS: $R_{AA}$ for isolated and non-isolated J/ψ
  - Non-isolated J/ψ more suppressed
  - Measure modification of J/ψ tagged jets structure
  - What about Upsilon production ?
- Also important in general for ccbar ?
  - ccbar stay for some time in a color octet state
  - Study suppression as a function of DD rel. angle



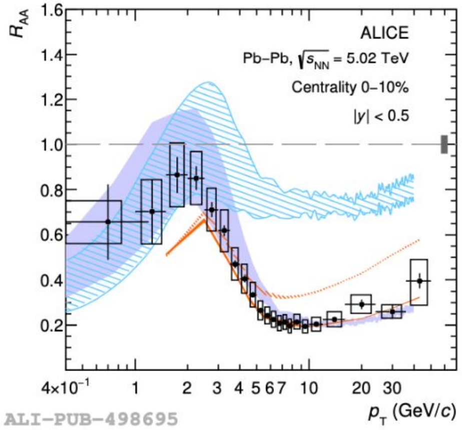

CMS, PLB 825 (2022) 136842

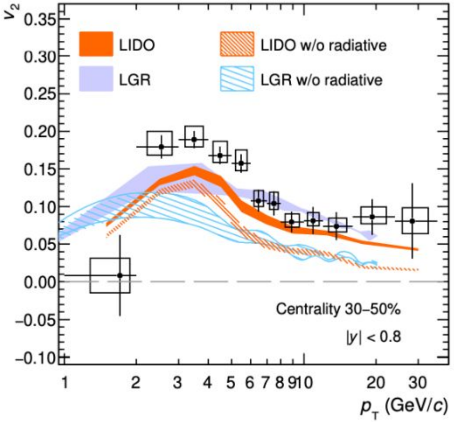
$$\boxed{z = \frac{p_T^{J/\psi}}{p_T^{jet}}}$$



# Heavy Quark Diffusion in the QGP

See also "Hadronization" summary talk

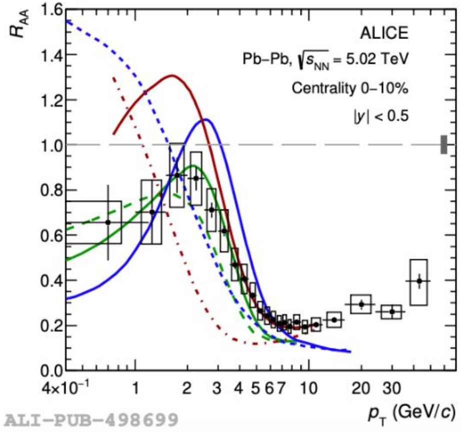


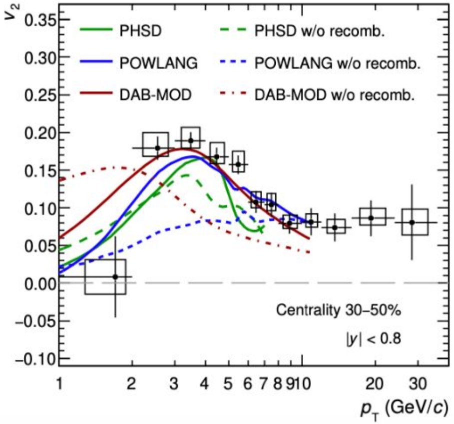




ALICE, arXiv:2110.09420

- Spatial diffusion coefficient is not the only key ingredient
- Collisional vs. radiative energy loss
  ➡ only collisional processes underestimate the energy loss
  → predict too high $R_{AA}$ and low $v_2$

- Relation between $p_{charm}$ and $p_D$ is different for fragmentation and recombination
  ➡ recombination → $p_D > p_{charm}$ and D meson inherits also the flow of light quark

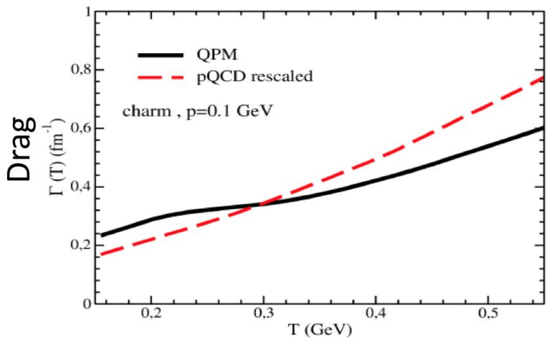


# Heavy Quark Diffusion in QGP

- Impact of hadronization description on diffusion coefficient estimate:
  - Restrict to models that simultaneously describe $R_{AA}$, $v_2$, $\Lambda_c$/D
- Other improvements:
  - Measurements at very low $p_T$
  - Important for models to provide uncertainty band (large effect on $\chi^2$/ndf)
  - Additional observables: $D^0$ ESE $v_2$, $D^0$ $v_2\{4\}$, $D^0$ $v_3$, correlation of $D^0$ $v_n$ vs. pion $v_n$ in ESE classes

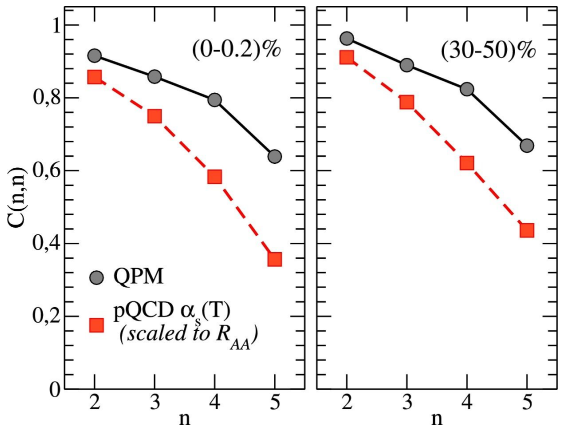
$$C(v_n^{light}, v_m^{heavy}) = \left\langle \frac{(v_n^{light} - \langle v_n^{light}\rangle)(v_m^{heavy} - \langle v_m^{heavy}\rangle)}{\sigma_{v_n^{light}} \sigma_{v_m^{heavy}}} \right\rangle$$




S. Plumari et al., Phys.Lett.B 805 (2020)

**[Prado, JNH et al.,**PRC 96(2017)

**Large sensitivity to *T* dependence**



# Heavy Quark Diffusion in QGP

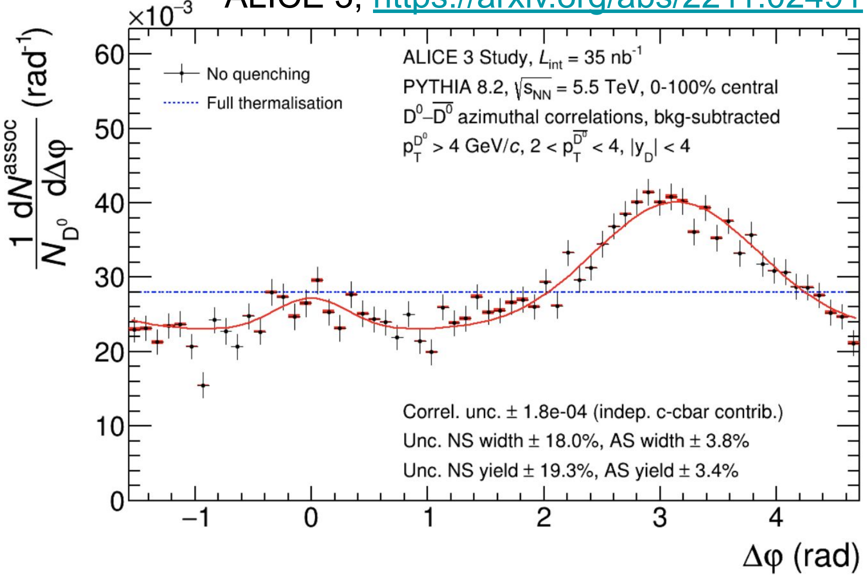
- Ultimately: use B mesons (LHC Run 3++, sPHENIX)
    - Less uncertainty on transport description (Boltzmann, Langevin ..)
    - Larger mass makes it closer to the infinite-mass approximation used in lattice QCD calculation of diffusion coefficient

# Signals for Heavy Flavor Thermalisation

## $D\bar{D}$ correlations

- Azimuthal correlations constrain energy loss and angular decorrelation simultaneously
- sensitivity to collisional vs radiative eloss vs momentum scale
- full isotropization at low $p_T$?
- Exploit also D-hadron correlations?
- Calculations with state-of-the-art models needed

ALICE 3, https://arxiv.org/abs/2211.02491



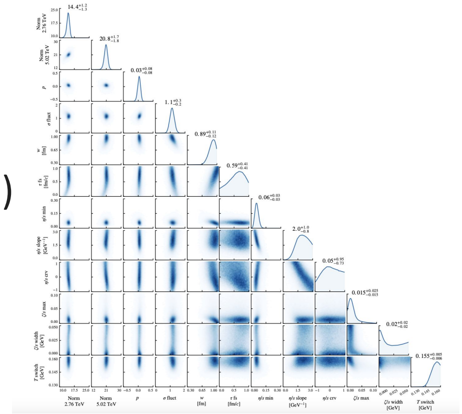
# Extraction of medium parameters from future high precision measurements - **Questions to theorists**

- Today: significant variability among models:
  - interactions with the medium
  - medium evolution
  - hadronisation
  - hadronic afterburner
  - + nuclear PDFs
  - ...
- Is the choice (and number) of modelling parameters under sufficient control?
- Are the observables that experiments provide now already optimal?
  - e.g.: would there an advantage in the $p_T$ distributions directly, instead of $R_{AA?}$
  - more importantly: are the observable we use clean enough for constraining the physics?

# Extraction of medium parameters from future high precision measurements - **Challenges for experimentalists**

- Results of Bayesian analysis, e.g., are crucially sensitive to uncertainties...
  - Wrong uncertainties equals to wrong result...
  - Are our experimental uncertainties under sufficient control for the high-precision era?
  - Do we always strive for the best possible estimate of the systematic uncertainties?
  - or do we sometimes opt for mechanically evaluated and/or “conservative” ones?

- ... and to their correlations!
  - within the same measured distribution
  - between different measurements performed by different analysers
  - even correlations with models used for the analysis (e.g. syst uncertainties)

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  - Olga Soloveva
  - Stefano Trogolo
- Co-Convener during preparation
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