Simulating Heavy Quarks in Quark Gluon Plasma

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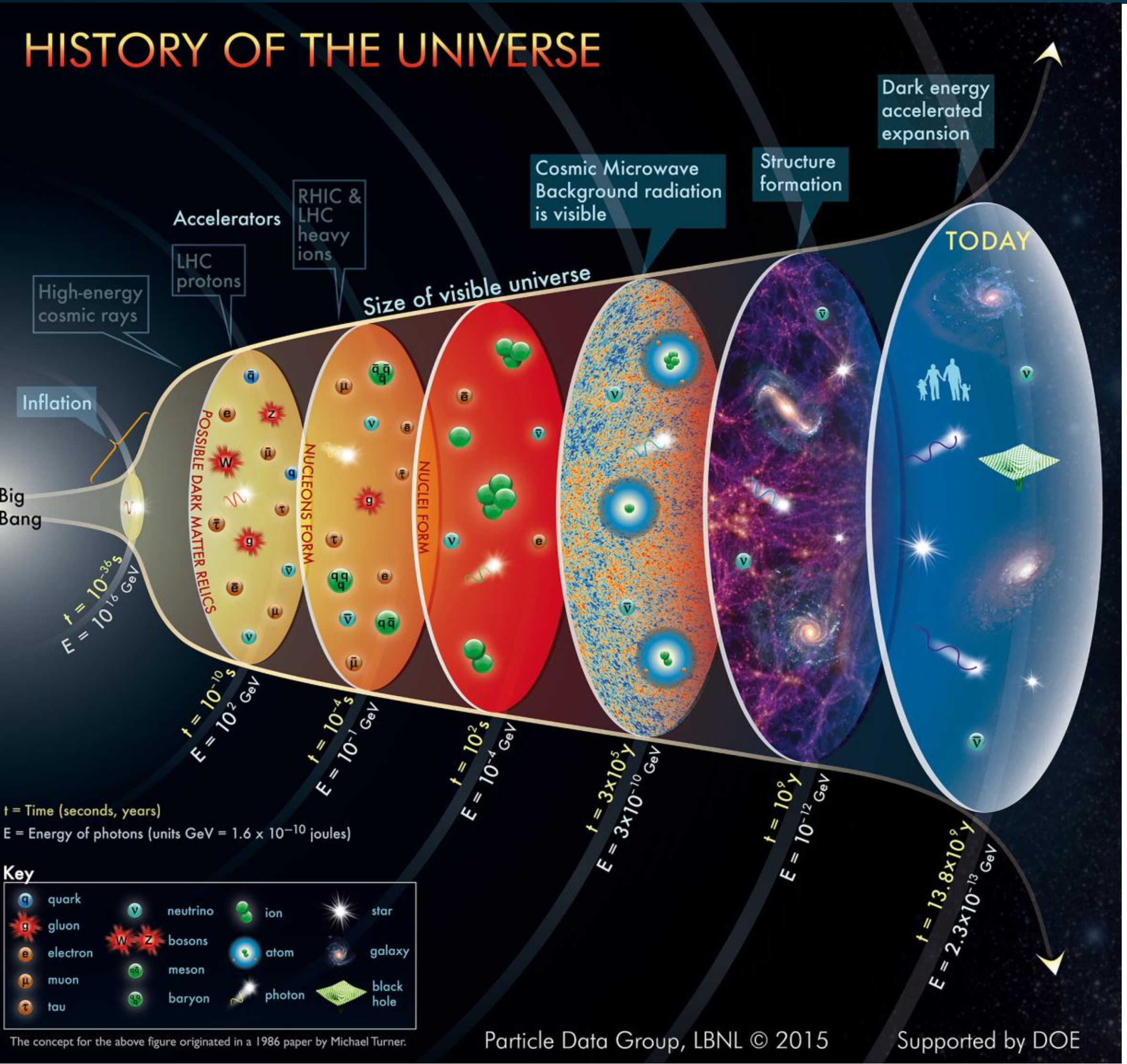
Submit User Meeting June 2025

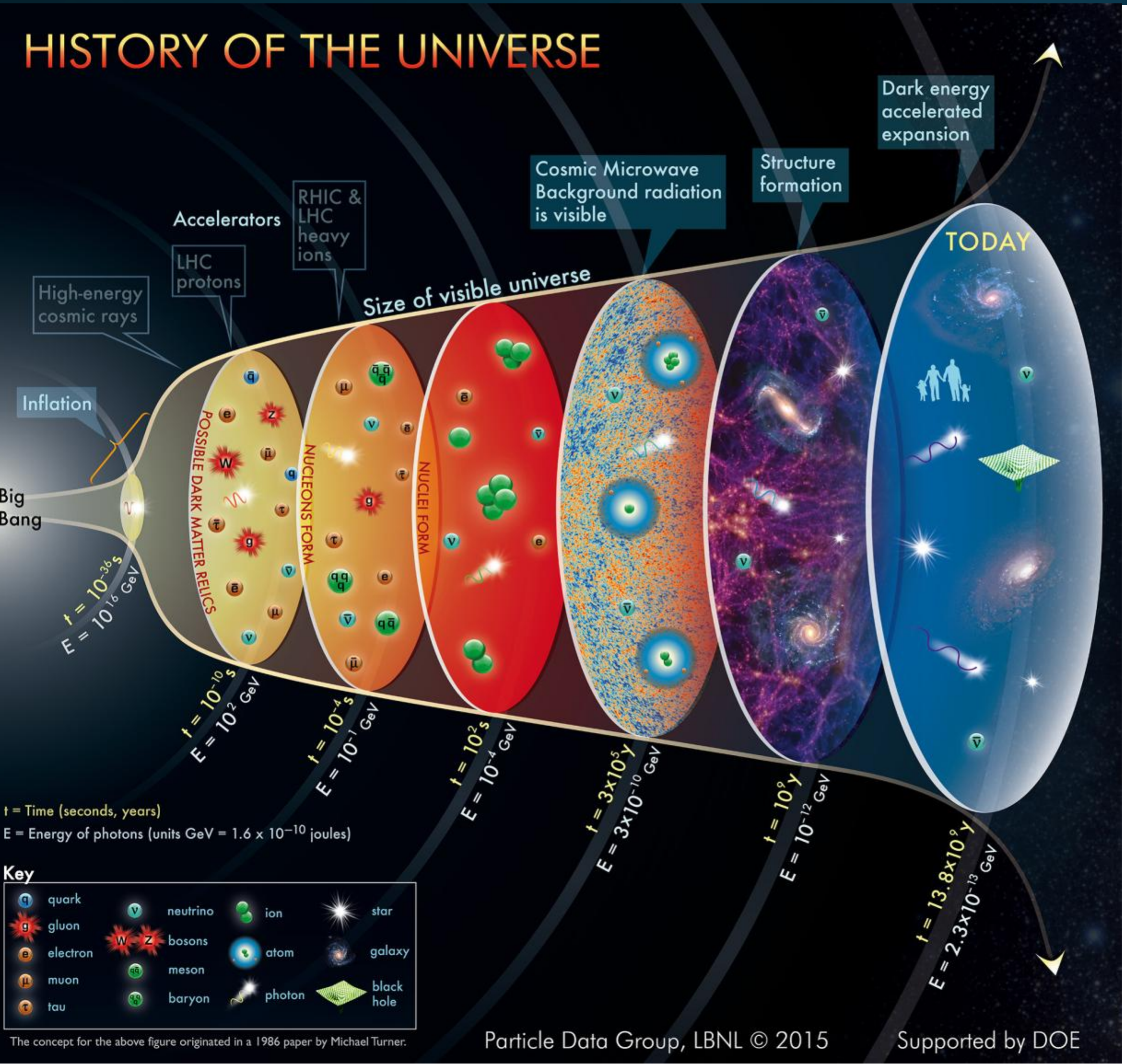
Done in collaboration with

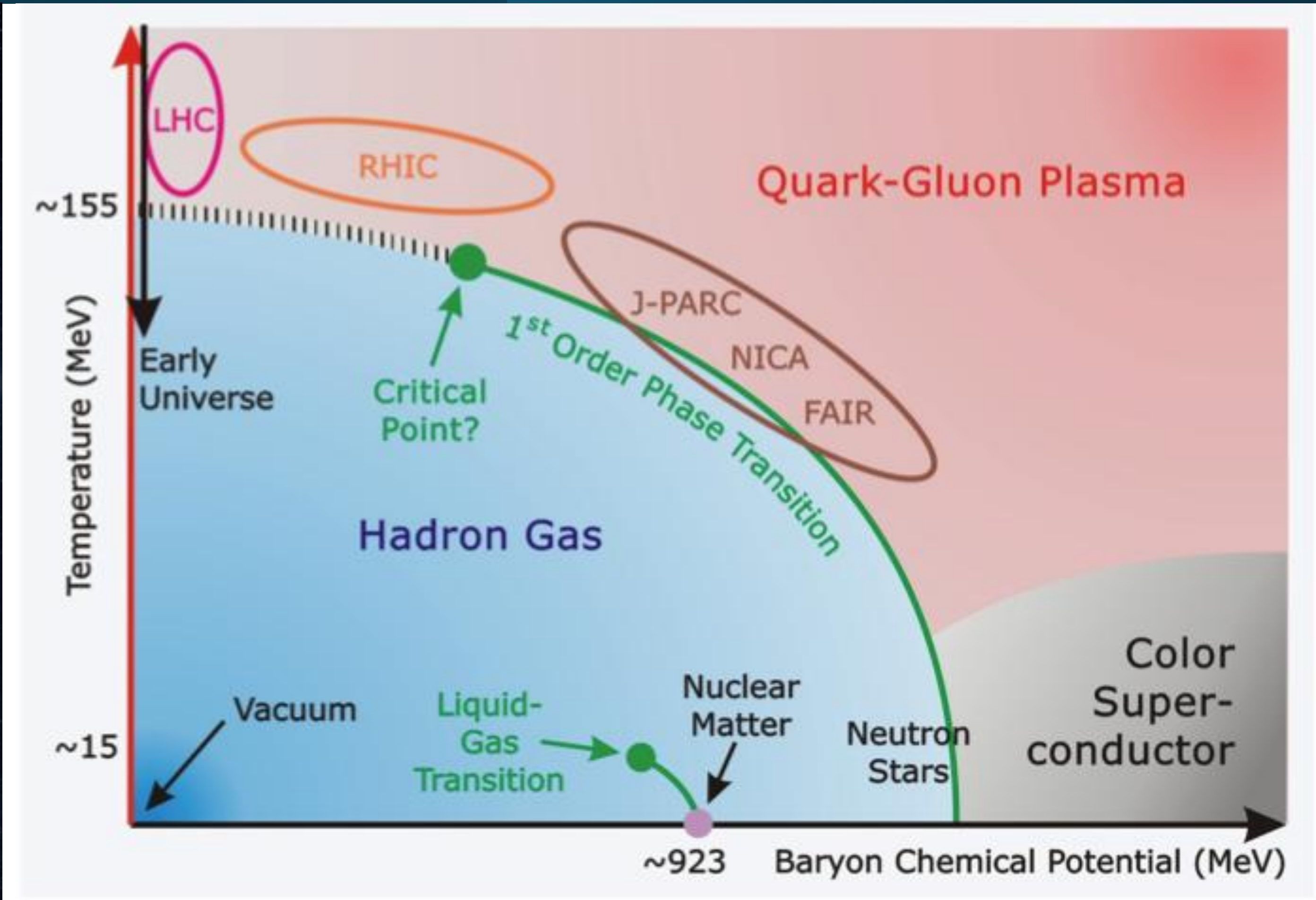
D. Pablos, K. Rajagopal, A. Beraudo

Why Quark Gluon Plasma?

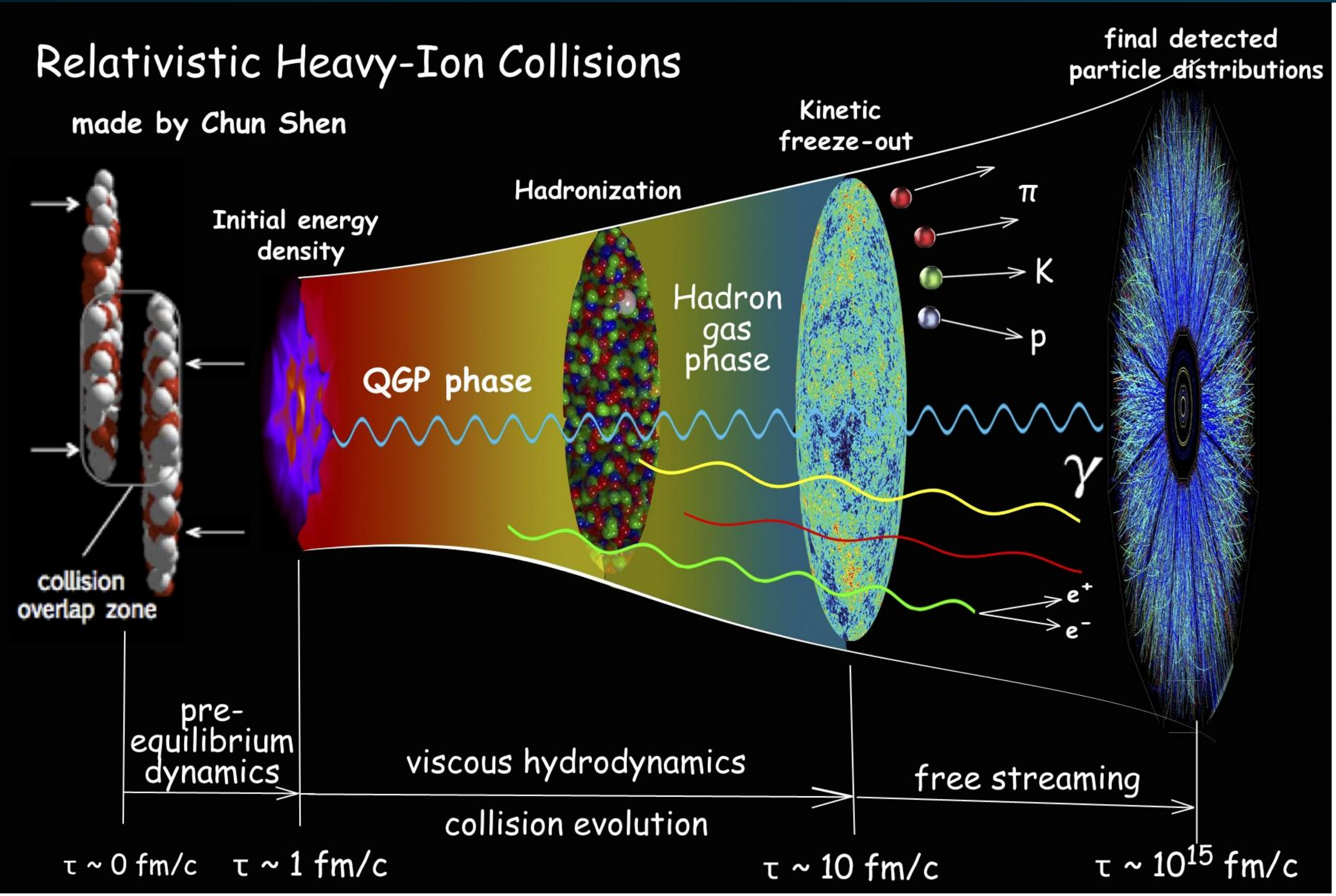


Why Heavy Ion Collisions?





Why Heavy Quarks



- Heavy ion collisions give a hard inverse problem; we measure outgoing particles, but can't choose the initial conditions of our probes
- Need probes of the medium that we have a handle on from proton-proton collisions
- Heavy Quarks are predominantly produced in the initial collision
- Too heavy to become part of the medium
- So Heavy Quarks have an 'identity'

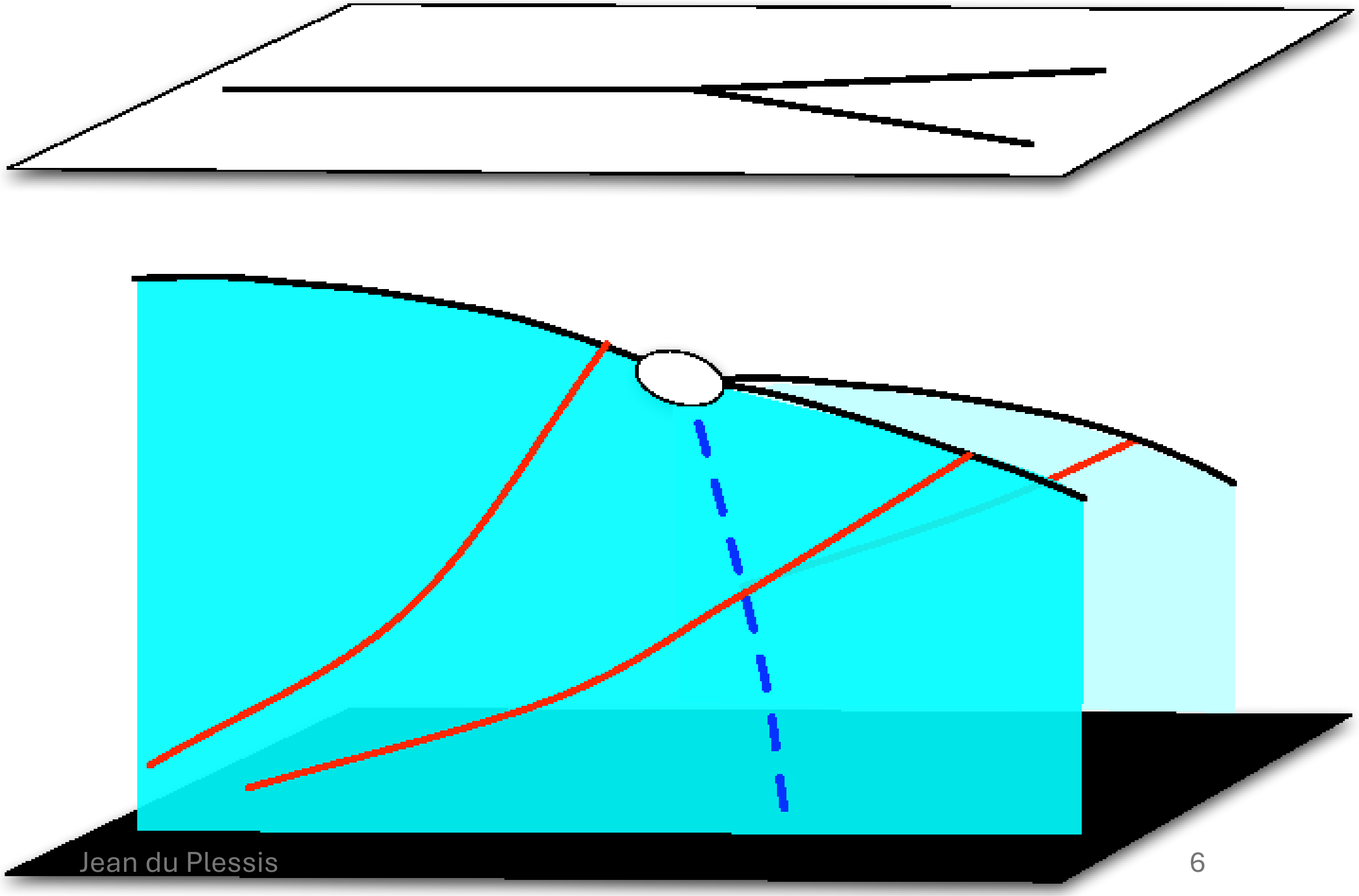
Goal and outline

- We want to model heavy quarks
- We need to model how heavy quarks get produced
- We need to model how heavy quarks lose energy
  - QCD is strongly coupled at these energies; can’t use perturbation theory
- We need to model heavy quark diffusion (‘Brownian motion’ of quarks in plasma)
- We need to model heavy quark hadronization
  - High energy quarks will hadronized with high energy particles
  - Low energy quarks can hadronized with particles from the medium
- We will implement all of this into the Hybrid Model

Hybrid model

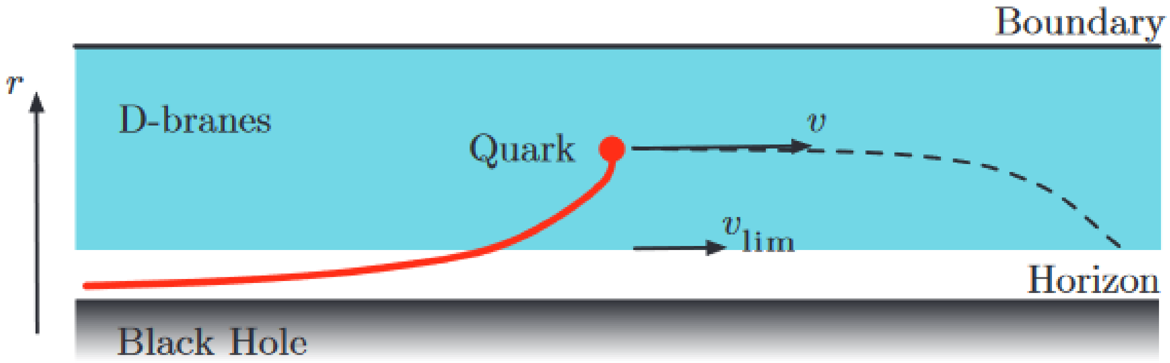
J. Casalderrey-Solana et al.
1405.3864 and 1808.07386

- Pythia 8 Monash 2013 tune for weak coupling parton showers
- Hydrodynamic background from simulations that correctly reproduces soft observables
- All particles undergo energy loss modeled using AdS/CFT
- Particles get hadronized with other particles in the same shower using Pythia Lund String hadronization



AdS/CFT

- Problem:
  - Want to model strongly coupled QGP ($\alpha_s \approx 0.3$)
- Solution:
  - Calculate strongly coupled results in N=4 SYM in $N_c \to \infty$ limit
  - Can do this using AdS/CFT by considering holographic dual
  - Can perform calculations using classical string theory in 5d asymptotically AdS spacetime when in $\lambda = 4\pi\alpha_s N_c \to \infty$ limit
  - Finite temperature plasma dual to black brane
  - Quarks dual to strings ending on $D7$ branes
- Note:
  - N=4 SYM is not QCD
  - Need to keep differences in mind



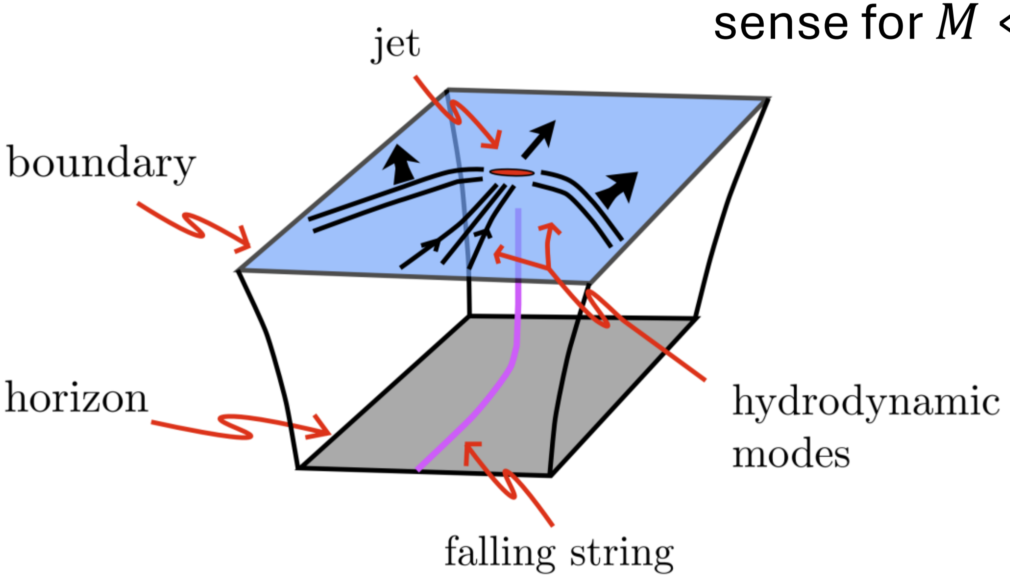
Light quark energy loss

P. Chesler and K. Rajagopal
1402.6756 and 1511.07567

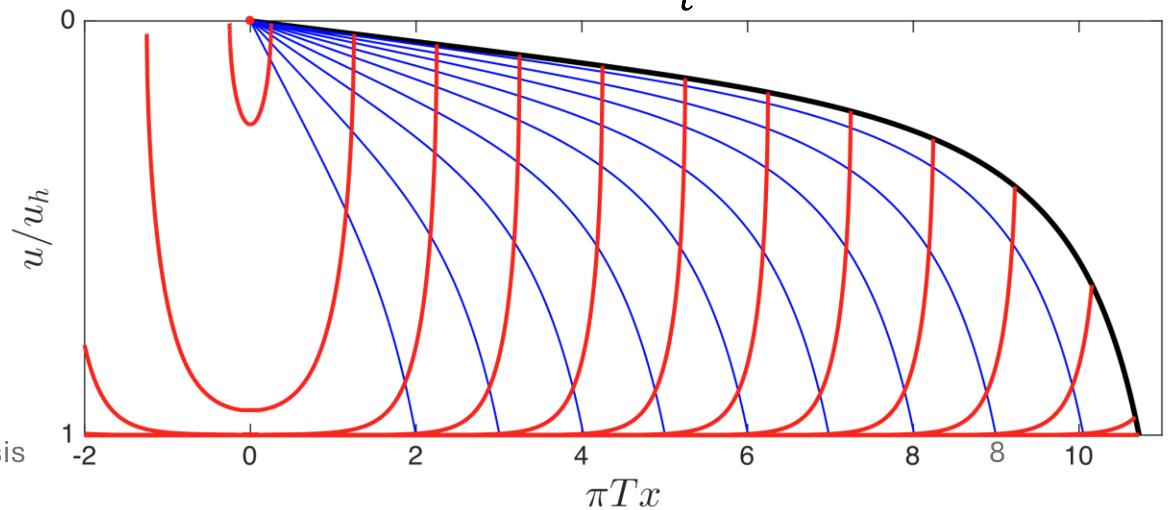
- $\frac{dE}{dx} = -\frac{4x^2 E_0}{\pi x_t^2 \sqrt{x_t^2 - x^2}}$
- $x_t = \frac{1}{2\kappa_{sc}} \left(\frac{E_0}{T^4}\right)^{\frac{1}{3}}$ stopping length

- $M = 0$
- κ_{sc} calculable in N=4; has been determined for QCD with fit to experimental data
- Quark thermalizes after stopping length; only makes sense for $M \ll T$

- Obtained from string propagating over and falling into black hole
- Dual to quark propagating through holographic plasma with constant T and thermalizing after traveling distance x_t



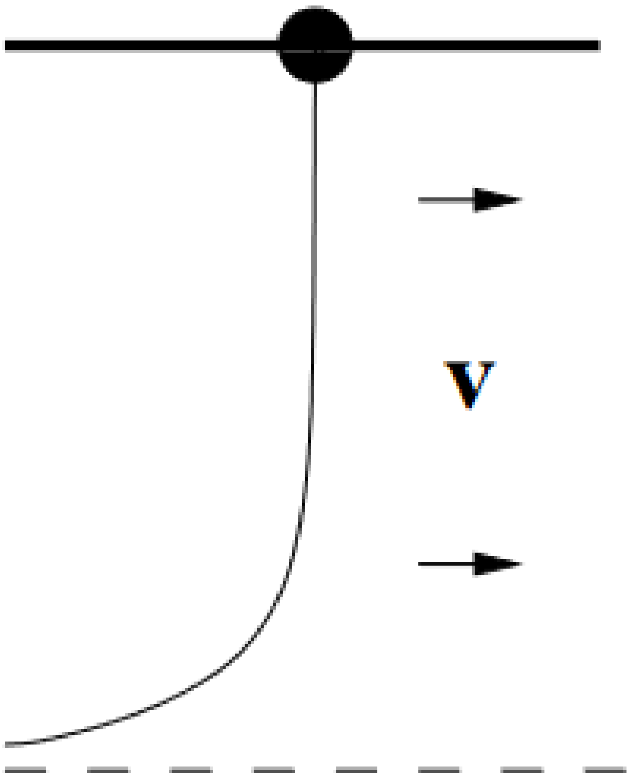
Jean du Plessis



Heavy quark energy loss

C.P. Herzog et al.
hep-th/0605158
S.S. Gubser
hep-th/0605182

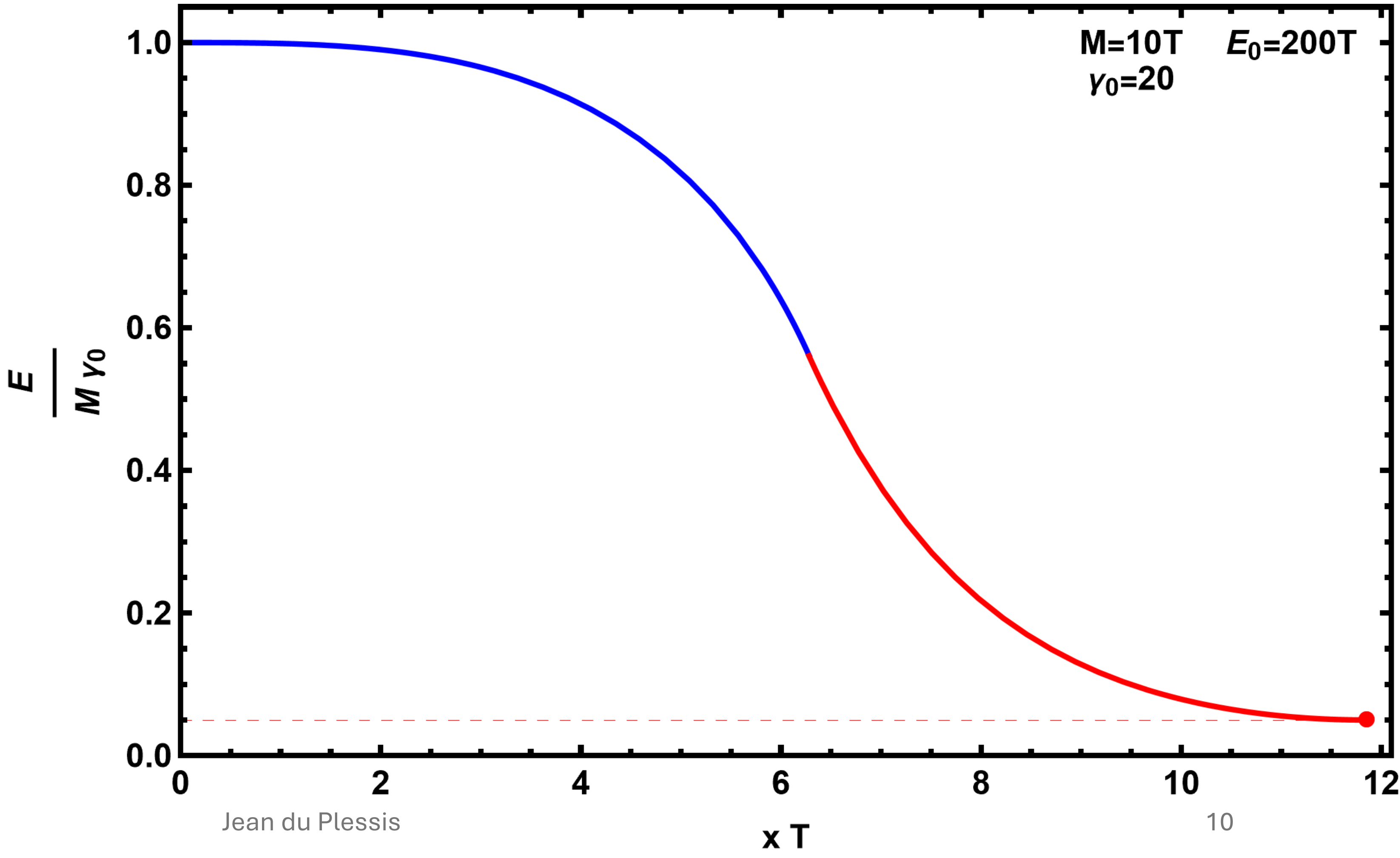
- $\frac{dE}{dx} = -\eta_D\sqrt{E^2 - M^2}$
- $\eta_D = \kappa_{HQ}\frac{T^2}{M}$ where $\kappa_{HQ}^{N=4} = \frac{\pi}{2}\sqrt{\lambda}$
- Valid in $\mathrm{M} \gg \sqrt{\lambda}T$ regime
- κ_{hq} will be a fitting parameter absorbing difference between QCD and N=4 SYM plasmas



Composite energy loss formula

$$-\frac{dE}{dx} = \min\left(\frac{4x^2E_0}{\pi x_t^2\sqrt{x_t^2 - x^2}}, \eta_D\sqrt{E^2 - M^2}\right)$$

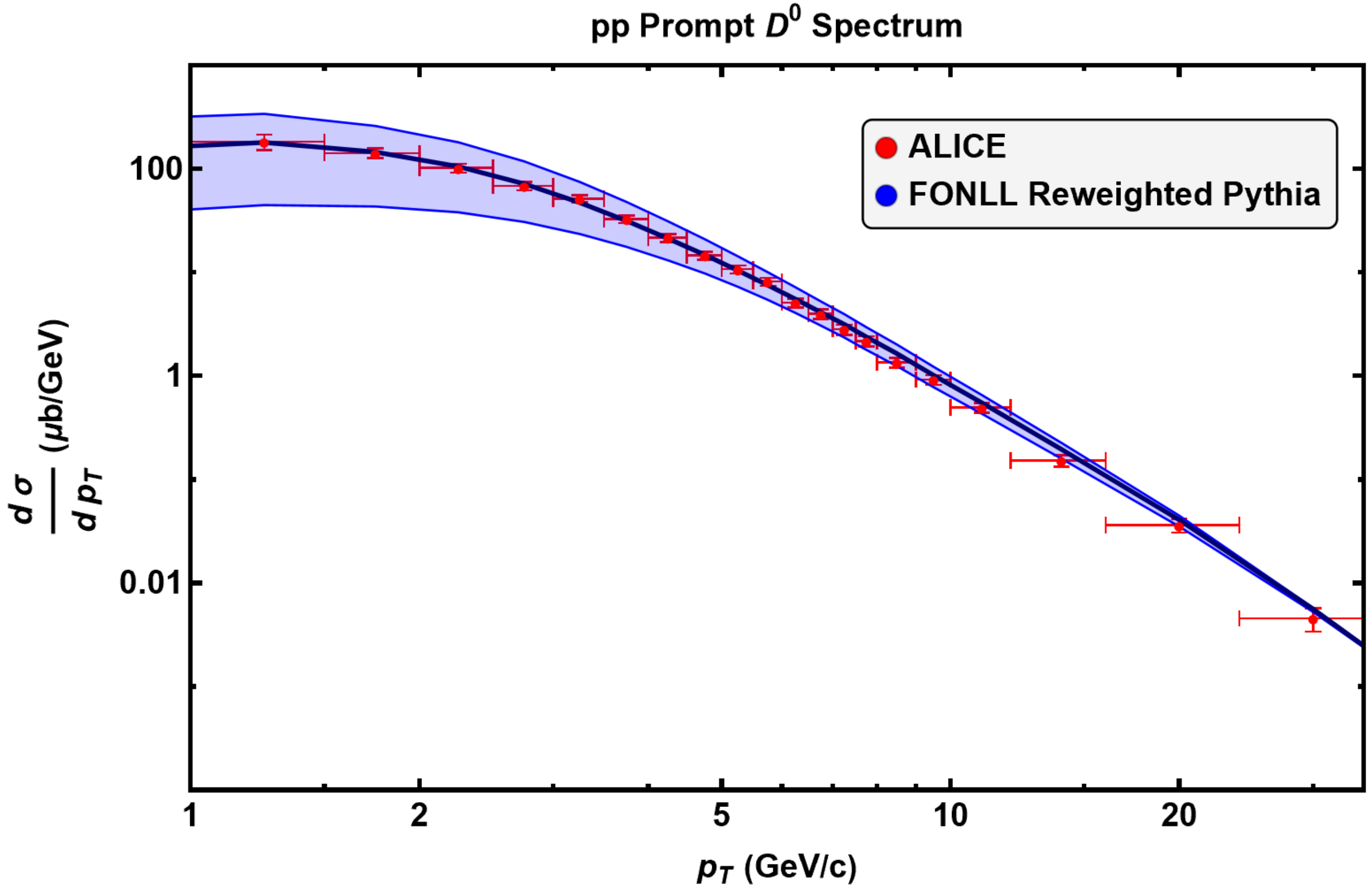
- Can uniquely match such that $E(x)$ and its first derivative are continuous due to opposite signs in second derivative
- At each step choose whether to lose energy as heavy or light quark; always choose least energy loss.
- Comes to rest at finite distance
- Starts off like massless quark, ends like heavy quark



FONLL Reweighting

M. M. Cacciari et al.
hep-ph/9803400

- PYTHIA charm spectrum disagrees with FONLL calculations at low p_t
- Leads to disagreement with D^0 spectrum data in pp
- We reweight our events as function of largest charm p_t produced
- Estimate theoretical uncertainty due to reweighting
- Gives good agreement with pp D^0 spectrum



Our Implementation of Momentum Diffusion

- Not our main focus
- Simply isotropic (in fluid rest frame) momentum diffusion
- Assume Gaussian Fluctuations
- Enforce Einstein relation to ensure thermalization is possible
- This is in conflict with strongly coupled results (see S.S. Gubser hep-th/0605182)
- Inclusion of higher moments (see Bruno Scheihing-Hitschfeld's talk and arXiv:2501.06289 for their importance) future work

$$P(\Delta\vec{p}|\Delta t) \propto exp\left(-\frac{\Delta p^2}{2\,\sigma^2}\right)$$

$$\sigma^2 = \kappa_L\,\Delta t$$

$$\kappa_L = \kappa_T = 2\kappa_{HQ}\gamma T^3$$

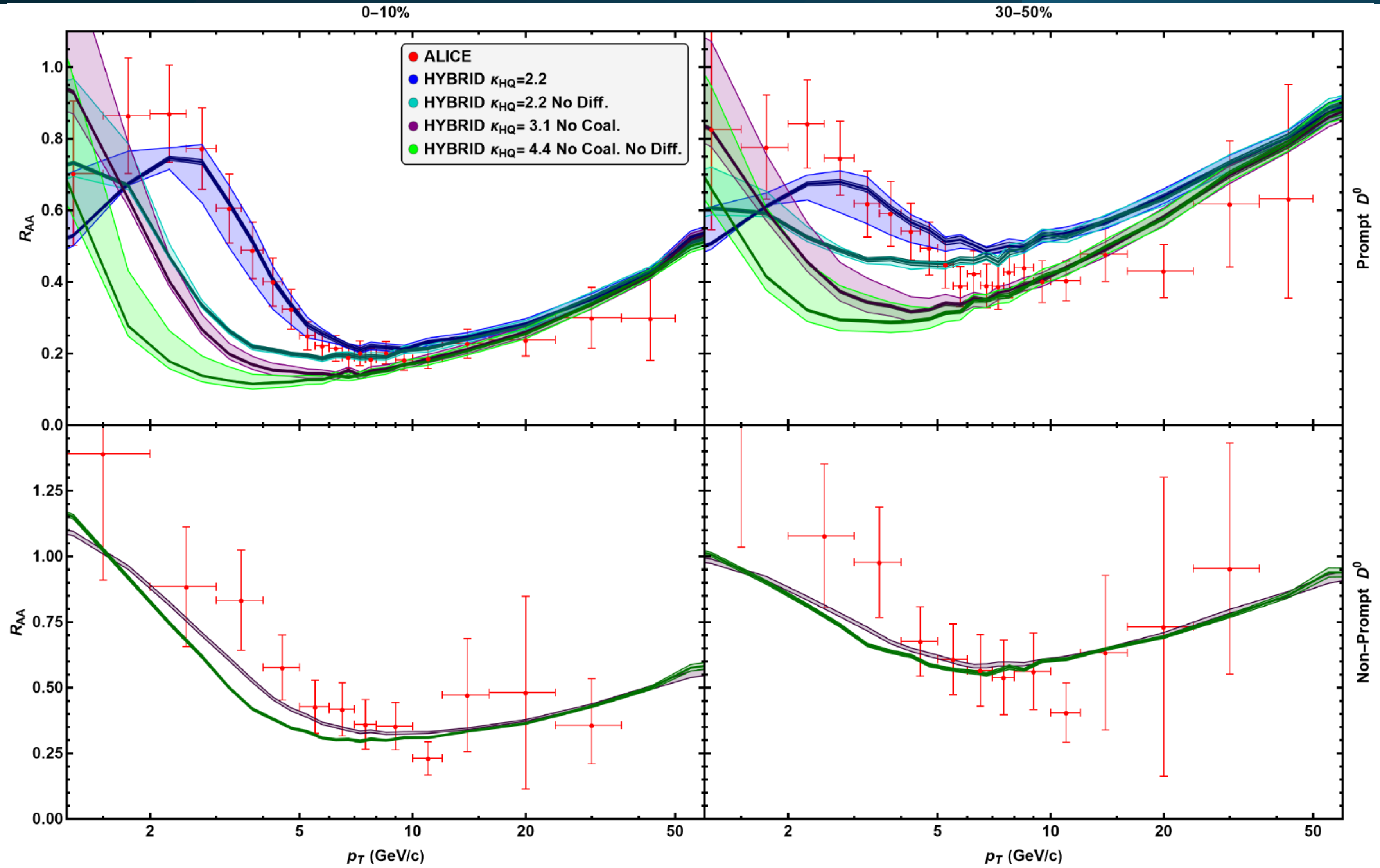
Coalescence for charm quark hadronization

A. Beraudo et al.
2202.08732

- To model hadronization between charm quarks and light quarks from the medium we implement the Torino model
- Need to choose between hadronizing charms in event in Pythia shower or using recombination with medium partons
- Hadronize with Pythia shower only in event that has charm that either:
  - Emitted a gluon outside the freezeout surface
  - Was created outside the freezeout surface
  - Would have to undergo string fragmentation if it were to hadronize with a medium parton
  - Is closer in momentum space to a shower parton than to a medium parton
- This is a modeling choice providing a “switchover” criterion that leads to most low p_t charms hadronizing with medium partons and most high p_t charms hadronizing with shower partons as expected
- Has model parameter M_{cut}, the minimum invariant mass for a string to undergo string fragmentation. Our results here are insensitive to its value, so we use previously obtained $M_{cut} = 3.8\ GeV$

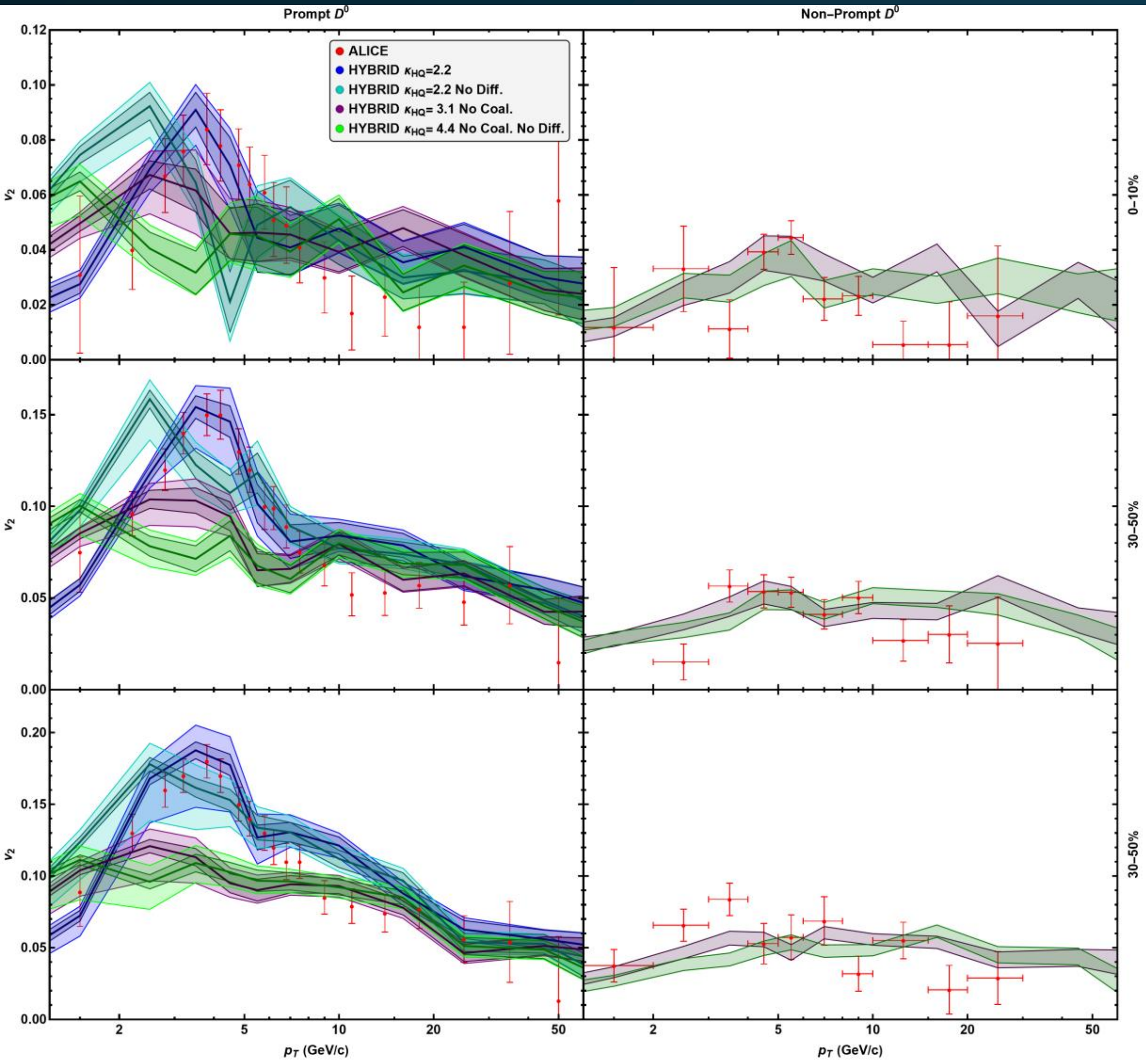
b and c Hadron R_{AA}

ALICE Data: 2202.00815



b and c Hadron v_2

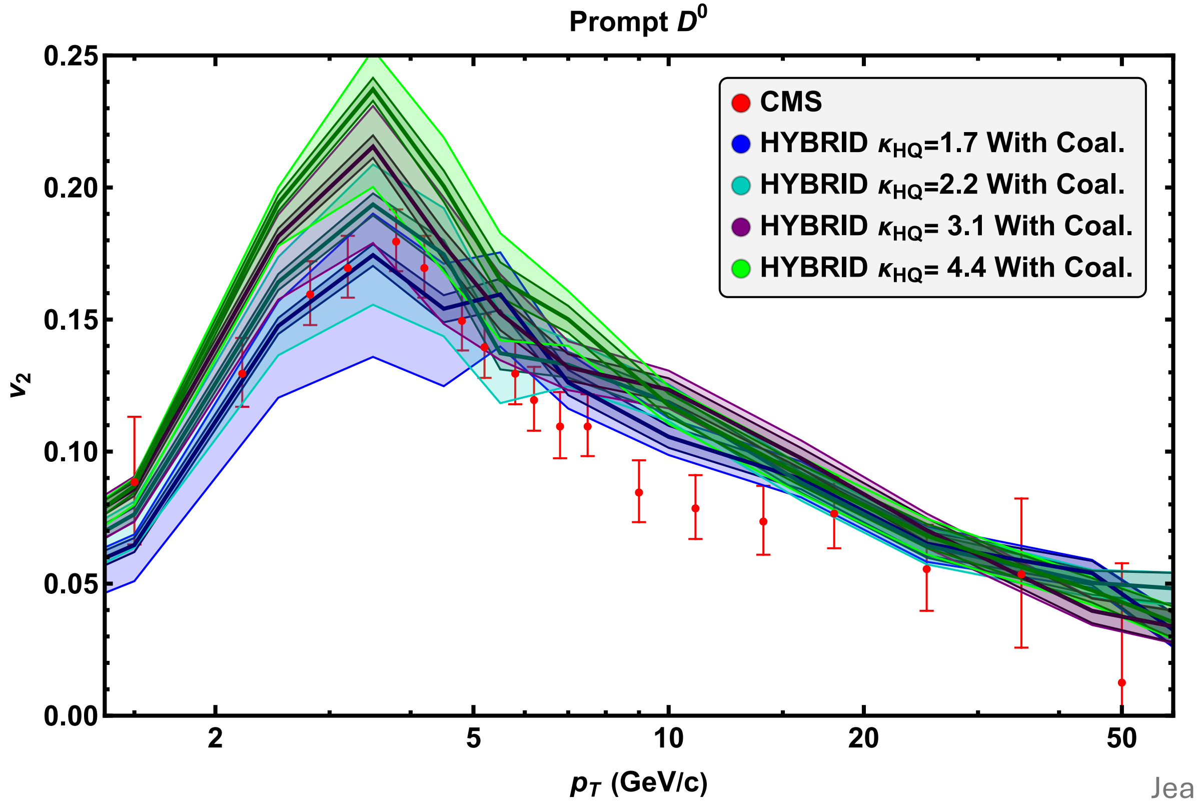
CMS Data: 2009.12628 and 2212.01636

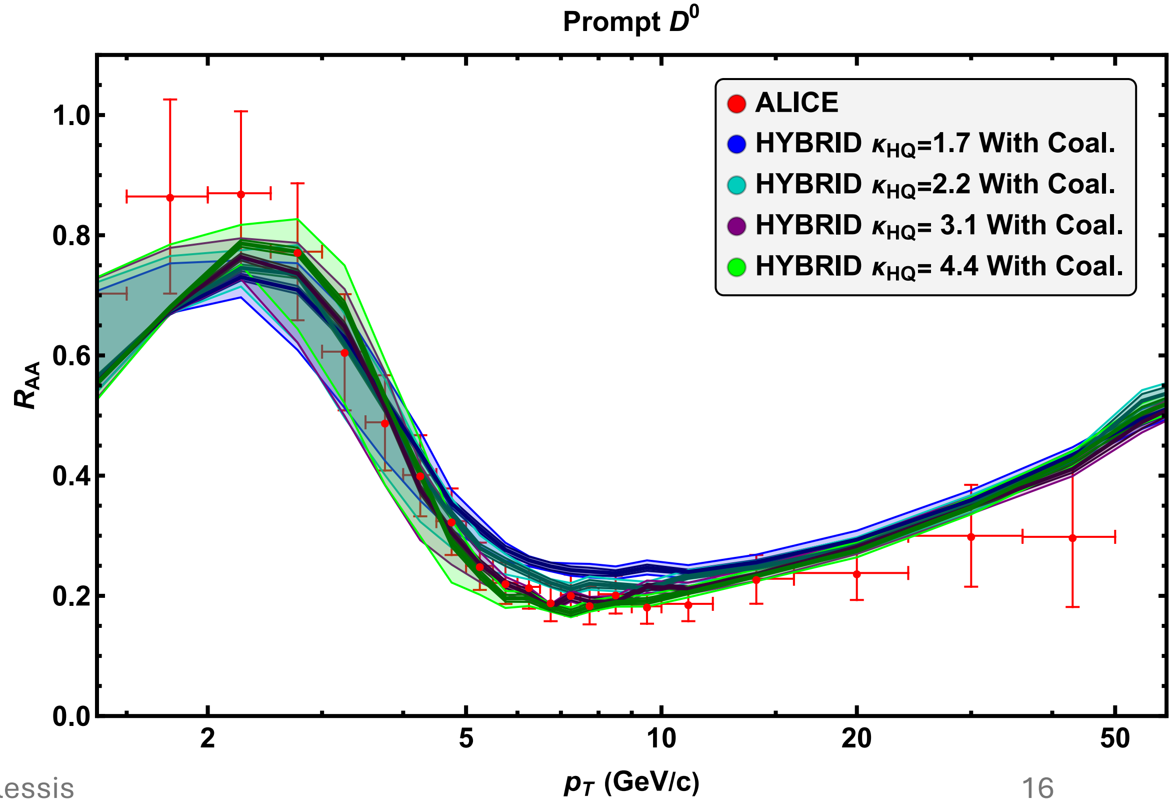


- Comparing to experiment shows that one needs to take both diffusion and hadronization effects into account to properly reproduce data for charm quarks, but they are not needed for bottom quarks.

Value of κ_{HQ}

- In N=4 SYM one finds $\kappa_{HQ} \approx 4.3 - 5.3$
- We find $\kappa_{HQ} \approx 2.2$ to give reasonable agreement with data for QCD; $2\pi T D_s \approx 2.86$ in $v \to 0$ limit
- We therefore find a relaxation time (or "stopping length") for heavy quarks that is 2-2.5 times longer in QCD





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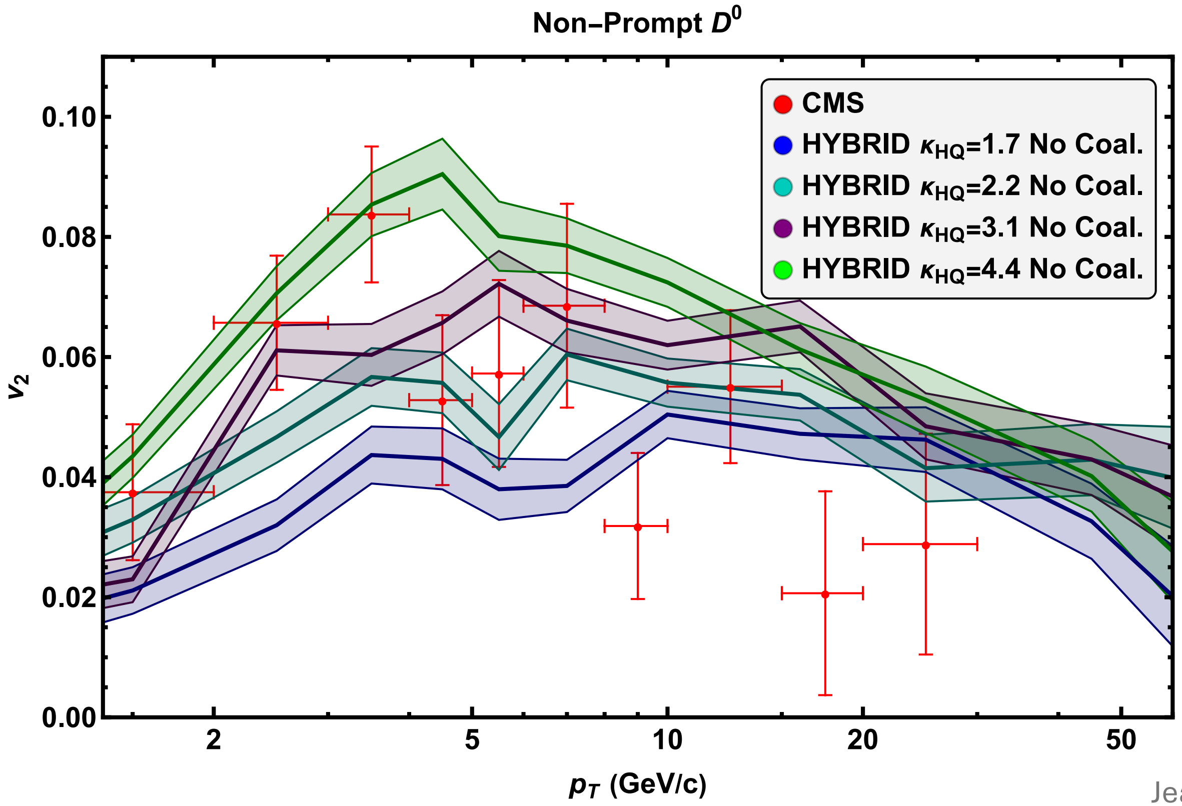
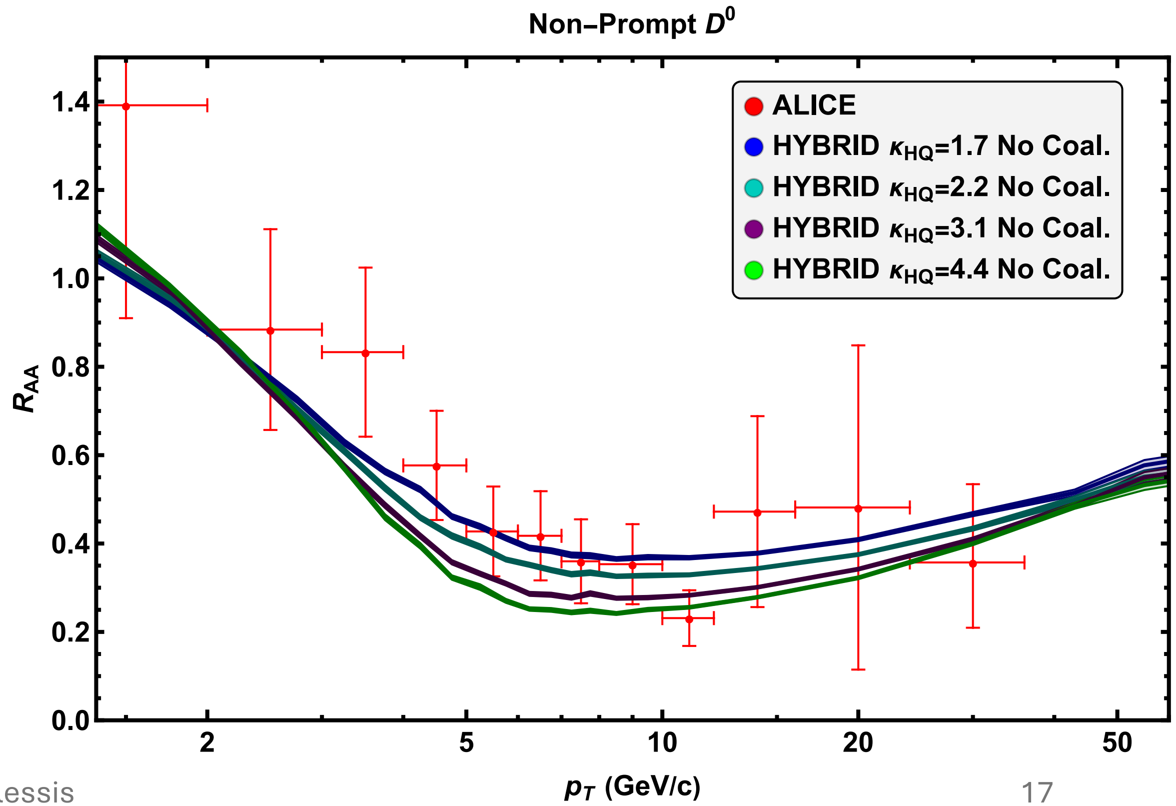
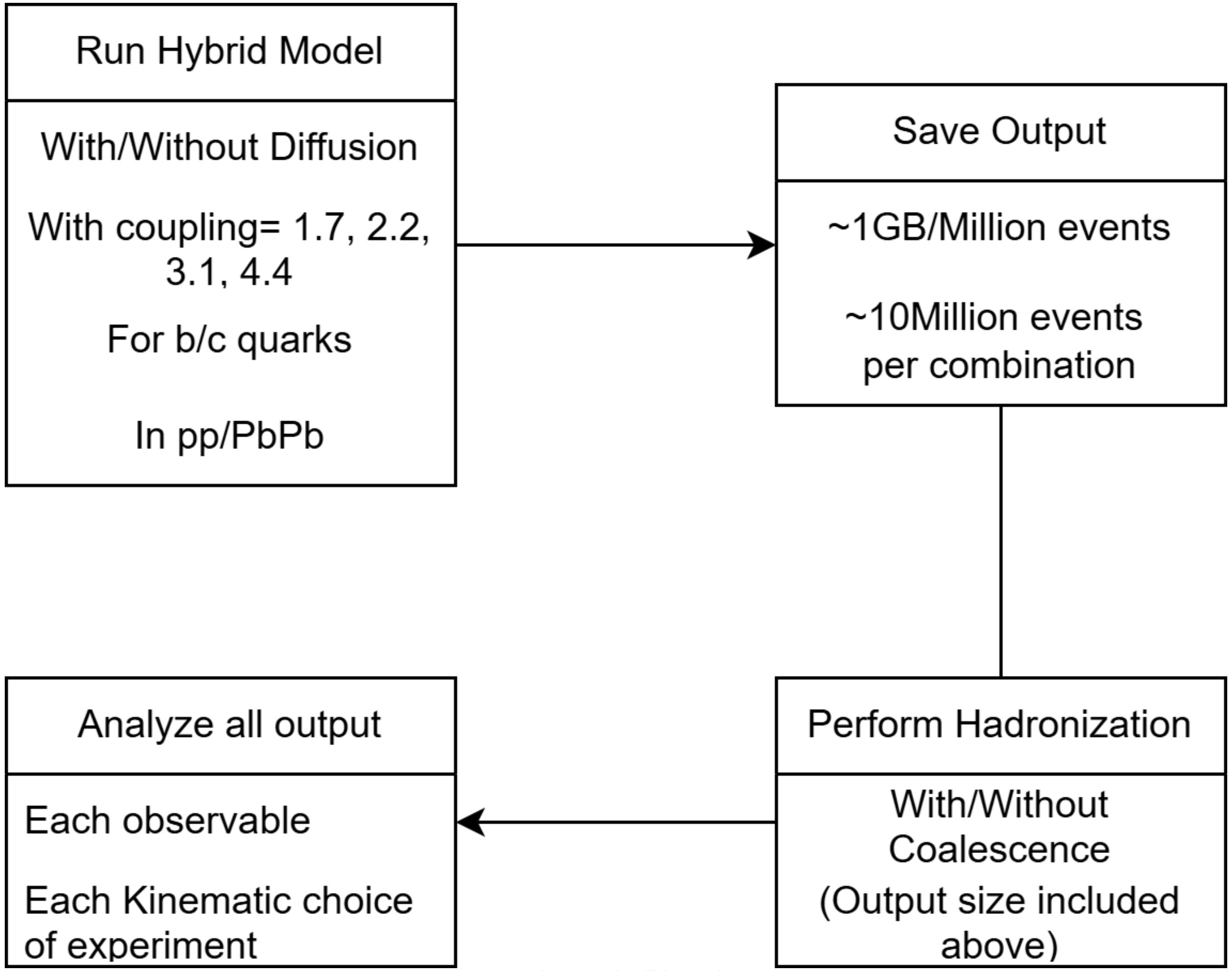




Computational Workflow

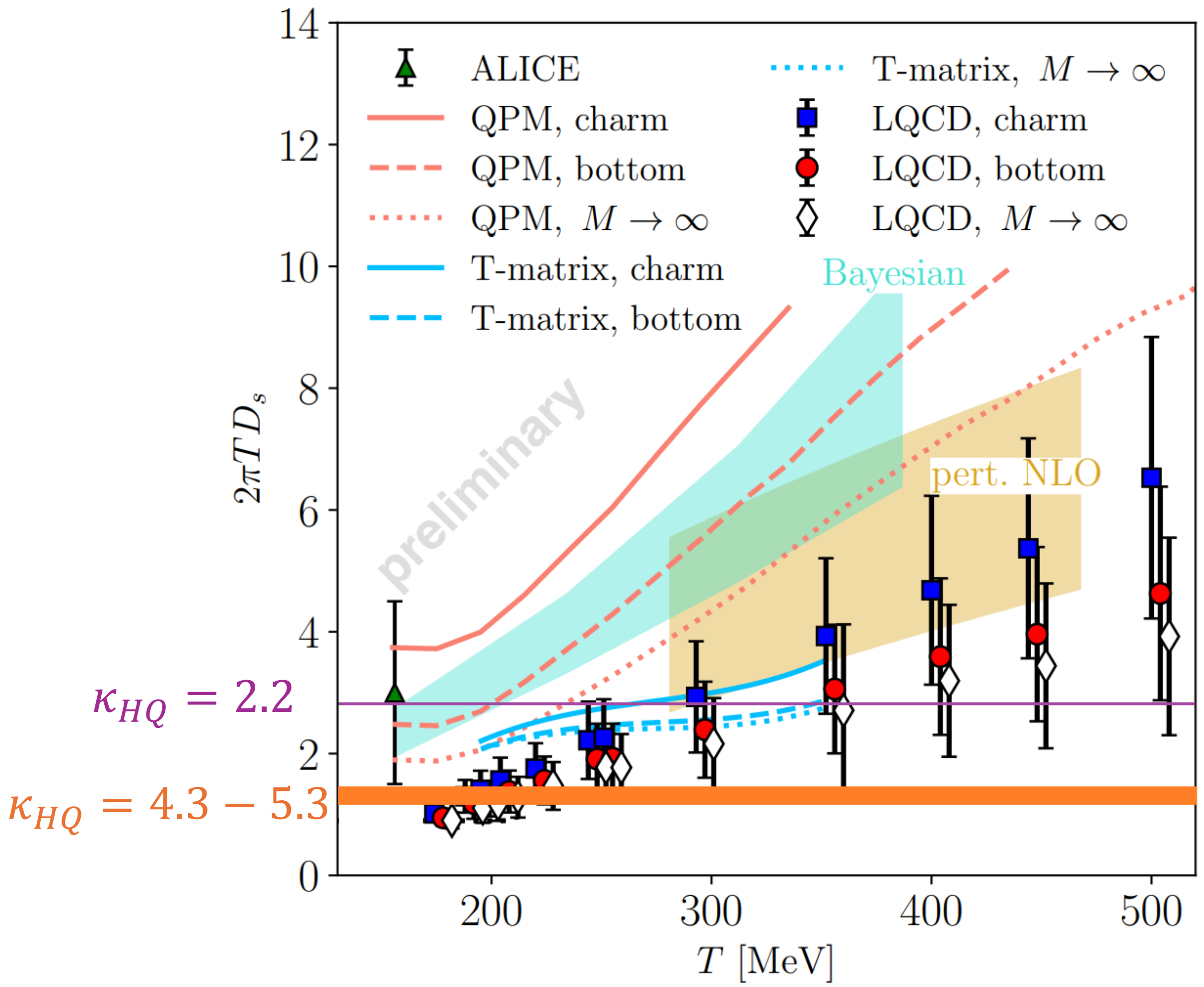


Outlook and next steps

- First time that heavy quark energy loss and coalescence have been incorporated in the hybrid model
- Allows us to compare hybrid model calculations to observables that the model could not address previously
- Early results very encouraging.
- Reasonable agreement with data when Coalescence is included
- Next Steps:
  - Perform unified holographic calculation of finite mass energy loss (work in progress with Carlos Hoyos, KR, DP)
  - Improve treatment of momentum diffusion
  - Full scale fit of κ_{HQ} to data

Backup: Diffusion Constant at $v = 0$ from the Lattice

L. Altenkort et al.
arXiv:2311.01525
Hai-Tao Shu
Hard Probes 2025



For a Heavy Quark at Rest

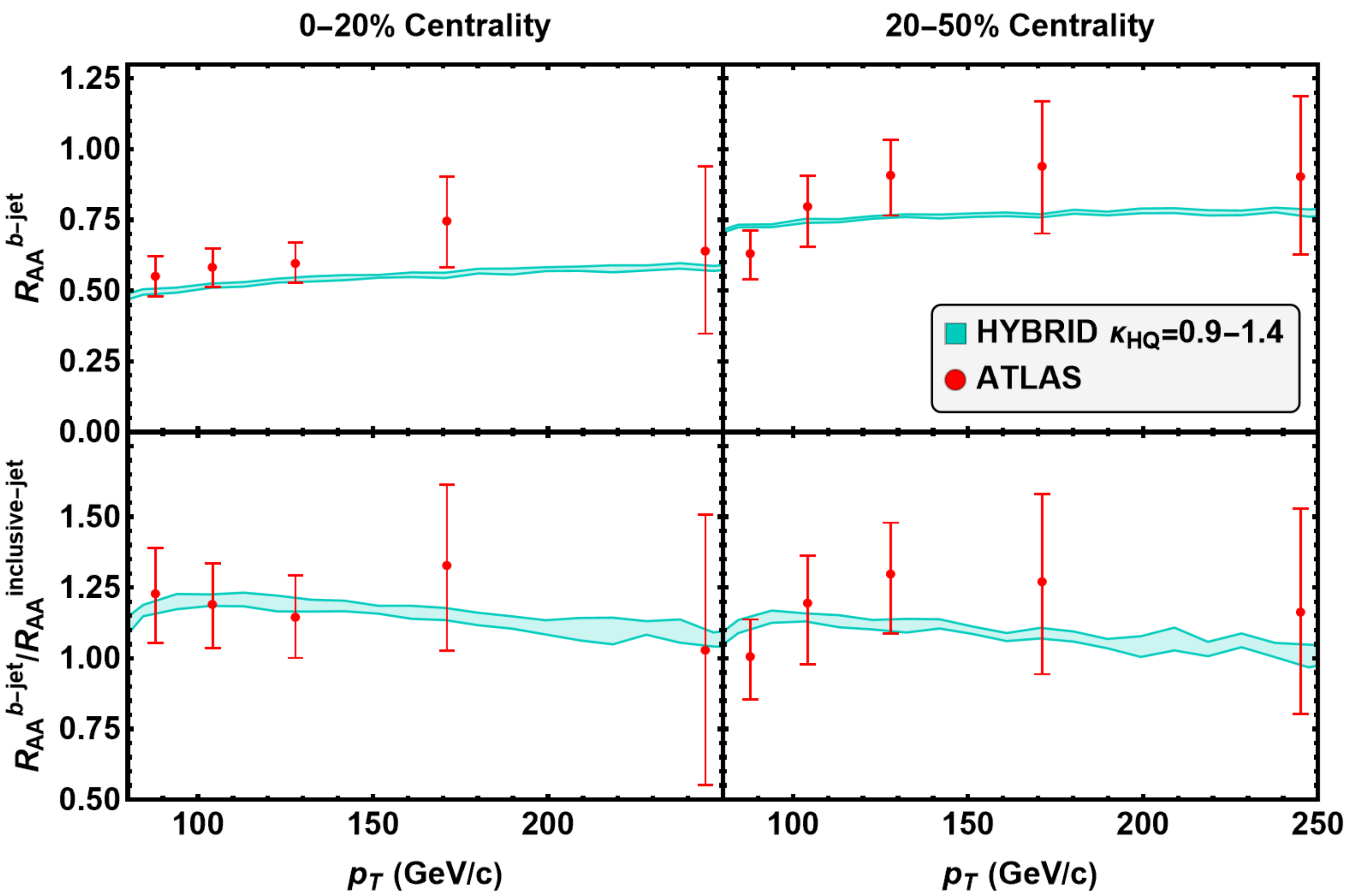
$$2\pi\ T\ D_s = \frac{2\pi}{\kappa_{HQ}}$$

[J.D. Golan, Swagato Mukherjee, P. Petreczky, HTS, J.H. Webber, work in progress]

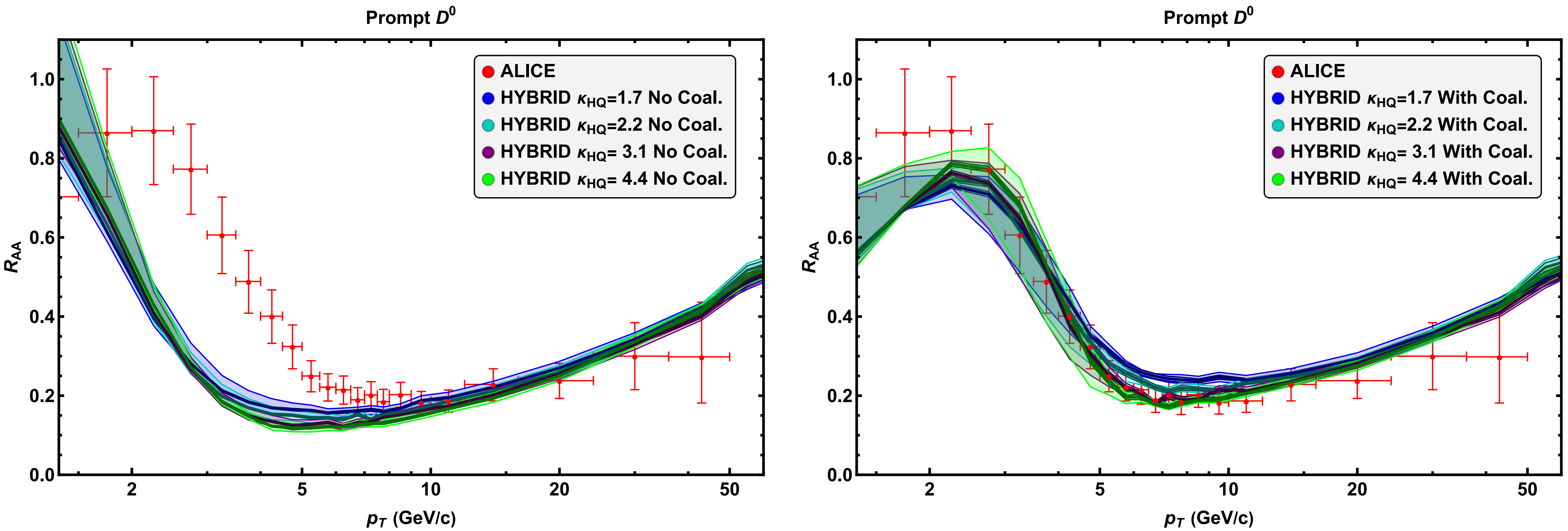
Backup: b-jets

ATLAS Data: 2204.13530

- Good agreement with data
- Great agreement for ratio since hybrid slightly over-quenches inclusive jets
- Insensitive to composite formula, since at these energies b and c quarks are like light quarks
- Good check of hybrid model treatment of light quark vs gluon energy loss



Backup: κ_{HQ} dependence of R_{AA} before and after Coalescence



Backup: κ_{HQ} dependence of v_2 before and after Coalescence