# Holographic Heavy Quark Energy Loss in the Hybrid Model

Jean F. Du Plessis

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Done in collaboration with

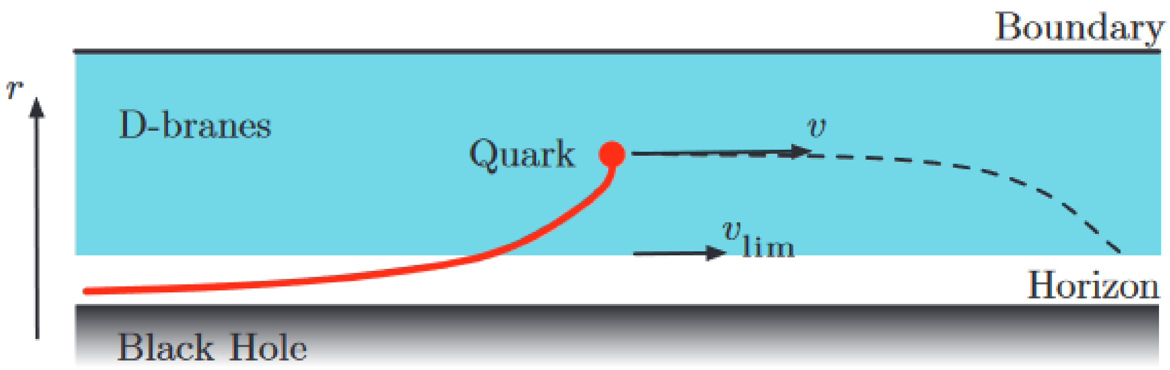
D. Pablos, K. Rajagopal , C. Hoyos, B. Scheihing-Hitschfeld

# Goal and outline

- We want to model heavy quarks in the hybrid model
- We need strongly coupled heavy quark energy loss for that
- I will introduce two existing AdS/CFT calculations of how quarks lose energy in a strongly coupled plasma (one for massless quarks; one for infinite mass quarks) and then motivate a model for interpolating between them
- I will compare to hadron and jet $R_{AA}$ and hadron $v_2$

# $AdS/CFT$

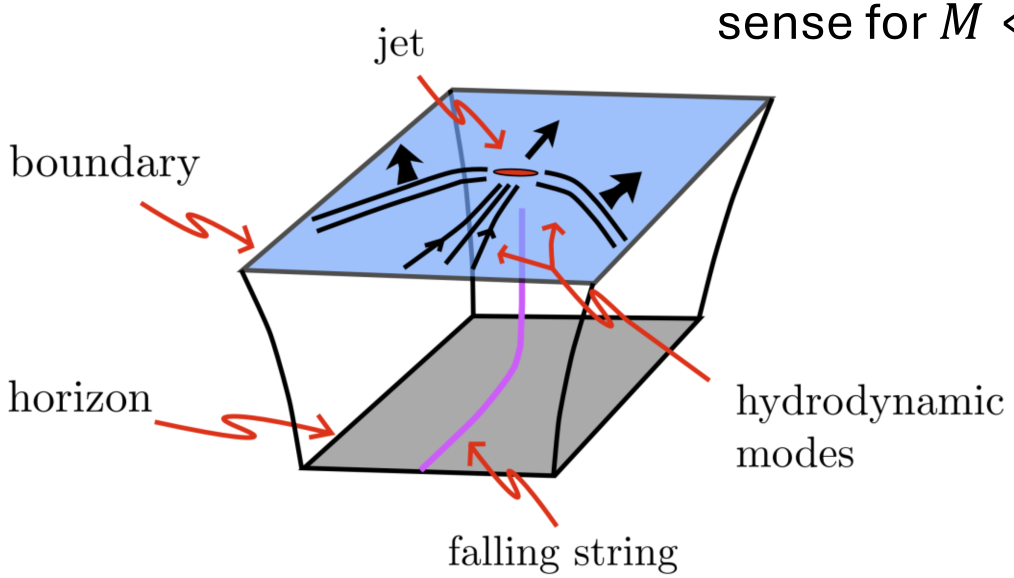
- Problem:
  - Want to model strongly coupled QGP
- Solution:
  - Calculate strongly coupled results in N=4 SYM in $N_c \to \infty$ limit
  - Can do this using AdS/CFT by considering holographic dual
  - Can perform calculations using classical string theory in 5d asymptotically AdS spacetime when in $\lambda = 4\pi\alpha_s N_c \to \infty$ 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

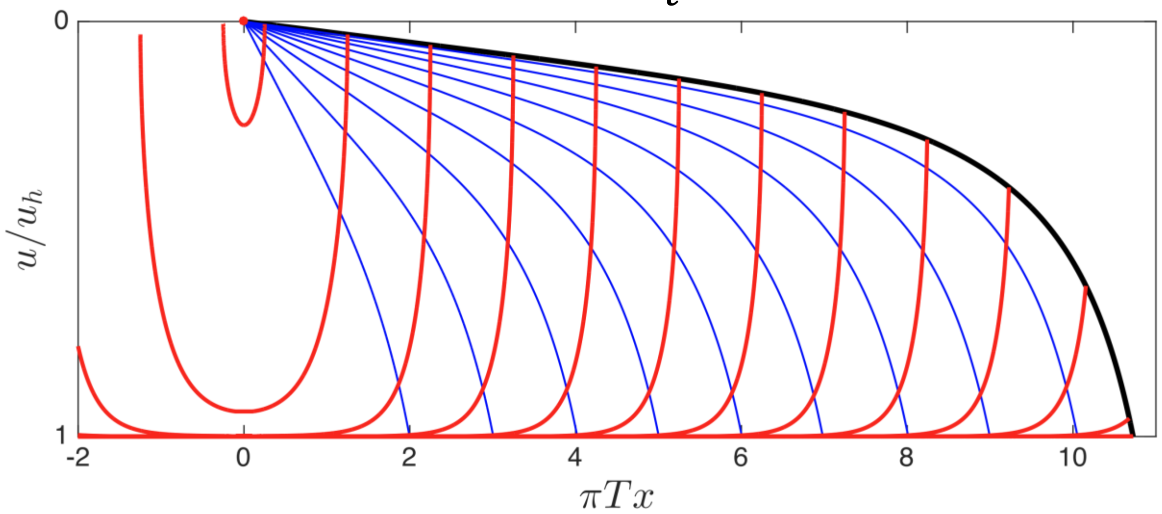
P. Chesler and K. Rajagopal
1402.6756 and 1511.07567

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




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

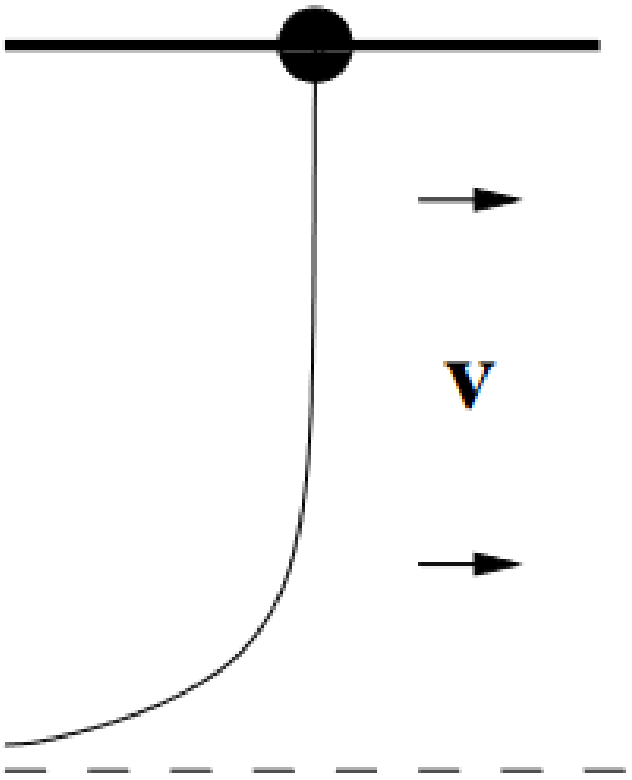
- Obtained from string propagating over and falling into black hole
- Dual to quark propagating through holographic plasma with constant $T$ and thermalizing after traveling distance $x_t$



# Heavy quark energy loss

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

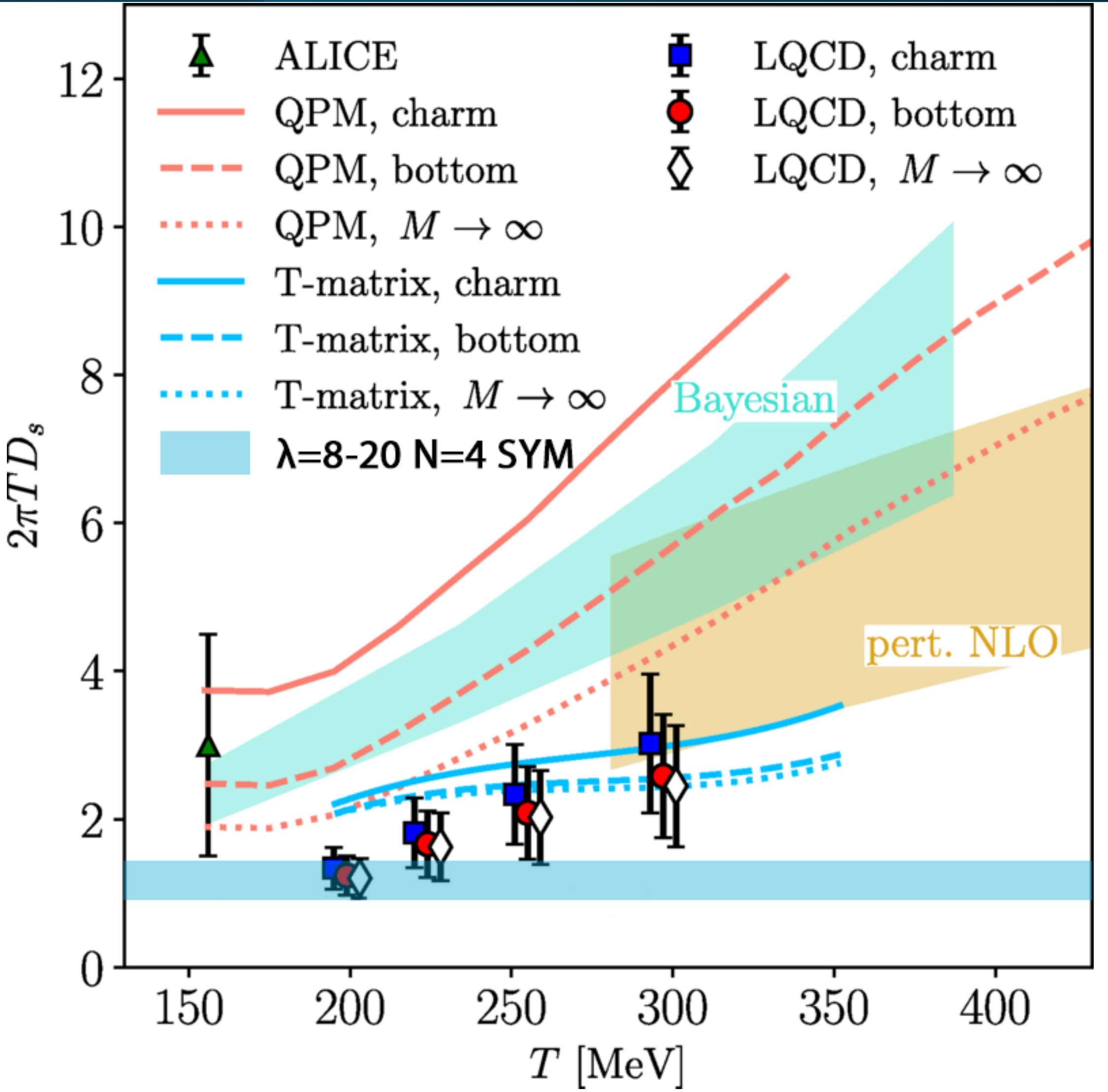
- $\frac{dE}{dx} = -\eta_D \sqrt{E^2 - M^2}$
- $\eta_D = \frac{\pi}{2}\frac{\sqrt{\lambda}T^2}{M}$ drag coefficient
- Valid in $\mathrm{M} \gg \sqrt{\lambda}T$ regime
- We have determined corrections at $\mathcal{O}\left(\frac{\sqrt{\lambda}T}{M}\right)$; their effects are small in what I will show here
- As $v \to 0$ we can compare to lattice computations of QCD



# Heavy quark Diffusion coefficient

Figure adapted from L. Altenkort et al. 2311.01525

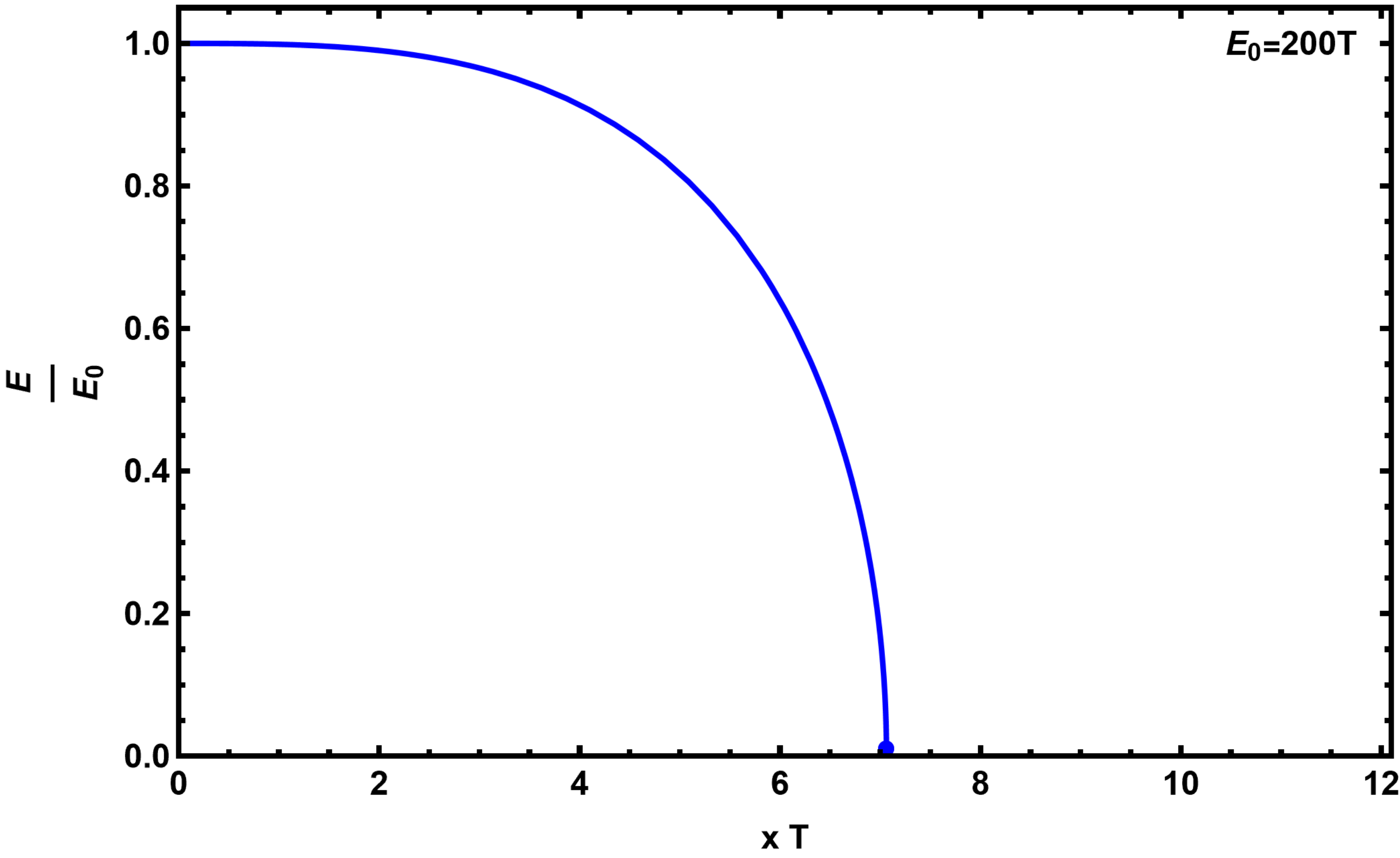
- Can get diffusion coefficient from drag coefficient (Einstein relation)
- Can compare to recent lattice QCD results
- Temperature dependence of the lattice QCD result is modest, and its value is rather close to what we expect in $N = 4\ SYM$ theory with 't Hooft coupling between 8 and 20, corresponding to $\alpha_{N=4}$ between 0.21 and 0.53
- Accounting for further temperature dependence future work
- Should expect more heavy quark quenching in N=4 SYM than QCD at high temperatures



# Centaur energy loss – The torso

$$\frac{dE}{dx} = -\frac{4x^2 E_0}{\pi x_t^2 \sqrt{x_t^2 - x^2}}$$

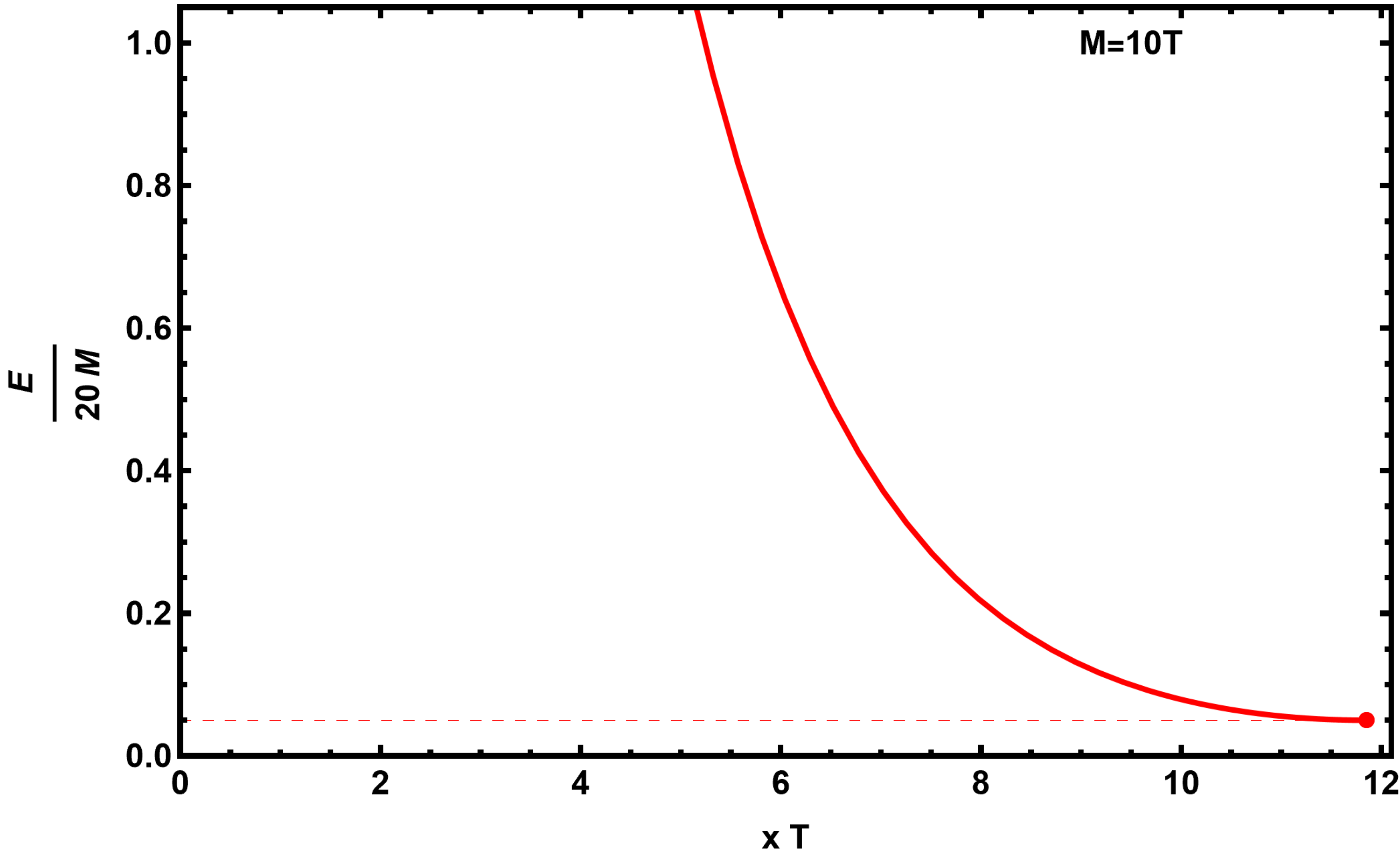
- Should describe any $M \ll E$ particle; even $M \gg T$ like sufficiently relativistic b or c quarks
- Little energy loss at the start
- Negative second derivative; loses energy faster over time
- Thermalizes at finite distance and time



# Centaur energy loss – The body

$$\frac{dE}{dL} = -\eta_D\sqrt{E^2 - M^2}$$

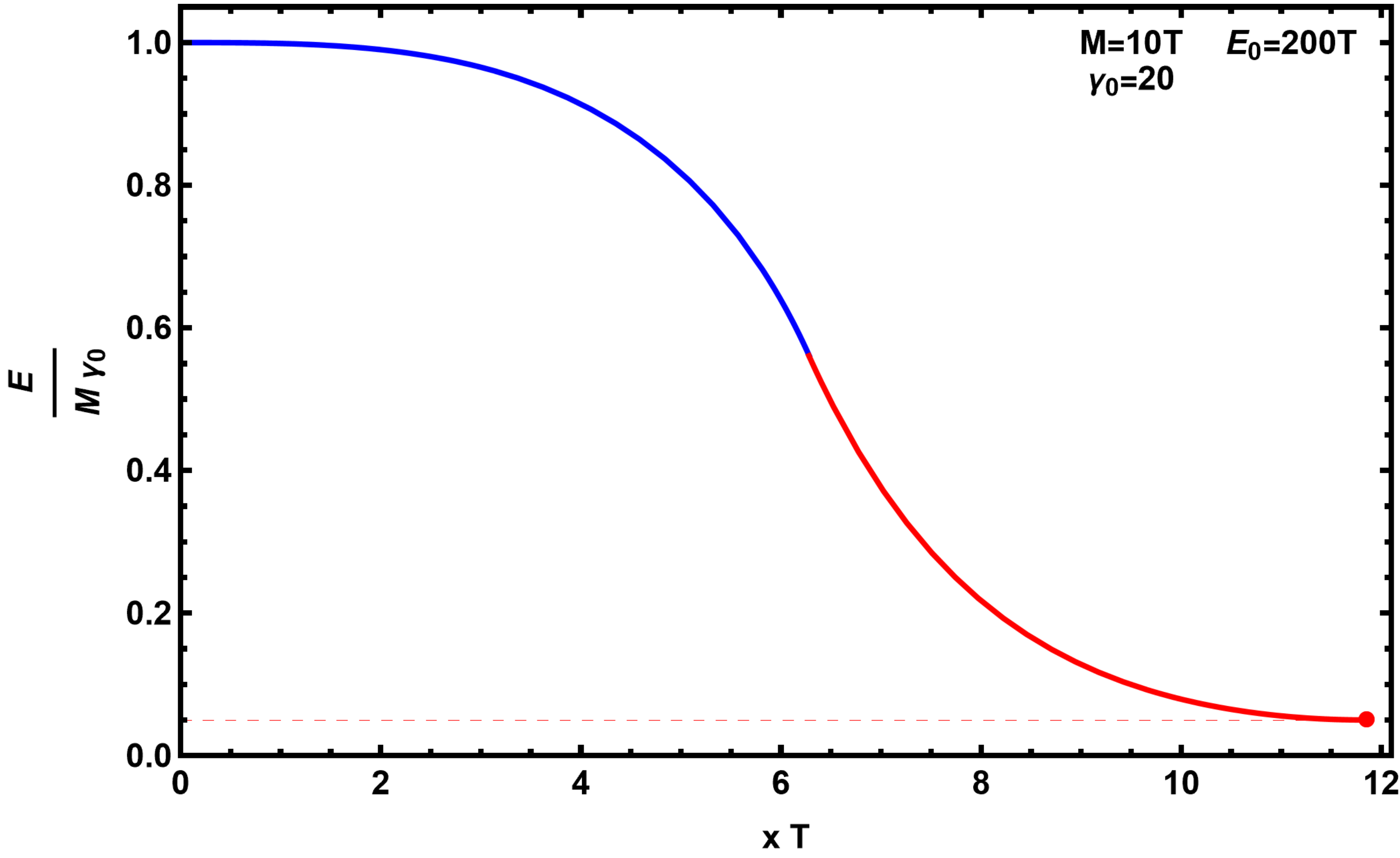
- Should describe late time behavior of $M \gg T$ particles
- Drag force
- Positive second derivative; loses energy slower over time
- Comes to rest at finite distance but at infinite time



# Centaur energy loss

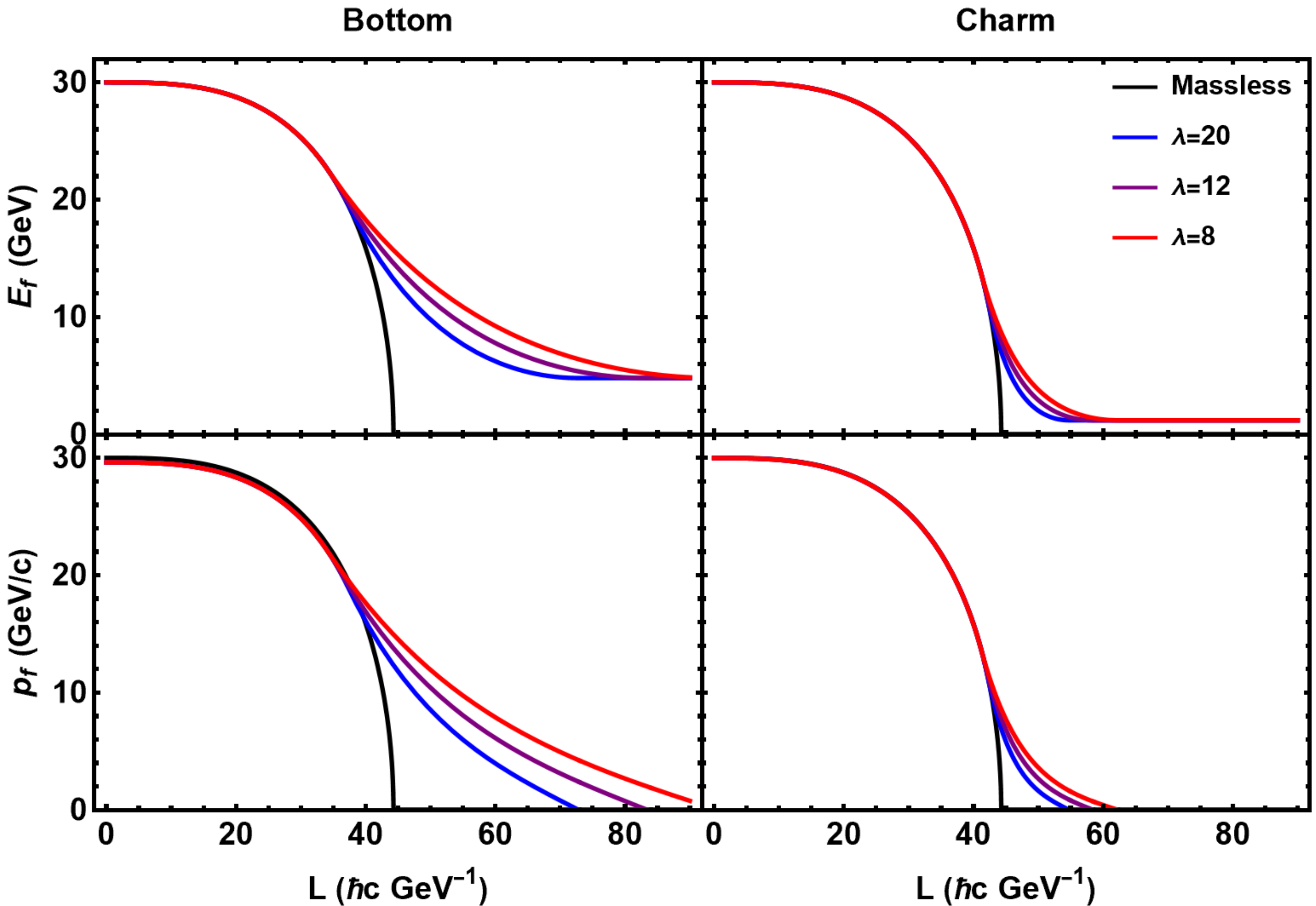
$$-\frac{dE}{dx} = \min\left(\frac{4x^2E_0}{\pi x_t^2\sqrt{x_t^2 - x^2}}, \eta_D\sqrt{E^2 - M^2}\right)$$

- 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



# Dependence on $\lambda$

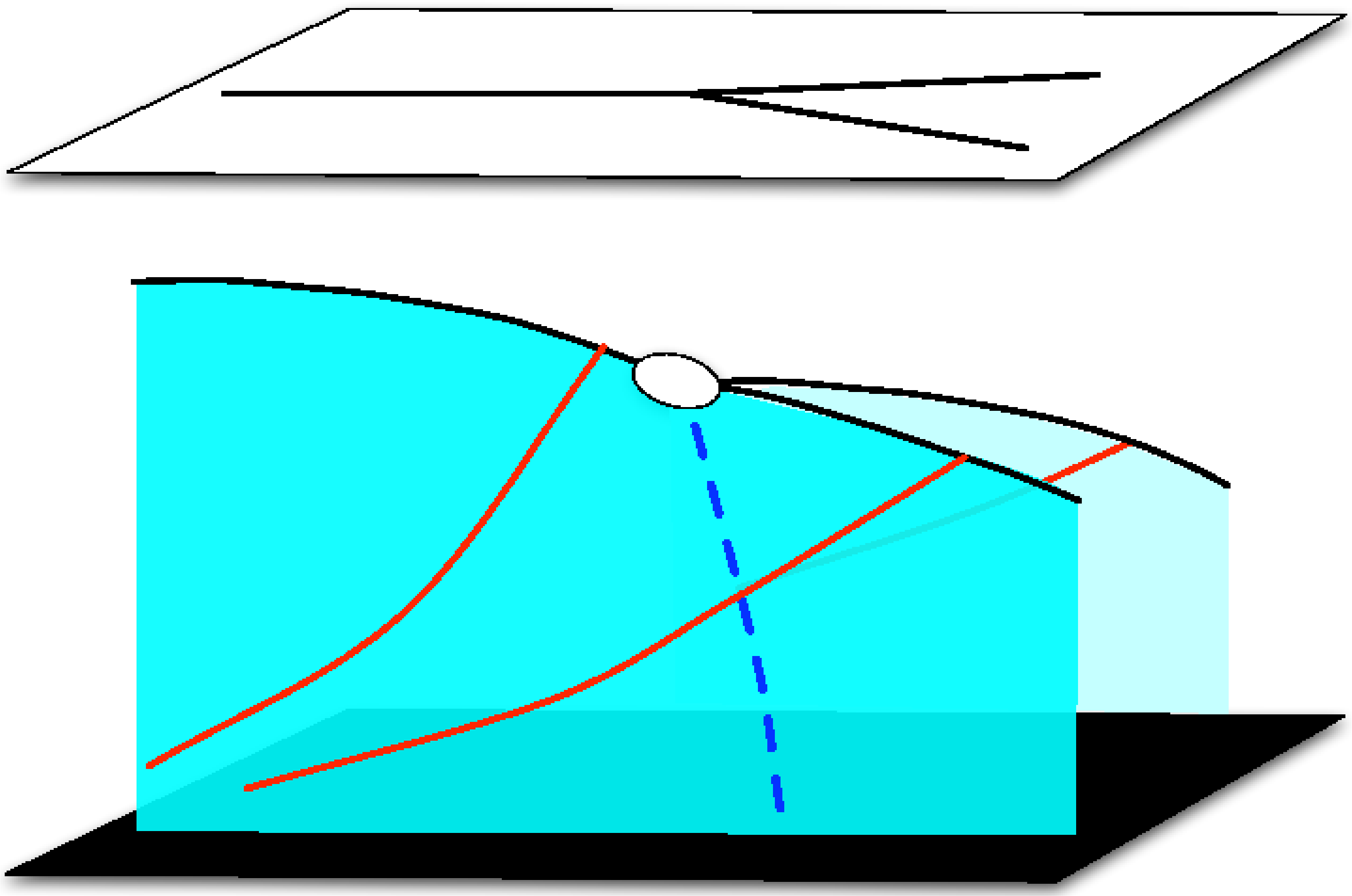
- Changing $\lambda$ changes when switch occurs and strength of drag after switch
- High energy partons and partons moving through little medium insensitive to heavy quark energy loss
- In general, little difference in reasonable range of $\lambda = 8$ to $\lambda = 20$; only bottom quarks sensitive to specifics



# Hybrid model

J. Casalderrey-Solana et al.
1405.3864 and 1808.07386

- Pythia 8 Monash 2013 tune for weak coupling parton showers
- Hydrodynamic medium
- Strongly coupled energy loss of every parton in shower
- $\kappa_{sc} = 0.404$ from global fit of hadron and jet $R_{AA}$
- Strongly coupled broadening/diffusion
- Lund string hadronization
- No wake in this analysis (not relevant)

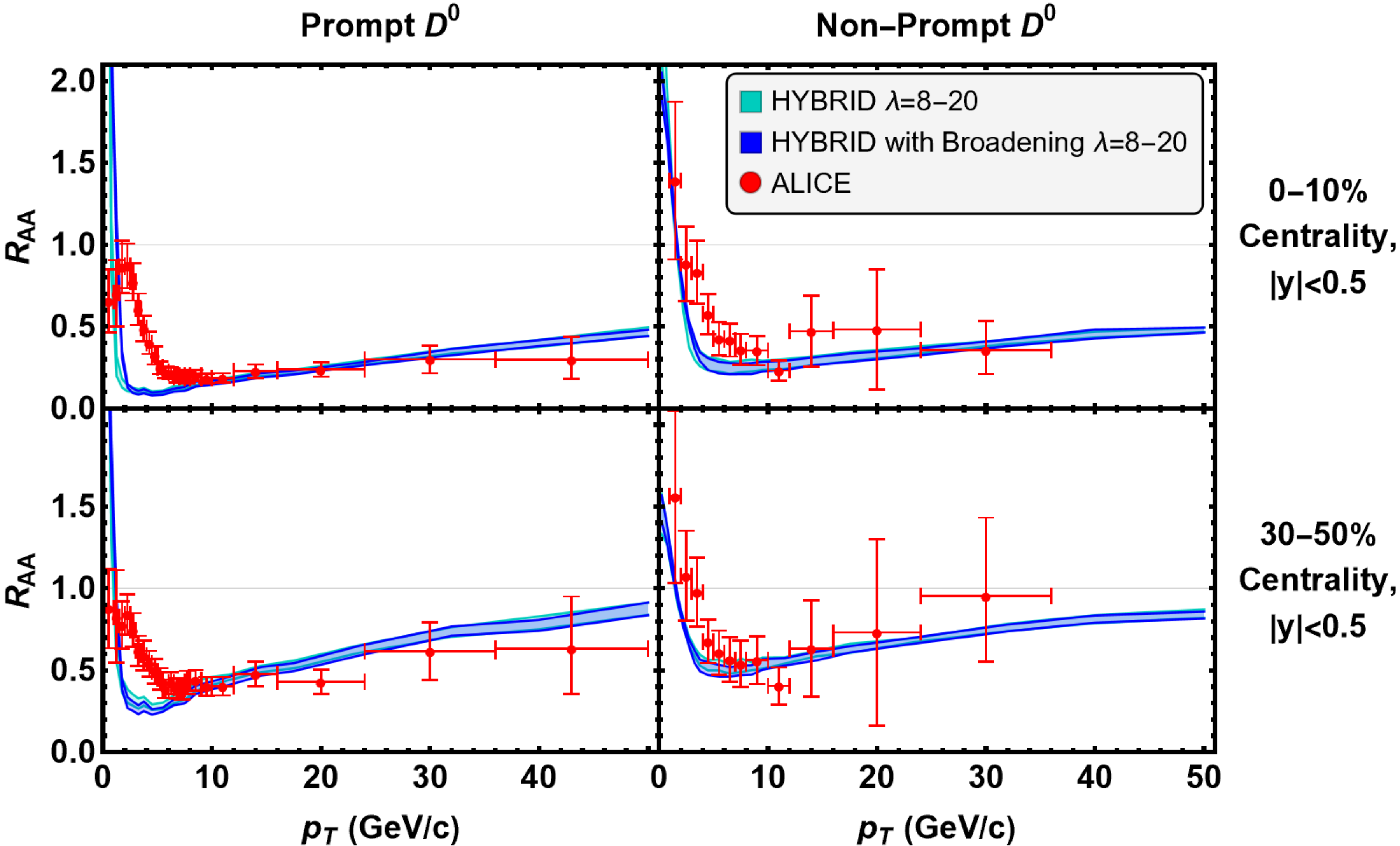


# b and c Hadron $R_{AA}$

ALICE Data: 2202.00815

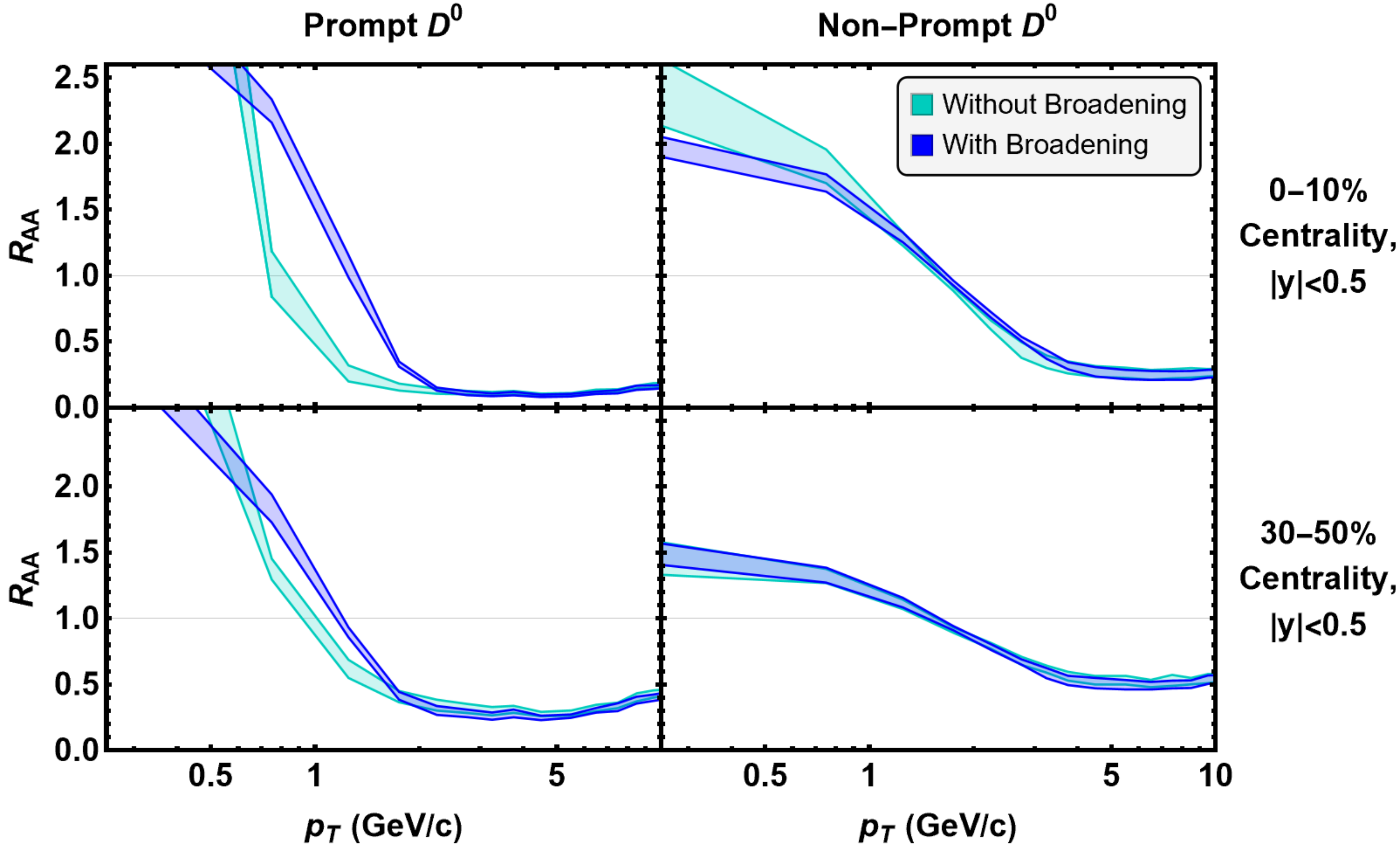
- Good agreement with D and B data at $p_T > 10$ GeV/c ; reasonable agreement with B data at lower $p_T$
- Missing effects coming from light quark flow; important at low $p_T$; less important for Bs than Ds

- Limited sensitivity to broadening, only at lowest $p_T$ where flow also relevant



# b and c Hadron $R_{AA}$

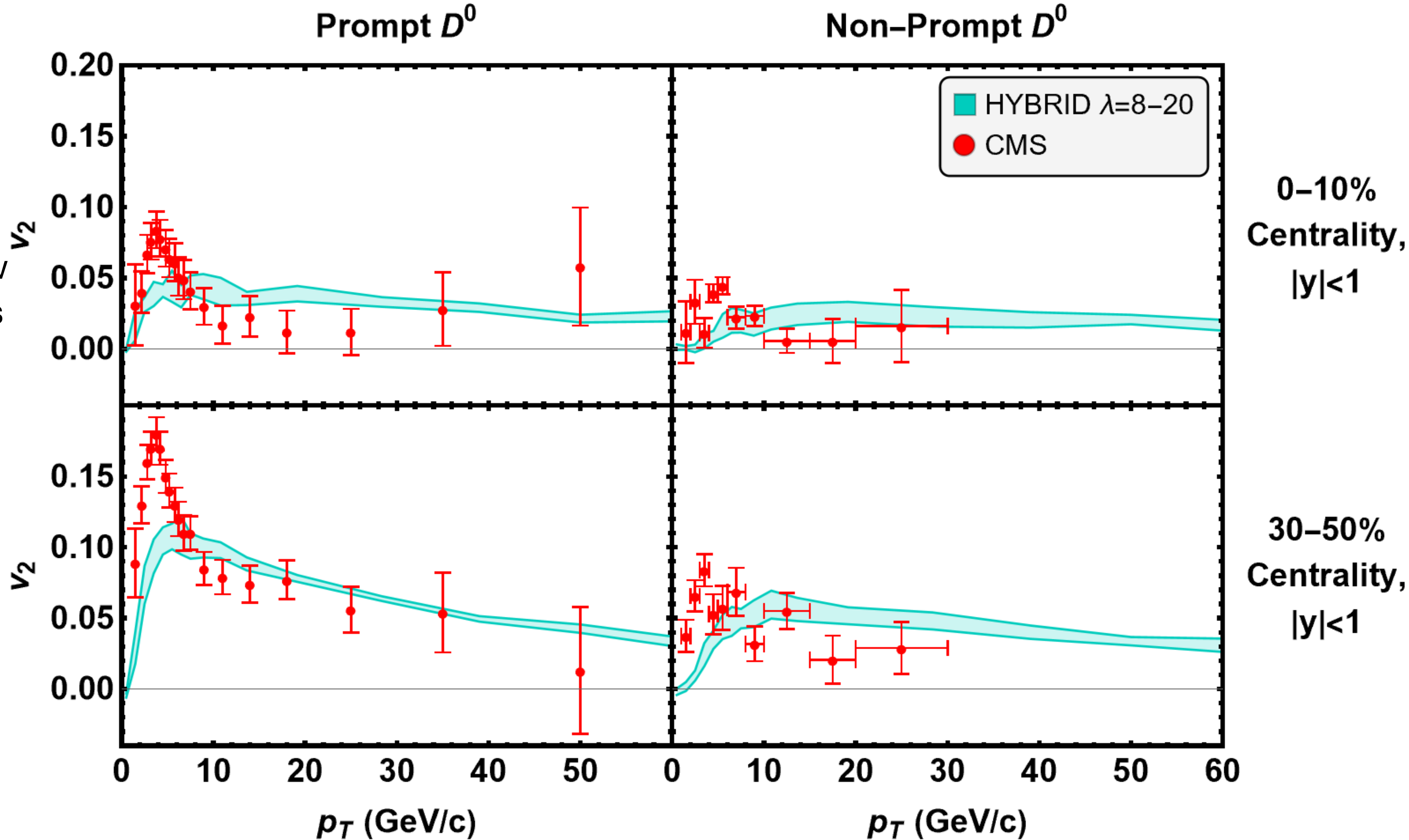
- Can see broadening effects only at very low $p_T$ where we are missing other effects.
- Can see c quarks more sensitive that b's as expected
- Will show plots without broadening from now (same sensitivity in other observables)



# b and c Hadron $v_2$

CMS Data: 2009.12628 and 2212.01636

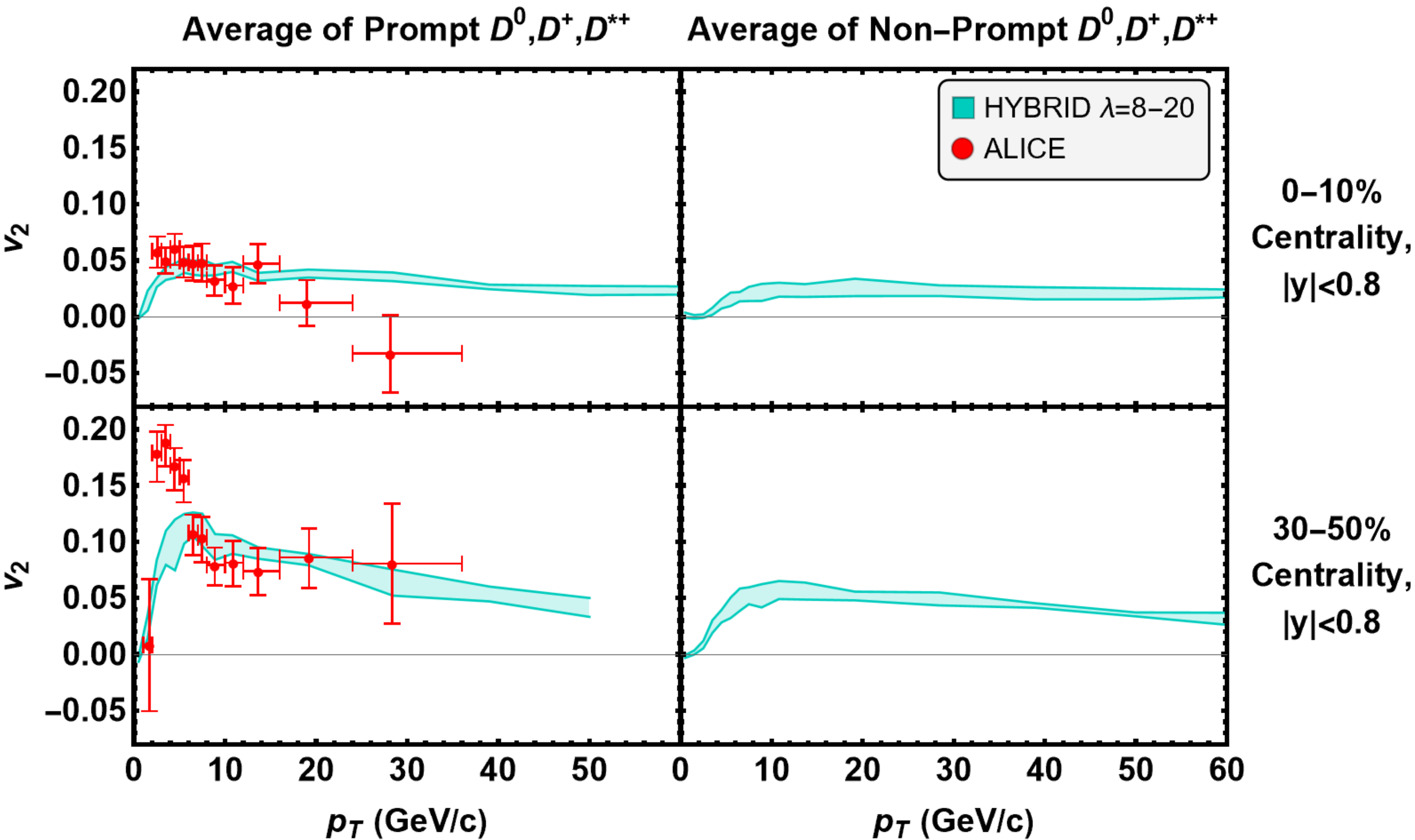
- Reasonable agreement with D and B data at $p_T > 10$ GeV/c ; reasonable agreement with B data at lower $p_T$
- Missing effects coming from light quark flow; important at low $p_T$; less important for Bs than Ds
- Limited sensitivity to broadening, only at lowest $p_T$ where flow also relevant
- Looking to forward to run 3 data comparison and to incorporating hadronization via coalescence



# D Meson $v_2$

ALICE Data: 2005.11131

- Reasonable agreement with D data at $p_T > 10$ GeV/c
- Missing effects coming from light quark flow; important at low $p_T$
- Limited sensitivity to broadening, only at lowest $p_T$ where flow also relevant
- Looking to forward to run 3 data comparison

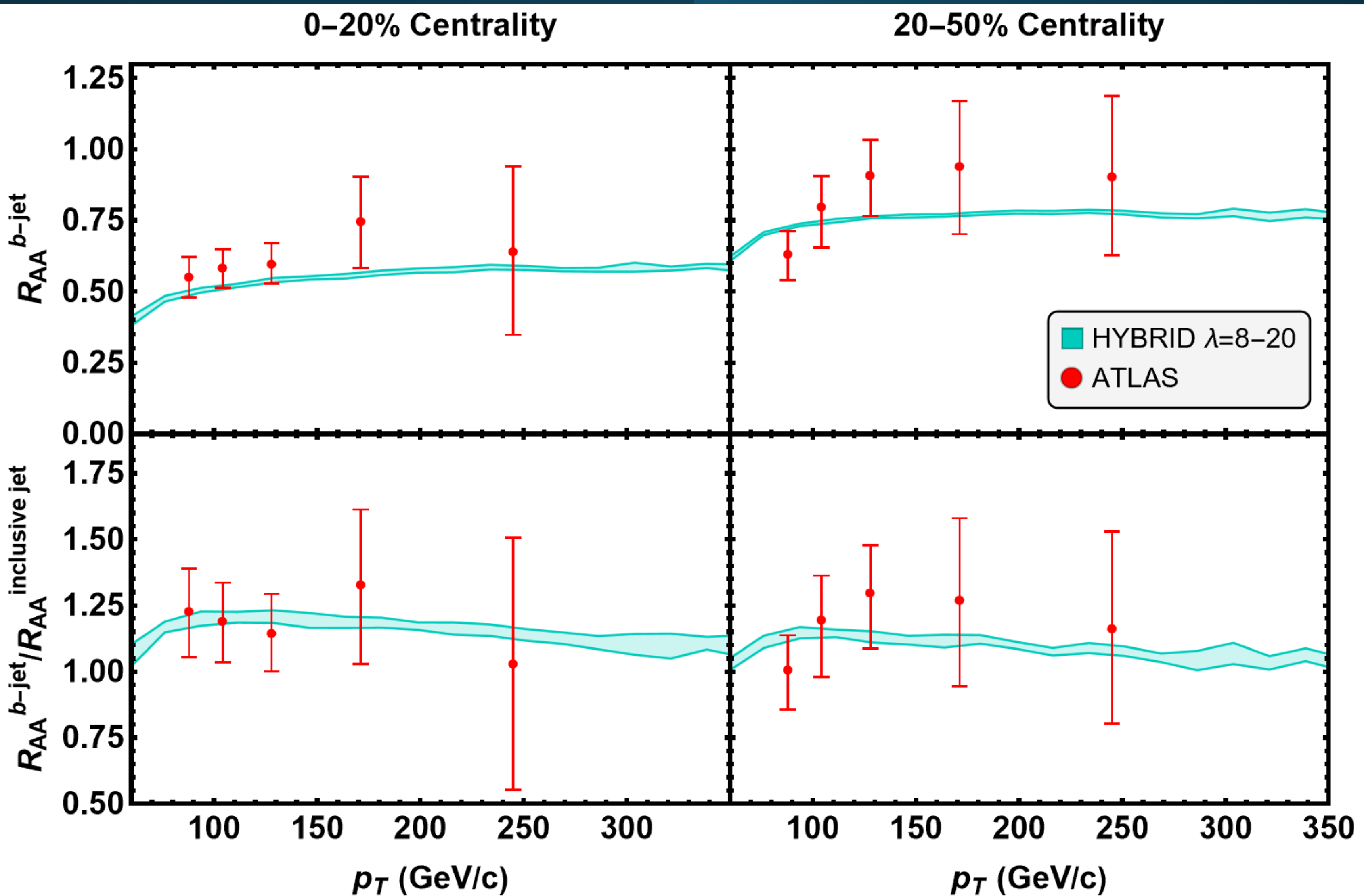


Good check of hybrid model treatment of light quark vs gluon energy loss

# $b$—jets

ATLAS Data: 2204.13530

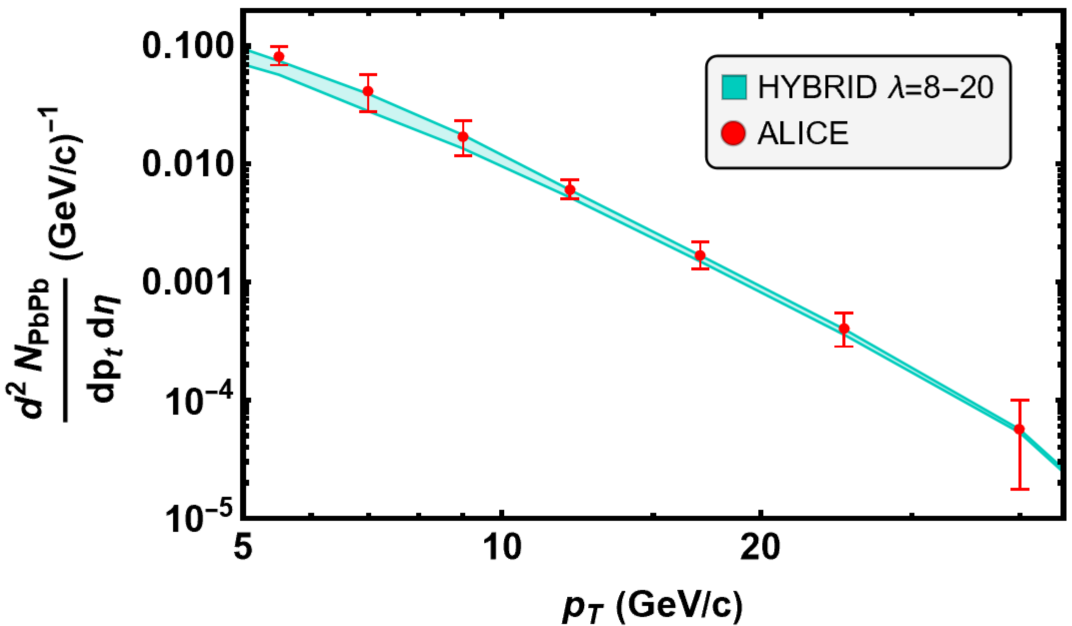
- Good agreement with data
- Great agreement for ratio since hybrid slightly over-quenches inclusive jets
- Insensitive to centaur formula, since at these energies b and c quarks are like light quarks
- Good check of hybrid model treatment of light quark vs gluon energy loss

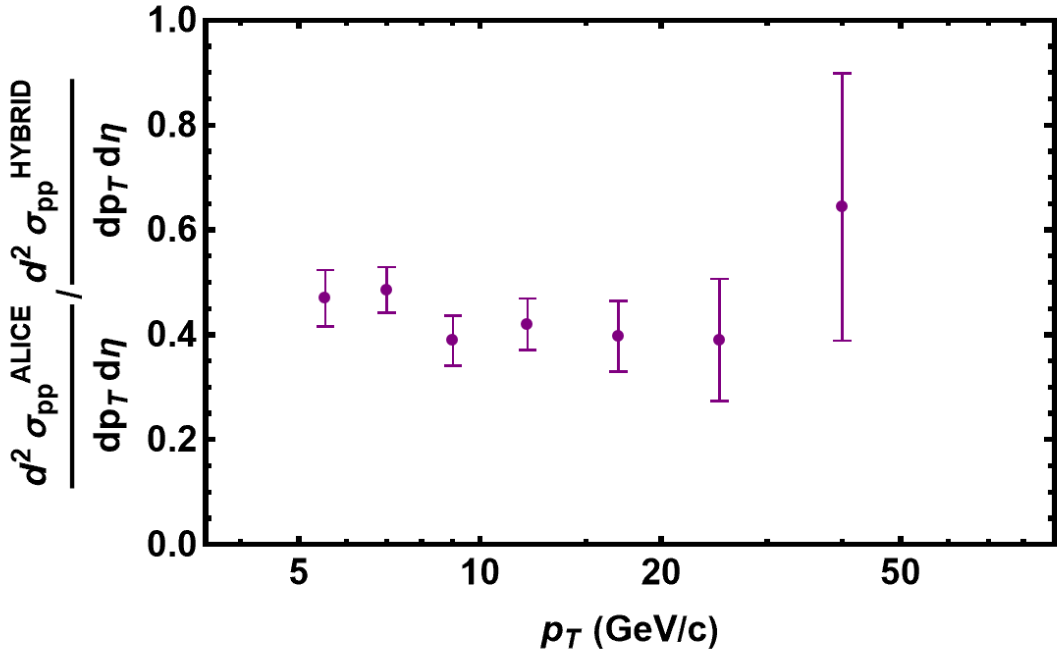


# $D-$jets: work in progress

ALICE Data: 2409.11939

- Ongoing
- Issues in our pp spectrum that need to be resolved
- Apparent agreement of PbPb spectrum despite our pp spectrum

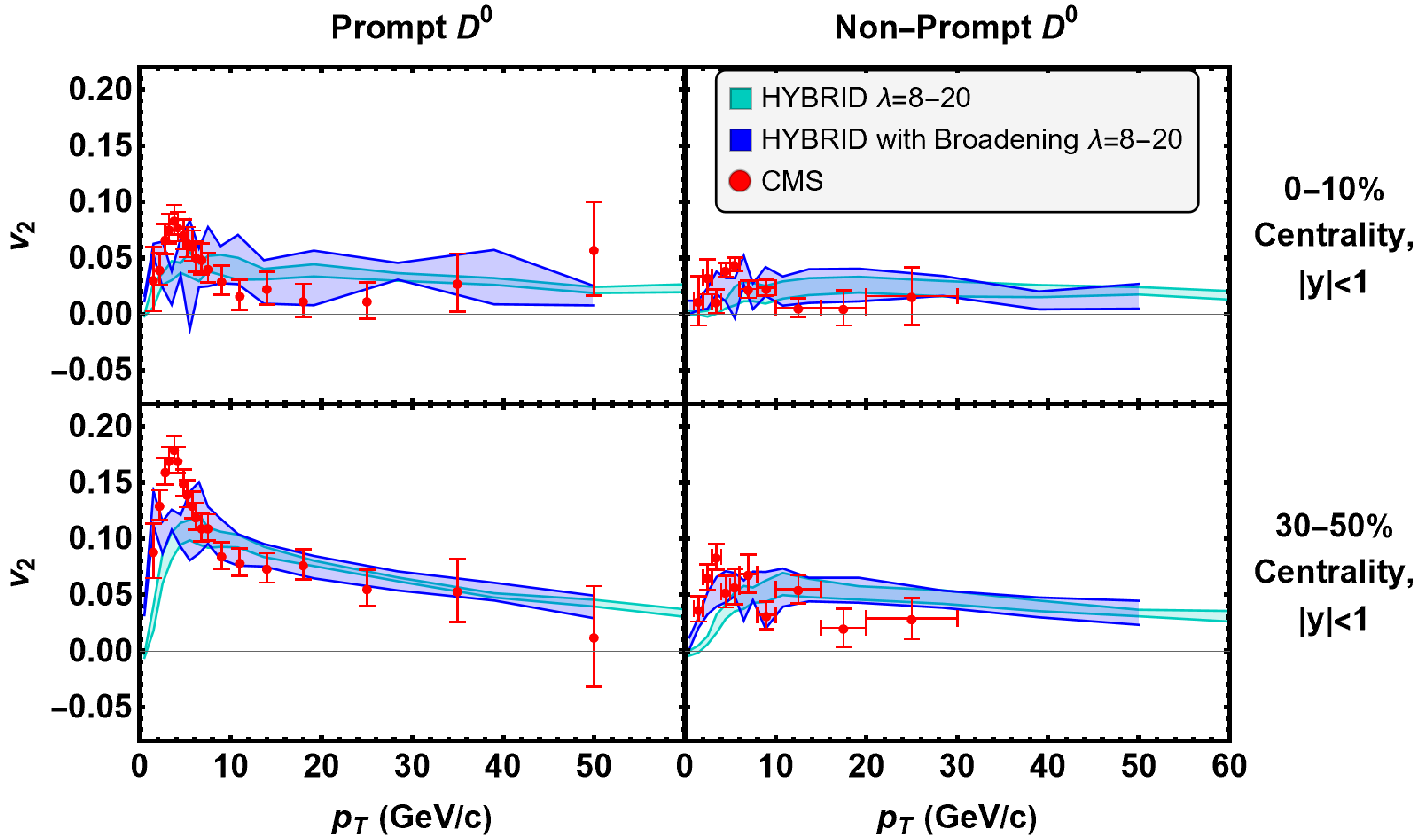


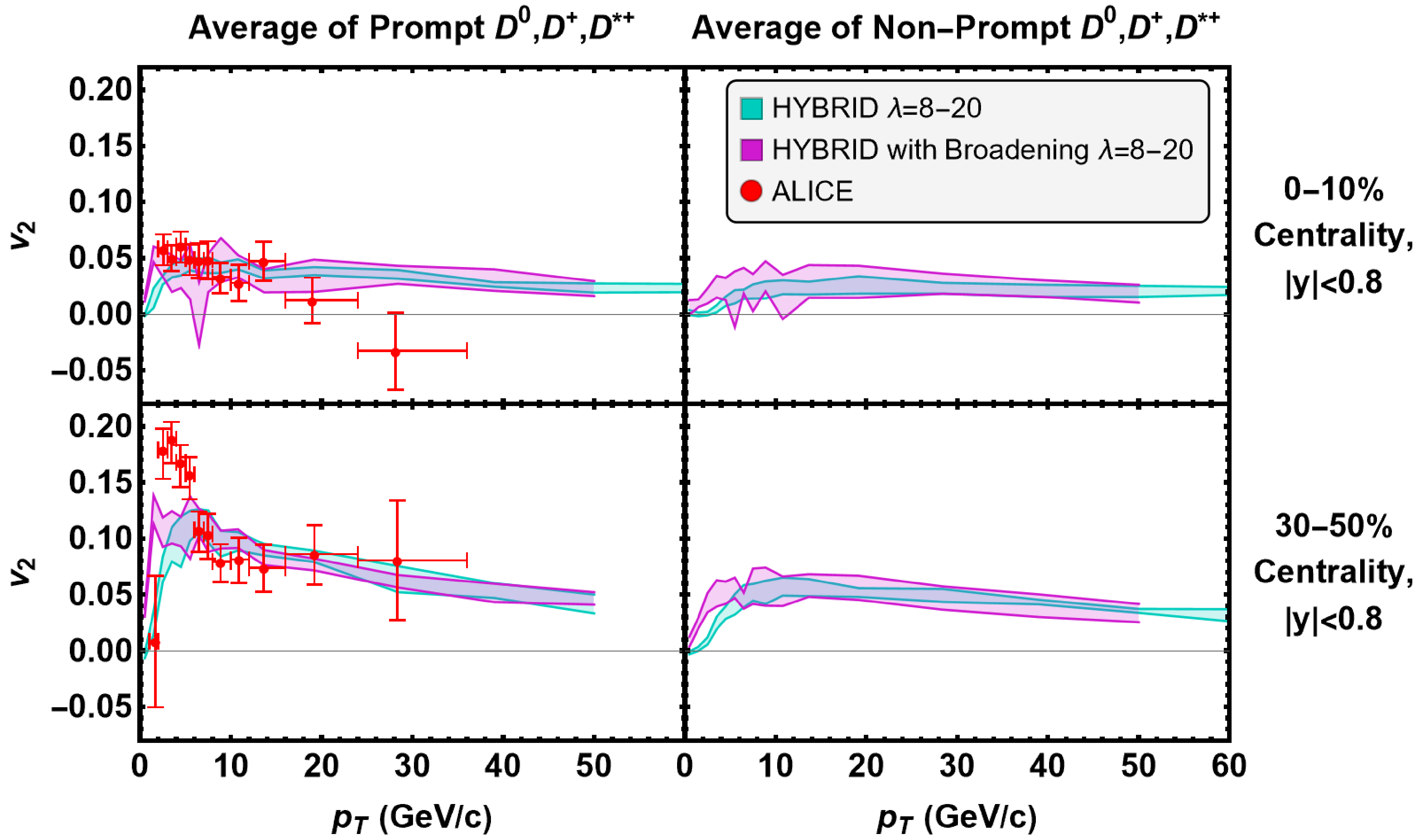
# Outlook and next steps

- First time that heavy quark energy loss has been incorporated in the hybrid model
- Allows us to compare hybrid model calculations to measurements of eight observables that we have never confronted before. $R_{AA}$ and $v_2$ for D mesons, B mesons, c-jets and b-jets.
- Early results very encouraging.
- Accurate down to $p_T \approx 10$ GeV/c even without effects such as coalescence
- Next Steps:
  - Fix D-jet pp spectrum
  - Implement coalescence
  - Perform unified holographic calculation of finite mass energy loss (easier said than done)
  - Perhaps find way to not over-quench heavy quarks at high temperatures
- Outlook:
  - Can look at distribution of heavy quarks in heavy-quark-jets
  - EECs (and EEECs) for heavy-quark-jets
  - Heavy-quark-jet $v_2$

# Backups



Prompt $D^0$
Non–Prompt $D^0$
HYBRID λ=8–20
HYBRID with Broadening λ=8–20
CMS
0–10%
Centrality,
|y|<1
30–50%
Centrality,
|y|<1
$v_2$
$v_2$
$p_T$ (GeV/c)
$p_T$ (GeV/c)
0.20
0.15
0.10
0.05
0.00
−0.05
0
10
20
30
40
50
60



Average of Prompt $D^0$,$D^+$,$D^{*+}$
Average of Non-Prompt $D^0$,$D^+$,$D^{*+}$
HYBRID λ=8–20
HYBRID with Broadening λ=8–20
ALICE
0–10% Centrality, |y|<0.8
30–50% Centrality, |y|<0.8
$v_2$
$p_T$ (GeV/c)
0.20
0.15
0.10
0.05
0.00
−0.05
0
10
20
30
40
50
60

- $T_c \approx 162\text{MeV}$
- $\lambda(T = 200\text{MeV}) \approx 8.7$