Overview of Heavy Quark Physics

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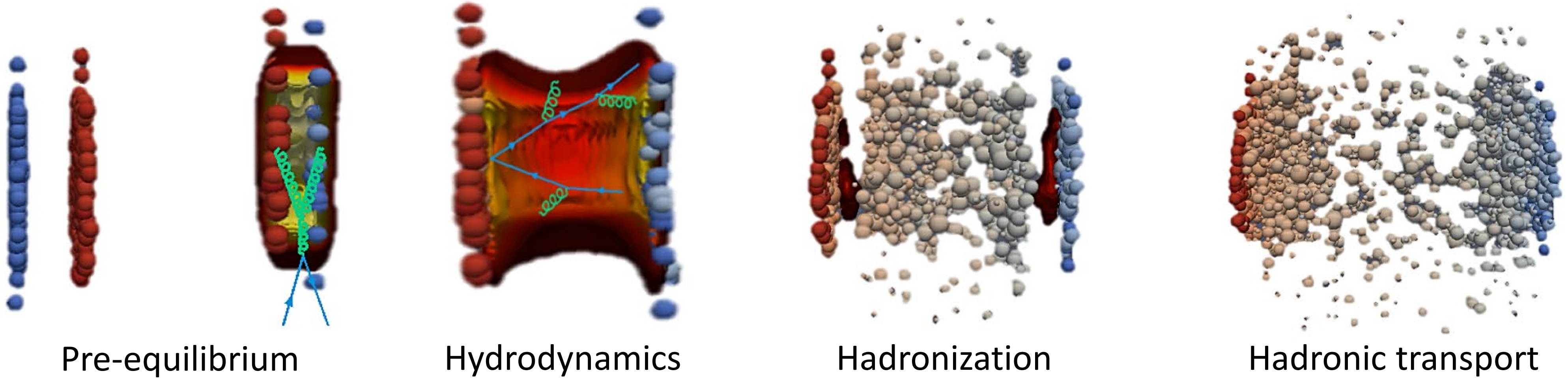
OUTLINE

- **Introduction**
- **A multistage evolution description to parton energy loss**
    1. In medium DGLAP evolution: the MATTER model
    2. Linearized Boltzmann dynamics
    3. Results
- **Other mechanisms involving heavy flavor**
- **Conclusion**

PART 1

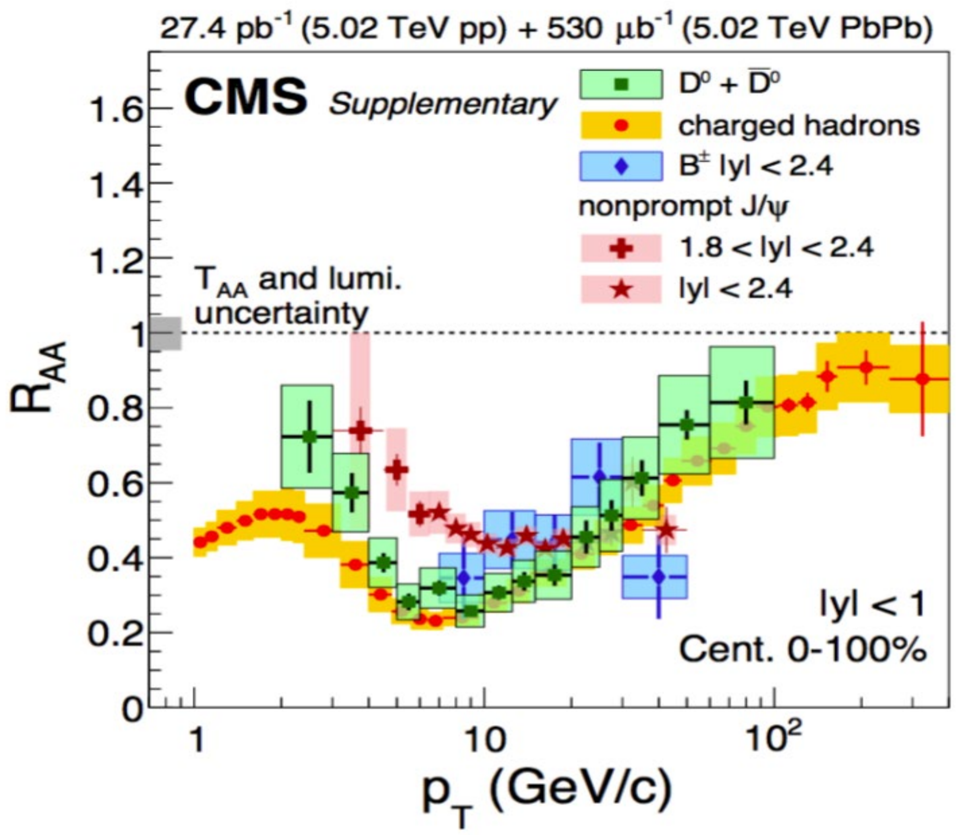
Introduction – Observations and Challenges

AuAu collision @ 200GeV figure credit: Hannah Elfner

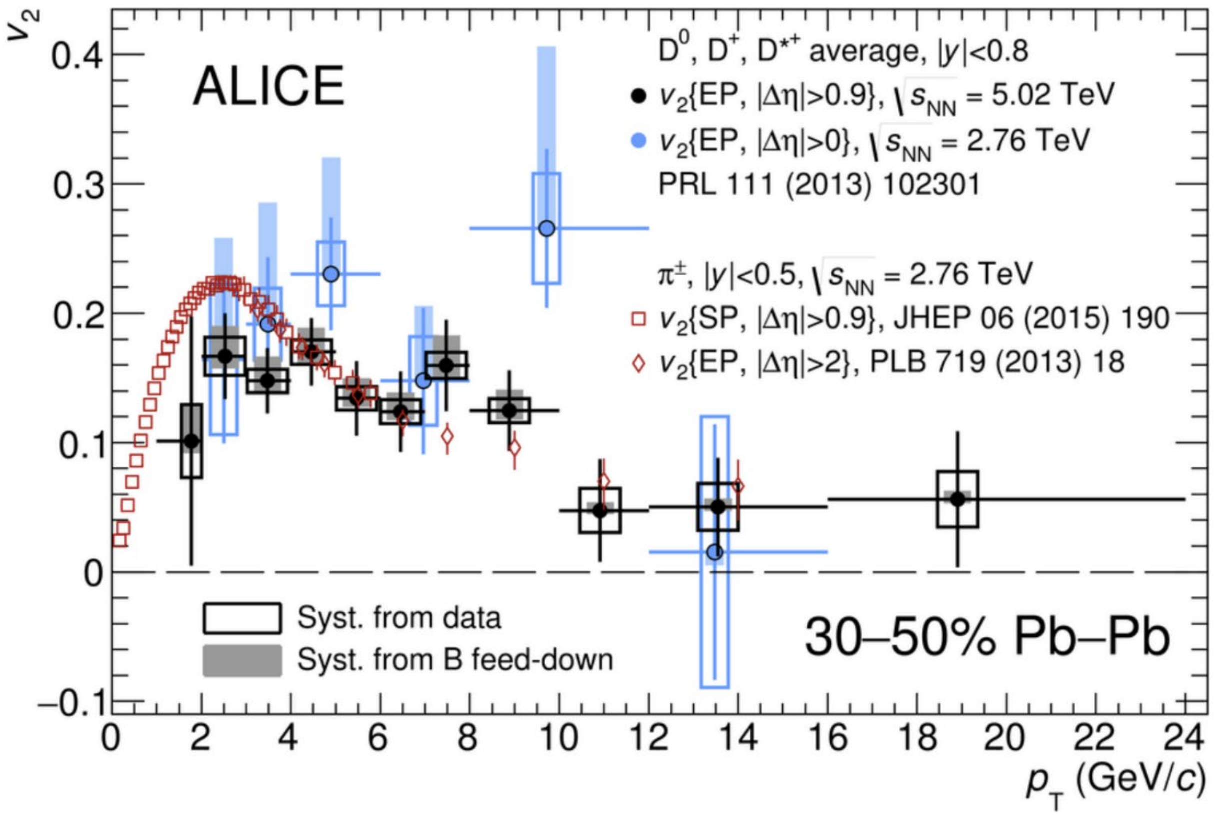


- **Multi-stage, multi-scale, many-body** problem.
- Key observations: collective flow, quenching of hard probes.
- **Heavy quark:** produced primarily at the early stage, experience full QGP evolution.

Introduction – Observations and Challenges



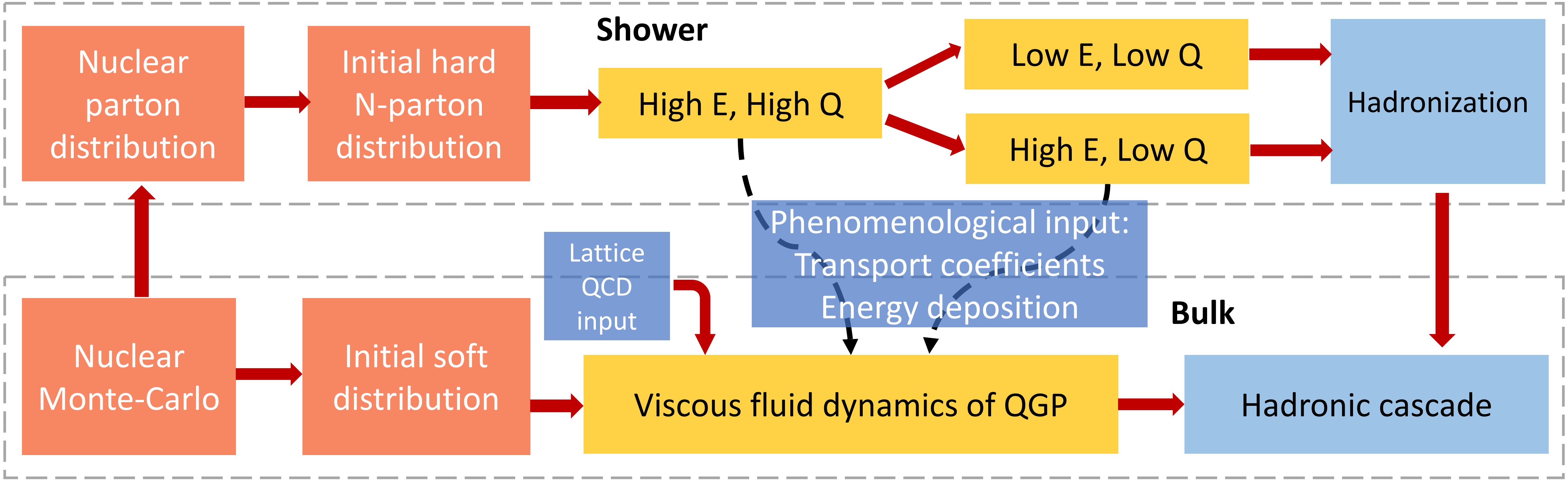
Nuclear modification factor



Anisotropic flow

Introduction – The JETSCAPE Framework

Jet **E**nergy Loss **T**omography with a **S**tatistically and **C**omputationally **A**dvanced **P**rogram **E**nvelope



- **Modular** framework; allows for study of different physics concepts in a consistent environment.
- Applicable to full range of heavy ion phenomenology.
- Bayesian analysis enables systematic model-to-data comparison.

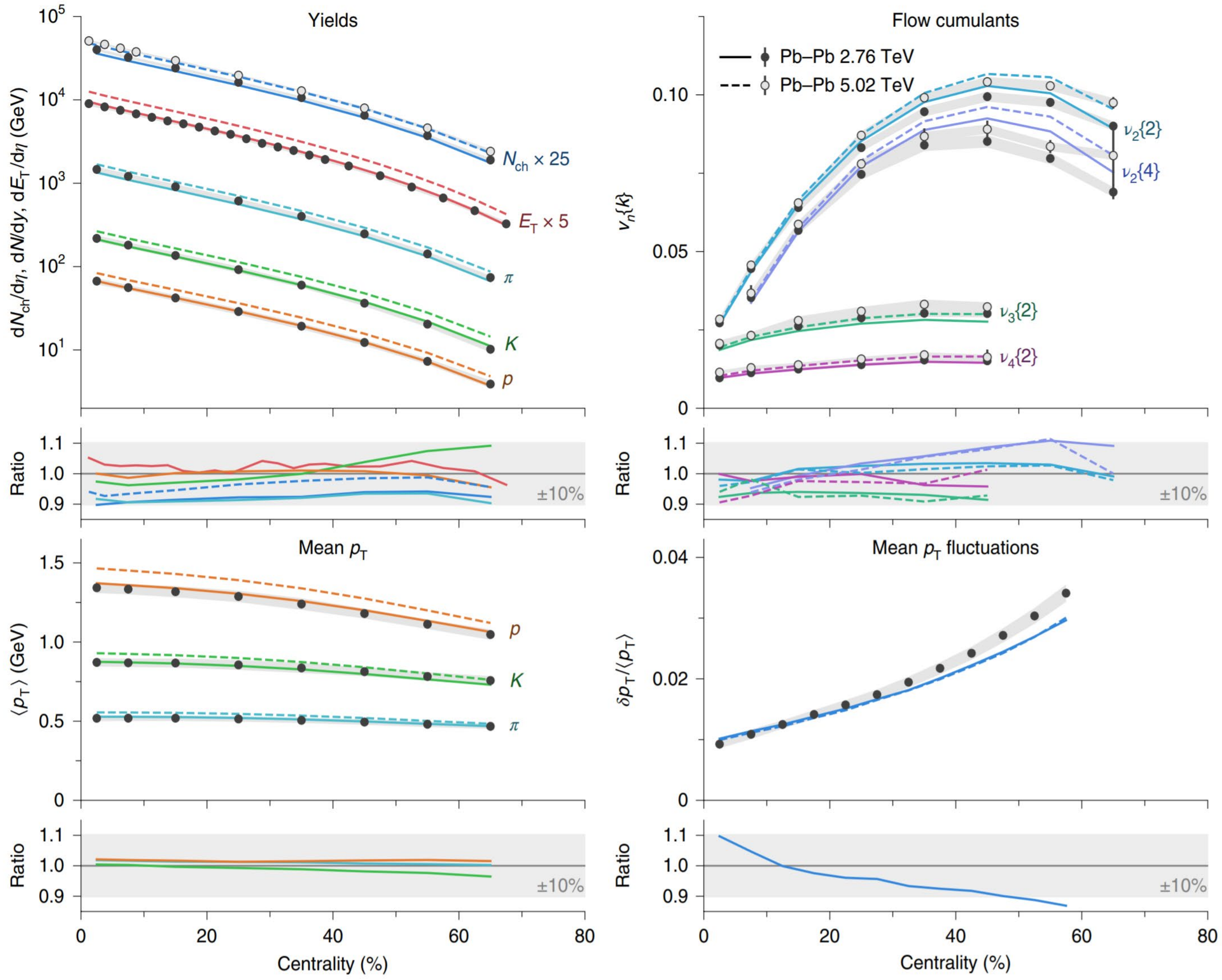
"The JETSCAPE framework", *arXiv preprint arXiv:1903.07706 (2019).* **Public version 3.4:** https://github.com/JETSCAPE/JETSCAPE

Introduction – Bulk Medium Evolution

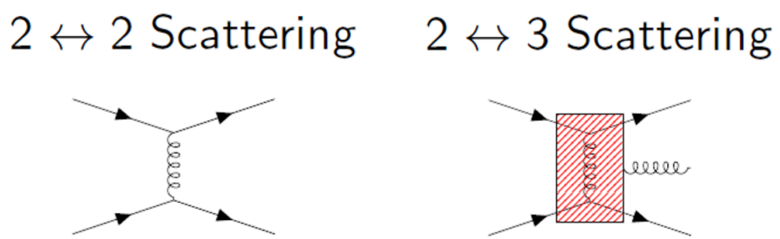
- Using “***best fit***” to hadronic observables (charged hadron yields, mean p_T, flow cumulants, etc).
- Event-by-event simulations consist of
  - TRENTO initial conditions
  - 2+1D Pre-equilibrium dynamics
  - 2+1D 2nd order dissipative hydrodynamics of QGP
- The same underlying QGP simulation is used to study
  - Light flavor leading hadrons and jets
  - Jet substructures
  - Heavy flavor observables

[Nature Physics 15.11 (2019): 1113-1117.]

Best fit to soft observables



Parton Energy Loss – Linearized Boltzmann Equation



- Linearized Boltzmann transport (LBT) equation:

$$p_1^{\mu}\,\partial_{\mu} f_1(x_1, p_1) = \mathcal{C}_{el}[f_1] + \mathcal{C}_{inel}[f_1]$$

- The elastic $2 \rightarrow 2$ scattering rate:

$$\Gamma_{el} = \frac{d_2}{2E_1} \int dP_2 \int dP_3 \int dP_4\; f_2(p_2) \times (2\pi)^4 \delta^{(4)}(p_1 + p_2 - p_3 - p_4) \left|\mathcal{M}_{1,2\rightarrow 3,4}\right|^2$$

- Average number of scattering during Δt: $\langle n \rangle = \Gamma \Delta t$
- Distribution of n:

$$P(n \mid n \geq 1) = e^{-\Gamma \Delta t} \frac{(\Gamma \Delta t)^n}{n!}$$

- Probability of no collision:

$$P(n = 0) = 1 - \sum_{1}^{\infty} P(n) = e^{-\Gamma \Delta t}$$

PART 2

Parton Energy Loss – Linearized Boltzmann Equation

- The inelastic $2 \rightarrow 3$ scattering rate:

Dead cone effect ↓ Interference ↓

$$\Gamma_{inel} = \int dy dk_{\perp}^{2} \frac{2\alpha_s P(y)}{\pi k_{\perp}^{4}} \hat{q} \left(\frac{k_{\perp}^{2}}{k_{\perp}^{2} + y^{2} M^{2}} \right)^{4} sin^{2} \left(\frac{t - t_i}{2\tau_f} \right)$$

where $k_{\perp}, \tau_f$ are the transverse momentum and formation time of the radiated gluon. M, t_i are the mass and production time of the parent parton. [*PRL* 93.7 (2004): 072301.]

- Jet transport coefficient $\hat{q} = \langle p_T^2 \rangle / L$ (transverse momentum broadening). The Hard Thermal Loop (HTL) result [PRC 91.5 (2015): 054908] reads:

$$\hat{q}^{HTL} = C_a \frac{42\zeta(3)}{\pi} \alpha_s^2 T^3 \ln[\frac{cET}{4m_D^2}]$$

PART 2

Parton Energy Loss – In Medium DGLAP

- LBT assumes on shell partons, typically initiated by Monte Carlo generators like PYTHIA.
- PYTHIA follows the QCD factorization theorem:

$$\frac{d\sigma_{p+p\to H+X}}{dy dp_T^2} = \frac{1}{\pi}\int dx_i\, dx_j f_i(x_i, Q^2) f_j(x_j, Q^2) \frac{d\sigma_{ij\to kl}}{d\hat{t}} \frac{1}{x_H} D^H(x_H, Q^2)$$

Initiate from some hard process, then evolve the parton shower following the vacuum DGLAP equation, simulated via the Sudakov form factor:

$$S_a(t_0, t) = \exp\{-\int_{t_0}^{t} C_F \frac{\alpha}{2\pi} \frac{dt'}{t'} \int_{y_{min}(t)}^{y_{max}(t)} P(y) dy\}$$

where $t = Q^2$. [*JHEP* 2006.05 (2006): 026.]

PART 2

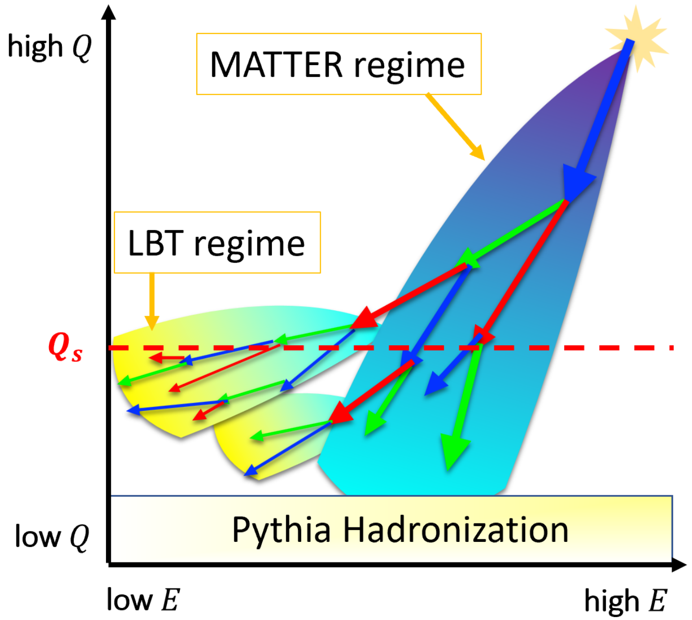
Parton Energy Loss – The MATTER Model

- In heavy ion collisions, the formation time of the radiated gluon may be longer than the length of the medium, the radiation pattern should be modified by scatterings with the medium.

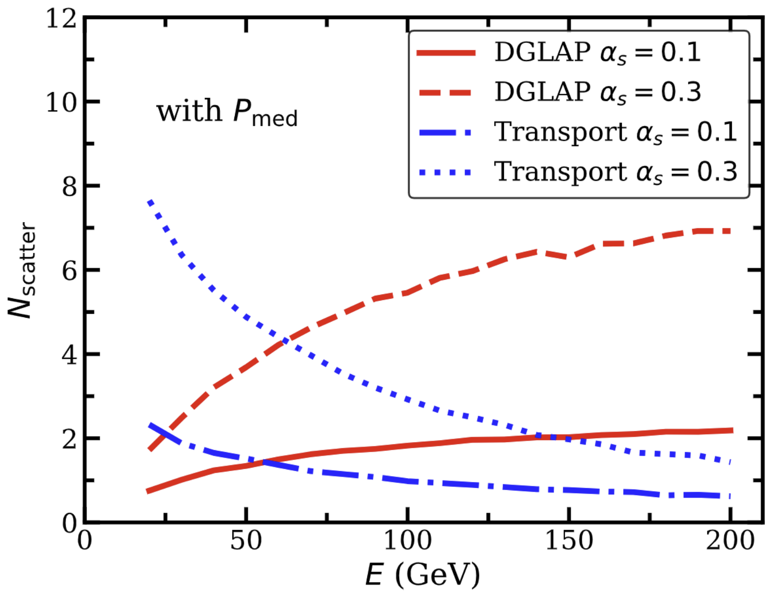
- The MATTER model suggests a linear correction to the splitting function [PRC 88.1 (2013): 014909]. For $Q \to Q + g$:

$$\tilde{P}(y) = P(y)[1 + \frac{\left(1-\frac{y}{2}\right)(\chi^2+1)-\chi}{y(1-y)t(1+\chi)^2}\int_{\xi_i}^{\xi_i+\tau_f} \hat{q}4\sin^2\left(\frac{\xi-\xi_i}{2\tau_f}\right)]$$

- $\chi = \frac{y^2M^2}{y(1-y)Q^2-y^2M^2}$
- $y_{max}(t) = \frac{t_0}{t} + \frac{M^2}{M^2+t} + \mathcal{O}\left(\left(\frac{t_0}{t}\right)^2\right)$
- $y_{min}(t) = 1 - \frac{t_0}{t} + \mathcal{O}(\left(\frac{t_0}{t}\right)^2)$



A multi-stage approach for parton energy loss



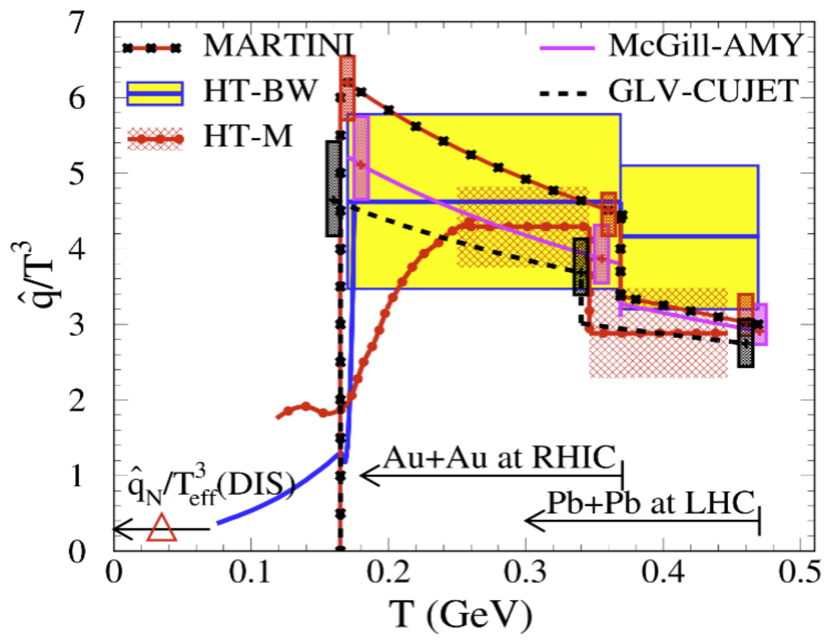
Number of scatterings in the DGLAP phase and the transport phase

[arXiv:2101.03681 (2021)]

Parton Energy Loss – Virtuality Dependent $\hat{q}$

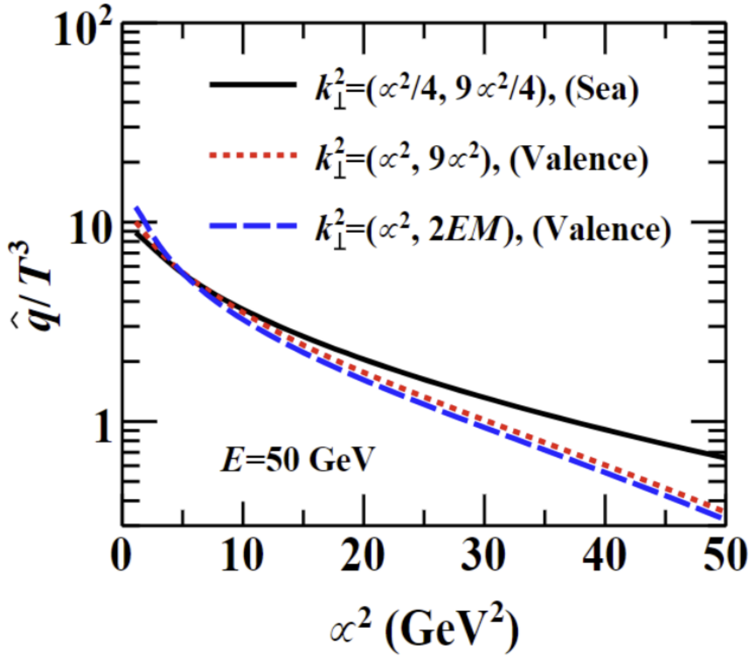
- $\hat{q}$ in the MATTER regime could also depend on virtuality. A simple parametrization:

$$\hat{q}(E,T,t) = \hat{q}^{HTL}(E,T)H(t) = \hat{q}^{HTL}(E,T)\frac{c_0}{1 + c_1 \ln^2 t + c_2 \ln^4 t}$$



Extracted effective $\hat{q}$ from different collision energies

[PRC 90.1 (2014): 014909]

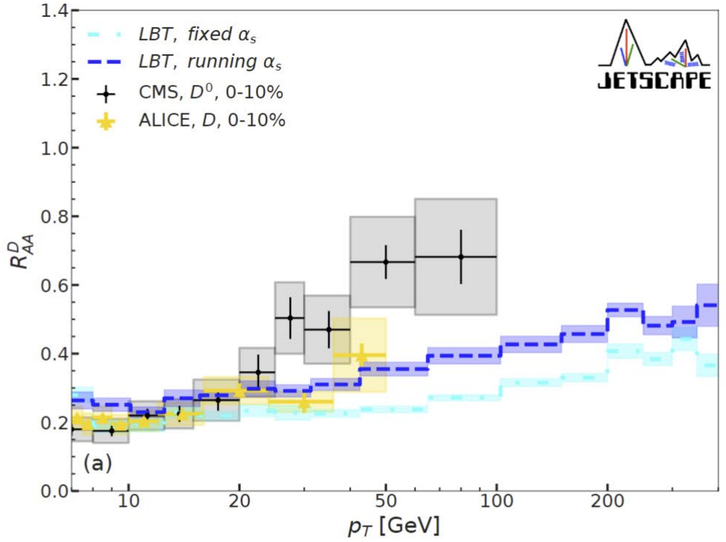


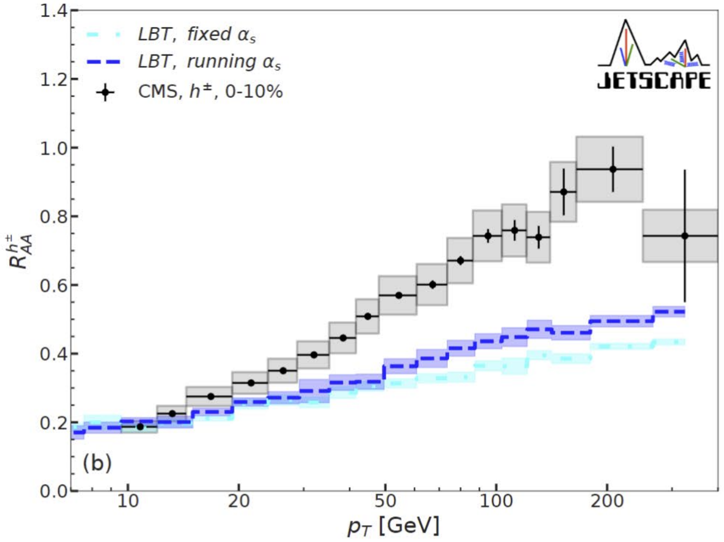
Simplified $\hat{q}/T^3$ *calculation*

[PRC 101.3 (2020): 034908]

Parton Energy Loss – R_{AA} using MATTER or LBT

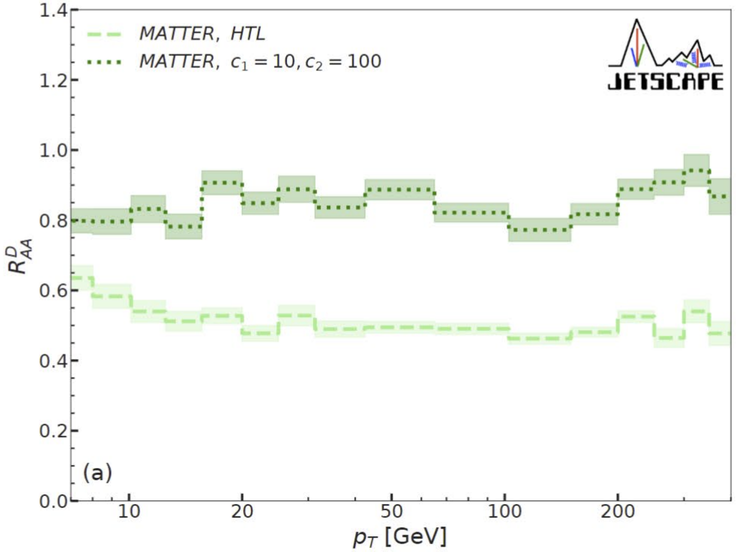
- Simulation for PbPb collision at $\sqrt{s_{NN}} = 5.02TeV$, 0-10% centrality.
- $\sim$10 million events generated for each curve.
- LBT only inconsistent with R_{AA} data at high p_T.
- MATTER with virtuality dependent $\hat{q}$ gives a R_{AA} close to 1.

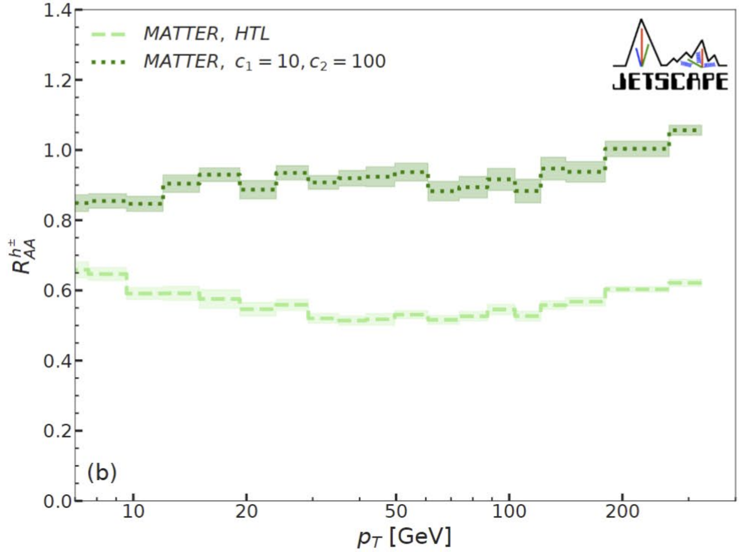




D meson R_{AA}

Charged hadron R_{AA}

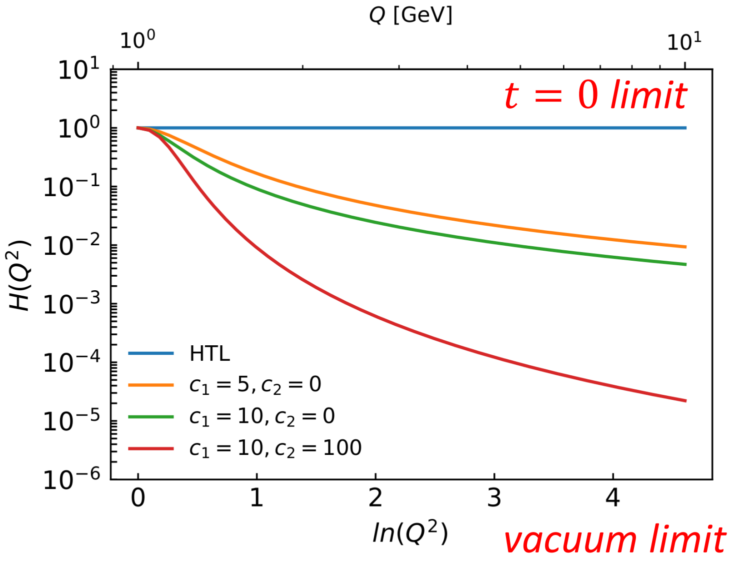




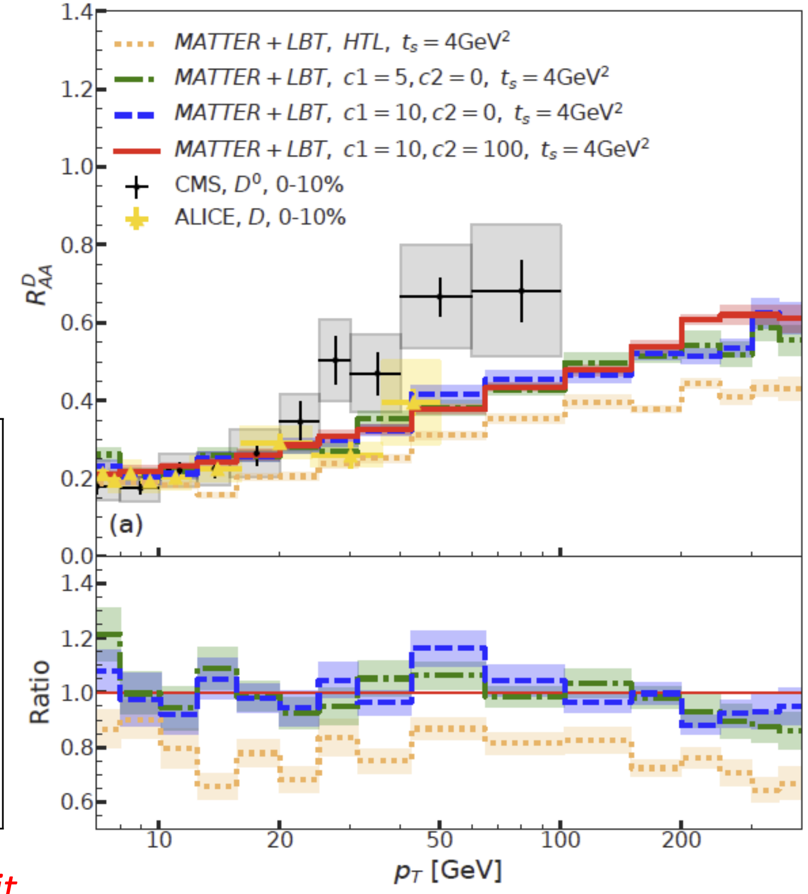
PART 2

Parton Energy Loss – R_{AA} Results with Different $\hat{q}(t)$

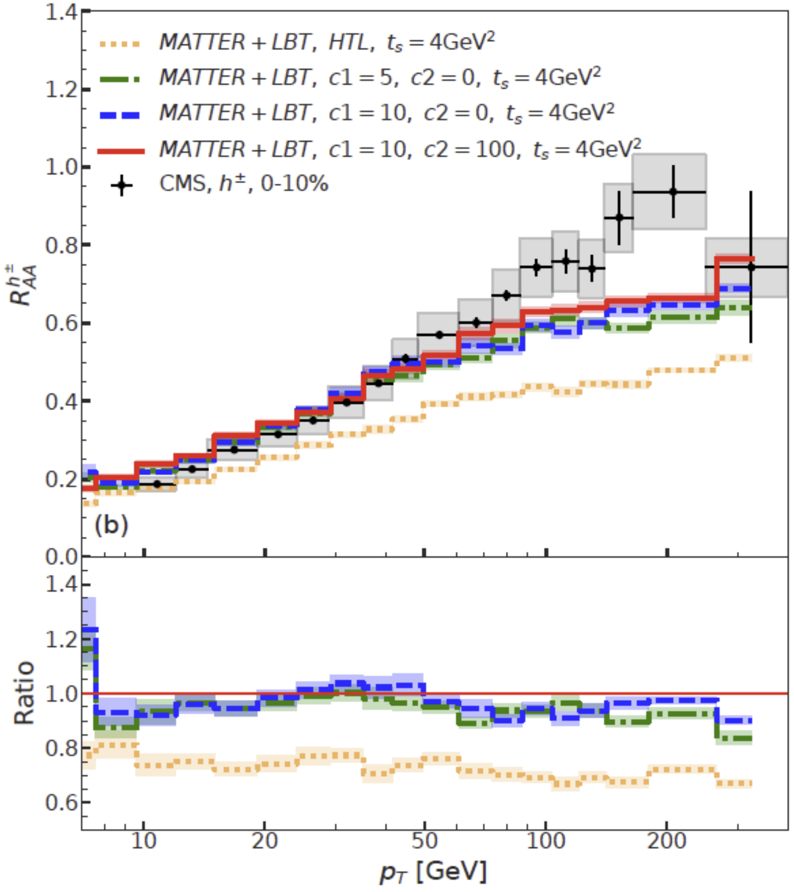
$$H(Q^2) = H(t) = \frac{\hat{q}(E,T,t)}{\hat{q}^{HTL}} = \frac{c_0}{1 + c_1 \ln^2(t) + c_2 \ln^4(t)}$$



***H(t)* comparison**



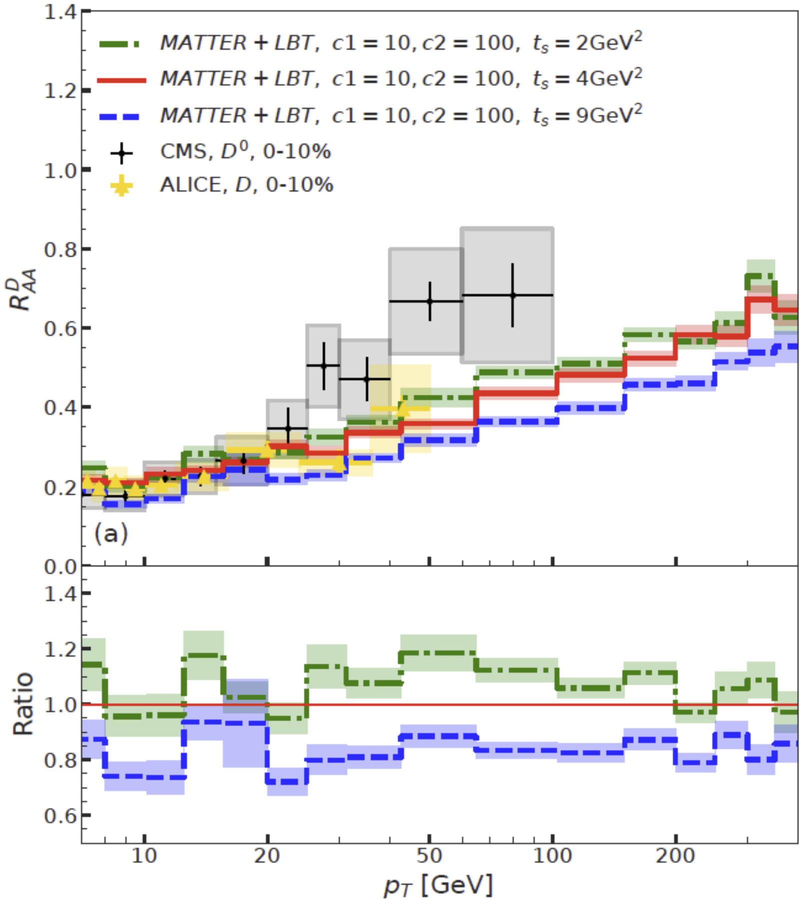
D meson R_{AA}



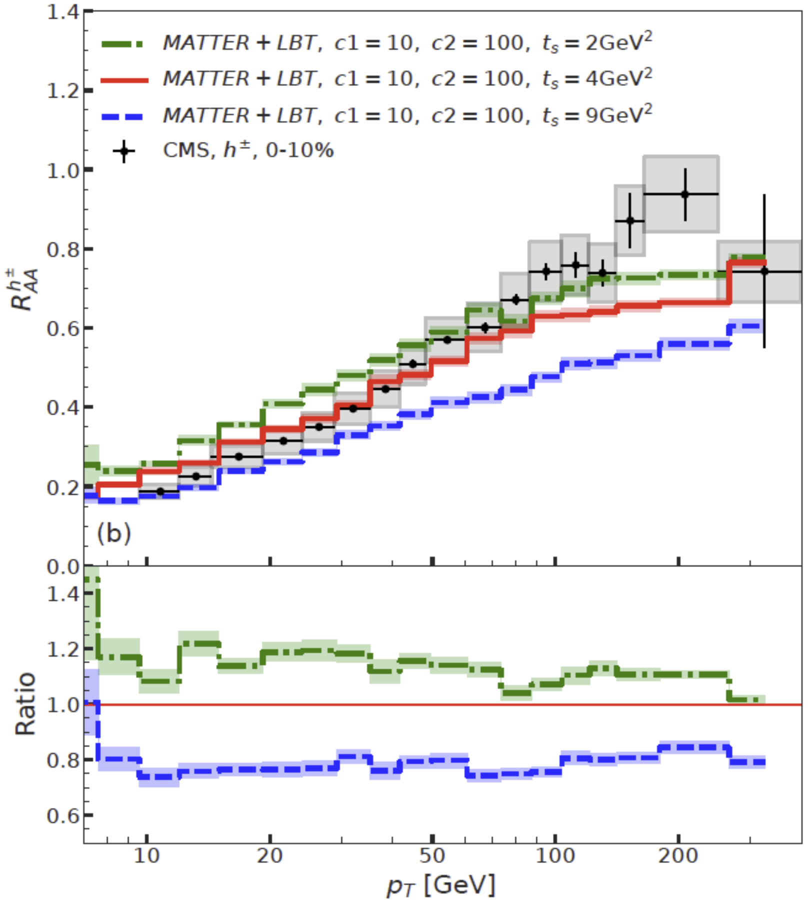
Charged hadronR_{AA}

Parton Energy Loss – R_{AA} Results with Different t_s

- $t_s = Q_s^2$ affects the time a parton spent in the LBT regime.



D meson R_{AA}



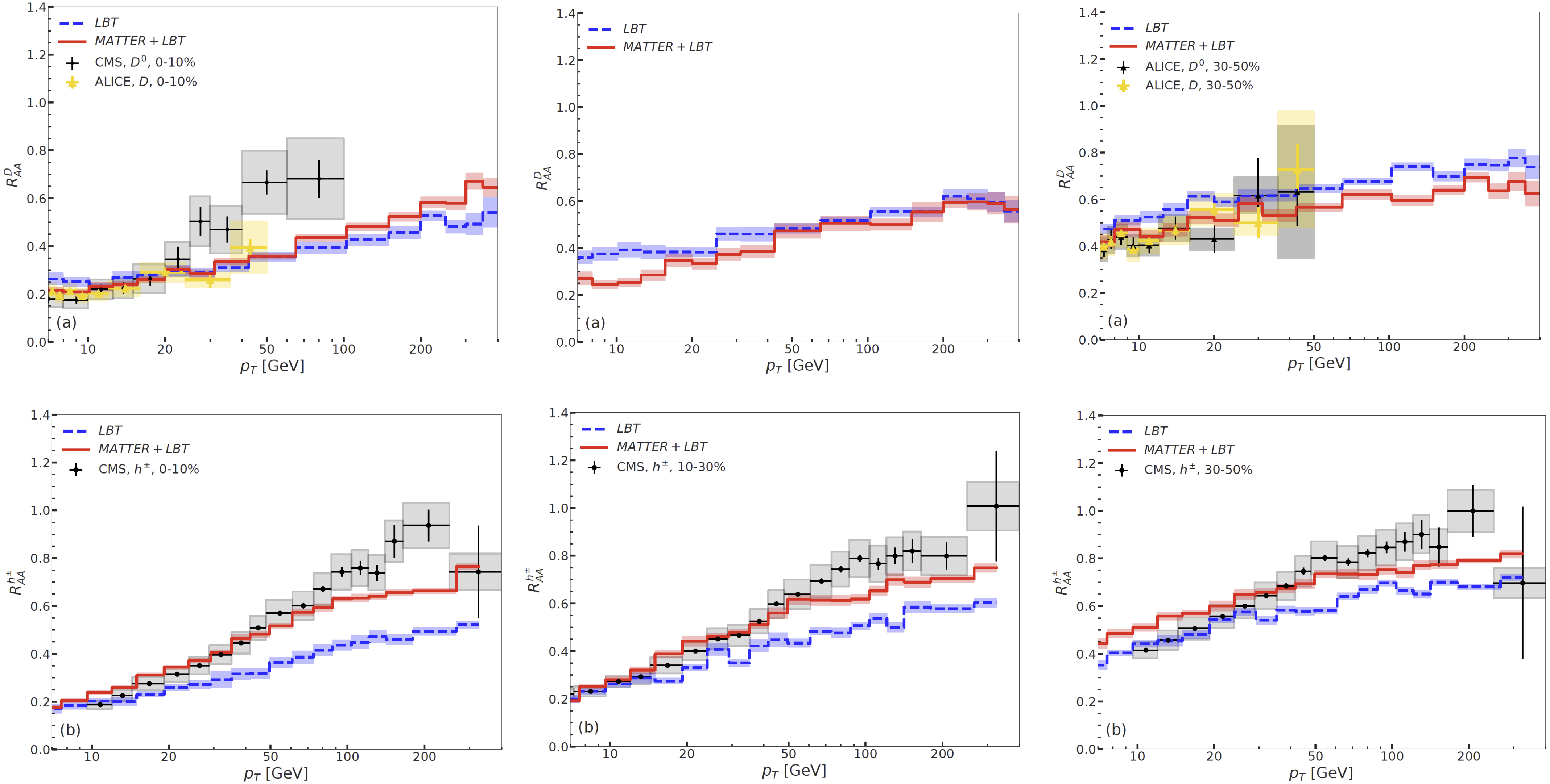
Charged hadron R_{AA}

Parton Energy Loss – R_{AA} Results at Three Centralities

- Current "best fit" ($\alpha_s = 0.3, c_1 = 10, c_2 = 100, Q_s = 2$) result at 0-10%, 10-30%, and 30-50% centralities.

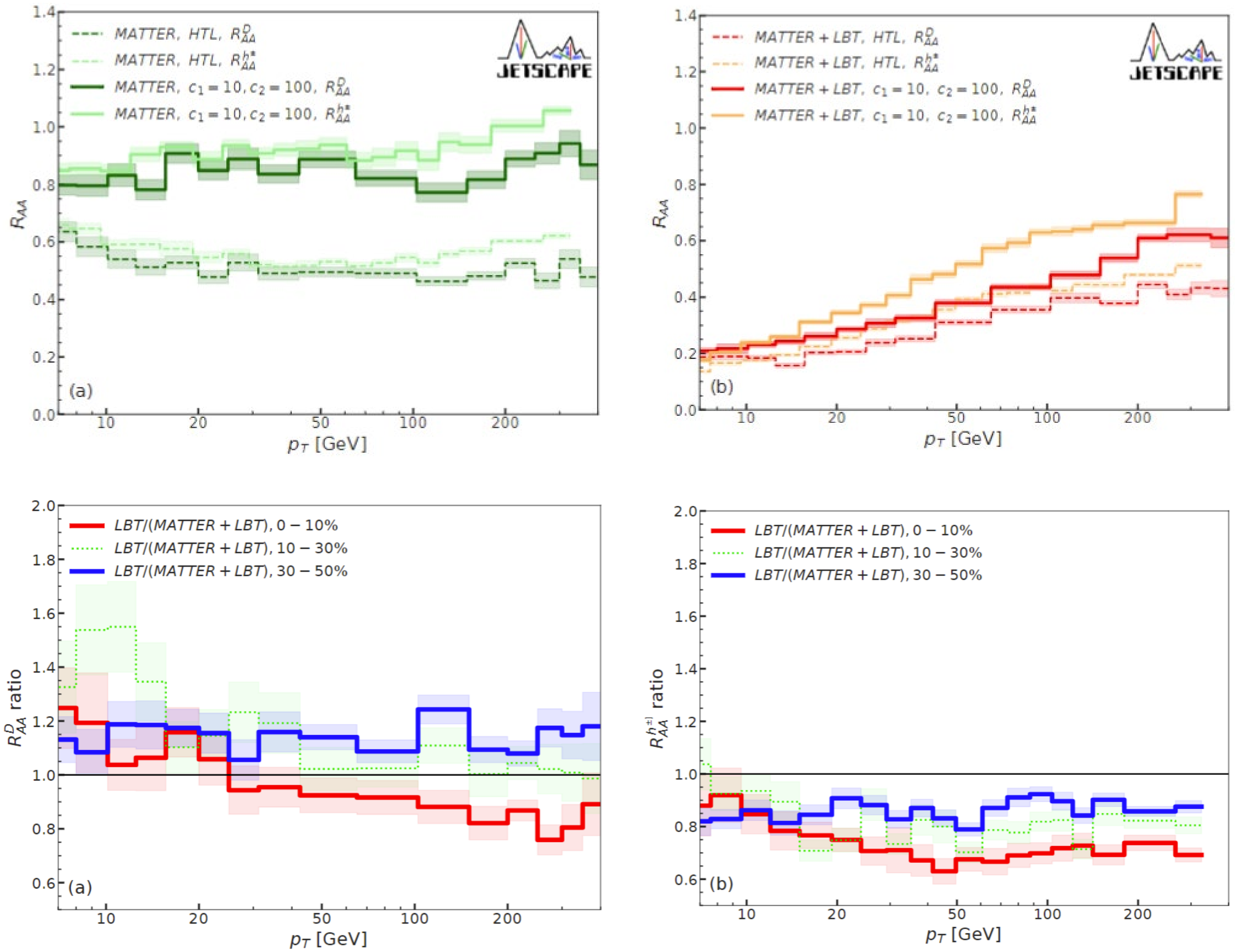
D meson R_{AA}

Charged hadron R_{AA}



Parton Energy Loss – Observations

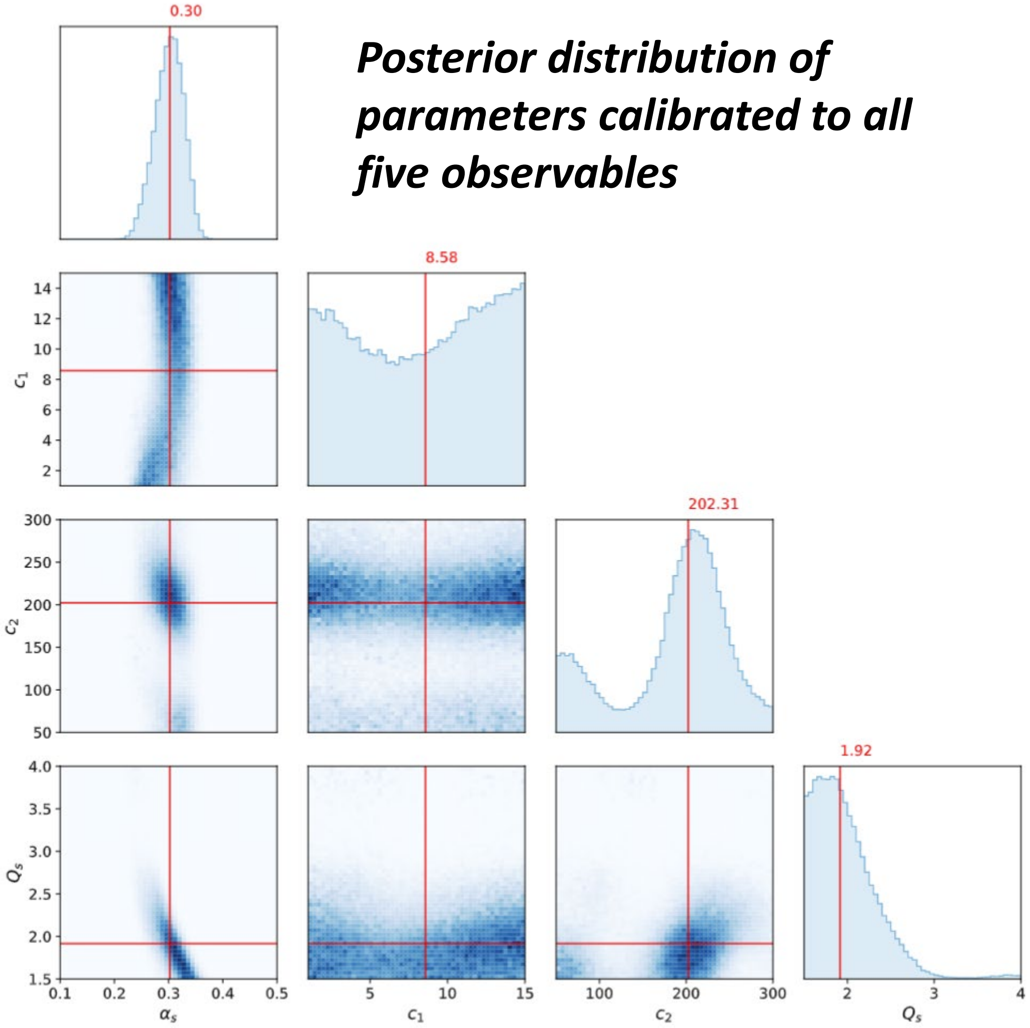
- MATTER with the virtuality dependent $\hat{q}$, does not incur much energy loss at high p_T, and effectively reduces the energy loss in the LBT phase. Thus MATTER+LBT predicts higher R_{AA} at high p_T compared to LBT only.
- Charm quarks are more suppressed than charged hadrons at high p_T.
- Weaker dependence on centrality for MATTER+LBT compared to LBT only.

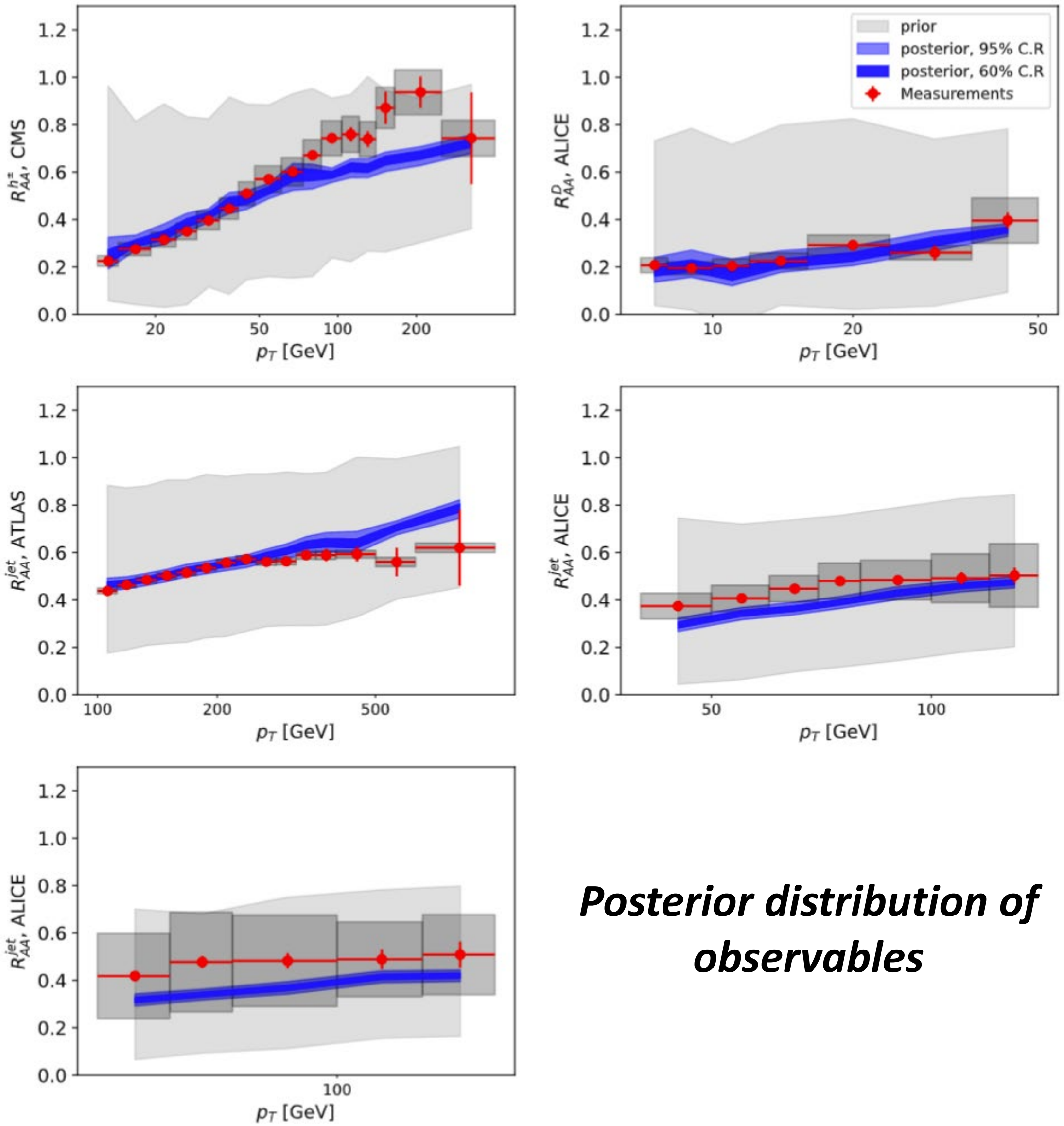


Parton Energy Loss – Bayesian Analysis Results

- Peaks for α_s, Q_s similar to previous study.
- Weak constraint on c_1, slight preference of large c_2.

Posterior distribution of parameters calibrated to all five observables





Posterior distribution of observables

PART 2

Parton Energy Loss – How to Simulate Heavy Flavor in JETSCAPE

- Settings for energy loss:

```
<Eloss>
    …
    <Matter>
      <name>Matter</name>
      …
      <Q0> 2.0 </Q0>
      <T0> 0.16 </T0>
      <in_vac> 0 </in_vac>
      <recoil_on> 1 </recoil_on>
      <hydro_Tc> 0.16 </hydro_Tc>
      <QhatParametrizationType> 5 </QhatParametrizationType>
      <alphas> 0.3 </alphas>
      <qhatA> 10.0 </qhatA>
      <qhatB> 100.0 </qhatB>
      <tStart> 0.6 </tStart>
    </Matter>

    <Lbt>
      <name> Lbt </name>
      <Q0> 2.0 </Q0>
      …
      <hydro_Tc> 0.16 </hydro_Tc>
      <alphas> 0.3 </alphas>
      <run_alphas>1</run_alphas>
      <tStart> 0.6 </tStart>
    </Lbt>
  </Eloss>
```

- Other settings include Trento initial conditions (pre generated), VISHNU 2+1D viscous hydrodynamics (pre generated), and colorless hadronization.
- In

```
src -> hadronization ->
ColorlessHadronization.cc ->
ColorlessHadronization::Init()
```

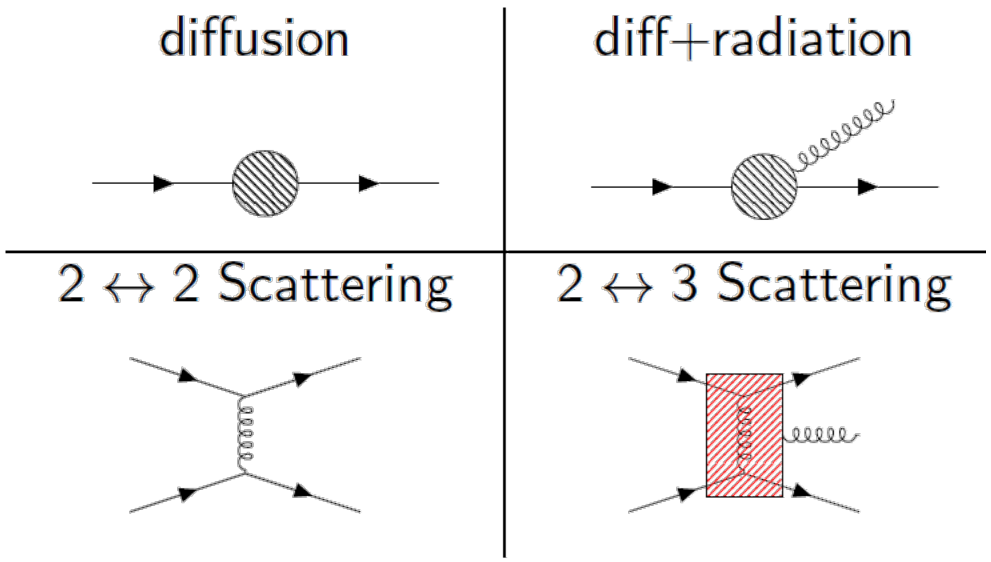
- Disable heavy meson decay:

```
pythia.readString("4:mayDecay=off");
pythia.readString("411:mayDecay=off");
pythia.readString("421:mayDecay=off");
pythia.readString("413:mayDecay=off");
```

Other Treatments - Heavy Quark Energy Loss

- Langevin dynamics: small momentum exchange. [PRC 97.1 (2018): 014907.]
- Drag force, thermal random force, recoil force from gluon emission.

$$\begin{cases} \dfrac{d\vec{x}}{dt} = \dfrac{\vec{p}}{E} \\ \dfrac{d\vec{p}}{dt} = -\eta_D(p)\vec{p} + \vec{\xi} + \vec{f}_g \end{cases}$$



- The LIDO model [*arXiv:1810.08177* (2018).], separation of momentum transfer between:

  Small-q ($q < Q_{cut}$): diffusion

  Large-q ($q > Q_{cut}$): scattering

$$p_1^{\mu}\,\partial_\mu f = \mathcal{D}[f] + \mathcal{C}^{1\leftrightarrow 2}[f] + \mathcal{C}^{2\leftrightarrow 2}[f] + \mathcal{C}^{2\leftrightarrow 3}[f]$$

Other Treatments – The Recombination Mechanism

- Heavy quark hadronization: fragmentation + recombination (coalescence)

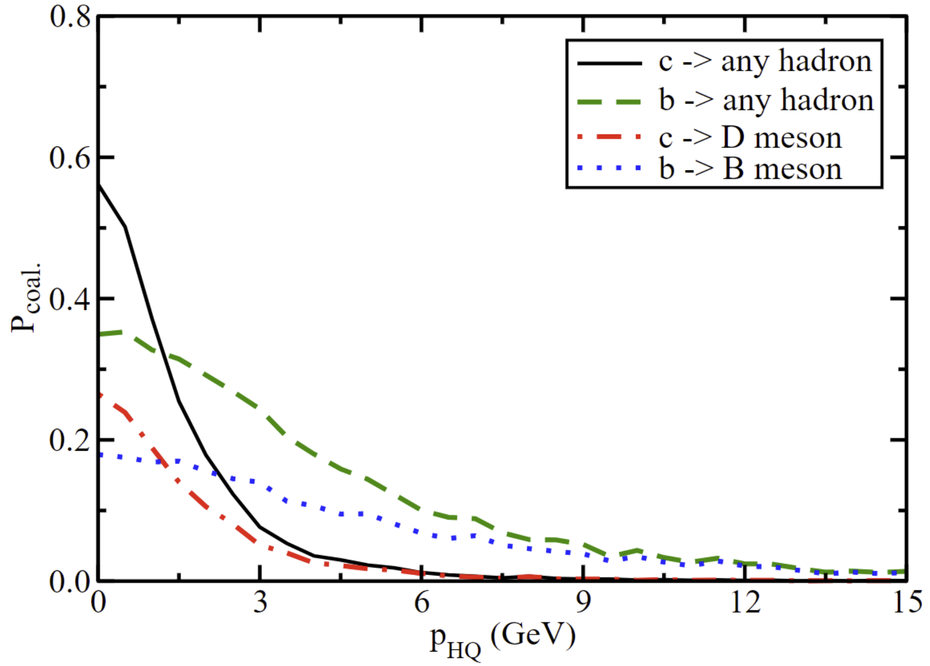
$$\frac{dN_M}{d^3p_M} = \int d^3p_1 d^3p_2 \frac{dN_1}{d^3p_1}\frac{dN_2}{d^3p_2} f_M^W(\vec{p}_1, \vec{p}_2)\delta(\vec{p}_M - \vec{p}_1 - \vec{p}_2)$$

$$\frac{dN_B}{d^3p_B} = \int d^3p_1 d^3p_2 d^3p_3 \frac{dN_1}{d^3p_1}\frac{dN_2}{d^3p_2}\frac{dN_3}{d^33} f_B^W(\vec{p}_1, \vec{p}_2, \vec{p}_3)\delta(\vec{p}_M - \vec{p}_1 - \vec{p}_2 -$$

where

$$f_M^W(q^2) = \frac{g_M\left(2\sqrt{\pi}\sigma\right)^3}{V} e^{-q^2\sigma^2}$$

$$f_B^W(q_1^2, q_2^2) = \frac{g_B\left(2\sqrt{\pi}\sigma_1\right)^3\left(2\sqrt{\pi}\sigma_2\right)^3}{V^2} e^{-q_1^2\sigma_1^2 - q_2^2\sigma_2^2}$$

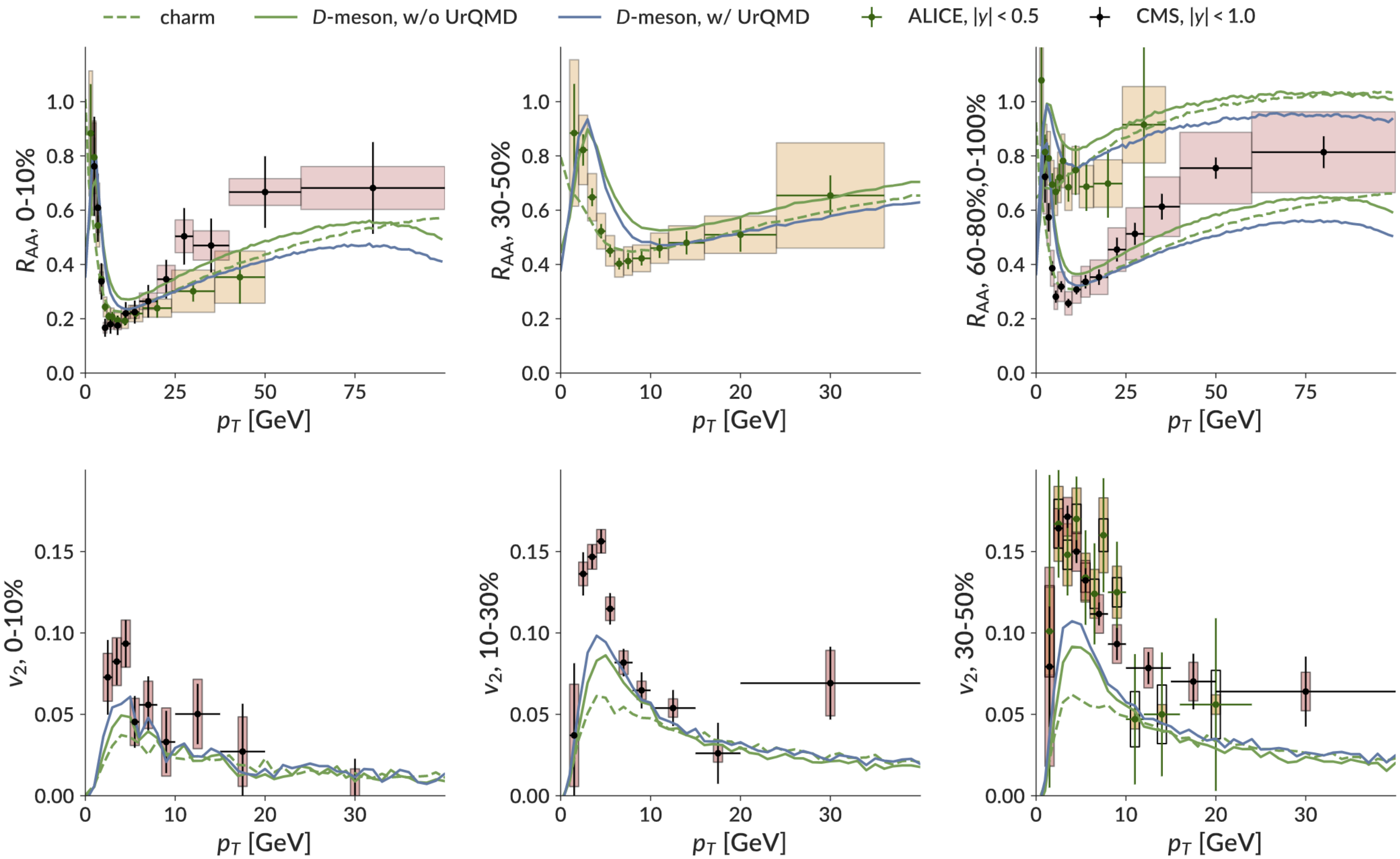


Coalescence probability as a function of the heavy quark momentum

[PRC 94.1 (2016): 014909]

Other Treatments – Effects of Hadronization and Hadronic Re-scattering

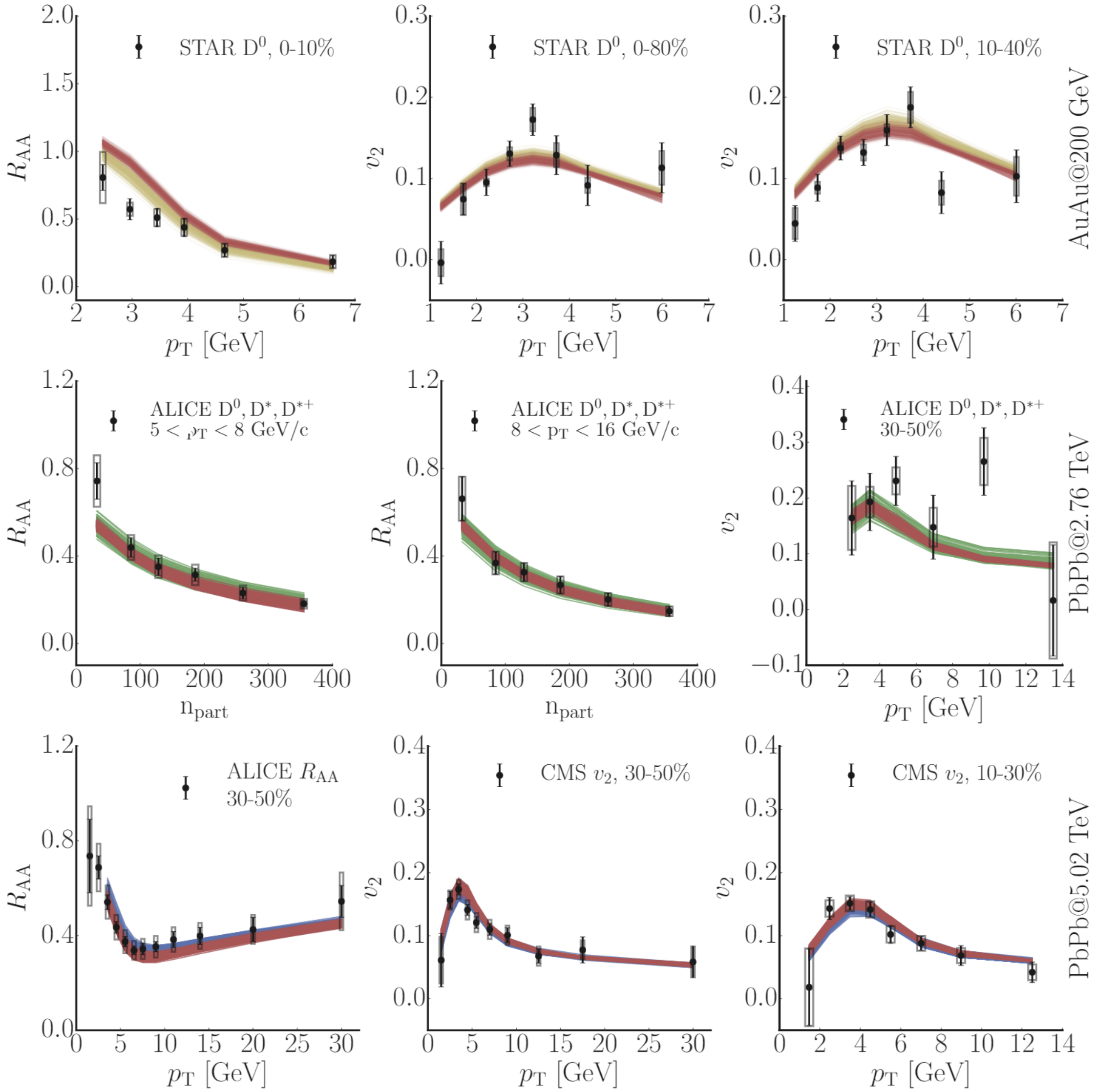
Pb-Pb 5.02 TeV, improved Langevin, $\alpha_s(\mu = 1)$



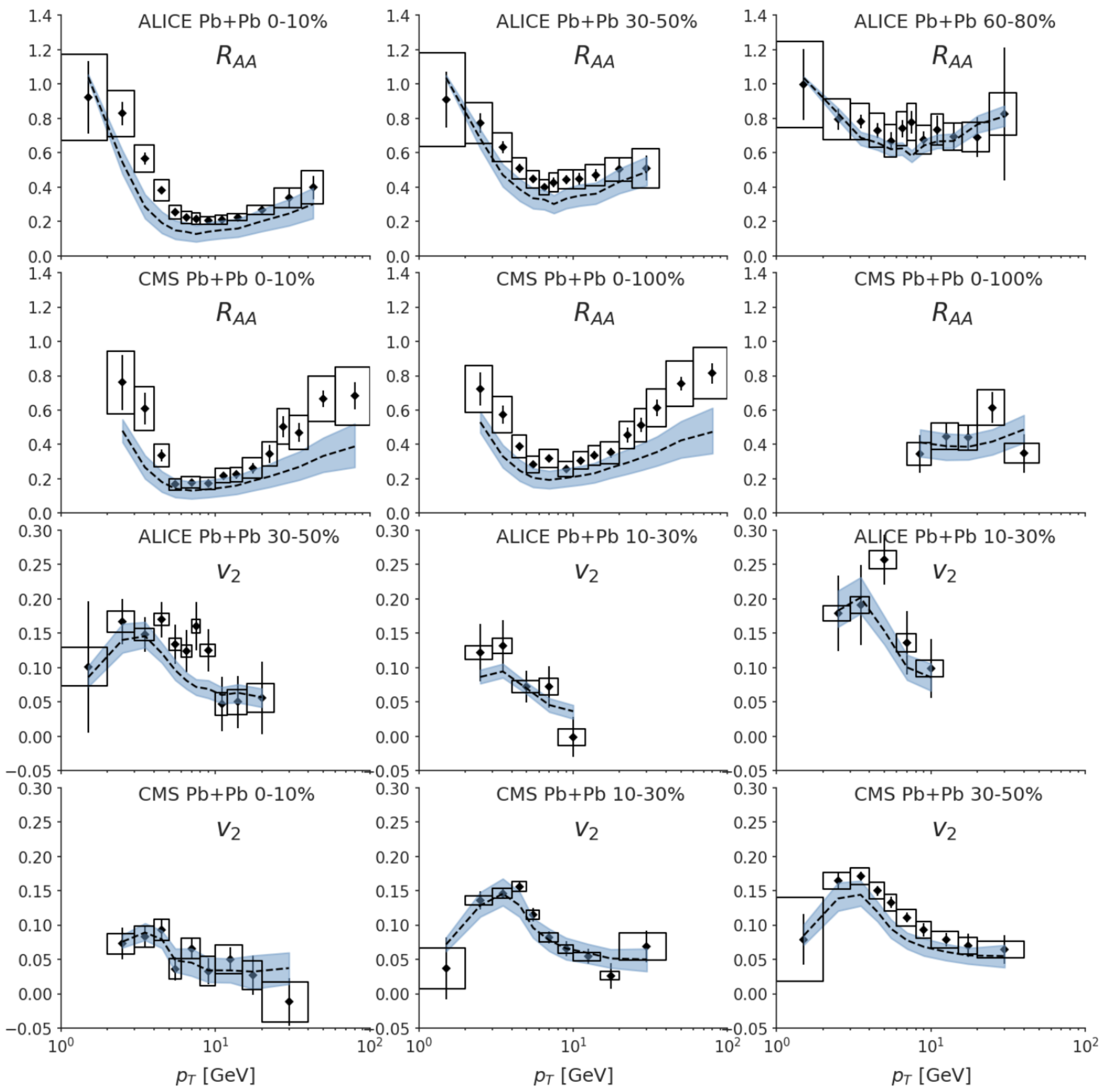
PART 3

Other Treatments – Best Fit to Data in Previous Studies

- The Duke-Langevin model [PRC 97.1 (2018): 014907.]



- The LIDO model [arXiv:2001.02766]



SUMMARY

- JETSCAPE employs a multi-stage evolution approach (MATTER+LBT) to jet energy loss. Simultaneous description of charged hadron, D meson, and inclusive jet observables ($p_T \geq$ 7 GeV). Needs more precise, high p_T R_{AA} data for further validation.
- Other LBT only simulations: [PLB 777 (2018): 255-259],[PLB 805 (2020): 135424],[PRC 105.4 (2022): 044904] for describing medium to high p_T R_{AA} calculation.
- Going to lower p_T, previous study considering diffusion (with effective modeling of the diffusion coefficients) and recombination, are able to describe the R_{AA} and v_2 data of heavy flavors.
- Heavy flavor related jet observables, measurements coming and modeling in progress.

Thank you!

The JETSCAPE Collaboration