Probing the multi-scale dynamical interaction between heavy quarks and the QGP using JETSCAPE

Wenkai Fan

On behalf of the JETSCAPE Collaboration

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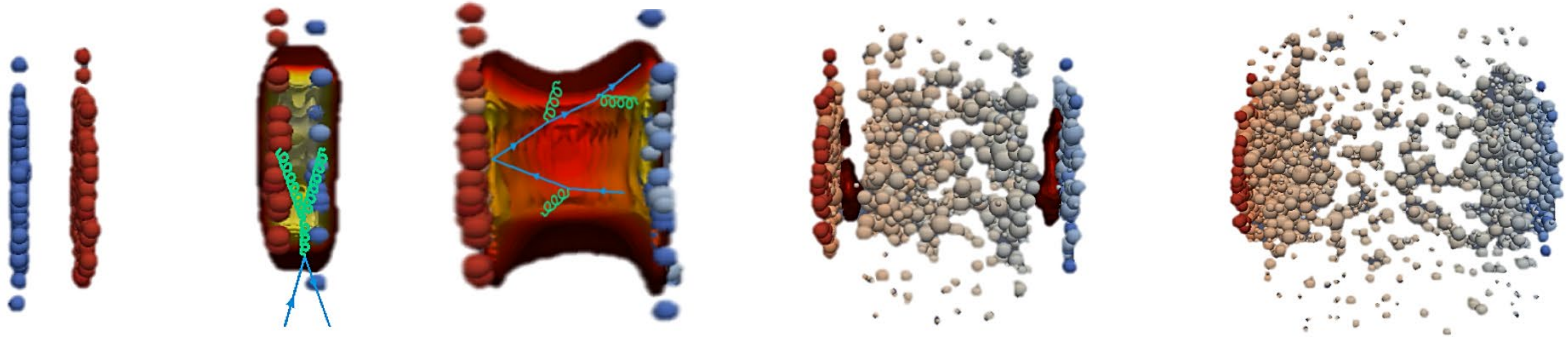
OUTLINE

- The JETSCAPE framework
- Heavy quark evolution (MATTER+LBT)
- Leading and jet observables
- D meson observables
- Conclusion and outlook

PART 1

The JETSCAPE framework



AuAu collision @ 200GeV, figure credit: Hannah Petersen (now Elfner)

Pre-equilibrium,
$t \sim 1\ \mathrm{fm}/c$

Viscous
hydrodynamics

Hadronization

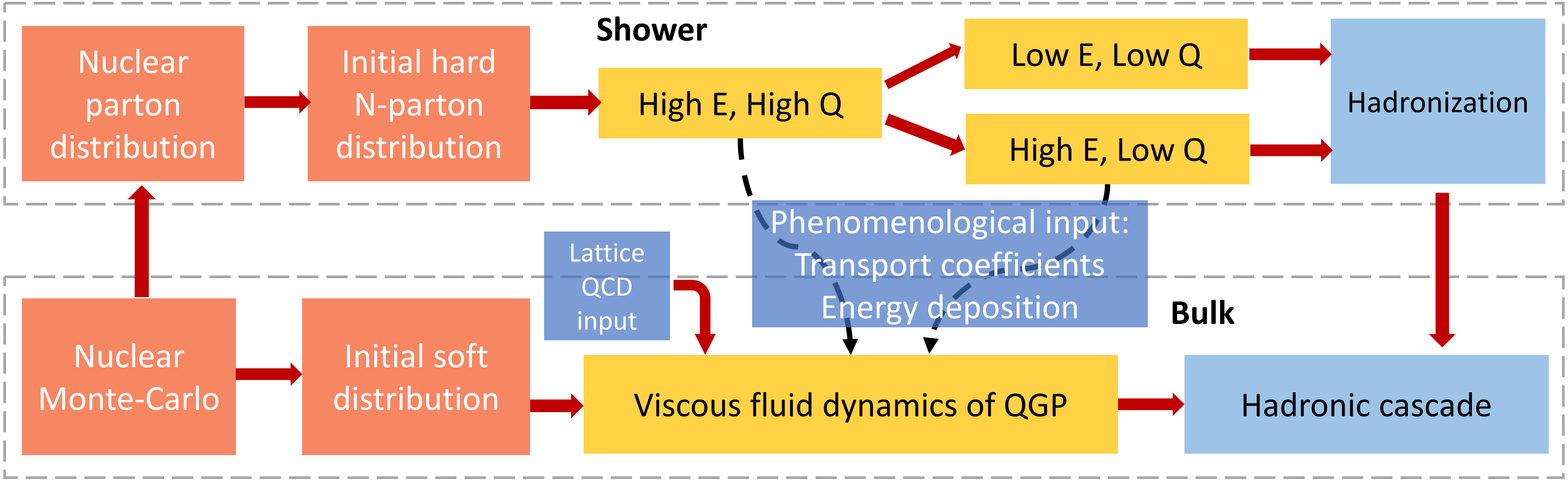
Hadronic transport,
$t \sim 10\ \mathrm{fm}/c$

- **Multistage, multiscale** problem. Need a framework that can make use of different models.
- Soft partons: initial condition, relativistic viscous hydrodynamics, particlization, etc.
- Hard partons: initial condition, transport models, hadronization, etc.
- **Heavy quarks**: produced at early stage, experience full QGP evolution.

PART 1

The JETSCAPE framework

Jet Energy Loss Tomography with a Statistically and Computationally Advanced Program Envelope



- 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

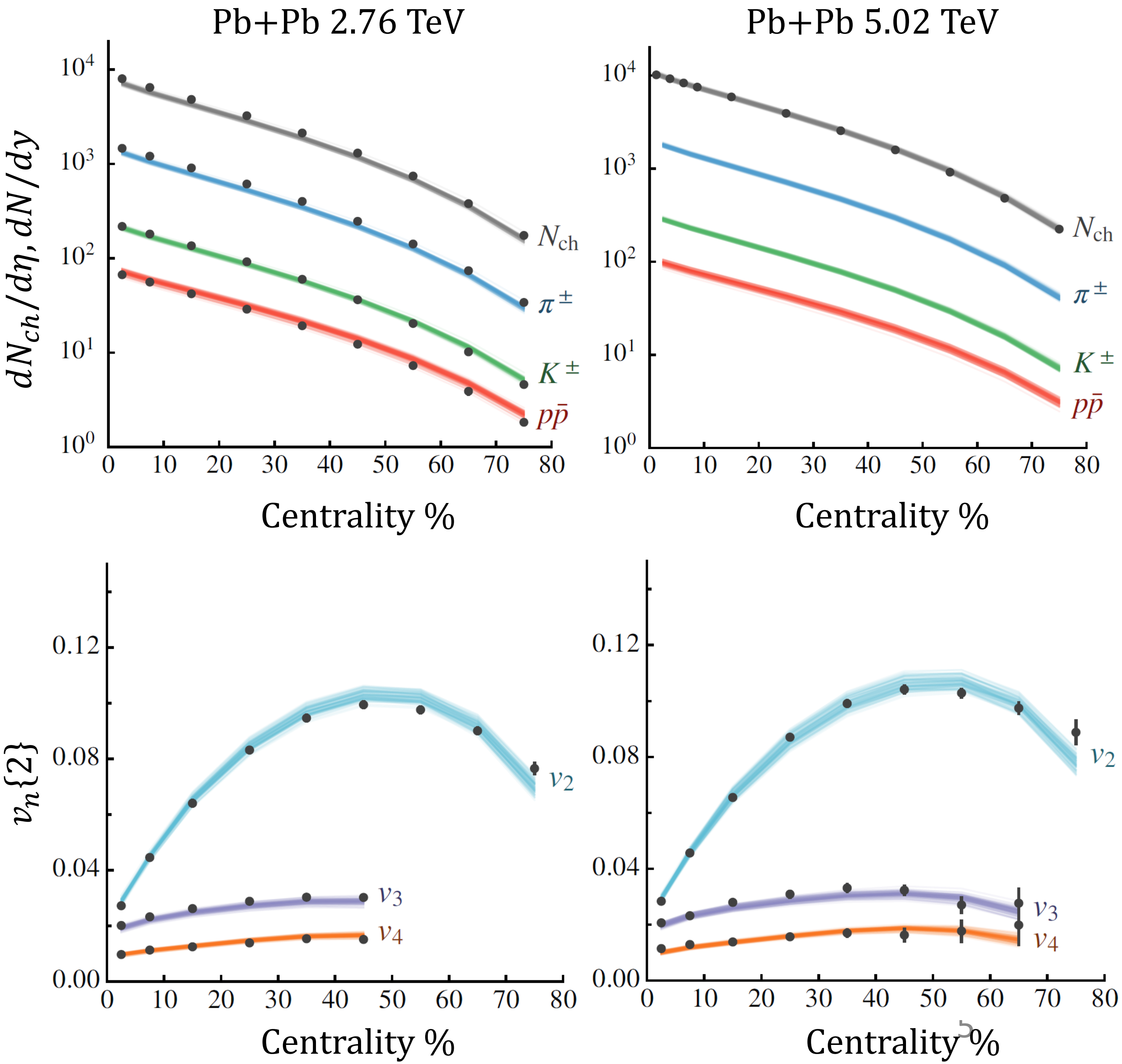
"The JETSCAPE framework", arXiv preprint arXiv:1903.07706 (2019). **Public version 3.0:** https://github.com/JETSCAPE/JETSCAPE

PART 1 Soft Observables

- Using “***best fit***” to hadronic observables (charged hadron yields, mean p_T, flow cumulants, etc). [*NPA 967 (2017): 67-73.*]

- 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



PART 2

The JETSCAPE framework – Hard parton evolution

- **MATTER**: Higher-Twist formalism. Virtuality-ordered shower with splittings above $Q \gg Q_0$. Splittings happen via the Sudakov form factor. *[Adv.Ser.Direct.HEP, 573 (1989); NPA 696, 788 (2001)]*

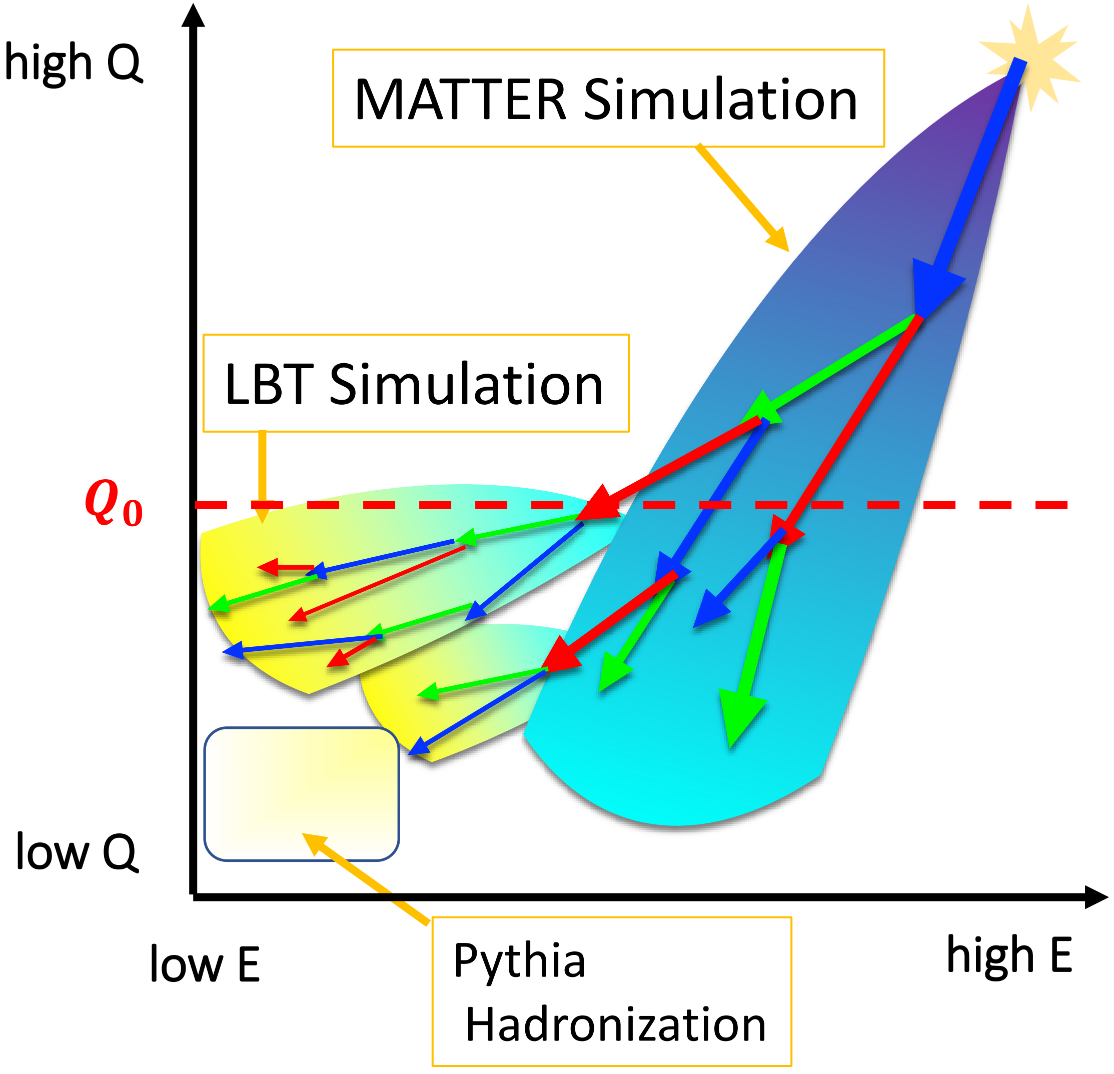
- Sudakov factor for $g \to \bar{Q}Q$:

$$\Delta(Q_{\max}, Q \geq Q_0) =$$

$$\exp\left[-\frac{\alpha_s}{2\pi}\int_{Q^2}^{Q^2_{\max}} \frac{d(Q^2)}{Q^2}\frac{\alpha_s(Q^2)}{2\pi}\int_{y_{\min}}^{y_{\max}} dy\, \mathcal{P}(y)\right]$$

$$\mathcal{P}(y) = P(y) + \frac{P(y)\int_{\tau_i}^{\tau_f} dt\, \hat{q}(t) 4\sin^2\left[\frac{t-\tau_i}{2\tau_f}\right]}{y(1-y)Q^2}$$

[PRC 94, 054902 (2016)].



Phase space evolution, figure credit: Gojko Vujanovic

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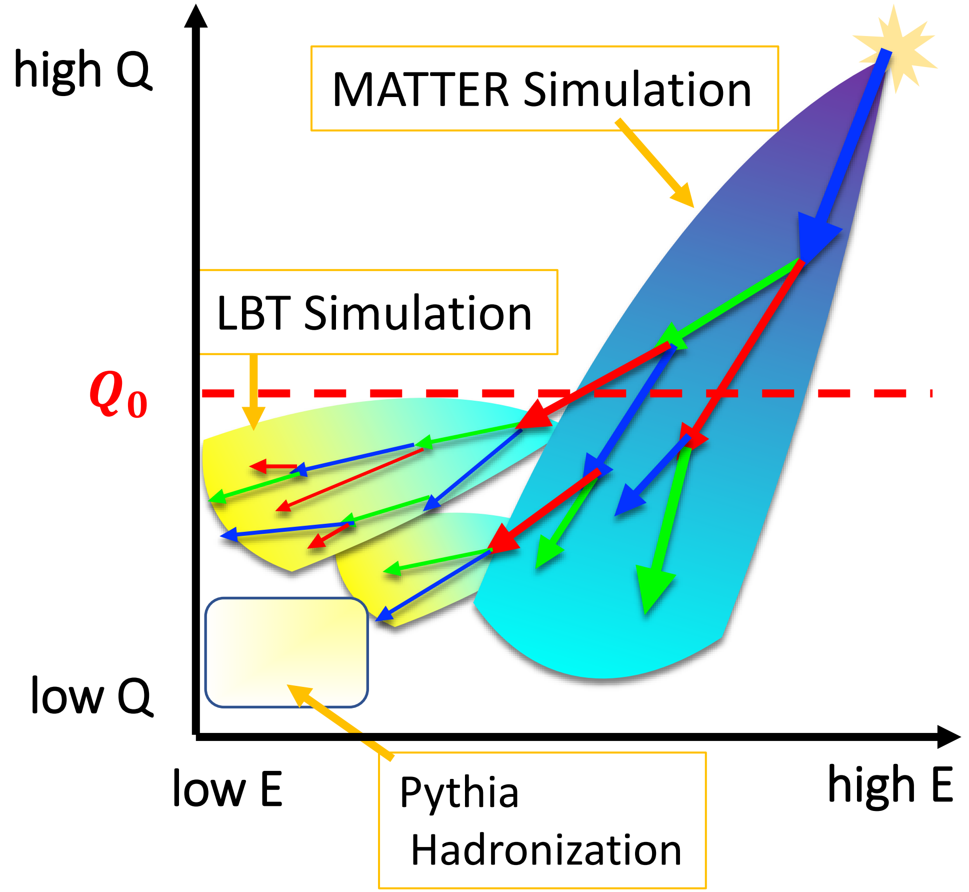
$$\mathcal{P}(y) = P(y) + \frac{P(y)\{(\left(1-\frac{y}{2}\right)(\chi^2+1)-\chi\}\int_{\tau_i}^{\tau_f} dt\,\hat{q}(t)4sin^2\left[\frac{t-\tau_i}{2\tau_f}\right]}{y(1-y)Q^2(1+\chi)^2}$$

$$\chi = \frac{y^2M^2}{y(1-y)Q^2-y^2M^2}, \qquad \hat{q} \propto \alpha_s^2T^3ln\left(\frac{cE}{\alpha_sT}\right)$$ *, [PRC 94, 054902 (2016)]*

Phase space evolution, figure credit: Gojko Vujanovic



The JETSCAPE framework – Hard parton evolution

- **LBT:** Linear Boltzmann transport equation.

$$p \cdot \partial f(x,p) = \mathcal{C}_{el} + \mathcal{C}_{inel}$$

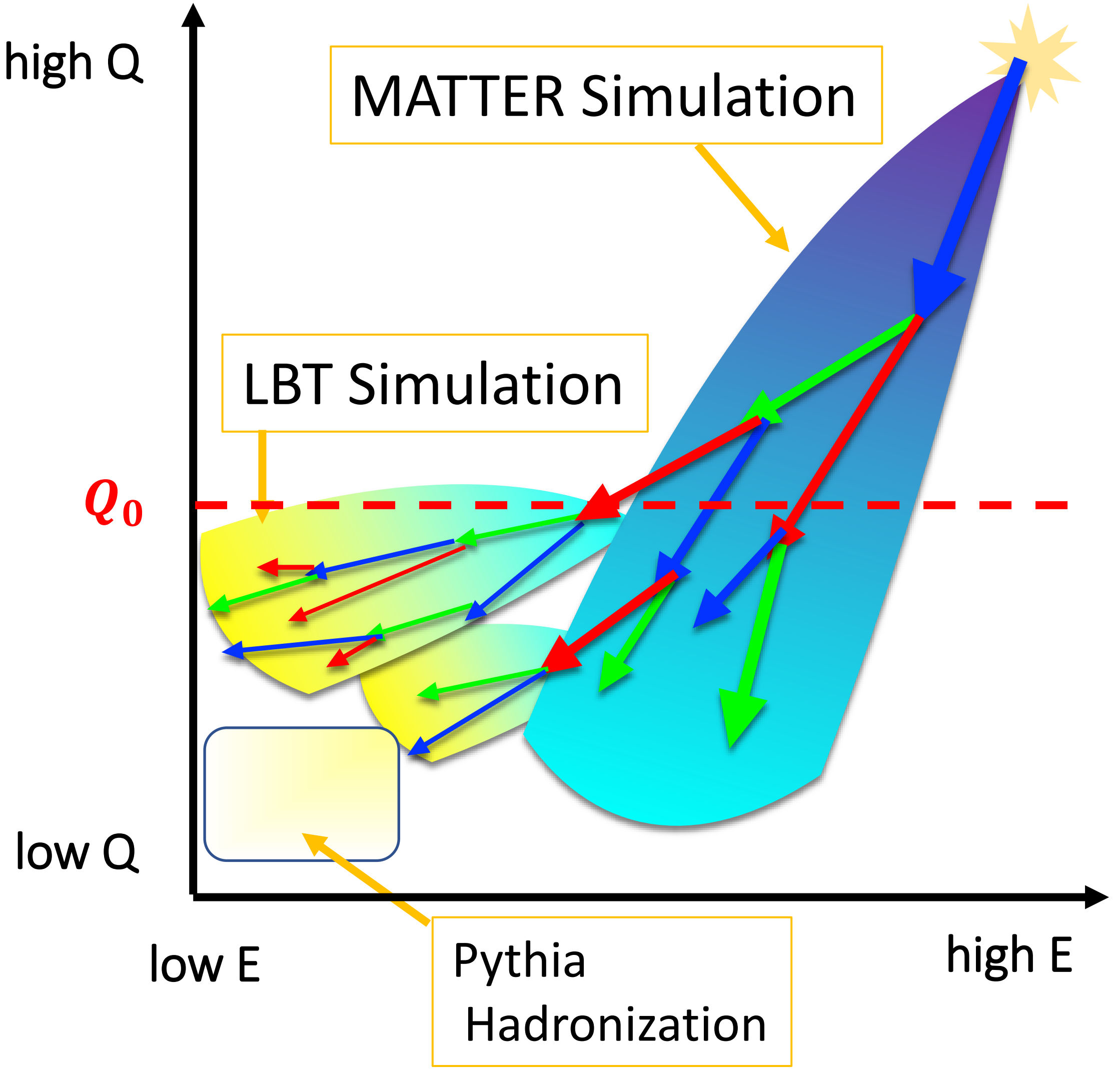
$$\mathcal{C}_{el} = \int \frac{d^3k}{2k^0(2\pi)^3} \int \frac{d^3l}{2l^0(2\pi)^3} \int \frac{d^3q}{2q^0(2\pi)^3} f(p) f(k)$$

$$f'(l) f'(q) |\mathcal{M}|^2 (2\pi)^4 \delta^{(4)}(p + k - l - q)$$

$$\mathcal{C}_{inel} = \int \frac{d(Q^2)}{Q^2} \frac{\alpha_s(Q^2)}{2\pi} \int dy\, \mathcal{P}(y)$$

[PRC 94, 054902 (2016)]

- Other energy loss modules are also added to the JETSCAPE framework. Example: MARTINI, Lido.
- Medium recoil is also treated on a parton-by-parton basis.

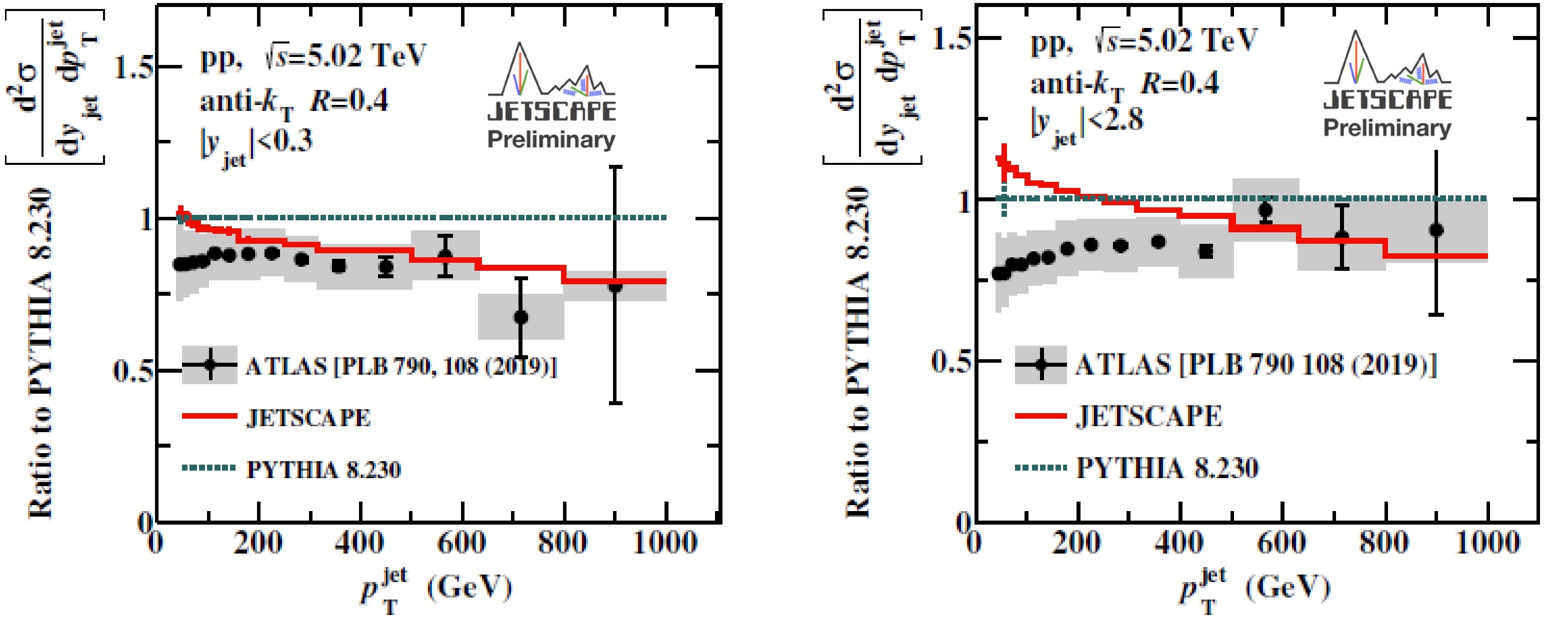


Phase space evolution, figure credit: Gojko Vujanovic

PART 3

The JETSCAPE framework – pp19 tune

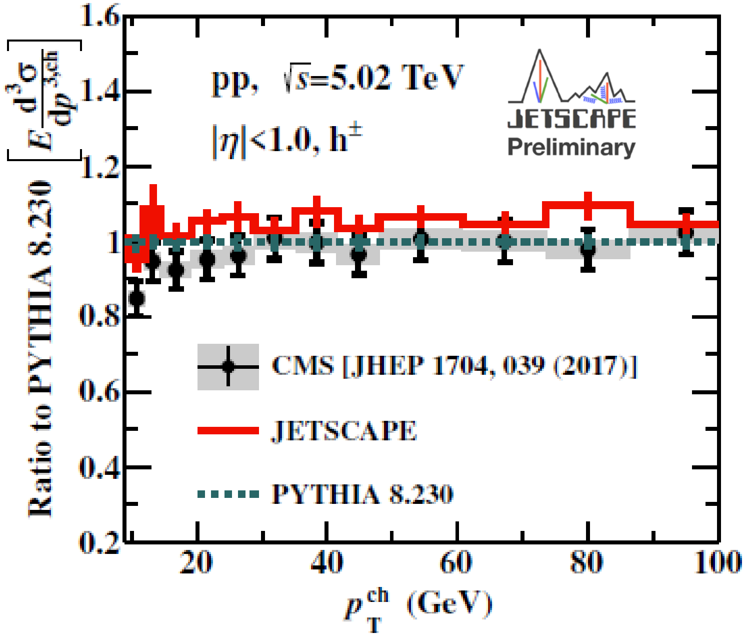
Inclusive jet cross section



(Mid-rapidity, $|y_{jet}| < 0.3$)

(Wide-rapidity, $|y_{jet}| < 2.8$)

Charged hadron yield

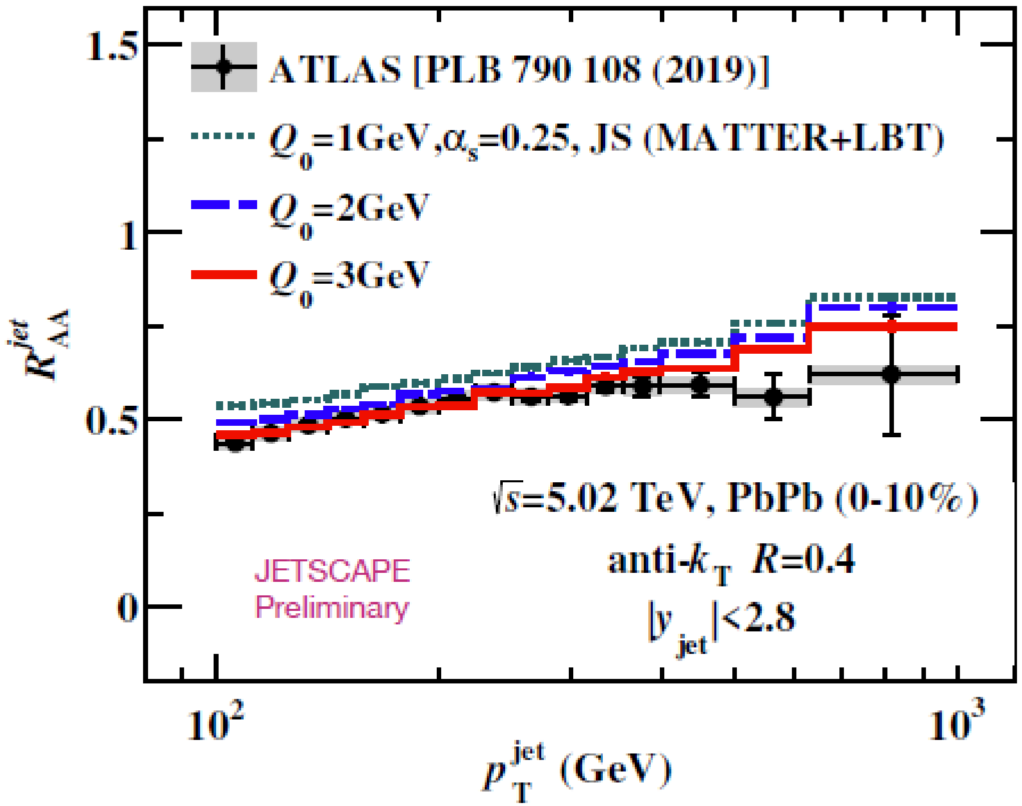


- Reasonable agreement with experiments and Pythia at mid-rapidity.
- Not able to evolve long enough causes artifacts at wide rapidity:

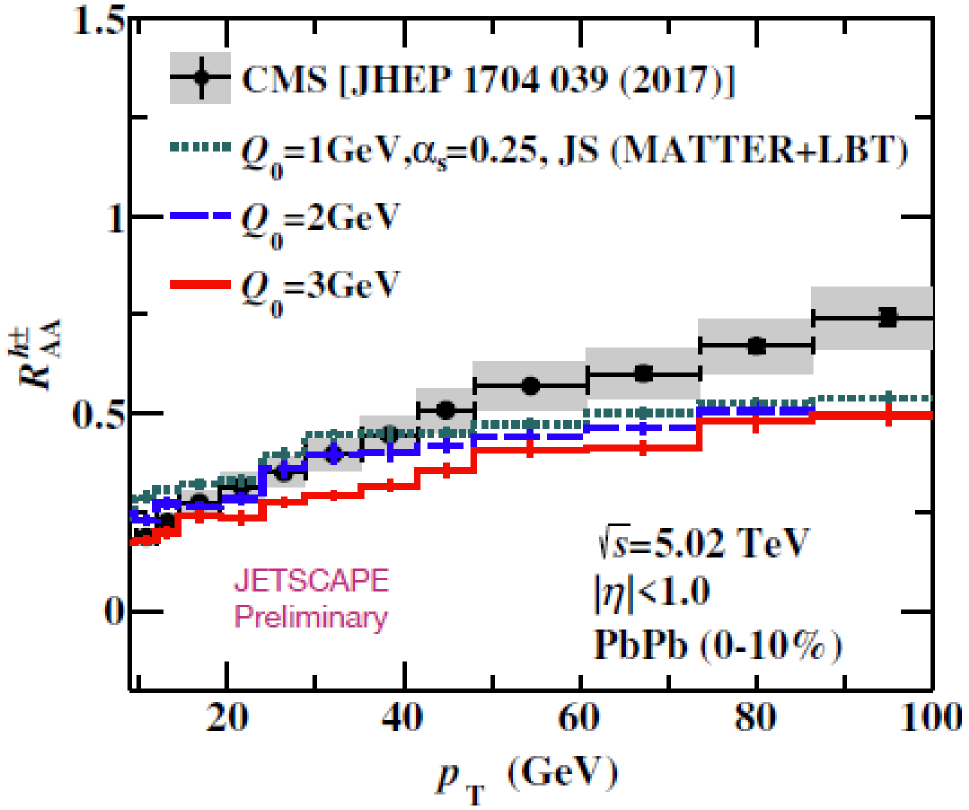
PART 3

The JETSCAPE framework – PbPb 5.02TeV

Jet R_{AA}



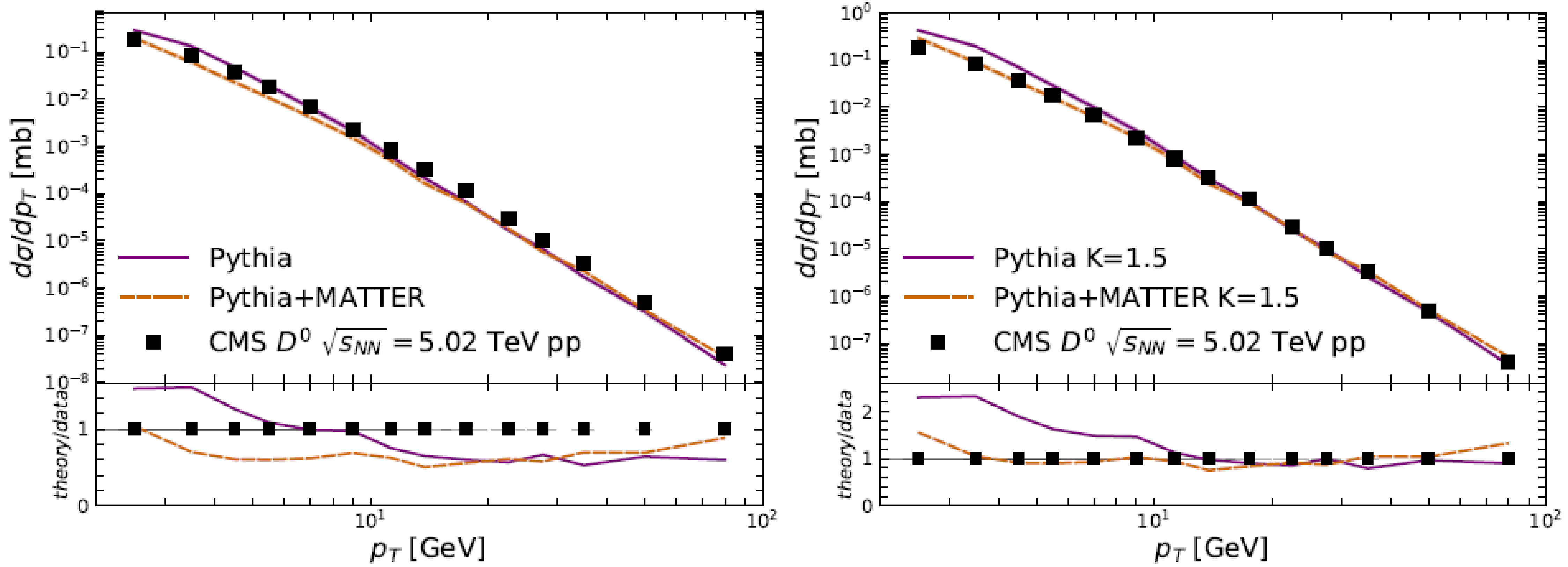
Charged Hadron R_{AA}



- A fixed α_s calculation shows reasonable agreement with data.
- For more recent results on jet and jet substructure observables, see **C. Park** talk (ID #163).
- $Q_0 = 2$ is preferred by light flavor data and is used for charm calculations later.

The JETSCAPE framework – Heavy quark pp baseline

D^0 cross section



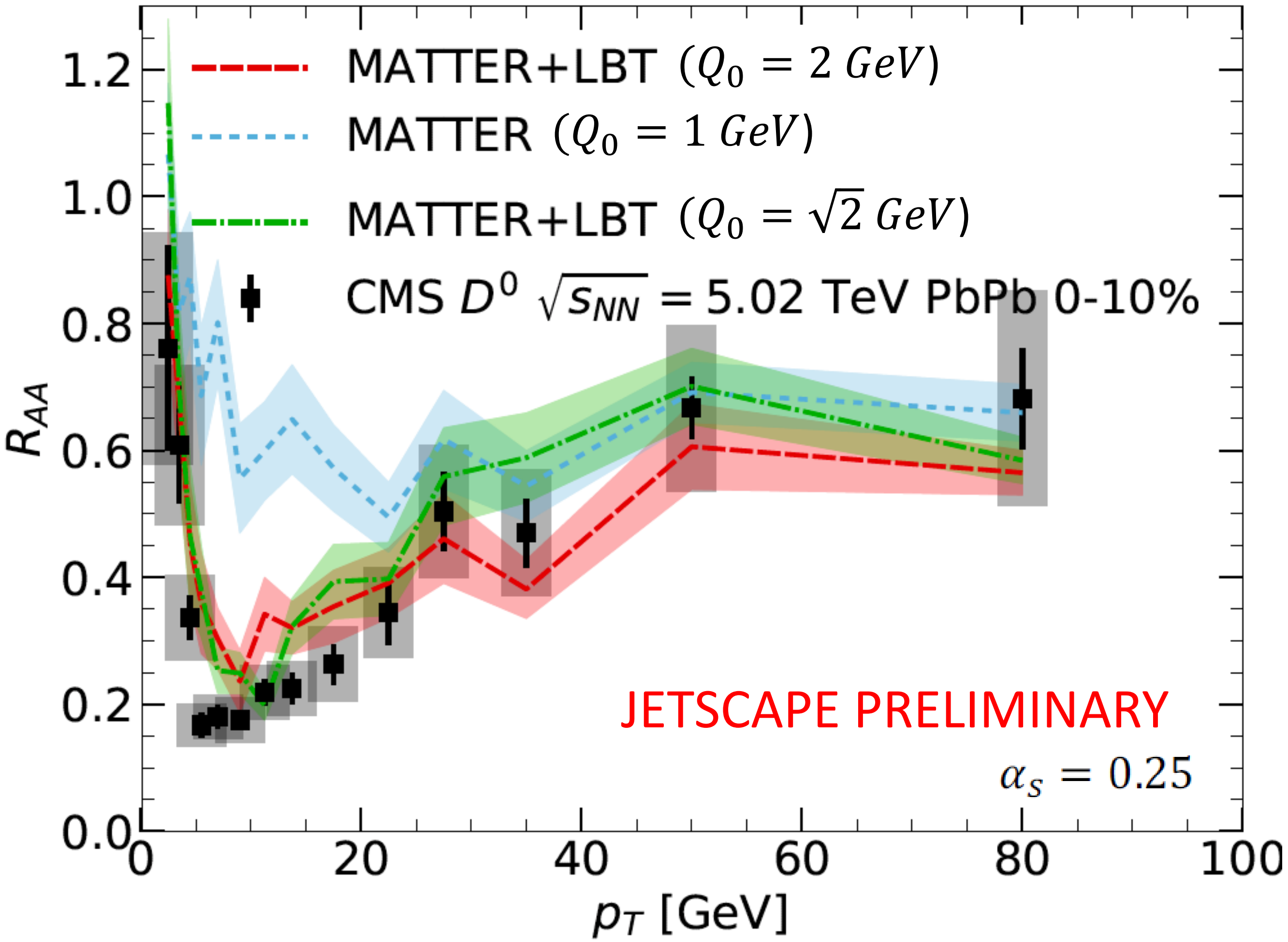
- The shape of the D^0 meson cross section is better when using Pythia + MATTER. When introducing a K factor 1.5, the agreement with experiment is further improved.

PART 4

The JETSCAPE framework – Heavy quark R_{AA}

- Jet and charged hadron R_{AA} used to tune parameters, i.e. $\alpha_s = 0.25$ and $Q_0 = 2GeV$
- No additional tuning was done for D^0 meson R_{AA}.
- MATTER along is not enough for D meson energy loss at low p_T, too few scattering.
- For bottom quark observables, will need a different Q_0 in future studies.

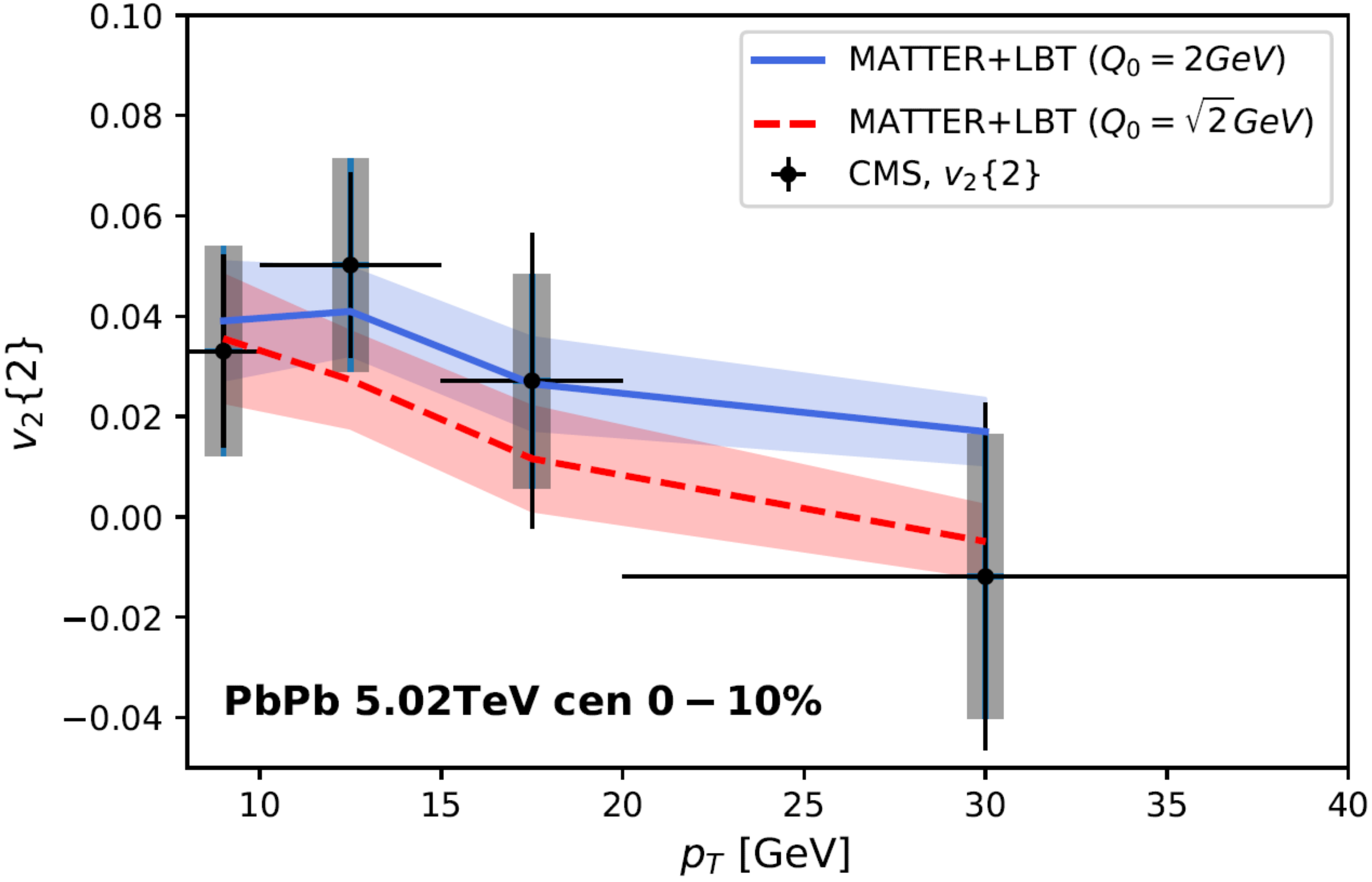
D^0 meson R_{AA}



The JETSCAPE framework – Heavy quark flow

- Reasonable agreement with data. Additional precision from experiments would be highly appreciated.
- Lower p_T results not shown: no recombination mechanism and hadronic transport considered now.
- MATTER+LBT can not only describe light parton observables, but charm quark as well.

D^0 meson v_2

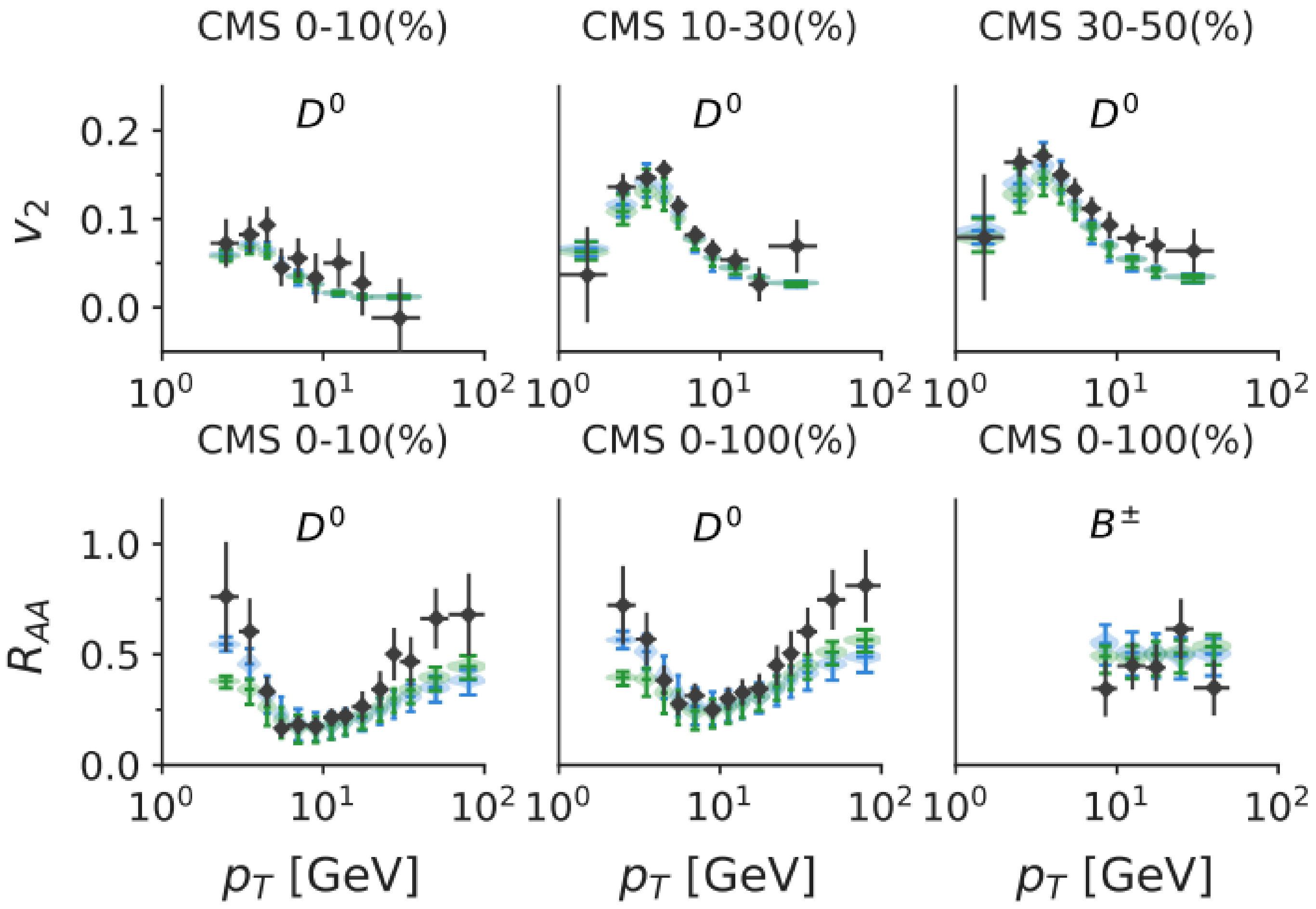


Data from: *Sirunyan, Albert M., et al. Physical Review Letters 120.20 (2018): 202301.*

PART 4

The JETSCAPE framework – D meson observables with the Lido transport model

- Lido 1.0: Transport model specifically for heavy quarks. collisional + diffusional energy loss; Parametrized transport coefficients. Recombination and hadronic transport models also used in this study.
- Linked to JETSCAPE as an external module.
- Use Bayesian analysis to find the posterior distribution that best describes the data.



D meson observables calculated with optimal posterior parameters (blue/green lines: EPPS /nCTEQ15np nuclear PDF)

Weiyao Ke, Yingru Xu, and Steffen A. Bass Physical Review C 98.6 (2018): 064901.

PART 5

Conclusion and Outlook

- JETSCAPE provides a **unified framework** where different energy loss formalisms can be studied, which allows for a simultaneous description of both **light** and **heavy** parton energy loss.
- Without further tuning, **current setup** (initial condition, viscous hydro, MATTER+LBT, hadronization, etc) describes different observables reasonably well (**soft, leading and jet, heavy flavor observables**). Additional physics would be studied in the future.
- **External modules** can significantly add capabilities and features to the framework: Lido as an alternative to heavy quark evolution.
- Future studies will explore:
  - Consider recombination and hadronic transport to improve the description of heavy meson flow.
  - Open bottom hadron observables
  - Heavy-flavor observables in small systems

Thank you!

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