Multi-stage evolution of heavy quarks in the quark-gluon plasma

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for the JETSCAPE Collaboration

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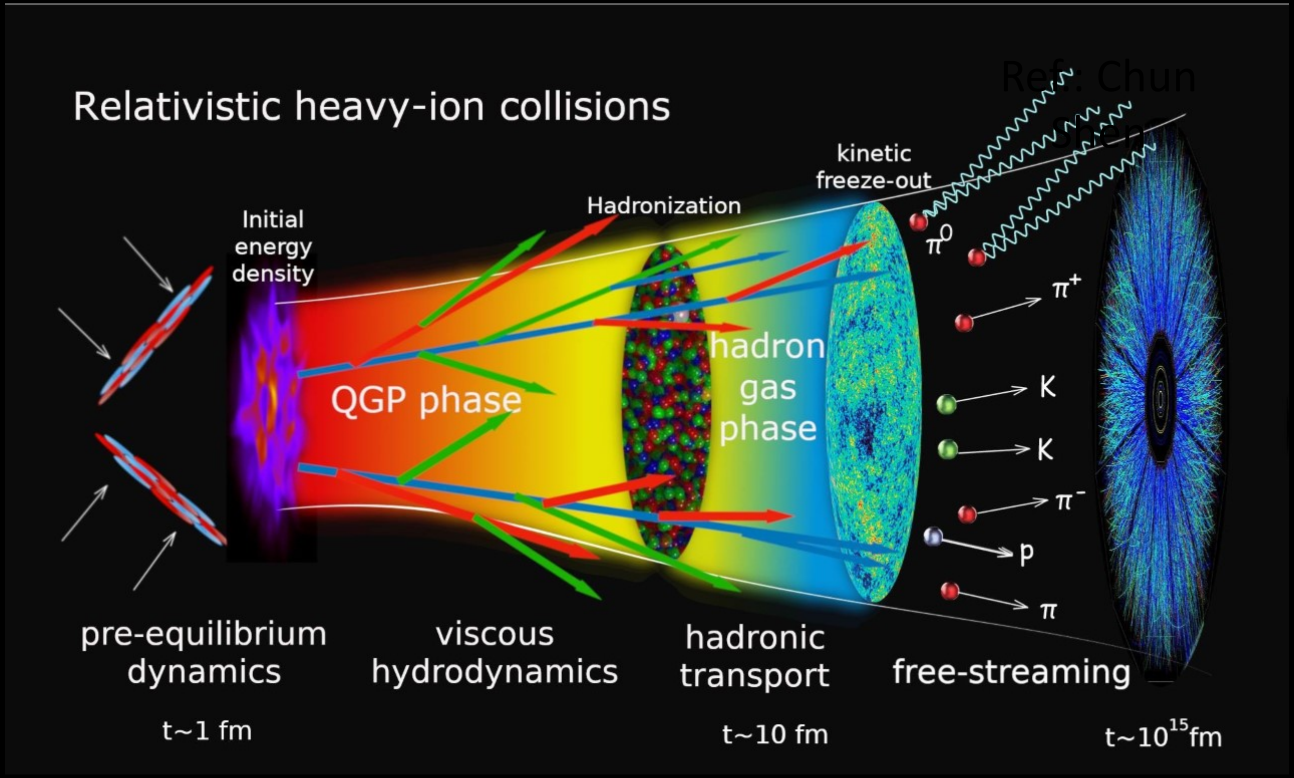
JETSCAPE

Natural Sciences and Engineering Research Council of Canada
Conseil de recherches en sciences naturelles et en génie du Canada

Canada

WAYNE STATE UNIVERSITY

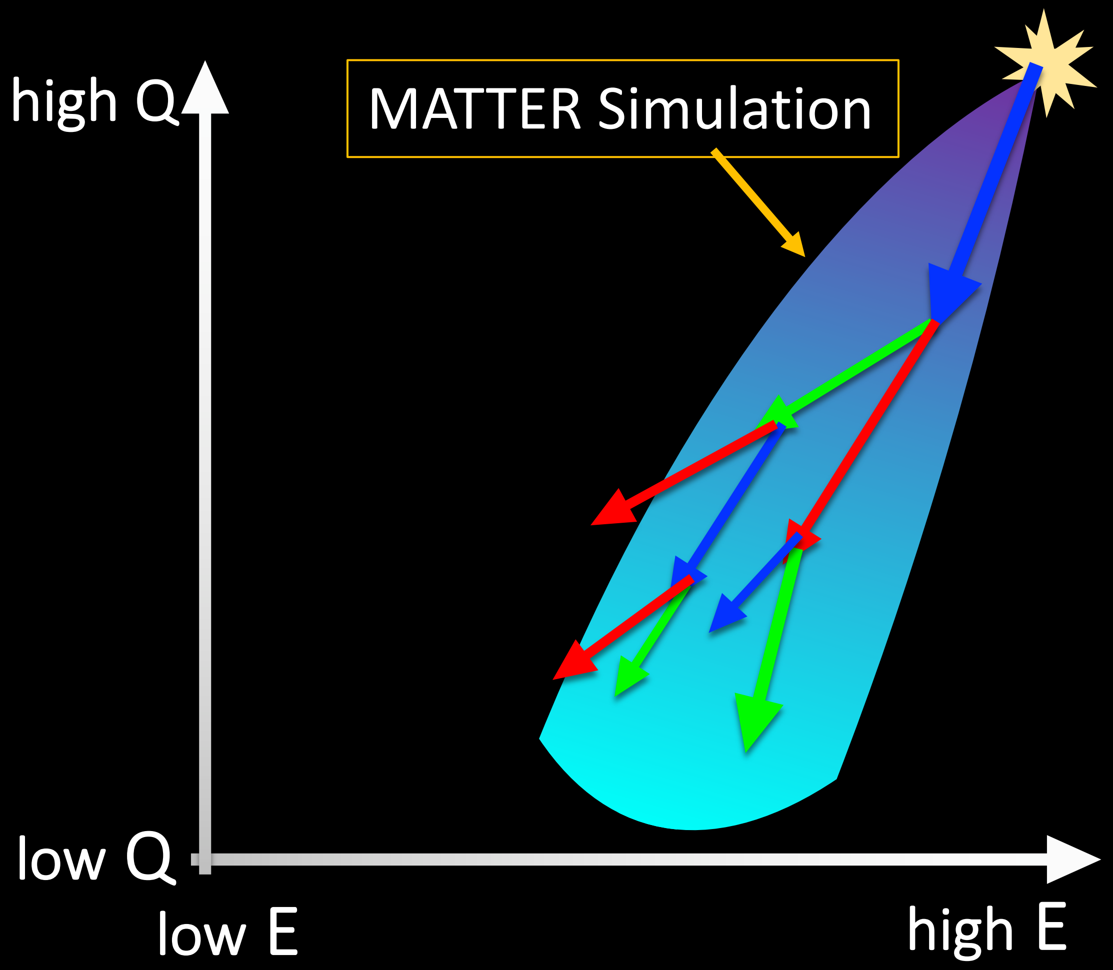
JETSCAPE simulates hard & soft sectors of heavy ion collisions



- Soft hadrons: Ongoing JETSCAPE Bayesian Analysis (see talk by **Jean-François Paquet**) constraining the QGP transport properties.
- Hard Partons: Ongoing multi-stage energy loss of hard partons with soft QGP (see also **Amit Kumar, Wed**) and jet-energy deposition into QGP (see talk by **Yasuki Tachibana, Tue**).

- **JETSCAPE Physics Working Group focused on describing interactions of hard probes with the QGP**: 38 members in total (see http://jetscape.org/phys/)

Multi-stage parton evolution in JETSCAPE



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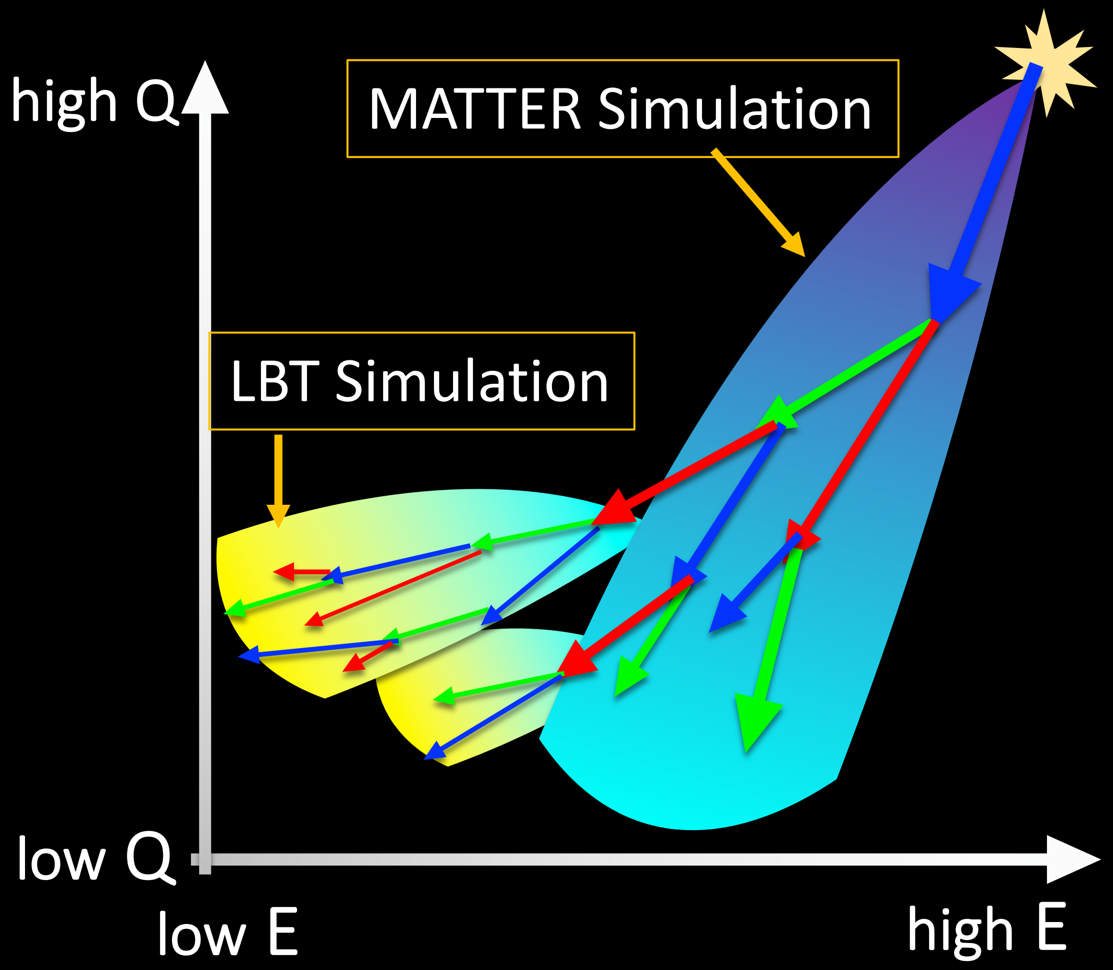

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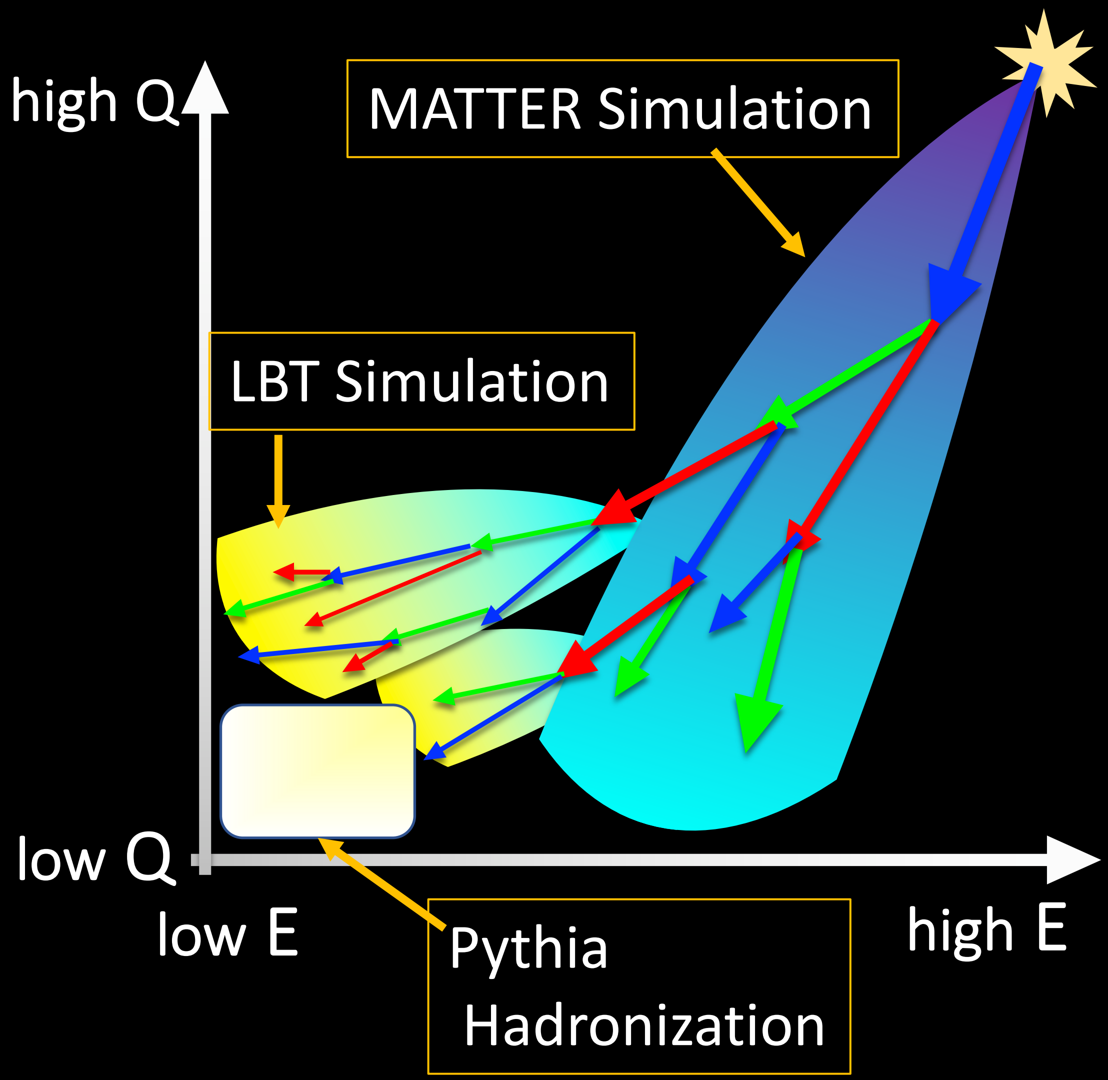

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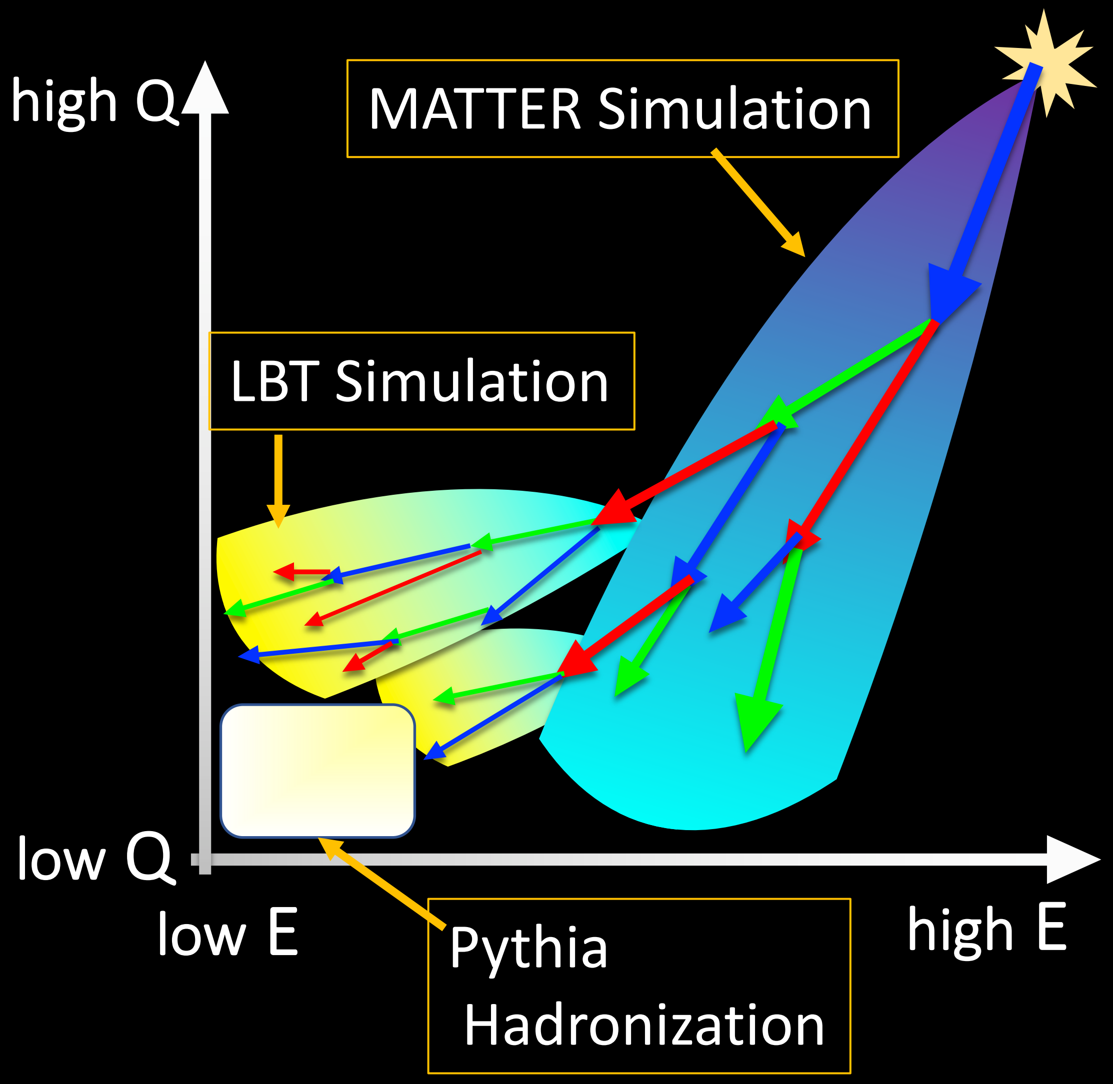

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Different physics mechanisms for in-medium energy loss in different kinematic regimes ⇒ a multi-stage approach is needed for accurate description

Higher Twist Energy Loss for Heavy Quarks

- **MATTER** (The **M**odular **A**ll **T**wist **T**ransverse-scattering **E**lastic-drag and **R**adiation) valid for High E, High Q
  - Virtuality-ordered shower with splittings above $Q \gg Q_{\mathrm{min}}$
  - Splittings happen via the Sudakov form factor [**Adv.Ser.Direct.HEP, 573 (1989); NPA 696, 788 (2001)**] valid for all partonic processes and can include in-medium corrections

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

  - The limits and of the integral and the splitting(s) $\mathcal{P}$ depend on the incoming and outgoing partons species and possible in-medium contributions.

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  - $Q_{\max}$ is set by hard cross section momentum exchange
  - Emission Kinematics dictates that:

$$Q^2_{\min} = \frac{\mathrm{Q}_0^2}{2}\left[1 + \sqrt{1 + \frac{4M^2}{Q_0^2}}\right] \qquad y_{\min} = \frac{Q_0^2}{2Q^2} + \frac{M^2}{M^2 + Q^2} \qquad y_{max} = 1 - \frac{Q_0^2}{2Q^2}$$

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  - $\mathcal{P}(y)$: vacuum/medium splitting derived via SCET [**PRC 94, 054902 (2016)**] at LO in $\left(\alpha_s, \frac{\mathrm{M}^2}{\mathrm{Q}^2}\right)$

$$\mathcal{P}(y) = P(y) + \frac{P(y)\left[\left\{\left(1 - \frac{y}{2}\right) - \chi + \left(1 - \frac{y}{2}\right)\chi^2\right\}\left\{\int_{\tau_i}^{\tau_f} dt\, \hat{q}(t)\left[4\sin^2\left[\frac{t - \tau_i}{2\tau_f}\right]\right]\right\} + \hat{e}\{\ldots\} + \hat{e}_2\{\ldots\}\right]}{y(1 - y)Q^2(1 + \chi)^2}$$

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

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  - $\mathcal{P}(y)$ not yet derived using SCET for heavy flavor, so the light flavor prescription at LO in $\left(\alpha_s, \frac{1}{Q^2}\right)$ is used as ansatz

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

$$\hat{q} \propto \alpha_s^2 T^3 \ln\left[\frac{cE}{\alpha_s T}\right]$$

Linear Boltzmann Transport for Heavy Quarks

- Valid for high E, assuming particles are on-shell
- Solves the time-ordered evolution for the phase space distribution function

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- The $\mathcal{G}_{inel}$ calculates medium-induced stimulated $1 \rightarrow 2$ emission at LO in $\left(\alpha_s, \frac{\mathrm{M}^2}{\mathrm{Q}^2}\right)$ [see **PRC 94, 054902 (2016)**]

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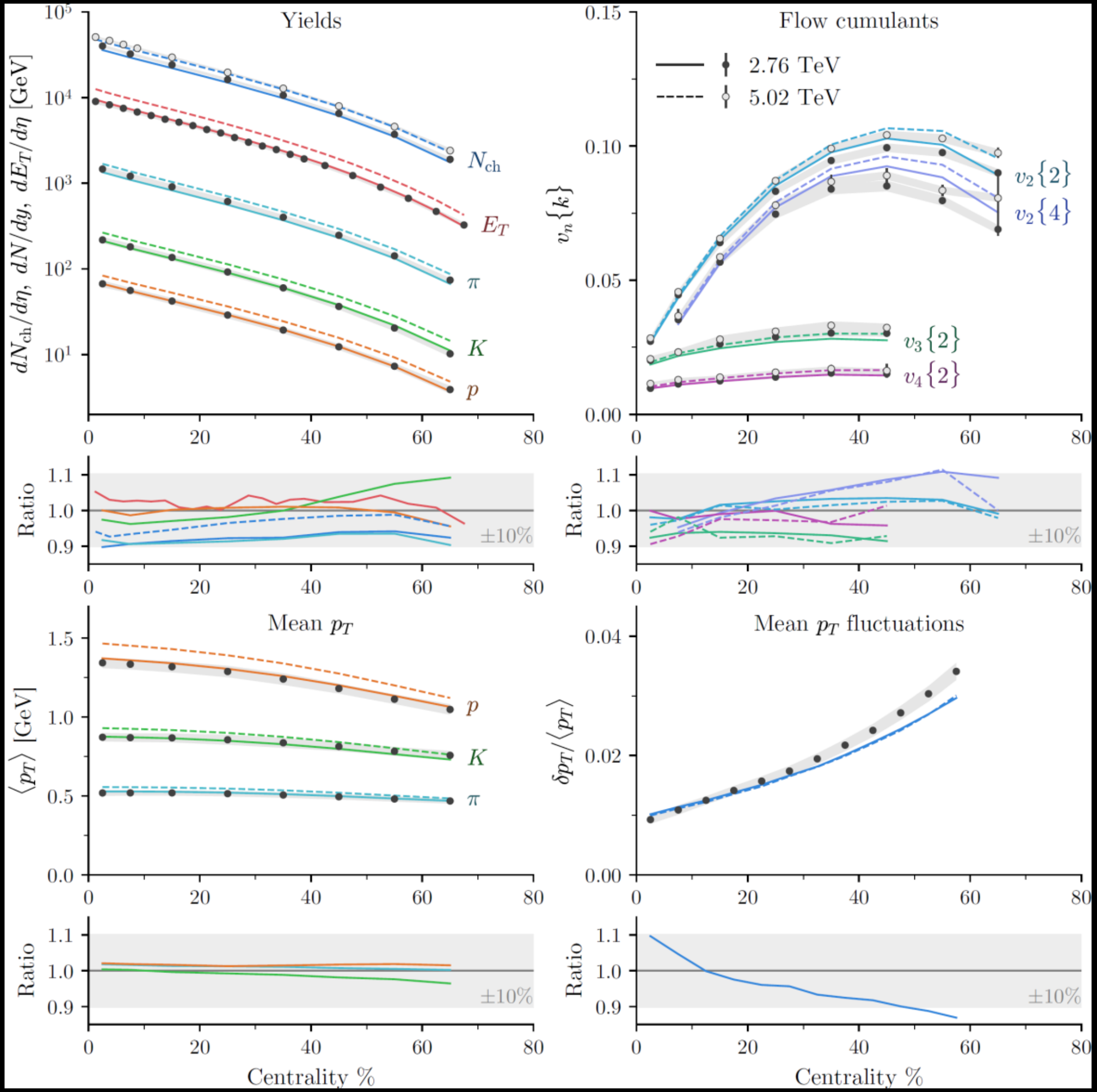
About the QGP medium simulations



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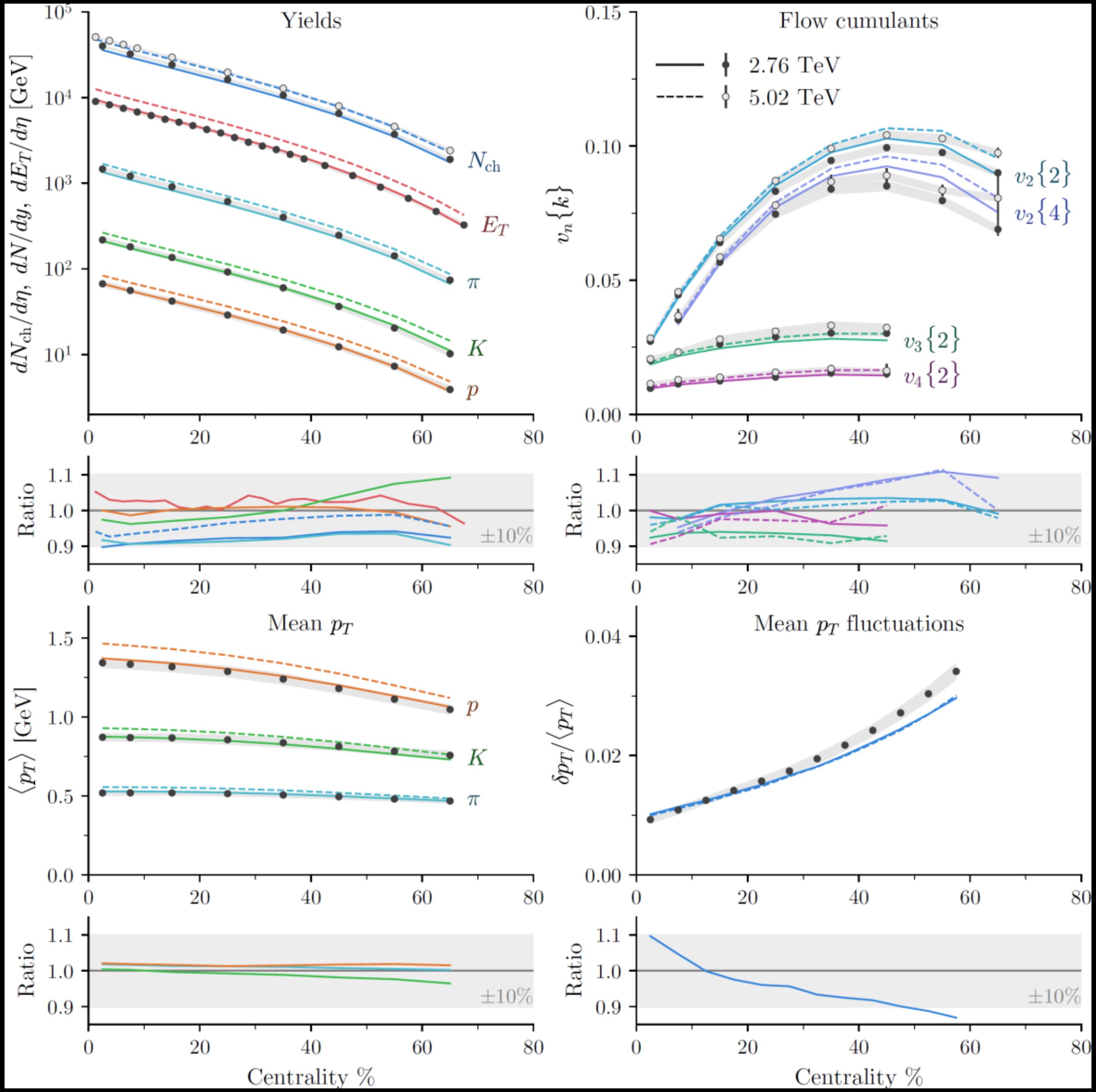

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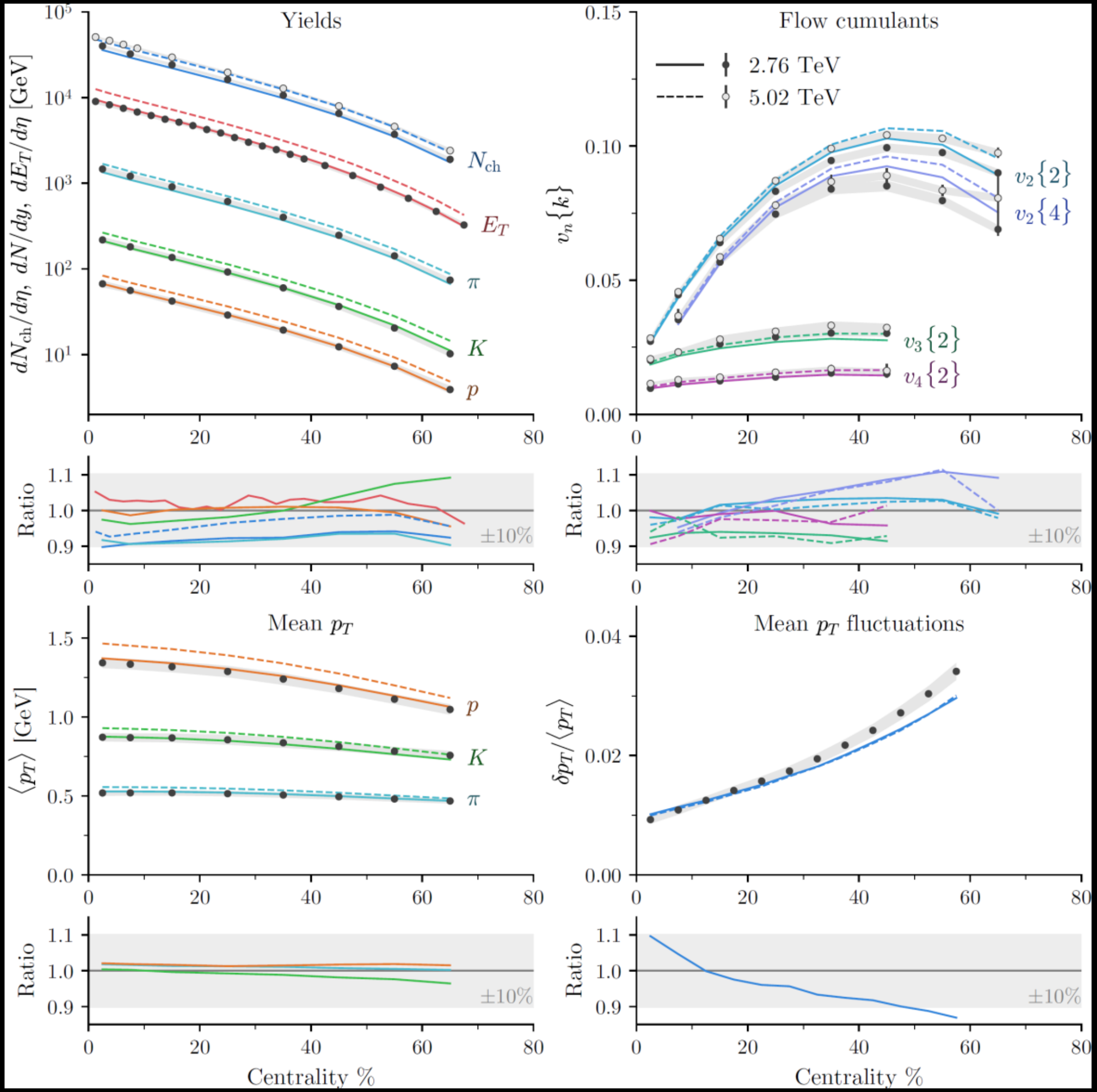

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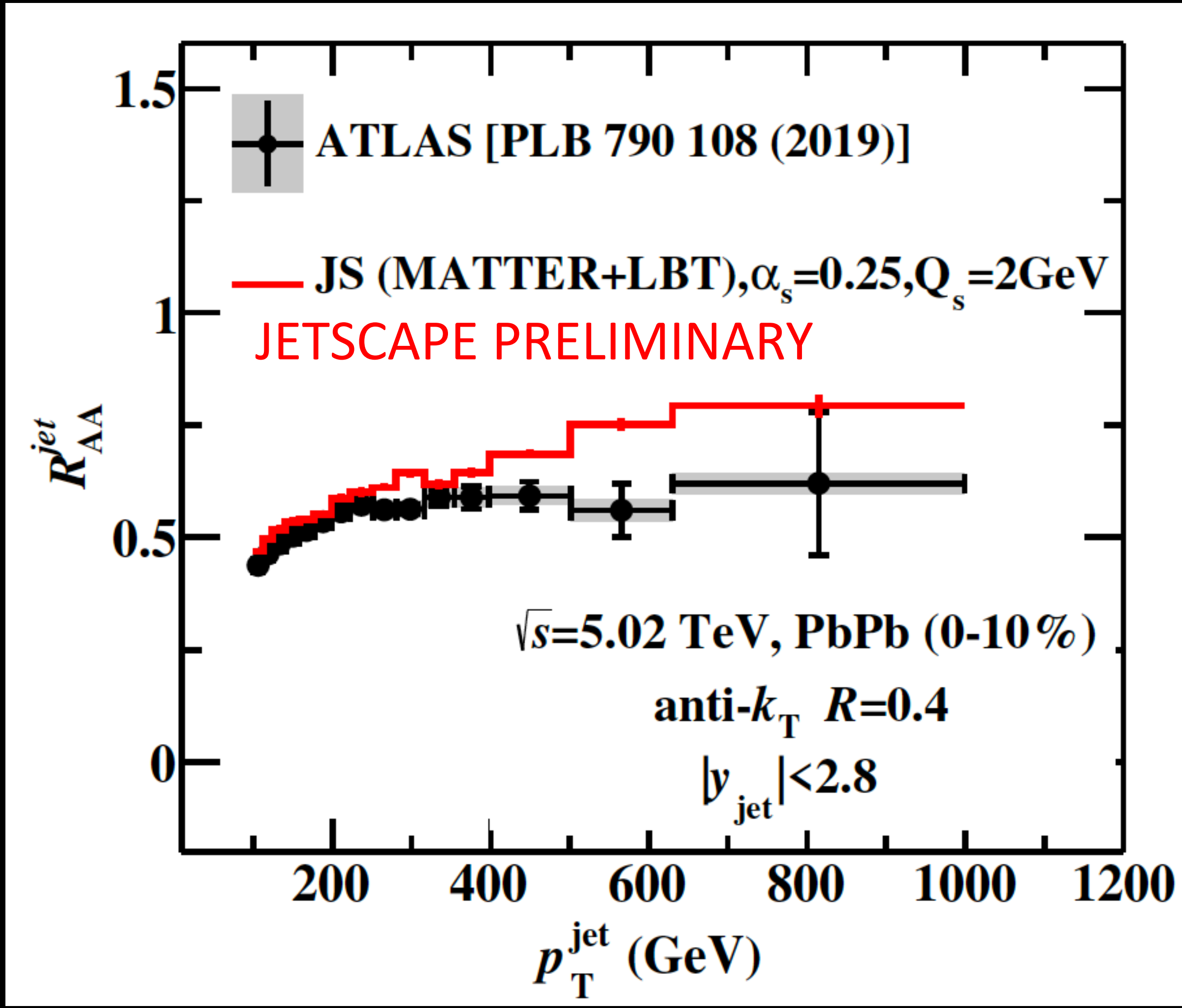
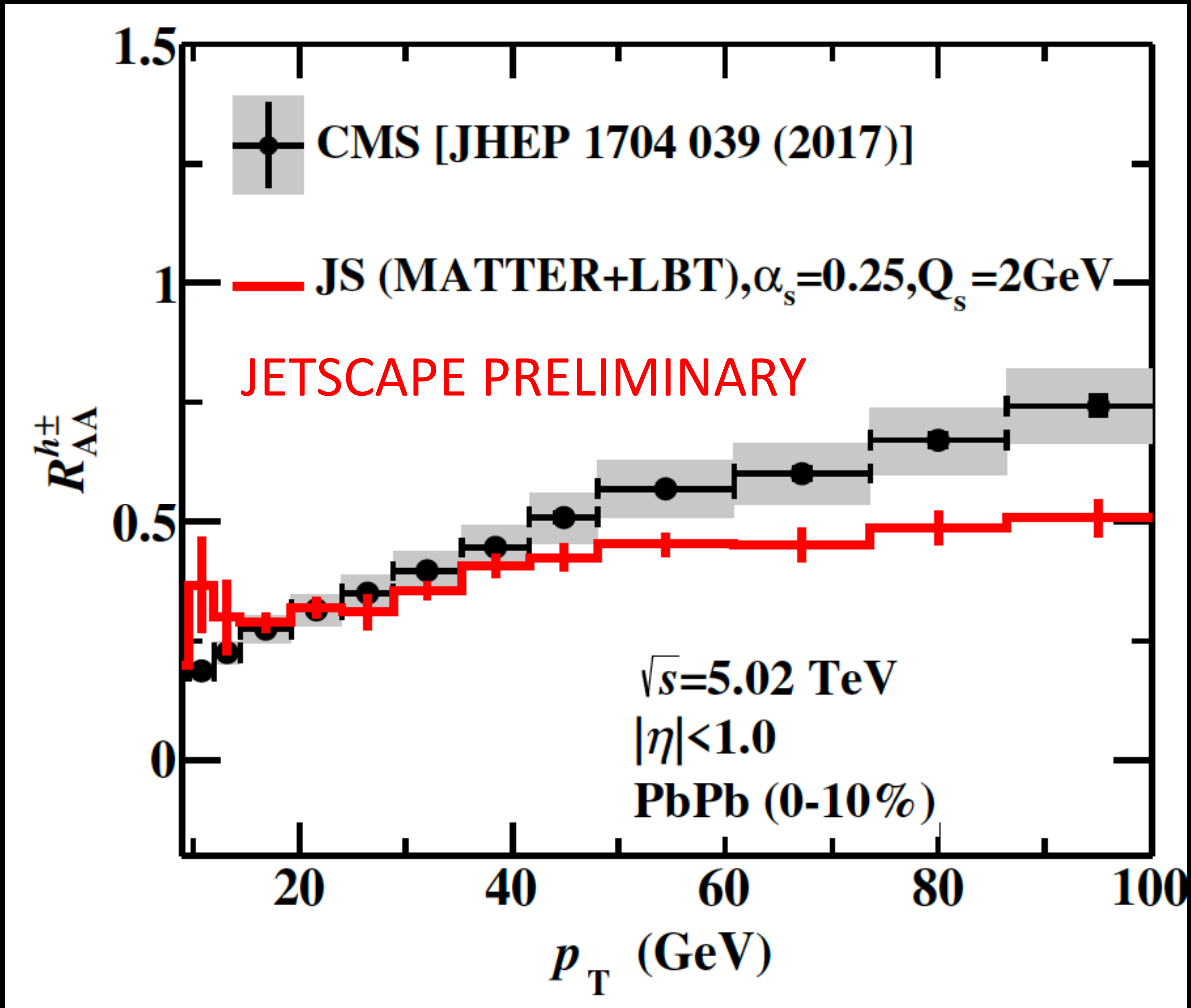
- The same underlying QGP simulation is used to study
  - Light flavor high-p_T hadrons and jets (see talk by **Amit Kumar, Wed**)
  - Jet-medium interactions (see talk by **Yasuki Tachibana, Tue**)
  - Heavy flavor interactions with the QGP (this talk)

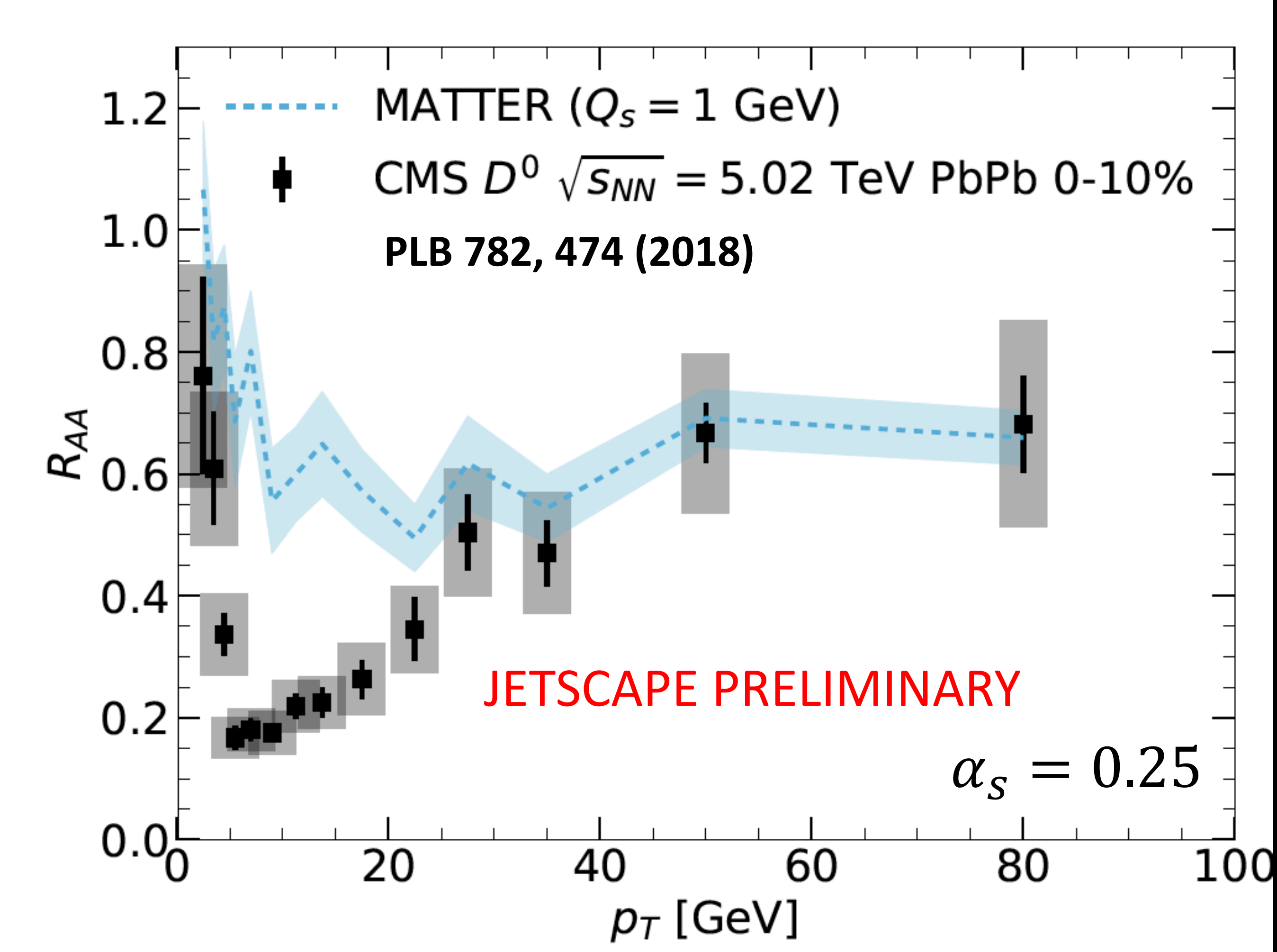
JETSCAPE tune to 0-10% PbPb at $\sqrt{s_{NN}} = 5.02\ TeV$ to data





- Jet and charged hadron R_{AA} used to tune parameters, i.e. $\alpha_s = 0.25$ and $Q_s = 2GeV$ (for more details see talk by **Amit Kumar**)
- No additional tuning was done for D^0 meson R_{AA}

D^0 mesons R_{AA} vs CMS data from PbPb at $\sqrt{s_{NN}} = 5.02\ TeV$



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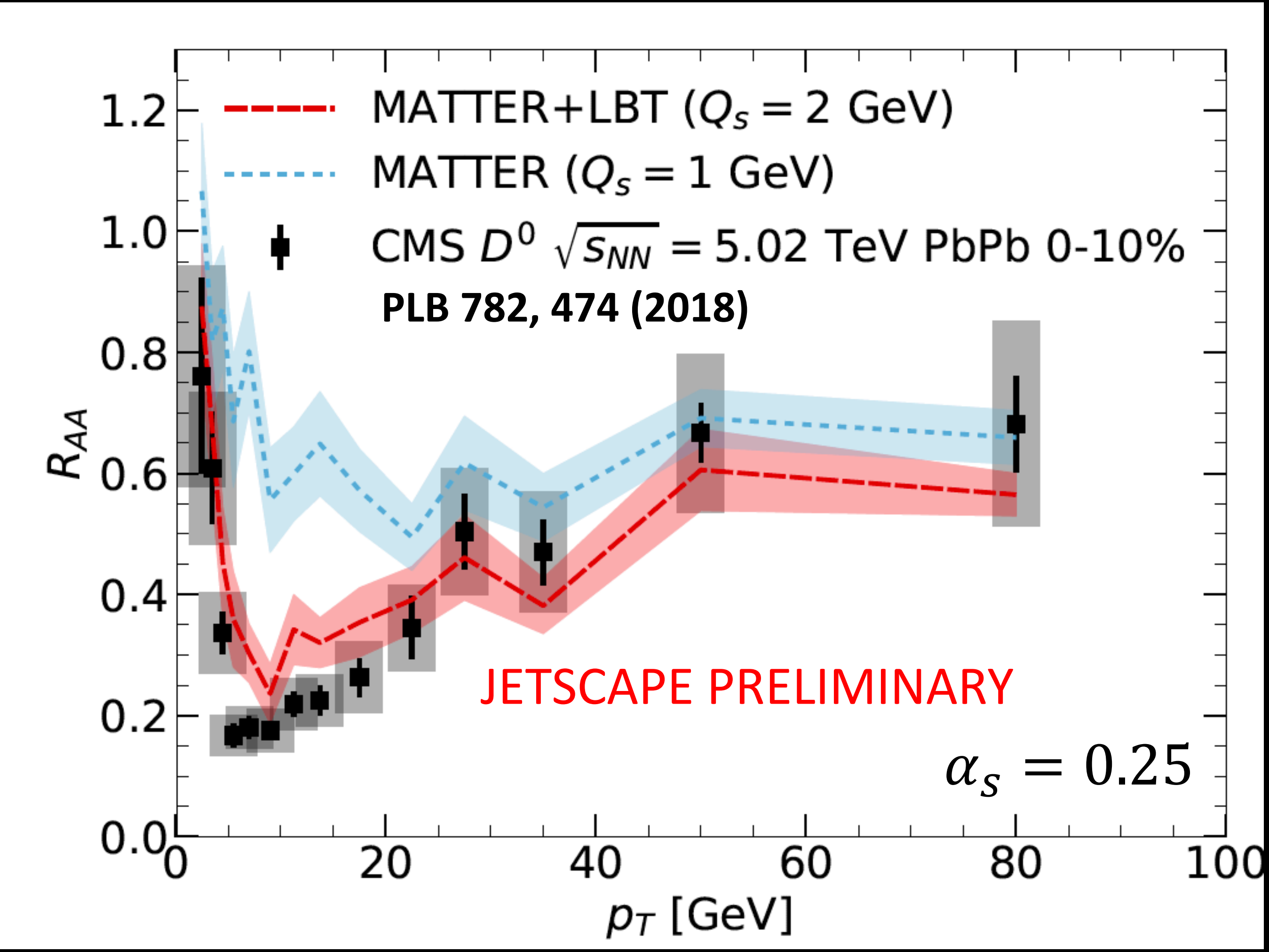

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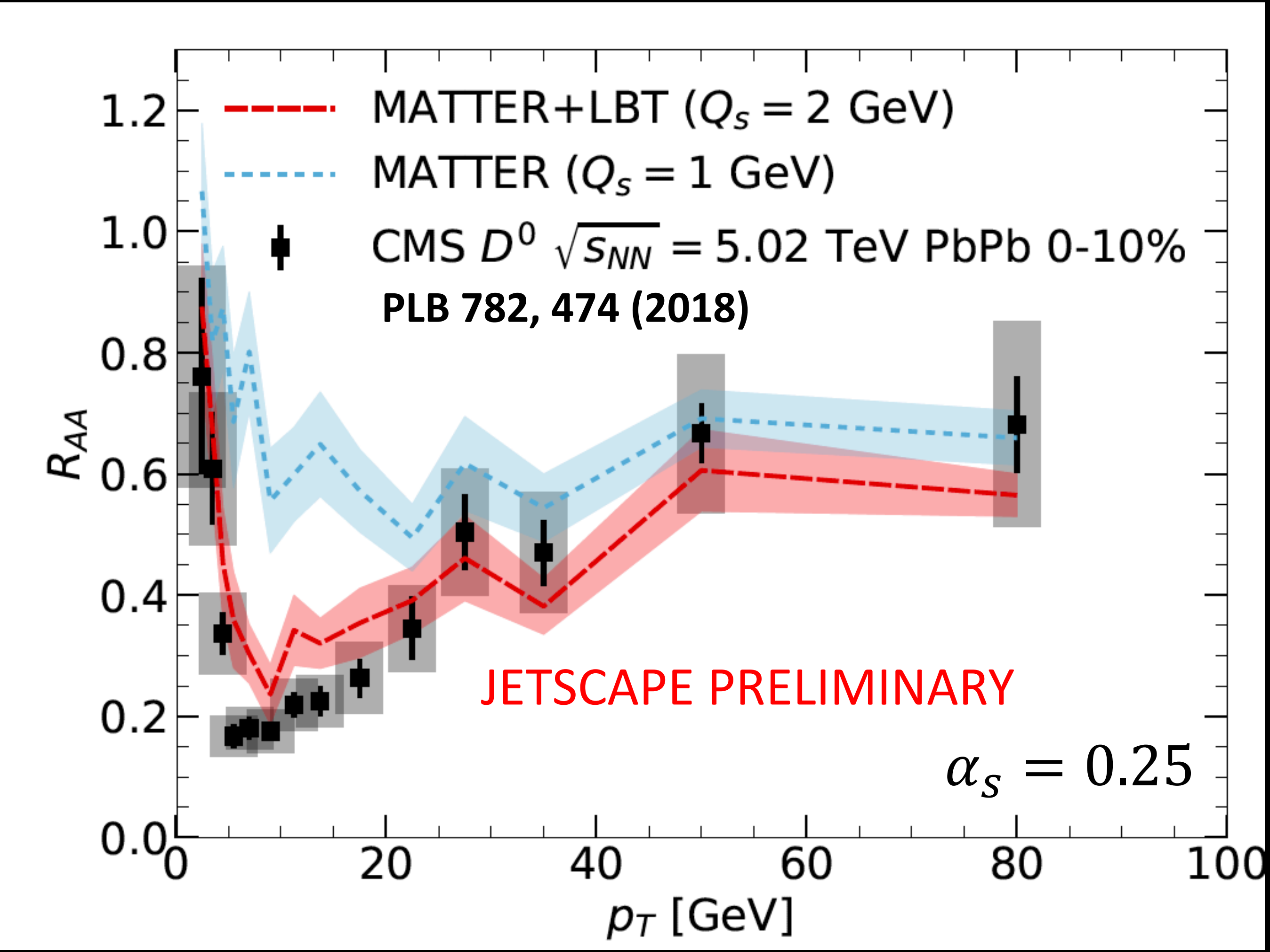

- MATTER alone has few scatterings with the QGP before Pythia hadronization
  $\Rightarrow$ R_{AA} close to 0.5
- MATTER +LBT has many scatterings with the QGP, owing to LBT, before Pythia hadronization
  $\Rightarrow$ R_{AA} can go much closer to 0.1
- Using a multi-scale approach allows to balance the contributions from few vs multiple scattering, and ultimately gives an improved description of R_{AA}

Conclusion and outlook

- A multi-scale formalism, such as that present inside the JETSCAPE framework, allows for an improved description of D^0 energy loss inside QGP, because the effects of multiple vs few scatterings is included.
- Furthermore, JETSCAPE provides a unified framework where these formalisms can be combined, which allows for a simultaneous description of both light and heavy parton energy loss.

- Future studies will explore:
  - Open bottom hadron R_{AA}
  - the effects of additional transport coefficients relevant for heavy flavor production, i.e. longitudinal drag ($\hat{e}$) and diffusion ($\hat{e}_2$) coefficients.