Mass hierarchy of parton energy loss in heavy-ion collisions

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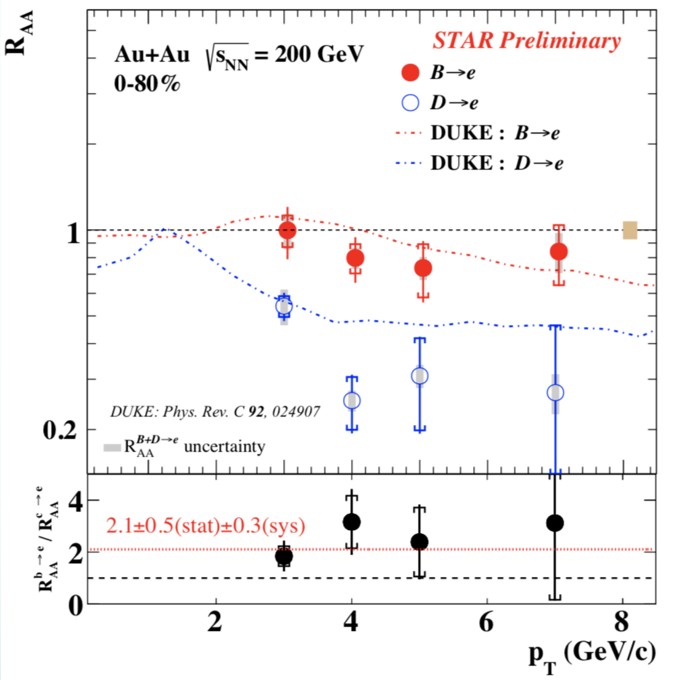
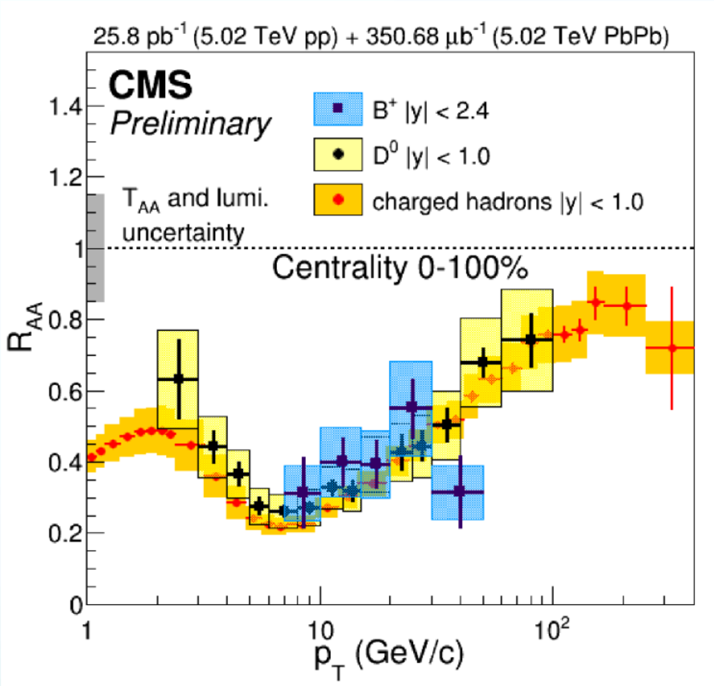
Mass effects in heavy quark energy loss

- Produced early and probe the full QGP history
- Provide unique opportunity to study mass effects on energy loss



R_{AA} (*b->e*) > R_{AA} (*c->e*) at low p_T



Comparable R_{AA} between light hadron, *B* and *D* at high p_T

This motivates a detailed theoretical investigation of the mass hierarchy of parton energy loss, especially its p_T dependence.

Outline

- A linear Boltzmann transport model (LBT) for heavy vs. light parton energy loss in QGP

- A multi-stage approach for heavy quark energy loss

- Effects of jet-induced medium excitation

Part I: A linear Boltzmann transport model

(In collaboration with T. Luo, G.-Y. Qin and X.-N. Wang, PRC 94 and PLB 777)

Boltzmann equation for parton “1” distribution:

$$p_1 \cdot \partial f_1(x_1, p_1) = E_1 C\left[f_1\right]$$

The collision term:

transition rate from p_1 to p_1-k

$$C\left[f_1\right] \equiv \int d^3k \left[w(\vec{p}_1 + \vec{k}, \vec{k}) f_1(\vec{p}_1 + \vec{k}) - w(\vec{p}_1, \vec{k}) f_1(\vec{p}_1)\right]$$

Elastic scattering (2->2 process)

$$w(\vec{p}_1, \vec{k}) \equiv \sum_{2,3,4} w_{12\to 34}(\vec{p}_1, \vec{k})$$

$$w_{12\to 34}(\vec{p}_1, \vec{k}) = \gamma_2 \int \frac{d^3p_2}{(2\pi)^3} f_2(\vec{p}_2) \left[1 \pm f_3(\vec{p}_1 - \vec{k})\right] \left[1 \pm f_4(\vec{p}_2 + \vec{k})\right] \times v_{\rm rel} d\sigma_{12\to 34}(\vec{p}_1, \vec{p}_2 \to \vec{p}_1 - \vec{k}, \vec{p}_2 + \vec{k})$$

microscopic cross section of 12->34

Inelastic scattering (2->2+n process)

Inelastic scattering rate (average gluon number per Δt):

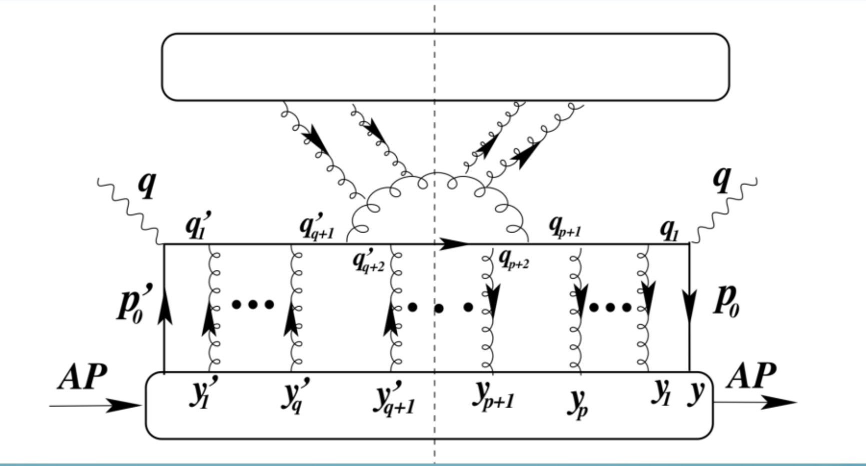
$$\Gamma^{\rm inel} = \langle N_g \rangle (E, T, t, \Delta t)/\Delta t = \int dx dk_\perp^2 \frac{dN_g}{dx dk_\perp^2 dt}$$

Medium-induced gluon spectrum

$$\frac{dN_g}{dx dk_\perp^2 dt} = \frac{2\alpha_s C_A P(x)}{\pi k_\perp^4} \hat{q} \left(\frac{k_\perp^2}{k_\perp^2 + x^2 M^2} \right)^4 \sin^2 \left(\frac{t - t_i}{2\tau_f} \right)$$

[Guo and Wang (2000), Majumder (2012); Zhang, Wang and Wang (2004)]

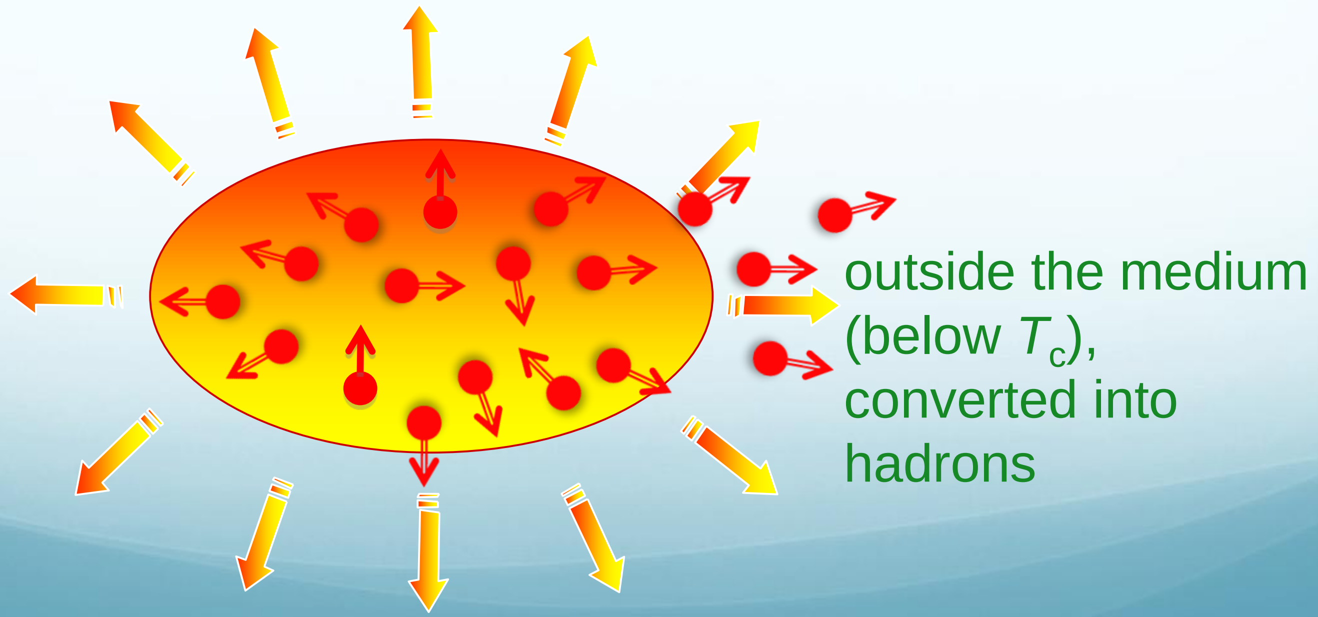
$\hat{q}$: $dp_\perp^2/dt$ of quark/gluon due to 2->2 scatterings



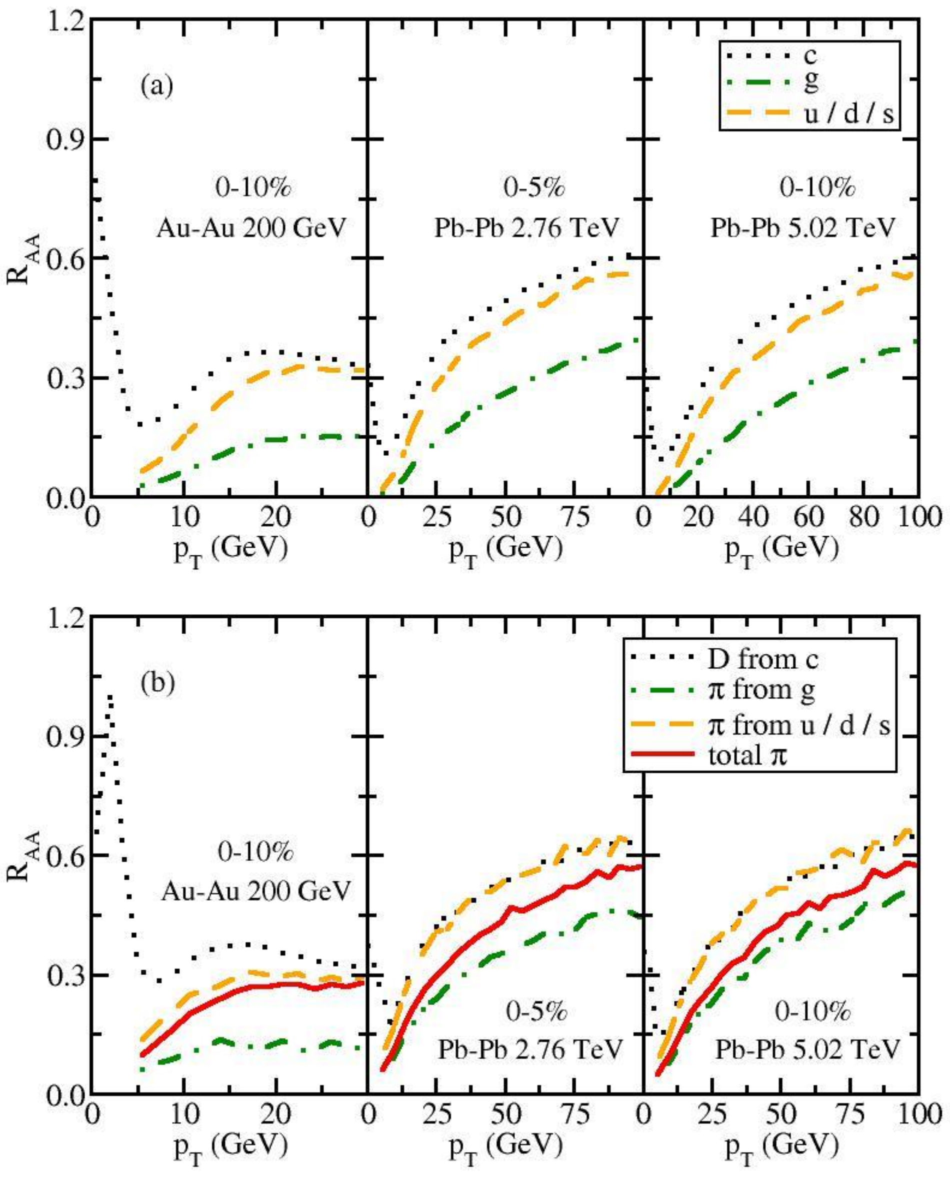
Framework overview

(Parton evolution inside the QGP)

- Generation of QGP medium: hydrodynamic model
- Initialization of hard partons: MC-Glauber for position space and pQCD calculation for momentum space (PDF: CTEQ5+EPS09)
- Simulation of parton evolution: the Boltzmann transport model in the local rest frame of the medium
- Hadronization: fragmentation + recombination model

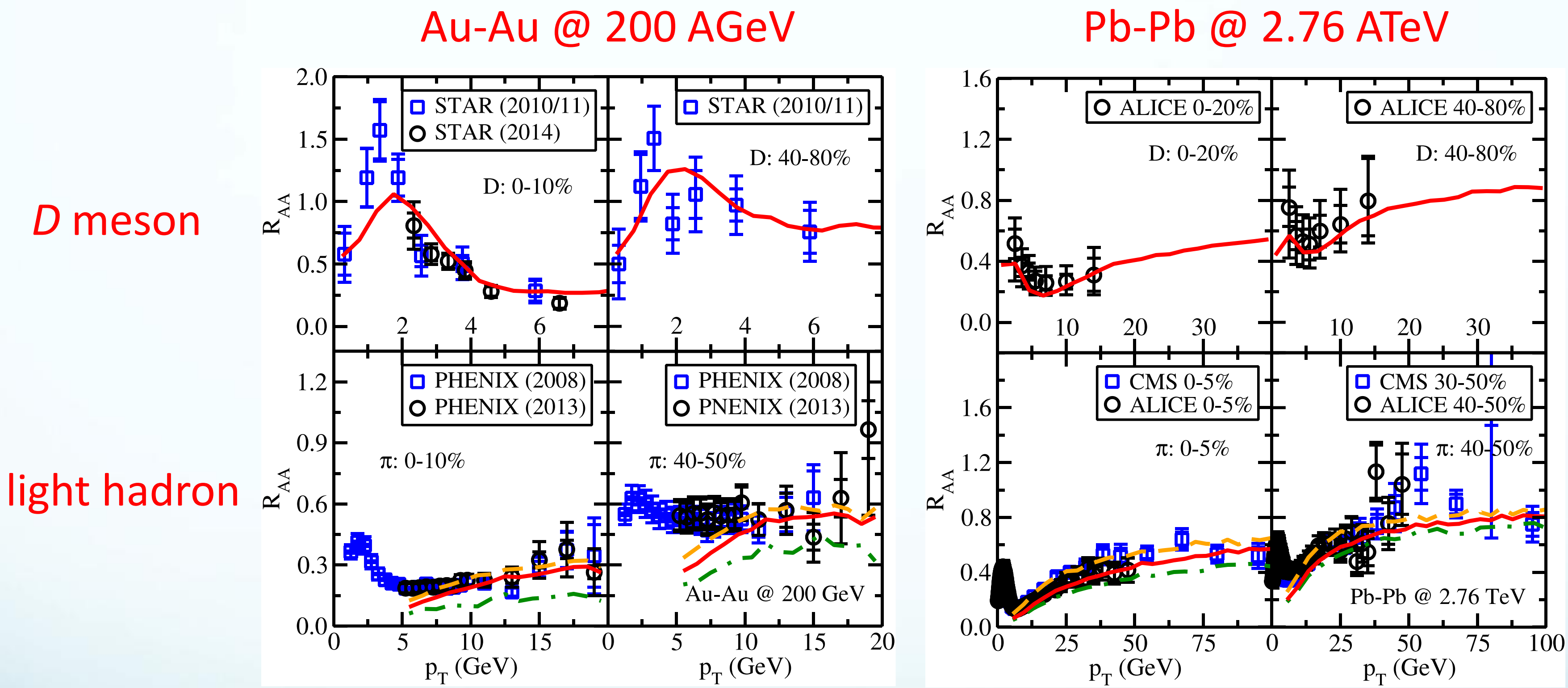


Heavy vs. light hadron suppression



- *u*/*d*/*s* are slightly more suppressed than *c* quark, *g* is significantly more suppressed
- Due to different fragmentation function, *π* from light quark has similar R_{AA} *to D, π* from gluon is still more suppressed

Simultaneous description of *D* and light hadron R_{AA}



- LBT treats heavy and light parton evolution on the same footing and simultaneously describes R_{AA} of *D* and light flavor hadrons.
- Predictions for the Xe-Xe collisions: Poster by G.-Y. Qin

Part II: Effects of multi-stage evolution

(In collaboration with G.-Y. Qin, C. Shen and A. Majumder, arXiv:1711.09053)

Particles in current transport models are usually on-shell

$$p^2 - m^2 = E^2 - \vec{p}^2 - m^2 = 0$$

Quantum fluctuation allows particles to be off-shell (virtual)

$$Q^2 = p^2 - m^2 \neq 0$$

within a finite splitting time

$$\tau_f \sim \gamma \frac{1}{Q} \sim \frac{E}{Q^2}$$

Partons produced in energetic collisions usually start with high *Q* and then evolve back to shell after several splittings

Parton evolution at high *Q* is usually treated by vacuum showers (Pythia) in transport without considering medium modification

Develop a combined approach that includes medium modification in different stages

A multi-stage approach

Stage 1 (Q>>M_{HM}) – rare scattering multiple emission

- HQ fragmentation function is treated with DGLAP equation

$$\frac{\partial}{\partial Q^2} D\left(z, E, Q^2\right) = \frac{\alpha_s}{2\pi}\frac{1}{Q^2}\int_z^1 \frac{dy}{y} P(y) D\left(\frac{z}{y}, E, Q^2\right)$$

- Splitting function:

$$P(y) = P_{\rm vac}(y) + P_{\rm med}(y)$$

$$P_{\rm med}(y, k_\perp^2) = \frac{2C_A\alpha_s}{\pi k_\perp^4} P_{\rm vac}(y) \int_{t_i}^{t_{\max}} dt\, \hat{q}(t) \sin^2\left(\frac{t-t_i}{2\tau_f}\right)$$

[HT: Guo and Wang (2000), Majumder (2012)]

- Input fragmentation function $D\left(z, E, Q_0^2\right)$

Extracted from transport model (in stage 2) – medium-modified fragmentation function at Q_0 ~ M_{HM}

A multi-stage approach

Stage 2 ($Q \sim M_{HM}$) – single scattering induced emission

- Transport model (elastic + inelastic processes)

Inelastic scattering rate

$$\Gamma_{\rm rad}(\zeta^-) = \int dy \int dl_\perp^2 \frac{dN}{dy dl_\perp^2 d\zeta^-}$$

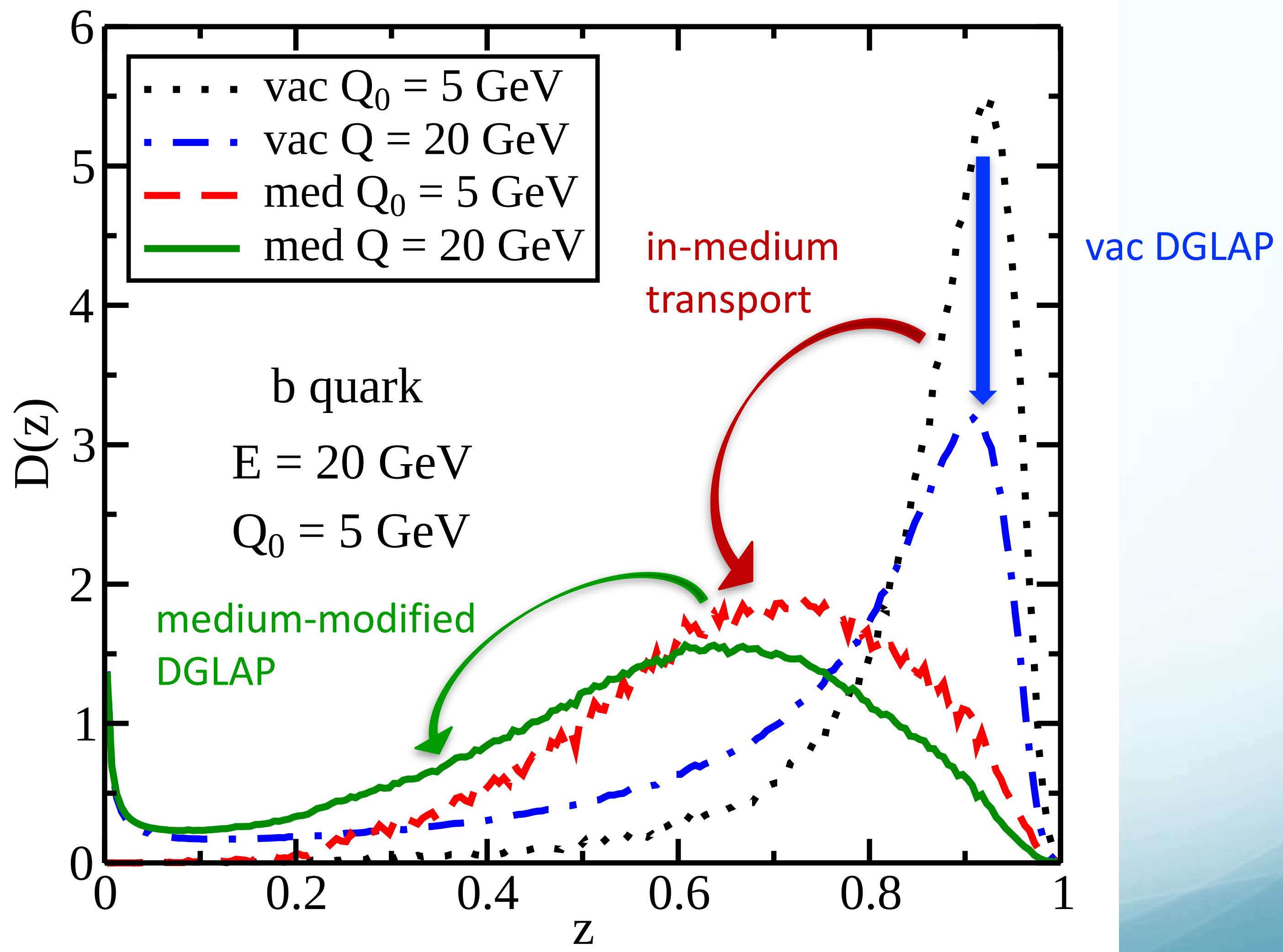
- Medium-induced gluon spectra (contribution from *longitudinal* drag and diffusion to *slowly moving heavy quark*)

$$\frac{dN}{dy dl_\perp^2 d\zeta^-} = \frac{2C_F\alpha_S}{2\pi} \frac{P(y)}{\left(l_\perp^2 + y^2M^2\right)^2} 2\sin^2\left(\frac{l_\perp^2 + y^2M^2}{4l^- y(1-y)}\zeta^-\right) \times \left[\hat{q}\left\{1 - \frac{y}{2} - \frac{y^2M^2}{l_\perp^2}\right\} + \hat{e}\frac{y^2M^2}{l^-} + \hat{e}_2\frac{y^2M^2}{2(l^-)^2}\right].$$

Abir, Kaur, Majumder, PRD 90 (2014) 114026
Abir, Majumder, PRC 94 (2016) 054902

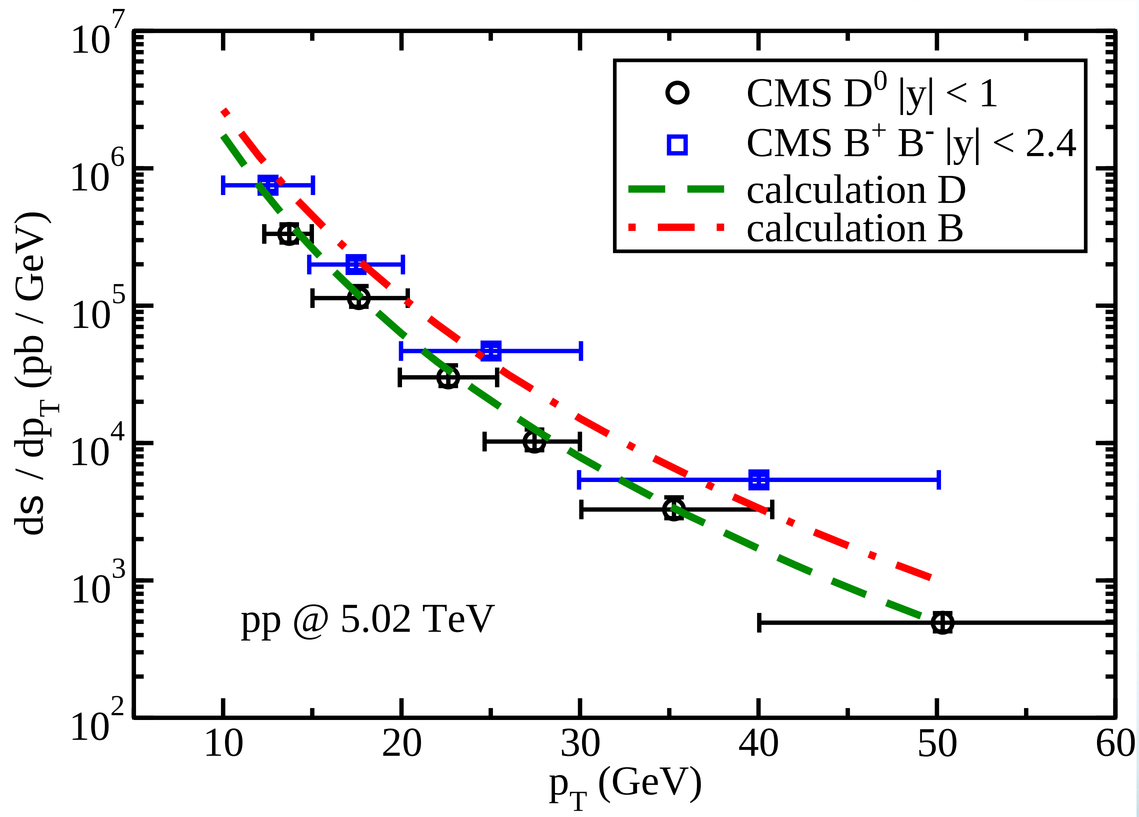
- Assume Einstein relation: $\hat{e} = \hat{e}_2/(2T), \quad \hat{q} = 2\hat{e}_2$
- Extract medium-modified $D\left(z, E, Q_0^2\right)$ for DGLAP in stage 1

Evolution of *b*-quark fragmentation function



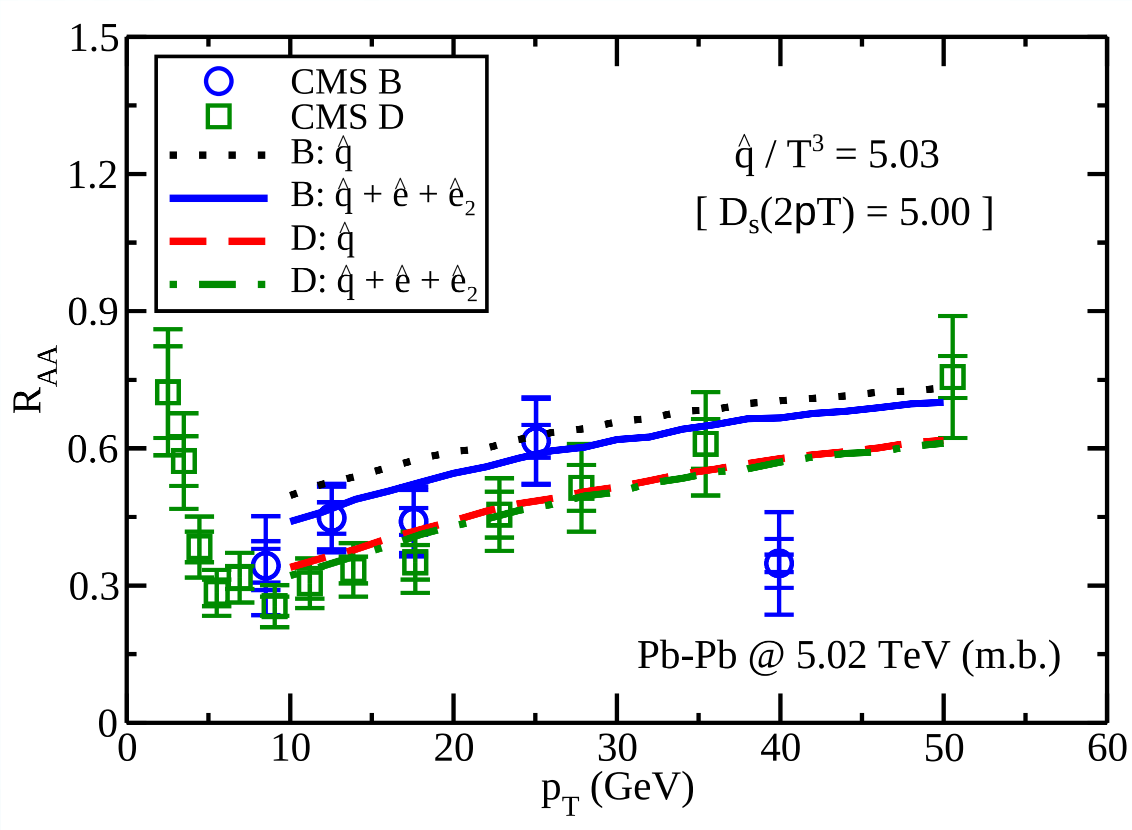
Heavy meson spectra

- Convolute vacuum/medium-modified fragmentation function with *c*/*b* initial spectra



- Vacuum fragmentation function -> *D*/*B* spectra consistent with p-p data

Nuclear modification of heavy mesons



Contributions from $\hat{e}$ and $\hat{e}_2$ terms

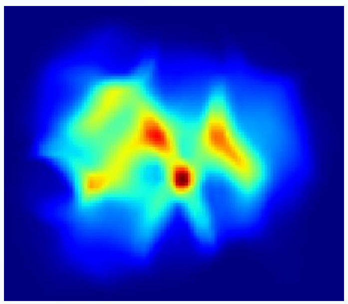
- More important to *b*-quark than *c*-quark (mass hierarchy)
- Non-negligible at low p_T but diminish at large p_T
- Decrease *B* meson R_{AA} and narrow the difference between *D* and *B*

Part III: Effects of jet-induced medium excitation

(In collaboration with Y. Tachibana, in progress)

- "Linear" Boltzmann: only consider medium modification of jet
- Jet-medium interaction also includes modification of the medium

Medium background

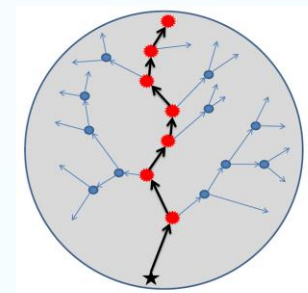


$(T,\, u^\nu)$ $\quad \frac{1}{p.u} p^\mu \partial_\mu f = C$

(j^ν) $\quad \partial_\mu T^{\mu\nu} = j^\nu$

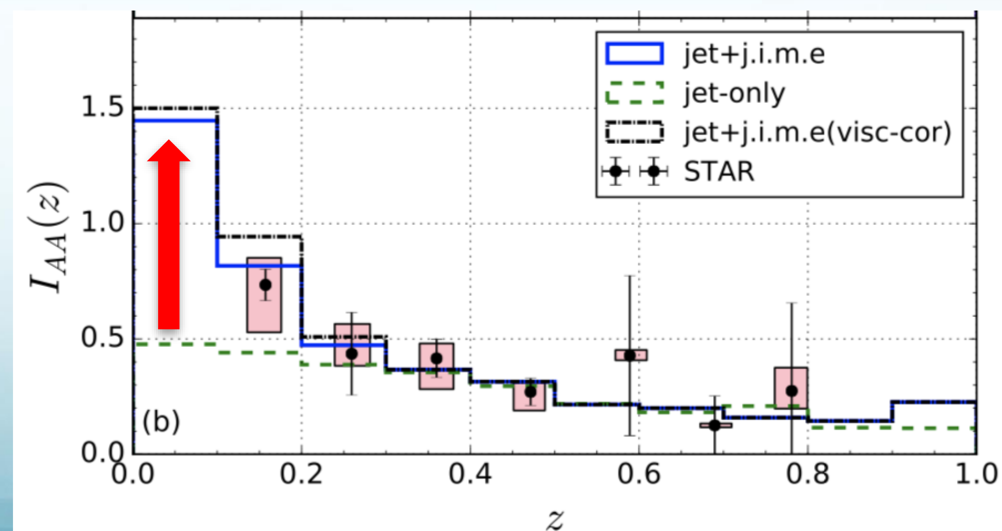
energy-momentum deposition

Hard parton



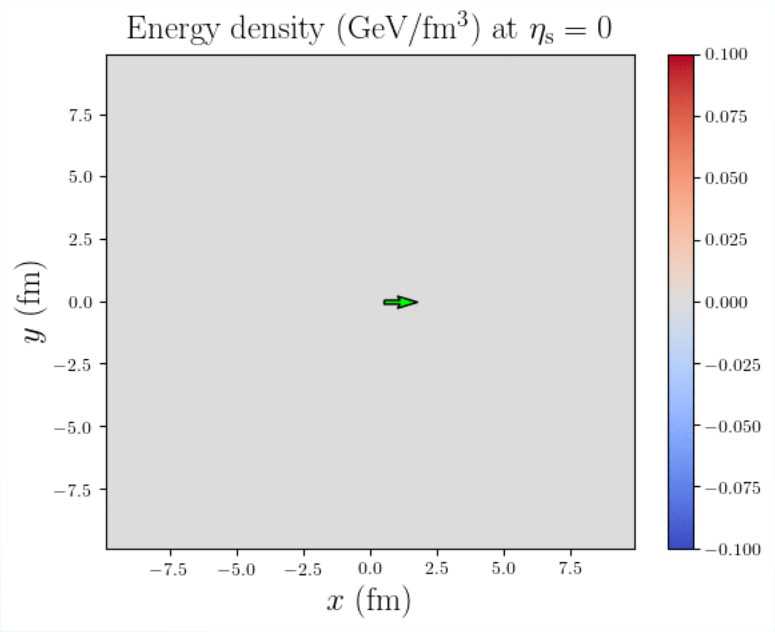
- Important effects in jet observables

  e.g. enhancement of soft hadron production in γ-jet [W. Chen, S. Cao, T. Luo, L.-G. Pang, X.-N Wang, PLB 777 (2018) 86-90]

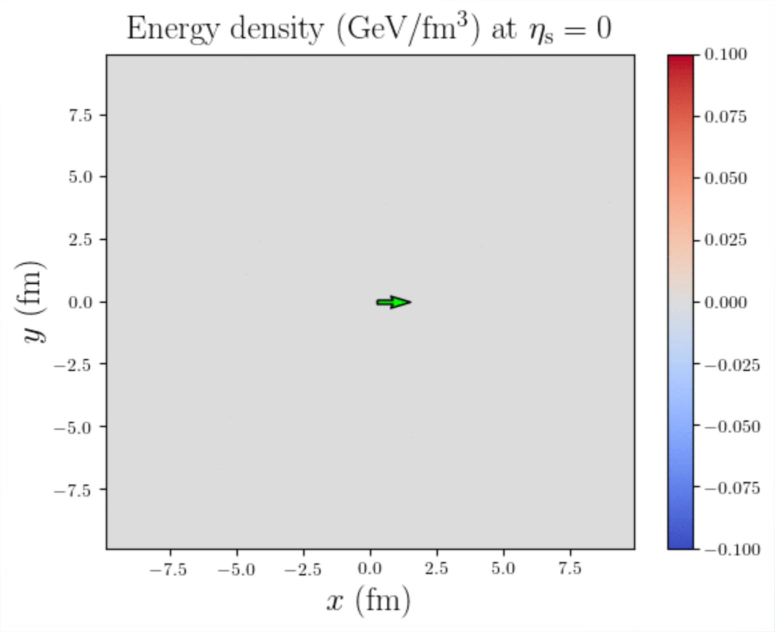


Energy deposition of heavy quarks into QGP

p = 2 GeV c-quark (E = 2.4 GeV)



p = 2 GeV b-quark (E = 4.7 GeV)



- Energy deposition from a slowly moving heavy quark can travel faster than the heavy quark affects its own subsequent motion

Summary

- Discussed the mass/flavor hierarchy of parton energy loss from different perspectives
- Presented a linear Boltzmann transport model (LBT) that treats heavy and light parton evolution on the same footing and simultaneously describes the nuclear modification of charm and light hadrons
- Introduced a multi-stage approach of heavy quark energy loss that further narrows down the difference between *D* and *B* meson R_{AA}
- Discussed possible mass/velocity dependences of medium response to heavy quark energy loss

Thankyou!

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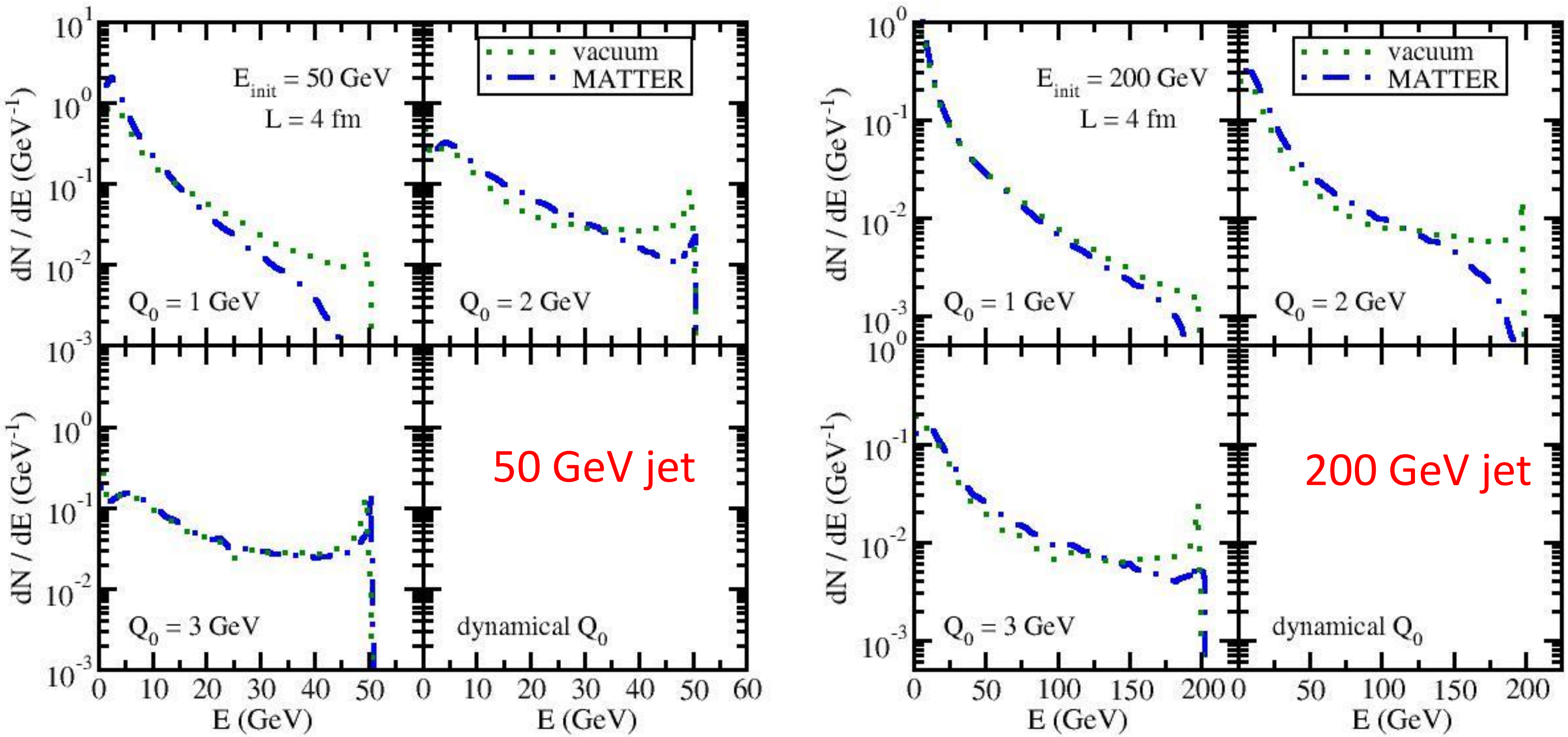
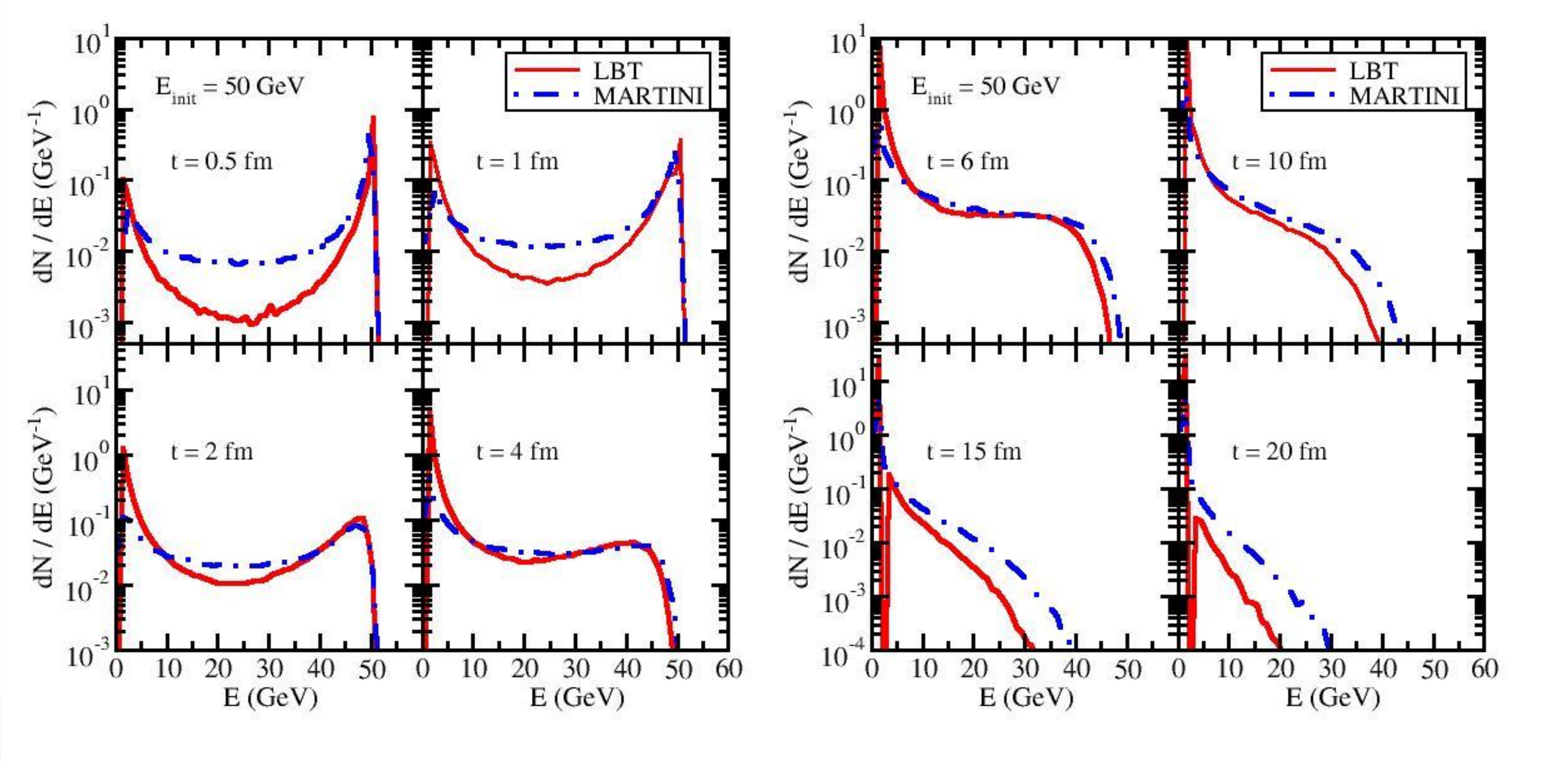
MATTER vs. vacuum shower



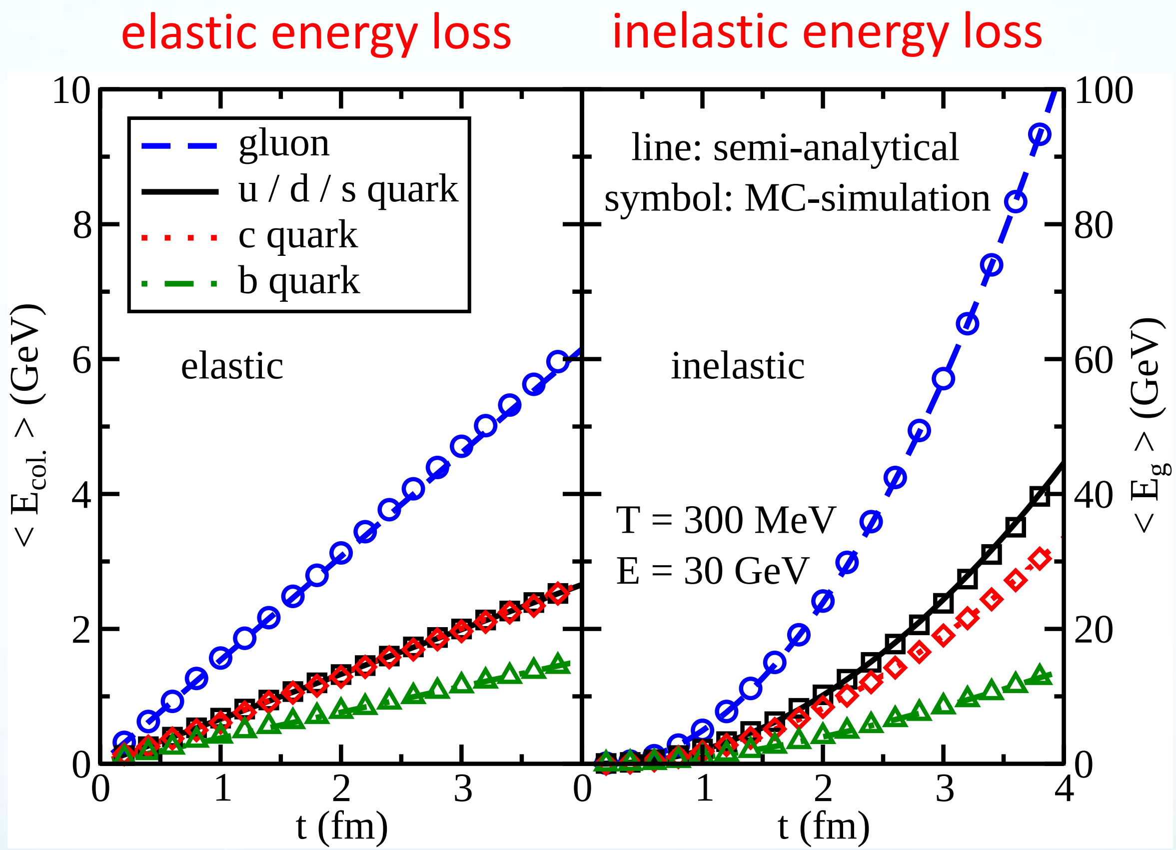
- Energy loss in MATTER is stronger when Q_0 is smaller
- Energy loss in MATTER disappears when $Q_0^2 > \hat{q}\tau_f$ (medium scale).
- $\hat{q}\tau_f$ increases with the jet energy; MATTER evolution is more important to high energy partons than to low energy ones

LBT vs. MARTINI at different times



- Parton energy loss in LBT (HT) is weaker than in MARTINI (AMY) at early *t*, but catches up and becomes stronger when *t* is large
- At *t* around the QGP lifetime, LBT and MARTINI are indistinguishable
- Need to explore observables beyond R_{AA} to distinguish them

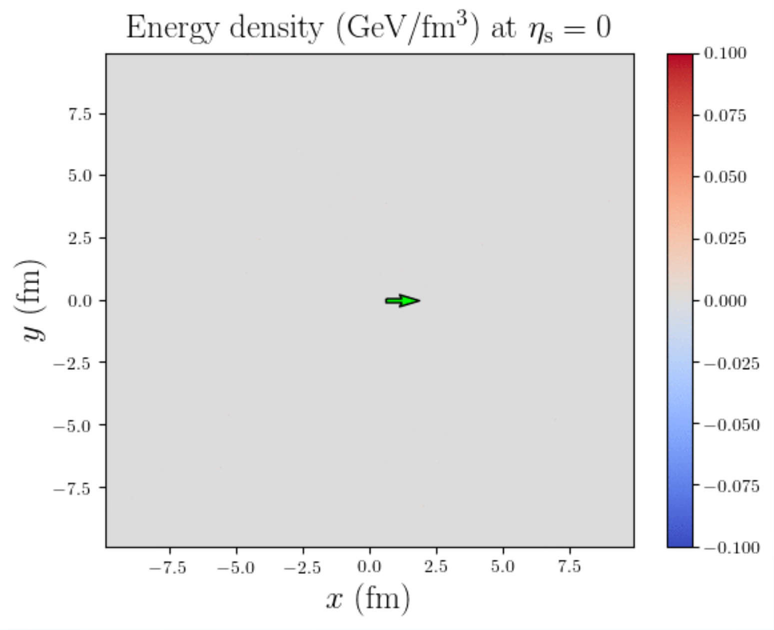
Flavor hierarchy of parton energy loss



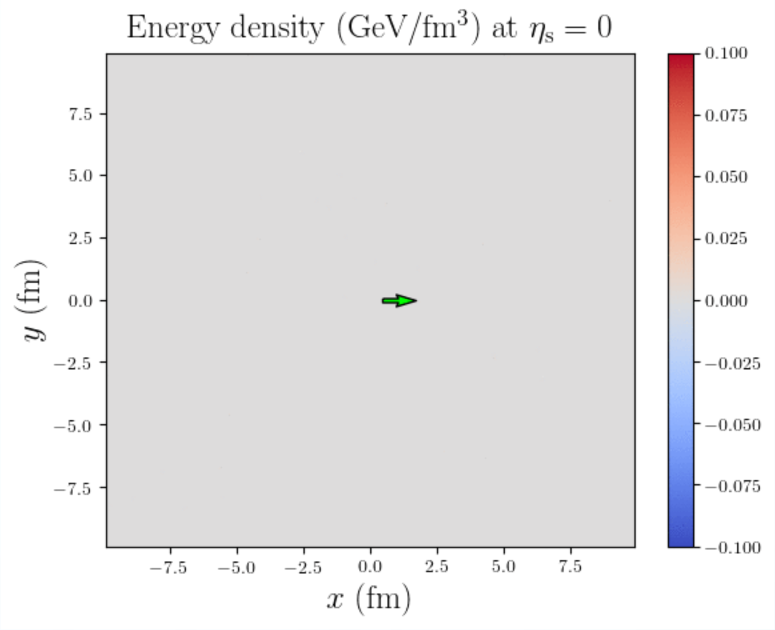
- Consistency between semi-analytical calculation and MC simulation with the assumption of fixed medium *T* and fixed parton *E*
- Clear flavor hierarchy within transport model: $\Delta E_g > \Delta E_q > \Delta E_c > \Delta E_b$

Energy deposition of heavy quarks into QGP

5 GeV charm quark



5 GeV beauty quark



Elastic vs. Inelastic Energy Loss

Divide scattering probability of jet parton into two regions:

1. Pure elastic scattering without radiated gluons: $P_{\rm el}(1-P_{\rm inel})$
2. Inelastic scattering: $P_{\rm inel}$

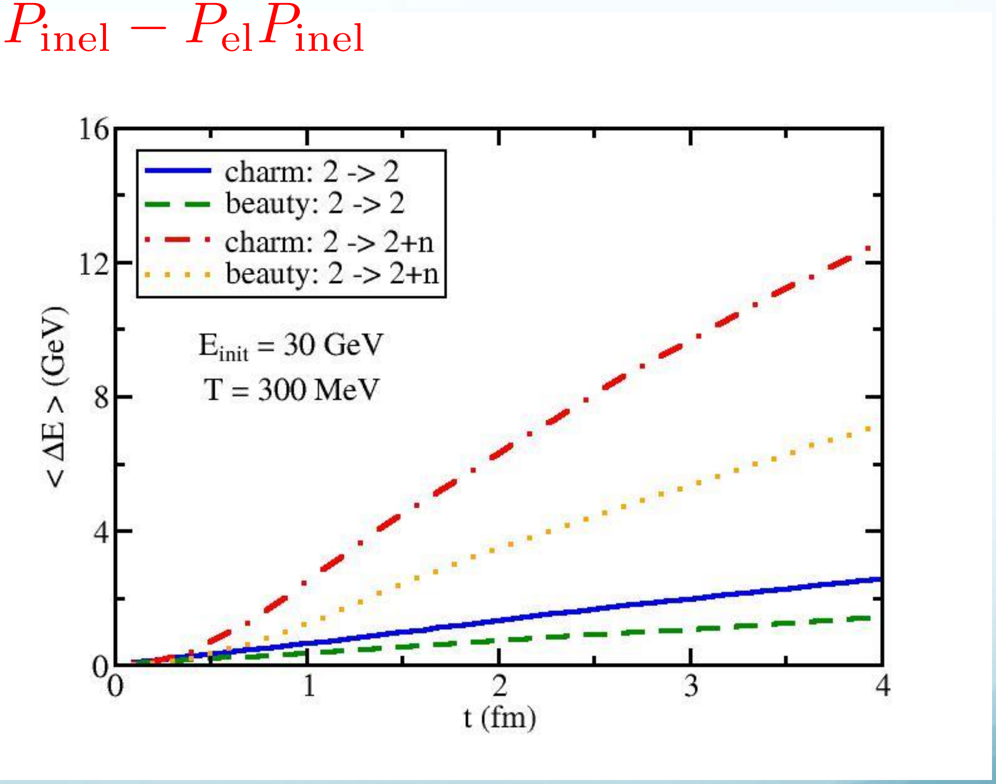
Total probability: $P_{\rm tot}=P_{\rm el}+P_{\rm inel}-P_{\rm el}P_{\rm inel}$

In model calculation:

1.Use $P_{\rm tot}$ to determine whether the jet parton scatter with the thermal medium

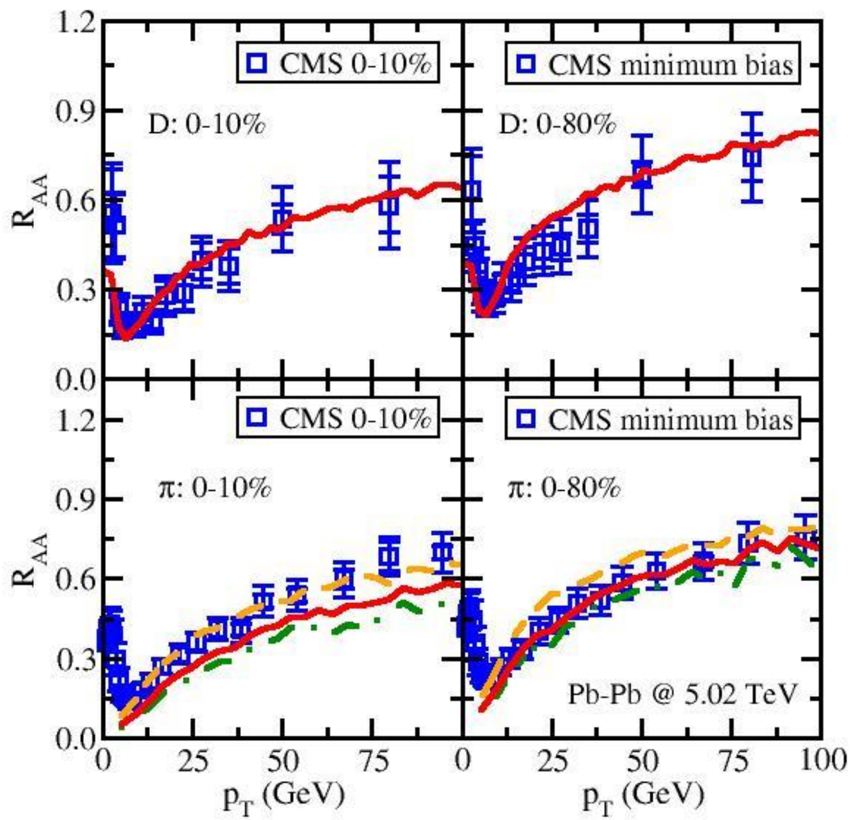
2.If so, we then determine whether this scattering is pure elastic or inelastic

3.Simulate the 2->2 or 2->2+n process



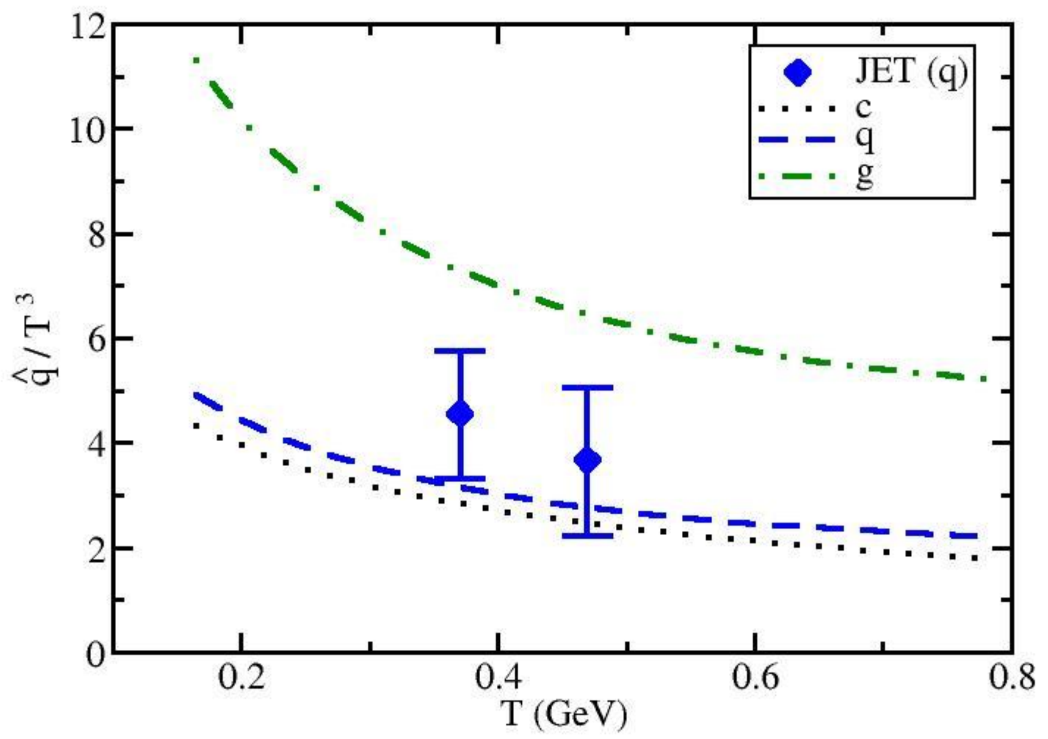
HQ energy loss due to elastic and inelastic processes are comparable at early time, but is dominated by the inelastic process at large *t*.

Simultaneous Description of *D* and *π* R_{AA} in 5.02 TeV Pb-Pb Collisions



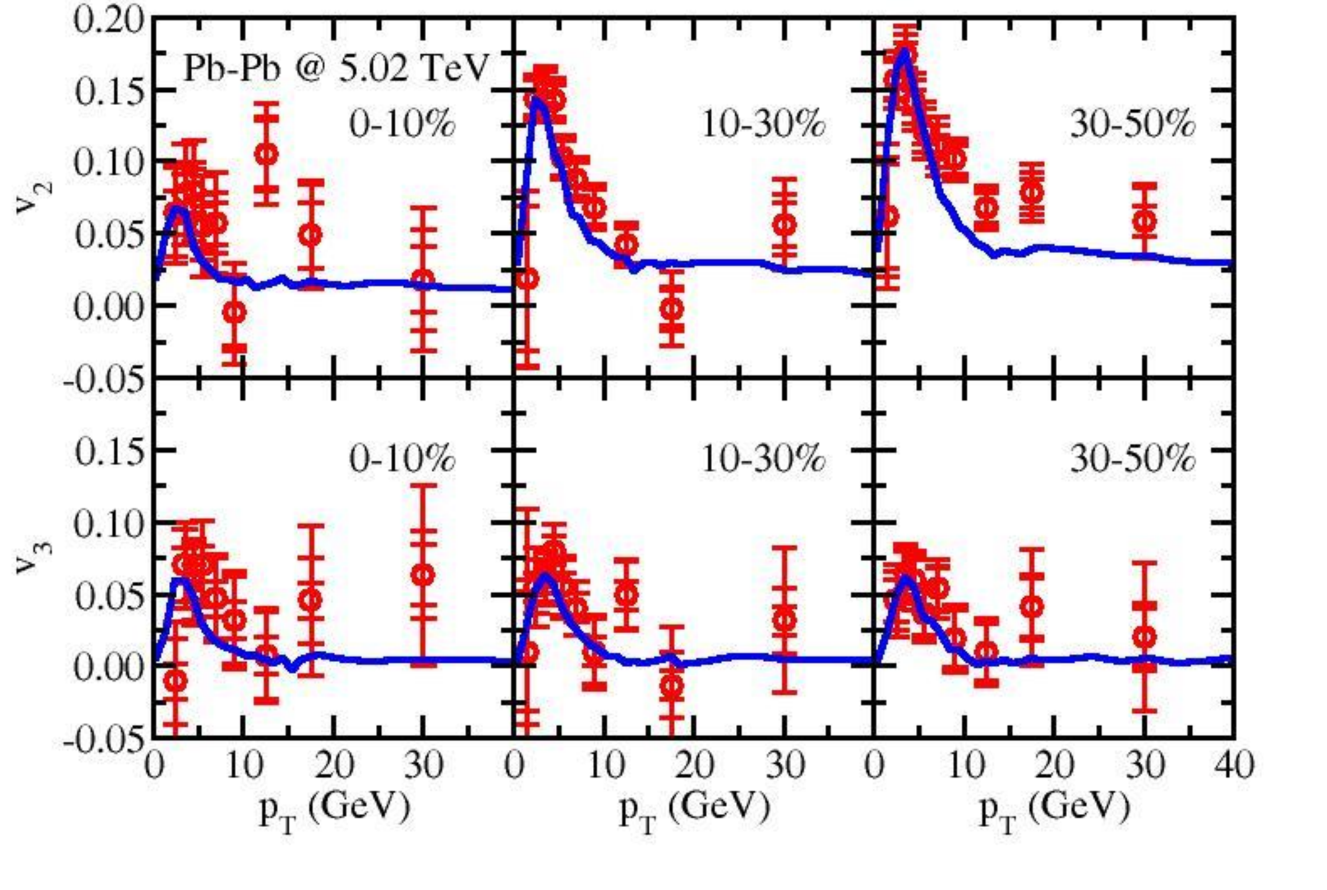
With a delicate treatment of heavy and light parton in-medium evolution and their hadronization, one may provide reasonable description of heavy and light hadron suppression simultaneously.

Quark and Gluon Transport Coefficient: *q*



The extracted $\hat{q}$ from model to data comparison within our LBT framework is consistent with the value constrained by the earlier work by the JET Collaboration [Phys. Rev. C90, 014909 (2014)].

Anisotropic Flow (v_2 and v_3) of *D* Mesons



- Predictions of v_2 and v_3 are consistent with CMS data at 5.02 TeV.
- Strong v_2 is observed for the full p_T range.
- Strong v_3 is observed at low p_T, but it is consistent with 0 at high p_T.