Charge Enhancement of Parton Showers in QCD Plasmas

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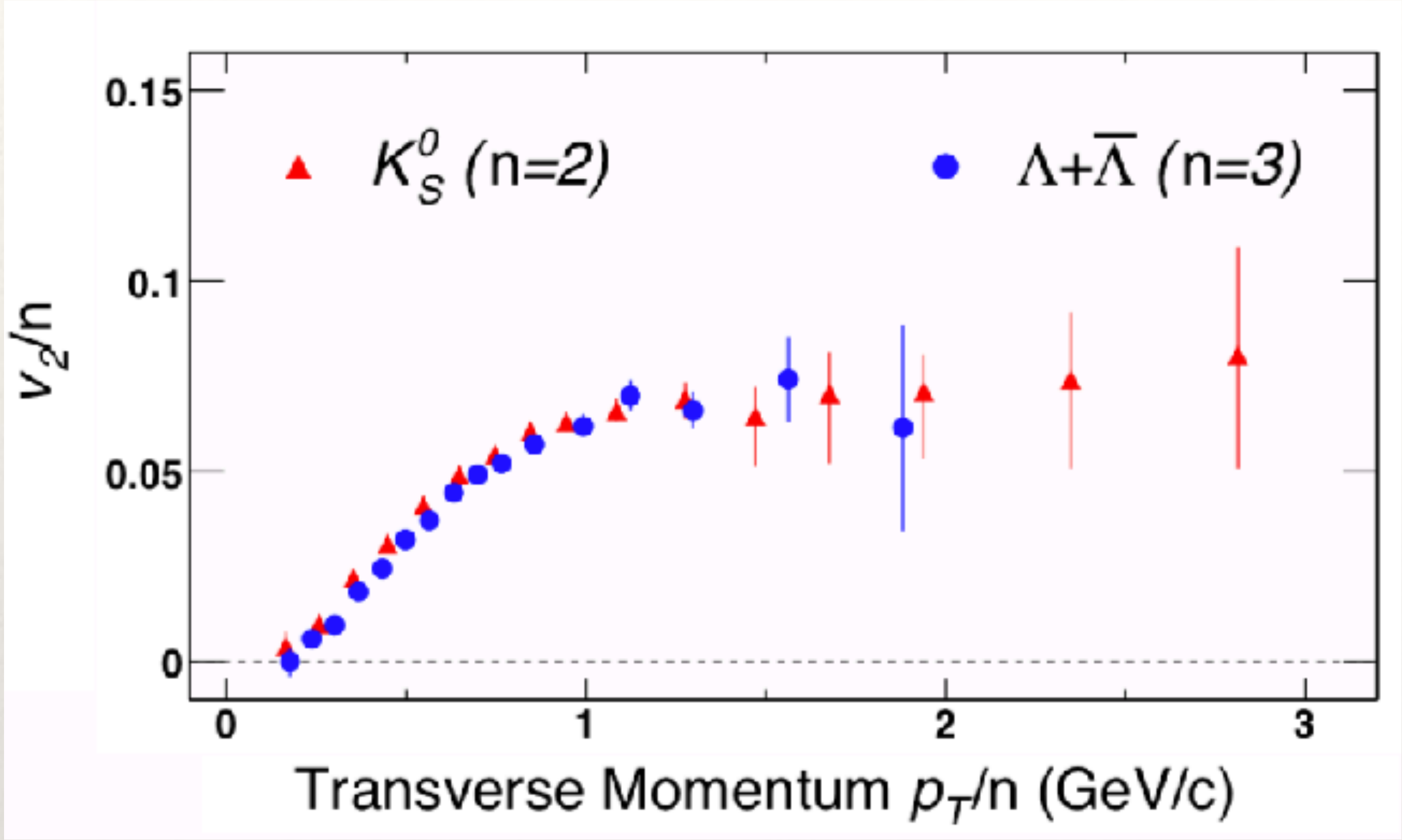
arXiv:2211:15553

Hadron chemistry in nuclear collisions

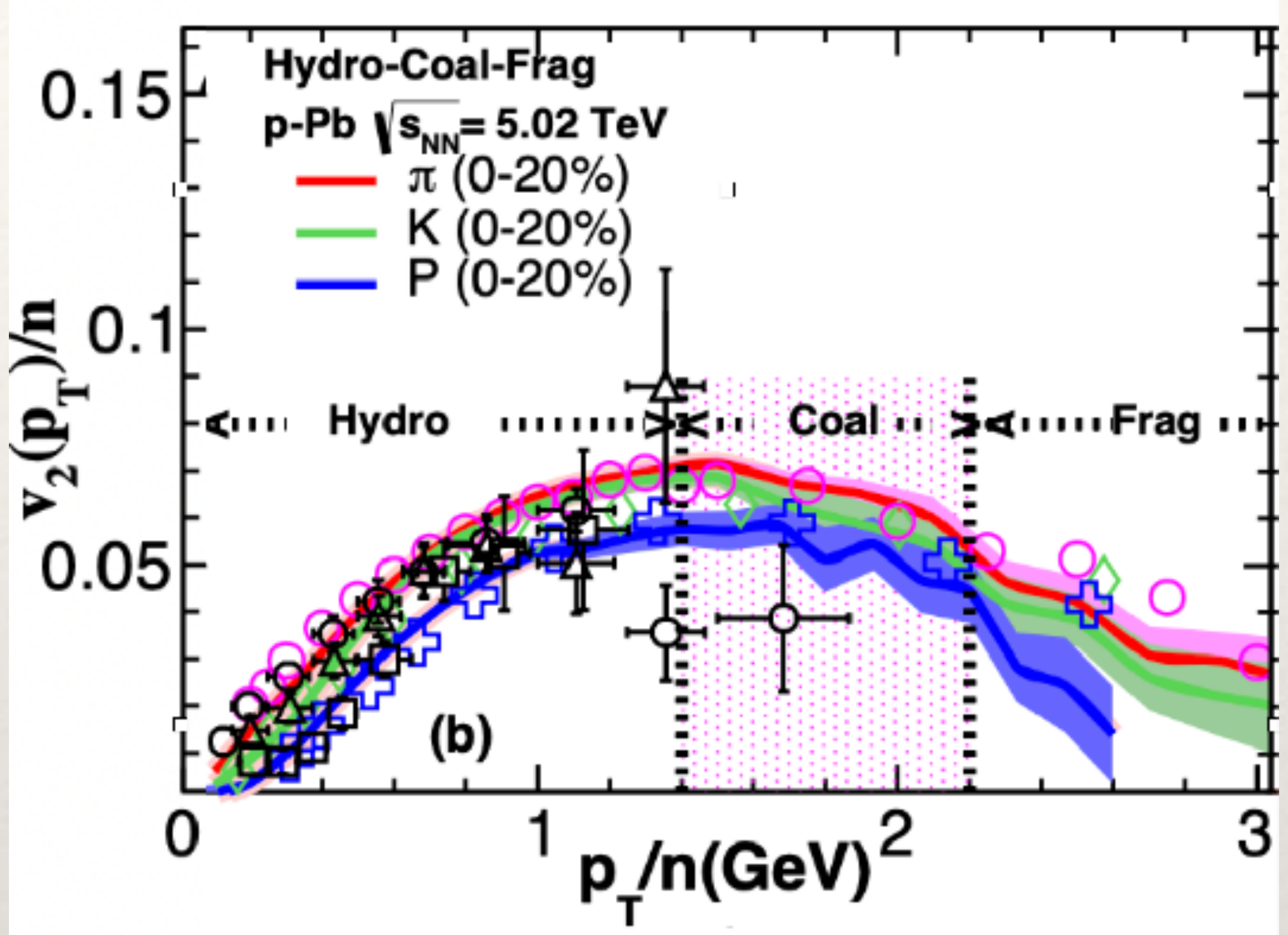
NCQ scaling in Au+Au collisions



[STAR, PRL 92 (2004)]

- Coalescence of quarks into hadron
- Quark degree of freedom inside the hot nuclear matter in heavy-ion collisions

NCQ scaling in p+Pb collisions

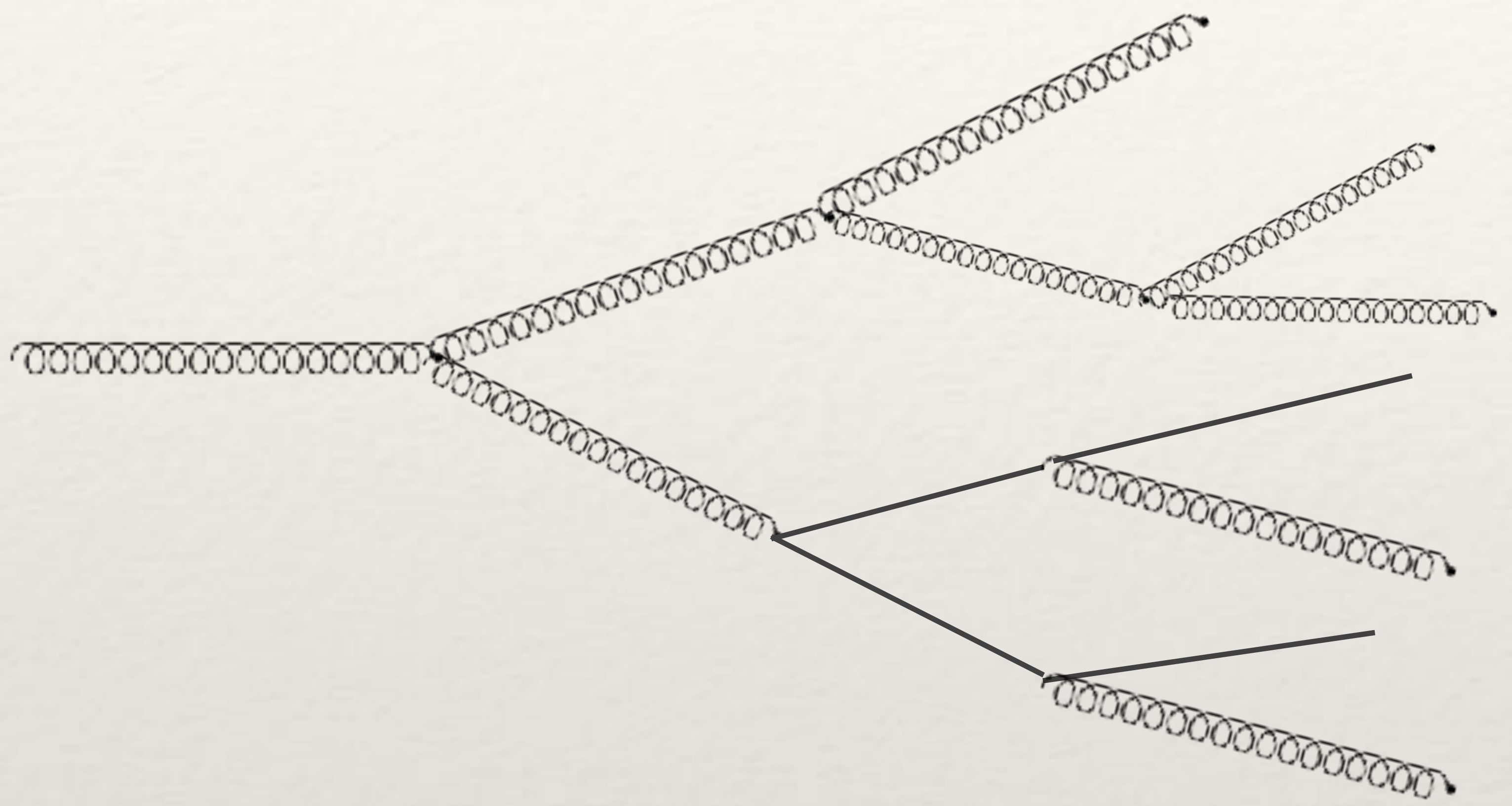


[Zhao, et. al., PRL 125 (2020)]

- Hydro + Coalescence + Fragmentation
- Quark degree of freedom produced in high-multiplicity p+Pb collisions

Chemistry within jets

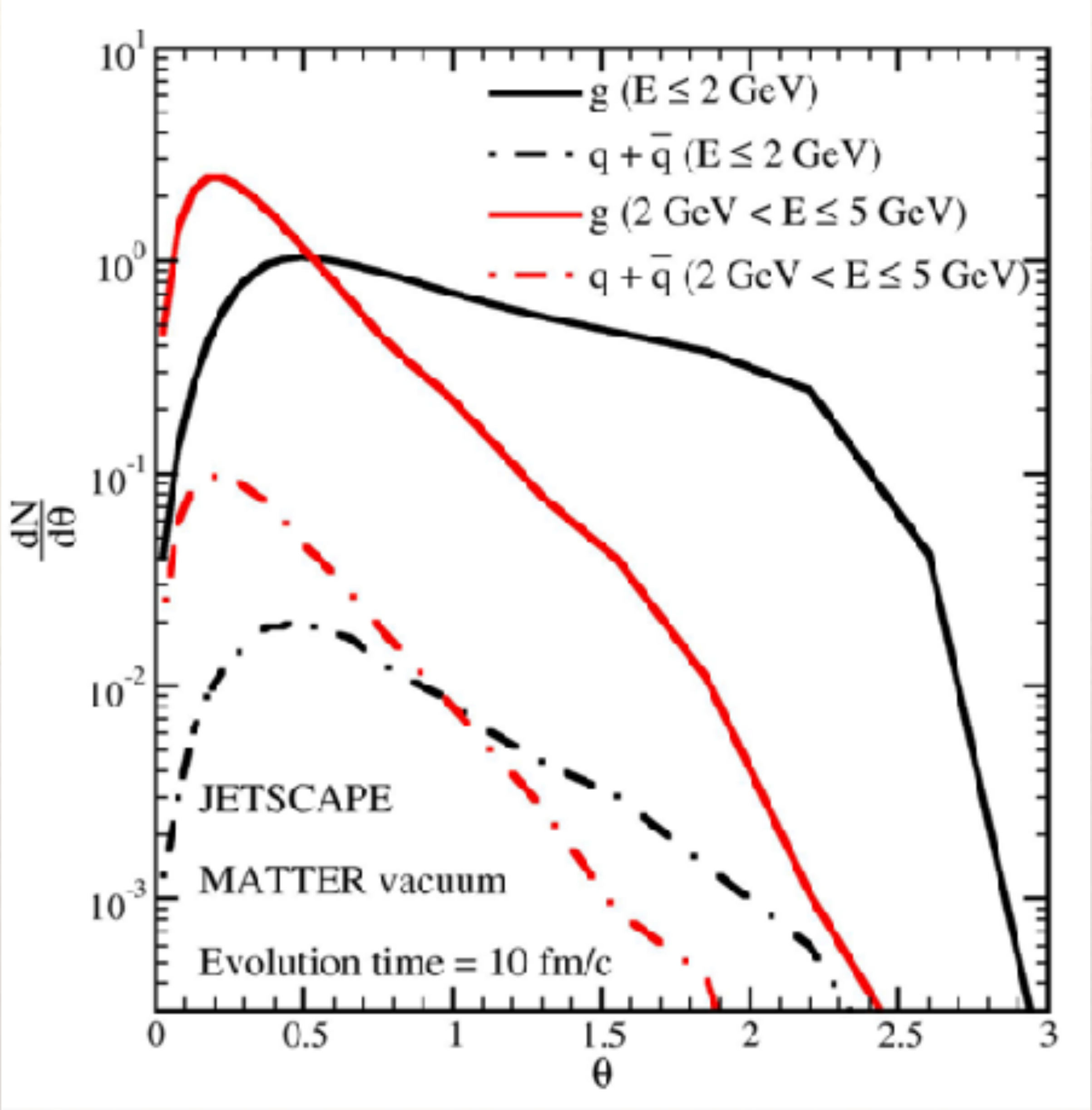
Vacuum shower



- Divergence in $P_{g\to gg}$, $P_{q\to qg}$, not in $P_{g\to q\bar{q}}$
- Final state dominated by gluons

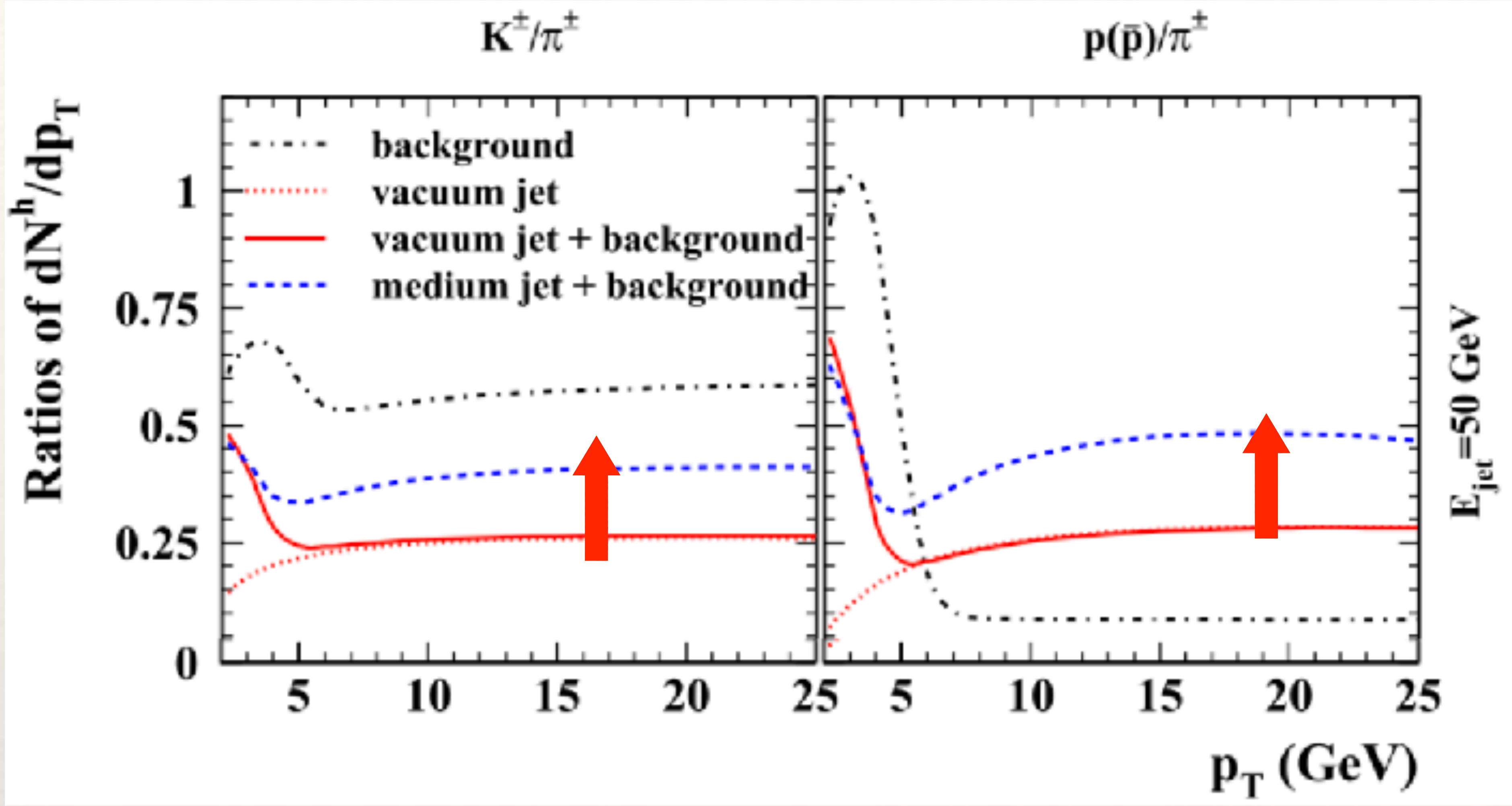
What about medium modified jets?

JESCAPE (vacuum) simulation



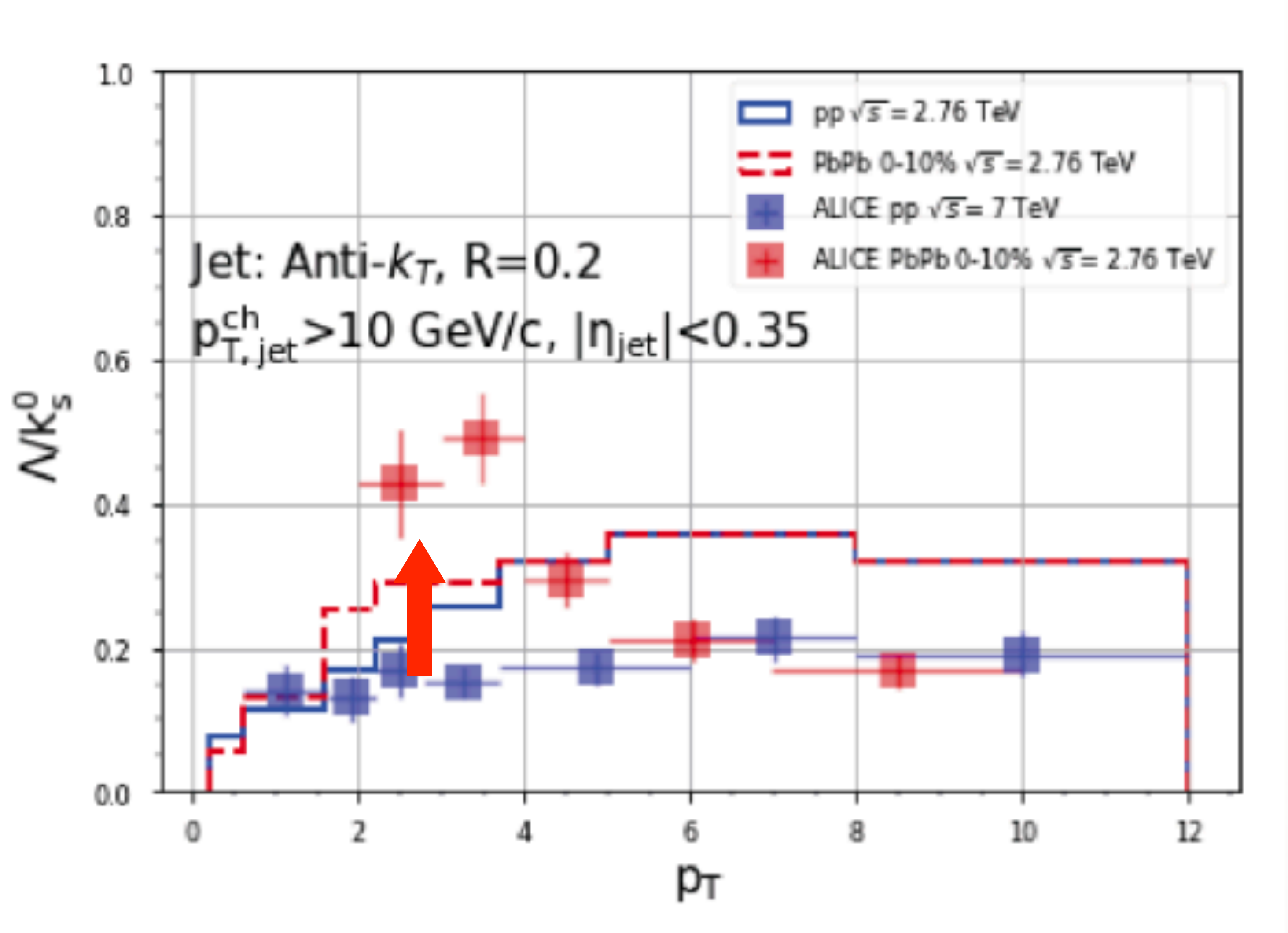
- Start with a 25 GeV gluon and analyze $q(\bar{q})$ and g distributions w.r.t. θ

Prior studies on hadrochemistry within jets



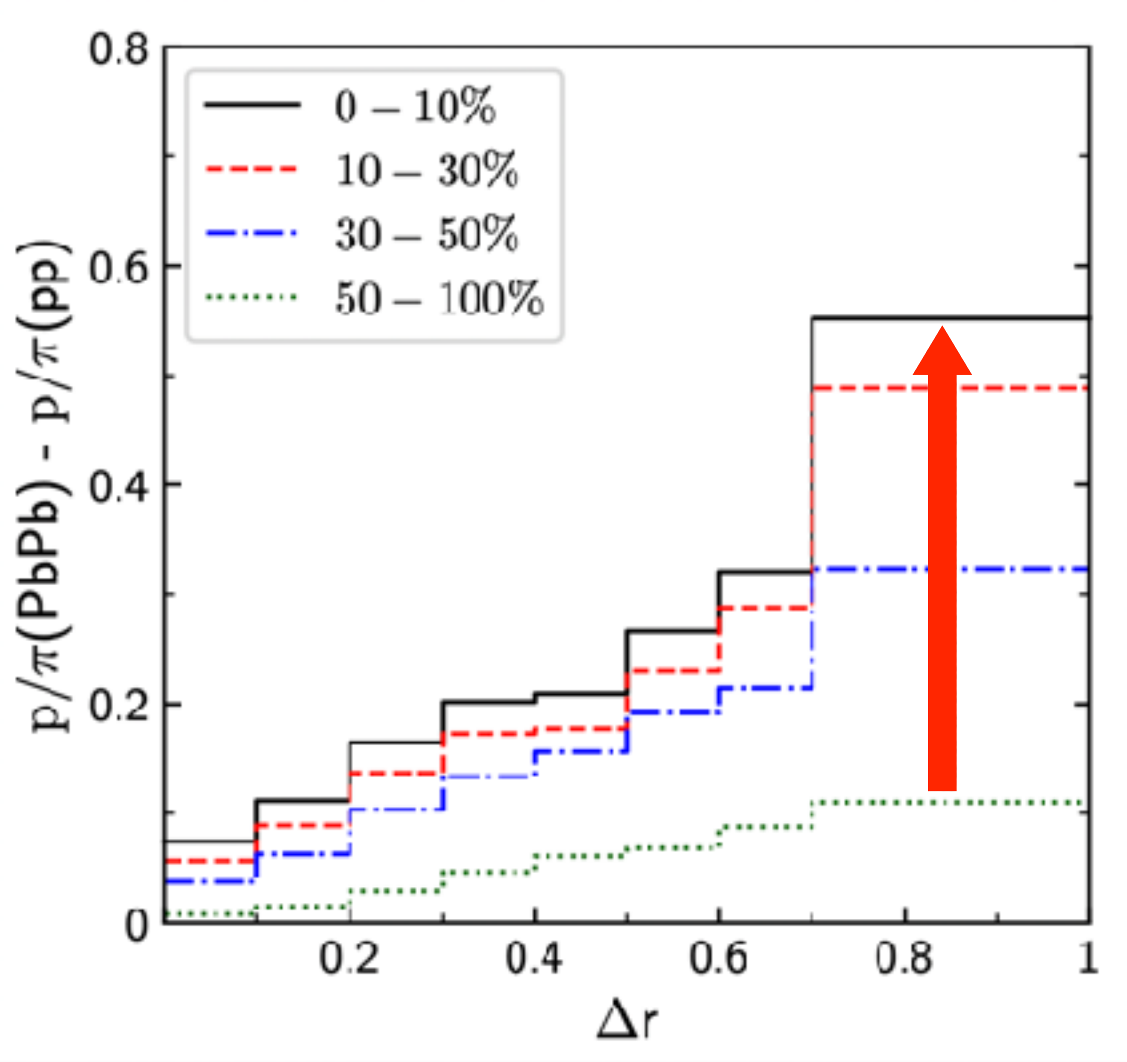
Medium-modified splitting + hadronization (frag. + coal.)

[Sapeta and Wiedemann EPJC 55 (2008)]



CoLBT + hadronization (frag. + coal.)

[Chen et. al. NPA 1005 (2021)]



AMPT

[Luo et. al. PLB 837 (2023)]

Enhancement of strangeness production and baryon-to-meson ratio within jets

- Medium modified splitting + hadronization
- Jet-induced medium excitation + hadronization

Can hard partons themselves (not soft, and without hadronization) change their flavor?

Flavor change due to scatterings

Strangeness production inside the QGP

[Rafelski and Müller PRL 48 (1982)]

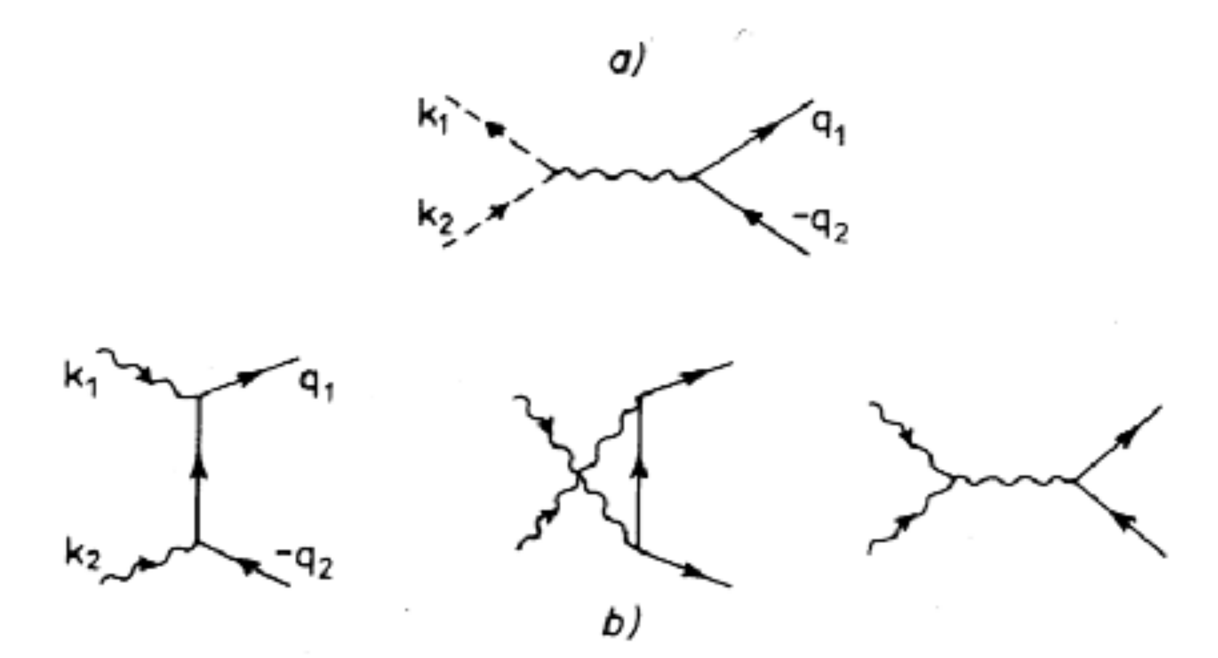
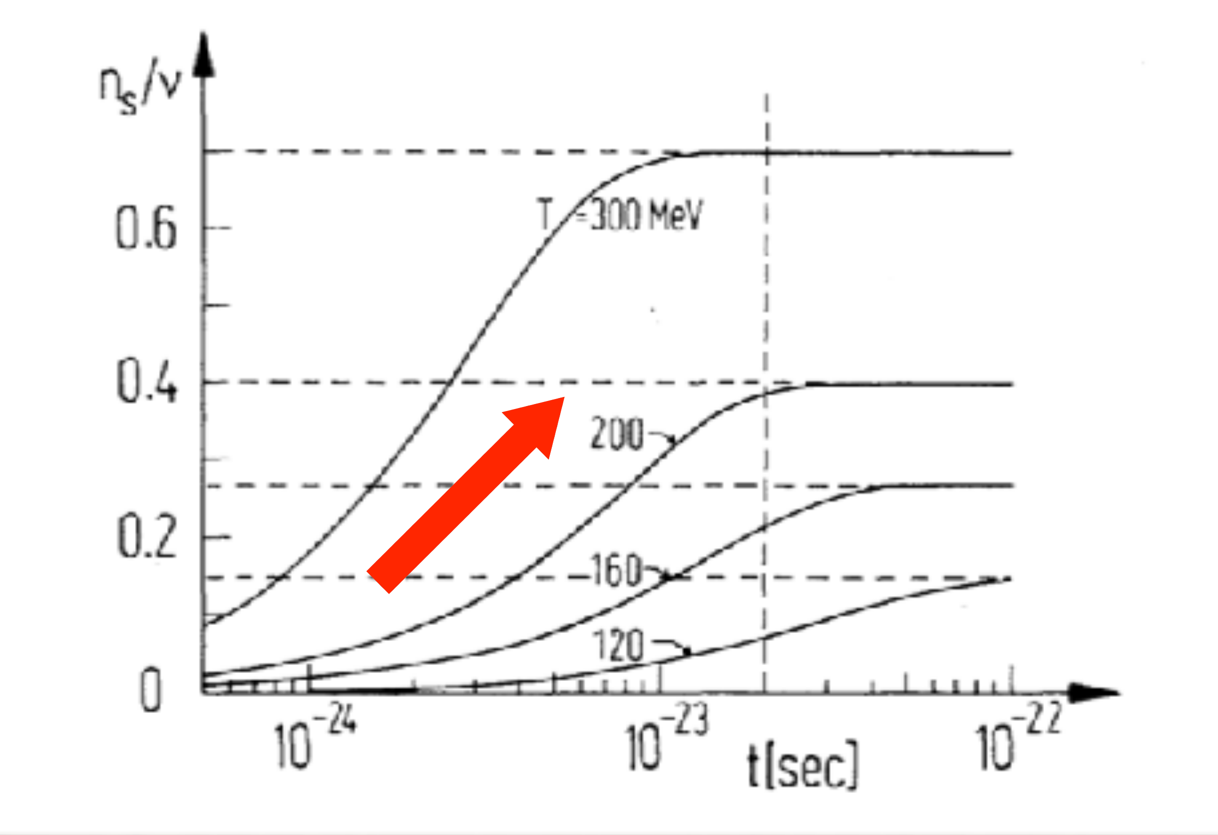


FIG. 1. Lowest-order QCD diagrams for $s\bar{s}$ production: (a) $q\bar{q}\to s\bar{s}$, (b) $gg\to s\bar{s}$.

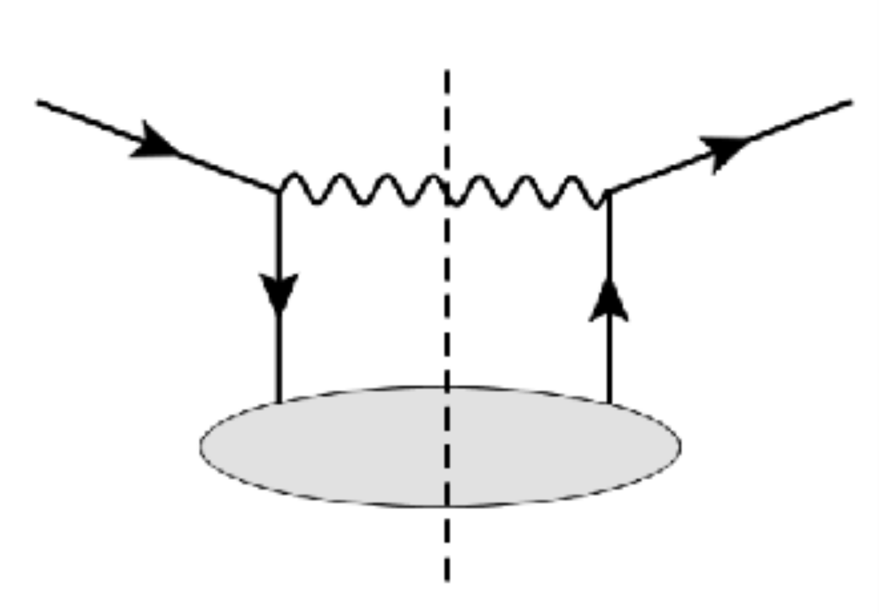


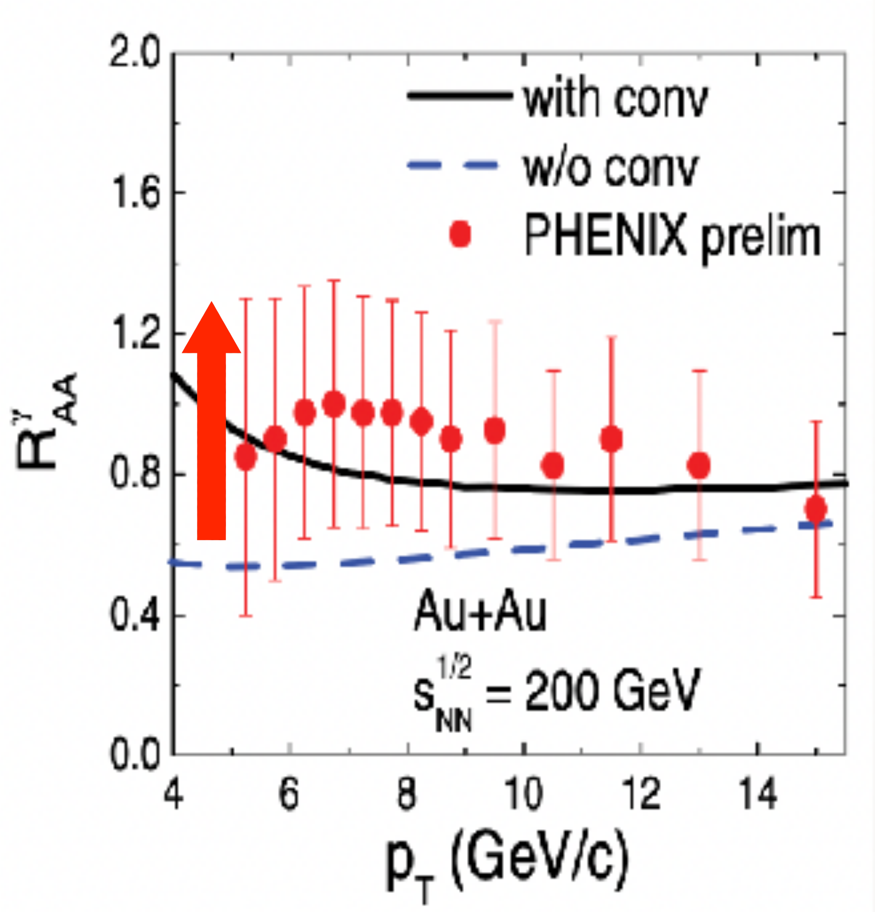
- Interactions between hard and thermal partons enhance strangeness as time evolves

Photon enhancement inside the QGP

[Fries, Müller and Srivastava PRL 90 (2003)]

[Liu and Fries, PRC 77 (2008)]



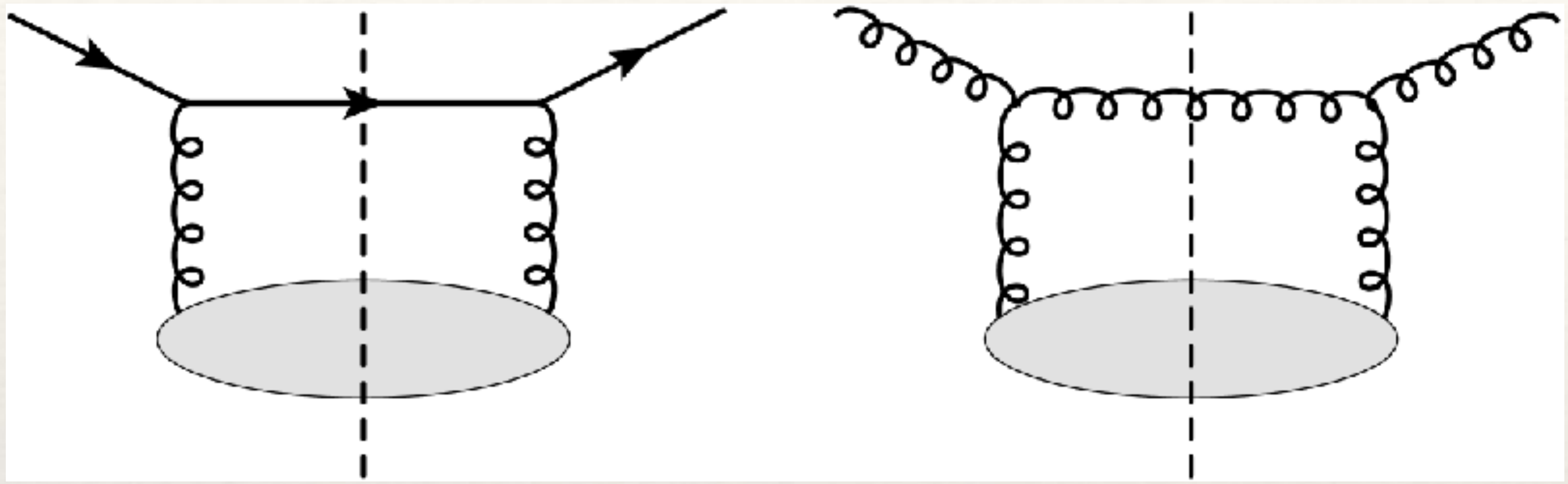


- Jets converts to photons as they travel through the QGP

This work: conversions between quarks and gluons within jet showers

Scattering diagrams

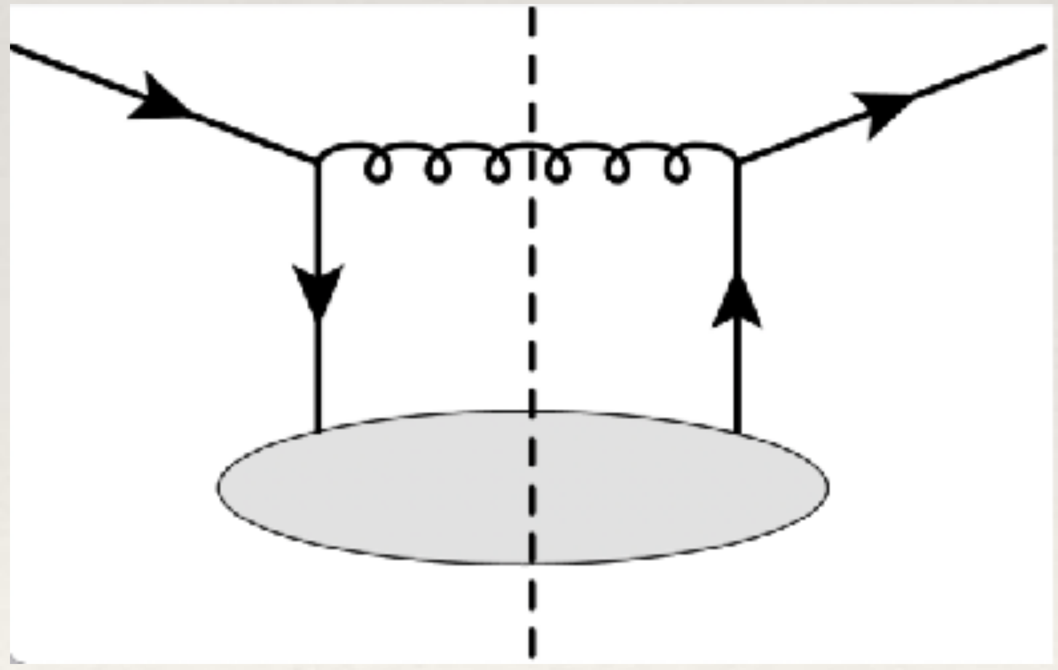
- Dominating diagrams of scattering rate, but no flavor conversion



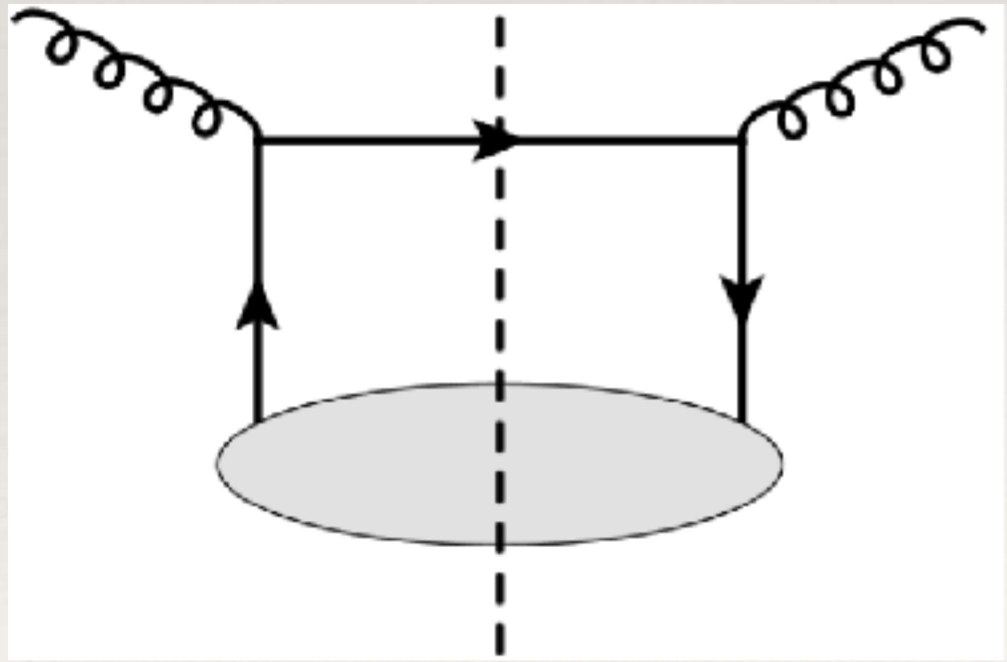
Jet transport coefficient [Kumar et. Al. PRD 106 (2022)]

$$\hat{q} = c_0 \int \frac{dy^- d^2 y_\perp}{(2\pi)^3} d^2 k_\perp e^{-i\frac{k_\perp^2}{2q^-}y^- + i\vec{k}_\perp \cdot \vec{y}_\perp} \times \sum_n \langle n | \frac{e^{-\beta E_n}}{Z} \mathrm{Tr}[F^{+j}(0) F_j^+(y^-, y_\perp)] | n \rangle$$

- Small contributions to scattering rate, but convert flavors



$q \to g$



$g \to q$

Conversion rate

$$\Gamma_{q\to g(g\to q)} = \frac{c_{q\to g(g\to q)}}{2E_{q(g)}} \int \frac{dy^- d^2 y_\perp}{(2\pi)^2} d^2 k_\perp e^{-i\frac{k_\perp^2}{2q^-}y^- + i\vec{k}_\perp \cdot \vec{y}_\perp} \times \sum_n \frac{e^{-\beta E_n}}{Z} \langle n | \bar{\psi}(0) \gamma^+ \psi(y^-, y_\perp) | n \rangle$$

c: spin-color degrees of freedom

Rates of flavor exchange within perturbative calculation

$$\Gamma_{ab\to cd} = \int \frac{d^3p_2}{(2\pi)^3}\frac{d^3p_3}{(2\pi)^3}\frac{d^3p_4}{(2\pi)^3} f_b(p_2)[1\pm f_c(p_3)][1\pm f_d(p_4)]$$
$$\times \frac{|\mathcal{M}_{12\to 34}|^2}{16E_1E_2E_3E_4}(2\pi)^4\delta^{(4)}\left(p_1+p_2-p_3-p_4\right)$$

a: initial hard parton with p_1

b: thermal parton with p_2

c and d: final states with p_3 and p_4

$ab \to cd$	$\nu_b \sum_{\nu_c \nu_d} \lvert\mathcal{M}_{ab\to cd}\rvert^2/g_s^4$
$gg \to 2\sum_i q_i\bar{q}_i$	$2N_f C_F\left(\frac{u}{t}+\frac{t}{u}-\frac{C_A}{C_F}\frac{t^2+u^2}{s^2}\right)$
$q_i\bar{q}_i \to gg$	$2C_F^2\left(\frac{u}{t}+\frac{t}{u}-\frac{C_A}{C_F}\frac{t^2+u^2}{s^2}\right)$
$\sum_i gq_i \to gq_i$ $\sum_i g\bar{q}_i \to g\bar{q}_i$	$-N_fC_F\left(\frac{u}{s}+\frac{s}{u}\right)+N_fC_A\frac{s^2+u^2}{t^2}$
$q_ig \to q_ig$ $\bar{q}_ig \to \bar{q}_ig$	$-2C_F^2\left(\frac{u}{s}+\frac{s}{u}\right)+2C_FC_A\frac{s^2+u^2}{t^2}$

QCD annihilation processes

$g \to q$: $\left|\mathcal{M}_{gg\to 2\sum_i q_i\bar{q}_i}\right|^2$ $\quad q \to g$: $\left|\mathcal{M}_{q_i\bar{q}_i\to gg}\right|^2$

QCD Compton scattering processes

$g \to q$: $\left|\mathcal{M}_{\sum_i gq_i\to gq_i}\right|^2$ $\quad q \to g$: $\left|\mathcal{M}_{q_ig\to q_ig}\right|^2$

with $\theta(|\vec{p_4}|-|\vec{p_3}|)$

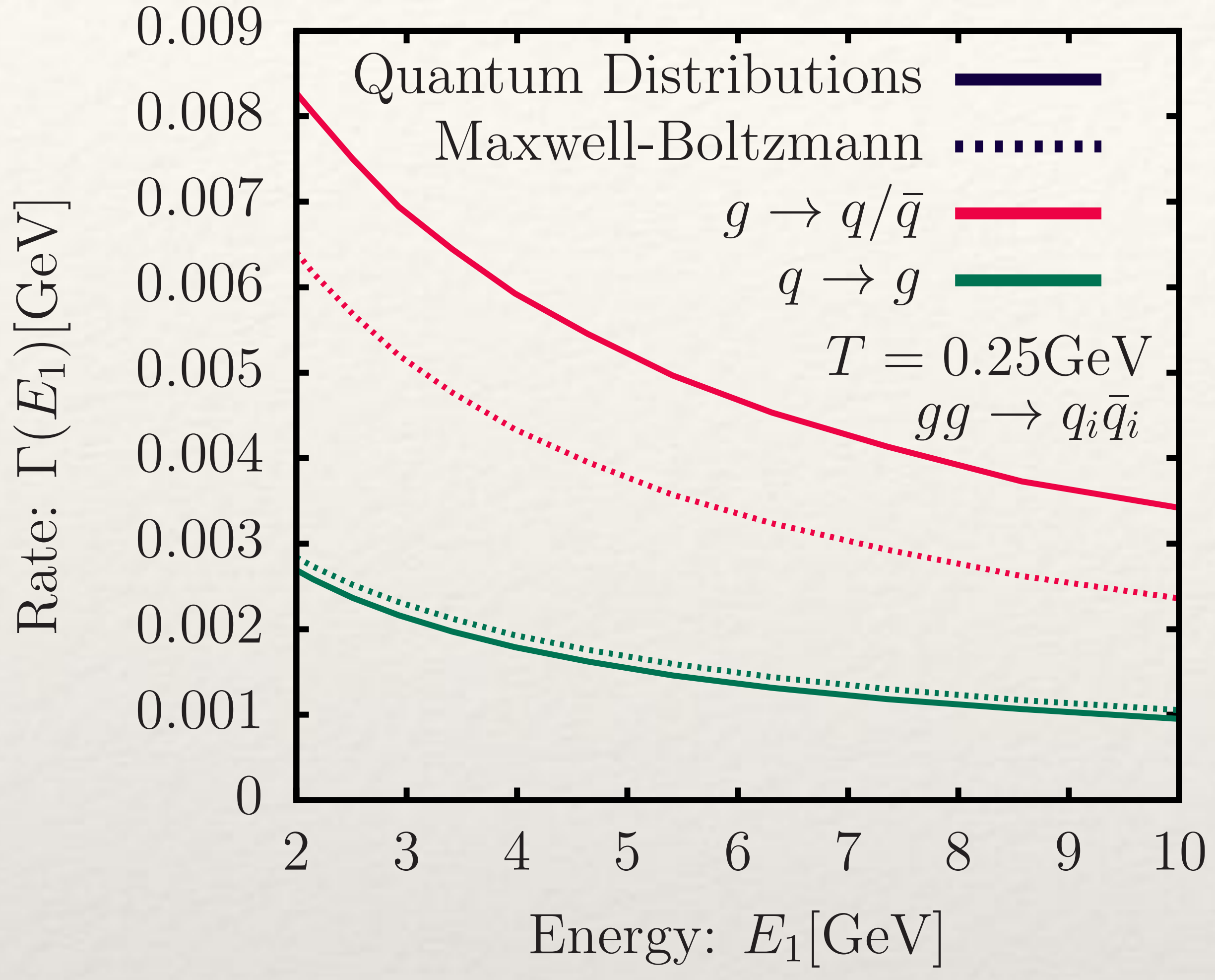
$$\frac{\Gamma_{gg\to 2\sum_i q_i\bar{q}_i}}{\Gamma_{q_i\bar{q}_i\to gg}} \text{ and } \frac{\Gamma_{\sum_i gq_i\to gq_i}+\Gamma_{\sum_i g\bar{q}_i\to g\bar{q}_i}}{\Gamma_{q_ig\to q_ig}}$$
$$\simeq \frac{N_f}{C_F} = 2.25$$

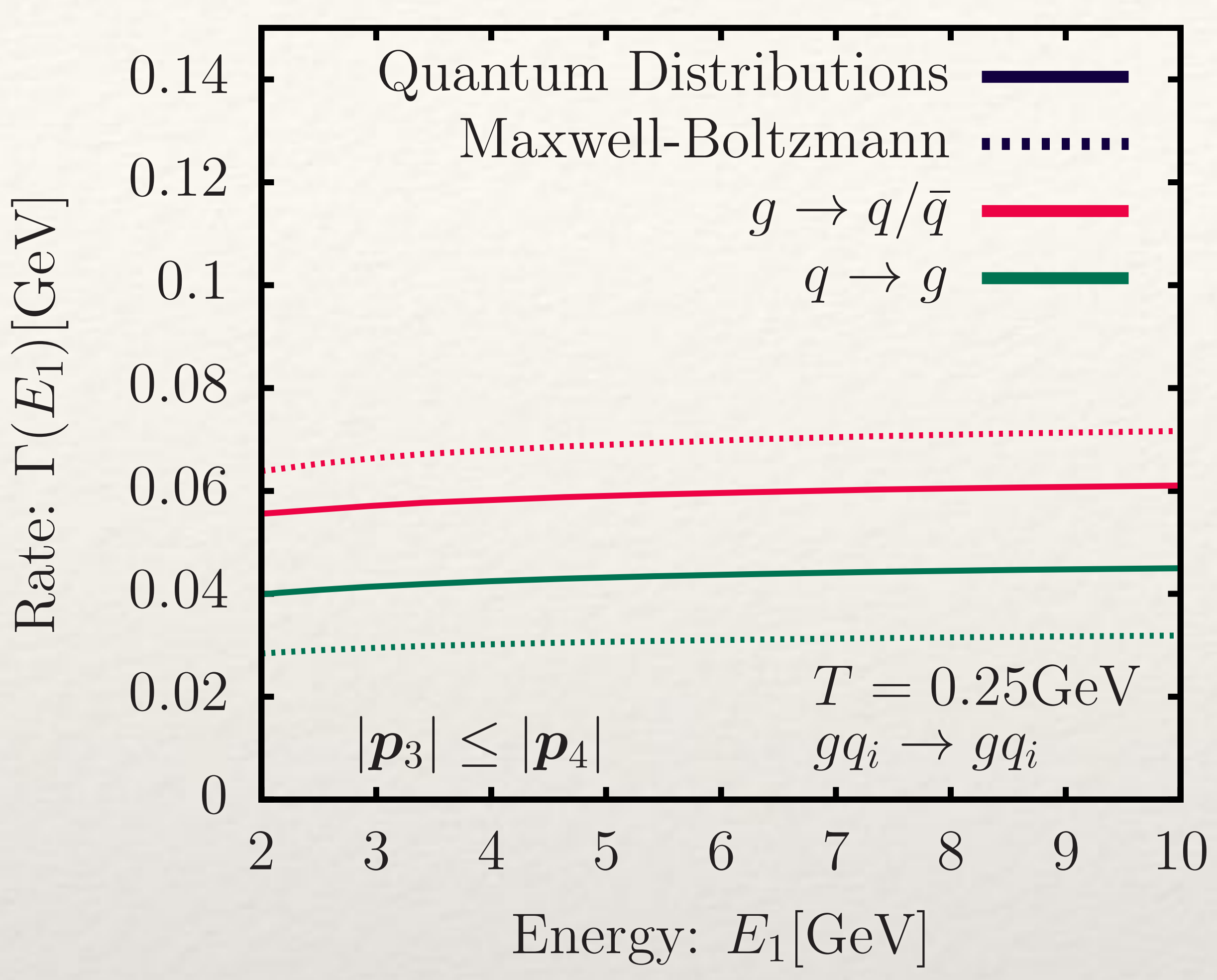
Conversion rates

QCD annihilation

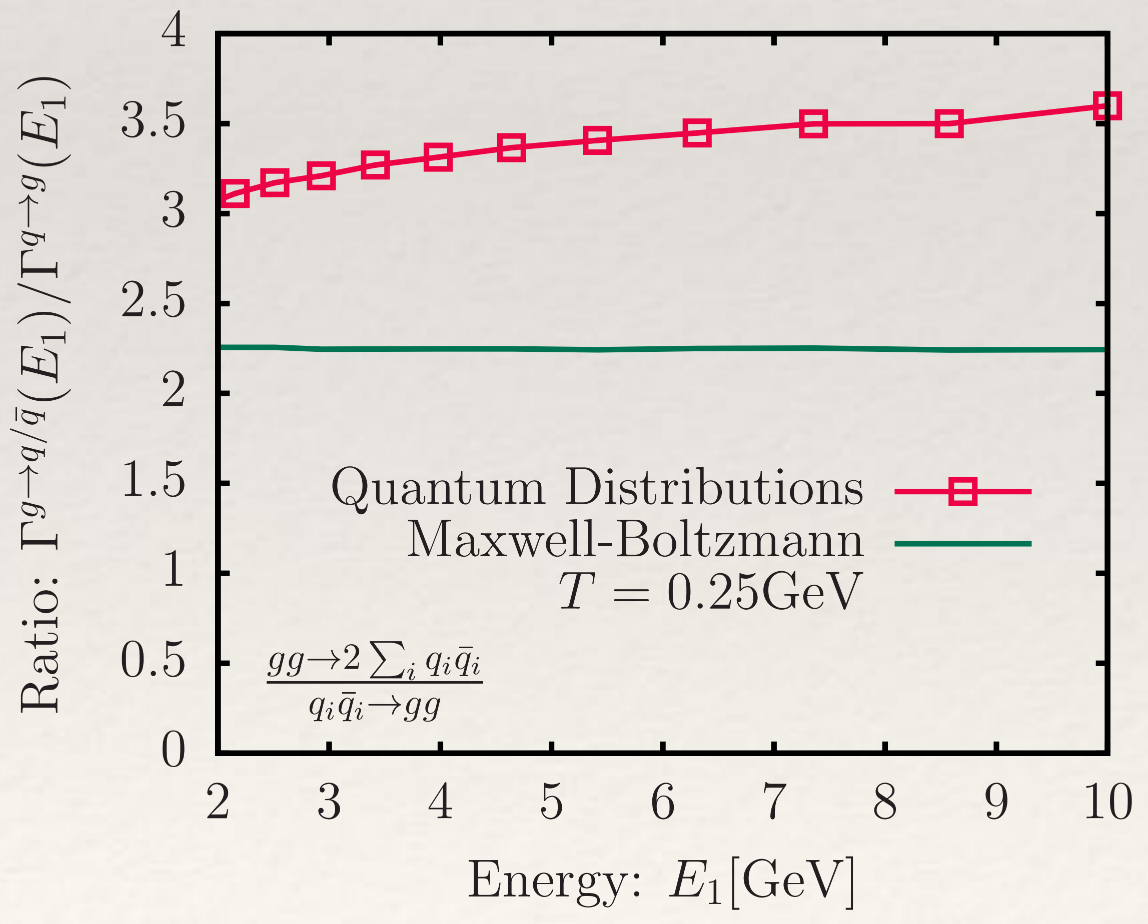
QCD Compton scattering

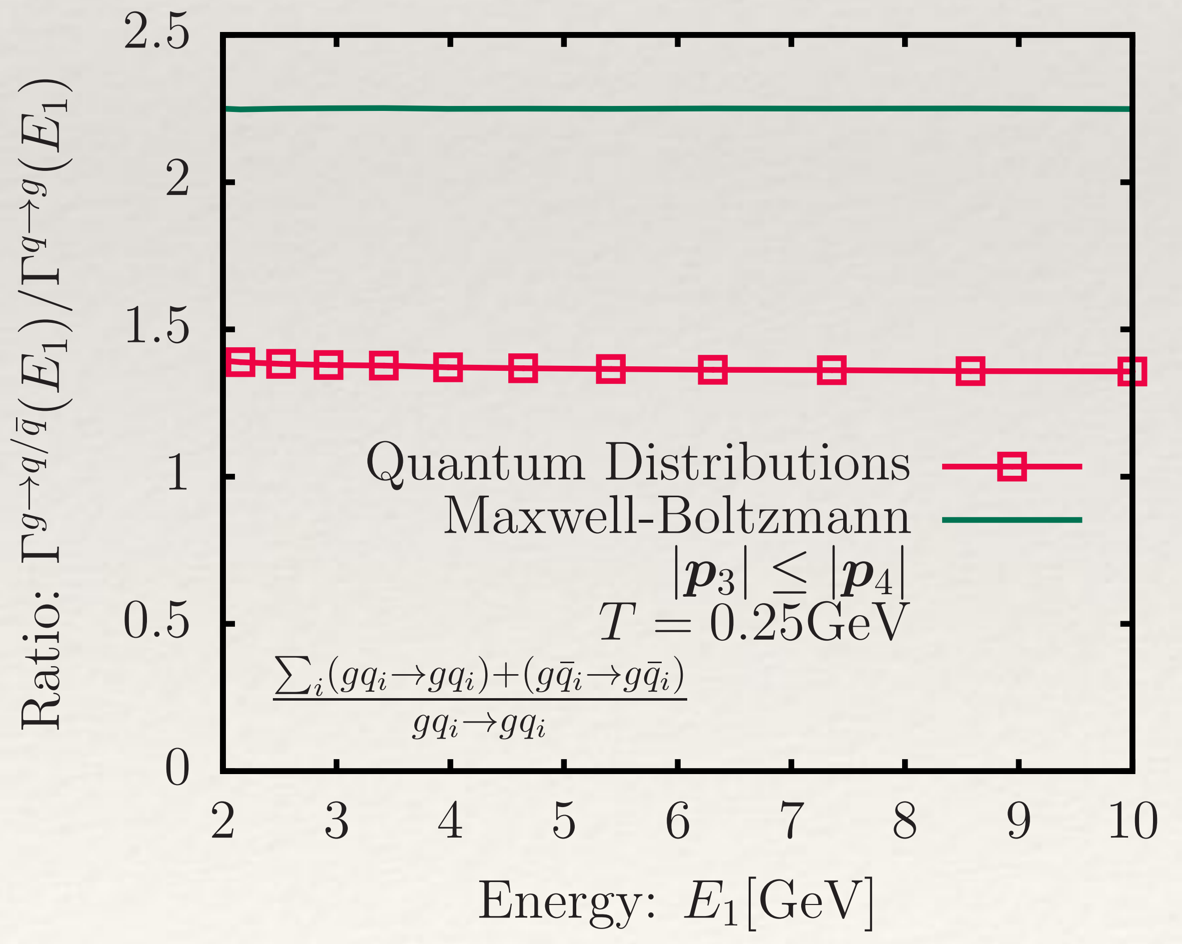
rate





ratio





- Fix T = 250 MeV
- Absolute rate of $g \to q$ is not small: 0.068 GeV ~ 0.34 fm^{-1}
- g converts to q in ~ 3 fm
- $g \to q$ vs. $q \to g$ is 1.5 ~3: once g converts to q, it seldom converts back
- More hard quarks are generated inside jets by scatterings with the medium

Quark vs. gluon distribution inside jets: model I

Semi-analytical calculation using the AMY approach

$$\partial_t f_a(p) = C_a^{2\leftrightarrow 2}[f] + C_a^{1\leftrightarrow 2}[f]$$

$2 \leftrightarrow 2$: leading-order pQCD scatterings, with HTL propagators for internal quark and gluon

$1 \leftrightarrow 2$: multiple scattering induced gluon emission [Arnold, Moore, Yaffe, JHEP 01 (2003)]

$$f_a(p_1) = \underbrace{n_a(p_1)}_{\text{equilibrium distribution}} + \underbrace{\delta f_a(p_1)}_{\text{hard parton and medium response (recoil + energy depletion)}}$$

equilibrium distribution — hard parton and medium response (recoil + energy depletion)

Initial condition

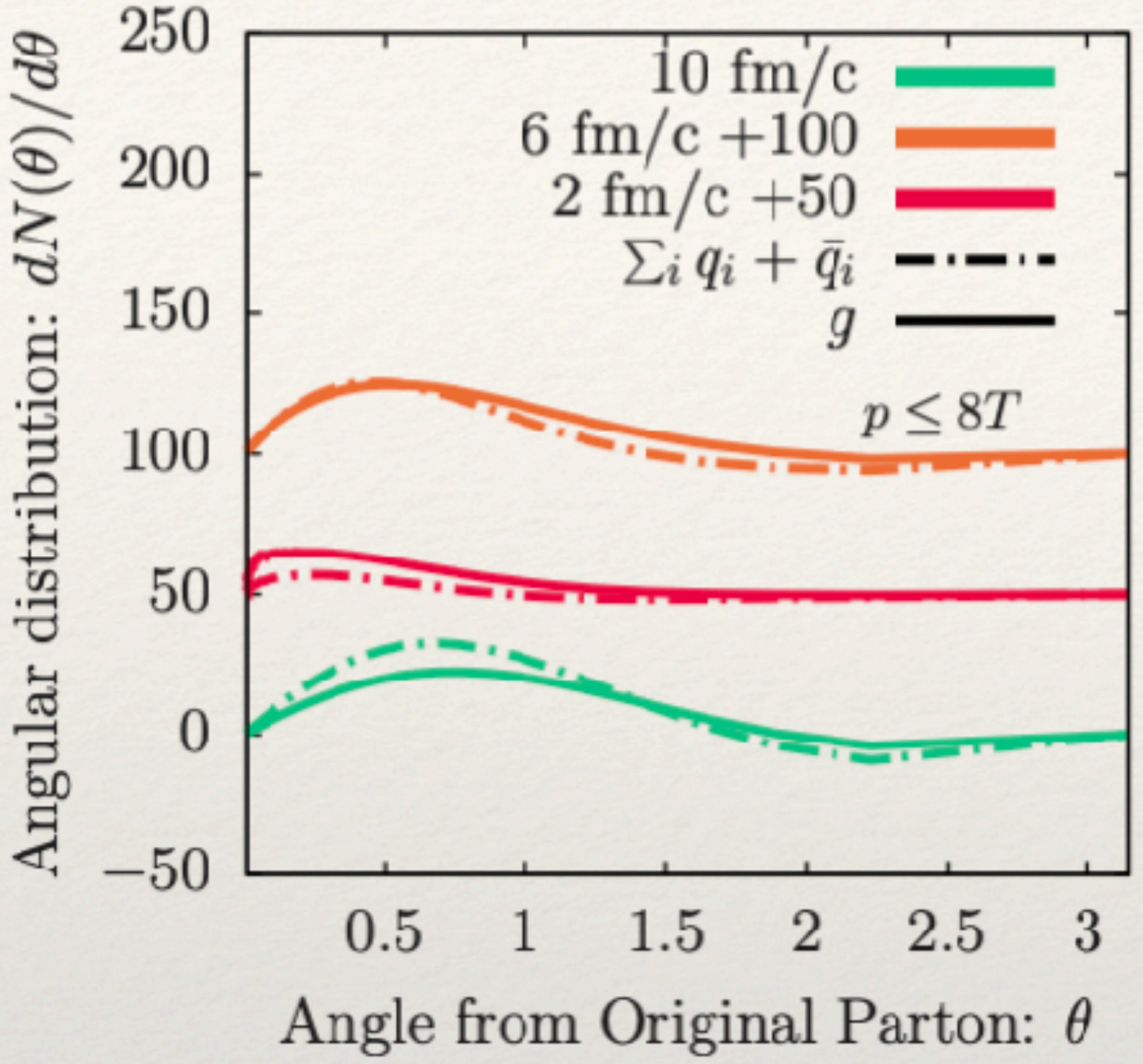
$$\delta f_g^{\text{in}}(p,\theta) = \exp\left[-\frac{(p-E_0)^2 + p^2\sin^2\theta}{2\sigma^2}\right] \Big/ (p^3 N)$$

$$\delta f_{q,\bar{q}}^{\text{in}}(p,\theta) = 0$$

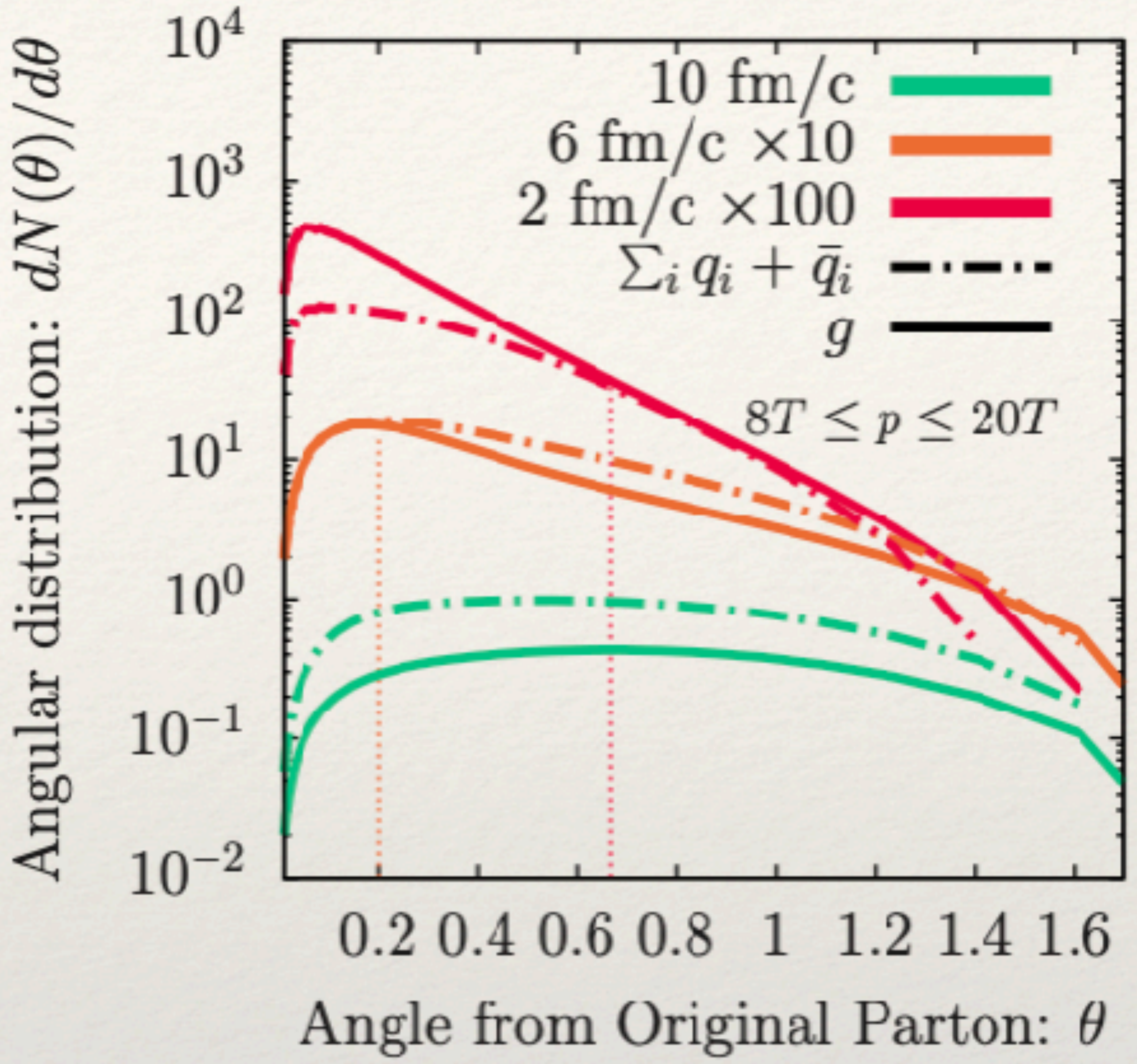
Angular distribution

$$\frac{dN_a}{d\theta}(\theta) = \sin\theta \int_{p_{\min}}^{p_{\max}} dp \int \frac{d\phi}{(2\pi)^2} p^2 \delta f_a(p)$$

Angular distribution of quarks vs. gluons from AMY



soft (p < 2 GeV)



semi-hard (2< p < 5 GeV)

T = 250 MeV

- Start with a 25 GeV gluon (allow both perturbative calculation and multiple scatterings)
- Soft region: dominated by gluons till very late time
- Semi-hard region: quarks dominate at large angle first and then over the entire angular regime at late time

Quark vs. gluon distribution inside jets: model II

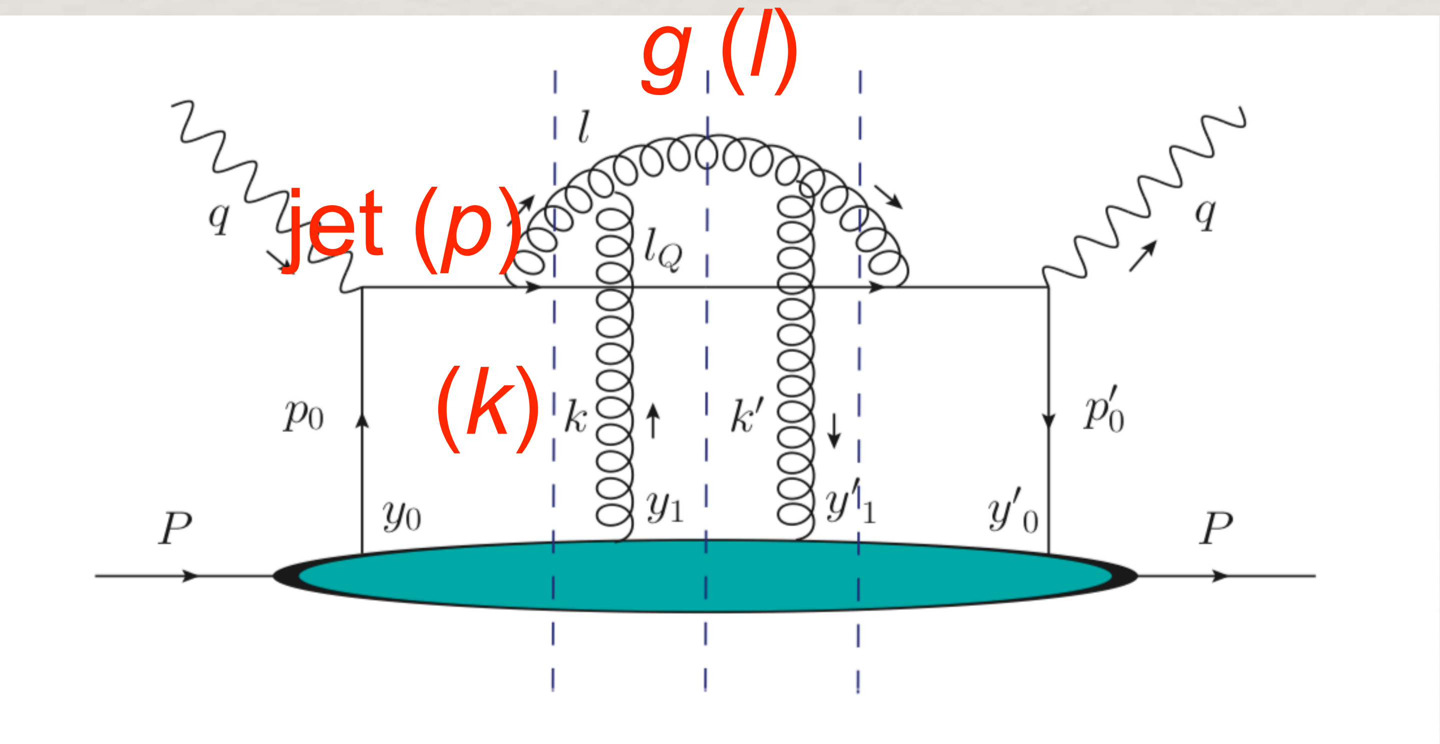
Linear Boltzmann Transport (LBT) model simulation [PRC 94 (2016)]

Implement $2 \leftrightarrow 2$ and $2 \rightarrow 3$ scattering rate with Monte Carlo method

$$\partial_t f_a(p) = C_a^{2\leftrightarrow 2}[f] + C_a^{2\rightarrow 2+3}[f]$$

$2 \leftrightarrow 2$: leading-order pQCD scatterings, with recoil and energy depletion taken into account

$2 \rightarrow 3$: Higher-Twist calculation of single scattering induced single gluon emission



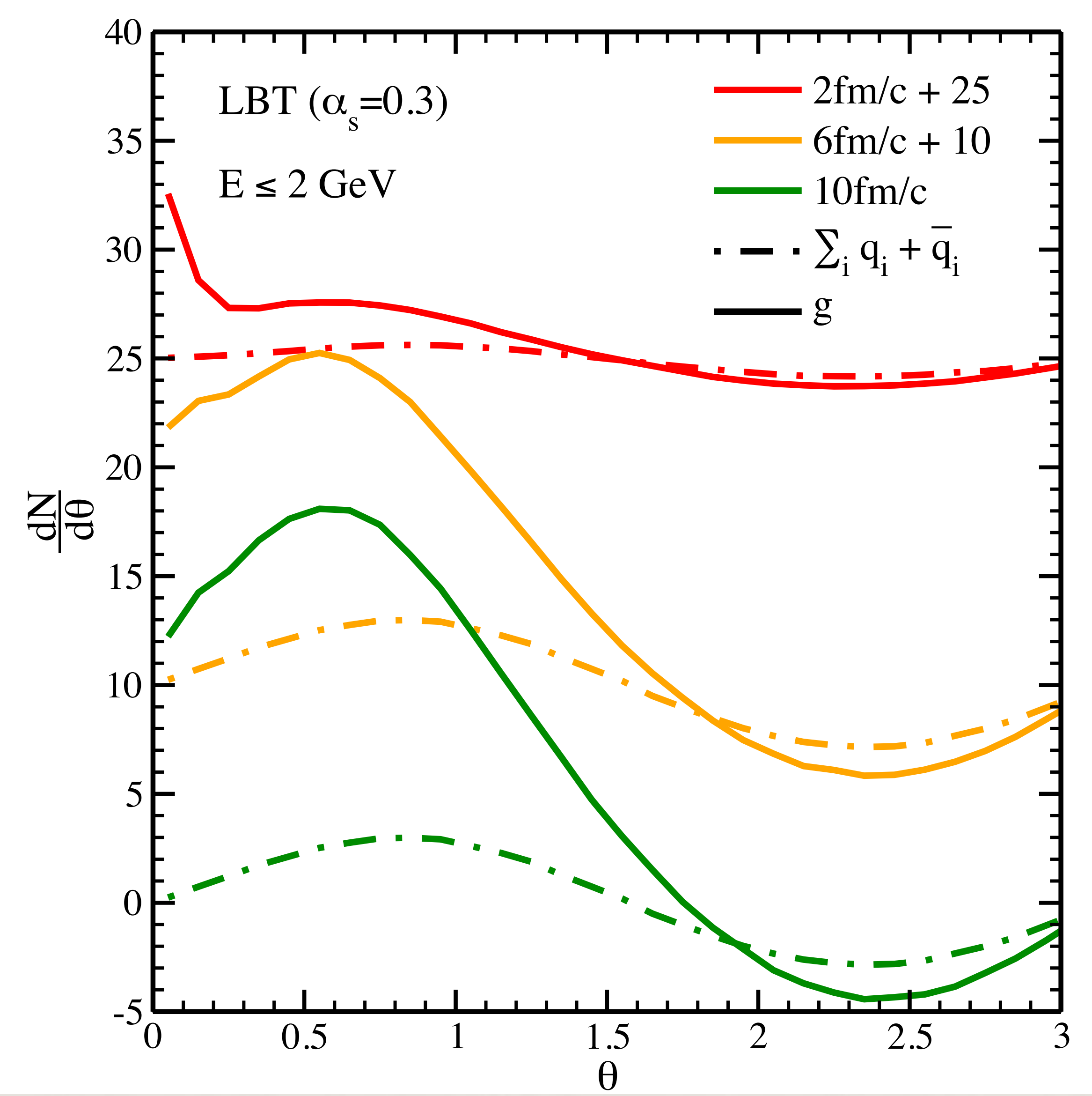
[Majumder PRD 85 (2012); Zhang, Wang and Wang, PRL 93 (2004)]

$$\frac{d\Gamma_a^{\mathrm{inel}}}{dz dl_\perp^2} = \frac{dN_g}{dz dl_\perp^2 dt} = \frac{6\alpha_s P(z) l_\perp^4 \hat{q}}{\pi(l_\perp^2 + z^2 M^2)^4} \sin^2\left(\frac{t - t_i}{2\tau_f}\right)$$

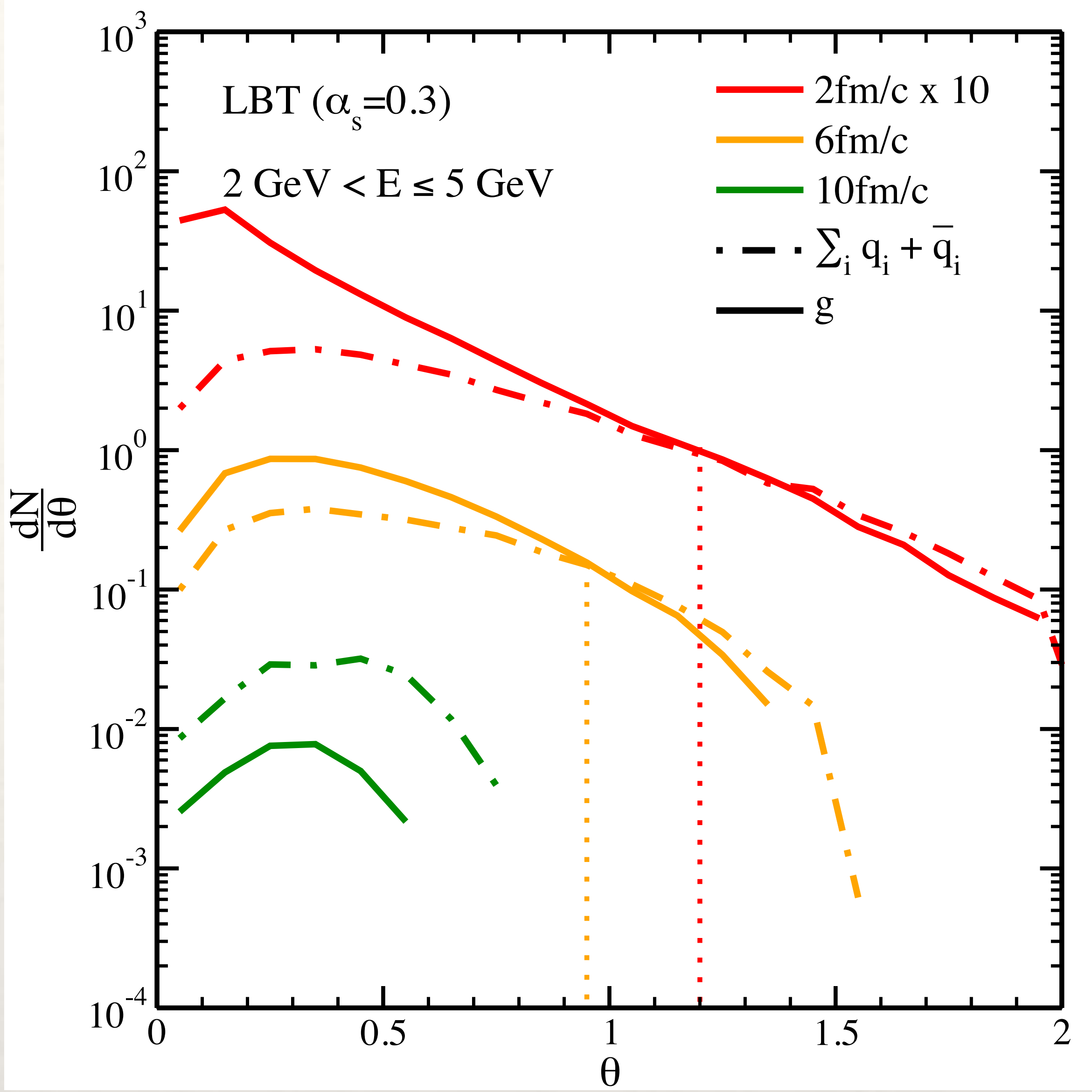
Medium information absorbed in $\hat{q} \equiv d\langle p_\perp^2 \rangle / dt$

— calculated using elastic scattering

Angular distribution of quarks vs. gluons from LBT



soft (p < 2 GeV)



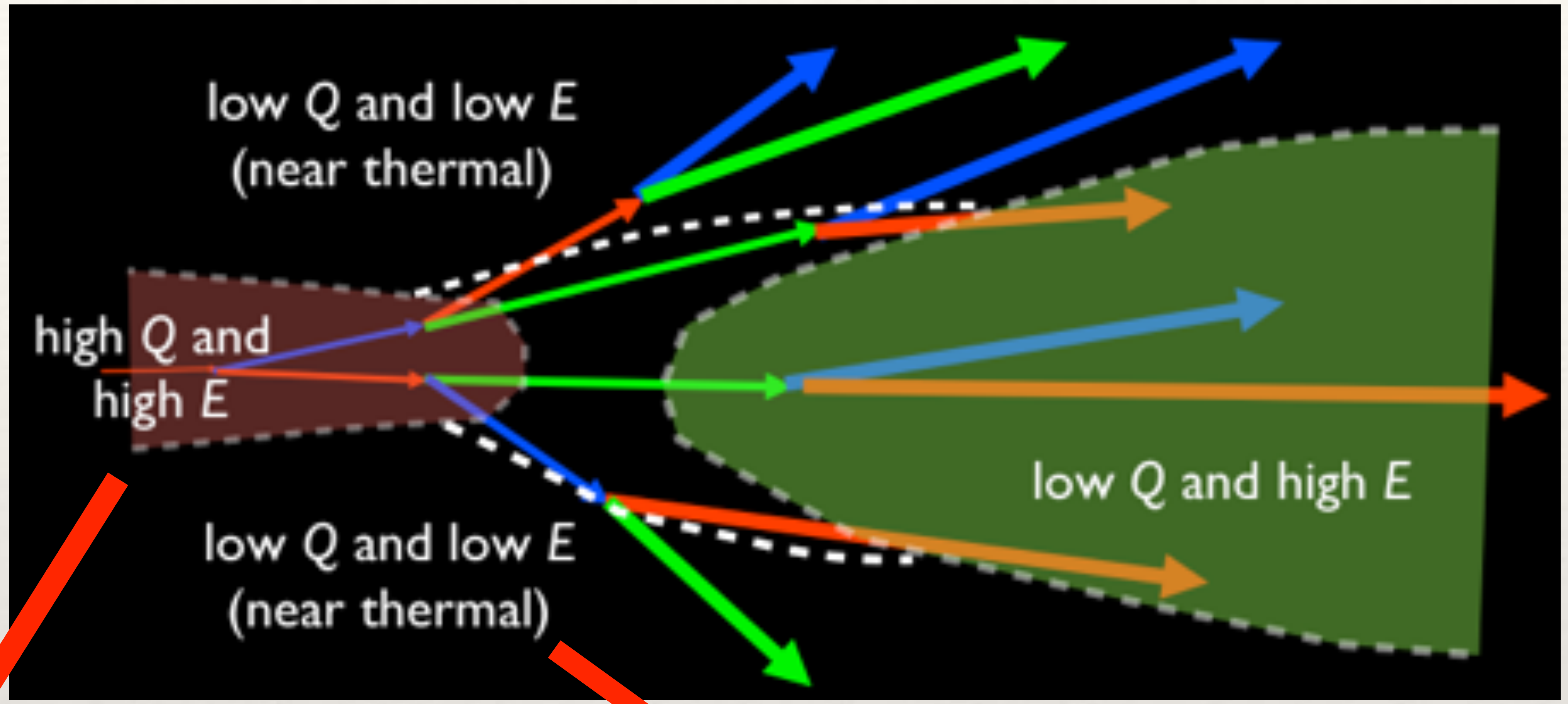
semi-hard (2< p < 5 GeV)

T = 250 MeV

- Start with a 25 GeV gluon
- Soft region: dominated by gluons, negative distributions at large angles (diffusion wake)
- Semi-hard region: quarks dominate at large angle first and then over the entire angular regime at late time

Quark vs. gluon distribution inside jets: model III

Multistage jet evolution JETSCAPE (MATTER+MARTINI) [PRC 96 (2017), arXiv:1903.07706]



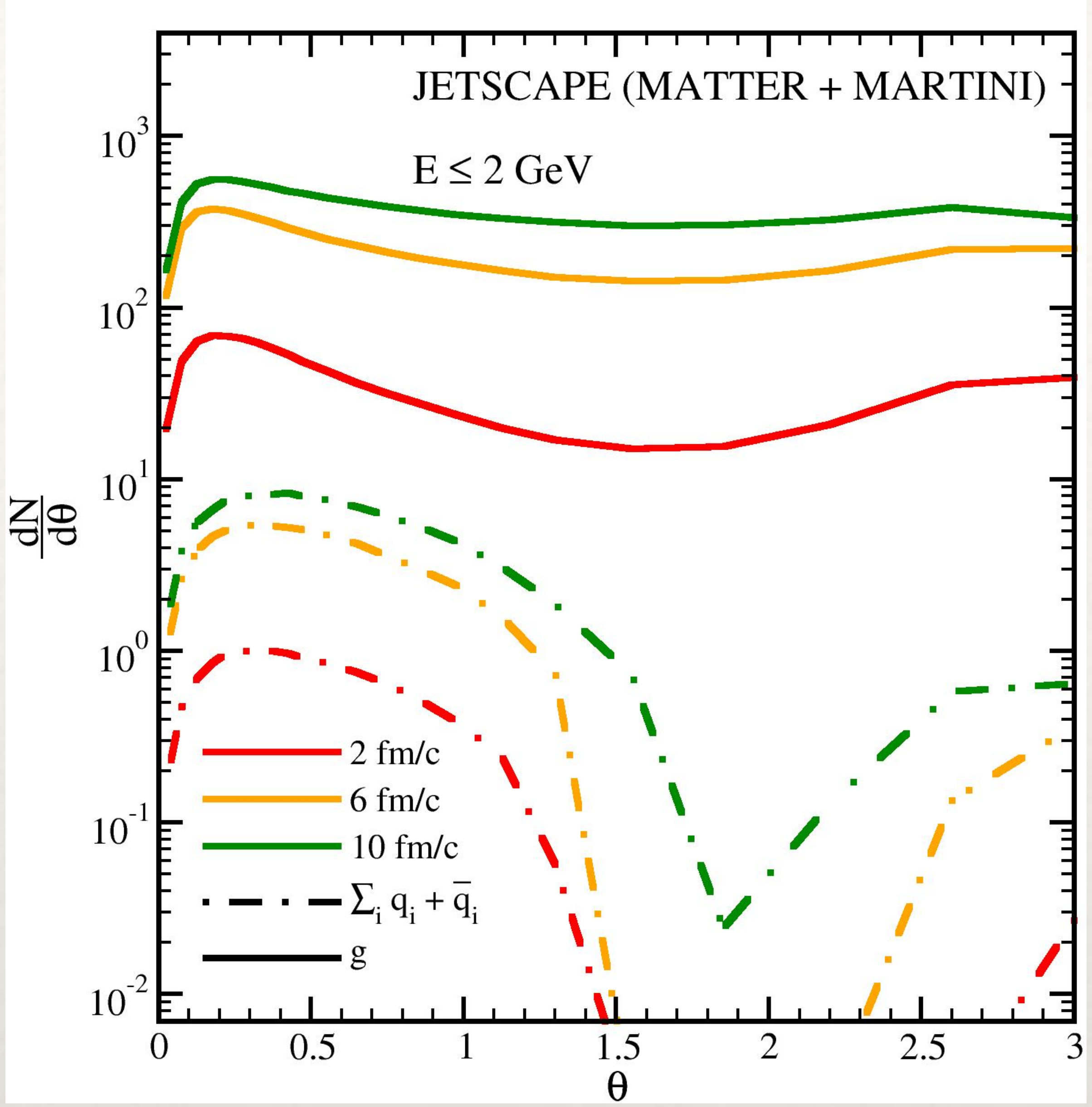
$$Q^2_{\rm med} = \sqrt{2E\hat{q}}$$

MATTER: medium-modified splitting function based on Higher-Twist formalism (rare scattering induced emission)

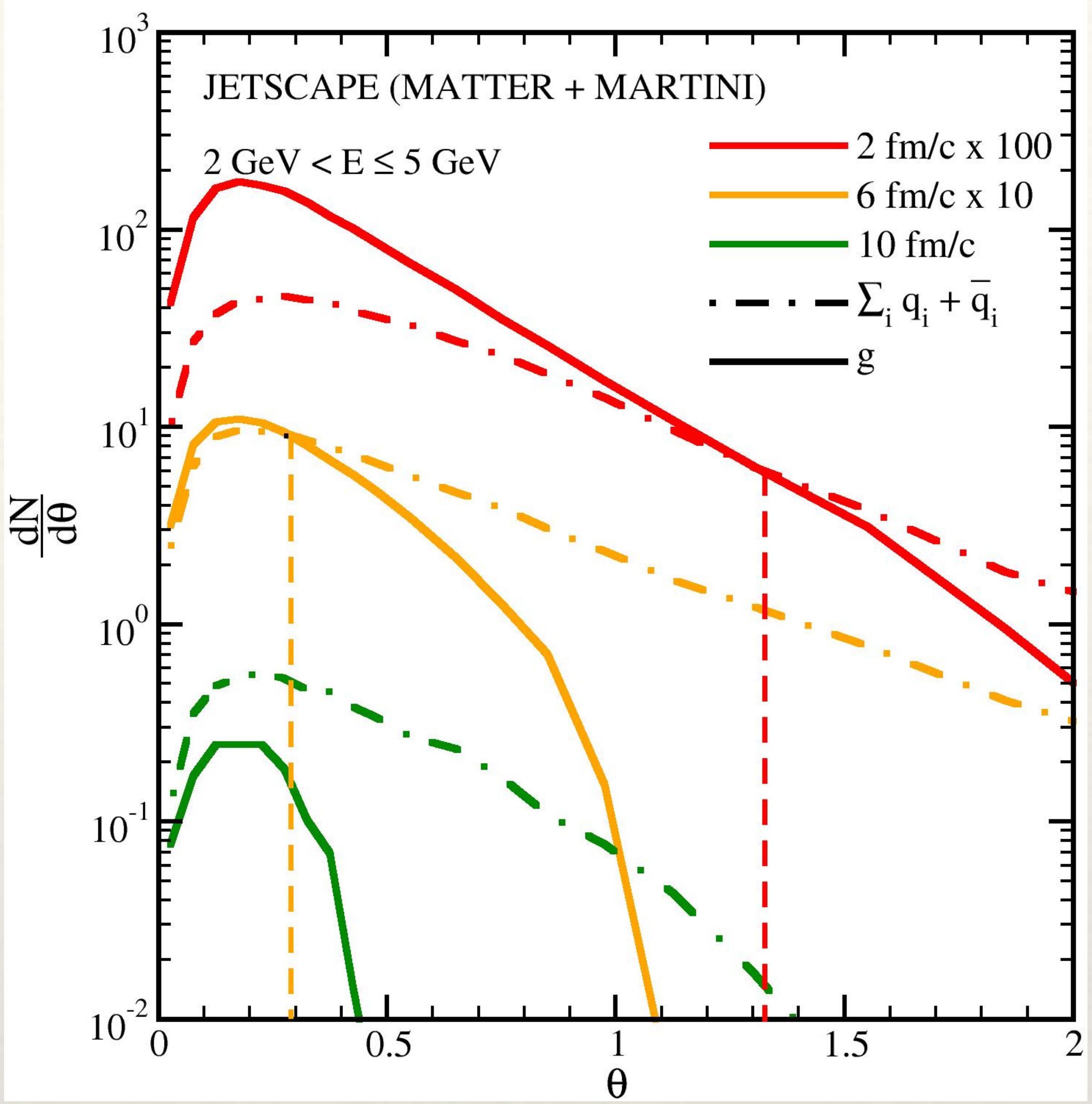
MARTINI: medium-modified splitting function based on AMY formalism (multiple scattering induced emission)

$2 \leftrightarrow 2$ scatterings (recoil + energy depletion) are implemented in both MATTER and MARTINI

Angular distribution of quarks vs. gluons from JETSCAPE



soft ($p < 2$ GeV)



semi-hard ($2 < p < 5$ GeV)

$T = 250$ MeV

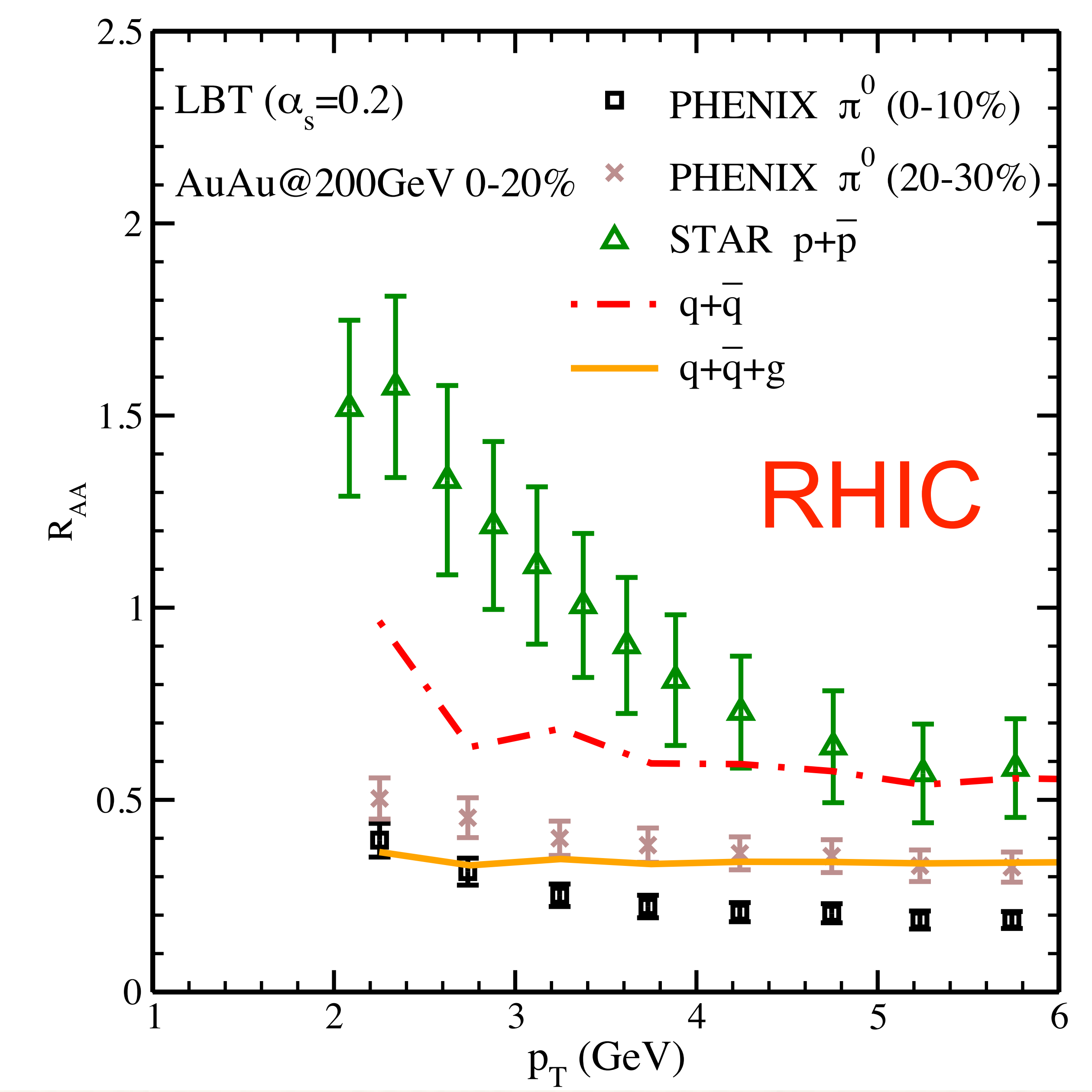
- Start with a 25 GeV gluon
- Soft region: dominated by gluons
- Semi-hard region: quarks dominate at large angle first and then over the entire angular regime at late time

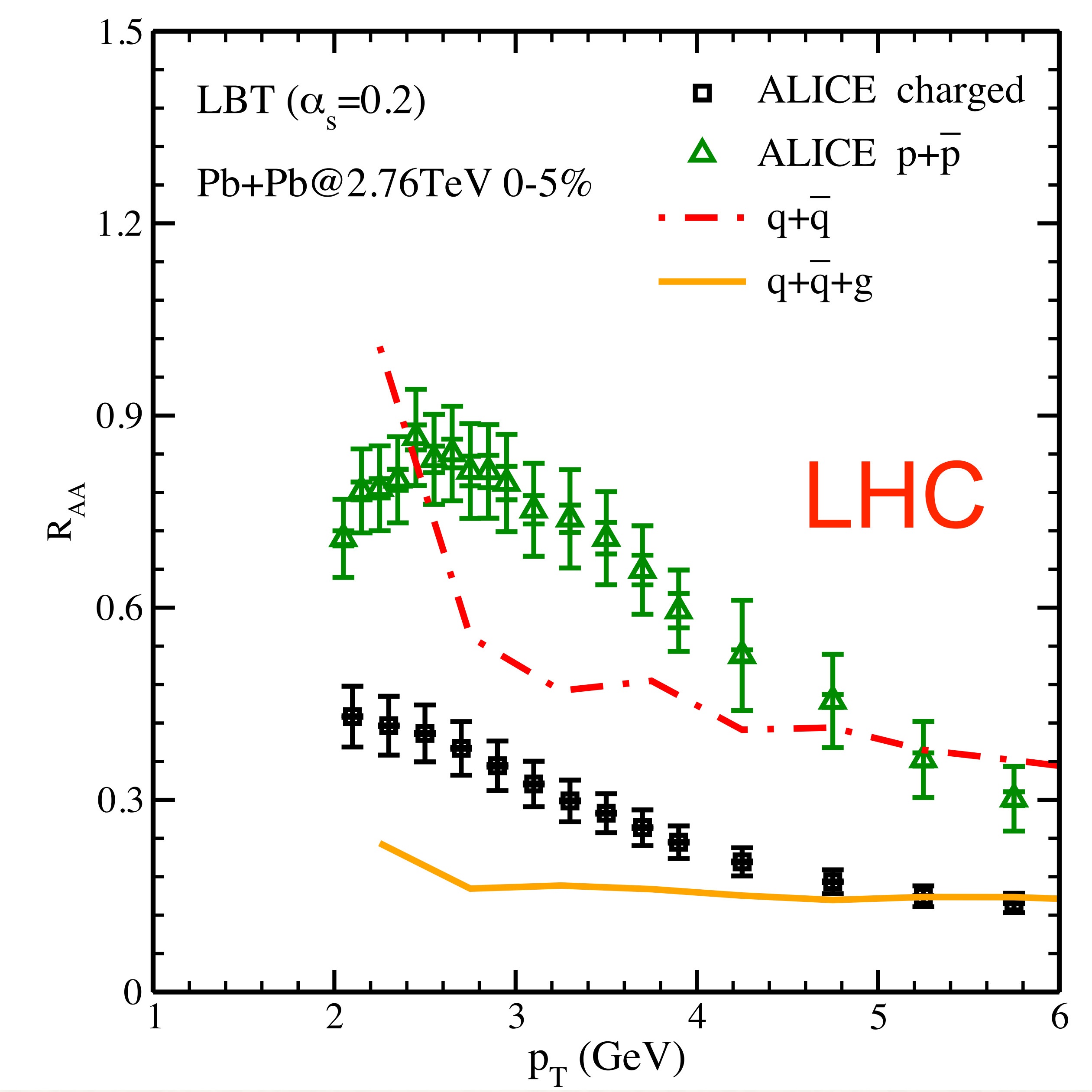
Implication on the final-state hadron chemistry

In the absence of a reliable hadronization model:

$$R_{AA}^{B+\bar{B}} \sim R_{AA}^{q+\bar{q}} \qquad R_{AA}^{h} \sim R_{AA}^{q+\bar{q}+g}$$

LBT simulation inside a realistic QGP medium:
initial parton spectra — LO pQCD, QGP — CLVisc hydrodynamic simulation





- Enhancement of baryon production in the semi-hard regime only due to scatterings
- Alternative mechanism of baryon enhancement besides the coalescence model
- Can be utilized for a better constraint on the hadronization model

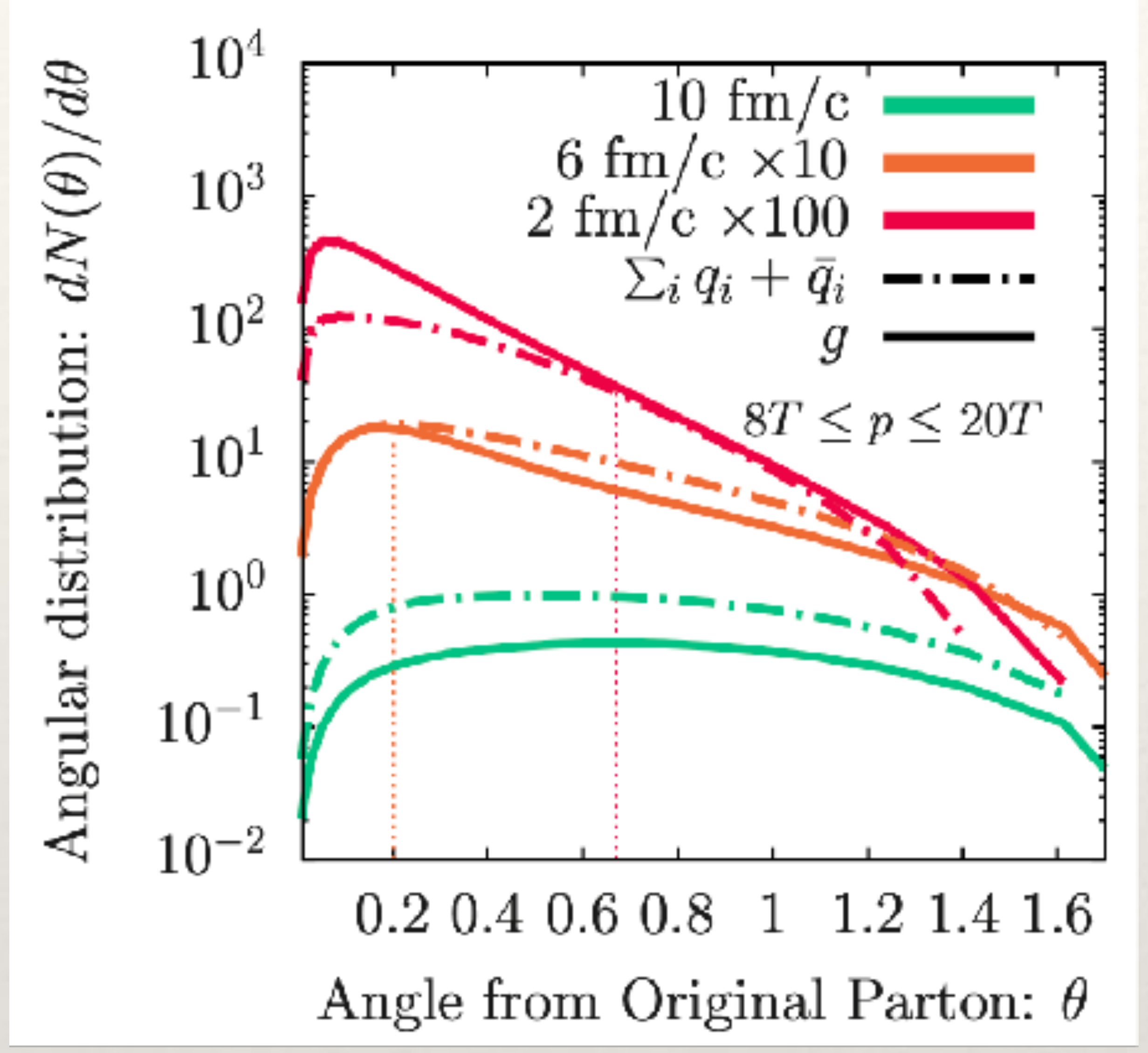
Summary and Outlook

- Studied flavor change processes inside quenched jets
- Found larger conversion rate from gluon to quark than the reverse within pQCD
- Showed significant quark enhancement inside gluon jet across 3 different models
- Proposed a new mechanism of semi-hard baryon enhancement: scatterings between jet showers and the QGP
- Require further efforts (e.g. non-perturbative interactions, hadronization, etc.) for a quantitative exploration of measurable effects

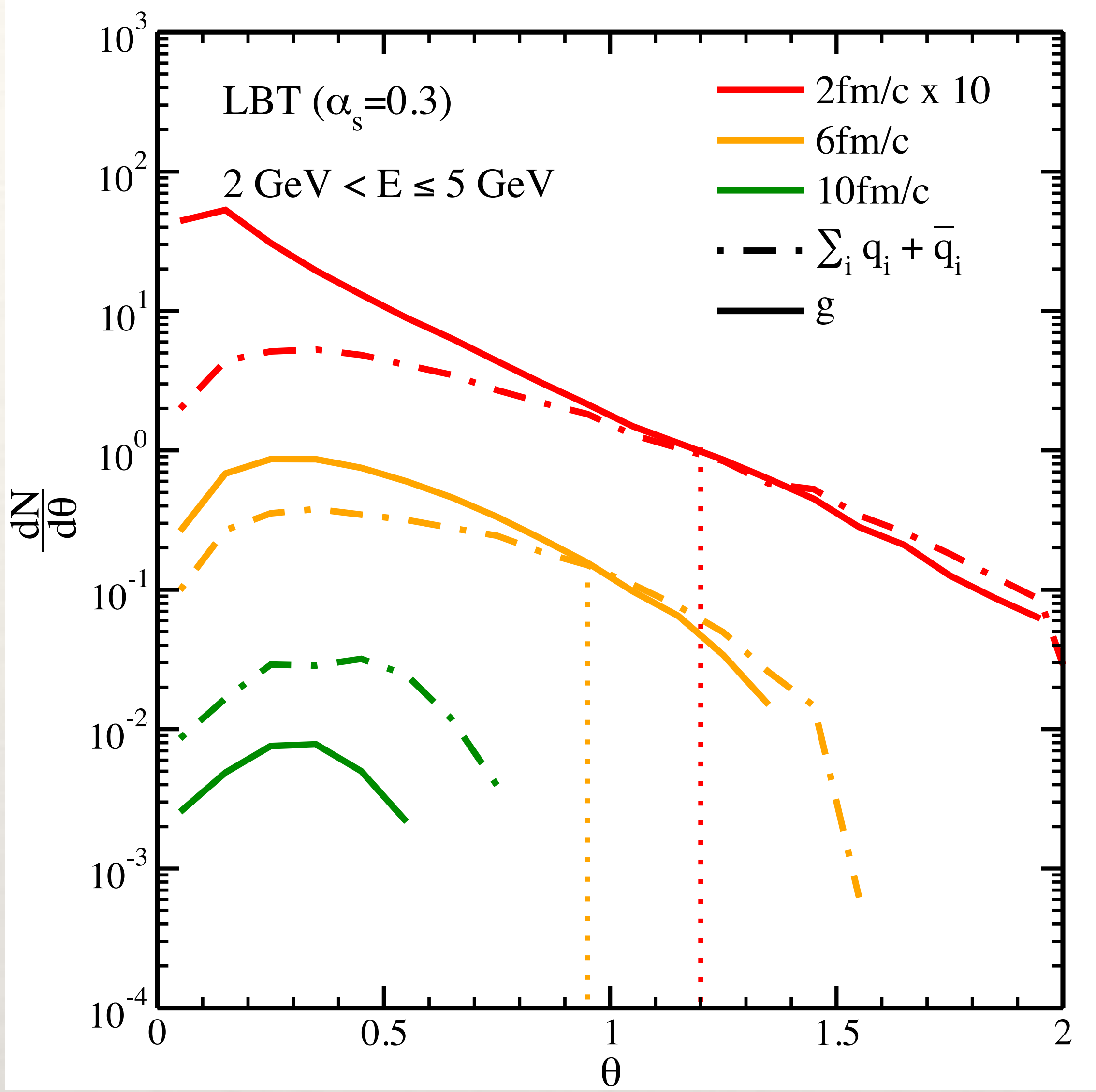
Thank you!

Comparison between three models

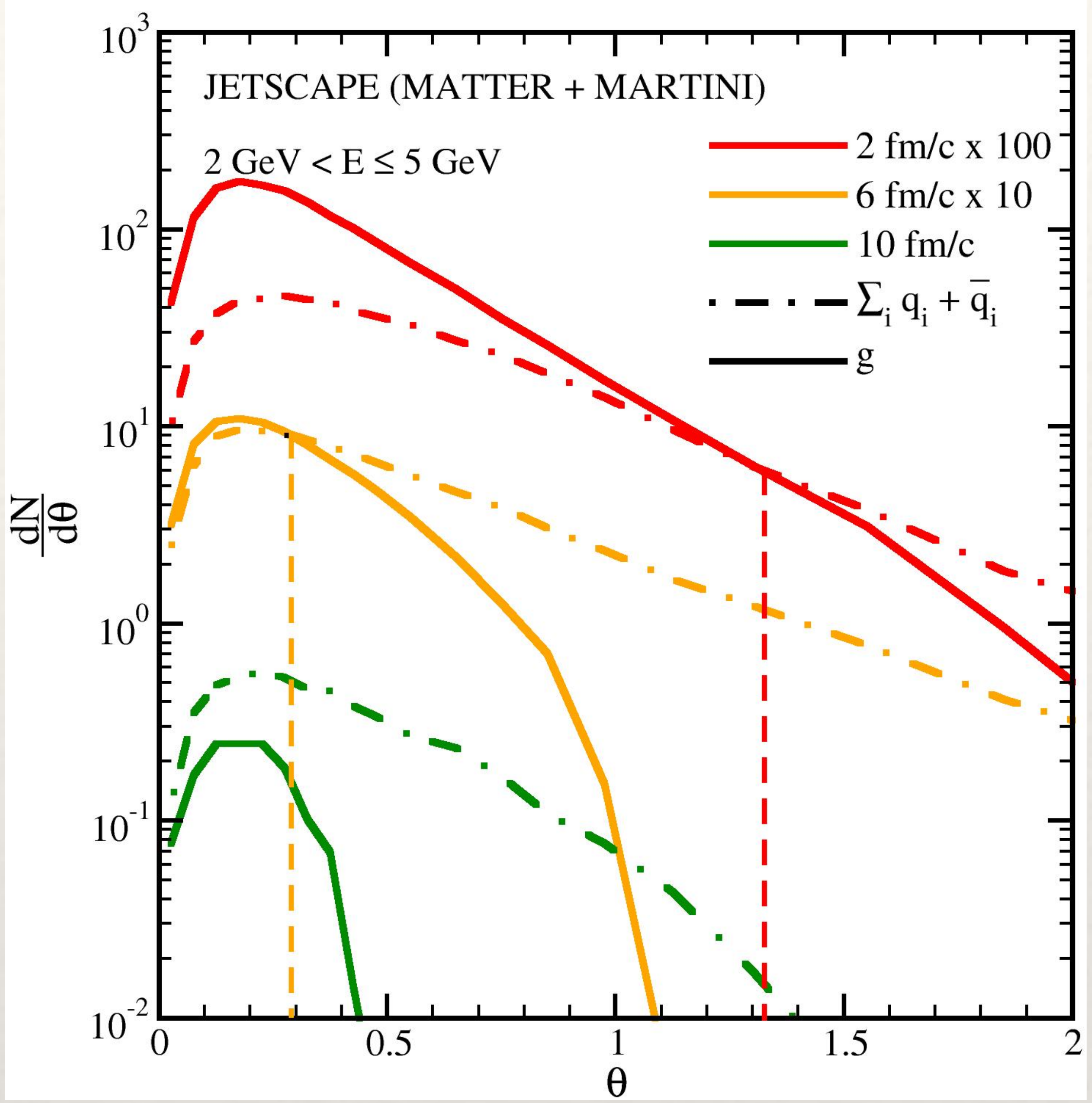
AMY semi-analytical



LBT



JETSCAPE (MATTER+MARTINI)



- Common feature: gluons convert to quarks in the semi-hard regions (just by scatterings)
- AMY/LBT vs. JETSCAPE: high-Q stage delays jet-medium scatterings, q and g crosses at higher θ at early time (2 fm)
- AMY/JETSCAPE vs. LBT: more jet-medium scatterings in AMY than higher-twist, q and g crosses at lower θ at later time (6 fm)