Flavor hierarchy of jet quenching in relativistic heavy-ion collisions

Wen-Jing Xing

Central China Normal University (CCNU)

Collaborator: Shanshan Cao, Guang-You Qin, Hongxi Xing

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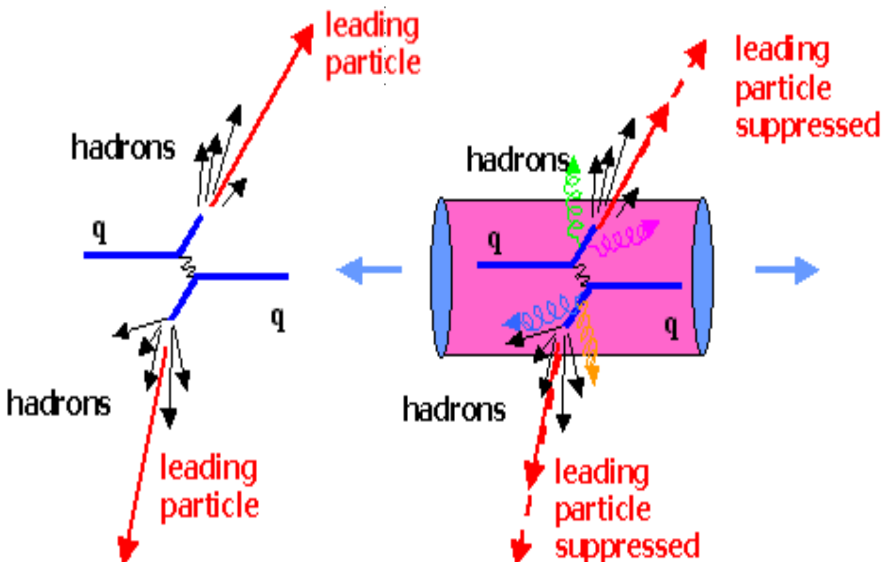
Outline

- **Introduction**
- **A next-to-leading-order (NLO) perturbative QCD framework for heavy and light flavor jet production**
- **A Linear Boltzmann Transport (LBT) model for heavy and light flavor jet evolution**
- **The nuclear modification factor of heavy and light hadrons**
- **Summary**

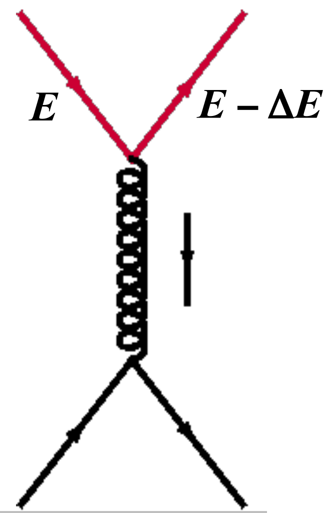
Jet Quenching in heavy-ion collisions

Jet quenching in quark-gluon plasma

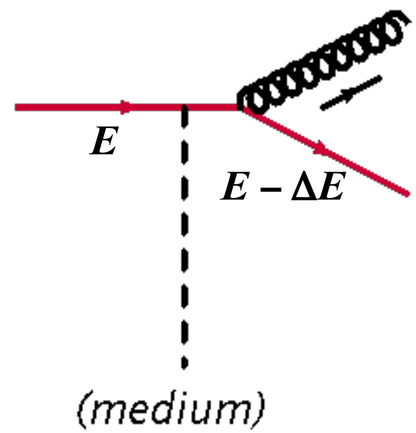


p+p **A+A**

parton-medium interaction



collisional



radiative

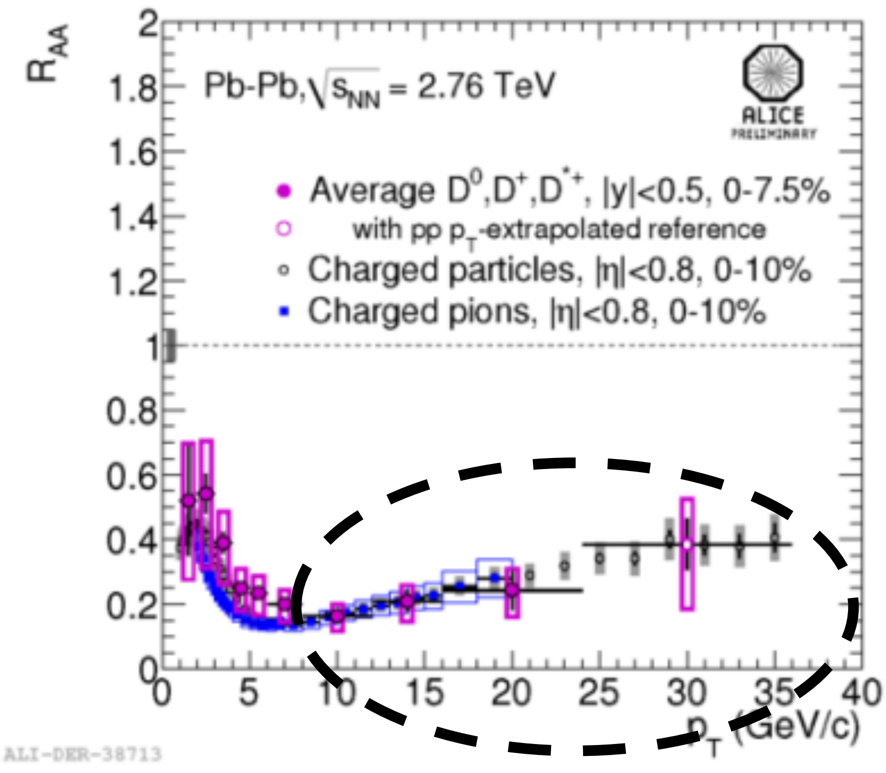
- **Probe QGP with jet : jet-medium interaction leads to parton energy loss.**
- **Jet-medium interaction depends on QGP properties and jet properties (color, mass and energy).**
- **Jet suppression — the spectra of high p_T hadrons will be modified, quantified with nuclear modification factor:**

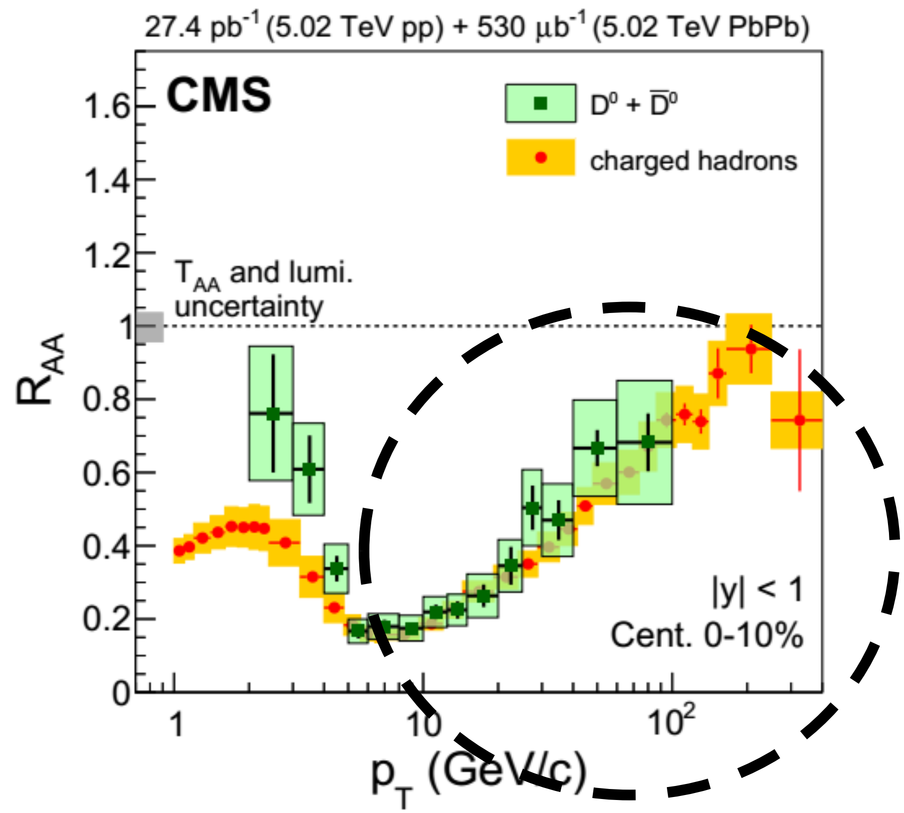
$$R_{AA} = \frac{dN^{AA} / d^2 p_T dy}{N_{\mathrm{coll}} dN^{pp} / d^2 p_T dy}$$

Flavor hierarchy PUZZLE of jet quenching

- **Color & flavor dependences of parton energy loss:** $\Delta E_g > \Delta E_{u,d} > \Delta E_c > \Delta E_b$

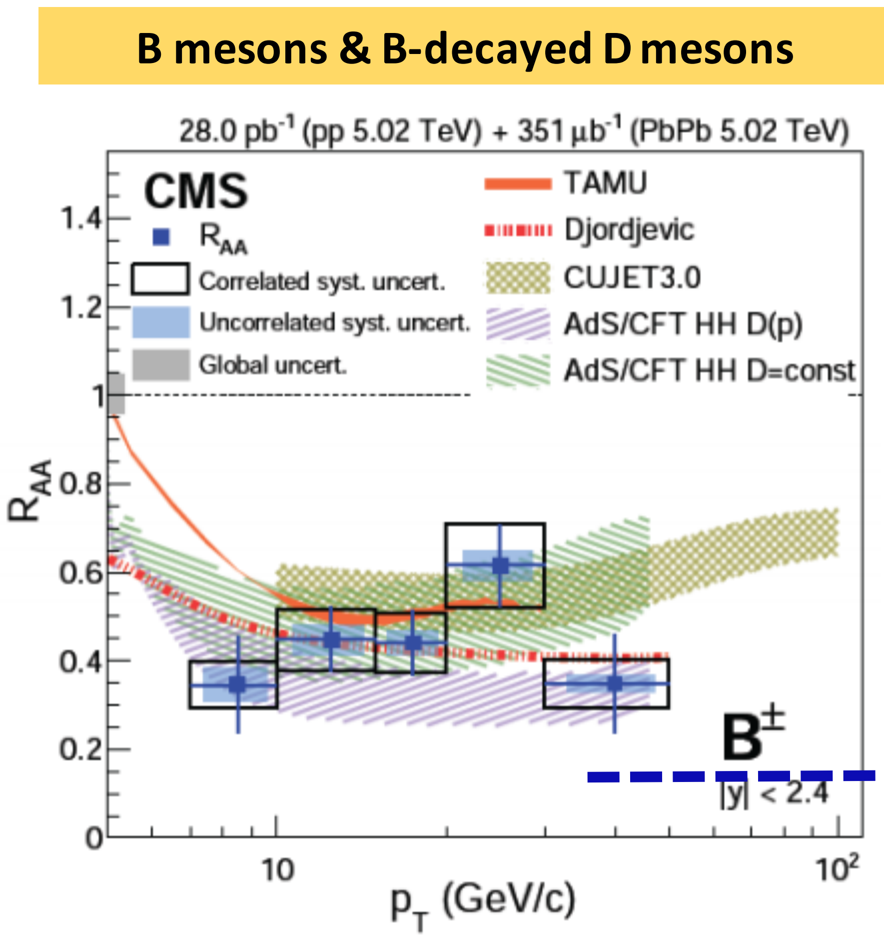
- **Have we observed less quenching effects for heavy flavor hadrons than light charged hadron ?**

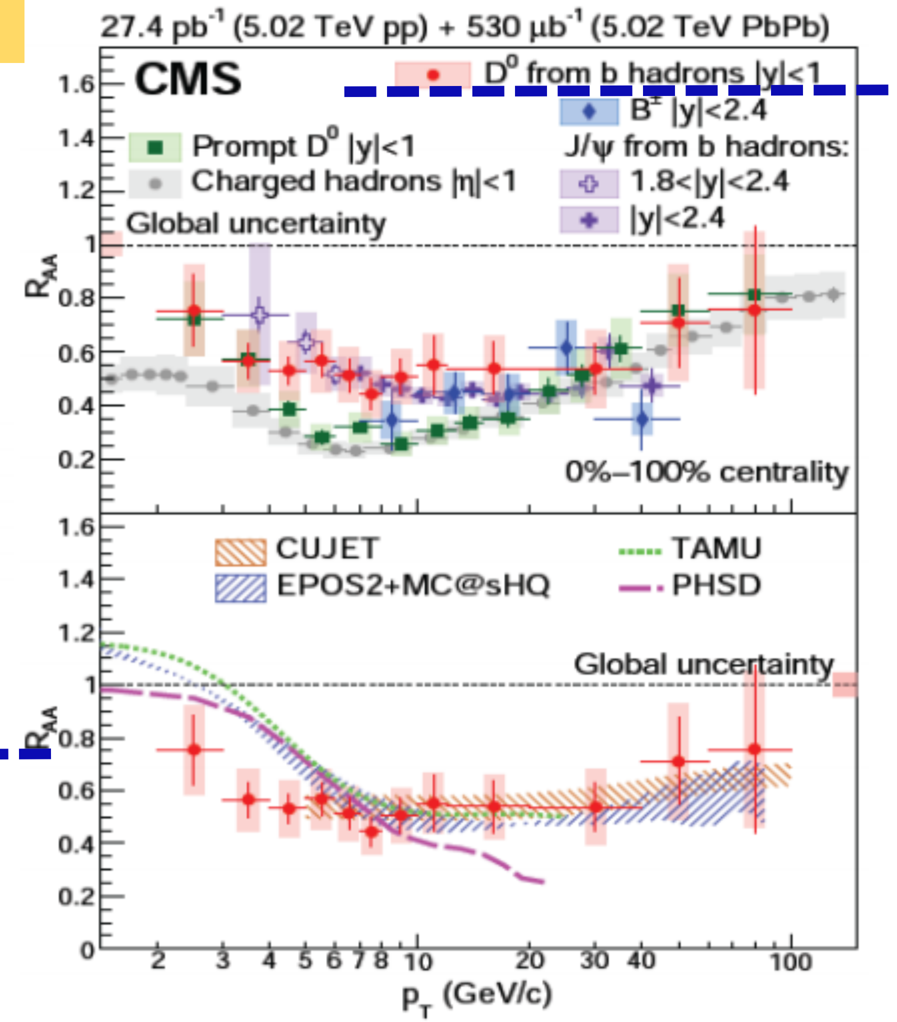




➢ **R_{AA} at high p_T: No significant flavor dependence observed.** $R_{AA}(D) \approx R_{AA}(h^{\pm})$

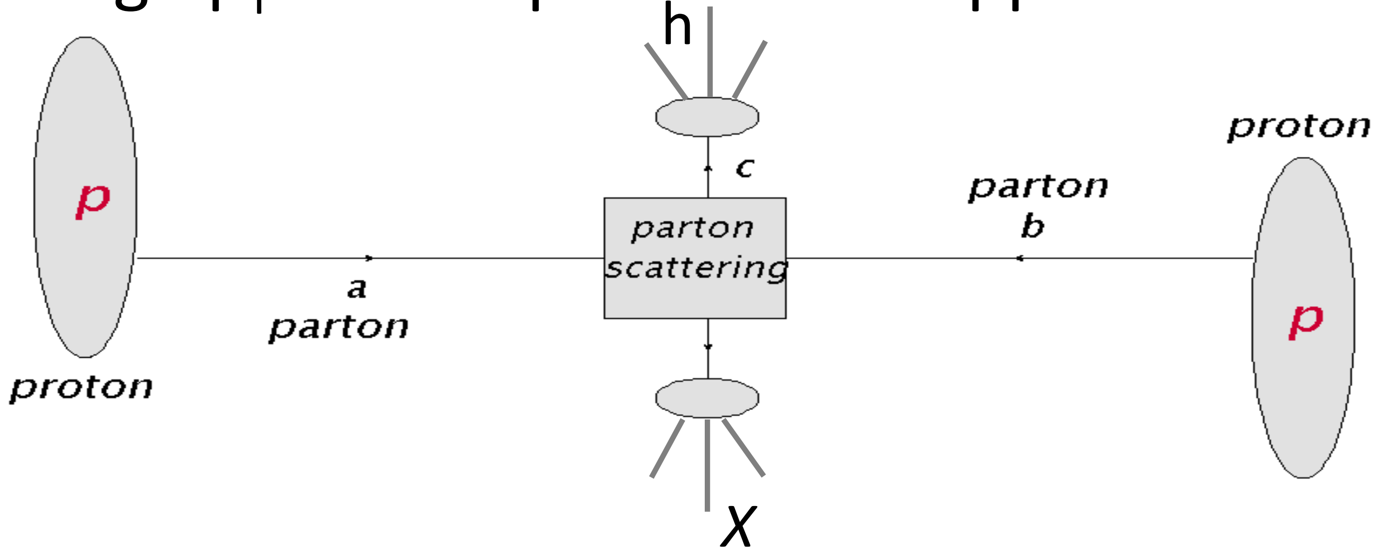
Flavor hierarchy **PUZZLE** of jet quenching





This provides a unique opportunity to study the flavor hierarchy of jet quenching.

High p_T hadron production in pp collisions



B. Jager, A. Schafer, M. Stratmann, and W. Vogelsang, Phys. Rev. D67, 054005 (2003)
F. Aversa, P. Chiappetta, M. Greco, and J. P. Guillet, Nucl, Phys. B327, 105 (1989)

In the **next-to-leading-order (NLO)** framework

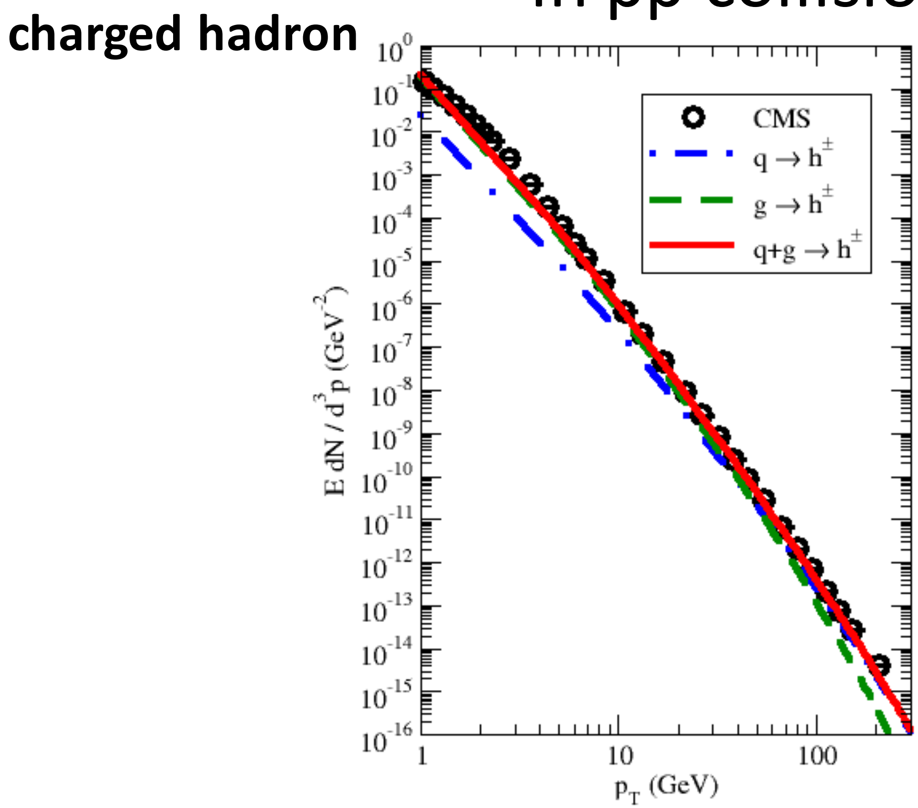
$$d\sigma_{pp\to hX} = \sum_{abc}\int dx_a \int dx_b \int dz_c\, f_a(x_a) f_b(x_b) d\hat{\sigma}_{ab\to c} D_{h/c}(z_c)$$

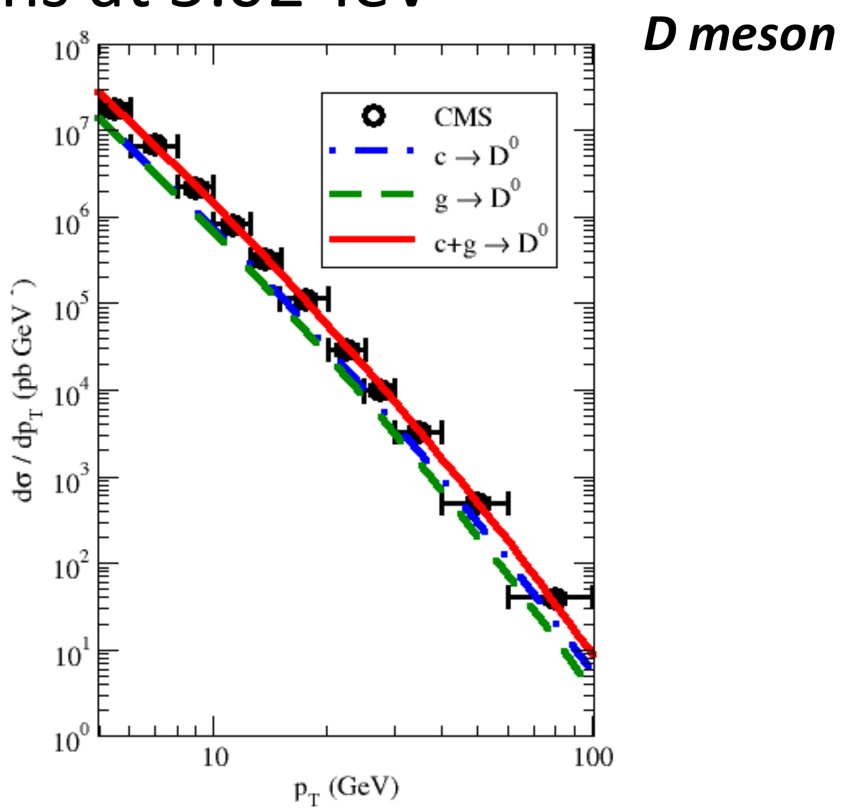
parton distribution functions (PDFs) : CTEQ parameterizations CTEQ, Eur. Phys. J. C12, 375 (2000)

fragmentation function (FF) : include both quark and gluon fragmentations to heavy and light hadron productions

charged hadrons: S. Kretzer, Phys. Rev. D62, 054001 (2000)
***D* mesons:** T. Kneesch, B. A. Kniehl, G. Kramer, and I. Schienbein, Nucl. Phys. B799, 34 (2008)
***B* mesons:** B. A. Kniehl, G. Kramer, and I. Schienbein, and H. Spiesberger, Phys. Rev. D77, 014011 (2008)

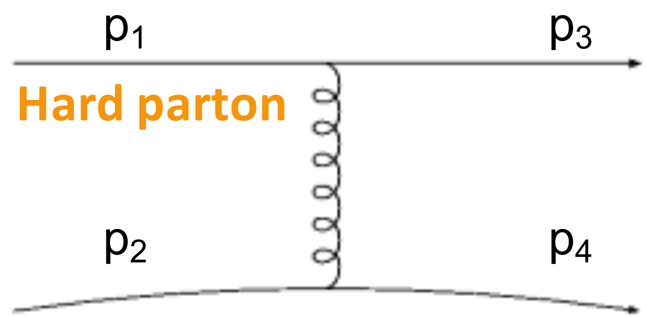
Light charged hadrons and *D* mesons production in pp collisions at 5.02 TeV





- **charged hadrons: gluon contribution dominates at low p_T and quark contribution becomes important at $p_T > 50$ GeV.**
- ***D* mesons: charm fragmentation and gluon fragmentation contribute almost equally at low p_T, then gluon contribution decreases with increasing p_T.**
- **Both contributions from quarks and gluons have to be taken into account when analyzing high p_T hadron suppression in AA collisons.**

A Linear Boltzmann transport (LBT) model



Elastic (collisional)

Boltzmann equation for parton "1" evolution:

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

The collisioin term is:

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

For elastic (2->2) process, the transition rate is related to microscopic cross section as:

$$\omega_{12\to34}(\vec{p}_1, \vec{k}) = \gamma_2 \int \frac{d^3 p_2}{(2\pi)^3} f_2(\vec{p}_2) \; \left[1 \pm f_3(\vec{p}_1 - \vec{k})\right] \left[1 \pm f_4(\vec{p}_1 - \vec{k})\right]$$

$$\times v_{rel} d\sigma_{12\to34}(\vec{p}_1, \vec{p}_2 \to \vec{p}_1 - \vec{k}, \vec{p}_2 + \vec{k})$$

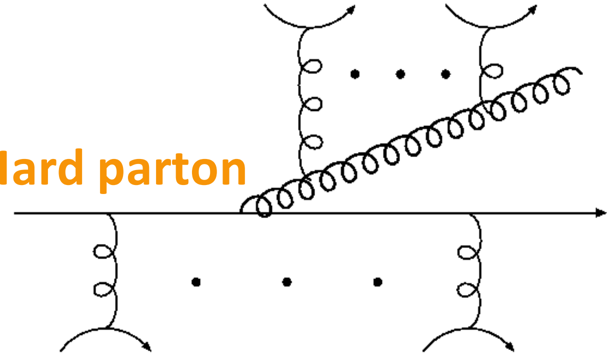
The elastic scattering rate for (2->2) process:

$$\Gamma(\vec{p}_1, \vec{k}) = \int d^3k\, \omega(\vec{p}_1, \vec{k})$$

$$\omega(\vec{p}_1, \vec{k}) \equiv \sum_{2,3,4} \omega_{12\to34}(\vec{p}_1, \vec{k})$$

S. Cao, T. Luo, G. -Y. Qin, and X. -N. Wang, Phys. Lett. B777, 255 (2018); S. Cao, T. Luo, G. -Y. Qin, and X. -N. Wang, Phys. Rev. C94, 014909(2016);Y. He, T. Luo, X. -N. Wang, and Y. Zhu, Phys. Rev. C91, 054908(2015)

A Linear Boltzmann transport (LBT) model



Include the inelastic process:

$$p_1 \cdot \partial f_1(x_1, p_1) = E_1\left(C_{el} + C_{inel}\right)$$

The inelastic scattering rate (average gluon number per unit time) is:

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

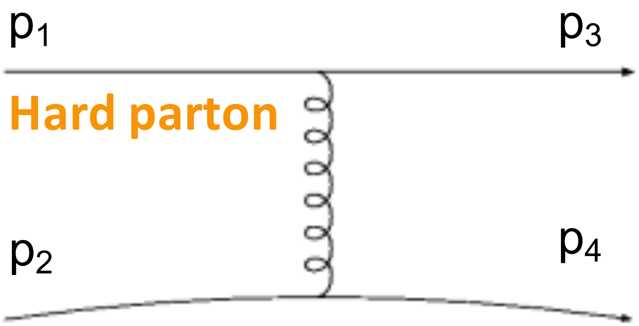
The medium-induced gluon spectrum is:

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

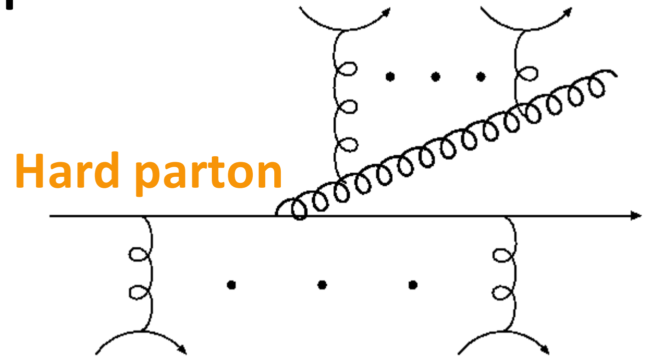
$\boxed{\hat{q} : \ dp_\perp^2 / dt}$ **is the momentum broadening due to (2->2) elastic process**

X.F. Guo and X.-N. Wang, Phys. Rev. Lett. 85, 3691(2000); A. Majumder, Phys. Rev. D85, 014023(2012); B.-W. Zhang, E. Wang, and X.-N. Wang, Phys. Rev. Lett. 93, 072301(2004)

A Linear Boltzmann transport (LBT) model



Elastic (collisional)



Inelastic (radiative)

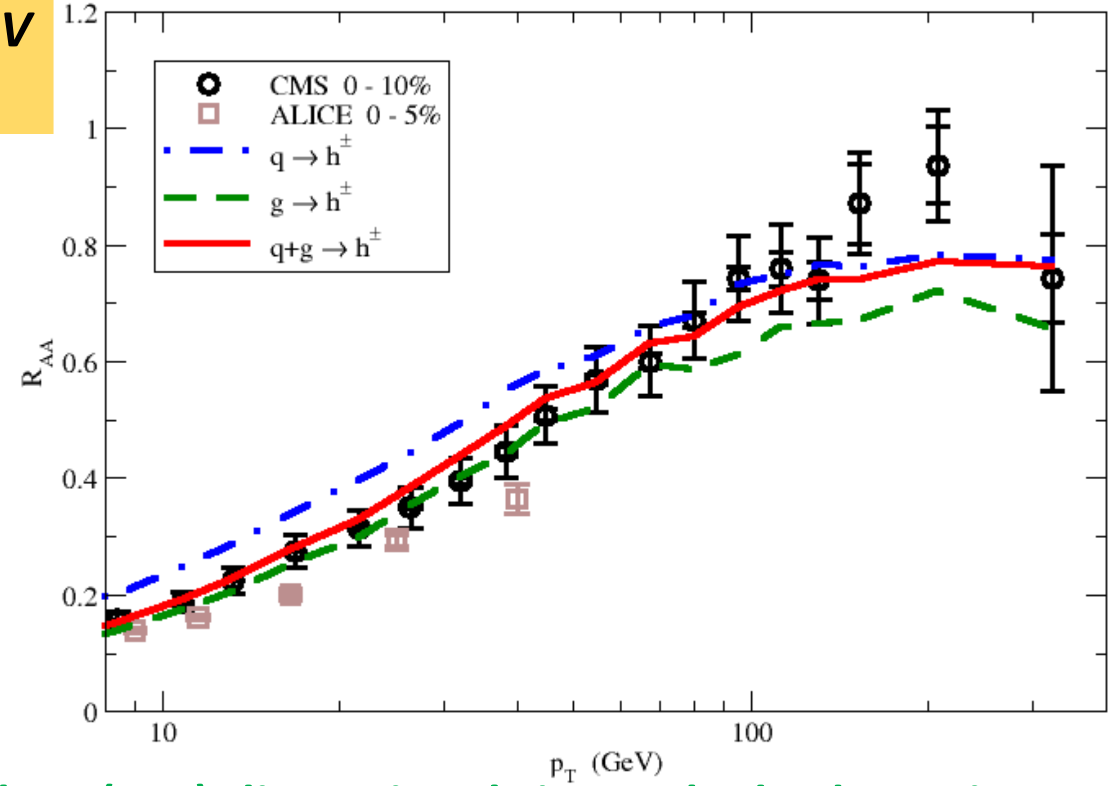
- $$\Gamma_{12\to34} = \frac{\gamma_2}{2E_1}\int\frac{d^3p_2}{(2\pi)^3 2E_2}\int\frac{d^3p_3}{(2\pi)^3 2E_3}\int\frac{d^3p_4}{(2\pi)^3 2E_4}$$
$$\times f_2(\vec{p}_2)\left[1 \pm f_3(\vec{p}_1 - \vec{k})\right]\left[1 \pm f_4(\vec{p}_2 + \vec{k})\right]S_2(s,t,u)$$
$$\times(2\pi)^4\delta^{(4)}(p_1 + p_2 - p_3 - p_4)\left|M_{12\to34}\right|^2$$
- $$\Gamma_{el} = \sum_i \Gamma_i$$
- $$P_{el} = 1 - e^{-\Gamma_{el}\Delta t}$$
- $$\langle N_g\rangle(E,T,t,\Delta t) = \Delta t\int dx dk_\perp^2 \frac{dN_g}{dx dk_\perp^2 dt}$$
- $$P_{inel} = 1 - e^{-\langle N_g\rangle}$$
- $$P(n) = \frac{\langle N_g\rangle^n}{n!}e^{-\langle N_g\rangle}$$

pure elastic inelastic

Elastic + Inelastic: $$\boxed{P_{tot} = P_{el} + P_{inel} - P_{el}P_{inel} = \underbrace{P_{el}(1 - P_{inel})}_{\text{pure elastic}} + \underbrace{P_{inel}}_{\text{inelastic}}}$$

Nuclear modifications of **charged hadrons**

Pb-Pb @5.02 TeV
0 - 10%



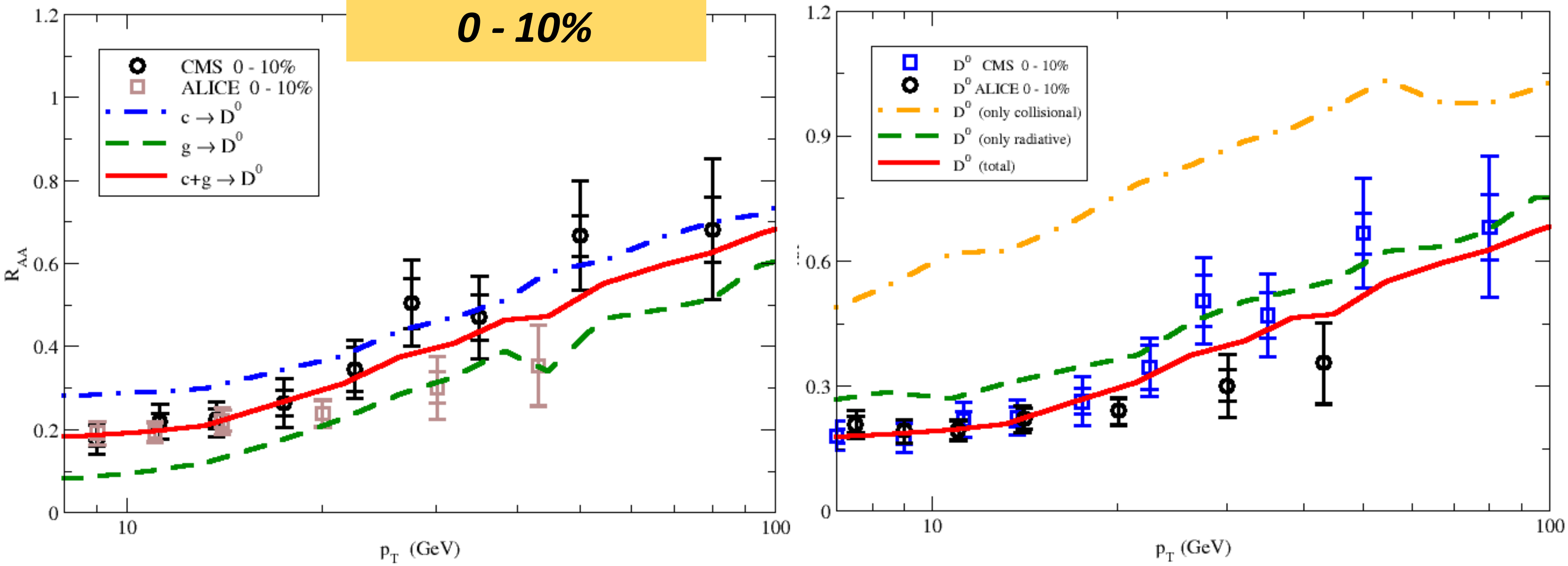
- **QGP fireball : a (3+1)-dimensional viscous hydrodynamics model CLVisc**

L. Pang, Q. Wang, and X. N. Wang, Phys. Rev. C86, 024911 (2012)
L. Pang, H. Petersen, and X. N. Wang, Phys. Rev. C97, 064918 (2018)

- **Due to color effect, quark-initiated hadrons exhibit less quenching effect than gluon-initiated hadrons.**
- **combining both quark and gluon fragmentaions to charged hadrons, we obtain a nice description of charged hadron R_{AA} over a wide range of p_T.**

Nuclear modifications of *D* mesons

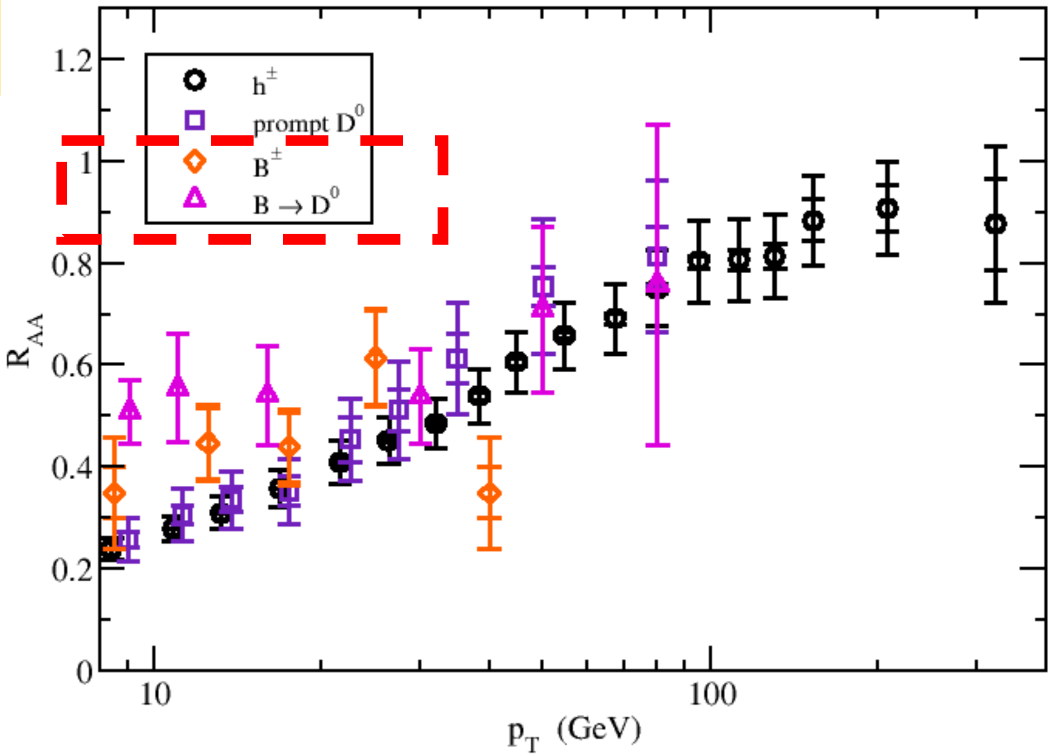
Pb-Pb @5.02 TeV
0 - 10%



- ***D*** **meosns produced from charm quark fragmentation have less quenching than *D* mesons from gluon fragmentation.**
- **Combining both charm quark and gluon contributions, we obtain successful description of *D* meson R_{AA}.**
- **Collisional energy loss gives non-negligible contributions to R_{AA} at not-very high p_T regime and diminishes with increasing p_T.**

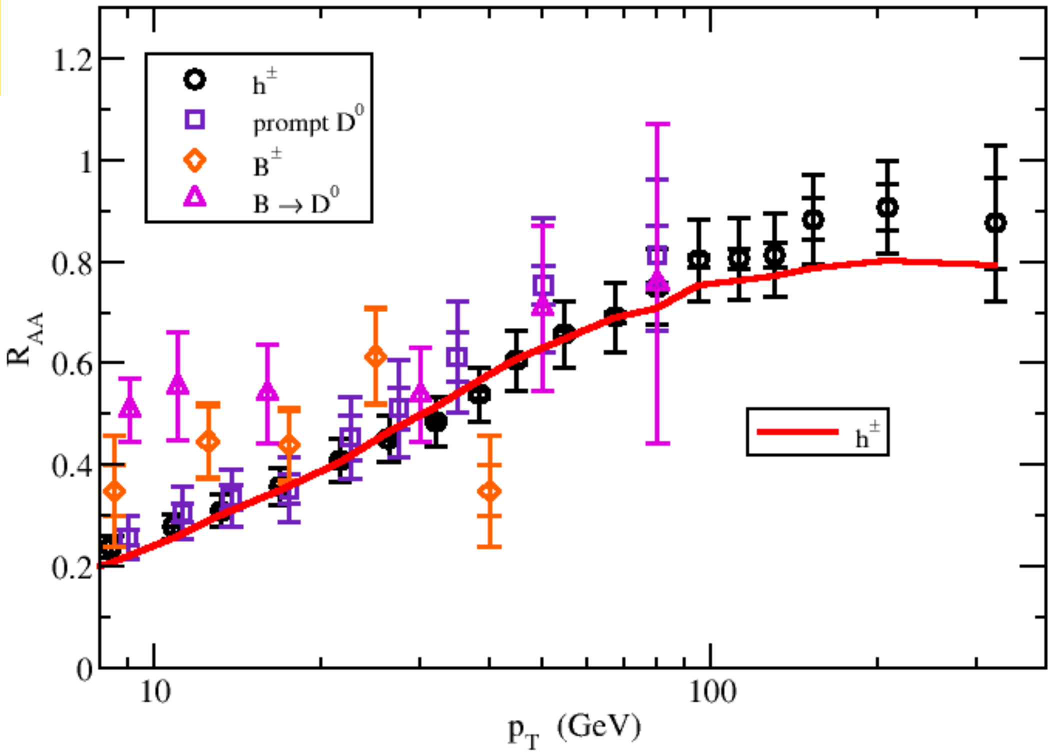
Flavor hierarchy of jet quenching

Pb-Pb @5.02 TeV
0 - 80%



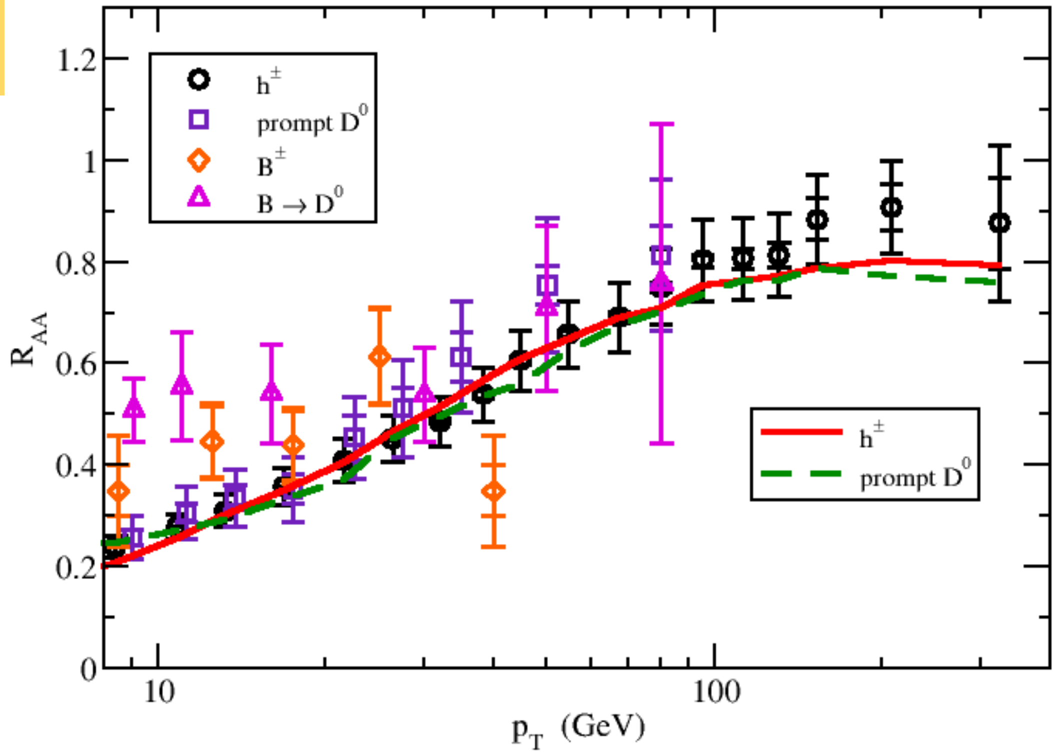
Flavor hierarchy of jet quenching

Pb-Pb @5.02 TeV
0 - 80%



Flavor hierarchy of jet quenching

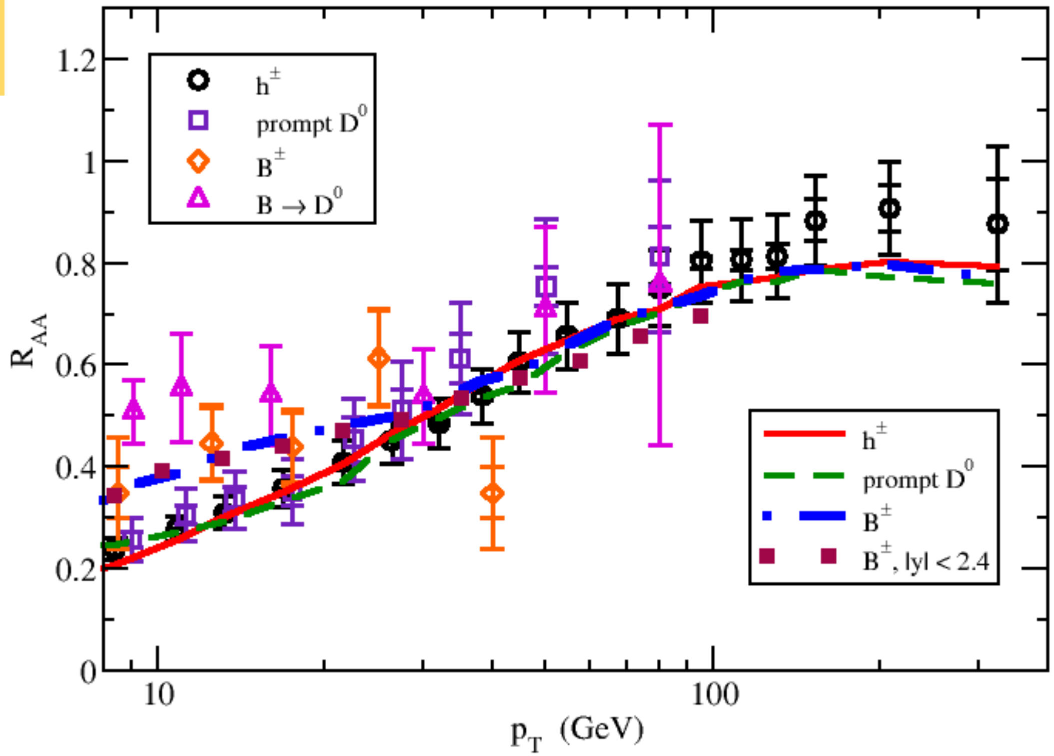
Pb-Pb @5.02 TeV
0 - 80%



- **A natual solution to the flavor hierarchy puzzle of jet quenching.**

Flavor hierarchy of jet quenching

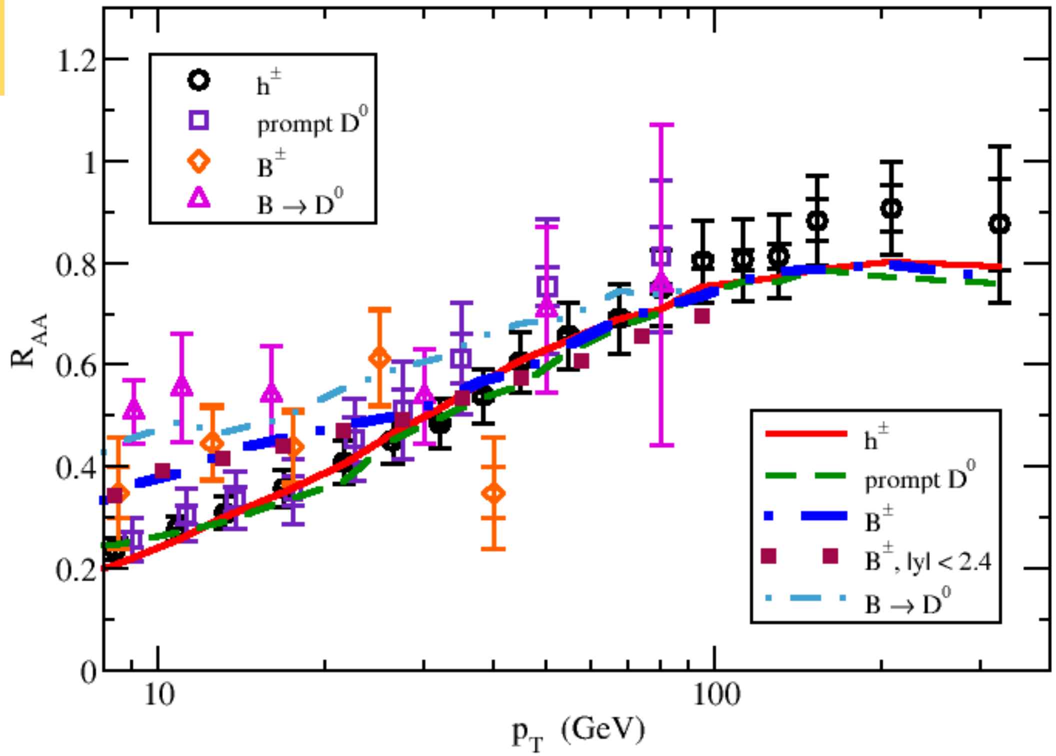
Pb-Pb @5.02 TeV
0 - 80%



- **A natual solution to the flavor hierarchy puzzle of jet quenching.**
- **Above 30-40 GeV, our model predicts similar suppression effects for *B* mesons to charged hadrons and *D* mesons, which can be tested by future measurements.**

Flavor hierarchy of jet quenching

Pb-Pb @5.02 TeV
0 - 80%



- **A natual solution to the flavor hierarchy puzzle of jet quenching.**
- **Above 30-40 GeV, our model predicts similar suppression effects for *B* mesons to charged hadrons and *D* mesons, which can be tested by future measurements.**
- **Our model can simultaneously describe the nuclear modifications of charged hadrons, prompt *D* mesons, *B* mesons and *B*-decayed *D* mesons.**

Summary

- **A next-to-leading-order perturbative QCD framework for calculating the productions of high p_T hadrons, consistently including quark and gluon fragmentations to light and heavy flavor hadrons.**

- **A Linear Boltzmann Transport (LBT) model for simulating the evolution of heavy and light flavor jet partons in QGP medium, including both elastic and inelastic interactions between jet partons and the medium constituents.**

- **A satisfactory description of the experimental data for the nuclear modification factors of charged hadrons, prompt *D* mesons, *B* mesons and *B*-decayed *D* mesons over the widest range of transverse momenta (p_T = 8-300 GeV), providing a natural solution to the flavor hierarchy puzzle of jet quenching.**

Thank You *!*

Back-up

B mesons production in pp collisions at 5.02 TeV