Flavor hierarchy of jet quenching in relativistic heavy-ion collisions

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arXiv:1906.00413

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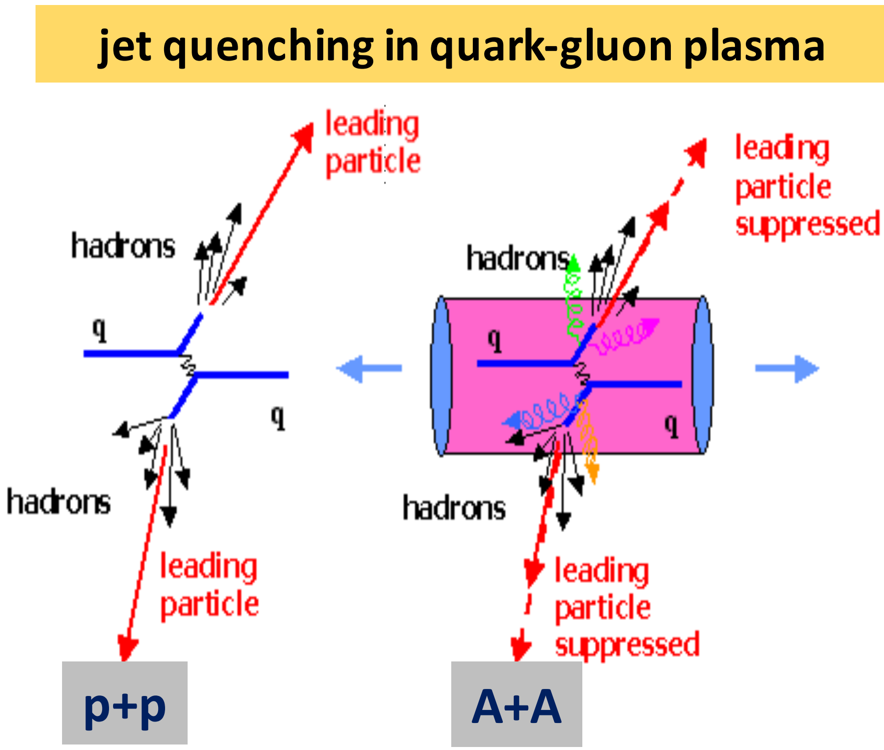
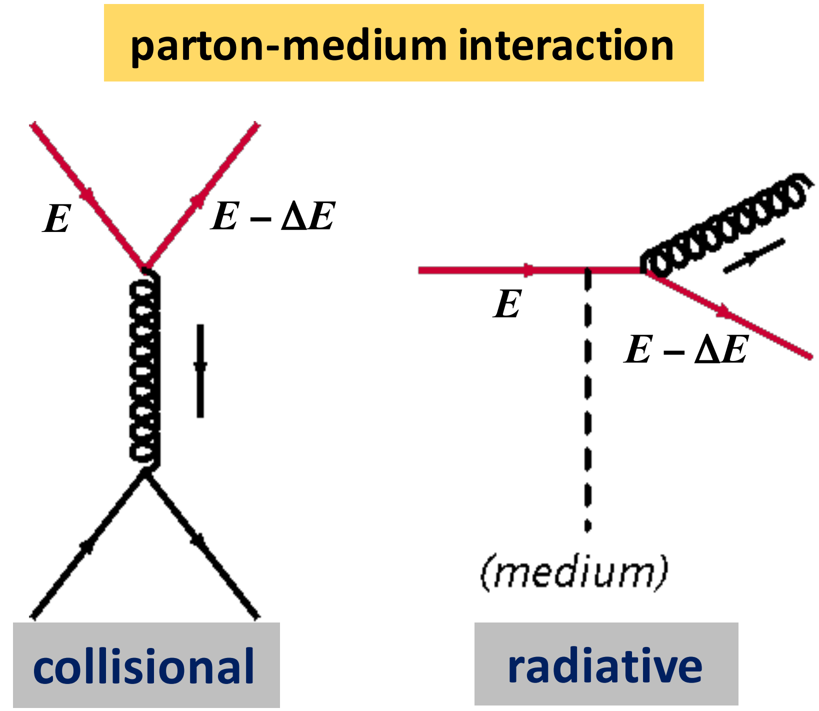
Outline

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

Jet quenching in heavy-ion collisions





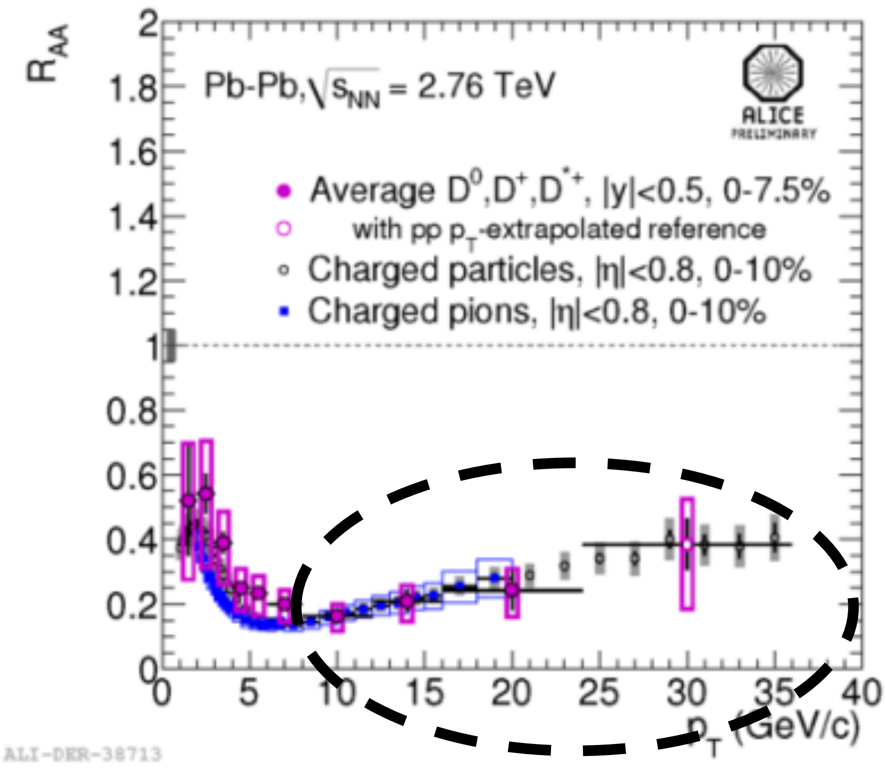
- Jet quenching (jet-medium interaction) provides valuable tools to probe QGP properties: parton energy loss.
- Jet-medium interaction depends on QGP properties and jet properties (color, mass and energy).
- Jet suppression — the spectra of high p_T hadrons will be modified, quantified with nuclear modification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

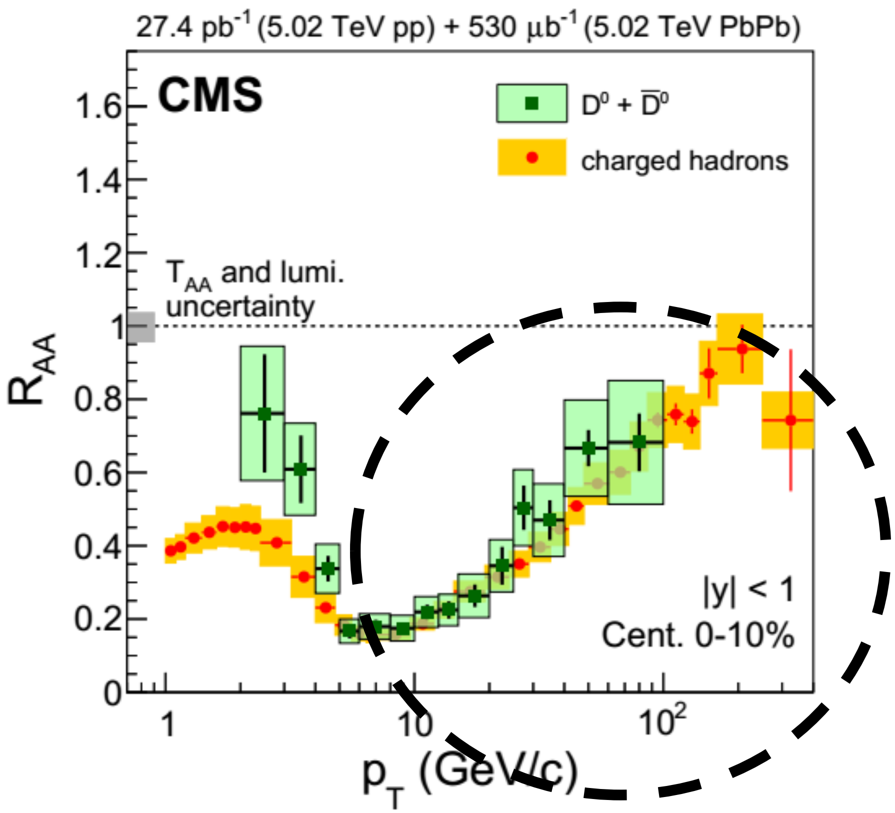
$$R_{AA} = \frac{dN^{AA} / d^2 p_T dy}{N_{coll} dN^{pp} / d^2 p_T dy}$$

Flavor hierarchy puzzle of jet quenching

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

- **Expect heavy flavor hadrons exhibit less quenching effects than light charged hadrons.**

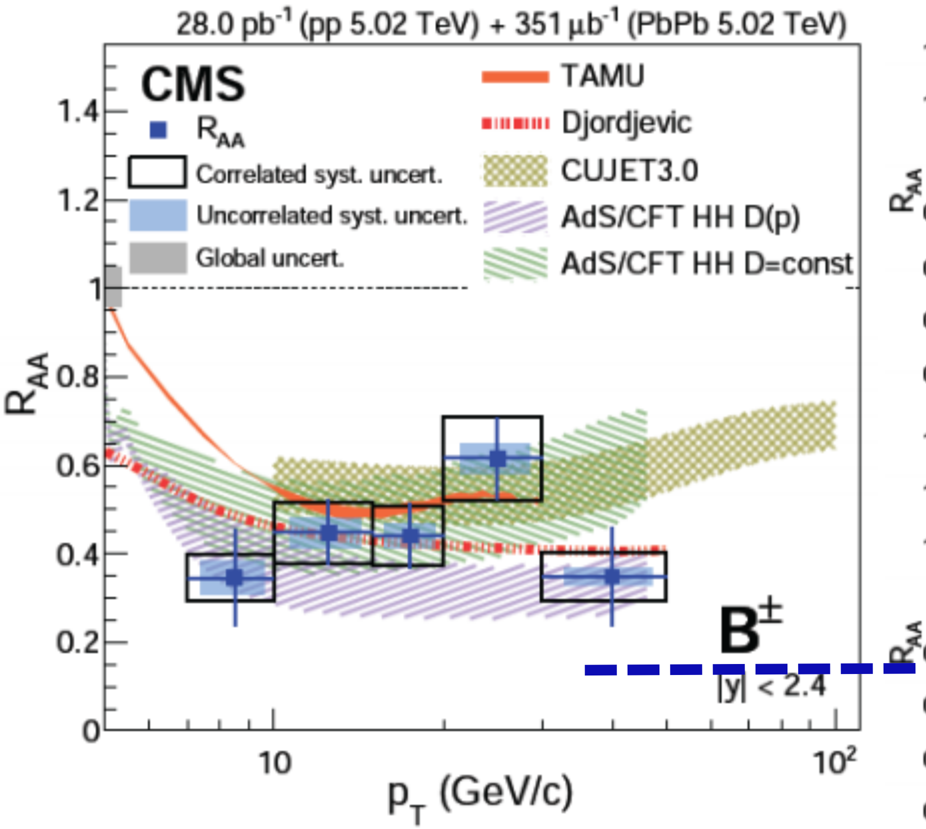


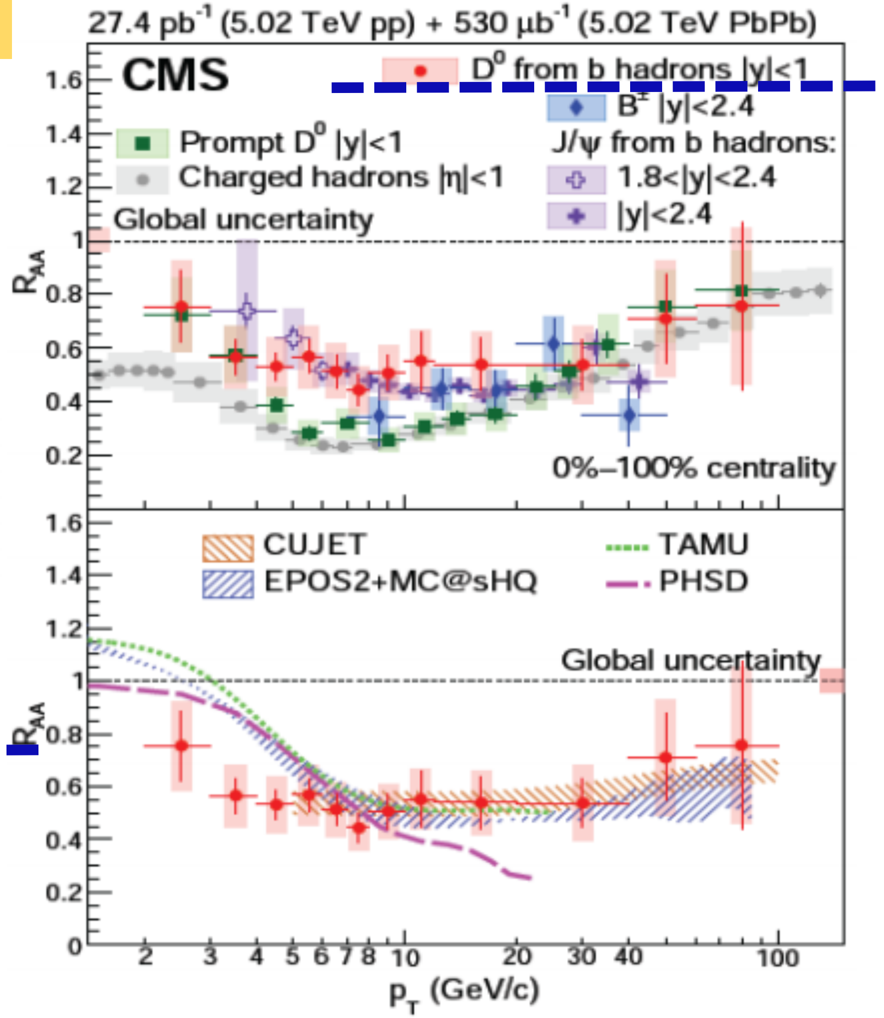


➢ **R_{AA} at high p_T: No significant flavor dependence observed.** $R_{AA}(D) \approx R_{AA}(h^{\pm})$

Flavor hierarchy of jet quenching

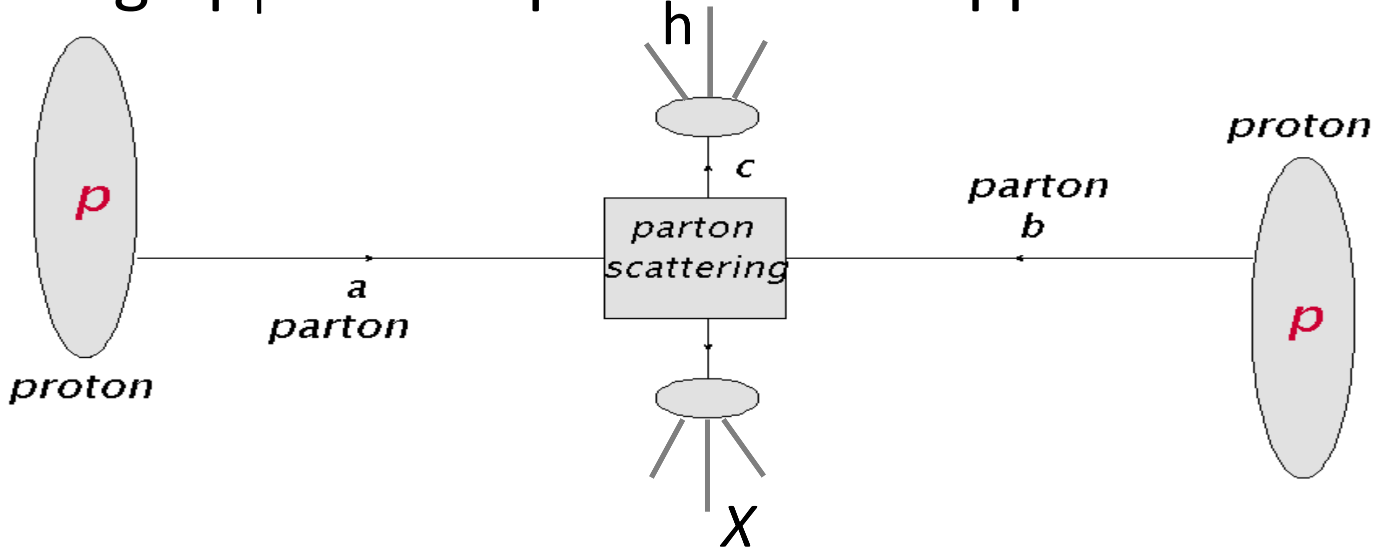
B mesons & B-decayed D mesons





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

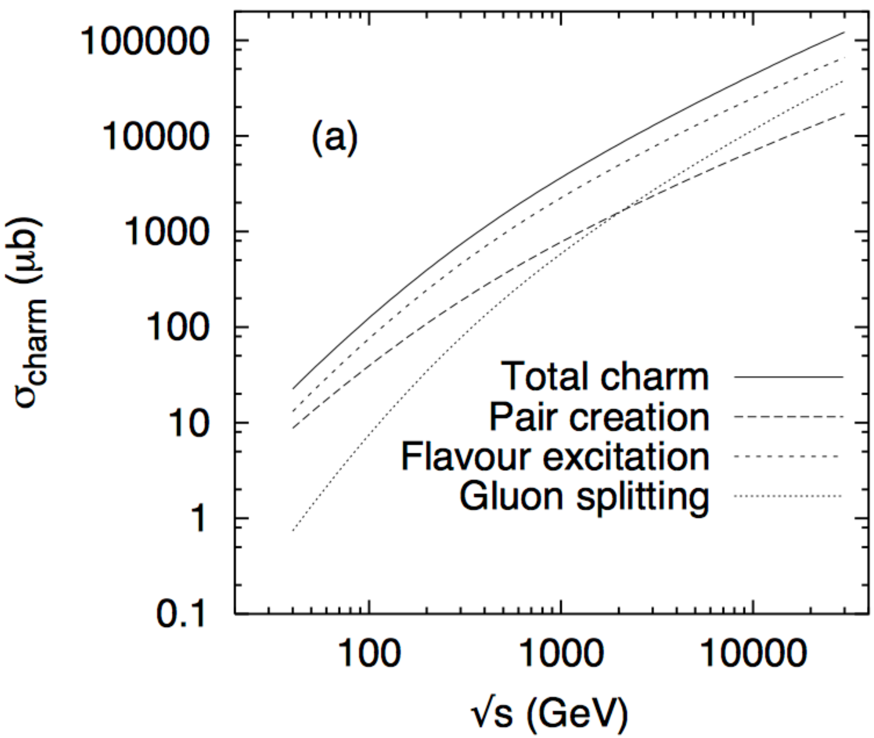
$$d\sigma_{pp\to hX} = \sum_{abc}\int dx_a \int dx_b \int dz_c\, f_a(x_a) f_b(x_b)\, d\hat{\sigma}_{ab\to c} D_{h/c}(z_c)$$

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

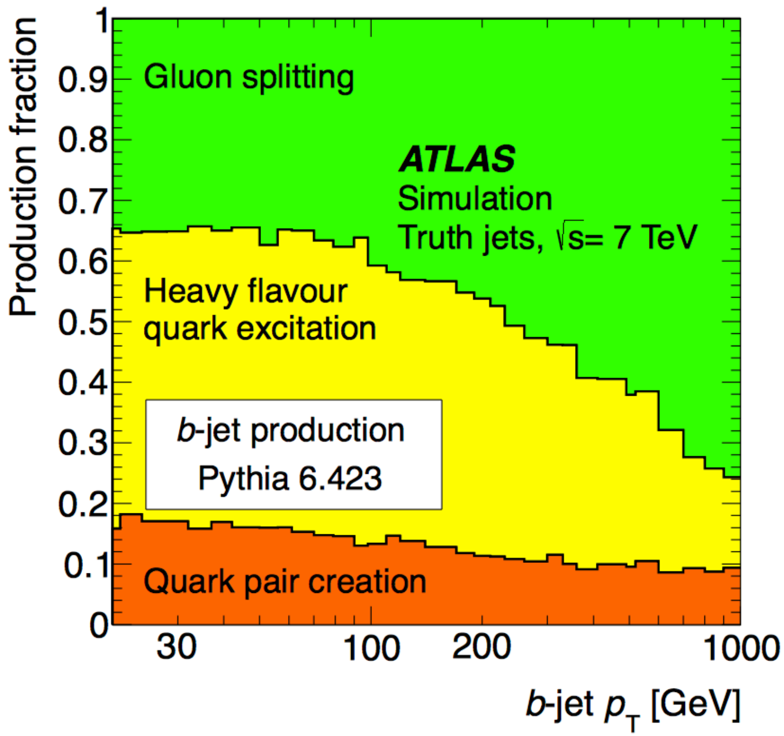
fragmentation function (FF) : include both quark and gluon fragmentations to heavy and light hadron productions

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)

Gluon contribution to heavy quark jet production



E. Norrbin and T. Sjostrand, Eur. Phys. J. C17, 137(2000)

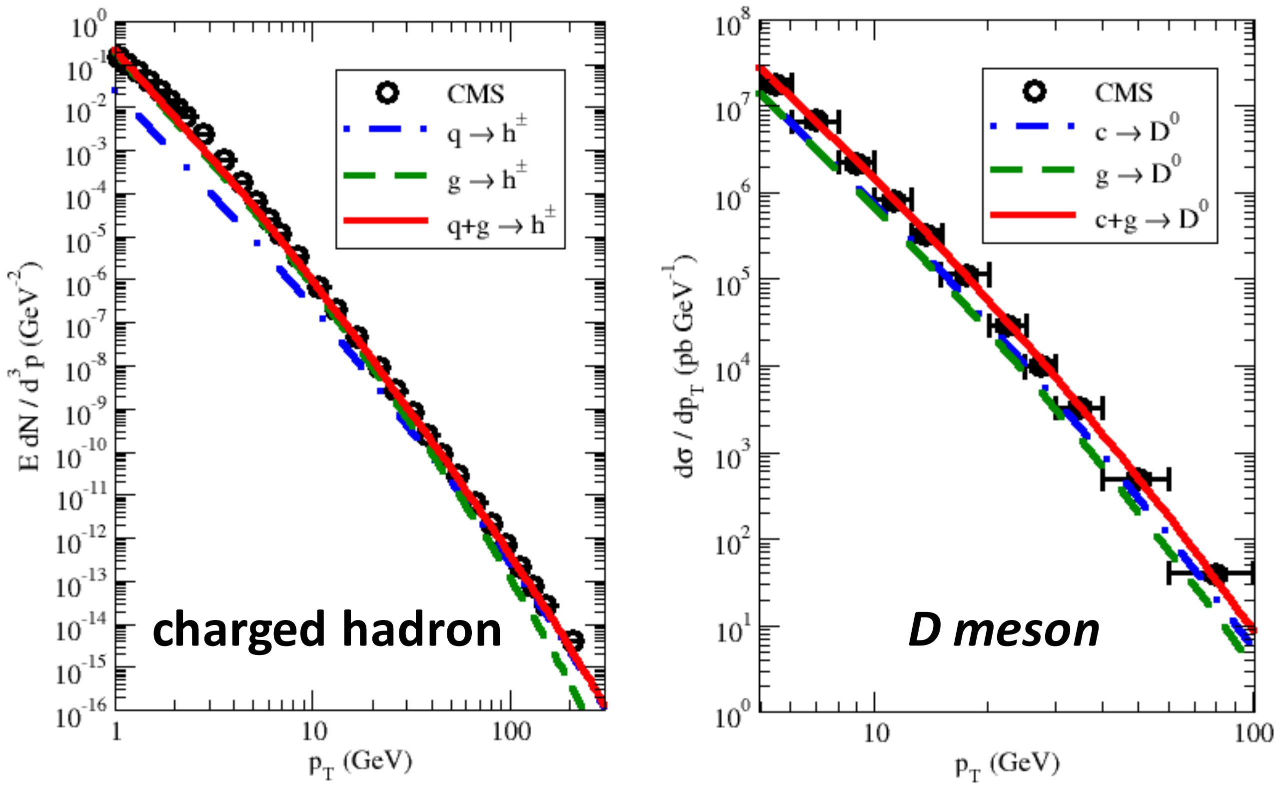


ATLAS, Eur. Phys. J. C73, 2301(2013)

- **Gluon splitting contribution increases with energy $\sqrt{s}$.**
- **Gluon splitting contribution increases with heavy quark jet p_T.**

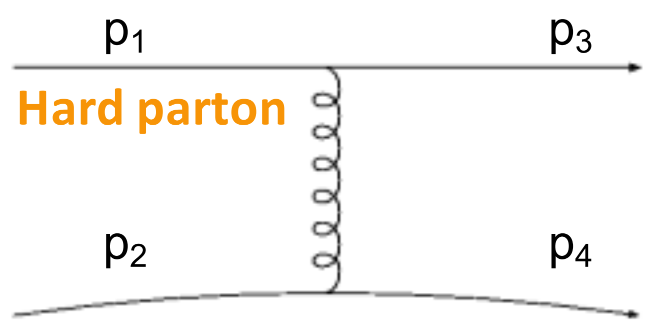
S. Cao, G.-Y. Qin, and X.-N. Wang, Phys. Rev. C93, 024912(2016); Z.-B. Kang, F. Ringer, and I. Vitev, JHEP 03, 146(2017)

Light charged hadron and *D* meson production in pp collisions at 5.02 TeV



- **Charged hadrons: gluon contribution dominates at low p_T and quark contribution becomes more important with increasing p_T.**
- ***D* mesons: charm and gluon 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 for high p_T hadron suppression in AA collisons.**

A linear Boltzmann transport (LBT) model



Boltzmann equation for parton "1" evolution:

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

The collision term is:

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

Elastic (collisional)

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

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

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

LO pQCD

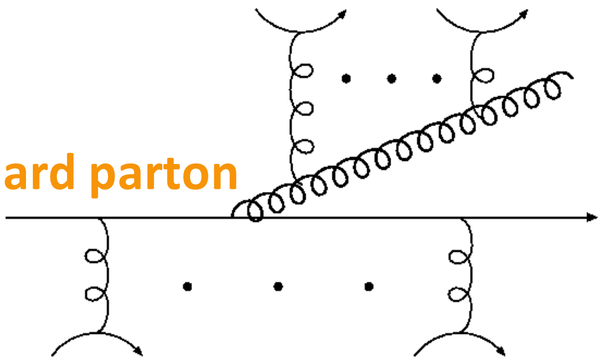
The elastic scattering rate for (2->2) process:

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

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

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:

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

The medium-induced gluon spectrum is:

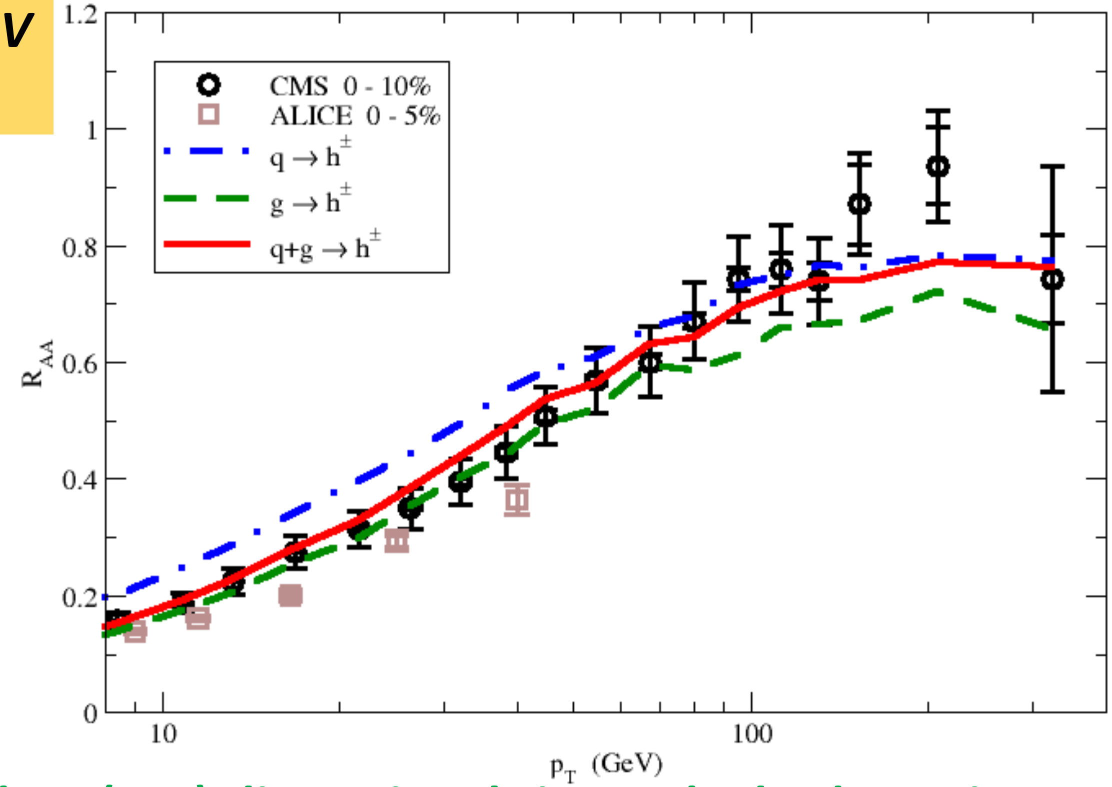
$$\frac{dN_g}{dx dk_\perp^2 dt} = \frac{2\alpha_s C_A P(x)}{\pi k_\perp^4} \hat{q} \left(\frac{k_\perp^2}{k_\perp^2 + x^2 M^2}\right)^4 \sin^2\left(\frac{t - t_i}{2\tau_f}\right)$$

$\hat{q}: \ dp_\perp^2 / dt$ **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)

Nuclear modifications of **charged hadrons**

Pb-Pb @5.02 TeV
0 - 10%



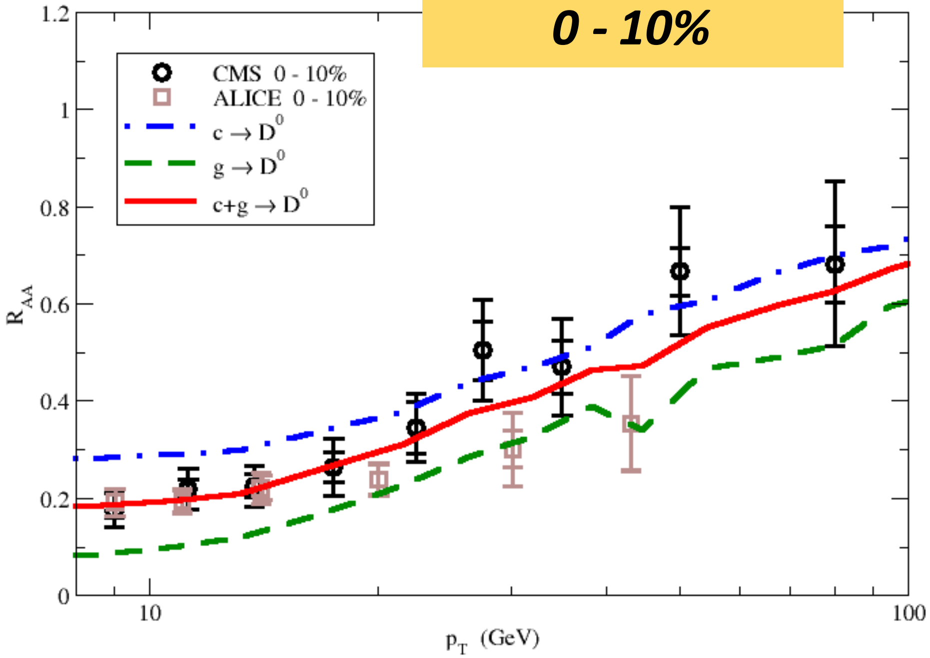
- **QGP fireball : a (3+1)-dimensional viscous hydrodynamics model CLVisc.**

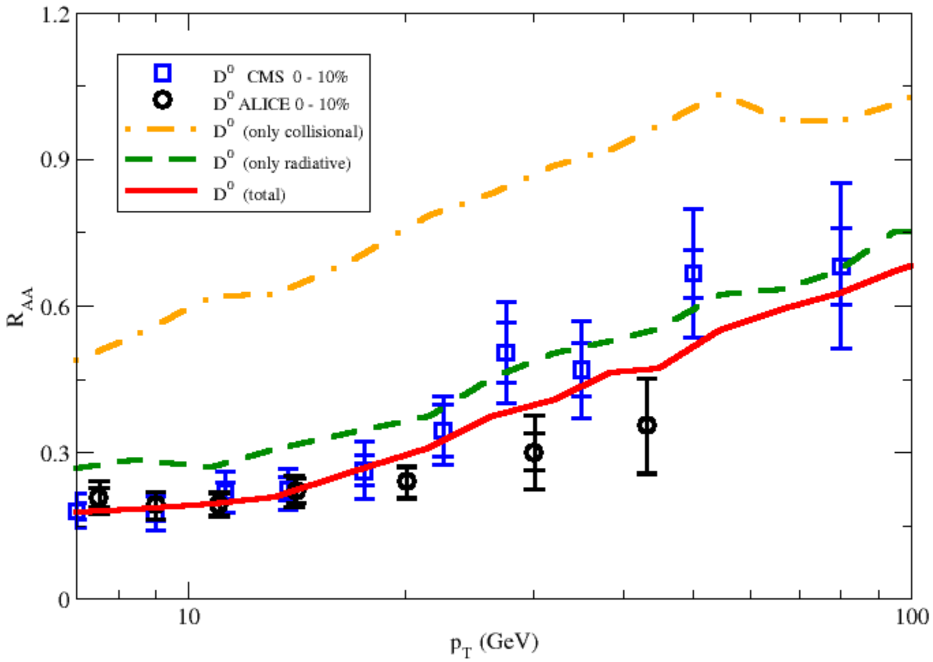
L. Pang, Q. Wang, and X. N. Wang, Phys. Rev. C86, 024911 (2012)
L. Pang, H. Petersen, and X. N. Wang, Phys. Rev. C97, 064918 (2018)

- **Due to color effect, quark-initiated hadrons exhibit less quenching effect than gluon-initiated hadrons.**
- **Combining both quark and gluon fragmentations 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%





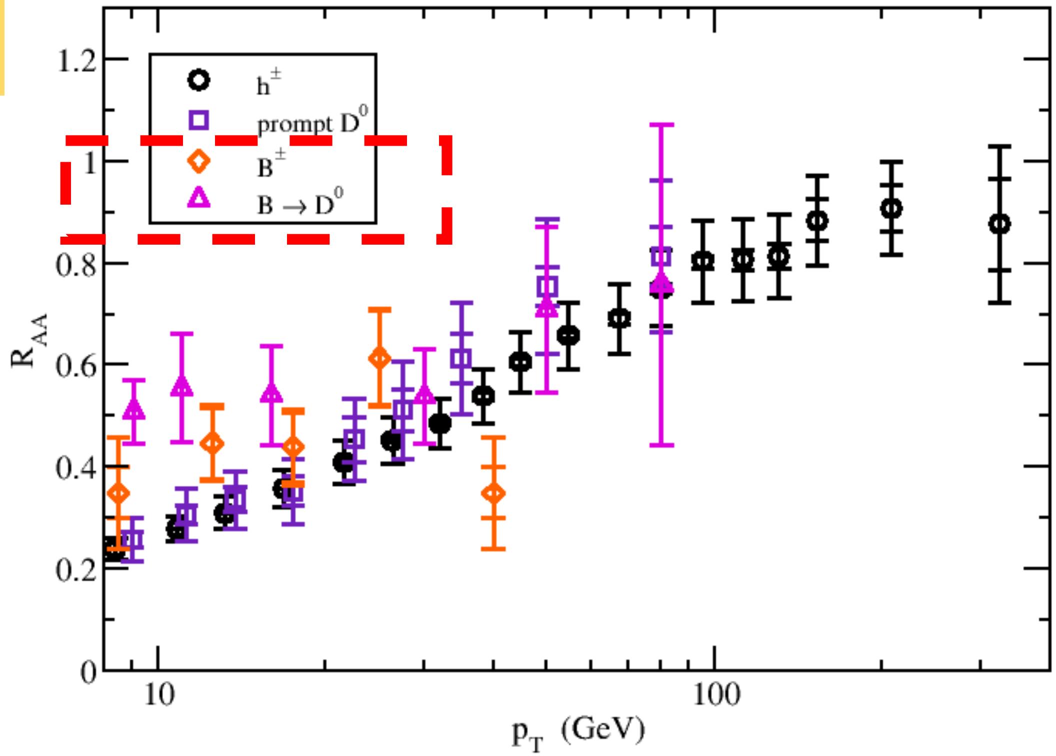
- **Combining both charm quark and gluon contributions, we obtain successful description of *D* meson R_{AA}.**

- **Collisional energy loss gives non-negligible contributions to R_{AA} at not-very high p_T regime and diminishes with increasing p_T .**

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

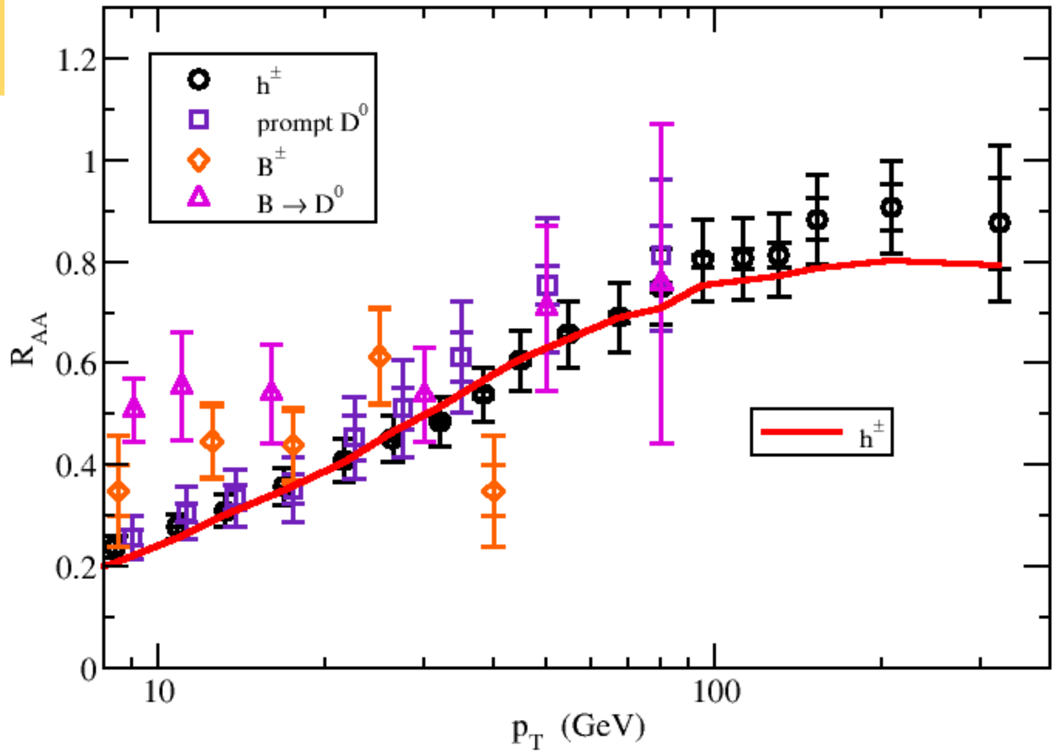
Flavor hierarchy of jet quenching

Pb-Pb @5.02 TeV
0 - 80%



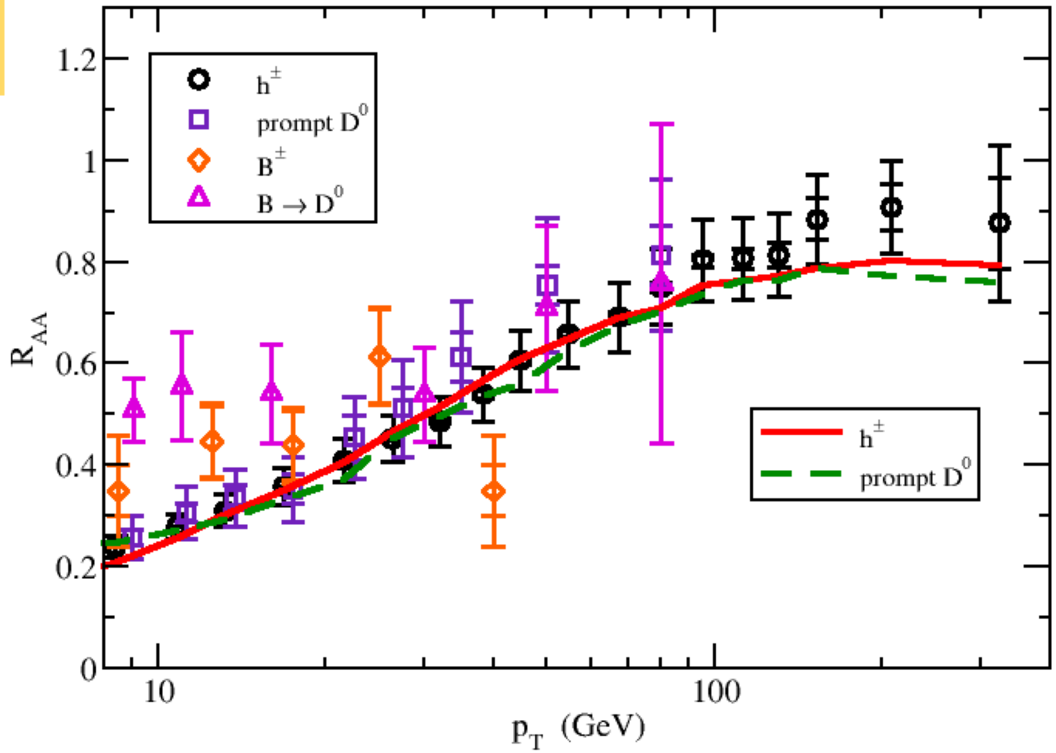
Flavor hierarchy of jet quenching

Pb-Pb @5.02 TeV
0 - 80%



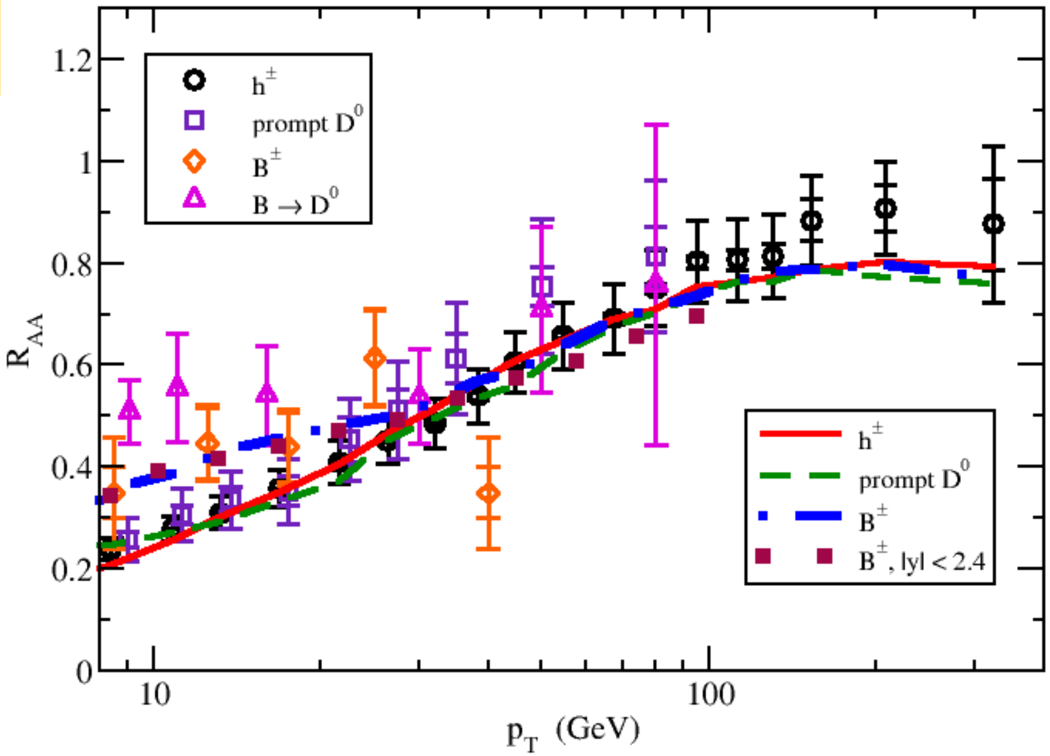
Flavor hierarchy of jet quenching

Pb-Pb @5.02 TeV
0 - 80%



Flavor hierarchy of jet quenching

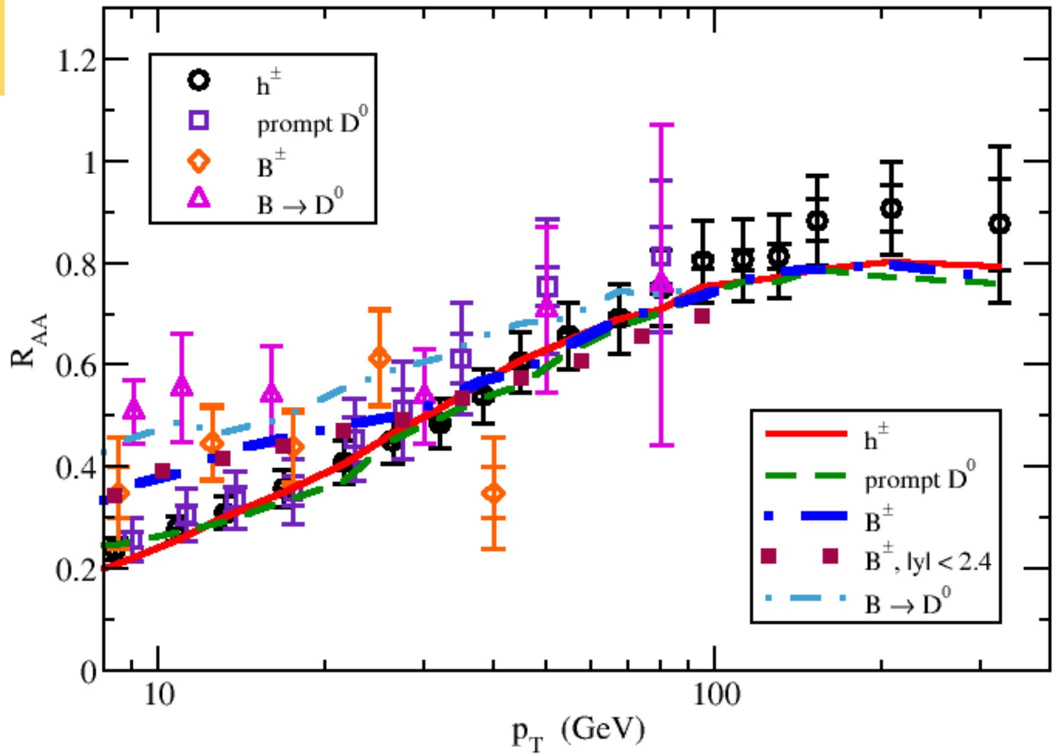
Pb-Pb @5.02 TeV
0 - 80%



- **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%



- **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

- **By incorporating all important ingredients in our pQCD-based jet quenching model, we obtain the first satisfactory description of R_{AA} for charged hadrons, prompt *D* mesons, *B* mesons and *B*-decayed *D* mesons for p_T=8-300 GeV).**

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

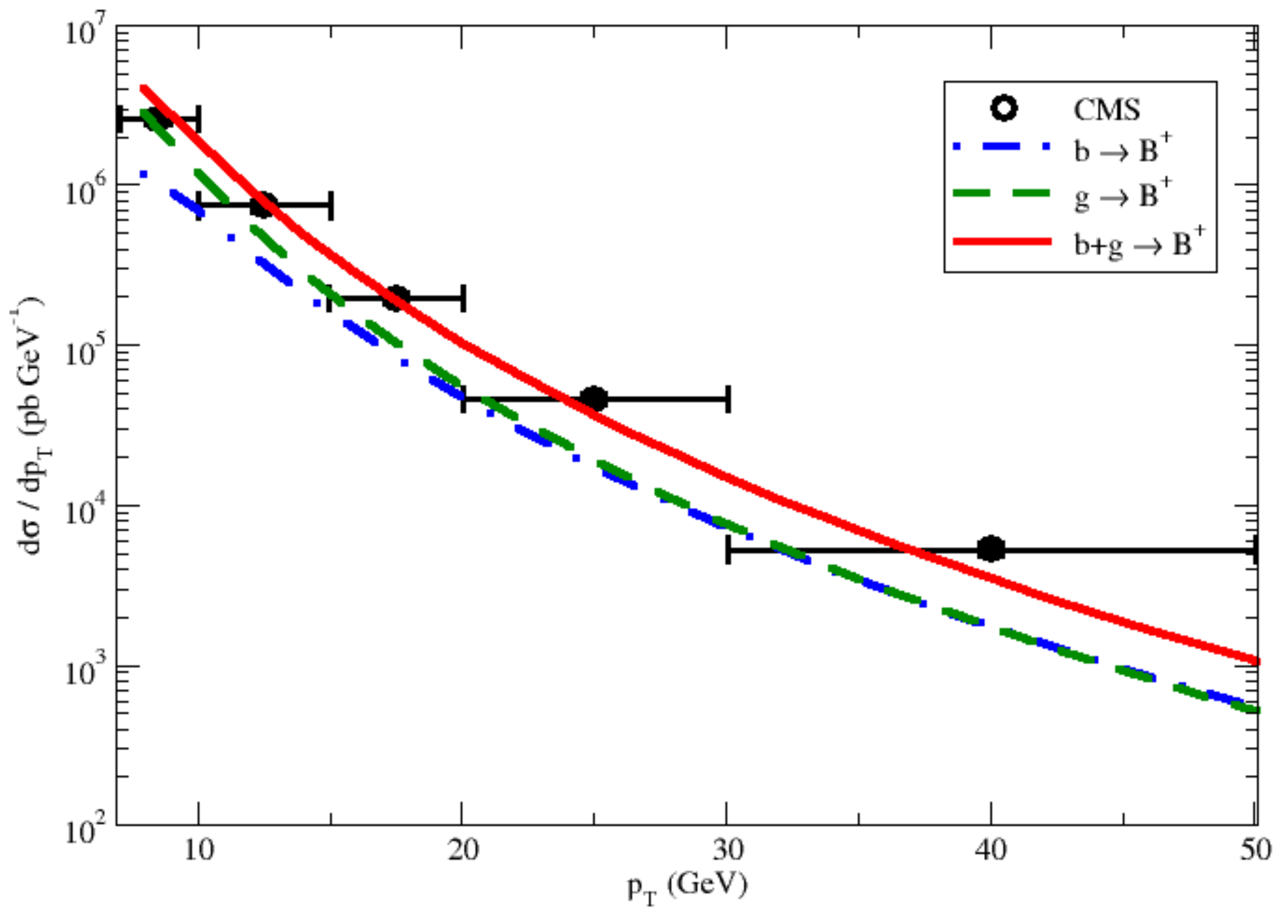
- **At p_T > 30-40 GeV, *B* mesons will exhibit similar suppression effects to charged hadrons and *D* mesons, which can be tested by future measurements.**

- **With a solid understanding on how jet-medium interaction depends on jet properties (color, mass and energy), we can now use jets to quantitatively probe the QGP properties.**

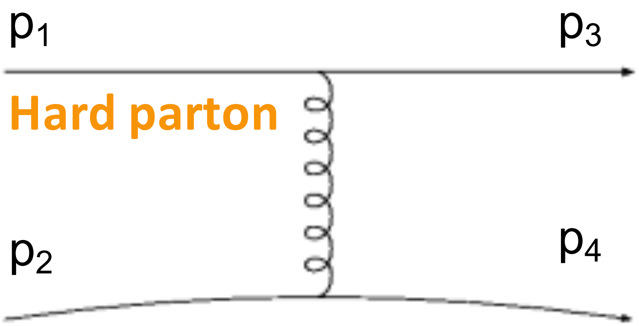
Thank You !

Back-up

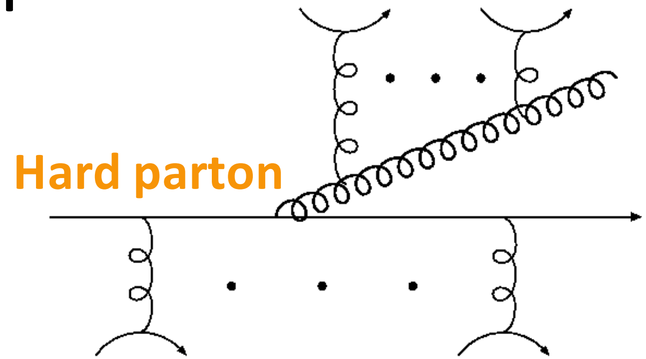
B mesons production in pp collisions at 5.02 TeV



A Linear Boltzmann transport (LBT) model



Elastic (collisional)



Inelastic (radiative)

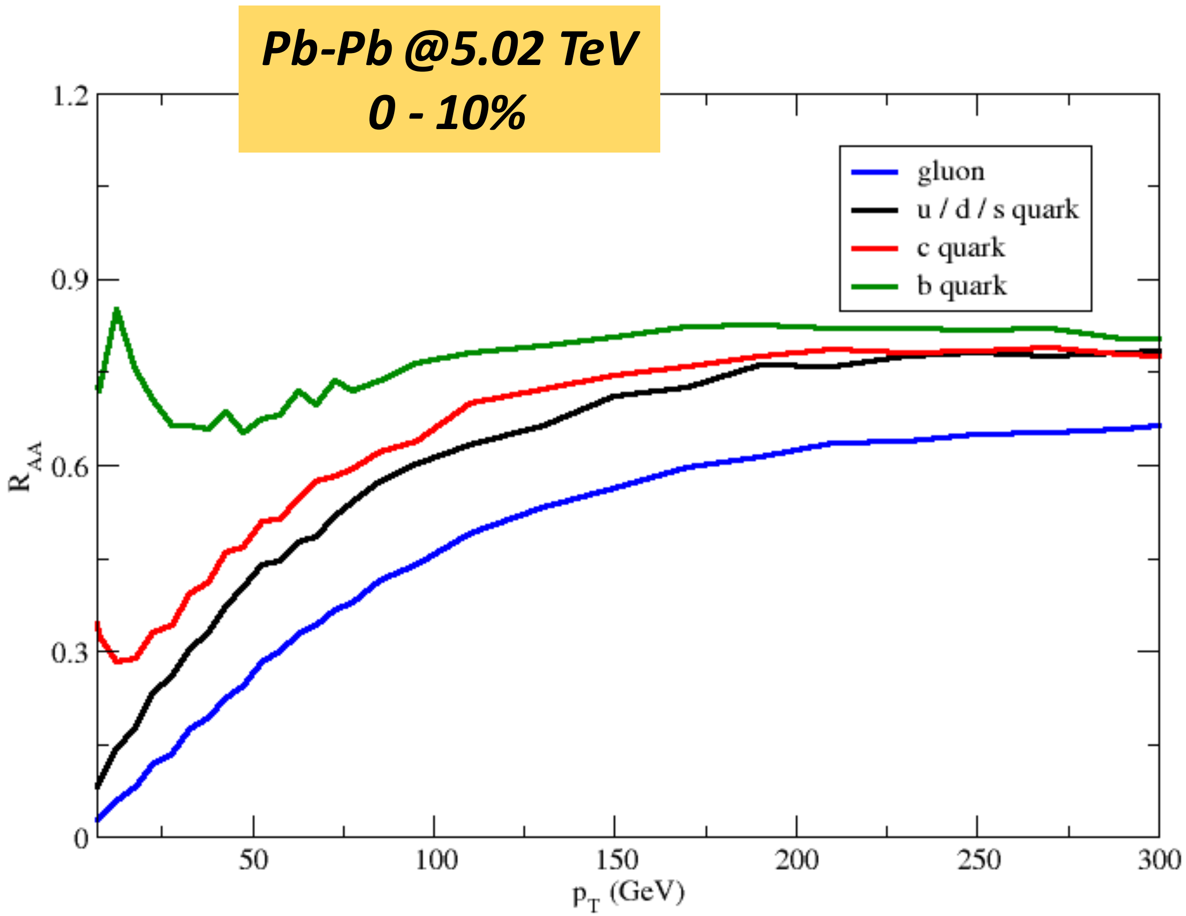
- $$\Gamma_{12\to 34} = \frac{\gamma_2}{2E_1}\int\frac{d^3p_2}{(2\pi)^3 2E_2}\int\frac{d^3p_3}{(2\pi)^3 2E_3}\int\frac{d^3p_4}{(2\pi)^3 2E_4}$$
  $$\times f_2(\vec{p}_2)\left[1 \pm f_3(\vec{p}_1 - \vec{k})\right]\left[1 \pm f_4(\vec{p}_2 + \vec{k})\right]S_2(s,t,u)$$
  $$\times (2\pi)^4 \delta^{(4)}(p_1 + p_2 - p_3 - p_4)\left|M_{12\to 34}\right|^2$$
- $\Gamma_{el} = \sum_i \Gamma_i$
- $P_{el} = 1 - e^{-\Gamma_{el}\Delta t}$

- $$\langle N_g\rangle(E,T,t,\Delta t) = \Delta t\int dx dk_\perp^2 \frac{dN_g}{dx dk_\perp^2 dt}$$
- $P_{inel} = 1 - e^{-\langle N_g\rangle}$
- $$P(n) = \frac{\langle N_g\rangle^n}{n!} e^{-\langle N_g\rangle}$$

pure elastic inelastic

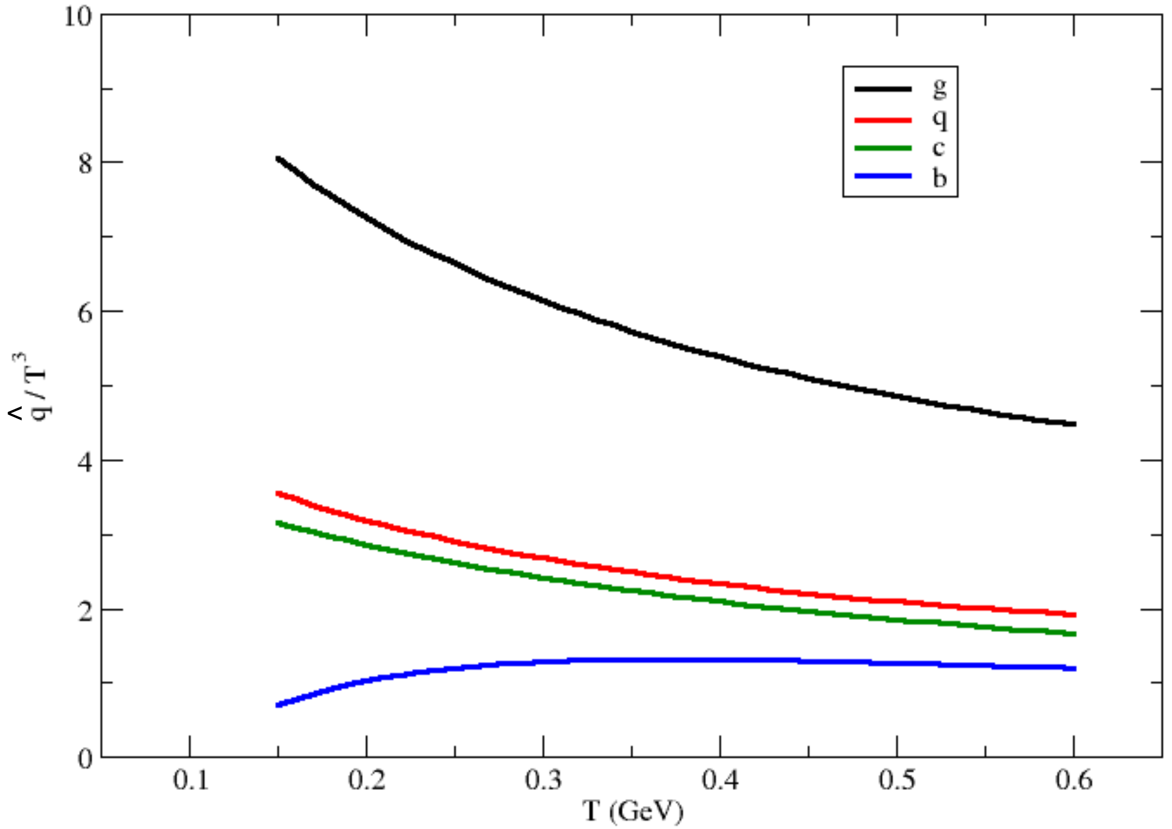
Elastic + Inelastic: $$P_{tot} = P_{el} + P_{inel} - P_{el}P_{inel} = P_{el}(1 - P_{inel}) + P_{inel}$$

Parton R_{AA}

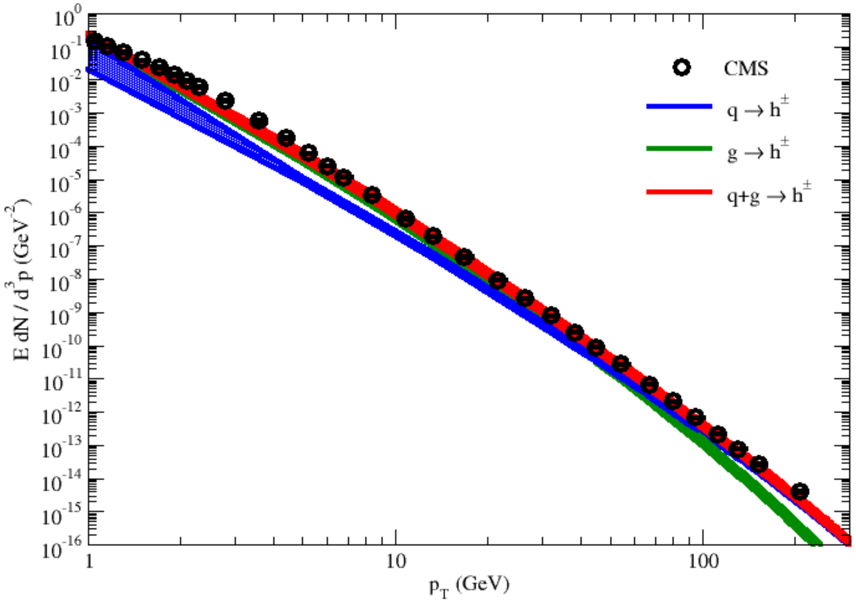


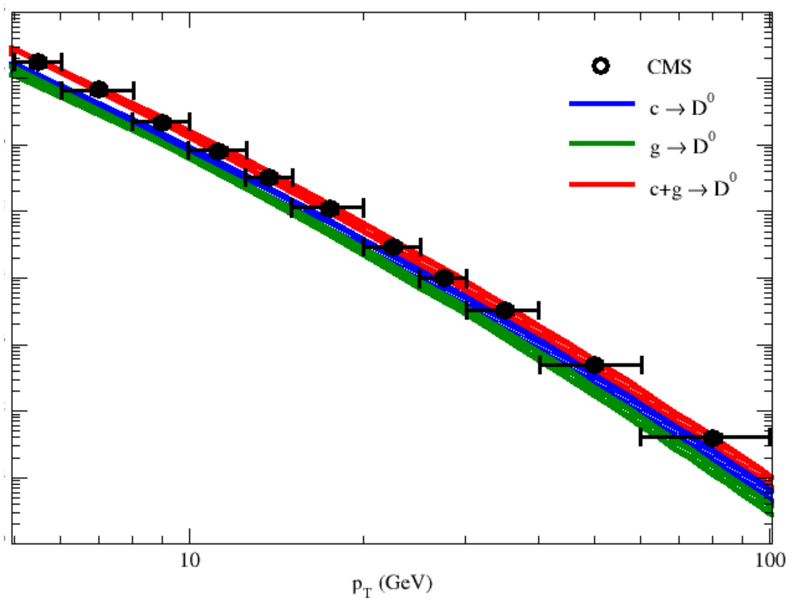
- $R_{AA}(g) < R_{AA}(q) < R_{AA}(c) < R_{AA}(b)$

Temperature dependence of $\hat{q}/T^3$ at $\mathrm{p} = 10\ GeV$



Effects of factorization and renormalization scales

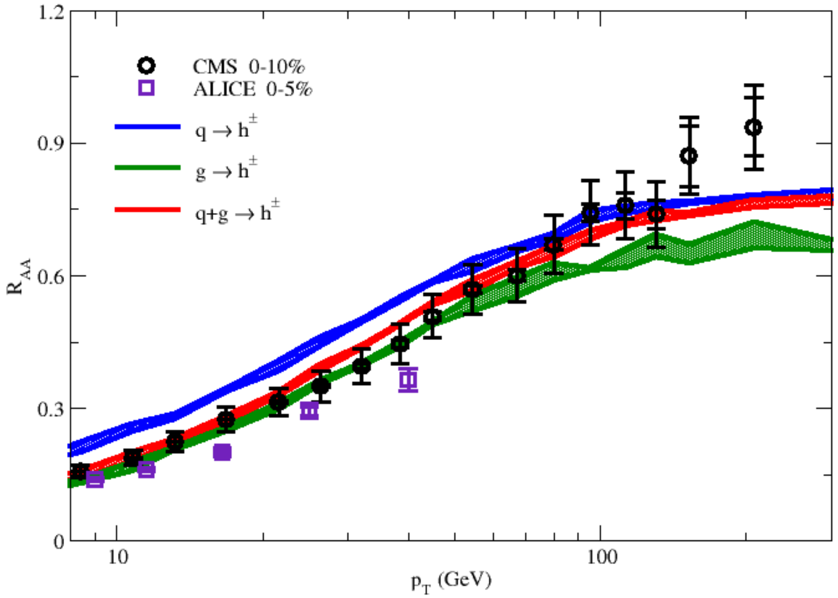


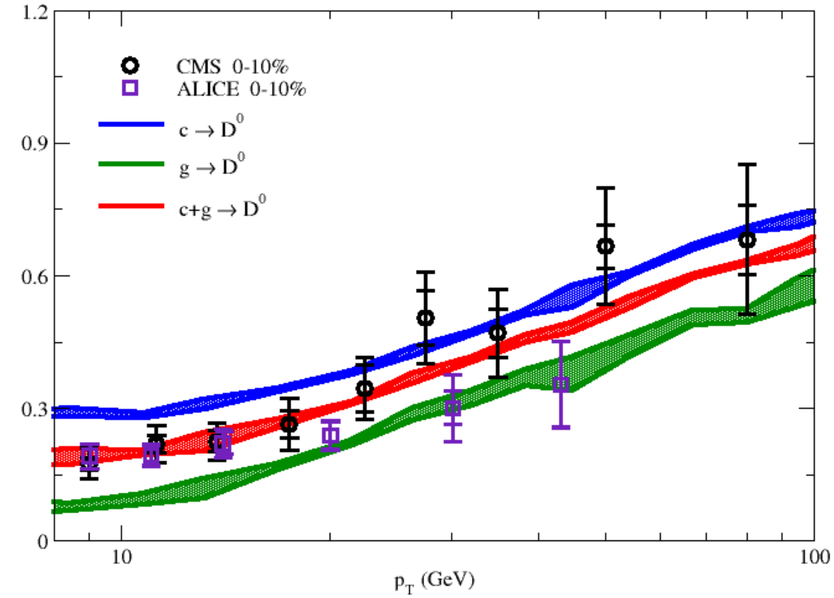


- **The value of the factorization and renormalization scales Q range from $0.5p_T$ to $2p_T$, with p_T the parton's transverse momentum.**

- **The light and heavy flavor hadron spectra is quite stable against the variation of the scale Q and its influence on PDFs and FFs.**

Effects of factorization and renormalization scales

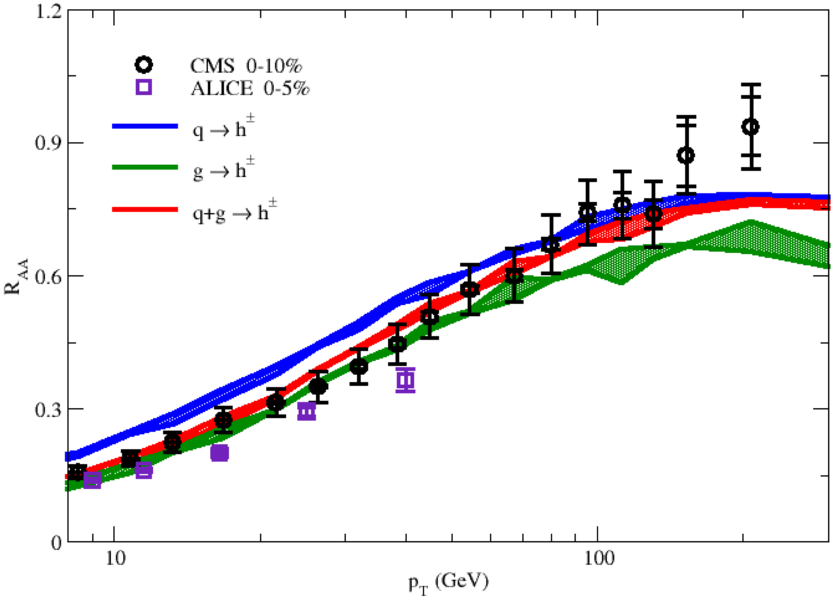


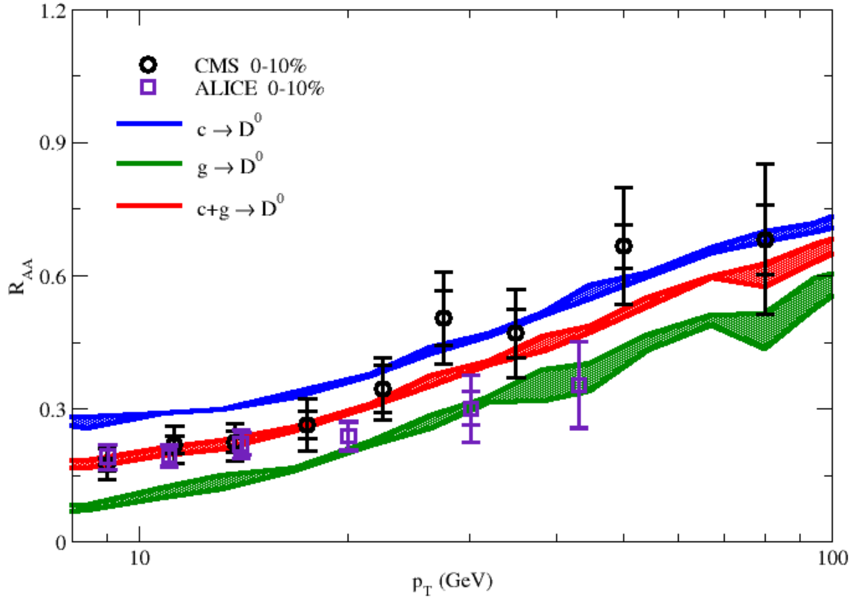


- **The value of the factorization and renormalization scales *Q* range from $0.5p_T$ to $2p_T$, with p_T the parton's transverse momentum.**

- **The nuclear modification factors of light and heavy flavor hadron are quite stable against the variation of the scale *Q* and its influence on PDFs and FFs.**

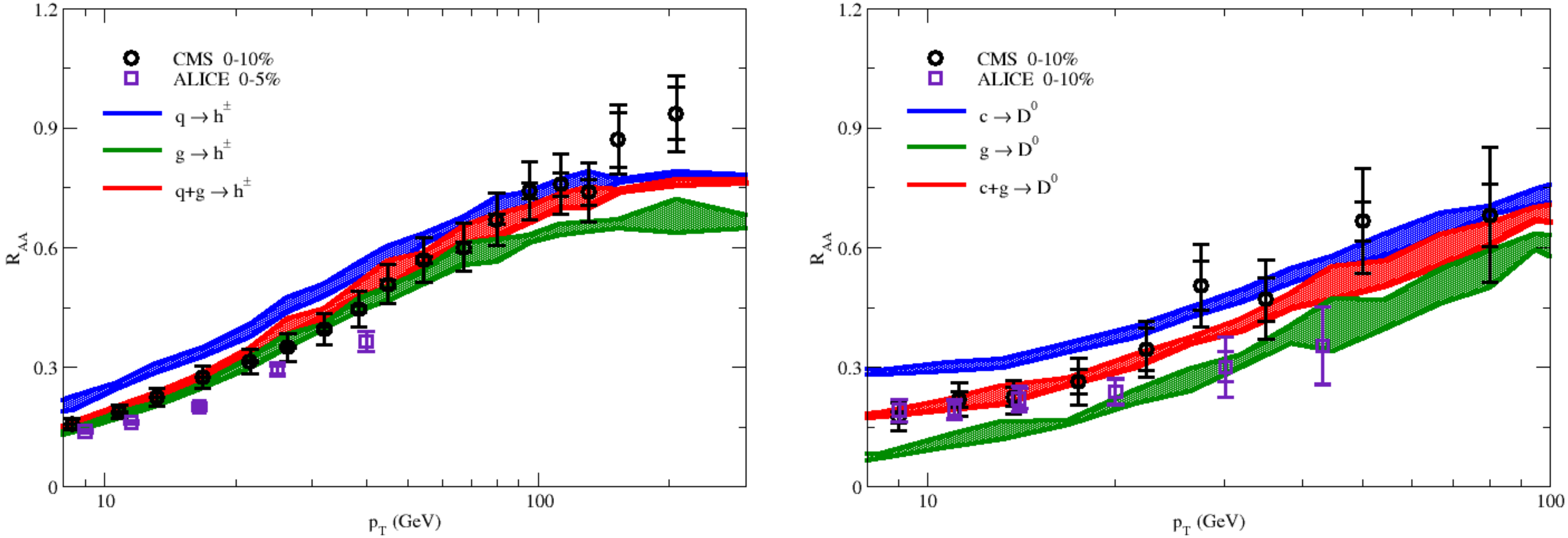
Effects of the lower temperature cutoff T_c





- **The lower temperature cutoff T_c varies from 145MeV to 165 MeV.**
- **The nuclear modification factors of light and heavy flavor hadron are quite stable against the variation of T_c.**

Effects of the exchanged $k_\perp$ cuttoff



- The exchanged transverse momentum cutoff $k_\perp$ varies from 9*T* to 11*T*.
- The nuclear modification factors of light and heavy flavor hadron are quite stable against the variation of the exchanged transverse momentum cutoff $k_\perp$.

Calculation of high p_T production

$$\frac{dN^h}{dP_T^h} = \int \frac{dN_p}{dP_T^p} \cdot D(z = \frac{P_T^h}{P_T^p}) \frac{dz}{z}$$

$$= \int \frac{1}{(P_T^p)^\alpha} \cdot D\left(z = \frac{P_T^h}{P_T^p}\right) \frac{dz}{z}$$

$$= \int \frac{z^\alpha}{\left(P_T^h\right)^\alpha} \cdot D\left(z = \frac{P_T^h}{P_T^p}\right) \frac{dz}{z}$$

$$= \frac{1}{\left(P_T^h\right)^\alpha} \cdot \int z^{\alpha-1} D(z) dz$$