Flavor hierarchy of jet quenching in heavy-ion collisions

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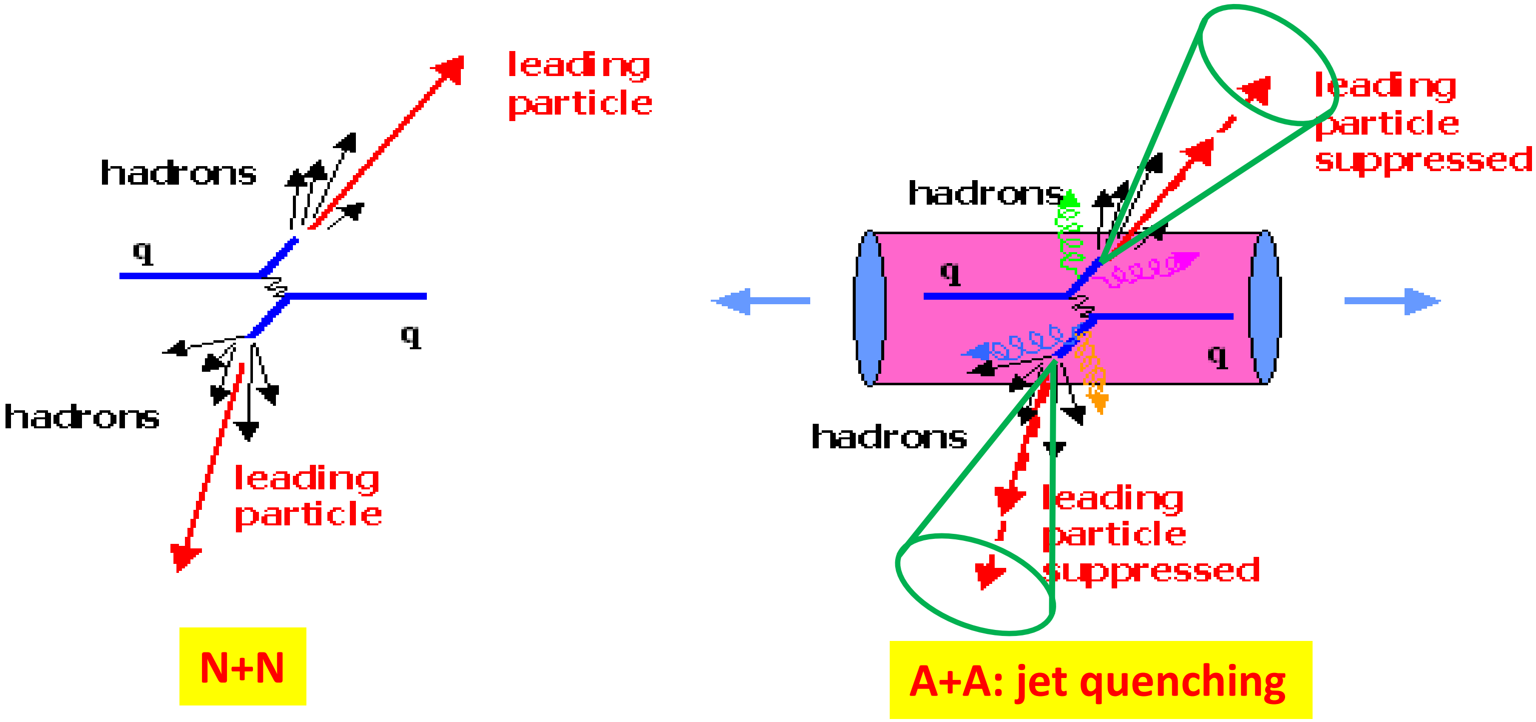
Outline

- **Introduction**
- **Medium-induced gluon emission**
  - Beyond collinear rescattering expansion and soft gluon emission limit for massive quarks
  - **Zhang, Hou, GYQ, PRC 2018 & arXiv:1812.11048; Zhang, GYQ, Wang, arXiv:1905.12699.**
- **Flavor hierarchy of jet quenching**
  - R_{AA} for heavy and light flavor hadrons
  - **Cao, Luo, GYQ, Wang, PRC 2016 & PLB 2018; Xing, Cao, GYQ, Xing, arXiv:1906.00413.**
- **Summary**

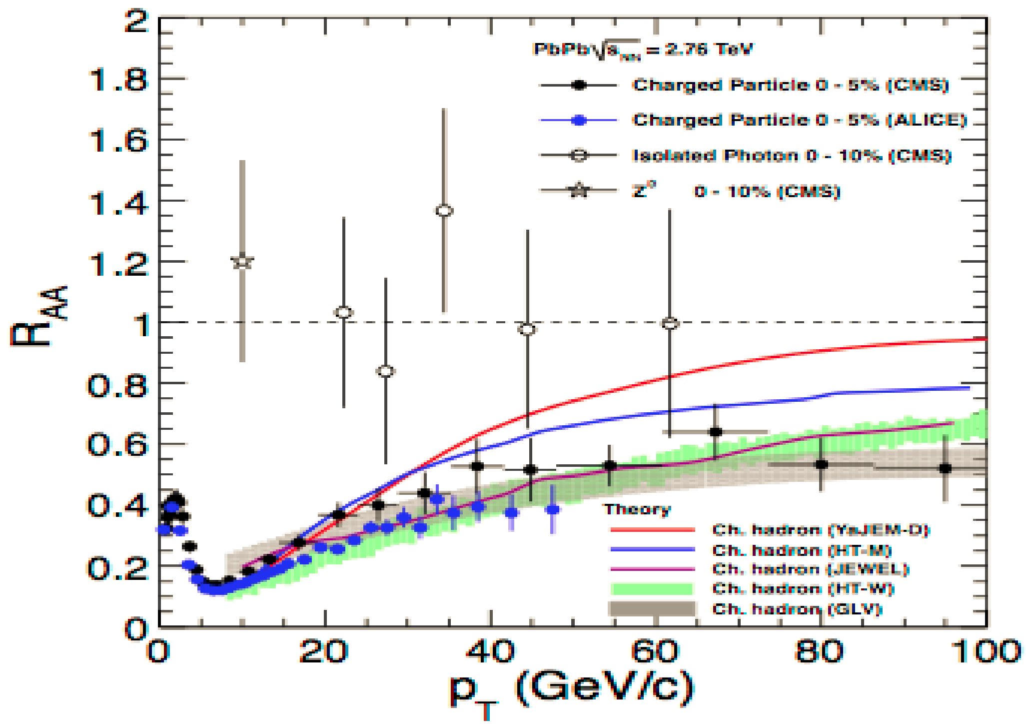
Jets are hard probes of QGP



Jets (and **jet-medium interaction, jet quenching**) provide valuable tools to probe hot & dense QGP in relativistic heavy-ion collisions (at RHIC & LHC):

(1) parton energy loss (2) deflection and broadening (3) modification of jet substructure (4) jet-induced medium excitation

Single inclusive hadrons



Nuclear modification factor:

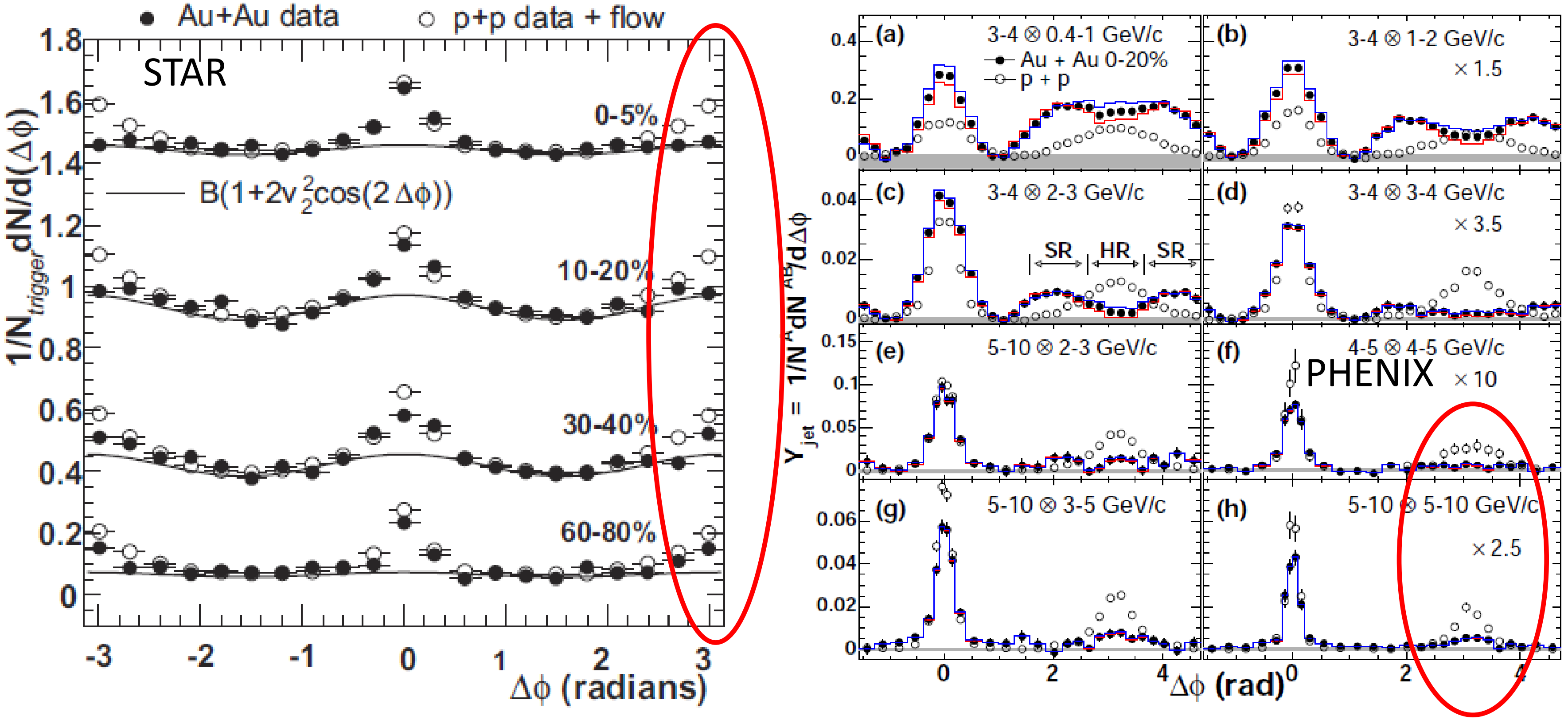
$$R_{AA} = \frac{dN^{AA} / d^2 p_T dy}{N_{\mathrm{coll}} dN^{pp} / d^2 p_T dy}$$

- **If AA collisions are a simple geometric combination of many NN collisions, then R_{AA}=1**
- **Hadron: R_{AA}<1**
- **Photon & Z boson: R_{AA}=1**

- **Due to final state interaction between high energy partons and QGP (i.e., parton energy loss), the production of high p_T hadrons (from the fragmentation of high energy partons) is suppressed**

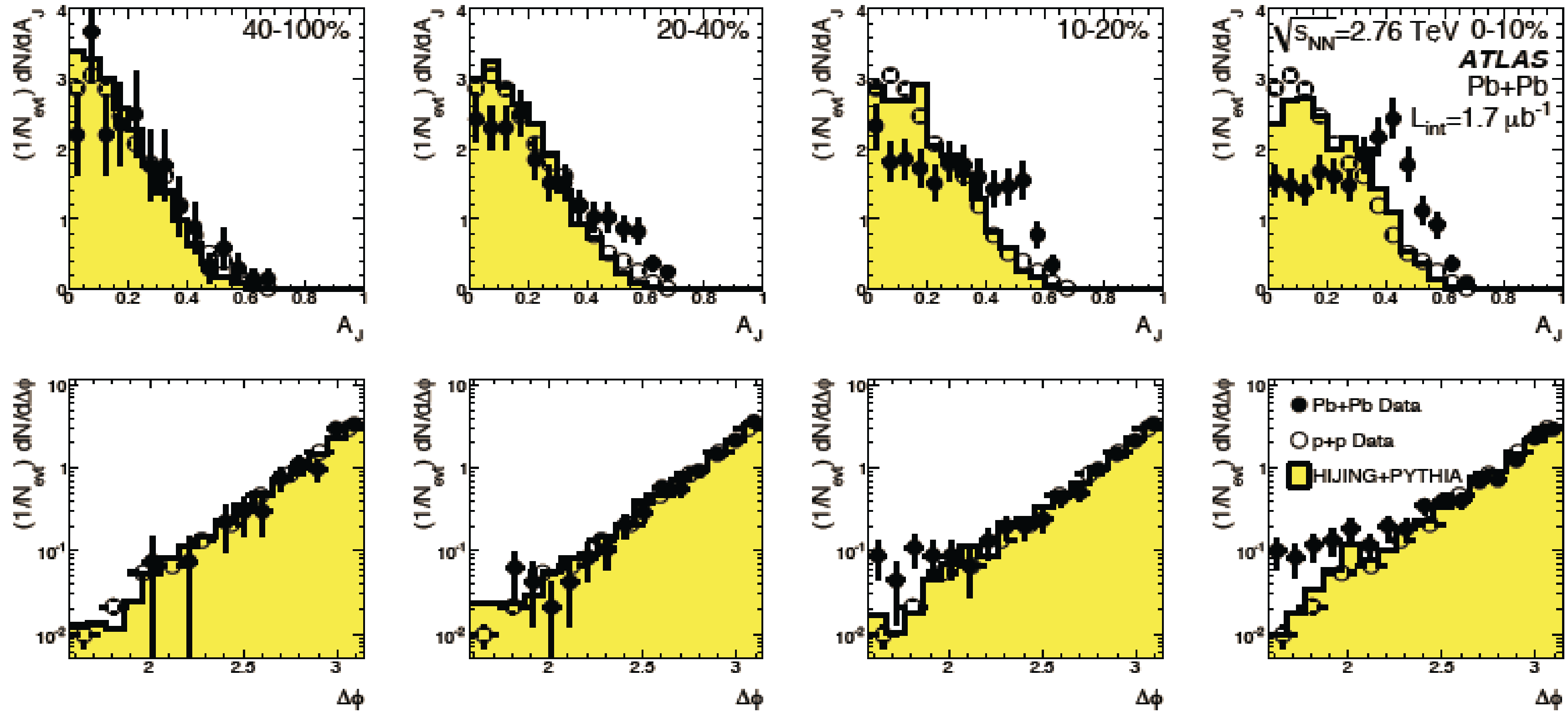
- **Jet quenching mainly originates from parton energy loss in hot QGP**

Jet-related (dihadron) correlations



Both per-trigger yield and the shape of angular distribution are modified by QGP. Can probe parton energy loss and angular deflection (broadening) effects.

Full jets (dijets)

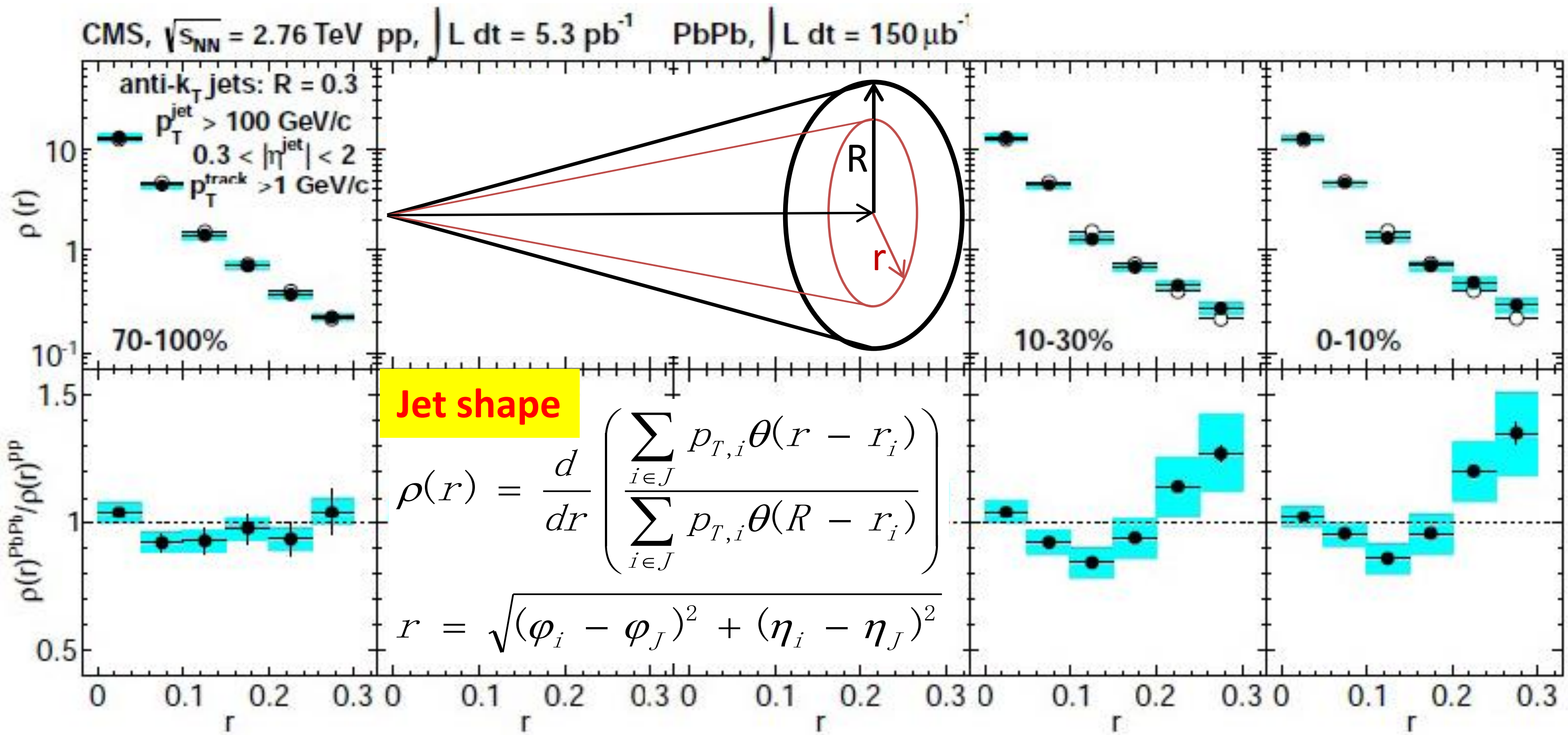


$$A_J = \frac{p_{T,1} - p_{T,2}}{p_{T,1} + p_{T,2}}$$

$$\Delta\phi = |\phi_1 - \phi_2|$$

Strong modification of momentum imbalance distribution
=> Significant energy loss experienced by the subleading jets
Largely-unchanged angular distribution
=> medium-induced broadening effect is quite modest (here)

Full jet structure

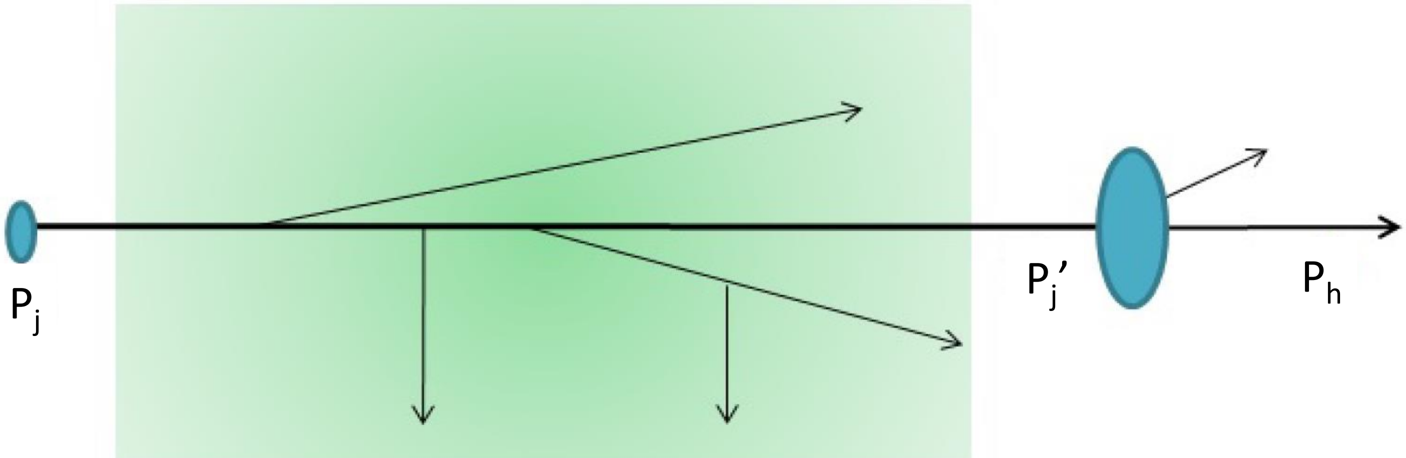


$$\rho(r) = \frac{d}{dr}\left(\frac{\sum_{i\in J} p_{T,i}\theta(r - r_i)}{\sum_{i\in J} p_{T,i}\theta(R - r_i)}\right)$$

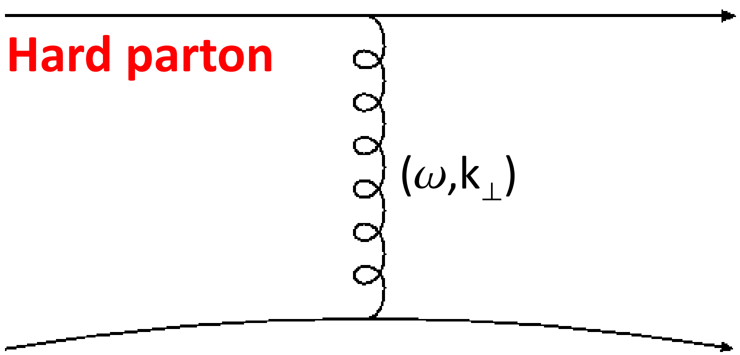
$$r = \sqrt{(\varphi_i - \varphi_J)^2 + (\eta_i - \eta_J)^2}$$

- **The observed enhancement at large r** is consistent with jet broadening (& medium-induced radiation)
- The soft outer part of the jet is easier to modify, while changing the inner hard cone is more difficult

Elastic and inelastic interactions

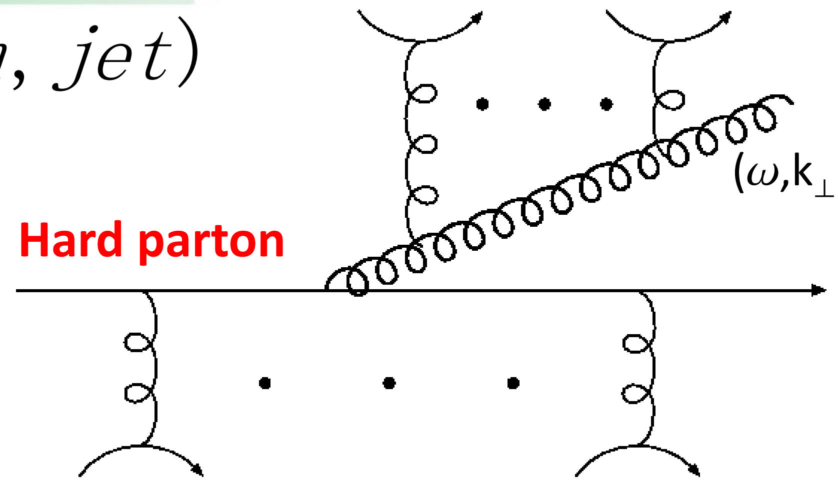


$$P_{j\to j'}(medium,\, jet)$$



Elastic (collisional)

$$\frac{d\Gamma_{coll}}{d\omega dk_\perp^2 dt}(T, E, \ldots) = ?$$

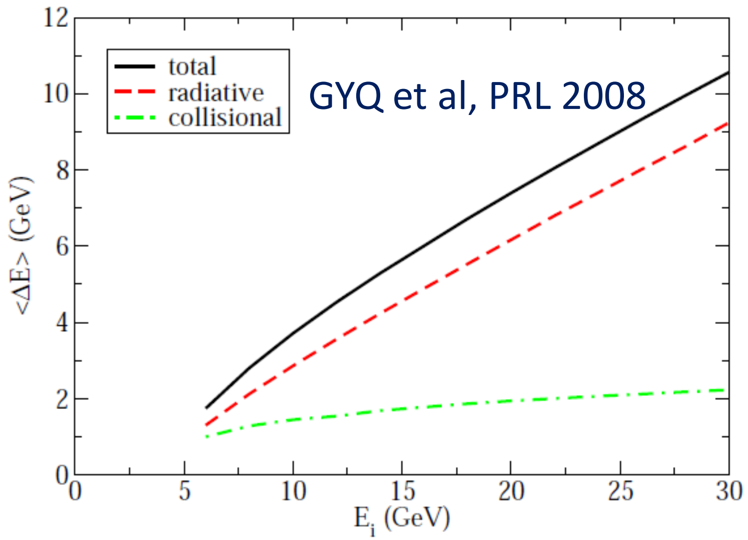


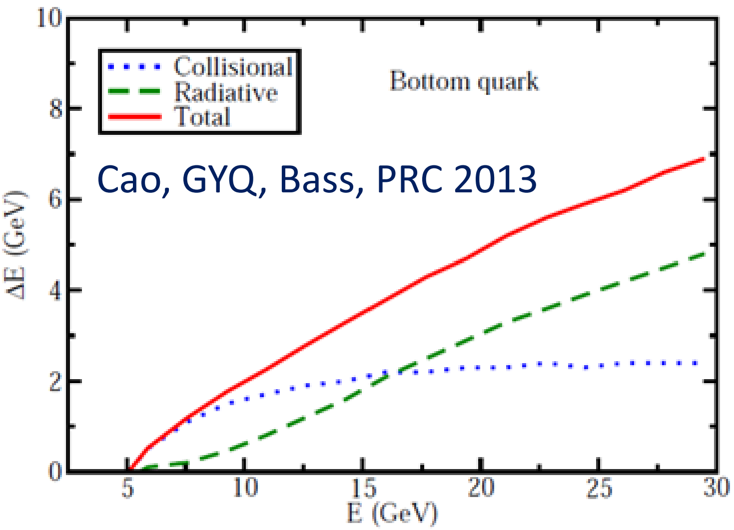
Inelastic (radiative)

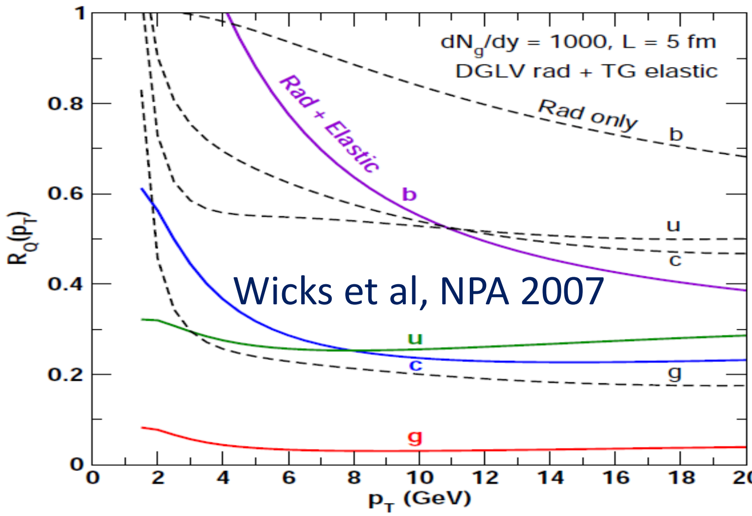
$$\frac{d\Gamma_{rad}}{d\omega dk_\perp^2 dt}(T, E, \ldots) = ?$$

Elastic (collisional) energy loss

- **First studied by Bjorken:**
  - Bjorken 1982; Bratten, Thoma 1991; Thoma, Gyulassy, 1991; Mustafa, Thoma 2005; Peigne, Peshier, 2006; Djordjevic, 2006; Wicks et al (DGLV), 2007; GYQ et al (AMY), 2008...
- **Main findings:**
  - **dE/E small compared to rad. for large E**
  - **But non-negligible in R_{AA} calculation (especially for heavy flavors)**
  - **Important when studying full jet energy loss and medium response**



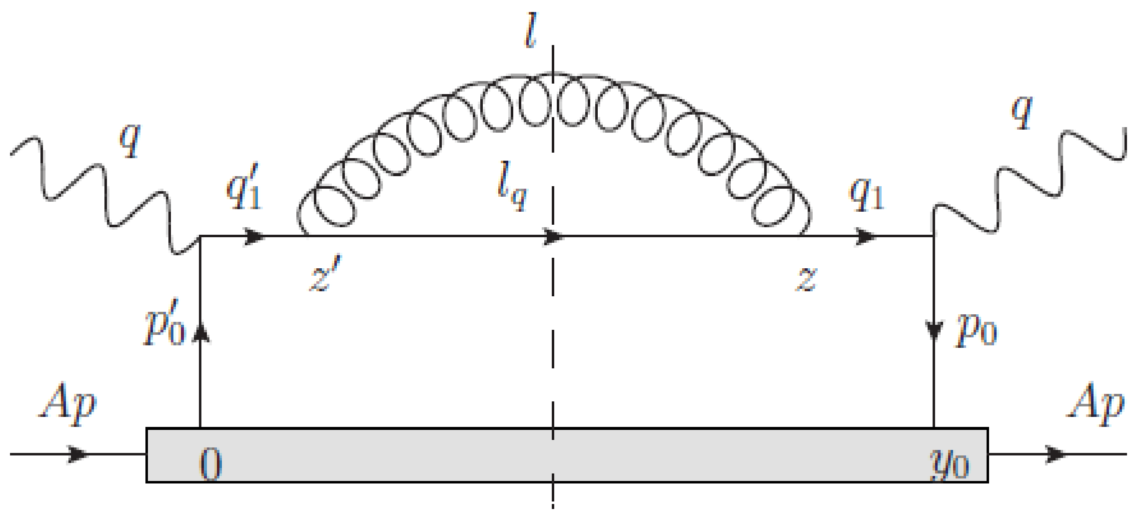




Medium-induced inelastic (radiative) process

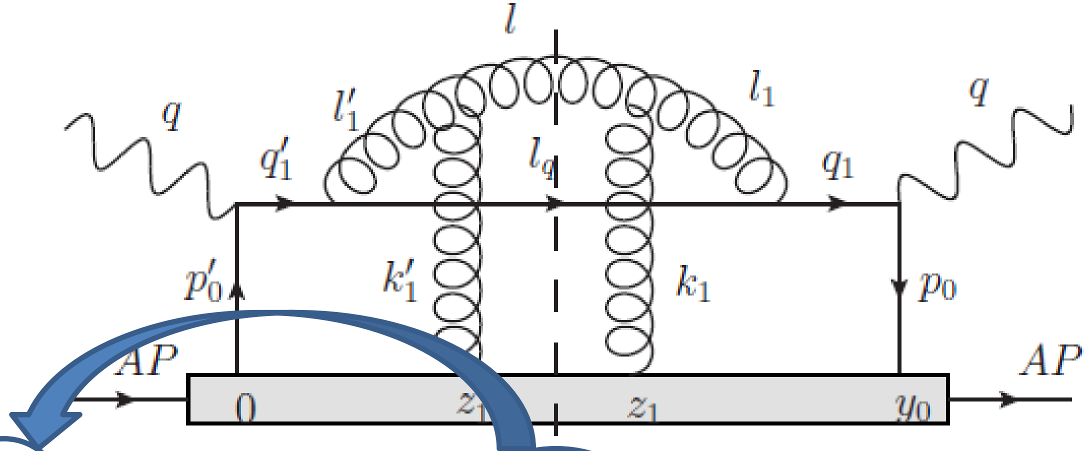
- **pQCD-based formalisms**
  - **BDMPS-Z**: Baier-Dokshitzer-Mueller-Peigne-Schiff-Zakharov
  - **ASW**: Amesto-Salgado-Wiedemann
  - **AMY**: Arnold-Moore-Yaffe (& Caron-Huot, Gale)
  - **GLV**: Gyulassy-Levai-Vitev (& Djordjevic, Heinz)
  - **HT**: Wang-Guo (& Zhang, Wang, Majumder)
- **Various approximations:**
  - High energy & eikonal approximations
  - Soft gluon emission approximation (ASW, GLV)
  - Collinear expansion (BDMPS-Z, HT)
  - Gluon emission induced by transverse scatterings
- **Recent improvements:**
  - **Include non-eikonal corrections within the path integral formalism** (Apolinrio, Armesto, Milhano, Salgado, JHEP (2015), arXiv:1407.0599)
  - **Reinvestigate the GLV formalism by relaxing the soft gluon emission approximation** (Blagojevic, Djordjevic, Djordjevic, arXiv:1804.07593; Sievert, Vitev, arXiv:1807.03799)
  - **Generalize the HT formalism by going beyond the collinear expansion and soft gluon emission approximation**, including both transverse and longitudinal scatterings, **for massless and massive quarks** (Zhang, Hou, GYQ, PRC (2018) arXiv:1804.00470; arXiv:1812.11048; Zhang, GYQ, Wang, arXiv:1905.12699)

Gluon emission in vacuum



$$\frac{dN_g^{\text{vac}}}{dy\, d^2 l_\perp} = C_F \frac{\alpha_s}{2\pi^2} P(y) \frac{l_\perp^2 + \frac{y^4}{1+(1-y)^2} M^2}{(l_\perp^2 + y^2 M^2)^2}.$$

Medium-induced inelastic (radiative) process



Zhang, Hou, GYQ, PRC 2018 & arXiv:1812.11048; Zhang, GYQ, Wang, arXiv:1905.12699.

+ other 20 diagrams

$$
\begin{aligned}
\frac{dN_g^{med}}{dy\,d^2\mathbf{l}_\perp} = {} & \frac{\alpha_s}{2\pi^2} P(y) \int dZ_1^- \int \frac{dk^- d^2\mathbf{k}_{1\perp}}{(2\pi)^3} \mathcal{D}(k_1^-, \mathbf{k}_{1\perp}) \\
& \times \left\{ \left[2 - 2\cos\left(\frac{y(1-y)}{(y-\lambda_1^-)(1+\lambda_1^- - y)} \frac{(\mathbf{l}_\perp - \mathbf{k}_{1\perp})^2 + (y-\lambda_1^-)^2 M^2}{l_\perp^2 + y^2 M^2} \frac{Z_1^-}{\tilde{\tau}^-_{\rm form}} \right) \right] \right. \\
& C_A \left[\frac{1 + (1+\lambda_1^- - y)^2}{1 + (1-y)^2} \left(\frac{y - \frac{\lambda_1^-}{2}}{y - \lambda_1^-} \right)^2 \frac{(\mathbf{l}_\perp - \mathbf{k}_{1\perp})^2 + \frac{(y-\lambda_1^-)^4 M^2}{1+(1+\lambda_1^- - y)^2}}{\left[(\mathbf{l}_\perp - \mathbf{k}_{1\perp})^2 + (y-\lambda_1^-)^2 M^2 \right]^2} \right. \\
& - \frac{1 + (1+\lambda_1^- - y)(1-y)}{2[1+(1-y)^2]} \left(\frac{y - \frac{\lambda_1^-}{2}}{y - \lambda_1^-} \right) \frac{\mathbf{l}_\perp \cdot (\mathbf{l}_\perp - \mathbf{k}_{1\perp}) + \frac{y^2 (y-\lambda_1^-)^2}{1+(1+\lambda_1^- - y)(1-y)} M^2}{[l_\perp^2 + y^2 M^2]\left[(\mathbf{l}_\perp - \mathbf{k}_{1\perp})^2 + (y-\lambda_1^-)^2 M^2 \right]} \\
& \left. \left. - \frac{1 + (1+\lambda_1^- - y)(1 - \frac{y}{1+\lambda_1^-})}{2[1+(1-y)^2]} \left(\frac{y - \frac{\lambda_1^-}{2}}{y - \lambda_1^-} \right) \frac{(\mathbf{l}_\perp - \mathbf{k}_{1\perp}) \cdot \left(\mathbf{l}_\perp - \frac{y}{1+\lambda_1^-} \mathbf{k}_{1\perp} \right) + \frac{\left(\frac{y}{1+\lambda_1^-} \right)^2 (y-\lambda_1^-)^2}{1+(1+\lambda_1^- - y)(1 - \frac{y}{1+\lambda_1^-})} M^2}{\left[\left(\mathbf{l}_\perp - \frac{y}{1+\lambda_1^-} \mathbf{k}_{1\perp} \right)^2 + (\frac{y}{1+\lambda_1^-})^2 M^2 \right] \left[(\mathbf{l}_\perp - \mathbf{k}_{1\perp})^2 + (y-\lambda_1^-)^2 M^2 \right]} \right] + \ldots\ldots \right\}
\end{aligned}
$$

$$\mathcal{D}(k_1^-, \mathbf{k}_{1\perp}) = (2\pi)^3 \frac{dP_{\rm el}}{dk_1^- d^2\mathbf{k}_{1\perp} dZ_1^-}$$

Medium-induced gluon emission beyond collinear expansion & soft emission limit with transverse & longitudinal scatterings for massive quarks

Only transverse scatterings

- **Modeling the traversed nuclear medium by heavy static scattering centers (only transverse scatterings)**

$$
\begin{aligned}
\frac{dN_g^{\rm med}}{dyd^2\mathbf{l}_\perp} &= \frac{\alpha_s}{2\pi^2}P(y)\int dZ_1^- \int d^2\mathbf{k}_{1\perp}\frac{dP_{\rm el}}{d^2\mathbf{k}_{1\perp}dZ_1^-} \\
&\times\Bigg\{C_A\left[2-2\cos\left(\frac{(\mathbf{l}_\perp-\mathbf{k}_{1\perp})^2+y^2M^2}{l_\perp^2+y^2M^2}\frac{Z_1^-}{\tilde{\tau}^-_{\rm form}}\right)\right]\times\left[\frac{(\mathbf{l}_\perp-\mathbf{k}_{1\perp})^2+\frac{y^4}{1+(1-y)^2}M^2}{\left[(\mathbf{l}_\perp-\mathbf{k}_{1\perp})^2+y^2M^2\right]^2}\right. \\
&-\frac{1}{2}\frac{\mathbf{l}_\perp\cdot(\mathbf{l}_\perp-\mathbf{k}_{1\perp})+\frac{y^4}{1+(1-y)^2}M^2}{[l_\perp^2+y^2M^2]\left[(\mathbf{l}_\perp-\mathbf{k}_{1\perp})^2+y^2M^2\right]}-\frac{1}{2}\left.\frac{(\mathbf{l}_\perp-\mathbf{k}_{1\perp})\cdot(\mathbf{l}_\perp-y\mathbf{k}_{1\perp})+\frac{y^4}{1+(1-y)^2}M^2}{\left[(\mathbf{l}_\perp-y\mathbf{k}_{1\perp})^2+y^2M^2\right]\left[(\mathbf{l}_\perp-\mathbf{k}_{1\perp})^2+y^2M^2\right]}\right] \\
&+\left(\frac{C_A}{2}-C_F\right)\left[2-2\cos\left(\frac{Z_1^-}{\tilde{\tau}^-_{\rm form}}\right)\right]\left[\frac{\mathbf{l}_\perp\cdot(\mathbf{l}_\perp-y\mathbf{k}_{1\perp})+\frac{y^4}{1+(1-y)^2}M^2}{[l_\perp^2+y^2M^2]\left[(\mathbf{l}_\perp-y\mathbf{k}_{1\perp})^2+y^2M^2\right]}-\frac{l_\perp^2+\frac{y^4}{1+(1-y)^2}M^2}{[l_\perp^2+y^2M^2]^2}\right] \\
&+C_F\left[\frac{(\mathbf{l}_\perp-y\mathbf{k}_{1\perp})^2+\frac{y^4}{1+(1-y)^2}M^2}{\left[(\mathbf{l}_\perp-y\mathbf{k}_{1\perp})^2+y^2M^2\right]^2}-\frac{l_\perp^2+\frac{y^4}{1+(1-y)^2}M^2}{[l_\perp^2+y^2M^2]^2}\right]\Bigg\}.
\end{aligned}
$$

Soft gluon emission approximation

- **Further taking soft gluon emission approximation** $y^2M \ll yM \sim l_\perp \sim k_{1\perp}$**:**

$$\frac{dN_g^{\rm med}}{dyd^2\mathbf{l}_\perp} = \frac{\alpha_s}{2\pi^2}P(y)\int dZ_1^- \int d^2\mathbf{k}_{1\perp}\frac{dP_{\rm el}}{d^2\mathbf{k}_{1\perp}dZ_1^-} \times C_A\left[2-2\cos\left(\frac{(\mathbf{l}_\perp-\mathbf{k}_{1\perp})^2+y^2M^2}{l_\perp^2+y^2M^2}\frac{Z_1^-}{\tilde{\tau}_{\rm form}^-}\right)\right]$$
$$\times\left[\frac{(\mathbf{l}_\perp-\mathbf{k}_{1\perp})^2}{\left[(\mathbf{l}_\perp-\mathbf{k}_{1\perp})^2+y^2M^2\right]^2} - \frac{\mathbf{l}_\perp\cdot(\mathbf{l}_\perp-\mathbf{k}_{1\perp})}{[l_\perp^2+y^2M^2]\left[(\mathbf{l}_\perp-\mathbf{k}_{1\perp})^2+y^2M^2\right]}\right].$$

- **This agrees with the DGLV first-order-in-opacity formula.**

- **Jet transport parameter is related to the differential elastic scattering rate as follows:**

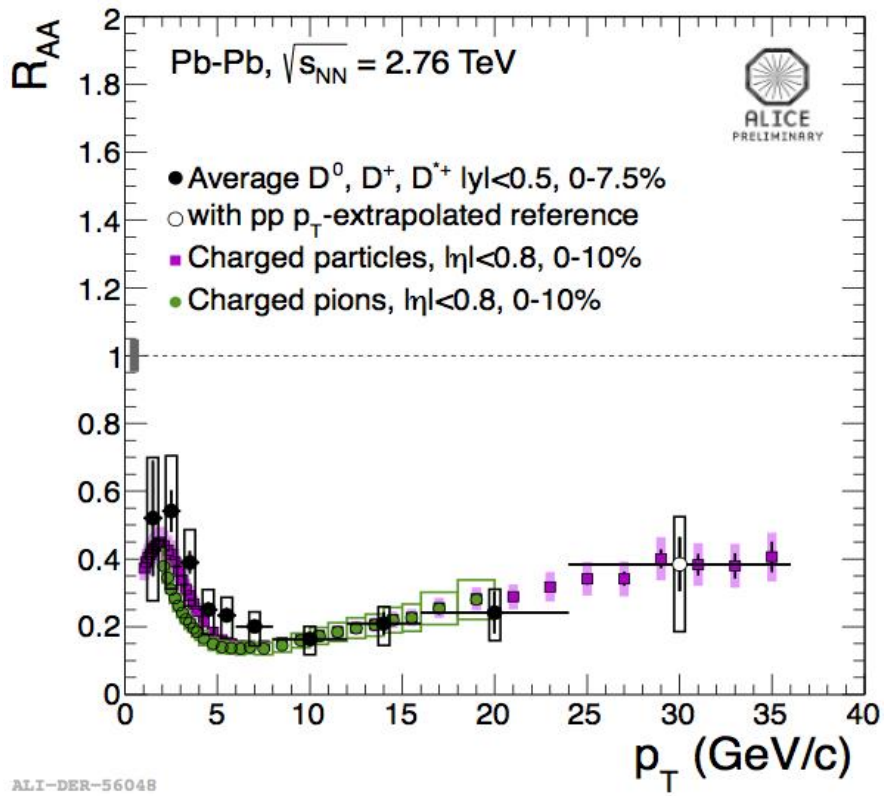
$$\hat{q}_{lc} = \frac{d\langle k_{1\perp}^2\rangle}{dL^-} = \int\frac{dk_1^- d^2\mathbf{k}_{1\perp}}{(2\pi)^3}\mathbf{k}_{1\perp}^2\mathcal{D}(k_1^-,\mathbf{k}_{1\perp}) = \int\frac{d^2\mathbf{k}_{1\perp}}{(2\pi)^2}\mathbf{k}_{1\perp}^2\mathcal{D}_\perp(\mathbf{k}_{1\perp}) = \int d^2\mathbf{k}_{1\perp}\mathbf{k}_{1\perp}^2\rho^-\frac{d\sigma_{\rm el}}{d^2\mathbf{k}_{1\perp}}.$$

Flavor puzzle of jet quenching

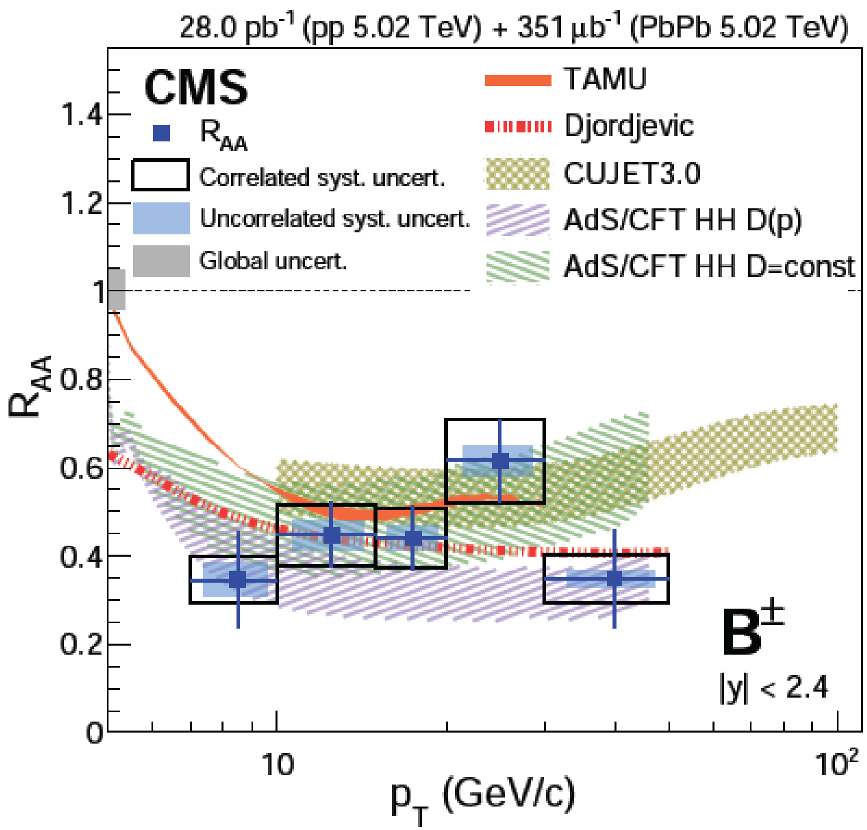
- Heavy quarks, due to their finite masses, are expected to lose less energies in QGP than light quarks
- Color & flavor dependences of parton E loss: $\Delta E_g > \Delta E_{uds} > \Delta E_c > \Delta E_b$
- Expects less quenching effects for heavy flavor hadrons than light charged hadrons.

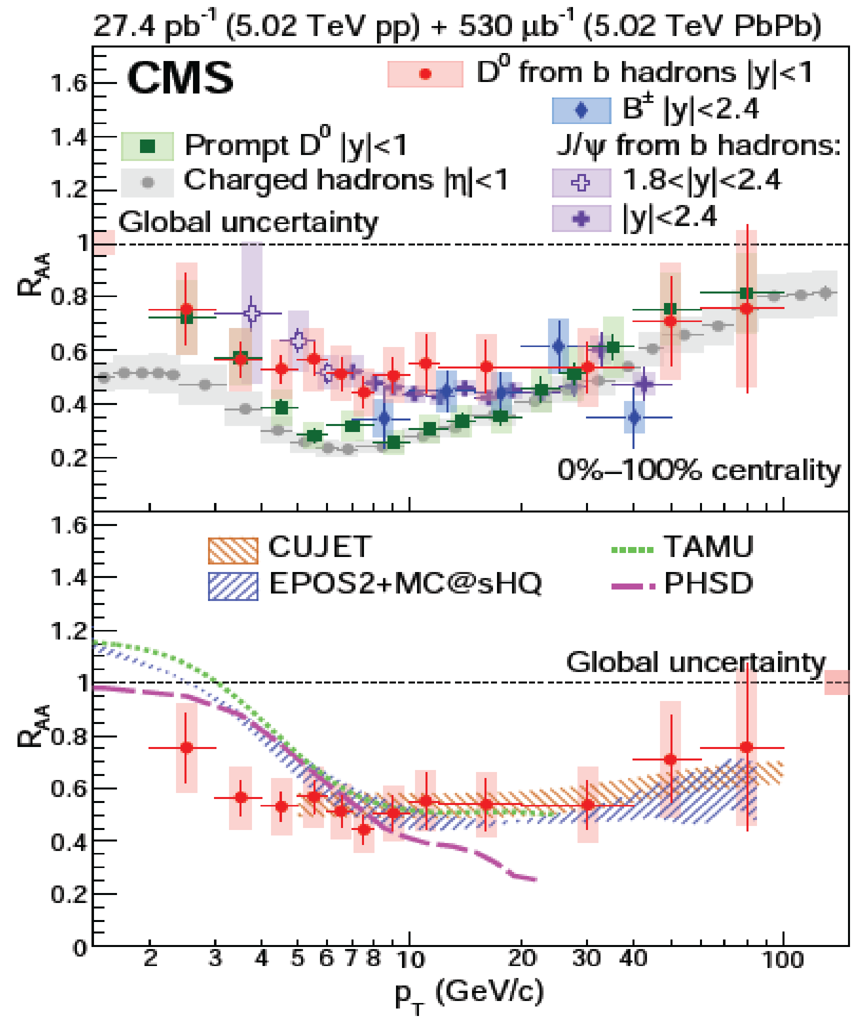
- Experiments observe similar quenching effects for (prompt) D mesons as compared to charged hadrons at p_T > 6-8 GeV

- Challenge for our understanding of the flavor dependence of jet-medium interaction and parton energy loss



B mesons & B-decayed D mesons





- **A unique opportunity to study the flavor hierarchy of jet quenching.**

Our framework and main result

- **A linear Boltzmann transport model combined with hydrodynamics simulation for studying the energy loss and medium modification of heavy and light flavor jets in QGP, taking into account both radiative and collisional interactions.**

- **A NLO pQCD framework for light and heavy flavor parton and hadron productions, taking into account both quark and gluon contributions to hadron production.**

- **The first satisfactory description of R_{AA} for charged hadrons, D mesons, B mesons and B-decayed D mesons simultaneously over a wide range of transverse momenta (8-300 GeV).**

Xing, Cao, GYQ, Xing, arXiv:1906.00413

Linearized Boltzmann Transport (LBT) Model

- **Boltzmann equation:** $p_1 \cdot \partial f_1(x_1, p_1) = E_1 C[f_1]$

- **Elastic collisions:**

$$\Gamma_{12\to34} = \frac{\gamma_2}{2E_1} \int \frac{d^3p_2}{(2\pi)^3 2E_2} \int \frac{d^3p_3}{(2\pi)^3 2E_3} \int \frac{d^3p_4}{(2\pi)^3 2E_4} \times f_2(\vec{p}_2) \left[1 \pm f_3(\vec{p}_1 - \vec{k})\right] \left[1 \pm f_4(\vec{p}_2 + \vec{k})\right] \times (2\pi)^4 \delta^{(4)}(p_1 + p_2 - p_3 - p_4) |\mathcal{M}_{12\to34}|^2$$

$$P_{el} = 1 - e^{-\Gamma_{el}\Delta t}$$

Matrix elements taken from LO pQCD

- **Inelastic collisions:**

$$\langle N_g \rangle = \Gamma_g \Delta t = \Delta t \int dx dk_\perp^2 \frac{dN_g}{dx dk_\perp^2 dt}$$

$$P_{inel} = 1 - e^{-\langle N_g \rangle}$$

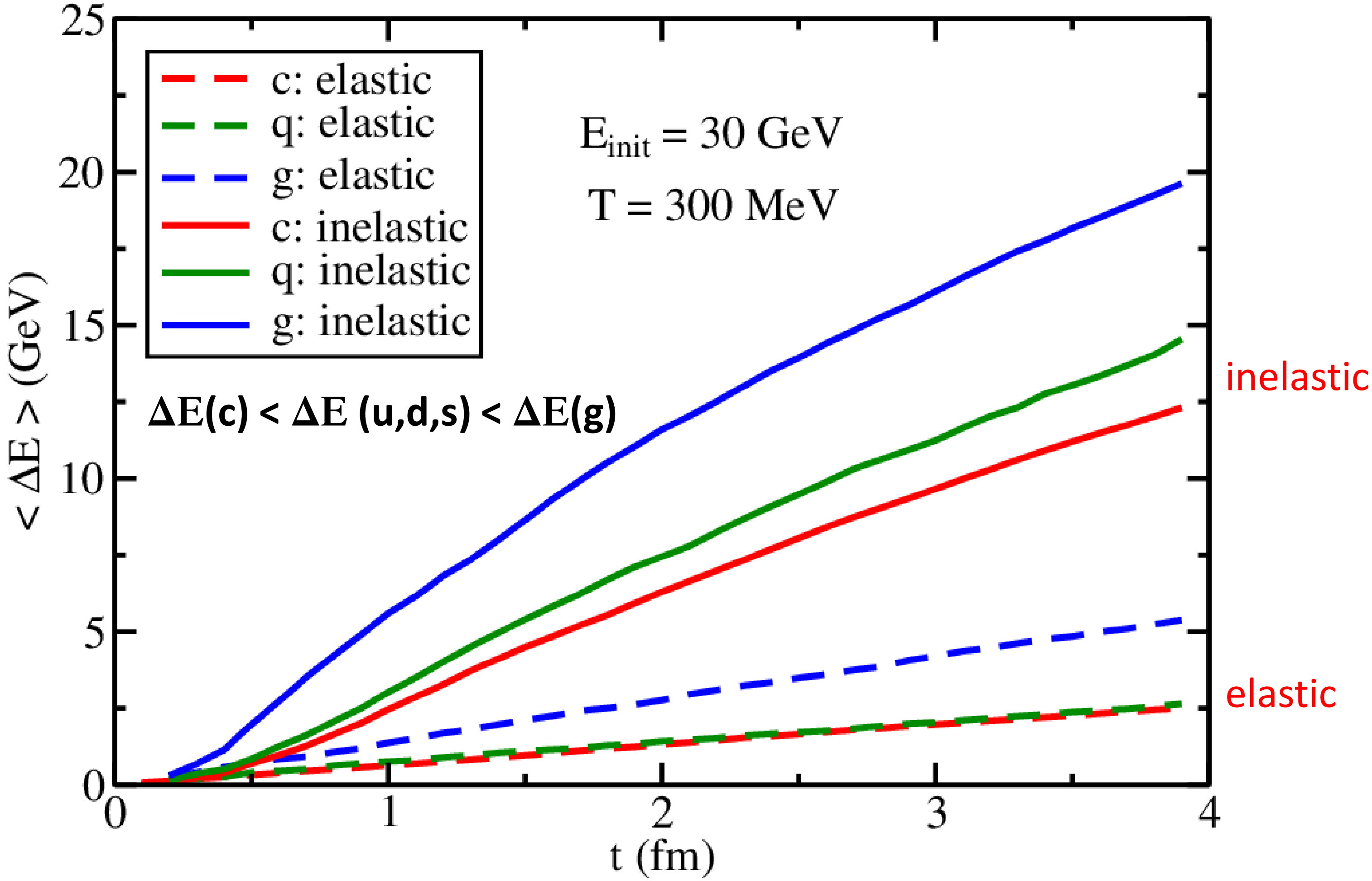
Radiation spectra taken from Guo, Wang PRL 2000; Zhang, Wang, Wang 2004

- **Elastic + Inelastic:**

$$P_{tot} = 1 - e^{-\Gamma_{tot}\Delta t} = P_{el} + P_{inel} - P_{el} P_{inel}$$

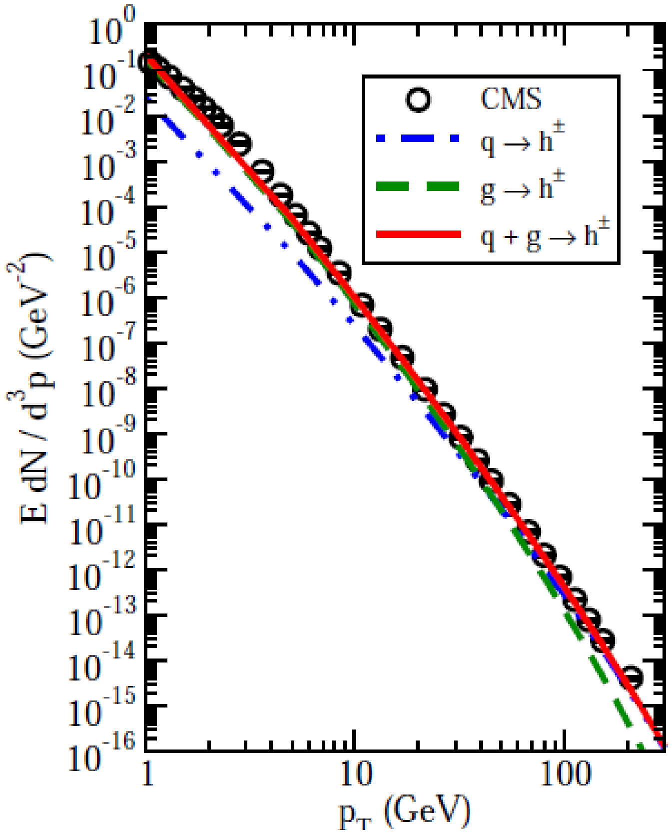
He, Luo, Wang, Zhu, PRC 2015; Cao, Luo, GYQ, Wang, PRC 2016, PLB 2018; etc.

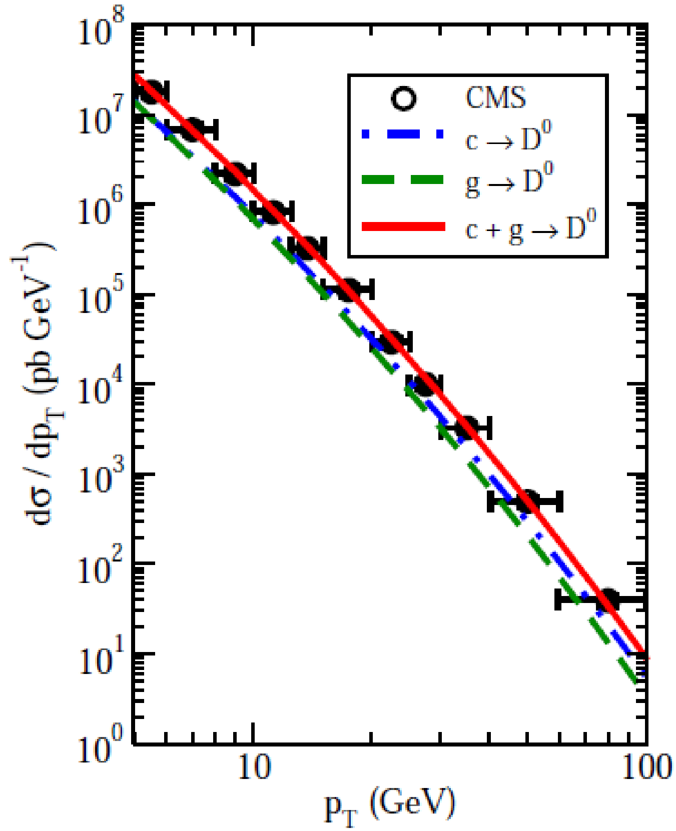
Parton energy loss in LBT



He, Luo, Wang, Zhu, PRC 2015; Cao, Luo, GYQ, Wang, PRC 2016 ; PLB 2018; etc.

Hadron productions in pp collisions

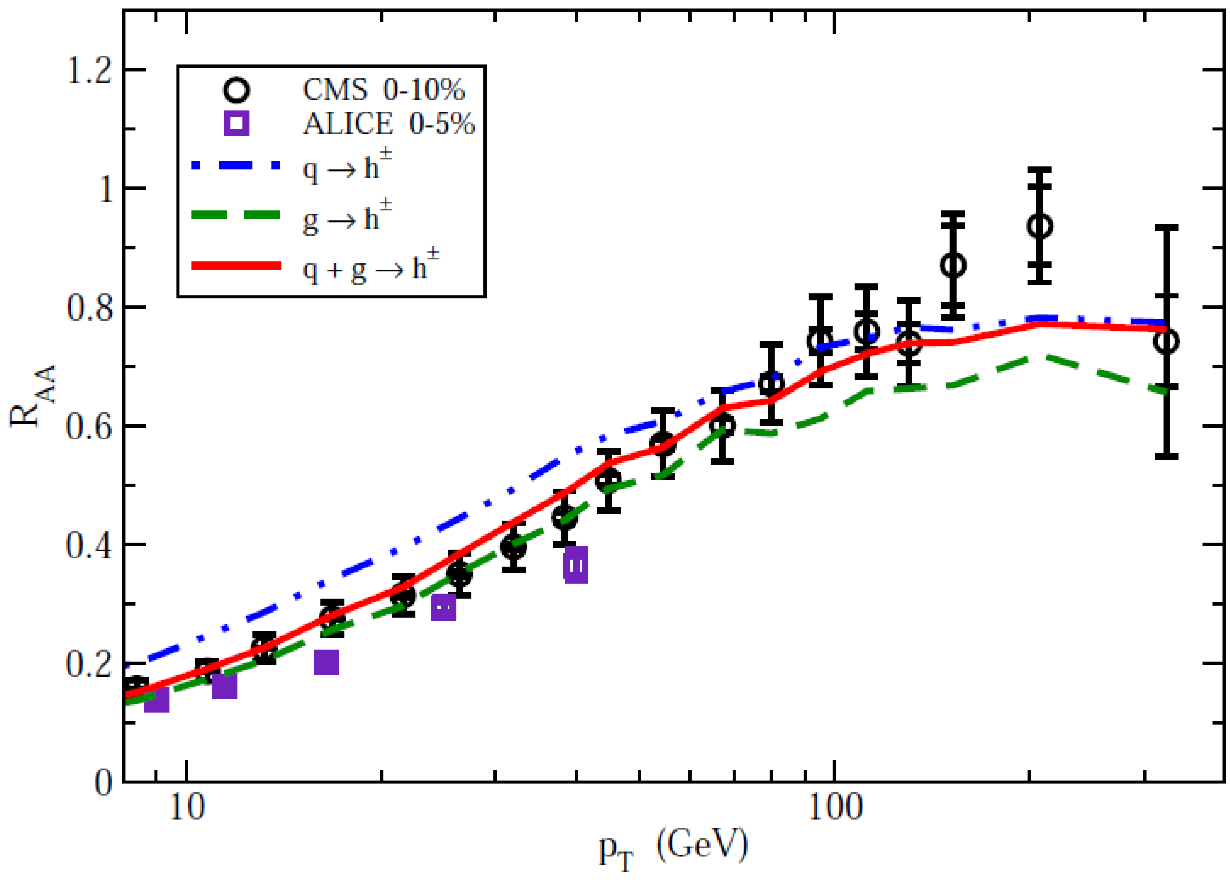




$$d\sigma_{pp\to hX} = \sum_{abc} \int dx_a \int dx_b \int dz_c f_a(x_a) f_b(x_b)\, d\hat{\sigma}_{ab\to c} D_{h/c}(z_c)$$

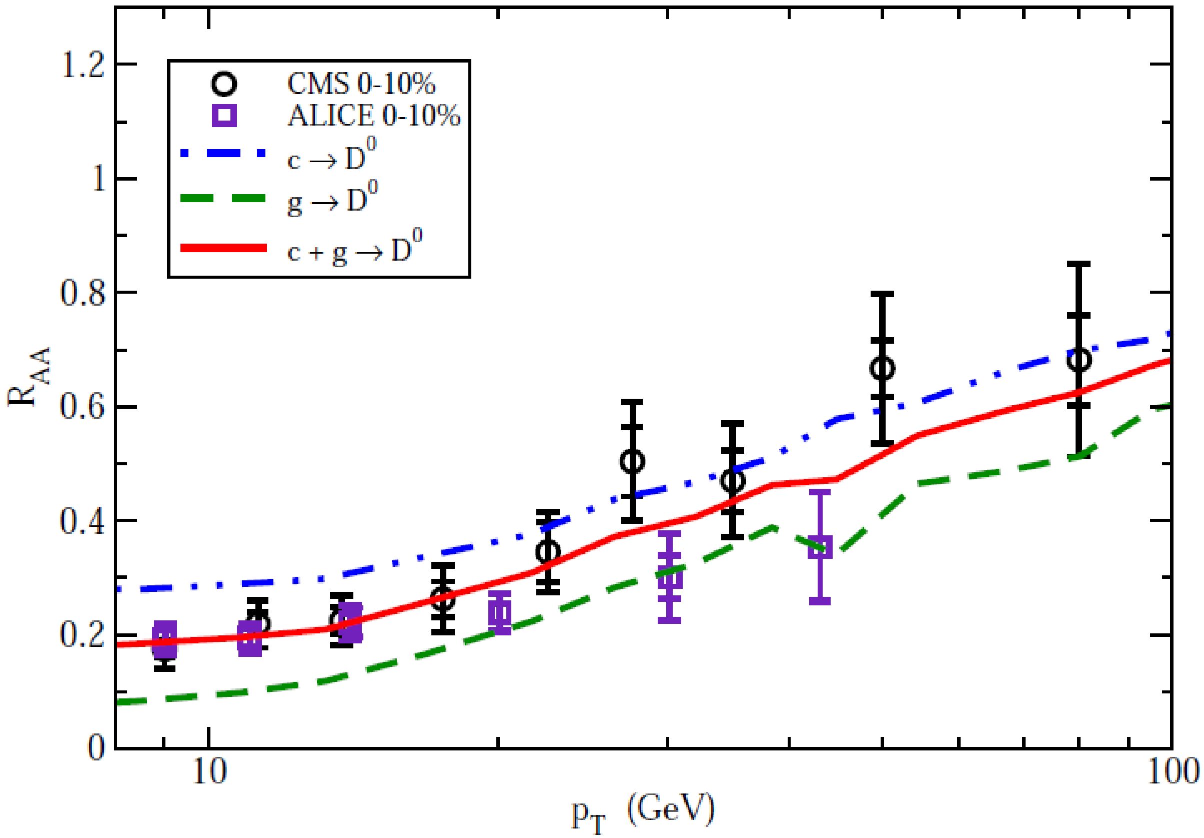
Based on B. Jager, A. Schafer, M. Stratmann, and W. Vogelsang, Phys. Rev. D67, 054005 (2003)
F. Aversa, P. Chiappetta, M. Greco, and J. P. Guillet, Nucl. Phys. B327, 105 (1989).

Charged hadron R_{AA}



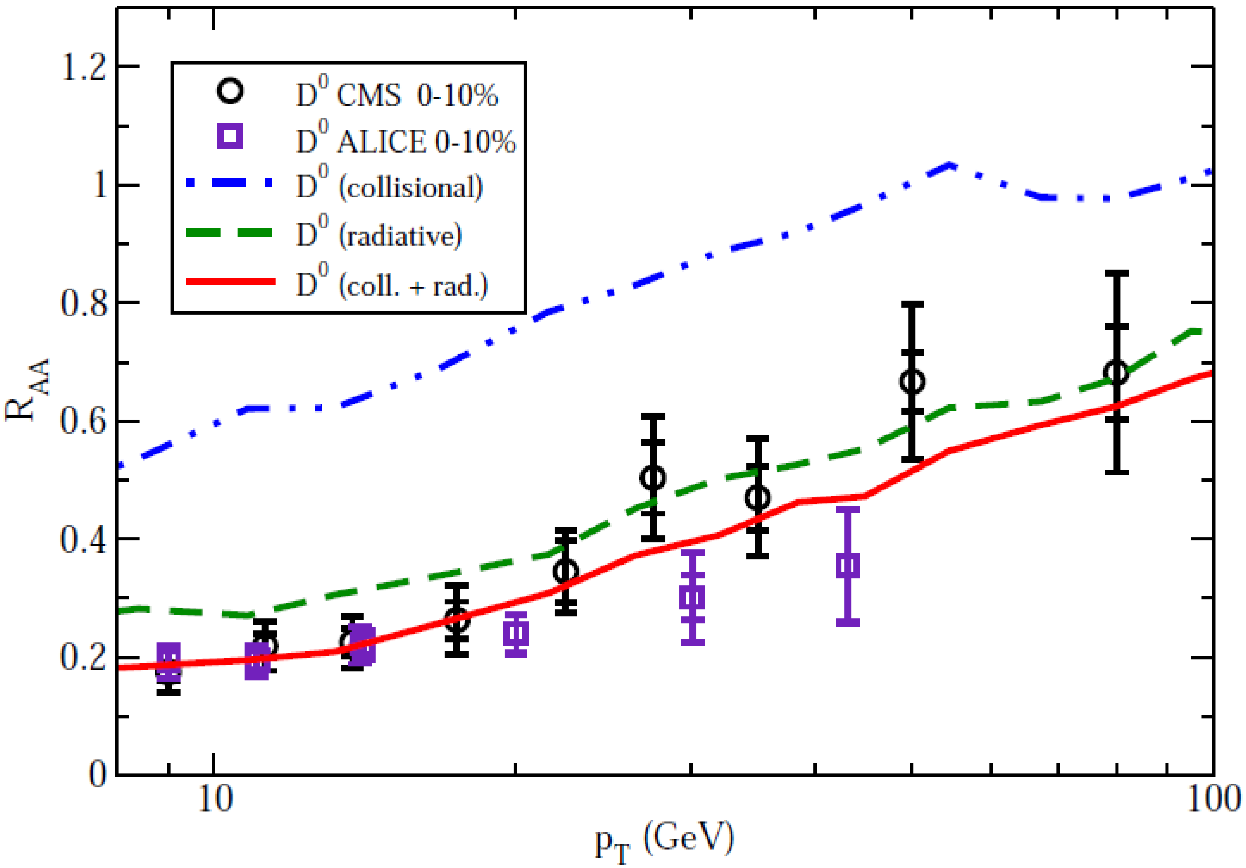
- Quark-initiated hadrons have less quenching effects than gluon-initiated hadrons.
- Combining both quark and gluon fragmentations, we obtain a nice description of charged hadron R_{AA} over a wide range of p_T.

D meson R_{AA}



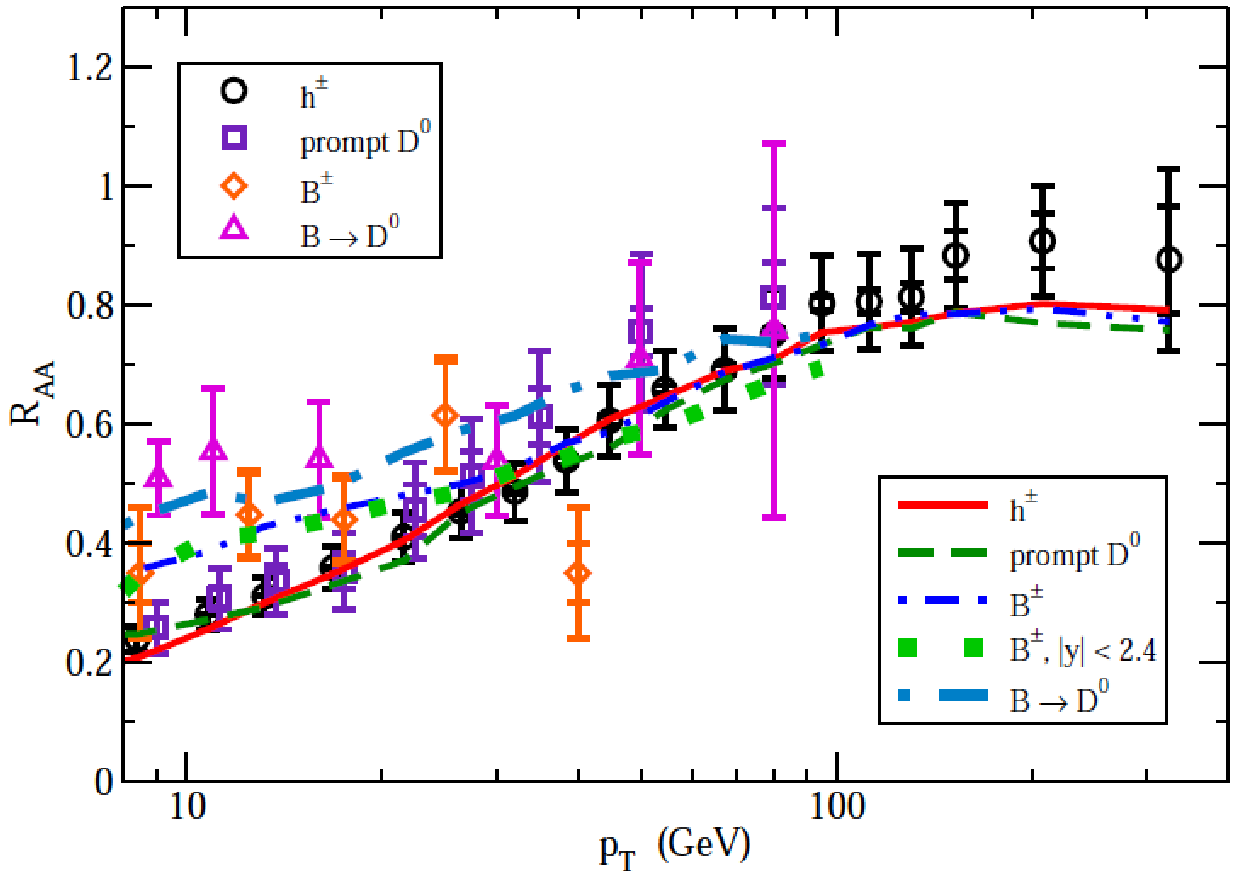
- D mesons produced from charm quark fragmentation have less quenching than D mesons from gluon fragmentation.
- Combining both charm quark and gluon contributions, we obtain successful description of D R_{AA}.

Radiative and collisional contributions



- **Radiative E loss provides more dominant contributions to R_{AA}, collisional E loss also has sizable contributions to R_{AA} at not-very-high p_T regime and diminishes with increasing p_T.**

Flavor hierarchy of jet quenching



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

Summary

- **Derive medium-induced gluon emission spectrum beyond collinear rescattering expansion and soft emission limit for massive quarks including transverse and longitudinal scatterings.**

- **By incorporating all important ingredients in our pQCD-based jet quenching model, we obtain the first satisfactory description of R_{AA} for charged hadrons, D mesons, B mesons and B-decayed D mesons over a wide range of p_T.**

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

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