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Understanding mass hierarchy in different energy loss mechanisms through heavy flavor data

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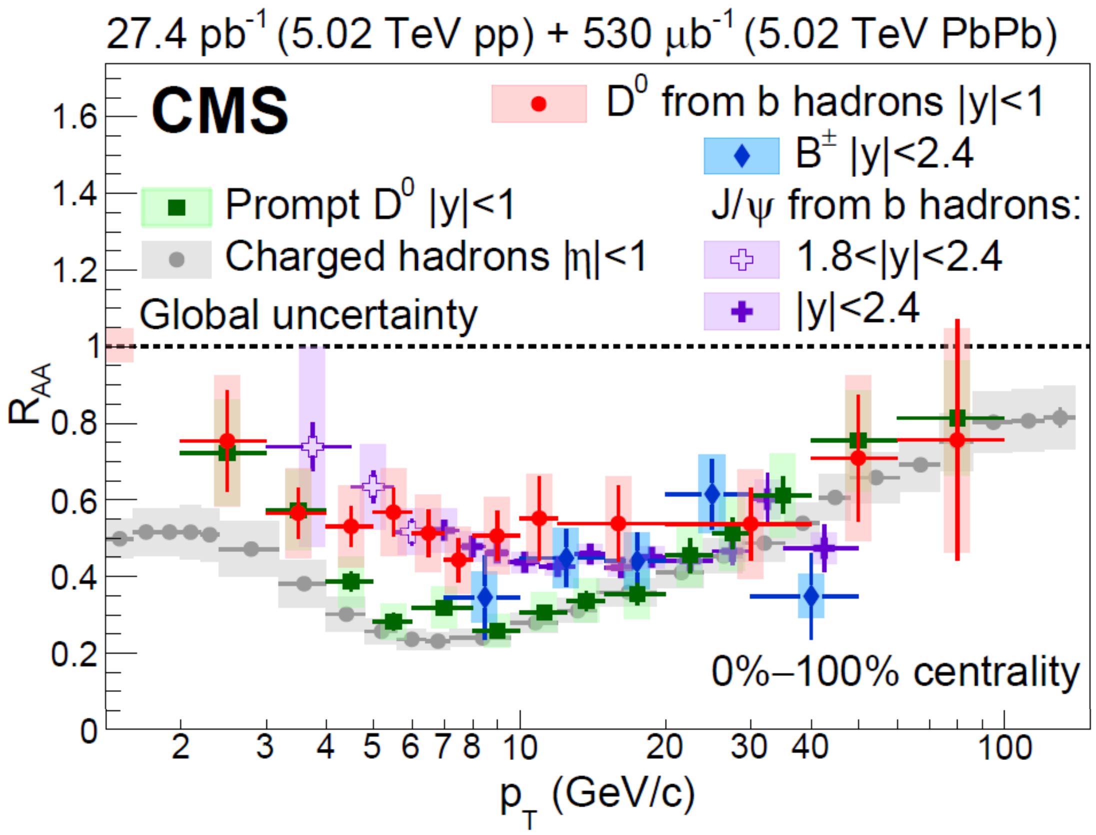
МИНИСТАРСТВО ПРОСВЕТЕ, НАУКЕ И ТЕХНОЛОШКОГ РАЗВОЈА

Mass hierarchy effect in energy loss mechanisms

- The experimental observations of R_{AA} mass hierarchy (i.e., dead cone) analyzed within radiative models
  PLB 519,199; PRD 85, 054012;
  PRD 69, 114003; NPA 733, 265; PRC 77, 024905; PLB 763, 439;
  PRL 93, 072301
- At intermediate-p⊥ range ($p_{\perp}\lesssim$10 GeV) charm and bottom collisional – comparable to (or larger) than radiative energy loss
  NPA 784, 426; PRC 74, 064907; JPG 42, 075105; PLB 273, 128; PRC 72, 014905; APHA 22, 93
- The mass hierarchy in collisional energy loss is not yet addressed
- The upcoming RHIC and LHC measurements – employ high-p_T heavy flavor data for studying interaction mechanisms in QGP



PRL 123 (2019) 022001

M. Djordjevic, PLB 763, 439
B. Ilic and M. Djordjevic, arXiv:2203.06646 [hep-ph], PRC in press

Our goals

I. Utilizing complex R_{AA} patterns to differentiate between major energy loss mechanisms

II. Focusing on the region p_T<50 GeV and addressing:

- Which observable could isolate collisional from radiative energy loss
- Analytical derivation of an explicit relation between collisional suppression/energy loss and heavy quark mass
- Analytical and numerical derivation of the mass ordering in collisional energy loss through this observable

M. Djordjevic, PLB 763, 439

B. Ilic and M. Djordjevic, arXiv:2203.06646 [hep-ph], PRC in press

Numerical framework: DREENA-C

D. Zigic, I. Salom, J. Auvinen, M. Djordjevic and M. Djordjevic, J. Phys. G 46, no.8, 085101

- Full-fledged DREENA-C (Dynamical Radiative and Elastic ENergy loss Approach, C stands for constant/average temperature profile) framework:
  - Dynamical energy loss formalism:
    - ✓Complex, unique and realistic features
    - ✓Dominant ingredient for generating high-$p_\perp$ suppression predictions
  - Constant (average) Temperature profile:
    - ✓Excludes complications from details of medium evolution
    - ✓Analytical derivations feasible
    - ✓Insignificant loss of accuracy in R_{AA} predictions (compared to DREENA-B (PLB 791, 236) and DREENA-A), low R_{AA} sensitivity to details of medium evolution

JPG 46, 085101; PLB 791, 236; PRC 99, 061902(R); PRC 85, 044903; NPA 932, 140

DREENA-C is an optimal framework for these studies (I and II), through R_{AA}, as it assumes sophisticated energy loss model.

JPG 42, 075105

The dynamical energy loss formalism

✓Includes:

- QCD medium of finite size and finite temperature
- The medium consists of dynamical (i.e., moving) partons
- Based on finite T field theory and generalized HTL approach

M. Djordjevic, PRC 74, 064907; PRC 80, 064909, M. Djordjevic, U. Heinz, PRL 101, 022302

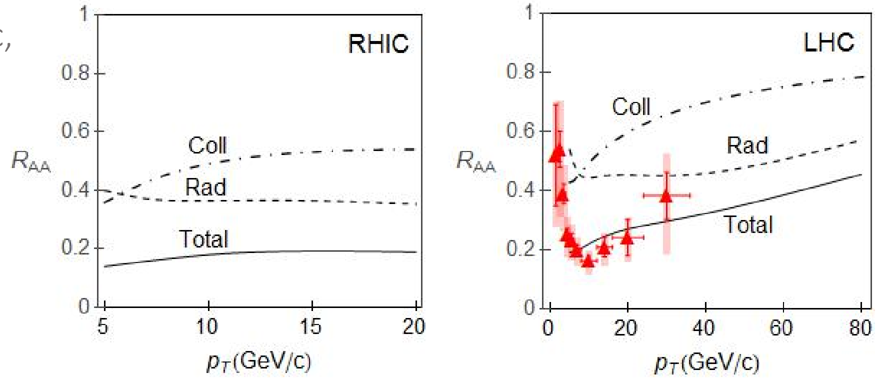
- The same theoretical framework for both radiative and collisional energy loss
- Applicable to both light and heavy flavor M. Djordjevic and M. Gyulassy, Nucl. Phys. A 733, 265
- Finite magnetic mass effects M. Djordjevic and M. Djordjevic, PLB 709, 229
- Running coupling M. Djordjevic and M. Djordjevic, PLB 734, 286
- Relaxed soft-gluon approximation B. Blagojevic, M. Djordjevic, M. Djordjevic, PRC 99, 024901

All ingredients necessary for reliable high-$p_\perp$ R_{AA} predictions!

M. Djordjevic, PLB 763, 439

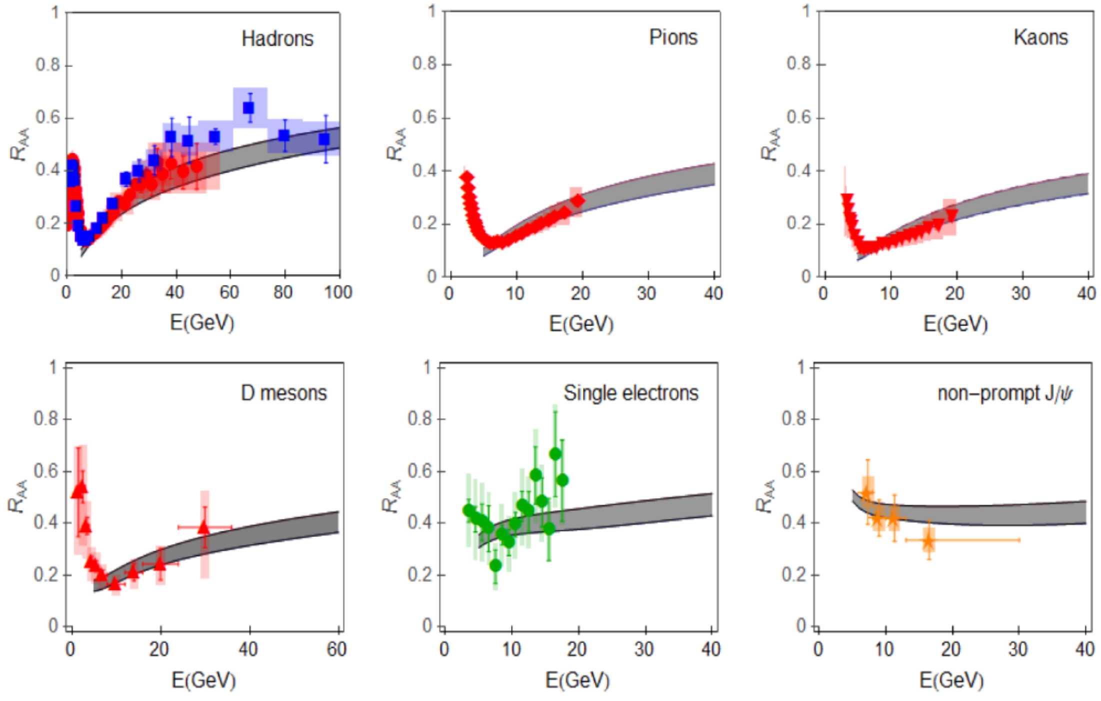
B. Ilic and M. Djordjevic, arXiv:2203.06646 [hep-ph], PRC in press

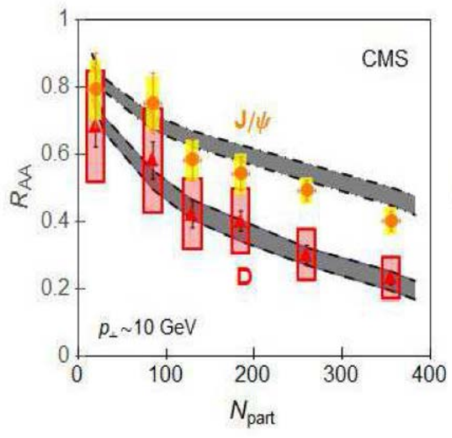
B.Blagojevic and M. Djordjevic, JPG 42, 075105



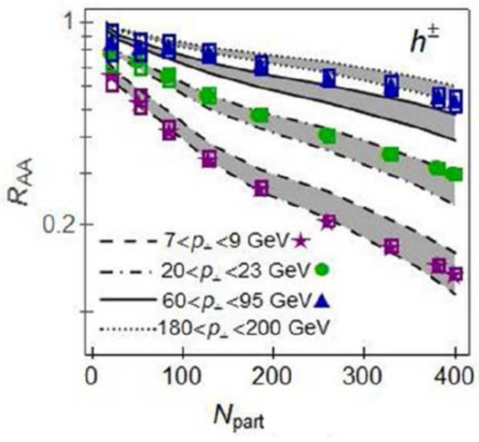
Experimental validation of DREENA-C framework

PLB 734, 286





PRC 94, 044908



PLB 763, 439

Explains high-p⊥ R_{AA} data for different probes, collision systems (experiments), energies and centralities!

Addresses heavy-flavor puzzle and has clear predictive power!

In generating all predictions we used:

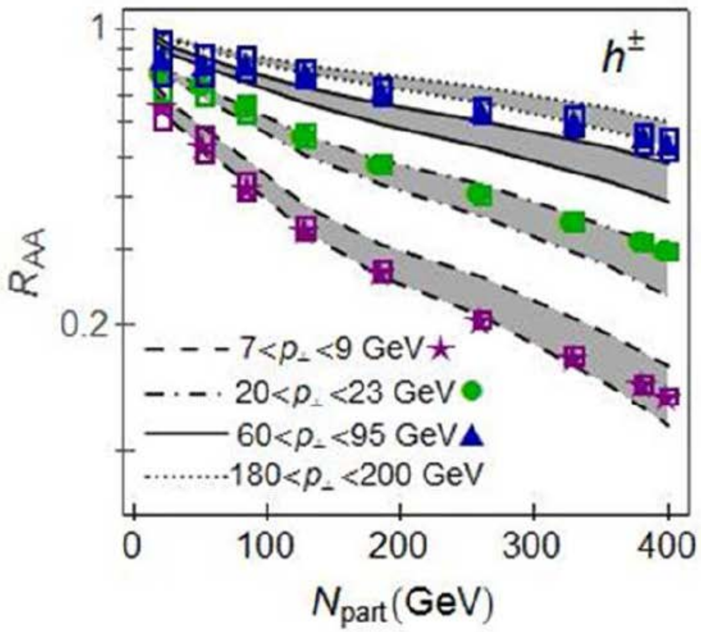
- ✓ The same numerical procedure (DREENA-C, D. Zigic, I. Salom, J. Auvinen, M. Djordjevic and M. Djordjevic, JPG 46, no.8, 085101)
- ✓ The same parameter set
- ✓ No fitting parameter

M. Djordjevic, B. Blagojevic and L. Zivkovic, PRC 94, 044908
JHEP 1704,) 039

DREENA-C accurately addresses high-p⊥ parton-medium interactions and is adequate for these studies.

M. Djordjevic, PLB 763, 439
B. Ilic and M. Djordjevic, arXiv:2203.06646 [hep-ph], PRC in press

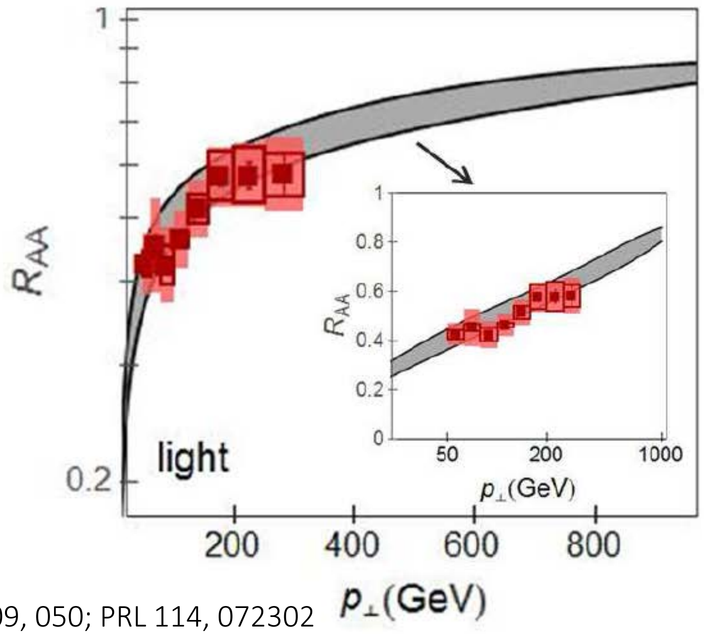
I. Nonintuitive suppression patterns (light or D probes)



With increasing p_T, R_{AA} vs. N_{part} :

- flatter
- difference between curves smaller

Saturation in R_{AA} vs. N_{part}.



With increasing p_T, R_{AA} vs. p_T flatter.

Saturation in R_{AA} vs. p_T.

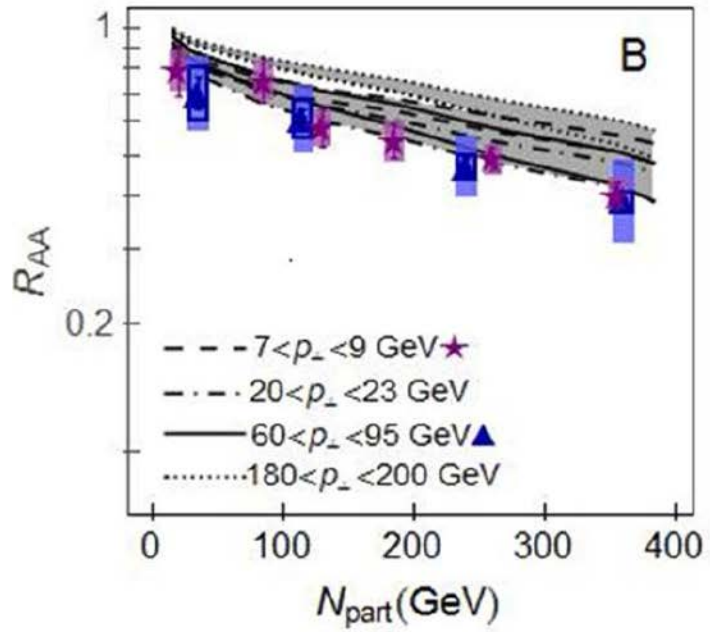
Nonintuitive observations in agreement with our framework!

Which energy loss mechanism is accountable for these observations?

ATLAS: JHEP 09, 050; PRL 114, 072302

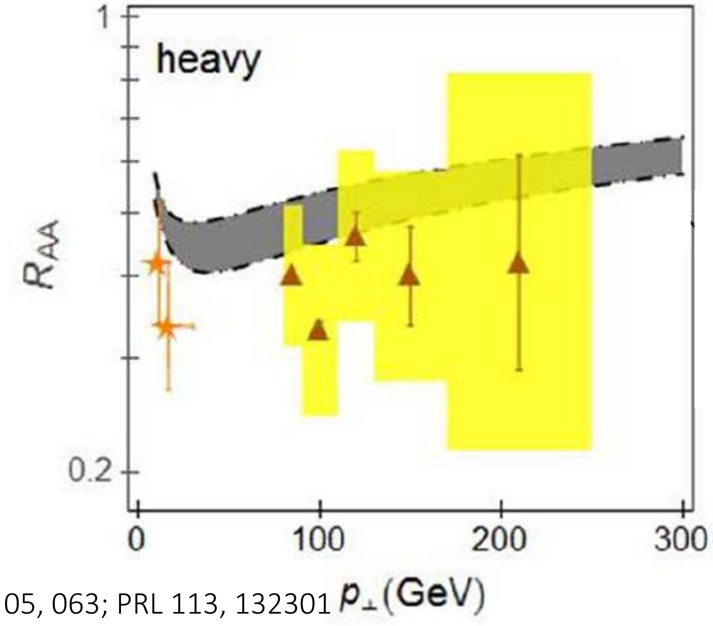
M. Djordjevic, PLB 763, 439

I. Nonintuitive suppression patterns (B probes)



R_{AA} vs. N_{part} pattern qualitatively different (compared to light probes)

Flatter R_{AA} vs. N_{part} across the p_T range



CMS: JHEP 05, 063; PRL 113, 132301

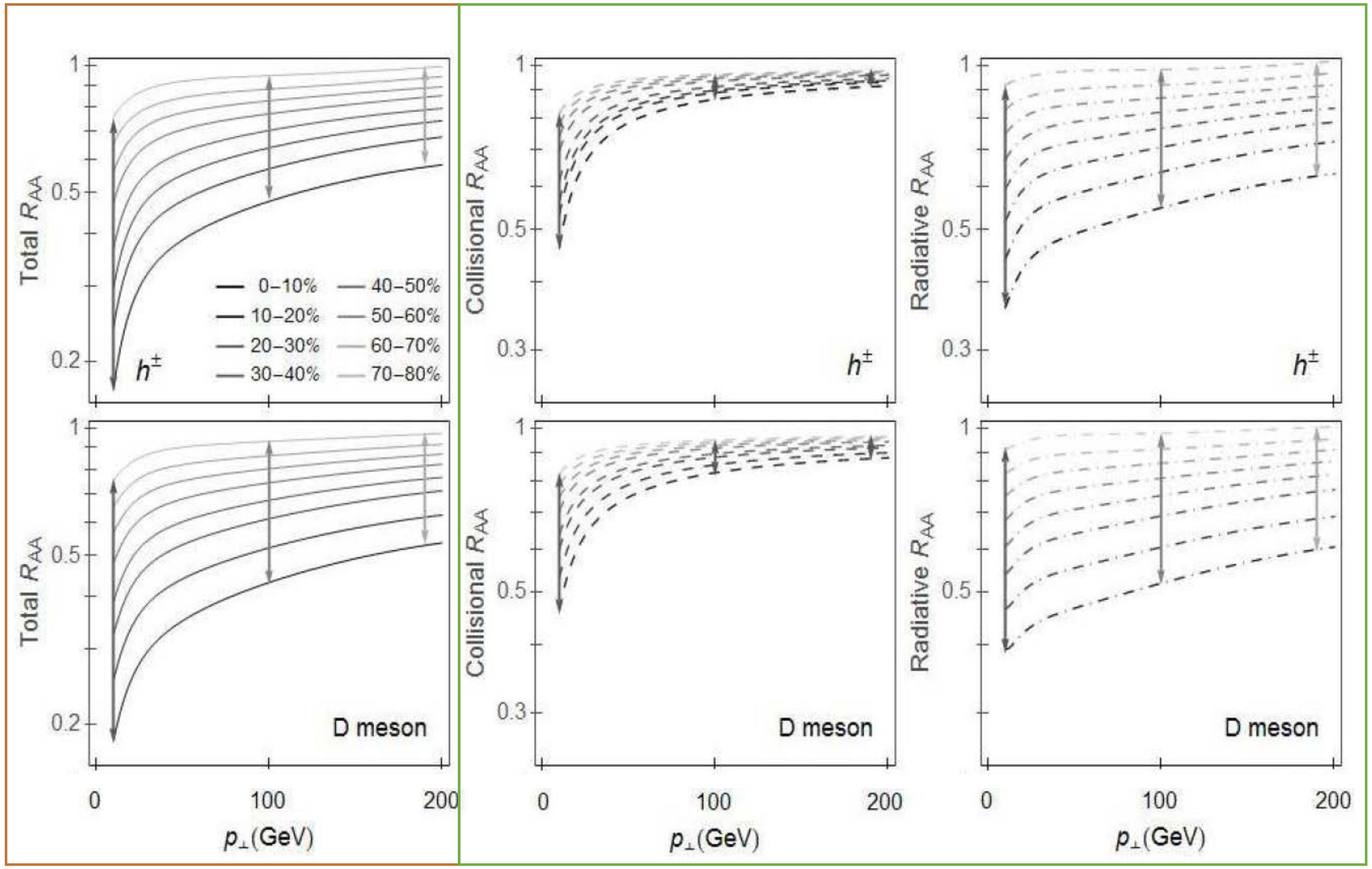
Slower R_{AA} vs. p_T change (compared to light probes)

M. Djordjevic, PLB 763, 439

Nonintuitive observation well reproduced within our framework!

Which energy loss mechanism is accountable for these observations?

Qualitative explanation of the observations (light or D probes)



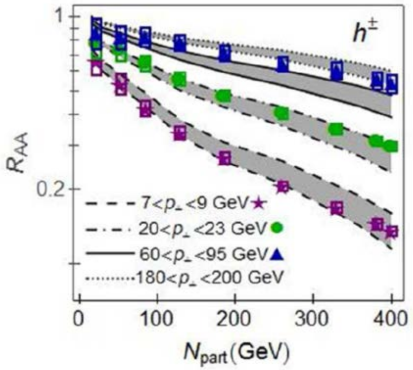
M. Djordjevic, PLB 763, 439

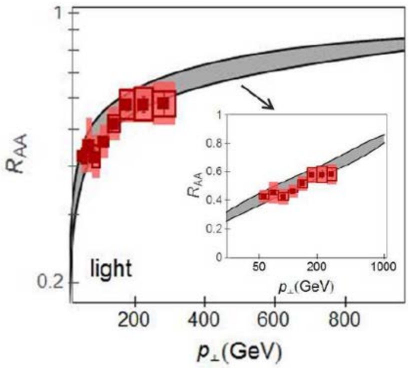
Collisional contribution: significant at lower p_T (steep increase)

Radiative contribution: important at entire p_T range (slow increase)

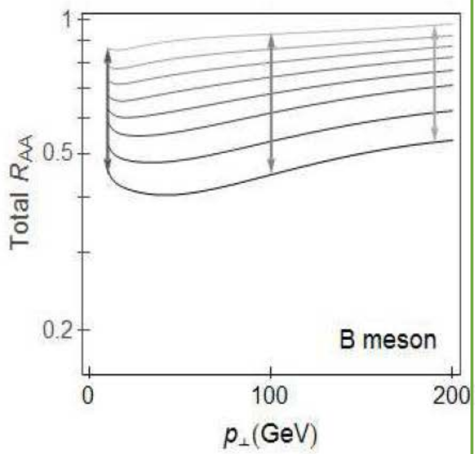
R_{AA} vs. p_T pattern result of interplay of collisional and radiative contributions.

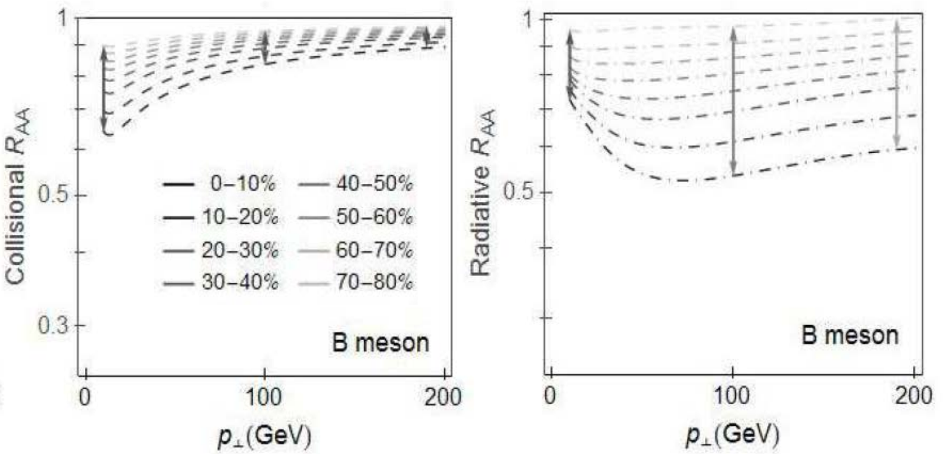
The lower p_T arrow spans a much larger R_{AA} range compared to the larger p_T arrows that are similar.





Qualitative explanation of the observations (B probes)





At lower p_T:

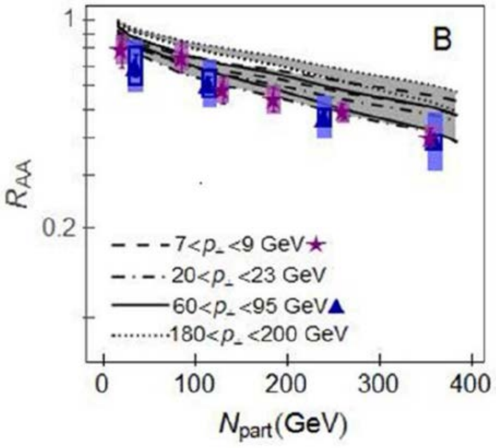
Both collisional and radiative contributions significant
(notably smaller than for light/D probes)

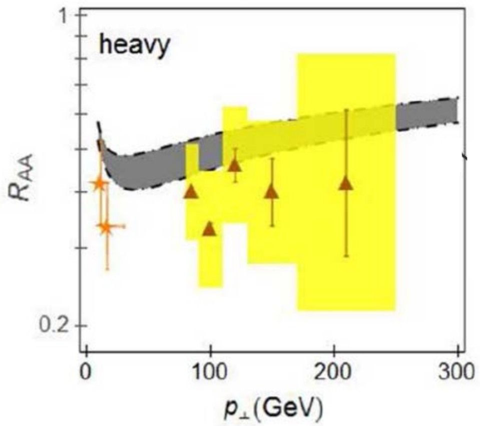
R_{AA} vs. p_T pattern consequence of mass hierarchy in collisional and radiative energy losses

At higher p_T:

Nearly flat radiative R_{AA} vs. p_T only important.

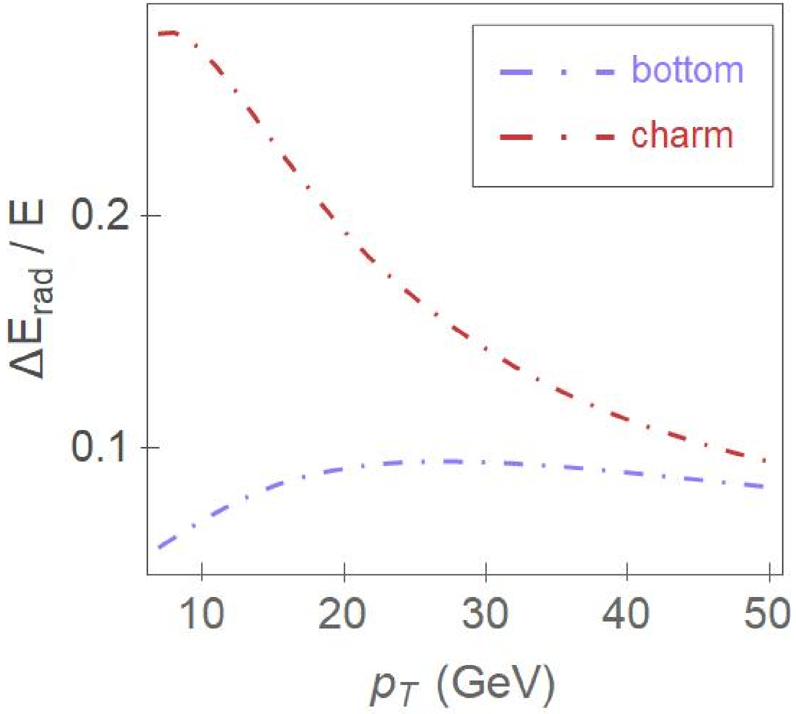
R_{AA} vs. p_T curves practically equidistant across the p_T range.





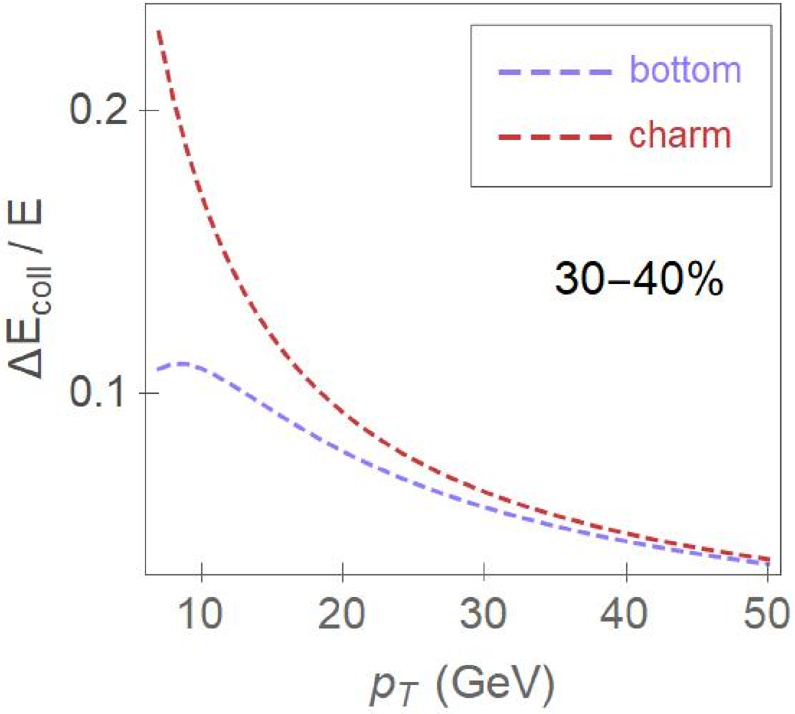
M. Djordjevic, PLB 763, 439

II. Mass hierarchy in energy loss mechanisms



M. Djordjevic, B. Blagojevic and L. Zivkovic, PRC 94, 044908

The dead-cone effect, i.e., the mass hierarchy in radiative energy loss.



PRC 74, 064907; PRC 93, 014901; NPA 931, 581; arXiv:0812.0270

Importantly: Obtained clear mass hierarchy in collisional energy loss also!

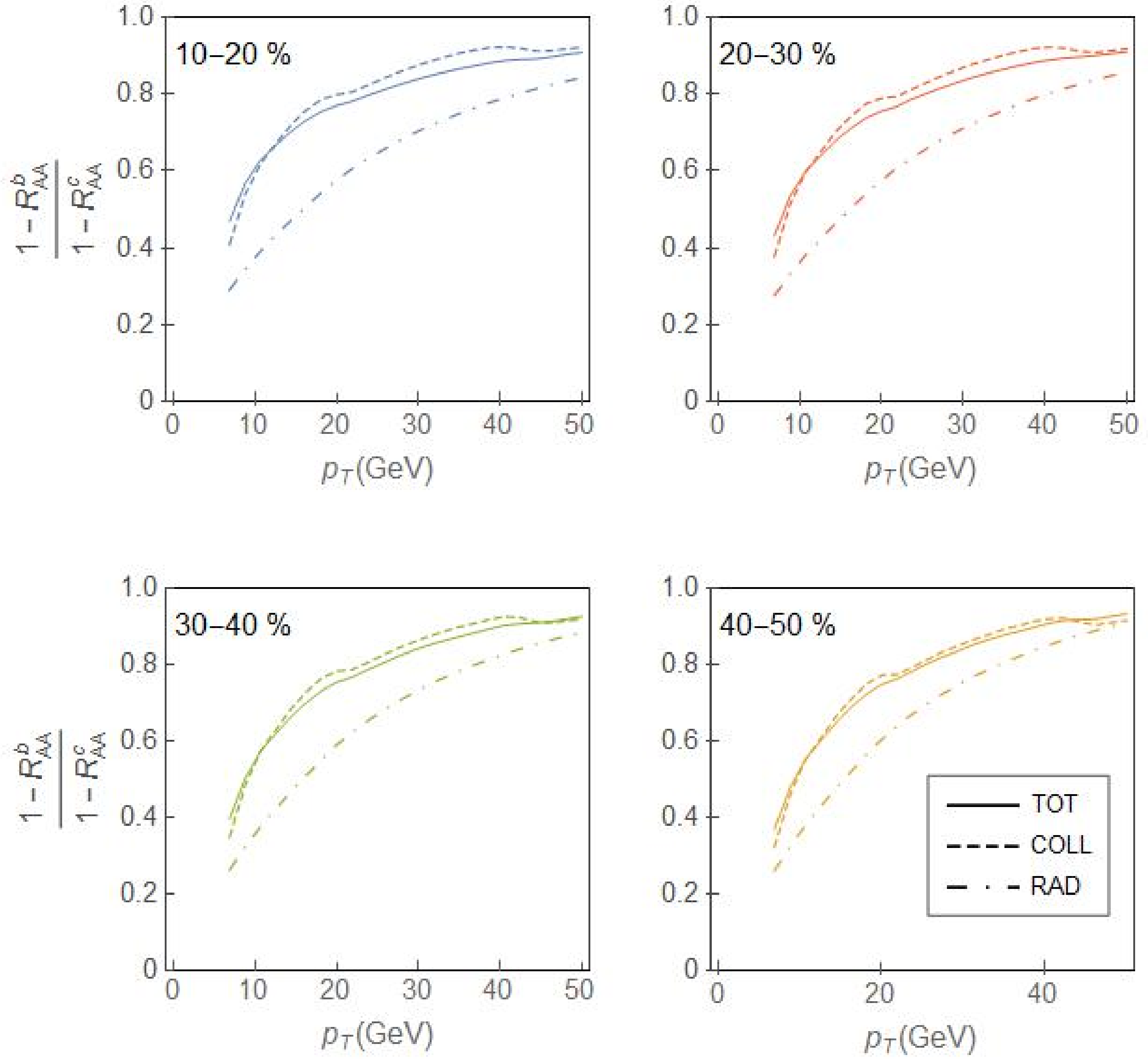
Which observable could quantify this effect?

Proposition:
$f(1 - R_{AA})$, as being particularly sensitive to parton energy loss solely.

PRC 99, 061902(R); PRC 103, 024908

B. Ilic and M. Djordjevic, arXiv:2203.06646 [hep-ph], PRC in press

Search for an observable



Unexpectedly: For all centralities TOT and COLL ratios nearly overlapping!

Collisional contribution in the origin of heavy flavor $1 - R_{AA}$

$1 - R_{AA}$ ratio might disclose mass hierarchy in collisional energy loss.

B. Ilic and M. Djordjevic, arXiv:2203.06646 [hep-ph], PRC in press

Analytical derivation: Which information does the new observable carry?

Convolution of initial parton p_T distribution and collisional energy loss:

$$\frac{d\sigma^f}{dp_T^2} = \int d\varepsilon D(\varepsilon) \frac{d\sigma^i(p_T+\varepsilon)}{dp_T^2} = \int d\varepsilon D(\varepsilon) \frac{d\sigma^i(p_T)}{dp_T^2} + \int d\varepsilon D(\varepsilon) \frac{\varepsilon}{1!} \frac{d}{dp_T}\left(\frac{d\sigma^i(p_T)}{dp_T^2}\right) + \ldots$$

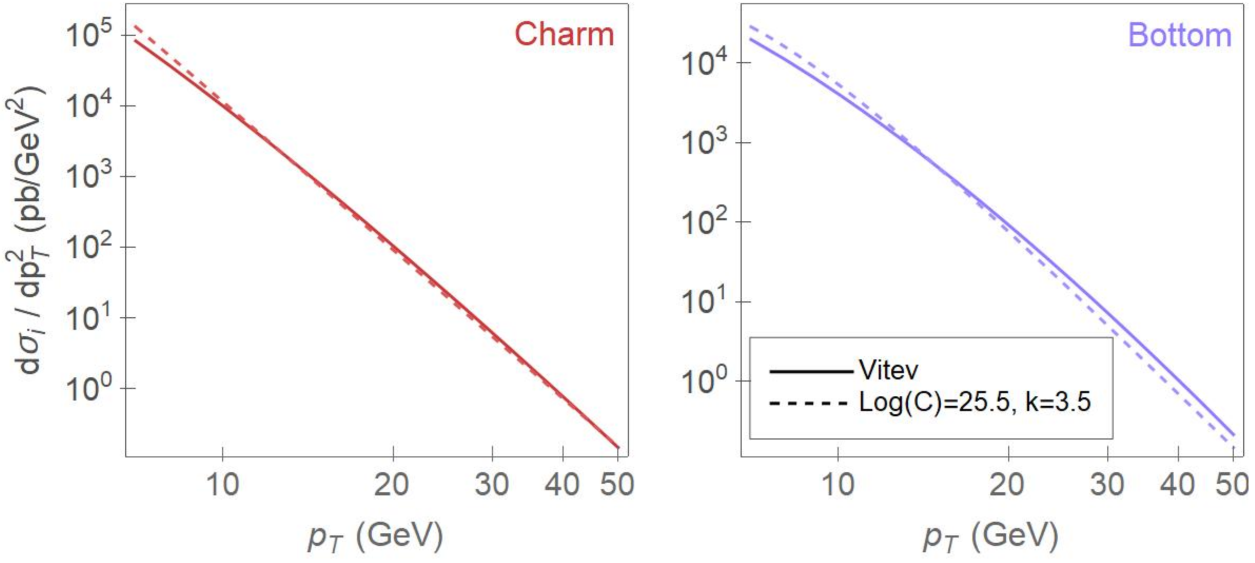
$$\simeq \frac{d\sigma^i}{dp_T^2} + \Delta E_{coll} \frac{d}{dp_T}\left(\frac{d\sigma^i}{dp_T^2}\right)$$

JHEP 09, 033; PRC 72, 014905

Initial distribution parameterization:

$$\frac{d\sigma^i}{dp_T^2} = \frac{C}{(p_T^2+M^2)^k}$$

PRC 71, 064904



PLB 718, 482; PRC 80, 054902

The same C and k for bottom and charm.

B. Ilic and M. Djordjevic, arXiv:2203.06646 [hep-ph], PRC in press

Analytical derivation: Which information does the new observable carry?

Suppression:

$$R_{AA} = \frac{d\sigma^f}{dp_T^2} / \frac{d\sigma^i}{dp_T^2}$$

PRC 71, 064904

$$1 - R_{AA} \simeq 2k \frac{p_T}{E} \frac{\Delta E_{coll}}{E}$$

Collisional energy loss:

$$\frac{\Delta E_{coll}}{E} \sim \frac{1}{Ev^2}\left(v + \frac{v^2-1}{2}\ln\left(\frac{1+v}{1-v}\right)\right) \qquad v = \frac{p_T}{\sqrt{p_T^2+M^2}}$$

NPB 351 (3), 491

Mass dependence of collisional energy loss:

$$\frac{\Delta E_{coll}}{E} \sim \frac{1}{p_T}\left(1 - \frac{M^2}{p_T^2}\ln(2) + \left(\frac{M}{p_T}\right)^{\frac{M}{p_T}+1} - \frac{M}{p_T}\right)$$

Mass dependence of $1 - R_{AA}$ ratio:

$$1 - R_{AA} \sim \frac{2k}{p_T}\left[1 - \frac{M^2}{p_T^2}\left(\ln 2 + \frac{1}{2}\right) + \left(\frac{M}{p_T}\right)^{\frac{M}{p_T}+1} - \frac{M}{p_T}\right]$$

Dominant terms

$$\frac{1-R_{AA}^b}{1-R_{AA}^c} \simeq \frac{1-\frac{M_b}{p_T}}{1-\frac{M_c}{p_T}}$$

Carries information about mass hierarchy in collisional energy loss!

New observable

B. Ilic and M. Djordjevic, arXiv:2203.06646 [hep-ph], PRC in press

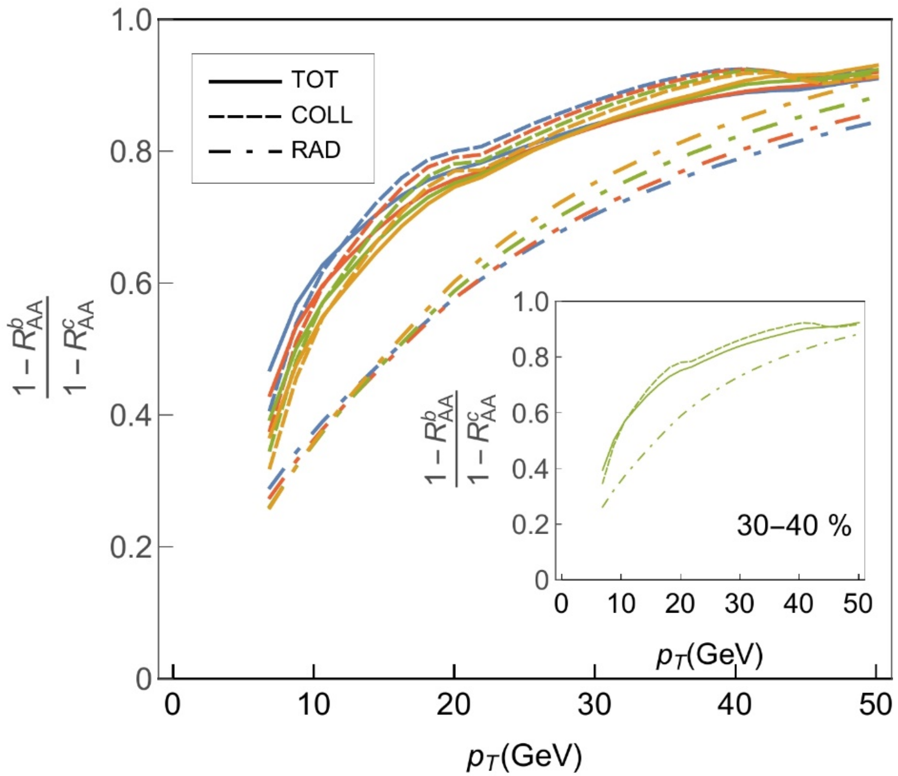
The new observable $\frac{1-R_{AA}^b}{1-R_{AA}^c}$

Unexpectedly simple relation:

$$\frac{1-R_{AA}^b}{1-R_{AA}^c} \simeq \frac{1-\frac{M_b}{p_T}}{1-\frac{M_c}{p_T}}$$

It is independent of:

- The collision centrality
- The collision system (size)
- The collision energy

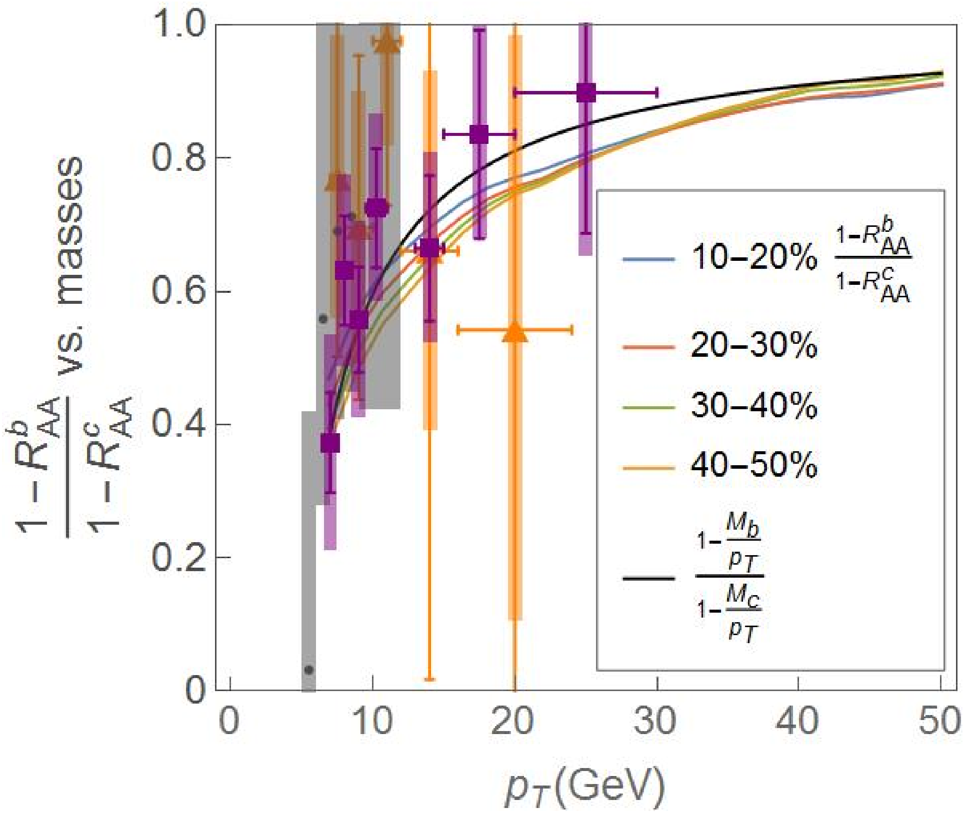


The new observable - applicable to both the RHIC and the LHC experiments.

B. Ilic and M. Djordjevic, arXiv:2203.06646 [hep-ph], PRC in press

Testing the adequacy of new observable $\frac{1-R_{AA}^b}{1-R_{AA}^c}$

$$\frac{1-R_{AA}^b}{1-R_{AA}^c} \simeq \frac{1-\frac{M_b}{p_T}}{1-\frac{M_c}{p_T}}$$



Non-prompt J/ψ CMS: EPJC 78,509
Average D ALICE: JHEP 1810,174

PHENIX Preliminary 20-40% b/c

ALICE Preliminary 30-50% non-prompt D0/D0

QM22 S. Lim
QM22 M. Puccio

A good agreement between:

Data and our predictions (qualitatively and quantitatively) ⇒ Confirms adequacy of DREENA-C.

DREENA-C predictions and our analytical estimate $\left(1-\frac{M_b}{p_T}\right)/\left(1-\frac{M_c}{p_T}\right)$ (for all centralities). ⇒ Implies validity of our analysis.

Data and our analytical mass estimate. ⇒ Supports adequacy of proposed observable.

B. Ilic and M. Djordjevic, arXiv:2203.06646 [hep-ph], PRC in press

Summary

I. Unexpected and significantly different suppression patterns for different flavors - for differentiating between radiative and collisional contributions

II. Focused on p_T <50 GeV region we:

- Proposed an observable to unravel collisional from radiative energy loss
- Derived an explicit relation between collisional suppression/energy loss and heavy quark mass
- Verified the adequacy of the proposed observable against the data
- Observable robust to collision centrality, system and energy

Outlook: Specific guidelines for future experimental efforts

I. Single particles measurements at higher p_T
II. Lower p_T, and higher precision measurements→ accessible at both RHIC and LHC
II. B meson suppression data would be beneficial
II. B meson (non-prompt J/Ψ, D0) and D meson suppression data should be provided for the same centrality bins

M. Djordjevic, PLB 763, 439

B. Ilic and M. Djordjevic, arXiv:2203.06646 [hep-ph], PRC in press

Thank you for your attention!

Backup

DREENA-C: Numerical framework

- Heavy flavor production

Z.B. Kang, I. Vitev, H. Xing, PLB 718, 482; R. Sharma, I. Vitev, and B. W. Zhang, PRC 80, 054902

- Dynamical energy loss in a finite size QCD medium

M. Djordjevic and M. Djordjevic, PLB 734, 286

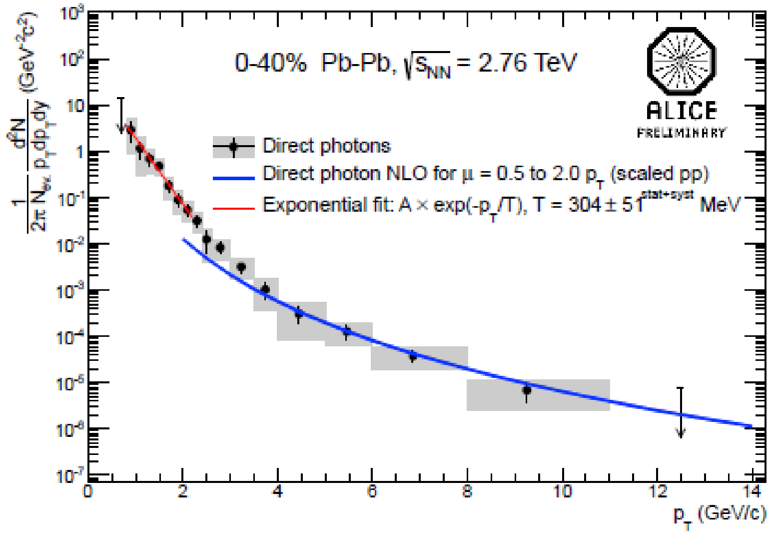
- Multi-gluon fluctuations

M. Gyulassy, P. Levai, I. Vitev, PLB 538, 282

S. Wicks, W. Horowitz, M. Djordjevic, M. Gyulassy, NPA 784, 426

- Path-length fluctuations

A. Dainese, EPJ C33, 495; S. Wicks, W. Horowitz, M. Djordjevic and M. Gyulassy, NPA 784, 426; D. Zigic, I. Salom, J. Auvinen, M. Djordjevic and M. Djordjevic, JPG 46, 085101



ALICE: NPA 904-905 573c

(T_{eff}) of 304 MeV for 0-40% centrality

2.76 TeV Pb+Pb

$$T^3 \sim \frac{\frac{dN_g}{dy}}{V} \rightarrow T = c\left(\frac{\frac{dN_g}{dy}}{N_{part}}\right)^{1/3}$$

For each centrality region.

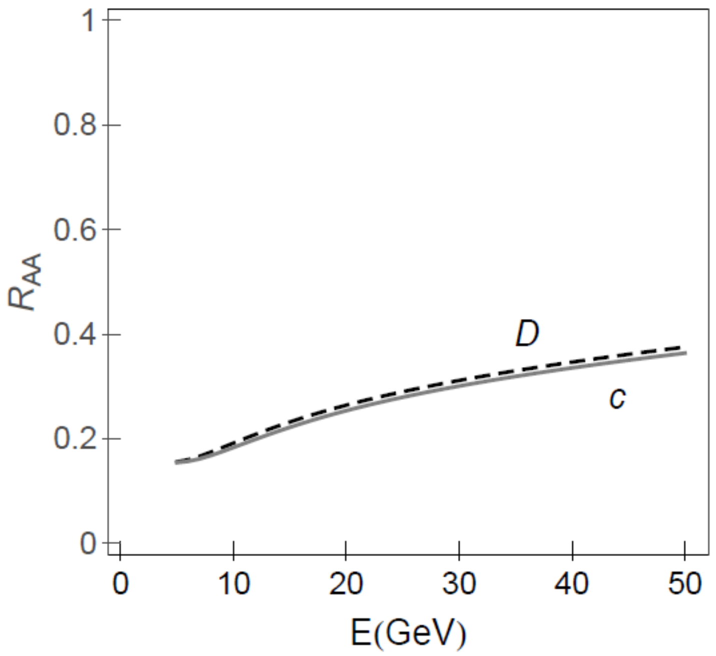
$$V \sim N_{part}$$

$$\frac{\frac{dN_g}{dy}}{N_{part}} \sim \frac{\frac{dN_{ch}}{dy}}{N_{part}/2}$$

measured

M. Gyulassy, P. Levai and I. Vitev, NPB 594 371

M. Djordjevic, M. Djordjevic and B. Blagojevic, PLB 737, 298

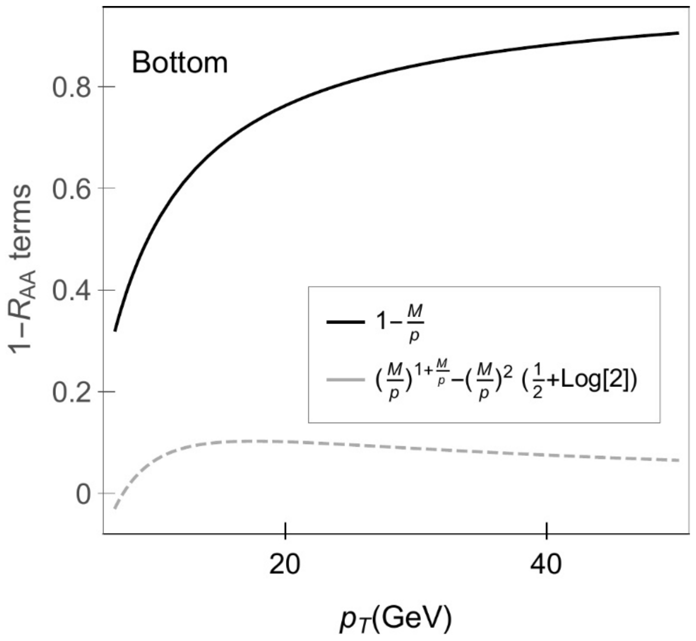


$$\frac{E_f d^3\sigma_f}{dp_f^3} = \frac{E_i d^3\sigma_i(Q)}{dp_i^3} \otimes P(E_i \to E_f)$$

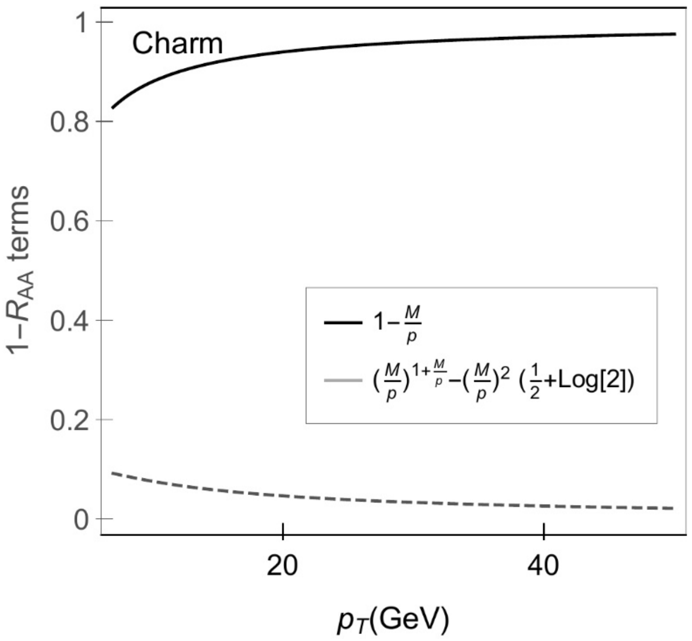
PRL 112, no.4, 042302 (2014)

D and B mesons (non-prompt J/Ψ….) present genuine charm and bottom probe’s suppression.

M. Djordjevic, M. Gyulassy, R. Vogt and S. Wicks, Phys. Lett. B 632, 81-86 (2006)
M. Djordjevic, Phys. Rev. Lett. 112, no.4, 042302 (2014)
M. Djordjevic, Phys. Lett. B 763, 439-444 (2016)



Bottom
1−R_{AA} terms
0.8
0.6
0.4
0.2
0
20
40
p_T(GeV)
$1-\frac{M}{p}$
$(\frac{M}{p})^{1+\frac{M}{p}}-(\frac{M}{p})^2\ (\frac{1}{2}+\text{Log}[2])$



Charm
1−R_{AA} terms
1
0.8
0.6
0.4
0.2
0
20
40
p_T(GeV)
$1-\frac{M}{p}$
$(\frac{M}{p})^{1+\frac{M}{p}}-(\frac{M}{p})^2\ (\frac{1}{2}+\text{Log}[2])$