中国物理学会高能物理分会
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Production of heavy-flavor decay lepton in high-energy nuclear collisions

王洒 (Sa Wang)
三峡大学 (China Three Gorges University)

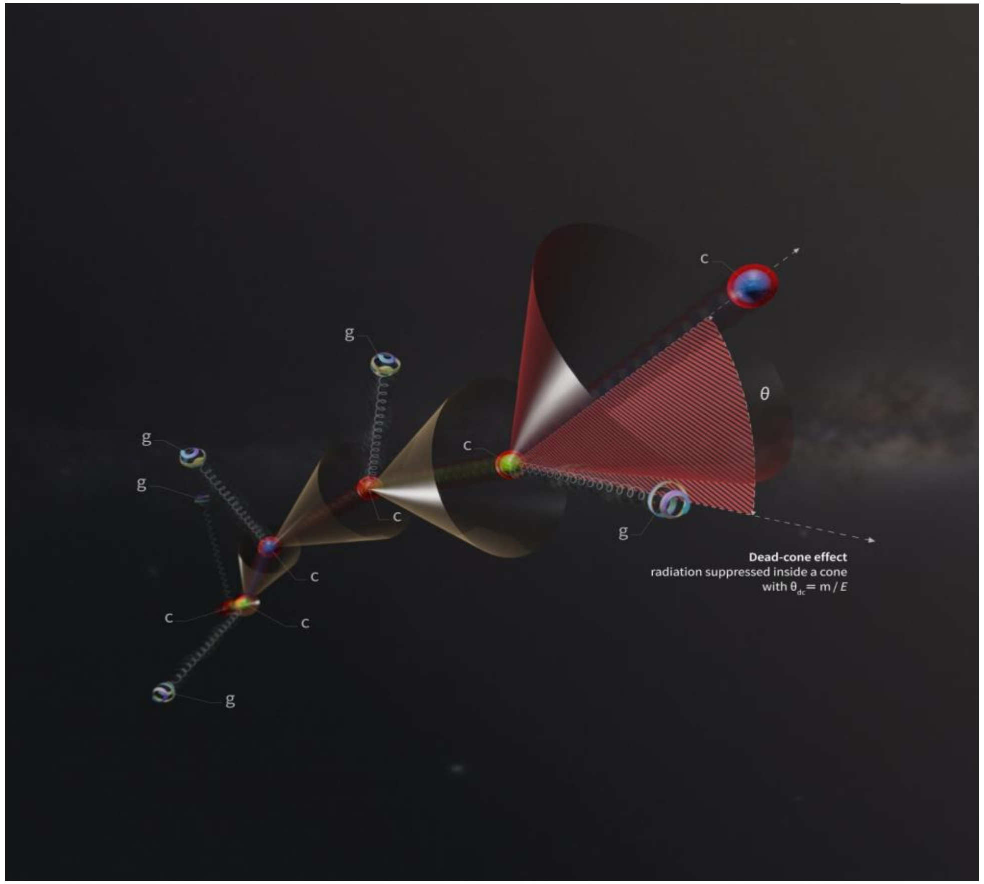
Collaborators: Prof. Ben-Wei Zhang (CCNU)
Prof. Enke Wang (SCNU)

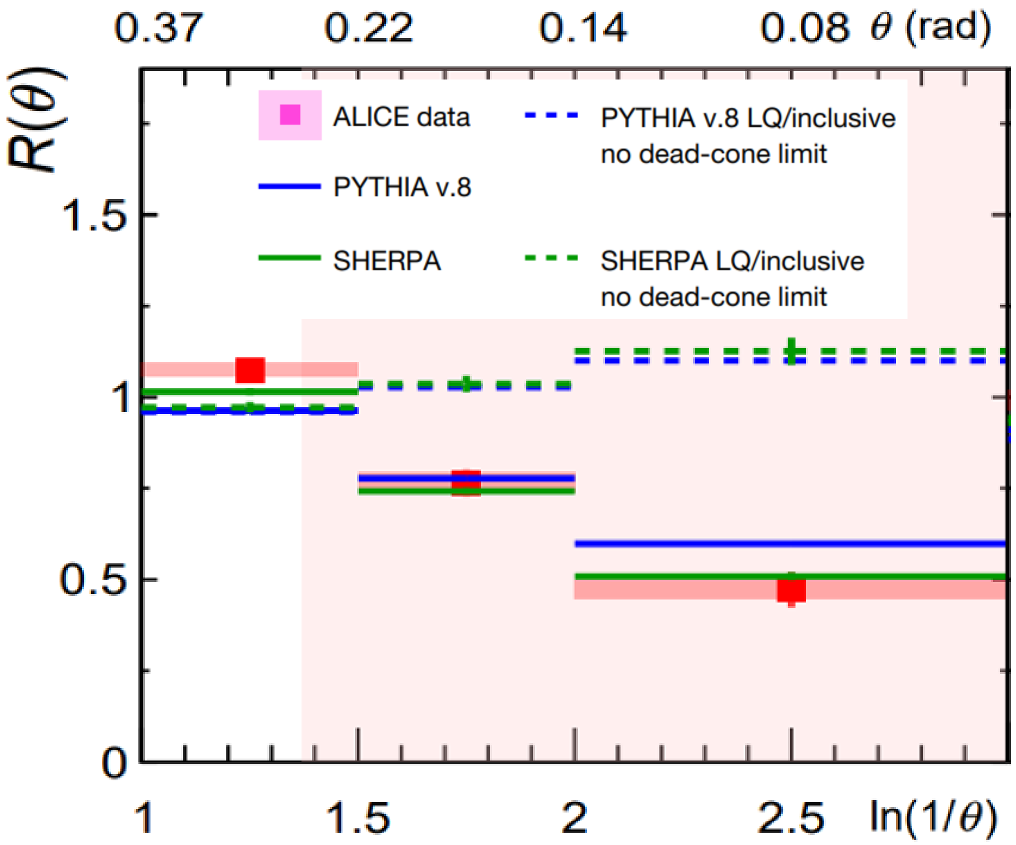
Outline

"Dead-cone" effect of heavy quark radiation

$$d\sigma_{Q\to Q+g} = \frac{\alpha_S}{\pi} C_F \frac{(2\sin\Theta/2)^2 d(2\sin\Theta/2)^2}{[(2\sin\Theta/2)^2+\Theta_0^2]^2} \frac{d\omega}{\omega}[1+O(\Theta_0,\omega)] \qquad \Theta_0 \equiv M_Q/E_Q \ll 1$$

Yuri L. Dokshitzer et al. J.Phys.G (1991); Phys.Lett.B (2001)

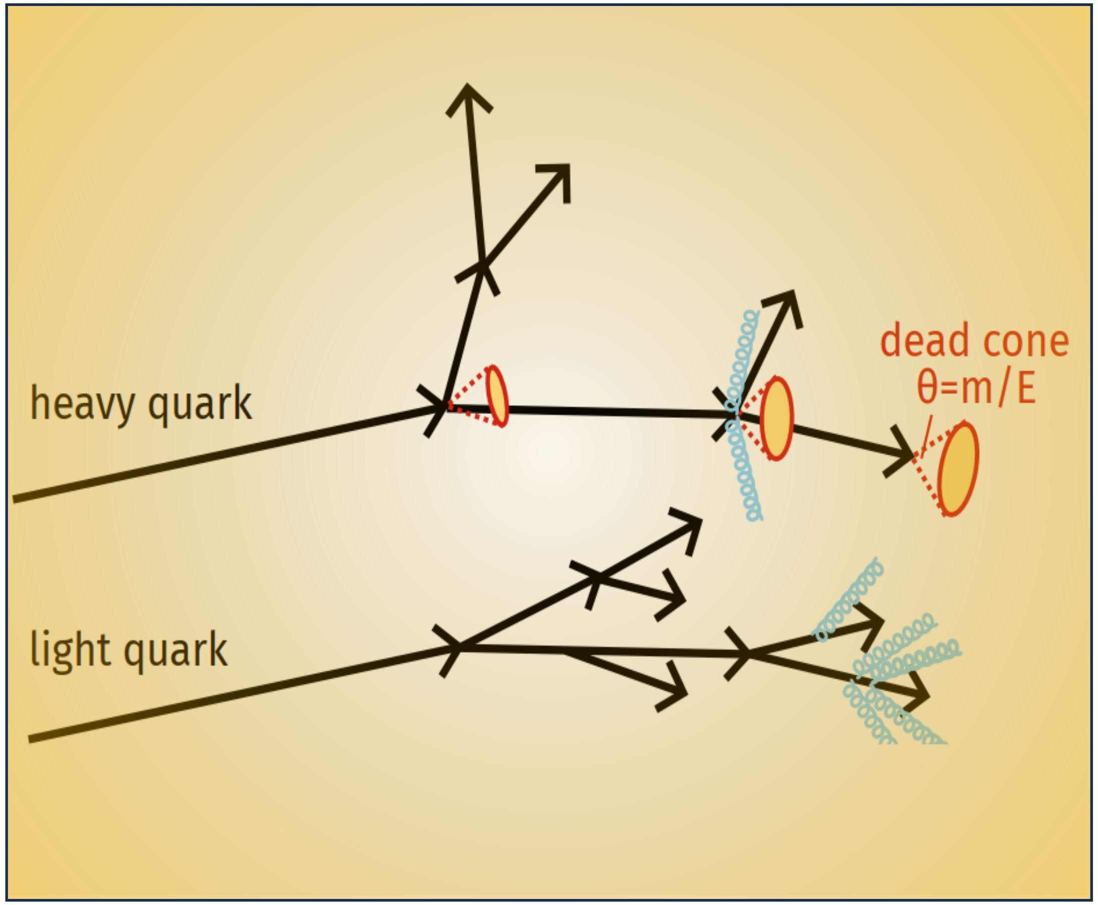


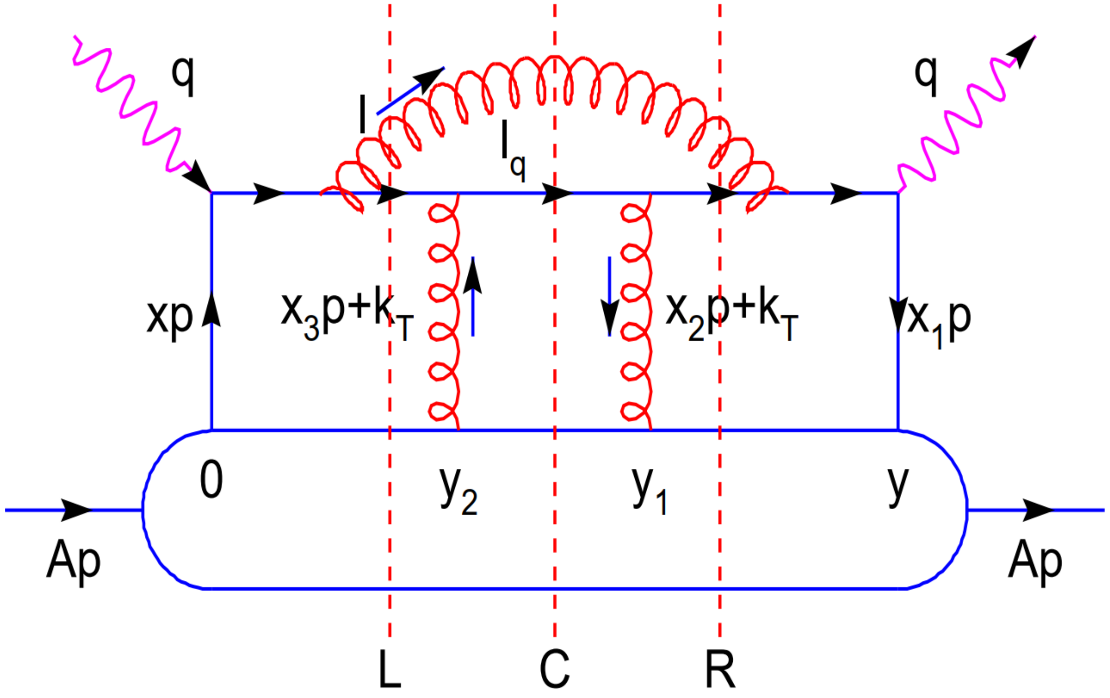


ALICE, Nature (2022)

"Dead-cone" effect of heavy quark in QGP

$$\Delta\gamma_{q\to qg}(z) = \left[\frac{1+z^2}{(1-z)_+}T^{A,C}_{qg}(x,x_L,M^2) + \delta(1-z)\Delta T^{A,C}_{qg}(x,\ell_T^2,M^2)\right]\times\frac{2\pi C_A\alpha_s\ell_T^4}{[\ell_T^2+(1-z)^2M^2]^3N_c f_q^A(x)}$$





B.-W. Zhang, X.-N. Wang, NPA (2003)

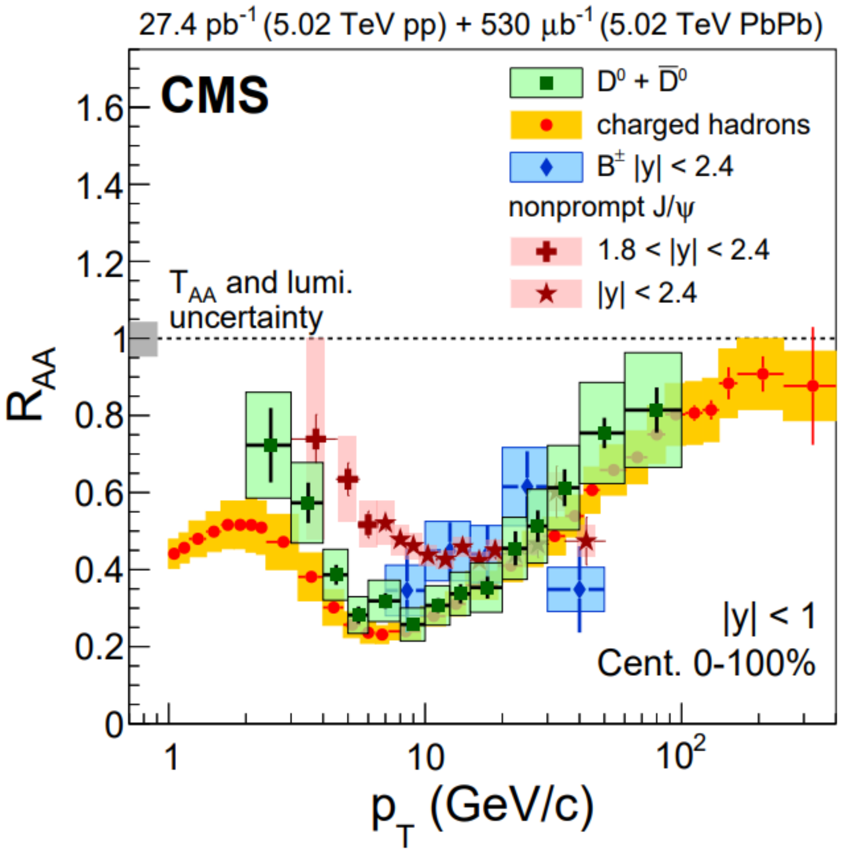
B.-W. Zhang, E. Wang, X.-N. Wang, PRL (2004)

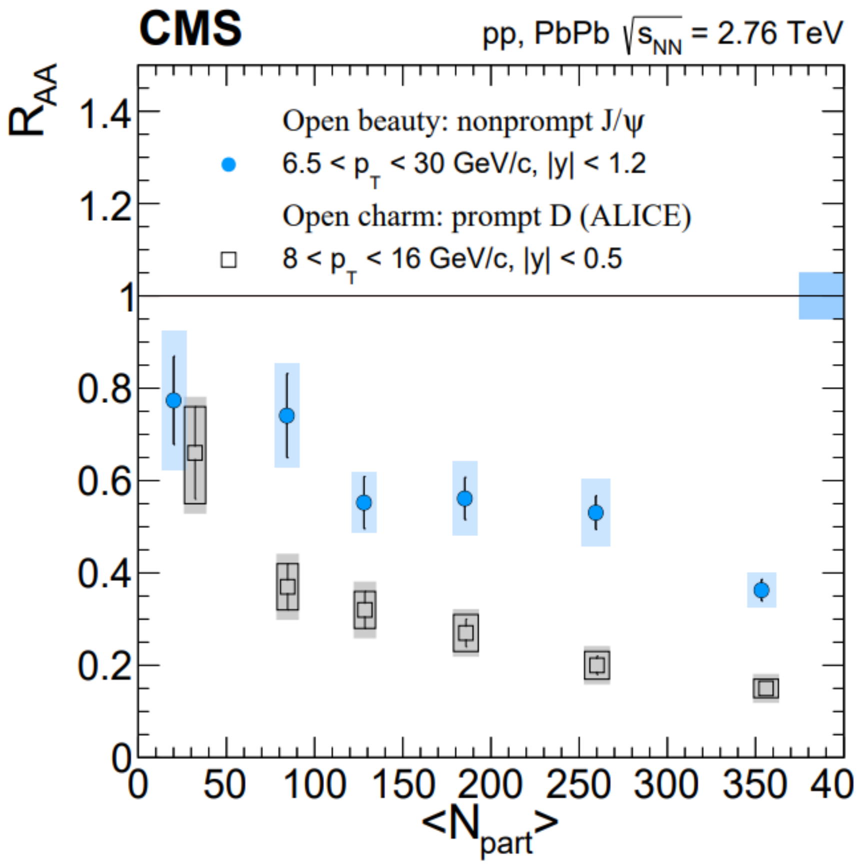
Mass hierarchy: $\Delta E_g > \Delta E_q > \Delta E_c > \Delta E_b$

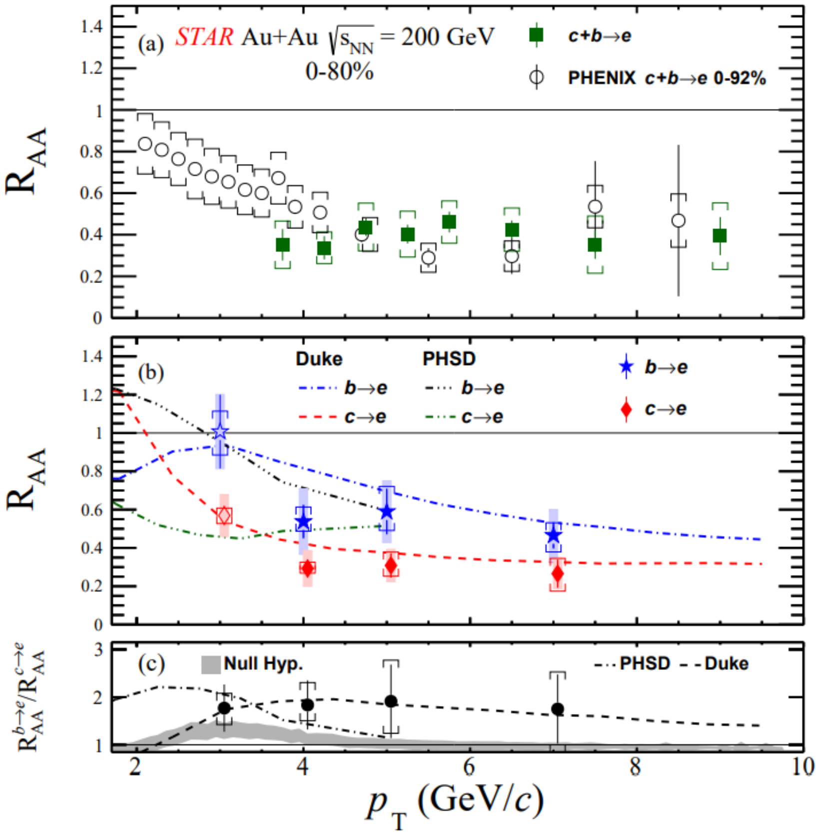
HF hadron

J/ψ← b hadron

Lepton ← HF hadron





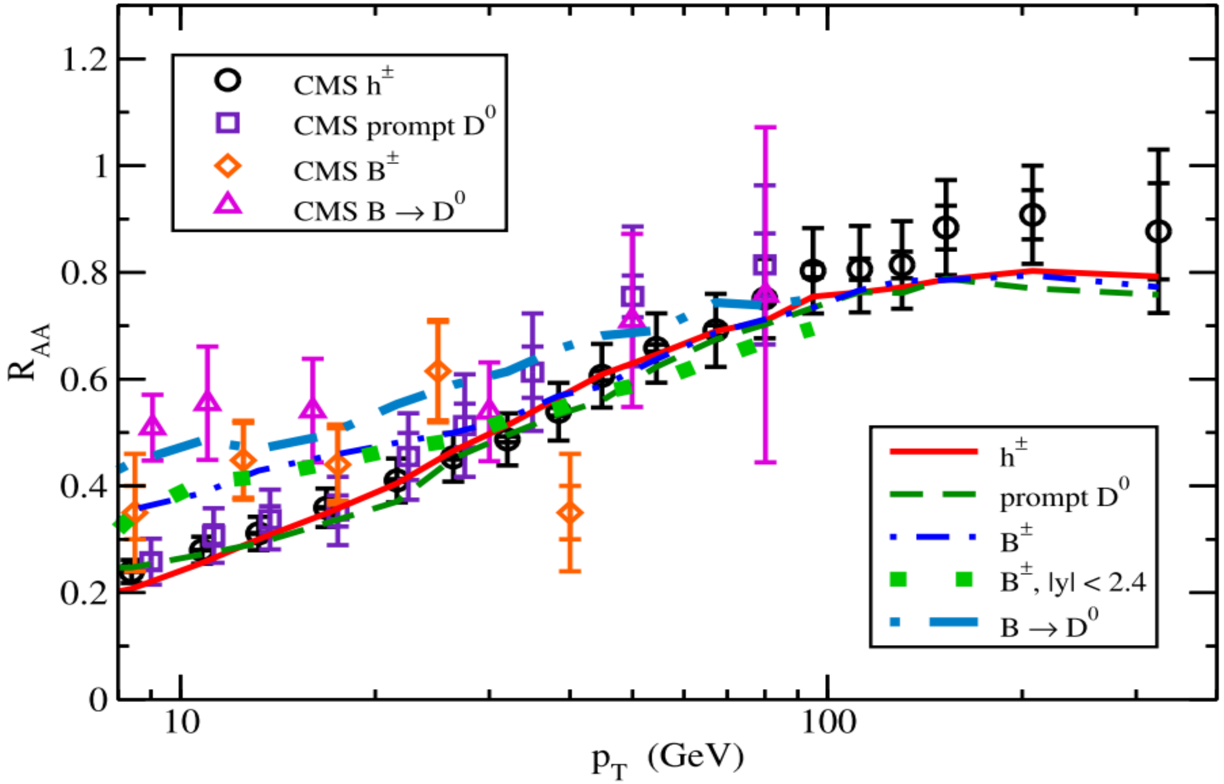


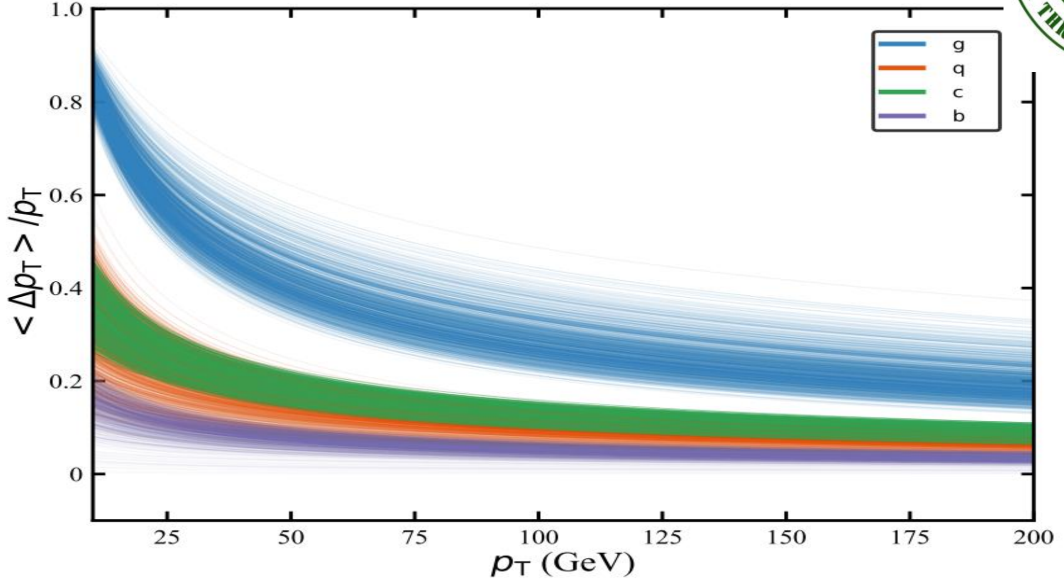
[ALICE, PLB (2018)](#)
[CMS, PRL (2017)](#)

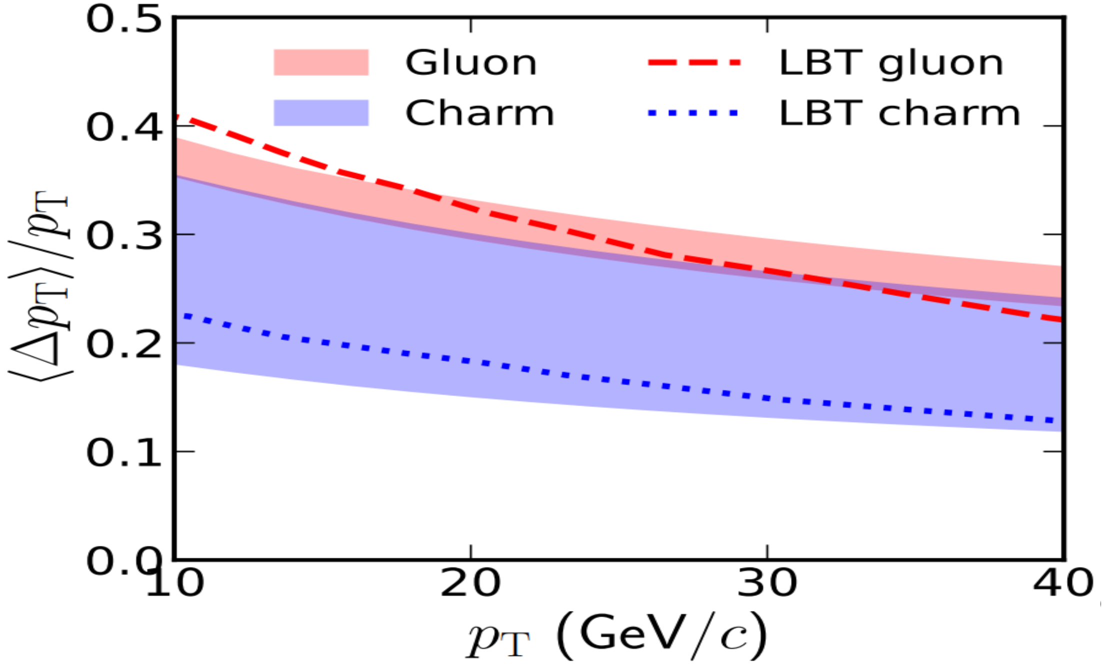
[ALICE, EPJC (2017)](#)

[STAR, EPJC (2023)](#)

Mass hierarchy: $\Delta E_g > \Delta E_q > \Delta E_c > \Delta E_b$





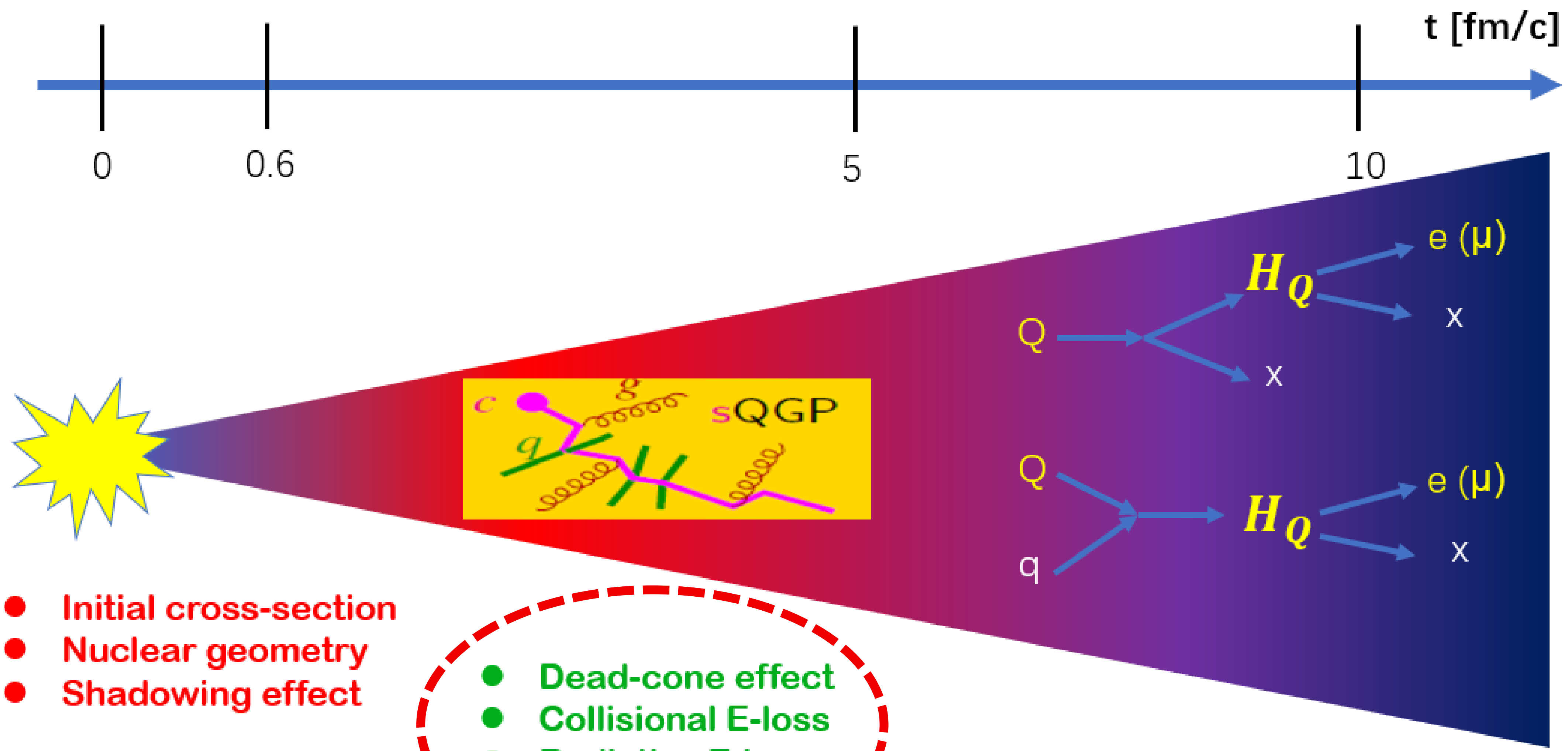


W. Xing, S. Cao, G. Qin, H. Xing, PLB (2020)

S. Zhang, J. Liao, G. Qin, E. Wang, H. Xing, Sci.Bull. (2023)

W. Xing, S. Cao, G. Qin, PLB (2024)

Evolution of heavy quarks in A+A collisions

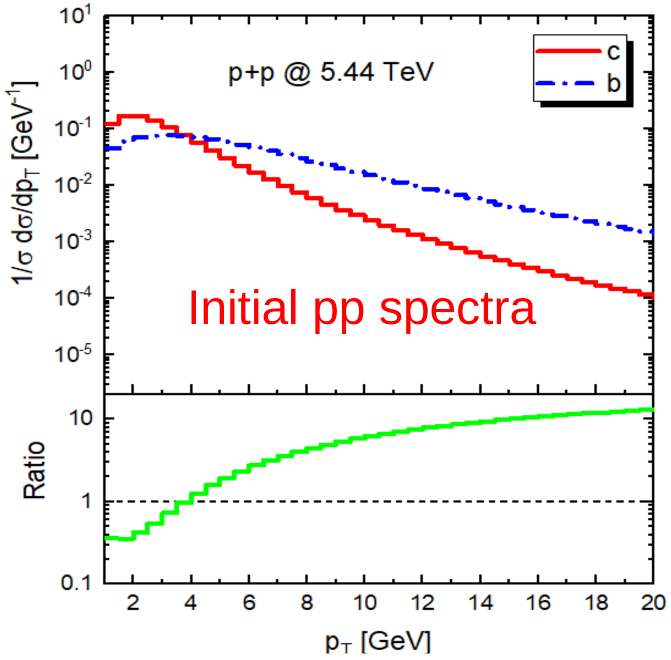


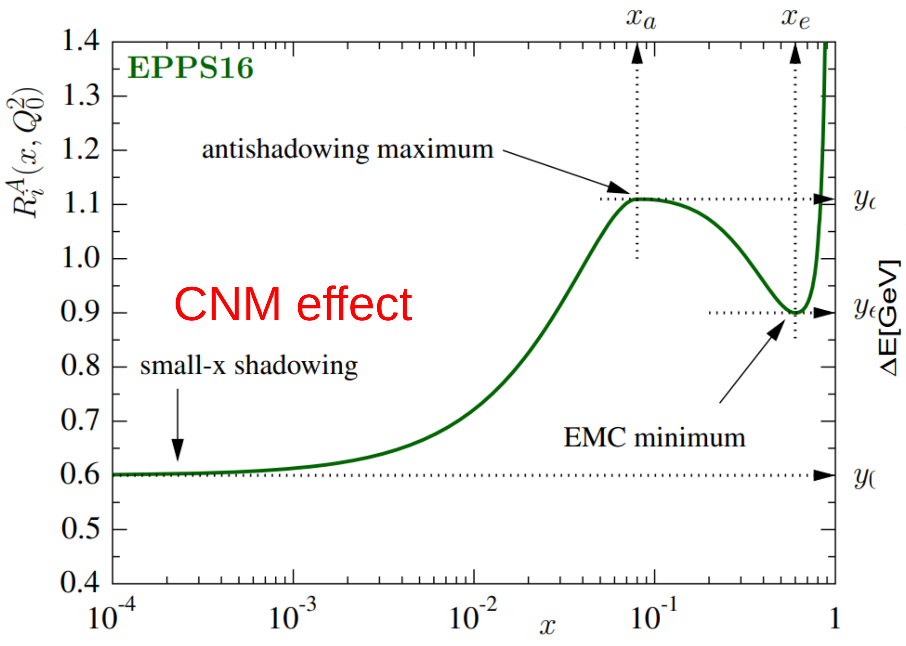
- Initial cross-section
- Nuclear geometry
- Shadowing effect

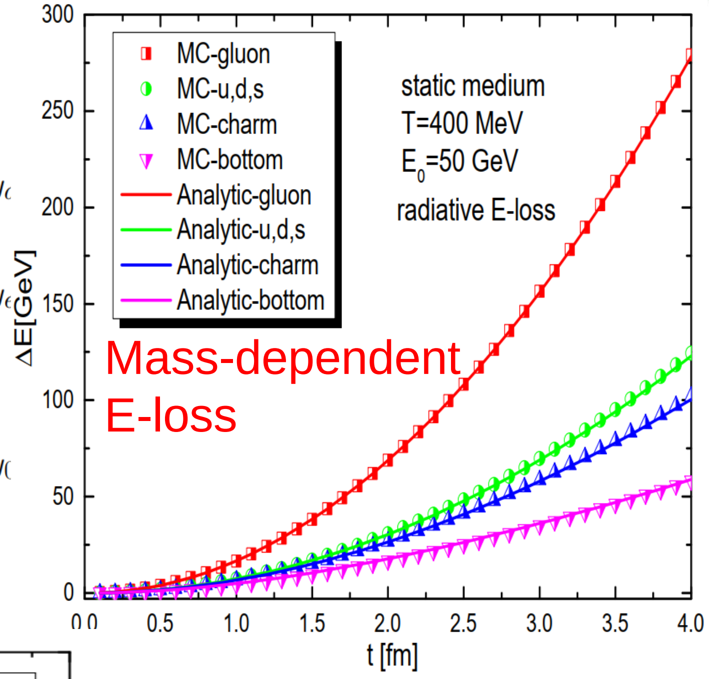
- Dead-cone effect
- Collisional E-loss
- Radiative E-loss

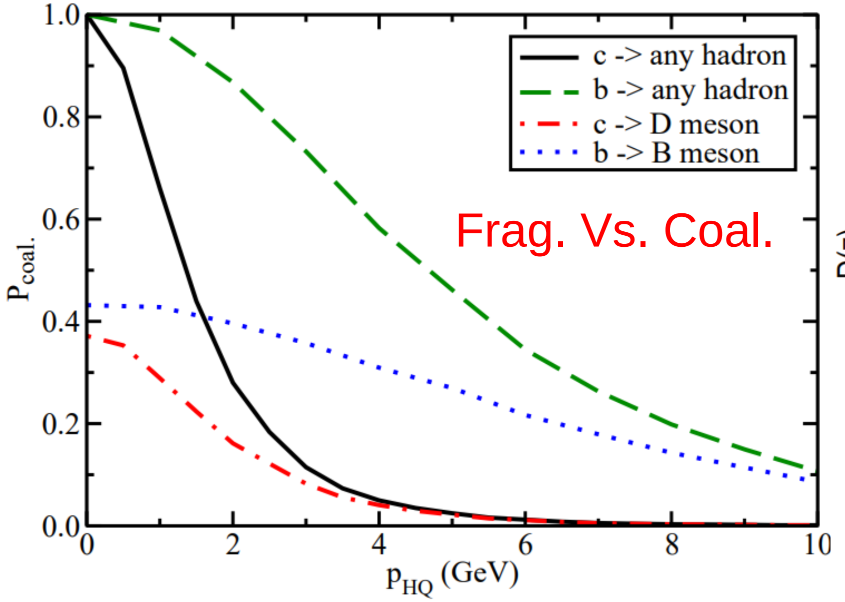
- Fragmentation
- Coalescence
- Decay channel

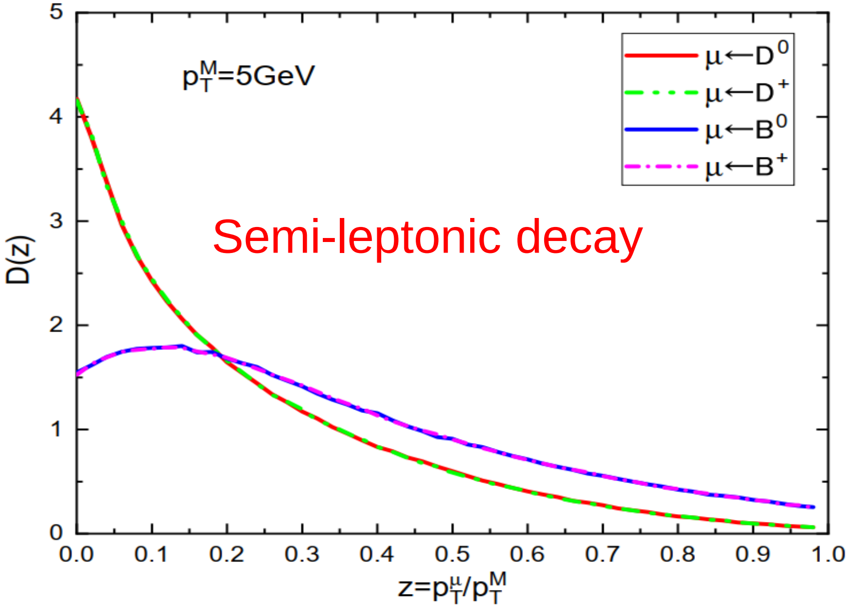
Evolution of heavy quarks in A+A collisions











Matteo Cacciari et al. JHEP (1998)

S. Cao, G.-Y. Qin et al. PRC (2013)

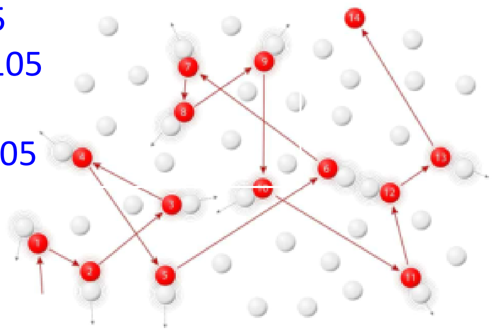
Kari J. Eskola et al. EPJC (2017)

S. Wang et al. CPC (2023)

Transport of heavy quarks in quark-gluon plasma

Eur.Phys.J.C 79 (2019) 9, 789
Chin.Phys.C 44 (2020) 104105
Chin.Phys.C 45 (2021) 6, 064105
Eur.Phys.J.A 58 (2022) 7, 135
Phys. Rev. C 108(2023)2,024905

Brownian motion



G.D. Moore and D. Teaney PRC 71 (2005) 064904; S. Cao, G.Y. Qin and S.A. Bass Phys.Rev. C88 (2013) 044907

- For heavy quark, $m_Q \gg T_{QGP}$, the modified discrete Langevin transport equations are used to describe the propagating of heavy quarks in the QGP.

$$\Delta\vec{x}(t+\Delta t) = \frac{\vec{p}(t)}{E}\Delta t \qquad (1)$$

$$\Delta\vec{p}(t+\Delta t) = -\Gamma(p)\vec{p}\Delta t + \vec{\xi}(t)\Delta t - \vec{p}_g \qquad (2)$$

The fluctuation-dissipation relation: $\kappa = 2ET\Gamma = \frac{2T^2}{D_s}$
Based on the LQCD calculation , D_s is fixed at $D_s(2\pi T) = 4$
Phys.Rev. D92 (2015) no.11, 116003

- Higher-twist radiative gluon spectra.

Phys.Rev.Lett. 85 (2000) 3591-3594;Phys.Rev.Lett. 93 (2004) 072301;Phys.Rev. D85 (2012) 014023

$$\frac{dN_g}{dxdk_\perp^2\, dt} = \frac{2\alpha_s C_A P(x)\hat{q}}{\pi k_\perp^4}\sin^2\left(\frac{t-t_i}{2\tau_f}\right)\left(\frac{k_\perp^2}{k_\perp^2 + x^2M^2}\right)^4 \qquad (3)$$

$P(x)$ is the QCD splitting function in vacuum :
W. T. Deng and X. N. Wang, Phys. Rev. C 81 (2010) 024902

$$P_{q\to qg}(x) = \frac{(1+(1-x)^2)(1-x)}{x} \qquad (4)$$

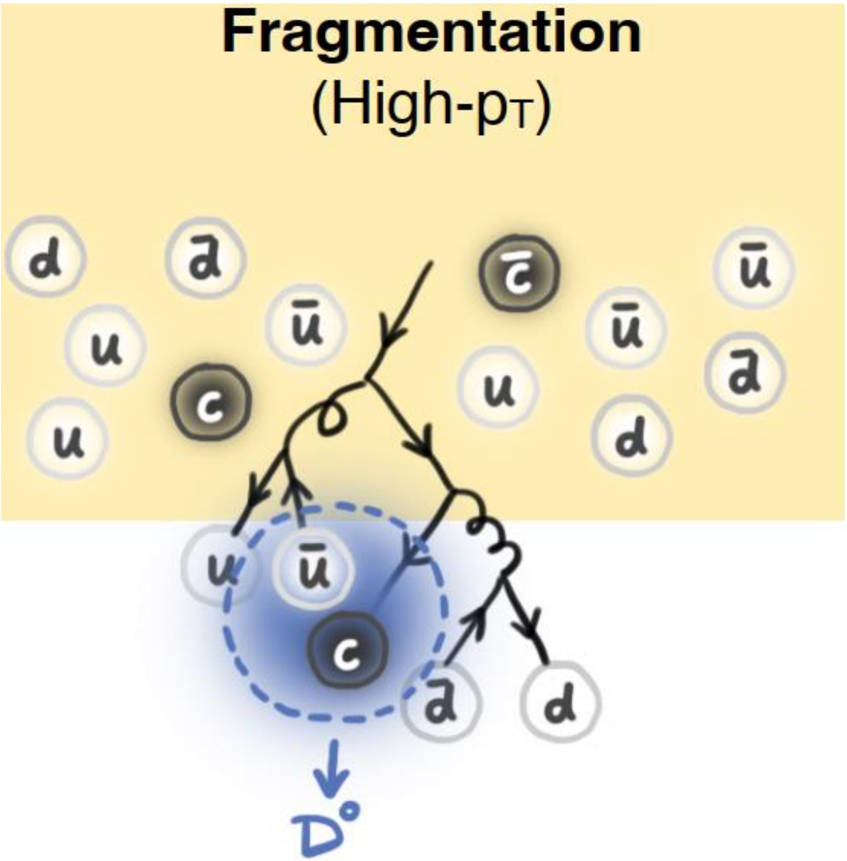
$$P_{g\to gg}(x) = \frac{2(1-x+x^2)^3}{x(1-x)} \qquad (5)$$

- $\hat{q}$ is the jet transport coefficient.

Phys.Rev. C81 (2010) 064908; Eur.Phys.J. C79 (2019) no.6, 518

$$\hat{q} = \hat{q}_0\left(\frac{T}{T_0}\right)^3\frac{p^\mu u_\mu}{p^0} \qquad (6)$$

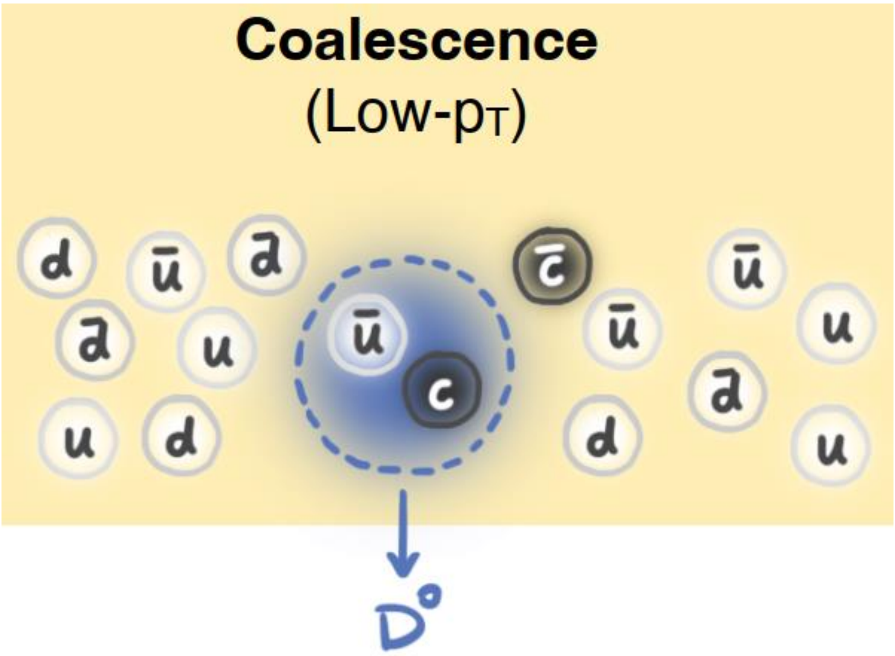
Hadronization of heavy quarks in A+A collisions



Peterson fragmentation function:

$$D(z) = \frac{N}{z\left(1 - \frac{1}{z} - \frac{\epsilon_Q}{1-z}\right)^2}$$

C. Peterson et al. PRC (1983)



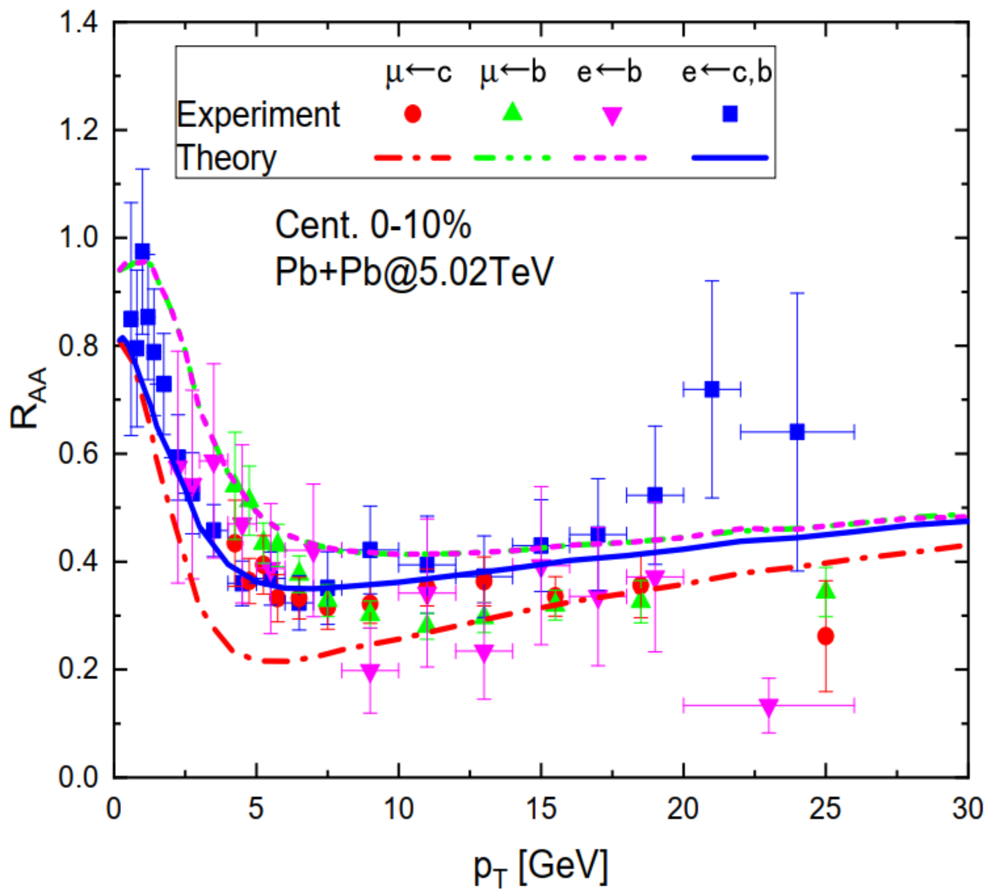
Wigner function:

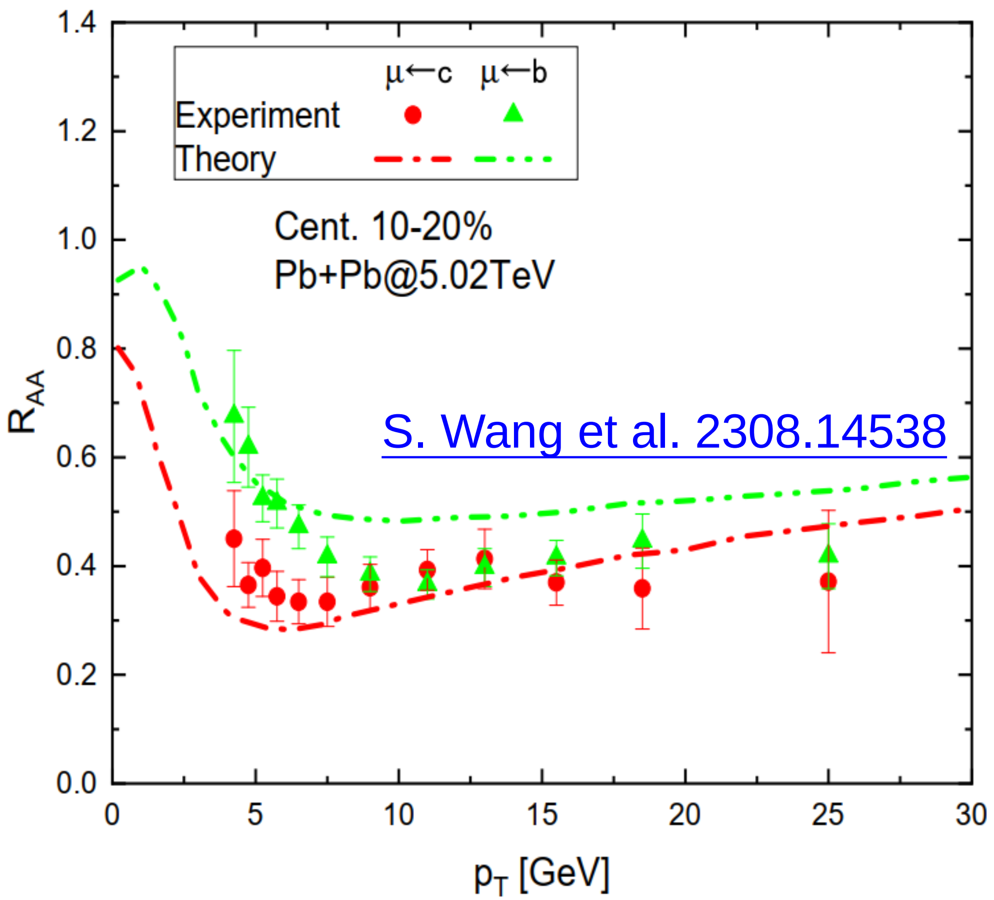
$$f_M^W(q^2) = g_M \frac{(2\sqrt{\pi}\sigma)^3}{V} e^{-q^2\sigma^2}$$

$$f_B^W(q_1^2, q_2^2) = g_B \frac{(2\sqrt{\pi})^6(\sigma_1\sigma_2)^3}{V^2} e^{-q_1^2\sigma_1^2 - q_2^2\sigma_2^2}$$

S. Cao, G. Qin et al. PRC (2013)

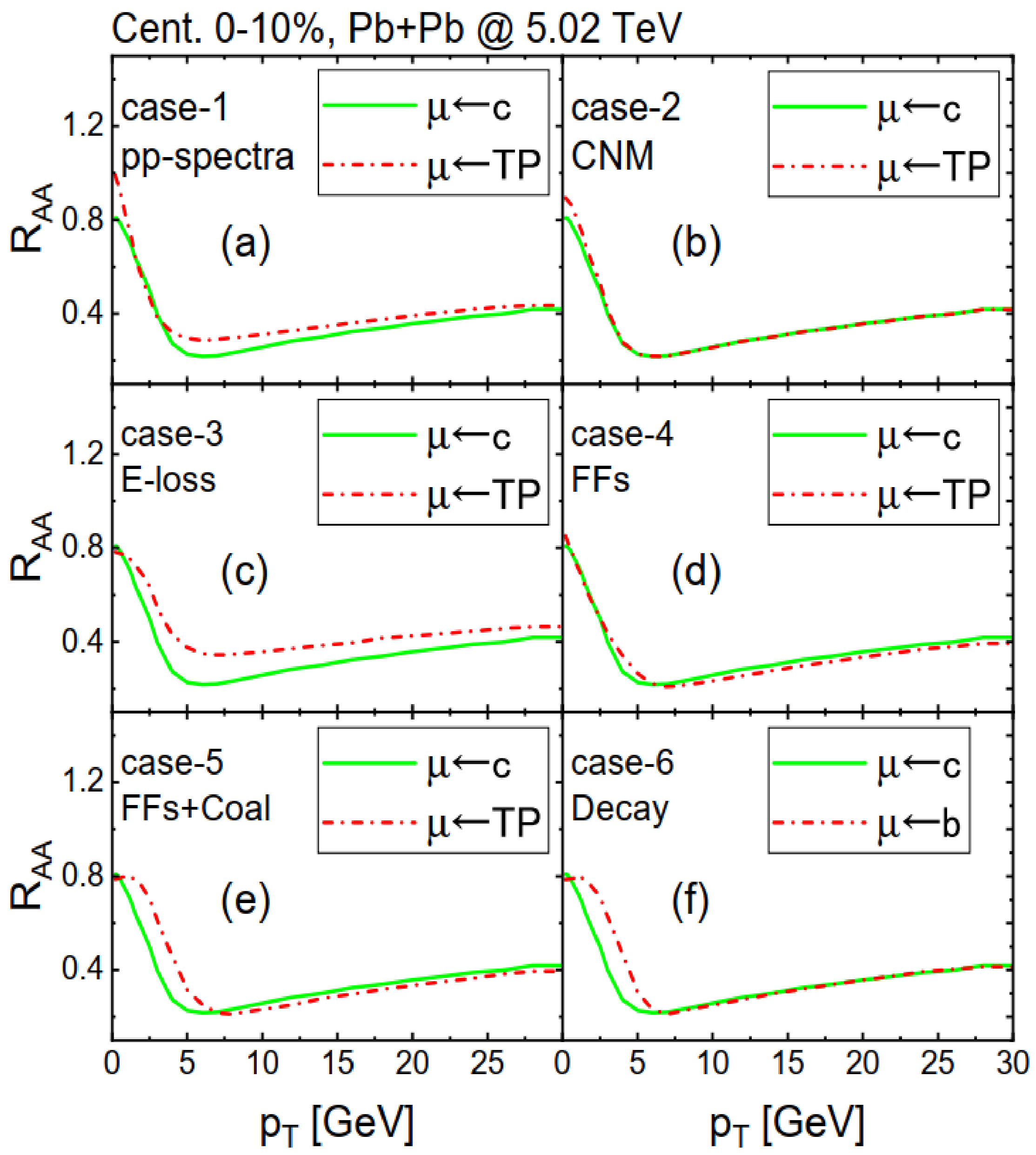
Yield suppression of heavy-flavor decay lepton

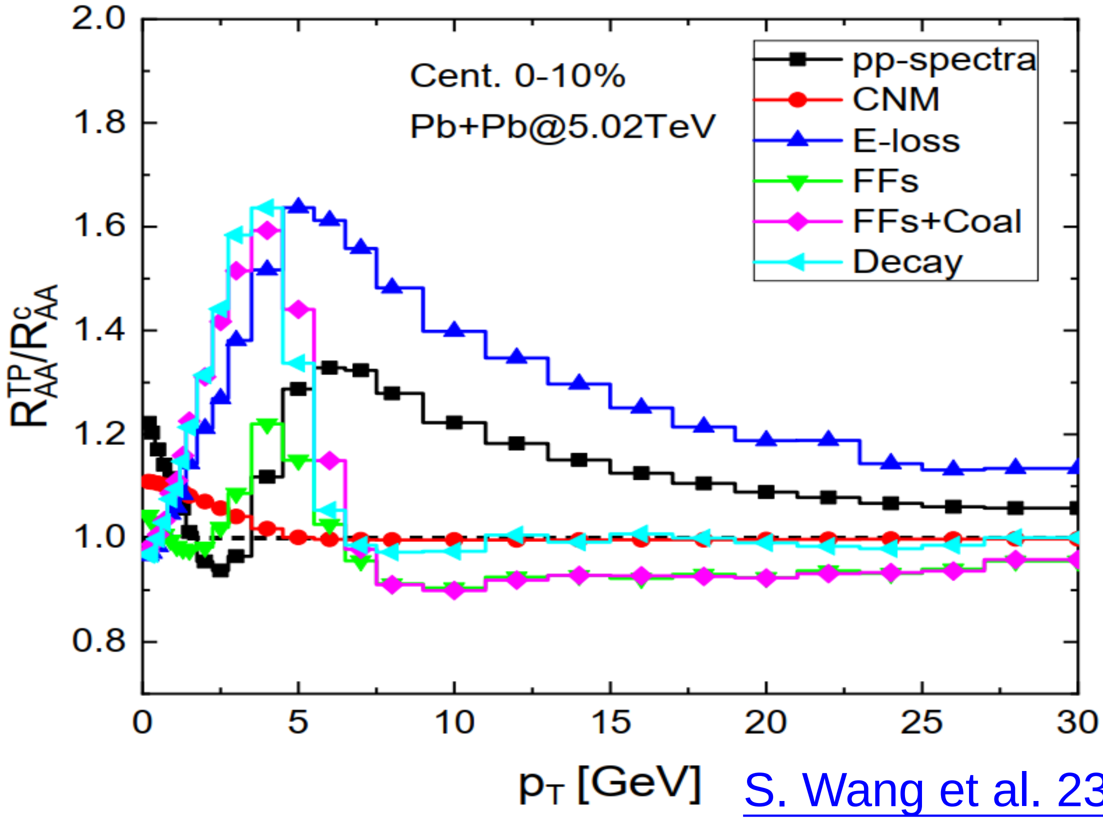




- μ ← c dominates the total lepton production at low p_T, while μ ← b dominates high p_T region.
- More significant yield suppression of μ ← c relative to μ ← b, consistent with the ALICE and ATLAS measurements.

Isolating the mass effect of heavy quarks

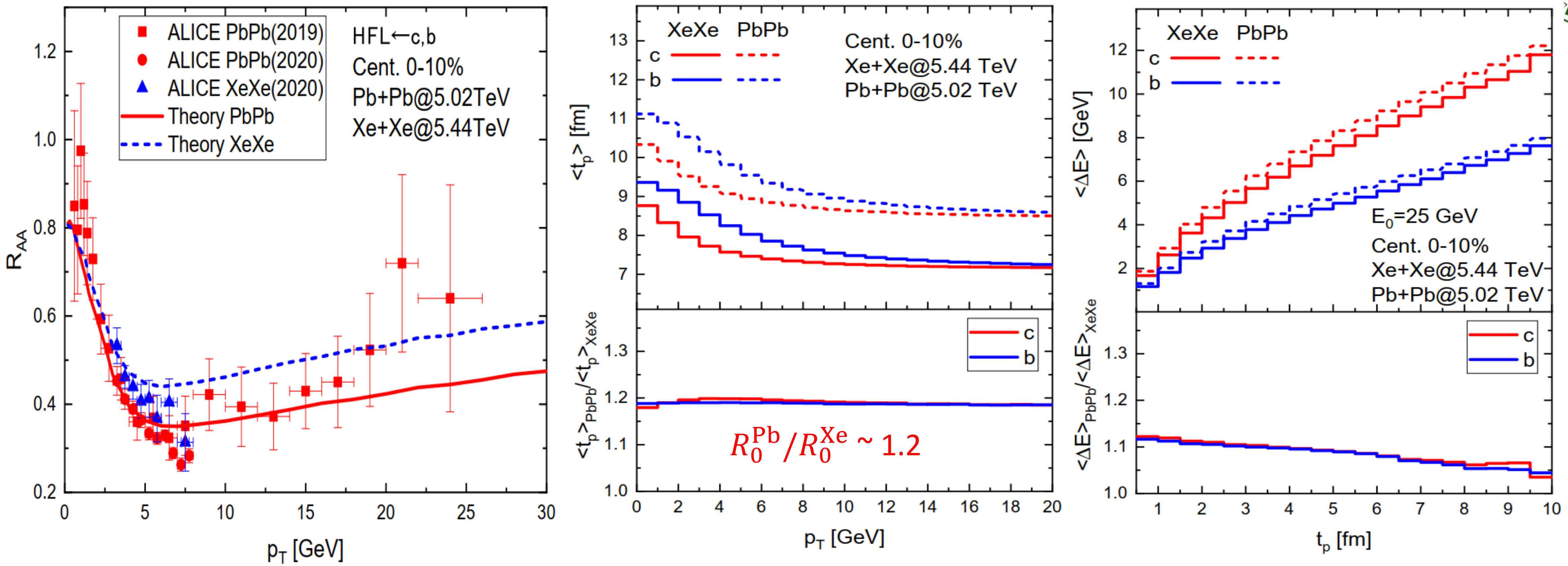




S. Wang et al. 2308.14538

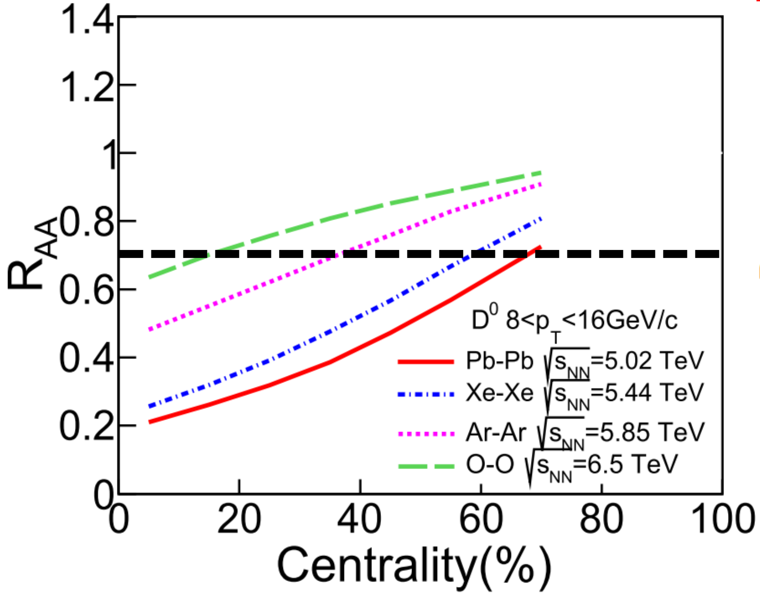
- Coalescence and decay channel play important roles at low p_T.
- Impact of pp-spectra are considerable at $p_T > 5$ GeV.
- Mass-dependent E-loss dominates the high-p_T region.
- Influence of CNM effect and fragmentation function are limited.

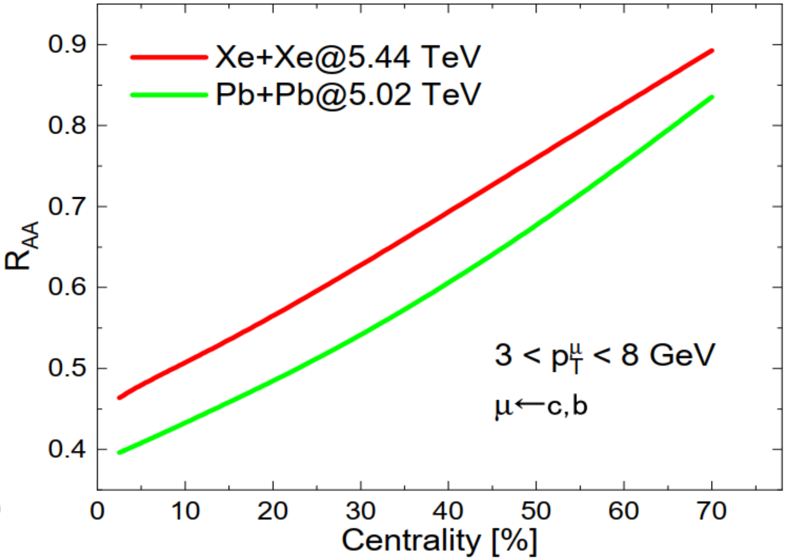
Path-length dependence of heavy quark E-loss



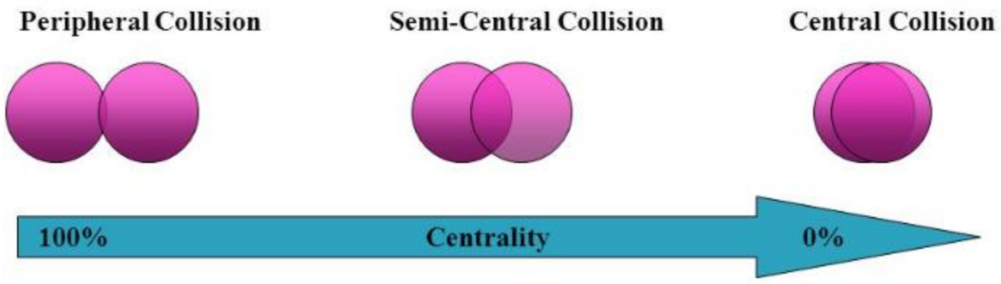
- Stronger yield suppression of heavy-flavor decay lepton in Pb+Pb collisions, consistent with the ALICE measurements.
- Longer propagation time and more efficient energy loss leads to in Pb+Pb collisions relative to Xe+Xe.

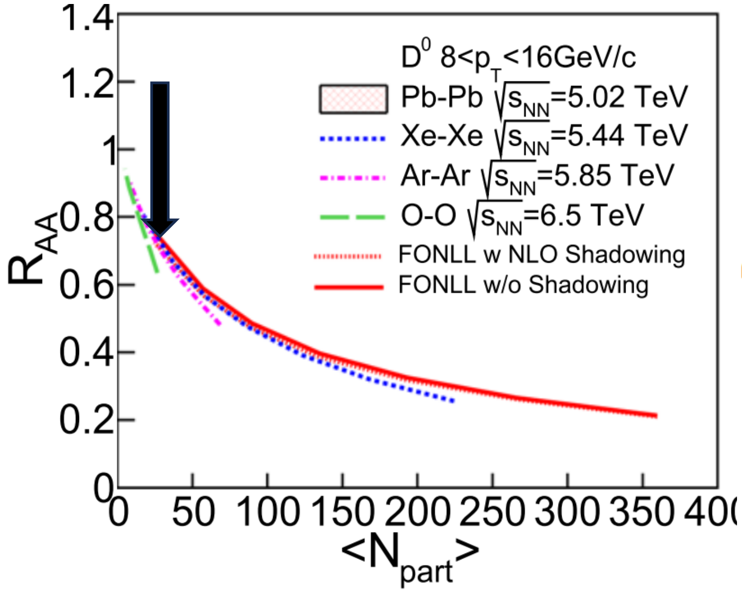
Scaling behaviors of heavy flavors suppression

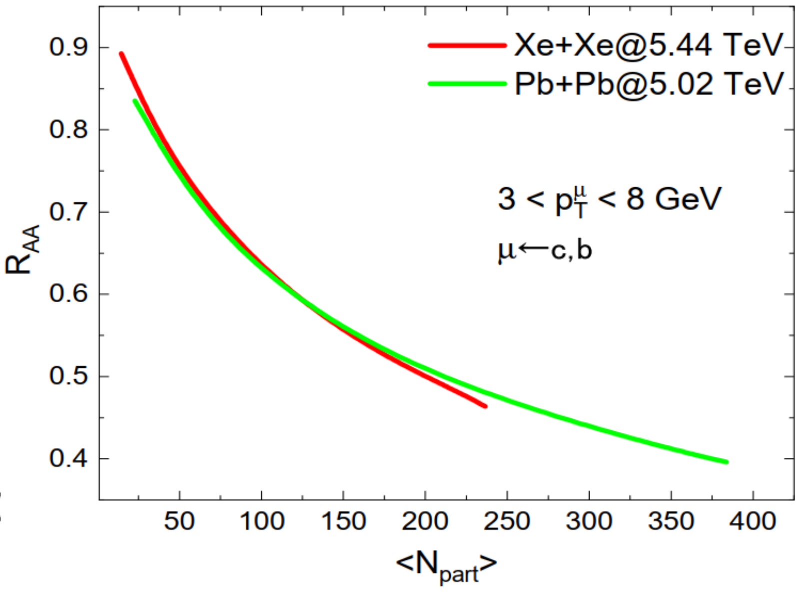




Centralities in nucleus-nucleus collisions







- For fixed centrality, lower R_{AA} in larger collision system.
- Scaling with N_{part}, HQ suffers the same yield suppression.
- Scaling behavior of HFL R_{AA}.

S.-Q. Li et al. EPJC (2021)

S. Wang et al. 2308.14538

Summary and outlook

Summary:

- Mass effect: coalescence and decay channel are critical at low p_T, while mass-dependent E-loss pp-spectra are important at high p_T.
- Path-length dependence: longer propagation time and more efficient energy loss leads to more energy loss in PbPb.
- Scaling behavior: scaling behavior of the HFL R_{AA}.

Outlook:

- Mass hierarchy at jet level: HQ jet production mechanism [2409.XXXX]
- Jet substructures: jet axis drift[2312.15518];HQ jet angularities; intra-jet broadening (γ-jet).