Heavy Flavor Jets in Primordial QCD Soup

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Outline

- Introduction
- Heavy flavor jet observables

1） jet yields

2) Dead-Cone

3） Energy-Energy Correlators

4) Jet FF, angularity, groomed z_g , R_g …

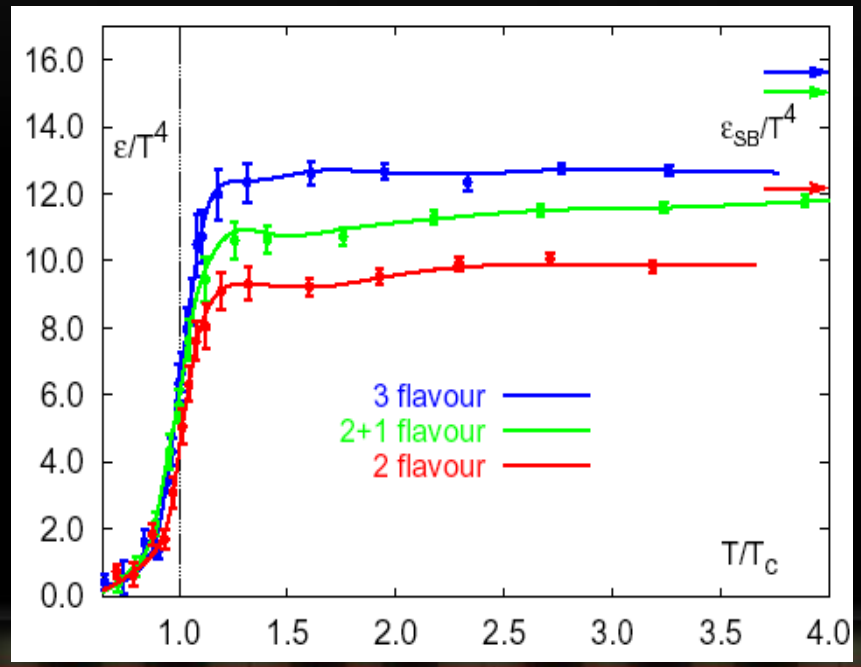
- Summary

Deconfinement and QGP

It would be interesting to explore new phenomena by distributing high energy or high nuclear density over a relatively large volume.

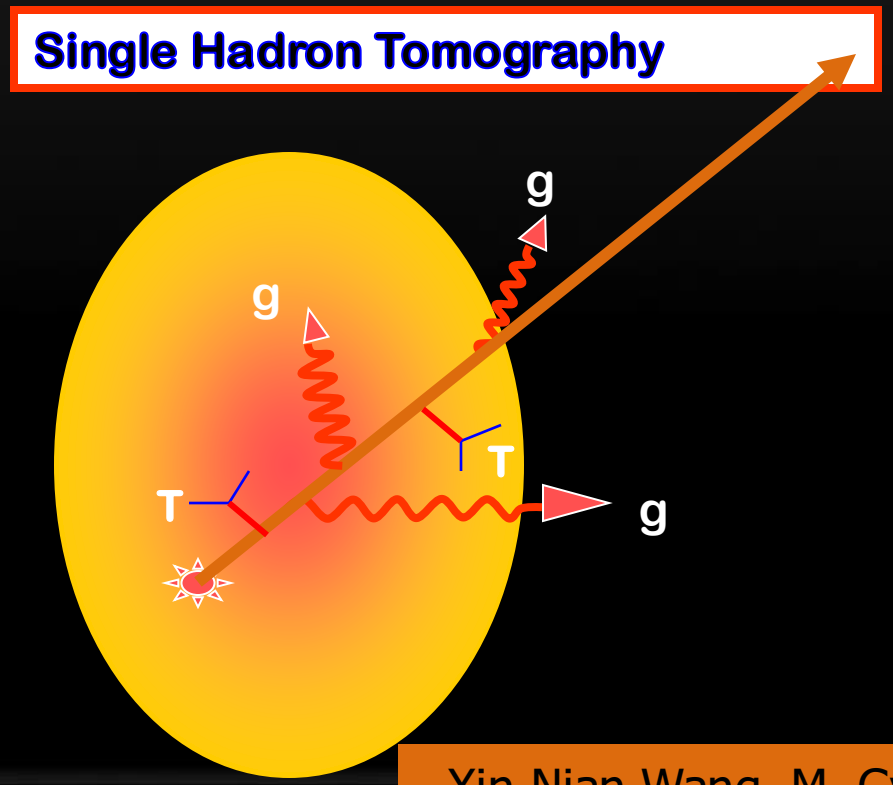
T. D. Lee (1978)

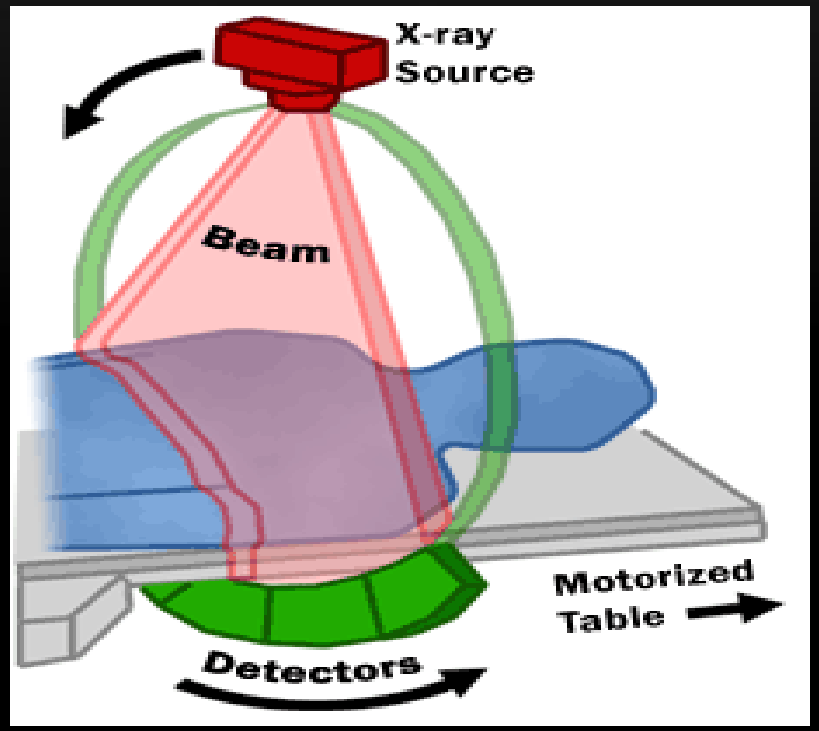
Lattice QCD predicts phase of thermal QCD matter with sharp rise in number of degrees of freedom near T_c=170MeV.



Jet quenching

Parton energy has been proposed as an excellent probe of the hot/dense matter created at HIC.

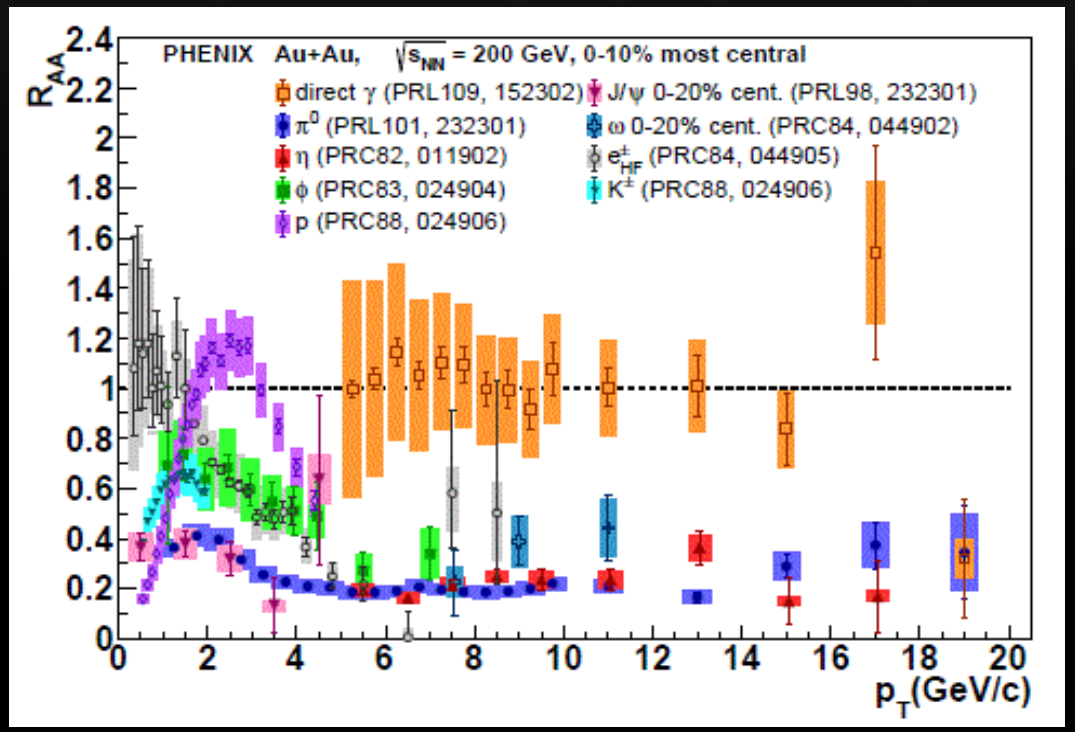


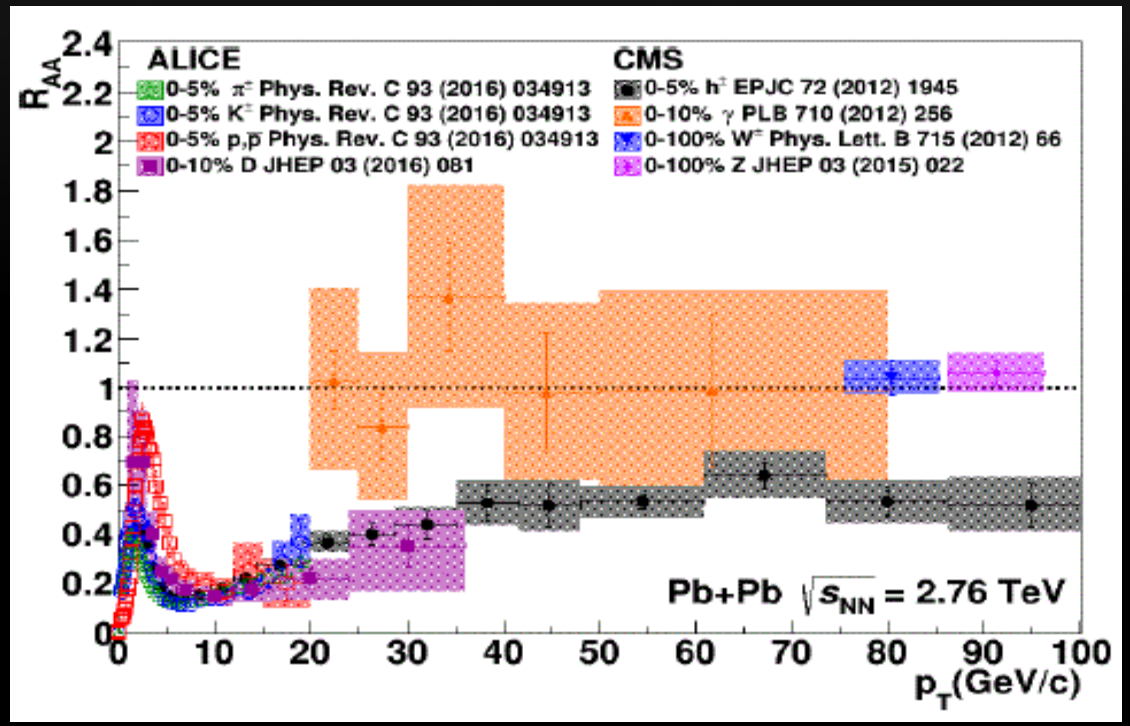


Xin-Nian Wang, M. Gyulassy, PRL68(1992)1480

Jet quenching at RHIC and LHC

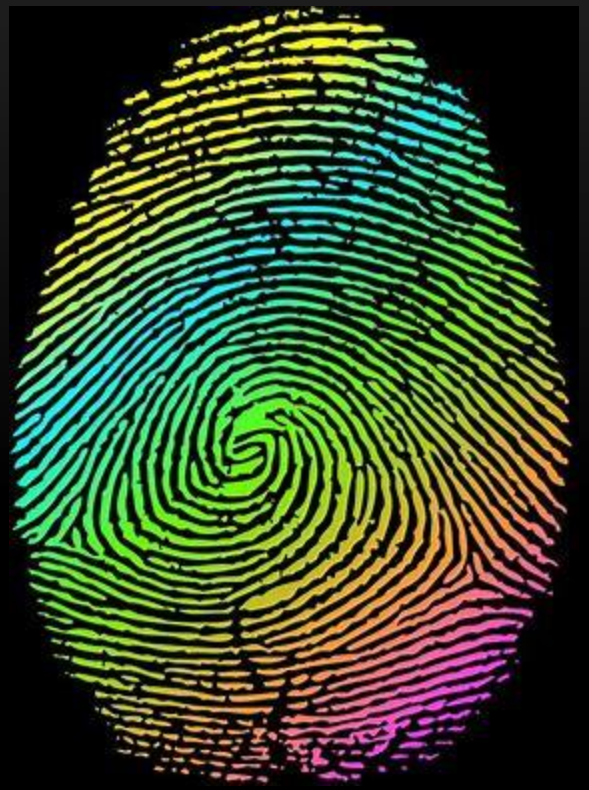
$$R_{AA} = \frac{\text{Yield}_{AA} / \langle N_{\text{binary}} \rangle_{AA}}{\text{Yield}_{pp}}$$





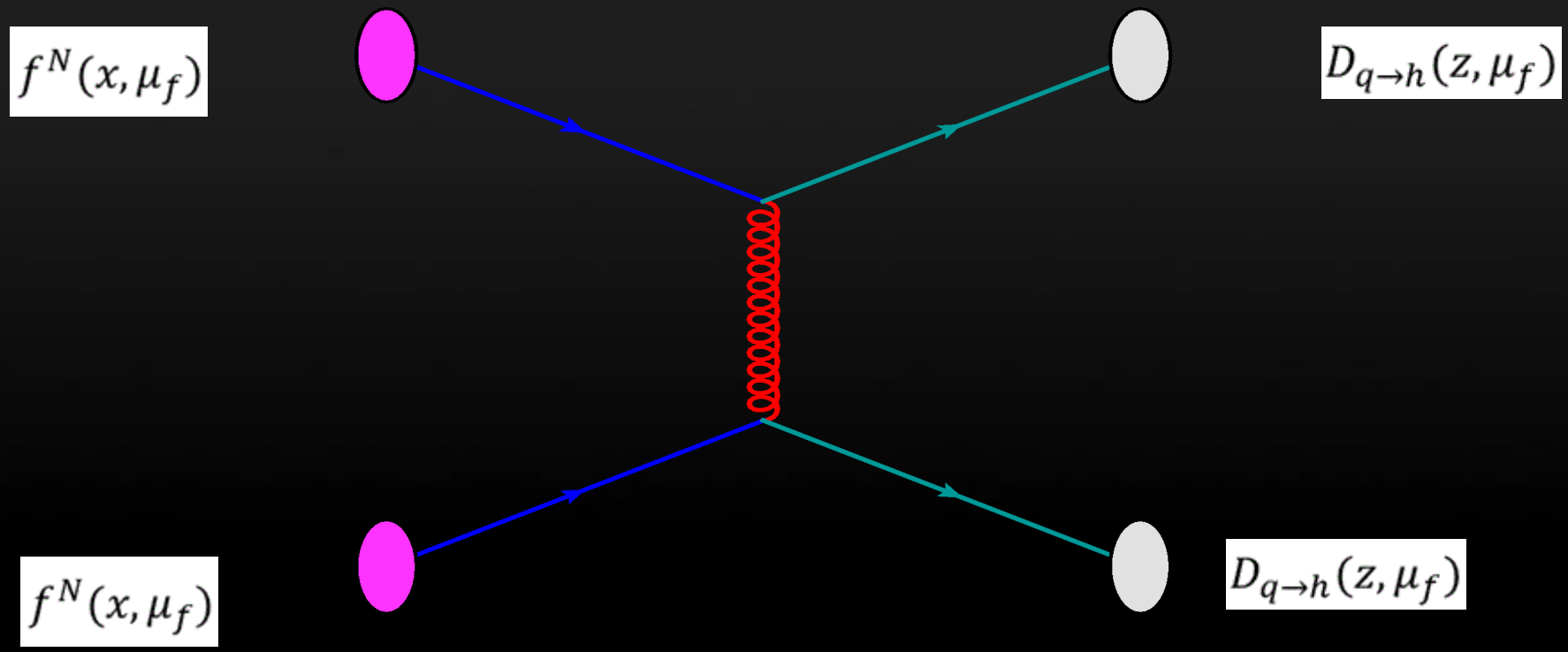
Fingerprints of jet quenching

leading hadron



full jet

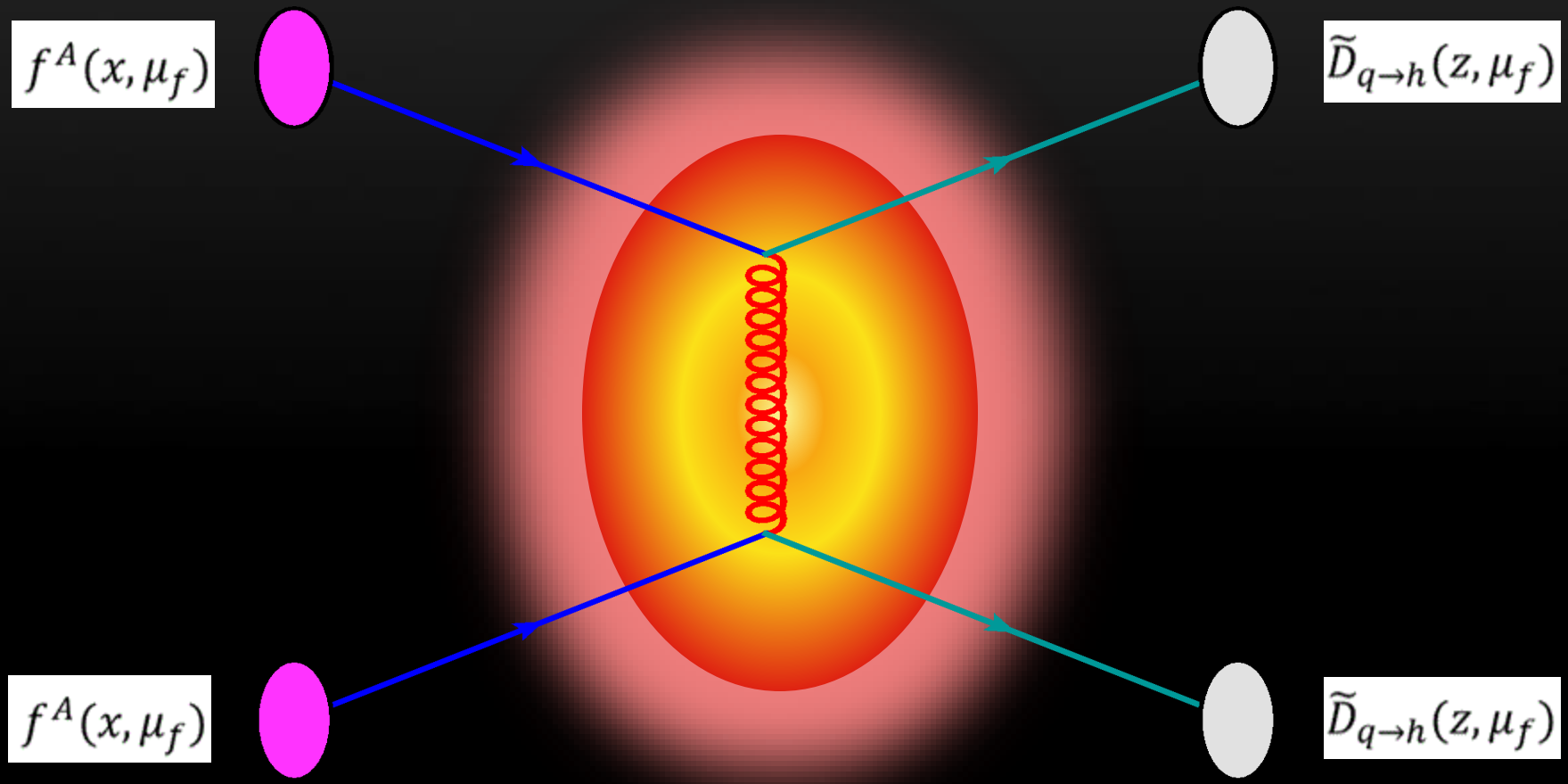
Leading hadron production



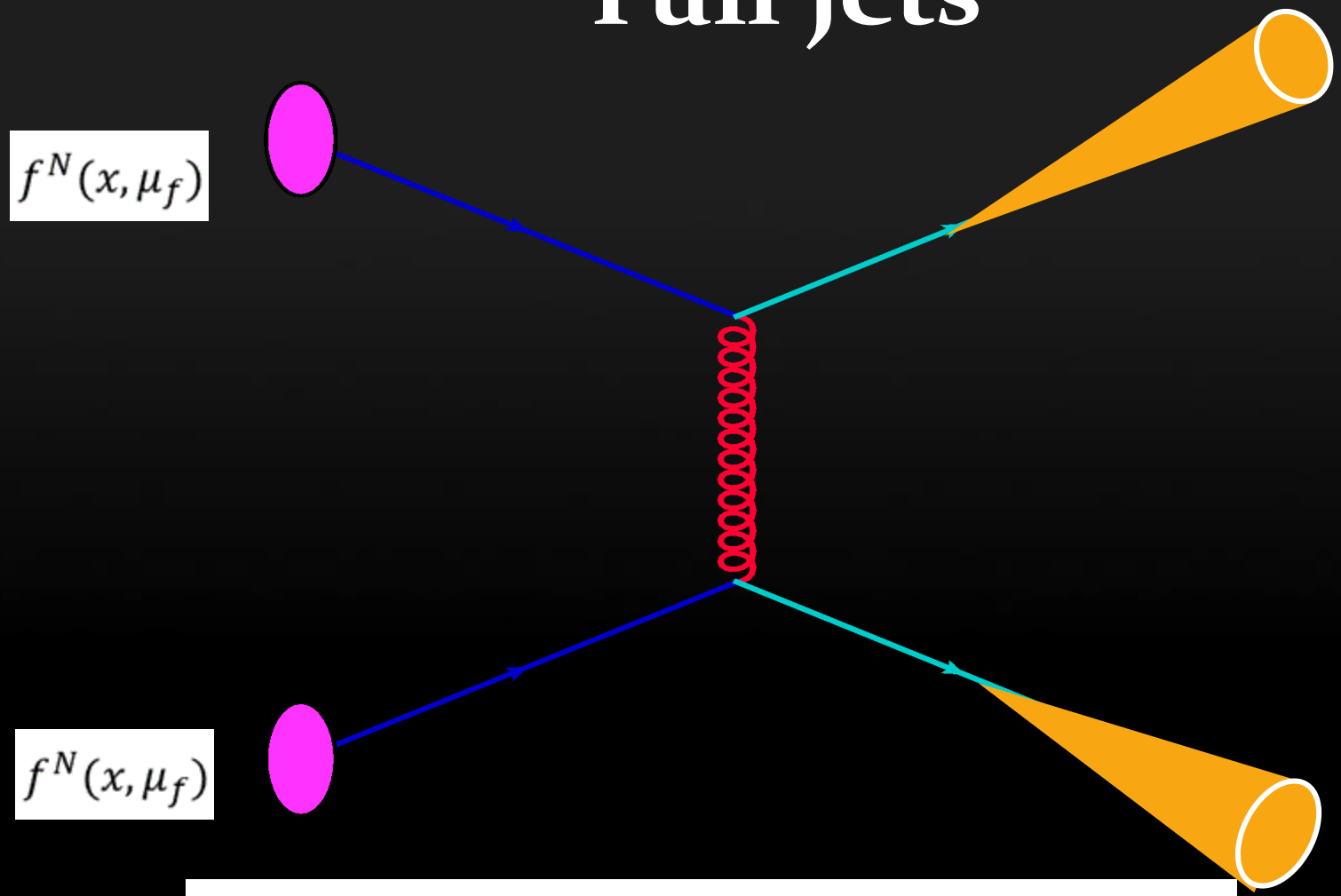
$$\frac{d\sigma_{pp}^{h}}{dyd^2p_T} = K\sum_{abcd}\int dx_a dx_b f_a(x_a,Q^2) f_b(x_b,Q^2) \frac{d\sigma}{d\hat{t}}(ab\to cd) \frac{D_{h/c}^0}{\pi z_c}$$

Parton distribution function	Matrix element	Fragmentation function
measured in DIS	pQCD	e^+e^-

Leading hadron production

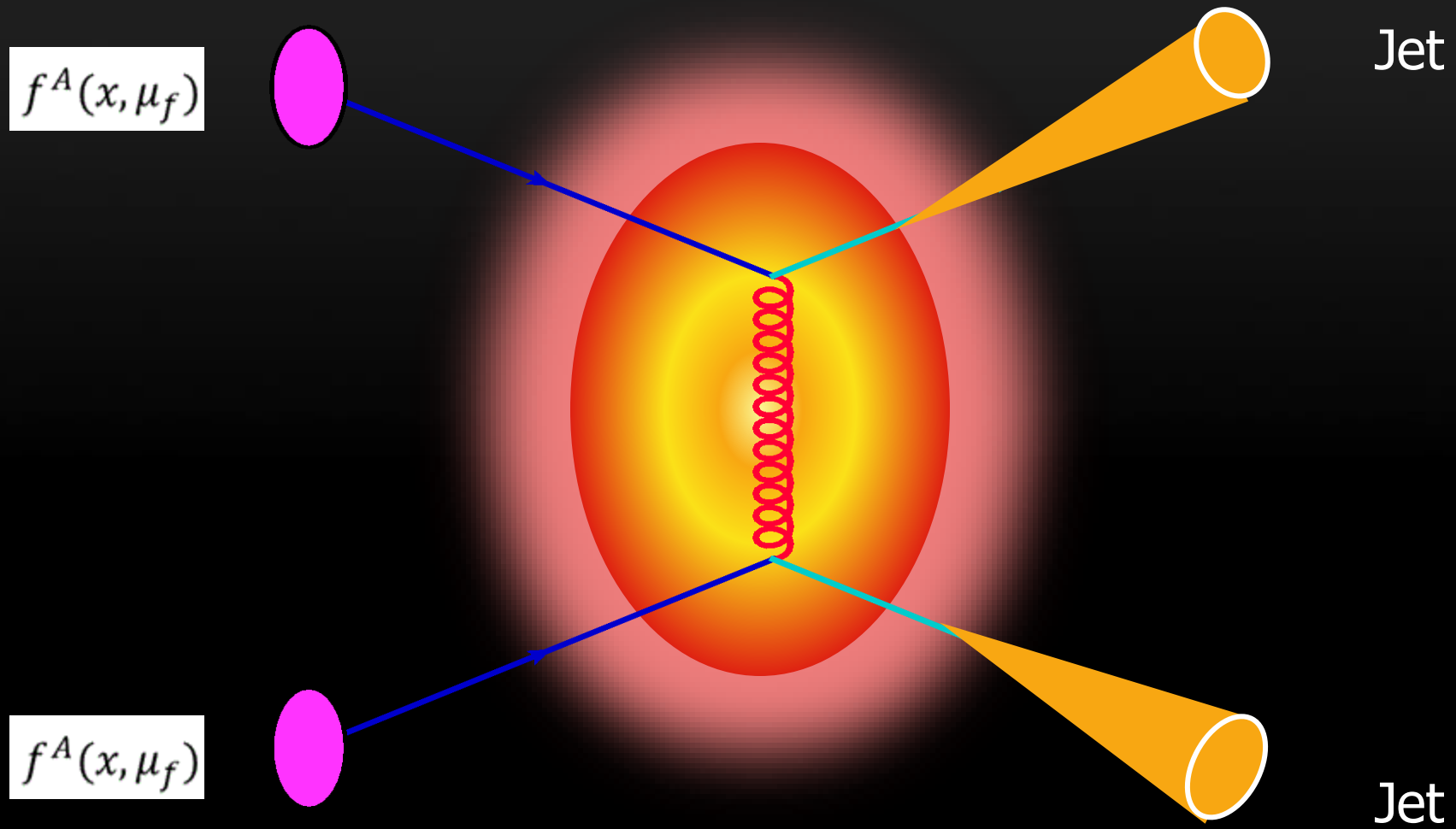


Full jets

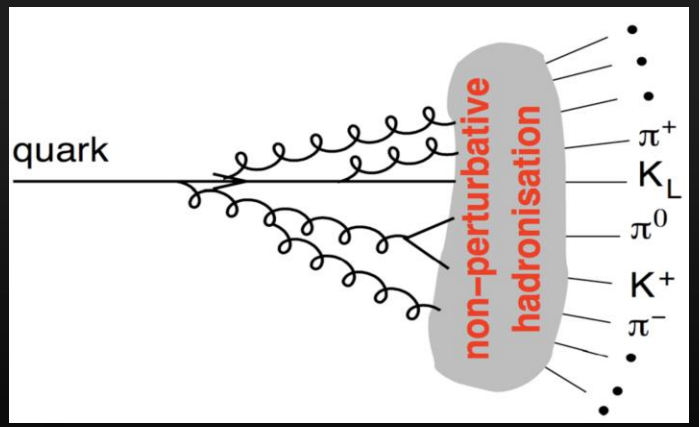


$$\frac{d\sigma^{\text{jet}}}{dE_T dy} = \frac{1}{2!}\int d\{E_T, y, \phi\}_2 \frac{d\sigma[2\to 2]}{d\{E_T, y, \phi\}_2} S_2(\{E_T, y, \phi\}_2)$$
$$+\frac{1}{3!}\int d\{E_T, y, \phi\}_3 \frac{d\sigma[2\to 3]}{d\{E_T, y, \phi\}_3} S_3(\{E_T, y, \phi\}_3)$$

Full jets



What is a Full Jet?

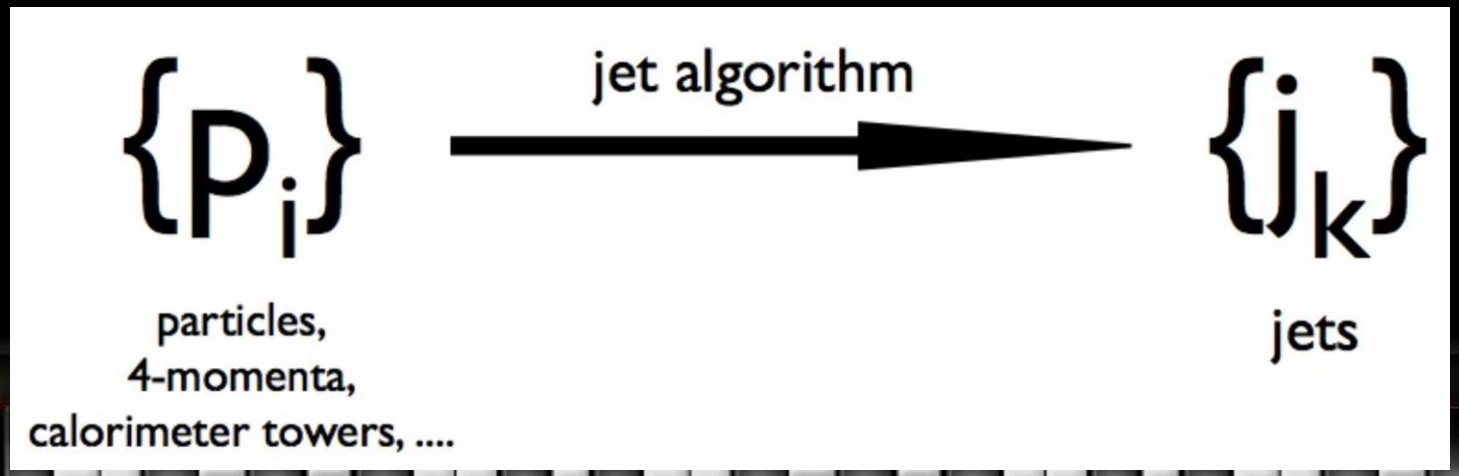


$$E_T = \sum_{i \in jet} E_{T,i}$$

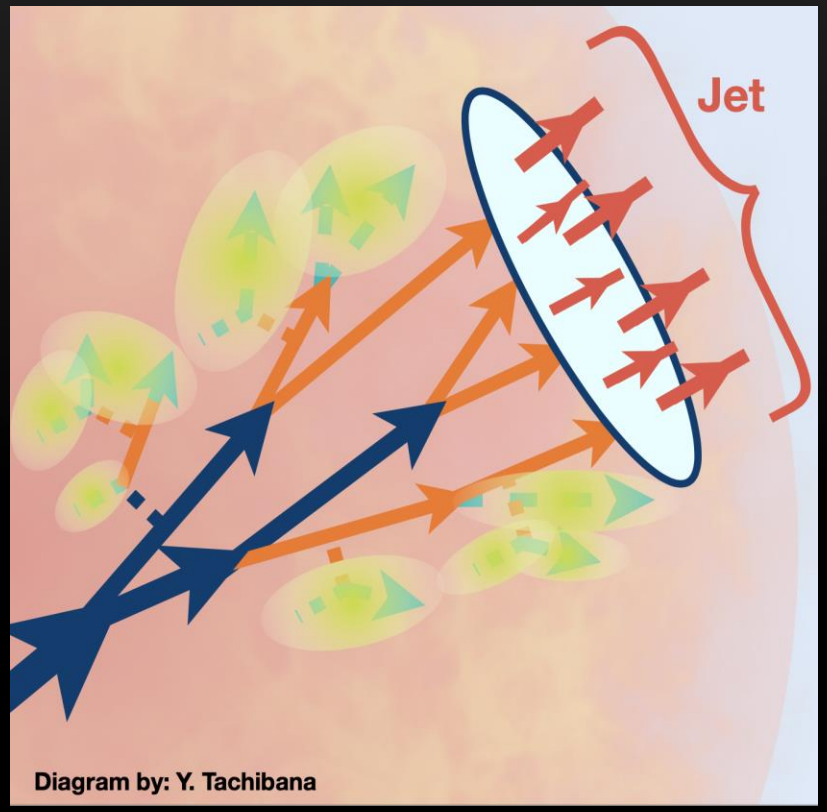
$$y = \sum_{i \in jet} y_i E_{T,i} / E_T$$

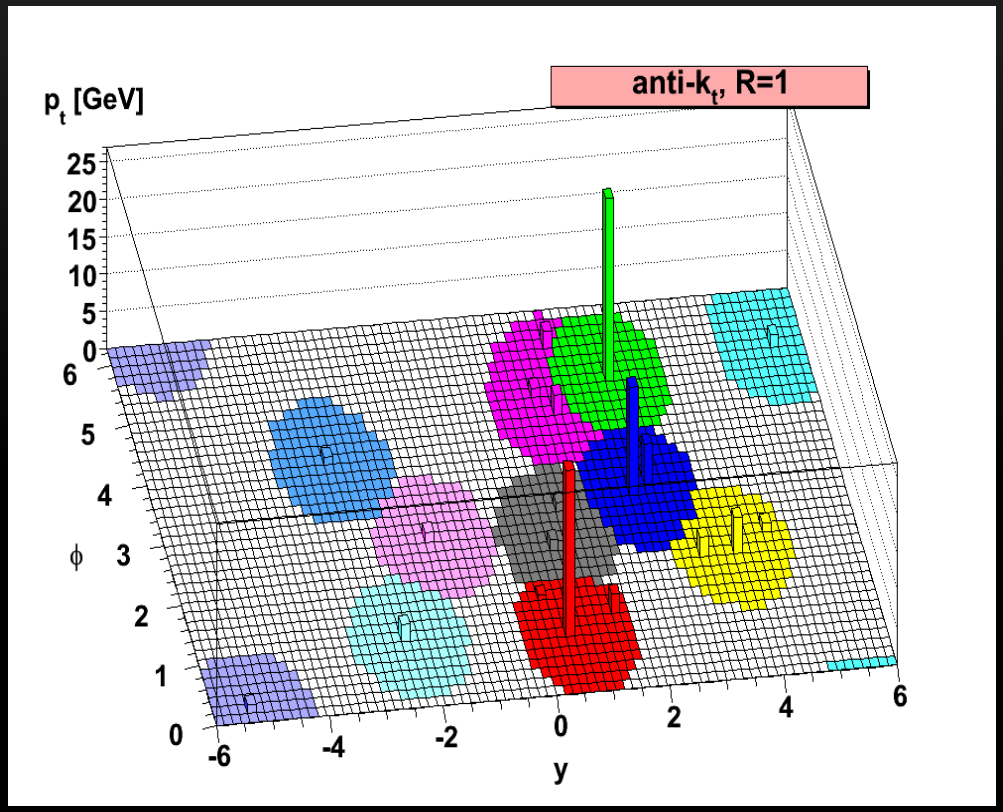
$$\phi = \sum_{i \in jet} \phi_i E_{T,i} / E_T$$

- Jet is an approximate image of the parent parton. Jet is defined by a jet finding algorithm, which maps the momenta of the final state particles into the momenta of a certain number of jets:



World inside a jet





Observables of heavy flavor jets

inclusive D/B jet;
b b\bar di-jets;
gamma + Q jet;
Z/W + Q jet;
……

HF jet yields

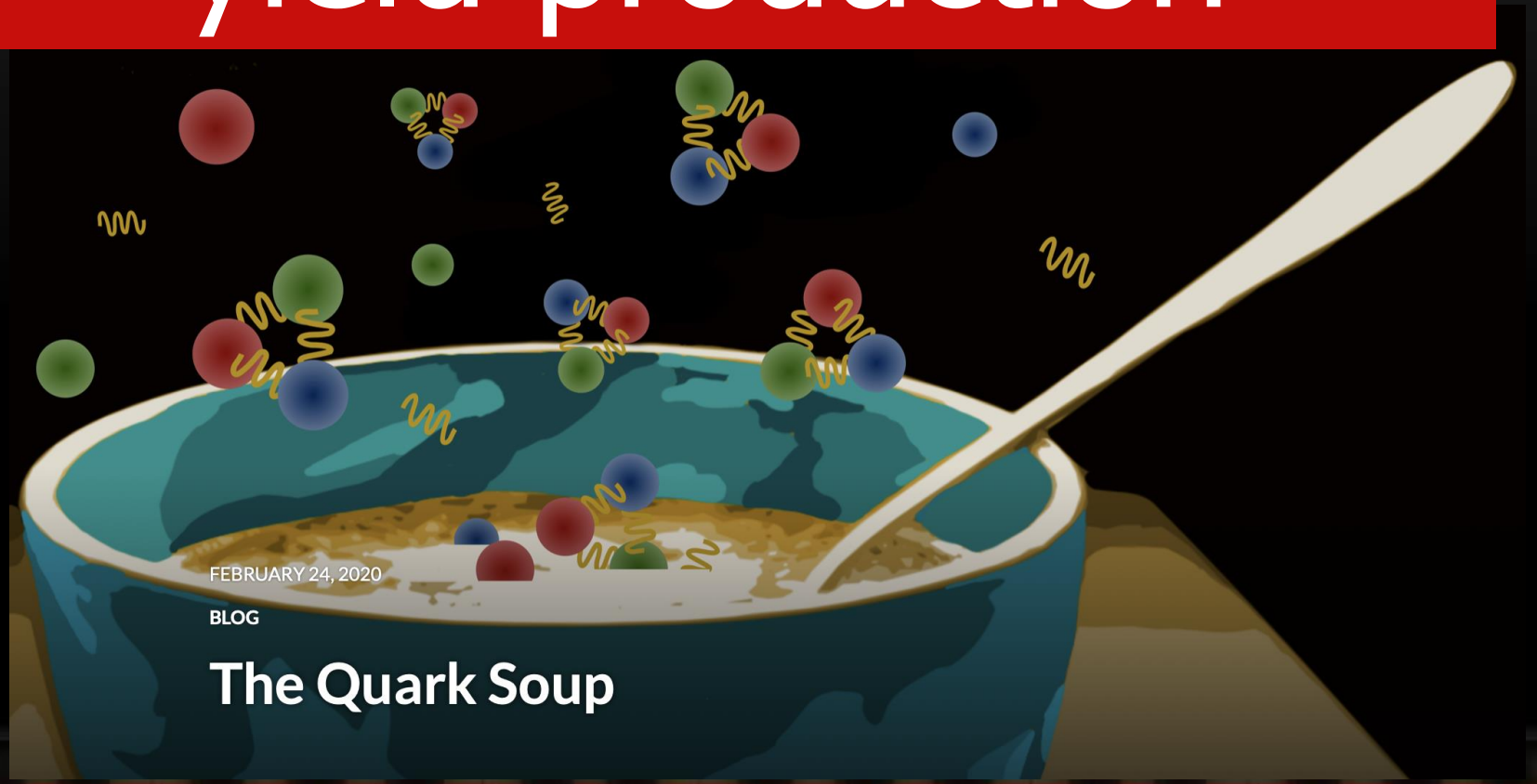
Q jet radial profile;
Q jet FF;
Dead-cone;
EEC;
Q jet angularity;
groomed jets;
……

HF jet substructure

sphericity;
thrust;
Jet broadening;
Fox-Wolfram
moment;
……

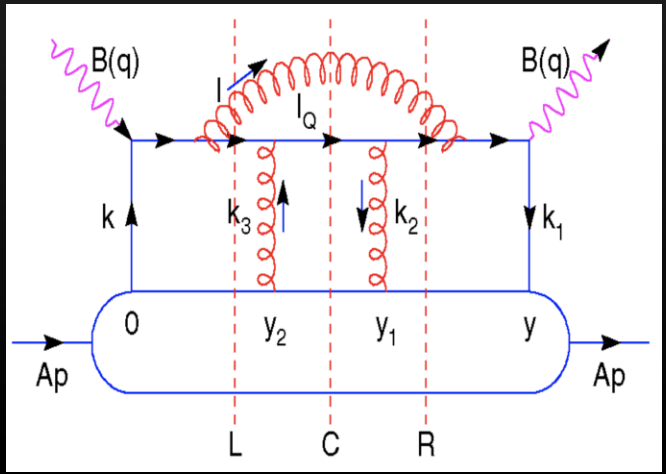
Inter-HF jet properties

HF jet in quark soup: yield production



Heavy quark energy loss

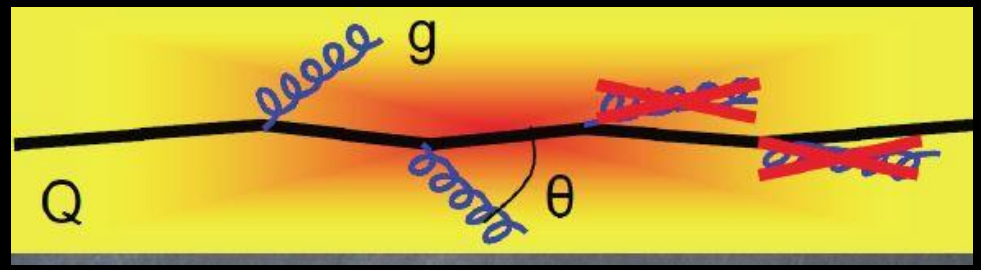
- Heavy quark energy loss will be suppressed due to deadl-cone effect relative to light quark.



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

$$\mathrm{k}_\perp = \omega\theta \qquad \omega = xE$$

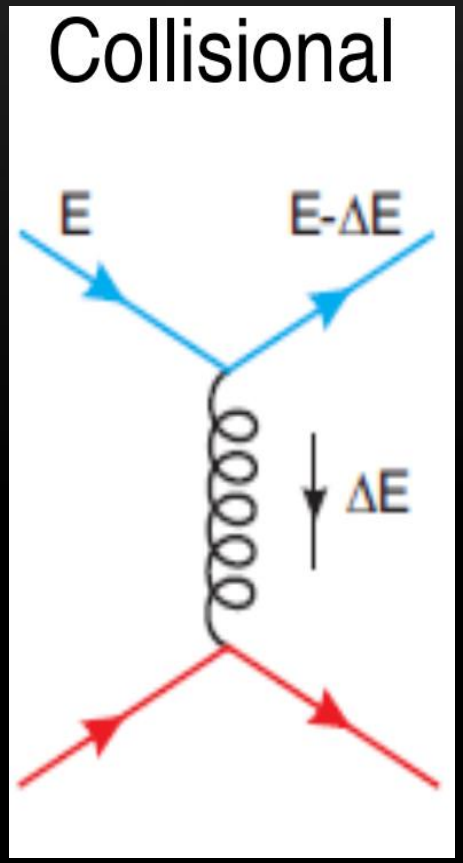
$$f_{Q/q} = \left(1 + \frac{\theta_0^2}{\theta^2}\right)^{-4}$$

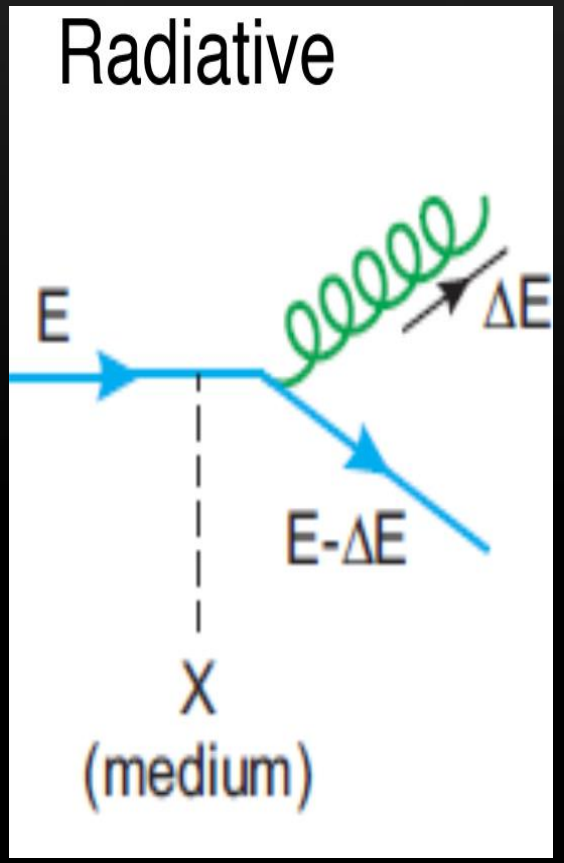


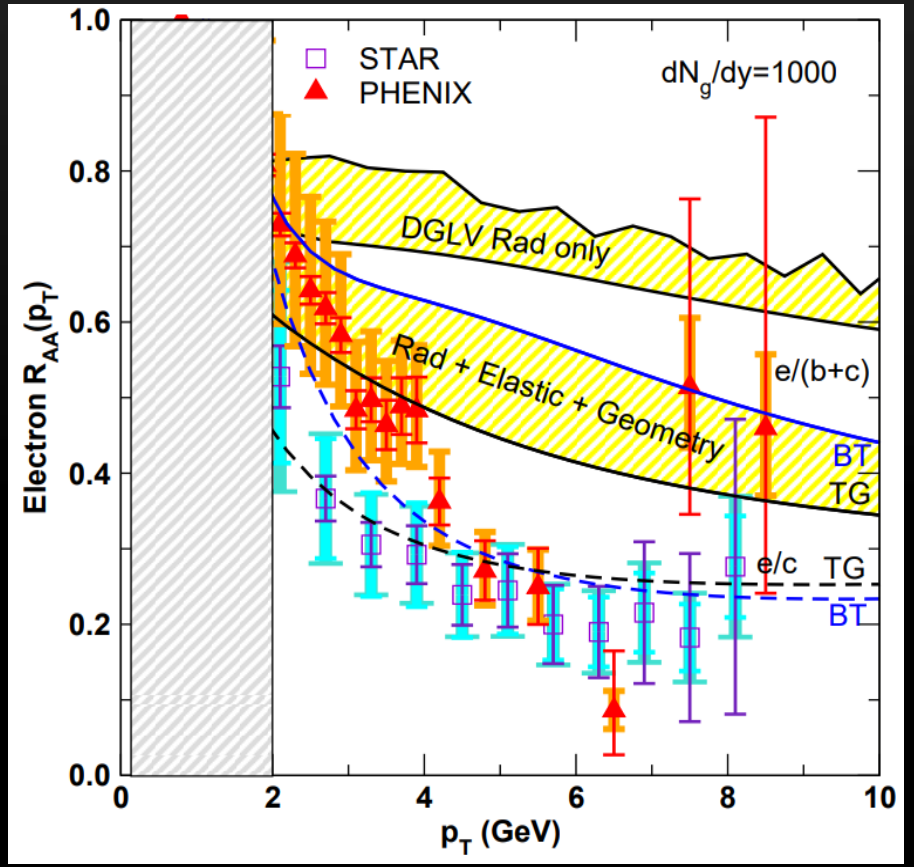
BWZ, E Wang, X N Wang, PRL (2004); NPA (2015)

Dokshitzer, Kharzeev, PLB (2011); Djordjevic, Gyulassy, PRC (2013)

Energy loss of heavy quark





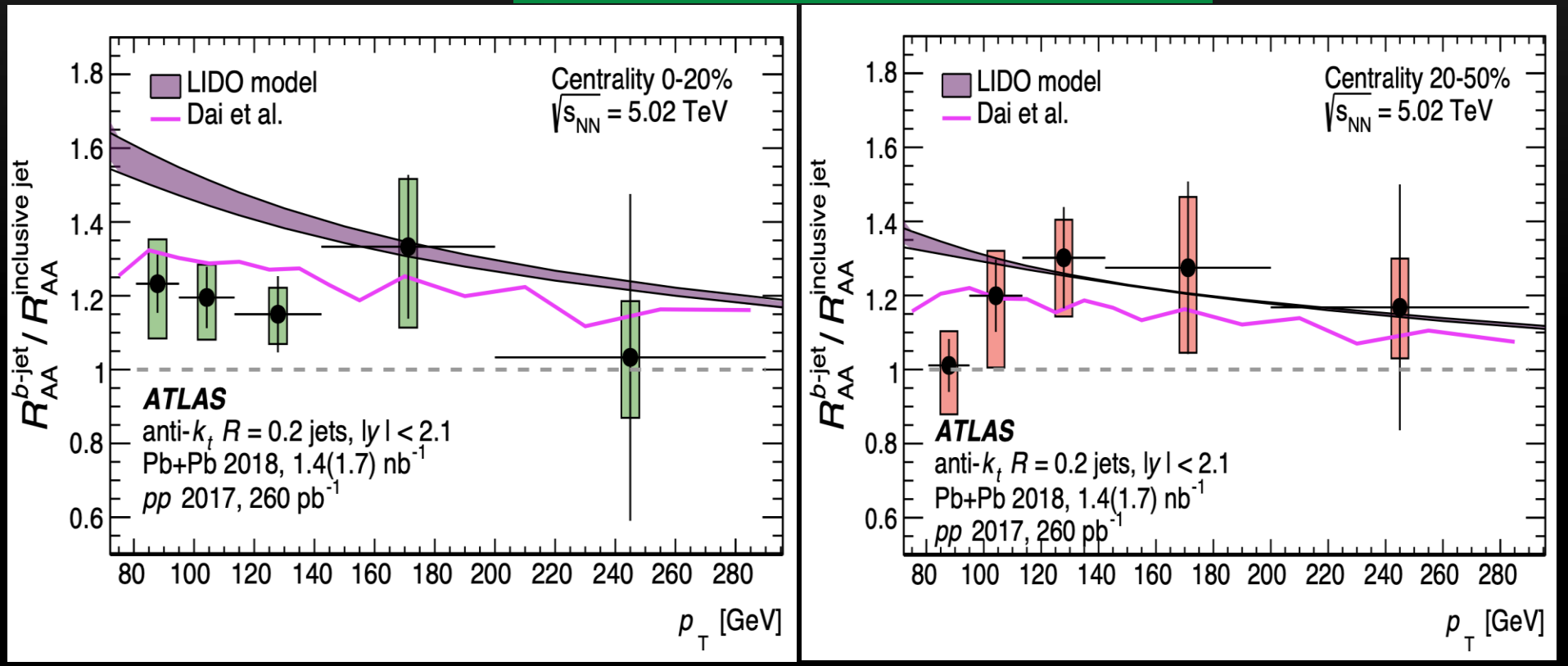


Simon Wicks et al. Nucl.Phys.A 784 (2007) 426-442

Suppression of HF jets

- Heavy flavor jet should be less suppressed as compared to inclusive jets due to dead-cone effect.

ATLAS, arXiv: 2204.13530

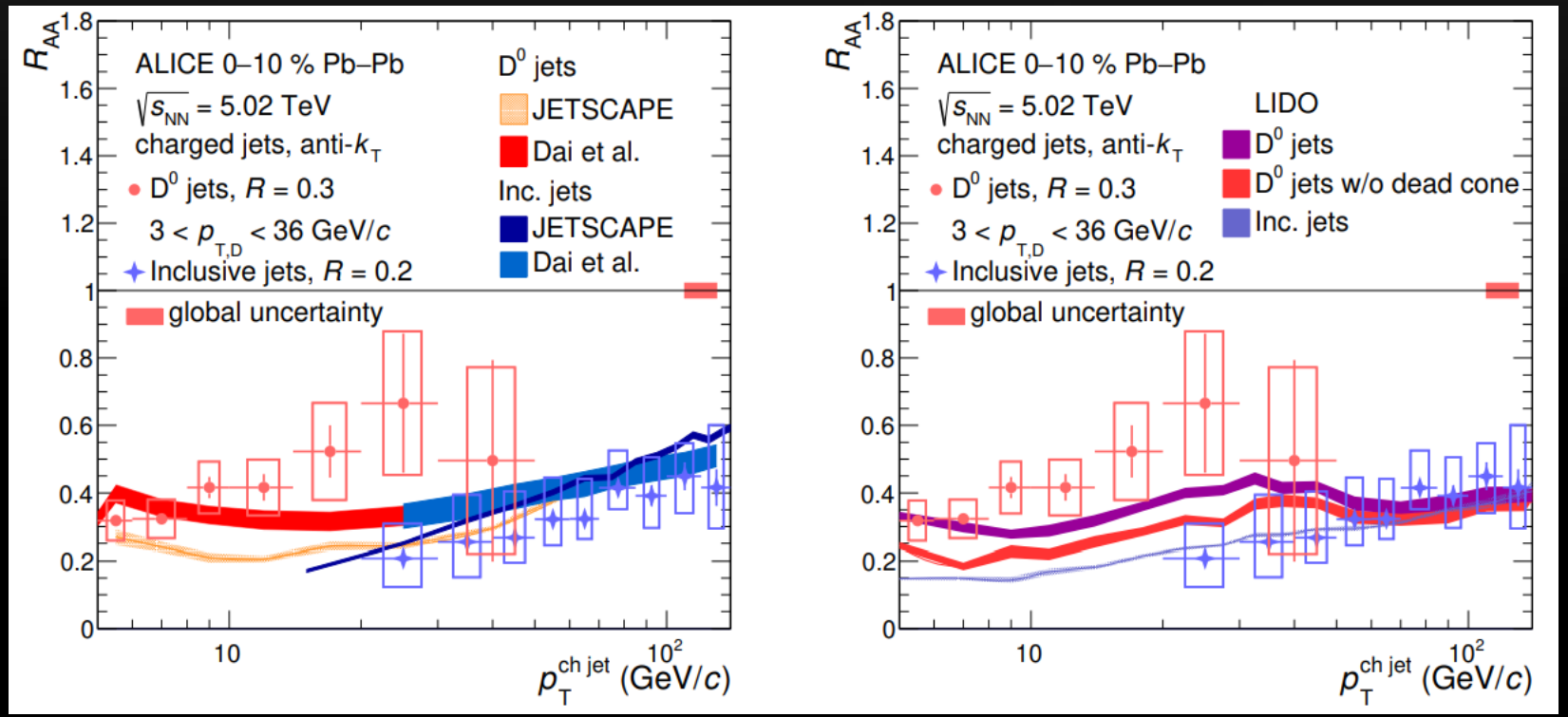


W Dai, S Wang, S Zhang, BWZ, E Wang, CPC (2020)

S Wang, Dai, E Wang, X Wang, BWZ, Symmetry (2023)

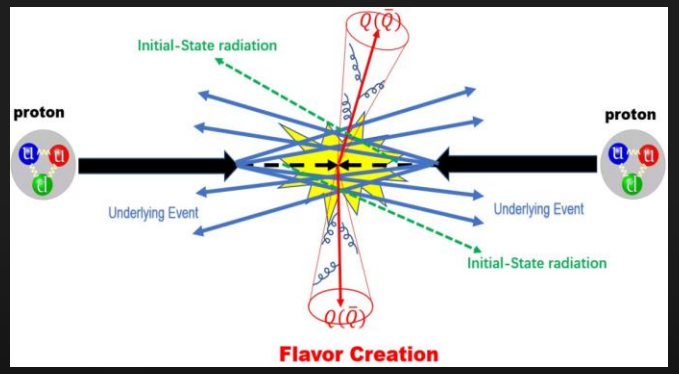
Nuclear modification factor of D^0 jets

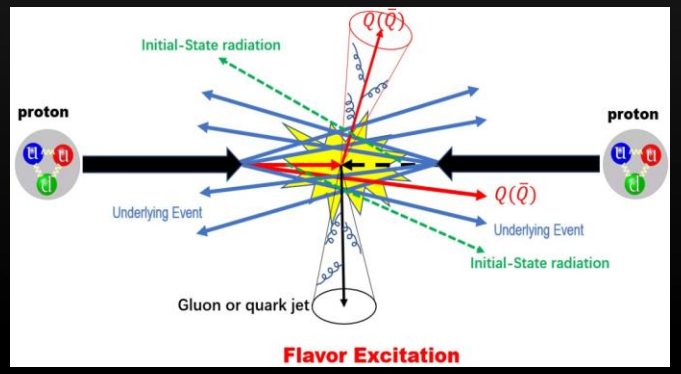
- In-medium energy loss depends on both the difference between quark and gluon coupling strength and quark mass.

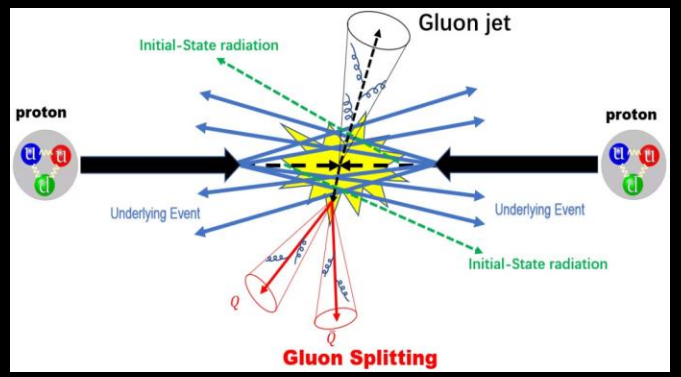


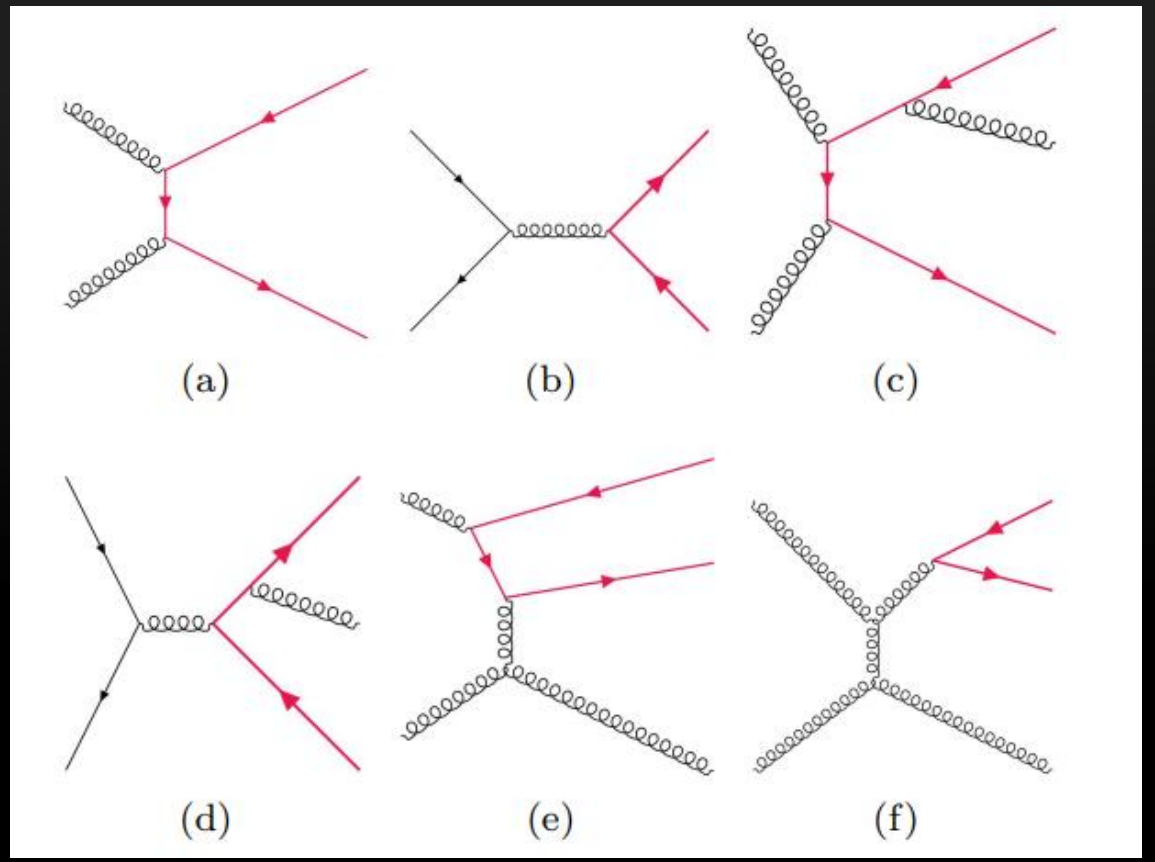
ALICE, 2409.11939

Heavy-flavor jet at NLO in p+p





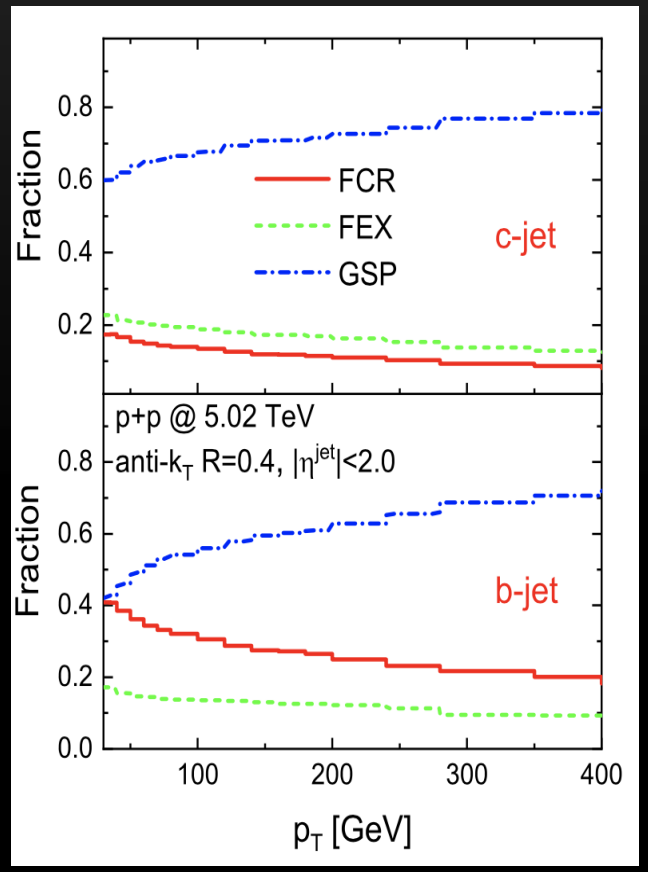


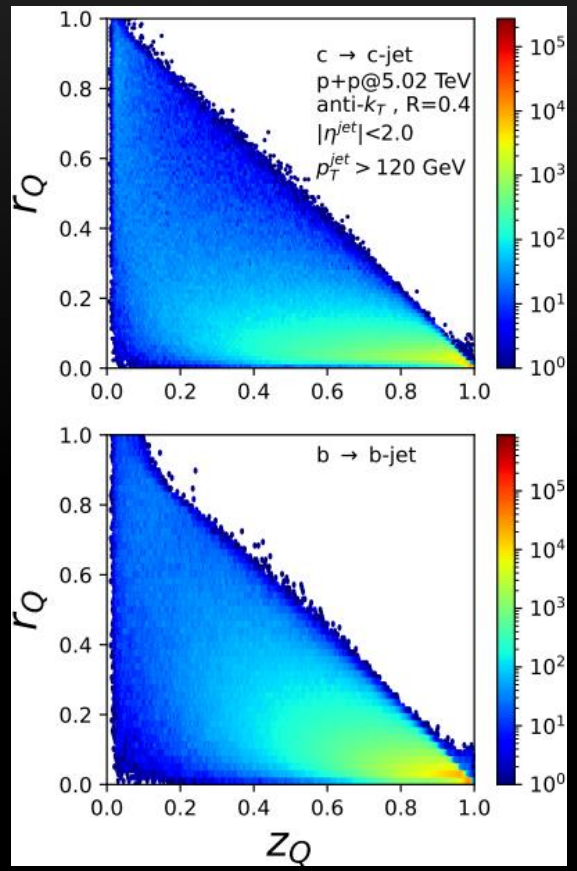


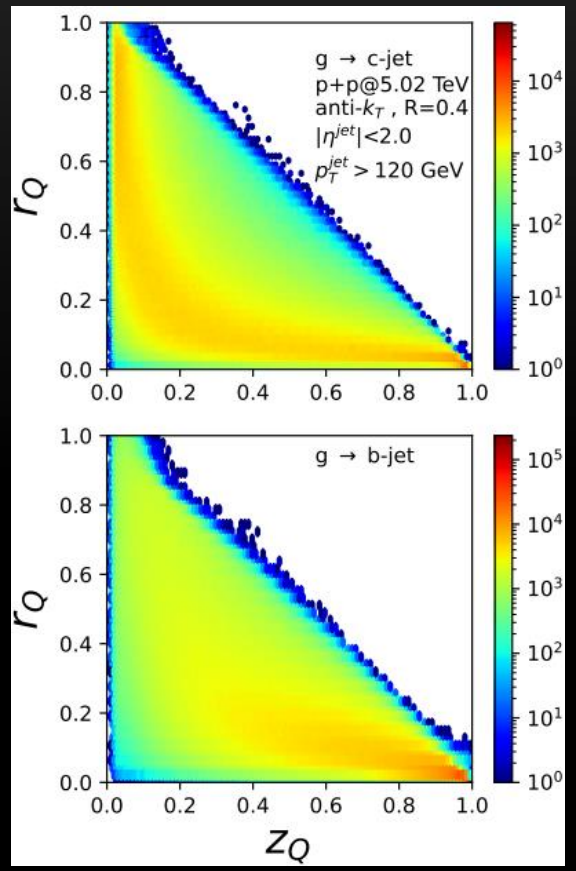
E. Norrbin, T. Sjöstrand, EPJC(2000);Andrea Banfi, Gavin P. Salam, Giulia Zanderighi, JHEP(2007)

Heavy-flavor jet yield in p+p

- g → Q-jet shows more dispersive structures than the HQ-initiated one, Q → Q-jet.







Sa Wang, Shuang Li, Yao Li, BWZ, Enke Wang, 2410.21834

Improved Langevin equations

SHELL: Simulating Heavy quark Energy Loss by Langevin equations

$$\vec{x}(t+\Delta t) = \vec{x}(t) + \frac{\vec{p}(t)}{E}\Delta t$$
$$\vec{p}(t+\Delta t) = \vec{p}(t) - \Gamma(p)\vec{p}\Delta t + \vec{\xi}(t)\Delta t - \vec{p}_g$$

G.D. Moore et al., PRC71(2005)064904;
S. Cao G.Y. Qin and S.A. Bass, PRC88 (2013) 044907

Diffusion coefficient κ and drag coefficient Γ are correlated by

$$\kappa = 2\Gamma ET = \frac{2T^2}{D_s}$$

$$\frac{dE}{dL} = -\frac{\alpha_s C_s \mu_D^2}{2} ln\frac{\sqrt{ET}}{\mu_D}$$

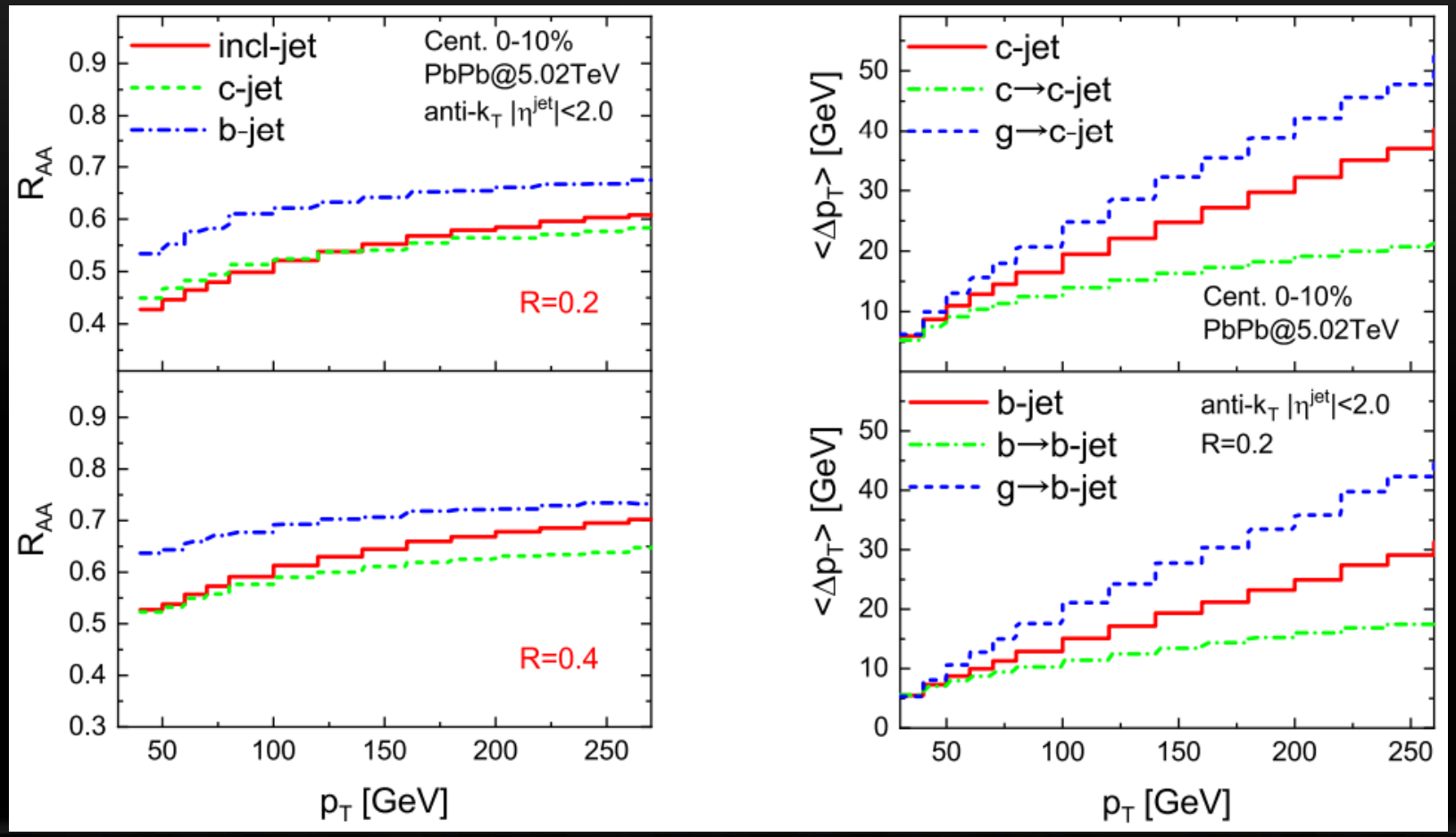
Higher-Twist approach:

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

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

Heavy-flavor jet yield suppression

- Due to the significant contribution of g → c-jet, R_{AA} of c-jet will be comparable or even smaller than that of inclusive jet.

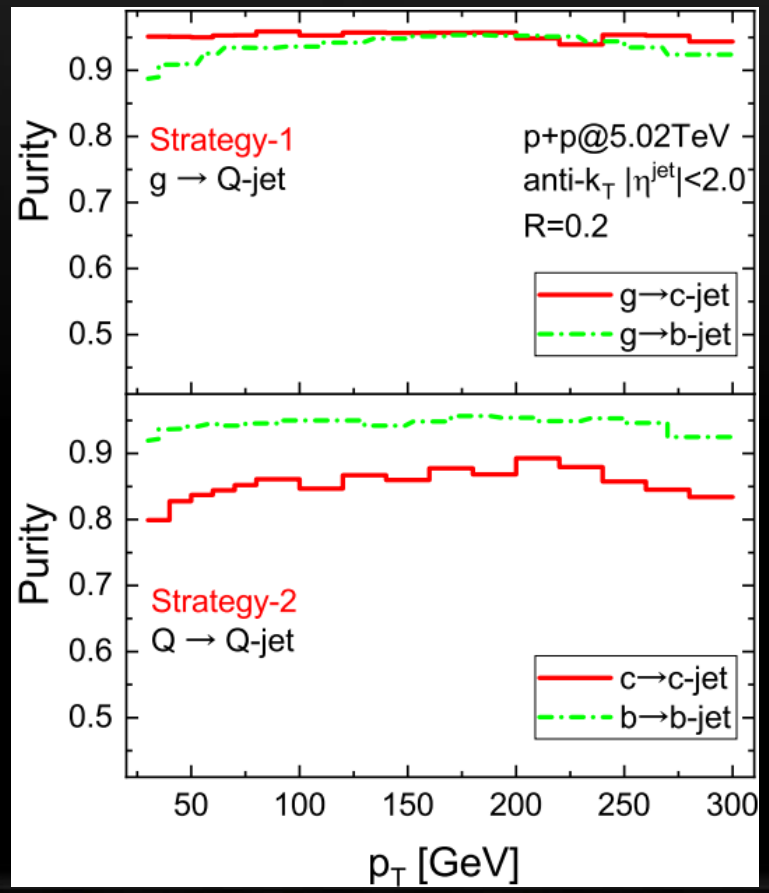


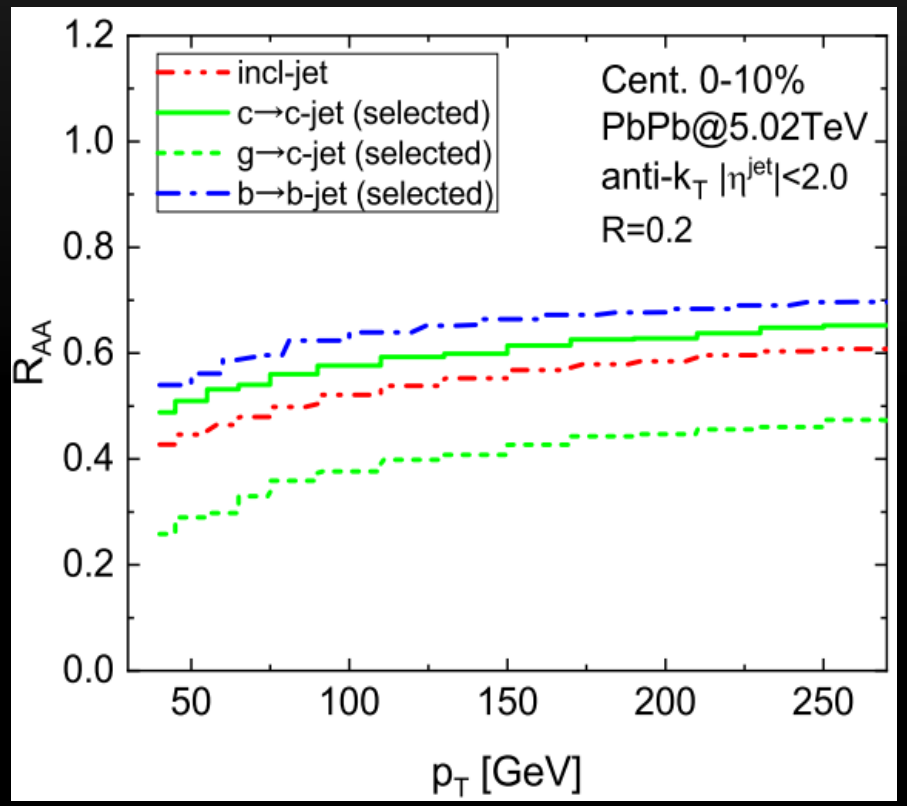
Sa Wang, Shuang Li, Yao Li, BWZ, Enke Wang, 2410.21834

Heavy-flavor jet yield suppression

Strategy 1: g→Q-jet two HF quarks in one jet, p_T>2 GeV

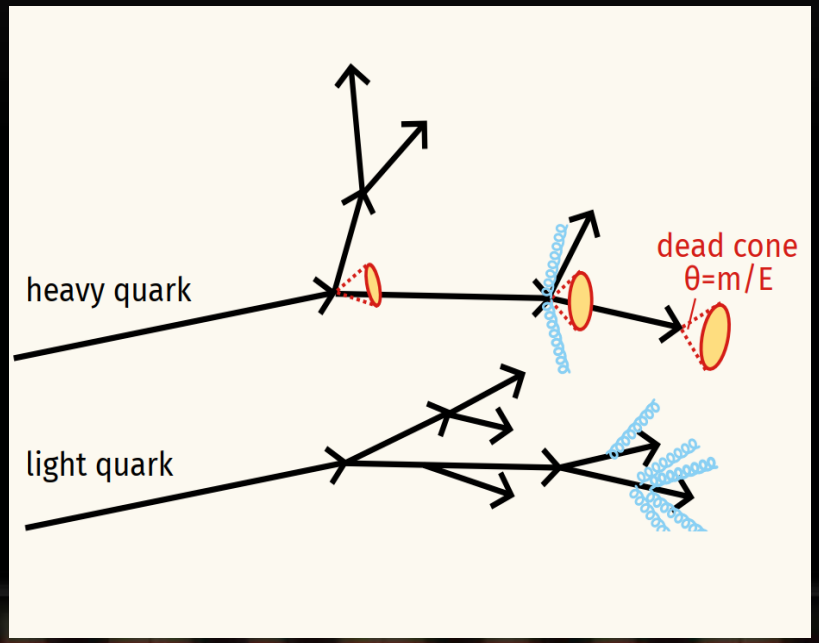
Strategy 2: Q→Q-jet only one HF quarks in the jet, with recoil jet p_T>10 GeV, with angle separation larger than 2/3π .





Sa Wang, Shuang Li, Yao Li, BWZ, Enke Wang, 2410.21834

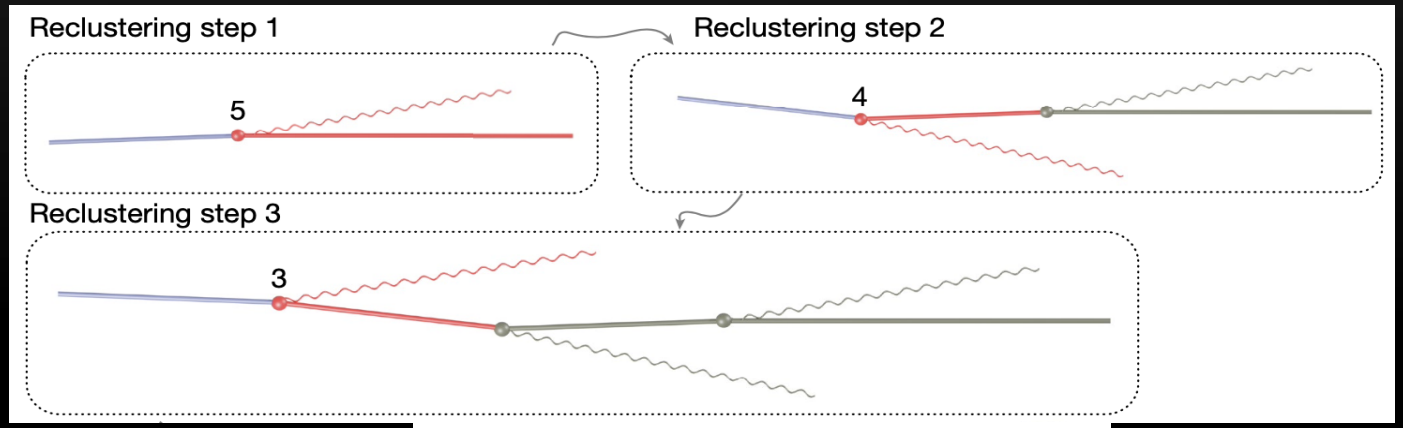
Dead-Cone: Direct Observation

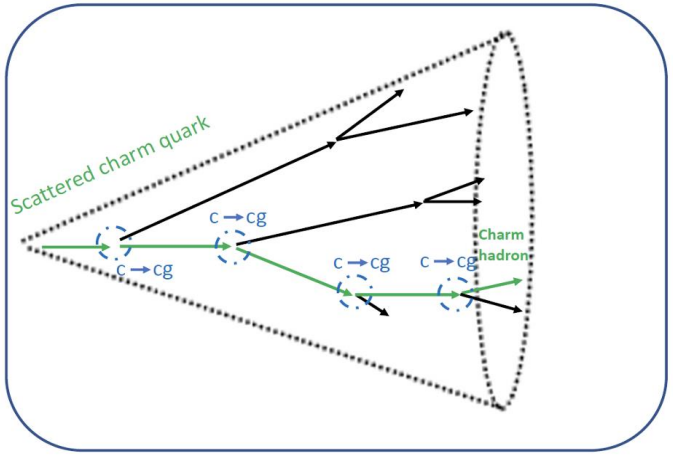


Dead-cone effect in vacuum

- A direct observation of dead-cone effect in p+p is made with an iterative declustering techniques by ALICE.

$$dP_{HQ} \simeq \frac{\alpha_s C_F}{\pi}\frac{d\omega}{\omega}\frac{k_\perp^2 dk_\perp^2}{(k_\perp^2+\omega^2\theta_0^2)^2} = dP_0\left(1+\frac{\theta_0^2}{\theta^2}\right)^2$$



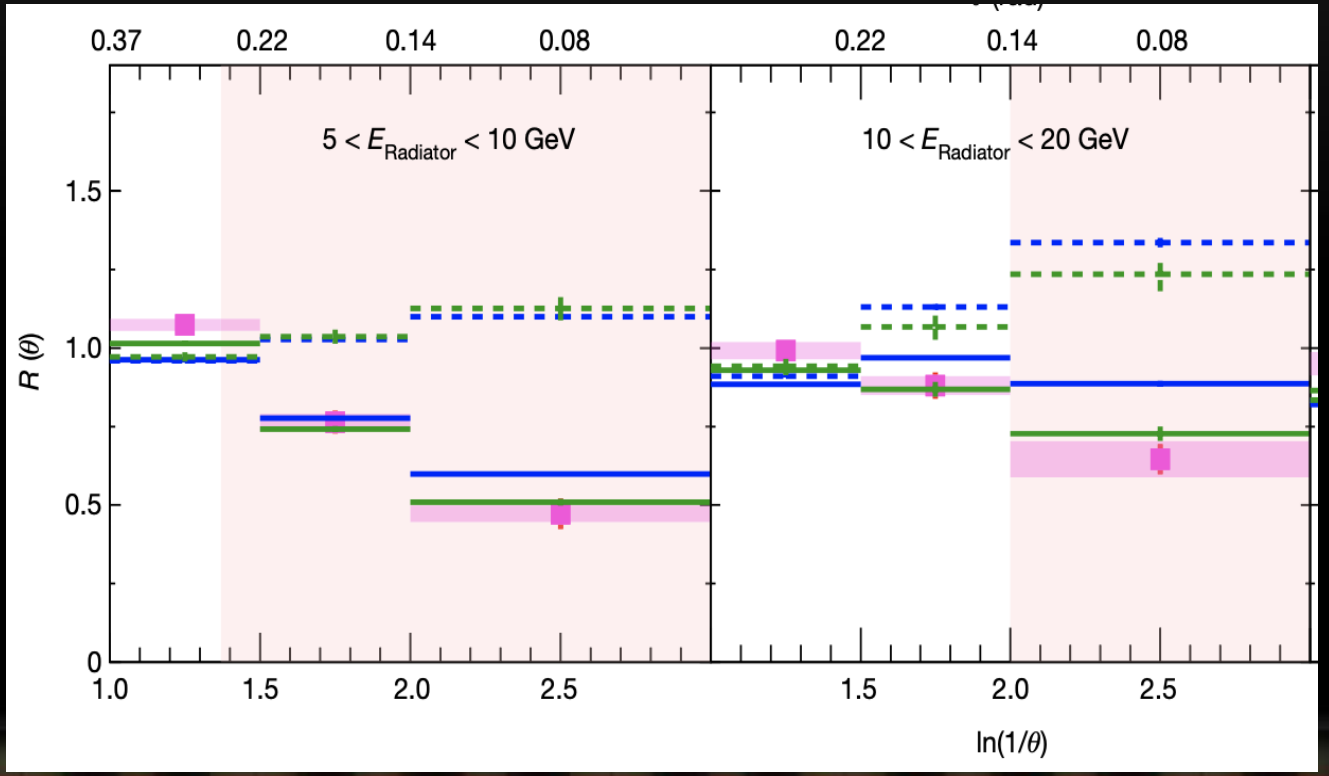


ALICE, Nature 605 (2022) 440

Dead-cone effect in vacuum

- A direct observation of dead-cone effect in p+p is made with an iterative declustering techniques by ALICE.

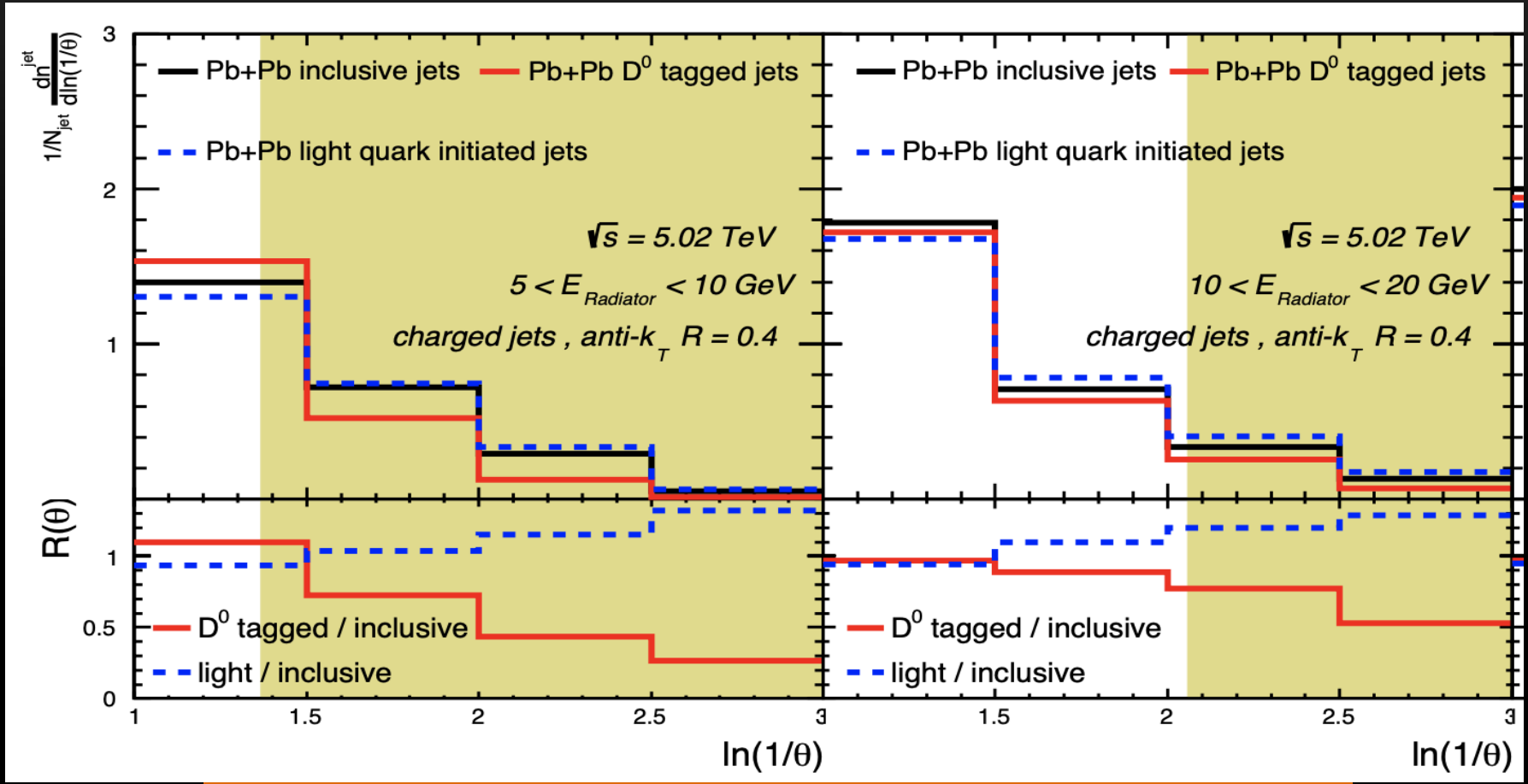
$$R(\theta) = \frac{1}{N^{D^0 jets}} \frac{dn^{D^0 jets}}{d\ln(1/\theta)} \Big/ \frac{1}{N^{inclusive\ jet}} \frac{dn^{inclusive\ jet}}{d\ln(1/\theta)}$$



ALICE, Nature 605 (2022) 440

Dead-cone effect in A+A

$$R(\theta) = \frac{1}{N^{D^0 jets}} \frac{dn^{D^0 jets}}{d\ln(1/\theta)} \Big/ \frac{1}{N^{inclusive\ jet}} \frac{dn^{inclusive\ jet}}{d\ln(1/\theta)}$$



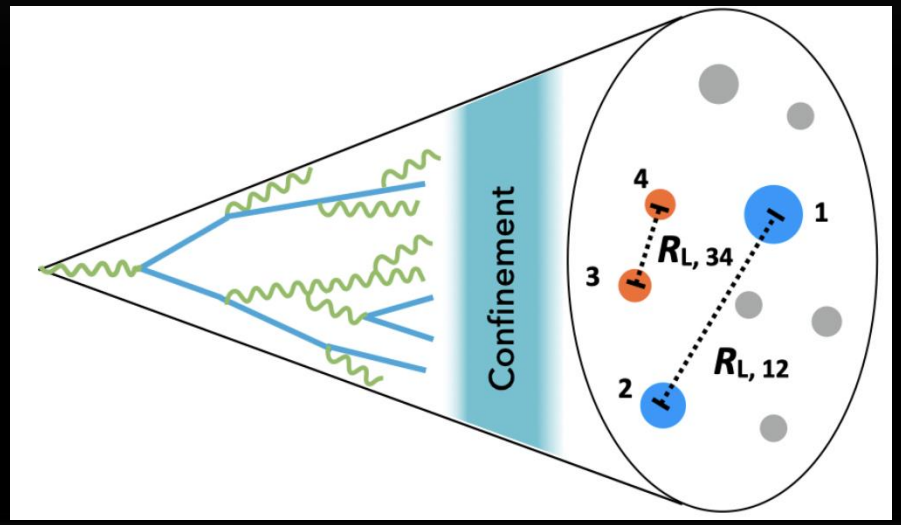
W Dai, M Z Li, BWZ, E Wang, arXiv: 2205.14668

Mean value of emission angle

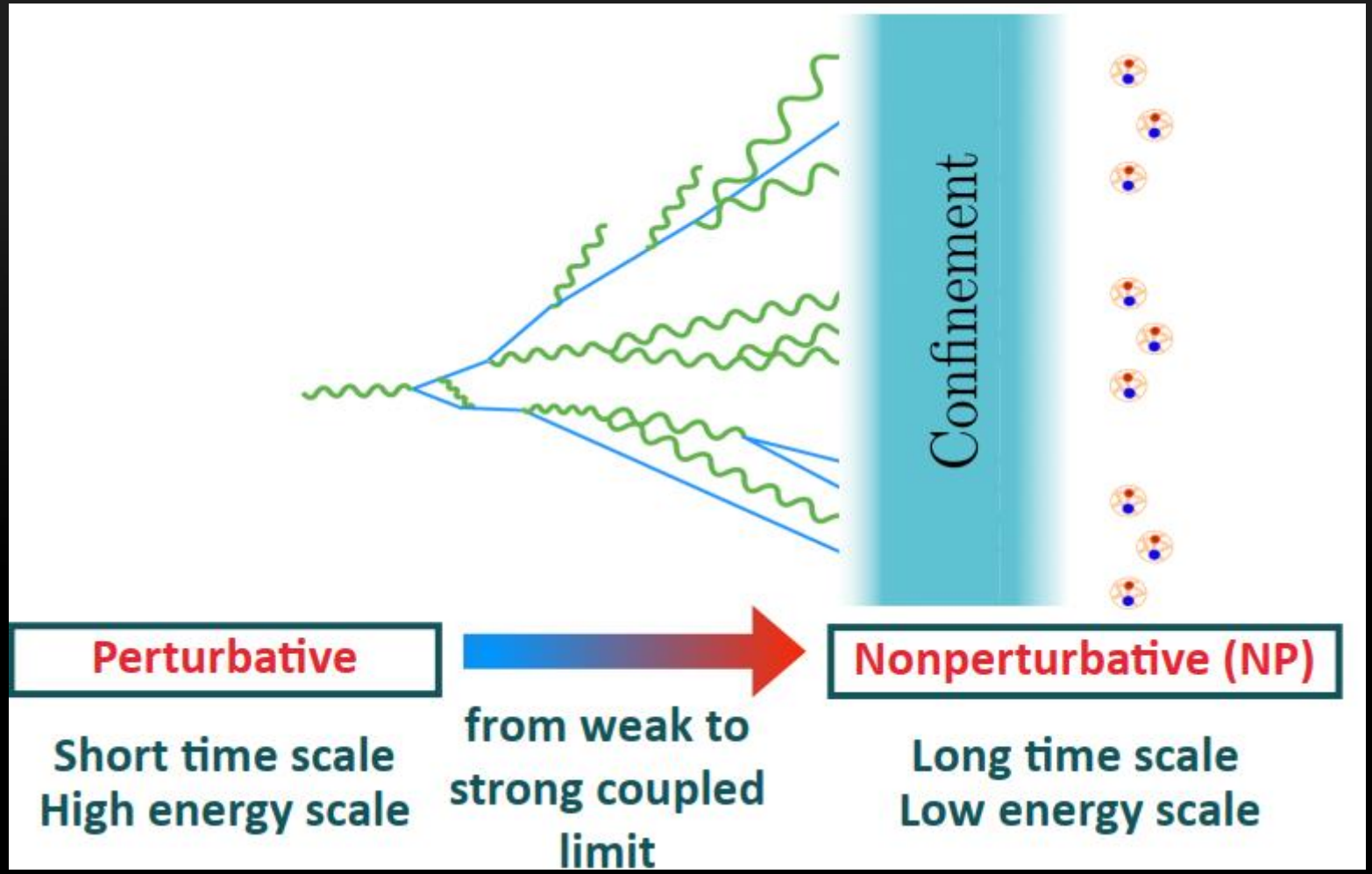
E_{Radiator}	Inclusive jets		D^0 jets		
	$\langle\theta\rangle_{\text{spl}}$	N_{spl}	$\langle\theta\rangle_{\text{spl}}$	N_{spl}	
$5-10$ GeV	0.227	1.358	0.277	1.233	pp
	0.256	1.405	0.280	1.280	AA
$10-20$ GeV	0.220	1.810	0.244	1.510	pp
	0.254	1.757	0.263	1.600	AA
$20-35$ GeV	0.232	2.040	0.232	1.822	pp
	0.249	1.977	0.251	1.860	AA

W Dai, M Z Li, BWZ, E Wang, arXiv: 2205.14668

Energy-Energy Correlator (EEC)



Energy-energy correlator of jets

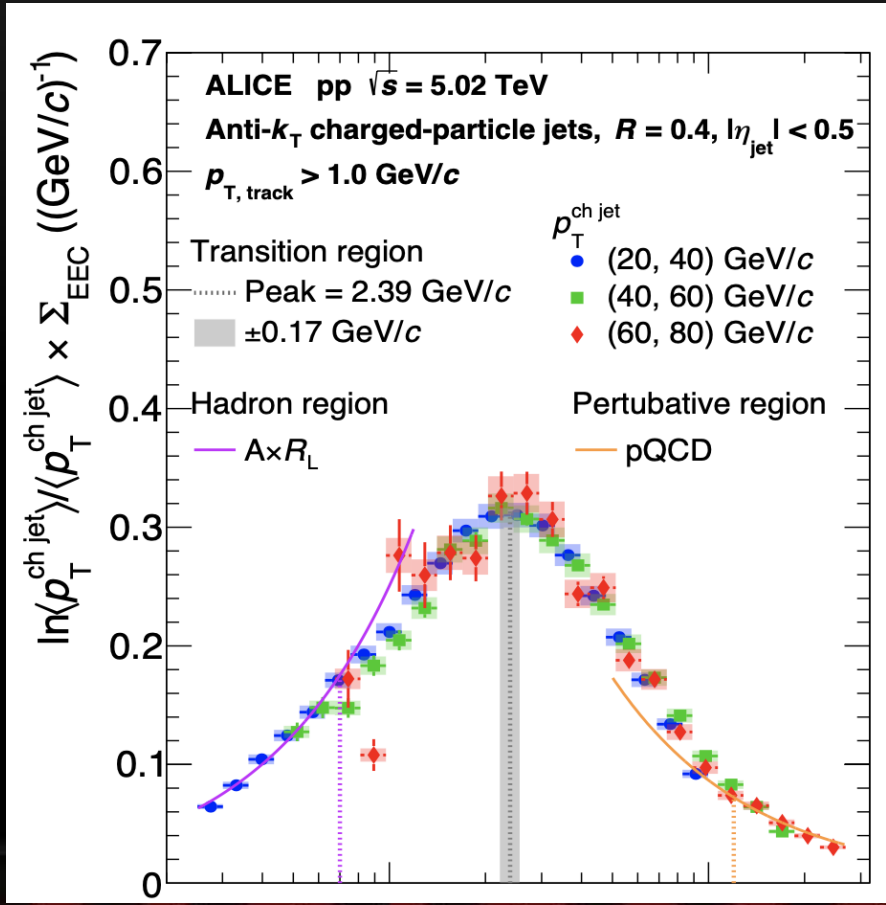


$$\frac{\mathrm{d}\sigma_{EEC}}{\mathrm{d}R_L} = \sum_{i,j} \int \mathrm{d}\sigma(R_L') \frac{p_{T,i} p_{T,j}}{p_{T,jet}^2} \delta(R_L' - R_L)$$

$$R_{\mathrm{L}} = \sqrt{\Delta\varphi_{ij}^2 + \Delta\eta_{ij}^2}$$

EEC of inclusive jets in vacuum

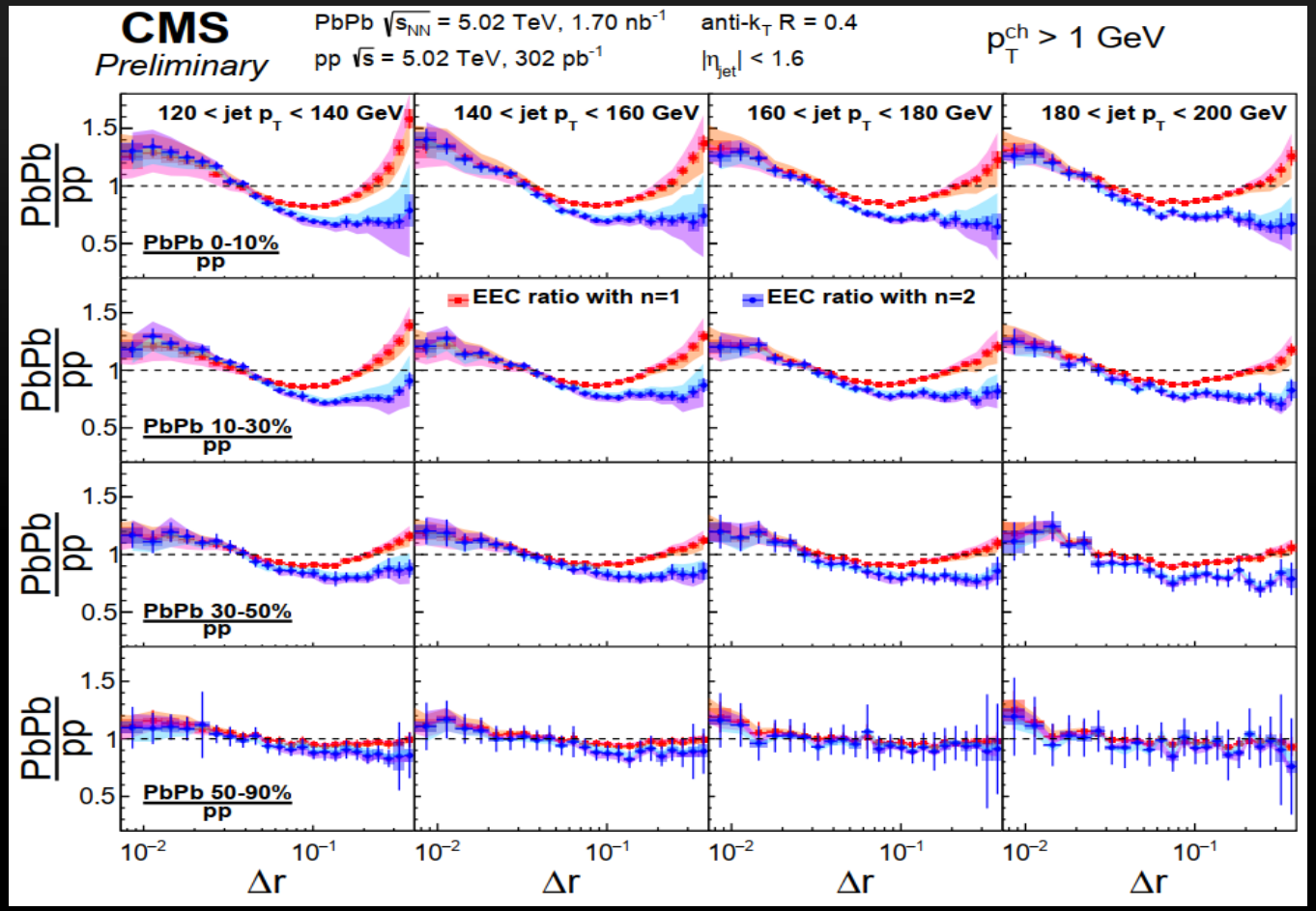
- ALICE Collaboration has measured EEC of inclusive jets in p+p collisions at 5.02TeV.



ALICE, 2409.12687

EEC of inclusive jets in HICs

- EEC of inclusive jet are measured in PbPb by CMS.

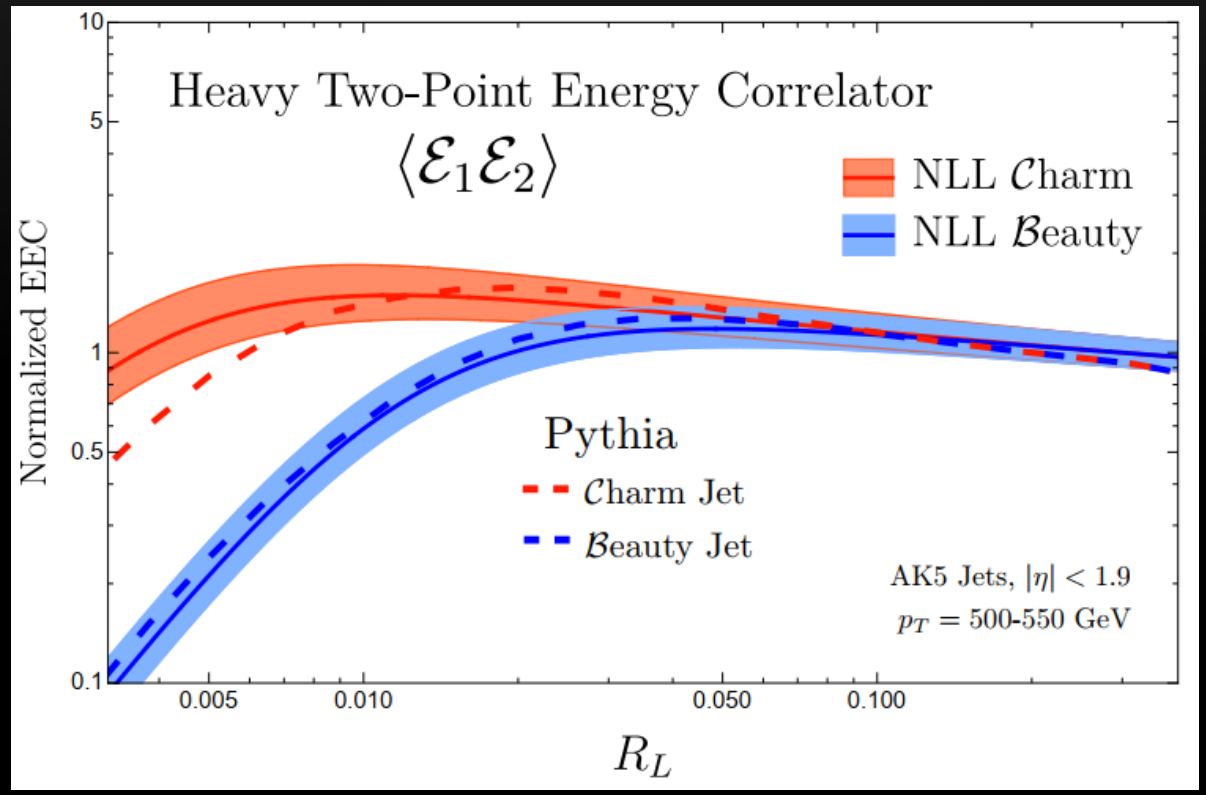


$$\mathrm{EEC}(\Delta r) = \frac{1}{W_{\mathrm{pairs}}}\frac{1}{\delta r}\sum_{\mathrm{jets}\in[p_{\mathrm{T},1},p_{\mathrm{T},2}]}\sum_{\mathrm{pairs}\in[\Delta r_a,\Delta r_b]}\left(p_{\mathrm{T},i}\,p_{\mathrm{T},j}\right)^n,$$

CMS, HIN-23-004-pas

EEC of heavy-flavor jet in vacuum

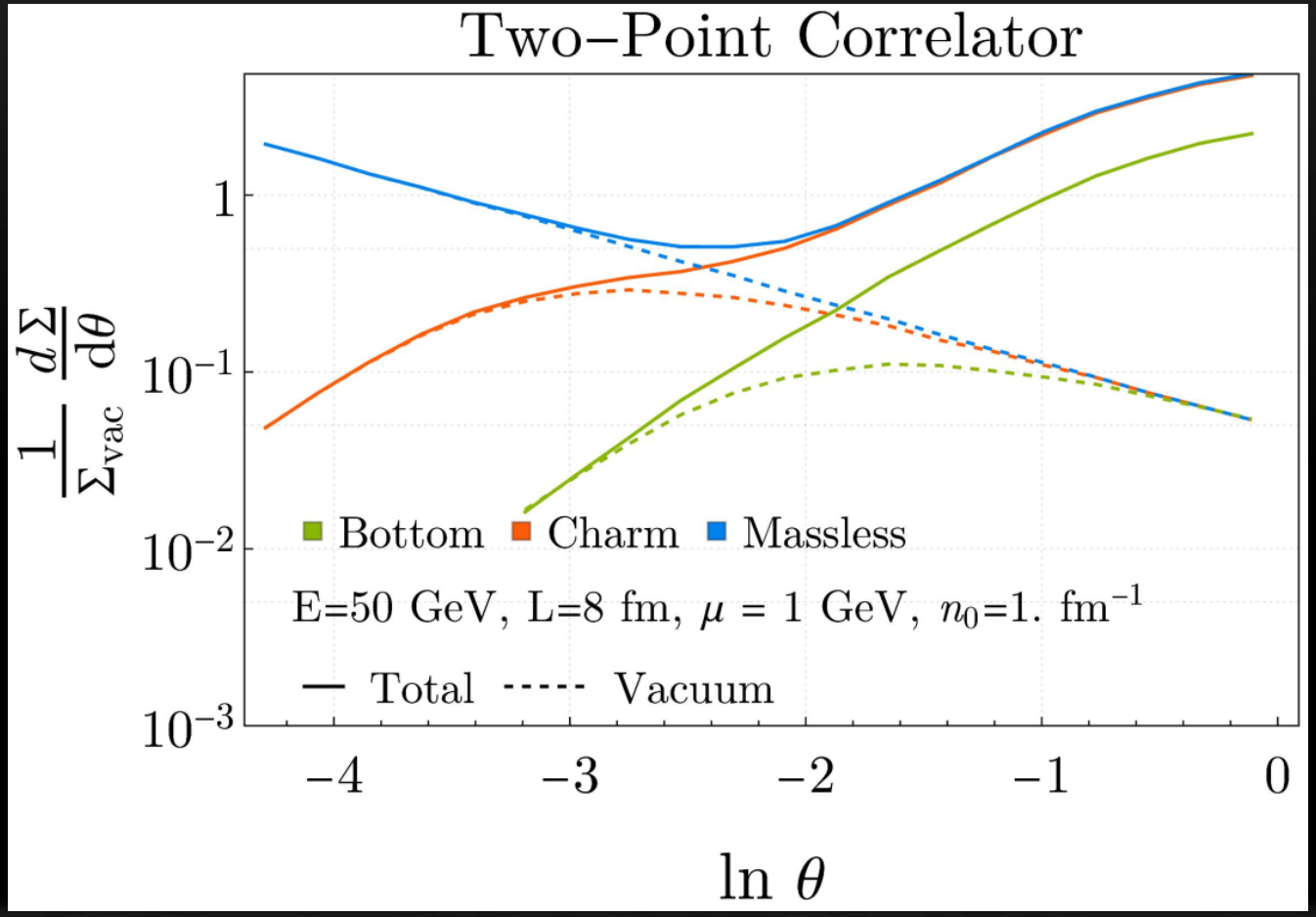
- The EEC for beauty and charm jets illustrating a UV scaling behavior at large angles, and a mass dependent suppression at small angles.



Evan Craft, Kyle Lee, Bianka Meçaj, Ian Moult, 2210.09311

EEC of HF jet in a brick QGP

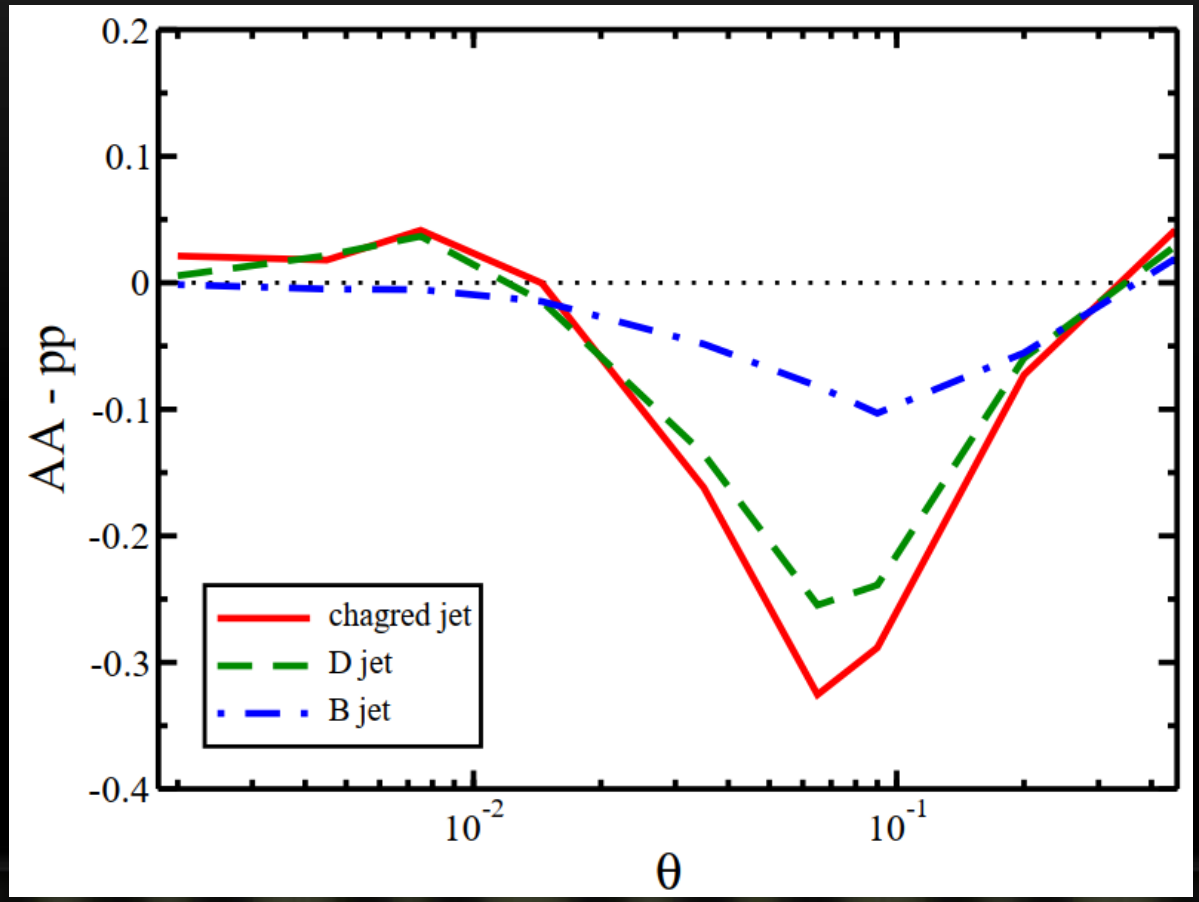
- Energy correlators of HF jets in a brick-QGP medium are calculated.



C Andres, F Dominguez, J Holguin, C Marquet, I Moult, 2307.15110

EEC of heavy-flavor jet in A+A

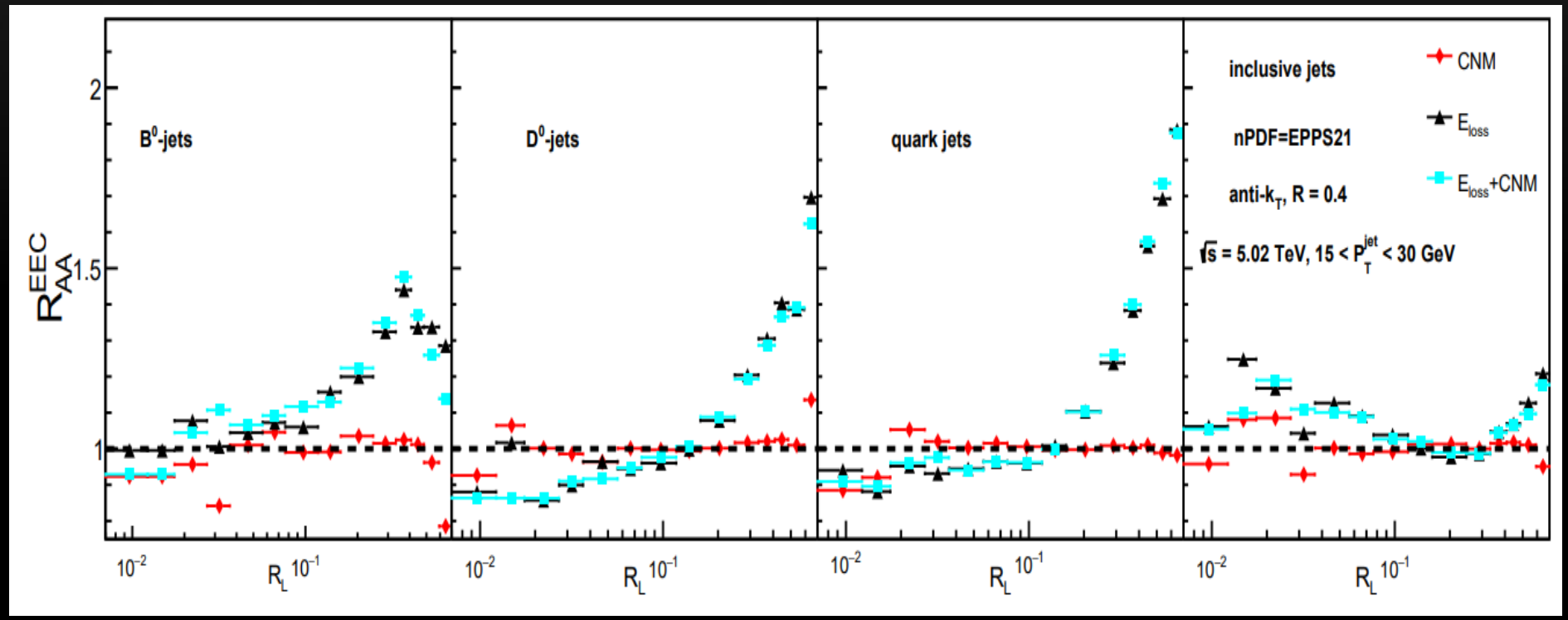
- A clear flavor hierarchy is observed for jet EEC in both vacuum and QGP due to the mass effect.



Wen-Jing Xing, Shanshan Cao, G.Y. Qin, X.N. Wang, 2409.12843

EEC of heavy-flavor jet in p+A and A+A

- The EEC distributions for all quark-tagged jets in A+A exhibit a noticeable shift towards larger R_L region.
- The CNM effect is moderate for jet EEC.



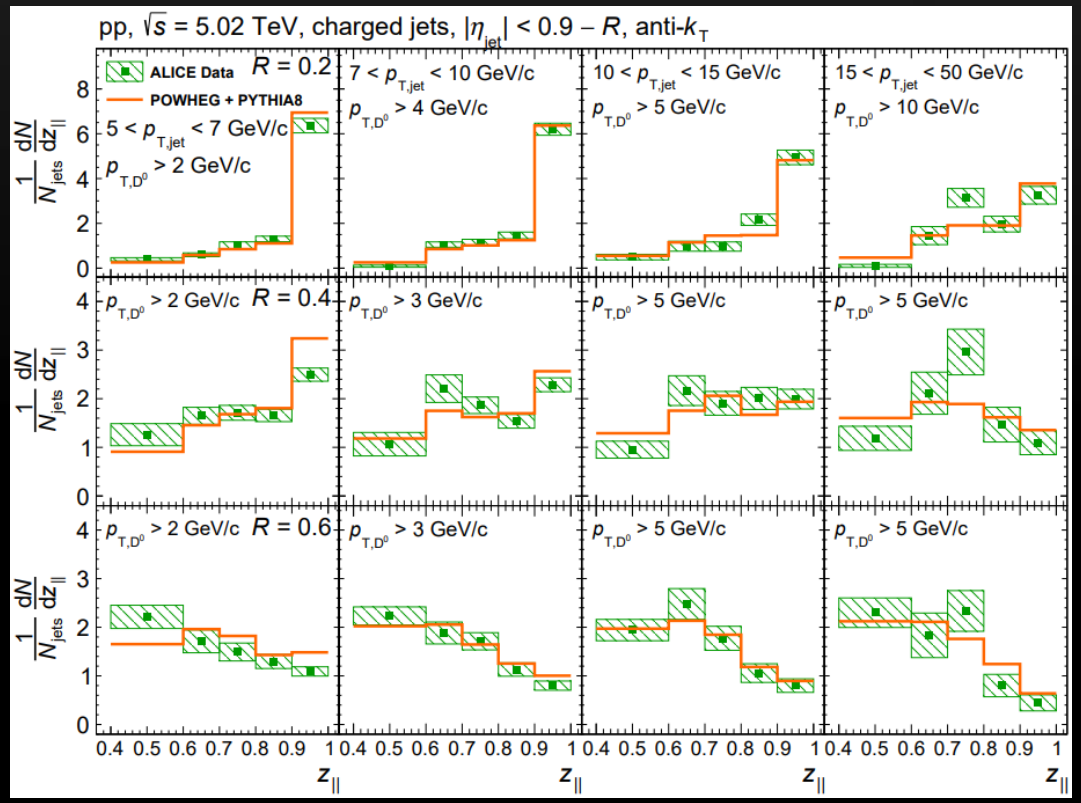
Wei Dai's talk, 12.10

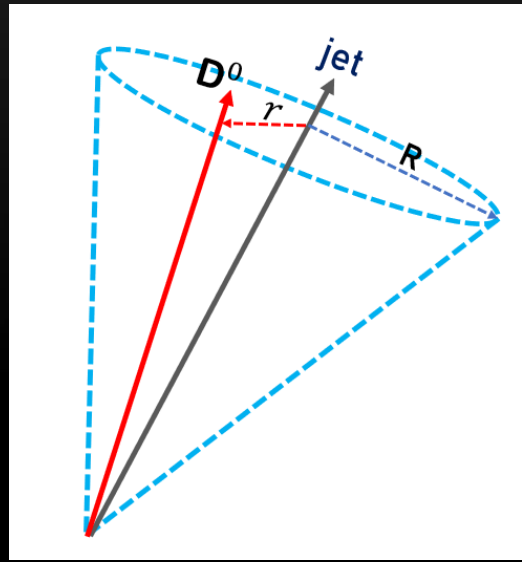
Ke-Ming Shen, Shi-Yong Chen, Yu-Jie Huang, Wei Dai, BWZ, 2410.05081

Other substructures

Heavy-flavor jet fragmentation function

- $z_{||}$ characterizes the jet momentum carried by the D^0 meson along the jet axis direction.



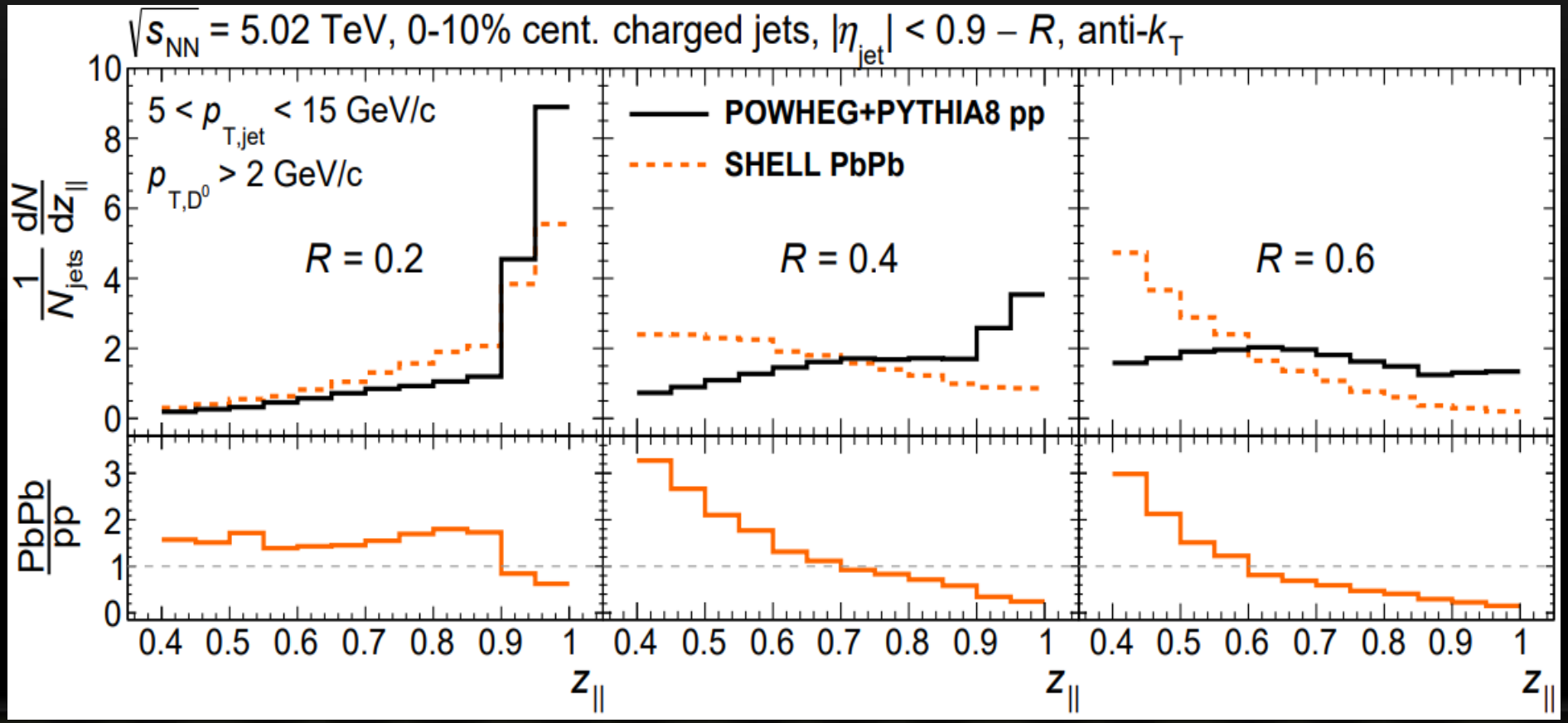


$$z_{||} = \frac{\vec{p}_{\rm jet} \cdot \vec{p}_{\rm D^0}}{\vec{p}_{\rm jet} \cdot \vec{p}_{\rm jet}} = \frac{|\vec{p}_{\rm D^0}|}{|\vec{p}_{\rm jet}|}\cos\theta$$

Yao Li, Sa Wang, BWZ, Phys. Rev. C 108, 024905 (2023)

Heavy-flavor jet fragmentation function

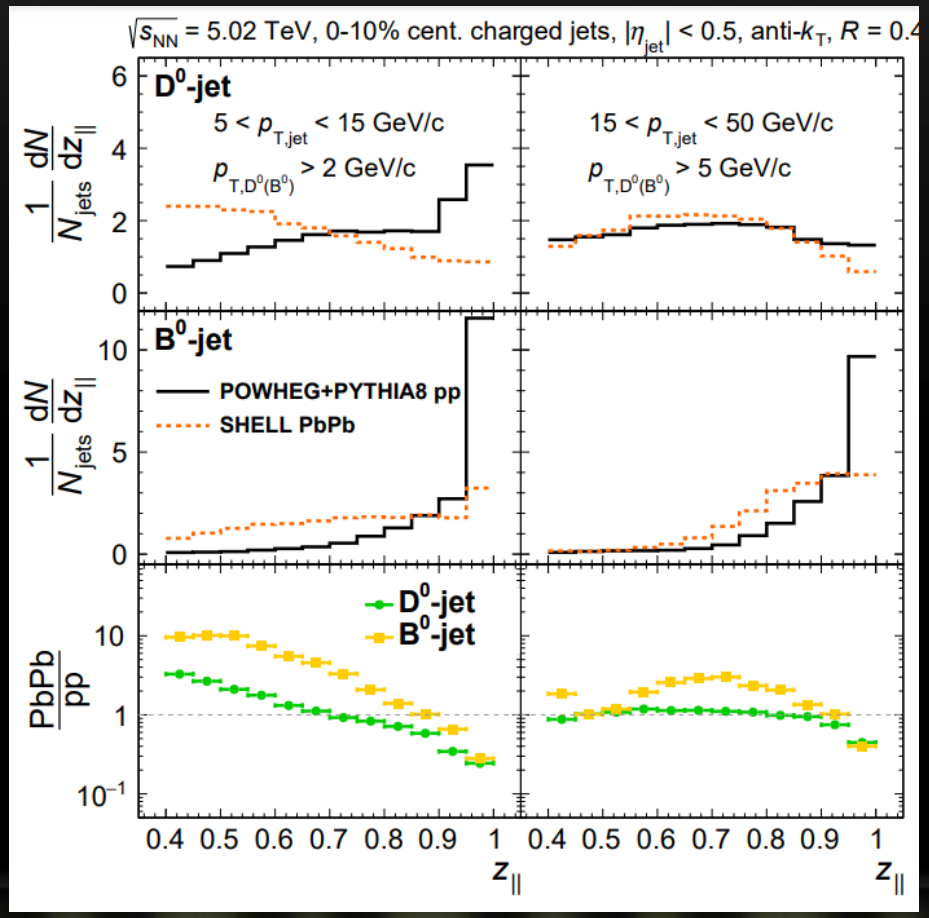
- The jet-cone size R does not influence the energy loss of charm quarks, but the energy loss of the tagged charged jet decreases with R.



Yao Li, Sa Wang, BWZ, Phys. Rev. C 108, 024905 (2023)

Heavy-flavor jet fragmentation function

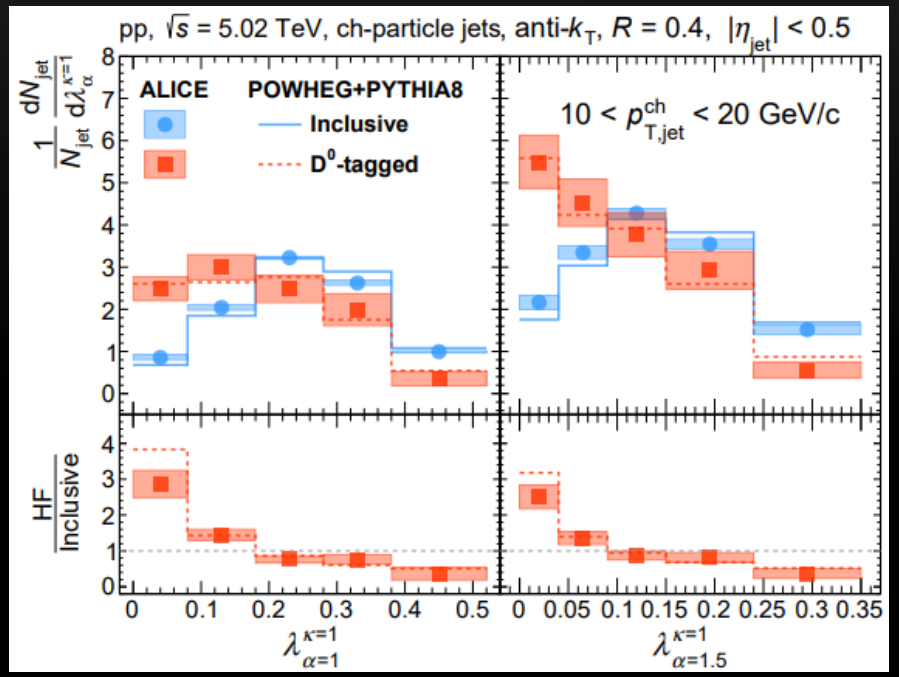
- Harder jet fragmentation function of b jets compared to c jets in vacuum. Stronger nuclear modifications of B^0-jet $z_{||}$ distributions compared to a D^0-jet.

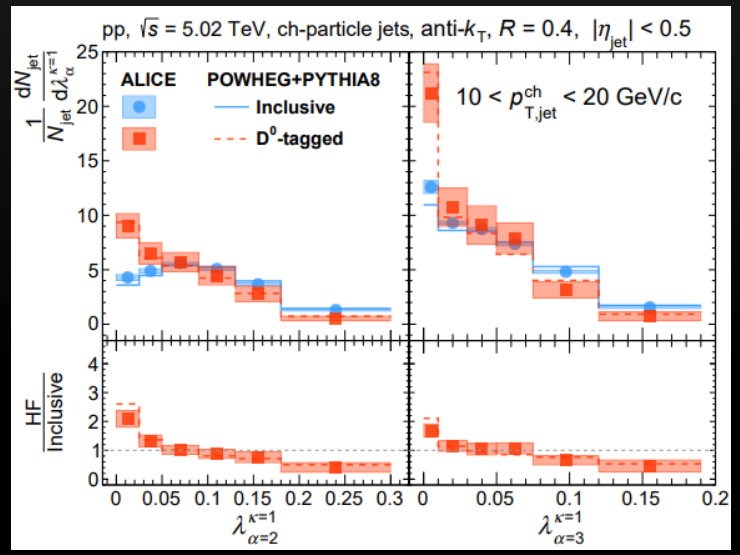


Yao Li, Sa Wang, BWZ, Phys. Rev. C 108, 024905 (2023)

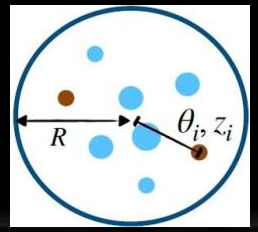
Generalized angularities

- The generalized jet angularities, quantifying the transverse momentum and angular distributions of constituents within the jet, form a class of jet substructure observables.





$$\lambda_\alpha^\kappa = \sum_{i \in jet} \left(\frac{p_{T,i}}{p_{T,jet}}\right)^\kappa \left(\frac{\Delta R_{jet,i}}{R}\right)^\alpha \equiv \sum_{i \in jet} (z_i)^\kappa (\theta_i)^\alpha$$

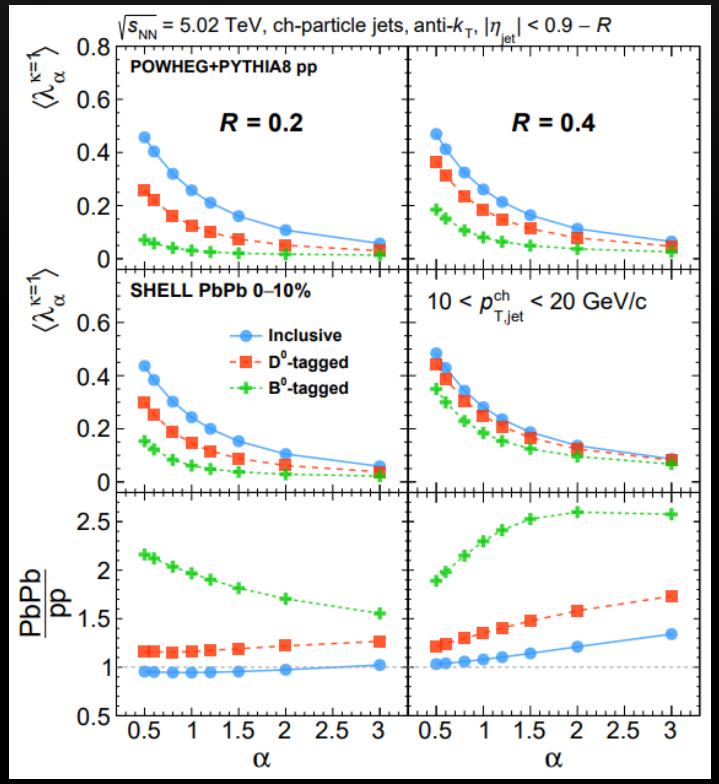


Y Li's talk, 12.8

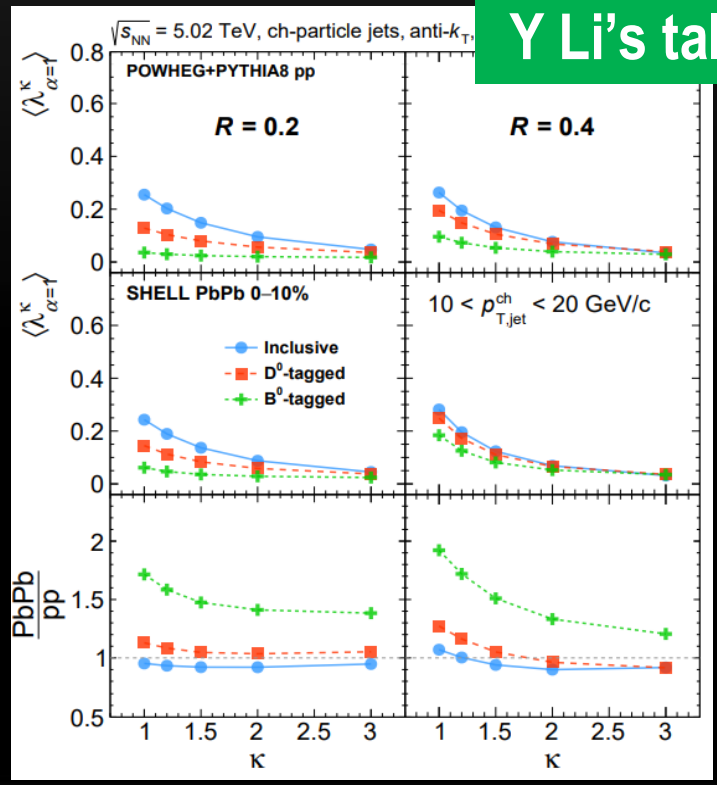
Yao Li, Shi-Yong Chen, Weixi Kong, Sa Wang, BWZ, 2409.12742

Angularities of heavy-flavor jets

- Jet quenching in the QGP may widen the angularity distributions of heavy-flavor jets in Pb+Pb relative to p+p.
- For a larger jet radius, a more significant broadening of jet angularities could be obtained.



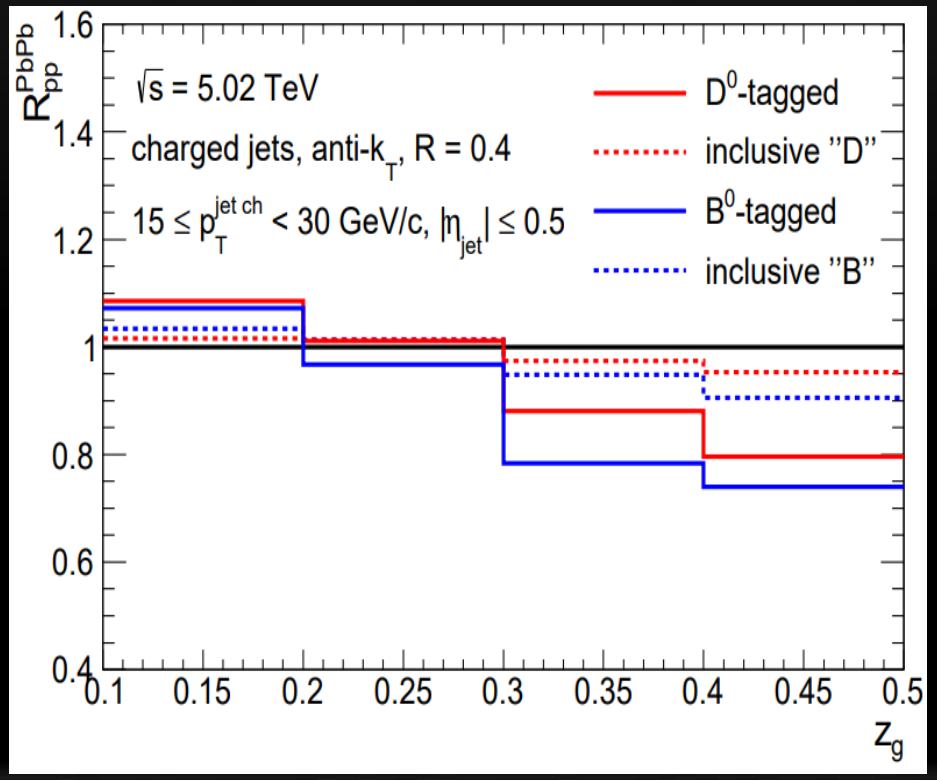
Y Li's talk, 12.8

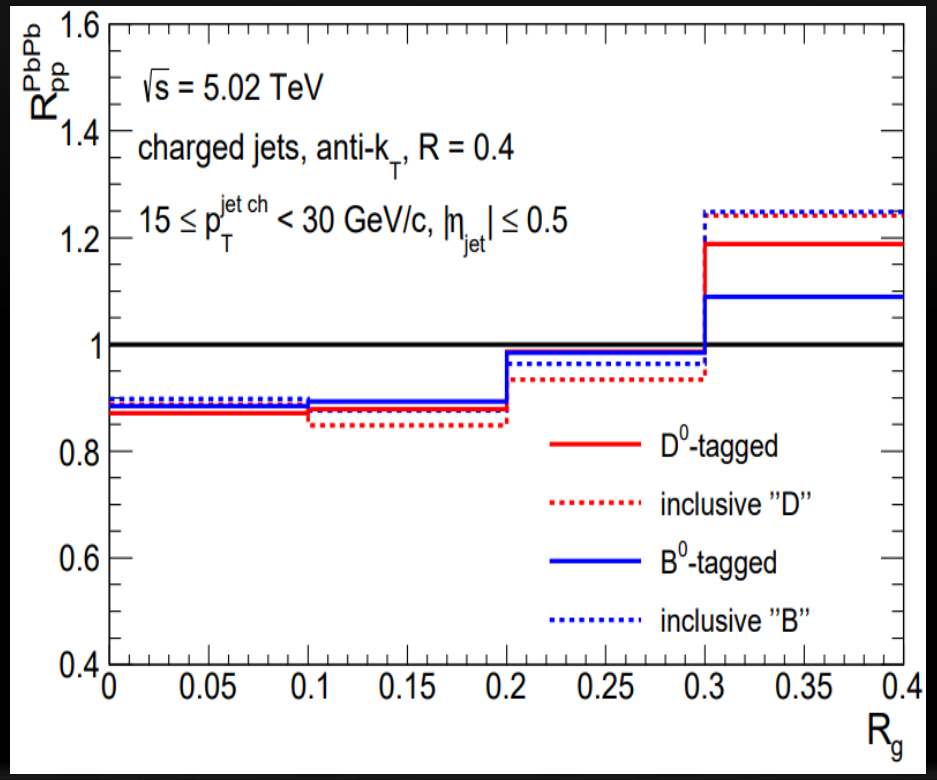


Yao Li, Shi-Yong Chen, Weixi Kong, Sa Wang, BWZ, 2409.12742

z_g and R_g of heavy-flavor jet

- The mass hierarchy in z_g of inclusive, D^0-tagged, B^0-tagged jets and competition between mass effects and Casimir color factors in R_g can also be observed in PbPb collisions.





Qing Zhang, Zi-Xuan Xu, Wei Dai, BWZ, Enke Wang, 2303.06820

Recap

- Heavy quark jets provide a very powerful tool to study QCD dynamics and the properties of the QGP.

- Several interesting HF jet observables in HICs are discussed: HF jet yields, dead-cone, ECC, jet FF, angularity, groomed HF jet z_g R_g, etc.

- The 'mass' is mysterious, but very powerful. It is silent most of the time, but when it speaks, it has a final say.

Backup

Improved Langevin equations

SHELL: Simulating Heavy quark Energy Loss by Langevin equations

$$\vec{x}(t+\Delta t) = \vec{x}(t) + \frac{\vec{p}(t)}{E}\Delta t$$
$$\vec{p}(t+\Delta t) = \vec{p}(t) - \Gamma(p)\vec{p}\Delta t + \vec{\xi}(t)\Delta t - \vec{p}_g$$

G.D. Moore et al., PRC71(2005)064904;
S. Cao G.Y. Qin and S.A. Bass, PRC88 (2013) 044907

Diffusion coefficient κ and drag coefficient Γ are correlated by

$$\kappa = 2\Gamma ET = \frac{2T^2}{D_s}$$

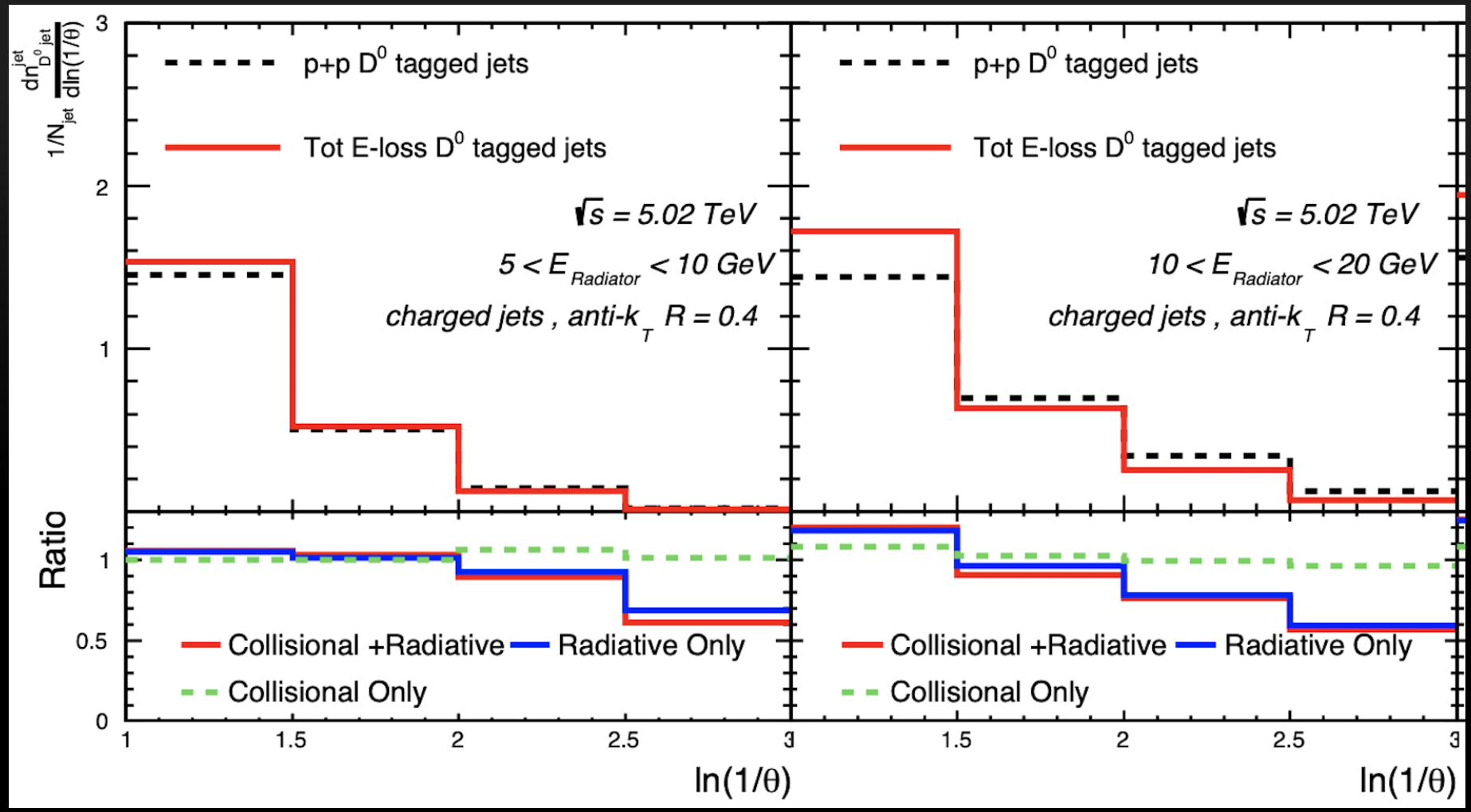
$$\frac{dE}{dL} = -\frac{\alpha_s C_s \mu_D^2}{2} ln\frac{\sqrt{ET}}{\mu_D}$$

Higher-Twist approach:

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

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

Dead-cone effect in A+A



W Dai, M Z Li, BWZ, E Wang, arXiv: 2205.14668

kt algorithm

$$d_{ij} = \min(p_{ti}^{2p}, p_{tj}^{2p}) \frac{\Delta y^2 + \Delta \phi^2}{R^2} \qquad d_{iB} = p_{ti}^{2p}$$

$$R_{ij} = \sqrt{(y_i - y_j)^2 + (\phi_i - \phi_j)^2}$$

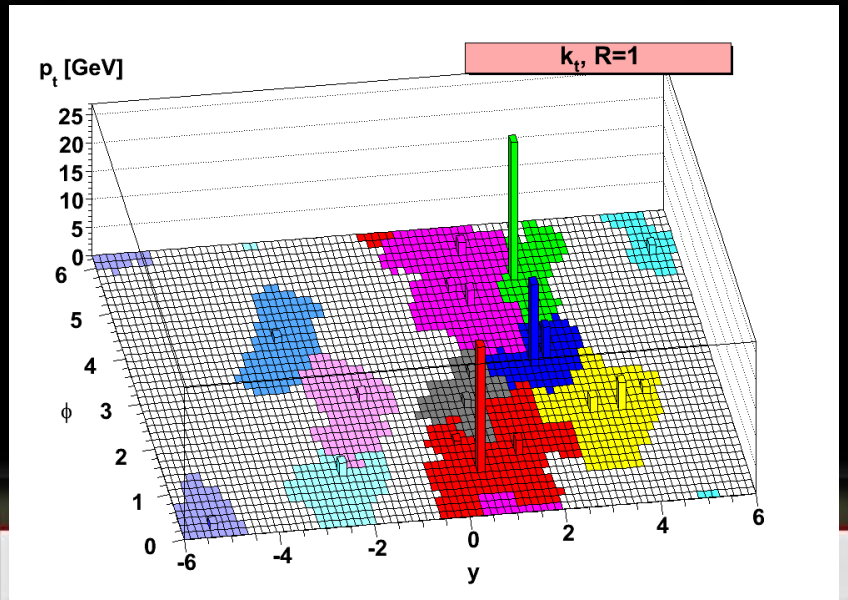
$$p = 1$$

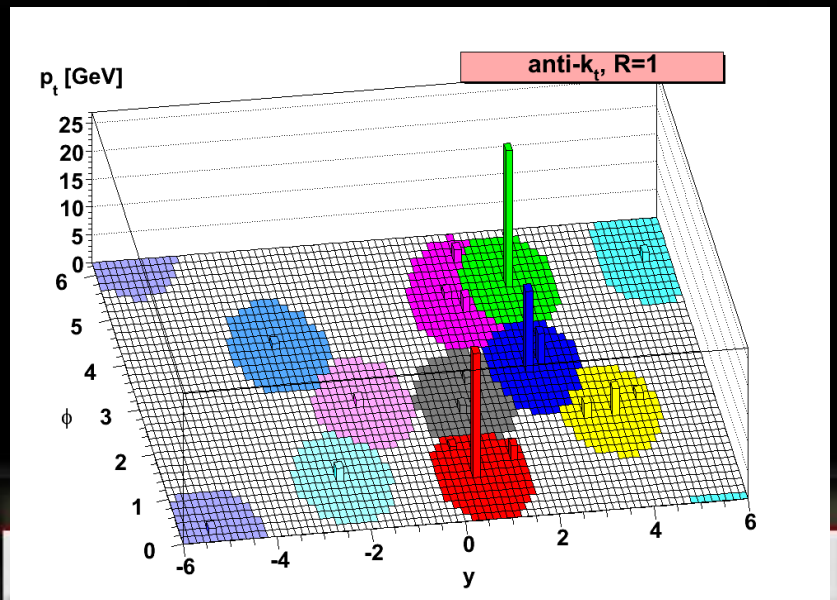
- Compute d_{ij} and d_{iB} for all particles in the final state, and find the minimum value.
- If the minimum is a d_{iB}, declare particle i a jet, remove it from the list, and go back to step one.
- If the minimum is a d_{ij}, combine particles i and j, and go back to step one.
- Iterate until all particles have been declared jets.

anti-kt and C/A algorithms

$$d_{ij} = \min(p_{ti}^{2p}, p_{tj}^{2p}) \frac{\Delta y^2 + \Delta\phi^2}{R^2} \qquad d_{iB} = p_{ti}^{2p}$$

- The Cambridge/Aachen algorithm: $p = 0$
- The anti-kt algorithm: $p = -1$





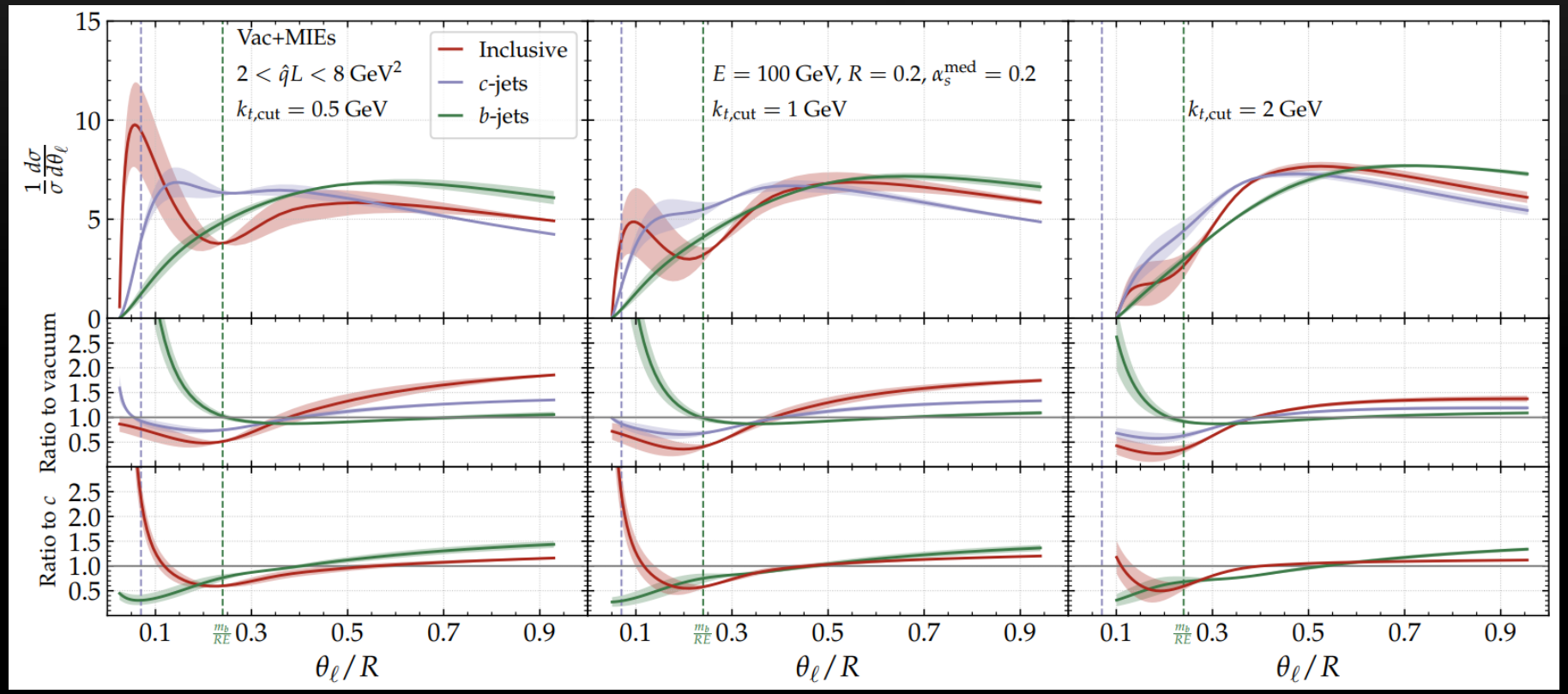
Mean value of emission angle

E_{Radiator}	Inclusive jets	D^0 jets	
	$\langle\theta\rangle_{\text{jets}}$	$\langle\theta\rangle_{\text{jets}}$	
$5-10$ GeV	0.31	0.34	pp
	0.36	0.36	AA
$10-20$ GeV	0.40	0.37	pp
	0.45	0.42	AA
$20-35$ GeV	0.47	0.42	pp
	0.49	0.47	AA

W Dai, M Z Li, BWZ, E Wang, arXiv: 2205.14668

Dead cone effect of heavy quarks

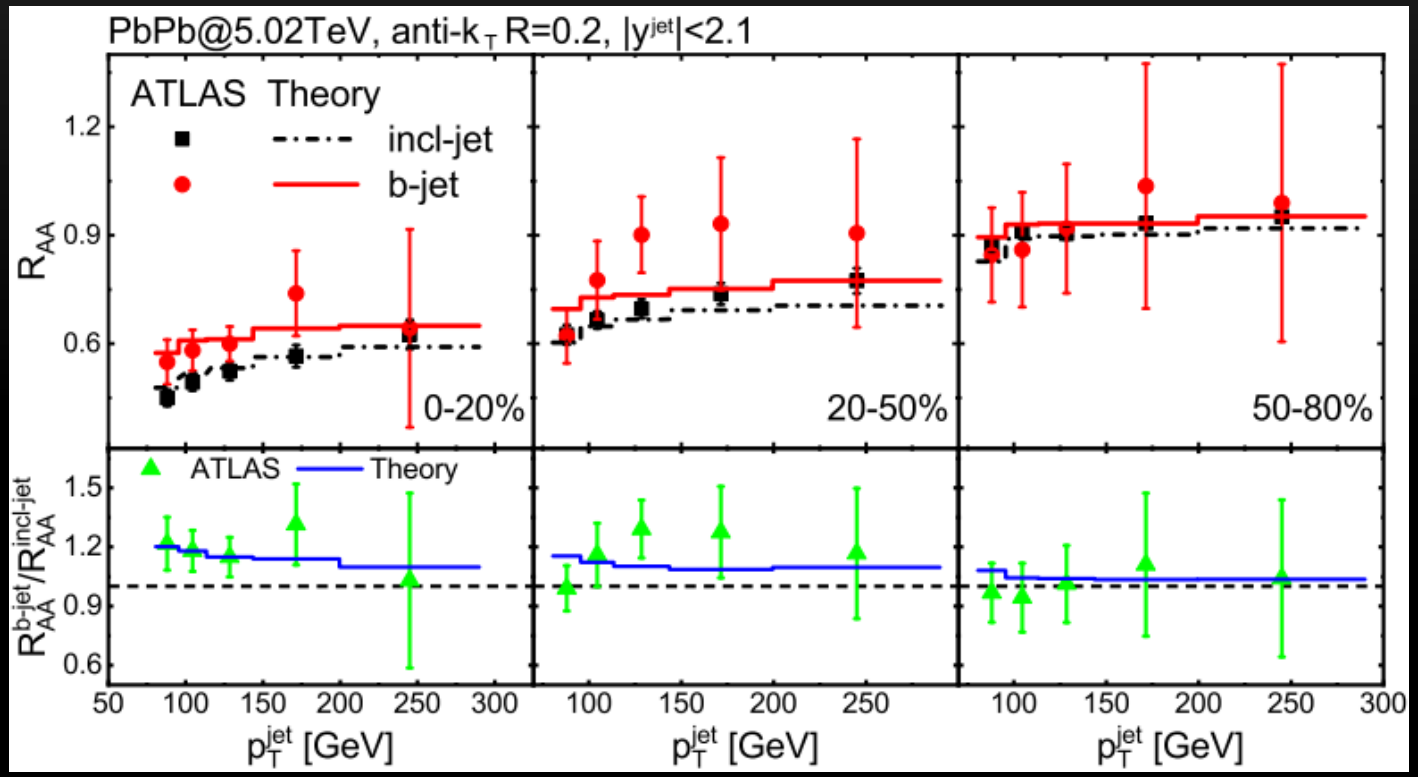
- The b-initiated jets show a significant excess of collinear radiation when compared to the purely vacuum case.



L Cunqueiro, D Napoletano, A Soto-Ontoso, 2211.11789

Heavy-flavor jet yield suppression

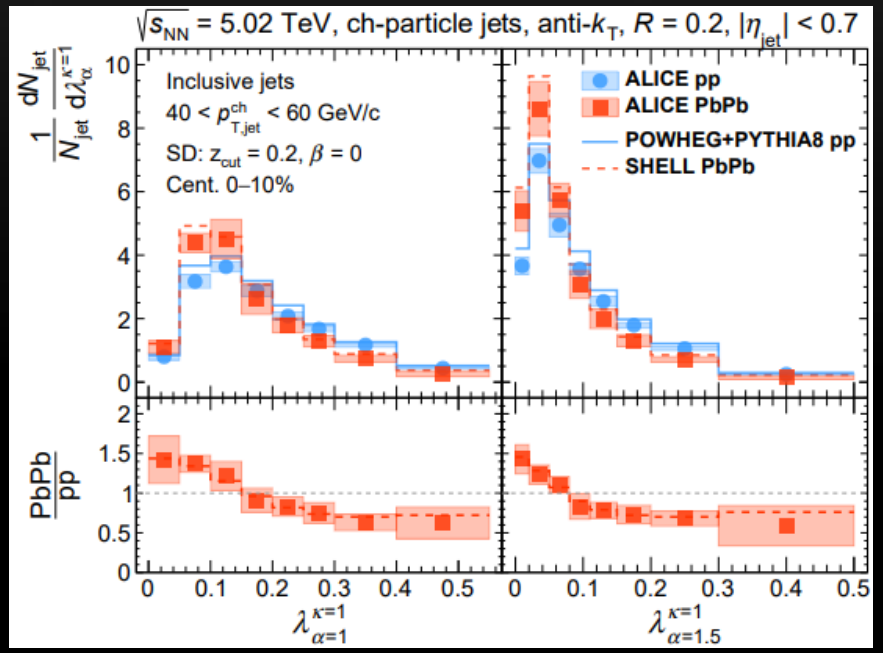
- Our calculations give decent descriptions of the inclusive jet and b-jet RAA measured by the ATLAS collaboration.

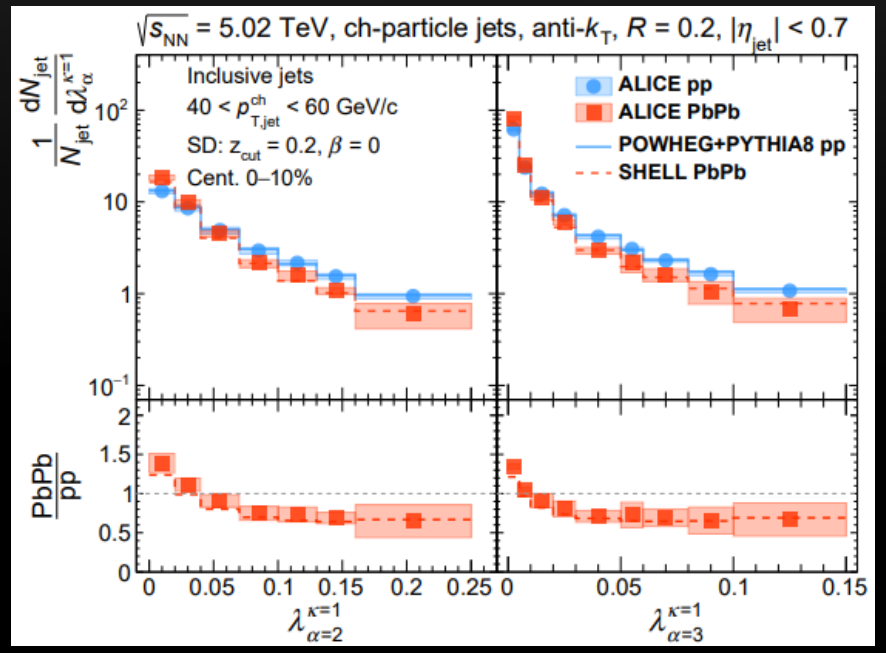


Sa Wang, Shuang Li, Yao Li, BWZ, Enke Wang, 2410.21834

Angularities of heavy-flavor jets

- The SHELL model can well describe the medium modification of inclusive jet angularities.

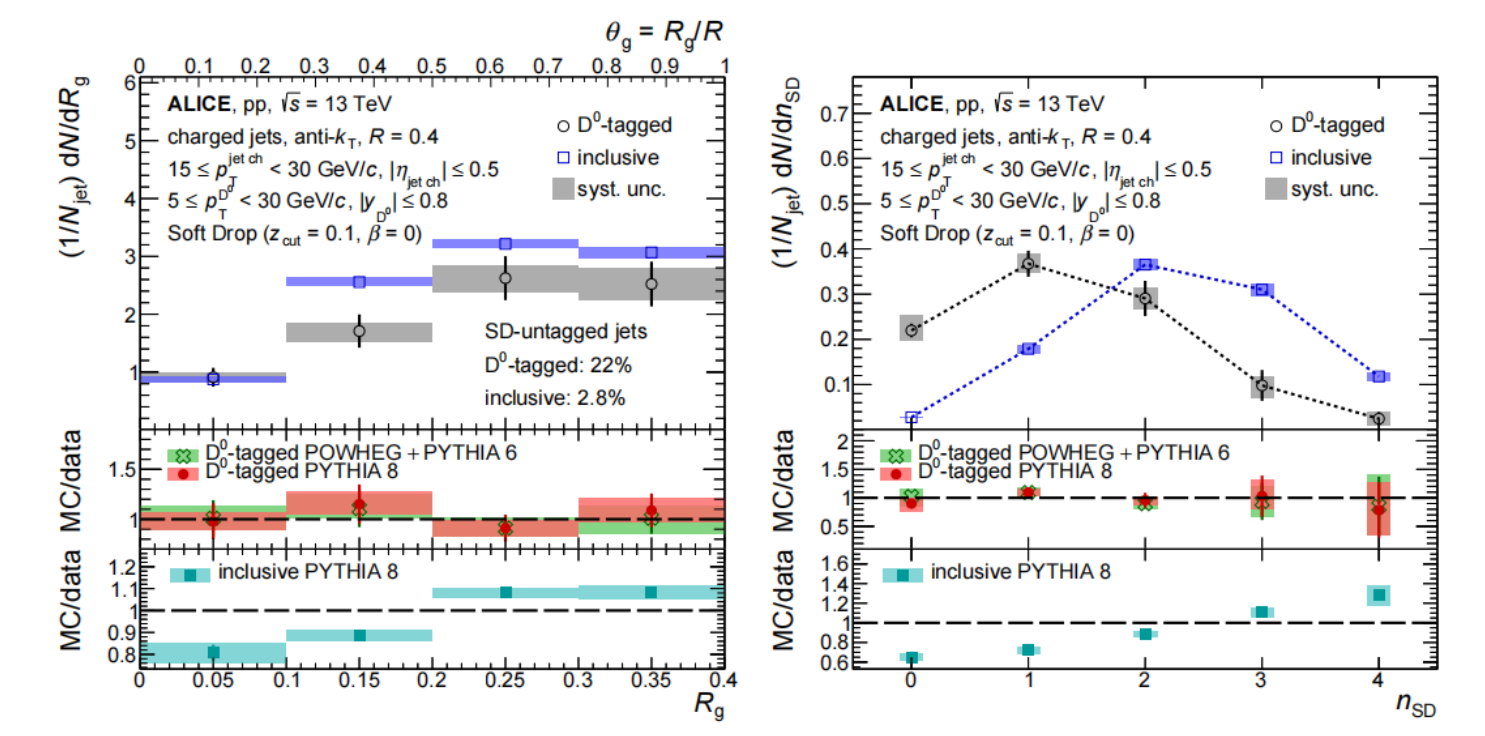




Yao Li, Shi-Yong Chen, Weixi Kong, Sa Wang, BWZ, 2409.12742

z_g and R_g of heavy-flavor jet

- Charm quarks undergo fewer perturbative emissions in the parton shower, with a reduced probability of large-angle emissions



ALICE, 2208.04857