The 9th International Symposium on Heavy Flavor Production in Hadron and Nuclear Collisions (HF-HNC 2024)

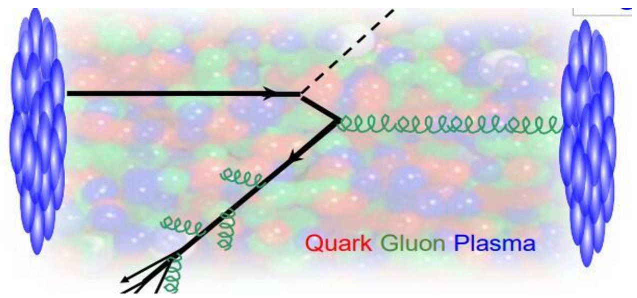
Flavor dependence of jet quenching for EEC in heavy-ion collisions

Wei Dai 代巍, China University of Geosciences (Wuhan)

Based on: arXiv.2409.13996
arXiv. 2410.05081

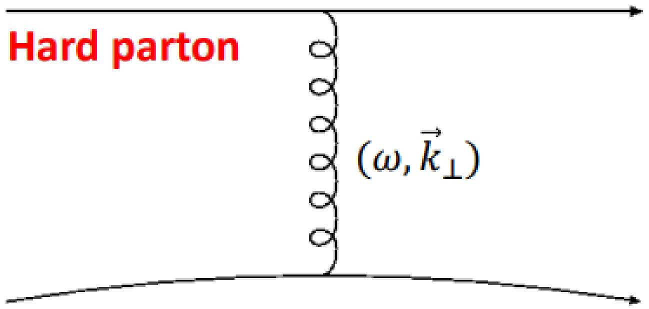
Motivation transport

Heavy-ion collisions: Quark Gluon Plasma



Jet quenching is one of the most powerfull hard probe to investigate QGP: parton energy loss, medium response.

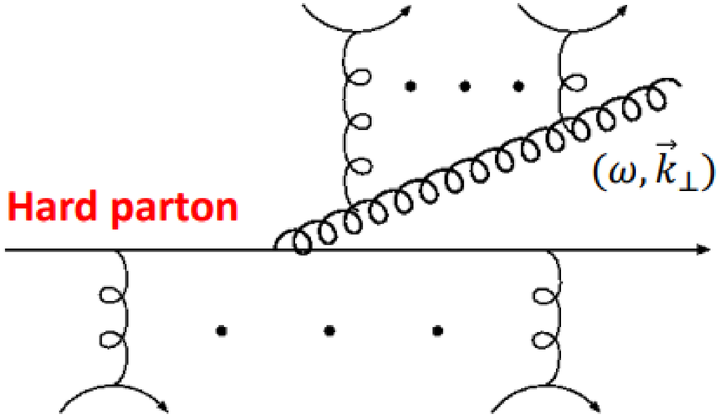
Xin-Nian Wang, M.Gyulassy, PRL68(1992)1480



Elastic (collisional)

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

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; ...



Inelastic (radiative)

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

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 & GYQ, Zhang, Hou)

Motivation I   massless quark vs gluon

中国地质大学 CHINA UNIVERSITY OF GEOSCIENCES 武汉 · WUHAN

Medium induced gluon radiation: Higher Twist

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

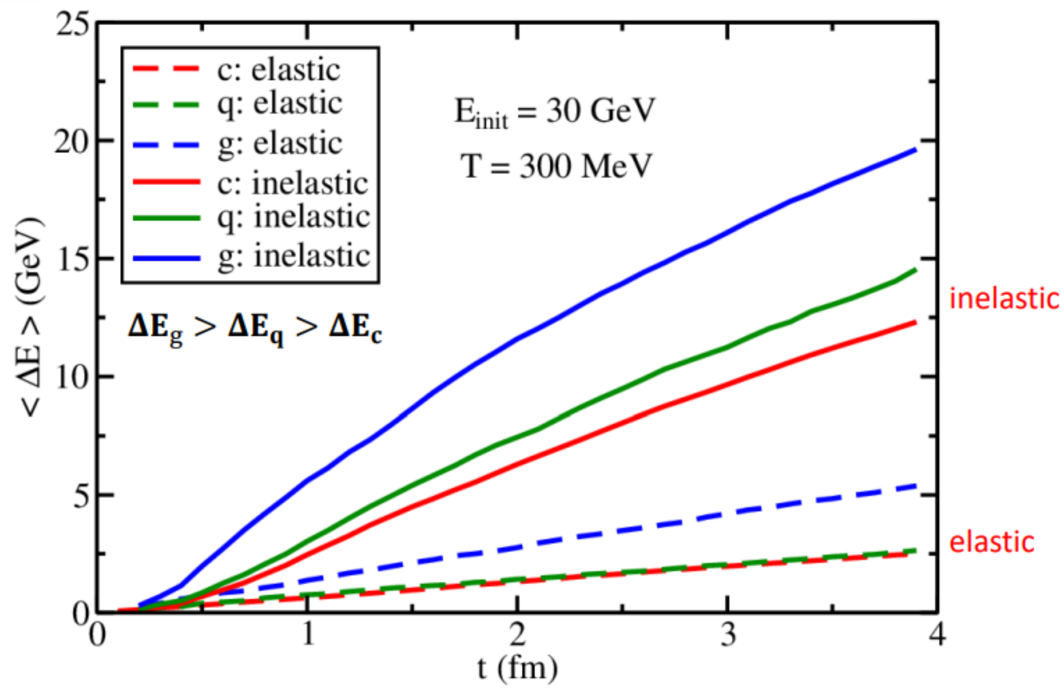
casmier factor : C_A *and* C_F

splitting function for quarks and gluons: *P(x)*

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

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

How to observe these differences?

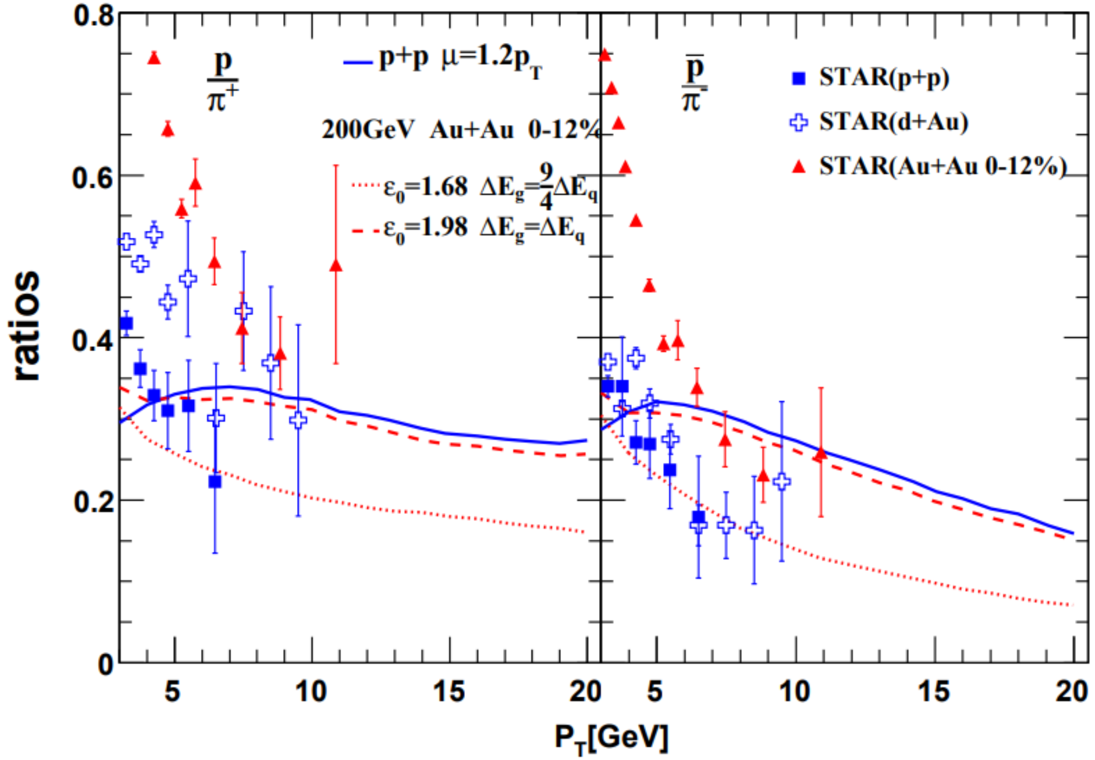


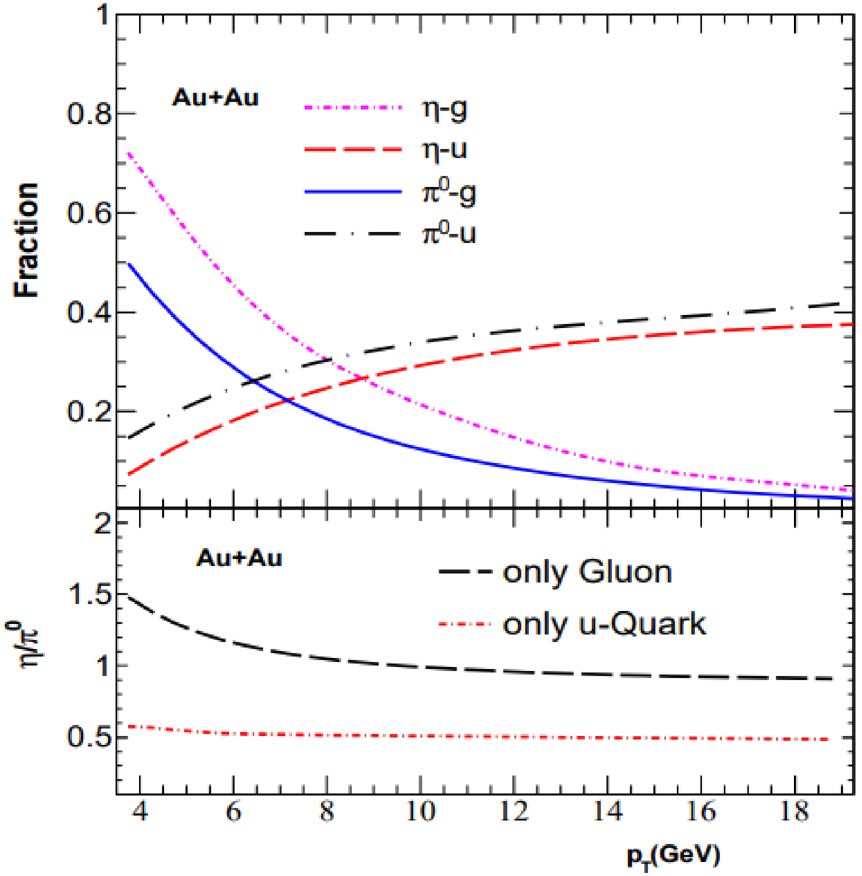
R_{AA} is not sufficient to expose the nature of parton-medium interaction

stopping

broadening

Motivation I　　Hadron chemistry （hadron）





gluon loses more energy than quark, therefore change the hardron chemistry in A+A

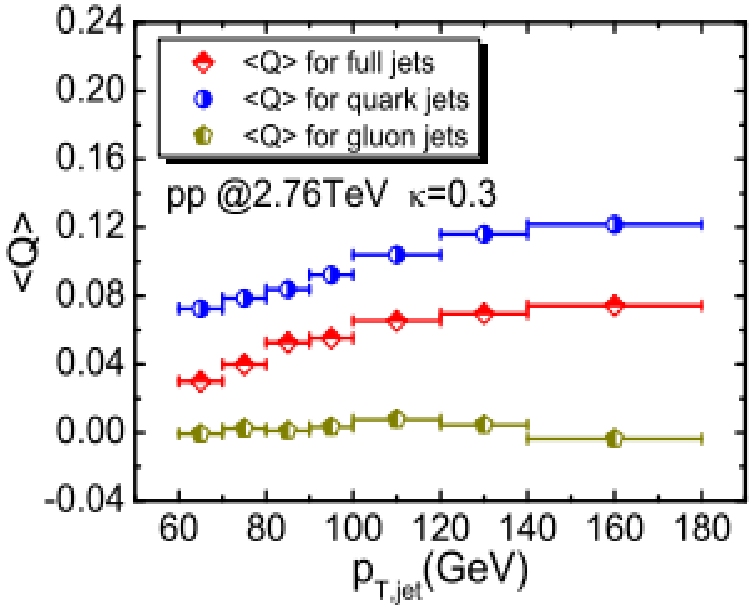
p、 η、 φ over π ratios are sensitive to $\Delta E_q/\Delta E_g$

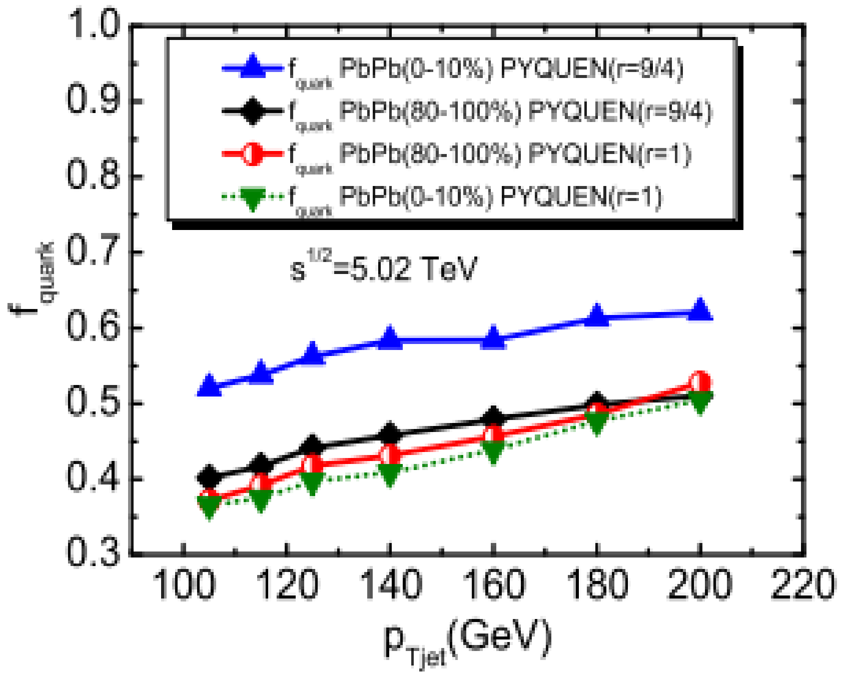
XF Chen, HZ Zhang, BW Zhang, EK Wang J.Phys.G37:015004,2010

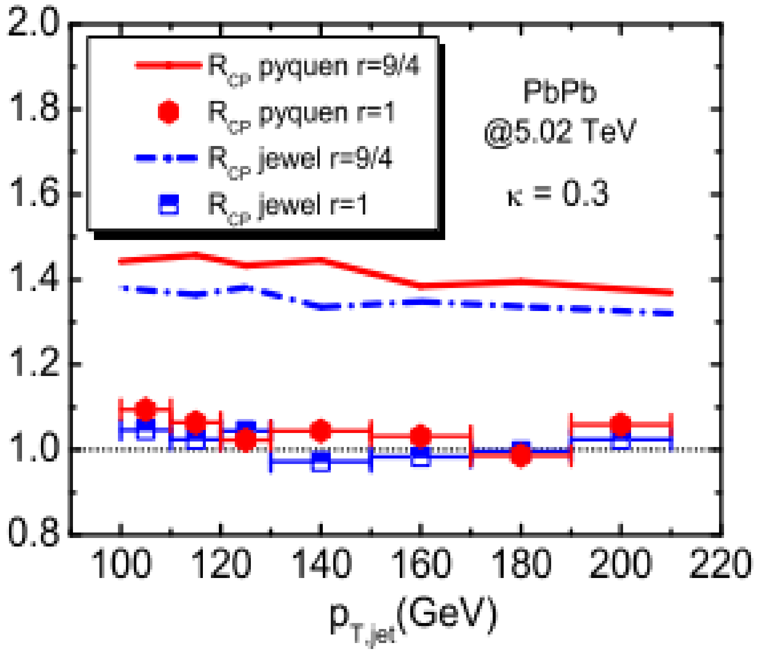
W Dai, XF Chen, BW Zhang, HZ Zhang, EK Wang, Phys.Lett. B750 (2015) 390-395

W Dai, XF Chen, BW Zhang, EK Wang, Eur.Phys.J.C 77 (2017) 8, 571

Motivation I   Jet charge (jet)







$$Q^{\kappa} = \sum_{i \in jet} z_h^{\kappa} Q_i$$

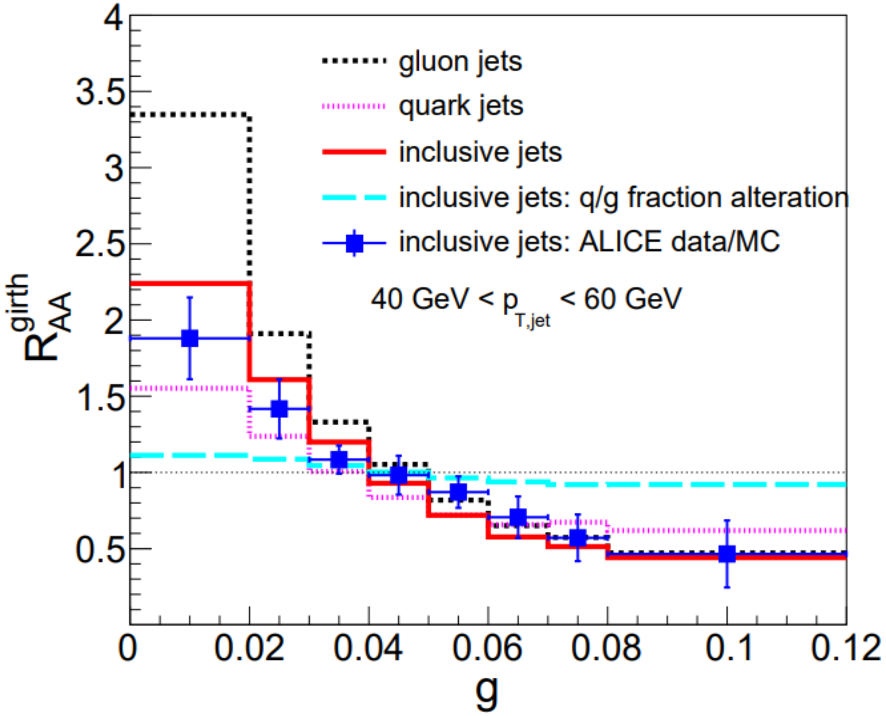
$$< Q_g > \approx 0$$
$$< Q_q > \neq 0$$

R_{cp} of averaged jet charge is sensitive to the changing portion of quarks and gluons

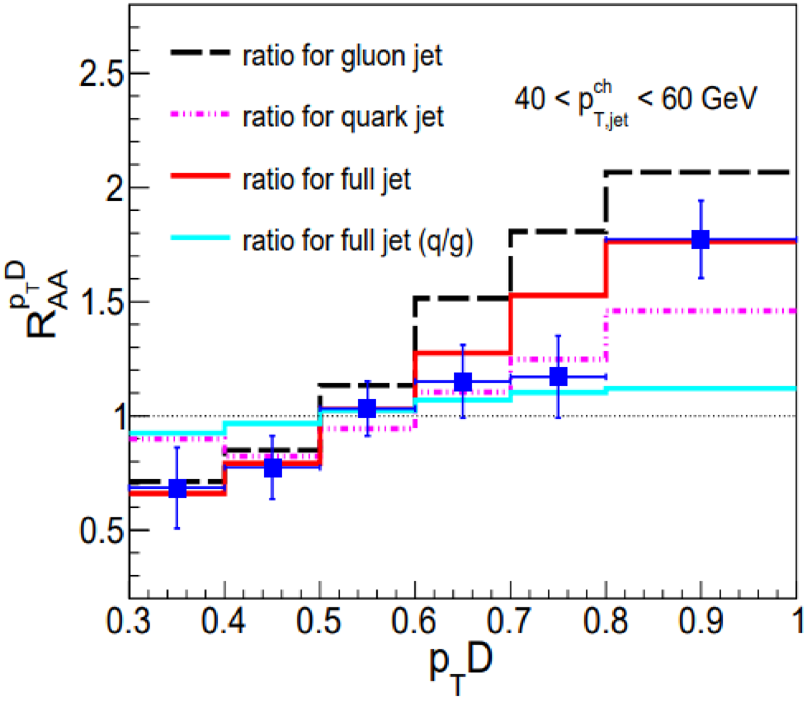
Shi-Yong Chen, Ben-Wei Zhang, En-Ke Wang
Chin.Phys.C 44 (2020) 2, 02410

Motivation I Jet substructure but one quantity one jet

jet girth: $g = \sum_i \frac{p_{T,i}}{p_{T,\text{jet}}} |\Delta R_{i,\text{jet}}|$



jet p_T dispersion: $p_T D = \frac{\sqrt{\sum_i p_{T,i}^2}}{p_{T,\text{jet}}}$



Jun Yan, Shi-Yong Chen, W Dai, BW Zhang, EK Wang Chin.Phys. C45 (2021) no.2, 024102

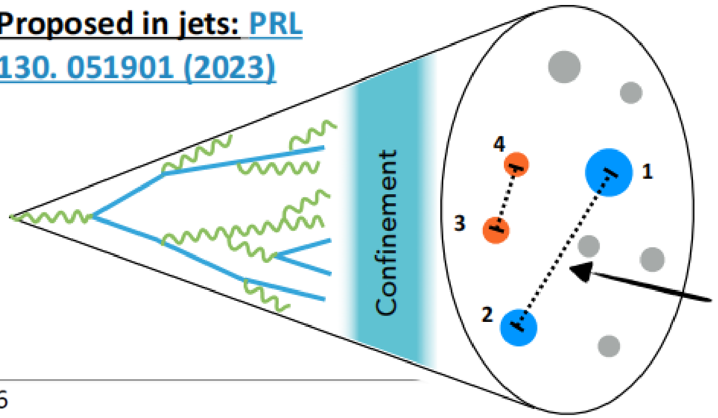
Shi-Yong Chen, Jun Yan, W Dai, BW Zhang, EK Wang Chin.Phys.C 46 (2022) 10, 104102

The nuclear modifications of girth/p_T dispersion distribution is much stronger for gluon jets than that for quark jets.

Relative change of the quark/gluon fractions.

Energy-Energy Correlator --- targeting splitting but w/o de-clustering process

Proposed in jets: PRL 130. 051901 (2023)

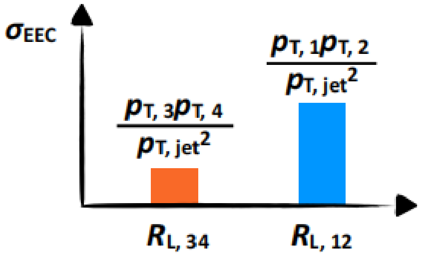


Count number of weighted pairs as function of R_L

$$R_L = \sqrt{\Delta\varphi_{ij}^2 + \Delta\eta_{ij}^2}$$

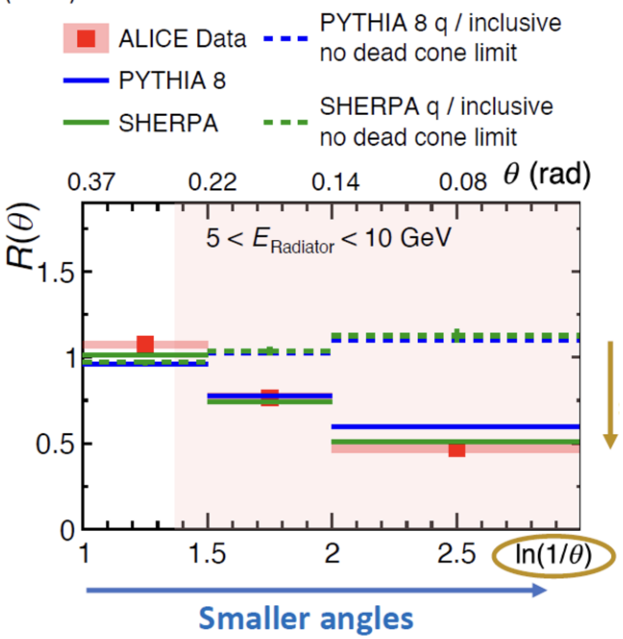
$$\frac{d\sigma_{EEC}}{dR_L} = \sum_{i,j} \int d\sigma(R'_L) \frac{p_{T,i}\, p_{T,j}}{p_{T,jet}^2} \delta(R'_L - R_{L,ij})$$

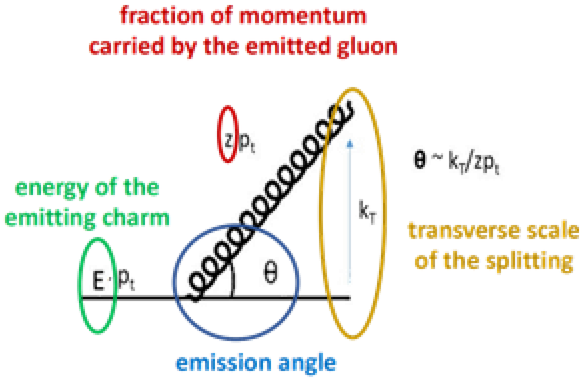
Energy weight

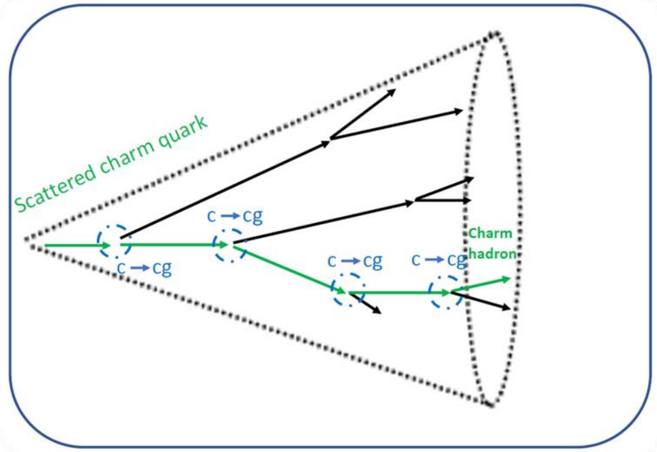


Splitting observable!

Nature 605 (2022) 440-446



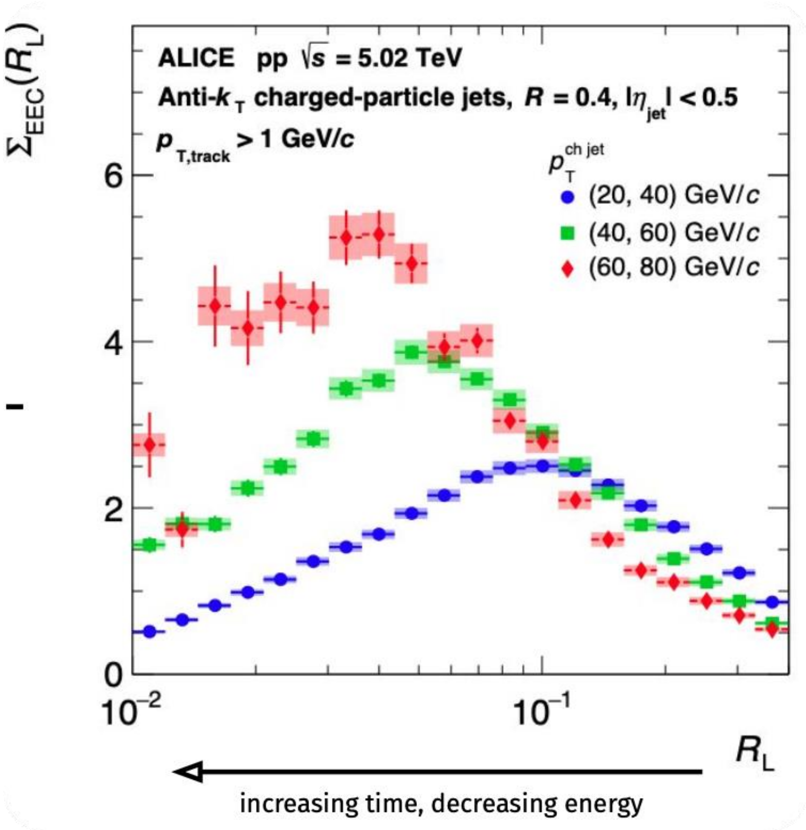




Motivation

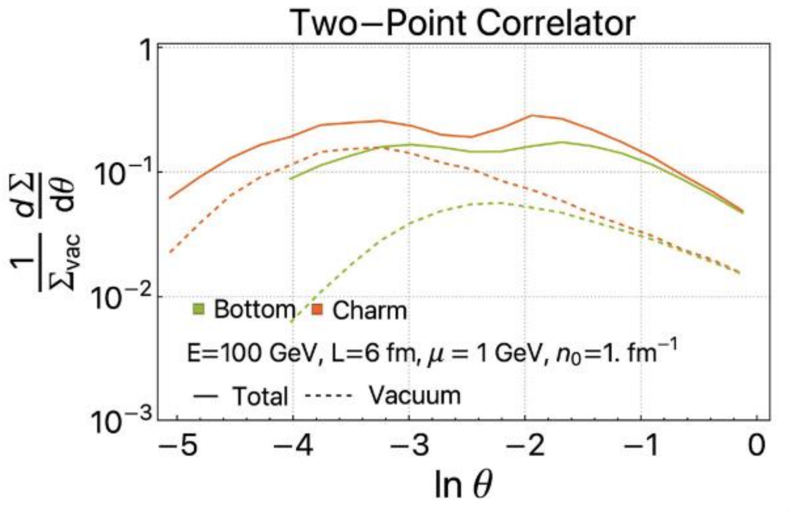
hard to compare in the splitting level.

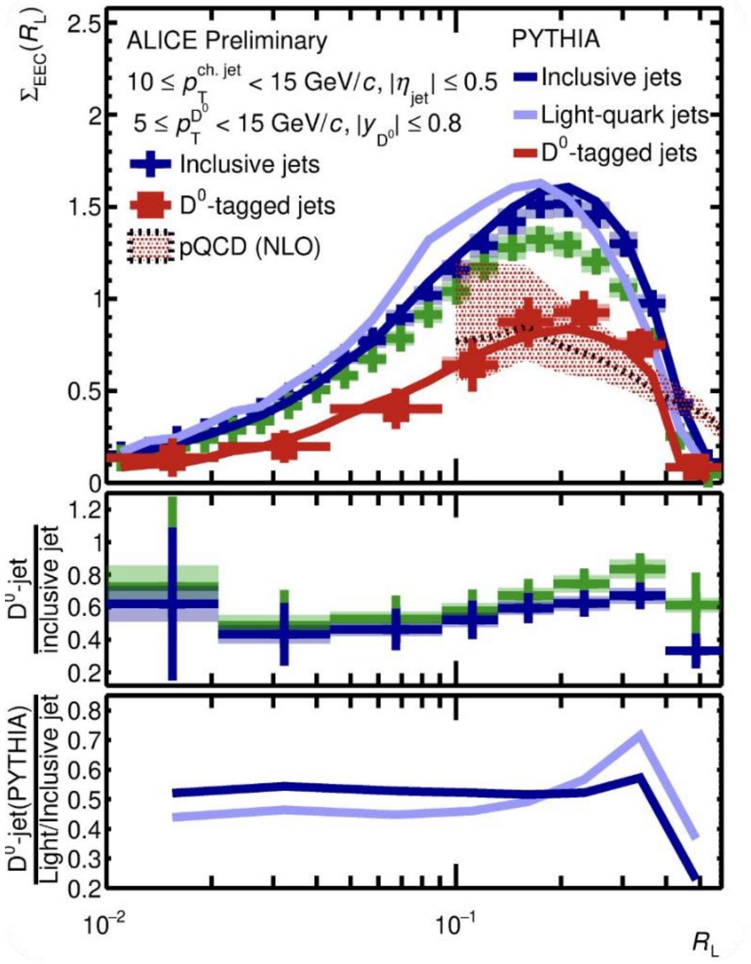
ALICE:arXiv:2409.12687 [hep-ex]



EEC peak and height are visibly dependent on jet p_T.

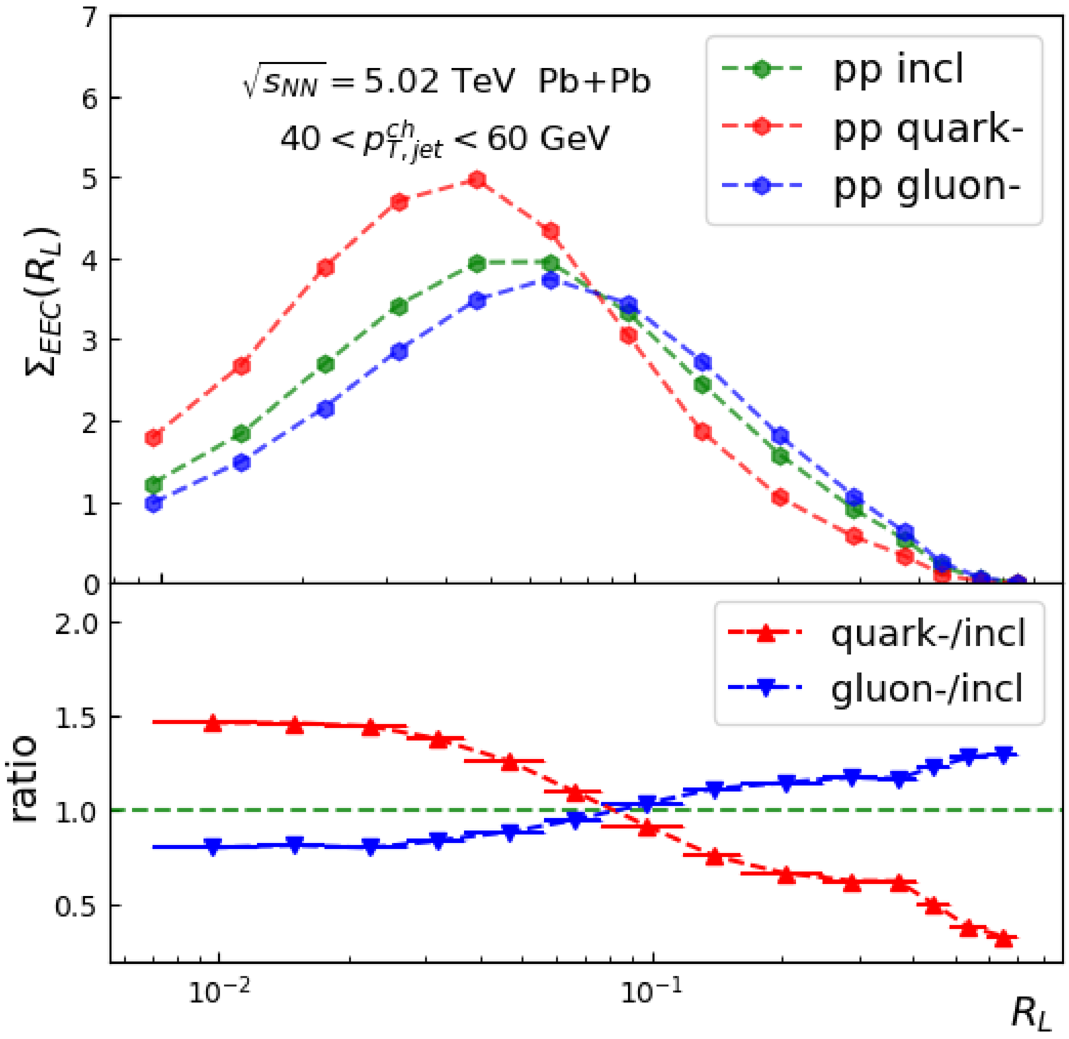
EEC height are visibly dependent on jet types.





C. Andres, F. Dominguez, J. Holguin, C. Marquet and I. Moult
Phys. Rev. D (2023)

EEC for pure quark, gluon, and inclusive charged jets



1. EEC for the quark-initiated jets distributed at smaller R_L compared to gluon-initiated ones.
2. EEC for the quark-initiated jet is distributed at a larger height than that for gluon-initiated ones.
3. Inclusive jets are dominated by gluon-initiated jets.
4. Investigate in such p_T window

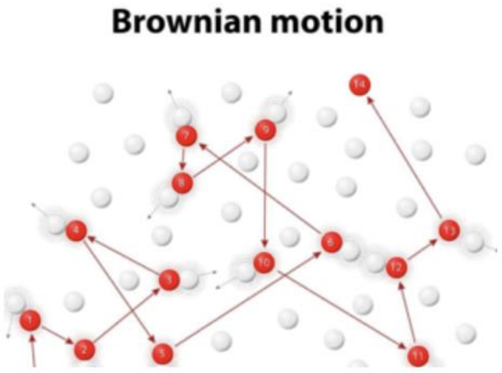
SHELL Model: Simulating Heavy quarks Energy Loss with Langevin equations

Simultaneously describe light and heavy quark transport in the medium

The motion of heavy quarks in hot dense medium can be regarded as Brownian motion and described by modified Langevin equations:

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

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



$\kappa = 2\eta_D ET = 2T^2/D_s$, $2\pi T D_s = 4.0$ is extracted by a χ^2 fitting to the D meson R_{AA} data measured by CMS and ALICE.

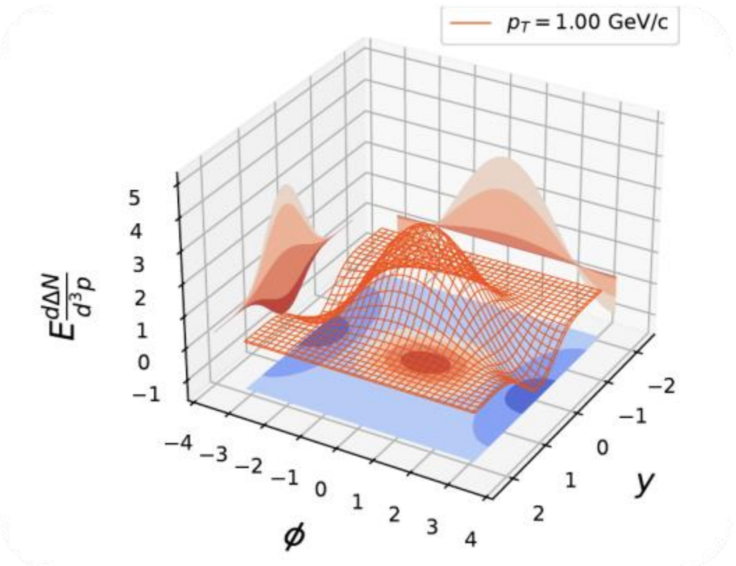
Hard Thermal Loop (HTL) approximation:

Light quark collisional :

$$\frac{\mathrm{d}E^{\mathrm{coll}}}{\mathrm{d}t} = \frac{\alpha_s C_s \mu_D^2}{2} \ln\frac{\sqrt{ET}}{\mu_D}$$

Radiative: higher twist approach

Hybrid treatment of medium response:



Hadronization: fragmentation + coalescence

Unveiling the EEC observable

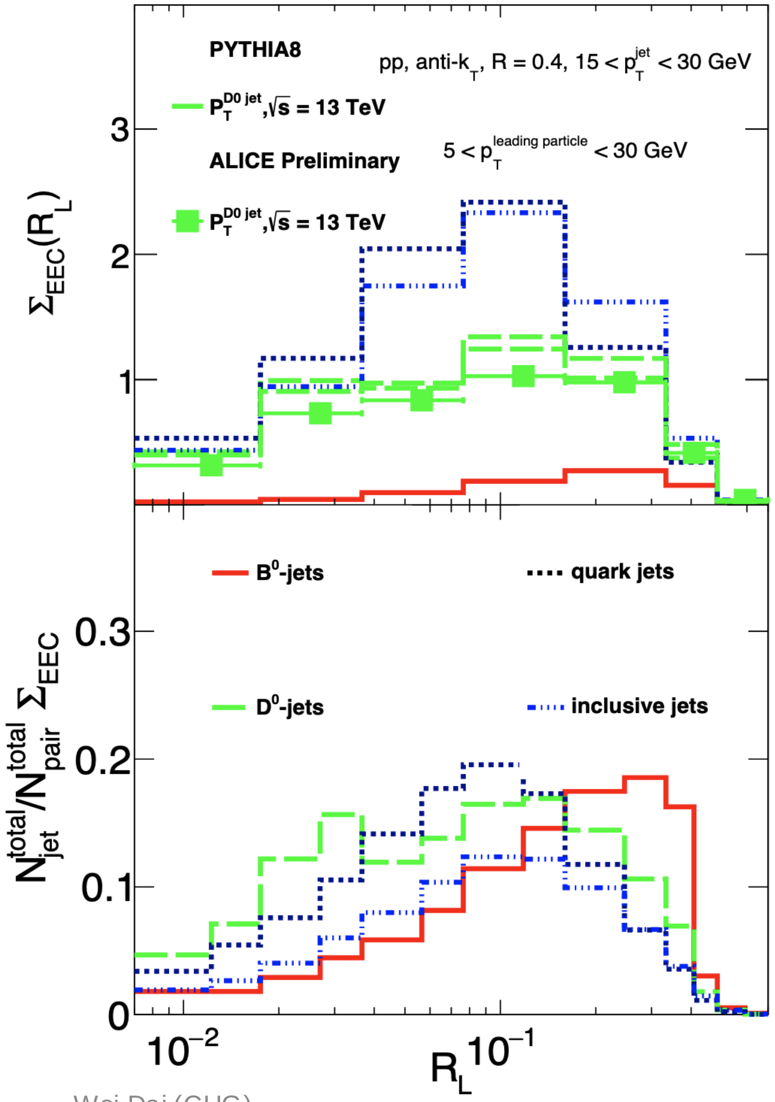
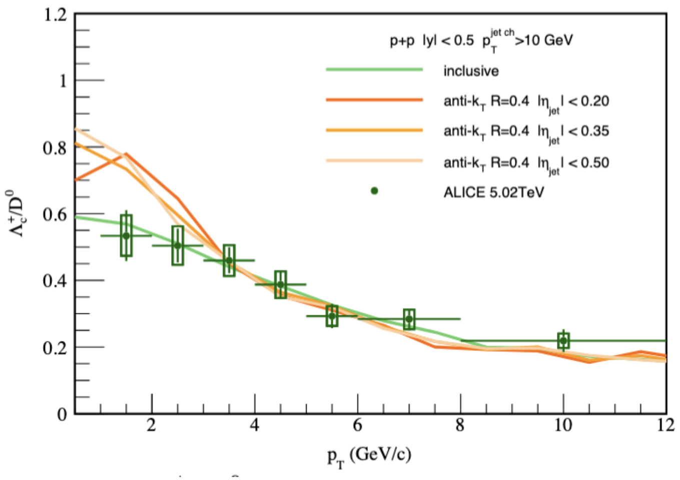


TABLE I: averaged number of particle pairs in jets: pp

jets type	B^0-	D^0-	light quark-	inclusive
$\langle N^{\rm jet}_{\rm pair}\rangle_{\rm pp}$	1.3751	7.4908	13.2147	19.2787

$N^{\rm total}_{\rm pair}/N^{\rm total}_{\rm jet}$ subtracted:

Peak: clear separation for quark jets
B^0- > D^0- > light quark



Height: $N^{\rm total}_{\rm pair}/N^{\rm total}_{\rm jet}$ has a serious impact on the magnitude of EEC

Still:
a magnitude difference ---> energy weight

$$\Sigma_{\rm EEC}(R_{\rm L}) = \frac{N^{\rm total}_{\rm pair}}{N^{\rm total}_{\rm jet}} \cdot \frac{\Delta N_{\rm pair}}{N^{\rm total}_{\rm pair}\Delta R}(R_{\rm L}) \cdot \langle {\rm weight}\rangle({\rm R_L})$$

Unveiling the EEC observable

Observable is different for collaboration:

Sum over pairs and jets

defined by ALICE, can not normalized to unity

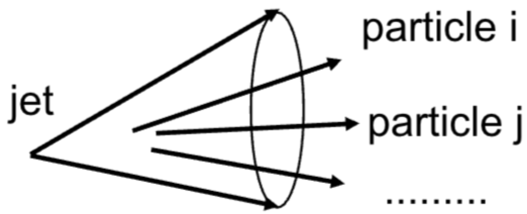
$$\Sigma_{\mathrm{EEC}}(R_{\mathrm{L}}) = \frac{1}{N_{\mathrm{jet}} \cdot \Delta R} \int_{R_{\mathrm{L}}-\frac{1}{2}\Delta R}^{R_{\mathrm{L}}+\frac{1}{2}\Delta R} \sum_{\mathrm{jets}} \sum_{i,j} \frac{p_{\mathrm{T},i}\, p_{\mathrm{T},j}}{p_{\mathrm{T,jet}}^{2}} \delta(R'_{\mathrm{L}} - R_{\mathrm{L},ij})\, \mathrm{d}R'_{\mathrm{L}}$$

Normalized to jets

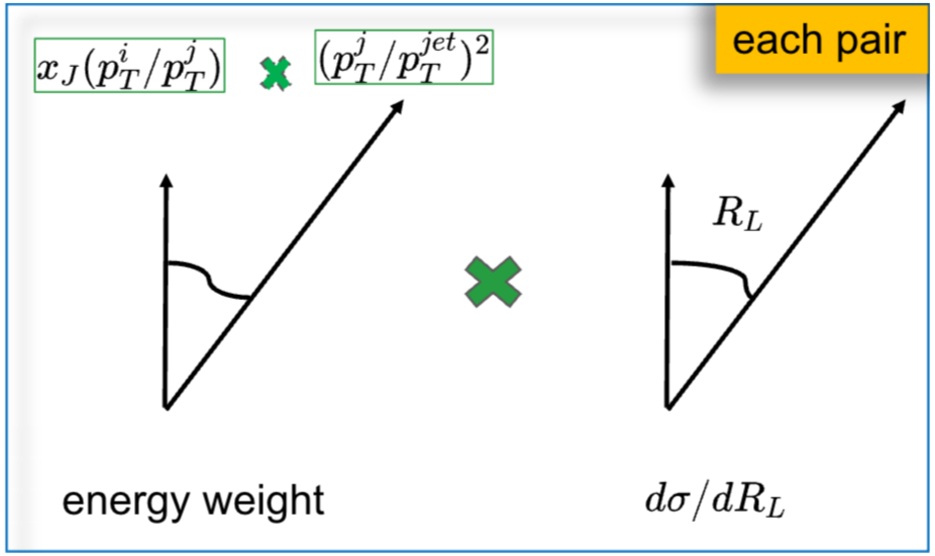
Energy weight

phenomenology understanding is needed!

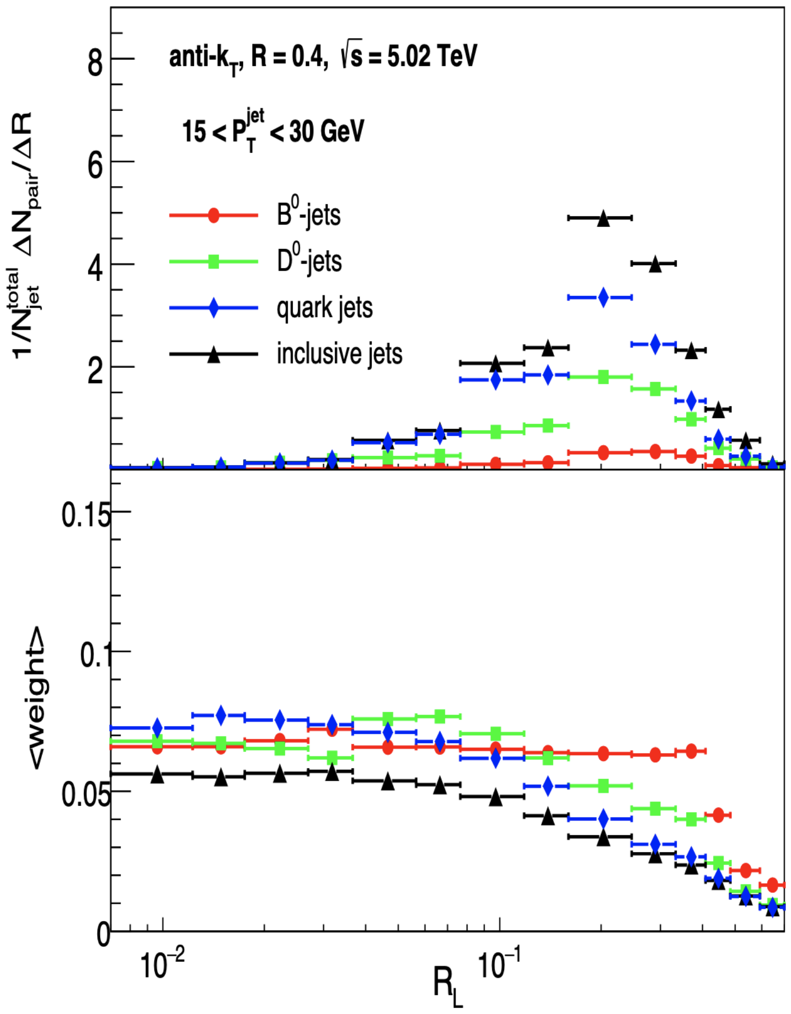
pairs in jet



number of particle pairs



Unveiling the EEC observable



Energy weight subtracted:

Peak: pair-angle distributions are similar.

lighter tagging quark mass, the smaller angular peak be pushed

energy weight determines the EEC peak position.

Height: $N_{\rm pair}^{\rm total}/N_{\rm jet}^{\rm total}$ determines the magnitude of EEC

therefore:

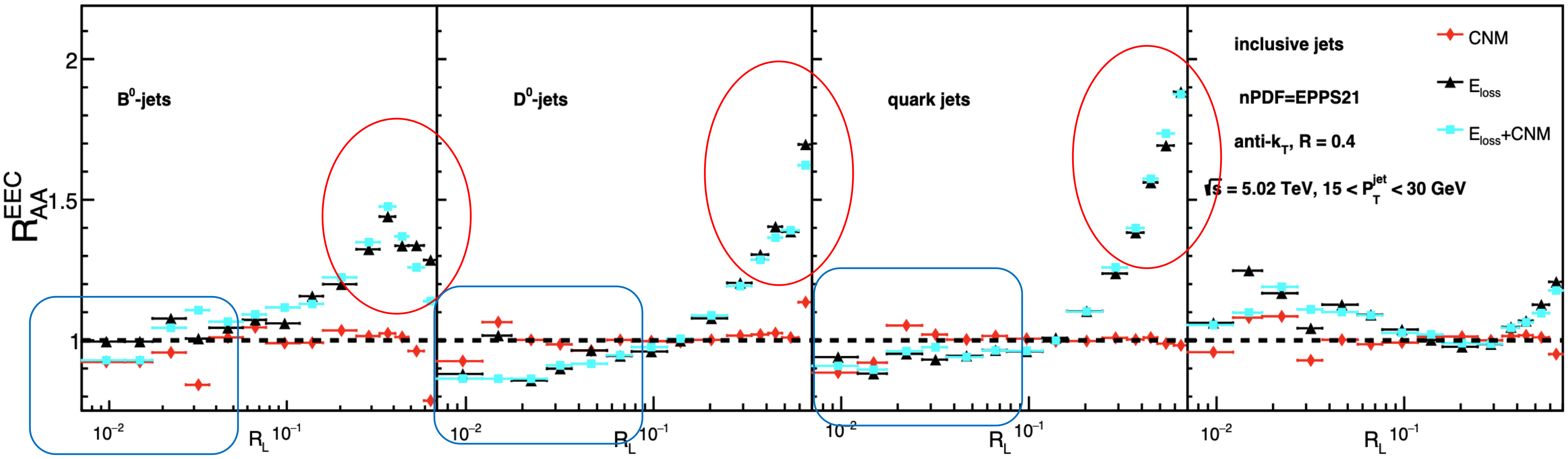
particle numbers in jets ↑ ---> pair-angular distribution height ↑

---> energy weight ↓

EEC observables for jet quenching

Pythia + SHELL

isolation study, weak is not considered

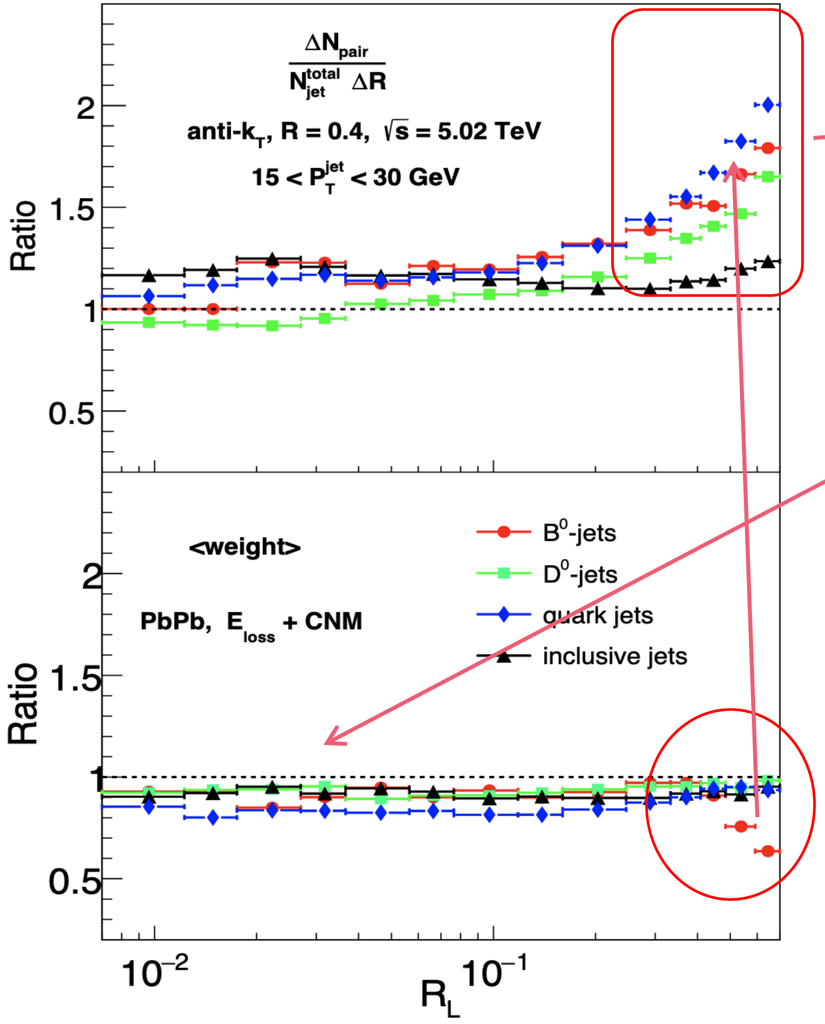


enhancement：light- > D^0- >B^0- jets

suppression： absence of a mass-hierarchical pattern

the enhanced distribution at larger angles is not fully restored at smaller angles to suppression.

EEC observables for jet quenching



jet type	B^0-	D^0-	light quark-	inclusive
$\langle N_{pair}^{jet} \rangle_{PbPb}$	1.8902	8.9286	17.6994	21.7357
AA/pp	1.3746	1.1919	1.3393	1.1274

1. the pair angular distribution,
2. the average number of pairs per jet,
3. the average energy weight

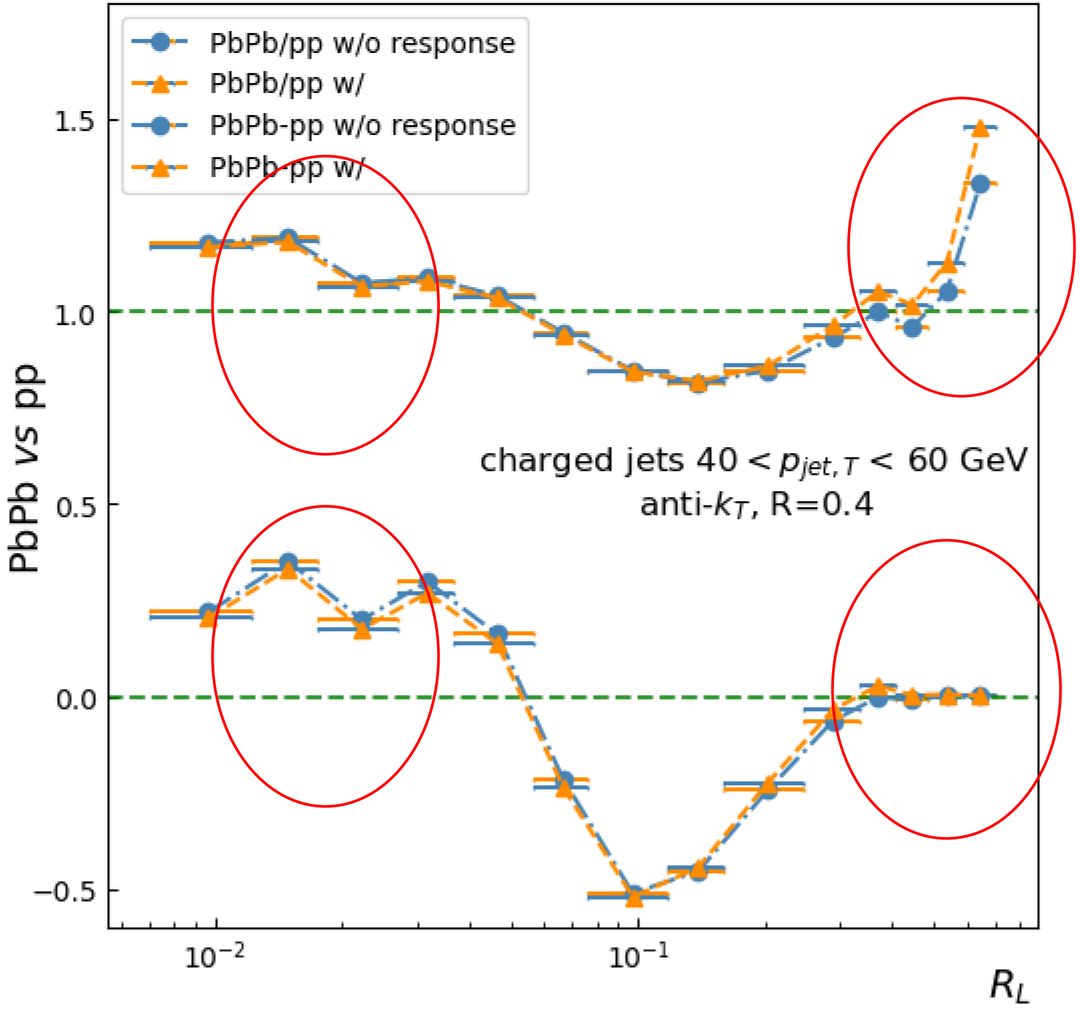
all impact the jet quenching of EECs.

A clear and unified broad shift of the pair-angular distributions towards larger RL.

flat distribution of the weight modification, and under unity:

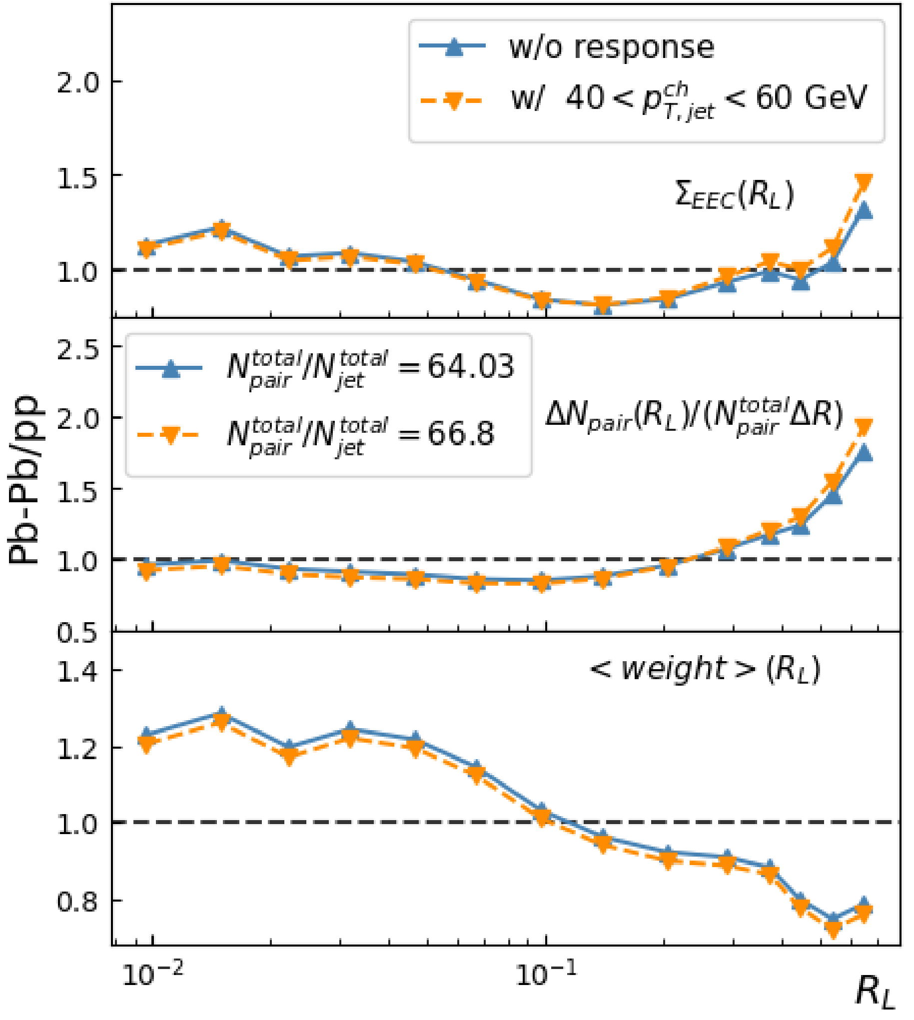
not only the loss of the total energy of the jet but also the increasing number of particles in the jet

AA/pp ratio of EEC for inclusive charged jets



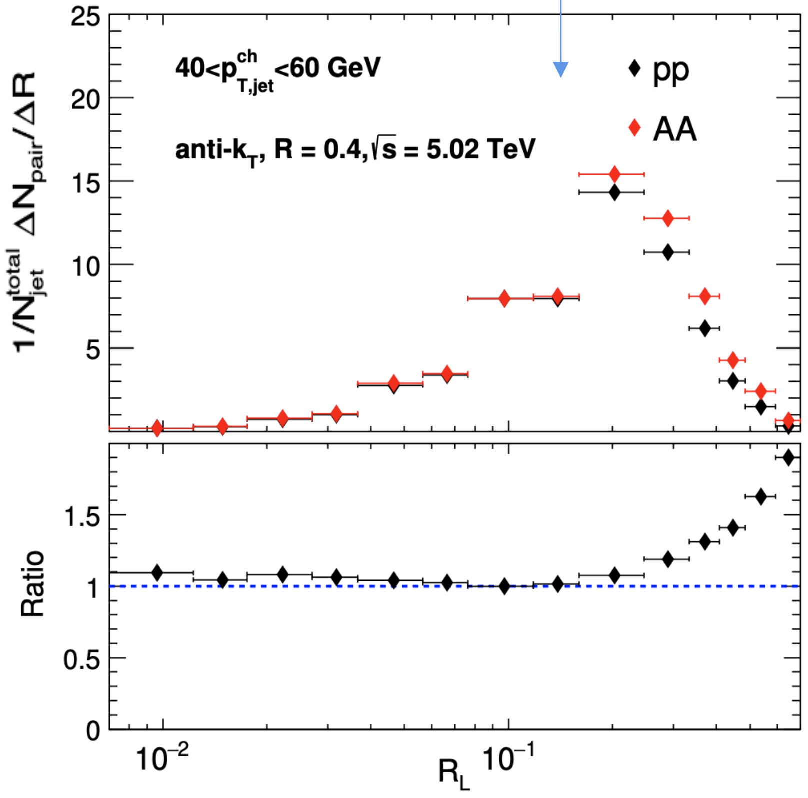
1. shifts toward larger RL and smaller RL at the same time.

2. It has to be two effects competing with each other.



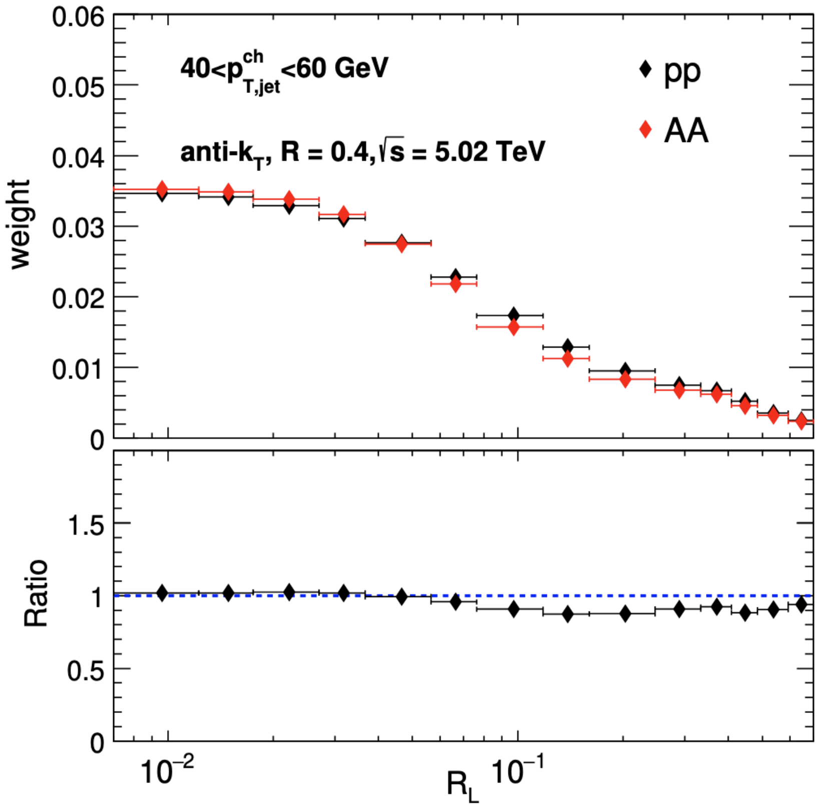
AA/pp ratio of the factors in EEC

$$\Sigma_{\mathrm{EEC}}(R_L) = \frac{N^{\mathrm{total}}_{\mathrm{pair}}}{N^{\mathrm{total}}_{\mathrm{jet}}} \cdot \frac{\Delta N_{\mathrm{pair}}}{N^{\mathrm{total}}_{\mathrm{pair}} \Delta R}(R_L) \cdot \langle \mathrm{weight} \rangle (R_L)$$



most of the particle pairs are distributed at RL =0.2

The A+A/pp ratio of angular explains the EEC ratio, with slight overall enhancement due to the pair number increasing

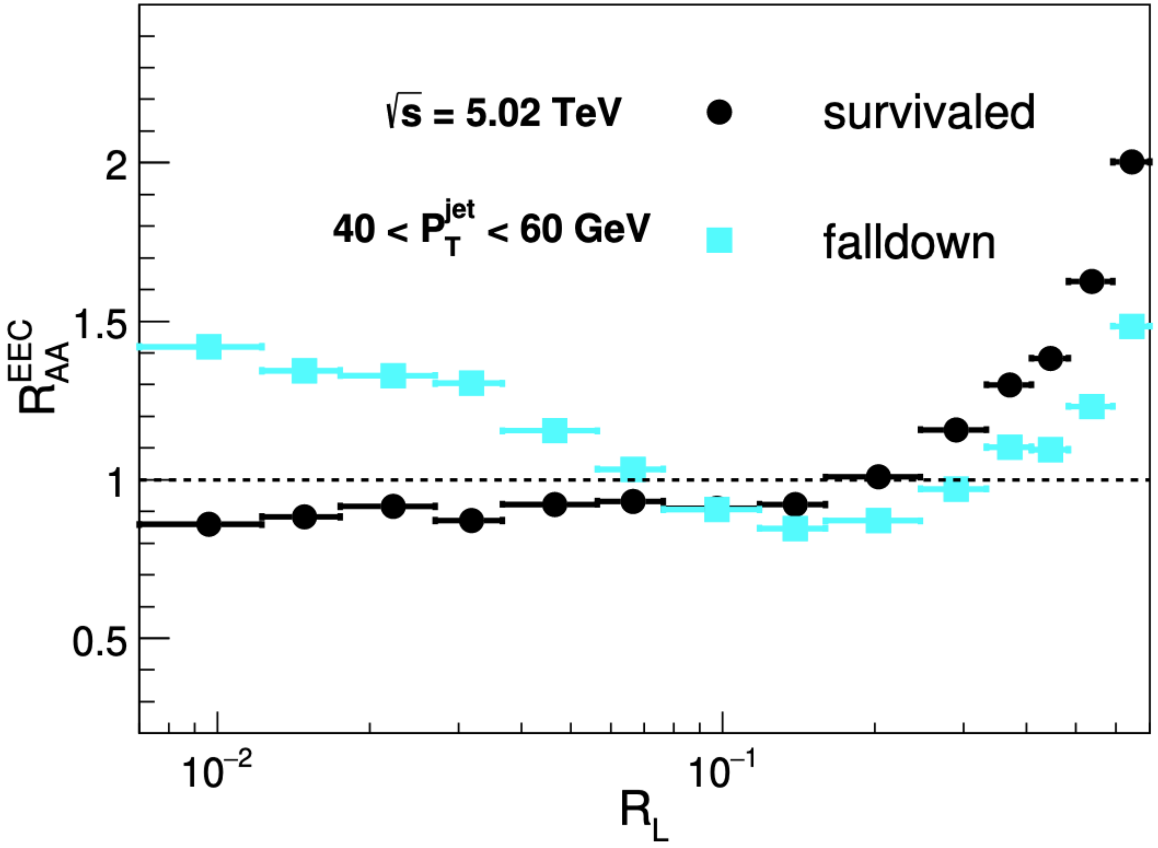


minor modification for energy weight.

Selection bias effect

[The global geometrical property of jet events in high-energy nuclear collisions]() S. Y. Chen, WD, S. L. Zhang, Q. Zhang and B. W. Zhang

Eur.Phys.J.C 80 (2020) 9, 865



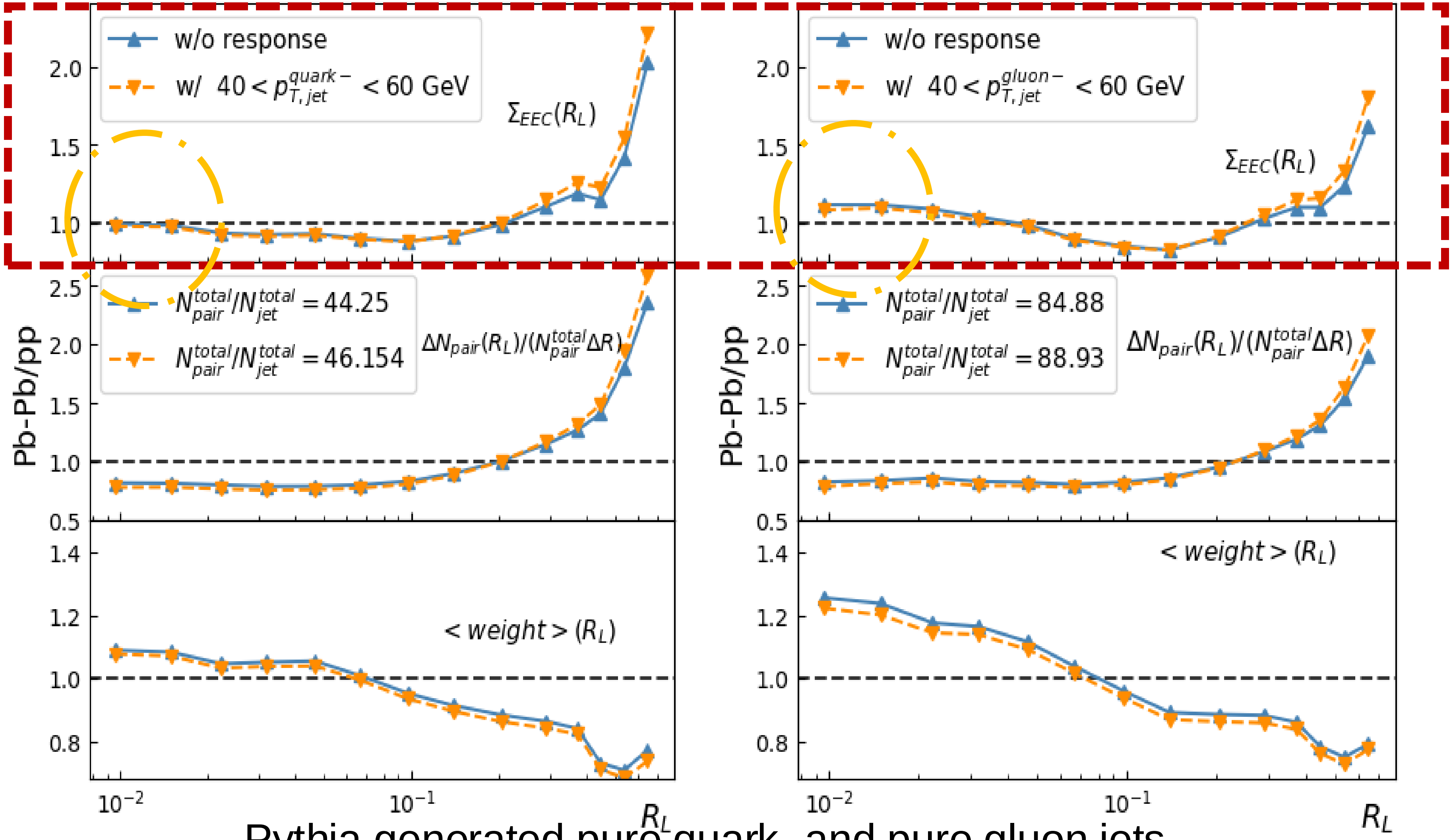
survived: $40 < p_{T,jet} < 60$ GeV in pp, remain in A+A

fall-down: $p_{T,jet} > 60$ GeV in pp, fall into A+A

Something we don't want, but influenced by jet quenching

Energy loss → particle pair angular wider → EEC shifting toward larger R_L
selection bias effects → → EEC shifting toward smaller R_L

Quark vs gluon



Pythia generated pure quark- and pure gluon jets

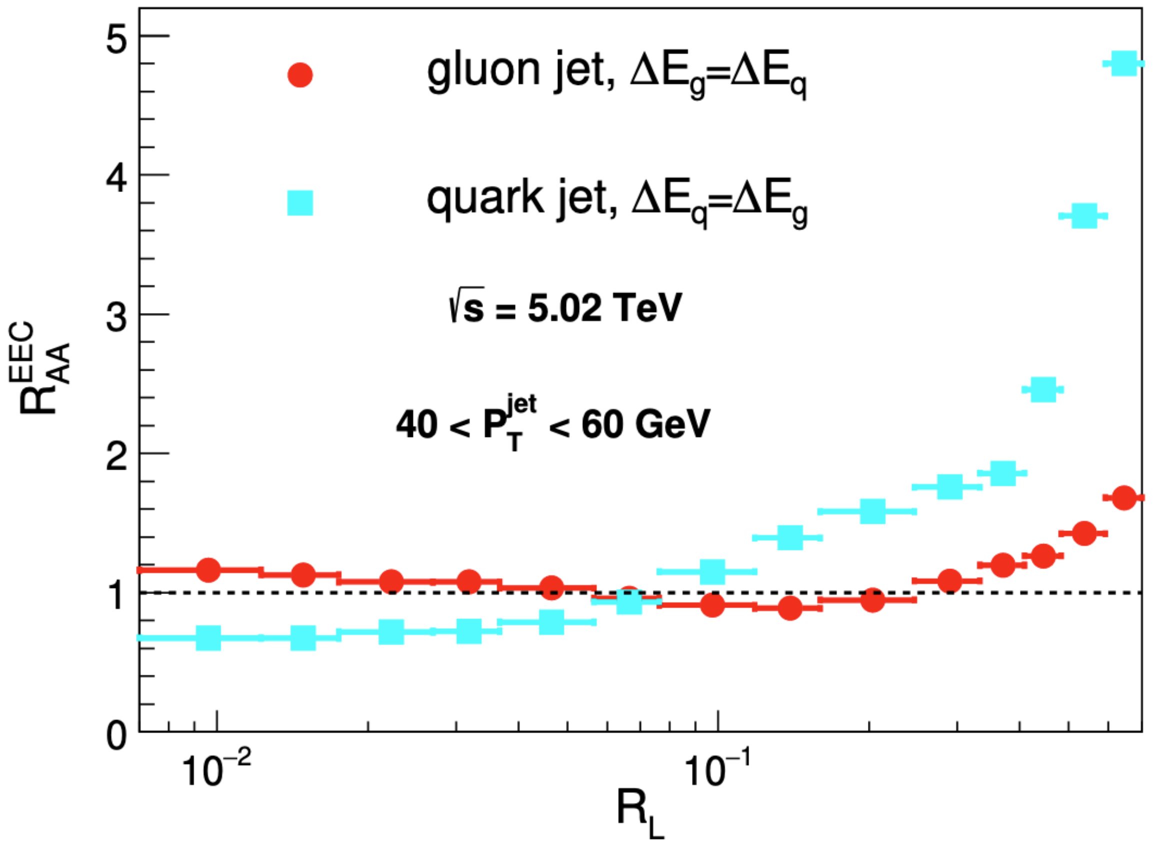
gluon jets:

shift toward two opposite directions in the AA/pp ratio

quark jets:

less selection bias

Quark vs gluon

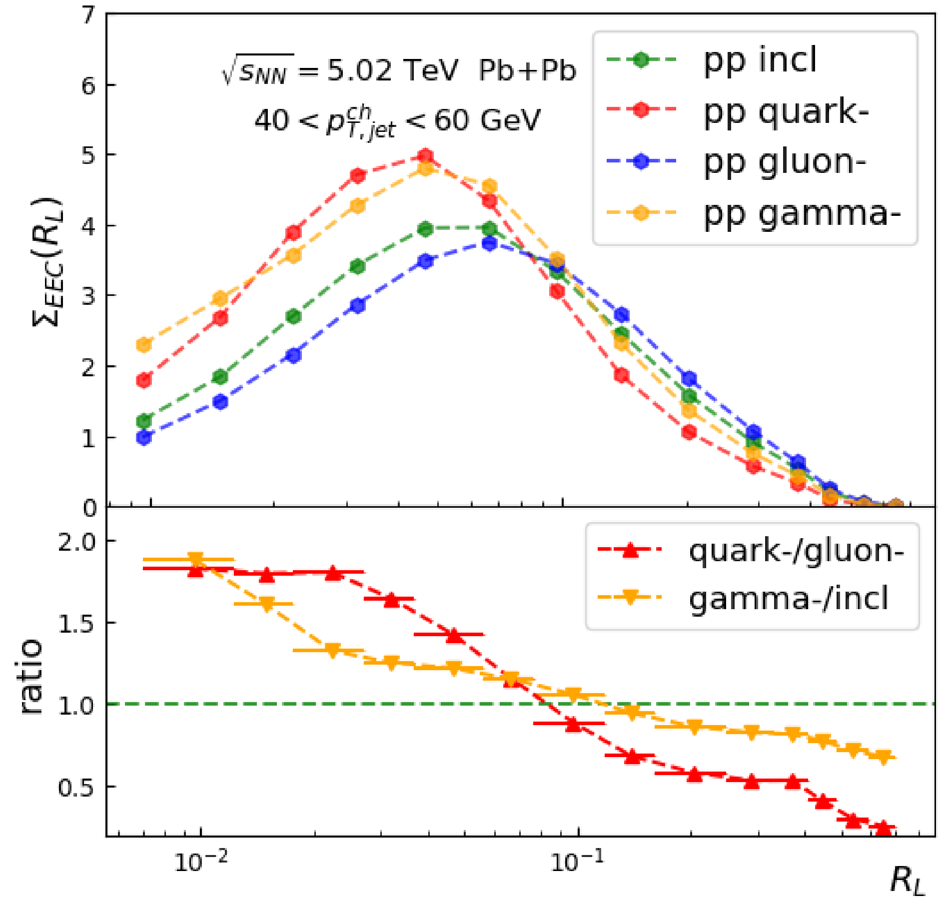


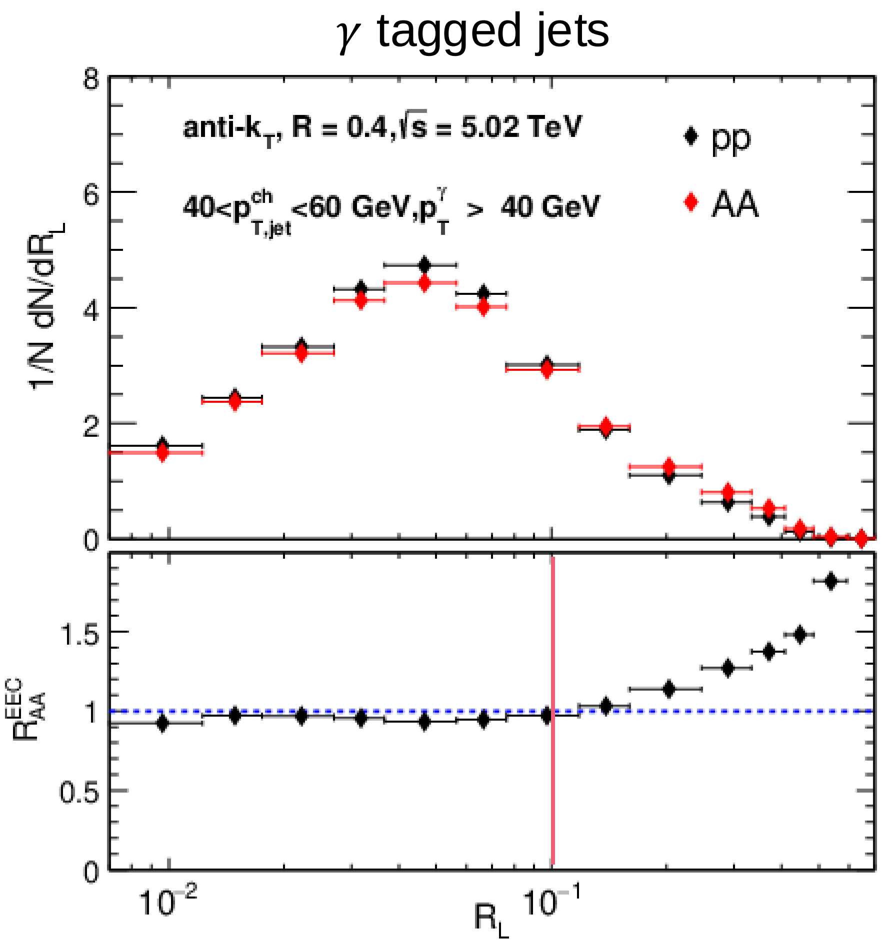
decrease gluon energy loss: two shifts both reduced but not vanish

Increase quark energy loss: shift toward larger R_L enhanced and keep the suppression at smaller R_L unchanged

mainly determined by the initial EEC distribution in p+p

AA/pp ratio of EEC for gamma jet

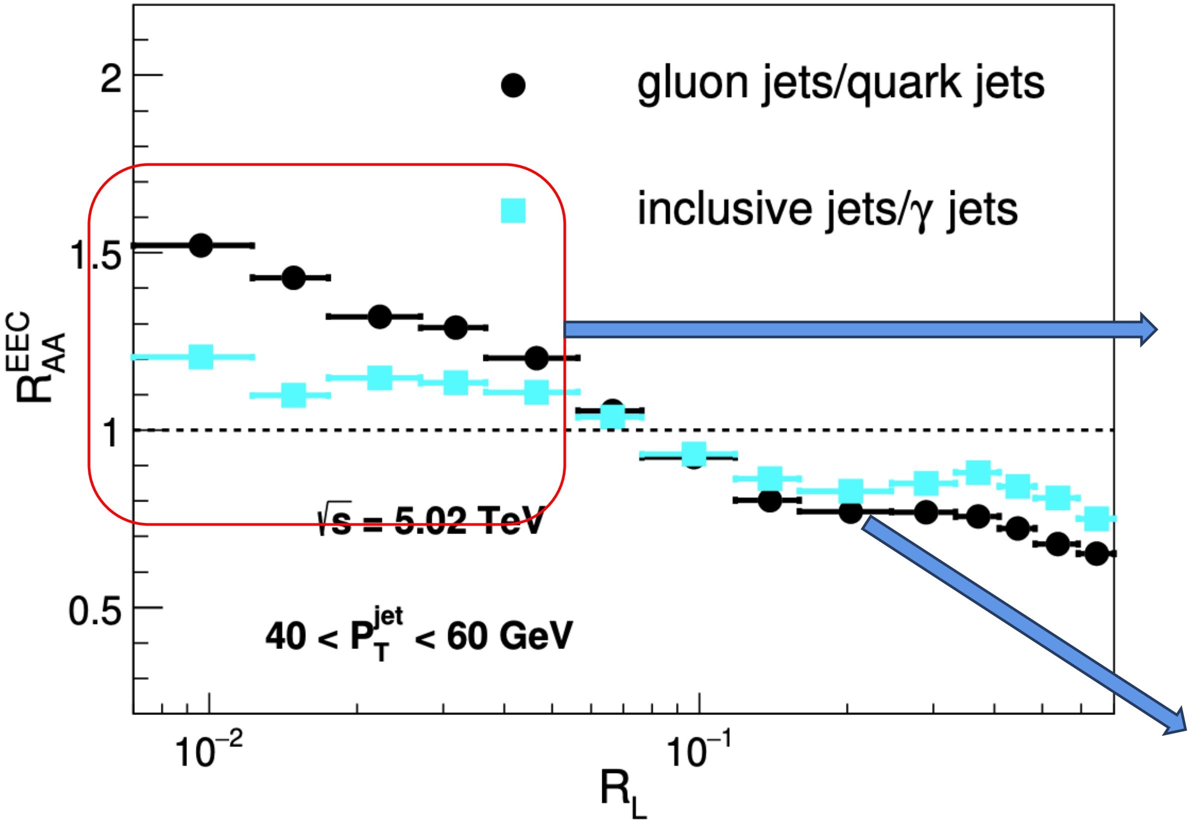




γ-tagged jets → quark jets

inclusive charged jets → gluon jets

double ratio of EEC



a clear enhancement with the decrease of R_L which show the enhancement of gluon EEC at smaller R_L corresponding to the stronger selection bias effect for gluon jets.

a suppression with the increase of R_L which shows a stronger broadening effect brought by the energy loss effect for quark jets.

conclusion

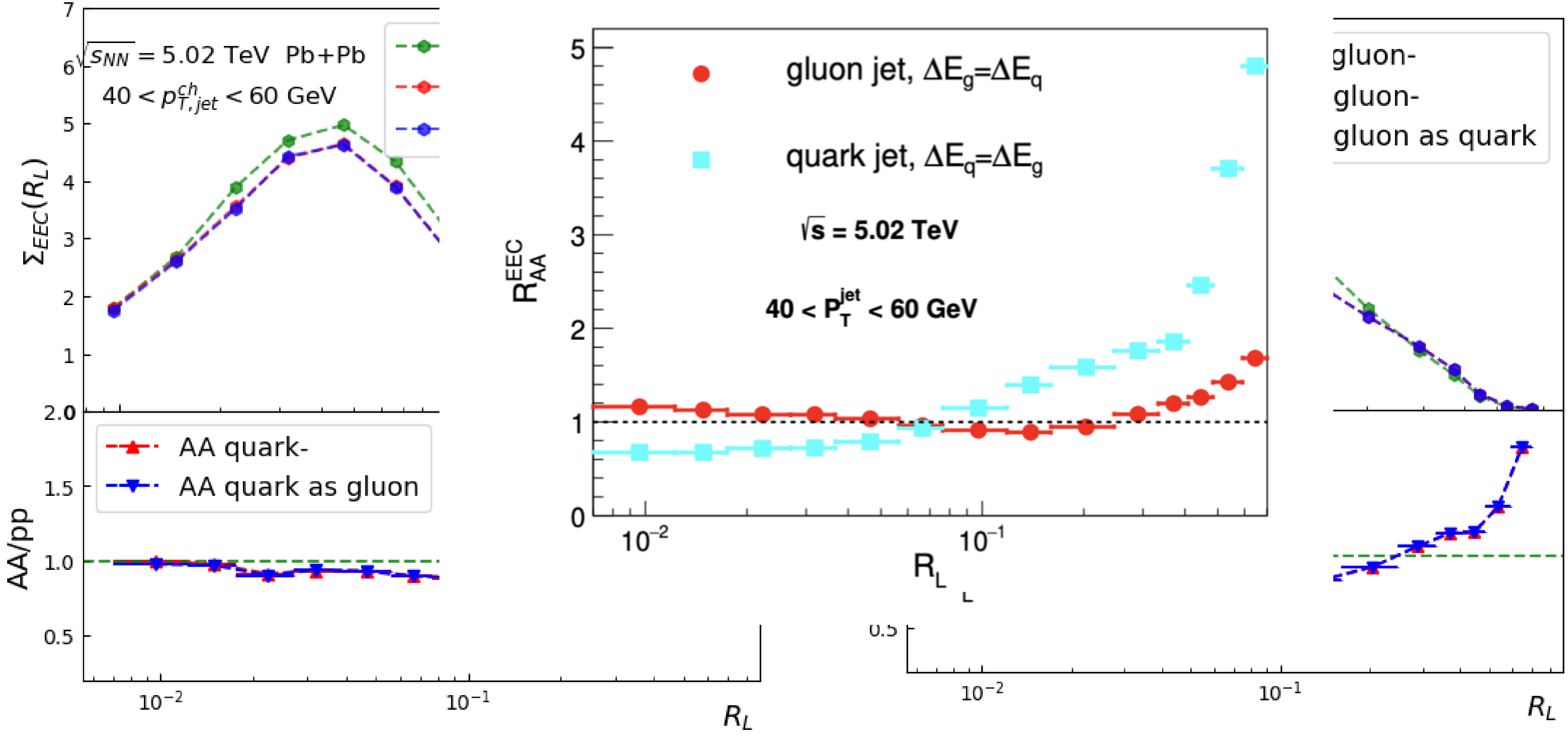
1. The jet quenching patterns (A+A/p+p) of the quark jets and the gluon jets can then be separated in the investigated region.

2. The differences are mainly determined by the initial EEC distribution in p+p and are not much affected by the energy loss differences between quark and gluon.

3. Propose the double-ratio of the A+A/p+p ratio of EEC for inclusive charged jets and the γ tagged jets to demonstrate the quark vs gluon discrimination in jet quenching.

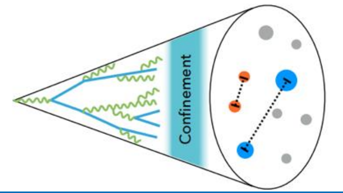
4. The jet quenching effect on the EEC observable was analyzed based on three unraveled factors.

5. The jet quenching effect will cause the pair angular distribution to shift towards larger values and increase the number of particles per jet. This redistribution of energy within the jets suggests that the already reduced jet energy is redistributed among a larger number of particles, leading to a reduced energy weight per pair. ----- an interplay

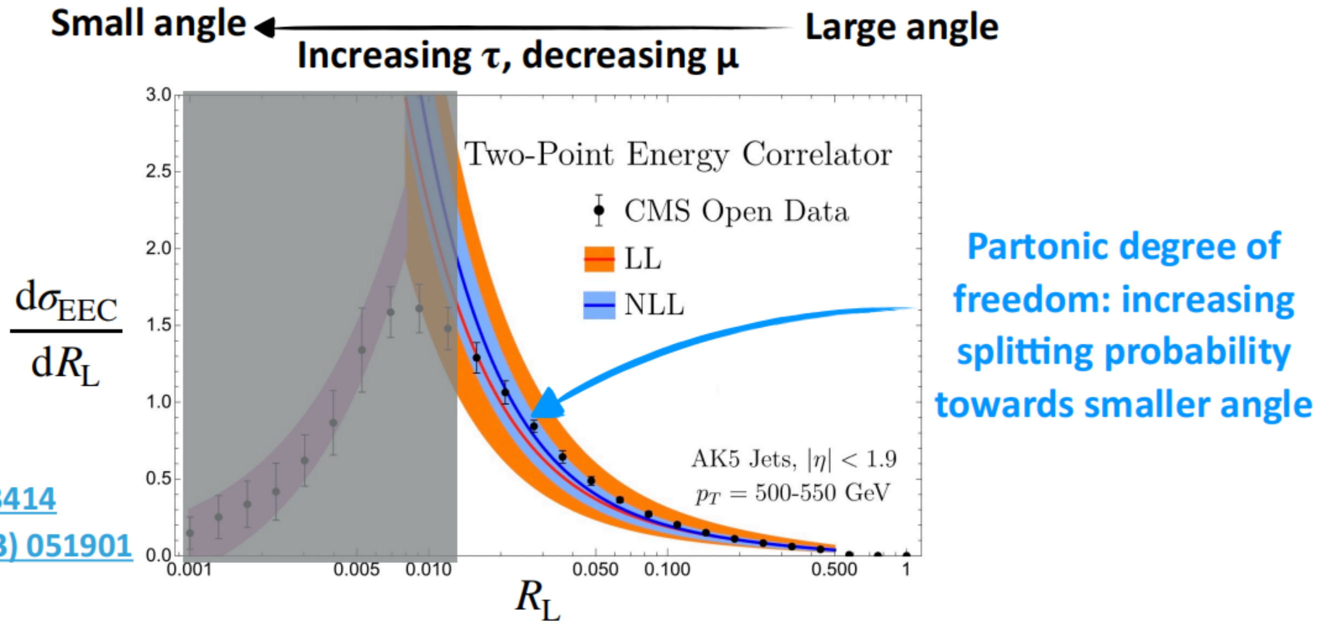

$\sqrt{s_{NN}}$ = 5.02 TeV Pb+Pb
$40 < p_{T,jet}^{ch} < 60$ GeV
$\Sigma_{EEC}(R_L)$
AA/pp
AA quark-
AA quark as gluon
R_L
gluon-
gluon-
gluon as quark
gluon jet, $\Delta E_g = \Delta E_q$
quark jet, $\Delta E_q = \Delta E_g$
$\sqrt{s}$ = 5.02 TeV
$40 < P_T^{jet} < 60$ GeV
R_{AA}^{EEC}

Motivation

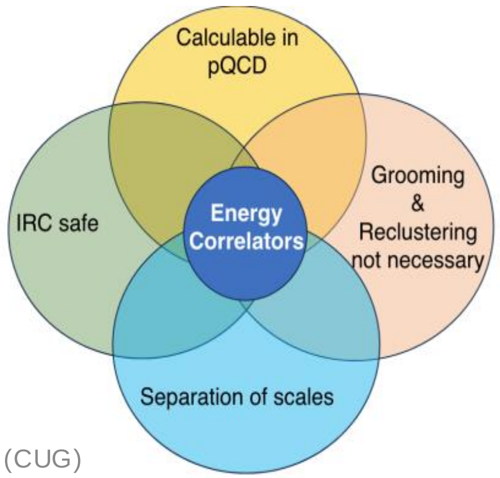
EEC state of art



Jet substructure ? Energy-Energy Correlator



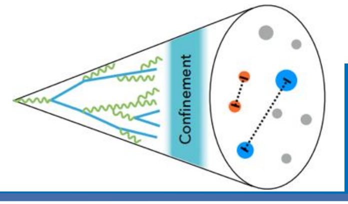
arXiv:2205.03414
PRL 130 (2023) 051901



Scaling: Different time scales of jet evolution imprinted in different angular scales

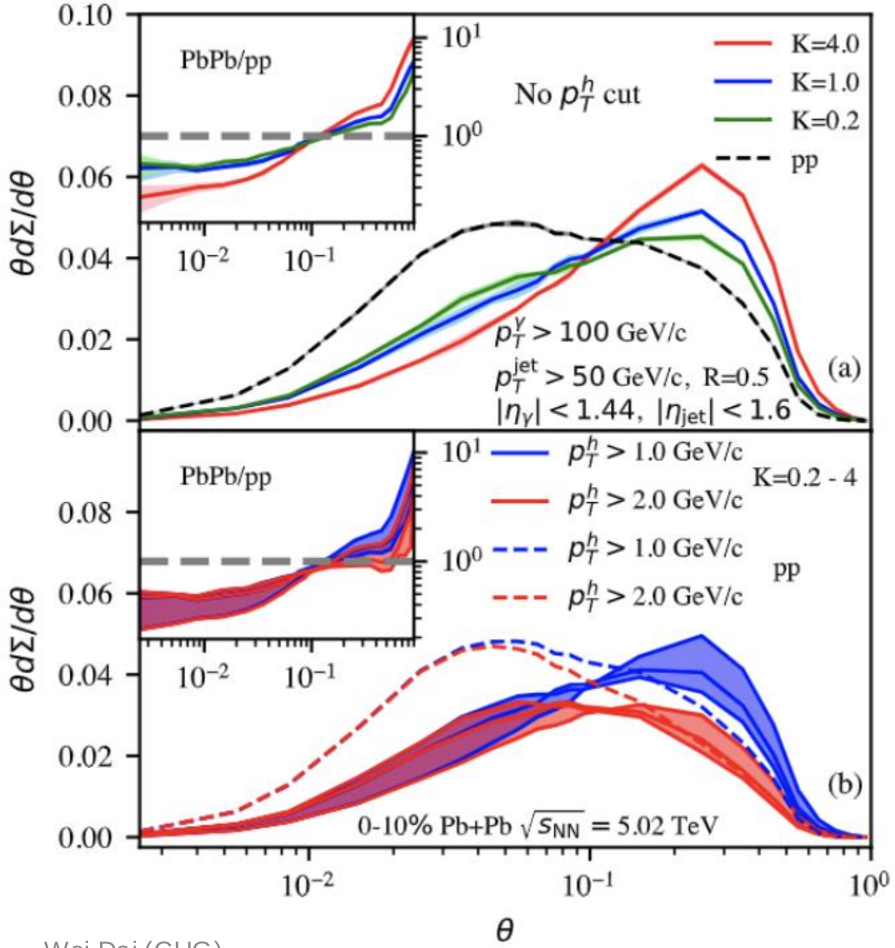
Simplicity: Soft contribution power suppressed by energy weight: no need for groomings

Control: Well understood pp baseline, medium modifications perturbatively calculable



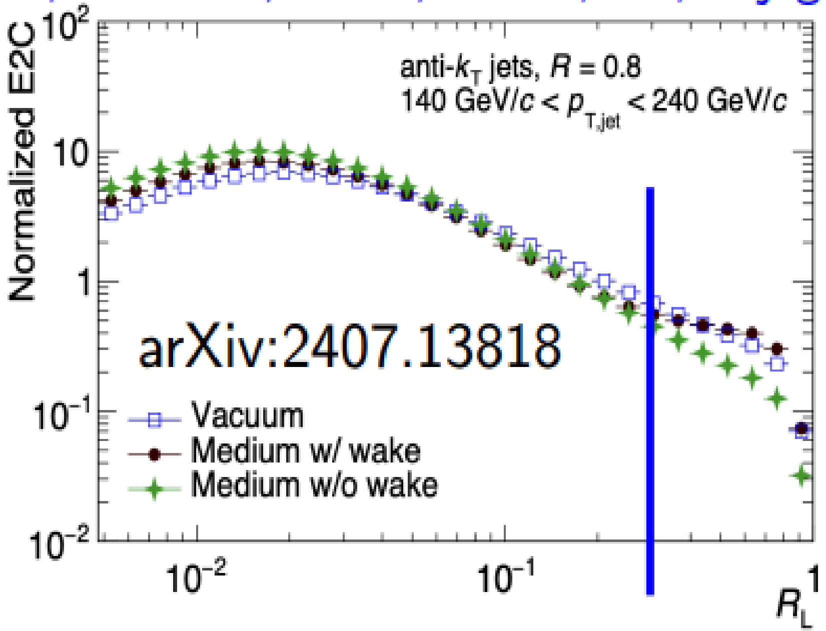
Jet substructure ? Energy-Energy Correlator in heavy-ion collisions

gamma-jets

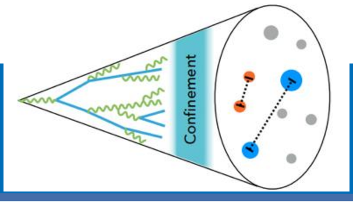


Yang, He, Moult & Wang, PRL 132, 011901 (2024)

Bossi, Kudinoor, Moult, Pablos, Rai, Rajagopal

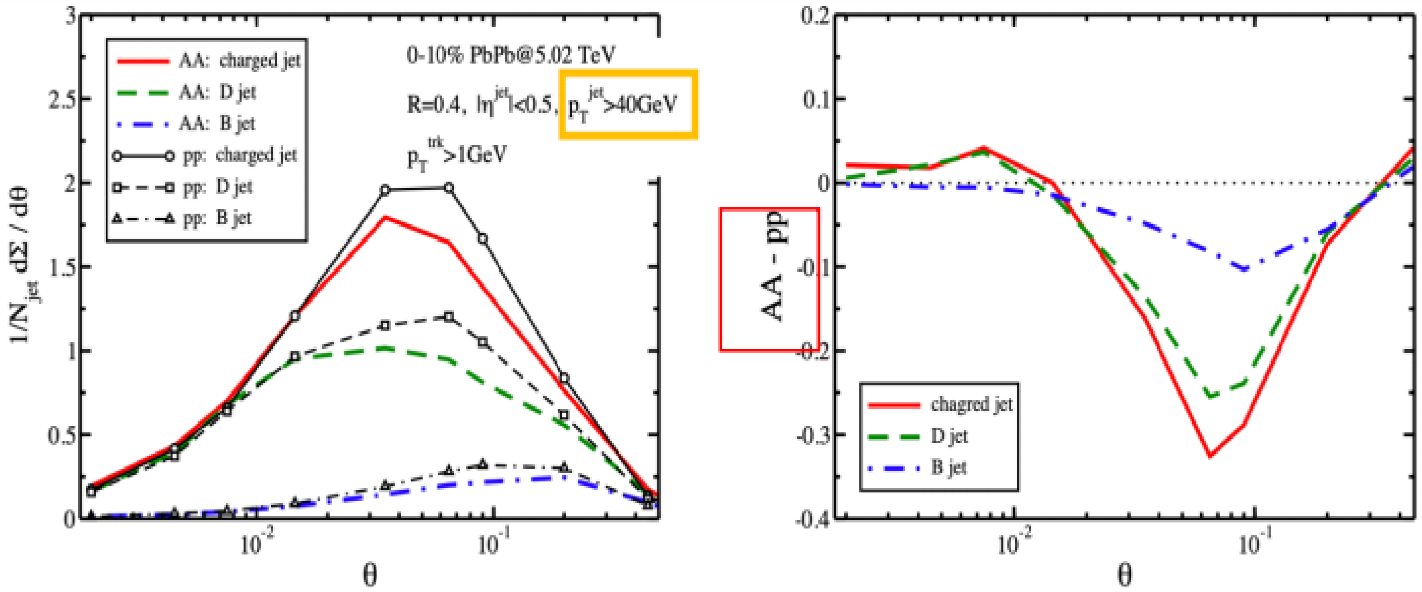


Jet wake effects expected to change the shape at $\theta \gtrsim 0.3$



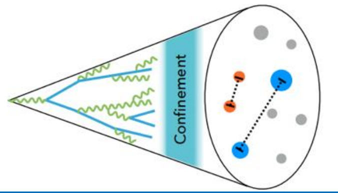
Jet substructure ? Energy-Energy Correlator in heavy-ion collisions

W. J. Xing, S. Cao, G. Y. Qin, and X. N. Wang arXiv. 2409.12843



Flavor (mass) hierarchy in the nuclear modification of jet EEC:

- For charged jets , the EEC spectra gets a strong suppression at intermediate angle, and gets enhanced at small and large angles.
- For heavy-meson-tagged jets, both suppression and enhancement become weaker.



Jet substructure ? Energy-Energy Correlator in heavy-ion collisions

In our work, we study nuclear modifications of EEC

to investigate: discrimination power on quark and gluon quenching effects in heavy-ion collisions

casmier factor : C_A *and* C_F

splitting function for quarks and gluons: $P(x)$

mass hierarchy of jet quenching in heavy-ion collisions

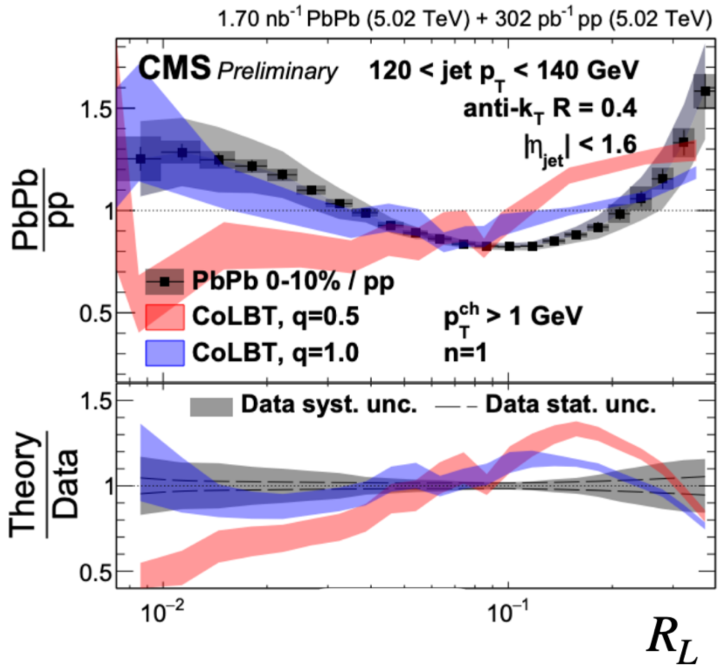
$$\Delta E_{light} > \Delta E_c > \Delta E_b$$

EEC observable-- state of art

Inclusive jets and gamma-jets

CoLBT

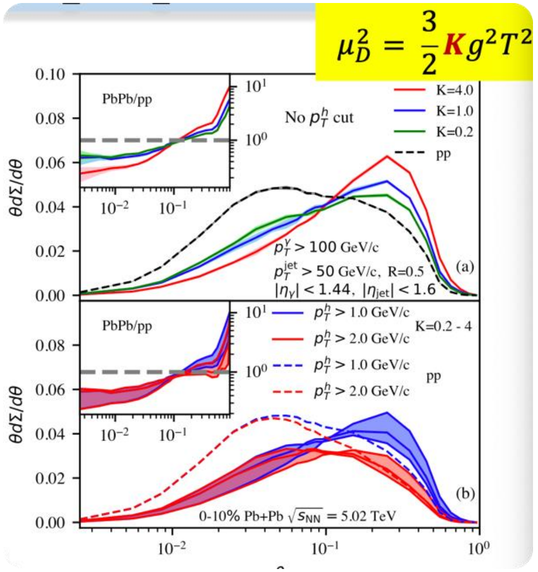
Yang, He, Wang



See also: Yang, He, Moult, Wang, 2310.01500

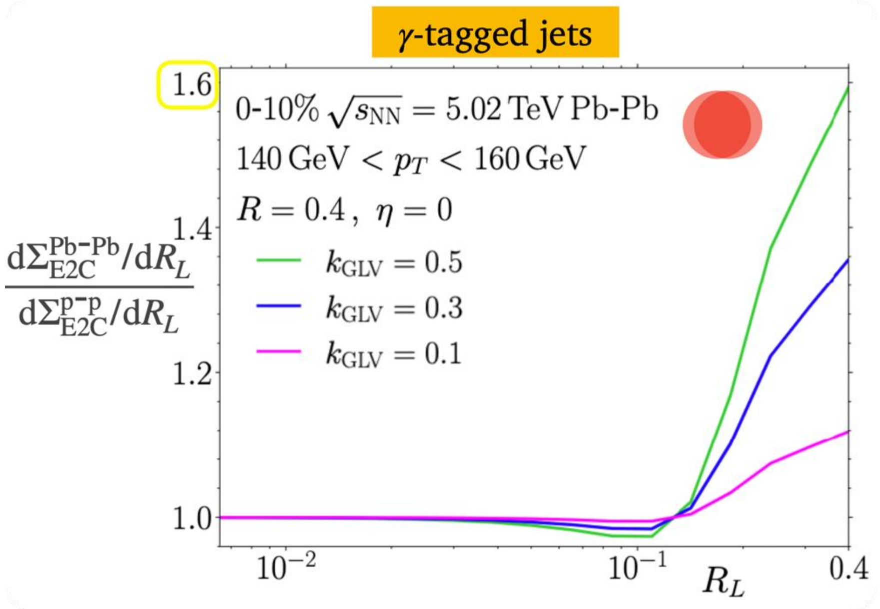
Hybrid model

Pablos, Kudinoor, Rajagopal



opportunity to probe jet-medium interaction

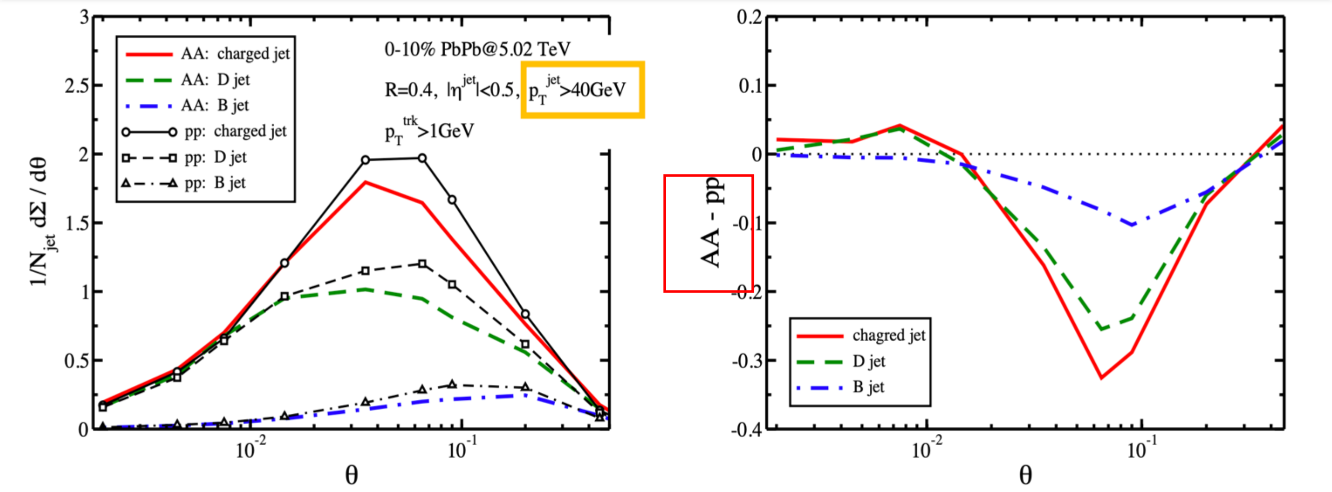
CA, Dominguez, Holguin, Marquet, Moult



EEC observable-- state of art

Inclusive jets and heavy flavor jets

W. J. Xing, S. Cao, G. Y. Qin, and X. N. Wang
arXiv. 2409.12843



Flavor (mass) hierarchy in the nuclear modification of jet EEC:

- **For charged jets , the EEC spectra gets a strong suppression at intermediate angle, and gets enhanced at small and large angles.**
- **For heavy-meson-tagged jets, both suppression and enhancement become weaker.**

hard to compare, only mass–effect?