Jet Tomography in high-energy nuclear collisions

张本威
(Ben-Wei Zhang)
华中师范大学
Central China Normal University

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热烈祝贺清华大学物理系复系40周年！

Outline

- Introduction
- Leading hadron production
- Full jet observables

1） splitting scales

2) W+jet

3） heavy flavor jets

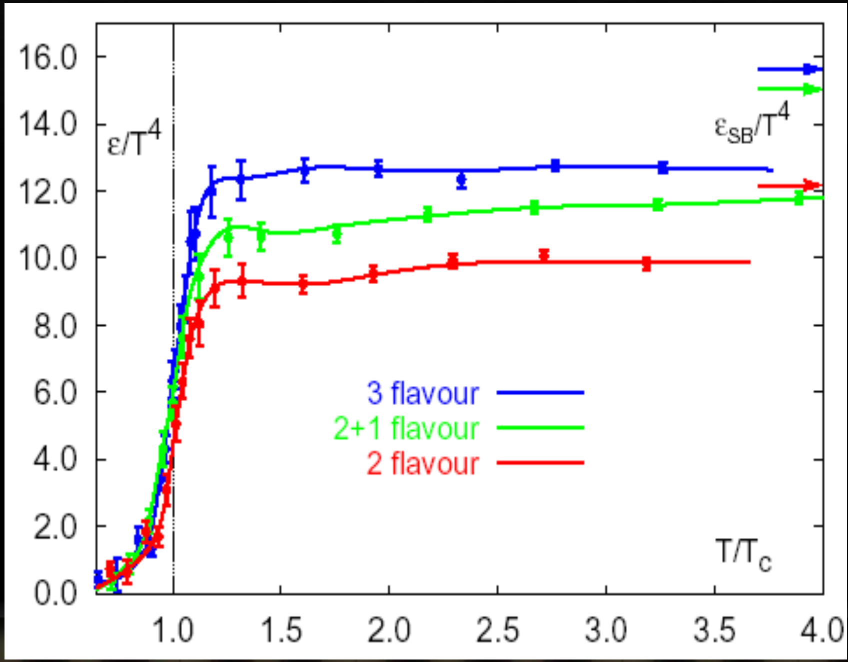
- Summary

Deconfinement and QGP

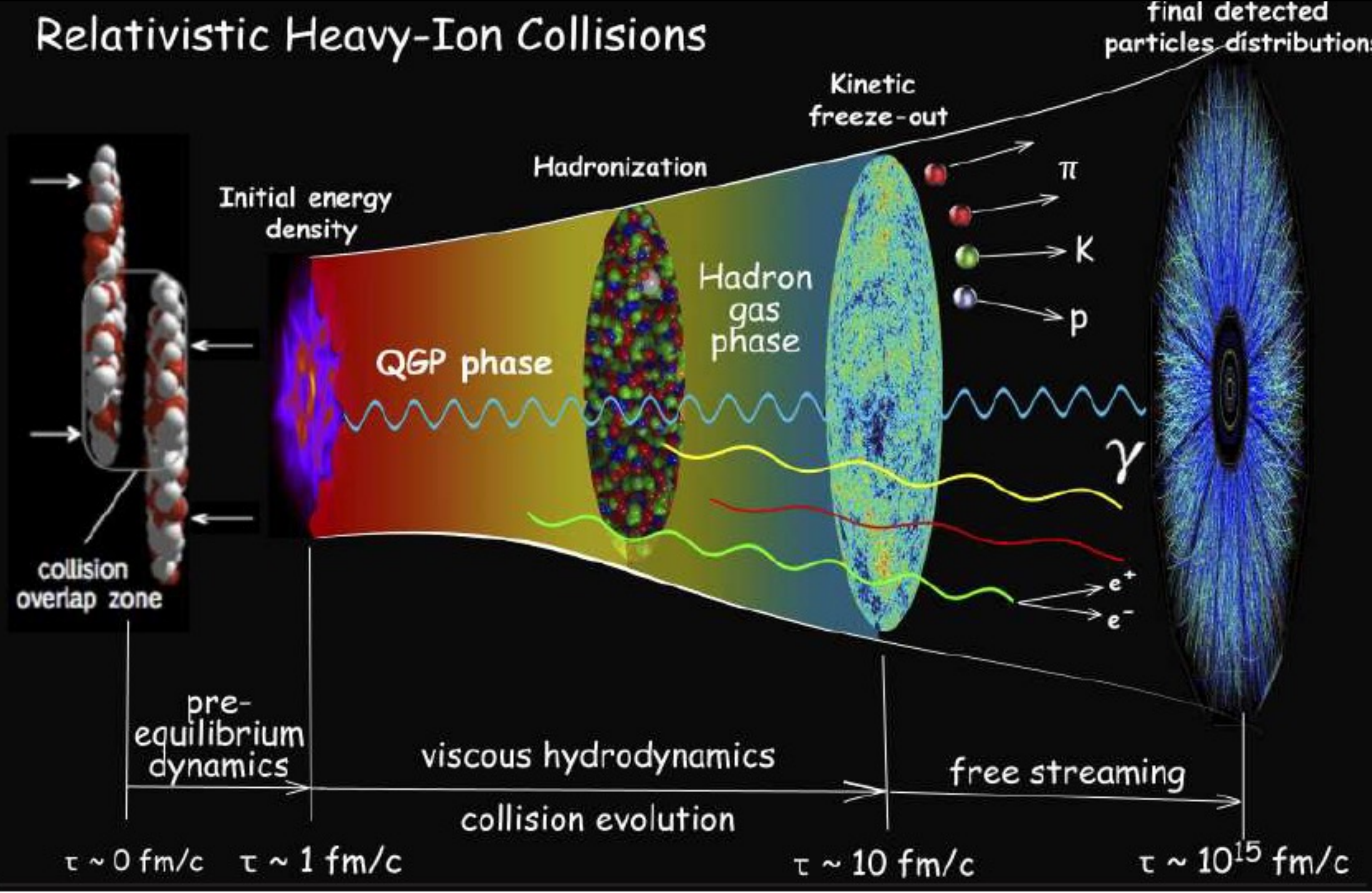
It would be interesting to explore new phenomena by distributing high energy or high nuclear density over a relatively large volume.

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.



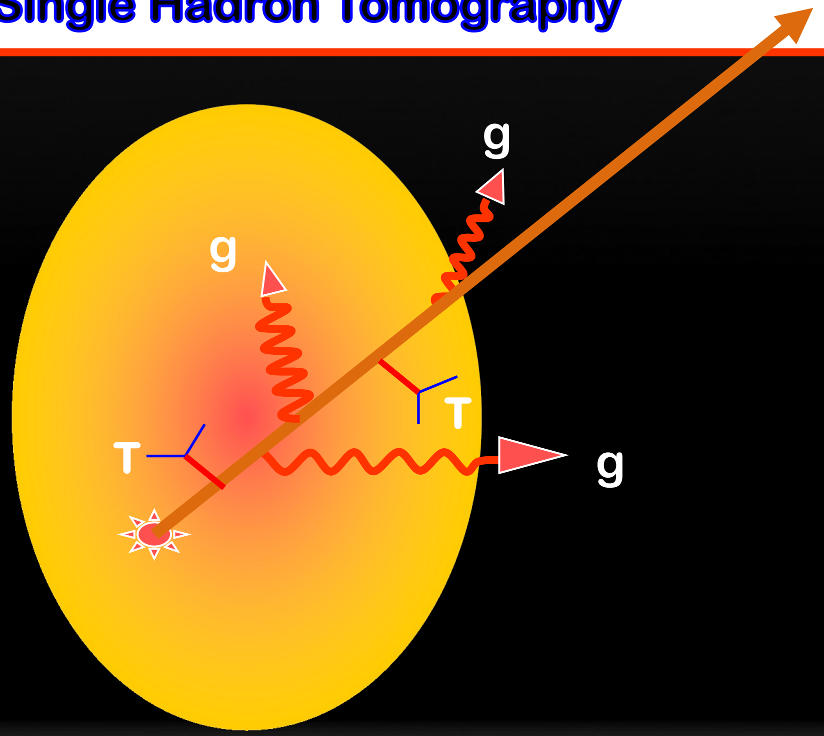
The Little Bang

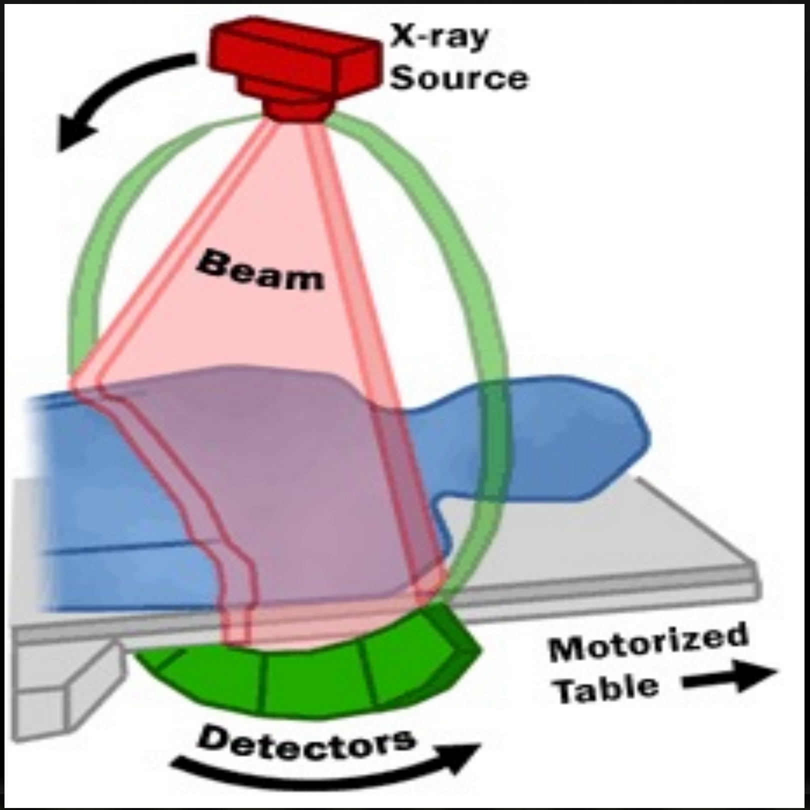


Jet quenching

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

Single Hadron Tomography

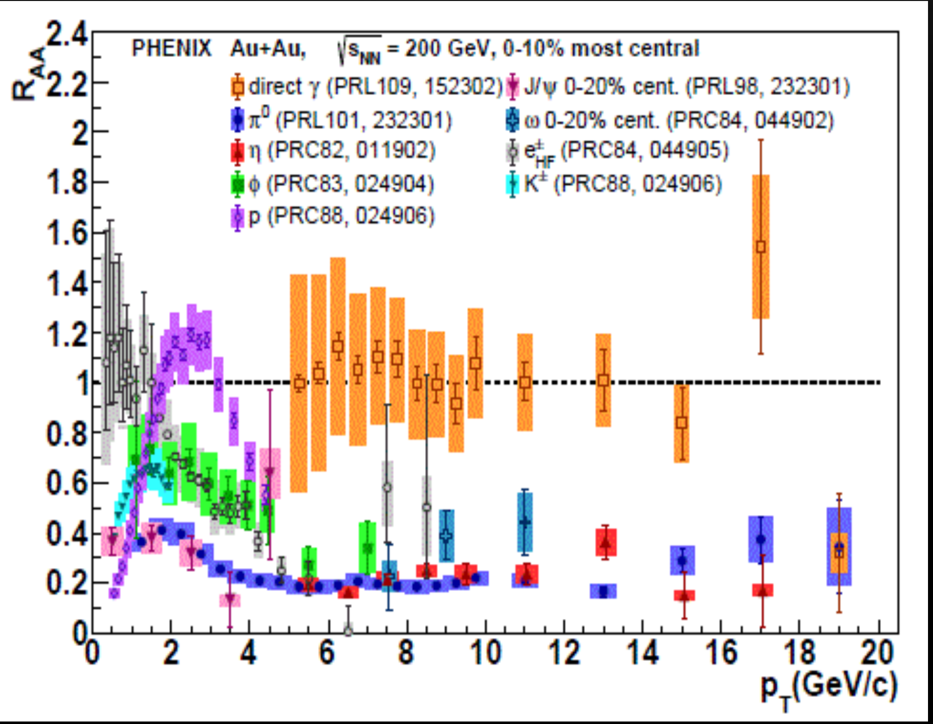


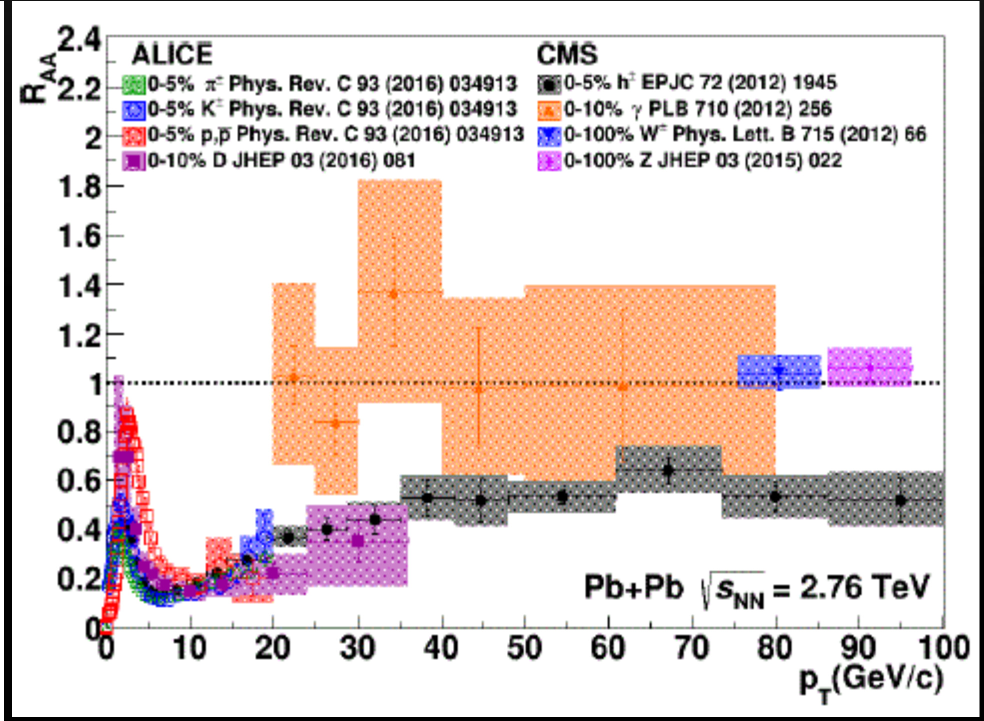


Xin-Nian Wang, M. Gyulassy, PRL68(1992)1480

Jet quenching at RHIC and LHC

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



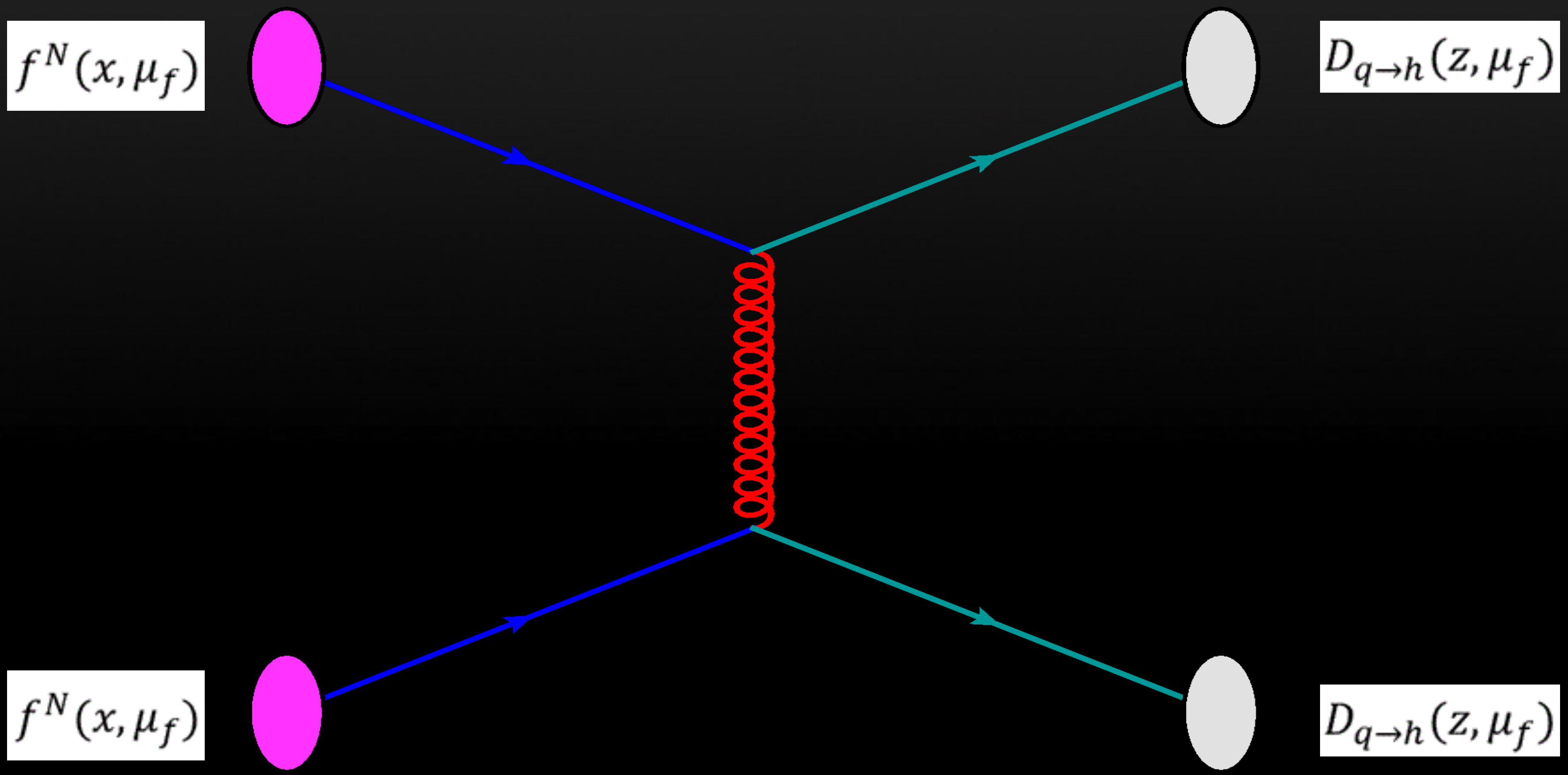


Fingerprints of jet quenching

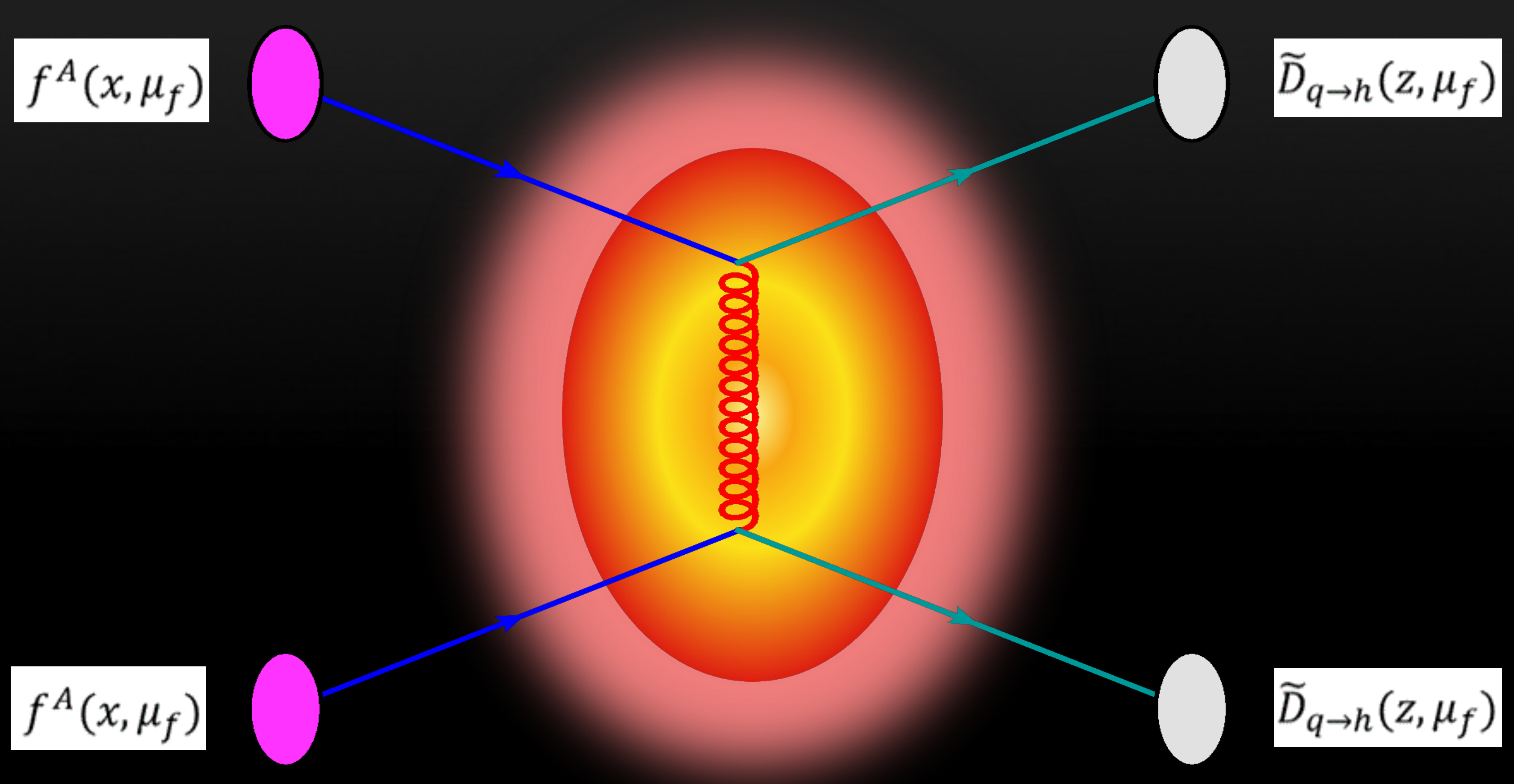
领头强子

整体喷注

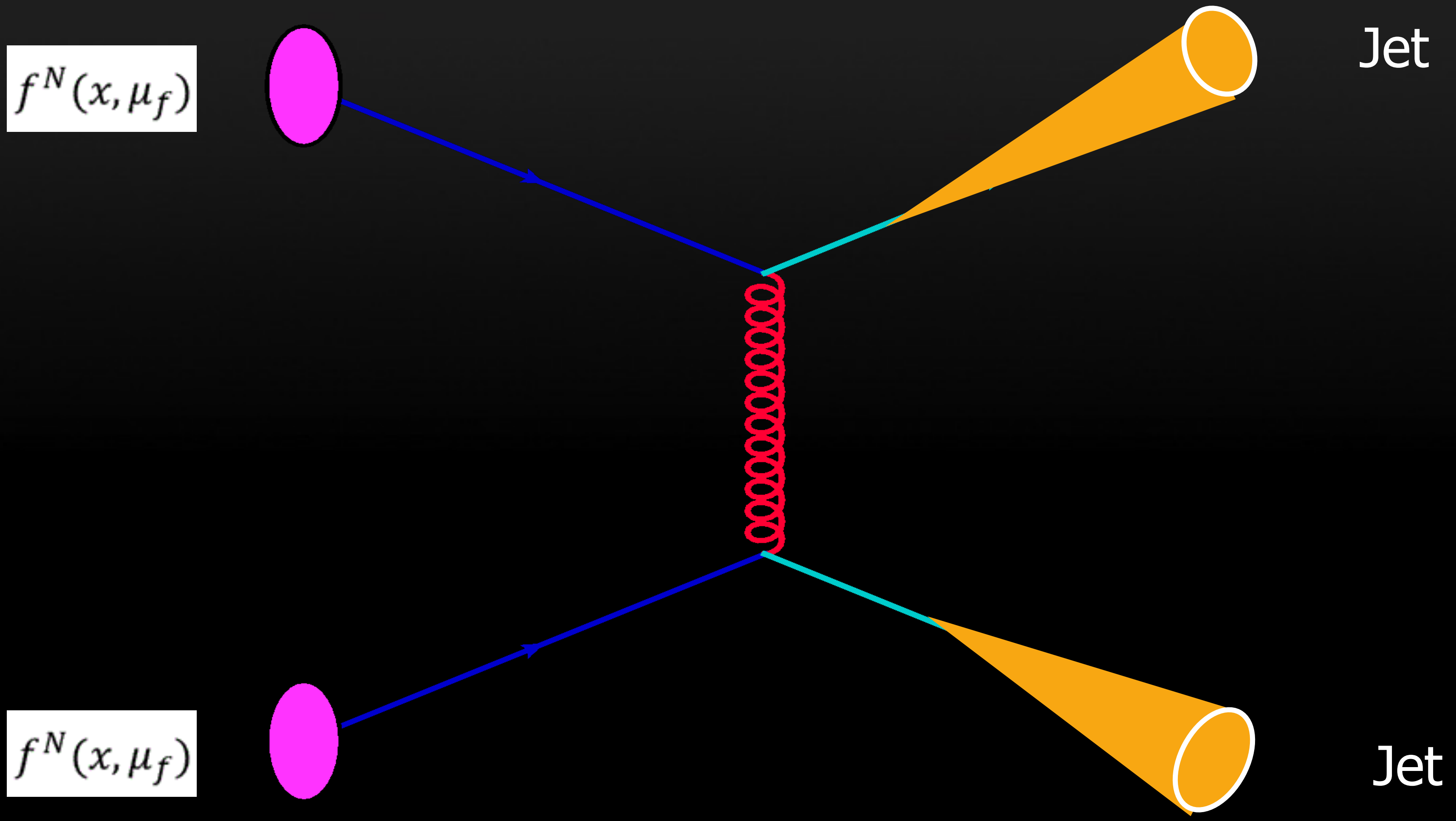
Leading hadron production



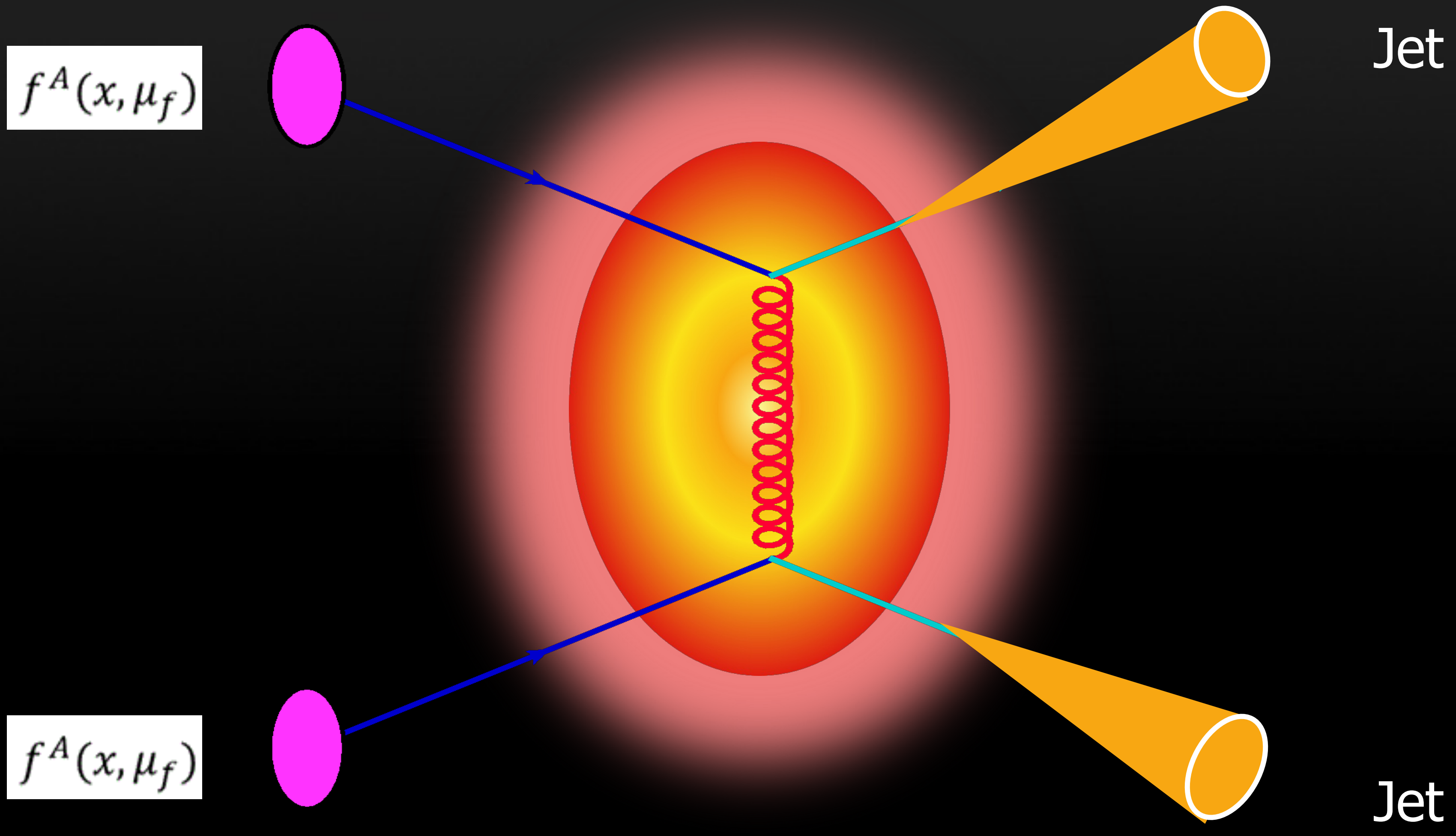
Leading hadron production



Full jets



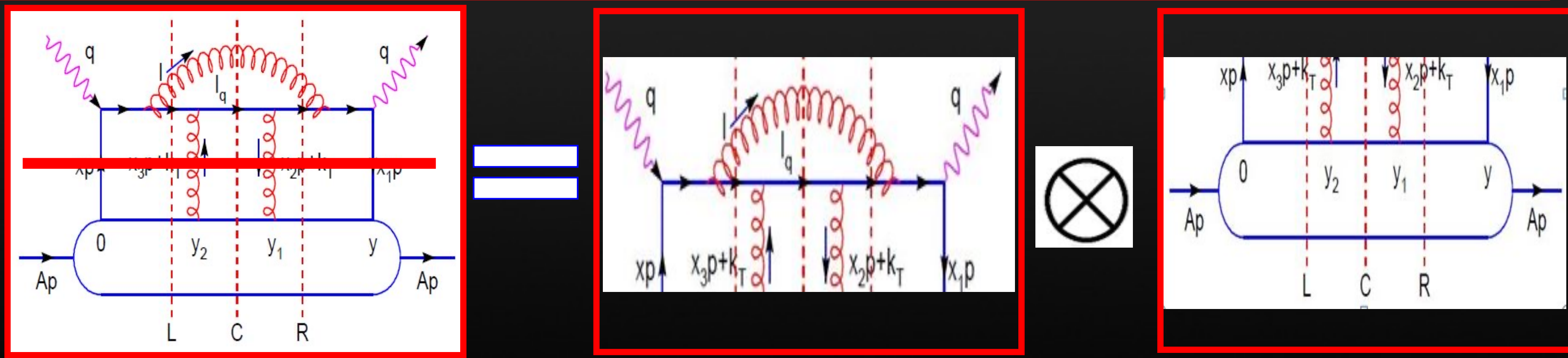
Full jets



Large p_T hadrons in HIC

Jet quenching with higher twist approach

The parton energy loss due to medium-induced gluon radiation has been calculated with higher twist approach.



$$\tilde{D}_{q\to h}(z_h,\mu^2) \equiv D_{q\to h}(z_h,\mu^2) + \int_0^{\mu^2} \frac{d\ell_T^2}{\ell_T^2}\frac{\alpha_s}{2\pi}\int_{z_h}^1 \frac{dz}{z}\left[\Delta\gamma_{q\to qg}(z,x,x_L,\ell_T^2)D_{q\to h}(z_h/z)\right.$$
$$\left. + \Delta\gamma_{q\to gq}(z,x,x_L,\ell_T^2)D_{g\to h}(z_h/z)\right] ,$$

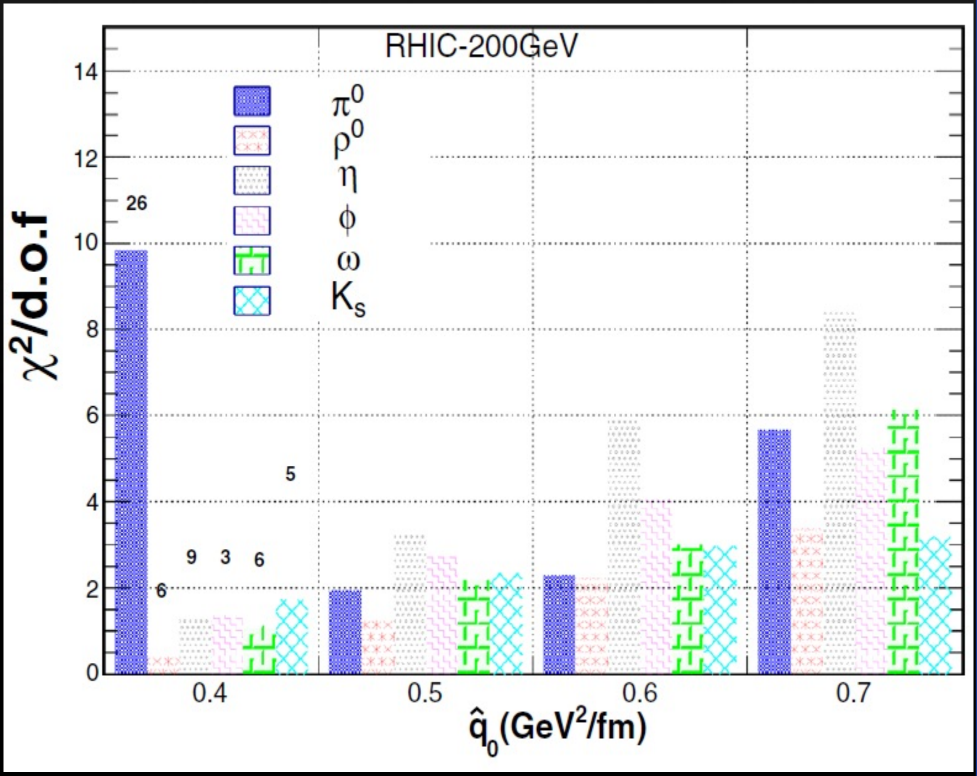
$$\frac{1}{N_{\rm bin}^{AB}(b)}\frac{d\sigma_{AB}^h}{dyd^2p_T} = \sum_{abcd}\int dx_a dx_b f_{a/A}(x_a,\mu^2) f_{b/B}(x_b,\mu^2)$$
$$\times \frac{d\sigma}{d\hat{t}}(ab\to cd)\frac{\langle \tilde{D}_c^h(z_h, Q^2, E, b)\rangle}{\pi z_c} + \mathcal{O}(\alpha_s^3).$$

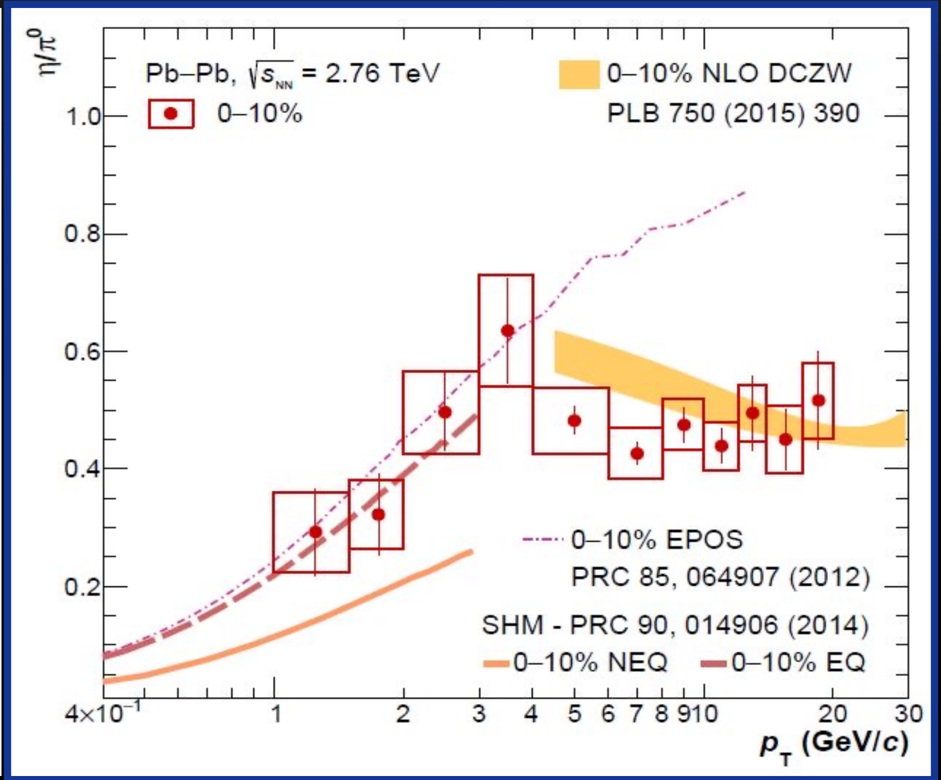
X Guo, X N Wang, PRL(2001); X Guo, X N Wang, NPA (2001);
BWZ, X N Wang, NPA(2003) ; BWZ, E Wang, X N Wang, PRL (2004)

η/π⁰ in HIC at NLO

- Yields of 6 species of hadrons and their ratios in Au+Au and Pb+Pb are calculated.

ALICE, PRC 98(2018)044901





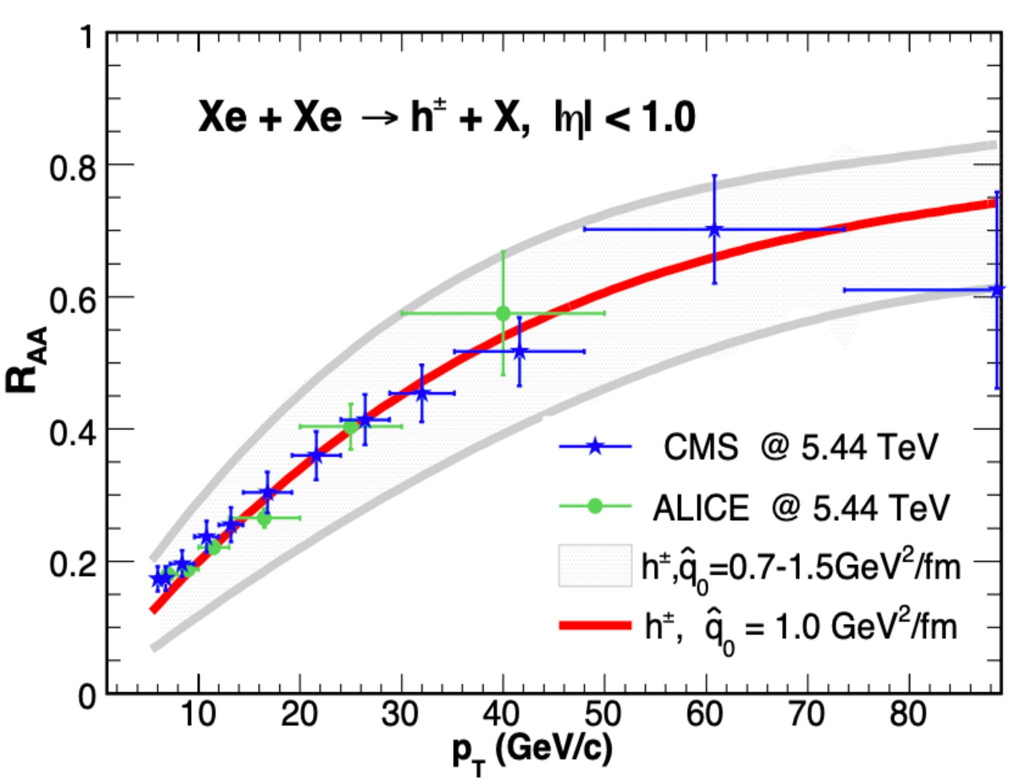
W Dai, X Chen, BWZ, et al， PLB (2015); EPJC (2017); PRC(2018)

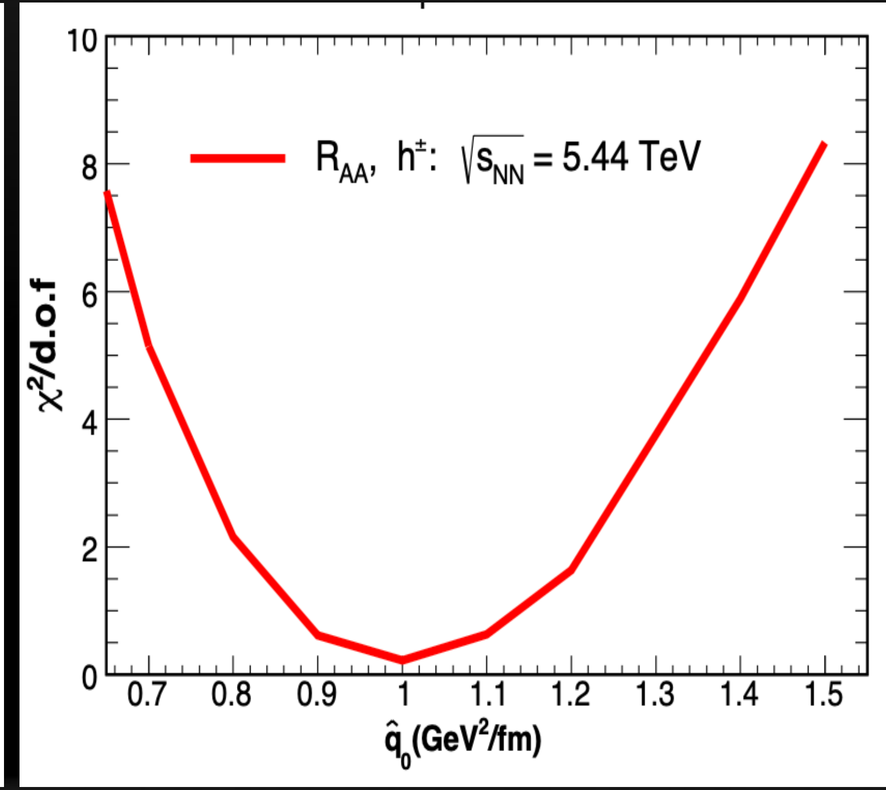
G Ma, W Dai, BWZ, E Wang, EPJC (2019)

Charged hadrons in Xe+Xe at NLO

- Charged hadron productions in Xe+Xe has been studied.
- Jet transport coefficient is extracted by fitting the data.

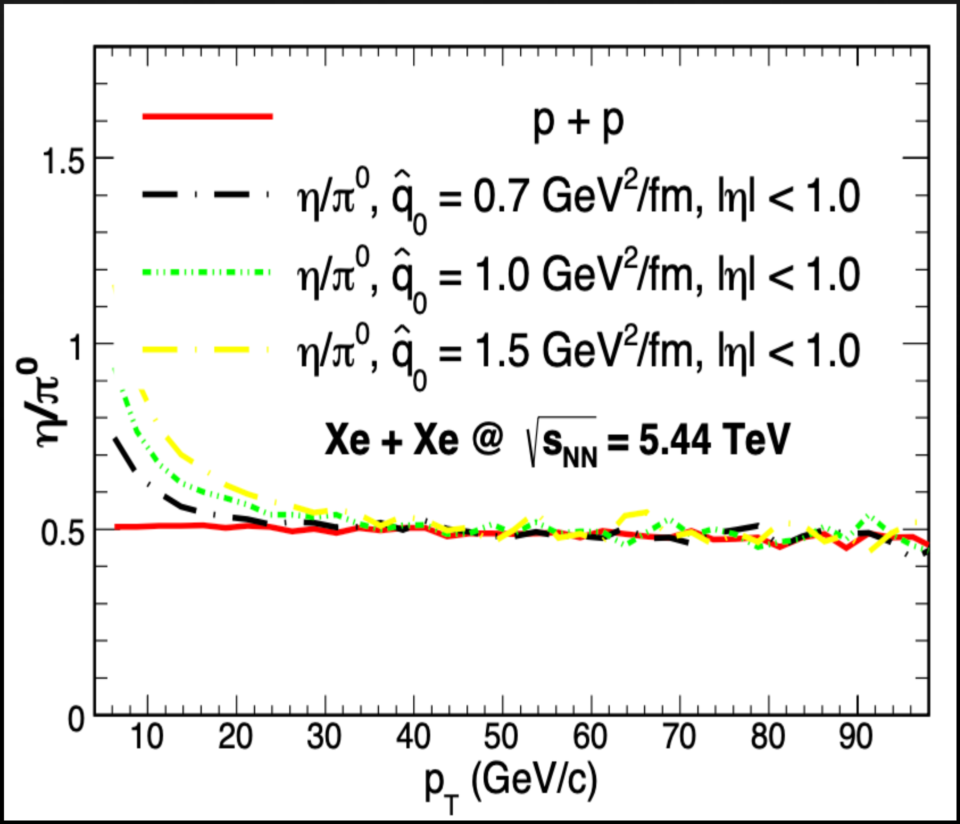
$$(dE/dx)_{\rm rad} = -C_2 \hat{q} L$$

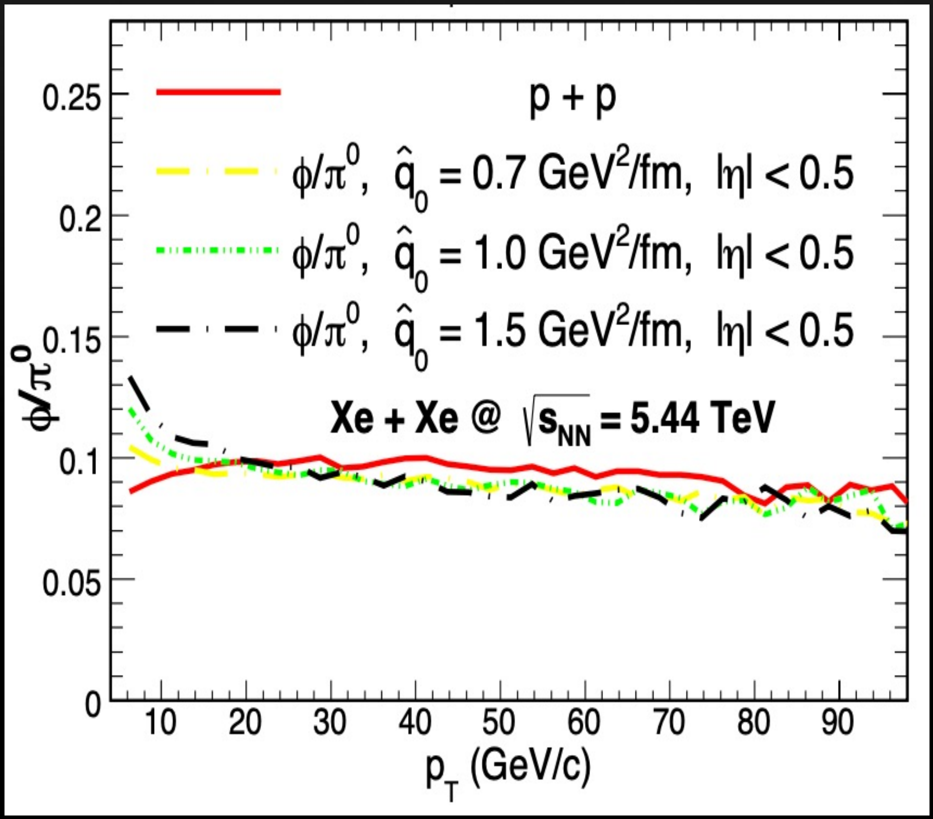




Q Zhang, W Dai, L Wang, BWZ, E Wang， arXiv: 2203.10742, CPC (in press)

Particle ratios in Xe+Xe at NLO

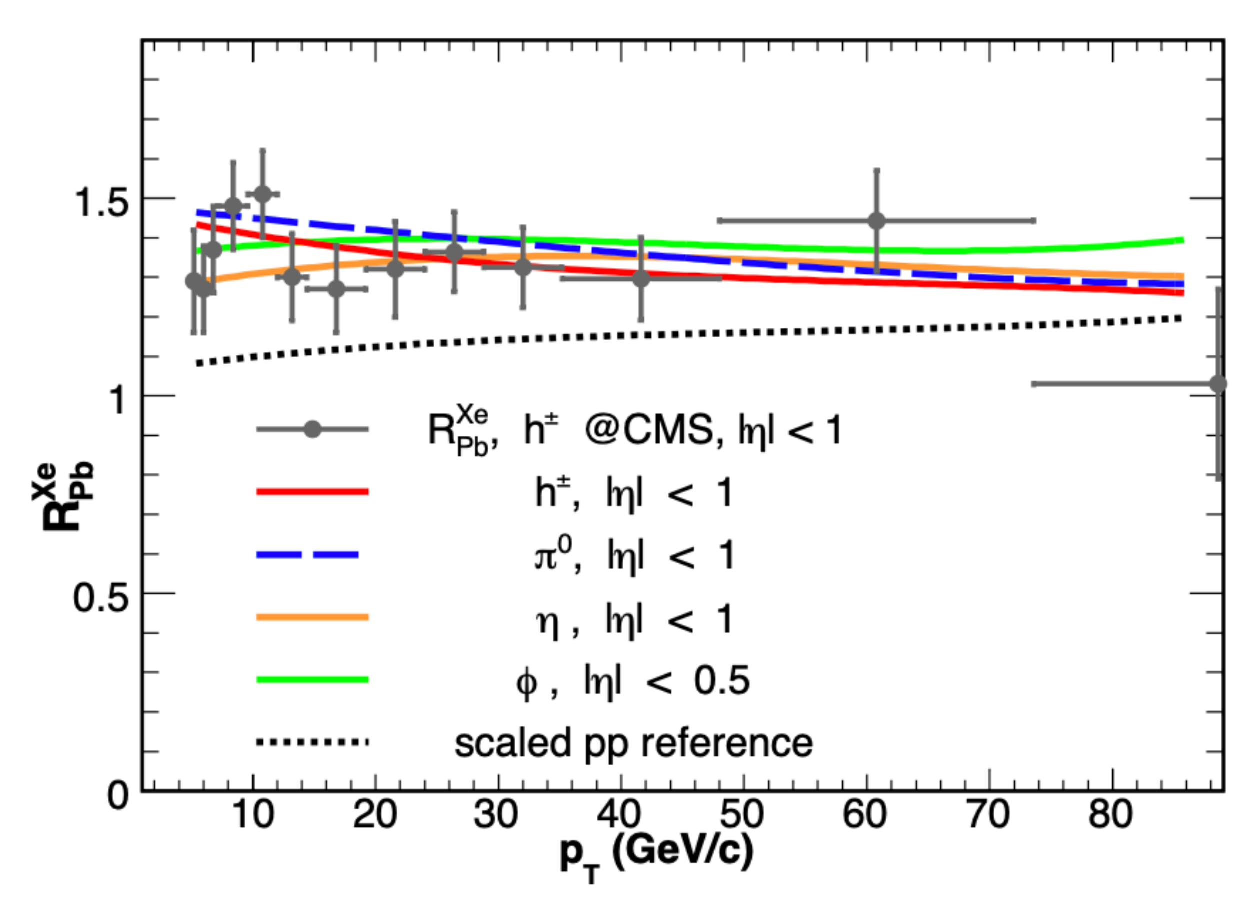




Q Zhang, W Dai, L Wang, BWZ, E Wang， arXiv: 2203.10742, CPC (in press)

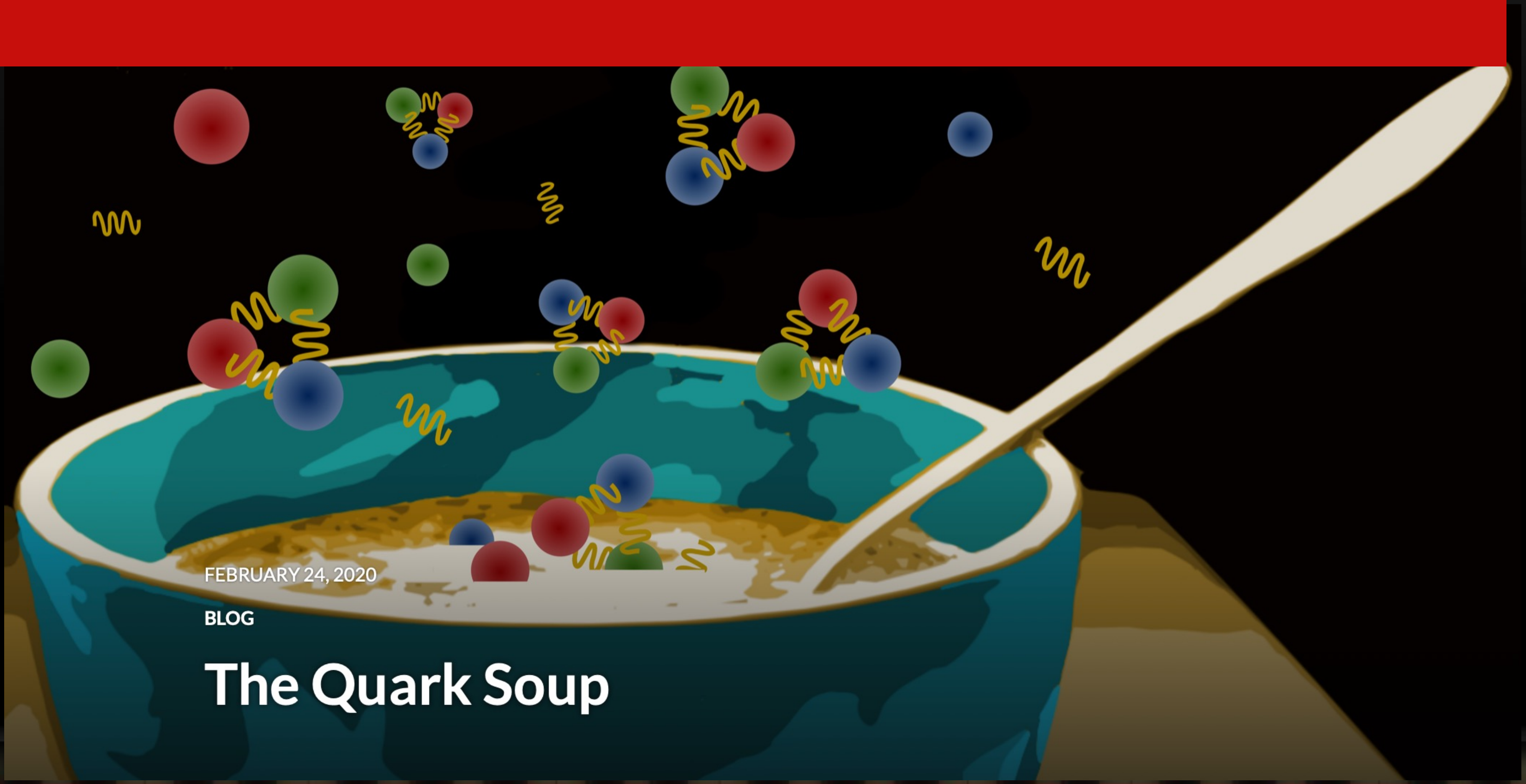
System size dependence of energy loss

$$R_{\mathrm{Pb}}^{\mathrm{Xe}}(p_{\mathrm{T}}) = \frac{dN^{\mathrm{XeXe}}/dp_{\mathrm{T}}}{dN^{\mathrm{PbPb}}/dp_{\mathrm{T}}} \frac{T_{\mathrm{PbPb}}}{T_{\mathrm{XeXe}}}$$



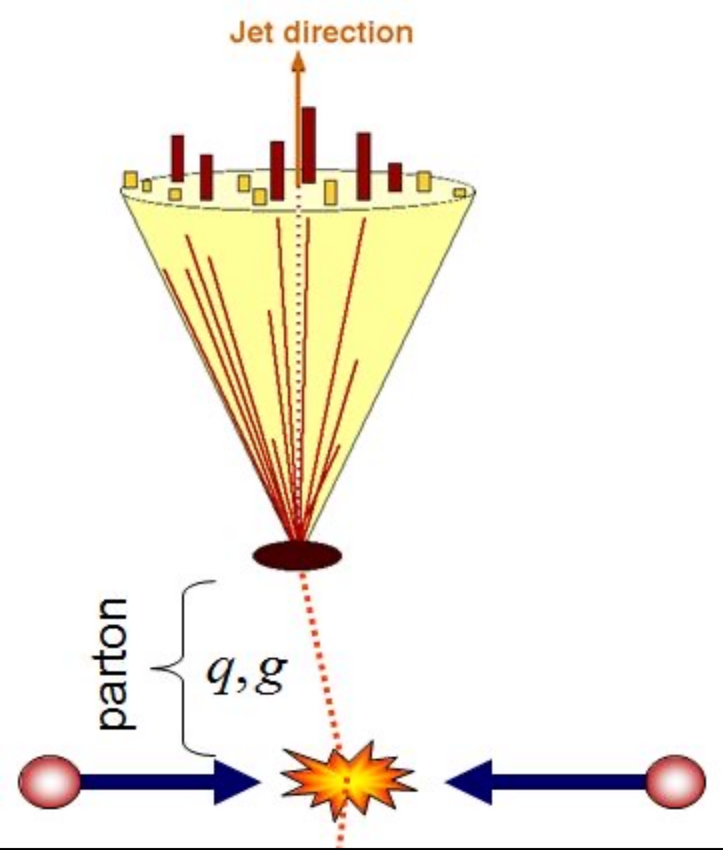
Q Zhang, W Dai, L Wang, BWZ, E Wang， arXiv: 2203.10742, CPC (in press)

Jets in quark soup



What is a jet?

- A jet is a spray of final-state particles roughly moving in the same direction and defined by jet finding algorithms.
- At LO pQCD, jet ≈parton.
- In pQCD local-parton-hadron duality (LPHD) is used
- Jet: more precise and powerful



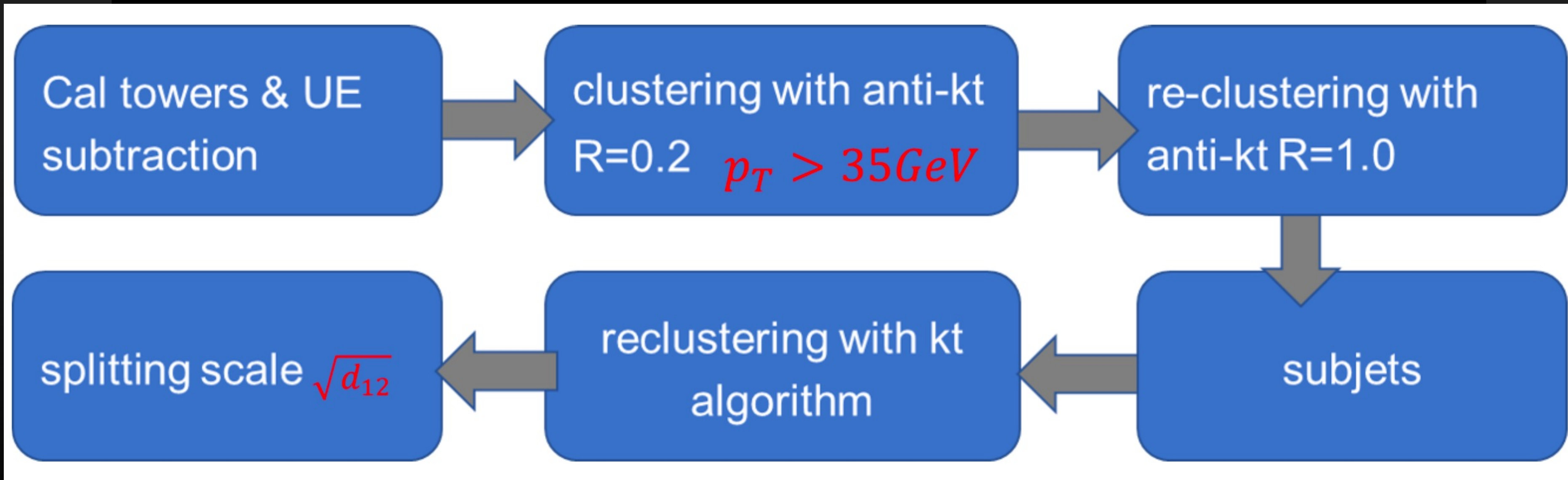
$$E_T = \sum_{i \in jet} E_{T,i}$$

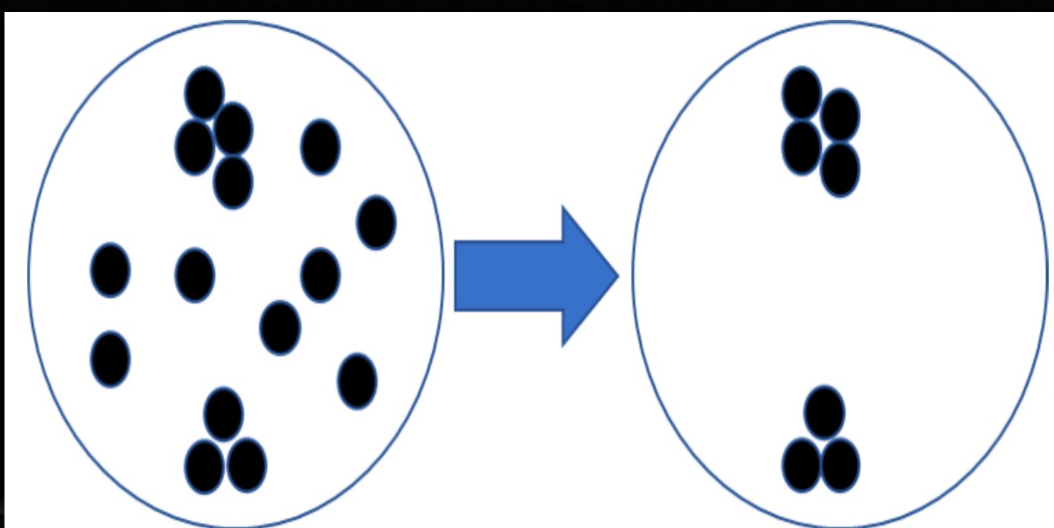
$$y = \sum_{i \in jet} y_i E_{T,i} / E_T$$

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

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

Reclustered large radius jets





remove soft radiation

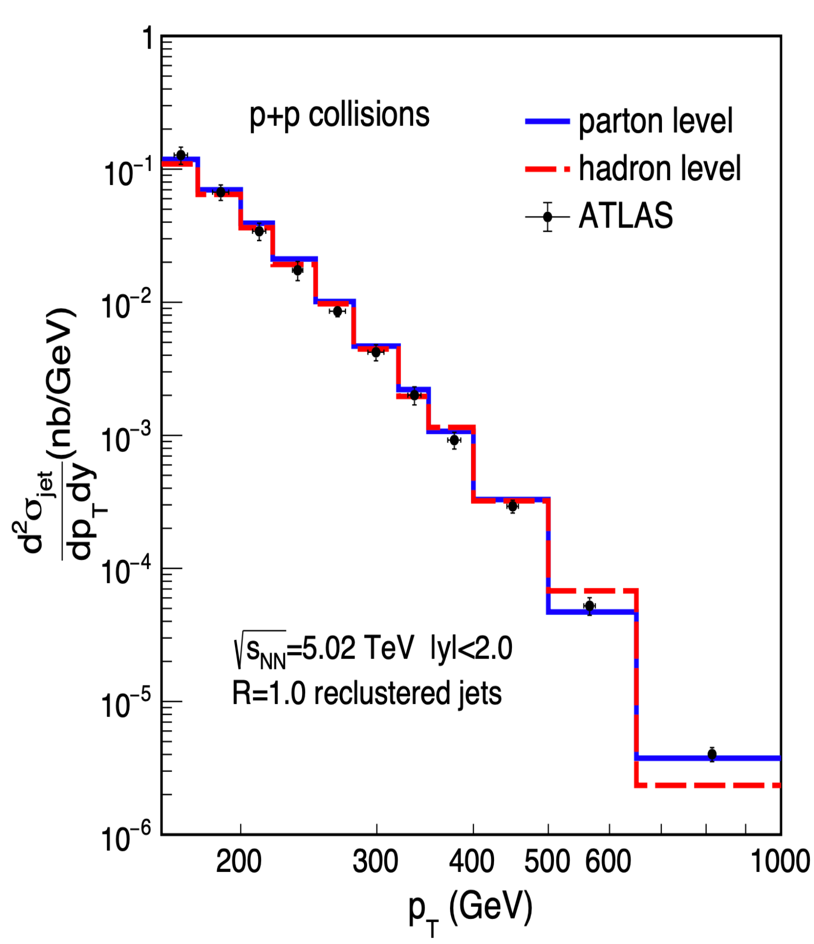
splitting scale

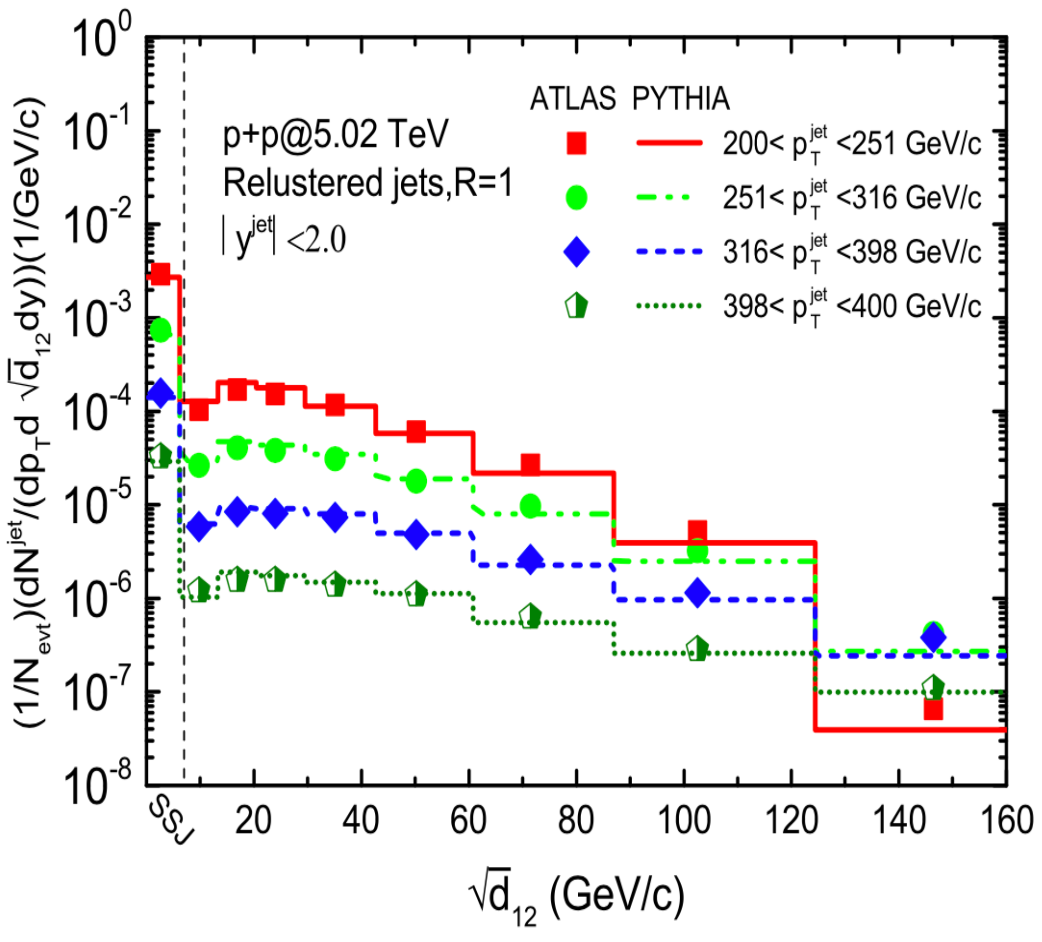
$$d_{12} = min(p_{T1}^2, p_{T2}^2) \cdot \Delta R_{12}^2 / R^2,$$

$$\Delta R_{12} = \sqrt{\Delta\phi_{12}^2 + \Delta y_{12}^2}$$

Reclustered LR jets in p+p

$$\sqrt{d_{12}} = \sqrt{min(p_{T,1}^2, p_{T,2}^2) * \Delta R_{12}^2}$$





Linear Boltzmann Transport Model

- Elastic scattering:

$$p_1 \cdot \partial f_1(p_1) = -\int dp_2 dp_3 dp_4 (f_1 f_2 - f_3 f_4) |M_{12\to 34}|^2 \times (2\pi)^4 \delta^4 (P_1 + P_2 - P_3 - P_4)$$

$$dp_i \equiv \frac{d^3 p_i}{2E_i (2\pi)^3}, \; |M_{12\to 34}|^2 = C g^2 (s^2 + u^2)/(t + \mu^2)^2$$

$$f_i = 1/(e_i^{p.u/T} \pm 1)(i = 2,4), f_i = (2\pi)^3 \delta^3 (\vec{p} - \vec{p}_i) \delta^3 (\vec{x} - \vec{x}_i)(i = 1,3)$$

X N Wang, Y Zhu, PRL(2013); He, Luo, Wang, Zhu, PRC (2015)

- Inelastic scattering by the higher twist approach:

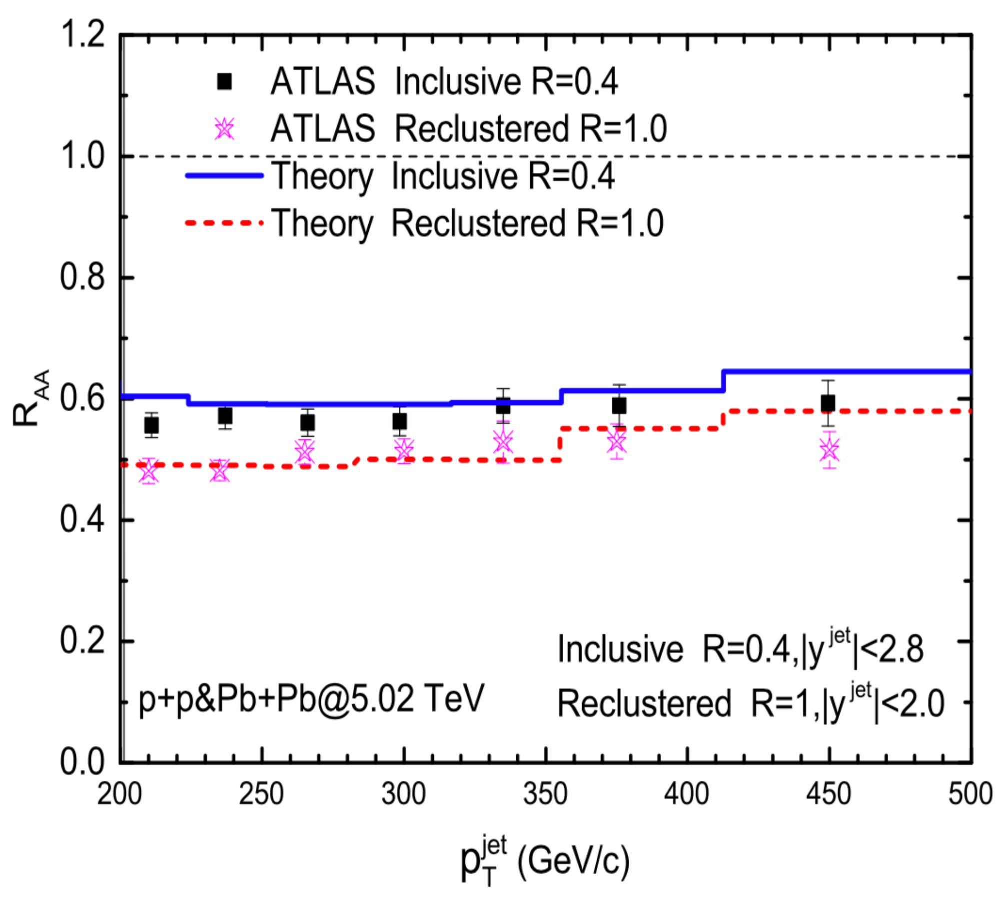
$$\frac{dN_g}{dx dk_\perp^2 dt} = \frac{2\alpha_s P(x)\hat{q}}{\pi k_\perp^4} Sin^2\left(\frac{t - t_i}{2\tau_f}\right)\left(\frac{k_\perp^2}{k_\perp^2 + x^2 M^2}\right)^4$$

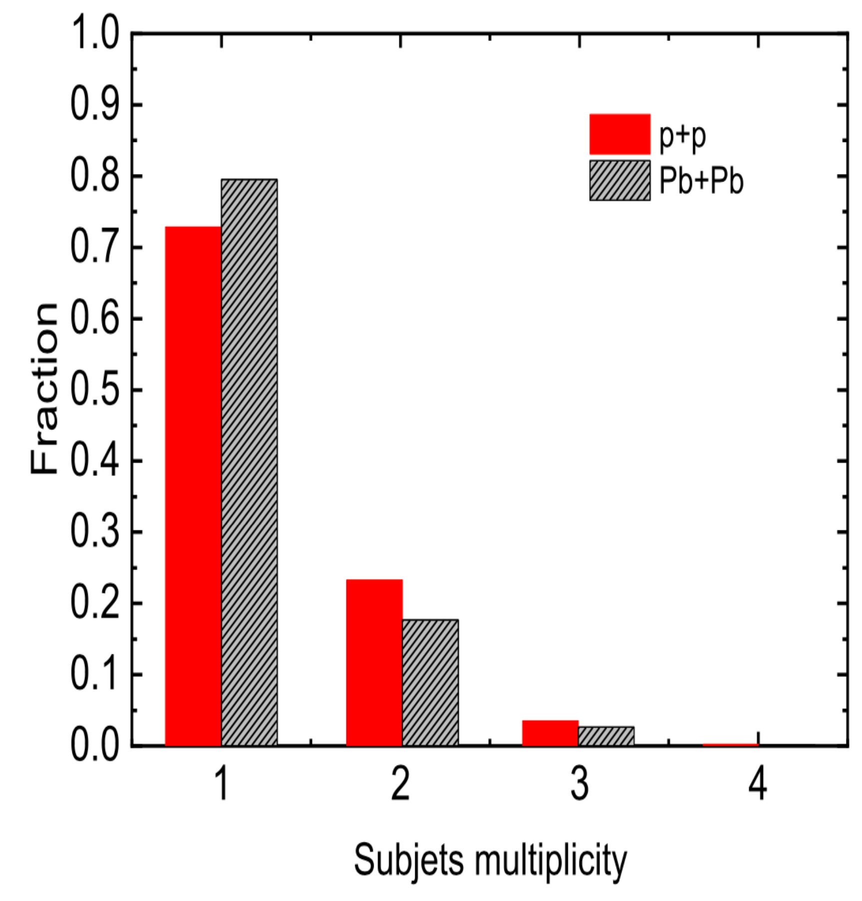
Guo, X N Wang, PRL(2002); BWZ, X Wang, NPA(2003);

BWZ, E Wang, X N Wang, PRL (2004); Majumder, PRD(2012)

Nuclear modifications

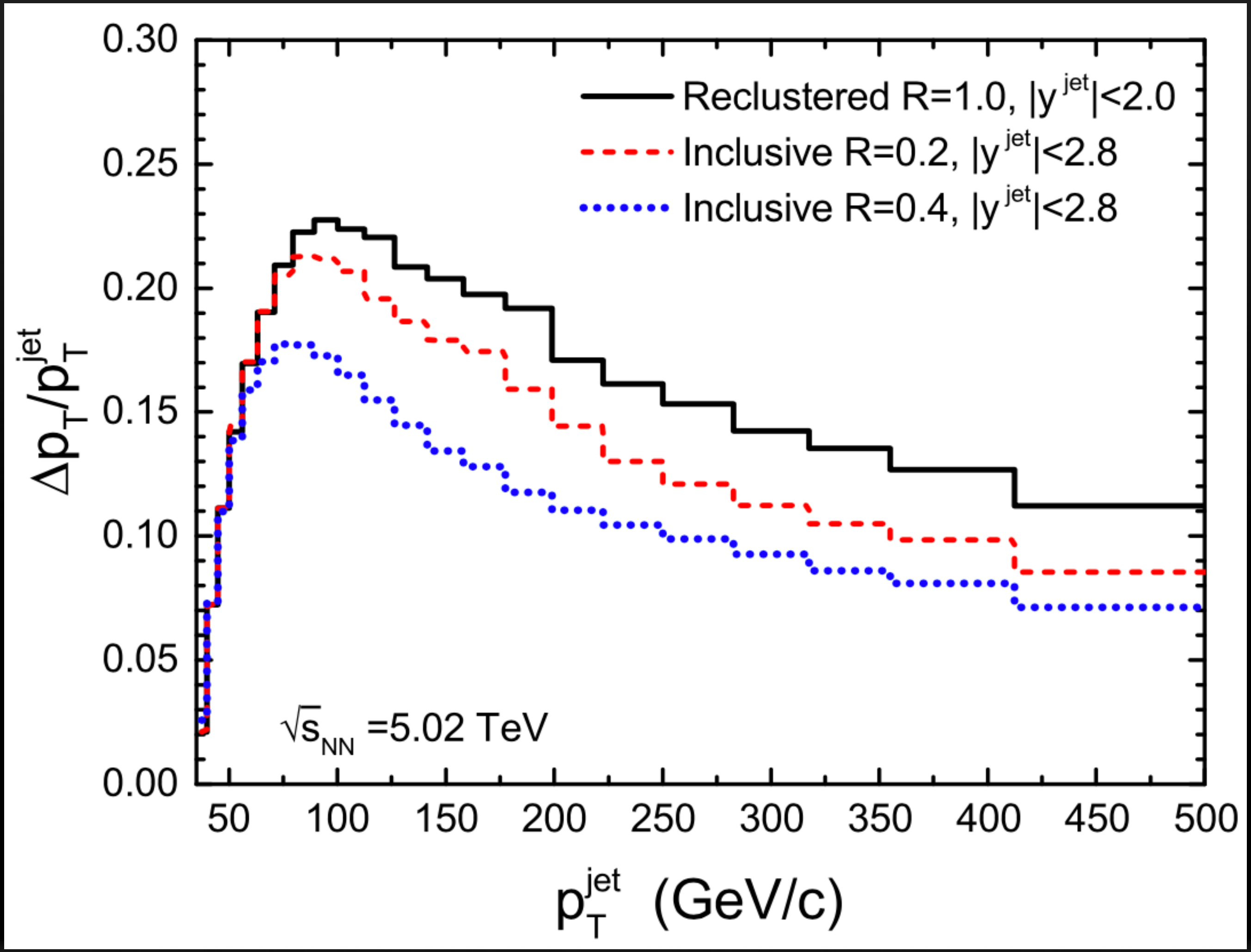
- Nuclear suppression of reclustered LR jets at R=1.0 is larger than that of inclusive jets with R=0.4.





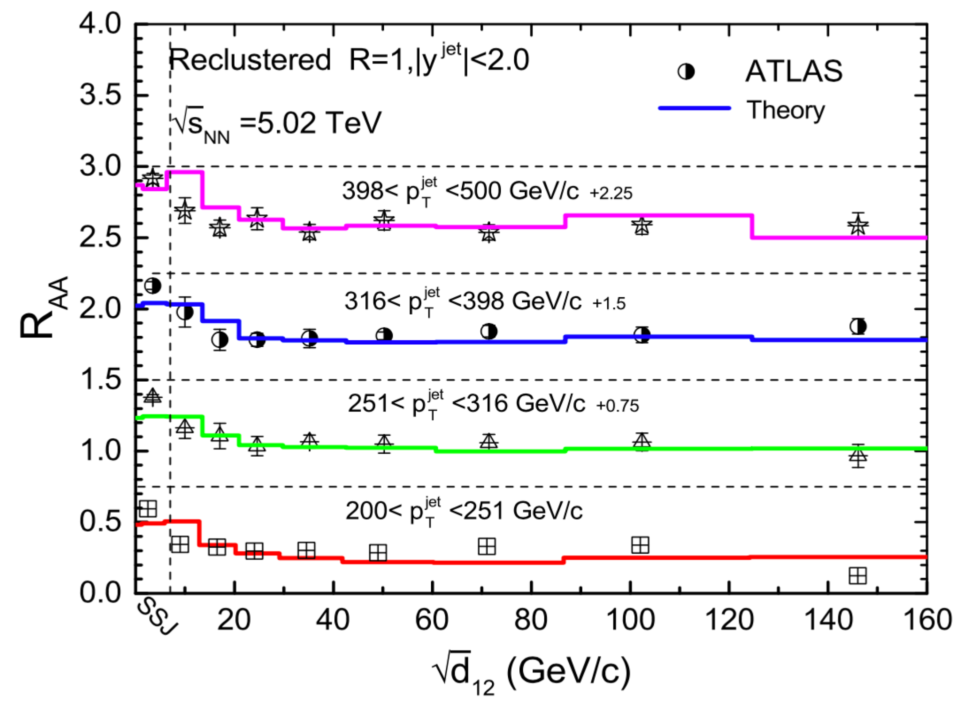
S L Zhang, M Q Yang, BWZ, EPJC (2022)

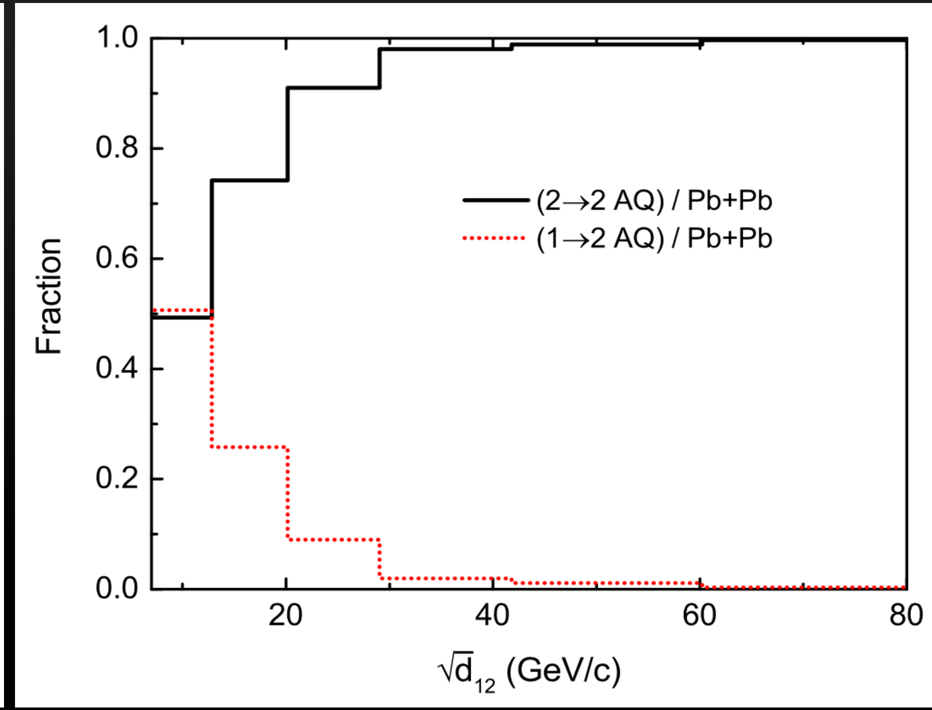
Energy loss fraction

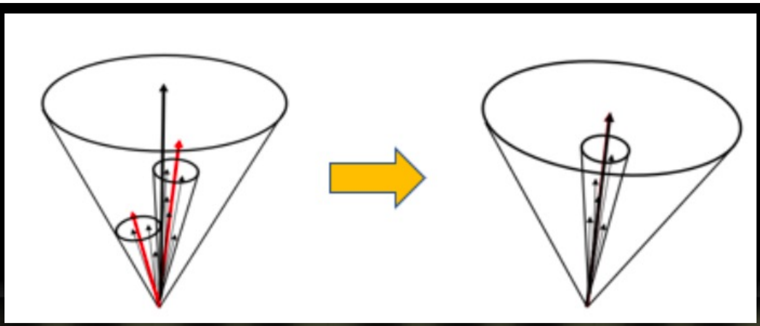


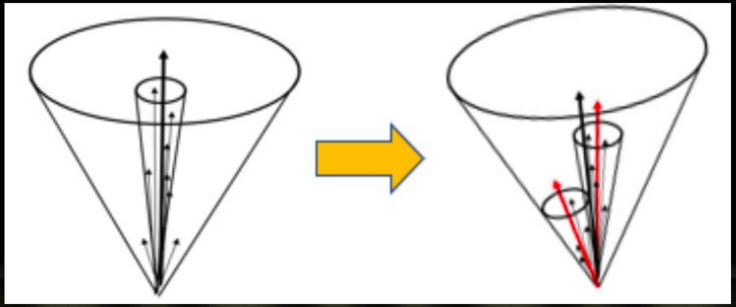
Energy loss of reclustered jets

$$\sqrt{d_{12}} = \sqrt{min(p_{T,1}^2, p_{T,2}^2) * \Delta R_{12}^2}$$



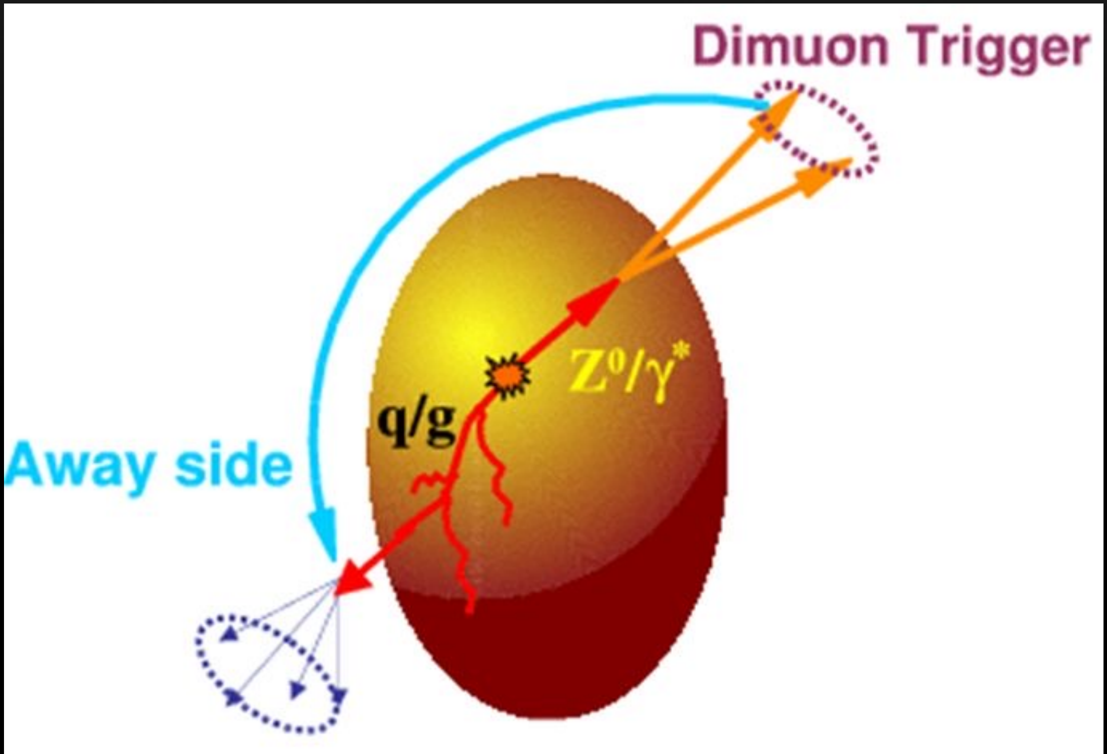


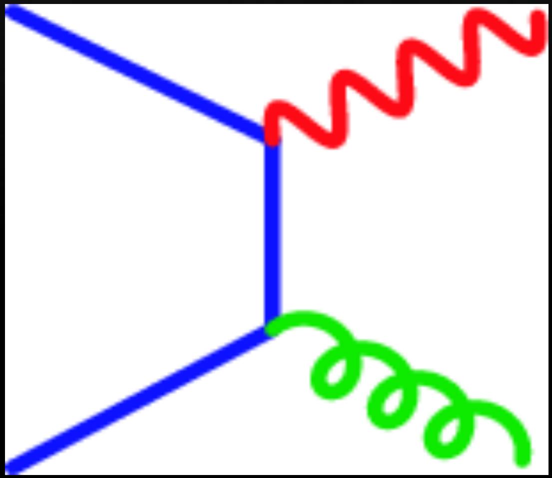




S L Zhang, M Q Yang, BWZ, EPJC (2022)

Tagged jet production in HIC

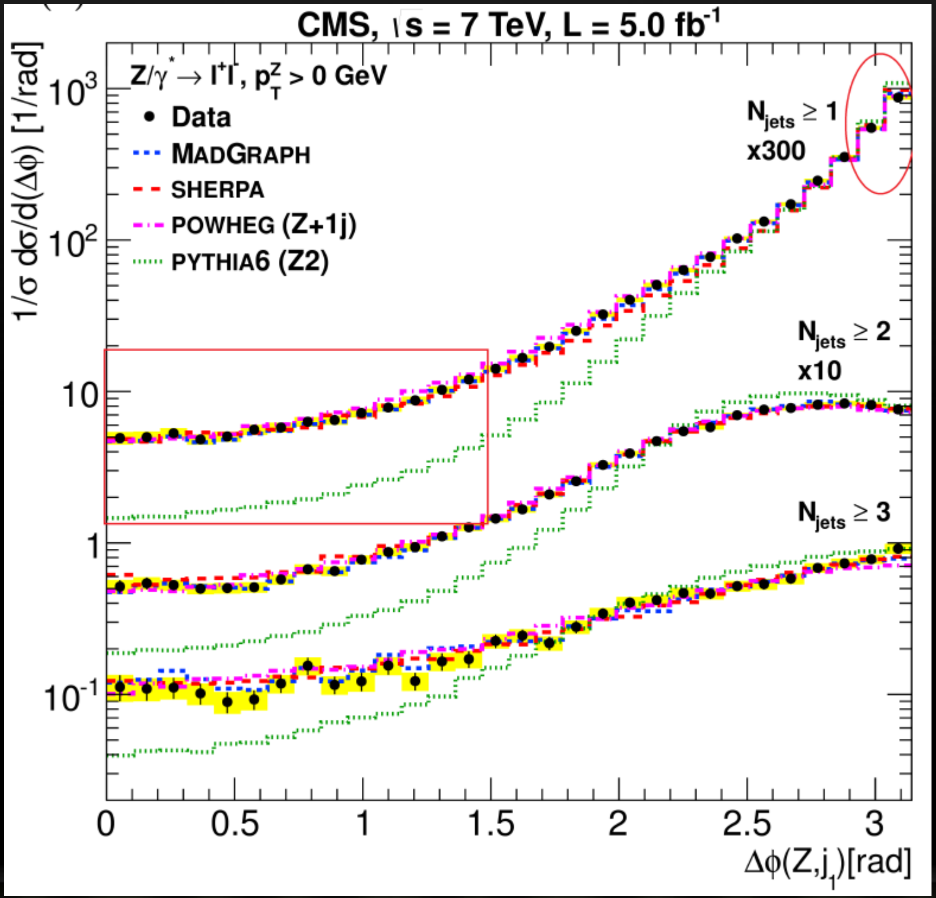




"golden channel"

Angular correlation in Z+jet

- NLO calculations fail at angular difference ~π;
- LO+PS calculations fail at small angular difference.
- Z+jet in A+A: NLO+PS+Eloss



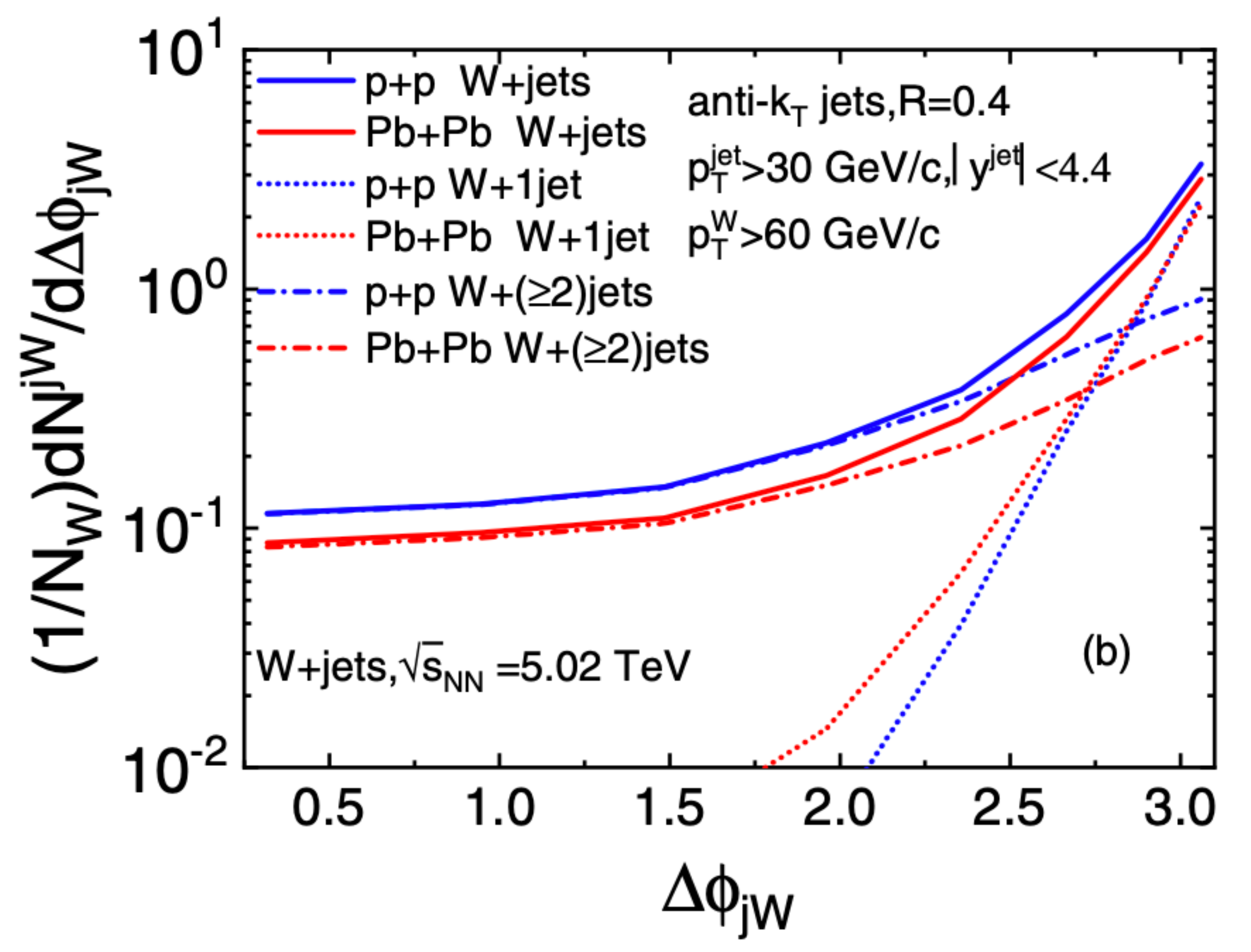
CMS, PLB 722 (2013) 238

Chen, Qin, Wei, Xiao, Zhang, PLB (2017)

NLO +PS +ELoss

S L Zhang, T Luo, X N Wang, BWZ, PRC (2018)

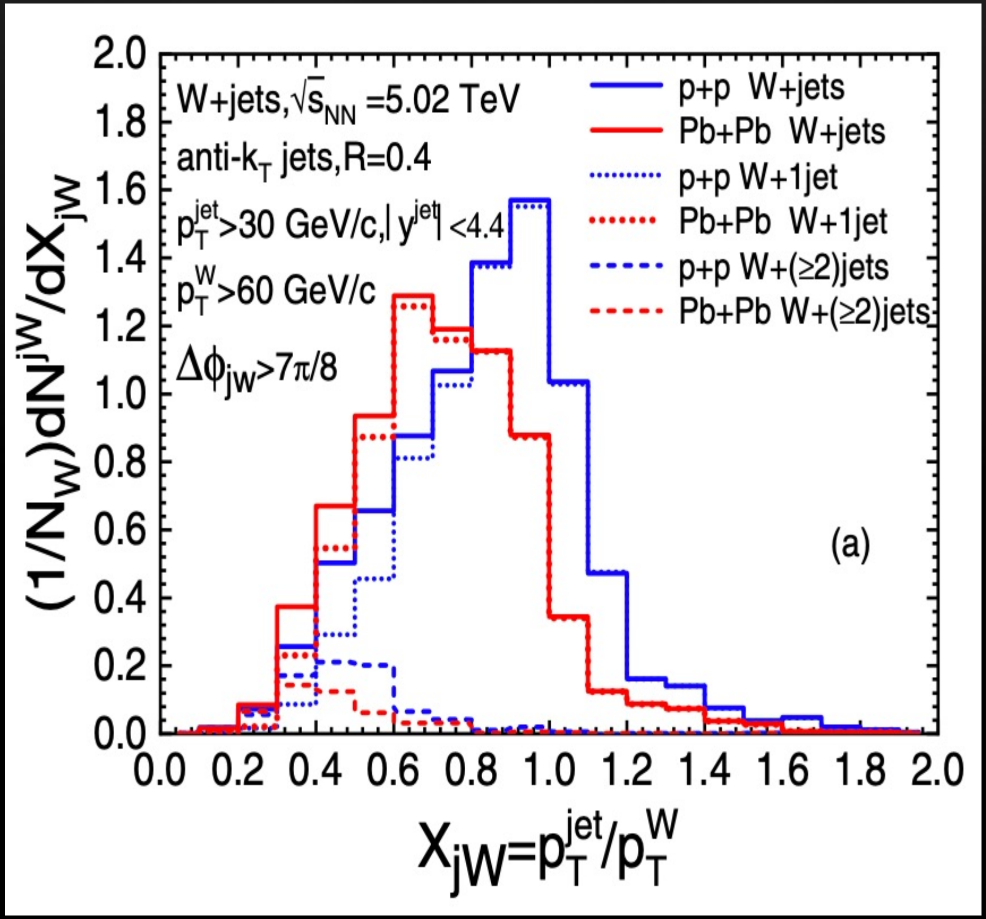
W+jet in HIC at the LHC

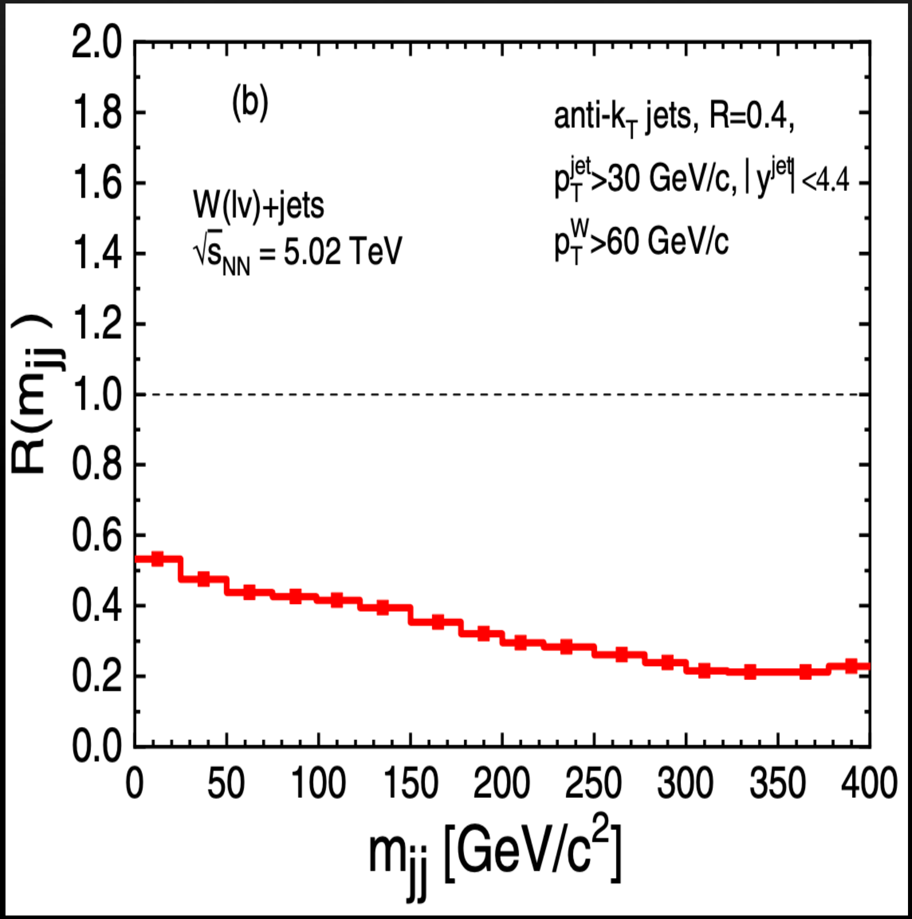


S L Zhang, X N Wang, BWZ, PRC (2022)

W+jet in HIC at the LHC

$$m_{jj} = [(E^L + E^{\mathrm{Sub}\,L})^2 - (\vec{p}^{\,L} + \vec{p}^{\,\mathrm{Sub}\,L})^2]^{1/2}$$



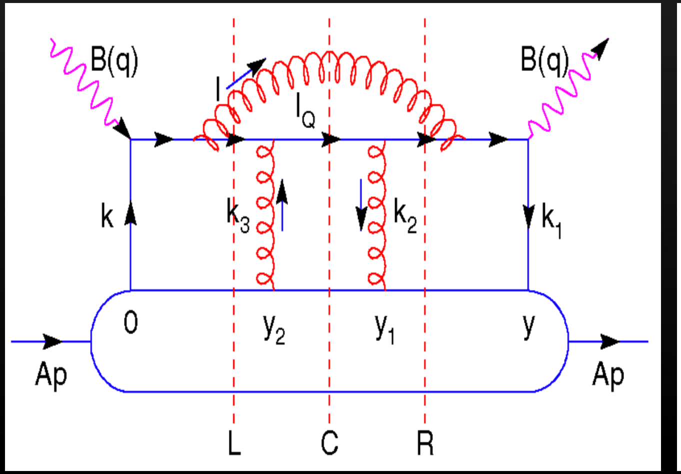


S L Zhang, X N Wang, BWZ, PRC (2022)

Heavy flavor jets

Heavy quark energy loss

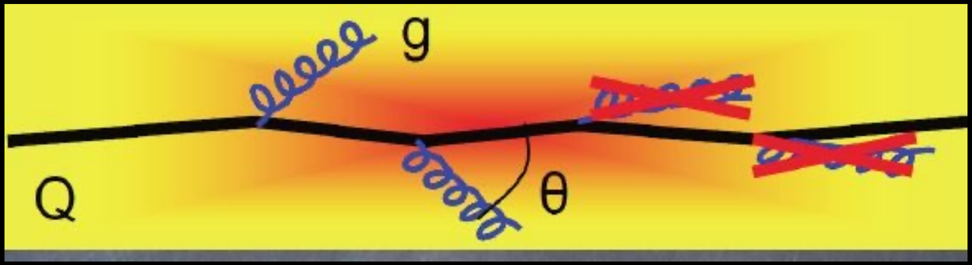
- Heavy quark energy loss will be suppressed due to deadl-cone effect relative to light quark.



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

$$k_\perp = \omega\theta \qquad \omega = xE$$

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



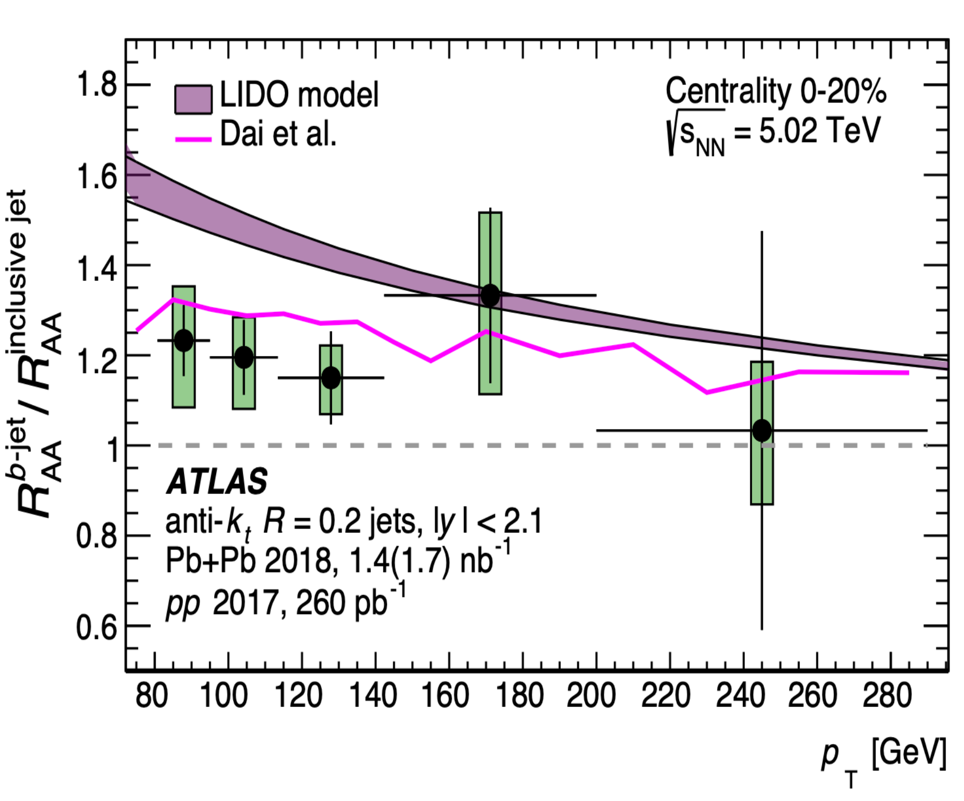
BWZ, E Wang, X N Wang, PRL (2004); NPA (2015)

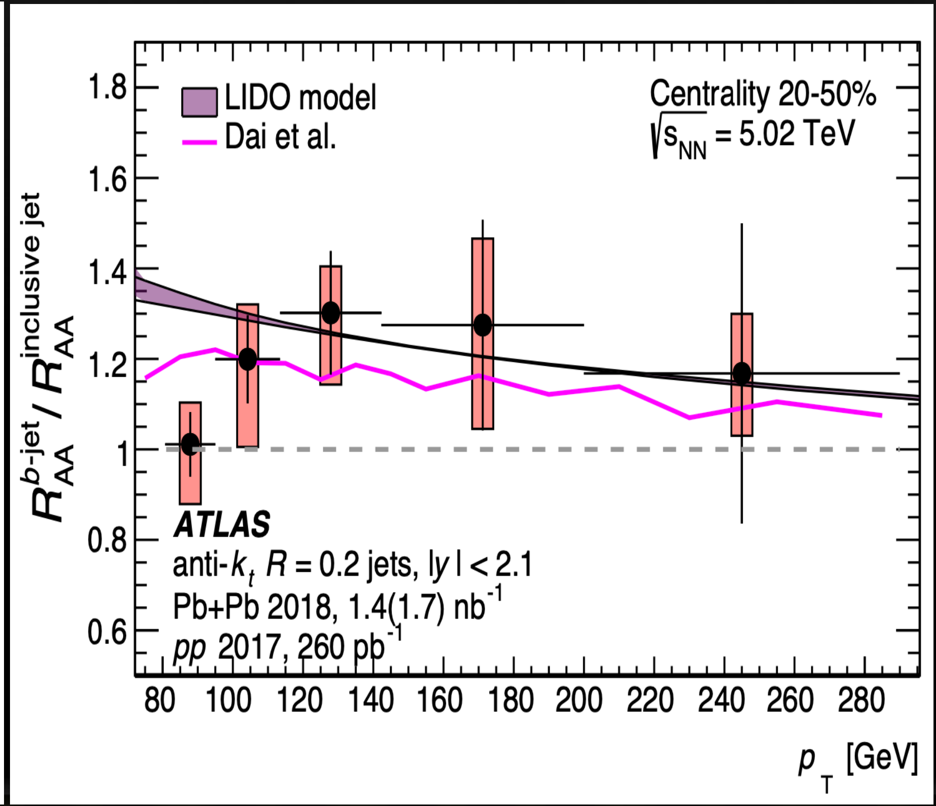
Dokshitzer, Kharzeev, PLB (2011); Djordjevic, Gyulassy, PRC (2013)

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



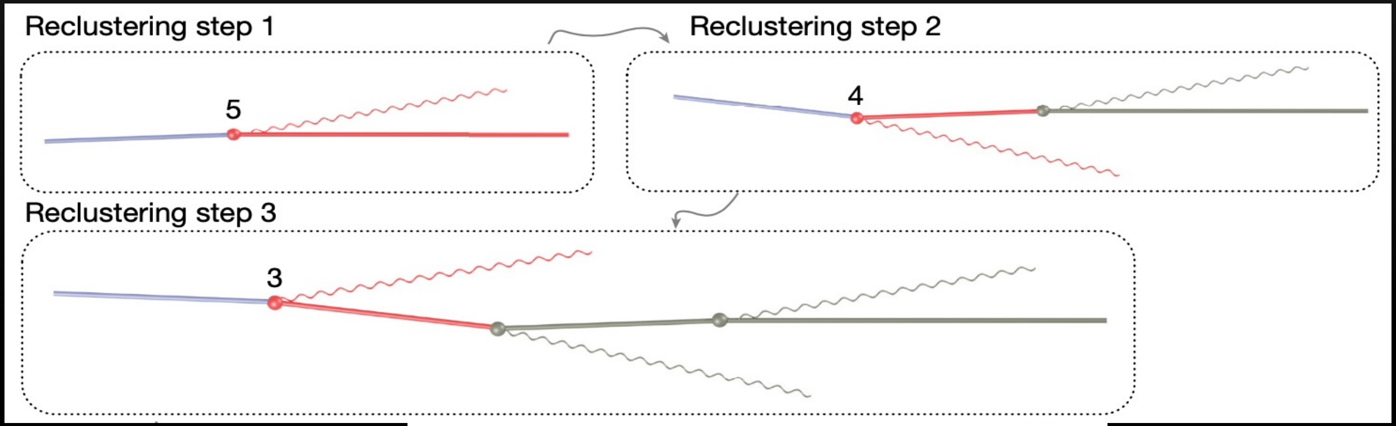


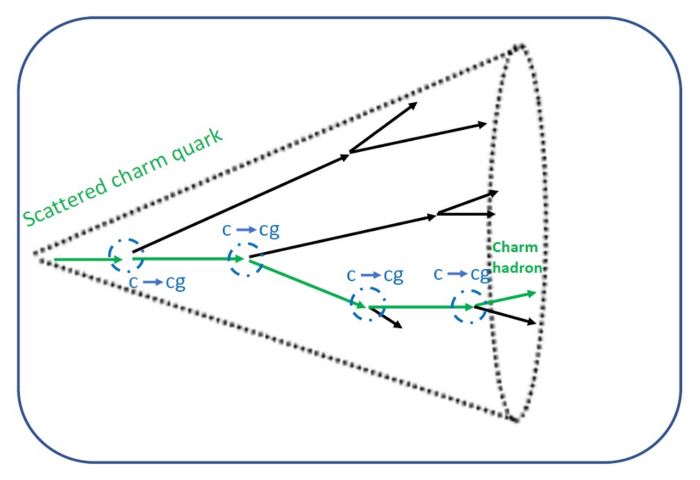
W Dai, S Wang, S Zhang, BWZ, E Wang, CPC (2020)

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

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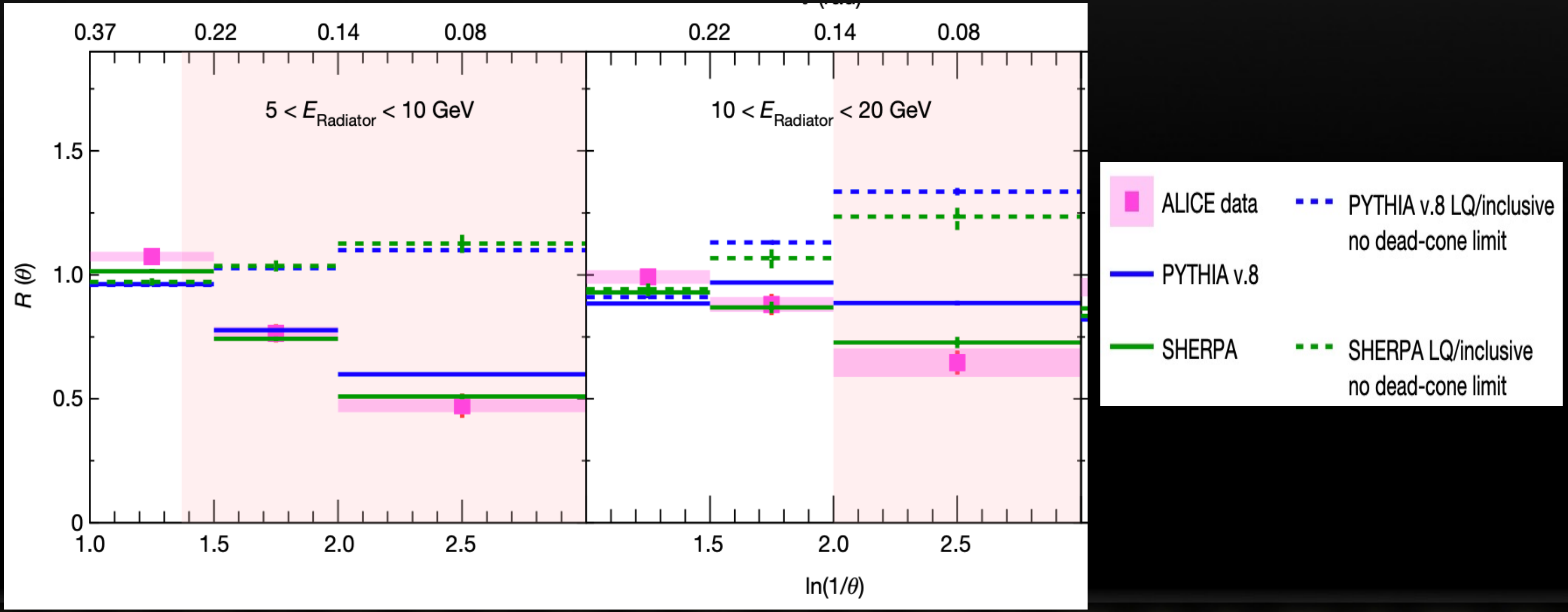
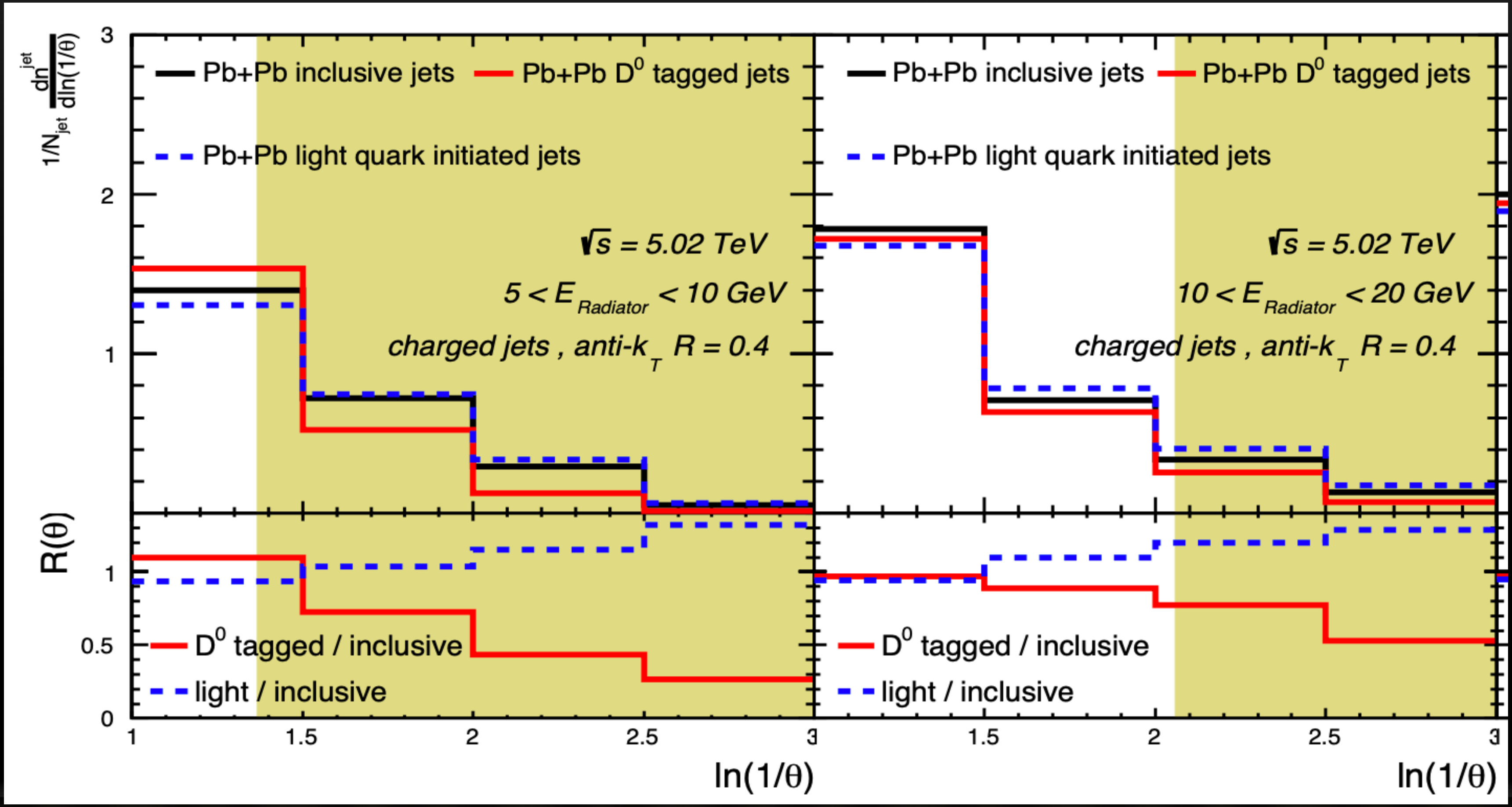
$$R(\theta) = \frac{1}{N^{D^0 \text{jets}}} \frac{dn^{D^0 \text{jets}}}{d\ln(1/\theta)} \Big/ \frac{1}{N^{\text{inclusive jet}}} \frac{dn^{\text{inclusive jet}}}{d\ln(1/\theta)}$$



ALICE, Nature 605 (2022) 440

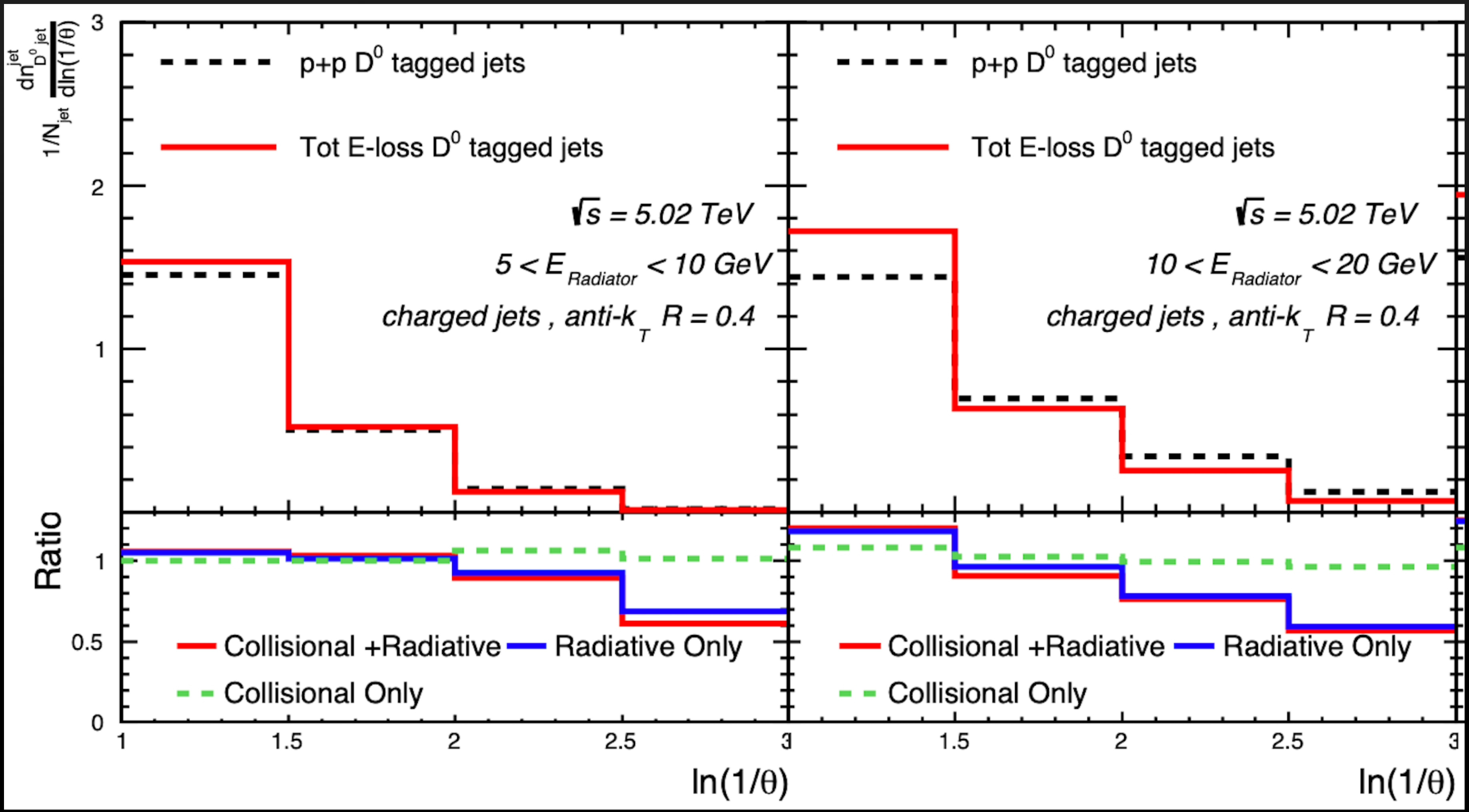
Dead-cone effect in A+A

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



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

Dead-cone effect in A+A



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

Mean value of emission angle

E_{Radiator}	Inclusive jets	D^0 jets	
	$\langle\theta\rangle_{\mathrm{jets}}$	$\langle\theta\rangle_{\mathrm{jets}}$	
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

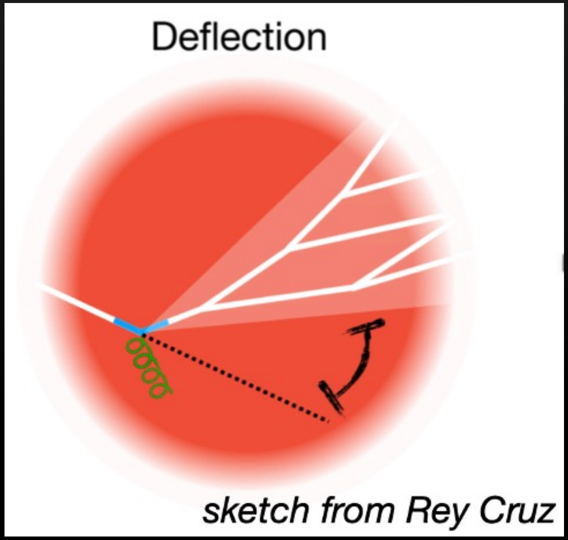
W Dai, M Z Li, BWZ, E Wang, arXiv: 2205.14668

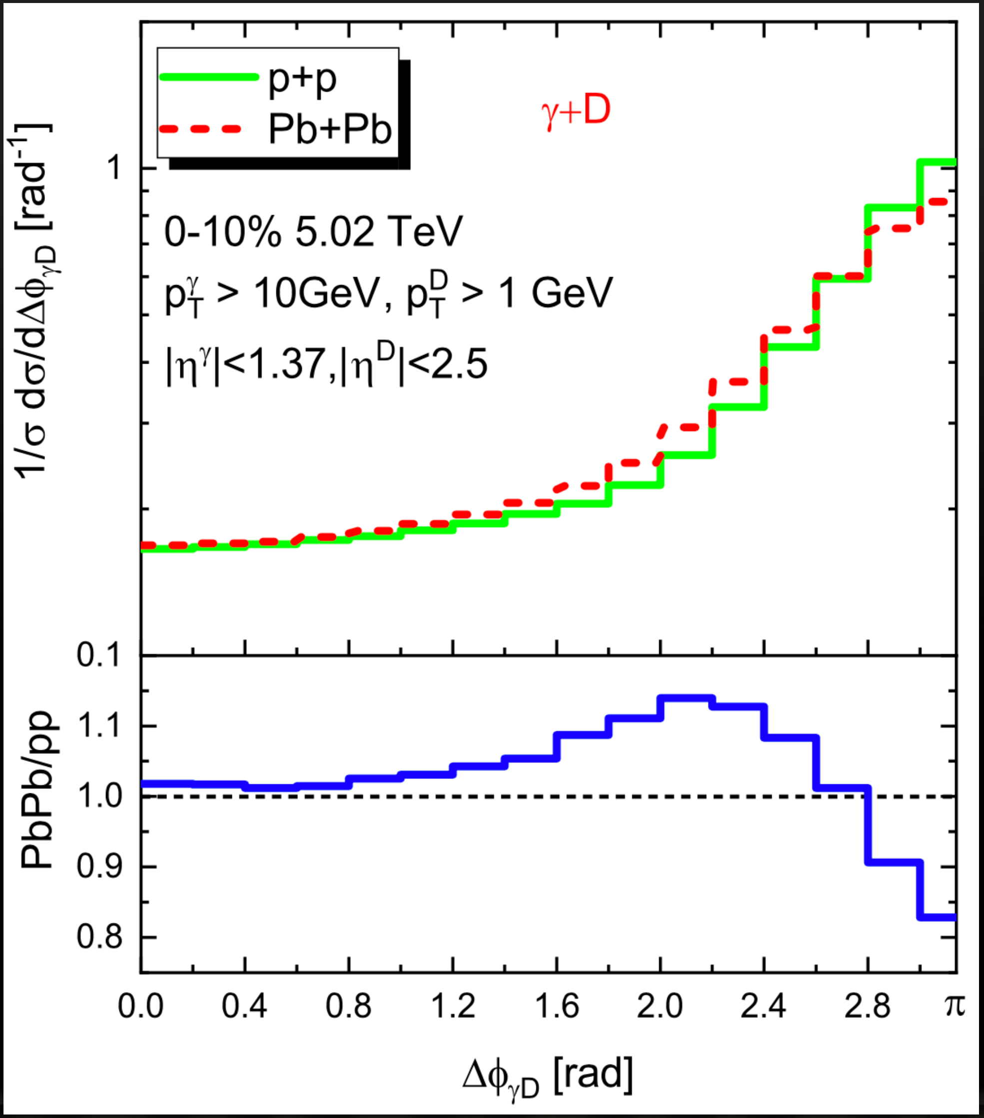
Mean value of emission angle

E_{Radiator}	Inclusive jets		D^0 jets		
	$\langle\theta\rangle_{\mathrm{spl}}$	$\mathrm{N}_{\mathrm{spl}}$	$\langle\theta\rangle_{\mathrm{spl}}$	$\mathrm{N}_{\mathrm{spl}}$	
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

Momentum deflection of gamma+D





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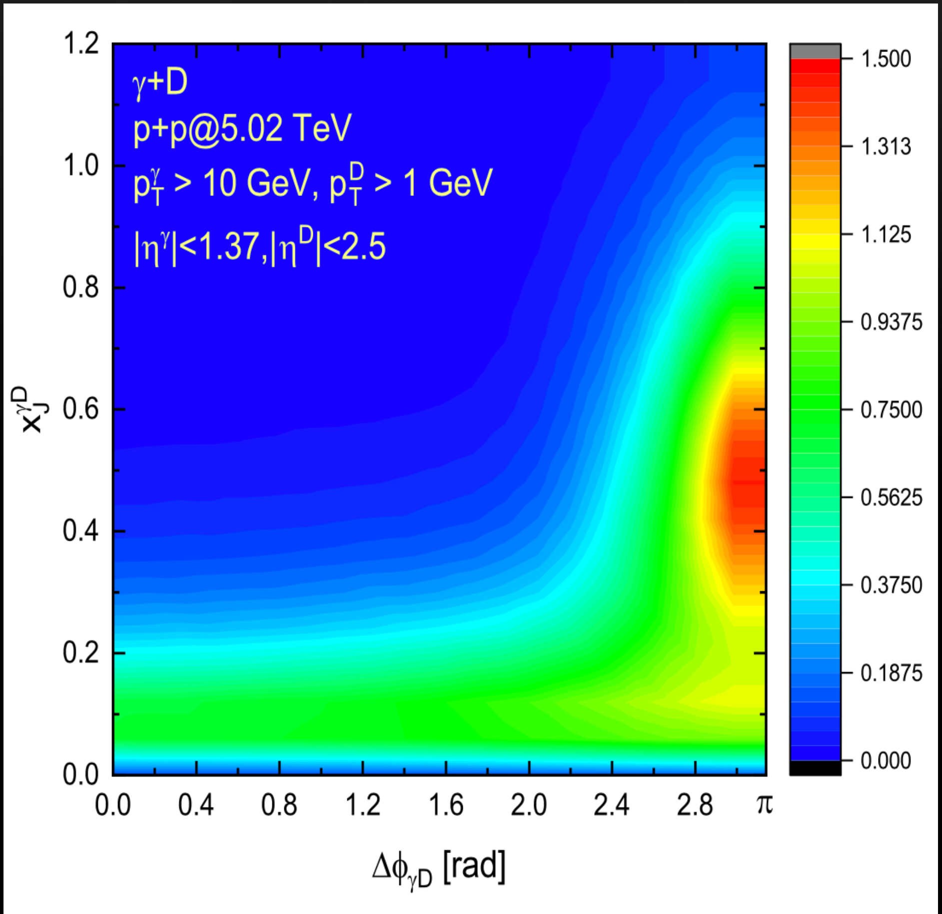
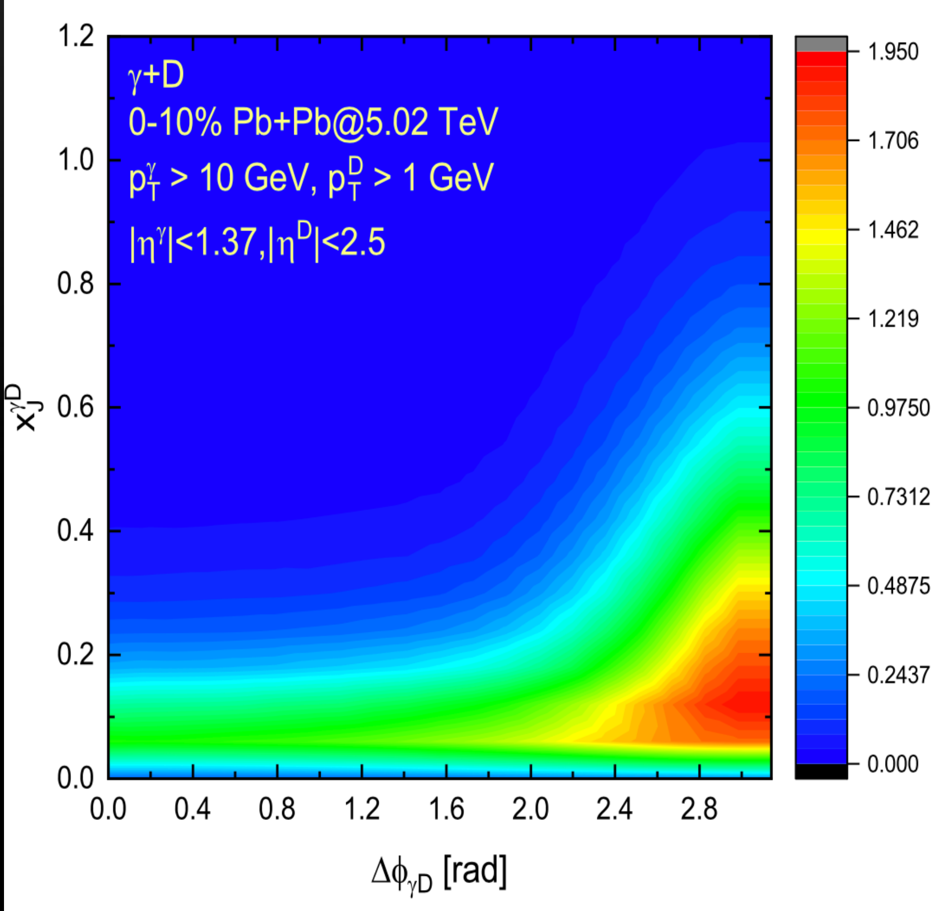
Momentum deflection of gamma+D

$$x_J^{\gamma D} = p_T^D / p_T^\gamma$$





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Summary

- A systematic study of identified mesons at NLO in HIC has been made.
- A framework of combining NLO+PS for initial hard production with parton energy loss in the QGP has been developed.
- Our calculations provide nice descriptions of experimental data on full jet observables.
- A direct observation of dead-cone effect of jet quenching is possible by studying the emission angle of heavy flavor tagged jets in HIC.

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