Rendezvous with the QGP: Jet Observables

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

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Outline

- Introduction
- Full jet observables

1） splitting scales

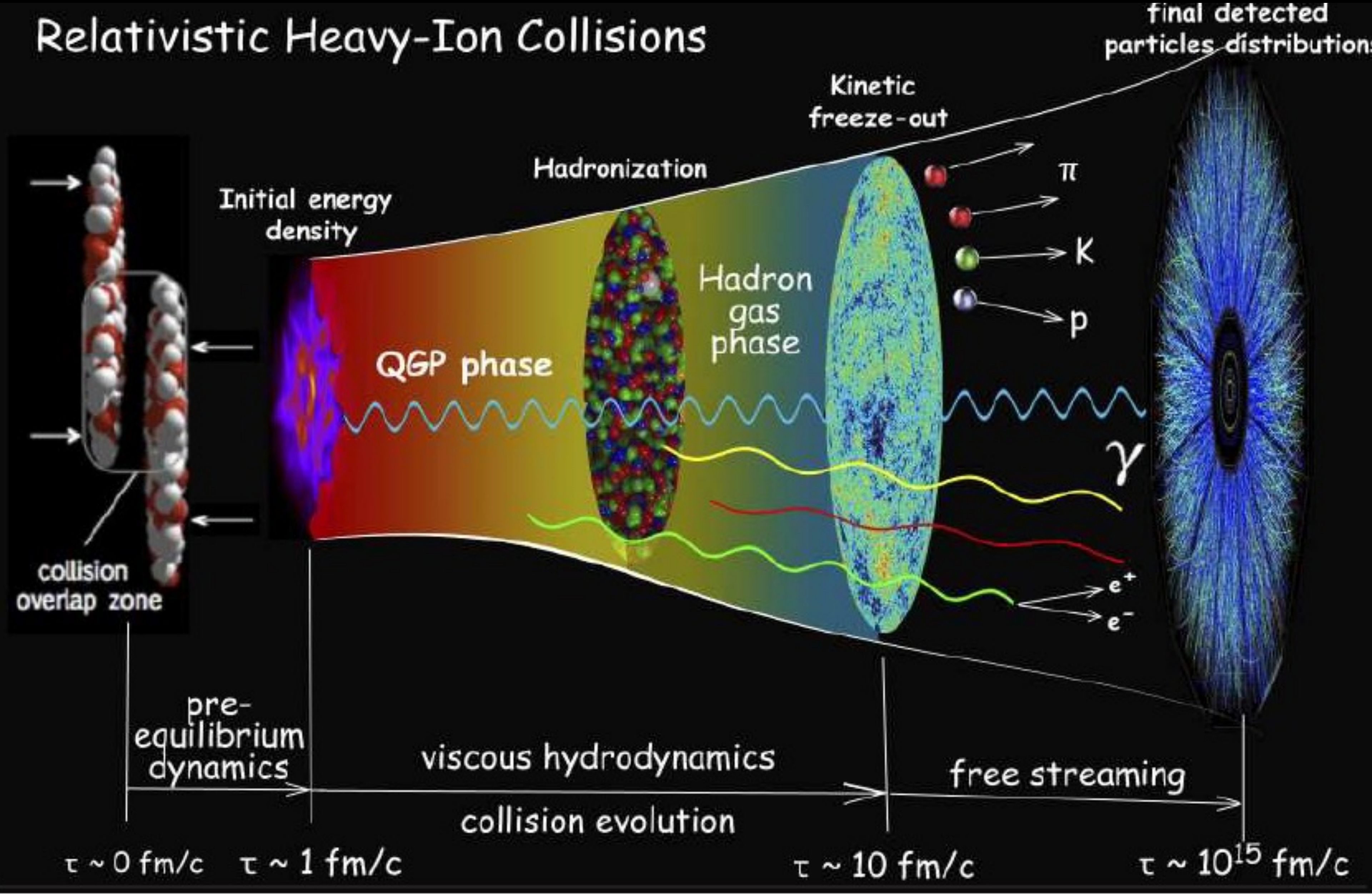
2) dead-cone effect of jet quenching

3） transverse sphericity

4) jet broadening

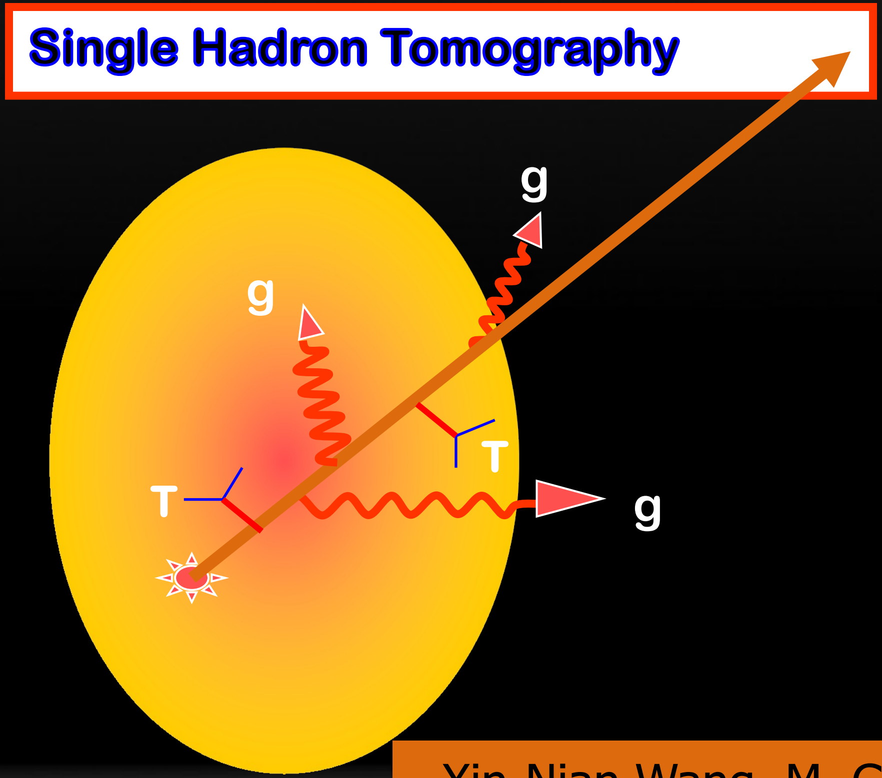
- Summary

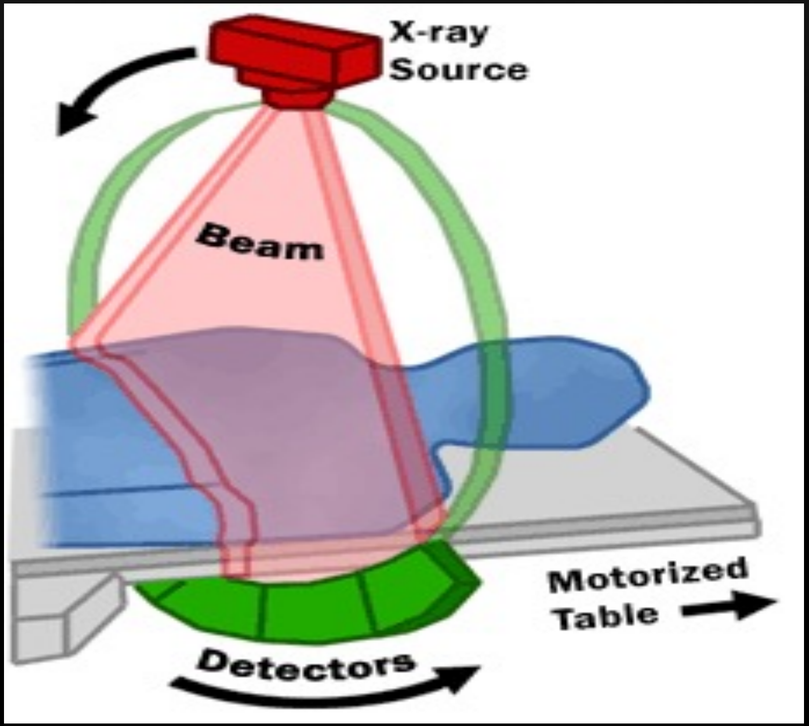
The Little Bang



Jet quenching

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

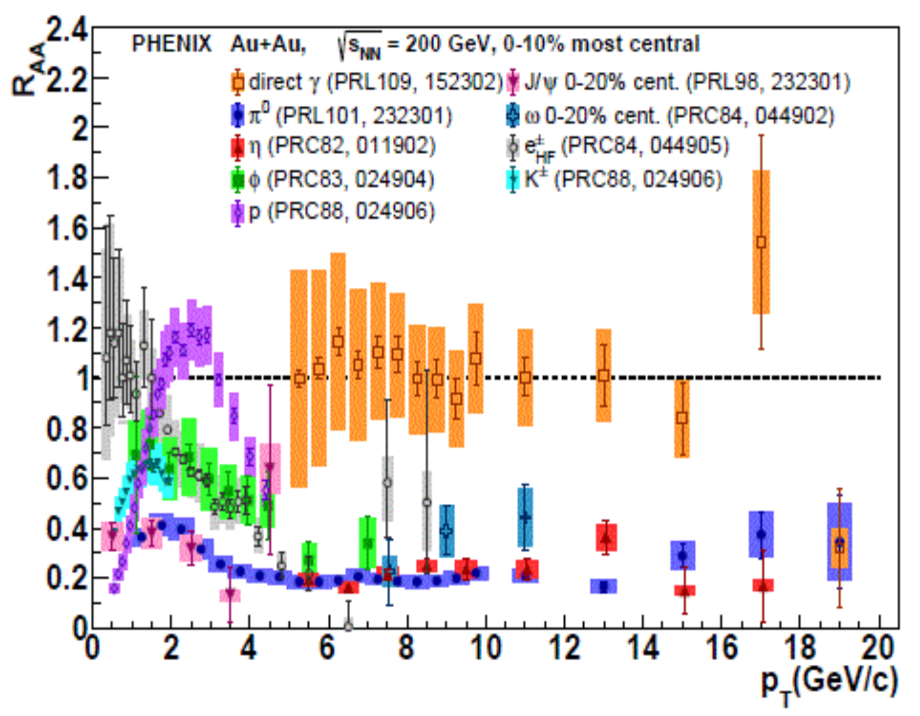


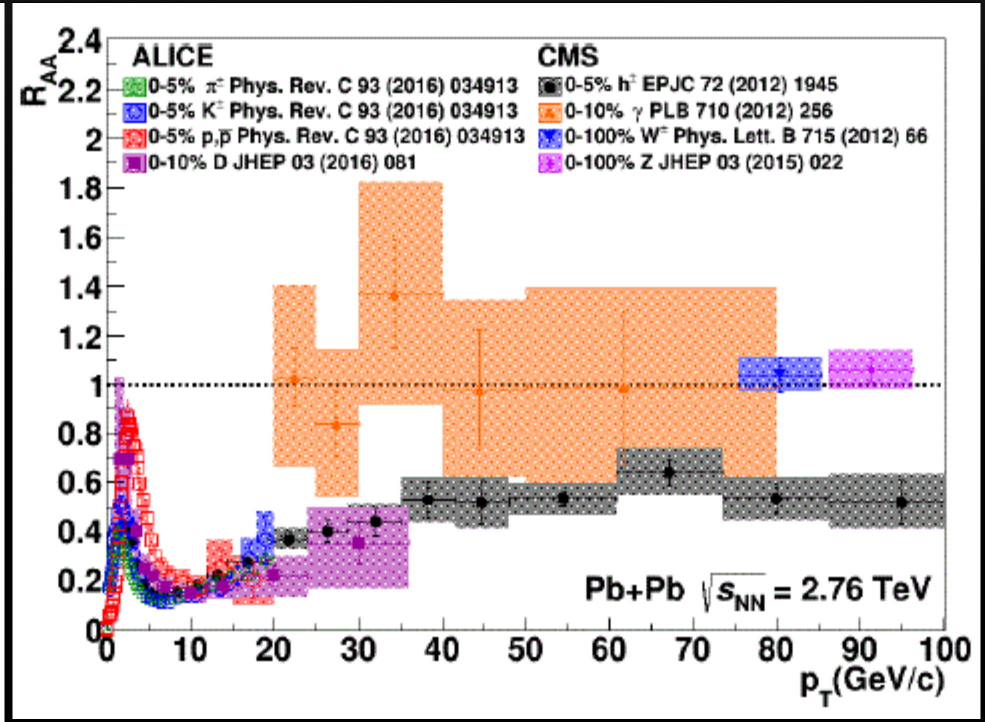


Xin-Nian Wang, M. Gyulassy, PRL68(1992)1480

Jet quenching at RHIC and LHC

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



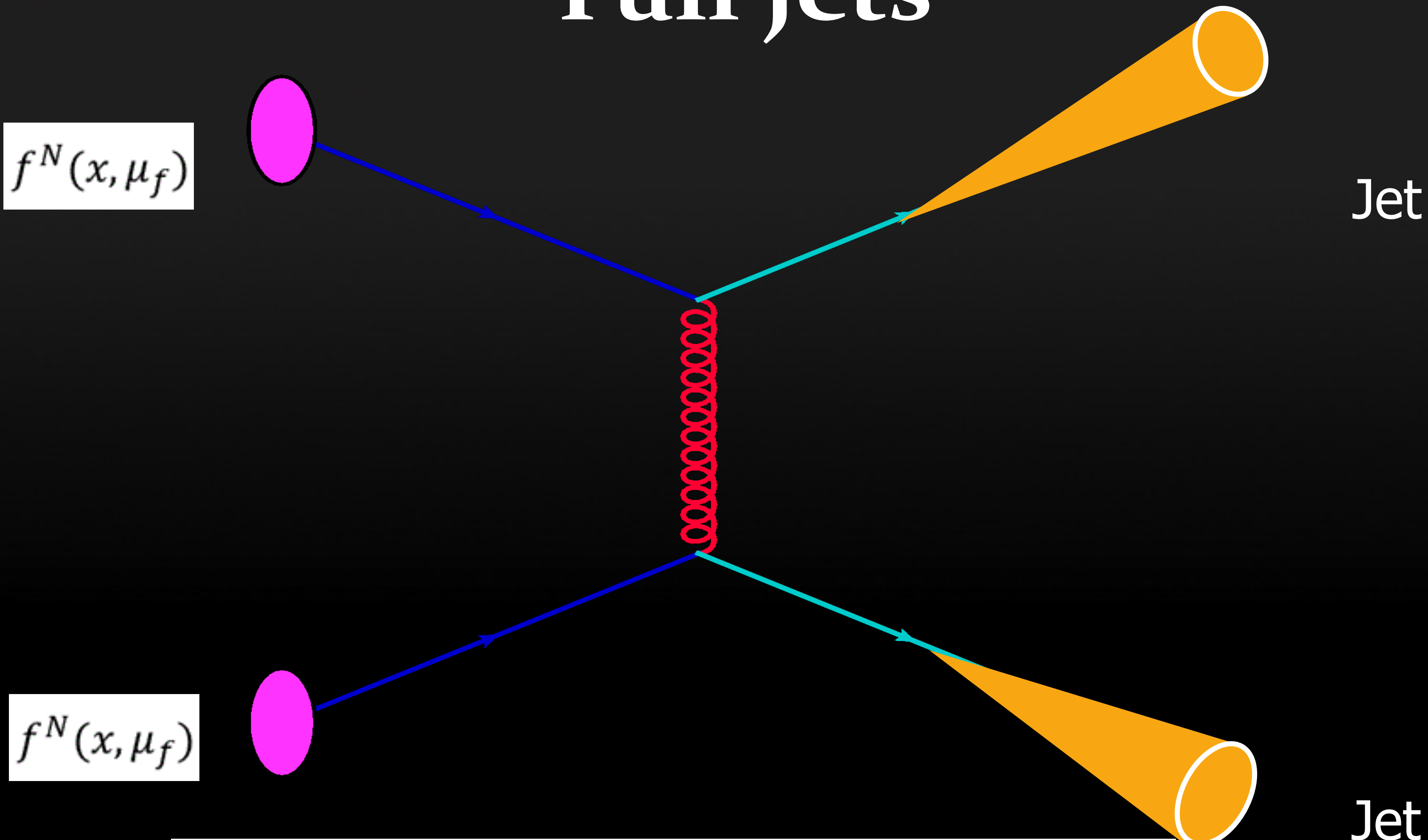


Fingerprints of jet quenching

领头强子

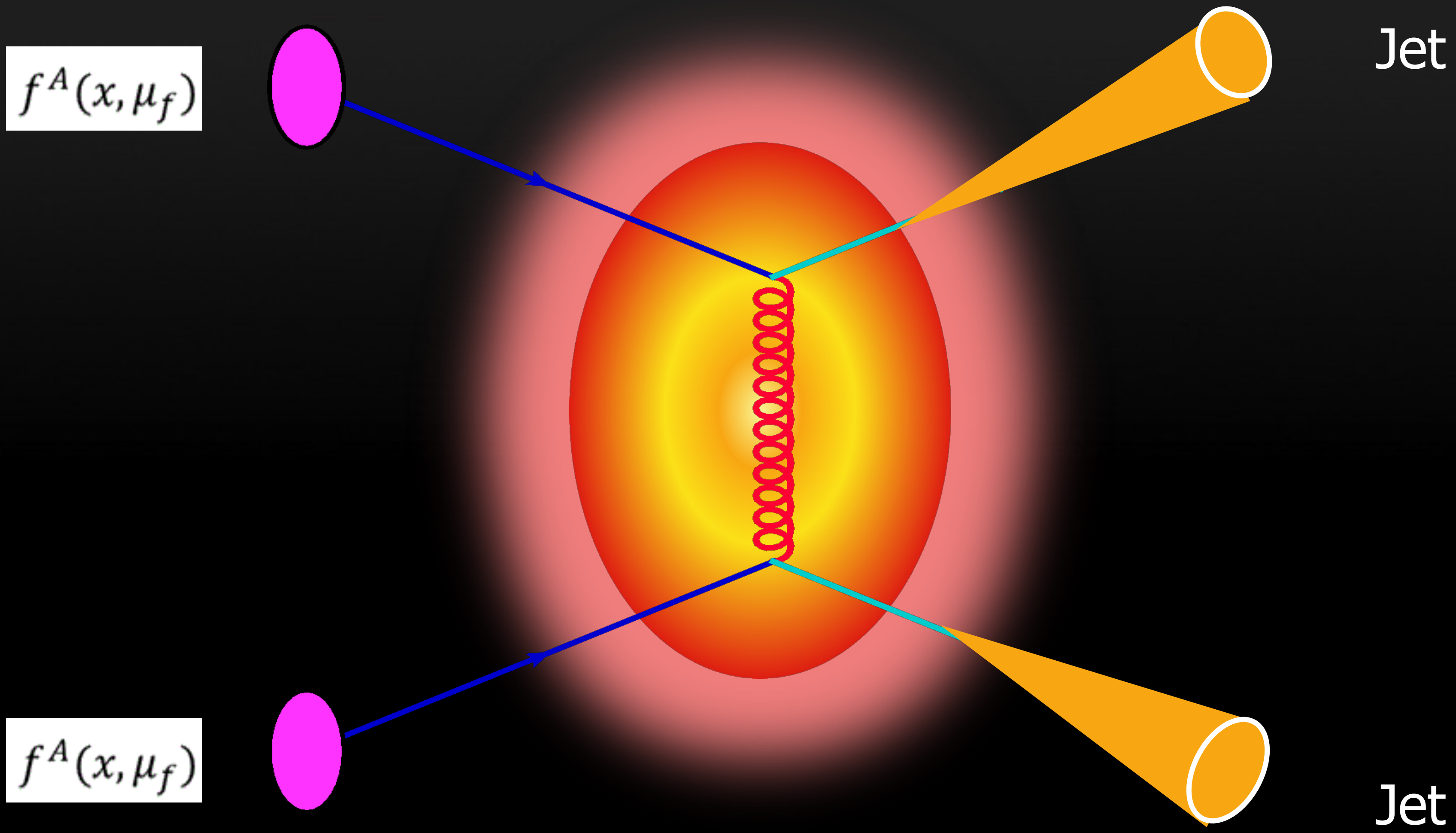
整体喷注

Full jets

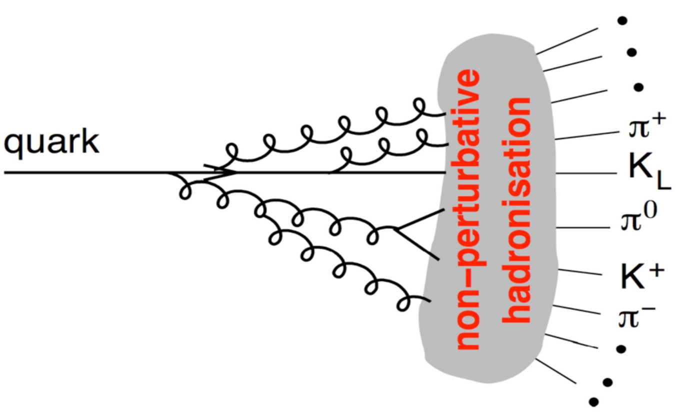


$$\frac{d\sigma^{\text{jet}}}{dE_T dy} = \frac{1}{2!}\int d\{E_T, y, \phi\}_2 \frac{d\sigma[2\longrightarrow 2]}{d\{E_T, y, \phi\}_2} S_2(\{E_T, y, \phi\}_2)$$
$$+\frac{1}{3!}\int d\{E_T, y, \phi\}_3 \frac{d\sigma[2\longrightarrow 3]}{d\{E_T, y, \phi\}_3} S_3(\{E_T, y, \phi\}_3).$$

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:

$$\{p_i\} \xrightarrow{\text{jet algorithm}} \{j_k\}$$

particles,
4-momenta,
calorimeter towers, ...

jets

World inside a jet

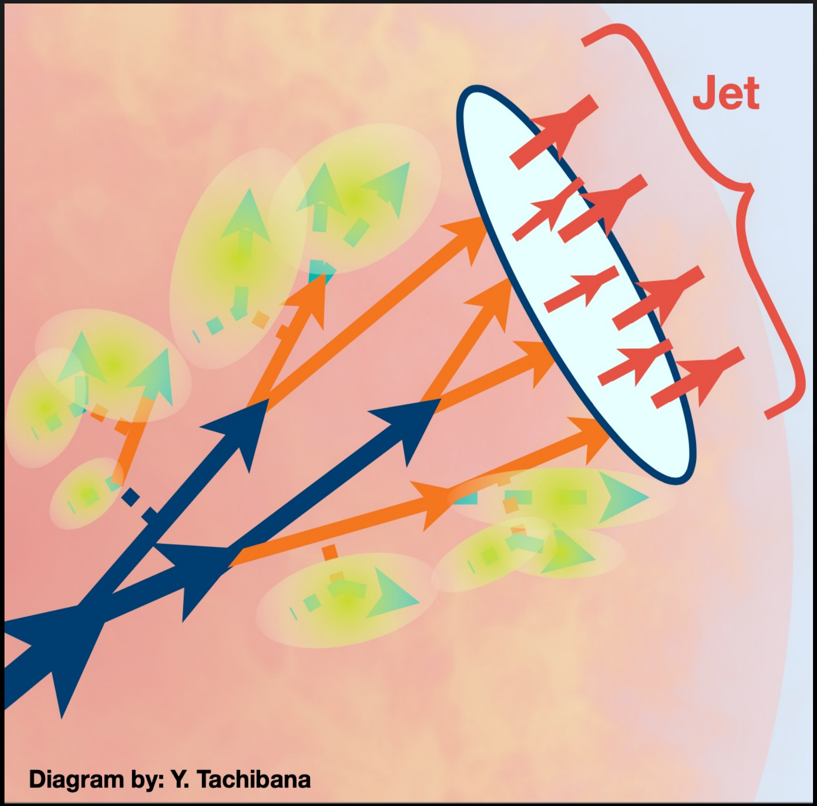
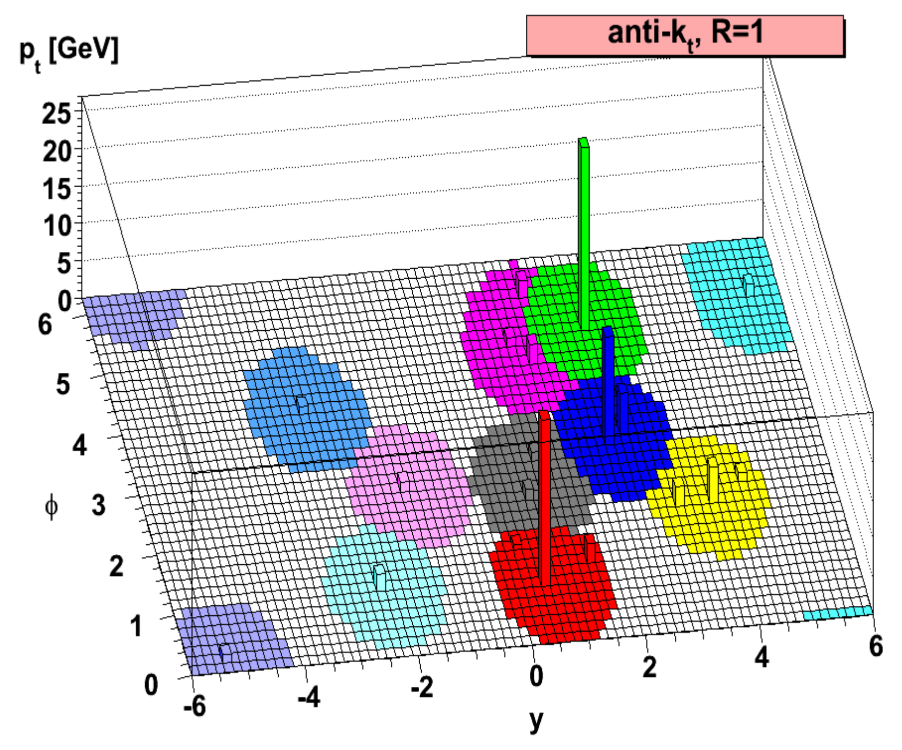


Diagram by: Y. Tachibana



Observables related to full jets

inclusive jets;
di-jets;
gamma + jet;
Z/W + jet;
heavy flavor jets;

……

jet yields

jet shape;
jet FF;
angularity;
splitting scale;
groomed jets;

……

jet substructure

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

……

Inter-jet properties

Jets in quark soup

FEBRUARY 24, 2020

BLOG

The Quark Soup

Reclustered large radius jets

Cal towers & UE subtraction

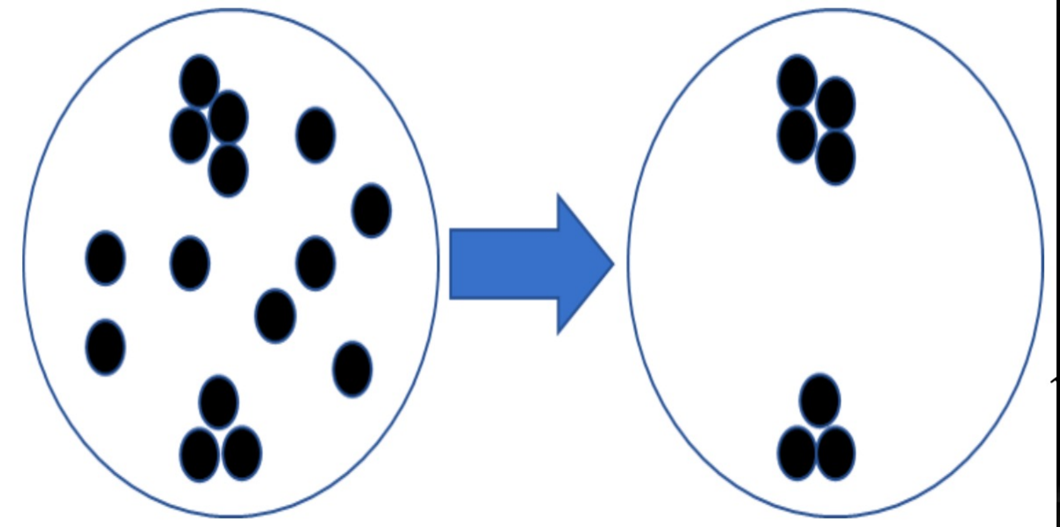
clustering with anti-kt R=0.2 $p_T > 35GeV$

re-clustering with anti-kt R=1.0

subjets

reclustering with kt algorithm

splitting scale $\sqrt{d_{12}}$



remove soft radiation

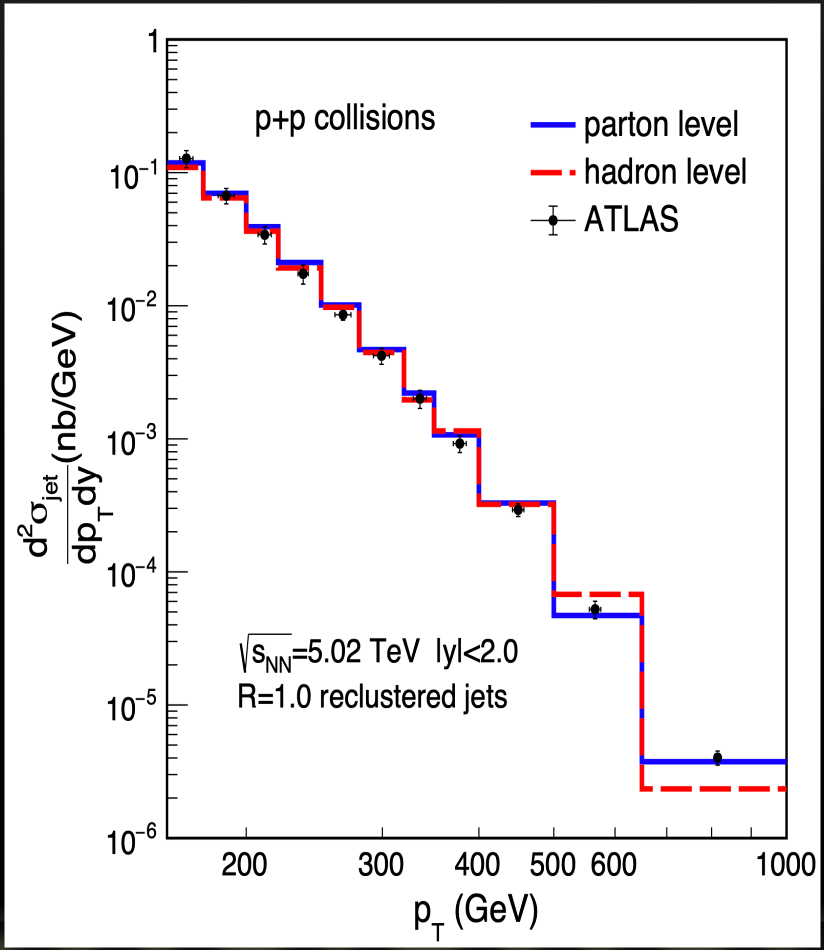
splitting scale

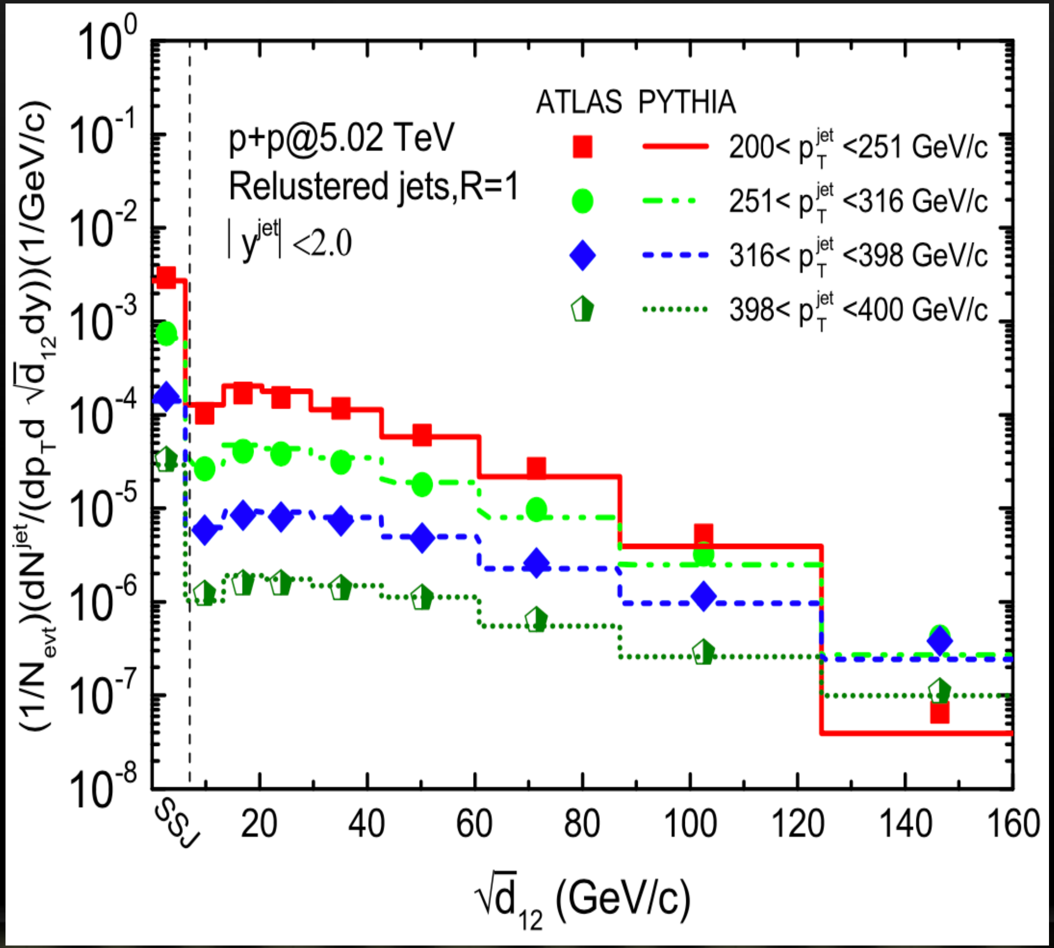
$$d_{12} = min(p_{T1}^2, p_{T2}^2) \cdot \Delta R_{12}^2 / R^2,$$

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

Reclustered LR jets in p+p

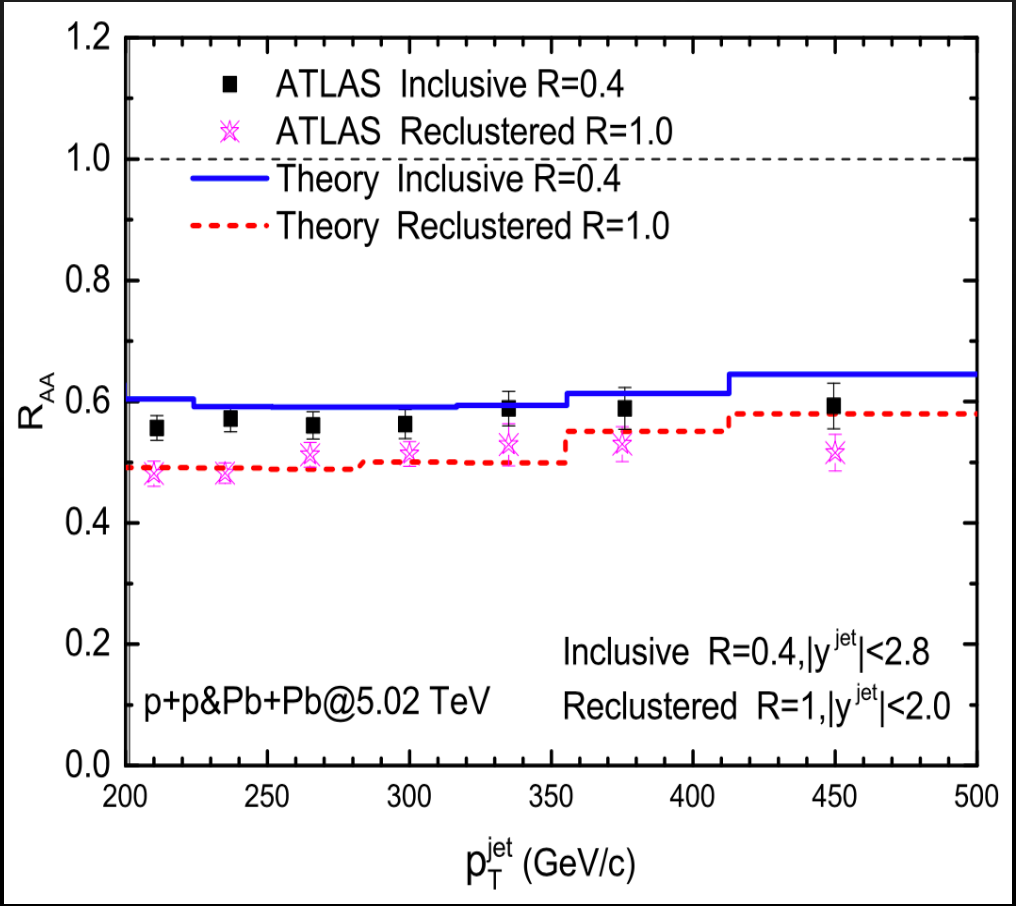
$$\sqrt{d_{12}} = \sqrt{min(p^2_{T,1}, p^2_{T,2}) * \Delta R^2_{12}}$$

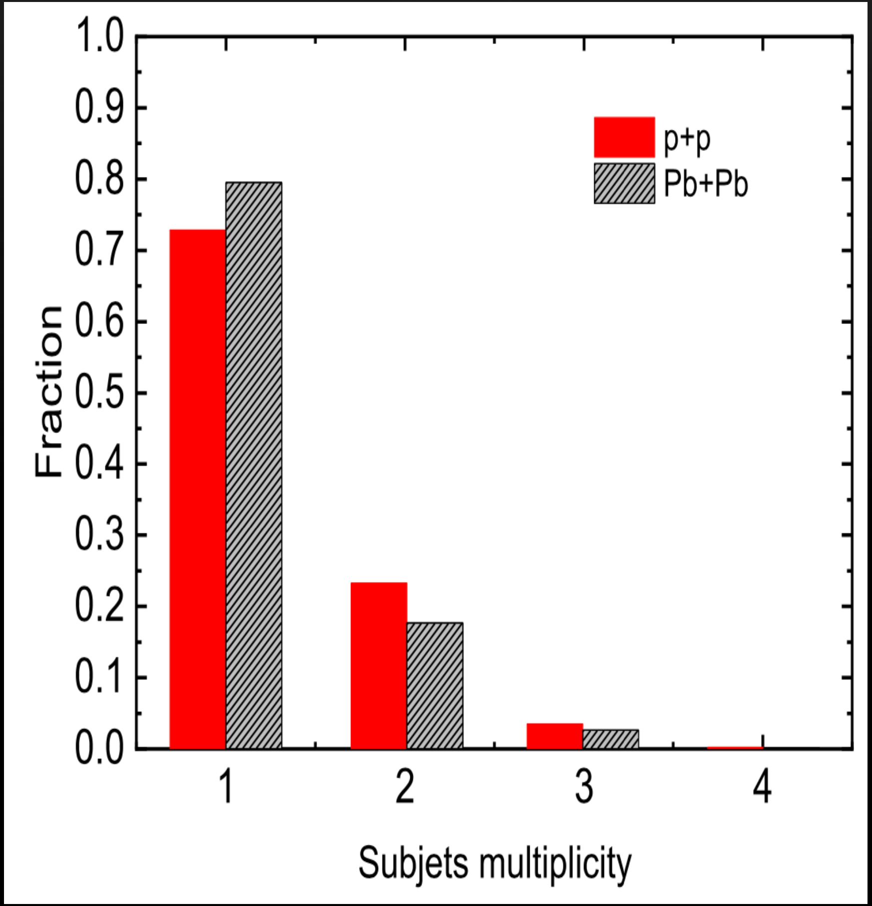




Nuclear modifications

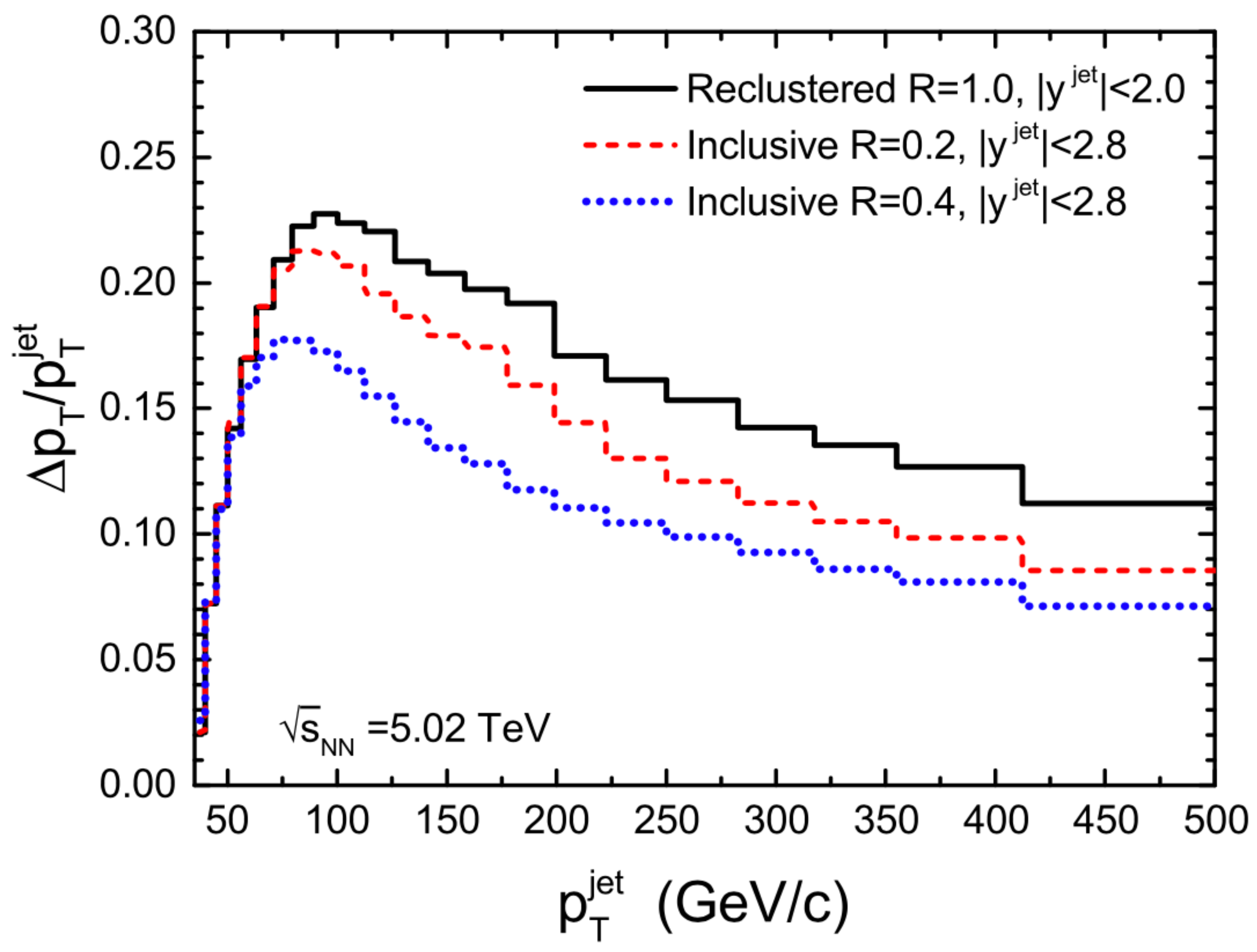
- Nuclear suppression of reclustered LR jets at R=1.0 is larger than that of inclusive jets with R=0.4.



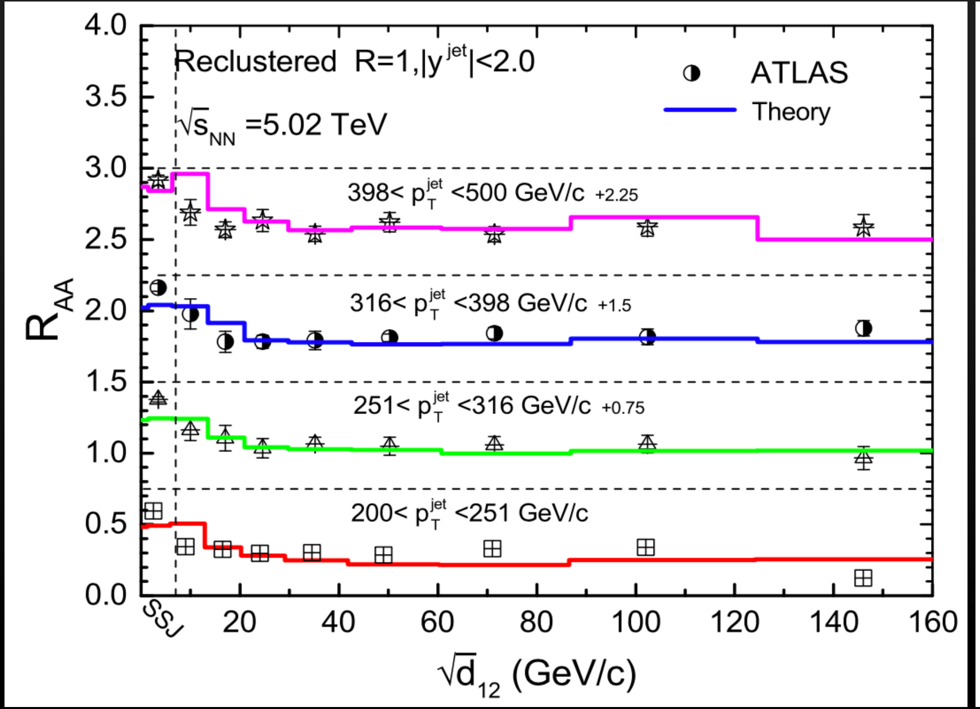


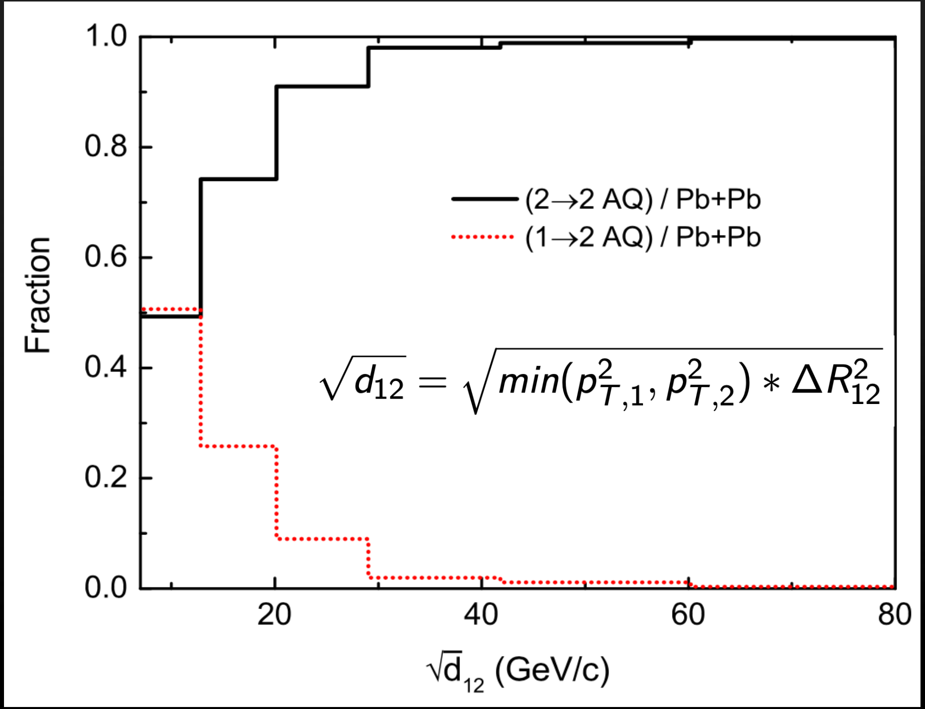
S L Zhang, M Q Yang, BWZ, EPJC (2022)

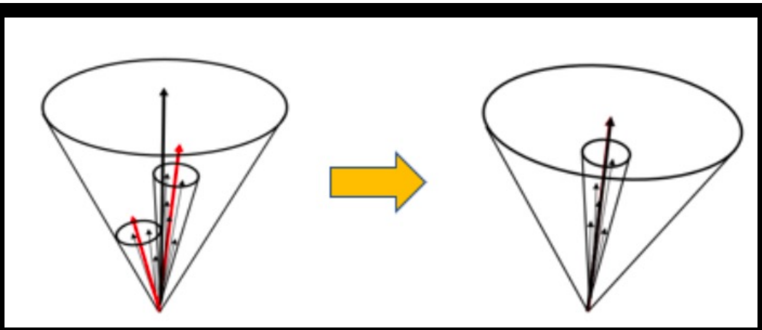
Energy loss fraction

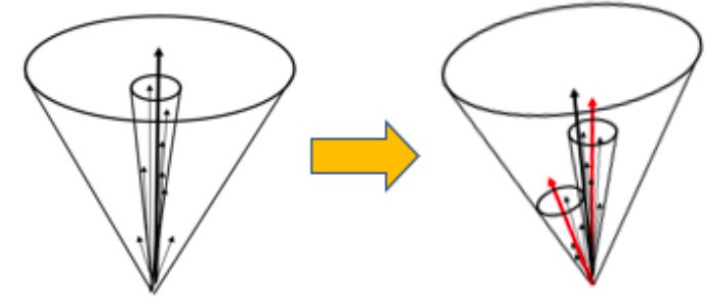


Energy loss of reclustered jets







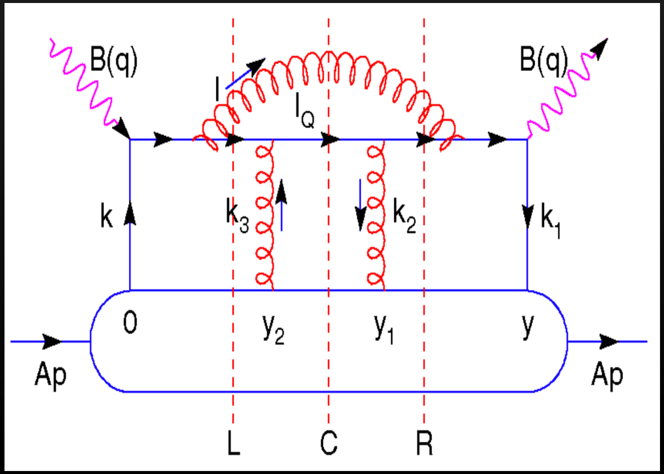


S L Zhang, M Q Yang, BWZ, EPJC (2022)

Heavy flavor jets

Heavy quark energy loss

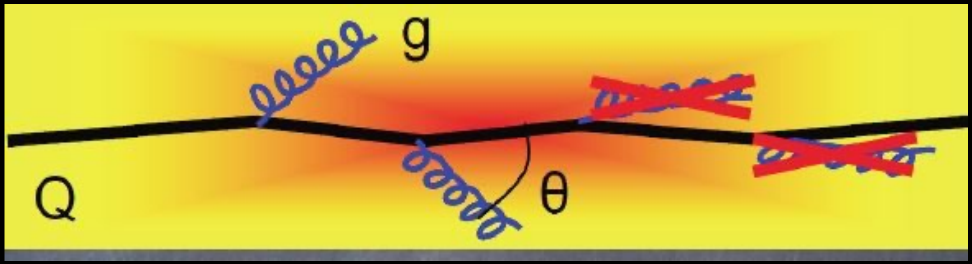
- Heavy quark energy loss will be suppressed due to deadl-cone effect relative to light quark.



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

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

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



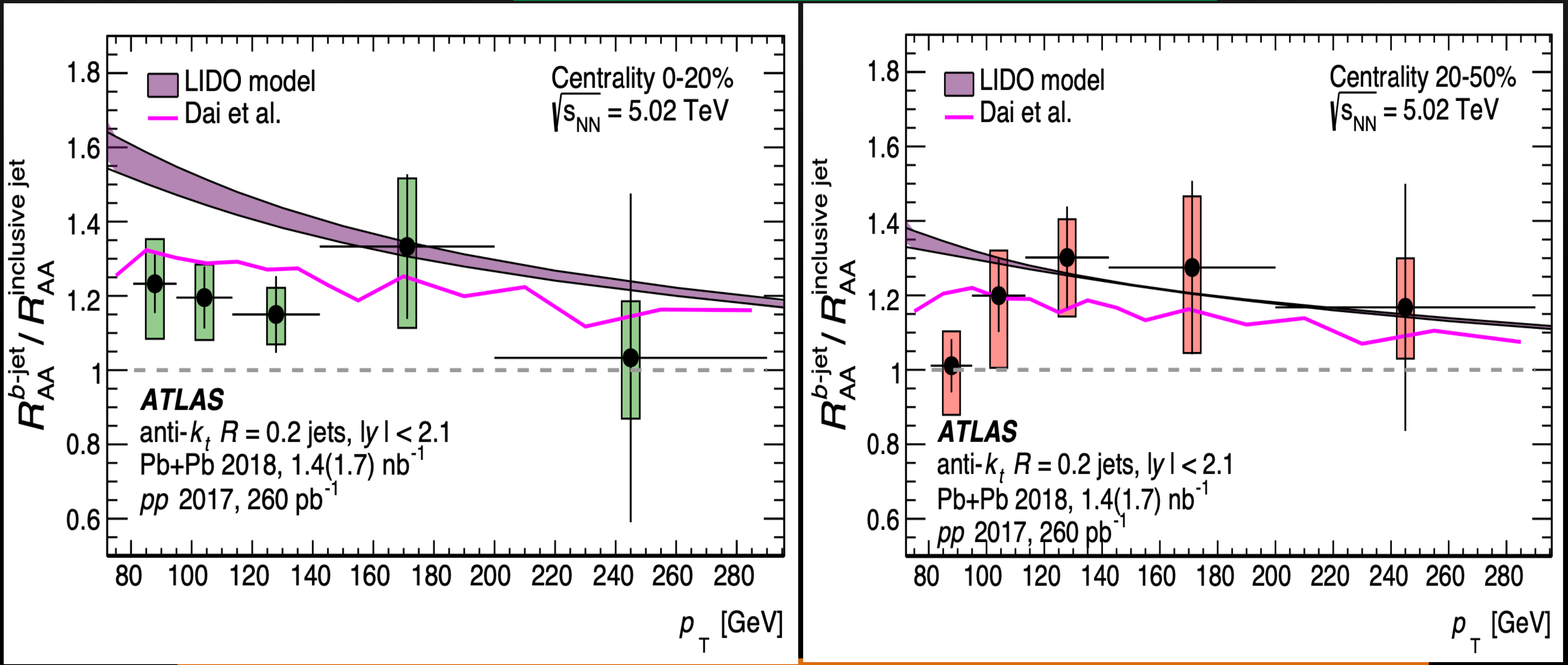
BWZ, E Wang, X N Wang, PRL (2004); NPA (2005)

Dokshitzer, Kharzeev, PLB (2001); Djordjevic, Gyulassy, PRC (2003)

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



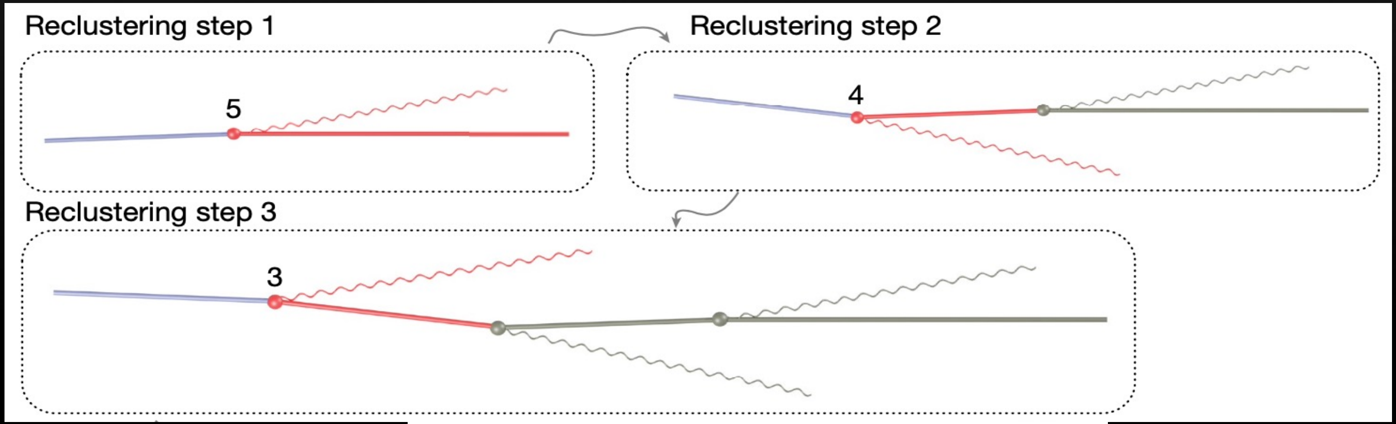
W Dai, S Wang, S Zhang, BWZ, E Wang, CPC (2020)

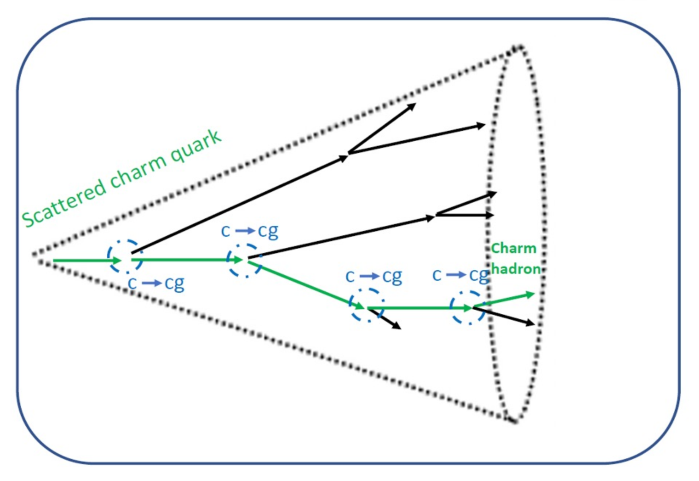
S Wang, Dai, E Wang, X Wang, BWZ, Symmetry (2023)

Dead-cone effect in vacuum

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

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

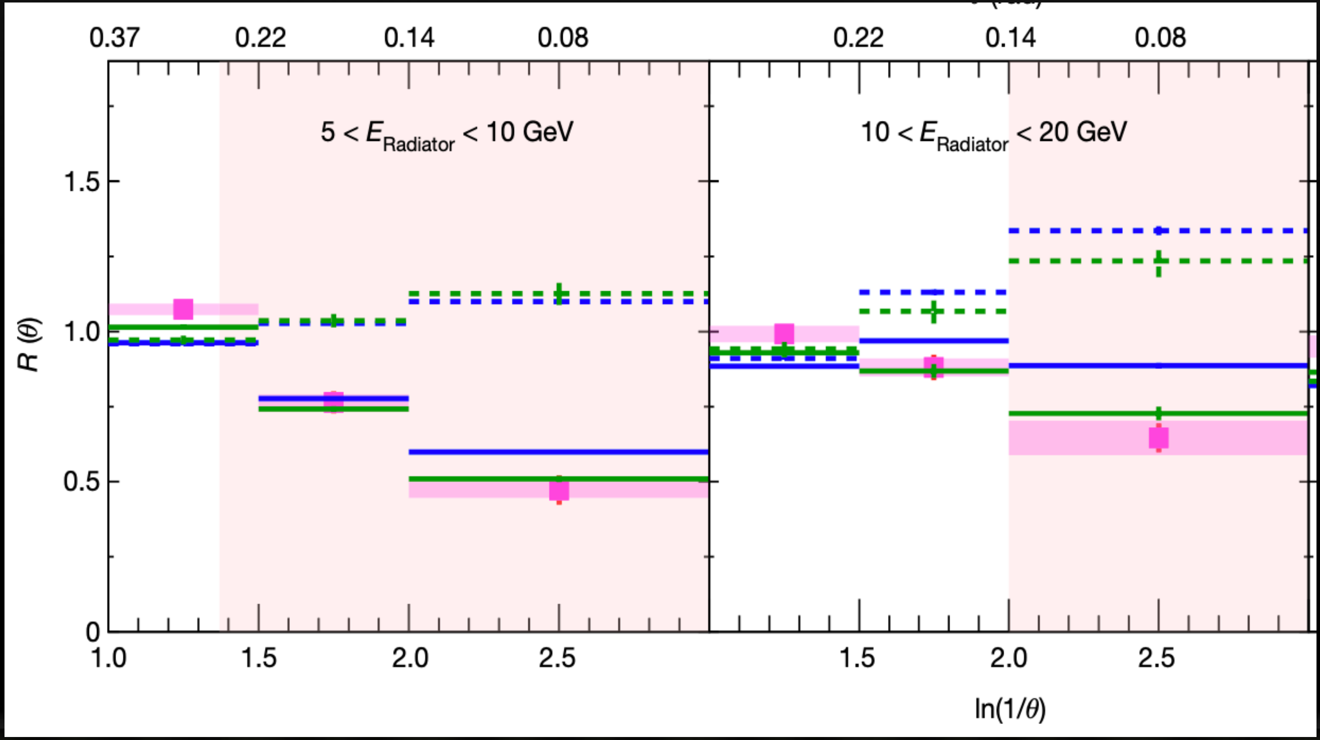




Dead-cone effect in vacuum

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

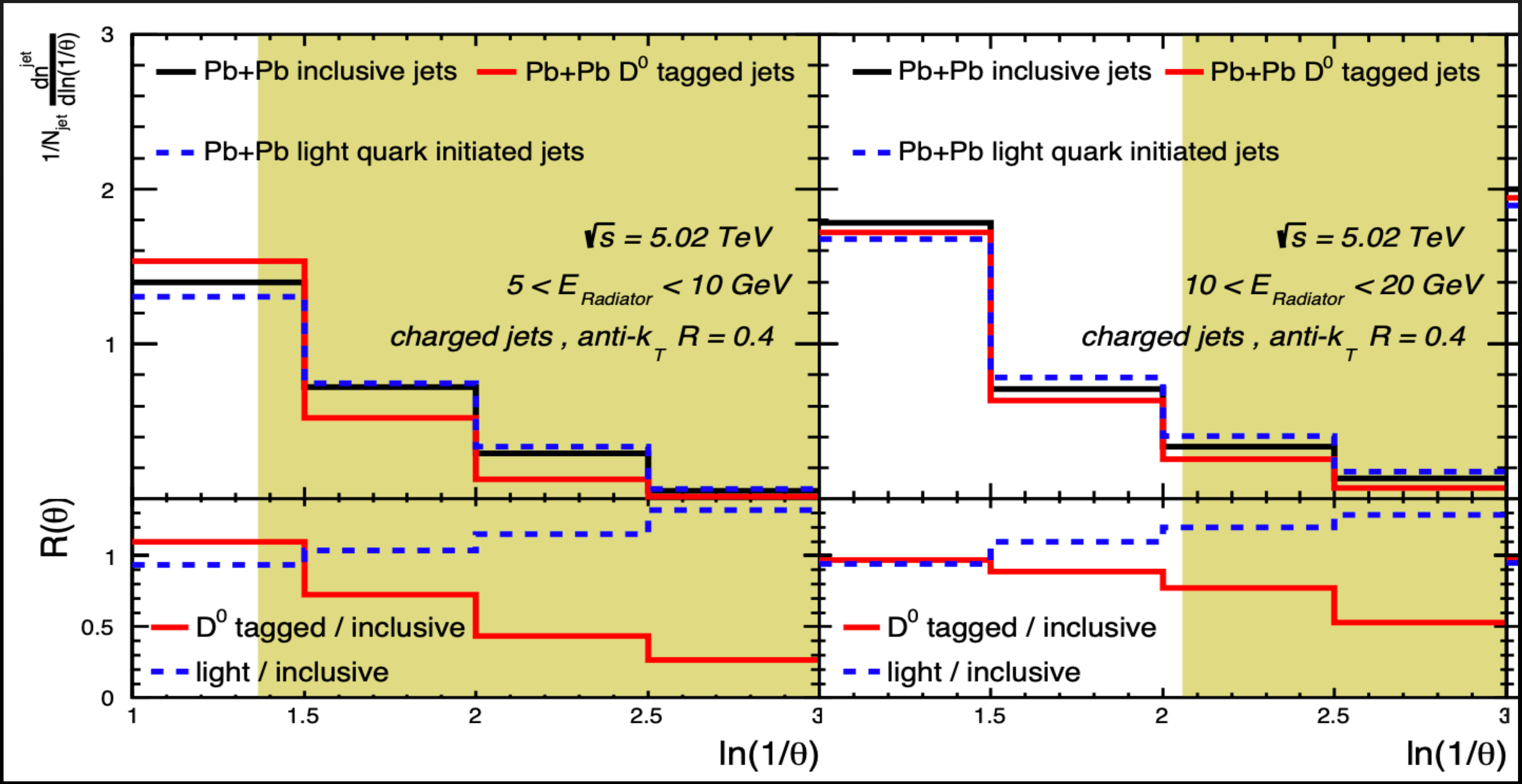
$$R(\theta) = \frac{1}{N^{D^0\text{jets}}}\frac{dn^{D^0\text{jets}}}{d\ln(1/\theta)} \Big/ \frac{1}{N^{\text{inclusive jet}}}\frac{dn^{\text{inclusive jet}}}{d\ln(1/\theta)}$$



ALICE, Nature 605 (2022) 440

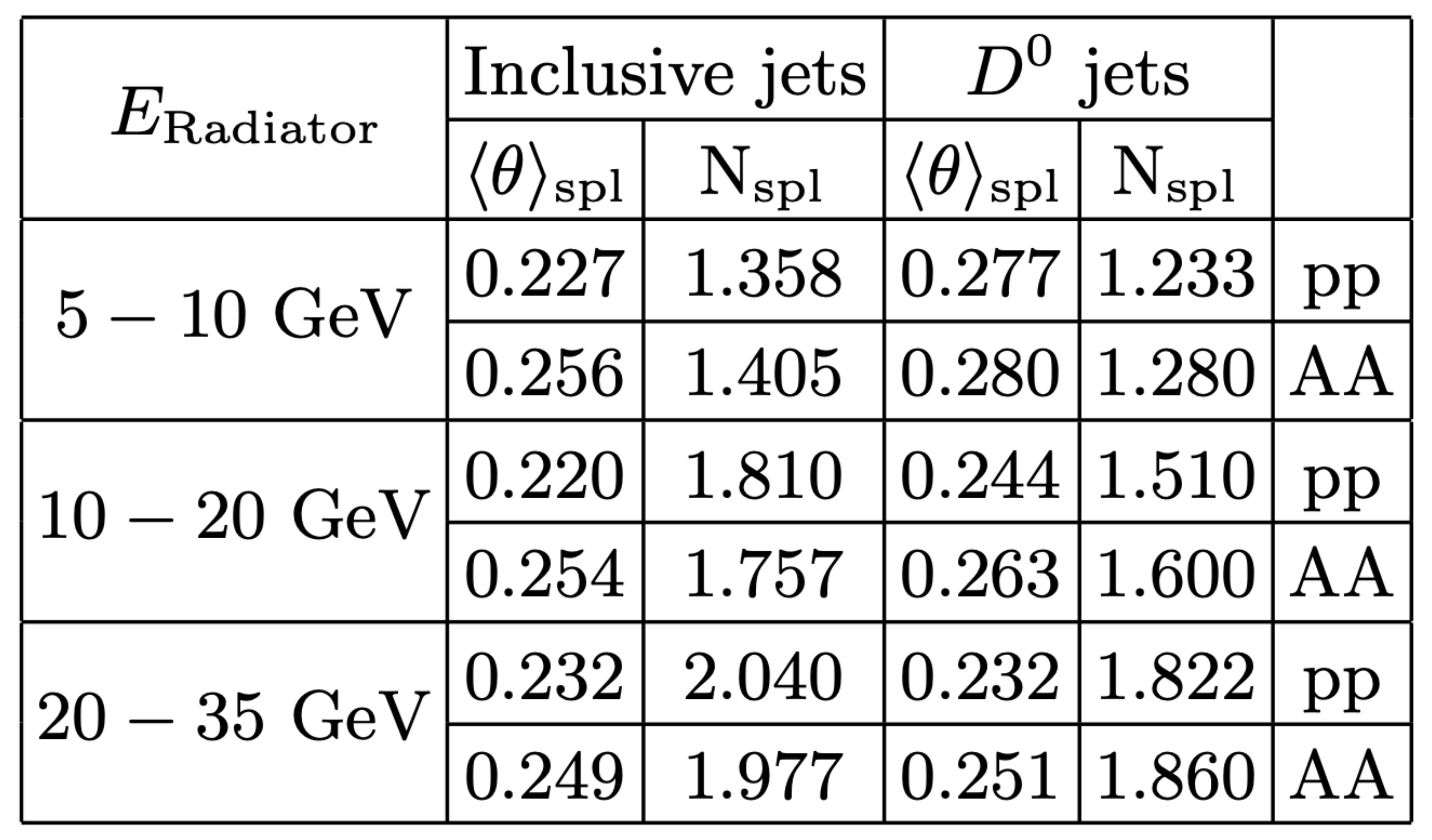
Dead-cone effect in A+A

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



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

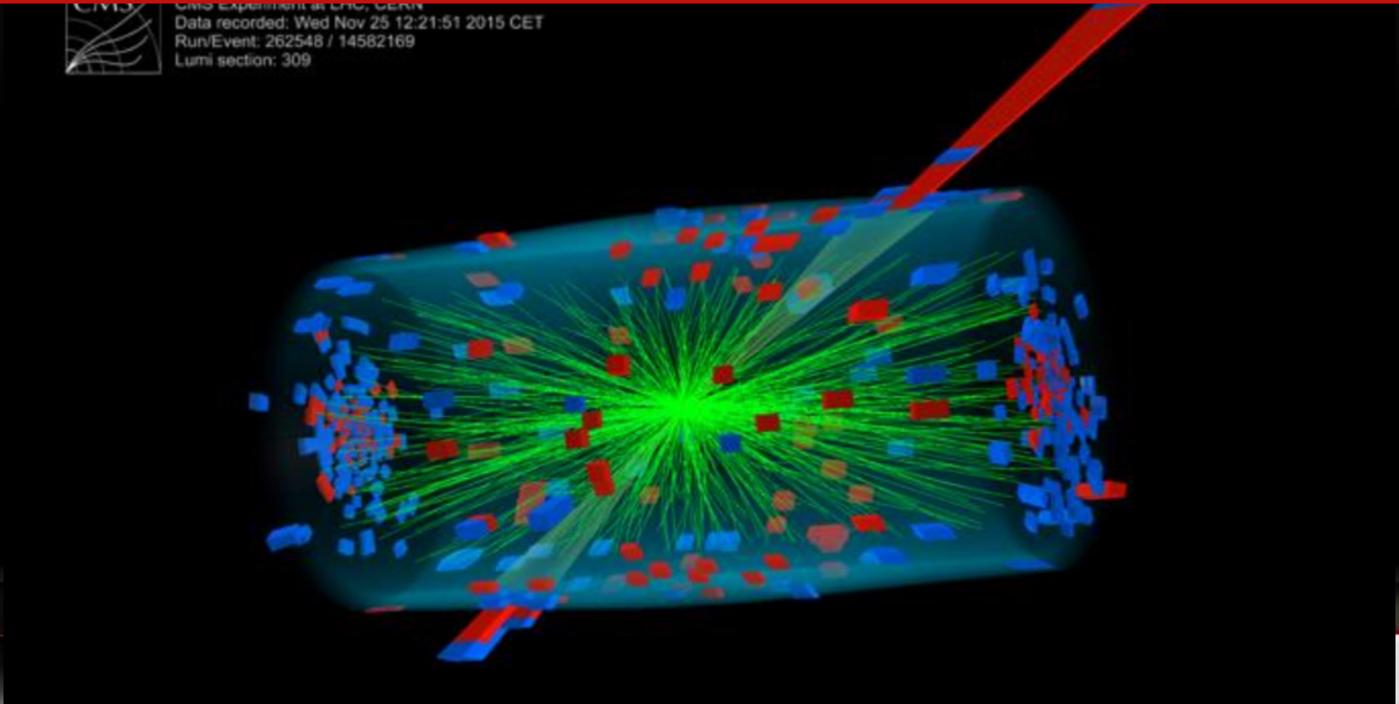
Mean value of emission angle



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

Global geometries of Multi-jet events



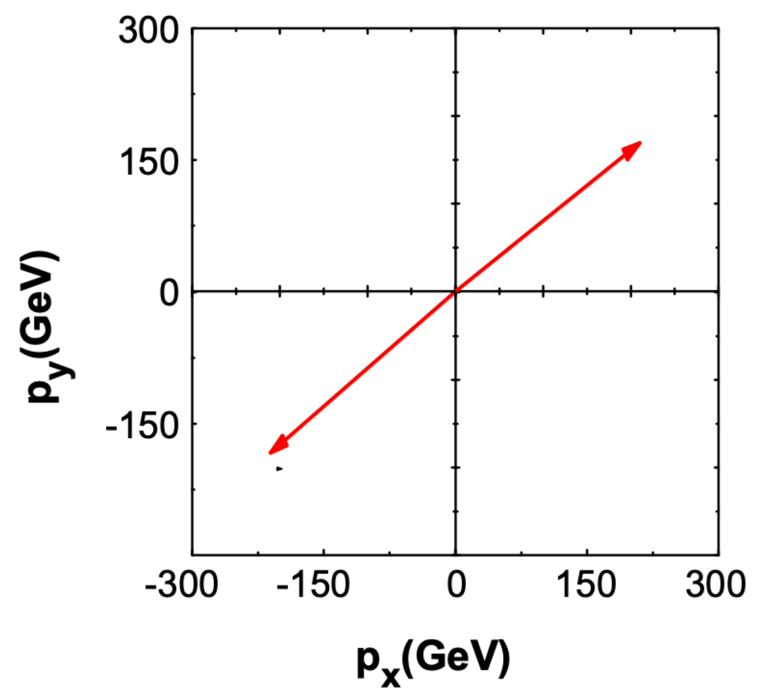
Event shape: sphericity

$$M = \sum_i \begin{pmatrix} p_{xi}^2 & p_{xi}p_{yi} & p_{xi}p_{zi} \\ p_{yi}p_{xi} & p_{yi}^2 & p_{yi}p_{zi} \\ p_{zi}p_{xi} & p_{zi}p_{yi} & p_{zi}^2 \end{pmatrix}$$

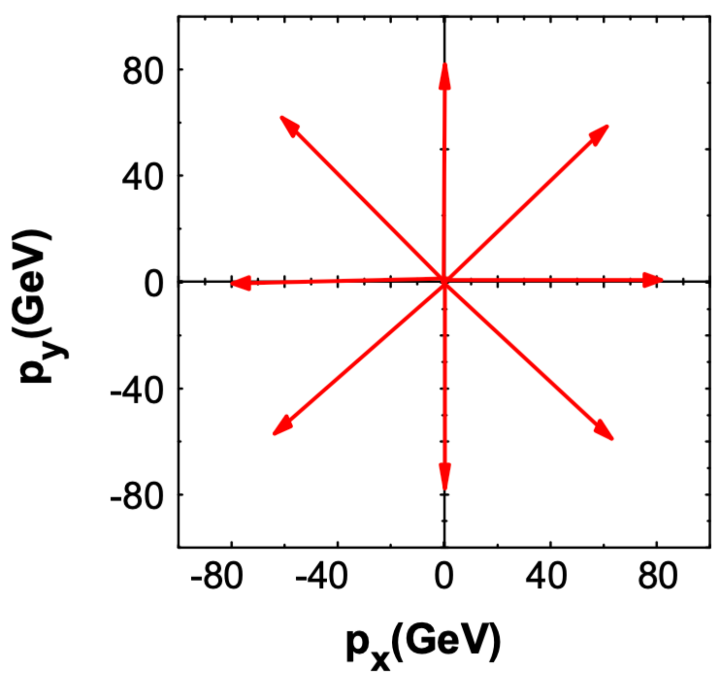
$$\lambda_1 > \lambda_2 > \lambda_3$$

$$S_\perp = \frac{2\lambda_2}{\lambda_1 + \lambda_2}$$

$$S_\perp = 0$$



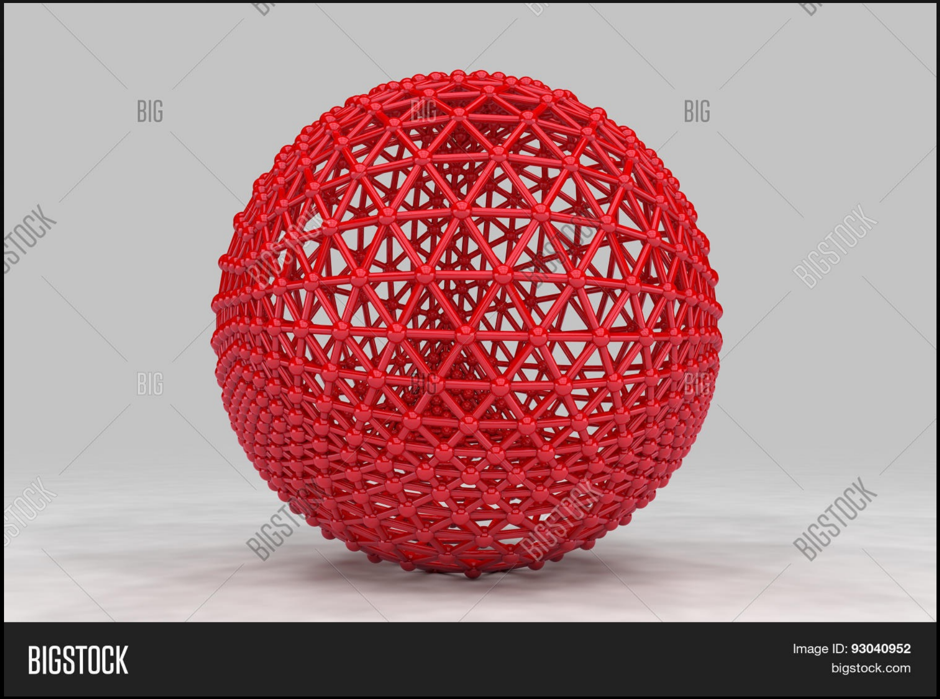
$$S_\perp = 1$$



Event shape: sphericity

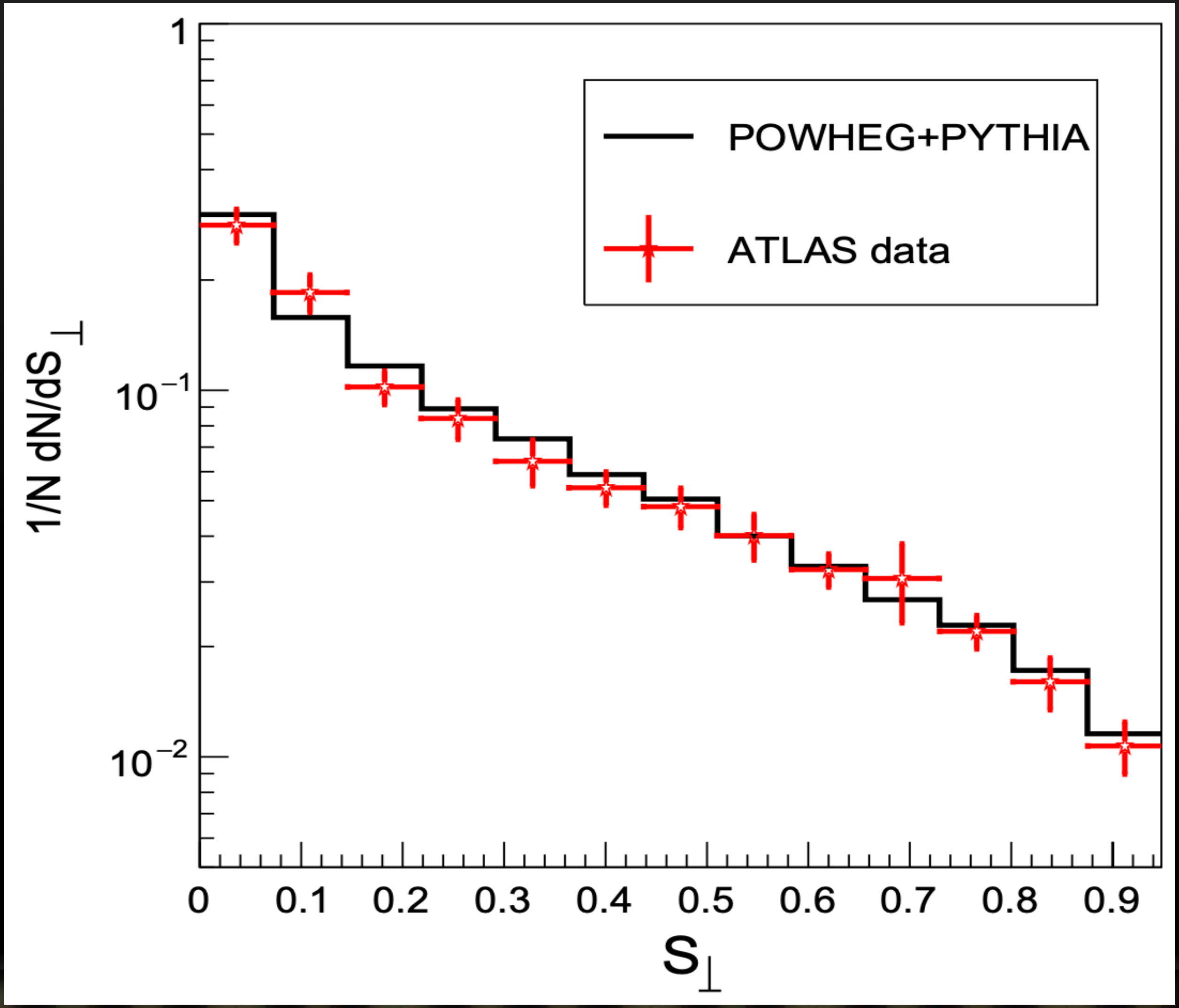
- What do multiple jets look like in p+p and A+A?
- What`s the change of event shapes in A+A relative to that in p+p?

$S_\perp = 0$



$S_\perp = 1$

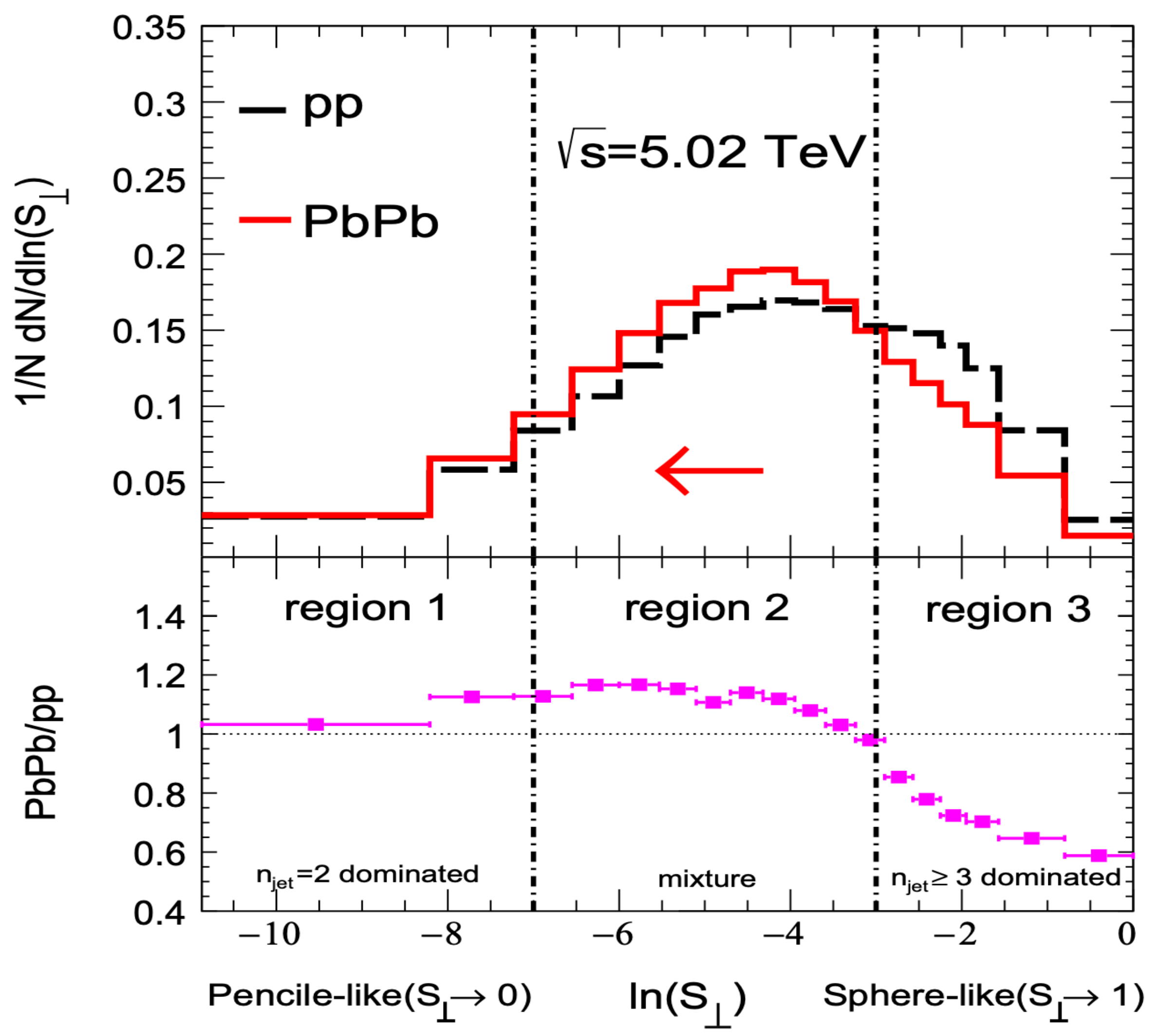
Sphericity in p+p



$$\left(p_{T,1leading} + p_{T,2leading}\right) > 500\,GeV$$
$$p_{T,3leading} > 30\,GeV$$
$$\left|y_{1,2}\right| < 1.0 \quad \text{anti}-K_T : R = 0.6$$
$$\left|y_3\right| < 1.5$$

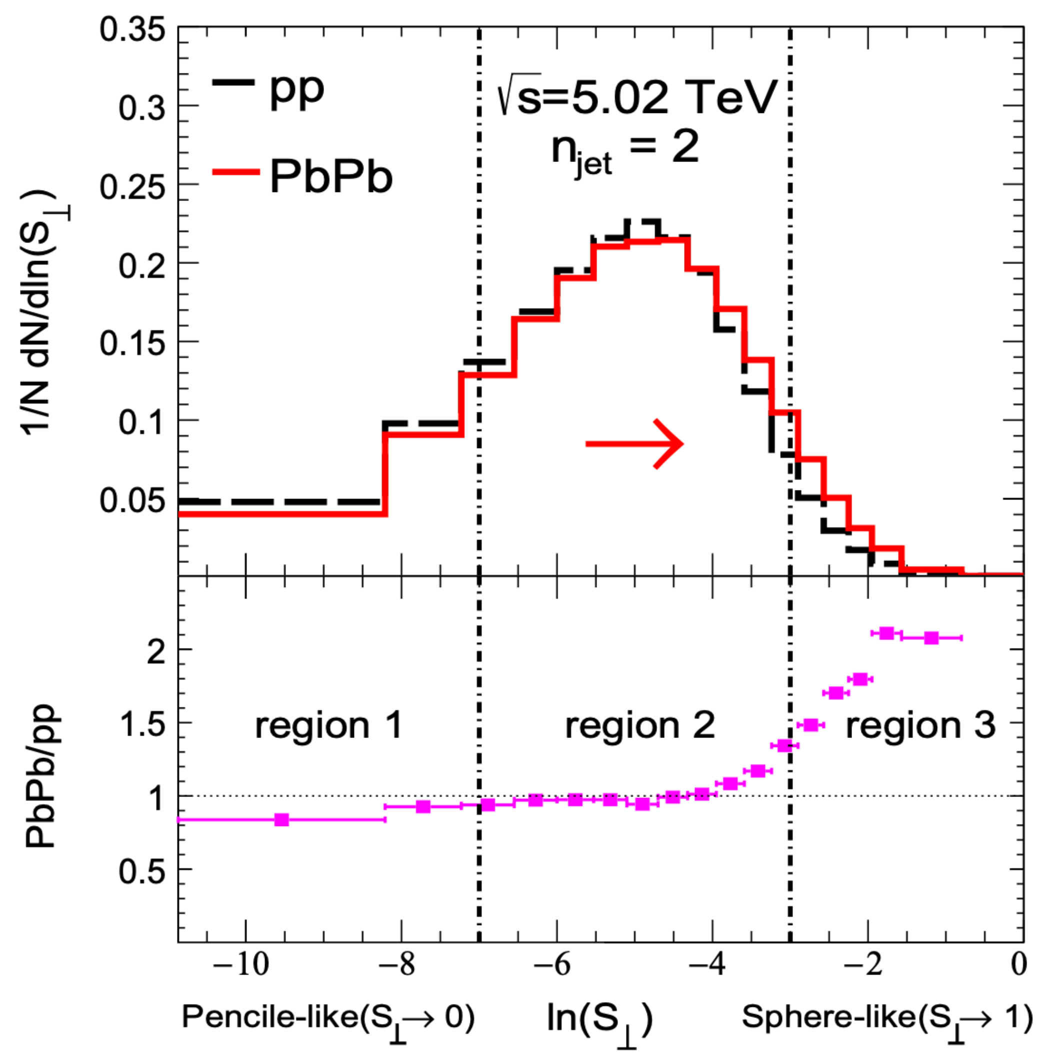
ATLAS (2012)

Sphericity in Pb+Pb

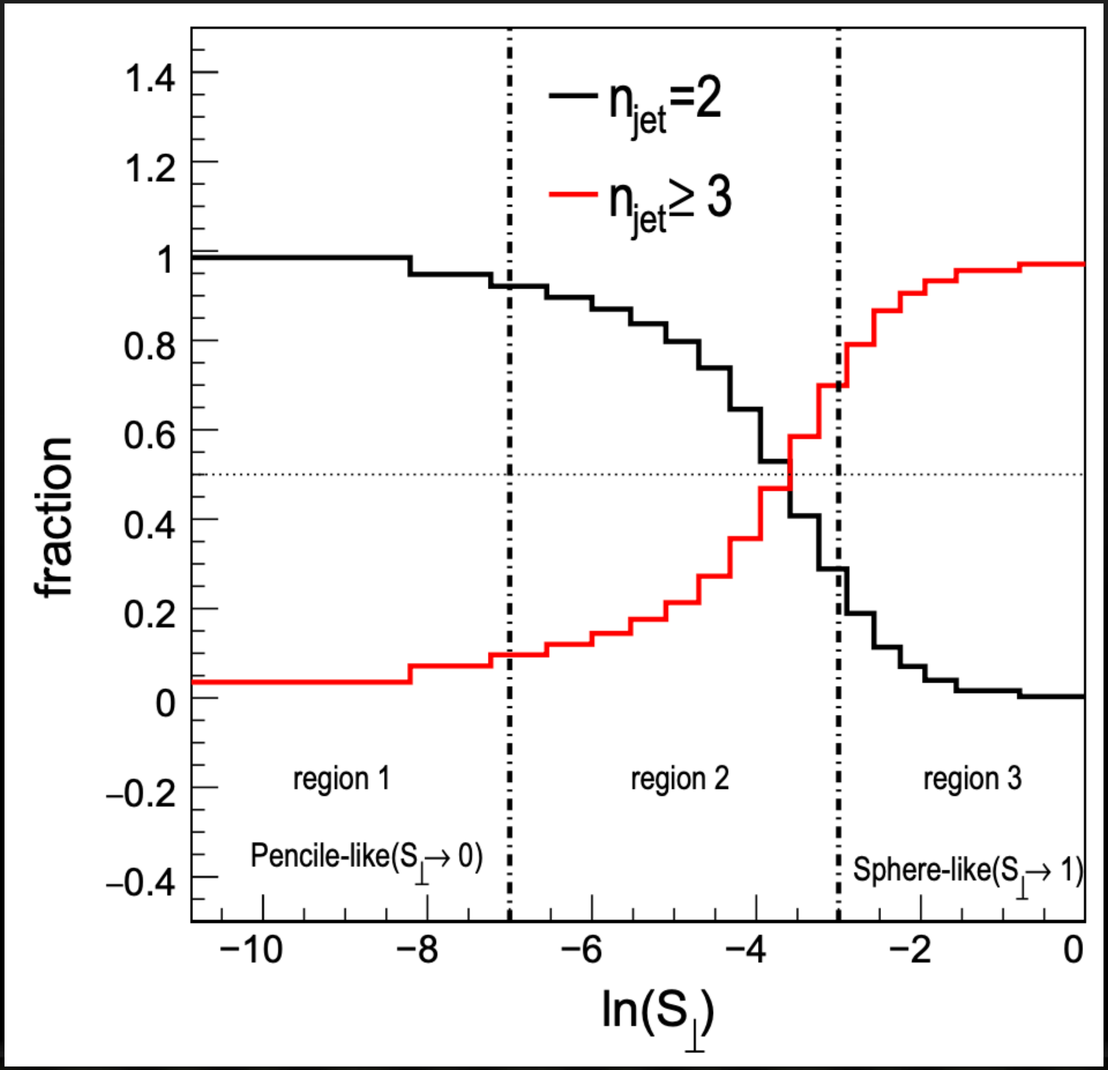


S Chen, W Dai, S Zhang, Q Zhang, BWZ, EPJC (2020)

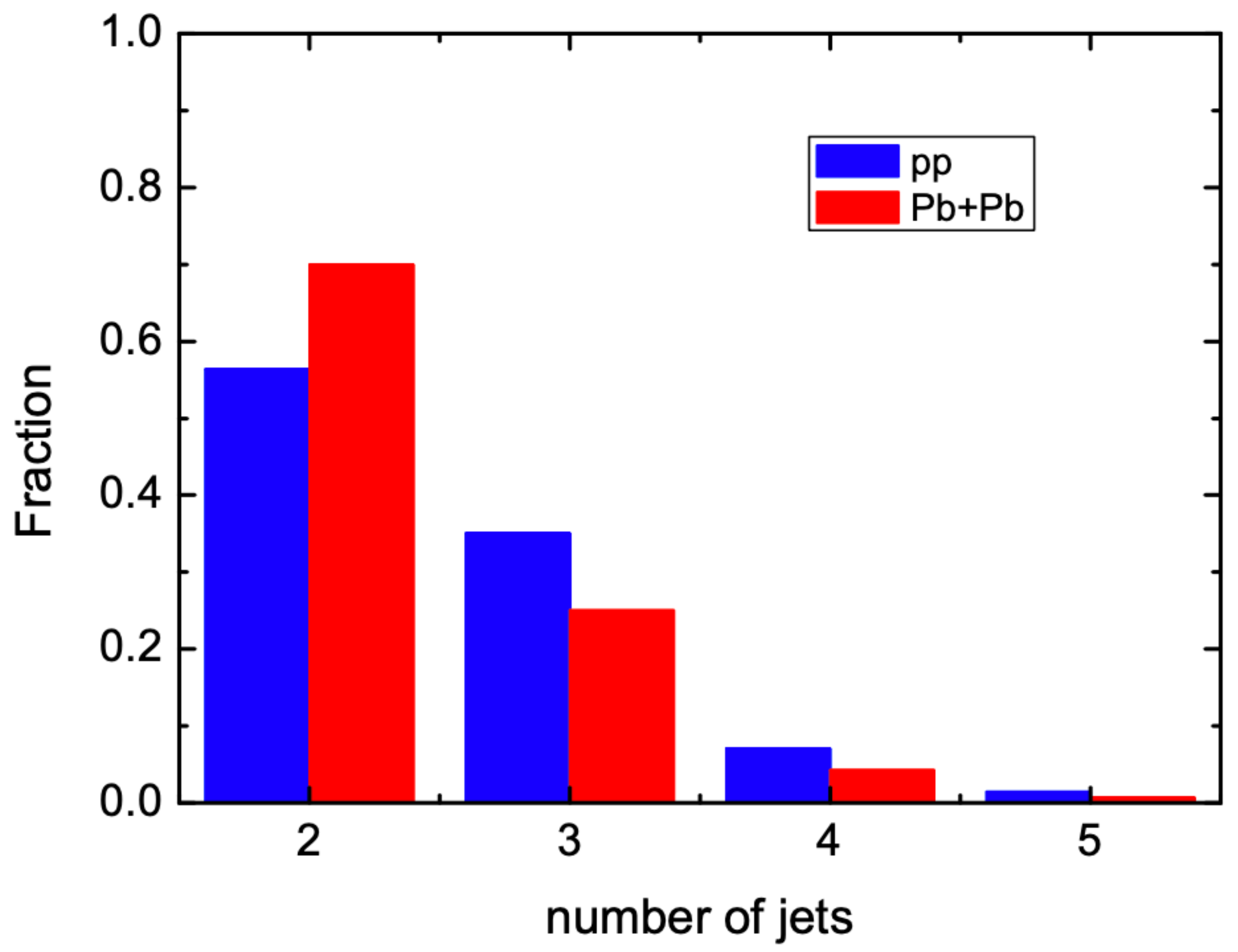
Sphericity in n_{jet}=2 events



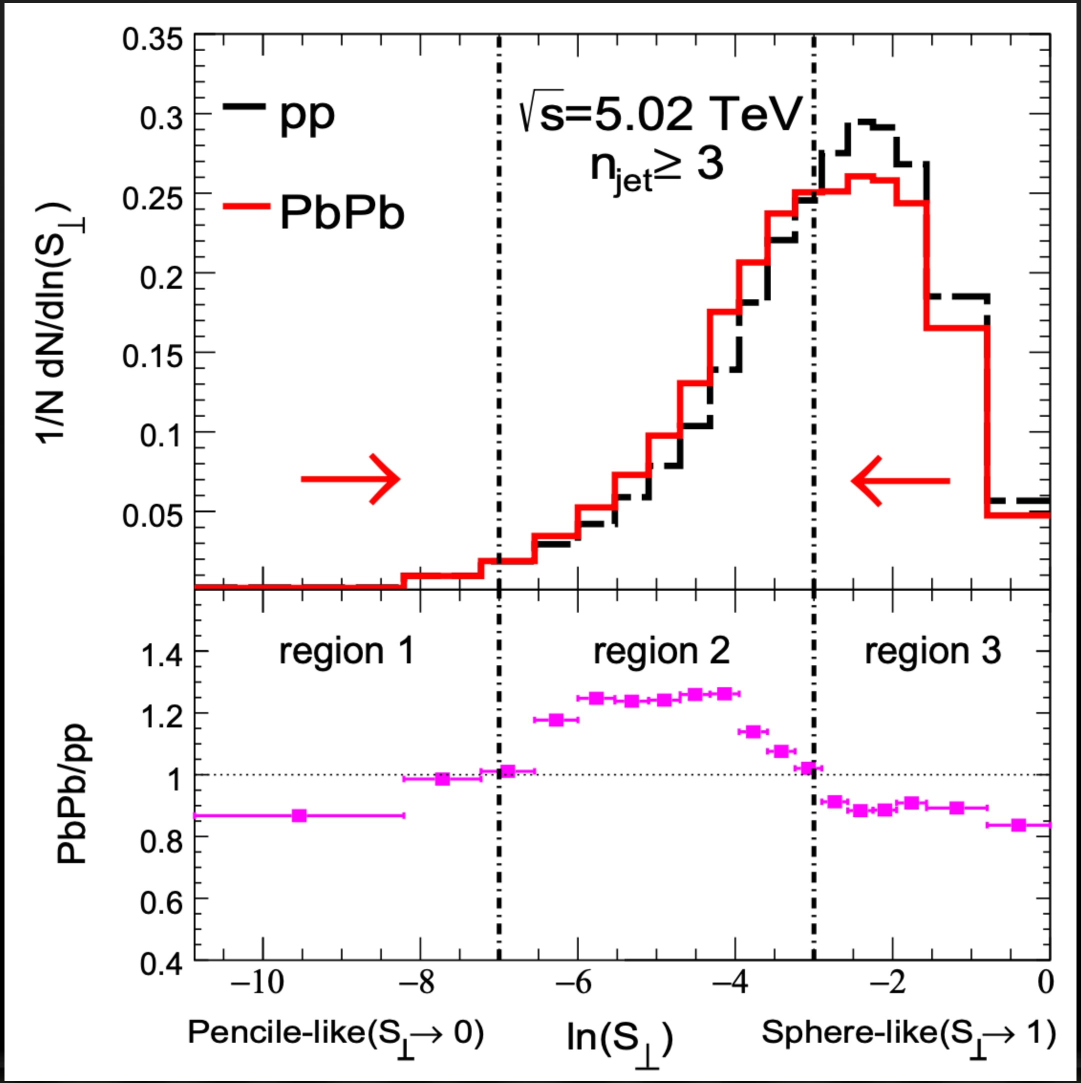
Sphericity in different n_{jet} events



Jet number reduction in Pb+Pb



Sphericity in n_{jet}>=3 events



Event Shape: jet broadening

Define an axis n_T

$$\max_{\hat{n}} \frac{\sum_i |\vec{p}_{T,i} \cdot \hat{n}_T|}{\sum_i p_{T,i}}$$

- one can separate the region $\mathcal{C}$ into an upper (U) side $\mathcal{C}_U$ consisting of all jets in $\mathcal{C}$ with $\vec{p}_T \cdot \hat{n}_T > 0$ and a lower (L) side $\mathcal{C}_L$ with $\vec{p}_T \cdot \hat{n}_T < 0$.

$$\eta_X \equiv \frac{\sum_{i \in \mathcal{C}_X} p_{T,i}\eta_i}{\sum_{i \in \mathcal{C}_X} p_{T,i}}, \quad \phi_X \equiv \frac{\sum_{i \in \mathcal{C}_X} p_{T,i}\phi_i}{\sum_{i \in \mathcal{C}_X} p_{T,i}},$$

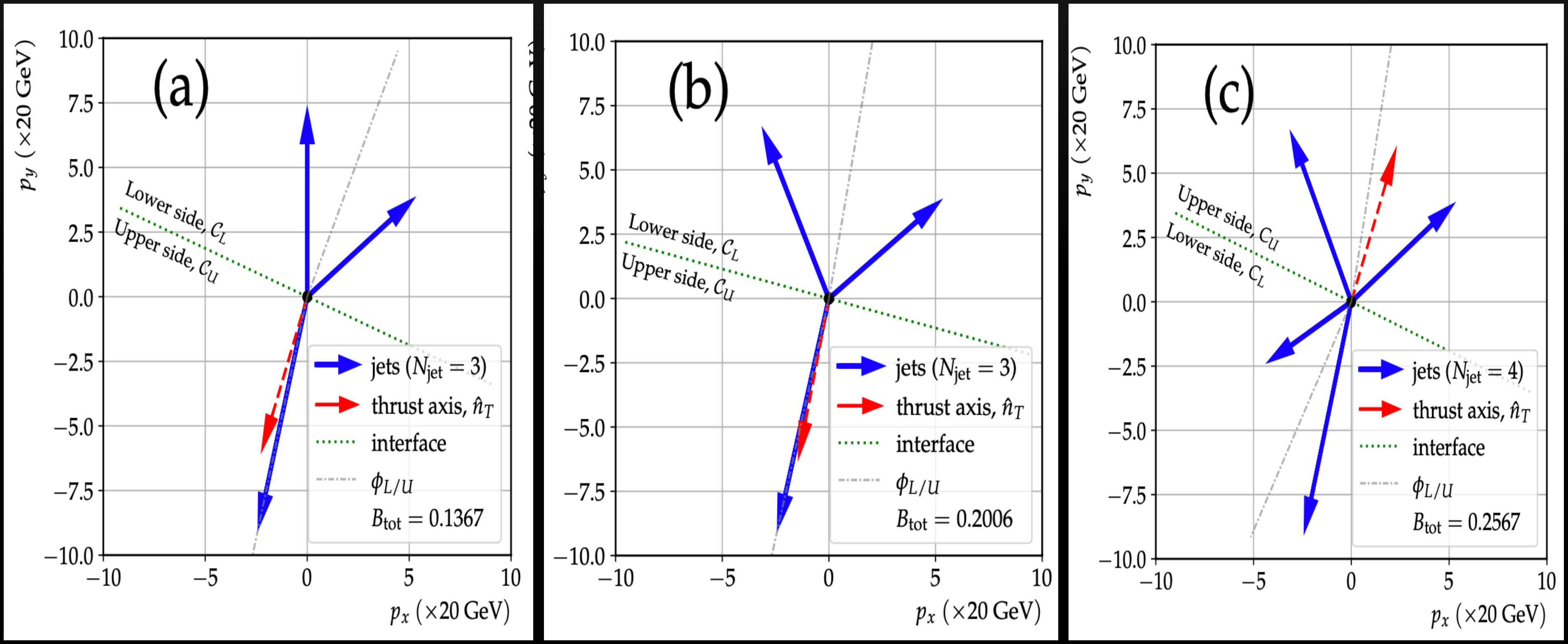
We define jet broadening

$$B_X \equiv \frac{1}{2P_T} \sum_{i \in \mathcal{C}_X} p_{T,i} \sqrt{(\eta_i - \eta_X)^2 + (\phi_i - \phi_X)^2},$$

$$B_{tot} \equiv B_U + B_L$$

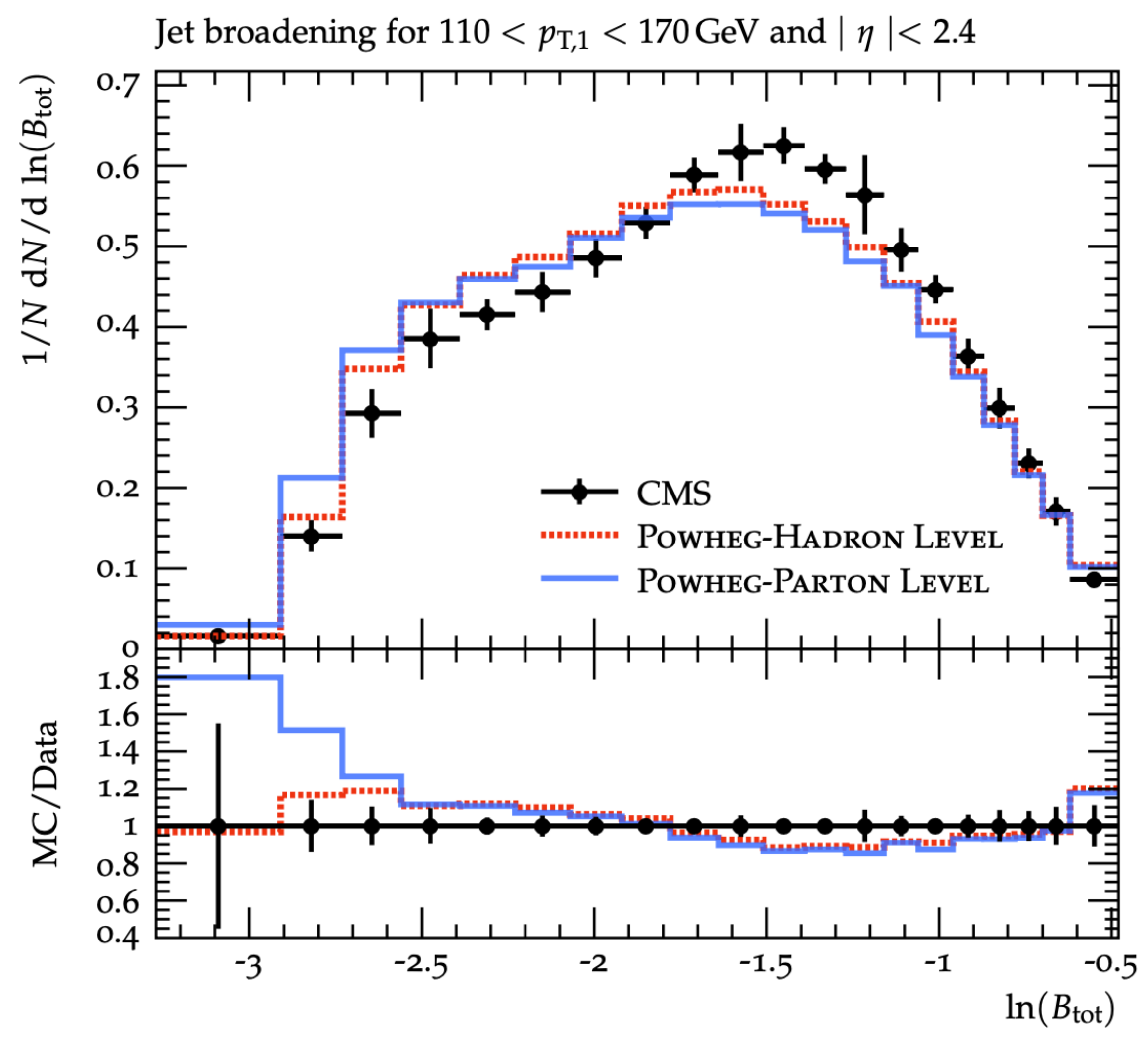
Jet broadening

- Jet broadening characterizes the weighted broadening of the jets relative to the center of the outgoing energy flow, the distribution of energy flow of multi-jets in the final-state.

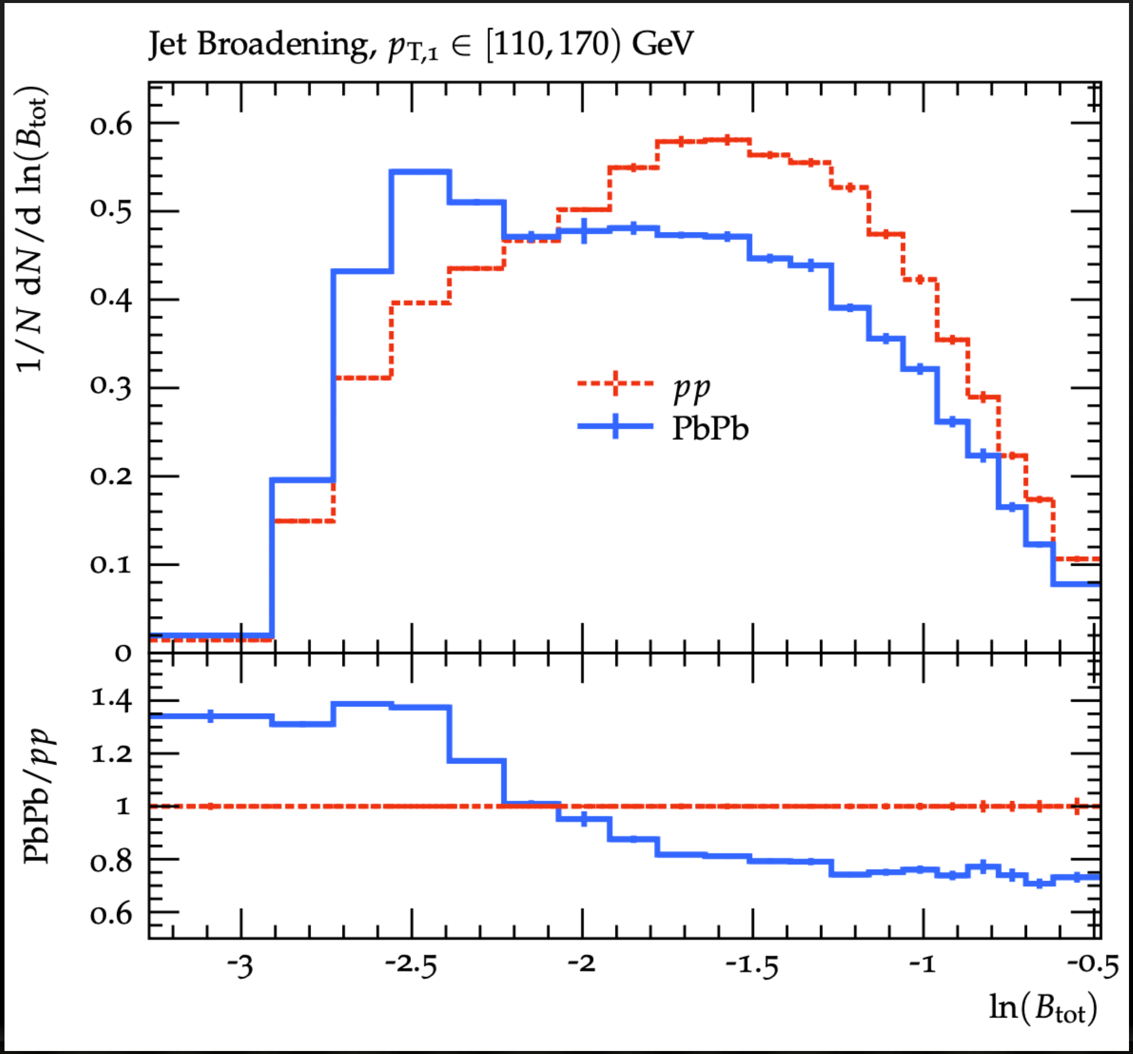


J Kang, L Wang, W Dai, S Wang, BWZ, arXiv: 2304.04649

Jet broadening in p+p



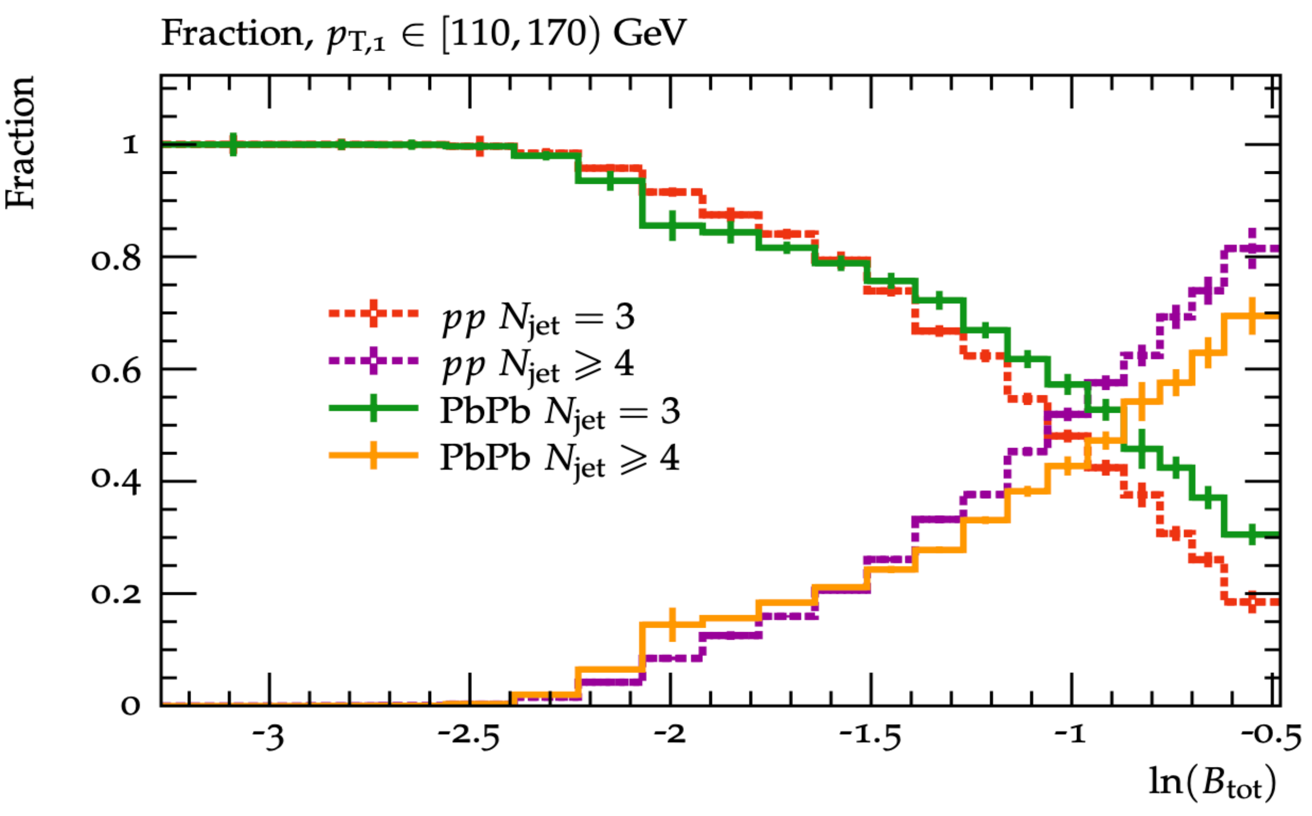
Jet broadening in Pb+Pb



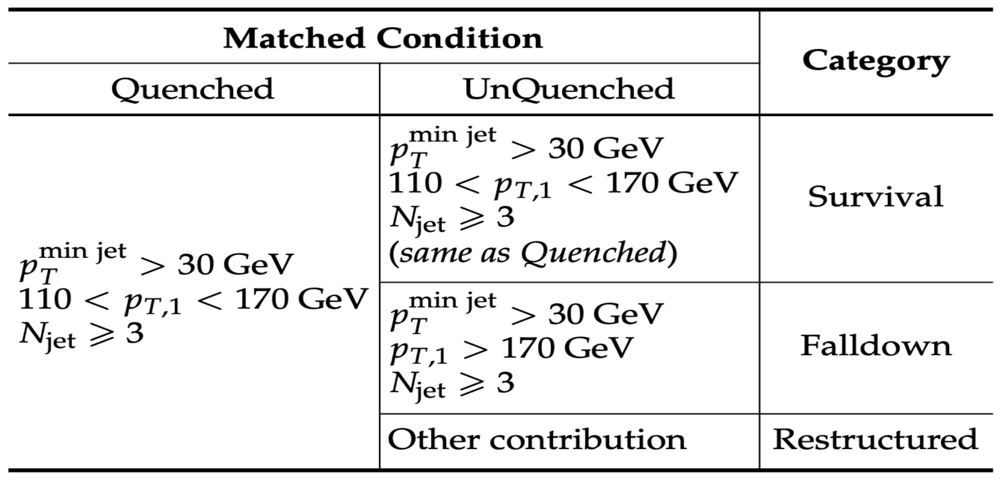
J Kang, L Wang, W Dai, S Wang, BWZ, arXiv: 2304.04649

Jet number reduction due to Eloss

	pp	PbPb
$N_{\text{jet}} = 3$	76.98±0.30%	81.17±0.39%
$N_{\text{jet}} = 4$	18.59±0.13%	15.53±0.25%
$N_{\text{jet}} \geqslant 5$	4.43±0.05%	3.30±0.05%



Multi-jet events Classifications

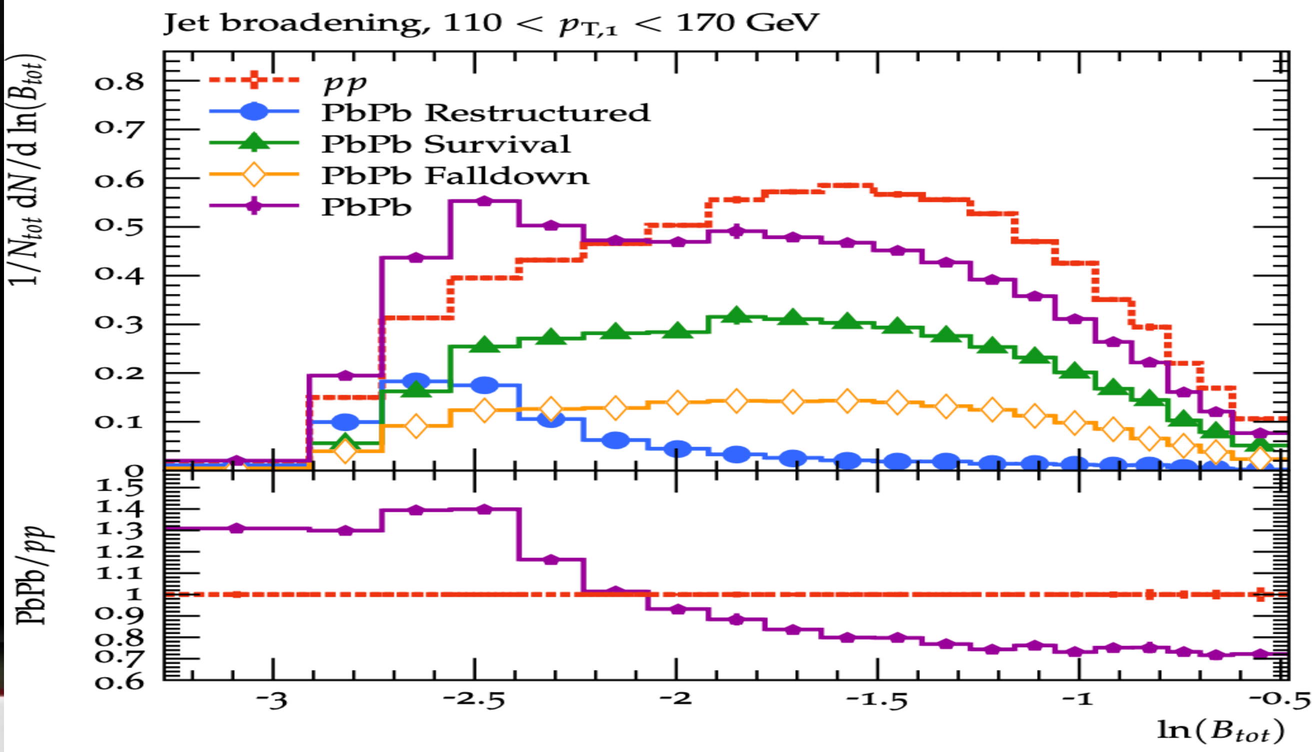


Matched Condition		Category
Quenched	UnQuenched	
$p_T^{\text{min jet}} > 30$ GeV $110 < p_{T,1} < 170$ GeV $N_{\text{jet}} \geqslant 3$	$p_T^{\text{min jet}} > 30$ GeV $110 < p_{T,1} < 170$ GeV $N_{\text{jet}} \geqslant 3$ (*same as Quenched*)	Survival
	$p_T^{\text{min jet}} > 30$ GeV $p_{T,1} > 170$ GeV $N_{\text{jet}} \geqslant 3$	Falldown
	Other contribution	Restructured

~ 58%

~ 27%

~ 15%



Recap

- The Splitting scale of Reclustered large radius jet in Pb+Pb is calculated, which is in good agreement with experiment data.

- The possibility of observing dead-cone effect of jet quenching is explored.

- Event shape observables with jet quenching in Pb+Pb are investigated: sphericity and jet broadening. Jet number reduction effect **VS** medium-induced gluon radiation

Backup

Linear Boltzmann Transport Model

- Elastic scattering:

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

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

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

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)

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

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

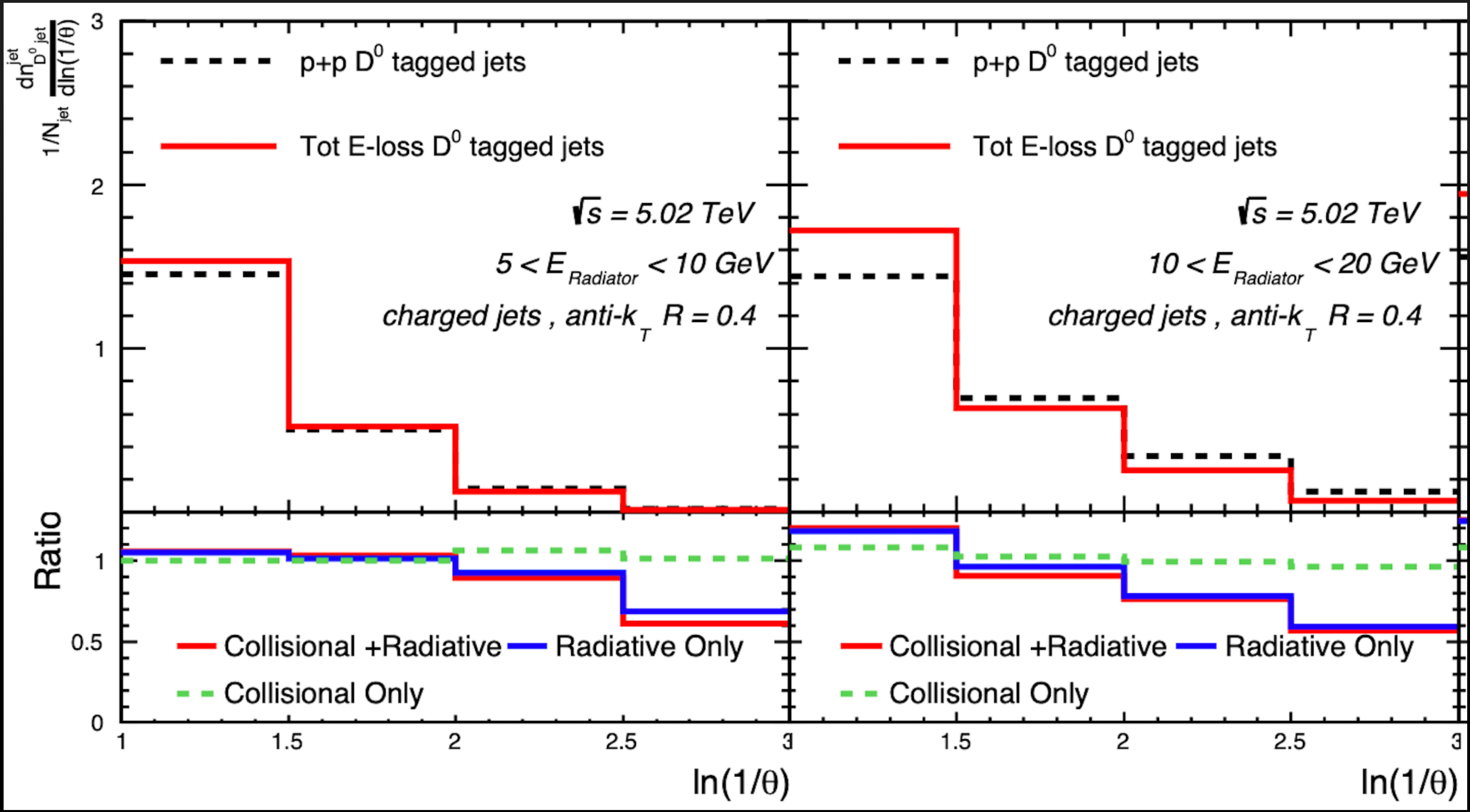
$$\frac{dE}{dL} = -\frac{\alpha_s C_s \mu_D^2}{2} ln \frac{\sqrt{ET}}{\mu_D}$$

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

Higher-Twist approach:

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

Dead-cone effect in A+A



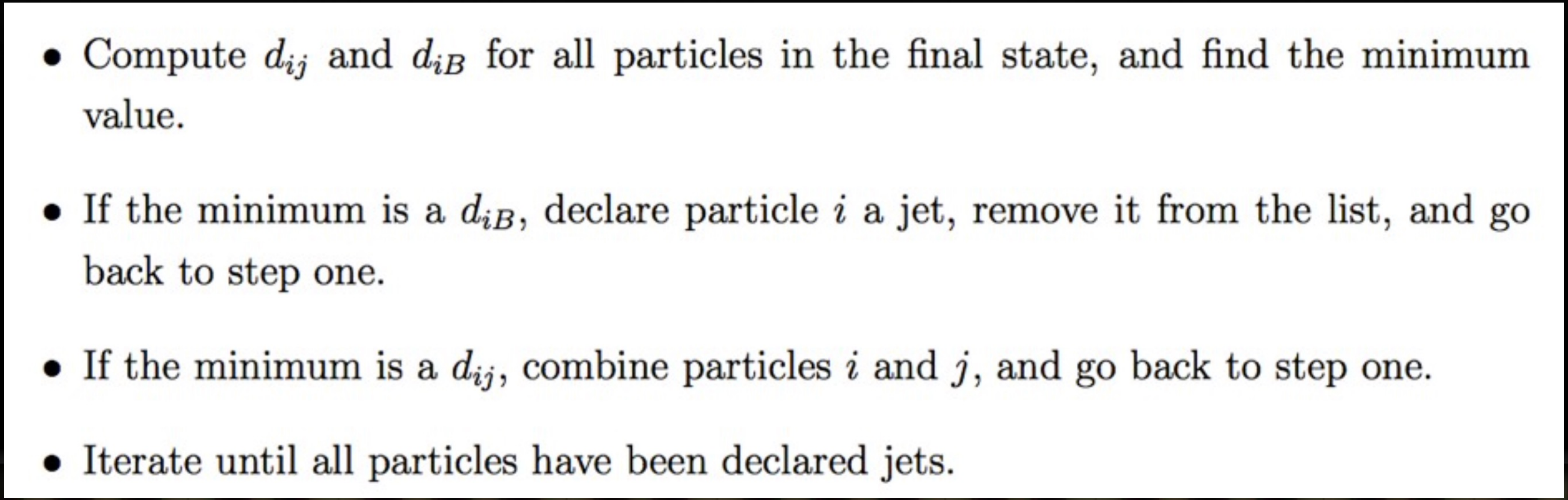
W Dai, M Z Li, BWZ, E Wang, arXiv: 2205.14668

kt algorithm

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

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

$$p = 1$$

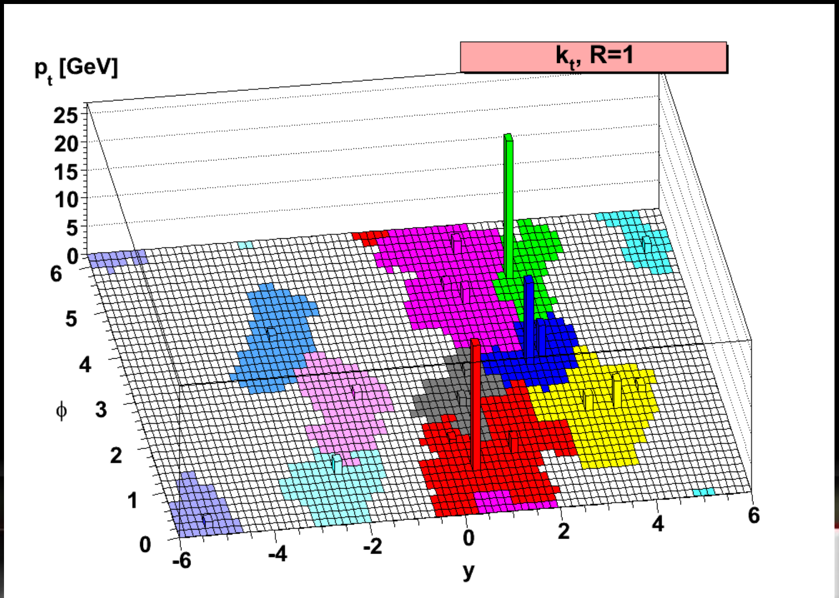


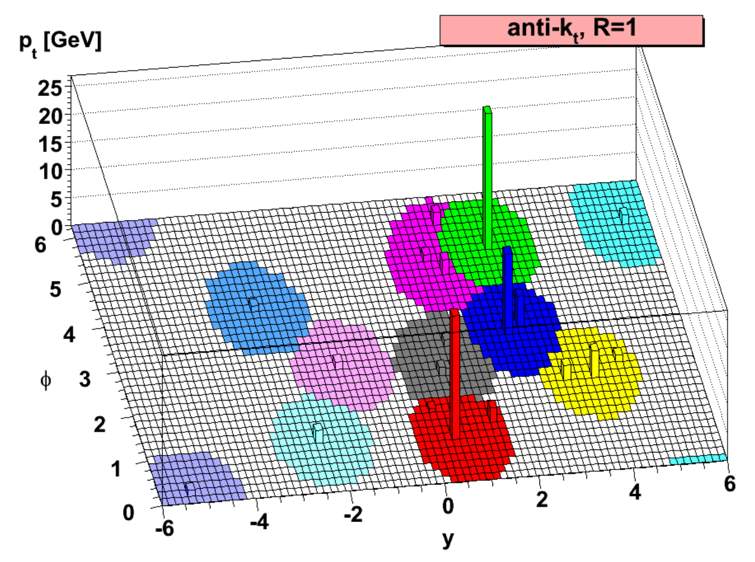
- Compute d_{ij} and d_{iB} for all particles in the final state, and find the minimum value.
- If the minimum is a d_{iB}, declare particle i a jet, remove it from the list, and go back to step one.
- If the minimum is a d_{ij}, combine particles i and j, and go back to step one.
- Iterate until all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

anti-kt and C/A algorithms

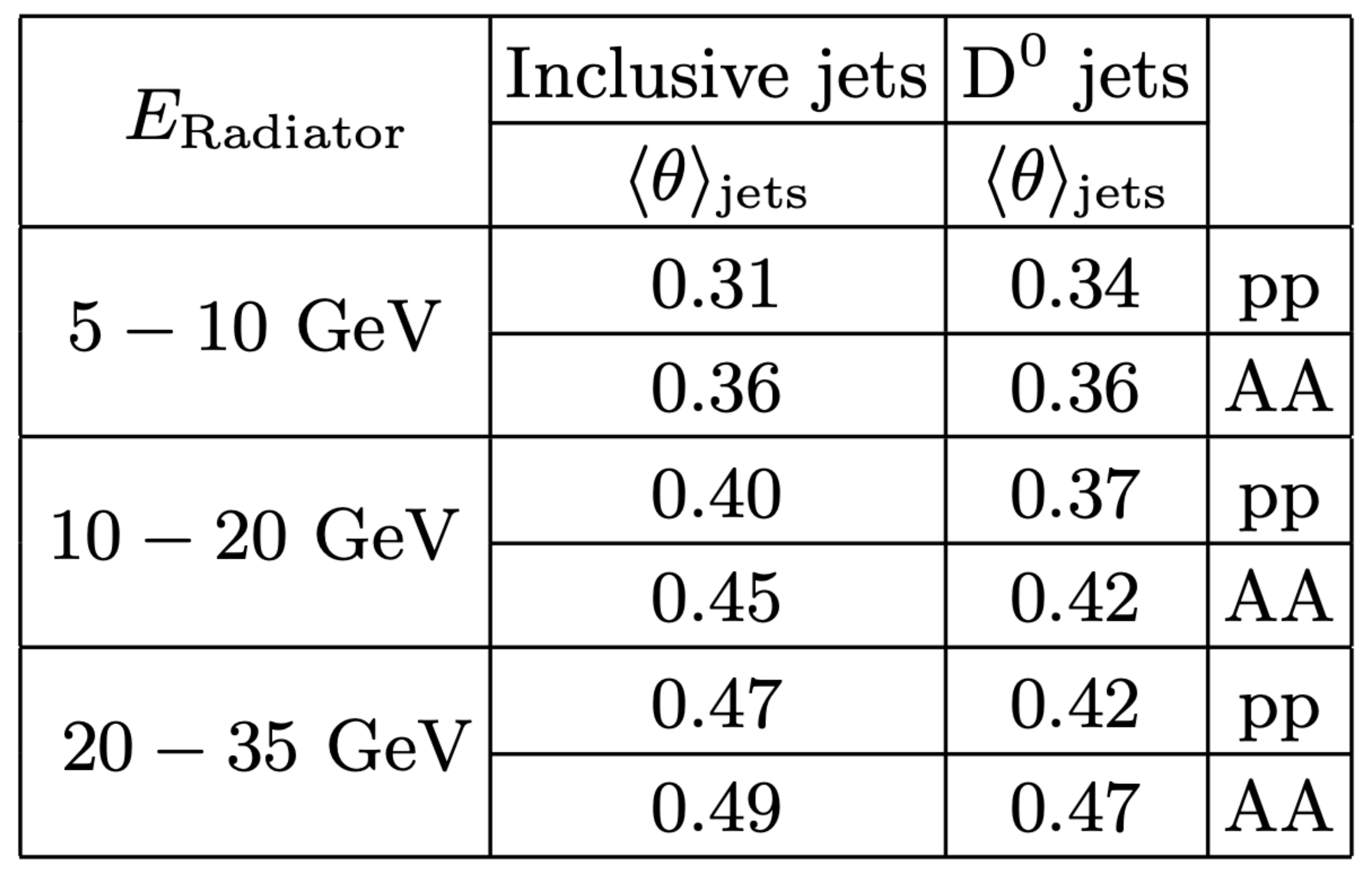
$$d_{ij} = \min(p_{ti}^{2p}, p_{tj}^{2p}) \frac{\Delta y^2 + \Delta \phi^2}{R^2} \qquad d_{iB} = p_{ti}^{2p}$$

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





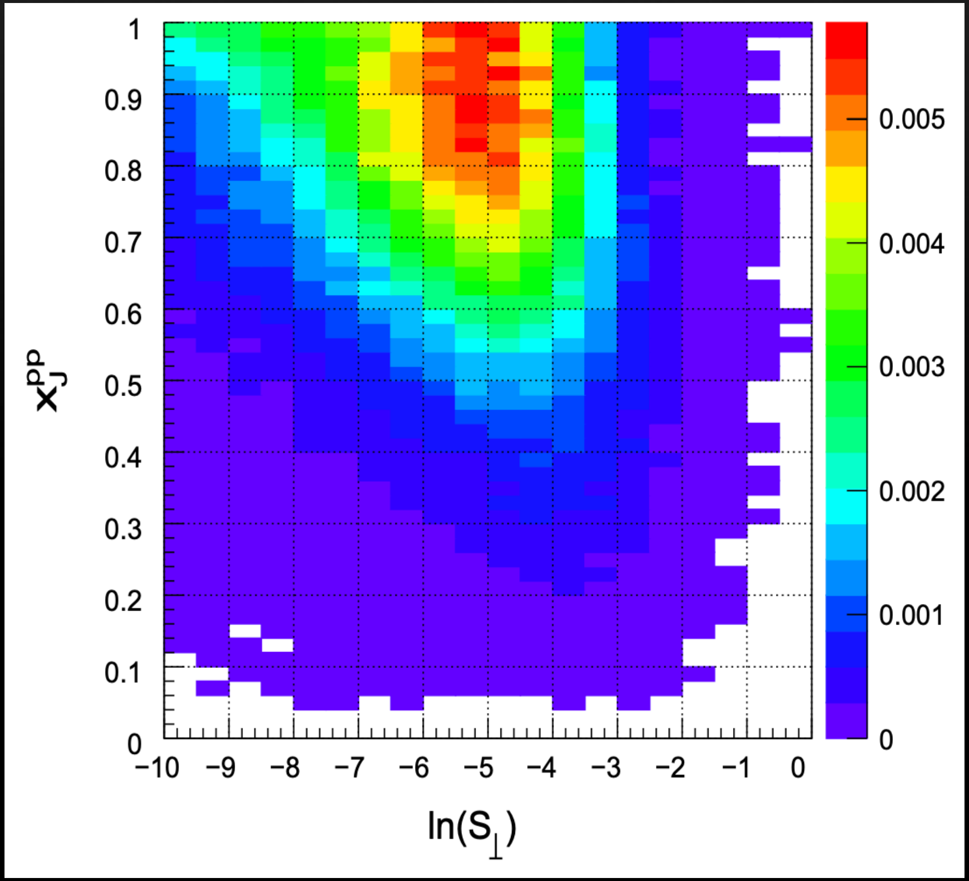
Mean value of emission angle

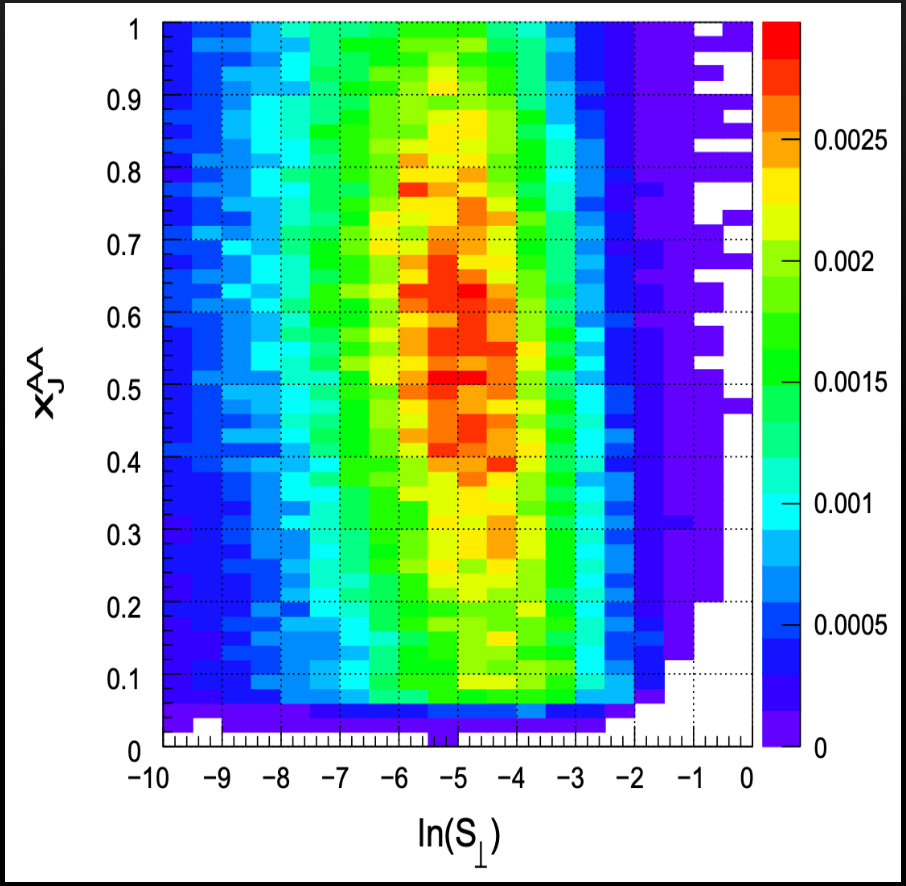


E_{Radiator}	Inclusive jets	D^0 jets	
	$\langle\theta\rangle_{\mathrm{jets}}$	$\langle\theta\rangle_{\mathrm{jets}}$	
5 – 10 GeV	0.31	0.34	pp
	0.36	0.36	AA
10 – 20 GeV	0.40	0.37	pp
	0.45	0.42	AA
20 – 35 GeV	0.47	0.42	pp
	0.49	0.47	AA

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

Energy correlation





S Chen, W Dai, S Zhang, Q Zhang, BWZ, EPJC (2020)