

QPT 2025

Multijet topology in high-energy nuclear collisions: Jet broadening

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Base on J. W. Kang, L. Wang, W. Dai, S. Wang, B. W. Zhang, *Phys. Rev. C* 112 (2025), 034903.

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- ⑤ Results
- ⑥ Summary

Outline



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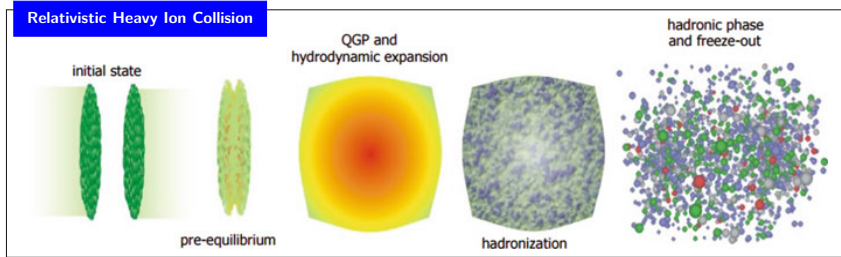
Results



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Heavy-ion Collisions and Jet Quenching



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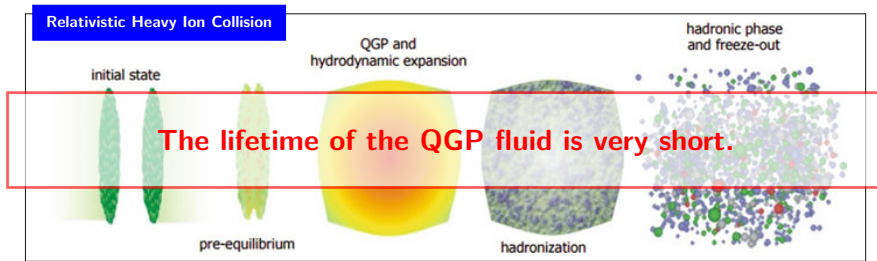
Results

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Heavy-ion Collisions and Jet Quenching



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Heavy-ion Collisions and Jet Quenching

Relativistic Heavy Ion Collision

initial state

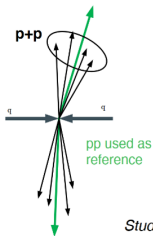
QGP and
hydrodynamic expansion

hadronic phase
and freeze-out

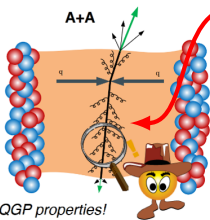
pre-equilibrium

hadronization

The lifetime of the QGP fluid is very short.



Study QGP properties!



energy loss: $\frac{dE}{dt}$, p_T -broadening: $\frac{dp_{\perp}}{dt}$

During the propagation and evolution in the QGP, the jet not only **loses energy and momentum**, but also **accumulates p_T -broadening** through medium-induced radiation and scattering.

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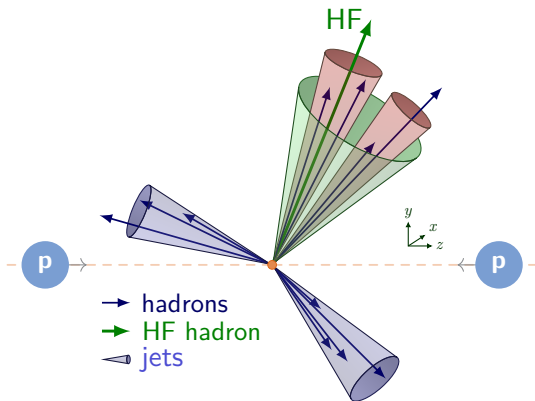
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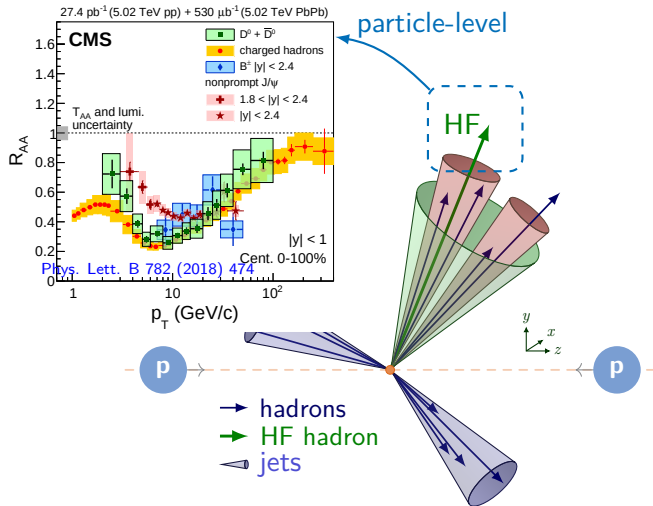
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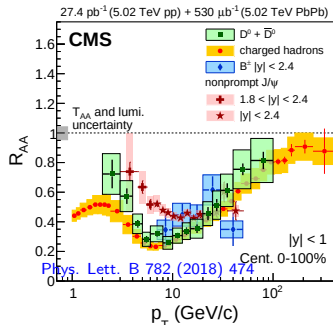
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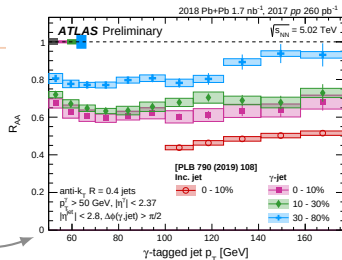
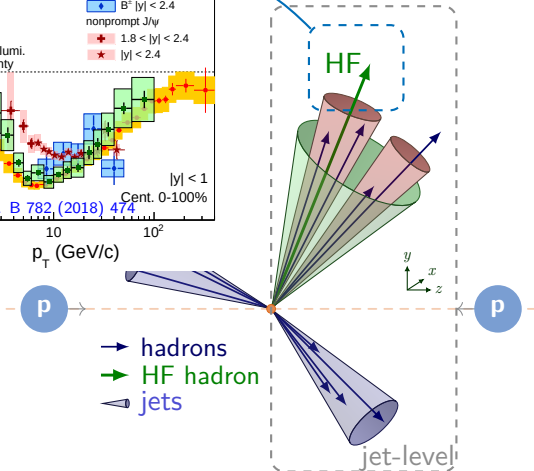
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particle-level



ATLAS-CONF-2022-019

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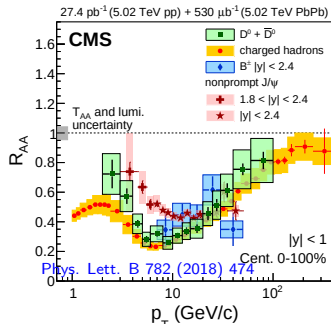
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Jet Observables



particle-level

intra-jet-level

HF

y

x

z

p

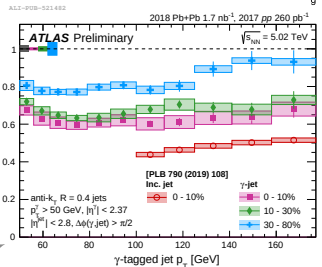
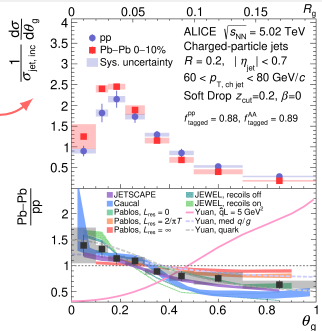
p

→ hadrons

→ HF hadron

→ jets

jet-level



Phys. Rev. Lett. 128 (2022), 102001

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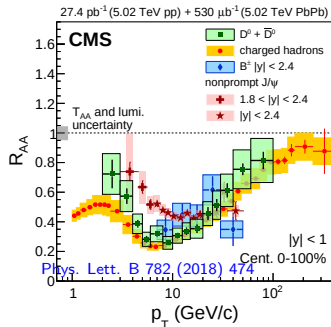
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Jet Observables



particle-level

intra-jet-level

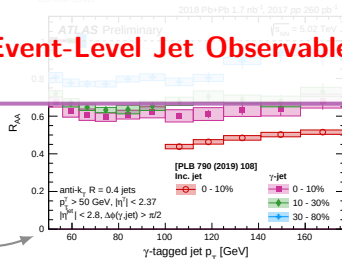
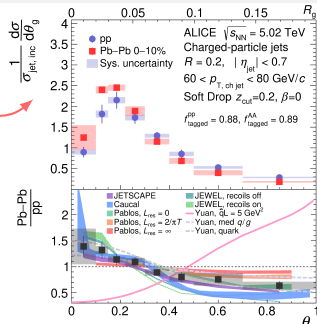
HF

Focus on Event-Level Jet Observables

event-level

jet-level

→ hadrons
 → HF hadron
 → jets



Phys. Rev. Lett. 128 (2022), 102001

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Definition of Jet Broadening

One of the Event-shape Variables

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Event-shape variables

Event-shape variables can be used to characterize the geometrical properties of energy flow in the final-states of high-energy particle collisions.

Definition of Jet Broadening

One of the Event-shape Variables

Use the transverse thrust axis $\hat{n}_t$ to divide the jets within the investigation region $\mathcal{C}$ into the upper and lower hemispheres,

$$\mathcal{C}_U : \vec{p}_t \cdot \hat{n}_t > 0, \quad \mathcal{C}_L : \vec{p}_t \cdot \hat{n}_t < 0.$$

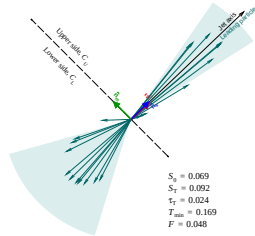
Introduce the mean transverse-energy weighted η_X and ϕ_X of each hemisphere $X = U, L$,

$$\eta_X \equiv \sum_{i \in \mathcal{C}_X} p_{t,i} \eta_i / \sum_{i \in \mathcal{C}_X} p_{t,i}, \quad \phi_X \equiv \sum_{i \in \mathcal{C}_X} p_{t,i} \phi_i / \sum_{i \in \mathcal{C}_X} p_{t,i}.$$

The jet broadening in each hemisphere is defined as

$$B_X \equiv \frac{1}{2 \sum_{j \in \mathcal{C}_{U,L}} p_{t,j}} \sum_{i \in \mathcal{C}_X} p_{t,i} \sqrt{(\eta_i - \eta_X)^2 + (\phi_i - \phi_X)^2}, \quad X = U, L.$$

The total jet broadening: $B_{\text{tot}} \equiv B_U + B_L$.



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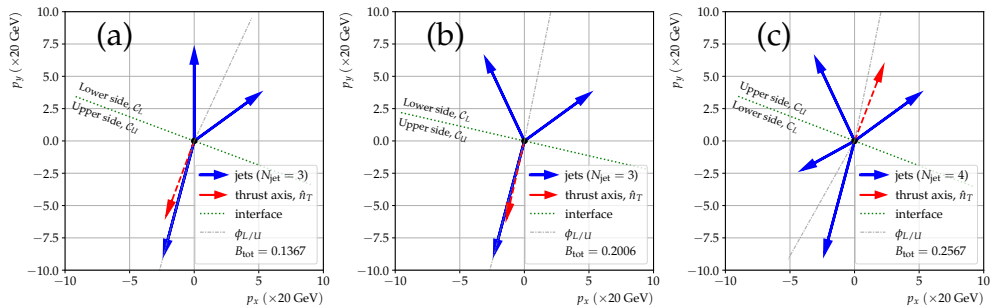
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► Go to Backup

Definition of Jet Broadening

One of the Event-shape Variables



B_{tot} increases

$$\eta_X = \frac{\sum_{i \in C_X} p_{t,i} \eta_i}{\sum_{i \in C_X} p_{t,i}}, \phi_X = \frac{\sum_{i \in C_X} p_{t,i} \phi_i}{\sum_{i \in C_X} p_{t,i}}$$

$$B_X = \frac{1}{2 \sum_{j \in C_{U,L}} p_{t,j}} \sum_{i \in C_X} p_{t,i} \sqrt{(\eta_i - \eta_X)^2 + (\phi_i - \phi_X)^2}$$

more narrower

more wider

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Modeling Jet-Medium Interaction and Jet Evolution in QGP

- $p + p$ baseline: **POWHEG + PYTHIA8**, dijet@NLO
COMPUT. PHYS. COMMUN. **191**, 159 (2015),
JHEP 0411 (2004) 040, JHEP 0711 (2007) 070, JHEP 1006
(2010) 043, JHEP 1104 (2011) 081.
- Initial state: **AMPT averaged initial state**
PHYS. REV. C **72** (2005) 064901.
- Partonic transport in the QGP: **LBT**
PLB 782 (2018) 707; PRC 98 (2018) 021901; PLB 777 (2018) 86;
PRC 94 (2016) 014909.
- Hydrodynamic evolution: **3+1D CLVisc**
PRC **86**, 024911 (2012); PRD **91**, 074027 (2015).
- Hadronization: **COLORLESS + LUND STRING**
ARXIV:1903.07706 [hep-ph].

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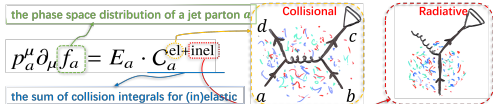
Summary

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Modeling Jet-Medium Interaction and Jet Evolution in QGP

- $p + p$ baseline: **POWHEG + PYTHIA8**, dijet@NLO
COMPUT. PHYS. COMMUN. **191**, 159 (2015)
JHEP 0411 (2004) 040, JHEP 0711 (2007) 070, JHEP 1006 (2010) 043, JHEP 1104 (2011) 081.
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PRC **86**, 024911 (2012); PRD **91**, 074027 (2015).
- Hadronization: **COLORLESS + LUND STRING**
ARXIV:1903.07706 [hep-ph].

LBT model



The inelastic scattering is described by the high-twist approach,

$$\frac{dN_g^a}{dz dk_\perp^2 dt} = \frac{2C_A \alpha_s \hat{q}_a P_a^{\text{vac}}(z) k_\perp^4}{\pi (k_\perp^2 + z^2 m^2)} \sin^2 \left(\frac{t - t_i}{2\tau_f} \right)$$

the parent parton a

the parton transport coefficient

the vacuum splitting function

the production time of parton a

the transverse momentum of the emitted gluon

the fractional energy of the emitted gluon

the mass of parton a

the formation time of the emitted gluon, $\tau_f = 2E_a z(1-z)/(k_\perp^2 + z^2 m^2)$

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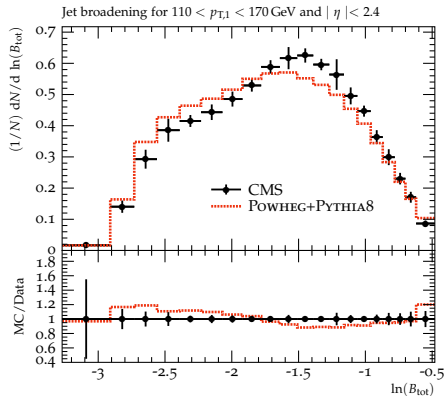
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Event Selection Criterion

- Jet reconstruction: anti- k_t , $R = 0.5$
- Jet p_t threshold > 30 GeV
- Jet geometric acceptance $|\eta_{\text{jet}}| < 2.4$
- Jet numbers $N_{\text{jet}} \geq 3$
- Leading jet p_t range 110-170 GeV



CMS, JHEP 10 (2014) 087
Phys. Rev. C 112 (2025), 034903

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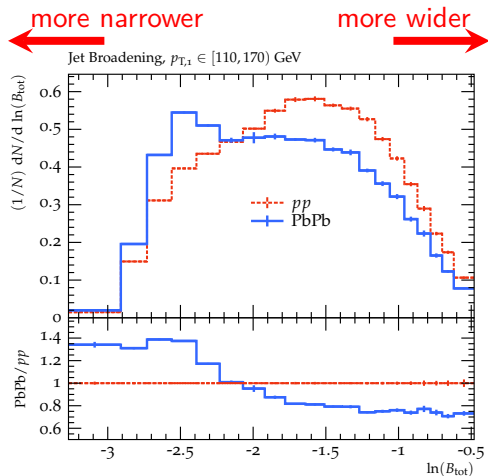
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Conclusions

- An enhancement at the small jet broadening region and suppression at the large jet broadening region
- Parton energy loss in the QGP leads to a more concentrated energy flow

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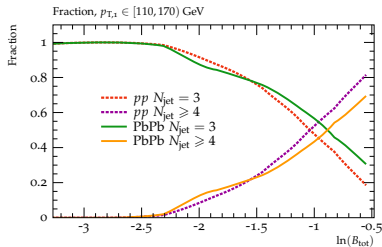
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Summary

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- The 3-jet events will give dominant contributions at the low B_{tot} region

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Effect of Jet Numbers

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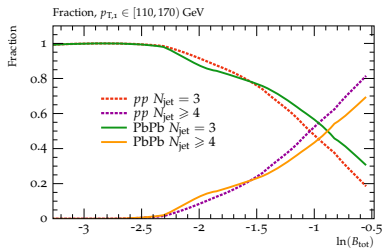
Framework



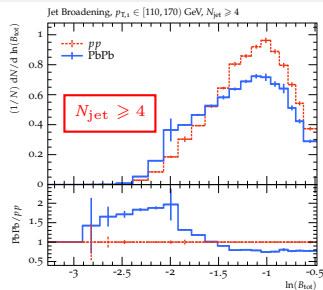
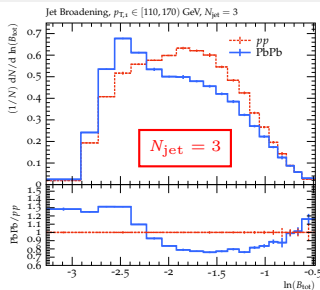
Results



Summary



- The 3-jet events will give dominant contributions at the low B_{tot} region



- The distribution of jets for most 3-jet events is narrower than those multi-jet events ($N_{\text{jet}} \geq 4$)
- The distribution of jets will become narrower after jet quenching

Effect of Jet Numbers

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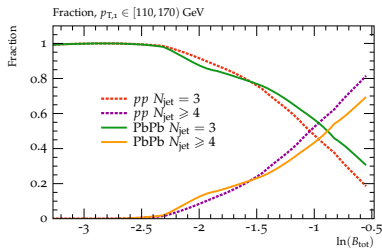
Framework



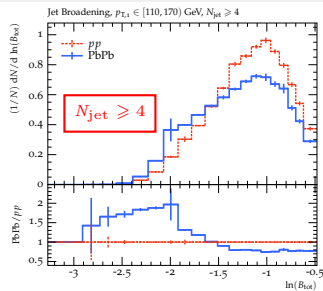
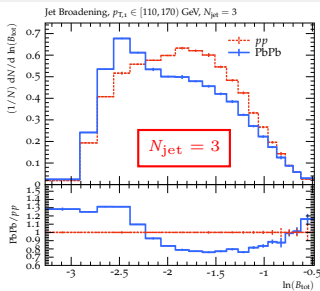
Results



Summary



- The 3-jet events will give dominant contributions at the low B_{tot} region



- The distribution of jets for most 3-jet events is narrower than those multi-jet events ($N_{\text{jet}} \geq 4$)
- The distribution of jets will become narrower after jet quenching

Phys. Rev. C 112 (2025), 034903

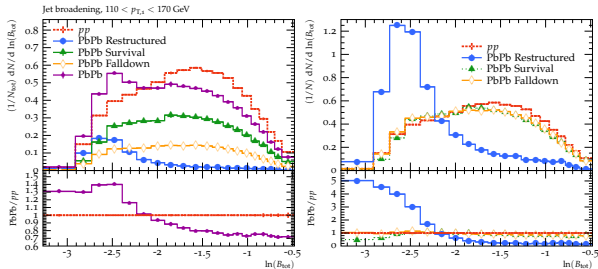
	pp	$PbPb$
$N_{\text{jet}} = 3$	$76.98 \pm 0.30\%$	$81.17 \pm 0.39\%$
$N_{\text{jet}} = 4$	$18.59 \pm 0.13\%$	$15.53 \pm 0.25\%$
$N_{\text{jet}} \geq 5$	$4.43 \pm 0.05\%$	$3.30 \pm 0.05\%$

Exploration of the Sources of Events

Classification of the unquenched versions of the selected quenched events.

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

- The leading jet p_t is greater than 110 GeV, and the number of jets with $p_t > 30 \text{ GeV}$ is less than three



- The $\ln(B_{\text{tot}})$ of the “restructured” part is mainly distributed in region -2.9 to -2.4

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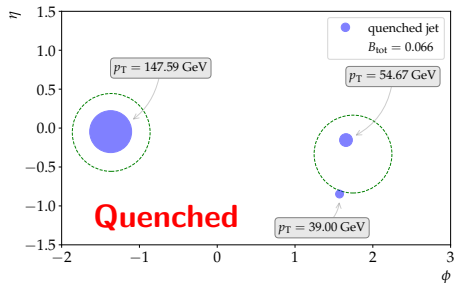
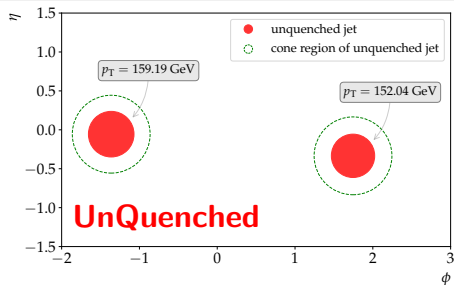
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Investigating the Origins of the Restructured Events



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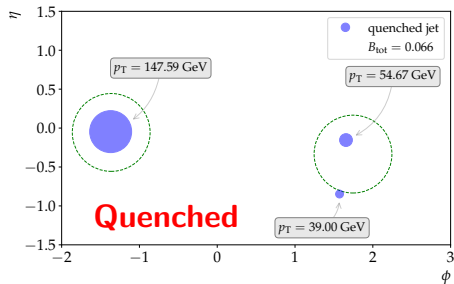
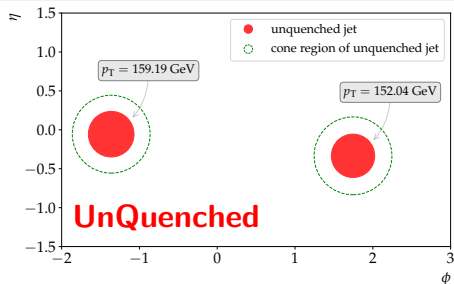
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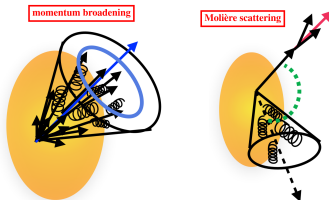
Investigating the Origins of the Restructured Events



Assumption:

- Medium-induced large-angle gluon radiation
- Molière scattering between jet and medium partons

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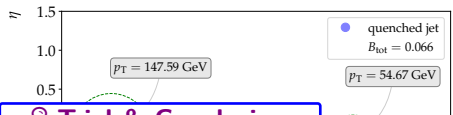
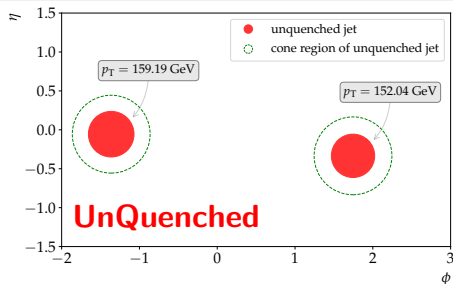
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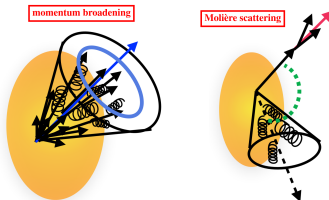
Investigating the Origins of the Restructured Events



Assumption:

- Medium-induced large-angle gluon radiation
- Molière scattering between jet and medium partons

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🔍 Trial & Conclusions

- Turn off the radiation energy loss mechanism of the LBT model
- The fraction of "restructured" events decreases from 14.63% (elastic + inelastic) to 8.99% (only elastic)
- Large-angle elastic Molière scattering may contribute to the production of restructured events

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Highlights

- The first theoretical study on the nuclear modification of total jet broadening in relativistic heavy-ion collisions
- Using event-shape variables to study jet quenching effects
- Confirmation that the mechanism of reduced jet number leads to the narrowing of the total jet broadening distribution
- The large-angle elastic Molière scattering may contribute to the production of restructured multijet events

Thank you for your attention!

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Determination of the Transverse Thrust Axis

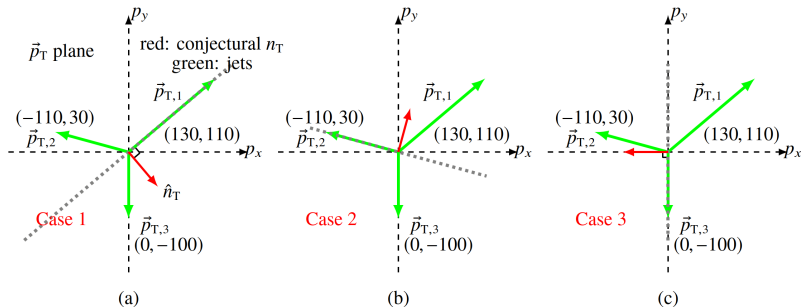


图 B.1 三次尝试的演示图。灰色点线是猜测的分界面，而红色箭头是分界面的法线。

Transverse thrust axis $\hat{n}_t$: the unit vector $\hat{n}_t$ that minimizes the transverse thrust $\tau_\perp$:

$$\tau_\perp \equiv 1 - \sum_i |\vec{p}_{t,i} \cdot \hat{n}_t| / \sum_i p_{t,i}.$$