



喷注淬火与介质响应 Jet quenching and medium response

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高能与低能核物理交叉学术研讨会

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Jet quenching in heavy-ion collisions

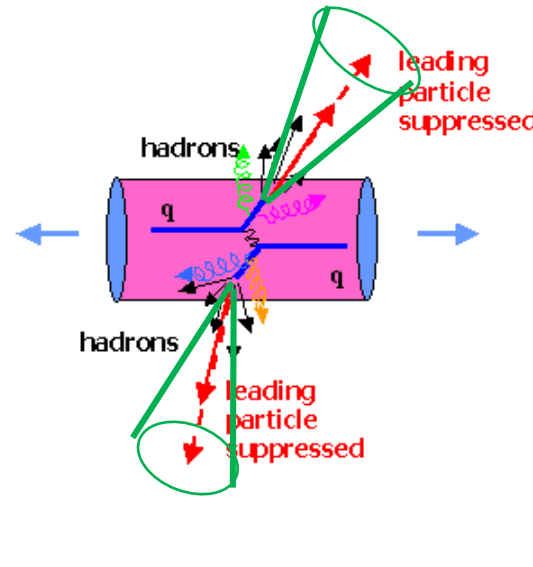
FERMILAB-Pub-82/59-THY
August, 1982

Energy Loss of Energetic Partons in Quark-Gluon Plasma:
Possible Extinction of High p_T Jets in Hadron-Hadron Collisions.

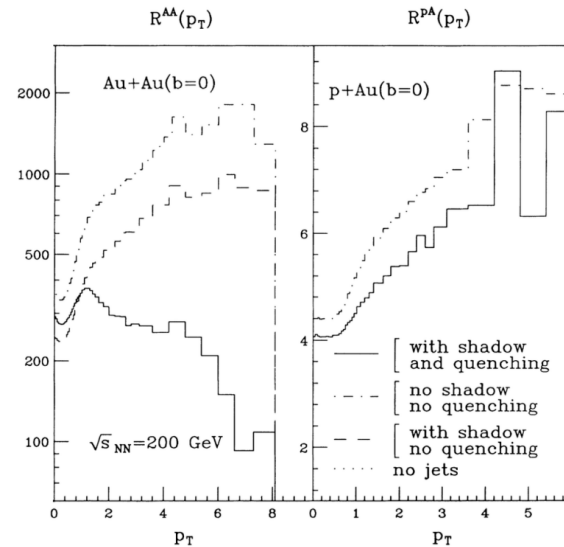
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Abstract

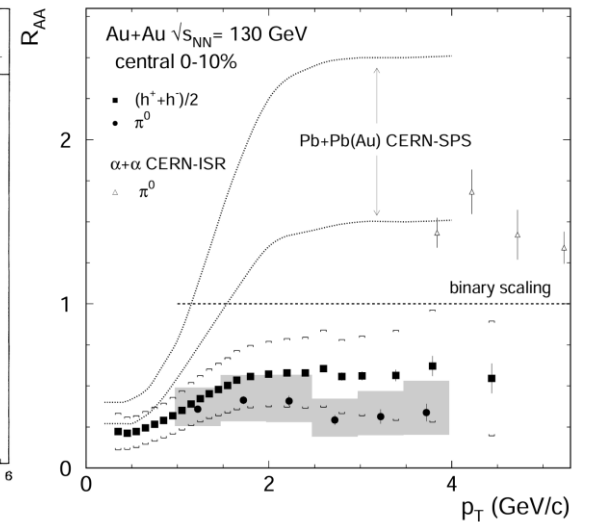
High energy quarks and gluons propagating through quark-gluon plasma suffer differential energy loss via elastic scattering from quanta in the plasma. This mechanism is very similar in structure to ionization loss of charged particles in ordinary matter. The dE/dx is roughly proportional to the square of the plasma temperature. For hadron-hadron collisions with high associated multiplicity and with transverse energy dE_T/dy in excess of 10 GeV per unit rapidity, it is possible that quark-gluon plasma is produced in the collision. If so, a produced secondary high- p_T quark or gluon might lose tens of GeV of its initial transverse momentum while plowing through quark-gluon plasma produced in its local environment. High energy hadron jet experiments should be analysed as function of associated multiplicity to search for this effect. An interesting signature may be events in which the hard collision occurs near the edge of the overlap region, with one jet escaping without absorption and the other fully absorbed.



jet quenching

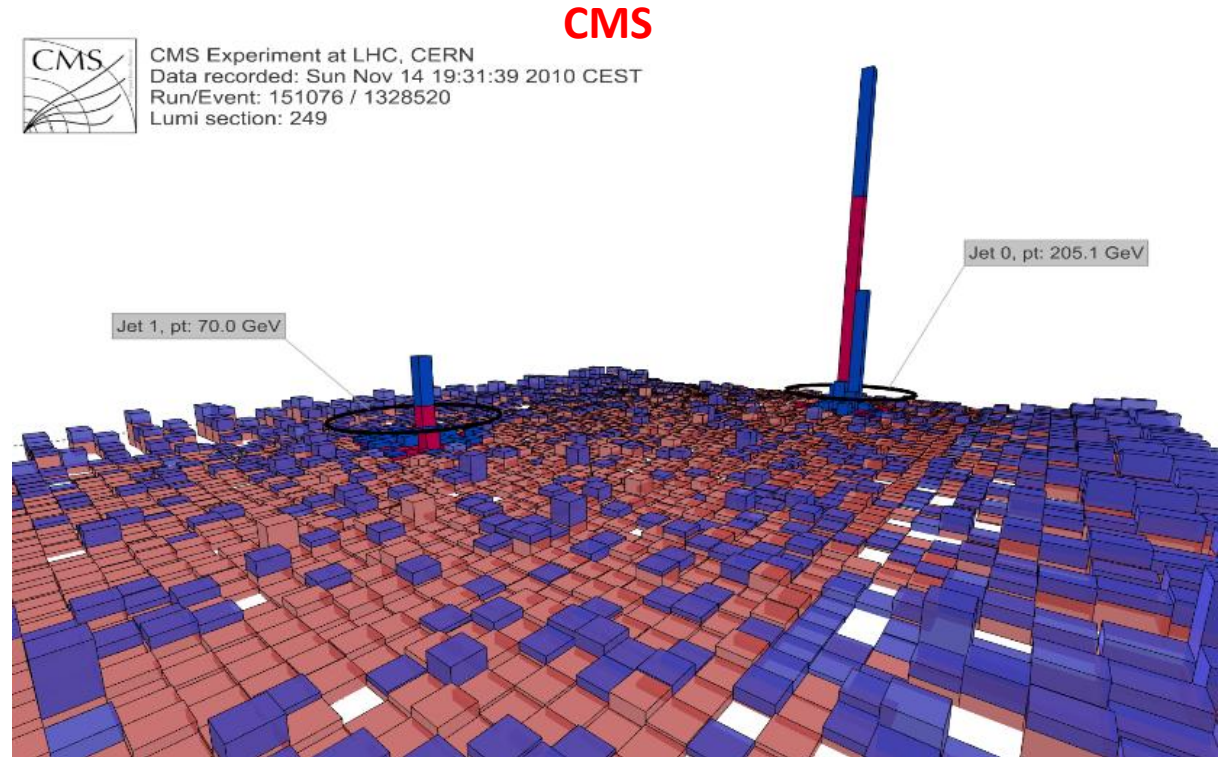
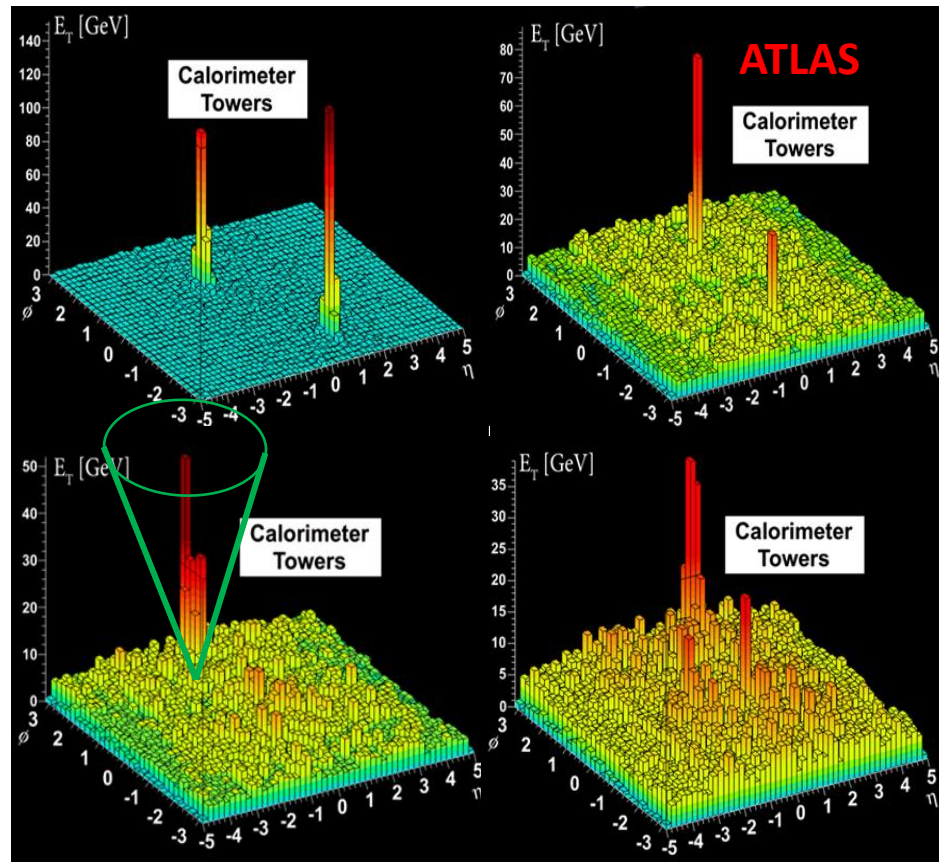


Wang, Gyulassy, PRL 1992

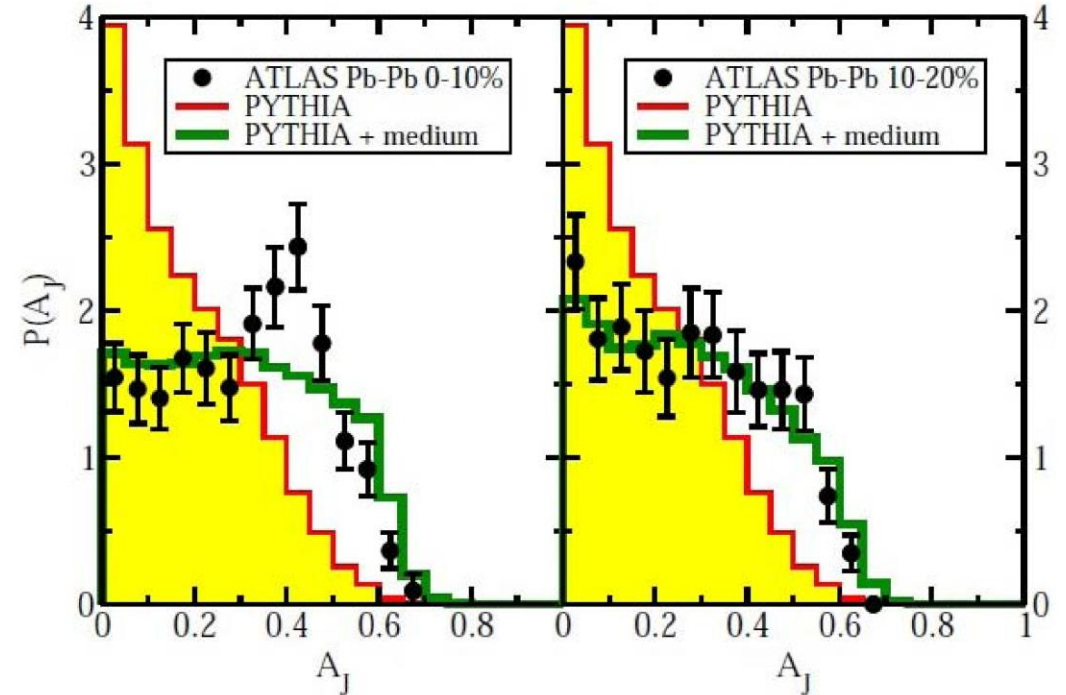
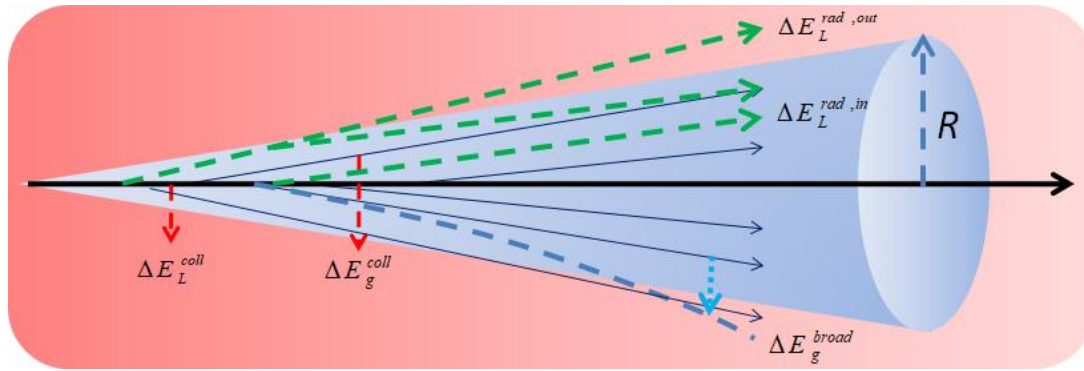


PHENIX, PRL 2002

First (full) jet quenching measurements in AA @LHC



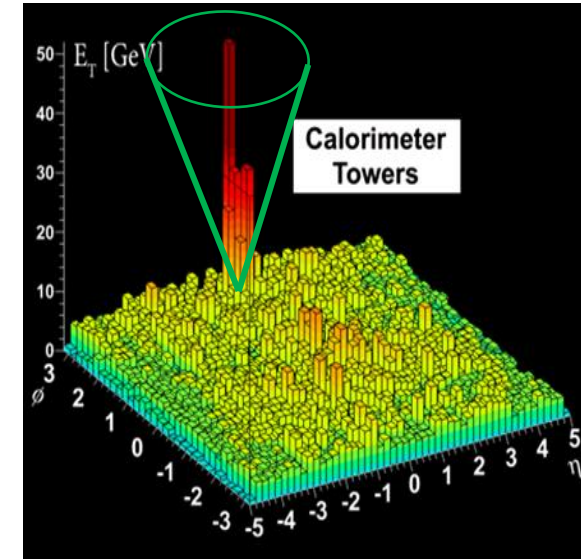
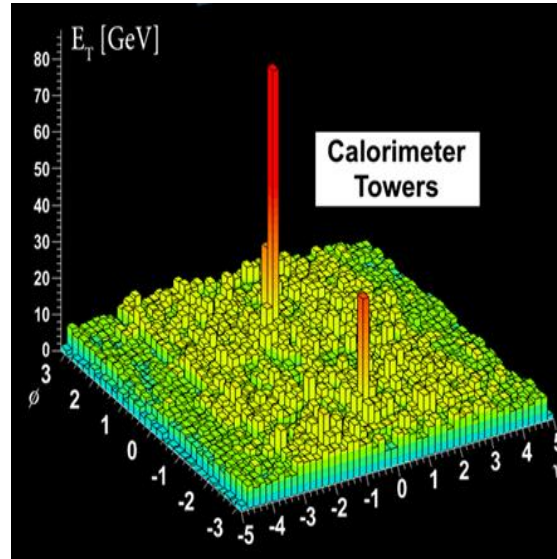
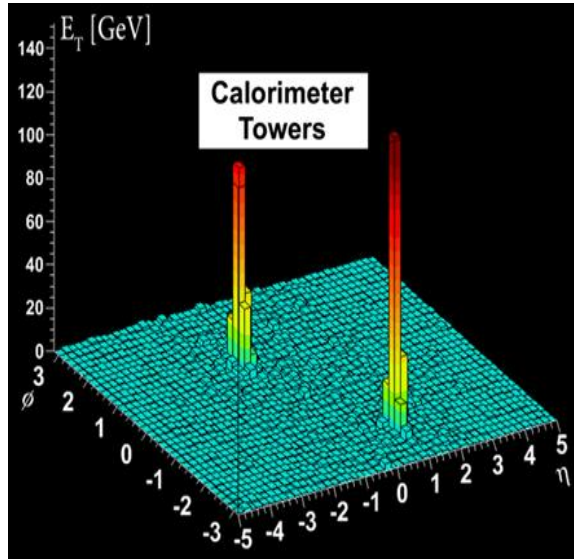
Jet evolution & energy loss in QGP



$$E_{jet} = E_{in} + E_{lost} = E_{in} + E_{rad,out} + E_{kick,out} + (E_{th} - E_{th,in})$$

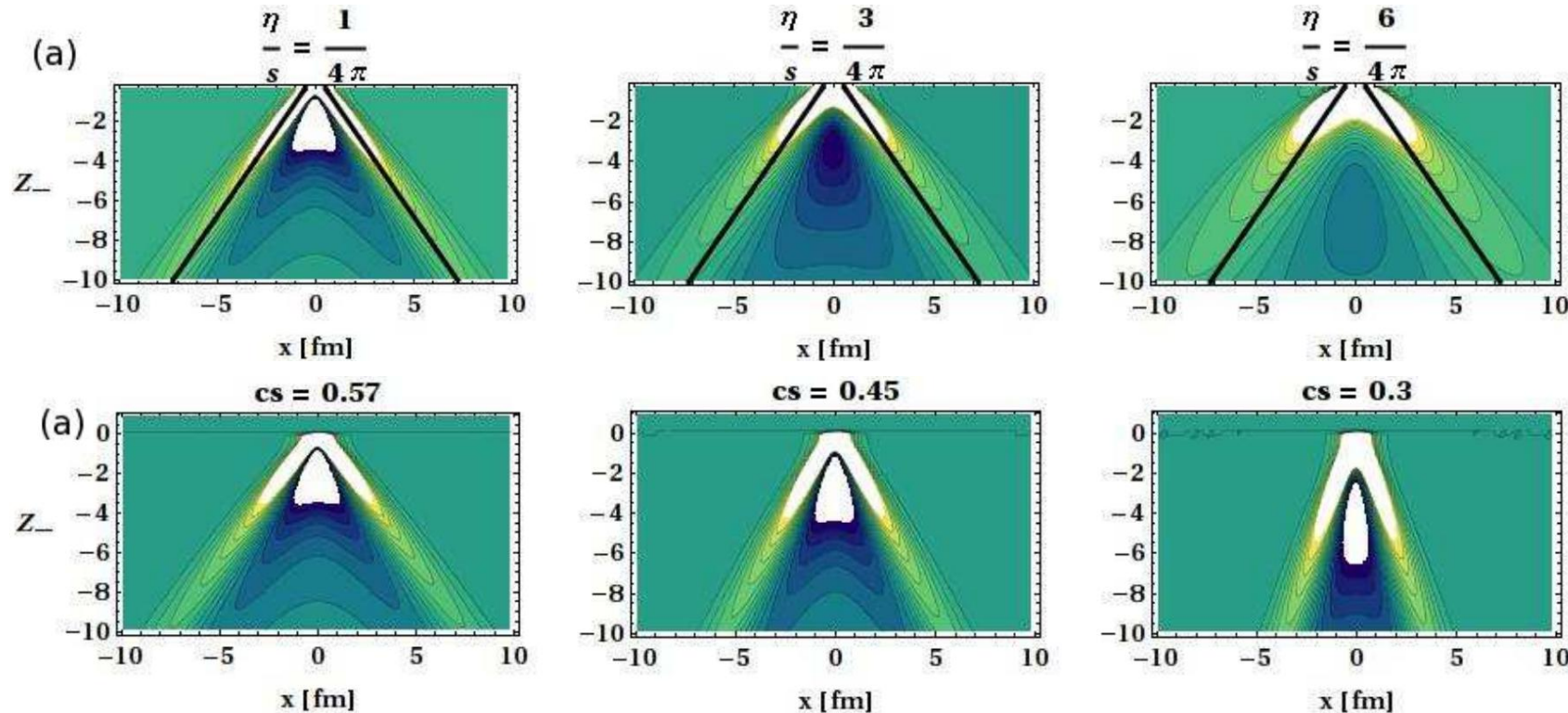
Vitev, Zhang, PRL 2010; GYQ, Muller, PRL, 2011; Casalderrey-Solana, Milhano, Wiedemann, JPG 2011; Young, Schenke, Jeon, Gale, PRC, 2011; Dai, Vitev, Zhang, PRL 2013; Wang, Zhu, PRL 2013; Blaizot, Iancu, Mehtar-Tani, PRL 2013; etc.

Where does the lost energy go?



- A significant energy is lost from the jet and deposited into medium.
- How does the medium respond to the lost/deposited energy?
- How does the lost energy redistribute and manifest in final state?
- Where to search for the signal of **medium response**?
- How to use jet-induced **medium response** to probe the medium properties?

Earlier works on medium response



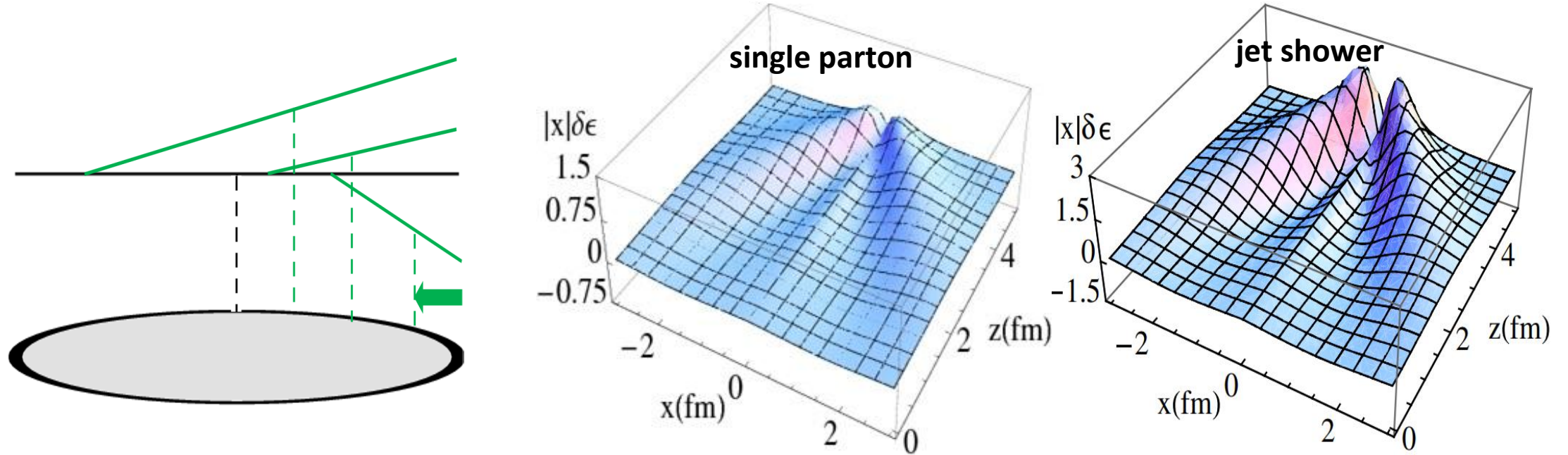
$$T^{\mu\nu} \simeq T_0^{\mu\nu} + \delta T^{\mu\nu}; \quad \partial_\mu T_0^{\mu\nu} = 0, \quad \partial_\mu \delta T^{\mu\nu} = J^\nu.$$

$$\delta T^{00} \equiv \delta\epsilon, \quad \delta T^{0i} \equiv g^i,$$

$$\delta T^{ij} = \delta_{ij} c_s^2 \delta\epsilon - \Gamma_s (\partial^i g^j + \partial^j g^i - \frac{2}{3} \delta_{ij} \nabla \cdot \vec{g}).$$

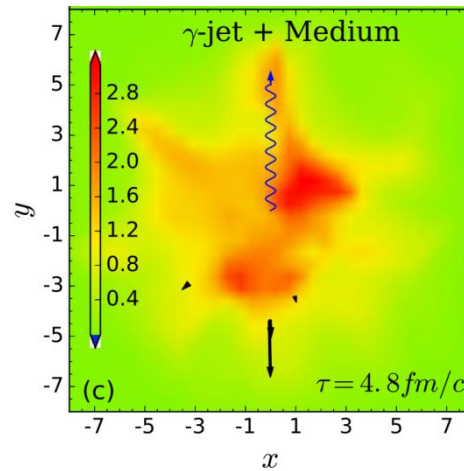
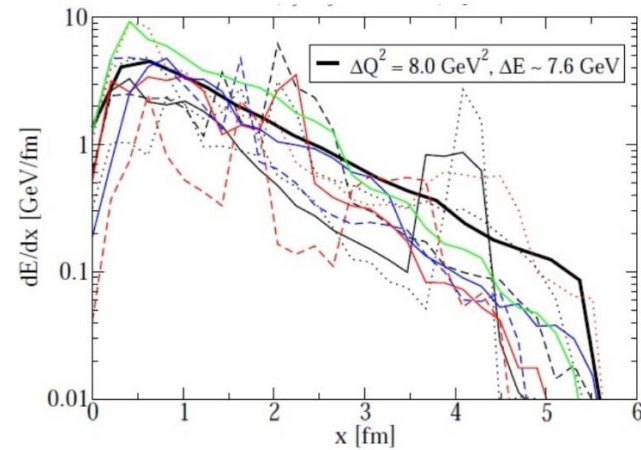
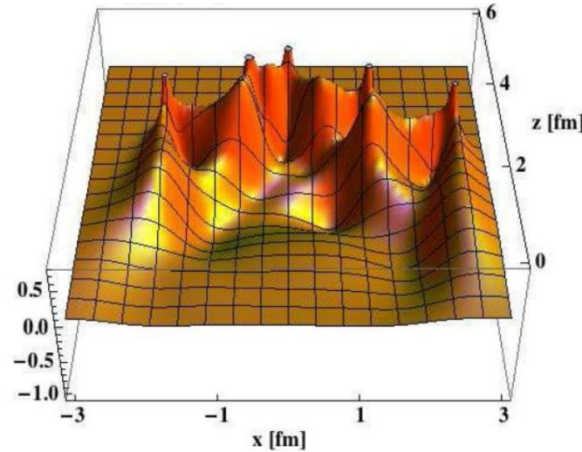
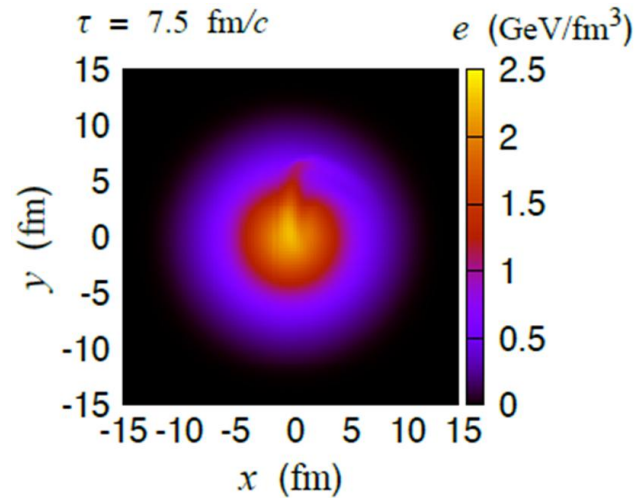
Casalderrey-Solana, Shuryak, Teaney, hep-ph/0411315;
 Stoecker, nucl-th/0406018; Ruppert, Muller, PLB 2005;
 Neufeld, PRC 2009; ...

Medium response to full jet shower



The radiations serve as many additional sources for the energy deposition, which leads to much stronger energy deposition and medium response.

Complications in medium response



- The flow of the expanding medium can distort the conic structure
- Detailed distributions of the energy and momentum deposition profiles
- Even-by-event fluctuations of jet shower evolution and energy loss
- Large and event-by-event fluctuating background medium

Frameworks for studying medium response

- **Jet + recoil**

- **LBT** (He, Luo, Cao, Zhu, Wang, Xing, GYQ, et al, 1503.03313; 1803.06785, 2409.12843)
- **JEWEL** (Elayavalli, Zapp, Milhano, Wiedemann, 1707.01539; 1707.04142)
- **MARTINI** (Park, Jeon, Gale, 1807.06550)

- **Jet + hydrodynamics**

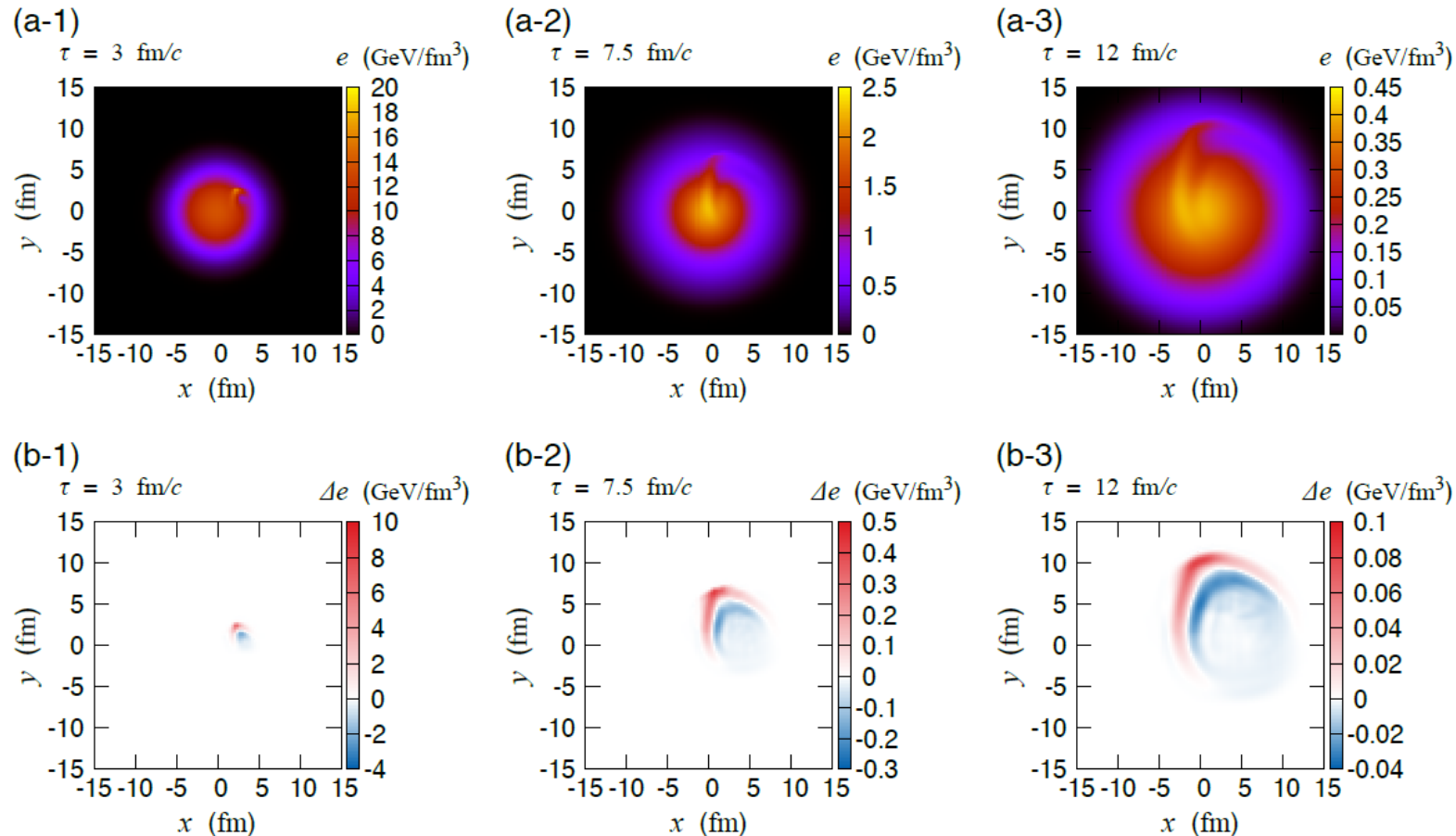
- **Coupled Jet-Fluid** (Tachibana, Chang, GYQ: 1701.07951; 1906.09562)
- **CoLBT-Hydro** (Chen, Yang, Luo, He, Cao, Ke, Pang, Wang, et al, 1704.03648; 2005.09678; 2101.05422; 2203.03683)
- **JETSCAPE** (2002.12250)
- **Minijet+Hydro** (Pablos, Singh, Jeon and Gale, 2202.03414)
- **Hybrid Model** (Casalderrey-Solana, Gulhan, Milhano, Pablos, Rajagopal, 1609.05842)

- **Full Boltzmann**

- **AMPT** (Gao, Luo, Ma, Mao, GYQ, Wang, Zhang, 1612.02548; 2107.11751; 2109.14314)
- **BAMPS** (Bouras, Betz, Xu, Greiner, 1201.5005; 1401.3019)

- **See Cao, GYQ, 2211.16821 for a recent review:** <https://doi.org/10.1146/annurev-nucl-112822-031317>

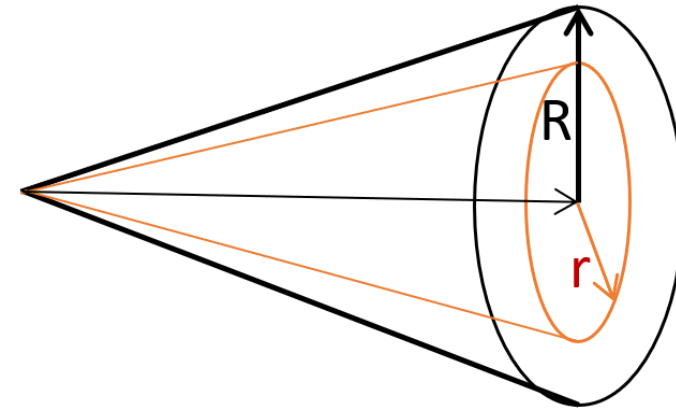
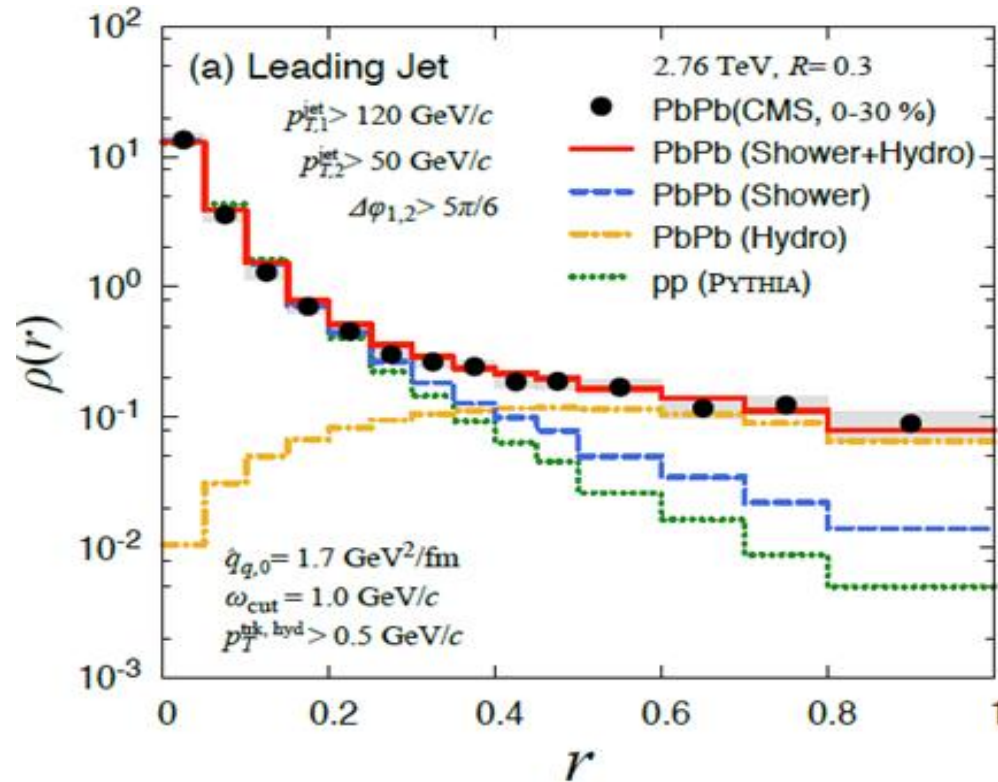
Jet energy loss & medium response



- **Coupled jet-fluid model:**

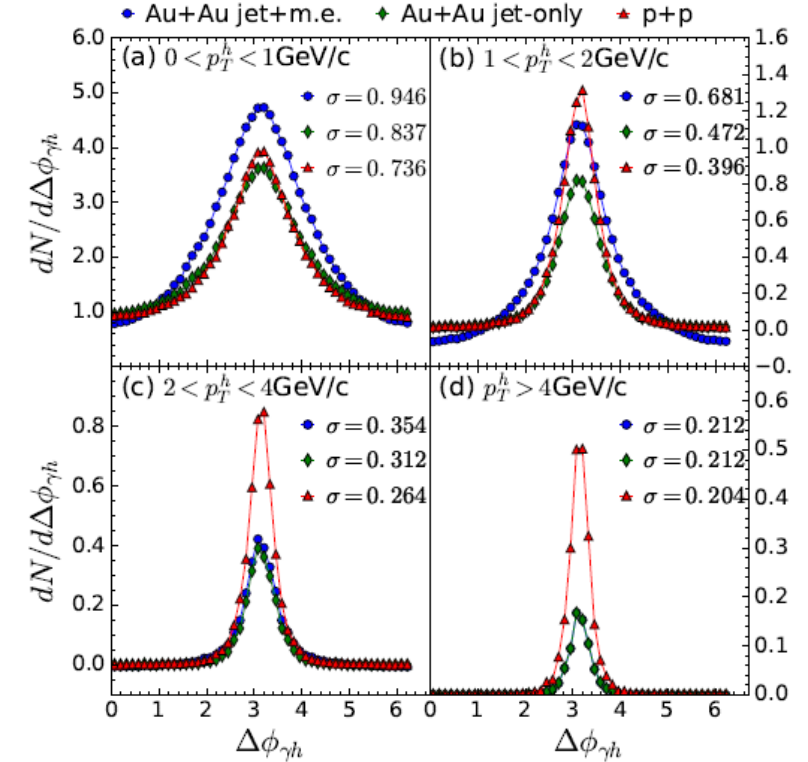
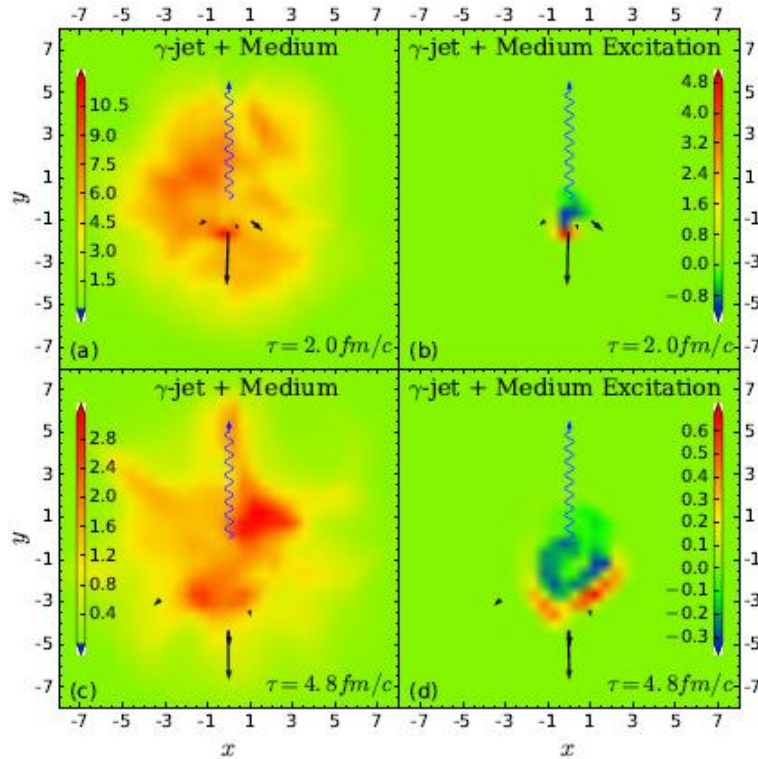
$$p^\mu \partial_\mu f = C[f], \partial_\mu T^{\mu\nu} = J^\nu$$
- Jet deposits energy and momentum into medium, and induces V-shaped wave fronts (**excitation**)
- The wave fronts carry energy and momentum, propagates forward and outward, and depletes the energy behind the jet (**diffusion wake**)
- Jet-induced flow and the radial flow of medium are pushed and distorted by each other

Jet-induced medium response (excitation)



The contribution from hydrodynamic response is flat and finally dominates in the large r region ---- the signal of medium response.

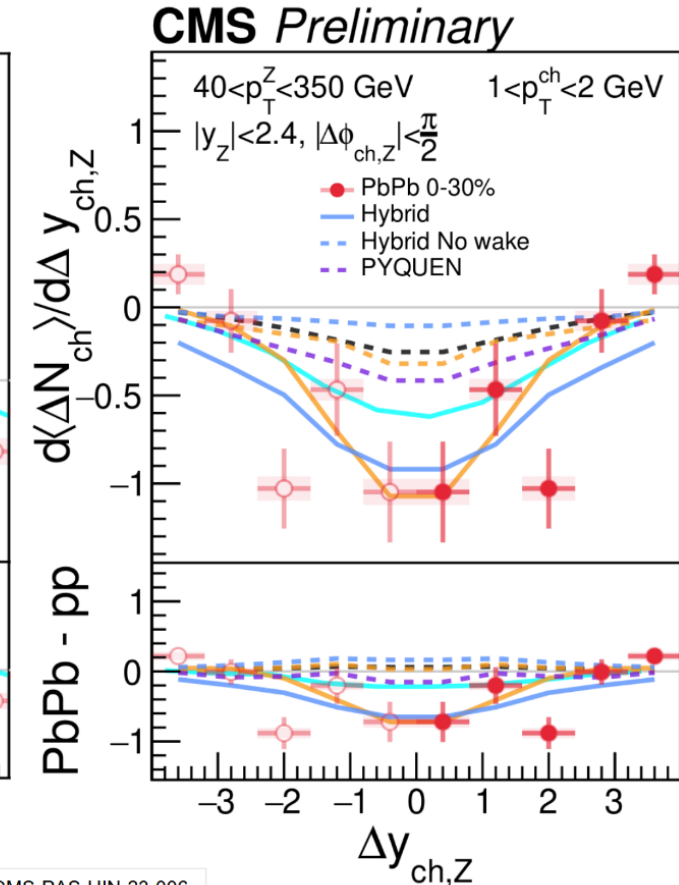
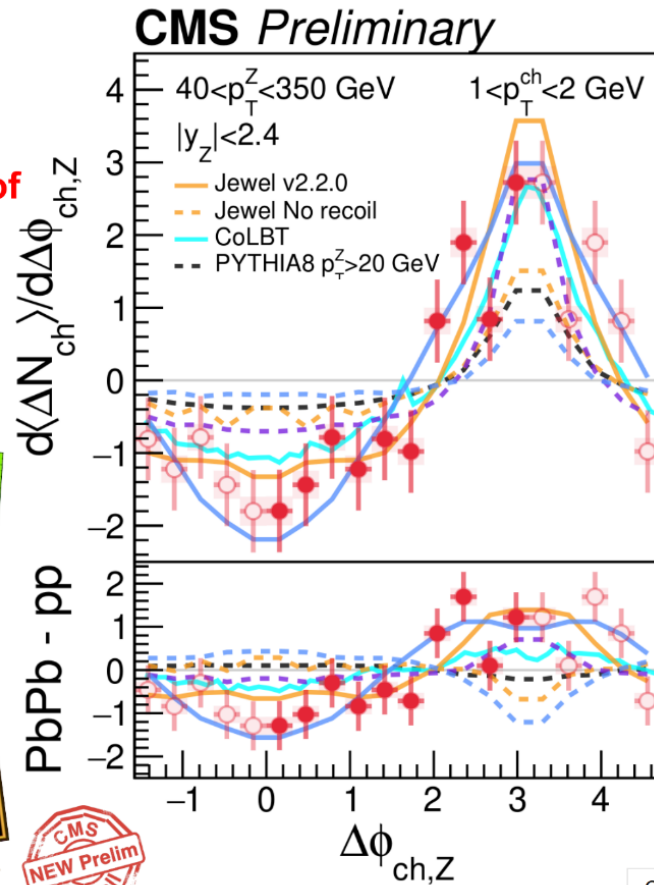
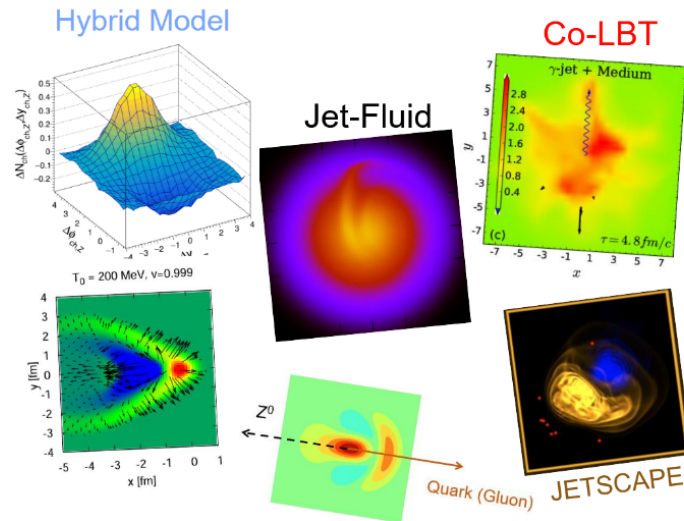
Diffusion wake from CoLBT-Hydro



- Hard hadrons in jet direction are suppressed due to **parton energy loss**.
- Soft hadrons in jet direction are enhanced due to jet-induced **medium excitation** and has significantly broadened azimuthal distribution relative to jet direction.
- Soft hadrons in γ direction are depleted due to a **diffusion wake** behind the jet.

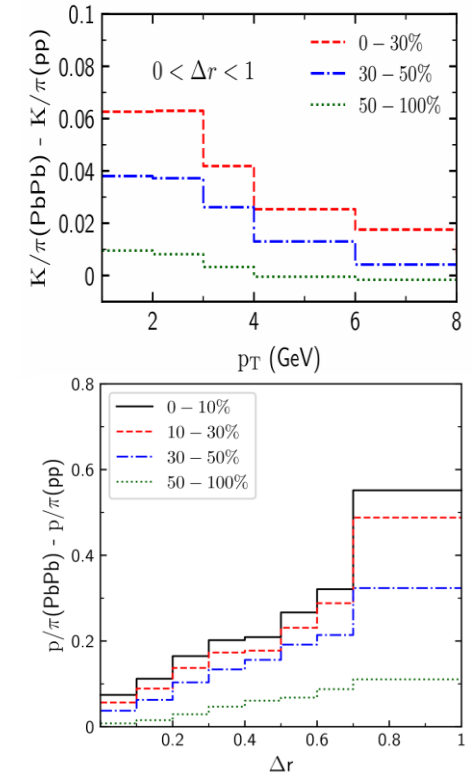
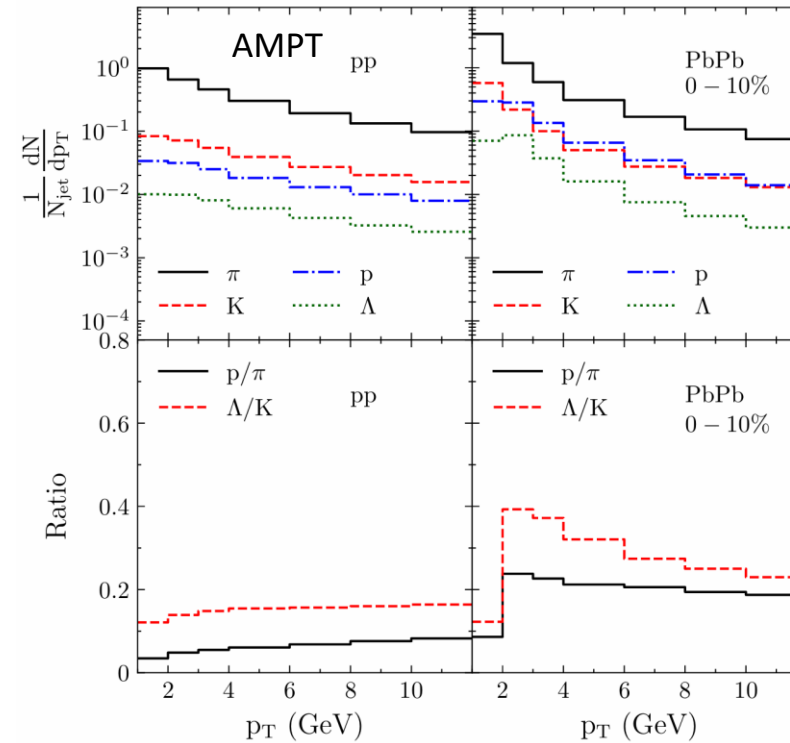
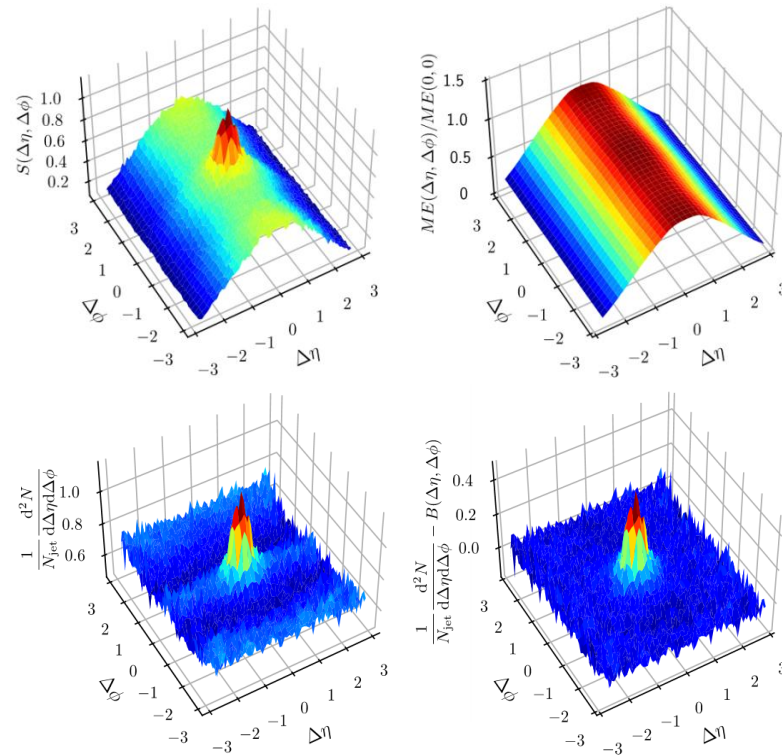
Evidence of diffusion wake from CMS

- First p_T^{ch} differential measurement of Z^0 -hadron correlation in azimuthal angle and rapidity
- We report the **first direct evidence of medium response in QGP**
- High statistics analysis with Run3+4 data in the near future



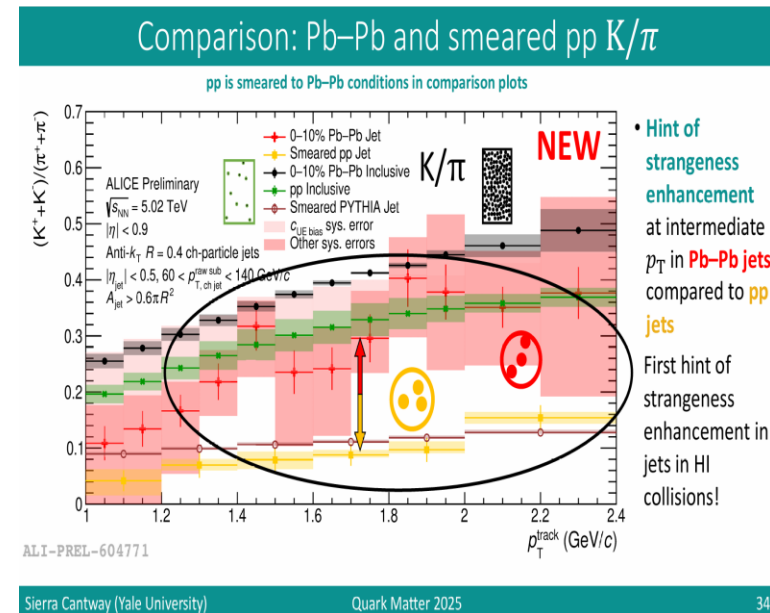
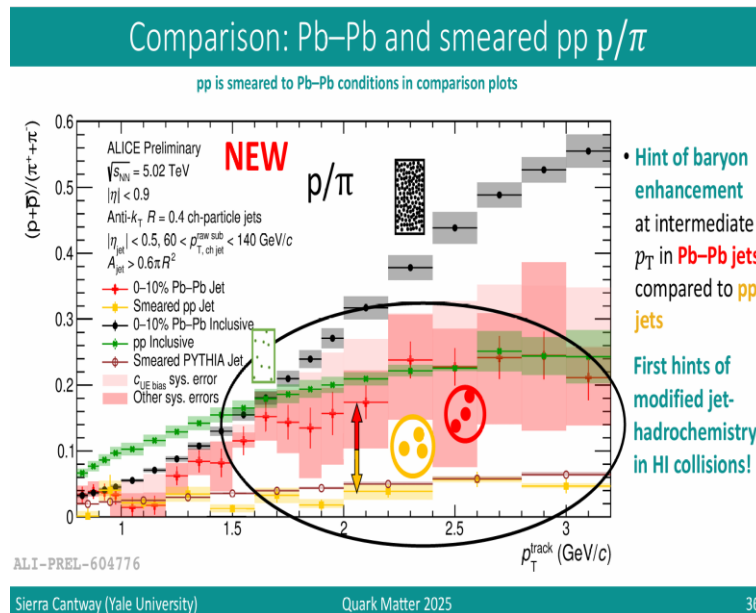
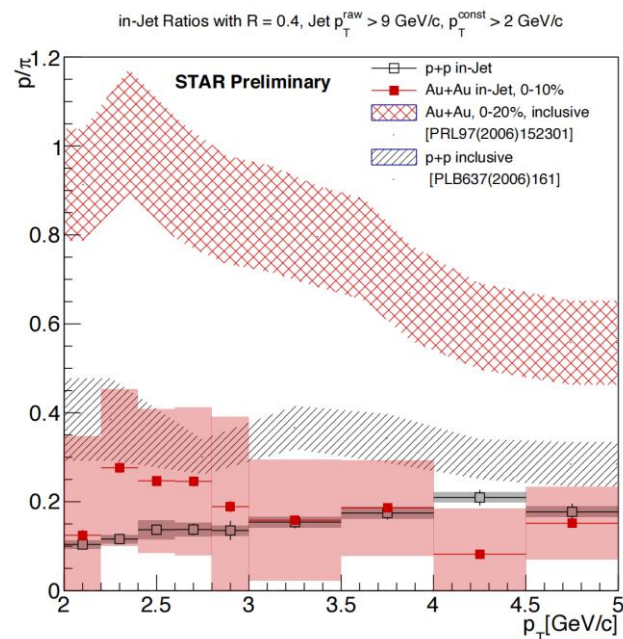
CMS-PAS-HIN-23-006

Hadron chemistry around jets



Strong **enhancement** of baryons/mesons and strangeness/non-strangeness particles around quenched jets. For intermediate p_T (2-4GeV) regime, the enhancement of jet-induced B/M & strange/non-strange is stronger for larger distance because the lost energy from quenched jets can diffuse to large angle.

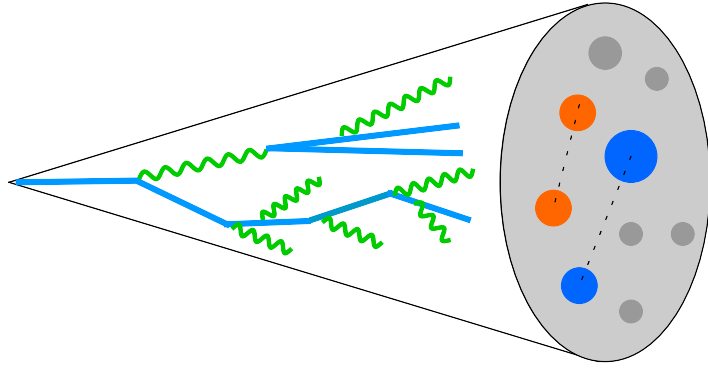
Experimental result on hadron chemistry in jets



Hint of baryon/meson & strange/non-strange enhancements at intermediate p_T in AA jets compared to pp jets.

Gabriel Dale-Gau (for STAR) & Sierra Cantway (for ALICE), talks at HP2024/QM2025

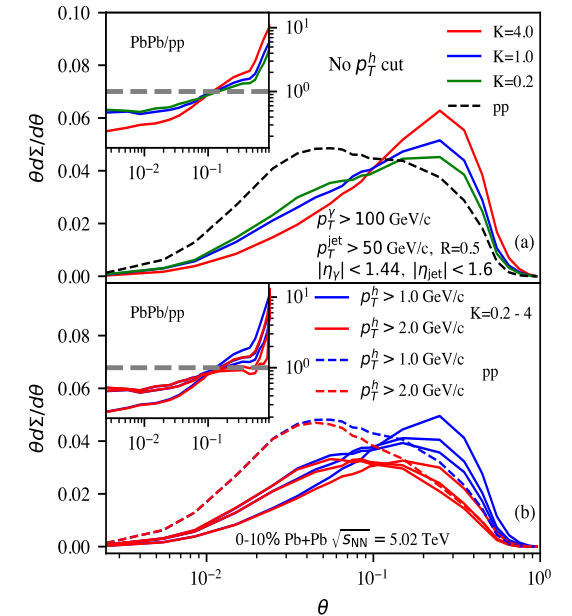
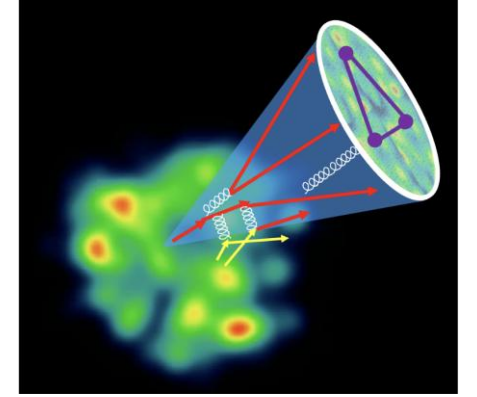
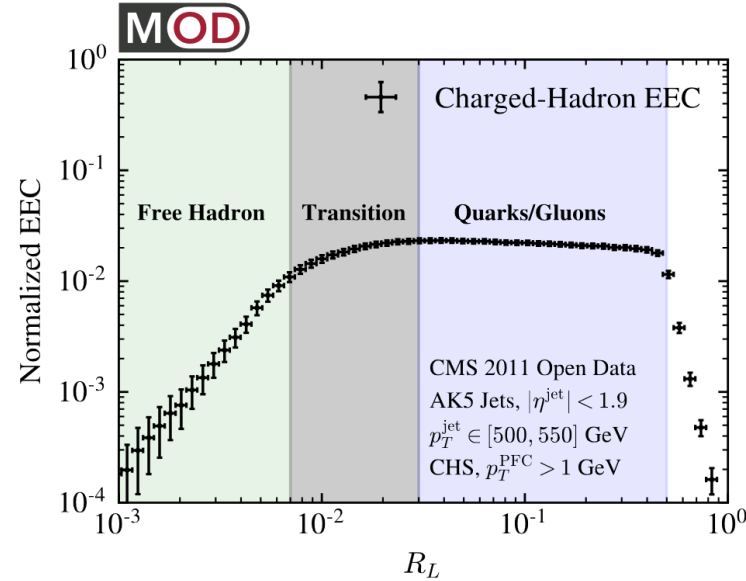
Jet energy-energy correlator (EEC)



$$\frac{d\sigma_{\text{EEC}}}{dR_L} = \int d\sigma(\Delta R_{ij}) \frac{p_{T,i} p_{T,j}}{p_{T,\text{jet}}^2} \delta(\Delta R_{ij} - R_L)$$

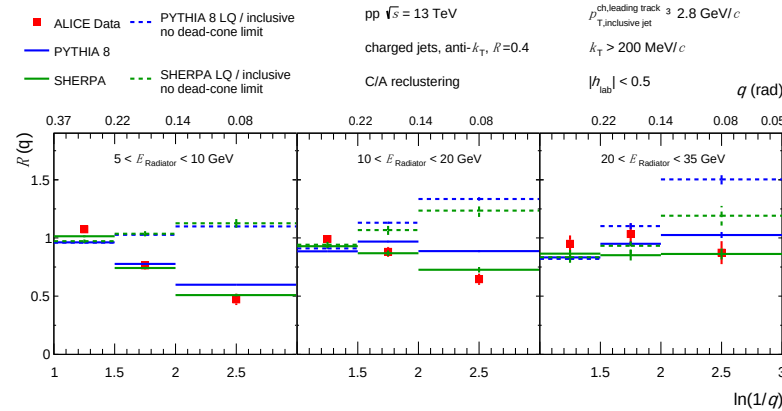
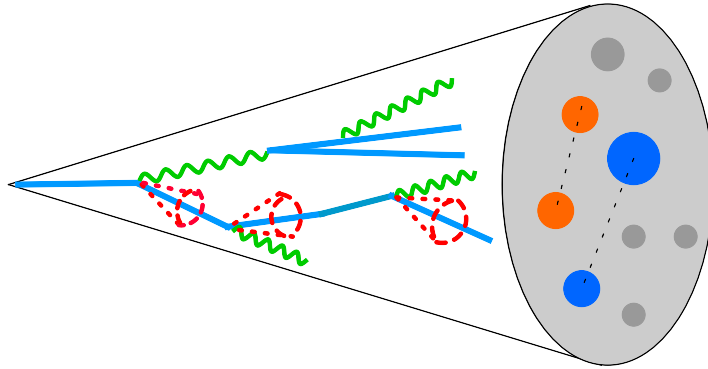
$$\Delta R_{ij} = \sqrt{\Delta\phi_{ij}^2 + \Delta\eta_{ij}^2}$$

Jet energy correlators are sensitive to various intrinsic or emergent scales.
 Jet EEC has a clear transition between perturbative and non-perturbative regions.
 Medium-modified jet EEC provides unique opportunity to probe jet-medium interaction mechanisms and QGP properties.

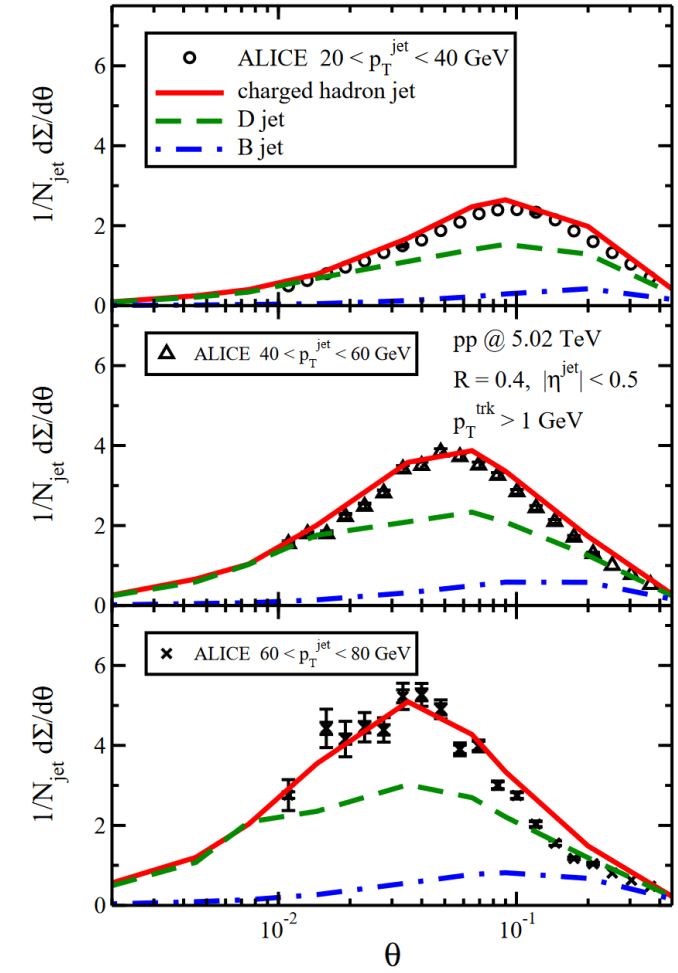


Komiske, IMoult, Thaler, Zhu, PRL 130, 051901 (2023); Liu, Zhu, PRL 130, 091901 (2023); Liu, Liu, Pan, Yuan, Zhu, PRL 130, 181901 (2023);
 Andres, Dominguez, Elayavalli, Holguin, Marquet, PRL 130 (2023) 26, 262301;
 Yang, He, Moult, Wang, PRL 132 (2024) 1, 1

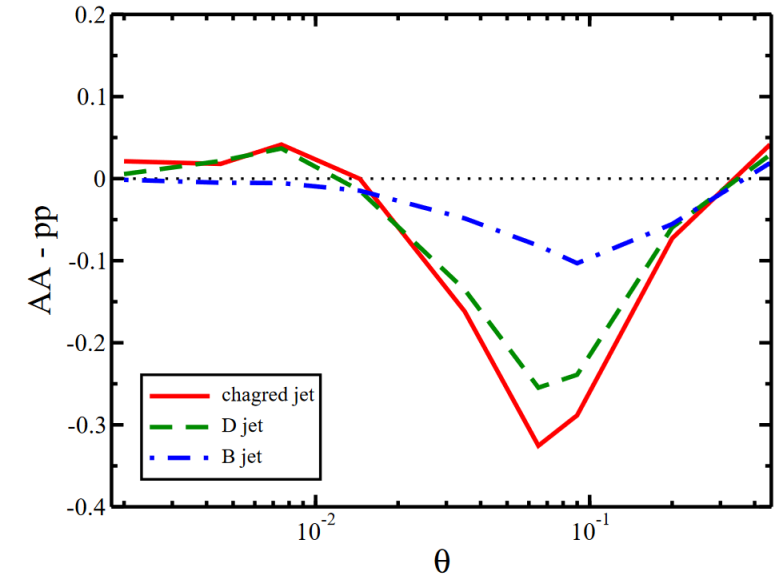
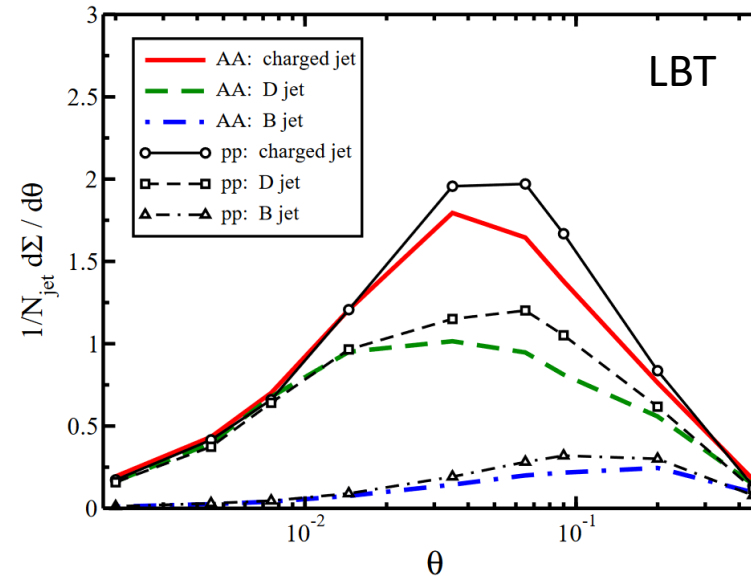
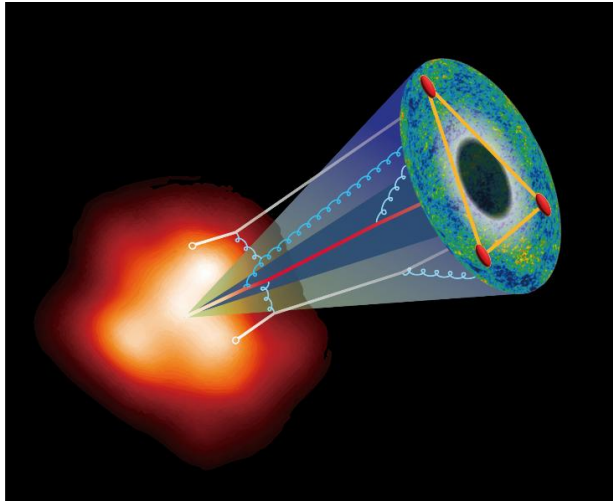
Flavor hierarchy of jet EEC in vacuum



- Heavy flavor jets provide direct access to mass effect on jet substructure
- Dead-cone effect in QCD: gluon emissions from massive quark are suppressed within a cone of $\theta_0 \sim m_Q/E$
- Flavor hierarchy of jet EEC in vacuum:
 $\Sigma(\text{ch. jet}) > \Sigma(\text{D jet}) > \Sigma(\text{B jet})$
 $\theta^{\text{peak}}(\text{ch. jet}) < \theta^{\text{peak}}(\text{D jet}) < \theta^{\text{peak}}(\text{B jet})$
- Higher p_T jets peaks at smaller angles.



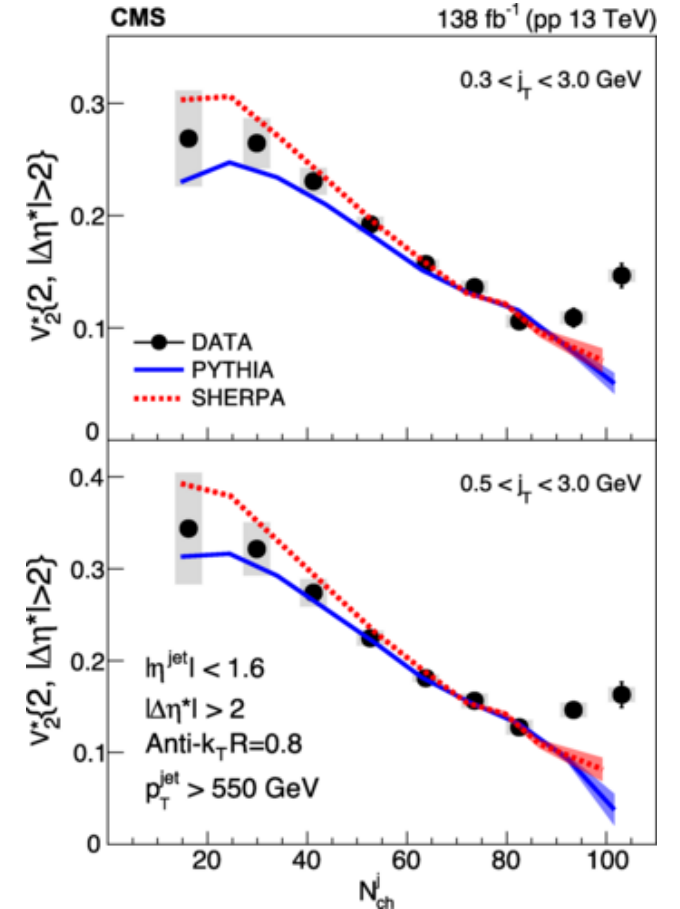
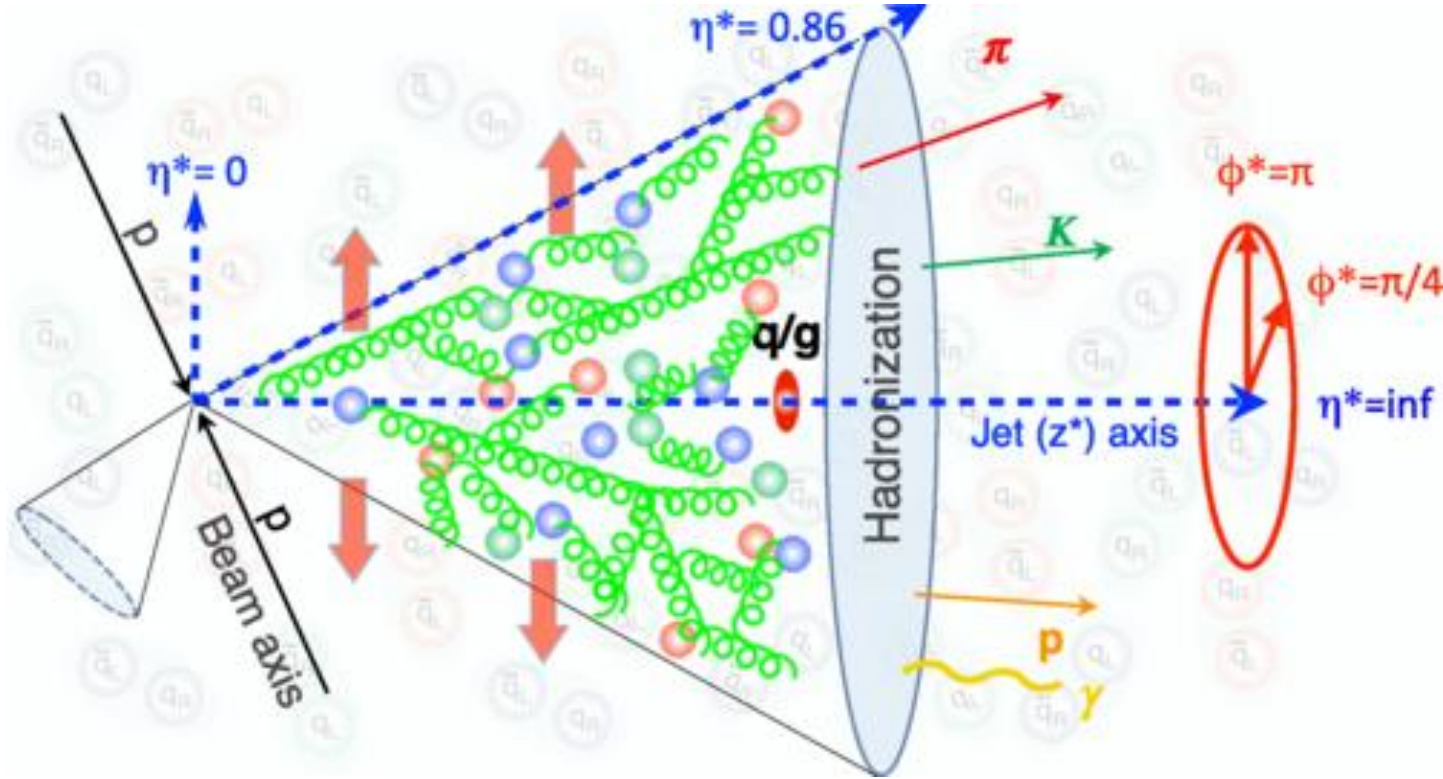
Flavor hierarchy of jet EEC in QGP



Flavor (mass) hierarchy in medium-modified jet EEC:

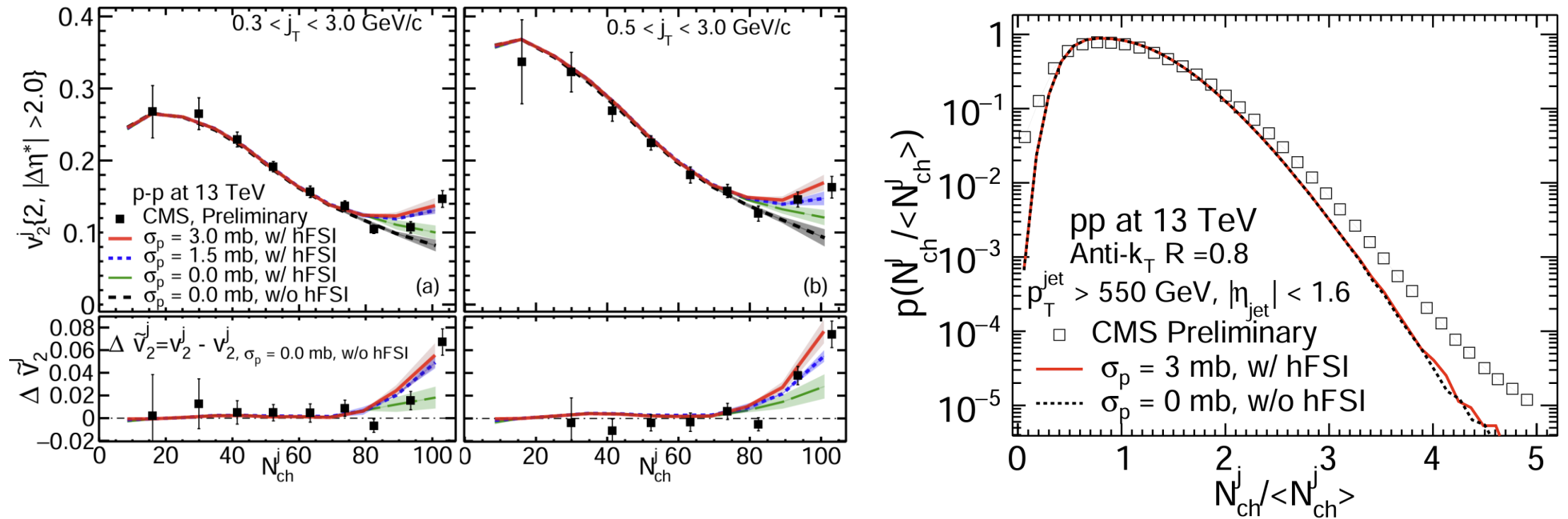
- For charged jets, the EEC spectra gets a strong suppression at intermediate angle (due to energy loss), and gets enhanced at small and large angles
- For heavy-meson-tagged jets, both suppression and enhancement effects become weaker

High multiplicity jets: v_2 enhancement



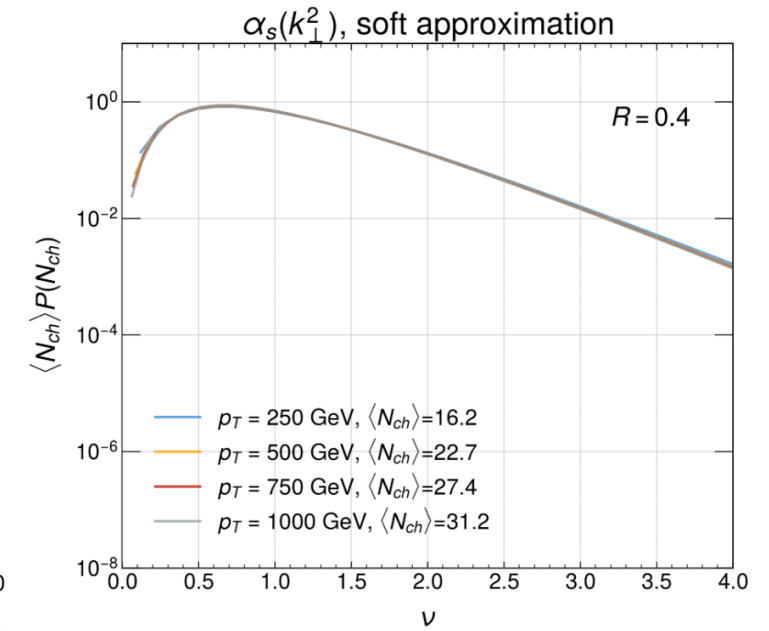
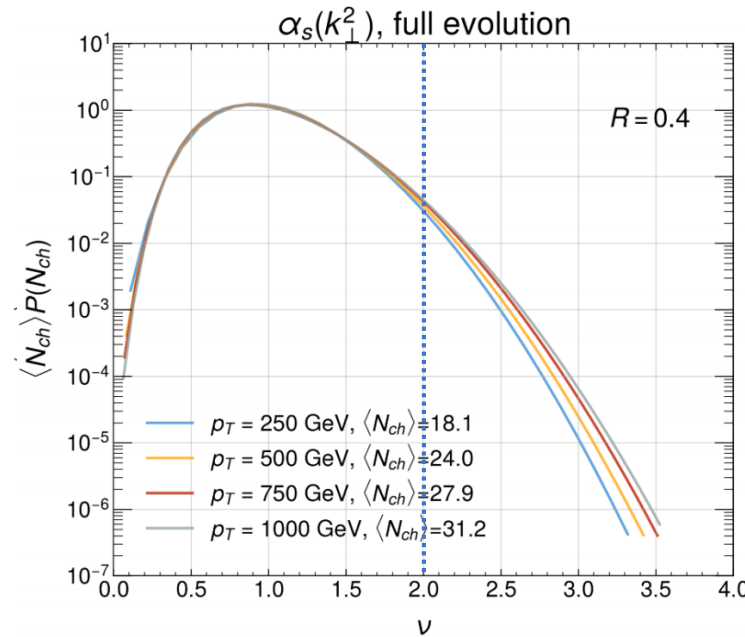
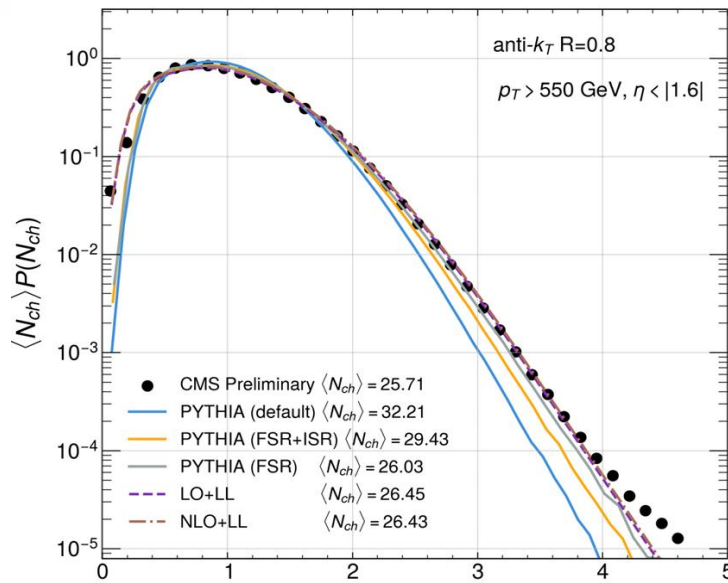
CMS has observed the enhancement of v_2 in high multiplicity jets? **What is critical for $N_{ch}=80-100$?**

High multiplicity jets: v_2 enhancement

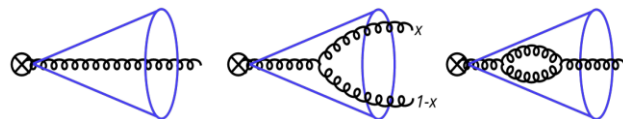


The Enhancement of v_2 in high multiplicity jets seems to be explained by final-state interactions?

Jet multiplicity distribution



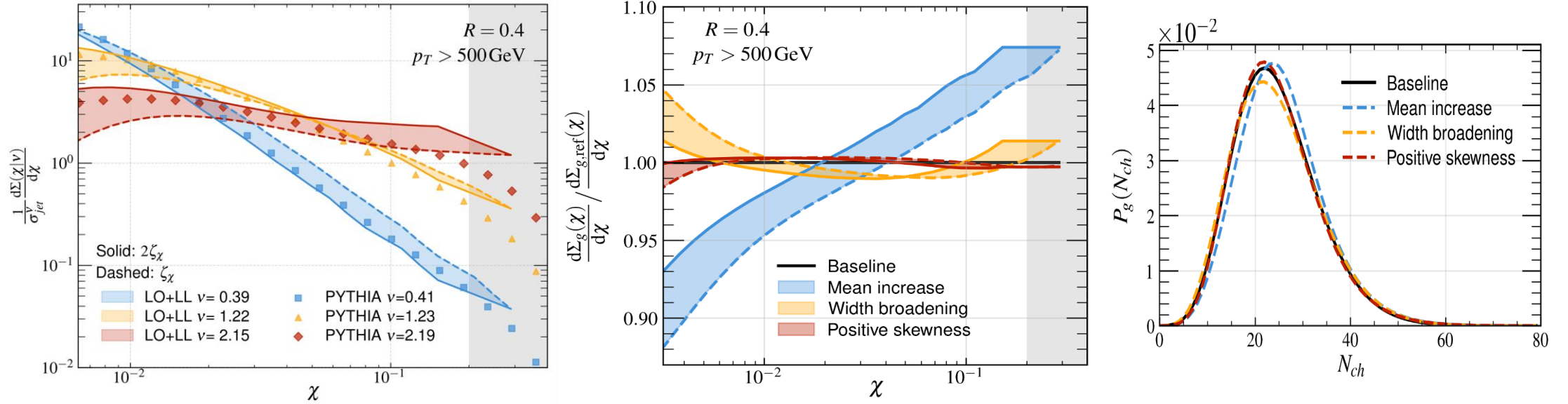
- The distribution of jet internal multiplicity: the contribution from parton splitting is described by coupled non-linear evolution equations; hadronization is described by the non-perturbative model.
- Koba-Nielsen-Olesen (KNO) scaling is violated for $\nu > 2$.
- A basis for studying multiplicity-conditioned jet substructure.



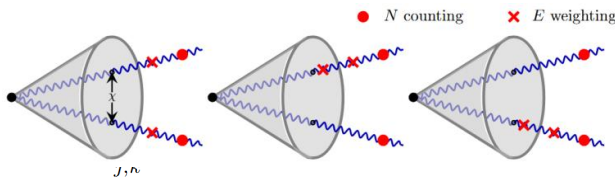
$$Z_i(s, \omega, \mu) = \mathcal{L}\{P\}(s) = \sum_{n=0}^{\infty} e^{-ns} P_i(n, \omega, \mu)$$

$$\frac{\partial Z_i(s, \omega, \zeta)}{\partial \ln \zeta} = S \int_0^1 dx \frac{\alpha_s(k_\perp^2)}{2\pi} \Theta(k_\perp^2 - Q_0^2) \times \sum_{j,k} \hat{P}_{ji}(x) Z_j(s, x\omega, \zeta) Z_k(s, (1-x)\omega, \zeta).$$

Jet multiplicity-conditioned EEC



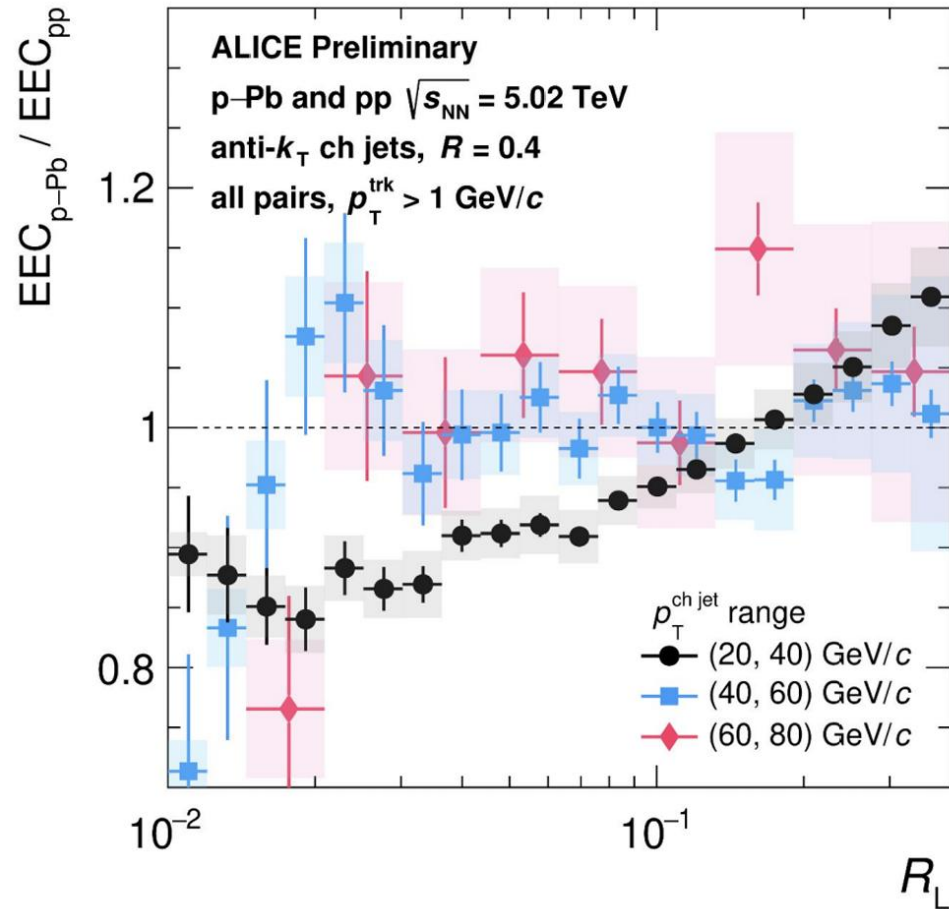
- Nontrivial correlation between jet EEC and internal multiplicity: the former characterizes the angular structure of energy flows, while the latter is sensitive to the entire history of particle production.
- Background-induced biases in reconstructed jet multiplicity distributions—common in heavy-ion collisions—may cause “apparent” modifications to the EEC.



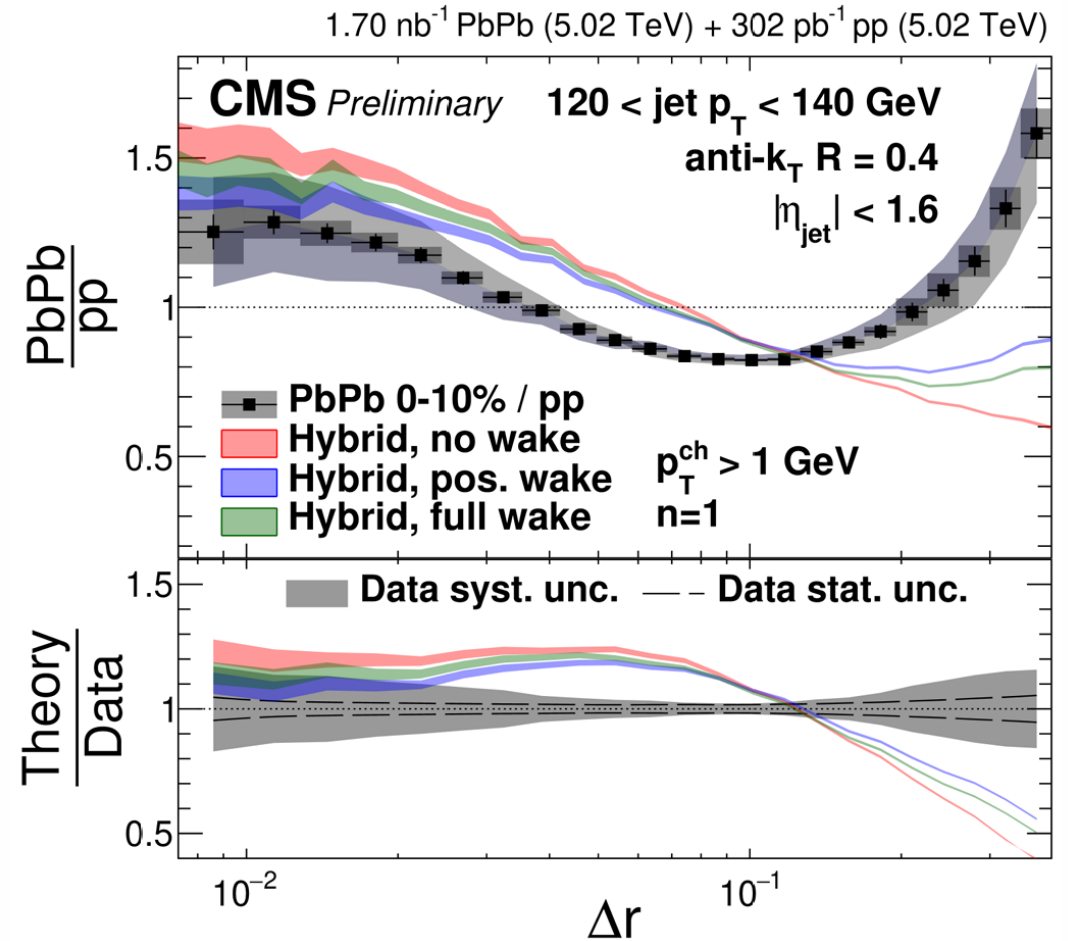
$$\mathcal{G}_i(\chi, s, \omega_J, \zeta_\chi) = \frac{\omega_J^2}{\chi} S \int dx \frac{\alpha_s(k_\perp^2)}{\pi} \Theta(k_\perp^2 - Q_0^2) \times \sum_{j,k} x(1-x) \hat{P}_{ji}(x) Z_j(x) Z_k(1-x).$$

$$\frac{\partial \mathcal{G}_i(\chi, s, \omega_J, \zeta)}{\partial \ln \zeta} = S \int dx \frac{\alpha_s(k_\perp^2)}{2\pi} \Theta(k_\perp^2 - Q_0^2) \times \sum_{j,k} \hat{P}_{ji}(x) \{ \mathcal{G}_j(x) Z_k(1-x) + \mathcal{G}_k(1-x) Z_j(x) \}.$$

Jet EEC in nuclear medium

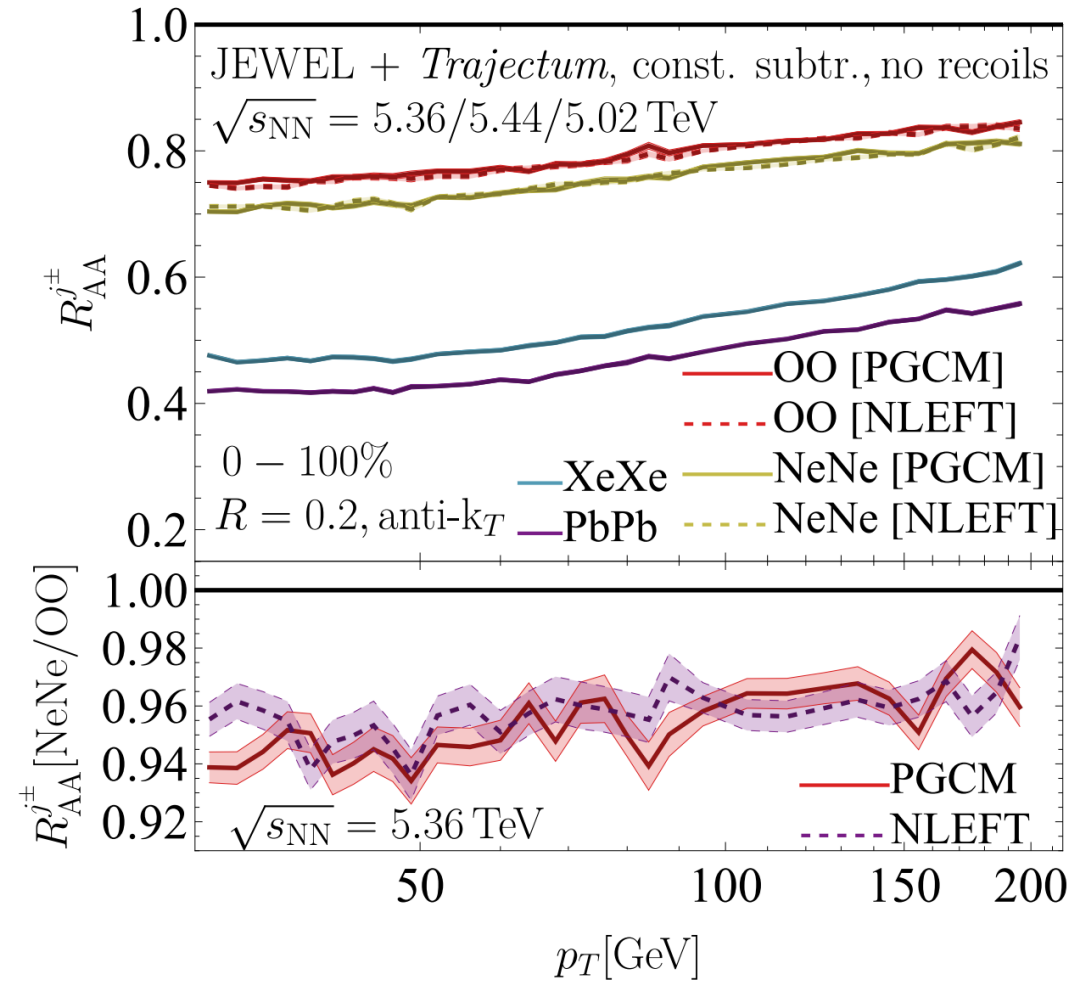
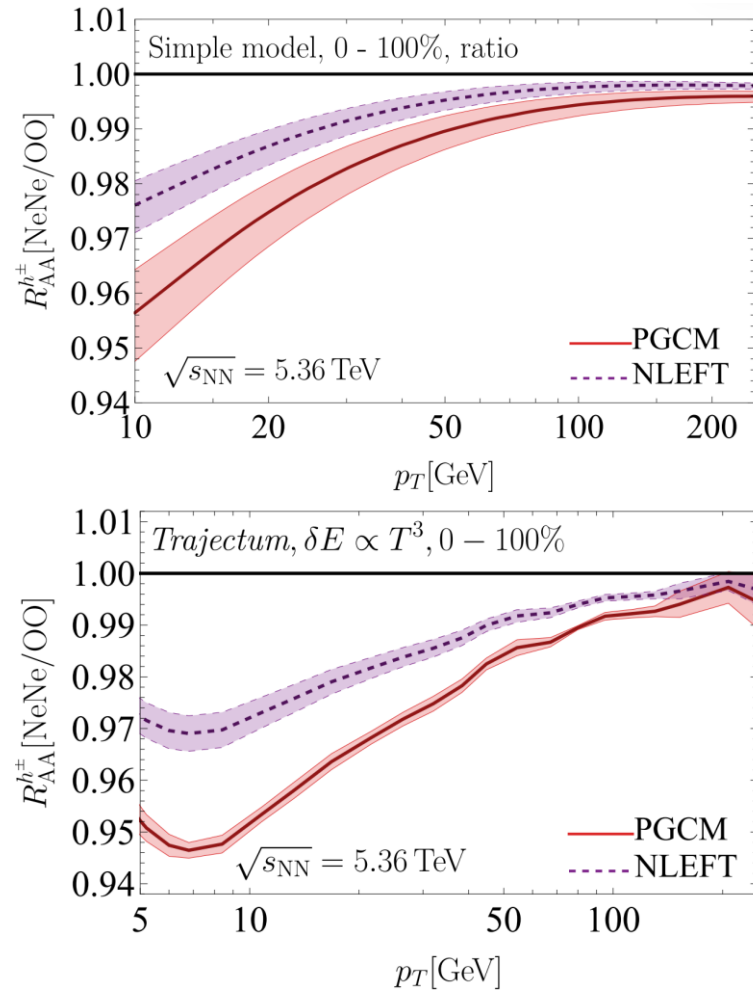


Jet multiplicity **mean** increase?



Jet multiplicity **variance** increase?

Probing initial conditions with jet quenching



Summary

- Jets are versatile probes of strongly-interacting quark-gluon plasma in relativistic heavy-ion collisions.
- The interaction of full jets and medium involves various mechanisms and effects (jet quenching & medium response).
- Medium response can affect energy (re)distribution, hadron yield and chemistry around quenched jets.
- Jet substructure (such as EEC) can probe jet-medium interaction at different scales.
- Jet multiplicity-conditioned EEC as a new tool to study jet evolution and substructure.

CoLBT-Hydro model

- **Linear Boltzmann Transport (LBT)** model for hard parton (jet shower and recoil) evolution
- **Hydrodynamics (CLVisc)** model for the bulk evolution
- Sort jet and recoil partons according to a cut-off parameter
 - Hard partons (**LBT**): $p \cdot \partial f(x, p) = \mathcal{C}[f]$ for $p \cdot u > p_{cut}^0$
 - Soft partons (**source**):

$$J^\nu(x) = \sum_i p_i^\nu \delta^{(4)}(x - x_i) \theta(p_{cut}^0 - p \cdot u)$$

- Update medium information by solving the hydrodynamics equation with source term

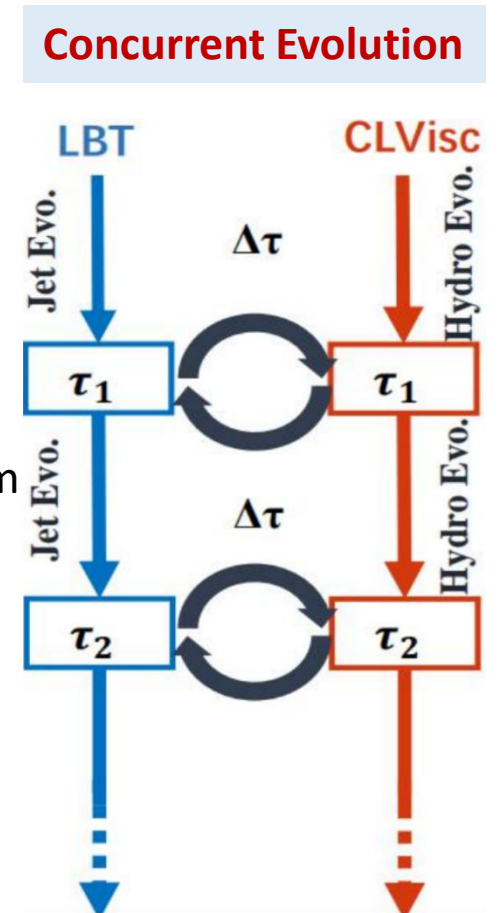
$$\partial_\mu T^{\mu\nu}(x) = J^\nu(x)$$

- Final hadron spectra:
 - Hadronization of hard partons
 - Jet-induced medium response via Cooper-Frye freeze-out

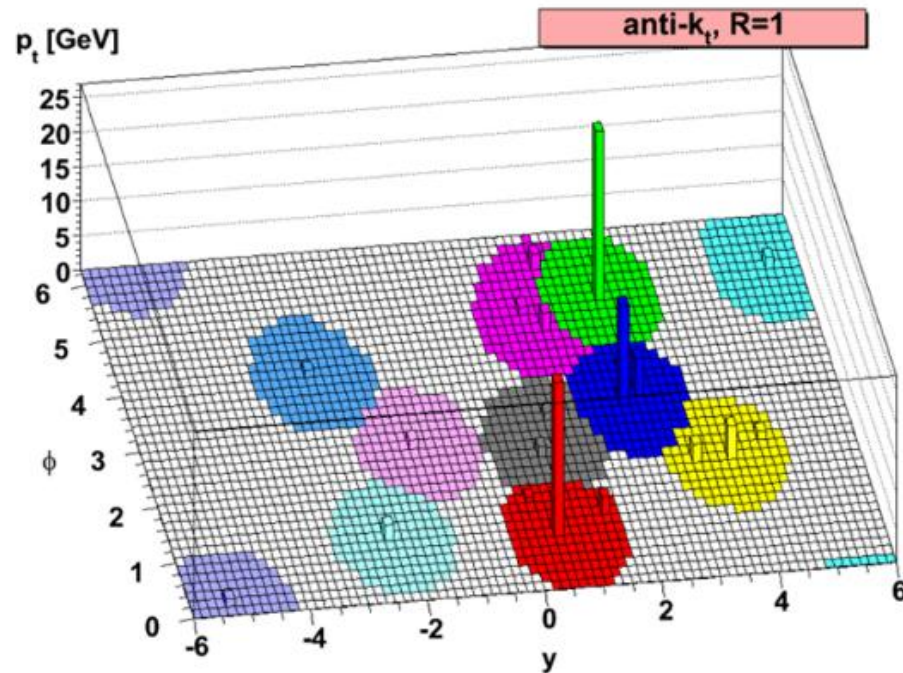
LBT: He, Luo, Wang, Zhu, Cao, GYQ, etc., 1503.03313, 1605.06447, 1703.00822, 2306.13742.

CLVisc: Pang, Wang, Wang, Petersen, Wu, GYQ, 1205.5019, 1802.04449, 2107.04949.

CoLBT: W. Chei, T. Luo, S. Cao, L.G. Pang, X. N. Wang, Phys.Lett.B 777 (2018) 86-90.



Anti- k_T algorithm



$$d_{ij} = \min\left(\frac{1}{p_{T,i}^2}, \frac{1}{p_{T,j}^2}\right) \frac{\Delta R_{ij}^2}{R^2}$$
$$d_{iB} = p_{T,i}^2$$
$$\Delta R_{ij}^2 = (\eta_i - \eta_j)^2 + (\phi_i - \phi_j)^2$$

1. For all particles, compute d_{ij}, d_{iB}
2. Find the smallest of d_{ij}, d_{iB}
3. If d_{iB} , call i particle a jet and remove it from the list of particles
4. If d_{ij} , recombine them to a new “particle”
5. Repeat from step 1 until no particle left

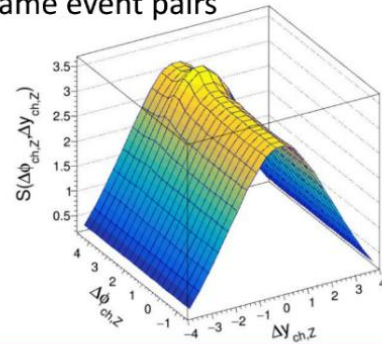
Anti- k_T algorithm clusters from **high** p_T particle. Clustered area has **circular** shape. It is now commonly used in heavy-ion (& pp) collisions by ALICE, ATLAS and CMS.

Background subtraction in CMS

Z⁰-Hadron Correlation Function: Event Mixing

Average **Signal** pair distribution:

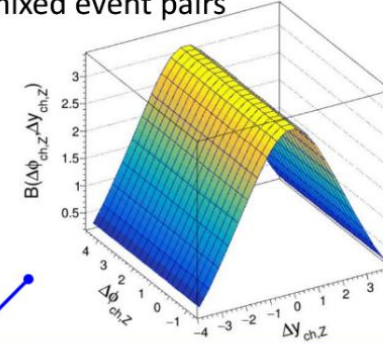
same event pairs



$$S(\Delta\phi_{ch,Z}, \Delta y_{ch,Z}) = \frac{1}{N_z} \frac{d^2 N^{same}}{d\Delta\phi_{ch,Z} d\Delta y_{ch,Z}}$$

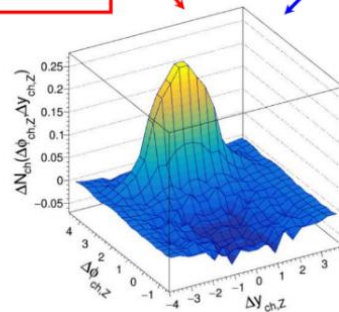
Average **Background** pair distribution:

mixed event pairs



$$B(\Delta\phi_{ch,Z}, \Delta y_{ch,Z}) = \frac{1}{N_z} \frac{d^2 N^{mix}}{d\Delta\phi_{ch,Z} d\Delta y_{ch,Z}}$$

$$\Delta N_{ch} = S - B$$



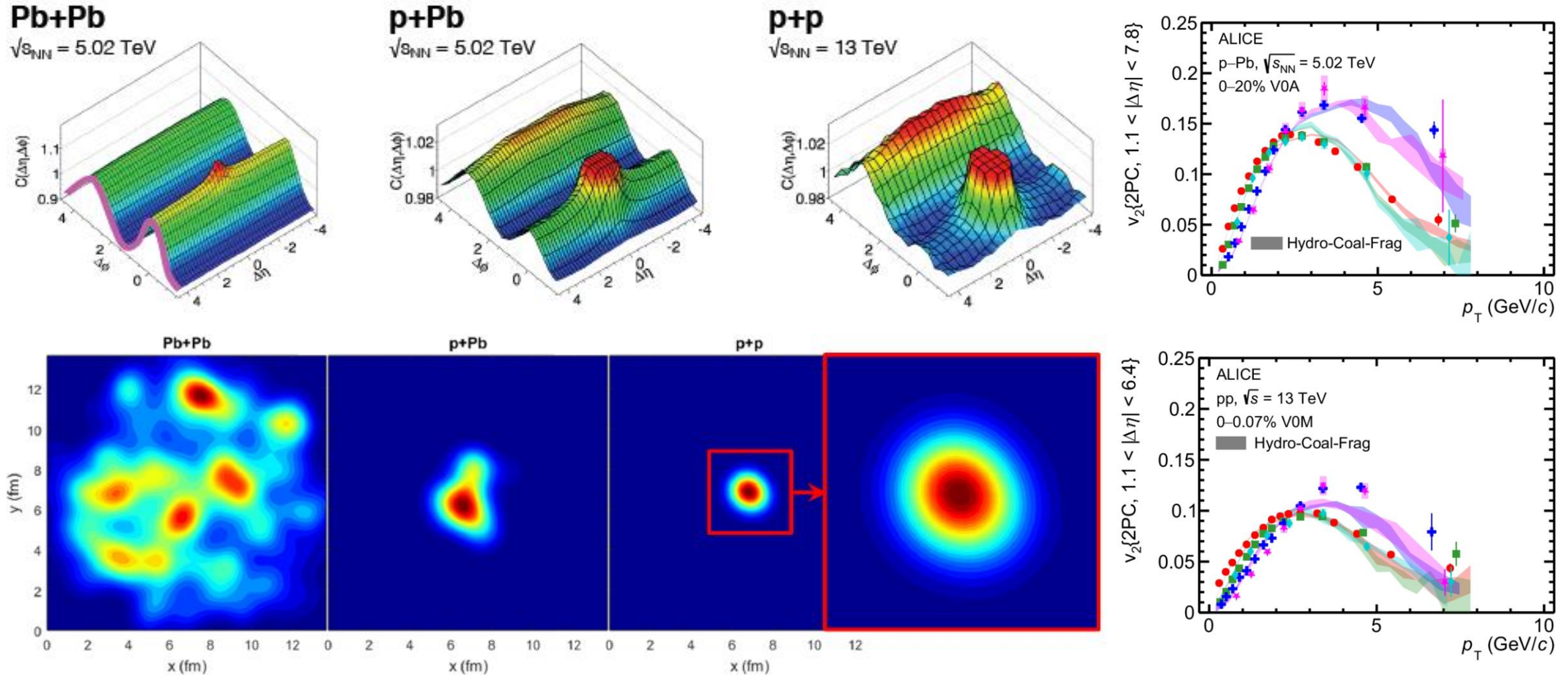
$$\Delta y_{ch,Z} = y_Z - \eta_{ch}$$

$$\Delta\phi_{ch,Z} = \phi_Z - \phi_{ch}$$

Demonstration with PYTHIA+HYDJET
(Generator level events)

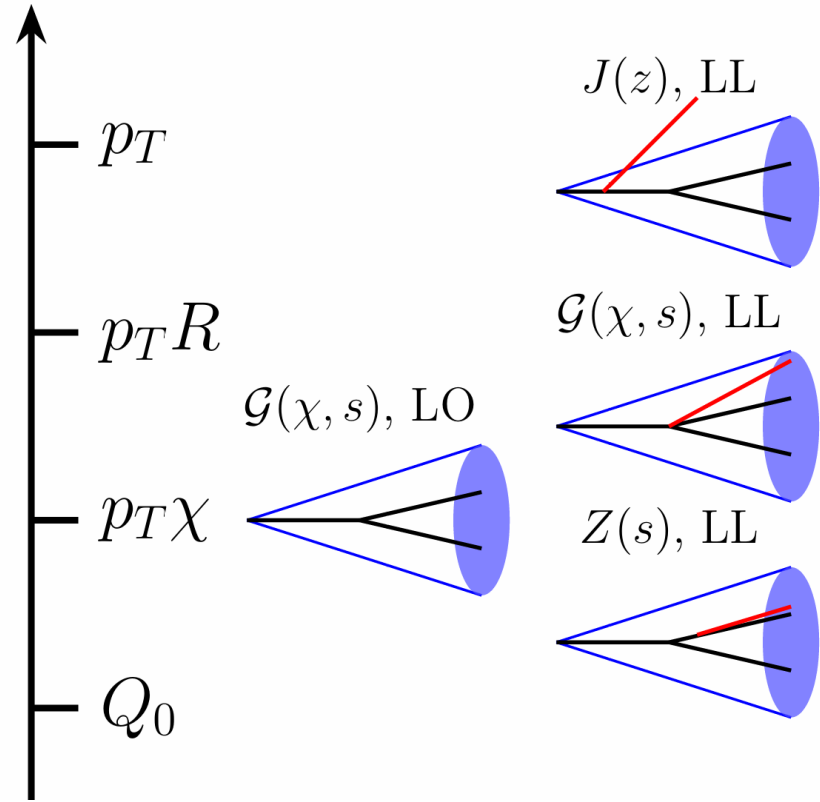
Integral of the ΔN_{ch} correlation function will be ~ 0

Collective flow in small system: mini-QGP?



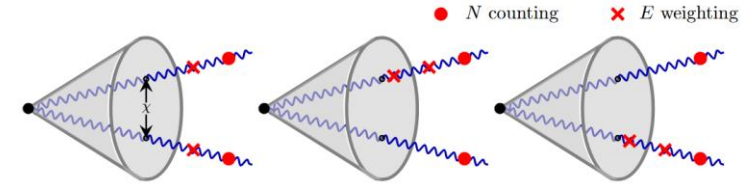
Weller, Romatschke, Phys.Lett.B 774 (2017) 351-356; ALICE, Nature Commun. 17 (2026) 1, 2585; Zhao, Ko, Liu, GYQ, Song, Phys. Rev. Lett. 125, 072301 (2020).

Jet multiplicity-conditioned EEC



$$\frac{\partial Z_i(s, \omega, \zeta)}{\partial \ln \zeta} = S \int_0^1 dx \frac{\alpha_s(k_\perp^2)}{2\pi} \Theta(k_\perp^2 - Q_0^2) \times \sum_{j,k} \hat{P}_{ji}(x) Z_j(s, x\omega, \zeta) Z_k(s, (1-x)\omega, \zeta).$$

- Radiation below $\chi \Rightarrow$ multiplicity
- Radiation at $\chi \Rightarrow$ EEC @ LO
- Radiation from χ to $R \Rightarrow$ correlation between EEC and multiplicity
- Radiation above $R \Rightarrow$ semi-inclusive jet function



$$\mathcal{G}_i(\chi, s, \omega_J, \zeta_\chi) = \frac{\omega_J^2}{\chi} S \int dx \frac{\alpha_s(k_\perp^2)}{\pi} \Theta(k_\perp^2 - Q_0^2) \times \sum_{j,k} x(1-x) \hat{P}_{ji}(x) Z_j(x) Z_k(1-x).$$

$$\frac{\partial \mathcal{G}_i(\chi, s, \omega_J, \zeta)}{\partial \ln \zeta} = S \int dx \frac{\alpha_s(k_\perp^2)}{2\pi} \Theta(k_\perp^2 - Q_0^2) \times \sum_{j,k} \hat{P}_{ji}(x) \{ \mathcal{G}_j(x) Z_k(1-x) + \mathcal{G}_k(1-x) Z_j(x) \}.$$