# FINAL STATE EFFECTS IN eA

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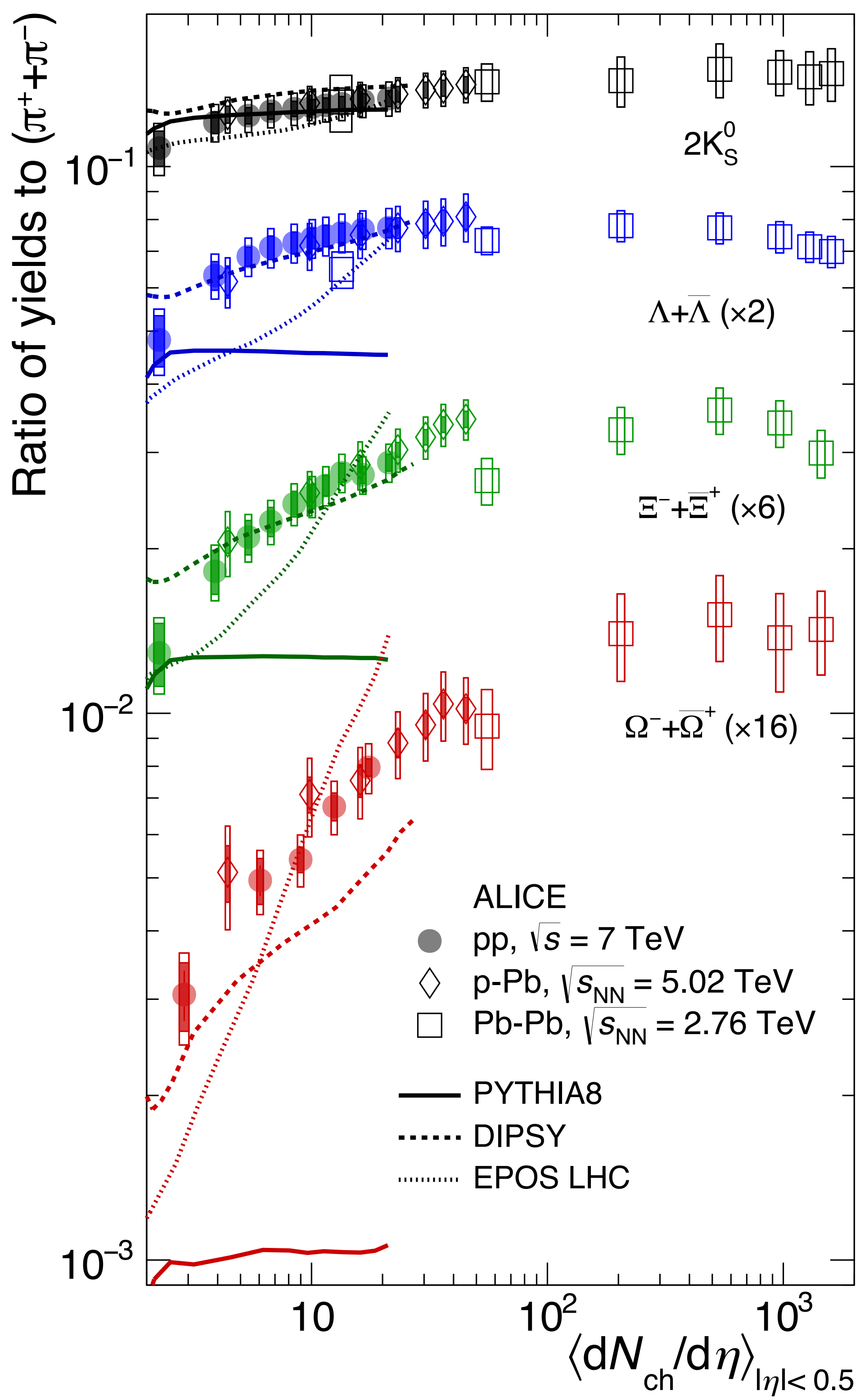
## Paradigm shift

- large systems (AA): final-state interactions, QGP effects (multi-particle correlations, jet quenching)
- small systems (pp, pA): initial-state effects, baseline?
  - multi-strange hadron enhancement
  - momentum anisotropies
- disentangling QCD dynamics & onset of collective medium response

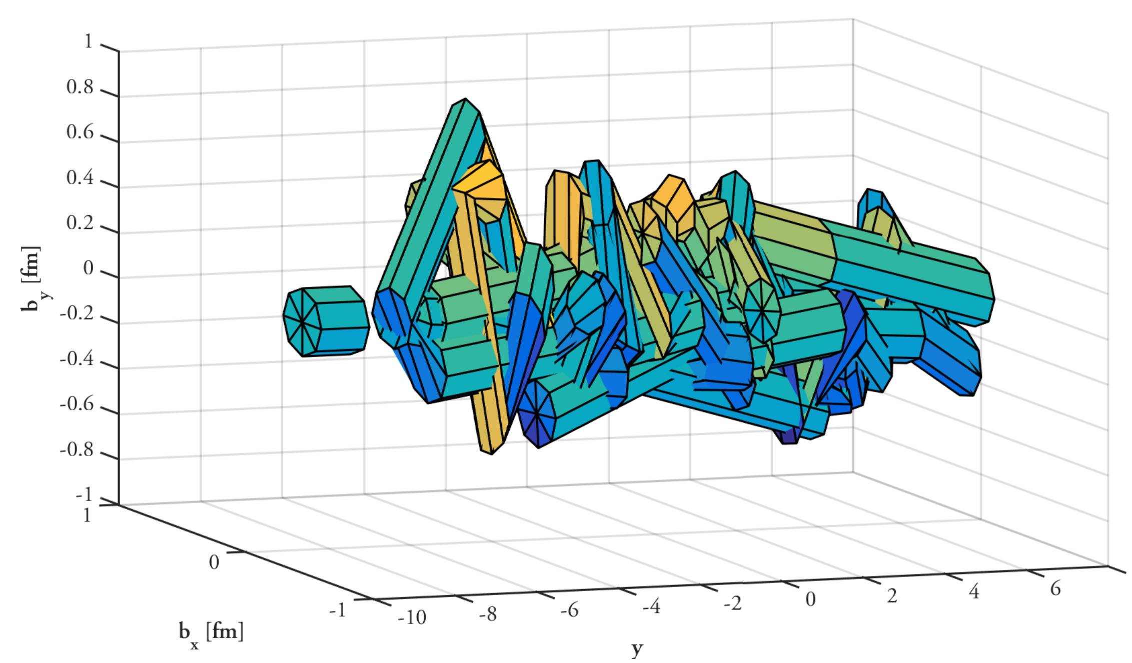
# MULTI-STRANGENESS PRODUCTION

ALICE arXiv:1606.07424

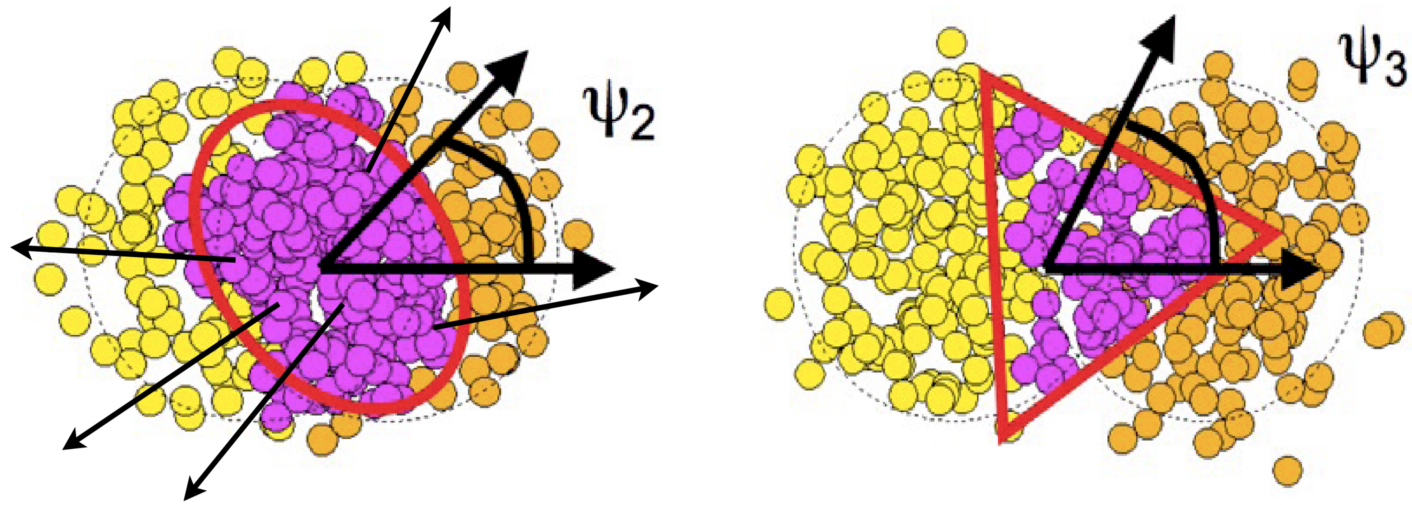



Bierlich, Gustafson and Lönnblad, arXiv:1612.05132
Bierlich, Christiansen: arXiv:1507.02091
Bierlich arXiv:1606.09456

- smooth dependence
- overlapping strings change string tension = modified hadronization (rope model)
- string shoving: local pressure



# COLLECTIVE RESPONSE



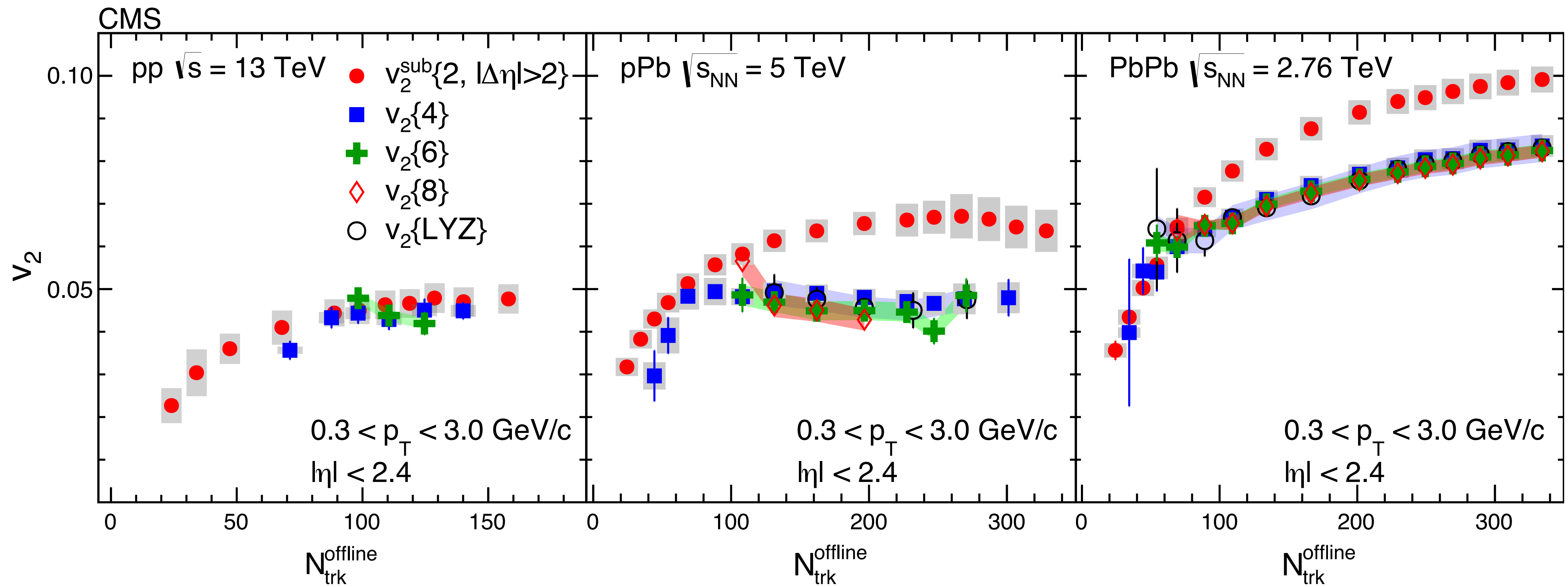

- fluctuating initial conditions (energy density)
  - centred around nucleon positions
- do produced particles "feel" initial shape?
- decomposition of particle yield in the azimuthal angle

$$\frac{dN^{(i)}}{dy\, p_T dp_T\, d\phi_p}(b) = \frac{dN^{(i)}}{dy\, p_T dp_T}(b) \left(1 + 2\sum_{n=1}^{\infty} \boldsymbol{v_n^{(i)}(y, p_T; b)} \cos(\phi_p - \Psi_n^{(i)})\right)$$

flow coefficients

# FLOW IN SMALL SYSTEMS

OBS: events chosen according to the same multiplicity

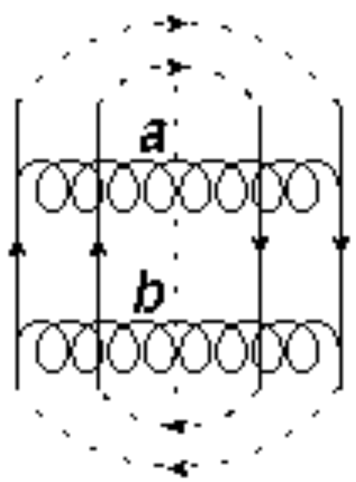



- collective response from many (all) particles in the system!
- (when) does hydrodynamics apply?
- universal feature of quantum theories?

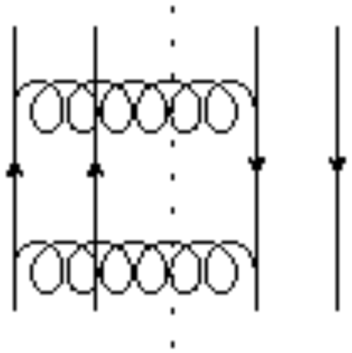
# "COLLECTIVITY" VS INTERFERENCE

Altinoluk, Armesto, Beuf, Kovner, Lublinsky arXiv:1503.07126 , arXiv:1610.03020
Lappi, Schenke, Schlichting, Venugopalan arXiv:1509.03499
Blok, Jäkel, Strikman, Wiedemann arXiv:1708.08241

- correlations in small systems observed
  - long-range in rapidity - related to initial state?
  - possible in eA?
- correlation from QCD interference
  - CGC
  - color domains
  - multi-parton interactions

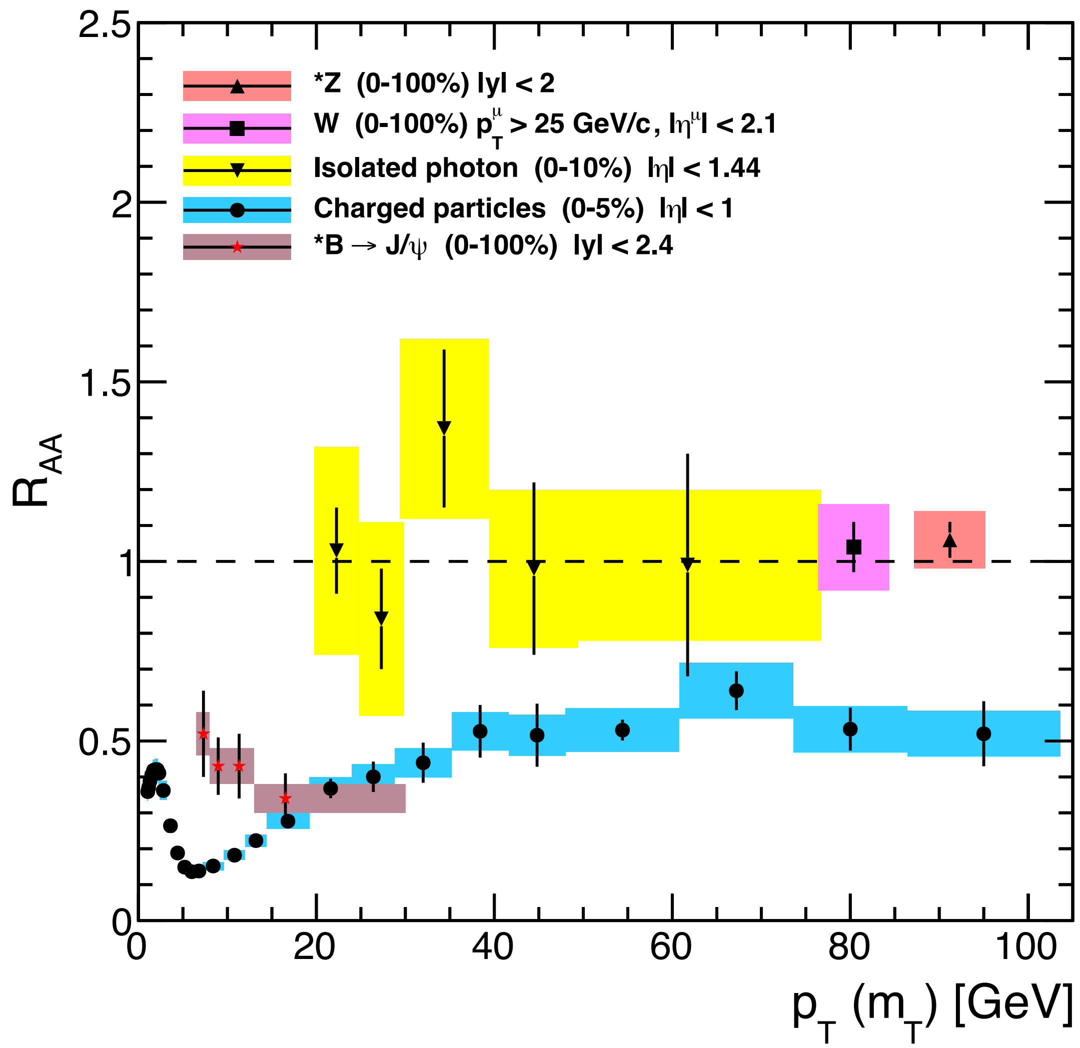


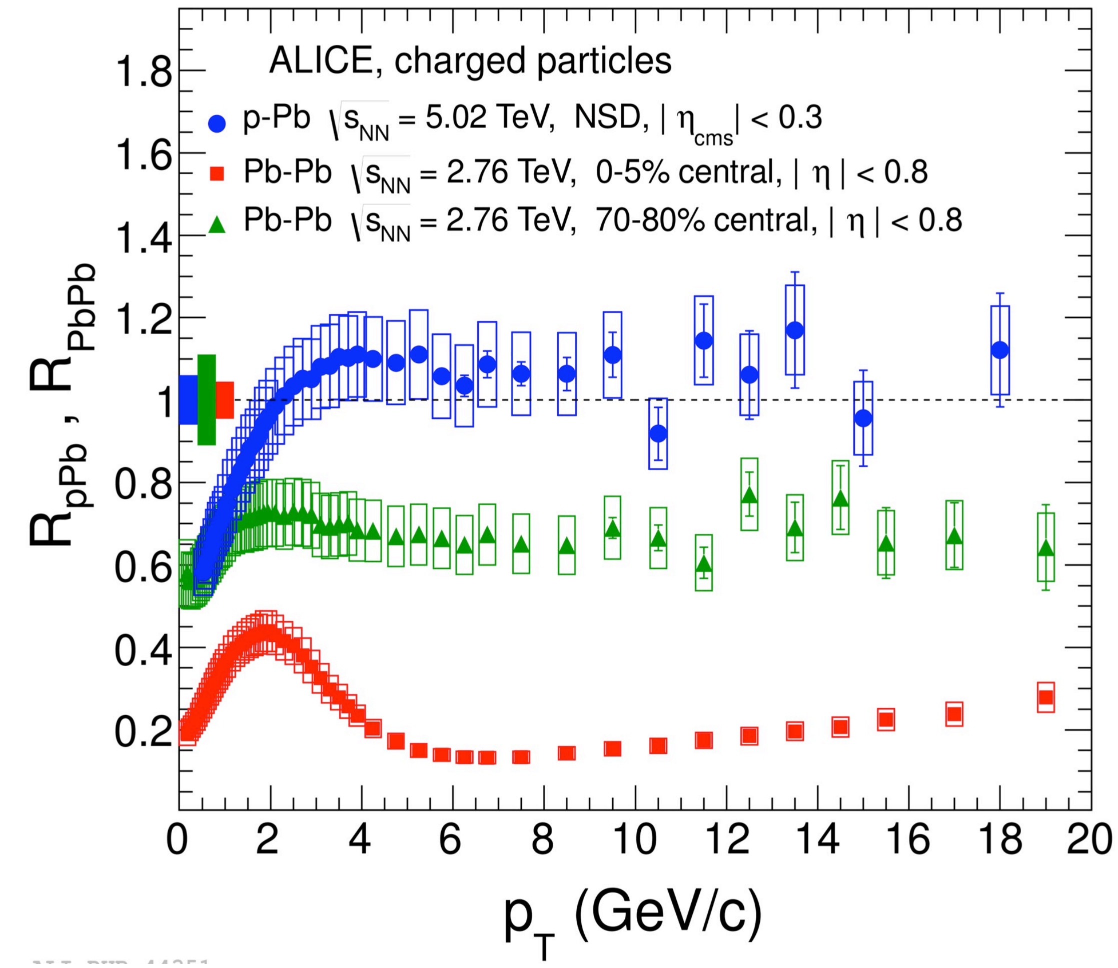
diagonal


off-diagonal

# JET QUENCHING

Bjorken '82; Gyulassy, Plumer, Wang 1995; Baier, Dokshitzer, Mueller, Peigne, Schiff 1996; Gyulassy, Levai, Vitev 1997

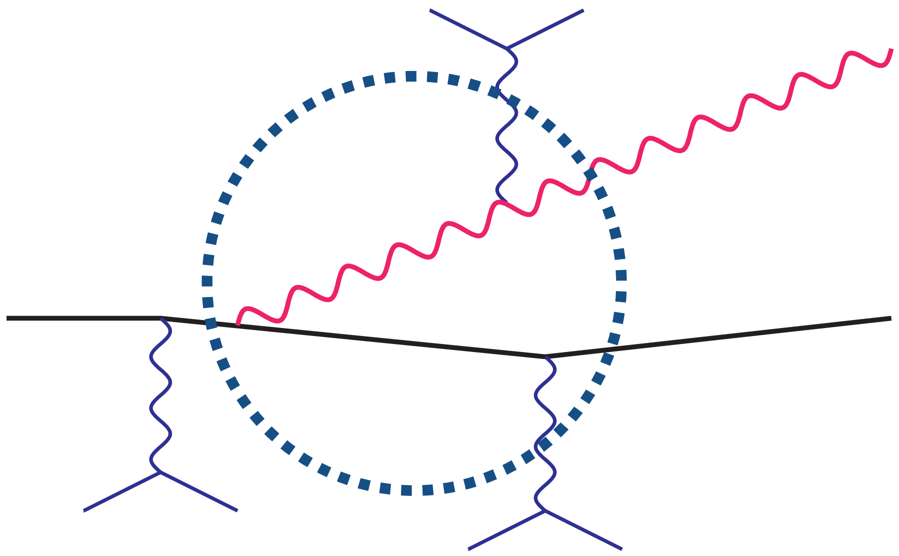



- suppression of yield in AA compared to pp :: large effect
- external probes of the underlying medium (jet tomography)
- $\hat{q}$ transport coefficient :: analog to shear viscosity
- small jet quenching = small final-state interactions?

# Medium induced radiation

Baier, Dokshitzer, Mueller, Peigné, Schiff (1997-2000); Zakharov (1996);...



momentum broadening $\langle k_\perp^2 \rangle \sim \hat{q}t$

modified splitting kinematics
**lack of collinear singularity!**

$$t_{\mathrm{f}} = \frac{\omega}{k_\perp^2} \sim \sqrt{\frac{\omega}{\hat{q}}}$$

$$\omega \frac{\mathrm{d}I}{\mathrm{d}\omega} = \frac{\alpha_s C_R}{2\pi} \sqrt{\frac{\hat{q}L^2}{\omega}}$$

rare, small-angle emission

$$\omega_c = \hat{q}L^2$$

$$\theta_{\mathrm{br}}(\omega_c) \sim \sqrt{\frac{1}{\hat{q}L^3}} \equiv \theta_c$$

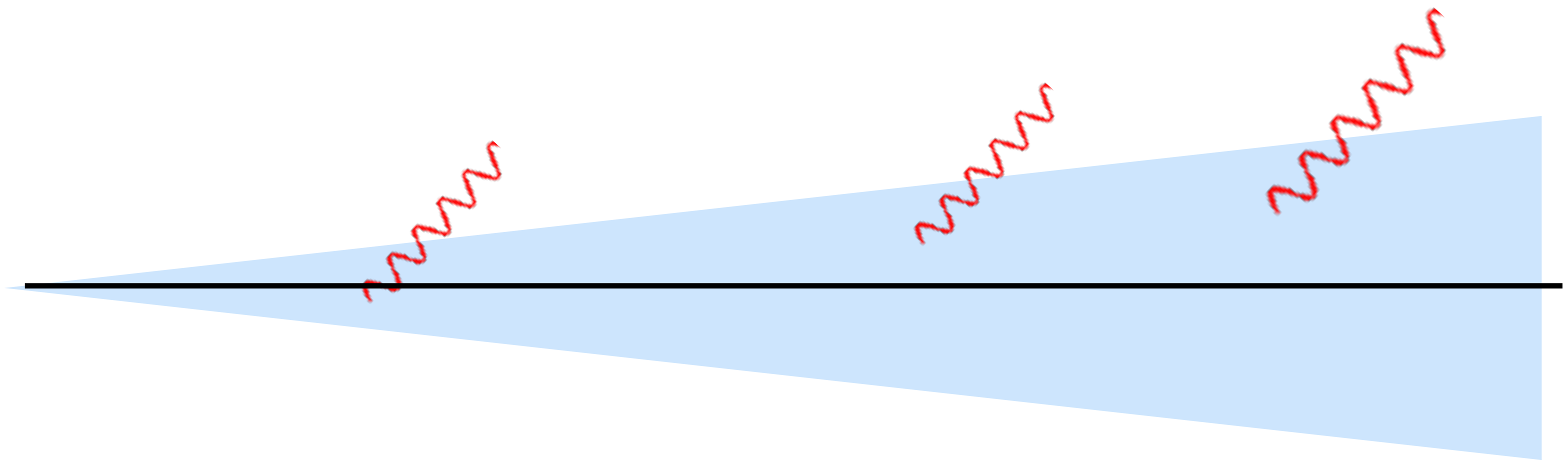
copious, large-angle emissions

$$\omega_s = \bar{\alpha}^2 \hat{q} L^2$$

$$\theta_{\mathrm{br}}(\omega_s) \sim \frac{1}{\bar{\alpha}^{3/2}} \theta_c$$

**leads to thermalization!**

# RADIATIVE ENERGY LOSS



Resummation of multiple (primary) emissions = Poisson distribution

$$\frac{\partial}{\partial t} P_1(\epsilon, t) = \int_0^\infty \mathrm{d}\omega \left[ \frac{\mathrm{d}I}{\mathrm{d}\omega \mathrm{d}t} - \delta(\omega) \int_0^\infty \mathrm{d}\omega' \frac{\mathrm{d}I}{\mathrm{d}\omega' \mathrm{d}t} \right] P_1(\epsilon - \omega, t)$$

- single color charge + soft gluons
- modest intra-jet modification of splitting function

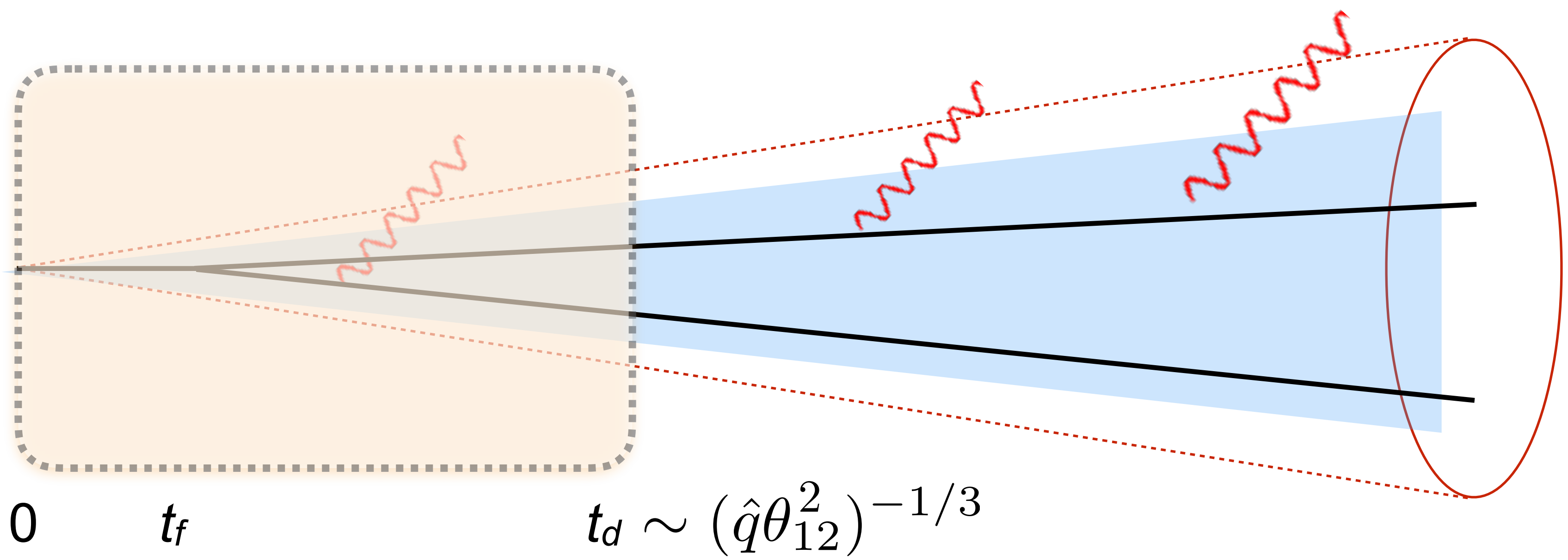
Chien, Vitev arXiv:1608.07283 ; Mehtar-Tani, KT arXiv:1610.08930

Energy loss dominated by *typical* emitted energy (large medium)

$$P_1(\epsilon, L) = \sqrt{\frac{\omega_s}{\epsilon^3}} \mathrm{e}^{-\frac{\pi \omega_s}{\epsilon}}$$

Baier, Dokshitzer, Mueller, Schiff (2001)

# NEIGHBORING JET ENERGY LOSS




Mehtar-Tani, KT arXiv:1706.06047

$$\theta_c \sim \sqrt{\frac{1}{\hat{q}L^3}}$$

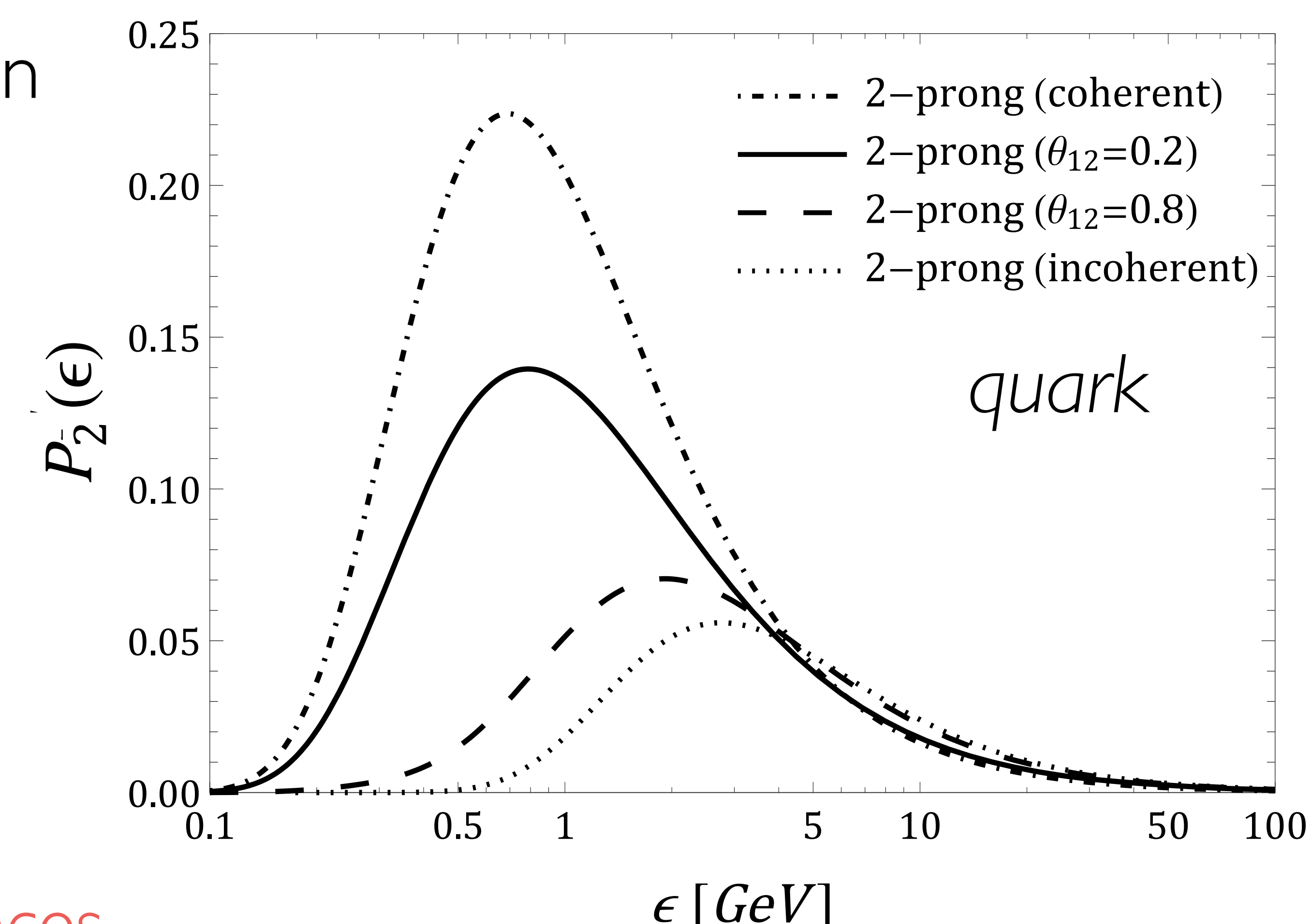
$$t_{\rm d}(\theta_c) \sim L$$

- affects splittings w/short formation time $t_{\rm f} \ll L$
- delay due to finite resolution power of the medium

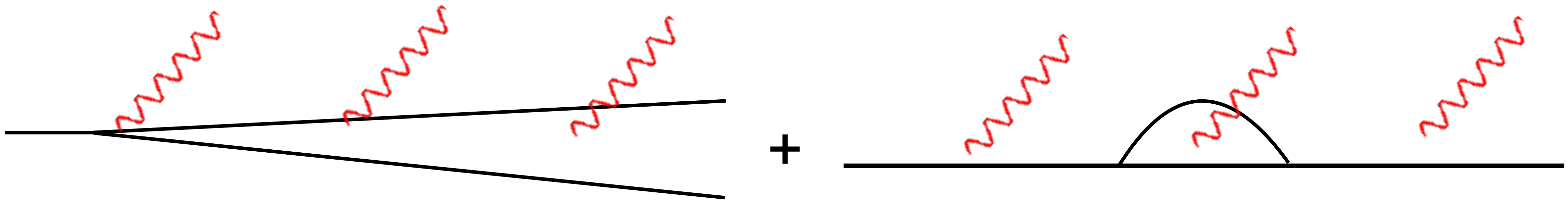
$$P_2(\epsilon) = P_1(\epsilon) \otimes P_{\rm sing}(\epsilon)$$

total color charge

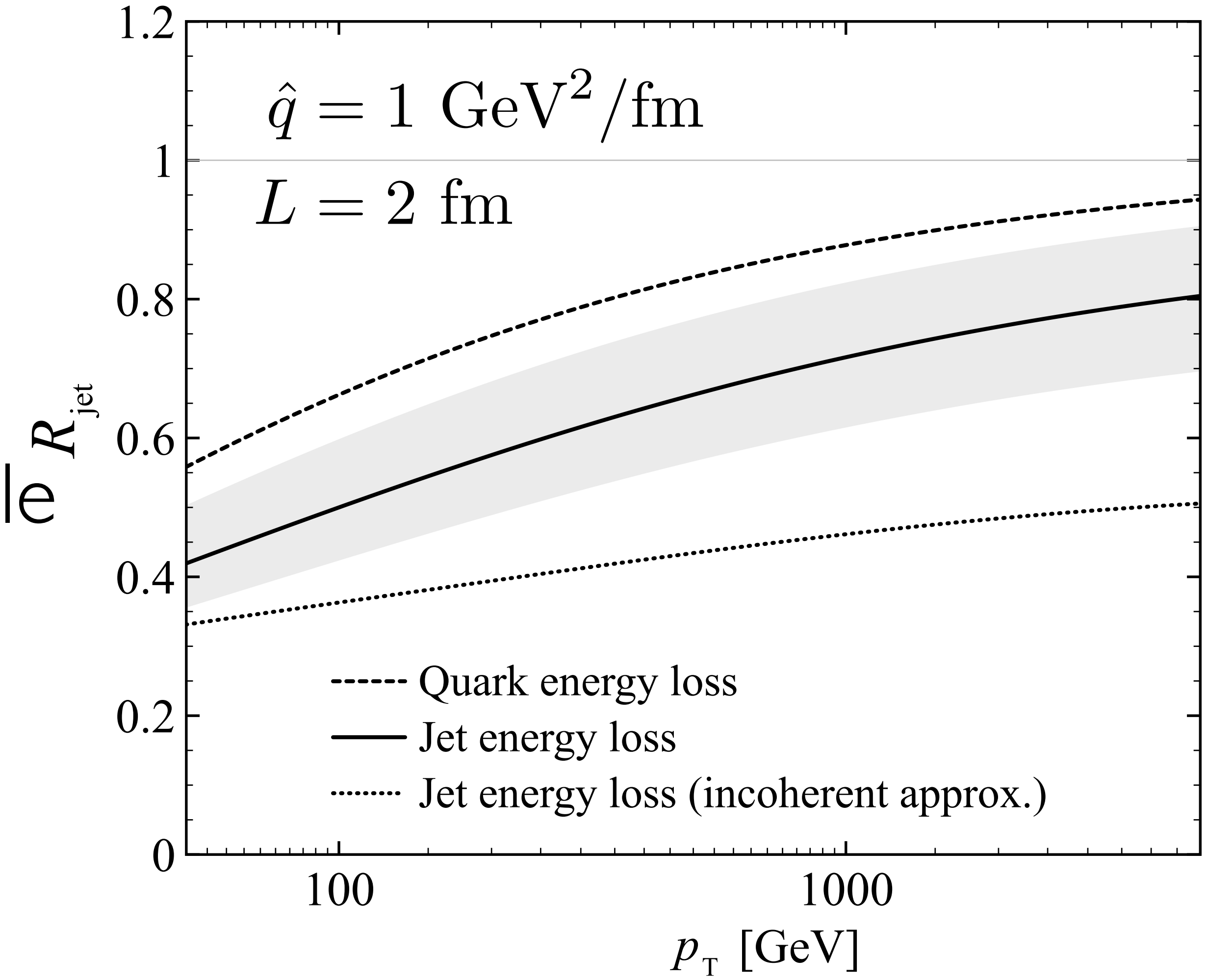
contributions from interferences



# QUENCHING OF HIGH-$P_T$ JETS



- mismatch of real and virtual ::
  different amount of energy-loss
- mismatch greatest for $t_\mathrm{f} \ll L$
- logarithmic enhancement w/ jet scale
- coherence play an important role!




$$R_\mathrm{jet} = Q_1(p_T) \times C(p_T)$$

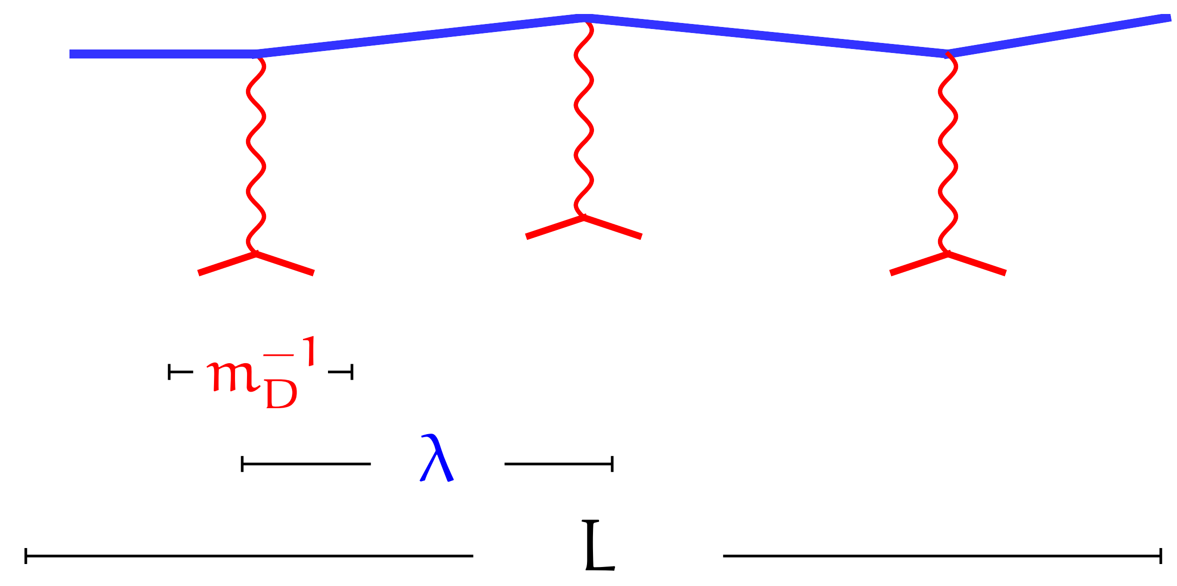
quenching of total colour charge

Sudakov suppression of jet substructure fluctuations

Y. Mehtar-Tani, KT arXiv:1707.07361

# RESCATTERING IN THE NUCLEUS

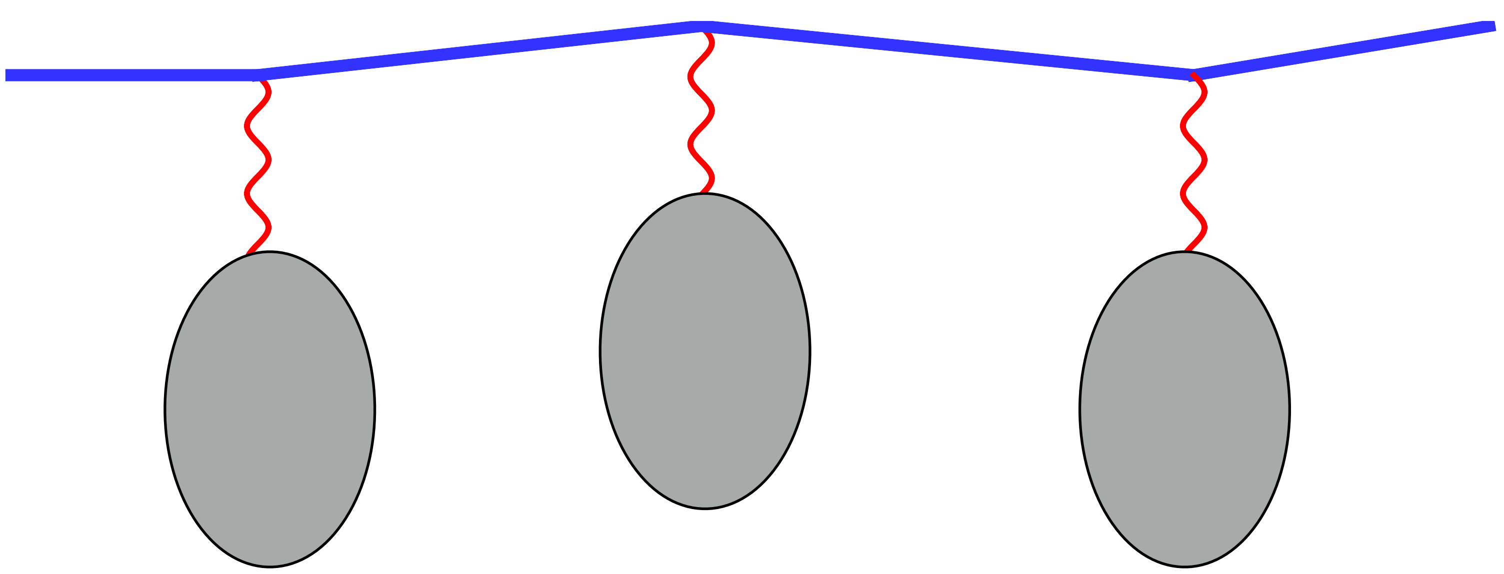
hierarchy of scales:
correlation length ≪ mean free path ≪ $L$




Relevant scale is size of nucleus $R_N$

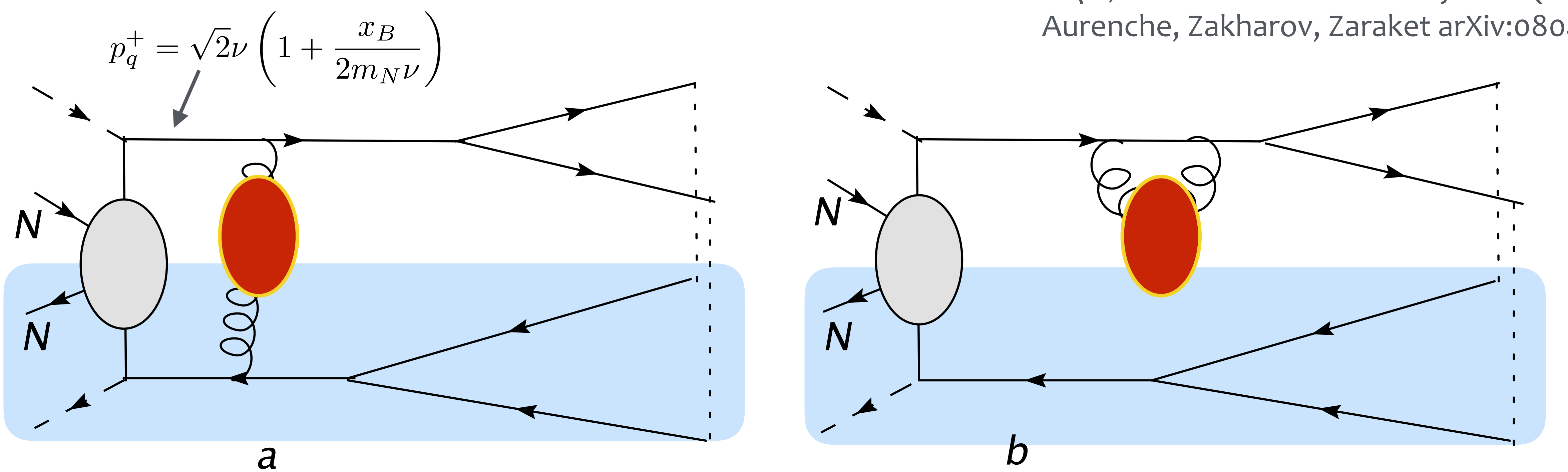
Similar picture emerges

$$\hat{q}_{\rm cold} \sim \frac{1}{50}\hat{q}_{\rm hot} \sim 0.05\,{\rm GeV}^2/{\rm fm}$$



# GLUON EMISSION IN DIS

Qiu, Sterman Int. J. Mod. Phys. E12 (2003) 14
Aurenche, Zakharov, Zaraket arXiv:0804.4282




Photon energy: $\nu = \frac{Q^2}{2m_N x_B}$

Ioffe length

$$\Delta t_\gamma \sim 1/m_N x_B$$

≪

Formation time

$$\Delta t_{qg} \sim \nu/M_{qg}^2$$

- higher-twist effects: detailed study of broadening
- full eA jet study?

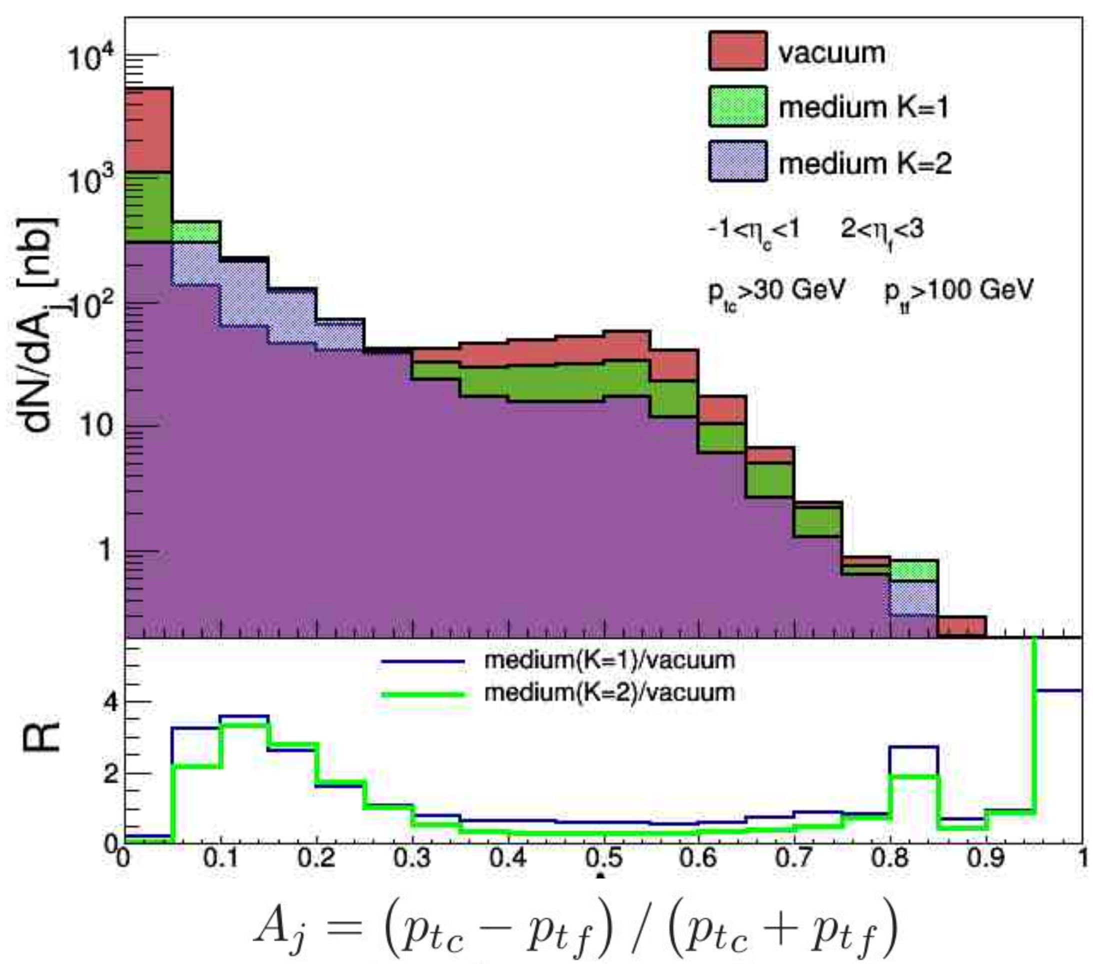
# Forward-central jets in AA

Deak., Kutak, KT arXiv:1706.08434

$$\frac{d\sigma_{acd}}{dy_1 dy_2 dp_{t1} dp_{t2} d\Delta\phi} = \frac{p_{t1} p_{t2}}{8\pi^2 (x_1 x_2 S)^2} \left|\overline{\mathcal{M}_{ag^* \to cd}}\right|^2 x_1 f_{a/A}^{Pb}(x_1, \mu^2)\, \mathcal{F}_{g/B}^{Pb}(x_2, k_t^2, \mu^2) \frac{1}{1+\delta_{cd}}$$

$$\frac{d\sigma}{dy_1 dy_2 dp_{t1} dp_{t2} d\Delta\phi} = \sum_{a,c,d} \int_0^\infty d\epsilon_1 \int_0^\infty d\epsilon_2\, P_a(\epsilon_1) P_g(\epsilon_2)\ \frac{d\sigma_{acd}}{dy_1 dy_2 dp'_{t1} dp'_{t2} d\Delta\phi}\bigg|_{\substack{p'_{1t}=p_{1t}+\epsilon_1 \\ p'_{2t}=p_{2t}+\epsilon_2}}$$

- final-state interactions in high-energy (kT) factorization
- treatment of initial- and final-state effects on same footing
- possible development in the future



# OUTLOOK

- “small systems”: relating QCD dynamics to “collectivity”
  - onset of thermalization
- jet modification as proxy for final-state interactions
  - importance of jet substructure fluctuations
- jets in eA DIS an interesting topic - deserves dedicated study