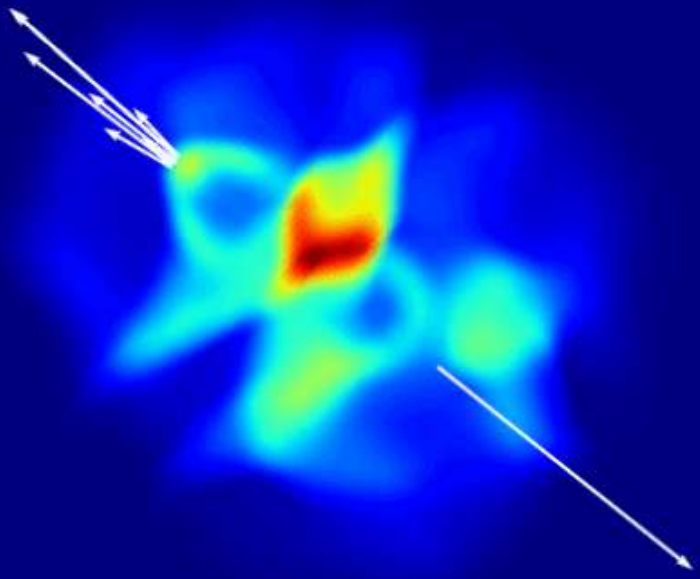
Theoretical Physics Colloquium (online) 2020.7.22

Jet tomography of hot and cold nuclear matter



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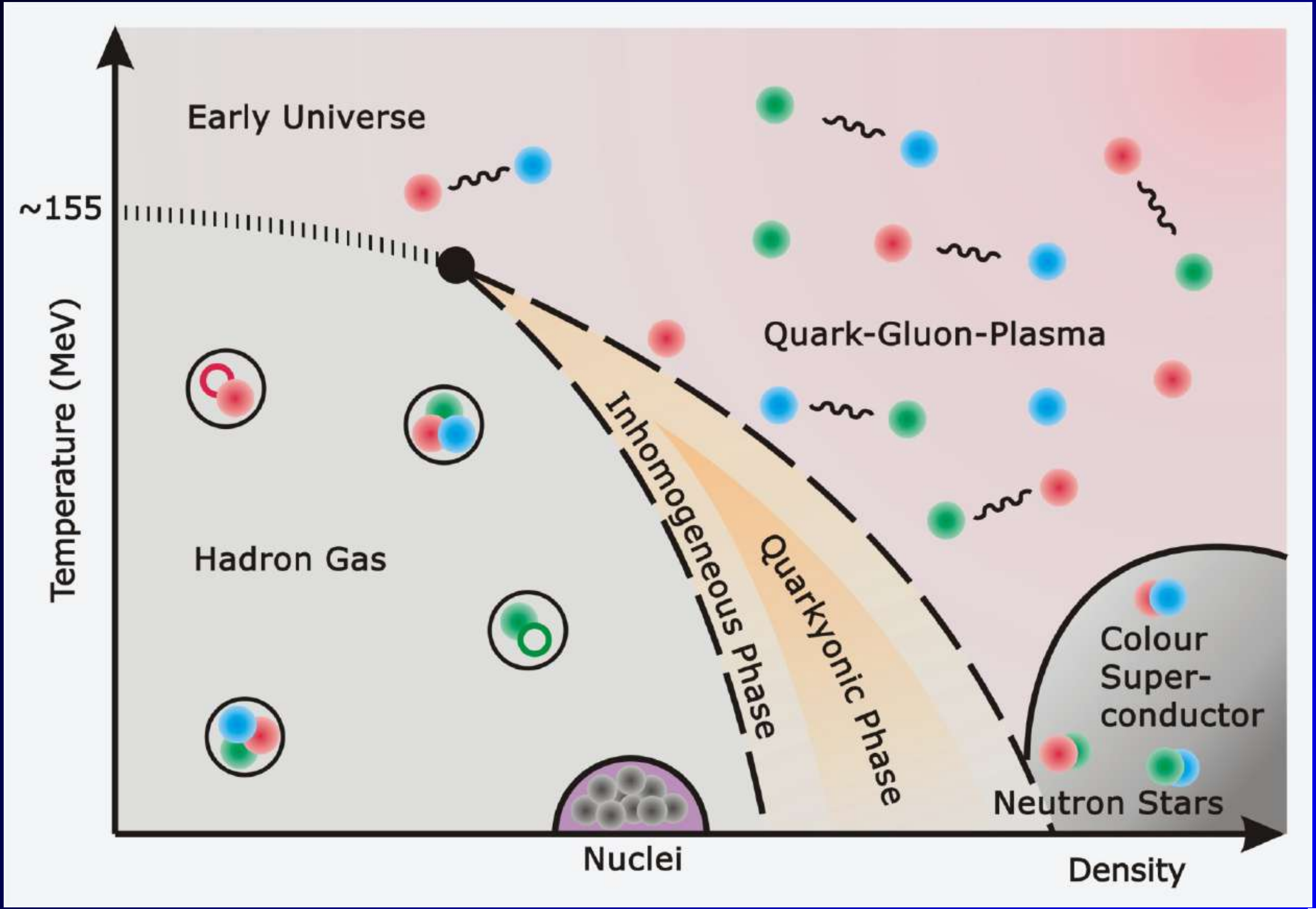
Lawrence Berkeley National Laboratory

QCD: Theory for strong interaction

$$L_{QCD} = \sum_{f=1}^{n_f} \bar{\psi}\gamma_\mu \left(i\partial^\mu - gA_a^\mu \frac{\lambda_a}{2} - m\right)\psi - \frac{1}{4}\sum_a F_a^{\mu\nu} F_{a,\mu\nu}$$

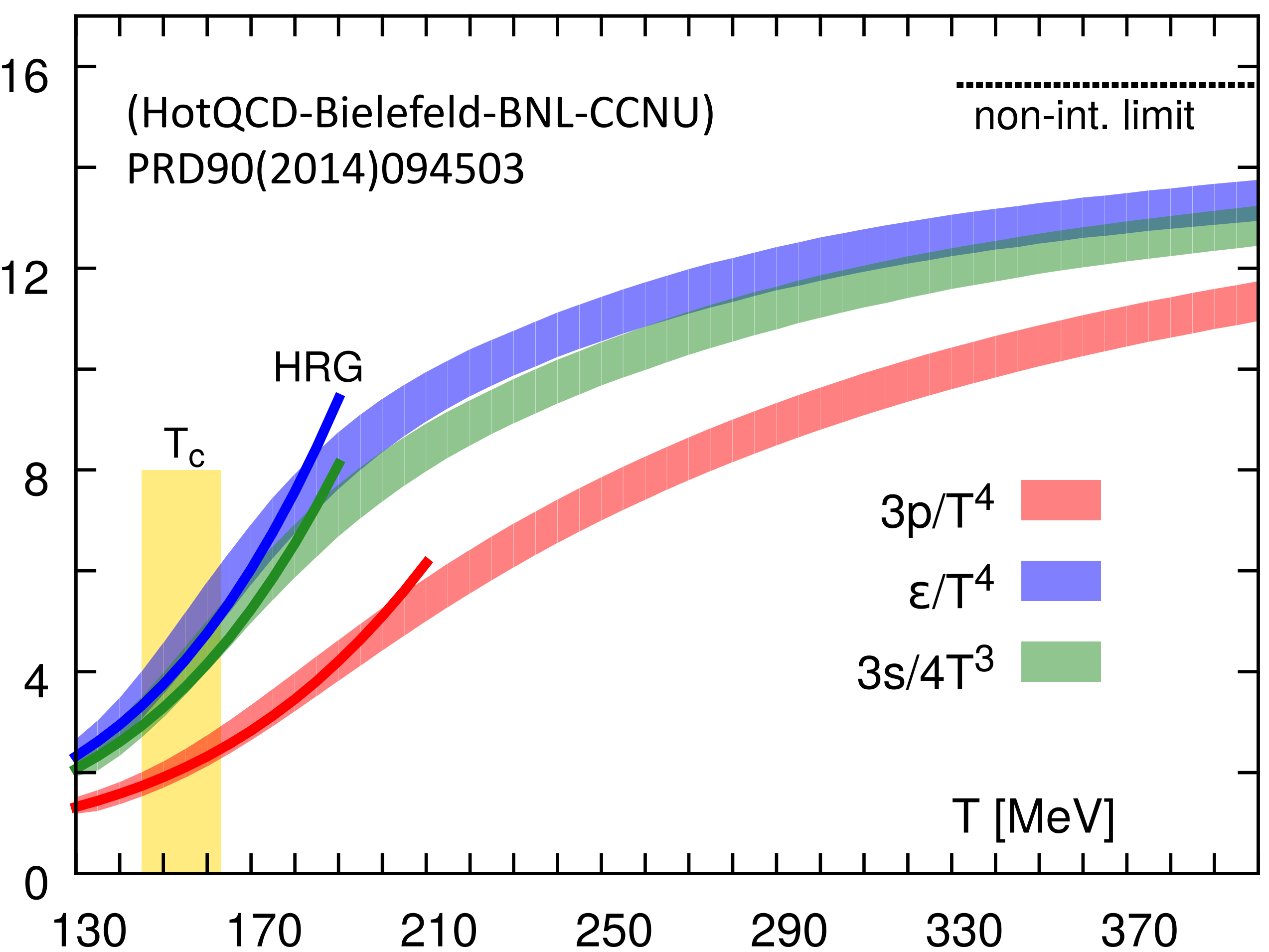
- SU(3) gauge symmetry (non-Abelian)
  - Asymptotic freedom at short distance
  - Confinement at long distance $\alpha_s(Q^2) = \dfrac{4\pi/(11 - 2n_f/3)}{\ln(Q^2/\Lambda^2_{\mathrm{QCD}})}$
- Chiral symmetry and its spontaneous breaking $\langle\bar{\psi}\psi\rangle \neq 0$
  - Goldstone boson and chiral condensate
- Scale and $U_A(1)$ anomaly $\langle F^{\mu\nu}F_{\mu\nu}\rangle \neq 0$
- ….

Phase structure of QCD Matter



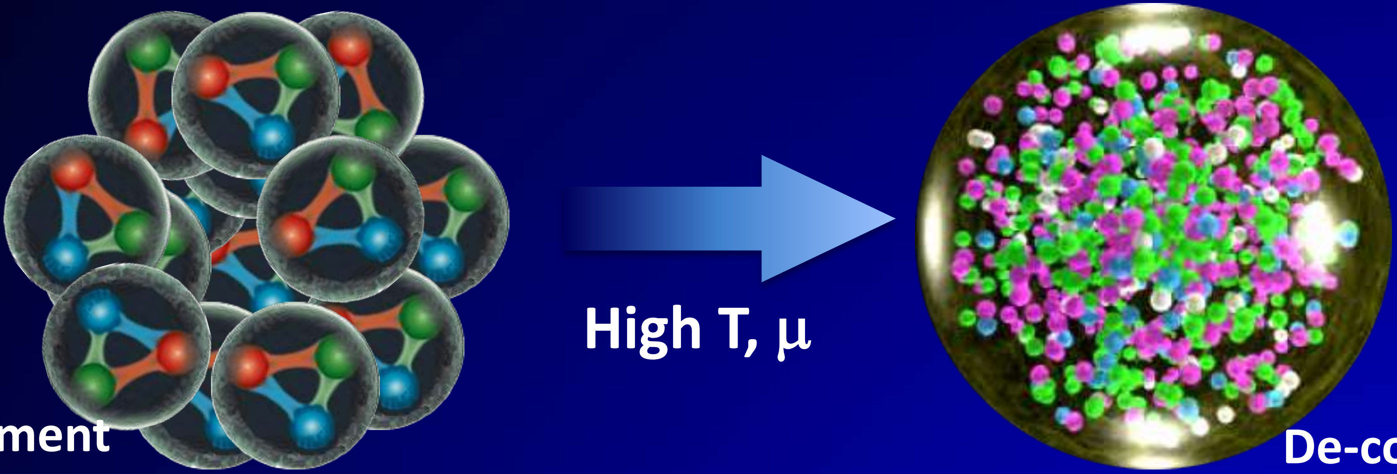
EOS from lattice QCD

$$\epsilon_{SB} = \left[6n_f\frac{7\pi^2}{120} + 16\frac{\pi^2}{30}\right]T^4$$



At $T \sim 5T_c$, ε still 80% of the Stefan-Boltzmann value: quasi-particle modes at high T

QGP in heavy-ion collisions



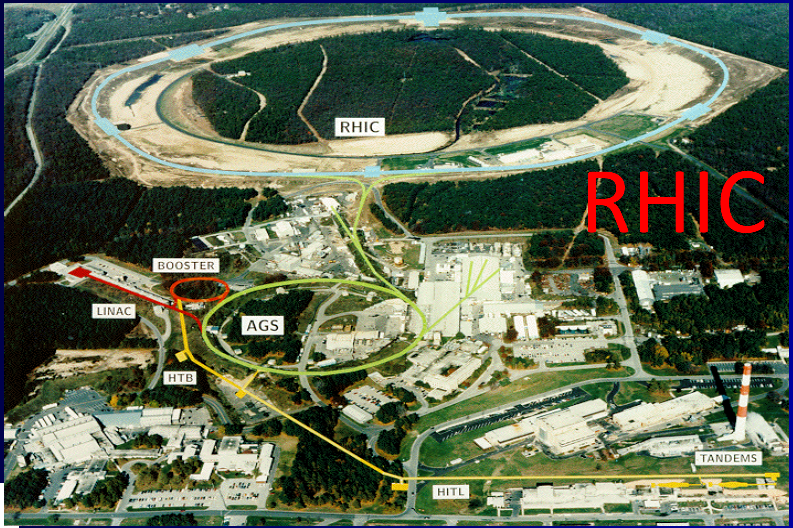
confinement

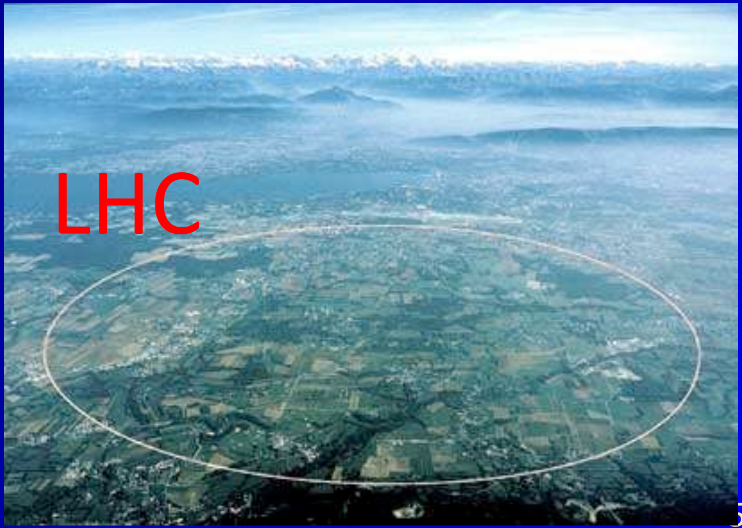
High T, μ

De-confinement

nucleus

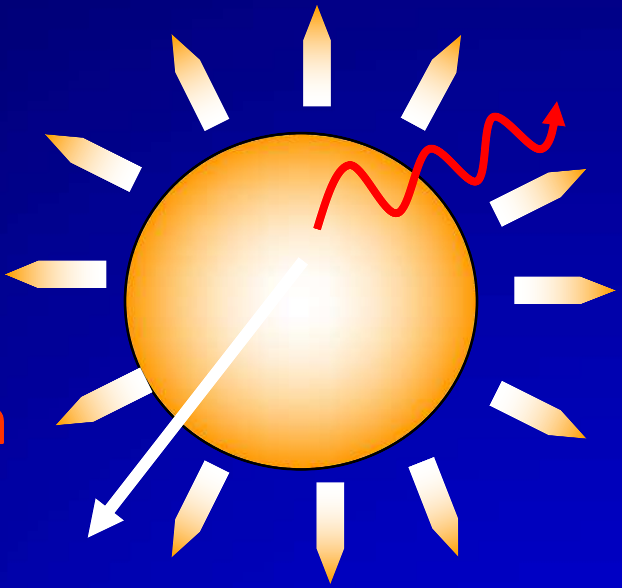
quark-gluon plasma (QGP)





Properties of QGP in A+A Collisions

Dynamic System:



- EM emission: Medium response
  to EM interaction

  γ production, J/Ψ suppression

- Hard probes: Medium response to strong interaction

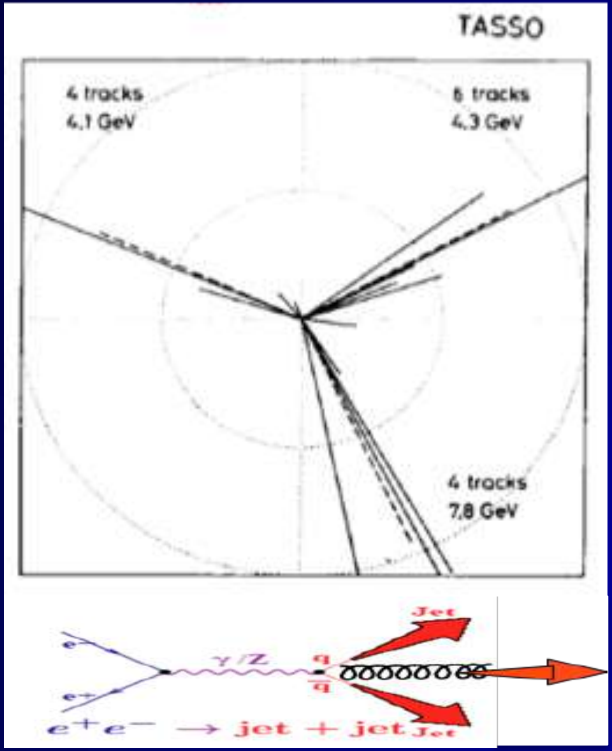
  Jet quenching

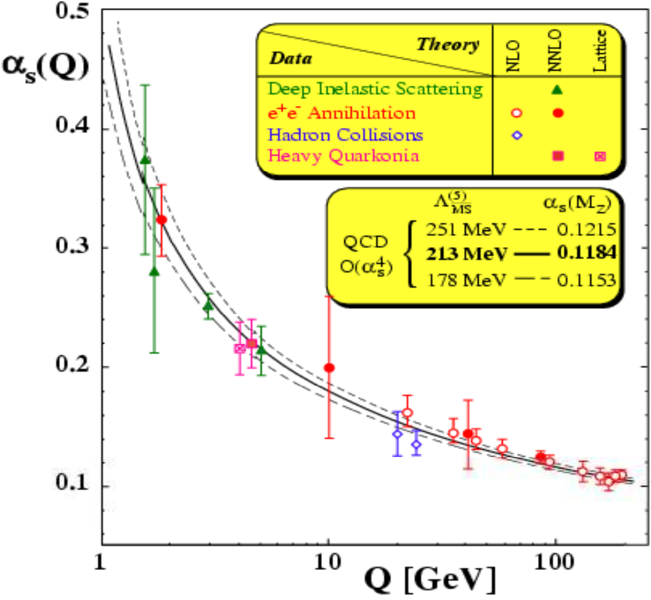
- Soft probes: Bulk properties of medium
  collective flow

Jets in high-energy collisions

- Uncorrelated jet model for hadron production: De Groot and Ruijgrok (1971)
- Asymptotic freedom of QCD: Gross & Wilczek, Politzer (1973)
- Partons in QCD: Ellis, Gaillard & Ross (1976), Georgi & Machacek (1977)
- Jets in QCD: Sterman & Weinberg (1977)

--tools for studying QCD and new discoveries

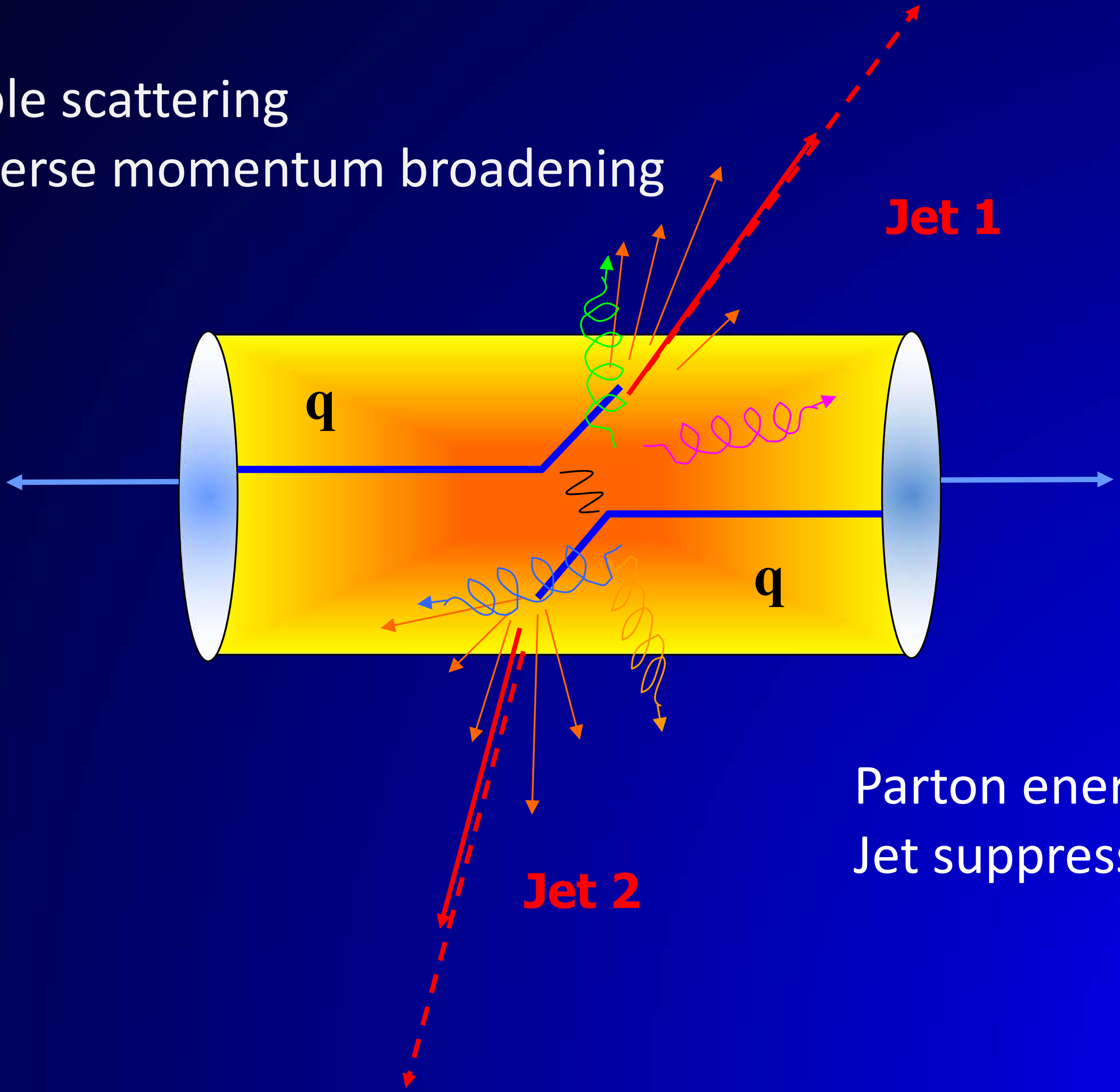




S Bethke J. Phys. G26 (2000) R27

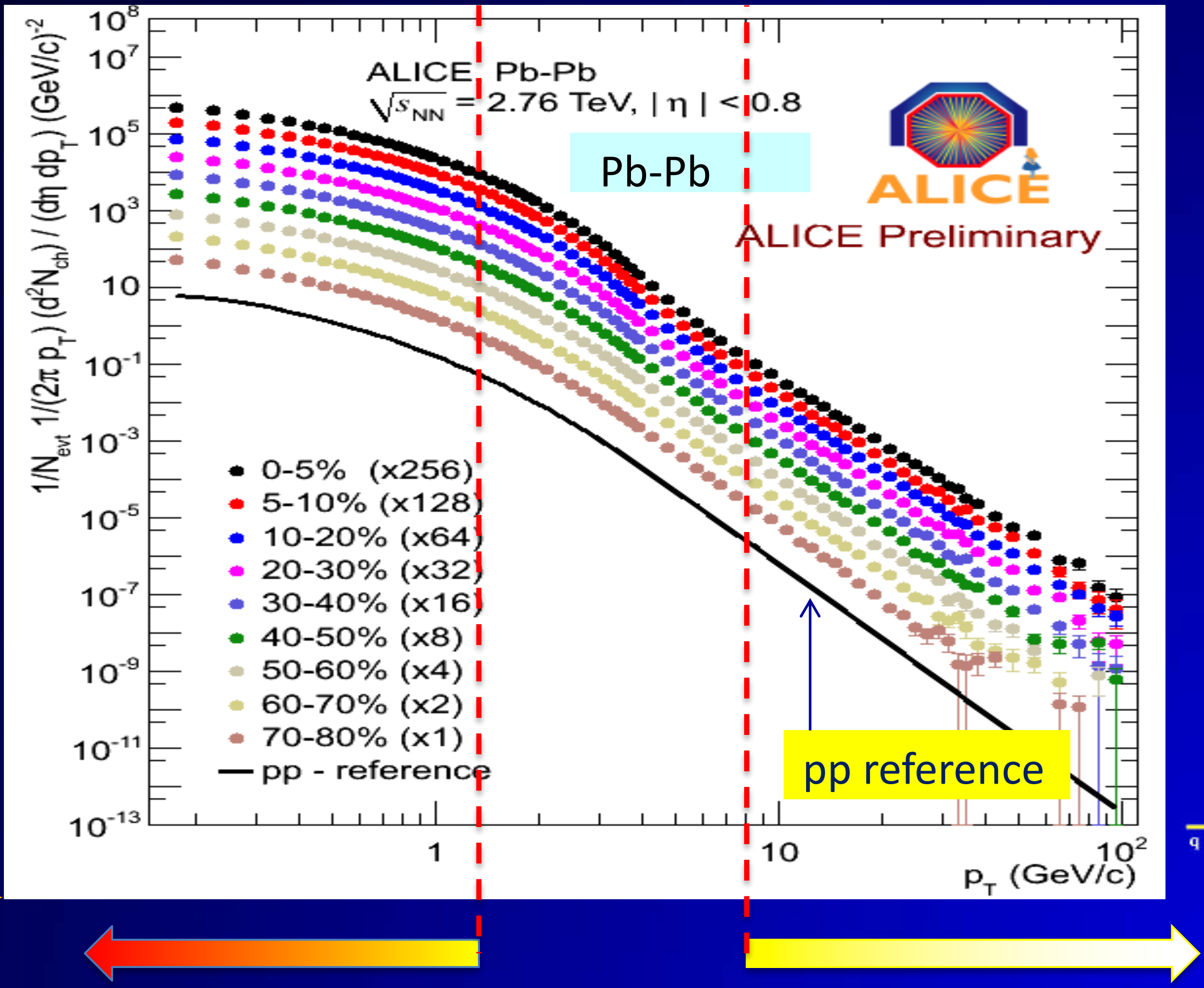
Jets in heavy-ion collisions

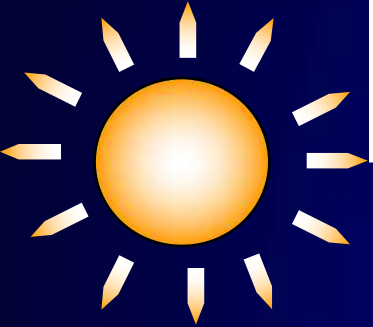
Multiple scattering
Transverse momentum broadening

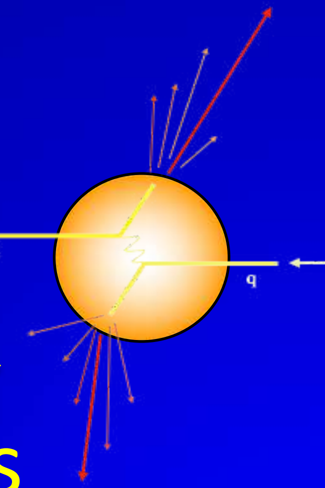


Parton energy loss
Jet suppression

Hard and soft probes





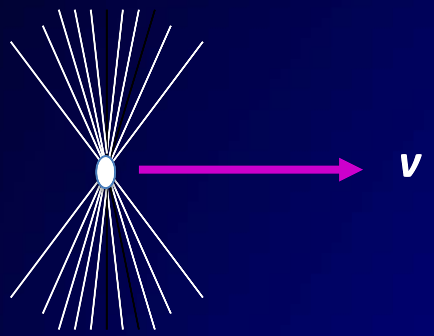


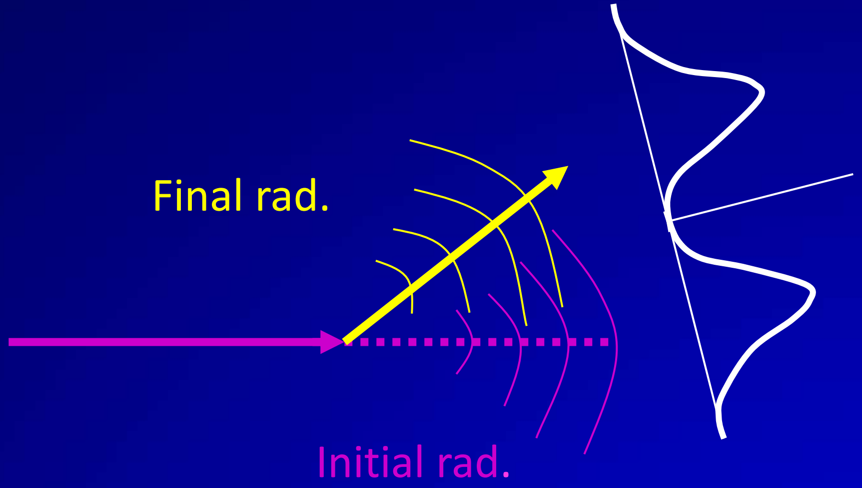
soft probes

hard probes

EM Radiation: Single scattering

EM field carried by a fast charge particle before and after scattering





EM Radiation by scattering:
Interference between initial
and final state radiation

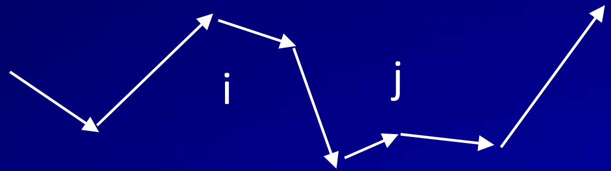
$$\omega \frac{d^2 I}{d\omega d\Omega} = \frac{e^2}{4\pi^2} \left| \frac{\vec{k} \times \vec{v}_i}{\vec{k} \cdot \vec{v}_i - \omega} - \frac{\vec{k} \times \vec{v}_f}{\vec{k} \cdot \vec{v}_f - \omega} \right|^2$$

$$\omega \frac{dI}{d\omega} \approx \frac{2\alpha}{\pi} \left[\ln \frac{2E^2(1 - \vec{v}_i \cdot \vec{v}_f)}{m^2} - 1 \right]$$

Bethe Heitler

EM Radiation: multiple scattering

Classical radiation of a point charge **(Jackson, p671)**



$$\omega \frac{d^2 I}{d\omega\, d\Omega} = \frac{e^2}{4\pi^2}\left|\sum_i \left(\frac{\vec{k}\times\vec{v}_i}{\vec{k}\cdot\vec{v}_i-\omega} - \frac{\vec{k}\times\vec{v}_{i+1}}{\vec{k}\cdot\vec{v}_{i+1}-\omega}\right) e^{i(\omega t_i - \vec{k}\cdot\vec{r}_i)}\right|^2$$

Lorentz Invariant form:

$$\omega \frac{d^3 I}{d^3 k} = \frac{e^2}{2(2\pi)^3}\sum_\lambda \left|\varepsilon_\lambda(k)\cdot\sum_i J_i(k)\, e^{ik\cdot x_i}\right|^2$$

$$J_i^\mu(k) = \frac{p_{i-1}}{k\cdot p_{i-1}} - \frac{p_i}{k\cdot p_i}$$

EM current of a charged through a scattering

Two Limits: (In)coherent radiation

$$\exp[ik \cdot (x_i - x_j)] = \exp[i\Delta x_{ij}/\tau_f]$$

Photon formation time: $$\tau_f = \frac{1}{\omega(1-\cos\theta)} \approx \frac{2}{\omega\theta^2}$$

Coherent Limit: $\tau_f \gg \Delta x_{ij}$ single coherent scattering

$$J\mu(k) = \sum_i \left(\frac{p_{i-1}}{k \cdot p_{i-1}} - \frac{p_i}{k \cdot p_i} \right) e^{ik \cdot x_i} \approx \frac{p_1}{k \cdot p_1} - \frac{p_N}{k \cdot p_N}$$

Incoherent Bethe Heitler Limit: $\tau_f \ll \Delta x_{ij}$

$$\omega \frac{d^3 I}{d^3 k} = \frac{e^2}{4\pi^2} \left[\sum_{i,\lambda} |\varepsilon_\lambda \cdot J_i|^2 + 2Re \xcancel{\sum_{i,\lambda} \sum_{j>i,\lambda'} (\varepsilon_\lambda \cdot J_i)(\varepsilon_{\lambda'} \cdot J_j) e^{ik \cdot (x_i - x_j)}} \right]$$

$$\omega \frac{dI}{d\omega} = \frac{L}{\lambda_{mfp}} \left(\omega \frac{dI}{d\omega} \right)_{\mathrm{BH}} \propto N \frac{2\alpha}{\pi}$$

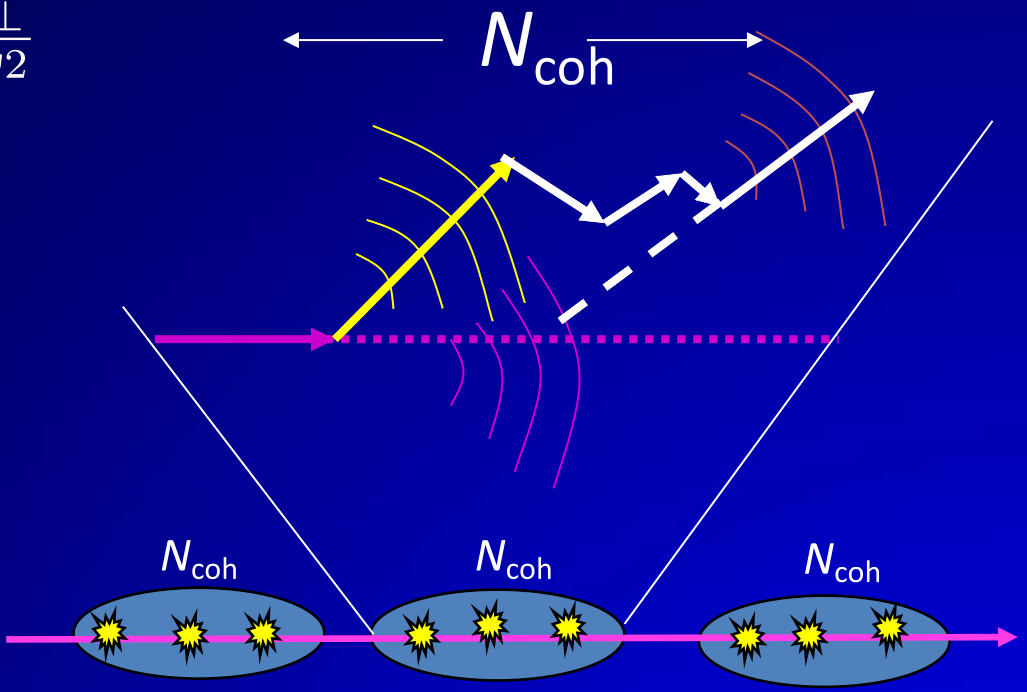
LPM Interference

$$\tau_f = \frac{2}{\omega\theta^2} \qquad \theta^2 = N_{\rm coh}\frac{q_\perp^2}{E^2}$$

$$N_{\rm coh}\lambda \approx \tau_f$$

$$\rightarrow N_{\rm coh} = \frac{2E}{\sqrt{\omega\langle q_\perp^2\rangle\lambda}}$$

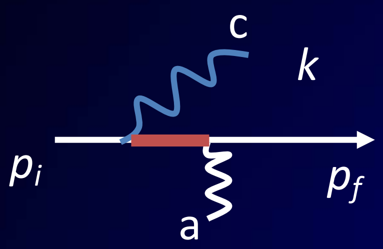
$N_{\rm coh}$ # of scattering for a coherent radiation

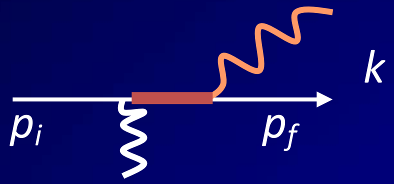


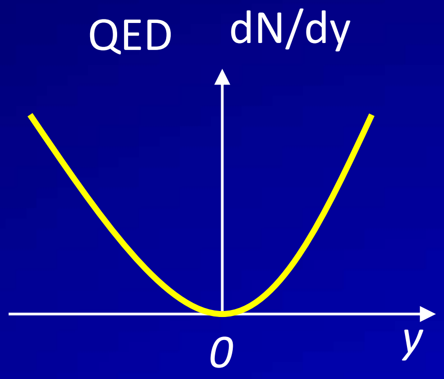
Effective spectra

$$\omega\frac{dI}{d\omega} = \frac{L}{\lambda}\left(\omega\frac{dI}{d\omega}\right)_{\rm BH}\frac{1}{N_{\rm coh}} \propto N\frac{\alpha}{\pi}\sqrt{\frac{\langle q_\perp^2\rangle}{E^2}\lambda\omega}$$

Radiation in QCD: Colors Makes the Difference

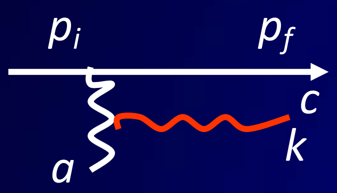




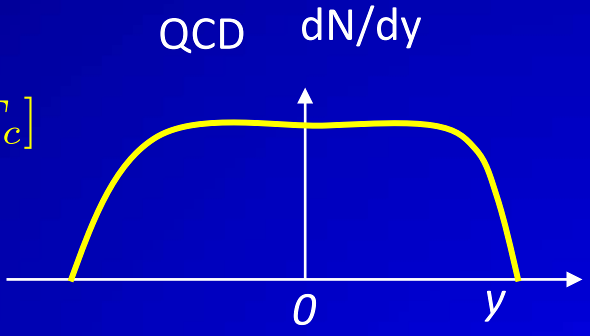


$$R_S^{(1)} \approx ig\frac{2\vec{\epsilon}_\perp\cdot\vec{k}_\perp}{k_\perp^2}[T_aT_c - T_cT_a]$$

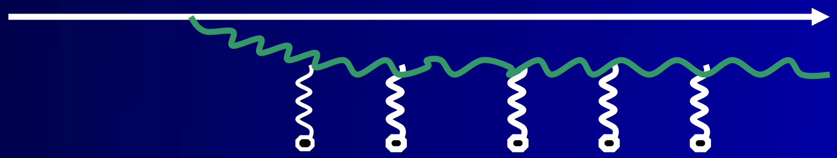
QCD: gluons carry **color**: interference incomplete



$$R_S^{(2)} \approx ig\frac{2\vec{\epsilon}_\perp\cdot(\vec{q}_\perp-\vec{k}_\perp)}{(\vec{q}_\perp-\vec{k}_\perp)^2}[T_a, T_c]$$

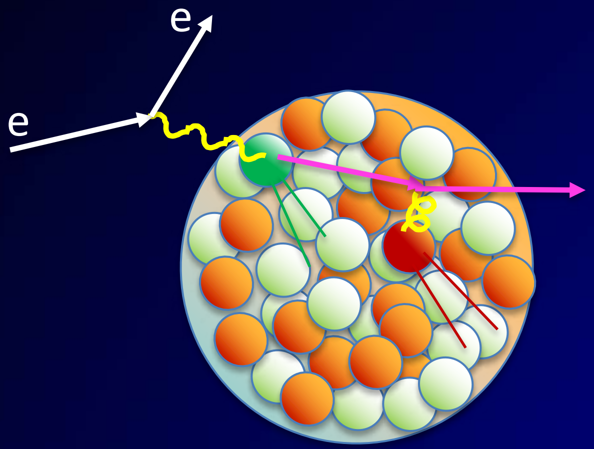


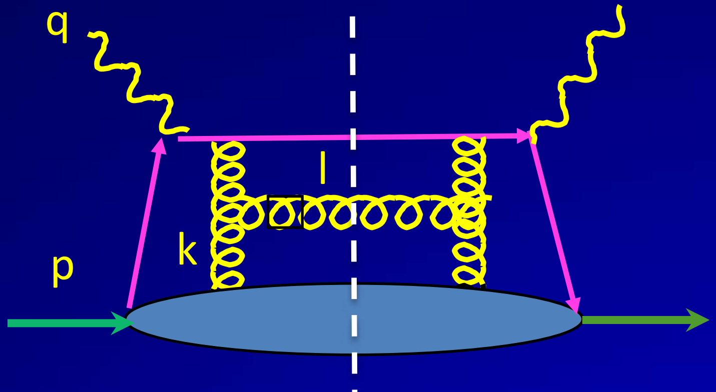
Gluon multiple scattering (BDMP’96)



$$\Delta E = \approx \frac{\alpha_s N_c}{4}\frac{\langle q_\perp^2\rangle}{\lambda}L^2$$

Parton propagation in nuclear medium





Zhang, Qin and XNW arXiv:1905.12699

$$\frac{dN_g}{dl_\perp^2\, dz} = \int_{y^-}^{\infty} dy_1^- \left[\rho_A(y_1^-,\vec{y}_\perp)\frac{2\pi\alpha_s}{N_c}\pi\int\frac{dk_\perp^2}{(2\pi)^2}\frac{\phi_N(0,\vec{k}_\perp)}{k_\perp^2}\right]\pi\frac{\alpha_s}{2\pi}P_{qg}(z)\frac{C_A}{l_\perp^2}\mathcal{N}_g(\vec{l}_\perp,\vec{k}_\perp)$$

↑

Nucleon TMD gluon distr.

$$\mathcal{N}_g^{static+soft} = \int\frac{d\varphi}{2\pi}\frac{2\vec{k}_\perp\cdot\vec{l}_\perp}{(\vec{l}_\perp-\vec{k}_\perp)^2}\left(1-\cos\left[\frac{(\vec{l}_\perp-\vec{k}_\perp)^2}{2q^-z(1-z)}y_1^-\right]\right) \longrightarrow \text{GLV}$$

↓

τ_f Formation time of the gluon emission y_1^-/τ_f

Parton energy loss and jet transport

$$\frac{dE_{rad}}{dx} \approx E\frac{2C_A\alpha_s}{\pi}\hat{q}(x)\int dz\frac{d\ell_\perp^2}{\ell_\perp^4}zP(z)\sin^2\frac{\ell_\perp^2(x-x_0)}{4z(1-z)E}$$

(High-twist approach)

$$\frac{dE_{el}}{dx} = \int\frac{d^3k}{(2\pi)^3}dq_\perp^2 f(k)\frac{q_\perp^2}{2k}\frac{d\sigma}{dq_\perp^2} \approx \langle\frac{1}{2\omega}\rangle\hat{q}$$

Elastic energy loss

Jet transport coefficient:

$$\hat{q}(y) = \frac{4\pi^2\alpha_s C_R}{N_c^2-1}\rho(y)xG(x)|_{x\approx 0} = \frac{\langle q_\perp^2\rangle}{\lambda}$$

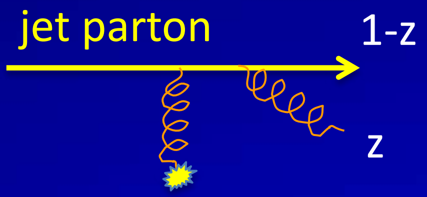
pQCD (BDMPS'96)
AdS/CFT (Liu,Rajagopal &Wideman'06)
lattice QCD (Majumder'12)

Extract jet transport coefficient from parton energy loss

Jet tomography via leading hadrons

Energy loss distribution or medium induced splitting function

$$\Delta\widetilde{P}_{a\to ag}(z) \approx \frac{2C_A\alpha_s}{\pi}\int dx\hat{q}(x)\int\frac{d\ell_\perp^2}{\ell_\perp^4}P(z)\sin^2\frac{\ell_\perp^2(x-x_0)}{4z(1-z)E}$$



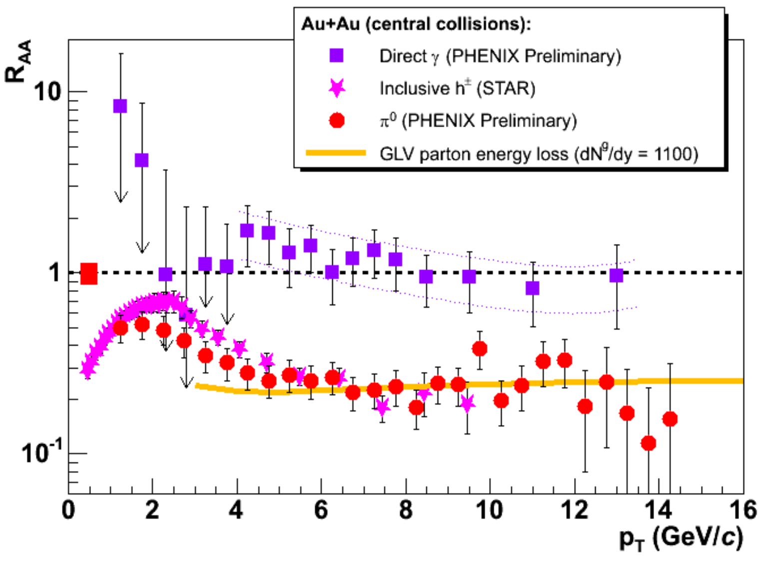
Modified frag function & hadron spectra:

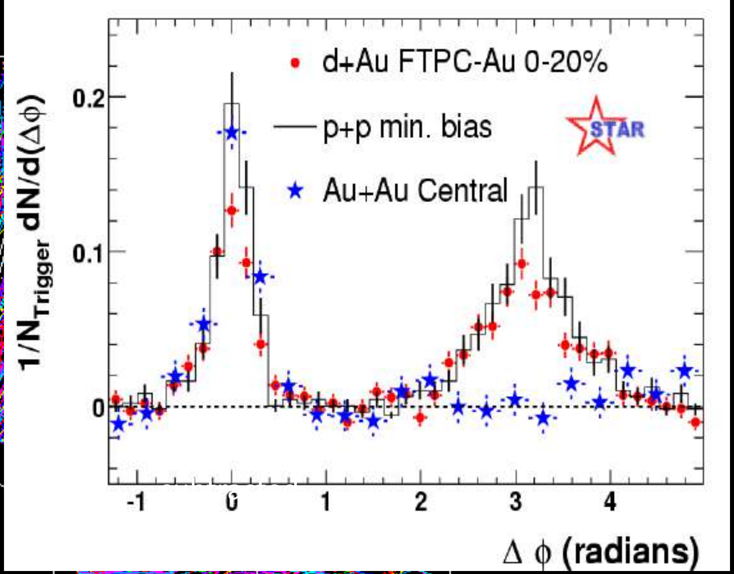
$$\widetilde{D}_{c/h}(z_h) \approx [P_{a\to ag}(z)+\Delta\widetilde{P}_{a\to ag}(z)]\otimes D_{a/h}(z_h)$$

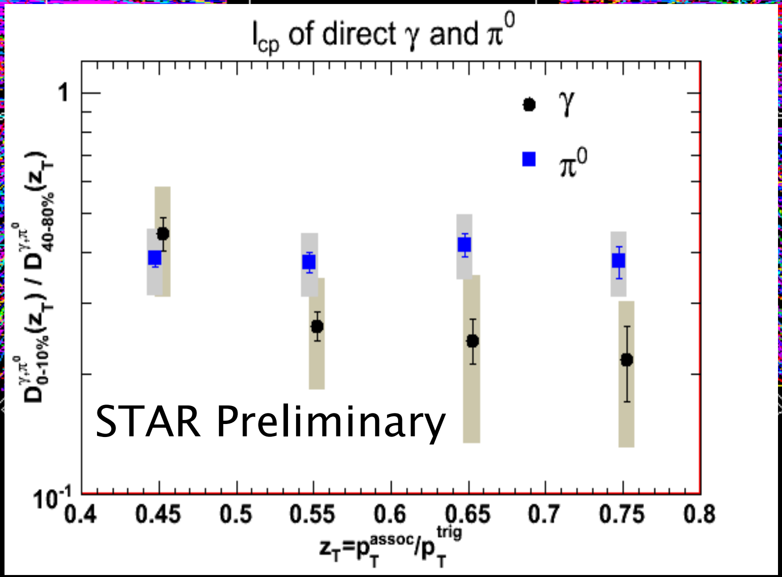
$$d\sigma_h = \sum_{a,b,c} f_a \otimes f_b \otimes d\sigma_{ab\to c+X} \otimes \widetilde{D}_{c/h}$$

Parton energy loss leads to suppression of leading hadrons

Jet Quenching phenomena at RHIC



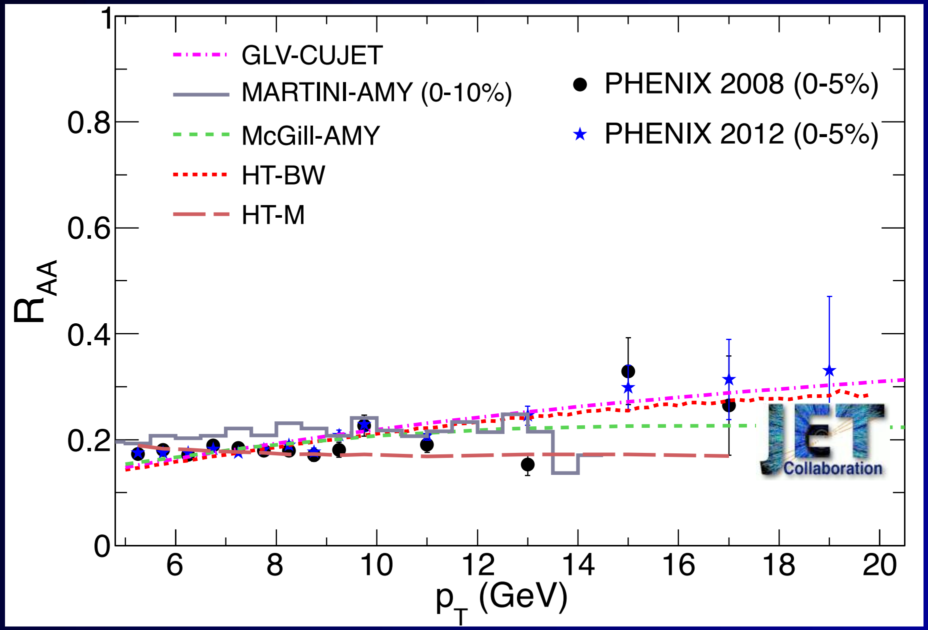




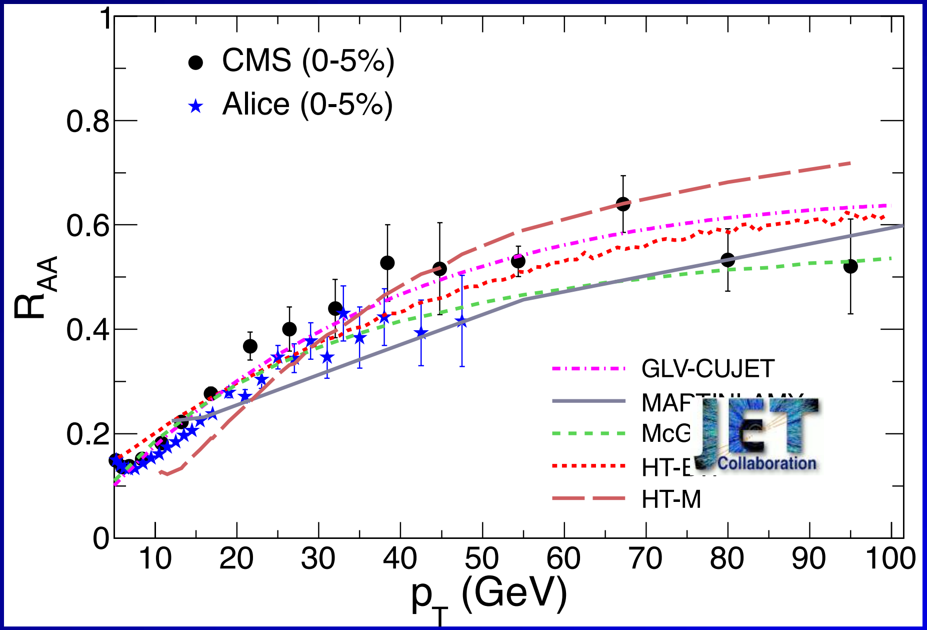
Jet quenching phenomenology

Suppression of single hadron spectra at RHIC and LHC

Best χ^2 fits with different model calculations :



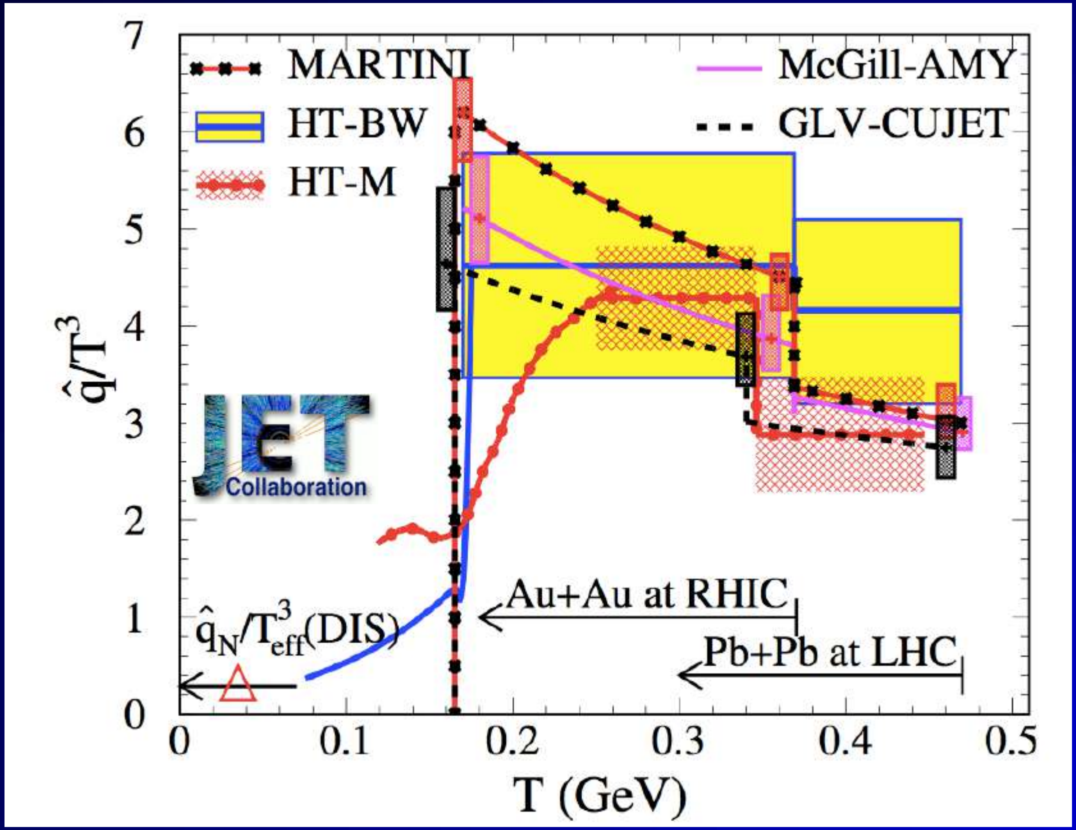
RHIC



LHC

Jet transport coefficient

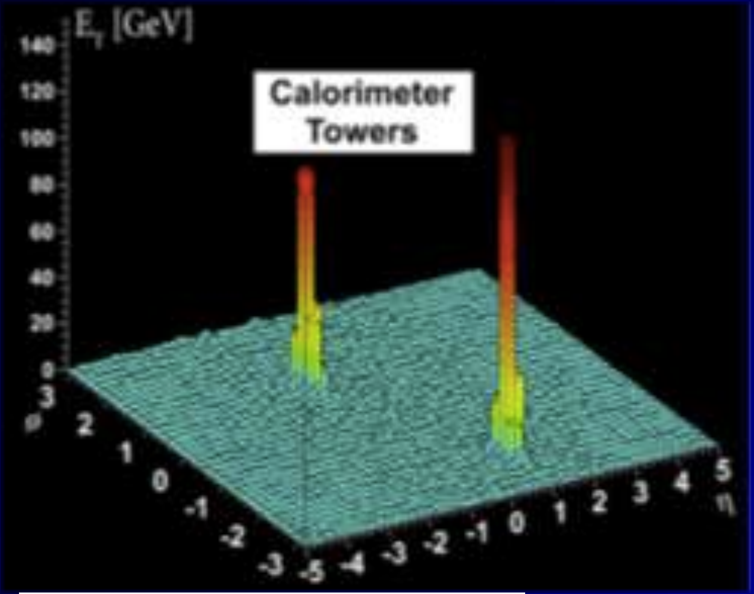
JET Collaboration: **arXiv:1312.5003**

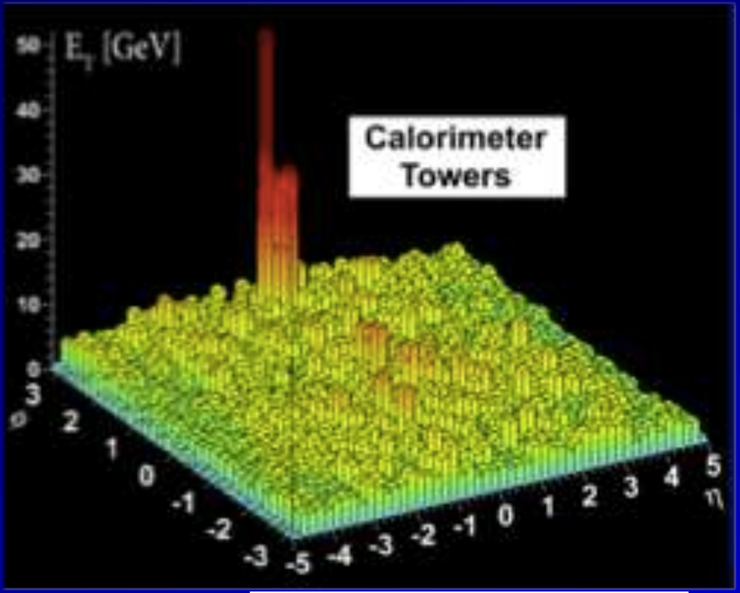


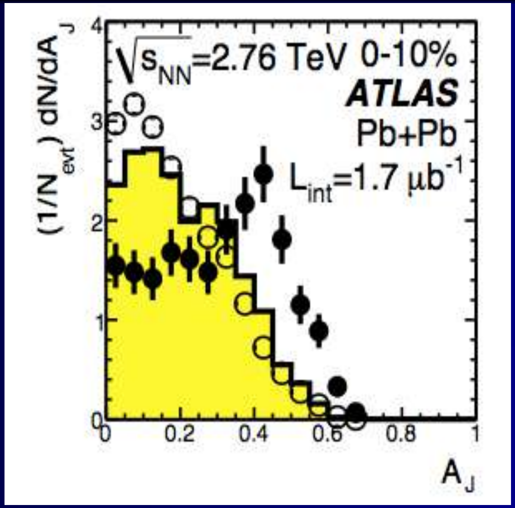
$$\hat{q} \approx \begin{cases} 1.2 \pm 0.3 \\ 1.9 \pm 0.7 \end{cases} \text{GeV}^2/\text{fm} \ \ \text{at} \quad \begin{matrix} \text{T=370 MeV,} \\ \text{T=470 MeV,} \end{matrix}$$

RHIC
LHC

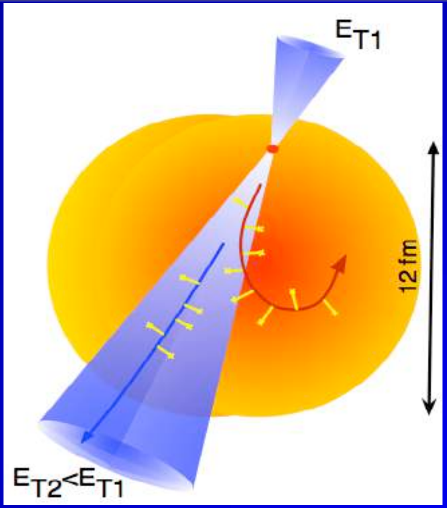
Dijet asymmetry at LHC



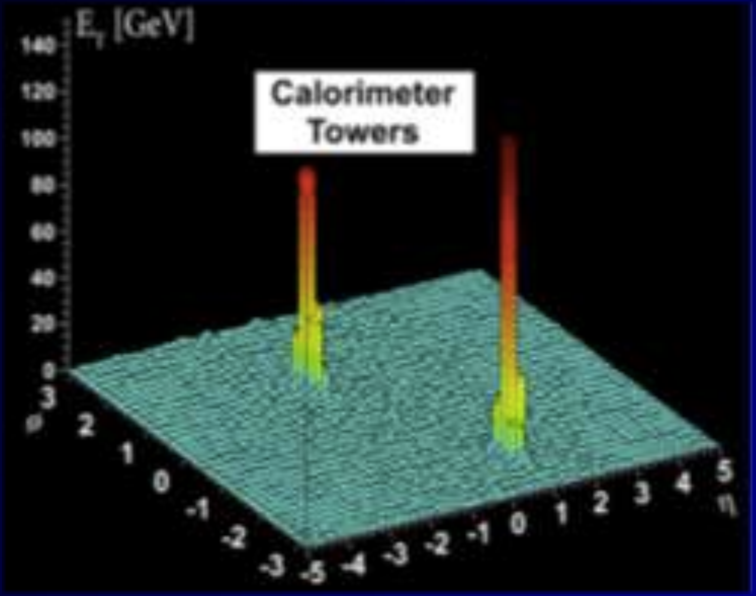


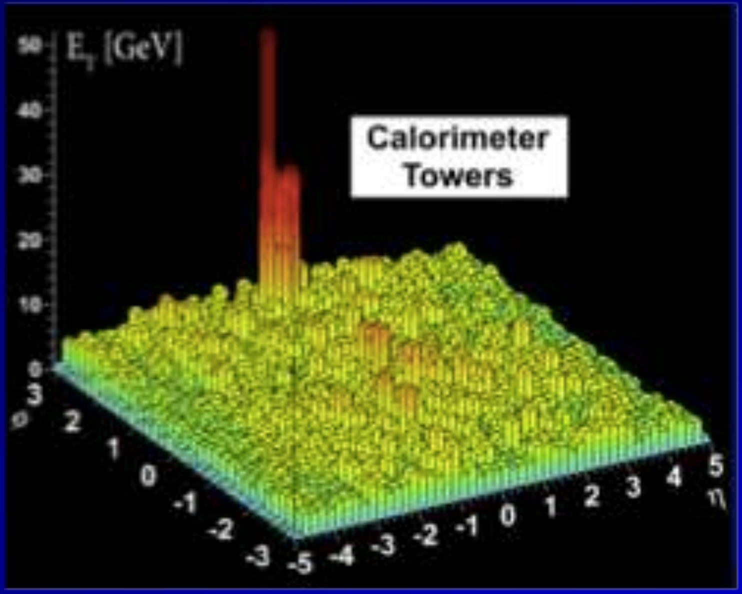


$$A_J = \frac{E_{T1} - E_{T2}}{E_{T1} + E_{T2}}$$



Jet energy and background subtraction

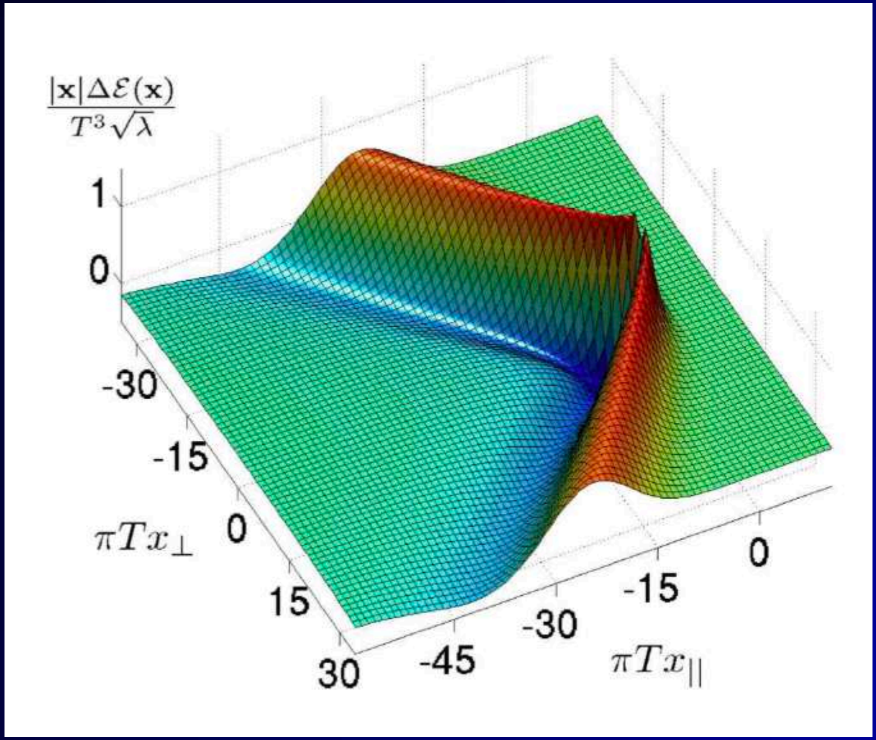




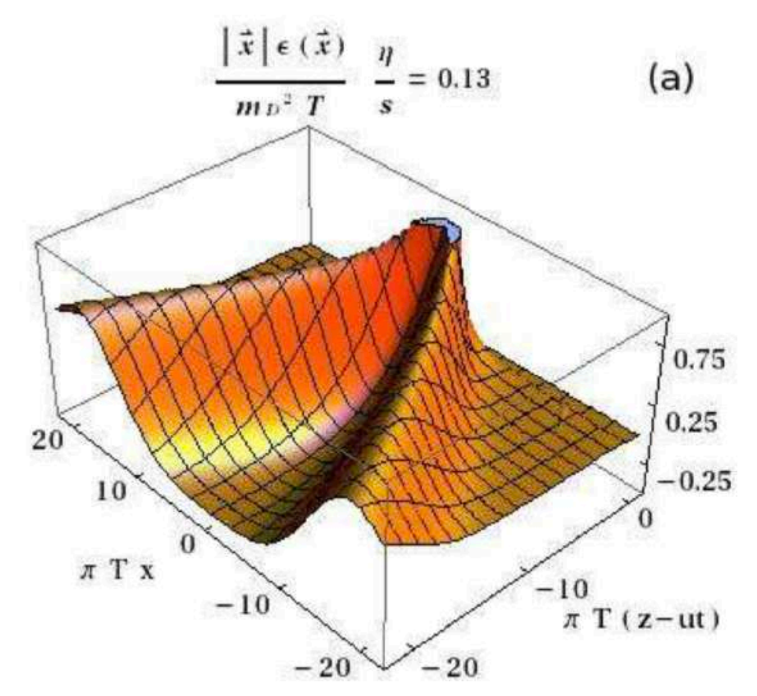
Jet energy as defined in the jet reconstruction algorithm
Uncorrelated background should be subtracted
Jet-induced medium response is correlated with jet: not background
Some of the energy lost by leading partons remain inside jet-cone

Mach-cone of medium excitation

Casalderrey-Solana, Shuryak; Stoecker, 2005



Chesler and Yaffe (0712.0050)



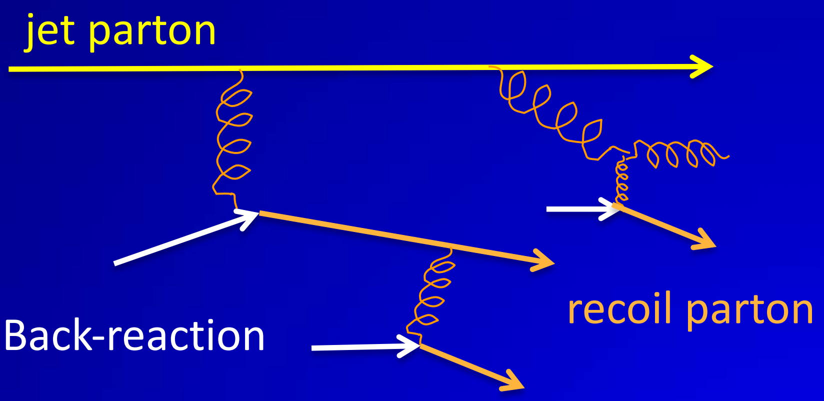
Nuefeld, Muller and Ruppert 0802.2254)

LBT: Linear Boltzmann Transport

$$p_1 \cdot \partial f_1 = -\int dp_2 dp_3 dp_4 (f_1 f_2 - f_3 f_4)|M_{12\to 34}|^2 (2\pi)^4 \delta^4(\sum_i p_i) + \text{inelastic}$$

Induced radiation $$\frac{dN_g}{dz d^2k_\perp dt} \approx \frac{2C_A\alpha_s}{\pi k_\perp^4} P(z)\hat{q}(\hat{p}\cdot u)\sin^2\frac{k_\perp^2(t-t_0)}{4z(1-z)E}$$

- pQCD elastic and radiative processes (high-twist)
- Transport of medium recoil partons (and back-reaction)
- CLVisc 3+1D hydro bulk evolution



Li, Liu, Ma, XNW and Zhu, PRL 106（2010）012301
XNW and Zhu, PRL 111 (2013) 062301; He, Luo, XNW & Zhu, PRC91 (2015) 054908;

CoLBT-hydro
(Coupled Linear Boltzmann Transport hydro)

$$p \cdot \partial f(p) = -C(p) \quad (p \cdot u > p^0_{cut})$$

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

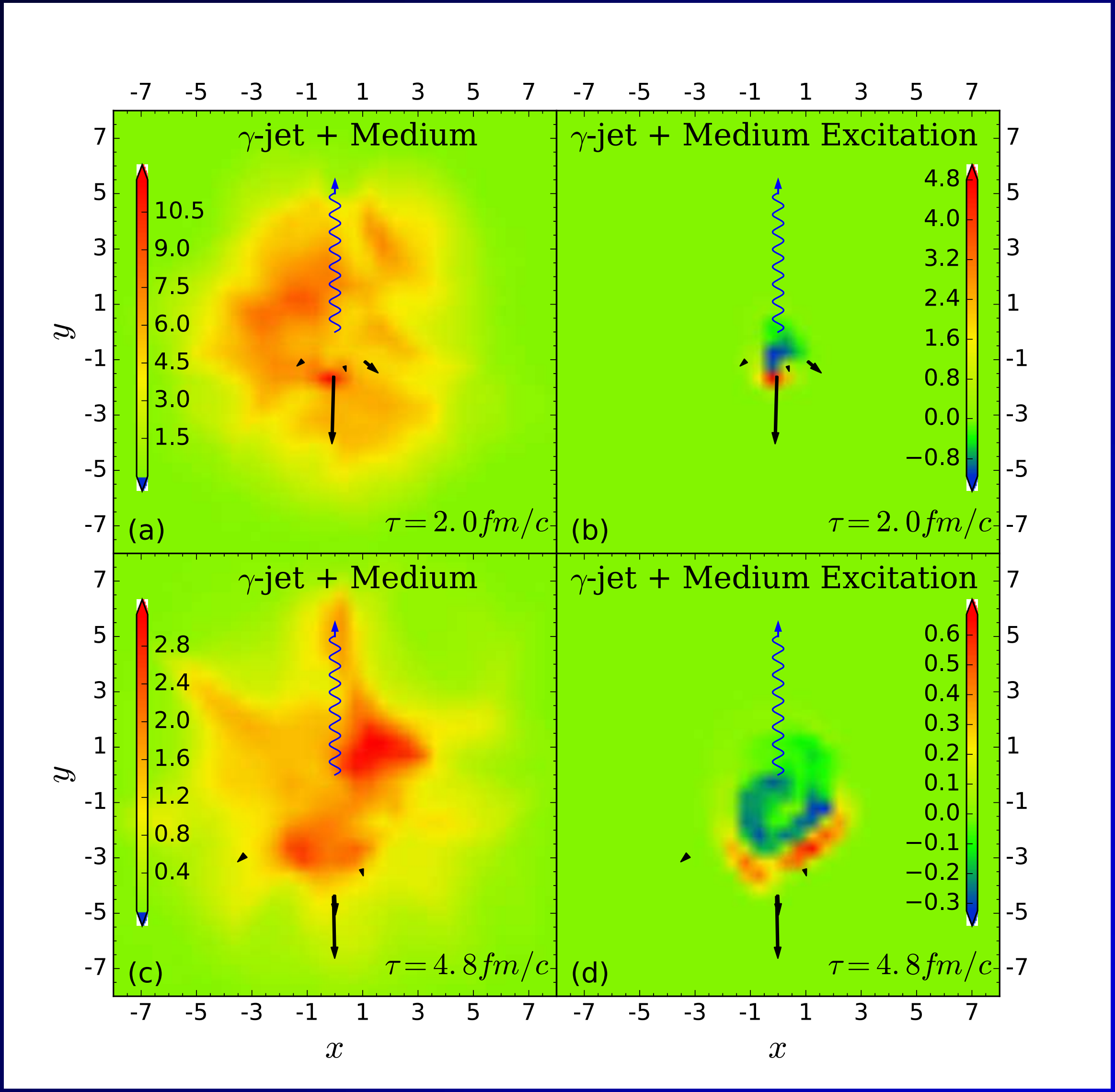
$$j^\nu(x) = \sum_i p_i^\nu \delta^{(4)}(x - x_i)\theta(p^0_{cut} - p \cdot u)$$

- LBT for energetic partons (jet shower and recoil)
- Hydrodynamic model for bulk and soft partons: CLVisc

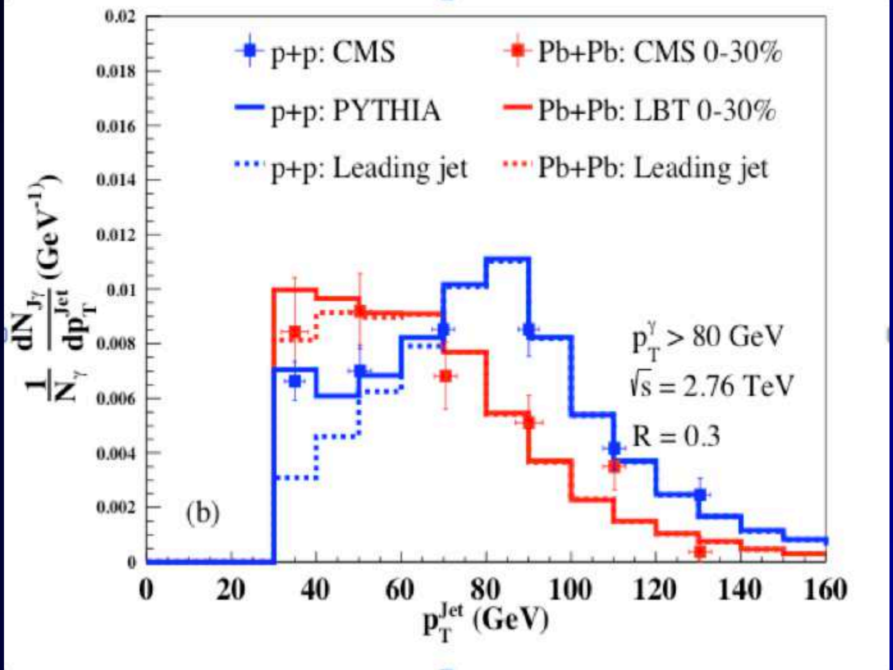
CLVisc: (3+1)D viscous hydro parallelized on GPU using OpenCL

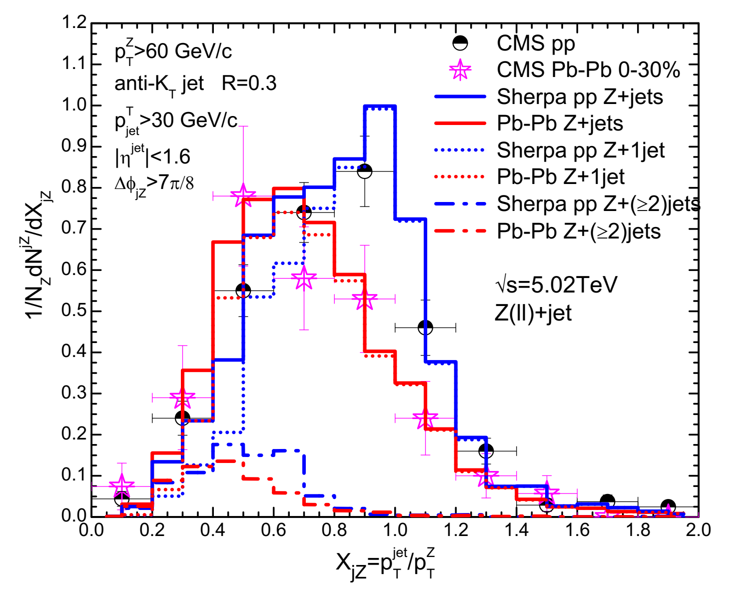
Chen, Cao, Luo, Pang & XNW, PLB777(2018)86

γ-jet propagation within CoLBT-hydro



Jet energy loss and $\gamma(Z^0)$-jet asymmetry

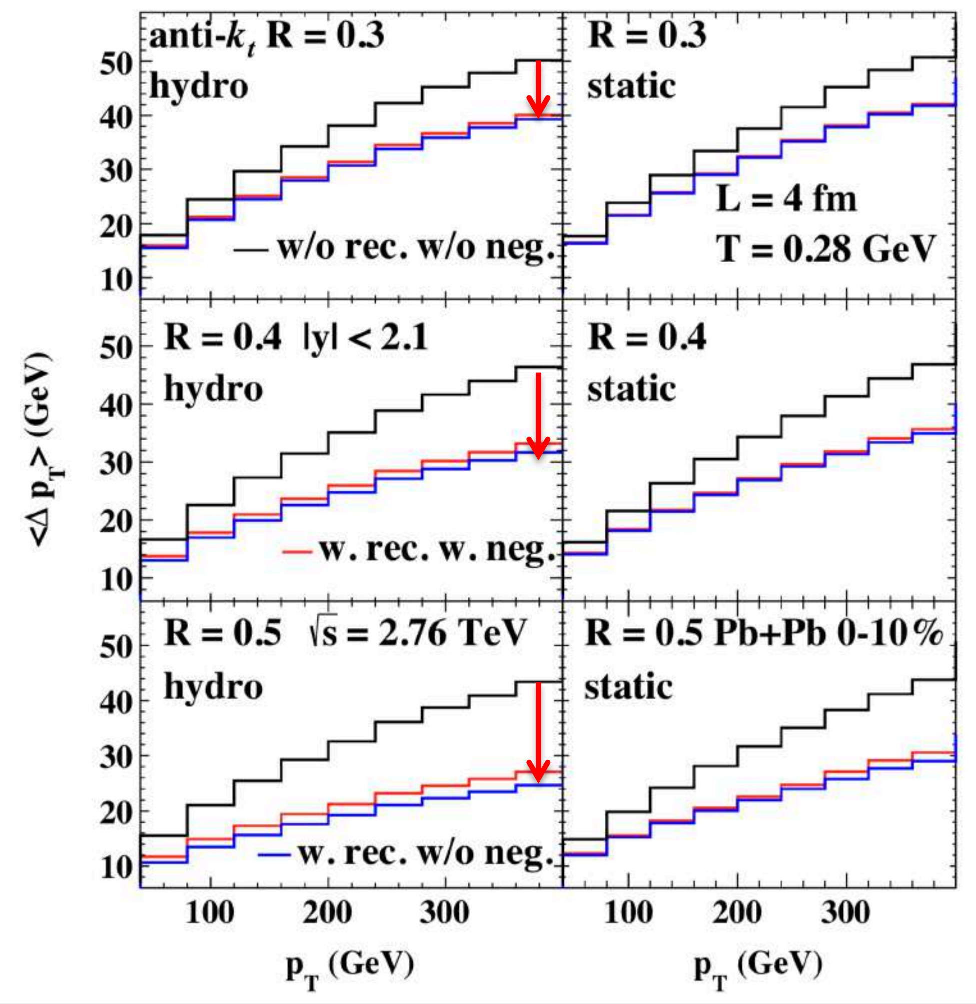




Luo, Cao, He & XNW, PLB782(18)707

Zhang, Luo, XNW, Zhang, arXiv:1804.11041

Medium response reduces jet energy loss



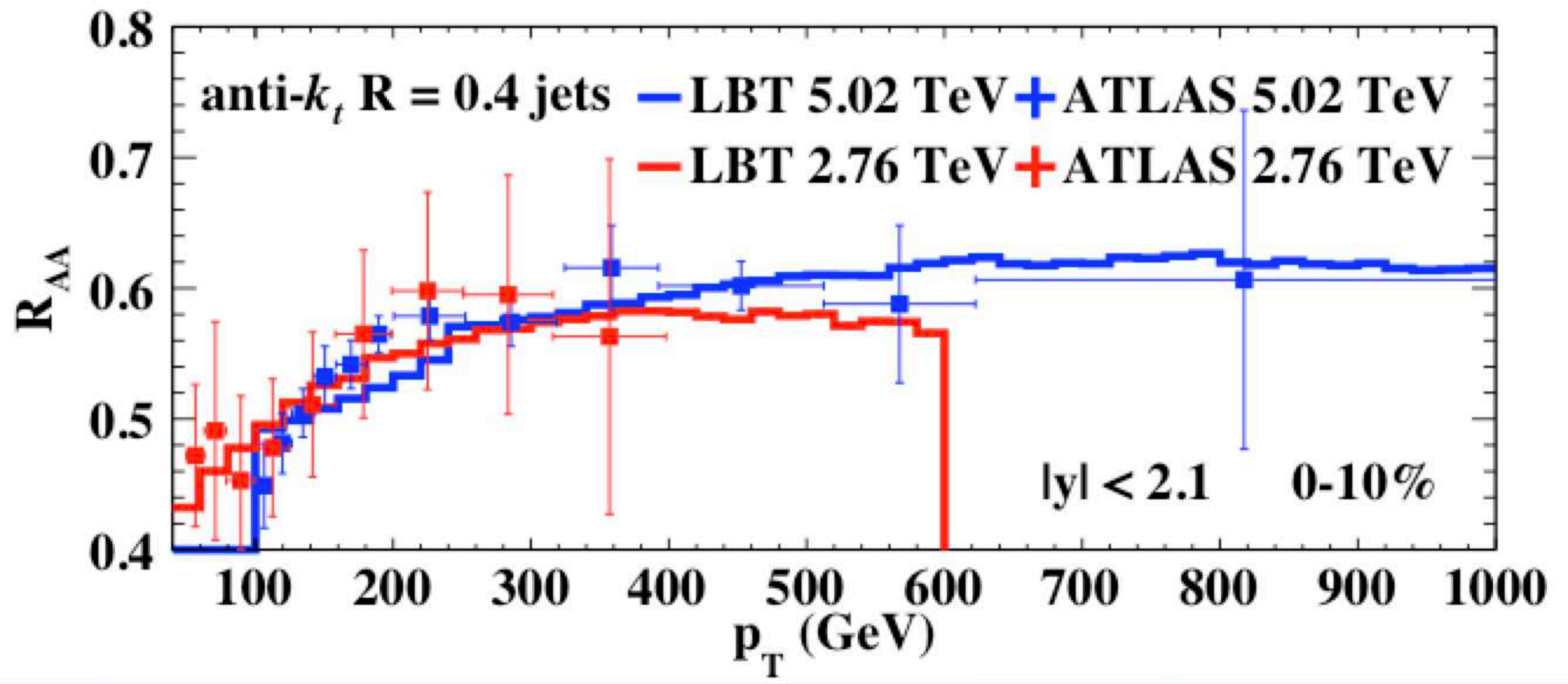
He, Cao, Chen, Luo, Pang & XNW 1809.02525

Recoil partons within the jet cone reduce the net jet energy loss –change pt dependence

Diffusion wake (backreaction) reduces the thermal background, if taken into account, increase the net jet Energy loss with given cone-size

Depend on jet cone-size R
Sensitive to radial flow

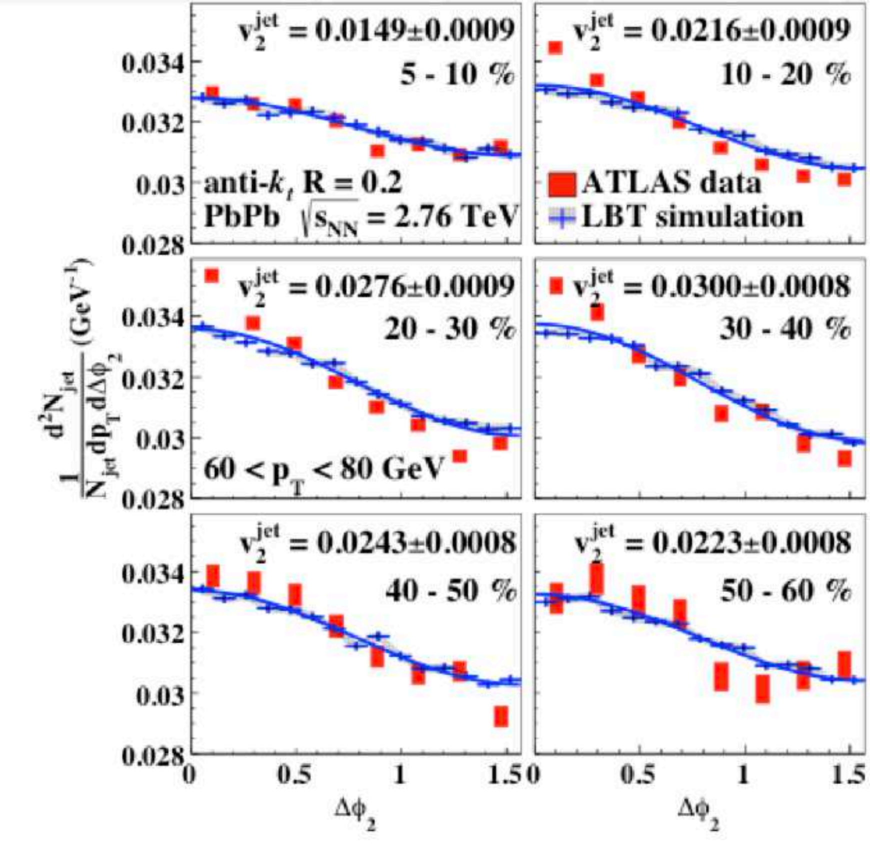
Energy and pT dependence

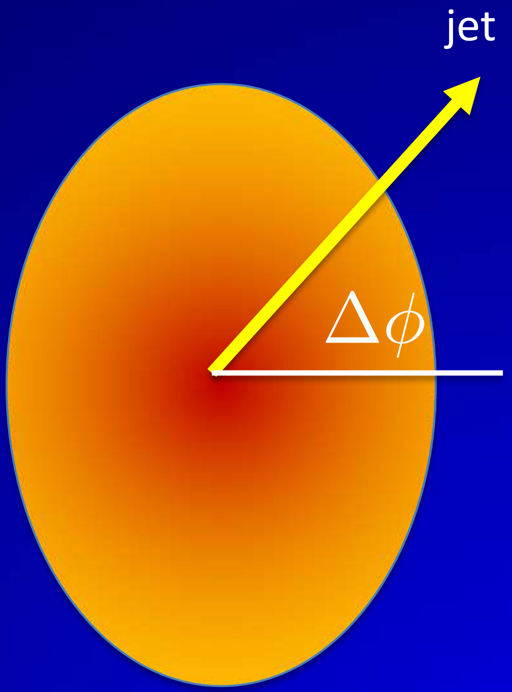


He, Cao, Chen, Luo, Pang & XNW 1809.02525

Weak pT dependence: initial jet spectra and pT dependence of energy loss ΔE
Week energy dependence: increase of jet energy loss and the slope of initial spectra

Single jet anisotropy



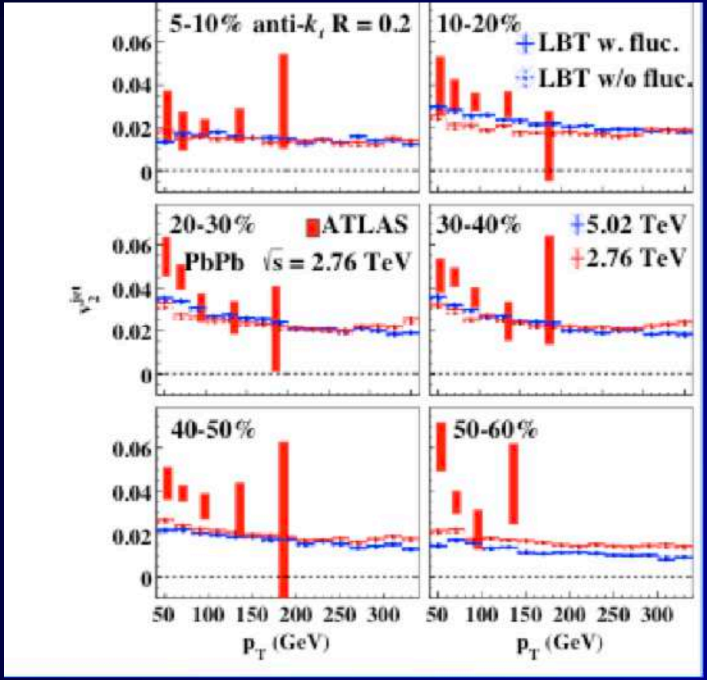


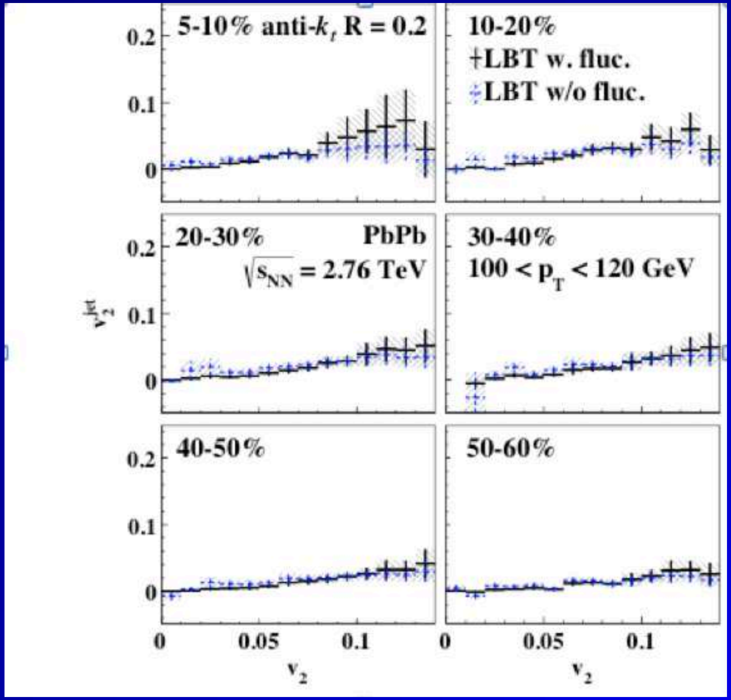
$\Delta\phi_2 = \phi^{jet} - \Psi_2$

Correlation btw jet and bulk anisotropy

$$v_n^{\text{jet}} = \frac{\langle\langle v_n \cos[n(\phi^{\text{jet}} - \Psi_n)]\rangle\rangle}{\sqrt{\langle v_n^2 \rangle}}$$

$$v_n^{\text{jet}} = \langle \cos[n(\phi^{\text{jet}} - \Psi_n)]\rangle$$



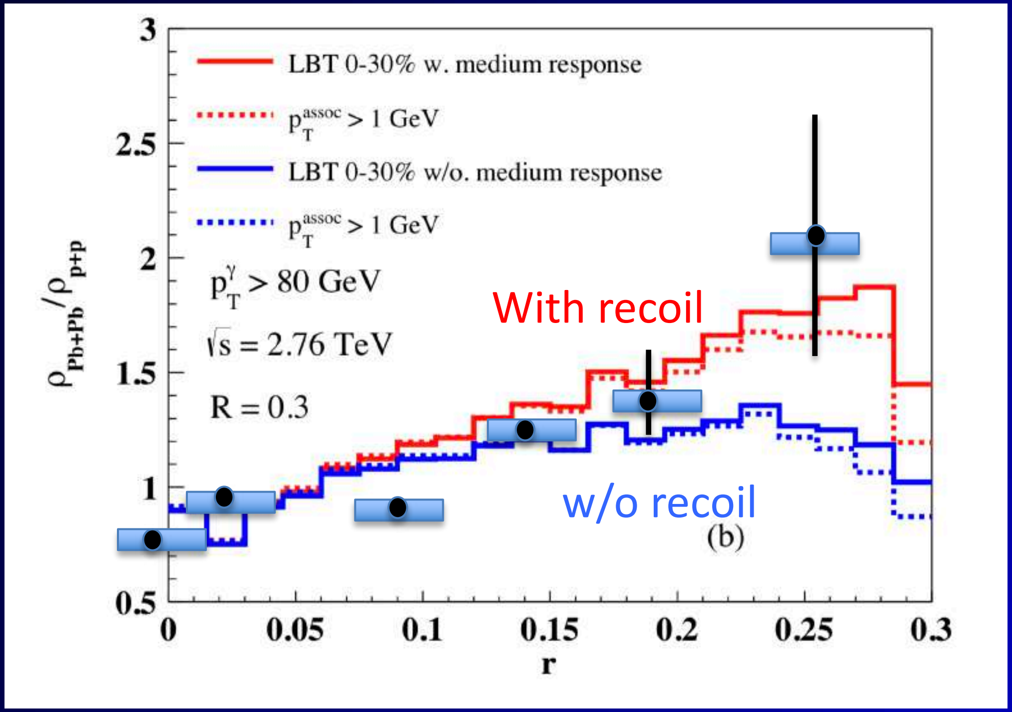


He, Cao, Chen, Luo, Pang & XNW to be published

Medium response in gamma-jet profile

Enhancement of jet shape at larger r

$$\rho(r) = \frac{1}{E_T}\frac{dE_T}{dr}$$

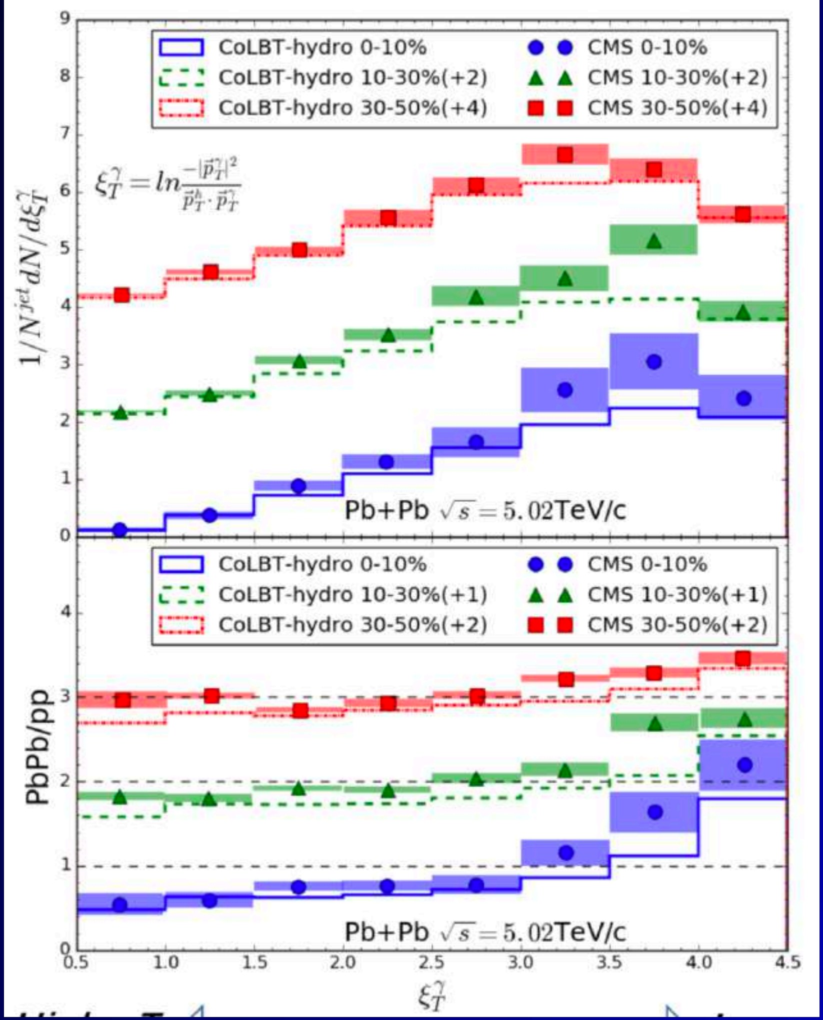


With recoil

w/o recoil

Luo, Cao, He & XNW, arXiv:1803.06785

Medium response in jet frag func

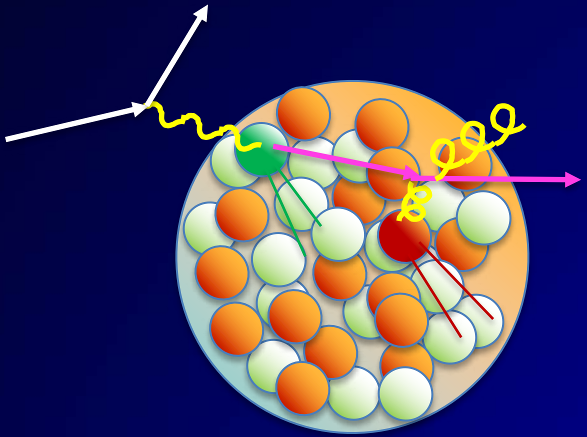


Particle distribution inside the jet

$$\xi_\gamma = \log(p_T^\gamma/p_T^h)$$

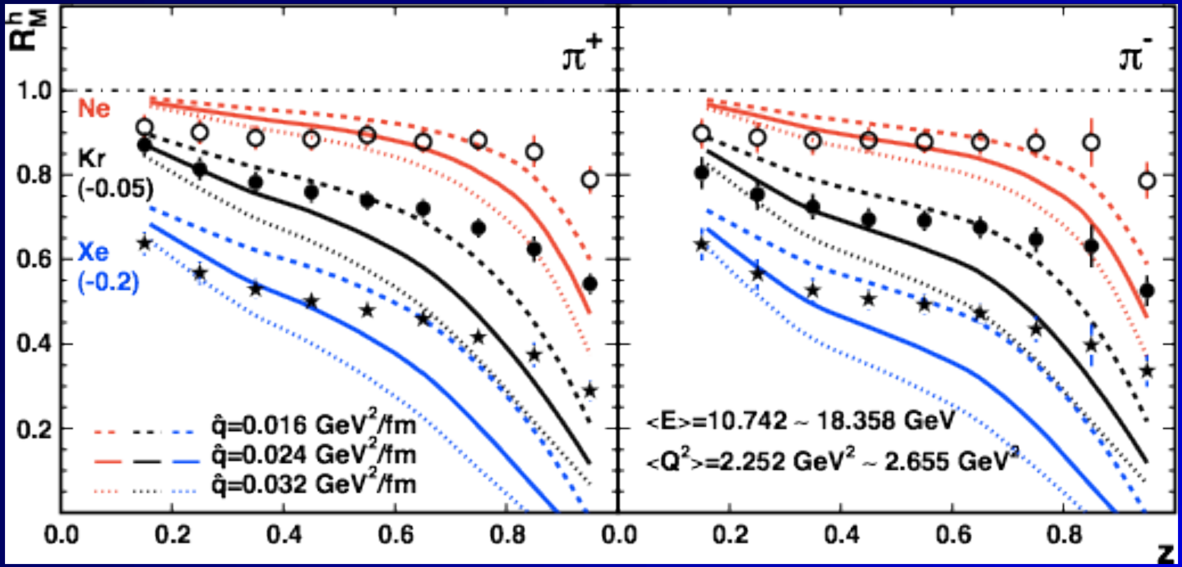
Wei Chen et all, 2005.09678

Jet tomography of nuclei at EIC



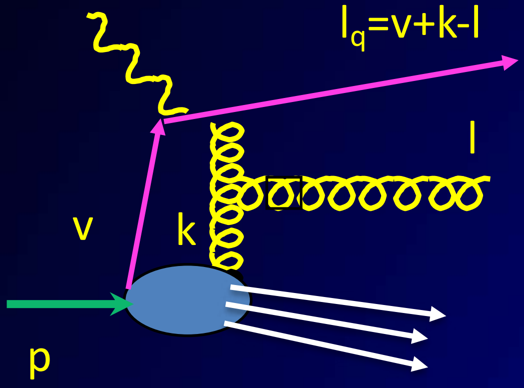
$$\hat{q}_N \approx 0.02\ \ \mathrm{GeV}^2/fm$$

$$R = \frac{N_h^{eA}}{N_h^{eD}}$$



Deng & XNW (2010) Chang, Deng & XNW (2015)

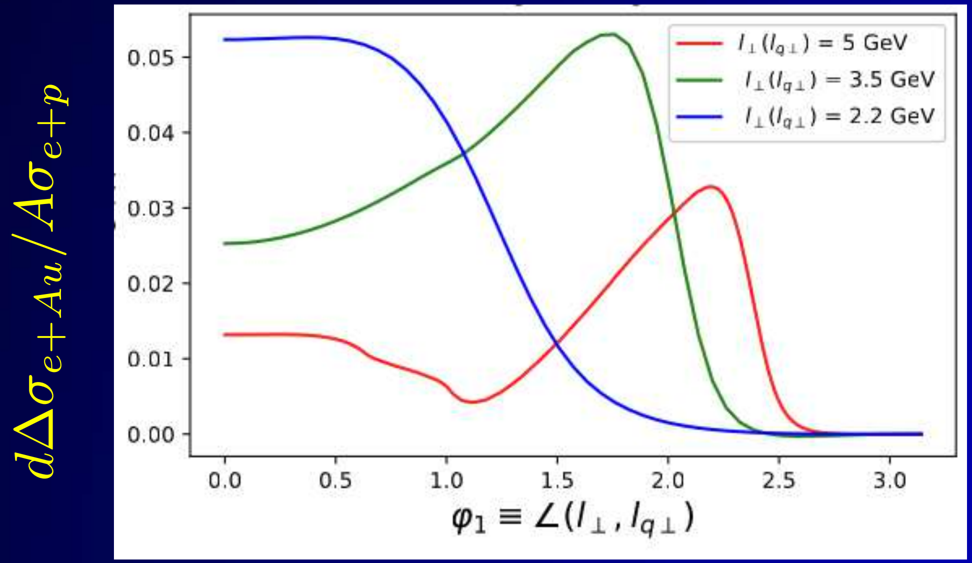
nuclear modification of dijet at EIC



$$\frac{d\hat{\sigma}_D}{dx_B dQ^2 dz d^2 l_\perp d^2 l_{q\perp}} = \sigma_0 \frac{1+z^2}{1-z} \frac{\alpha_s^2}{N_c} \int dy_1^- \rho(y_1^-, \vec{y}_{N\perp})$$

$$\otimes \int d^2\vec{v}_\perp \int \frac{d^2\vec{k}_\perp}{(2\pi)^2} f_q^A(x_B, \vec{v}_\perp) \frac{\phi(0,\vec{k}_\perp)}{k_\perp^2} \mathcal{N}_g(\vec{l}_\perp, \vec{l}_{q\perp}, \vec{k}_\perp, \vec{v}_\perp)$$

$$\vec{l}_\perp + \vec{l}_{q\perp} = \vec{k}_\perp + \vec{v}_\perp$$



$$\frac{d\Delta\sigma_{e+A}}{A\sigma_{e+p}} \propto A^{2/3}$$

Quadratic nuclear-size dependence due to LPM interference

Yuanyuan Zhang & XNW to be published

Summary

- Jet quenching has been used successfully to study properties of QGP
- Extraction of jet transport coefficient
- Jet suppression is influenced by many competing efforts
  - Parton energy loss & medium response
  - Medium response leads to modification of jet shape, jet frag function
- Jet quenching and modification of dijet can provide information about nuclear TMD parton distributions

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