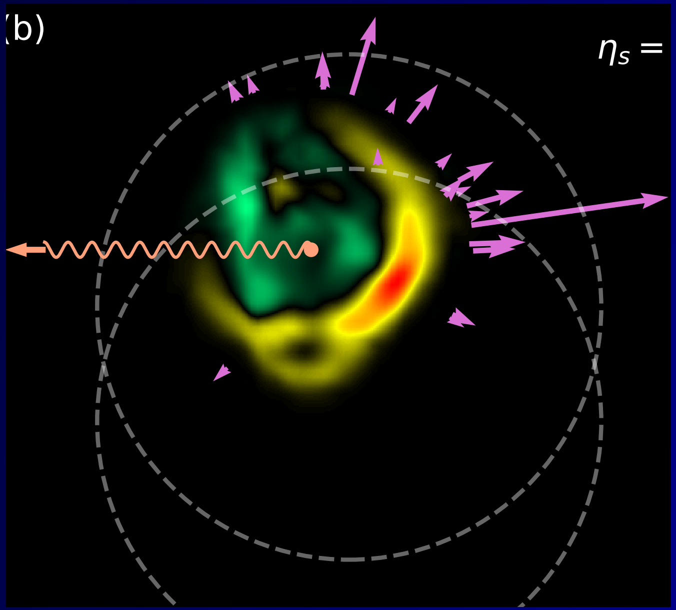
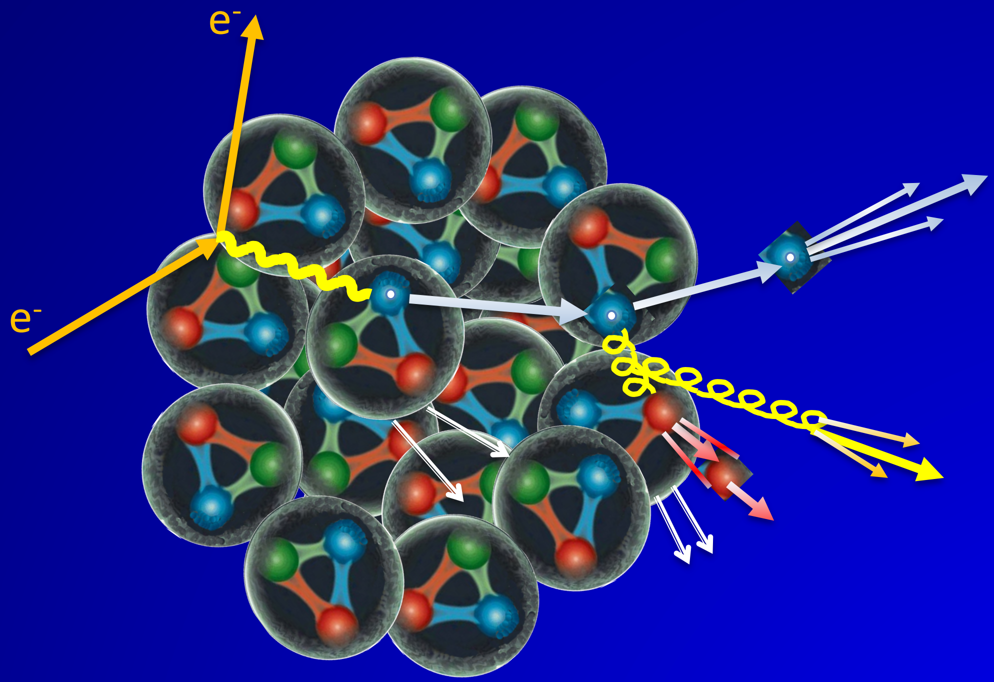
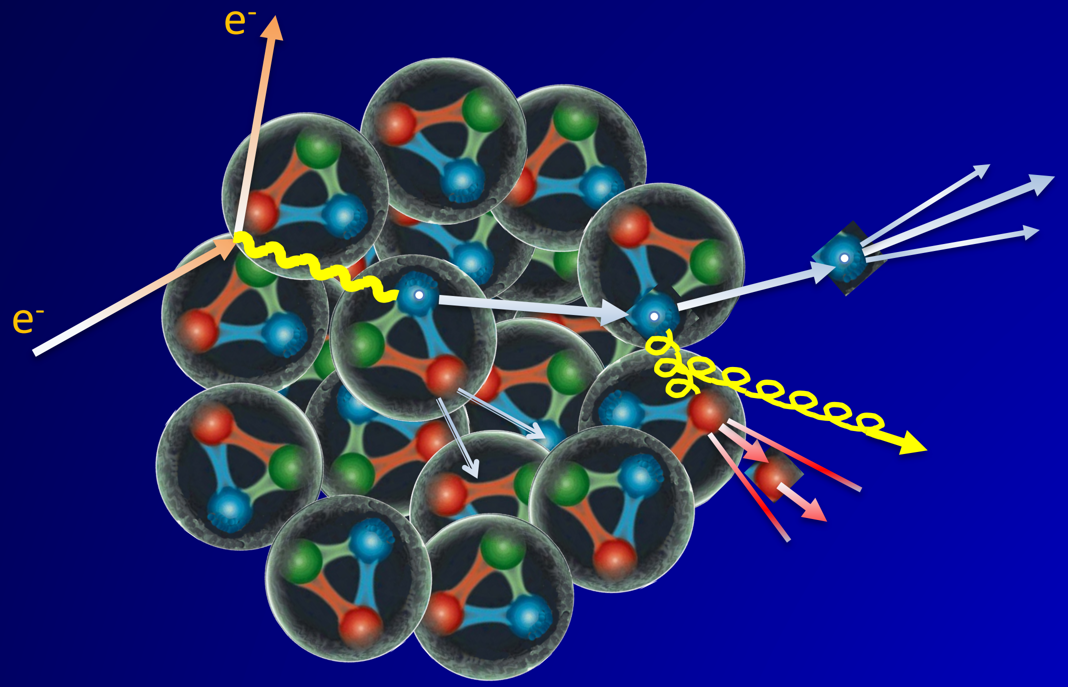
Jet quenching in A+A and e+A Collisions





Xin-Nian Wang
Lawrence Berkeley National Laboratory

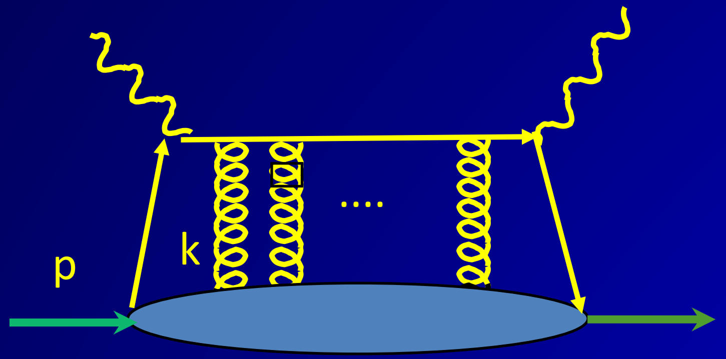
Jet production in DIS off nuclei



Multiple scattering, p_T broadening, parton energy loss, hadronization, hadronic interaction in nuclei

Multiple parton scattering in nuclear medium

$$f_A^q(x,\vec{k}_\perp) = \int \frac{dy^-}{4\pi}\frac{d^2y_\perp}{(2\pi)^2} e^{ixp^+y^- - i\vec{k}_\perp\cdot\vec{y}_\perp}\langle A|\bar{\psi}(0)\gamma^+\mathcal{L}(0,y)\psi(y)|A\rangle$$



Liang, XNW & Zhou, *PRD* 77 (2008) 125010

$$\Delta = \int dy\hat{q}(y)$$

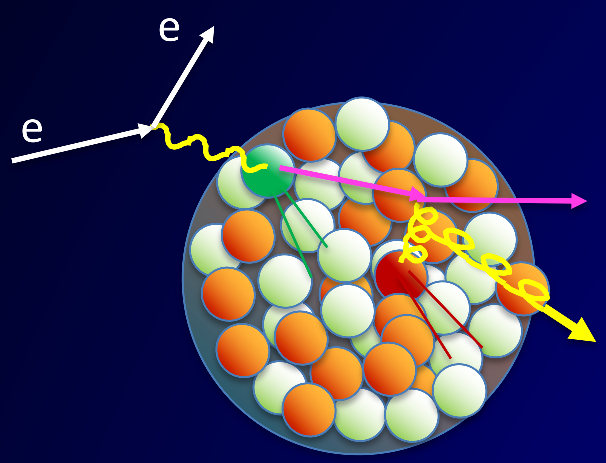
$$f_A^q(x,\vec{k}_\perp) \approx \frac{A}{\pi\Delta}\int d^2q_\perp \exp\left[-\frac{(\vec{k}_\perp-\vec{q}_\perp)^2}{\Delta}\right] f_N^q(x,\vec{q}_\perp)$$

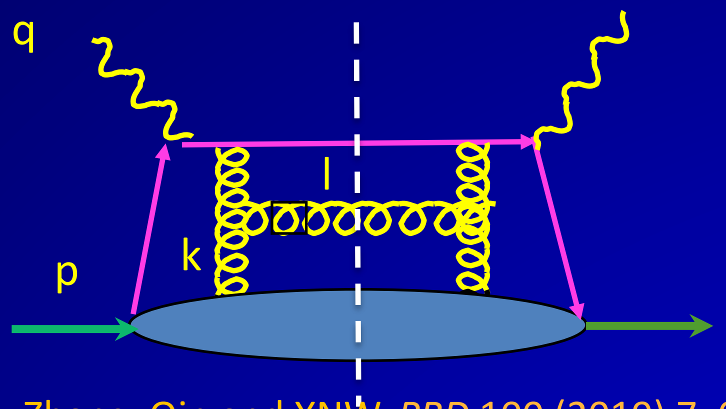
p_T broadening and Jet transport coefficient:

Saturation scale probed by jet

$$\hat{q}(y) = \frac{4\pi^2\alpha_s C_R}{N_c^2-1}\rho(y)xG(x)|_{x\approx 0} \longleftrightarrow Q_s^2 = \int dy\hat{q}(y)$$

Parton energy loss in nuclear medium





Zhang, Qin and XNW, *PRD* 100 (2019) 7, 074031

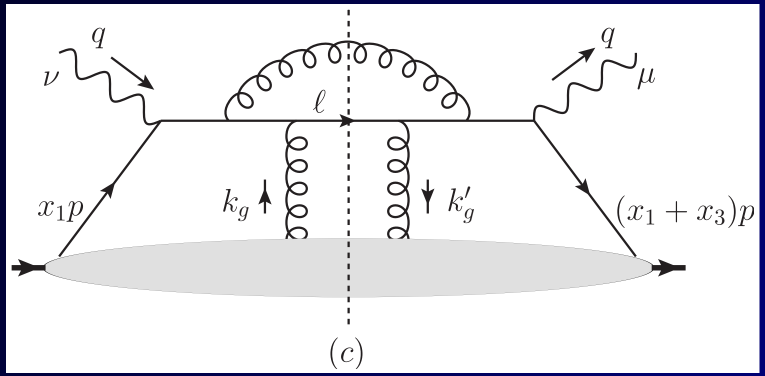
$$\frac{dN_g}{dl_\perp^2\,dz} = \int_{y^-}^{\infty} dy_1^- \left[\rho_A(y_1^-, \vec{y}_\perp)\frac{2\pi\alpha_s}{N_c}\pi\int\frac{dk_\perp^2}{(2\pi)^2}\frac{\phi_g(0,\vec{k}_\perp)}{k_\perp^2}\right]\pi\frac{\alpha_s}{2\pi}P_{qg}(z)\frac{C_A}{l_\perp^2}\mathcal{N}_g(\vec{l}_\perp,\vec{k}_\perp)$$

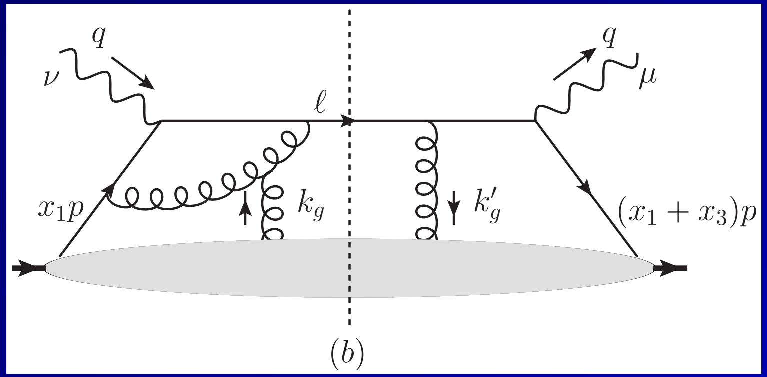
Nucleon TMD gluon distr.

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

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

Factorization and qhat of the cold & hot medium





- Cancellation of soft-collinear divergence
- Factorization of the collinear divergence

Kang, Wang, Xing & Wang, *PRL* 112, 102001(2014); *PRD* 94 (2016) 11; *PRD* 94 (2016) 7, 074038

$$\frac{d\langle k_\perp^2 \sigma\rangle_{\rm NLO}}{dz_h} = \sigma_0 D_h(z, \mu_f^2) \otimes H_{\rm NLO}(x, x_B, Q^2, \mu_f^2) \otimes T_{qg}(x, x_1, x_2, \mu_f^2)$$

$$\frac{\partial}{\partial \ln \mu_f^2} T_{qg}(x_B, 0, 0, \mu_f^2) = \frac{\alpha_s}{2\pi} \int_{x_B}^{1} \frac{dx}{x} \left[\mathcal{P}_{qg\to qg} \otimes T_{qg} + P_{qg}(\hat{x}) T_{gg}(x, 0, 0, \mu_f^2) \right]$$

$$T_{qg}(x_B, 0, 0, \mu_f^2) \Longrightarrow \hat{q} \Longrightarrow \hat{q}(E, Q^2)$$

for both DIS and DY

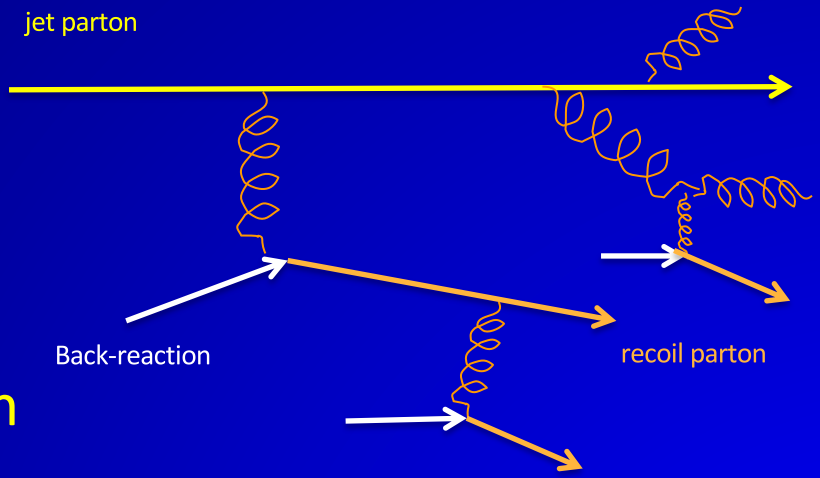
CoLBT-hydro

(Coupled Linear Boltzmann Transport hydro)

Concurrent and coupled evolution of bulk medium and jet showers

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

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



- LBT for energetic partons (jet shower and recoil)
- Hydrodynamic model for bulk and soft partons: CLVisc
- Parton coalescence (thermal-shower)+ jet fragmentation
- Hadron cascade using UrQMD

Phys. Lett. B 777 (2018) 86, *Phys. Lett. B* 810 (2020) 135783, e-Print: 2101.05422

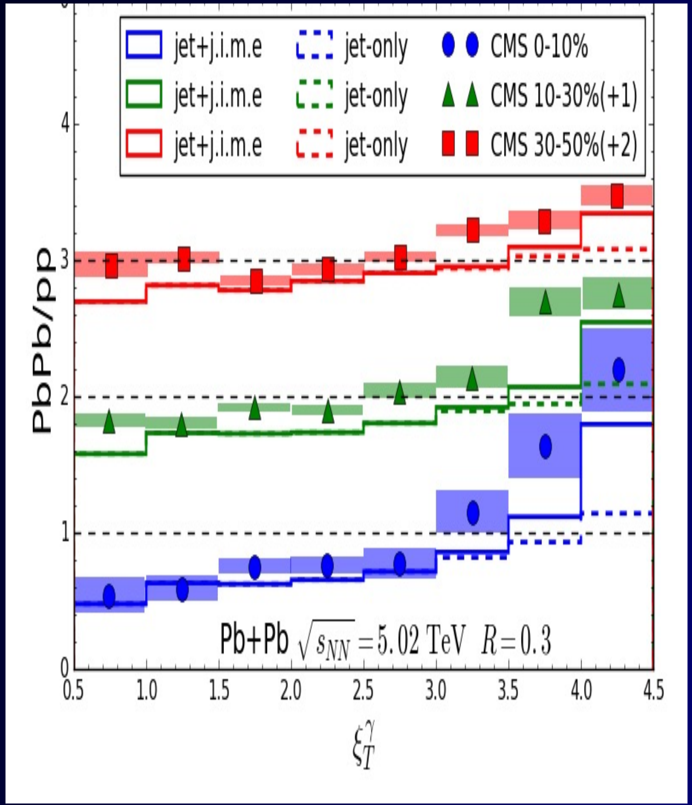
Phys. Rev. C 96 (2017) 3, 034903, *Phys. Lett. B* 777 (2018) 255-259, *Phys. Rev. C* 98 (2018) 021901, *Phys. Rev. Lett.* 122 (2019) 25, 252302, *Phys. Rev. C* 99 (2019) 5, 054911, *Phys. Rev. Lett.* 125 (2020) 12, 122301

Berkeley Lab

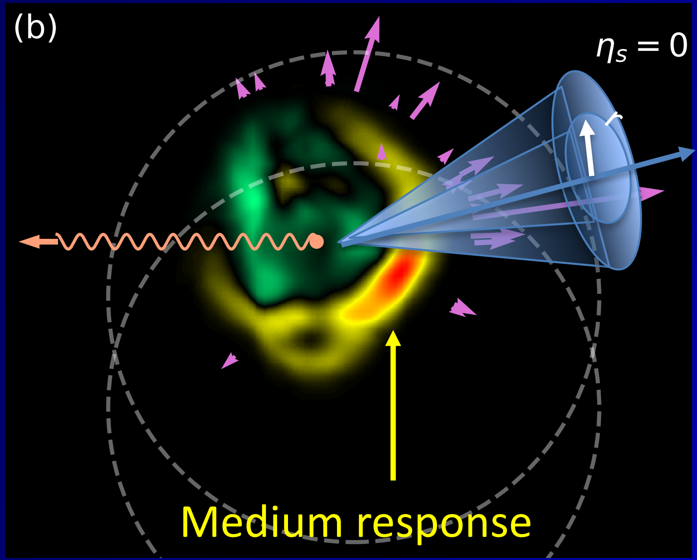
Jet quenching in heavy-ion collisions

Luo *et al*, Phys. Lett. B 782 (2018) 707-716

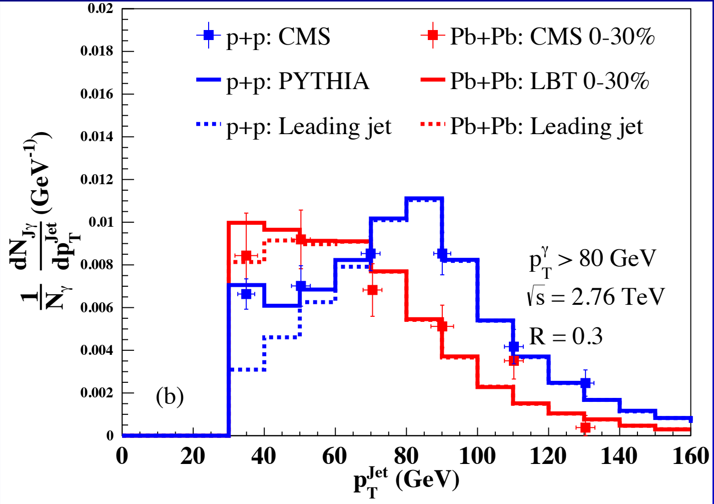
γ-jet fragmentation function



Chen, *et al.*, Phys. Lett. B 810 (2020)

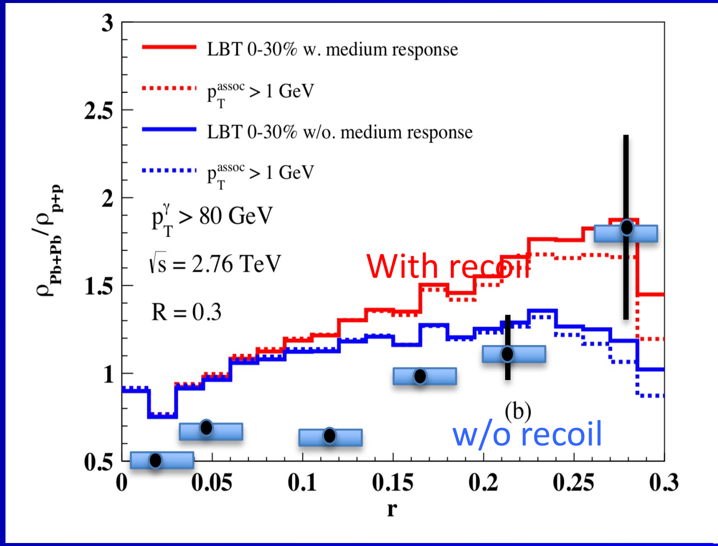


γ-jet asymmetry

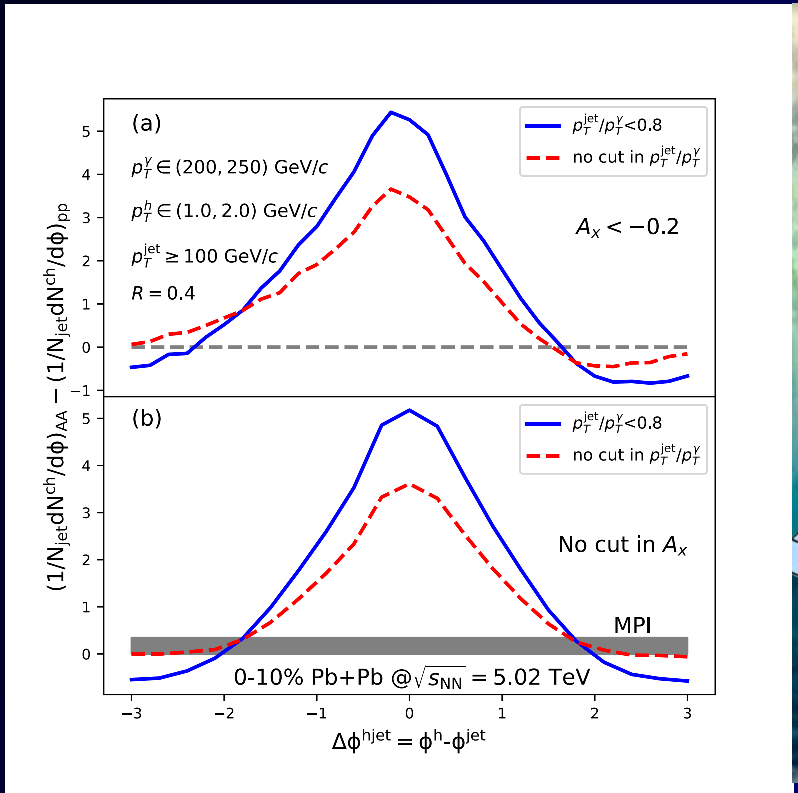


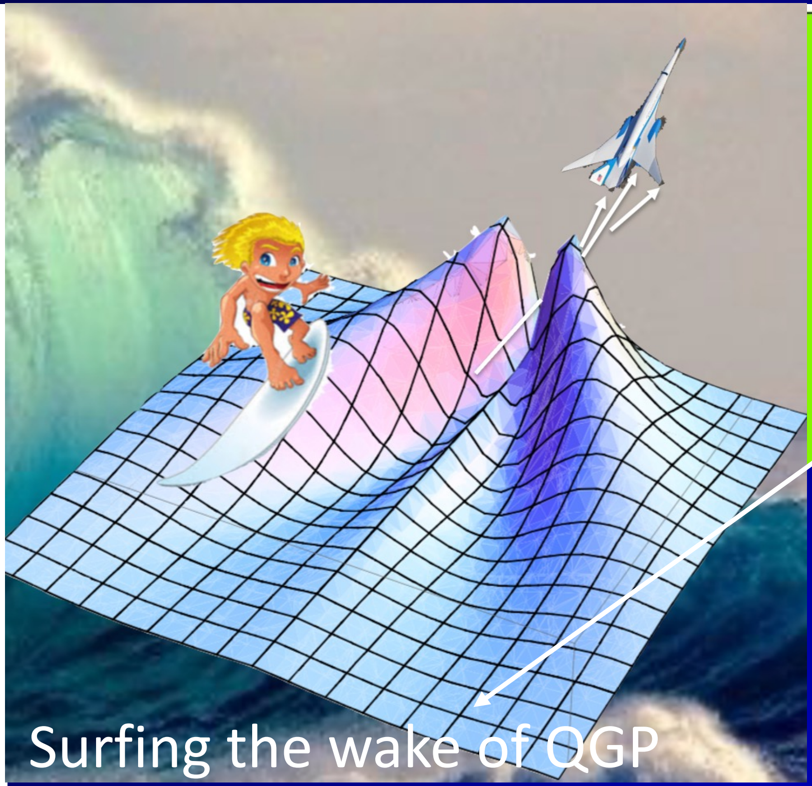
γ-jet profile

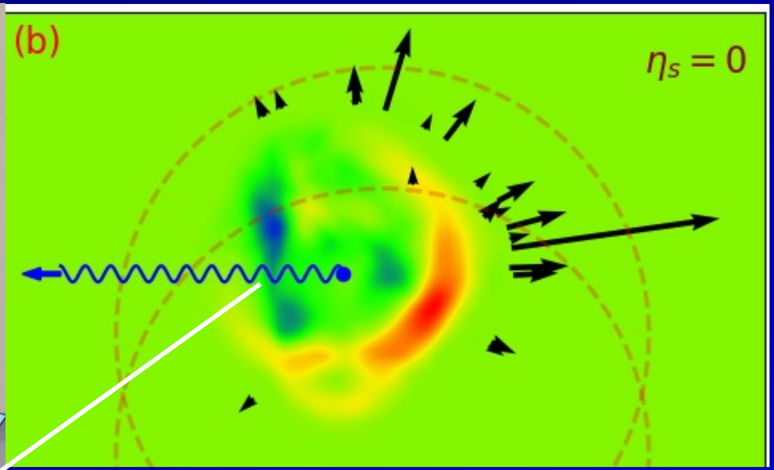
$$\rho(r) = \frac{1}{E_T}\frac{dE_T}{dr}$$

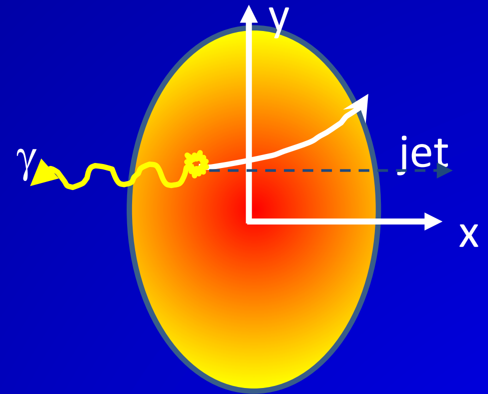


Enhancing the diffusion wake









e-Print: 2101.05422

3D jet tomography

$$A_{E_\perp}^{\vec{n}} = \frac{\int d^3r d^3p f_a(\vec{p},\vec{r})\vec{p}_T \cdot \vec{n}}{\int d^3r d^3p f_a(\vec{p},\vec{r})}$$

He, Pang & XNW, *PRL* 125 (2020) 12, 122301

Effect of flow: Sadofyev, Sievert & Vitev 2104.09513

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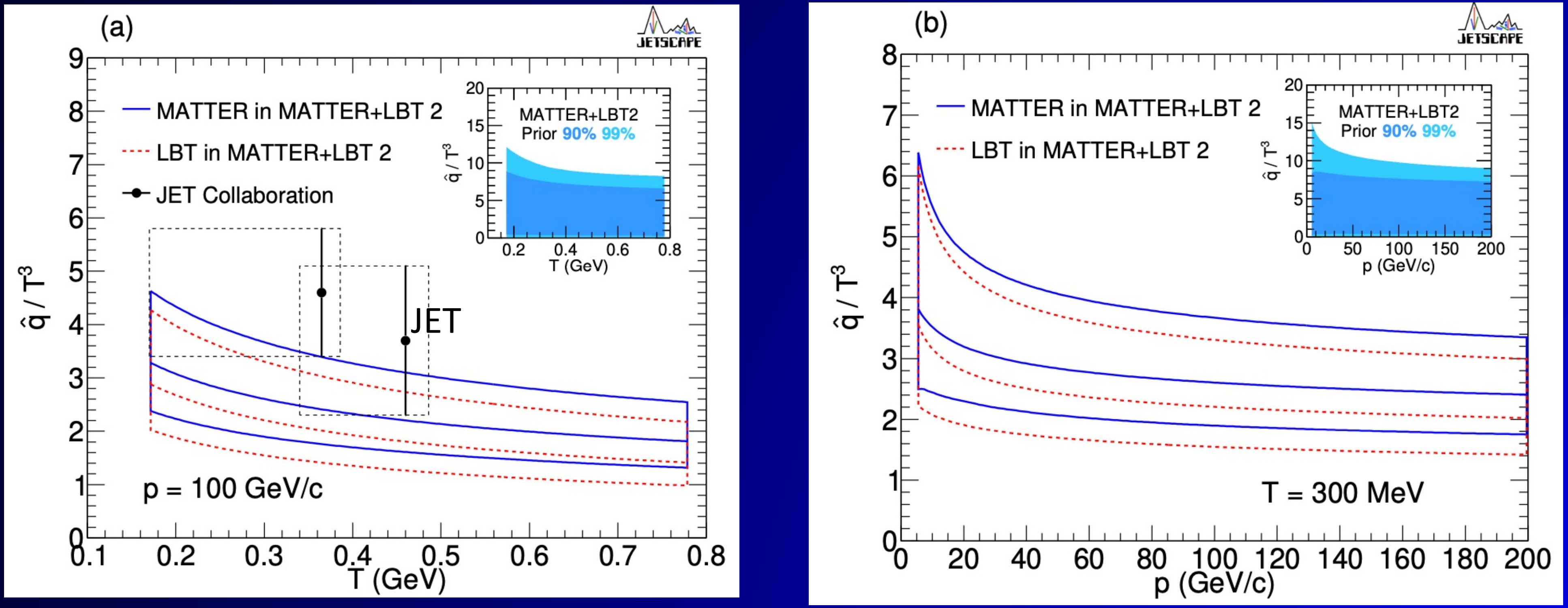
Jet transport coefficient

JETSCAPE: Combine the evolving Monte Carlo simulators and fluid dynamic models

Statistical analysis package using advanced Bayesian techniques (MADAI)



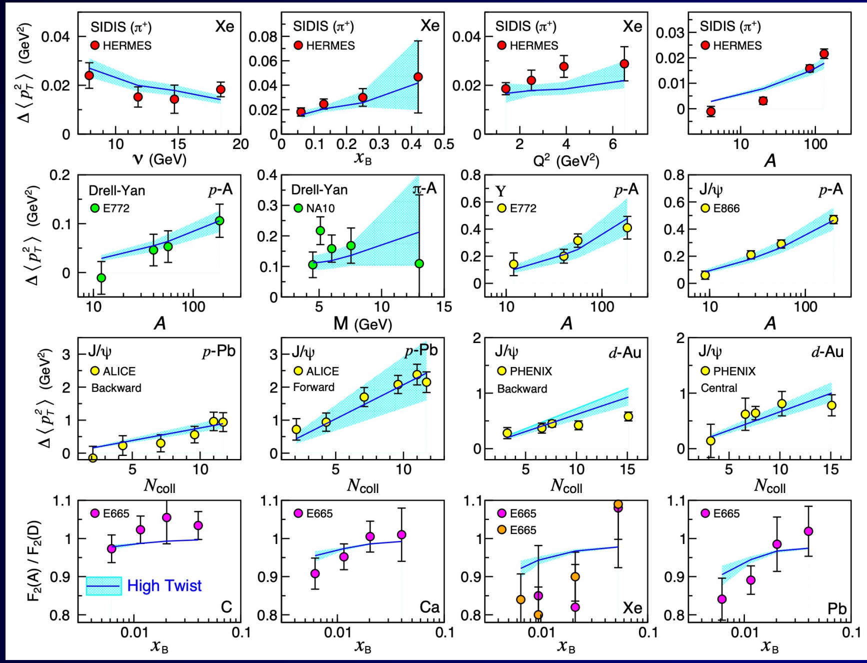
JET: *Phys. Rev. C* 90 (2014) 1, 014909

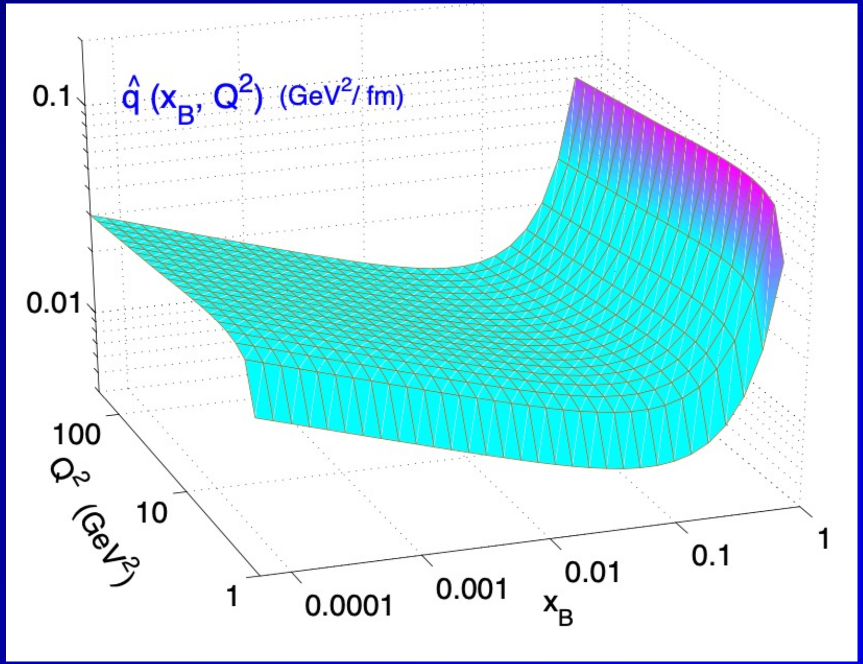
JETSCAPE: e-Print: 2102.11337

Jet transport coefficient in nuclei

A global extraction of the jet transport coefficient in nuclei

$$\hat{q}_0 \approx 0.02 \ \ \mathrm{GeV}^2/\mathrm{fm}$$





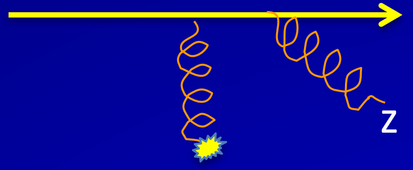
Data on: DIS, SIDIS(π), Drell-Yan, J/ψ (pA), Υ (pA)

Ru, Kang, Wang, Xing & Zhang *PRD* 103 (2021) 3, L031901 Yuanyuan Zhang & XNW 2104.04520

Suppression of leading hadrons

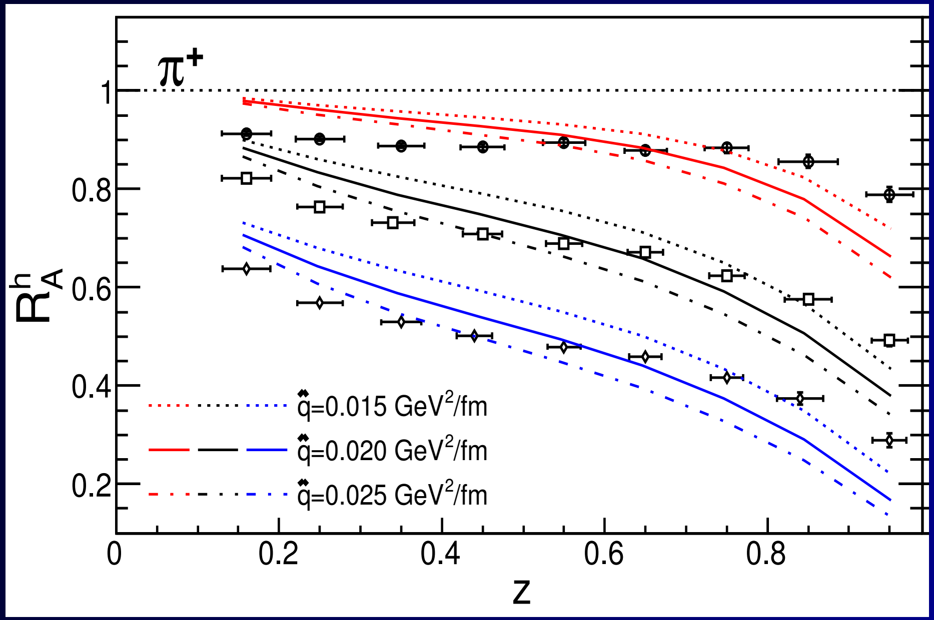
Medium induced splitting function (fractional energy loss distribution)

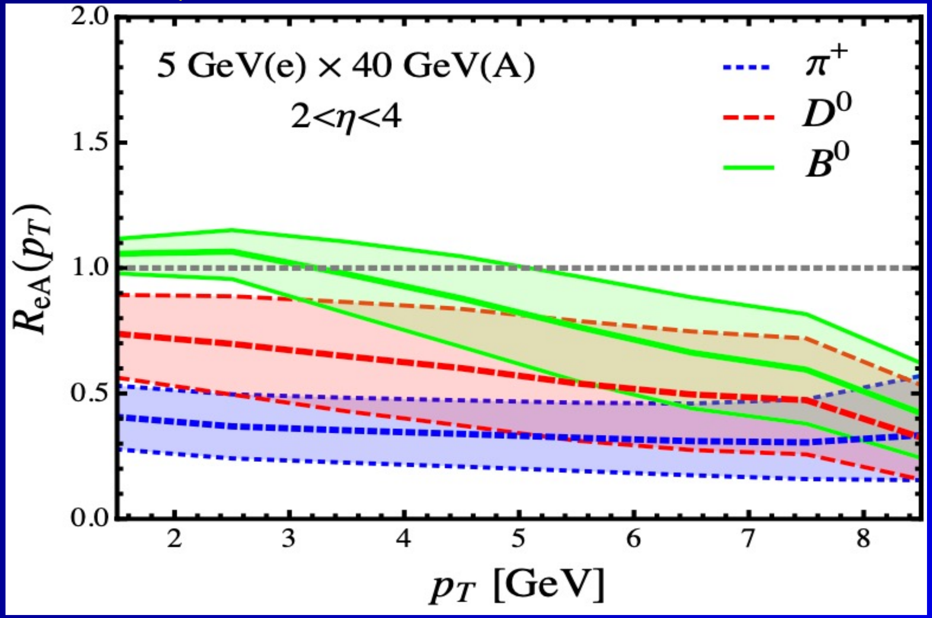
$$\Delta\widetilde{P}_{a\to ag}(z) \approx \frac{2C_A\alpha_s}{\pi}\int dx\hat{q}(x)\int\frac{d\ell_\perp^2}{\ell_\perp^4}P(z)\sin^2\frac{\ell_\perp^2(x-x_0)}{4z(1-z)E}$$



Modified frag function & hadron spectra: $\widetilde{D}_{c/h}(z_h) \approx [P_{a\to ag}(z) + \Delta\widetilde{P}_{a\to ag}(z)] \otimes D_{a/h}(z_h)$

$$\hat{q}_0 \approx 0.02\ \text{GeV}^2/\text{fm}$$

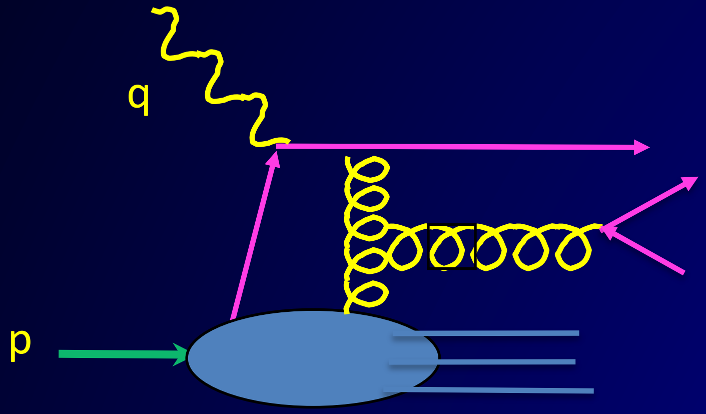




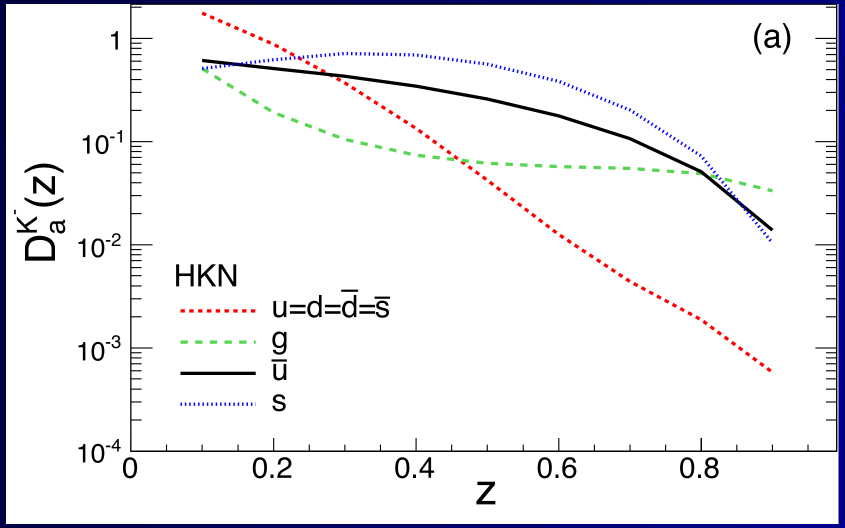
Chang, Deng & XNW *PRC* 89 (2014) 3, 034911

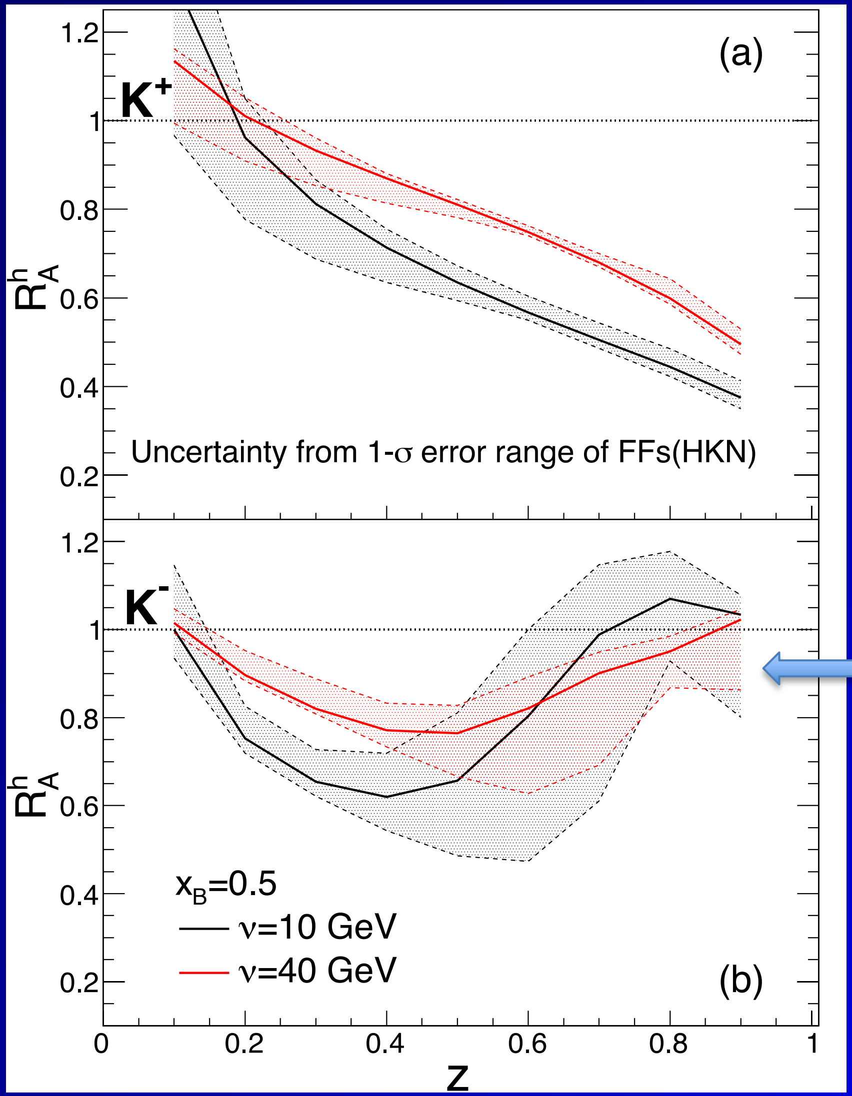
Li, Liu & Vitev, *PLB* 816 (2021) 136261

Flavor conversion in eA SIDIS



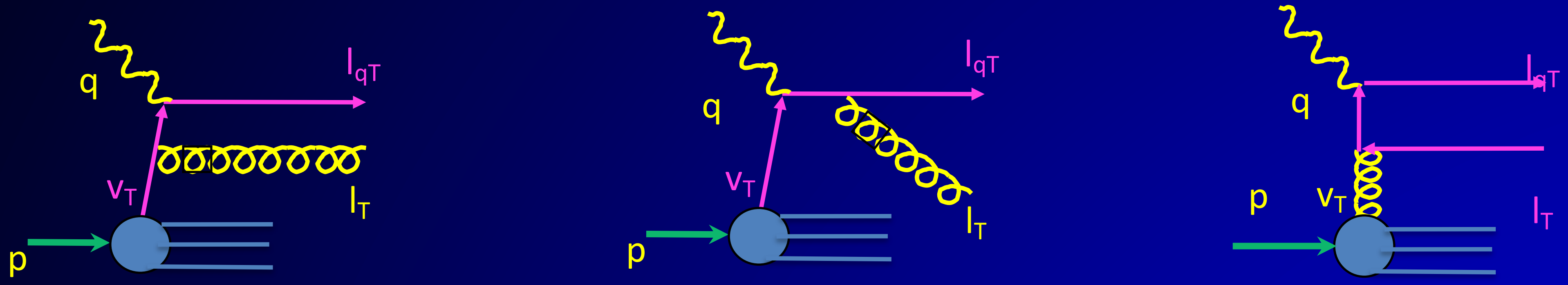
Chang, Deng & XNW, PRC 92 (2015) 5, 055207





enhancement

Dijets production in DIS



TMD quark distribution: $f_q^A(x_B, \vec{v}_\perp)$

$$v_\perp = |\vec{l}_\perp + \vec{l}_{q\perp}|$$

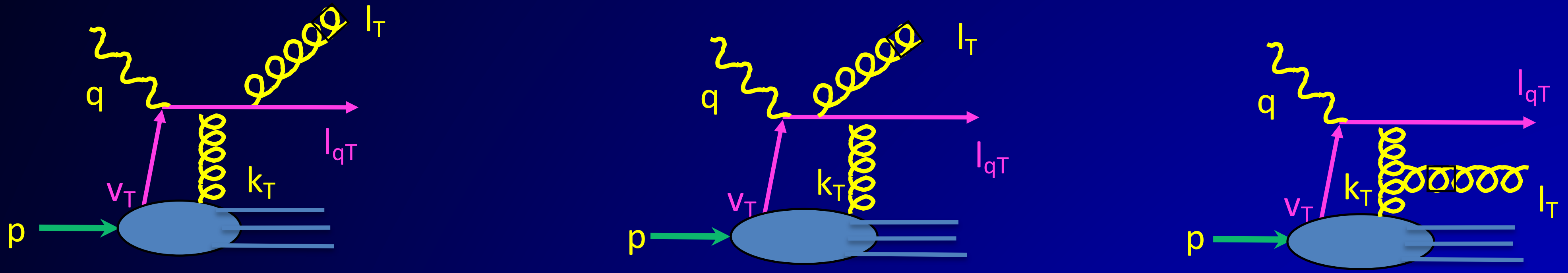
$$\sqrt{l_\perp^2 + l_{q\perp}^2 + 2 l_\perp l_{q\perp} \cos \Delta\phi}$$

LO leading order contribution at large x_B

$$\frac{d\hat{\sigma}_S}{dx_B dQ^2 dz d^2 l_\perp d^2 l_{q\perp}} = \sigma_0 \frac{\alpha_s}{2\pi} \frac{1+z^2}{1-z} f_q^A(x_B, \vec{v}_\perp) \frac{C_F}{[\vec{l}_\perp - (1-z)(\vec{l}_\perp + \vec{l}_{q\perp})]^2}$$

Angular correlation of dijets with fixed l_T and l_{qT}

Dijets from double scattering in EIC



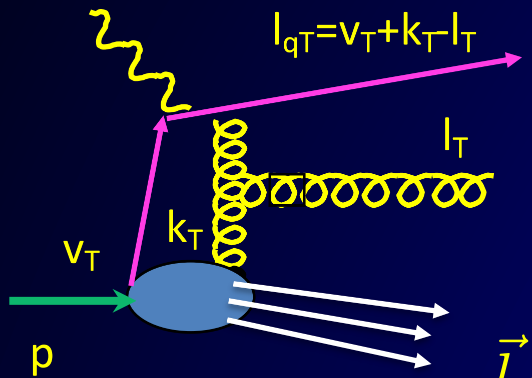
$$\frac{d\hat{\sigma}_D}{dx_B dQ^2 dz d^2 l_\perp d^2 l_{q\perp}} = \sigma_0 \frac{1+z^2}{1-z} \frac{\alpha_s^2}{N_c} \int dy_1^- \rho(y_1^-, \vec{y}_{N\perp})\, d^2\vec{v}_\perp \frac{d^2\vec{k}_\perp}{(2\pi)^2} \underline{f_q^A(x_B, \vec{v}_\perp) \frac{\phi(0,\vec{k}_\perp)}{k_\perp^2}}$$

$$\otimes \delta^2(\vec{l}_\perp + \vec{l}_{q\perp} - \vec{k}_\perp - \vec{v}_\perp) \Big\{ C_F \mathcal{N}_{\mathrm{coh}}(\vec{l}_\perp, \vec{l}_{q\perp}, \vec{k}_\perp, \vec{v}_\perp)$$

$$+ \frac{1}{N_c} \mathcal{N}_{\mathrm{qLPM}}(\vec{l}_\perp, \vec{l}_{q\perp}, \vec{k}_\perp, \vec{v}_\perp) \left(1 - \cos \frac{[\vec{l}_\perp - (1-z)\vec{v}_\perp]^2}{2p^+ q^- z(1-z)} p^+ y_1^- \right)$$

$$+ C_A \mathcal{N}_{\mathrm{gLPM}}(\vec{l}_\perp, \vec{l}_{q\perp}, \vec{k}_\perp, \vec{v}_\perp) \left(1 - \cos \frac{[\vec{l}_\perp - (1-z)\vec{v}_\perp - k_\perp]^2}{2p^+ q^- z(1-z)} p^+ y_1^- \right) \Big\}$$

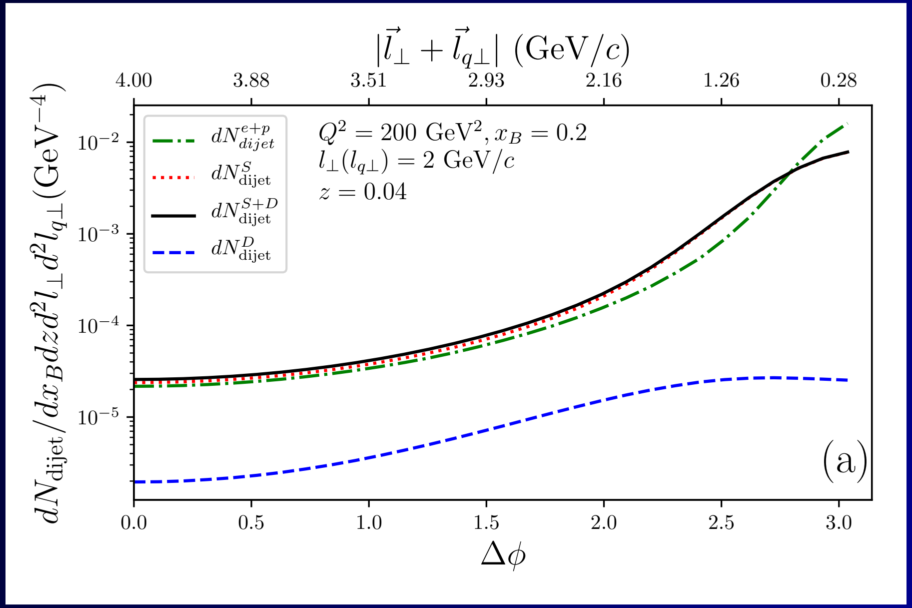
Nuclear modification of dijets & TMD pdf at EIC



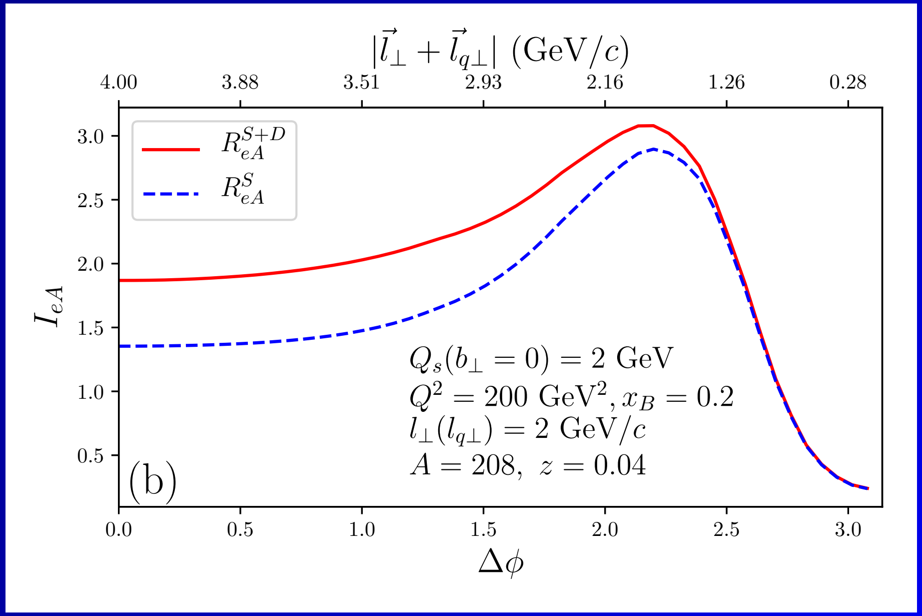
$$\frac{d\hat{\sigma}_D}{dx_B dQ^2 dz d^2l_\perp d^2l_{q\perp}} = \sigma_0 \frac{1+z^2}{1-z}\frac{\alpha_s^2}{N_c}\int dy_1^- \rho(y_1^-, \vec{y}_{N\perp})$$

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

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



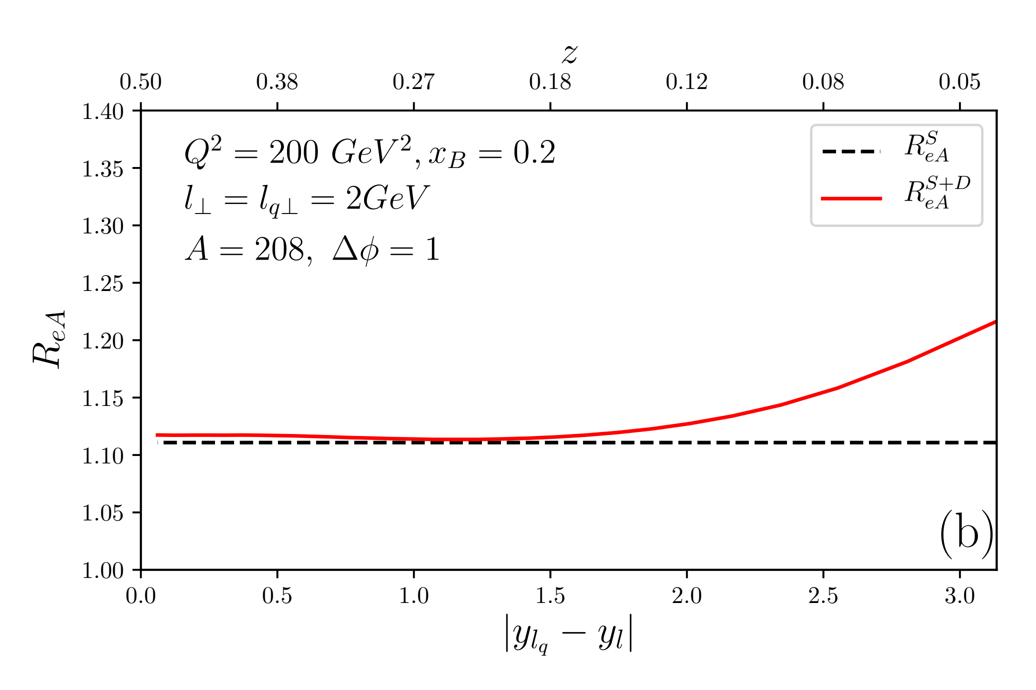
$\Delta\sigma_{e+Pb}/A\sigma_{e+p}$

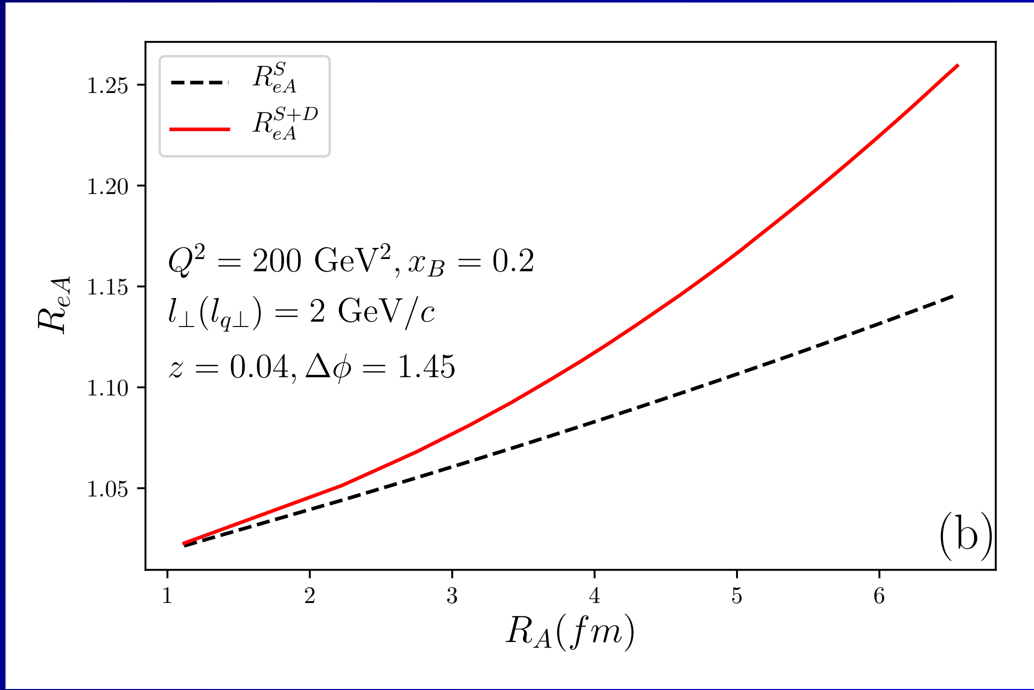


Yuanyuan Zhang & XNW 2104.04520

LPM interference and rapidity & R_A dependence

Gluon splitting formation time: $$\tau_f = \frac{2Ez(1-z)}{(\vec{l}_\perp - (1-z)\vec{v}_\perp - \vec{k}_\perp)^2}$$

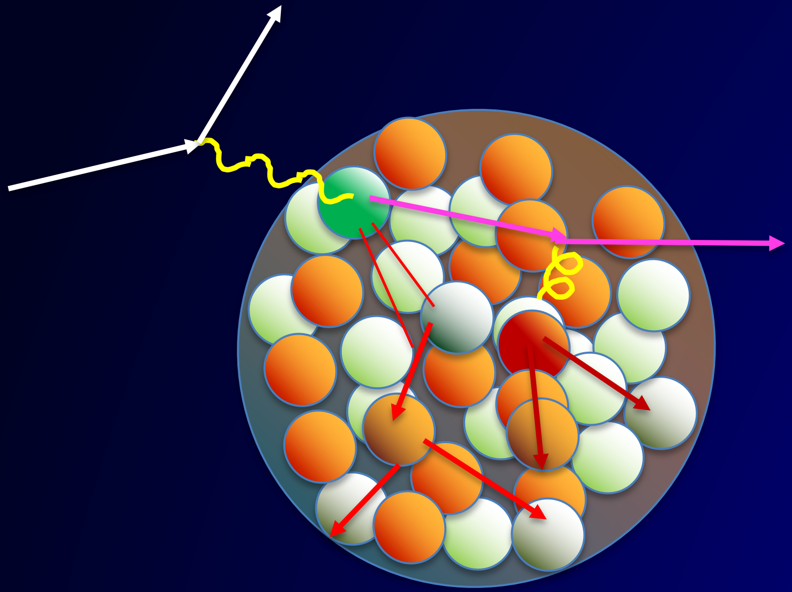




Dijet rapidity gap: $$\Delta y = \log\frac{z}{1-z}$$

Quadratic nuclear-size dependence due to LPM interference $$\frac{\Delta\sigma_{e+A}}{A\sigma_{e+p}} \propto A^{2/3}$$

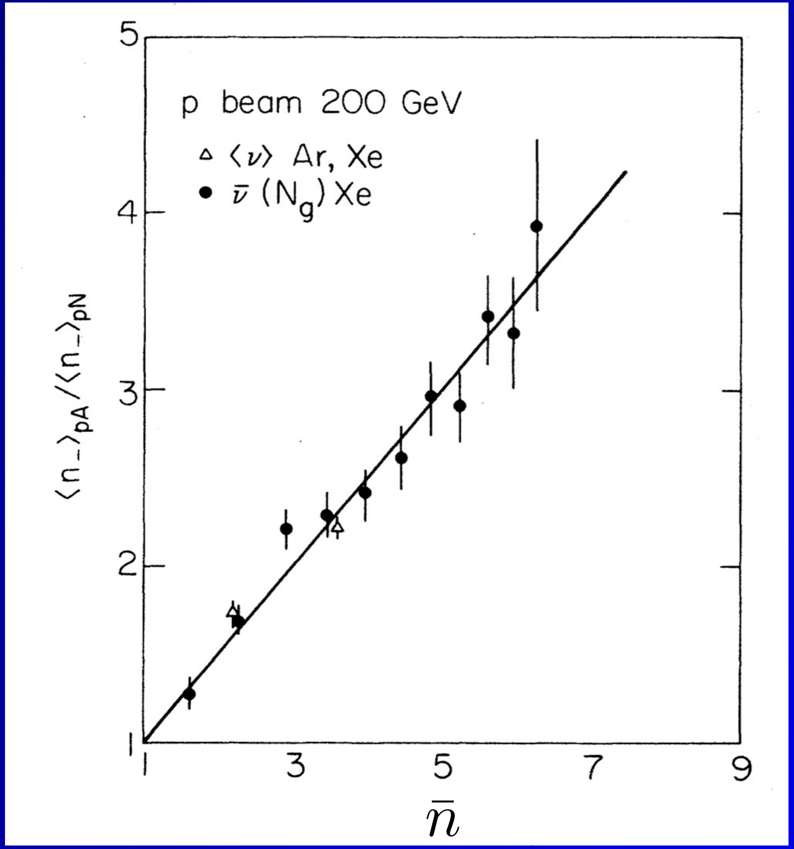
Medium response in nuclei: grey particles



Grey particles: slow recoiling target nucleons due to multiple interaction inside the nucleus

N_{grey} as a trigger for the number of scattering

$$\bar{n} \approx \frac{A\sigma_N}{\sigma_A}\left(\frac{N_{grey}}{\langle N_{grey}\rangle}\right)^{1/2}$$



$$P_n = \binom{N_{grey}+n-1}{N_{grey}} X^{N_{grey}}(1-X)^n$$

$$X = \frac{\langle N_{grey}\rangle}{\langle n\rangle + \langle N_{grey}\rangle} \qquad \langle n\rangle = \frac{A\sigma_N}{\sigma_A}$$

Hwa & XNW, PRD39, 2561 (1989)

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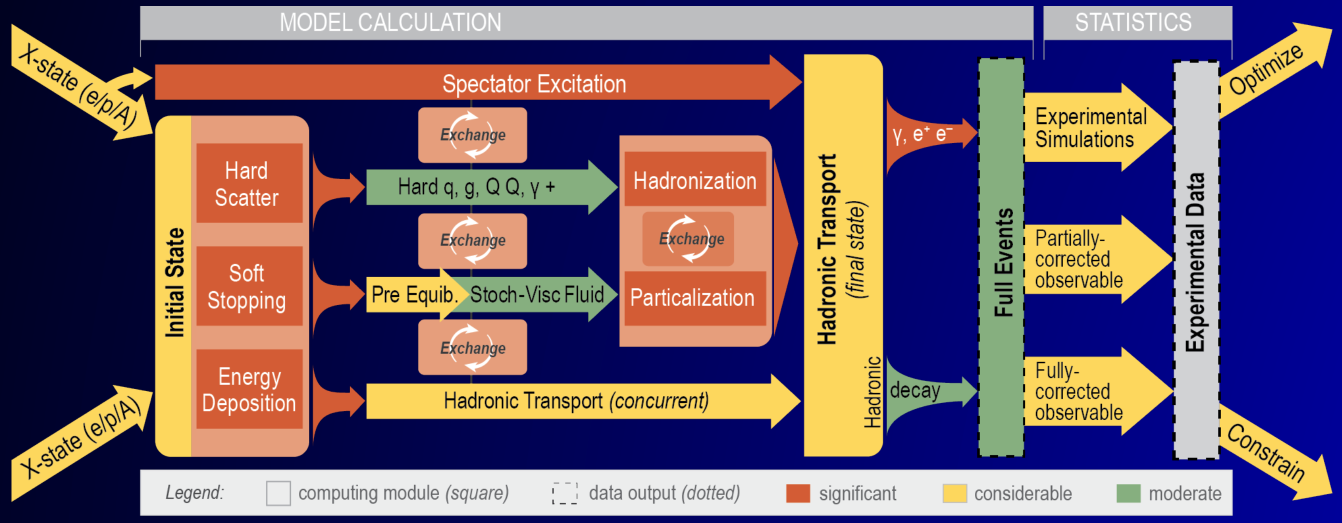
e-HIJING (electron Heavy-Ion Jet INteraction Generator)

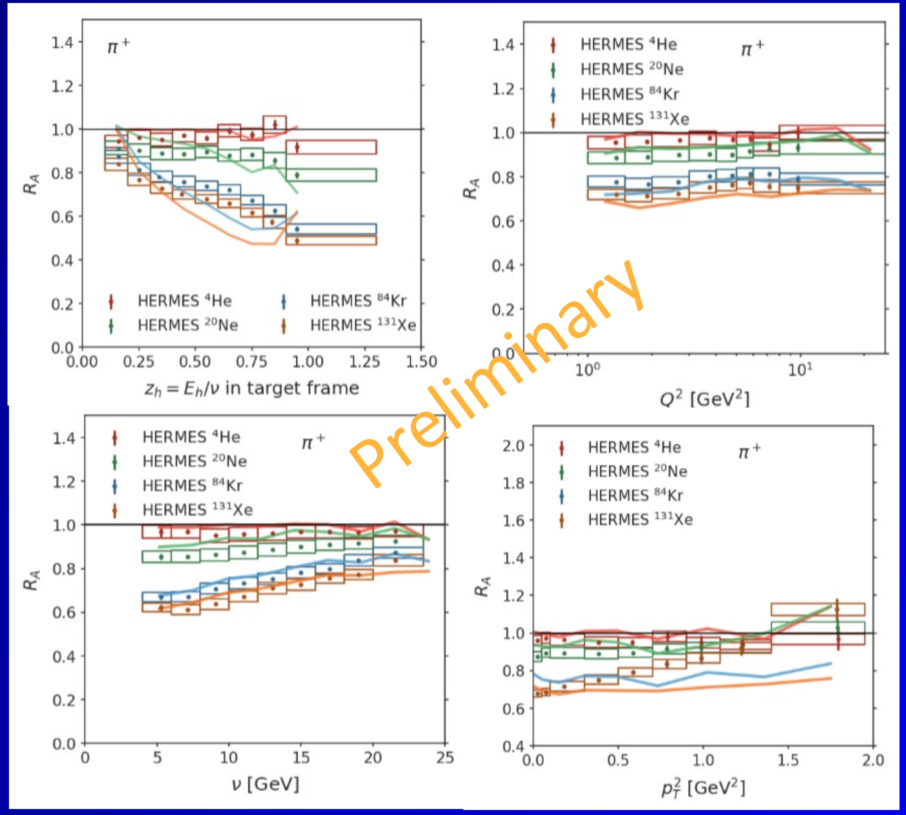
Weiyao Ke (UCB/LBNL), Yayun He (SCNU), Hongxi Xing (SCNU) & XNW

Gluon saturation initial TMD PDF → DIS → Multiple scattering in parton propagation → Fragmentation & Hadronization → Hadron propagation

TMD $\hat{q}$ in nuclei TMD high-twist



XSCAPE



Summary

- Many similarities between jet transport in QGP and cold nuclei
- Generalized high-twist approach for both
  - Jet transport coefficient is related to gluon distribution density in medium
  - LPM effect in induced gluon bremsstrahlung
- Differences
  - qhat = 1-2 GeV^2/fm vs qhat=0.02 GeV^2/fm in large nuclei
  - Jet induced QGP response vs recoiling nucleons inside nuclei
- Jet medium interaction leads to flavor conversion in SIDIS
- Modification of dijets at EIC can provide information about TMD parton distributions in nuclei

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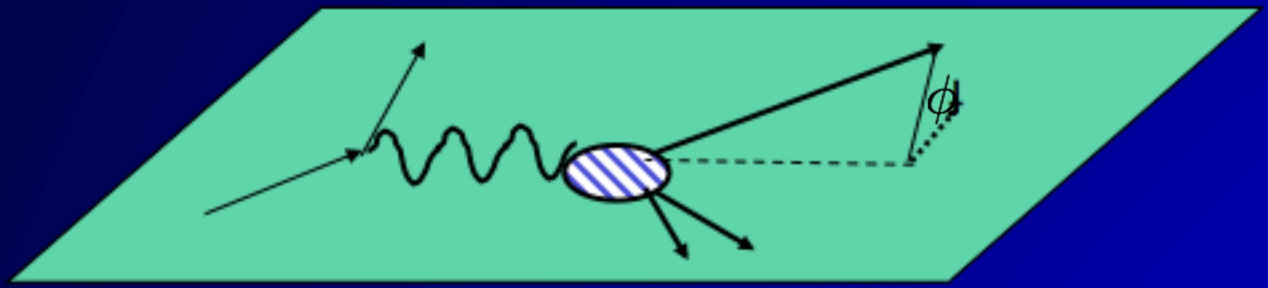
Azimuthal Asymmetry

Gao, Liang & XNW（2010）

$$\langle \cos\phi\rangle_{eA} = \frac{2(2-y)\sqrt{1-y}}{1+(1-y)^2}\frac{k_T}{Q}\frac{x_B f^q_{A\perp}(x_B,k_T)}{f^q_A(x_B,k_T)} \qquad k_T \ll Q$$



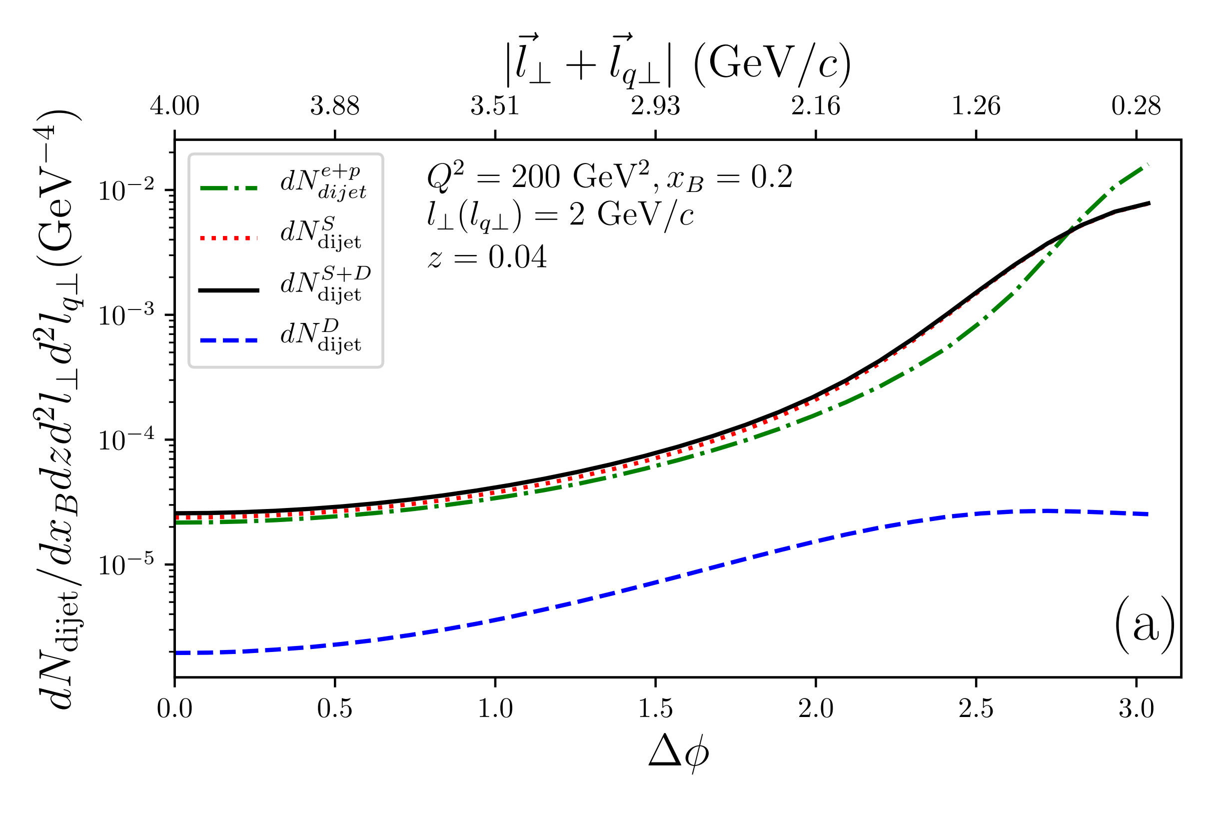
Twist-3 quark matrix elements

$$f^q_{A\perp}(x,k_T) = p^+\int \frac{dy^-}{4\pi}\frac{d^2y_\perp}{(2\pi)^2} e^{ixp^+y^- - i\vec{k}_\perp\cdot\vec{y}_\perp}\langle A|\bar{\psi}(0)\frac{\gamma\cdot k_T}{k_T^2}\mathcal{L}(0,y)\psi(y)|A\rangle$$

$$\frac{\langle\cos\phi\rangle_{eA}}{\langle\cos\phi\rangle_{eN}} \approx \sqrt{\frac{\langle k_T^2\rangle_N}{\langle k_T^2\rangle_N + \Delta}}$$

LO dijet angular correlation

$$\frac{d\hat{\sigma}_S}{dx_B dQ^2 dz d^2 l_\perp d^2 l_{q\perp}} = \sigma_0 \frac{\alpha_s}{2\pi} \frac{1+z^2}{1-z} f_q^A(x_B, \vec{v}_\perp) \frac{C_F}{[\vec{l}_\perp - (1-z)(\vec{l}_\perp + \vec{l}_{q\perp})]^2}$$



Jet quenching in heavy-ion collisions