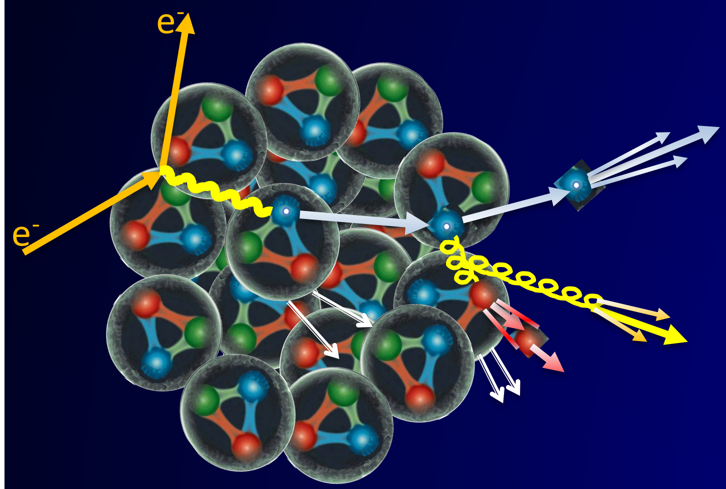
SURGE Collaboration meeting and workshop, June 28-30, 2023

Overview of the Final State WG



Xin-Nian Wang
Lawrence Berkeley National Laboratory

Final State WG: Physics goals and timelines

Physics focus:

- p_T broadening and medium-induced bremsstralung
- Hadronization in a dense gluon environment
- Final state hadronic interaction

Members:

- Faculty: Jaki Noronha-Hostler, Zhongbo Kang, Dima Kharzeev , Alex Kovner, Bjoern Schenke, Vladmir Skokov, Xin-Nian Wang
- Postdoc: Weiyao Ke, Farid Salazar, Wenbin Zhao
- Student: Jordi Salinas

Welcome joining our Final State WG

Final State WG: Physics goals and timelines

Year 1:

- Explore improved hadronization prescriptions for dense gluon environments (BS);
- Formulate multiple parton interaction and induced gluon bremsstrahlung within generalized high-twist or opacity approach. Find out the connection to the gluon saturation processes in the initial state (XW)

Year 2:

- Model TMD gluon distributions inside nuclei consistent with saturation picture to use in transverse momentum broadening and induced gluon bremsstrahlung (XW);
- Provide first hadron level results in processes in e+A and p+A collisions using simplified color flow and study systematic uncertainties (BS)
- Implement improved descriptions of hadronization in dense media via modification of vacuum calculations (BS)

Year 3:

- Implement multiple parton scattering and induced bremsstrahlung into a MC simulation of parton showering in nuclear medium with proper inclusion of the LPM interference (W)
- Consider the NLO corrections to the jet transport coefficient and the medium-induced gluon radiation with LPM effect (XW)
- Begin implementation of SMASH final state hadronic interactions with various ansatz for the interpolation between hadronic and partonic cross sections based on the formation times (JNH)

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Final State WG: Physics goals and timelines

Year 4:

- Develop and validate the Monte Carlo code for final state effects and combine it with the hadronization scheme(s); Combine all components into one final state package ranging from sampling partonic cross sections, MC description of final state effects and hadronization, to hadronic rescattering (JNH, BS, VS, XW)
- Incorporate smooth transitions from partonic cross sections into hadronic cross sections using SMASH (JNH)

Year 5:

- Finalize final state and hadronization framework and make it user-friendly; Study the effect of transverse momentum broadening, induced gluon bremsstrahlung and final hadronic interaction in the final hadron spectra, investigate how to disentangle these effects from the initial state gluon saturation (JNH, BS, XW)
- Produce final state results for processes in different collision systems. Study systematic uncertainties of the complete calculation (JNH, FO, BS, XW)
- Incorporate cold nuclear matter effects, e.g. 2-body interactions in SMASH (JNH)

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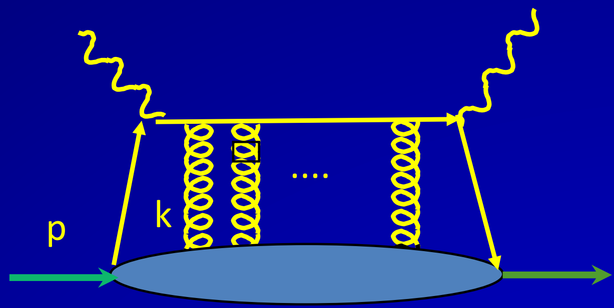
Multiple parton scattering in nuclear medium

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



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

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

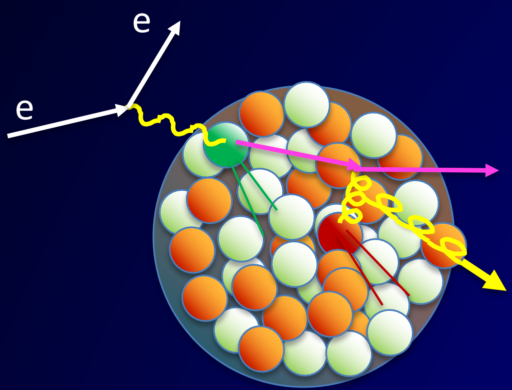
p_T broadening and Jet transport coefficient:

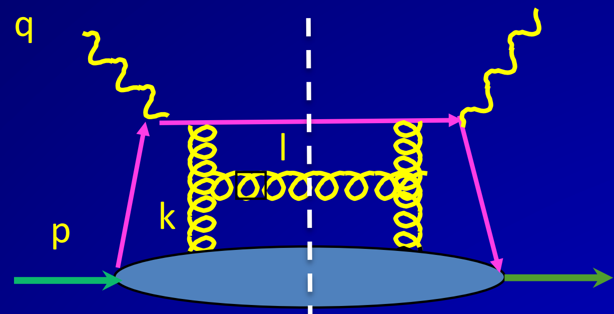
$$\hat{q}(y) = \frac{4\pi^2 C_A}{N_c^2 - 1}\rho(y)\int \frac{d^2k_\perp}{(2\pi)^2}\alpha_s(\mu)\phi(x_G, k_\perp, \mu^2), \quad \longleftrightarrow \quad Q_s^2 = \int dy \hat{q}(y)$$

$$x_G = \frac{x_B k_\perp^2}{Q^2}$$

Saturation scale probed by jet

Parton energy loss in generalized high-twist approach





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.

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

⟶ GLV

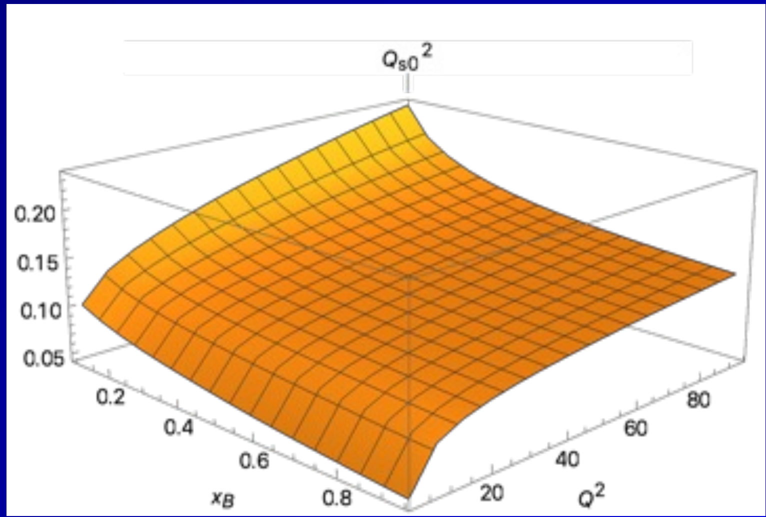
τ_f Formation time of the gluon emission y_1^-/τ_f

Gluon Saturation and qhat in cold nuclei

Yuanyuan Zhang & XNW 2104.04520

$$Q_s^2(x_B, Q^2, b_\perp) = \frac{4\pi^2 C_A}{N_c^2 - 1} t_A(b_\perp) \int \frac{d^2 k_\perp}{(2\pi)^2} \alpha_s(\mu) \phi(x_G, k_\perp, \mu^2),$$

$$\phi(x_G, k_\perp, \mu^2) = \begin{cases} \phi^0(\frac{Q_s^2}{Q^2} x_B, Q_s, \mu^2)|_{\mu^2 = Q_s^2}, k_\perp < Q_s; \\ \phi^0(x_G, k_\perp, \mu^2)|_{\mu^2 = k_\perp^2}, \quad k_\perp > Q_s, \end{cases}$$



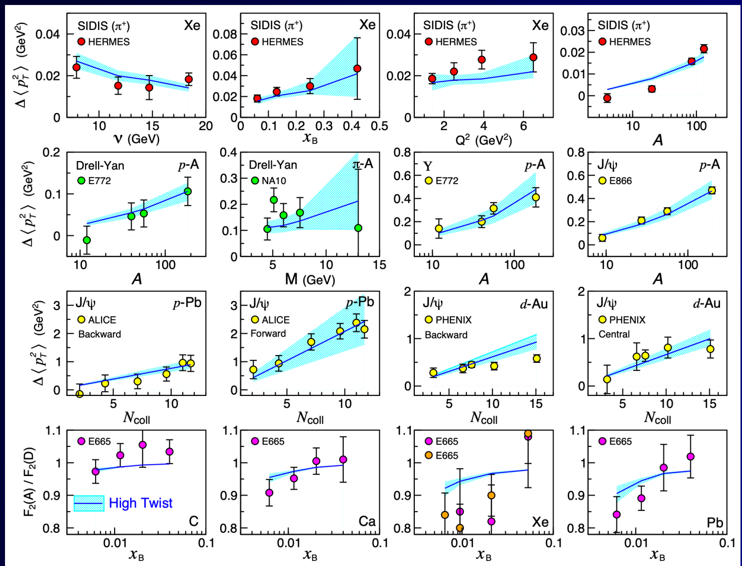
$$Q_s^2(x_B, Q^2, b_\perp) \equiv \int dy^- \hat{q}_A(y^-)$$

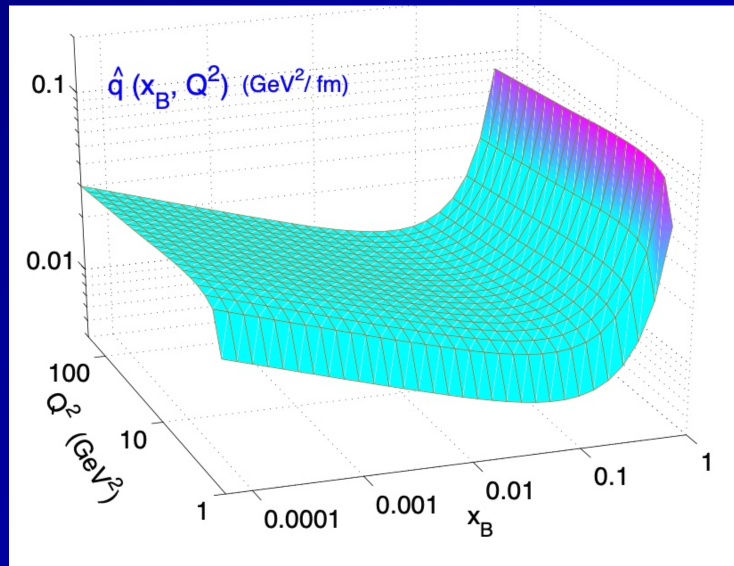
$$\approx Q_{s0}^2(x_B, Q^2) A^{1/3} \sqrt{1 - \frac{b_\perp^2}{R_A^2}}$$

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

eHIJING: electron Heavy Ion Jet Interaction Generator

Ke, Zhang, Xing & XNW e-Print: 2304.10779

HIJING

- Pythia for γ^*+N → jet shower processes
- Simple model for saturation in gluon TMD distribution
- Elastic scattering with TMD distr.

$$\alpha_s \phi_g(x_g, k_\perp^2, Q^2) = \frac{(1-x_g)^p x_g^\lambda}{q_\perp^2 + Q_s^2},$$

- Induced gluon emission

Kharzeev & Levin PLB 523 79-87]

$$\frac{dN_g}{dz dl_\perp^2} = \frac{P_{qg}^0(z)}{l_\perp^2}\left\{1 + \tilde{T}_A \int_0^L dt^+ \int \frac{d^2 k_\perp}{\pi} \frac{\alpha_s \phi_g(x_g, k_\perp^2)}{k_\perp^2} \frac{2\vec{k}_\perp \cdot \vec{l}_\perp}{(\vec{l}_\perp - \vec{k}_\perp)^2}\left[1 - \cos\frac{t^+}{\tau_f}\right]\right\}$$

- Multi-scale evolution for multiple gluon emission
  – Q^2, Q_s^2, μ_0^2

$$\alpha_s \phi_g(x_g, k_\perp^2, Q^2) = \frac{(1-x_g)^p x_g^\lambda}{q_\perp^2 + Q_s^2},$$

- String hadronization

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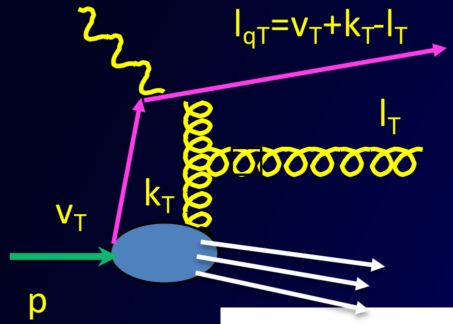
See Weiyao Ke's talk on Friday

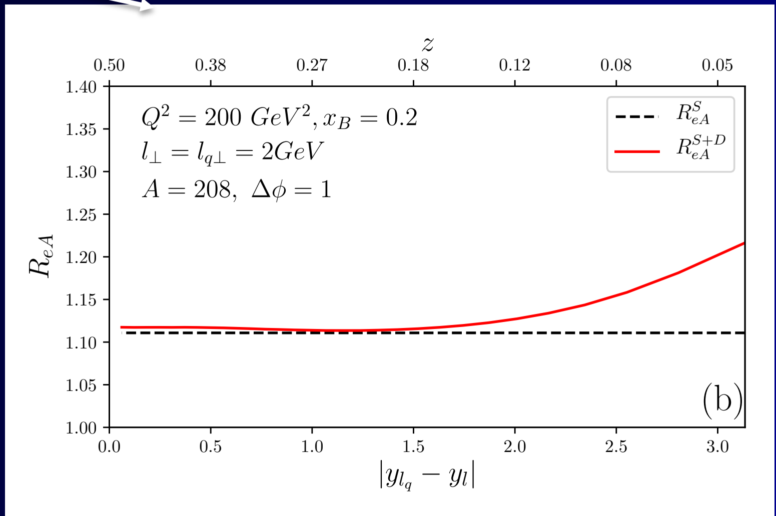
LPM interference and rapidity & R_A dependence

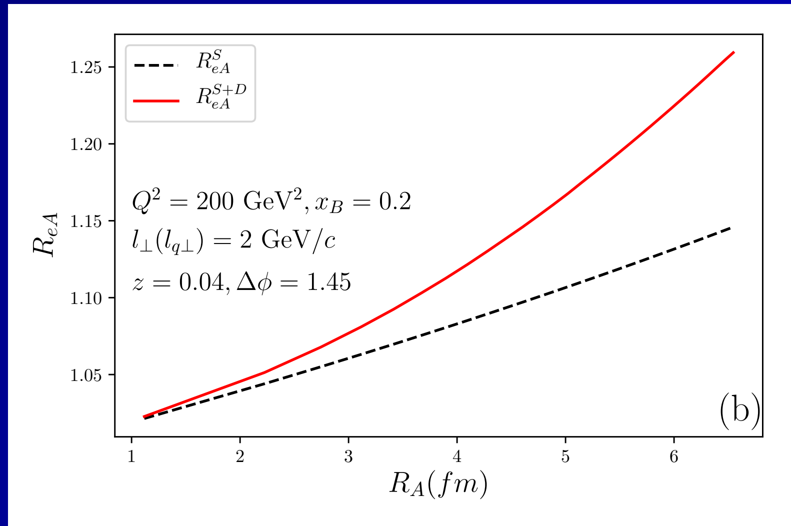


formation time: $\tau_f = \dfrac{2Ez(1-z)}{(\vec{l}_\perp - (1-z)\vec{v}_\perp - \vec{k}_\perp)^2}$

Nuclear enhancement of dijet or dihedron cross section

Zhang & XNW 2104.04520

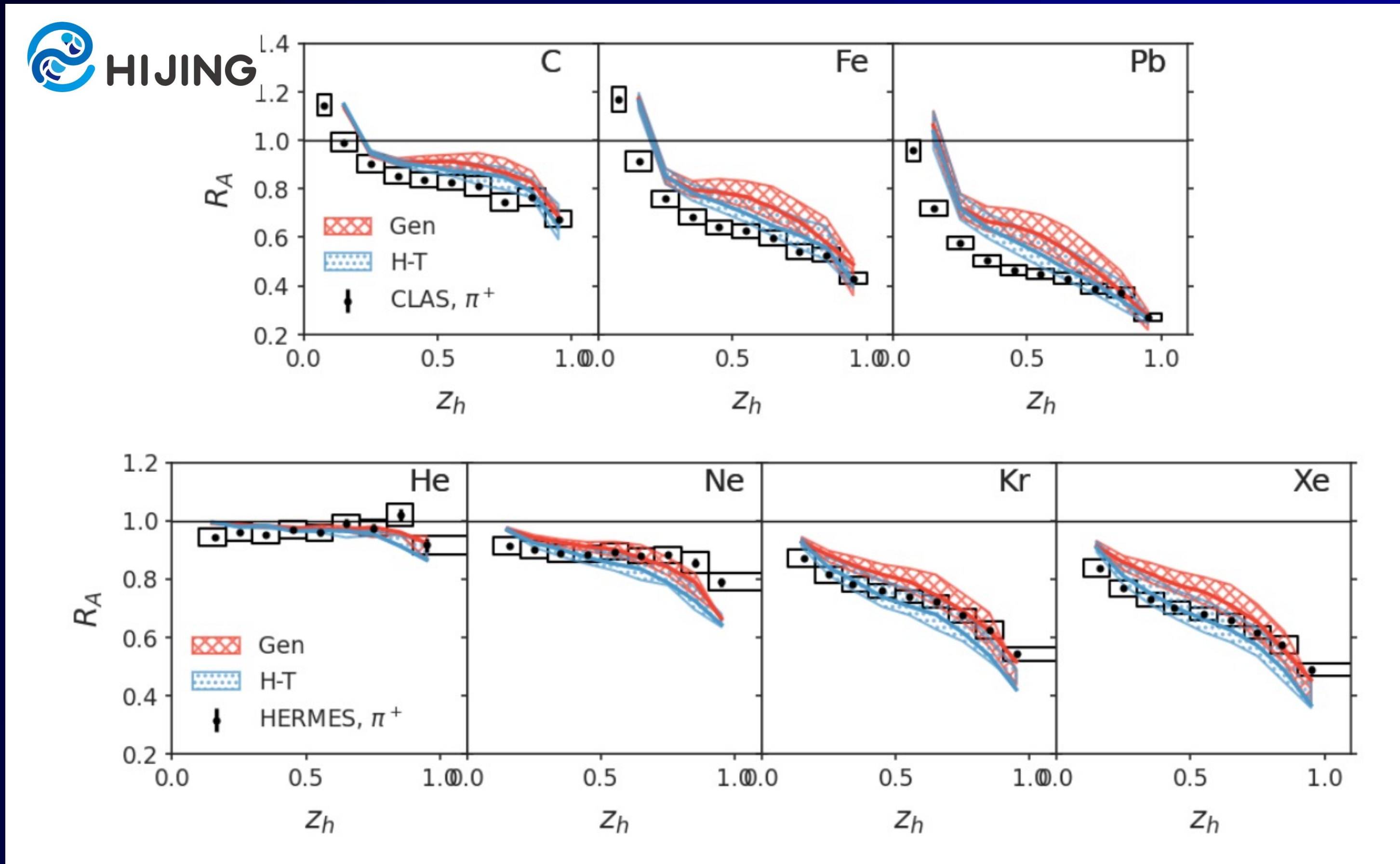




Dijet rapidity gap: $\Delta y = \log \dfrac{z}{1-z}$

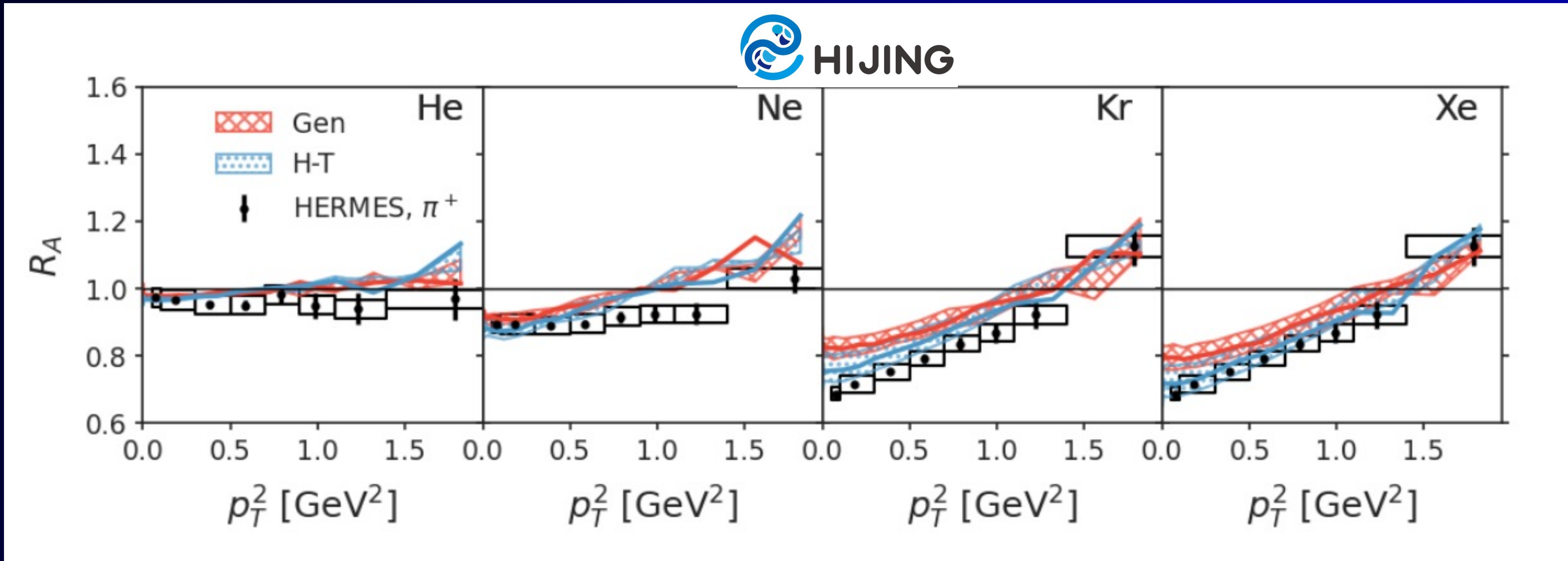
Quadratic nuclear-size dependence due to LPM interference $\dfrac{\Delta\sigma_{e+A}}{A\sigma_{e+p}} \propto A^{2/3}$

Suppression of single hadron spectra



Effect of hadron absorption in CLAS?

Transverse momentum broadening



modification of p_T spectra due to suppression of low p_T hadrons due to parton energy loss + p_T broadening

Hadronic rescattering in DIS eA

- Incorporate SMASH in eHIJING for final state hadronic rescattering
- Adopt the latest list of resonances (immediate states) from PDG
- Compare thermodynamics of HRG with LQCD results
- Time-dependent hadronic cross sections with formation time
- Test with on CLAS12 data at low energies

See talk by Jordi Salinas

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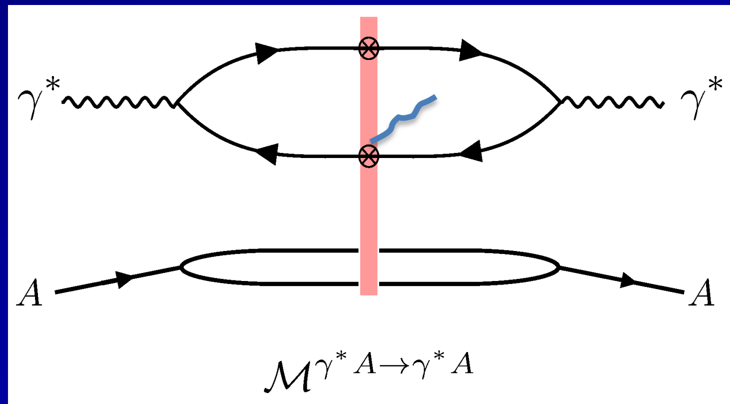
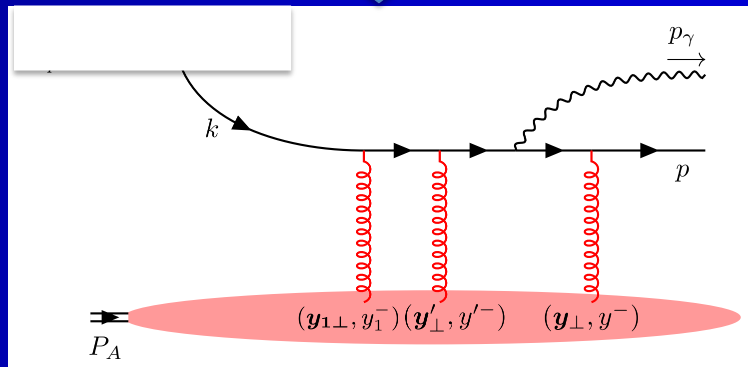
Next improvement of eHIJING

- Extension to small x_B
  - dipole approximation of multiple scattering
  - Initial state evolution: gluon saturation
  - LPM interference: finding back the phases

See Farid Salazar's talk

- Inclusion of final-state hadronic scattering
  - Adopt SMASH in eHIJING
  - Hadronization, Baryon junctions





Summary

- eHIJING
  - Multiple parton scattering in the final state
  - Modified DGLAP evolution with medium-induced emission
  - LPM effect in induced gluon bremsstrahlung
  - Validation with existing eA data
  - Next step: include dipole multiple scattering at small x_B
- Adopt SMASH for eHIJING
  - Latest list resonances from PDG
  - Next step: couple to eHIJING for final state hadronic interaction

Welcome joining our Final State WG