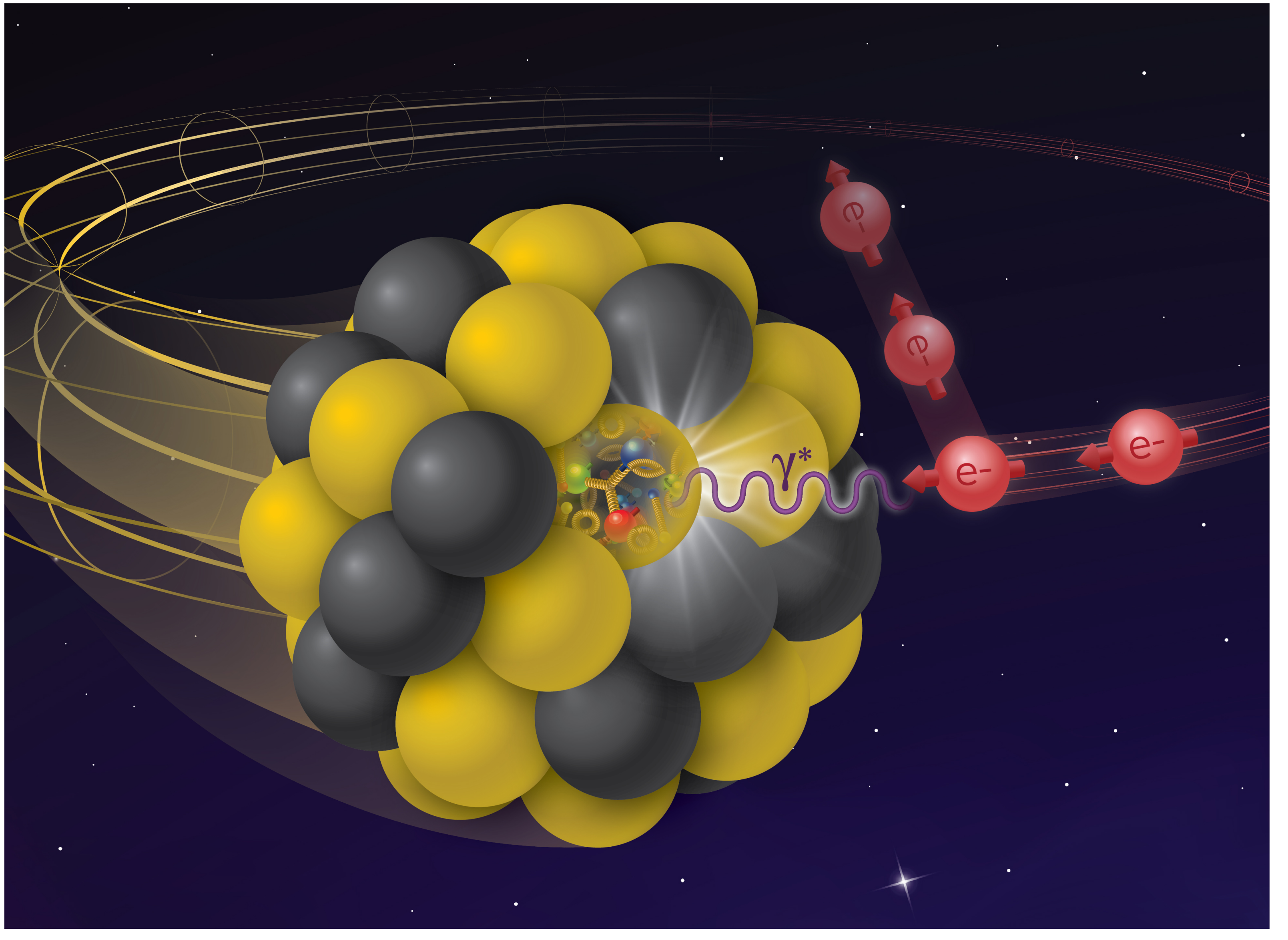


EIC science: eA reactions

Anna Staśto

Penn State University

2022 Town Hall meeting on Hot & Cold QCD, MIT, September 23 2022

What can be explored at EIC in eA collisions ?

Capabilities of EIC

Beams with different A: from **light nuclei** to the **heaviest nuclei**

Polarized electron and nucleon beams. Possibility of polarized light ions.

Variable center of mass energies 20 -140 GeV

High luminosity $10^{33} - 10^{34} cm^{-2} s^{-1}$

Physics with nuclear beams

How are parton distributions changed in nuclei ? Nuclear PDFs, neutron structure

How and when partons saturate in nuclei ? Parton saturation

How nucleons/nuclei stay intact in high energy collision?
What is the nature of color singlet exchange ? Diffraction and shadowing

How partons interact with nuclear medium ? Hadronization in medium

Nature of the strong force, correlations in nuclei ? EMC effect, short range correlations

Global structure of nuclei

$$Y_+ = 1 + (1-y)^2$$

$$\frac{d^2\sigma}{dx dQ^2} = \frac{2\pi\alpha_{\rm em}^2}{xQ^4}\, Y_+\, \sigma_{\rm r}(x,Q^2)$$

$$\sigma_{\rm r}(x,Q^2) = F_2(x,Q^2) - \frac{y^2}{Y_+} F_L(x,Q^2)$$

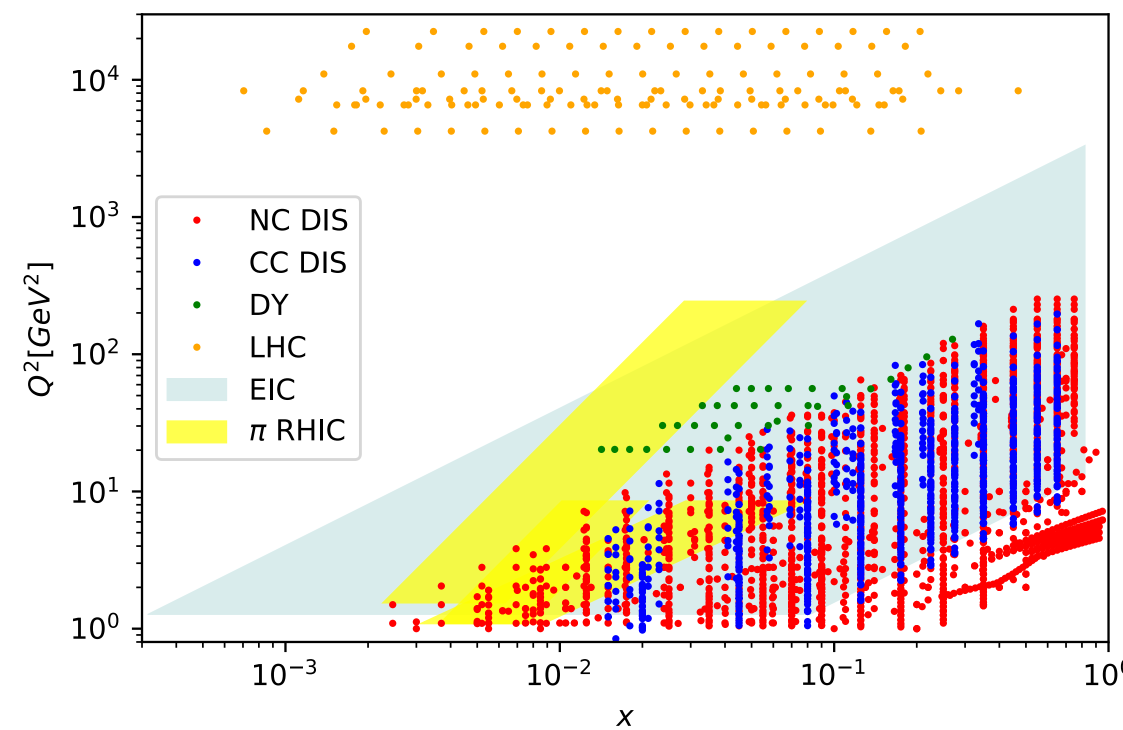
Precise measurement of **nuclear structure functions** for wide range of nuclei and **wide kinematic range**

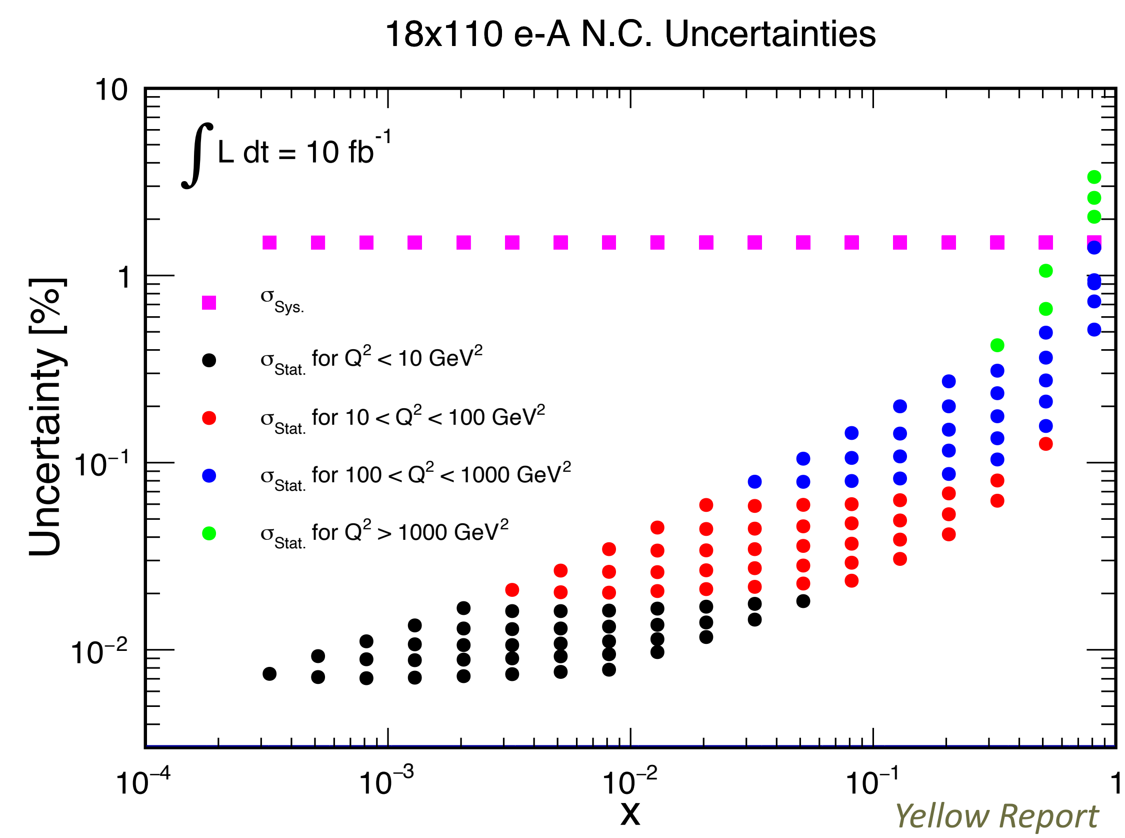
Extraction of **nuclear PDFs** which are essential for understanding **nuclear structure**

Initial conditions for Quark-Gluon Plasma

Sys. uncertainties at most few %, stat. negligible

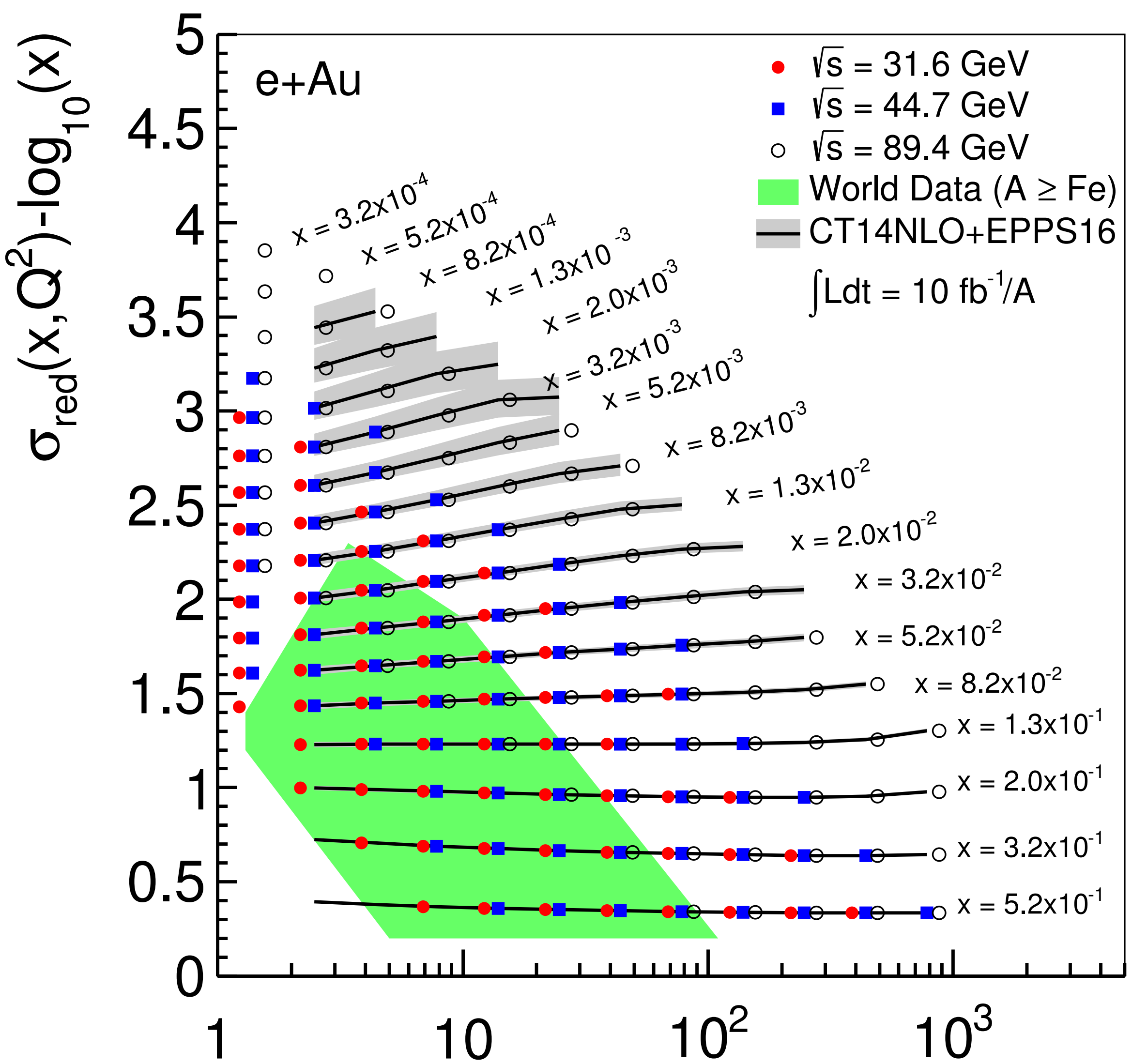
Proton, deuteron and wide range nuclei structure function within **one facility:** reduction of uncertainties



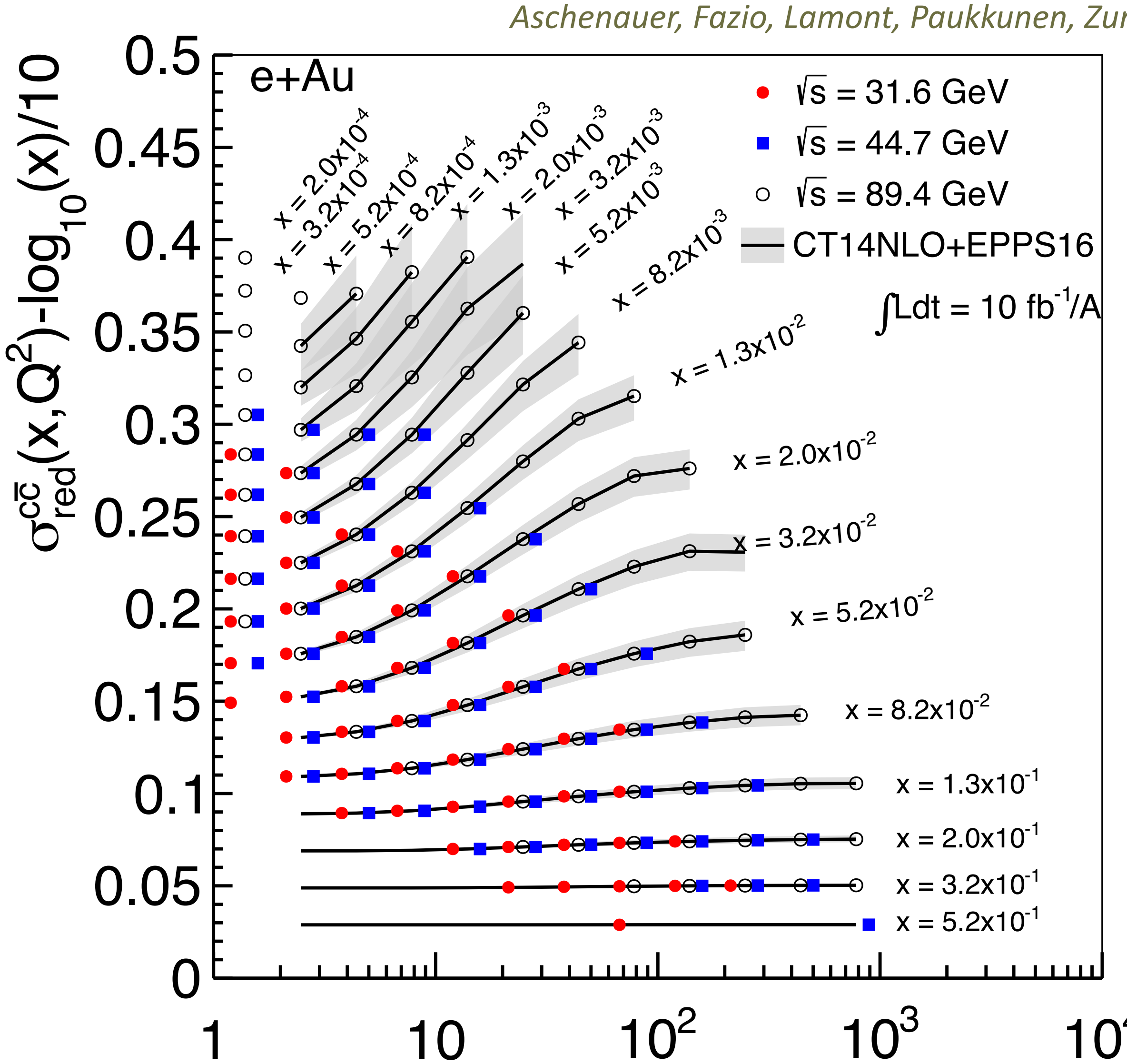


Global nuclear structure: structure functions

Aschenauer, Fazio, Lamont, Paukkunen, Zurita



Inclusive



Charm

Precision measurements of the reduced cross section: inclusive and charm component in nuclei
Errors much smaller than the uncertainties of QCD predictions

Impact of EIC on nuclear PDFs

Collinear factorization

$$F_{2,L}(x,Q^2) = \sum_j \int_x^1 dz\, C_{2,L}(Q/\mu, x/z; \alpha_s)\, f_j(z,\mu) + \ldots$$

DGLAP evolution : linear evolution with scale

$$\frac{d}{d\ln\mu^2} f_j(z,\mu) = \sum_k \int \frac{d\xi}{\xi} P_{jk}(\xi,\alpha_s) f_k(z/\xi,\mu)$$

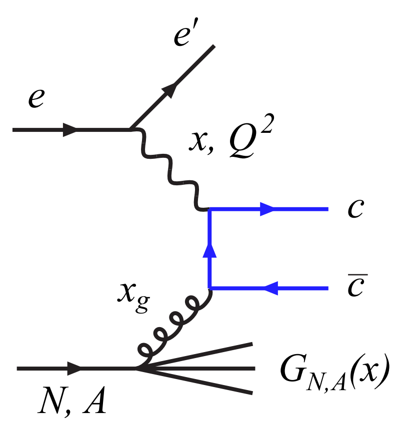
Nuclear modification in this framework:

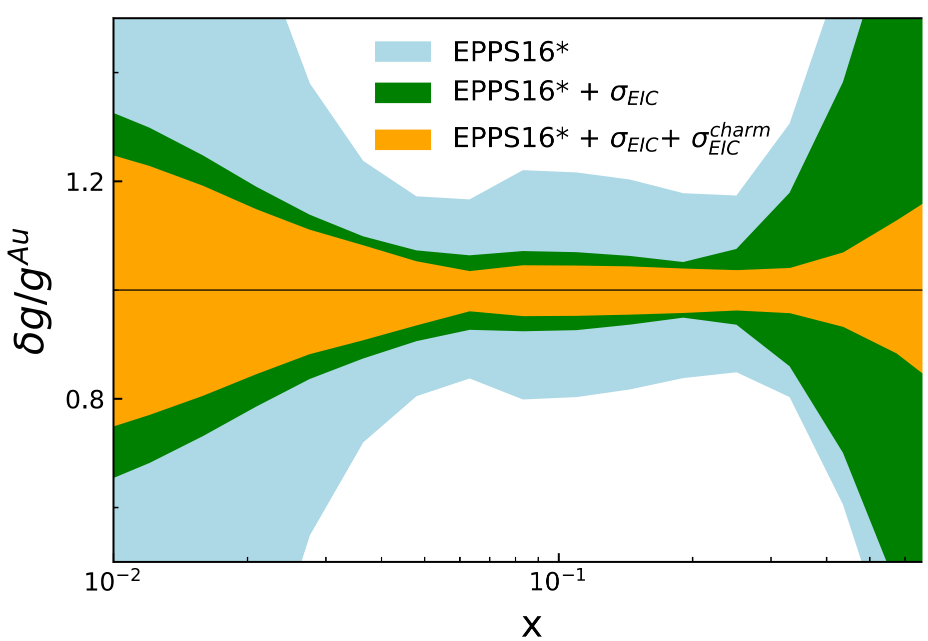
initial condition at low scales, **linear evolution with scale**

Impact of **charm cross section** on the gluon PDF at high x

Charm is produced mainly in the photon-gluon fusion process

Further constraints: F_L





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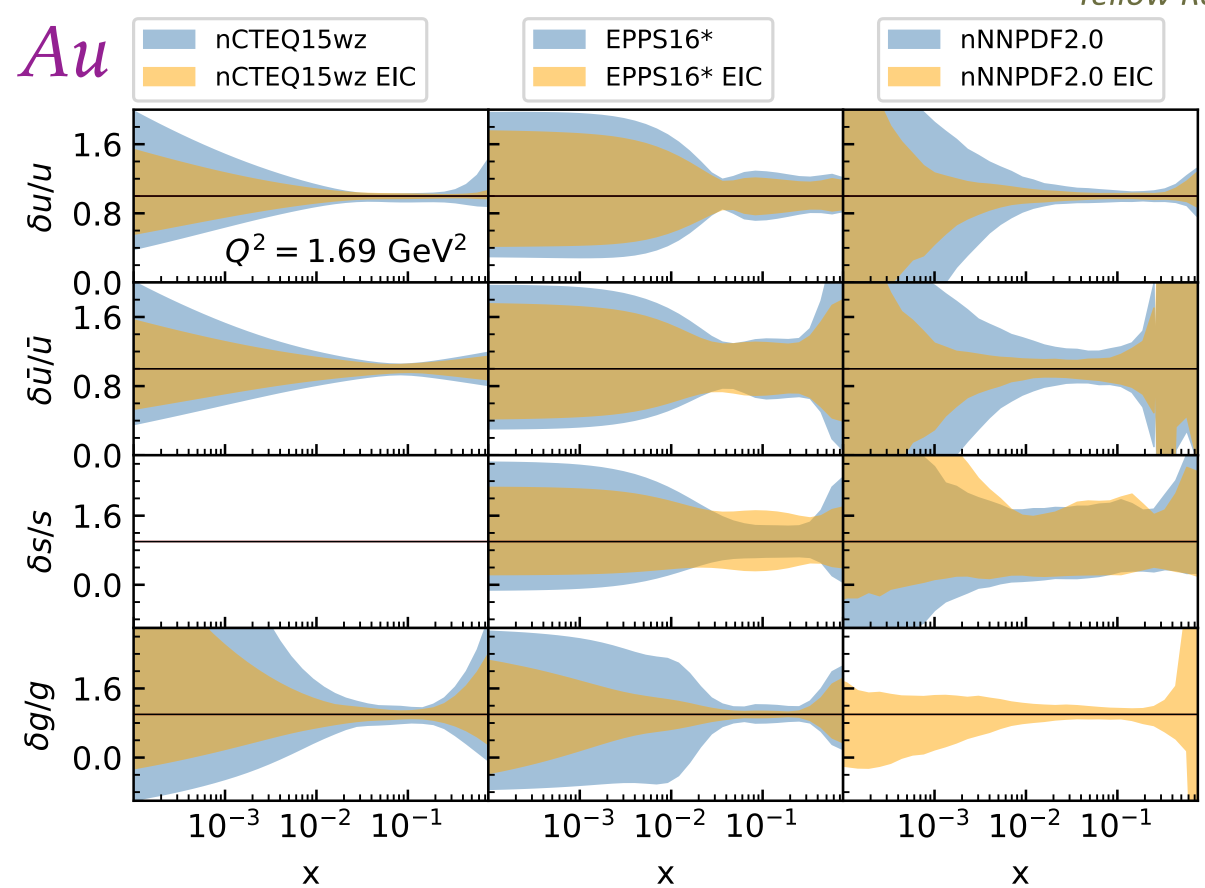
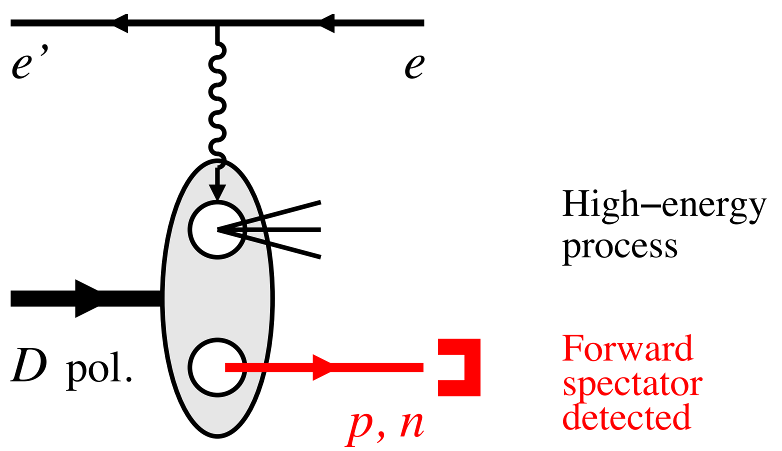


Significant impact of EIC measurements on nuclear PDFs

DIS on a deuteron with spectator tagging



Spectator tagging allows to control the **nuclear configuration** in the deuteron initial state : active nucleon and relative momentum. Differential analysis of the nuclear effects

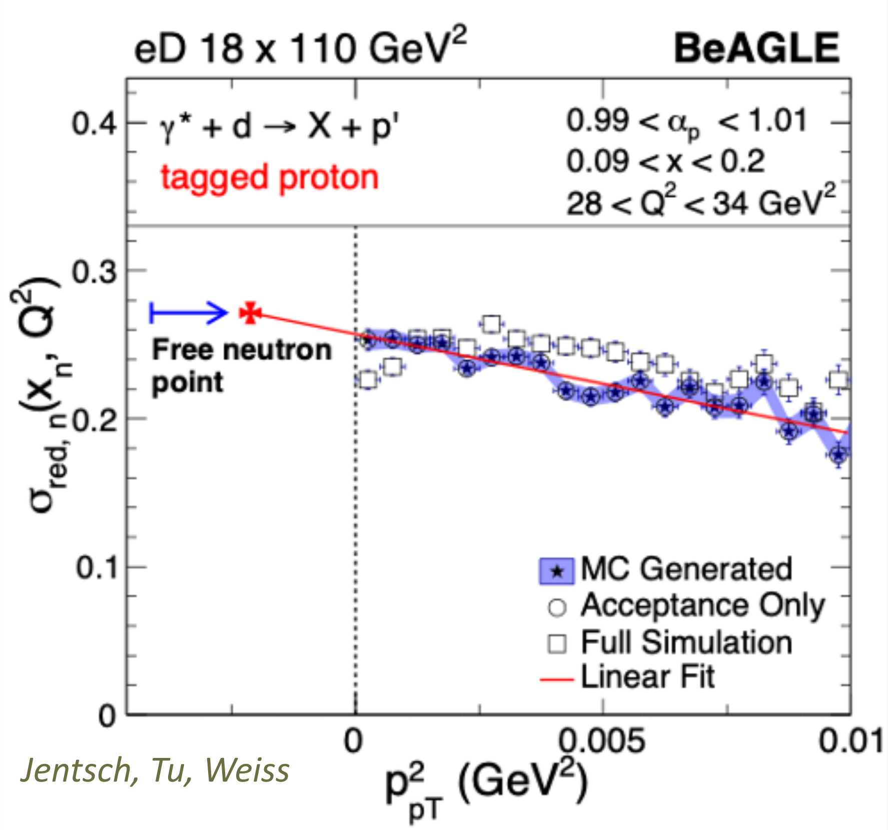
Unique method with several applications:

Free neutron structure function

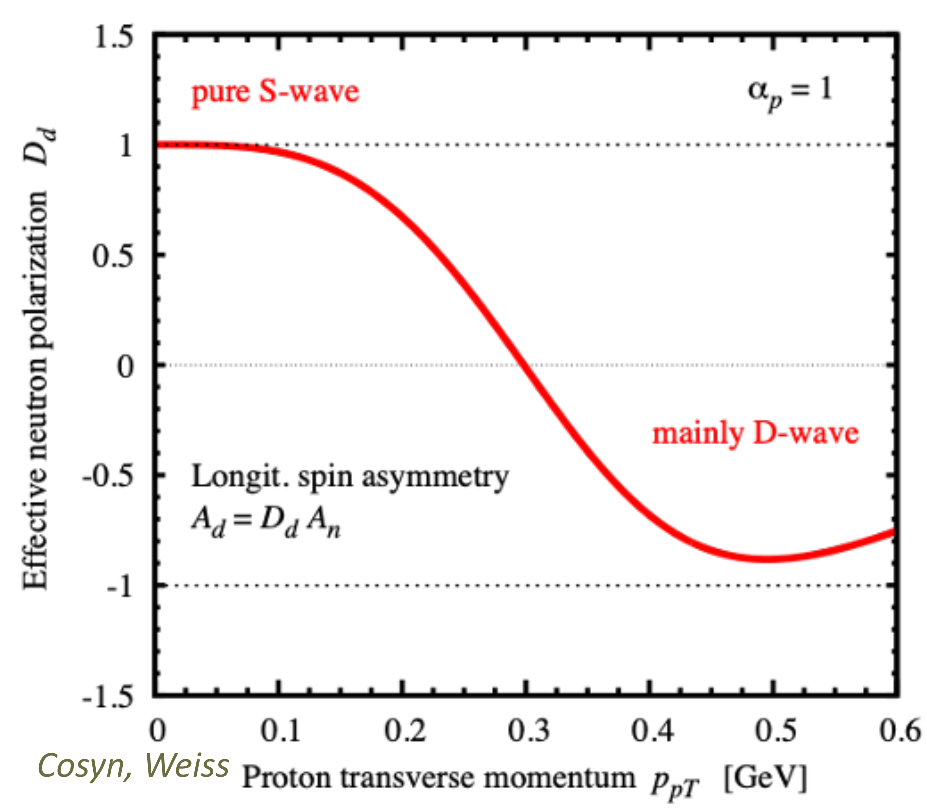
Configuration dependence of the **EMC effect**

Proton structure function (analysis of nuclear effects)

Neutron polarization in polarized DIS (S, D waves)



Jentsch, Tu, Weiss



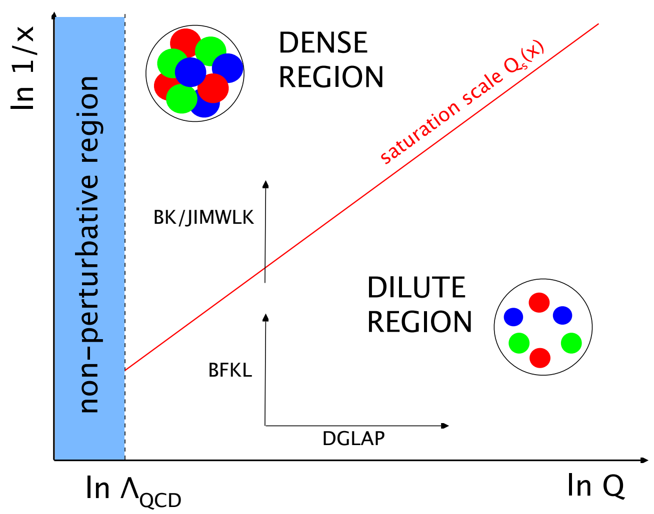
Cosyn, Weiss

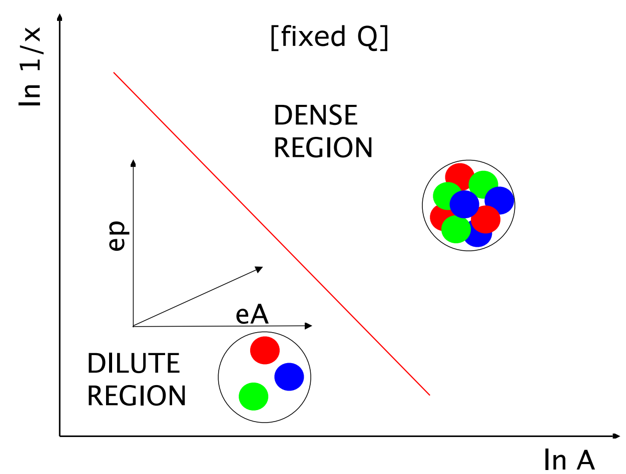
Double tagging can be done with light nuclei: ^3He,^3H. Neutron, proton structure nuclear modifications

Color Glass Condensate: effective theory at high energy/density

QCD at high energy (low x) and/or high density (large A) predicts **saturation** of gluons

$$Q_s^2(x, A) \sim \frac{A^{1/3}}{x^\lambda}$$





Cross sections in DIS at high energy/density

$$F_{2,L}(x, Q^2) = \sum_f \int d^2\mathbf{b}\, d^2\mathbf{r}\, dz\, \Phi_f(\mathbf{r}, z, Q^2)\, N(\mathbf{b}, \mathbf{r}, x)$$

Dipole scattering amplitude $N(\mathbf{b}, \mathbf{r}, x)$ encodes all the dynamics of dipole hadron interaction(related to unintegrated gluon density $f(x, \mathbf{k})$)

$$\frac{\partial}{\partial \ln 1/x} N(\mathbf{b}, \mathbf{r}, x) = K \otimes [N - N^2]$$

Nuclei provide enhancement of the density : opportunities to test saturation at EIC

Impressive progress in higher order calculations at NLO in CGC in the context of DIS:

Nonlinear evolution equations to NLO in QCD and to NNLO in N=4 SYM
Resummation of higher orders in nonlinear evolution
Impact factors for inclusive structure functions
Impact factors for heavy quarks
Exclusive vector meson production and diffractive dijets
Inclusive dijet and hard photon final states

CGC calculations entering era of high precision

Testing saturation through inclusive structure functions at EIC

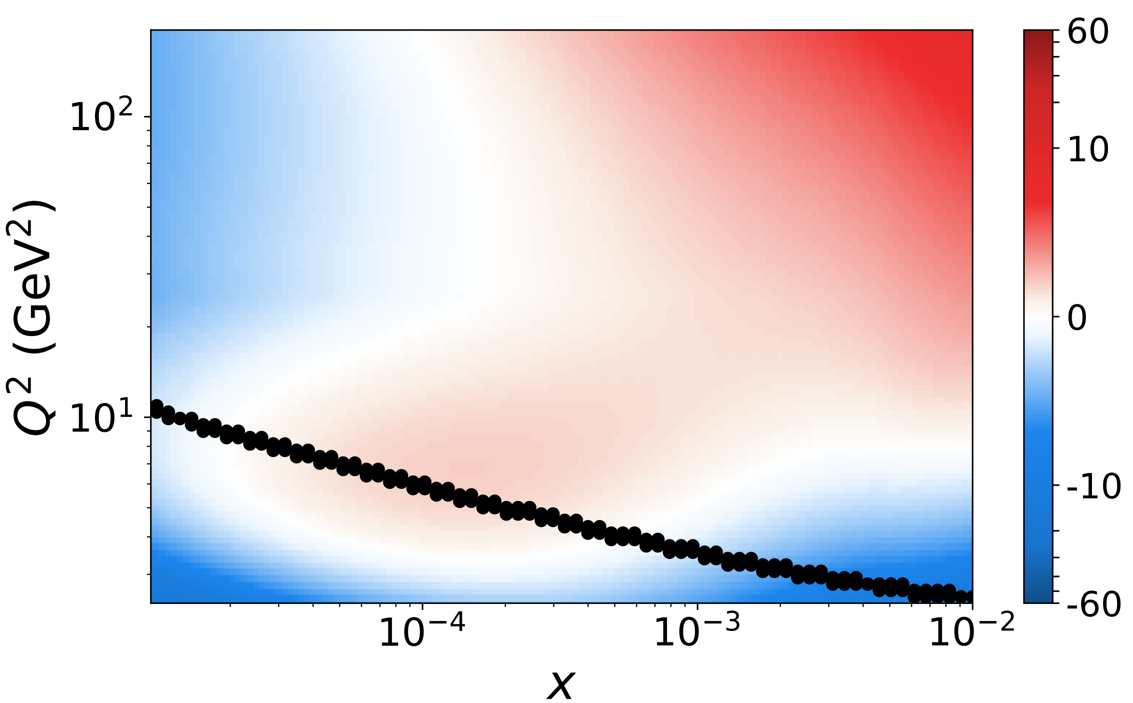
Study differences in evolution between **linear DGLAP** evolution and **nonlinear** evolution with **saturation**

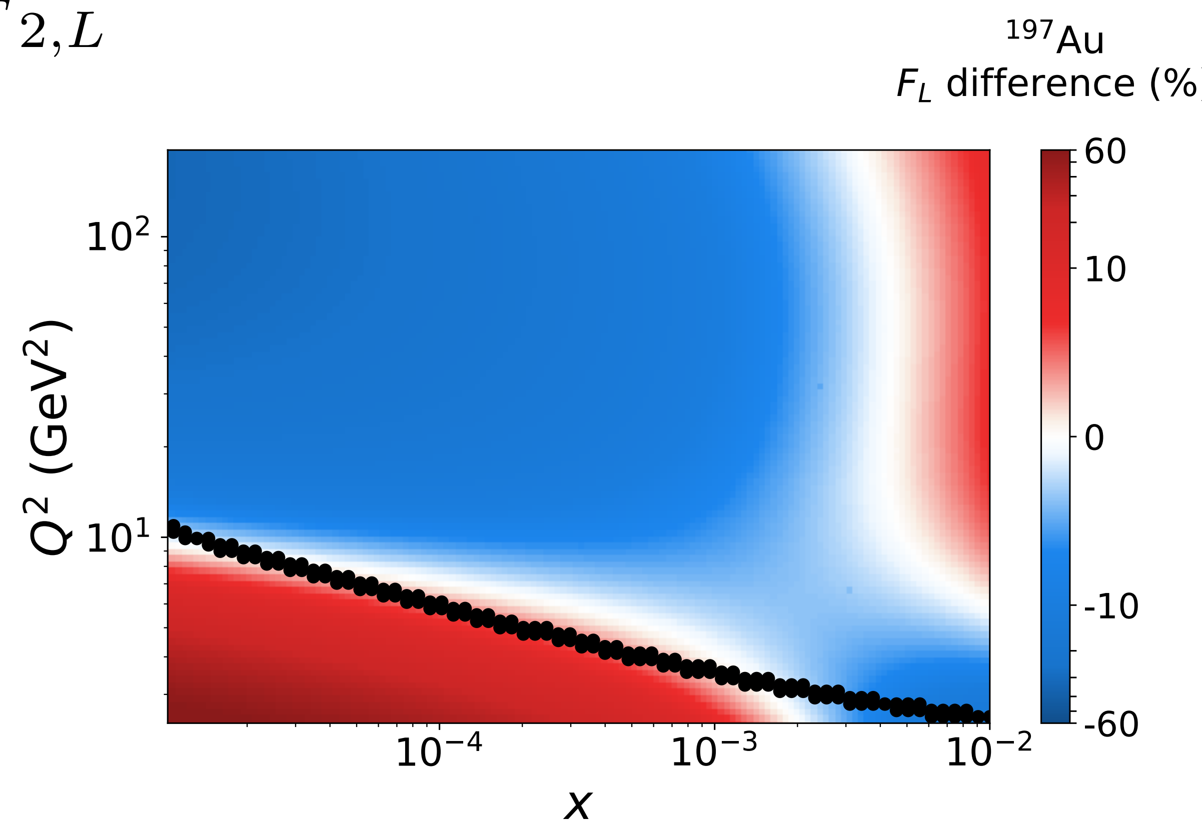
Matching of both approaches in the region where saturation effects expected to be small

Quantify differences away from the matching region: **differences in evolution dynamics**

$$\frac{F_{2,L}^{\rm BK} - F_{2,L}^{\rm Rew}}{F_{2,L}^{\rm BK}}$$

Armesto, Lappi,Mantysaari,PaukkunenmTevio



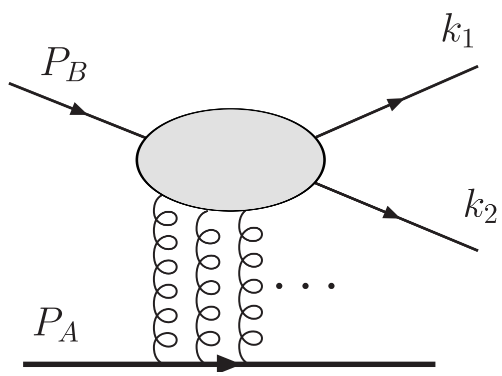


Heavy nucleus: difference between DGLAP and nonlinear are few % for F_2^A and up to 20% for F_L^A.

Longitudinal structure function can provide good sensitivity at EIC

Testing saturation through (de)correlations of hadrons

Azimuthal (**de)correlations of two hadrons** (dijets) in DIS in eA: direct test of the **Weizsacker -Williams unintegrated gluon distribution**

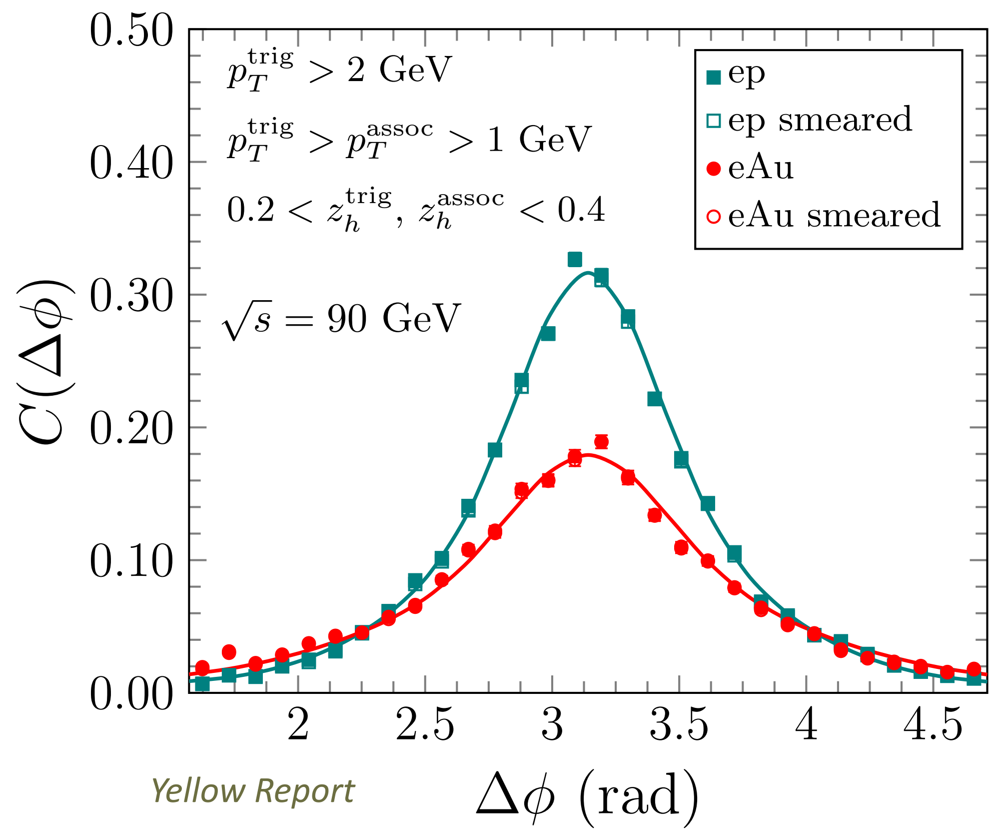


$$C(\Delta\phi) = \frac{1}{\frac{d\sigma_{\rm SIDIS}^{\gamma^*+A\to h_1+X}}{dz_{h1}}} \frac{d\sigma_{\rm tot}^{\gamma^*+A\to h_1+h_2+X}}{dz_{h1}dz_{h2}d\Delta\phi}$$

$$\frac{d\sigma^{\gamma^*+A\to h_1+h_2+X}}{dz_{h1}dz_{h2}d^2p_{h1T}d^2p_{h2T}} \sim \mathcal{F}(x_g,q_T)\otimes\mathcal{H}(z_q,k_{1T},k_{2T})\otimes D_q(z_{h1}/z_q,p_{1T})\otimes D_q(z_{h2}/z_q,p_{2T})$$

Clear differences between the ep and eA: **suppression** of the correlation peak in **eA** due to **saturation** effects (including the **Sudakov resummation)**

Further observables: azimuthal correlations of dihadrons/ dijets in diffraction, photon+jet/dijet. These processes will allow to test various **CGC correlators**



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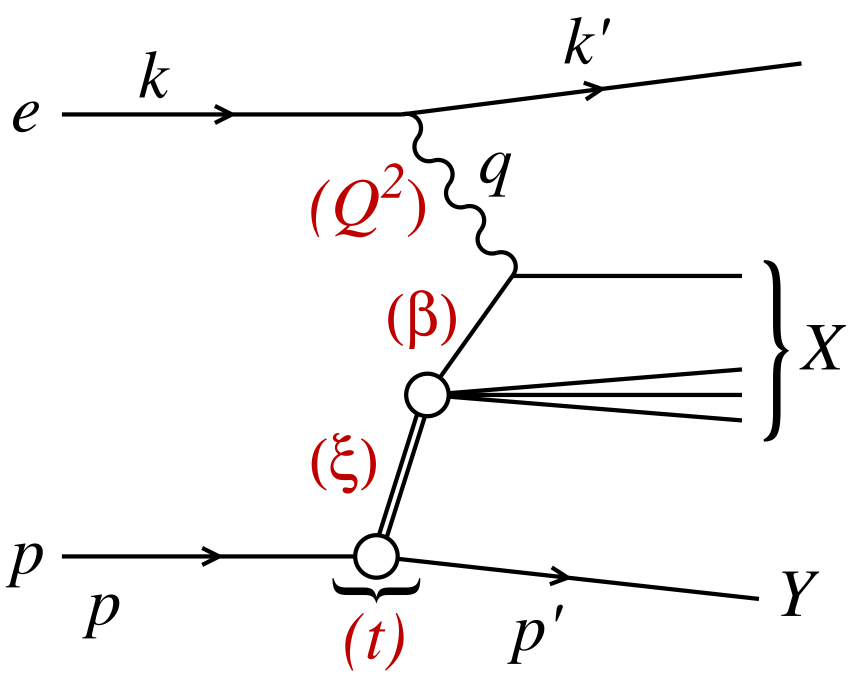
Diffraction in DIS



Diffraction: a reaction characterized by a large rapidity gap in the final state

Diffractive DIS variables:

$$x = \xi\beta$$

$$\xi \equiv x_{IP} = \frac{Q^2 + M_X^2 - t}{Q^2 + W^2}$$

momentum fraction of the Pomeron w.r.t hadron

$$\beta = \frac{Q^2}{Q^2 + M_X^2 - t}$$

momentum fraction of parton w.r.t Pomeron

$$t = (p - p')^2$$

4-momentum transfer squared

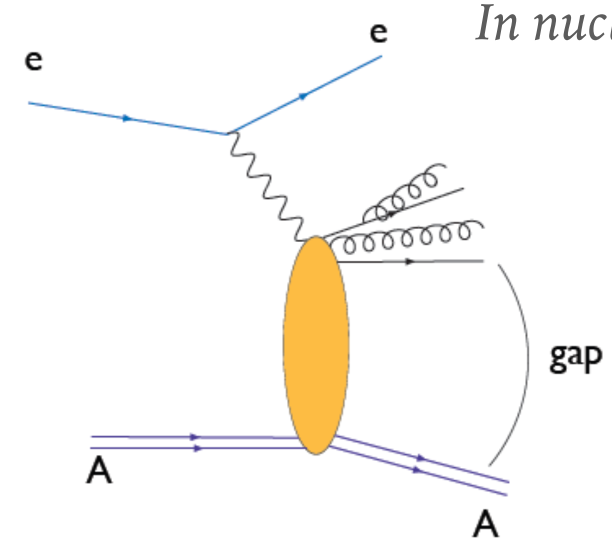
Why diffraction ?

- Dynamics of color singlet object (Pomeron). Relation to confinement
- Sensitivity to gluon content, low x dynamics and saturation
- Relation to shadowing
- Limits of factorization and universality of diffractive PDFs

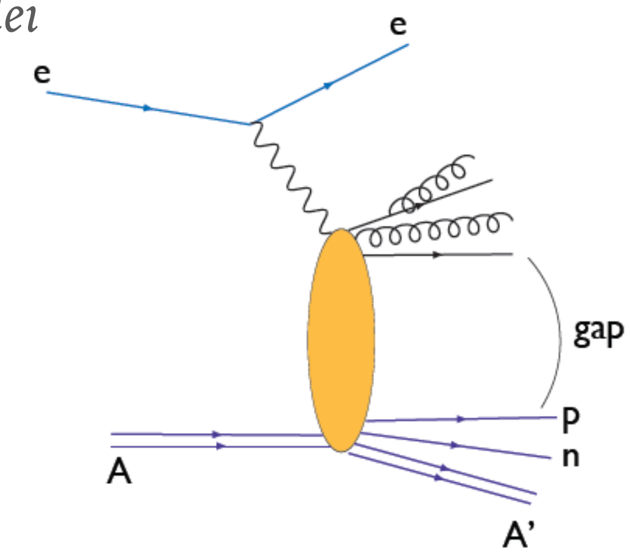
Collinear factorization in diffractive DIS of hard partonic cross section and diffractive PDF

$$d\sigma^{ep\to eXY}(\beta,\xi,Q^2,t) \;=\; \sum_i \int_\beta^1 dz\, d\hat{\sigma}^{ei}(\frac{\beta}{z},Q^2)\, f_i^{\rm D}(z,\xi,Q^2,t)$$

In nuclei



coherent

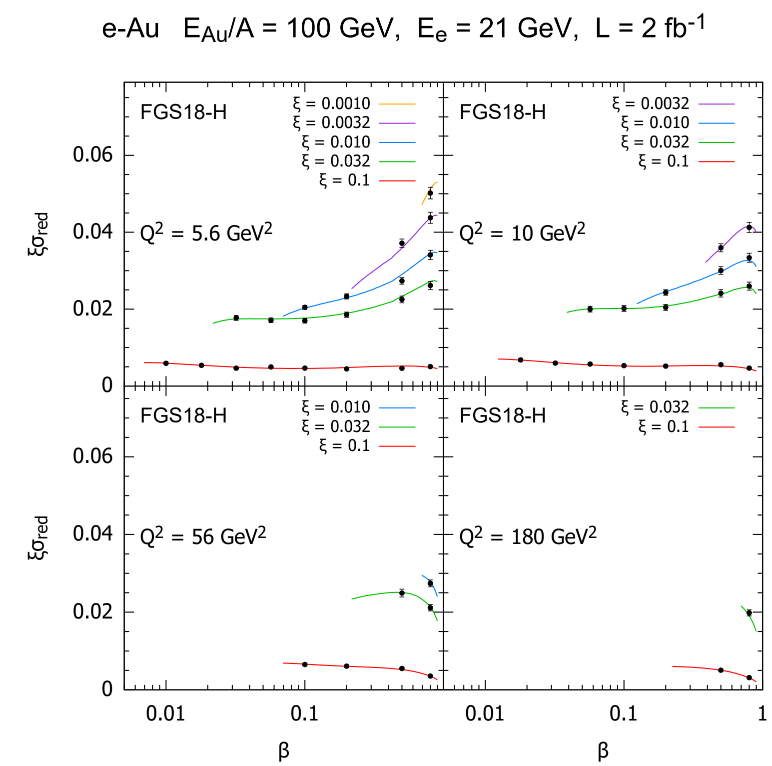


incoherent

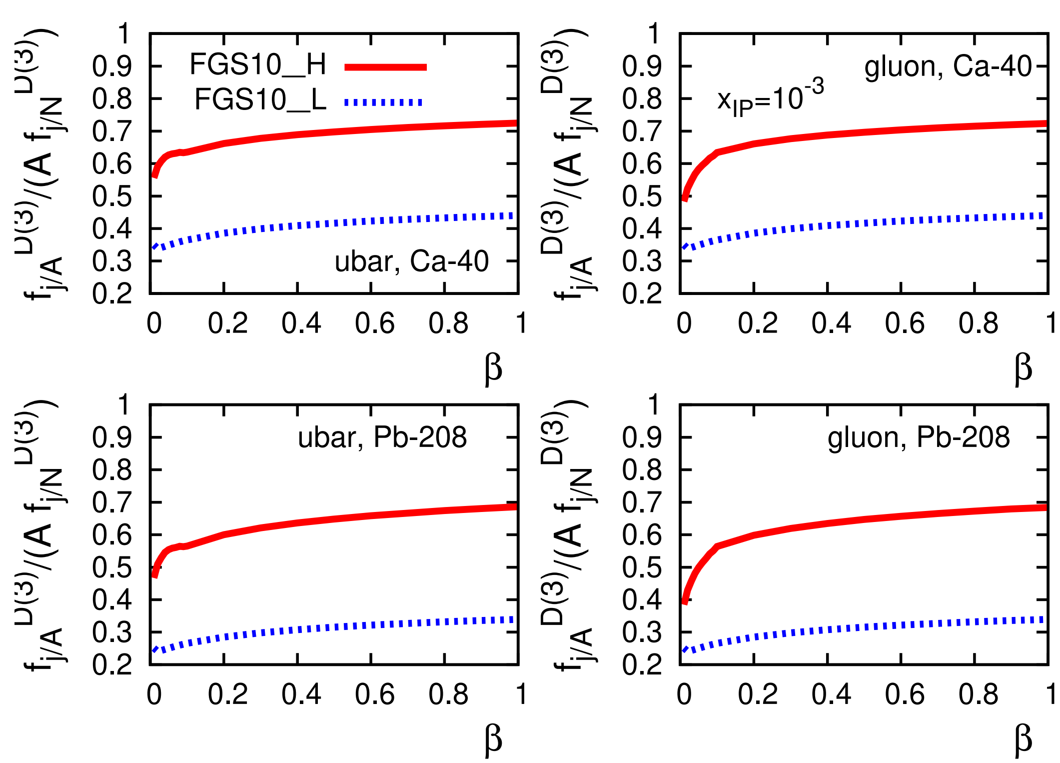
Inclusive diffraction in DIS

- **Coherent** diffraction: sensitive to **global shape**; **incoherent** to **fluctuations**
- Extraction of **nuclear diffractive parton distributions** would be possible for the first time
- Diffractive to inclusive ratio of cross sections **sensitive probe to different models** (ex. saturation vs leading twist shadowing)

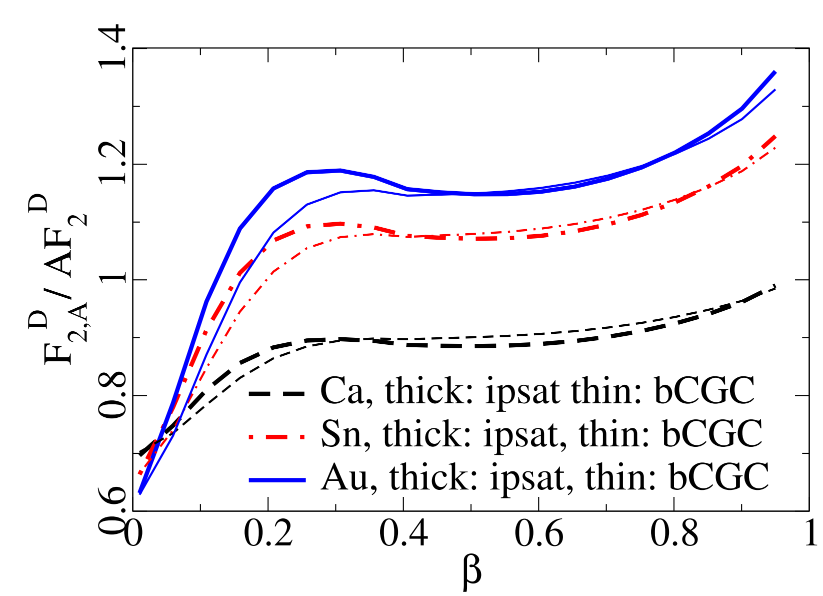
Inclusive diffractive structure function in eA



Ratio in LT shadowing : suppression



Ratio in saturation model: enhancement



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Diffraction in ep/eA

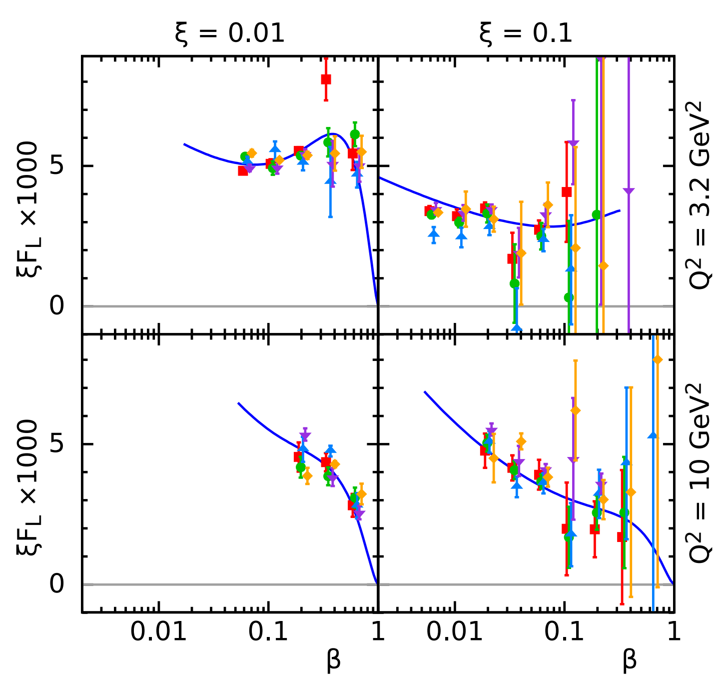
F_L^D diffractive longitudinal structure function

$$\sigma_r^{D(4)}(\xi,\beta,Q^2,t) = F_2^{D(4)}(\xi,\beta,Q^2,t) - \frac{y^2}{Y_+} F_L^{D(4)}(\xi,\beta,Q^2,t)$$

Sensitive to **diffractive gluon density** (saturation, higher twists…). Only one extraction at HERA by H1, large errors. Challenging measurement.

EIC : excellent prospects for F_L^D measurement, need careful choice of energy combinations. Studied in **ep**, need study in **eA**

Armesto, Newman, Slominski, Stasto



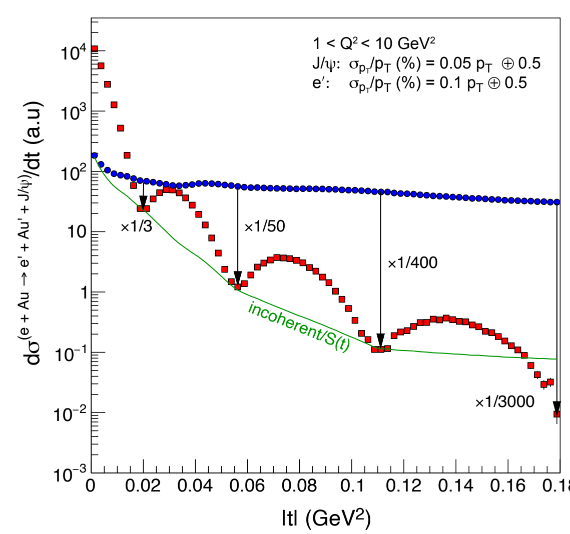
Exclusive diffraction of VM

$$e + Au \to e + Au + J/\psi$$

Best process to extract the shape of nucleus, sensitive to saturation

Experimental challenges: coherent vs incoherent background

Question for theory: how robust are position and width and depth of minima



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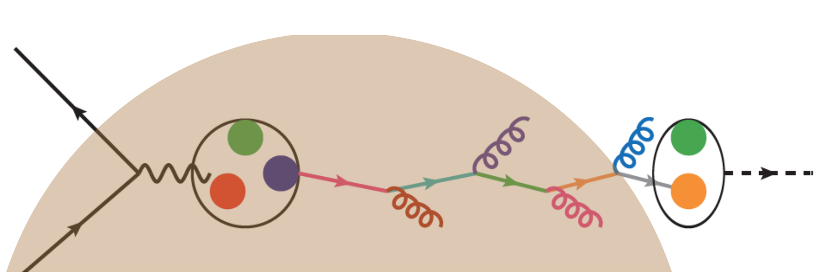
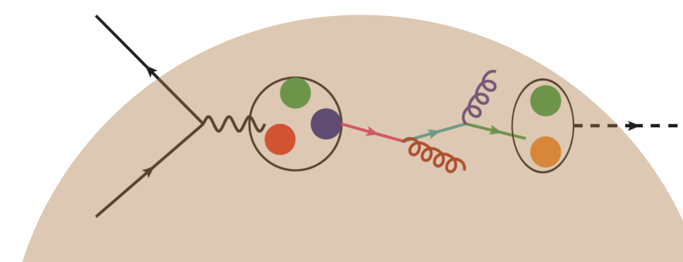
Prospects for this process with **deuteron** and **light ions:** probing shadowing in a more controlled environment, separate **double**, **triple** scattering;
spectator **tagging** on deuteron allows to study **SRC** and role of **gluons**

Passage of color charges through cold nuclear matter

- Modern theories of QCD in matter (such as $SCET_G$ and $NRQCD_G$) have enabled novel understanding of parton showers on matter. Capabilities to calculate higher order and resumed calculations in reactions with nuclei
- EIC will provide important input on **hadronization** mechanism in eA
- Different scenarios: **parton evolution in medium** or **hadron absorption**





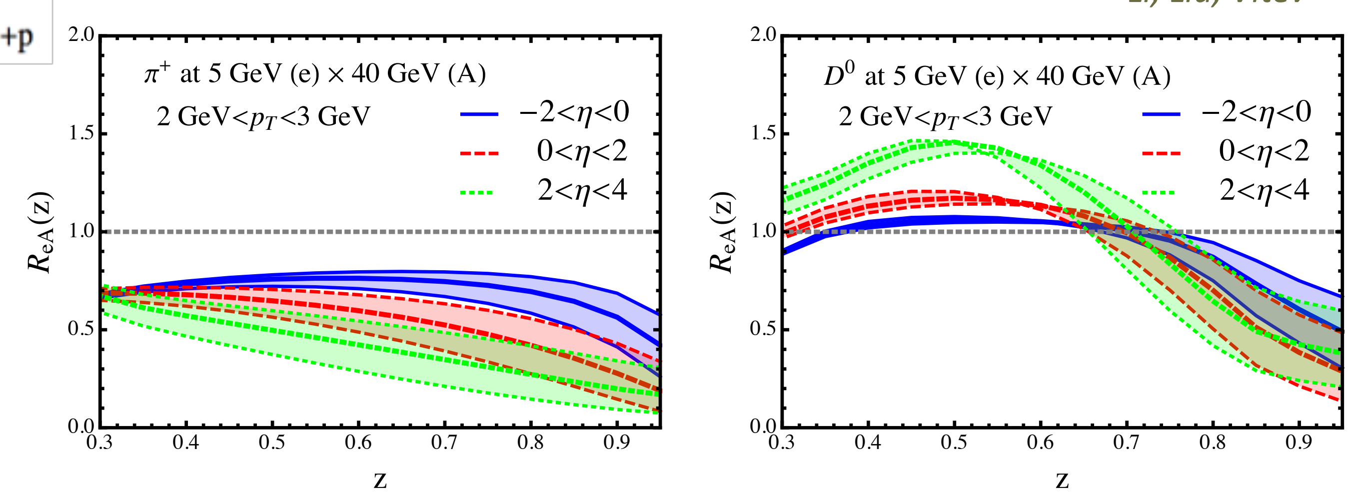
Parton energy loss and in-medium fragmentation function modification

$$\frac{d}{d\ln\mu^2}\tilde{D}^{h/i}(x,\mu) = \sum_j \int_x^1 \frac{dz}{z}\tilde{D}^{h/j}\left(\frac{x}{z},\mu\right)\left(P_{ji}(z,\alpha_s(\mu)) + P_{ji}^{\text{med}}(z,\mu)\right)$$

$$R_{eA}^h(p_T,\eta,z) = \frac{\left.\frac{N^h(p_T,\eta,z)}{N^{\text{inc}}(p_T,\eta)}\right|_{\text{e+Au}}}{\left.\frac{N^h(p_T,\eta,z)}{N^{\text{inc}}(p_T,\eta)}\right|_{\text{e+p}}}$$

Modification (e+A vs e+p) of light vs heavy mesons vs the fragmentation fraction z

Li, Liu, Vitev



Constrain the space-time picture of hadronization.

Differentiate **energy loss** and **hadron absorption** models (based on ability to measure heavy flavors)

Lower energy beams better for this process

Jets as probes of cold nuclear matter

Jets emerged as a premier diagnostic tool for **hot** nuclear matter at RHIC and LHC

Also excellent probes for **cold** nuclear matter. Using jets, elucidate the properties of in-medium parton showers.

PDF — partonic cross section — jet function

$$d\sigma \sim f_a(z,\mu) \otimes H_{ab}(x,z;p_T,\eta) \otimes J_b(z,\mu,R)$$

initial — final

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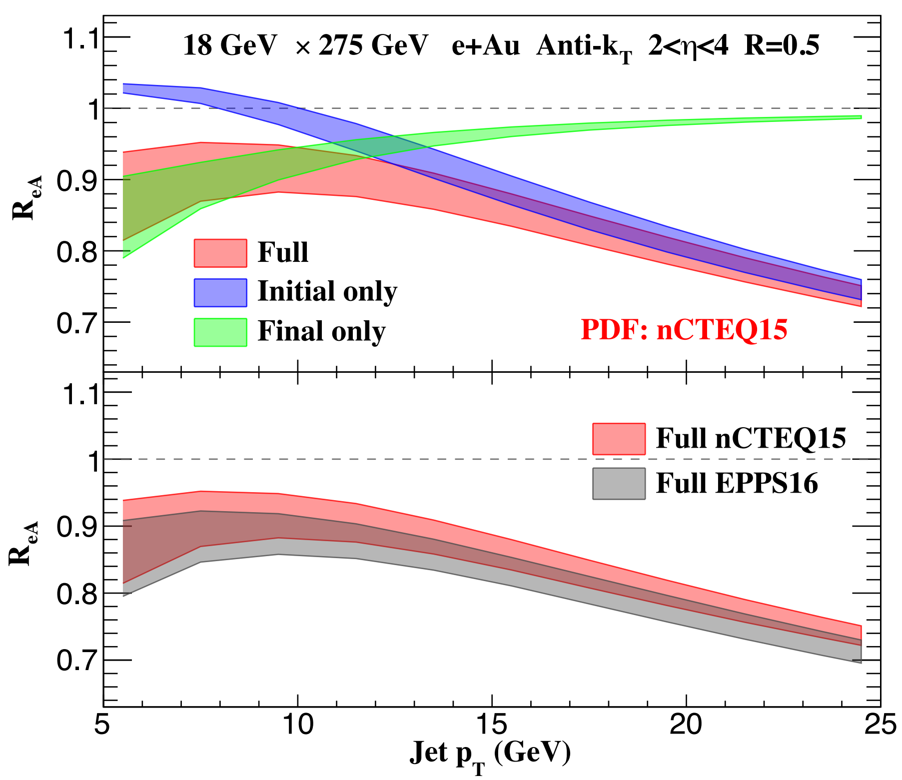
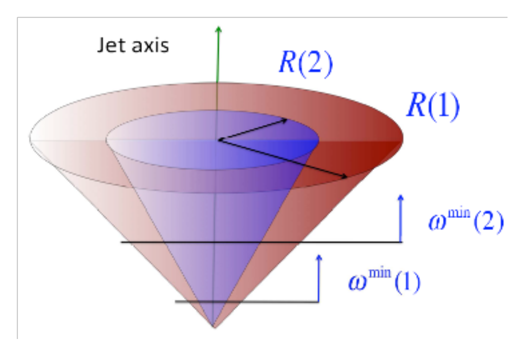
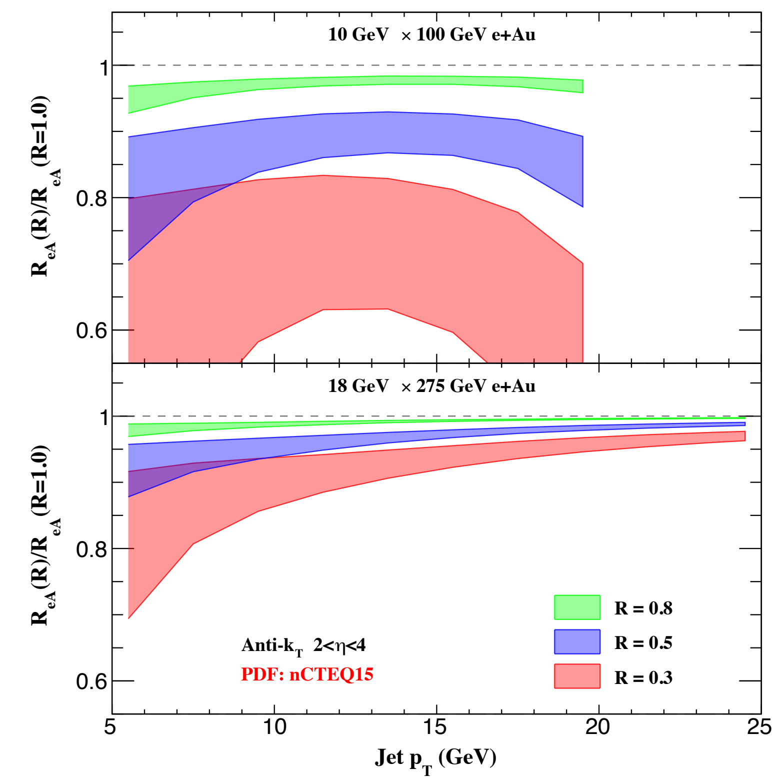


- IS (large and small p_T) vs FS (small p_T) contributions to nuclear ratio
- Small nPDF effects
- Ratios with different jet cone allow to separate parton shower effects





Li, Vitev

- Pioneer jet **substructure** studies with heavy quark initiated jets performed in a EIC regime very different from the one probed in heavy ion collisions *Li, Liu, Vitev*
- Pave the way to a qualitatively new level of understanding of the role of **heavy quark mass**

Summary

EIC : precision tool for high energy nuclear physics

Nuclear structure functions, precision extraction of nuclear PDFs, testing the limits of collinear factorization in nuclei. Initial conditions for hot QCD.

Explore the onset of saturation in eA, DGLAP vs non-linear evolution, x,A, and Q dependence. Precise measurement of F_L needed (variable energies)

Extraction of diffractive nuclear PDFs possible for the first time, potential for F_L^D. Diffractive to inclusive ratios needed to distinguish between the different scenarios.

Test the mechanism of hadronization with hadrons and jets (heavy flavors, low energy beams). Initial vs final state effects.

Rich program with light ions: spectator tagging, configuration dependence, neutron structure, SRC, coherent nuclear processes, polarization