eA physics
at
Electron-Ion Collider (EIC)

Jianwei Qiu
Brookhaven National Laboratory

RIKEN workshop on “Future Directions in High Energy QCD”
RIKEN, Wakoshi, Japan, October 20-22, 2011

Outline of my talk

- ❑ **Surprises from high energy nuclear collisions**
- ❑ **EIC will be the first eA collider (if built before LHeC)**
  - ✧ Non-linear gluon dynamics of QCD – dynamical mass scale?
  - ✧ Could a nucleus acts as a big proton – color correlation?
  - ✧ 3-D spatial imaging of a nucleus?
  - ✧ Could nuclear matter be an effective filter for hadronization?
- ❑ **Effort of the community:**

  INT workshop:

  http://www.int.washington.edu/PROGRAMS/10-3/

  Report: arXiv: 1108.1713

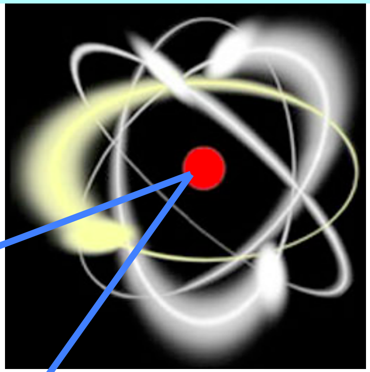
  EIC Whitepaper: under intensive construction now

The matter

- The atom:

  Electrons: zooming around at high *v*

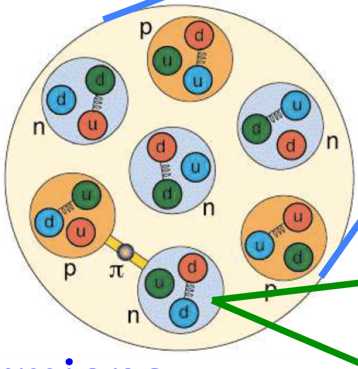
  Nucleus: localized "point-like" charge source



- The nucleus:

  Pions: short-range force

  Nucleons: Color-charge neutral

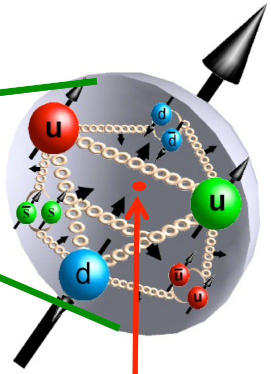


- The nucleon (so as pions):

  Quarks: "point-like" spin-1/2 fermions

  Gluons: "point-like" spin-1 bosons

  Zooming around at v ~ c: No localized charge source



- QCD hard probes (Q > 2 GeV ~ r < 1/10 fm):

  See only quarks and gluons!

< 1/10 fm

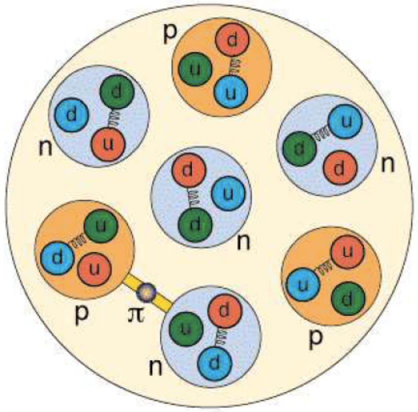
Quark-Gluon Nuclear Physics

Is Quark-Gluon Nuclear Physics interesting?

❑ **Facts:**

Hard probe: Q > GeV

Nuclear binding: ~ MeV



❑ **Naïve expectation:**

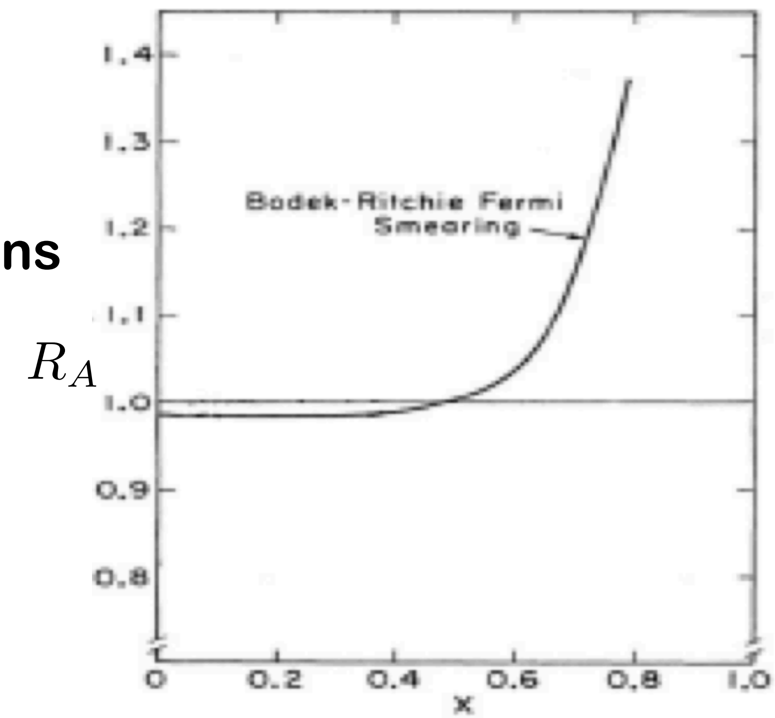
DIS off a bound nucleon in a nucleus

≈ DIS off a free nucleon

✧ **Probably with some small corrections from Fermi motion of nucleons**

$$\sigma_{eA}(x,Q) \approx Z\sigma_{ep}(x,Q) + (A-Z)\sigma_{en}(x,Q)$$

✧ **Nuclear target was used to enhance the production rate**



Quark-Gluon Nuclear Physics might not be very interesting?

EMC Effect – 1983

- **Anomalous A-dependence:**
  - **Process:**

$$\ell(l) + A(p_A) \to \ell'(l') + X$$

  - **Inclusive observable – structure functions:**

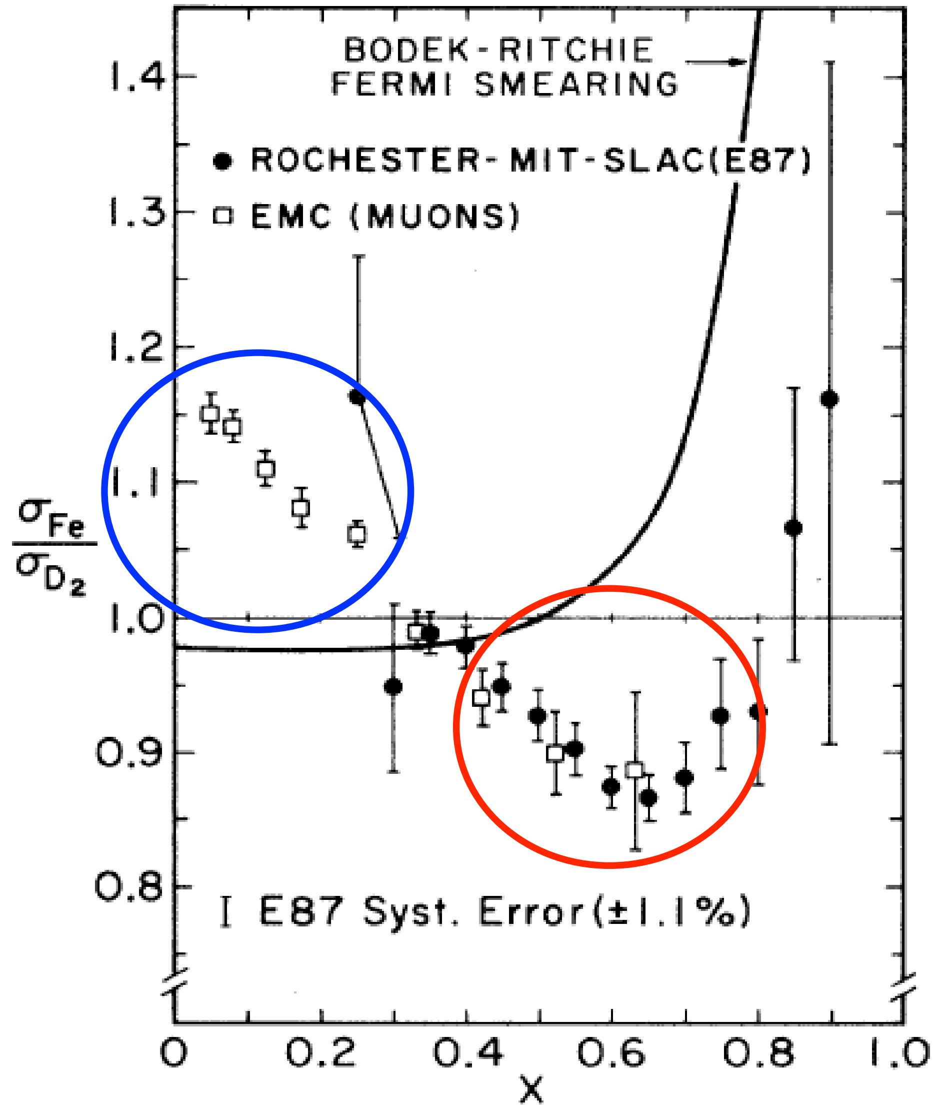
$$R_{F_2} = \frac{\frac{1}{A} F_2^A(x, Q^2)}{\frac{1}{2} F_2^D(x, Q^2)} \neq 1$$

  - **Variables:**

$$x = \frac{Q^2}{2(p_A/A) \cdot q}$$

$$Q^2 = -q^2 = -(l - l')^2$$

Nucleus =\= simple sum of free nucleons!

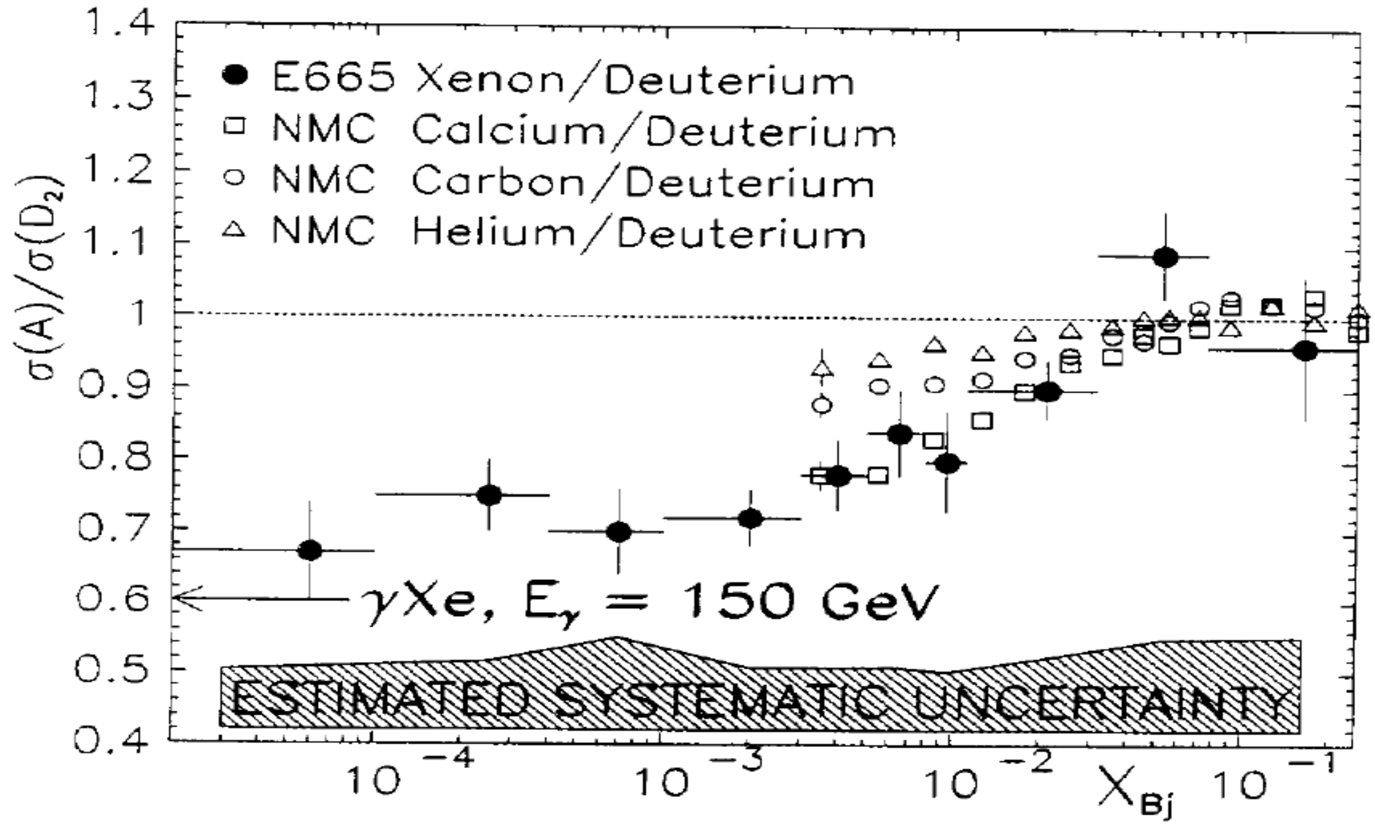


Aubert et al., Phys. Lett. B123, 275 (1983)

Nuclear shadowing

E665 Collaboration, PRL 68, 3266 (1992)

❑ Strong suppression at small-x:



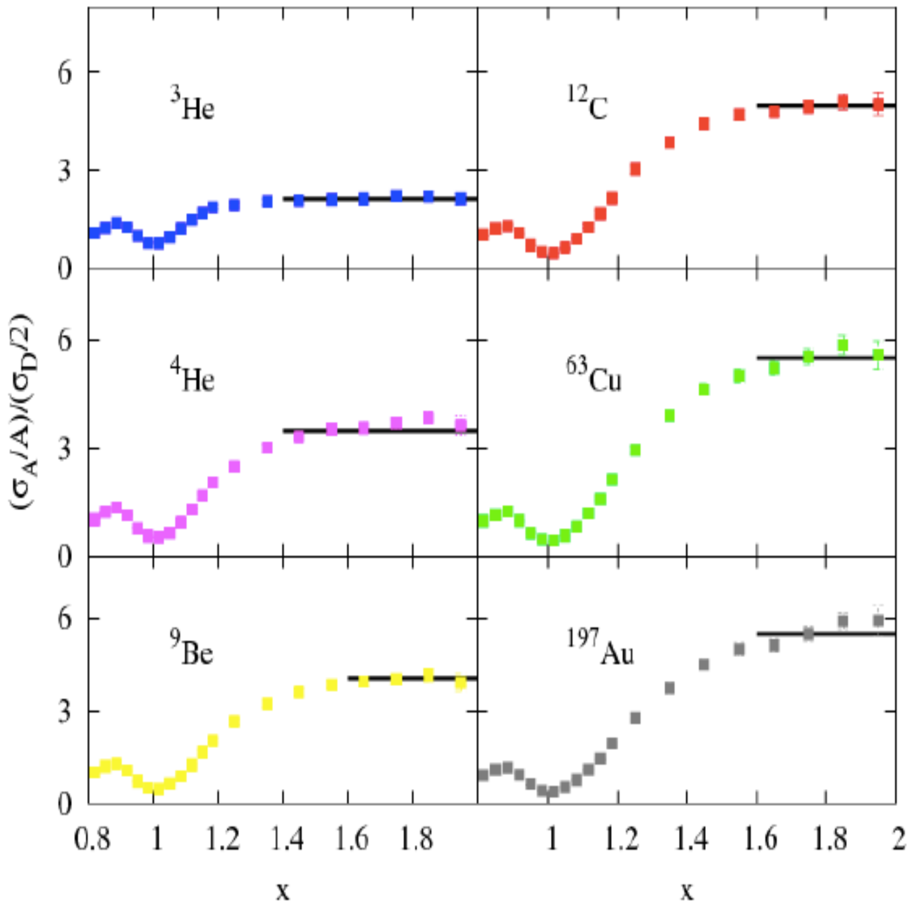
✧ Hard probe is not localized in "z" direction: $\frac{1}{xp} > 2R\frac{m}{p}$

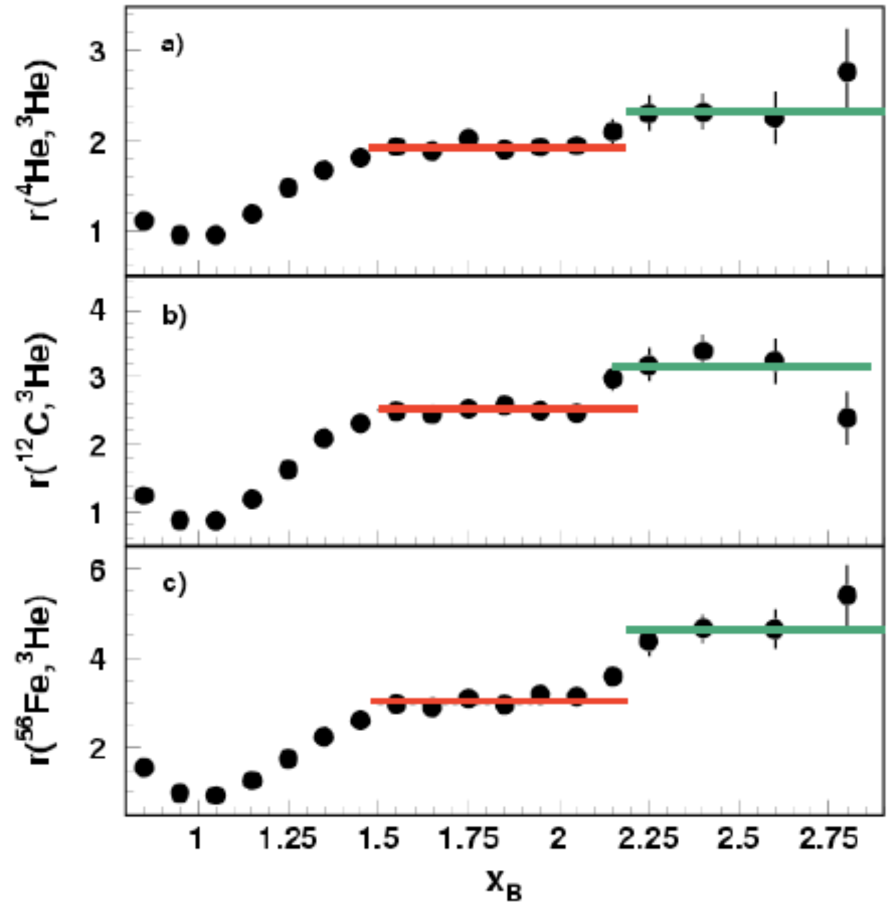
✧ Parton recombination, saturation, CGC, …

Super fast quarks

- Strong enhancement at large x: $\langle Q^2 \rangle = 2.7\ \mathrm{GeV}^2$

$$r(A,{}^2H) = \frac{\sigma_A/A}{\sigma_2/2} \equiv \alpha_{2n}(A) \qquad r(A,{}^3He) = \frac{\alpha_{2n}(A)}{\alpha_{2n}({}^3He)}$$





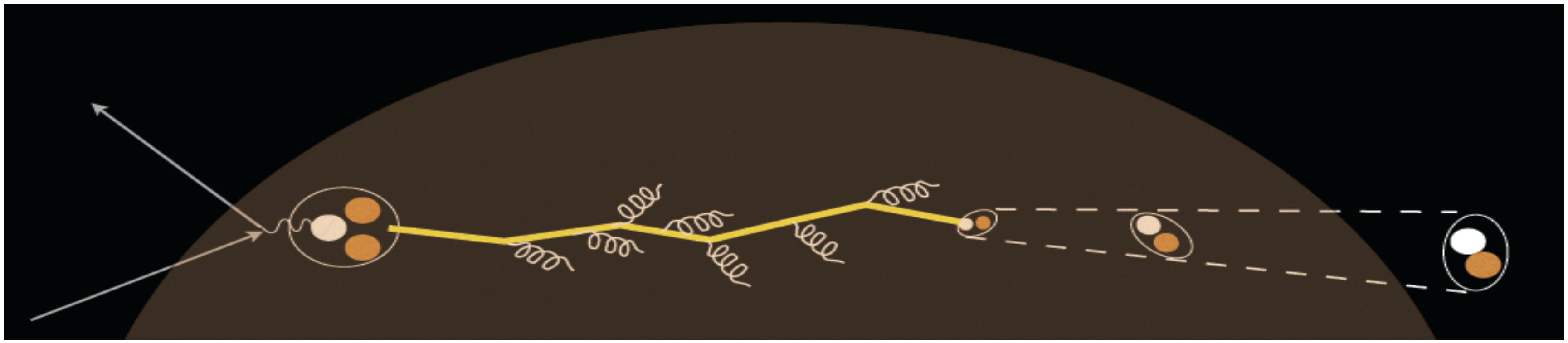
N. Fomin, et al., arXiv:1107.3583

Egiyan et al, PRL 96, 2006

Nuclear filter for hadronization

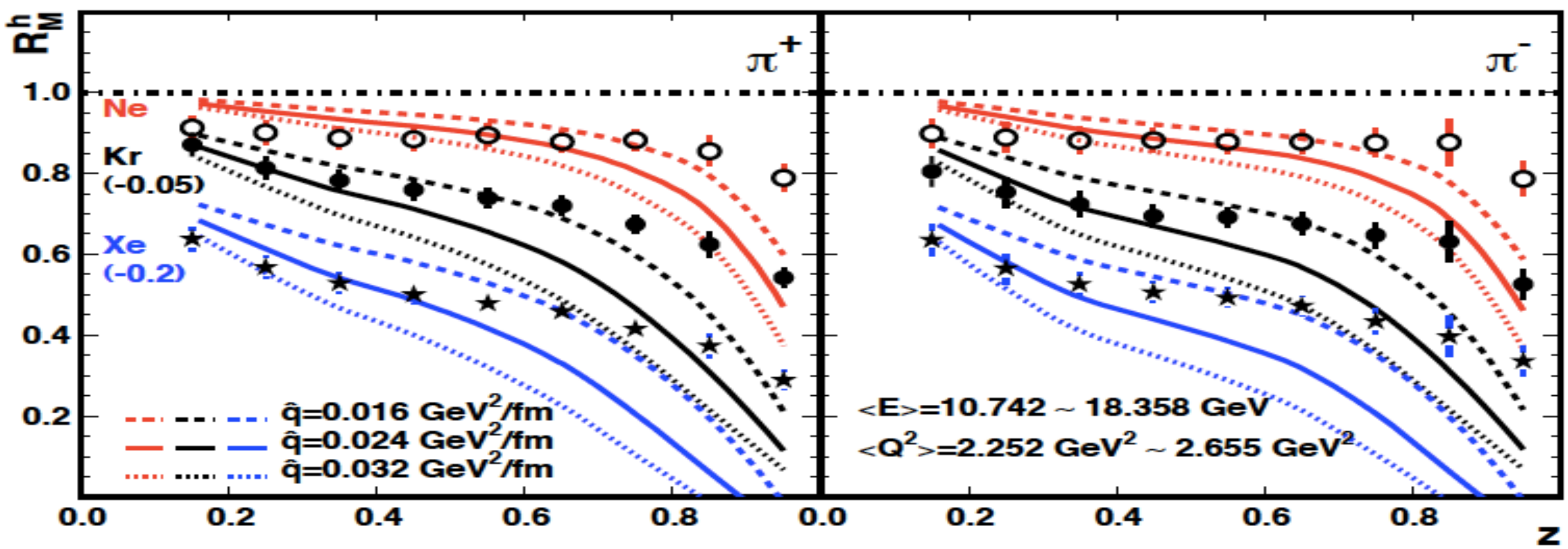
Brooks, PINAN11

- **SIDIS:** $\ell(l) + A(p_A) \to \ell'(l') + h(p) + X$



Deng, Wang, 2010

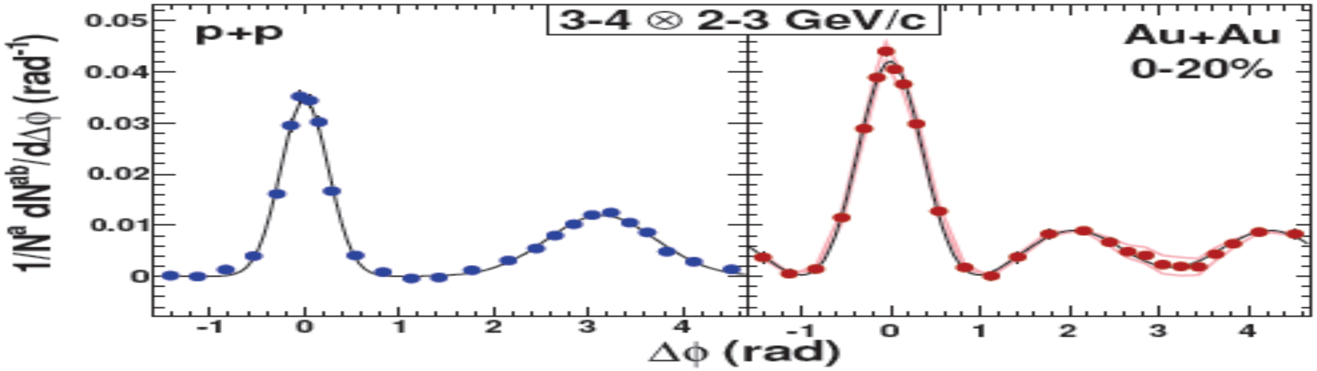
- **Suppression in leading particle – energy loss?** $\hat{q}_N = 0.02\ \mathrm{GeV/fm}$



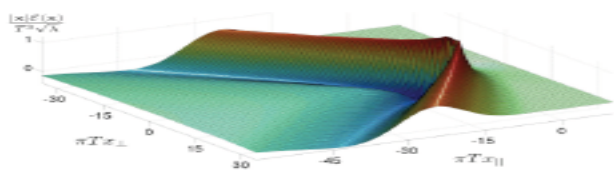
Nuclear quantum fluctuations

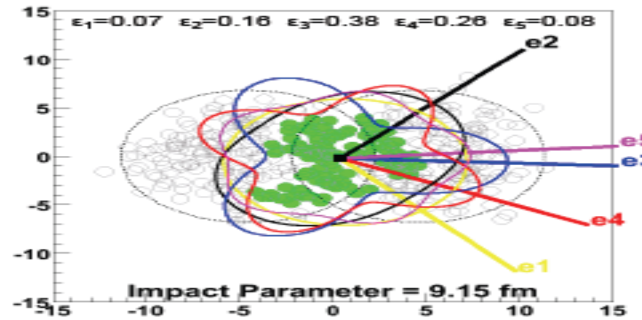
- ❑ Two particle correlation:

Alver, Roland, PRC81 (2010) 054905
Sorensen, J.Phys.G G37 (2010) 094011



Stefan Bathe's talk





Initial-state fluctuations – triangular component – flow v_n

- ❑ Fluctuations in nuclear density, color fields, … "hot spots"

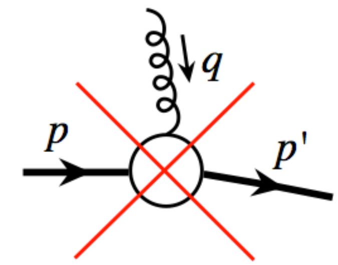
Initial condition for heavy ion collisions

See Itakura's talk

Quark-Gluon Nuclear Physics is very important & insteresting!

Gluon and color

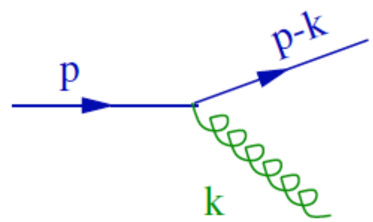
- ❑ **QCD – gluons carry color charge:**



  - ✧ **No color form factor!**
    - – color distribution inside a hadron or a nucleus?

- ❑ **QCD color fluctuation taken place at various time scales:**

  - ✧ **Radiation:**

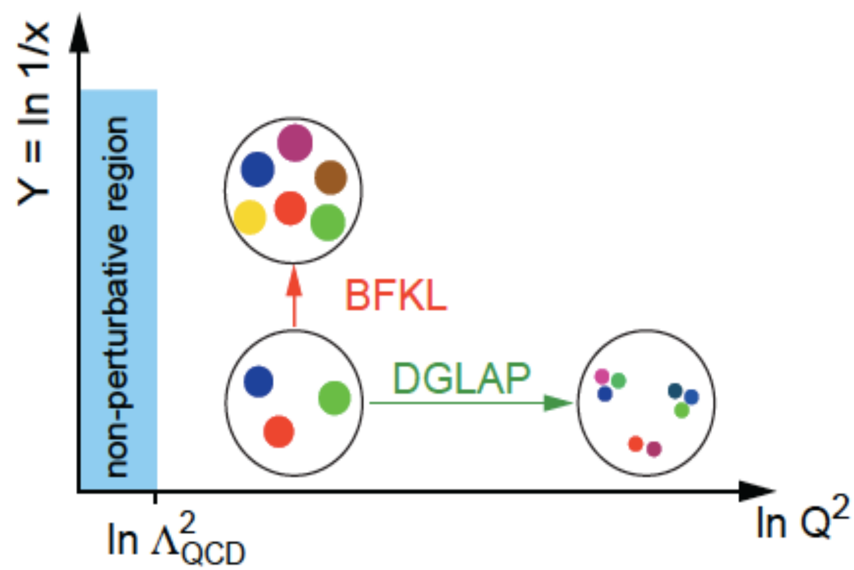


$$dP \sim \alpha_s \frac{dk_T^2}{k_T^2} \frac{dx}{x}$$

  - ✧ **Leads to change of distributions – evolution:**

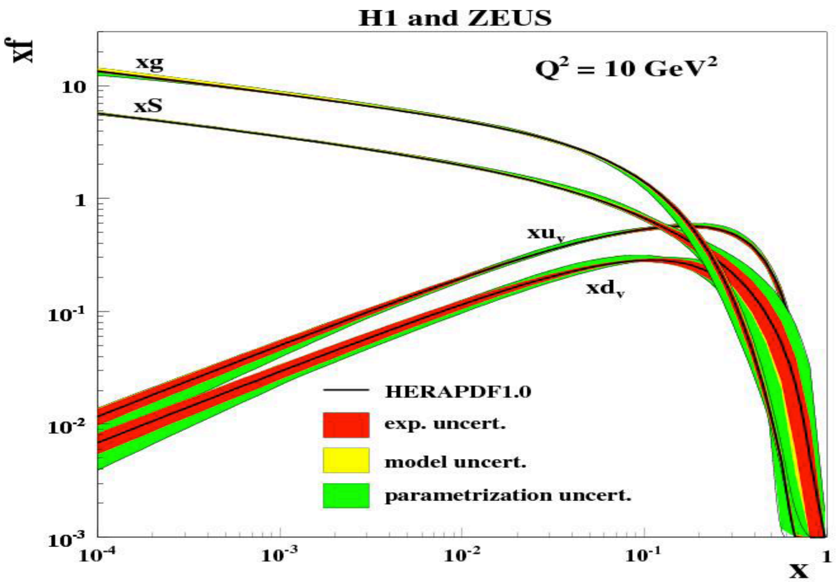
DGLAP $\frac{dk_T^2}{k_T^2} \to d\log(Q^2)$

BFKL $\frac{dx}{x} \to d\log(1/x)$



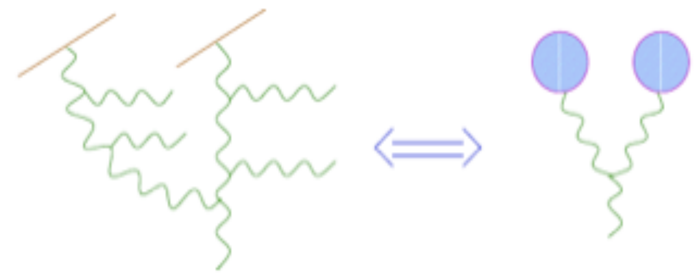
Non-linear gluon dynamics

- Huge gluon density at small x:

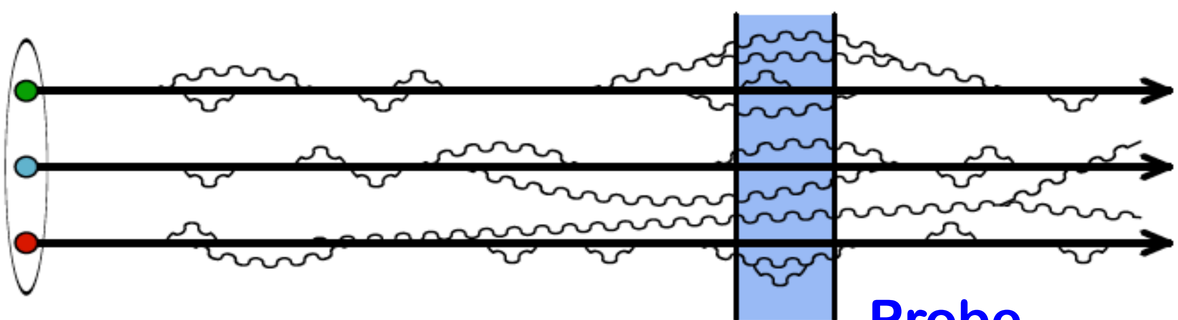


$$\gamma_{g/g}(x) \propto \frac{1}{x}$$

Parton recombination:



- Gluon recombination and saturation ought to be there:

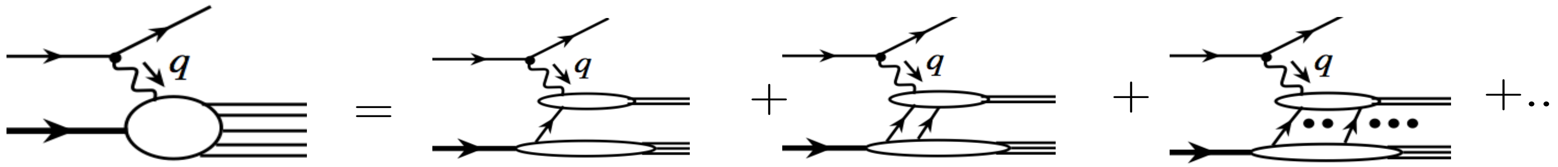


Probe

Parton recombination, saturation, color glass condensate, …

DIS at small-x

- ❑ **We measure cross sections, not parton distributions:**



  - ✧ **Every parton can participate the hard collision!**
  - ✧ **eA cross section depends on matrix elements of all fields**

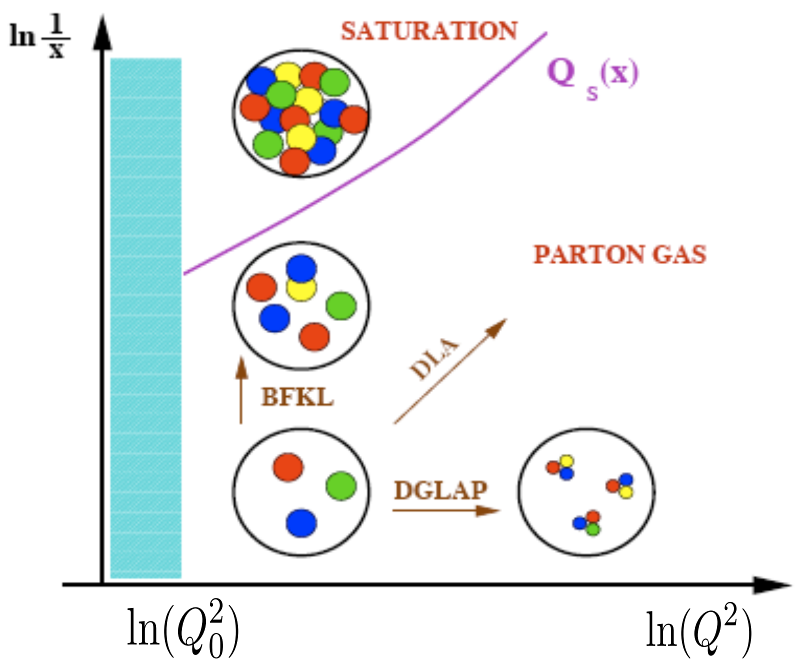
$$\sigma(Q) = \sigma^{\rm LP}(Q) + \frac{Q_s}{Q}\sigma^{\rm NLP}(Q) + \frac{Q_s^2}{Q^2}\sigma^{\rm NNLP}(Q) + \ldots \approx \sigma^{\rm LP}(Q)$$

- ❑ **Recombination – Saturation:**
  - ✧ **All terms are important!**
  - ✧ **Wave feature > particle feature!**
- ❑ **Saturation scale – dynamical:**

$$Q_s^2(x) \simeq \alpha_s \frac{xG(x,Q_s^2)}{\pi R^2} \sim \frac{1}{x^\lambda}$$

$$\propto \langle F^{+\perp}F^{+\perp}\rangle$$

See Itakura's talk



Reaching the saturation region

- **HERA(ep):**

  $$Q_s^2 \leq 1 \text{ GeV}^2$$

  for all values of x

- **Local probe:**

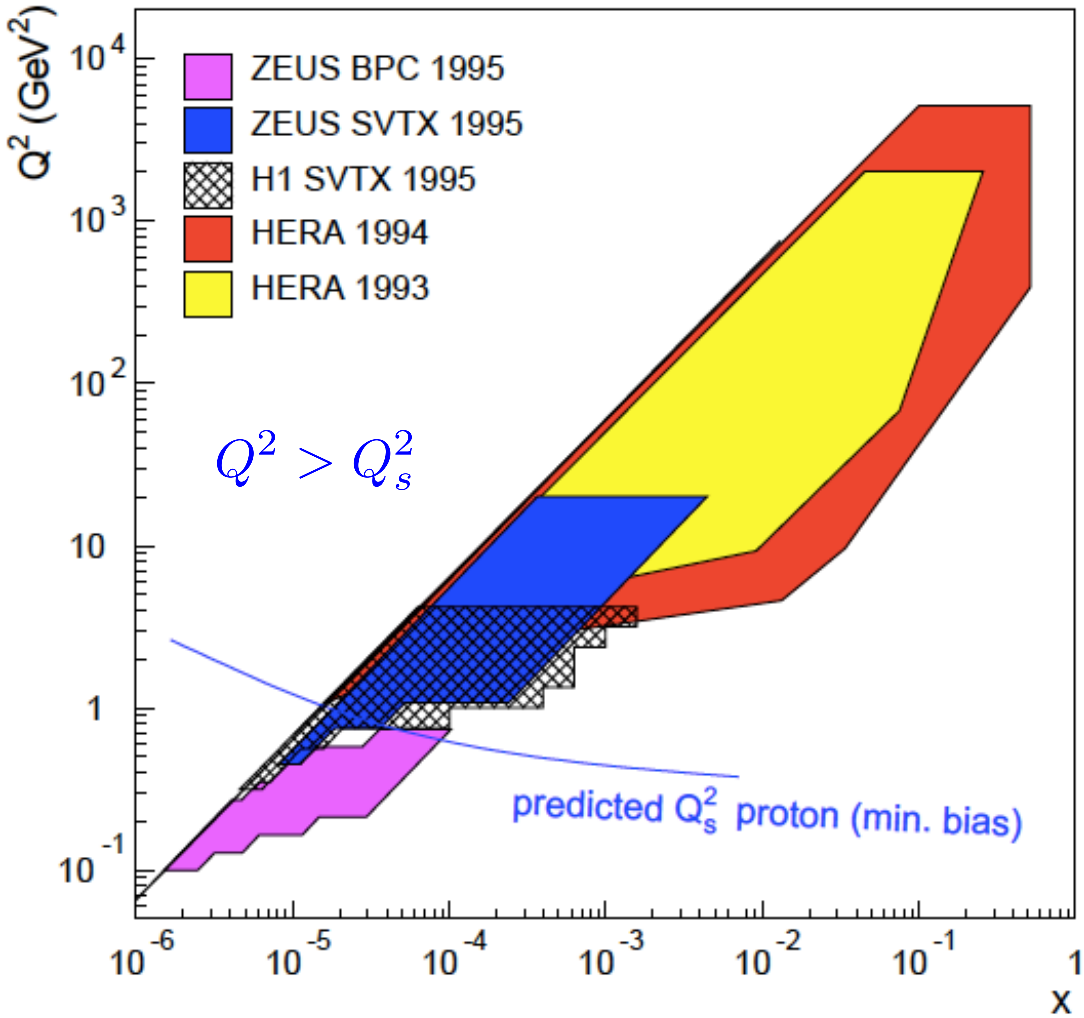
  If $Q^2 \geq 1 \text{ GeV}^2$,

  whole HERA kinematics is outside the saturation region $Q^2 > Q_s^2$

- **Need a super "ep":**

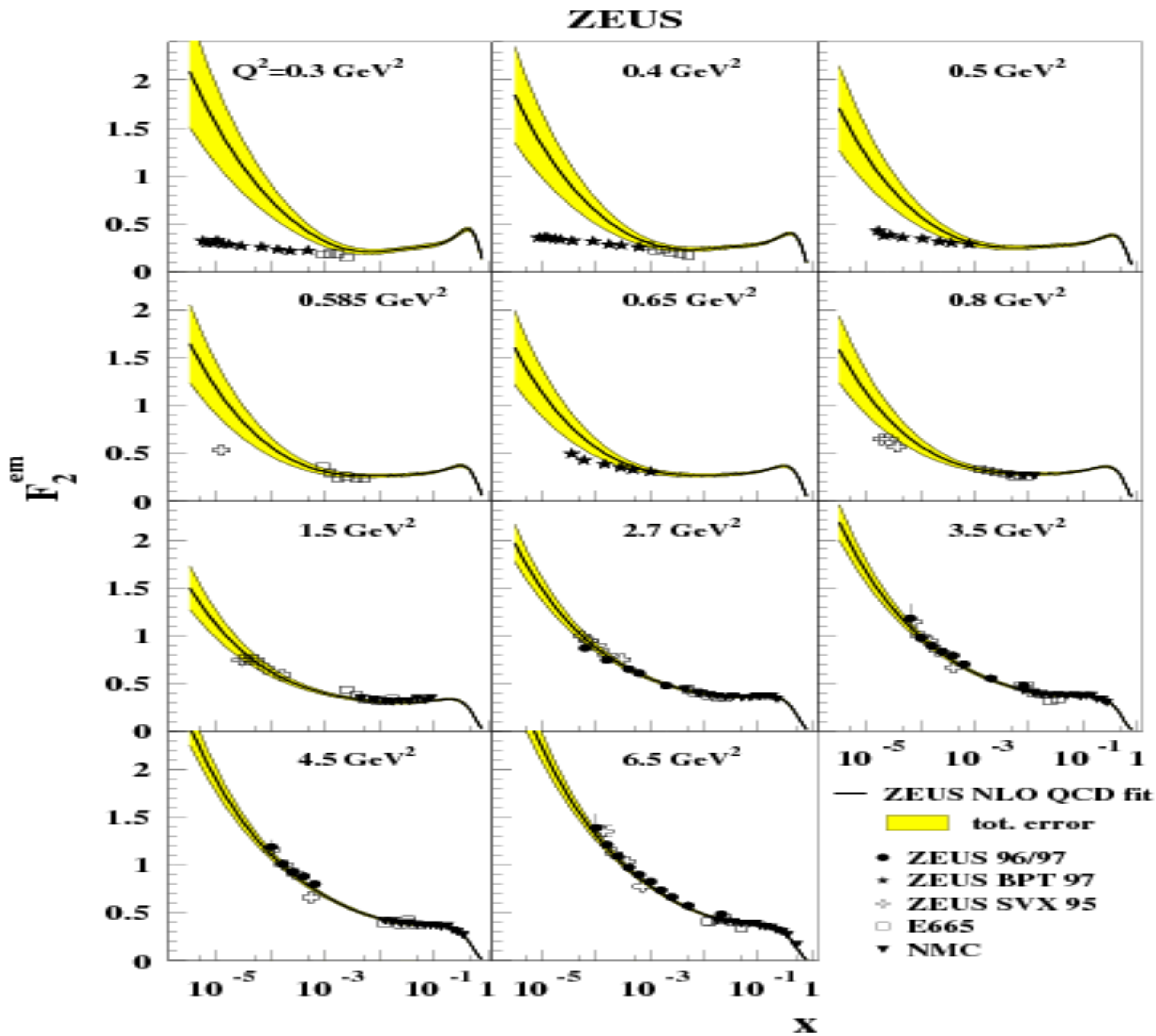
  $$\sqrt{s} > \text{TeV},$$

  for some range of Q



Only hope to see saturation in ep: LHeC?

Breakdown of leading power QCD



Visible failure only when Q < 1 GeV and x is small

DGLAP works well if Q > 2 GeV

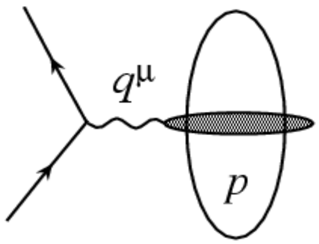
Can a large nucleus help?

❑ **Hard probe – process with a large momentum transfer:**

$$q^\mu \qquad \text{with} \qquad Q \equiv \sqrt{|q^2|} \gg \Lambda_{\rm QCD}$$

❑ **Size of a hard probe is very localized and much smaller than a typical hadron at rest:**

$$\frac{1}{Q} \ll 2R \sim \text{fm}$$



❑ **But, it might be larger than a Lorentz contracted hadron:**

$$\frac{1}{Q} \sim \frac{1}{xp} \geq 2R\left(\frac{m}{p}\right) \qquad \text{or equivalently} \qquad x \leq x_c \equiv \frac{1}{2mR} \sim 0.1$$

Frame independent condition

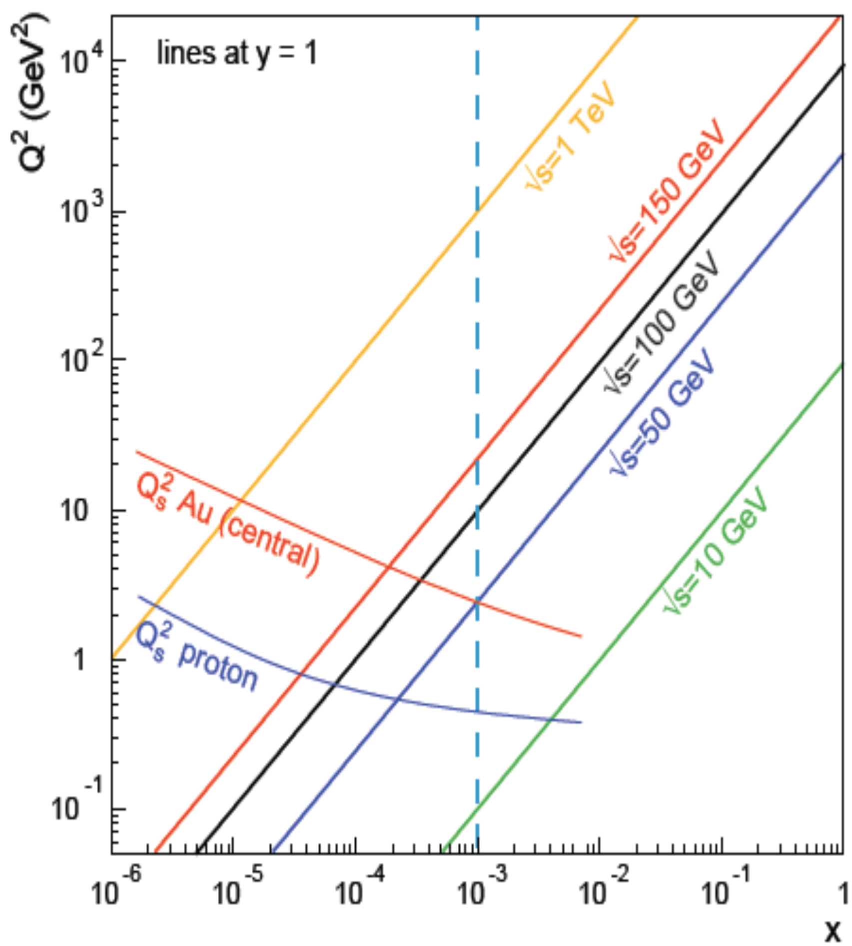
If an active parton *x* is small enough the hard probe could cover several nucleons in a Lorentz contracted large nucleus! ⟹ **More coherent partons at an impact parameter**

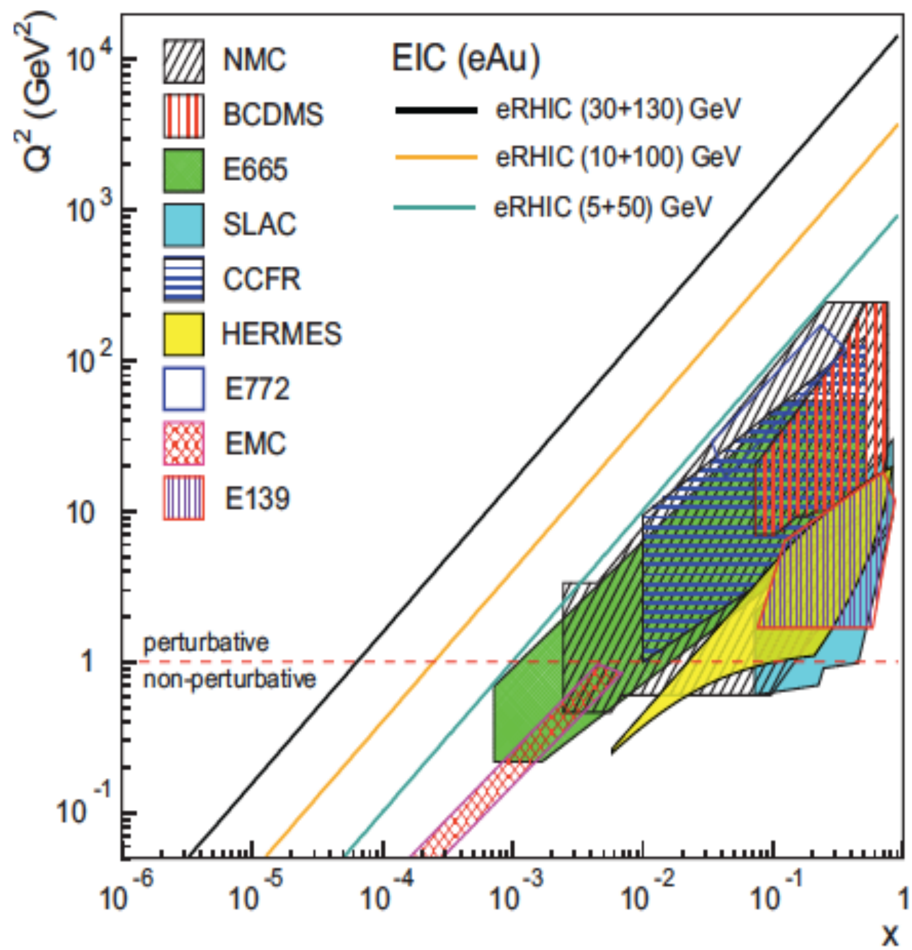
Reaching the saturation with eA

- ❑ **small-x probe interacts with partons from all nucleons at a given impact parameter:**

$$Q_s^2(eA) \propto Q_s^2(ep)\ A^{1/3}$$

See Ullrich's talk





Golden measurements

The INT report

QCD matter in nuclei				
Deliverables	Observables	What we learn	Phase I	Phase II
integrated gluon distributions	$F_{2,L}$	nuclear wave function; saturation, Q_s	gluons at $10^{-3} \leq x \leq 1$	explore sat. regime
k_T-dep. gluons; gluon correlations	di-hadron correlations	non-linear QCD evolution/universality	onset of saturation; Q_s	RG evolution
transp. coefficients in cold matter	large-x SIDIS; jets	parton energy loss, shower evolution; energy loss mech.	light flavors, charm bottom; jets	precision rare probes; large-x gluons

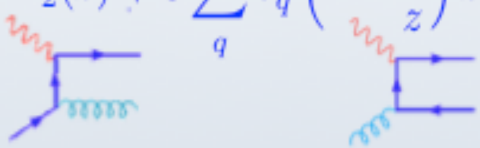
Three-dimensional structure of the nucleon and nuclei: spatial imaging			
Deliverables	Observables	What we learn	Requirements
sea quark and gluon GPDs	DVCS and $J/\psi, \rho, \phi$ production cross sect. and asymmetries	transverse images of sea quarks and gluons in nucleon and nuclei; total angular momentum; onset of saturation	$\mathcal{L} \geq 10^{34}$ cm^{-2}s^{-1}, Roman Pots wide range of x_B and Q^2 polarized e^- and p beams e^+ beam for DVCS

"See" gluons

- **F_2 – gluon comes at NLO:**
  scheme dependent

- **F_L – gluon comes at LO:**

$$F_L = \frac{\alpha_s}{4\pi} x^2 \int_x^1 \frac{dz}{z^3} \left[\frac{16}{3} F_2(z) + 8 \sum_q e_q^2 \left(1 - \frac{x}{z}\right) z g(z) \right]$$



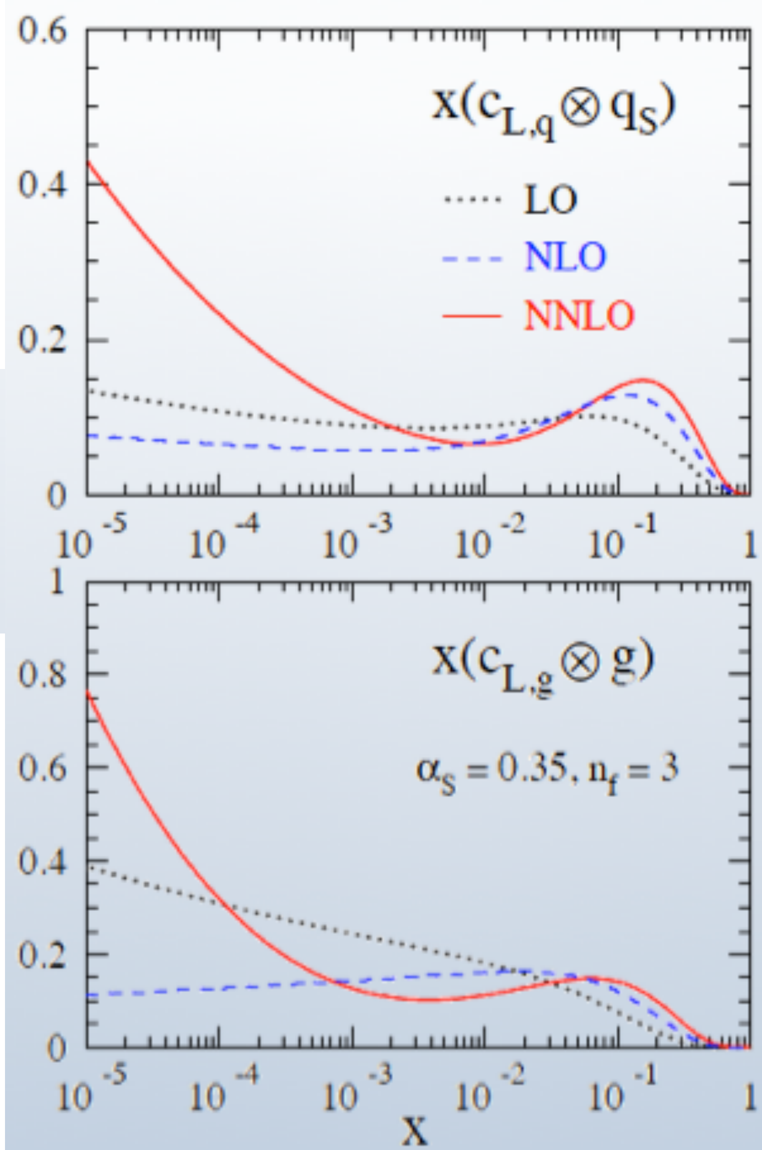
No small-x growth until NNLO

- **Unfinished business at HERA:**

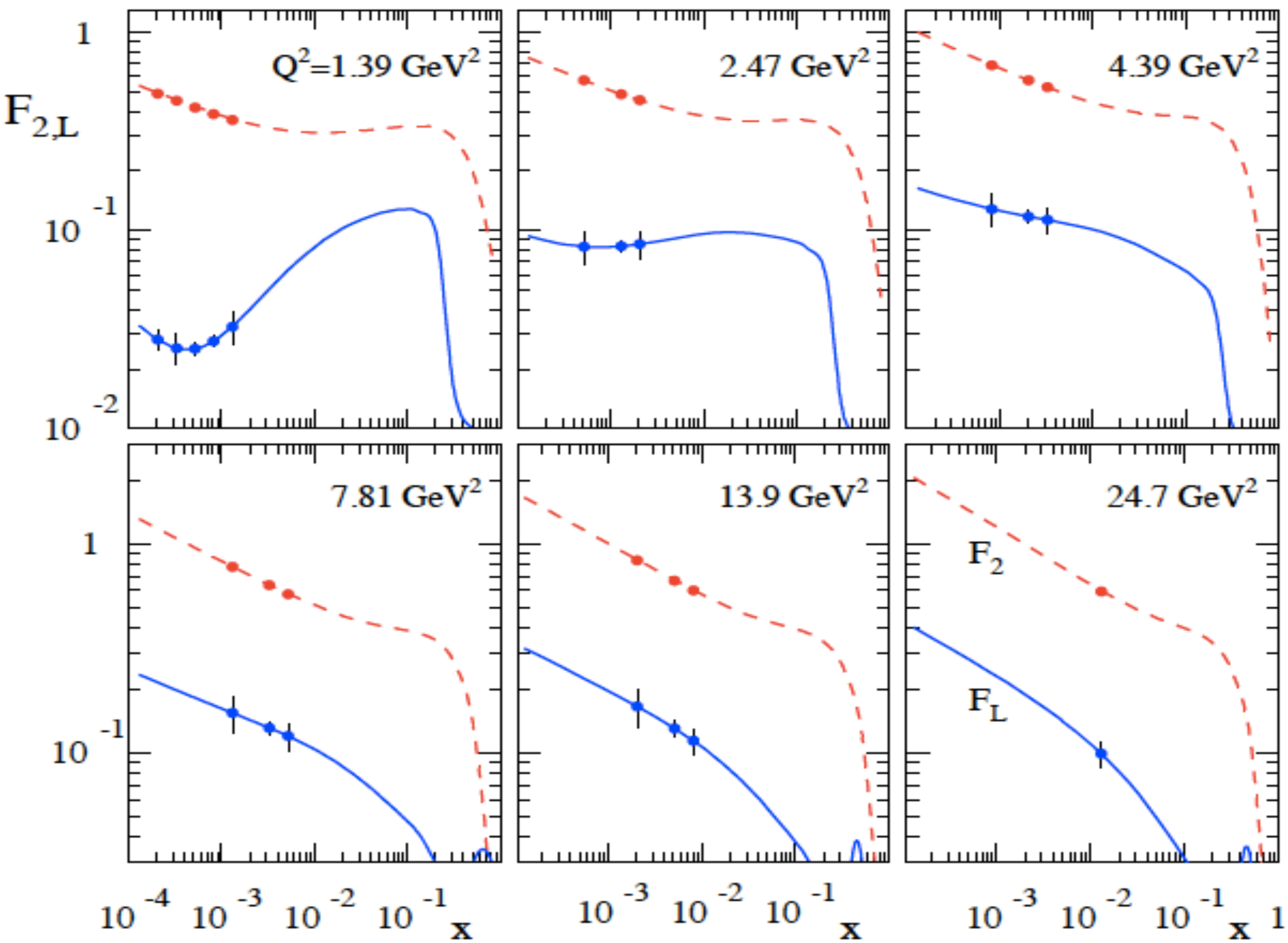
Need good coverage on y-dependence

or energy scan

EIC should be able to do that



F_L measurement at EIC



Energy: 5 GeV + 100 (250, 325) GeV

INT report

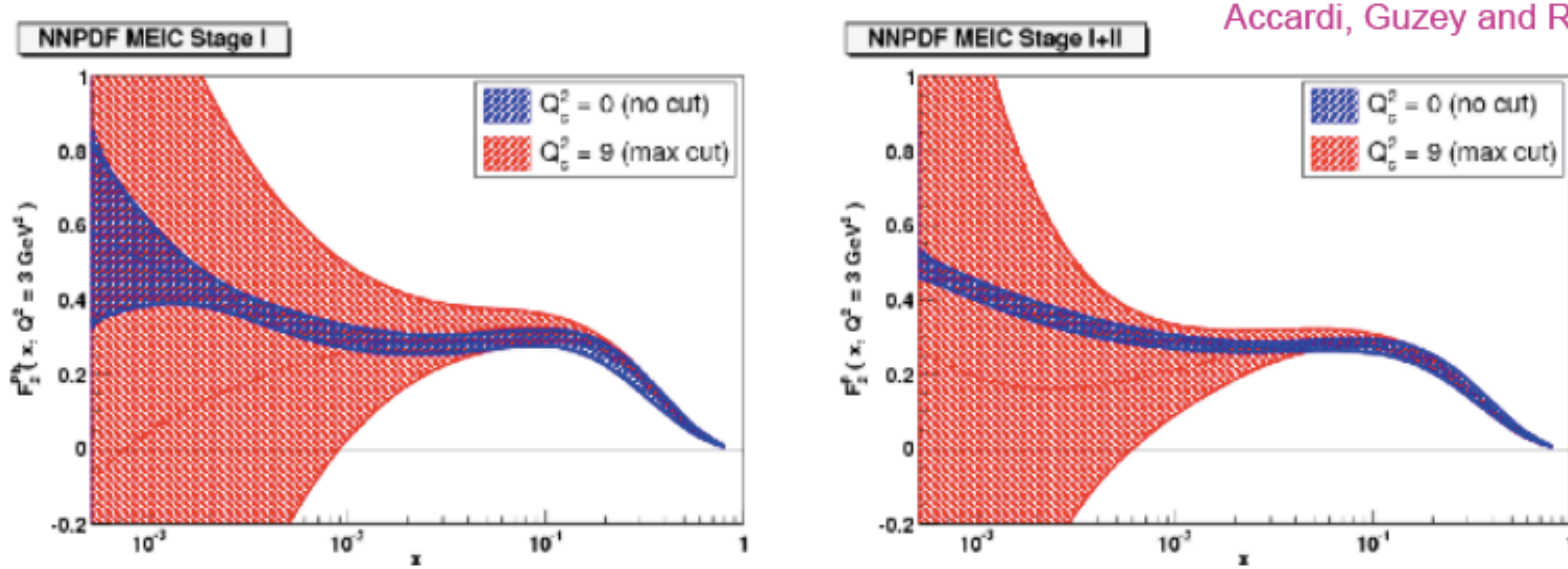
F_2 - Seek deviation from DGLAP

Marquet@EICAC

❑ **DGLAP cannot describe the saturation region:**

- create small-x pseudo-data with non-linear QCD evolution
- perform a DGLAP fit only in the “safe region” large Q^2 region
- evolve into the “saturation” region using DGLAP
- compare to what a full DGLAP fit would have produced

Accardi, Guzey and Rojo

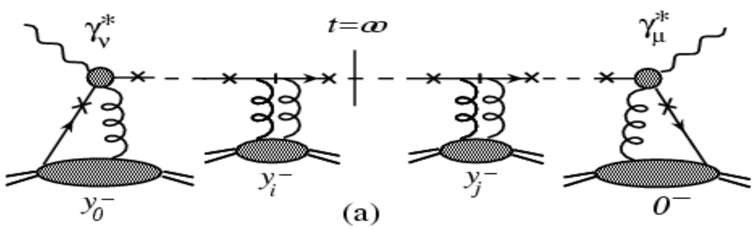


systematic downward shift: signal of deviations from DGLAP

for a Pb nucleus, deviations from DGLAP would be unambiguously identified within the x range of the full-energy EIC

Transition region – close to saturation

❑ Power corrections:



$$x_B^N \left[(-1)^N \frac{1}{N!} \frac{d^N}{dx^N} \delta(x - x_B) \right]$$

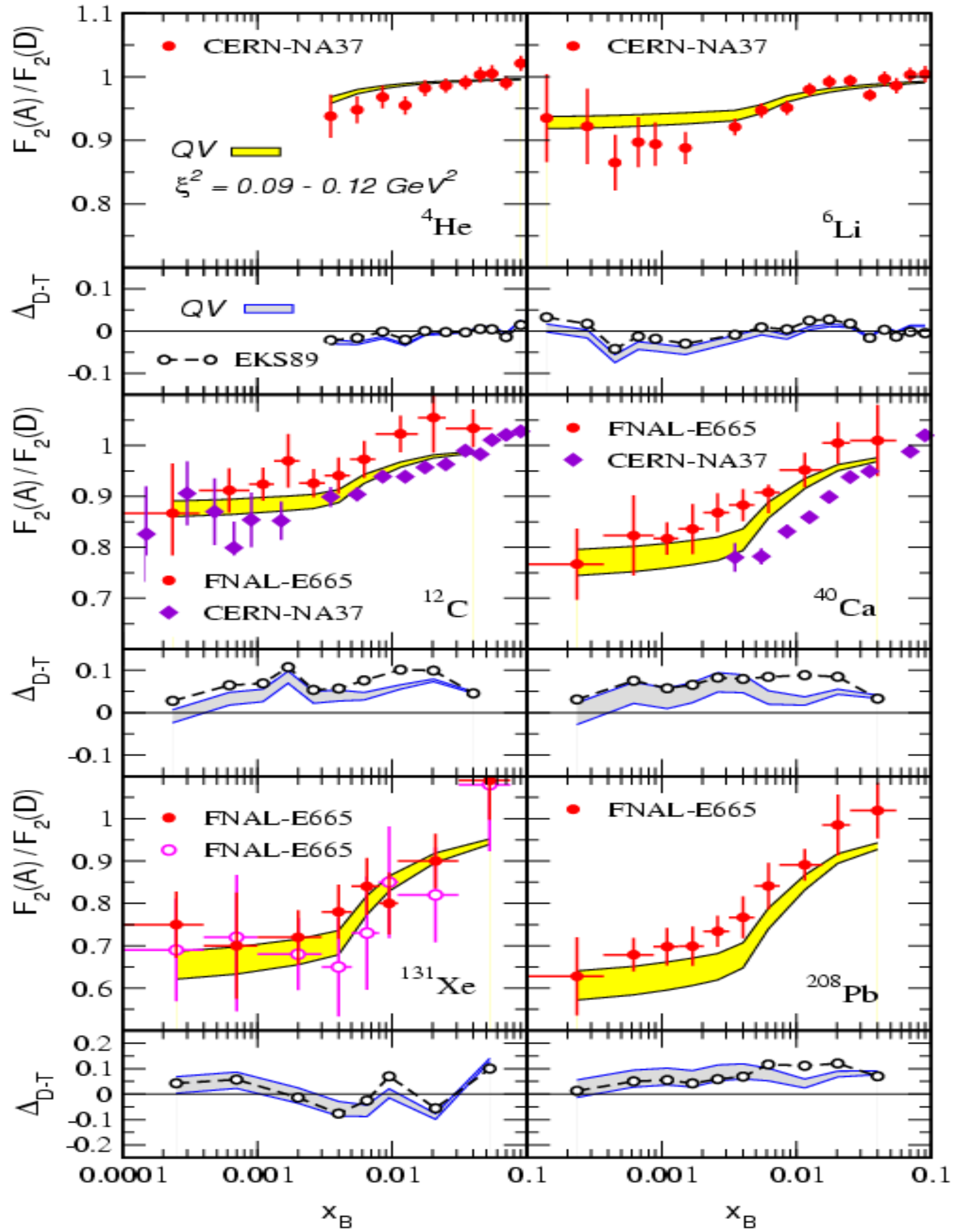
$$F_T(x_B, Q^2) = \sum_{n=0}^{N} \frac{1}{n!} \left[\frac{\xi^2}{Q^2} \left(A^{1/3} - 1\right) \right]^n x_B^n \frac{d^n}{dx_B^n} F_T^{(0)}(x_B, Q^2)$$

$$\approx F_T^{(0)}(x_B(1+\Delta), Q^2)$$

$$\Delta \equiv \frac{\xi^2}{Q^2} \left(A^{1/3} - 1\right)$$

$$\xi^2 = \frac{3\pi\alpha_s}{8R^2} \langle F^{+\alpha} F_\alpha{}^+ \rangle$$

$$\xi^2 = 0.09 - 0.12 \ \mathrm{GeV}^2$$



for all A-, Q-, and x-dependence!

Nuclear PDFs

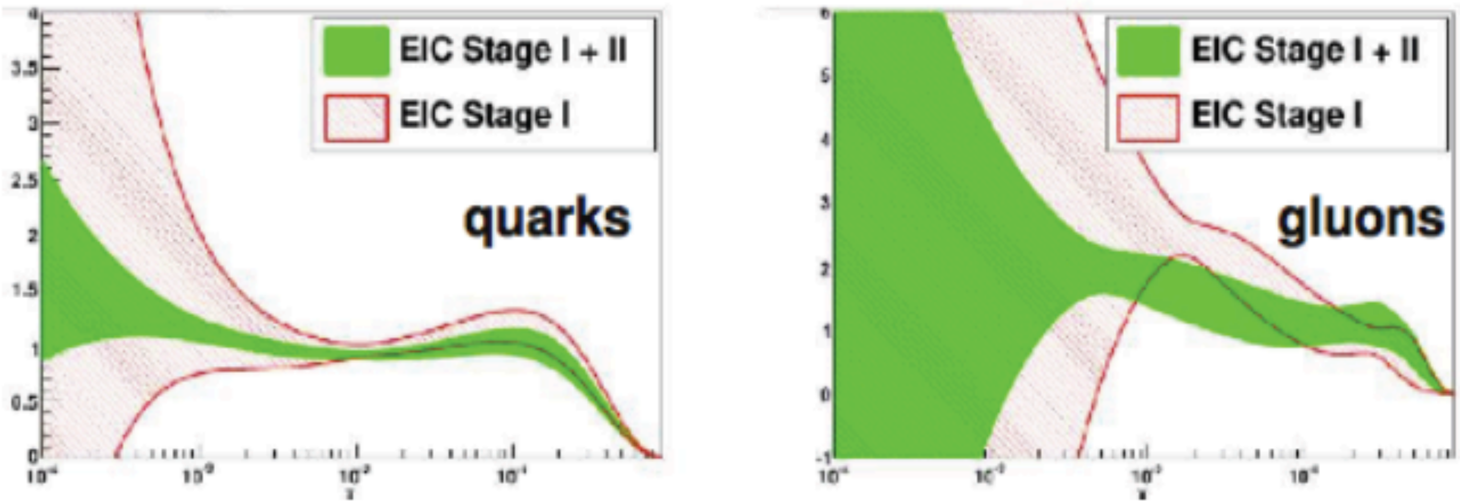
Marquet@EICAC

❑ **EIC is much better to map out nuclear PDFs:**

- QCD fits on e+A pseudo-data

with $\sqrt{s}$ = 12, 17, 24, 32, 44 GeV (medium energy EIC – stage I)
63, 88, 124 GeV (full energy EIC – stage I)

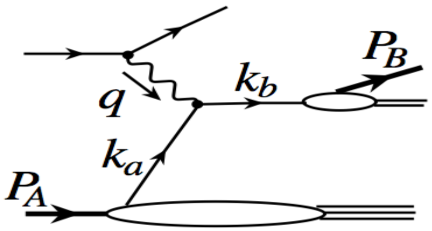
allows to estimate nuclear quark and gluon distributions and their uncertainties



the EIC has constraining power, it will be to nuclei what HERA is to the proton

- Nuclear GPDs, nuclear TMDs

SIDIS - TMD factorization

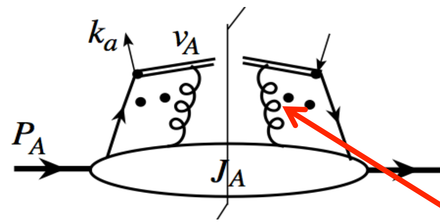


$$\sigma_0\, \phi(x,\mu) \otimes D(z,\mu)\delta^2(p_{BT})$$

$$\sigma_0\ \widetilde{\phi}(x,k_{aT}) \otimes \widetilde{D}(z,k_{bT})\ \delta^2(p_{BT} - k_{aT} - k_bT)$$

- **TMD parton distribution:**

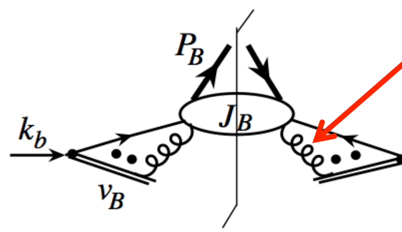
$$\widetilde{\phi}^{(0)}_{f/A}(x,k_{aT}) = \mathrm{Tr}_{\mathrm{color}}\mathrm{Tr}_{\mathrm{Direc}}\frac{\gamma^+}{2}\int\frac{dk_a^-}{2\pi}$$



Gauge links

- **TMD fragmentation function:**

$$\widetilde{D}^{(0)}_{f\to B}(z,k_{bT}) = \frac{\mathrm{Tr}_{\mathrm{color}}}{N_c}\frac{\mathrm{Tr}_{\mathrm{Direc}}}{4}\frac{\gamma^+}{z}\int\frac{dk_b^-}{2\pi}$$



- **Naturally 2-scale observable:** $Q^2 \gg p_T^2 \sim Q_s^2$

Direct probe of the saturation scale!

Di-hadron angular distributions in pA

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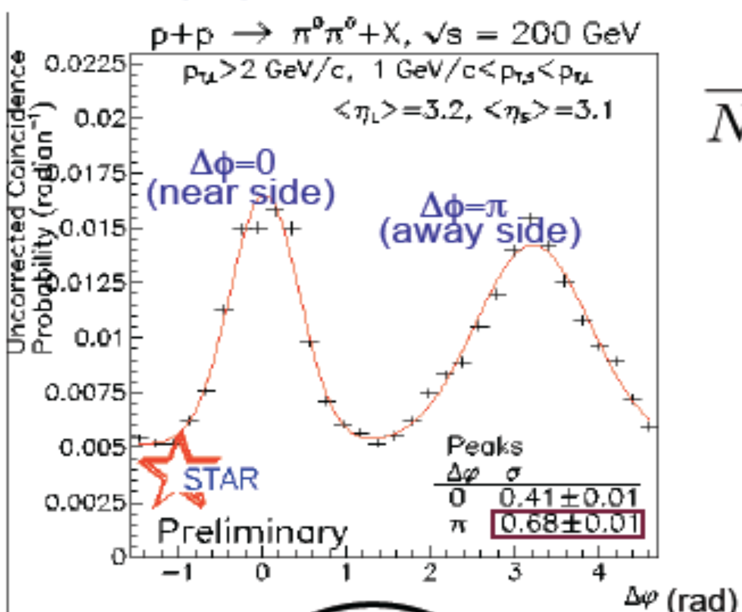
❑ Di-hadron correlation:

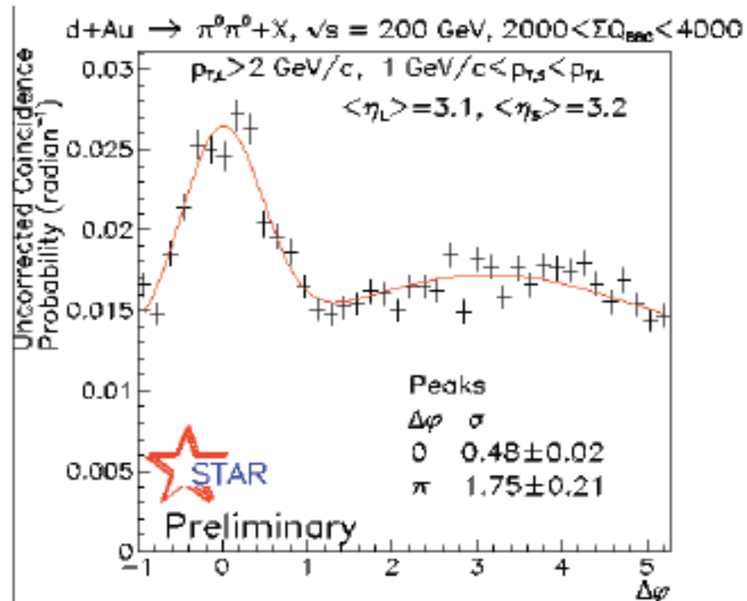
comparisons between d+Au → h_1 h_2 X (or p+Au → h_1 h_2 X) and p+p → h_1 h_2 X

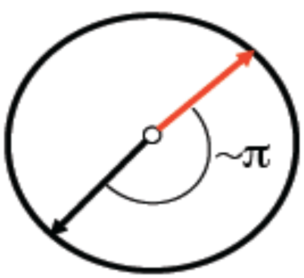
p+p collisions



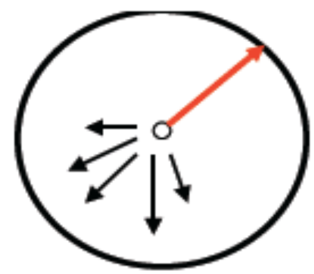
$$\frac{1}{N_{trig}} \frac{dN_{pair}}{d\Delta\varphi}$$

central d+Au collisions





$$x_A = \frac{k_1\, e^{-y_1} + k_2\, e^{-y_2}}{\sqrt{s}} << 1$$

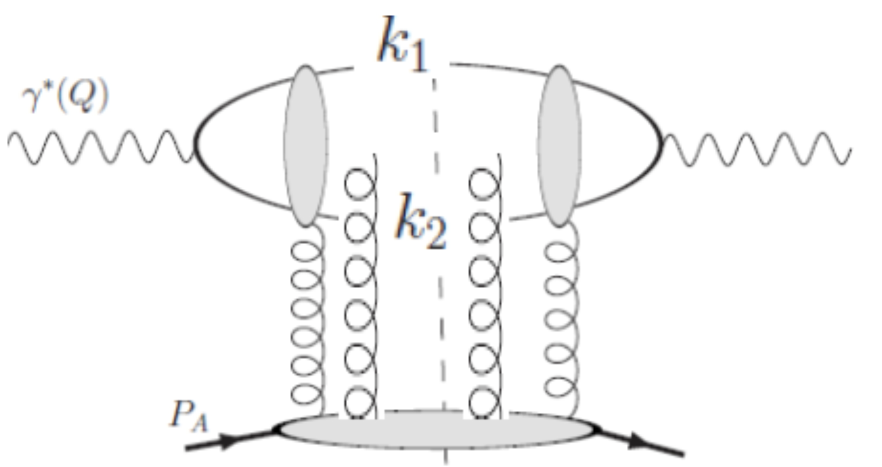


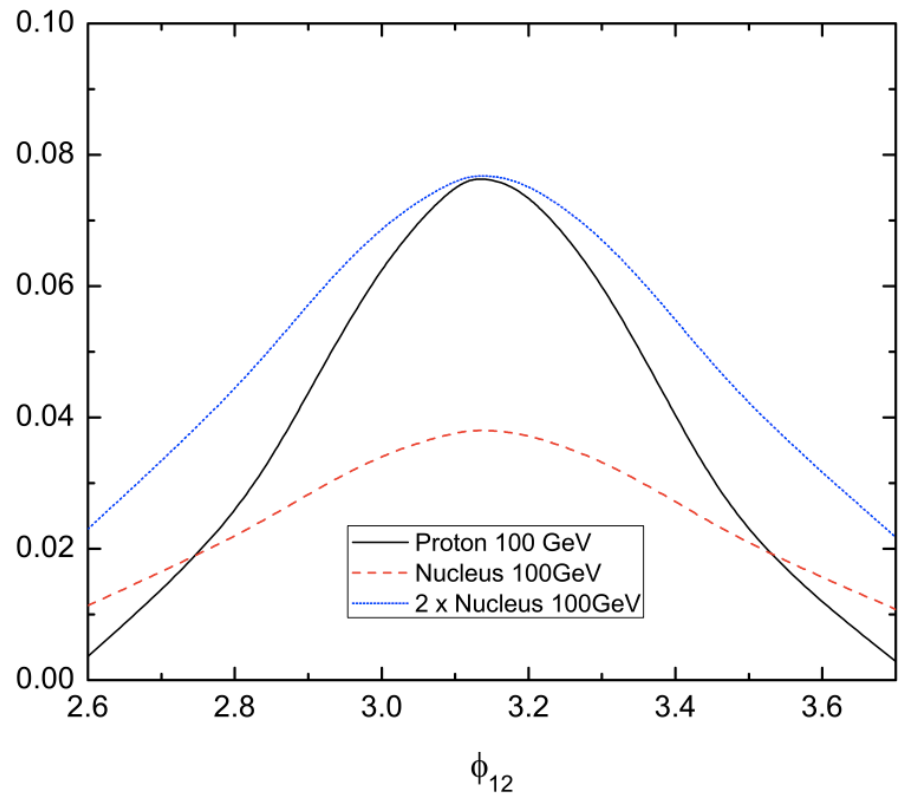
however, when $y_1 \sim y_2 \sim 0$ (and therefore $x_A \sim 0.03$), the p+p and d+Au curves are almost identical

Di-hadron angular distributions in eA

Dominguez, Xiao, Yuan (2010)

❑ CGC/color dipole calculation:





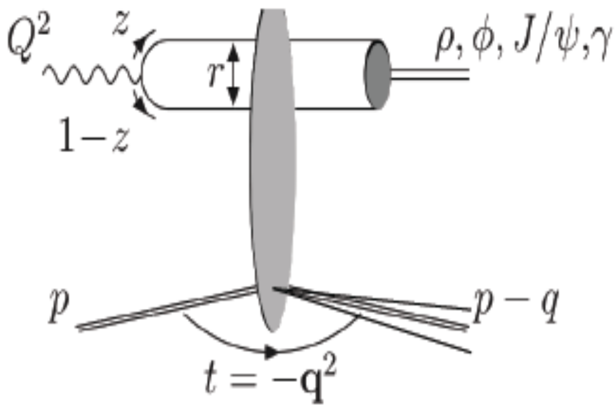
✧ Never be measured!

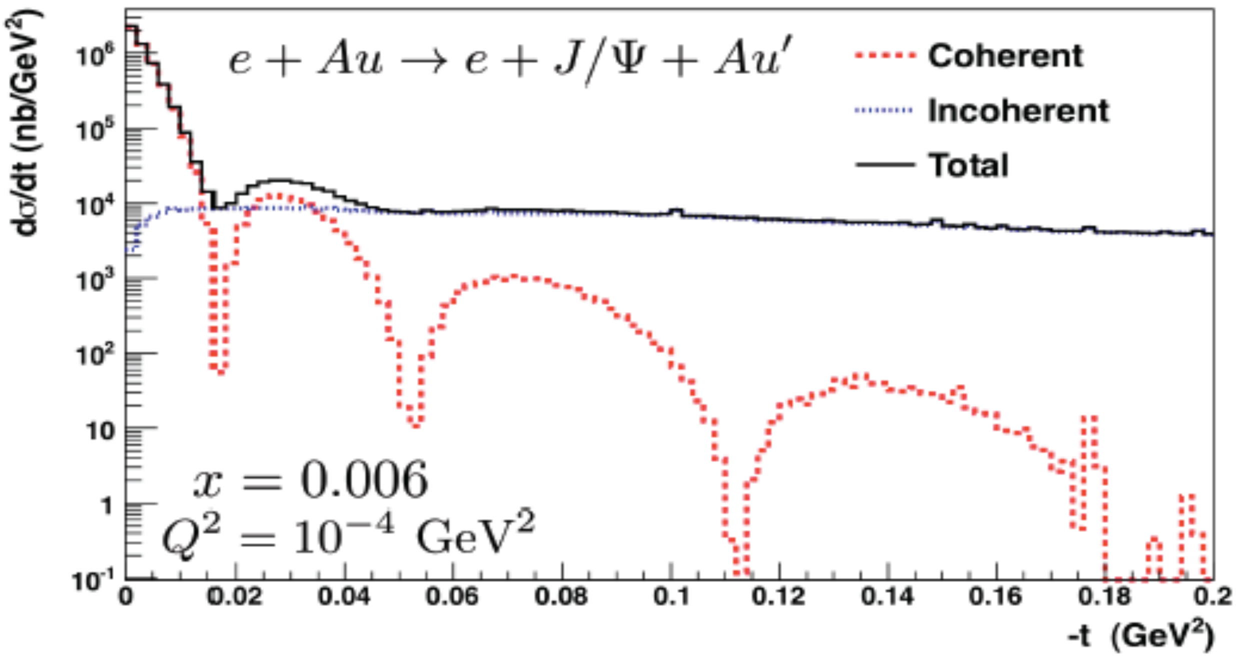
✧ Directly probe Weizsacker-Williams gluon distribution in nucleus

✧ A factor of 2 suppression of away-side hadron-correlation!

Diffractive vector meson production

Toll and Ullrich (2011)



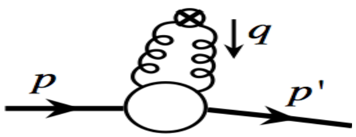


- as a function of t

❑ **Exclusive (coherent):**

✧ **Fourier transform of t dependence:**

➡ **Gluon GPD's**

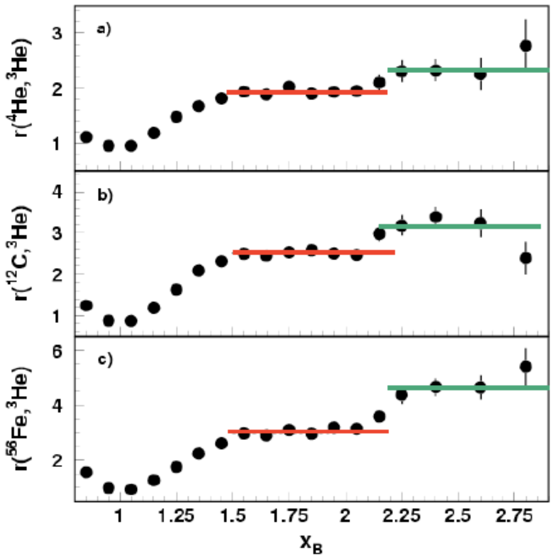


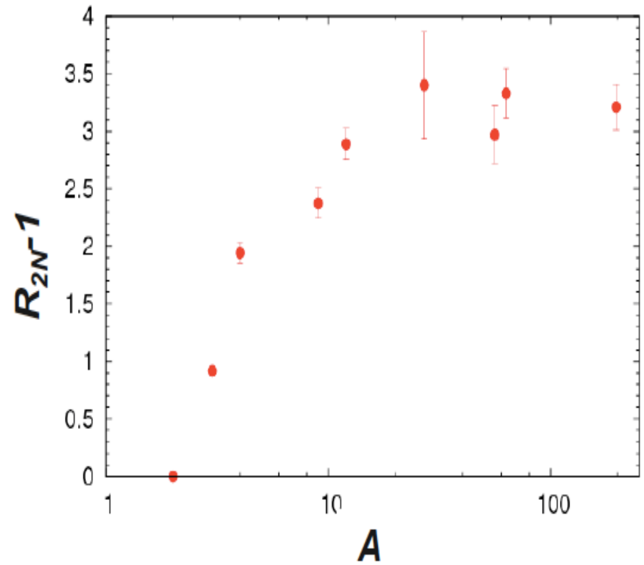
✧ **3-D gluon density imaging of a nucleus**

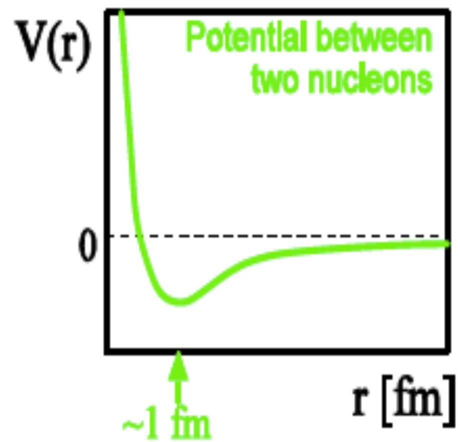
Could be very useful tool to probe the short-range correlations!

Short-range correlations (SRCs)

❑ Superfast quarks:

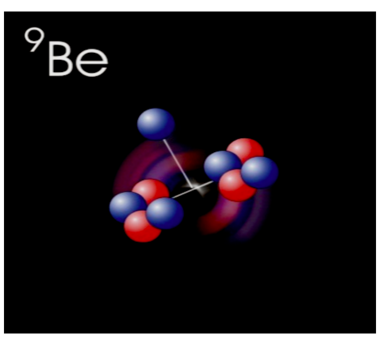


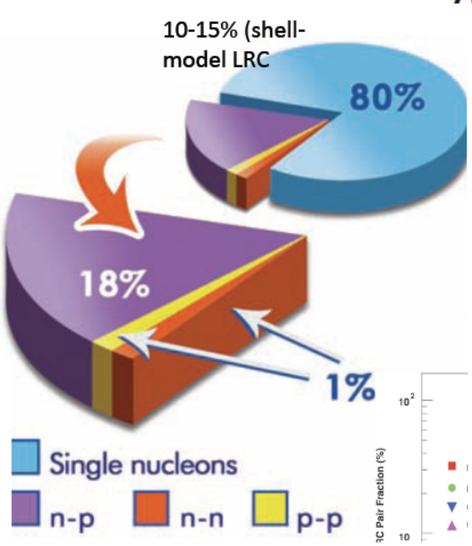




❑ Structure of ^{12}C:

3-D imaging?



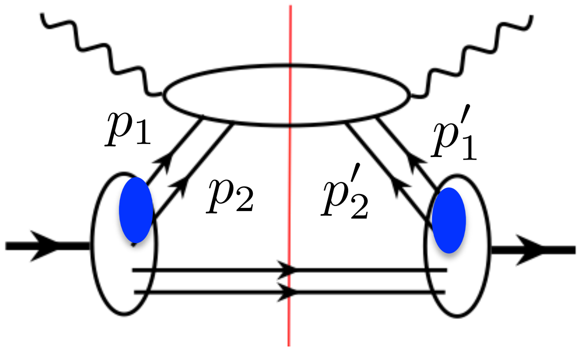


❑ What is the range of color correlation?

Size of nucleon
or longer?

Color coherence inside a nucleus

- GPDs in nuclear collisions:



In a nucleus: $p_i \neq p_i'$

At large x: GPDs $\rightarrow$ PDFs

"color singlet nucleon"

At small x: GPDs with large Δ !

- A-dependence of structure functions, …

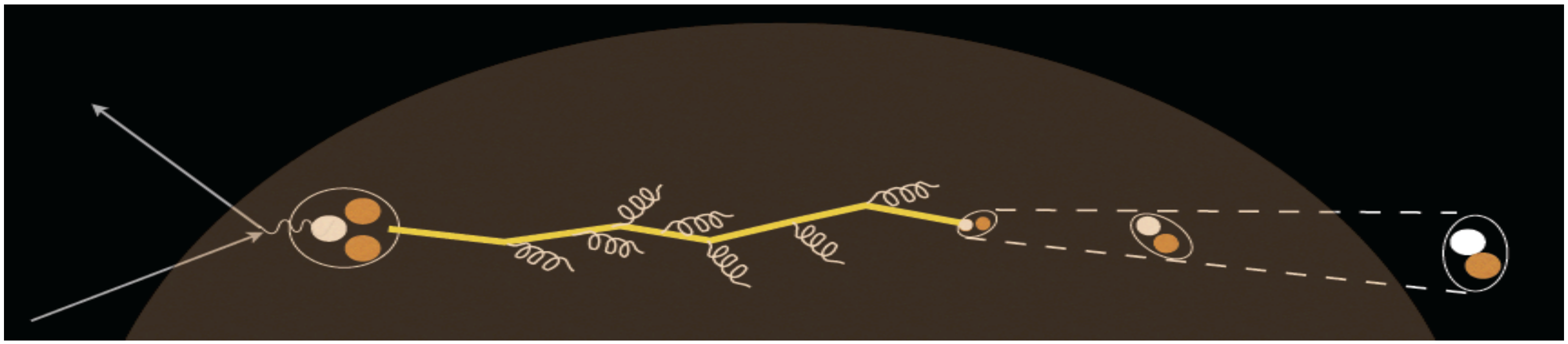
$A^{1/3}$ – No color coherence between amplitude and its c.c.

$A^{2/3}$ – Complete long range color coherence inside nucleus
– more like a large proton case

- Is there a "universality" for proton and nucleus
  - – long range color coherence – more close to $A^{2/3}$?
  - – or superposition of color singlet nucleons – to $A^{1/3}$?

In-medium hadronization

- ❑ **Unprecedented range of photon energy ν at EIC:** $\nu = \frac{Q^2}{2mx}$



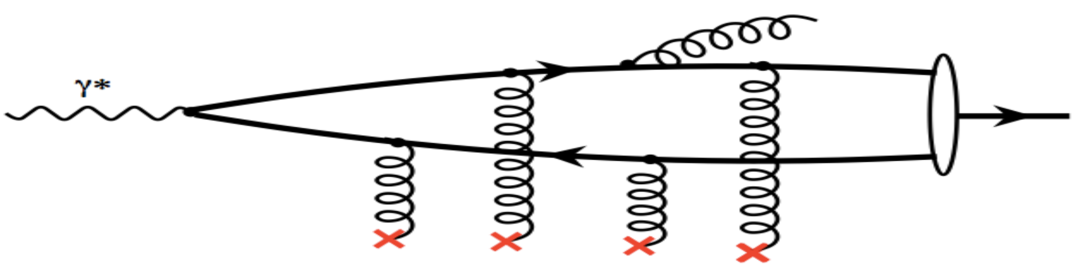
- ✧ **Small ν - in medium hadronization:**

  Stages of hadronization: parton, pre-hadron, hadron

- ✧ **Large ν - parton multiple scattering:**

  Parton energy loss – cold nuclear matter $\hat{q}$

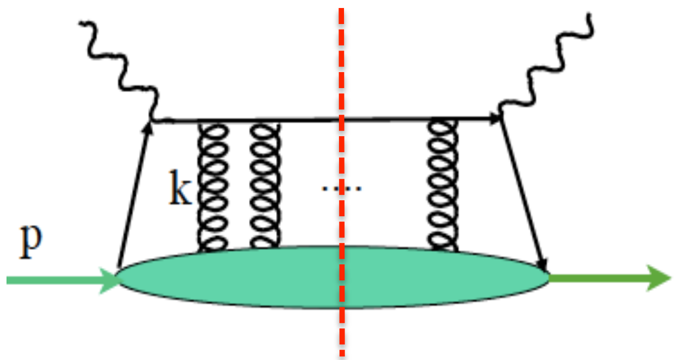
- ❑ **Heavy quark and quarkonium production:**



Filter for production mechanism!

Transverse momentum broadening

- Multiple scattering – transverse momentum broadening:



$$\langle p_T^2 \rangle_{eA} \equiv \int dp_T^2 \; p_T^2 \; \frac{d\sigma_{eA}}{dx_B dQ^2 dp_T^2} \Big/ \frac{d\sigma_{eA}}{dx_B dQ^2}$$

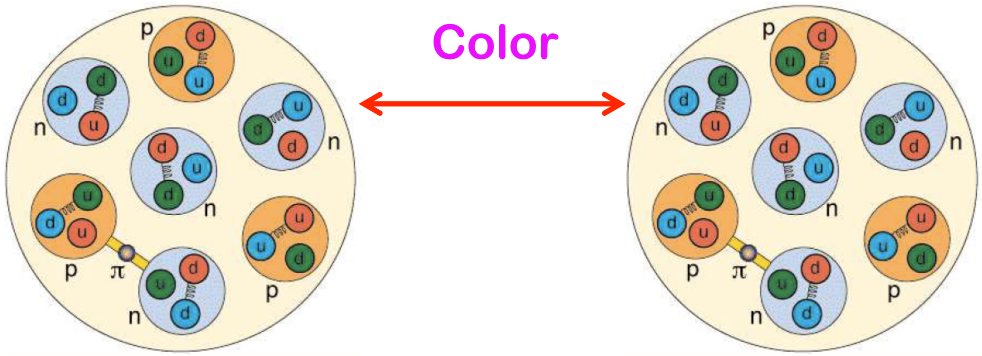
$$\Delta \langle p_T^2 \rangle_{A/N} = \langle p_T^2 \rangle_{eA} - \langle p_T^2 \rangle_{eN}$$

Guo, 1996

- A-dependence of the broadening:

$$\Delta \langle p_T^2 \rangle_{A/N} \propto A^{1/3}$$

– No long-range color correlation

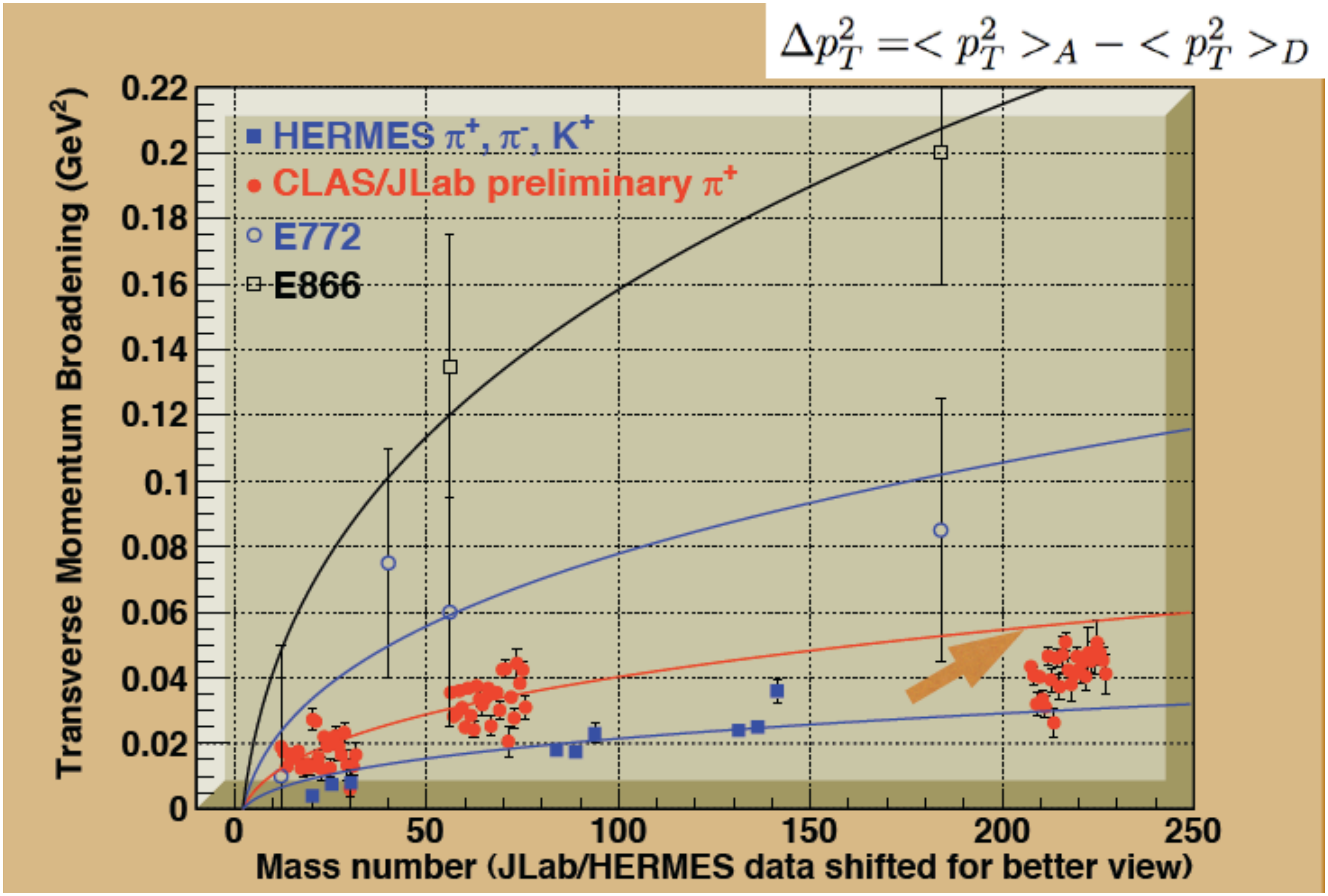


- x_B – dependence? - EIC

Transverse momentum broadening

❑ **Low energy Drell-Yan and SIDIS:**

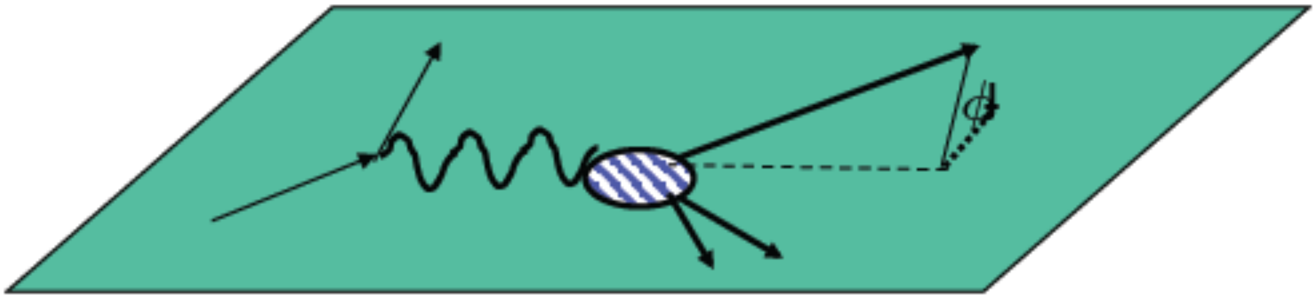
$$\Delta p_T^2 = < p_T^2 >_A - < p_T^2 >_D$$



Density distribution – Fluctuation

- **Azimuthal distribution:**

Guo, Liang, Wang, 2010



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

- **A-dependence of the k_T-dependent distribution:**

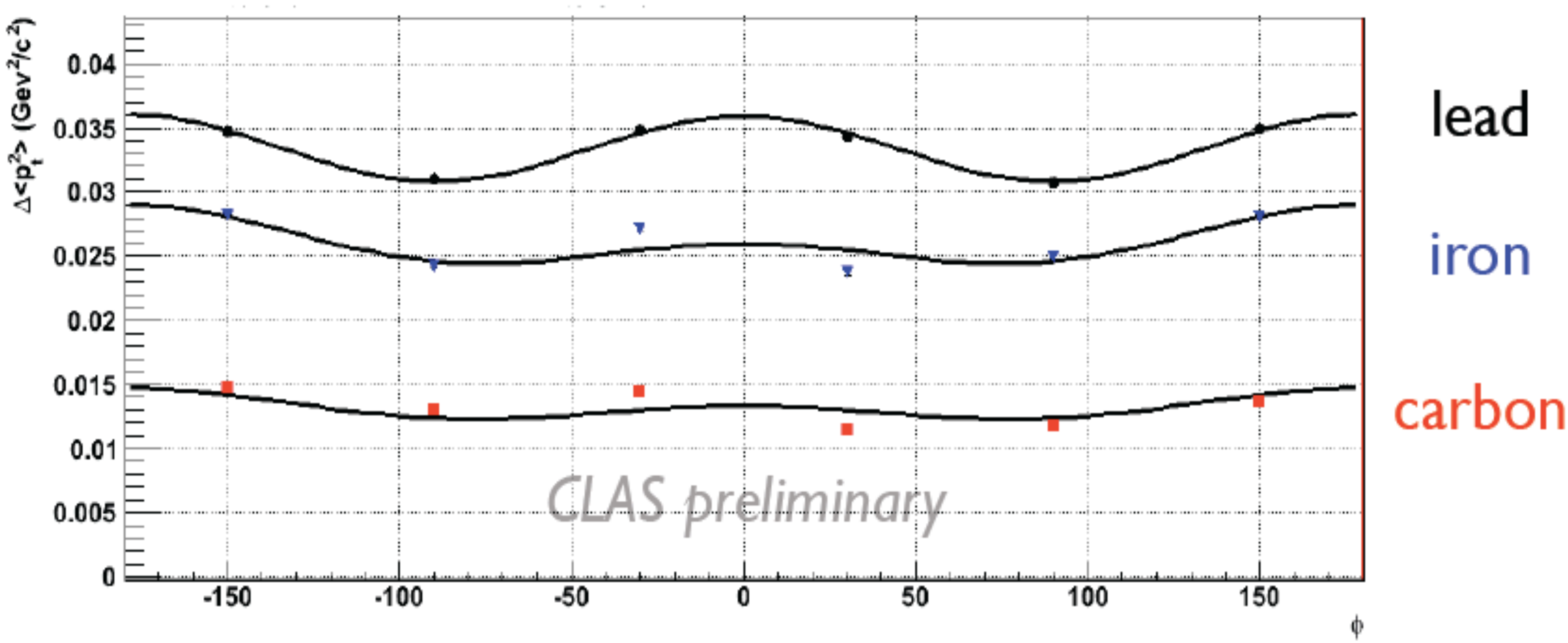
$$f^q_{A\perp}(x, k_T) \approx \left(1 + \frac{\Delta}{2k_T^2}\vec{k}_T \cdot \vec{\partial}_{k_T}\right) \frac{A}{\pi\Delta} \int d^2q_\perp \exp\left[-\frac{(\vec{k}_\perp - \vec{q}_\perp)^2}{\Delta}\right] f^q_{N\perp}(x, \vec{q}_\perp)$$

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

Azimuthal asymmetry

❑ **Preliminary low energy data:**

Brooks, PINAN2011



✧ **Classical expectation:**

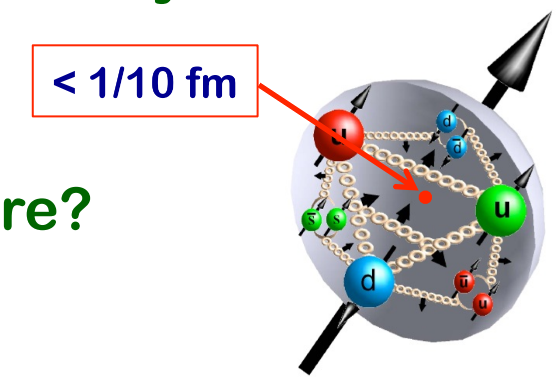
Any distribution seen in Carbon should be washed out in heavier nuclei

✧ **Surprise:**

Quantum effect in transverse momentum broadening – fluctuation!

Summary

- QCD factorization/calculation have been very successful in interpreting HEP scattering data



- What about the hadron/nuclear structure?

  Not much!

- EIC is a much needed machine to study hadron/nuclear structure in terms of quarks and gluons

  Quark-Gluon Nuclear Physics

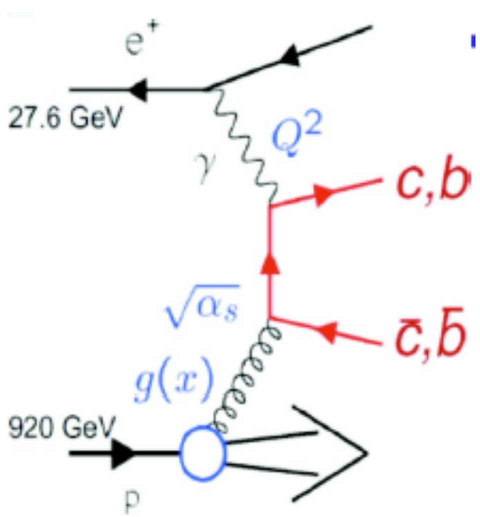
- The challenge:
  – to identify new and calculable observables that carry rich information on partonic structure
  – to make measureable predictions – much needed simulations

Thank you!

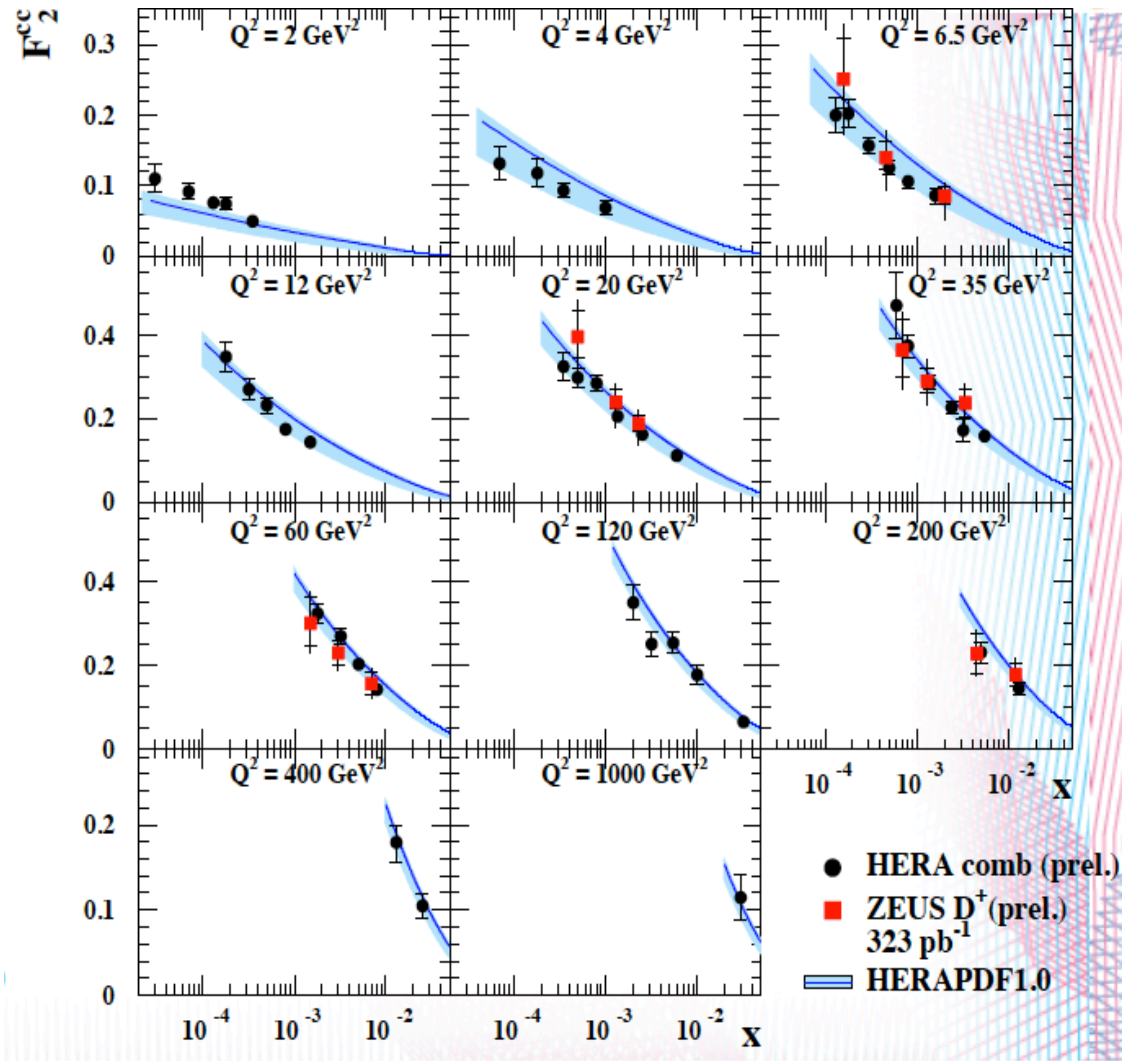
Backup slices

Direct information on gluon distribution

❑ Heavy flavor production in SIDIS:



H1+ZEUS



Gluon continues to grow at $x=10^{-5}$ and $Q^2=2$ GeV^2

EIC could explore even smaller x region!