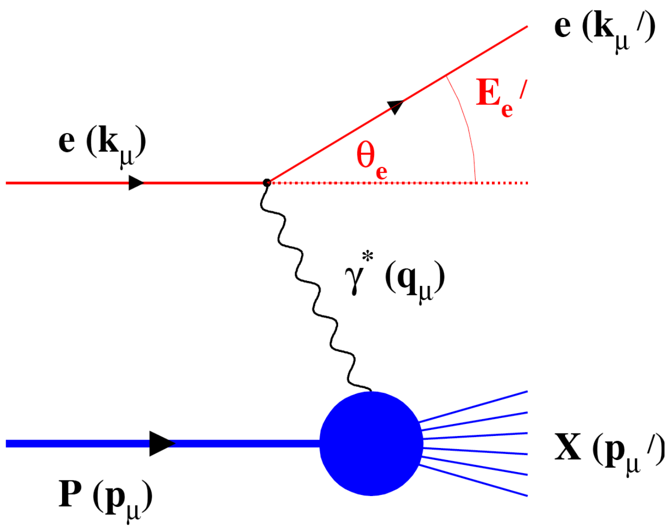

# Connection to Electron-Ion Collider and the opportunities

**Jianwei Qiu**
*Brookhaven National Laboratory*

Acknowledgement: Much of the physics presented here are based on the work of EIC White Paper Writing Committee put together by BNL and JLab managements, …

# The lepton-hadron scattering facility




$Q^2$ → Measure of resolution

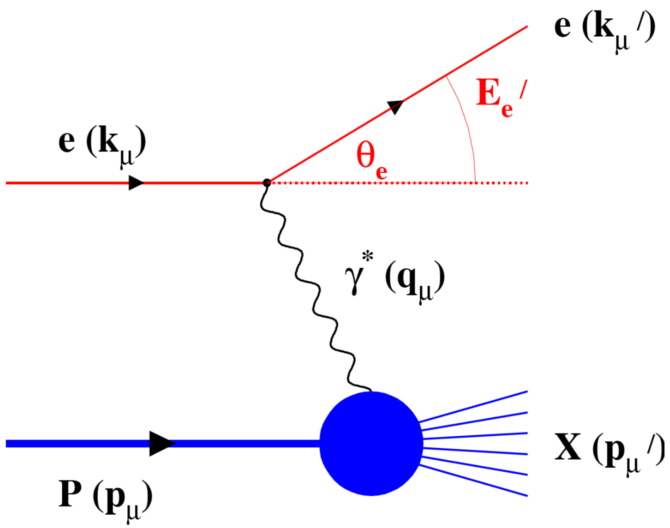
$y$ → Measure of inelasticity

$x$ → Measure of momentum fraction of the struck quark in a proton

$Q^2 = S\ x\ y$

- Complimentary to lepton-lepton and hadron-hadron scattering
- Have a number of important advantages:
  - A well-controlled hard scale: $Q^2$ – a clean short-distance probe
  - Better control of the partonic kinematics
  - Natural event structure with one large and one small scales – TMDs
  - Large momentum transfer, $Q^2 >> (1/fm)^2$, without breaking the proton – GPDs
  - Well-defined leptonic scattering plan, angular modulation, fluctuation, …

# The lepton-hadron scattering facility

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$$Q^2 = S\, x\, y$$

- Full of the rich and well-defined observables:

**Inclusive events**: e+p/A → e'+X

Detect only the scattered lepton in the detector

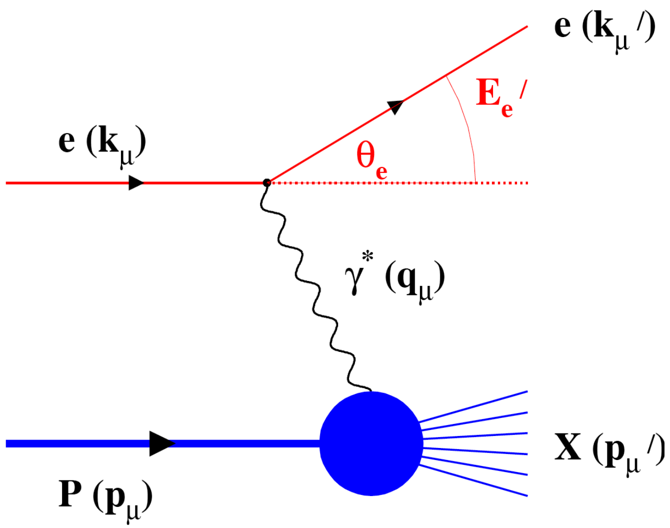
**Semi-Inclusive events**: e+p/A → e'+h($\pi$,K,p,jet)+X

Detect the scattered lepton in coincidence with identified hadrons/jets

**Exclusive events:** e+p/A → e'+ p'/A'+ h($\pi$,K,p,jet)

Detect every things including scattered proton/nucleus (or its fragments)

# New opportunities from pp/pA to ep/eA

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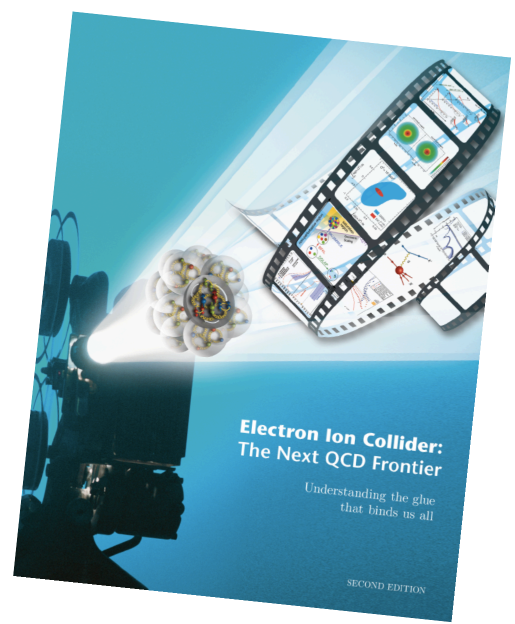
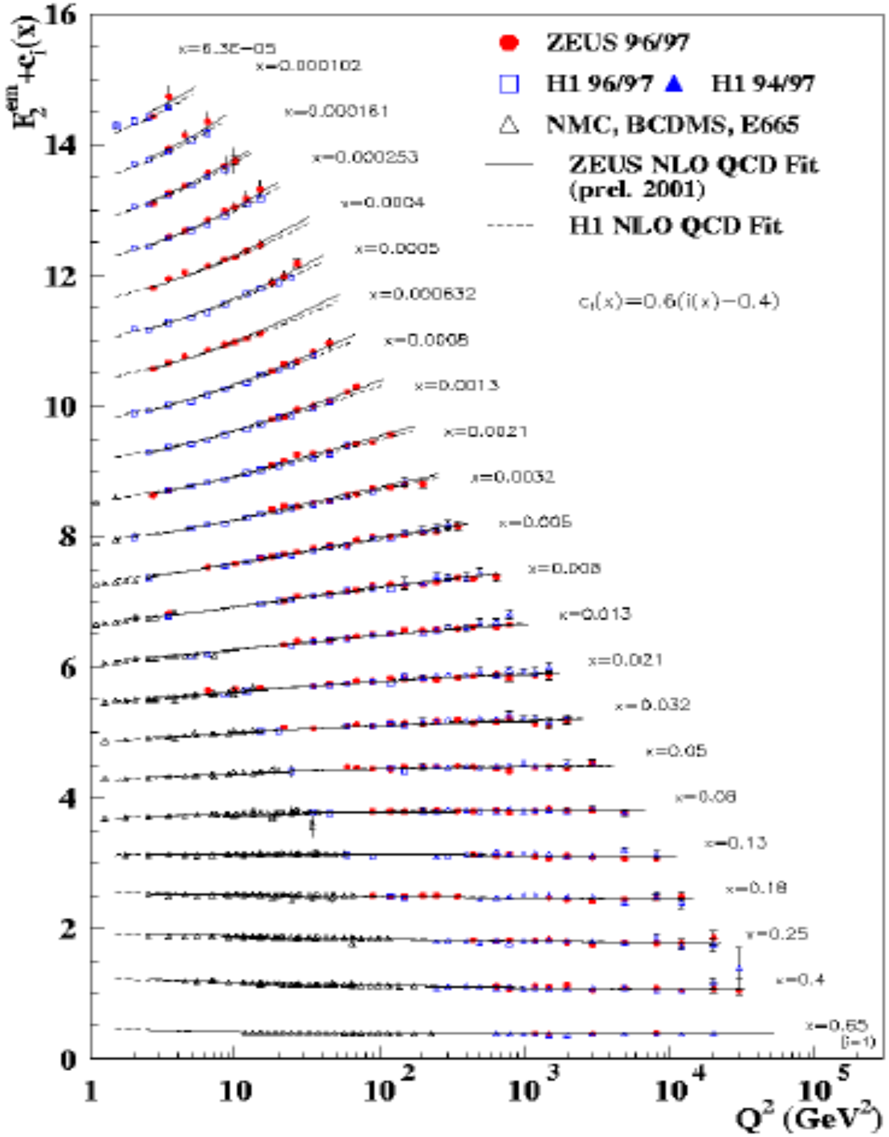
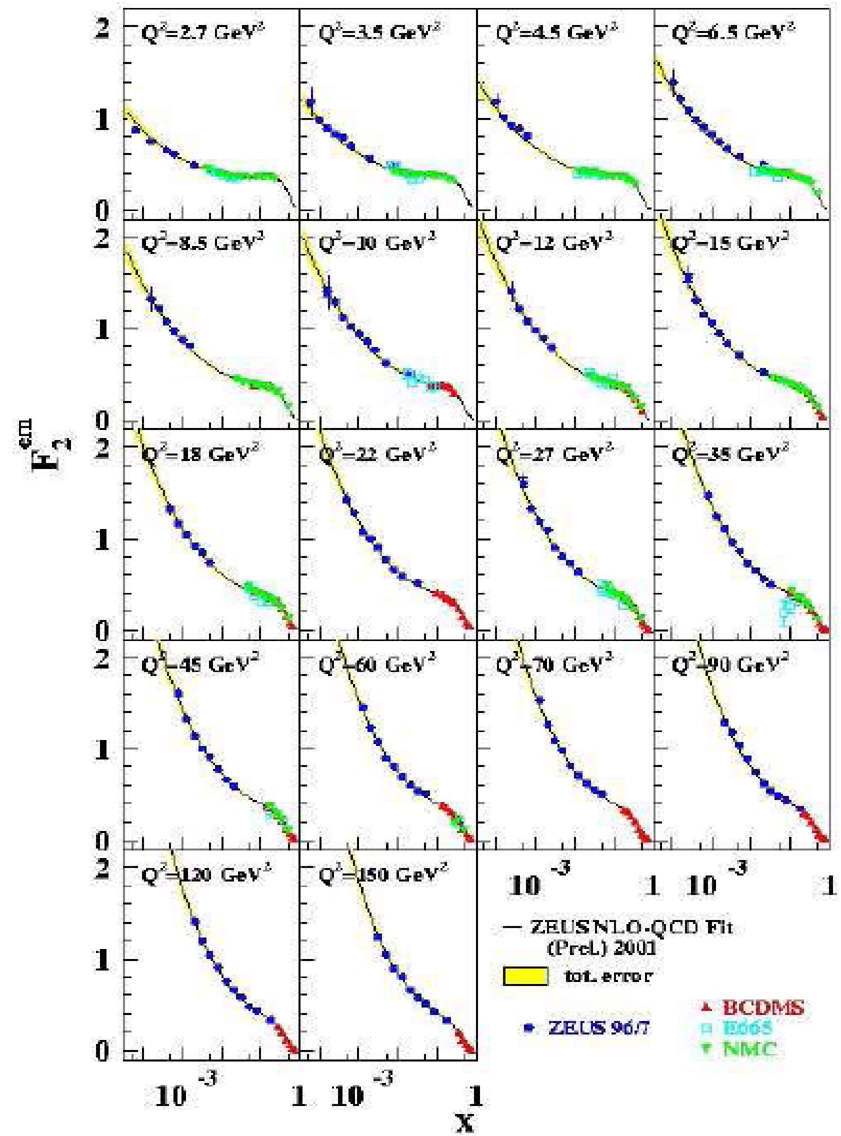
❑ Documentations:

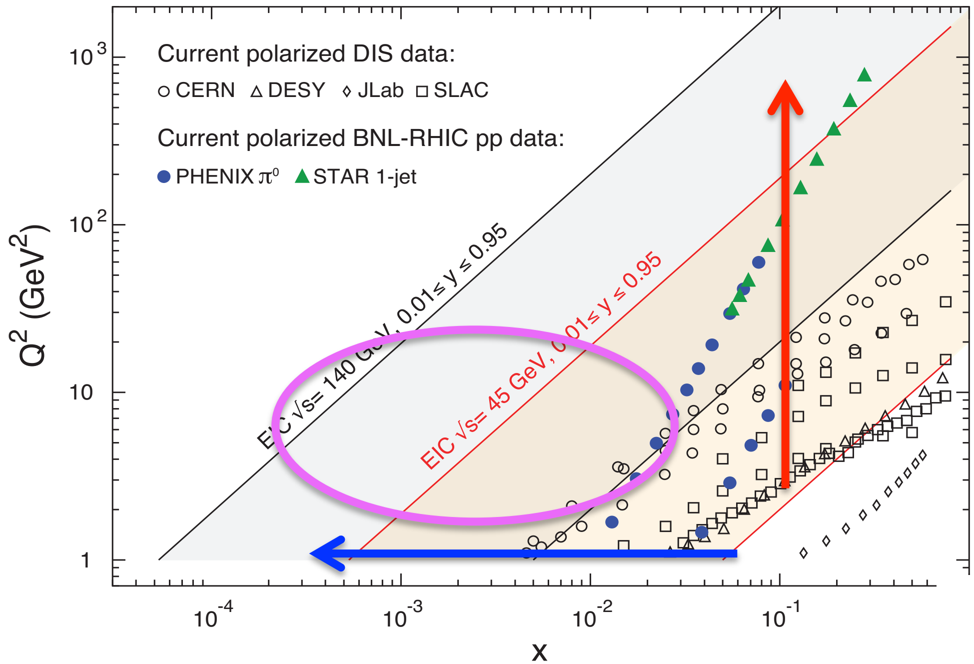
# What have we learned from HERA?




*Precision tests of QCD and hadron structure*

# US EIC – Kinematic reach & properties




## For e-N collisions at the EIC:

- ✓ Polarized beams: e, p, d/$^3$He
- ✓ Variable center of mass energy
- ✓ Wide $Q^2$ range → evolution
- ✓ Wide x range → spanning from valence to low-x physics
- ✓ 100-1K times of HERA Luminosity

## For e-A collisions at the EIC:

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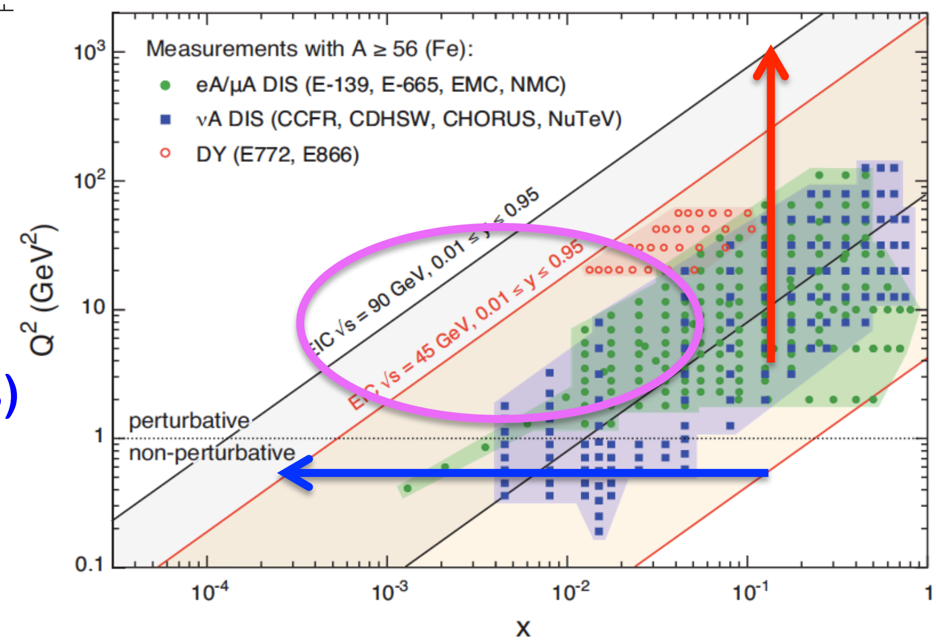

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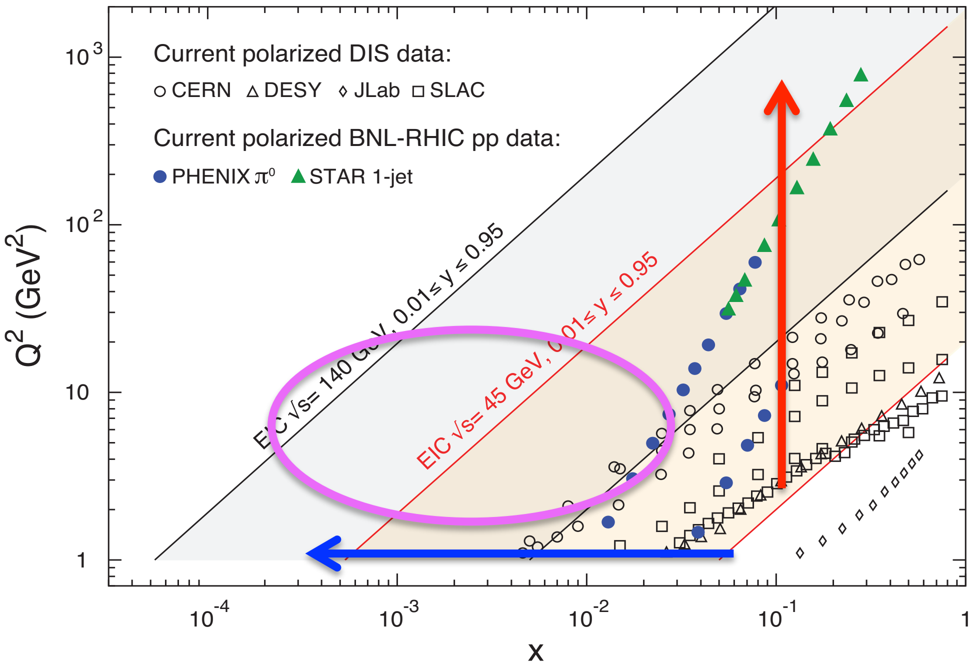


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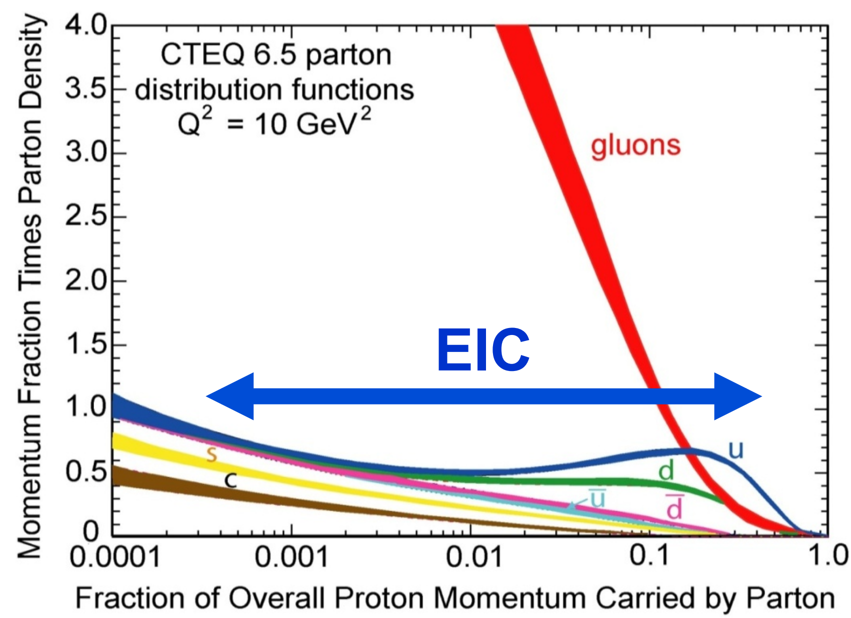
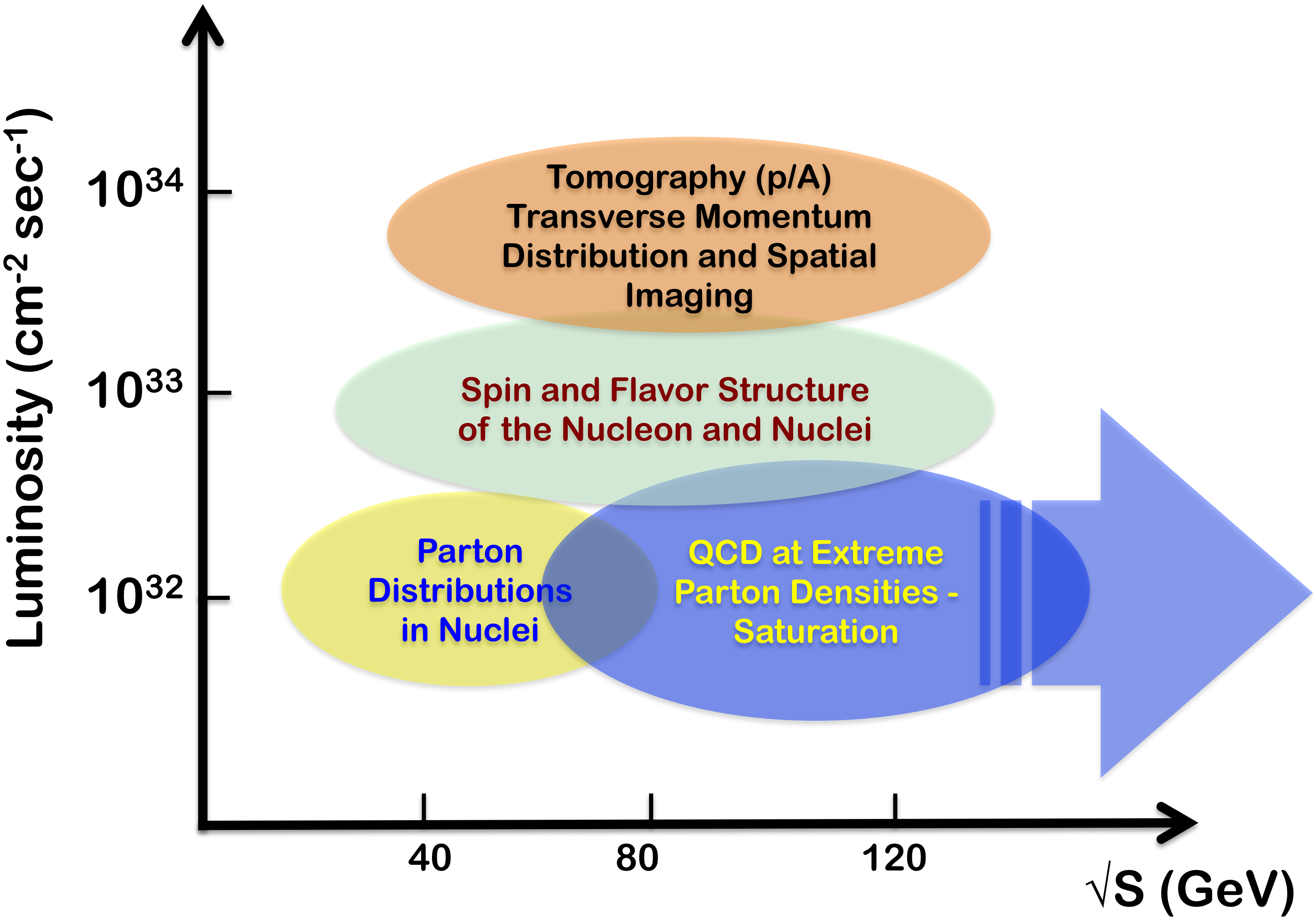
*EIC explores the "sea" and the "glue", the "valence" with a huge level arm*

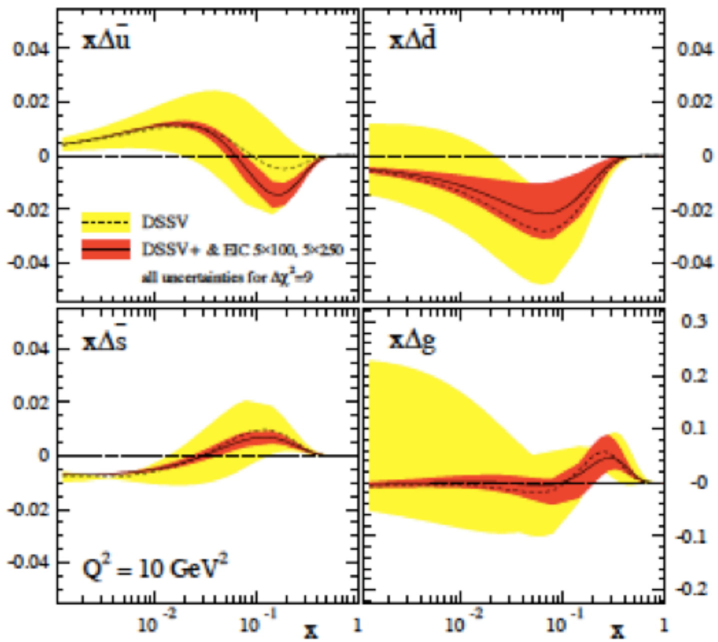


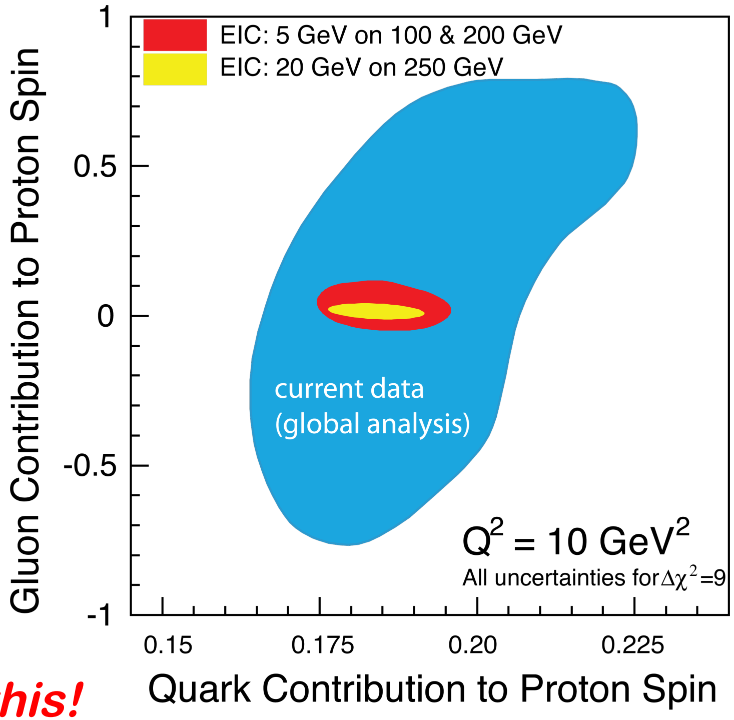
# US EIC – Physics vs. Luminosity & Energies



# Inclusive DIS

- **Observable:** e+p/A → e'+X
  - *Detect only the scattered lepton in the detector – single scale*
    - ✧ Structure functions: F1, F2, g1, g2, …
    - ✧ PDFs, Helicity PDFs: q(x), g(x), Δq(x), Δg(x)
- **Golden measurements:**
  - *Parton helicity contribution to proton's spin*




***No other machine in the world can achieve this!***

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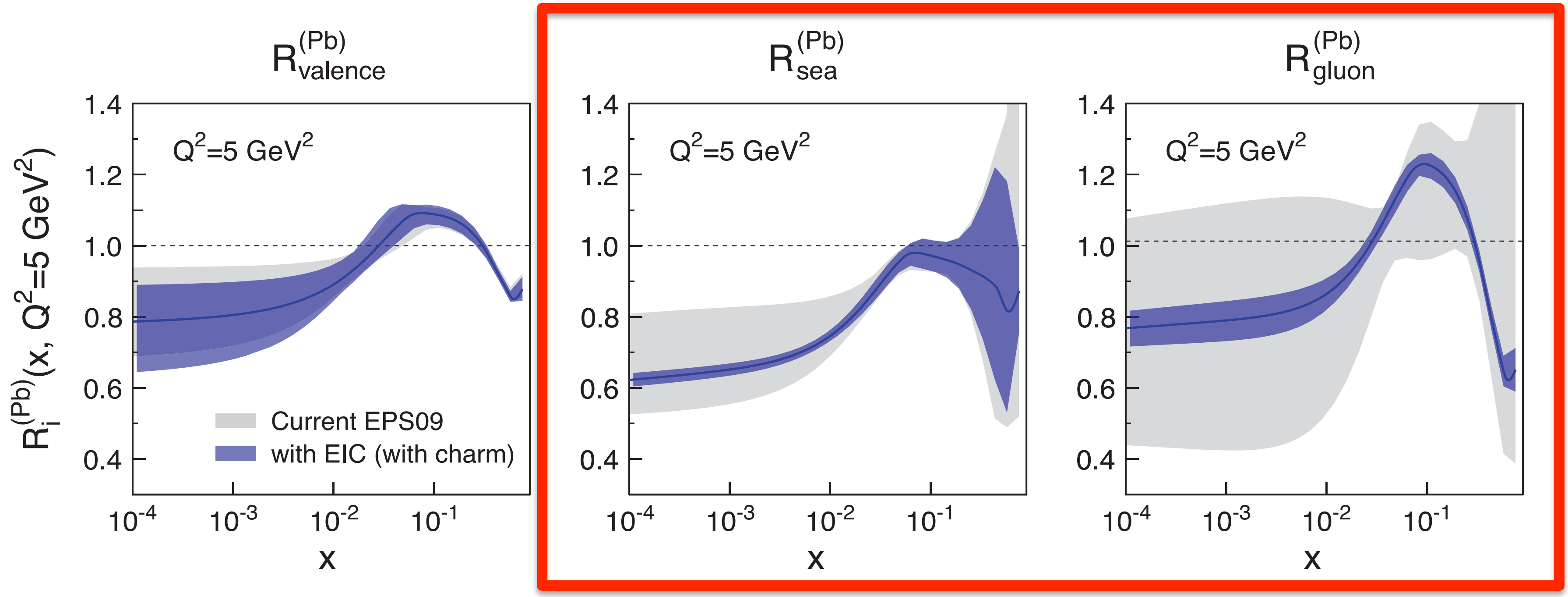
- **Golden measurements:**
  - *Nuclear landscape – EIC impact on nuclear PDFs*



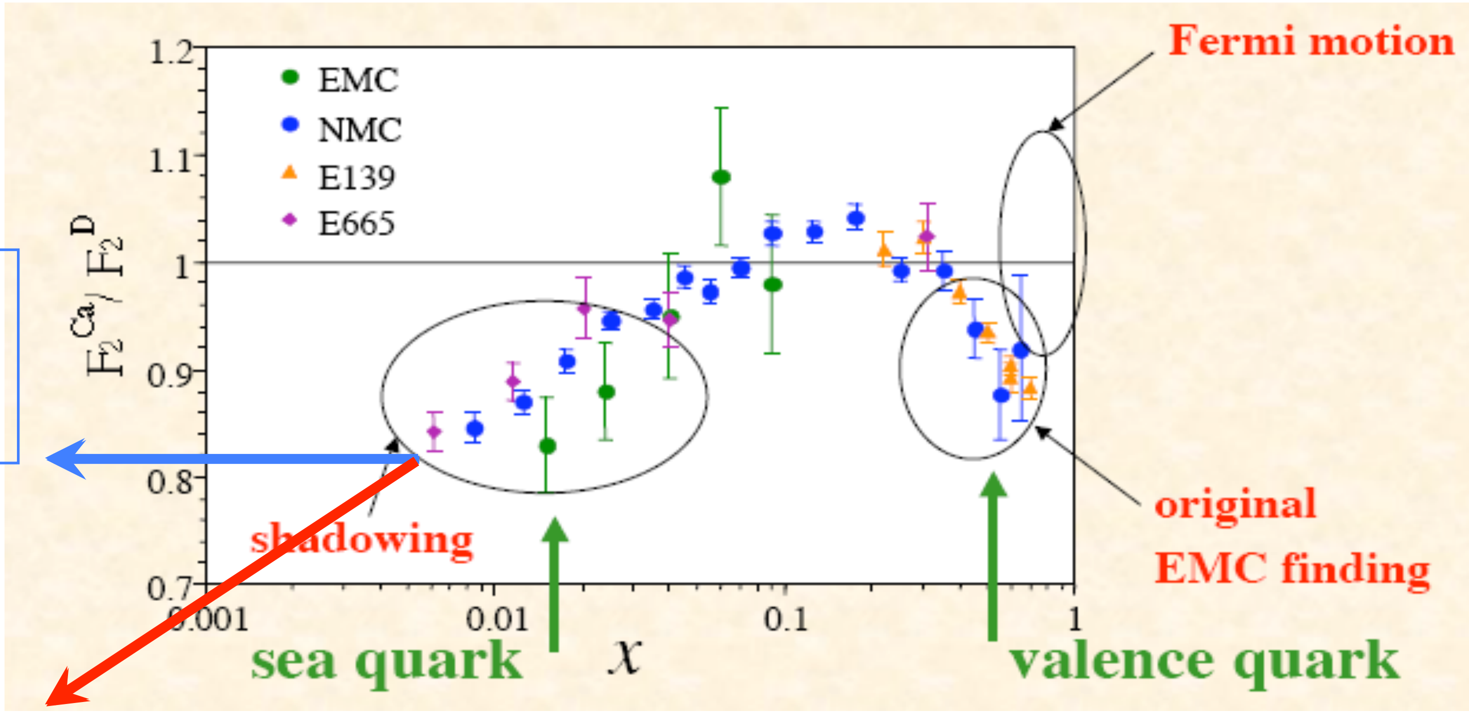
# An “easy” measurement for the saturation

## ❑ EMC effect, Shadowing and Saturation:

Saturation in $R_{F2}$

$\neq$

Saturation in $F_2^A$




## ❑ Questions:

Will the suppression/shadowing continue fall as x decreases?

Could nucleus behaves as a large proton at small-x?

*Range of color correlation – could impact the center of neutron stars!*

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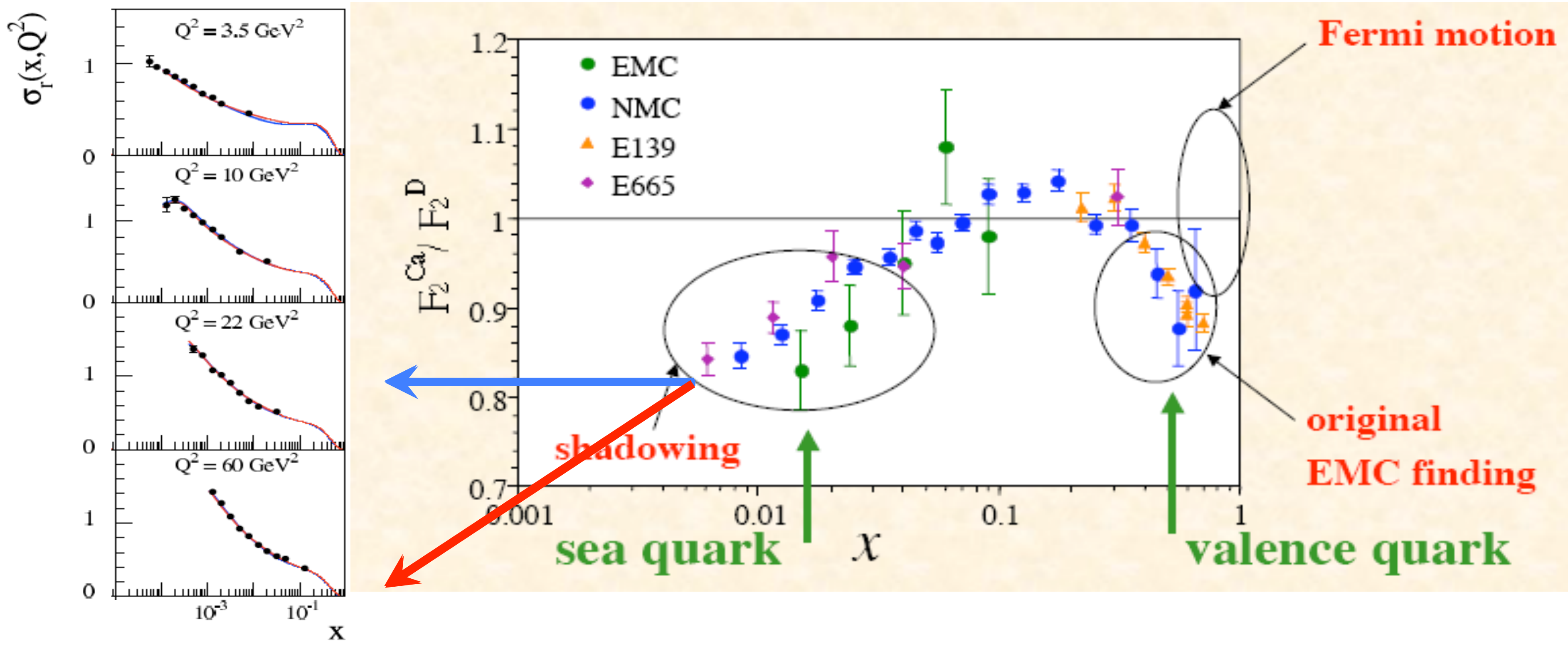


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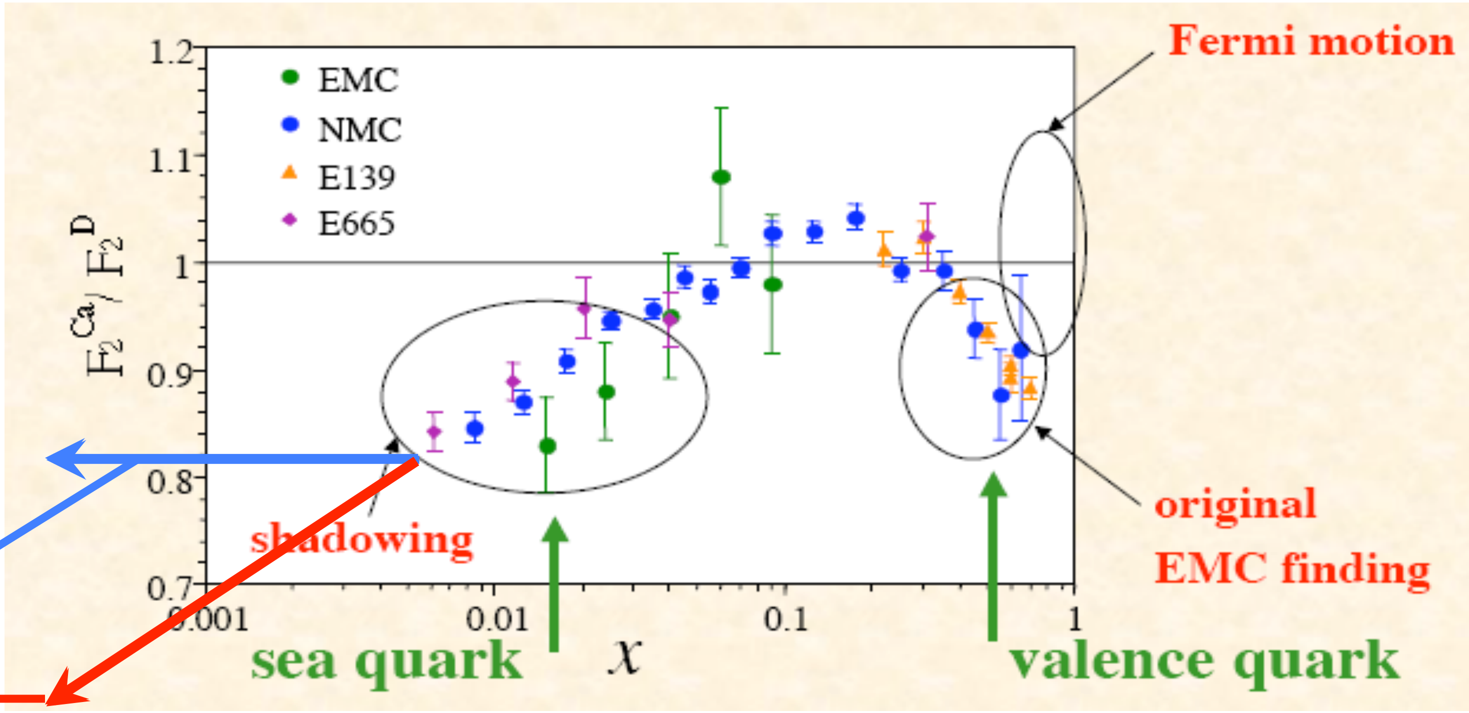



$F_2(A)$ saturates *Sooner* than $F_2(D)$

Saturation in $F_2(A)$ – $R_{F2}$ decreases until saturation in $F_2(D)$

## ❑ Questions:

Will the suppression/shadowing continue fall as x decreases?

Could nucleus behaves as a large proton at small-x?

*Range of color correlation – could impact the center of neutron stars!*

# Semi-Inclusive DIS

❑ **Observable:** e+p/A → e'+h(π,K,p,jet)+X

– *Detect the scattered lepton in coincidence with identified hadrons/jets*

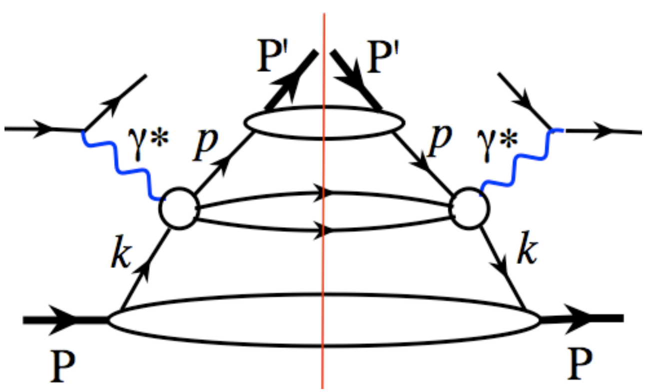
✧ Differential cross sections, asymmetries, …

✧ Polarized & unpolarized TMDs, PDFs, FFs, …

❑ **Natural event structure:**

$Q \gg P_{h_T} \gtrsim \Lambda_{\rm QCD}$ in the photon-hadron frame

❑ **Collinear QCD factorization holds if $P_{hT}$ integrated:**




$$d\sigma_{\gamma^* h\to h'} \propto \phi_{f/h} \otimes d\hat{\sigma}_{\gamma^* f\to f'} \otimes D_{f'\to h'}$$

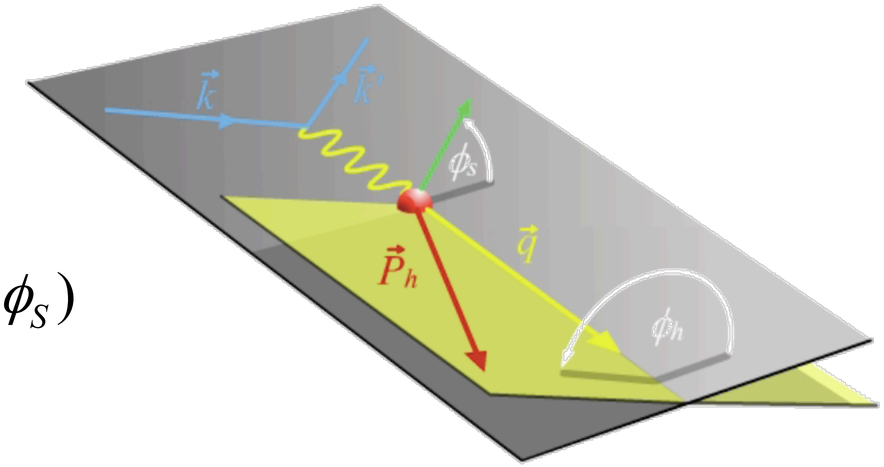
$$z = \frac{P_h \cdot p}{q\cdot p} \qquad y = \frac{q\cdot p}{k\cdot p}$$

❑ **"Total c.m. energy":**

$$s_{\gamma^* p} = (p+q)^2 \approx Q^2\left[\frac{1-x_B}{x_B}\right] \approx \frac{Q^2}{x_B}$$

# SIDIS is the best for probing TMDs

- **Naturally, two planes:**




$$A_{UT}(\varphi_h^l, \varphi_S^l) = \frac{1}{P}\frac{N^\uparrow - N^\downarrow}{N^\uparrow + N^\downarrow}$$

$$= A_{UT}^{Collins}\sin(\phi_h + \phi_S) + A_{UT}^{Sivers}\sin(\phi_h - \phi_S)$$

$$+ A_{UT}^{Pretzelosity}\sin(3\phi_h - \phi_S)$$

- **Separation of TMDs:**

$$A_{UT}^{Collins} \propto \langle \sin(\phi_h + \phi_S) \rangle_{UT} \propto h_1 \otimes H_1^\perp$$

$$A_{UT}^{Sivers} \propto \langle \sin(\phi_h - \phi_S) \rangle_{UT} \propto f_{1T}^\perp \otimes D_1$$

$$A_{UT}^{Pretzelosity} \propto \langle \sin(3\phi_h - \phi_S) \rangle_{UT} \propto h_{1T}^\perp \otimes H_1^\perp$$

**Collins frag. Func. from $e^+e^-$ collisions**

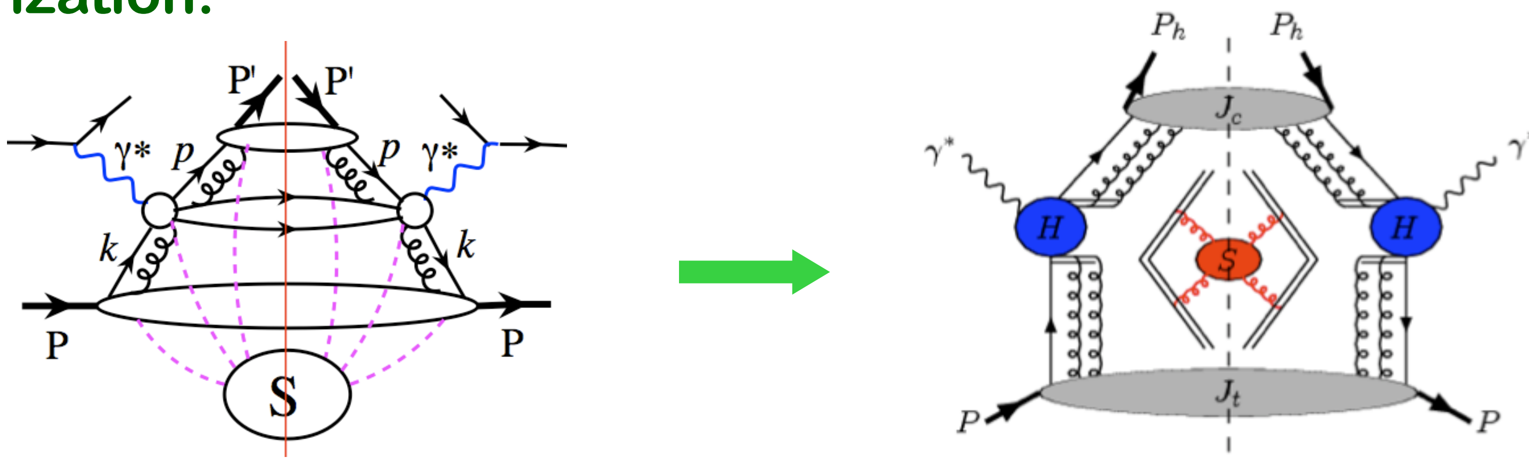
***Hard, if not impossible, to separate TMDs in hadronic collisions***

**Using a combination of different observables (not the same observable): jet, identified hadron, photon, …**

# QCD factorization for SIDIS

Ji, Ma, Yuan

## ❑ Factorization:




## ❑ Low $P_{hT}$ – TMD factorization:

$$\sigma_{\rm SIDIS}(Q, P_{h\perp}, x_B, z_h) = \hat{H}(Q) \otimes \Phi_f \otimes \mathcal{D}_{f\to h} \otimes \mathcal{S} + \mathcal{O}\left(\frac{P_{h\perp}}{Q}\right)$$

## ❑ High $P_{hT}$ – Collinear factorization:

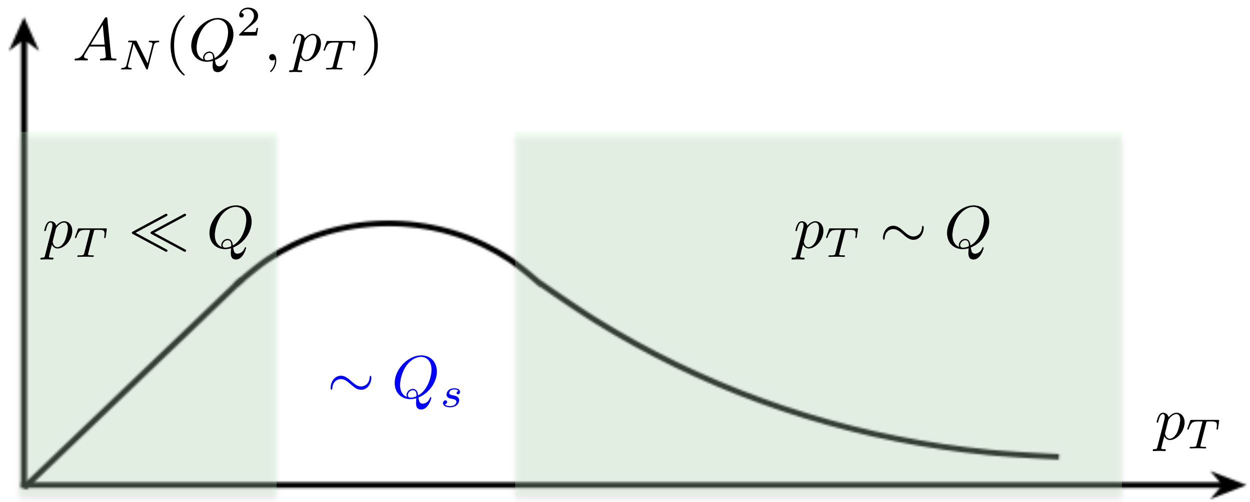
$$\sigma_{\rm SIDIS}(Q, P_{h\perp}, x_B, z_h) = \hat{H}(Q, P_{h\perp}, \alpha_s) \otimes \phi_f \otimes D_{f\to h} + \mathcal{O}\left(\frac{1}{P_{h\perp}}, \frac{1}{Q}\right)$$

## ❑ $P_{hT}$ Integrated - Collinear factorization:

$$\sigma_{\rm SIDIS}(Q, x_B, z_h) = \tilde{H}(Q, \alpha_s) \otimes \phi_f \otimes D_{f\to h} + \mathcal{O}\left(\frac{1}{Q}\right)$$

# Transition from low $p_T$ to high $p_T$

- Two-scale becomes one-scale:




TMD

Collinear Factorization

- TMD factorization to collinear factorization:

Ji,Qiu,Vogelsang,Yuan,
Koike, Vogelsang, Yuan

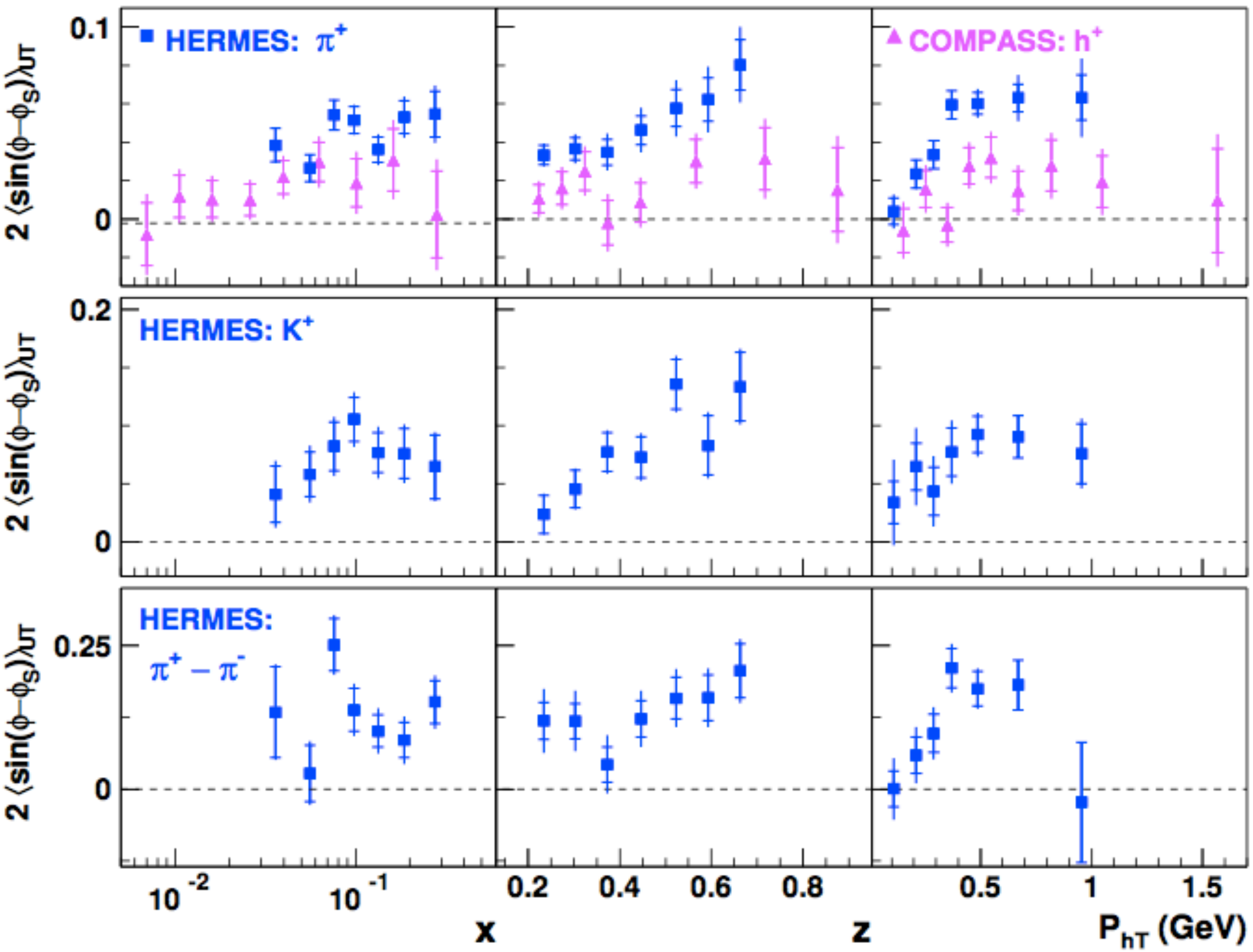
Two factorization are consistent in the overlap region: $\Lambda_{\rm QCD} \ll p_T \ll Q$

$A_N$ finite – requires correlation of multiple collinear partons

No probability interpretation! New opportunities!

# Sivers asymmetries from SIDIS

❑ From SIDIS (HERMES and COMPASS) – low Q:




Non-zero Sivers effects Observed in SIDIS!

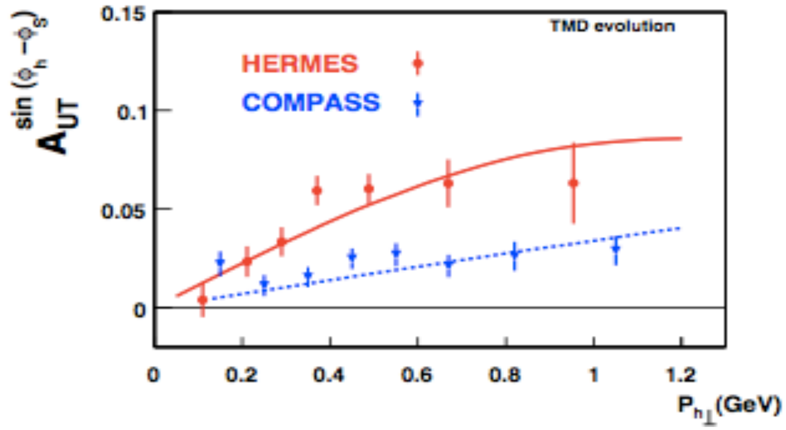
Visible $Q^2$ dependence

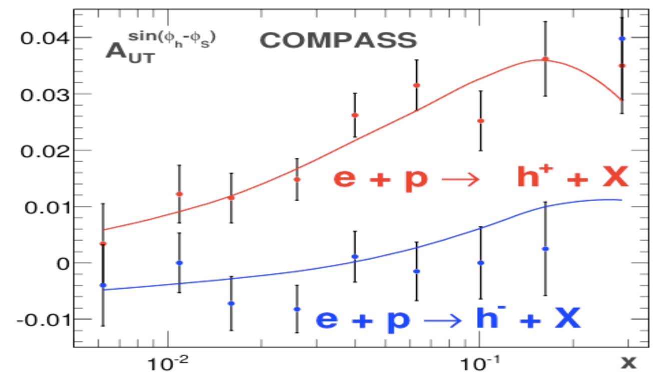
Major theory development in last few years

Drell-Yan $A_N$: COMPASS, RHIC run 17$^{th}$, Fermilab Drell-Yan, …

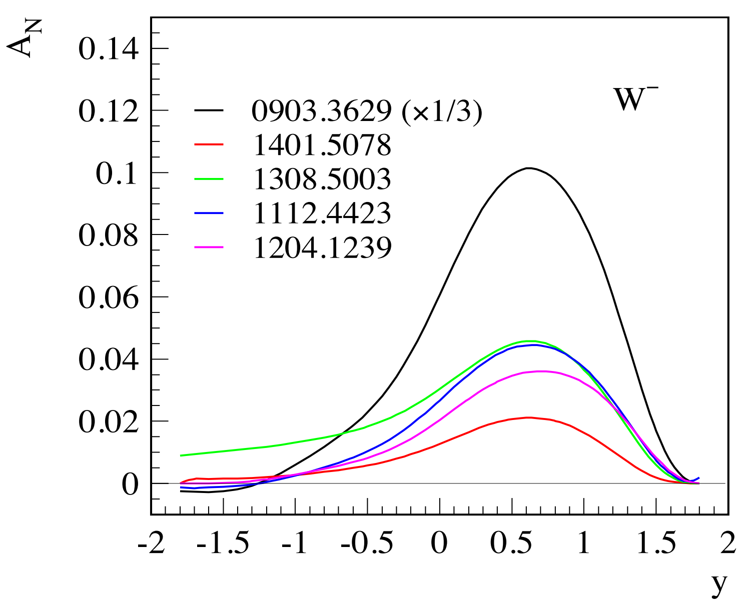
# A surprise story for TMDs

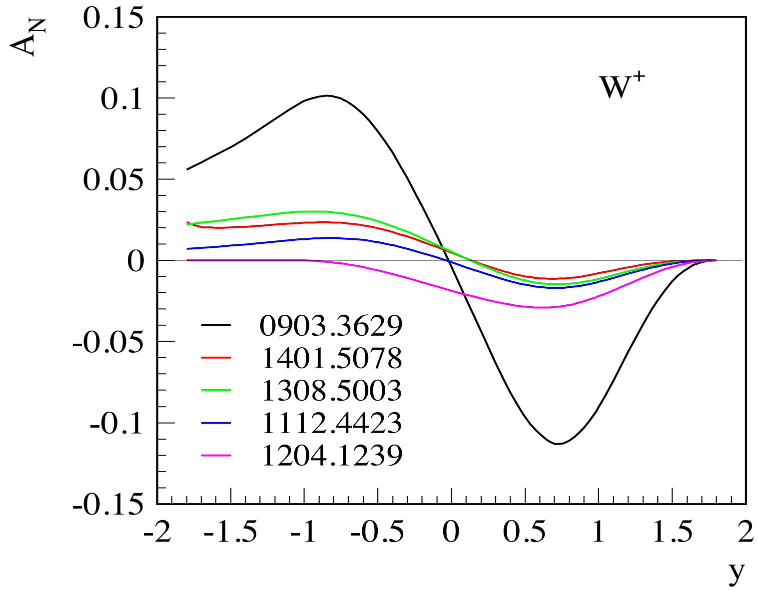
- Fit the same low energy data – Sivers function:



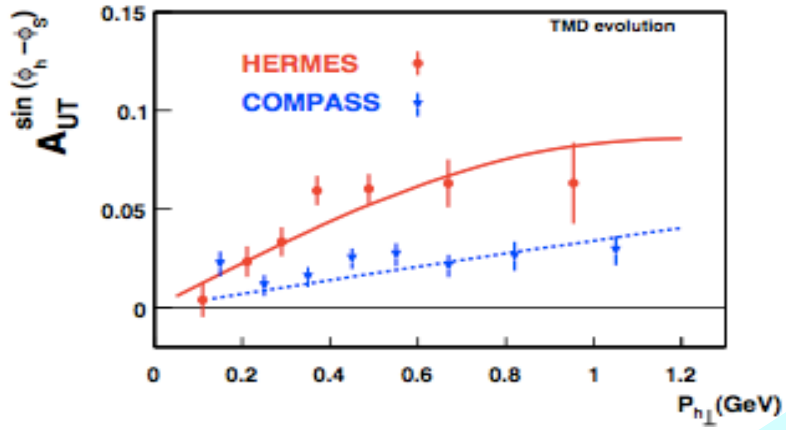

- Very different "predictions" for $A_N$ at a higher energy:

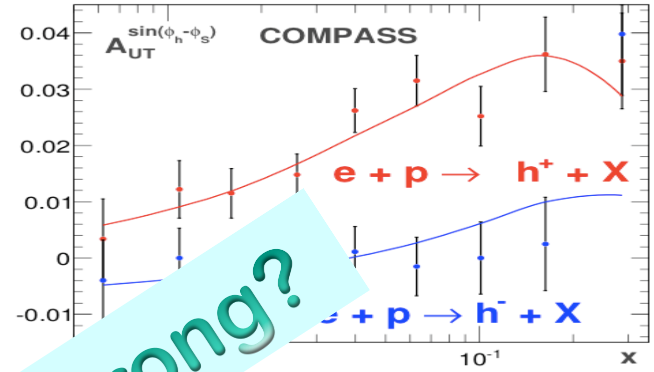


# A surprise story for TMDs

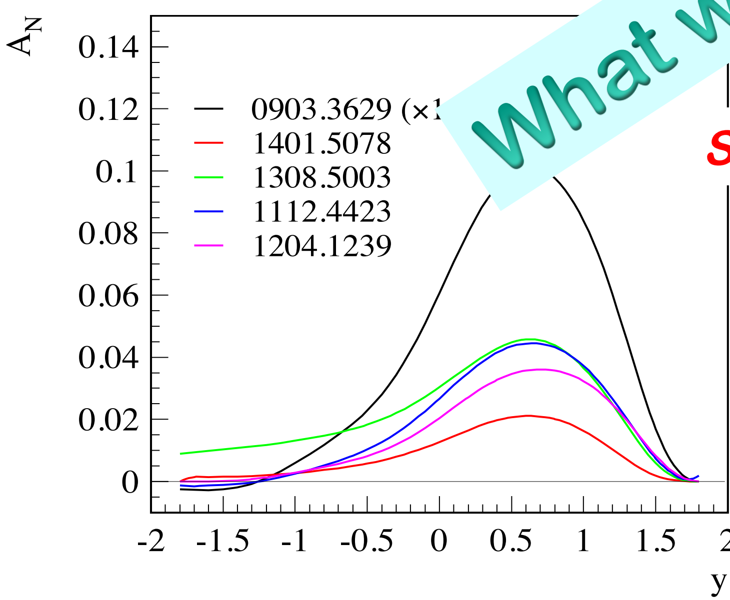
- ❑ **Fit the same low energy data – Sivers function:**

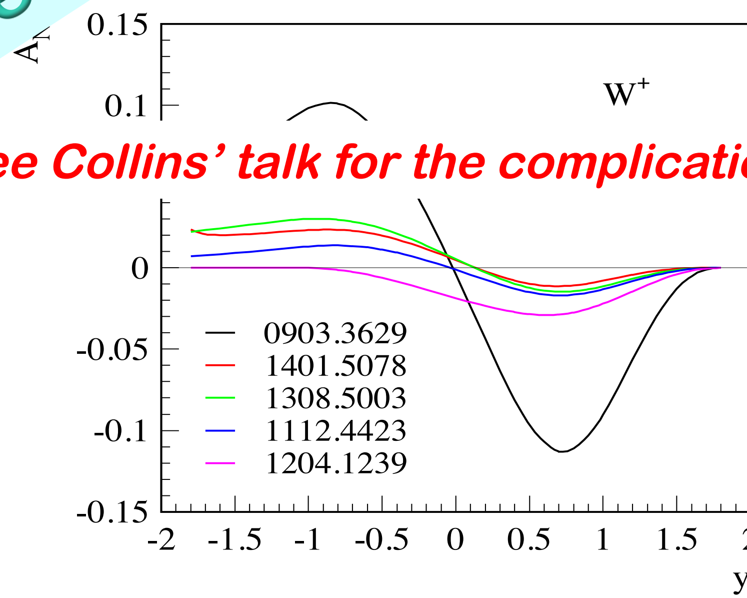



What went wrong?

- ❑ **Very different “predictions” $_N$ at a higher energy:**



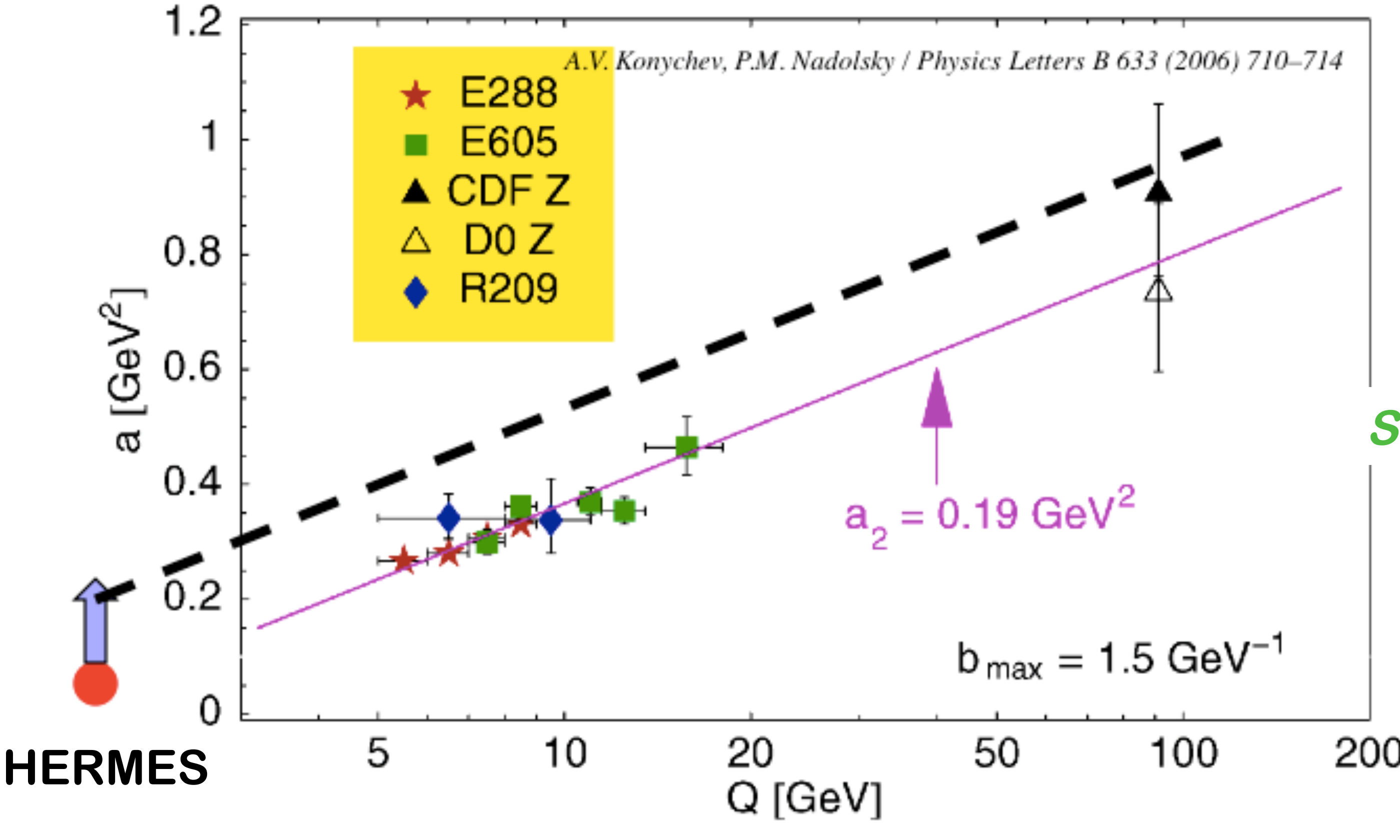

*See Collins’ talk for the complication!*

# Q-dependence of the "form" factor

- Q-dependence of the "form factor" :

Konychev, Nadolsky, 2006

$$\mathcal{F}^{\rm NP}(b,Q) = a(Q^2)\, b^2$$




*See Collins' talk!*

**At Q ~ 1 GeV, ln($Q/Q_0$) term may not be the dominant one!**

$$\mathcal{F}^{\rm NP} \approx b^2(a_1 + a_2 \ln(Q/Q_0) + a_3 \ln(x_A x_B) + \ldots) + \ldots$$

**Power correction?** **($Q_0/Q$)$^n$-term?** ***Better fits for HERMES data?***

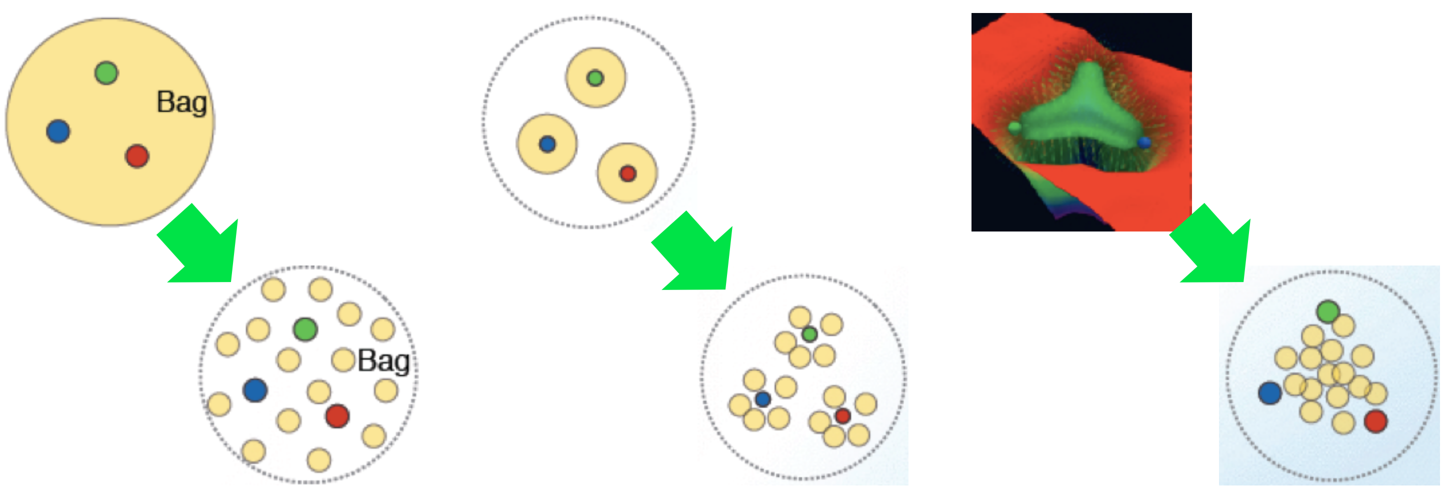
***A sufficiently large $Q^2$-range at EIC***

# Exclusive DIS

- ❑ **Observable:** e+p/A → e'+ p'/A'+ h($\pi$,K,p,jet)
  - – *Detect every things including scattered proton/nucleus (or its fragments)*
    - ✧ Diffractive cross sections: DVCS, J/psi, …
    - ✧ Polarized & unpolarized GPDs – tomographic images, …
- ❑ **Golden measurements:**
  - – *Charge radius, radius of quark distribution, or gluon distribution*
  - – *gluon saturation, …*
- ❑ **What does the proton look like?**

Static:

Hard probe:




Bag Model | Quark Model | Lattice

# Boosted 3D nucleon structure

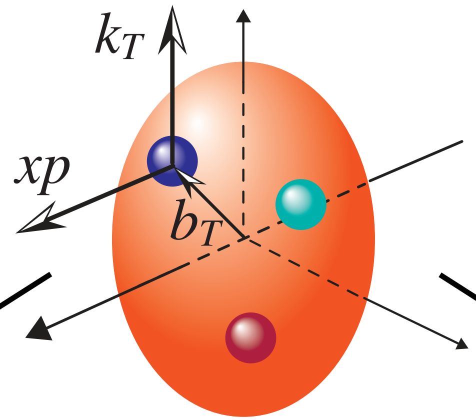
- High energy probes "see" the boosted partonic structure:

***Momentum Space***

***TMDs***

***Coordinate Space***

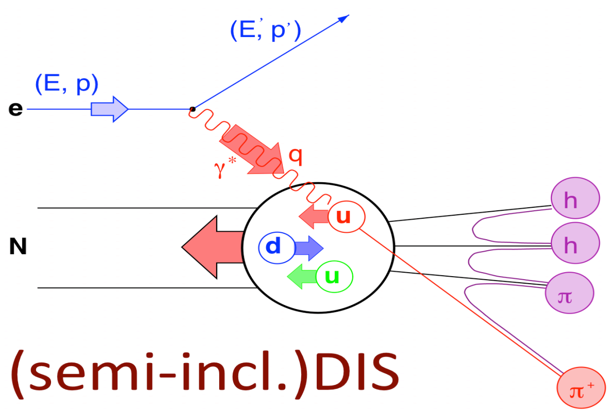
***GPDs***



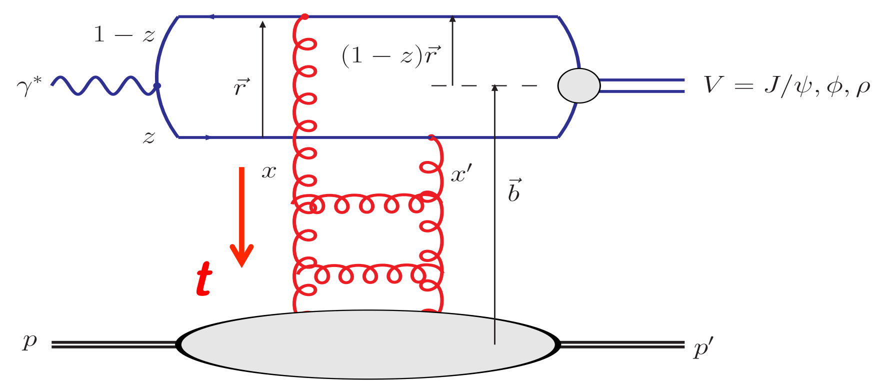

$\int d^2b_T$ $\quad$ $\int d^2k_T$

$f(x,k_T)$ $\quad$ $f(x,b_T)$

**3D momentum space images**




**2+1D coordinate space images**




**JLab12 for valence region, EIC for sea and gluon structure**

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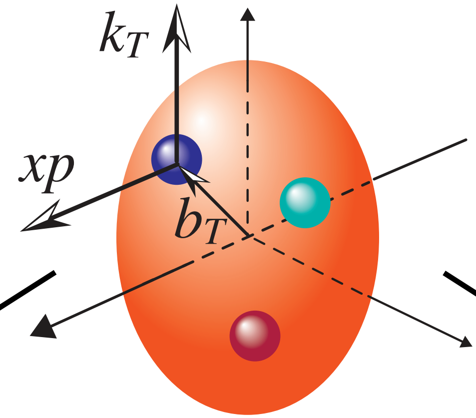
*Momentum Space*

*TMDs*

*Coordinate Space*

*GPDs*

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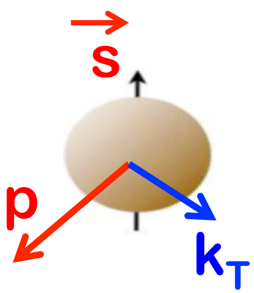
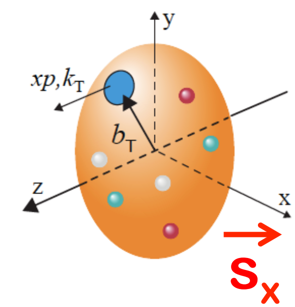
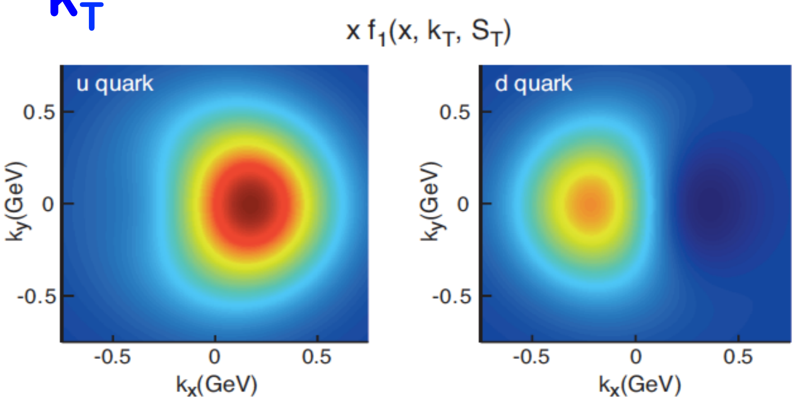
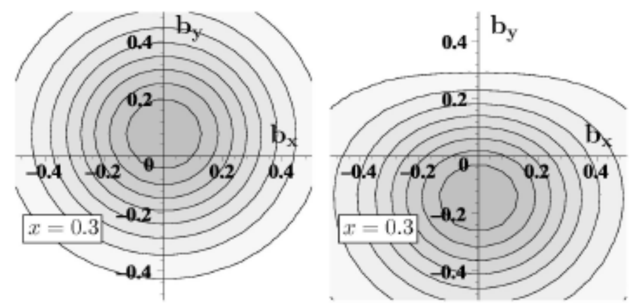
$f(x,k_T)$ $\quad\quad$ $f(x,b_T)$




"Role of hadron spin"



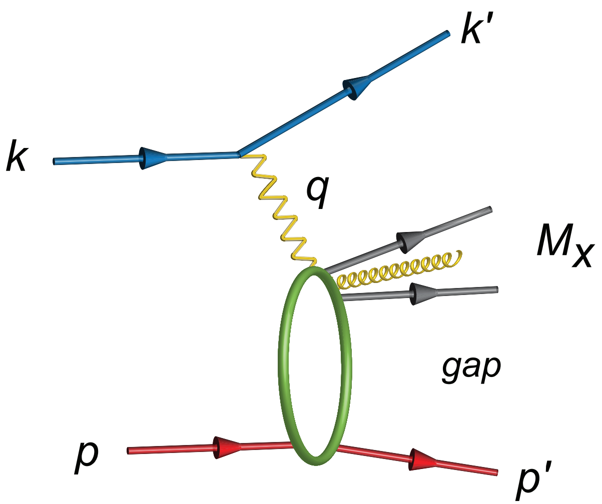

**Deformation of parton's *confined motion***

**Deformation of parton's *spatial distribution***

# Another signature for gluon saturation

❑ **Diffrative cross section:**

$$\sigma_{\text{diff}} \propto [g(x,Q^2)]^2$$

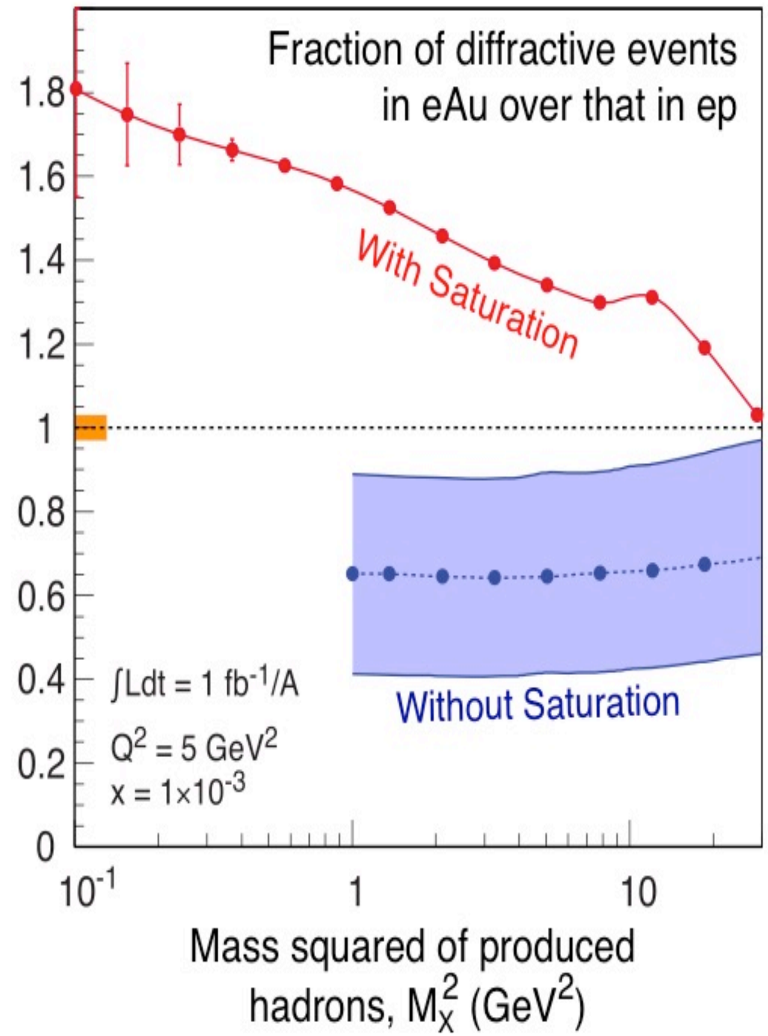



**At HERA**

**ep: 10-15% diffractive**

**At EIC eA, if Saturation/CGC**

**eA: 25-30% diffractive**



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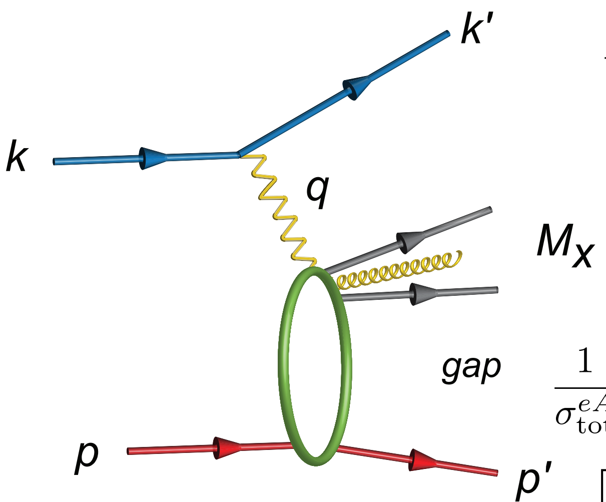
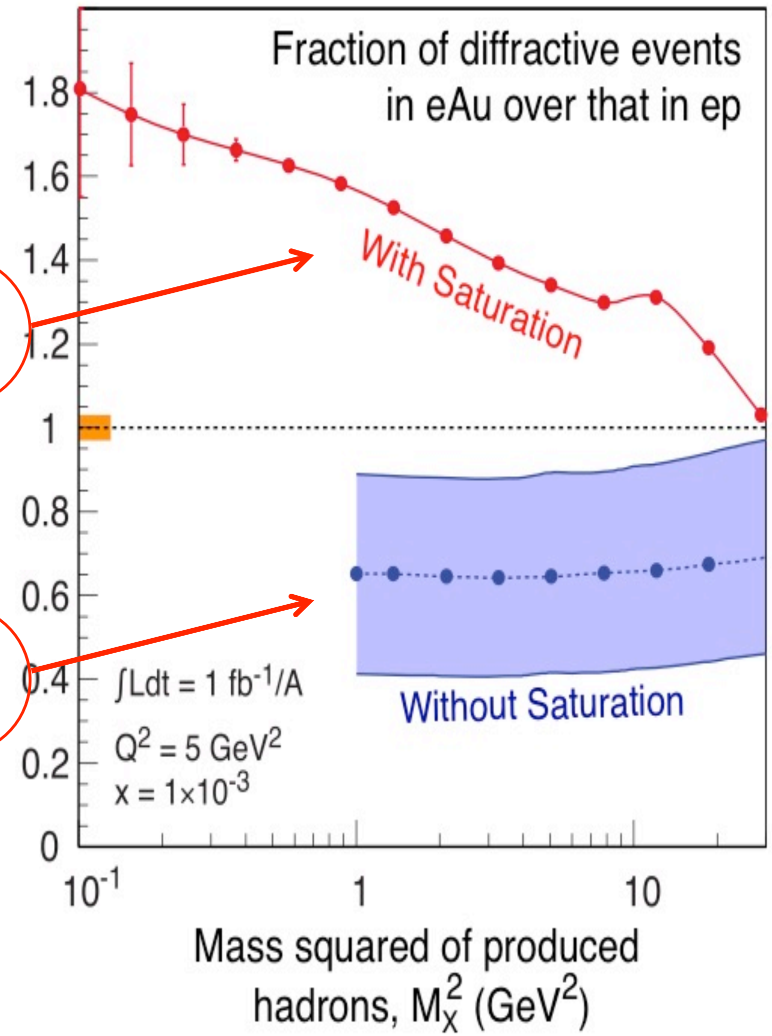



$$\frac{1}{\sigma_{\rm tot}^{eA}}\frac{d\sigma_{diff}^{eA}}{dM_x^2}\Bigg/\frac{1}{\sigma_{\rm tot}^{ep}}\frac{d\sigma_{diff}^{ep}}{dM_x^2} \sim \frac{25-30\%}{10-15\%} > 1$$

$$\frac{1}{\sigma_{\rm tot}^{eA}}\frac{d\sigma_{diff}^{eA}}{dM_x^2}\Bigg/\frac{1}{\sigma_{\rm tot}^{ep}}\frac{d\sigma_{diff}^{ep}}{dM_x^2} \sim \left[\frac{g^p(x)}{g^A(x)}\right]_{\rm tot}\left[\frac{g^A(x)}{g^p(x)}\right]^2_{\rm diff} < 1$$




**At HERA**

**ep: 10-15% diffractive**

**At EIC eA, if Saturation/CGC**

**eA: 25-30% diffractive**

**Early work – E665 @ FNAL:**

**Nuclear shadowing, diffractive scattering and low momentumprotons in $\mu$ Xe interactions at 490 GeV** Z. Phys. C 65, 225–244 (1995)

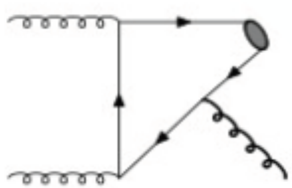
# Emergence of hadrons/Jets

## ❑ Hadronization:

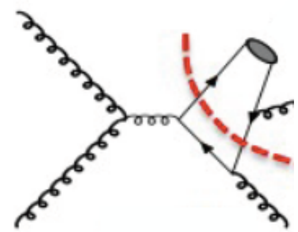
- ✧ Single-Parton Fragmentation functions – necessary for SIDIS
- ✧ Double-Parton Fragmentation functions – new

Heavy quarkonium production - $c\bar{c}\ (b\bar{b})$ fragmentation
(rate, polarization, hadronization mechanism, …)

Kang, et al.
Fleming et al.



$$\frac{d\hat{\sigma}^{LO}}{dp_T^2} \approx \alpha_s^3 \frac{m_Q^4}{p_T^8}$$

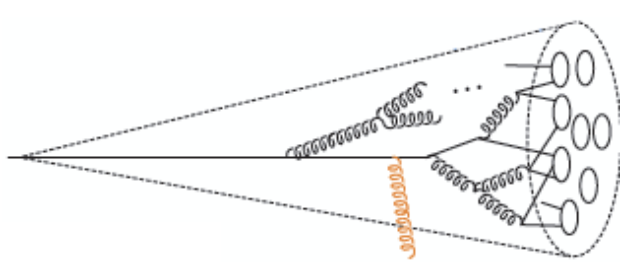


$$\frac{d\hat{\sigma}^{NLO}}{dp_T^2} \approx \alpha_s^4 \frac{m_Q^2}{p_T^6}$$

Light meson production - $u\bar{d}(u\bar{s}, \ldots)$ fragmentation
(suppressed in production, enhanced in fragmentation, …)

## ❑ Jet substructure:

See also Kang's talk



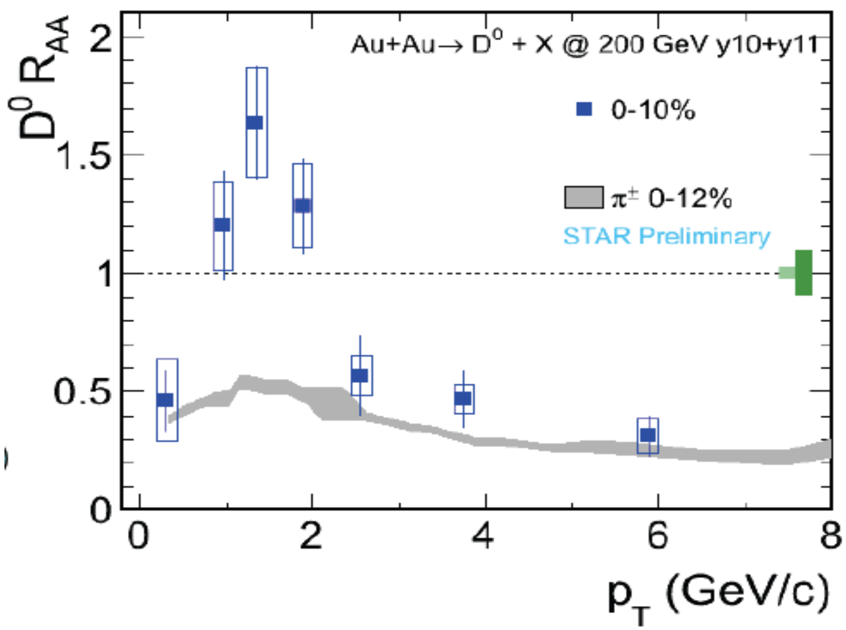
Two-scales: Jet energy >> Jet "mass"

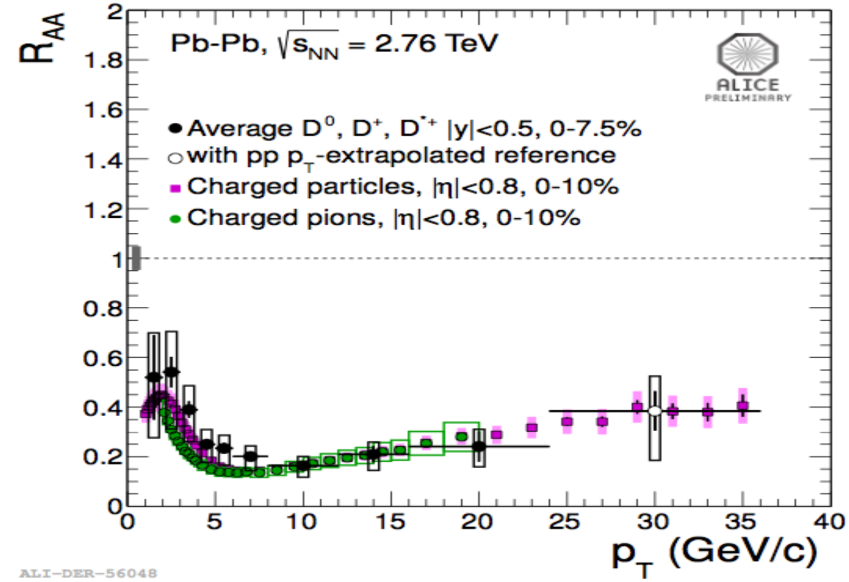
Tool: Soft-Collinear Effective Theory (SCET)

Challenge: Jet in medium?

# Hadronization puzzle

- Strong suppression of heavy flavors in AA collisions:




- Emergence of hadrons:

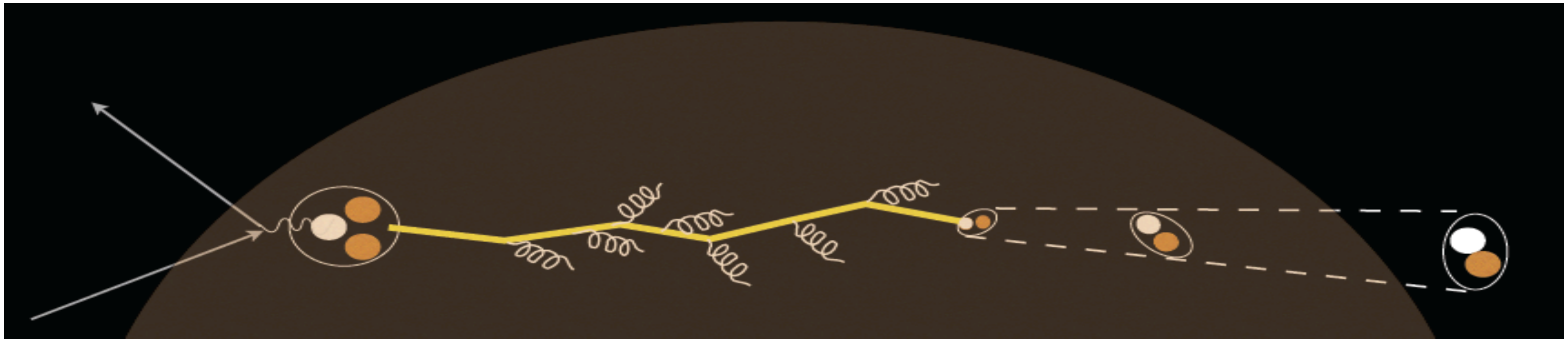
*How do hadrons emerge from a created quark or gluon?*
*How is the color of quark or gluon neutralized?*

- Need a femtometer detector or “scope”:

Nucleus, a laboratory for QCD
Evolution of partonic properties

# In-medium hadronization

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



  - ✧ Small $\nu$ - in medium hadronization:

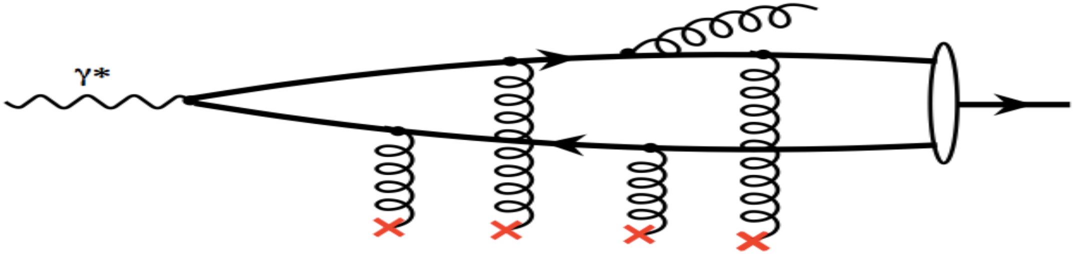
    Stages of hadronization: parton, pre-hadron, hadron

  - ✧ Large $\nu$ - parton multiple scattering:

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

- Heavy quark and quarkonium production:

Nucleus:
Femtometer size
Vertex detector

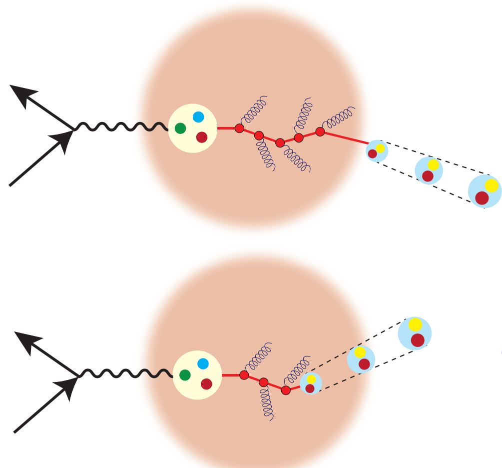



Filter for production mechanism!

# Emergence of hadrons from partons

How hadrons emerge from colored quarks and gluons?

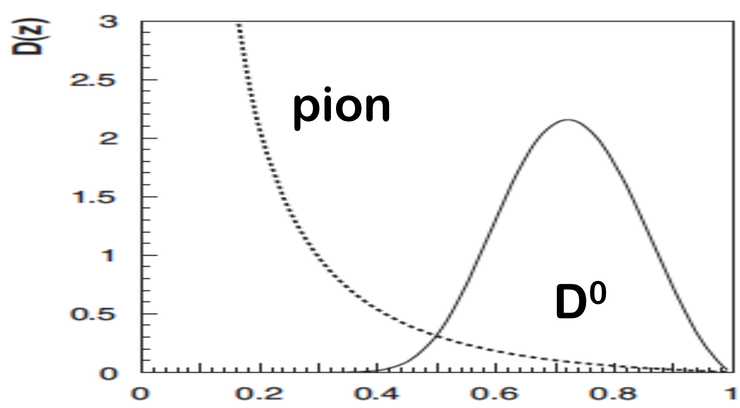
- **Unprecedented ν range at EIC:**

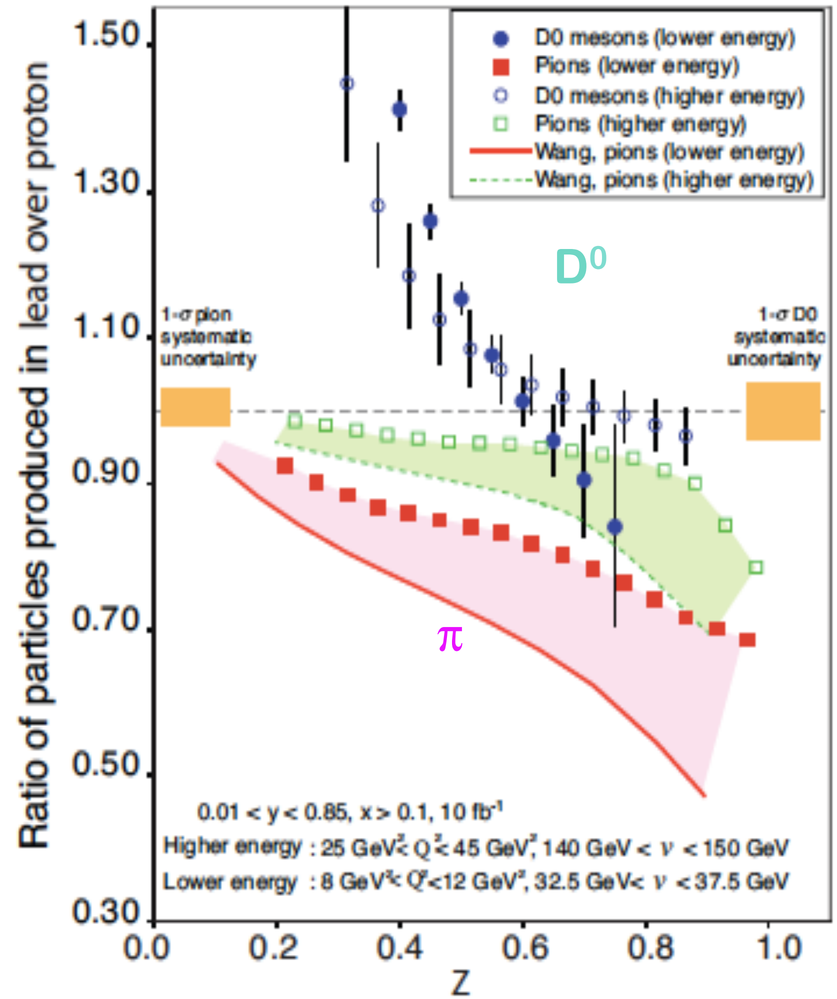


$$\nu = \frac{Q^2}{2mx}$$

Control of $\nu$ and medium length!

- **Heavy quark energy loss:**
  - Mass dependance of fragmentation



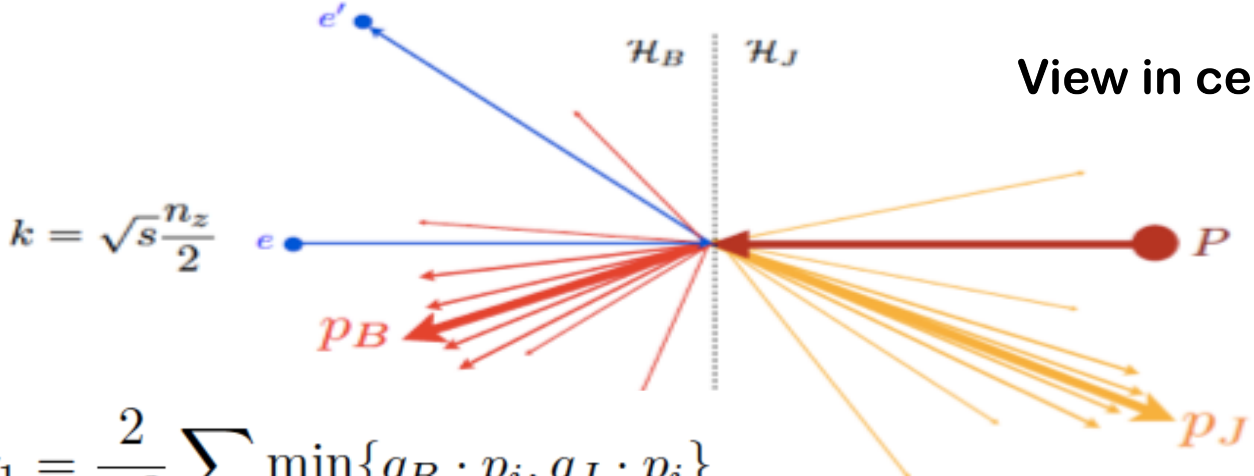




*Need the collider energy of EIC and its control on parton kinematics*

# 1-Jettiness cross section in e-A – event shape

Z. Kang, Mantry, Qiu, 2012

View in center of mass frame

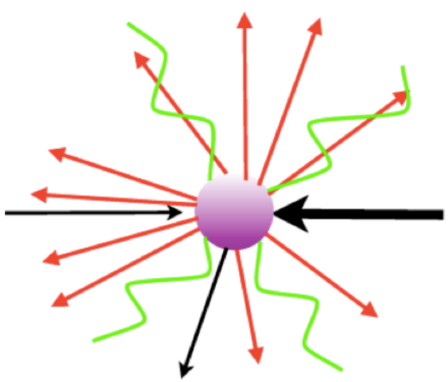



$$P = \sqrt{s}\frac{\bar{n}_z}{2}$$

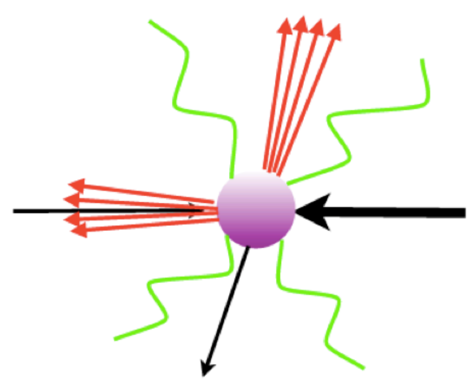
$$\tau_1 = \frac{2}{Q^2}\sum_i \min\{q_B \cdot p_i, q_J \cdot p_i\}$$

$$d\sigma_A \equiv \frac{d^3\sigma(e^- + N_A \to J + X)}{du\, dP_{J_T}\, d\tau_1}$$

1-jettiness: global event shape



$\tau_1 \sim P_{J_T}$



$\tau_1 \ll P_{J_T}$

Good measurement of the radiation pattern!

D. Kang, Lee, Stewart, 2013

# Summary

- EIC is a ultimate QCD machine:
  1) to discover and explore the quark/gluon structure and properties of hadrons and nuclei,
  2) to search for hints and clues of color confinement, and
  3) to measure the color fluctuation and color neutralization

- EIC is a tomographic machine for nucleons and nuclei with a resolution better than 1/10 fm

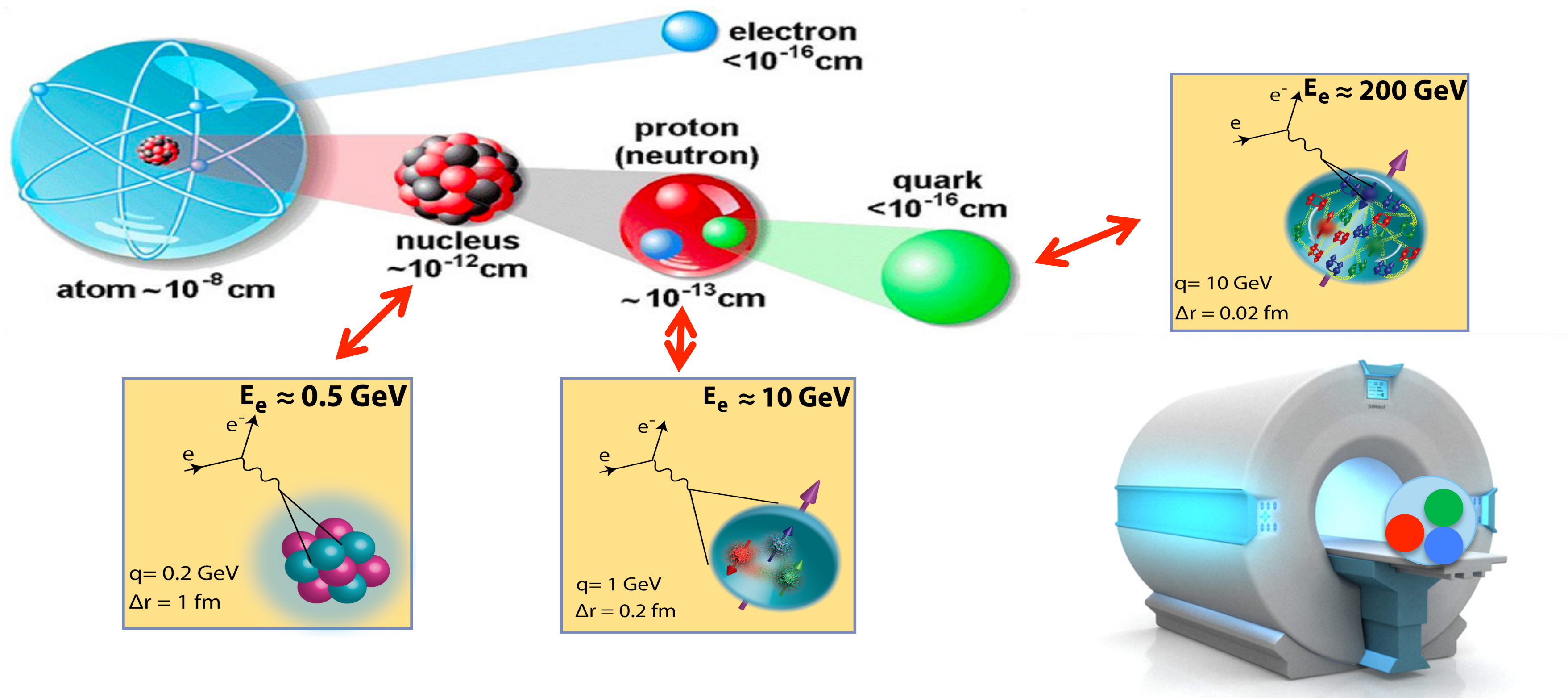
- EIC designs explore the polarization and intensity frontier, as well as the frontier of new accelerator/detector technology

- What EIC can do is not only complementary to, but also unique and better than what current facilities around the world can do for exploring QCD and hadron structure

**Thanks!**

# Electron-Ion Collider (EIC)

- A giant "Microscope" – "see" quarks and gluons by breaking the hadron

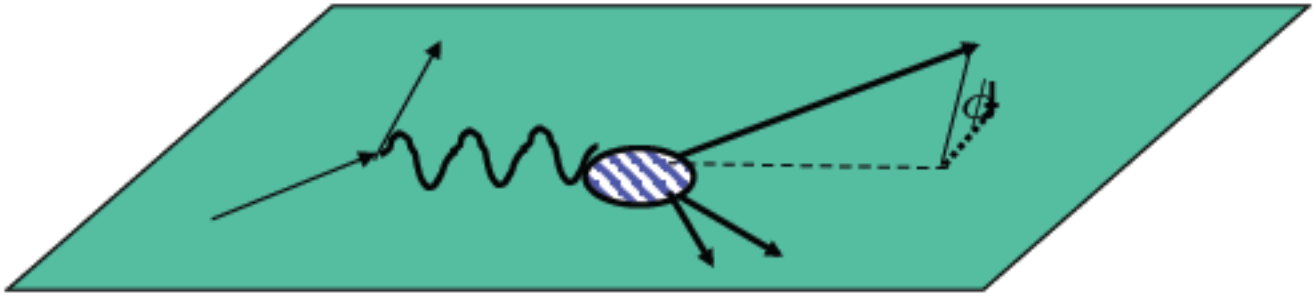



- Also a sharpest "CT" – "imagine" them without breaking the hadron
  – "cat-scan" the nucleon and nuclei with better than 1/10 fm resolution
- Why now?
  Exp – advances in luminosity, energy reach, detection capability, …
  Thy – breakthrough in factorization – "see" confined quarks and gluons, …

# Density distribution – Fluctuation

- Azimuthal distribution:

Guo, Liang, Wang, 2010
Pitonyak, Qiu




*$V_n$ in SIDIS?*

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

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

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

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