Spin and Saturation: A Convergence of Theories at the EIC

Los Alamos NATIONAL LABORATORY

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2017 RHIC / AGS Users' Meeting:

From Protons to Heavy Ions, and Back Again

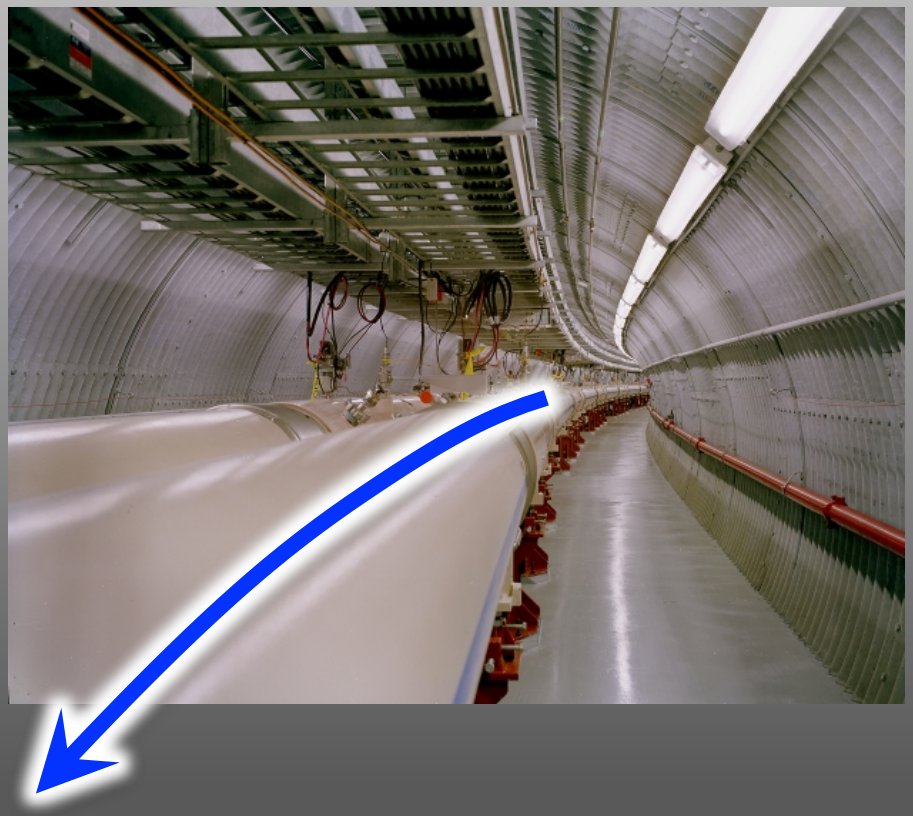
Two Roads Diverged…

"Two roads diverged in a yellow wood,
And sorry I could not travel both
And be one traveler, long I stood
And looked down one as far as I could
To where it bent in the undergrowth…"

– Robert Frost, "The Road Not Taken"

… I Looked Down One As Far as I Could …

High Energy QCD



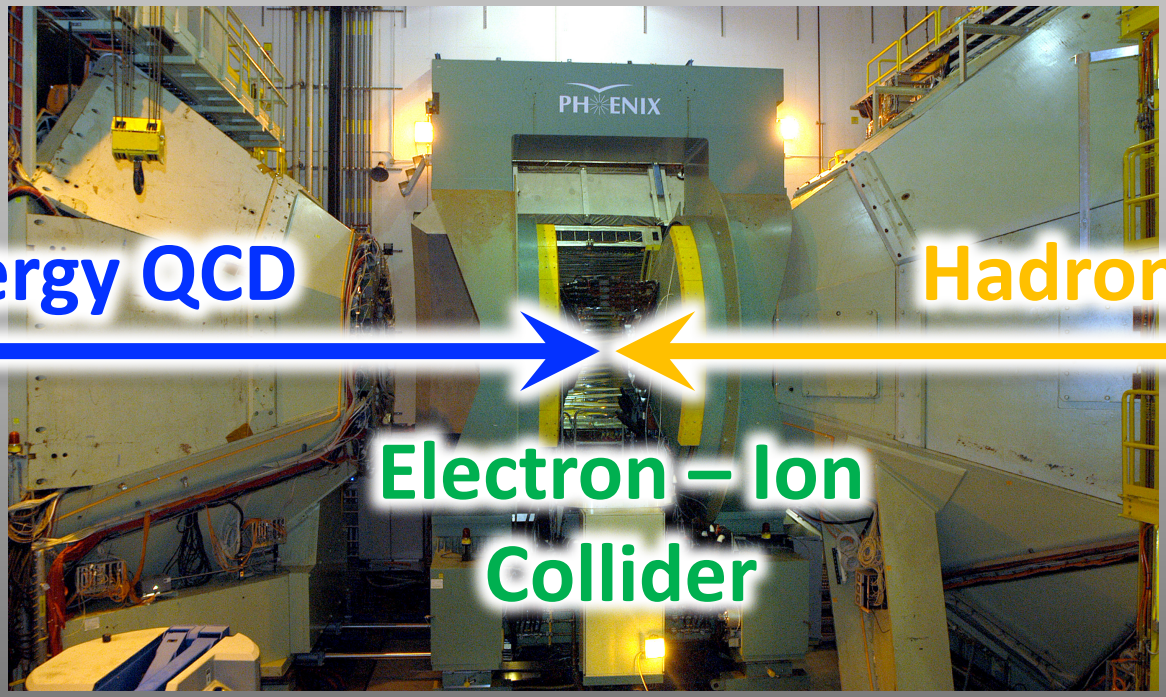
- 1959 – Regge Theory
- 1969 – Ioffe Time
- 1973 – QCD
- 1977 – BFKL Evolution
- 1981 – Dipole Picture of DIS
- 1994 – MV Model of Nucleus
- 1996 – BK / JIMWLK Evolution

… And then the Other, Just as Fair …

- 1919 – Proton Discovered
- 1964 – Quark Model
- 1969 – Parton Model
- 1973 – QCD
- 1988 – Proton Spin Crisis
- 1991 – Transverse Single Spin Asymmetries

Hadron Structure

… And that Will Make All the Difference.



High Energy QCD → ← **Hadron Structure**

Electron – Ion Collider

<u>The EIC is custom designed:</u>

- To probe the **nonlinear saturation region**
- To precisely **image 1D / 3D / 5D hadron structure**
- To unlock the **novel intersections between them**

Outline

1. Partonic Structure of the Nucleon

2. Saturation in High-Energy QCD

3. Opportunities at an EIC

4. Conclusions

Partonic Structure of the Nucleon

J. Collins, *Foundations of Perturbative QCD* (2013)

M. Diehl, Phys. Rept. **388** (2003)

A. Accardi et al., Eur. Phys. J. **A52** (2016)

H. Mantysaari and B. Schenke, Phys. Rev. Lett. **117** (2016)

T. Lappi and H. Mantysaari, Phys. Rev. **C83** (2011)

J. C. Collins, Phys. Lett. **B536** (2002)

S. J. Brodsky, D. S. Hwang, and I. Schmidt, Phys. Lett. **B530** (2002)

J. C. Collins, Nucl. Phys. **B396** (1993)

S. J. Brodsky et al., Phys. Rev. **D88** (2013)

T. C. Rogers and P. J. Mulders, Phys. Rev. **D81** (2010)

T. C. Rogers, Phys. Rev. **D88** (2013)

G. A. Chirilli et al., JHEP **12** (2015)

J. More et al., Phys. Rev. **D95** (2017)

E. Aschenauer et al., Phys. Rev. **D92** (2015)

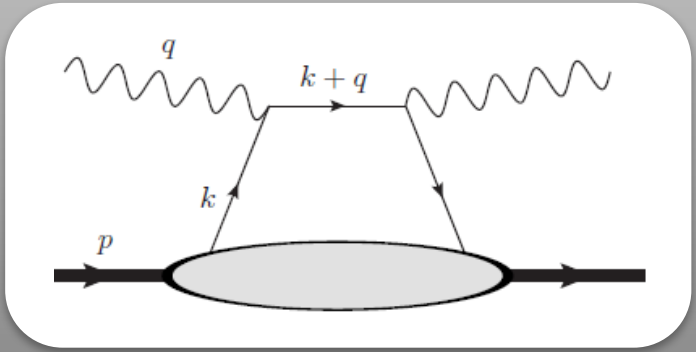
STAR Collaboration, Phys. Rev. Lett. **116** (2016)

What Is a Parton Distribution, *Really*?

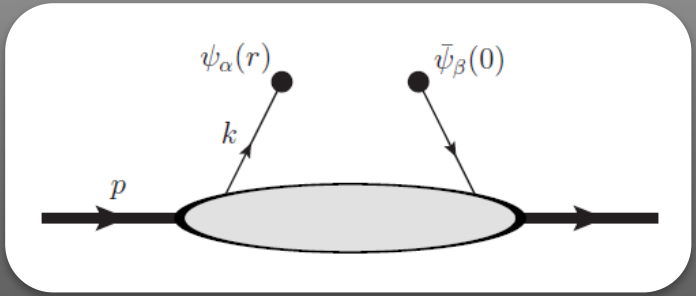
- Intuitively, a number density:

$$E_k \frac{dN}{d^3k} \sim \langle p| \, a_k^\dagger \, a \, |p\rangle$$

- Practically, a 1-1 correspondence with deep inelastic scattering:

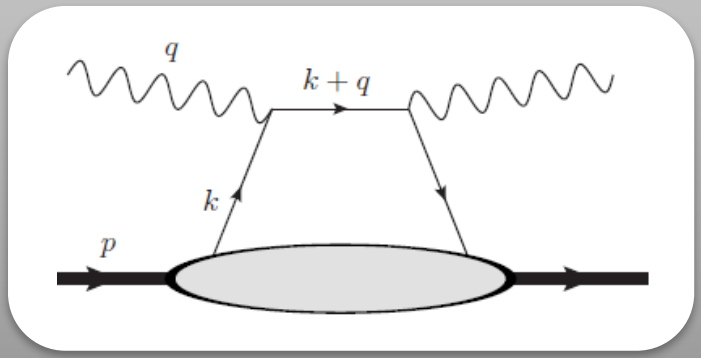


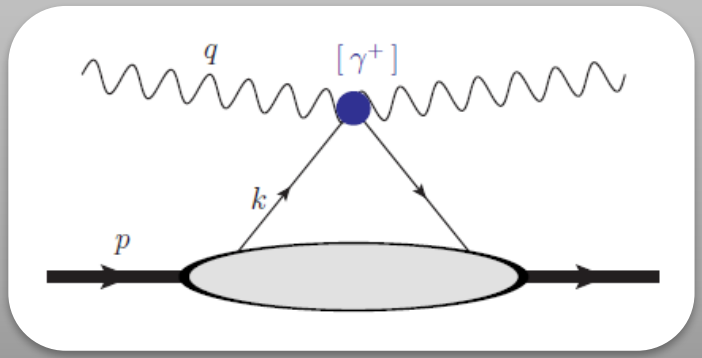
- Formally, the expectation value of quark / gluon fields, Fourier transformed to momentum space:



$$\phi_{\alpha\beta}(x) = \int \frac{dr^-}{2\pi} \, e^{ixp^+ r^-} \, \langle p, S| \, \bar{\psi}_\beta(0) \, \psi_\alpha(r^-) \, |p, S\rangle$$

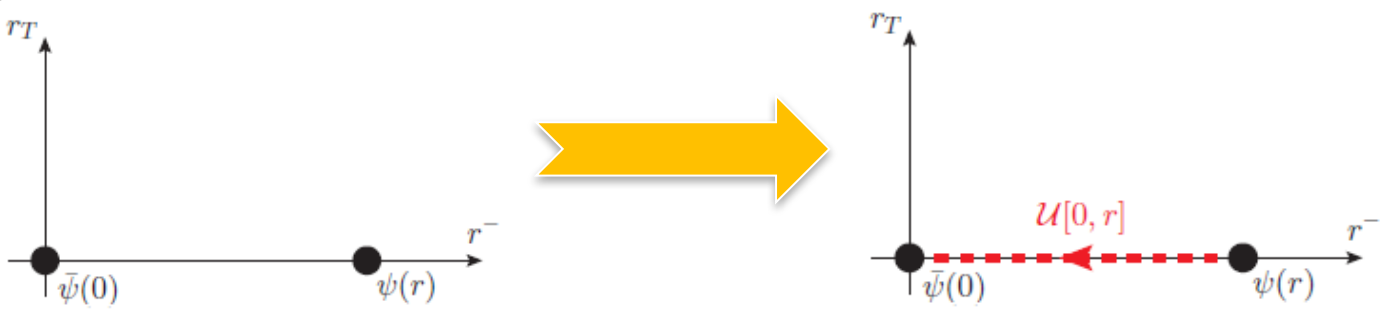
1D Collinear Distributions





- An effective vertex selects the various parton spins:
  - Unpolarized: $f_1(x, Q^2)$ $\langle p| \bar{\psi}\, \gamma^+ \psi \,|p\rangle$
  - Helicity: $g_1(x, Q^2)$ $\langle p, S_L| \bar{\psi}\, \gamma^+ \gamma^5 \psi \,|p, S_L\rangle$
  - Transversity: $h_1(x, Q^2)$ $\langle p, S_\perp^i| \bar{\psi}\, \gamma^+ \gamma_\perp^i \gamma^5 \psi \,|p, S_\perp^i\rangle$

Gluons, Ep. 1: "The Phantom Menace"



$$\bar{\psi}(0)\,\psi(r^-) \;\rightarrow\; \bar{\psi}(0)\,\underline{\mathcal{U}[0,r^-]}\,\psi(r^-)$$

- The quark / gluon fields are nonlocal and not gauge invariant
  - Must be connected by a Wilson line gauge link

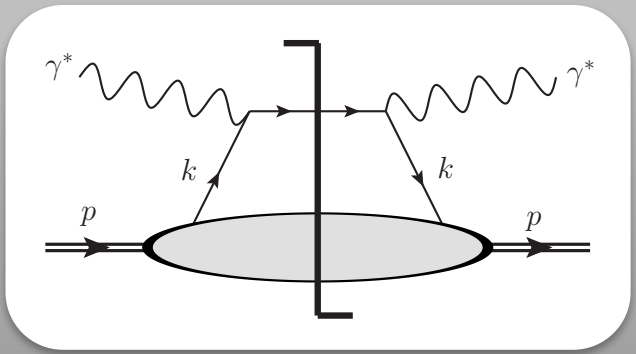
$$\mathcal{U}[0,r^-] = \mathcal{P}\exp\left[ig\int_{r^-}^{0} dx^- A^+(0^+,x^-,0_\perp)\right]$$

- Describes the physics of final-state rescattering
  - Can be removed in light-cone gauge

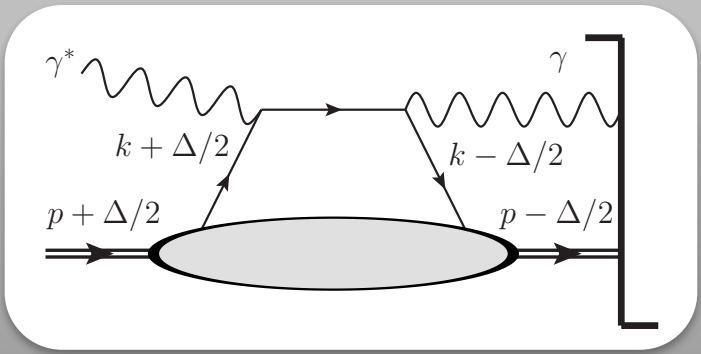
$$A^+ = 0$$

Diffraction: The Back Door In

DIS: Inclusive



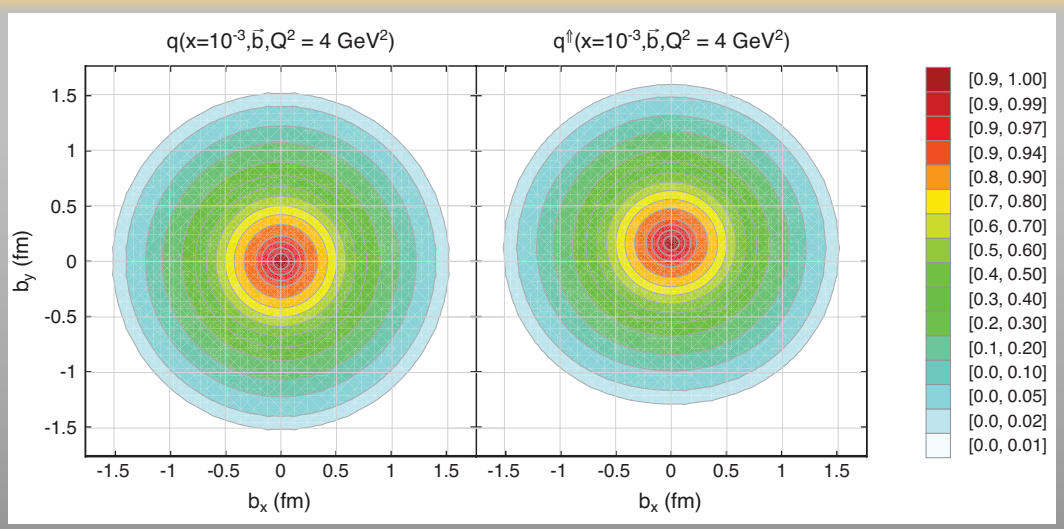
DVCS: Exclusive



- Exclusive measurements like deeply virtual Compton scattering are sensitive to parton distributions at the amplitude level
  - These "Generalized Parton Distributions" are off-forward

$$\int \frac{dr^-}{2\pi}\, e^{ixp^+r^-} \left\langle p - \tfrac{1}{2}\Delta \right| \bar{\psi}(-\tfrac{1}{2}r^-)\frac{\gamma^+}{2}\psi(\tfrac{1}{2}r^-) \left| p + \tfrac{1}{2}\Delta \right\rangle$$

GPDs: 3D Spatial Distributions



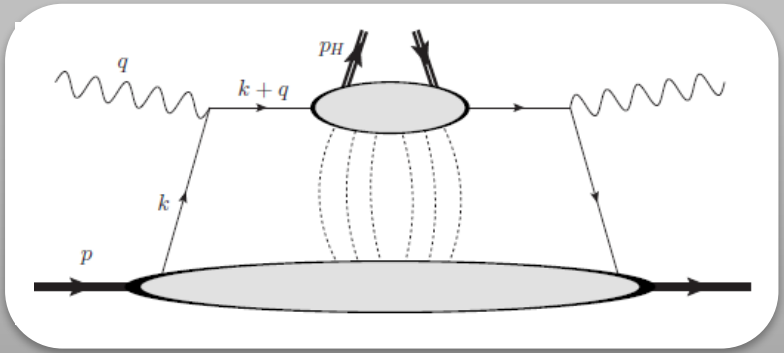
- The t-dependence is Fourier-conjugate to the spatial distribution:

$$f(x,\vec{b_\perp}) = \int \frac{dr^-}{2\pi}\frac{d^2\Delta}{(2\pi)^2}\, e^{ixp^+r^-}\, e^{-i\vec{\Delta}_\perp\cdot\vec{b}_\perp}\, \left\langle p-\tfrac{1}{2}\Delta\right|\bar{\psi}(-\tfrac{1}{2}r^-)\frac{\gamma^+}{2}\psi(\tfrac{1}{2}r^-)\left|p+\tfrac{1}{2}\Delta\right\rangle$$

- Coherent diffraction: Average density $\sim \left|\left\langle f(x,\vec{b_\perp})\right\rangle\right|^2$
- Incoherent diffraction: Fluctuations $\sim \left\langle\left|f(x,\vec{b}_\perp)\right|^2\right\rangle - \left|\left\langle f(x,\vec{b}_\perp)\right\rangle\right|^2$

TMDs: 3D Momentum Distributions

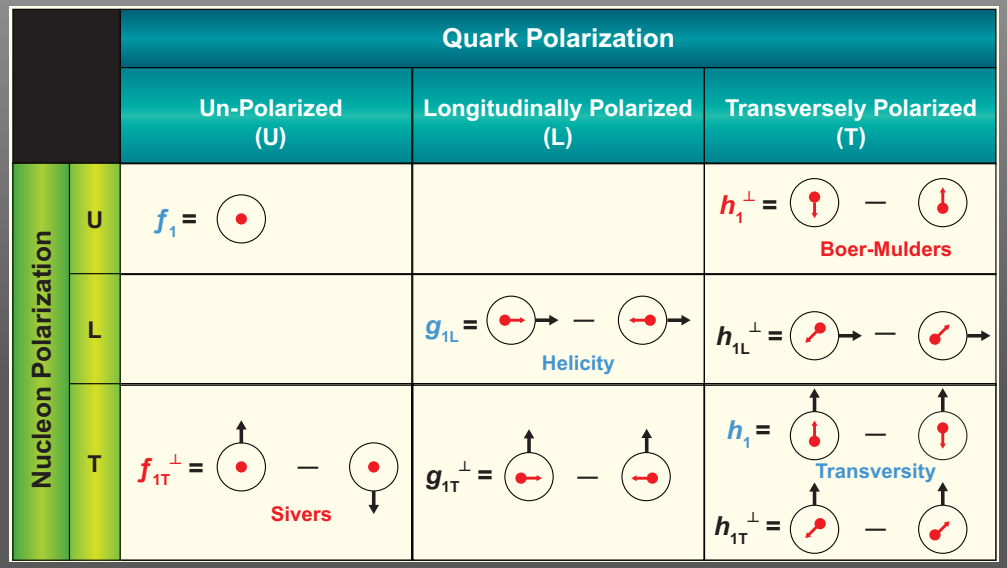
- Semi-inclusive measurements: sensitive to transverse momentum distributions



➢ Two scale process: a hard scale and soft scale

$$Q^2 \gg p_T^2 \, , \, \Lambda_{QCD}^2$$

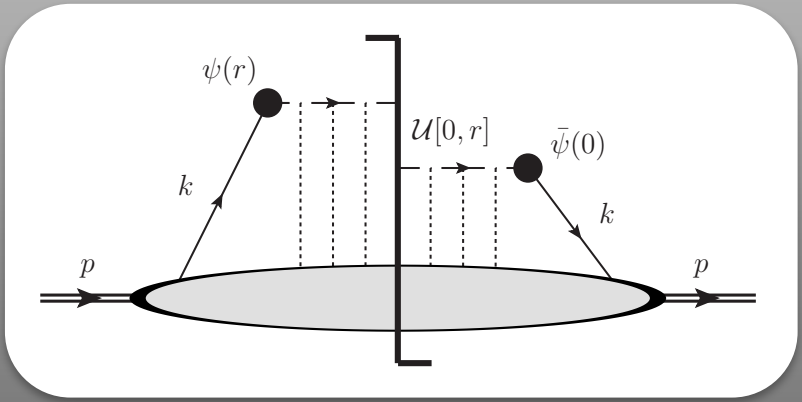
- Opens up a wealth of spin-spin and spin-orbit correlations!

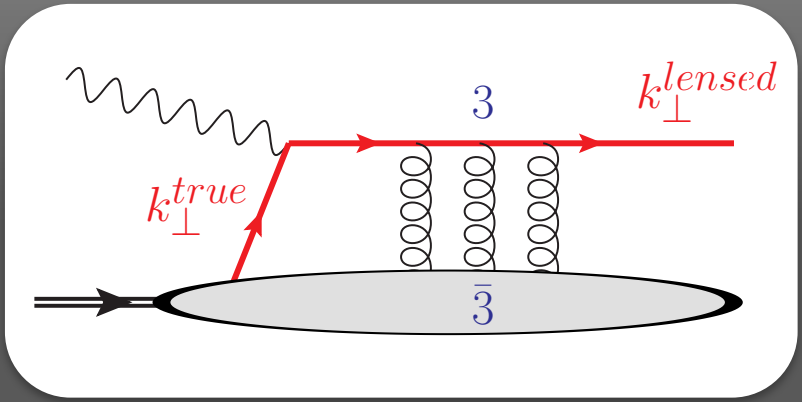


Gluons, Ep. 3: "Revenge of the Gauge Link"

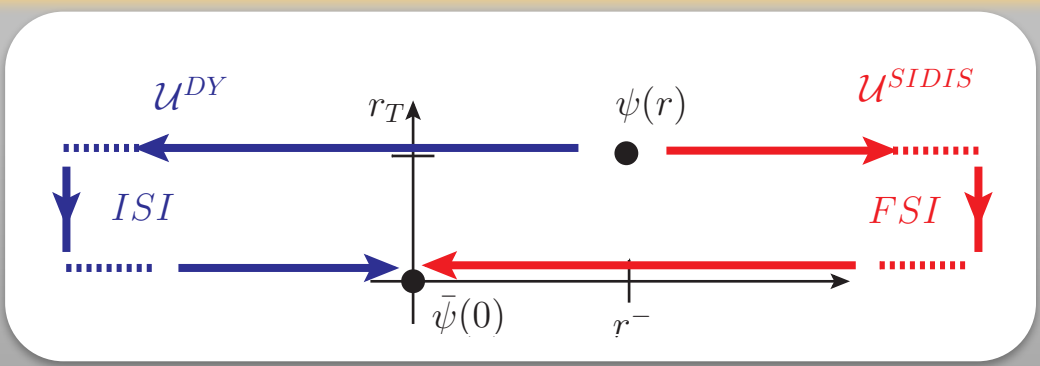
$$f(x, k_T^2) = \int \frac{d^2r\, dr^-}{(2\pi)^3}\, e^{ixp^+ r^-}\, e^{-i\vec{k}_\perp \cdot \vec{r}_\perp}\, \langle p|\, \bar{\psi}(0)\, \mathcal{U}[0,r]\, \frac{\gamma^+}{2} \psi(r)\, |p\rangle$$

- TMDs: expectation value of non-collinear operator
  - Sensitive to the intrinsic momentum distribution of the proton…
  - …But warped due final-state interactions!
  - Not purely initial-state wave functions!





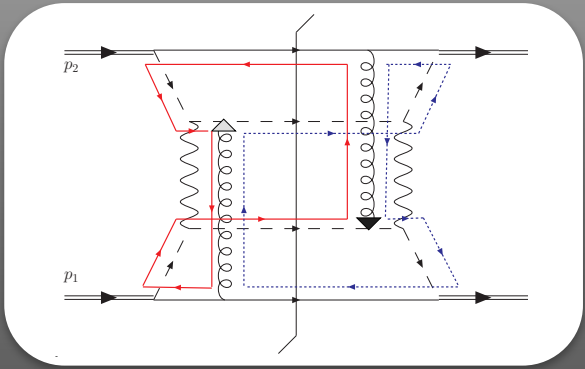
Opening Pandora's Box



"Bugs" or "Features"?

- Non-universality + QCD dynamics
- Factorization breaking + color entanglement
- Factorization-breaking spin asymmetries enhanced
- Number density interpretation ... sometimes

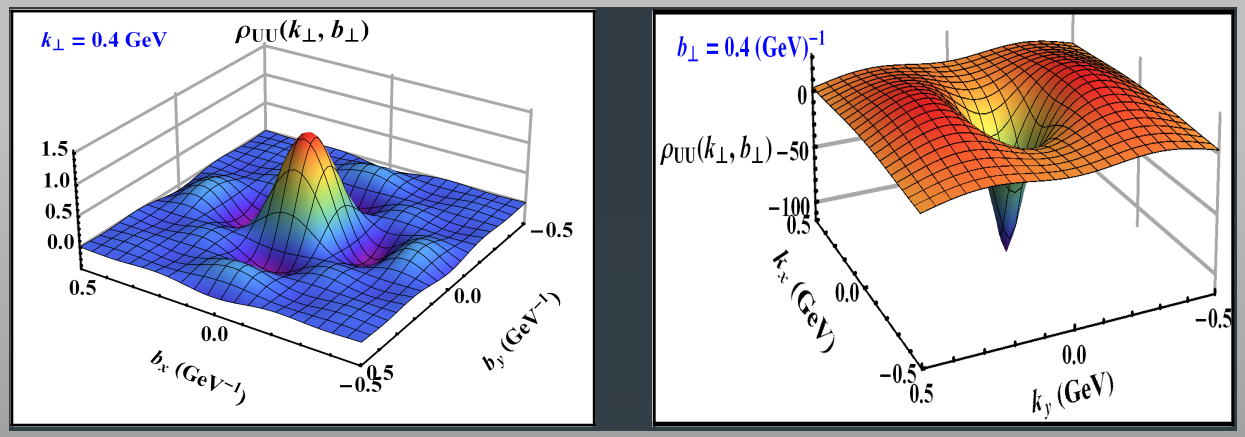
$$f_{1T}^{\perp}\big|_{SIDIS} = -\, f_{1T}^{\perp}\big|_{DY} \neq 0$$



$$A^+ = 0$$

$$(\vec{\nabla}_\perp \cdot \vec{A}_\perp)\Big|_{x^- = \pm\infty} = 0$$

Wigner Functions: 5D Distributions

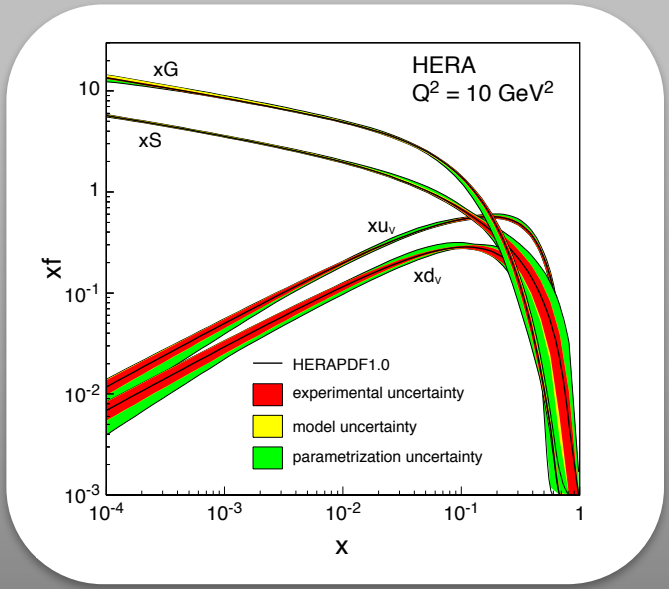


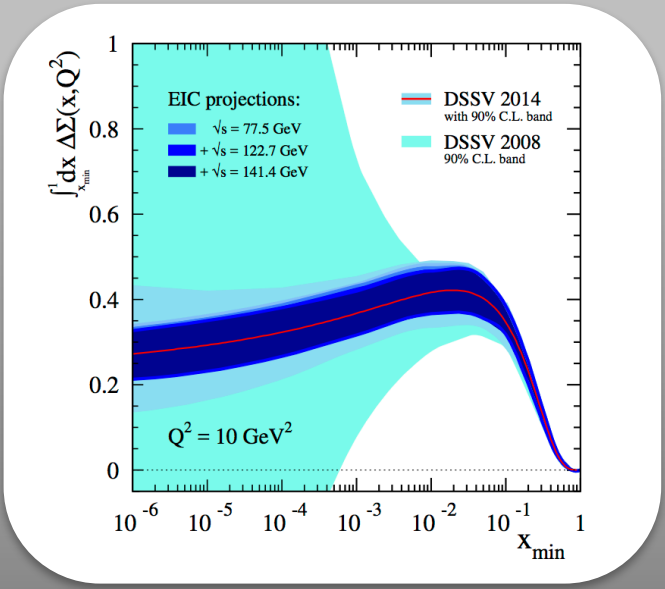
$$W(x,\vec{k}_\perp,\vec{b}_\perp) = \int \frac{dr^-}{2\pi}\frac{d^2r}{(2\pi)^2}\frac{d^2\Delta}{(2\pi)^2}\, e^{ixp^+r^-}\, e^{i\vec{k}_\perp\cdot\vec{r}_\perp}\, e^{i\vec{\Delta}_\perp\cdot\vec{b}_\perp}\, \langle p-\tfrac{1}{2}\Delta|\,\bar{\psi}(-\tfrac{1}{2}r)\,\mathcal{U}[0,r]\,\frac{\gamma^+}{2}\,\psi(r)\,|p+\tfrac{1}{2}\Delta\rangle$$

Having your cake and eating it too:

- "Master distributions" of partons in phase space
- Best and worst of both worlds (universality, factorization…)
- Non-probabilistic: contain purely quantum negative regions
- Allows direct access to parton angular momentum

Nucleon Structure: What Do We Know?



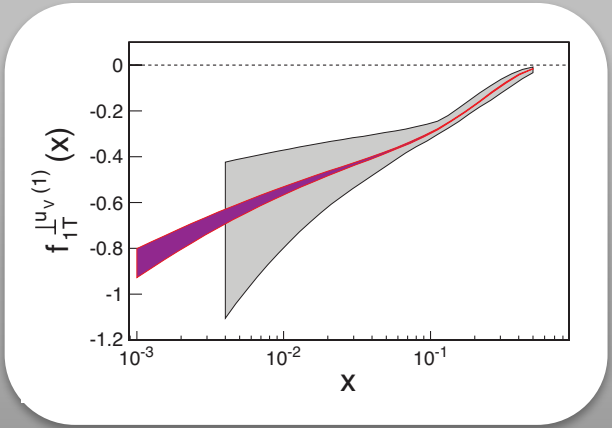


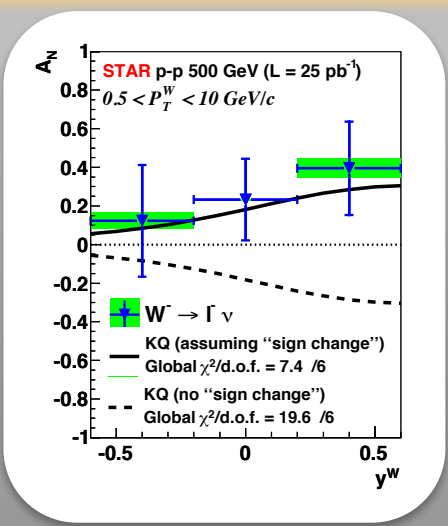
- 1D PDFs are very well constrained from HERA
- The proton spin puzzle is still an open question….

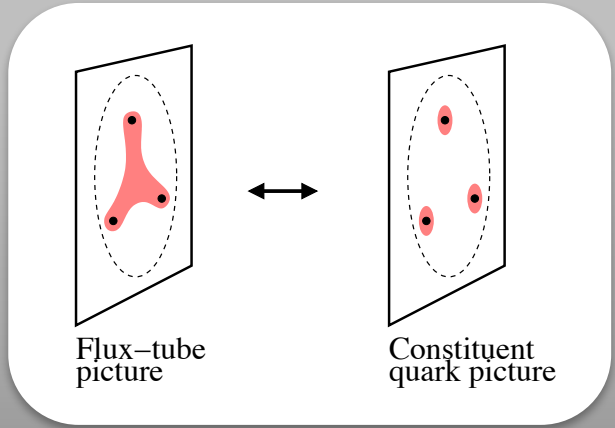
$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_q + L_G$$

➢ Uncertainties at small x due to kinematic limitations

Nucleon Structure: What Do We Know?







credit: C. Weiss

- 3D TMDs: maturing into a coherent picture
  - ➢ Hints of Sivers sign flip in STAR W asymmetries?
- 3D GPDs: promising but require a lot of data to extract

$$\int_{-1}^{1} dx\, f(x,\xi,t)\,\frac{1}{x-\xi+i\epsilon}$$

- 5D Wigner distributions: no longer "science fiction"

Saturation in High-Energy QCD

Y. V. Kovchegov and E. Levin, *Quantum Chromodynamics at High Energy* (2012)

V. S. Fadin et al., Sov. Phys. JETP **45** (1977)

I. I. Balitsky and L. N. Lipatov, Sov. J. Nucl. Phys. **28** (1978)

L. V. Gribov et al., Phys. Rept. **100** (1983)

A. H. Mueller and J. W. Qiu, Nucl. Phys. **B268** (1986)

L. McLerran and R. Venugopalan, Phys. Rev. **D49** (1994)

A. M. Stasto et al., Phys. Rev. Lett. **86** (2001)

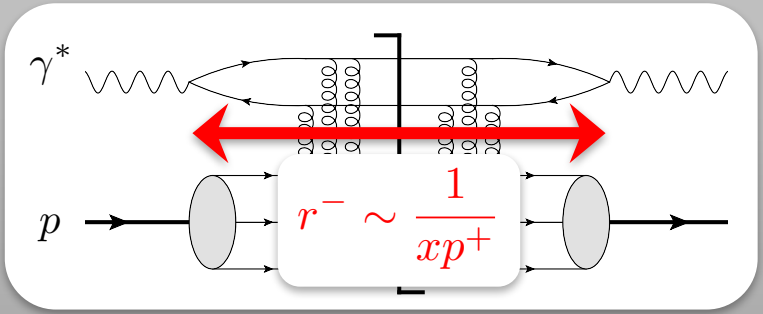
A. H. Rezaeian et al., Phys. Rev. **D87** (2013)

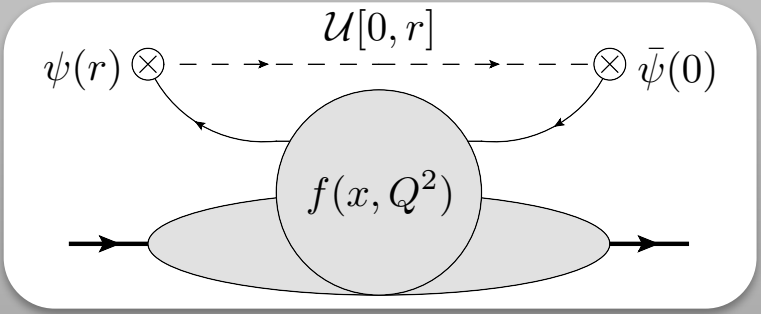
D. Kharzeev et al., Phys. Lett. **B599** (2004)

J. Albacete and C. Marquet, Prog. Part. Nucl. Phys. **76** (2014)

B. Schenke et al., Phys. Rev. **C86** (2012)

The Small-x, High-Energy Limit



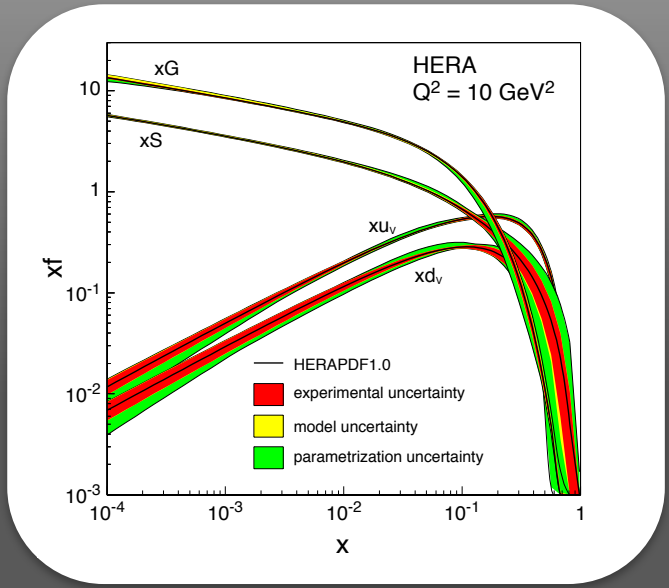


- The high-energy (Regge) limit corresponds to the small x limit
- DIS (and the PDFs) look like dipoles scattering in the target field
- Gluons dominate the small-x PDFs

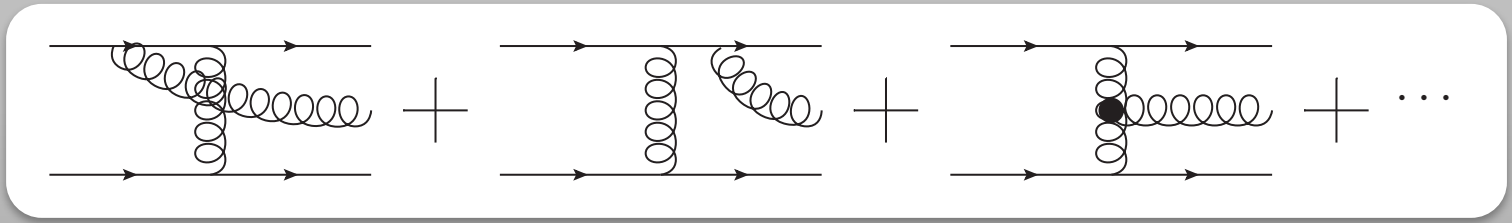
➢ Dipole / Wilson line degrees of freedom

$$V_{\underline{x}} = \mathcal{P}\exp\left[ig\int dz^-\,\hat{A}^+(0^+,z^-,\underline{x})\right]$$

$$\frac{1}{x} \approx \frac{s}{Q^2}$$



BFKL Evolution

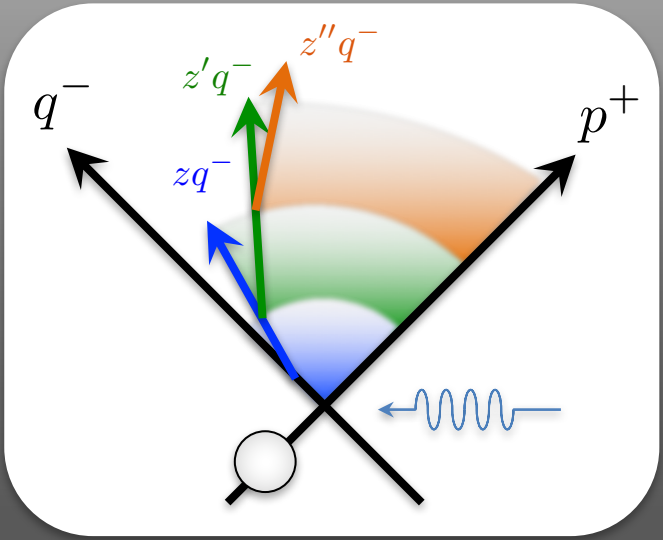


- In QCD, high-energy scattering radiates a cascade of soft gluons
- The greater the energy, the larger the rapidity window for soft gluons

➢ At high enough energies, the resummed cascade leads to exponentially growing gluon density

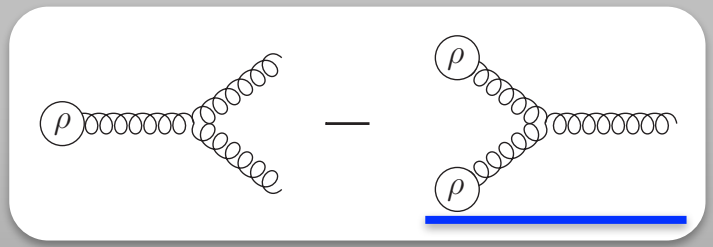
➢ The proton cross-section becomes more and more "opaque"

$$\frac{d\sigma}{dy} = const$$



$$\alpha_s \ln \frac{1}{x} \sim 1$$

Saturation

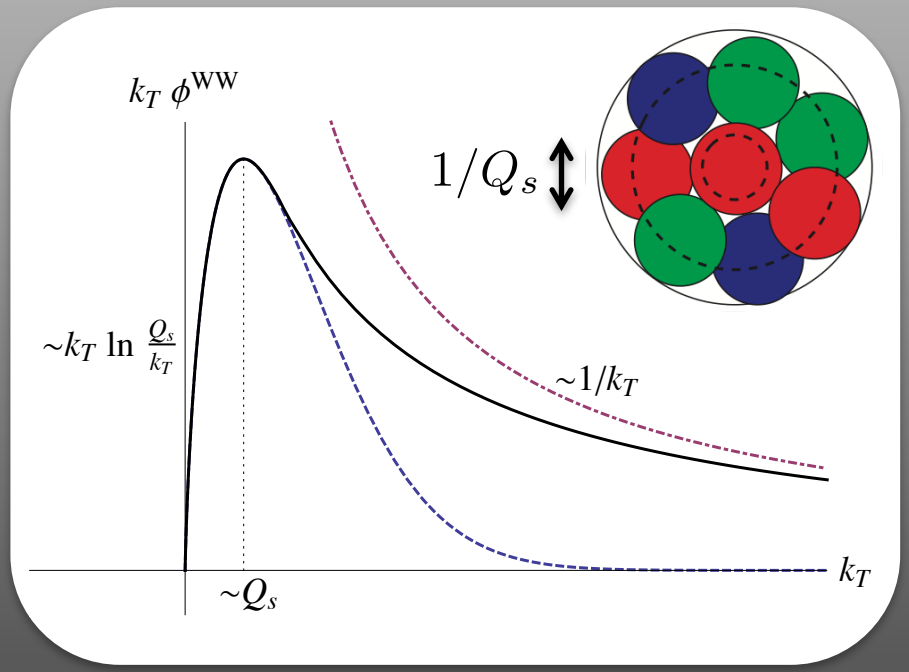


$$Q^2 \frac{d^2\rho}{dy\, dQ^2} = \left(\frac{\alpha_s N_c}{\pi}\right)\rho - \left(\frac{\alpha_s^2 N_c \pi}{2 C_F Q^2}\right)\rho^2$$

- At high densities, nonlinear gluon fusion competes with linear bremsstrahlung

➢ At equilibrium, the gluon density saturates to a classically large occupation number

➢ Gaussian fluctuations in color charge lead to dynamical IR screening on a characteristic scale



$$Q_s^2 \sim \alpha_s \rho$$

Heavy Nuclei and High-Density QCD

- The high-energy limit of QCD is the high-density limit as well

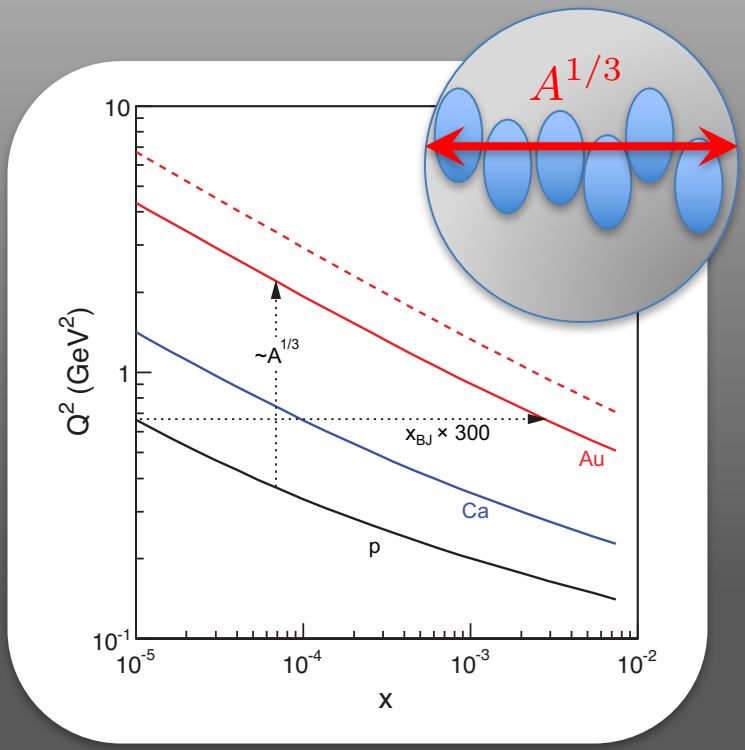
$$\alpha_s \rho \sim Q_s^2 \gg \Lambda_{QCD}^2$$

➢ An effective theory in a background of classical gluon fields

$$A^\mu = A^\mu_{cl} + a^\mu_q$$

- Heavy nuclei (A >> 1) get a head start toward the high-density limit

$$Q_s^2 \approx Q_{s0}^2 \left(\frac{A}{x}\right)^{1/3}$$

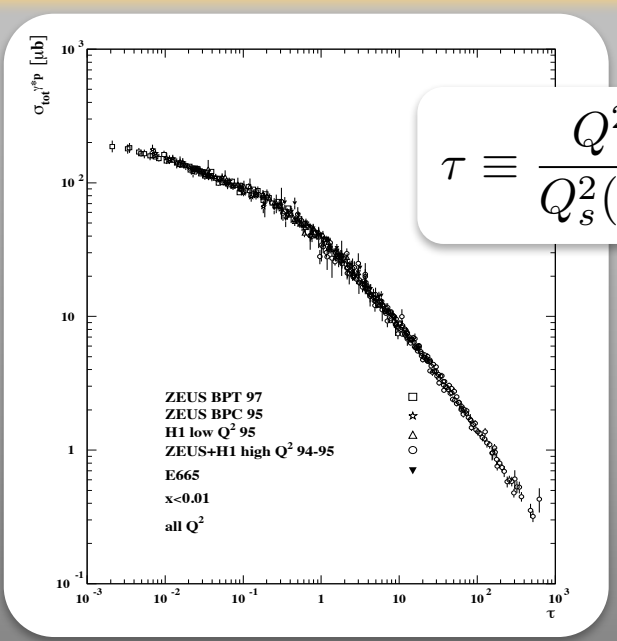


➢ Practically: cheaper than high energy

➢ Theoretically: an external dial!

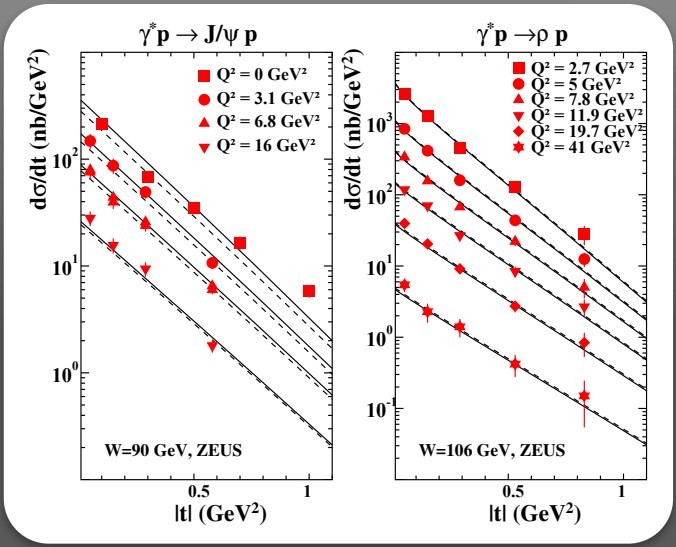
Saturation: What Do We Know?

- The structure functions from HERA are consistent with the dipole picture of DIS
  - For x < 0.01 HERA data exhibits geometric scaling

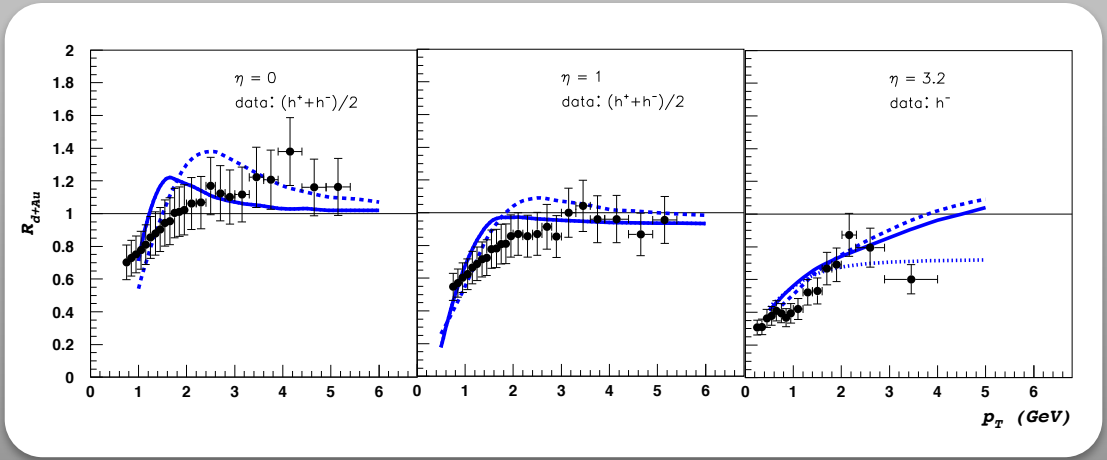


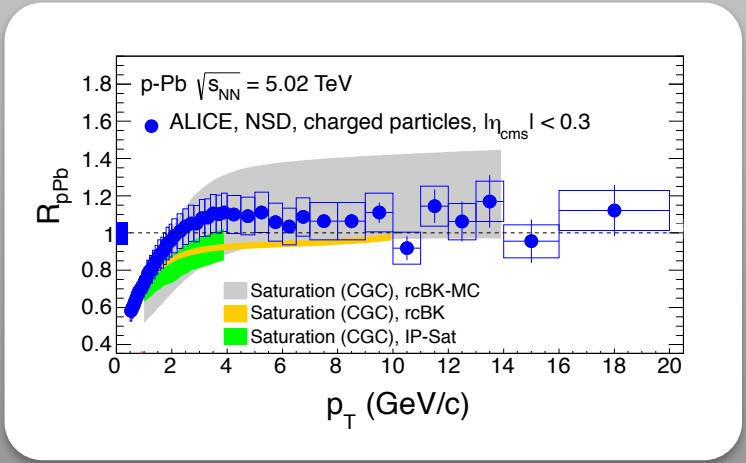
$$\tau \equiv \frac{Q^2}{Q_s^2(x)}$$

- Diffractive processes couple to the gluon density at the amplitude level
  - Diffractive rates ~ 10% at HERA
  - Diffractive meson production at HERA is well-described by saturation calculations



Saturation: What Do We Know?





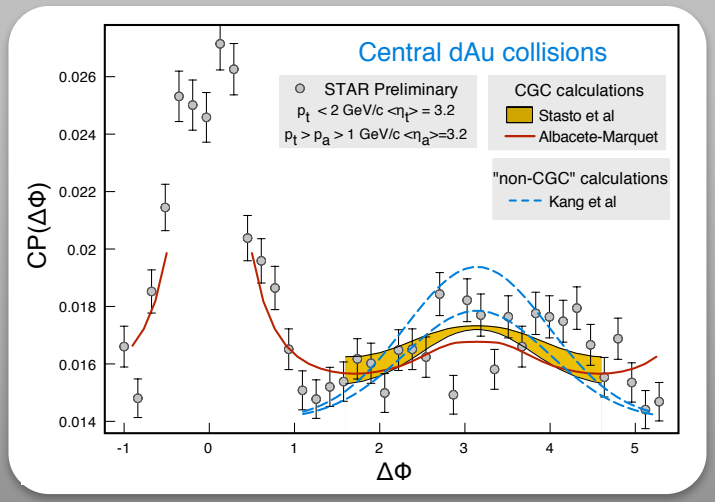
- The Cronin peak in R_{pA} for inclusive hadron spectra is a natural consequence of nonlinear multiple scattering
  - ➢ Its disappearance at forward rapidities and higher energies is characteristic of gluon saturation in nonlinear small-x evolution

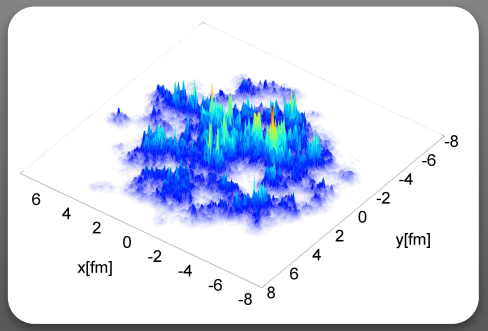
Saturation: What Do We Know?

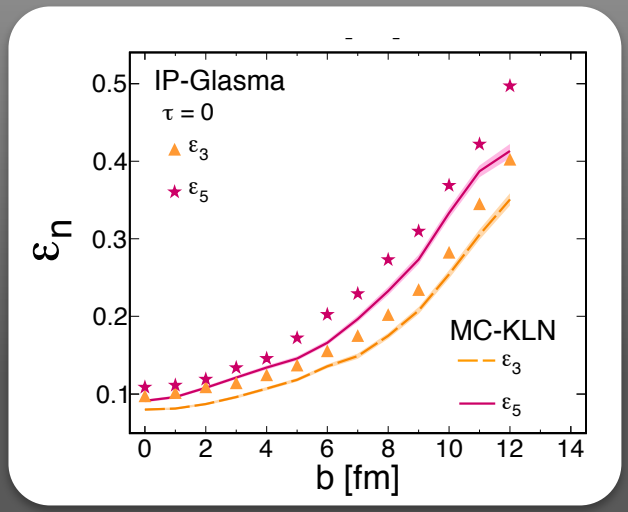
- In pp collisions, forward dihadron pairs are produced back-to-back

➢ In pA collisions, the back-to-back peak is washed out by rescattering

- Small-scale fluctuations can enhance anisotropies in heavy-ion collisions







- The Ridge in pp / pA / AA: natural for initial-state, boost-invariant correlations

Opportunities at an EIC

L. Zheng et al., Phys. J. **A50** (2014)

Y. V. Kovchegov et al., arXiv: 1706.04236

Y. V. Kovchegov et al., Nucl. Phys. **B903** (2016)

Y. V. Kovchegov et al., Phys. Rev. Lett. **118** (2017)

A. Dumitru et al., Phys. Rev. Lett. **115** (2015)

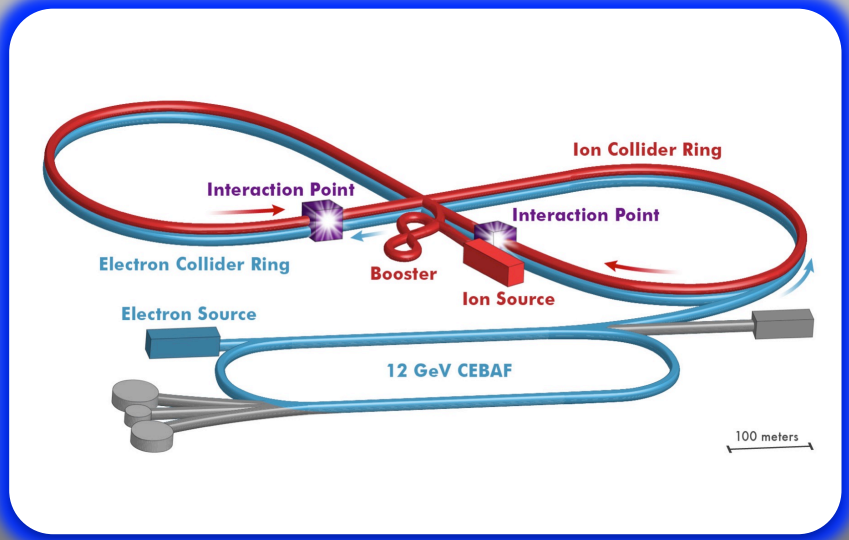
Y. Hatta et al., Phys. Rev. Lett. **116** (2016)

S. Bhattacharya et al., Phys. Lett. **B771** (2017)

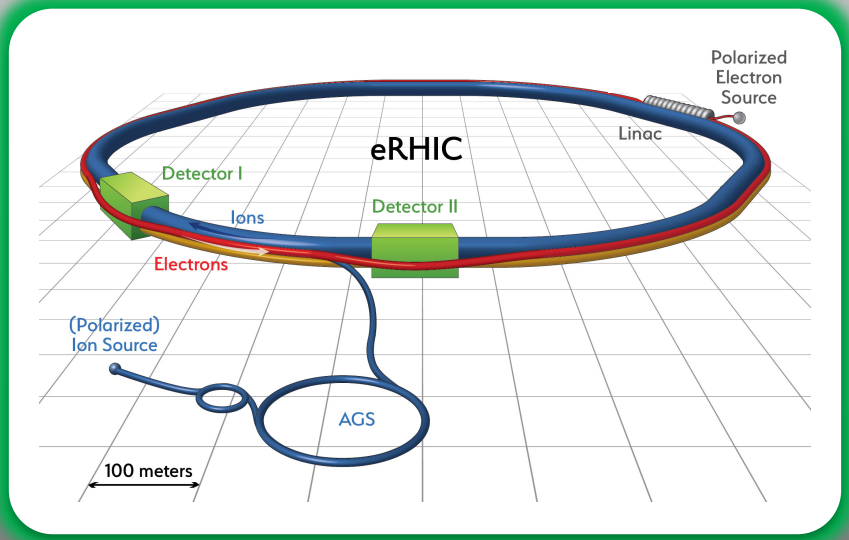
I. Balitsky and A. Tarasov, JHEP **10** (2015)

The Electron-Ion Collider

JLEIC



eRHIC



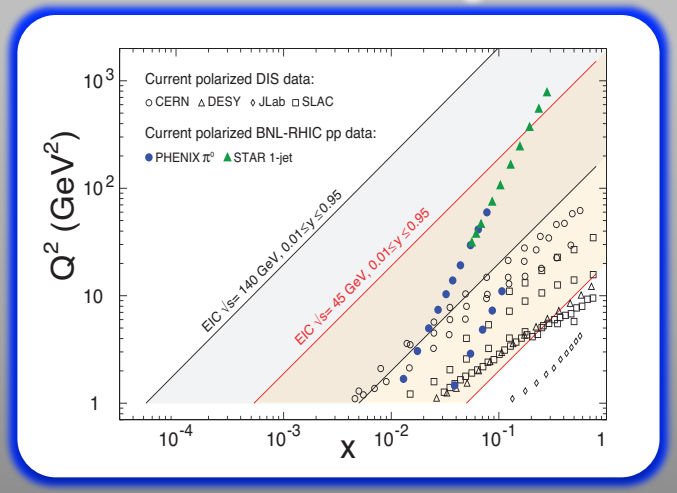
- The EIC combines the technology and expertise of CEBAF (JLab) and RHIC (BNL) into a single electron + ion collider facility

➢ Consolidates two world-leading facilities into one

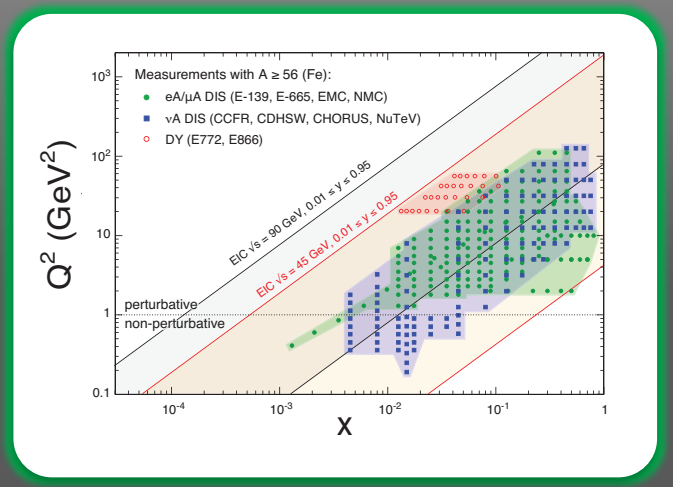
➢ Re-uses existing architecture to upgrade either CEBAF or RHIC

A Unique Niche at the QCD Frontier

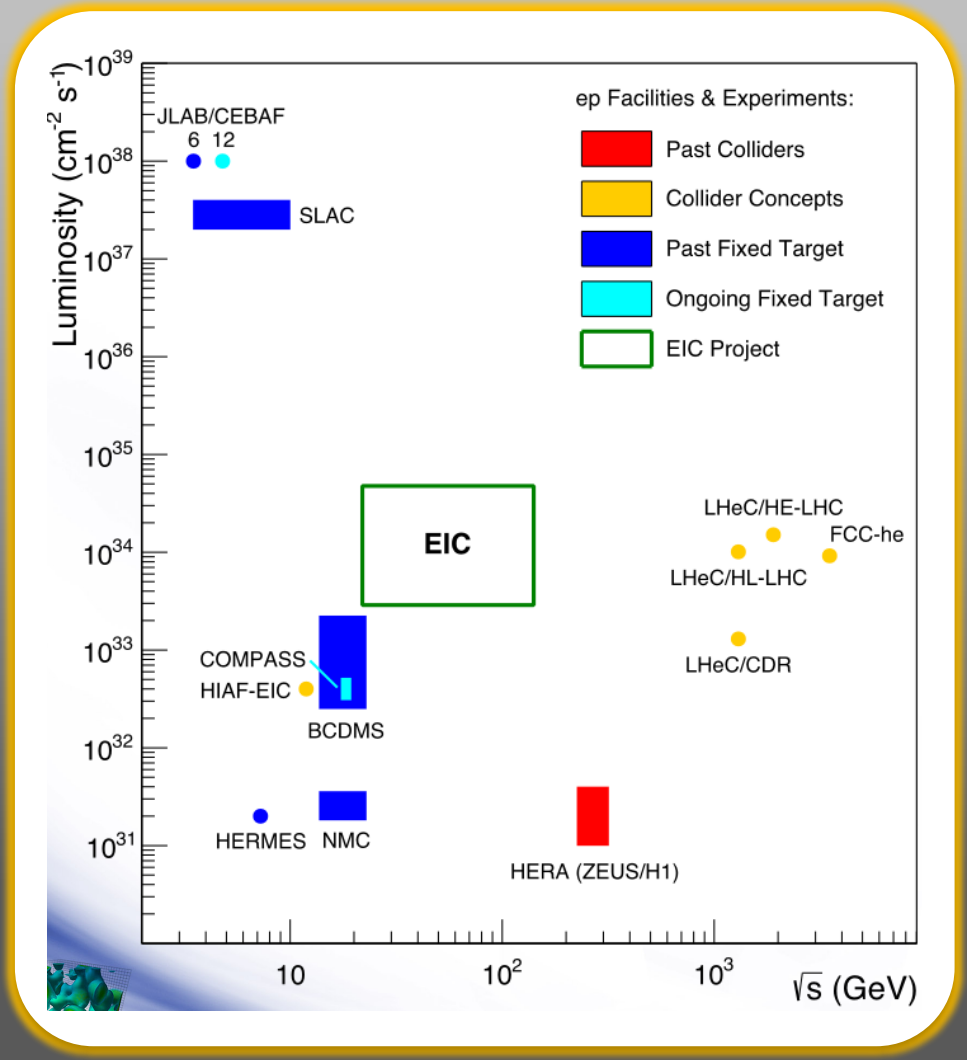
Kinematic Reach: Spin



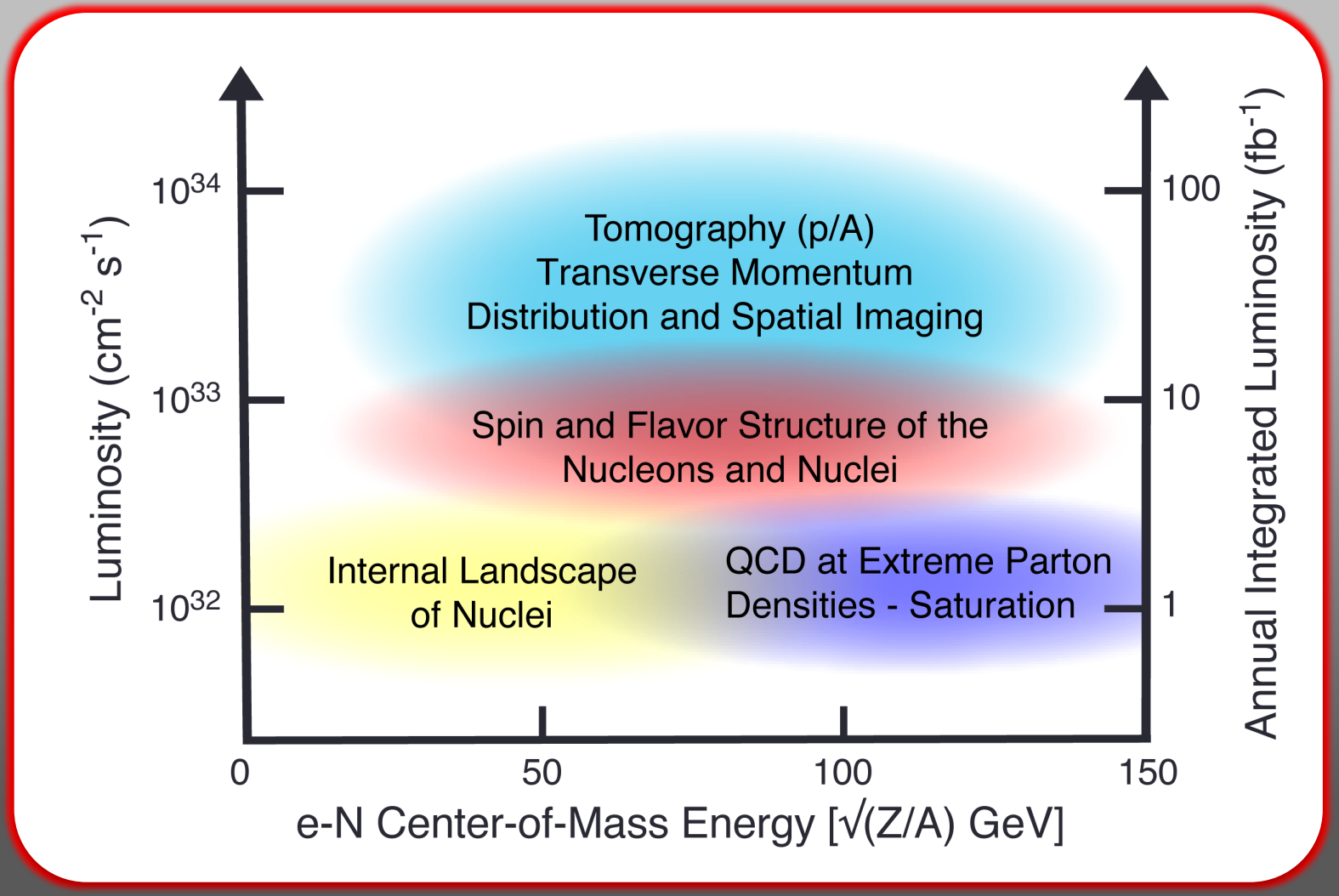
Kinematic Reach: Nuclei



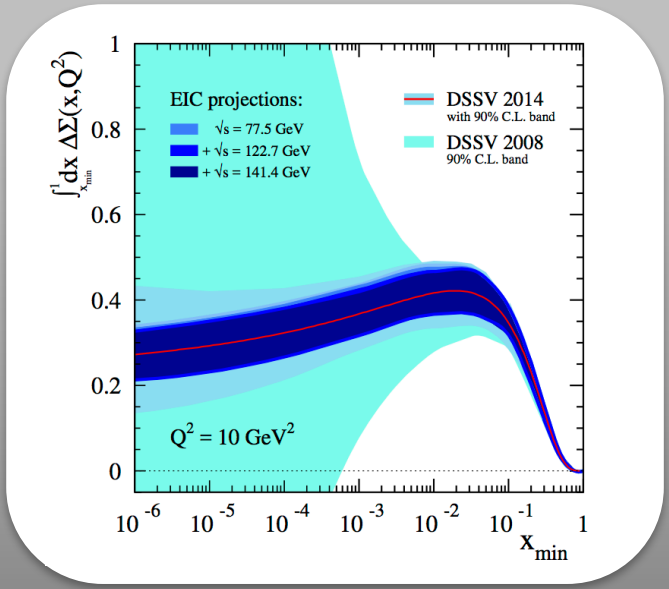
A Peerless Machine

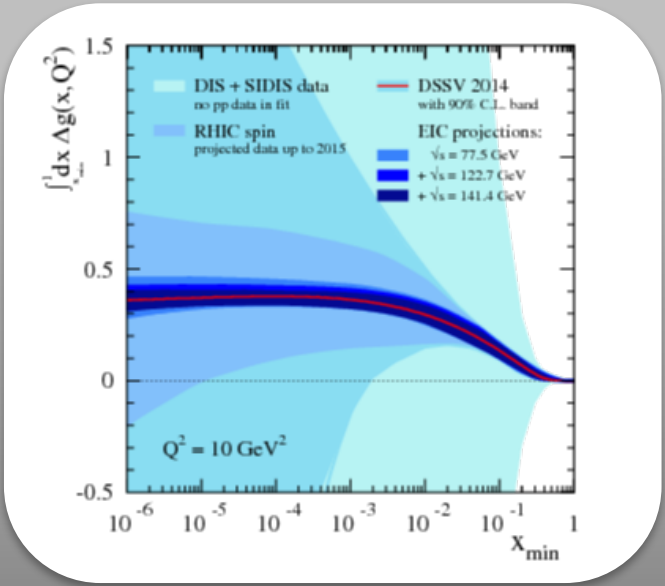


Design Requirements for the EIC Program



A Discovery Machine: Nucleon Structure

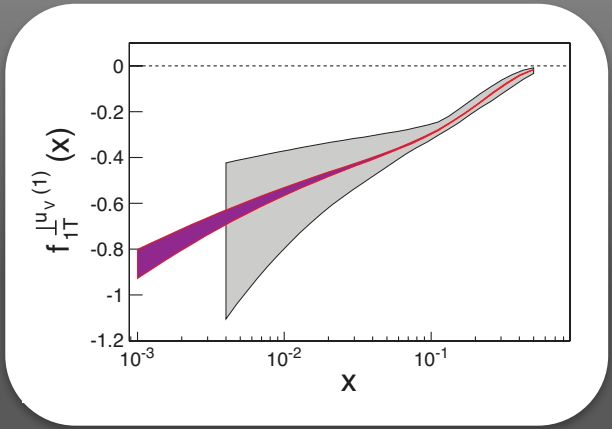




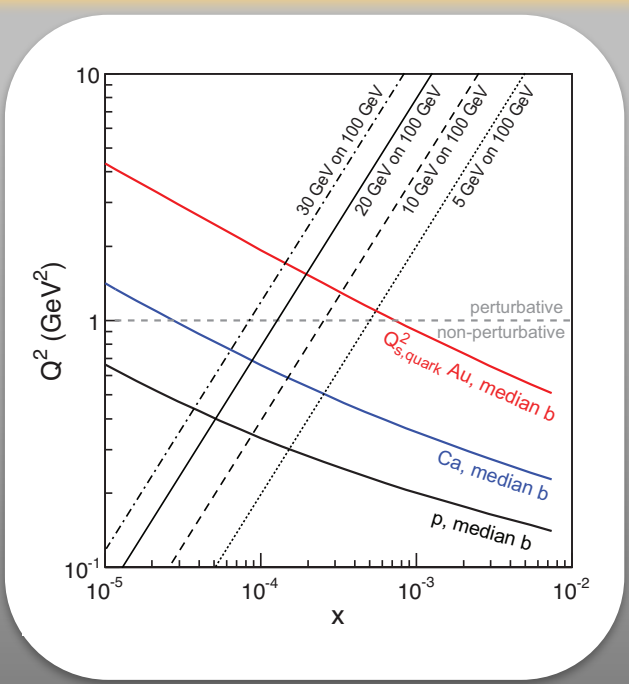
- Engineered to definitively resolve the proton spin puzzle

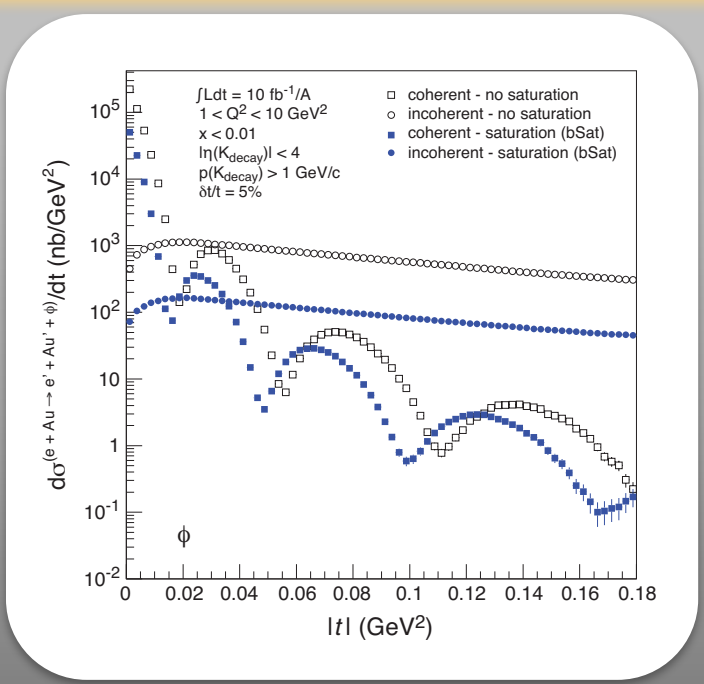
$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_q + L_G$$

- Polarization and luminosity to image nucleon structure over a wide lever in x and Q^2



A Discovery Machine: Saturation

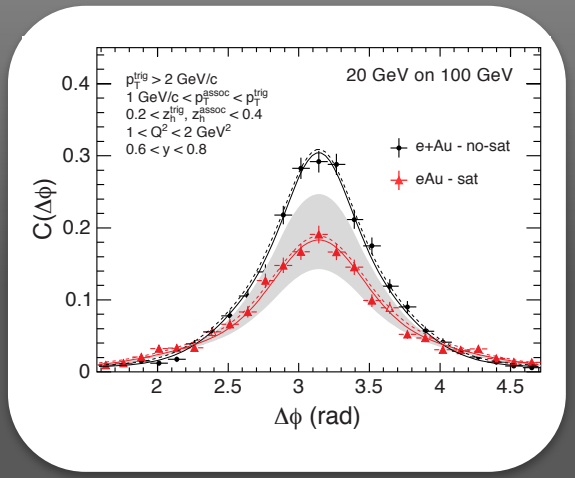




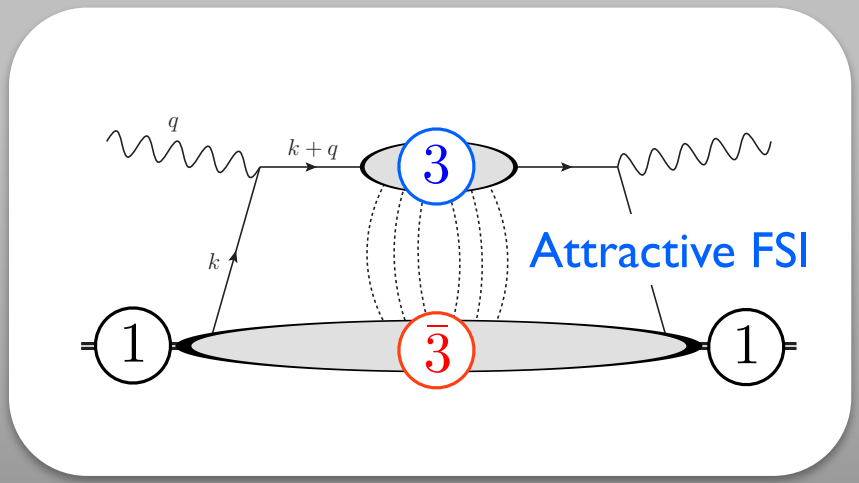
- Nuclear beams with EIC kinematics can achieve perturbative saturation scales

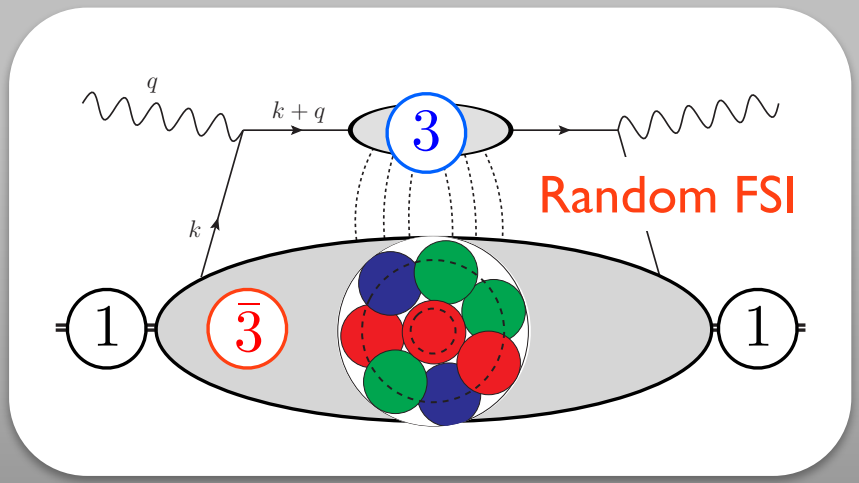
➢ Diffraction: a sensitive test of saturation

➢ Dihadron correlations: free of underlying flow

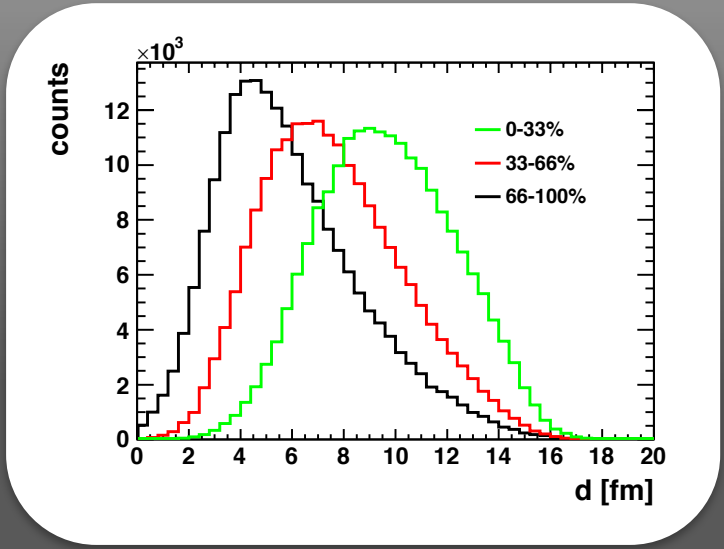


Intersections: Beyond the Standard Paradigm

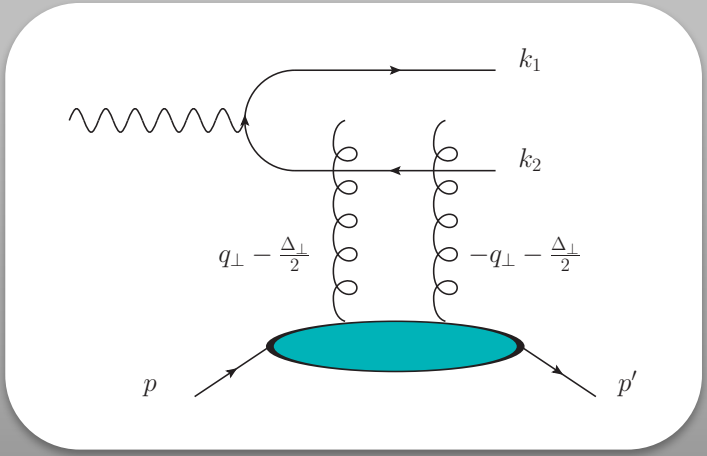


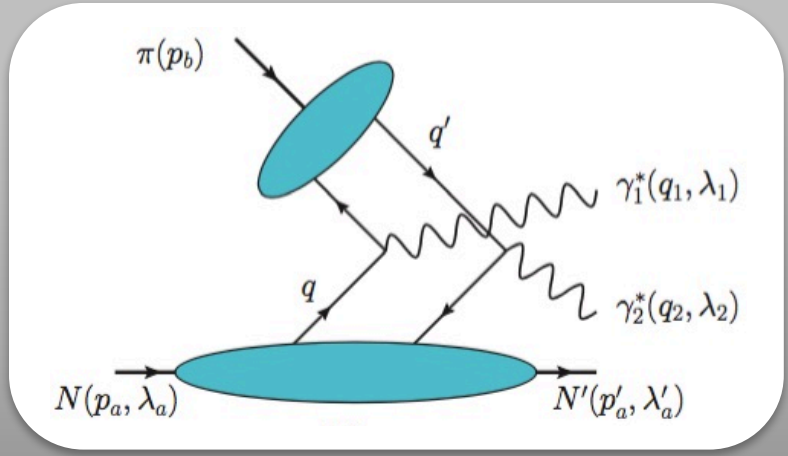


- TMDs of nuclei: very different final-state interactions from the dilute limit
  - Broadening mediated by saturation vs. coherent lensing
  - An experimental dial: path-length binning using a ZDC



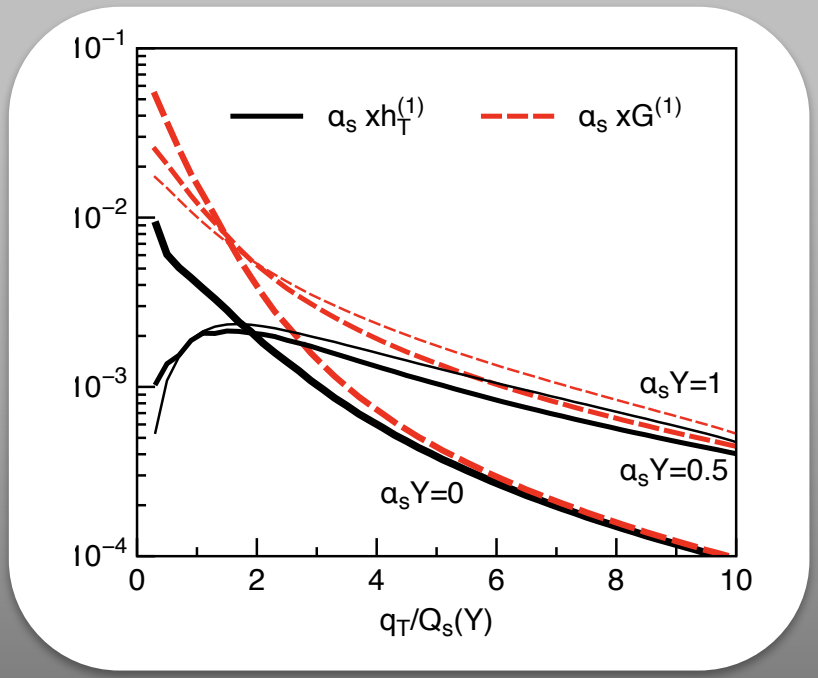
Intersections: Beyond the Standard Paradigm

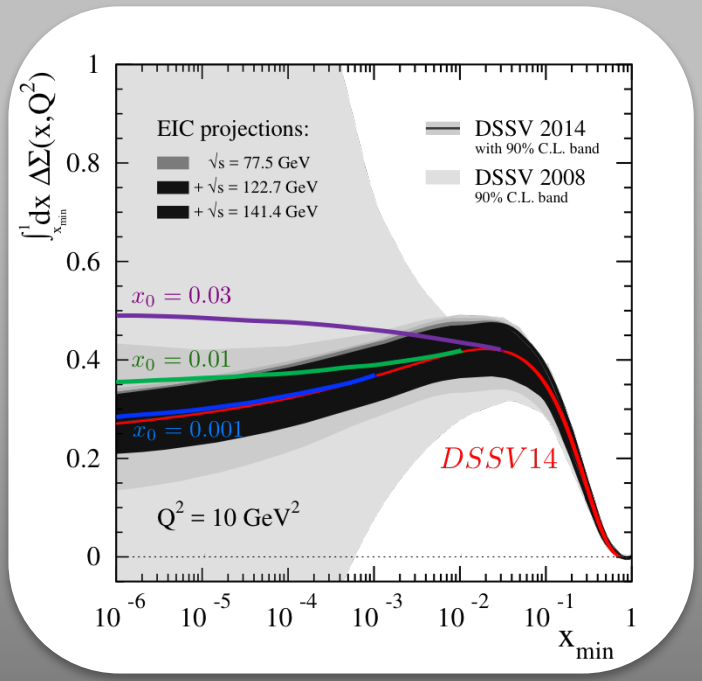




- First proposal for how the 5D Wigner distributions can be measured: diffractive dijet production at small x
  - Couples to the gluon Wigner distribution with dials on both the spatial and momentum dependence
  - Inspired the proposal of an analogous measurement (exclusive double Drell-Yan) which can couple to the quark Wigner distribution

Intersections: Beyond the Standard Paradigm





- Novel small-x properties of polarized parton distributions
  - Large linear polarization of gluons at small x
  - Small-x enhancement of quark / gluon helicity
  - "Master" gluon evolution formalism: BK + CSS + DGLAP

Conclusions

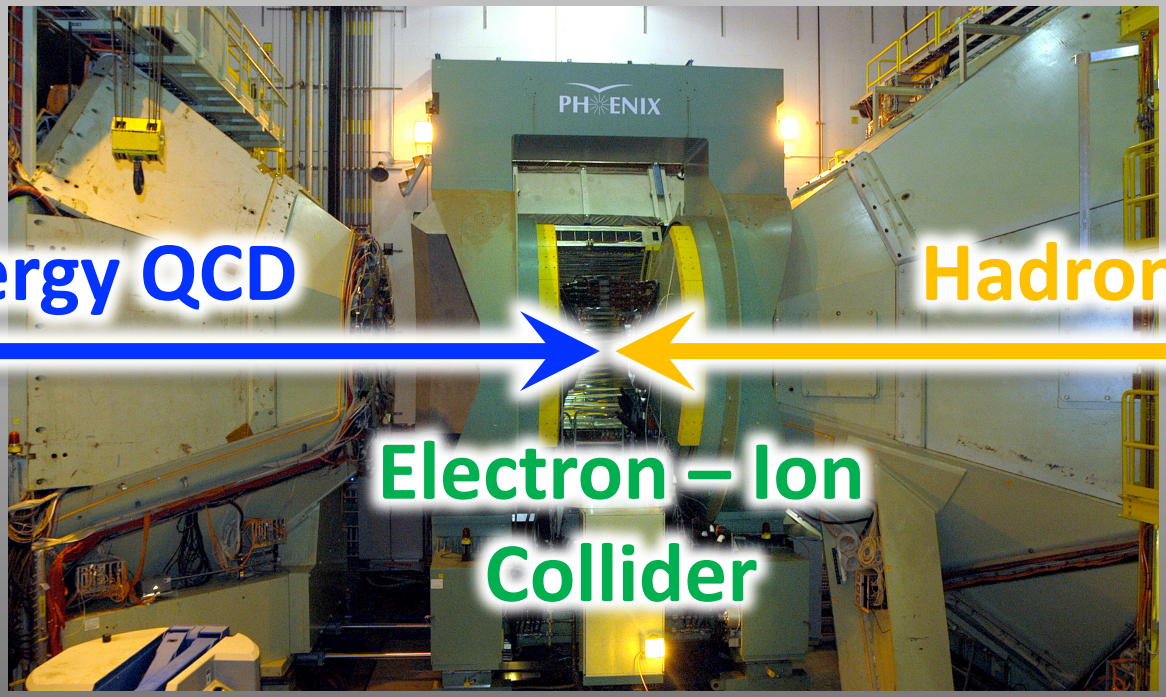
Two Roads Diverged…

High Energy QCD

Hadron Structure

- For decades, the subfields of **high energy QCD** and **hadron structure** have developed independently…
- …But they are on a **collision course for the EIC**

… But Not for Long.

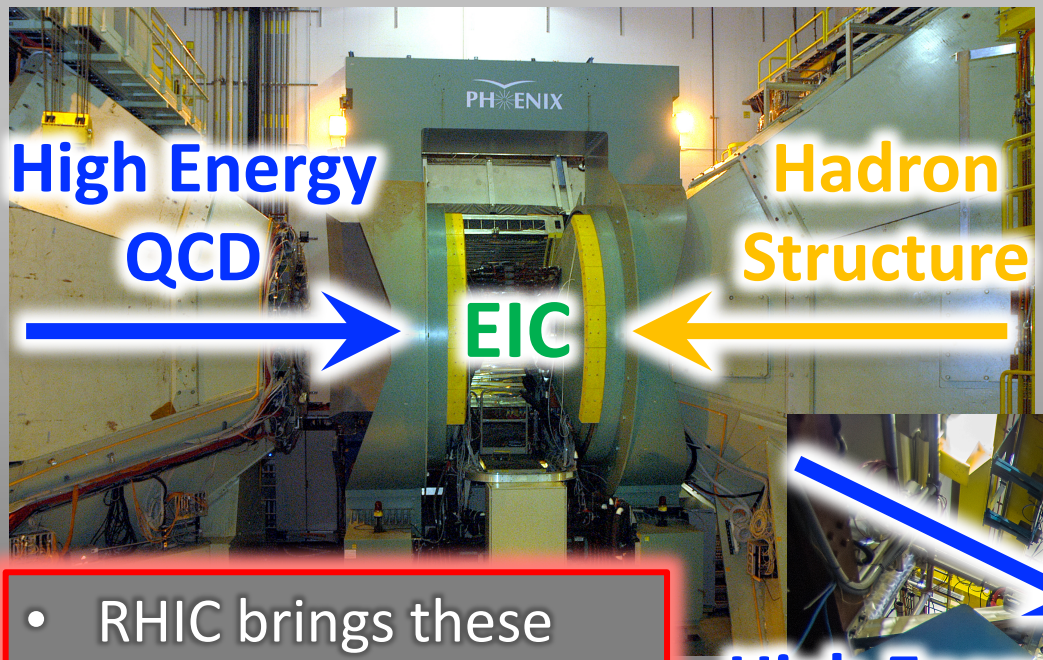


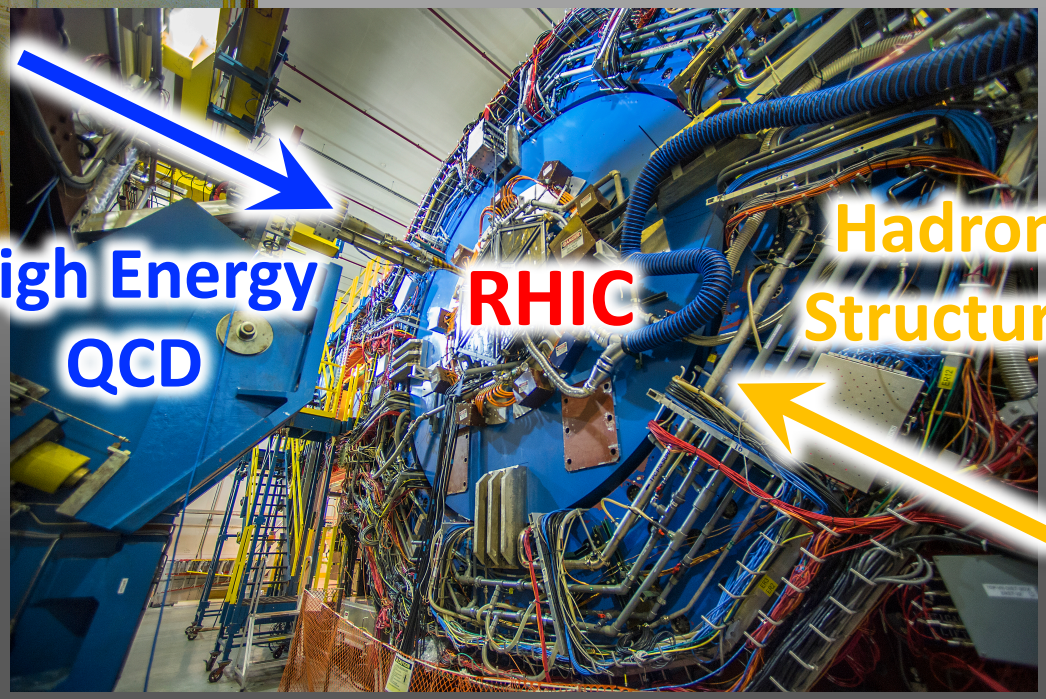
High Energy QCD → ← **Hadron Structure**

Electron – Ion Collider

- The EIC is specifically tailored to both reach into the nonlinear saturation regime in nuclei and to perform multidimensional tomography of the nucleon
- And it will also open new opportunities for cross-fertilization

A Second Beam Crossing





- RHIC brings these elements together in a unique and complementary way: **$p^{\uparrow}A$ collisions**

An Invitation

- **Factorization and its Breaking**
- **New and Critical Observables**
- **Saturation and Small x**

- Where are the **opportunities** and **loopholes** in the **factorization paradigm**?
- What do we need to **take advantage of new observables**?
- What are the **most effective uses of pp / pA run time** to prepare for an EIC?

The Secret Sits