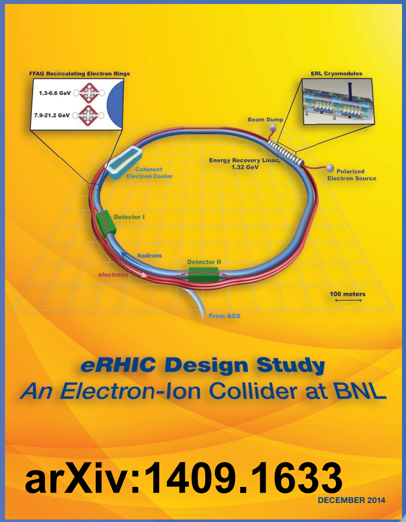
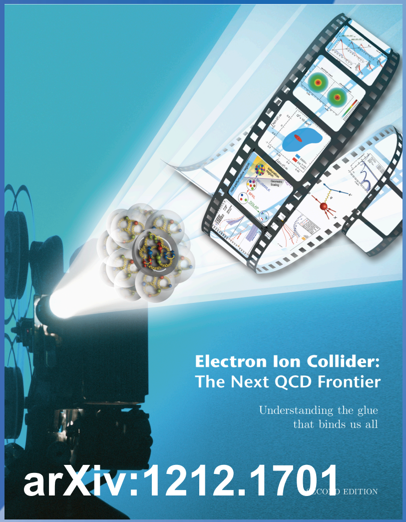
eRHIC: Studying the Glue That Binds Us All

- Physics Program
- Requirements to Realize Program
- Examples of *ep* Key Measurements
- Examples of *e*A Key Measurements



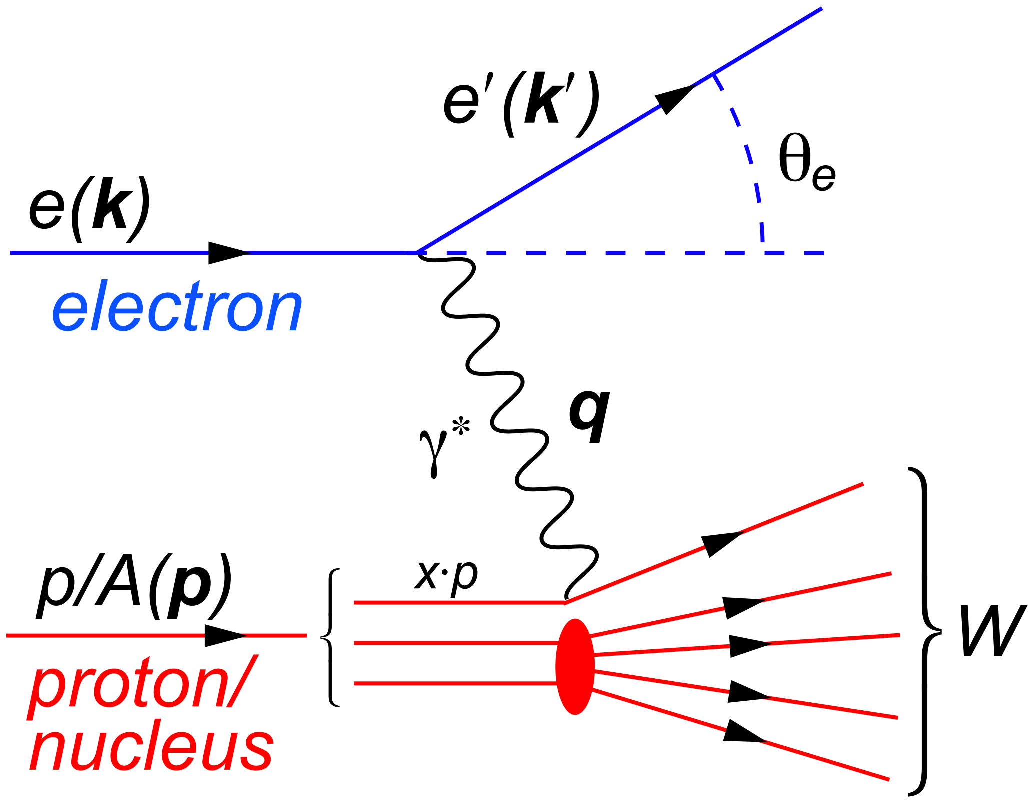


Thomas Ullrich

NSAC Subpanel EIC Cost Estimate Review
January 26 – 28, 2015

BROOKHAVEN NATIONAL LABORATORY
a passion for discovery
Office of Science
U.S. DEPARTMENT OF ENERGY

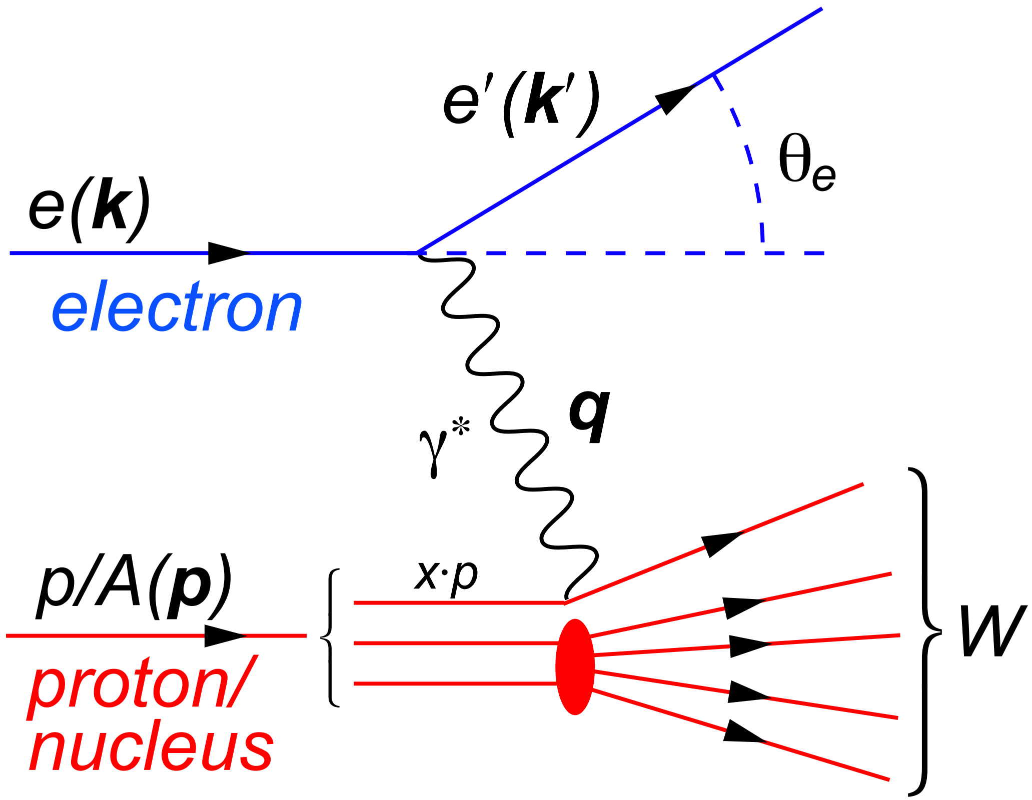
Deep Inelastic Scattering (DIS)



DIS:

- As a probe, electron beams provide unmatched precision of the electromagnetic interaction
- Direct, model independent, determination of kinematics of physics processes

Deep Inelastic Scattering (DIS)



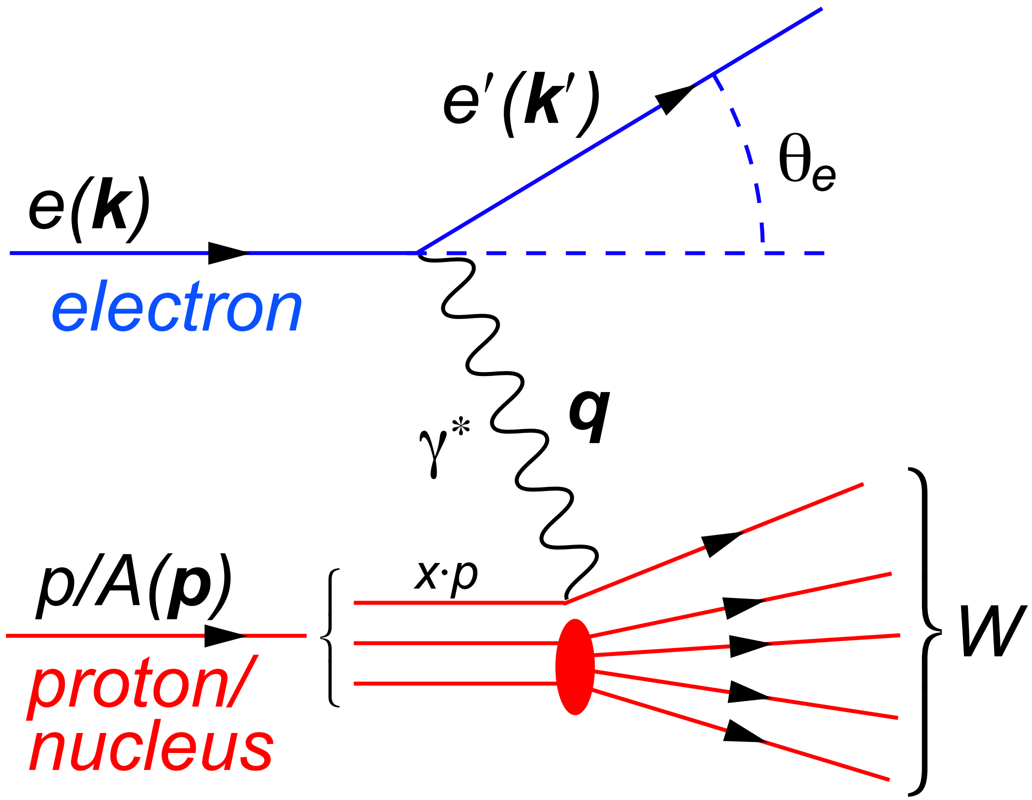
s: center-of-mass energy squared

s:

- square of center-of-mass energy of electron-hadron system

$$\sqrt{s} \simeq 2\sqrt{E_e E_p}$$

Deep Inelastic Scattering (DIS)



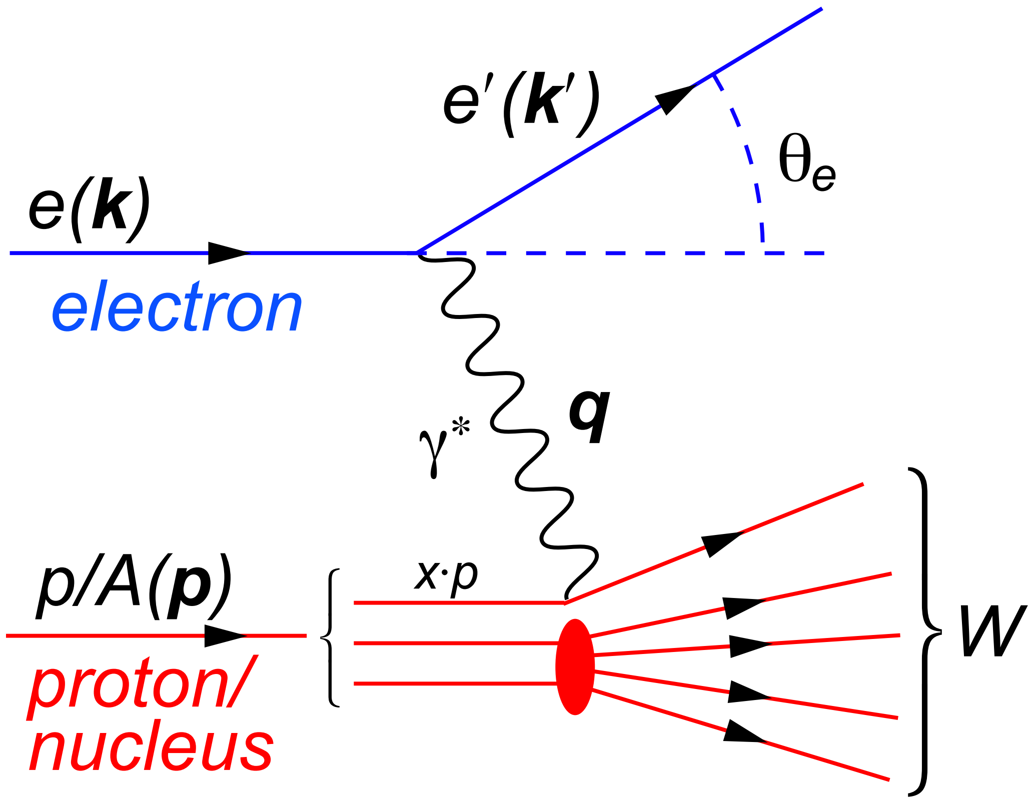
Q^2:

- squared momentum transfer from scattered electron
- Virtuality
- "Resolution" power

s: center-of-mass energy squared

Q^2: resolution power

Deep Inelastic Scattering (DIS)



x:

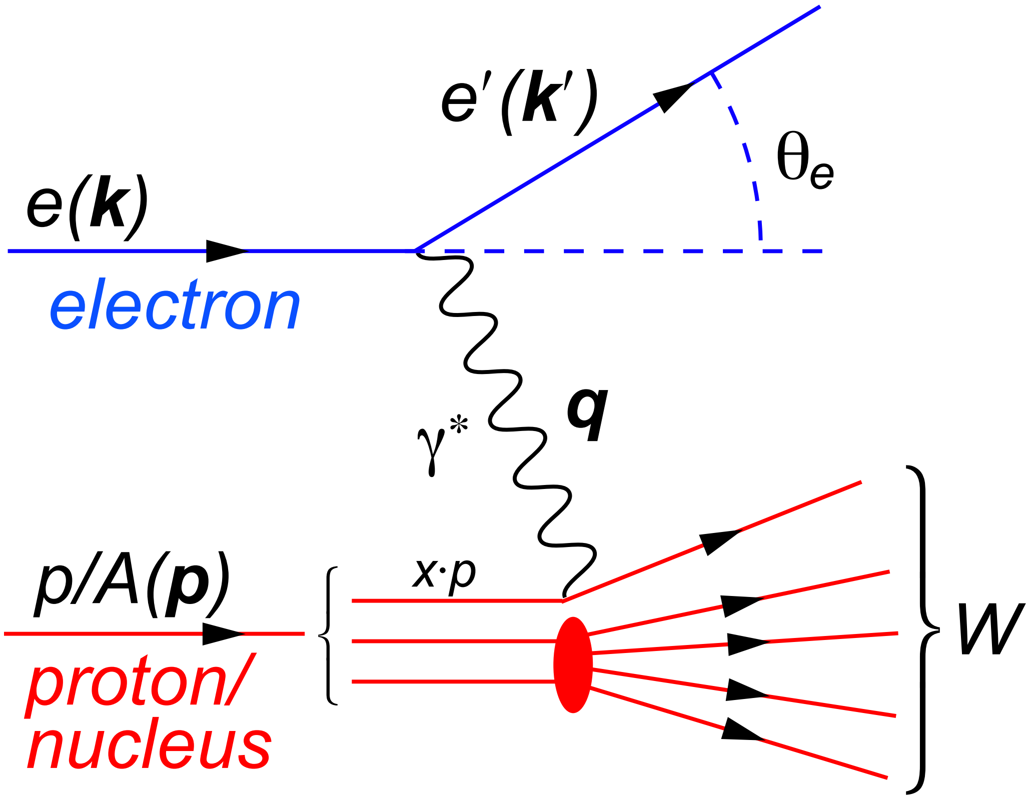
- Bjorken-x
- x is fraction of the nucleon's momentum carried by the struck quark
- $0 < x < 1$

s: center-of-mass energy squared

Q^2: resolution power

x: momentum fraction of parton

Deep Inelastic Scattering (DIS)



y:

- Inelasticity
- Fraction of electron's energy lost in nucleon restframe
- $0 < y < 1$

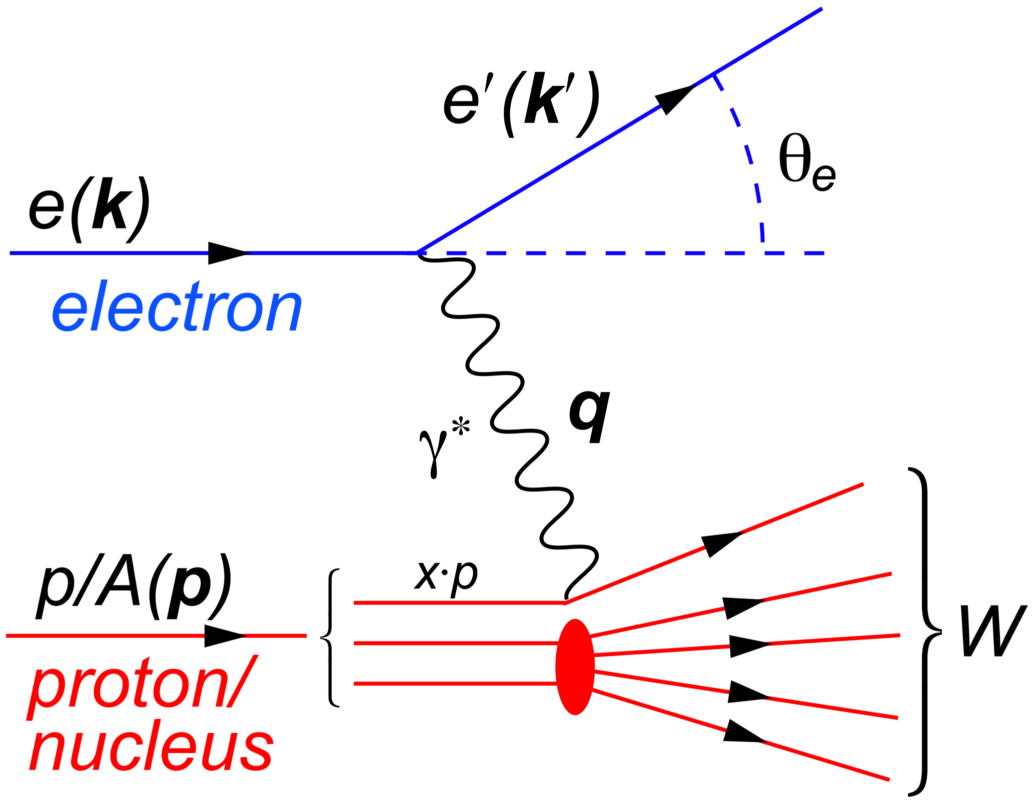
s: center-of-mass energy squared

Q^2: resolution power

x: momentum fraction of parton

y: inelasticity

Deep Inelastic Scattering (DIS)

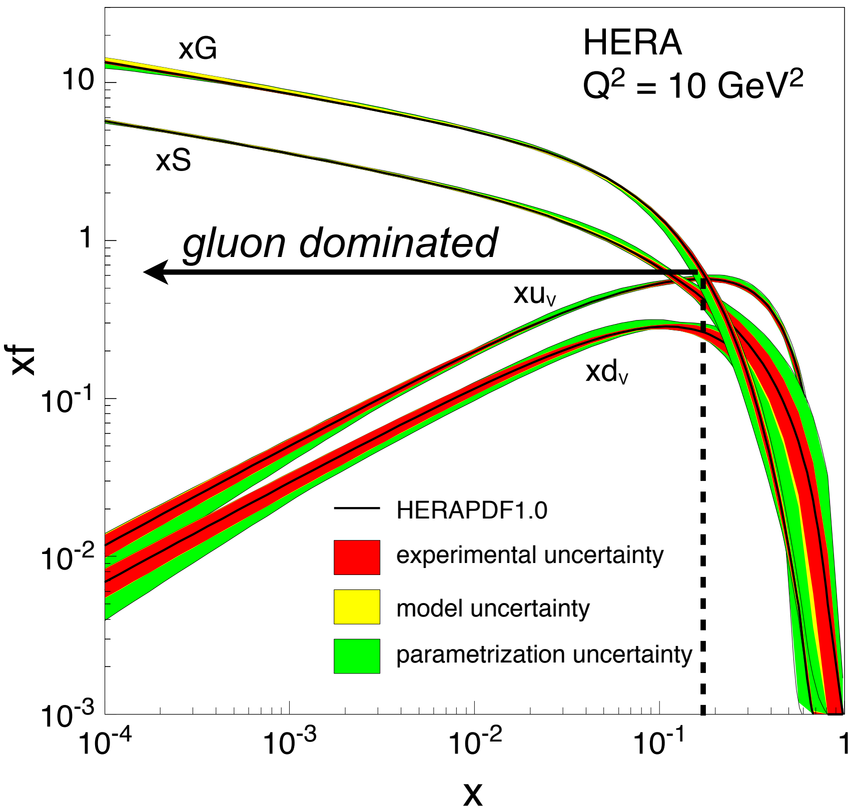


s: center-of-mass energy squared
Q²: resolution power
x: momentum fraction of parton
y: inelasticity

$$Q^2 \approx s \cdot x \cdot y$$

EIC: The Physics Program

Investigate with precision the universal dynamics of **gluons** and **sea quarks** that fundamentally make up nearly all the mass of the visible universe



All strongly interacting matter is an emergent consequence of many-body quark-gluon dynamics.

Example: Mass from massless gluons and (nearly) massless quarks

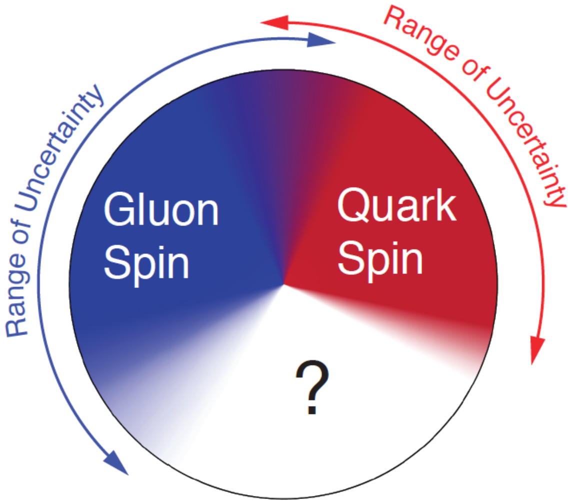
Understanding the origins of matter demands that we develop a deep and varied knowledge of this emergent dynamics

Two branches ⇒ polarized ep and eA

Key Topic in ep: Proton Spin Puzzle

What are the appropriate degrees of freedom in QCD that would explain the "spin" of a proton?

- After 20 years effort
  - Quarks (valence and sea): ~30% of proton spin in limited range
  - Gluons (latest RHIC data): ~20% of proton spin in limited range
  - Where is the rest?



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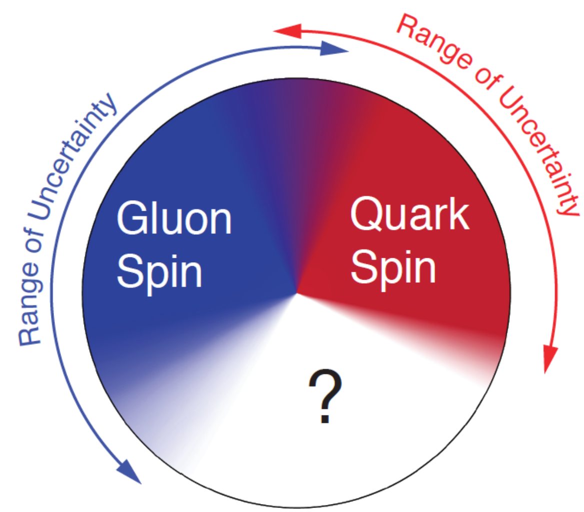
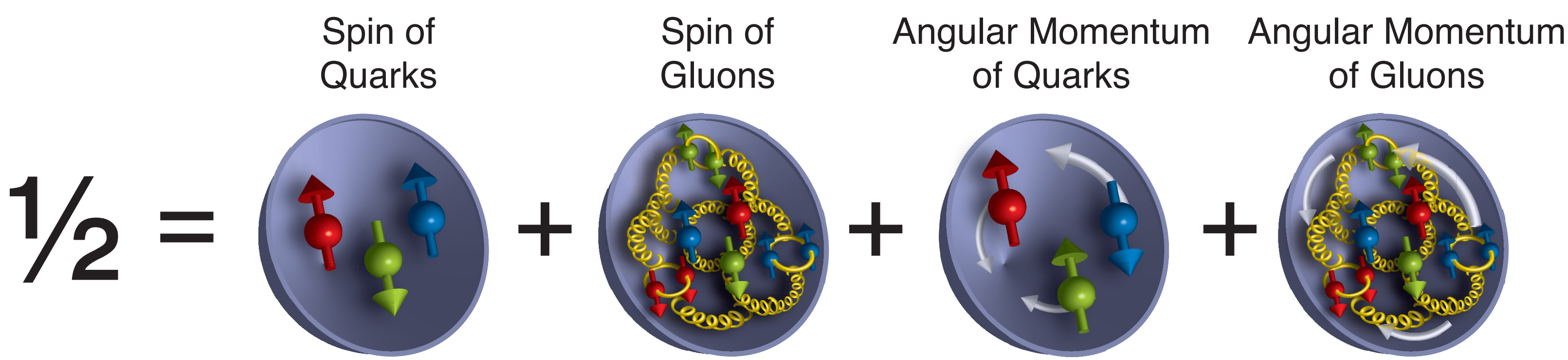


It is more than the number ½! It is the interplay between the intrinsic properties and interactions of quarks and gluons

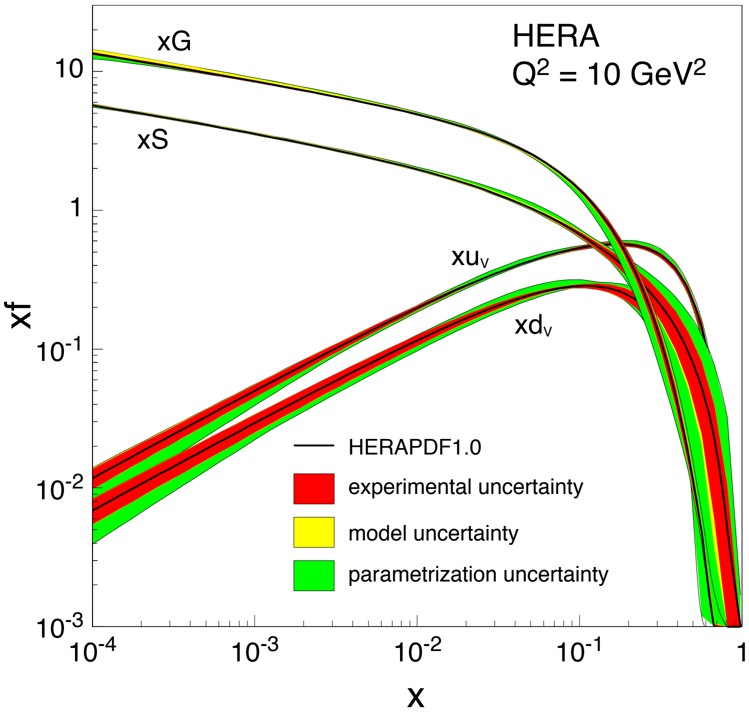


Driving Fundamental Questions in ep

- How do quark and gluon dynamics generate the proton spin?
- What is the role of the orbital motion of sea quarks and gluons in building up the nucleon spin?
- How are the sea quarks and gluons distributed in space and transverse momentum inside the nucleon?
- How are these distributions correlated with overall nucleon properties, such as spin direction?

Key Topic in eA: Gluon Saturation (I)

Is the proton a runaway popcorn machine at high energies ?



In QCD, the proton is made up of quanta that fluctuate in and out of existence

- Boosted proton:
  - Fluctuations time dilated on strong interaction time scales
  - Long lived gluons can radiate further small x gluons…
  - Explosion of gluon density ⇒ violates unitarity

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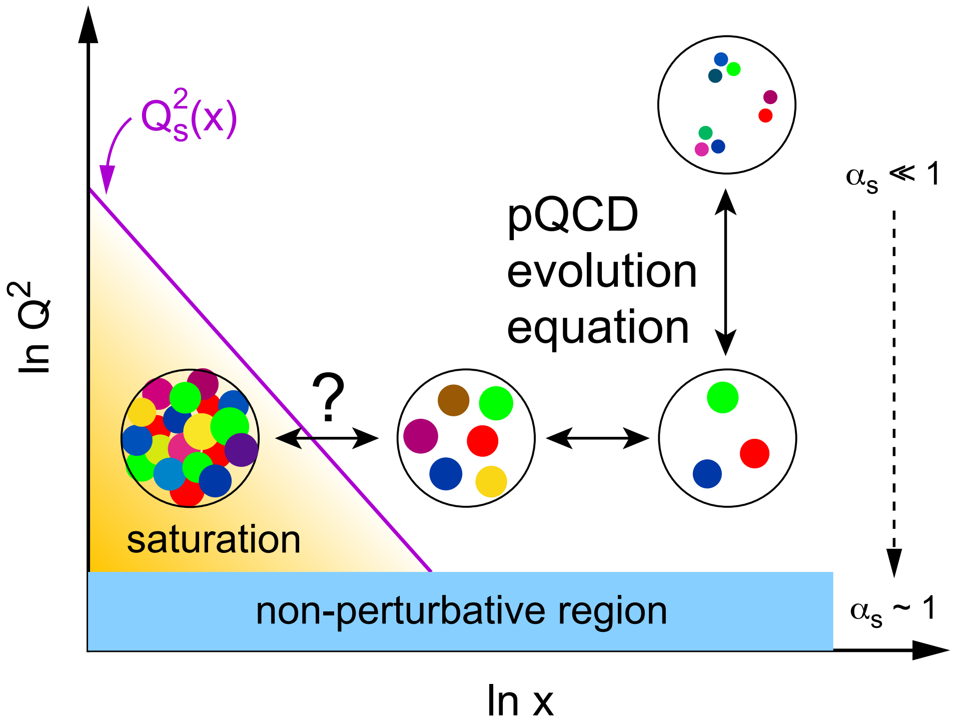

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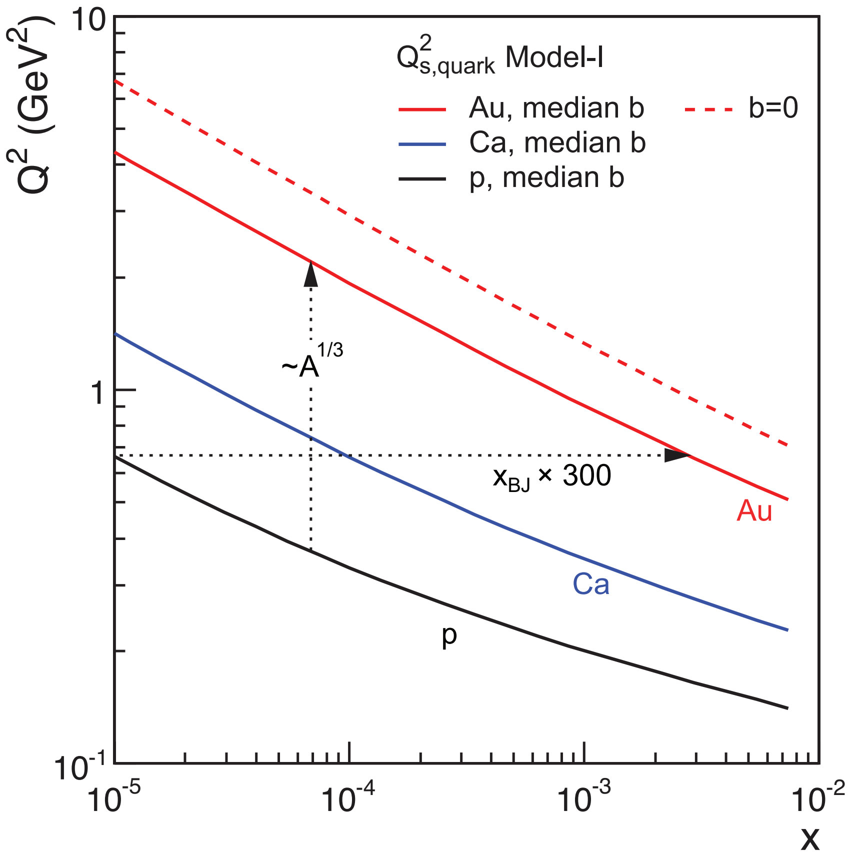
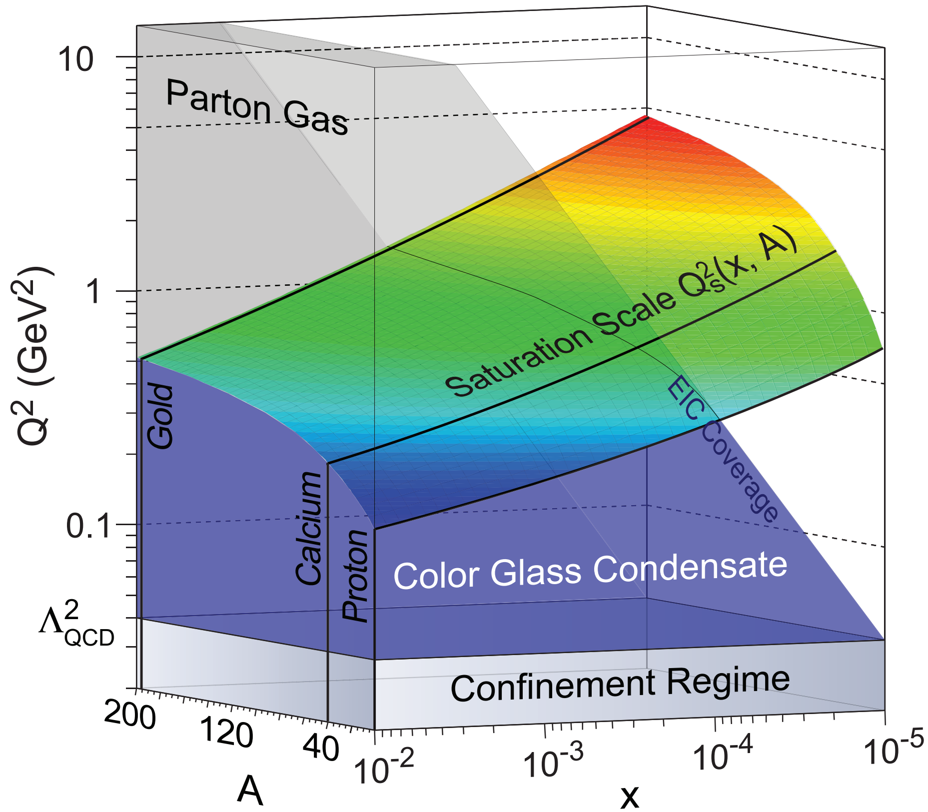
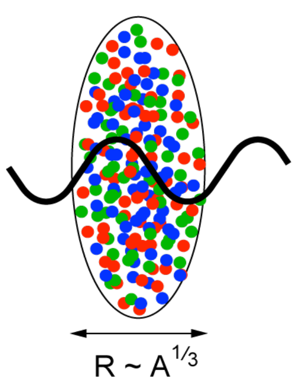
New Approach: Non-Linear Evolution

- New evolution equations at low-x & low to moderate Q^2
- Saturation of gluon densities characterized by scale $Q_s(x)$
- Wave function is Color Glass Condensate

Key Topic in eA: Gluon Saturation (II)







$$(Q_s^A)^2 \approx c Q_0^2 \left(\frac{A}{x} \right)^{1/3}$$

Enhancement of Q_S with A:

saturation regime reached at significantly lower energy in nuclei (and lower cost)

Driving Fundamental Questions in eA

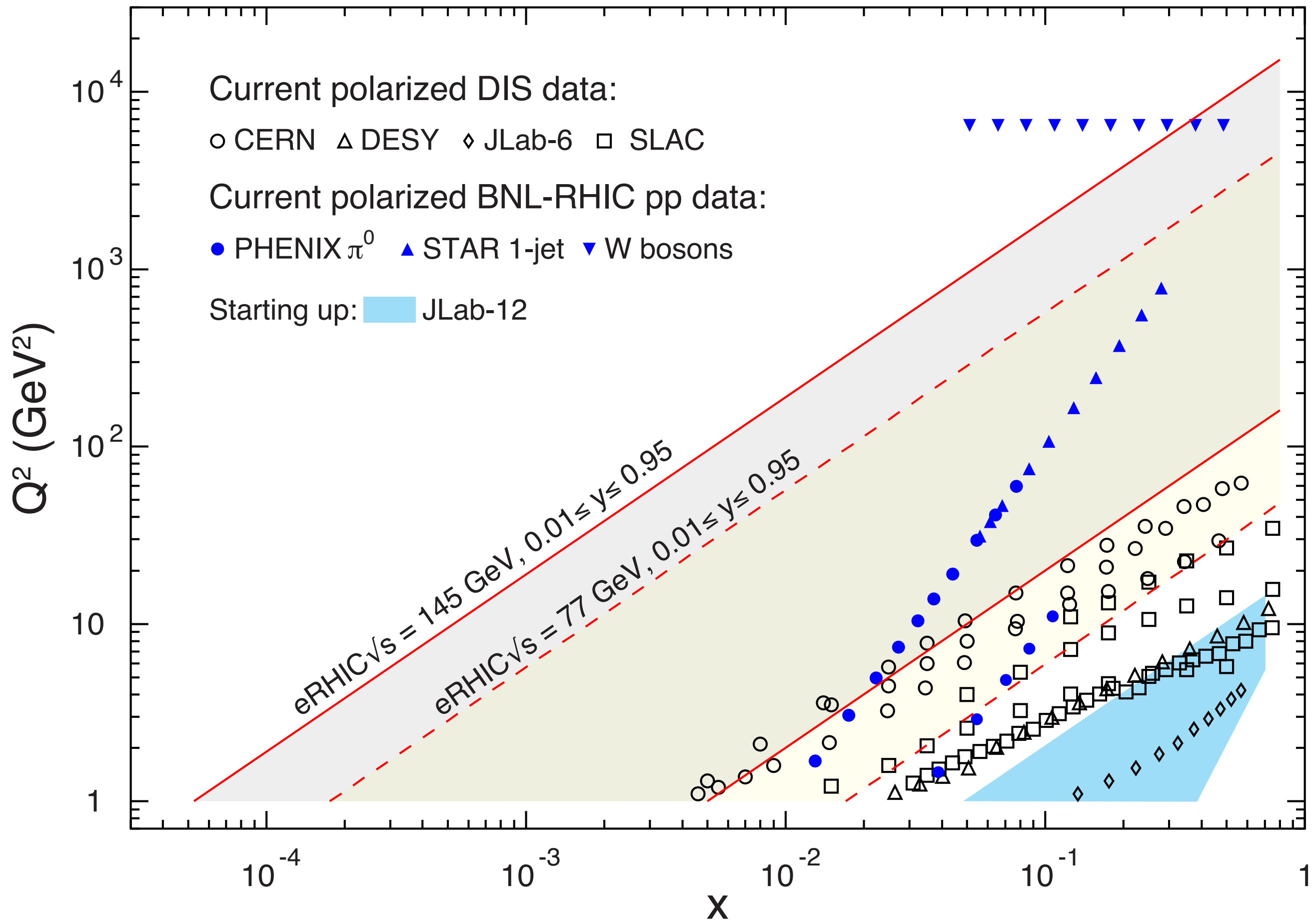
Nucleus serves as:

- What is the fundamental quark-gluon structure of atomic nuclei? } **Object of Interest**
- Can we experimentally find and explore a novel universal regime of strongly correlated QCD dynamics?
- What is the role of saturated strong gluon fields, and what are the degrees of freedom in this strongly interacting regime?

} **Amplifier**

- Can the nuclear color filter provide novel insight into propagation, attenuation and hadronization of colored probes? } **Analyzer**

Requirements: √s and Polarization



polarized
ep, *μp*, *pp*

$$Q^2 \approx s \cdot x \cdot y$$

- Need to reach low-x where gluons dominate (ΔG, ΔΣ range!)
- Flexible energies (see also structure functions later)
- Need sufficient lever arm in Q^2 at **fixed** x (evolution eq. along Q^2 or x)
- Electrons and protons/light nuclei (p, He^3 or D) highly polarized (70%)

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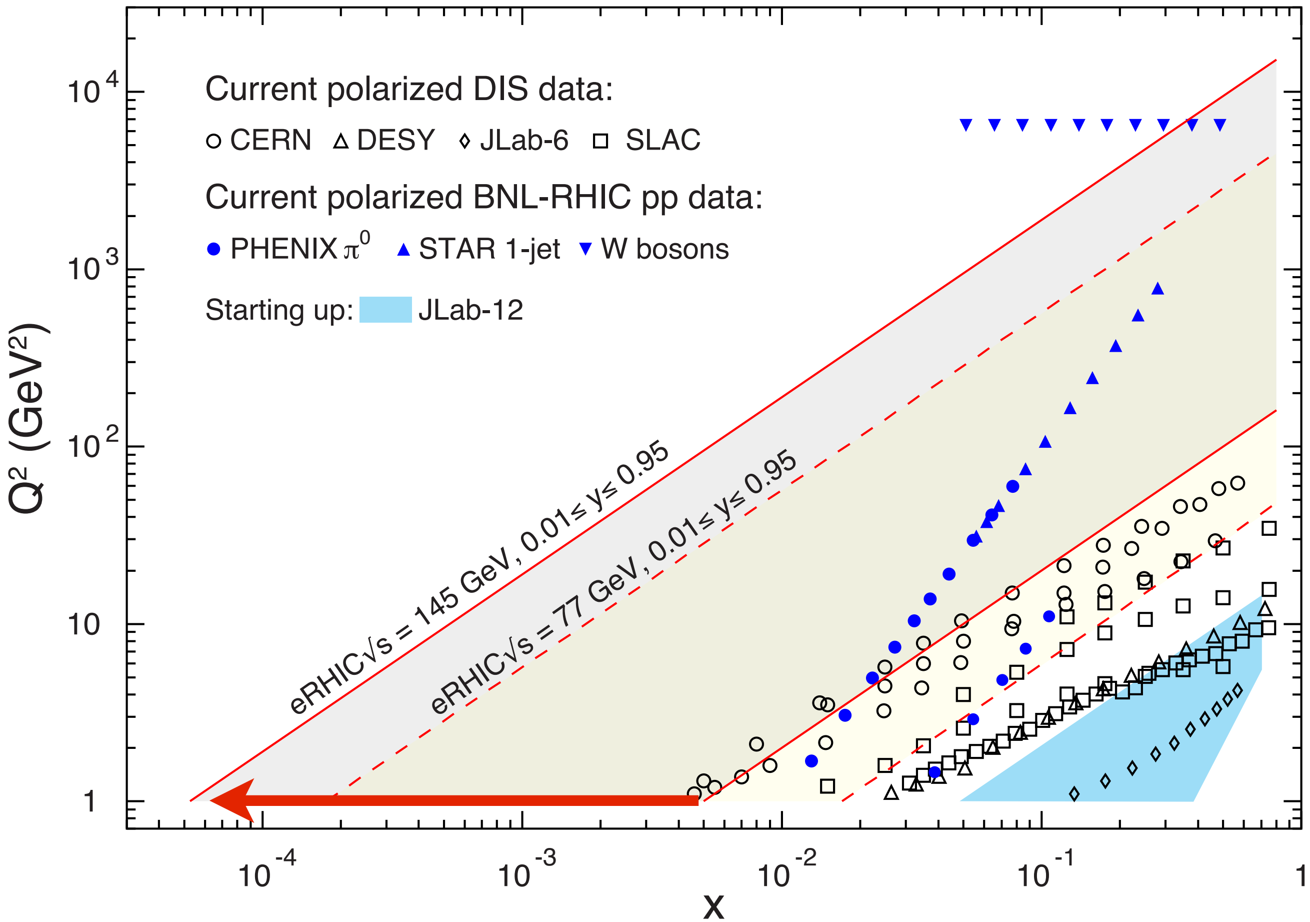

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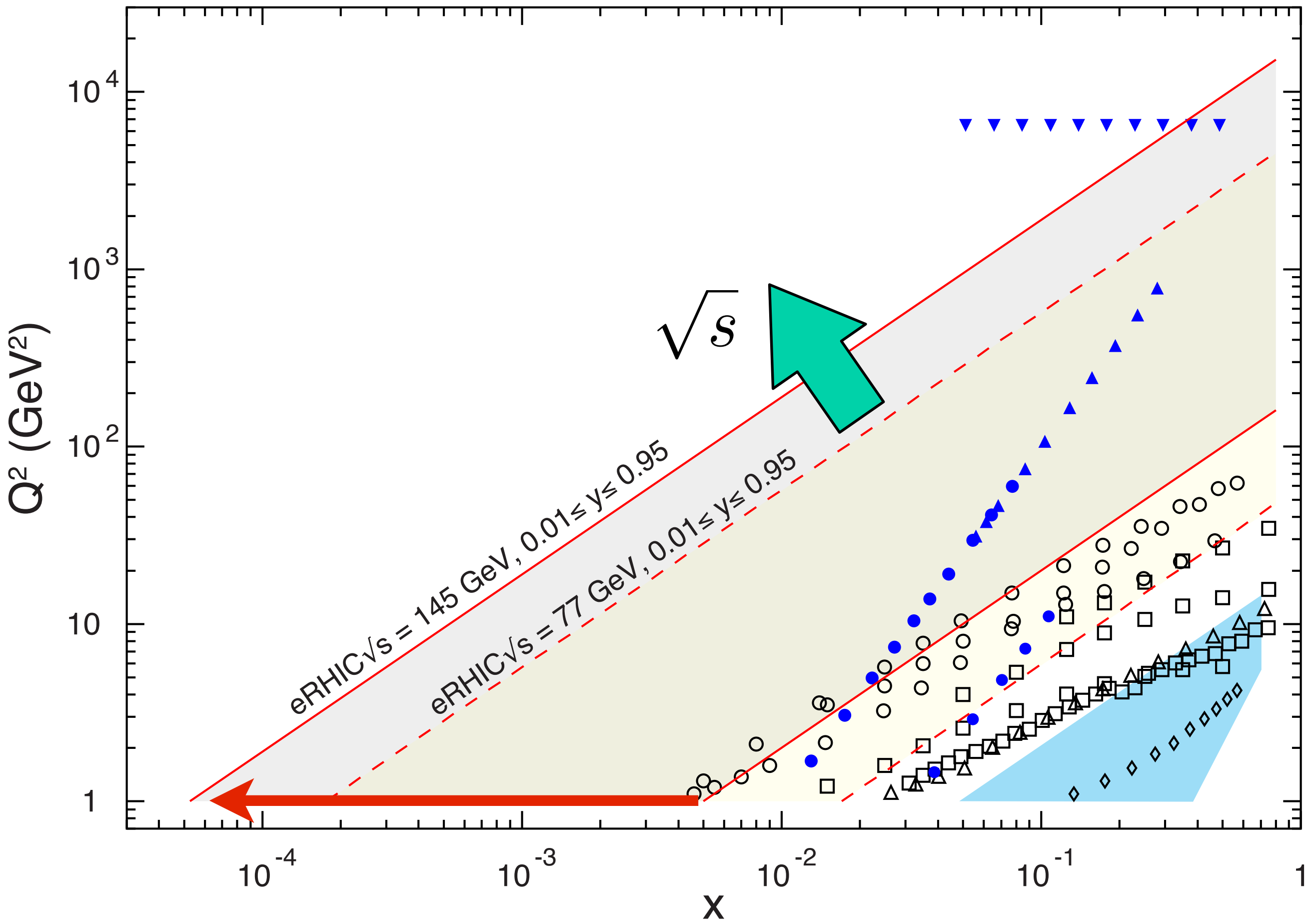

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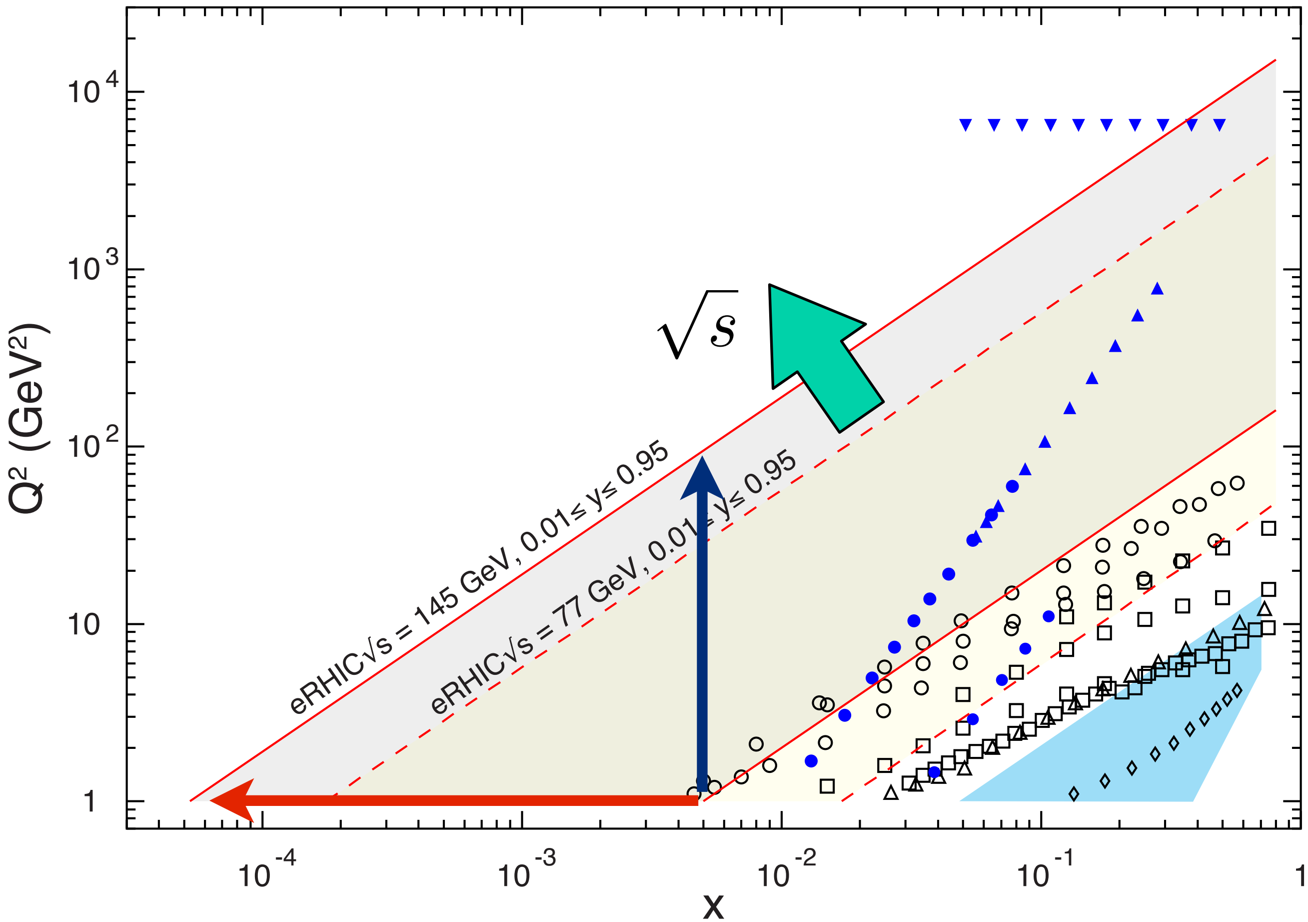

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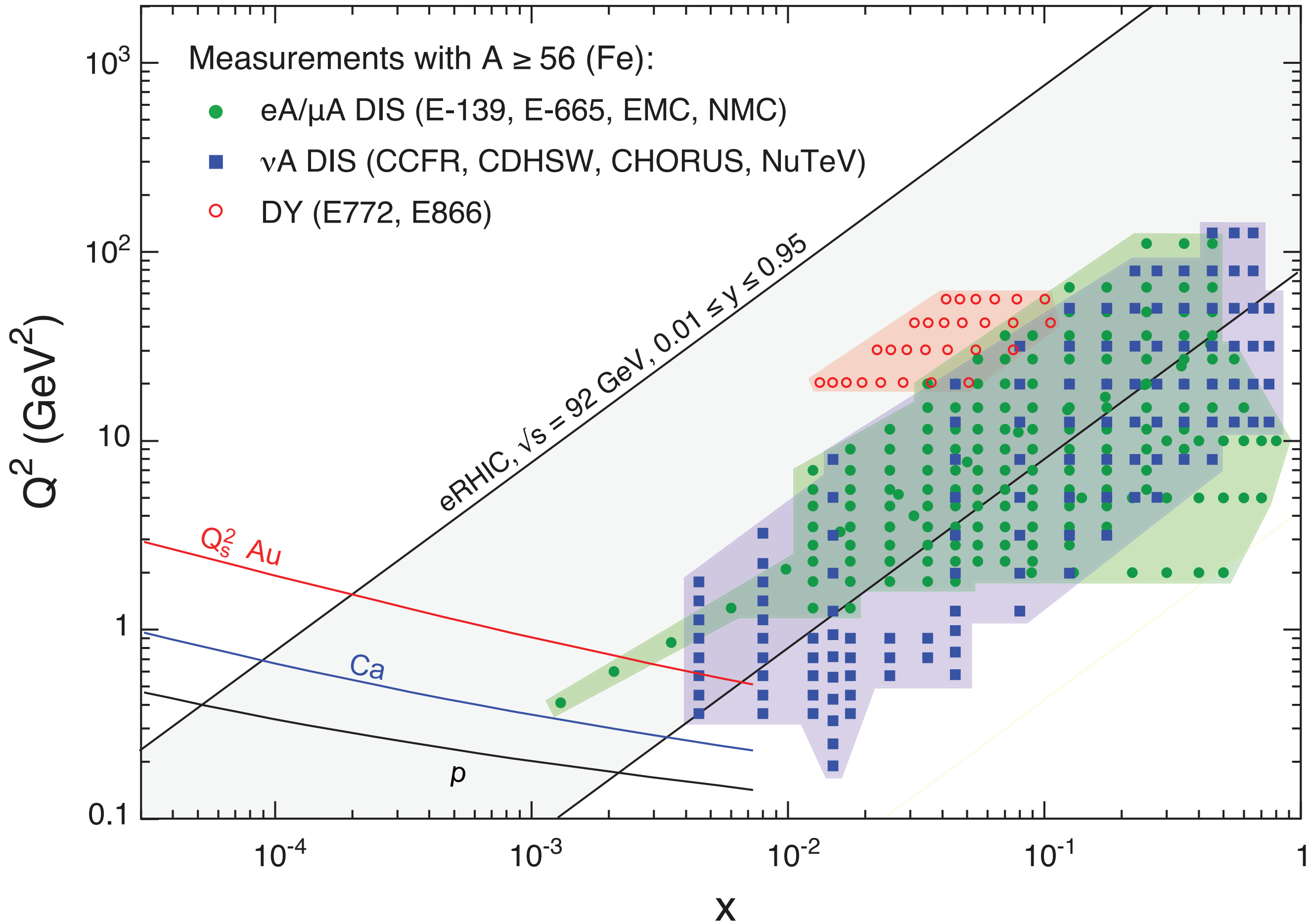
Requirements: √s and Beam Masses



eA, μA, νA
(A ≥ Fe)

- Saturation physics needs low-x reach and wide range of nuclei (A dependence) up to the heaviest A (Q_s enhancement): d ➟ U
- Need sufficient lever arm in Q^2 up to at least $x = 10^{-3}$ to verify non-linear evolution equations of CGC

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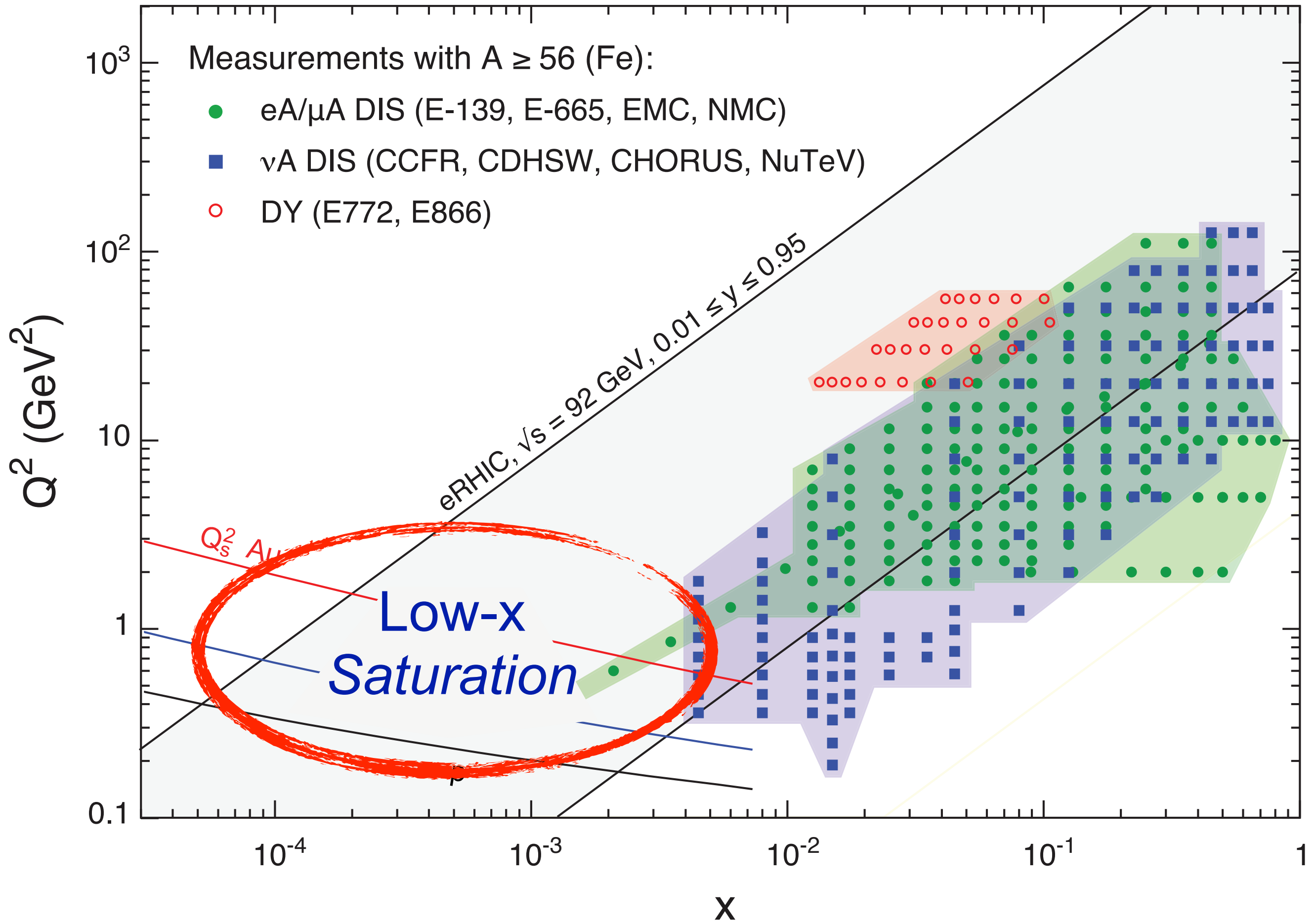

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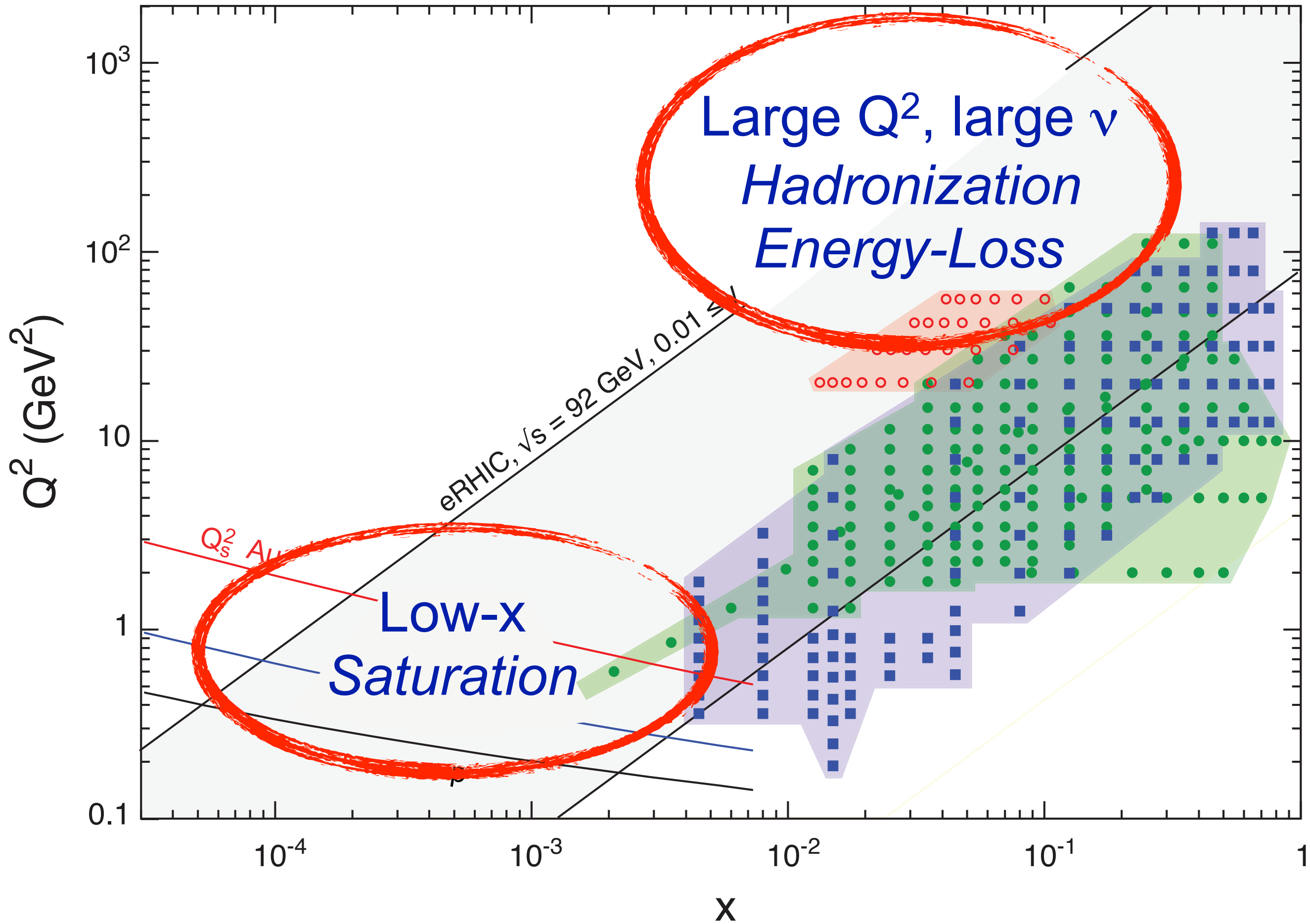

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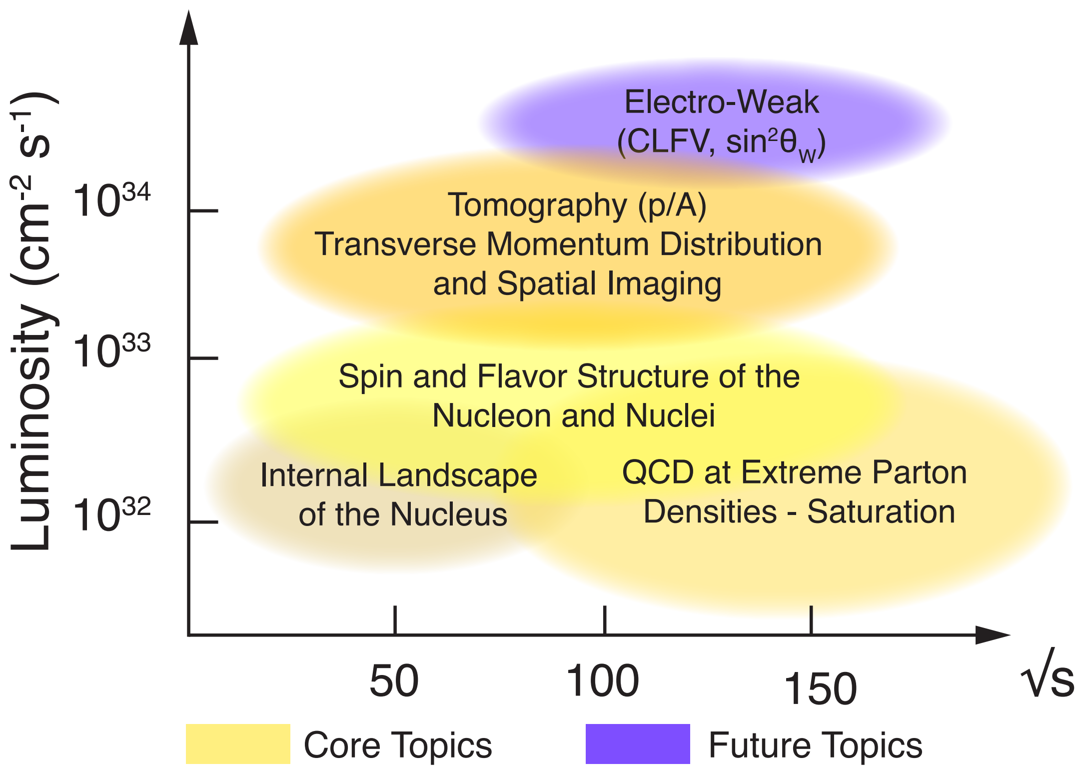
Requirements: Luminosity & Detector

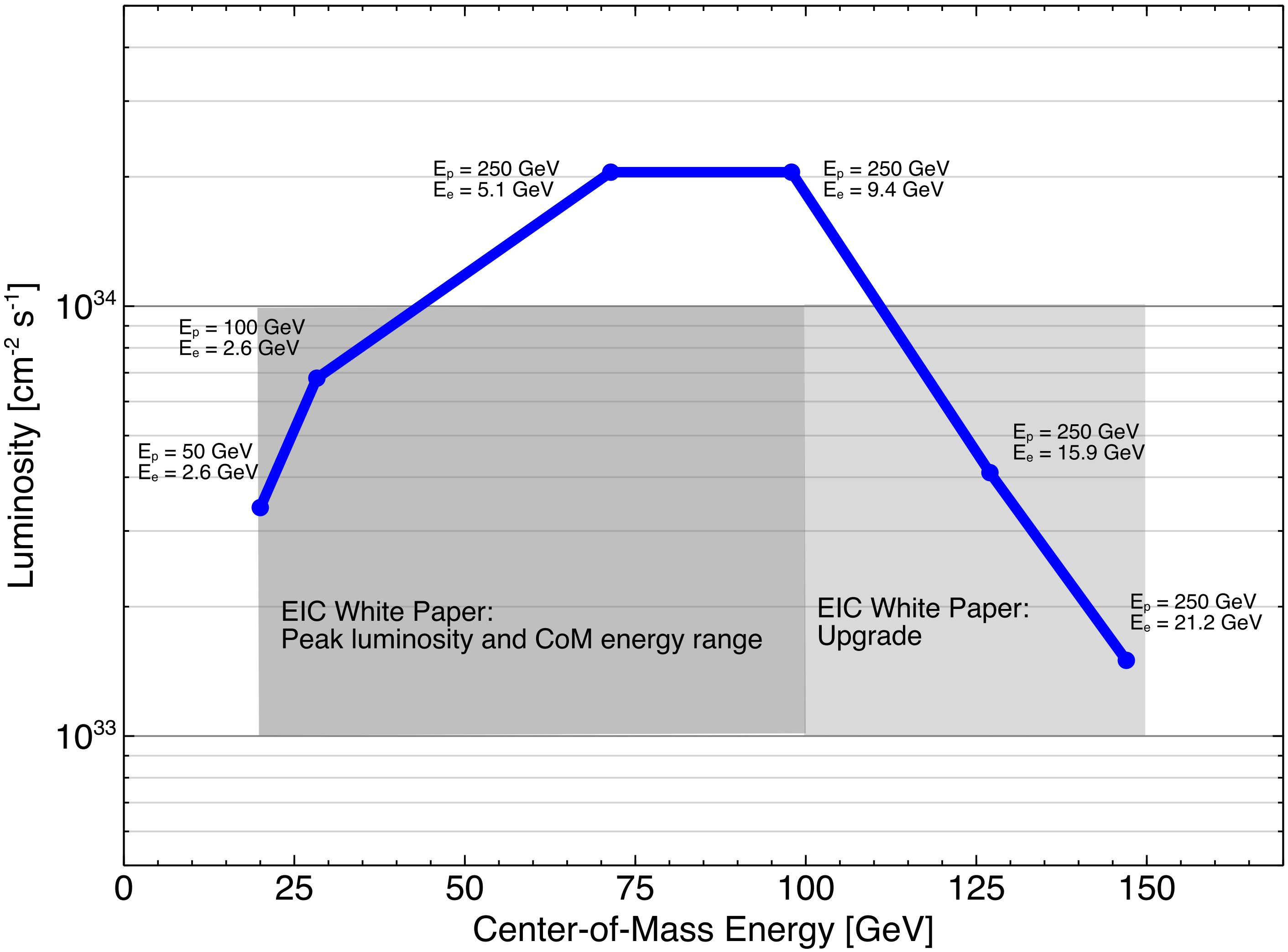
- High Luminosity ~ 10^{33} $cm^{-2}s^{-1}$ and higher
  - Requirement affected by binning (N-differential distribution always more powerful the higher N) ⇔ close collaboration with theory
  - Affected by systematic uncertainties dominated by luminosity and polarization measurements (use past and existing facilities as a guide, e.g. HERA)



- Detector to explore full capabilities
  - with good PID (e/h and π, K, p)
  - wide acceptance to reach edges of kinematic range

See talk by Elke

eRHIC: A Design that Matches Physics Goals



Ions: d up to U

Polarization ~70%/80%

for eA: $E_A = E_p{*}Z/A$, $L \propto 1/A$

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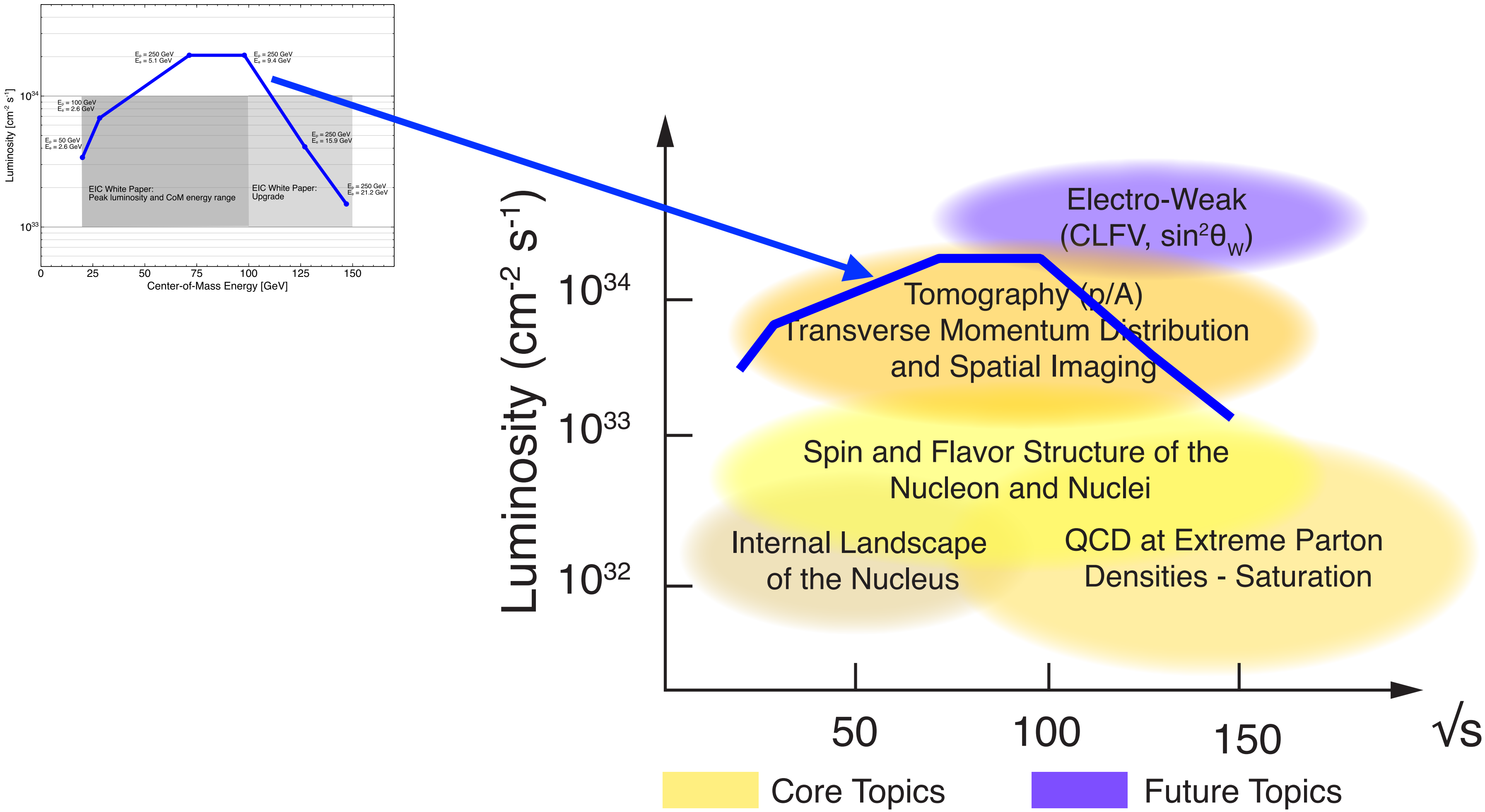

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eRHIC: Longitudinal Spin of the Proton (I)

Inclusive Measurement:
e+p $\rightarrow$ e′+X

$$\frac{1}{2}\left[\frac{\mathrm{d}^2\sigma^{\rightleftarrows}}{\mathrm{d}x\,\mathrm{d}Q^2} - \frac{\mathrm{d}^2\sigma^{\rightrightarrows}}{\mathrm{d}x\,\mathrm{d}Q^2}\right] \simeq \frac{4\pi\,\alpha^2}{Q^4} y\,(2-y)\,g_1(x,Q^2)$$

Leading Order:

$$g_1(x,Q^2) = \frac{1}{2}\sum e_q^2\,\left[\Delta q(x,Q^2) + \Delta\bar{q}(x,Q^2)\right]$$

$$\Delta\Sigma(Q^2) = \int_0^1 dx\;g_1(x,Q^2) \quad \text{(Quark Spin)}$$

Higher Order:

$$\frac{dg_1}{d\log Q^2} \propto \Delta g(x,Q^2) \quad \text{(Gluon Spin)}$$

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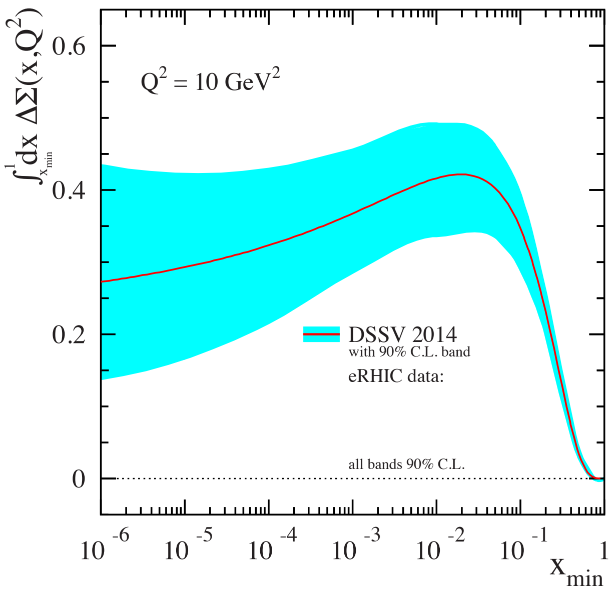
Quark Spin



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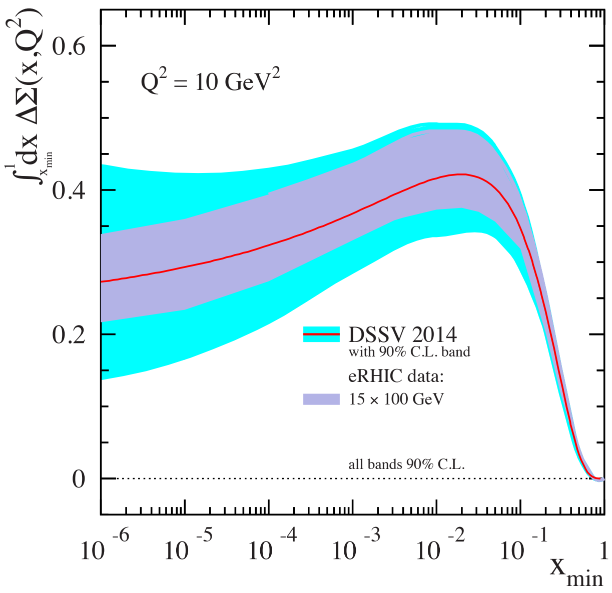

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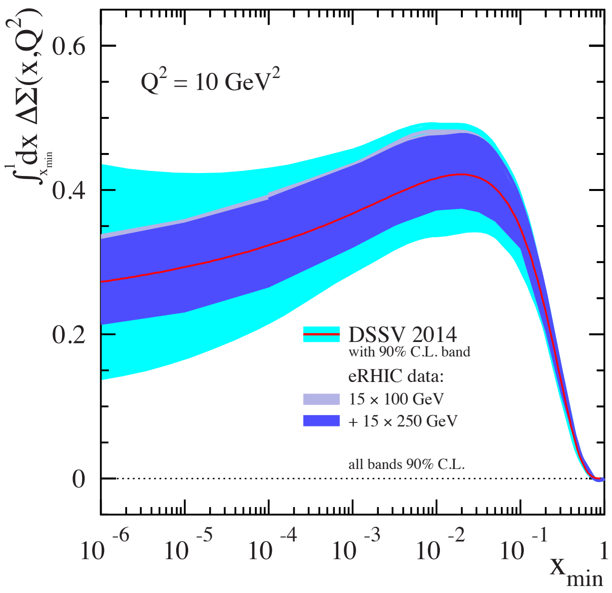

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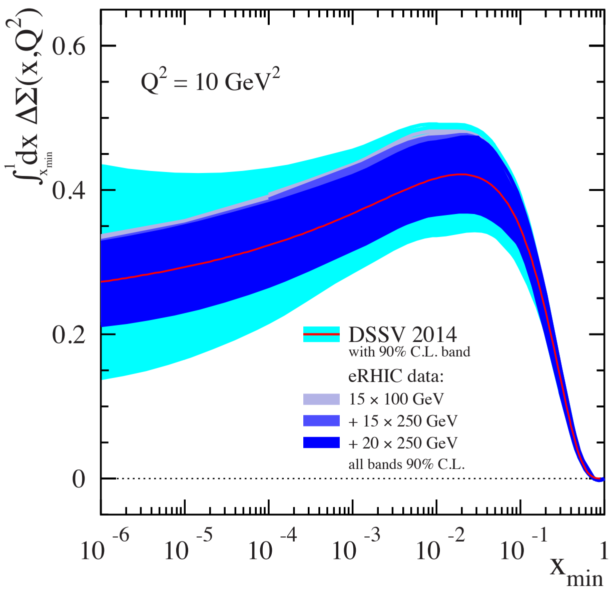

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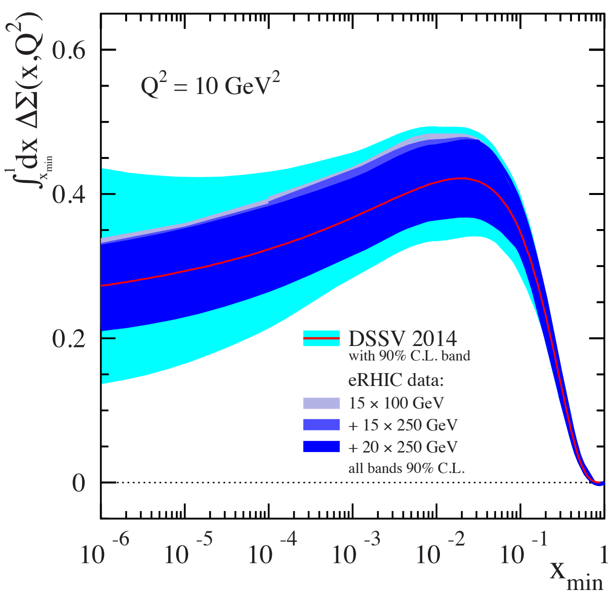
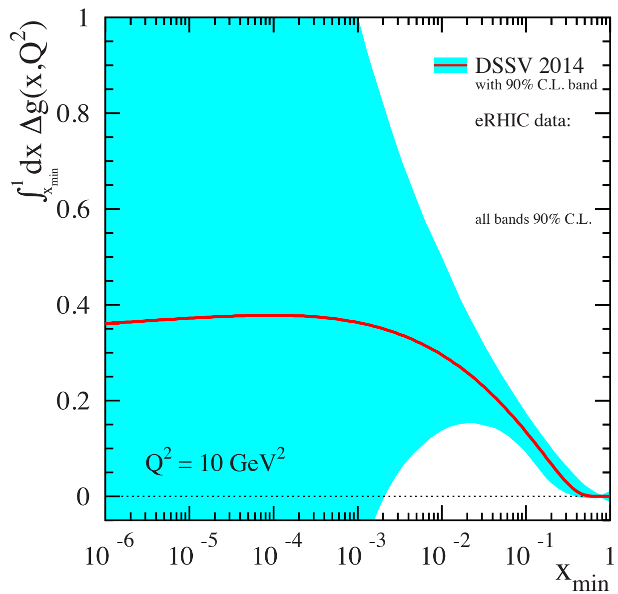


Gluon Spin



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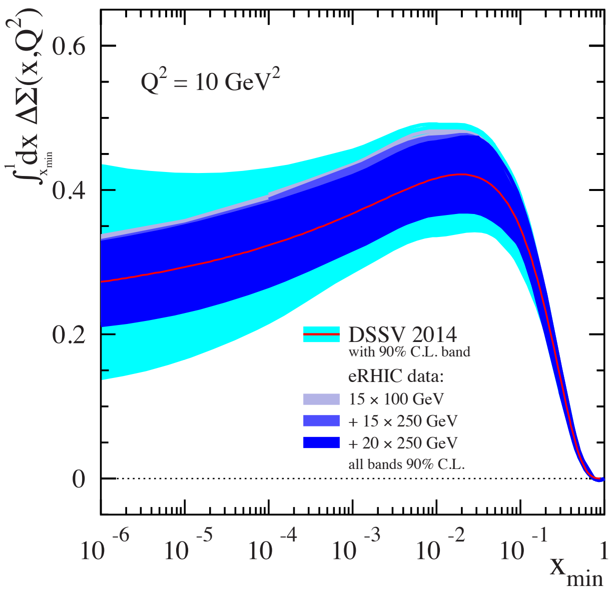

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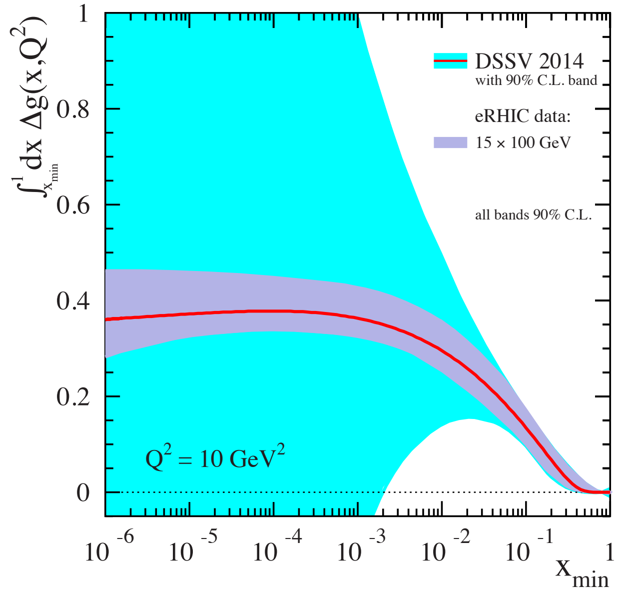

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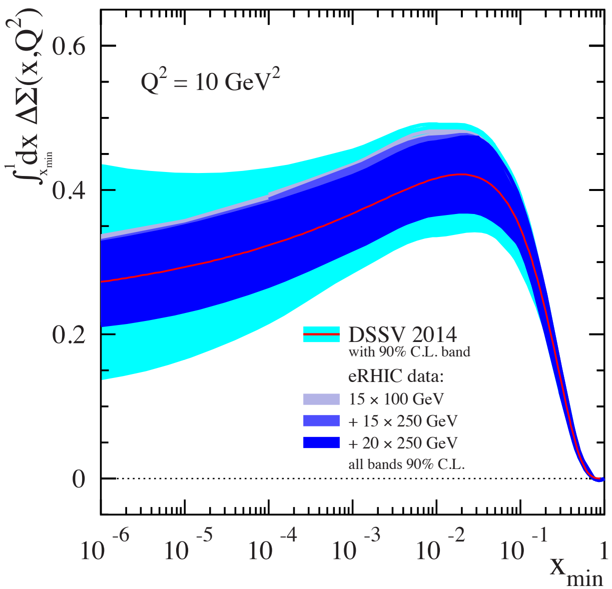

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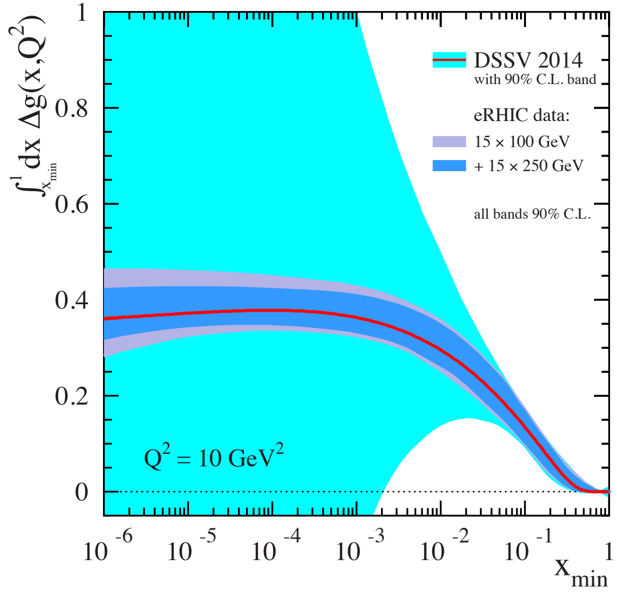

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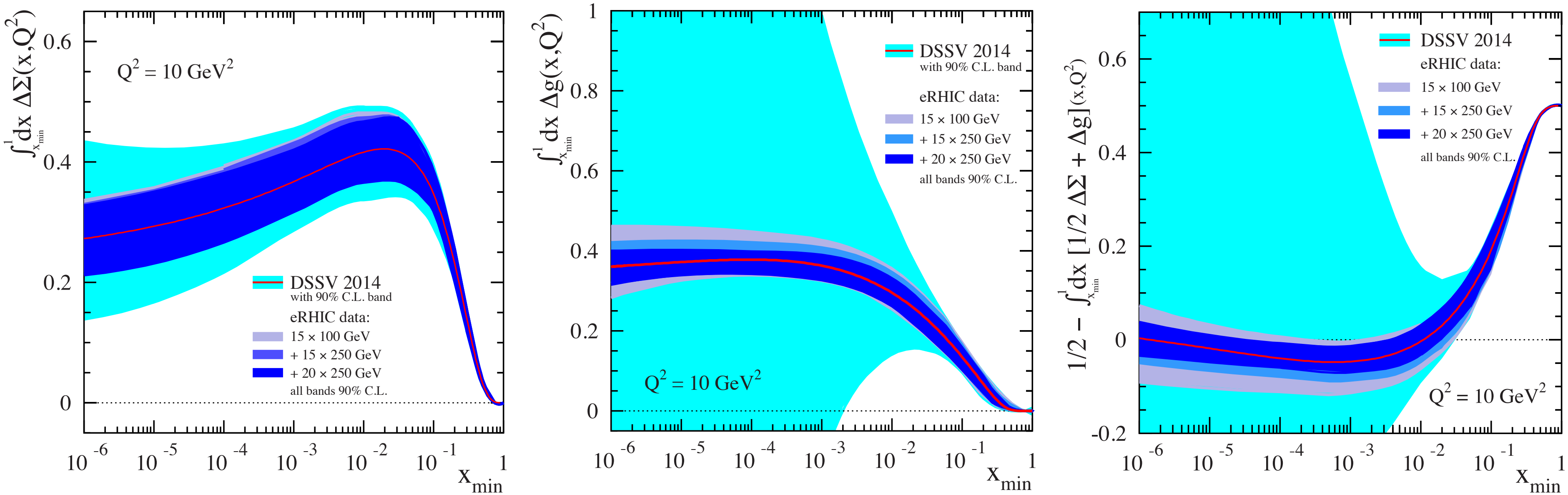
Quark Spin | Gluon Spin | ½-Gluon-Quark Spin



For ∫Ldt = 10 fb^{-1} and 70% polarization

Current knowledge (DSSV): uses strong theoretical constraints

eRHIC projections do not ⇒ test w/o assumptions

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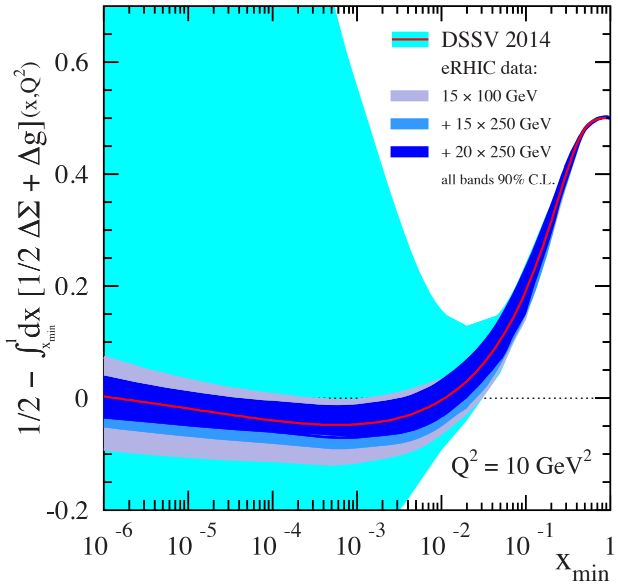
½-Gluon-Quark Spin



Combining information on ΔΣ and Δg constrains angular momentum

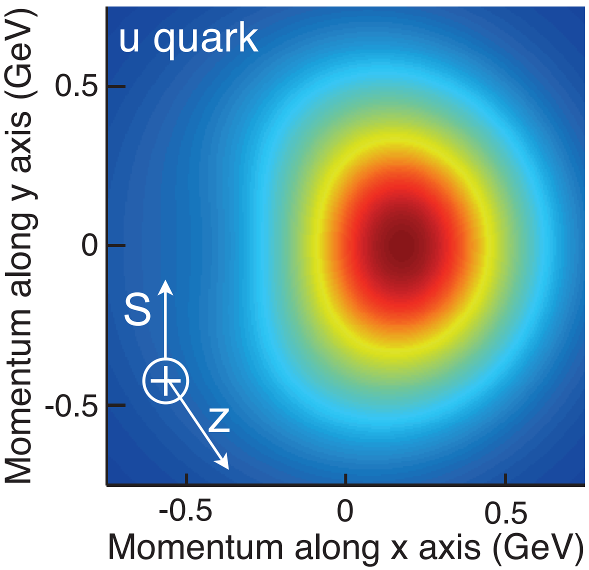
For ∫Ldt = 10 fb^{-1} and 70% polarization

Current knowledge (DSSV): uses strong theoretical constraints

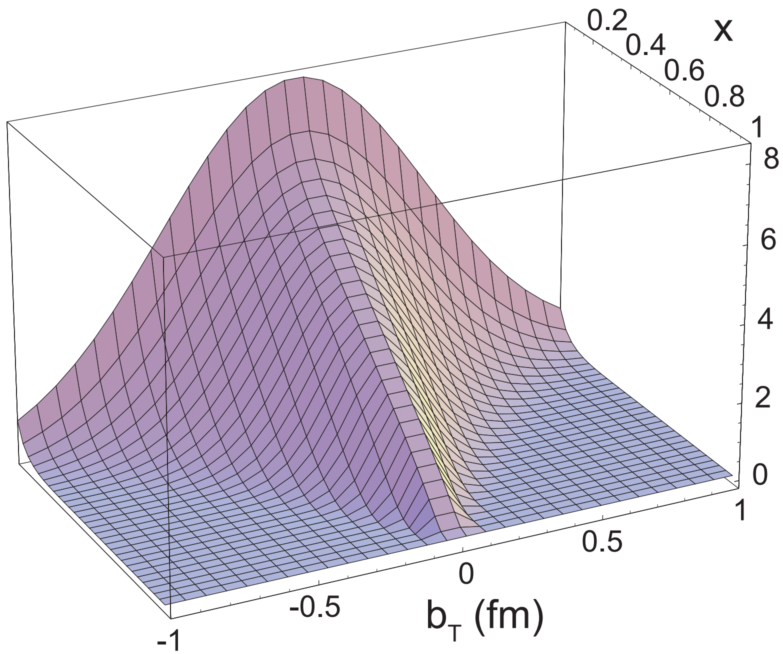
eRHIC projections do not ⇒ test w/o assumptions

3D Imaging at *e*RHIC: TMDs & GPDs

- **Transverse Momentum Distributions (TMDs):**
  - 2D+1 picture in momentum space (k_T)



- **Generalized Parton Distributions (GPDs):**
  - 2D+1 picture in coordinate space (b_T)



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- **Generalized Parton Distributions (GPDs):**
  - 2D+1 picture in coordinate space (b_T)

- Study through azimuthal asymmetries in semi-inclusive DIS
- Requires π/K/p PID

- Study through exclusive processes (DVCS, diffraction, VM production)
- Luminosity hungry

eRHIC: Nuclear Structure Functions (I)

Inclusive DIS on eA:

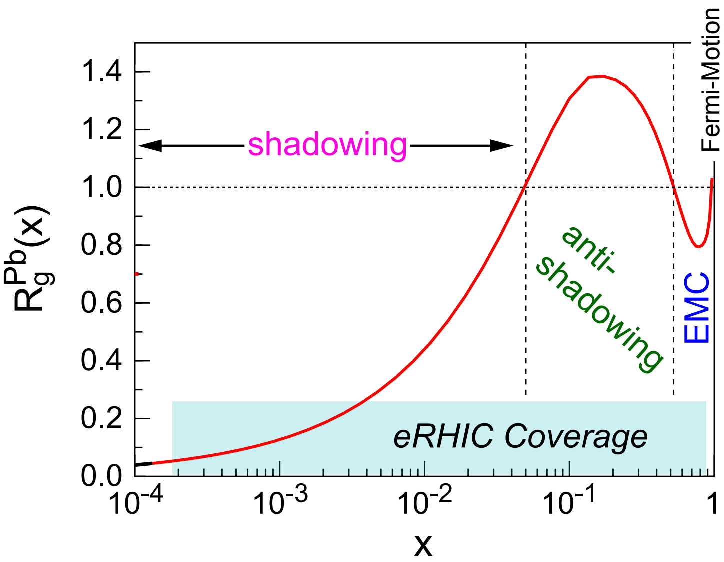
$$\frac{d^2\sigma^{eA\to eX}}{dx\,dQ^2} = \frac{4\pi\alpha^2}{xQ^4}\left[\left(1 - y + \frac{y^2}{2}\right) F_2(x,Q^2) - \frac{y^2}{2} F_L(x,Q^2)\right]$$

quark+anti-quark (F_2) **gluon** (F_L)

F_2 and F_L are benchmark measurements:

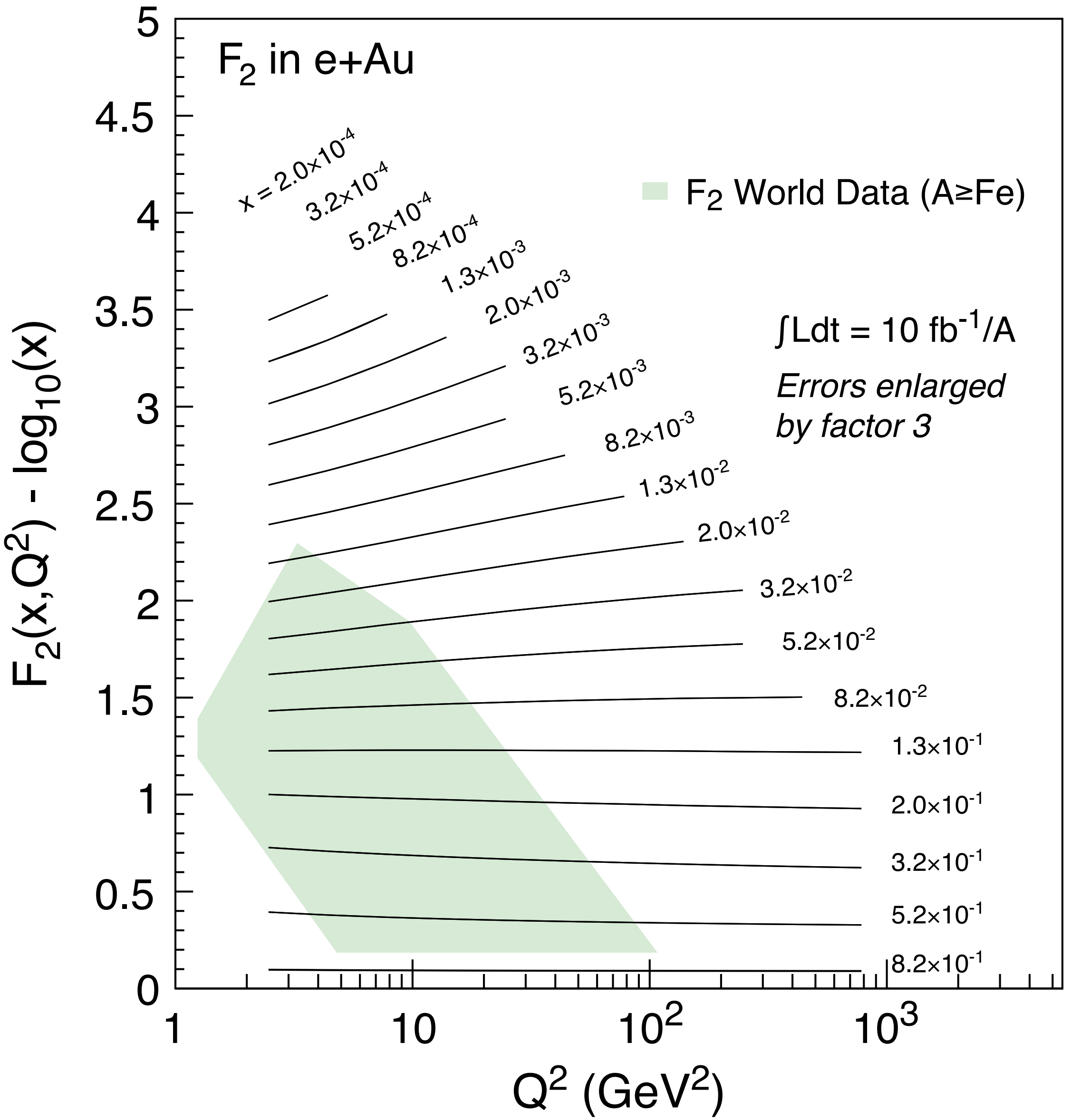
Theory/models have to be able to describe the structure functions and their evolution.

Leading twist pQCD models parameterize the observed suppression of the structure function with decreasing x using *nuclear parton distribution functions* (nPDFs)



Aim at extending our knowledge on structure functions into the realm where gluon saturation effects emerge

eRHIC: Nuclear Structure Functions (II)



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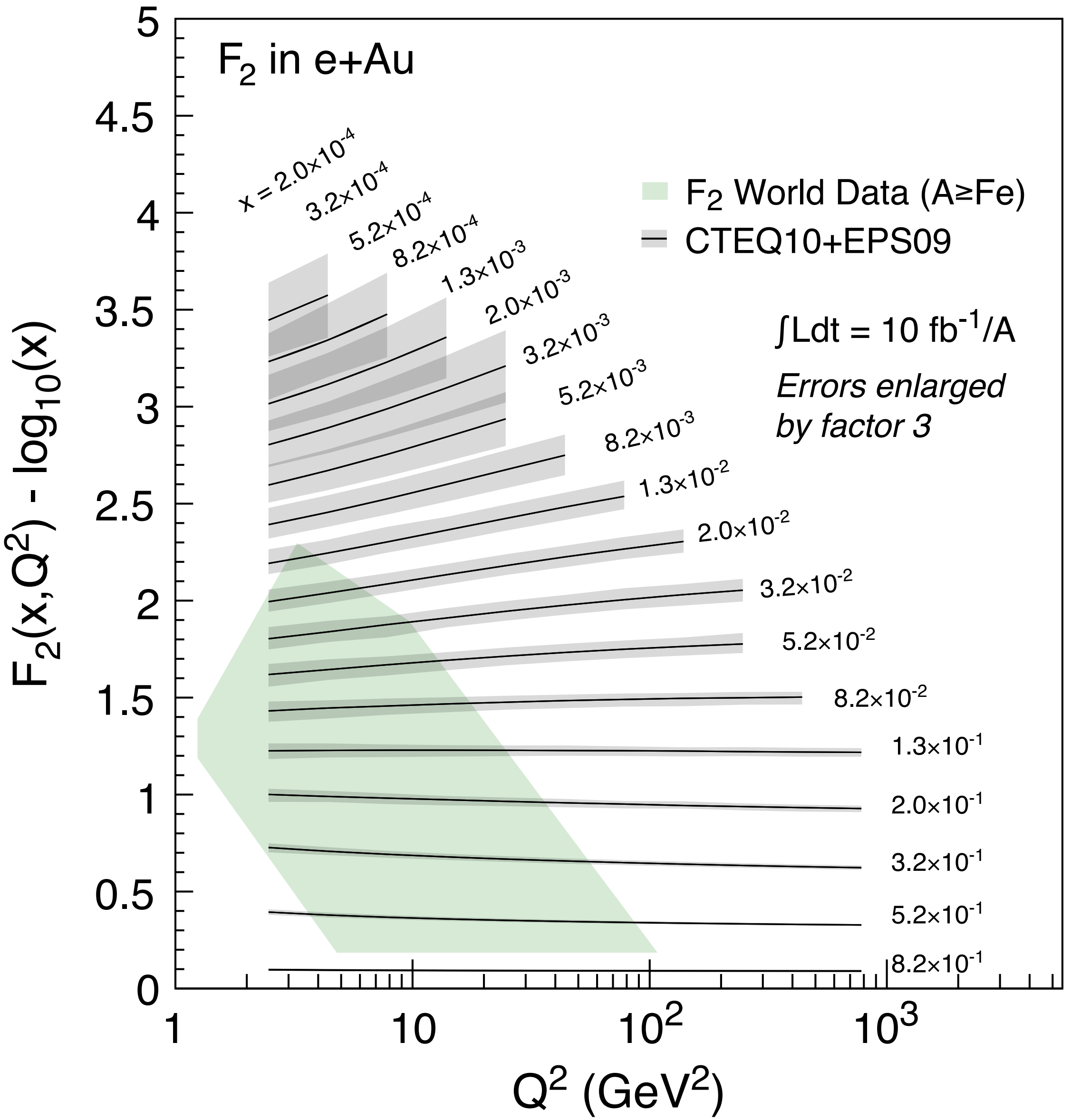

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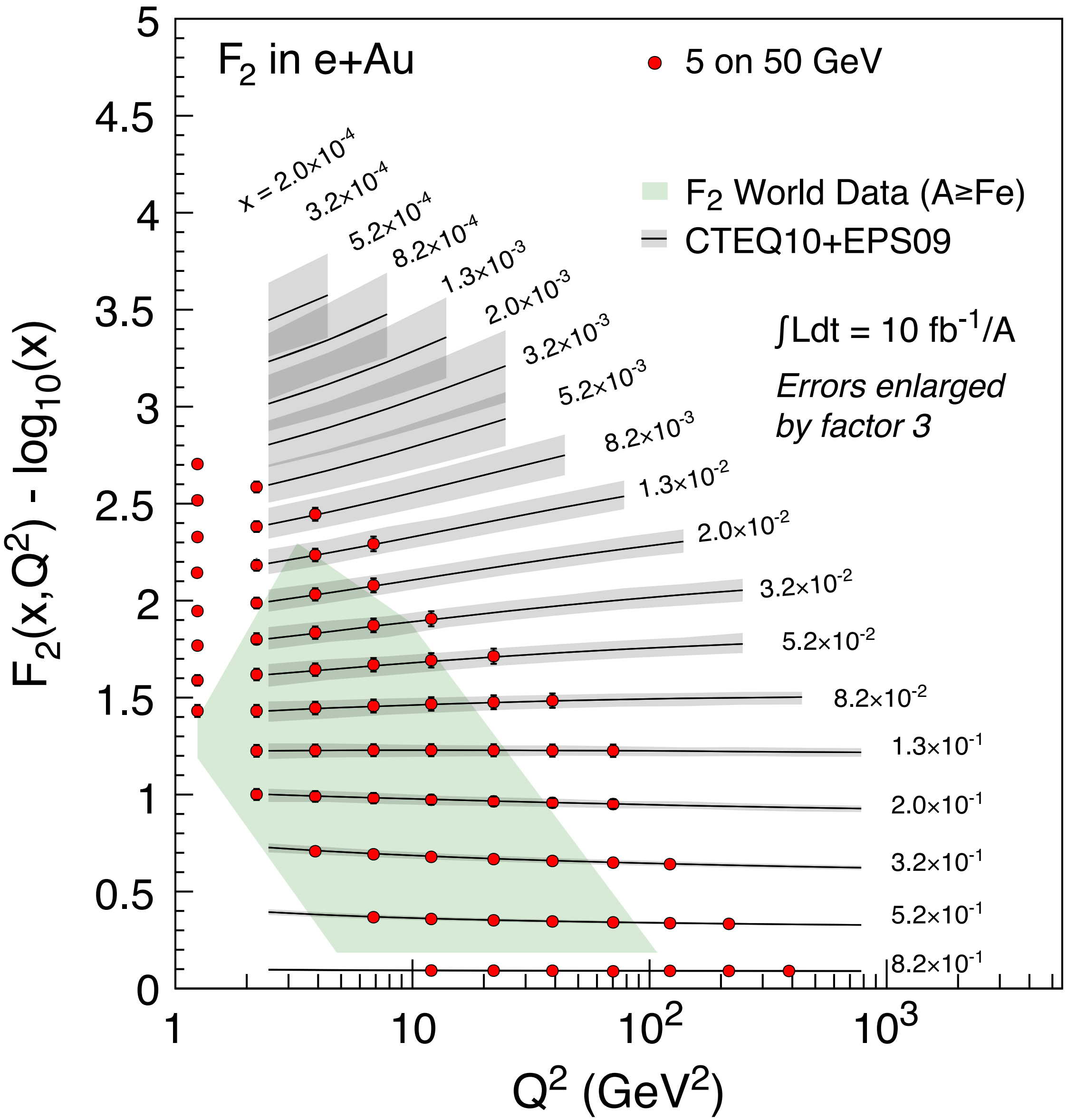

- Assume 3% systematic uncertainty
- Systematic uncertainties dominate, not L hungry

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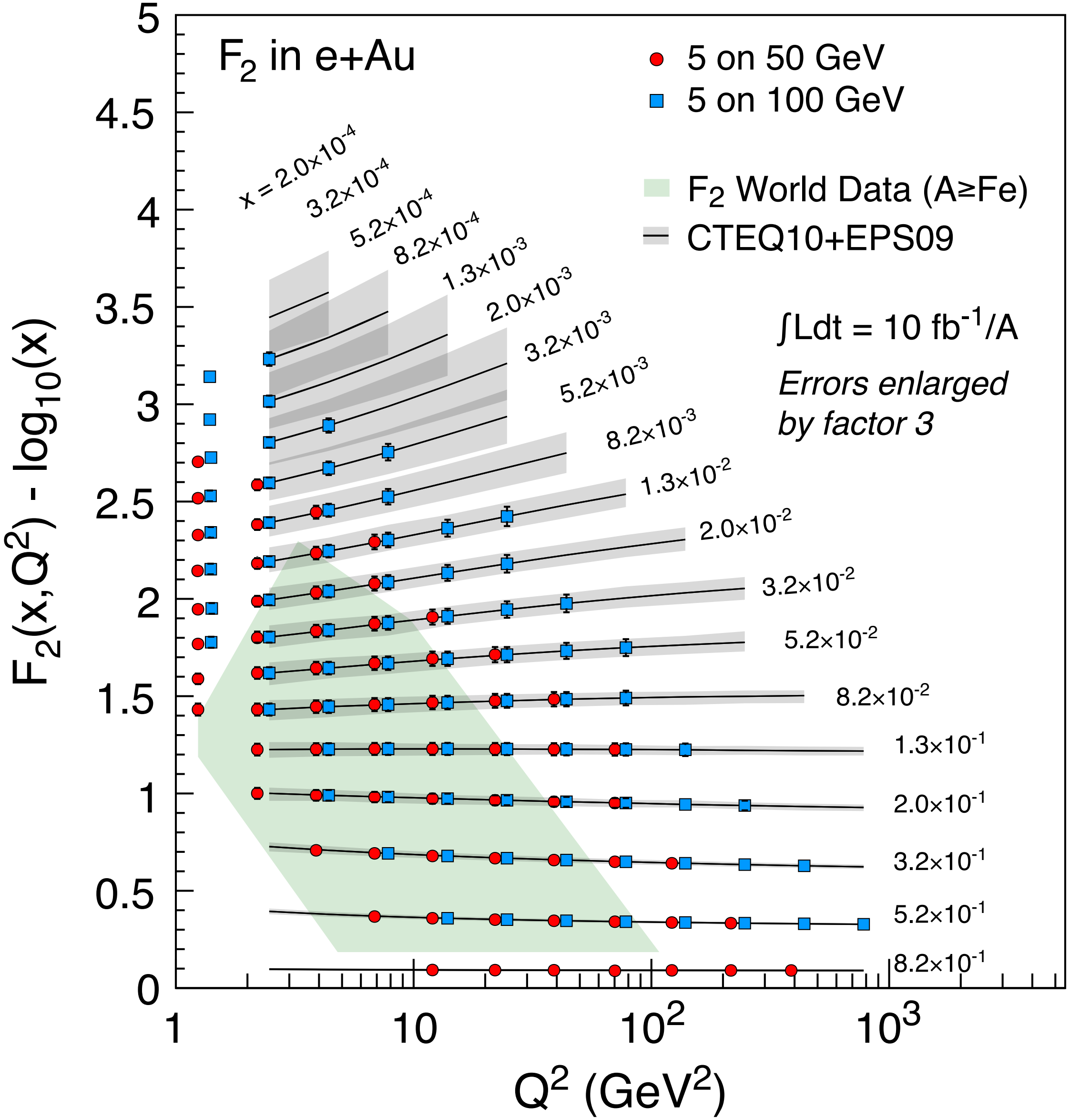

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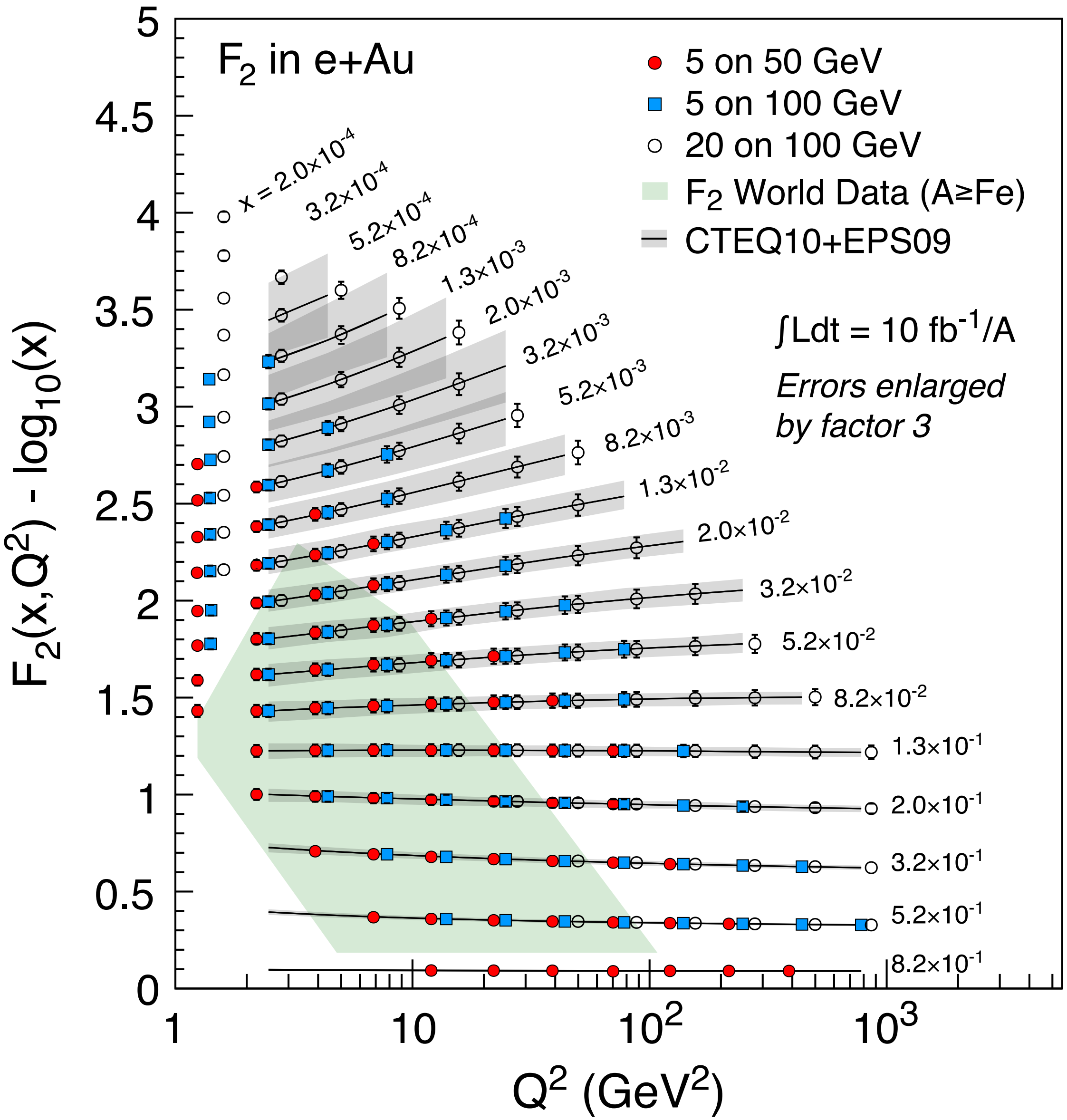

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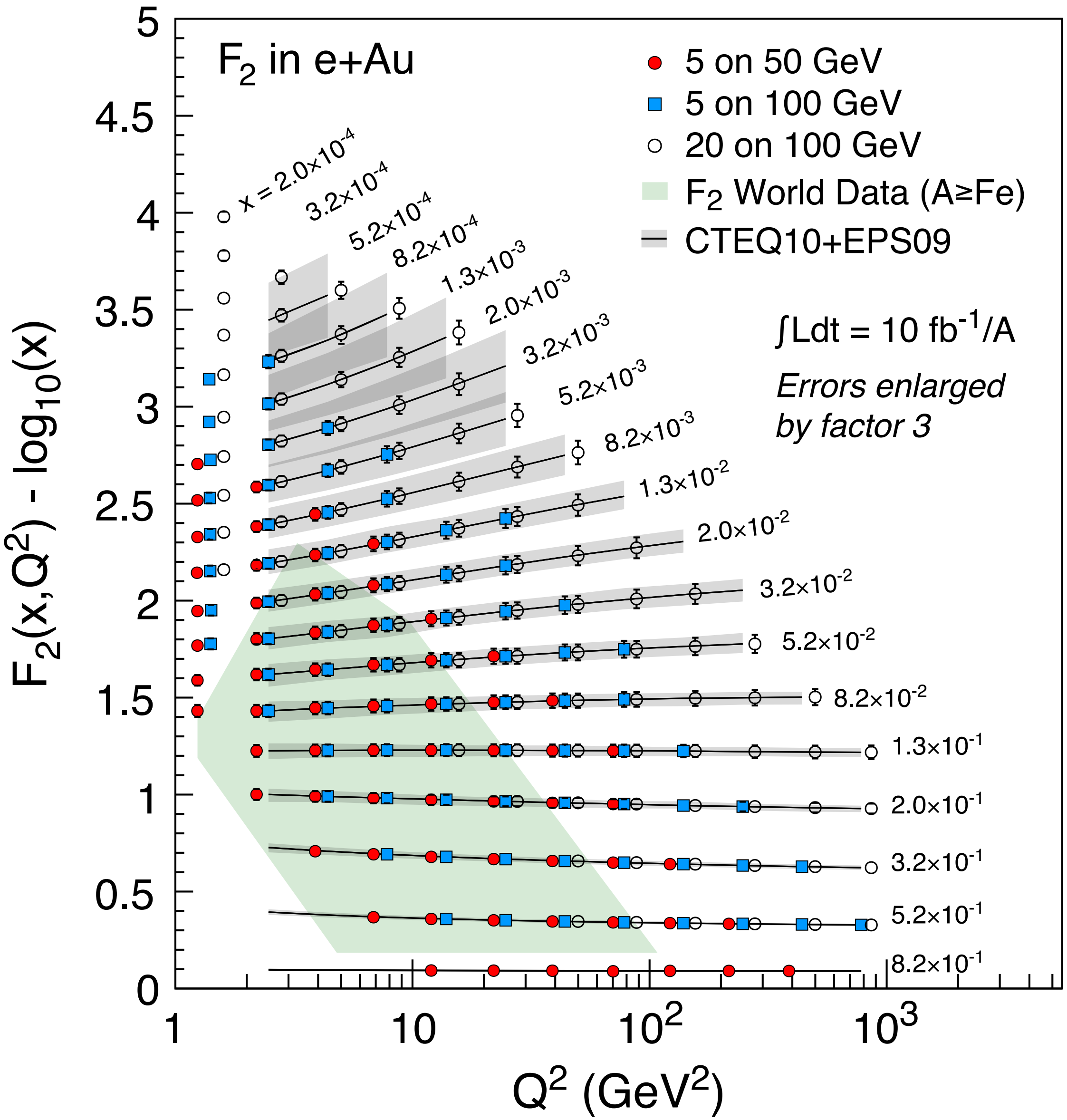

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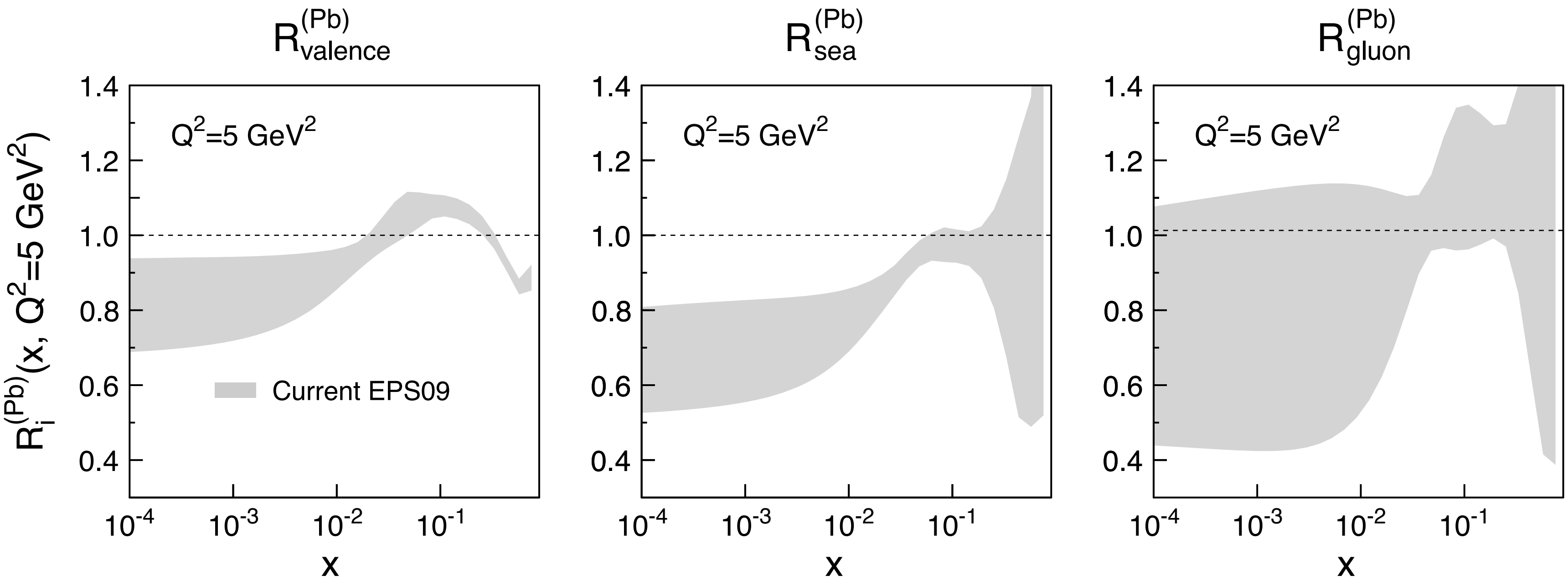
Also studied:

- F_L
  - statistics hungry
  - requires runs at various $\sqrt{s}$
- $F_{2,charm}$
  - provides compelling alternative to F_L, sensitive to glue

eRHIC: Impact on Knowledge on nPDFs



- Ratio of PDF(Pb)/PDF(p)
  - Without EIC, large uncertainties for sea quarks and gluons
  - Adding in EIC, pseudo-data significantly reduces the uncertainties, particularly at small-x
  - Fitting the charm pseudo-data has a dramatic effect at high-x
  - Something *p*A at RHIC & LHC will not be able to address

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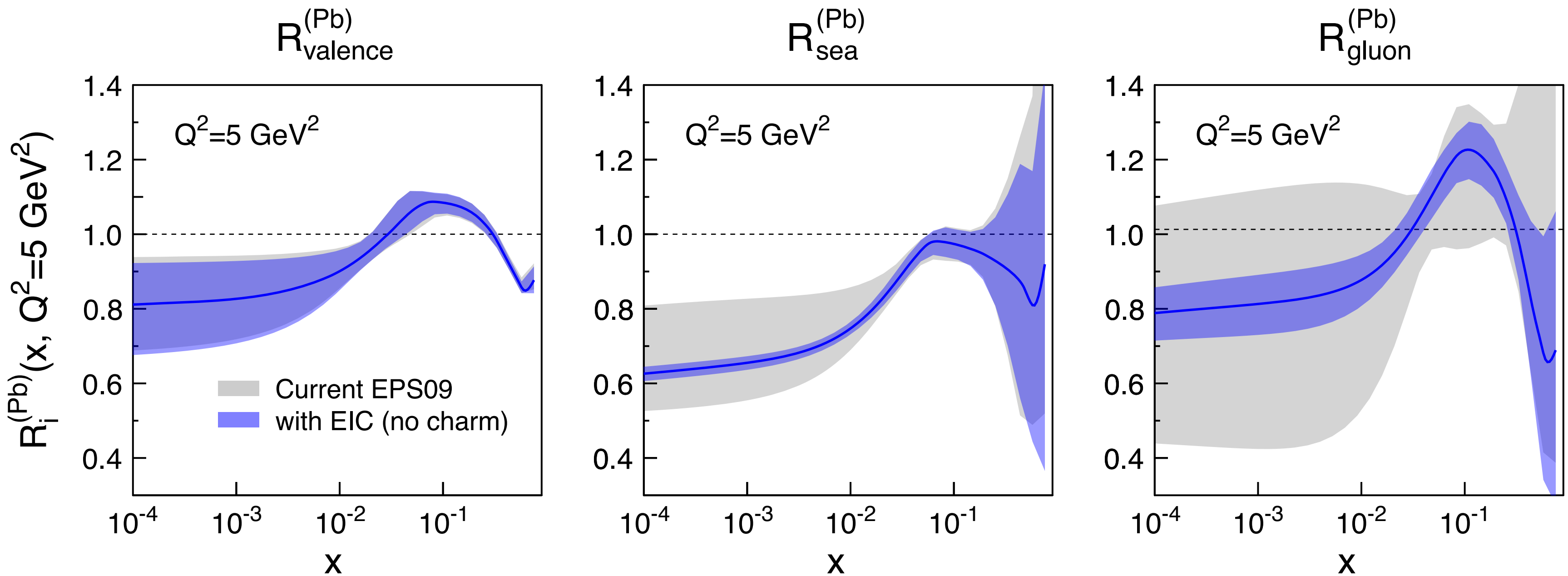

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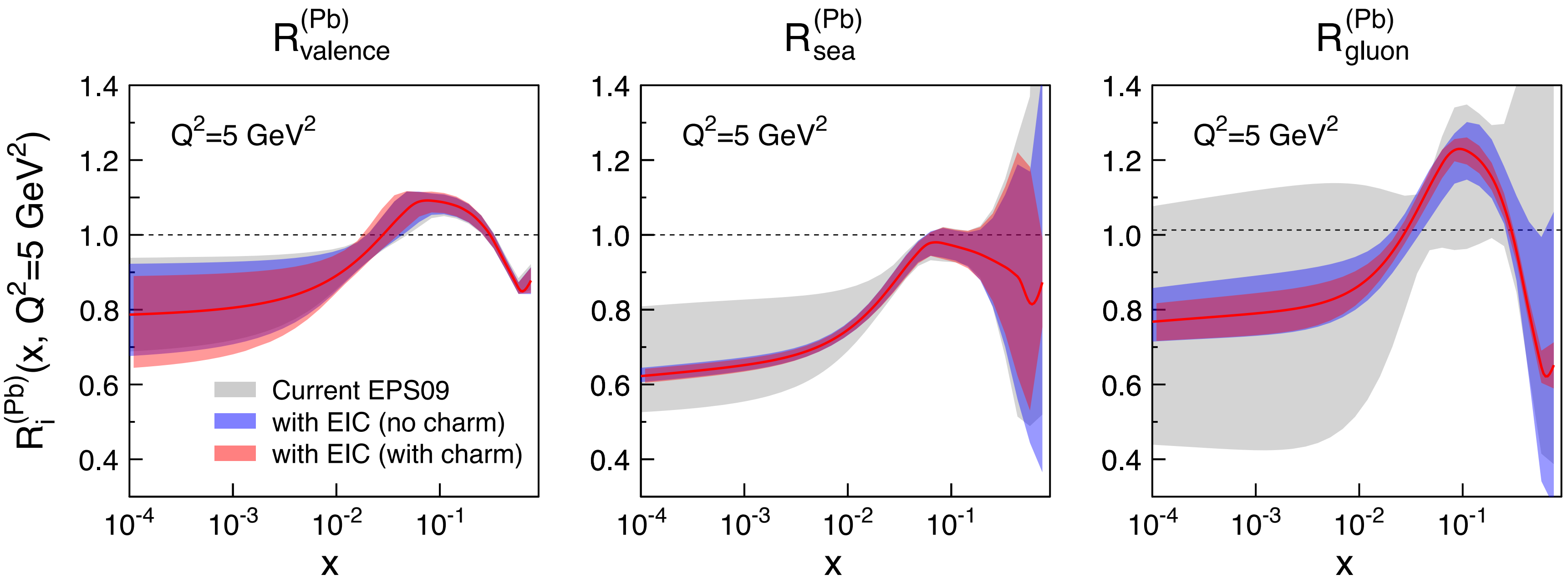

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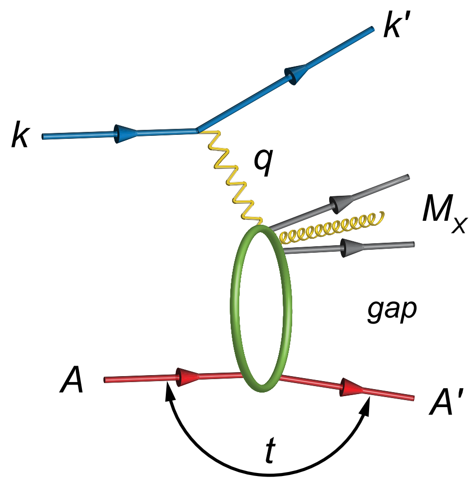
eRHIC: Diffractive Events in eA

Diffractive physics will be a major component of the eA program at an EIC



- High sensitivity to gluon density: $\sigma\sim[g(x,Q^2)]^2$ due to color-neutral exchange
- Only known process where spatial gluon distributions of nuclei can be extracted

- 2 Types: Coherent (A stays intact) & Incoherent (A breaks up)
- Experimental challenging to identify
  - Rapidity gap ⇒ hermetic detector
  - Breakup needs to be detected ⇒ n and γ in Zero Degree Calorimeter, spectator tagging (Roman Pots), IR design!

See also talks by Vadim and Elke

*e*RHIC: Spatial Gluon Distribution from $d\sigma/dt$

1950-60: Measurement of charge (proton) distribution in nuclei
Ongoing: Measurement of neutron distribution in nuclei
EIC ⇒ Gluon distribution in nuclei

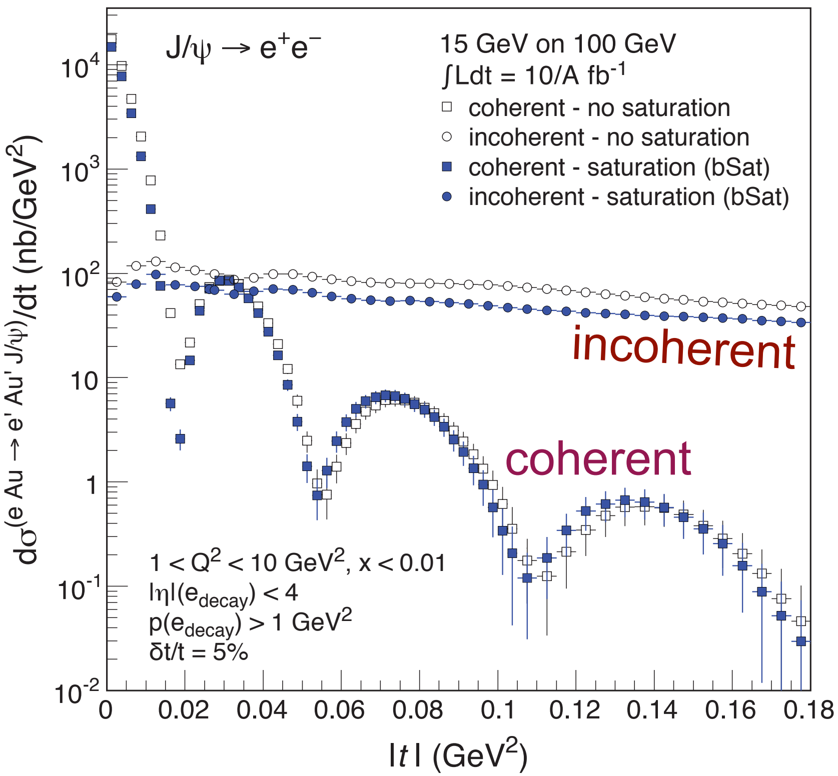
Method:

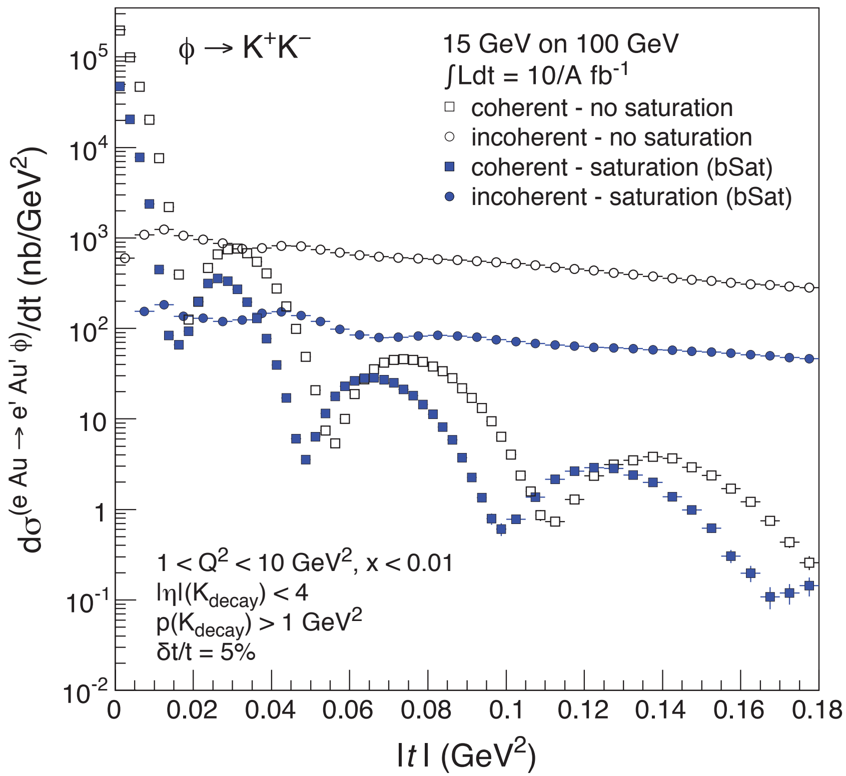
Diffractive vector meson production: $e + Au \rightarrow e' + Au' + J/\psi, \phi, \rho$

- Momentum transfer $t = |\mathbf{p}_{Au} - \mathbf{p}_{Au'}|^2$ conjugate to b_T

eRHIC: Spatial Gluon Distribution from dσ/d*t*

Diffractive vector meson production: $e + Au \rightarrow e' + Au' + J/\psi, \phi, \rho$

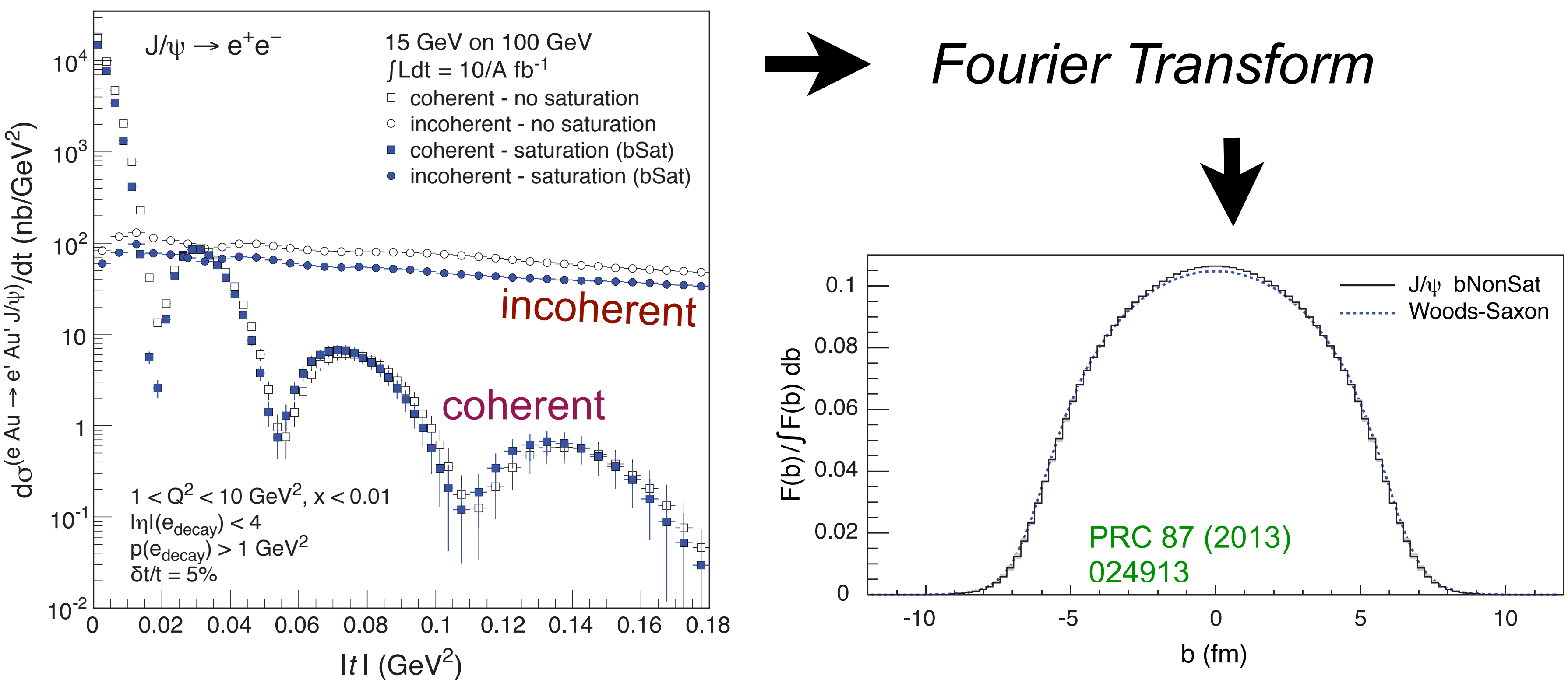




- dσ/d*t:* diffractive pattern known from wave optics
- φ sensitive to saturation effects, smaller J/ψ shows no effect
- J/ψ perfectly suited to extract source distribution

*e*RHIC: Spatial Gluon Distribution from dσ/d*t*

Diffractive vector meson production: $e + Au \rightarrow e' + Au' + J/\psi, \phi, \rho$



- Converges to input F(b) rapidly: $|t| < 0.1$ almost enough
- Recover accurately any input distribution used in model used to generate pseudo-data (here Wood-Saxon)
- Systematic measurement requires $\int \mathbf{L}dt >> 1\ fb^{-1}/A$

Summary

eRHIC, with its high energy, high luminosity eA and polarized ep collisions, will provide answers to long-standing fundamental questions in QCD

- **ep:** Precision studies of structure functions, TMDs, and GPDs will lead to the most comprehensive picture of the nucleon ever: its flavor, spin, and spatial structure
- **eA:** Unprecedented study of matter in a new regime of QCD. New capabilities open a new frontier to study the saturation region, measure the gluonic structure of nuclei, and investigate color propagation, and fragmentation using the nucleus as analyzer.
- **eRHIC:** Provides *unique* capabilities for the study of QCD well beyond those available at existing facilities worldwide. Its design matches the physics goals in **all** aspects, allowing us to study the broad range of topics detailed in the EIC White Paper.