

High-Energy DIS Studies with Nuclei

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Driving Fundamental Questions in e+A

Nucleus is:

- What is the fundamental quark-gluon structure of light and heavy nuclei?

Object of Interest

Driving Fundamental Questions in e+A

Nucleus is:

- What is the fundamental quark-gluon structure of light and heavy nuclei?
 - ▶ Quark & gluon distribution in nuclei (nPDF, nTMD, nGPD)
 - ▶ Source of nuclear modification?
 - ▶ Short range forces in nuclei: Can they be described in terms of the quark and gluon degrees of freedom?
 - ▶ Impact: High-Temperature QCD, Nuclear Structure

Driving Fundamental Questions in e+A

Nucleus is:

- What is the fundamental quark-gluon structure of light and heavy nuclei?
- Can we experimentally find and explore a novel regime in QCD of weakly coupled high density matter?
- What is the role of saturated strong gluon fields, and what are the degrees of freedom in this strongly interacting regime?
 - ▶ Gluon saturation, $Q_S^A(x) \sim Q_S(x) \cdot A^{1/3}$
 - ▶ Color Glass Condensate
 - ▶ New evolution equations (JIMWLK, BK)
 - ▶ Universality?

Object of Interest

Amplifier

Driving Fundamental Questions in e+A

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 - What is the role of saturated strong gluon fields, and what are the degrees of freedom in this strongly interacting regime?
 - Can the nuclear color filter provide novel insight into propagation, attenuation and hadronization of colored probes?
 - ▶ Energy loss in cold nuclear matter
 - ▶ Fragmentation Functions
-
- The diagram consists of a vertical list of four bullet points. To the right of each point is a black curly brace that spans from the point to the right edge of the slide. The first two points are grouped by a brace labeled "Object of Interest" in blue text. The next two points are grouped by a brace labeled "Amplifier" in blue text. The last point is grouped by a brace labeled "Analyzer" in blue text.

Object of
Interest

Amplifier

Analyzer

Electron-Ion Collider Initiatives

Past

Future

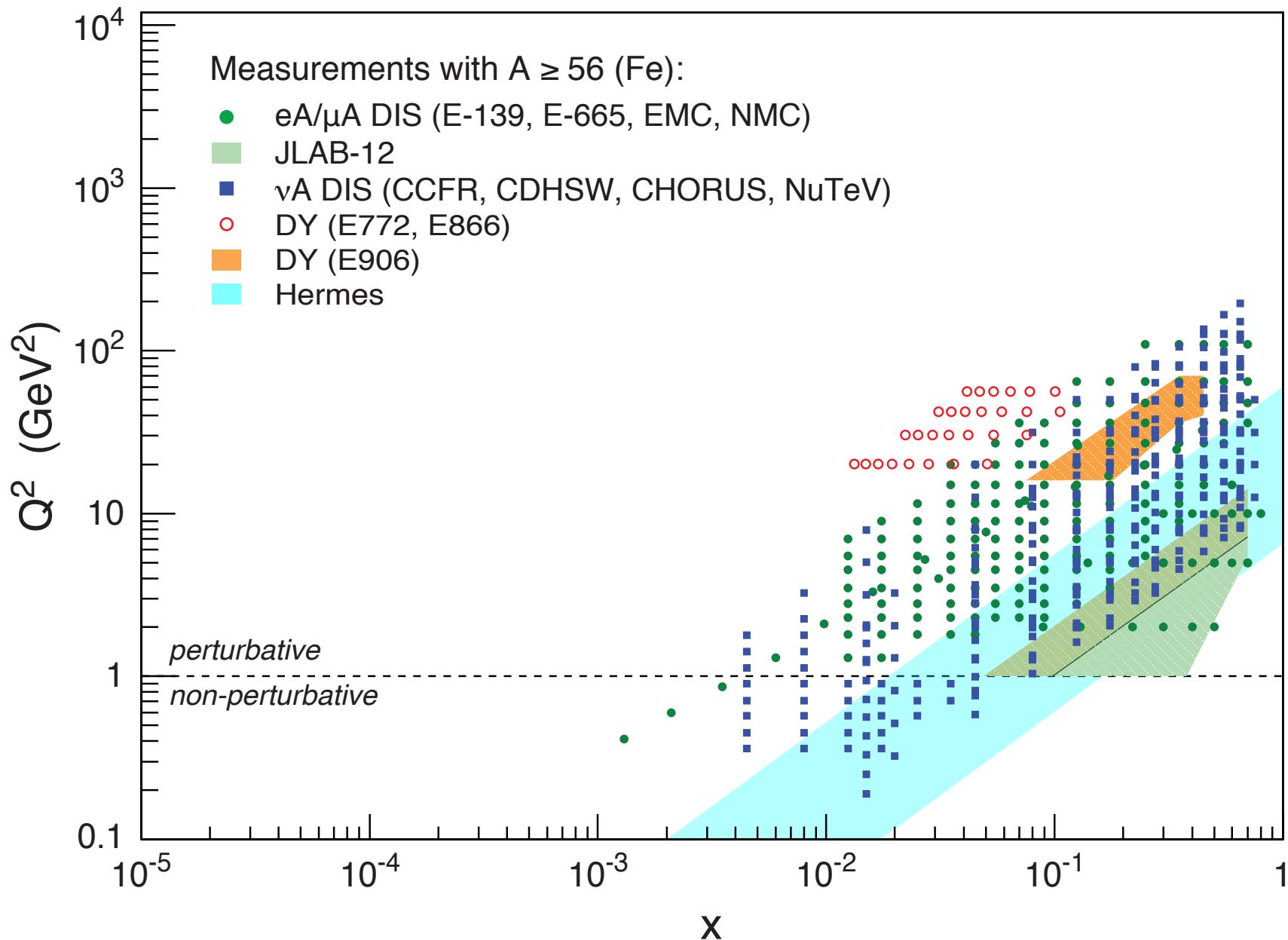
	HERA@DESY	LHeC@CERN	HIAF@CAS	ENC@GSI	JLEIC@JLab	eRHIC@BNL
\sqrt{s} (GeV)	320	800-1300	12-65	14	20-64	32-140
Proton x_{\min}	1×10^{-5}	5×10^{-7}	3×10^{-4}	5×10^{-3}	3×10^{-4}	5×10^{-5}
Ions	p	p ... Pb	p ... U	p ... Ca	p ... Pb	p ... U
L ($\text{cm}^{-2}\text{s}^{-1}$)	2×10^{31}	$\sim 10^{34}$	$\sim 10^{32-35}$	$\sim 10^{32}$	$\sim 10^{33-35}$	$\sim 10^{33-34}$
IRs	2	1	1	1	2+	2+
Year	1992-2007	post ALICE	> 2020	Fair Upgrade	post 12 GeV	post RHIC

High-Energy Physics

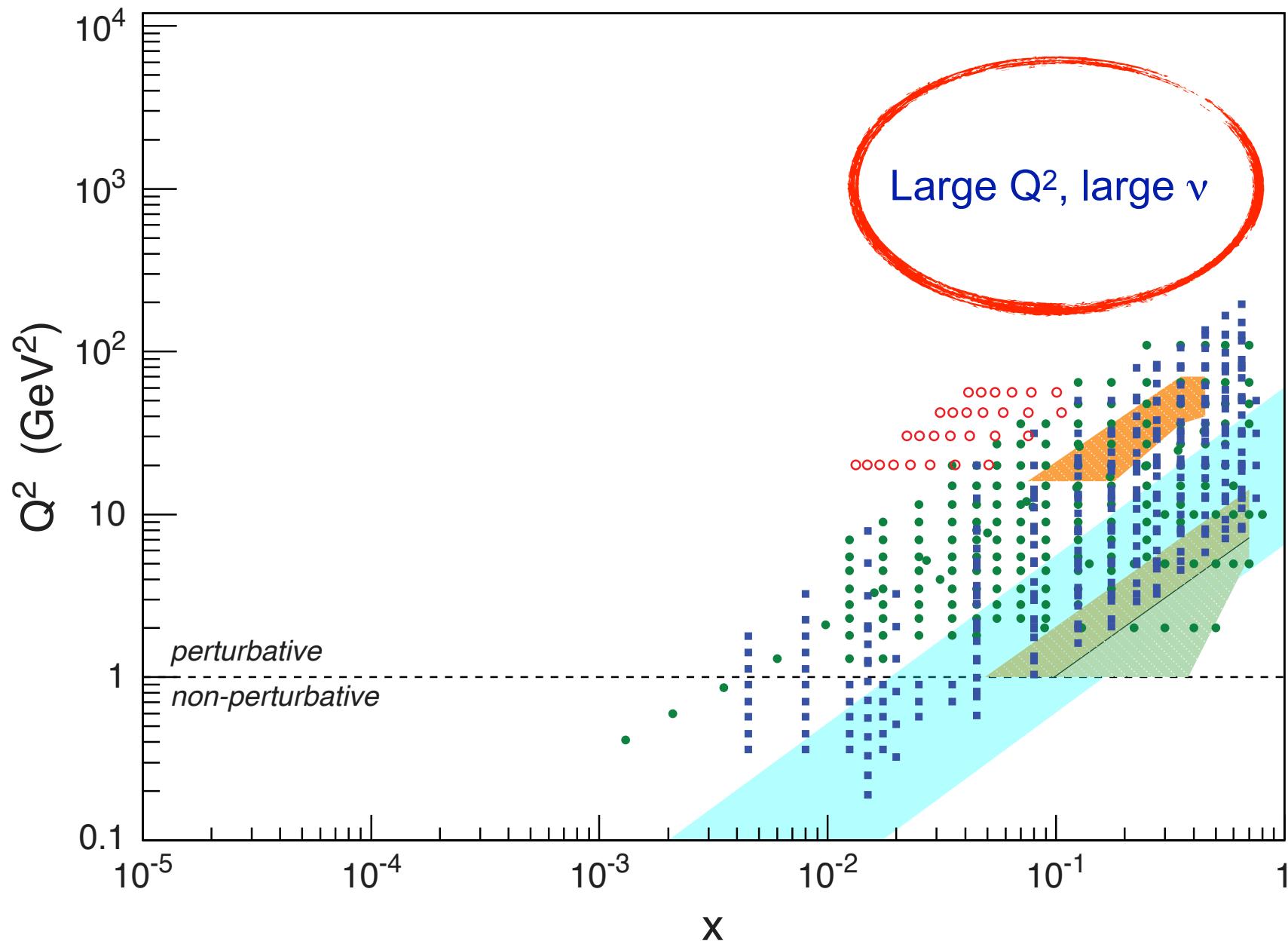
Nuclear Physics

- World-wide interest in e+A collisions
- All future collider include e+A in their planning
 - ▶ typically up to heaviest nuclei

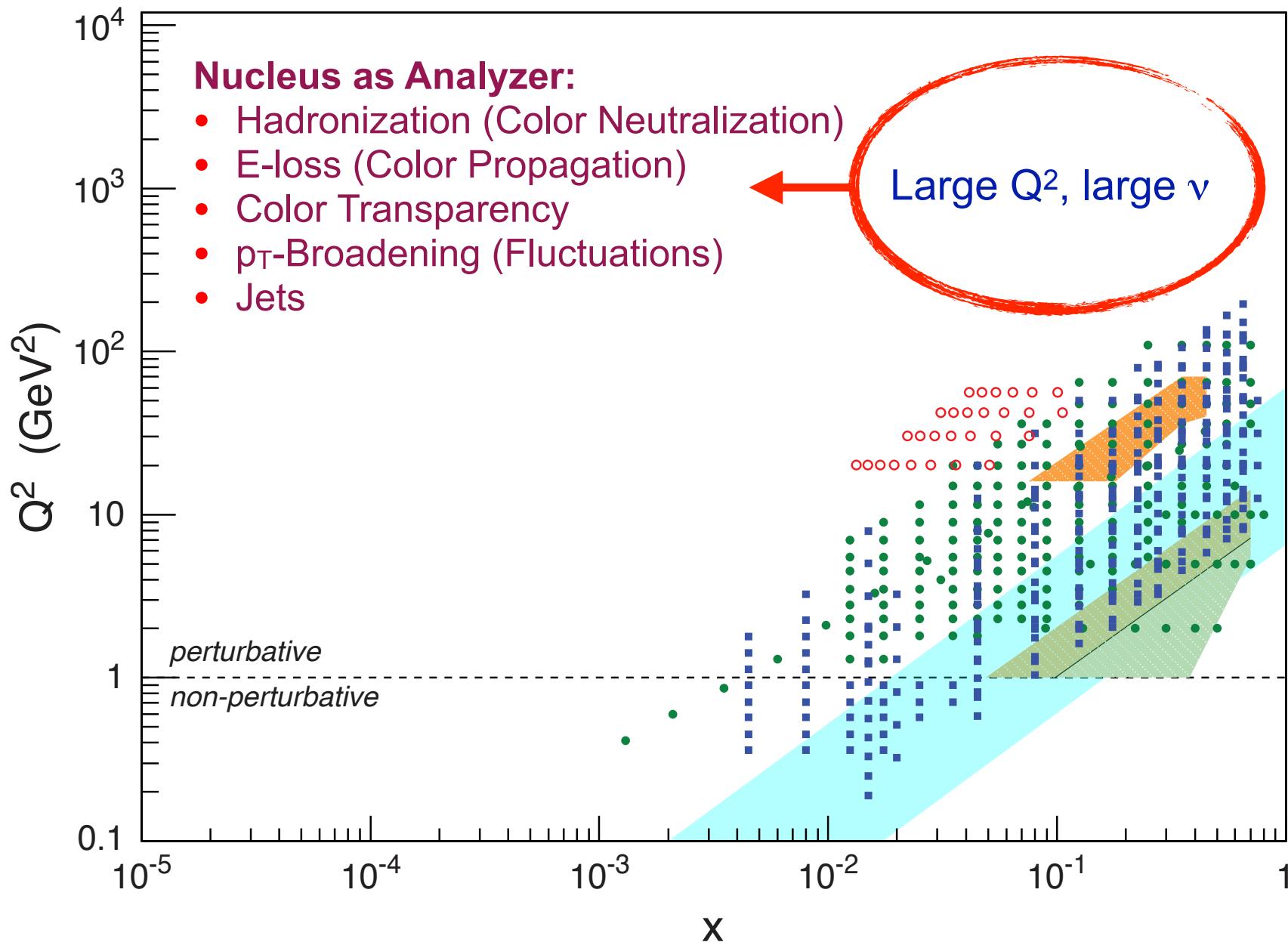
Landscape of e+A Physics



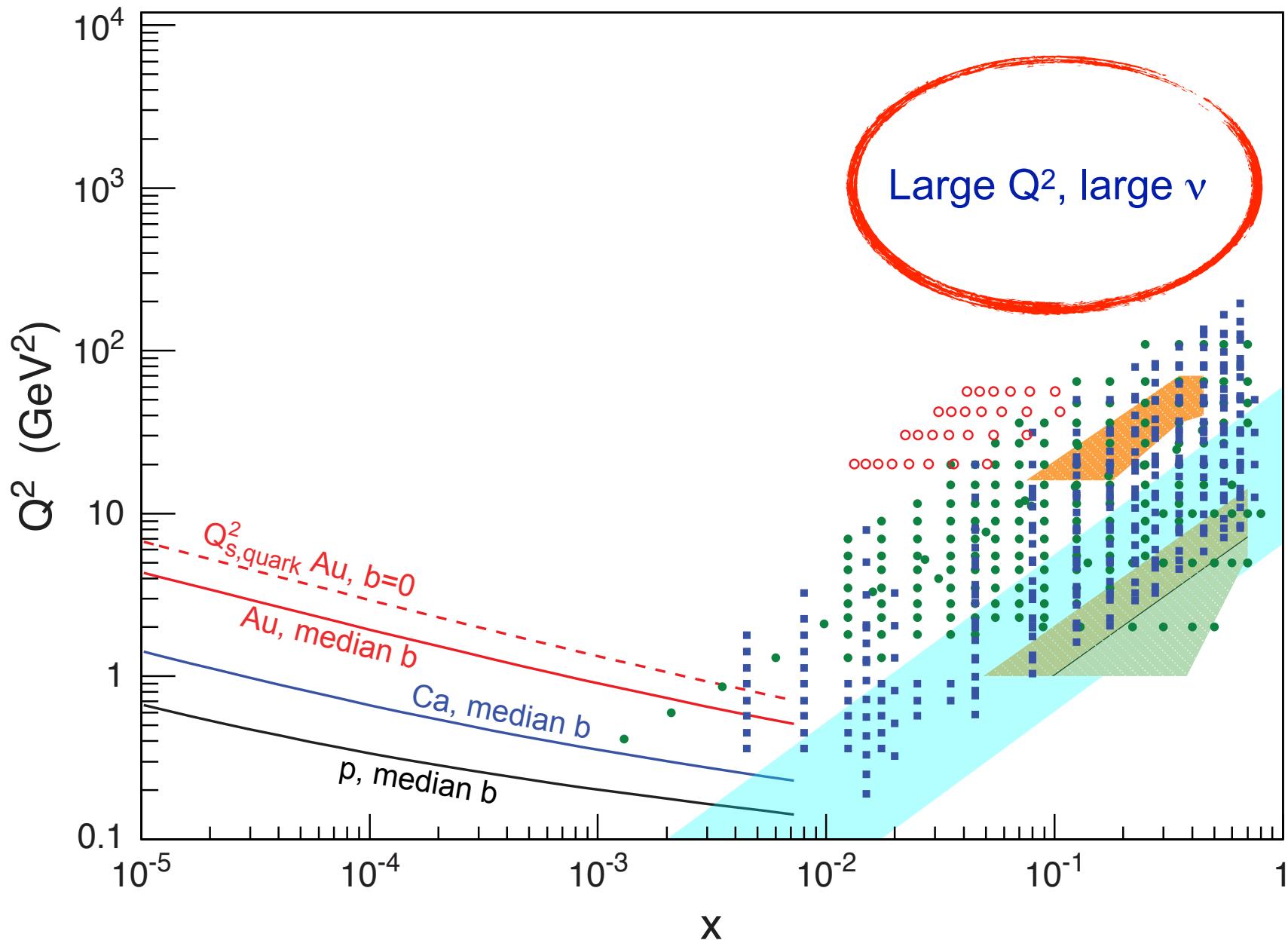
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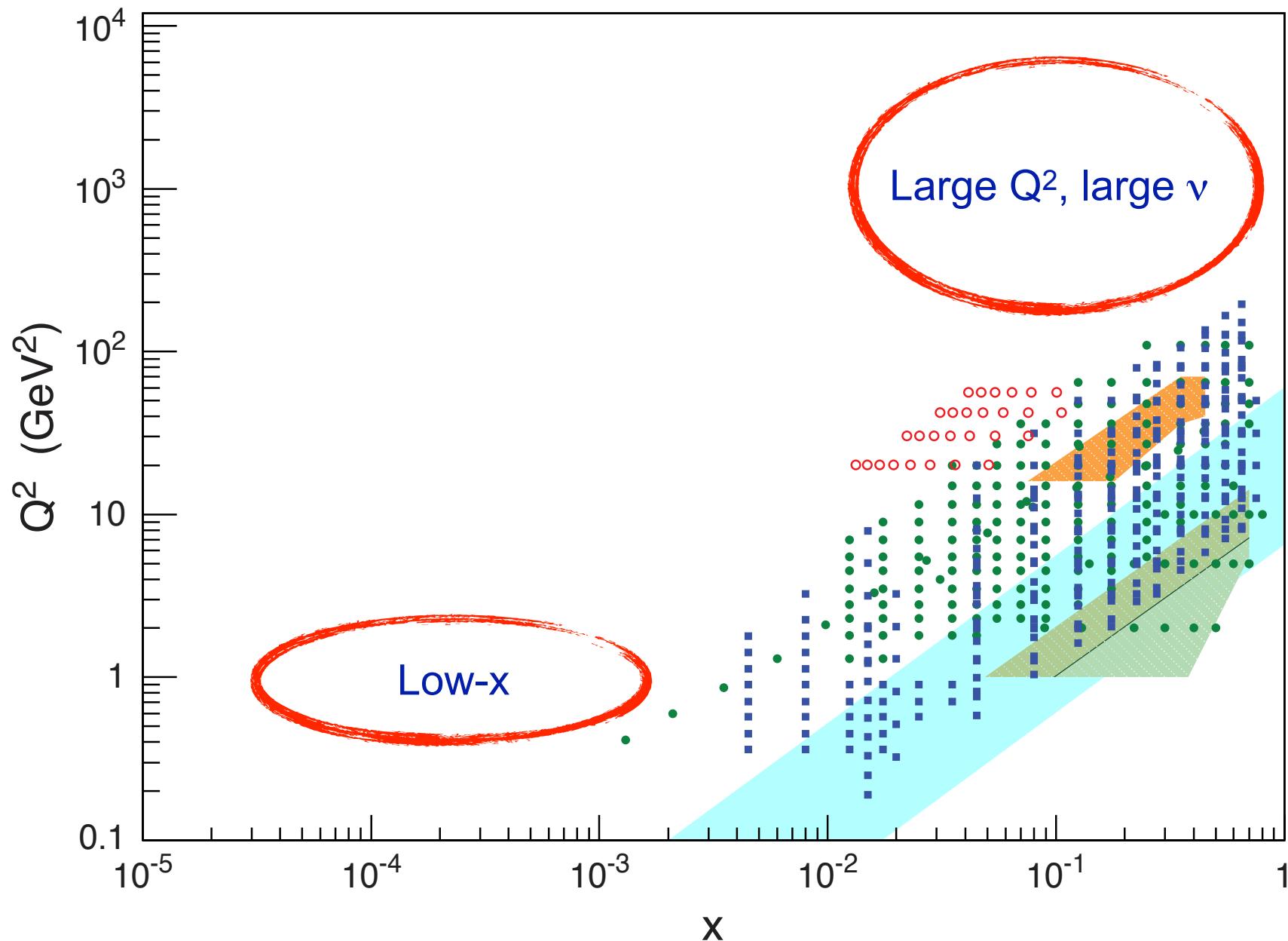
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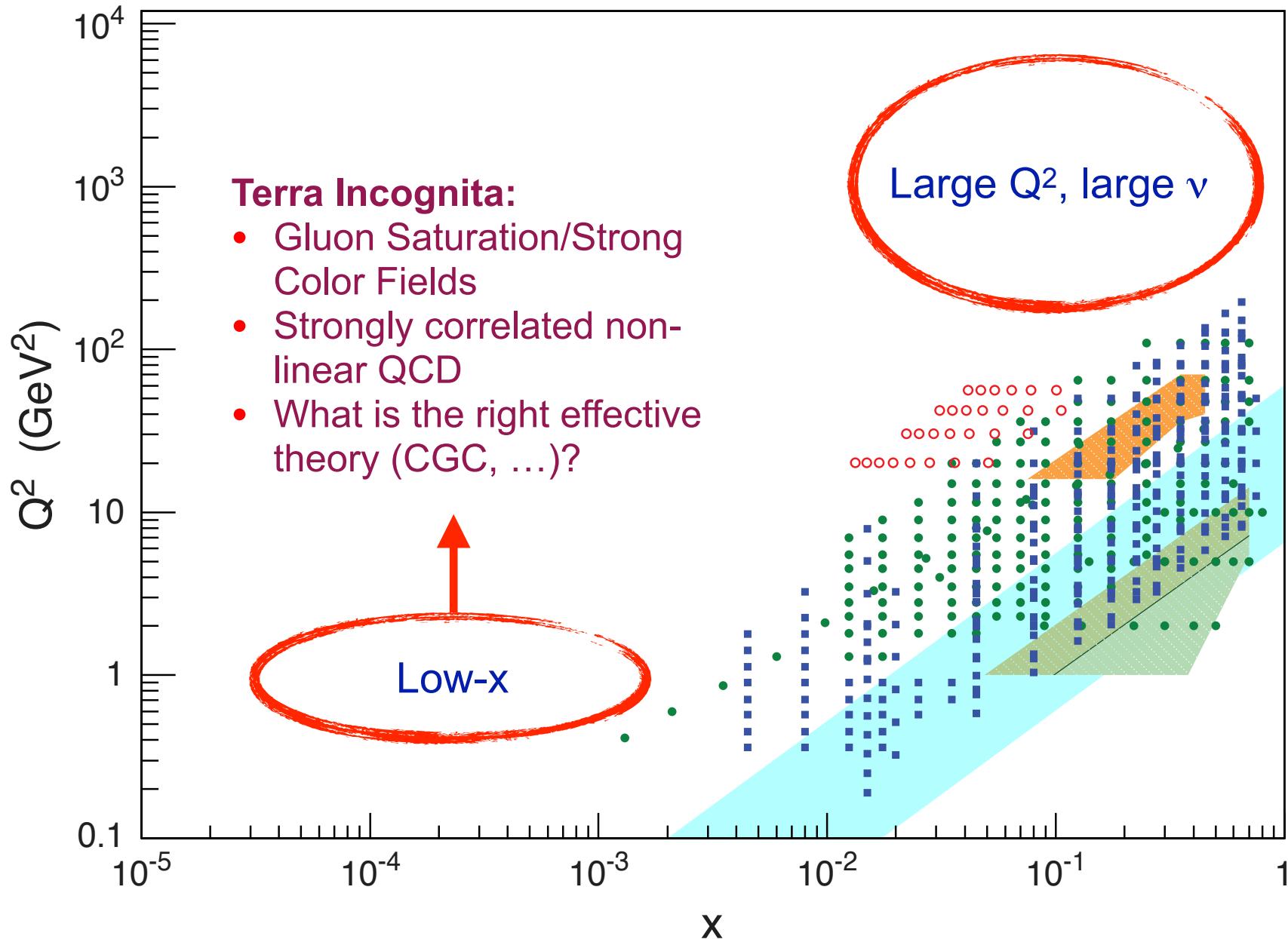
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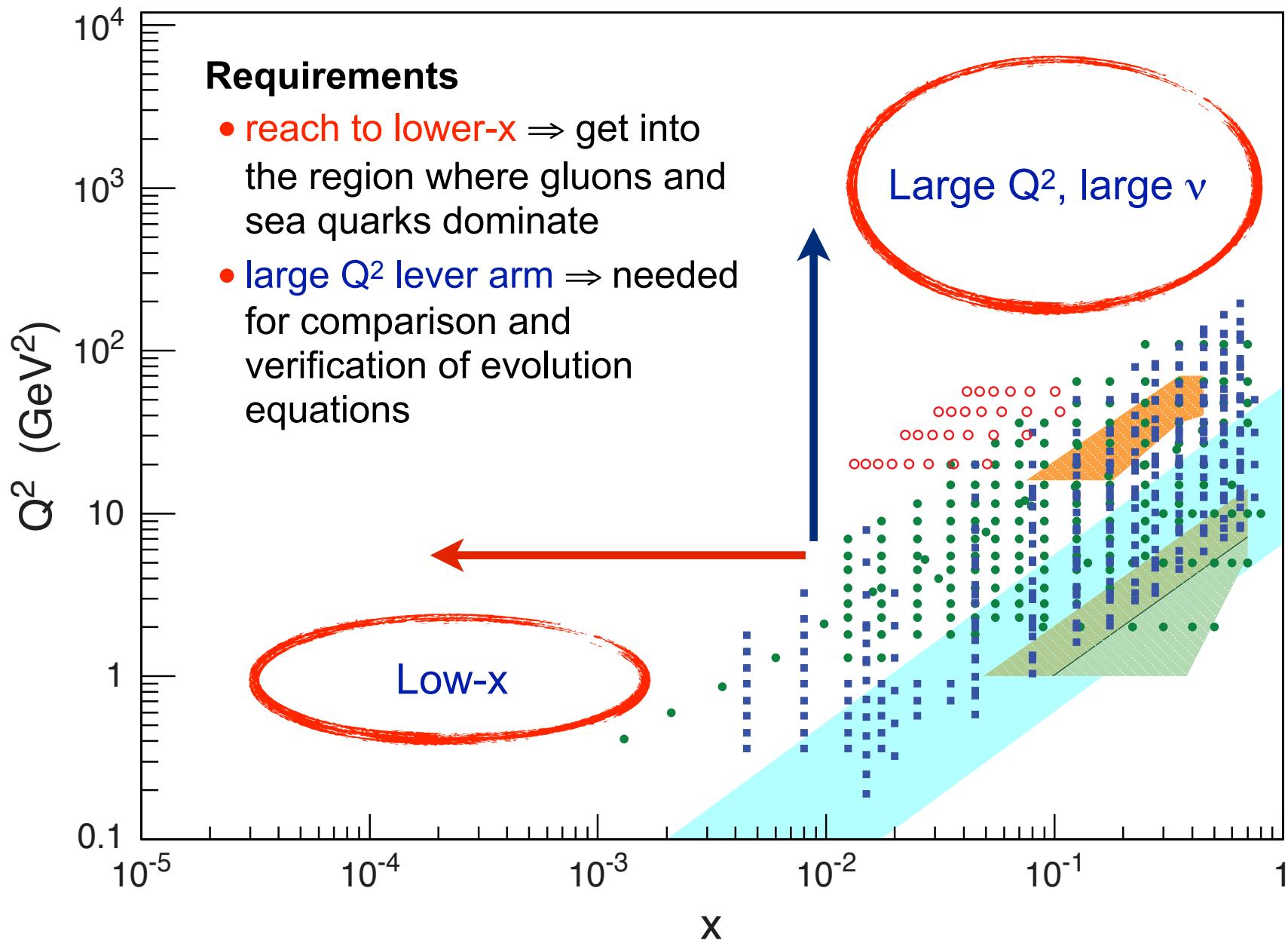
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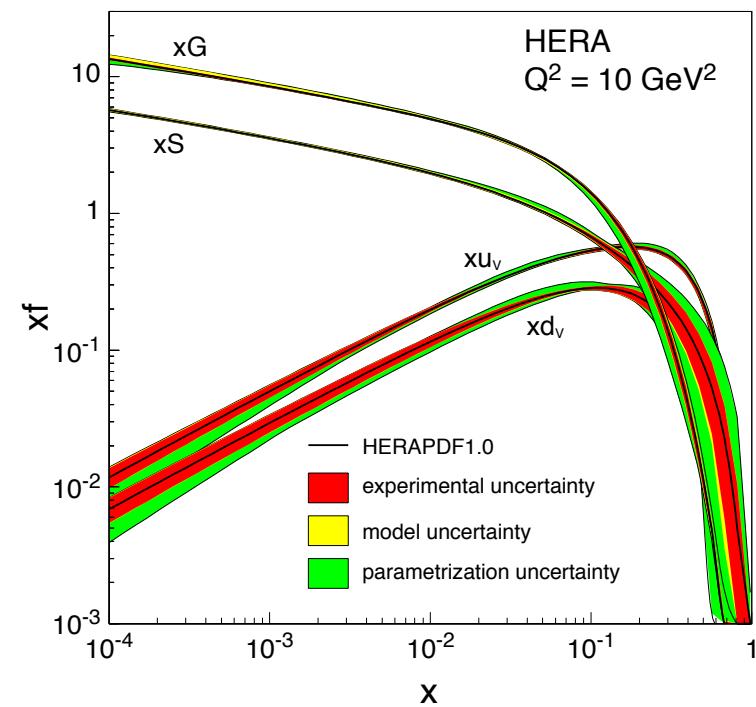
Landscape of e+A Physics



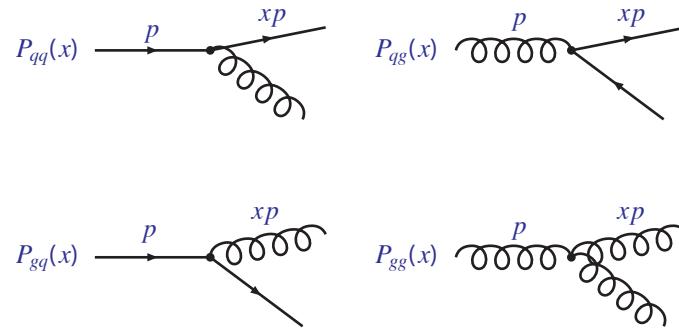
Landscape of e+A Physics



Key Topic in e+A: Gluon Saturation



QCD evolution drives the gluon distribution rising at small- x

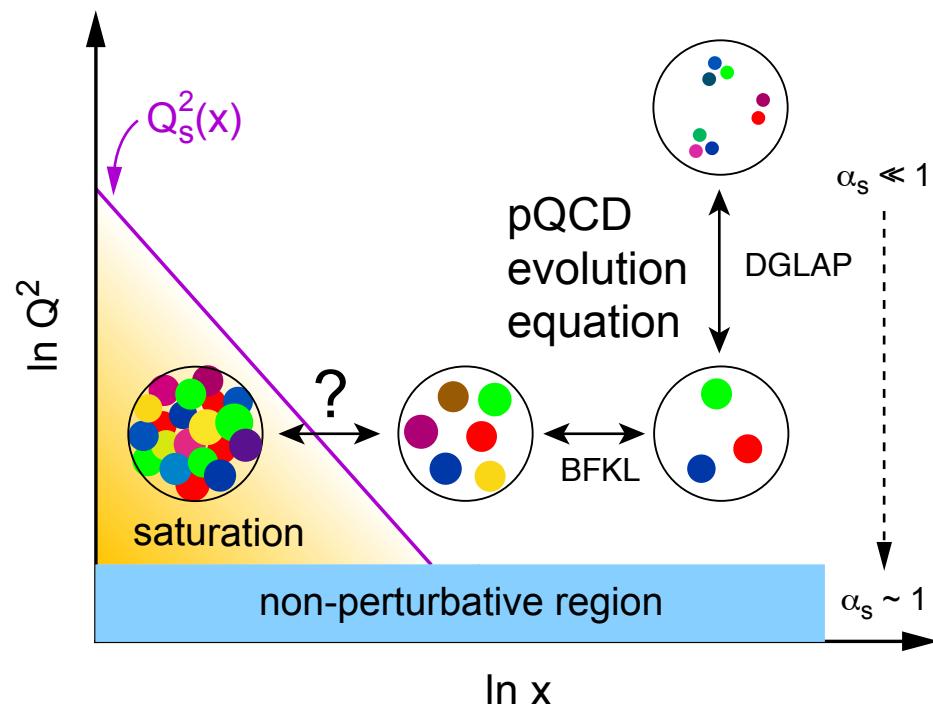
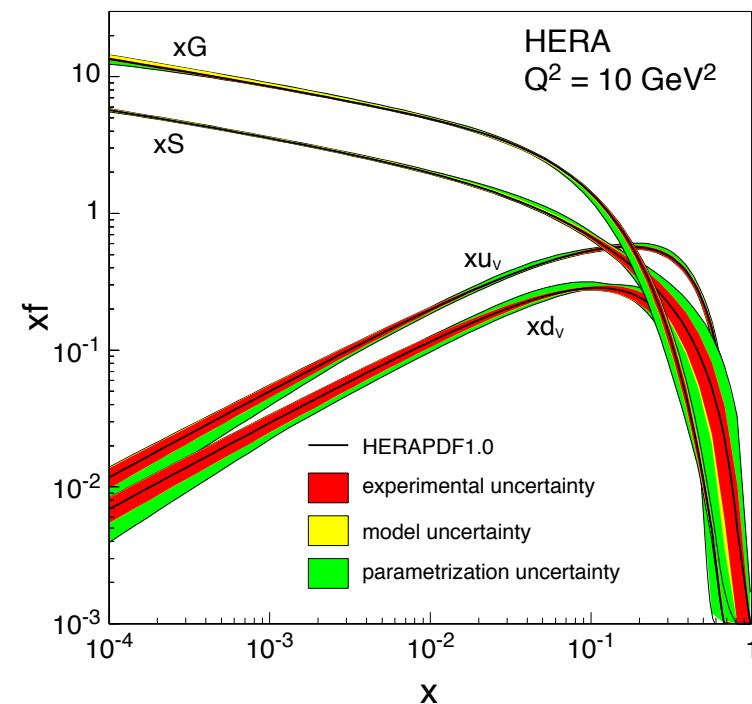


Lowest order QCD splitting function

$$\mathcal{P}_{gg}(x) = \frac{x}{(1-x)_+} + \frac{1-x}{x} + x(1-x) + \delta(x-1)\beta_0 .$$

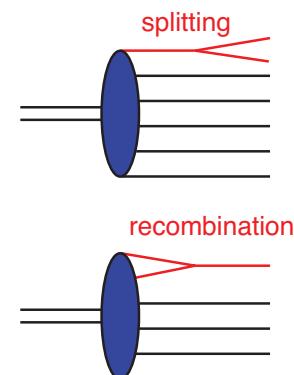
Explosion of gluon density \Rightarrow violates unitarity

Key Topic in e+A: Gluon Saturation

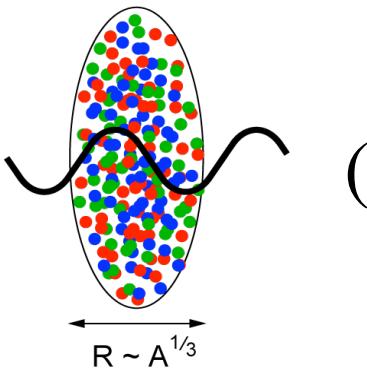
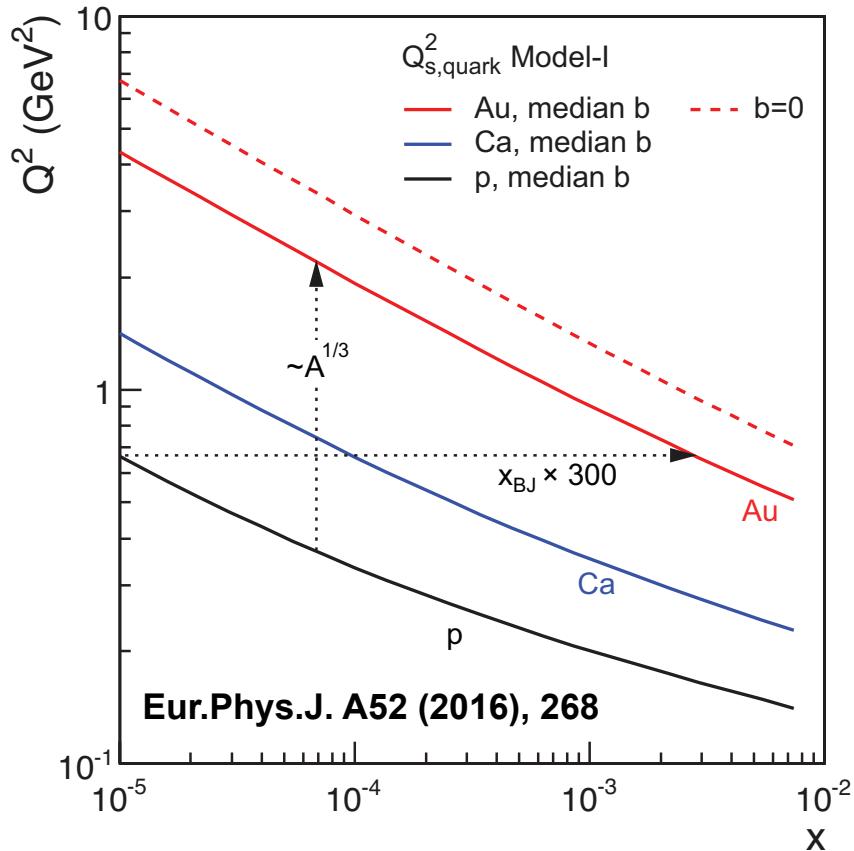


New Approach: Non-Linear Evolution

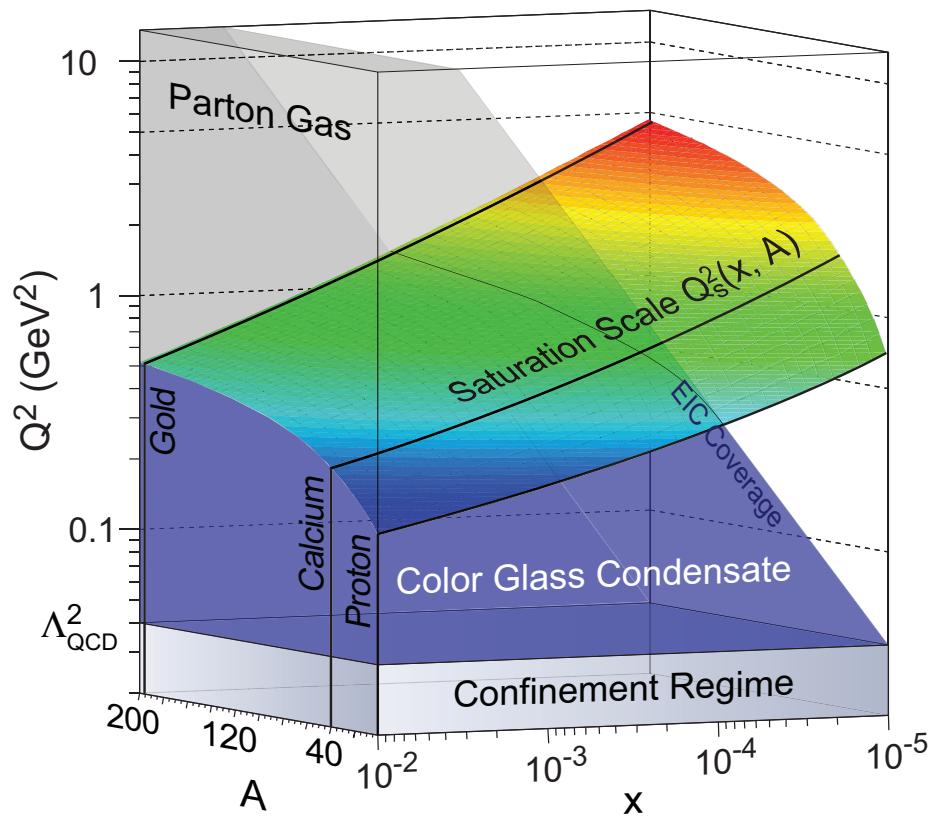
- BFKL \rightarrow BK: *Recombination* compensates gluon splitting
- **Saturation** of gluon densities characterized by scale $Q_s(x)$
- New evolution equations at low- x (JIMWLK)
- Effective theory: **Color Glass Condensate**



Nuclear Oomph: Gluon Saturation in e+A



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

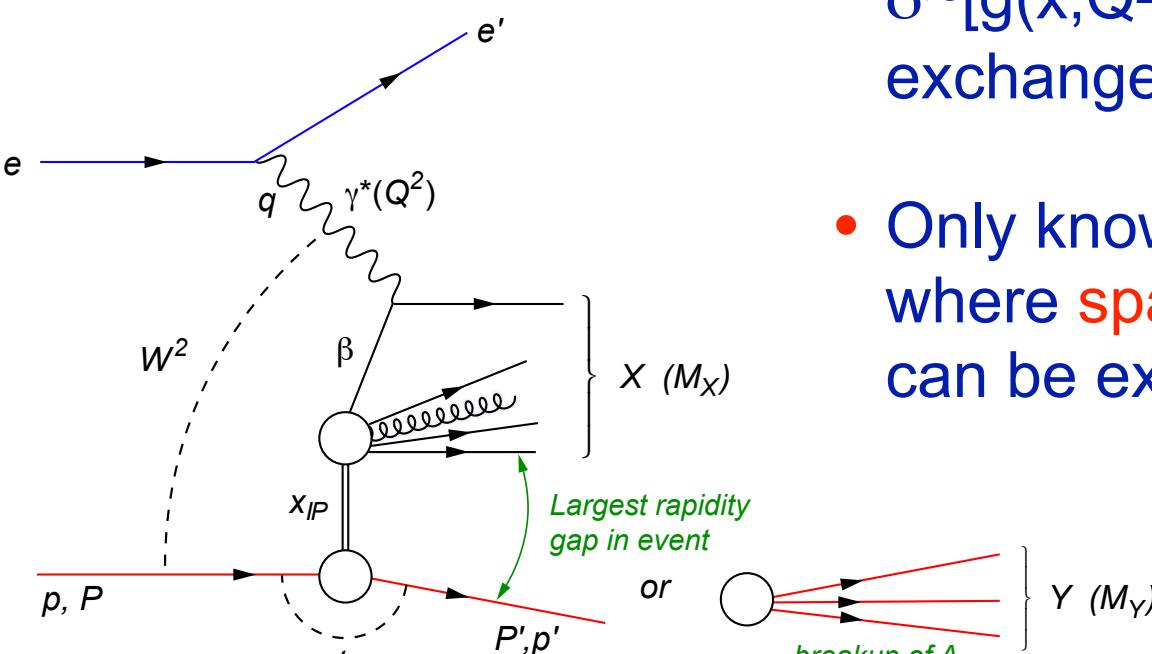


Enhancement of Q_s with A :
 saturation regime reached at significantly lower energy in nuclei (and lower cost)

Diffraction for the 21st Century

Diffraction is most precise probe of **non-linear dynamics** in QCD
Will be major component of any e+A program

HERA: $\sigma_{\text{diff}}/\sigma_{\text{tot}} \sim 14\%$



coherent

p/A stays intact

incoherent

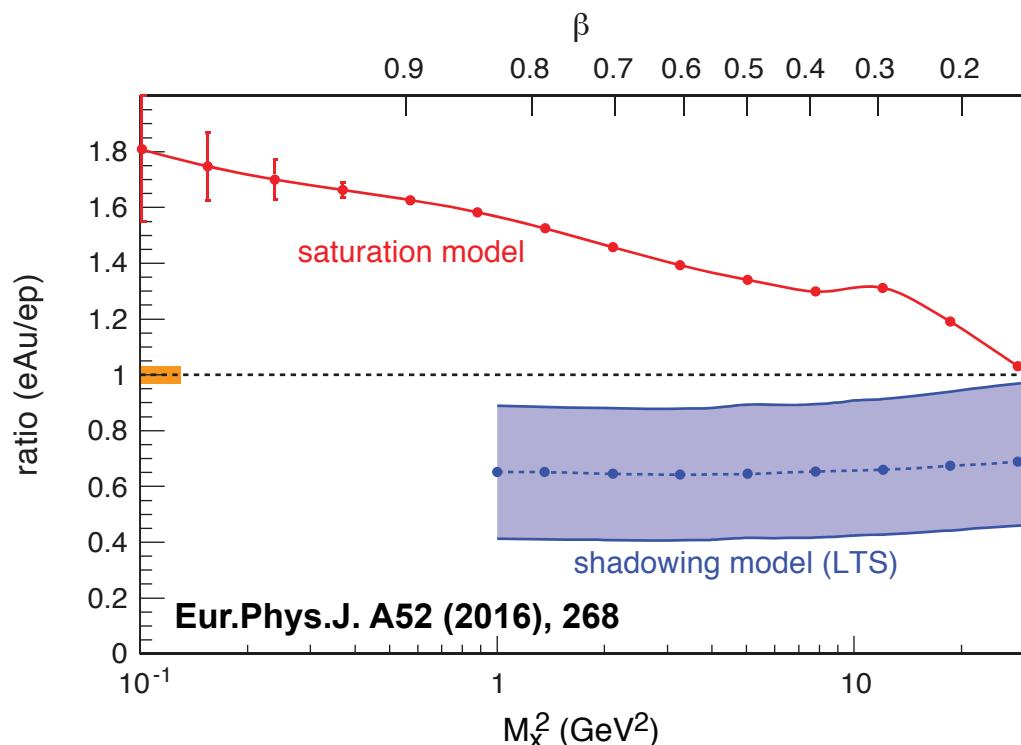
p/A breaks up

- High sensitivity to gluon density:
 $\sigma \sim [g(x, Q^2)]^2$ due to color-neutral exchange (e.g. in exc. VM prod.)

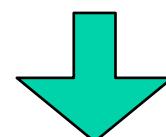
- Only known process in e+A where **spatial gluon distributions** can be extracted (relevant for HI)

t: momentum transfer squared
M_X: mass of diffractive final-state

$\sigma_{\text{diffractive}}/\sigma_{\text{total}}$

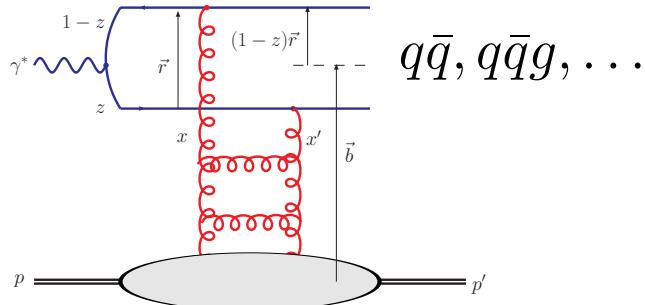


- HERA observed: ~14% of all events are diffractive
- Saturation models (CGC) predict up to $\sigma_{\text{diff}}/\sigma_{\text{tot}} \sim 25\%$ in eA
- Ratio *enhanced* for small M_x and *suppressed* for large M_x
- Standard QCD predicts no M_x dependence and a moderate suppression due to shadowing.

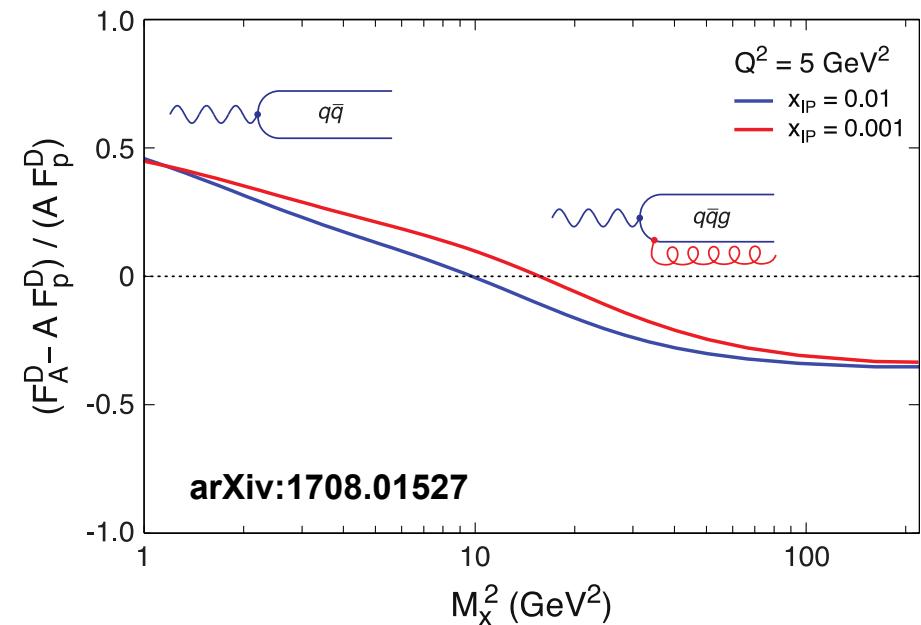


Unambiguous signature for reaching the saturation limit

$\sigma_{\text{diffractive}}/\sigma_{\text{total}}$

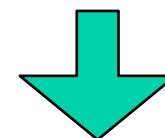


Sign Change:



Observing these M_x dependencies over wide range in x and Q^2 is crucial!

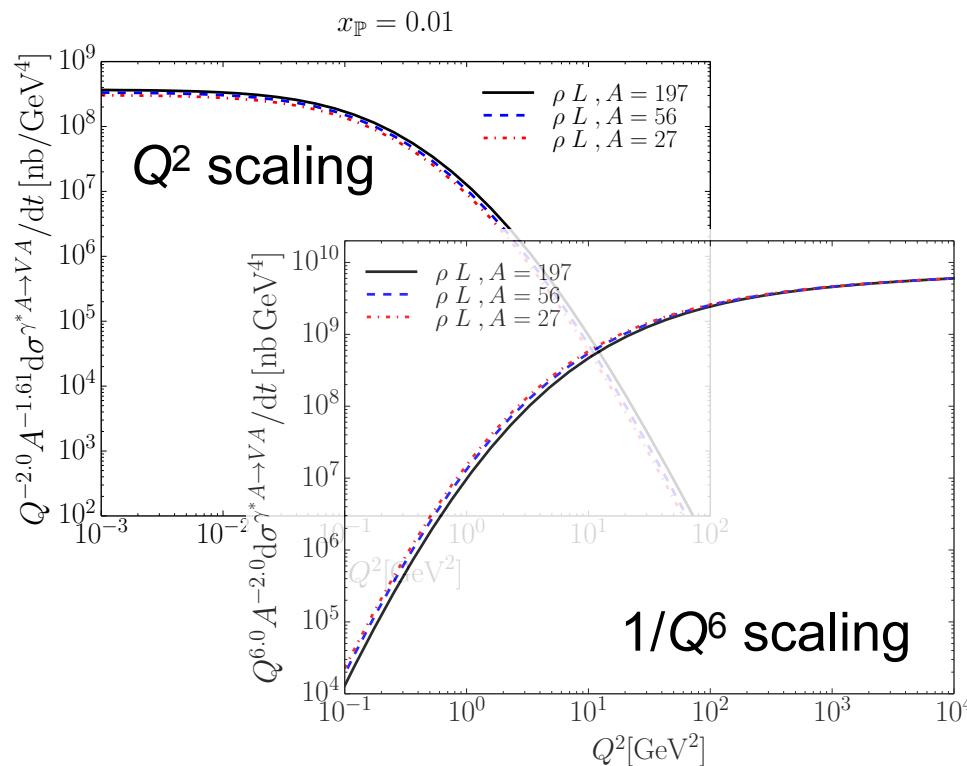
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Unambiguous signature for reaching the saturation limit

Q^2 and A Scaling of Diffractive VM Production

- Saturation models predict very special and strong dependencies in A and Q^2 that are different above and below Q^2_S

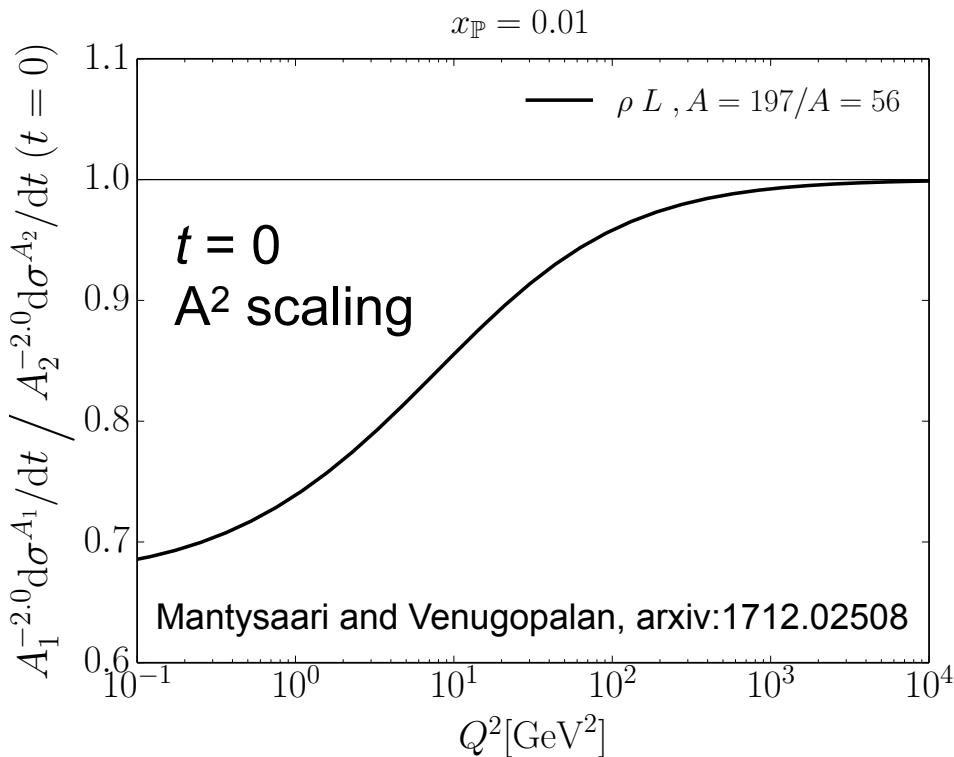


- $Q^2 > Q^2_S$
 - ▶ $\sigma \sim 1/Q^6$
 - ▶ $\sigma(t=0) \sim A^2$
 - ▶ $\sigma \sim A^{4/3}$
- $Q^2 < Q^2_S$
 - ▶ $\sigma \sim Q^2$
 - ▶ $\sigma(t=0) \sim A^{4/3} \leftrightarrow A^{5/3}$
 - ▶ $\sigma \sim A^{2/3} \leftrightarrow A$

- Non-Saturation scenarios do not show this behavior making A, Q^2 dependencies a key measurement

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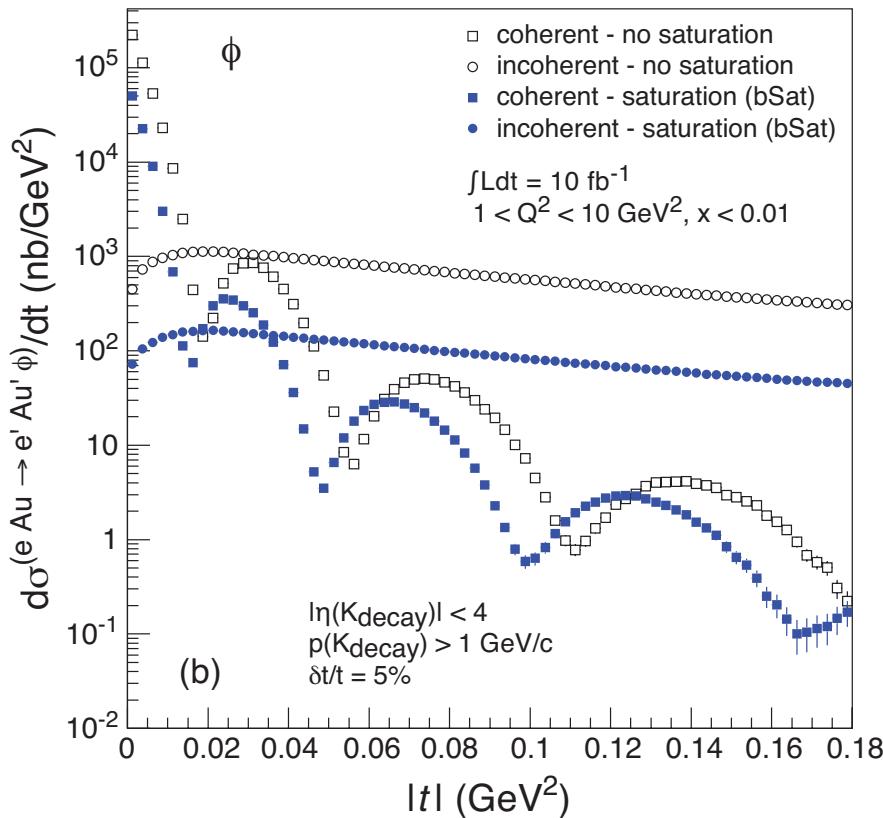
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EIC: Spatial Gluon Distribution from $d\sigma/dt$

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

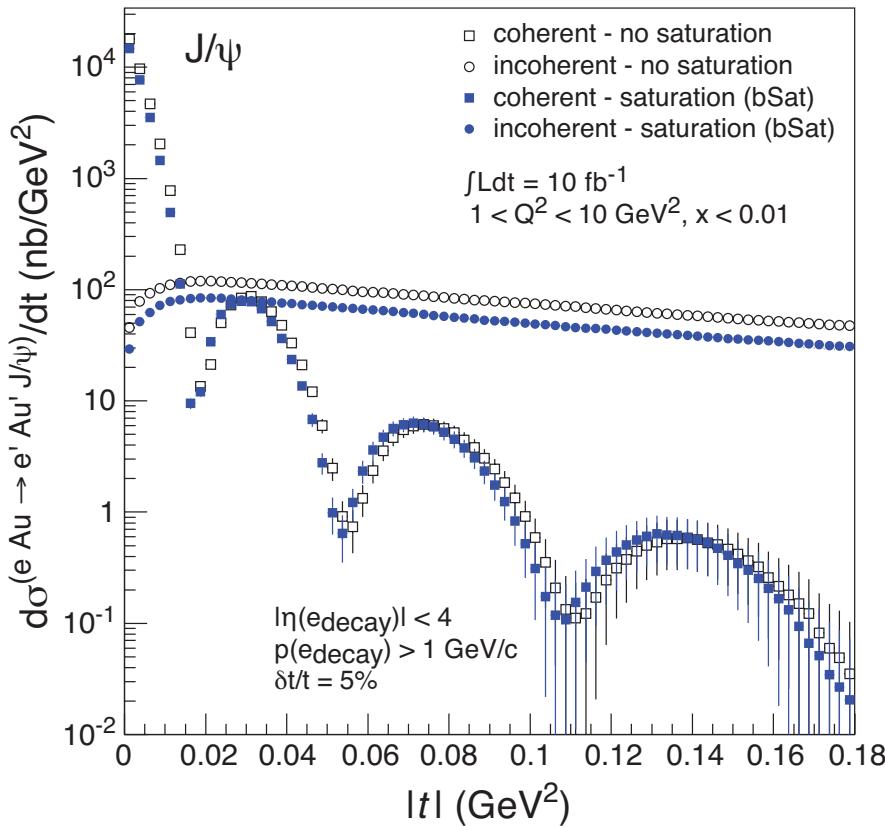
- Momentum transfer $t = |\mathbf{p}_{Au} - \mathbf{p}_{Au'}|^2$ conjugate to b_T



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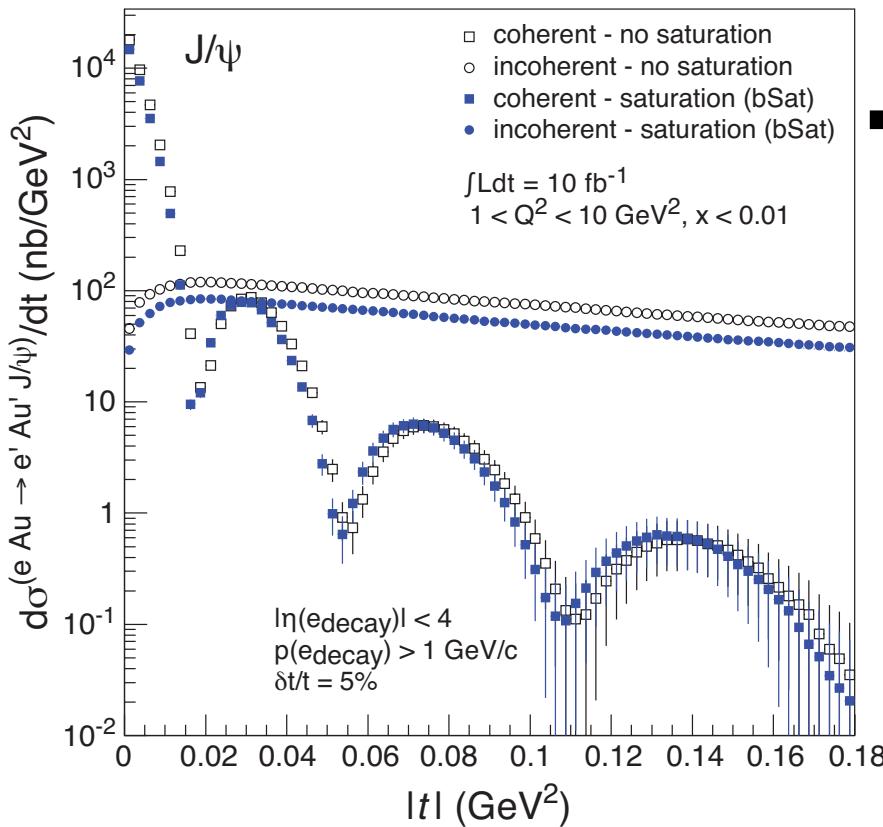
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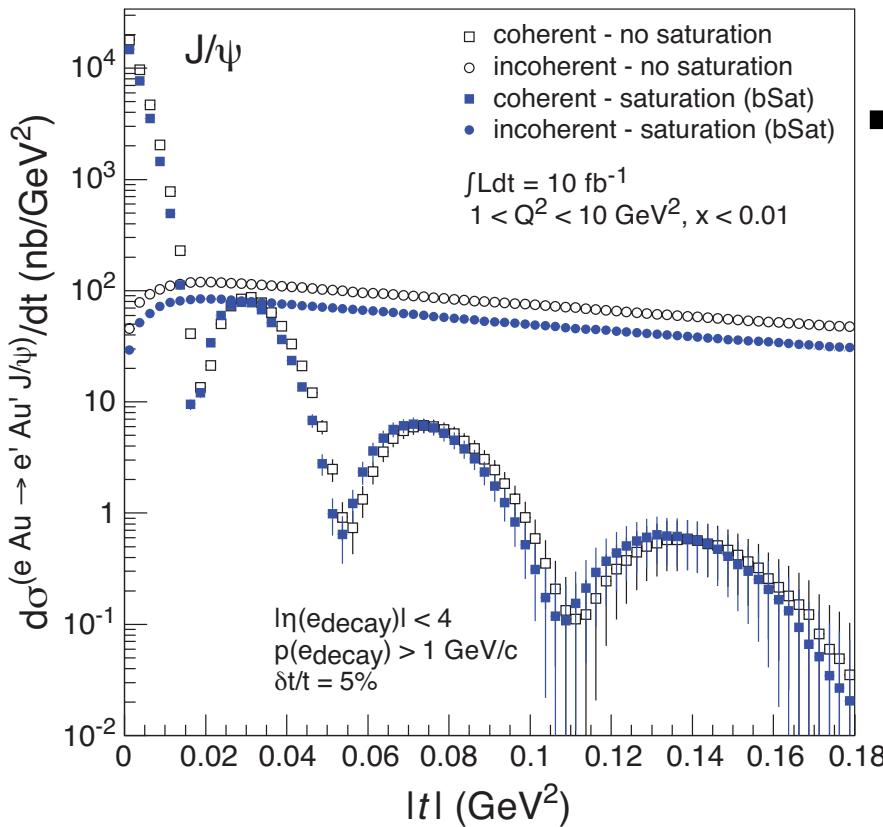
$$F(b) \sim \frac{1}{2\pi} \int_0^\infty d\Delta \Delta J_0(\Delta b) \sqrt{\frac{d\sigma}{dt}}$$

$$t = \Delta^2/(1-x) \approx \Delta^2$$

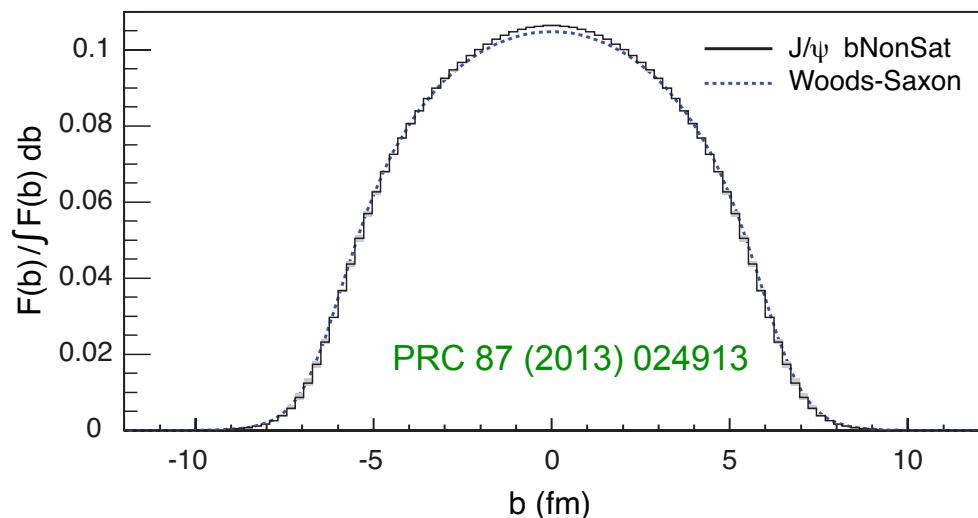
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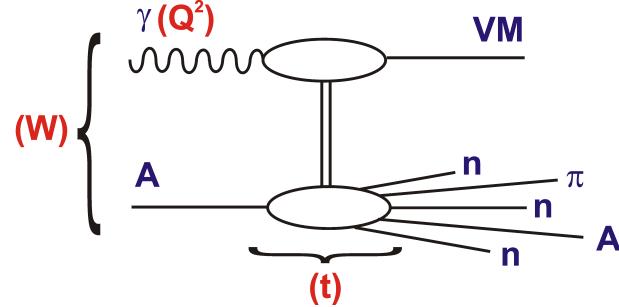
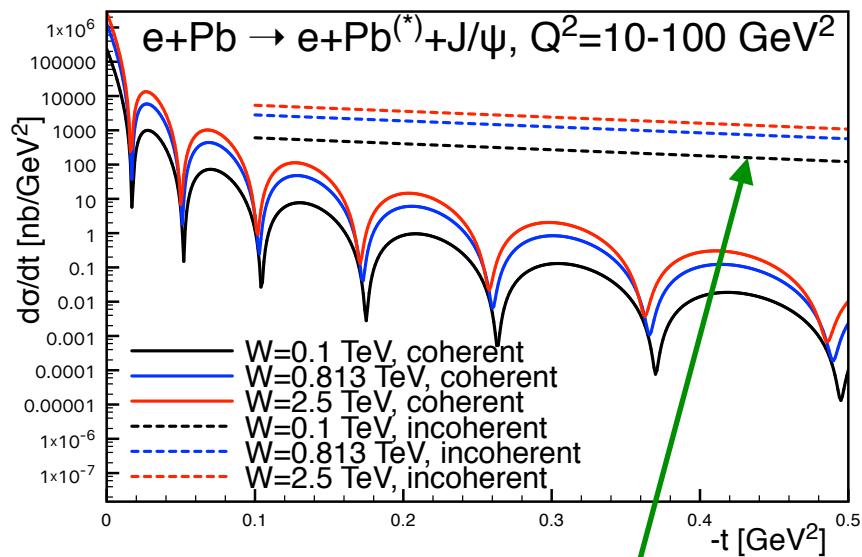
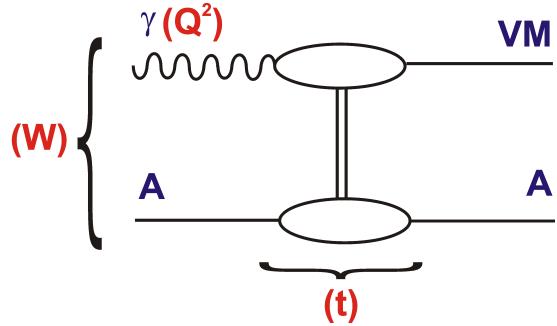
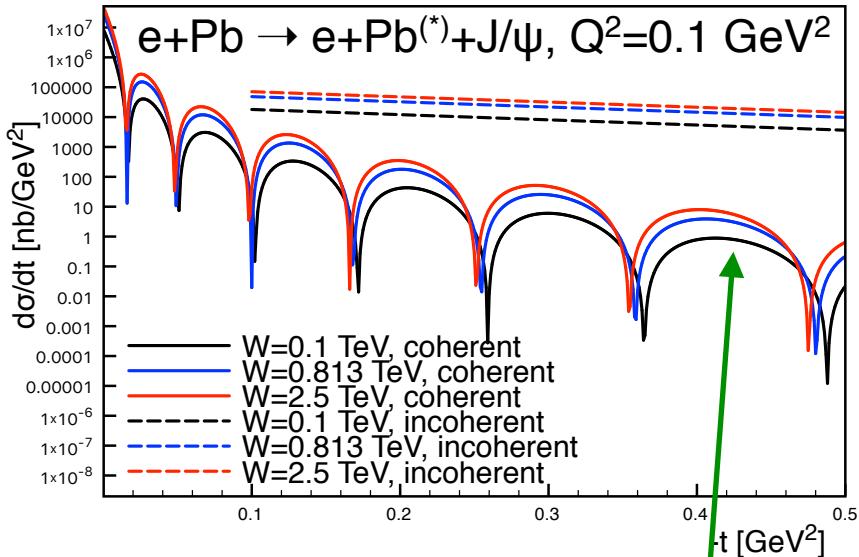
$$\rightarrow F(b) \sim \frac{1}{2\pi} \int_0^\infty d\Delta \Delta J_0(\Delta b) \sqrt{\frac{d\sigma}{dt}}$$



- Converges to input $F(b)$ rapidly: $|t| < 0.1$ almost enough
- Provides constraints on nuclear GPDs

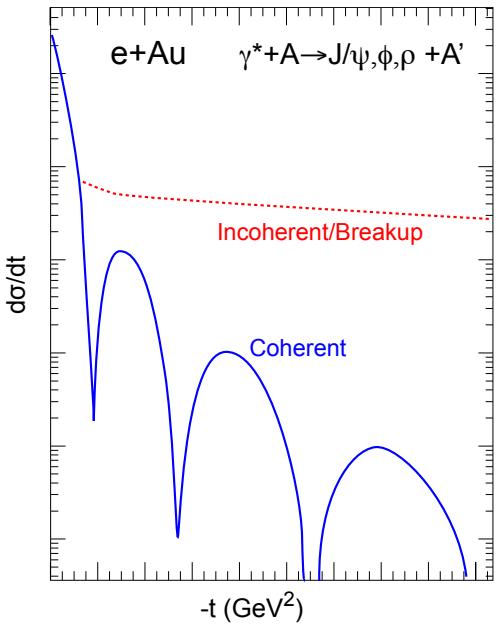
LHeC: Diffractive vector meson production

Mantysaari, 10.11.1988, IPsat



- Detecting incoherent diffraction is experimental challenge in e+A affecting detector and IR design
- Need suppression of > 1000 for $|t| > 0.2 \text{ GeV}^2$

Importance of Incoherent Diffraction

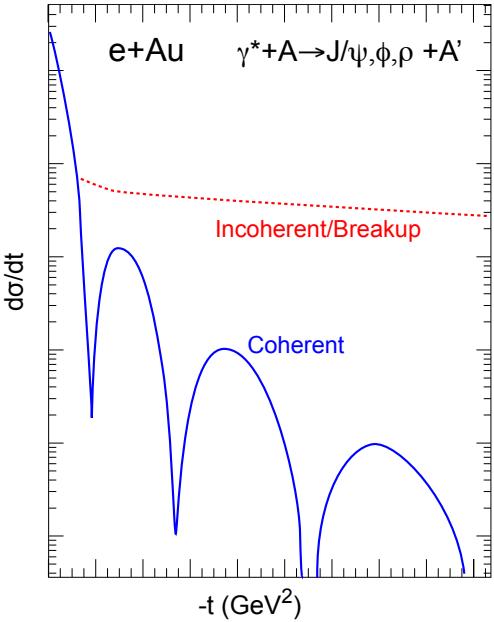


Nucleus dissociates: $f \neq i$

$$\begin{aligned}\sigma_{\text{incoherent}} &\propto \sum_{f \neq i} \langle i | \mathcal{A} | f \rangle \langle f | \mathcal{A} | i \rangle \\ &= \langle |\mathcal{A}|^2 \rangle - \langle |\mathcal{A}| \rangle^2 \\ \frac{d\sigma_{\text{total}}}{dt} &= \frac{1}{16\pi} \langle |\mathcal{A}|^2 \rangle \\ \frac{d\sigma_{\text{coherent}}}{dt} &= \frac{1}{16\pi} \langle |\mathcal{A}| \rangle^2\end{aligned}$$

- Incoherent CS is the **variance** of the amplitude \Rightarrow **measure of fluctuation of the source** $G(x, Q^2, b)$
- Important for understanding of A+A, p+A correlations/shape fluctuations
- **Note:** Incoherent contribution disappears in black disk limit (see talk by H. Mäntysaari)

Importance of Incoherent Diffraction

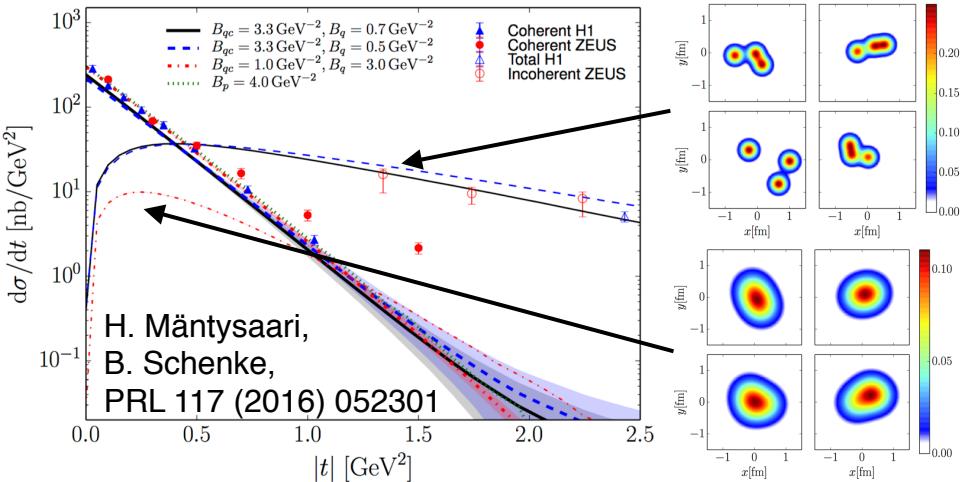


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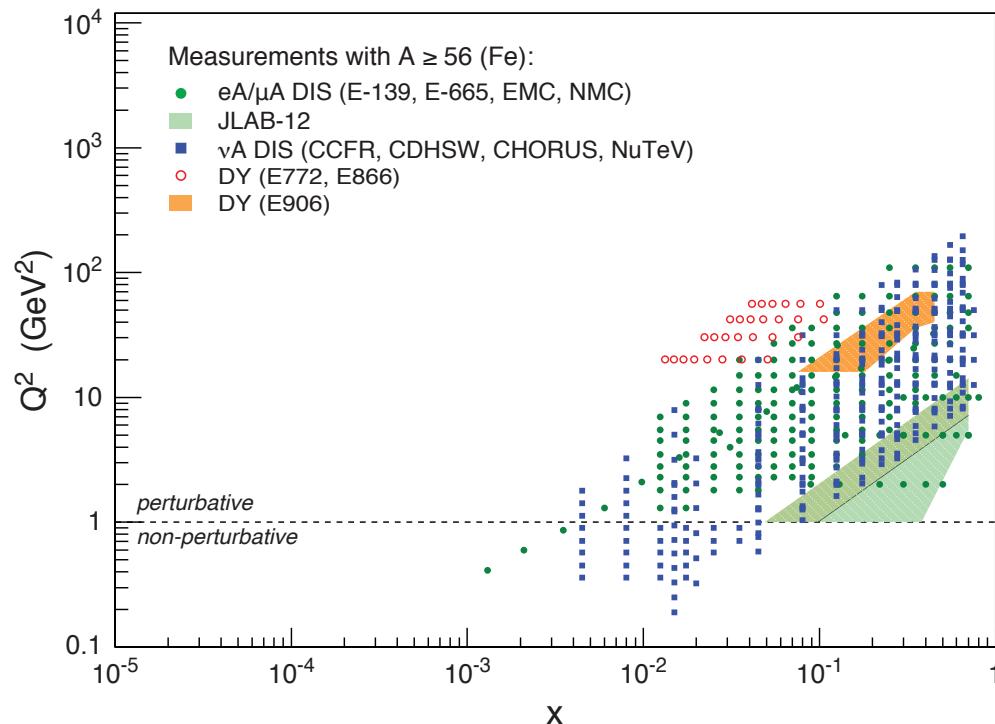
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Example from ep:



Nuclear PDFs

nPDFs less well known due to lack of data



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

- DGLAP:
 - ▶ predicts Q^2 but not A and x dependence
- Saturation models (JIMWLK):
 - ▶ predict A and x dependence but not Q^2
- Need: large Q^2 lever-arm for fixed x , A -scan

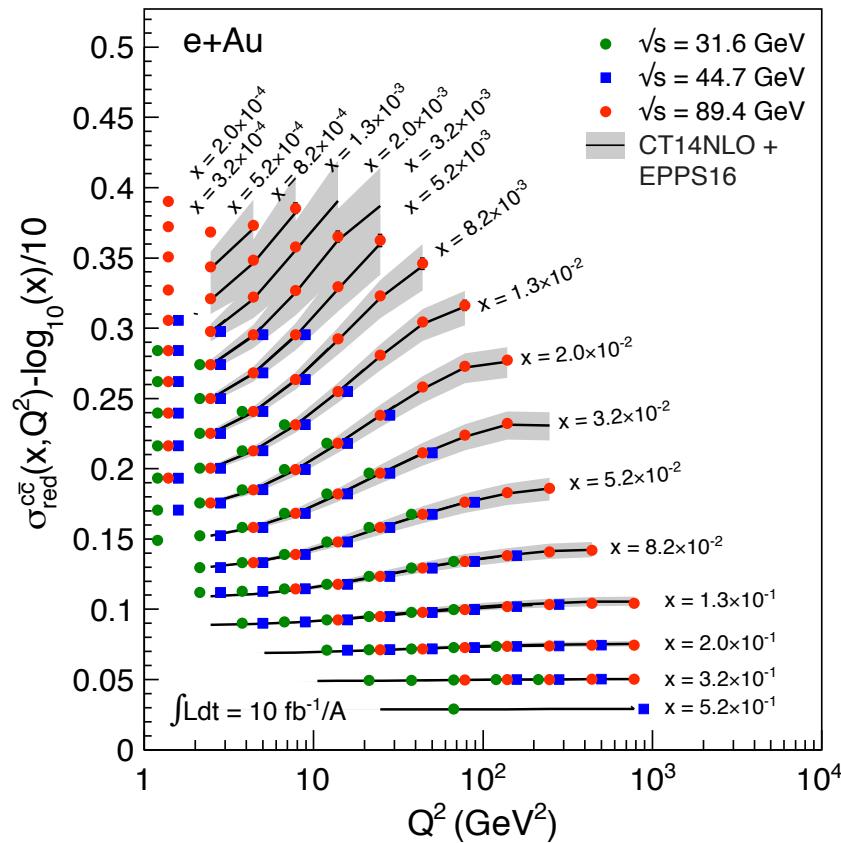
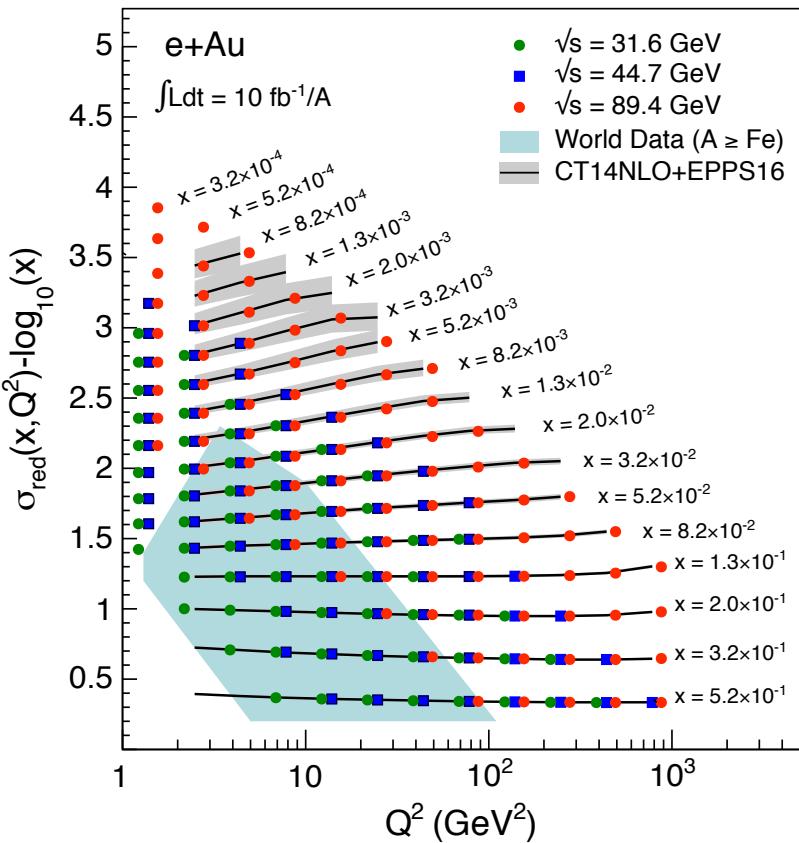
e+A: Aim at extending our knowledge on structure functions into the realm where gluon saturation (higher twist) effects emerge
⇒ different evolution (JIMWLK)

EIC: Structure Functions in eA

EIC pseudo-data

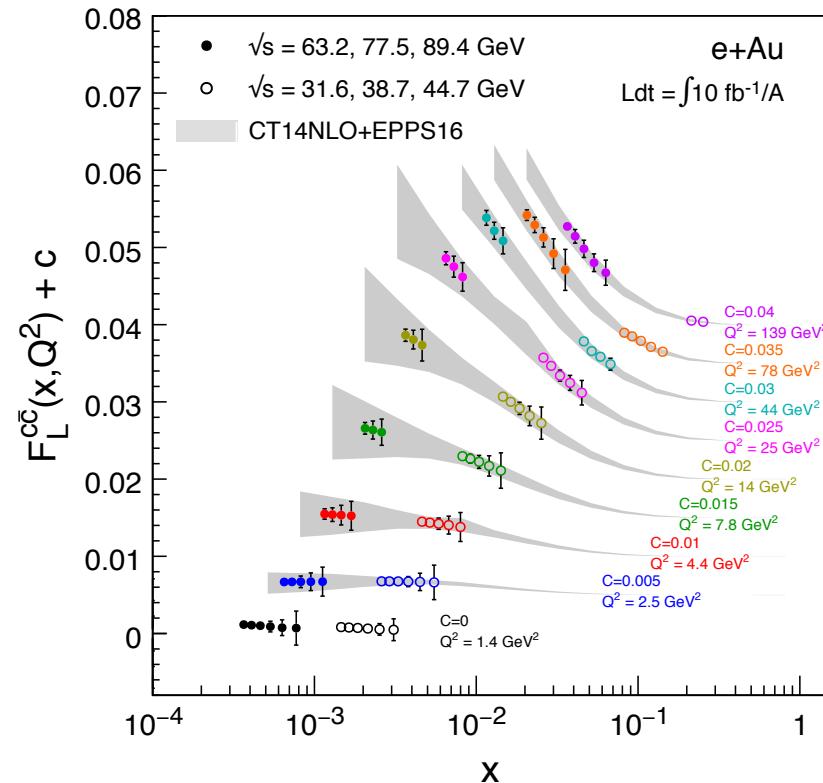
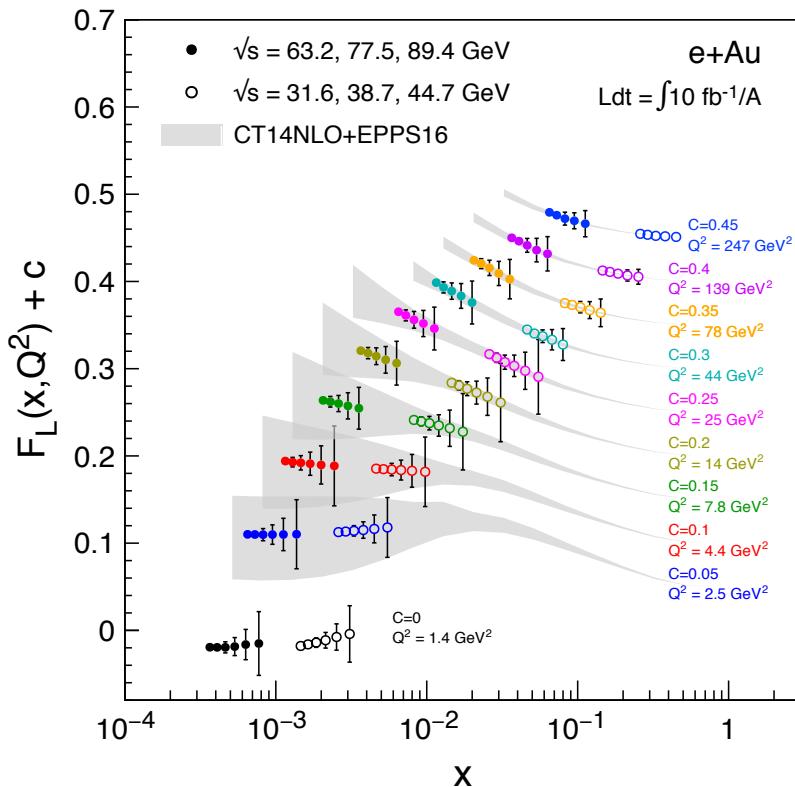
- σ_{red} , F_L , F_2 , F_2^{cc} values from EPPS16 (state-of-the-art nPDF)
- Errors (sys and stat.) from simulations for $\int L dt = 10 \text{ fb}^{-1}/\text{A}$

$$\sigma_{\text{red}}(x, Q^2) = F_2(x, Q^2) - \left(\frac{y^2}{1 + (1 - y)^2} \right) F_L(x, Q^2)$$



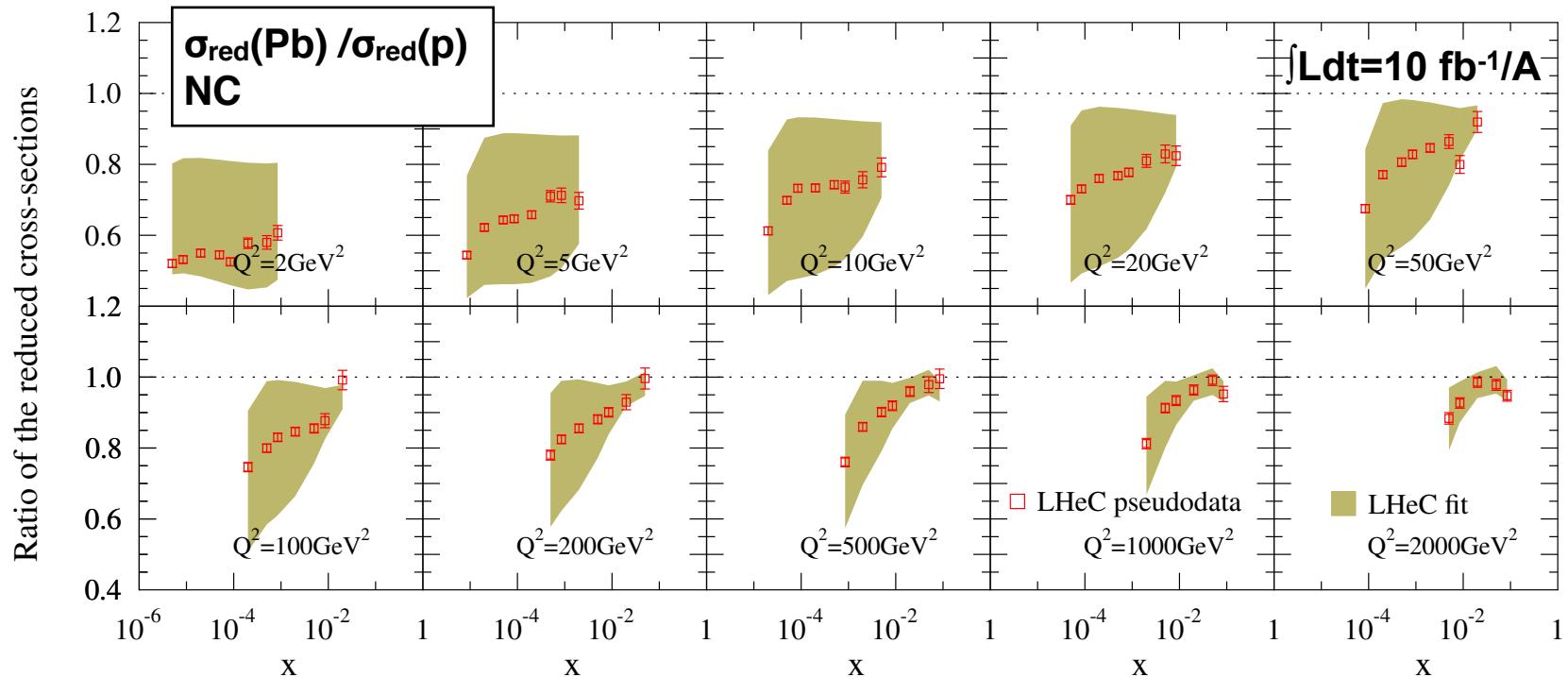
EIC: F_L Structure Function

- F_L probes glue more directly
- F_L is small and requires running at different \sqrt{s} and thus has larger systemic uncertainties than F_2



LHeC: F_2 Structure Functions

Similar studies at LHeC \Rightarrow Pseudo-data

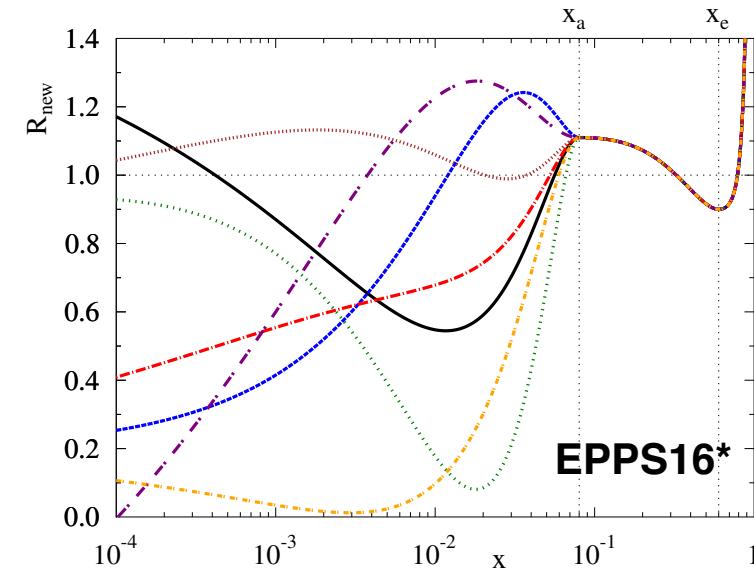
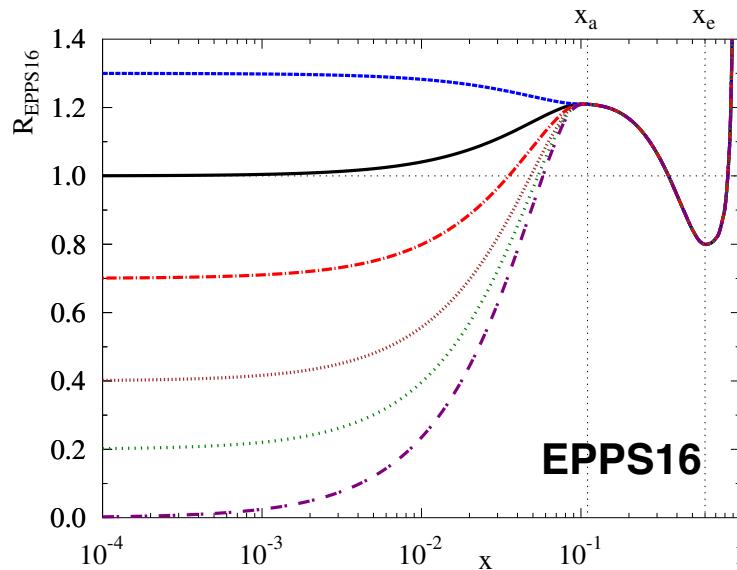


- Advantage at LHeC
 - ▶ NC+extended reach for CC
 - ▶ substantial lower-x reach
- Errors in F_L larger due to (voluntarily) restriction in \sqrt{s} range
- Neither at EIC nor LHeC luminosity is essential: σ_{sys} is key

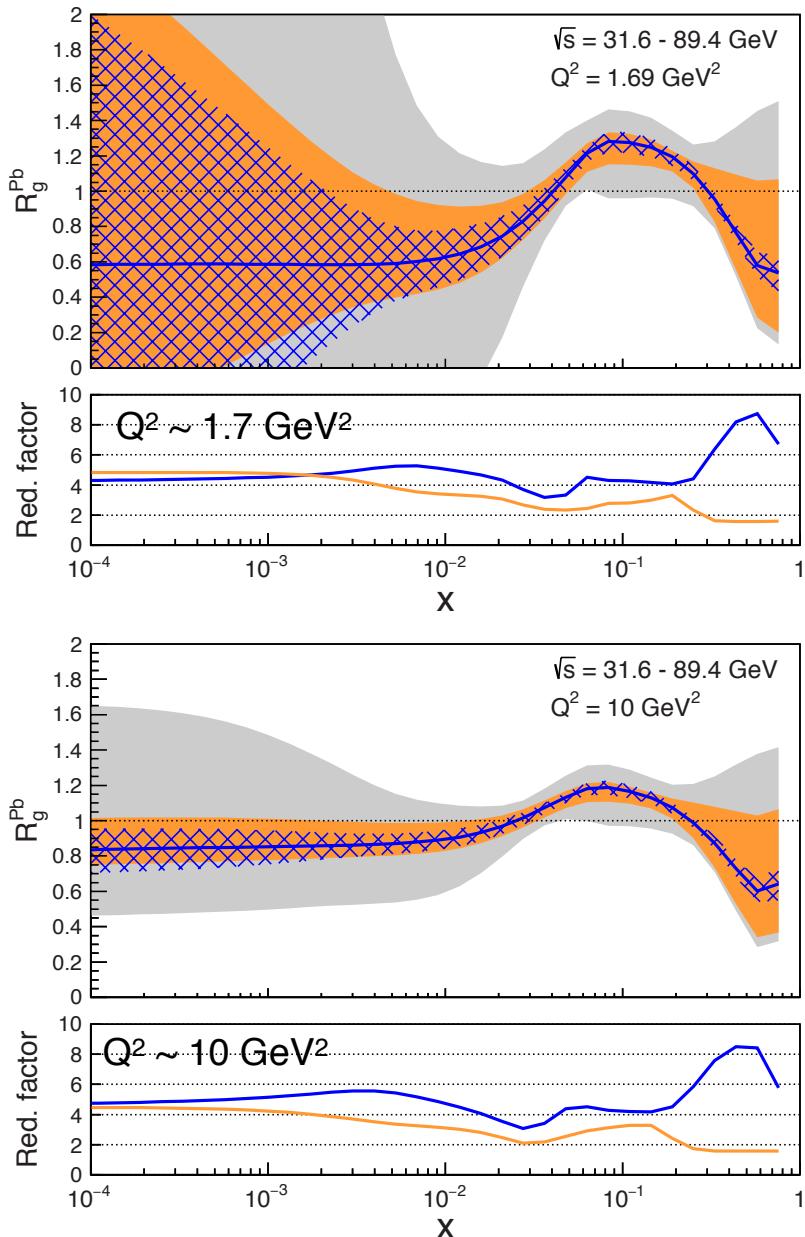
The Problem of Estimating nPDF Constraints

Methods:

- Use σ_{red} (includes F_2 and $F_L(F_3)$) pseudo data
- Re-weighting EPPS16
 - ▶ EPPS16 is a bit stiff at low- x , over-constraints at low- x
- EPPS16* (arXiv:1708.05654, Hannu Paukkunen)
 - ▶ more flexible form cures EPPS16 problem (low- x bias)
 - ▶ might underestimate impact?



EIC's Impact on nPDFs (R_{glue})

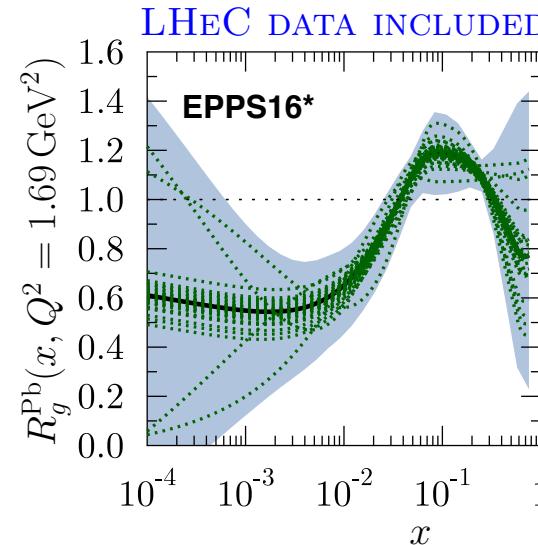
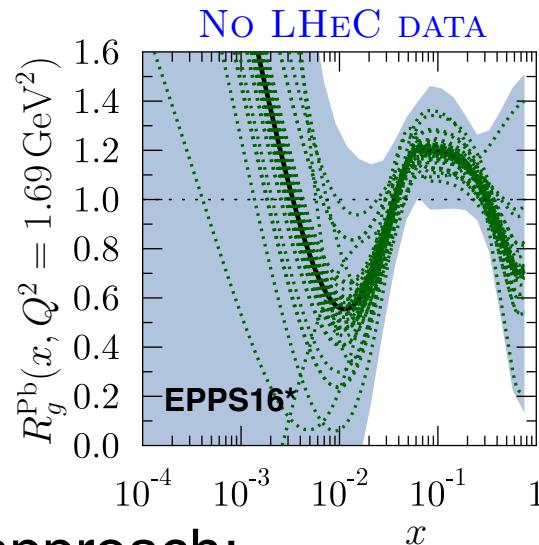


EPPS16* + EIC (inclusive + charm)
 EPPS16* + EIC (inclusive only)
 EPPS16*

- Improves uncertainties substantially out to 10^{-4}
- Shrinks uncertainty band by factors 4-8
- Charm: no additional constraint at low- x but dramatic impact at large- x

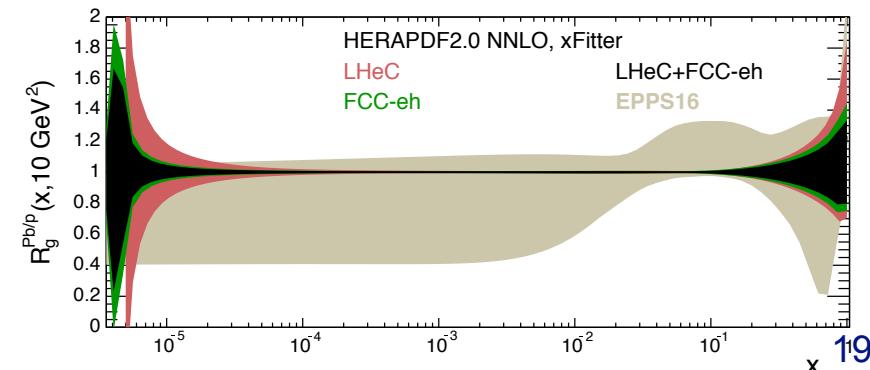
LHeC's Impact on nPDFs (R_{glue})

- Work in progress
 - ▶ Large correlations among the fit parameters
 - ▶ Need MC methods to more reliably map the uncertainties
- A typical result using a more flexible form for the gluons:



Alternative approach:

Use same pseudodata as above but within xFitter and HERAPDF2.0 parametrisation to estimate the ‘ultimate’ precision (Armesto & Agostini):

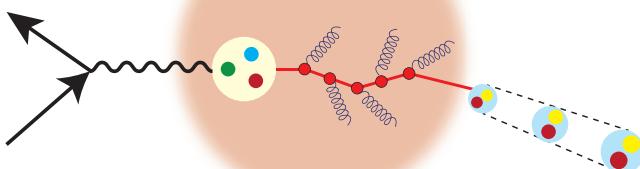


Exploring QCD at Large Q^2, v

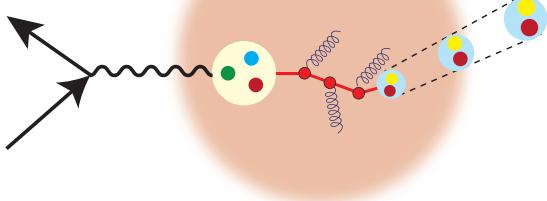
Color propagation and neutralization

- Fundamental QCD Processes:
 - ▶ Partonic elastic scattering
 - ▶ Gluon bremsstrahlung in vacuum and in medium (E-loss)
 - ▶ Color neutralization
 - ▶ Hadron formation
- } dynamic confinement

High Energy: hadronization outside
→ partonic evolution altered in medium

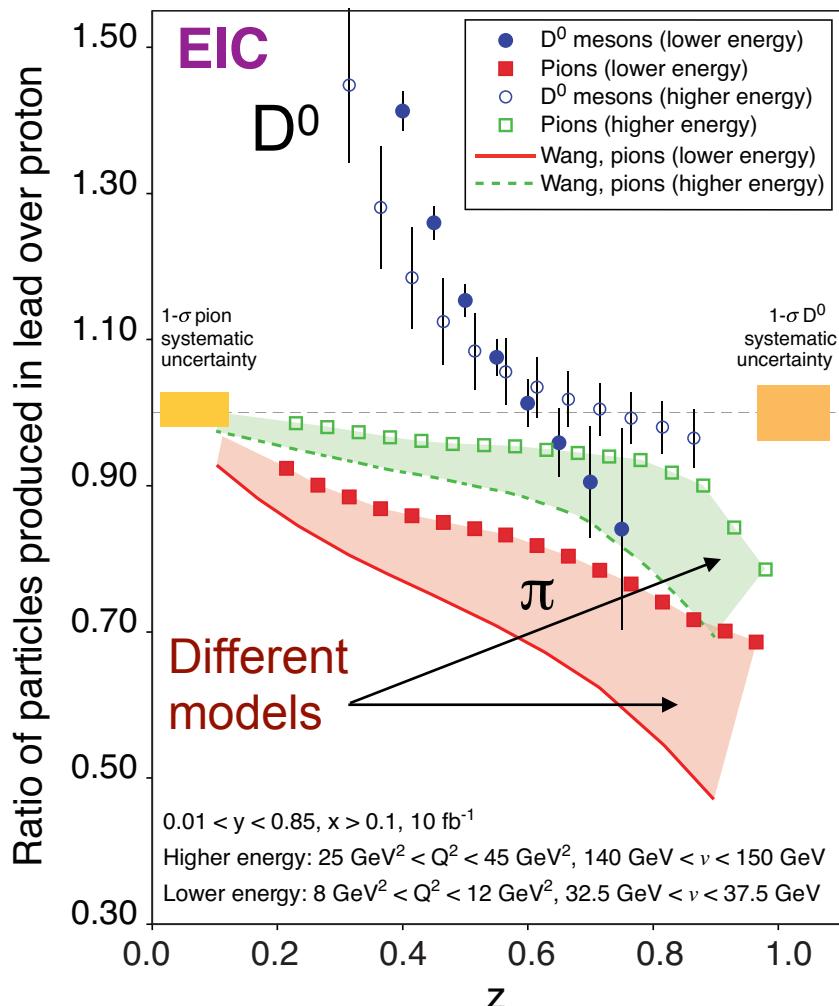


Low Energy: hadronization inside
→ formation time, (pre-) hadronic absorption



- Nuclei as space-time analyzer
 - ▶ high Q^2 and v (\rightarrow large x):
 - Energy of struck quark (the probe) is known
 - No color spectators (as in p+A)
 - Hadronization in and out of medium can be varied (v)

Multiplicity Ratios: Semi-Inclusive Studies

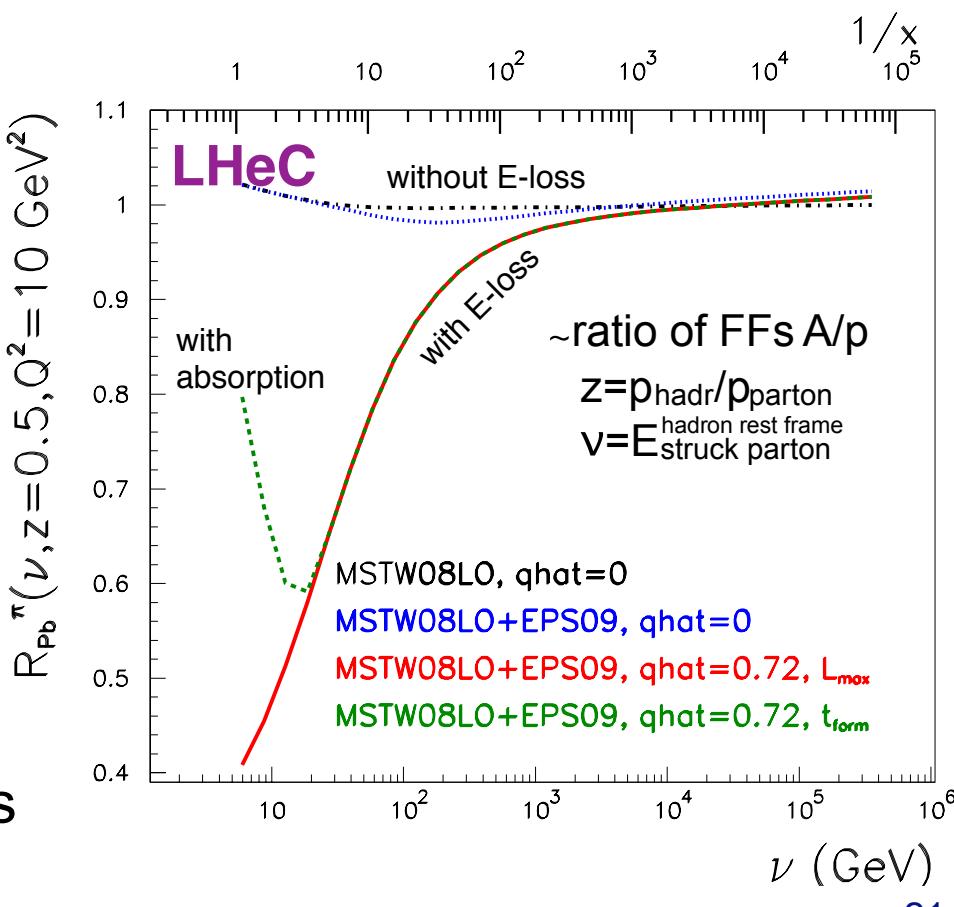


HERMES: $\nu = 2\text{-}25 \text{ GeV}$

EIC: $10 < \nu < 1600 \text{ GeV}$

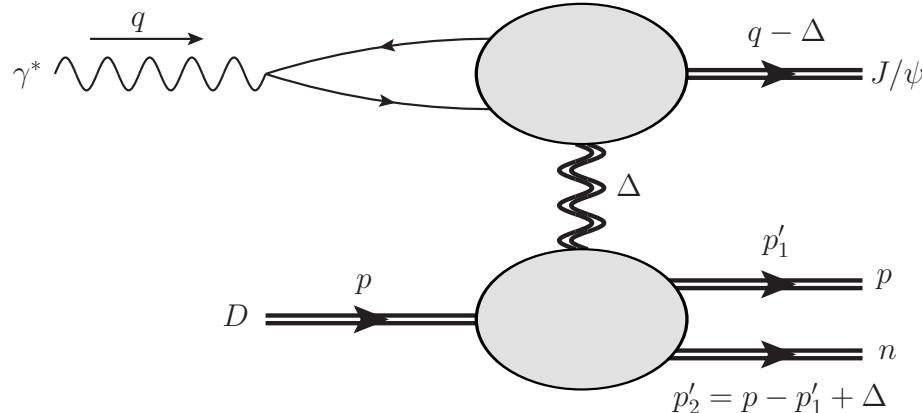
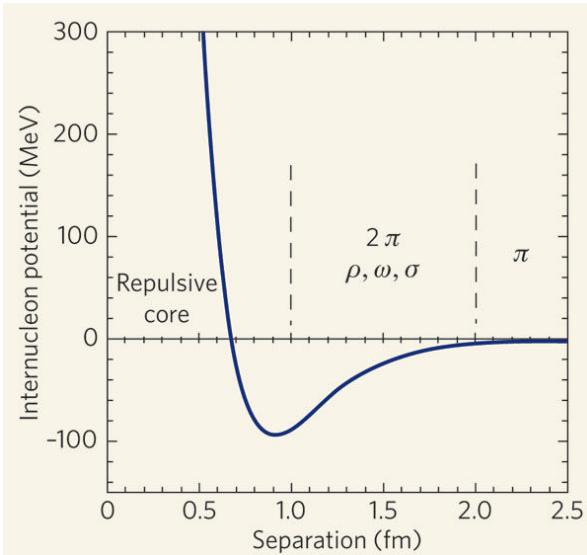
LHeC: $\nu < 5 \cdot 10^5 \text{ GeV}$

LHeC+EIC: *heavy flavor!*



- Slope of D's sensitive to \hat{q} and FF
- Strong Sensitivity of Shape on ν is powerful tool

Exploring Short Range Nuclear Forces



Miller, Sievert, Venugopalan, Phys.Rev. C93 (2016)

- Can the short range contributions to NN scattering be described directly in terms of the quark and gluon DoF in QCD?
- Vector meson production in e+D collisions
 - ▶ Cross-section can be expressed in terms of a gluon Transition Generalized Parton Distribution (T-GPD)
 - ▶ The hard scale in the final state makes the T-GPD sensitive to the short distance nucleon-nucleon interaction.
- New opportunities - needs more studies (in progress)

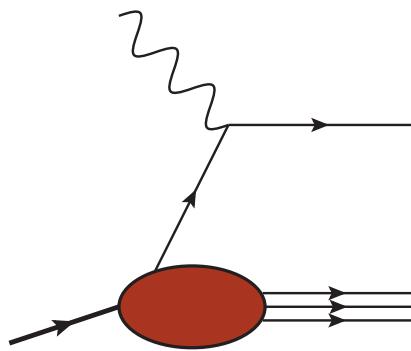
e+A - Take Away Message

- e+A collisions will allow the 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
- Physics connects many fields: Heavy-ions, Hadron Physics, Nuclear Structure, HEP, ...
- Important: Theory is making excellent progress: higher orders, robust calculations, new ideas are being explored
- An e+A program at a collider is also an experimental challenge
 - ▶ new difficulties compared to e+p
 - ▶ never conducted in a collider
 - ▶ IR & detector designs, roman pots, forward spectrometer, machine integration and many more

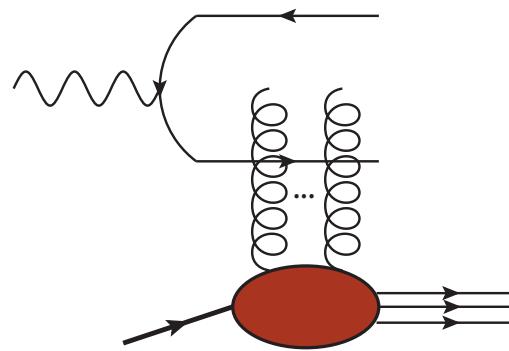
Backup Slides



N.B.: Important Dual Description of DIS



Bjorken frame



Dipole frame

Bjorken frame

$$F_2(x, Q^2) = \sum_q e_q^2 x \left[f_q(x, Q^2) + f_{\bar{q}}(x, Q^2) \right].$$

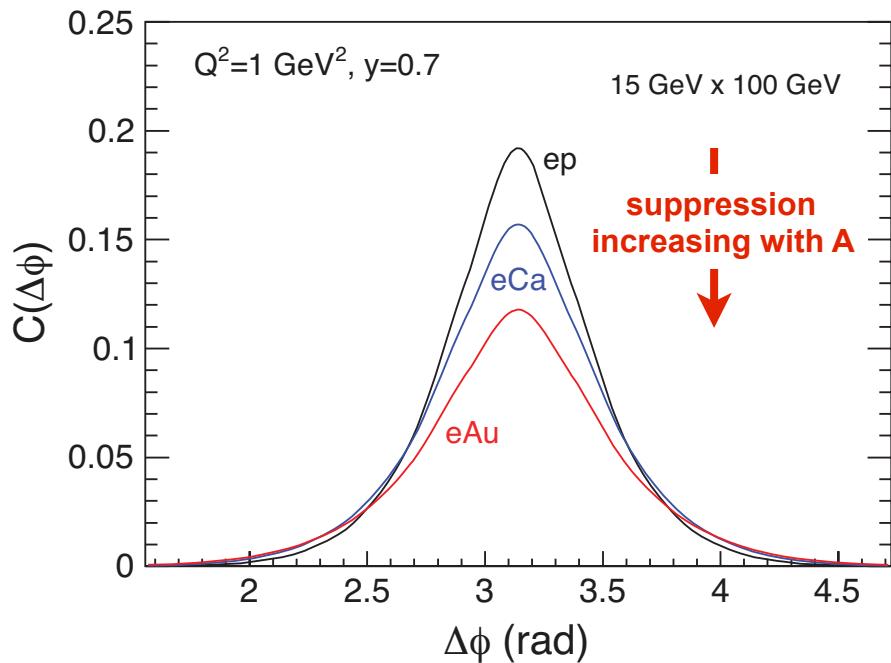
Dipole frame [A. Mueller, 01; Parton Saturation-An Overview]

$$F_2(x, Q^2) = \sum_f e_f^2 \frac{Q^2}{4\pi^2 \alpha_{\text{em}}} S_\perp \int_0^1 dz \int d^2 r_\perp |\psi(z, r_\perp, Q)|^2 \left[1 - S^{(2)}(Q_s r_\perp) \right]$$

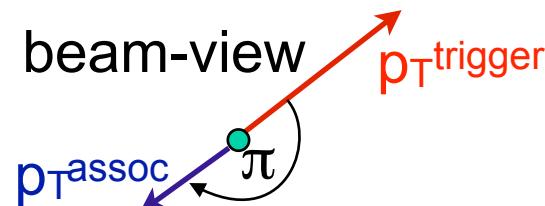
- **Bjorken:** Partonic picture of a hadron is manifest. Saturation shows up as a limit on the occupation number of quarks and gluons.
- **Dipole:** Partonic picture is no longer manifest. Saturation appears as the unitarity limit (black disk) for scattering. Convenient to resum the multiple gluon interactions.

Dihadron Correlations (I)

Forward dihadron correlation in Dilute-Dense factorizations as a probe to saturation.

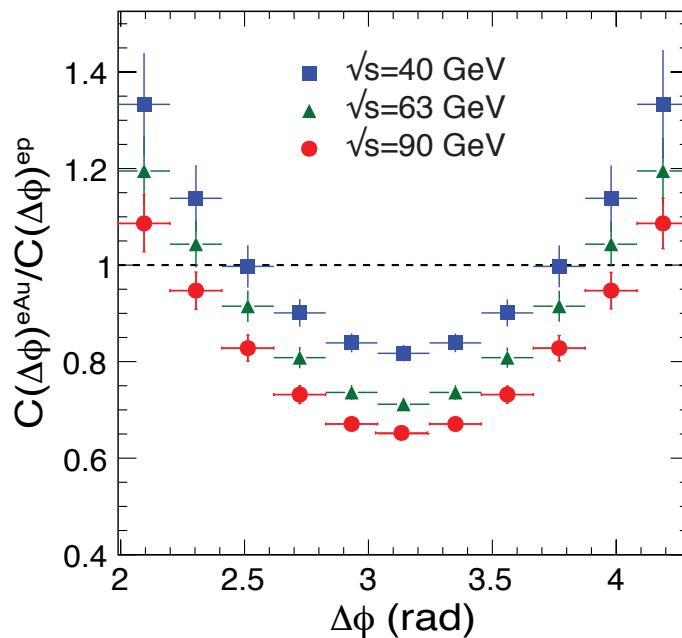
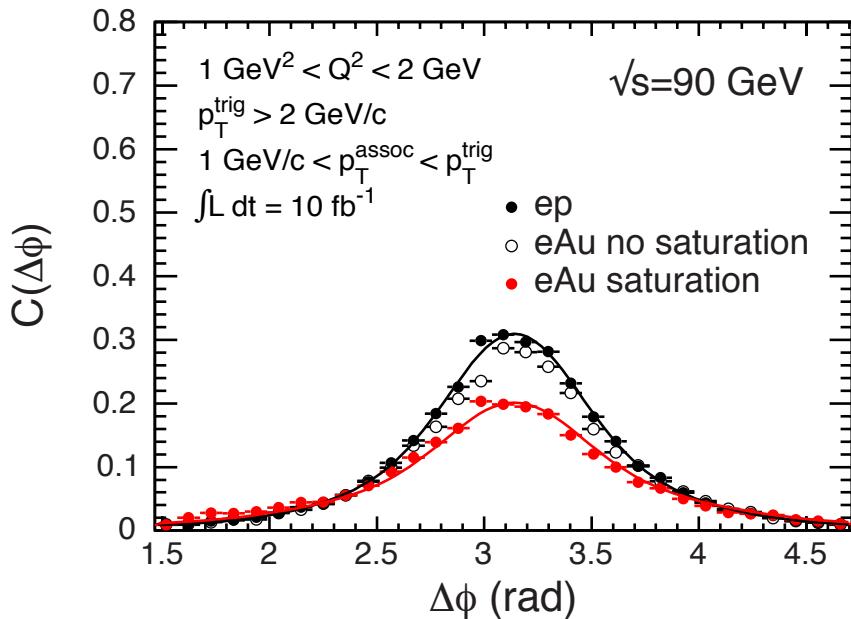


Experimental Simple Measurement

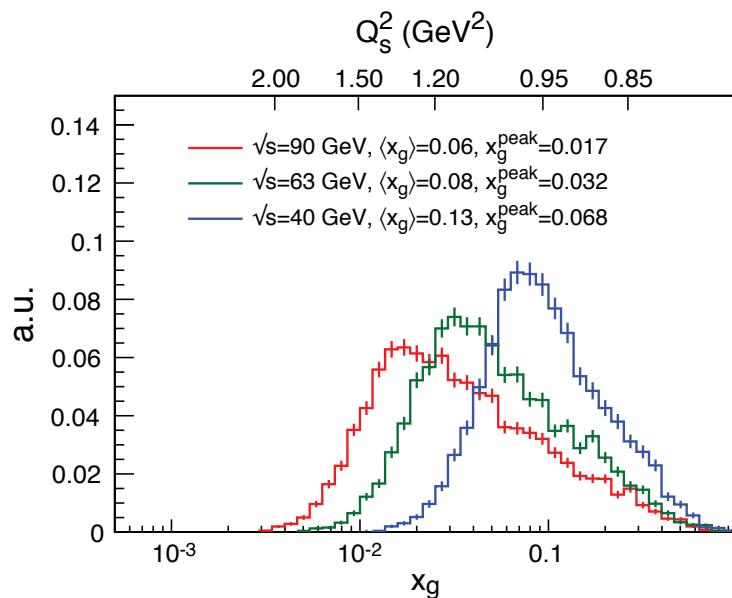


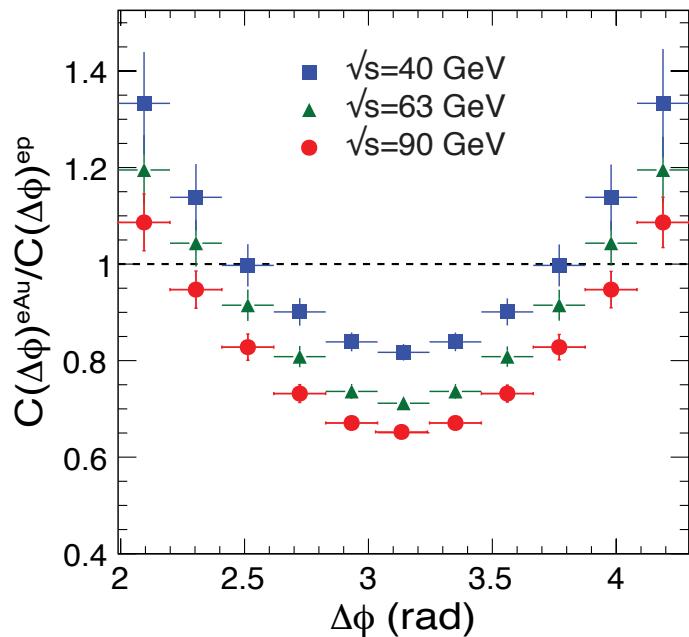
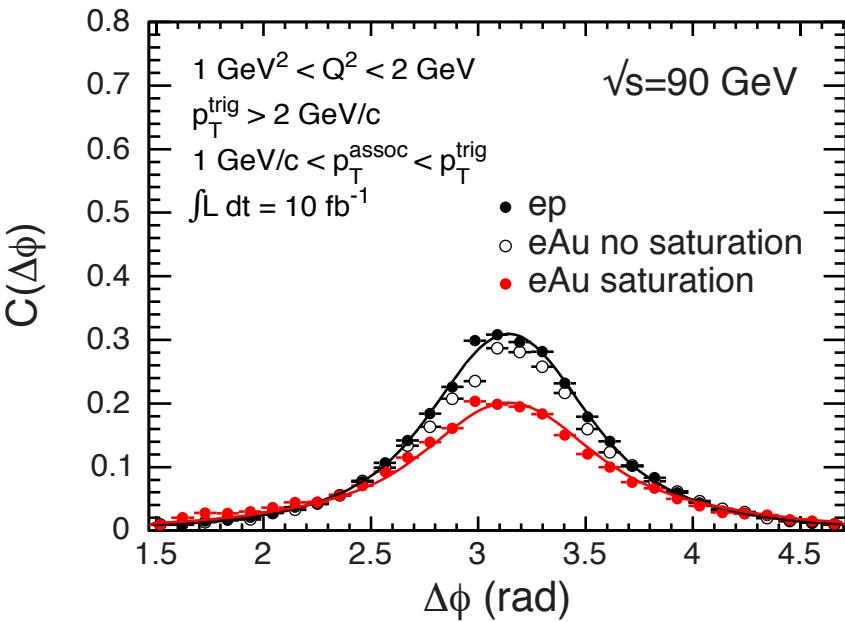
Already tantalizing hints from p+A studies at RHIC

- Predicted [C. Marquet, 09] as important hint of saturation
- Interpretation: decorrelation due to interaction with low- x gluonic matter
- Robust calculations available (Albacete, Dominguez, Lappi, Marquet, Stasto, Xiao) including Sudakov resummation in dijet processes



- Back-to-back Correlations
 - ▶ Substantial suppression, \sqrt{s} helps
 - ▶ Also LHeC simulation (CDR/ J.Phys. G39 (2012) 075001)
- Similar Dijet Correlations
 - ▶ Unique measurement of WW Gluon Distributions (nTMDs)
 - ▶ see arXiv:1508.04438, 1708.01527





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