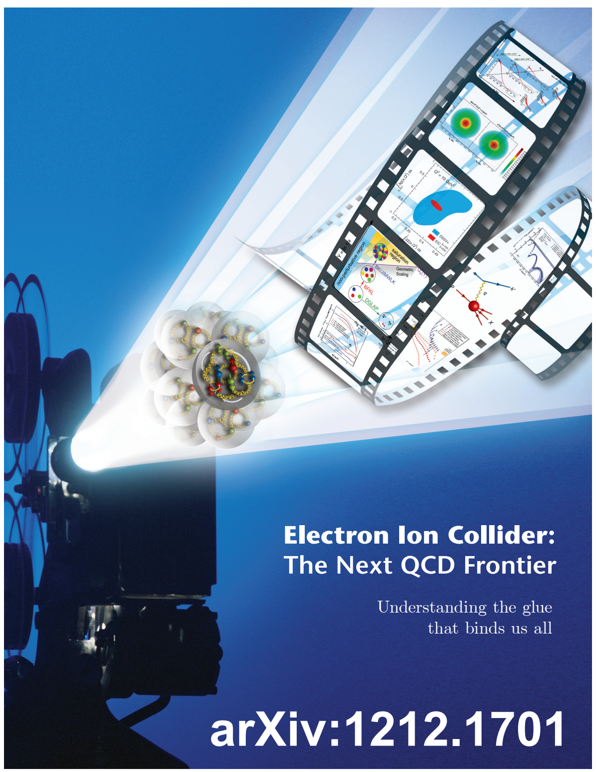
Probing the Properties of QCD with Atomic Nuclei

Experimental Aspects



Thomas Ullrich (BNL)

LRP Joint Town Hall Meeting on QCD
Temple University

September 14, 2014

Office of Science
U.S. Department of Energy

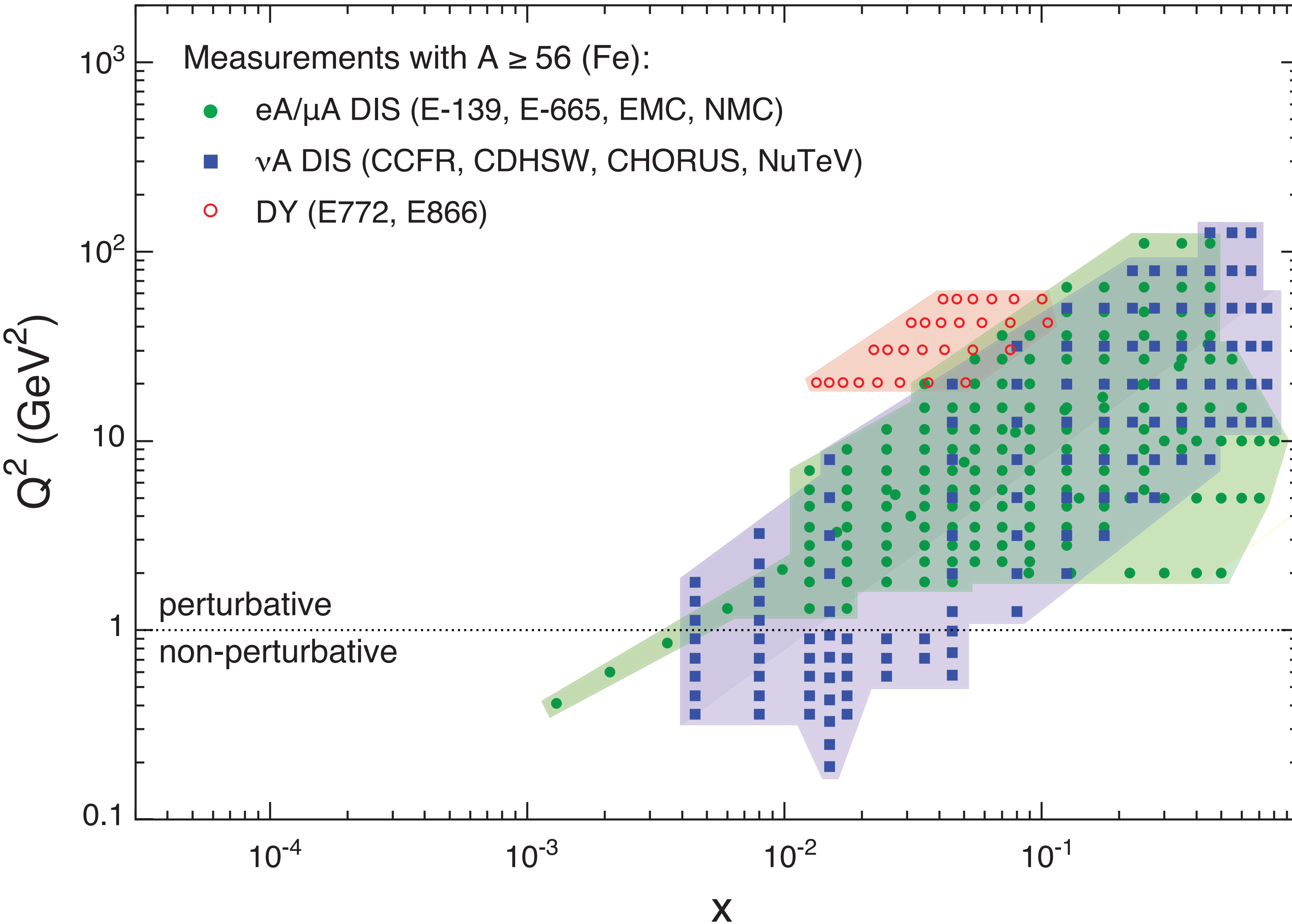
BROOKHAVEN
NATIONAL LABORATORY

Driving Fundamental Questions in e+A

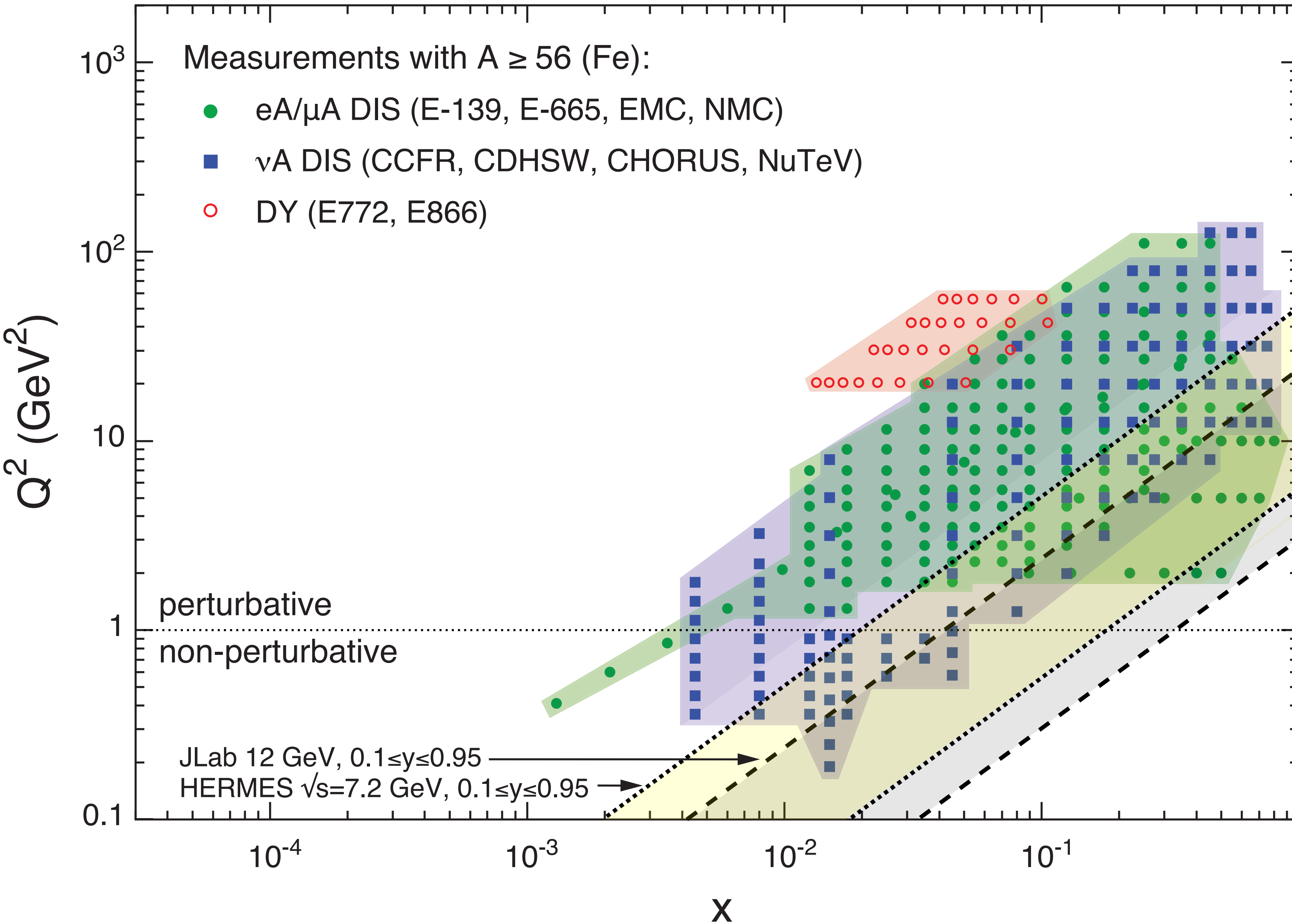
Nucleus serves as:

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

Landscape of e+A Physics



Landscape of e+A Physics



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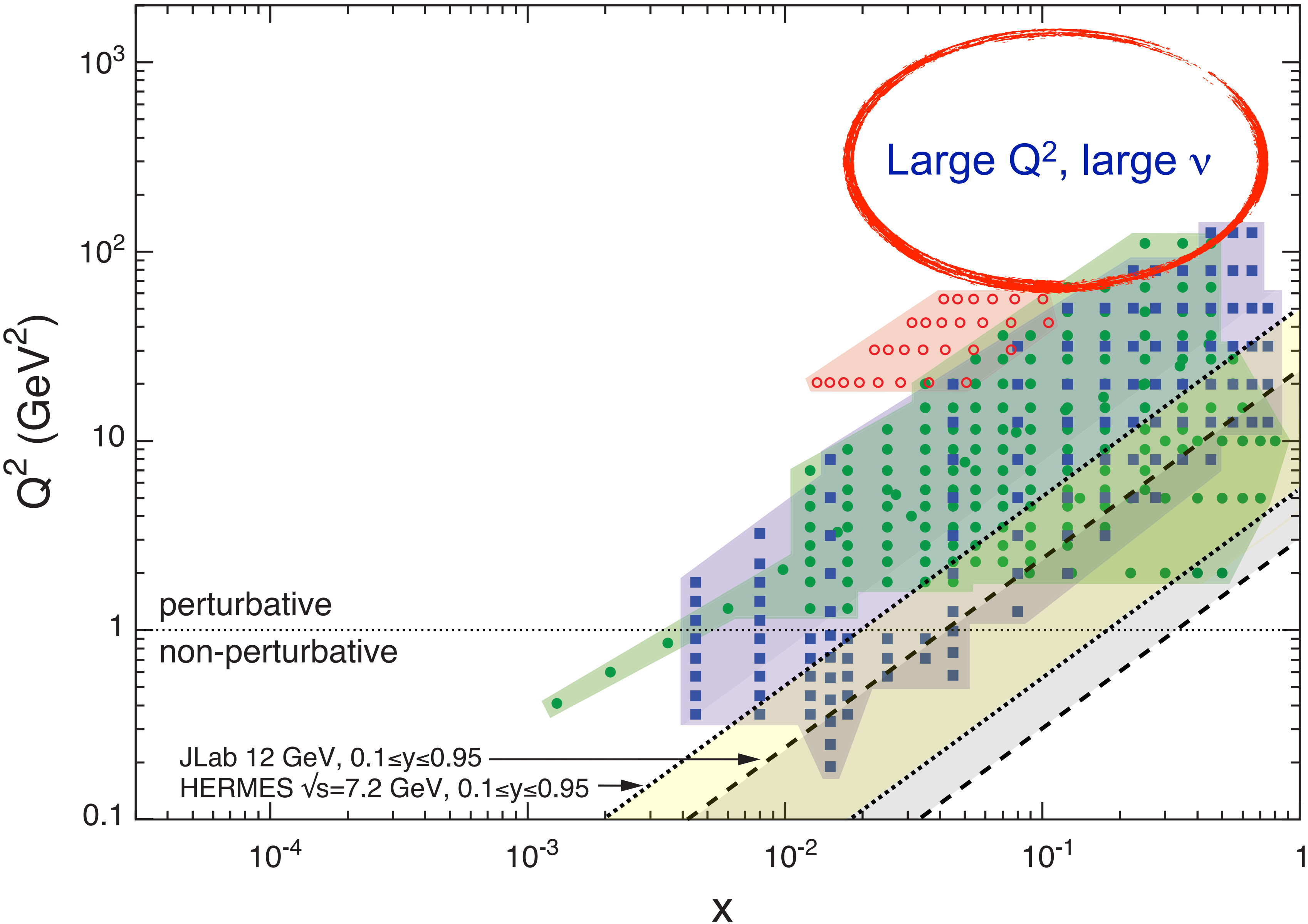

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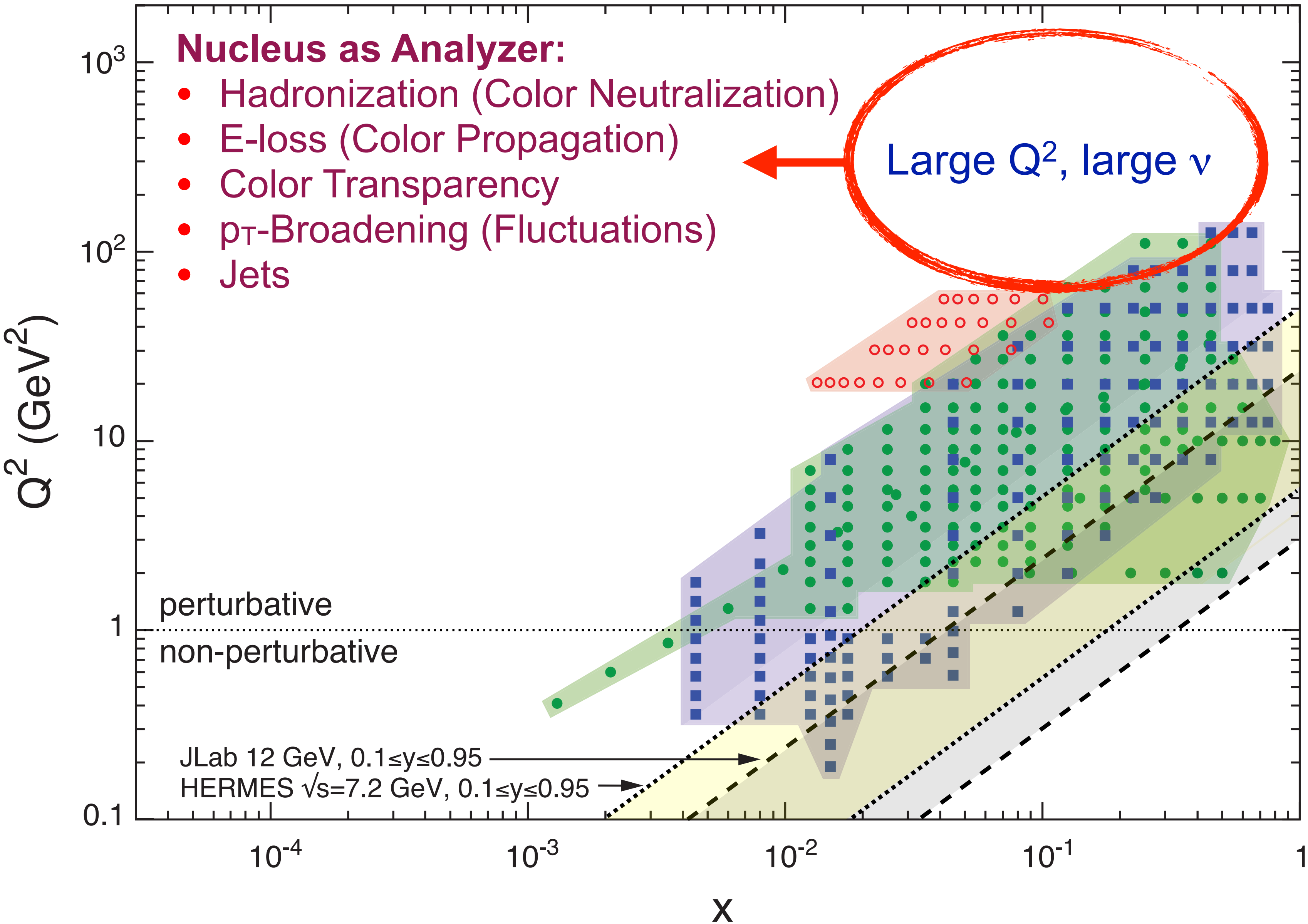

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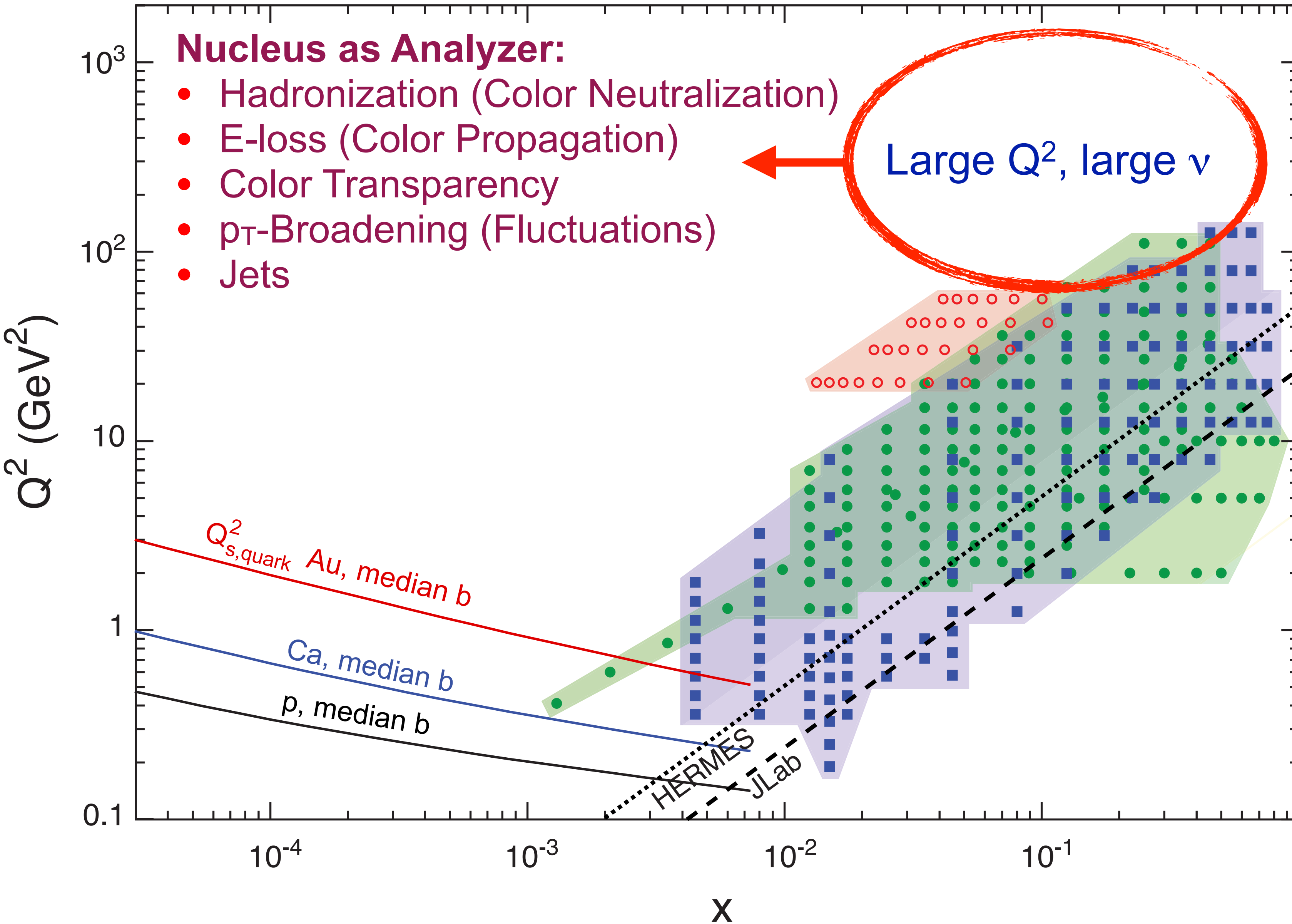

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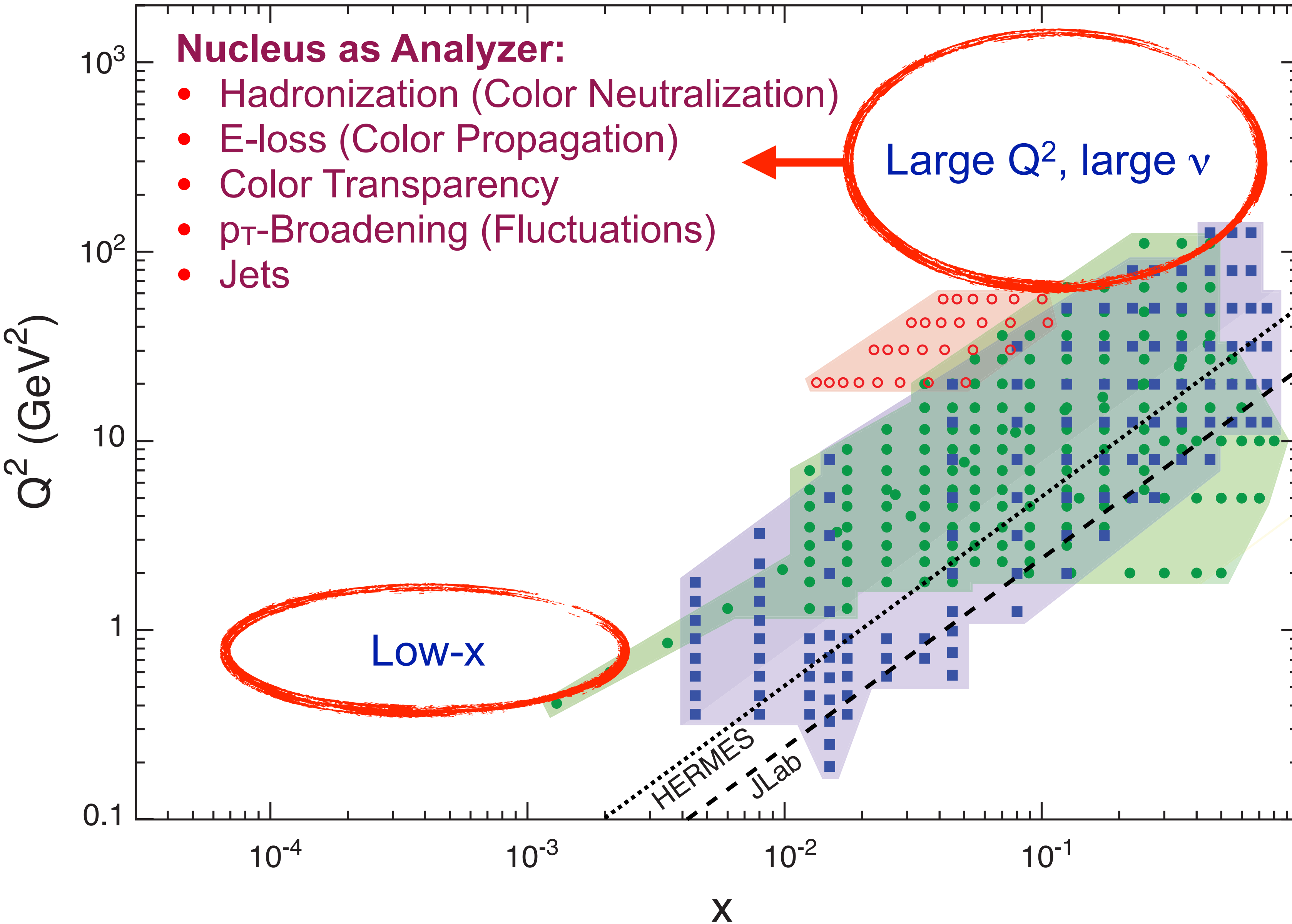

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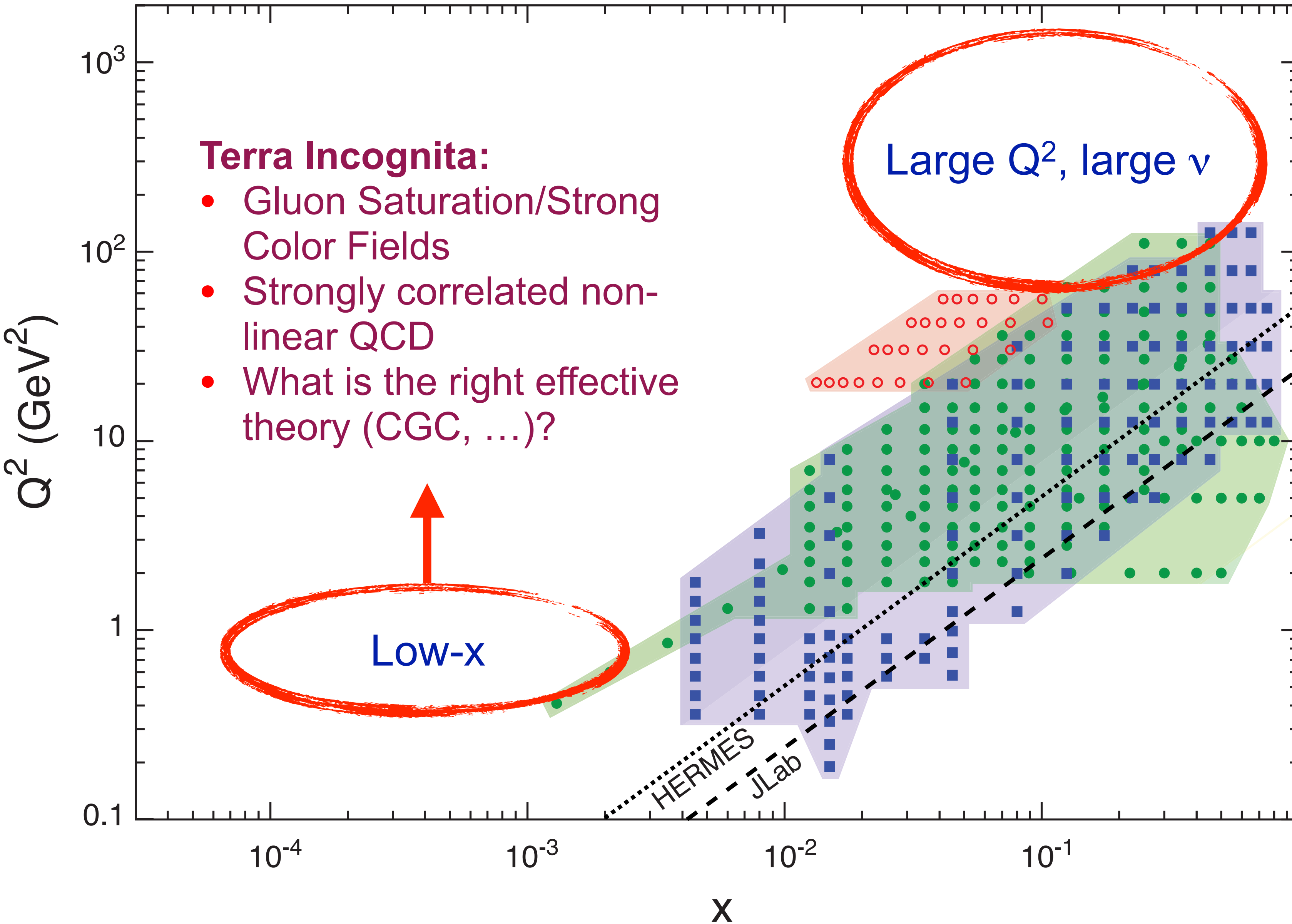

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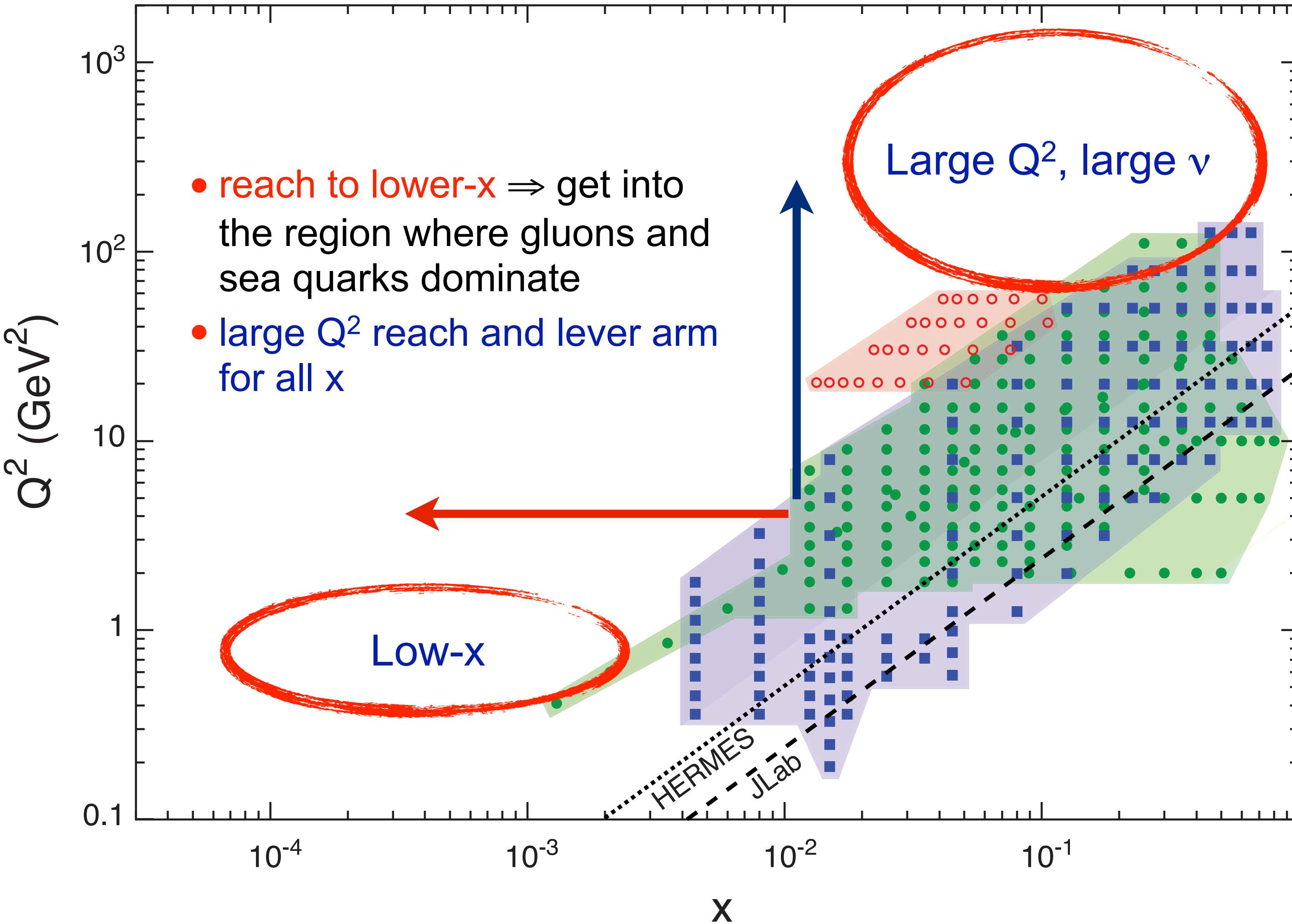

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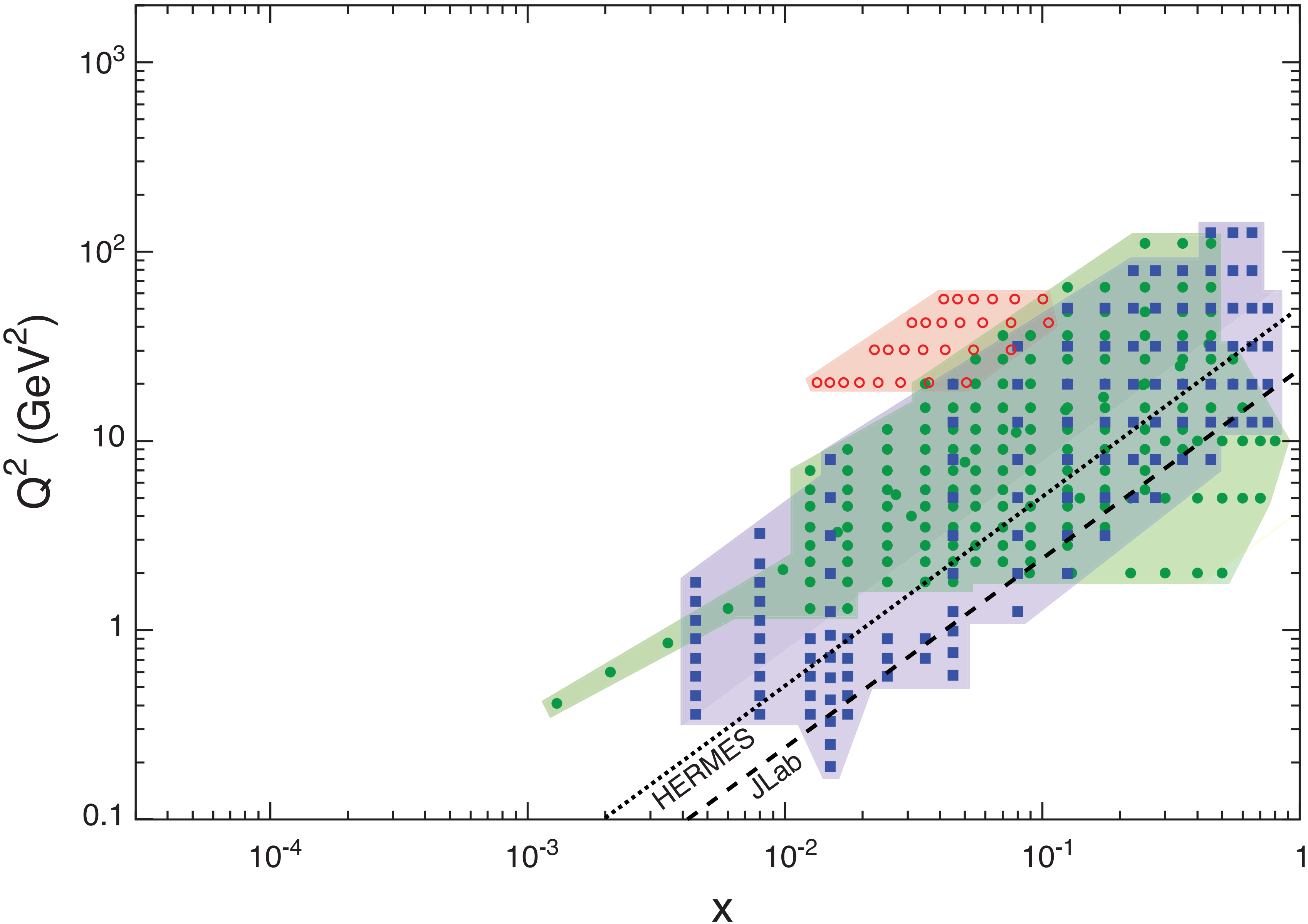

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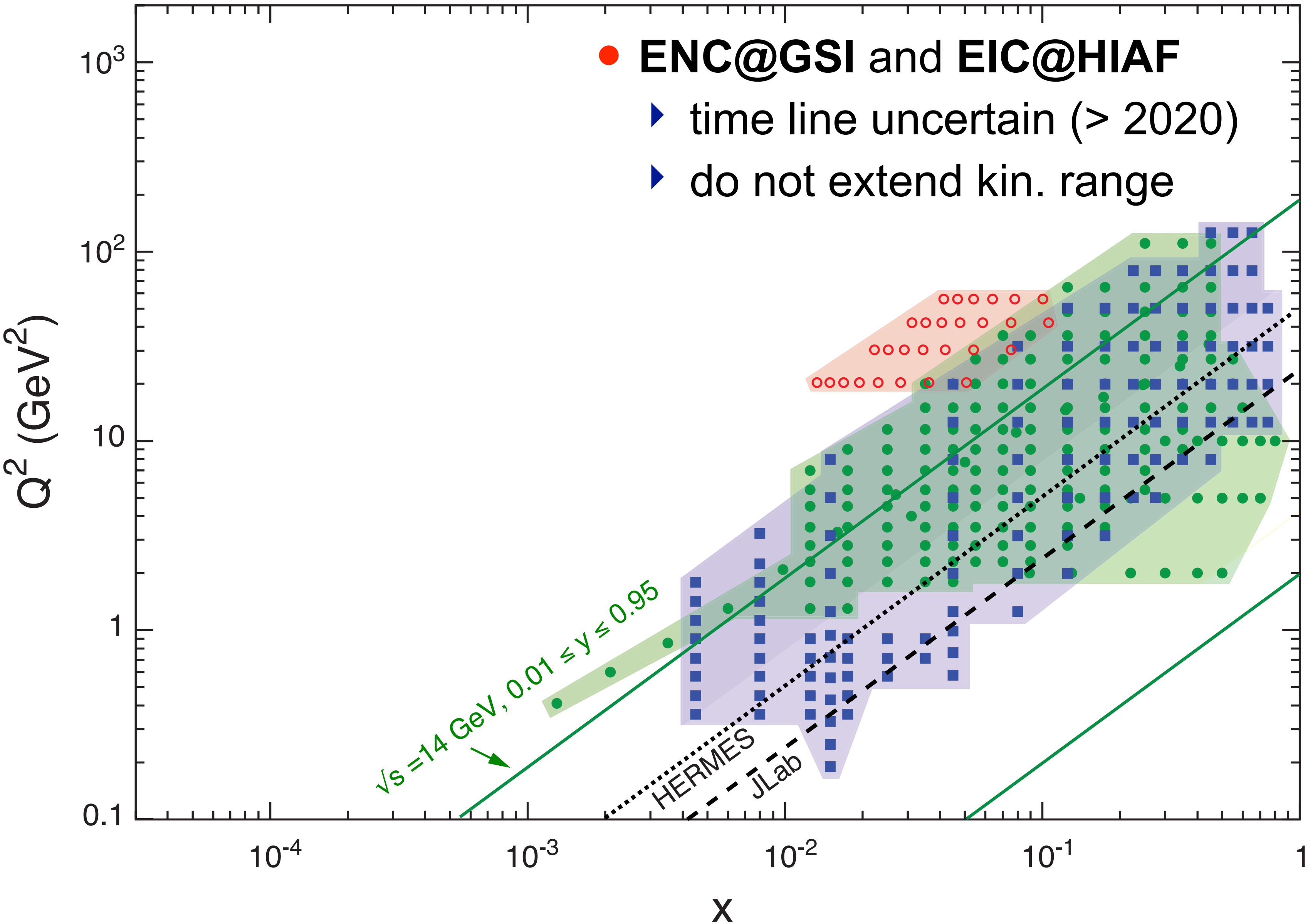

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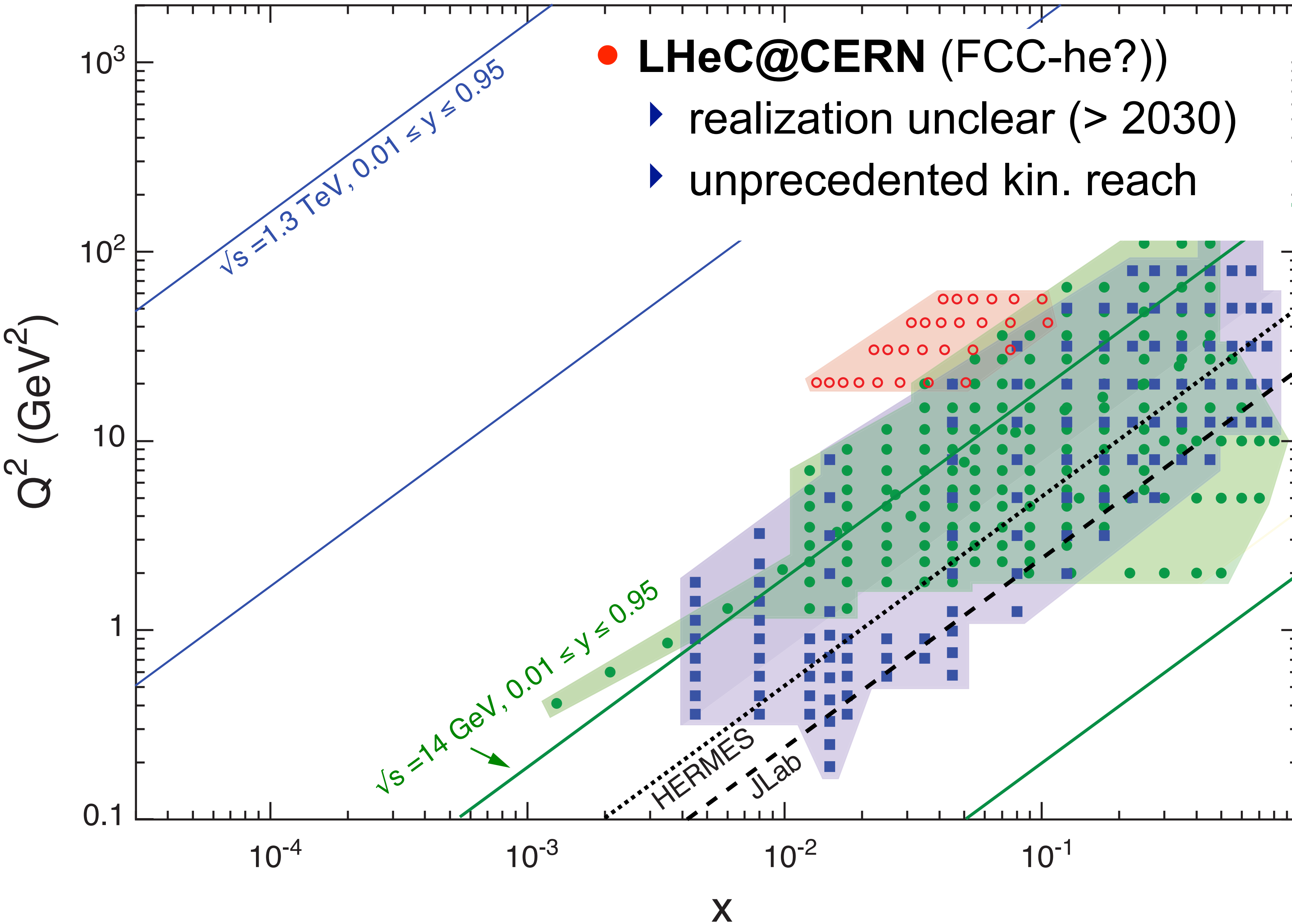

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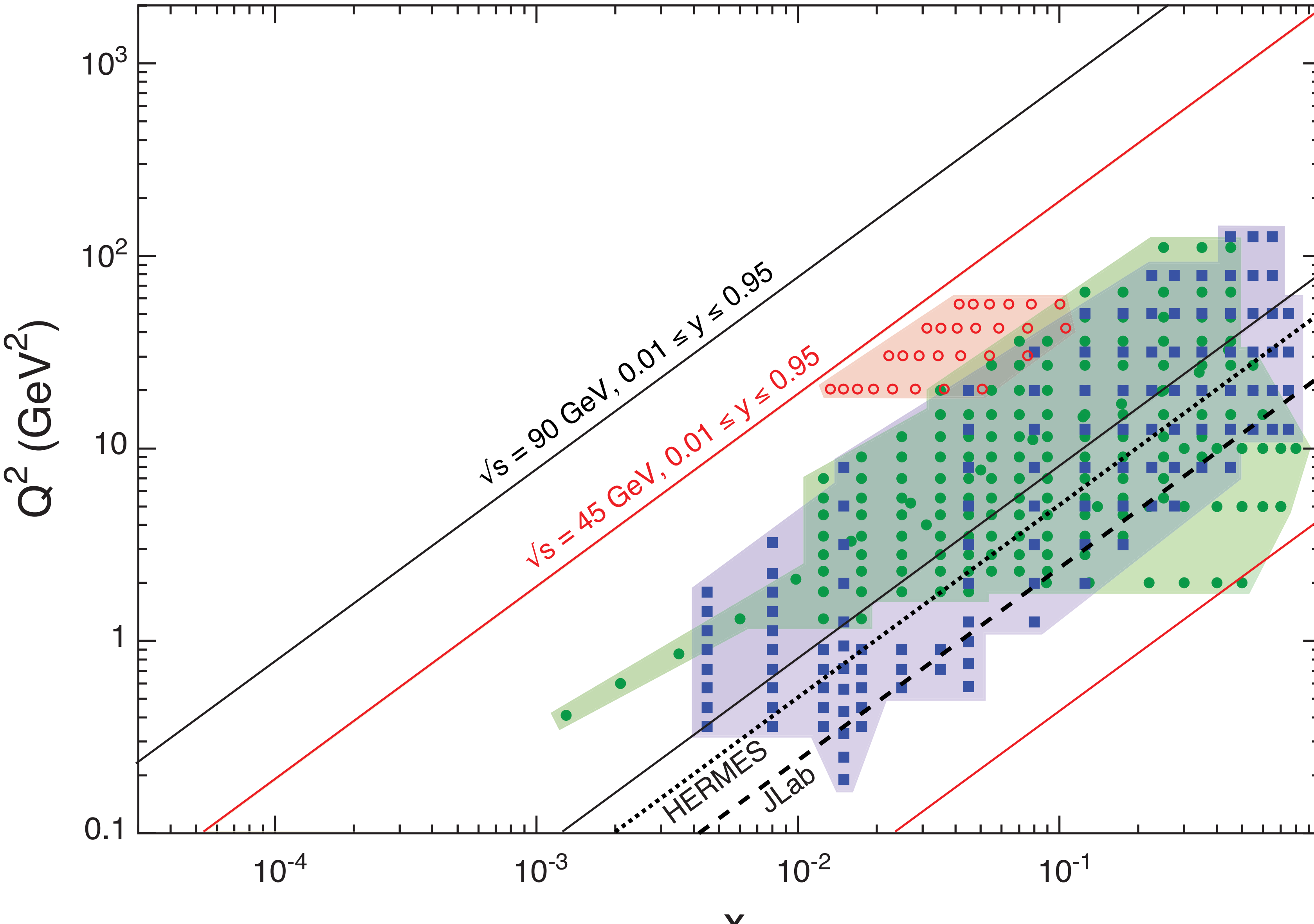

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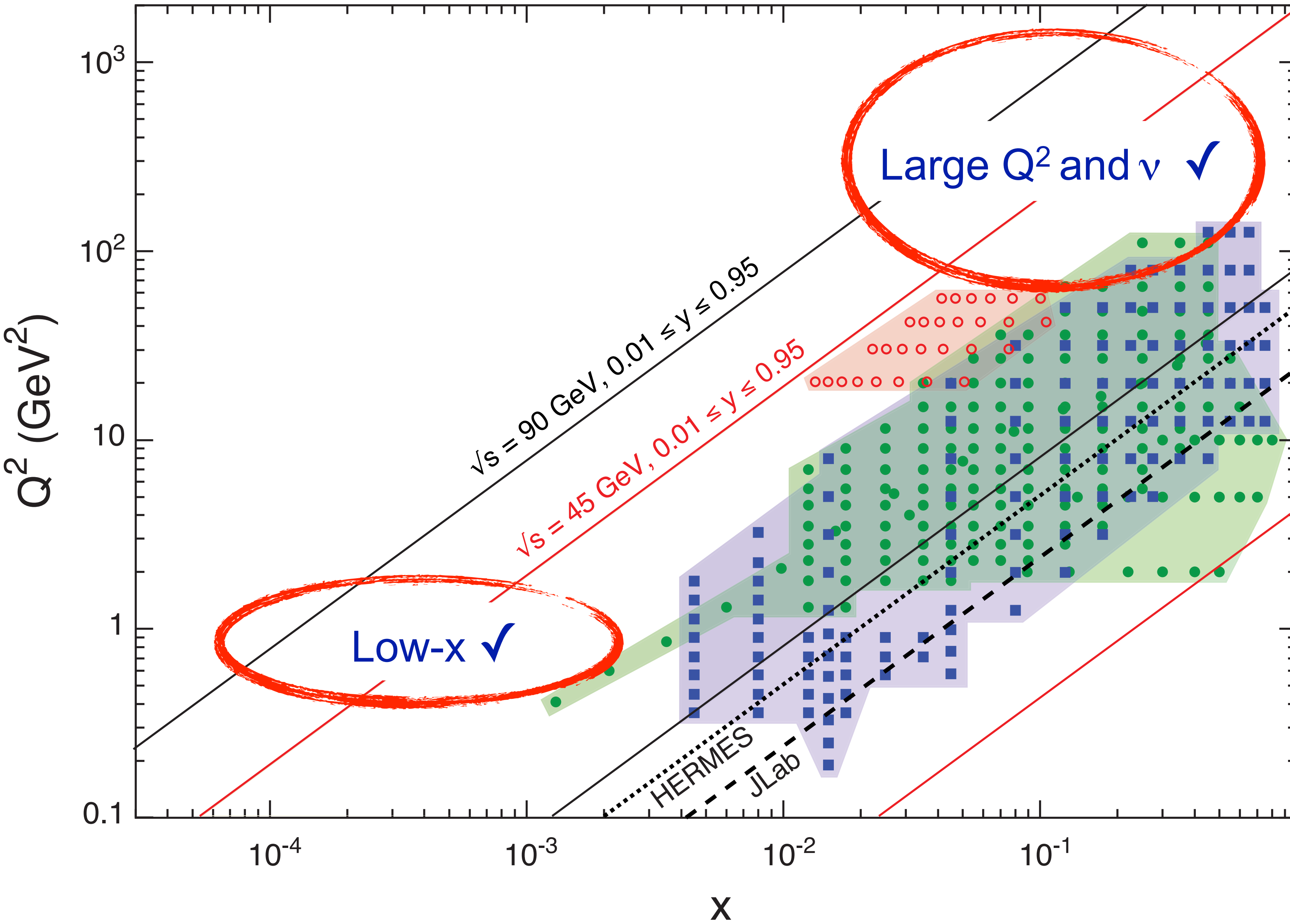

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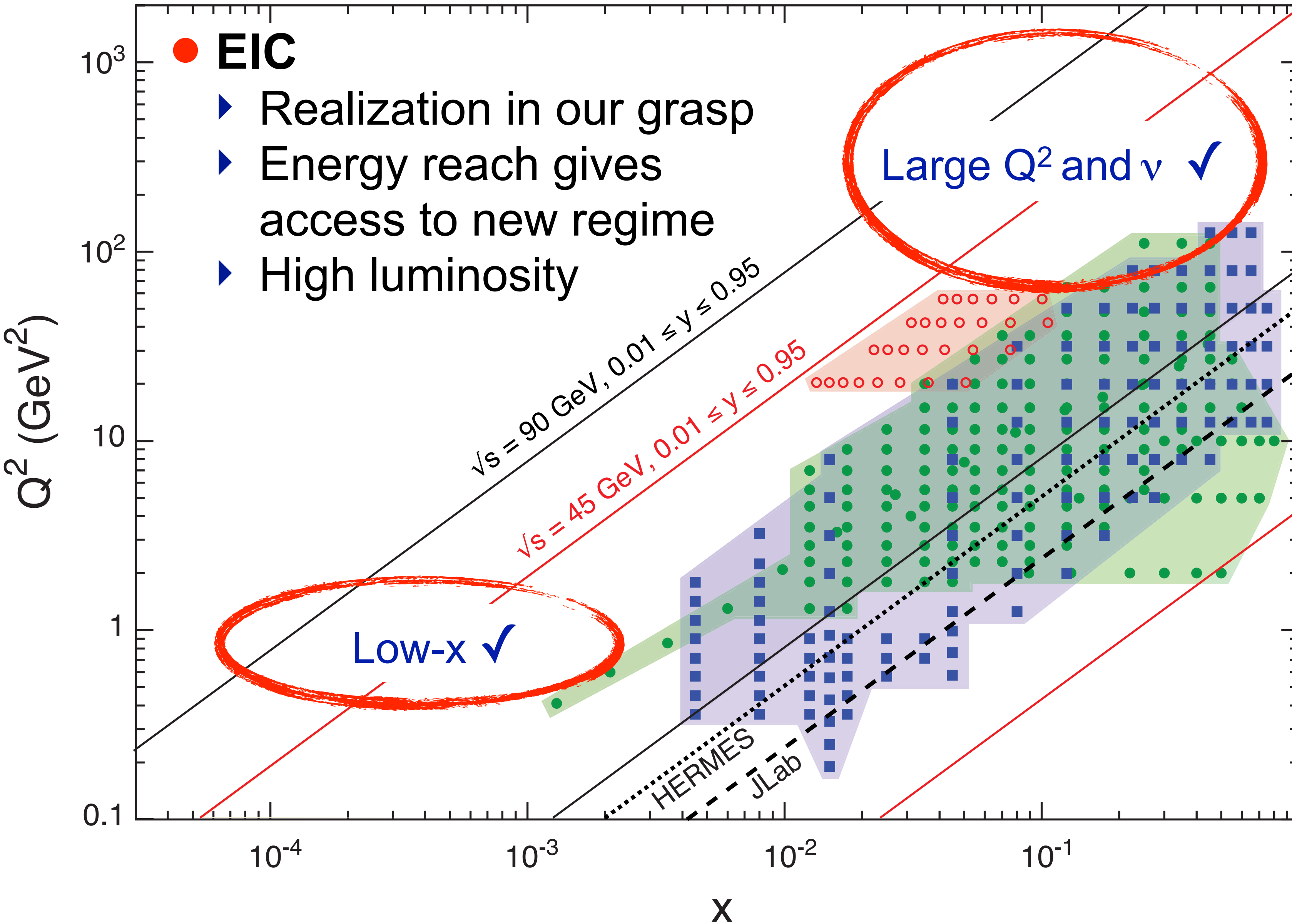
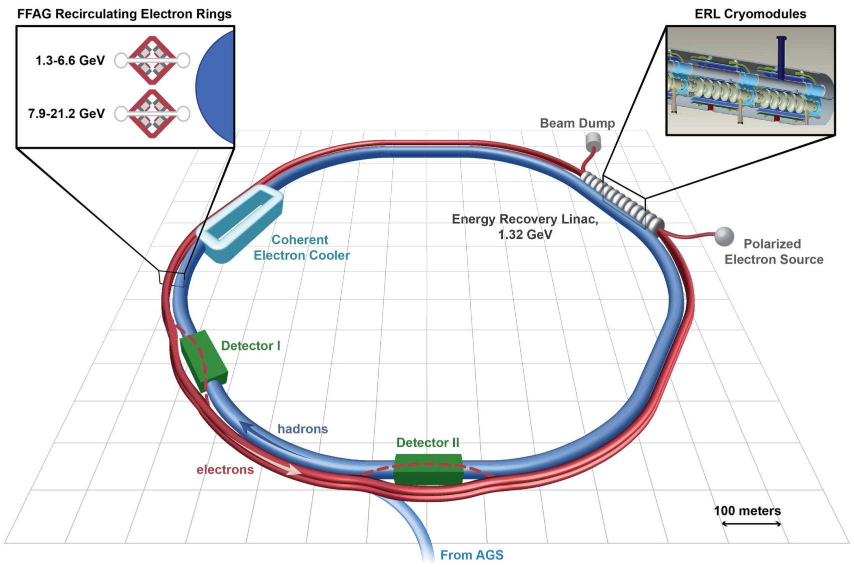
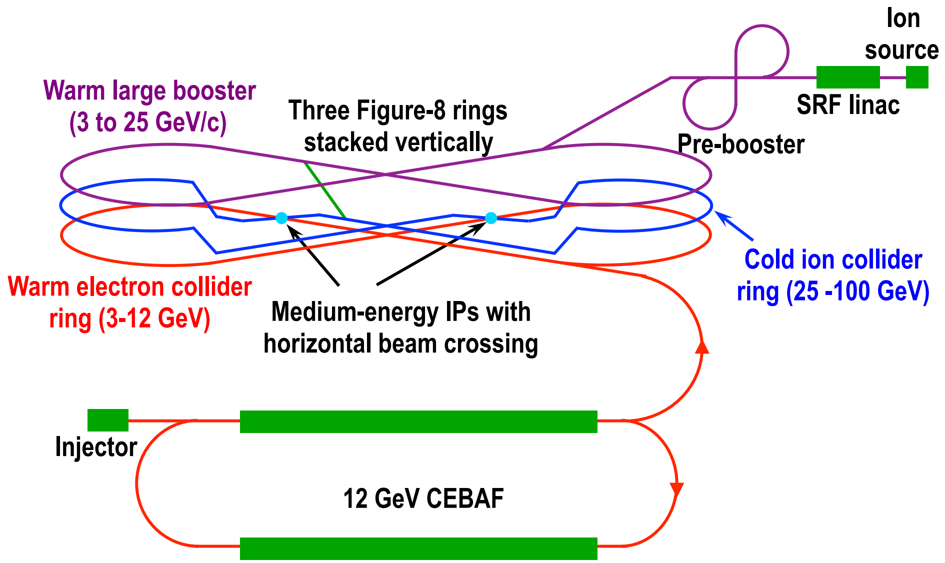


EIC Realization (e+A) - Basic Design

- **eRHIC (BNL)**
  - Add ERL+FFAG Recirculating e Rings to RHIC facility
  - Electrons 6.3-15.9 & 21.2 GeV
  - Ions (Au) up to 100 GeV/u
  - $\sqrt{s} \approx 20$ - 93 GeV
  - $L \approx 1.7\times10^{33}$ cm^{-2} s^{-1}/A at $\sqrt{s}$=80 GeV



- **MEIC (JLab)**
  - Figure-8 Ring-Ring Collider, use of CEBAF
  - Electrons 3-12 GeV
  - Ions 12-40 GeV/u
  - $\sqrt{s} \approx 11$-45 GeV
  - $L \approx 2.4\times10^{34}$ cm^{-2} s^{-1}/A at $\sqrt{s}$=22 GeV



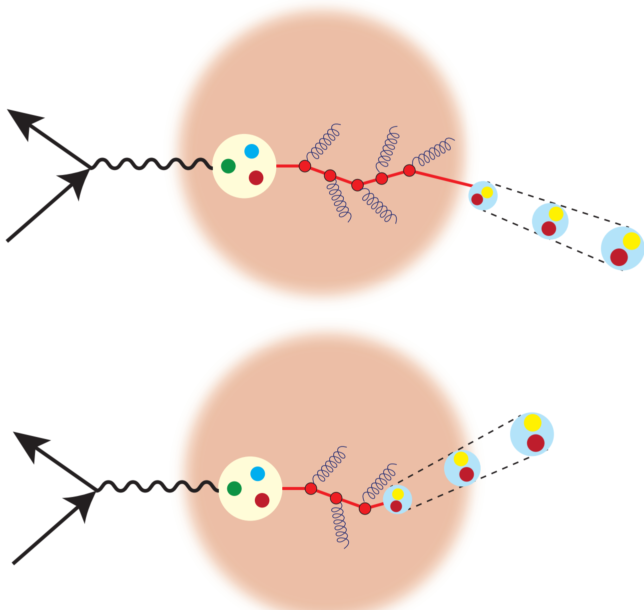
eRHIC: arXiv:1409.1633, MEIC: arXiv:1209.0757

Exploring QCD at Large Q^2, ν

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



- Nuclei as space-time analyzer
  - high Q^2 and ν ($\rightarrow$ large x):
    - Energy of struck quark (the probe) is known
    - No initial-state interactions
    - No color spectators (as in pA)
    - Hadronization in and out of medium can be varied (ν)

Color Propagation in Nuclei

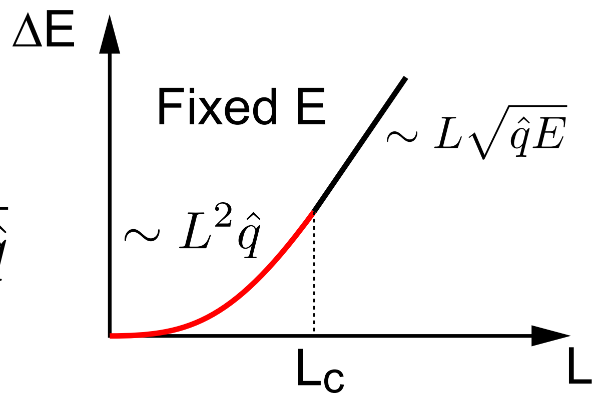
- Partonic energy loss in pQCD (e.g. BDMPS*) exhibits a critical system length L_c below which energy loss is independent of the parton energy

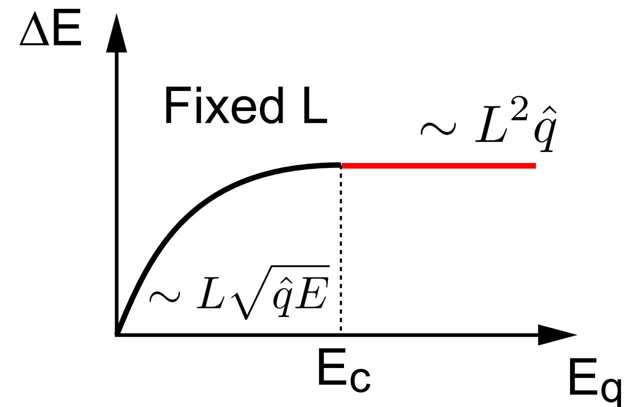
$$L_c \propto \sqrt{E_q/\hat{q}}$$

$$E_c \propto L^2\hat{q}$$

$$L < L_c: \ \Delta E \propto L^2\hat{q}$$

$$L > L_c: \Delta E \propto L\sqrt{E\hat{q}}$$





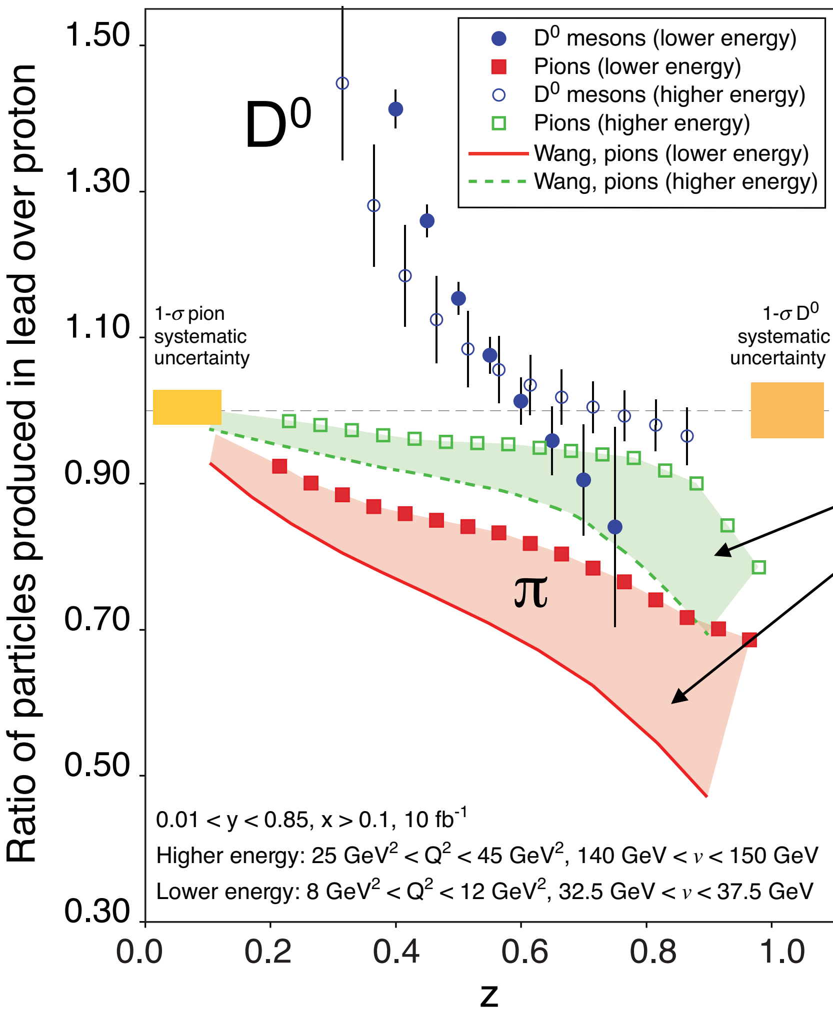
EIC access to quadratic region - Extract and study $\hat{q}$

- Observables/Tools
  - Multiplicity Ratio: $R_h = \dfrac{\frac{1}{N_e^A(Q^2,\nu)} N_h^A(Q^2,\nu,z,p_T)}{\frac{1}{N_e^D(Q^2,\nu)} N_D^A(Q^2,\nu,z,p_T)}$

$$z_h = \frac{E_h}{\nu}$$

*Baier et al., NP B483 (1997) 291

Multiplicity Ratios: Semi-Inclusive Studies



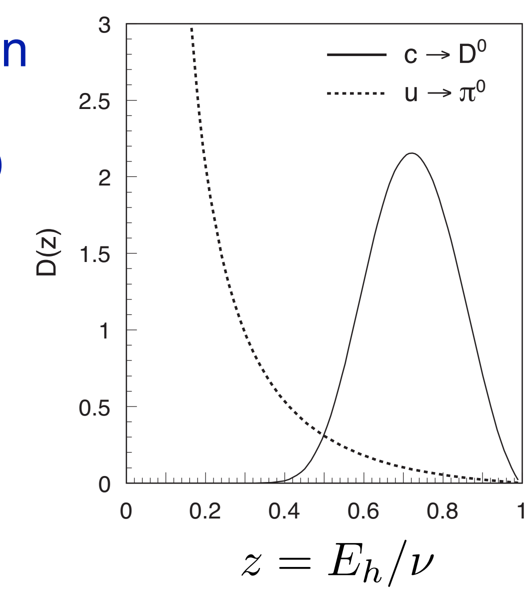
HERMES: ν = 2-25 GeV

EIC: 10 < ν < 1600 GeV

EIC: *heavy flavor*!

Lines/Points: different models

Large difference in fragmentation function (FF) of D and π



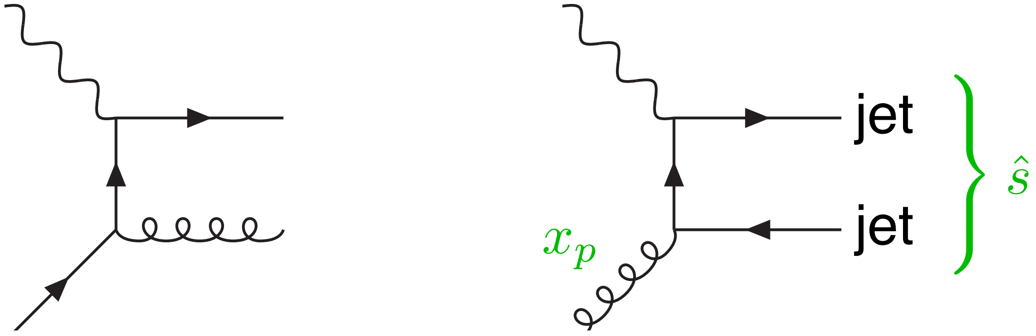
- Slope of D's sensitive to $\hat{q}$ and FF
- Strong Sensitivity of Shape on ν is powerful tool

Gluon Distribution from Jets at EIC

Jets: window to partons, DIS is a clean environment

- Color propagation in cold medium, gluon distribution from 2+1-jet, modification of jet fragmentation, …

"2+1" jets
most interesting



Cross-Section: $$\frac{d^2\sigma^{2+1}}{dx_p dQ^2} = \alpha_s \left[a\, g(x_p, Q^2) + b\, q(x_p, Q^2)\right]$$

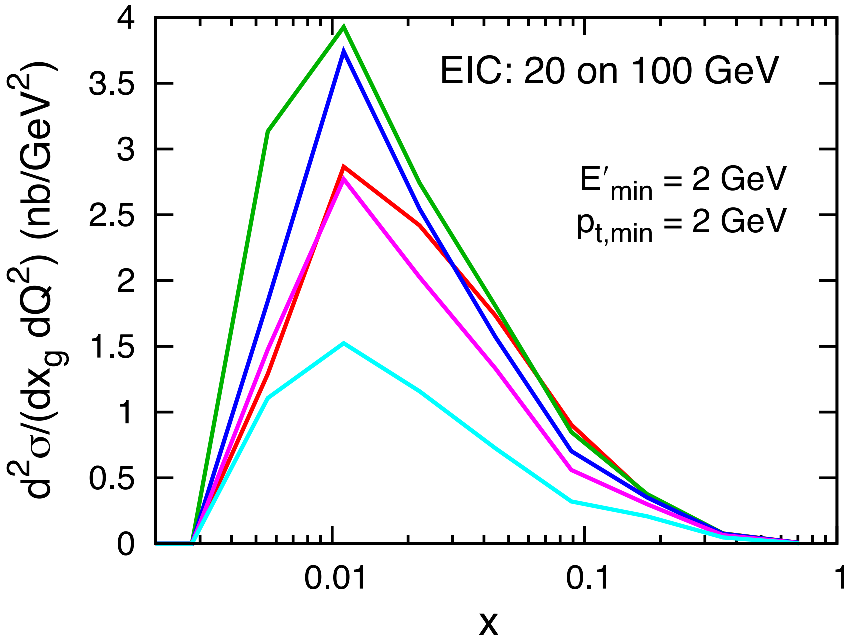
- Technique
  - a and b: matrix elements from pQCD (use MC due to cuts)
  - $x_p = x\,(1 + \hat{s}/Q^2)$, $\hat{s}$ is inv. mass of dijet system
  - Extract gluon distr. via: $g = (\sigma_{meas.} - b\, q)/a$

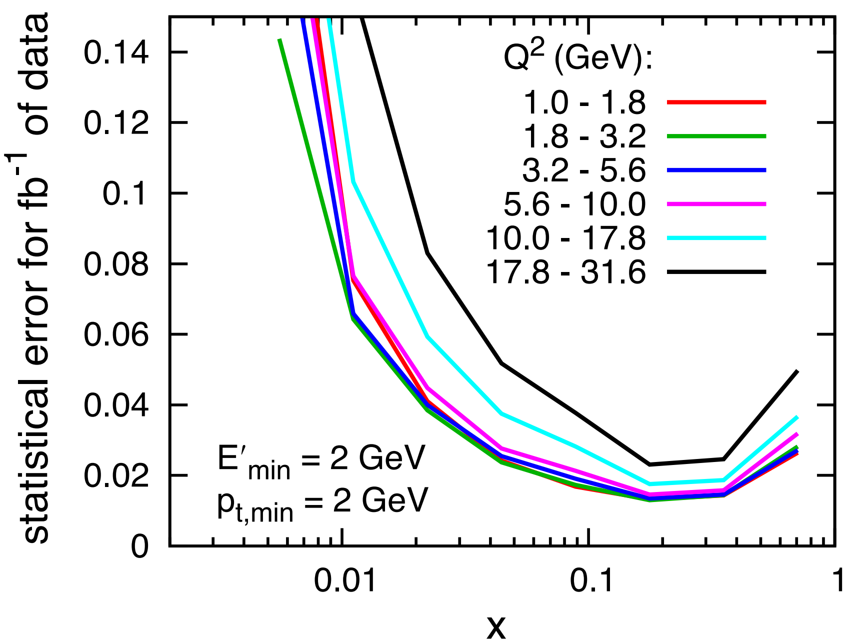
Gluon Distribution from Jets at EIC

Preliminary simulations:

- Outgoing electron energy: E'_{min}, minimal jet p_T : $p_{T,min}$
- Azimuthal separation between the 2 jets: $\Delta\phi > \pi - \varepsilon$ (in the Breit frame — ensures that the 2 jets come from the hard scattering)
- Clustering: k_T algorithm with R=1 (large but OK in DIS)

Gluon-initiated dijet events (LEPTO), stat. errors for $\int L dt$ = 1 fb^{-1}/A





Gregory Soyez, EIC Note (2008)

More detailed studies under way

Take Away Message: Large Q^2, ν

- EIC provides new capabilities to open a new QCD frontier: access to study color propagation, neutralization, and fluctuations (Δp_T^2)
- EIC can shed light on the hadronization process and on what governs the transition from patrons to hadrons
- It offers an unprecedented ν reach and, for the first time, allows the study of heavy flavor propagation and correlations in nuclear matter.
- EIC allows jet studies at $x > 0.01$ which open an alternative door into fragmentation and E-loss studies, as well as a measurement of the gluon momentum distribution.
- Many other interesting studies not discussed here (EMC, …)

EIC: Structure Functions (Inclusive DIS)

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

quark+anti-quark

gluon

F_2 and F_L are benchmark measurements:
Theory/models have to be able to describe the structure functions and their evolution.

Reduced cross-section:

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

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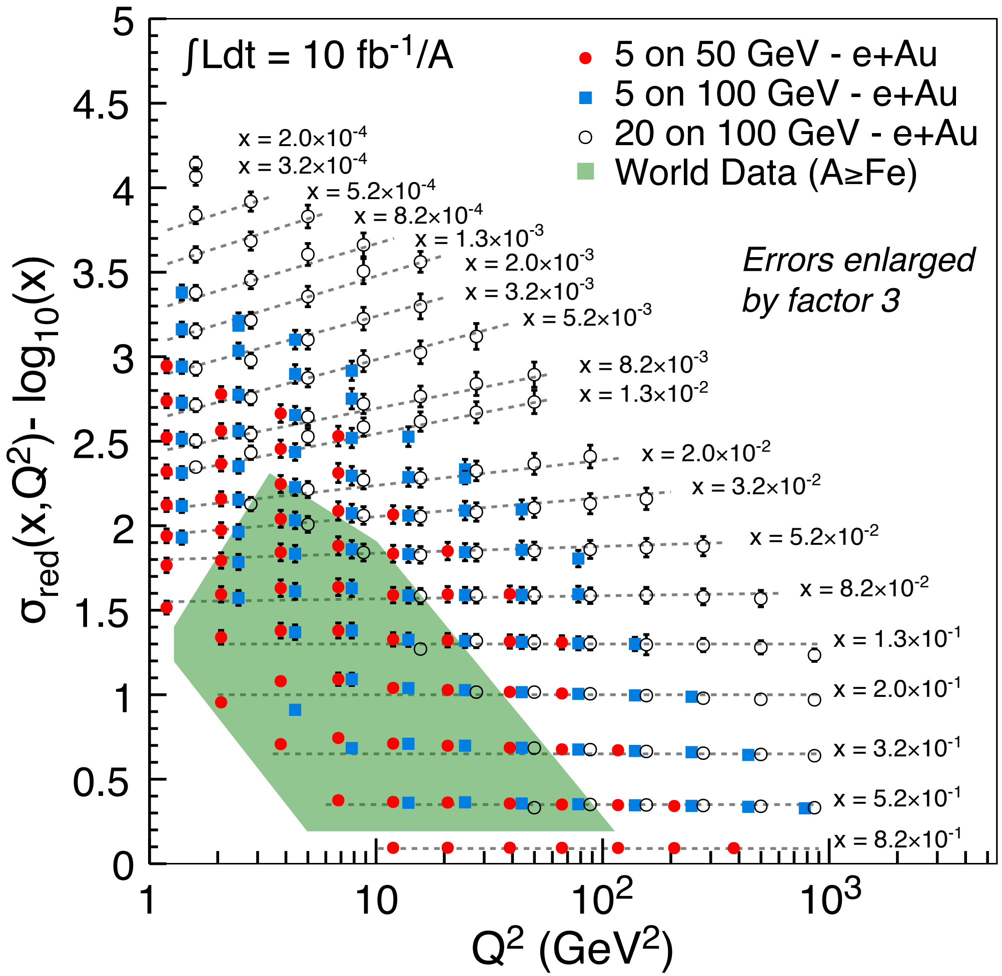
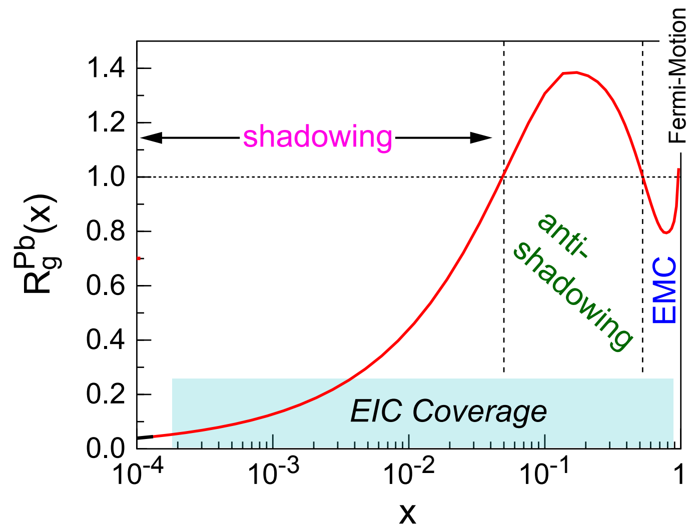
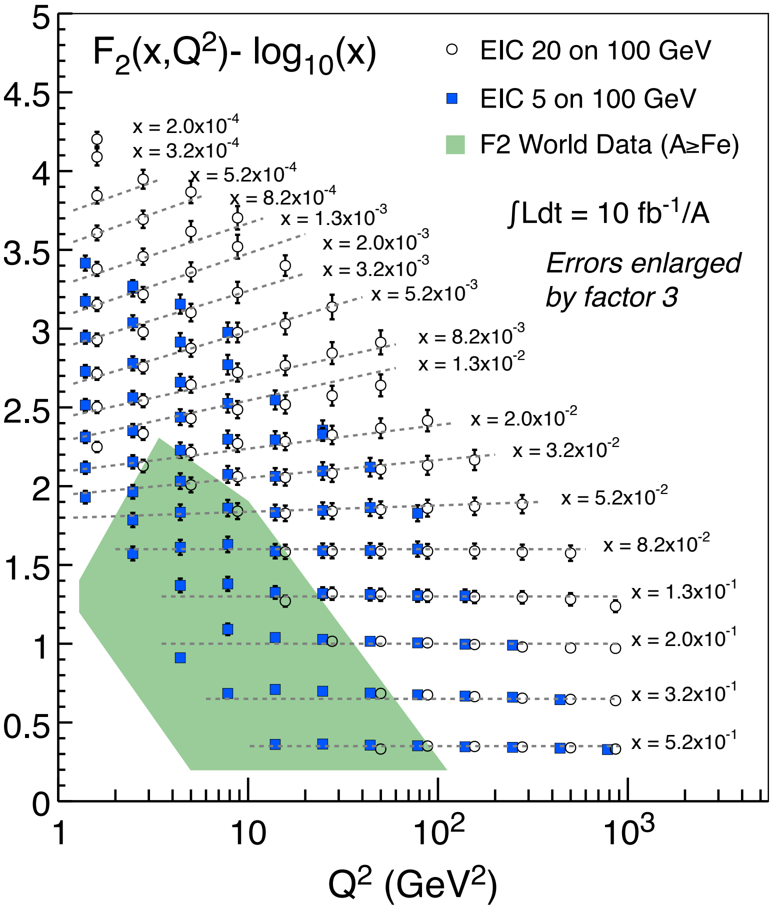


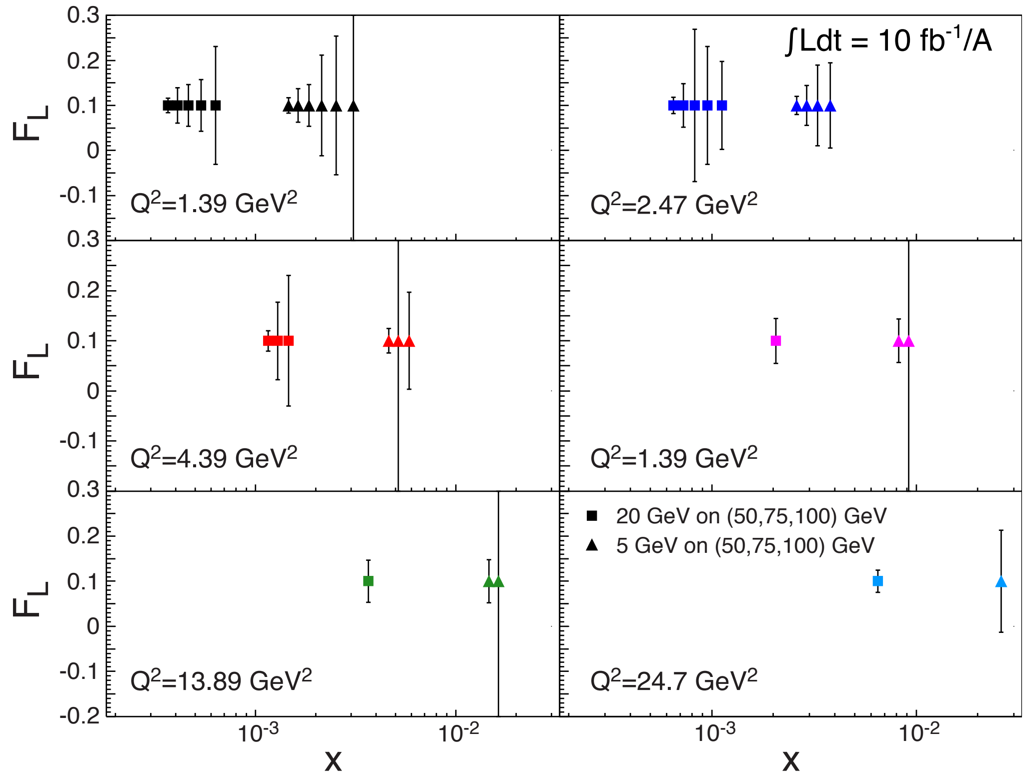


- Pythia + EPS09
- Assume 3% systematic uncertainty
- Measurement dominated by systematic, not $\mathcal{L}$ hungry

Structure Functions (Inclusive DIS)

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





Extending knowledge on structure function into realm where gluon saturation effects emerge

Structure Functions (Inclusive DIS)

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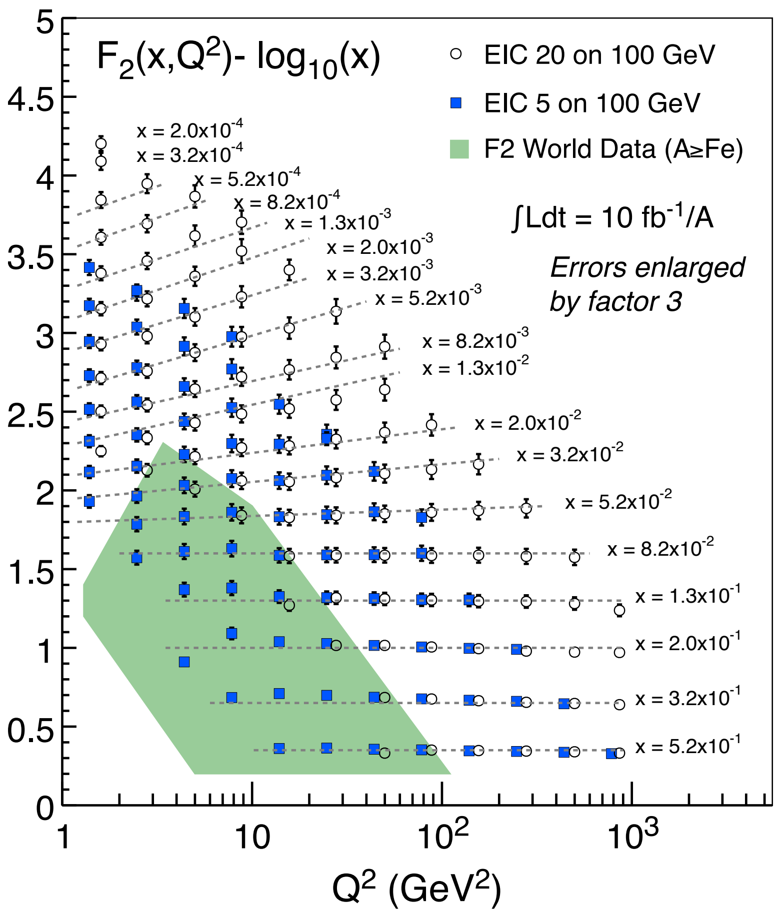
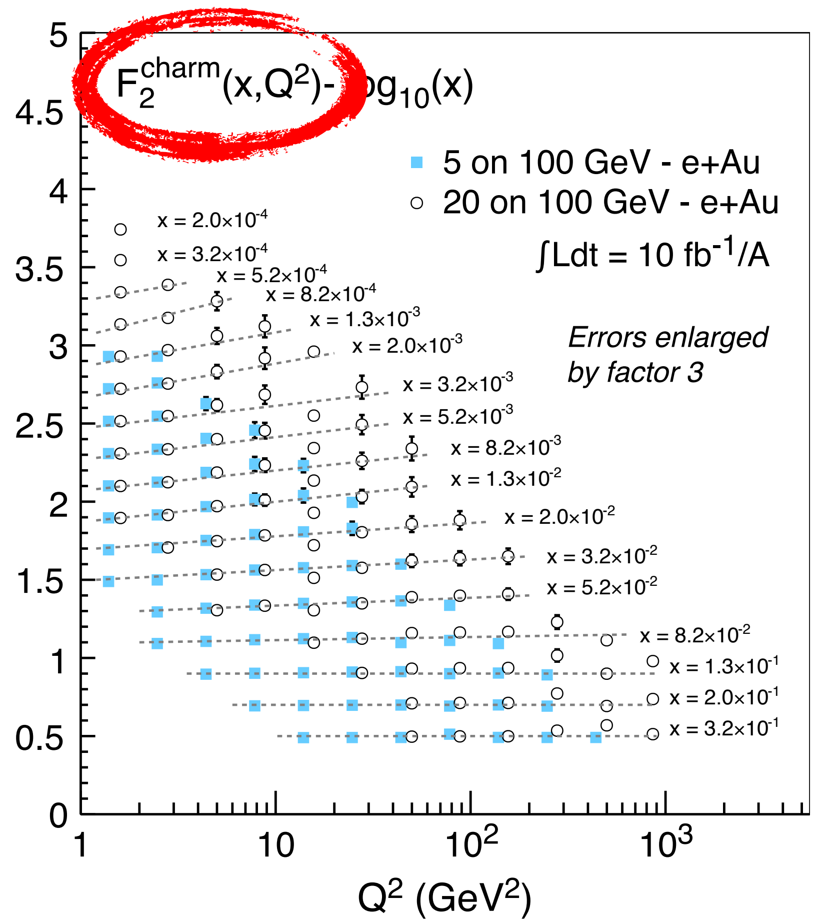
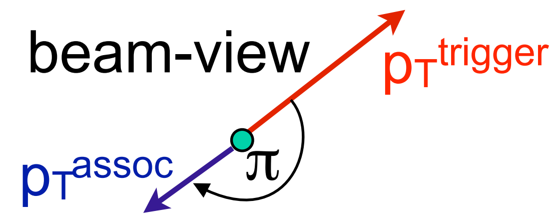




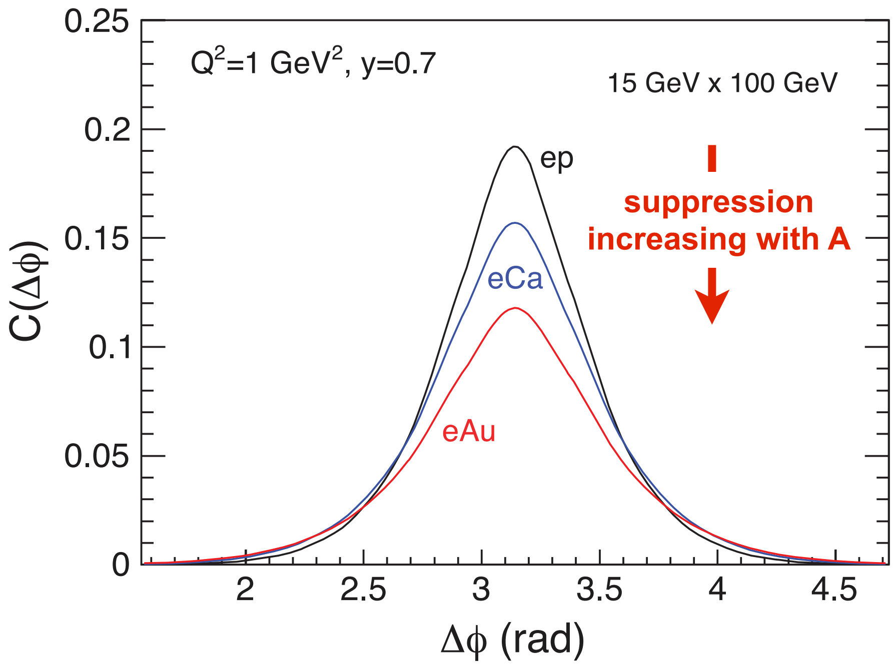
Extending knowledge on structure function into realm where gluon saturation effects emerge

Dihadron Correlations

"Simple" measurement
giving access to multi-parton
correlations

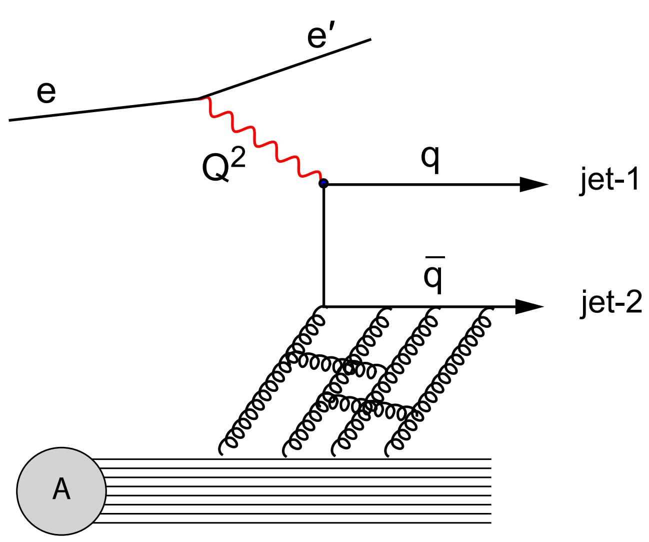


Predictions:
Pronounced saturation effect



Dominguez et al. PRD83, 105005 (2011),
PRL 106, 022301 (2011)

Dihadrons:
Less restrictive acceptance and cuts than for 2+1 dijet analysis



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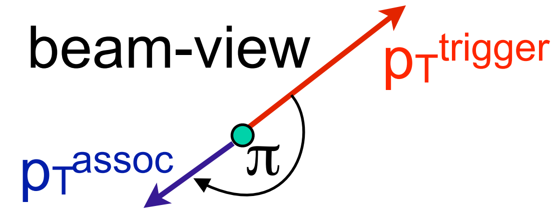

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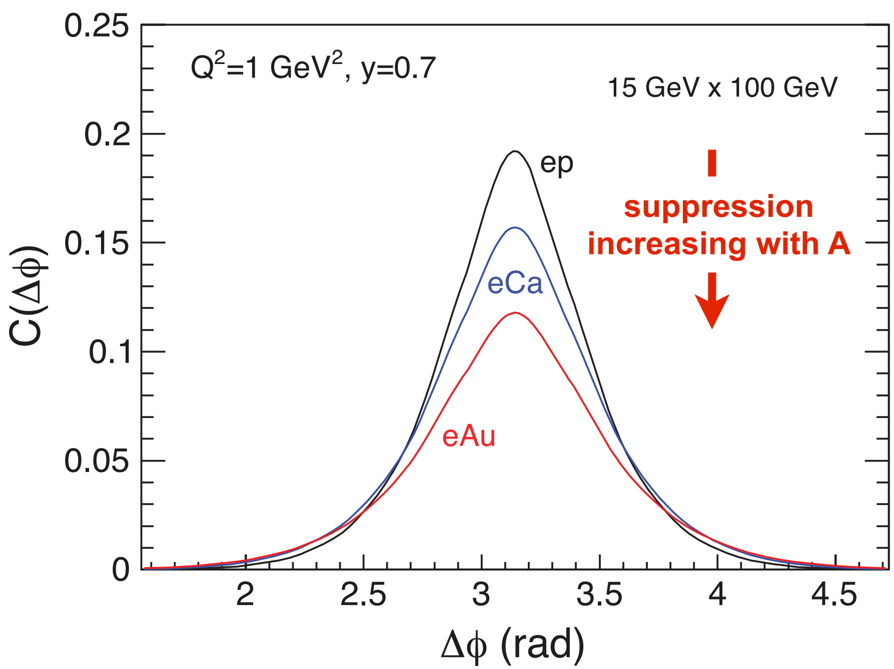

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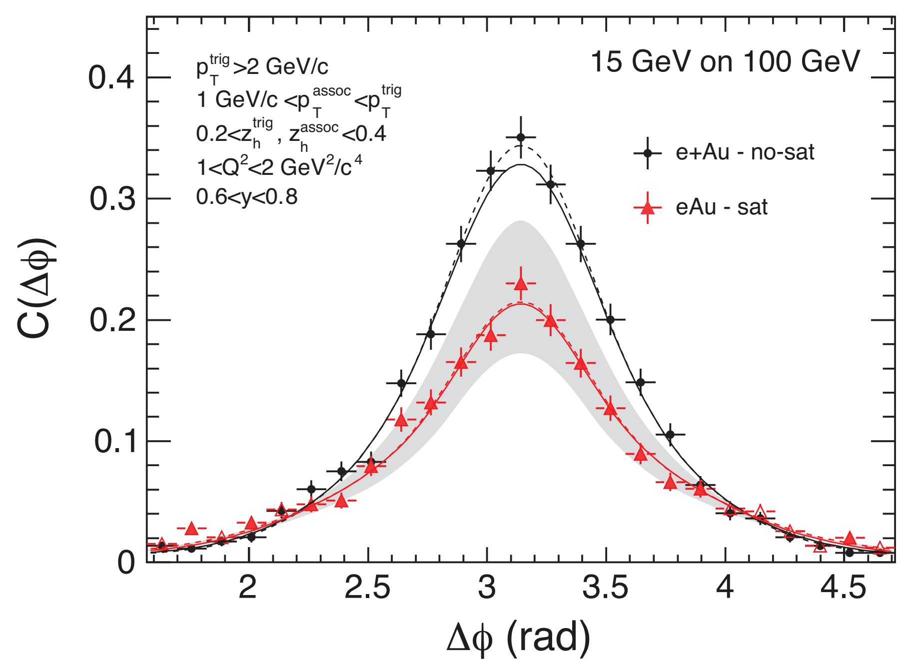

Zheng et al., PRD89 (2014) 074037

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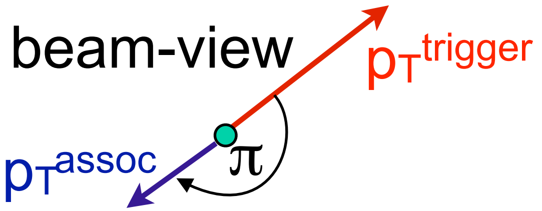
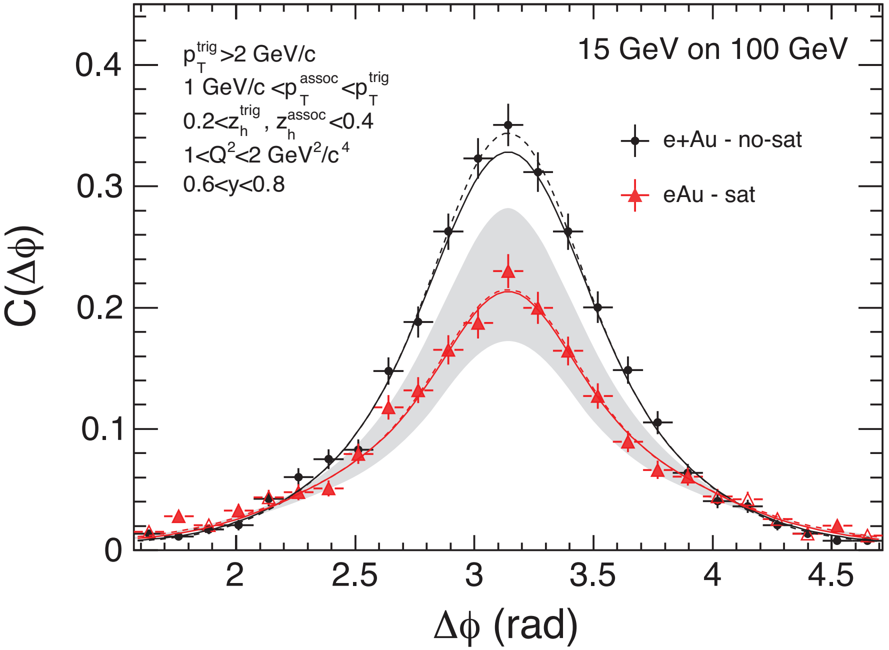


Simulations (no-sat):

Pythia+DPMJet+Fluka +EPS09+E-loss

Include Sudakov form factor to account for generated radiation through parton showers. Reduced difference between sat and no-sat. Includes sys+stat errors.



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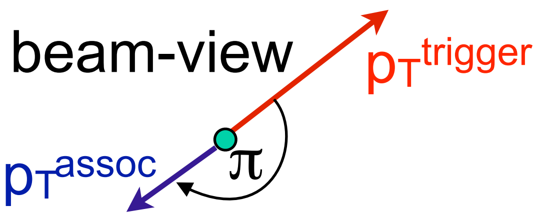
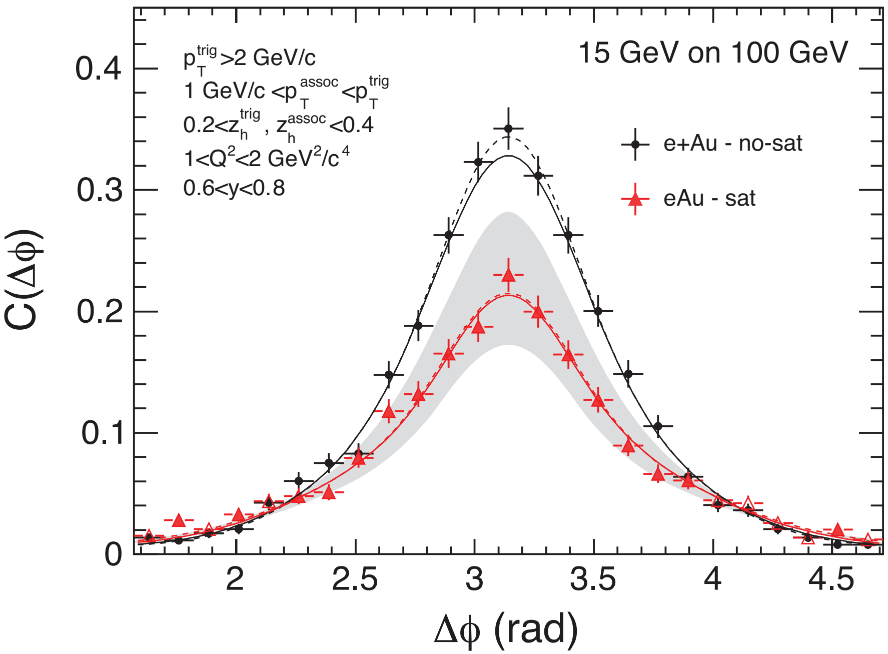


Clear saturation/CGC signatures with access to the relevant kinematic variables x, Q^2



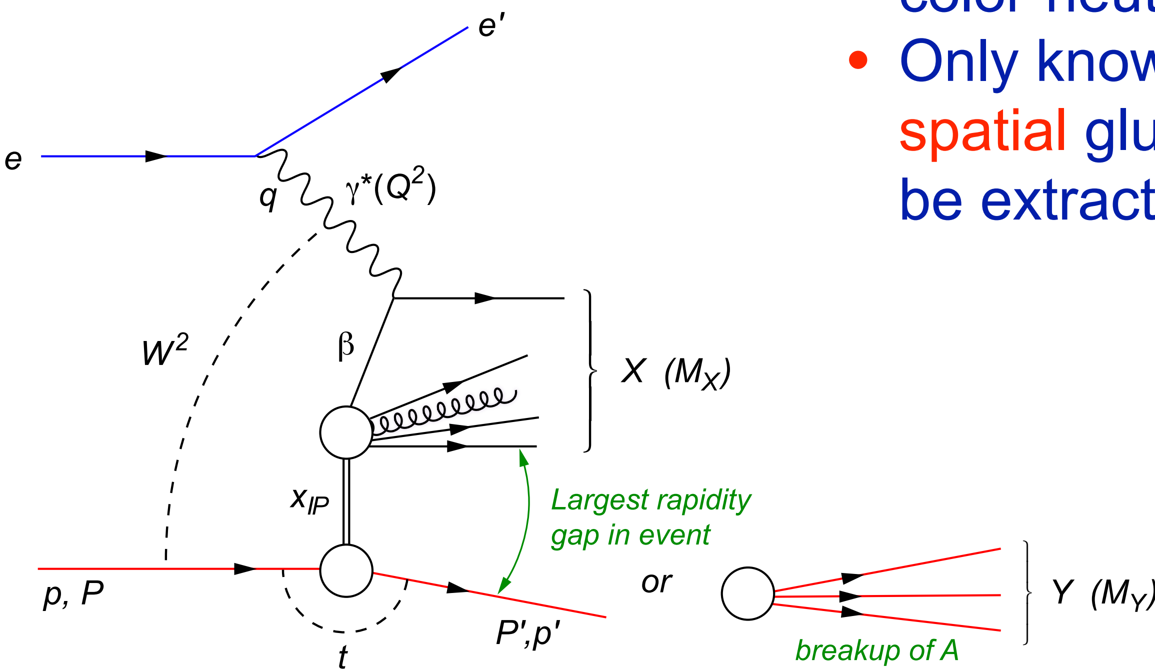
Zheng et al., PRD89 (2014) 074037

Key Measurements - Diffraction

Diffractive physics will be a major component of the e+A 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 can be extracted

HERA: $\sigma_{diff}/\sigma_{tot} \sim 15\%$



coherent
p/A stays intact

incoherent
p/A breaks up

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

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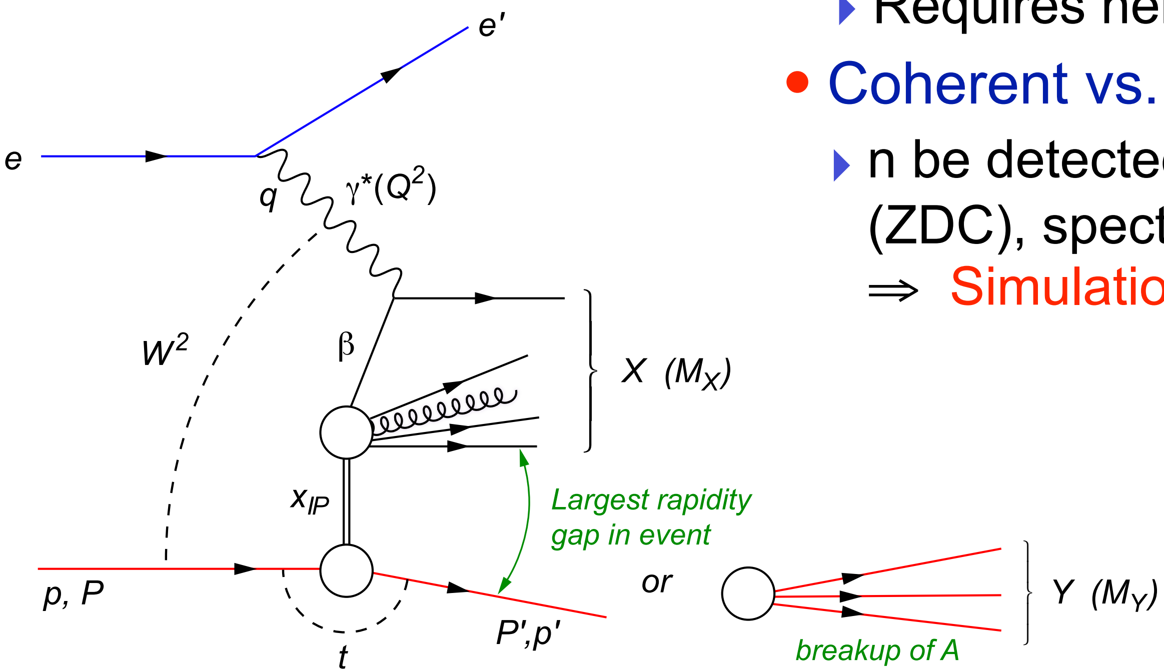


coherent
p/A stays intact

incoherent
p/A breaks up

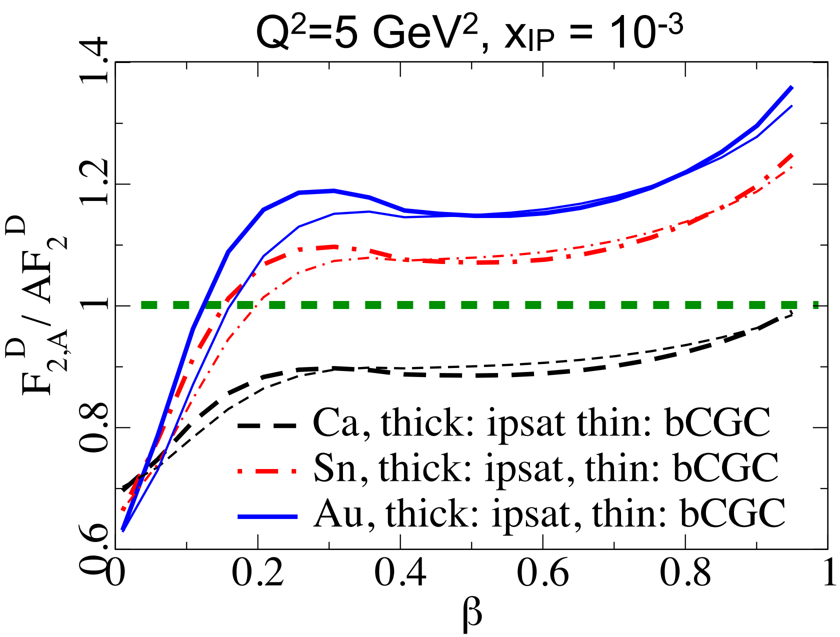
How to identify diffractive events?

- Rapidity Gap
  - Requires hermetic detector
- Coherent vs. Incoherent Diffraction
  - n be detected using emitted *n* and γ (ZDC), spectator tagging (Roman Pots) ⇒ Simulations shows it works

t: momentum transfer squared
M$_X$: mass of diffractive final-state

Diffractive over Total Cross-Section

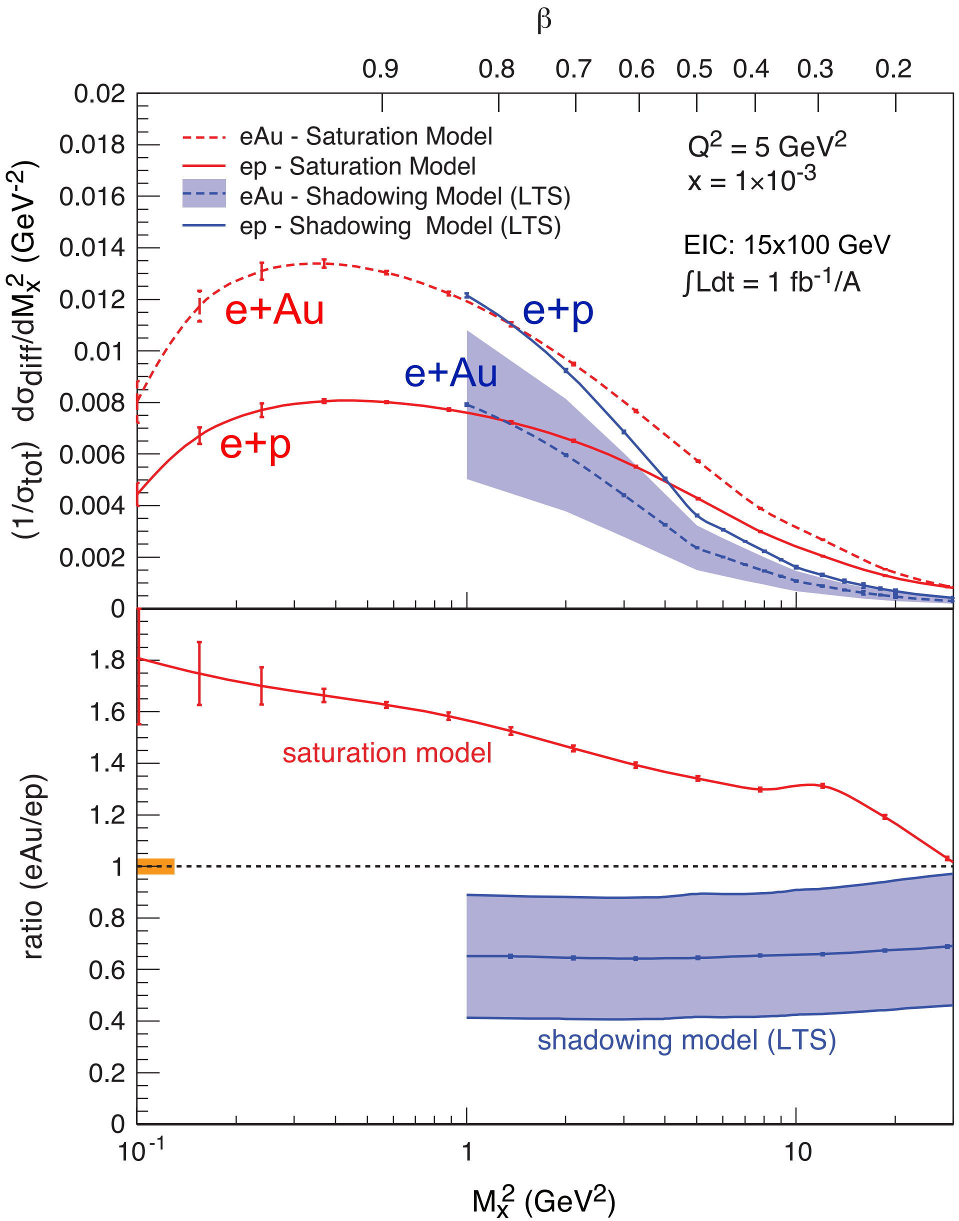
- Predicted to be enhanced in eA compared to ep at large β, i.e. small M_X^2 ($\beta \sim Q^2(Q^2+M_X^2)$)
  - β = momentum fraction of the struck parton with respect to the Pomeron



Kowalski et al. Phys.Rev. C78 (2008) 045201

- Large β: small Fock states ($q\bar{q}$) scattering off the nucleus
  - absorbed in nuclei
- Small β: large Fock states with one or more gluons scattering
  - enhanced (scatter off)

Diffractive over Total Cross-Section



Dramatic prediction:

Saturation models: ~25% or more of all events are diffractive.

Not seen in Leading Twist Shadowing pQCD models

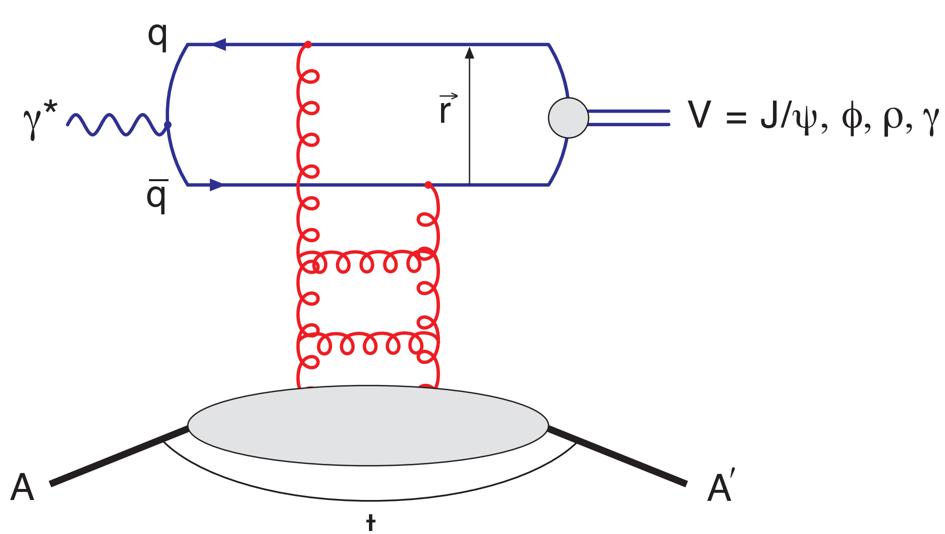
Day-1 measurements that will give clear evidence for saturation

M_X^2 (β) dependency needs to be measured

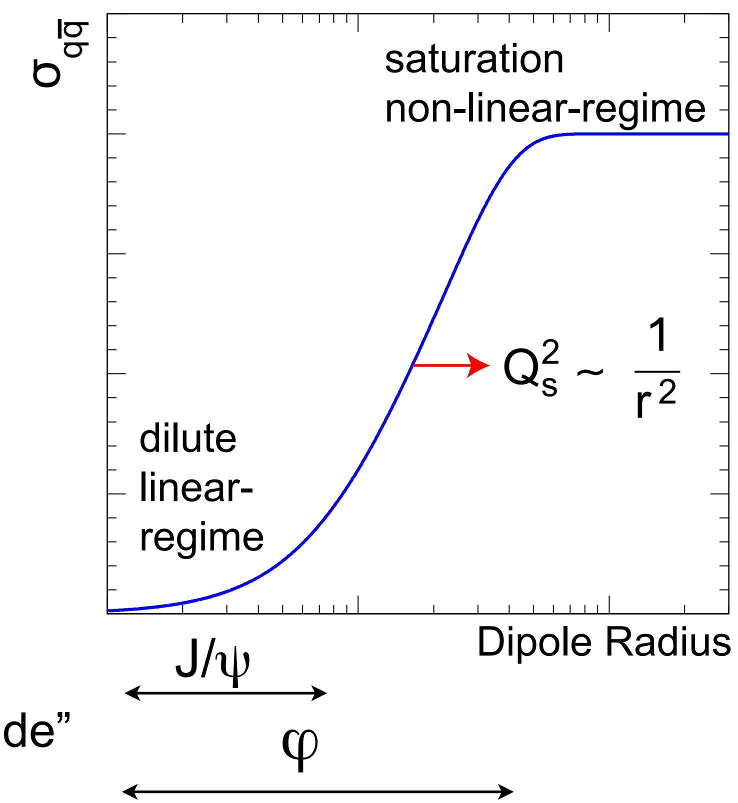
Exclusive Diffractive Vector Meson Production

- Allows to measure momentum transfer *t* in eA
  - in general, one cannot detect the outgoing nucleus and its momentum
  - here:

$$t = (\boldsymbol{p}_A - \boldsymbol{p}_{A'})^2 = (\boldsymbol{p}_{\mathrm{VM}} + \boldsymbol{p}_{e'} - \boldsymbol{p}_e)^2$$



Dipole Cross-Section:



- **small size (J/Ψ)**: cuts off saturation region
- **large size (φ,ρ, ...)**: “sees more of dipole amplitude” → more sensitive to saturation

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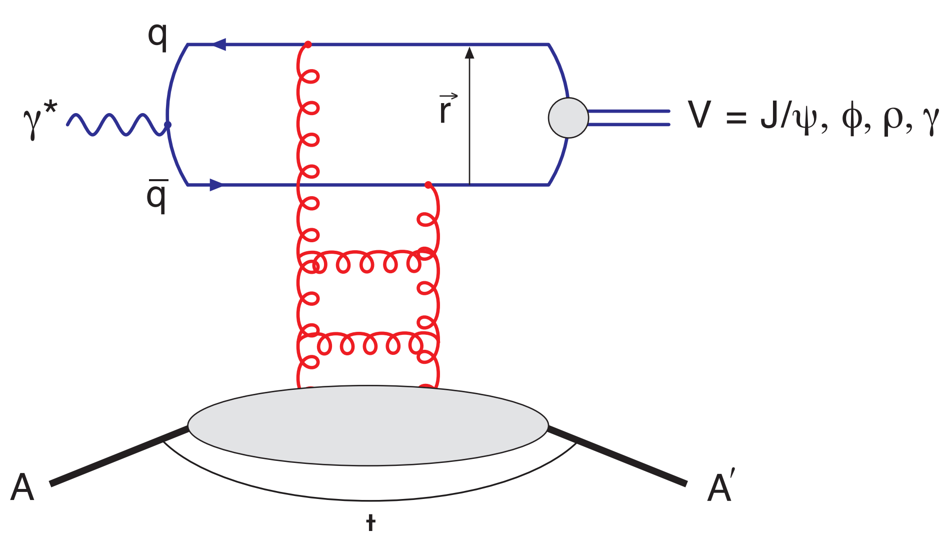
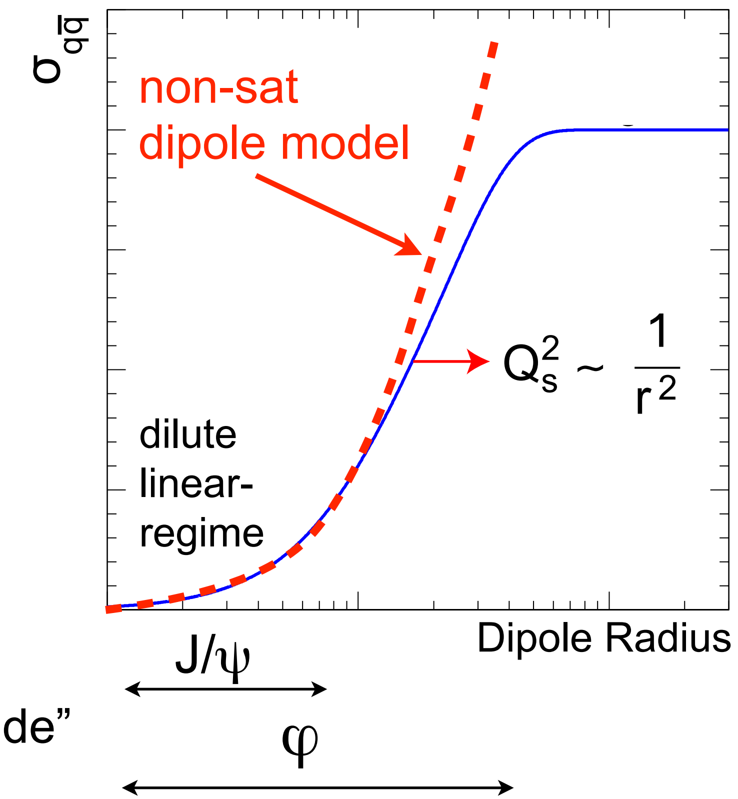
  - here:

$$t = (\boldsymbol{p}_A - \boldsymbol{p}_{A'})^2 = (\boldsymbol{p}_{\mathrm{VM}} + \boldsymbol{p}_{e'} - \boldsymbol{p}_e)^2$$

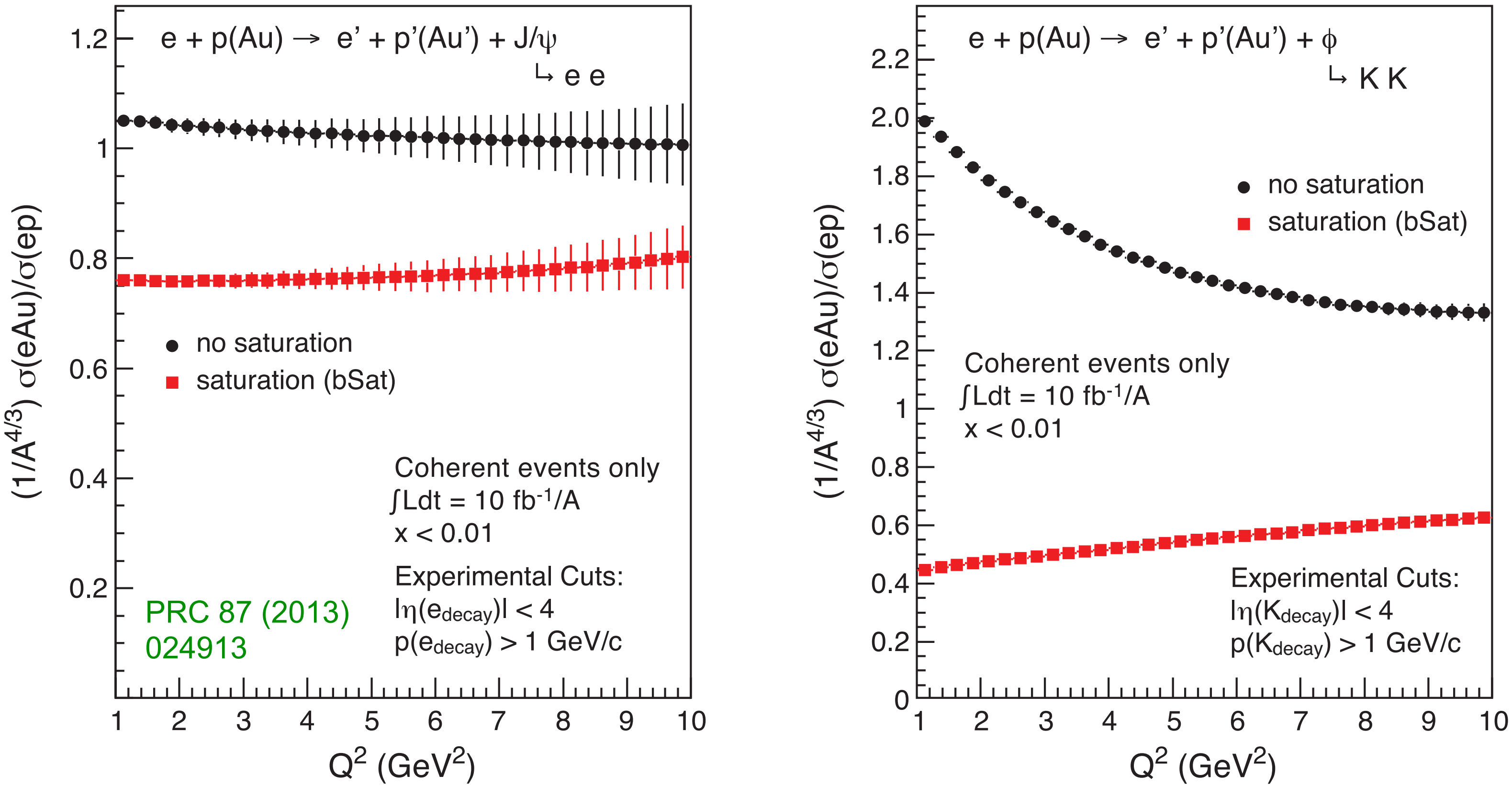


Dipole Cross-Section:



- **small size (J/Ψ)**: cuts off saturation region
- **large size (φ,ρ, ...)**: “sees more of dipole amplitude” → more sensitive to saturation

Exclusive Vector Meson Production

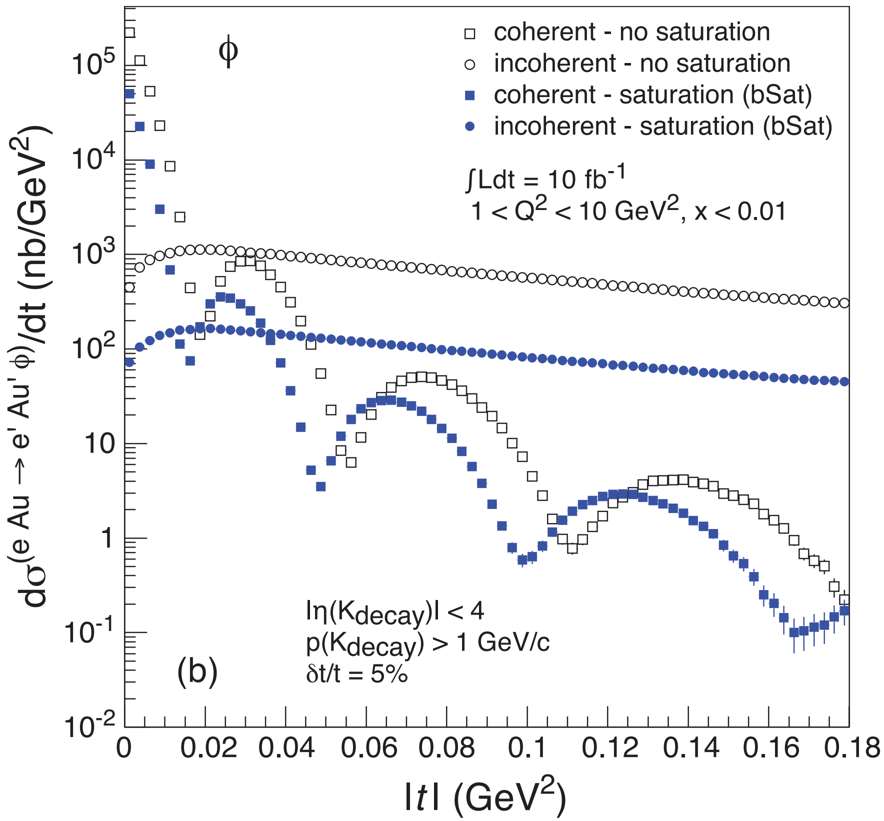


- Sartre event generator (bSat & bNonSat = linearized bSat)
- As expected: big difference for ϕ less so for J/ψ
- Note: $A^{4/3}$ scaling strictly only valid at large Q^2
- Day-1 measurements that will give clear evidence for saturation

Spatial Gluon Distribution from dσ/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



Spatial Gluon Distribution from dσ/dt

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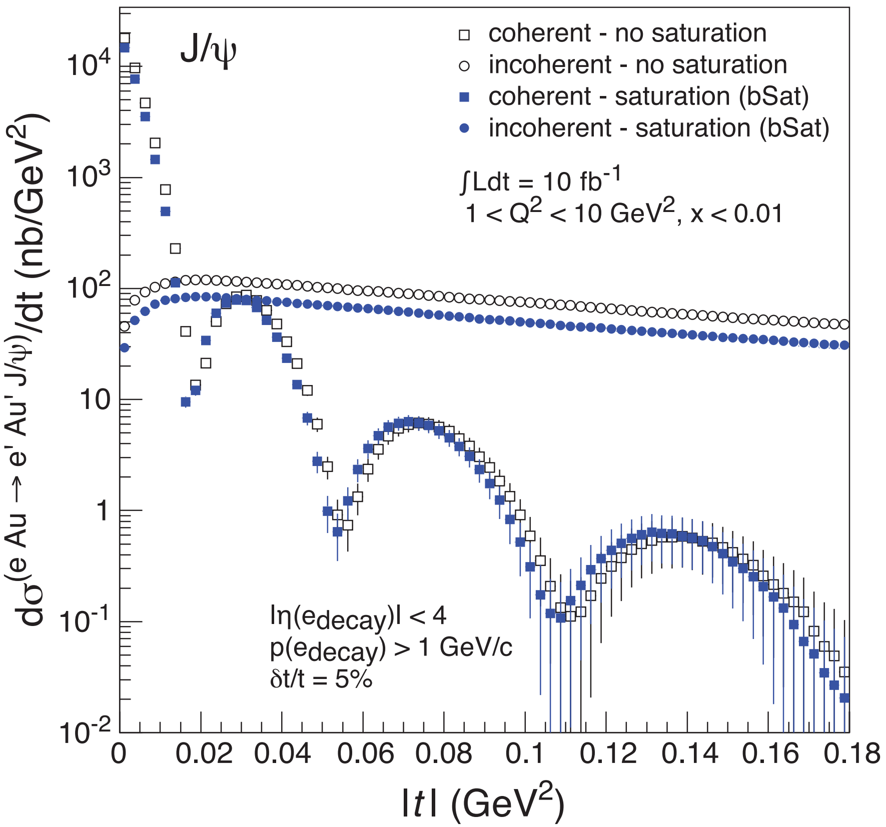
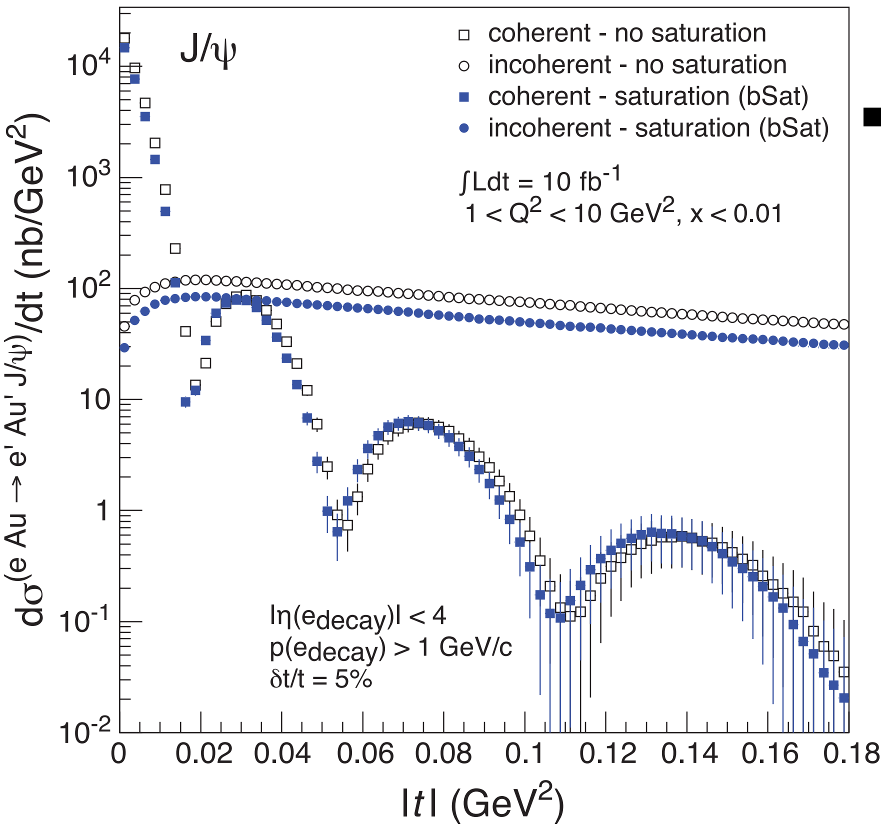


Spatial Gluon Distribution from dσ/d*t*

Diffractive vector meson production: e + Au → e′ + Au′ + J/ψ, φ, ρ

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



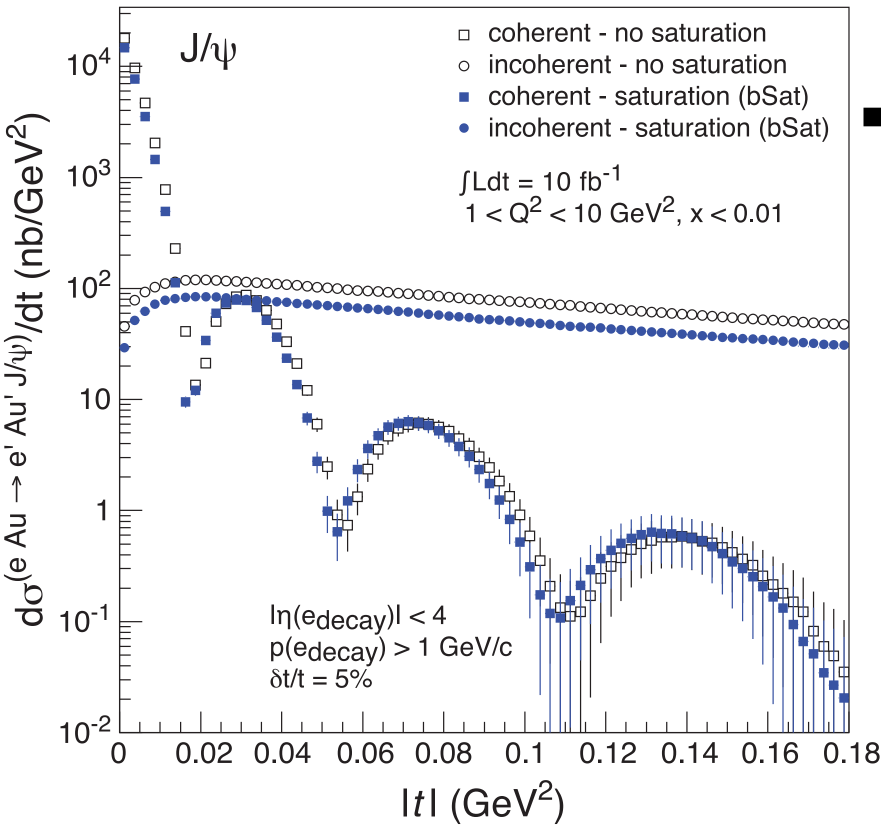
$$F(b) \sim \frac{1}{2\pi}\int_0^\infty d\Delta\,\Delta\,J_0(\Delta b)\sqrt{\frac{d\sigma}{dt}}$$

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

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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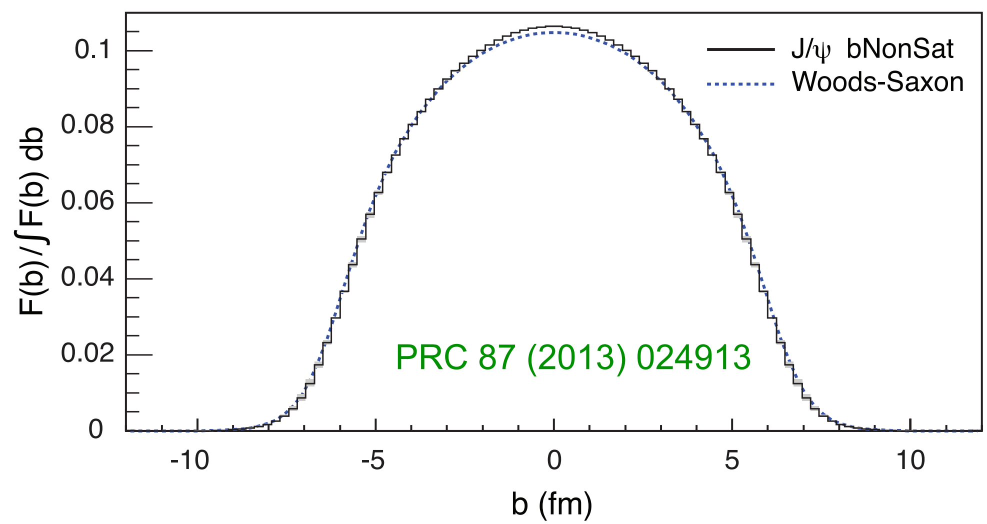


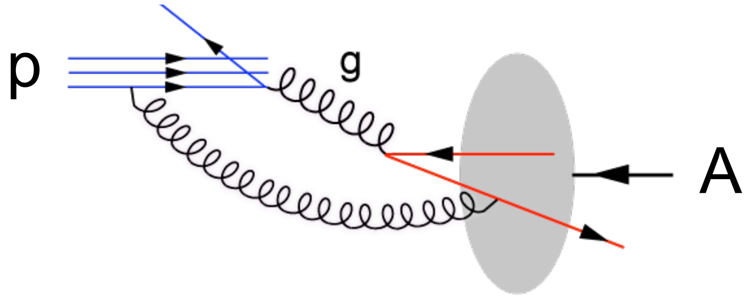
- Converges to input F(b) rapidly: $|t| < 0.1$ almost enough
- Fourier transformation requires $\int \mathcal{L} dt > 1\ fb^{-1}/A$

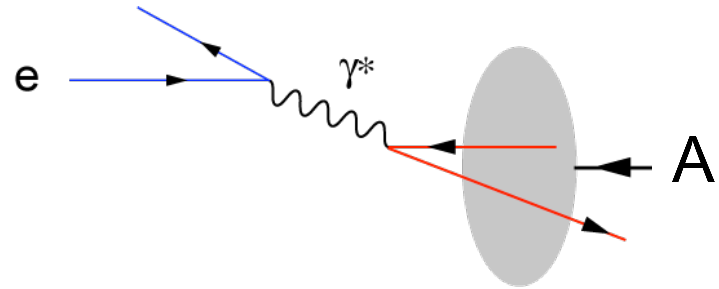
Take Away Message: Small-x

- We identified key measurements that will allow to unambiguously establish and study with precision a novel strongly correlated regime of QCD
- The EIC will allow to study the spatial and momentum distributions of gluons and sea quarks in light an heavy nuclei
- Diffractive events play a vital role in the e+A Program due to its sensitivity to the gluon distributions. They allow us to study distributions and correlation in a fully intact system while no net color is exchanged with the probe.

Complementary of e+A and p+A

- e+A: high precision & access to partonic kinematics (Q^2, x, ν)
- p+A: probe glue directly, higher cross-sections
- Flood of interesting features of p+A
  - initial state effects, cold matter energy loss
  - ridge, flow coefficients v_n, 2/3-particle correlations, …
- Same physics is accessible in e+A
  - photoproduction ($Q^2 \approx 0$), tagging of high N_{ch} events
  - ridge, v_n, 2/3-particle correlations?
- e+A will provide crucial input for A+A not provided by p+A
  - e.g. initial state (spatial and momentum distribution of glue)





Summary

The e+A program at an EIC is unprecedented, allowing the study of matter in a new regime where physics is not described by "ordinary" QCD. New capabilities open a new QCD frontier to access color propagation, neutralization, and fluctuations

- We identified and studied key measurements whose ability to extract novel physics is beyond question

Summary

The e+A program at an EIC is unprecedented, allowing the study of matter in a new regime where physics is not described by "ordinary" QCD. New capabilities open a new QCD frontier to access color propagation, neutralization, and fluctuations

- We identified and studied key measurements whose ability to extract novel physics is beyond question

Realizing this exciting program in high-energy QCD demands an Electron-Ion Collider!