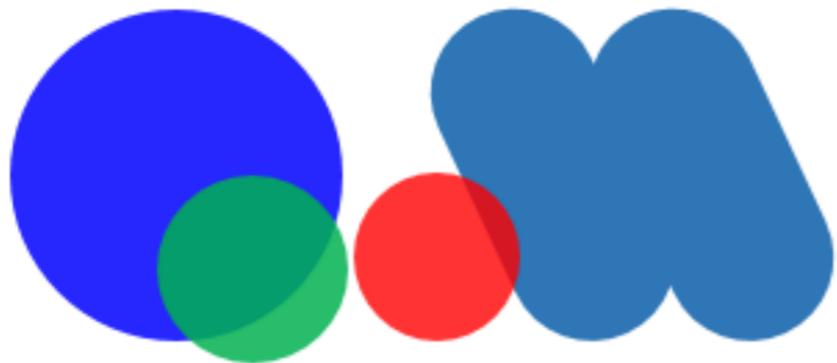




# Gluon Saturation and EIC

Ernst Sichtermann, LBNL

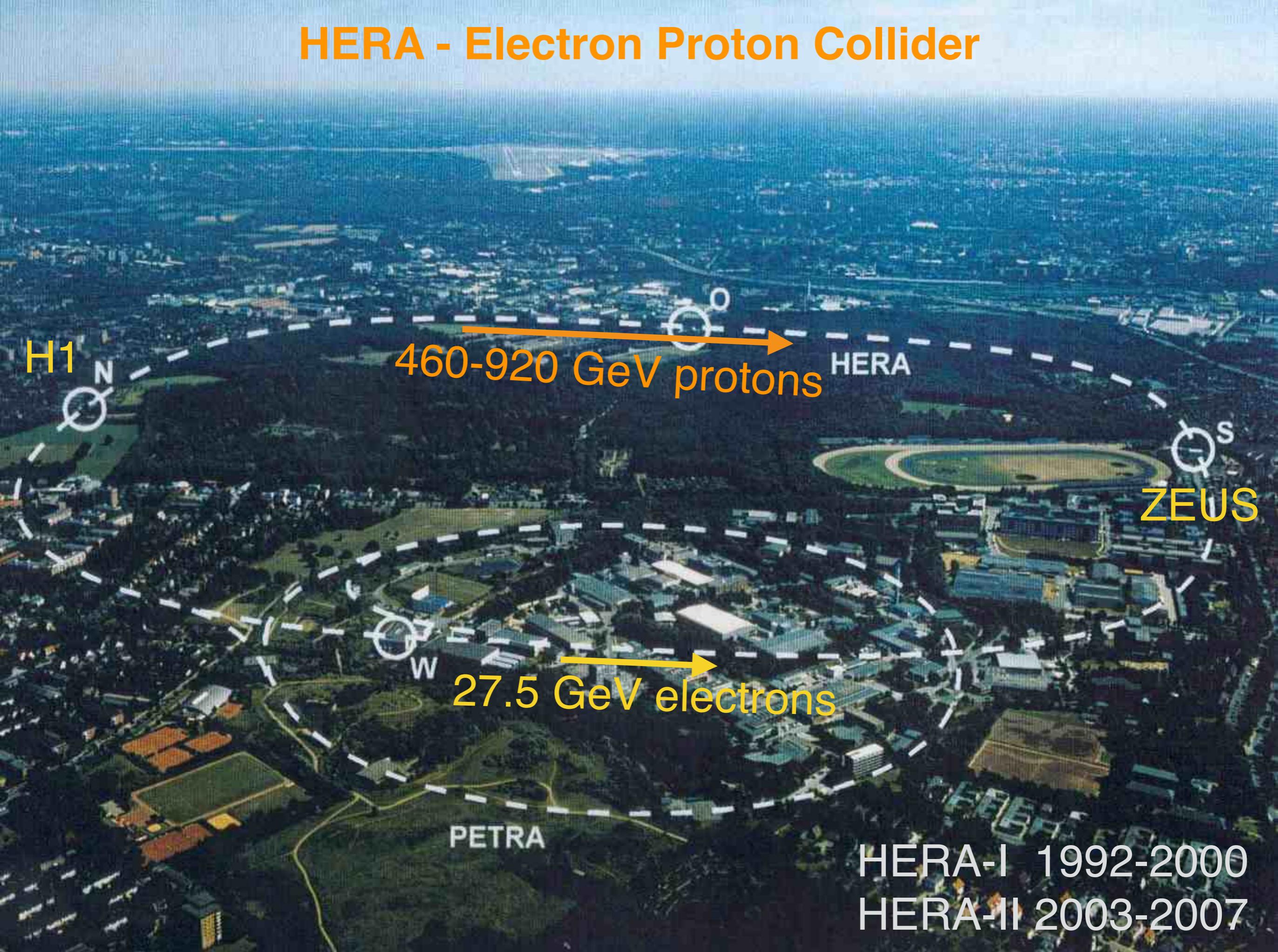


Quark Matter 2015, Kobe, Japan



Office of Science  
U.S. Department of Energy

# HERA - Electron Proton Collider



H1

460-920 GeV protons

HERA

ZEUS

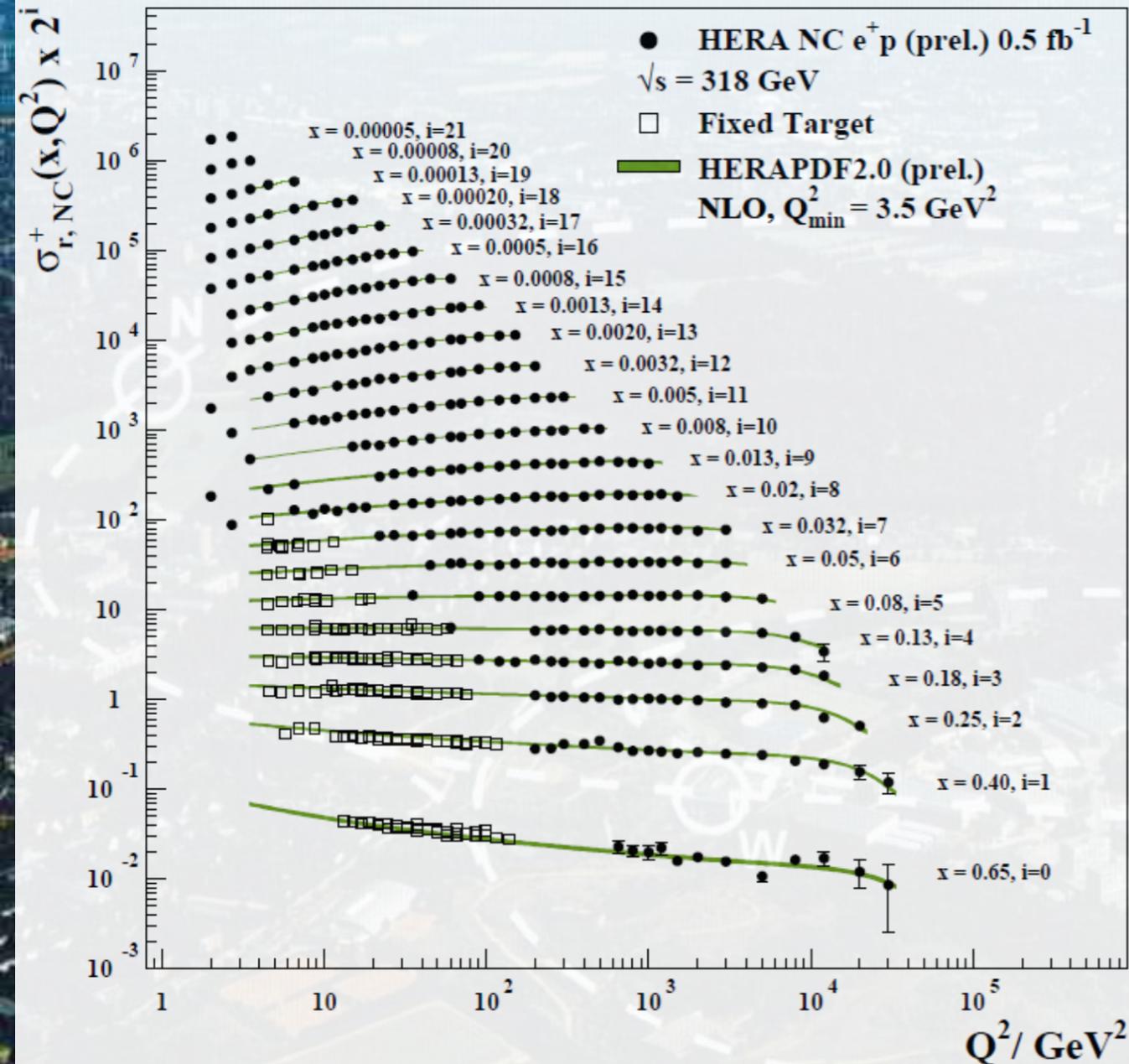
27.5 GeV electrons

PETRA

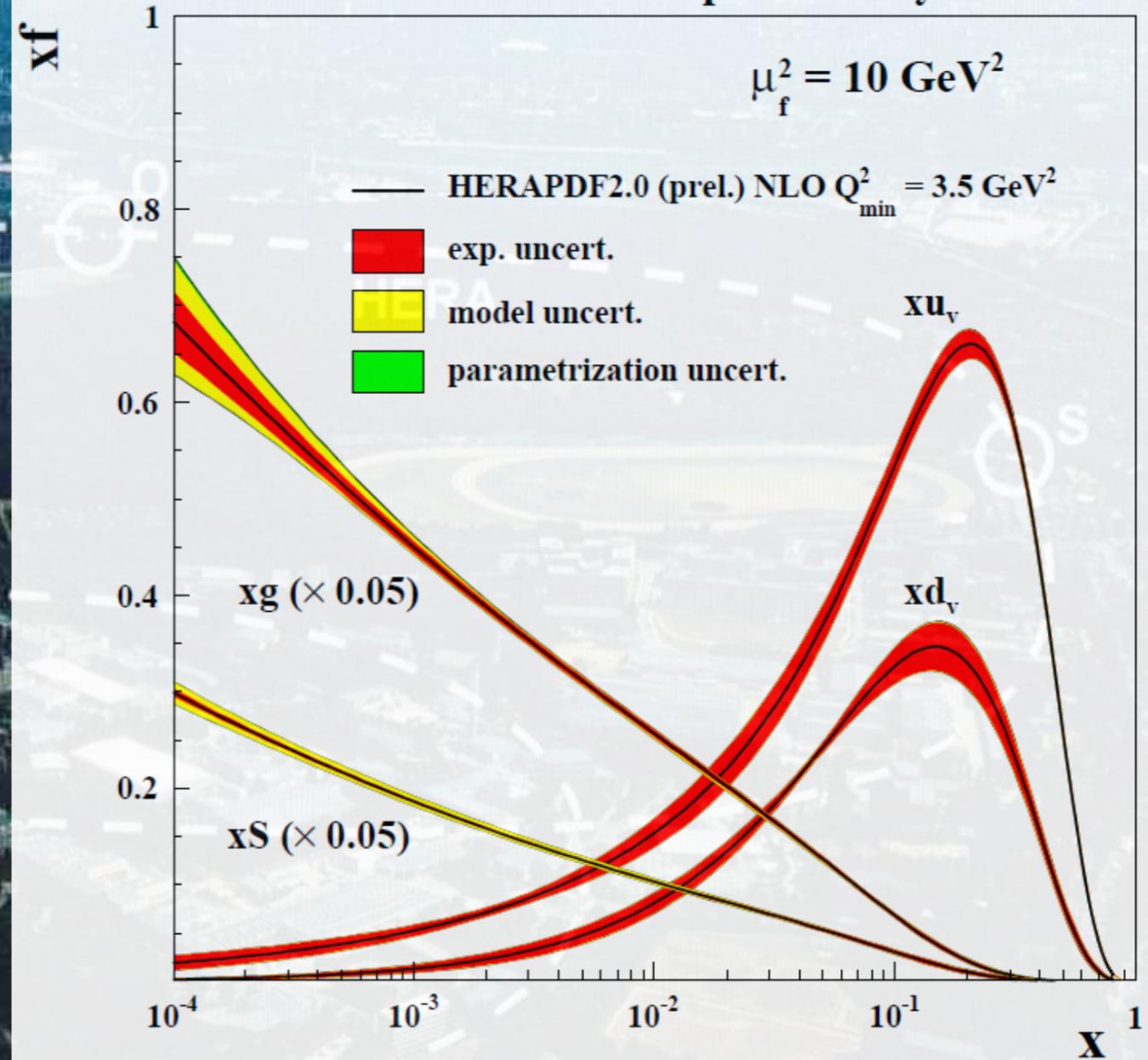
HERA-I 1992-2000  
HERA-II 2003-2007

# HERA's Legacy

H1 and ZEUS preliminary

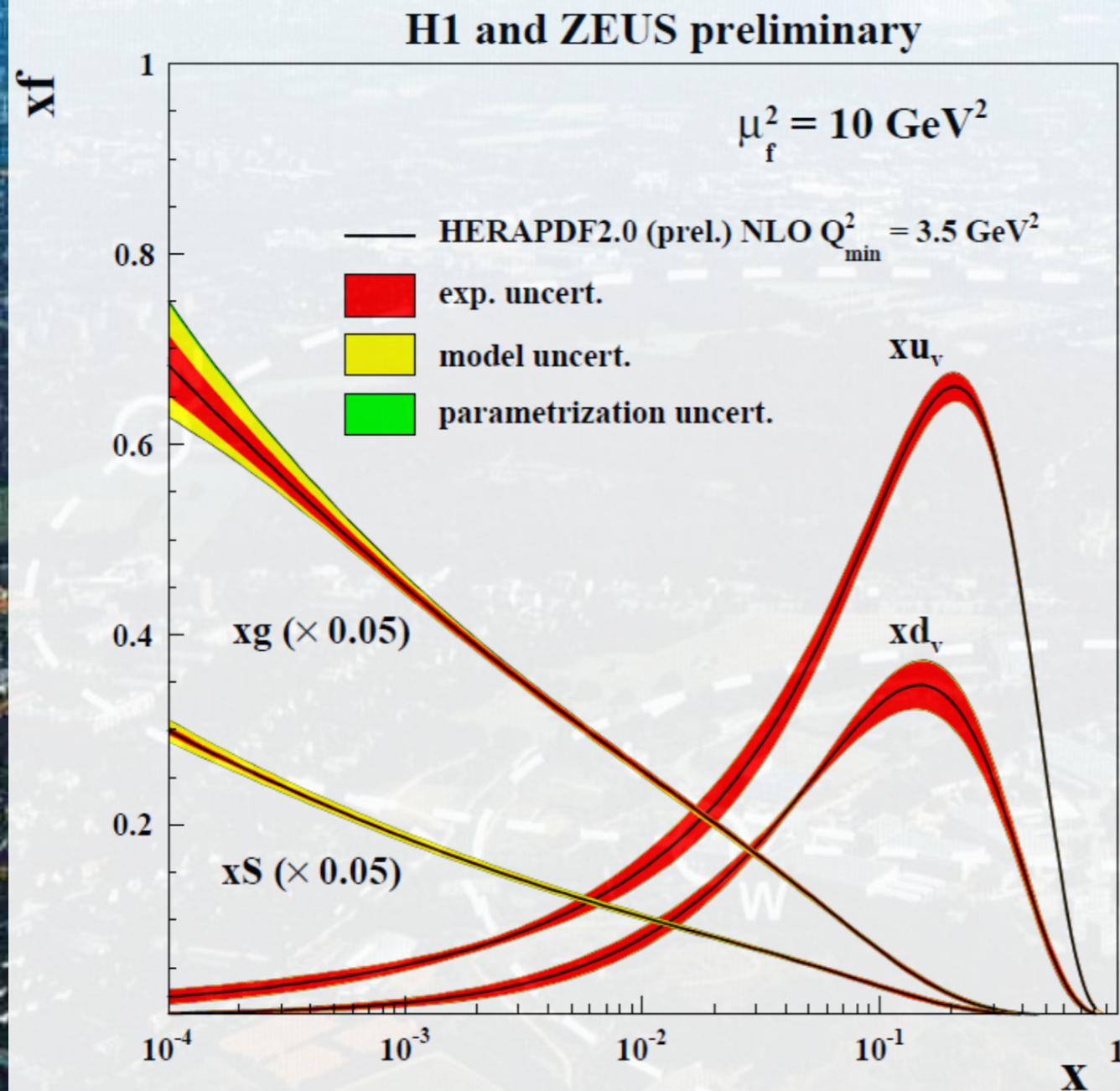


H1 and ZEUS preliminary



Vast body of *precision* measurements over a wide kinematic range,  
 Best possible insight in high-energy proton structure to date.

# HERA's Legacy



Proton structure at high-energy is:

- *far* from elementary,
- gluon-dominated for  $x < 0.1$ ,

Gluon content increases with decreasing  $x$ ,

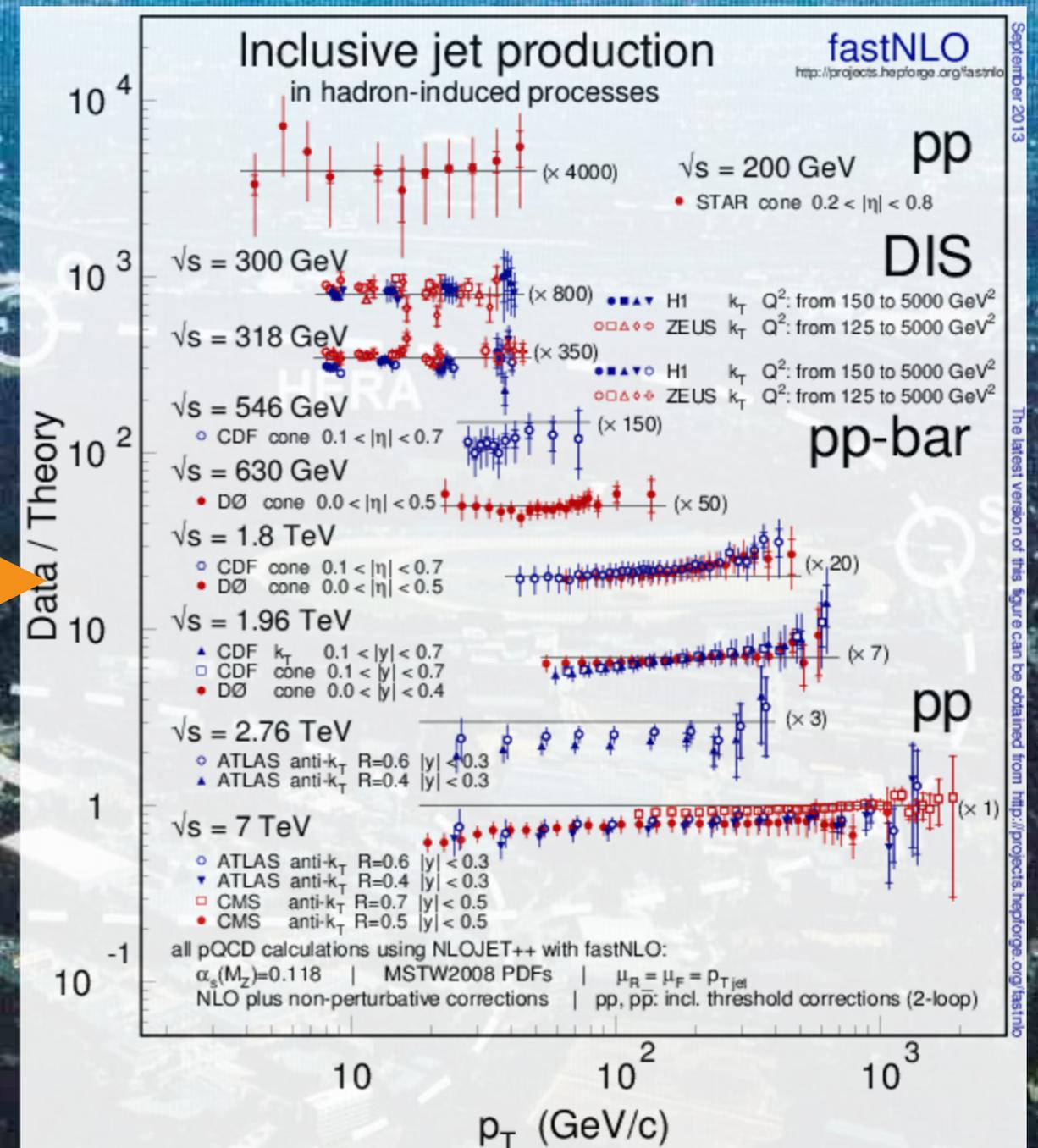
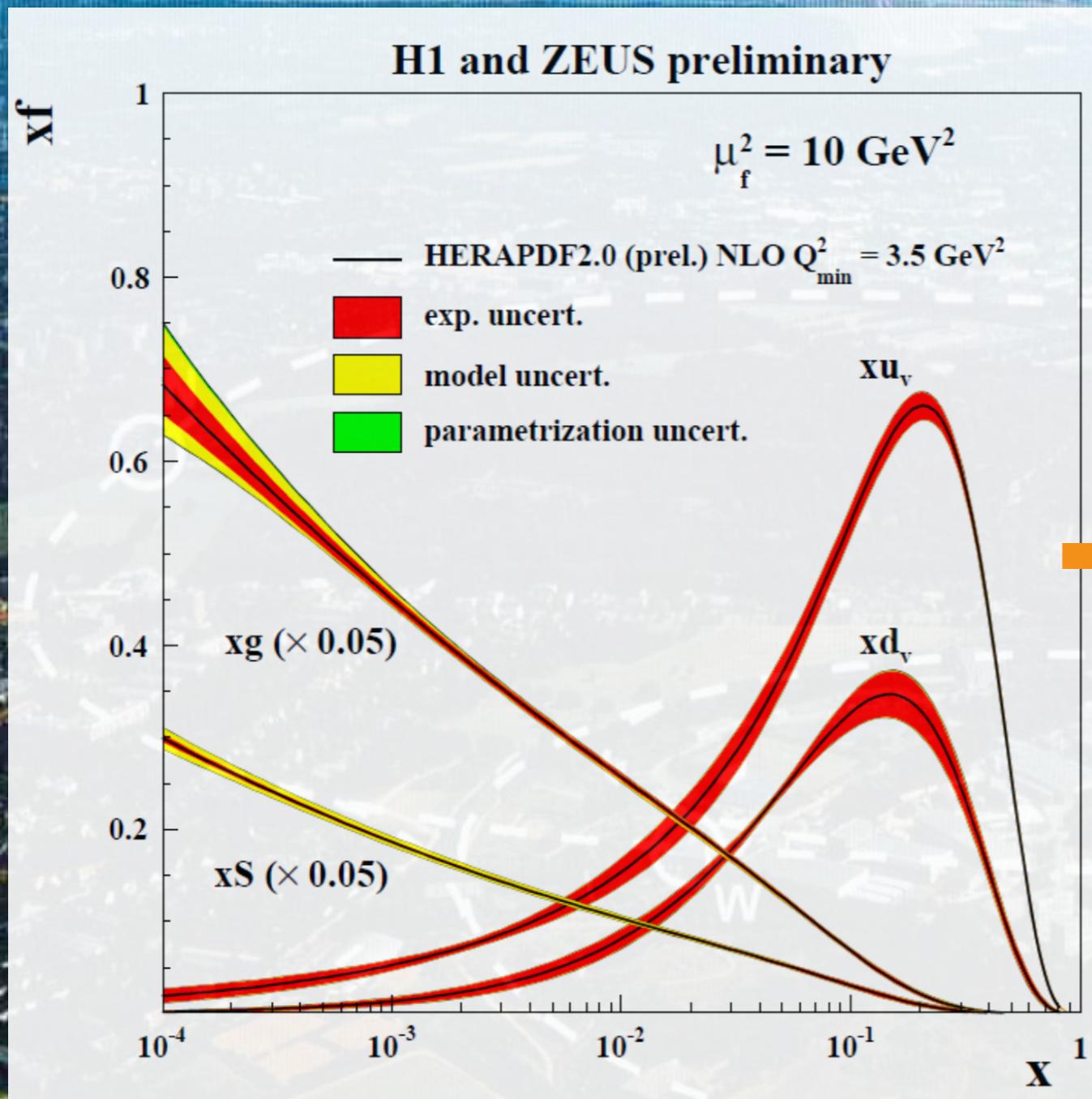
Gluons pose a number of questions

HERAPDF2.0:

- 15 parameters,
- $\sim 1400$  combined data points,

PETRA

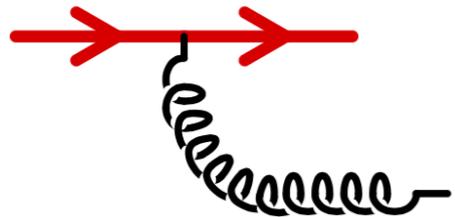
# HERA's Legacy



Factorization, the separation of short distance and long distance physics, combined with PDFs are 'universally invaluable' in hard scattering processes.

# QCD radiation and saturation

QCD **splitting**:



$$dP \propto \alpha_s \frac{d^2 k_{\perp}}{k_{\perp}^2} \frac{dx}{x}$$

is calculable; it is soft and collinear divergent - these divergencies must be resummed,

Density of gluons per unit of transverse area:

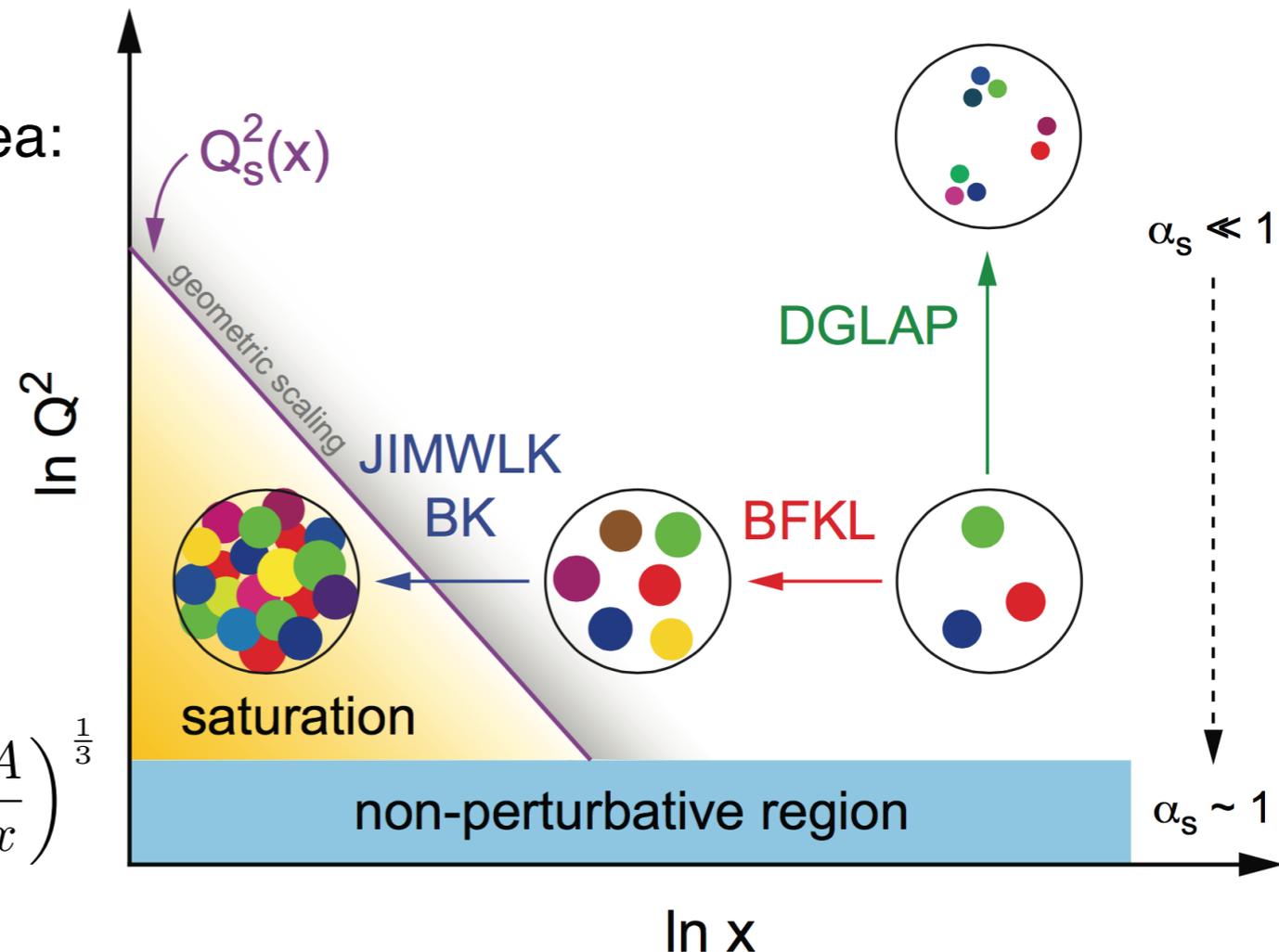
$$\rho \propto x g(x, Q^2) / \pi R^2$$

Cross section for gluon **recombination**:

$$\sigma \propto \alpha_s / Q^2$$

**Saturation:**

$$1 < \rho\sigma \rightarrow Q^2 < Q_s^2(x) \sim \left(\frac{A}{x}\right)^{1/3}$$

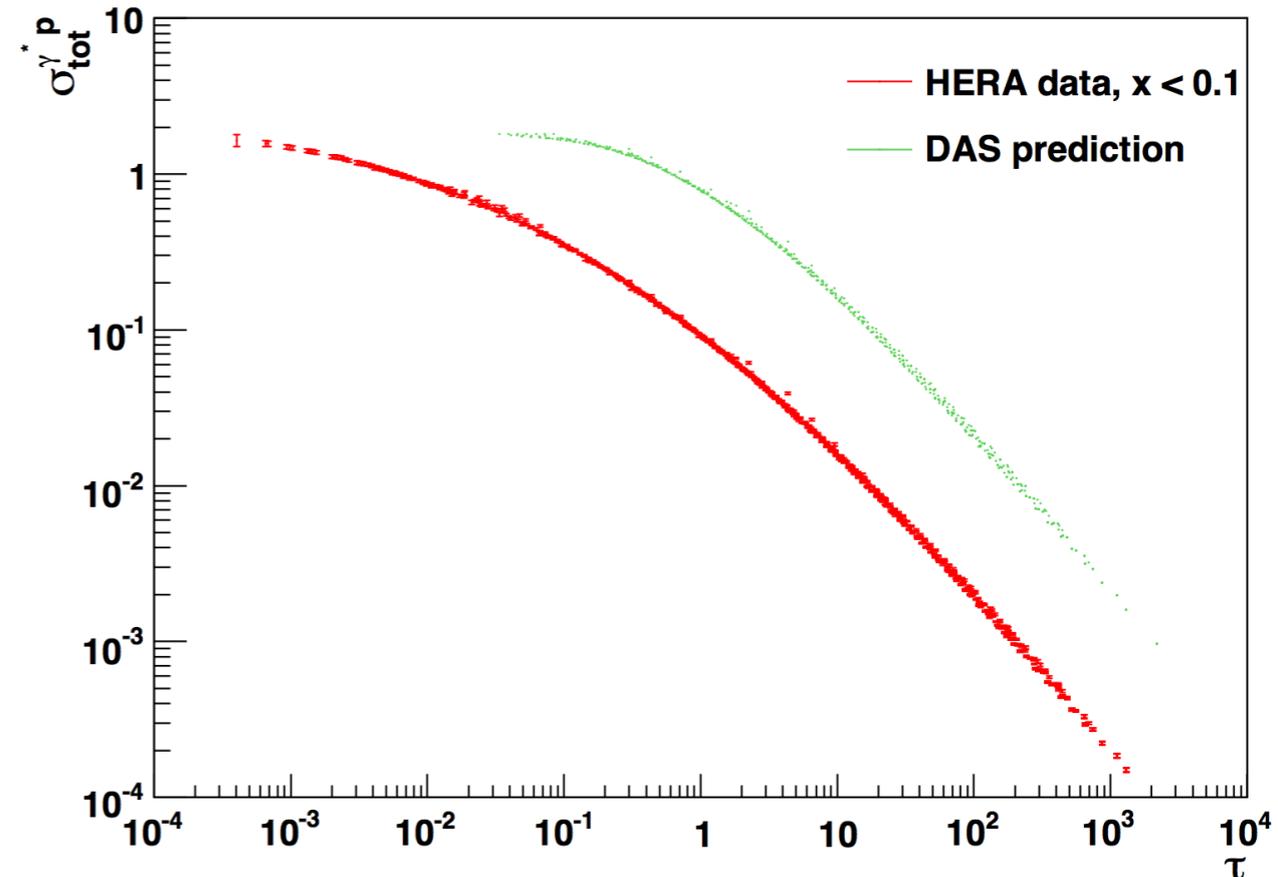
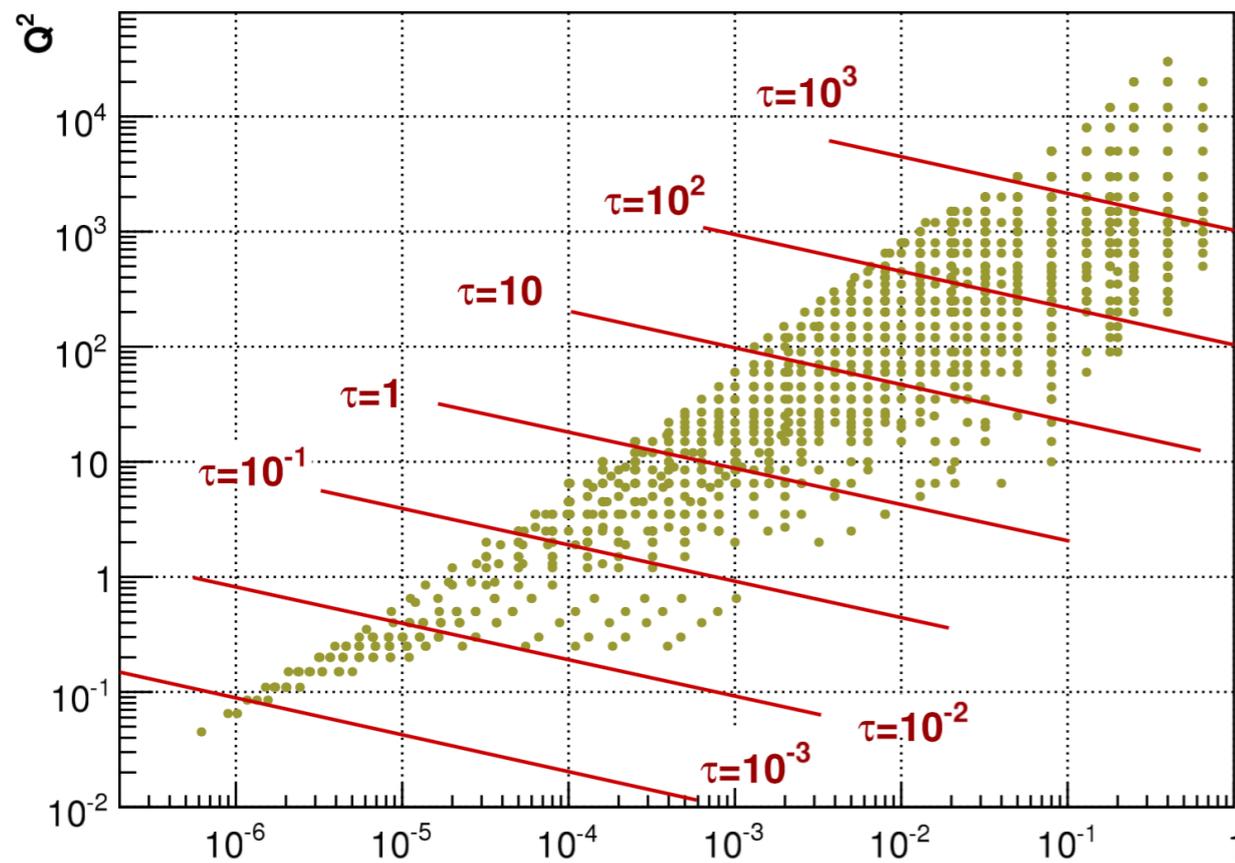


Gribov, Levin, Ryskin 1983

Dense system, non-linear evolution - onset is largely an experimental question, effective theory/theories.

# Saturation at HERA? - Think outside the PDF!

- No evidence from DGLAP fits in sub-ranges, comparison with  $F_L$ , ...



- HERA c.s. data exhibit geometrical scaling with respect to

$$\tau = \frac{Q^2}{Q_s^2(x)} = \frac{Q^2}{Q_0^2} \frac{x^\lambda}{x_0} \quad \text{for } x < 0.01$$

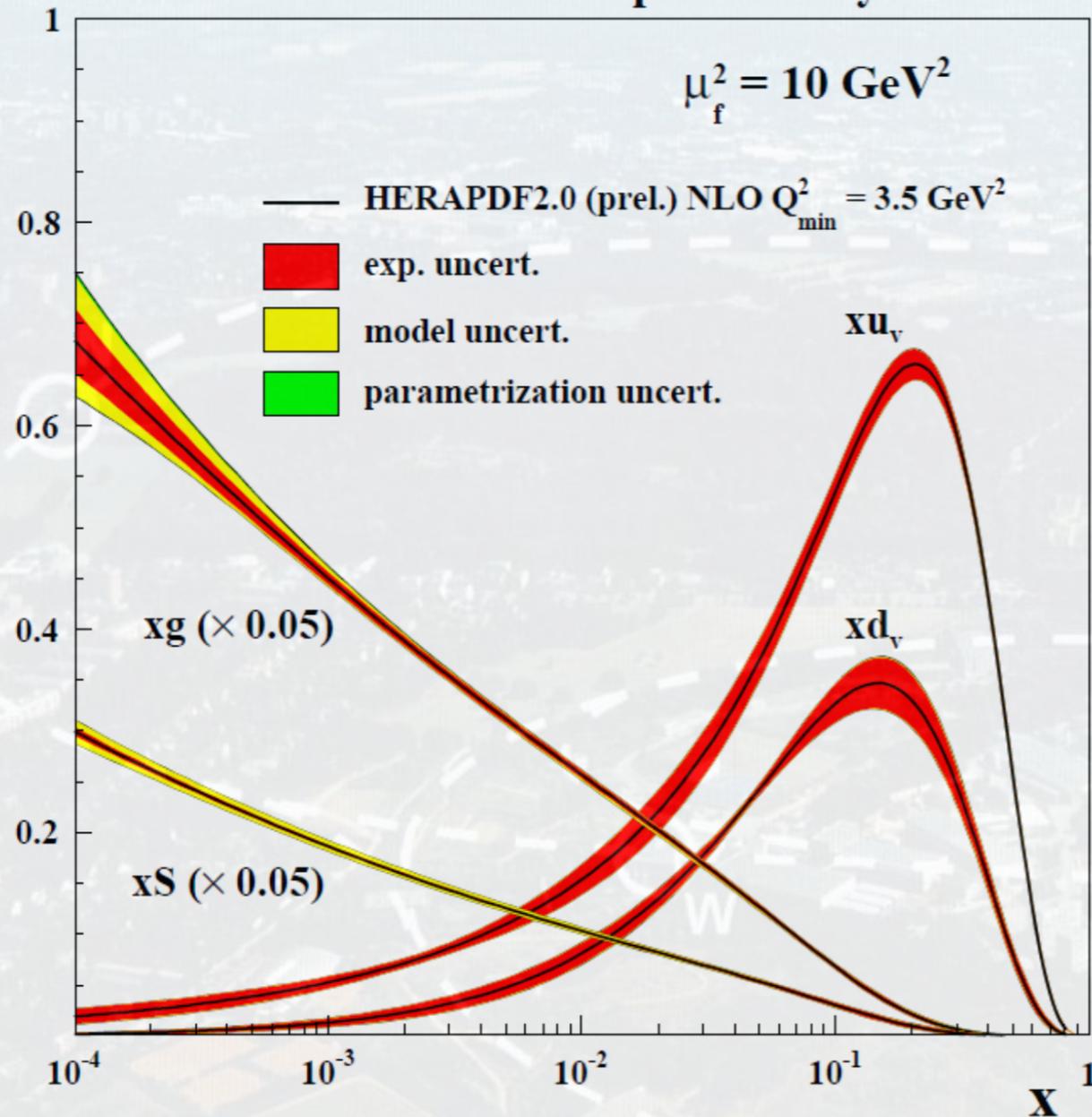
*not* seen in prior fixed-target experiments - Stasto et al.

However, DLL LO solution to DGLAP *also* scales - Caolo et al.

- ~15% of events is diffractive (!).

# HERA's Legacy

H1 and ZEUS preliminary



Exquisite insight in proton structure in terms of quark and gluon degrees of freedom,

... and also some quite remarkable voids;

Precision  $F_L$  - insufficient time,

Test isospin, u-d, - no deuterons,

d/u at large  $x$  - luminosity,

Strange quark distributions - luminosity,

Spin puzzle - no hadron beam polarization,

Quark-gluon dynamics in nuclei - no nuclei,

Saturation - insufficient  $\sqrt{s}$  / no nuclei,

...

PETRA

# Electron Ion Collider Initiatives

Past

Possible Future

	HERA @ DESY	LHeC @ CERN	HIAF @ CAS	ENC @ GSI	MEIC/ELIC @ JLab	eRHIC @ BNL
$\sqrt{s}$ [GeV]	320	800 - 1300	12 - 65	14	20 - 140	78 - 145
proton $x_{min}$	$1 \times 10^{-5}$	$5 \times 10^{-7}$	$7 \times 10^{-3} - 3 \times 10^{-4}$	$5 \times 10^{-3}$	$1 \times 10^{-4}$	$5 \times 10^{-5}$
ion	p	p to Pb	p to U	p to $\sim^{40}\text{Ca}$	p to Pb	p to U
polarization	-	-	p, d, $^3\text{He}$	p, d	p, d, $^3\text{He}$ ( $^6\text{Li}$ )	p, $^3\text{He}$
L [ $\text{cm}^{-2}\text{s}^{-1}$ ]	$2 \times 10^{31}$	$10^{34}$	$10^{32-33} - 10^{35}$	$10^{32}$	$10^{33-34}$	$10^{33}$
Interaction Points	2	1 (?)	1	1	2+	1-2
Year	1992 - 2007	post ALICE	2019 - 2030	upgrade to FAIR	post 12 GeV	2025

High-Energy Physics

Nuclear Physics

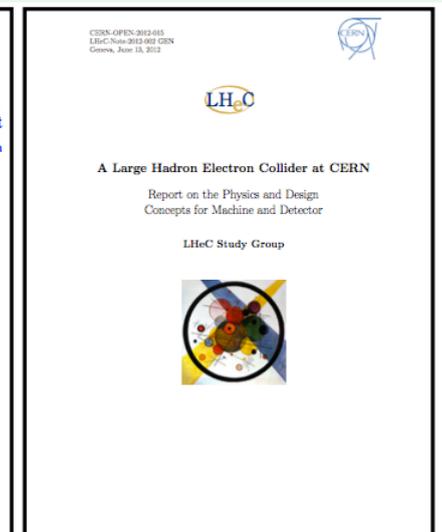
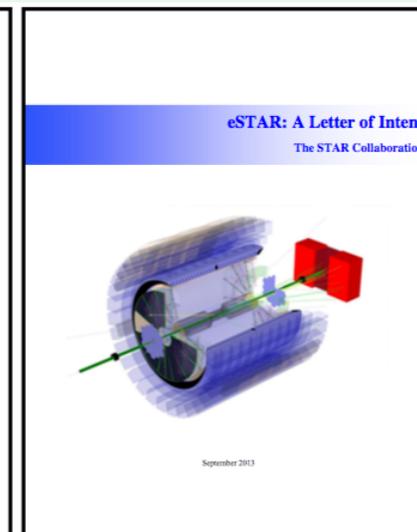
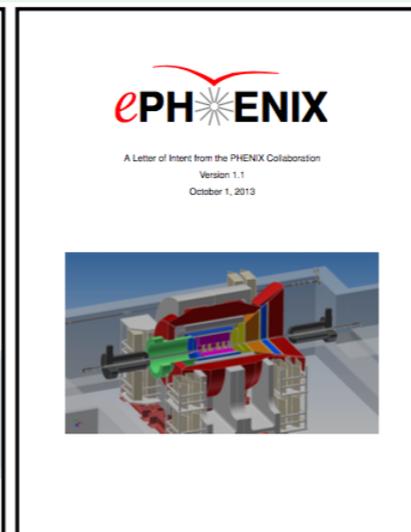
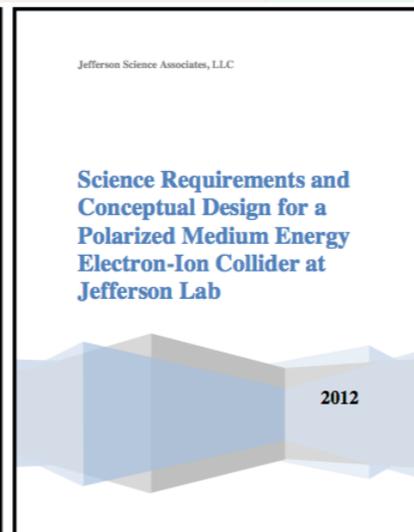
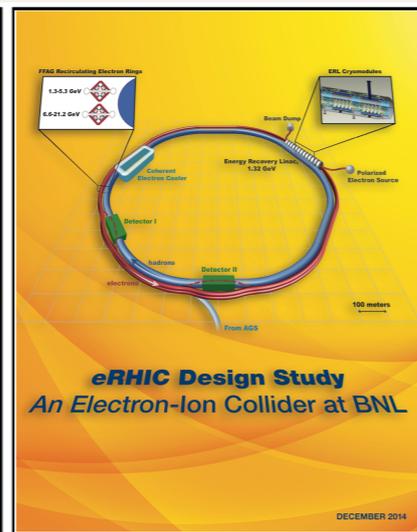
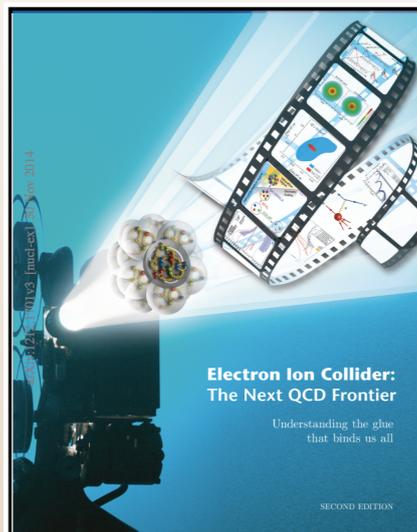
World Wide Interest

# Electron Ion Collider Initiatives

Past

Strategy: optimally use existing investments, pursue luminosity; 10x - 100x HERA nuclei and *polarization* (eRHIC, MEIC), nuclei and *energy* (LHeC), optimized instrumentation.

	HERA @ DESY	LHeC @ CERN	HIAF @ CAS	ENC @ GSI	MEIC/ELIC @ JLab	eRHIC @ BNL
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+ popular press, most recently "Les gluons nous posent encore des colles", Ent, Ullrich, Venugopalan, Pour La Science 455, Sept. '15

# U.S.-based EIC - Two Facility Concepts

eRHIC:

- upgrade to RHIC hadron beam,



MEIC:

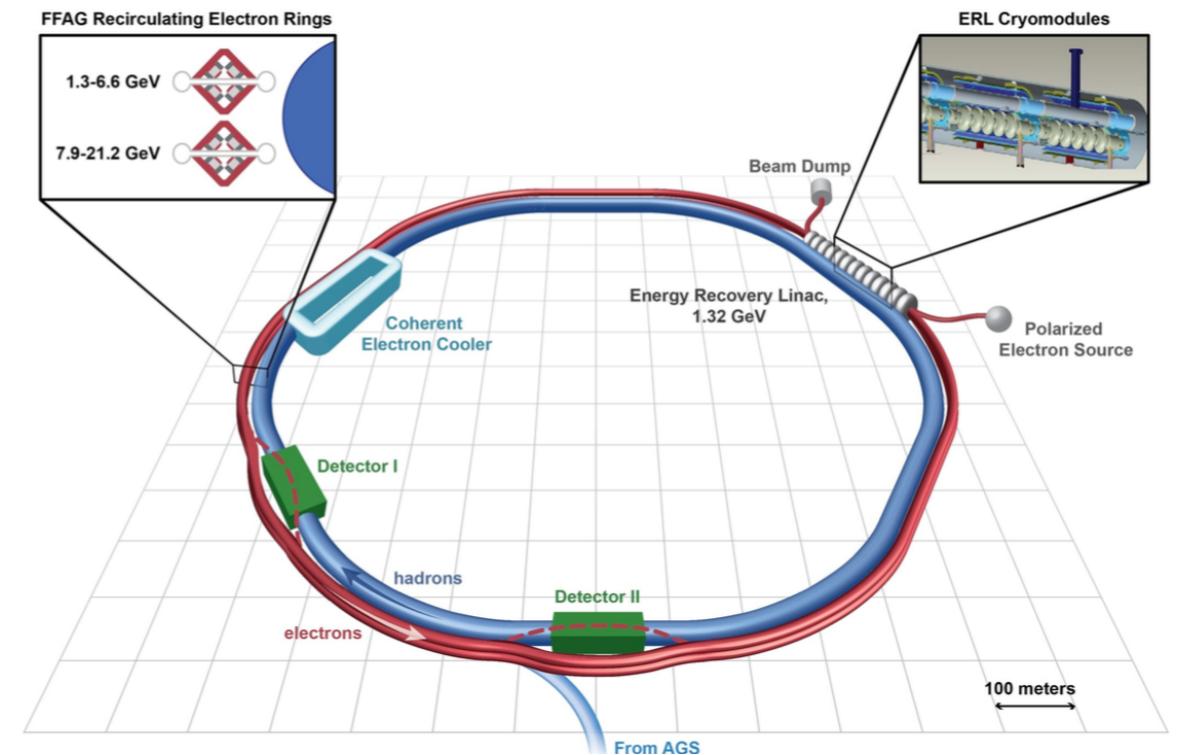
- upgrade to CEBAF 12 GeV electron beam,



# U.S.-based EIC - Two Facility Concepts

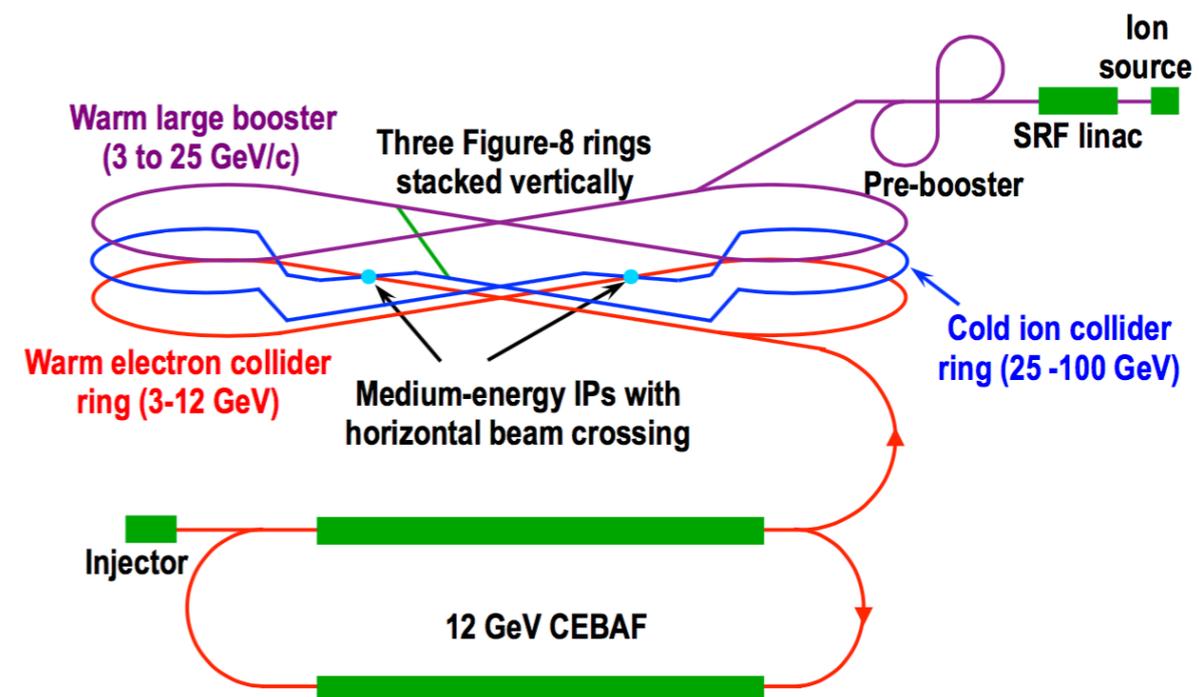
## eRHIC:

- upgrade to RHIC hadron beam,
- add ERL and FFAG Recirculating electron ring,
- 6.3 - 15.9 and 21.2 GeV e energy,
- Heavy Ions up to 100 GeV/u
- $\sqrt{s}$  up to 93 GeV
- $L \sim 10^{33} \text{ cm}^{-2}\text{s}^{-1}/A$  base design.

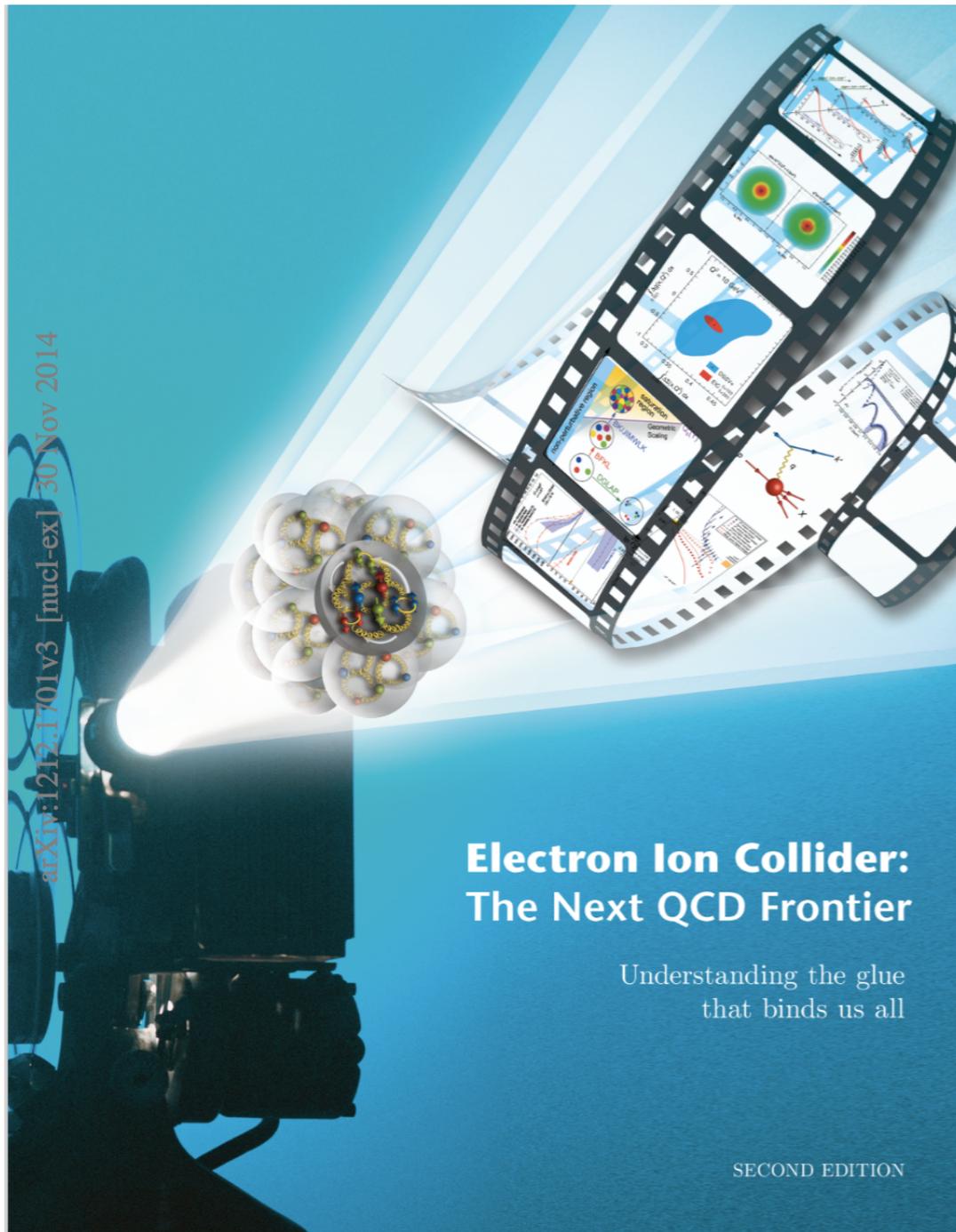


## MEIC:

- upgrade to CEBAF 12 GeV electron beam facility,
- new hadron injector,
- new figure-8 collider configuration,
- 3-12 GeV electron energy,
- 12-40 GeV/u Heavy Ion energy,
- $L \sim 10^{34} \text{ cm}^{-2}\text{s}^{-1}/A$



# U.S.-based EIC - Science Focus



coherent contributions from many nucleons effectively amplify the gluon density being probed.

The EIC was designated in the 2007 Nuclear Physics Long Range Plan as "embodying the vision for reaching the next QCD frontier" [1]. It would extend the QCD sci-

ence programs in the U.S. established at both the CEBAF accelerator at JLab and RHIC at BNL in dramatic and fundamentally important ways.

The most intellectually pressing questions that an EIC will address that relate to our detailed and fundamental understanding of QCD in this *frontier* environment are:

- **How are the sea quarks and gluons, and their spins, distributed in space and momentum inside the nucleon?** How are these quark and gluon distributions correlated with overall nucleon properties, such as spin direction? What is the role of the orbital motion of sea quarks and gluons in building the nucleon spin?
- **Where does the saturation of gluon densities set in?** Is there a simple boundary that separates this region from that of more dilute quark-gluon matter? If so, how do the distributions of quarks and gluons change as one crosses the boundary? Does this saturation produce matter of universal properties in the nucleon and all nuclei viewed at nearly the speed of light?
- **How does the nuclear environment affect the distribution of quarks and gluons and their interactions in nuclei?** How does the transverse spatial distribution of gluons compare to that in the nucleon? How does nuclear matter respond to a fast moving color charge passing through it? Is this response different for light and heavy quarks?

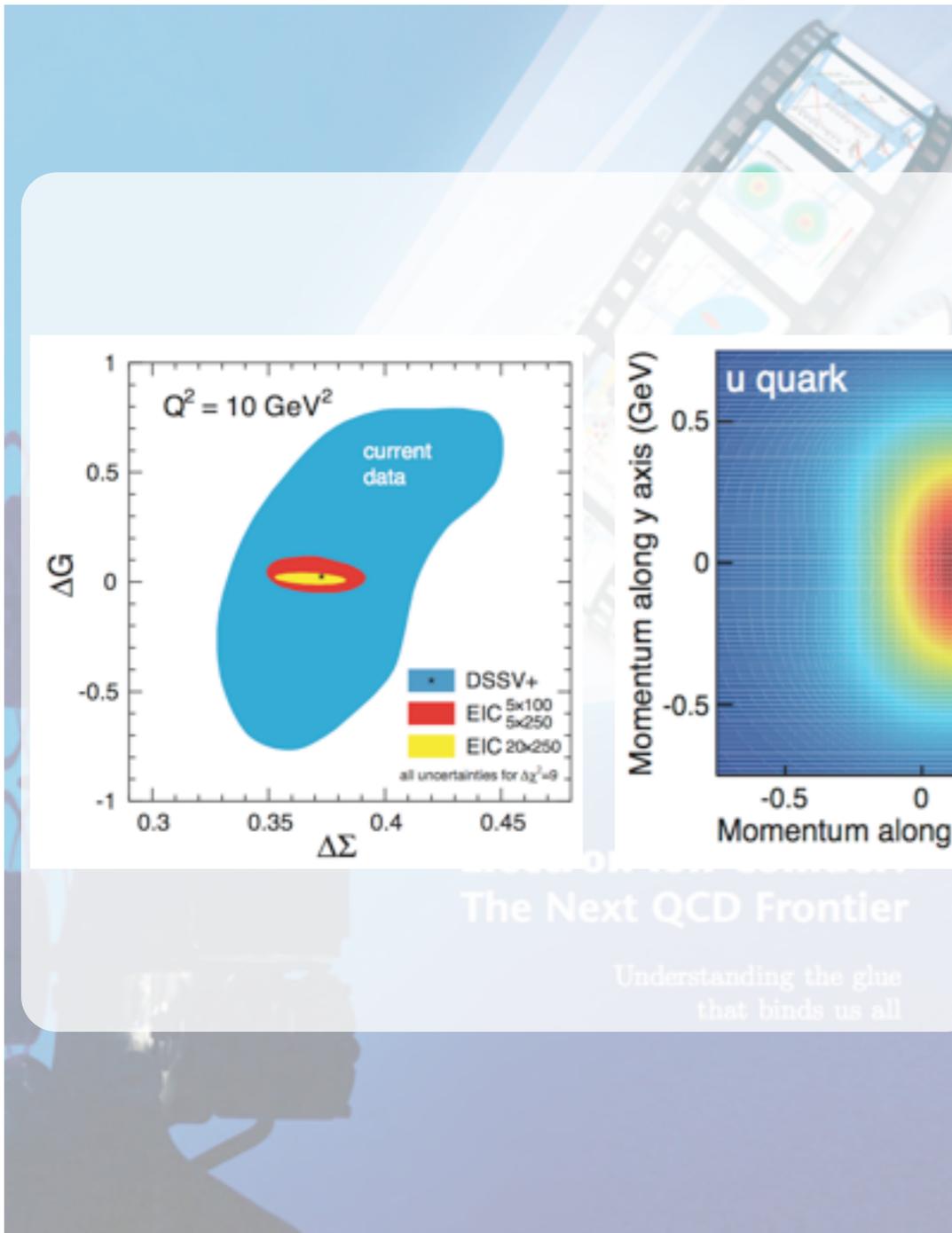
Answers to these questions are essential for understanding the nature of visible matter. An EIC is the ultimate machine to provide answers to these questions for the following reasons:

- A collider is needed to provide kinematic reach well into the gluon-dominated regime;
- Electron beams are needed to bring to bear the unmatched precision of the electromagnetic interaction as a probe;
- Polarized nucleon beams are needed to determine the correlations of sea quark and gluon distributions with the nucleon spin;
- Heavy ion beams are needed to provide precocious access to the regime of saturated gluon densities and offer a precise dial in the study of propagation-length for color charges in nuclear matter.

The EIC would be distinguished from all past, current, and contemplated facilities around the world by being at the intensity frontier with a versatile range of kinematics and beam polarizations, as well as beam species, allowing the above questions to be tackled at one facility. In particular, the EIC design exceeds the capabilities of HERA, the only electron-proton collider

to date, by adding a) polarized proton and light-ion beams; b) a wide variety of heavy-ion beams; c) two to three orders of magnitude increase in luminosity to facilitate tomographic imaging; and d) wide energy variability to enhance the sensitivity to gluon distributions. Achieving these challenging technical improvements in a single facility will extend U.S. leadership in accelerator sci-

# U.S.-based EIC - Science Focus

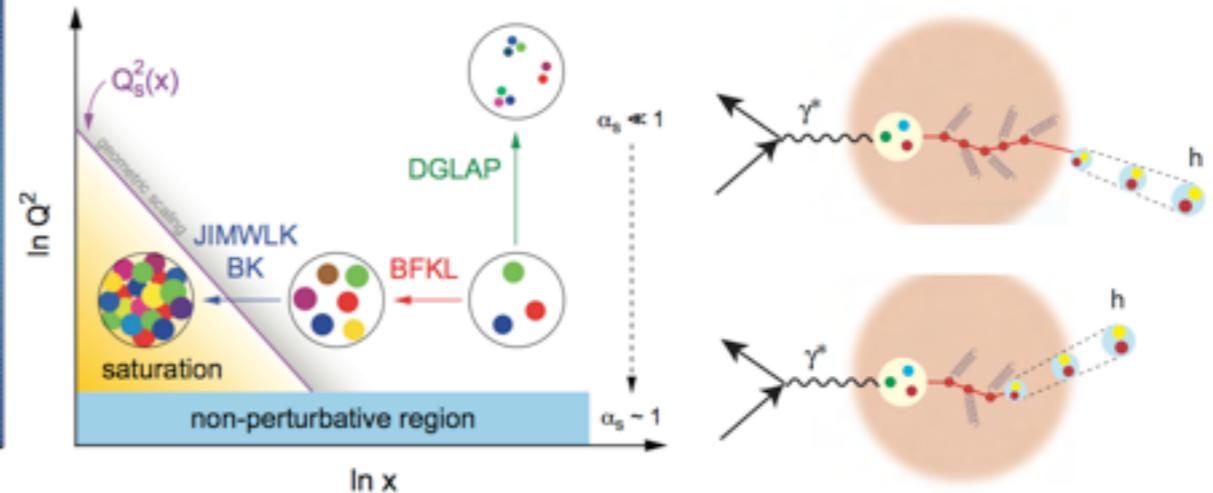


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# U.S.-based EIC - Observables

## Key questions:

- How are the sea quarks and gluons, and their spins, distributed in space and momentum inside the nucleus?
- Where does the saturation of gluon densities set in?
- How does the nuclear environment affect the distribution of quarks and gluons and their interactions in nuclei?

## Key measurements:

- Inclusive Deep-Inelastic Scattering,
- Semi-inclusive deep-inelastic scattering with one or two of the particles in the final state,
- Exclusive deep-inelastic scattering,
- Diffraction.

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

- Where does the saturation of gluon densities set in? Is there a simple boundary between the perturbative and non-perturbative regimes? If so, how is the distribution of quarks and gluons changed at this boundary? Does this saturation produce matter of universal properties in the nucleon and all nuclei viewed at nearly the speed of light?

- How does the nuclear environment affect the distribution of quarks and gluons and their interactions in nuclei? How does the transverse spatial distribution of quarks and gluons change as a function of the nuclear size?

Answers to these questions are essential for understanding the nature of visible matter. An EIC is the ultimate machine to provide answers to these questions for the following reasons:

- A collider is needed to provide kinematic reach well into the gluon-dominated regime;
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# U.S.-based EIC - Observables

## Key requirements:

- *Electron identification - scattered lepton*
- *Momentum and angular resolution -  $x, Q^2$*
- *$\pi^+, \pi^-, K^+, K^-, p^+, p^-, \dots$  identification, acceptance*
- *Rapidity coverage,  $t$ -resolution*

## Key measurements:

- *Inclusive Deep-Inelastic Scattering,*
- *Semi-inclusive deep-inelastic scattering with one or two of the particles in the final state,*
- *Exclusive deep-inelastic scattering,*
- *Diffraction.*

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- Where does the saturation of gluon densities set in? Is there a simple boundary to the distribution of quarks and gluons in the nucleon? If so, how does this saturation produce matter of universal properties in the nucleon and all nuclei viewed at nearly the speed of light?

- How does the nuclear environment affect the distribution of quarks and gluons and their interactions in nuclei? How does the transverse spatial distribution of quarks and gluons change as the nucleus is viewed at nearly the speed of light?

Answers to these questions are essential for understanding the nature of visible matter. An EIC is the ultimate machine to provide answers to these questions for the following reasons:

- A collider is needed to provide kinematic reach well into the gluon-dominated regime; the EIC will provide a unique probe of the electromagnetic interaction as a probe;

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Electron Ion Collider:  
The Next QCD Frontier

Understanding the glue  
that binds us all

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- Momentum and angular resolution -  $x, Q^2$
- $\pi^+, \pi^-, K^+, K^-, p^+, p^-, \dots$  identification, acceptance
- Rapidity coverage,  $t$ -resolution

## Key measurements:

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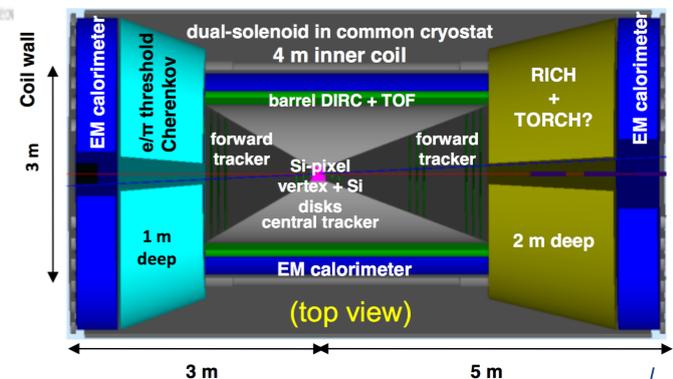
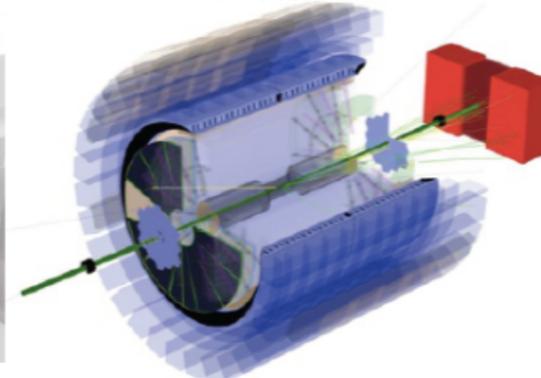
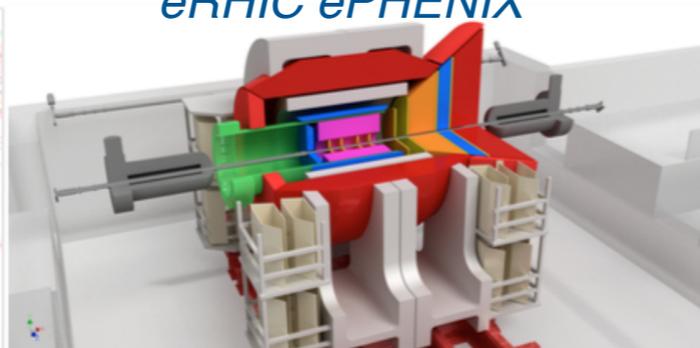
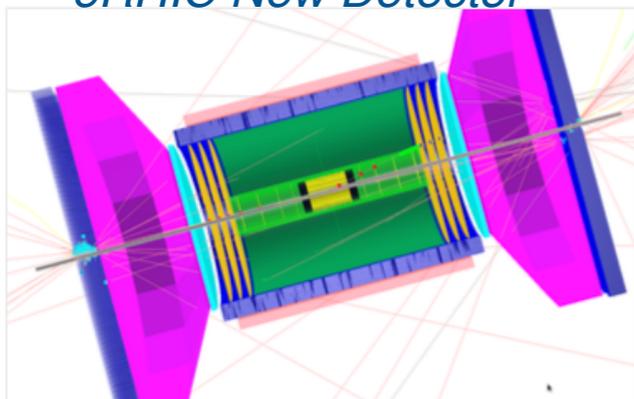
Electron Ion Collider:  
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eRHIC New Detector

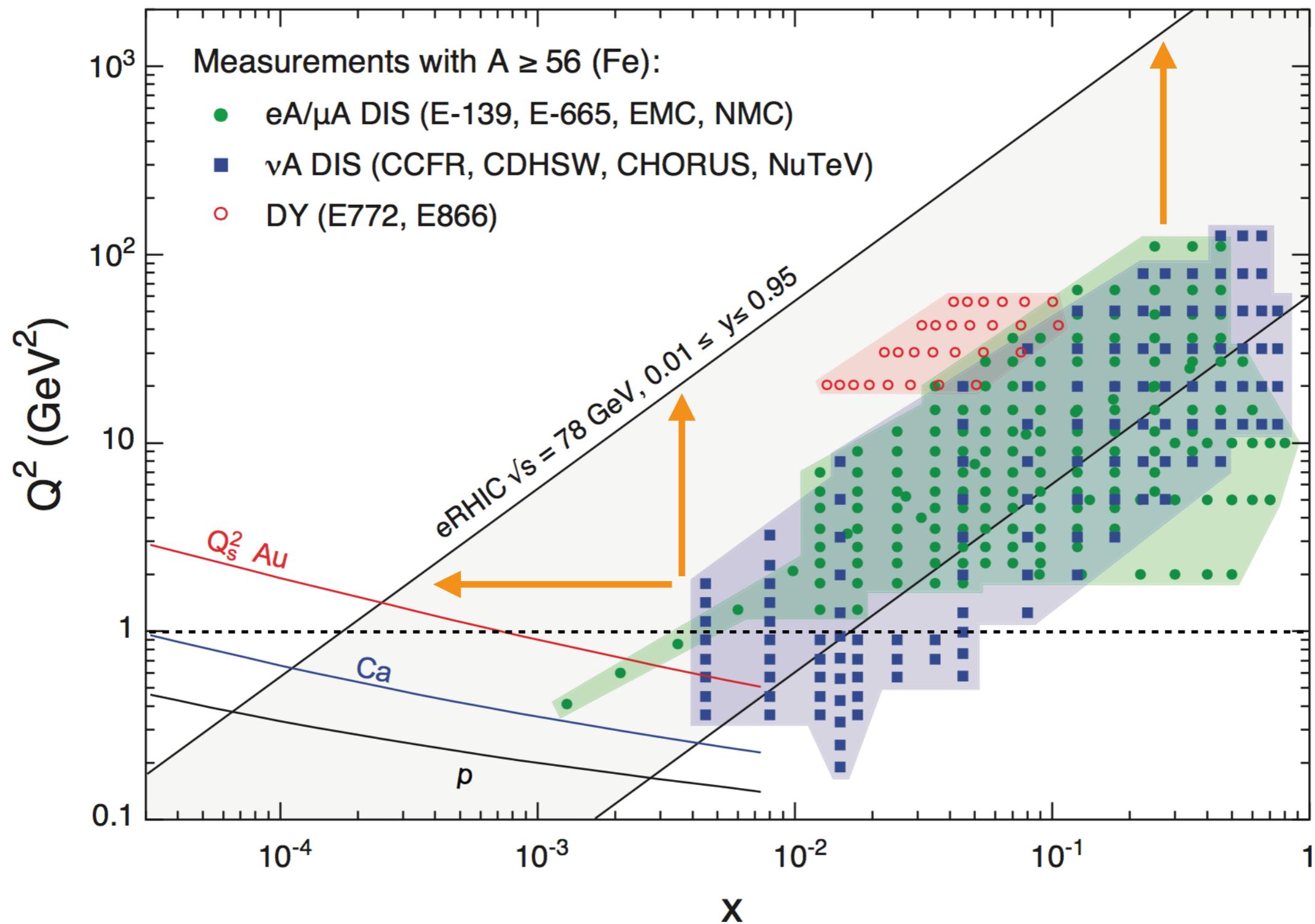
eRHIC ePHENIX

eRHIC eSTAR

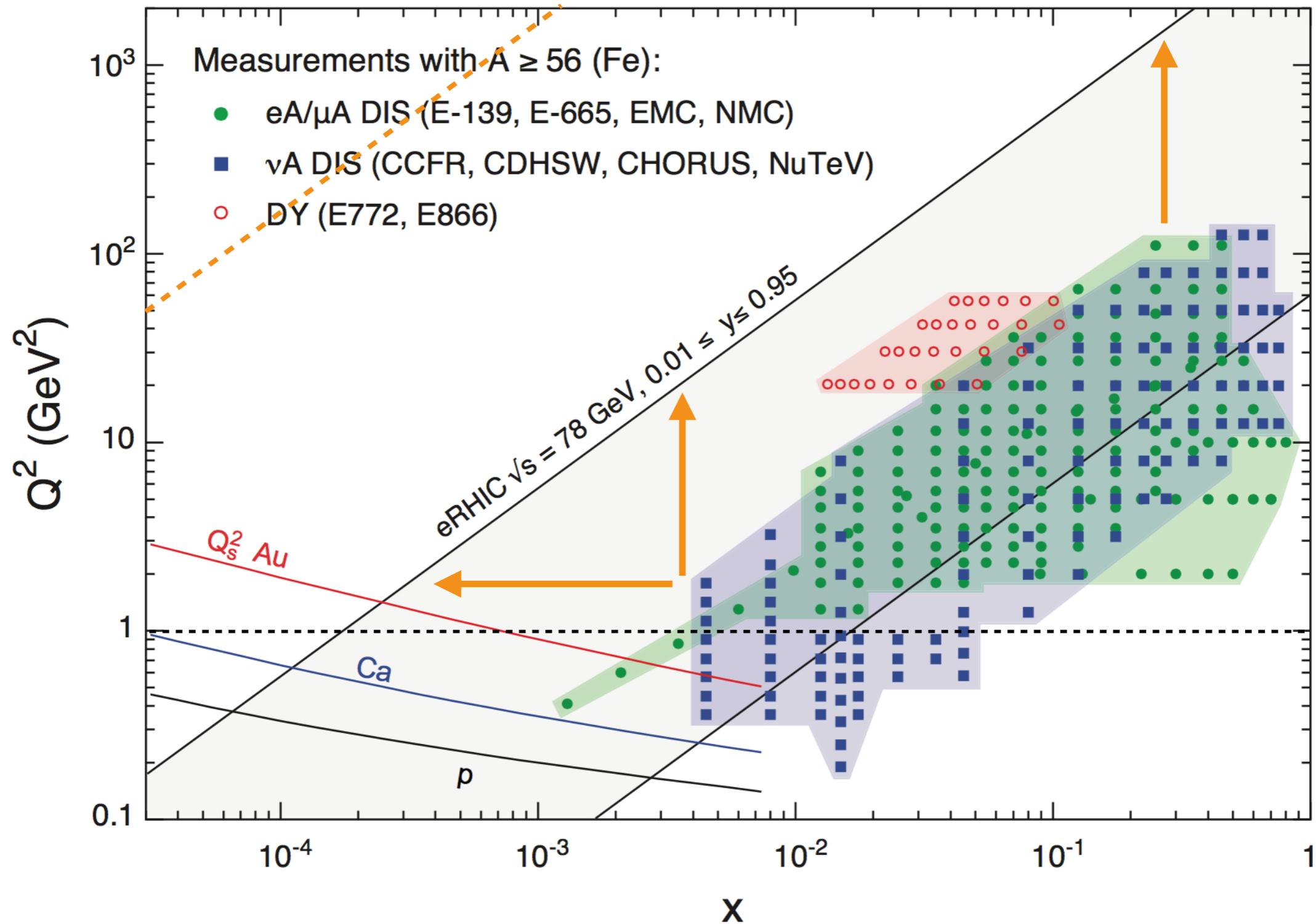
MEIC new detector



# Existing eA landscape - eRHIC kinematic range



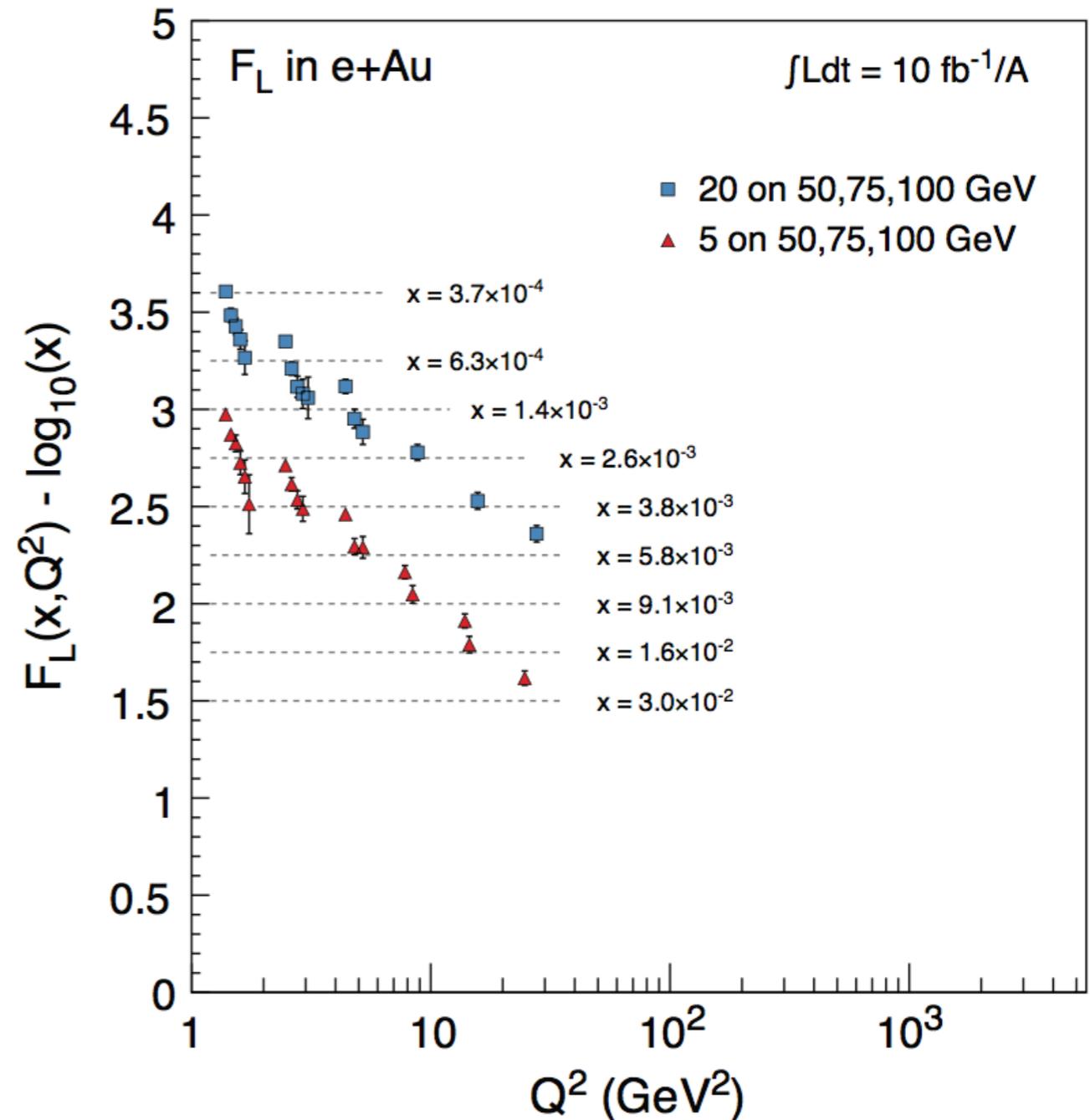
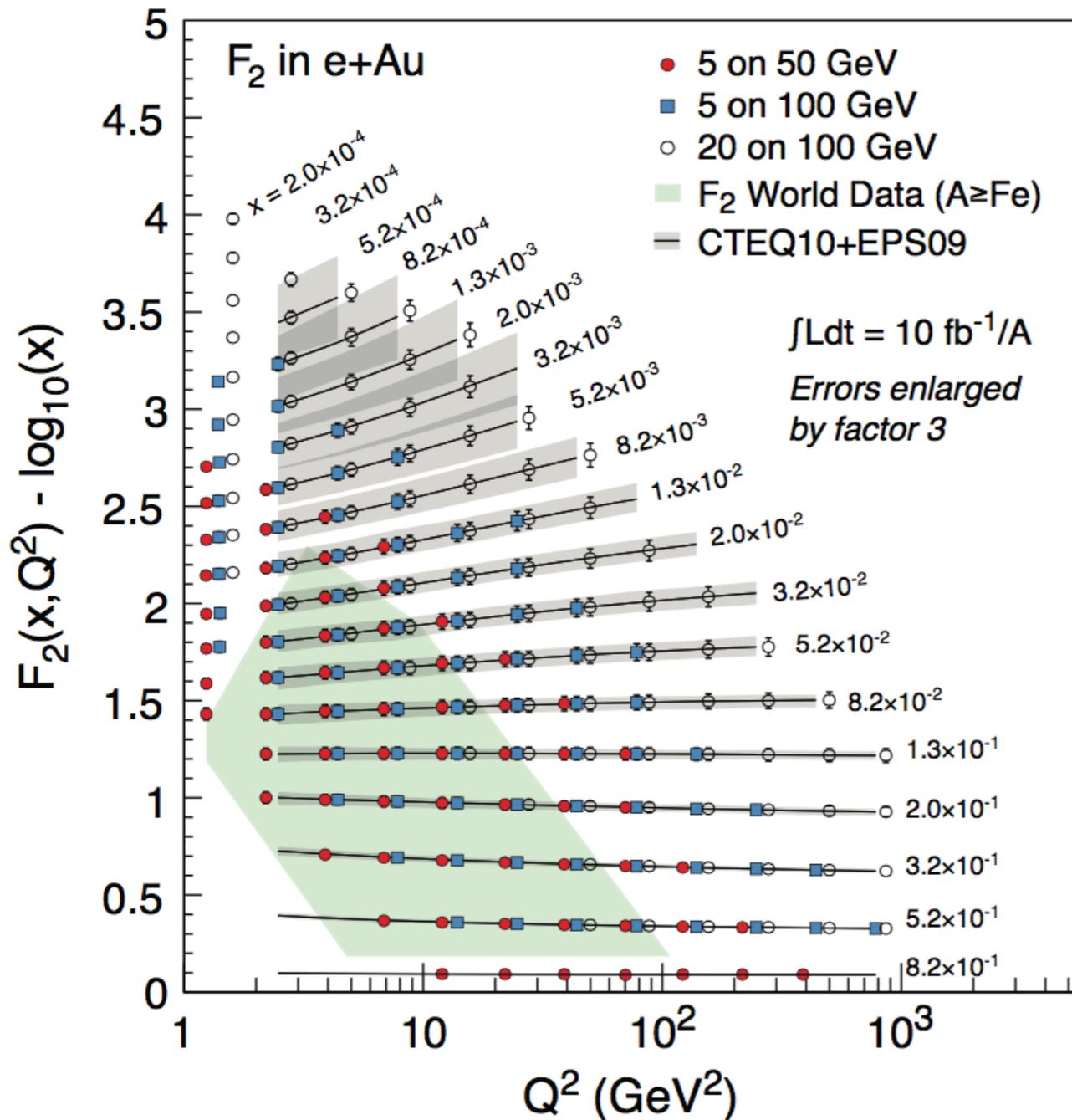
# Existing eA landscape - eRHIC kinematic range



**LHeC, if realized, will obviously provide unprecedented kinematic reach, complementarity in polarization,  $A$  capabilities.**

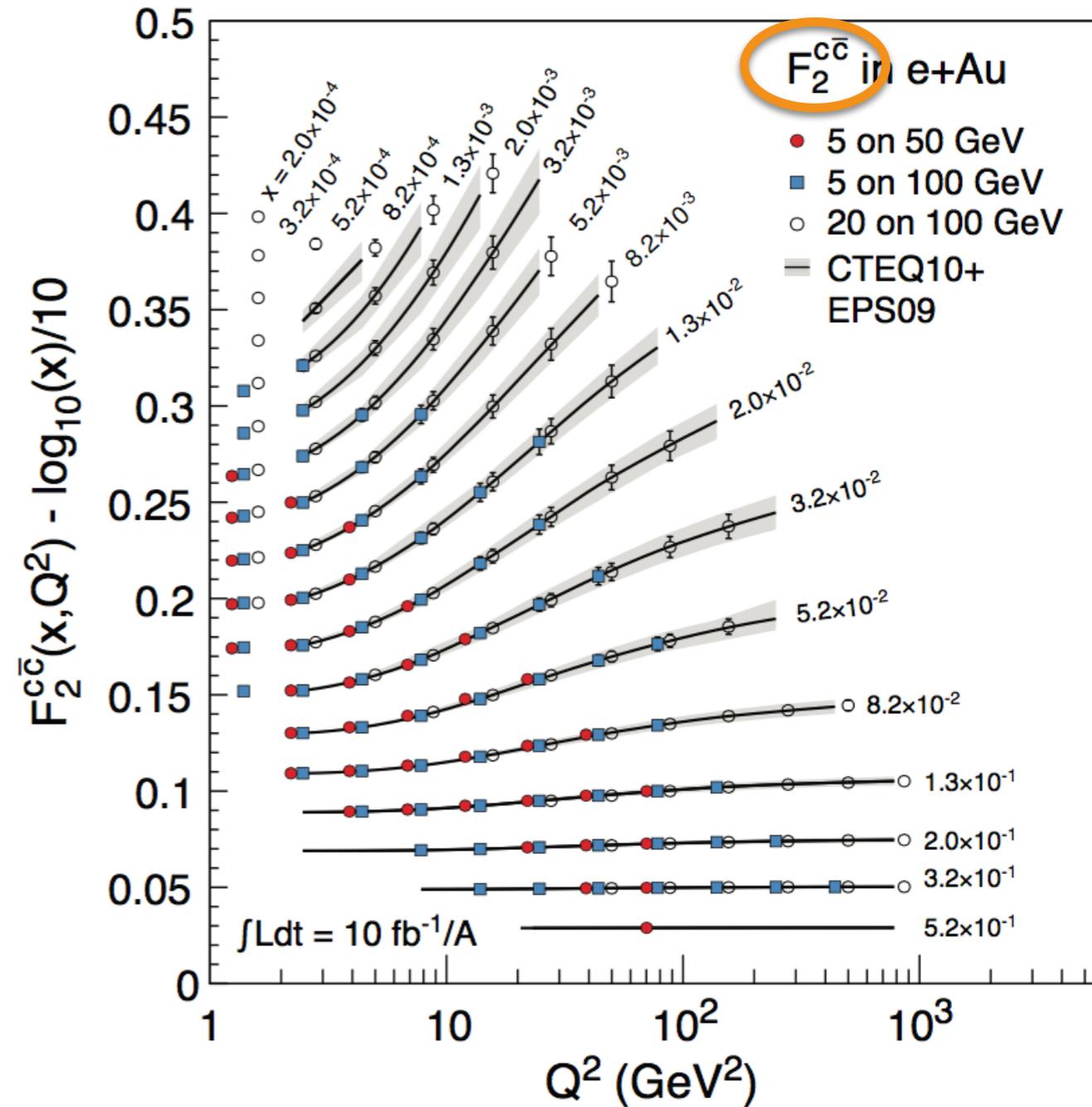
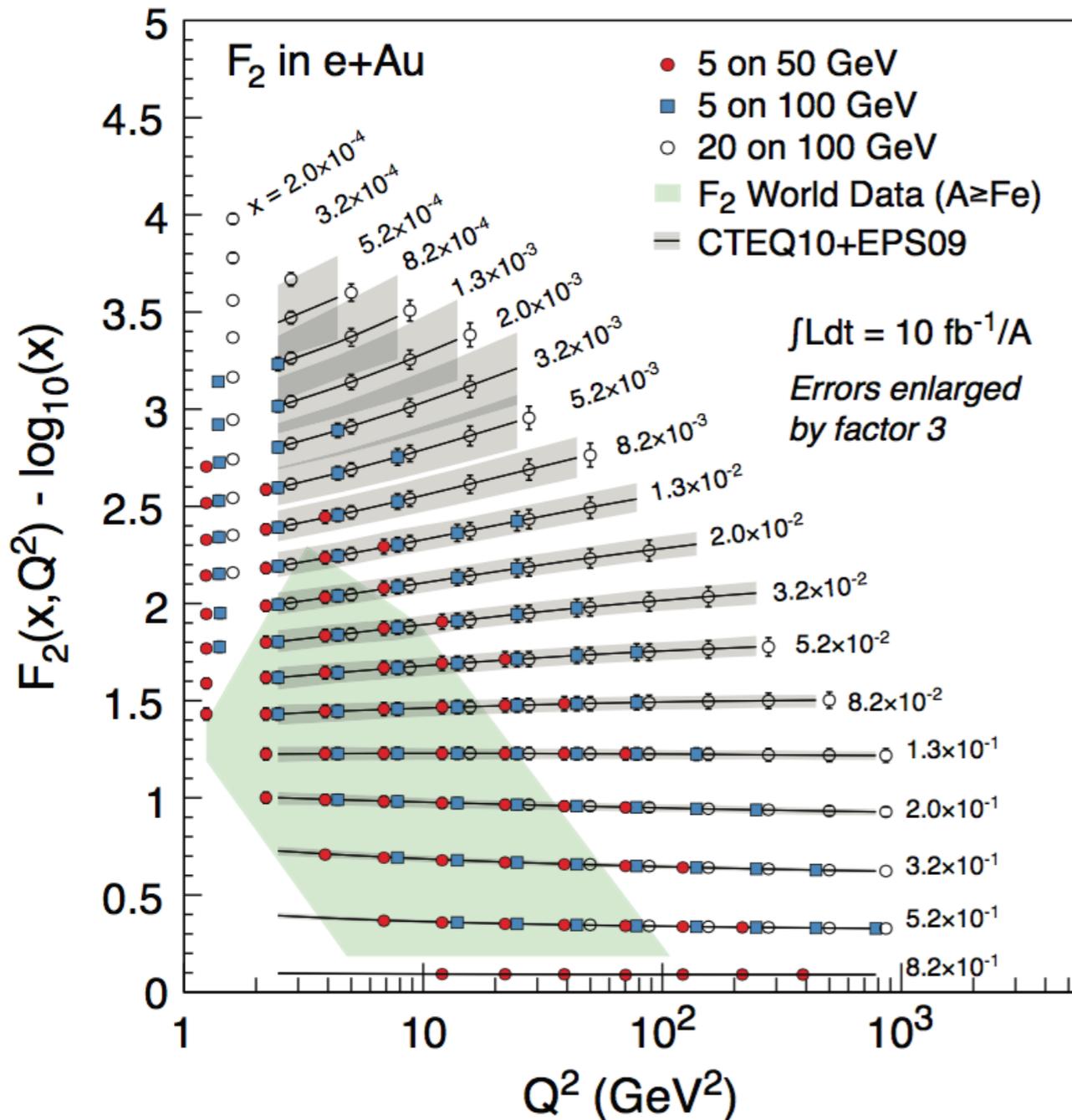
# eRHIC - selected baseline measurements

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

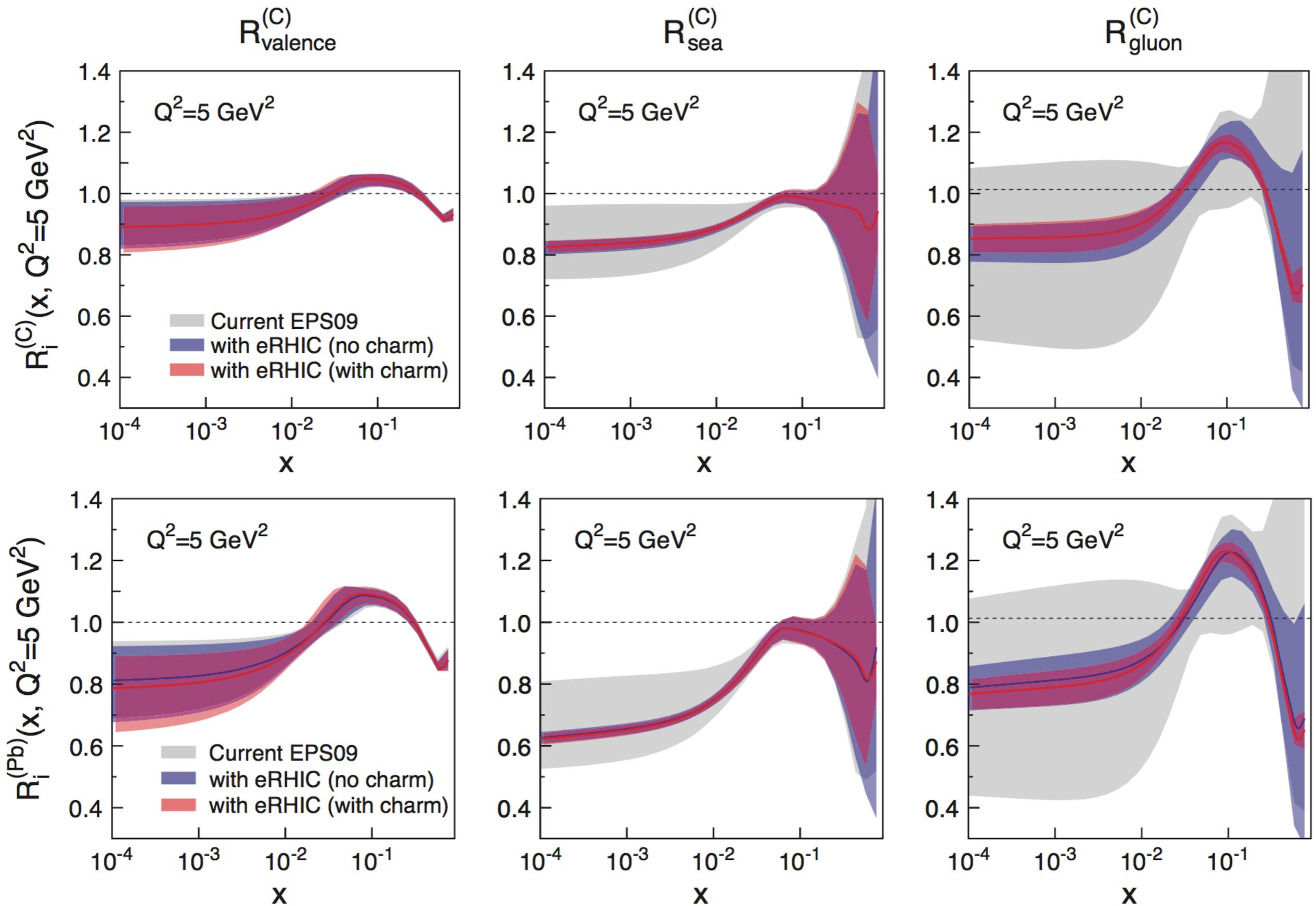


# eRHIC - selected *baseline* measurements

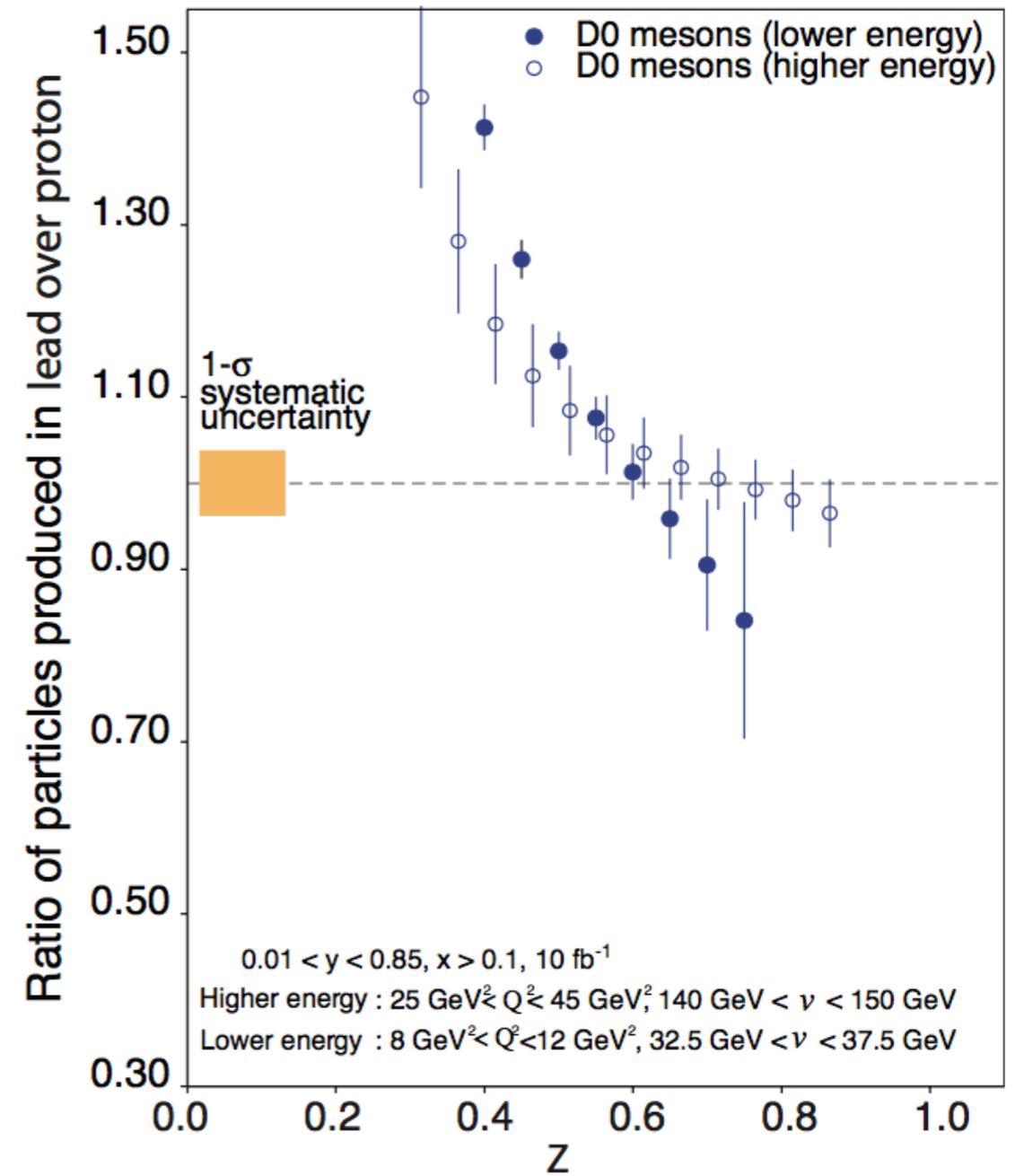
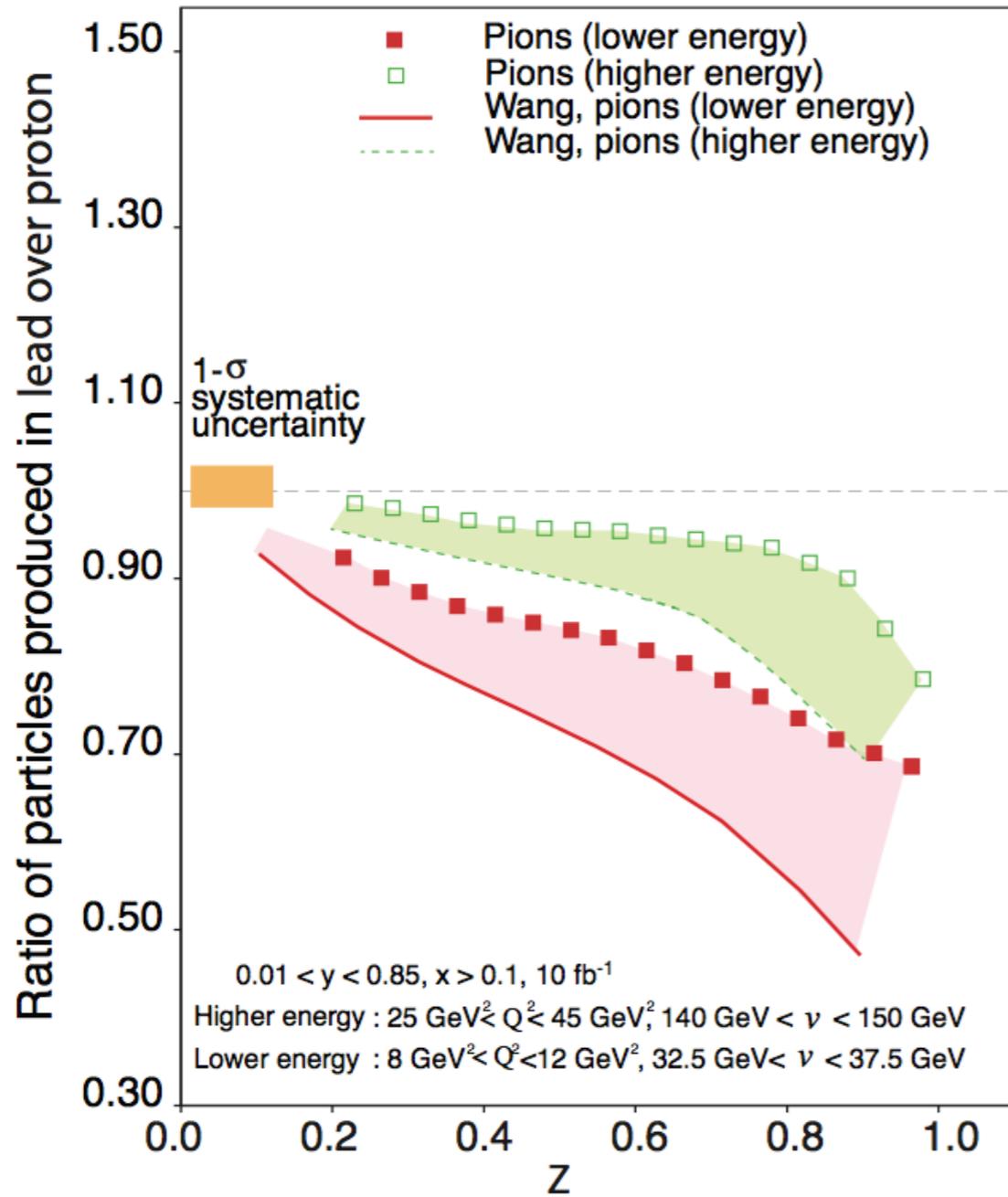
$$\frac{d^2\sigma^{eA\rightarrow eX}}{dx dQ^2} = \frac{4\pi\alpha^2}{xQ^4} \left[ \left(1 - y + \frac{y^2}{2}\right) F_2(x, Q^2) - \frac{y^2}{2} F_L(x, Q^2) \right]$$



# eRHIC - impact on nuclear modification

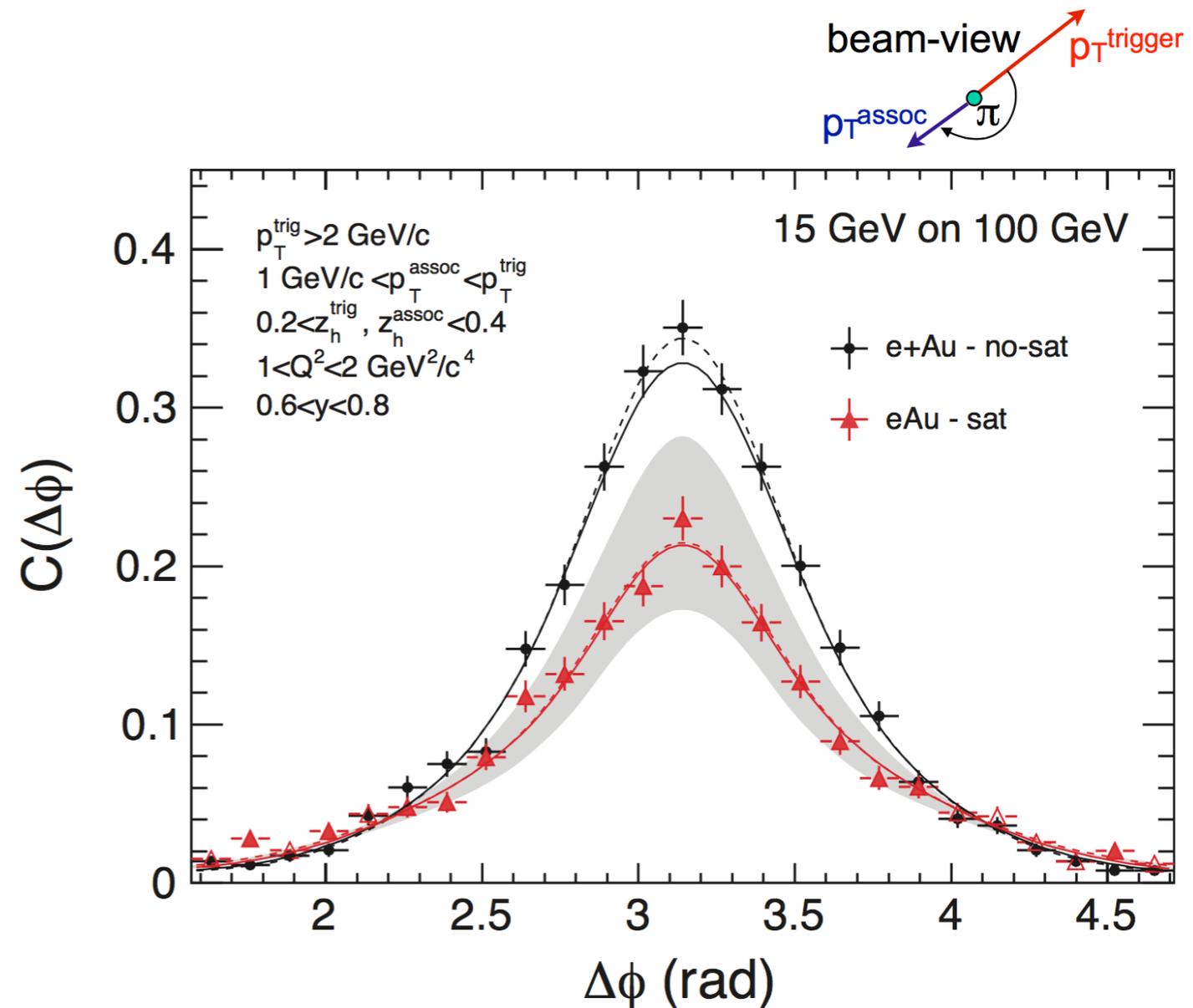
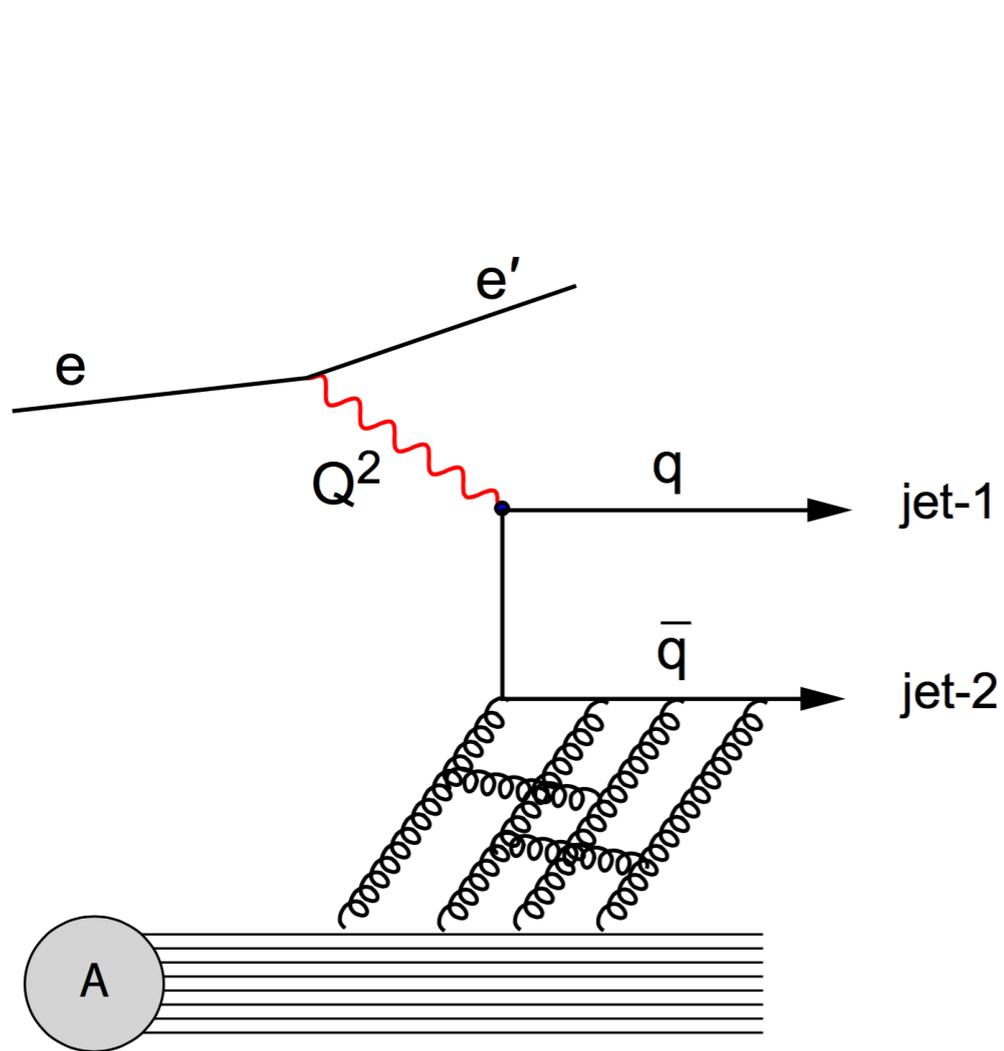


# eRHIC - *baseline semi-inclusive measurements*



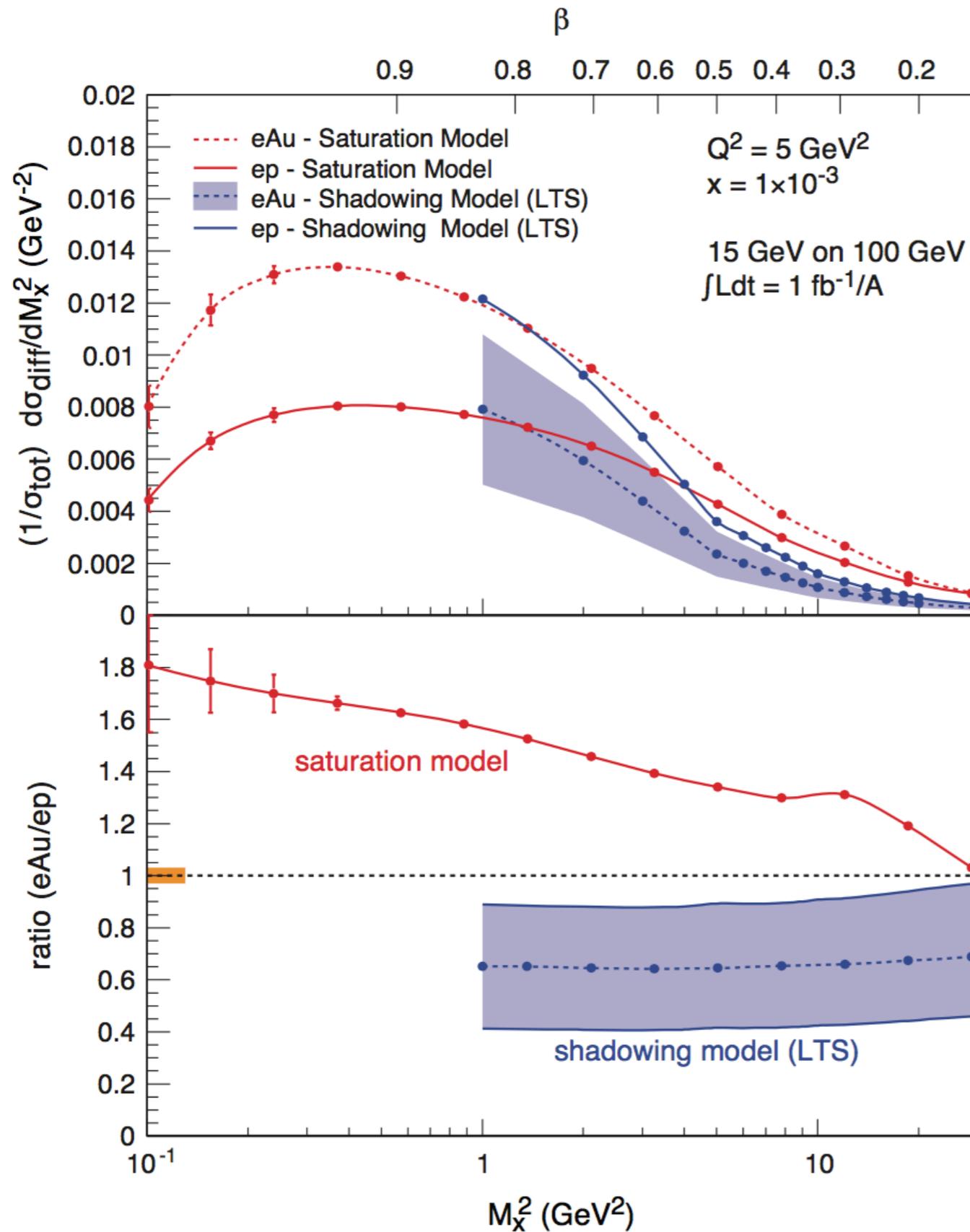
Combined sensitivity to hadronization, energy loss

# eRHIC - dihadron probes of saturation



Suppression of back-to-back hadron or jet correlation directly probes the (un-)saturated gluon distributions in nuclei,

# eRHIC - diffractive probes of saturation

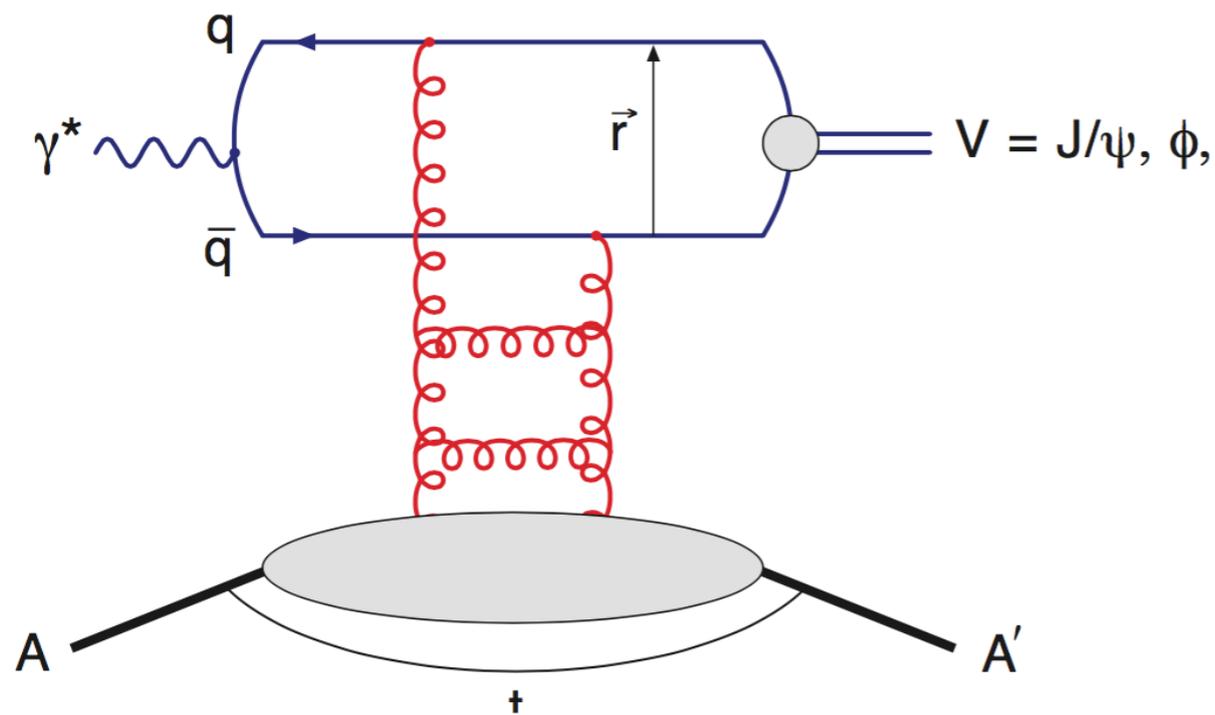


Sizable fraction of events is diffractive in saturation models;

Enhancement not seen in Leading Twist Shadowing pQCD model.

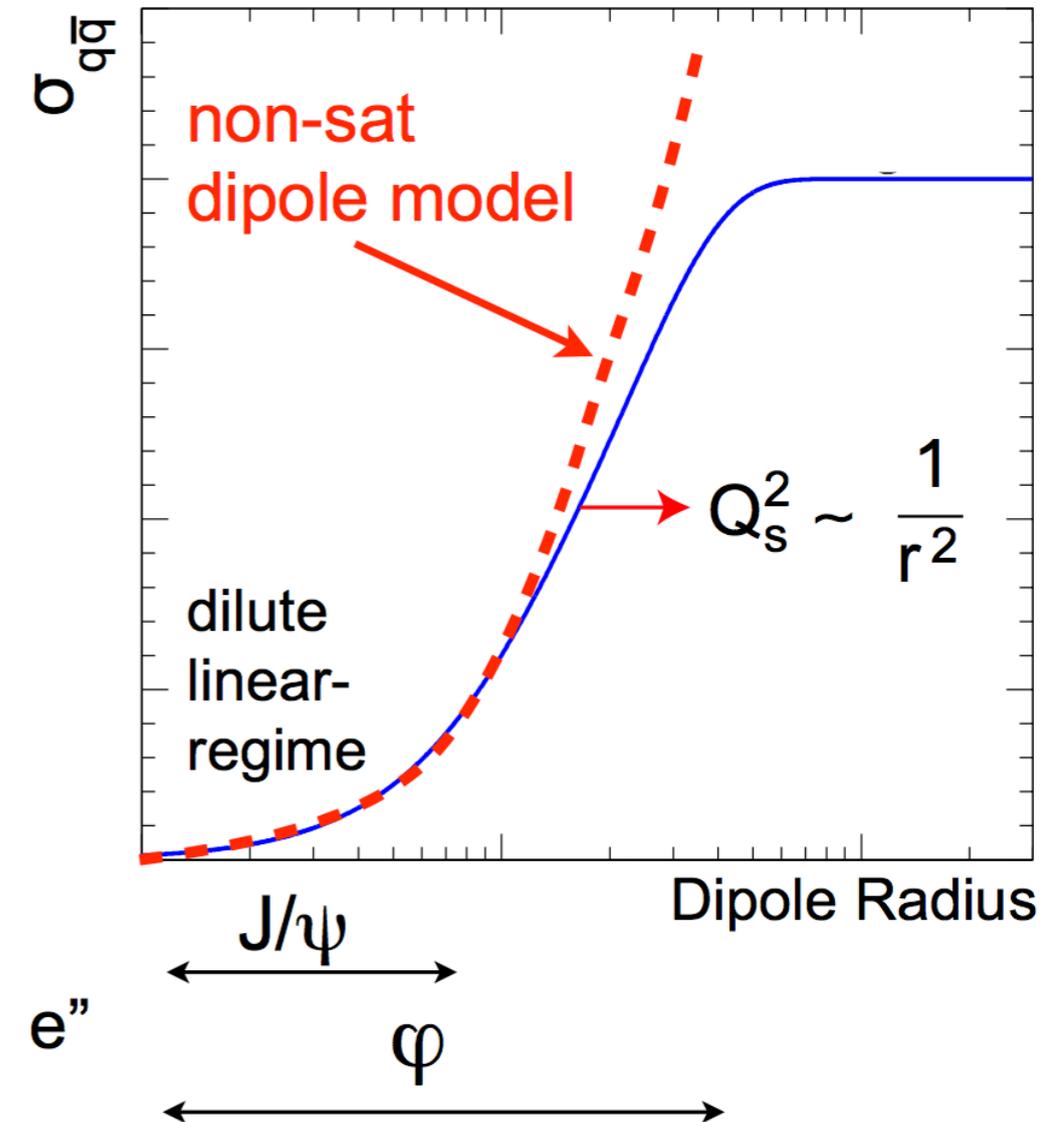
# eRHIC - exclusive vector meson production

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

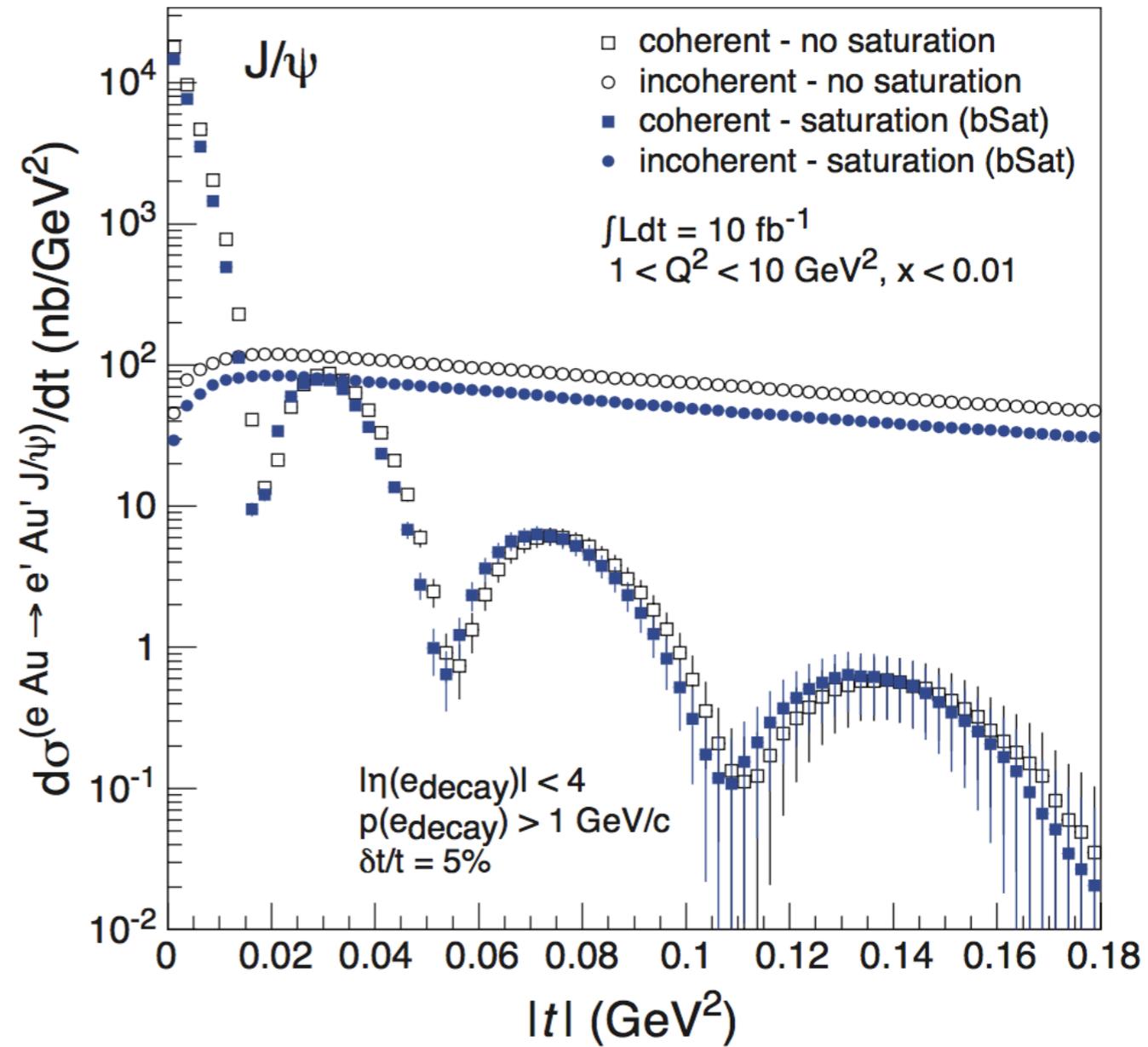
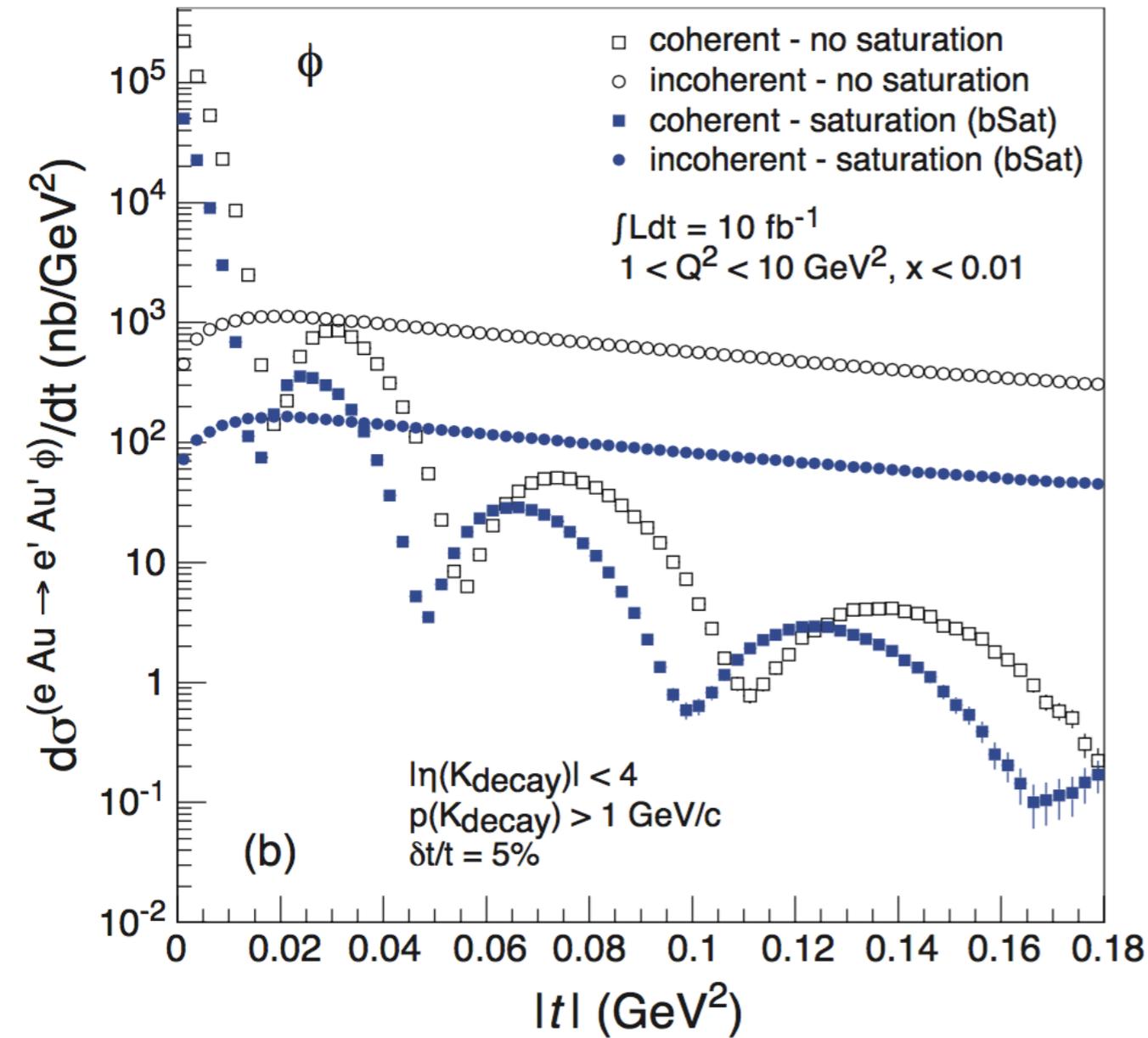


Nucleus escapes down the beampipe  
(In)coherence tagged with ZDC

## Dipole Cross-Section:



# eRHIC - exclusive vector meson production



*Towards Imaging!*

# Closing Comments

*I hope to have convinced you that EIC will answer:*

ArXiv:1212.17010

## Key questions:

- How are the sea quarks and gluons, and their spins, distributed in space and momentum inside the nucleus?
- Where does the saturation of gluon densities set in?
- How does the nuclear environment affect the distribution of quarks and gluons and their interactions in nuclei?

## Identified measurements and quantified uncertainties

- Inclusive Deep-Inelastic Scattering,
- Semi-inclusive deep-inelastic scattering with one or two of the particles in the final state,
- Exclusive deep-inelastic scattering,
- Diffraction.

coherent contributions from many nucleons effectively amplify the gluon density being probed.

The EIC was designated in the 2007 Nuclear Physics Long Range Plan as "embodying the vision for reaching the next QCD frontier" [1]. It would extend the QCD science of QCD in this frontier environment:

• How are the sea quarks and gluons, and their spins, distributed in space and momentum inside the nucleus? How are these quark and gluon distributions correlated with overall nucleus properties, such as spin direction? What is the role of the orbital motion of sea quarks and gluons in building the nucleus spin?

• Where does the saturation of gluon densities set in? Is there a simple boundary? If so, how does this saturation produce matter of universal properties in the nucleus and all nuclei viewed at nearly the speed of light?

• How does the nuclear environment affect the distribution of quarks and gluons and their interactions in nuclei? How does the transverse spatial distribution of quarks and gluons affect the distribution of quarks and gluons in the final state?

Answers to these questions are essential for understanding the nature of visible matter. An EIC is the ultimate machine to provide answers to these questions for the following reasons:

• A collider is needed to provide kinematic reach well into the gluon-dominated regime; the EIC provides the necessary kinematic reach of the electromagnetic interaction as a probe;

• Polarized nucleus beams are needed to determine the correlations of sea quark and gluon distributions with the nucleus spin;

• Heavy ion beams are needed to provide precocious access to the regime of saturated gluon densities and offer a precise dial in the study of propagation-length for color charges in nuclear matter.

The EIC would be distinguished from all past, current, and contemplated facilities around the world by being at the intensity frontier with a versatile range of kinematics and beam polarizations, as well as beam species, allowing the above questions to be tackled at one facility. In particular, the EIC design exceeds the capabilities of HERA, the only electron-proton collider to date, by adding a) polarized proton and light-ion beams; b) a wide variety of heavy-ion beams; c) two to three orders of magnitude increase in luminosity to facilitate tomographic imaging; and d) wide energy variability to enhance the sensitivity to gluon distributions. Achieving these challenging technical improvements in a single facility will extend U.S. leadership in accelerator sci-

Understanding the glue that binds us all

*Look forward to a strong recommendation in the soon-to-be-finalized/released U.S. Long-Range-Plan.*

*Thank you!*