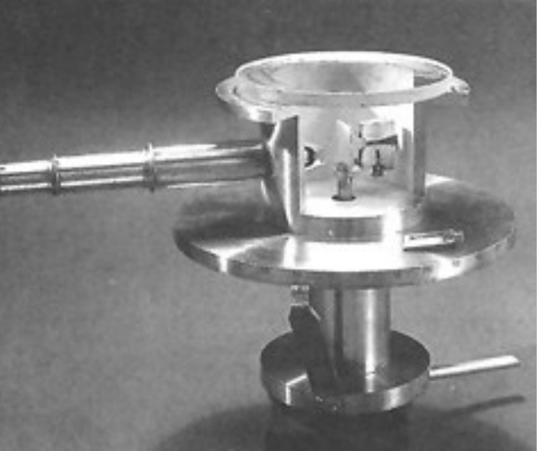
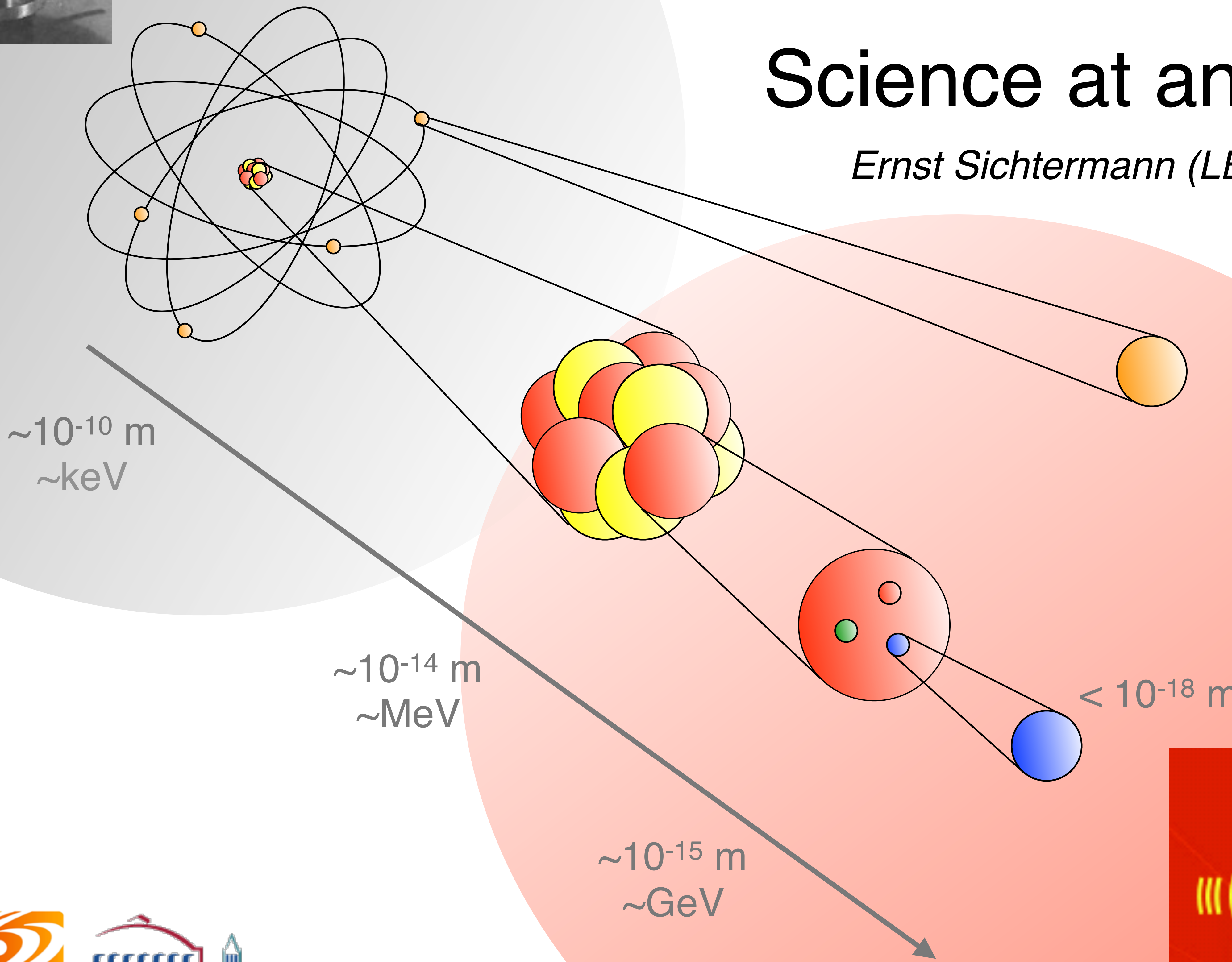
New Progress in Heavy Ion Collisions:
What is Hot in the QGP
CCNU - Wuhan, China, October 5-9, 2015

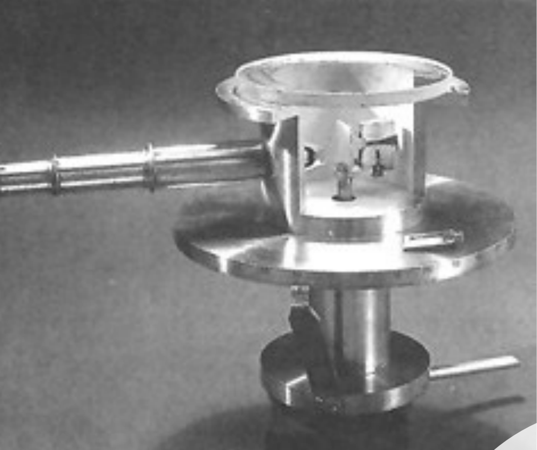


Science at an EIC

Ernst Sichtermann (LBNL)



Office of Science
U.S. Department of Energy
BERKELEY LAB



Many Thanks to the Organizers,

in particular Prof. Nu Xu

~10^{-10} m
~keV

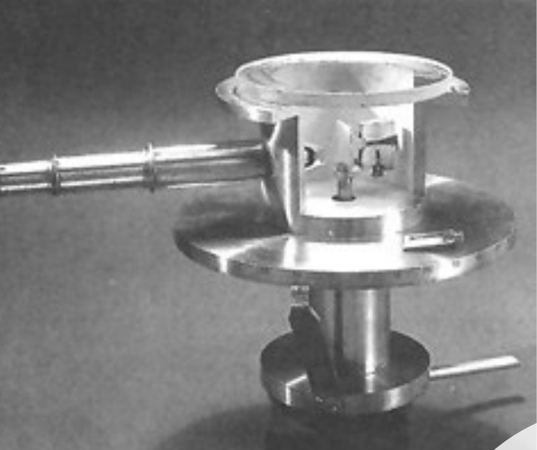
~10^{-14} m
~MeV

~10^{-15} m
~GeV

~10^{-18} m

And many thanks to <u>you</u>

for taking part in this <u>discussion</u>



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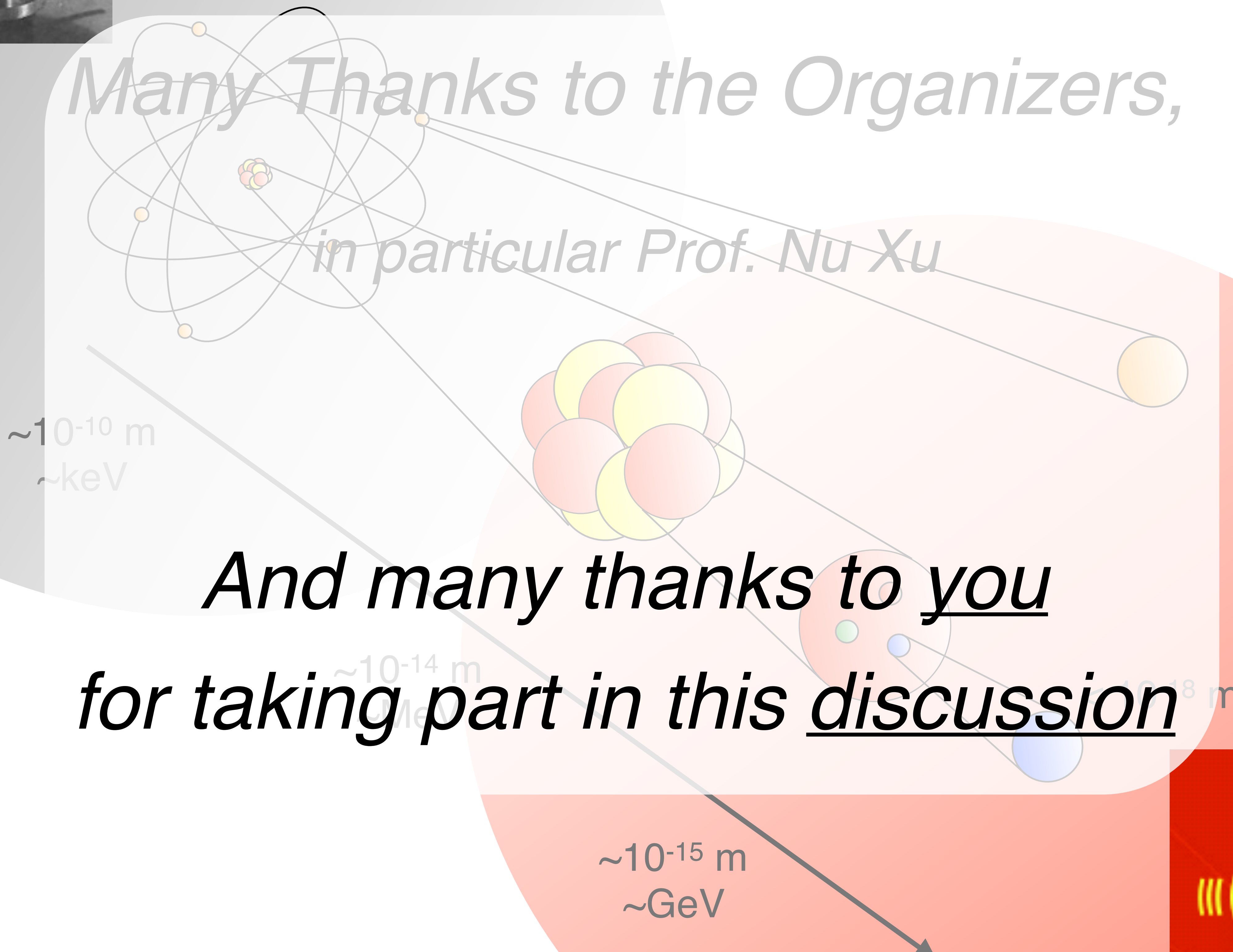

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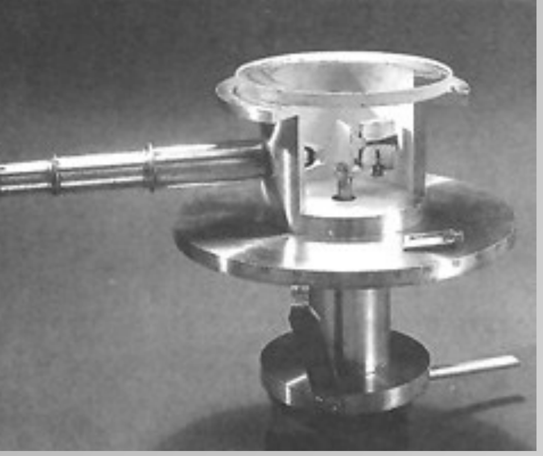
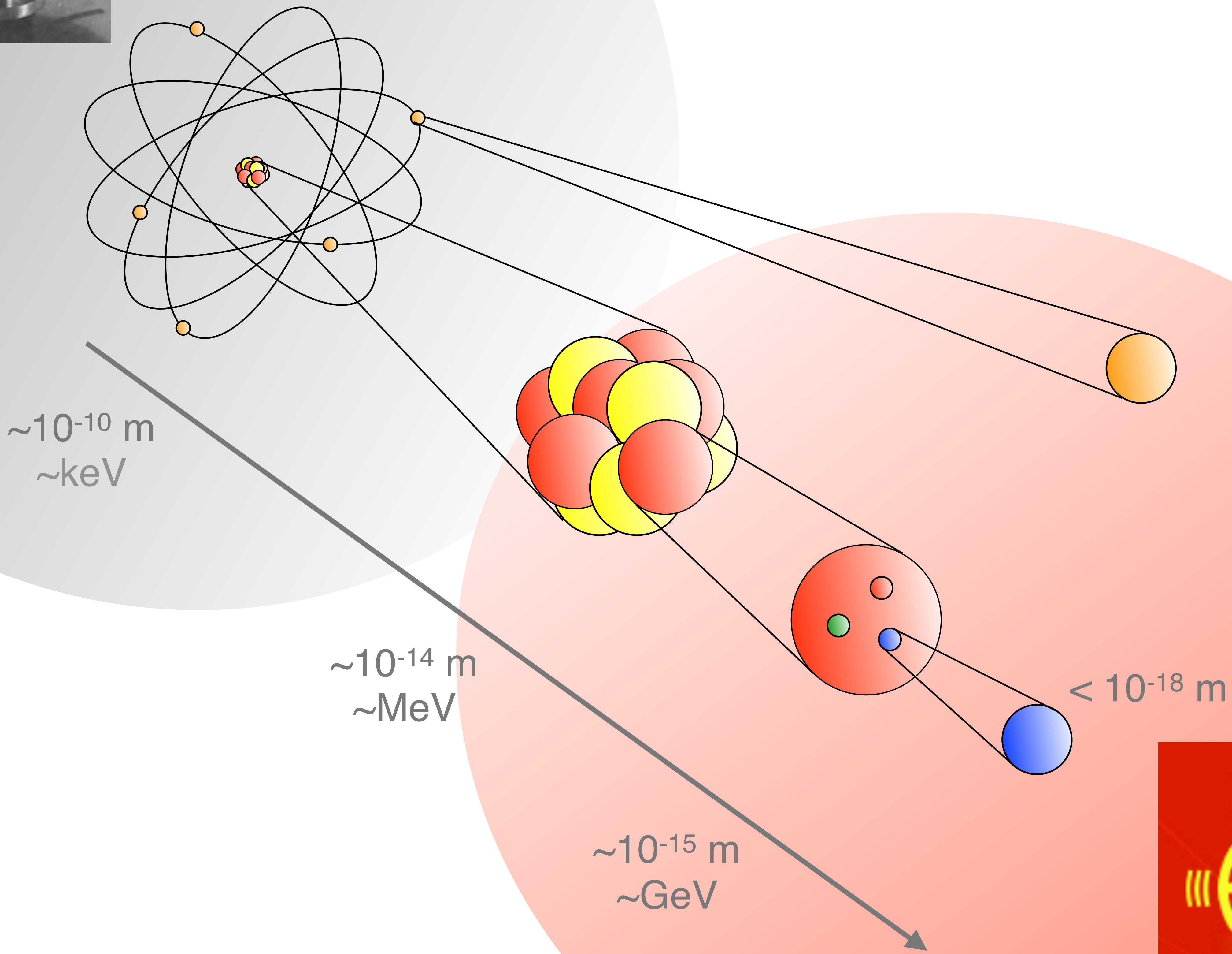


What *is* a proton, neutron, nucleus?



What *is* a proton, neutron, nucleus?

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At high energy: an unseparated, broadband beam of quarks, anti-quarks, and gauge bosons (primarily gluons), and perhaps other constituents, yet unknown.

40 years of an amazingly robust idealization:
Renormalization group-improved Parton Model

Factorization theorem(s) + one-dimensional parton distributions,
no correlations among the partons

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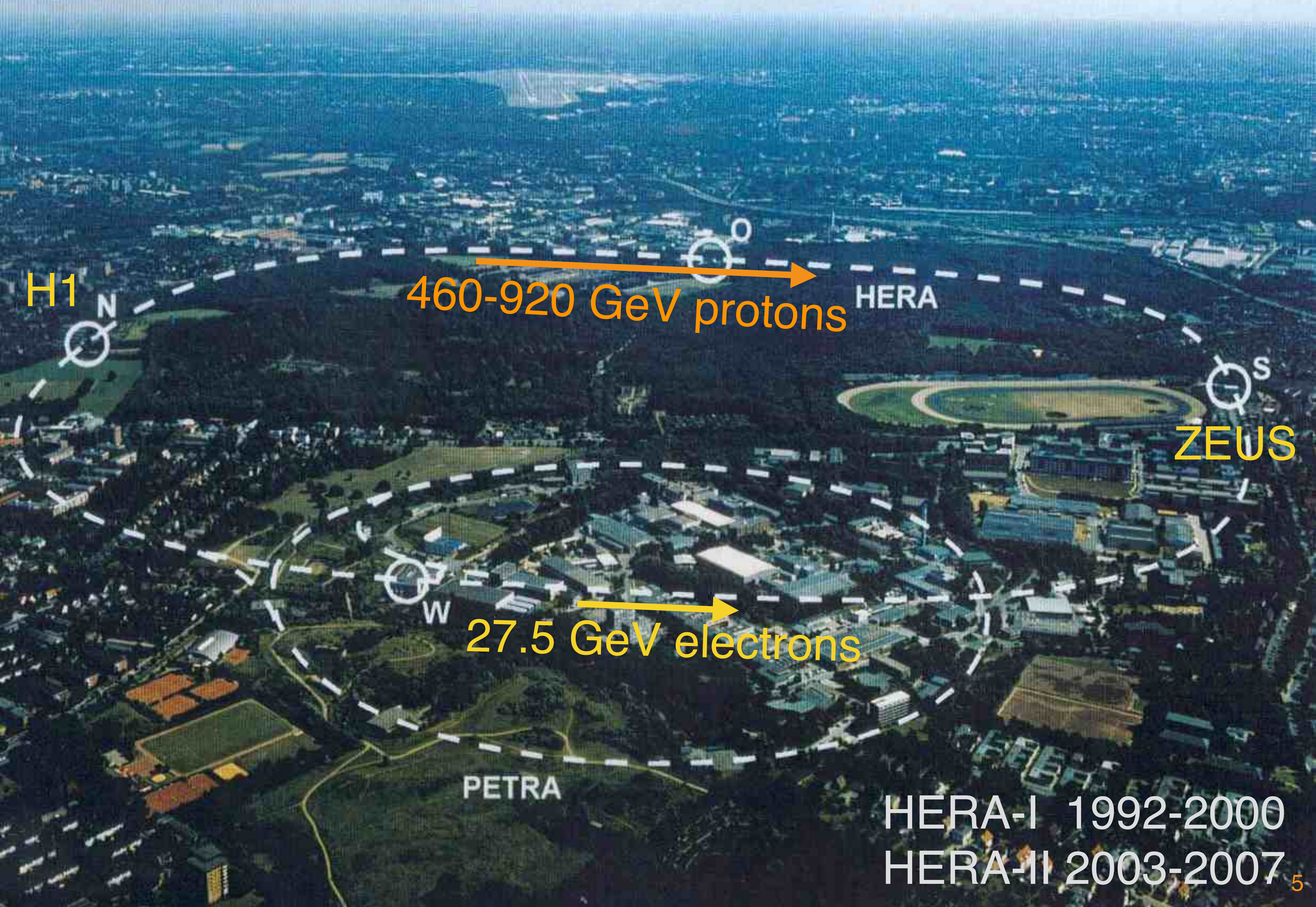
Why and what about an Electron Ion Collider?

HERA - Electron Proton Collider



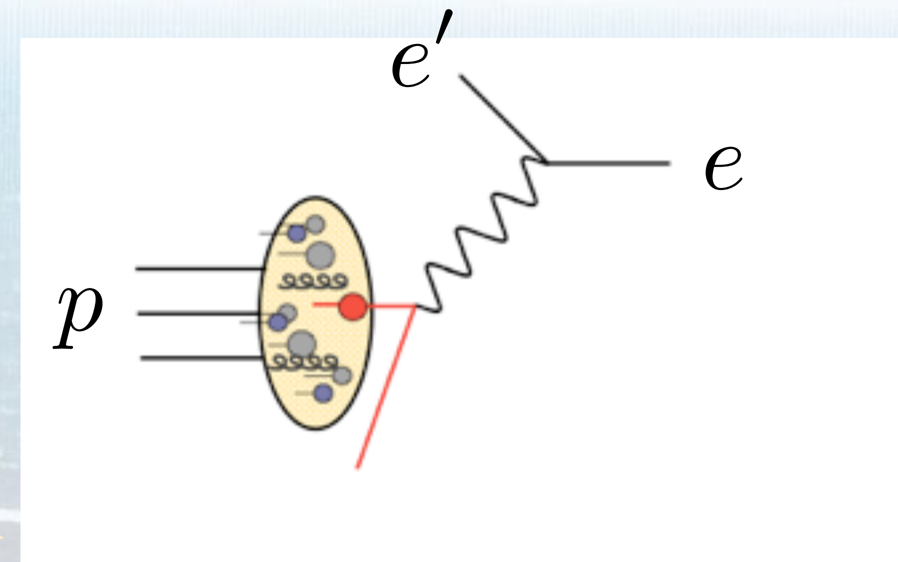
HERA - Electron Proton Collider

Observed (or known):

$$e = (0, 0, -E_e, E_e)$$

$$e' = (E'_e \sin\theta'_e, 0, E'_e \cos\theta'_e, E_e)$$

$$p = (0, 0, E_p, E_p)$$



H1

460-920 GeV protons

i.e. angles are defined *w.r.t. the hadron beam direction* (HERA-convention).

Relevant invariants:

$$s = (e + p)^2$$ Square of total c.m. energy

ZEUS

$$q = e - e' \qquad Q^2 = -(e - e')^2$$ Square of (4-)momentum transfer

$$x = \frac{Q^2}{ys}$$ Bjorken-x, ~parton mom. fraction

27.5 GeV electrons

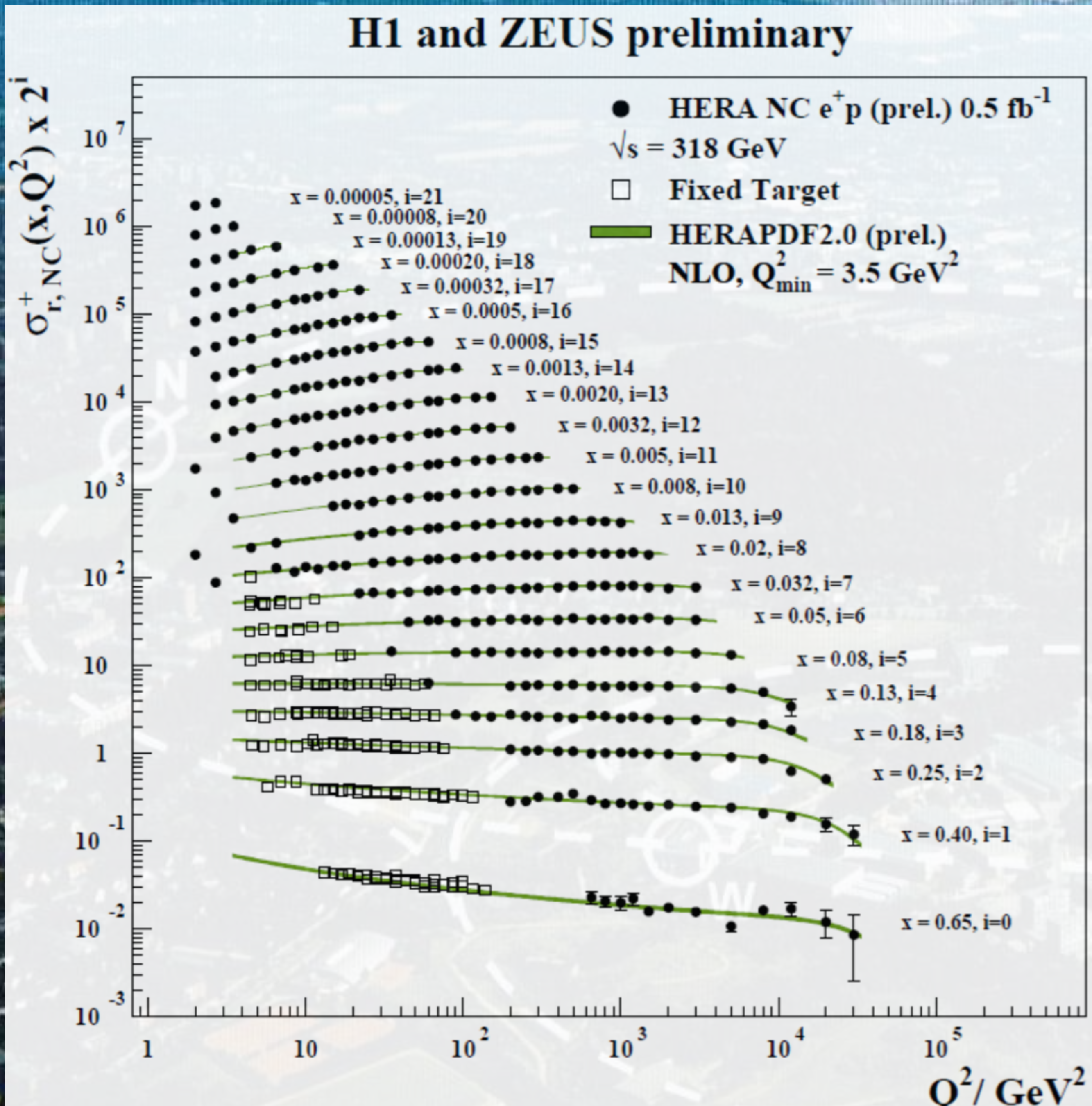
$$y = (q.p)/(e.p)$$ Fractional energy transfer

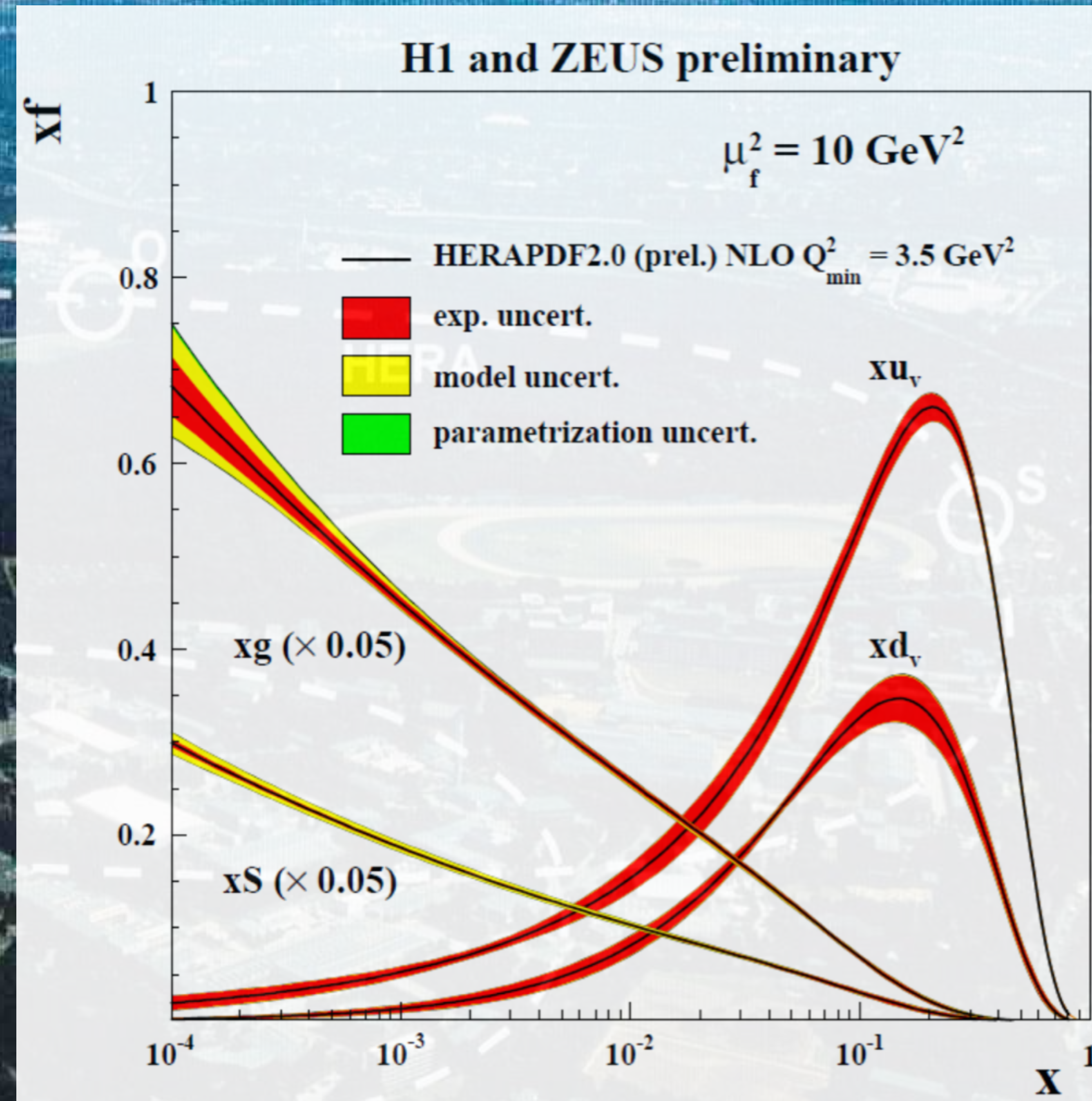
x, Q ^{2} can be reconstructed from the scattered electron, the "current jet", or hybrids.

HERA-I 1992-2000

HERA-II 2003-2007

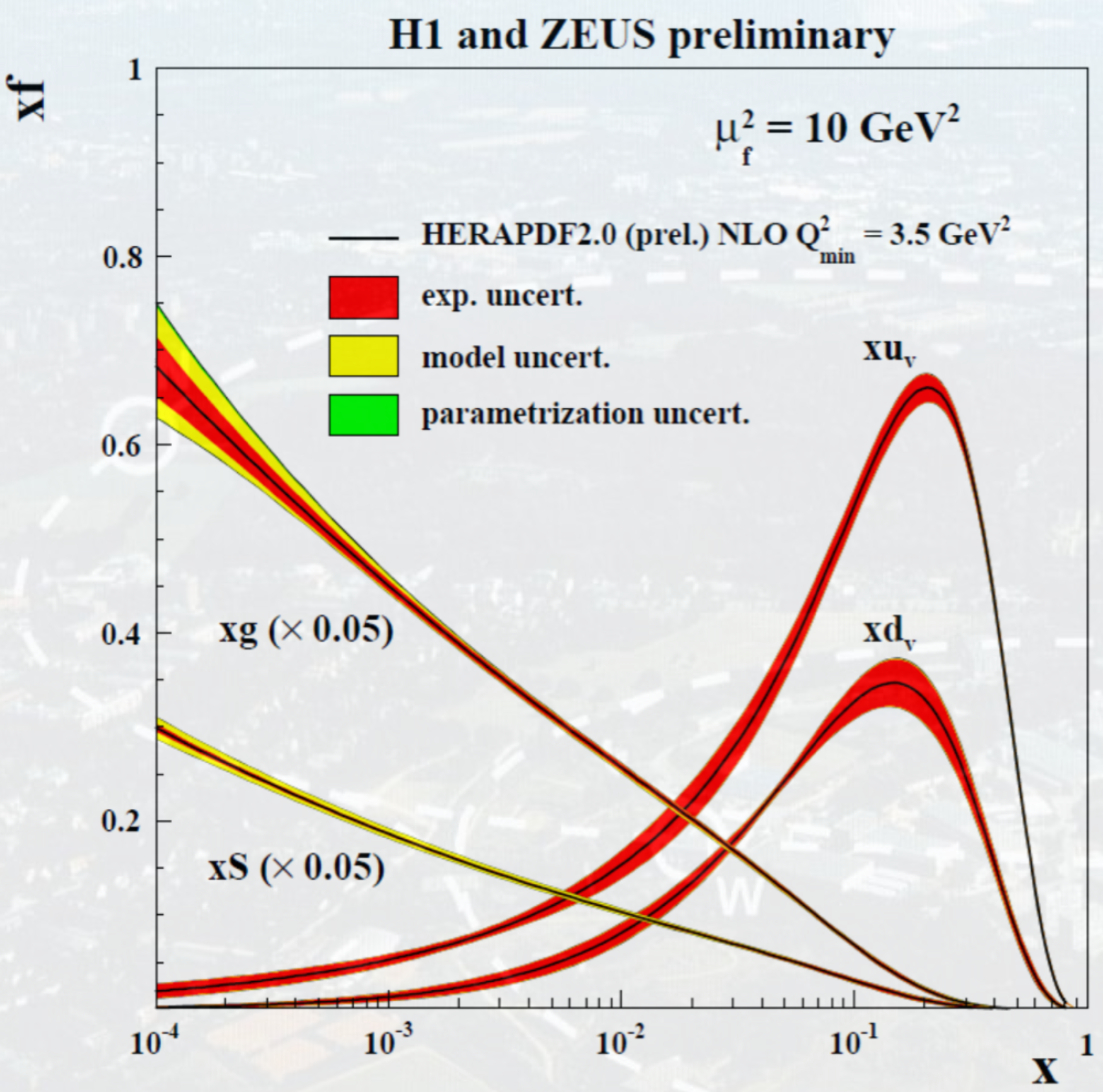
HERA's Legacy





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*,

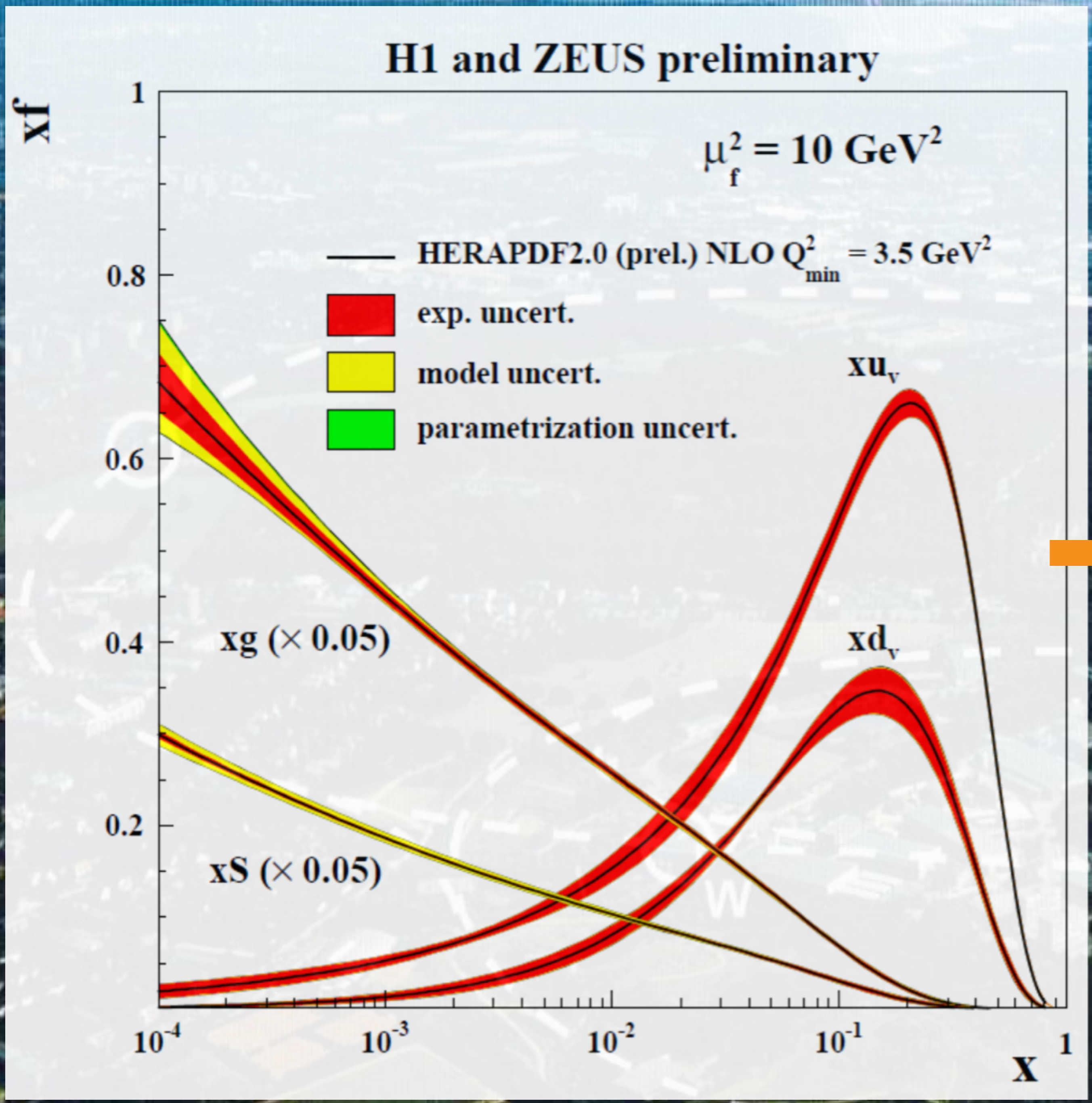
Gluons pose a number of questions

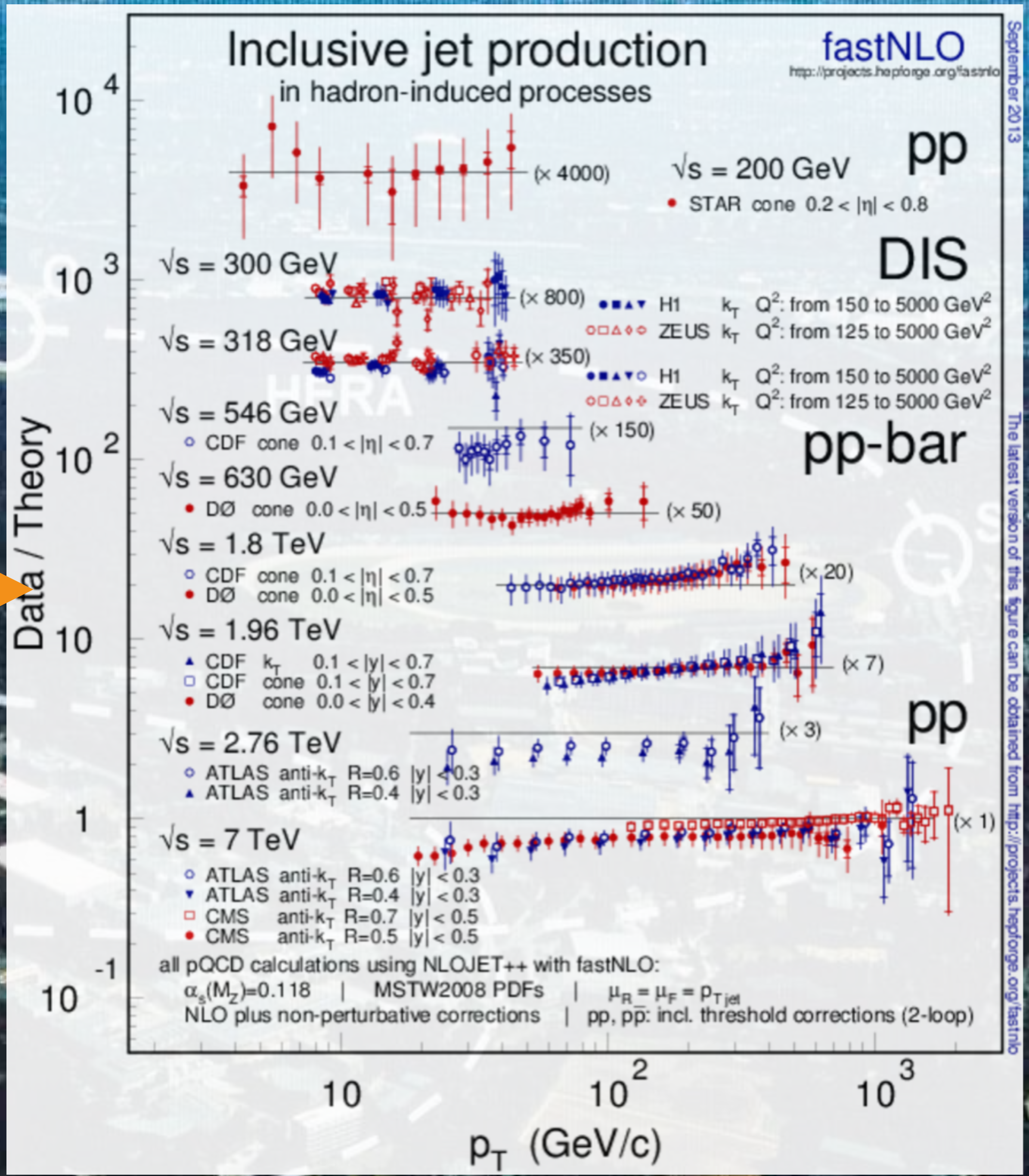
HERAPDF2.0:

15 parameters,

~1400 combined data points,

HERA's Legacy





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

What *is* a proton, neutron, nucleus?

At high energy: an unseparated, broadband beam of quarks, anti-quarks, and gauge bosons (primarily gluons), and perhaps other constituents, yet unknown.

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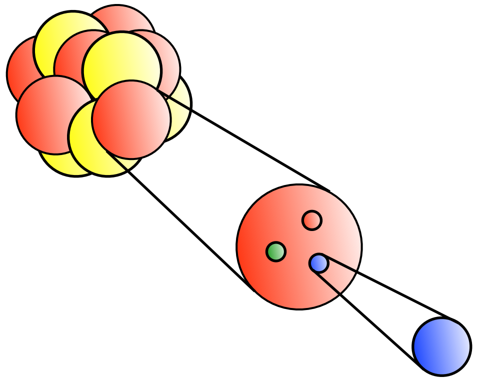
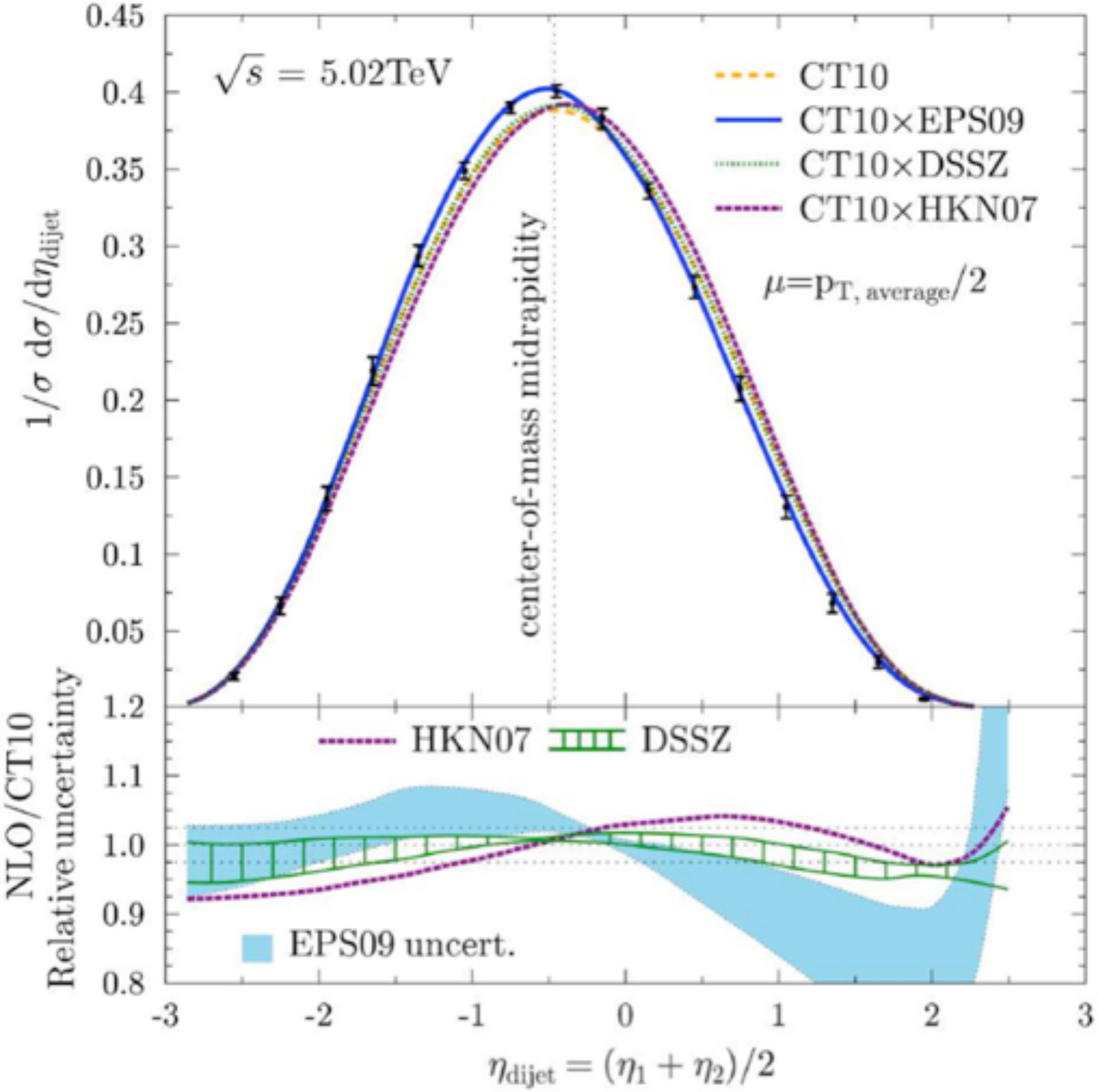
Really?

Really? - Nuclear Modification



CMS, ArXiv:1401.4433
H. Paukkunnen, ArXiv:1401.2345



Textbook nuclear EMC effect, shadowing, and anti-shadowing remain in search of a comprehensive explanation.

Experimental opportunities:

Near-term:
- (polarized) p+A scattering,
- continued DIS, DY,
- ...

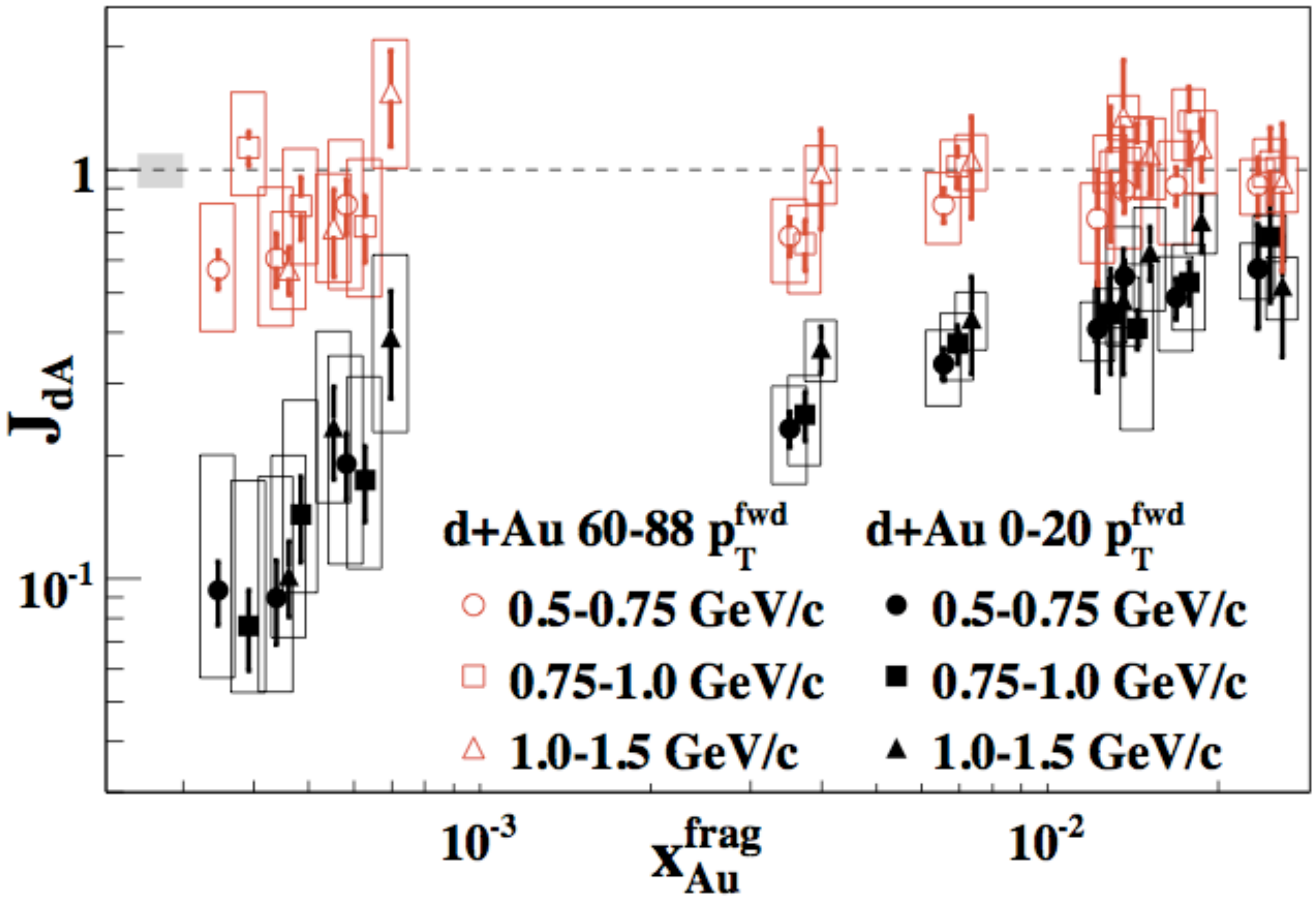
EIC-term:
- QCD-evolution, esp. gluon region,
- NC, CC probes,
- 1-particle semi-inclusive data,
- n-particle correlations,
- diffraction,
- exclusive reactions (imaging),
- ...

Simply this student's list - input sought.

Really? - Forward Particle Suppression

Forward-Forward

Mid-forward correlation

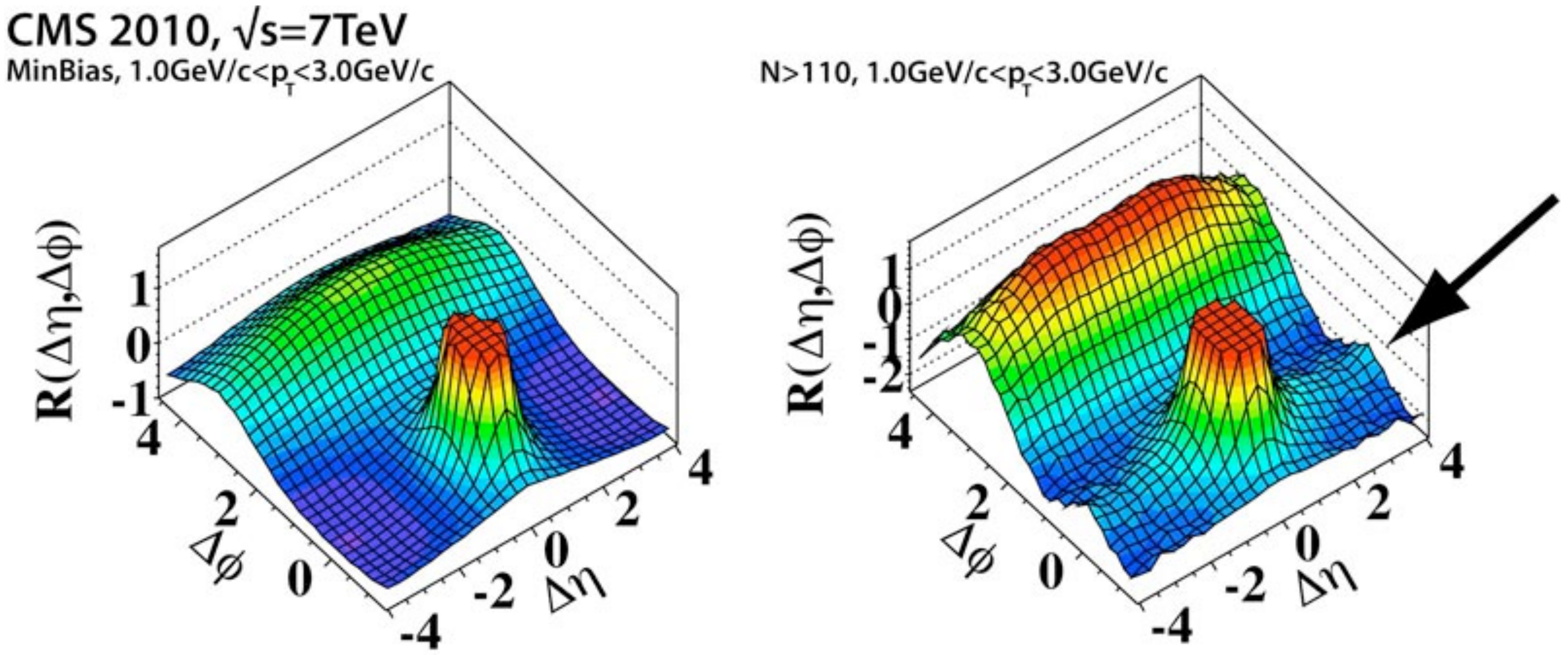


Peripheral

Central

Phenix, Phys.Rev.Lett. 107 (2011) 172301

Really? - Ridges, ridges, ridges

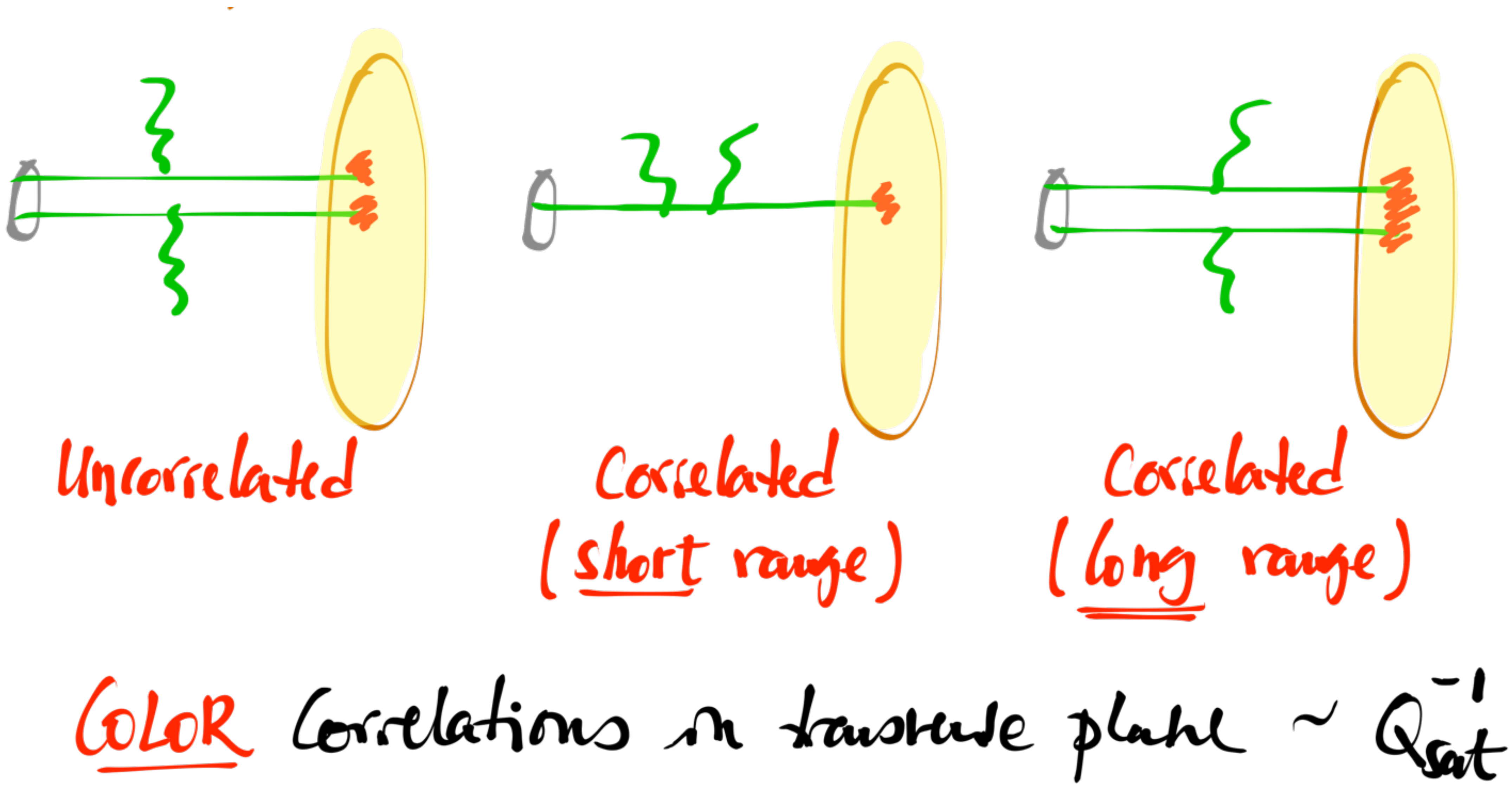


Seen in p+p, p+A at the LHC, A+A at RHIC and the LHC…

Causality implies that this structure is formed very early,

Initial state, final state, both?

Really? - Ridges, ridges, ridges



Salgado, QM'14

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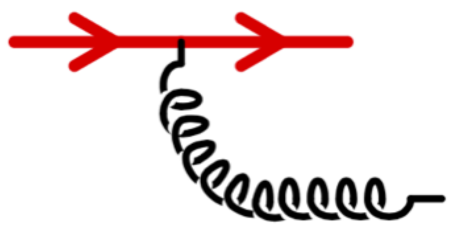
Initial state, final state, both?

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:

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

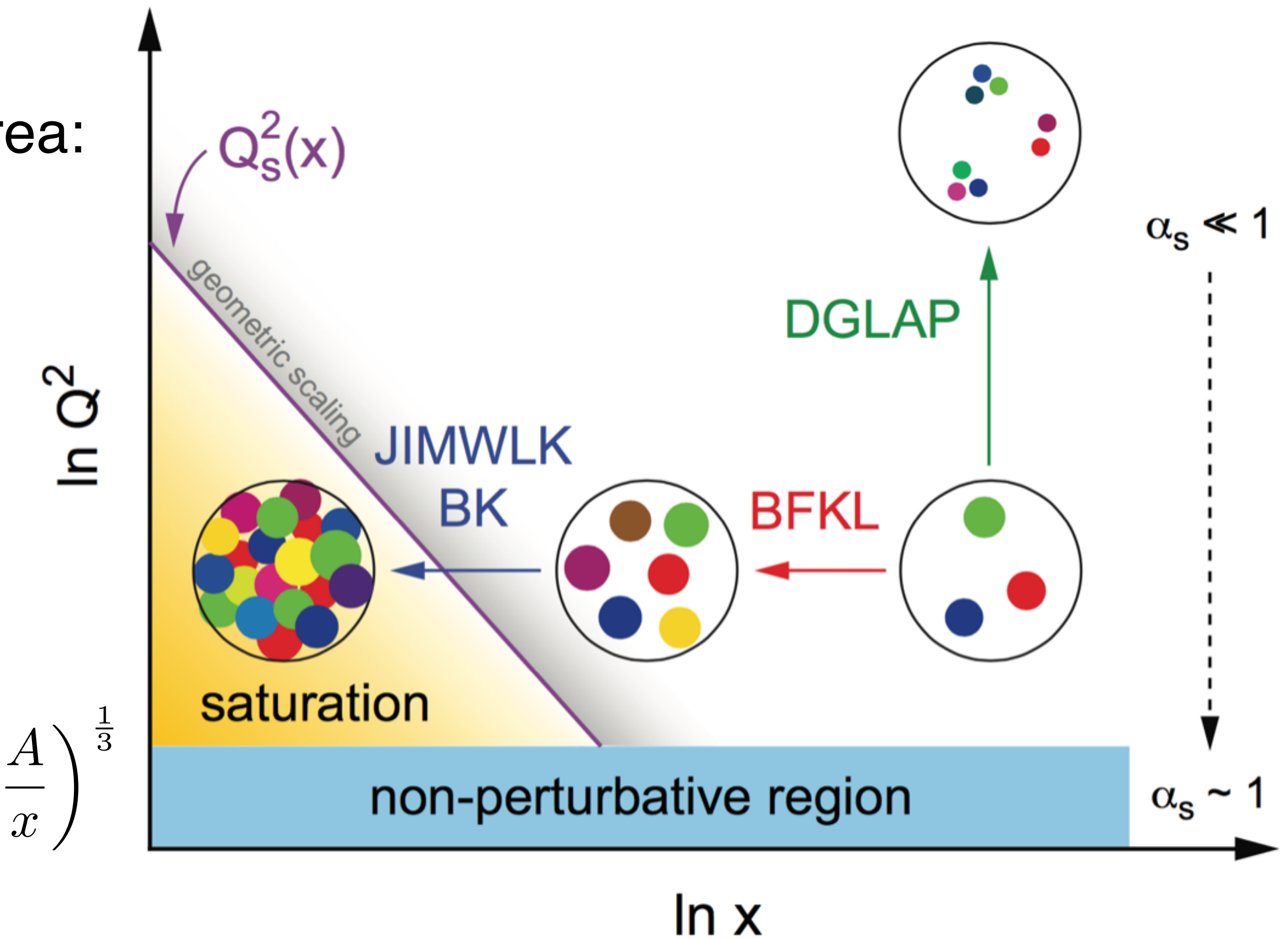
Cross section for gluon **recombination:**

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

Saturation:

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

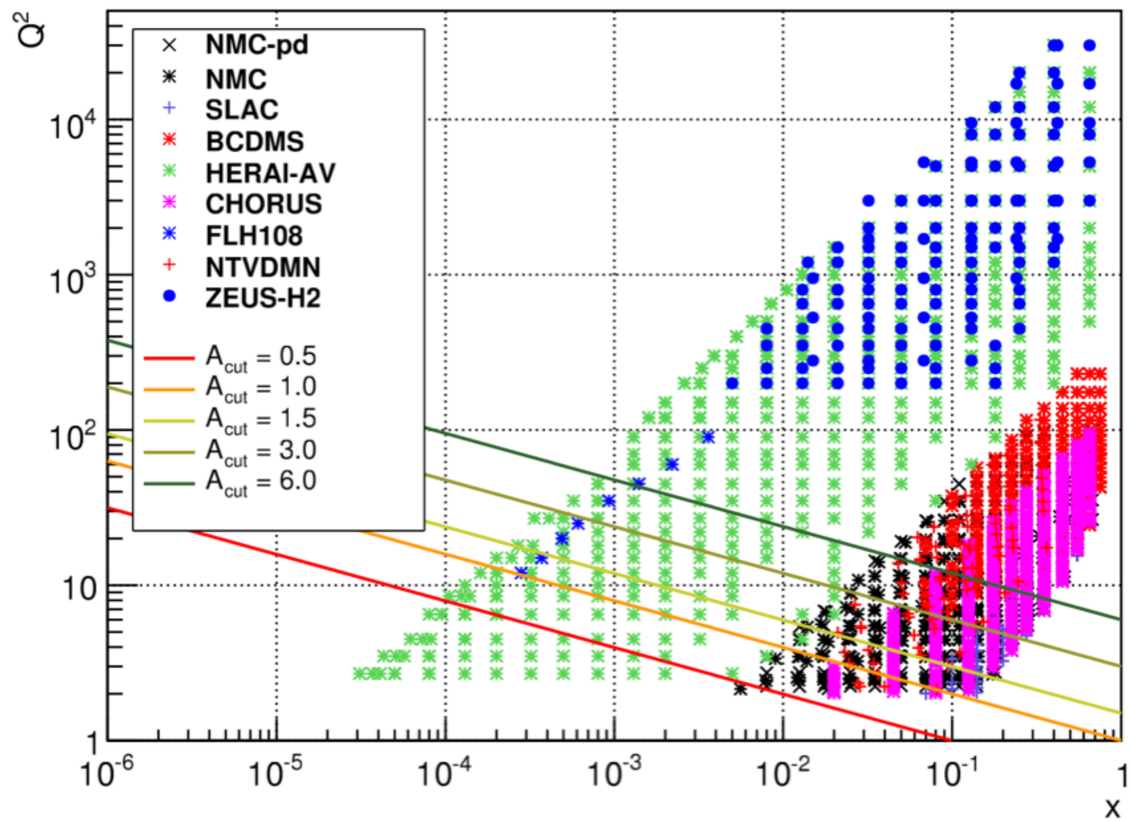
Gribov, Levin, Ryskin 1983



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

Saturation at HERA? - Think outside the PDF!

- No/limited evidence from DGLAP fits in sub-ranges,

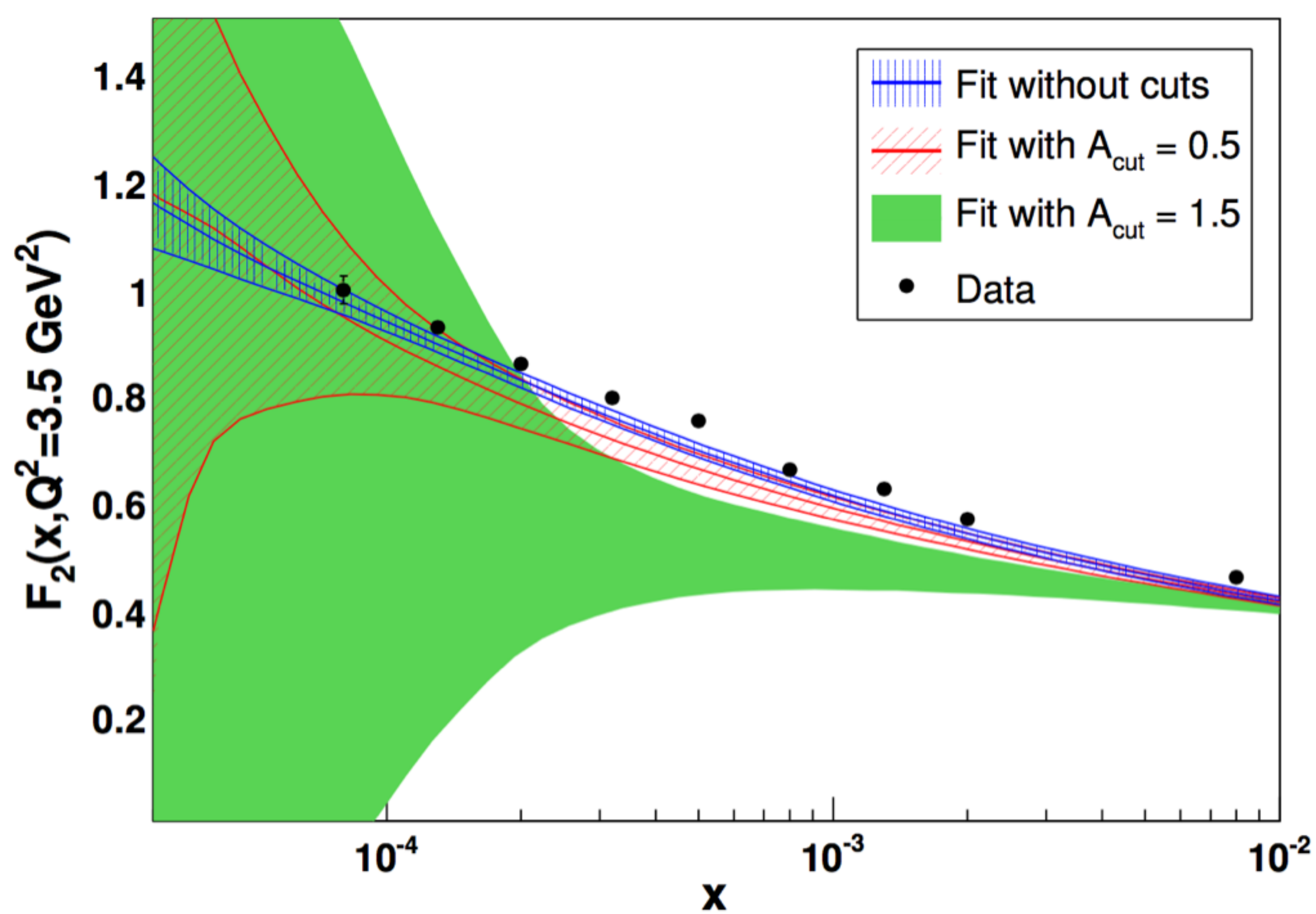


Idea (Gellis, Caolo et al):

- cut out data in a presumed saturation region,
- determine PDFs from remaining data,
- evolve down and compare with all data

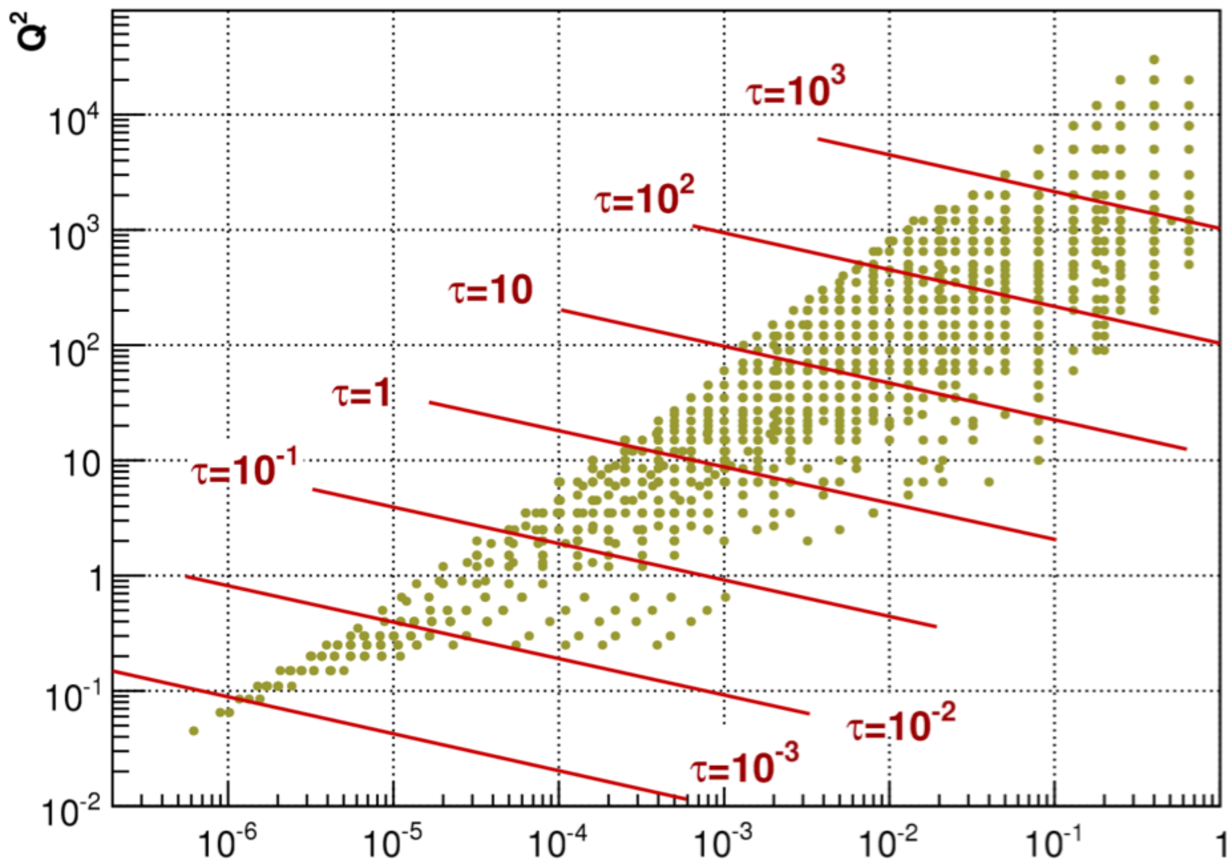
Tendency to undershoot the data, however, do note the uncertainties.

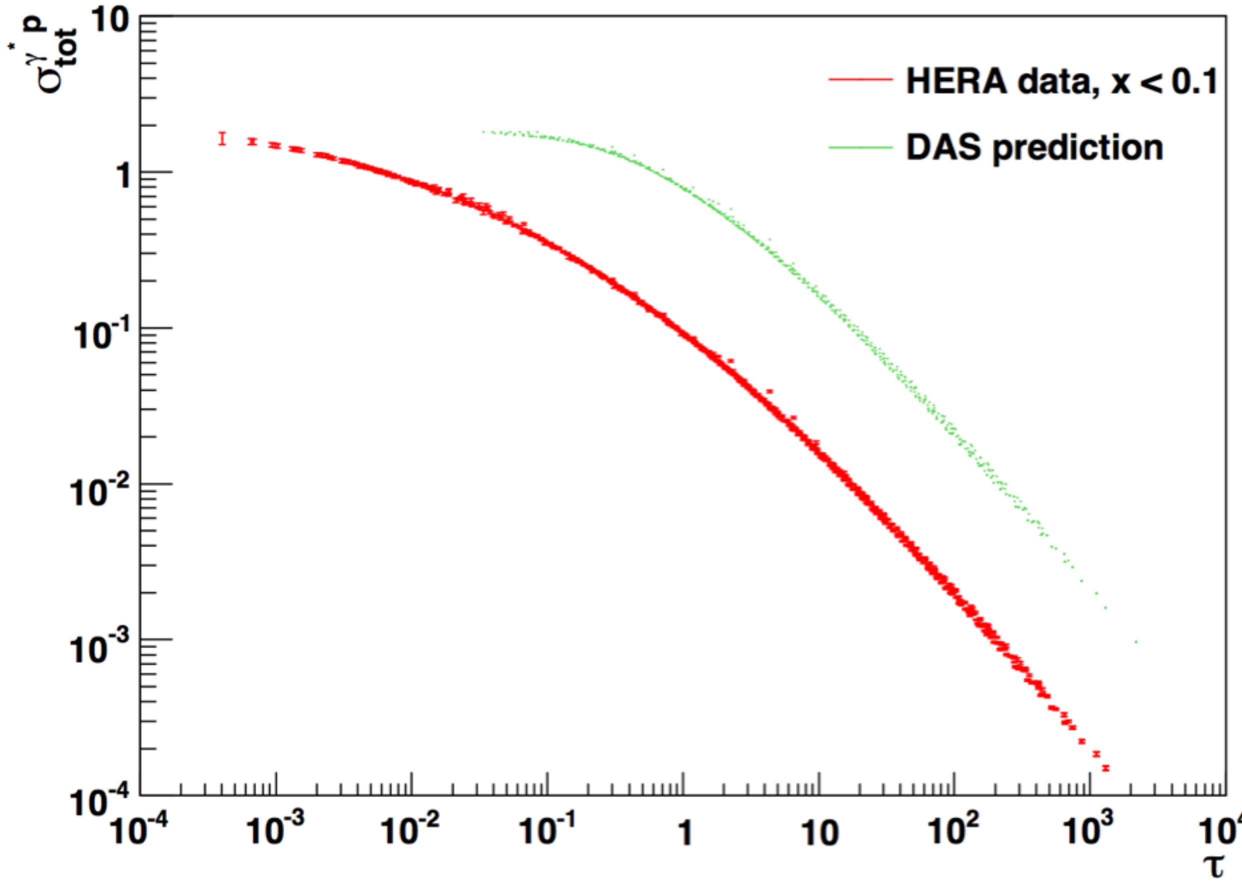
Authors have studied NNLO and reject this as a possible cause.



- Likewise, no evidence from comparisons with F_L or F_2-charm

Saturation at HERA? - Think outside the PDF!





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

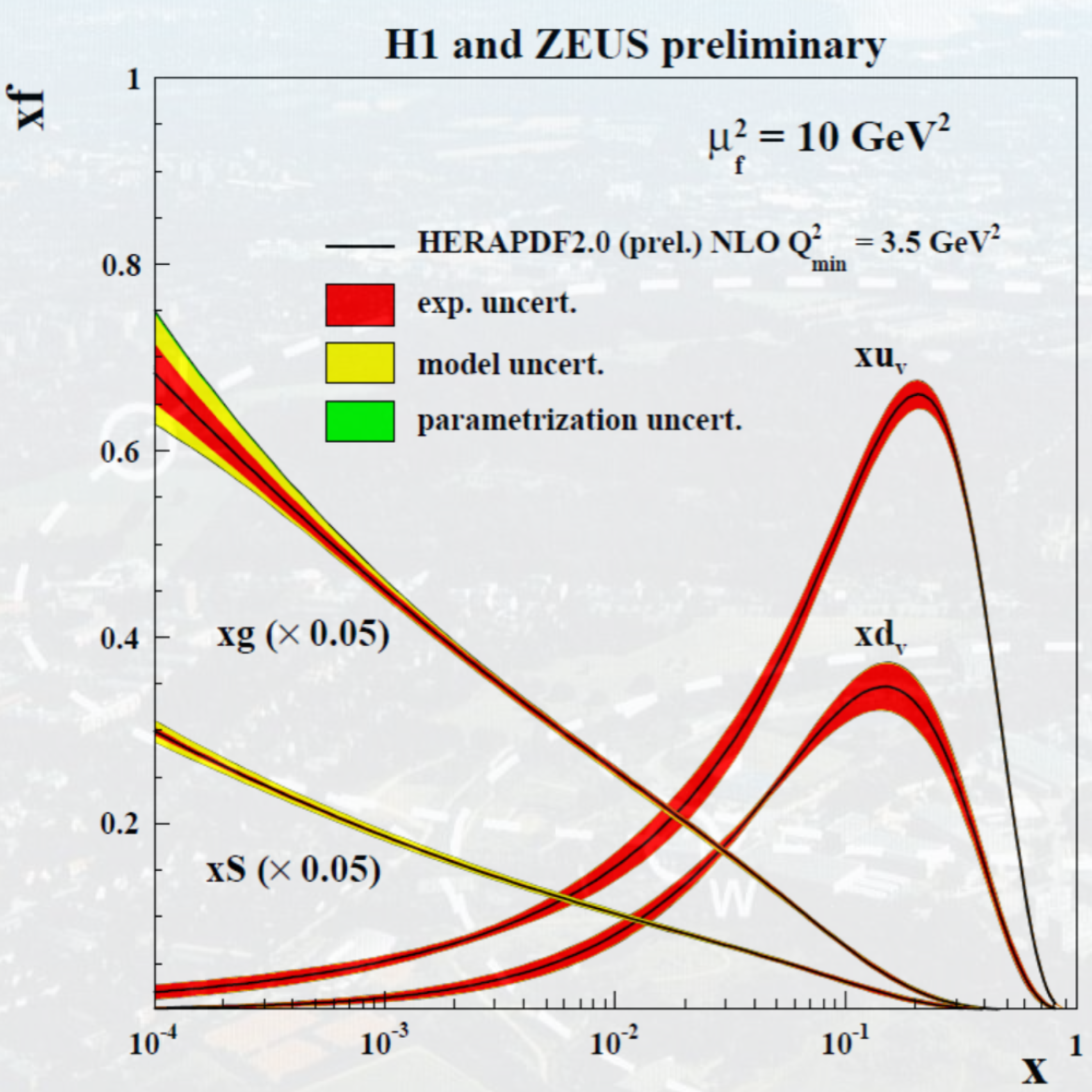
$$\tau = \frac{Q^2}{Q_s^2(x)} = \frac{Q^2}{Q_0^2} \frac{x}{x_0}^{\lambda} \quad \text{for } x < 0.01$$

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



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 √s / no nuclei,
- ...

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}	1×10^{-5}	5×10^{-7}	7×10^{-3} - 3×10^{-4}	5×10^{-3}	1×10^{-4}	5×10^{-5}
ion	p	p to Pb	p to U	p to ~^{40}Ca	p to Pb	p to U
polarization	-	-	p, d, ^{3}He	p, d	p, d, ^{3}He (^{6}Li)	p, ^{3}He
L [$cm^{-2}s^{-1}$]	2×10^{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
√s [GeV]	320	800 - 1300	12 - 65	14	20 - 140	78 - 145
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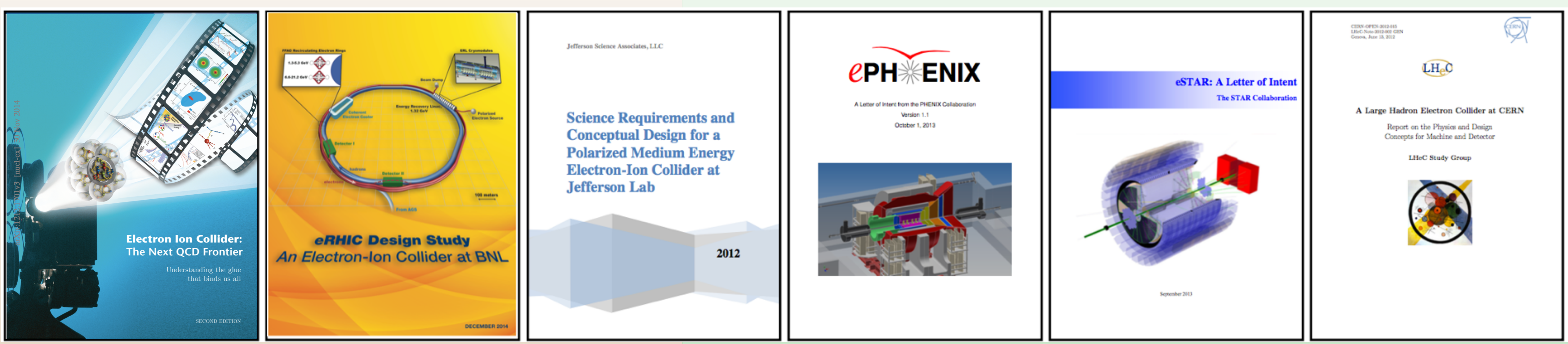


+ *popular press, most recently "Les gluons nous posent encore des colles", Ent, Ullrich, Venugopalan, Pour La Science 455, Sept. '15*

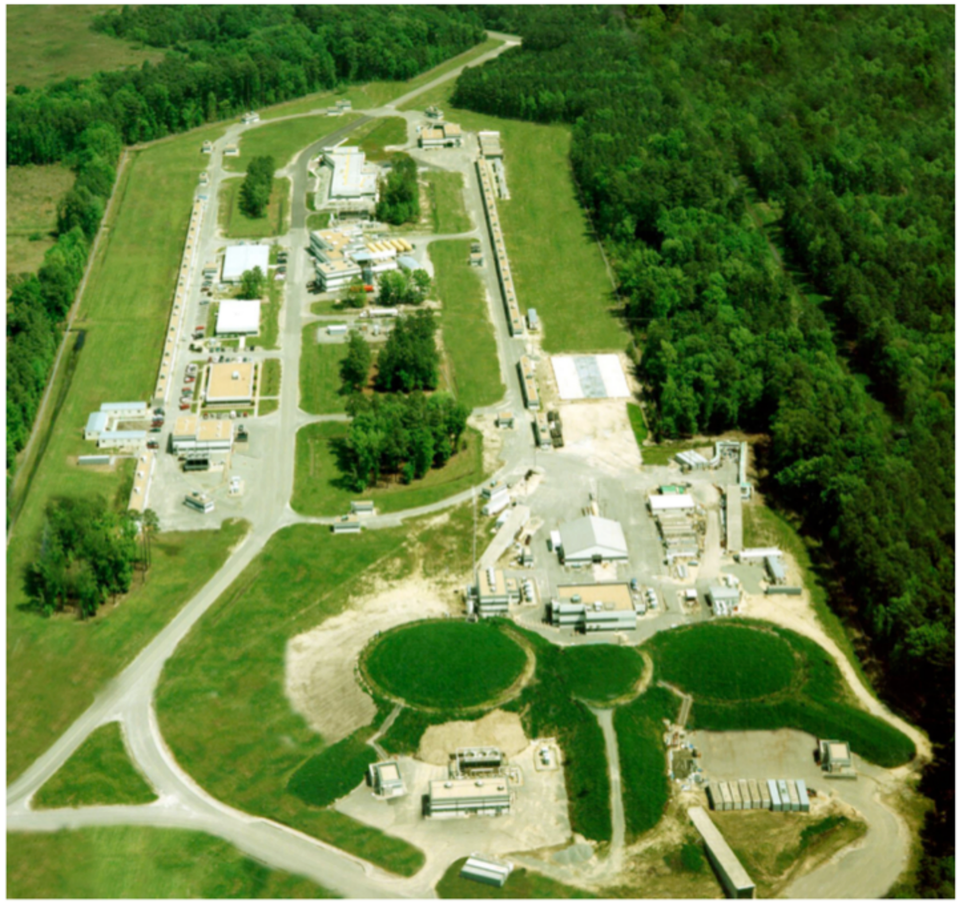
U.S.-based EIC - Two Facility Concepts

eRHIC:

- upgrade to RHIC hadron beam,

MEIC:

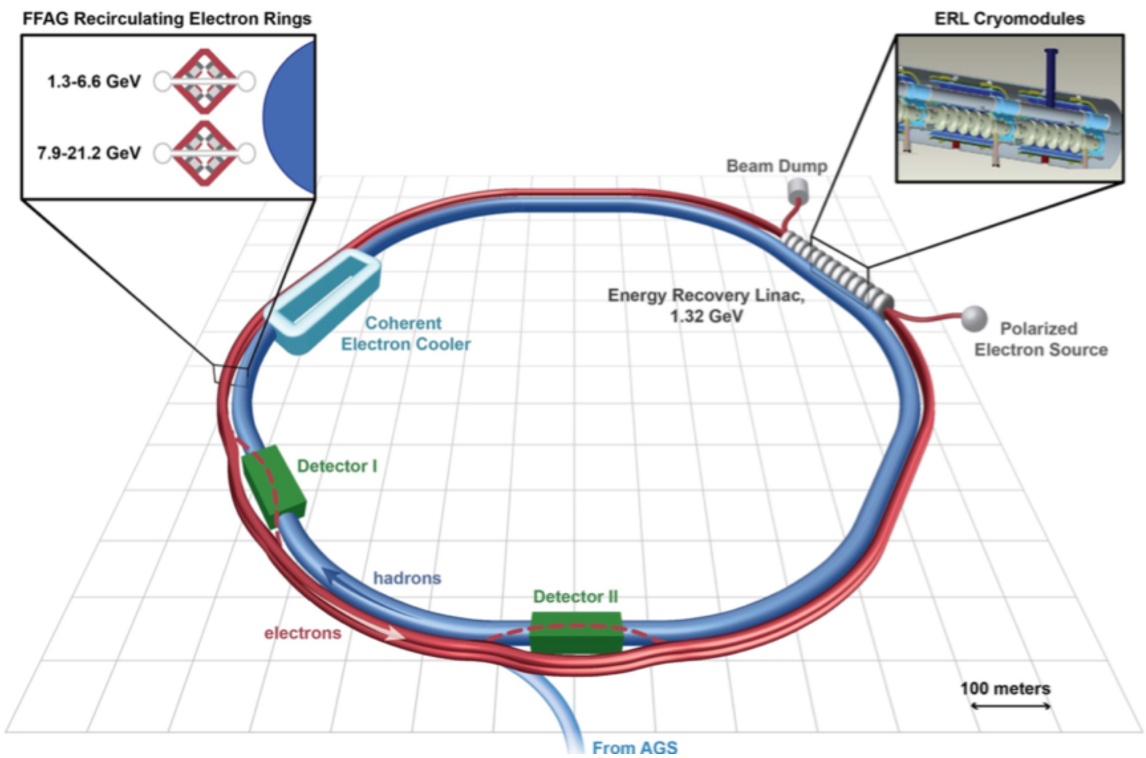
- upgrade to CEBAF 12 GeV electron beam,



U.S.-based EIC - Two Facility Concepts

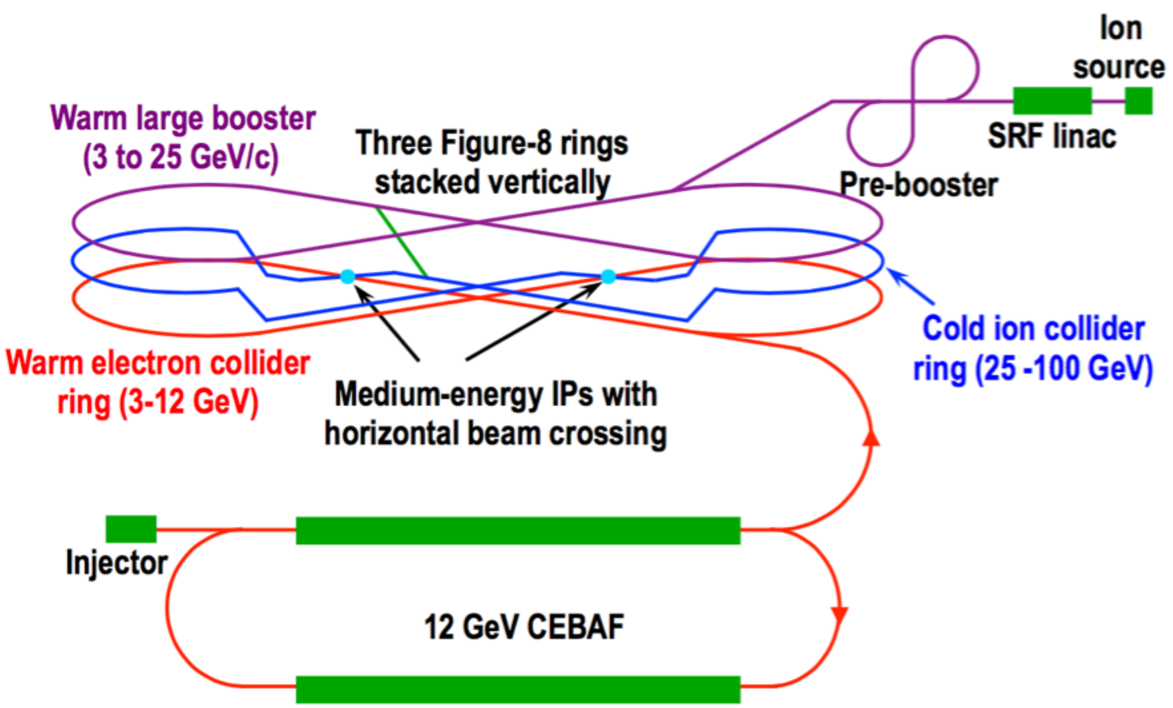
eRHIC:

- 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 ~ 10^{33} $cm^{-2}s^{-1}$/A base design.

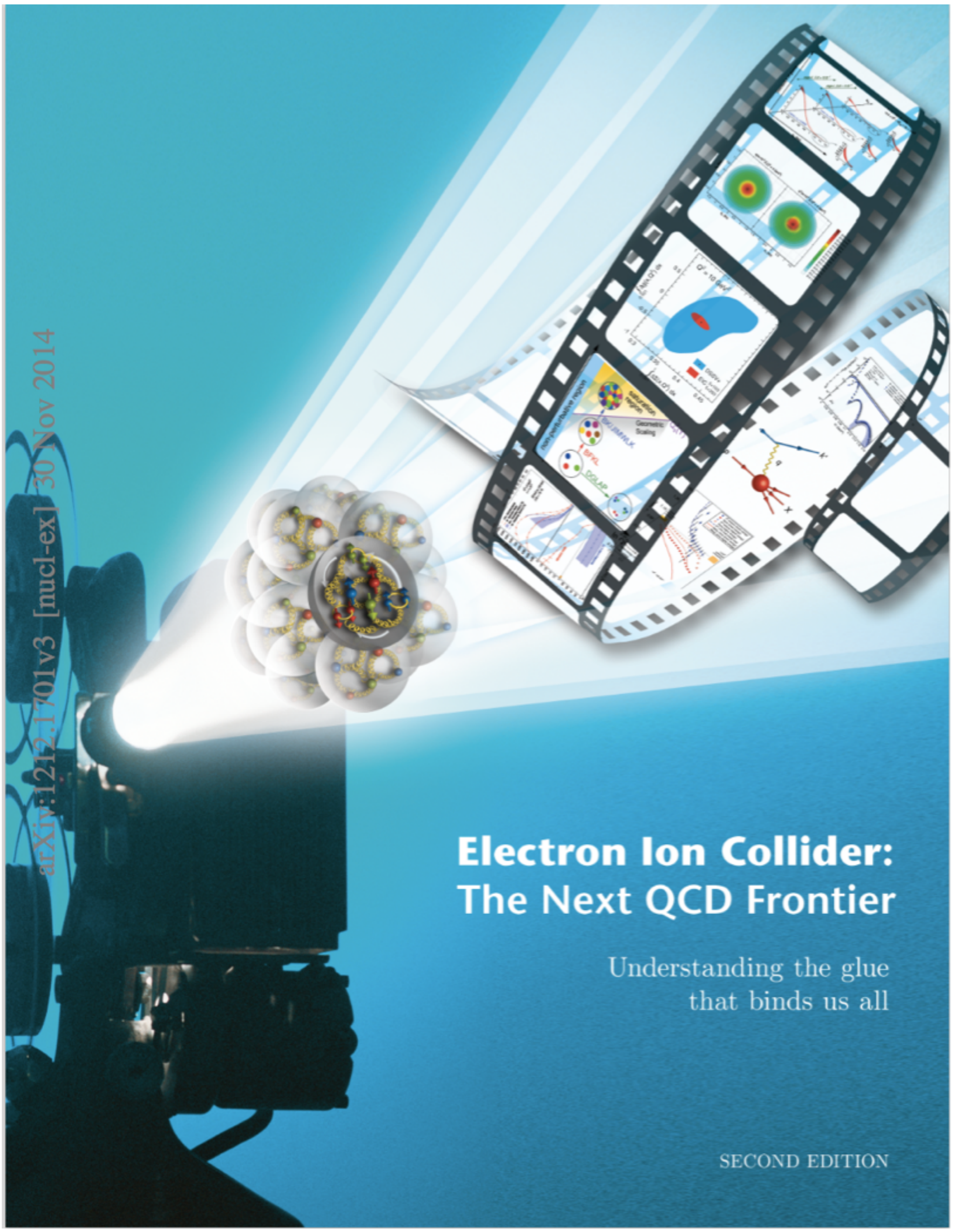


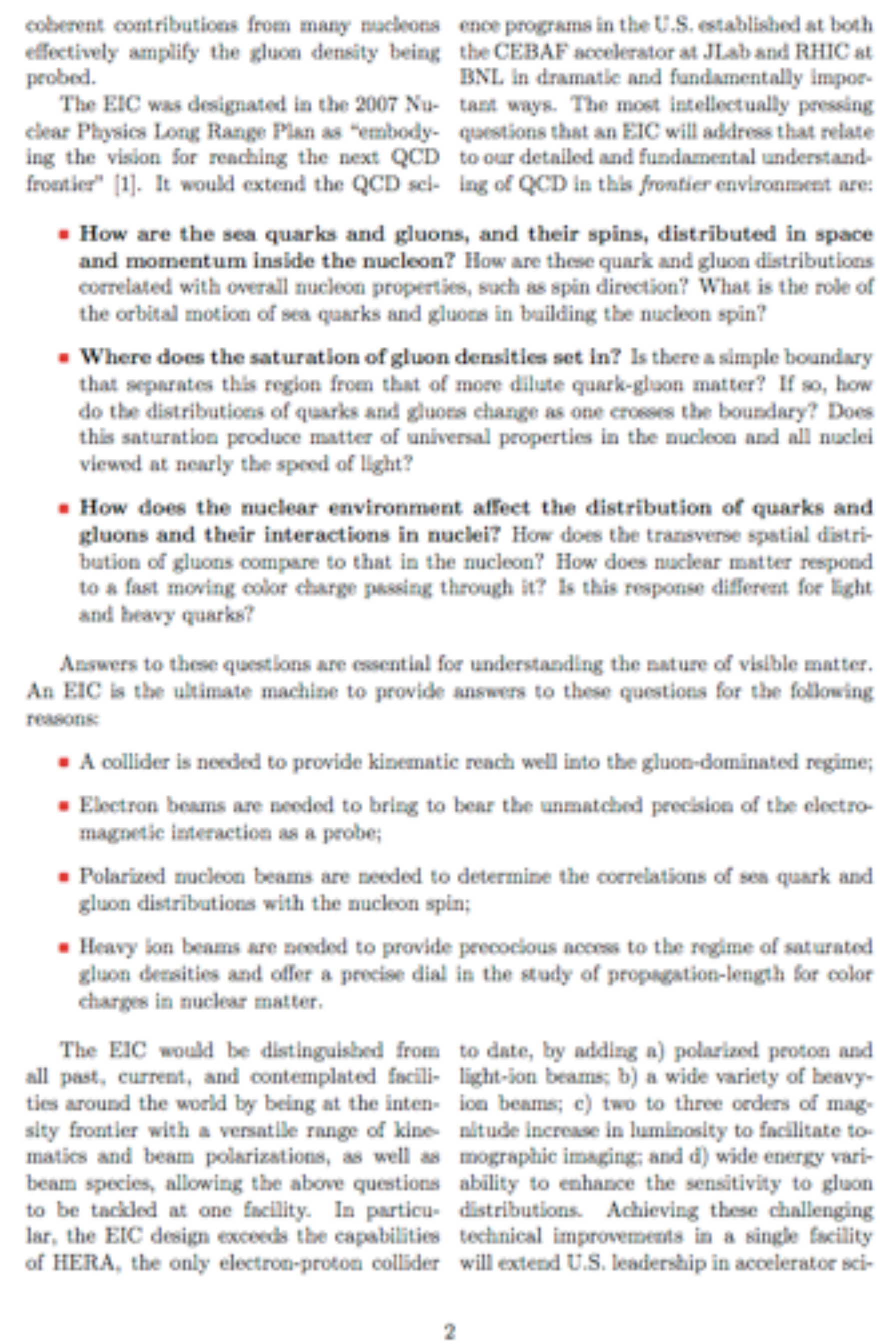
MEIC:

- 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 ~10^{34} $cm^{-2}s^{-1}$/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 science 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?

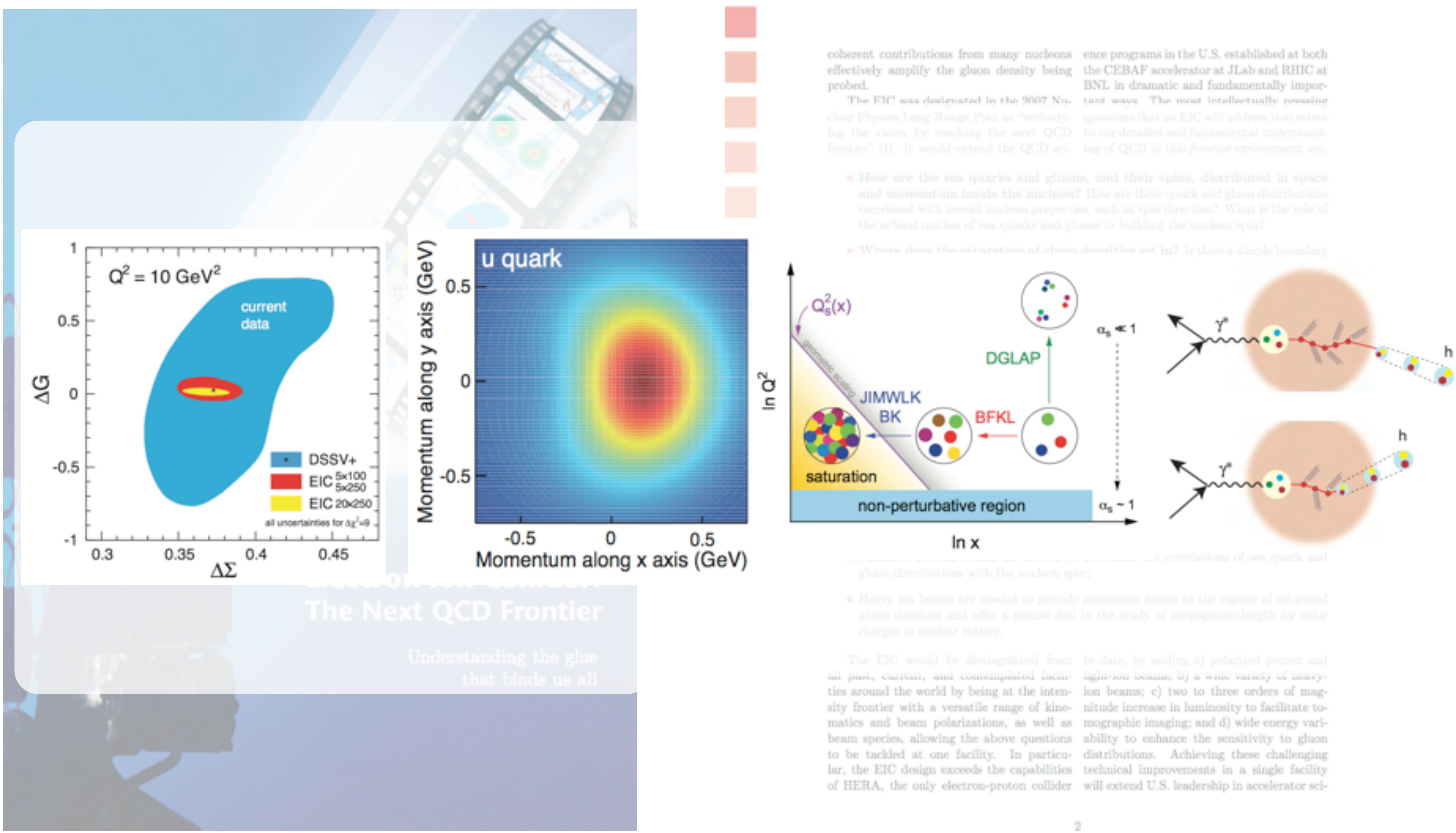
Answers to these questions are essential for understanding the nature of visible matter. An EIC is the ultimate machine to provide answers to these questions for the following reasons:

- 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-

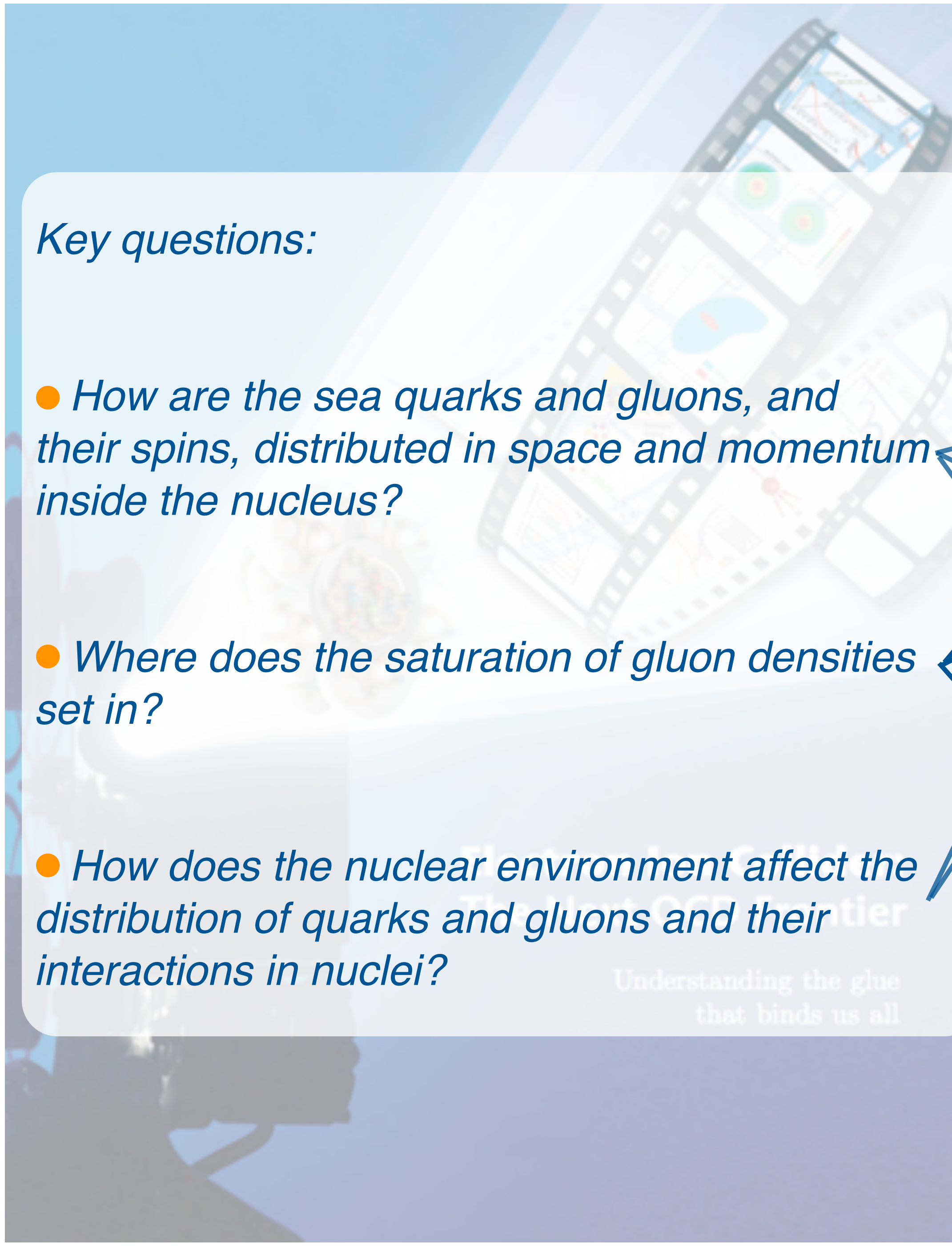
2

U.S.-based EIC - Science Focus



ArXiv:1212.17010

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.*

ArXiv:1212.17010

U.S.-based EIC - Observables

Key requirements:

- *Electron identification - scattered lepton*
- *Momentum and angular resolution - x, Q^2*
- *π^+, π^-, K^+, K^-, p^+, p^-, ... identification, acceptance*
- *Rapidity coverage, t-resolution*

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U.S.-based EIC - Detector Concepts

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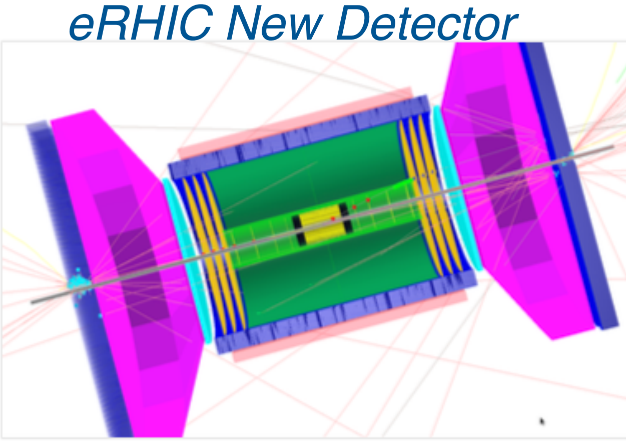
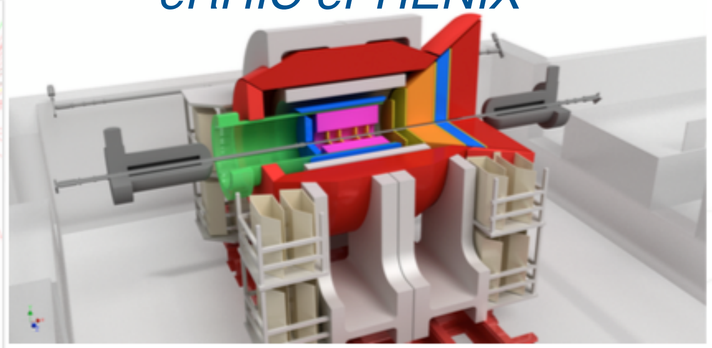
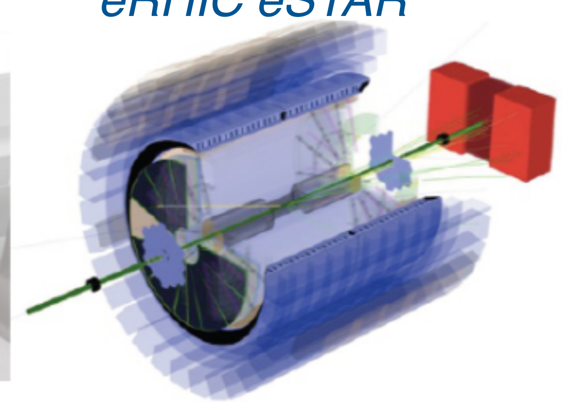
eRHIC New Detector



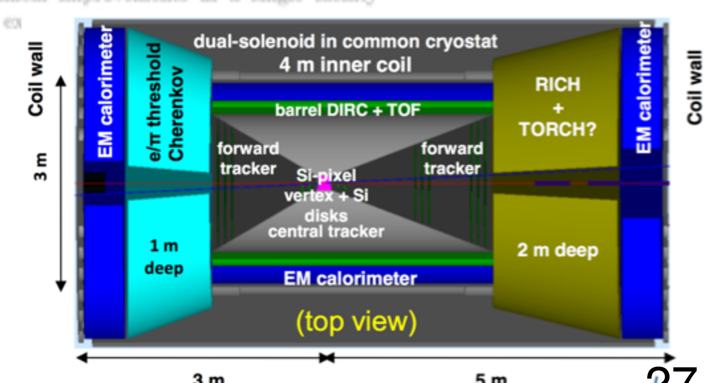
eRHIC ePHENIX



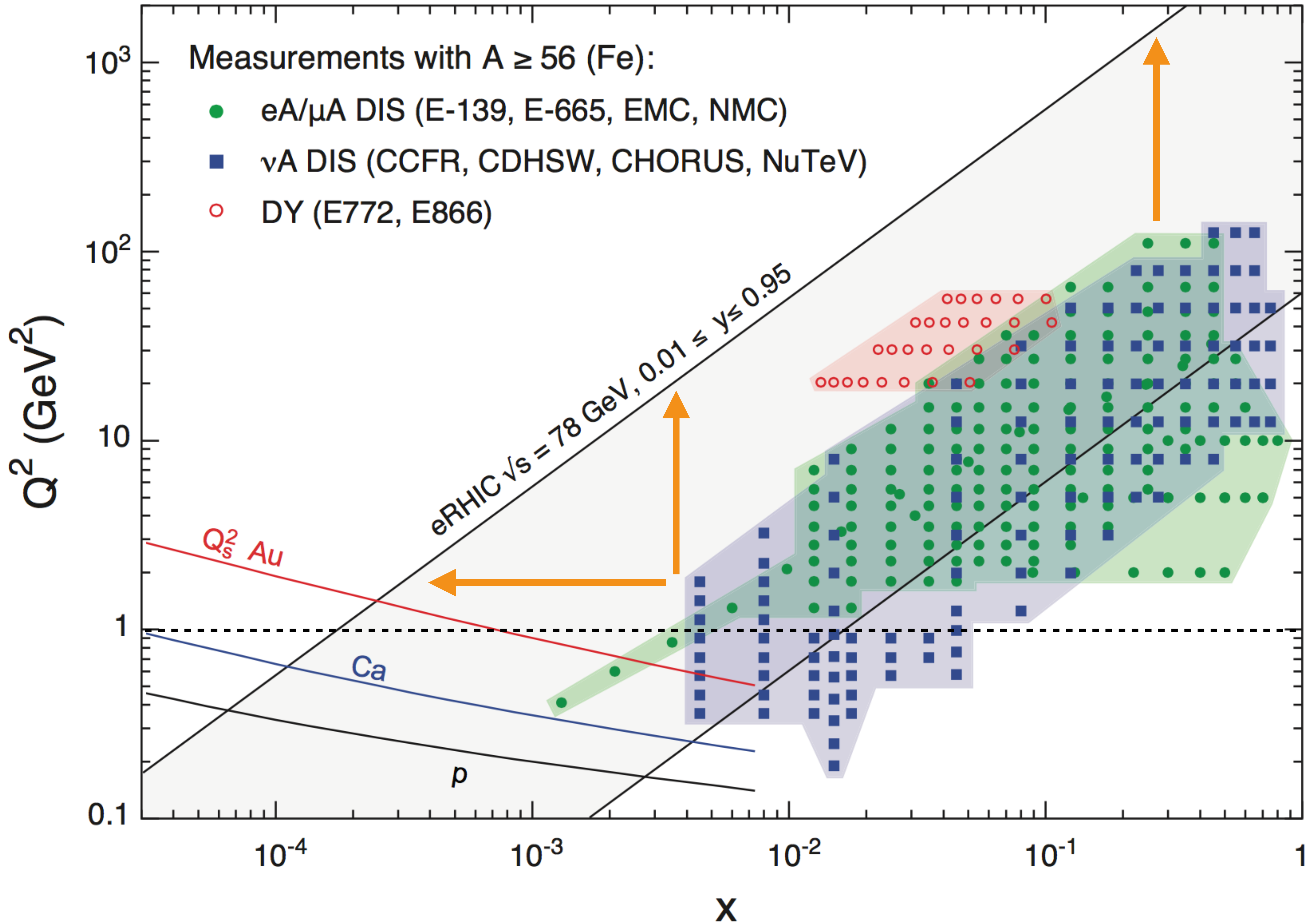
eRHIC eSTAR



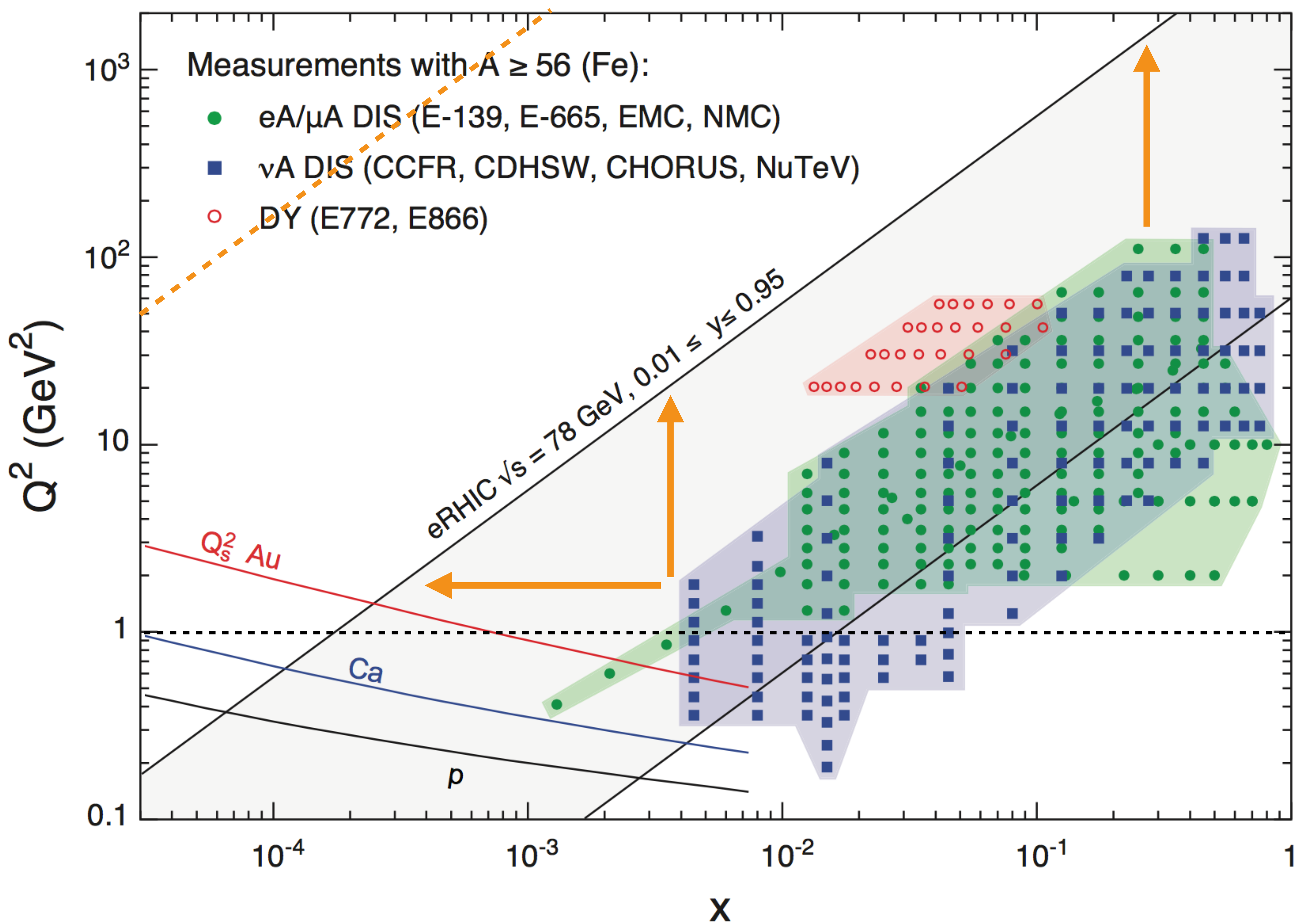
MEIC new detector



Existing eA landscape - eRHIC kinematic range



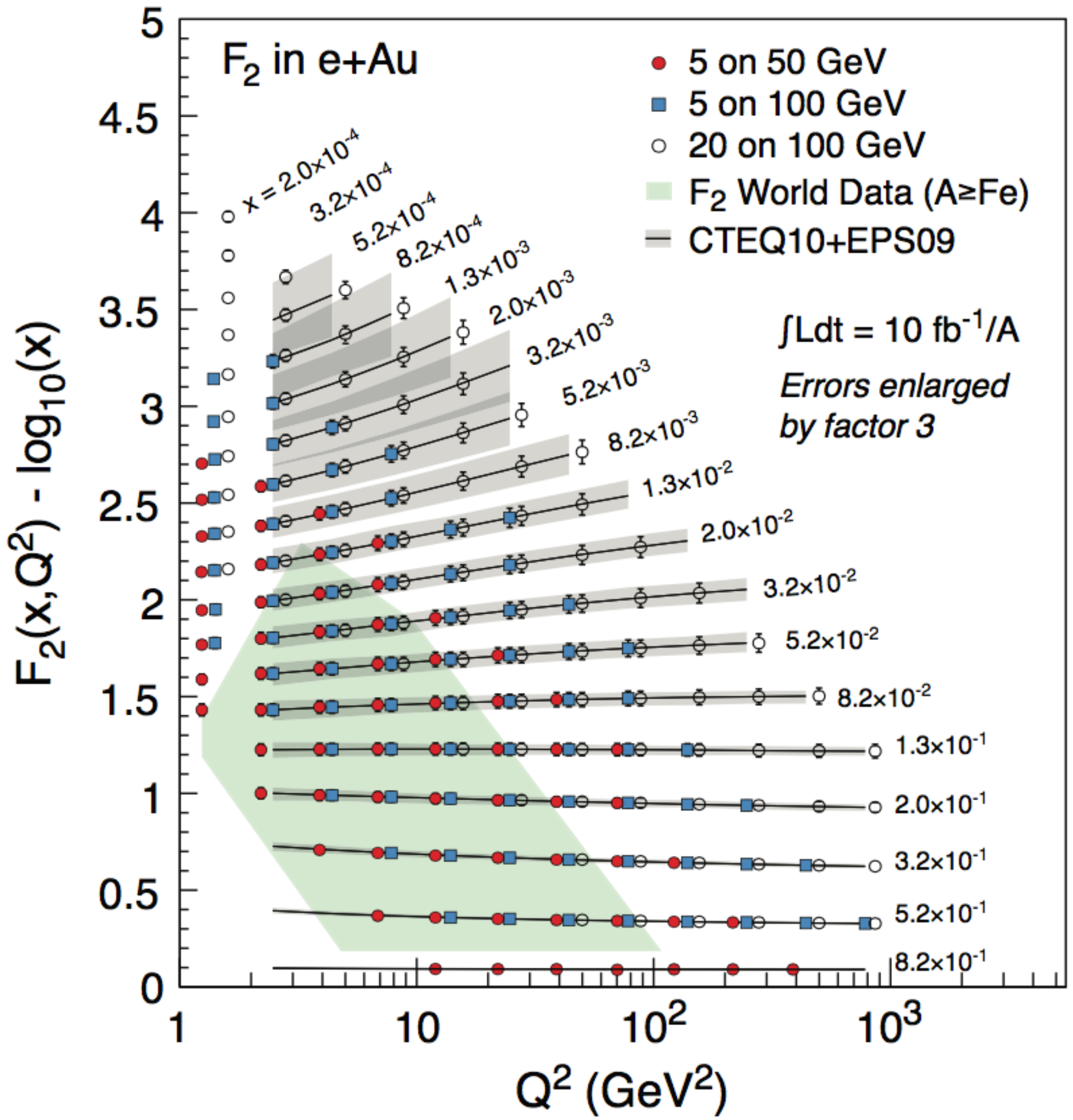
Existing eA landscape - eRHIC kinematic range

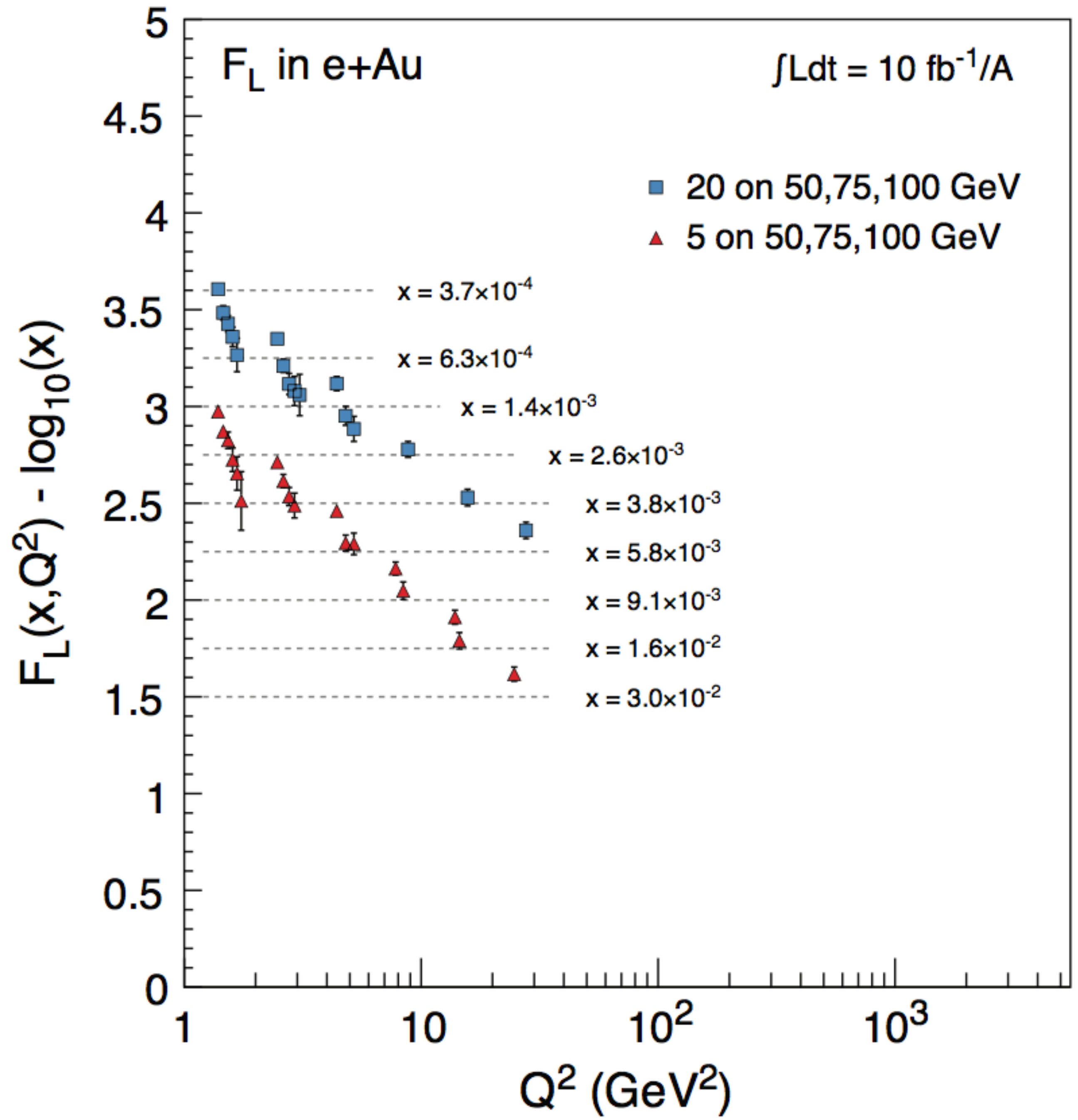


LHeC, if realized, will obviously provide unprecedented kinematic reach, complementarity in polarization, A capabilities.

eRHIC - selected baseline measurements

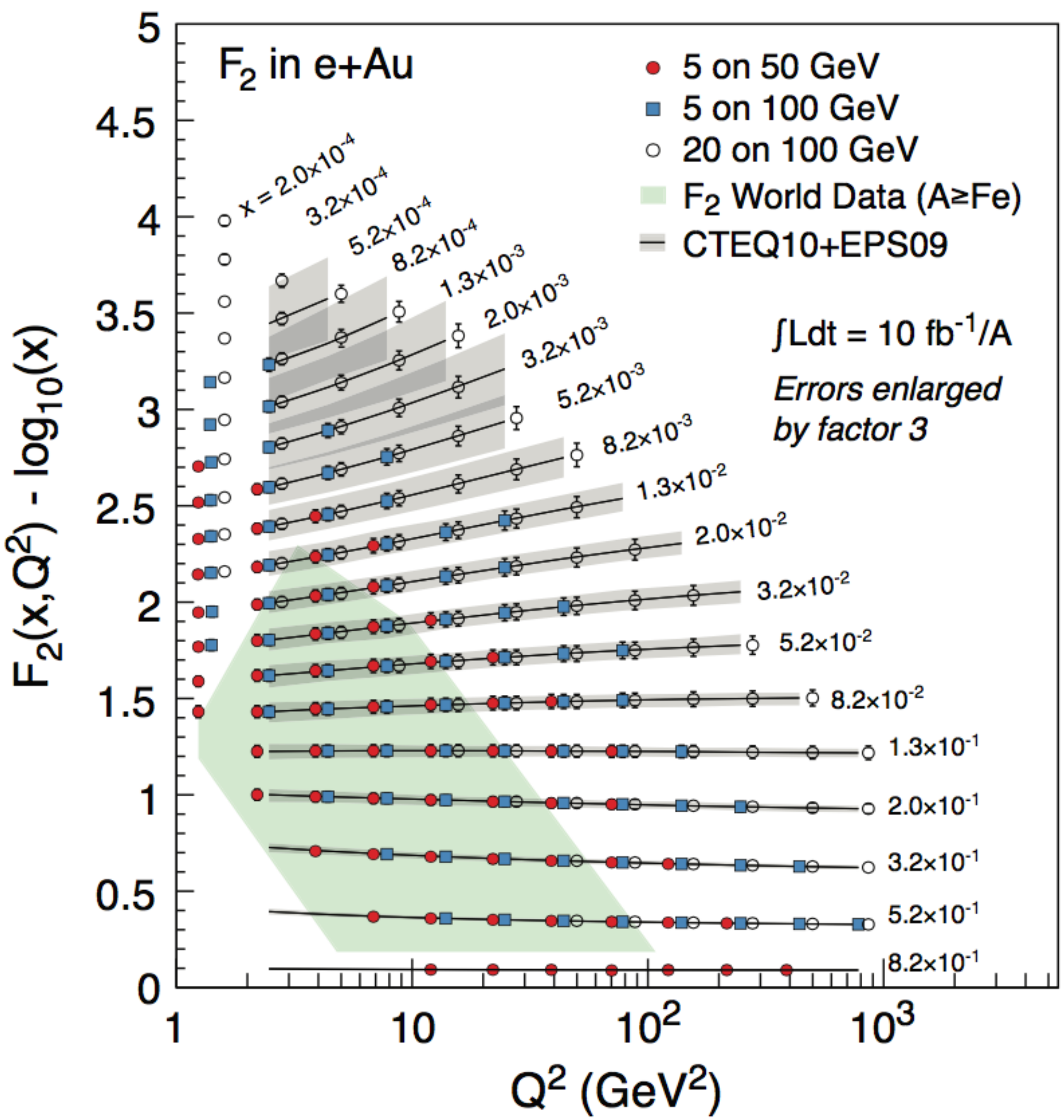
$$\frac{d^2\sigma^{eA\to eX}}{dxdQ^2} = \frac{4\pi\alpha^2}{xQ^4}\left[\left(1-y+\frac{y^2}{2}\right)F_2(x,Q^2) - \frac{y^2}{2}F_L(x,Q^2)\right]$$

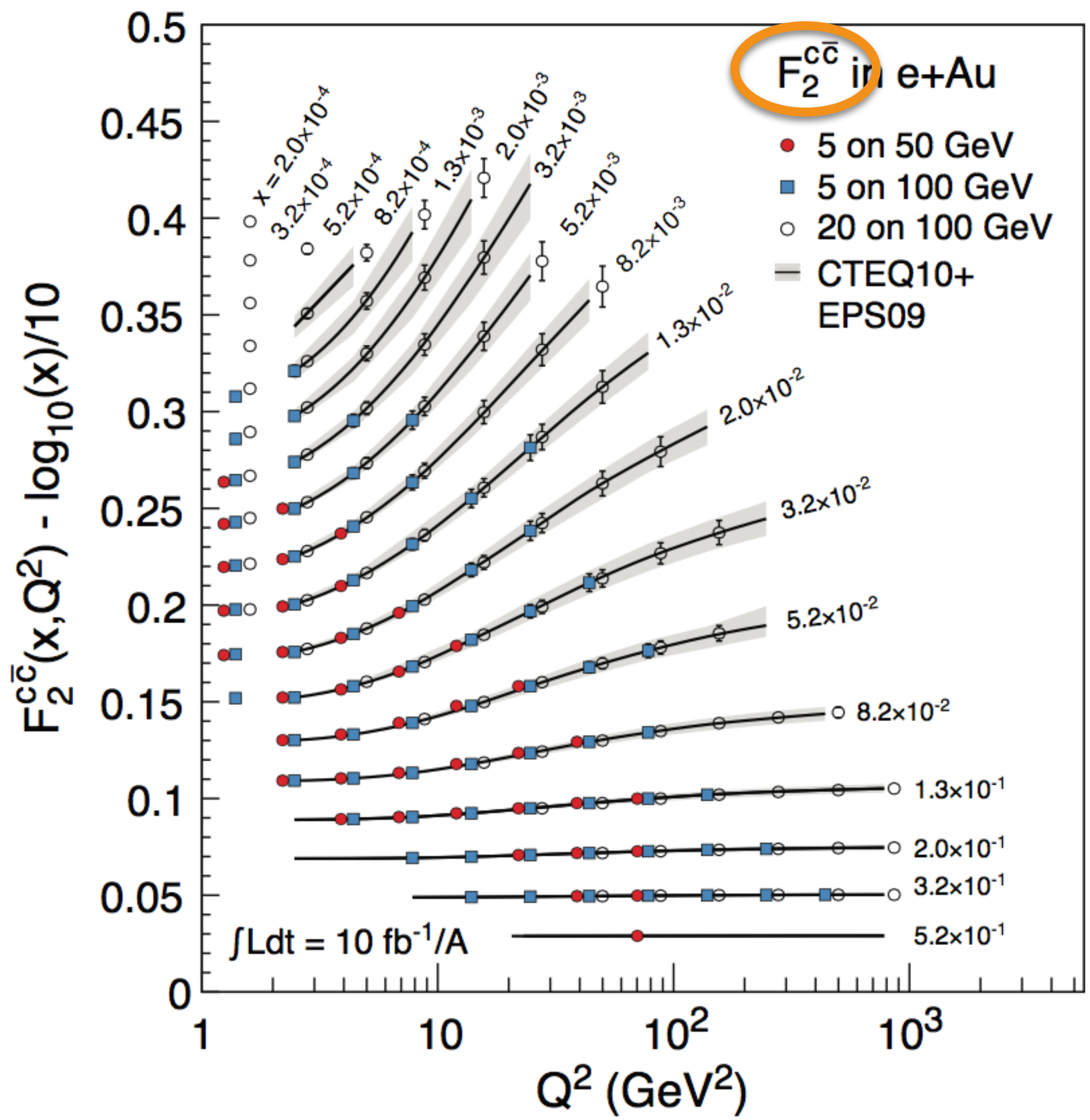




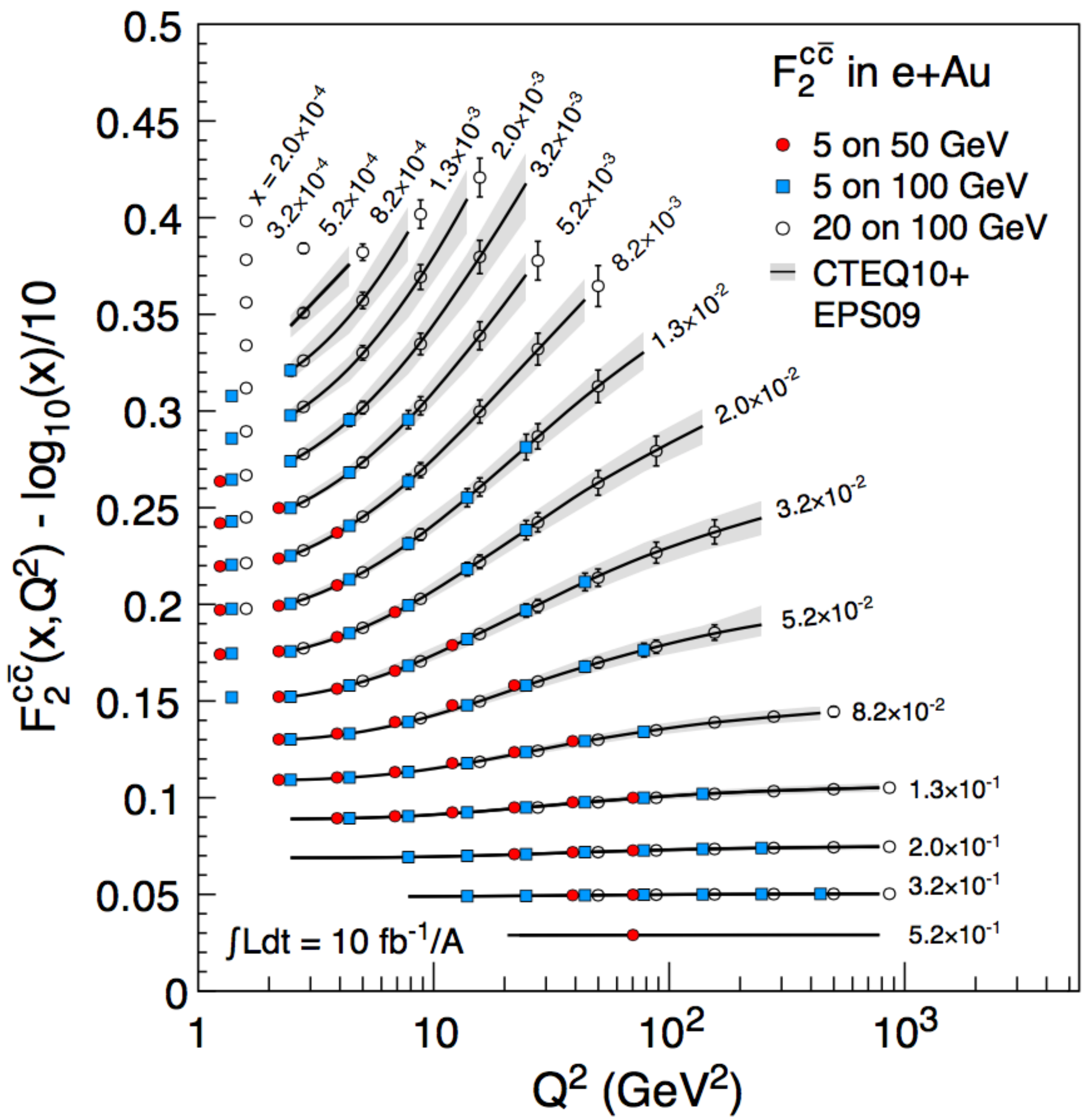
eRHIC - selected *baseline* measurements

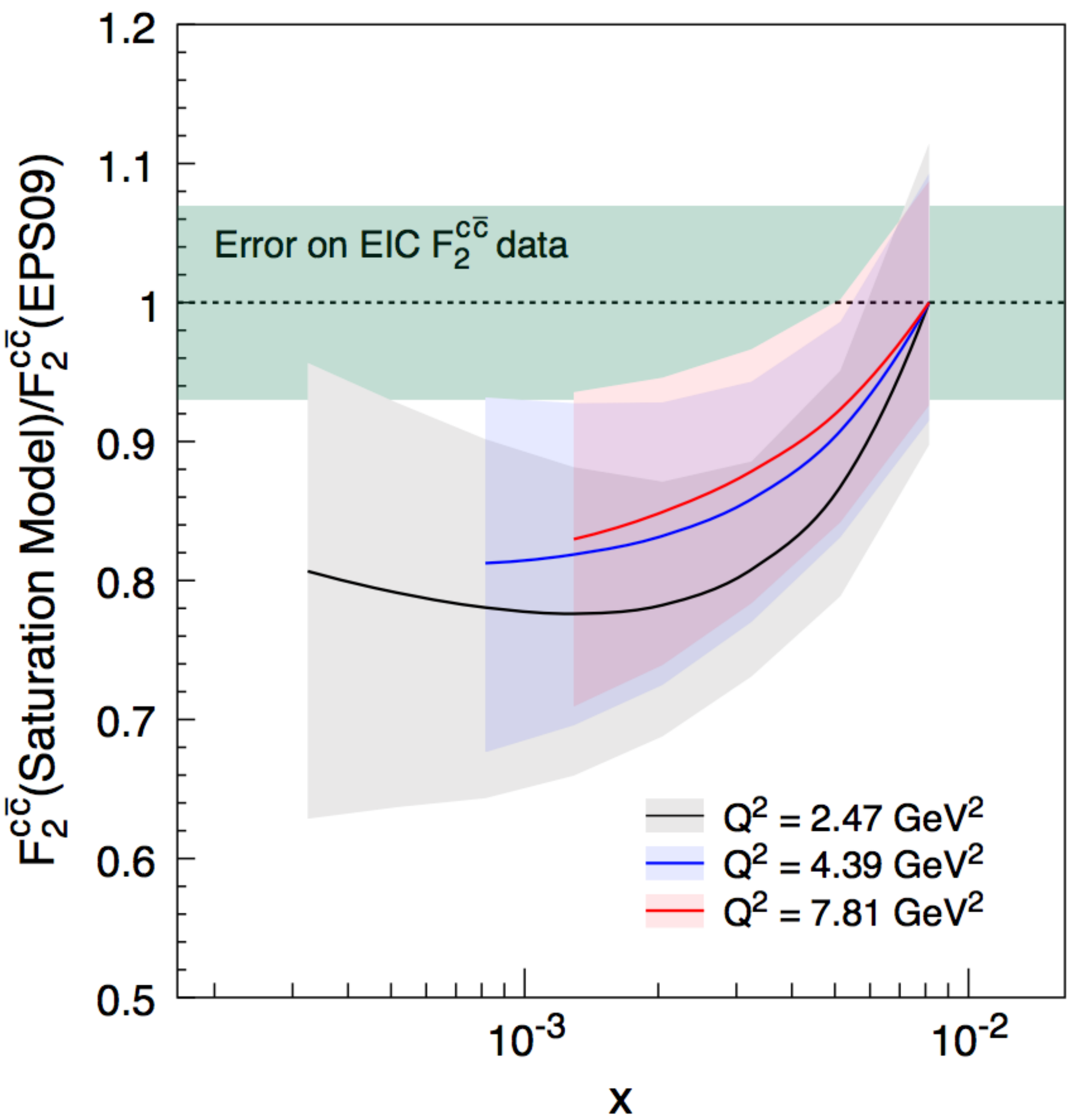
$$\frac{d^2\sigma^{eA\to eX}}{dxdQ^2} = \frac{4\pi\alpha^2}{xQ^4}\left[\left(1-y+\frac{y^2}{2}\right)F_2(x,Q^2) - \frac{y^2}{2}F_L(x,Q^2)\right]$$





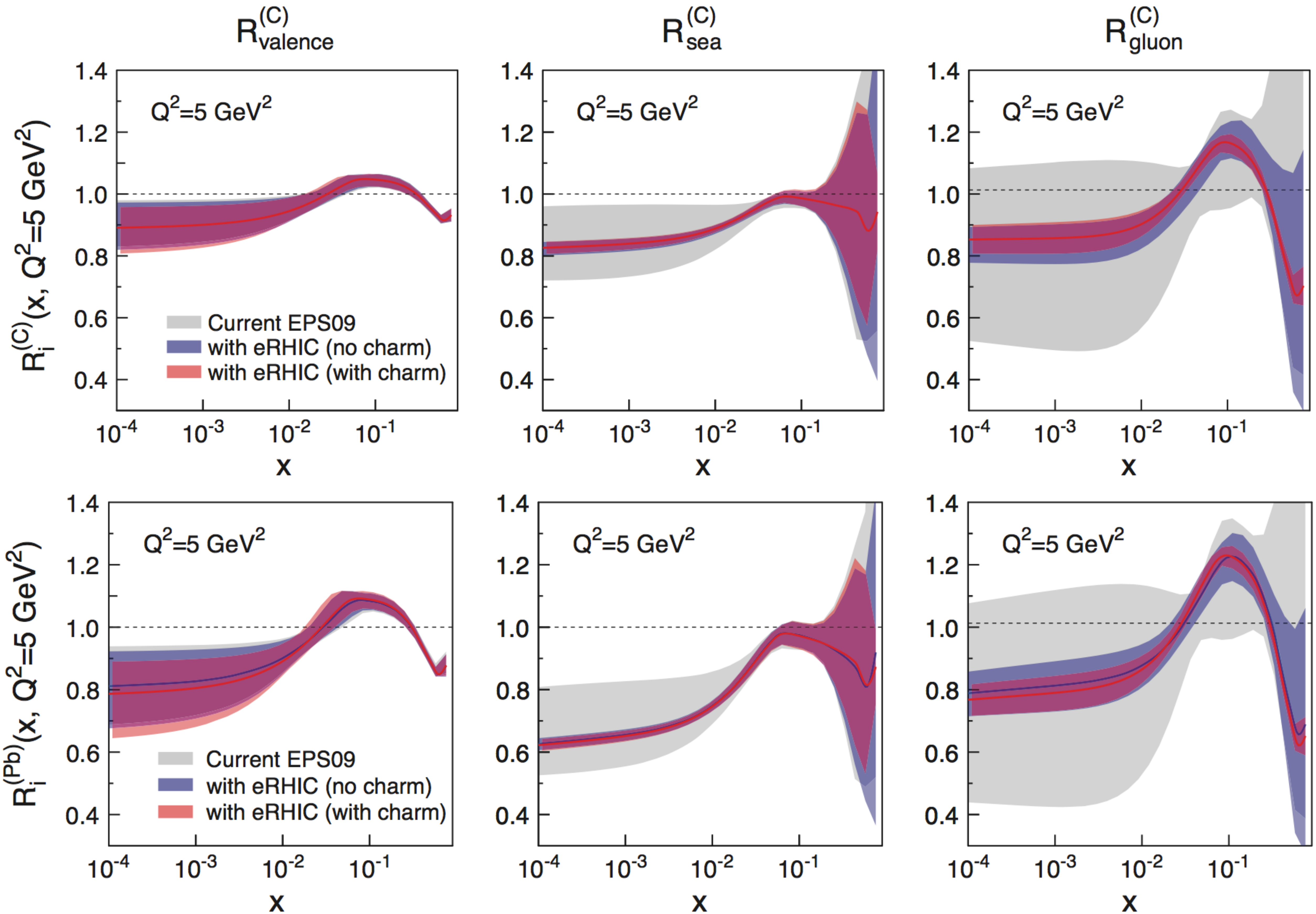
eRHIC - observing saturation inside the PDF?



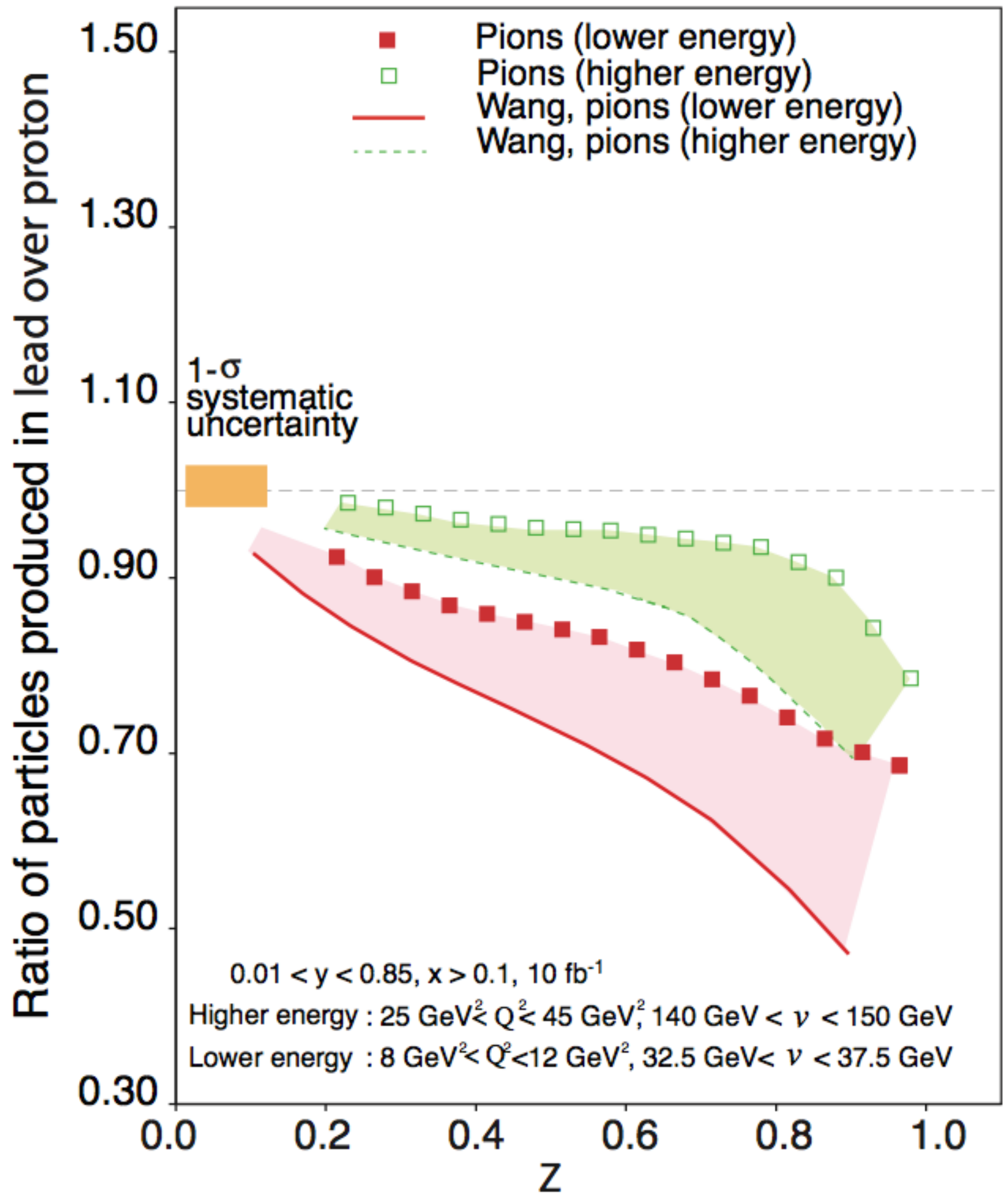


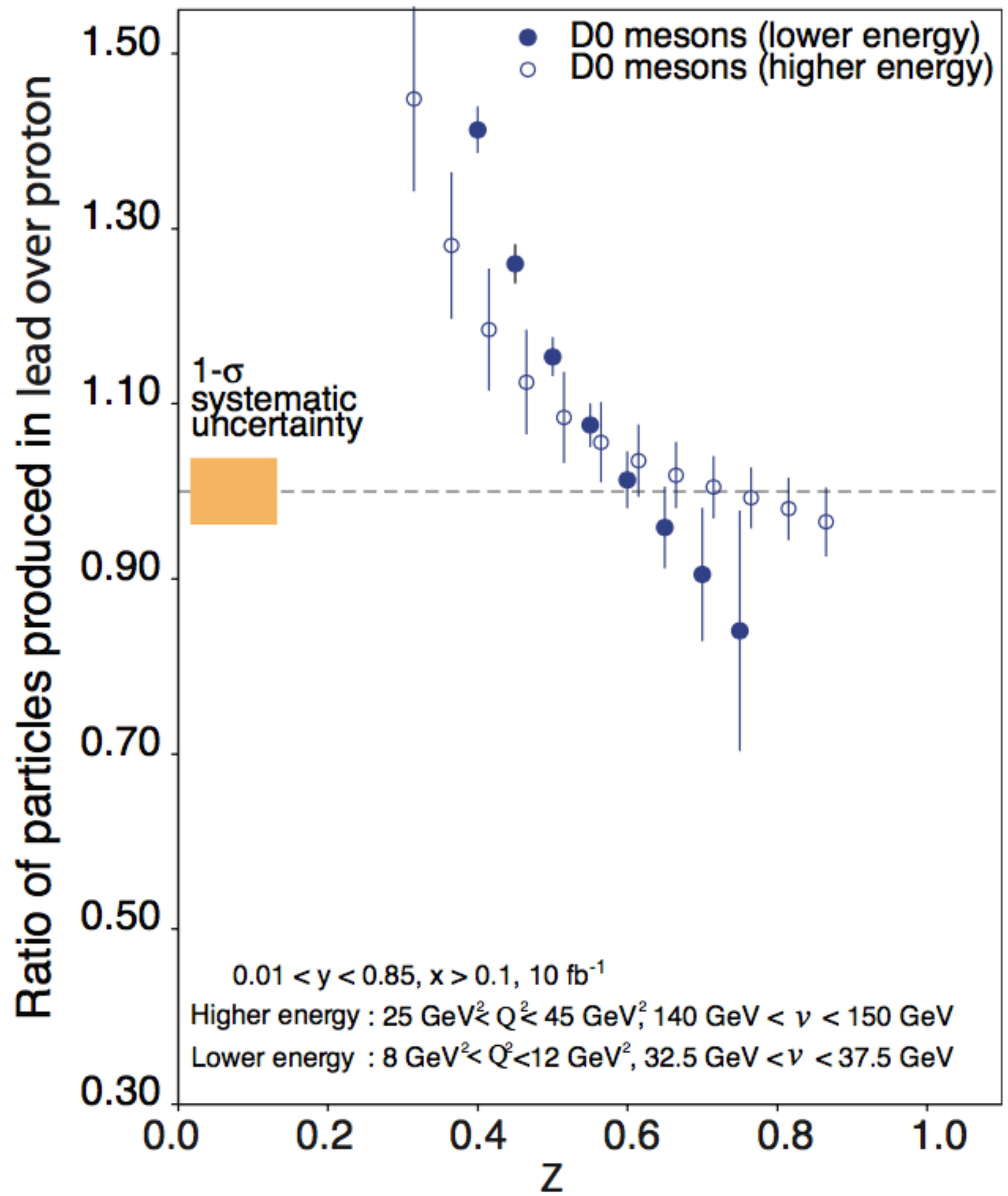
***Perhaps*, but no substitute for thinking *outside* the PDF!**

eRHIC - impact on nuclear modification



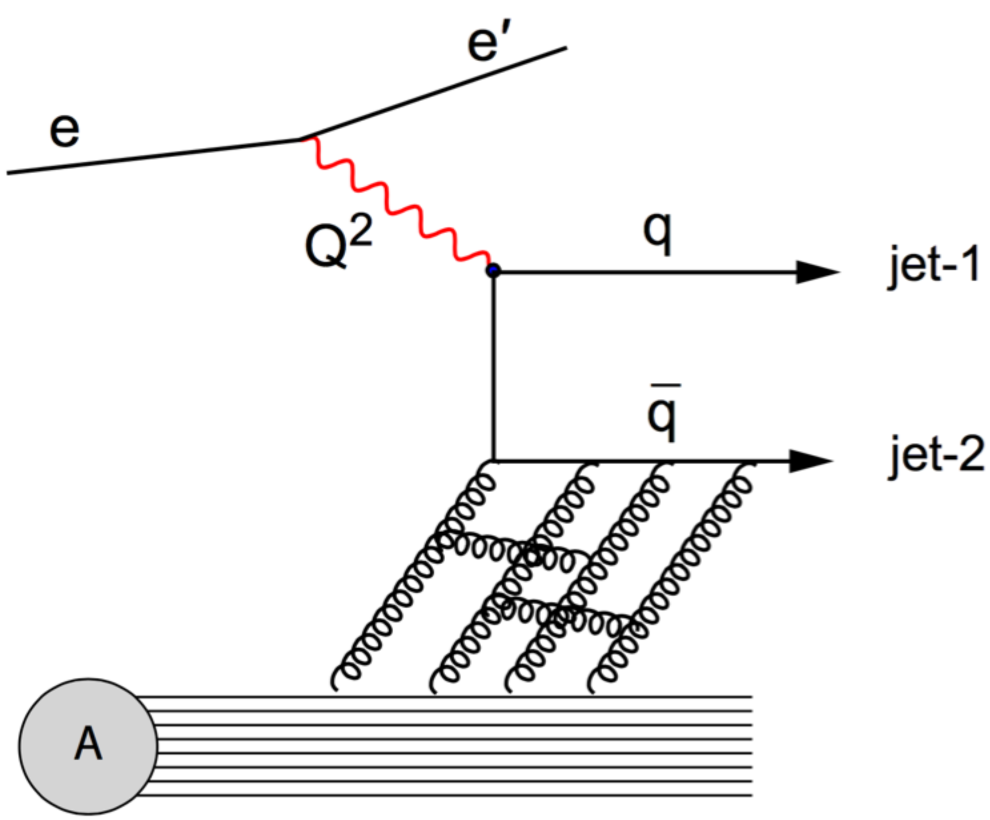
eRHIC - *baseline* semi-inclusive measurements



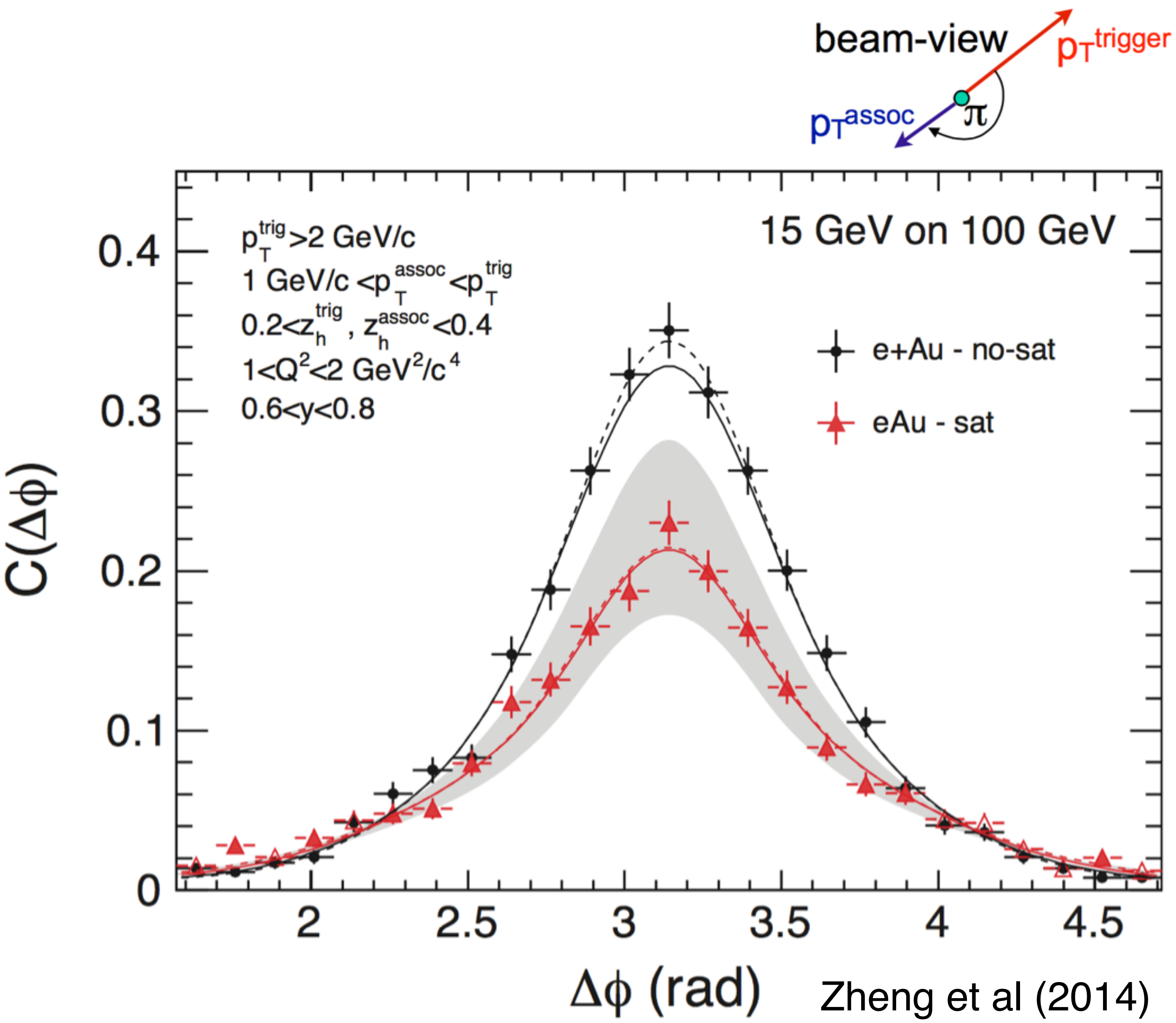


Combined sensitivity to hadronization, energy loss

eRHIC - dihadron probes of saturation



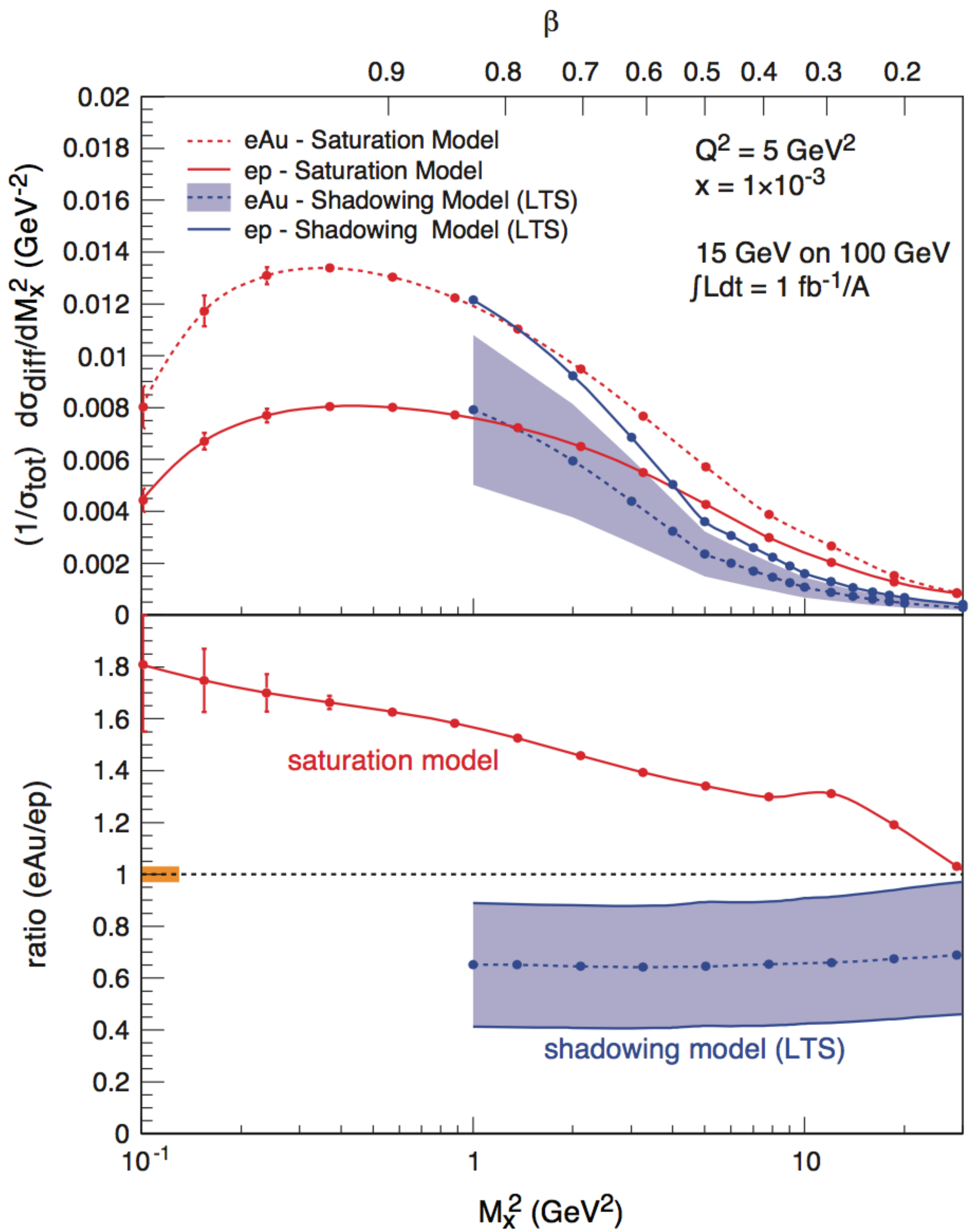
Dominguez, Xiao, Yuan (2011)



Zheng et al (2014)

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

eRHIC - diffractive probes of saturation



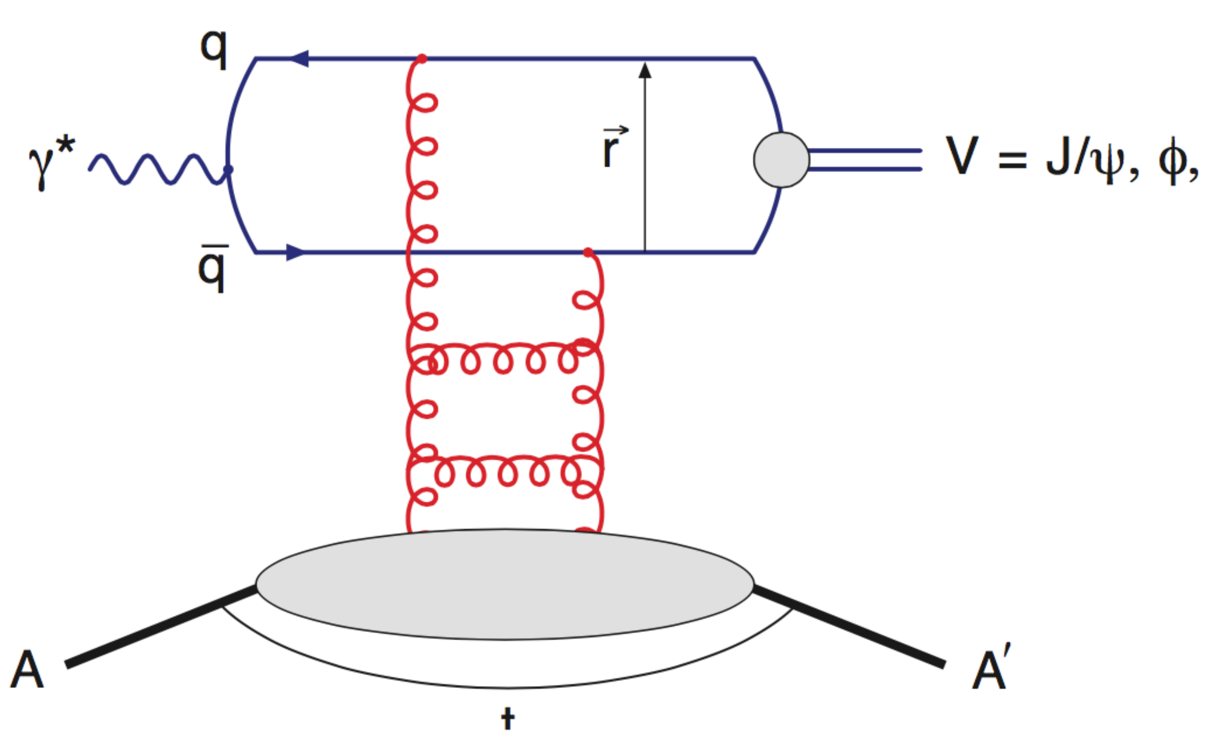
Sizable fraction of events is diffractive in saturation models;

Enhancement not seen in Leading Twist Shadowing pQCD model.

LTS: Frankfurt, Guzey, Strikman PLB586 (2004) 41

eRHIC - exclusive vector meson production

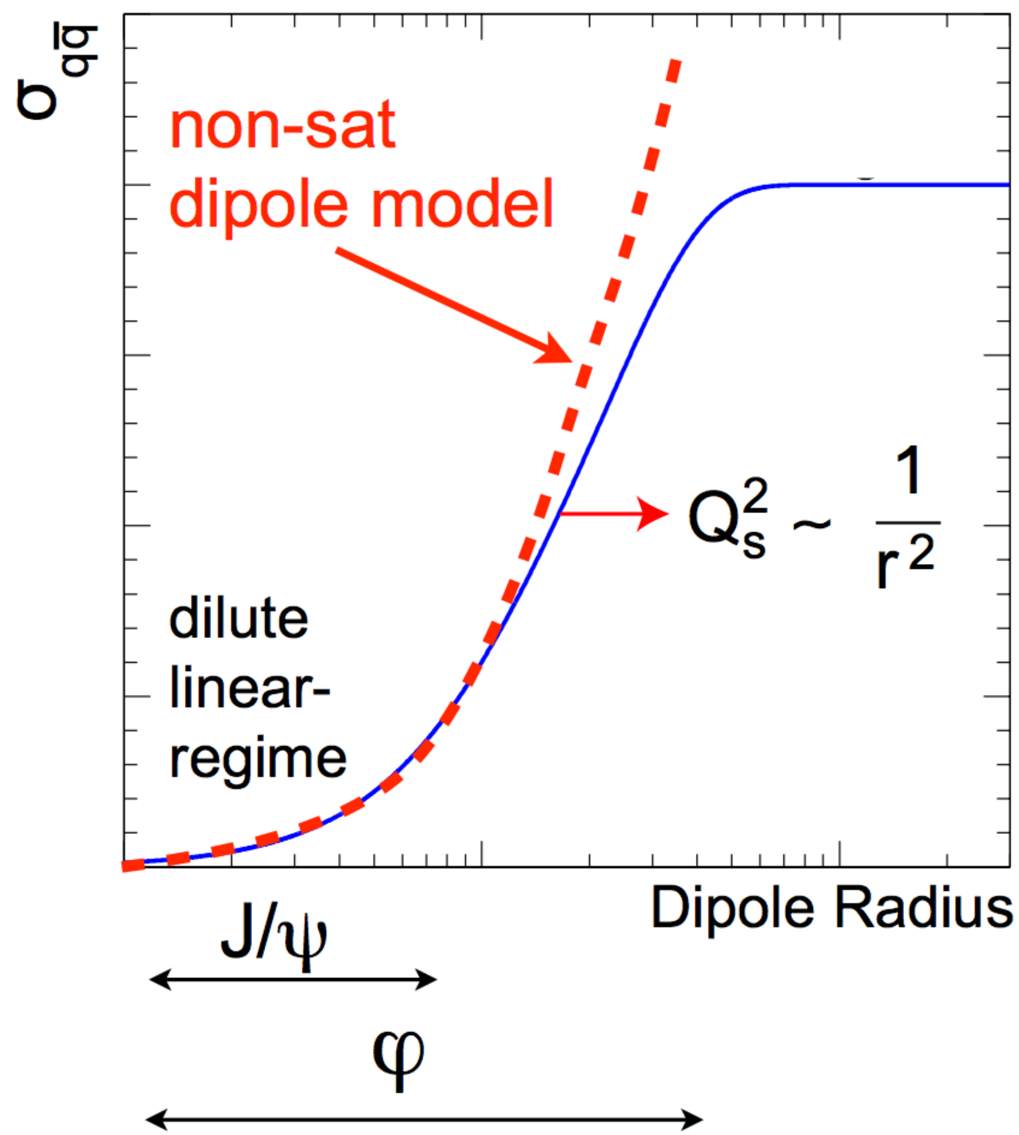
$$t = (\boldsymbol{p}_A - \boldsymbol{p}_{A'})^2 = (\boldsymbol{p}_{\mathrm{VM}} + \boldsymbol{p}_{e'} - \boldsymbol{p}_e)^2$$



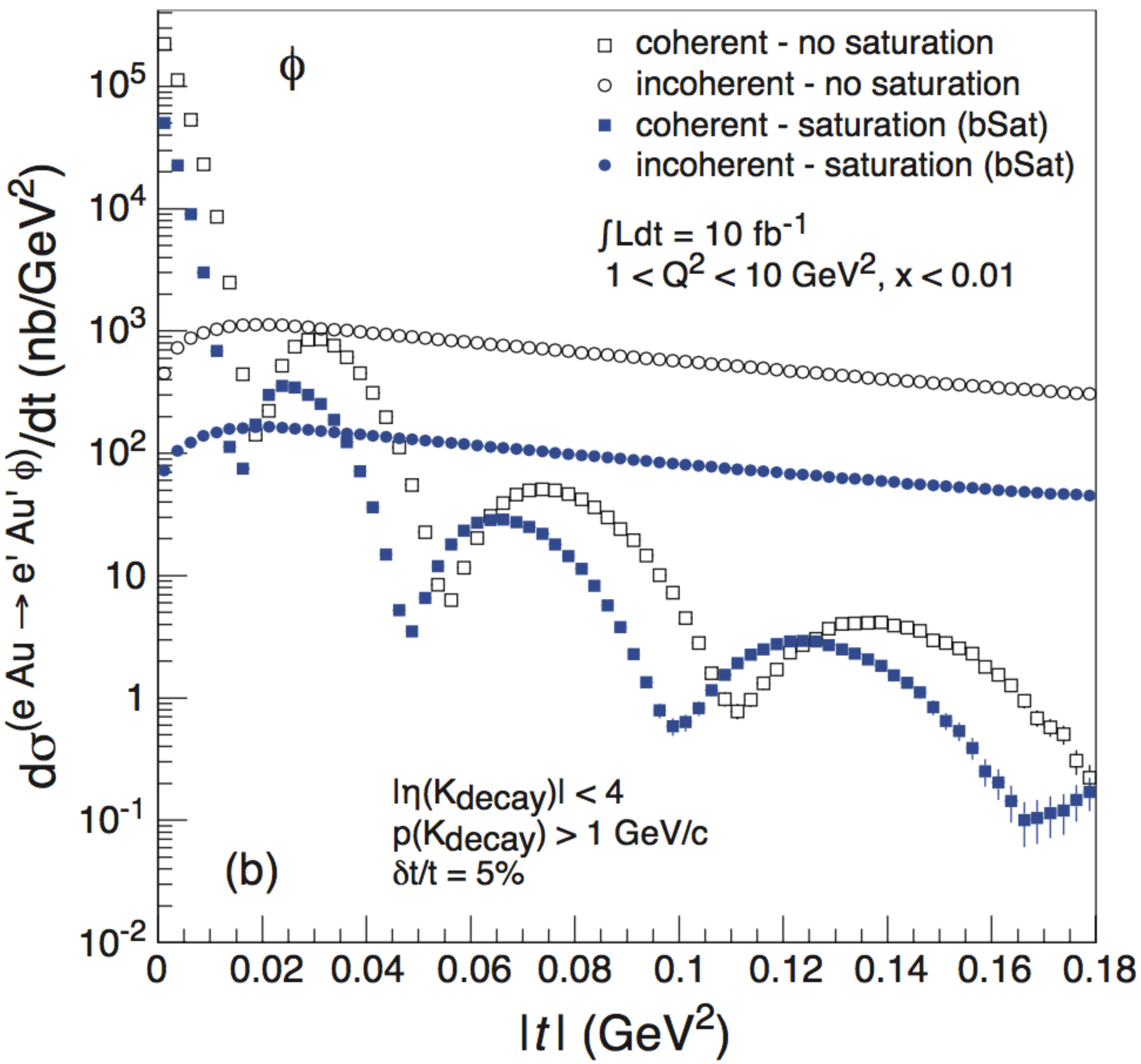
Nucleus escapes down the beampipe

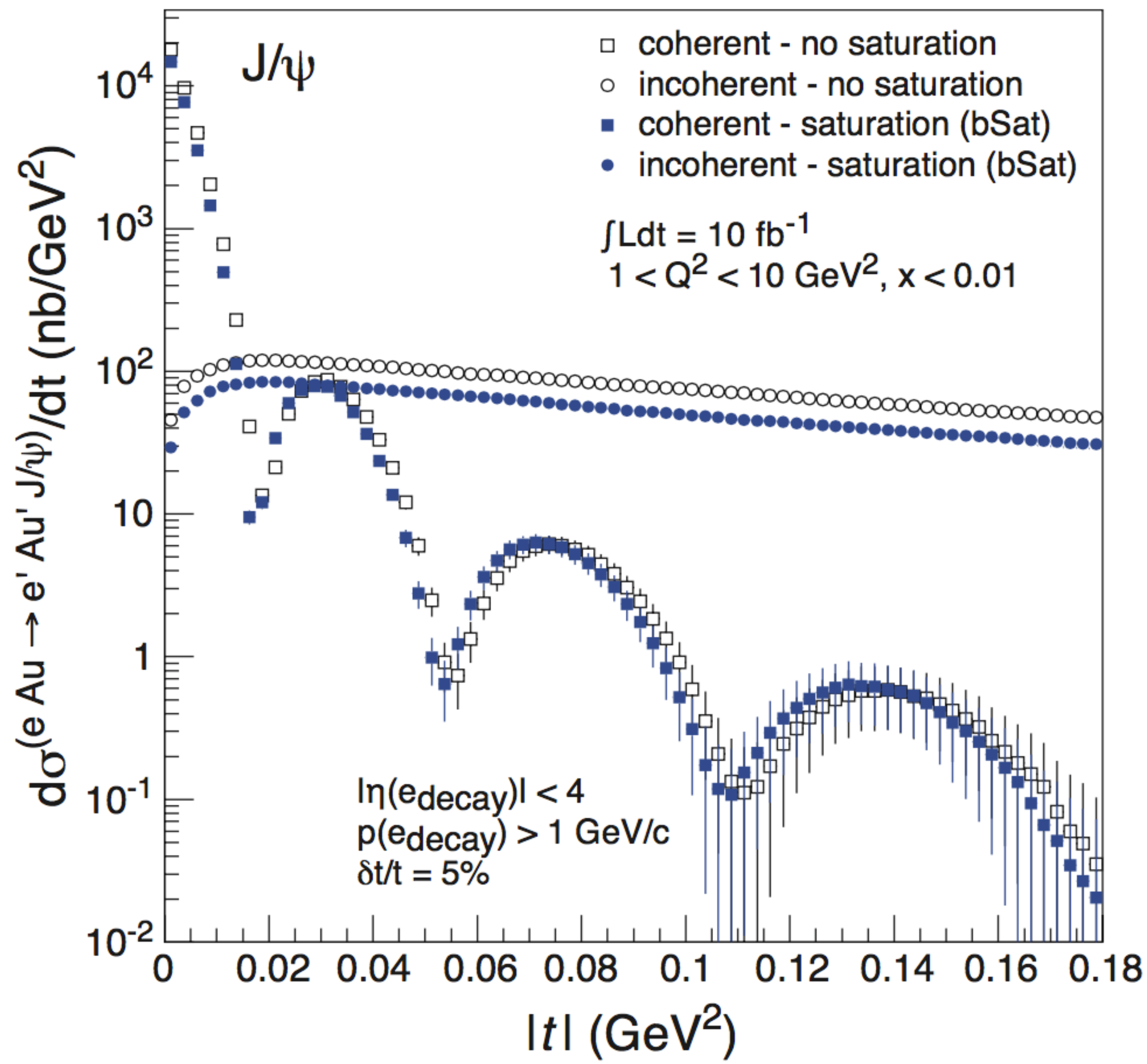
(In)coherence tagged with ZDC

Dipole Cross-Section:



eRHIC - exclusive vector meson production

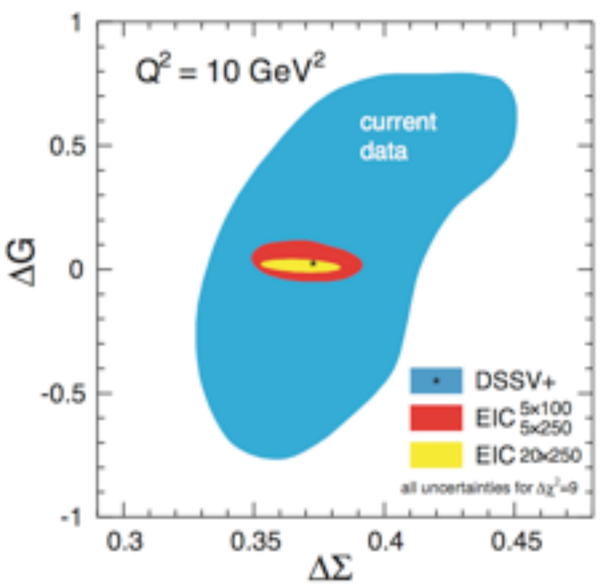


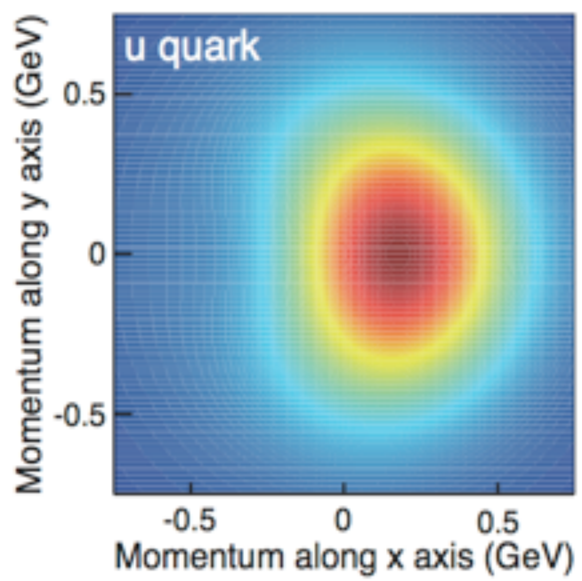


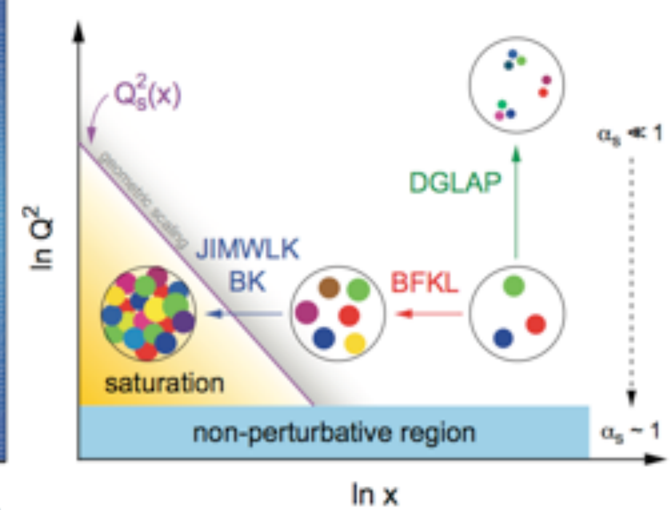
Towards Imaging!

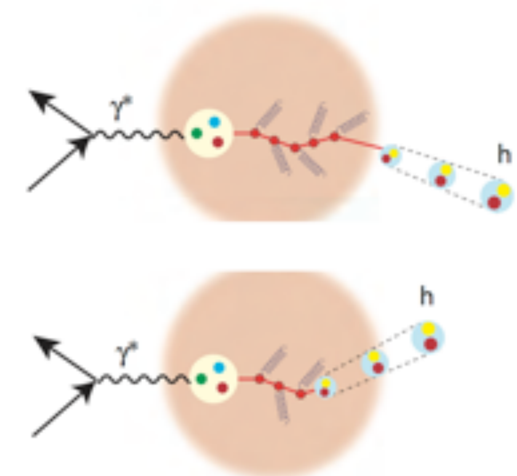
Closing Comments

- ***EIC will address compelling 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?*









ArXiv:1212.17010

*through **identified** measurements - inclusive, semi-inclusive, exclusive and diffractive - with quantified **impact**.*

- ***There is precedent for surprises in nature, provided you look,***
- ***U.S. Nuclear Science Community is finalizing its 2015 Long-Range-Plan; look forward to a strong recommendation.***
- ***Next EIC User Meeting will be upcoming January 6-9, 2016 at U.C. Berkeley; look forward to seeing many of you engage.***
- ***Thank you and many contributors to the EIC case over the years!***