# *Review of initial state, color glass condensate, and EIC physics*

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BROOKHAVEN NATIONAL LABORATORY

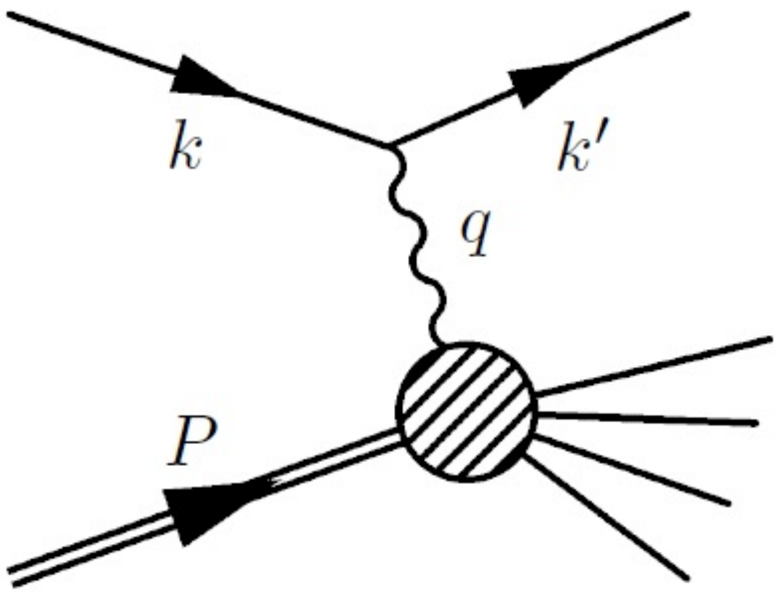
Hot Quarks'18, Texel, Netherlands, Sept. 7-14, 2018

# *Outline*

- The proton structure in pQCD
- Initial state for nuclei in pQCD
- The Color Glass Condensate and saturation
- The future Electron-Ion Collider
- Summary

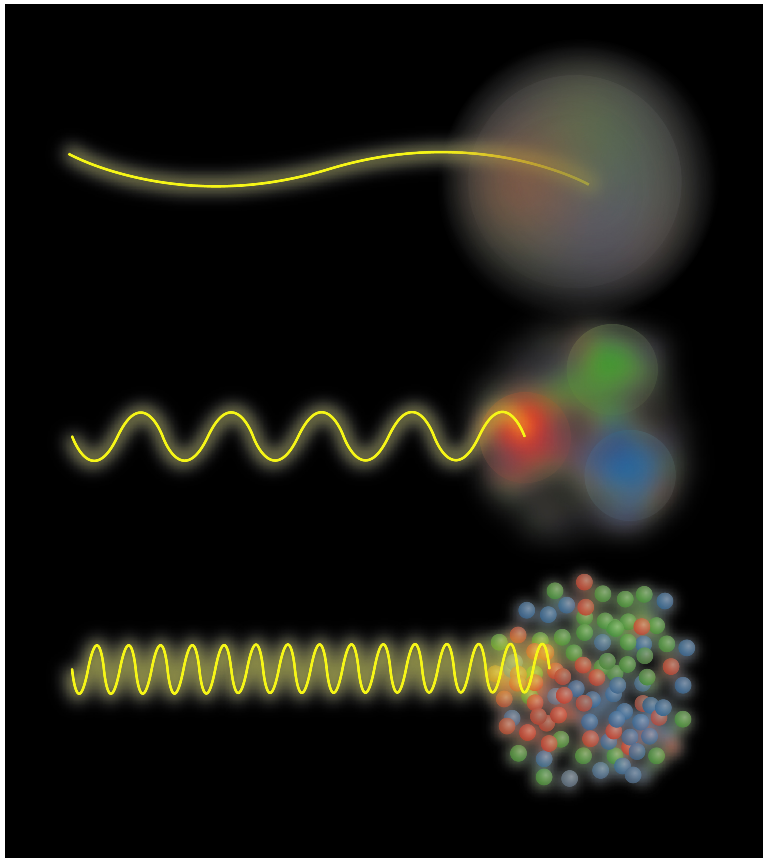
# *The proton structure in pQCD*

# ***Deep Inelastic Scattering (DIS)***

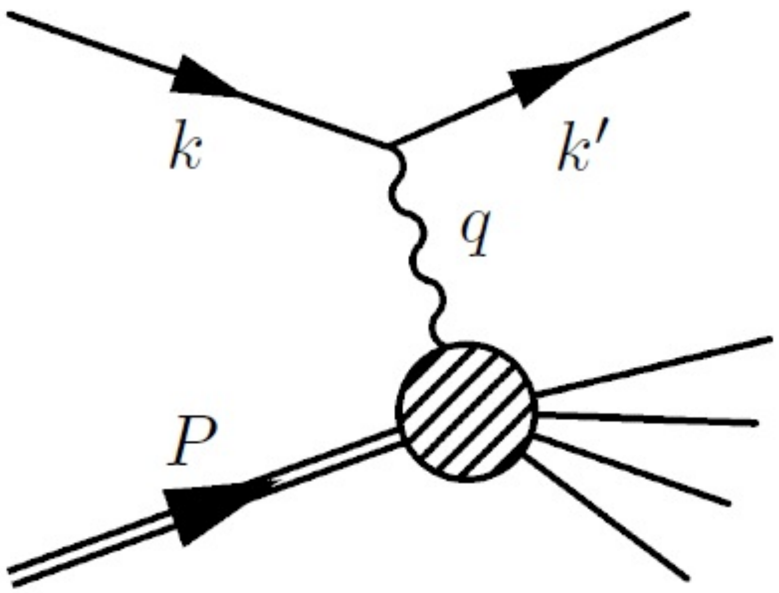



$$Q^2 \equiv -q^2$$

scale resolution



# *Deep Inelastic Scattering (DIS)*

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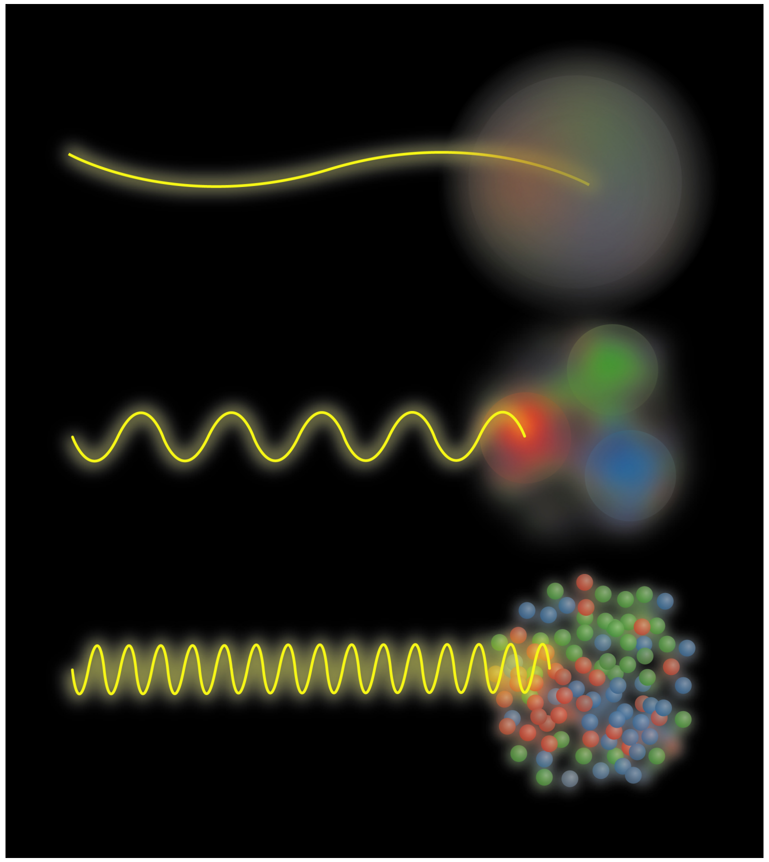
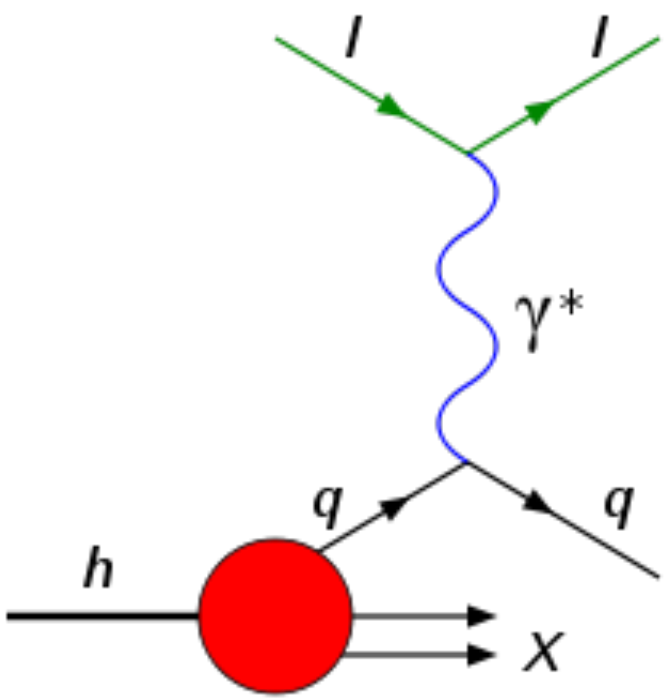





$$p(P) + l(k) \rightarrow X + l(k') \equiv \sum_i q_i(xP) + l(k) \rightarrow X + l(k')$$

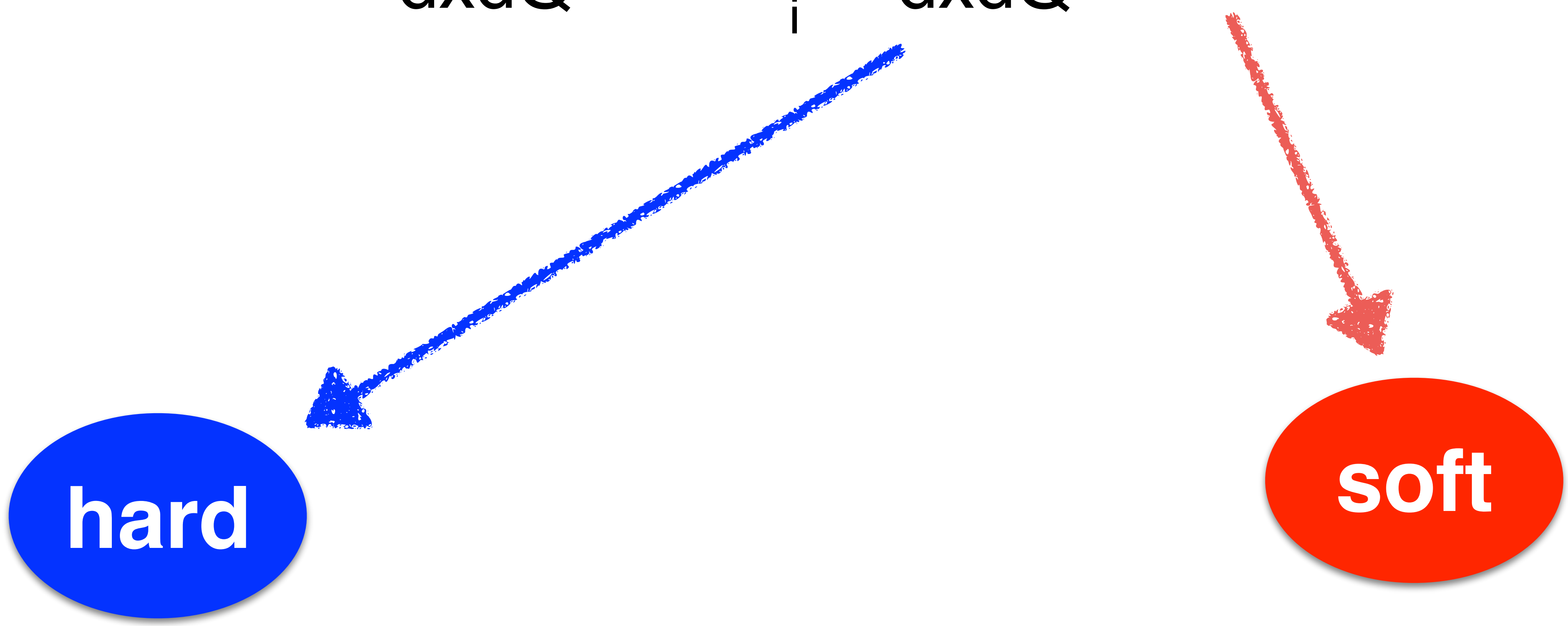
$$x \equiv \frac{Q^2}{2P \cdot q}$$

fraction of the proton momentum carried by the struck quark

But at high scales the coupling constant becomes small and

we can compute observables in **perturbative** QCD

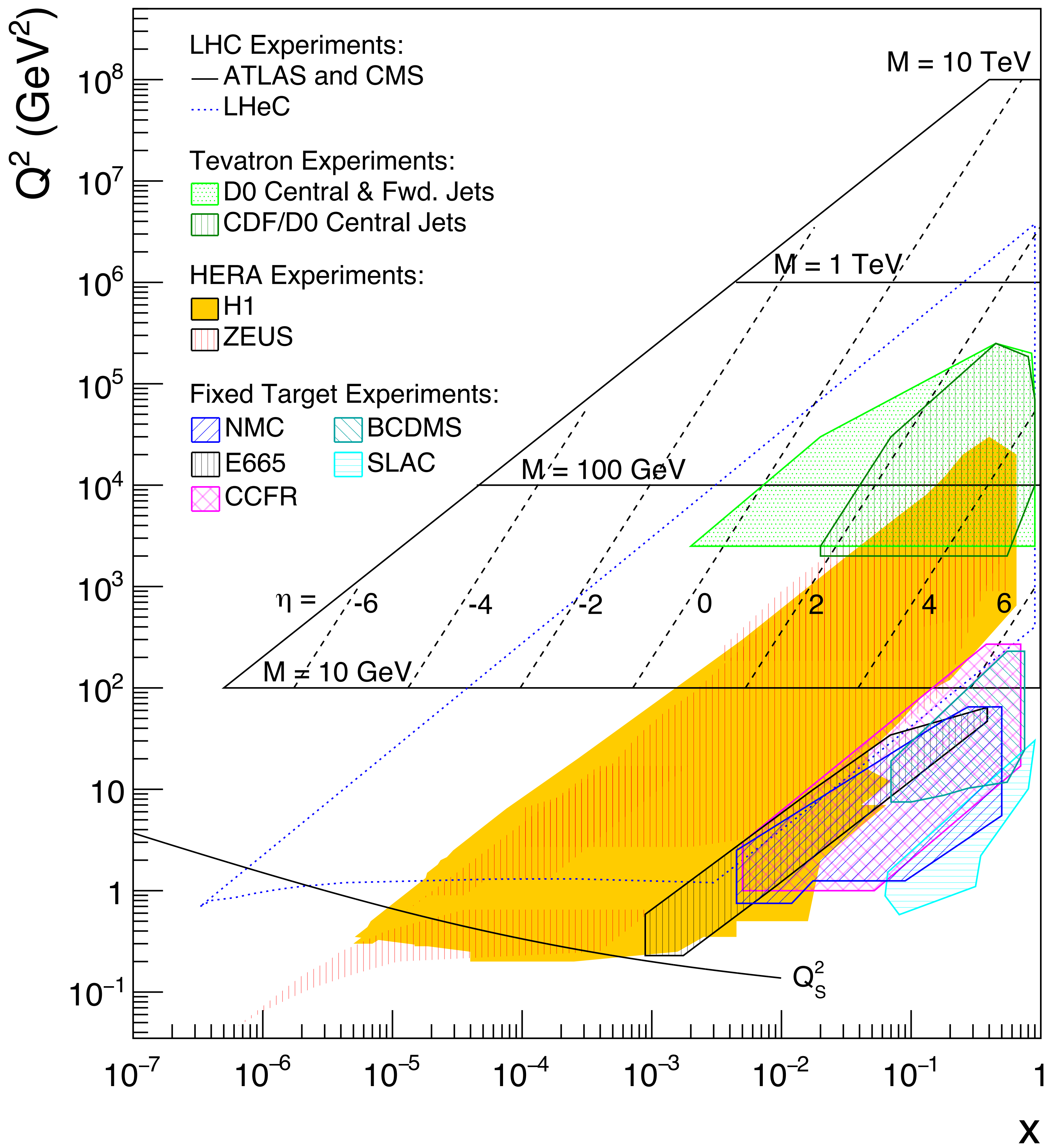
$$\frac{d^2\sigma}{dxdQ^2} \propto \sum_{i}^{N_{partons}} \frac{d^2\hat{\sigma}_i}{dxdQ^2} \otimes f_i$$



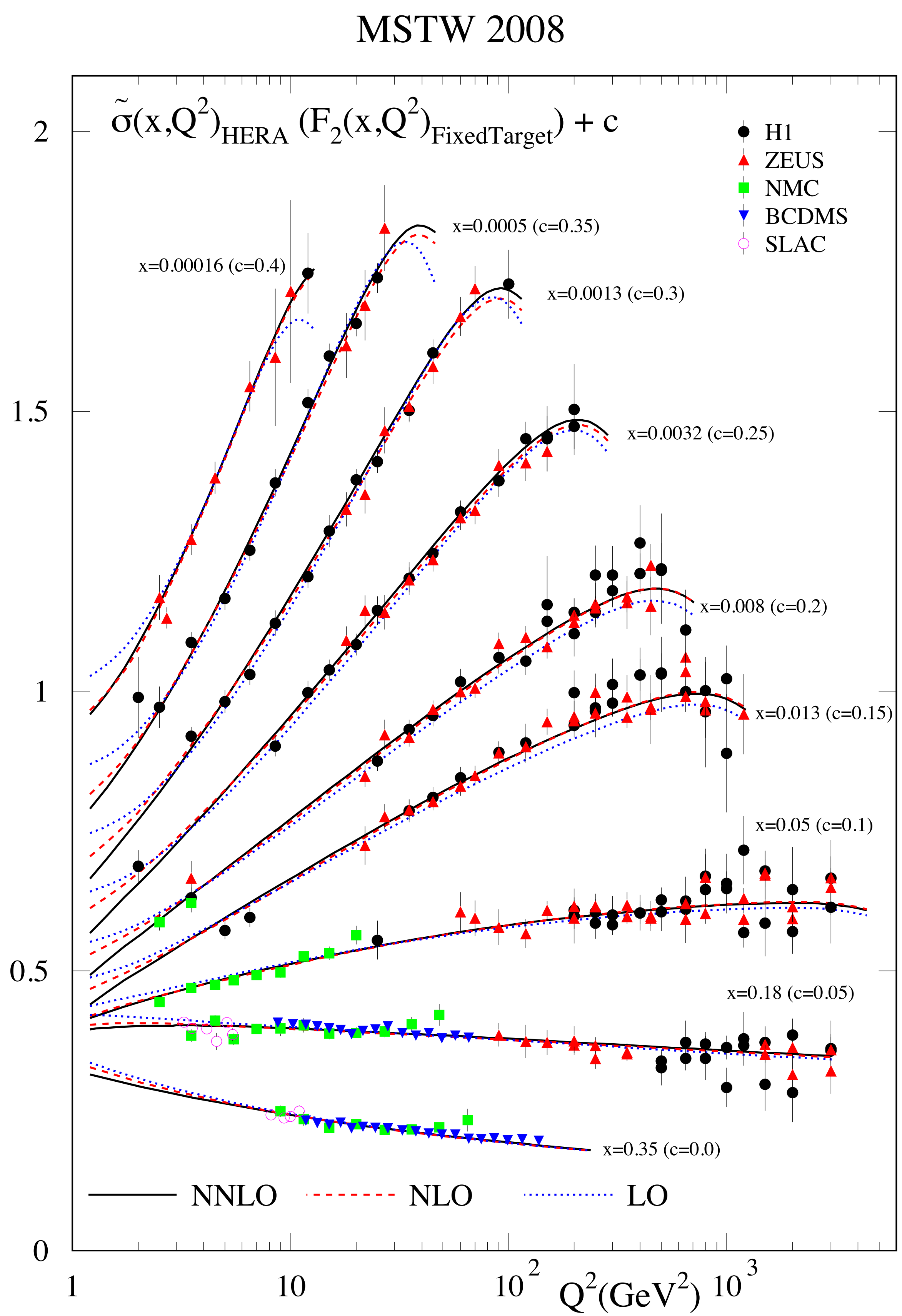

a.k.a. PDFs

we can compute, truly a hard work

we can't compute, but we know how they evolve

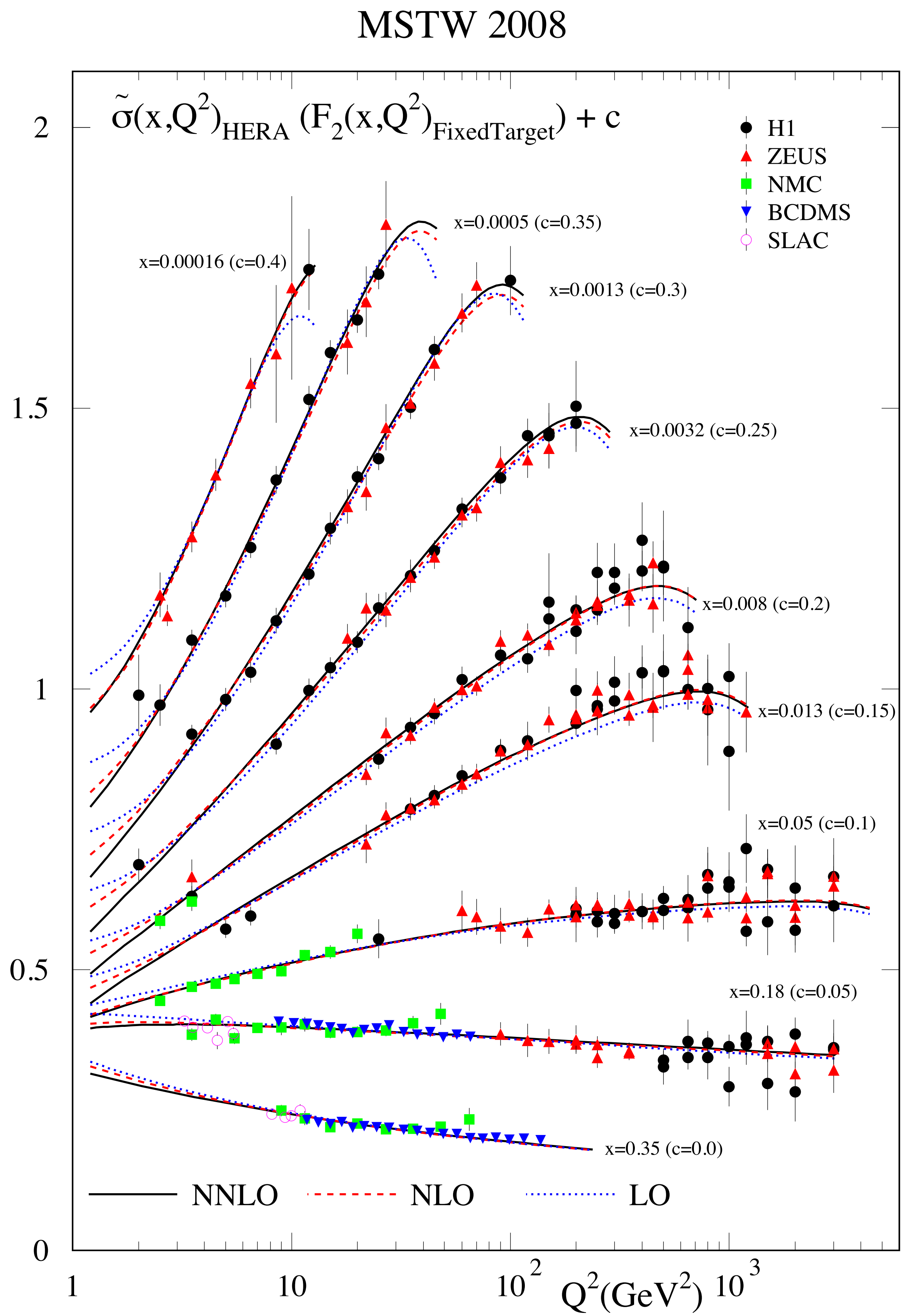


Q$^2$ (GeV$^2$)
x
LHC Experiments:
ATLAS and CMS
LHeC
Tevatron Experiments:
D0 Central & Fwd. Jets
CDF/D0 Central Jets
HERA Experiments:
H1
ZEUS
Fixed Target Experiments:
NMC
BCDMS
E665
SLAC
CCFR
M = 10 TeV
M = 1 TeV
M = 100 GeV
M = 10 GeV
η = -6 -4 -2 0 2 4 6
Q$^2_S$




Martin, Stirling, Thorne and Watt,
EPJC 63 (2009) 189

# The proton structure in pQCD




Martin, Stirling, Thorne and Watt,
EPJC 63 (2009) 189

$$\sigma_r = F_2 - \frac{y^2}{1+(1-y)^2} F_L$$

$$F_2^{NLO} = \sum_i^{N_f} e_i^2 \left(q_i + \bar{q}_i\right) \otimes \left(C_{2,q}^{(0)} + \alpha_s C_{2,q}^{(1)}\right) + \alpha_s g \otimes C_{2,g}^{(1)}$$

$$F_L^{NLO} = \alpha_s \left[ \sum_i^{N_f} e_i^2 \left(q_i + \bar{q}_i\right) \otimes C_{L,q}^{(1)} + g \otimes C_{L,g}^{(1)} \right]$$

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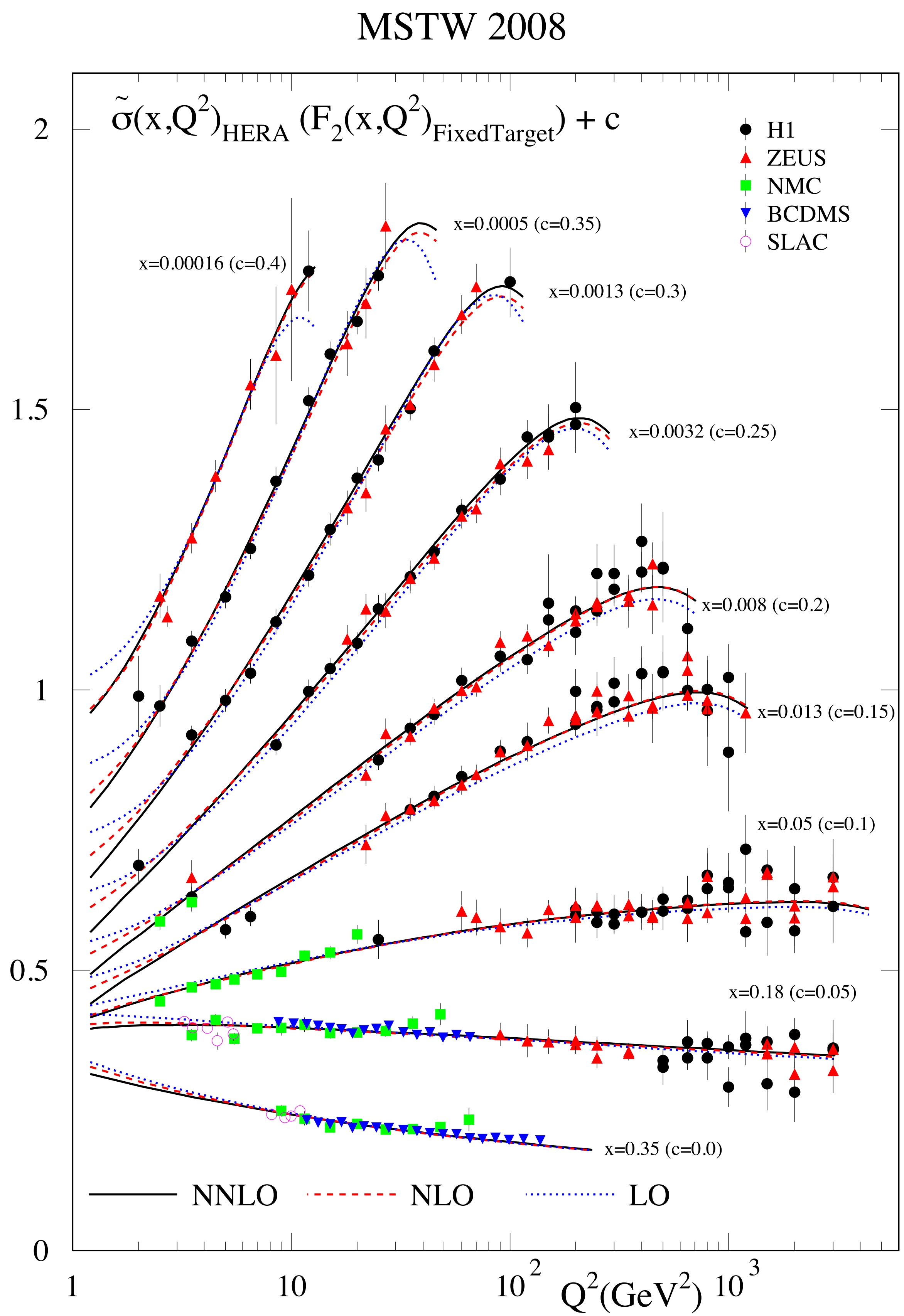


Martin, Stirling, Thorne and Watt,
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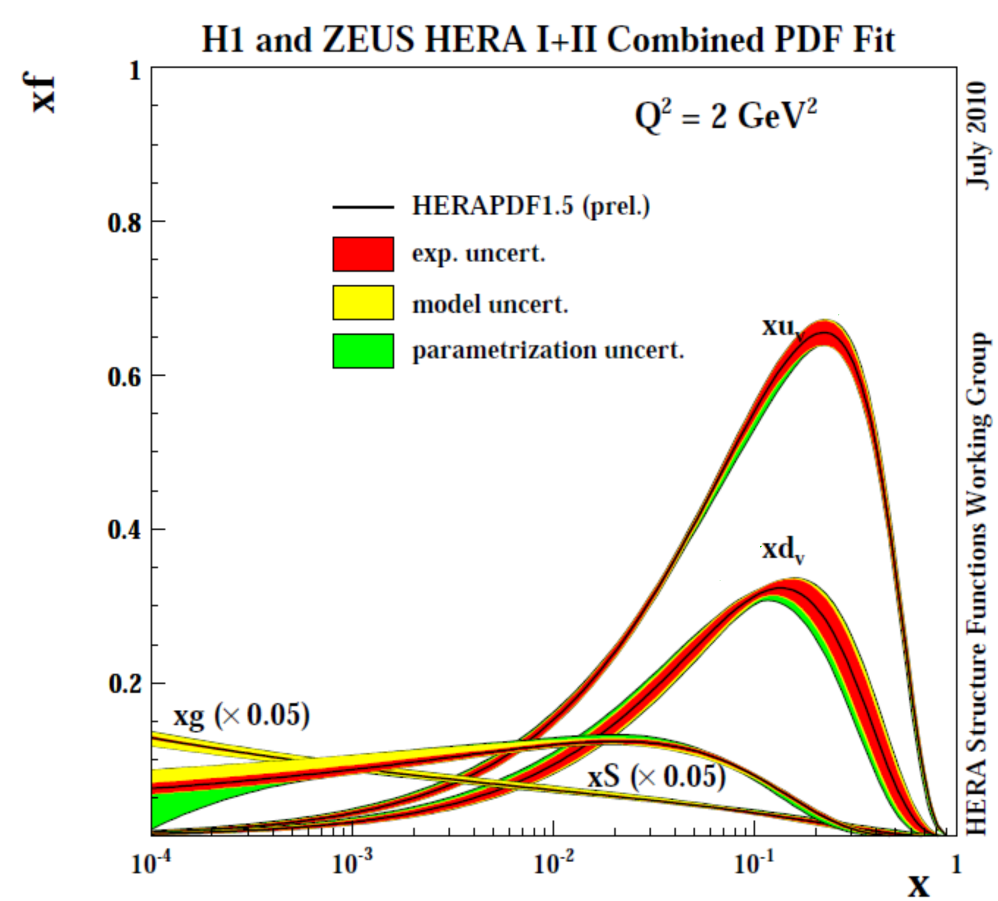


R. Plačakytė, Moriond
QCD, 9-16 March

# *Initial state for nuclei in pQCD*

Once upon a time people decided to do e+A collisions for fun

because a nucleus **A** is just a collection of anti-social nucleons

so nothing new would come up

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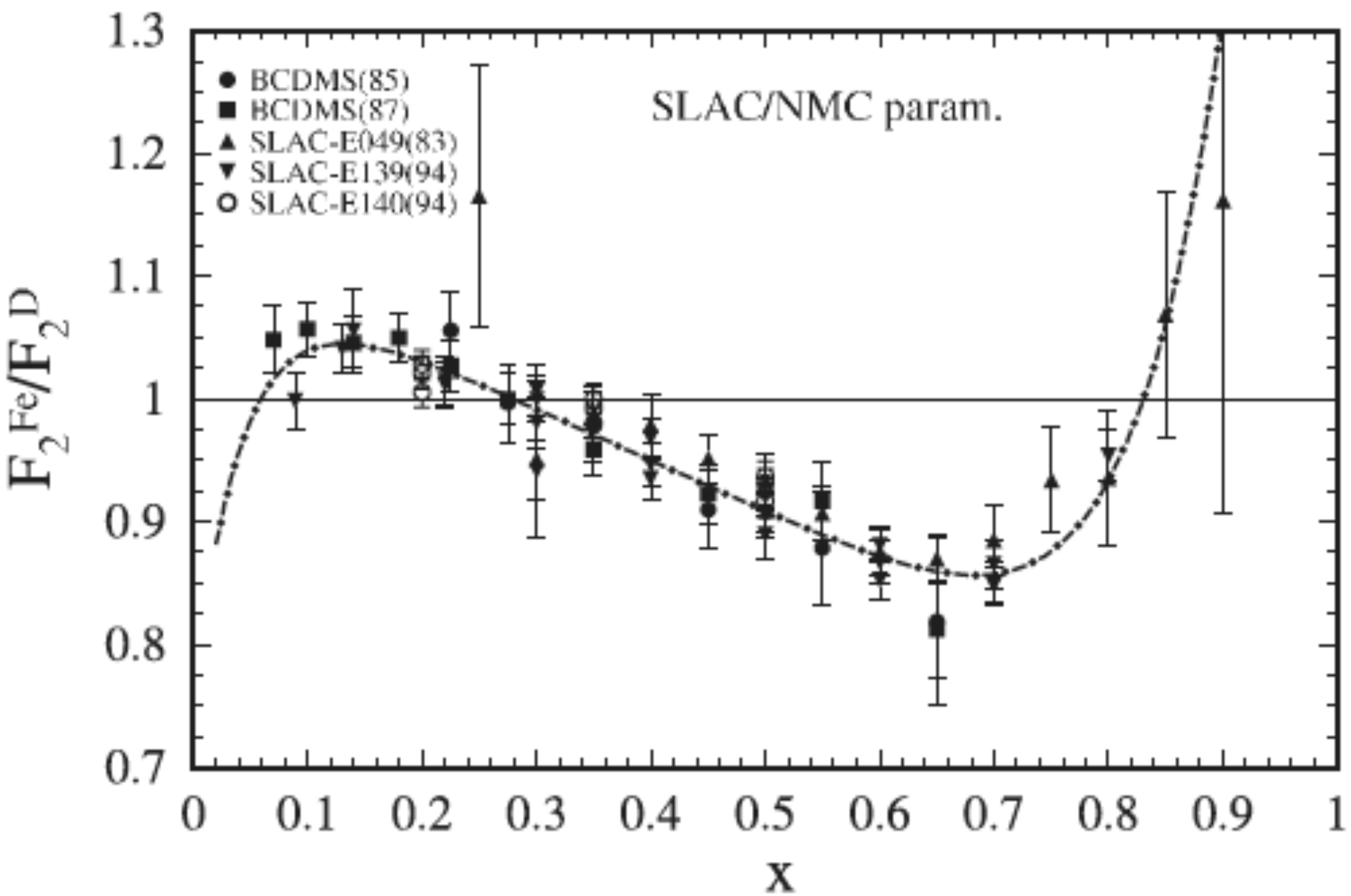
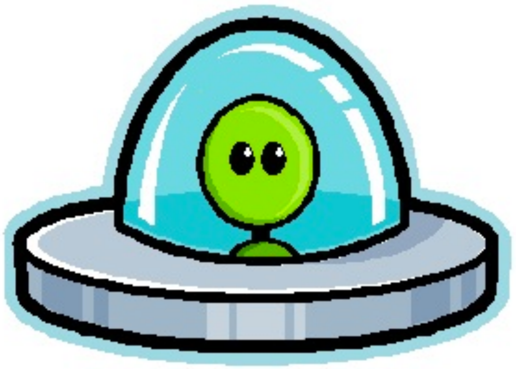
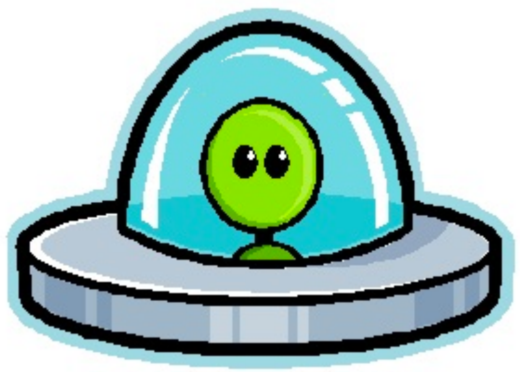



- the partons know that they are not alone





✦ the partons know that they are not alone

The simplest proposal:

✦ introduce **nuclear** PDFs

✦ use the same evolution equations

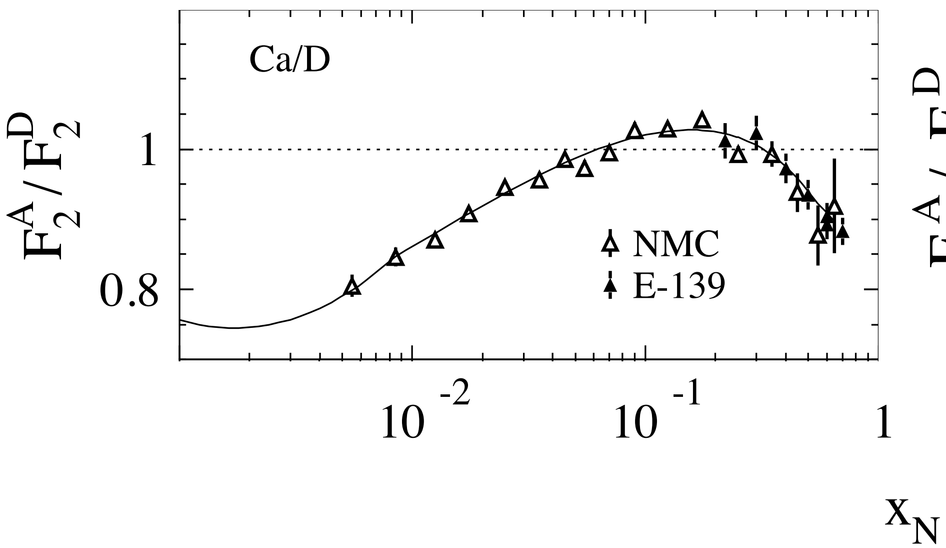
✦ same perturbative expansion for the observables

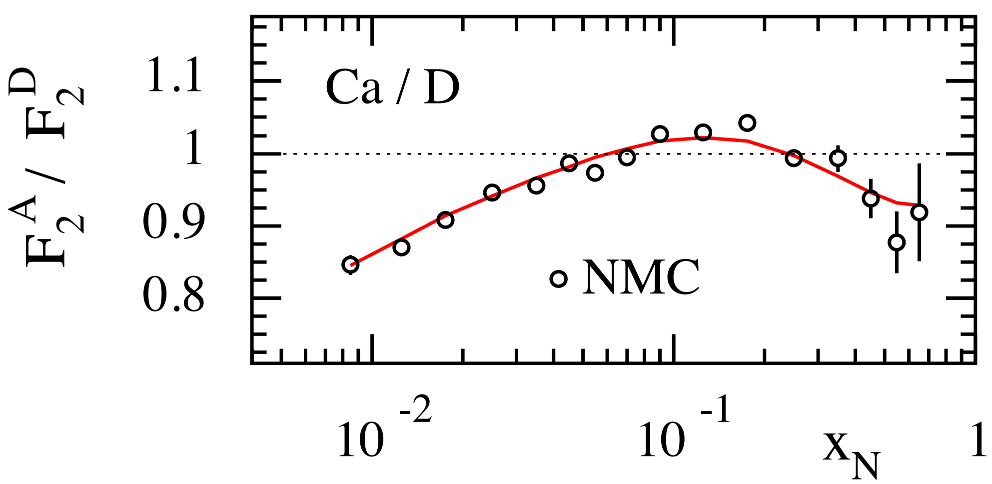
✦ and try to perform a global fit to the world data*

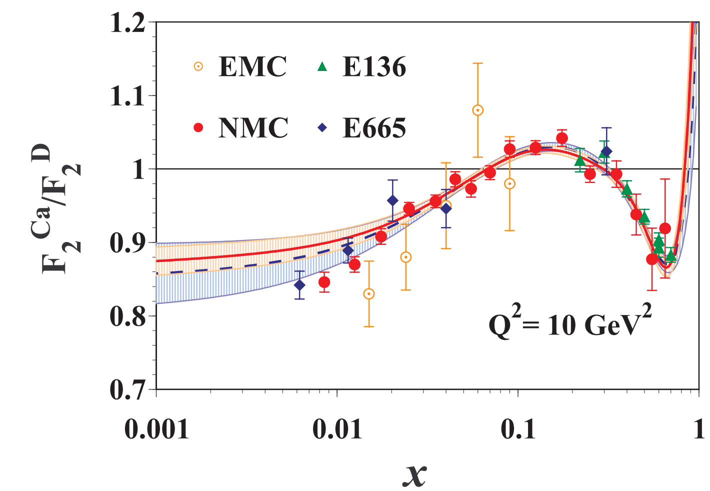
$$f_i^A(x, Q^2) = \frac{Z f_i^{p/A}(x, Q^2) + (A - Z) f_i^{n/A}(x, Q^2)}{A}$$

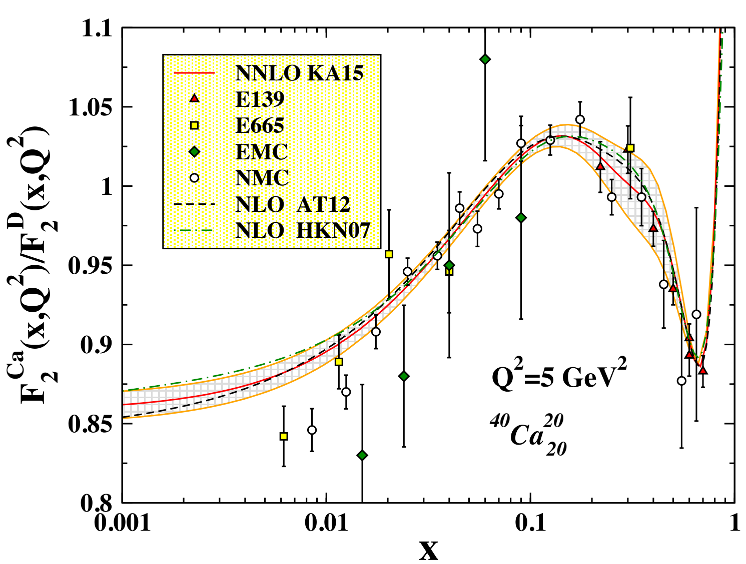
***results usually shown as the ratio of the parton in nucleus to parton in proton PDF. Other depictions may be used**

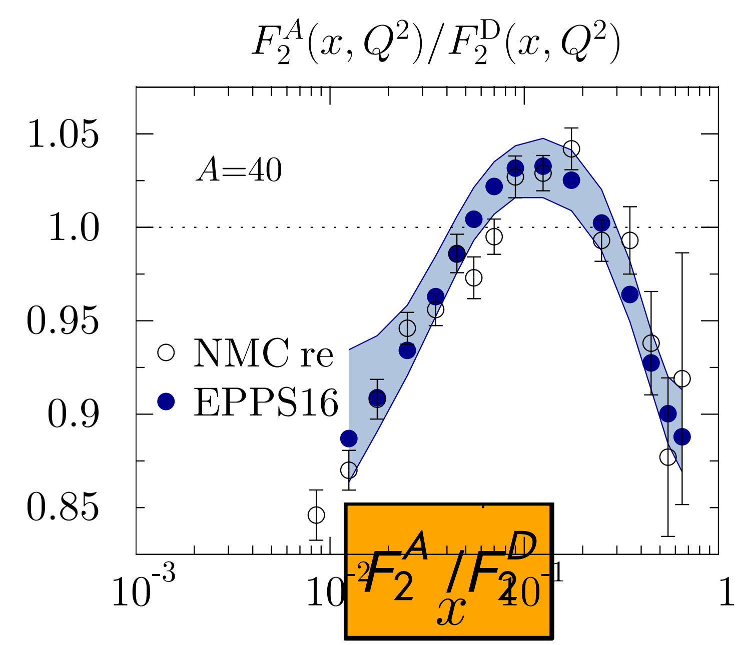
# all give **NICE** descriptions of the data

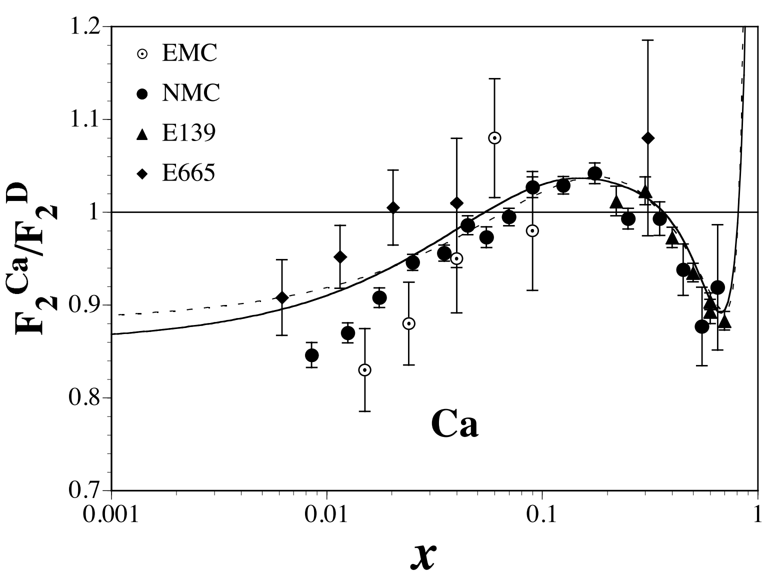


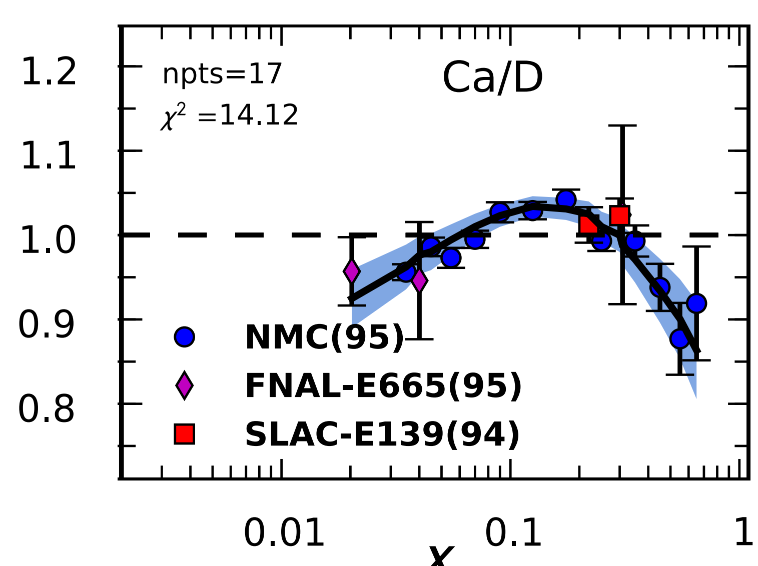




**HKM**

**nDS**

**HKN**

**EPS09**

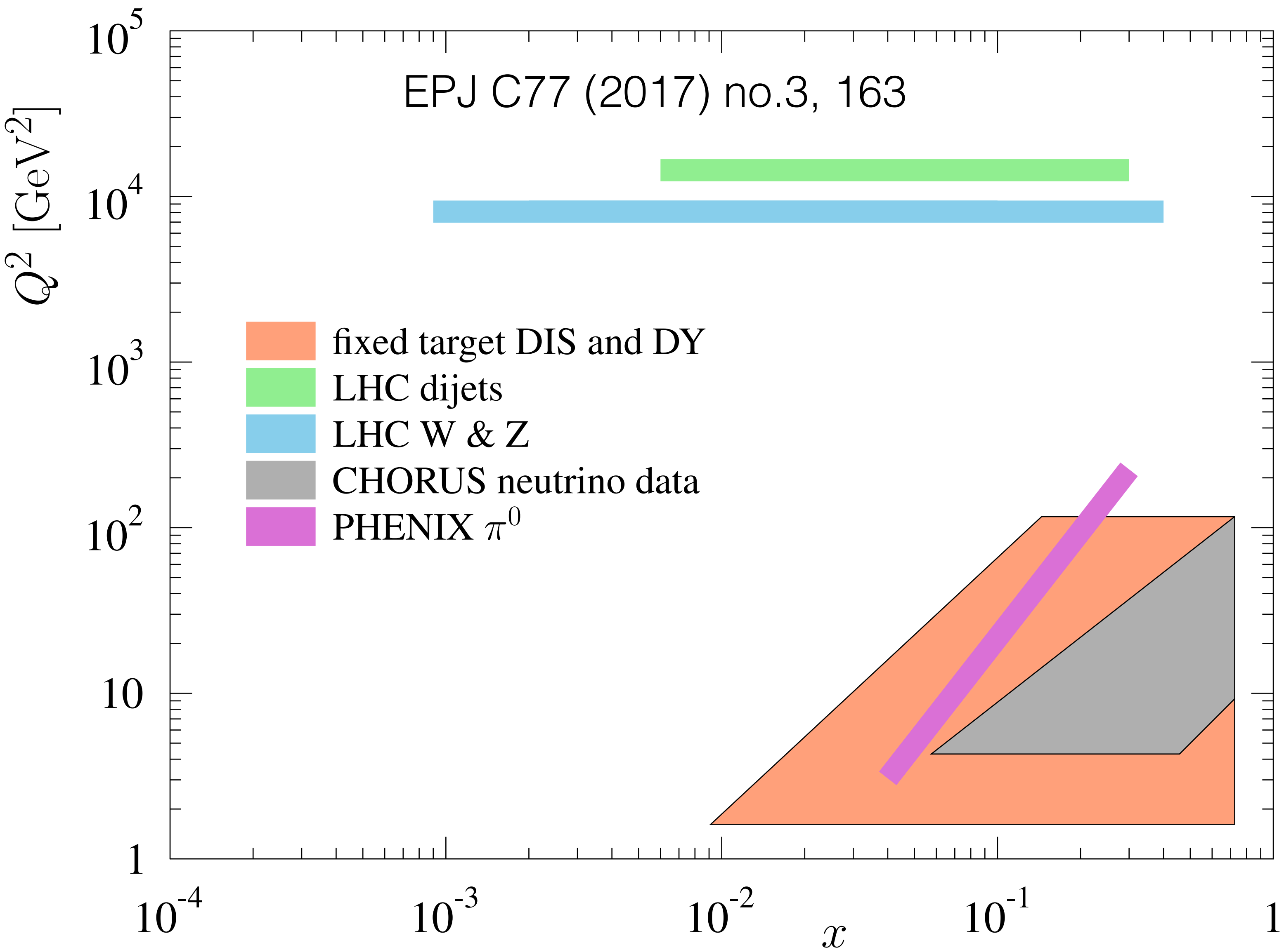
**DSSZ**

**nCTEQ15**

**KA15**

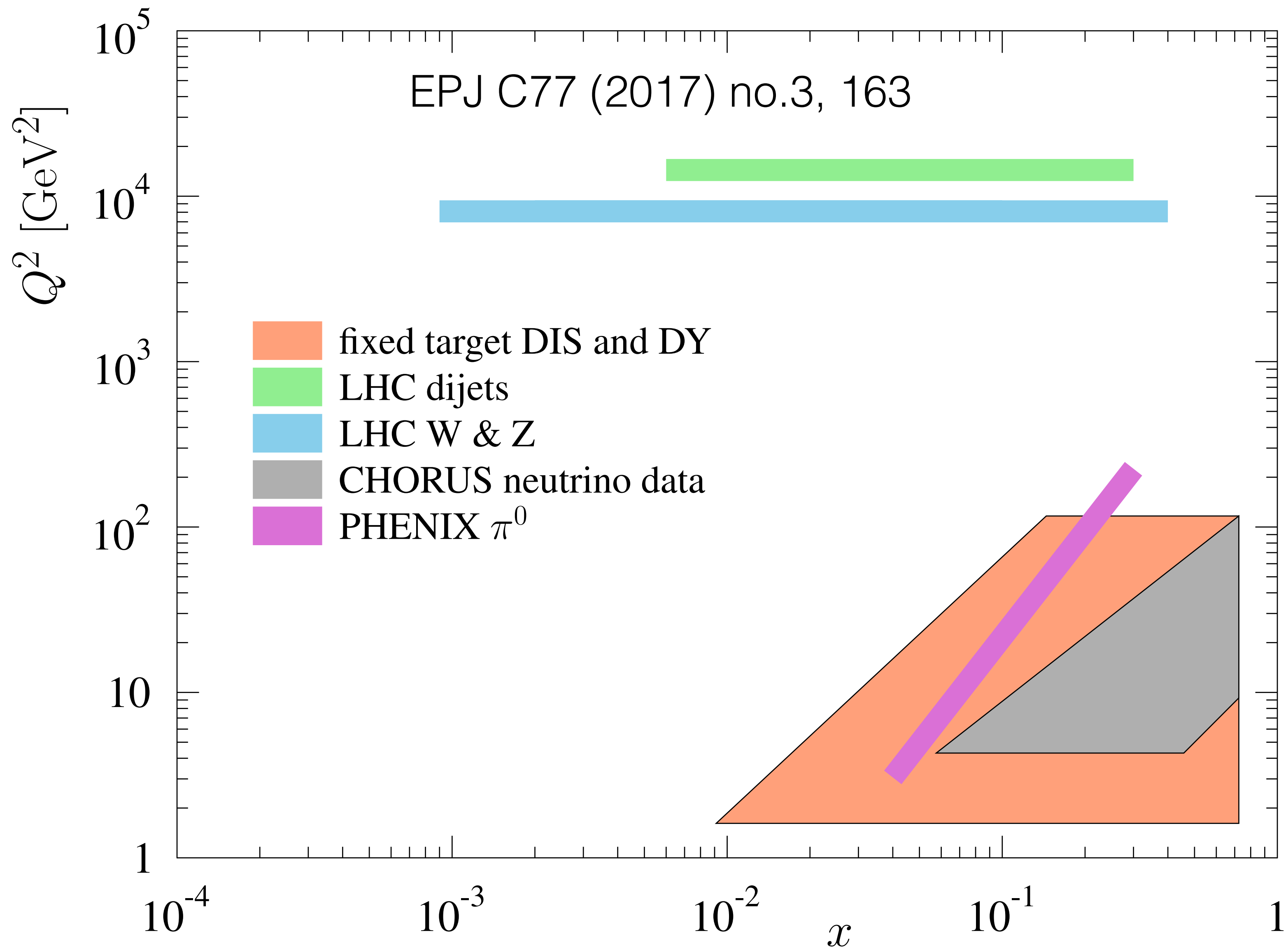
**EPPS16**

# e+A, ν+A and p(d)+A experiments
# ~ 1800 data points




| A | He | Li | Be | C | Al | Ca | Fe | Cu | Ag | Sn | W | Pt | Au | Pb |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| # points | 37 | 168 | 35 | 232 | 35 | 66 | 78 | 19 | 7 | 159 | 58 | 7 | 41 | 869 |

# e+A, ν+A and p(d)+A experiments
# ~ 1800 data points




limited kinematic coverage
+ lack of precision in most data
+ maybe not the best observables
+ fitting choices
+ theory uncertainties

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unconstrained nPDFs

| A | He | Li | Be | C | Al | Ca | Fe | Cu | Ag | Sn | W | Pt | Au | Pb |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
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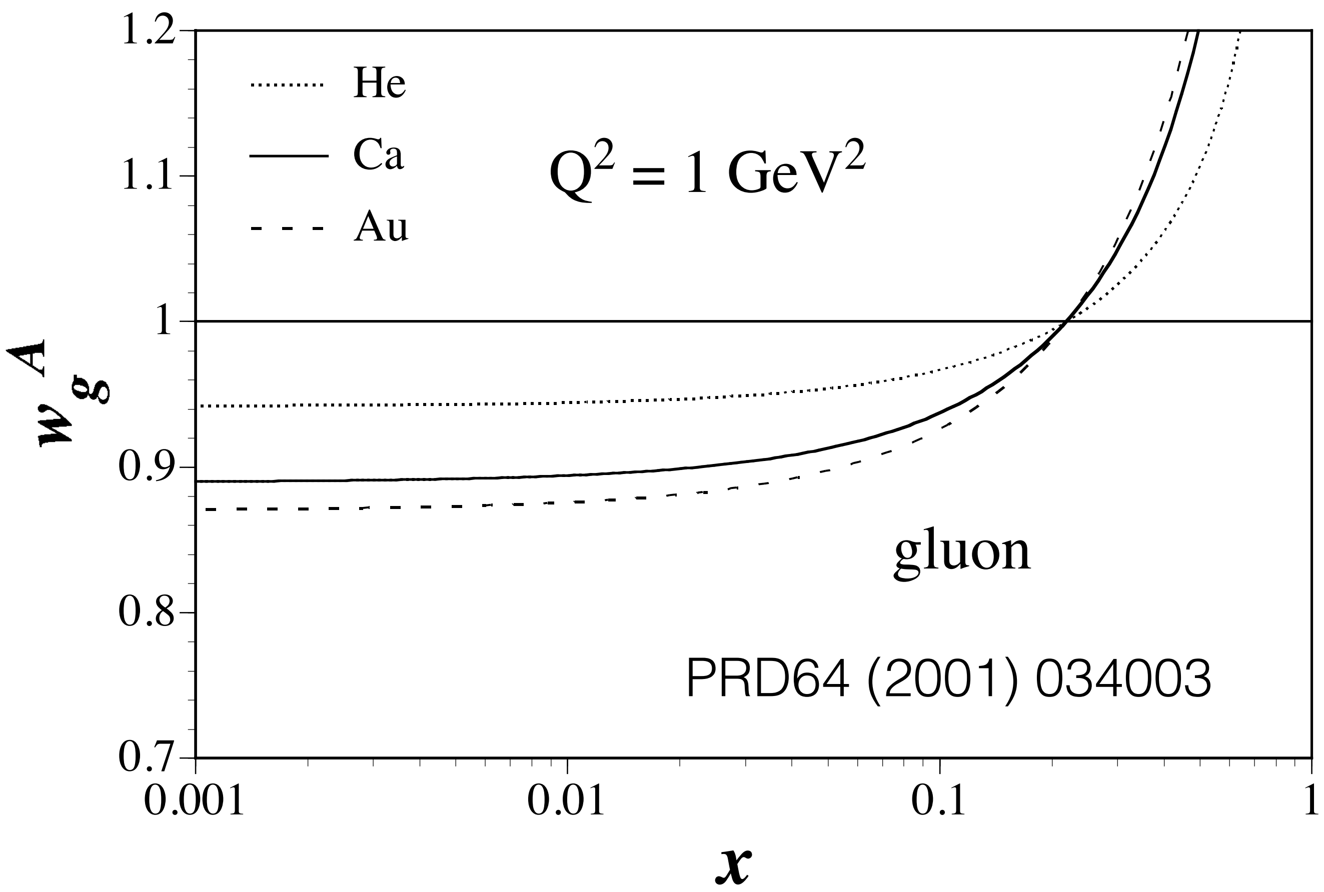
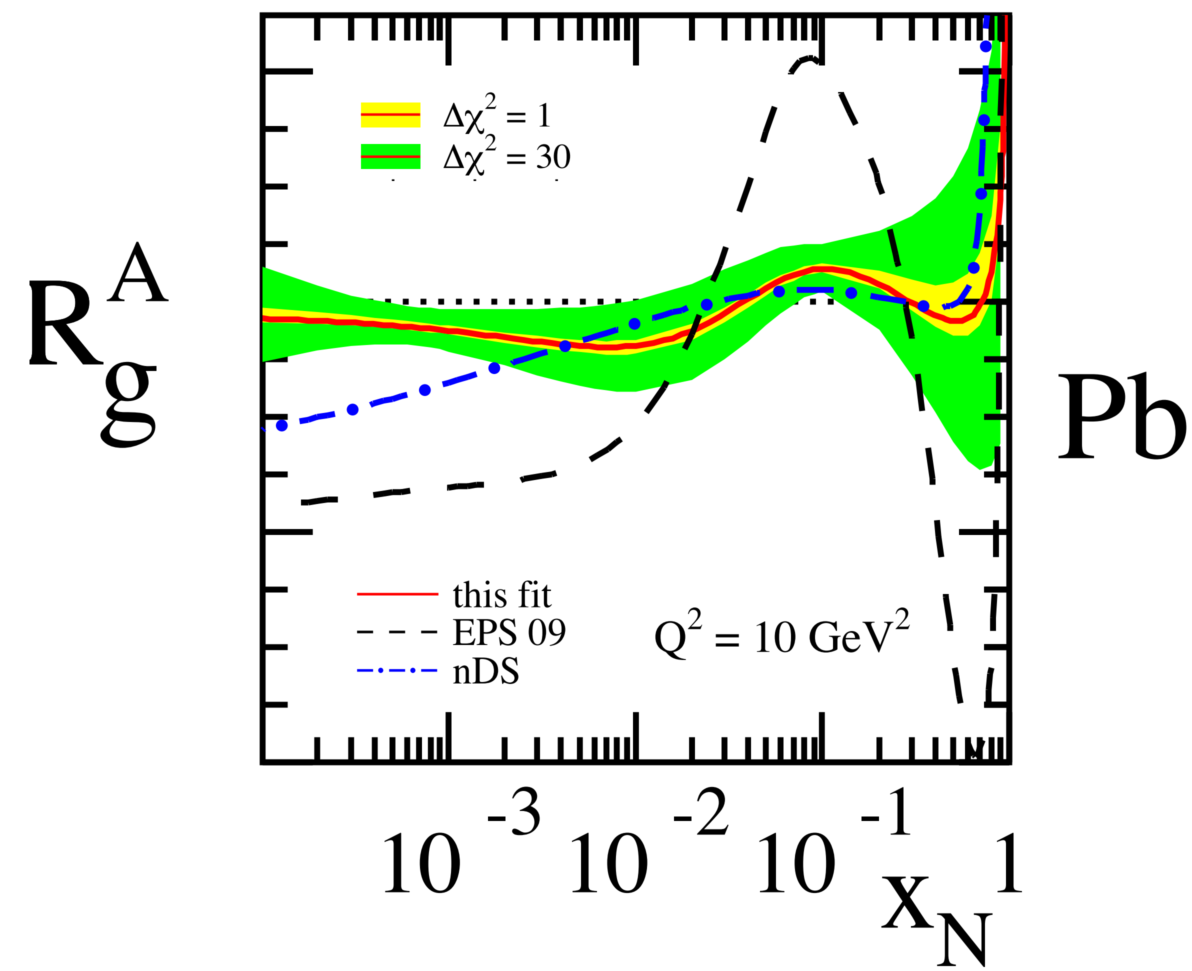
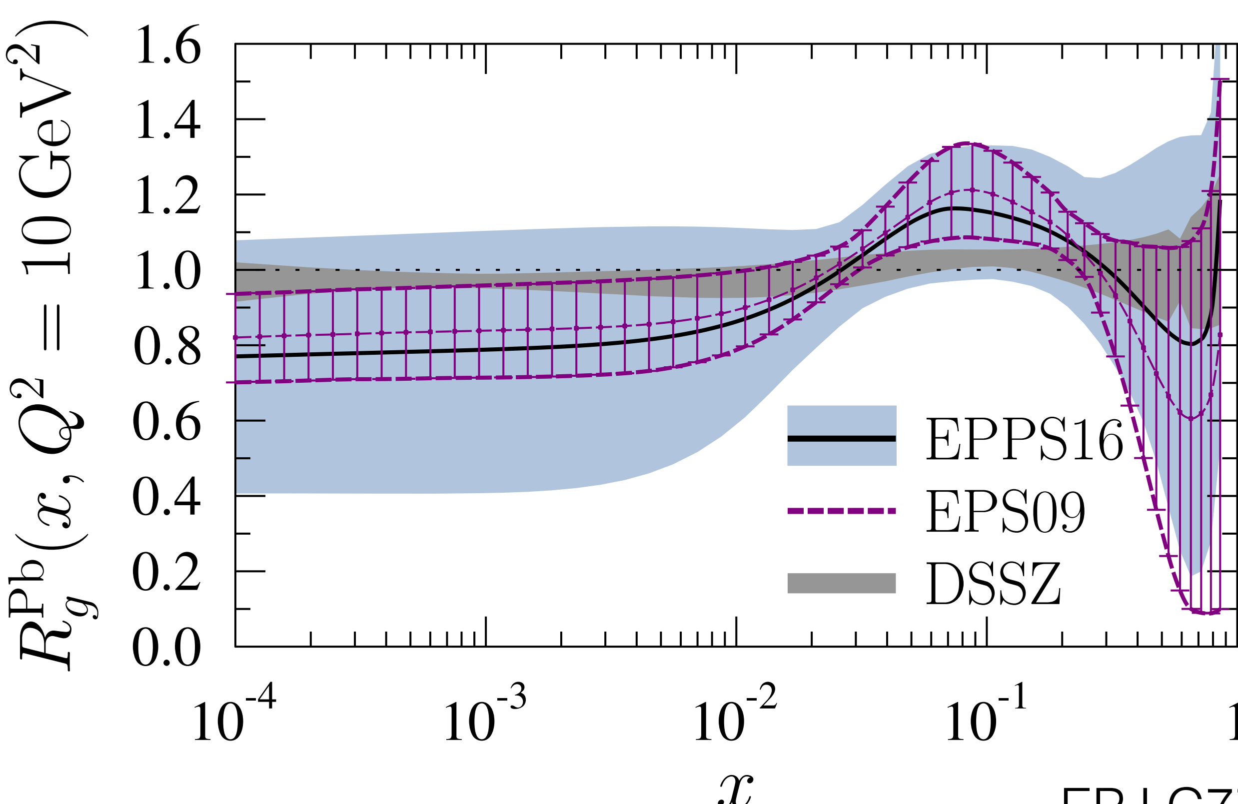
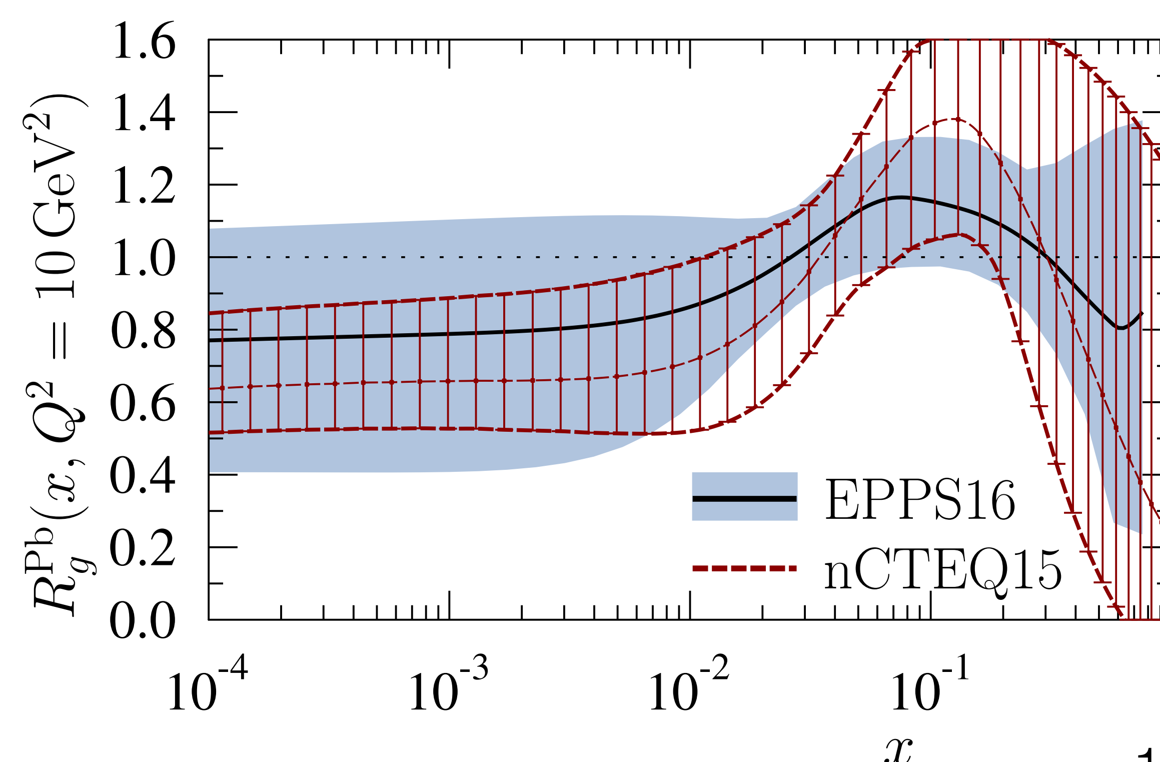
Initial state for nuclei in pQCD




PRD85 (2012) 074028



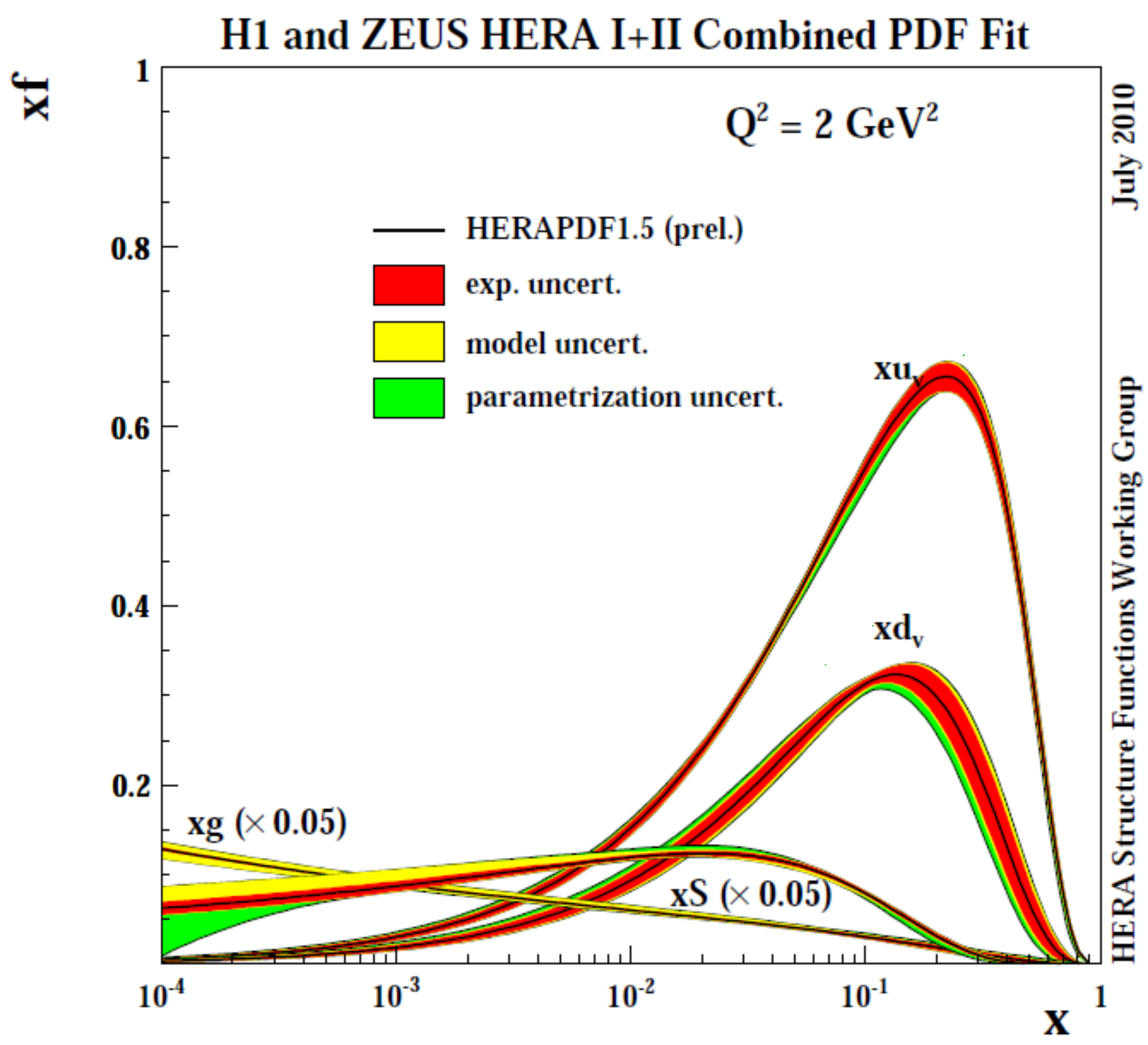



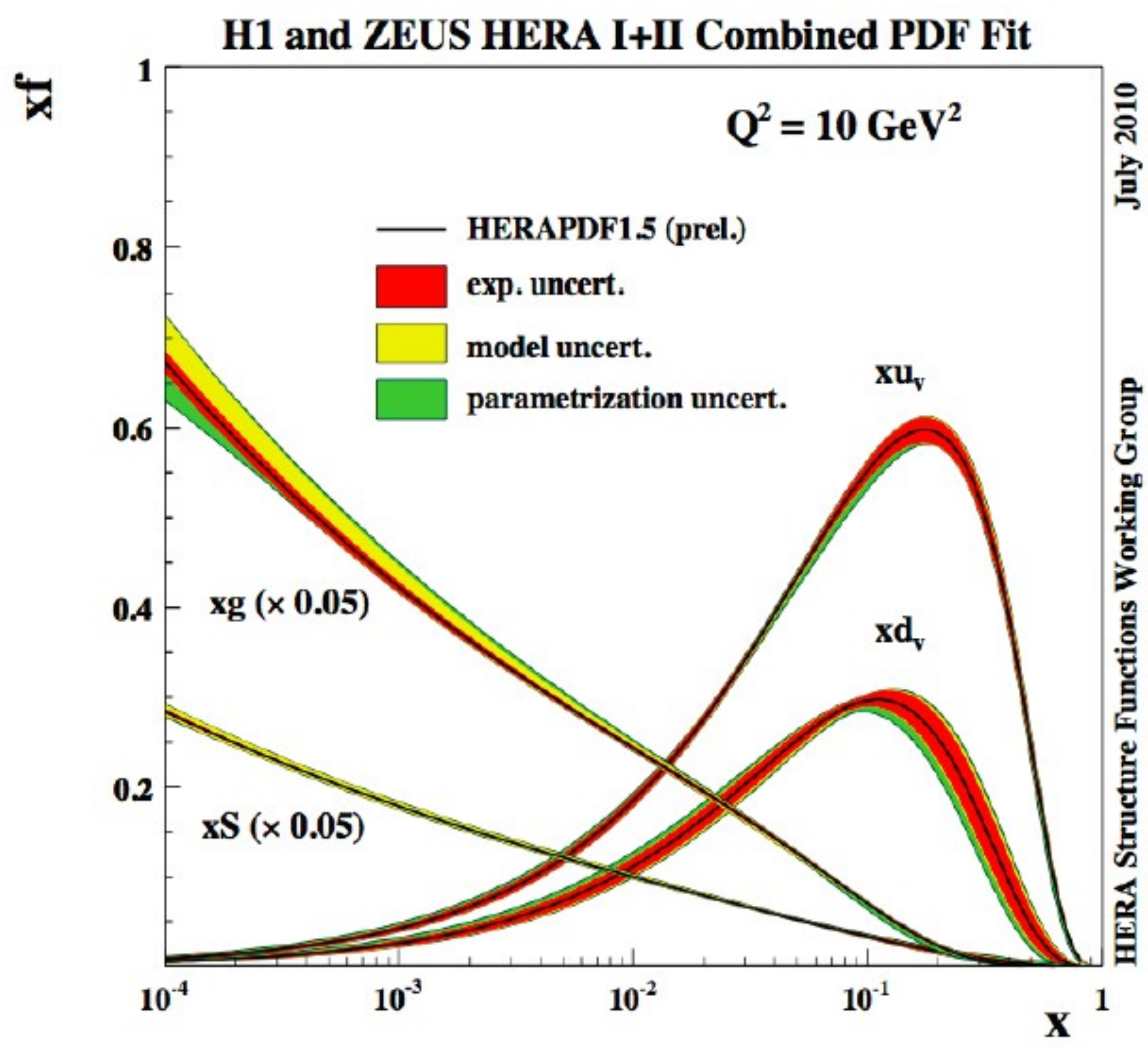




EPJ C77 (2017) no.3, 163

# *The Color Glass Condensate and saturation*

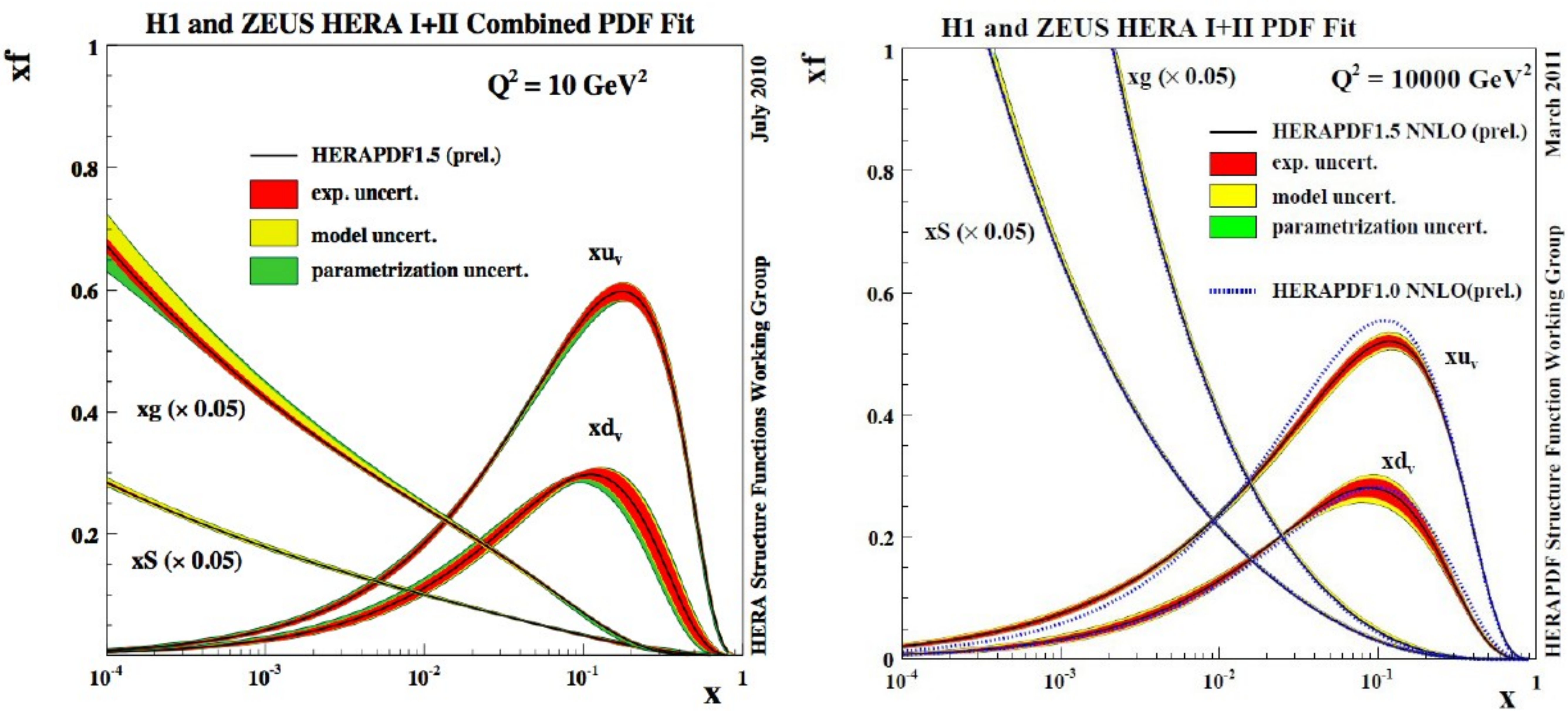
# The higher the resolution, the more details we see



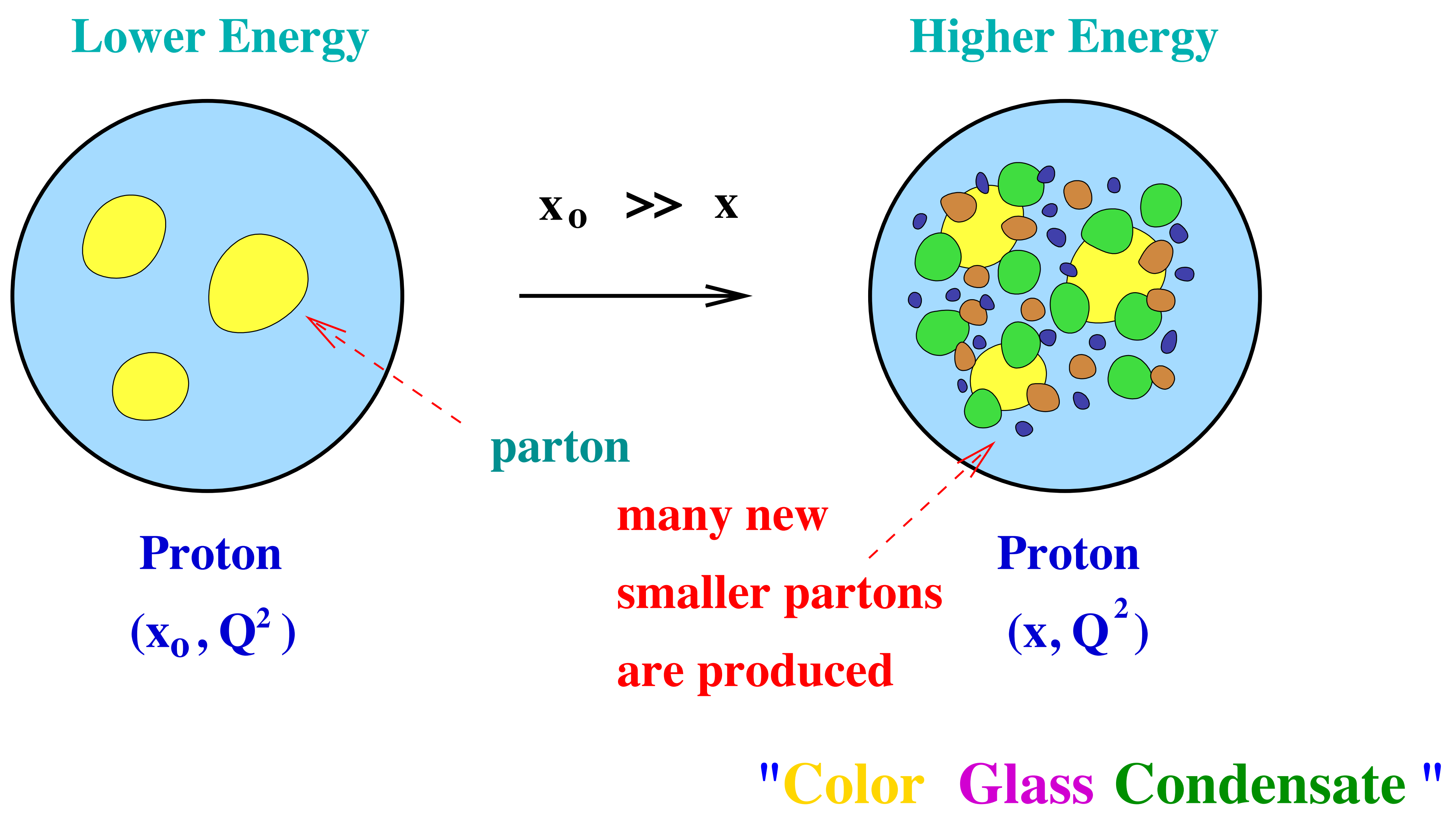

Julia Grebenyuk, 23rd Rencontres de Blois, 1 June 2011

# and more gluons at low x!

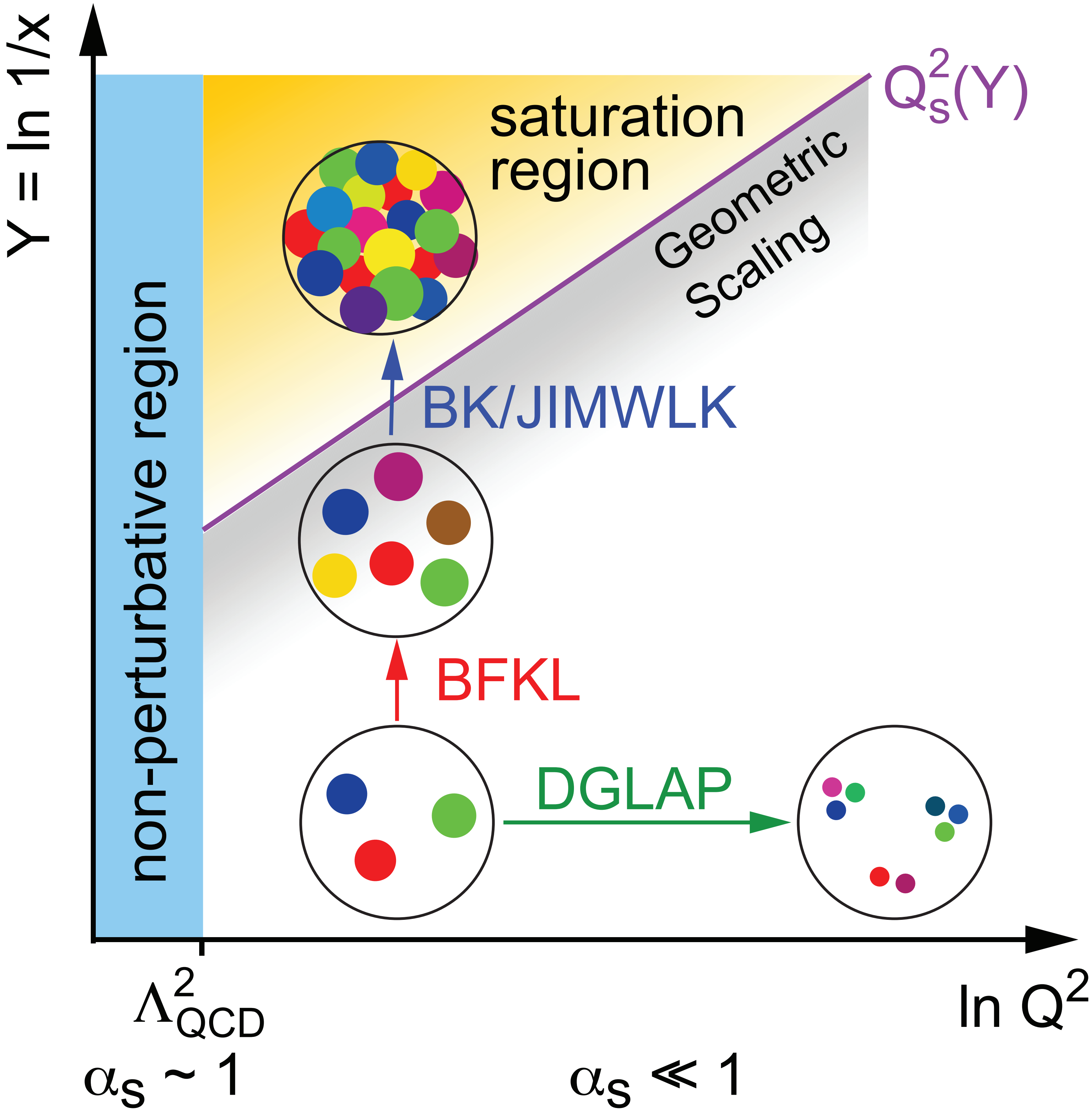


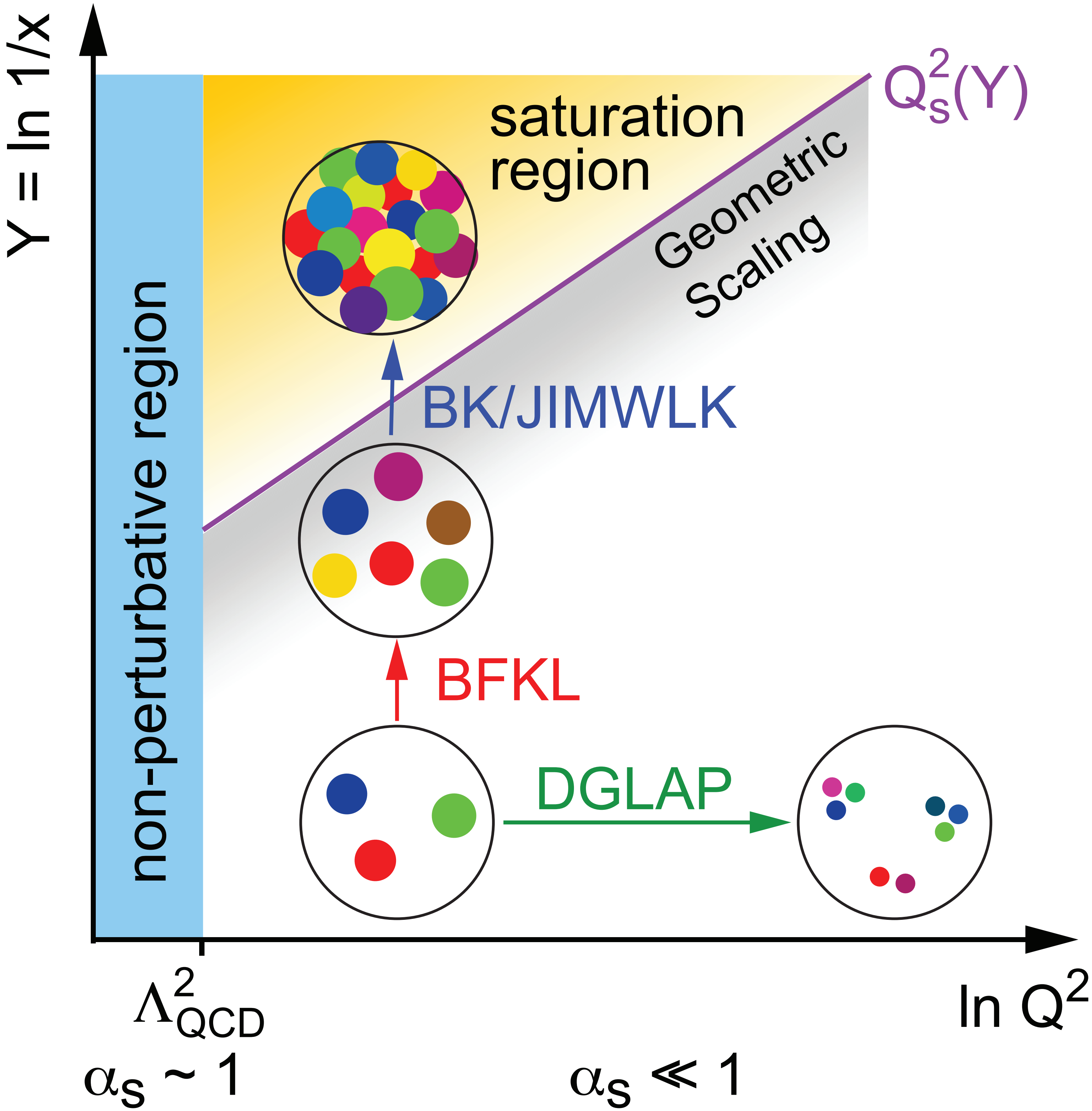

$$xg\left(x, Q^2\right) \sim \frac{1}{x^{0.3}}$$

Julia Grebenyuk, 23rd Rencontres de Blois, 1 June 2011 for low x we can describe the proton as composed only of gluons, densely packed




T. Toll, 2012 RHIC & AGS Annual Users' Meeting


Y = ln 1/x
non-perturbative region
saturation region
$Q_s^2(Y)$
Geometric Scaling
BK/JIMWLK
BFKL
DGLAP
$\Lambda^2_{QCD}$
ln $Q^2$
$\alpha_s \sim 1$
$\alpha_s \ll 1$

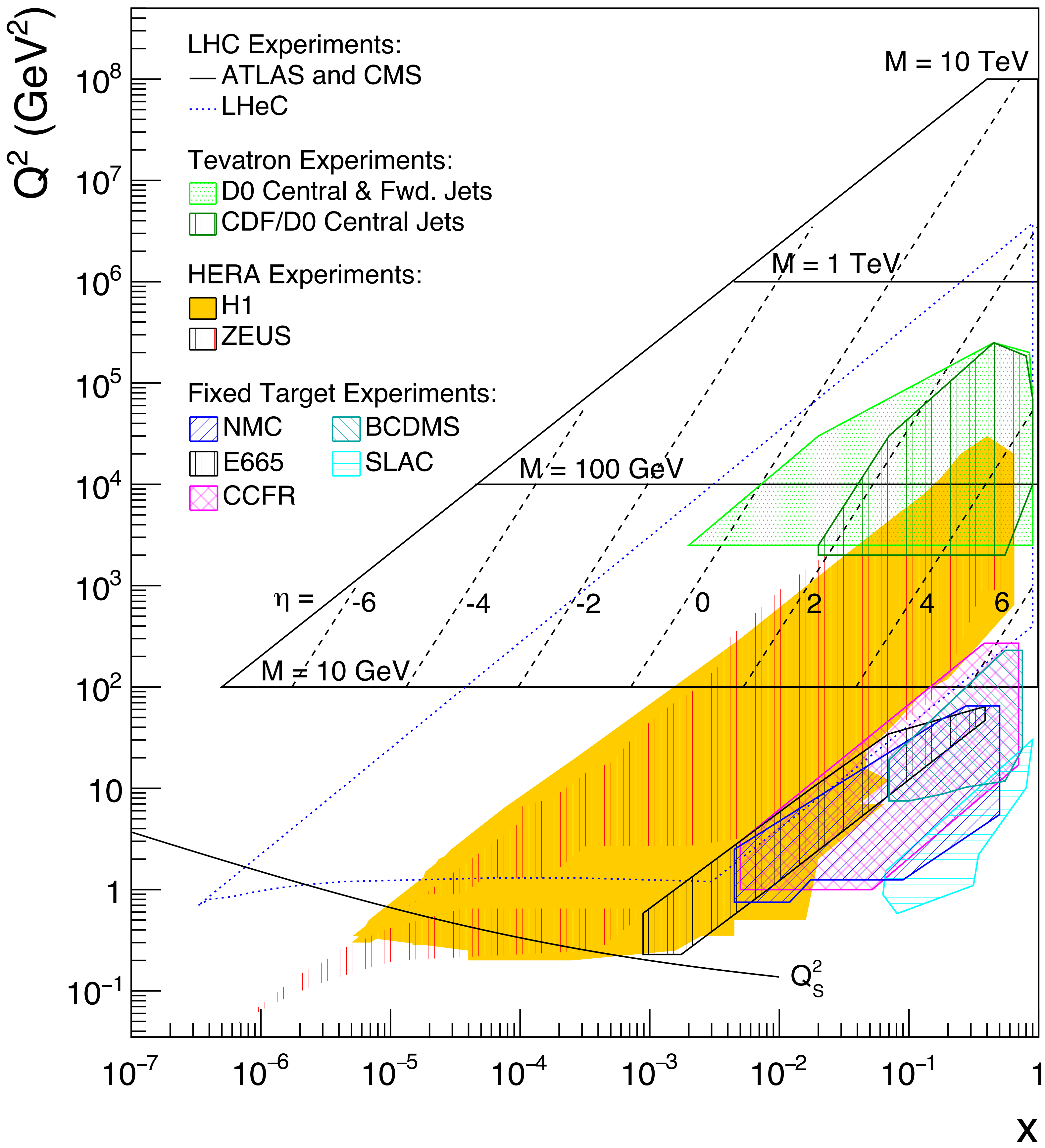



at some point the gluon density has to stop growing


$$Q_s^2(x) \sim \left(\frac{1}{x}\right)^\lambda$$

for a nucleus

$$Q_s^2(x) \sim A^{1/3}\left(\frac{1}{x}\right)^\lambda$$




## Saturation yet to be found!

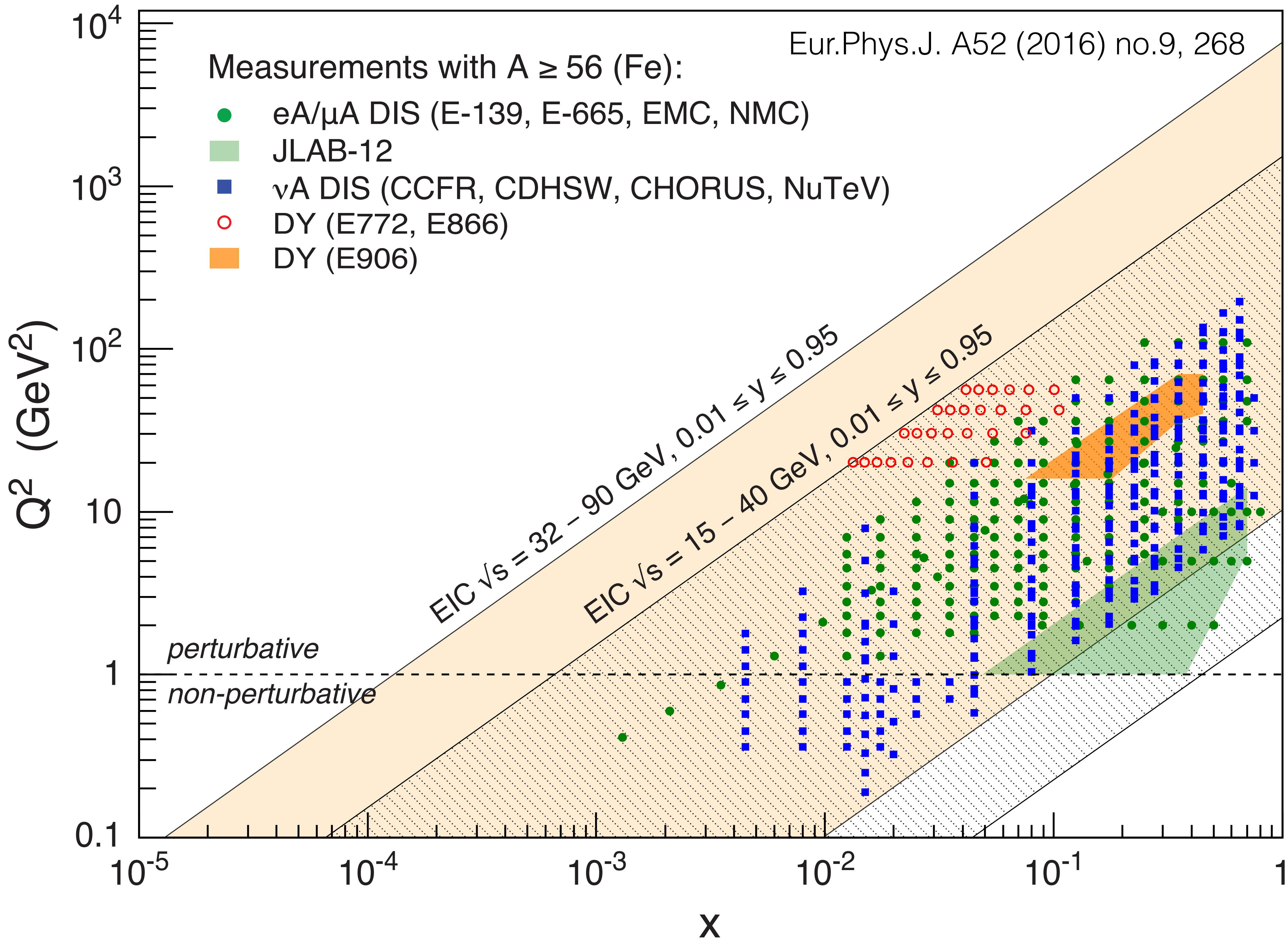
- HERA: too low Q2 to be perturbative
- LHC: too high Q2
- FTE: nowhere near close

*The future*

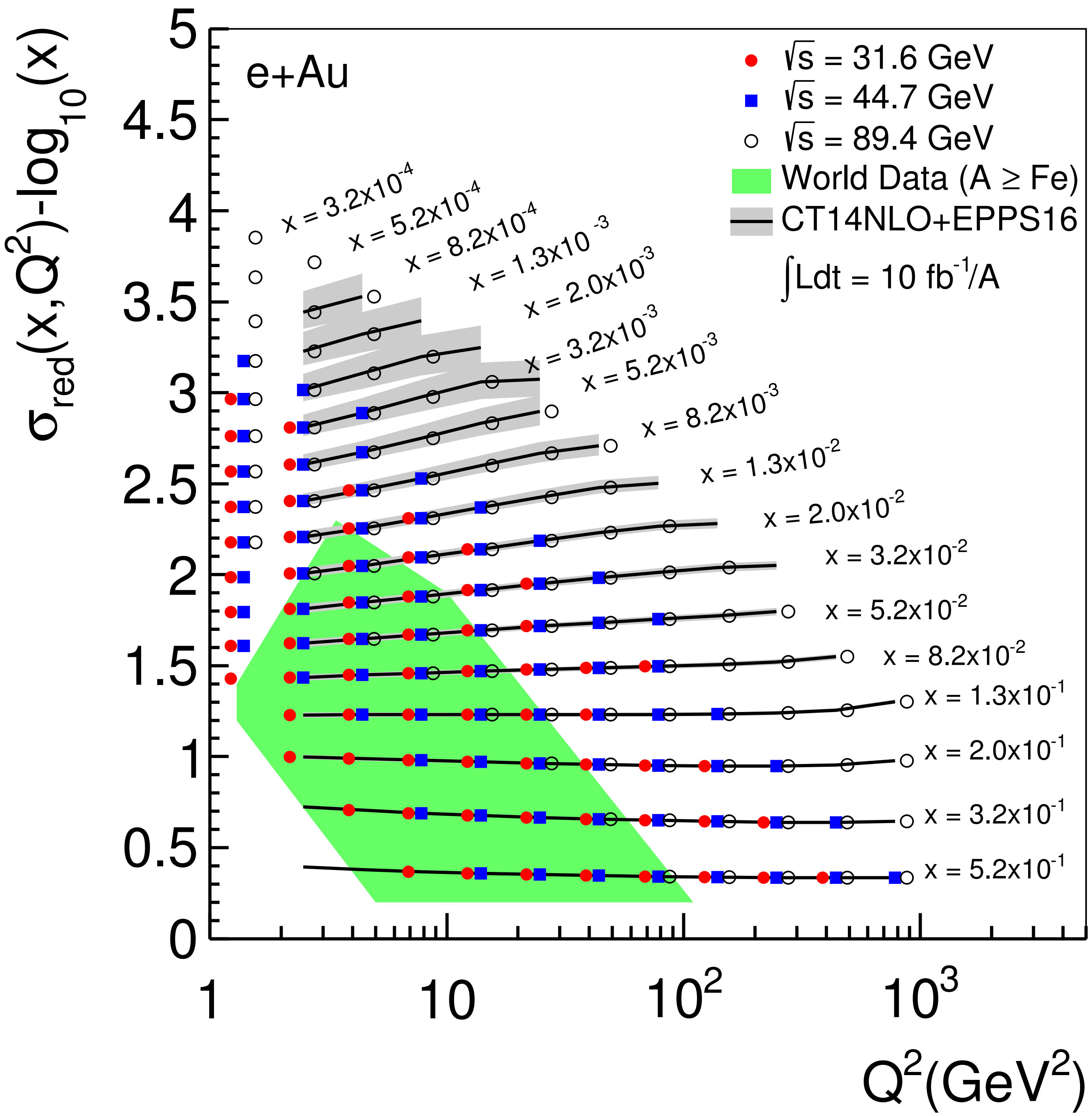
***E****lectron* ***I****on*

***C****ollider*

visit **http://www.eicug.org/** for more info


Eur.Phys.J. A52 (2016) no.9, 268
Measurements with A ≥ 56 (Fe):
eA/μA DIS (E-139, E-665, EMC, NMC)
JLAB-12
νA DIS (CCFR, CDHSW, CHORUS, NuTeV)
DY (E772, E866)
DY (E906)
EIC √s = 32 – 90 GeV, 0.01 ≤ y ≤ 0.95
EIC √s = 15 – 40 GeV, 0.01 ≤ y ≤ 0.95
perturbative
non-perturbative
Q² (GeV²)
x

# *Inclusive reduced cross-section*




Aschenauer, Fazio, Lamont, Paukkunen, PZ, PRD96 (2017) no.11, 114005

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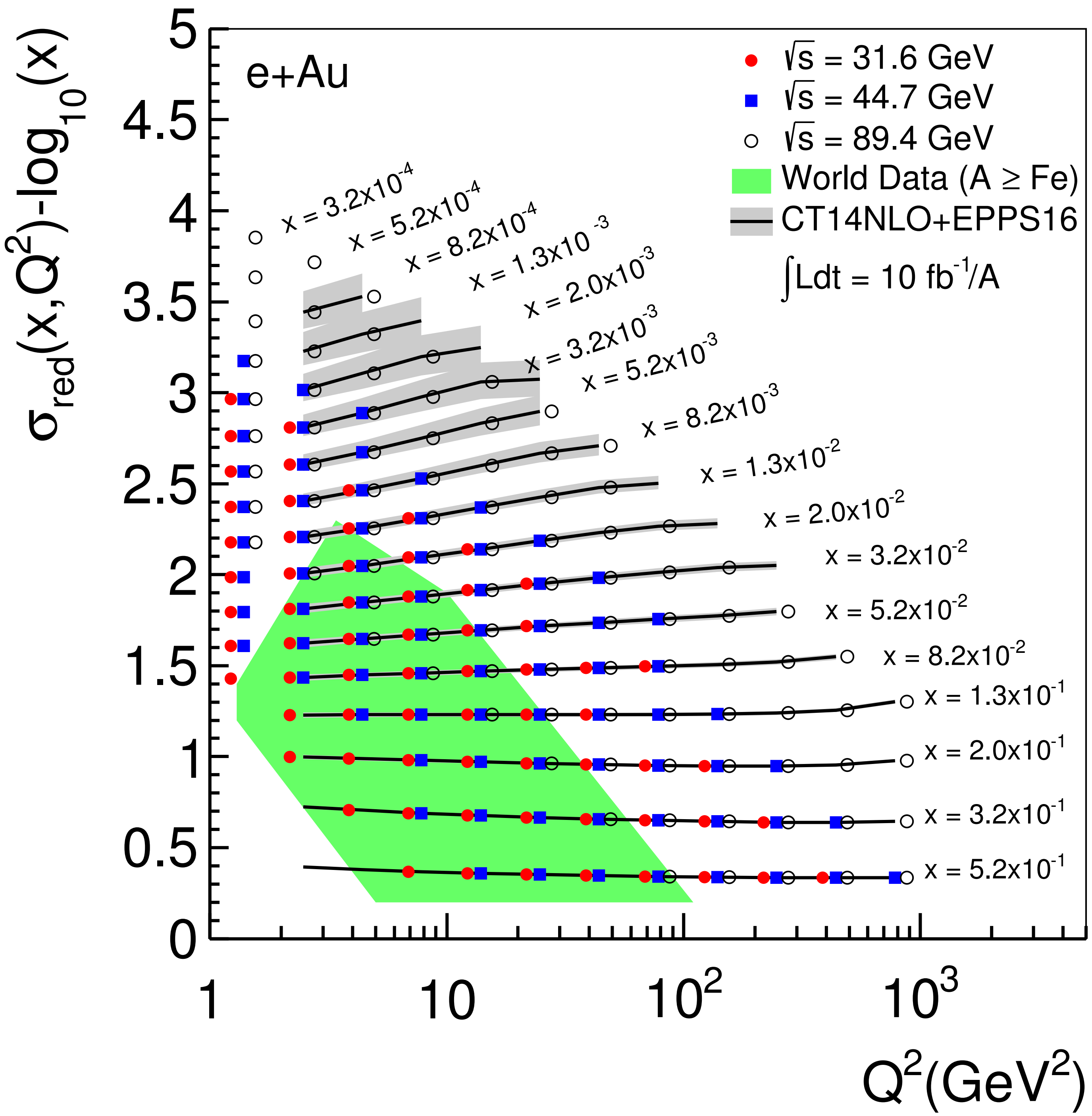
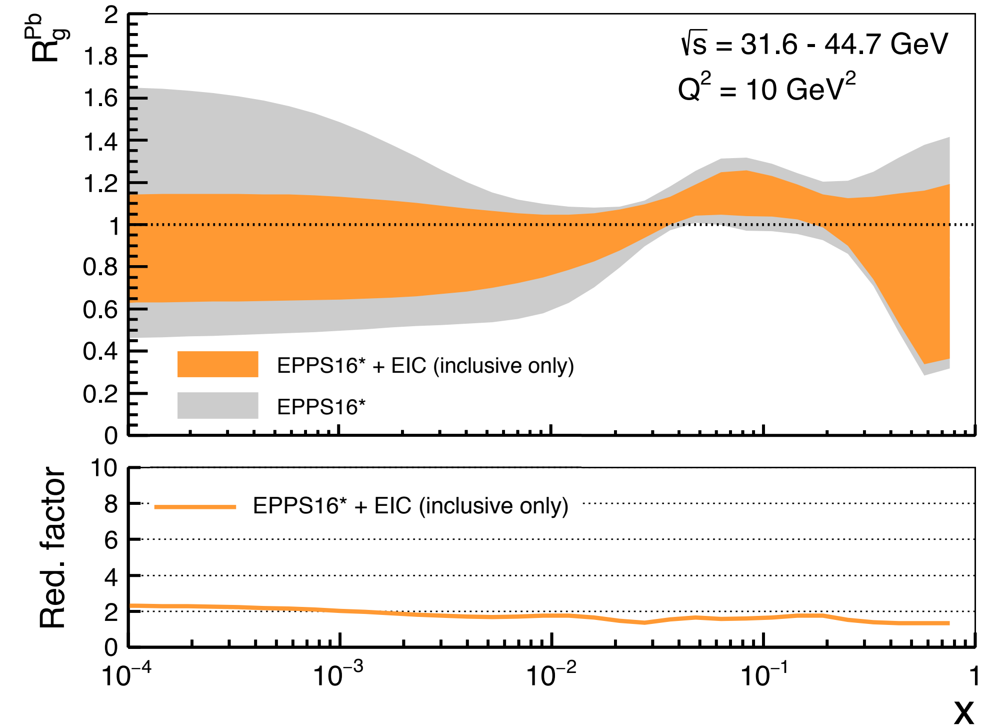
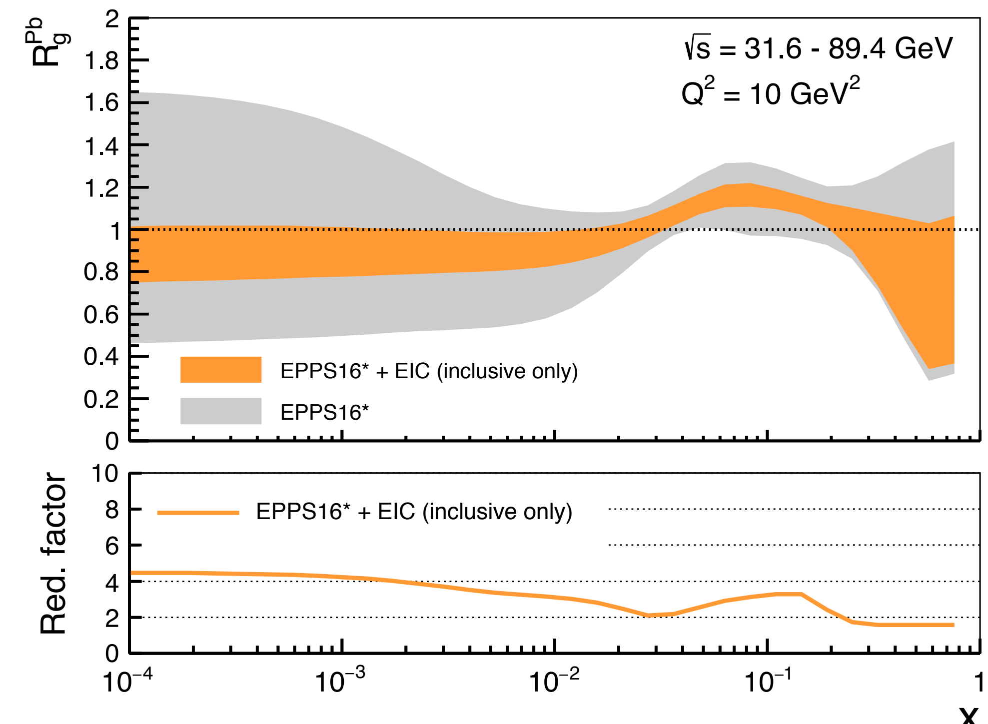
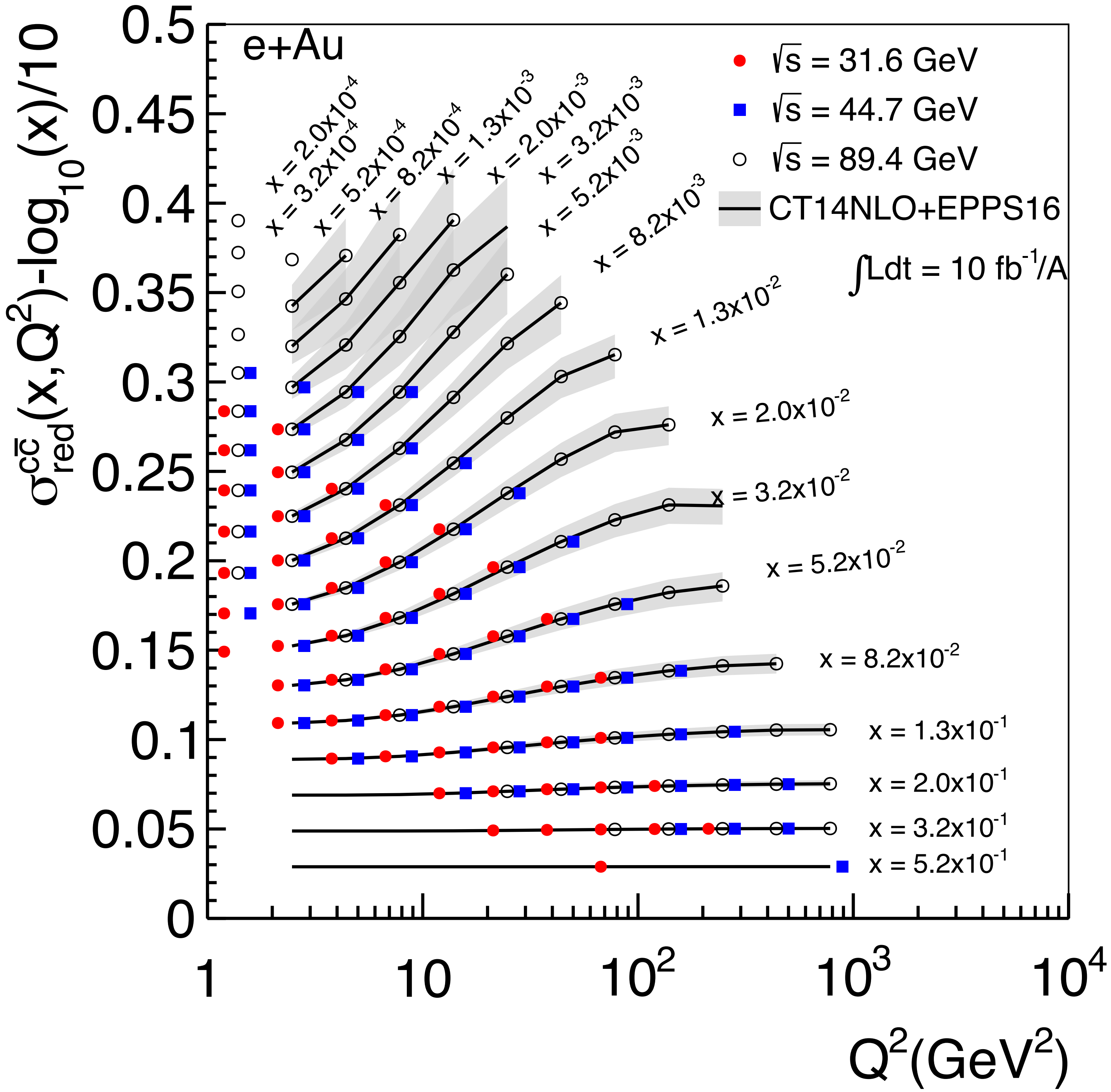


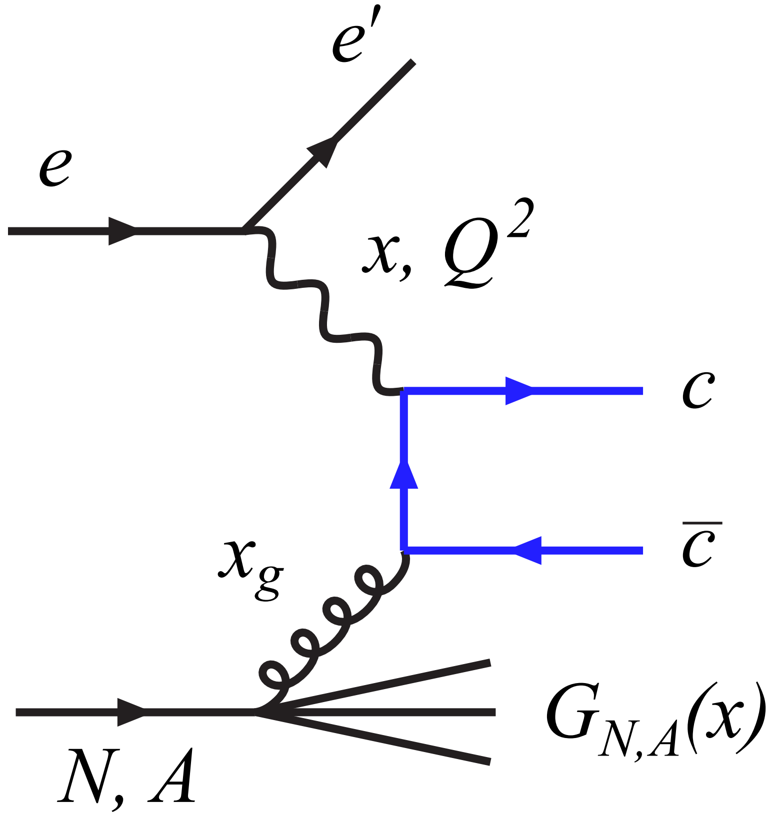




Aschenauer, Fazio, Lamont, Paukkunen, PZ, PRD96 (2017) no.11, 114005

# Charm reduced cross-section



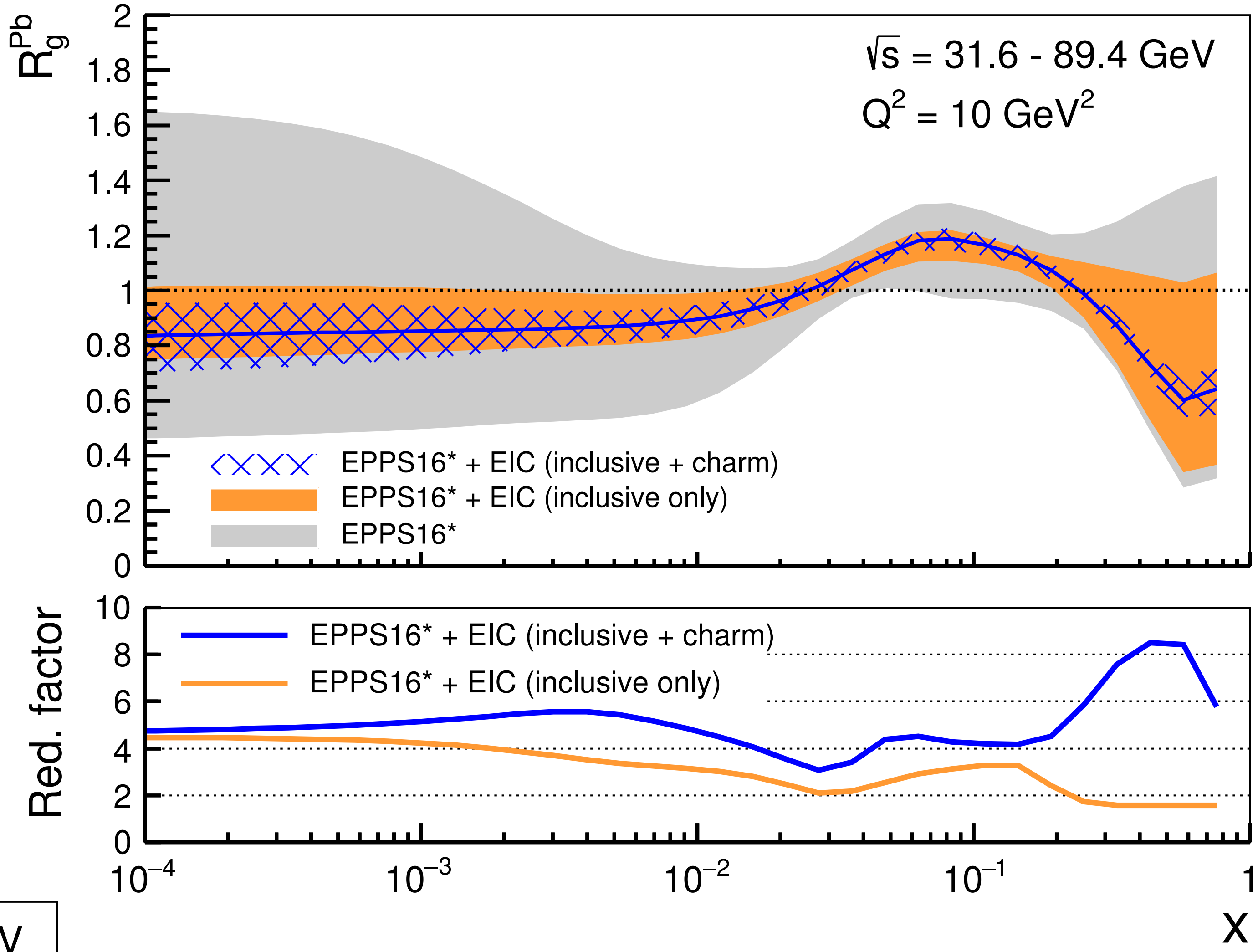



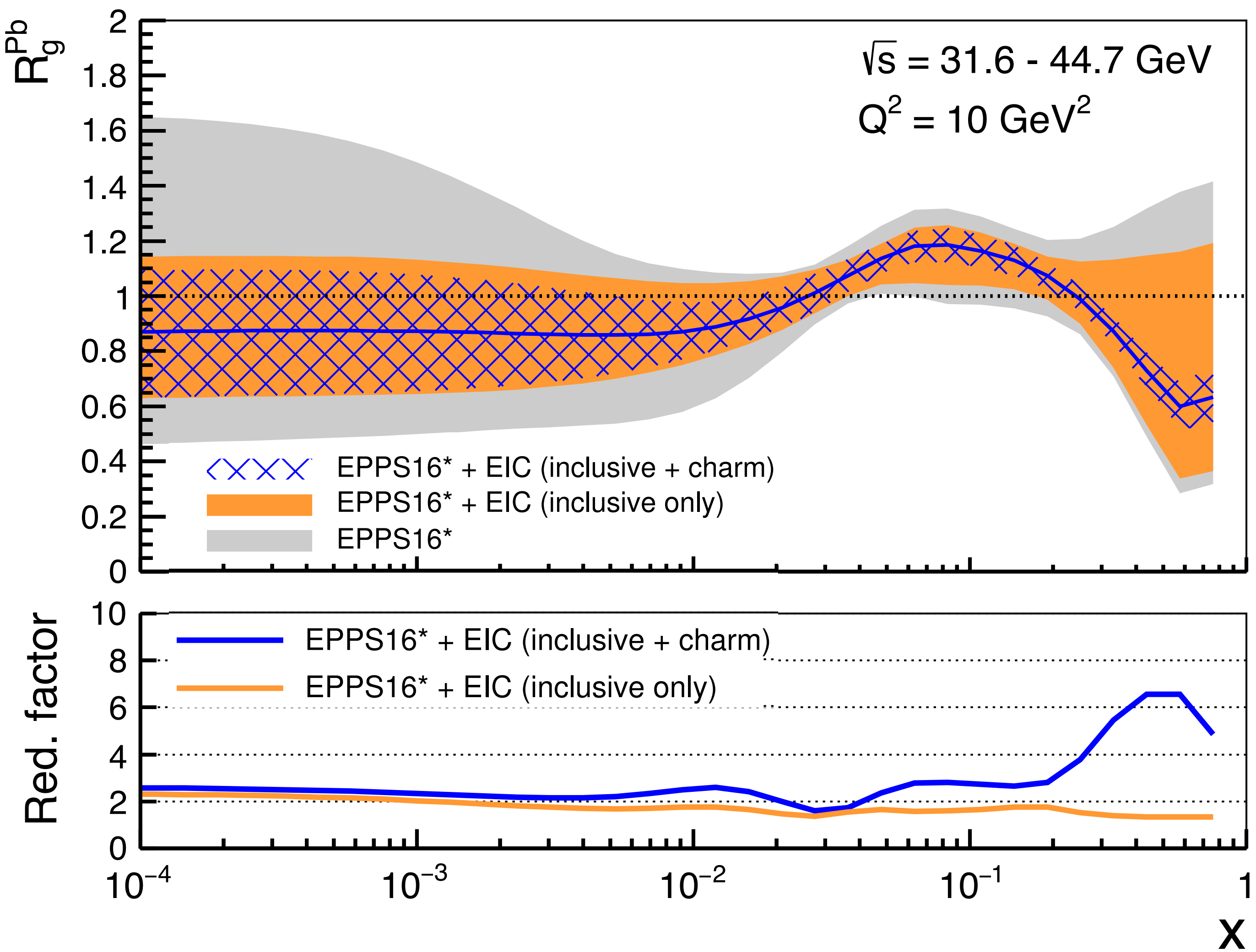

$$F_2^{c\bar{c}} \propto \alpha_s C_{2,g}^{(1)} \otimes g + [C_{2,HH}^{(0)} + \alpha_s C_{2,HH}^{(1)}] \otimes (c + \bar{c})$$

Aschenauer, Fazio, Lamont, Paukkunen, PZ, PRD96 (2017) no.11, 114005

# The future EIC: nPDFs

PRD96 (2017) no.11, 114005

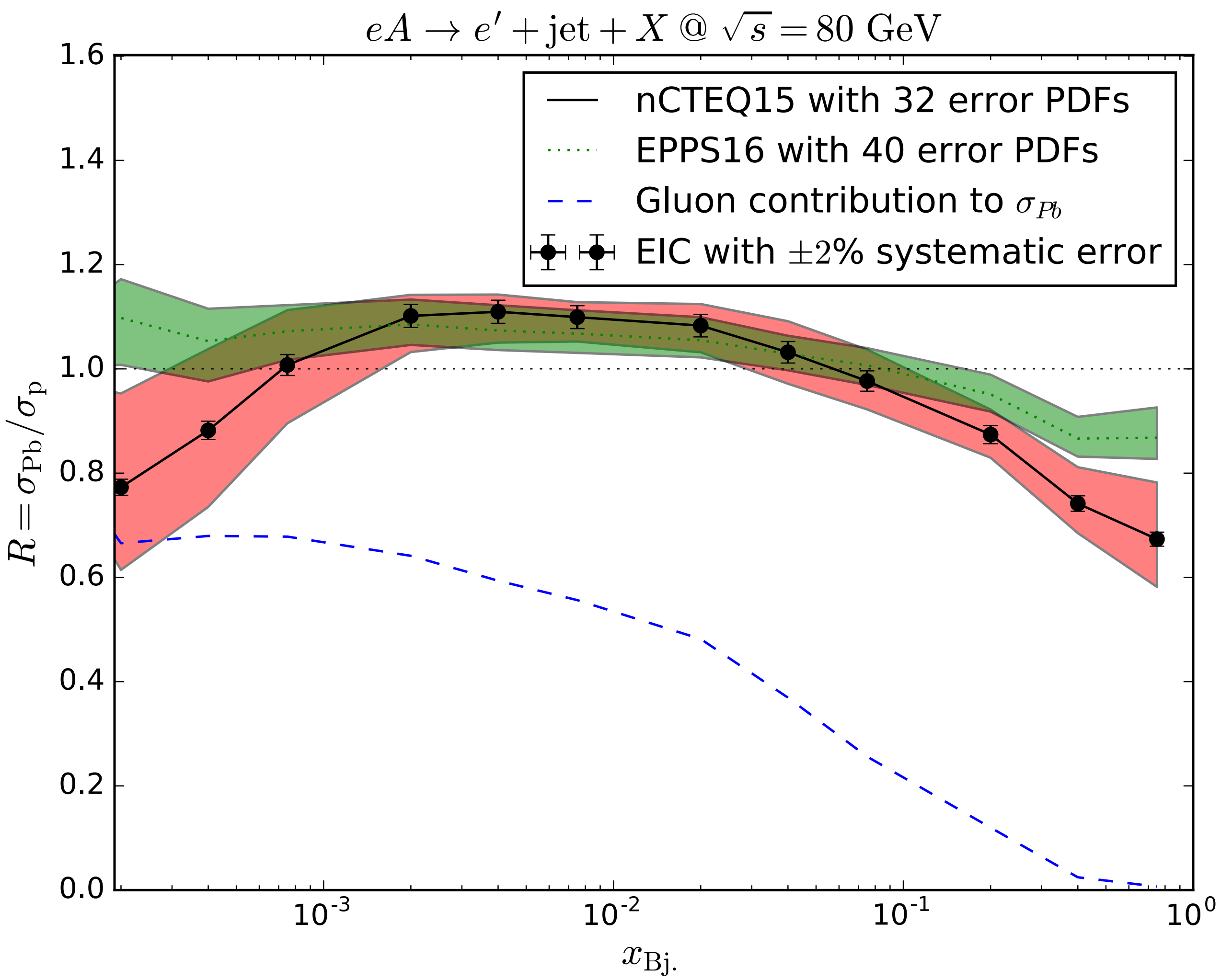


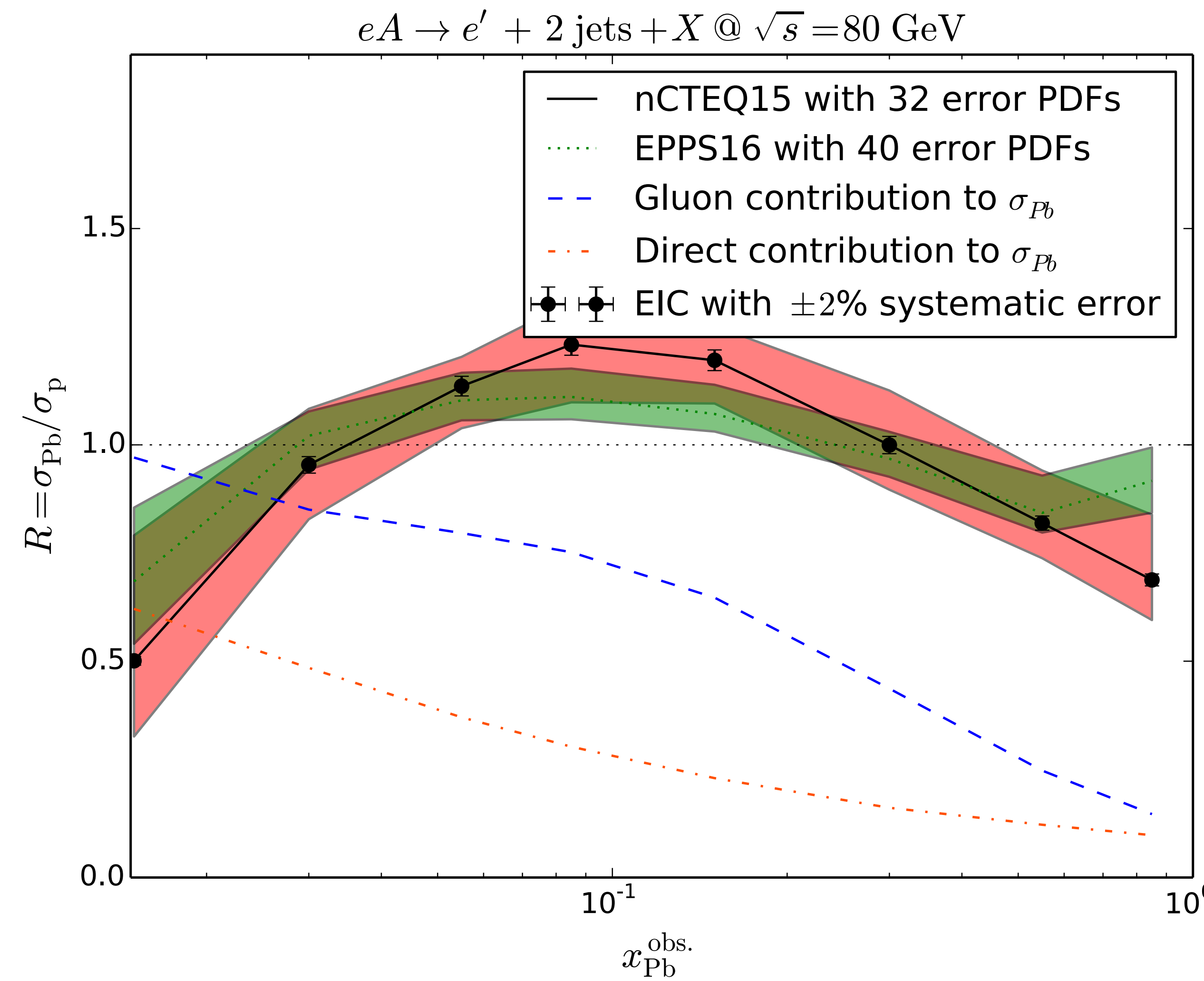




huge impact at high x!

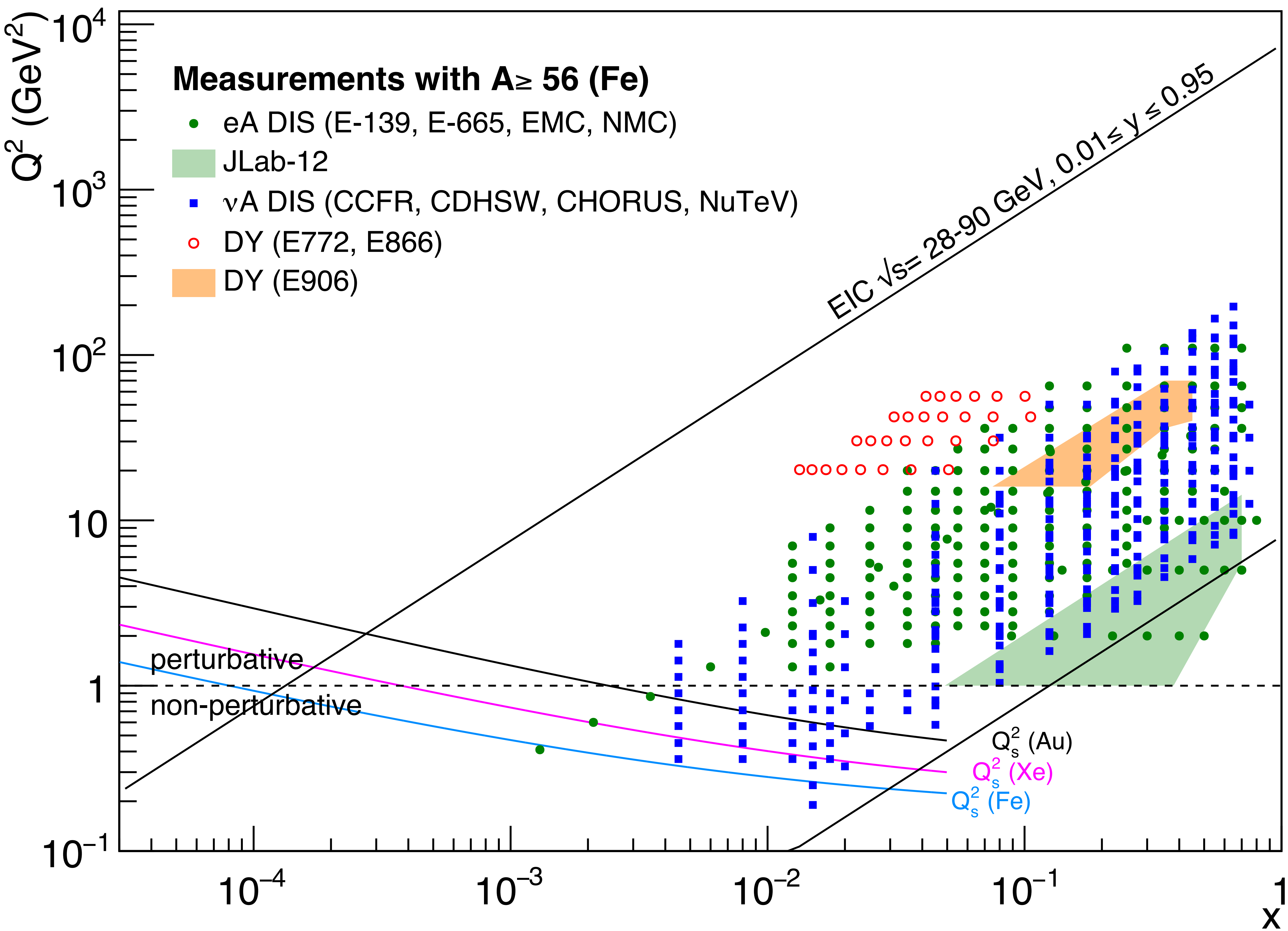
# Jets and di-jets

Klasen and Kovarik, arXiv:1803.10985 [hep-ph].




Klasen, Kovarik, Potthoff, PRD95 (2017) no.9, 094013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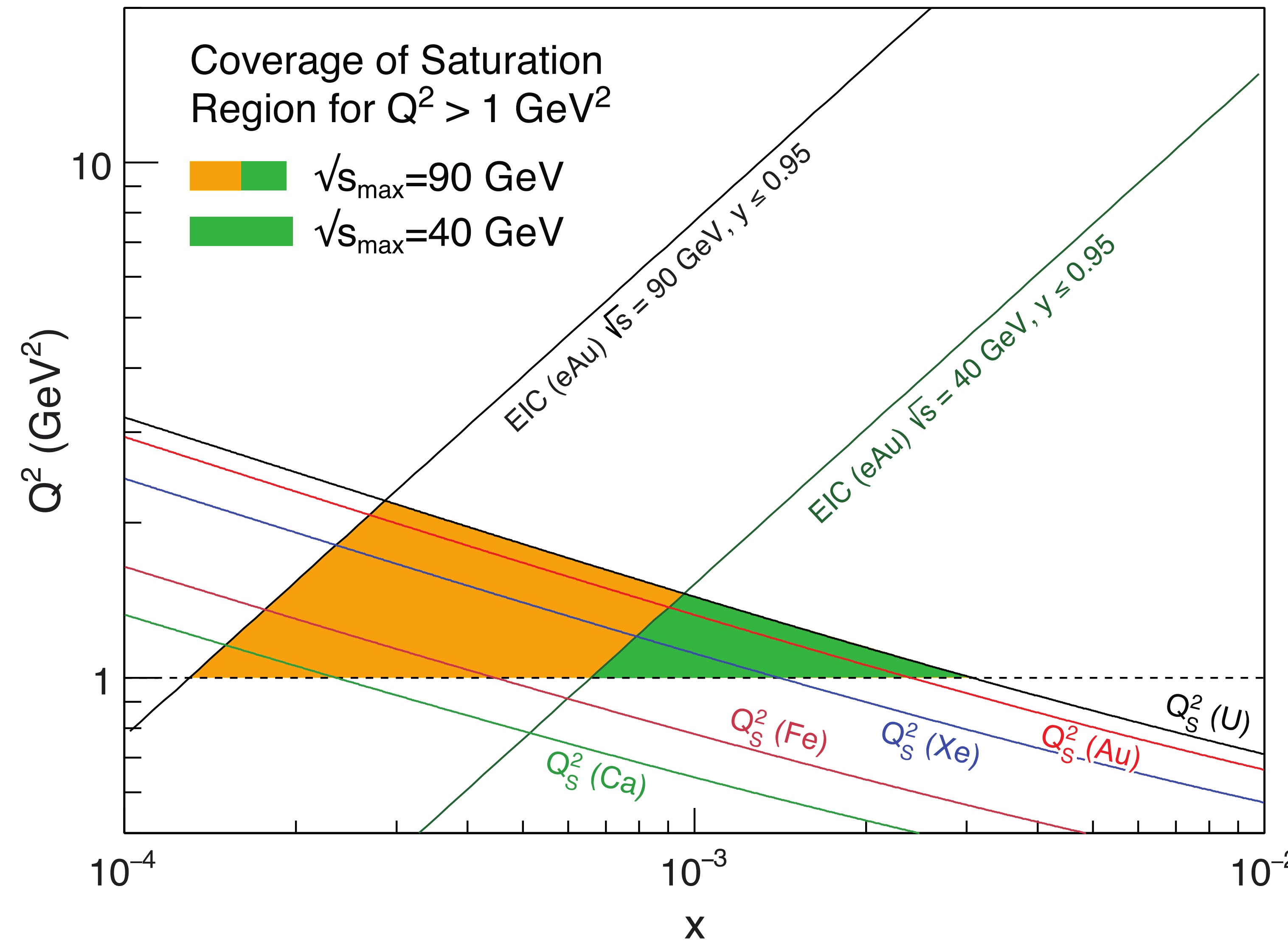
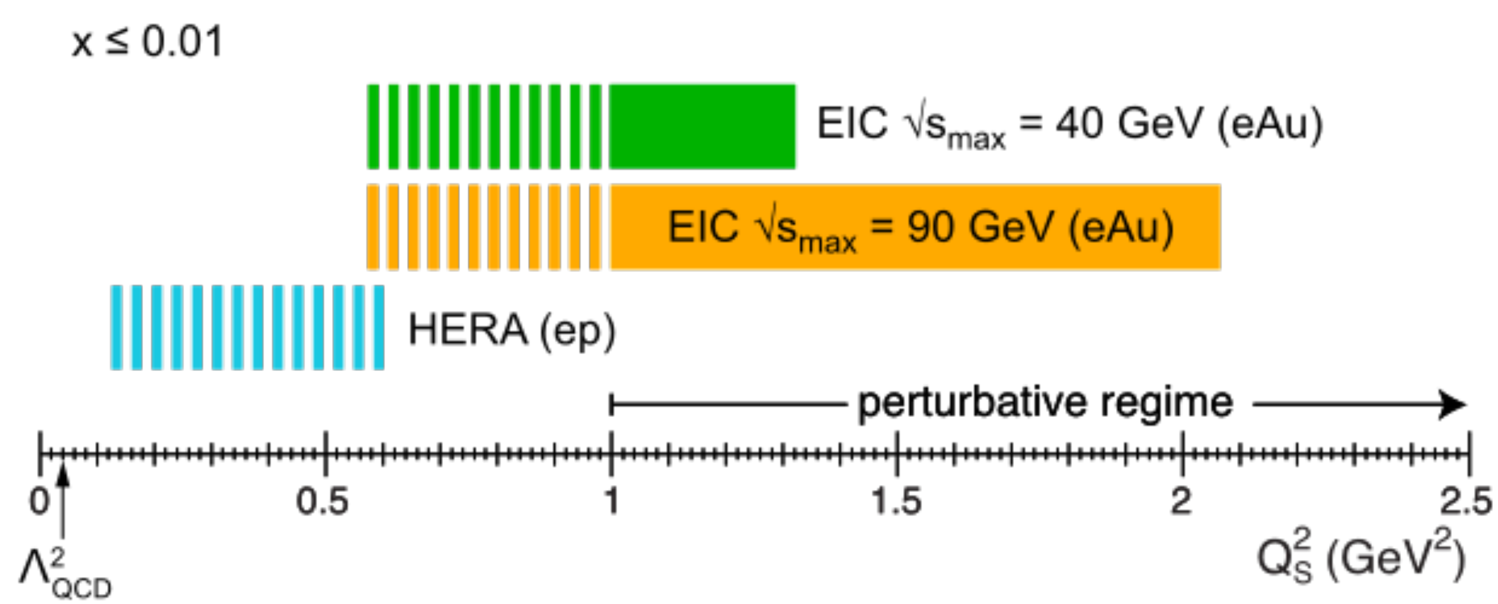
perturbative
non-perturbative
$Q^2_s$ (Au)
$Q^2_s$ (Xe)
$Q^2_s$ (Fe)
$Q^2$ (GeV$^2$)
x
$10^{-1}$
1
10
$10^2$
$10^3$
$10^4$
$10^{-4}$
$10^{-3}$
$10^{-2}$
$10^{-1}$
1

# The future EIC: Saturation

we must study saturation in the region where we **know** how to make reliable calculations



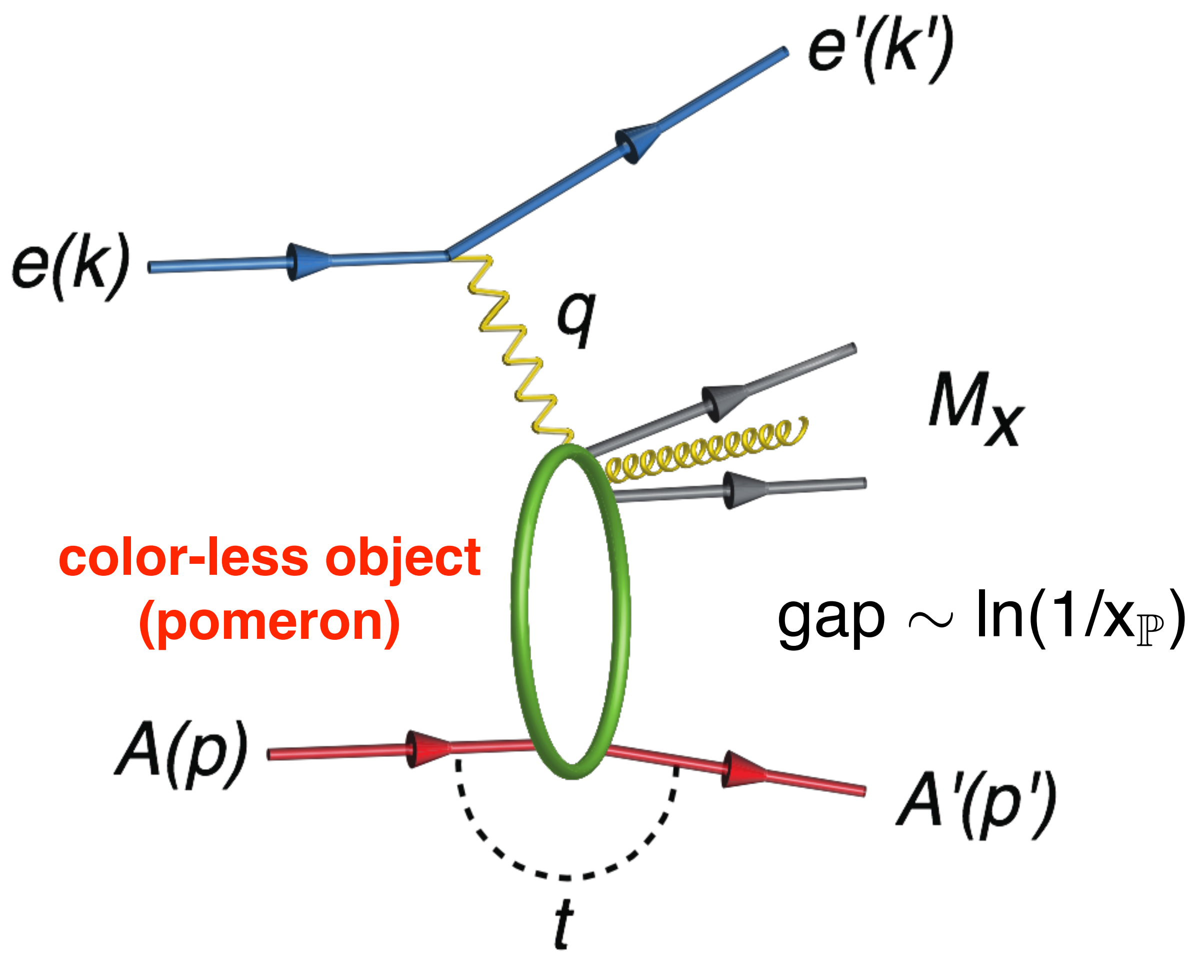

lever arm in **A** is crucial



# What can we measure in the relevant region that is sensitive to saturation?

- ✦ strong tension with older data sets and deviations from the DGLAP predictions for (n)PDFs
- ✦ diffractive events
- ✦ di-hadron correlations

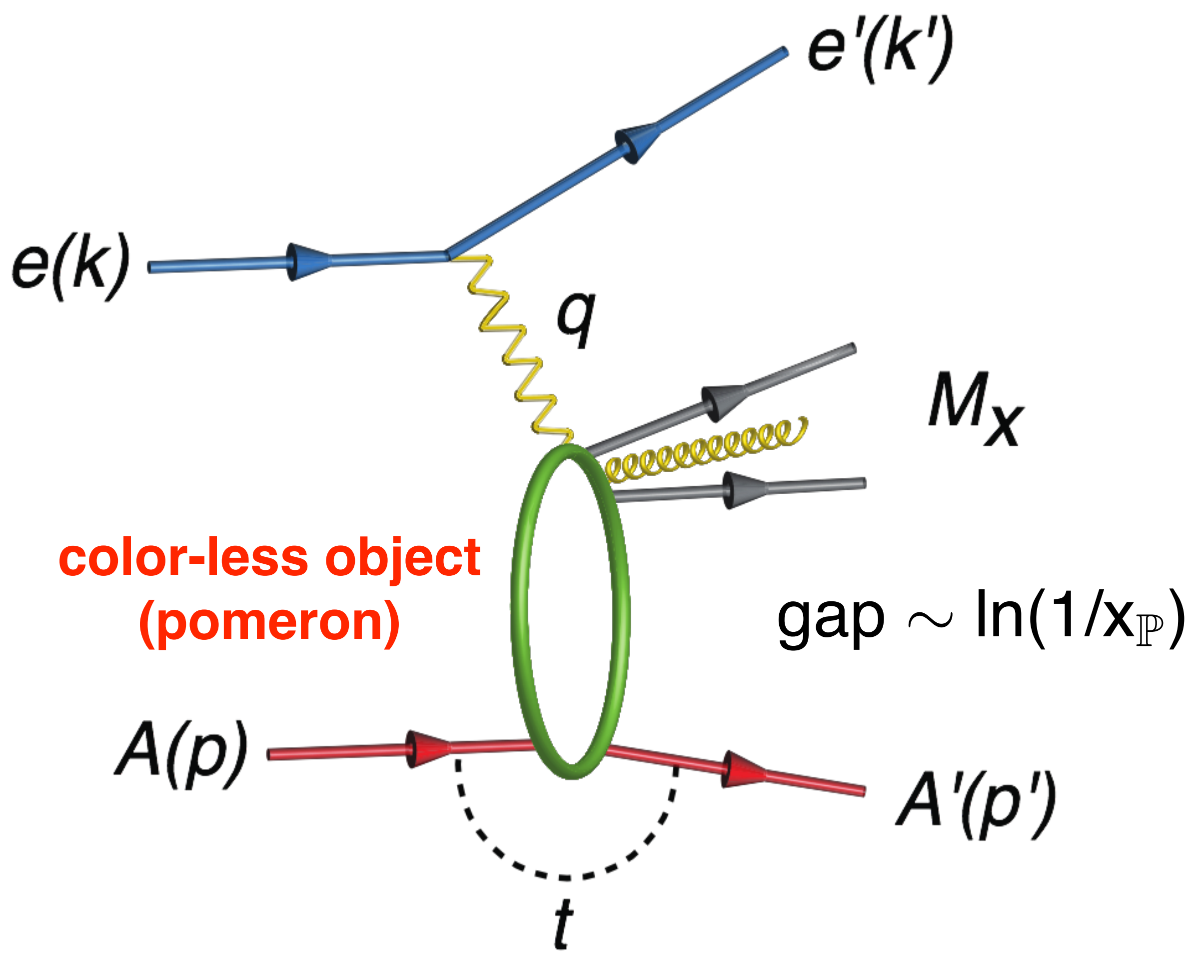
# Inclusive diffraction

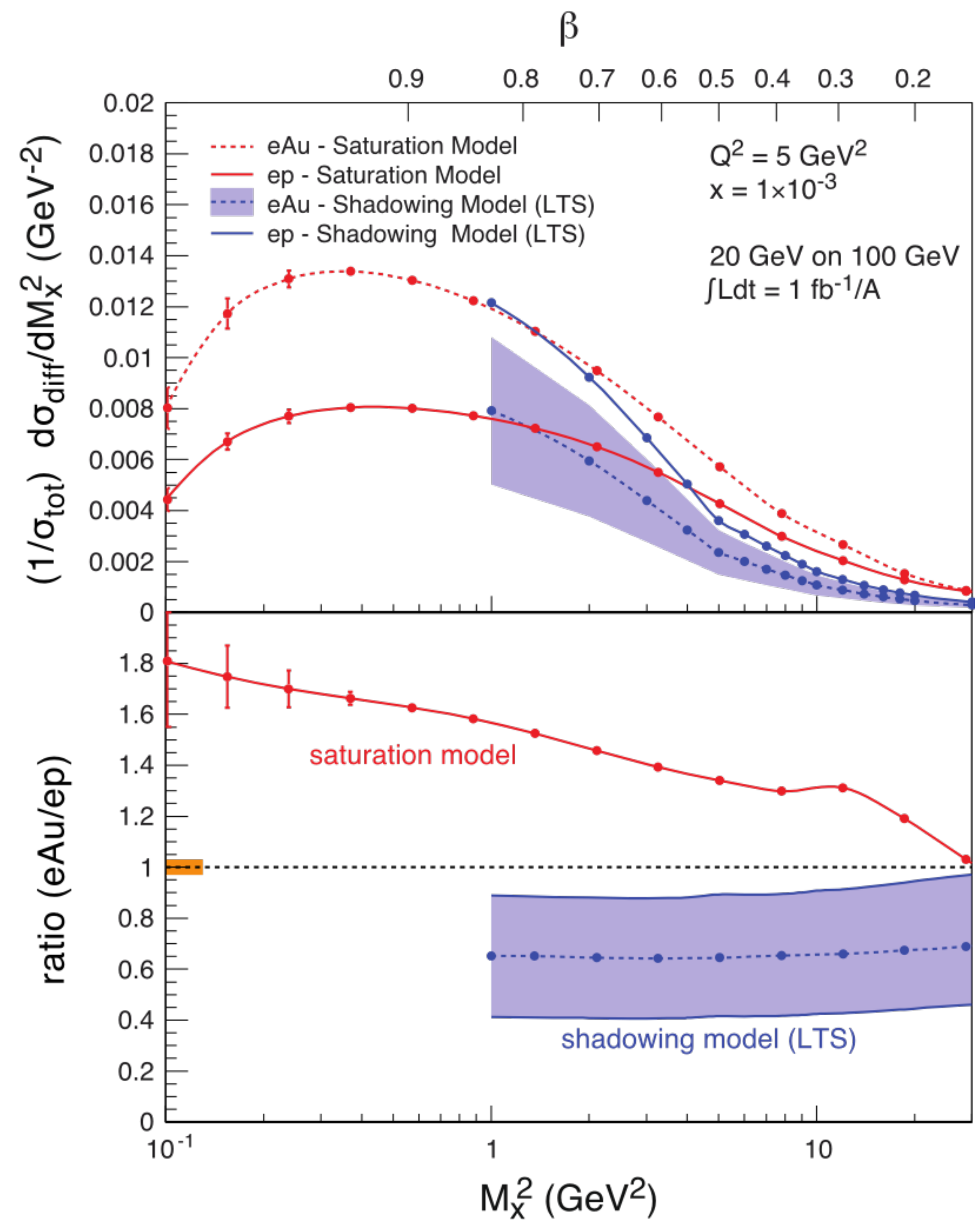



- coherent (nucleus intact)
- incoherent (nucleus break up)
- 25-40% of the total σ!
- due to pomeron exchange, it is sensitive to:

$$\sigma \propto g\left(x, Q^2\right)^2$$

# Inclusive diffraction



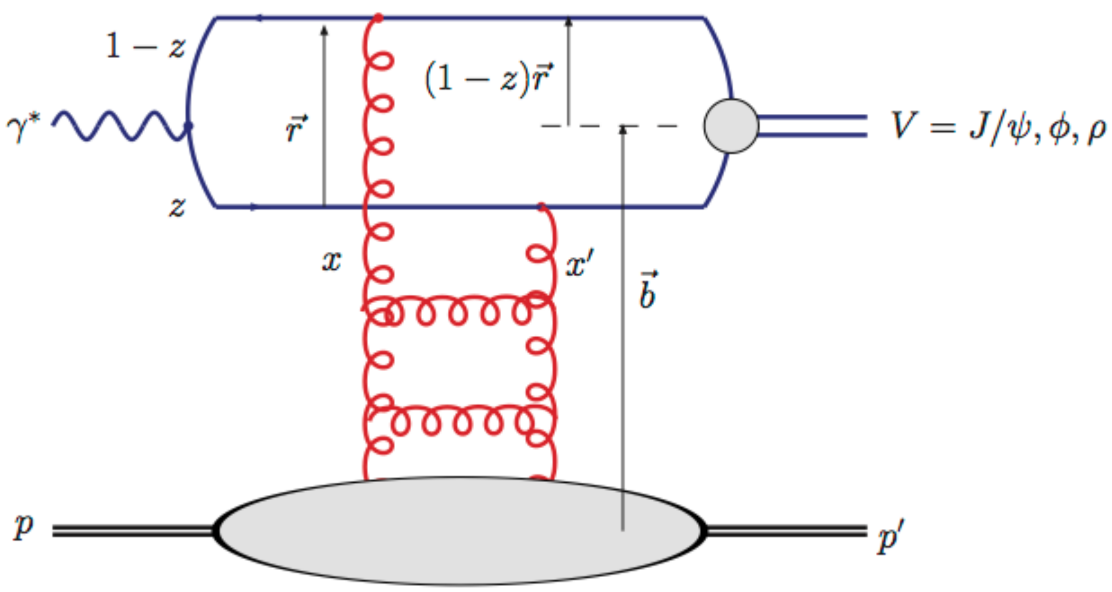




- coherent (nucleus intact)
- incoherent (nucleus break up)
- 25-40% of the total σ!
- due to pomeron exchange, it is sensitive to:

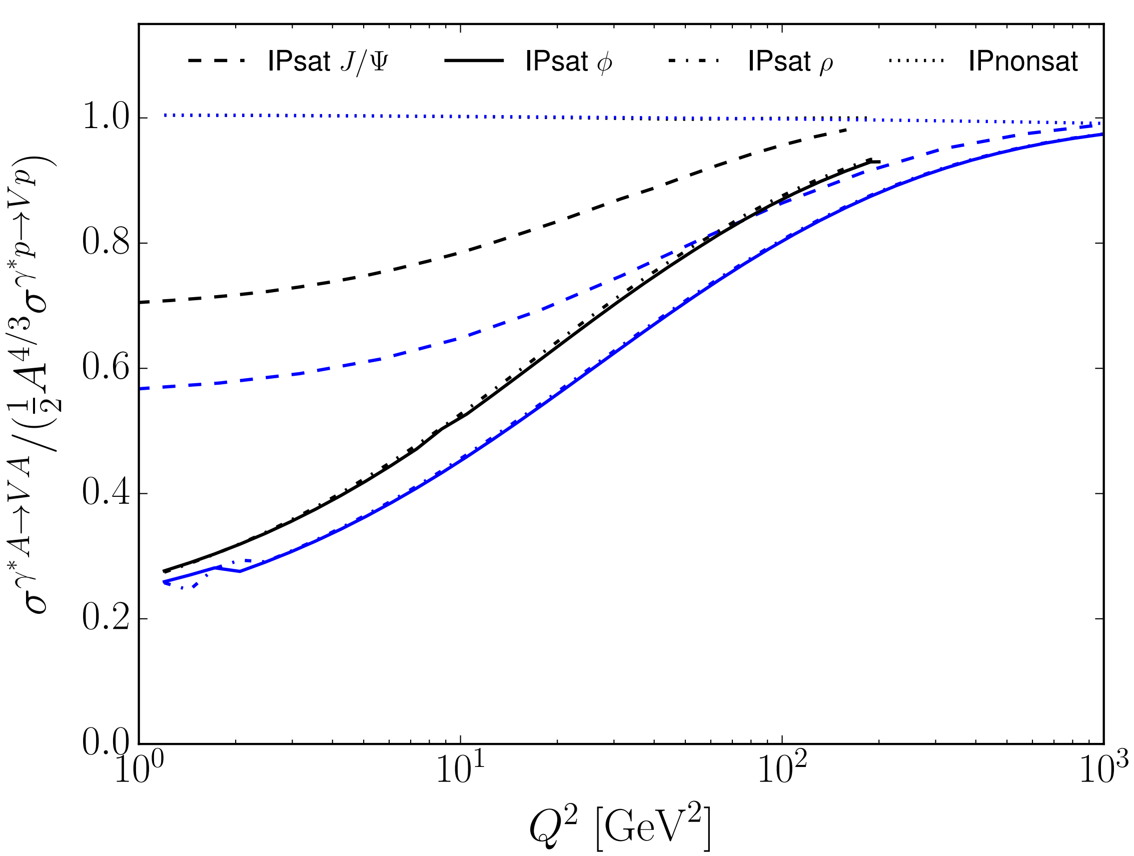
$$\sigma \propto g\left(x, Q^2\right)^2$$

E.C. Aschenauer,
“The Electron-Ion Collider in the US”

# Exclusive diffraction

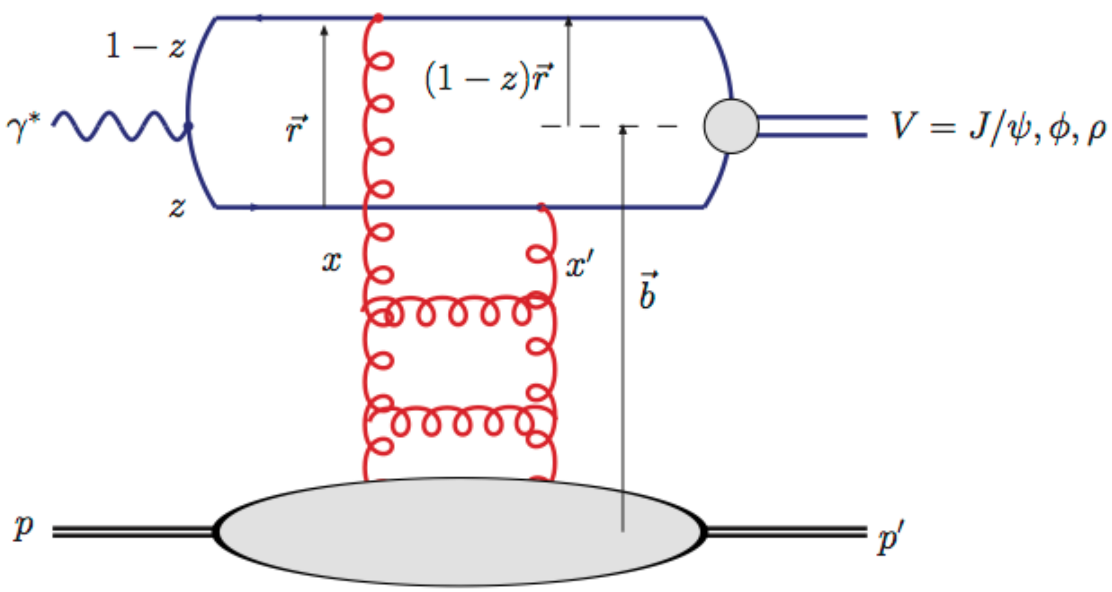



W = 100, 1000 GeV

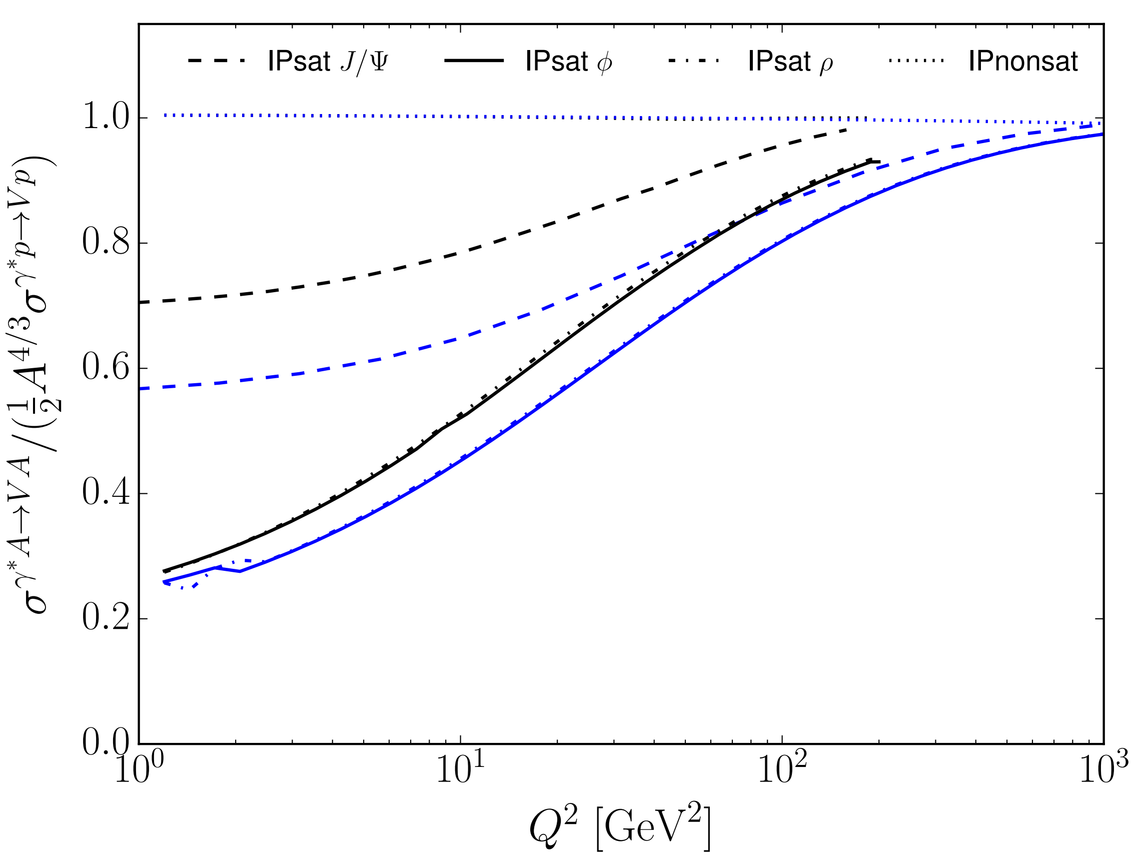



H. Mäntysaari and PZ, PRD98 (2018) 036002

# Exclusive diffraction

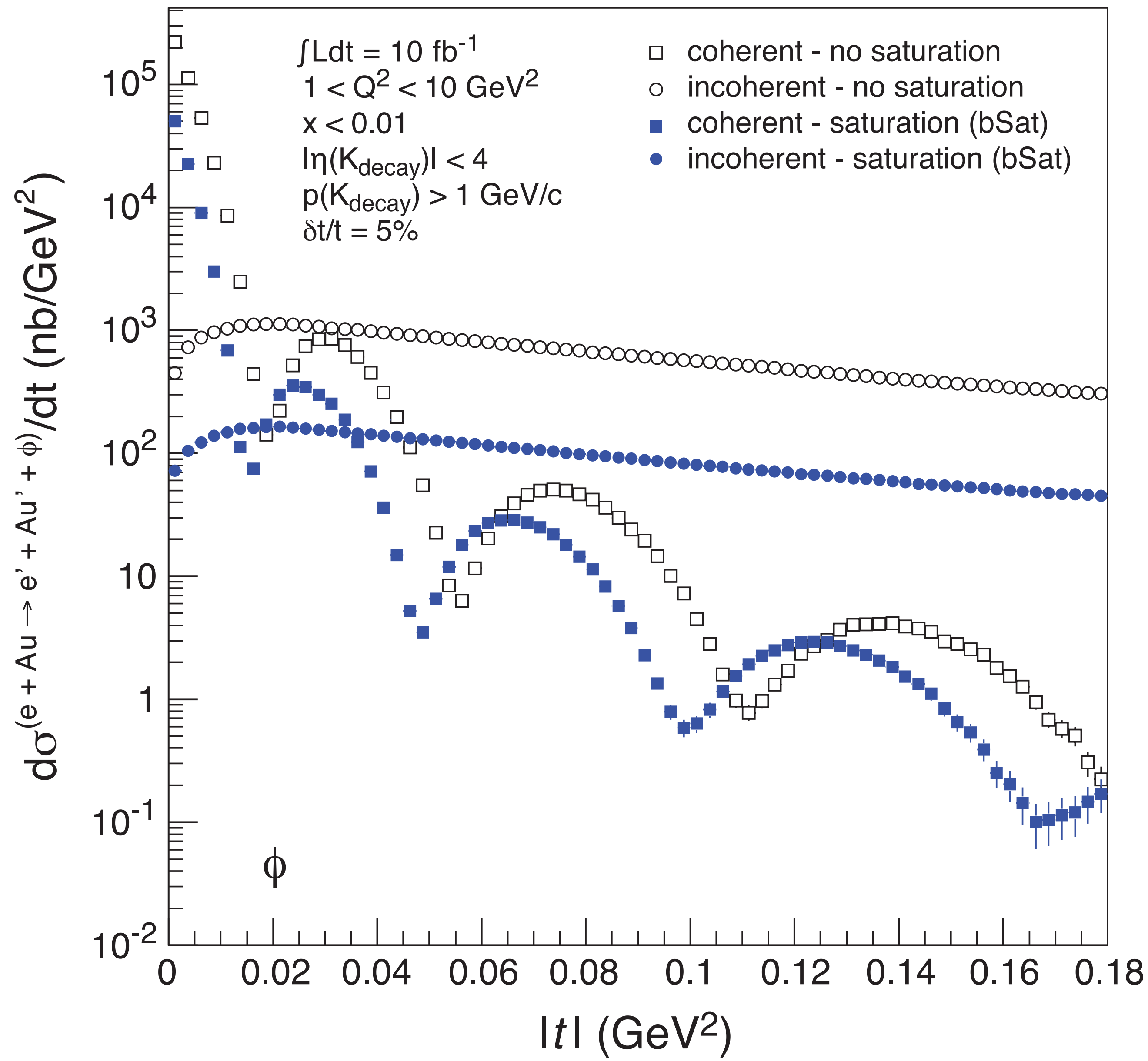



$W = 100, 1000\,\mathrm{GeV}$




H. Mäntysaari and PZ, PRD98 (2018) 036002

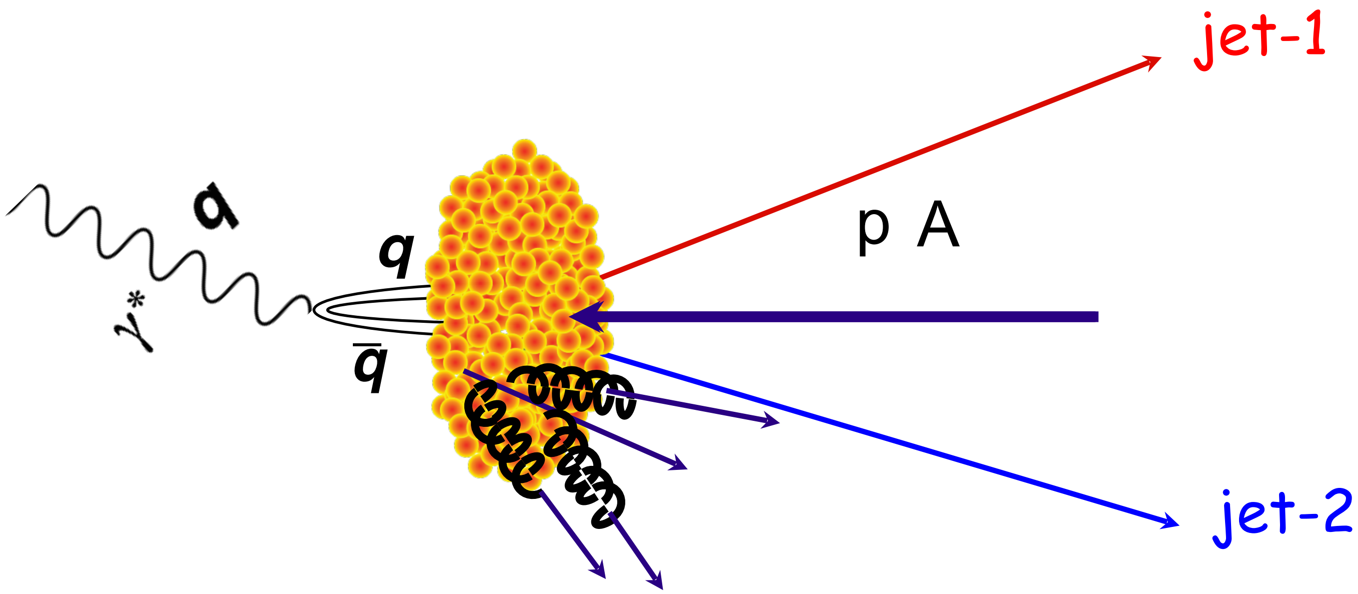
$$e + Au \to e' + \phi + Au'$$



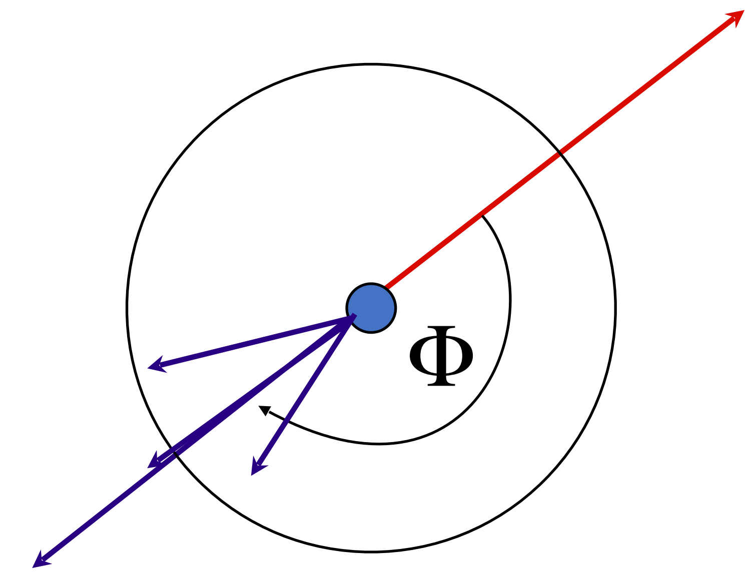

T. Toll, 2012 RHIC & AGS Annual Users' Meeting

# di-hadron correlation

side-view:




beam-view:

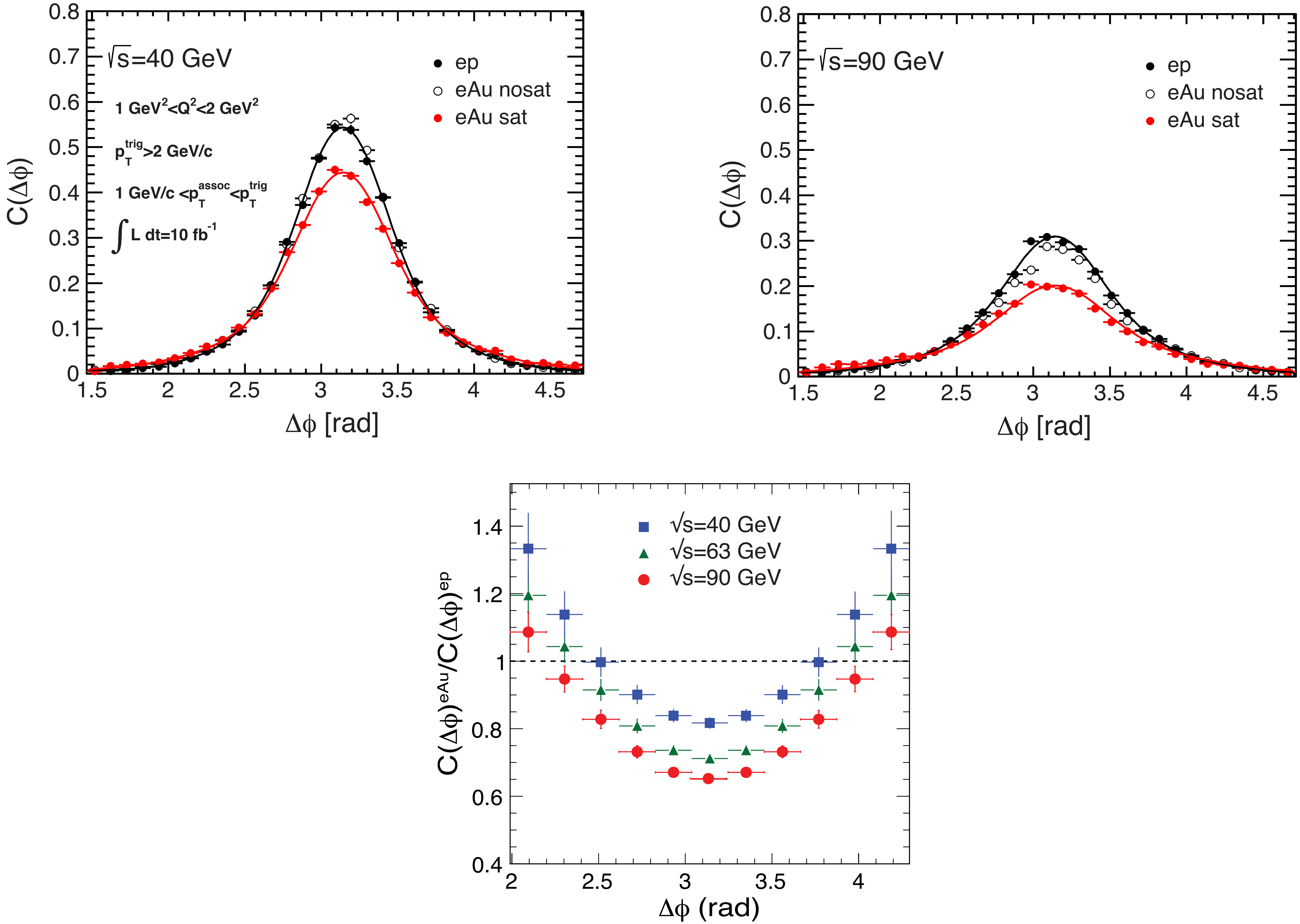



Low gluon density (ep):

pQCD predicts 2→2 process ⇒ back-to-back di-jet

High gluon density (eA):

2 → many process ⇒ expect broadening of away-side




E.C. Aschenauer et *al.*, arXiv:1708.01527

# *Summary*

- The proton structure in QCD is quite well understood in the dilute regime
- Very low-x limit not well known, CGC is an option
- Something expected to tame the cross-section
- No clear experimental signal of saturation
- The EIC has the potential to improve our description of the proton/nucleus

# some **EIC** publicity!

Center for Frontiers in Nuclear Science

- Established in Fall 2017 with generous support from the Simon's Foundation and NY State

- A collaboration between Stony Brook & BNL to create a frontier research center to support the US EIC

**https://www.stonybrook.edu/cfns/**

Contact: abhay.deshpande@stonybrooke.edu

# some **EIC** publicity!

**Activities in 2018**

- Workshops: 9

  7 finished, one this week, one in October

  ~200 scientists visit CFNS
- Bi-monthly SBU/BNL joint seminars: 40+ seminars and special talks
- Visitors program started & exchange visitor program being established
- Post doctoral fellow program: local and joint-remote post docs with remote institutions

- **Annual summer school for 30+ students being planned starting in 2019**

current open jobs:

**https://www.stonybrook.edu/cfns/jobs/index.php**