Constraining Nuclear PDFs at an EIC

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INT-17-3 Program (2017) - Seattle

U.S. DEPARTMENT OF ENERGY
Office of Science

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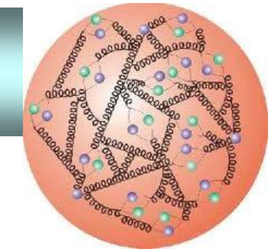
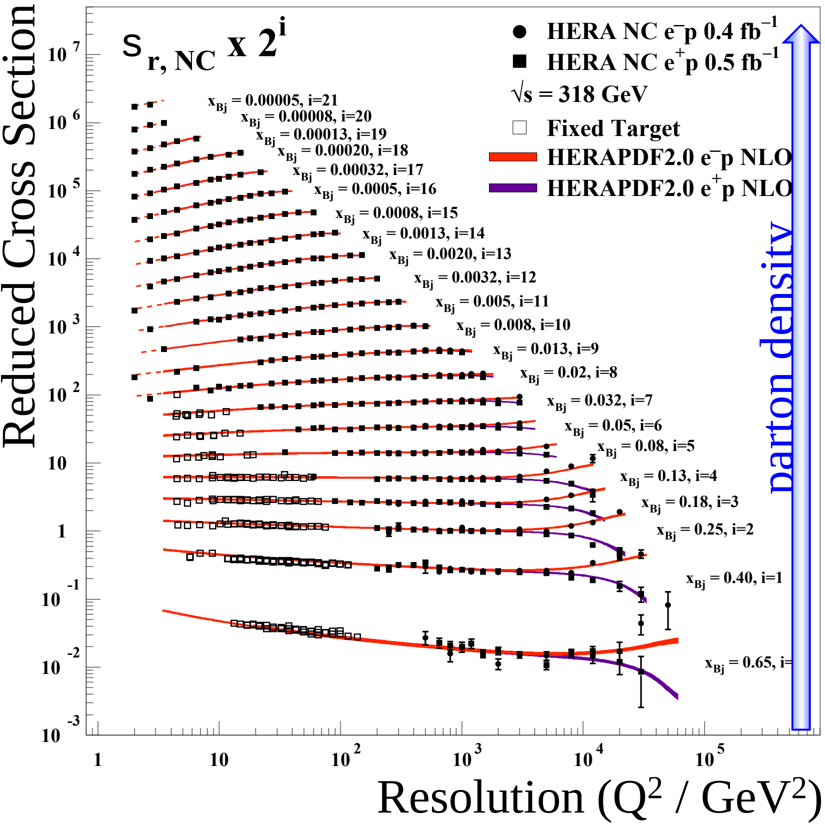
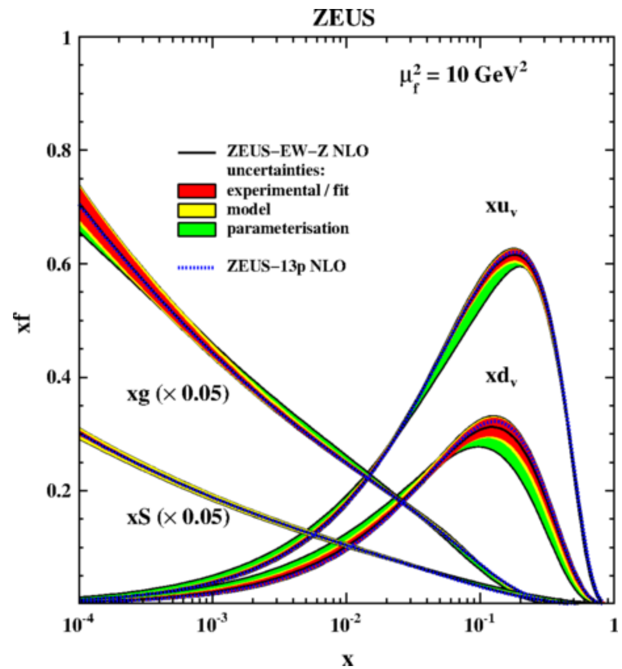
Proton PDFs from HERA





What we Know:

- ✓ Extensive program carried at HERA
- ✓ F_2 precisely measured in a large-*x* range
- ✓ At low-*x* gluons dominate



Differential cross section:

$$\frac{ds^{e^{\pm}p}}{dxdQ^2} = \frac{2pa^2Y_+}{xQ^4} s_r(x,Q^2)$$

Reduced cross section:

$$s_r(x,Q^2) = F_2(x,Q^2) - \frac{y^2}{Y^+} F_L(x,Q^2)$$

Nuclear Structure Functions

Inclusive DIS on e+A analog to e+p:

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

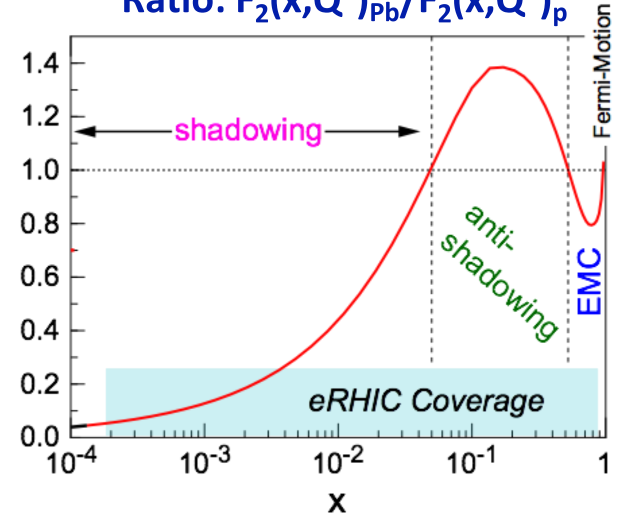
quark+anti-quark

gluons
(or tag on F_2-charm)

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

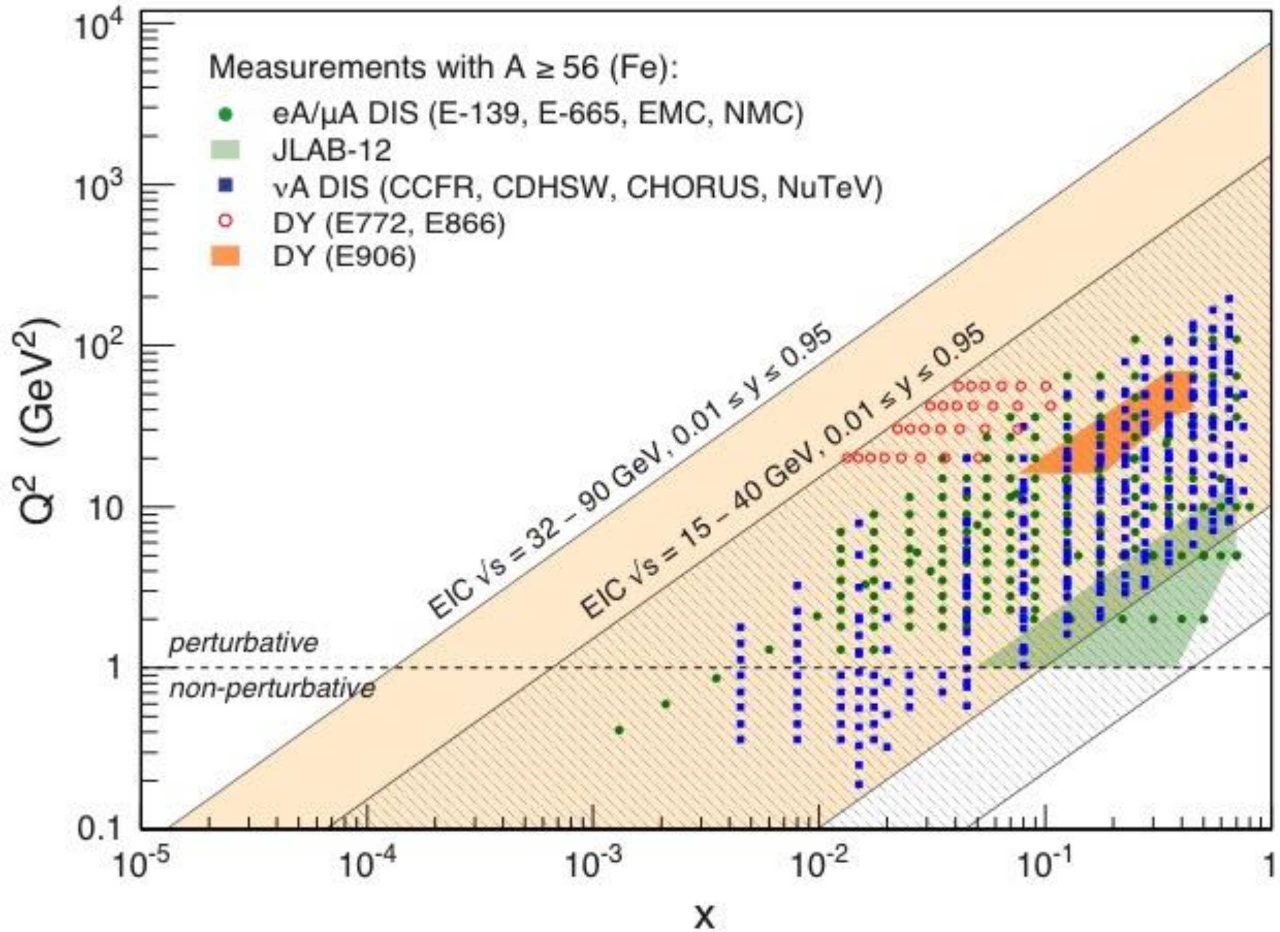
DGLAP:
predicts Q^2 but not A-dependence and x-dependence
Saturation models:
predict A-dependence and x-dependence but not Q^2
→ Need: large Q^2 lever-arm for fixed x, A-scan

Ratio: $F_2(x,Q^2)_{Pb}/F_2(x,Q^2)_p$



Aim at extending our knowledge on structure functions into the realm where gluon saturation effects emerge ®different evolution

Electron-Ion Collider's Phase Space



An EIC at its highest extends kinematic coverage for e+A data by a decade in x at a fixed Q^2 by a decade in Q^2 at a fixed x

Nuclear Modifications – Present Knowledge

Measure different structure functions in e+A → constrain nPDF

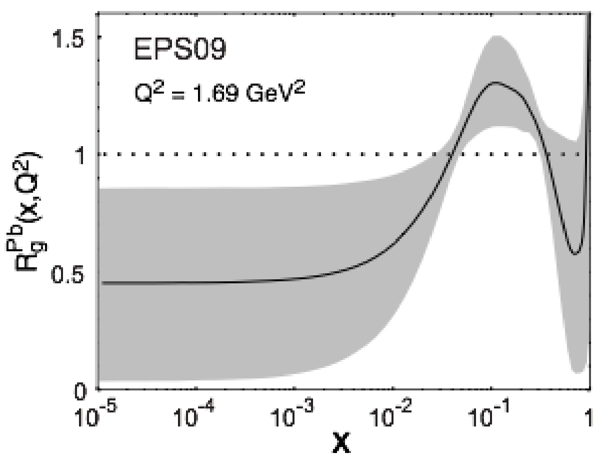
Latest state-of-the-art nPDF is EPPS16

K. J. Eskola, P. Paakkinen, H. Paukkunen, C. A. Salgado [Eur.Phys.J. C77 (2017) no.3, 163]

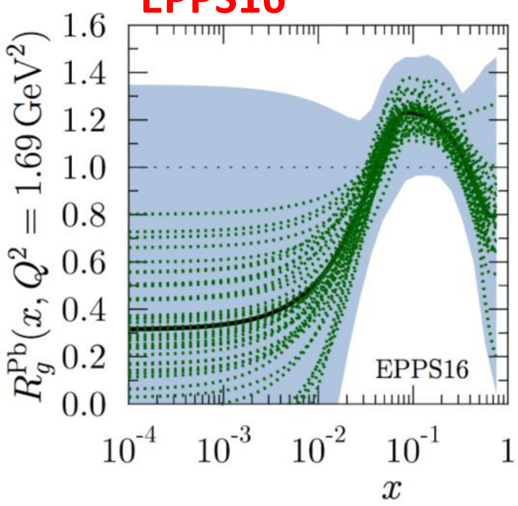
- Replacing EPS09. Quark flavors are now separated
- includes latest LHC data
- **EPPS16*→ functional form** with less constraints (for gluons) in extrapolating for $x < x_{data}$
  ®critical to study the impact of the high precision EIC data!
- **What is the possible impact of an Electron-Ion Collider?**

Ratio: $g(x,Q^2)_{Pb}/g(x,Q^2)_p$

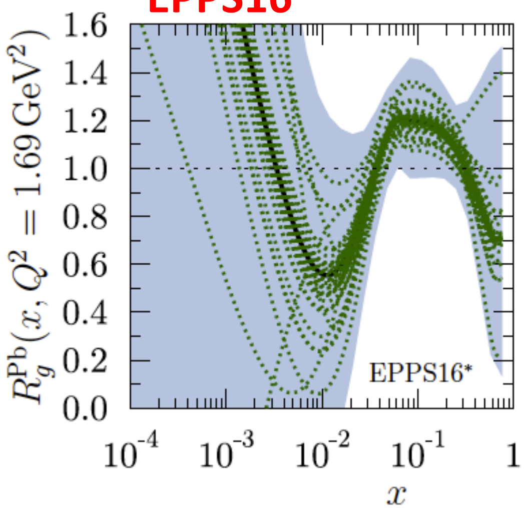
EPS09



EPPS16



EPPS16*



Reduced Cross Section & Structure Functions

$$\sigma_r = F_2\left(x,Q^2\right) - \frac{y^2}{1+(1-y)^2} F_L\left(x,Q^2\right) \qquad \frac{y^2}{1+(1-y)^2} = Y^+$$

- Structure functions can be extracted from the reduced cross section
- Pseudo-data are generated using **PYTHIA** and according to **EPS09** central values
- In order to extract F_2 from the reduced cross section, we adopted the same method used at HERA [e.g. see HERMES paper on arXiv:1103.5704]
- F_L extracted from the reduced cross section by fitting the slopes in Y^+ for different √s at fixed x, Q^2 → requires running at (at least) three different c-o-m energies

Simulation:

e+Au sample simulated using PYTHIA

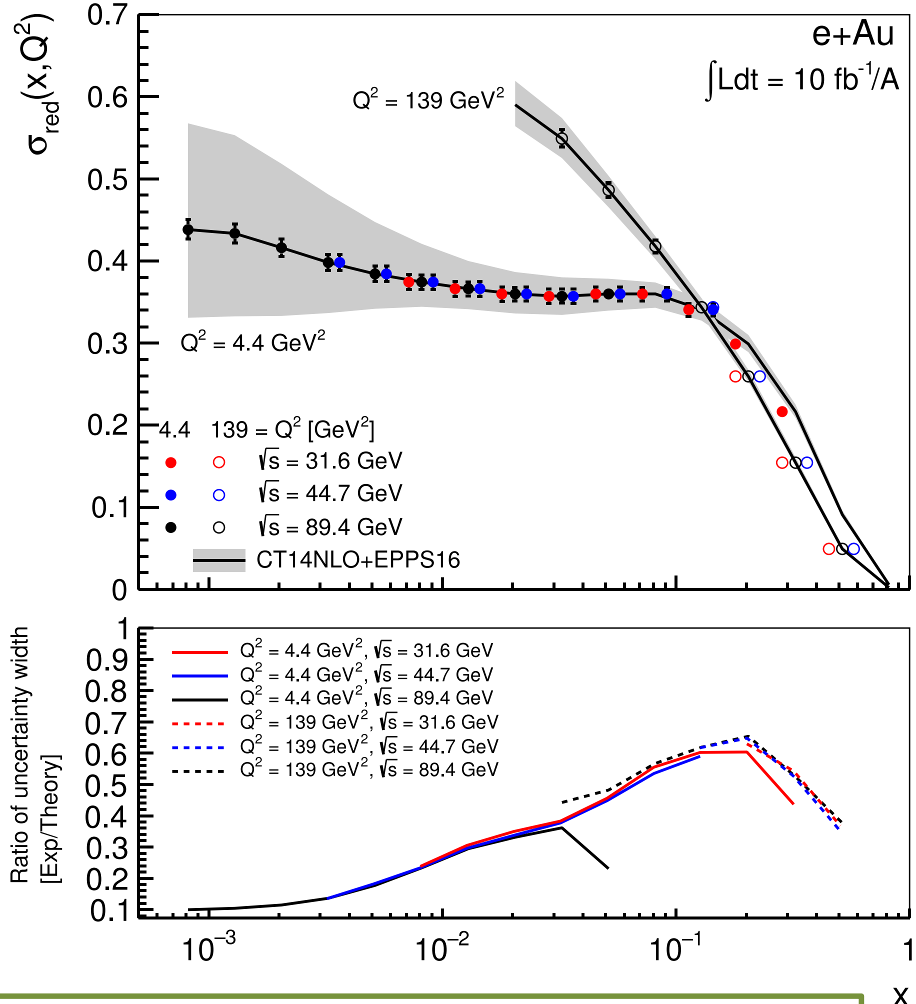
5(20) GeV electrons X 50 GeV Au [√s = 32(63) GeV] –> L = 2 fb^{-1}/A

5(20) GeV electrons X 75 GeV Au [√s = 39(78) GeV] –> L = 4 fb^{-1}/A

5(20) GeV electrons X 100 GeV Au[√s = 45(89) GeV] –>L = 4 fb^{-1}/A

Total simulated event sample (for each electron energy) **L = 10 fb^{-1}/A**

Reduced Cross Section & F_2 (e+Au)



$$s_r = F_2(x,Q^2) - \frac{y^2}{1+(1-y)^2} F_L(x,Q^2)$$

- **Systematics = 3%**
- Stat. and Sys. error summed in quadrature **(Sys. dominate!)**
- Gluon extraction via scaling violation → $d\sigma(x,Q^2)/d\ln Q^2$ (requires ~> 1 decade in Q^2 at a fixed x)
- Comparison of linear with non-linear evolution in x will signal saturation

®needs low-x reach

Large expected impact on current theory uncertainty, especially at low-x and low-Q^2

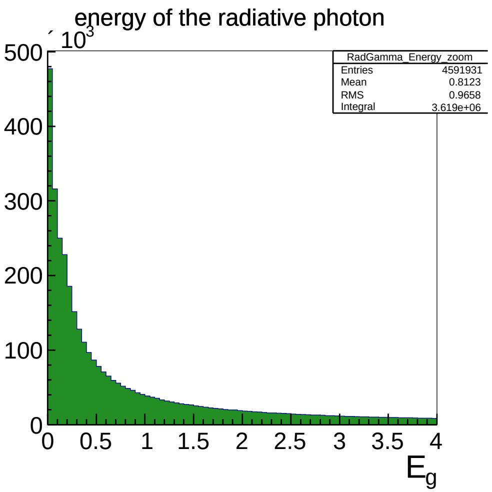
An EIC at its highest energy provides a factor 10 larger reach in Q^2 and low-x compared to available data

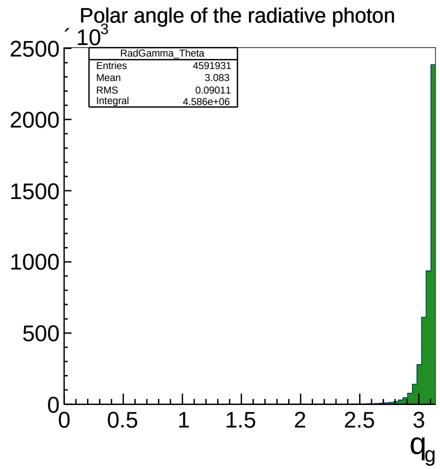
Radiated photons

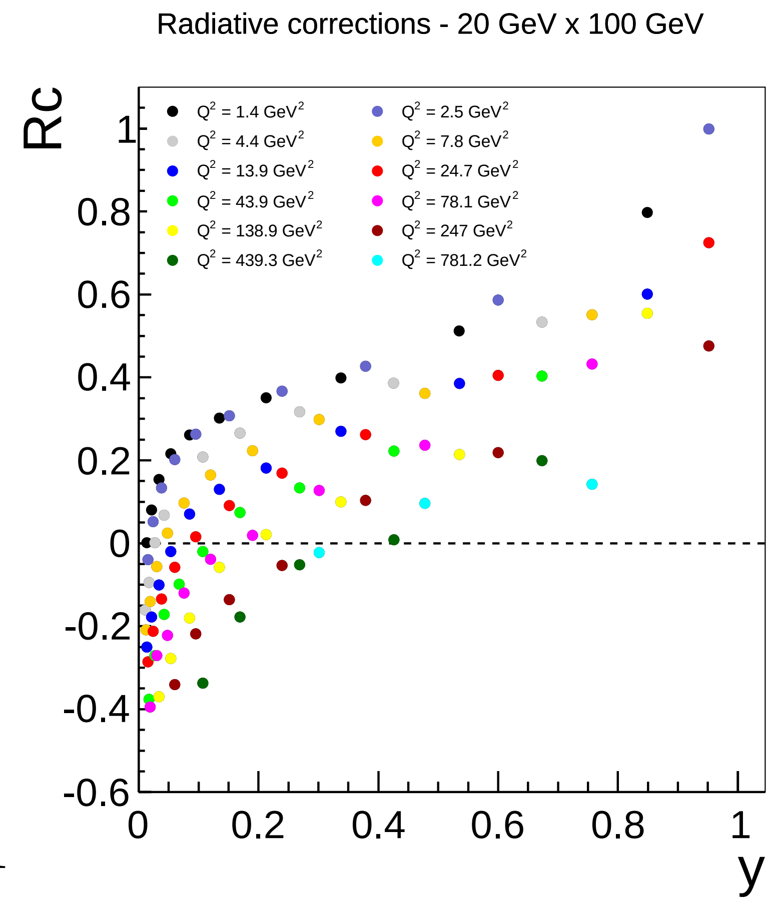
We use **Django simulator** including O(α) radiative effects

We look at photons radiated from the electron before or after the interaction

50% events radiate a photon







Radiated photons are

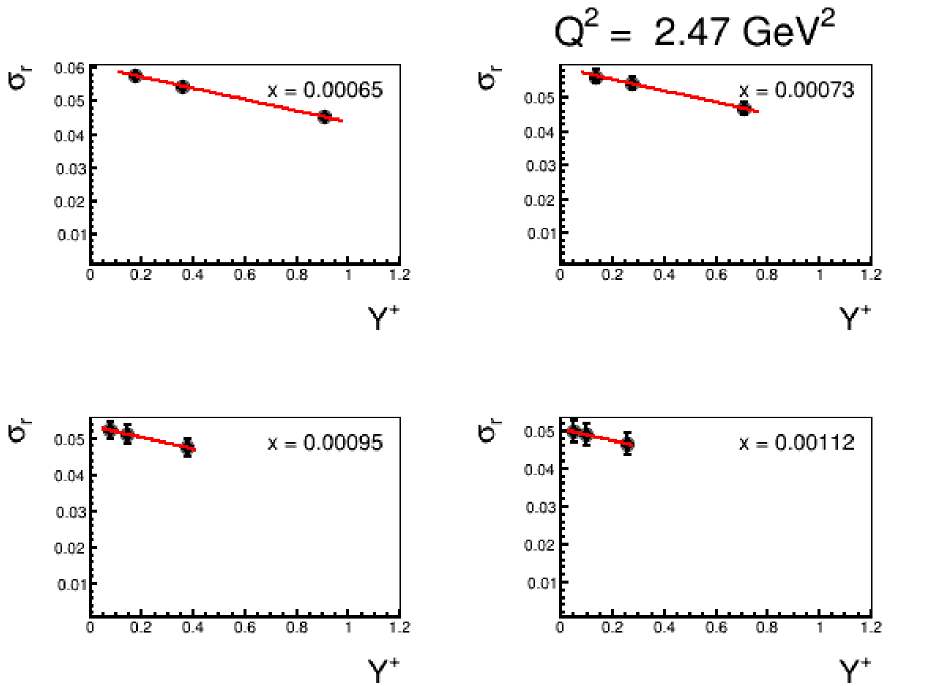
- Low energy (most of them < 1 GeV)
- uniformly distributed in the azimuthal angle
- collinear to the scattered electron ($\theta_\gamma > 3$ rad)

Correction factor:

$$Rc = \frac{\sigma_{red}(O(\alpha))}{\sigma_{red}(Born)} - 1$$

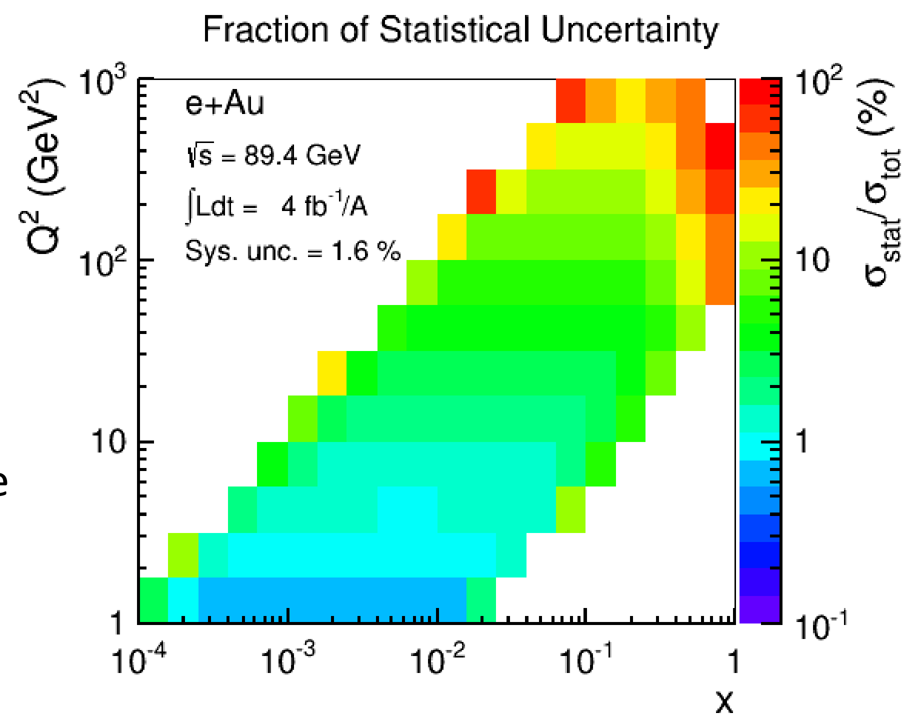
Extracting F_L (e+Au)

Higher energy EIC: √s = 63, 78, 89 GeV



Enough Lever Arm required (three points, $Y^+ > 0.2$)

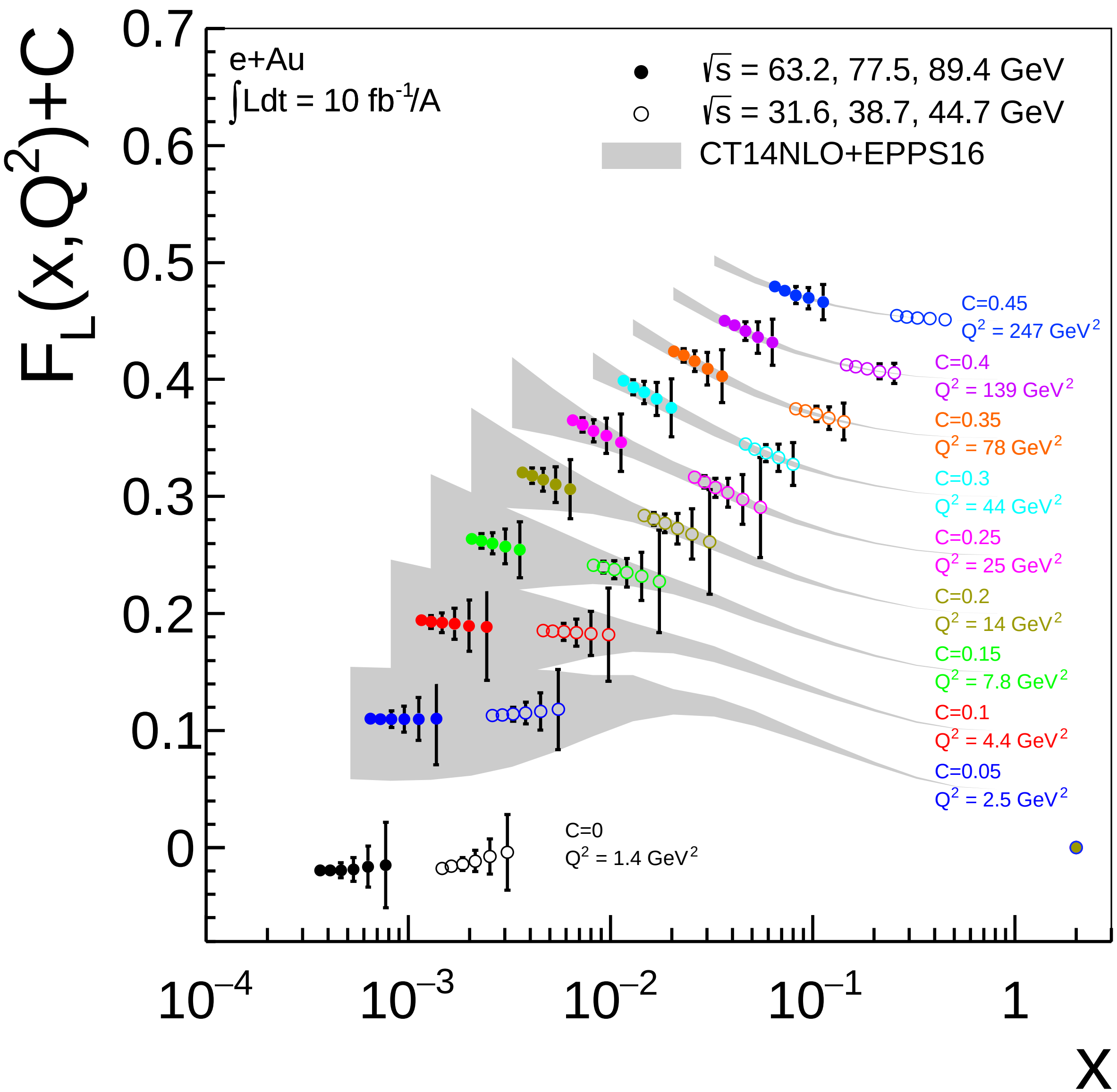
Errors still dominated by systematics



Fraction of statistical uncertainty over total uncertainty in measuring σ_r

- total error = stat. + sys. summed in quadrature
- assumed sys. = 3%
- Star error dominates only at large-x and very large Q^2

F_L (e+Au)

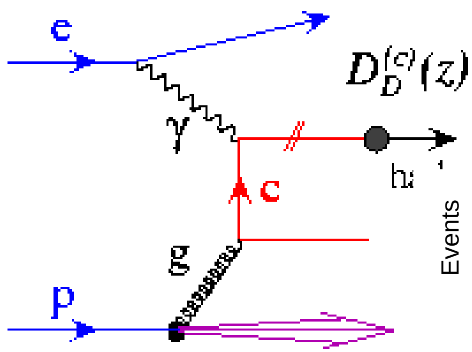


Errors dominated by the systematics in the cross section measurement

→Not luminosity hungry!

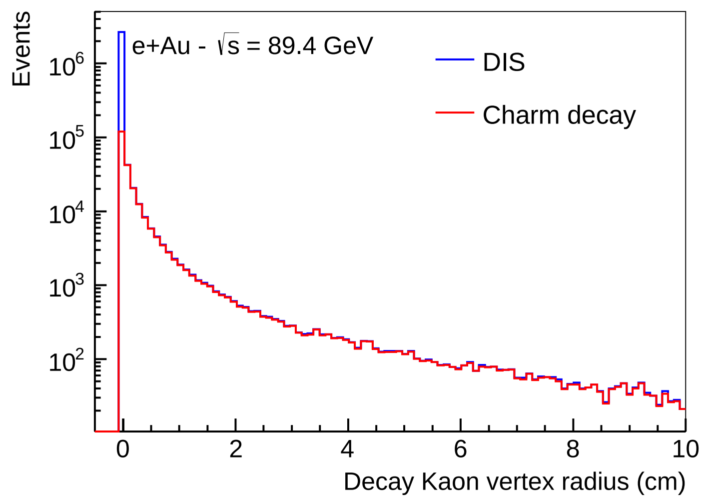
Study: 10 fb^{-1} →100 fb^{-1} has negligible impact (see backup slide)

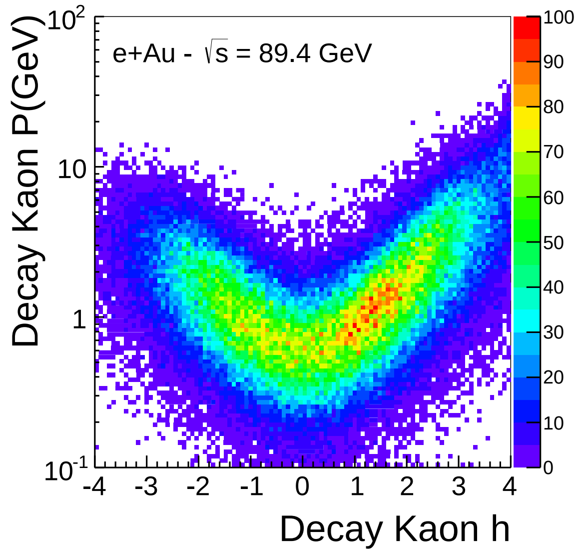
Charm production: a unique tool!



- Direct access to gluons at medium to high *x* by tagging photon-gluon
- Helps determining heavy quarks mass scheme

Novel probe!





Selection of charm-production events

We select **kaons** in the final state of the ***D*** meson decay, looking for:

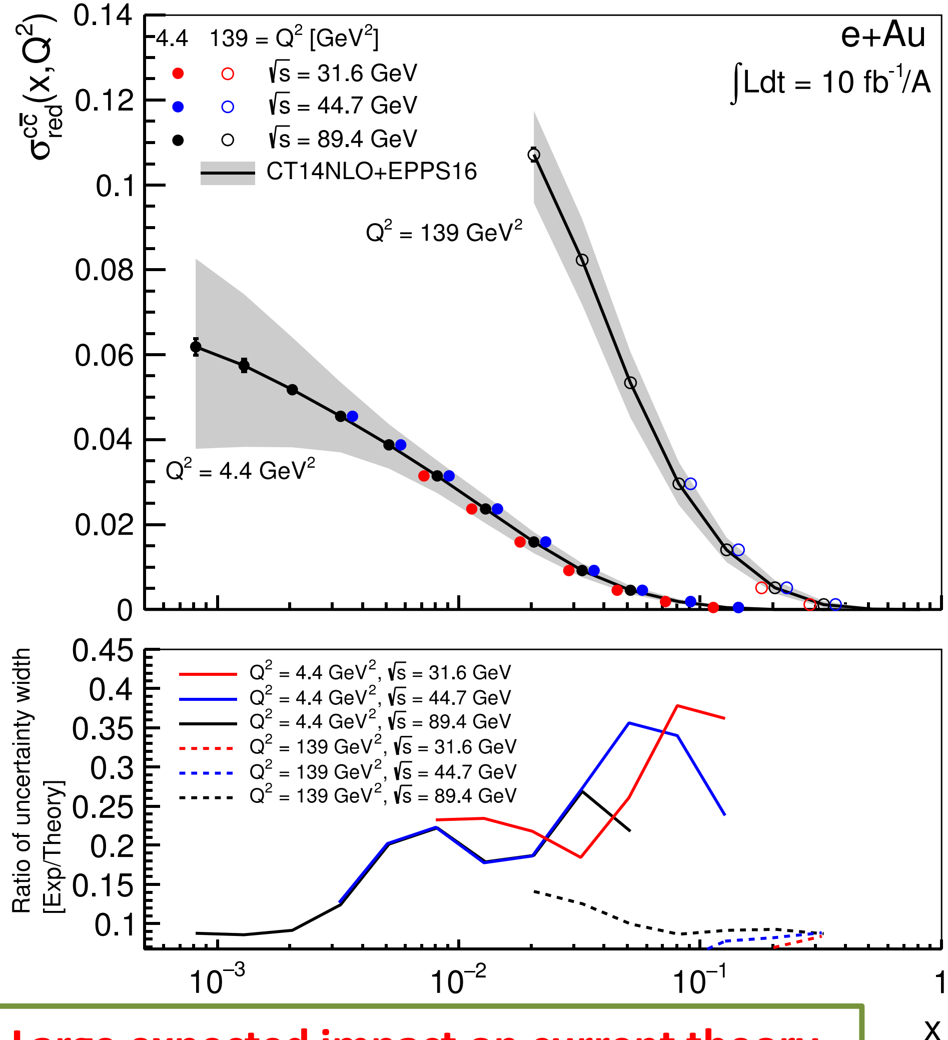
- a displaced vertex: 0.01 cm <|Vertex|< 3 cm
- Momentum within the acceptance of an EIC model detector (BeAST @ eRHIC)

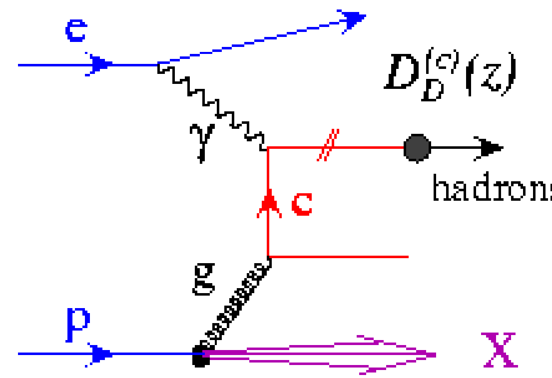
CENTRAL DETECTOR (-1 < η < 1)
dE/dx -> 0.2 GeV < P < 0.8 GeV
RICH -> 2 GeV < P < 5 GeV

FORWARD (1 < η < 3.5)
RICH -> 2 GeV < P < 40 GeV

REAR (-3.5 < η < -1)
RICH -> 2 GeV < P < 15 GeV

Charm - reduced Cross Section & F_2 (e+Au)





- Systematics = 7%
- Stat. and Sys. error summed in quadrature **(Sys. dominate!)**
- No world data exist!

Sources of Uncertainty	Value in σ_r (%)	Value in $\sigma_r^{c\bar{c}}$ (%)
Luminosity	1.4	1.4
Electron id. and eff.	1.6	1.6
RICH and dE/dx PID	0	3
Vertex finding	0	1

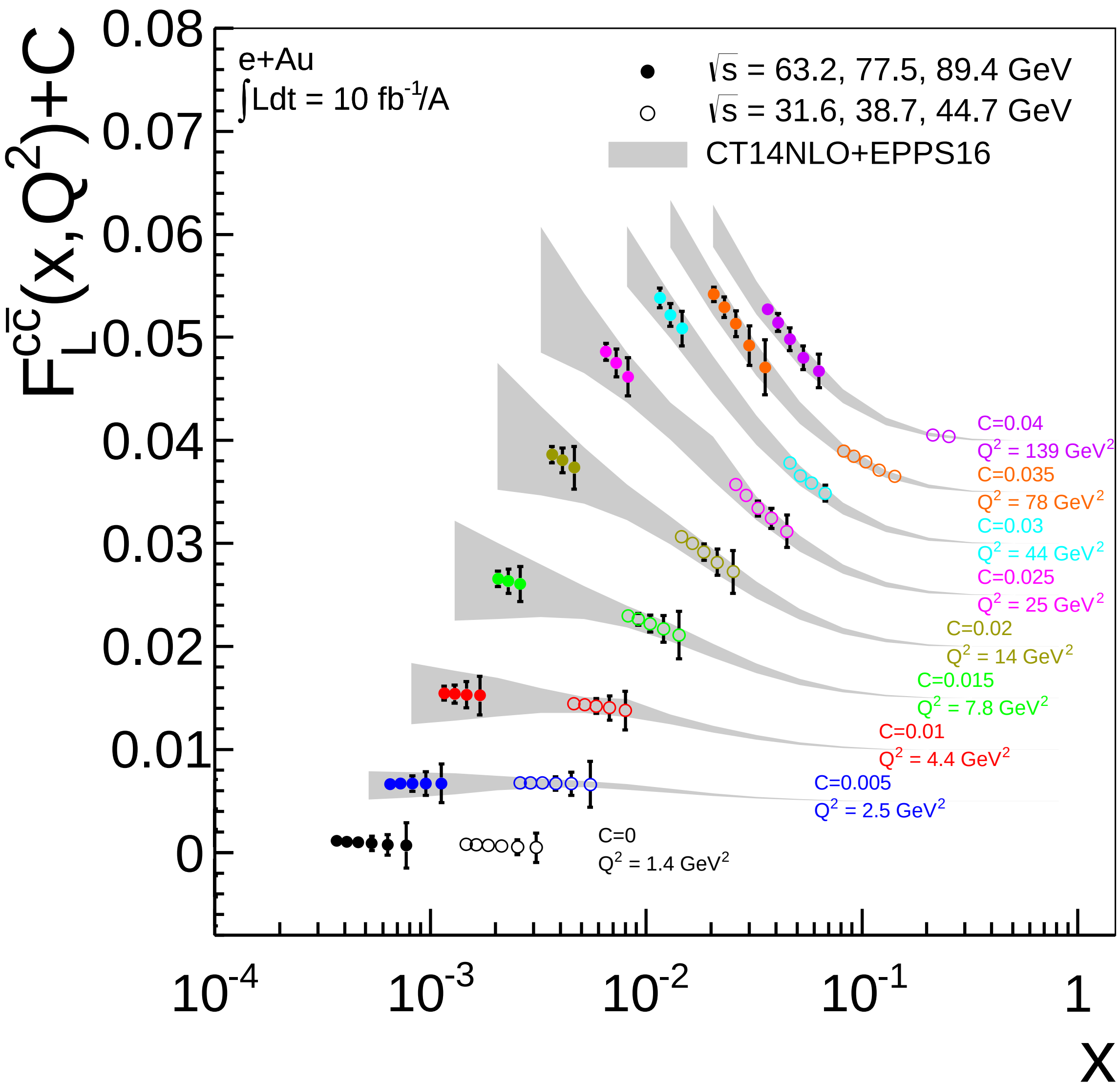
Large expected impact on current theory uncertainty, especially at low-x and low-Q²

Large expected impact on current theory uncertainty, in the whole x range

$Q^2(GeV^2)$

Charm - F_L (e+Au)

Enough Lever Arm required (three points, y+ > 0.2)



Errors dominated by the systematics in the cross section measurement

→Not luminosity hungry!

Study: 10 fb⁻¹ →100 fb⁻¹ has negligible impact (see backup slide)

→High energy EIC: huge impact on current predictions

Charm selection: background & efficiency

Background study

We look at background from DIS events with kaons that pass the whole selection but are not coming from a charm decay.

The fraction of background over signal events is:

(selected bkg events) / (selected Charm Events)

Conclusion:

The B/S fraction is expected in the order of ~1% with a very light energy dependence

Efficiency study

We look at the efficiency of selection charm production events. The efficiency is defined as:

(selected Charm Events) / (charm Events in Acceptance)

Conclusion:

The charm selection efficiency is expected in the order of ~28% with no significant energy dependence

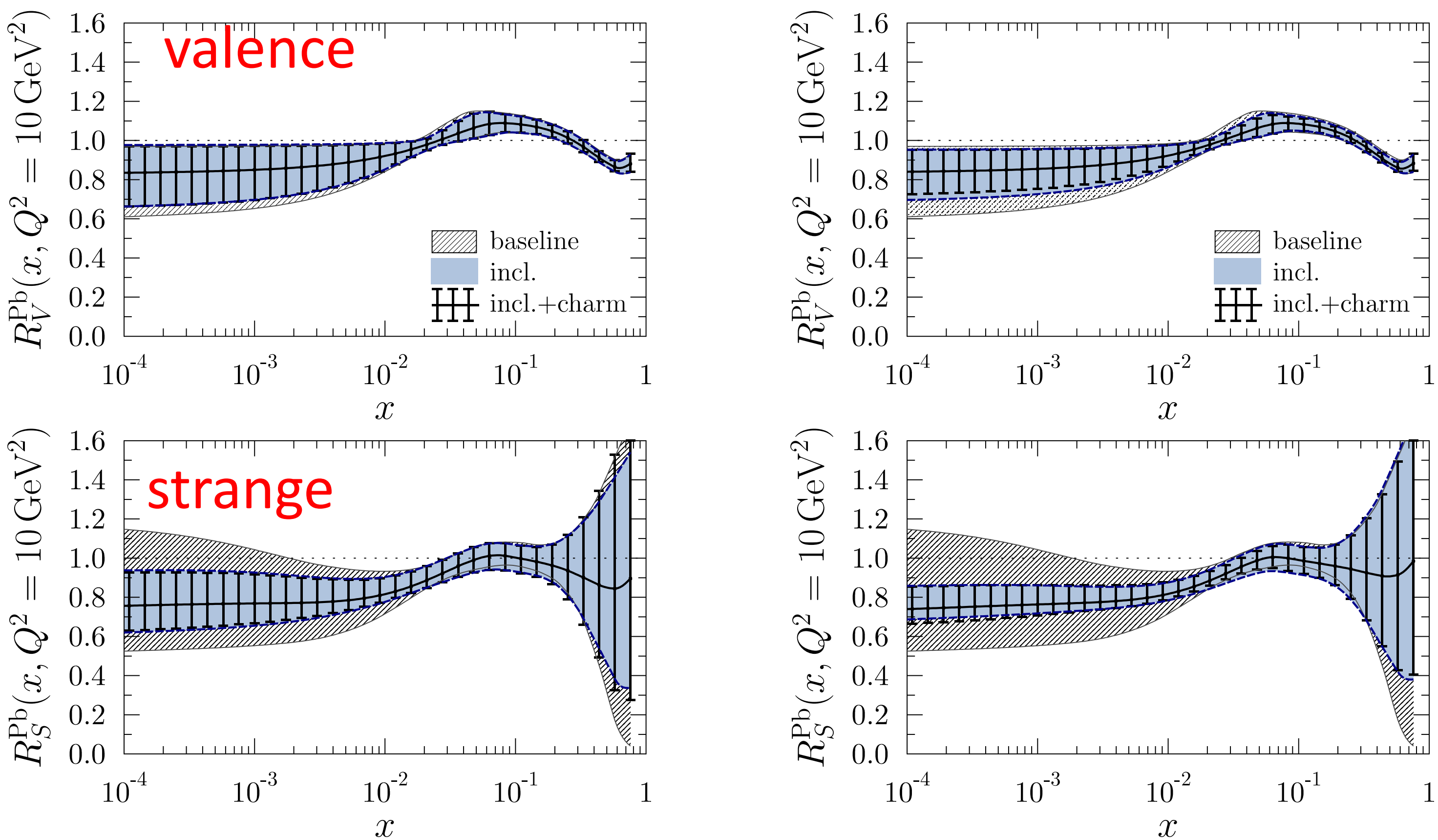
The EIC impact

Fits to the EIC simulated data

EPPS16* → EPPS16 using a flexible function with a couple of extra free parameters at small x for gluon (not for the quarks)

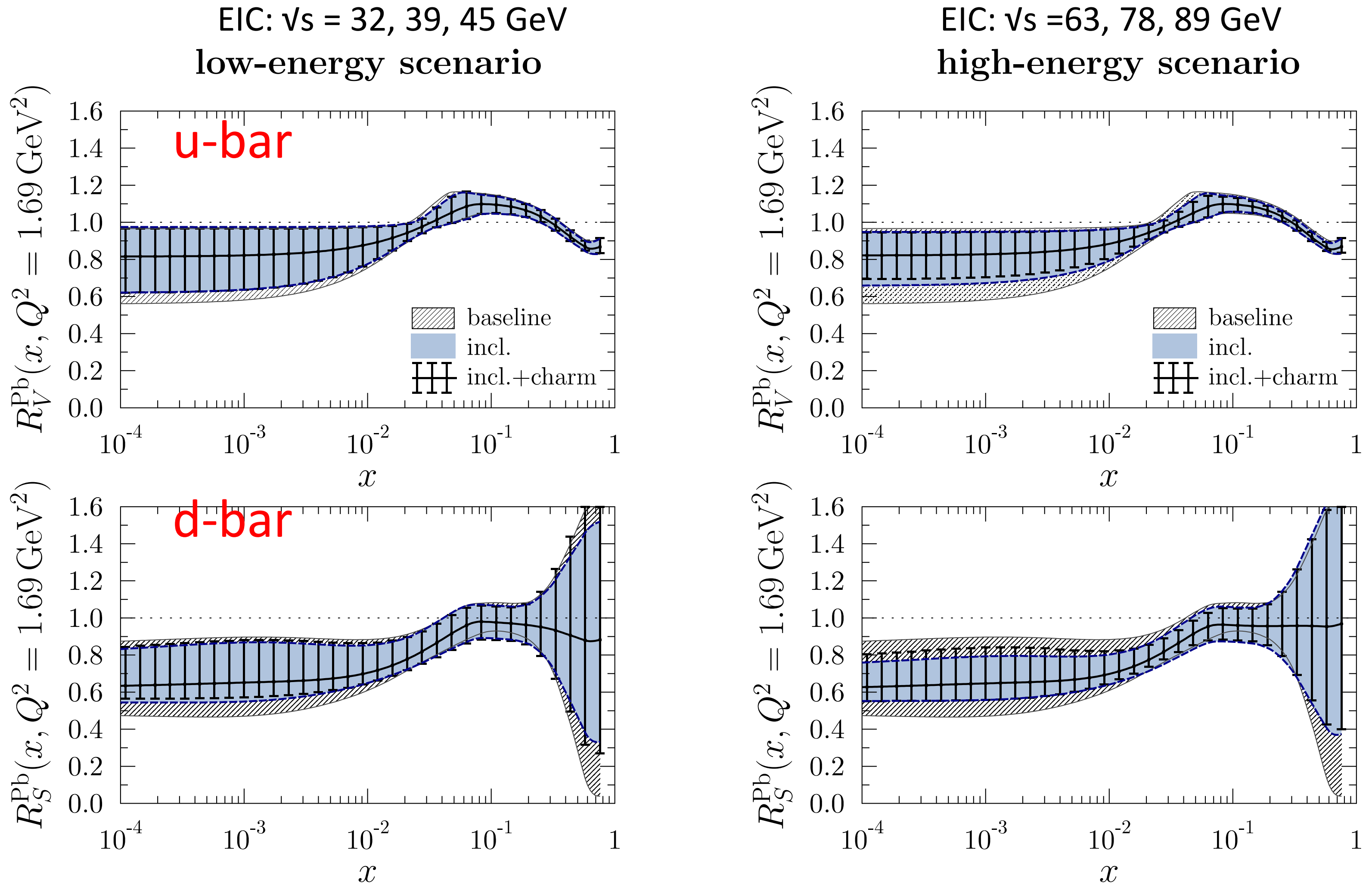
EIC: √s = 32, 39, 45 GeV — **low-energy scenario**

EIC: √s =63, 78, 89 GeV — **high-energy scenario**

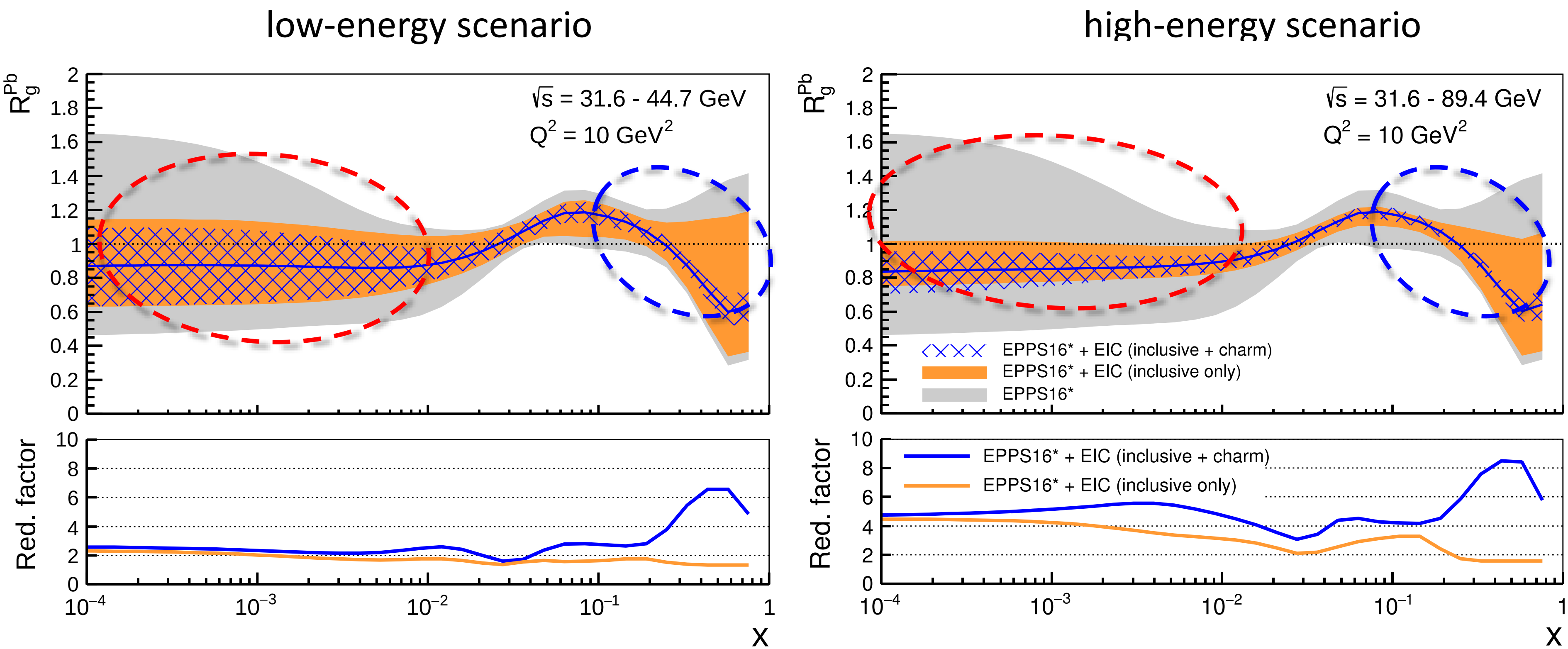


The EIC impact – sea quarks

Fits to the EIC simulated data



The EIC impact – gluons

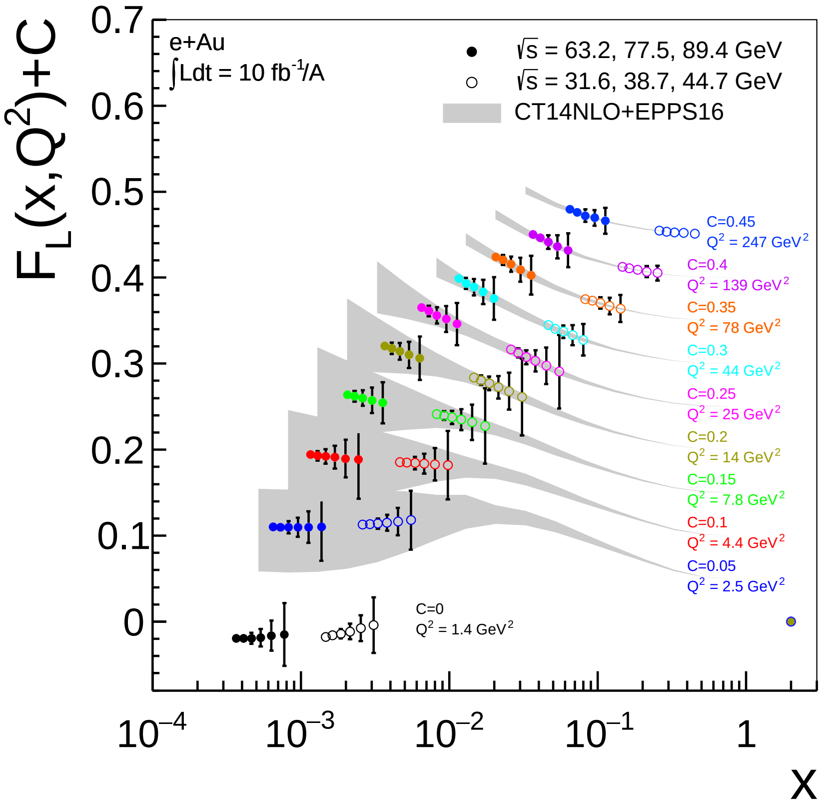


Inclusive DIS alone has a huge effect at low-*x*

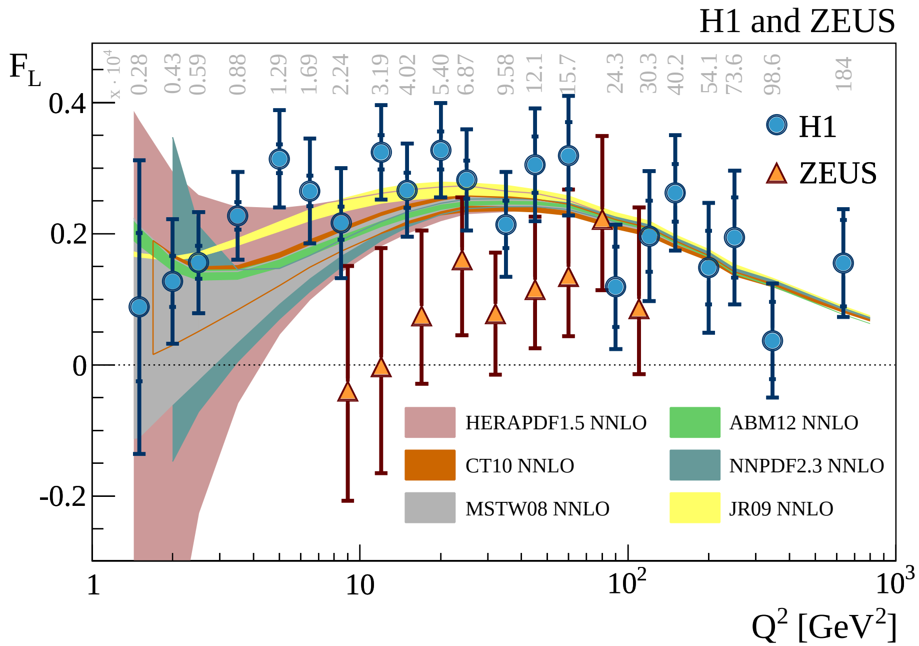
Charm has a dramatic effect at high-*x*

Proton SFs

e+Au F_L - EIC



Proton F_L - HERA



Not only for nuclei!

Comparable precision for proton Structure Functions in e+p scattering, to even higher Q^2 at high x

→ Beyond what HERA achieved: precise measurement of proton F_L

Proton PDFs

Therefore EIC can have large impact on proton PDFs too!

- ✓ **e+Deutrium data** are sensitive to u/d quark flavor separation (need to correct for nuclear modifications)
- ✓ **Electroweak data** allow to constrain s quark PDFs as well as **SIDIS +FF**

Conclusions

e+A physics program at a future Electron-Ion Collider provides an unprecedented opportunity to study quarks and gluons in nuclei

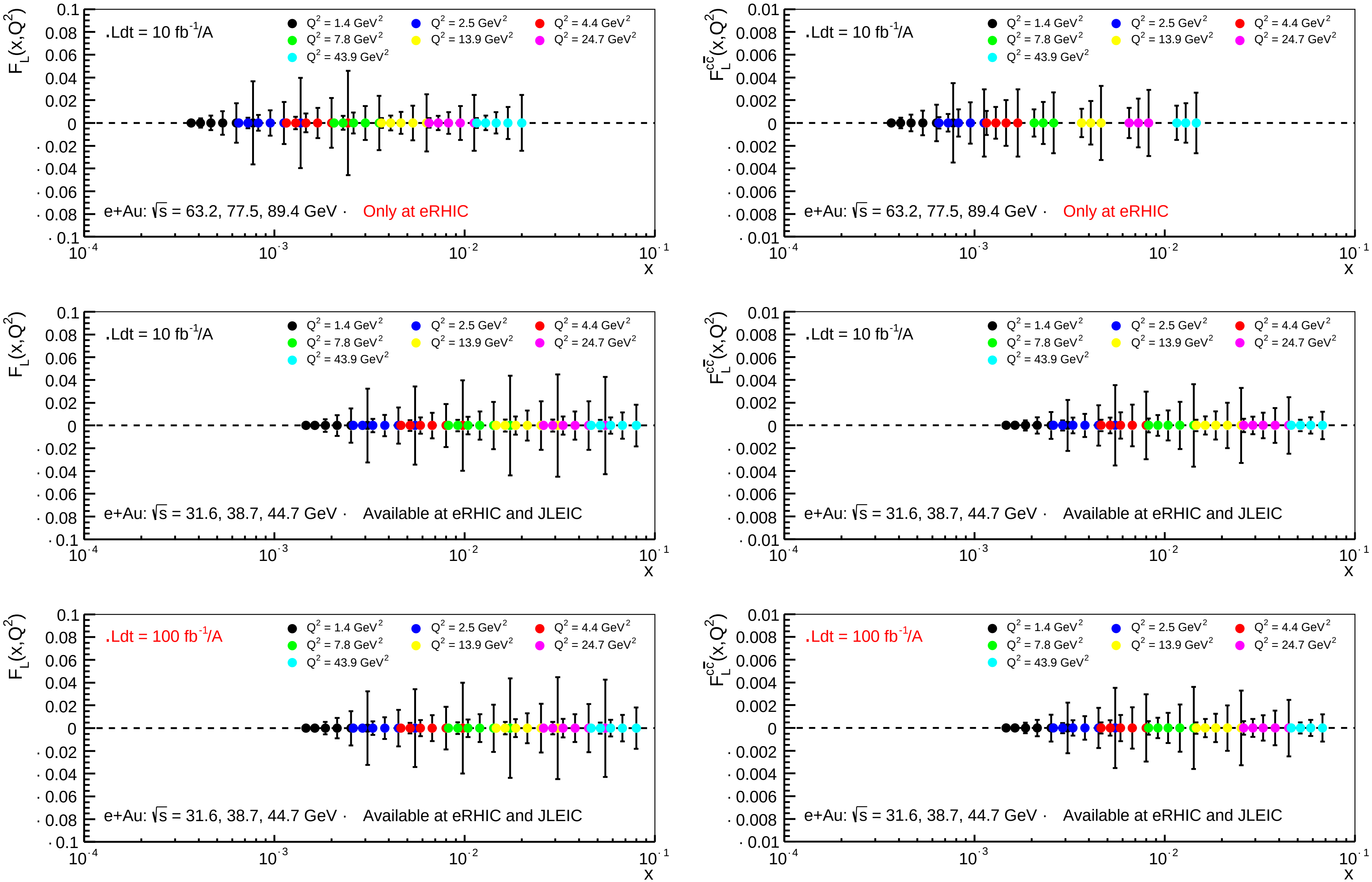
- Precise measurements of nuclear structure functions in a large phase-space
- Constrain gluon nPDFs at large-*x* by tagging photon-gluon fusion through precise measurements of charm production
- Large impact in constraining gluon nPDFs at low-*x*
- Same or better precision expected for proton SFs too, Plus constraining large x gluons and separate u/d/s flavors

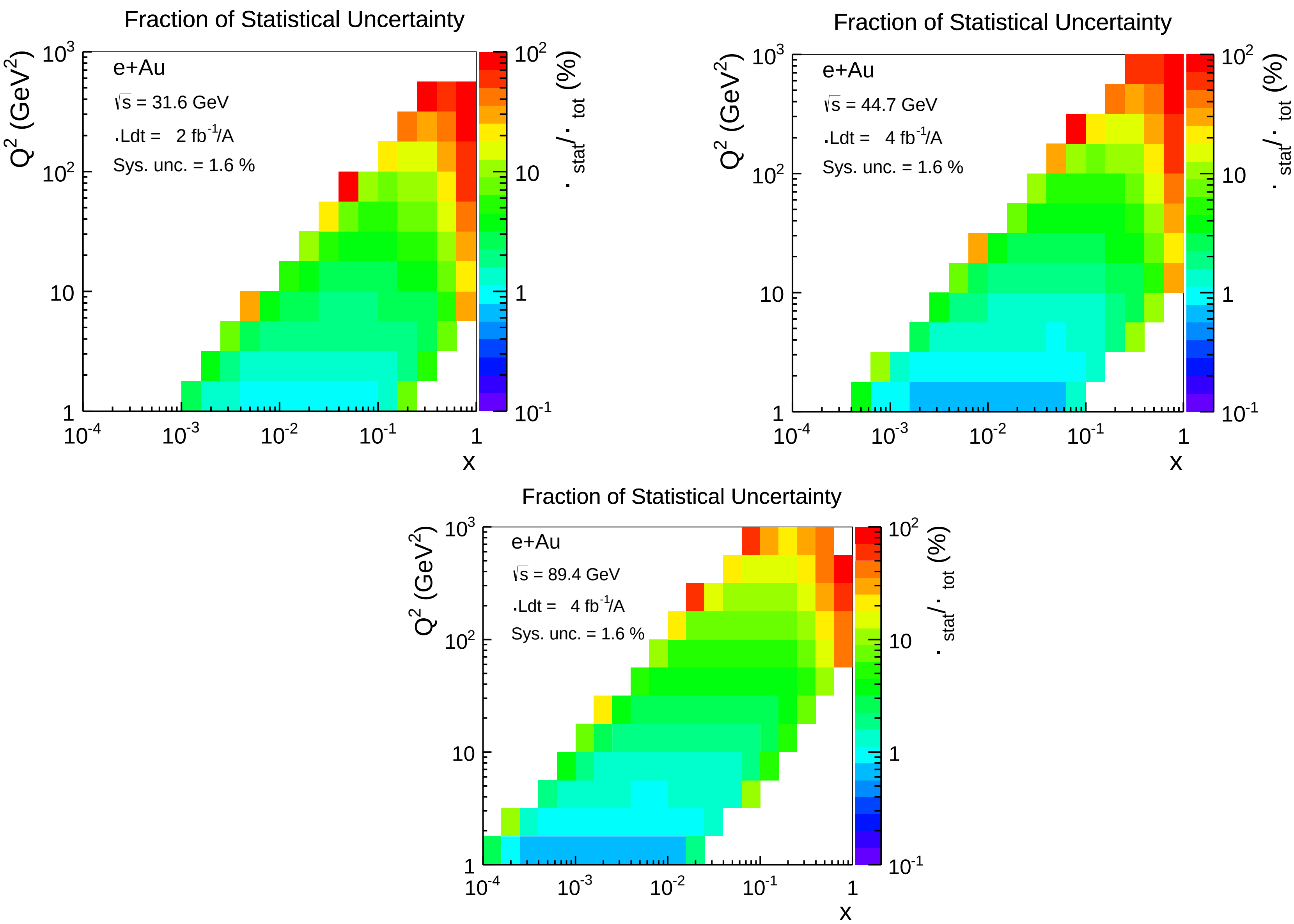
This is day 1 high impact physics!

Recent publication:

E.C. Aschenauer, S. F., M.A.C. Lamont, H. Paukkunen, P. Zurita
[arXiv:1708.05654]


BACKUP

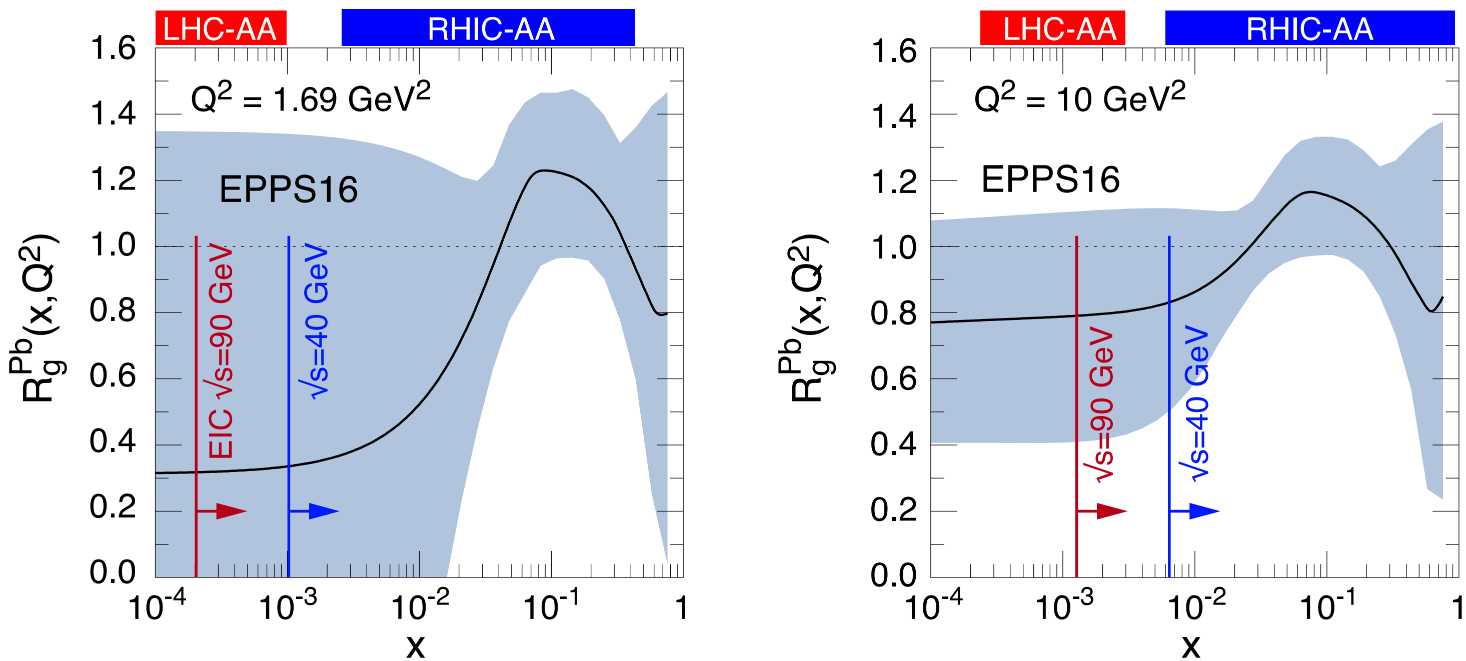

F_L(x,Q^2)
F_L^cc̄(x,Q^2)
.Ldt = 10 fb-1/A
.Ldt = 100 fb-1/A
Q2 = 1.4 GeV2
Q2 = 2.5 GeV2
Q2 = 4.4 GeV2
Q2 = 7.8 GeV2
Q2 = 13.9 GeV2
Q2 = 24.7 GeV2
Q2 = 43.9 GeV2
e+Au: √s = 63.2, 77.5, 89.4 GeV
Only at eRHIC
e+Au: √s = 31.6, 38.7, 44.7 GeV
Available at eRHIC and JLEIC
x


Fraction of Statistical Uncertainty
e+Au
√s = 31.6 GeV
∫Ldt = 2 fb⁻¹/A
Sys. unc. = 1.6 %
Fraction of Statistical Uncertainty
e+Au
√s = 44.7 GeV
∫Ldt = 4 fb⁻¹/A
Sys. unc. = 1.6 %
Fraction of Statistical Uncertainty
e+Au
√s = 89.4 GeV
∫Ldt = 4 fb⁻¹/A
Sys. unc. = 1.6 %
Q² (GeV²)
x
σ_stat/σ_tot (%)

Impact from and on p+A and A+A physics

- nPDFs required as input to physics in A+A
- p+A @ LHC has so far only moderate impact (see arXiv:1612.05741) on constraining nPDFs

LHC/RHIC x coverage at rapidity |y|<1



Higher energy configurations of an EIC

constrain nPDFs in an x-range critical for the A+A program at the LHC