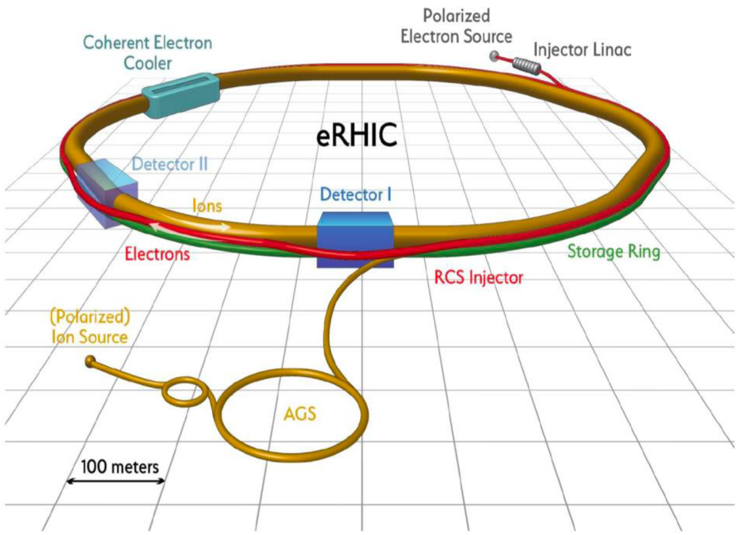
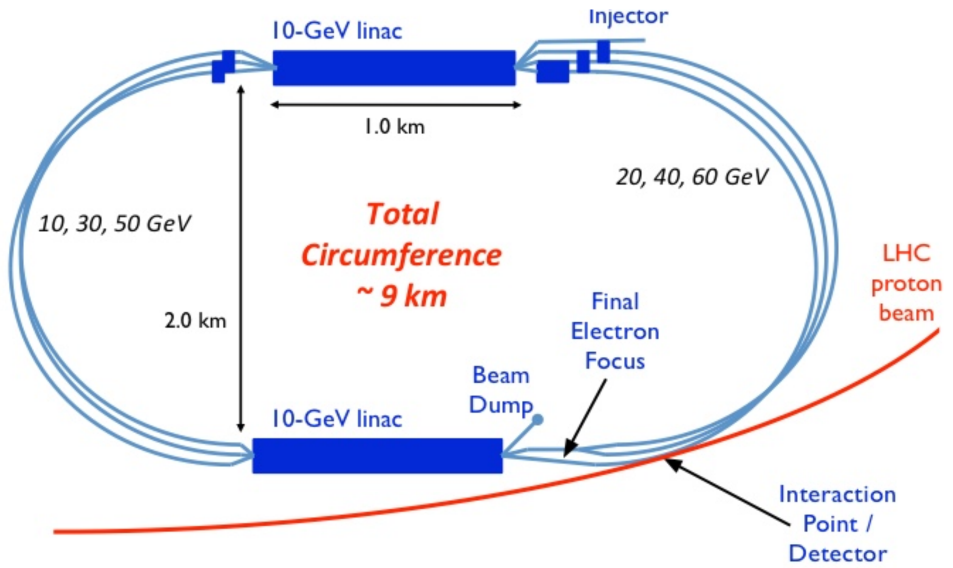
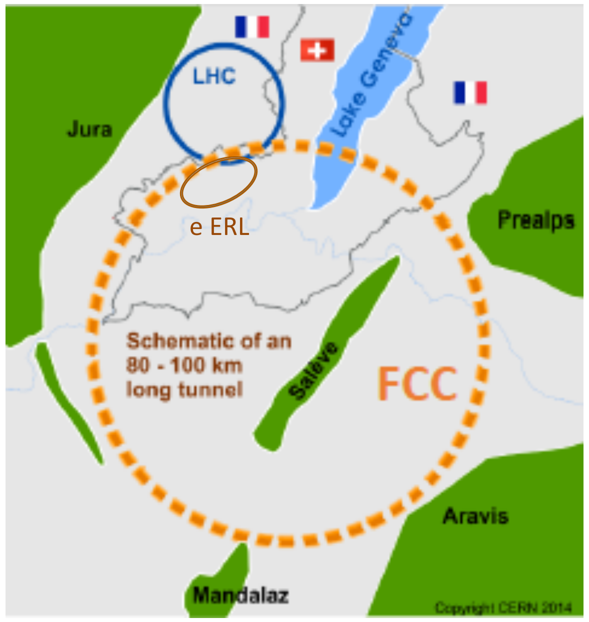






Physics possibilities at future DIS facilities

Anna Staśto

Penn State University

LXI Cracow School of Theoretical Physics, 22.09.2021

Legacy of HERA ep collider

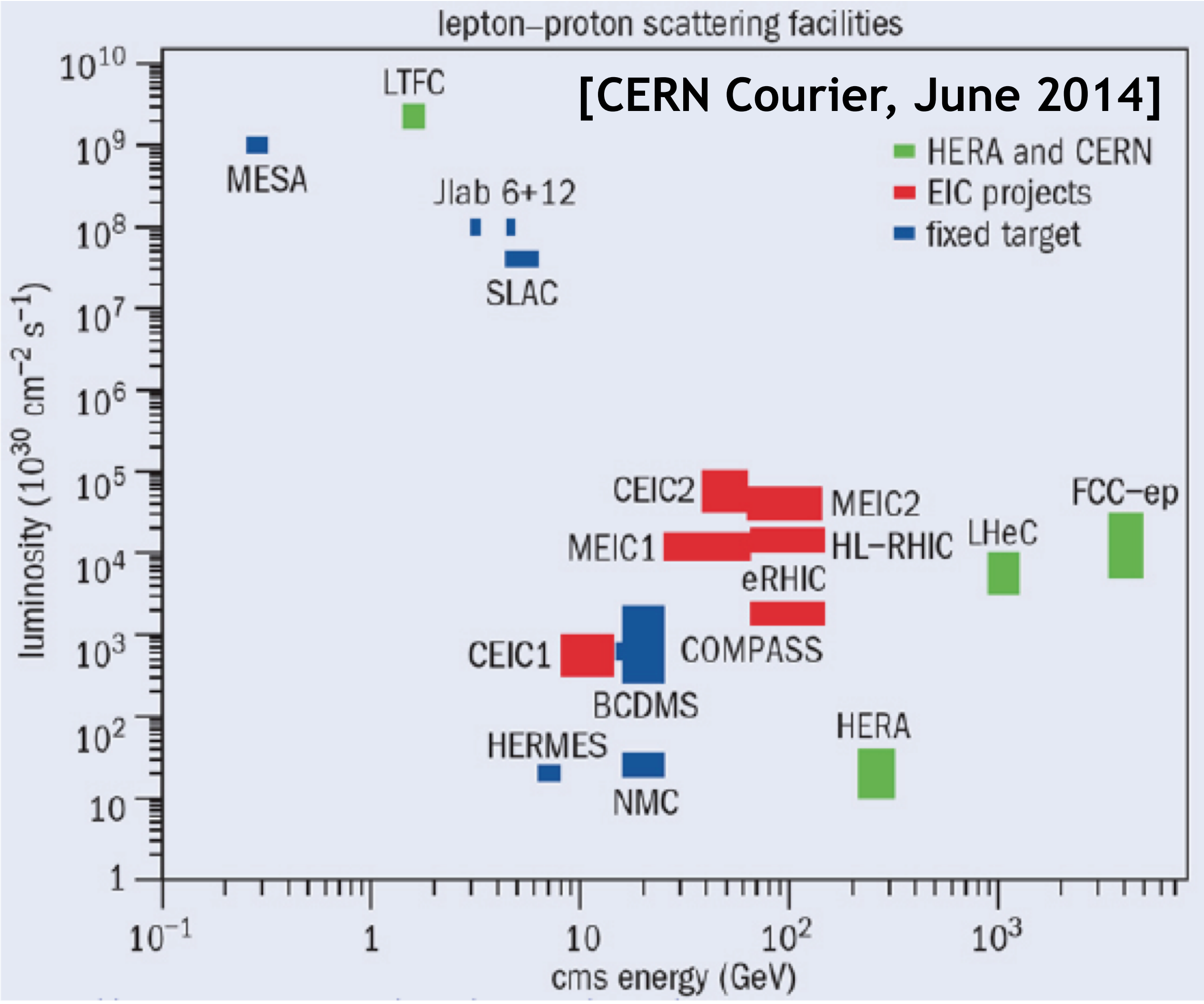
HERA: (1992-2007)
27.5 GeV electrons/positrons
820/920 GeV protons
318 GeV CoM energy
Lumi: 10^{31} cm^{-2} s^{-1}
Electrons, positrons and protons

Physics:
Structure functions
Parton density functions
Established growth of gluon with decreasing Bjorken x
Measurement of coupling constant
Diffraction
Jets, heavy quarks
BSM searches

Future high energy DIS ep collider projects

“Limitations” of HERA

- → **Luminosity 1-4•10^{31} cm^{-2} s^{-1}**
- → **No eA collisions**
- → **No polarised protons**



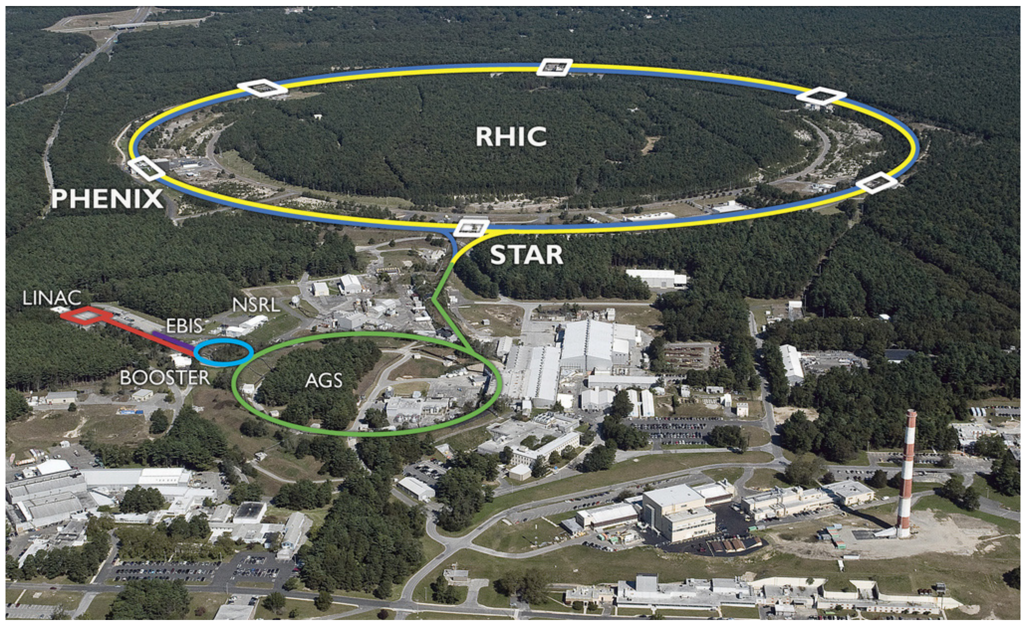
EIC: 5-20 GeV electrons
20-140 GeV CoM energy
Lumi: 10^{34} cm^{-2} s^{-1}
Polarized e,p,d,3He
Wide range of nuclei

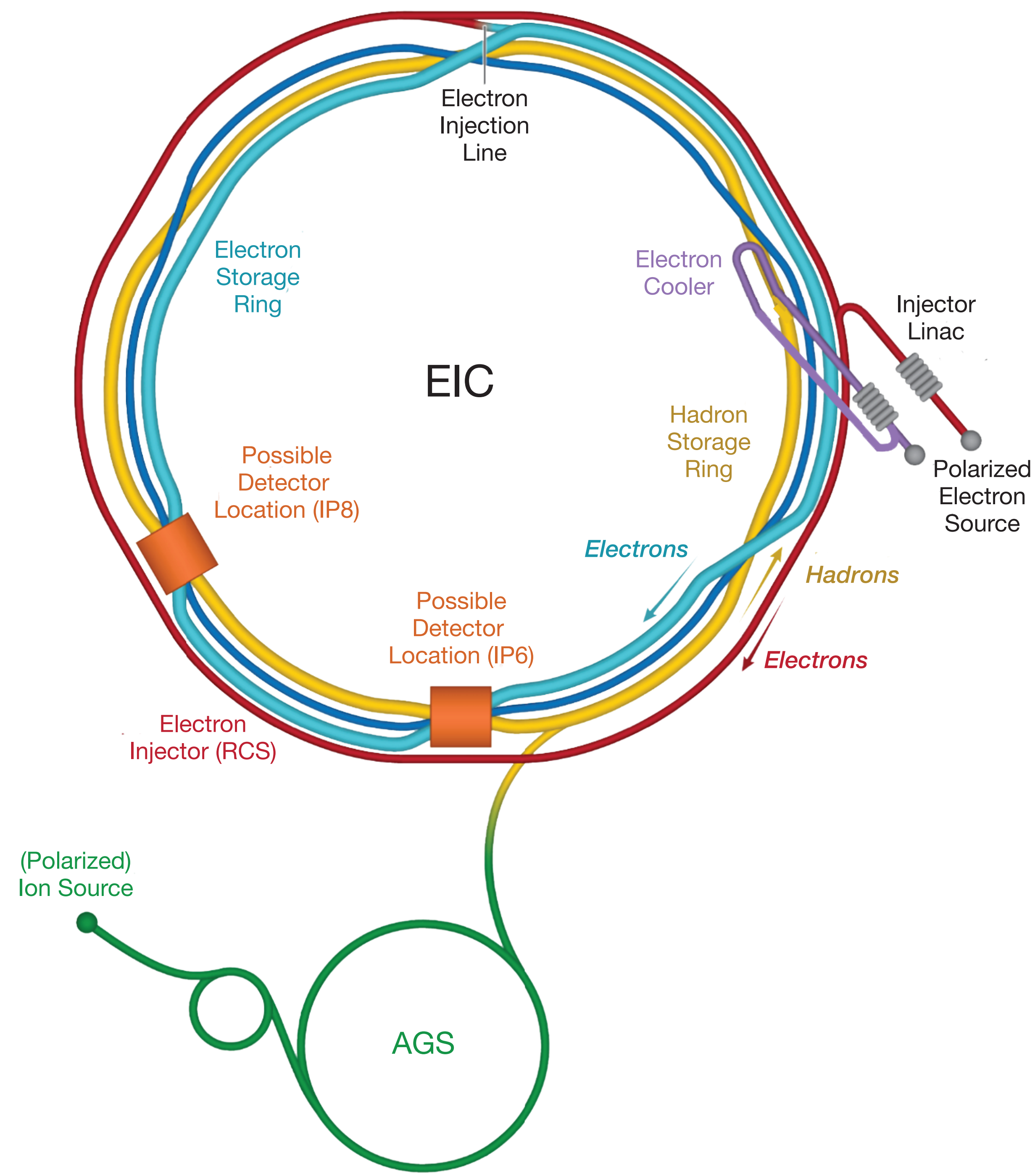
LHeC: 60 GeV electrons x LHC protons and ions
1.3 TeV ep, 812 GeV eA CoM
Lumi: 10^{34} cm^{-2} s^{-1}
Simultaneous running with ATLAS and CMS in HL-LHC period

FCC-ep: 60 GeV electrons x 50 TeV protons from FCC, lead beams 19.7 TeV/per nucleon
3.5 TeV ep, 2.2 TeV eA CoM
Lumi: 10^{34} cm^{-2} s^{-1}

Electron Ion Collider concept

Use existing RHIC complex at Brookhaven National Laboratory (with minimal upgrades) for hadron beams and add the electron complex.





At EIC:

Highly polarized (70%) electron and nucleon beams

Ion beams from deuterons to the heaviest nuclei (gold, lead or uranium)

Variable center of mass energies 20 -140 GeV

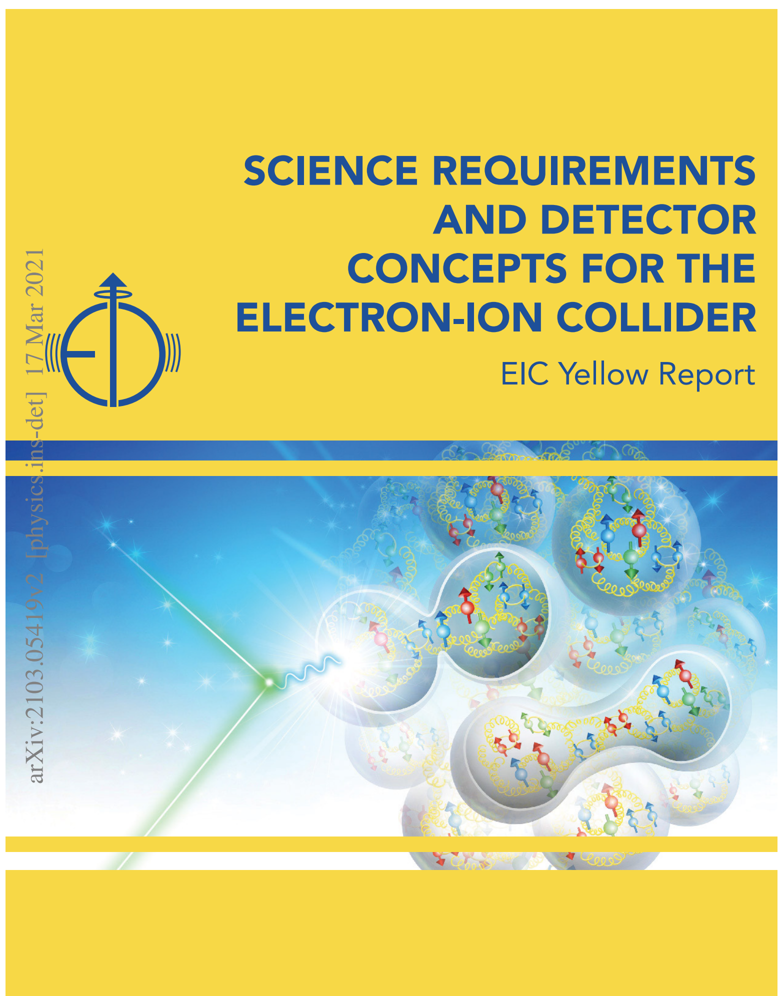
High luminosity 10^{33} - 10^{34} $cm^{-2}s^{-1}$

Possibility of more than one interaction region

EIC Yellow Report 2021

From the Yellow Report Chapter 1:

The purpose of the Yellow Report Initiative is to advance the state and detail of the documented physics studies (White Paper, Institute for Nuclear Theory program proceedings) and detector concepts (Detector and R&D Handbook) in preparation for the realization of the EIC. The effort aims to provide the basis for further development of concepts for experimental equipment best suited for science needs, including complementarity of two detectors towards future Technical Design Reports.



Yellow Report arXiv:2103.05419

One year effort

4 workshops, 902 pages, 415 authors, 151 institutions

Organisation

Physics Working Group
- Inclusive Reactions
- Semi-Inclusive Reactions
- Jets & Heavy Quarks
- Exclusive Reactions
- Diffraction & Tagging

Detector Working Group
- Tracking
- Particle ID
- Calorimetry (EM + Hadronic)
- Far-forward detectors
- DAQ/Electronics
- Central Detector/Integration & Magnet
- Forward Detector/IR integration
- Polarimetry/Ancillary Detectors
- Detector Complementarity

Physics Questions to be explored at EIC

How do the nucleonic properties such as mass and spin emerge from partons and their underlying interactions?

How do the confined hadronic states emerge from these quarks and gluons?

How are partons inside the nucleon distributed in both momentum and position space?

How do the quark-gluon interactions create nuclear binding?

How do color-charged quarks and gluons, and jets, interact with a nuclear medium?

Do quarks/gluons saturate at high densities in nuclei ?

EIC Yellow Report 2021

EIC Yellow Report 2021

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- 2.2 Origin of Nucleon Spin
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- 2.4 Multi-Dimensional Imaging of the Nucleon
- 2.5 Imaging the Transverse Spatial Distributions of Partons
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Global structure of nuclei

EIC will be first ever eA collider

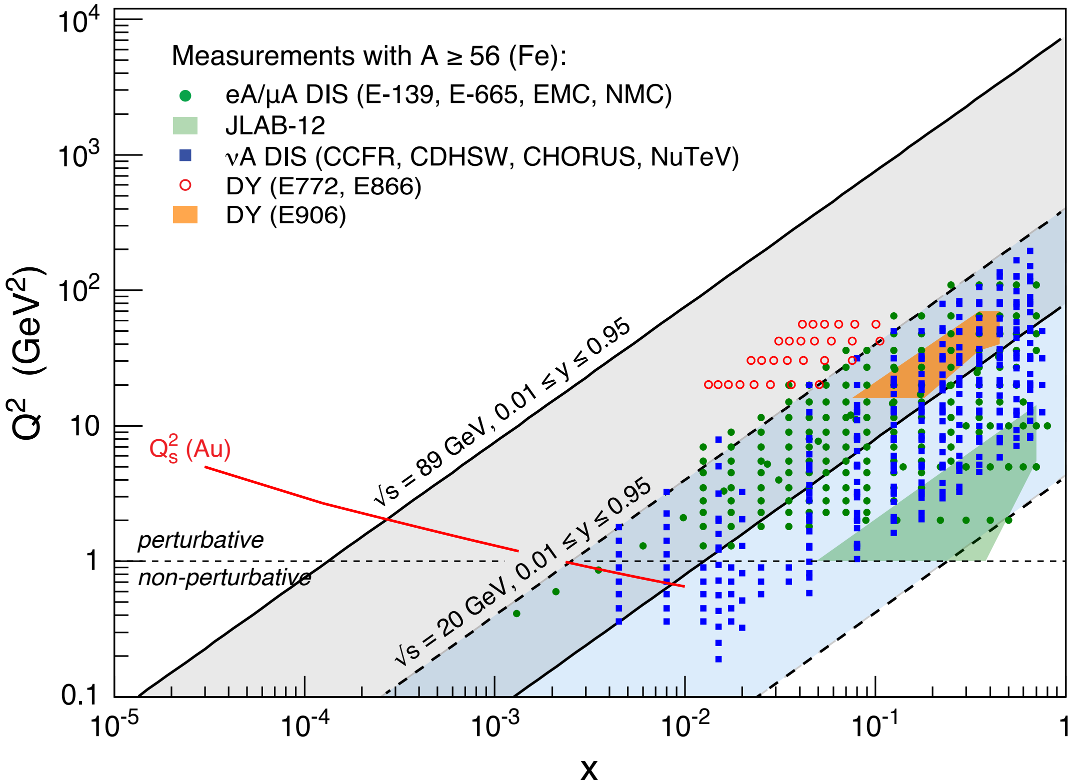
Precise measurement of nuclear structure functions for a range of nuclei

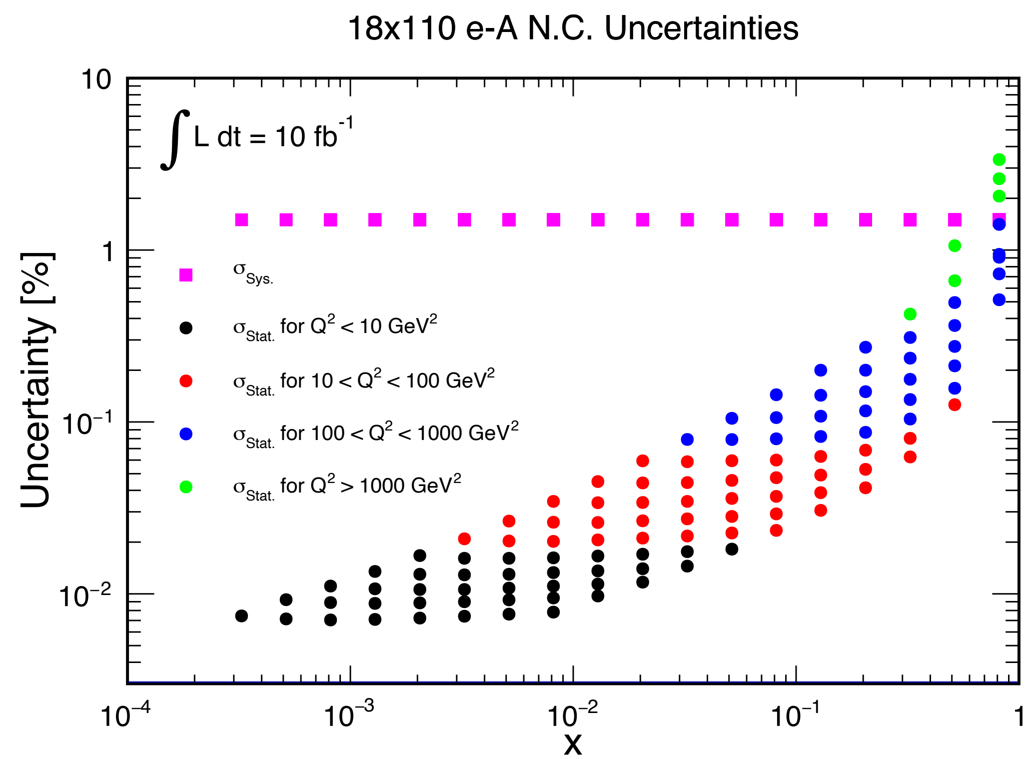
Extraction of nuclear PDFs which are essential for understanding nuclear structure

Initial conditions for Quark-Gluon Plasma. Disentangle initial and final state effects

Systematic uncertainties at most few %

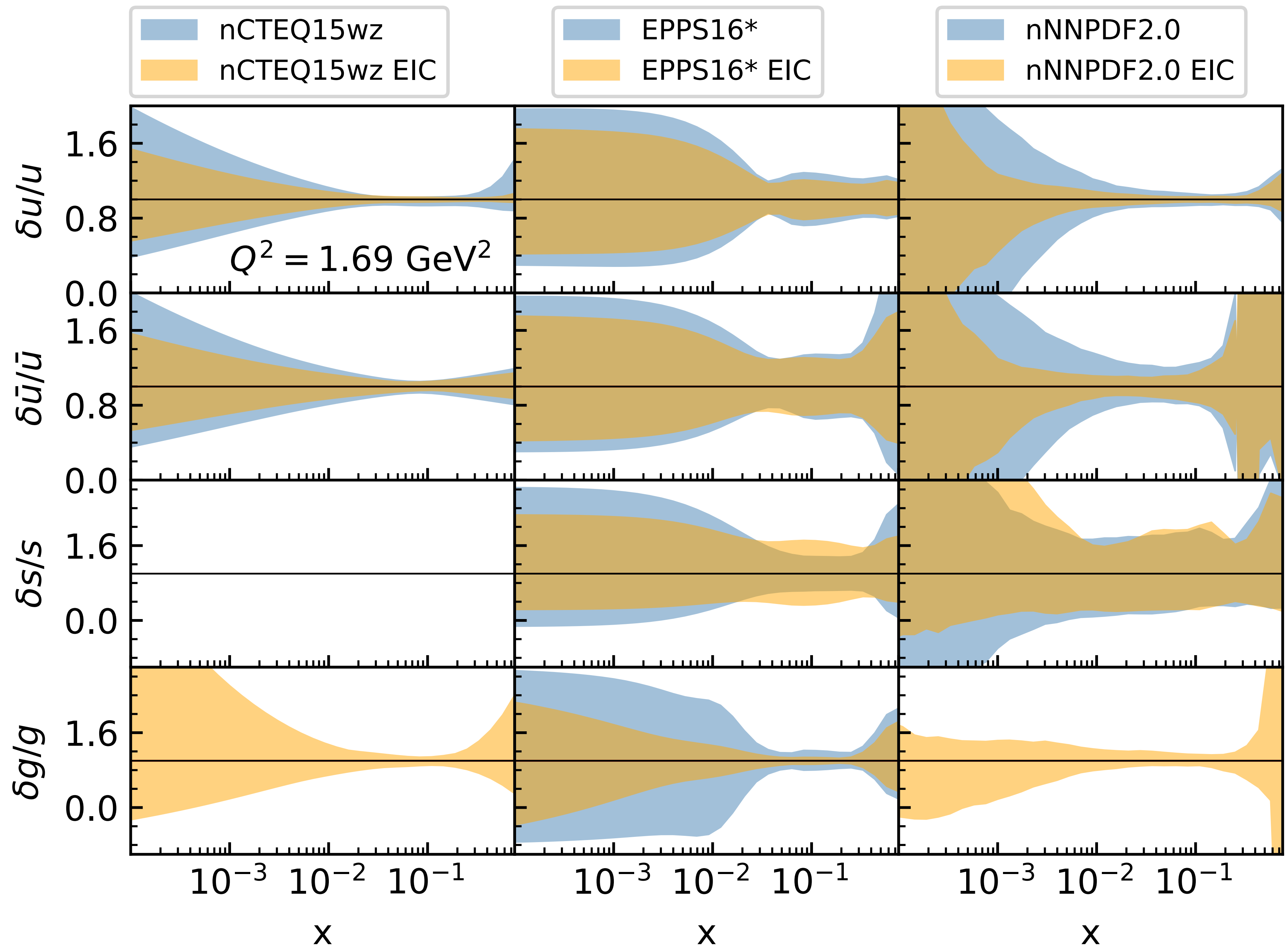
Statistical errors negligible





Impact of EIC on nuclear PDFs

Au



Significant impact of EIC measurements on nuclear PDFs

Impact at moderate and low x

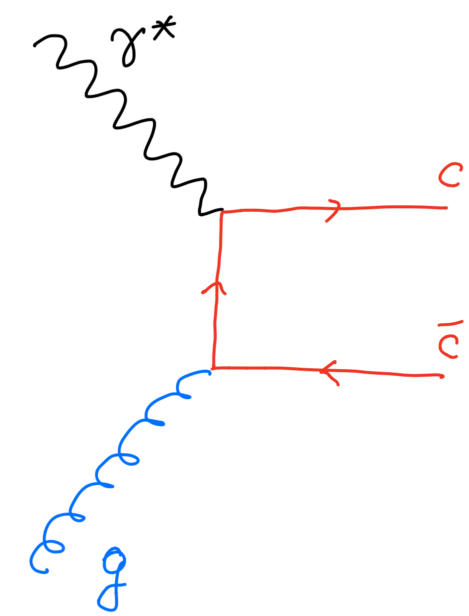
Heavy flavor impact on gluon PDF

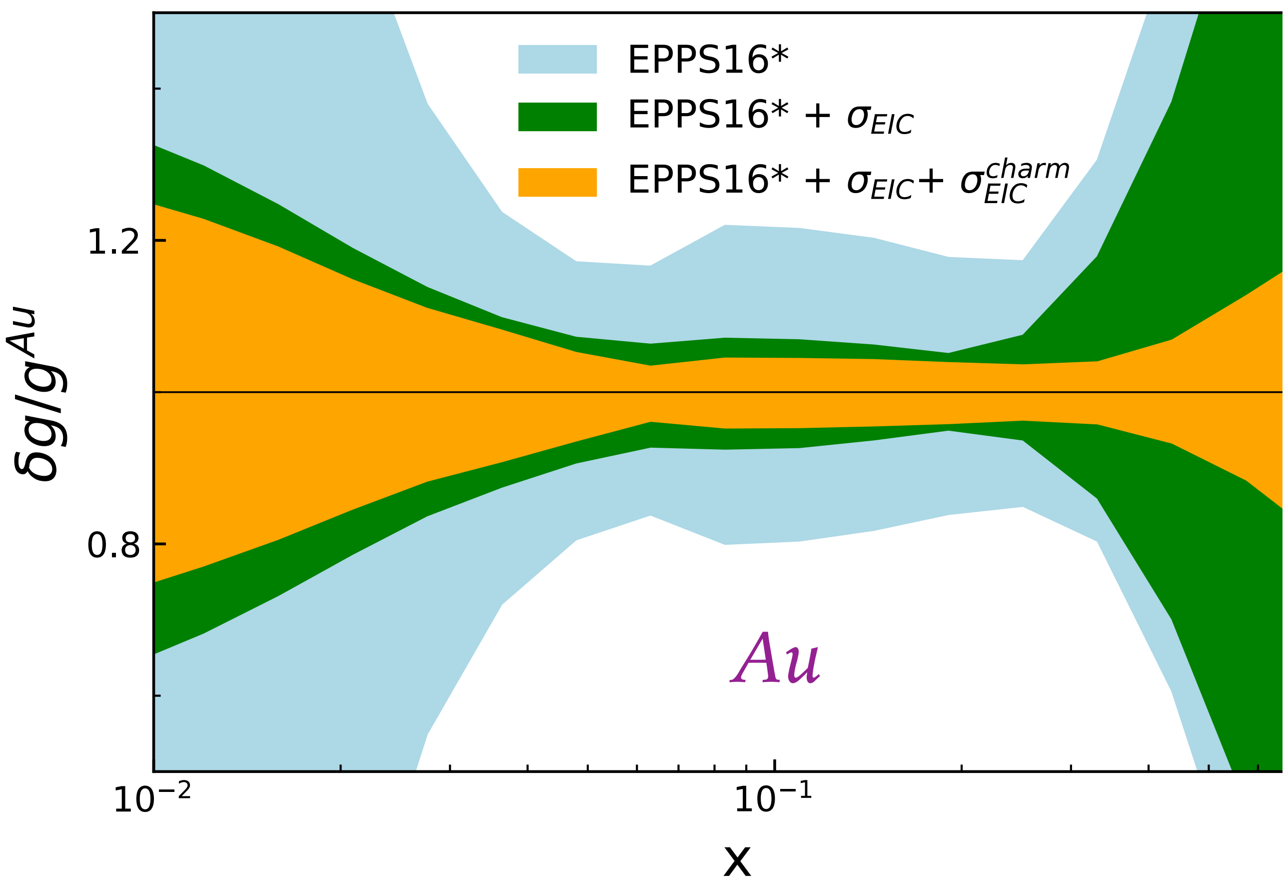
Impact of charm cross section on the gluon PDF at high x

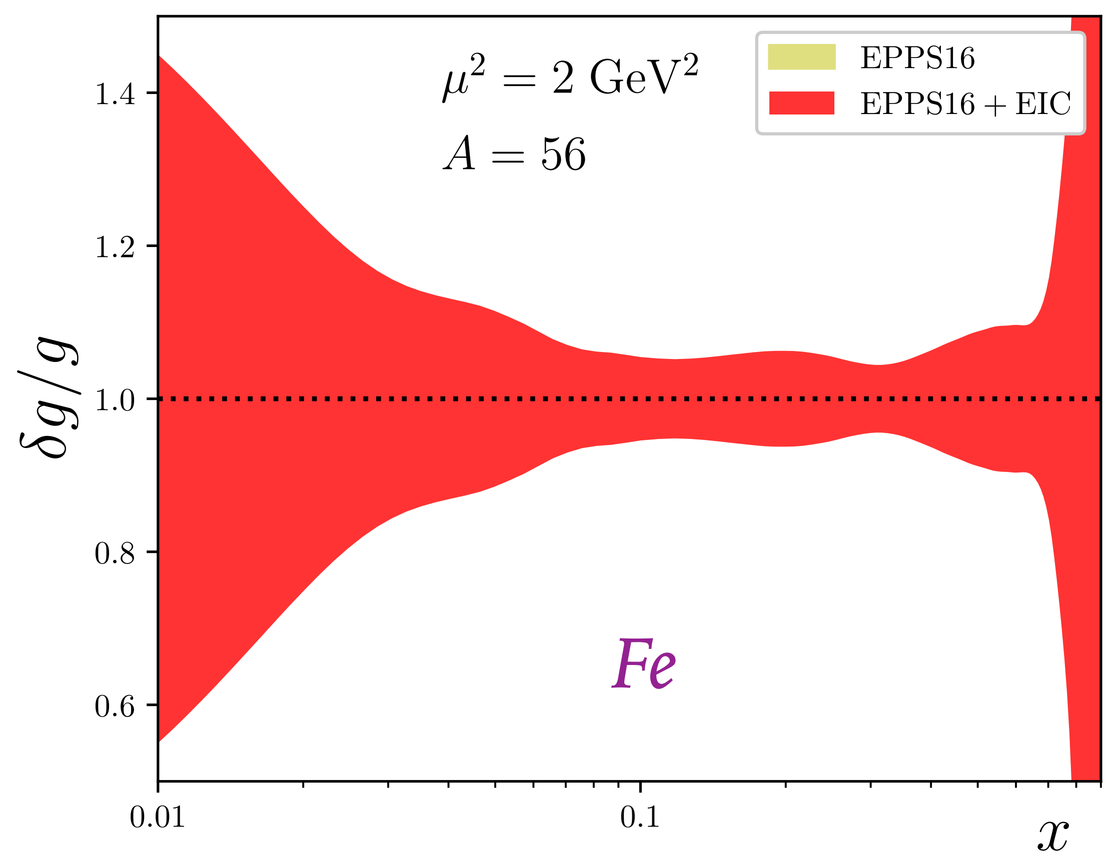
Charm is produced mainly in the photon-gluon fusion process

Dedicated efforts to study of feasibility of measurement of charm from D decays to K and pion

Significant impact on gluon at x>0.1. Sensitivity to EMC effect.







Proton PDFs

EIC will offer high luminosity to improve measurement in ep

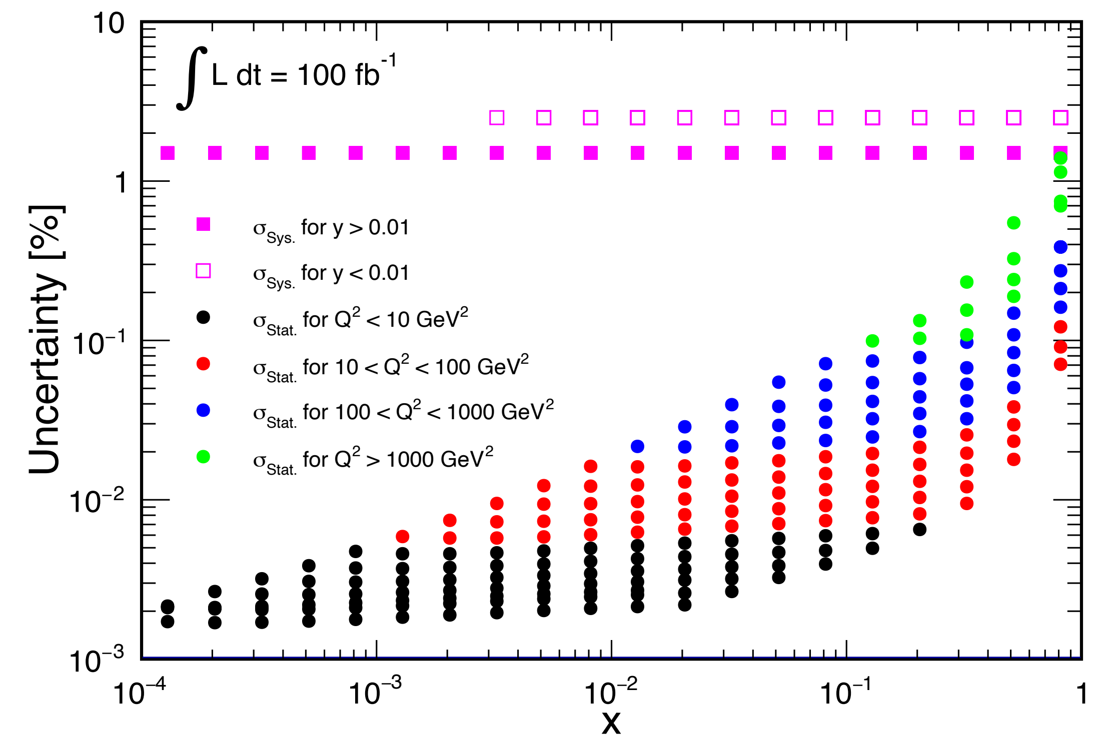
Systematic uncertainties at most few %

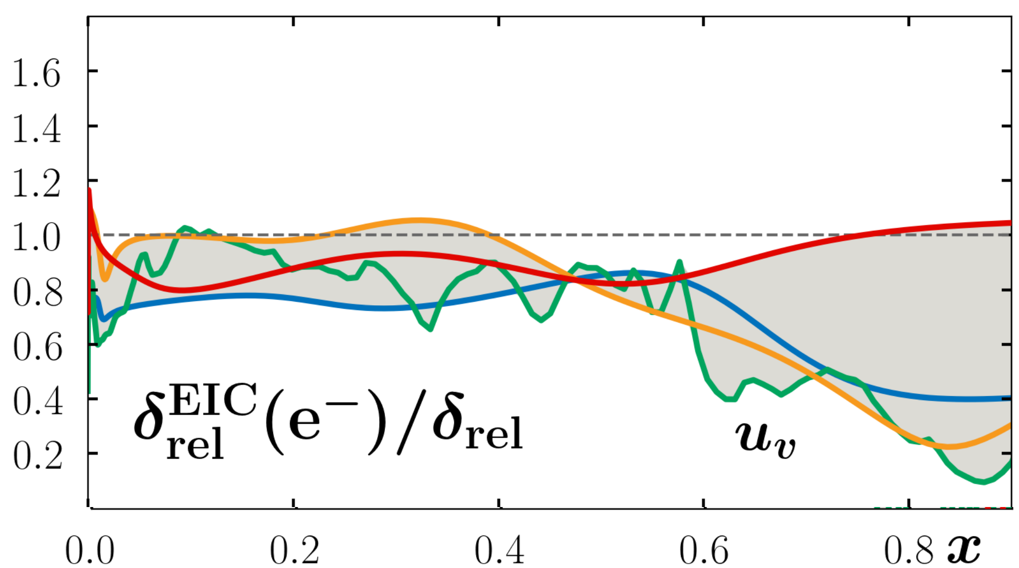
Statistical errors negligible

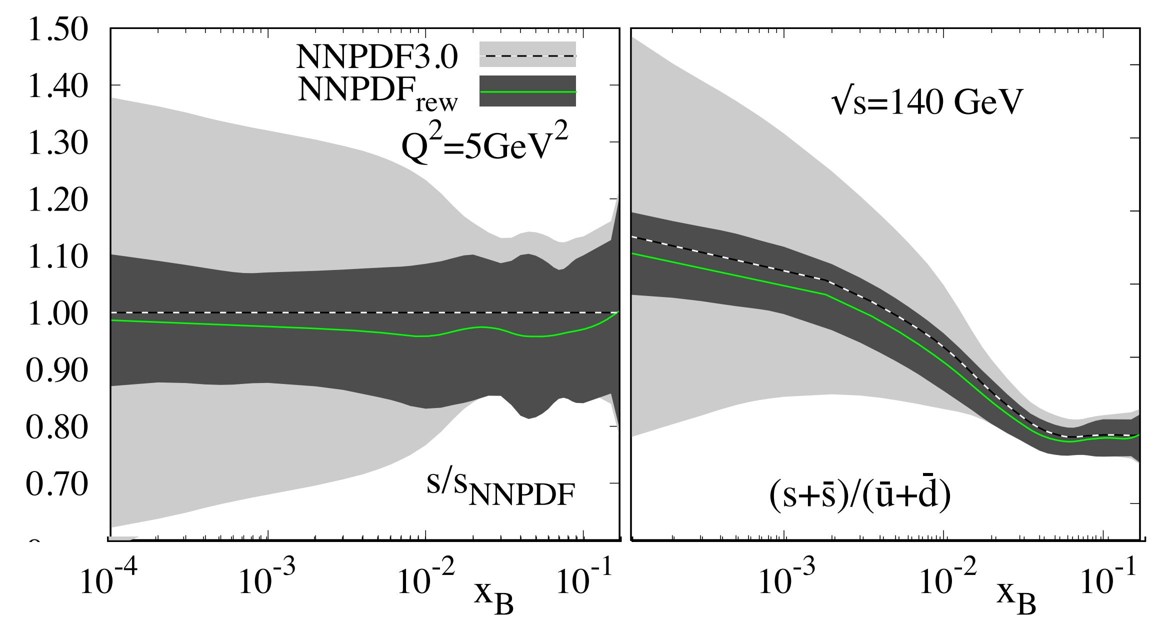
Potential for substantial improvement in the valence region

SIDIS with pions and kaon measurement can provide additional constraints.

Substantial improvement of the strange component







Pion and kaon structure at EIC

Key science questions:

Origin of masses of light hadrons

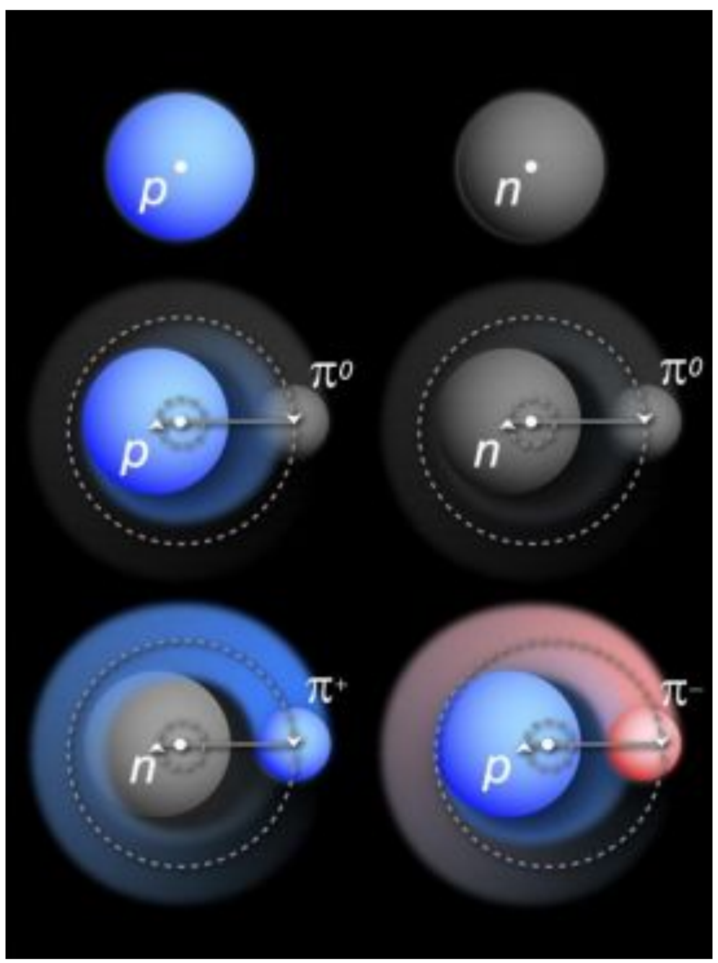
Role of gluons in the chiral limit

Quantities to study:

Quark and gluon distributions in the pion and kaon

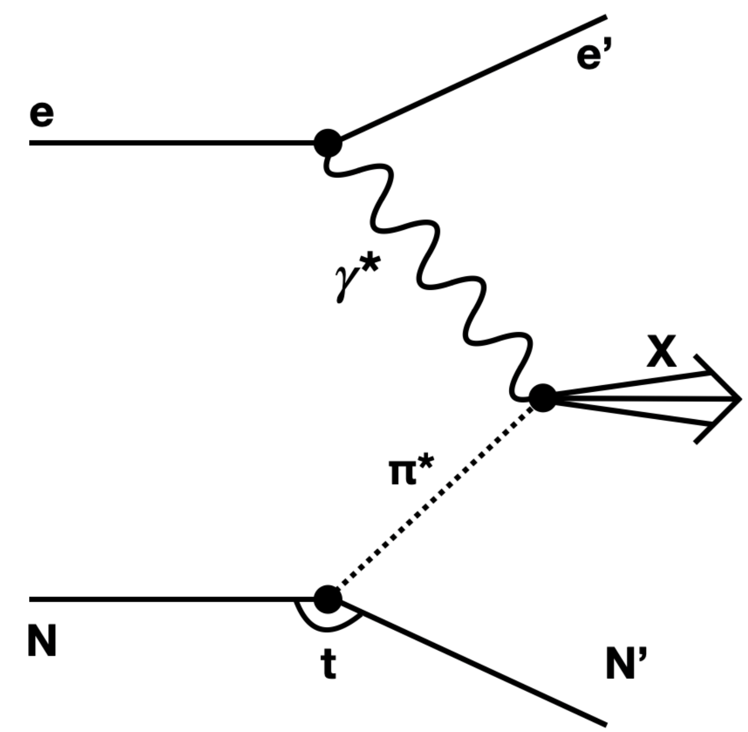
Generalized parton distributions in the pion and kaon

Pion and kaon form factors



Sullivan process :

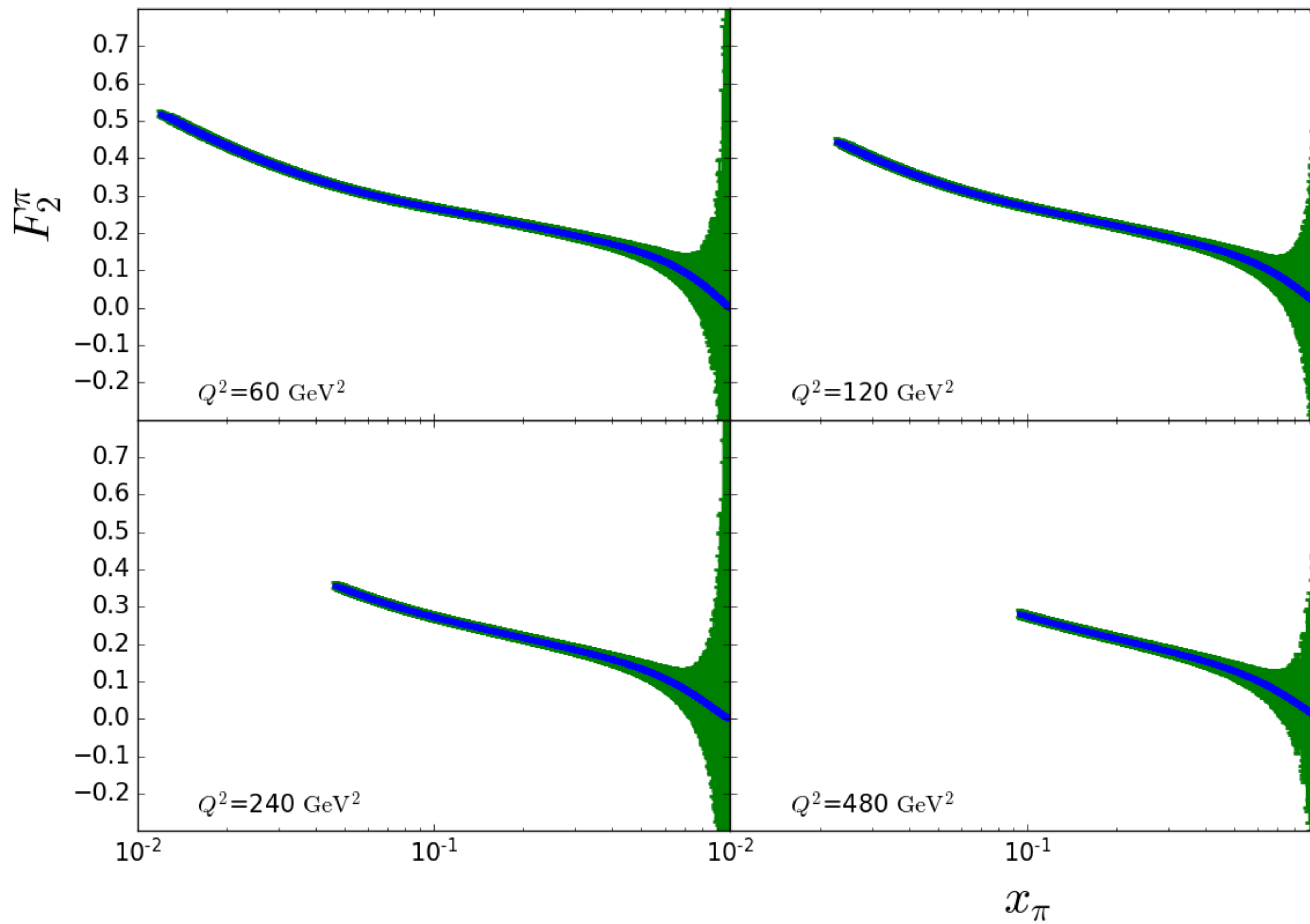
Scattering off the nucleon - meson fluctuations



Pion structure function at the EIC

10 GeV x 135 GeV

Projections based on model that reproduces HERA data an GRV extrapolation at large x

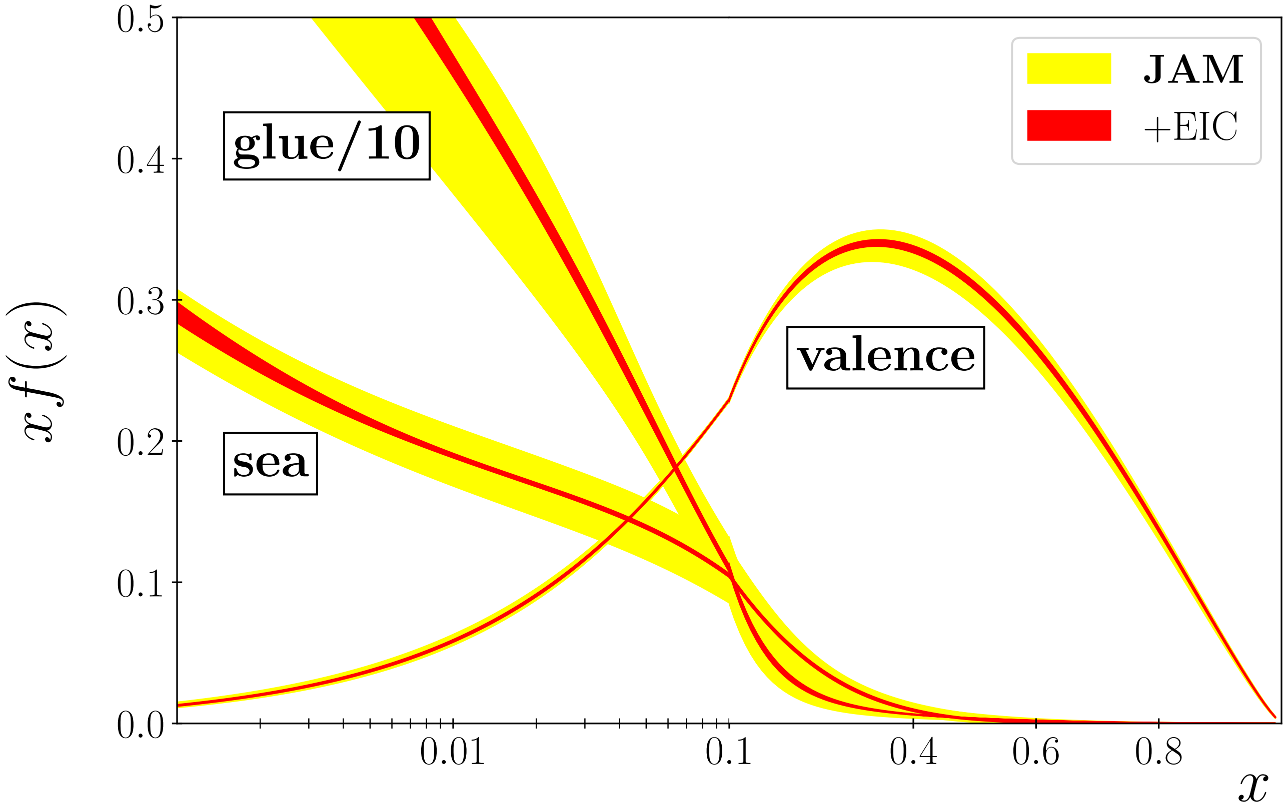


Green band: statistical uncertainty from luminosity of 100 fb^{-1}

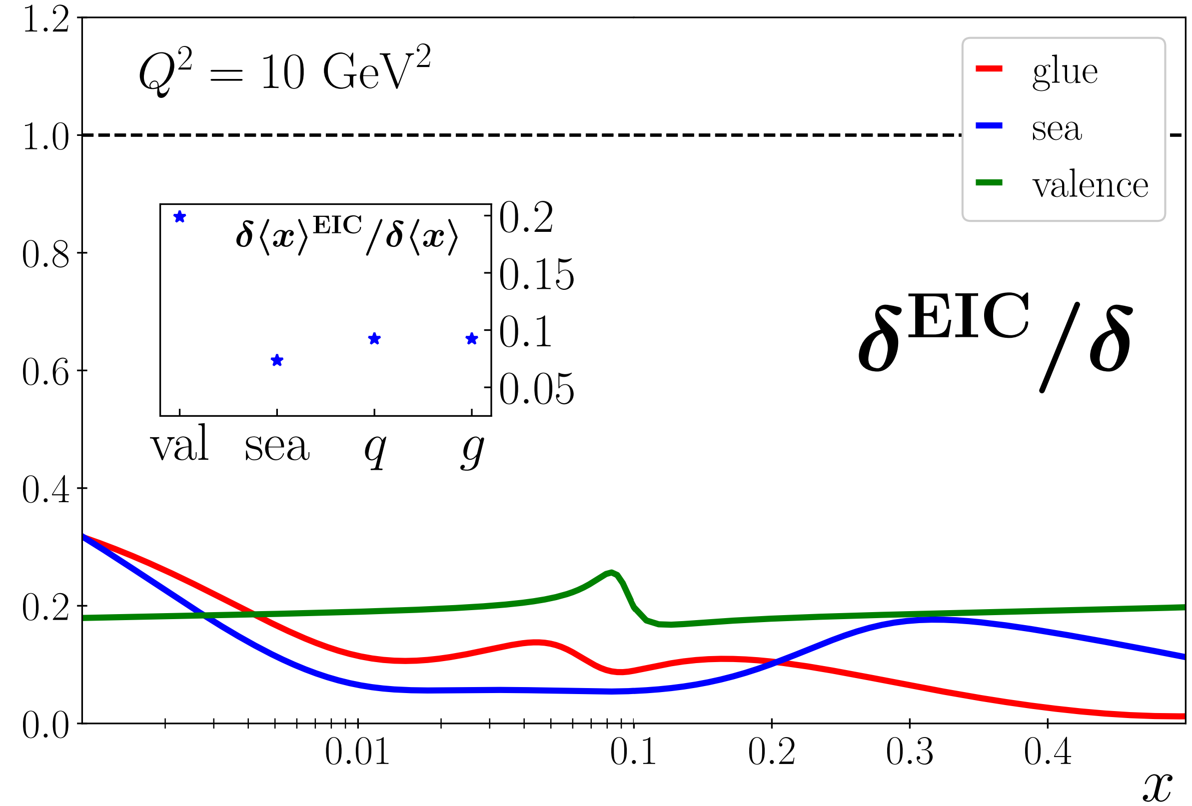
Largest systematic uncertainty coming from the pion flux factor

Impact on pion PDFs

Pion PDFs



Ratio of uncertainties with and w/o EIC



Luminosity 100 fb^{-1}

Center of mass energy 73.5 GeV

Systematic uncertainty 1.2% (does not include model dependence)

Reduction of uncertainties: 5-10 for sea quark & gluon, 5 for valence

DIS on a deuteron with spectator tagging

$$e + d \to e' + X + N$$

$$N = n \text{ or } p$$

Detection of the spectator nucleon identifies the active nucleon in DIS

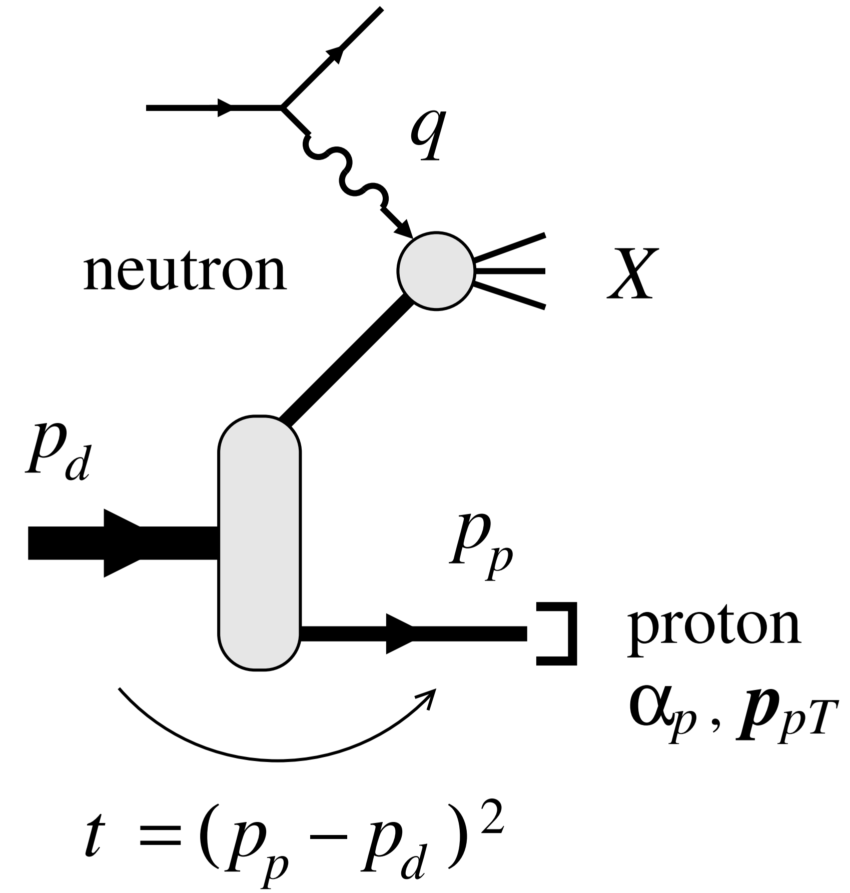
Measurement of the spectator nucleon momentum controls the nuclear configuration in the deuteron initial state and permits differential analysis of the nuclear effects

DIS with proton tagging allows for extraction of the neutron structure function

Spectator tagging allows to study the EMC effect

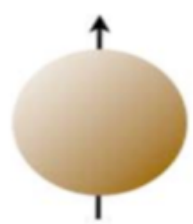
Neutron tagging allow for measurement of the proton structure function in deuteron DIS, allow for analysis of nuclear effects

Example: deuteron DIS with spectator proton tagging



Proton spin

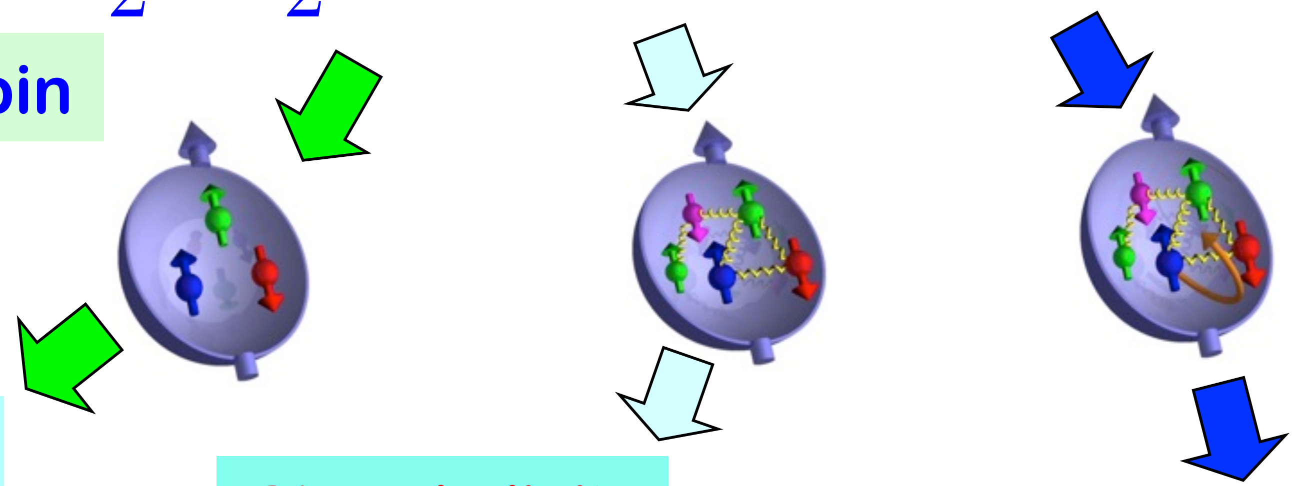
Proton spin: intrinsic property of a hadron.
Spin puzzle: how it emerges from internal degrees of freedom?



Proton Spin

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + (L_q + L_g)$$

Jaffe-Manohar, 90
Ji, 96, …

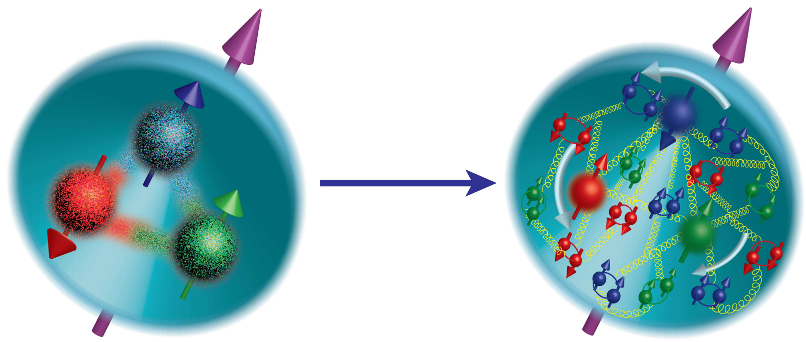


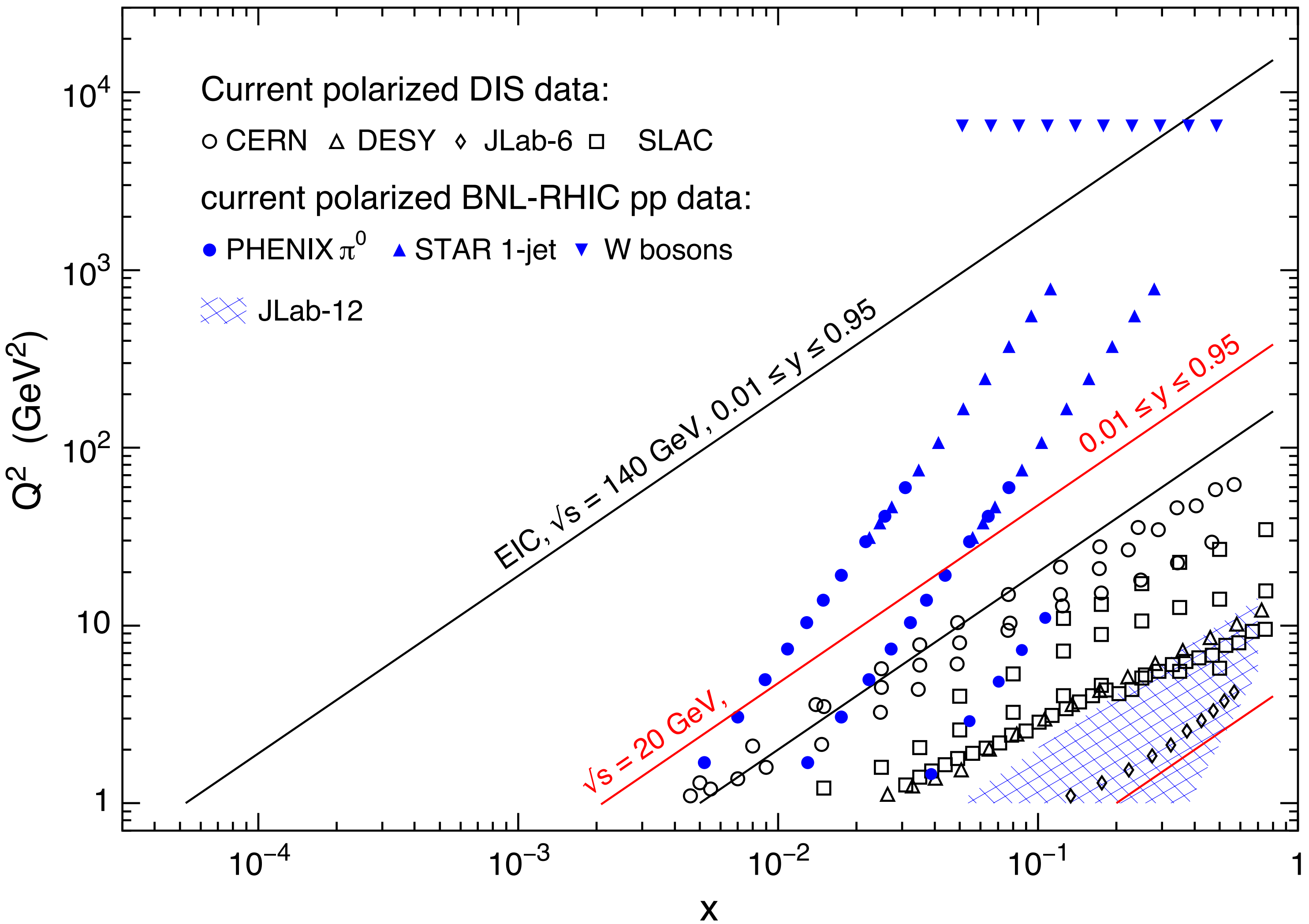
Quark helicity
Best known

Gluon helicity
Start to know

Orbital Angular Momentum of quarks and gluons
Little known

Proton spin





70% polarization of beams at EIC for leptons, protons and light nuclei

EIC extends range in (x,Q^2) by 1-2 orders of magnitude for polarized measurements.

Precision measurements: structure function g_1, gluon contribution to proton spin, quark contribution, strange quark contribution also accessible, polarized deuterons allow for measurement of g_1 in a neutron, different TMDs

Proton spin

Difference between cross section with longitudinally polarized electron and proton beams

$$\frac{1}{2}\left[\frac{d^2\sigma^{\rightleftarrows}}{dx\,dQ^2} - \frac{d^2\sigma^{\rightrightarrows}}{dx\,dQ^2}\right] \simeq \frac{4\pi\,\alpha^2}{Q^4} y\,(2-y)\,g_1(x,Q^2)$$

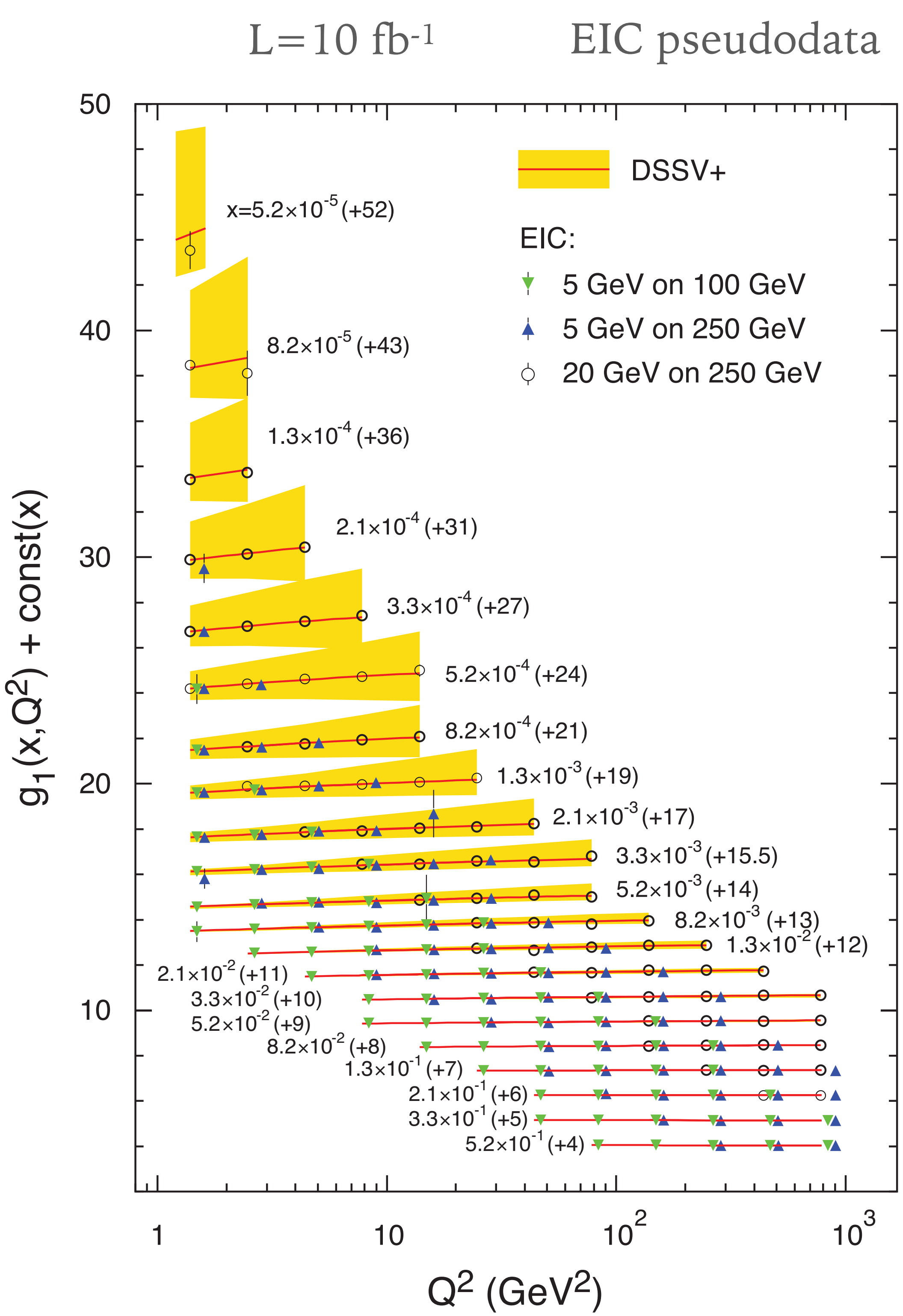
Helicity PDF: difference between number density of partons with the same (opposite) helicity as the nucleon

$$g_1(x,Q^2) = \frac{1}{2}\sum e_q^2\left[\Delta q(x,Q^2) + \Delta\bar{q}(x,Q^2)\right]$$

$$\Delta f(x,Q^2) \equiv f^+(x,Q^2) \; - \; f^-(x,Q^2)$$

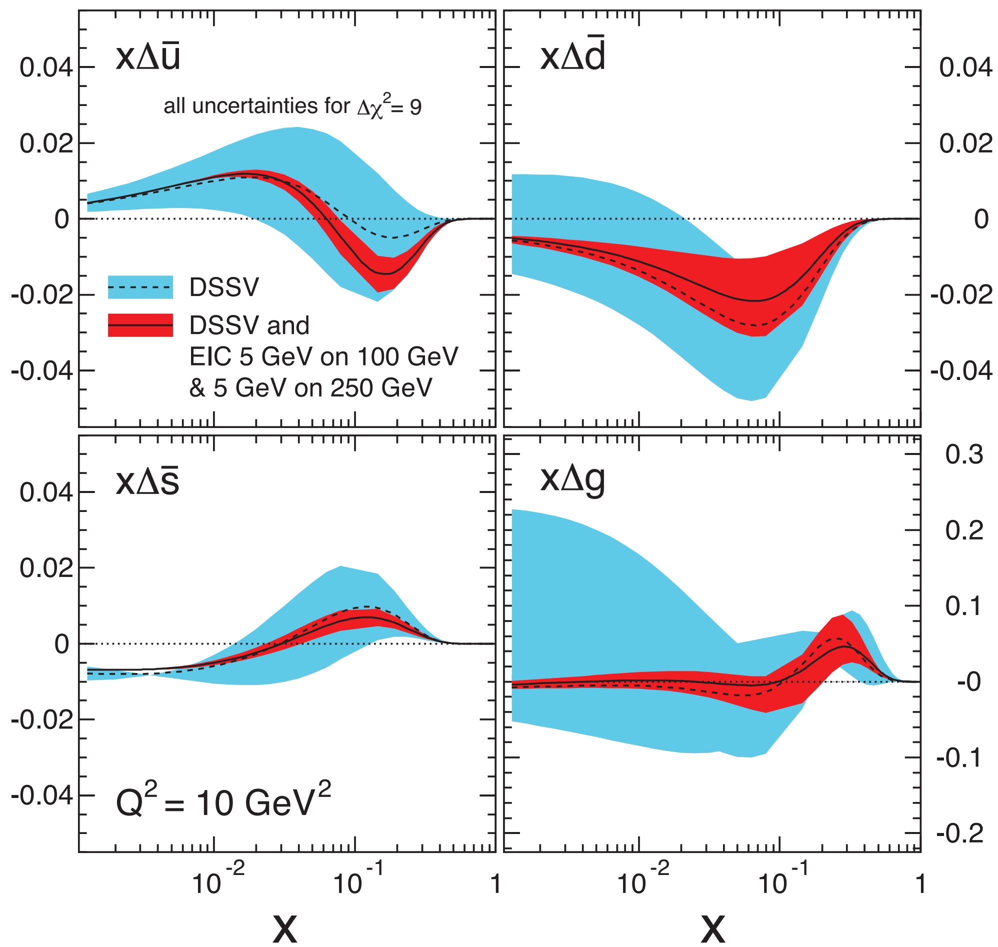
Sensitive to gluons Δg at higher orders: drive the scaling violations

$$\frac{dg_1(x,Q^2)}{d\log Q^2} \sim \Delta g$$



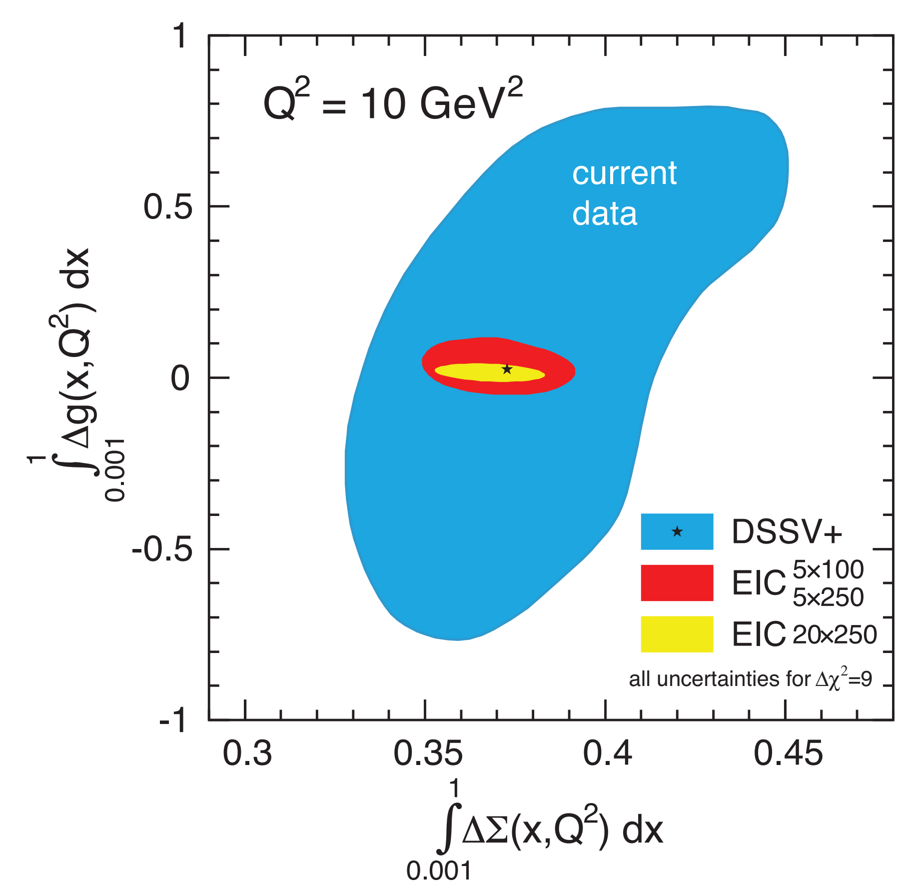
Proton spin

$$\Delta f(x,Q^2) \equiv f^+(x,Q^2) \; - \; f^-(x,Q^2)$$



Extraction of helicity parton distributions from the global analysis of inclusive and semi-inclusive simulated data from EIC.

EIC, White paper



- ✦ Insight into quark and gluon contribution to proton spin.
- ✦ By subtracting these contributions one can constrain the parton orbital angular momentum contribution $L_q + L_g$.

From 1D to 3D: imaging of nucleon : tomography

Integrated PDFs provide limited information about the details of the nucleon structure: only distribution of partons in the longitudinal momentum fraction

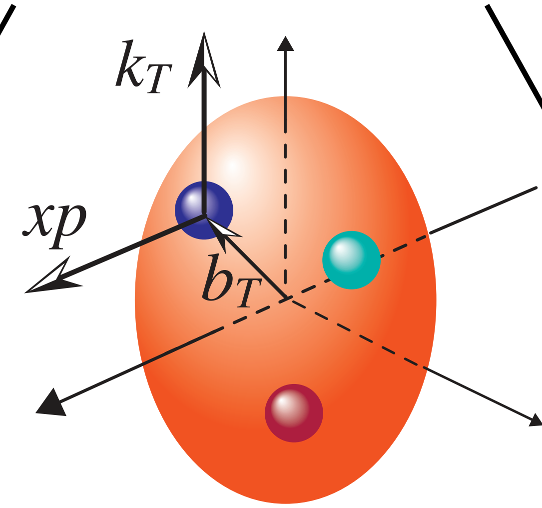
$$f(x)$$

(and scale dependent)

Wigner function or Generalized Transverse Momentum Dependent Distribution GTMD (in momentum space)

$$W(x, b_T, k_T)$$

$$\int d^2 b_T \qquad\qquad \int d^2 k_T$$



$$f(x, k_T) \qquad\qquad f(x, b_T)$$

Transverse Momentum Dependent — Generalized Parton Distribution

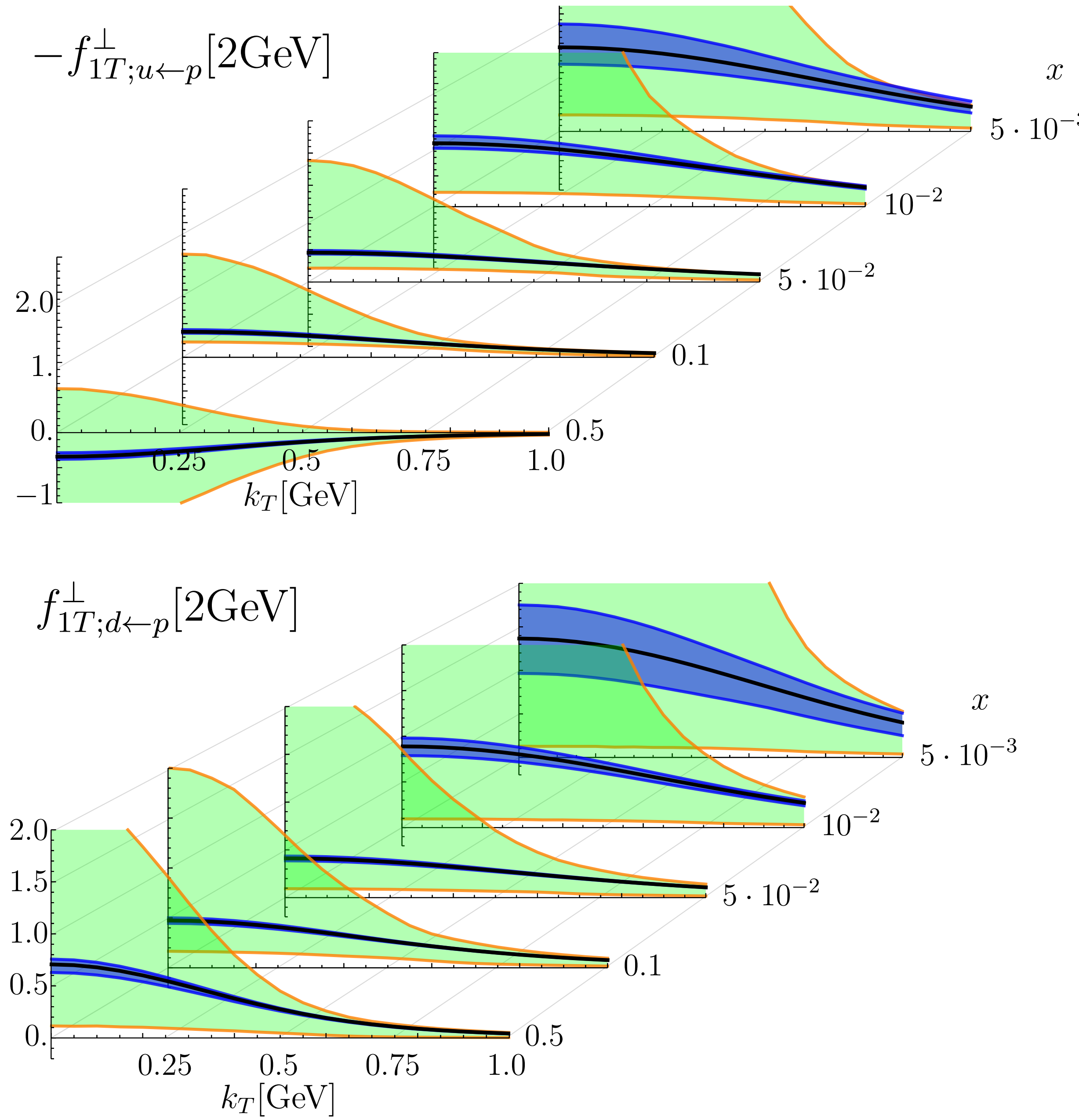
Exploring TMD at EIC: Sivers function example

Example: Measurement of the Sivers function

Transverse momentum distribution of quarks correlated with the transverse polarization vector of the nucleon

Extracted from semi-inclusive DIS : pseudodata on pions and kaons included

Reduction of uncertainties by order of magnitude when including EIC.



Green: without EIC

Blue: with EIC

Probing saturation in di-hadron at the EIC

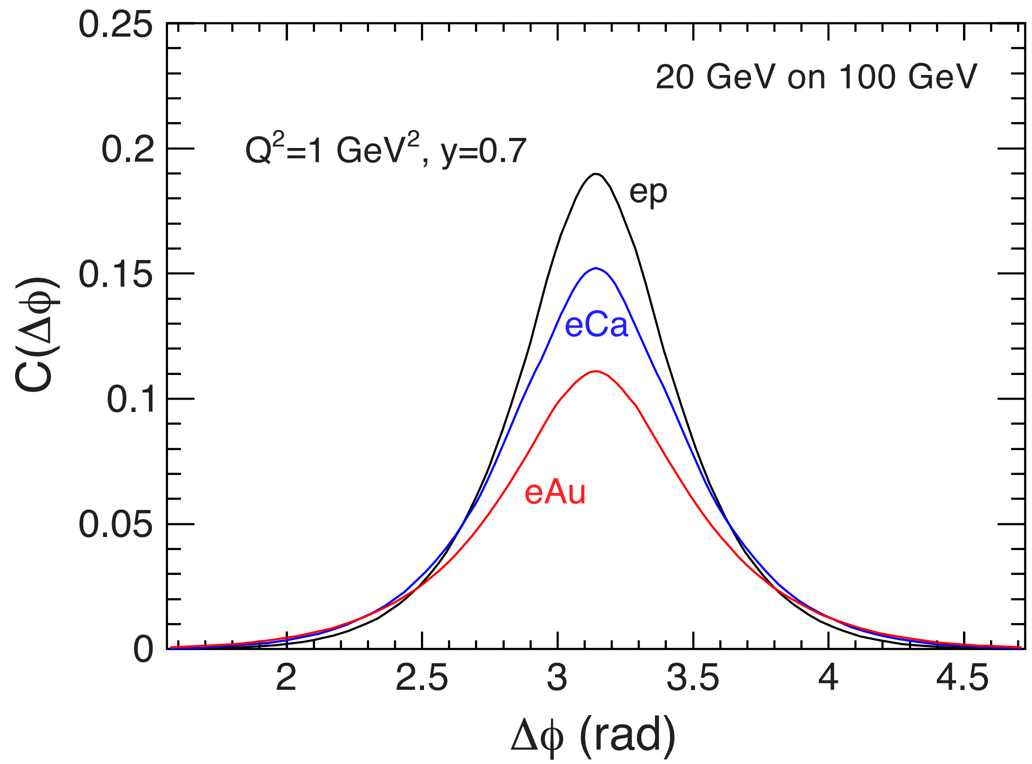
Di-Hadron azimuthal correlations in eA

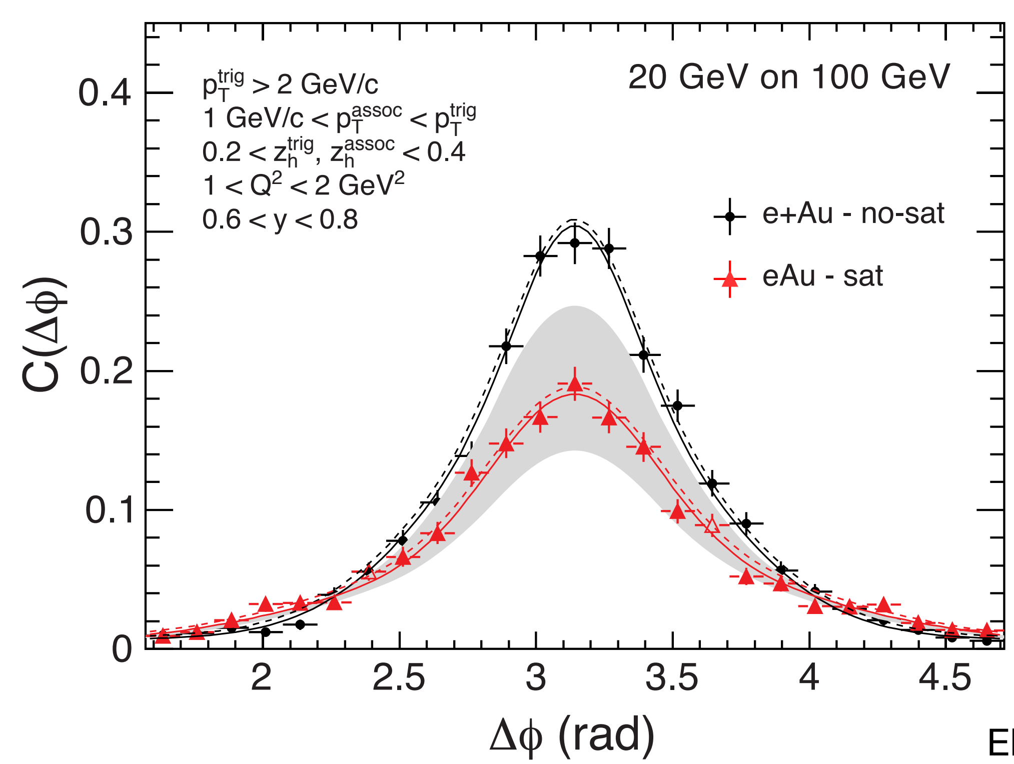
$$e + A \to e' + h_1 + h_2 + X$$

Sensitive to transverse momentum dependence of the gluon distribution

In particular to the saturation which is expected in the Color Glass Condensate theory

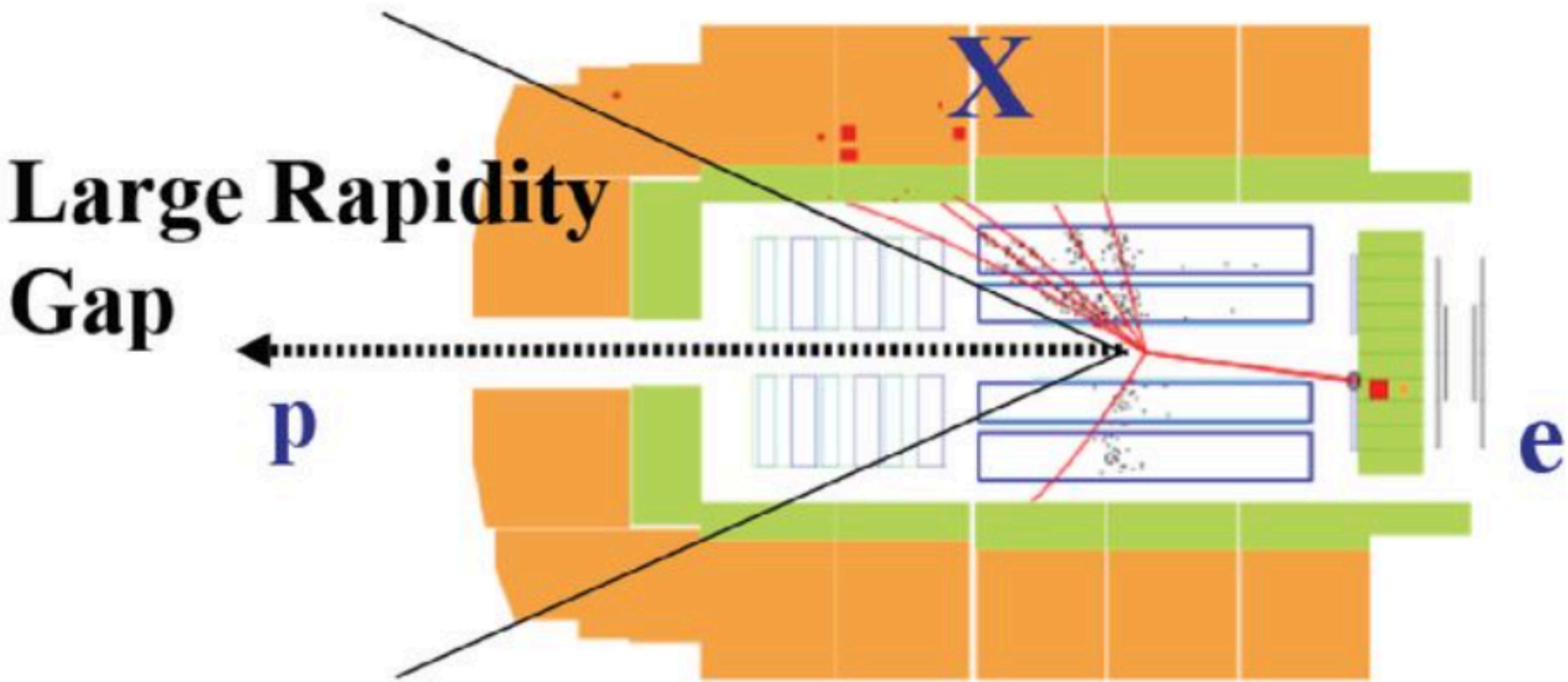
Saturation predicts disappearance of the back-to-back correlations with increasing A





EIC, White paper

Diffraction at HERA

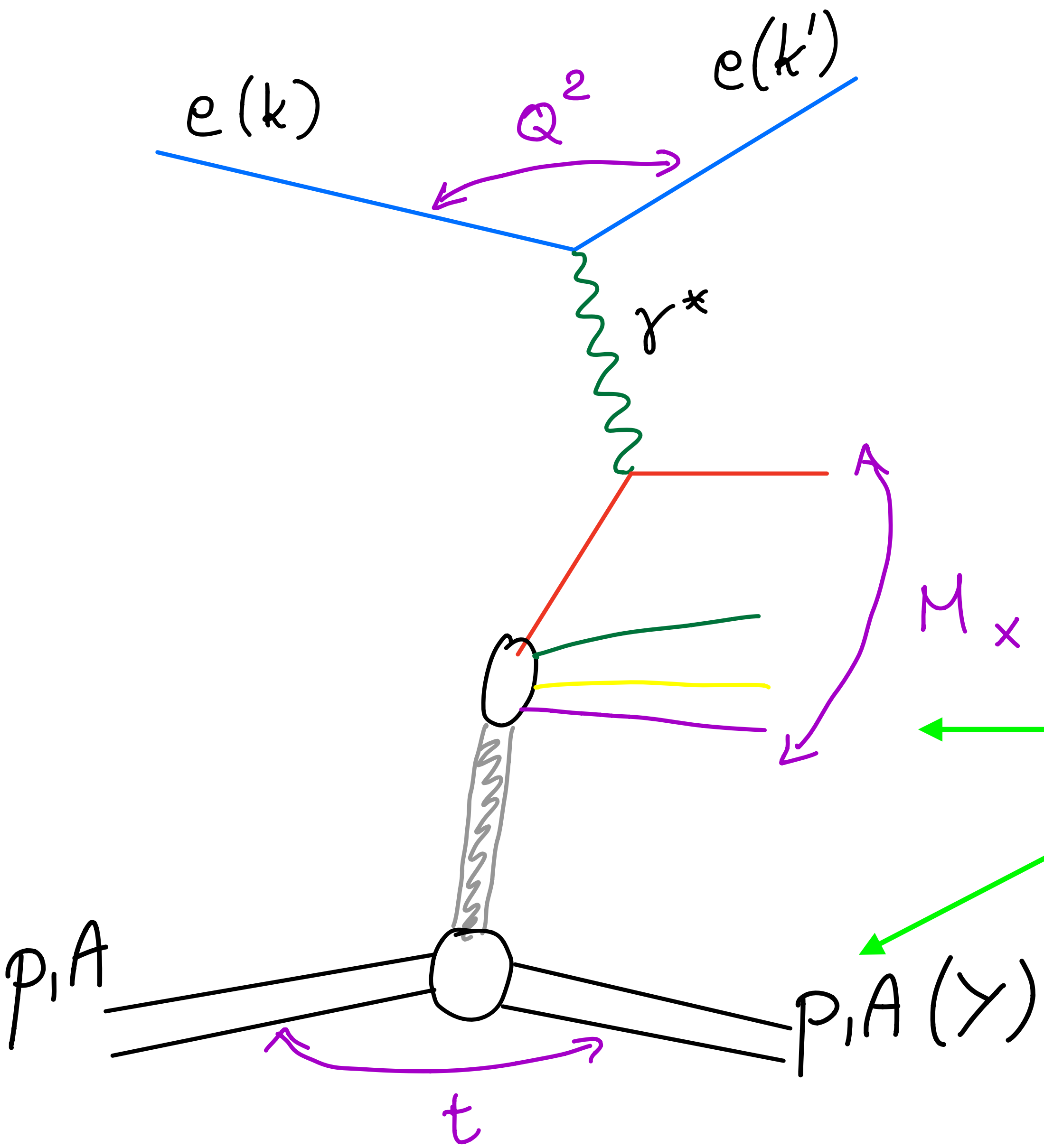


10% events at HERA were of diffractive type

Large portion of the detector void of any particle activity: **rapidity gap**

Proton stays intact despite undergoing violent collision with a 50 TeV electron (in its rest frame)

Diffraction in electron - proton(nucleus)



t Momentum transfer at the proton vertex (target recoil)

X Diffractive system with mass M_x

Rapidity gap

Target is scattered elastically: elastic scattering

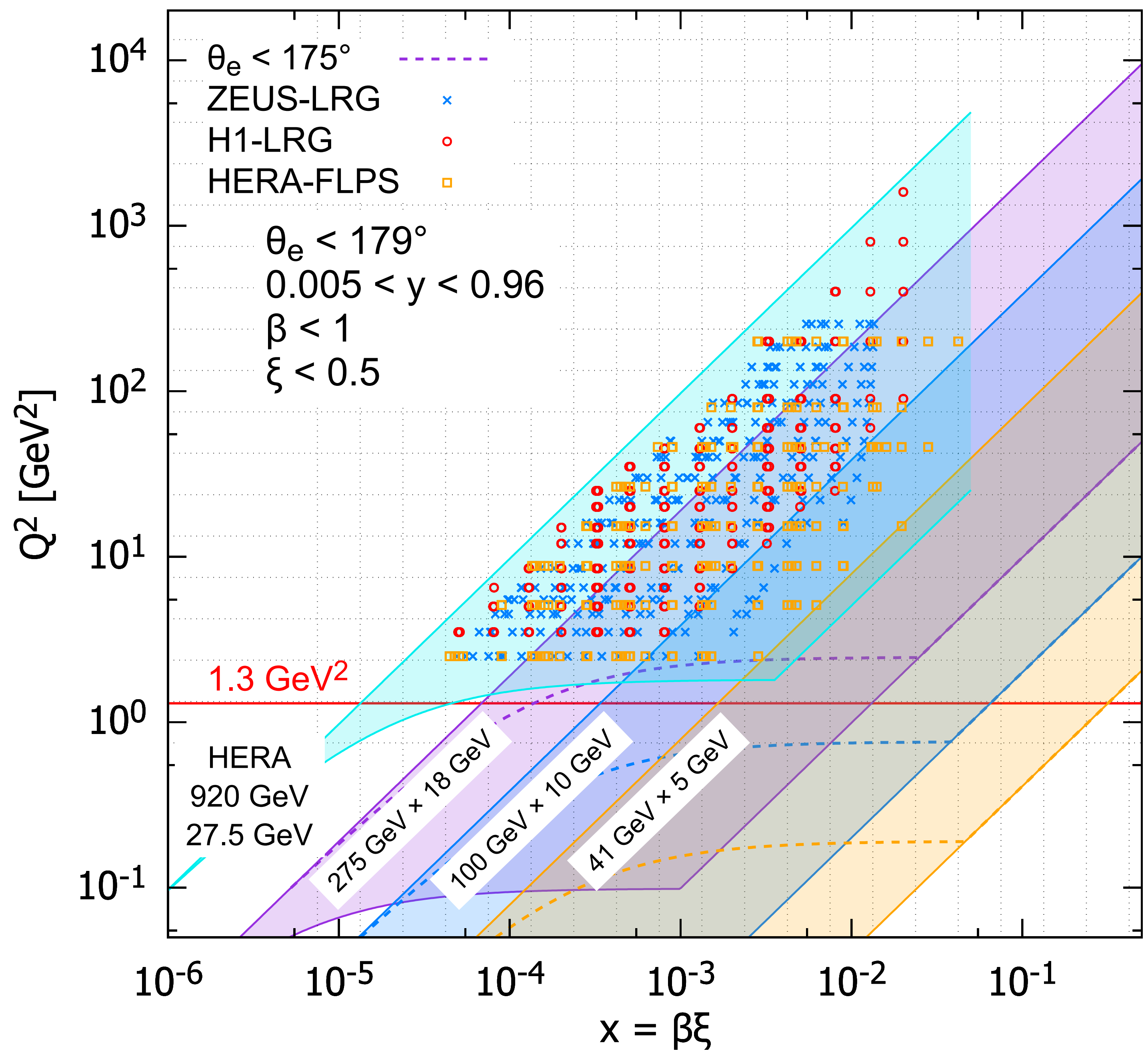
It can also dissociate into a state Y with the same quantum numbers, but still separated from the rest of particles

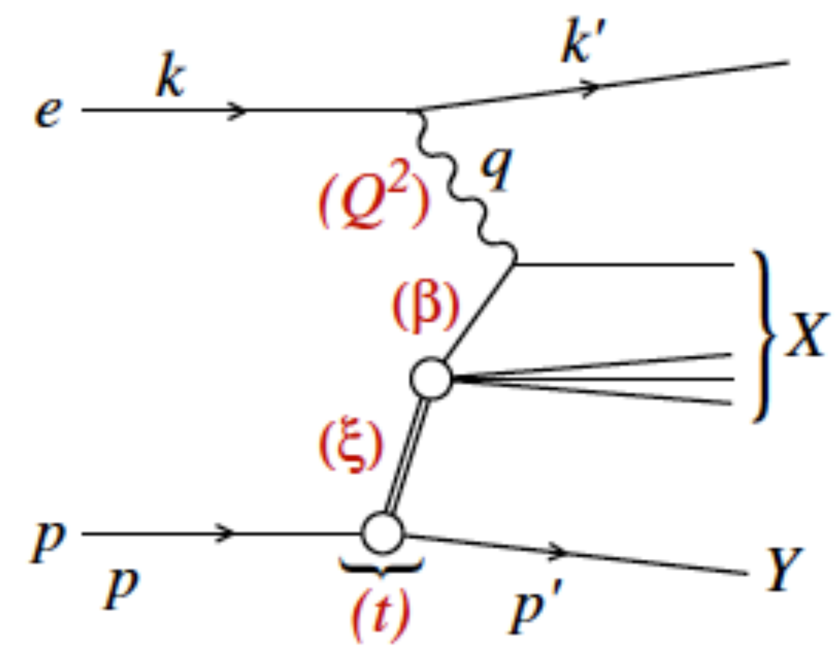
In order for the rapidity gap to exist it needs to be mediated by the *colorless* exchange

Diffraction: a reaction characterized by a large rapidity gap in the final state

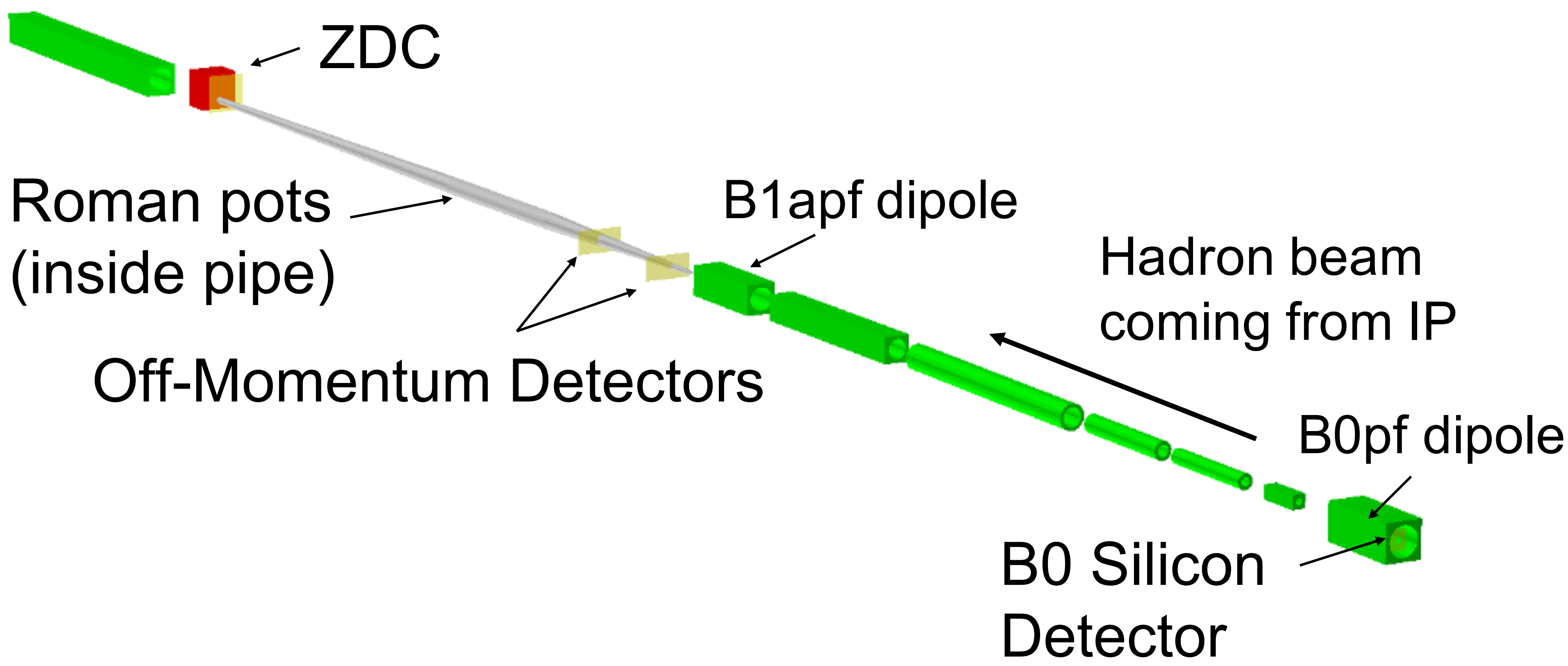
Phase space (x,Q^2) EIC-HERA in diffraction

EIC 3 scenarios - HERA



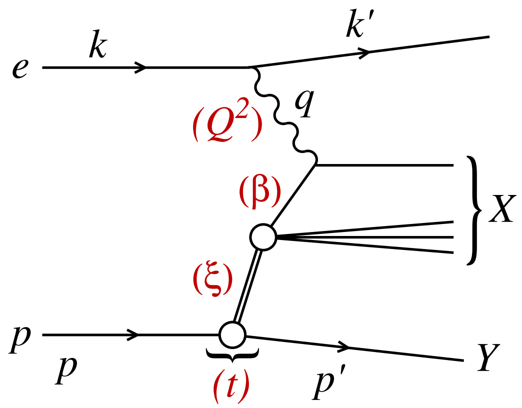


Far forward detectors at EIC



Detector	Angle	Position [m]
ZDC	θ<5.5 mrad	37.5
Roman Pots	0.5<θ<5.0 mrad	26.0, 28.0
Off-momentum detectors	θ<5.0 mrad	22.5, 25.5
B0	6.0<θ<20.0 mrad	5.4<z<6.4

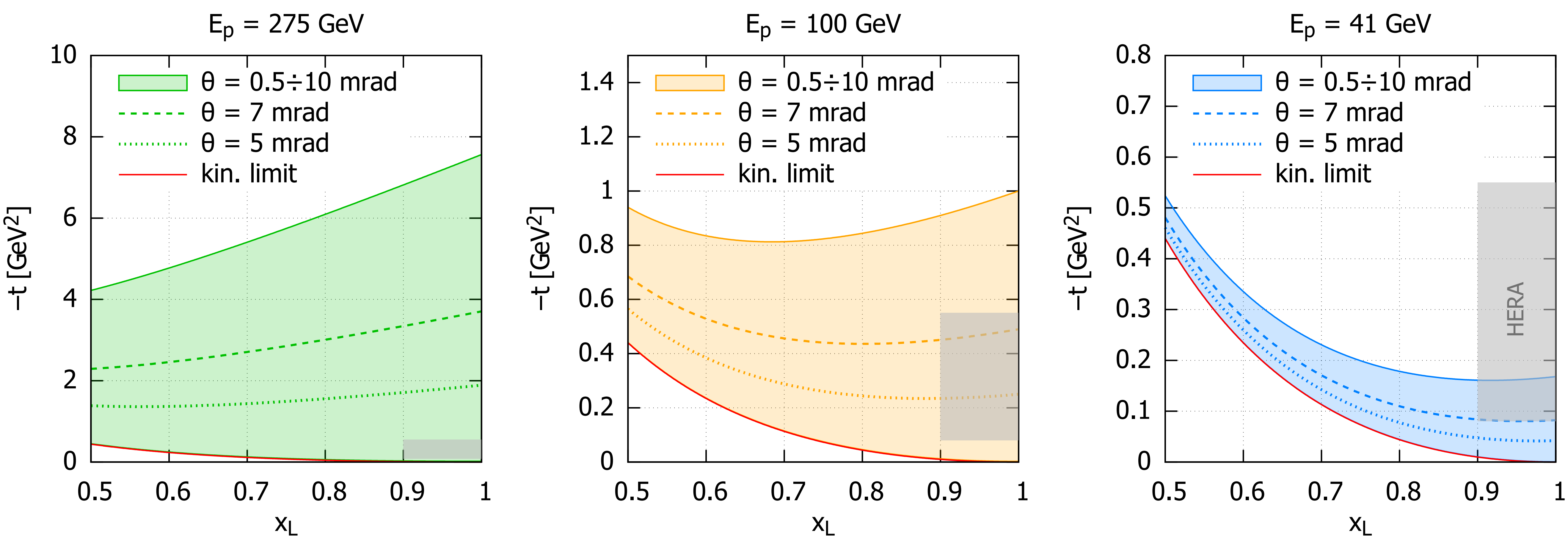
Final proton tagging



$(x_L, p_\perp)$

Small angle acceptance i.e. Roman pots

$(x_L, p_\perp, \theta)$ measured in LAB, collinear (e,p) frame

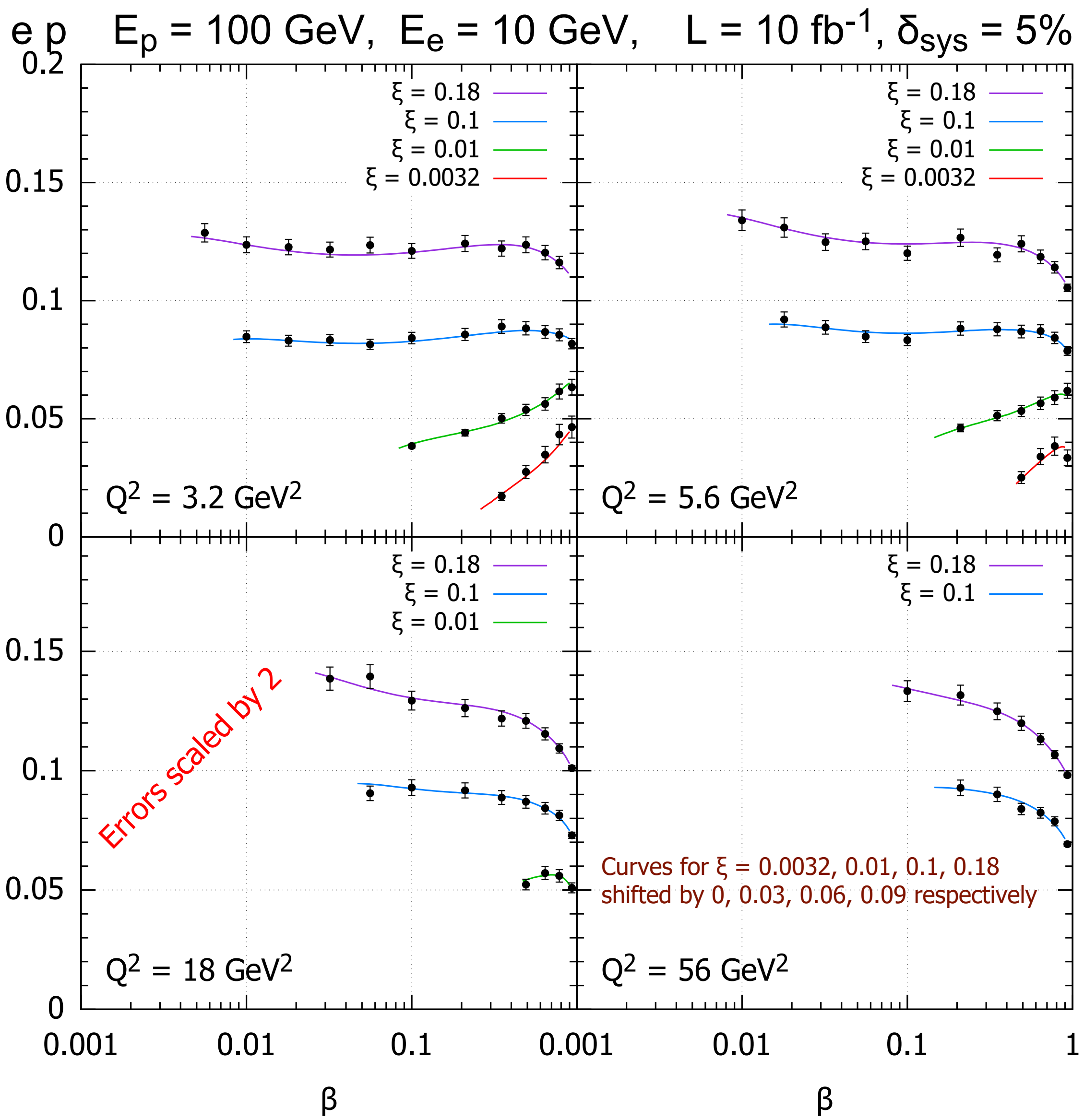


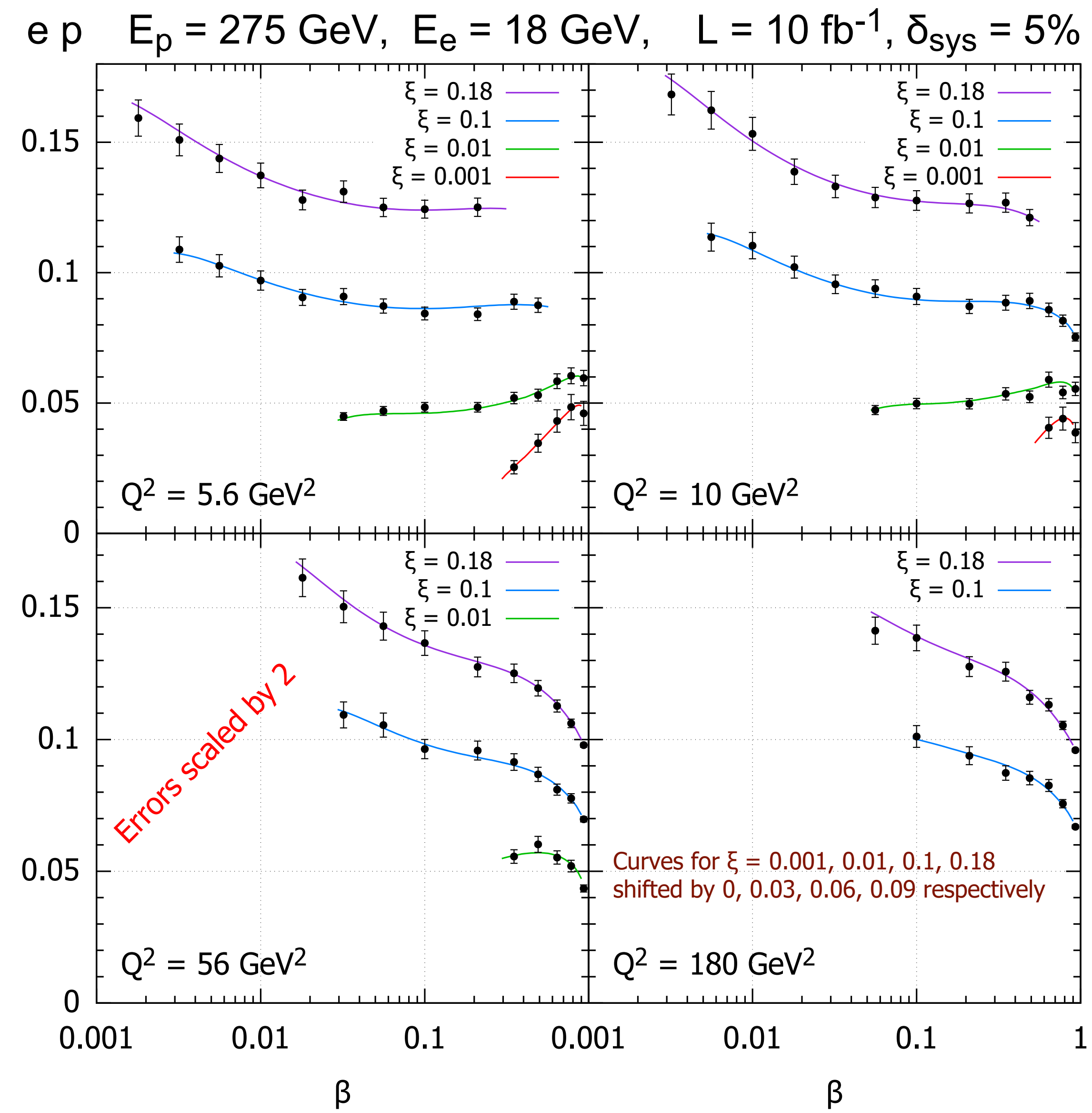
Much better than at HERA

Best way to select diffractive events through proton tagging

$$t = -\frac{p_\perp^2}{x_L} - \frac{(1-x_L)^2}{x_L} m_p^2$$

Pseudodata for $\sigma^{D(3)}$ at EIC





In total:
482 points for $1.3 < Q^2 < 1330\ \mathrm{GeV}^2$

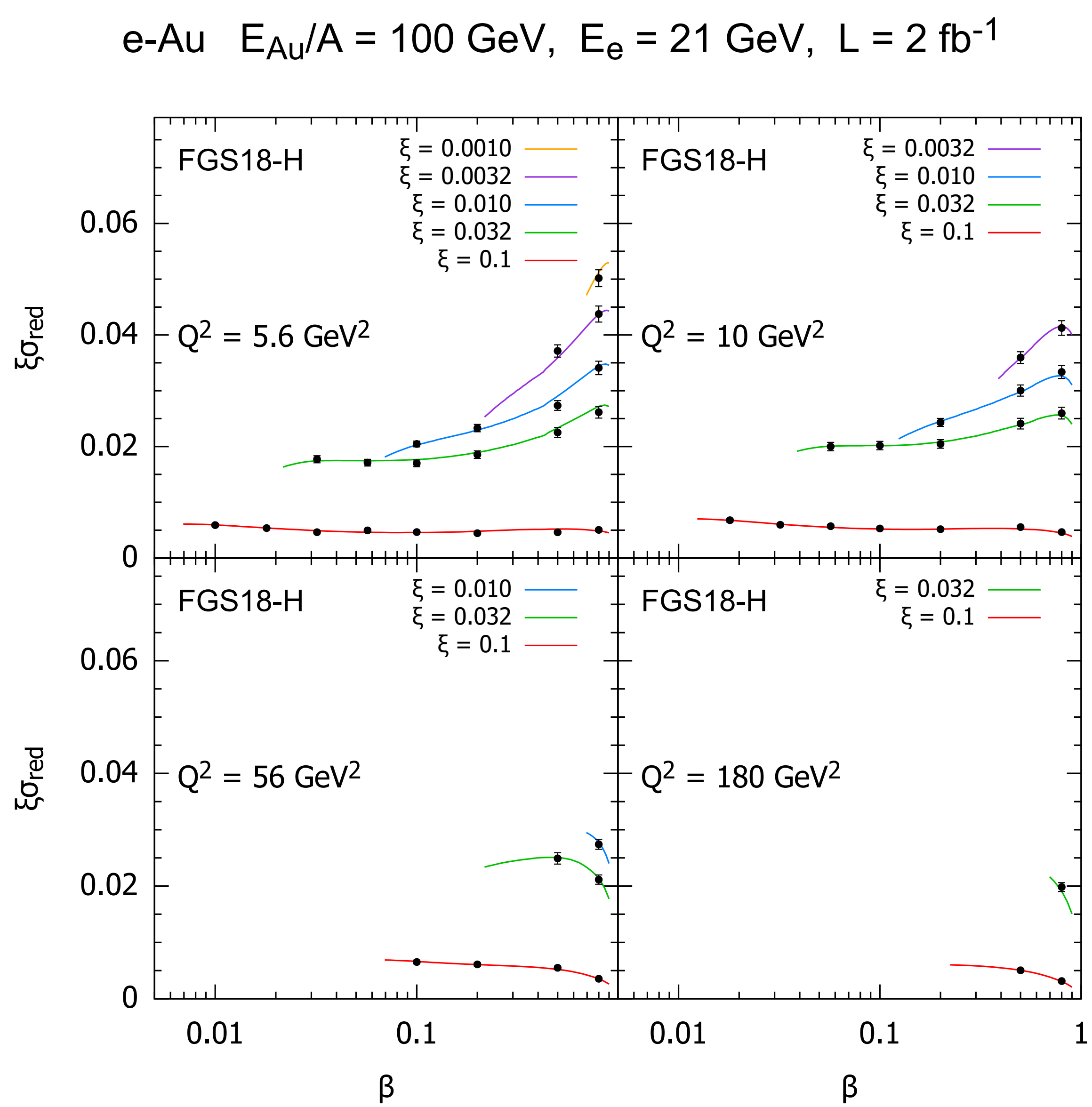
In total:
792 points for $1.3 < Q^2 < 4220\ \mathrm{GeV}^2$

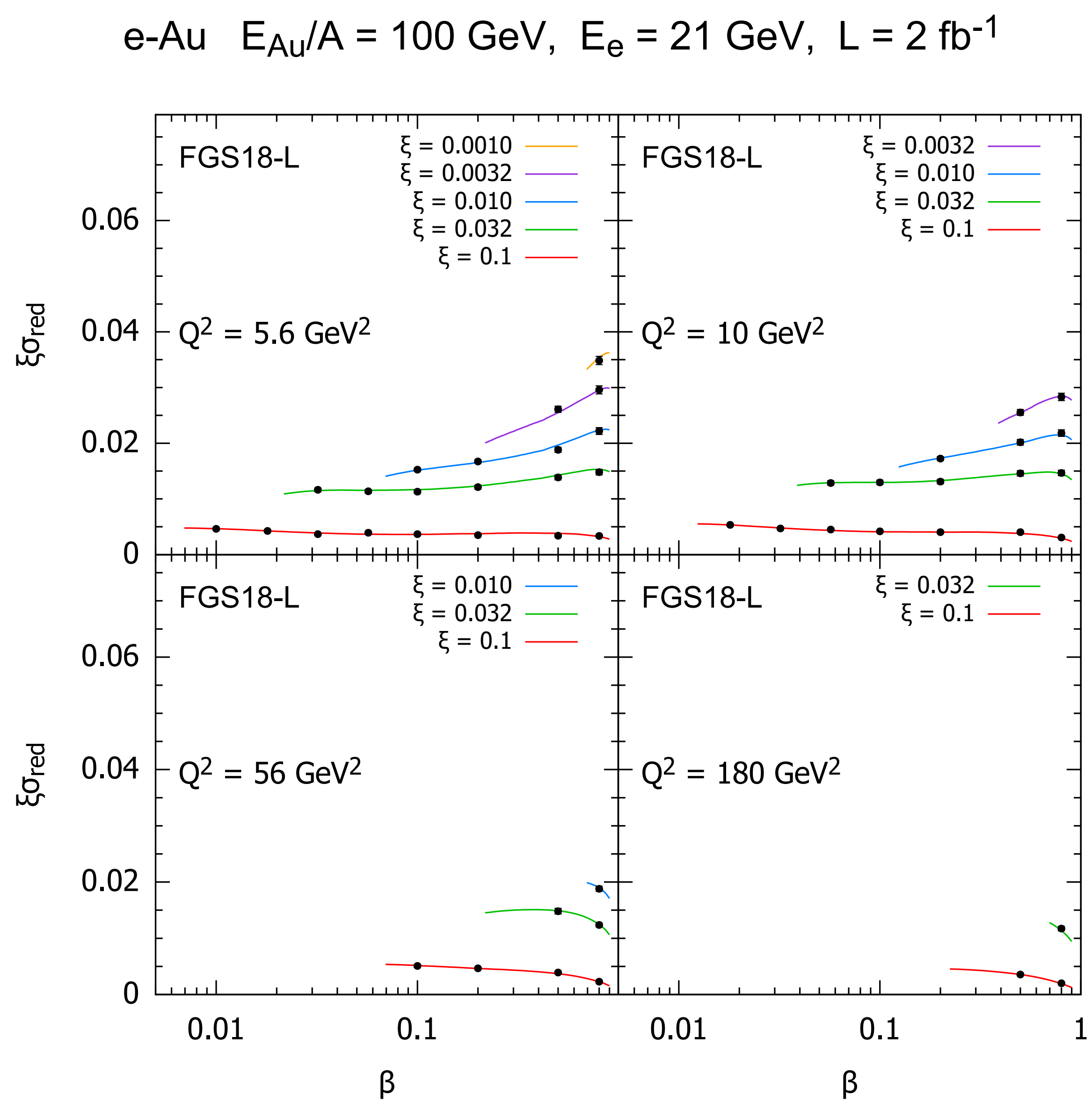
Inclusive diffraction on nuclei

Nuclear shadowing and diffraction are related (Gribov)

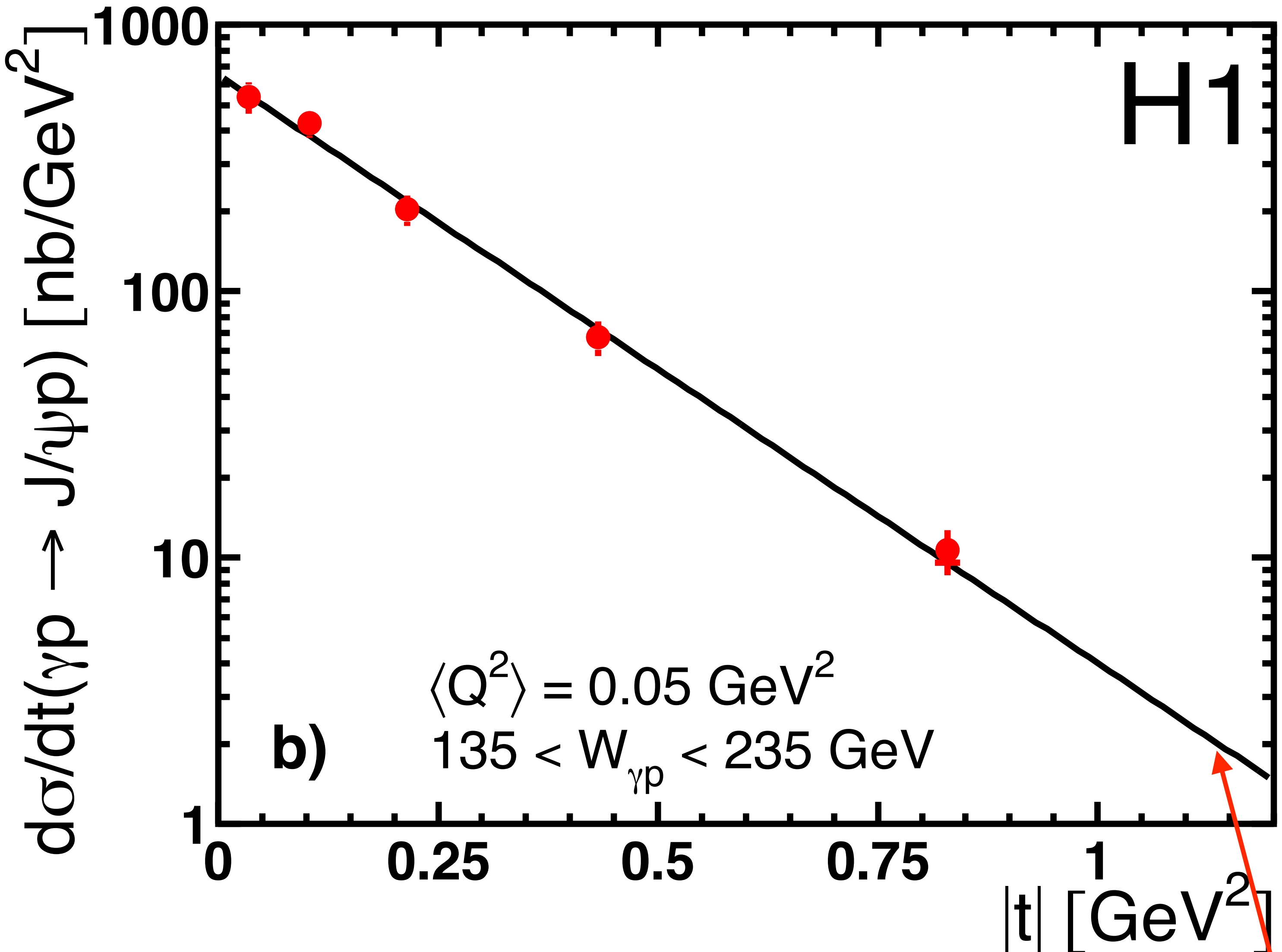
Nuclear modification factors from the model by Frankfurt-Guzey-Strikman **High quality data**

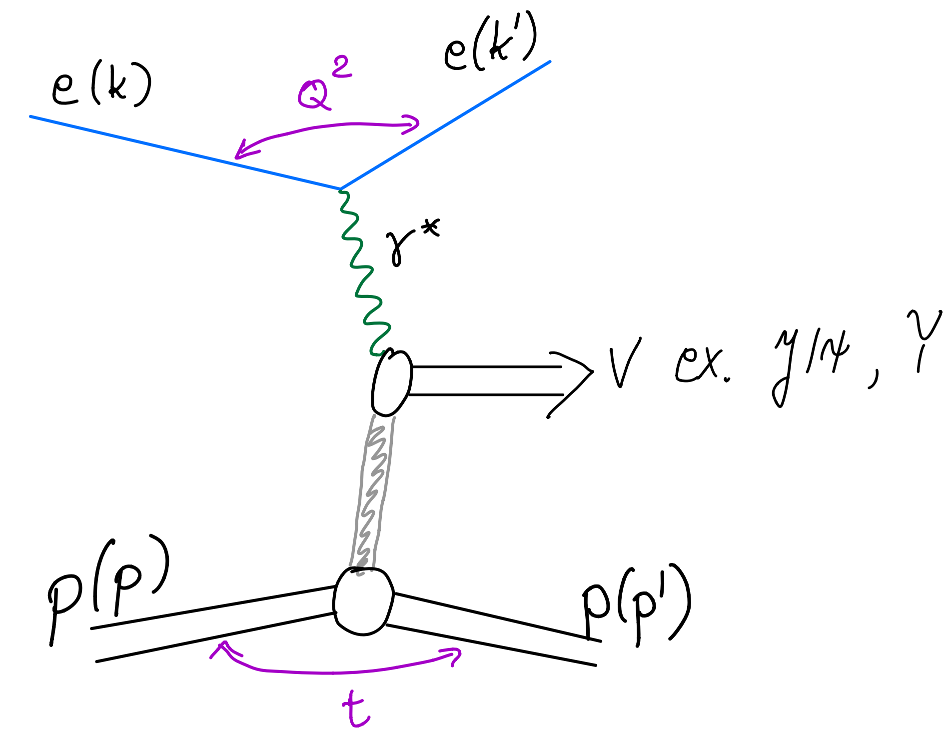
Two scenarios for high (H) and low (L) shadowing considered





Elastic diffractive vector - meson production





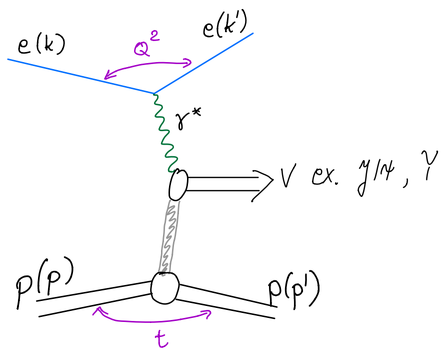
$$t = (p - p')^2 < 0$$

momentum transfer at the proton vertex

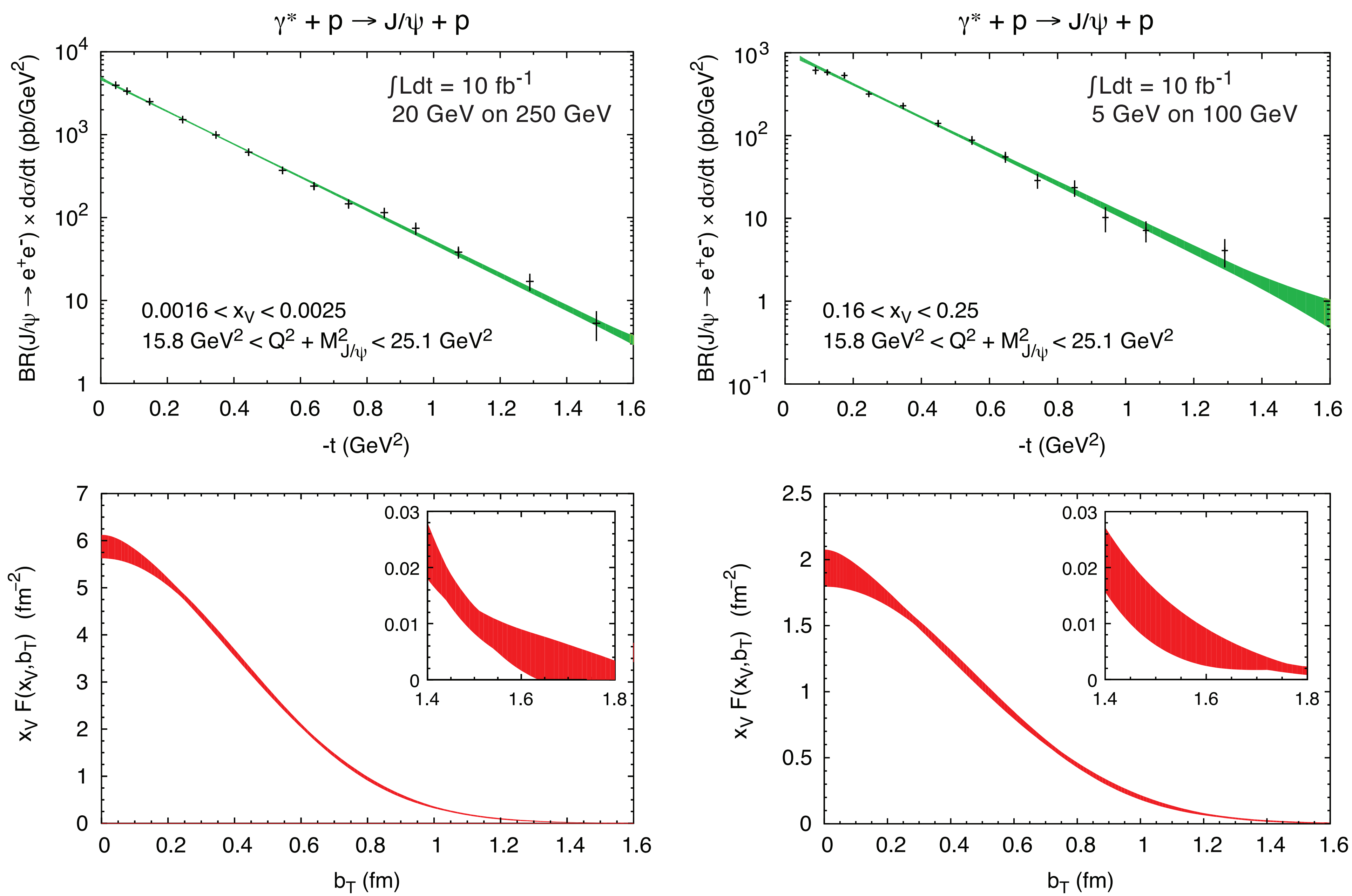
$$\frac{d\sigma}{dt} \sim e^{bt}$$

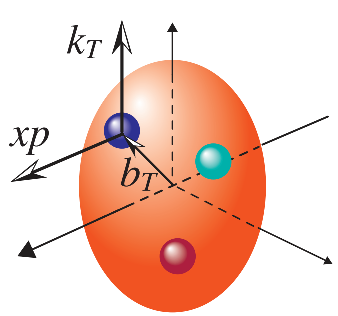
Exponential fit

Elastic vector – meson production at EIC



Fourier transform



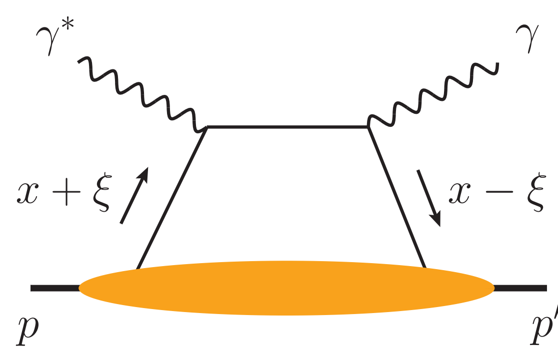


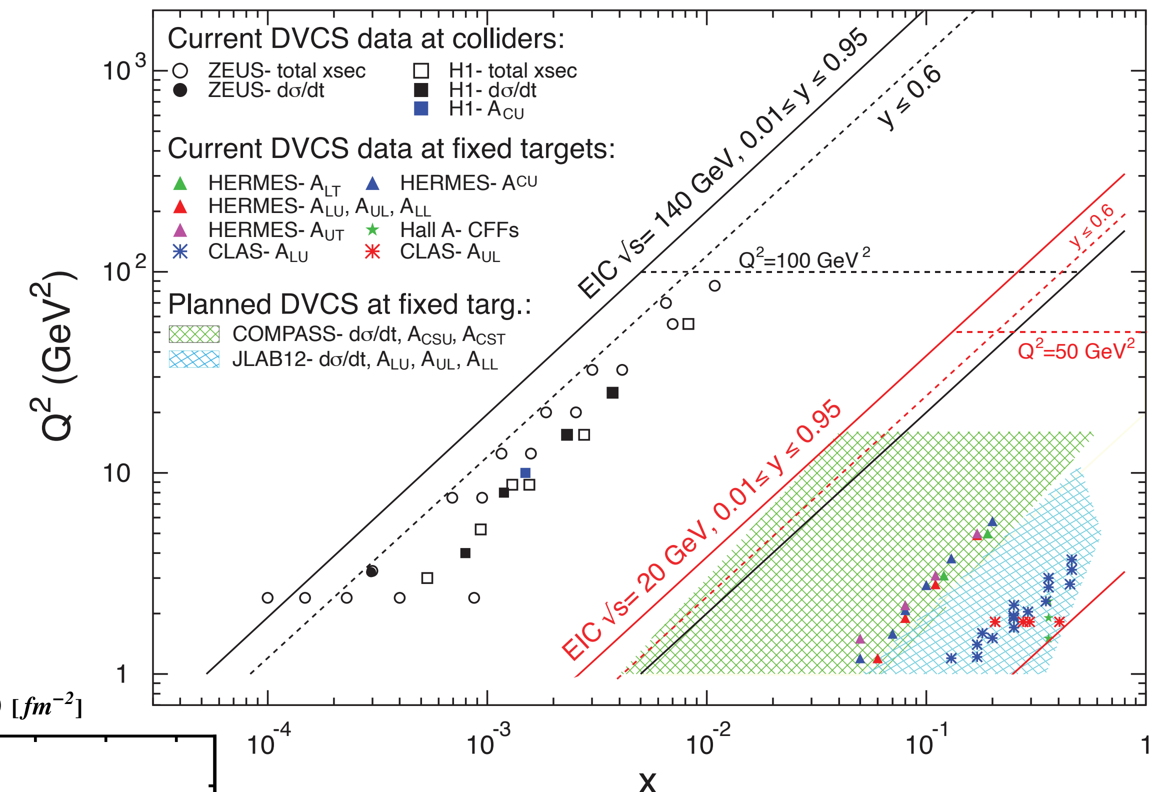
EIC, White paper

EIC: lower energy than HERA, different kinematics.
Very high statistics, high precision

Deeply Virtual Compton scattering

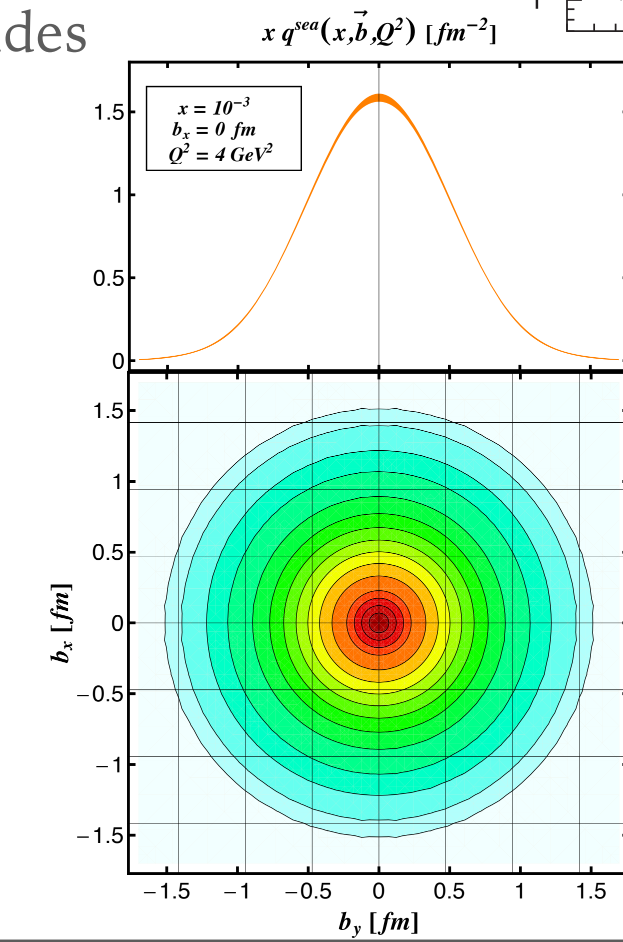
$$\gamma^* N \;\rightarrow\; \gamma N'$$





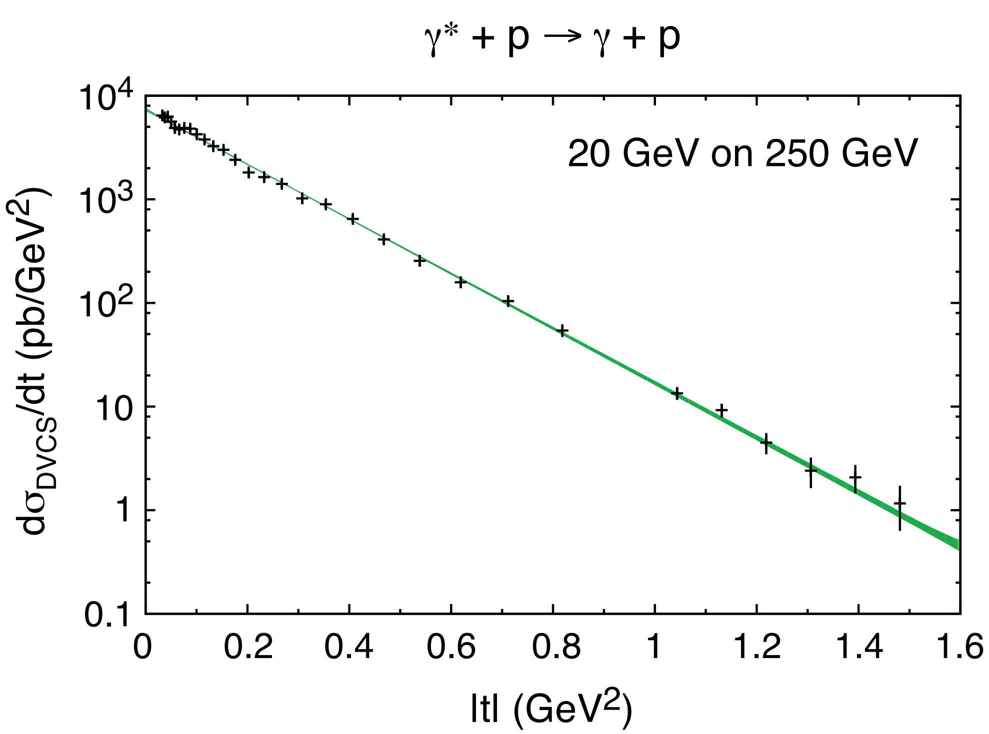
DVCS provides access to GPD generalized parton distribution. Information on quarks

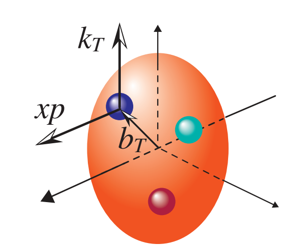
Measurement of the t-dependence provides info on b-dependence



Distribution in impact parameter of quarks.

Details of extraction depend crucially on the range of measured t.



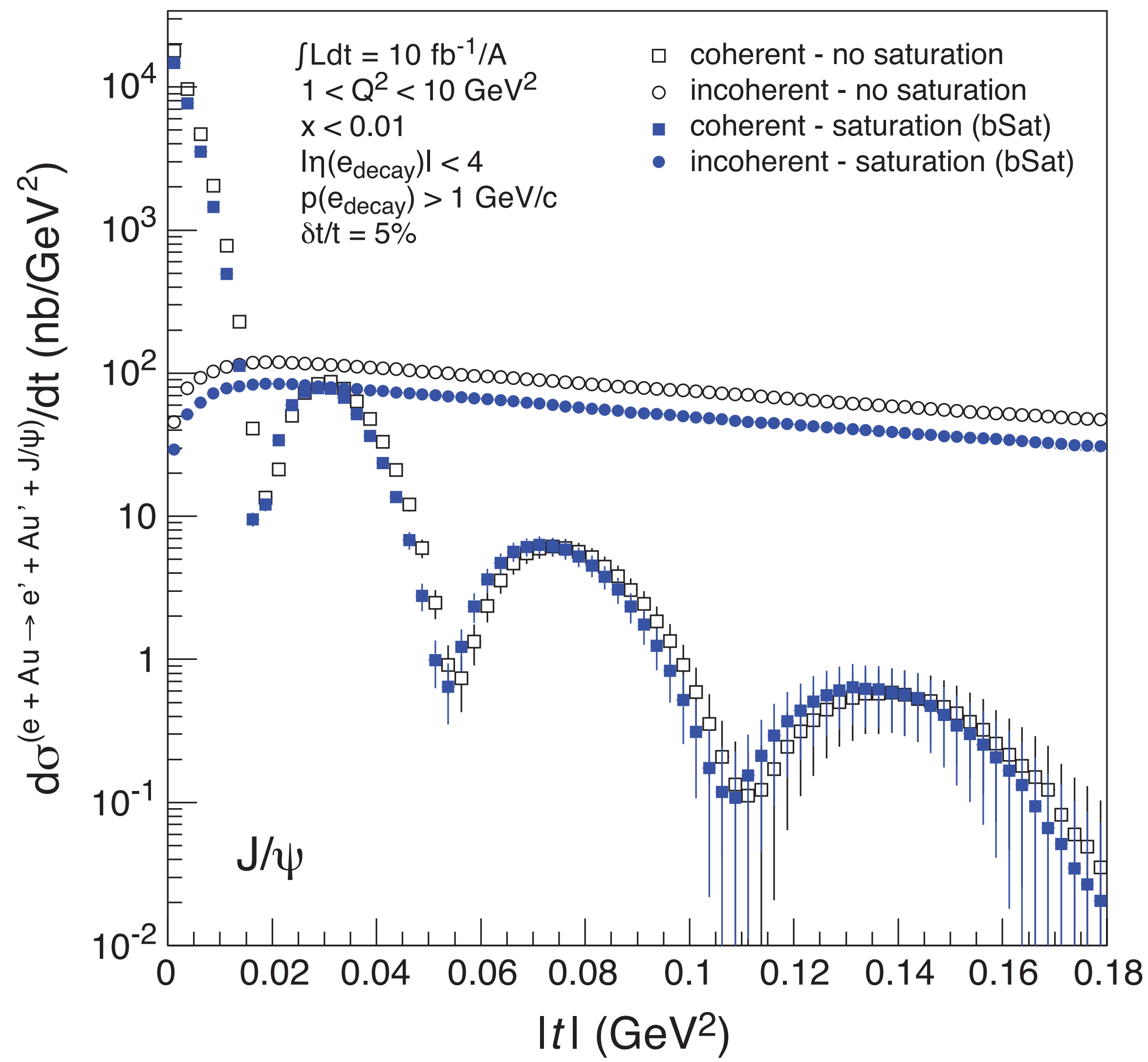


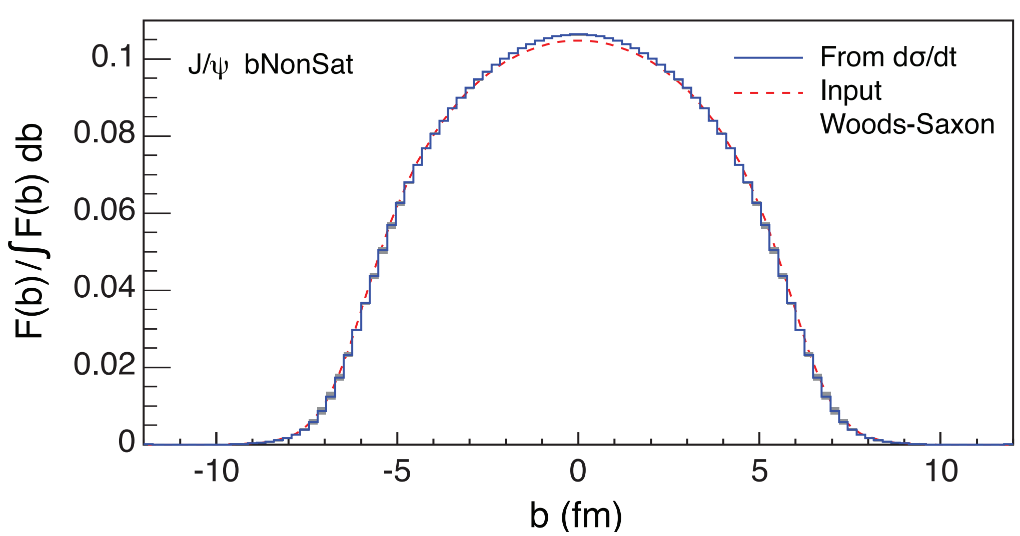
Elastic vector-meson production on nuclei

Nuclear target: Au

$$e + Au \rightarrow e + Au + J/\psi$$

Characteristic ‘dips’ in t-distribution

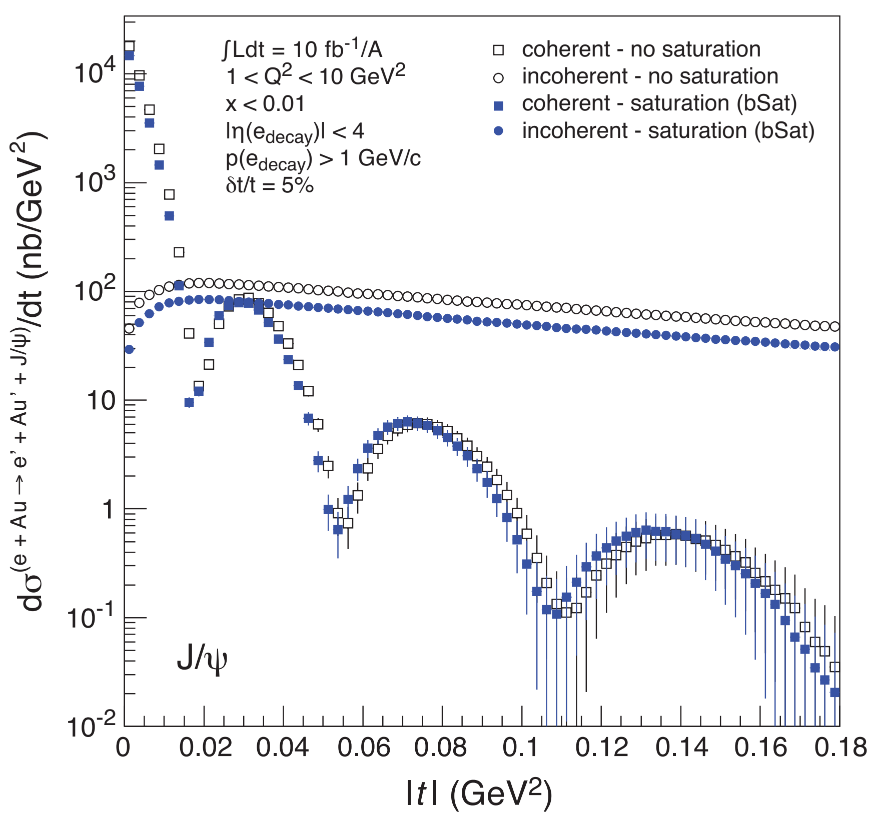


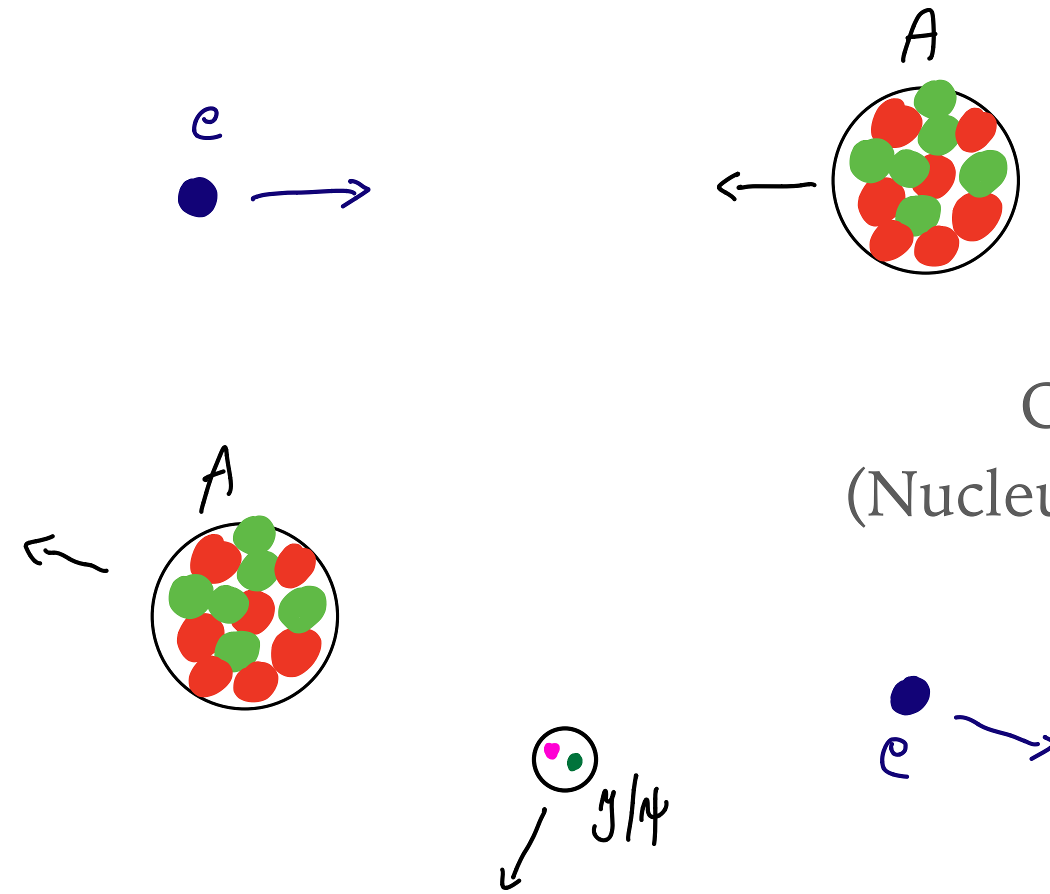


$$F(b) = \int_0^\infty \frac{q\,dq}{2\pi} J_0(qb) \sqrt{\frac{d\sigma_{\rm coherent}}{dt}}$$

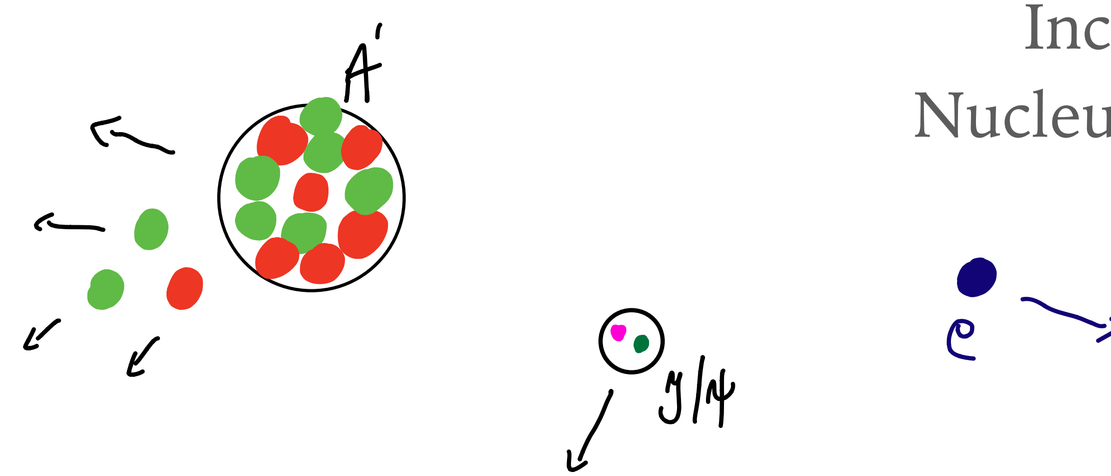
$$t = -q^2$$

Coherent vs incoherent





Coherent
(Nucleus stays intact)



Incoherent
Nucleus breaks up

Coherent:

Depends on the shape of the source, average distribution

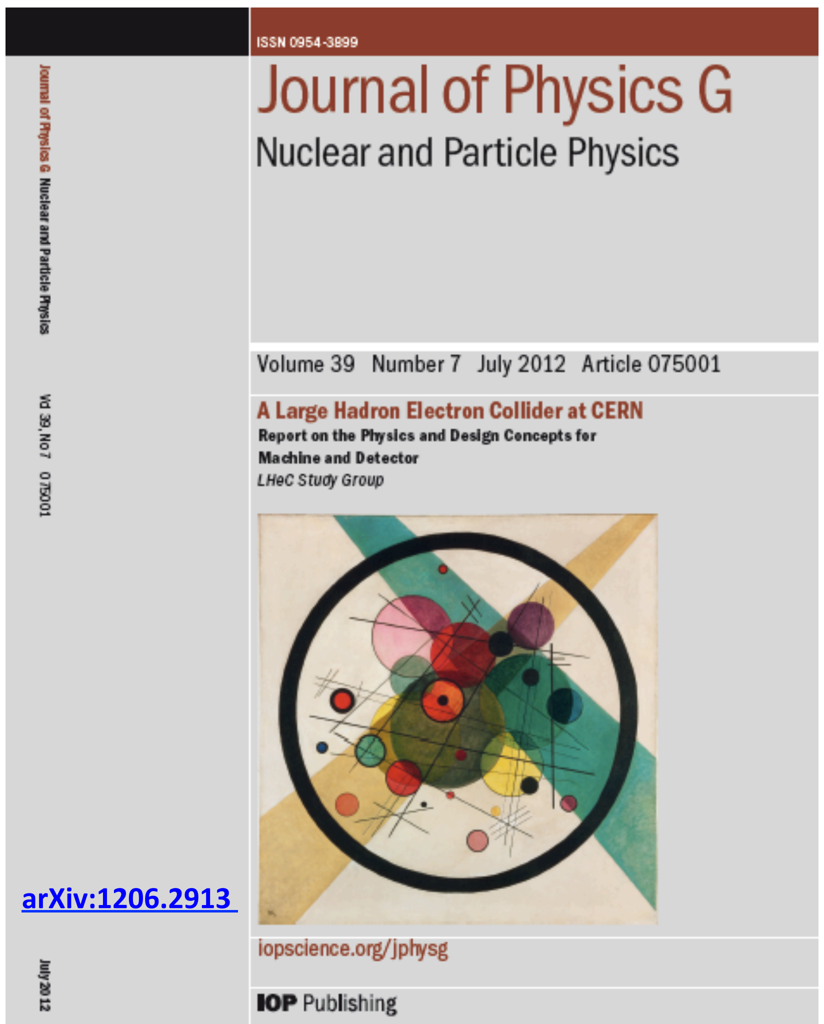
Incoherent:

Provides information about the fluctuations or lumpiness of the source

LHeC conceptual design report and beyond

CDR 2012: commissioned by CERN, ECFA, NuPECC, 200 authors, 69 institutions

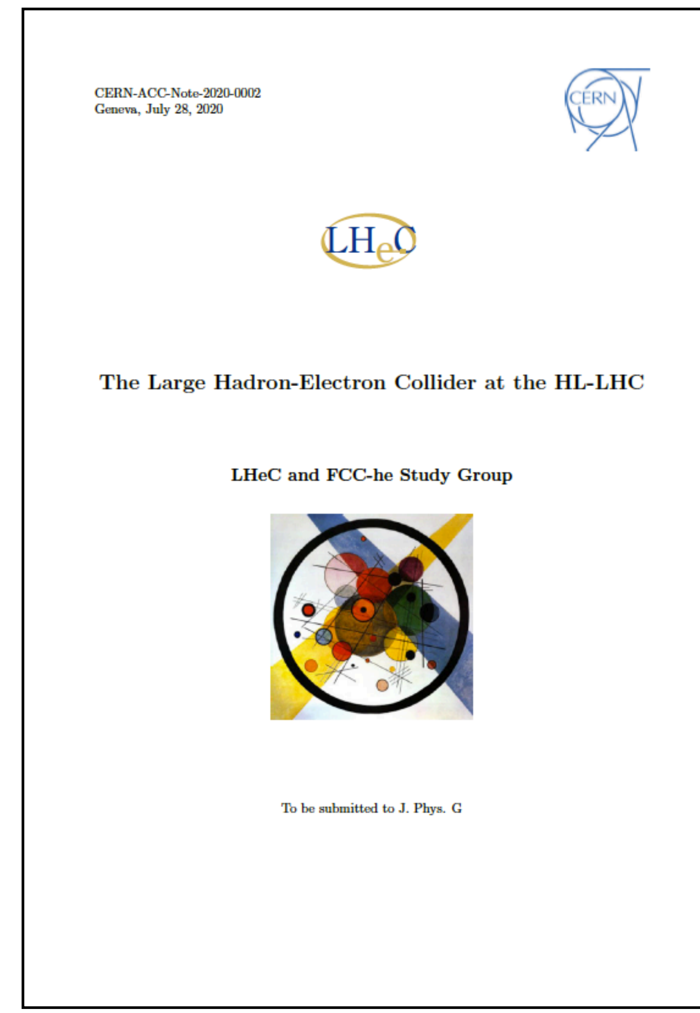
CDR update 2020: 300 authors, 156 institutions



arXiv:1206.2913

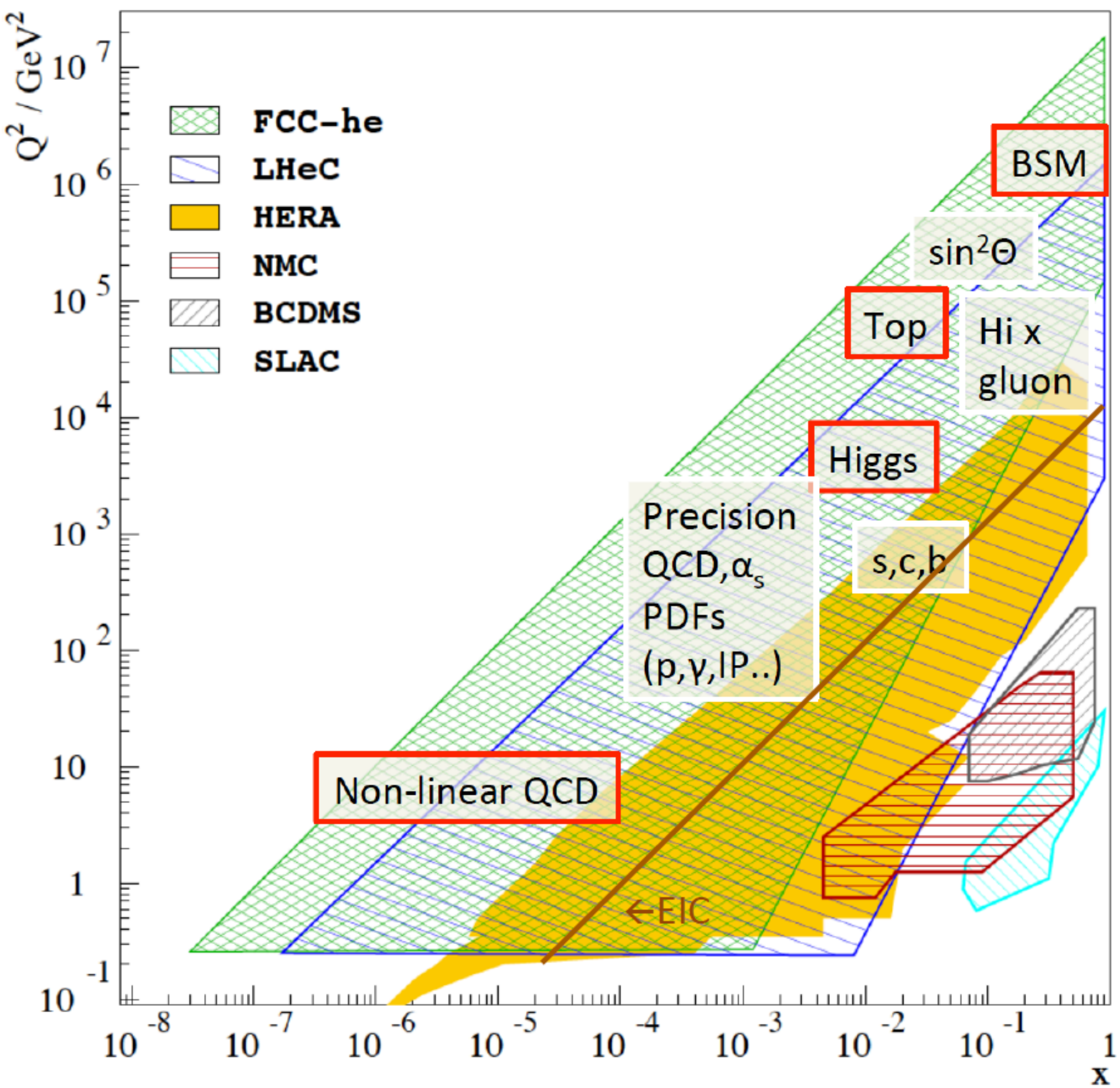
Further selected references:

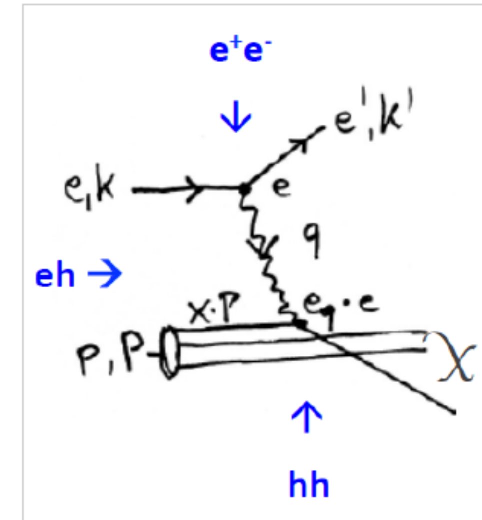
- 'On the relation of the LHeC and the LHC' arXiv:1211.5102
- 'The Large Hadron electron Collider' arXiv:1305.2090
- 'Dig Deeper' Nature Physics 9 (2013) 448
- 'Future Deep Inelastic Scattering with the LHeC' arXiv:1802.04317



arXiv:2007.14491

Physics with LHeC and FCC-eh





ep/eA collider: cleanest high resolution microscope

Precision and discovery in QCD

Study of EW physics, multi-jet final states

Empower the LHC/FCC search programme

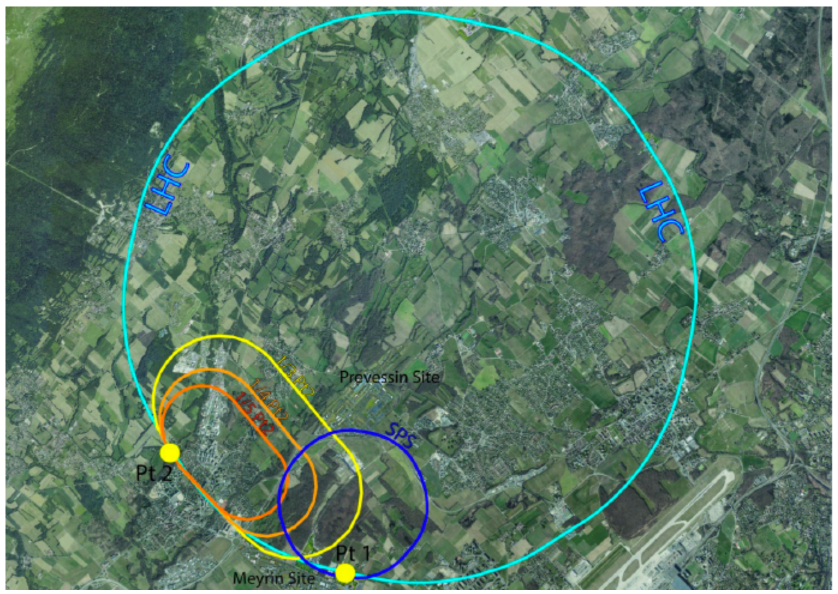
Transform the LHC/FCC into a high precision Higgs facility

Unique and complementary potential for the BSM particles (prompt and long lived)

Overall: a unique Particle and Nuclear Physics Facility

Accelerator concepts for ep scattering

LHeC, PERLE and FCC-eh



50 x 7000 GeV^2: 1.2 TeV ep collider

Operation: 2035+, Cost: O(1) BCHF

CDR: 1206.2913 J.Phys.G (550 citations)

Upgrade to 10^{34} cm^{-2}s^{-1}, for Higgs, BSM

CERN-ACC-Note-2018-0084 (ESSP)

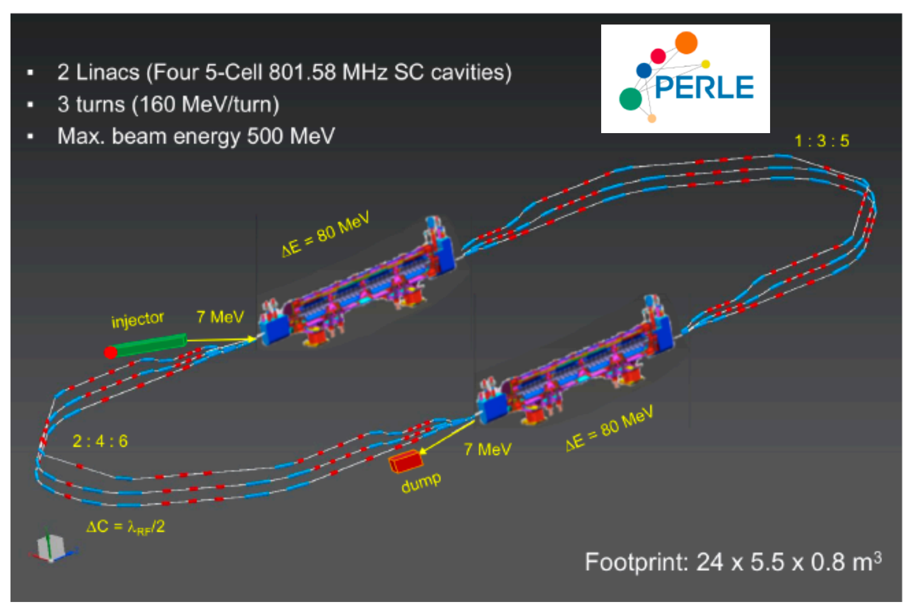
arXiv:2007.14491, subm J.Phys.G

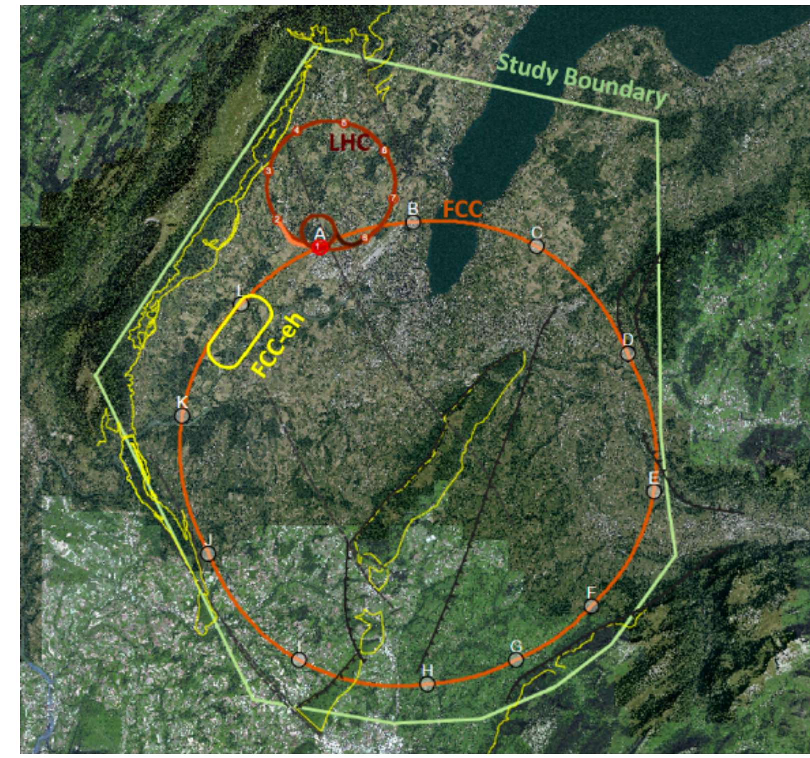
Powerful ERL for Experiments @ Orsay
CDR: 1705.08783 J.Phys.G
CERN-ACC-Note-2018-0086 (ESSP)

Operation: 2025+, Cost: O(20) MEuro

LHeC ERL Parameters and Configuration
I_e=20mA, 802 MHz SRF, 3 turns →
E_e=500 MeV → first 10 MW ERL facility

BINP, CERN, Daresbury, Jlab, Liverpool, Orsay (IJC), +





60 x 50000 GeV^2: 3.5 TeV ep collider

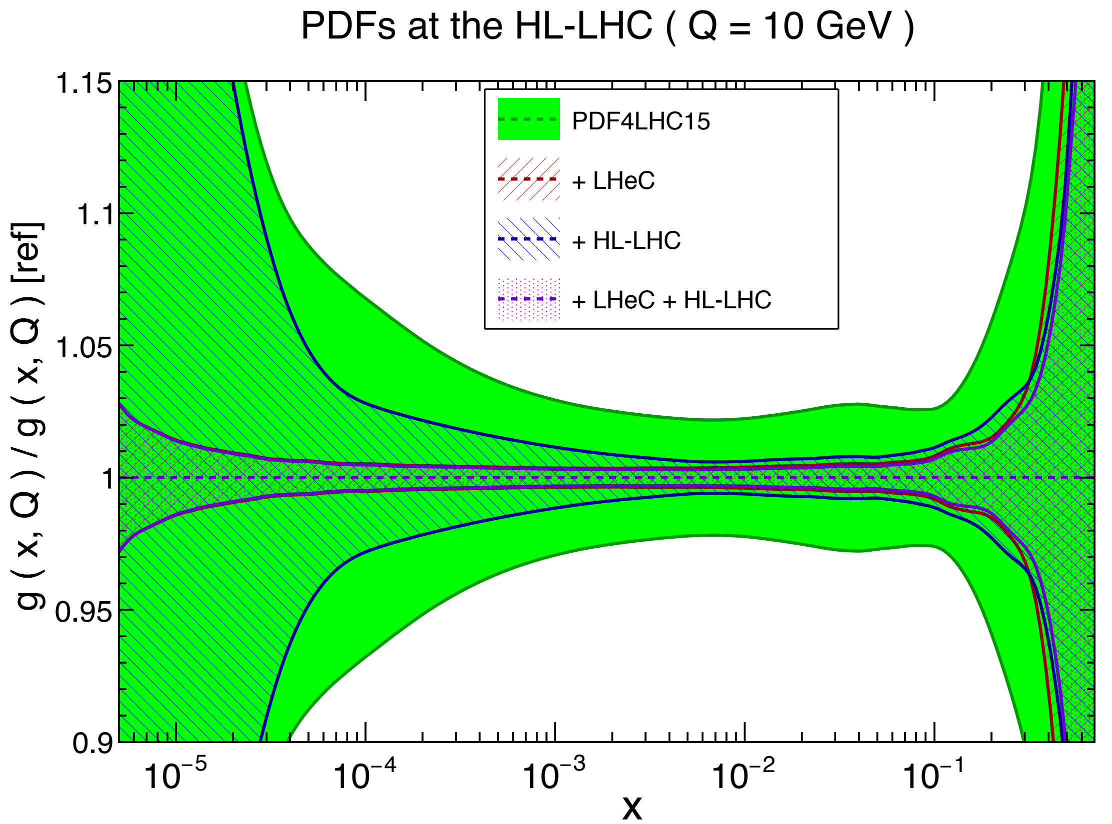
Operation: 2050+, Cost (of ep) O(1-2) BCHF

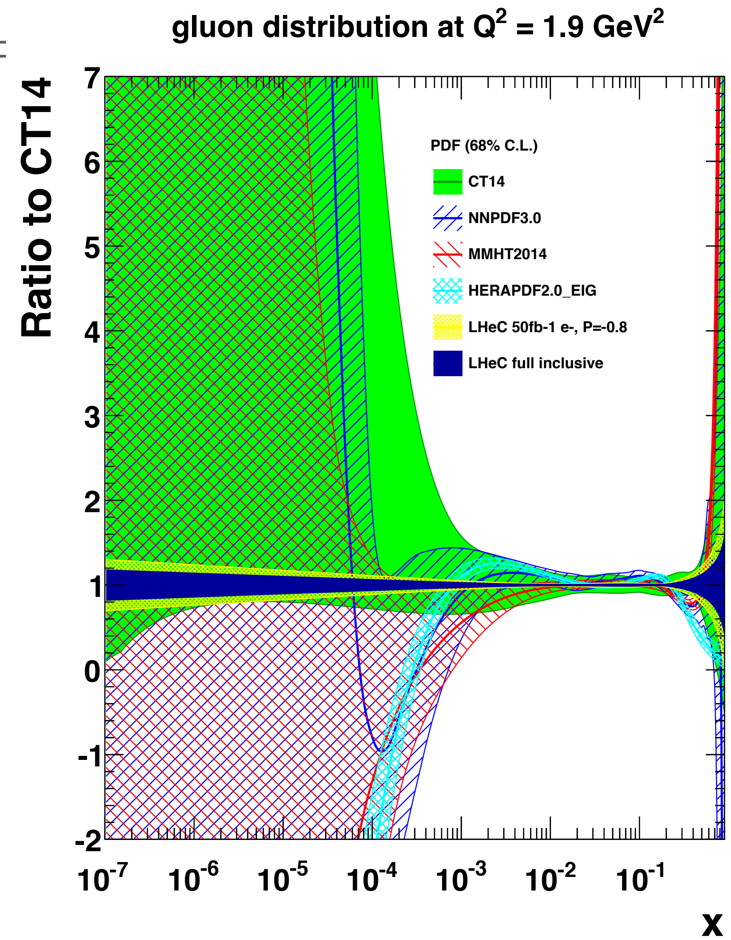
Concurrent Operation with FCC-hh

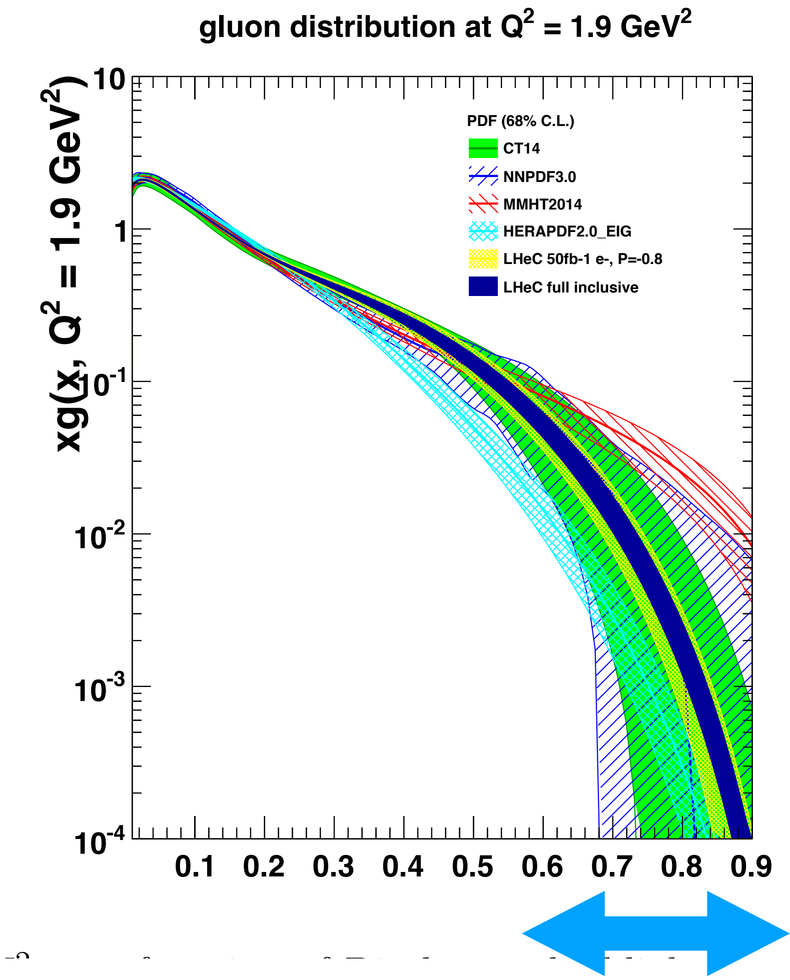
FCC CDR:
Eur.Phys.J.ST 228 (2019) 6, 474 Physics
Eur.Phys.J.ST 228 (2019) 4, 755 FCC-hh/eh

Future CERN Colliders: 1810.13022 Bordry+

QCD parton densities at LHeC





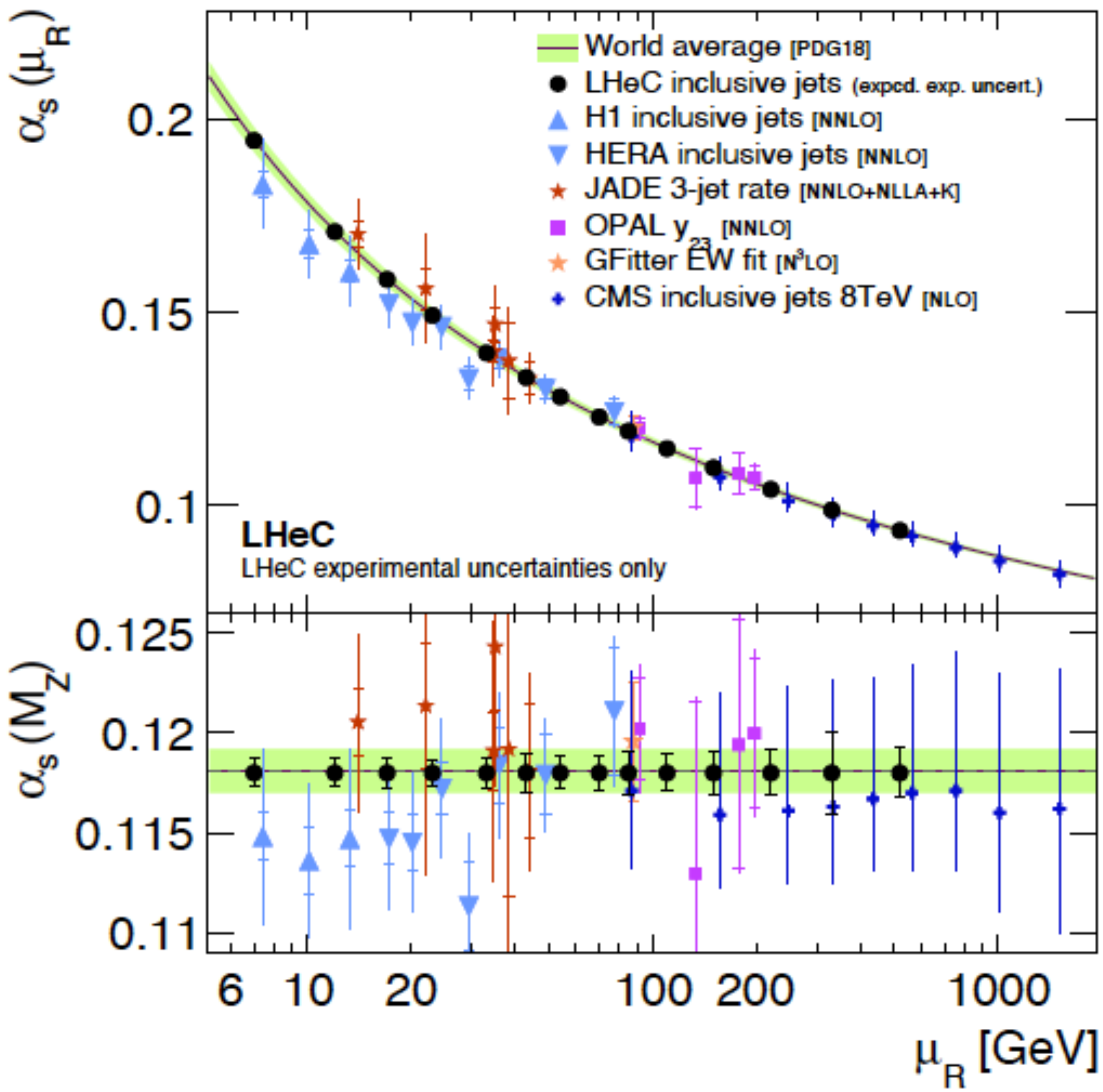


Range relevant for production of heavy states

- ✦ Complete unfolding of parton contents in unprecedented kinematic range: u,d,s,c,b,t,g
- ✦ Low x : novel QCD dynamics, BFKL and/or saturation
- ✦ Medium x: precision Higgs and EW
- ✦ High x: new particle frontier

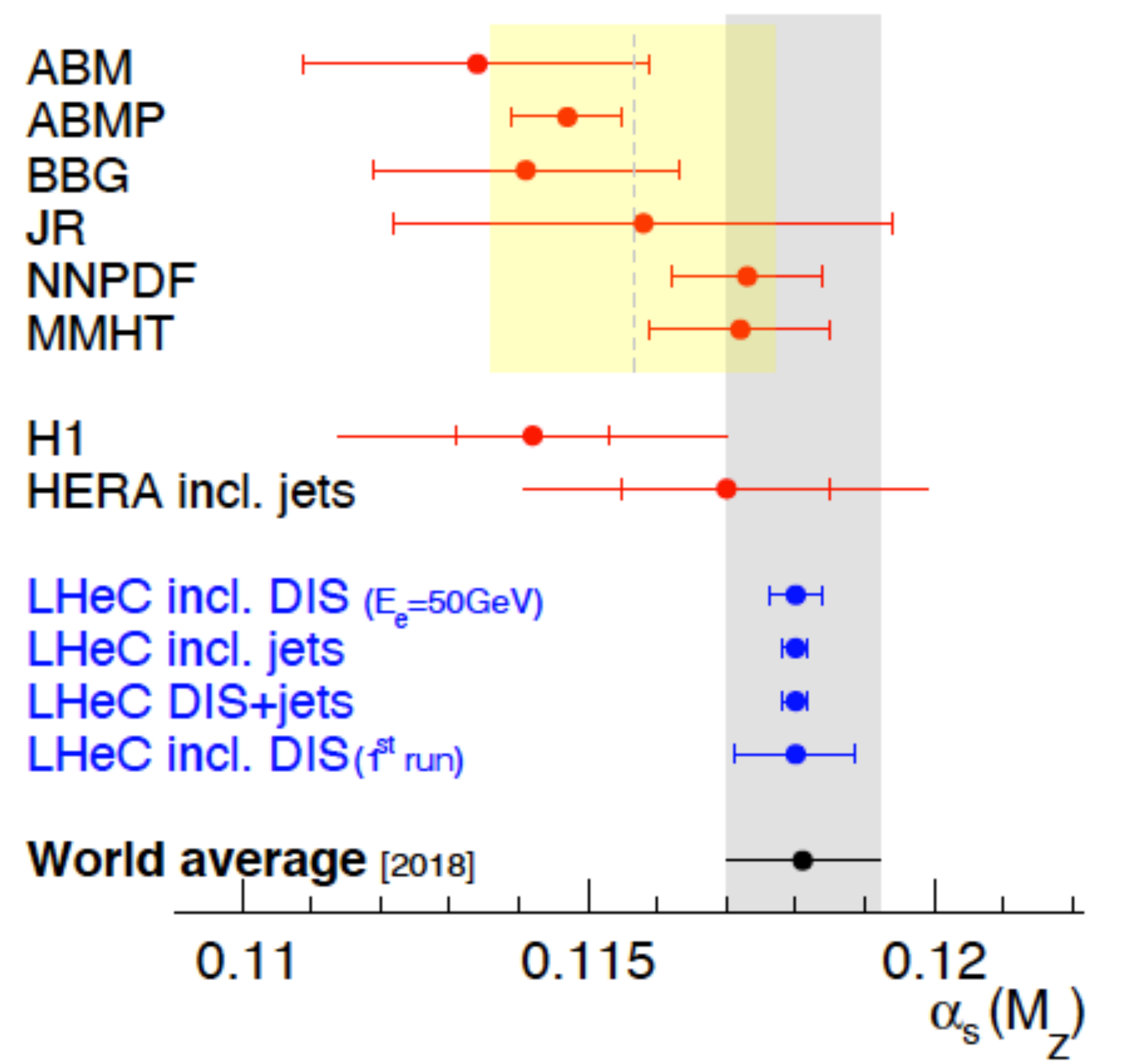
Determination of the strong coupling constant at LHeC

Strong coupling determined to permille accuracy (inclusive + jets)



$$\Delta\alpha_s(M_Z)(\text{incl. DIS}) = \pm 0.00022_{(\text{exp+PDF})}$$

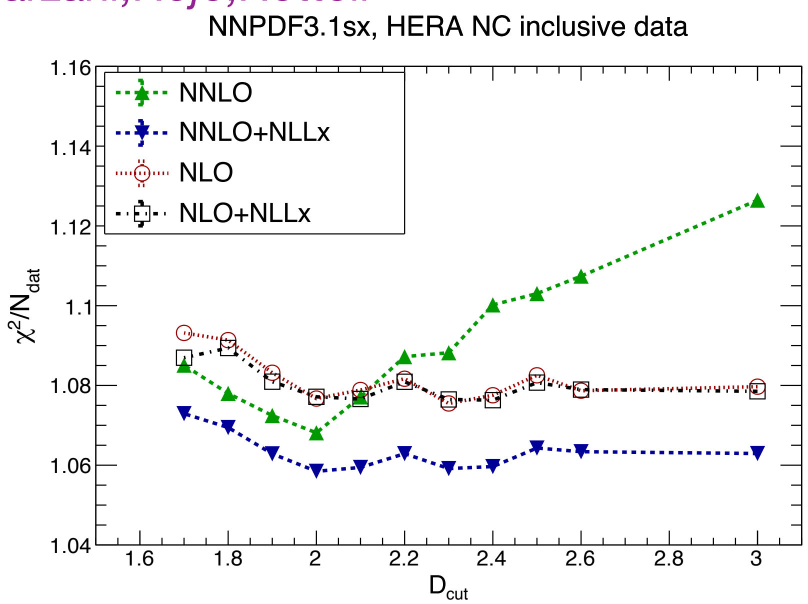
$$\Delta\alpha_s(M_Z)(\text{incl. DIS \& jets}) = \pm 0.00018_{(\text{exp+PDF})}$$



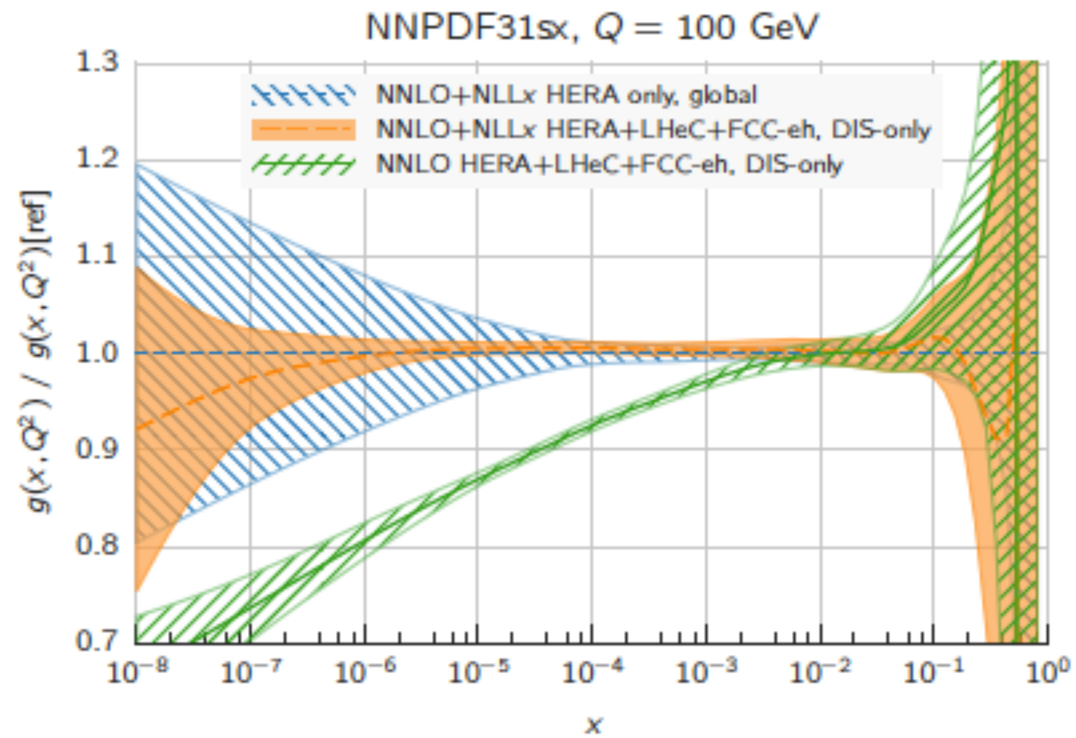
Novel dynamics at small x: resummation

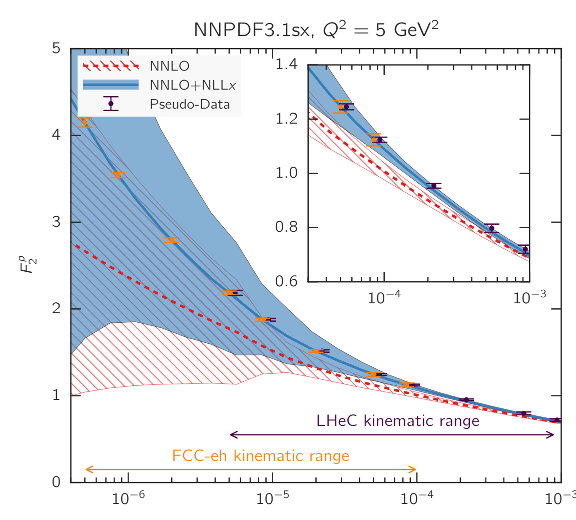
Ball, Bertone, Bonvini, Marzani, Rojo, Rottoli

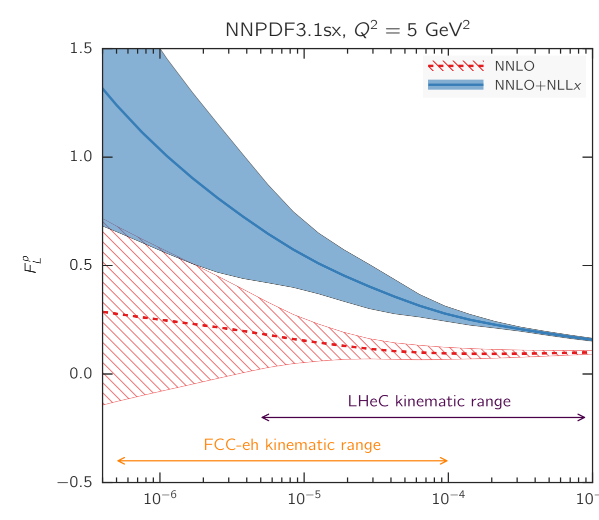
Resummation at low x needed to stabilize the BFKL expansion



Marked improvement of the quality of the fit at NNLO + small x resummation

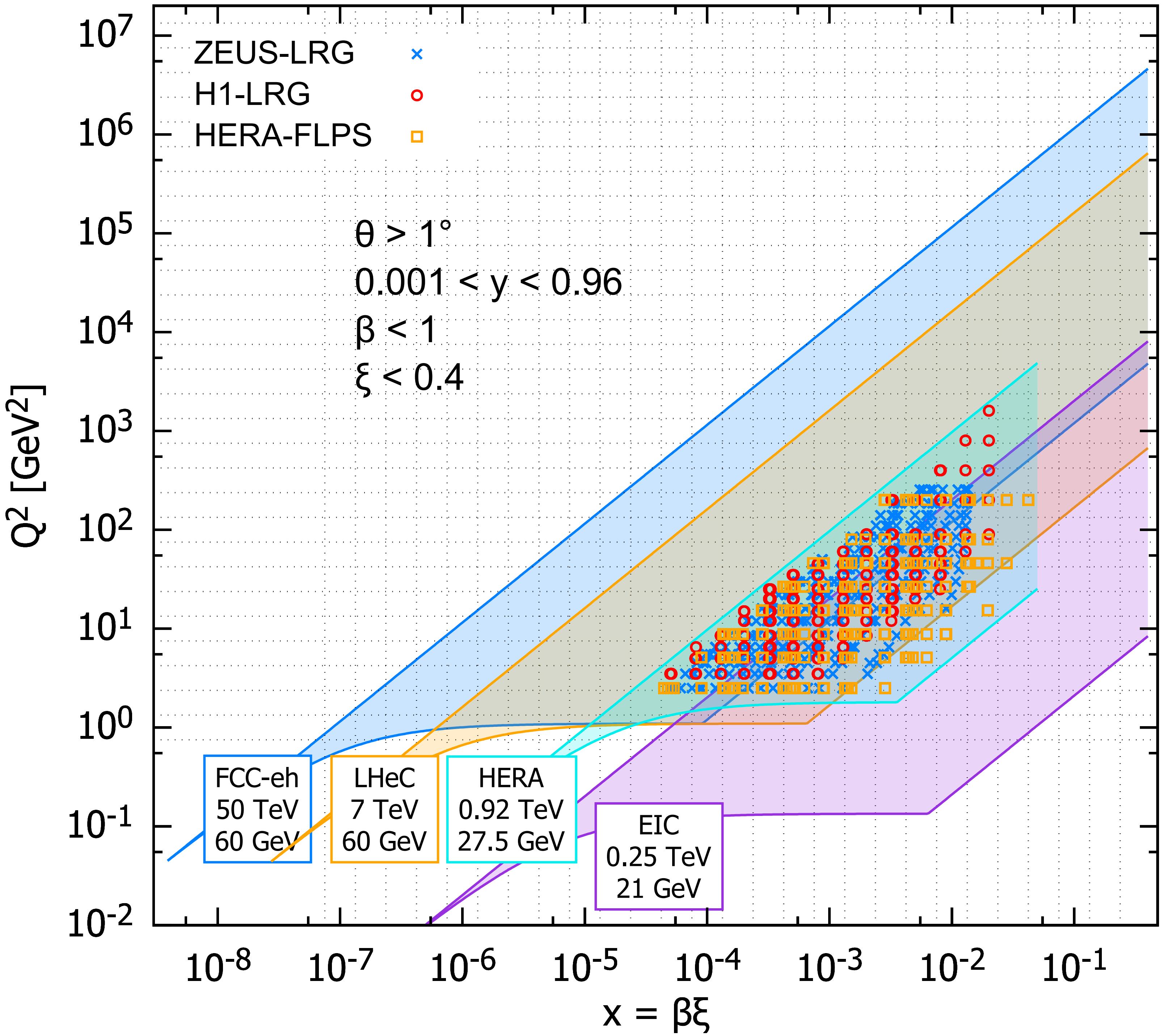






Important consequences for the LHeC and FCC-eh: large differences!

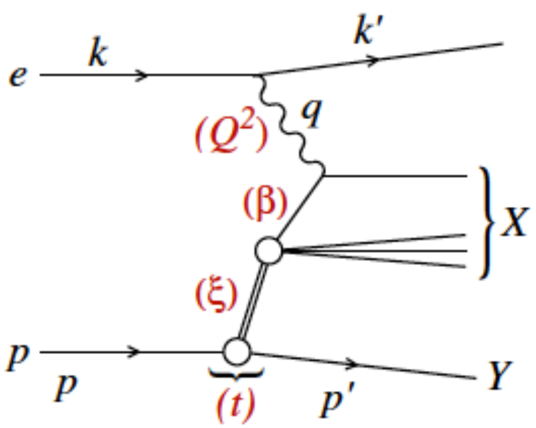
Diffraction phase space EIC-HERA-LHeC-FCC-eh



LHeC: x down to 10^{-6}-10^{-7}, Q^2 to 10^5 GeV^2

FCC-eh: x down to 10^{-8}, Q^2 to 5 x 10^6 GeV^2

Prospects for diffraction

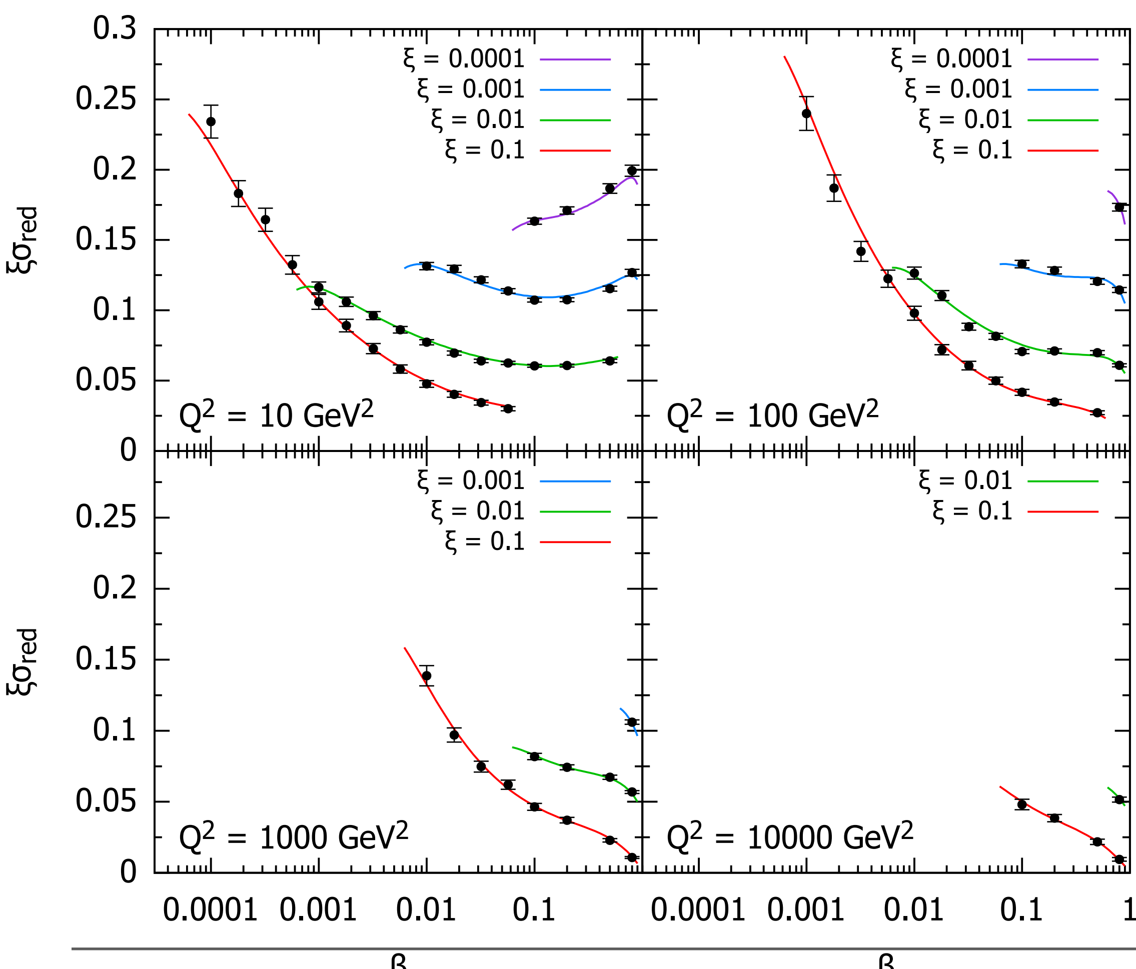


$$x = \xi\beta$$

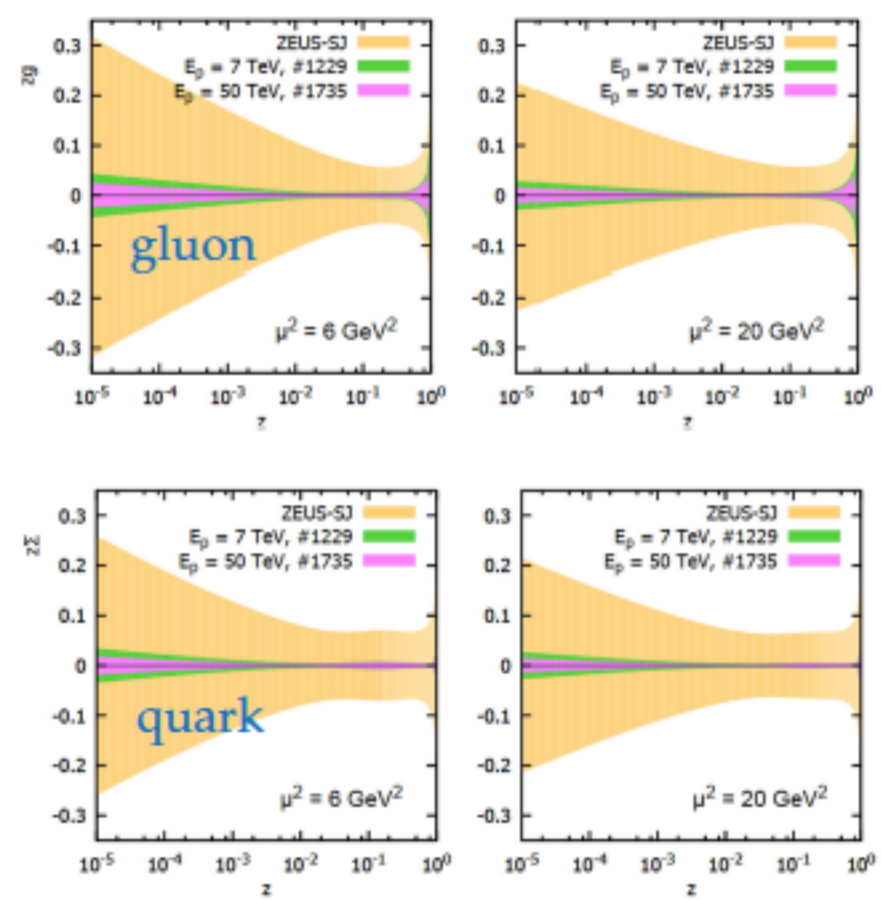
- Substantial extension of diffractive kinematic regime
- Precision measurement of inclusive diffraction already with very conservative luminosity
- Improvement of diffractive PDFs by order of magnitude, precision checks of collinear and soft factorization
- Diffraction in nuclei, relation between diffraction and shadowing
- Charged currents, top contribution

Diffractive reduced cross section at LHeC

e p $E_p = 7$ TeV, $E_e = 60$ GeV, $L = 2\ fb^{-1}$



Diffractive PDFs

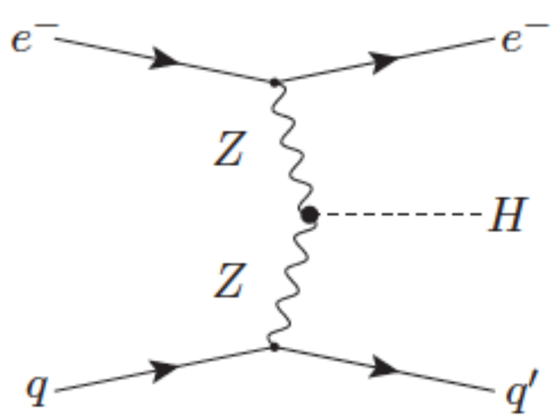


$Q^2_{\min} \approx 5\ \text{GeV}^2$

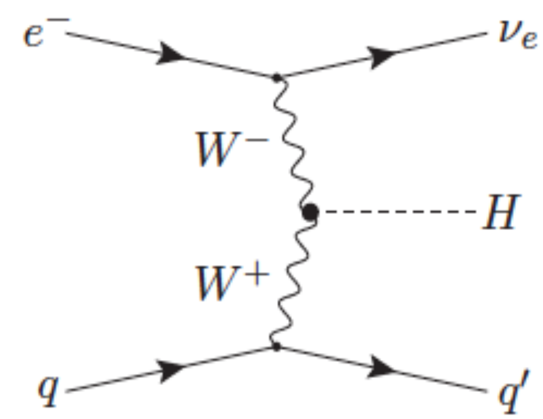
Accuracy increased by
- ✓ factor ~10 for LHeC
- ✓ factor ~20 for FCC-he

Higgs physics at high energy ep collider

neutral current



charged current



Parameter	Unit	LHeC	HE-LHeC	FCC-eh	FCC-eh
E_p	TeV	7	13.5	20	50
$\sqrt{s}$	TeV	1.30	1.77	2.2	3.46
σ_{CC} $(P=-0.8)$	fb	197	372	516	1038
σ_{NC} $(P=-0.8)$	fb	24	48	70	149
σ_{CC} $(P=0)$	fb	110	206	289	577
σ_{NC} $(P=0)$	fb	20	41	64	127
HH in CC	fb	0.02	0.07	0.13	0.46

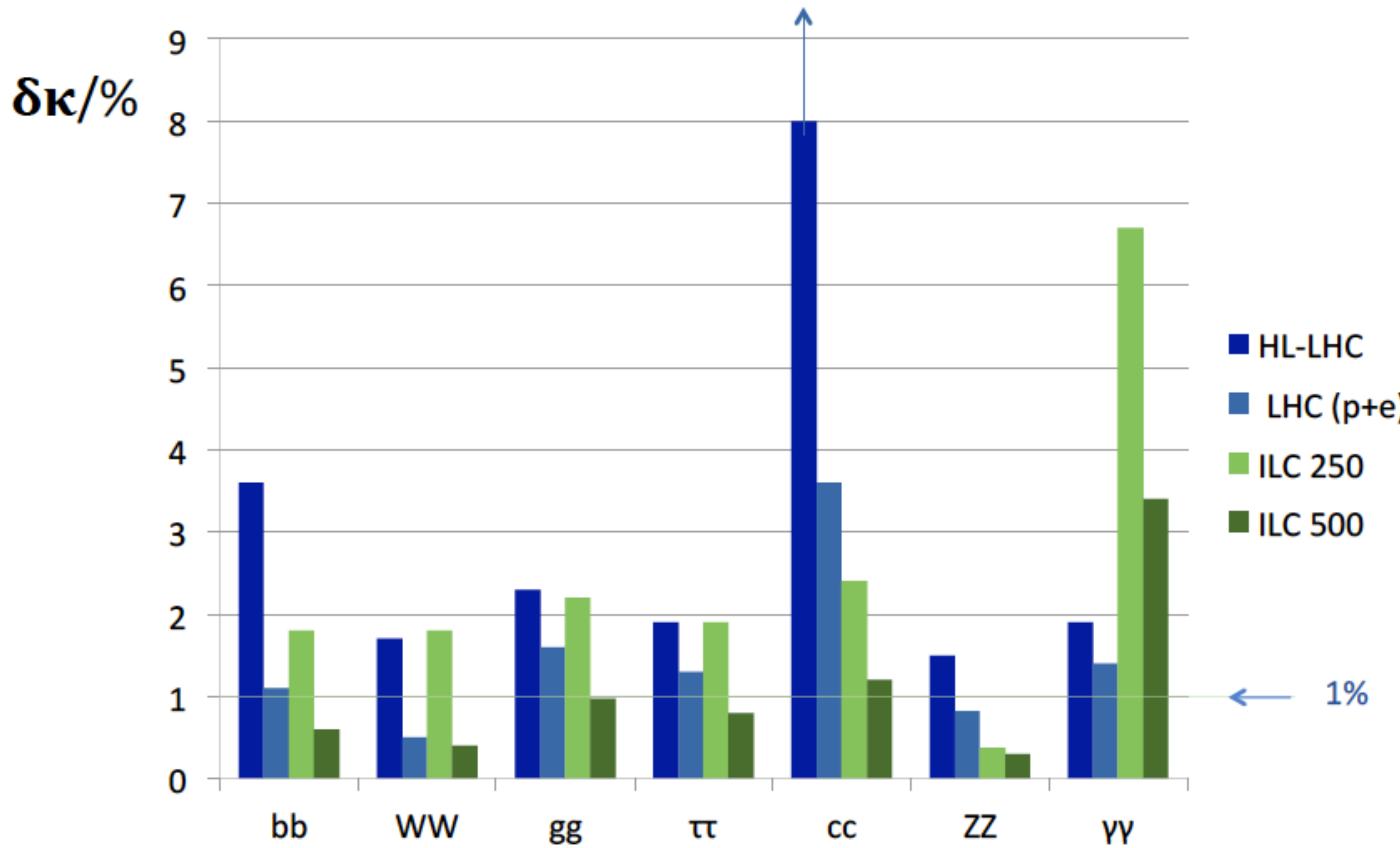
- Cross section for NC and CC Higgs production through vector boson fusion makes study possible with foreseen luminosities

- Large Higgs dataset for precision measurements.

		Number of Events			
		Charged Current		Neutral Current	
Channel	Fraction	LHeC	FCC-eh	LHeC	FCC-eh
$b\bar{b}$	0.581	114 500	1 208 000	14 000	175 000
W^+W^-	0.215	42 300	447 000	5 160	64 000
gg	0.082	16 150	171 000	2000	25 000
$\tau^+\tau^-$	0.063	12 400	131 000	1 500	20 000
$c\bar{c}$	0.029	5700	60 000	700	9 000
ZZ	0.026	5 100	54 000	620	7 900
$\gamma\gamma$	0.0023	450	5 000	55	700
$Z\gamma$	0.0015	300	3 100	35	450
$\mu^+\mu^-$	0.0002	40	410	5	70
σ [pb]		0.197	1.04	0.024	0.15

Integrated lumi: LHeC 1 ab^{-1} FCC-eh 2 ab^{-1}

Higgs couplings: ep+pp combination



K_i : coupling strength modified parameters
Powerful method to parametrise possible deviations from SM couplings
Can directly compare the different colliders

- HL-LHC and LHeC analyzed jointly
- Evident substantial improvement to HL-LHC by addition of ep
- Leads to precision of 1% for most couplings
- LHeC adds charm with precision of 3-4%, which is likely not accessible at HL-LHC
- Results comparable (or better) with ILC 250 GeV (2 ab^{-1}) , less precise than ILC 500 GeV (4 ab^{-1})

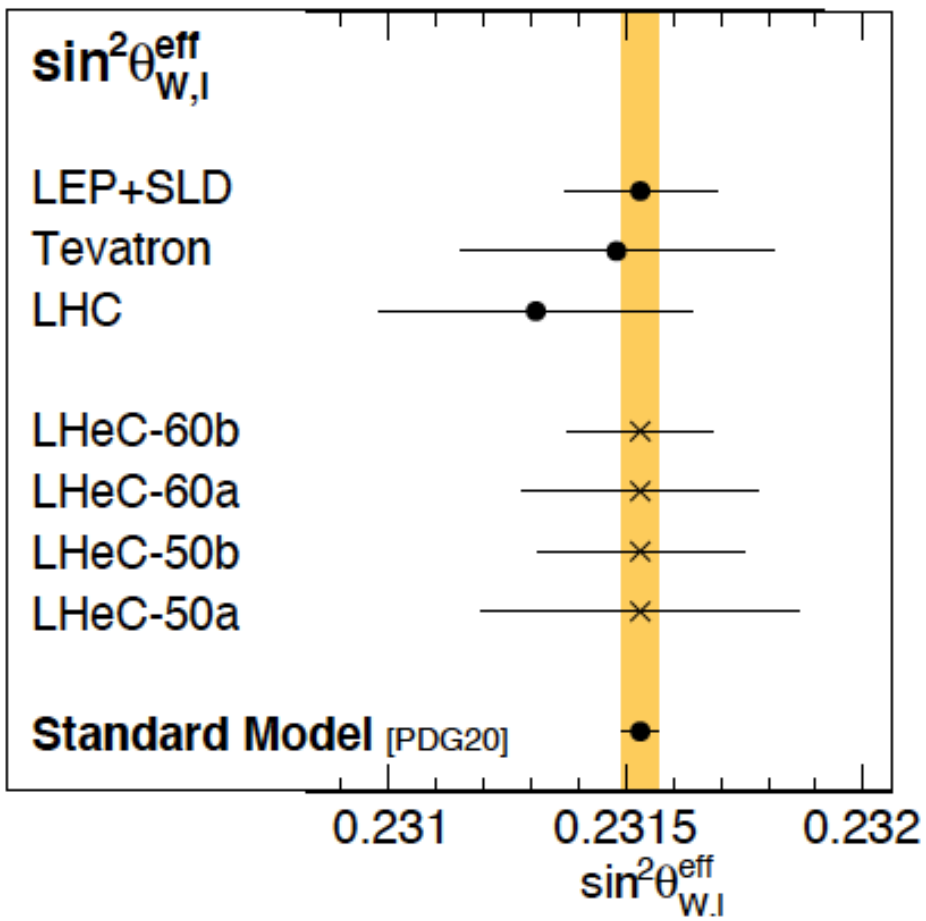
EW Physics: $\sin^2\theta_W$

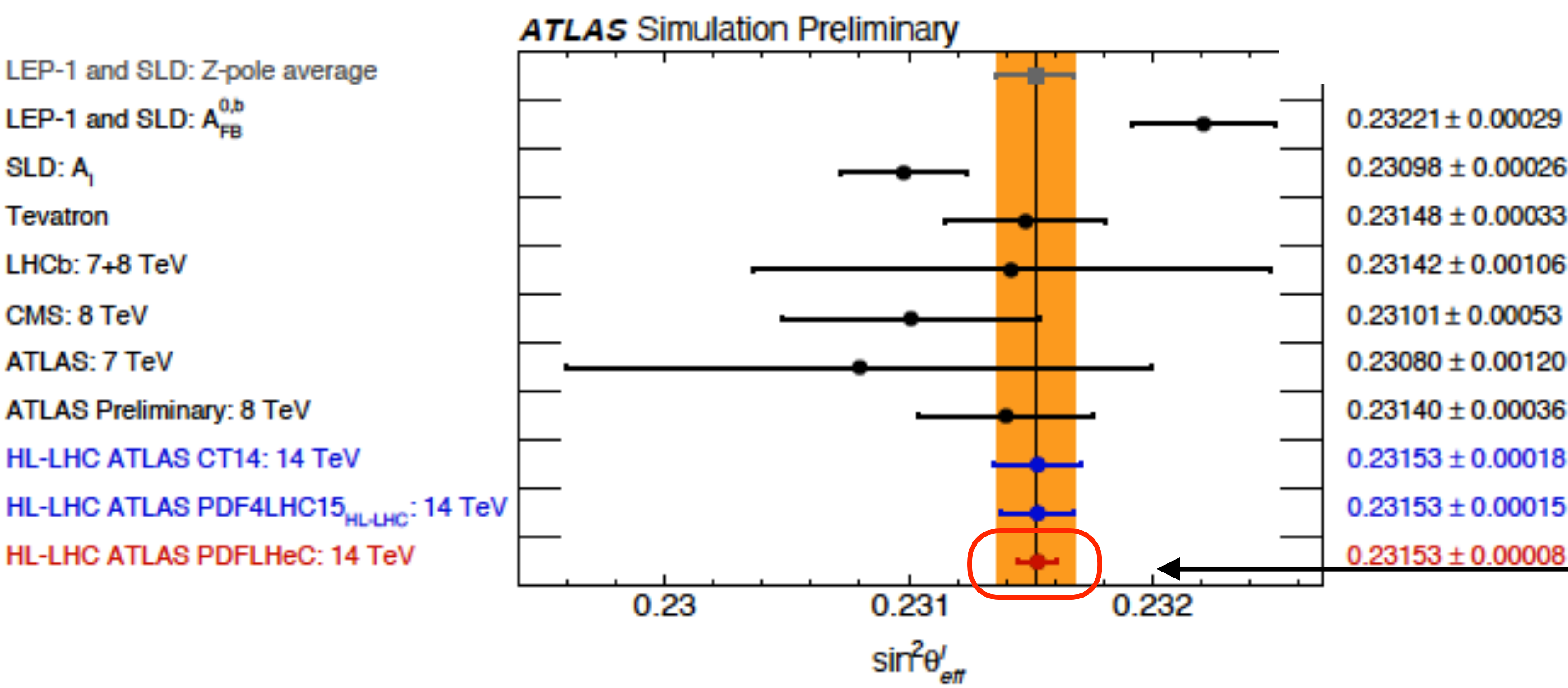
- Direct constraints on $\sin^2\theta_W^{\text{eff}}$ through higher order corrections:

$$\sin^2\theta_{W,f}^{\text{eff}}(\mu^2) = \kappa_f(\mu^2)\sin^2\theta_W$$

- Scale dependence through simultaneous fits with PDFs.

- Indirect measurements through improving LHC measurements (FB asymmetries).





LHeC PDFs

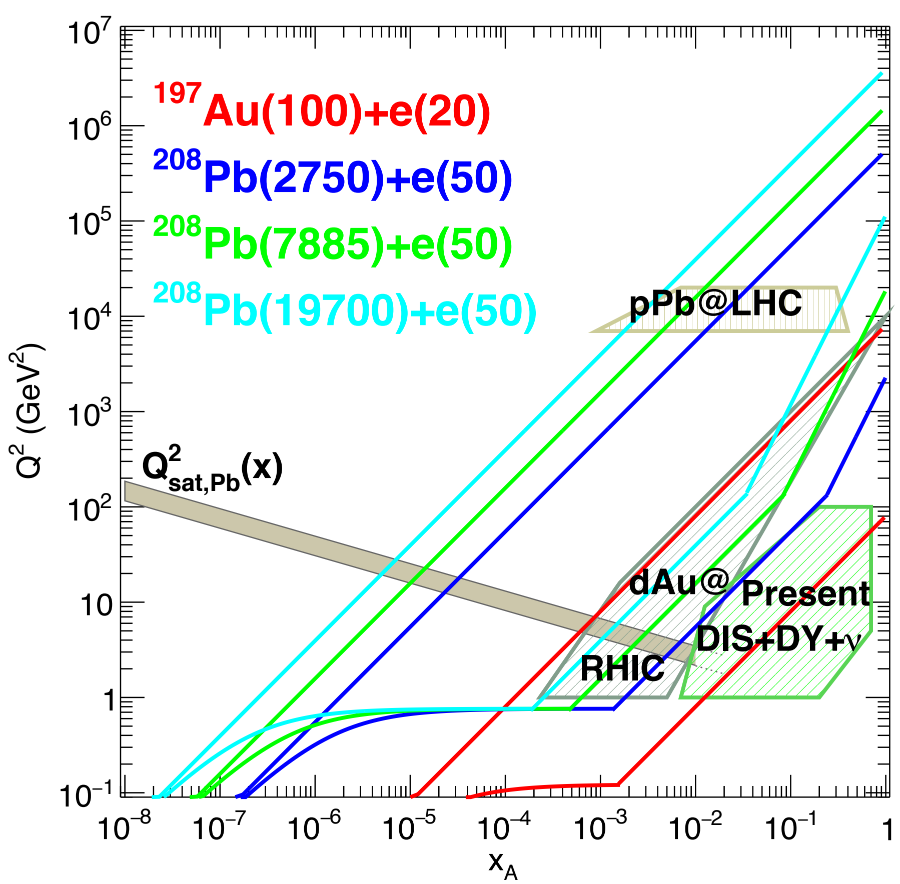
Other prospects:

W,Z mass, weak couplings, top physics

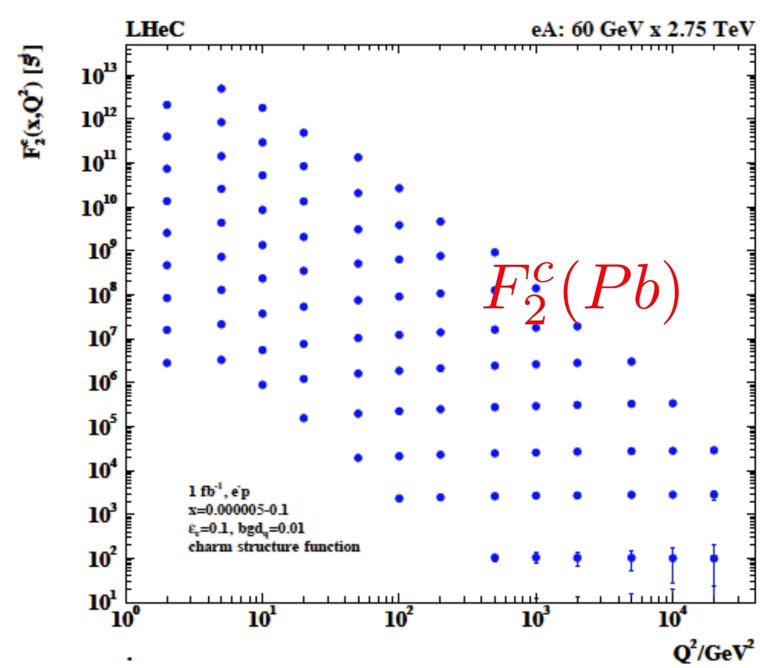
LHeC as eA collider

- eA collisions at LHeC/FCC-eh: region presently explored in DIS extended by 4 decades down in x and Q^2
- Determination of inclusive and diffractive nuclear parton densities for a single nucleus, with flavour unfolding.
- Studies of transverse structure: 3D picture
- Saturation (ep & eA, nuclear enhancement).
- Flavour dependent anti shadowing, Gribov relation with diffraction,…
- with strong implications on the pA/AA programmes at the HL-LHC and FCC-hh.

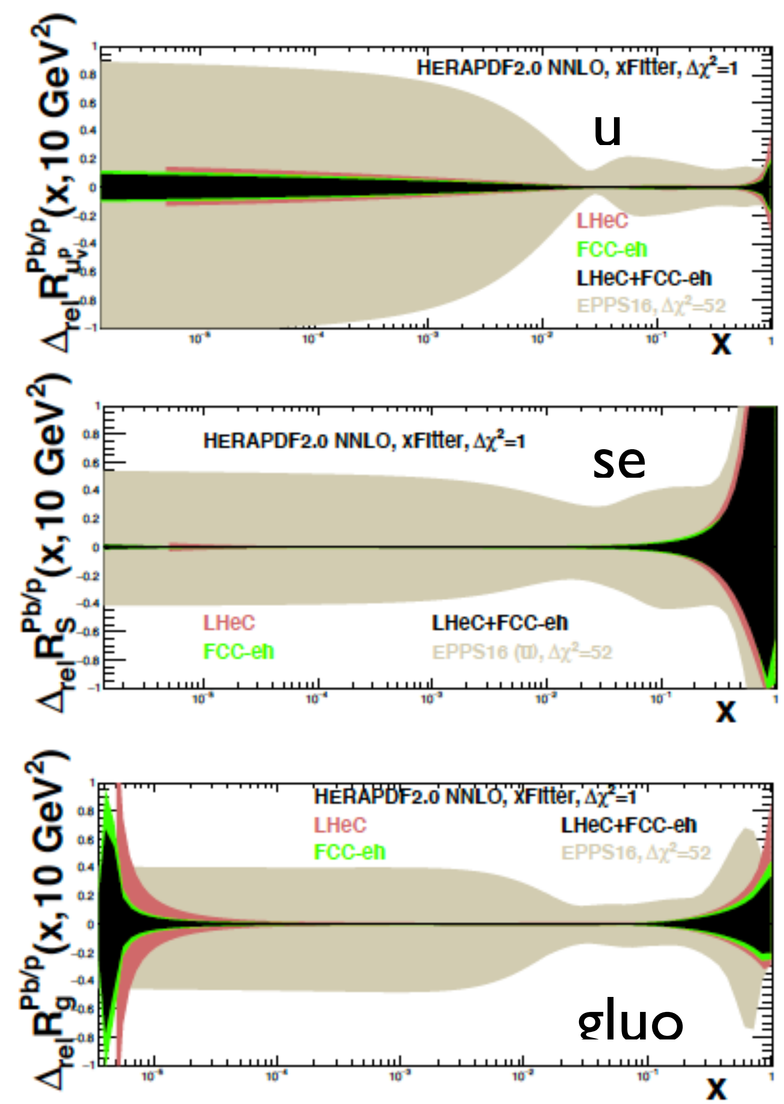
Kinematic plane for eA



Precision structure functions, also for heavy flavors



Relative uncertainties for nuclear modification factor



Unconstrained for x below 0.01

Summary

Deep Inelastic Scattering continues to be primary process to explore the details of the hadronic structure with unmatched precision.

Complementary to electron-positron and hadron-hadron colliders.

Short term future: COMPASS/AMBER upgrades. Semi-inclusive DIS on polarized deuterons; elastic muon-proton scattering, measurement on proton radius.

Intermediate future: Electron Ion Collider, high luminosity machine. Precision measurements of nuclear structure functions, 3D tomography, spin physics.

Long term: higher energies, LHeC, FCC-eh. Very low Bjorken x, potential to unravel novel QCD dynamics, performing precision Higgs and EW physics.

Opportunities to utilize existing physics accelerators (RHIC→EIC, LHC→LHeC, FCC→FCC-eh) and maximize their potential while keeping the overall costs down.