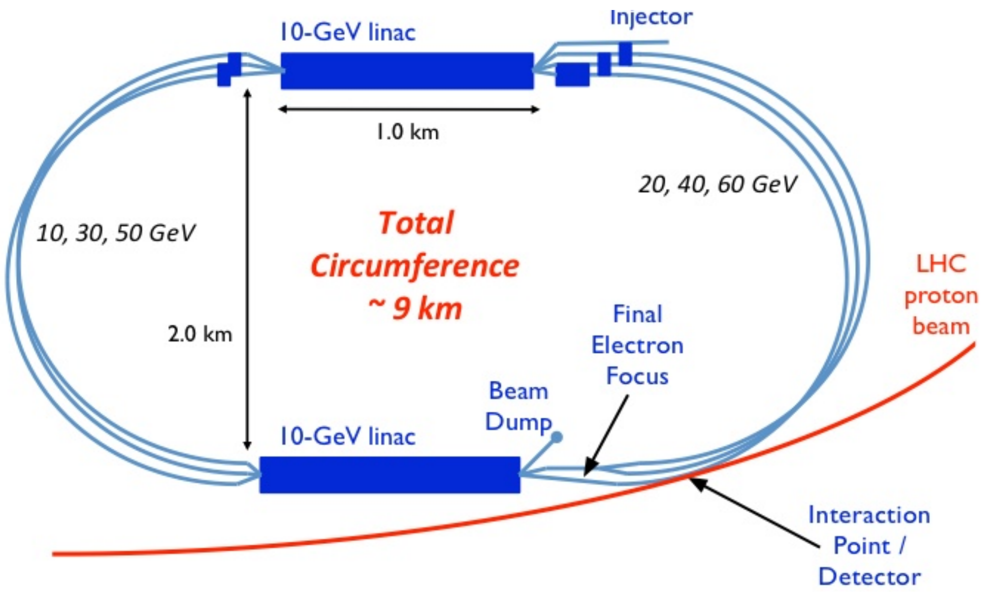
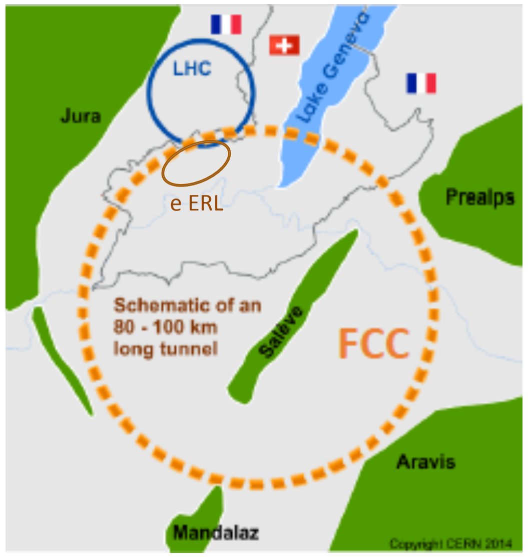
Nuclear Particle Physics with eA on LHeC / FCC-eh

Anna Staśto

PennState
Eberly College of Science





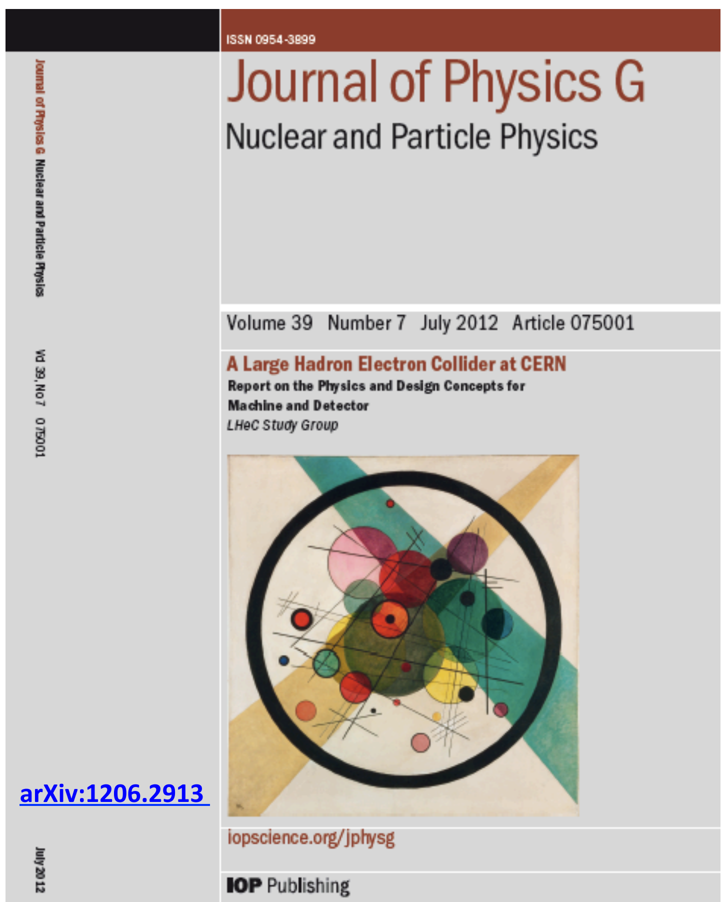
Epiphany Conference, Kraków, Poland, 19 January 2023

Outline

- Motivation for eA Deep Inelastic Scattering in TeV range
- LHeC and FCC-eh kinematics
- Example of simulations for eA in TeV range:
  - Constraints on nuclear Parton Distribution Functions (nPDFs)
  - Novel QCD dynamics in ep/eA at large A and/or small x
  - Heavy Flavors
  - Inclusive diffraction
  - Exclusive vector meson production
  - Hadronization and fragmentation
  - Azimuthal decorrelation

LHeC Conceptual Design Report and beyond

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



arXiv:1206.2913

Further selected references:

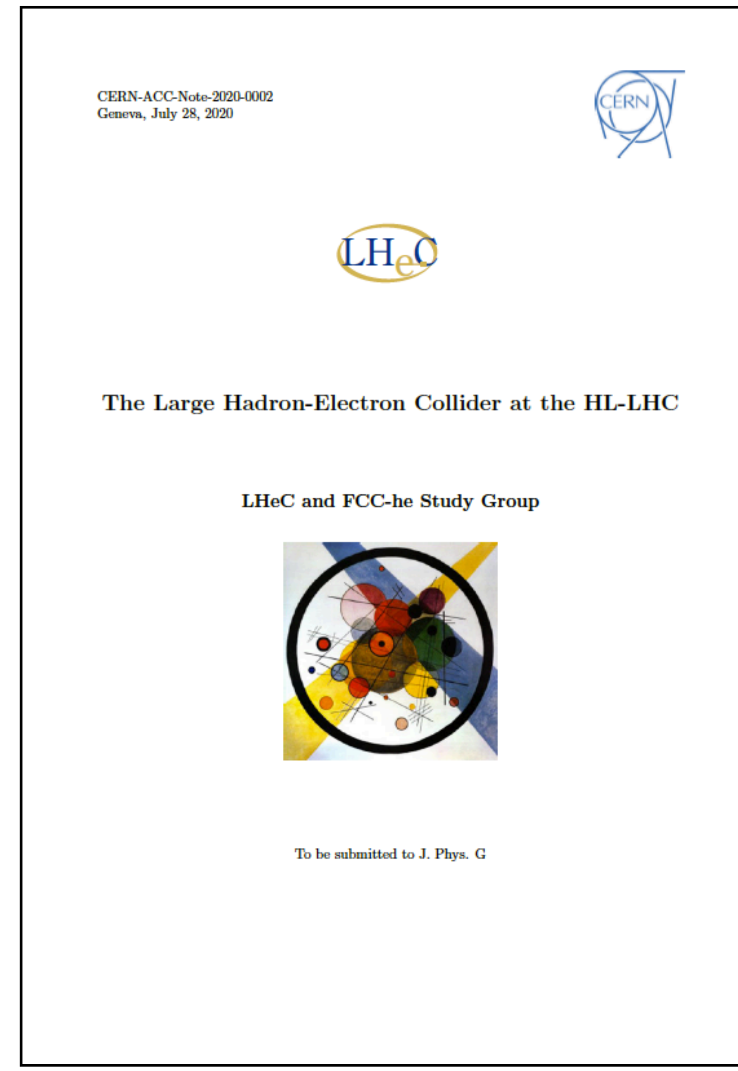
On the relation of the LHeC and the LHC
arXiv:1211.5102

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

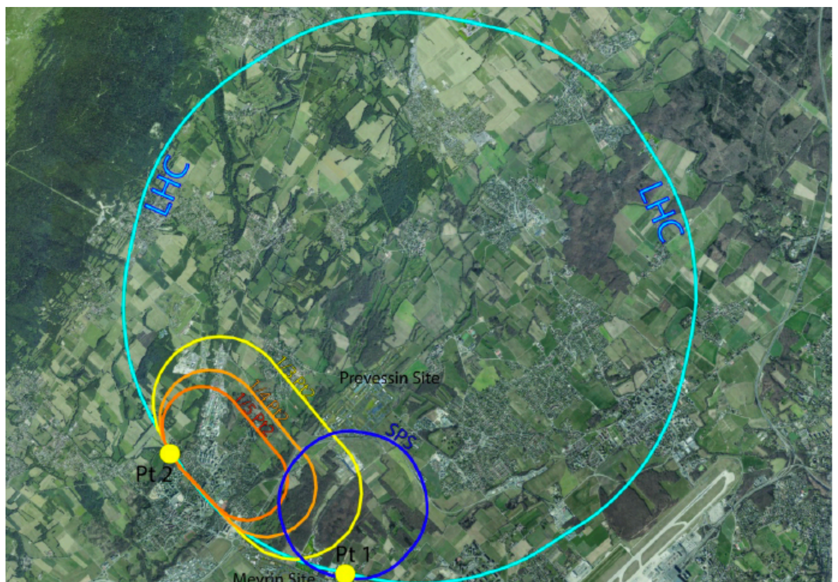
CDR update 2020
300 authors, 156 institutions



arXiv:2007.14491

Accelerator concepts for electron-proton collisions

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)

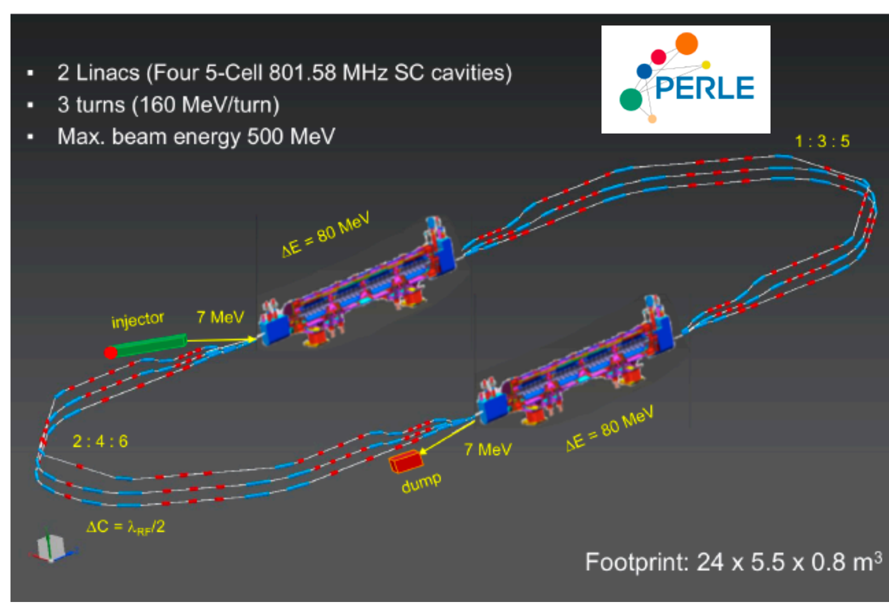
arXiv:2007.14491, subm J.Phys.G

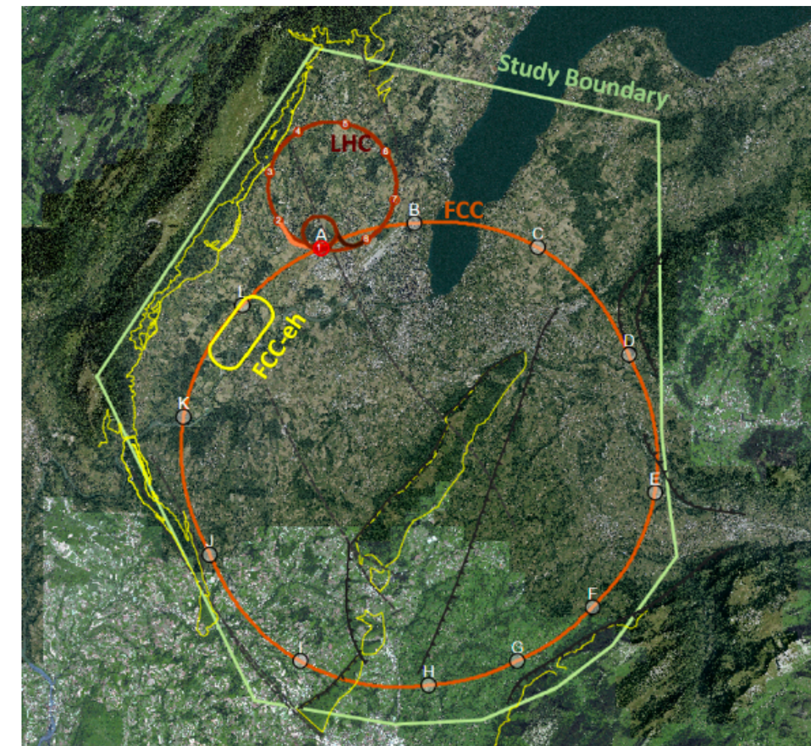
Powerful ERL for Experiments @ Orsay
CDR: 1705.08783 J.Phys.G
CERN-ACC-Note-2018-0086 (ESSP)

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+

eA parameters

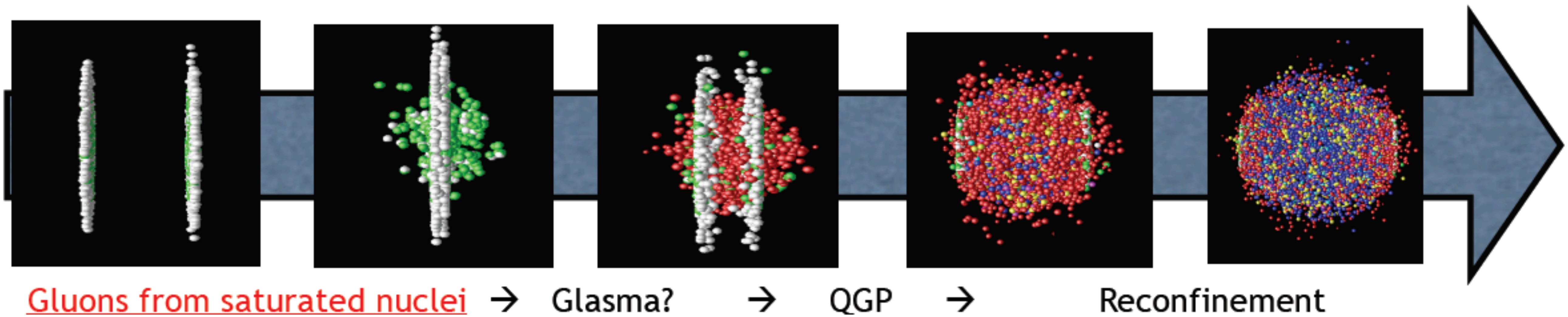
parameter [unit]	LHeC (HL-LHC)	eA at HE-LHC	FCC-he
E_{Pb} [PeV]	0.574	1.03	4.1
E_e [GeV]	60	60	60
$\sqrt{s_{eN}}$ electron-nucleon [TeV]	0.8	1.1	2.2
bunch spacing [ns]	50	50	100
no. of bunches	1200	1200	2072
ions per bunch [10^8]	1.8	1.8	1.8
$\gamma\epsilon_A$ [μm]	1.5	1.0	0.9
electrons per bunch [10^9]	4.67	6.2	12.5
electron current [mA]	15	20	20
IP beta function β_A^* [cm]	7	10	15
hourglass factor H_{geom}	0.9	0.9	0.9
pinch factor H_{b-b}	1.3	1.3	1.3
bunch filling H_{coll}	0.8	0.8	0.8
luminosity [$10^{32}\mathrm{cm}^{-2}\mathrm{s}^{-1}$]	7	18	54
Integrated lumi. in 10 y. (fb^{-1}) ~~	*6*	*15*	*45*

CERN-ACC-2017-0019

100 times larger luminosity than HERA, full HERA integrated luminosity in less than a month.

Nuclear physics in eA :complementarity to pA, AA at LHC

Heavy ion collisions



Precision measurement of the initial state.

Nuclear structure functions.

Particle production in the early stages.

Factorization eA/pA/AA.

Modification of the QCD radiation and hadronization in the nuclear medium.

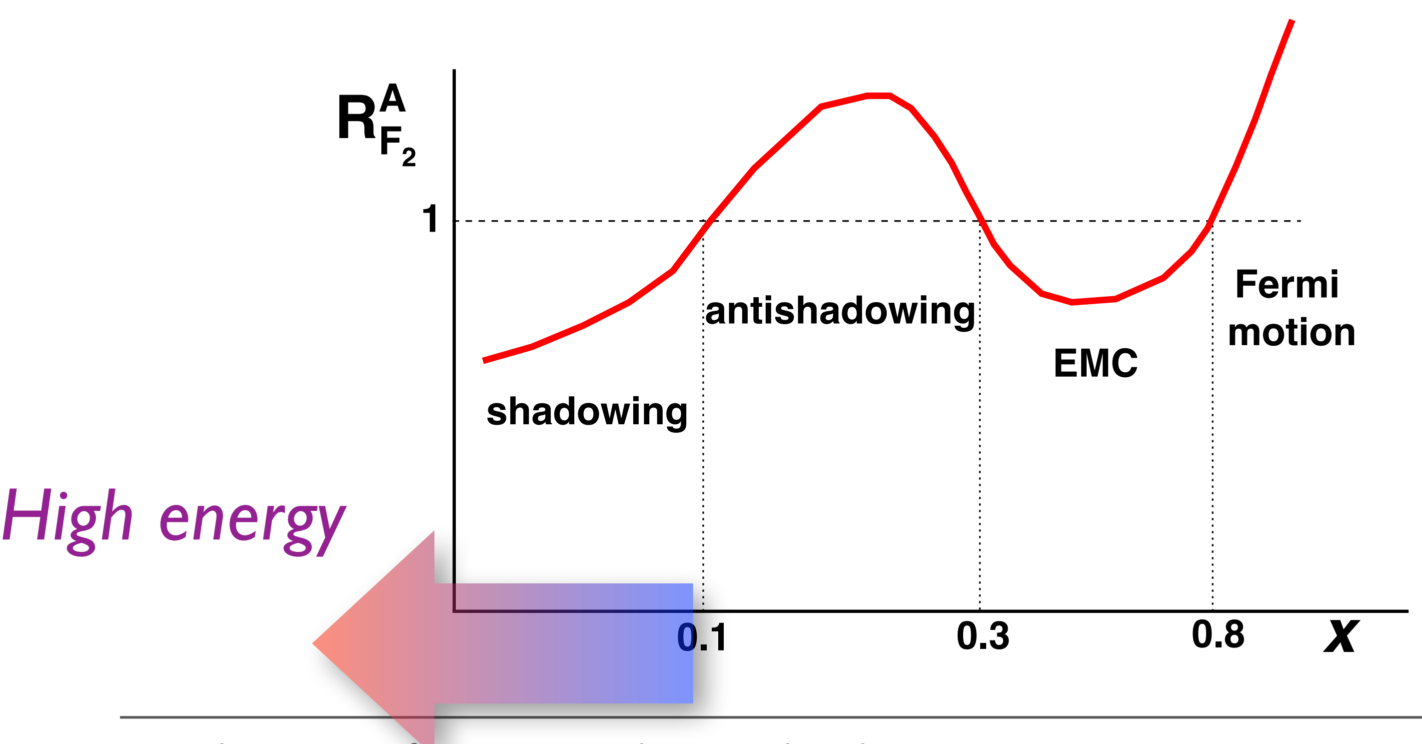
Nuclear structure

Deep Inelastic Scattering: $$\frac{d^2\sigma^{ep\to eX}}{dxdQ^2} = \frac{4\pi\alpha_{e.m.}^2}{xQ^4}\left[\left(1-y+\frac{y^2}{2}\right)F_2(x,Q^2) - \frac{y^2}{2}F_L(x,Q^2)\right]$$

Nuclear ratio for structure function

$$R_{F_2}^A(x,Q^2) = \frac{F_2^A(x,Q^2)}{A\,F_2^{\text{nucleon}}(x,Q^2)}$$

Nuclear effects $$R^A \neq 1$$



- *Fermi motion* $$x \geq 0.8$$
- *EMC region* $$0.25 - 0.3 \leq x \leq 0.8$$
- *Antishadowing region* $$0.1 \leq x \leq 0.25 - 0.3$$
- *Shadowing region* $$x \leq 0.1$$

Nuclear structure

Deep Inelastic Scattering:
$$\frac{d^2\sigma^{ep\to eX}}{dx\,dQ^2} = \frac{4\pi\alpha^2_{e.m.}}{xQ^4}\left[\left(1-y+\frac{y^2}{2}\right)F_2(x,Q^2) - \frac{y^2}{2}F_L(x,Q^2)\right]$$

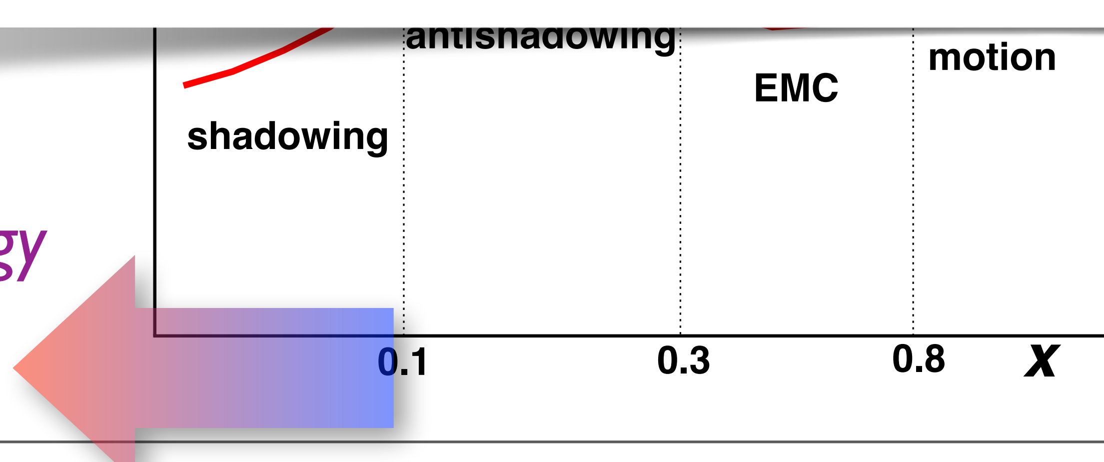
At an ep/eA collider:

➜ PDF of a single nucleus possible

➜ Same method of extraction in both ep and eA.

➜ Physics beyond standard collinear factorisation can be studied in a single setup, with size effects disentangled from energy effects and a large lever arm in x at perturbative Q^2.

High energy



)$.8$

n

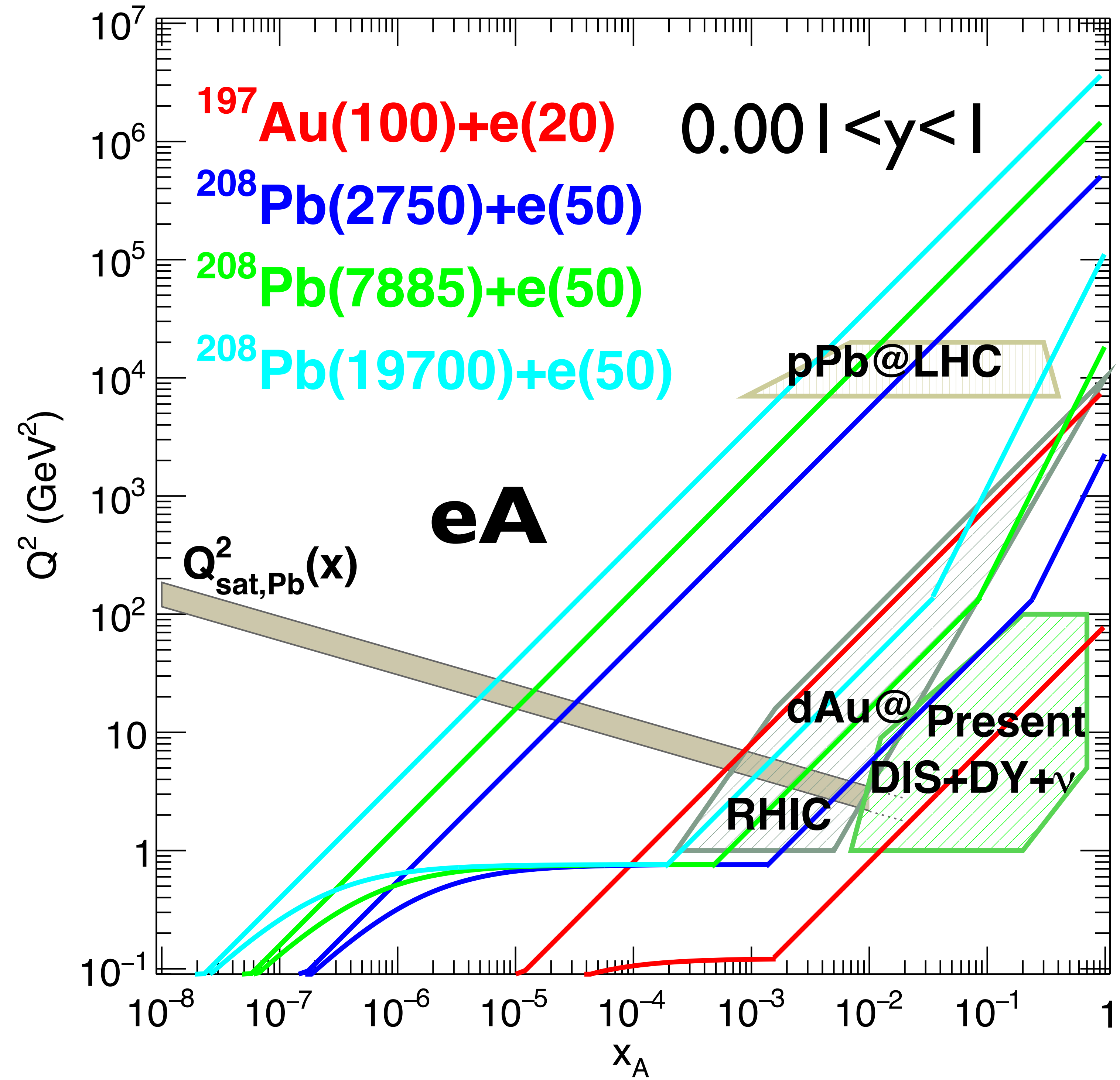
$0.1 \leq x \leq 0.25 - 0.3$

- *Shadowing region*

$x \leq 0.1$

DIS eA: kinematics

Extension up to 4-5 orders of magnitude in x and Q^2 wrt. existing DIS data, ~3 wrt EIC

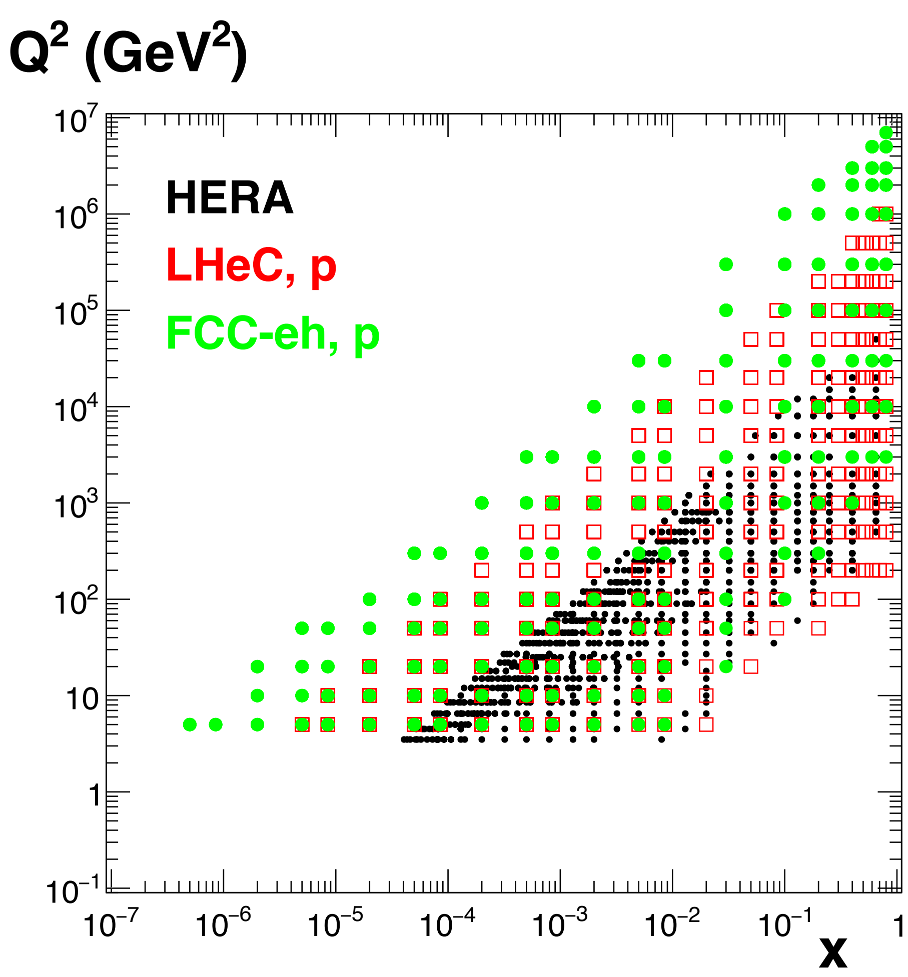


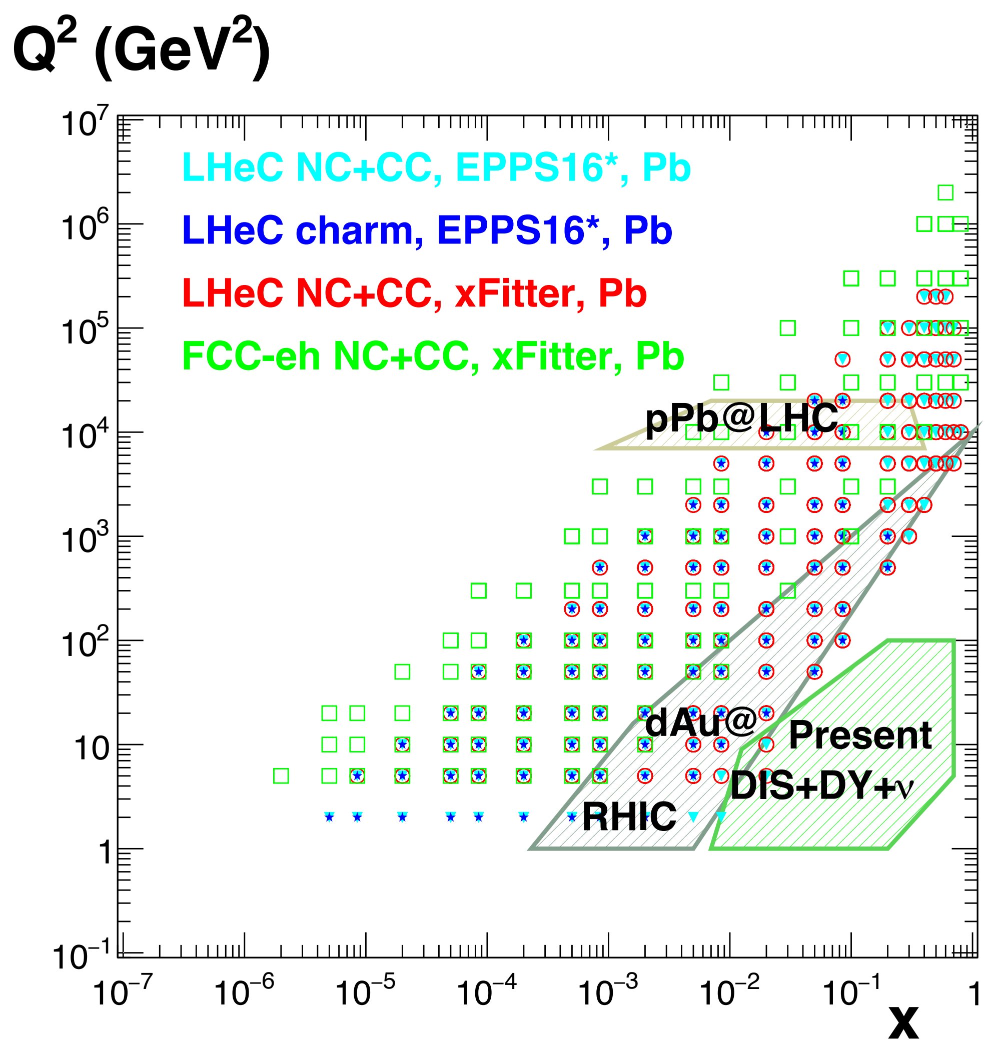
- DIS offers:
- Complementarity to pA and UPC
- A clean experimental environment: low multiplicity, no pileup, fully constrained kinematics;
- A more controlled theoretical setup: many first-principles calculations in collinear and non-collinear frameworks.

Pseudodata

	E_e (GeV)	E_h (TeV/	Polarisatio	Luminosity	NC/CC	# data
ep@LHeC, 1005 data points for $Q^2 \geq 3.5$ GeV^2	60 (e^-)	1 (p)	0	100	CC	93
	60 (e^-)	1 (p)	0	100	NC	136
	60 (e^-)	7 (p)	-0.8	1000	CC	114
	60 (e^-)	7 (p)	0.8	300	CC	113
	60 (e^+)	7 (p)	0	100	CC	109
	60 (e^-)	7 (p)	-0.8	1000	NC	159
	60 (e^-)	7 (p)	0.8	300	NC	159
	60 (e^+)	7 (p)	0	100	NC	157
ePb@LHeC, 484 data points for $Q^2 \geq 3.5$ GeV^2	20 (e^-)	2.75 (Pb)	-0.8	0.03	CC	51
	20 (e^-)	2.75 (Pb)	-0.8	0.03	NC	93
	26.9 (e^-)	2.75 (Pb)	-0.8	0.02	CC	55
	26.9 (e^-)	2.75 (Pb)	-0.8	0.02	NC	98
	60 (e^-)	2.75 (Pb)	-0.8	1	CC	85
	60 (e^-)	2.75 (Pb)	-0.8	1	NC	129
ep@FCC-eh, 619 data points for $Q^2 \geq 3.5$ GeV^2	20 (e^-)	7 (p)	0	100	CC	46
	20 (e^-)	7 (p)	0	100	NC	89
	60 (e^-)	50 (p)	-0.8	1000	CC	67
	60 (e^-)	50 (p)	0.8	300	CC	65
	60 (e^+)	50 (p)	0	100	CC	60
	60 (e^-)	50 (p)	-0.8	1000	NC	111
	60 (e^-)	50 (p)	0.8	300	NC	110
	60 (e^+)	50 (p)	0	100	NC	107
ePb@FCC-eh, 150 data points for $Q^2 \geq 3.5$ GeV^2	60 (e^-)	20 (Pb)	-0.8	10	CC	58
	60 (e^-)	20 (Pb)	-0.8	10	NC	101

Pseudodata

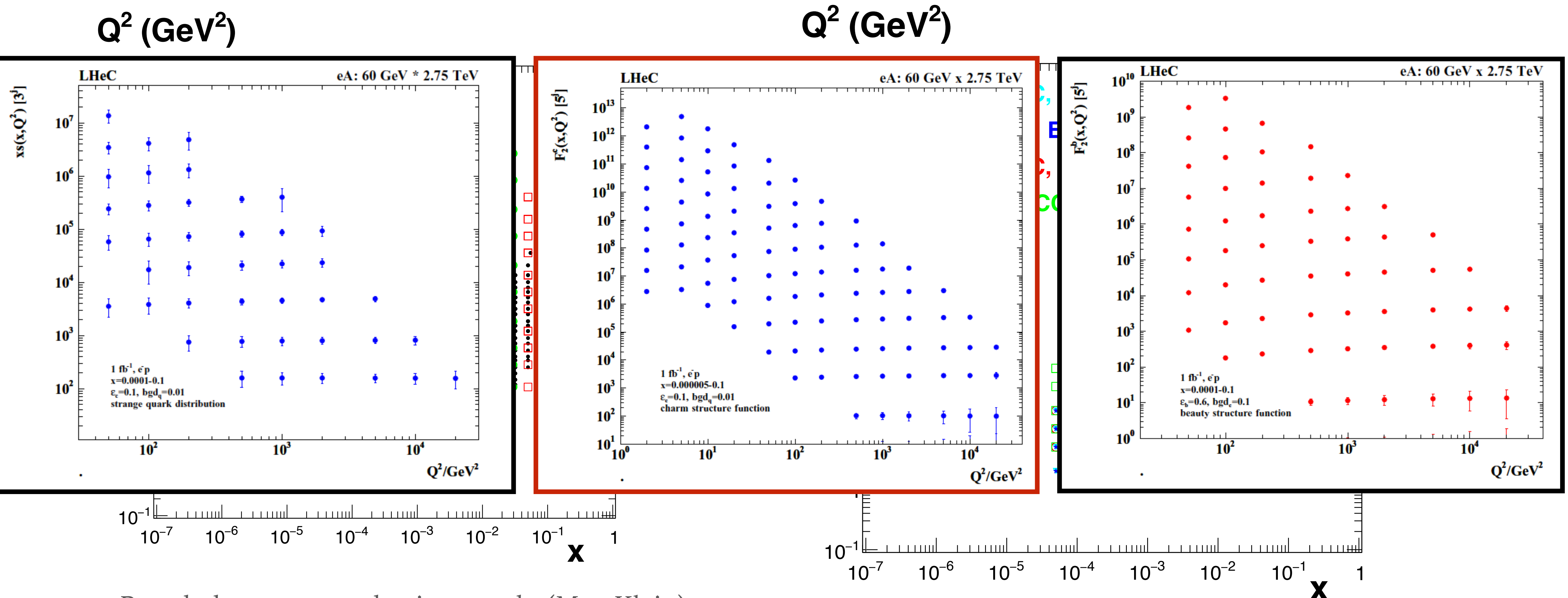




- Pseudodata generated using a code (Max Klein) validated with the H1 MC.
- Cuts: $|\eta_{max}|=5$, $0.95< y< 0.001$.
- Error assumptions ~ factor 2 better than at HERA (luminosity uncertainty kept aside).
- Stat./syst. errors (ePb@FCC-eh) from 0.1/1.2% (small x, NC) to 37/6% (large x & Q^2, CC).

Source of uncertainty	Error on the source or cross section
scattered electron energy scale	0.1 %
scattered electron polar angle	0.1 mrad
hadronic energy scale	0.5 %
calorimeter noise ($y < 0.01$)	1-3 %
radiative corrections	1-2 %
photoproduction background	1 %
global efficiency error	0.7 %

Pseudodata



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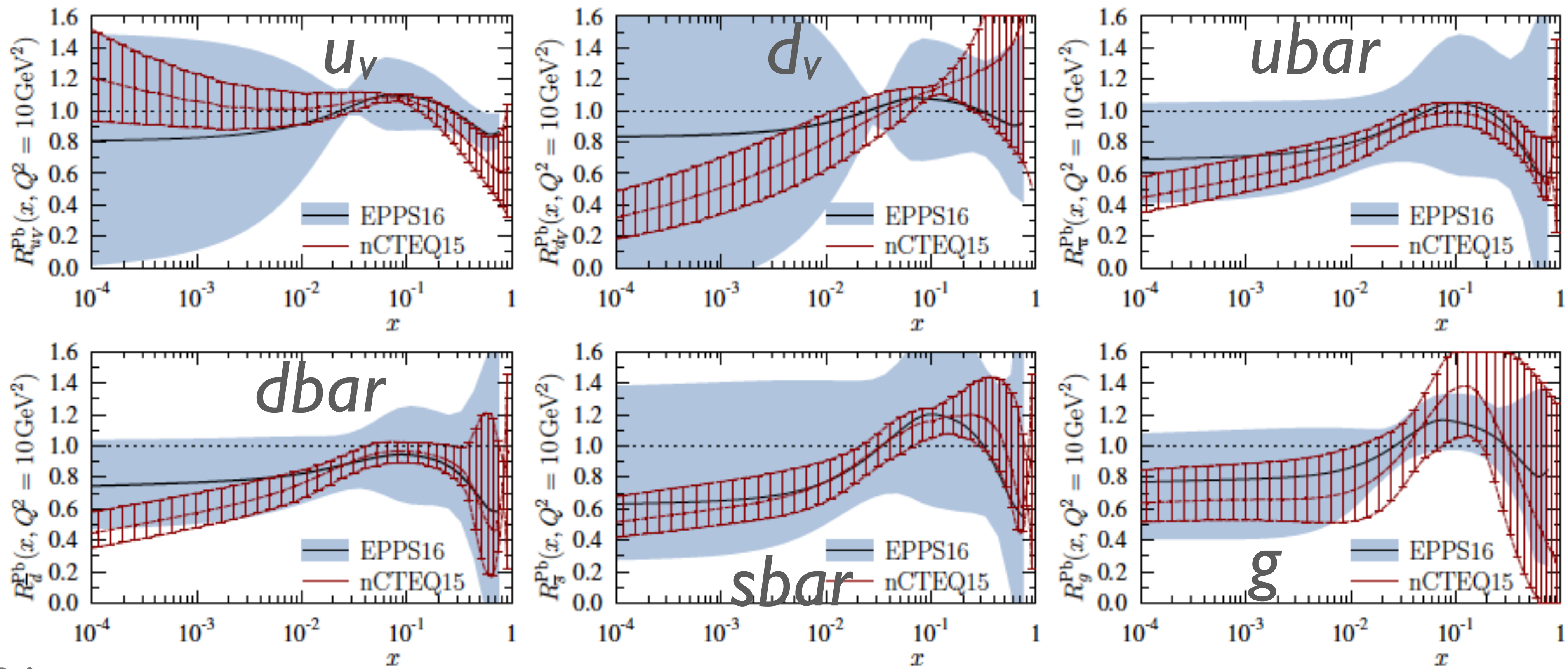
EPPS16*: simulation

- nCTEQ15 vs. EPPS16: note the parametrisation bias.

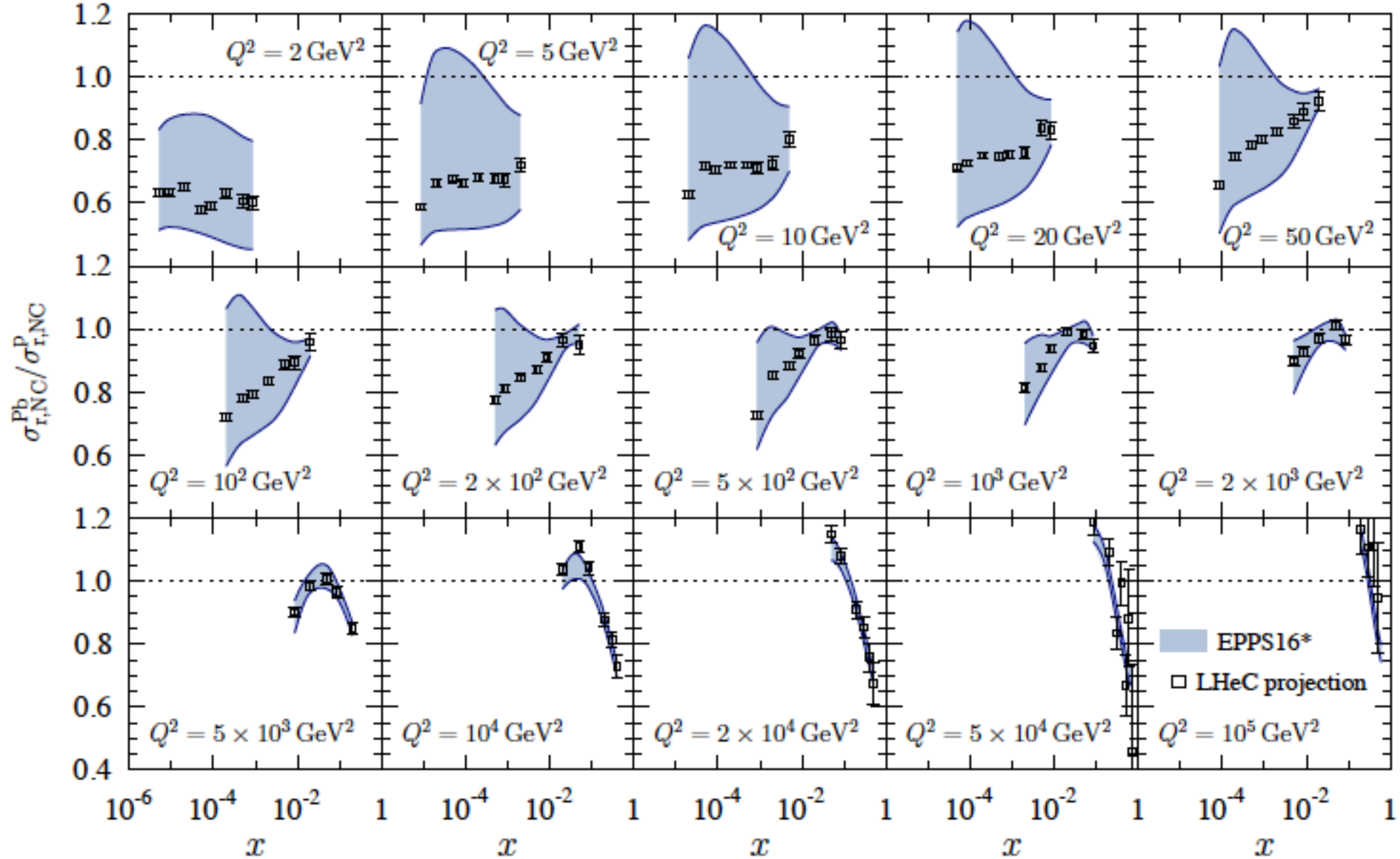


EPPS16* setup

- EPPS16-like analysis updated, with the same data sets plus LHeC NC, CC and charm reduced cross sections.
- Central values generated using EPS09.
- Same methods and tolerance as in EPPS16, but more flexible functional form at small x.

EPPS16*: results

- Large effect of NC+CC LHeC pseudodata, and of charm on the glue at small x.
- Limitation on u/d decomposition inherent to almost isospin symmetric nuclei (u/d difference suppressed by 2Z/A-1).



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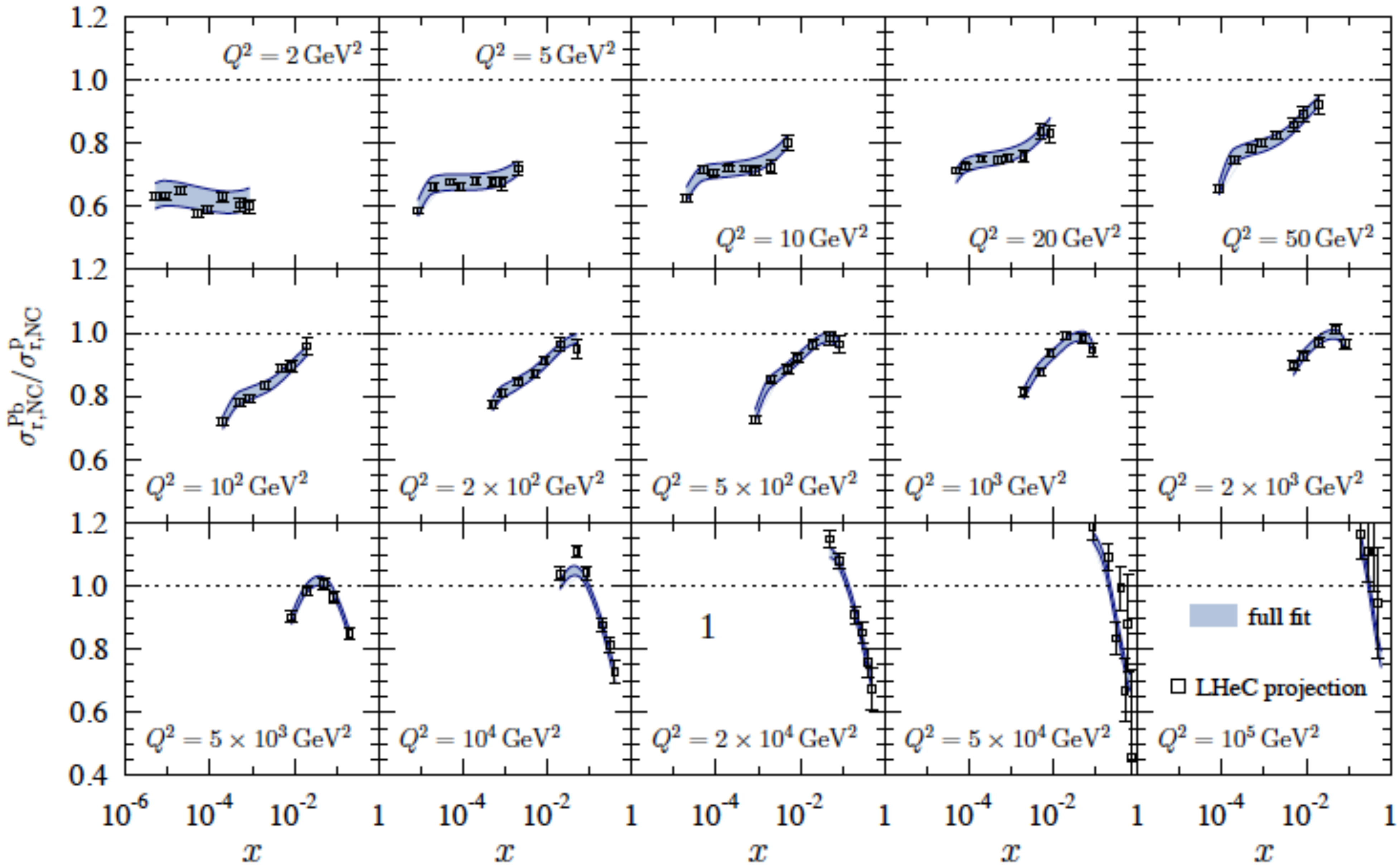

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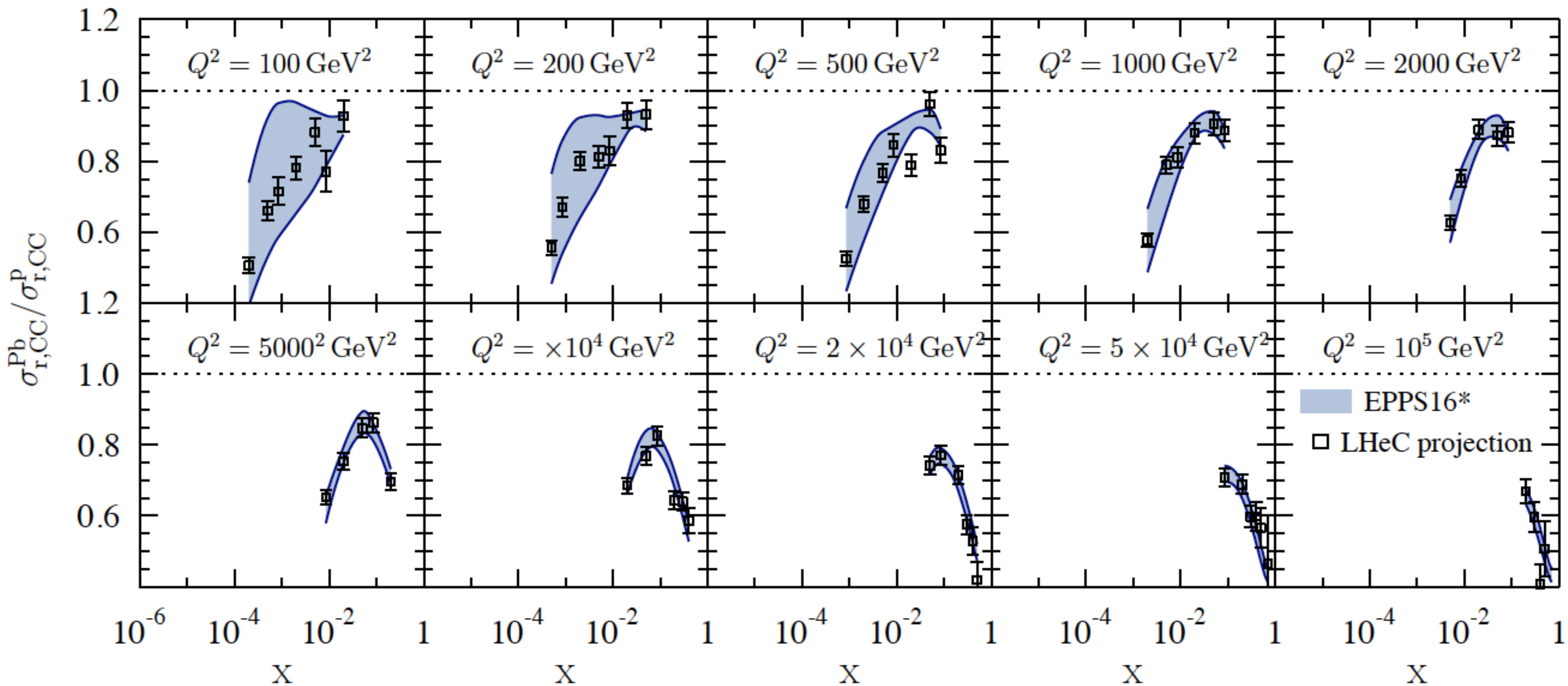

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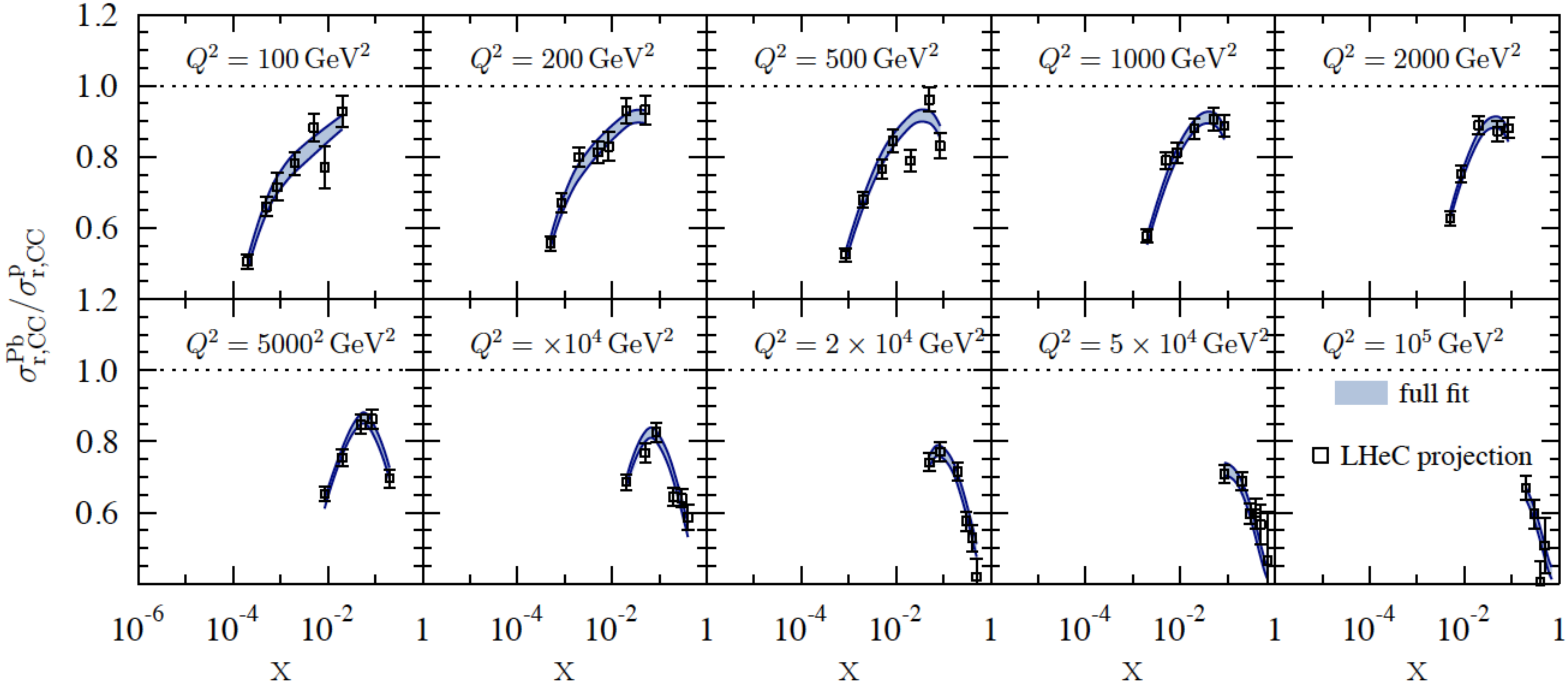

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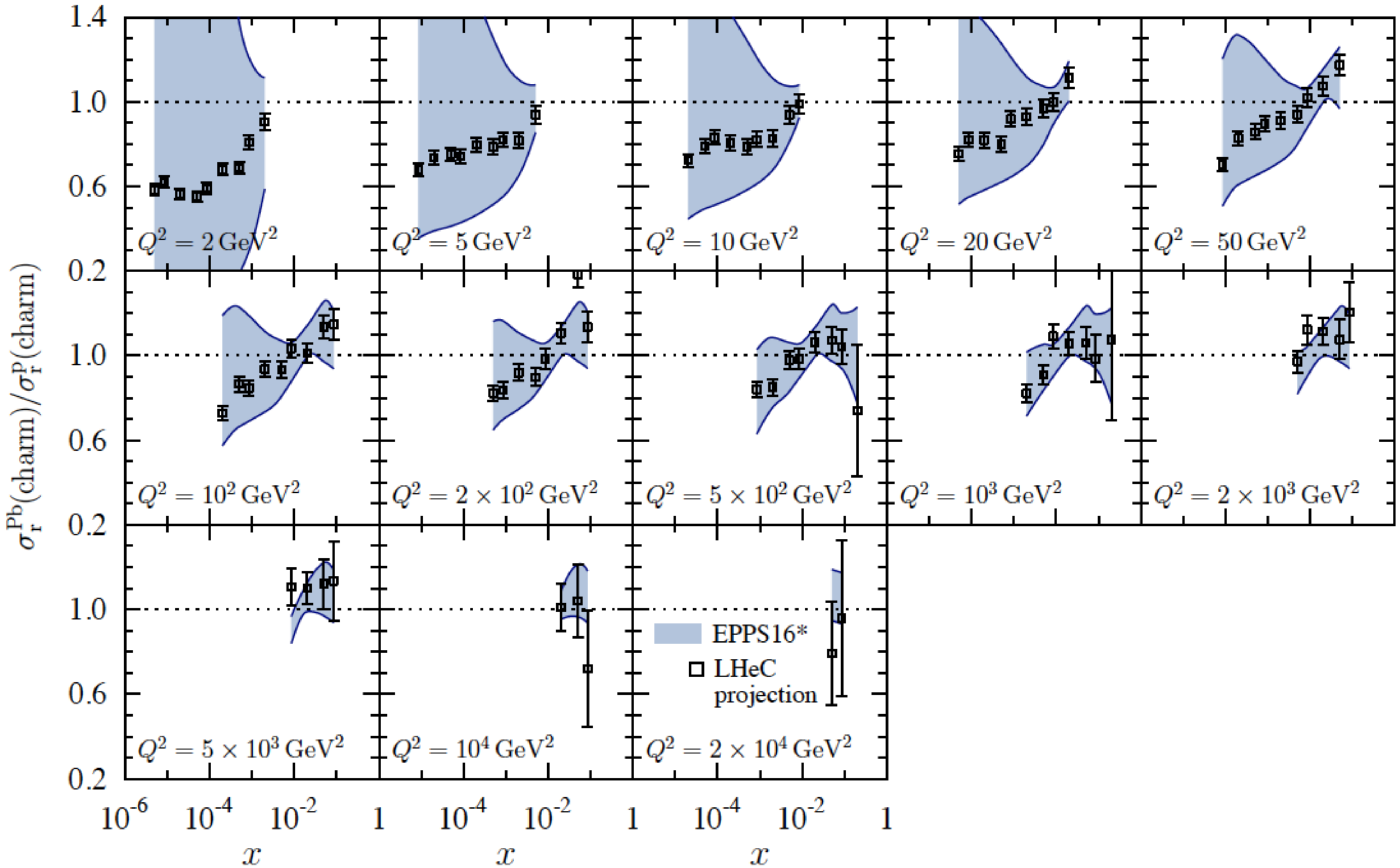

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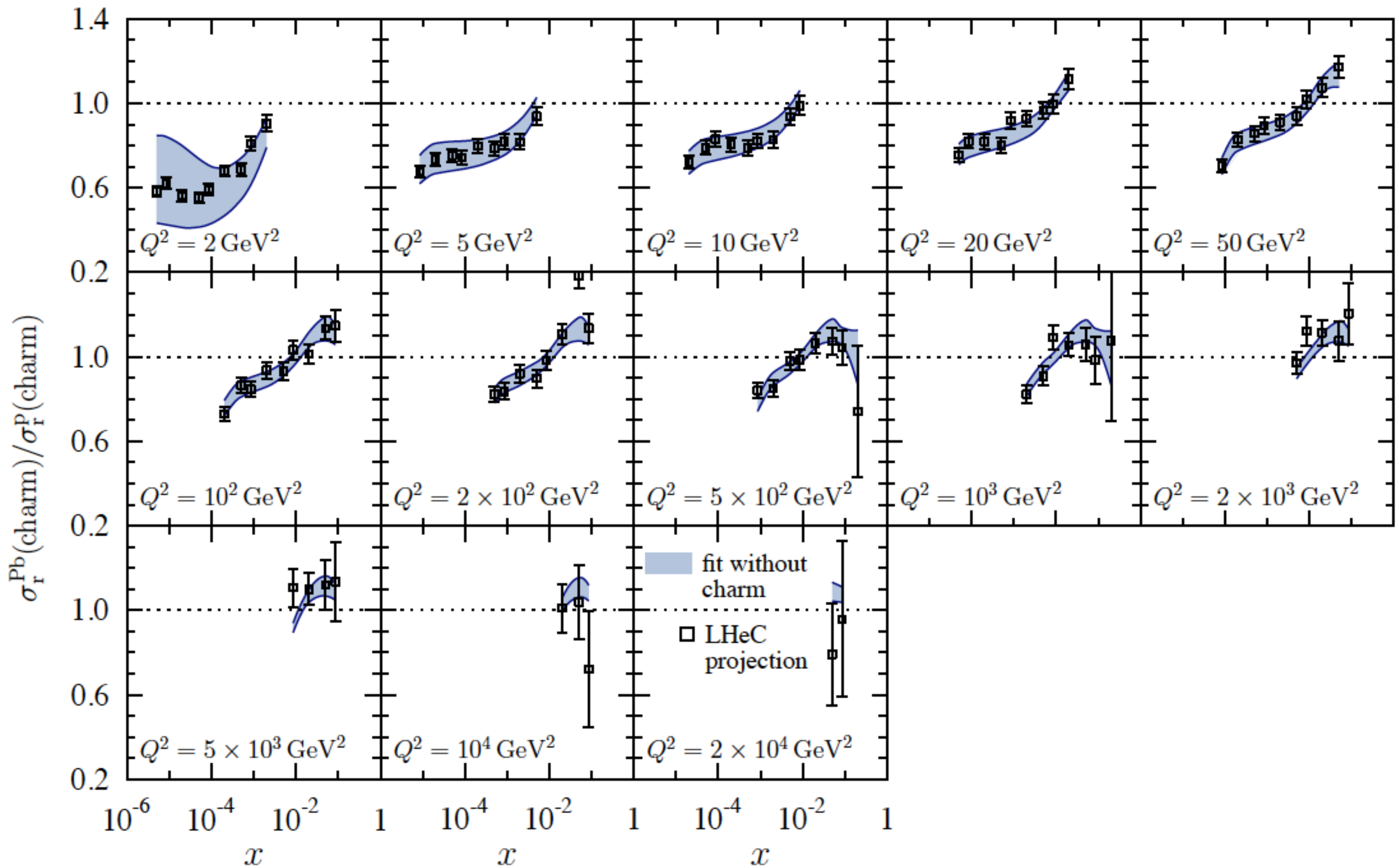

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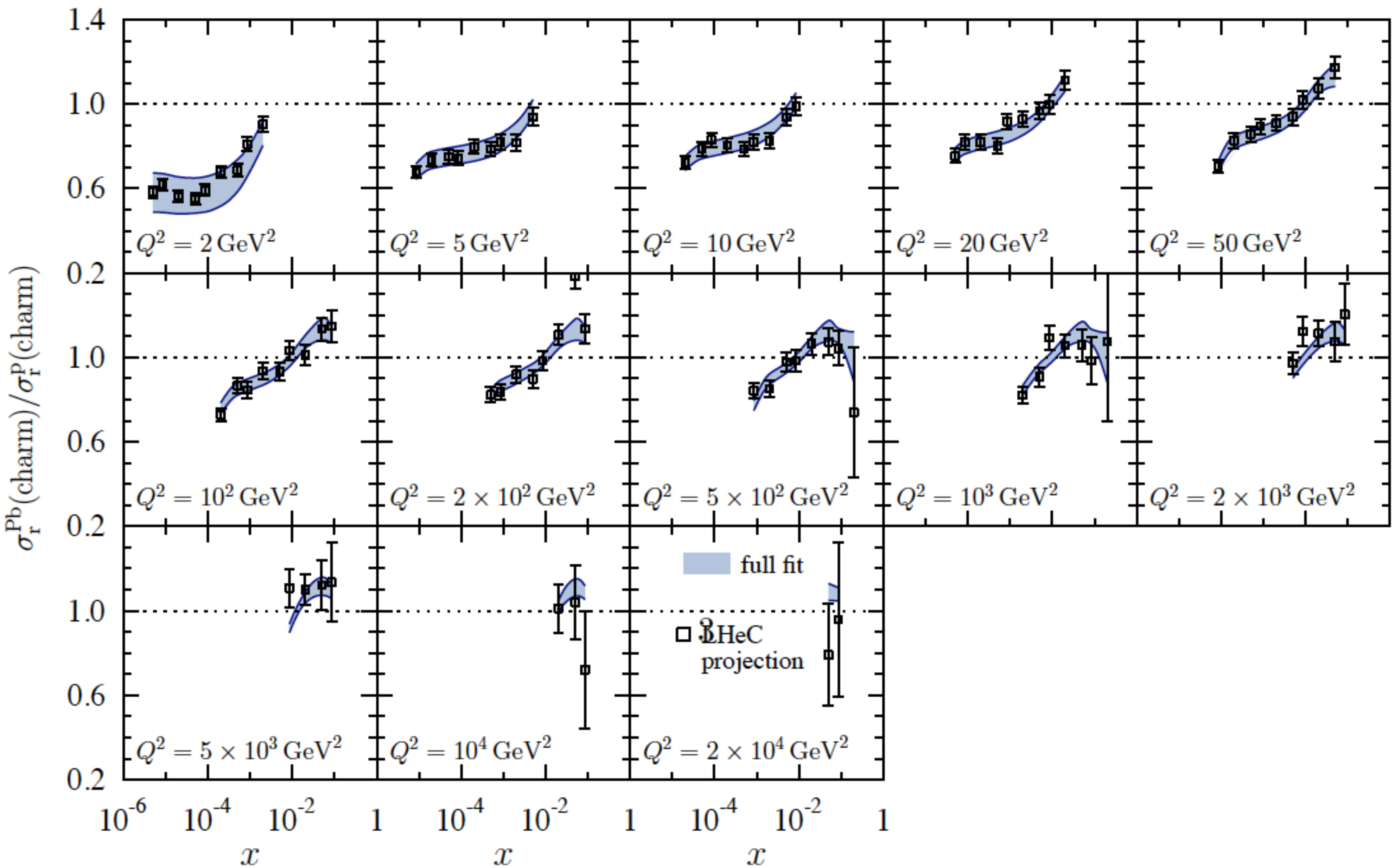


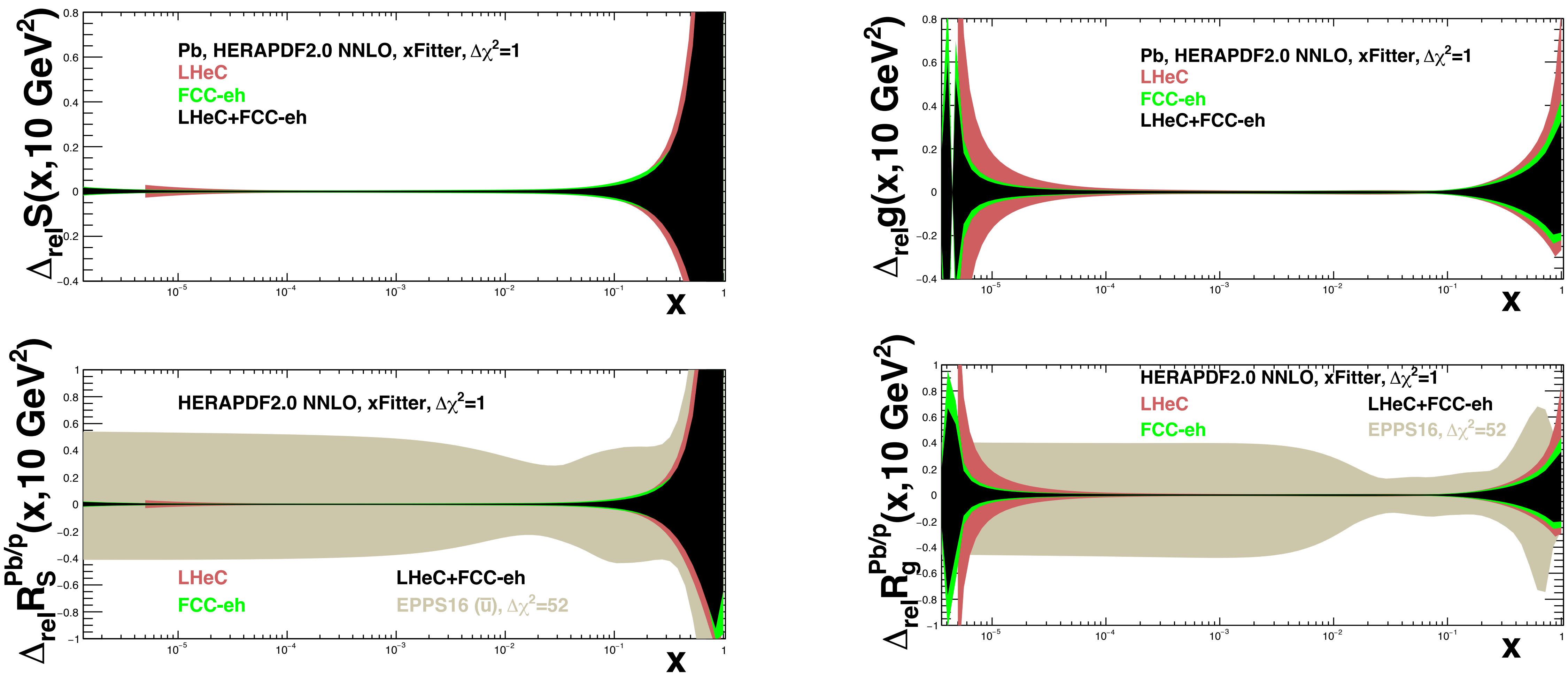
xFitter simulation

Extraction of Pb PDFs by fitting NC+CC pseudodata using xFitter

Uncertainties coming only from experimental precision

No parametrisation or theory uncertainties

Only data with $Q^2 \geq 3.5$ GeV^2, initial evolution scale 1.9 GeV^2.

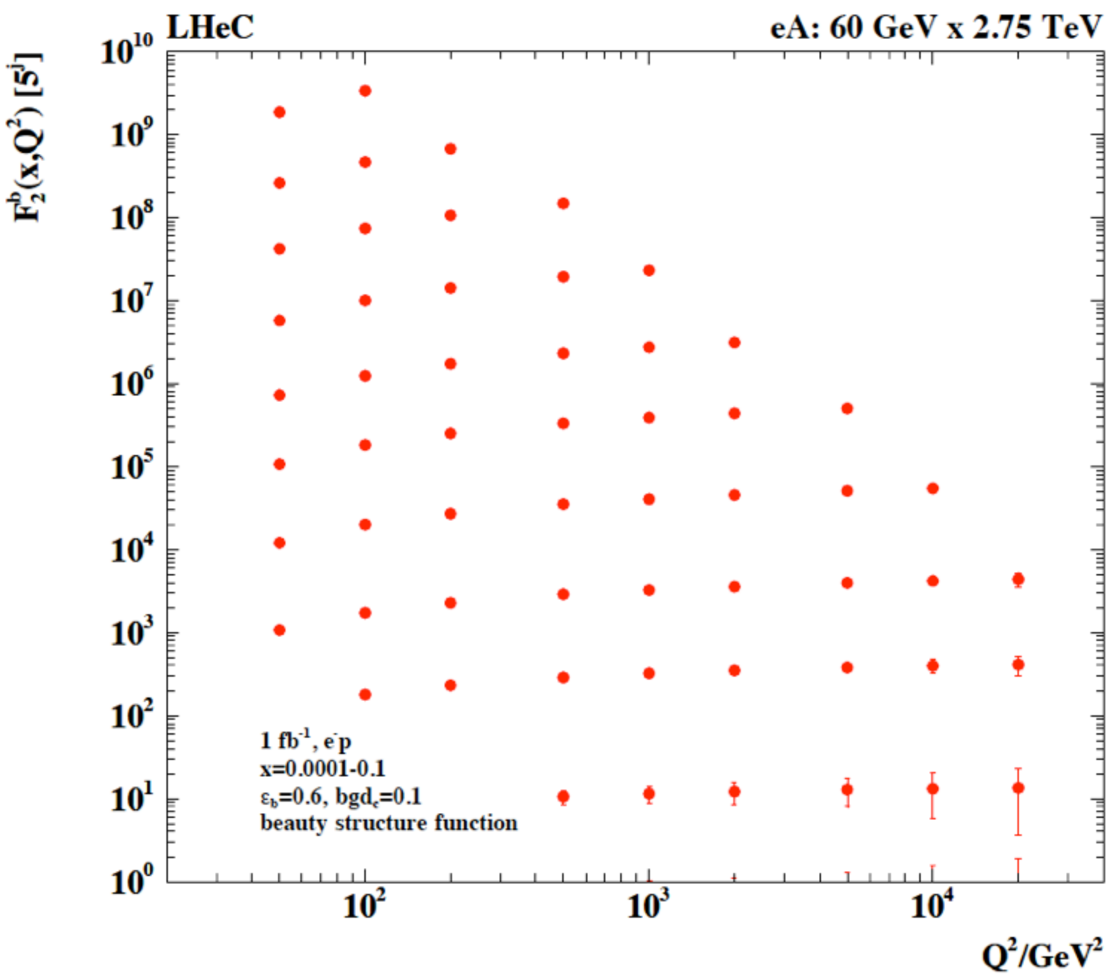


Large reduction of uncertainty at all x.

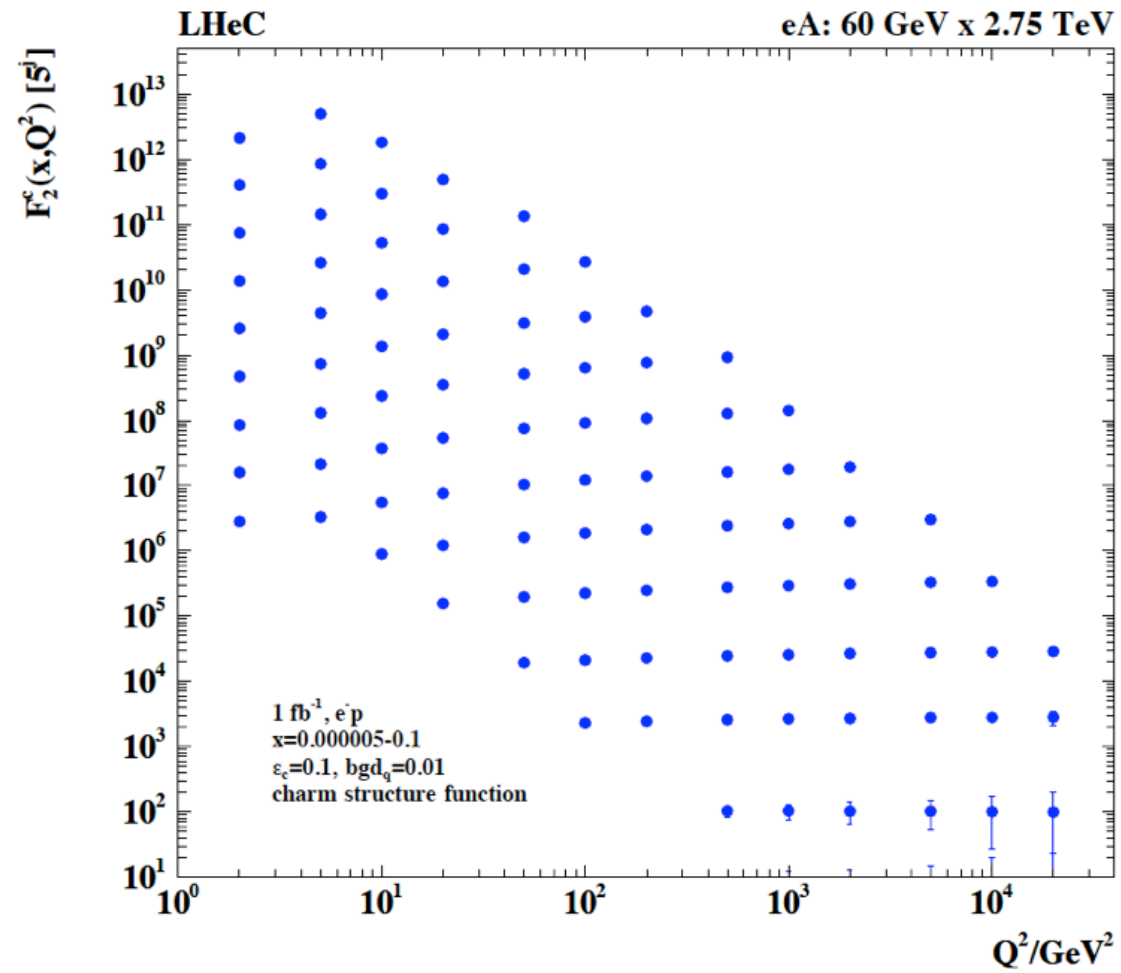
Possible further improvements : charm, beauty, CC with tagged charm for strange distribution

Heavy flavors: LHeC simulation

Heavy Flavour – Beauty in ePb - from NC



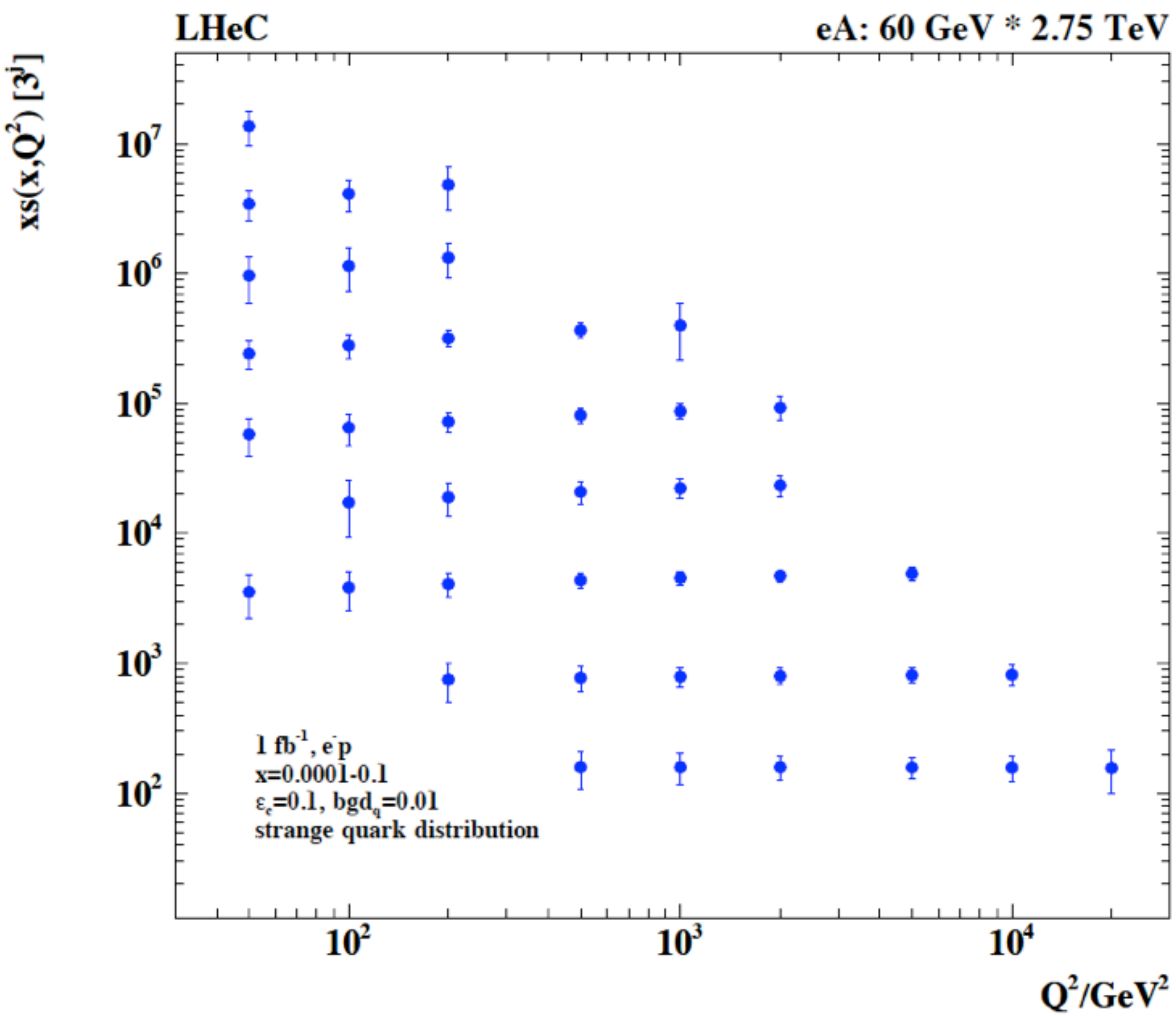
Heavy Flavour – Charm in eA - from NC



Possibility of precision measurements of heavy flavors in eA DIS at LHeC.

Heavy flavors: LHeC simulation

Heavy Flavour – Strange in ePb - from CC

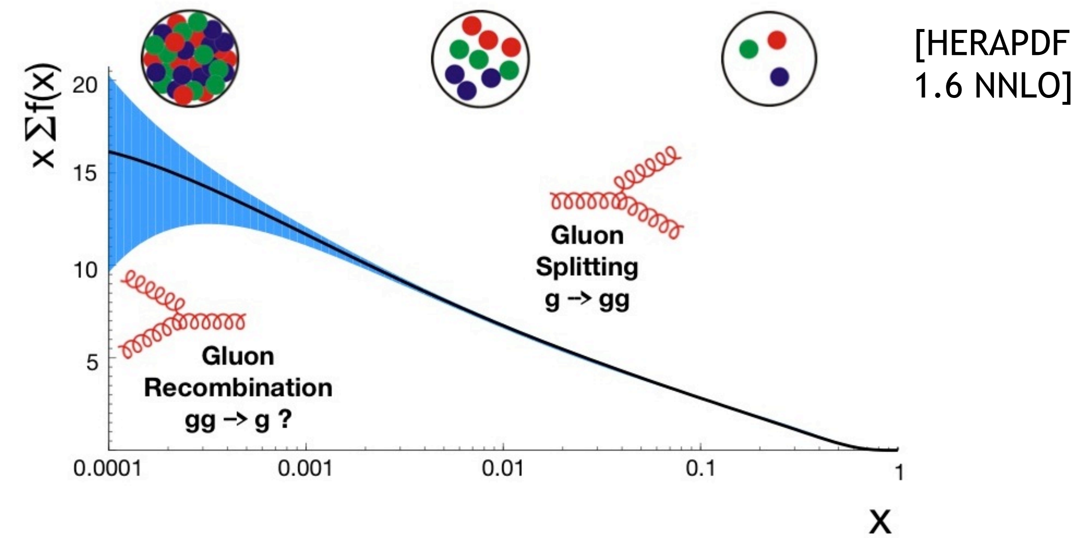


$$W^- \bar{s} \to \bar{c}$$

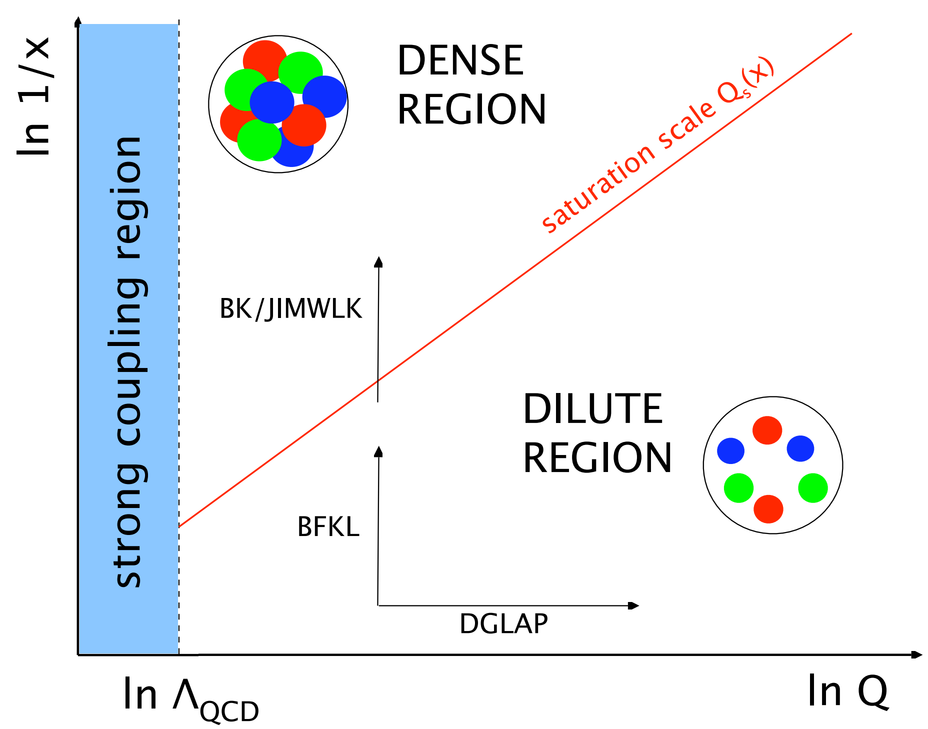
Extraction of strange quark distribution in eA through CC interaction.

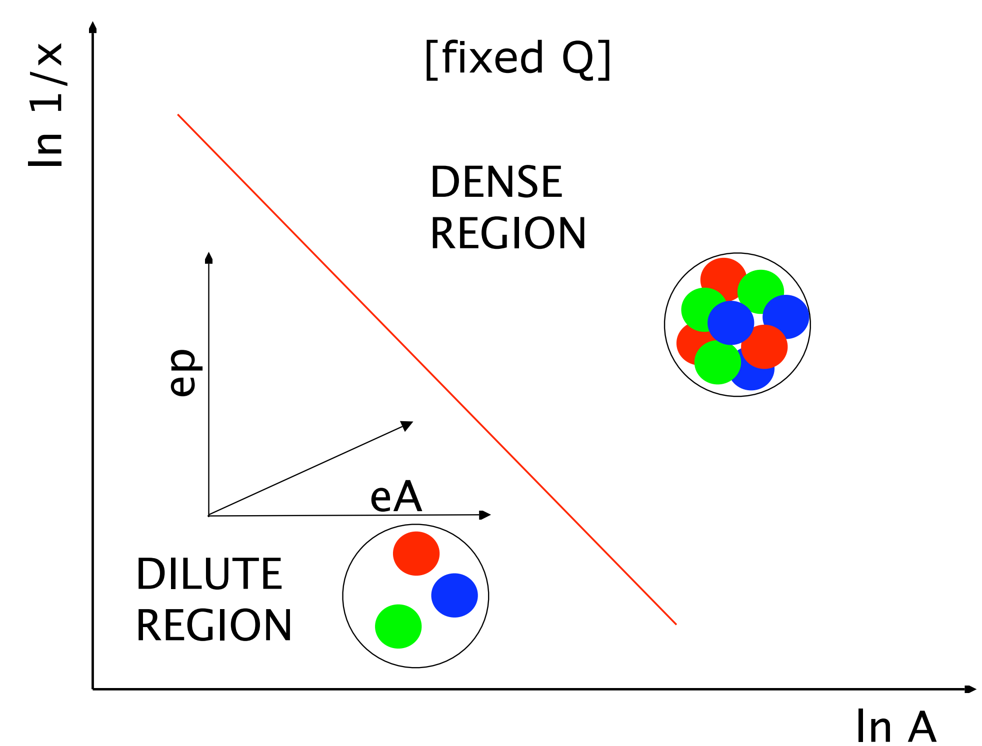
Novel QCD dynamics at low x and/or large A

- At small x the linear evolution gives strongly rising gluon density.
- Parton evolution needs to be modified to include potentially very large logs, resummation of log(1/x)
- Further increase in the energy could lead to the importance of the recombination effects.
- Modification of parton evolution by including non-linear or saturation effects in the parton density.



$$\frac{xG_A(x,Q_s^2)}{\pi R_A^2 Q_s^2} \sim 1 \longrightarrow Q_s^2 \sim A^{1/3} x^{-\lambda}$$





Novel QCD dynamics at low x and/or large A

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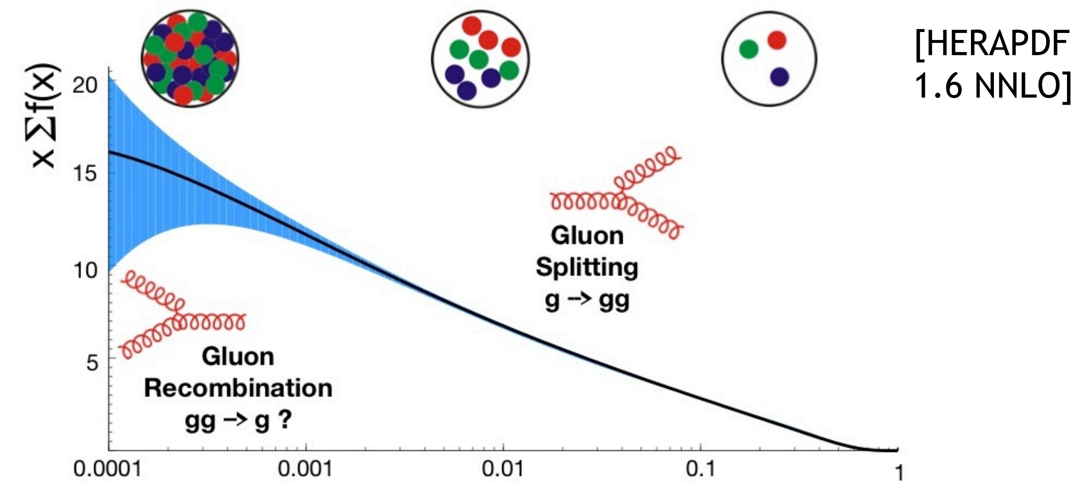
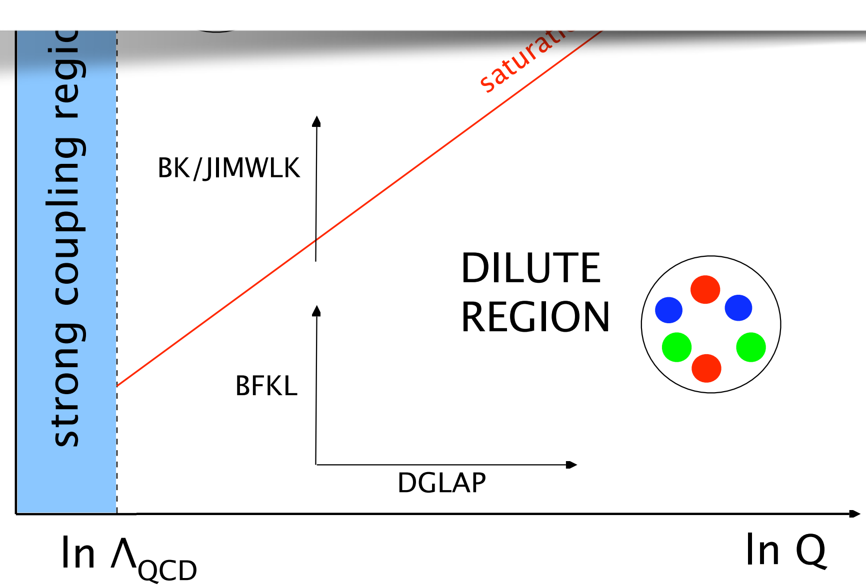
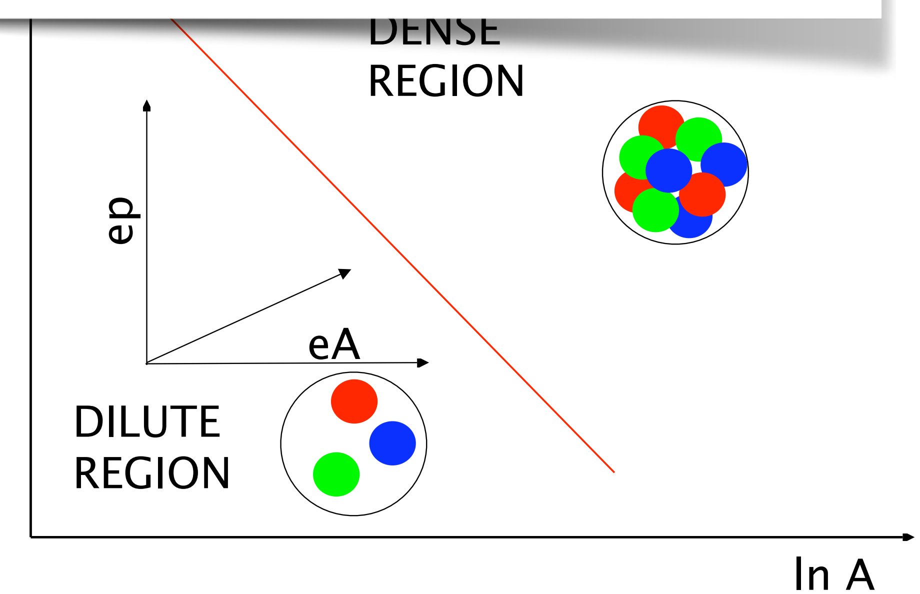
- Mo…
  lin…



ep/eA at LHeC/FCC-eh allows to test novel QCD dynamics (resummation + parton saturation) through two-prong approach: low x and large A



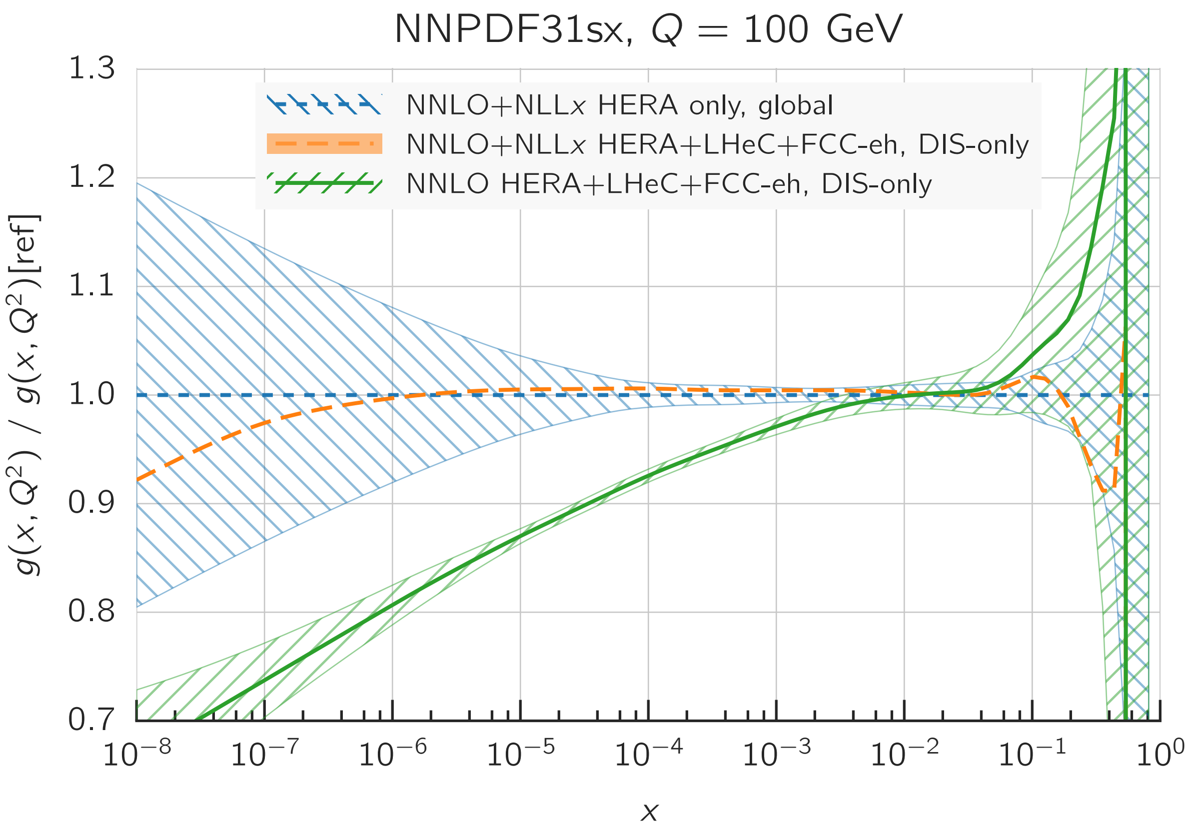


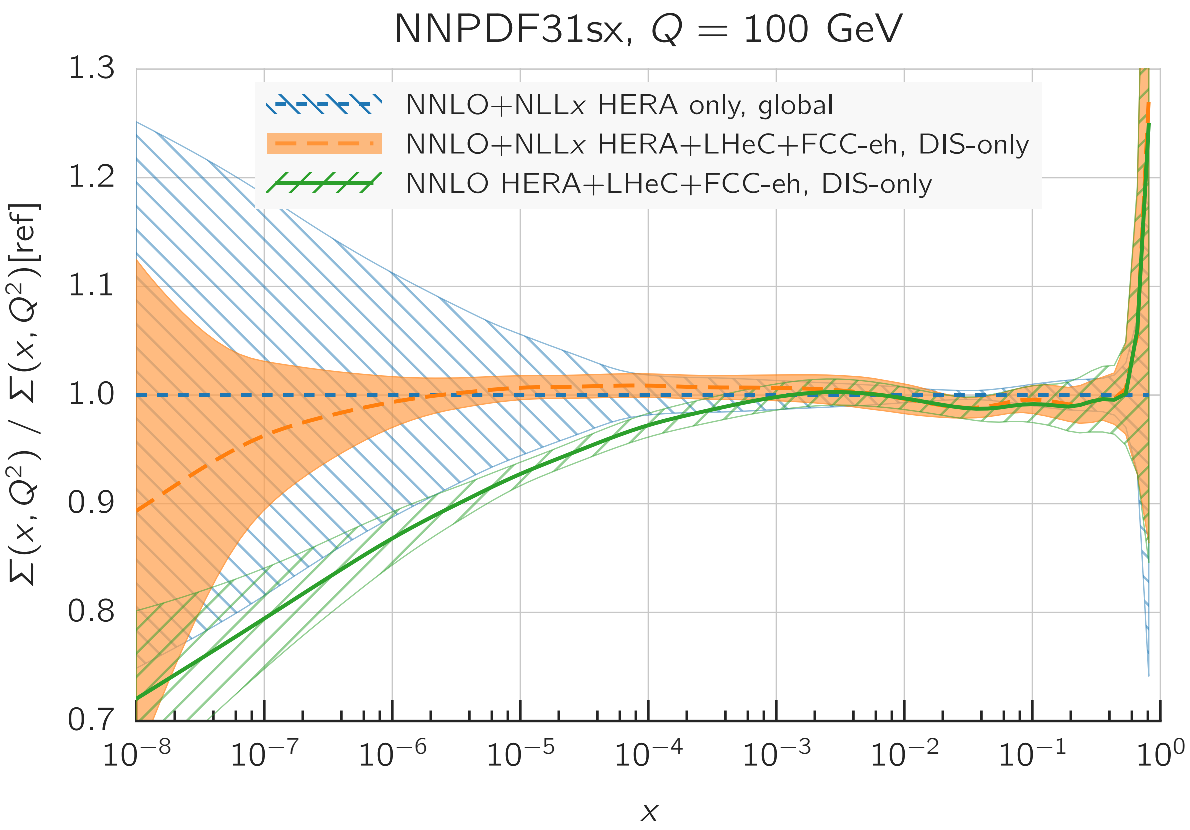
Novel dynamics at small x : resummation

Resummation at low x needed to stabilize BFKL expansion

Fits to HERA data: DGLAP + resummation, improve the description at low x

Ball, Bertone, Bonvini, Marzani, Rojo, Rottoli



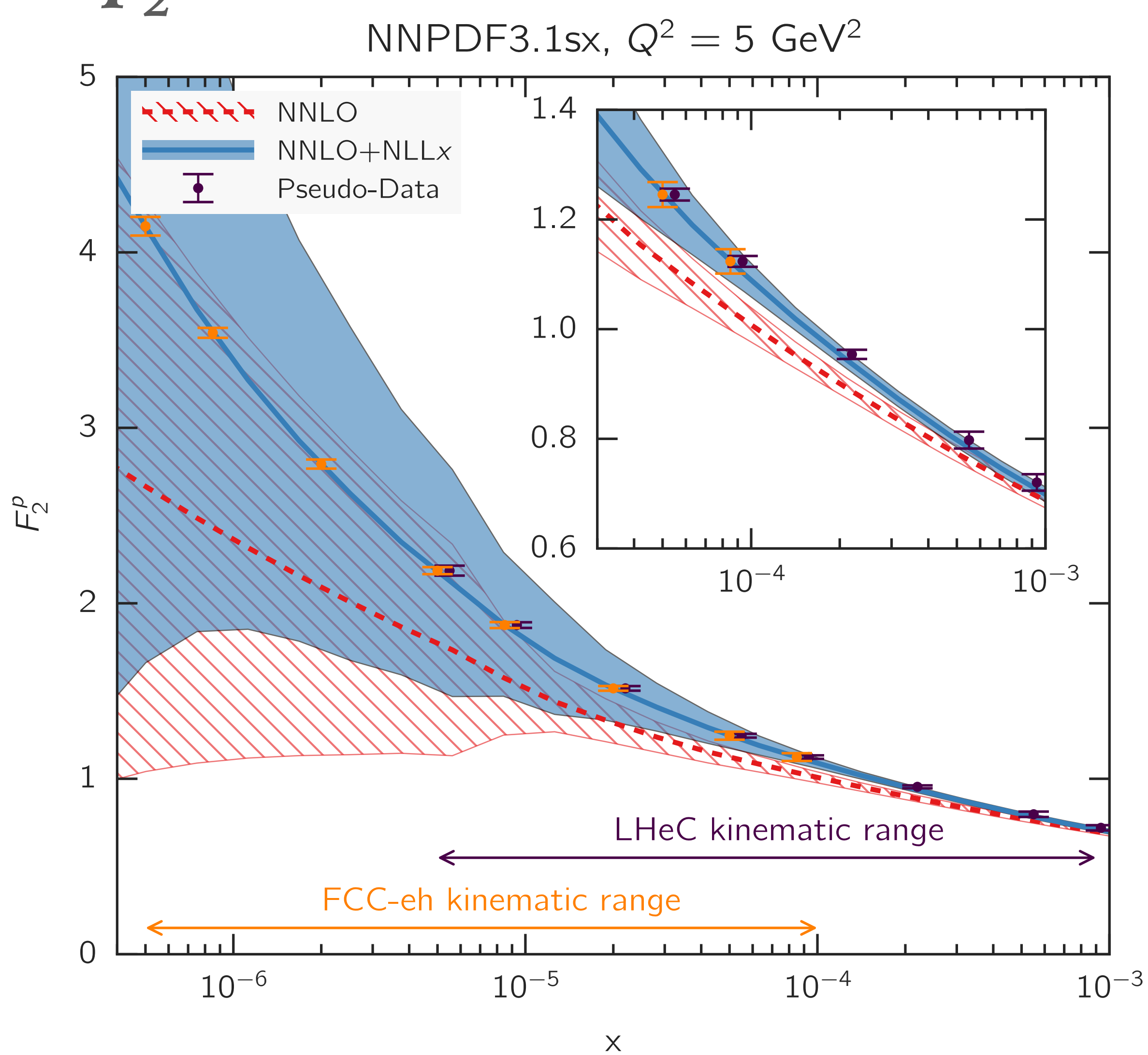


Large differences in the parton density at low x.

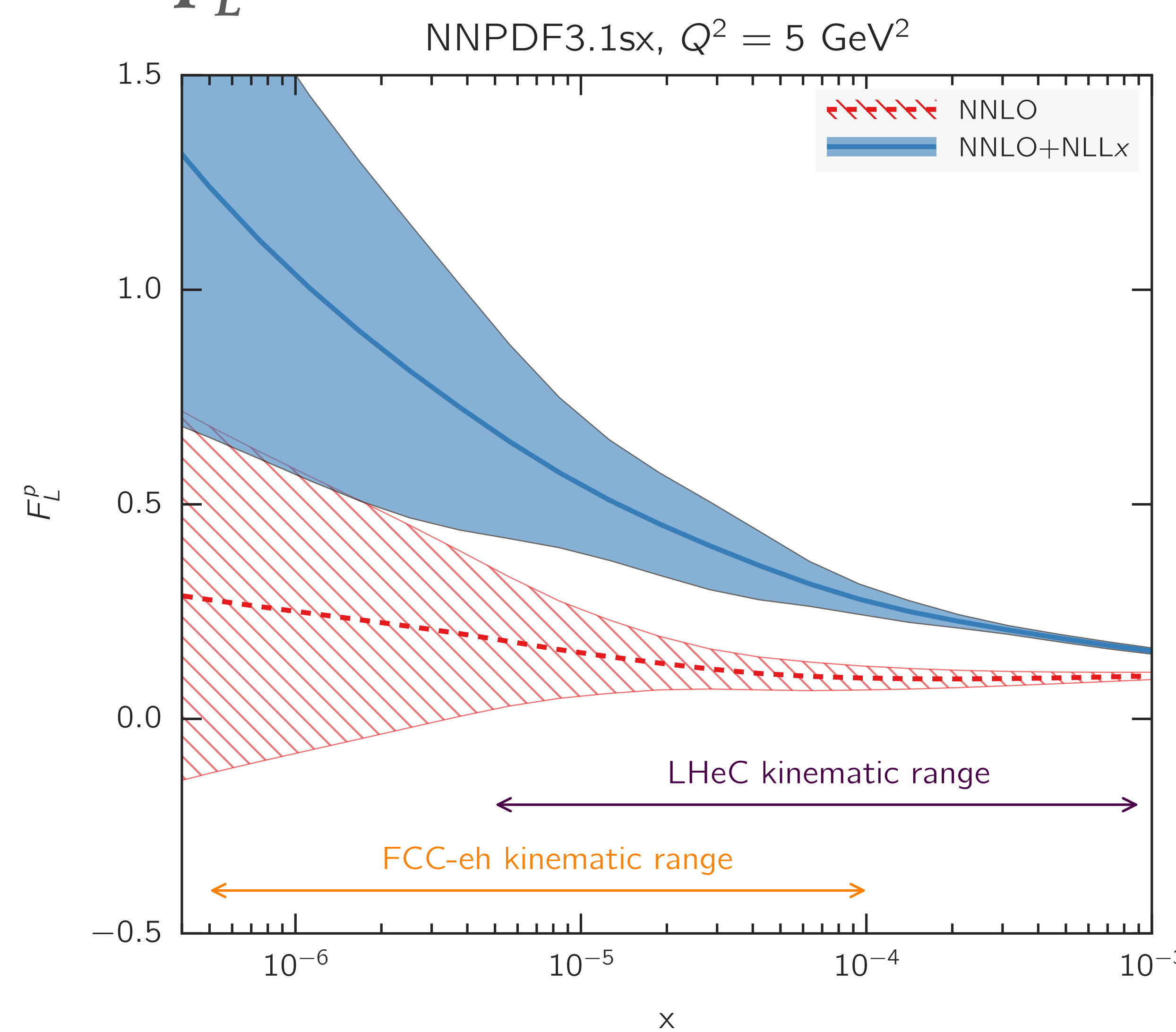
Essential for LHeC and FCC-eh

Novel dynamics at small x : resummation

F_2



F_L



Important consequences for LHeC and FCC-eh

20-40% difference of central values for F_2

Factor 2 to 4 for F_L

DGLAP fit will likely fail at the LHeC range

Resummation mandatory for LHeC and FCC-eh

Testing saturation through inclusive structure functions

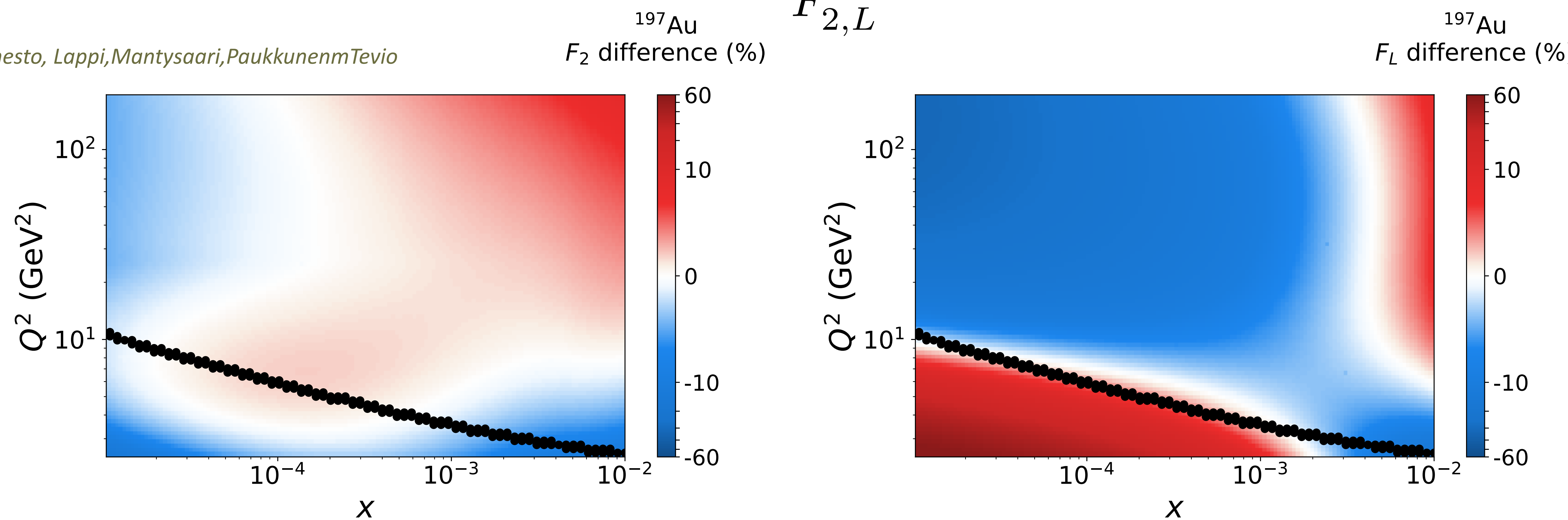
Study differences in evolution between **linear DGLAP** evolution and **nonlinear** evolution with **saturation**

Matching of both approaches in the region where saturation effects expected to be small

Quantify differences away from the matching region: **differences in evolution dynamics**

$$\frac{F_{2,L}^{\mathrm{BK}} - F_{2,L}^{\mathrm{Rew}}}{F_{2,L}^{\mathrm{BK}}}$$

Armesto, Lappi,Mantysaari,PaukkunenmTevio



Heavy nucleus: difference between DGLAP and nonlinear, 10% for F_2 and 60% for F_L

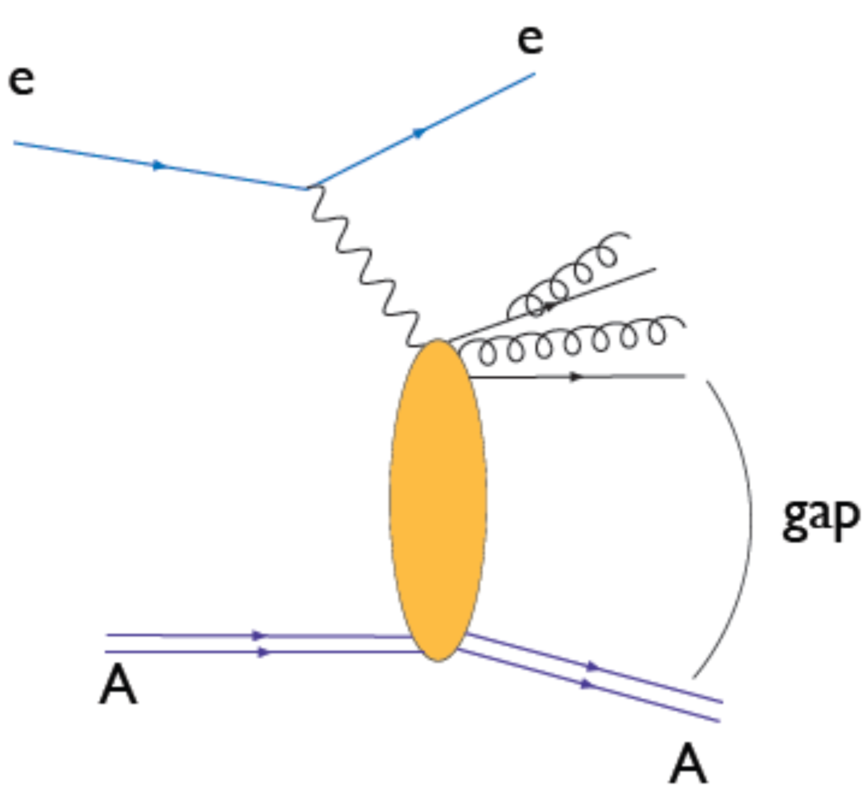
Longitudinal structure function can provide additional good sensitivity to saturation

Diffraction in eA

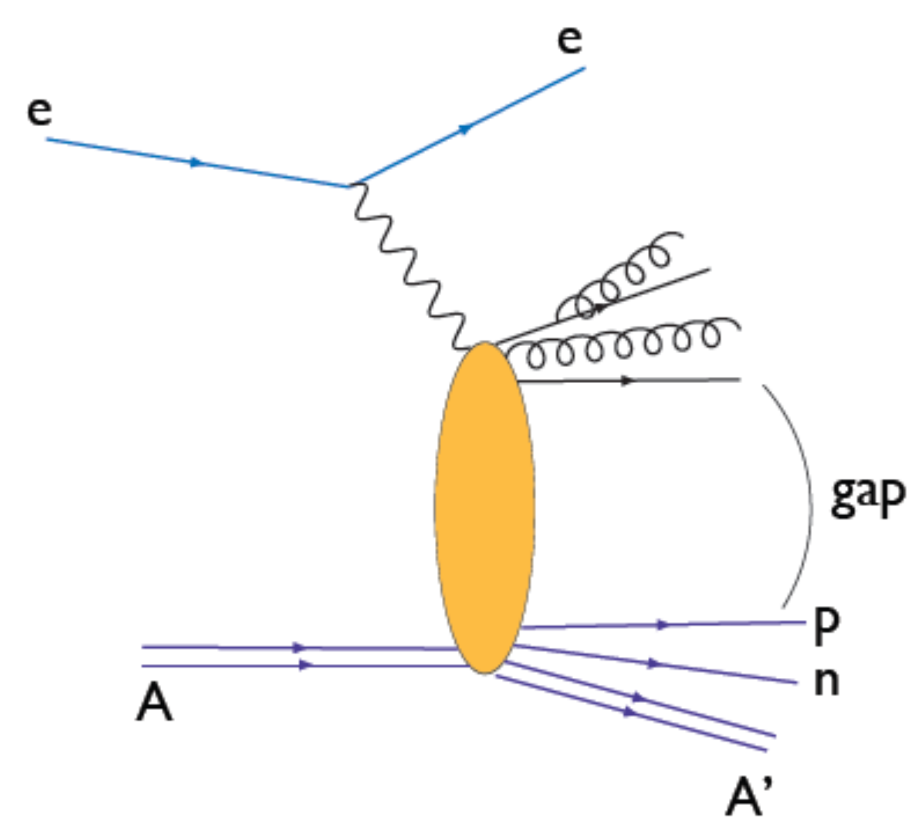
Diffraction: event in hadronic collisions characterized by the large rapidity gap, void of any activity

From theoretical perspective: requires exchange of colorless object in the t-channel

Diffraction on nuclei: possible coherent (nucleus stays intact) or incoherent (nucleus breaks but still rapidity gap present)

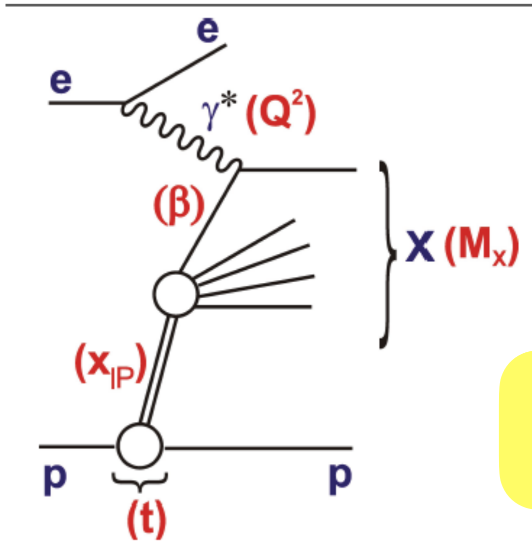


coherent



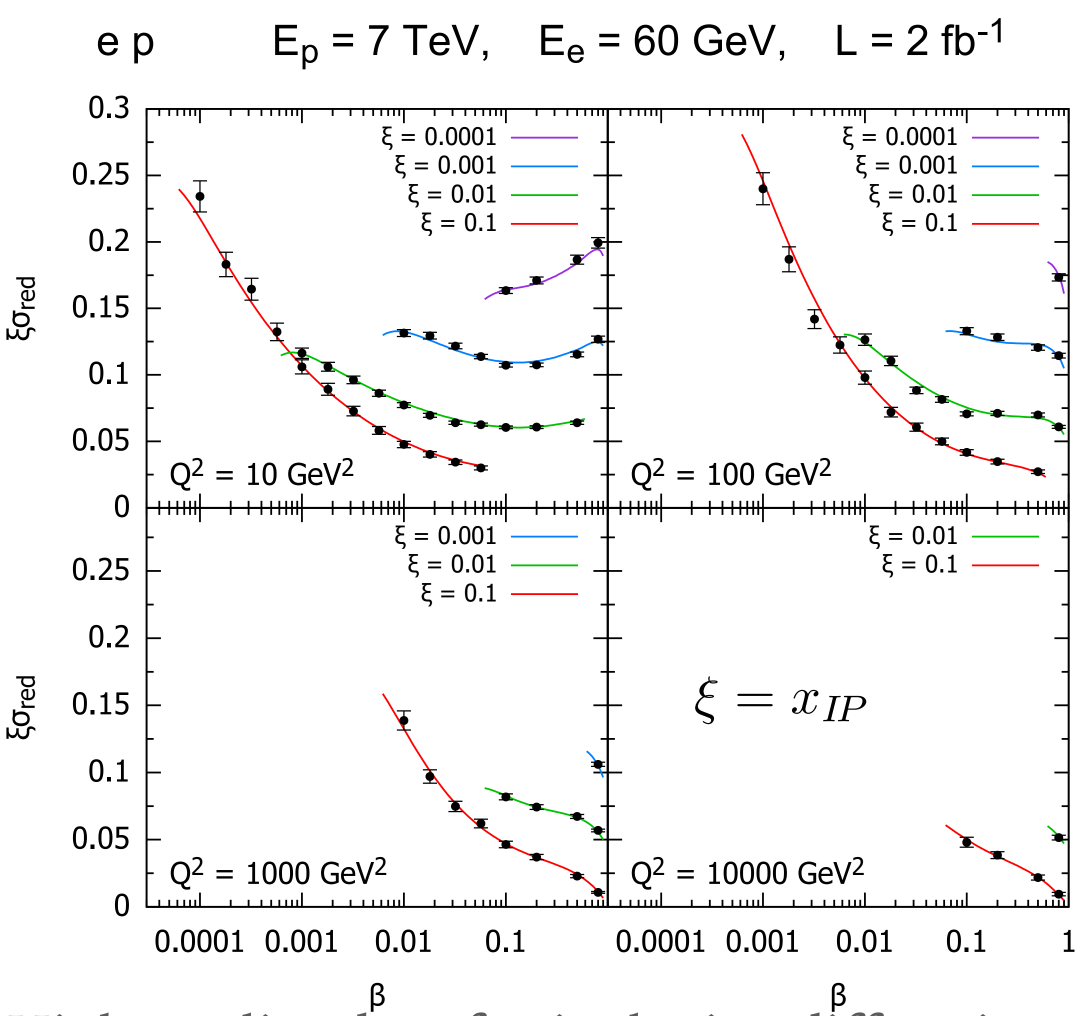
incoherent

Inclusive diffraction

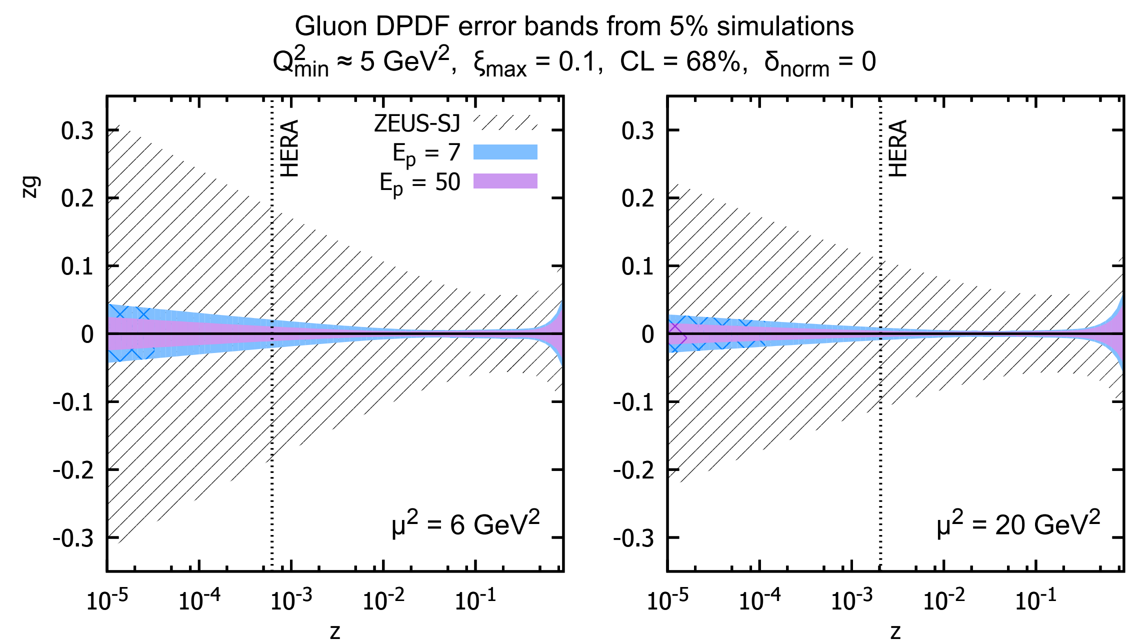


$$x_{Bj} = x_{IP}\beta$$

- Low x_{IP} → cleanly separate diffraction
- Low β → Novel low x effects
- High Q^2 → Lever-arm for gluon,flavour decompositio
- Large M_x → Jets, heavy flavours, W/Z …
- Large E_T → Precision QCD with jets …



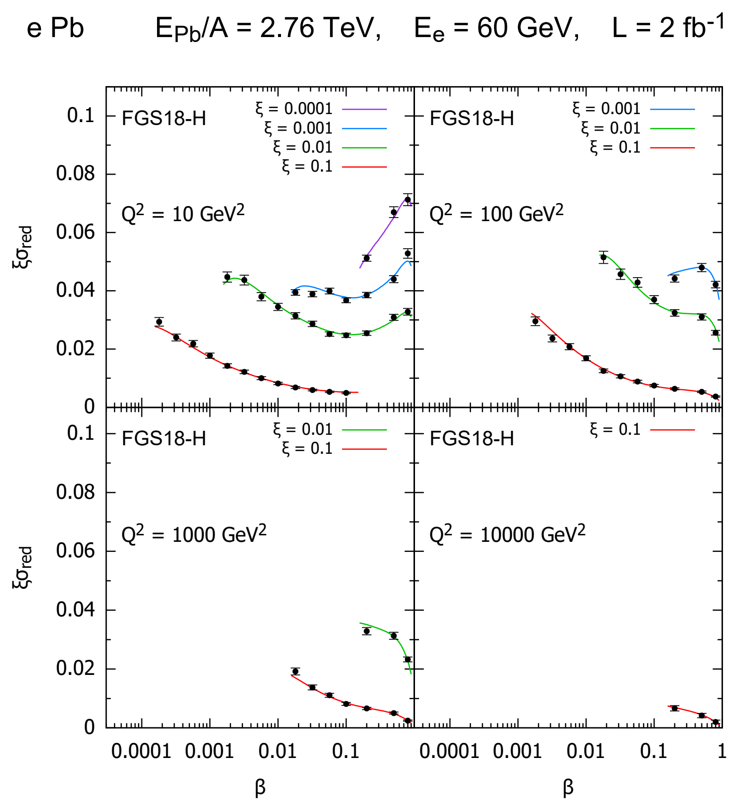
DPDFs uncertainty reduction by pseudodata of LHeC and FCC-eh

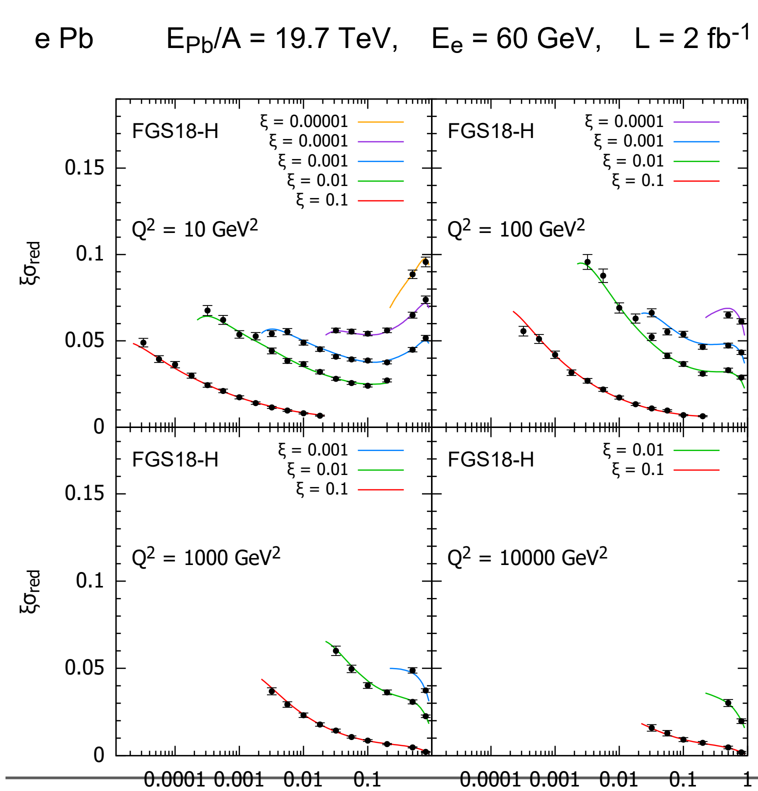


Precise extraction of diffractive PDFs
Tests of factorization in QCD
First extraction of diffractive PDFs in eA

High quality data for inclusive diffraction on protons. The same could be done for nuclei.

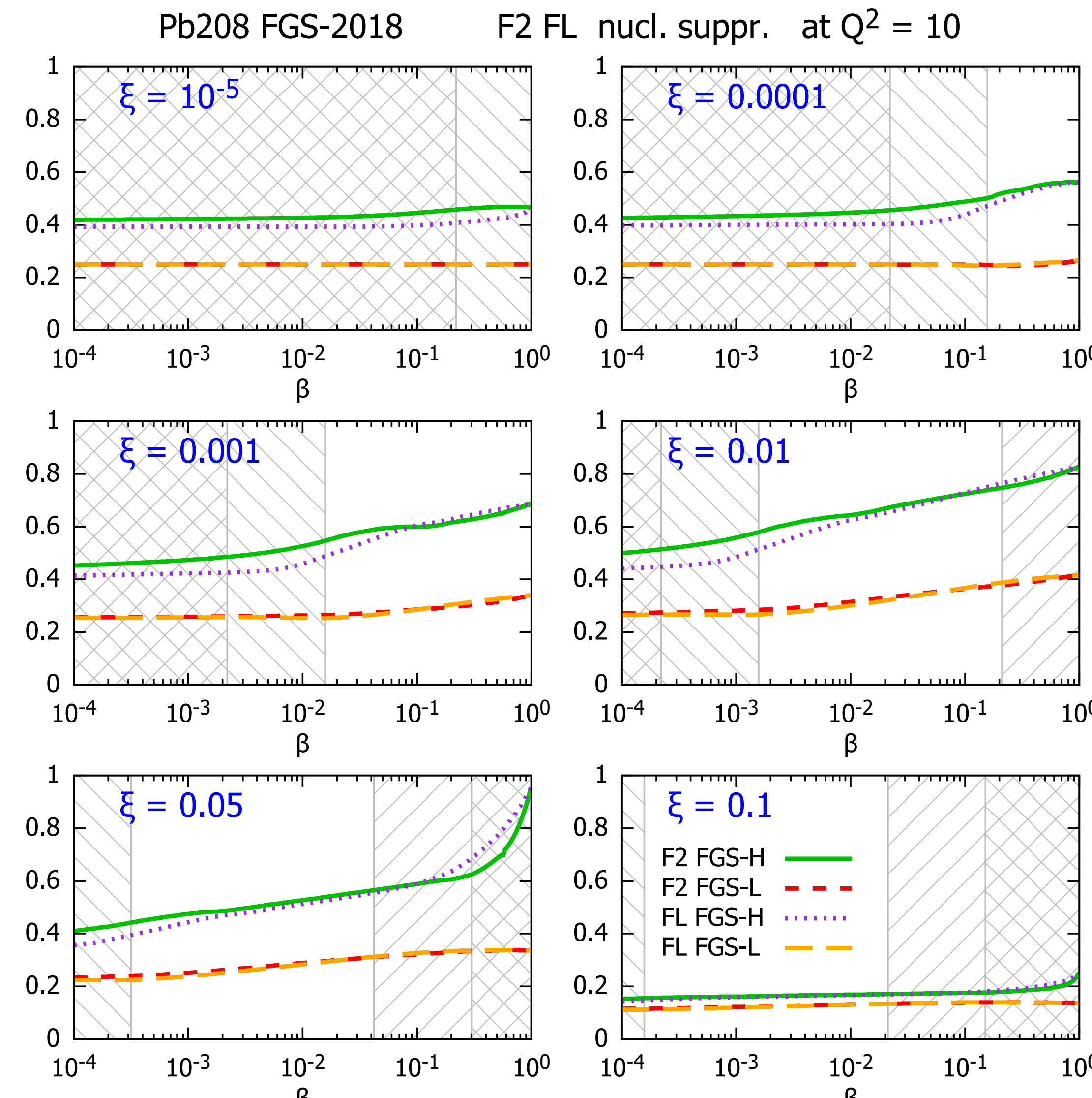
Inclusive diffraction: nuclei





Similar high quality data for diffraction in eA

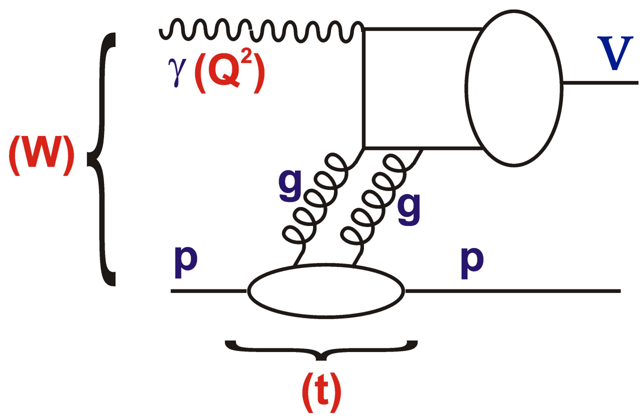
Possible extraction of diffractive nuclear PDFs for the first time!

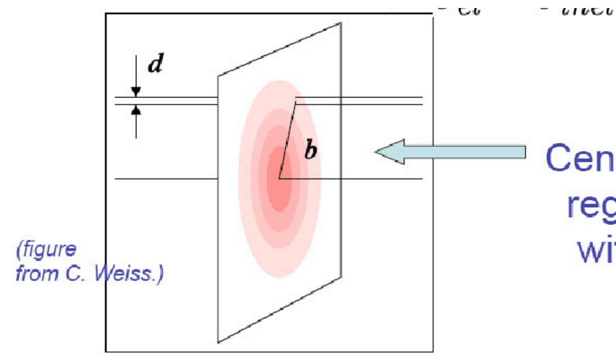


Examples of nuclear ratios for structure functions

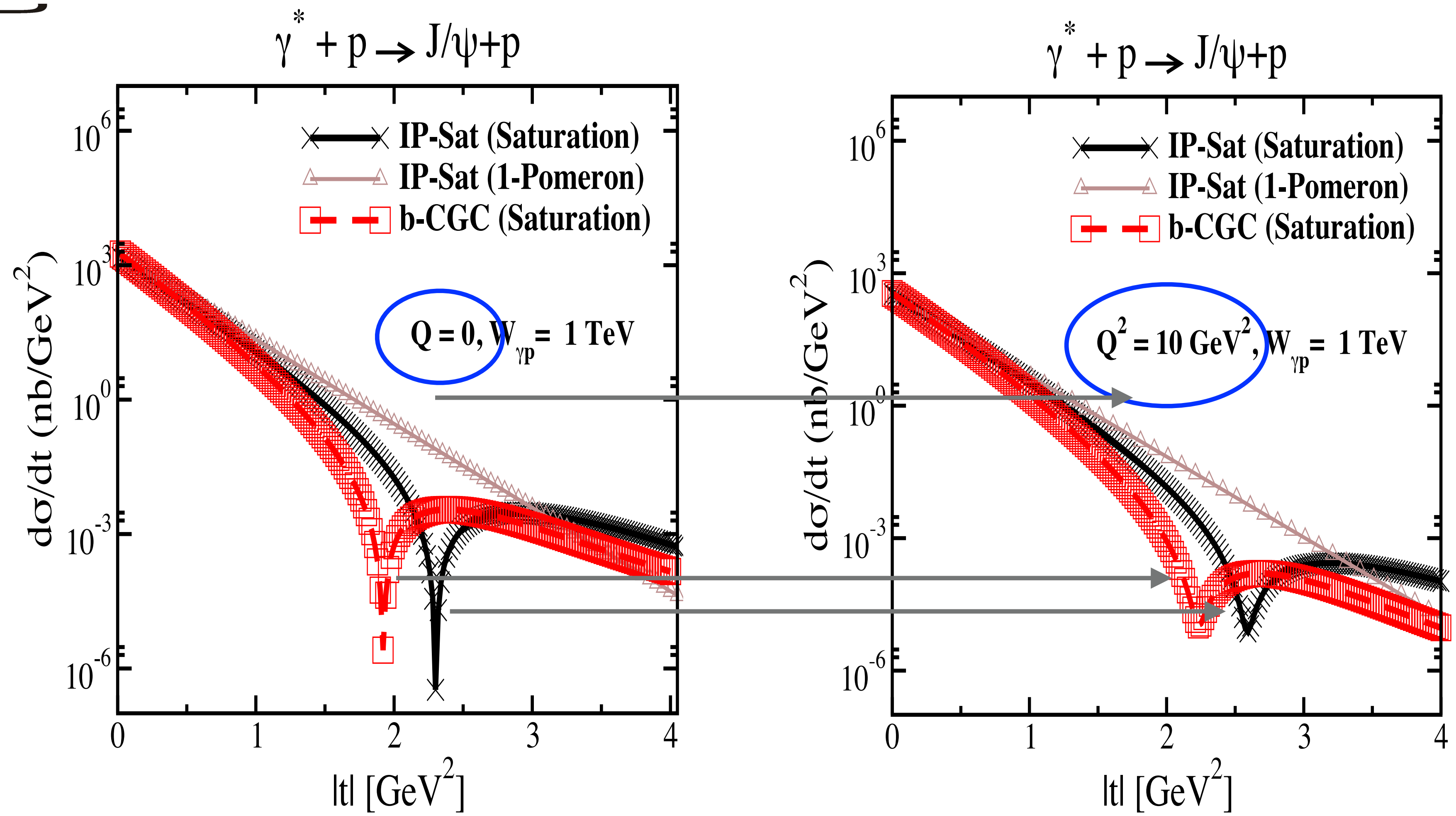
In different scenarios for Frankfurt, Guzey, Strikman model.

Elastic diffraction of vector mesons





Central black region growing with decrease of x.



Advantage over UPC:

Q^2 dependence

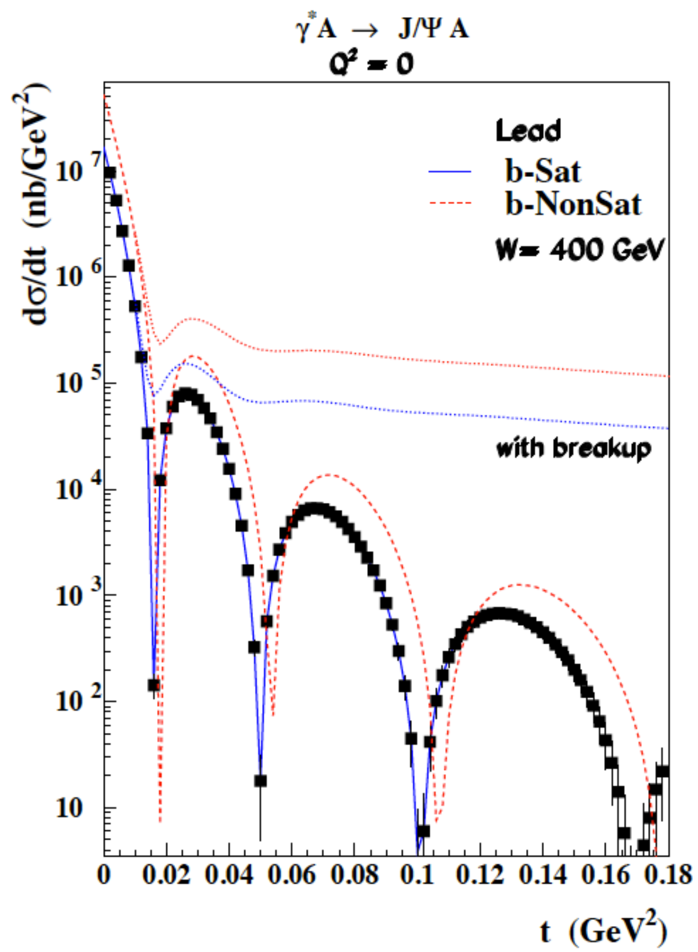
Precision t, W and Q^2 dependence of vector mesons

Example : tests of saturation from the slope in t

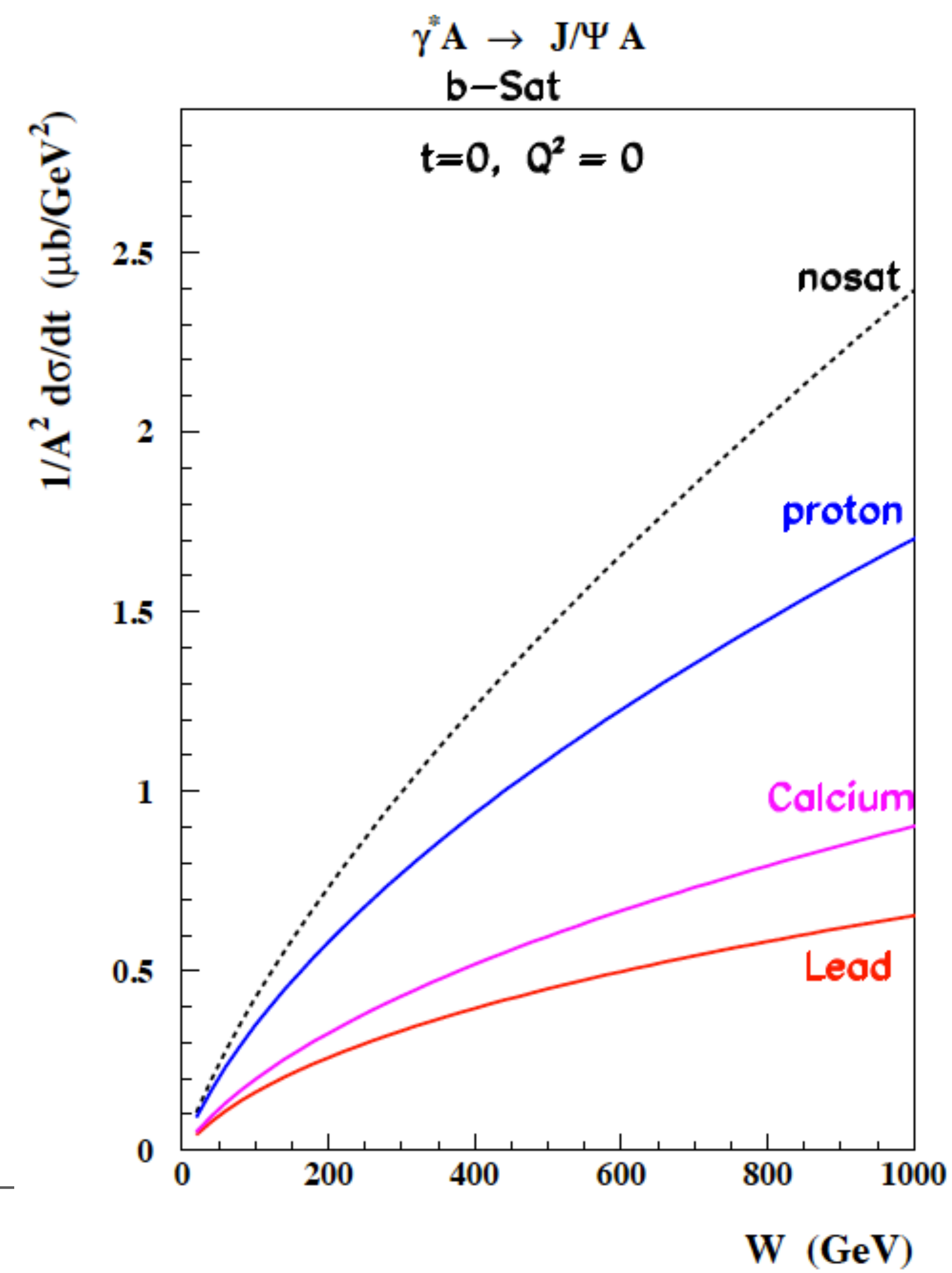
One of the best processes to test for novel small *x* dynamics

Exclusive diffraction on nuclei

Possibility of using the same principle to learn about the gluon distribution in the nucleus. Possible nuclear resonances at small t?



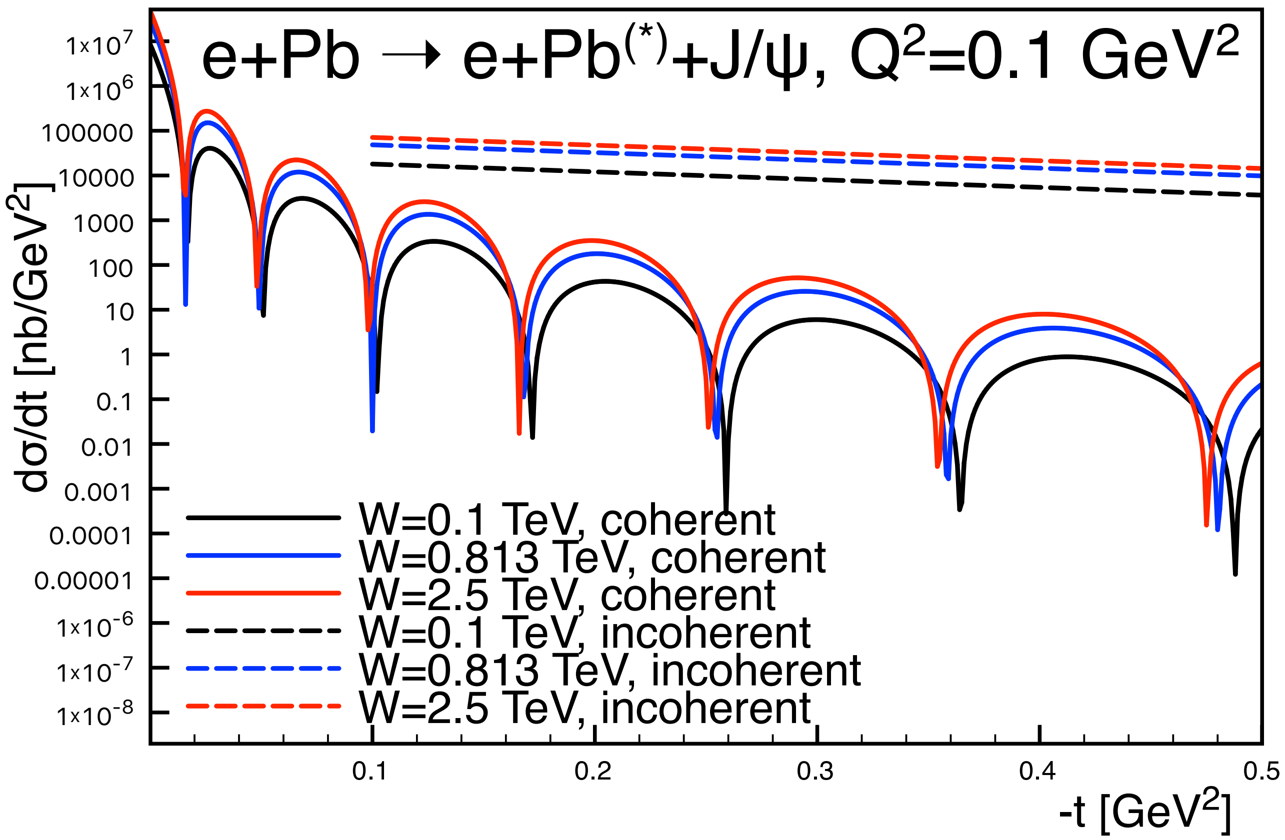
Energy dependence for different targets.

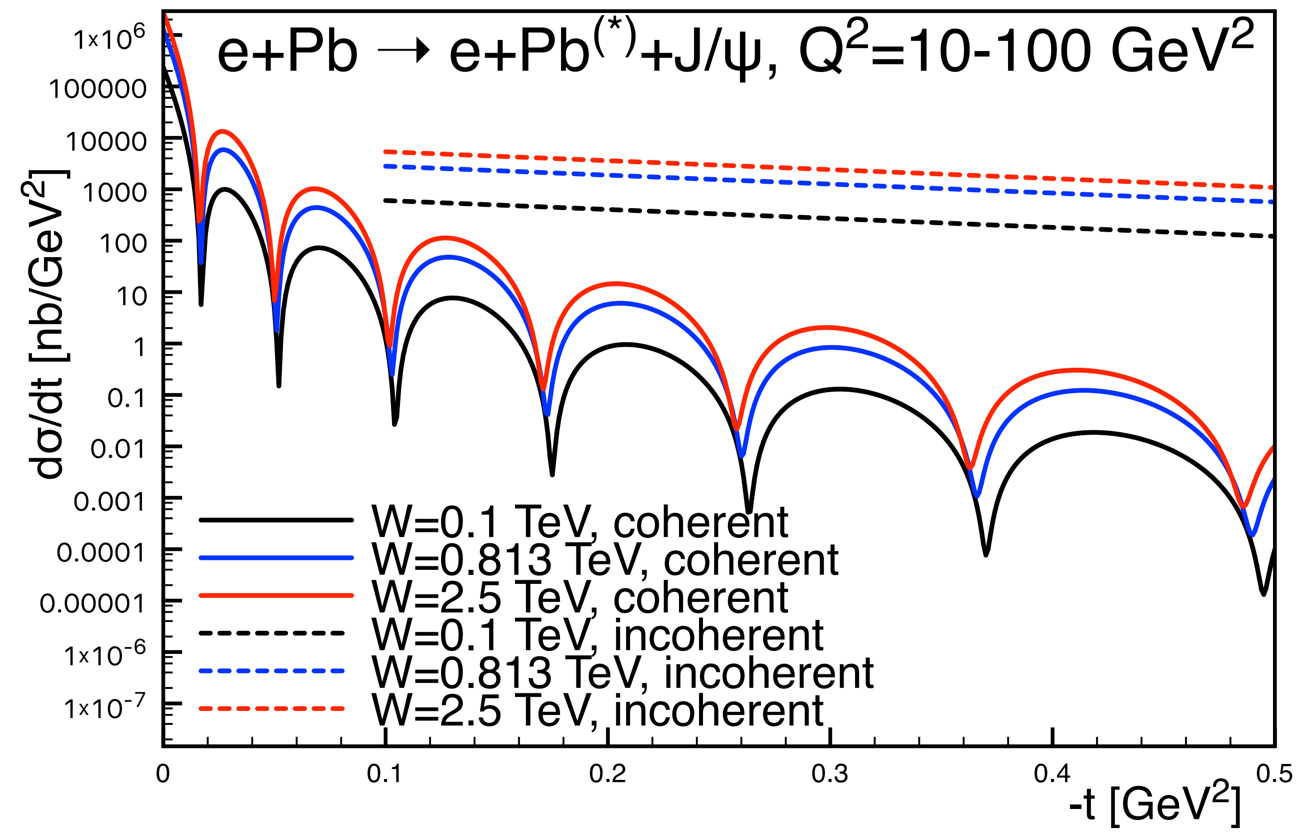


t-dependence: characteristic dips.

Challenges: need to distinguish between coherent and incoherent diffraction. Need dedicated instrumentation, zero degree calorimeter.

Exclusive diffraction on nuclei



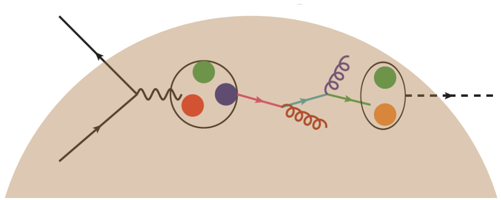


Energy and scale dependence of the position of dips in $|t|$. Provides information about nuclear structure. Can perform similar measurements on proton target to estimate the saturation in proton vs nuclei. Challenging experimentally.

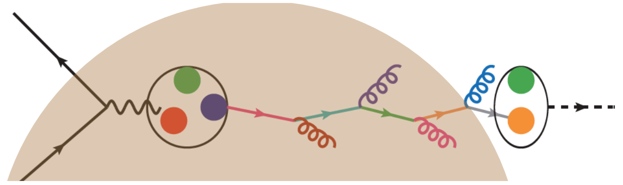
Fragmentation and hadronization

- LHeC can provide information on radiation, fragmentation and hadronization.
- Large lever arm in energy allows probing different timescales: parton radiation, pre-hadron formation, hadron.
- Different stages can happen inside or outside nuclear matter depending on the energy of the parton.
- Important for heavy ion collisions .

Low energy: hadronization inside



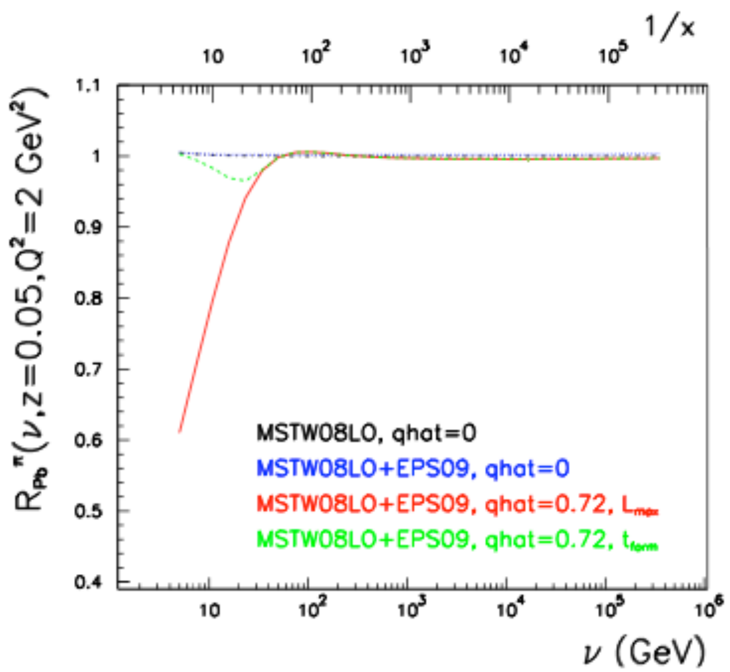
High energy: partonic evolution altered in nuclear medium

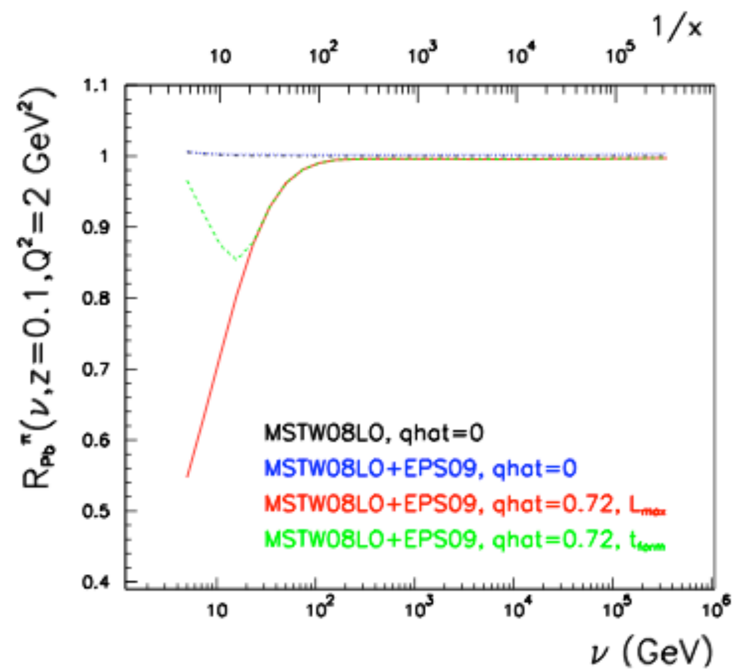


$$R_A^k(\nu, z, Q^2) = \frac{1}{N_A^e}\frac{dN_A^k}{d\nu dz} \Bigg/ \frac{1}{N_p^e}\frac{dN_p^k}{d\nu dz}$$

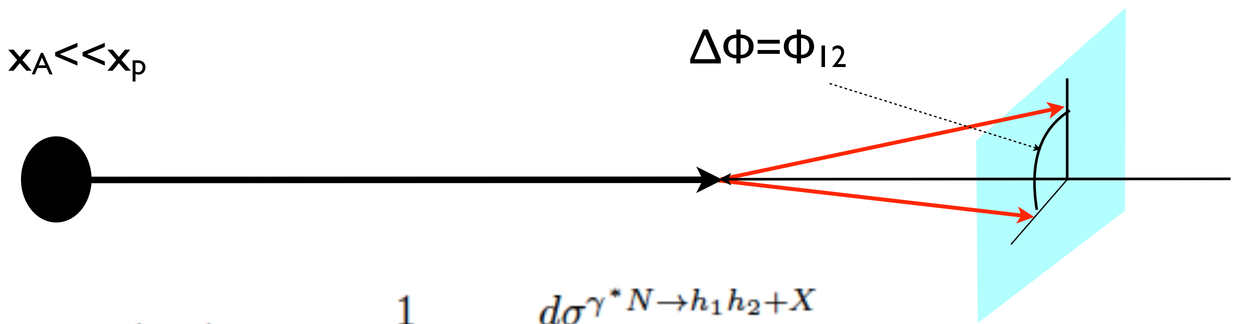
$$z = E_h/\nu$$

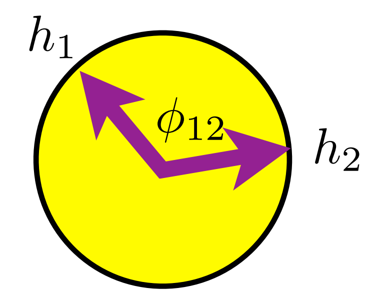
ν energy of struck parton





Azimuthal decorrelation



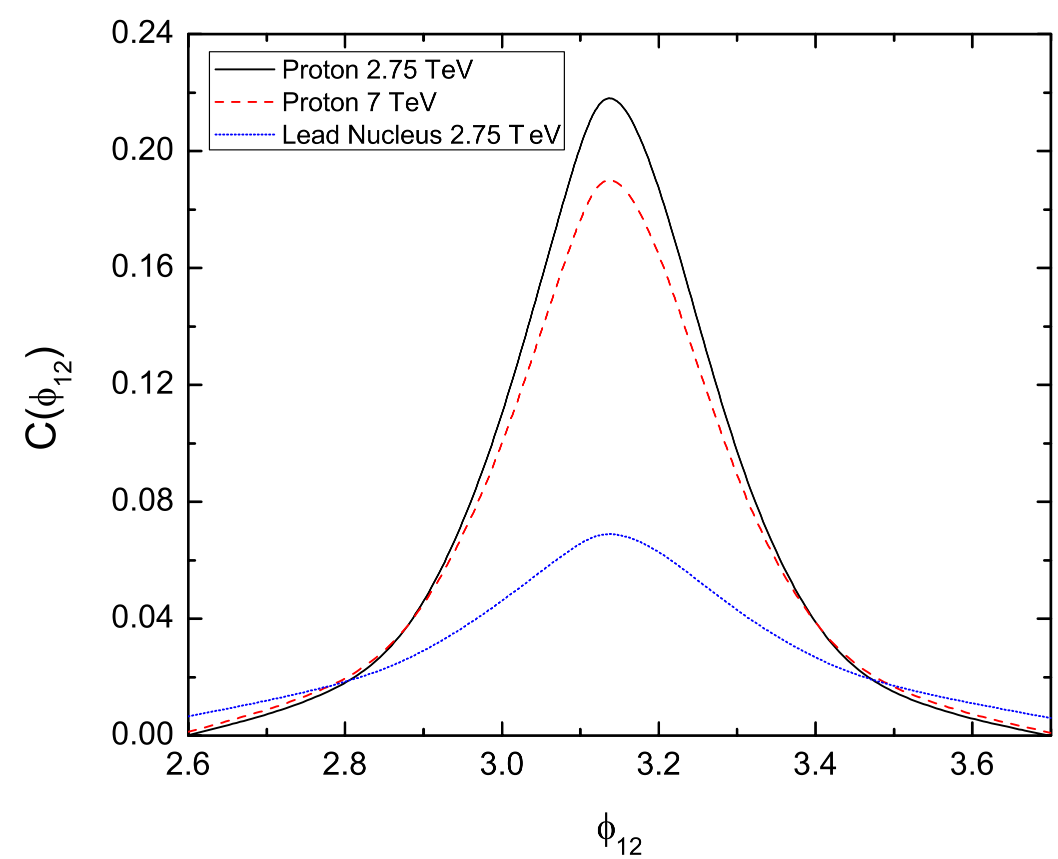


$$C(\phi_{12}) = \frac{1}{\frac{d\sigma(\gamma^* N \to h_1 X)}{dz_{h1}}} \frac{d\sigma^{\gamma^* N \to h_1 h_2 + X}}{dz_{h1} dz_{h2} d\phi_{12}}$$

Azimuthal decorrelation of dijets or hadrons

Can be used to test the saturation effects at low x

Sensitivity to the transverse momentum dependence of the unintegrated gluon distribution in the nucleus



$p_T^{lead} > 3$ GeV
$p_T^{ass} > 2$ GeV
$z_{lead} = z_{ass} = 0.3$
$y = 0.7$
$Q^2 = 4$ GeV^2

h-h in ePb

Summary

- The LHeC and FCC-eh will explore a completely new region in (x,Q) for eA collisions. Enlarge the kinematic space by 4 orders of magnitude over what was previously measured in DIS.
- Precise determination of nuclear PDFs which cannot be matched at hadron colliders.
- Coupled with ep, would allow to test the saturation at low x and with different A dependence. Test two-pronged approach to saturation: large A and/or small x.
- Precise measurements of heavy flavors in eA.
- Exclusive VM diffractive production would allow to explore the nuclear structure in impact parameter.
- New possibilities for the inclusive diffraction: extraction of nuclear diffractive parton densities. Checks of QCD factorization and relation between diffraction in ep and shadowing in eA.
- Other processes studied: azimuthal decorrelations, radiation and hadronization.