

Nuclear structure from energy frontier DIS

LHeC/FCC-eh @ CERN

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Outline

- Motivation for ep/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)
 - Heavy Flavors
 - Diffraction
 - Radiation and hadronization in cold nuclear matter

More talks on LHeC at ICHEP2016:

Christian Schwanenberger , *Top, EW and BSM physics at LHeC and FCC-he*, Aug. 4

Max Klein, *Options for energy frontier electron-hadron scattering at CERN*, Aug. 5

Bruce Mellado Garcia, *Higgs physics at the LHeC and FCC-he*, Aug. 6

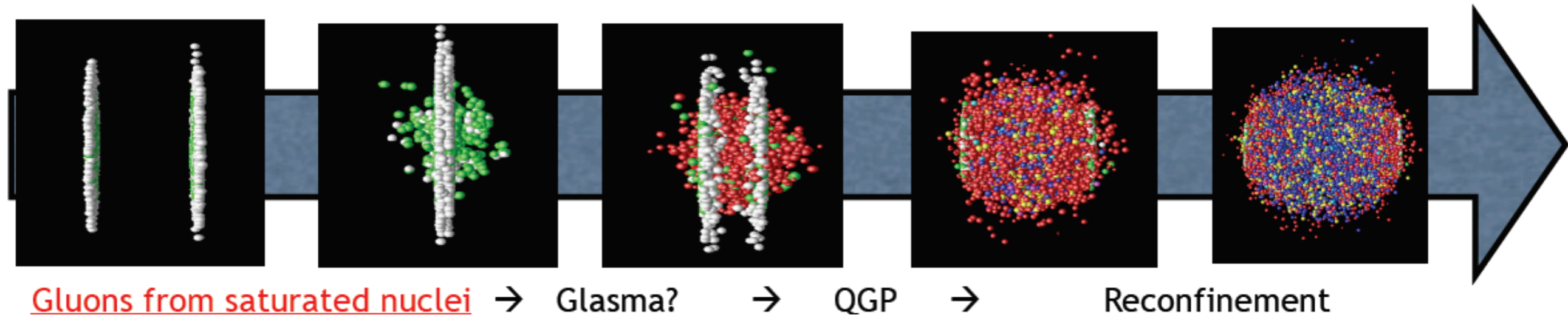
Physics motivation for ep/eA in TeV range

- Details of parton structure of the nucleon (from ep,ed/eA), full unfolding of PDFs. Measurement of Generalized Parton Distribution functions and unintegrated PDFs.
- Mapping the gluon field down to very low x. Parton saturation physics.
- Heavy quarks, factorization, diffraction, electroweak processes.
- Properties of the Higgs. Precision studies, i.e. very good sensitivity to: H to bbar, H to WW coupling
- Searches of new physics. Leptoquarks, excited leptons...
- Very precise measurement of the strong coupling constant.
- Deep inelastic scattering off nuclei. Nuclear parton distributions. Pinning down the initial state for heavy ion collisions.

Resources:

*Conceptual Design Report, arXiv:1206.2913, J.Phys. G 39(2012) 075001
arXiv:1211.4831; arXiv:1211.5102, arXiv:1305.2090
Klein & Schopper, CERN Courier, June 2014
Newman & AS, Nature Physics 9 (2013) 448
See also website: lhec.web.cern.ch for recent presentations*

Nuclear physics in eA complementarity to pA, AA at LHC



Precision measurement of the initial state.

Nuclear structure functions.

Particle production in the early stages.

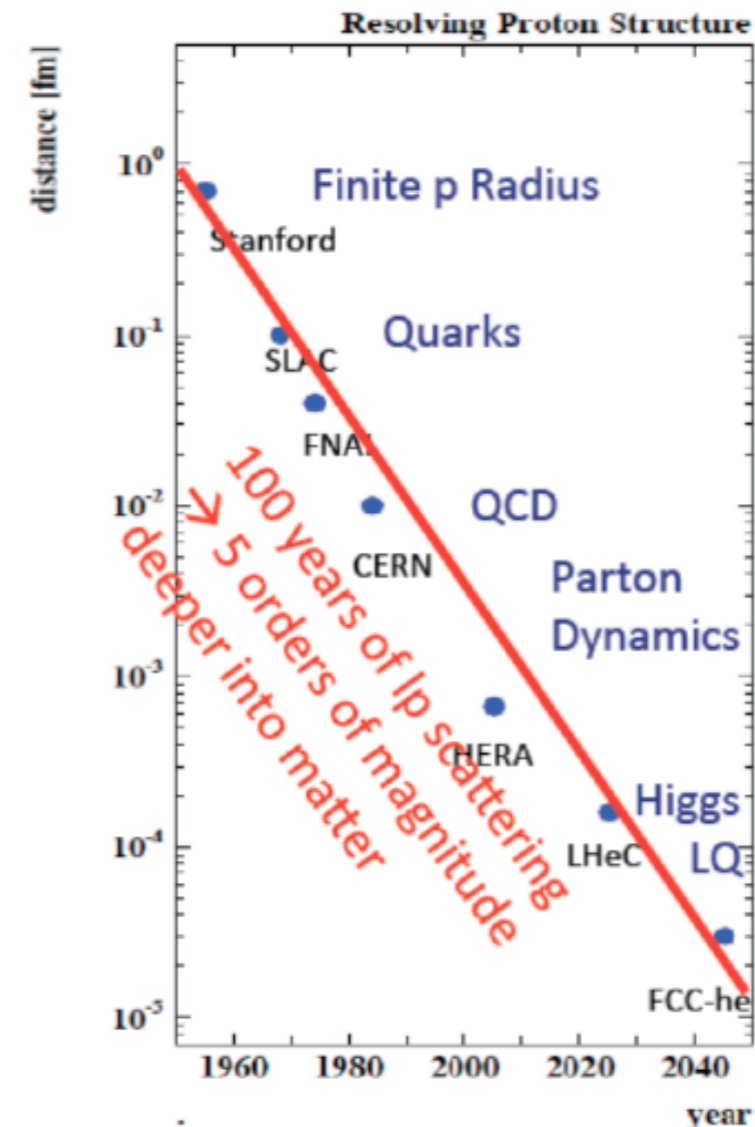
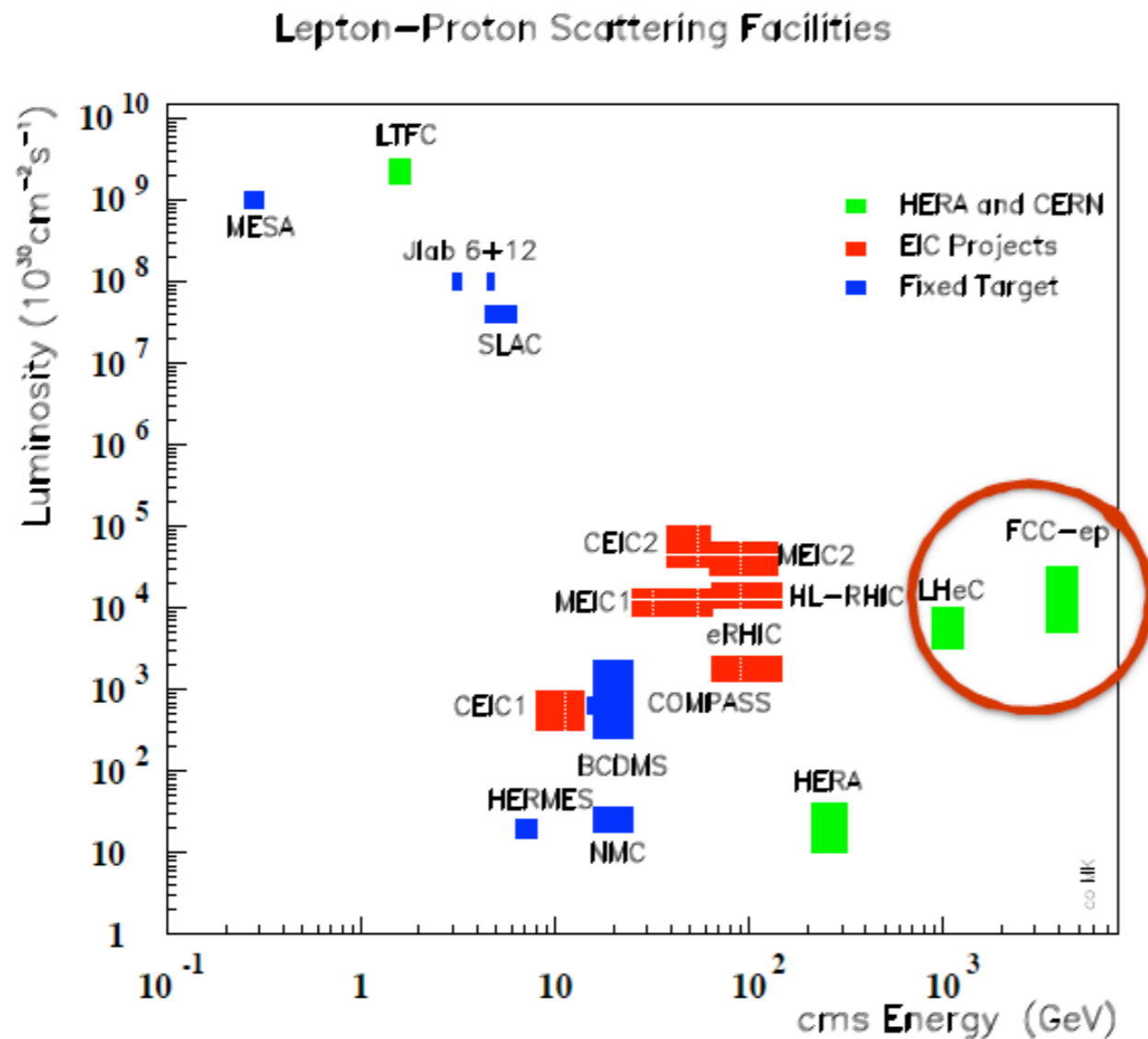
Factorization eA/pA/AA.

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

Future lepton-proton/ion collider proposals at CERN

Large Hadron Electron Collider (LHeC): combining the hadron/ion beam from LHC with electrons accelerated in Energy Recovery Linac

Future Circular Collider-ep option (FCC-ep): DIS on hadron/ion beam from FCC



LHeC kinematics

LHeC ep/eA collisions

$$E_p = 7 \text{ TeV}$$

$$E_A = 2.75 \text{ TeV/nucleon}$$

$$E_e = 60(50) - 140 \text{ GeV}$$

$$\sqrt{s} \simeq 1 - 2 \text{ TeV}$$

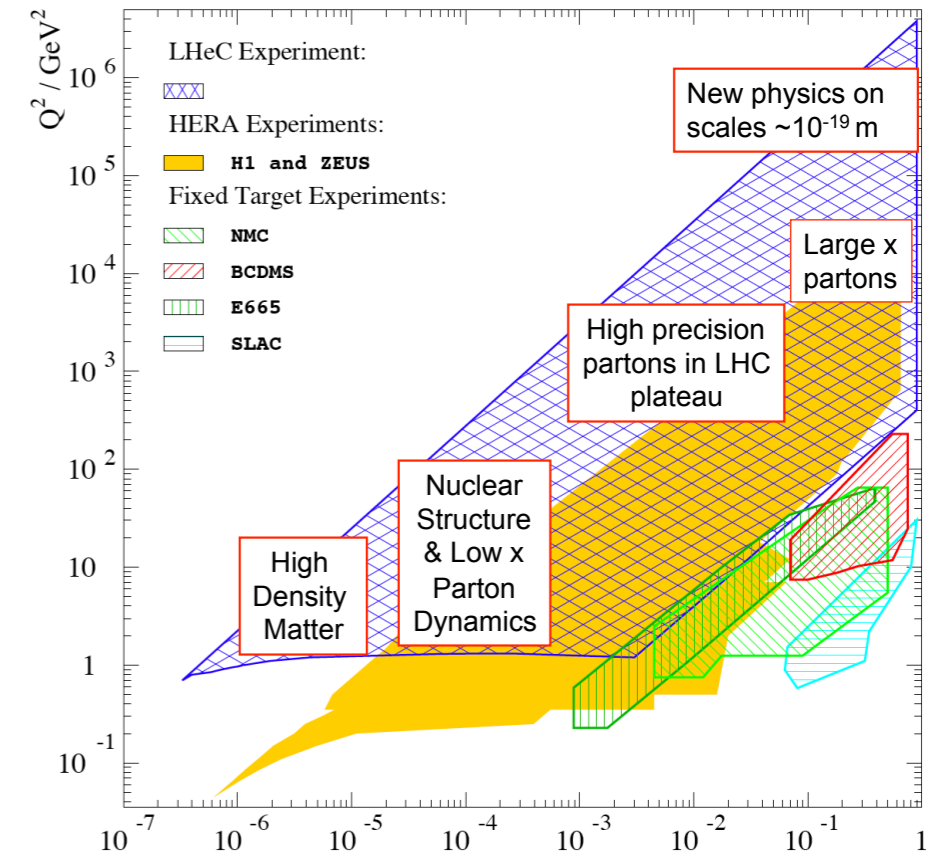
FCC-eh

$$E_p = 50 \text{ TeV}, E_A = 19.7 \text{ TeV/nucleon}$$

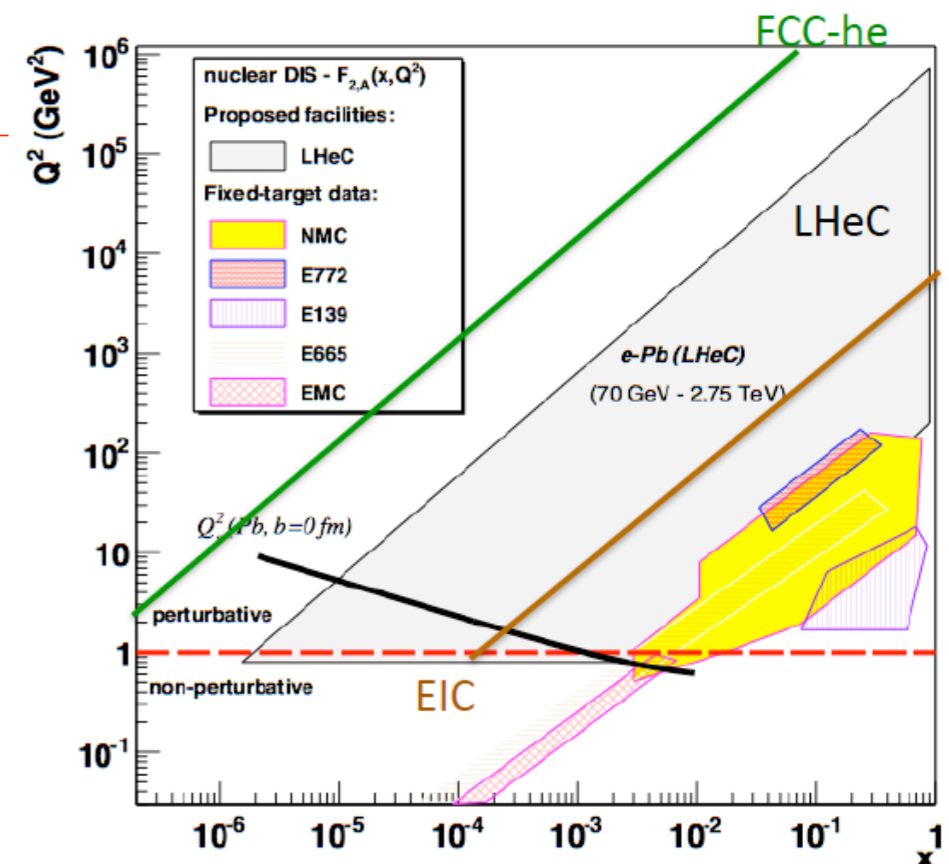
● Requirements:

- * Luminosity $\sim 10^{33} \text{ cm}^{-2}\text{s}^{-1}$. eA: $L_{\text{en}} \sim 10^{32} \text{ cm}^{-2}\text{s}^{-1}$
- * Acceptance: 1-179 degrees (low-x ep/eA).
- * Tracking to 1 mrad.
- * EMCAL calibration to 0.1 %.
- * HCAL calibration to 0.5 %.
- * Luminosity determination to 1 %.
- * Compatible with LHC operation.

ep



eA



Nuclear structure

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

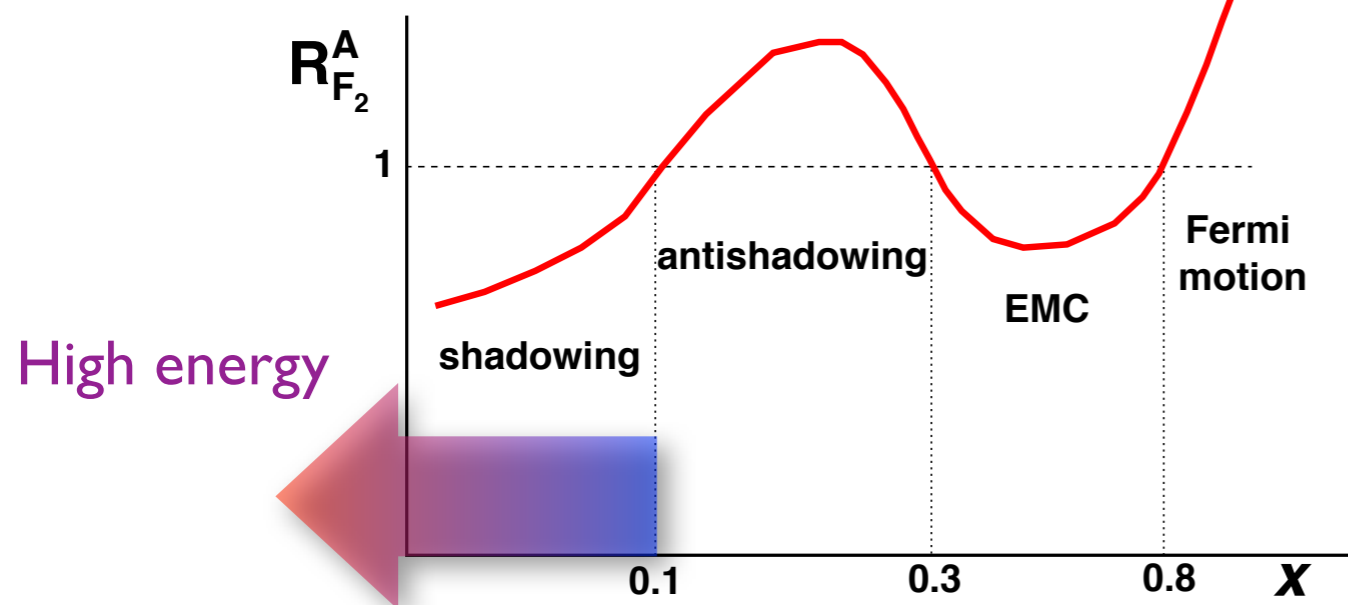
Nuclear ratio for structure function

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

Nuclear effects

$$R^A \neq 1$$

Schematic picture



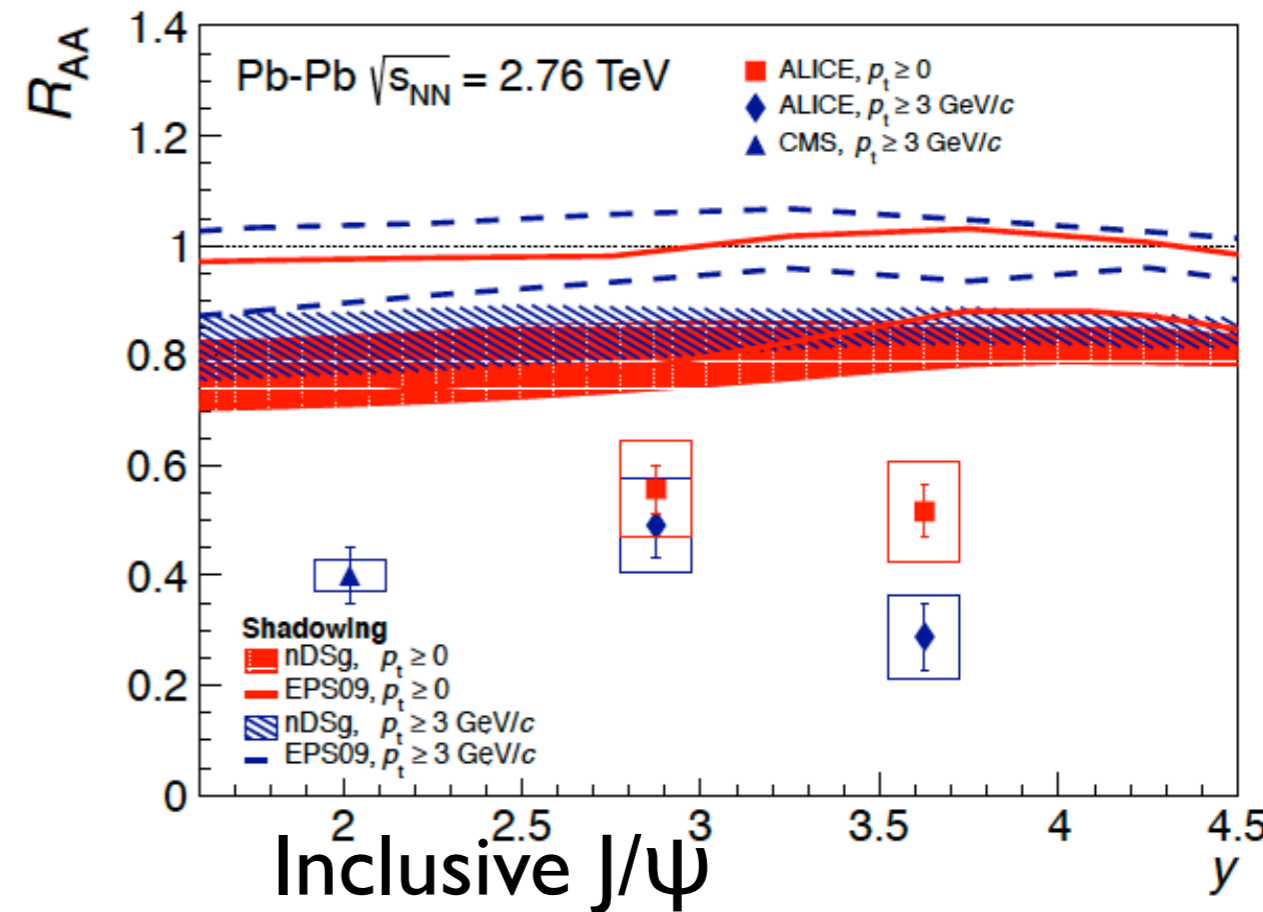
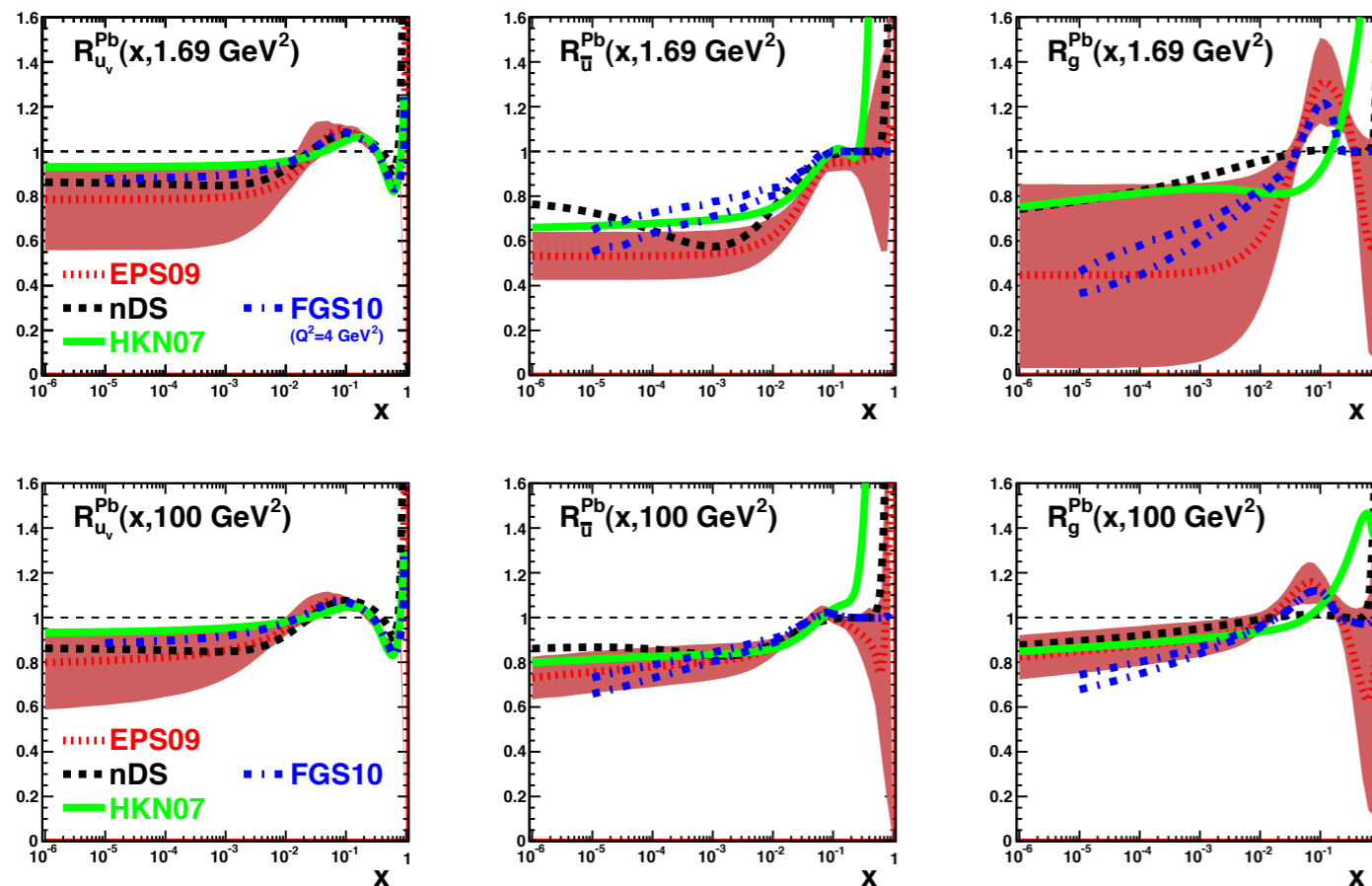
- Fermi motion
 $x \geq 0.8$
- EMC region
 $0.25 - 0.3 \leq x \leq 0.8$
- Antishadowing region
 $0.1 \leq x \leq 0.25 - 0.3$
- Shadowing region
 $x \leq 0.1$

Nuclear parton distributions: uncertainty

Collinear factorization in DIS:

$$F_{2,L}^A(x, Q^2) = C_i(\alpha_s; x, Q^2/\mu^2) \otimes x f_i^A(x, \mu^2)$$

Uncertainties of the parton distribution in nuclei



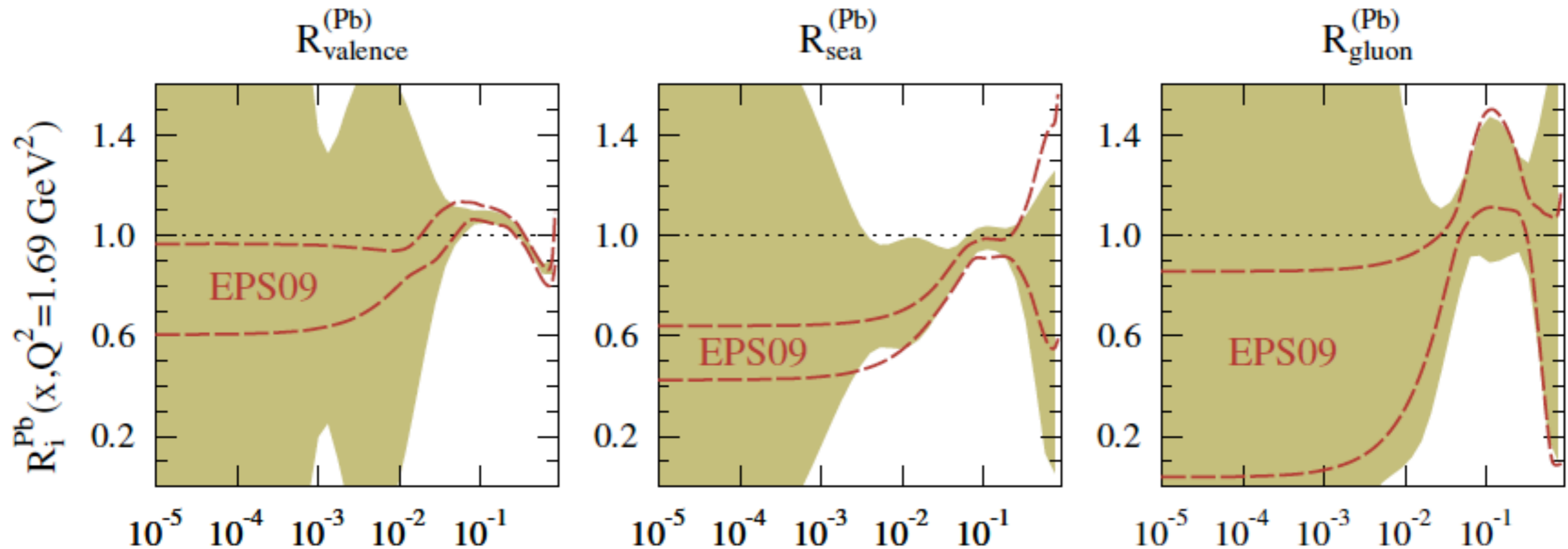
Large uncertainty at small values of x especially in the gluon and sea quark sector
 Translate into uncertainties in the evaluation of benchmarking for variety of processes at LHC
 and disentangling the effects of initial state from quark - gluon plasma in AA

New analysis of nPDFs with simulated data from LHeC

Much more flexible initial condition.

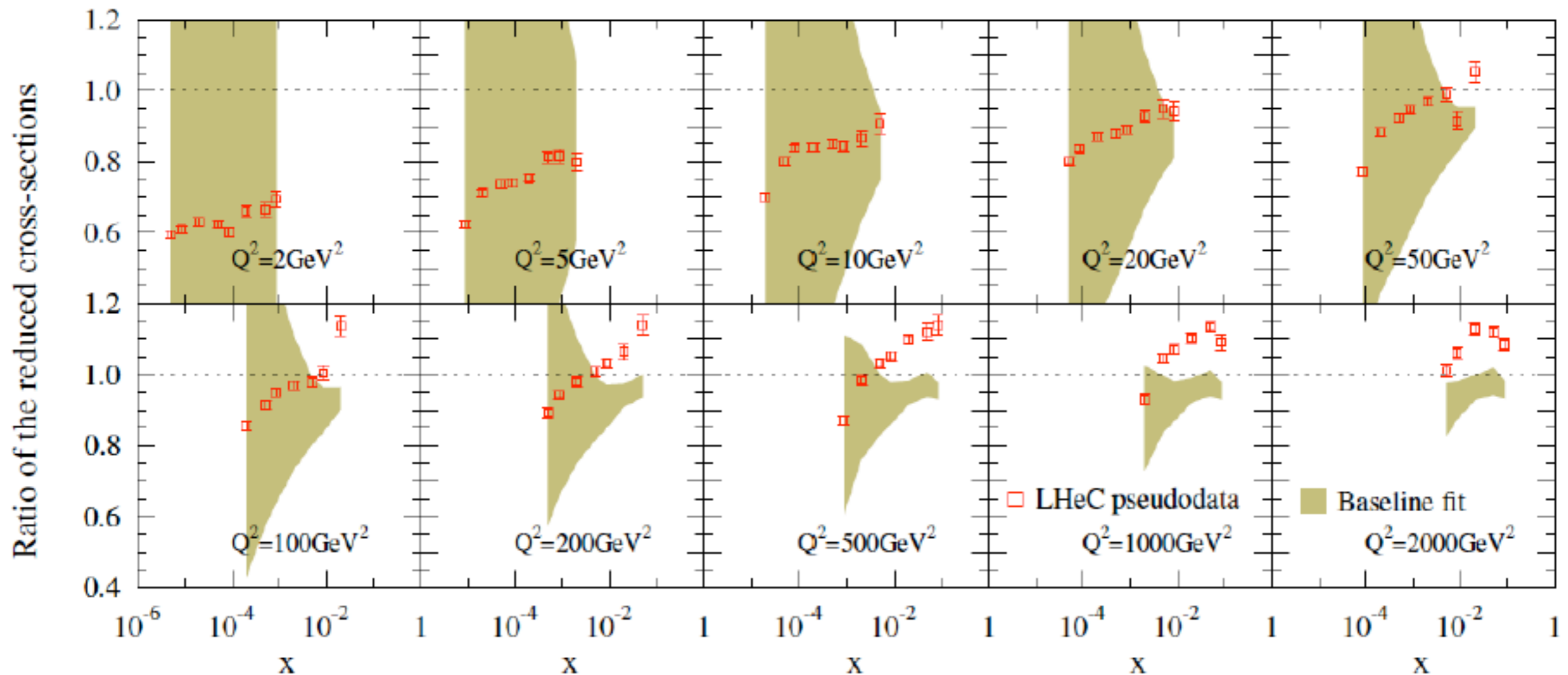
Results in larger spread at low x .

There are no data at low x so the uncertainty reflects lack of constraints.



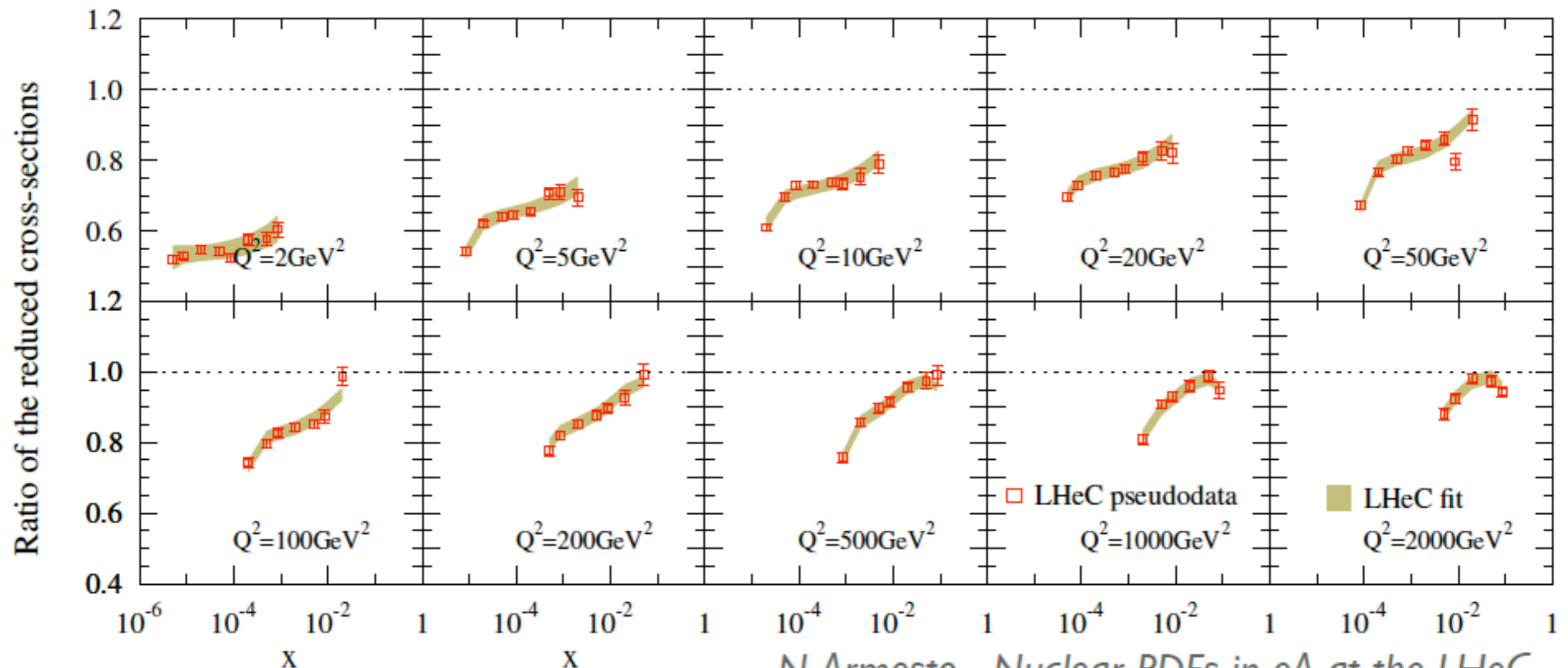
New analysis of nPDFs with simulated data from LHeC

LHeC simulated data are in the region where large uncertainties exist.



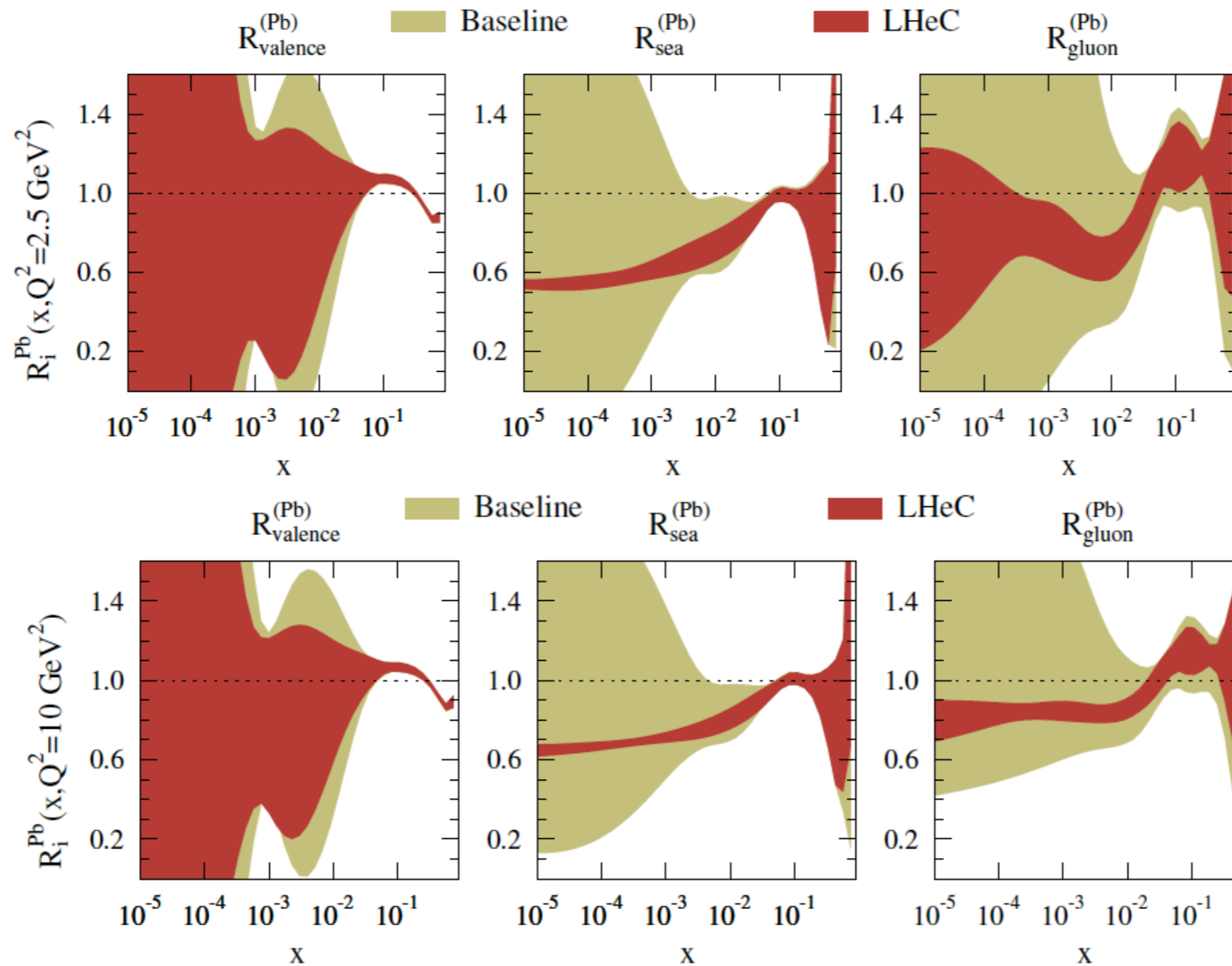
New analysis of nPDFs with simulated data from LHeC

Uncertainties shrink substantially after including LHeC simulated data in the fit!



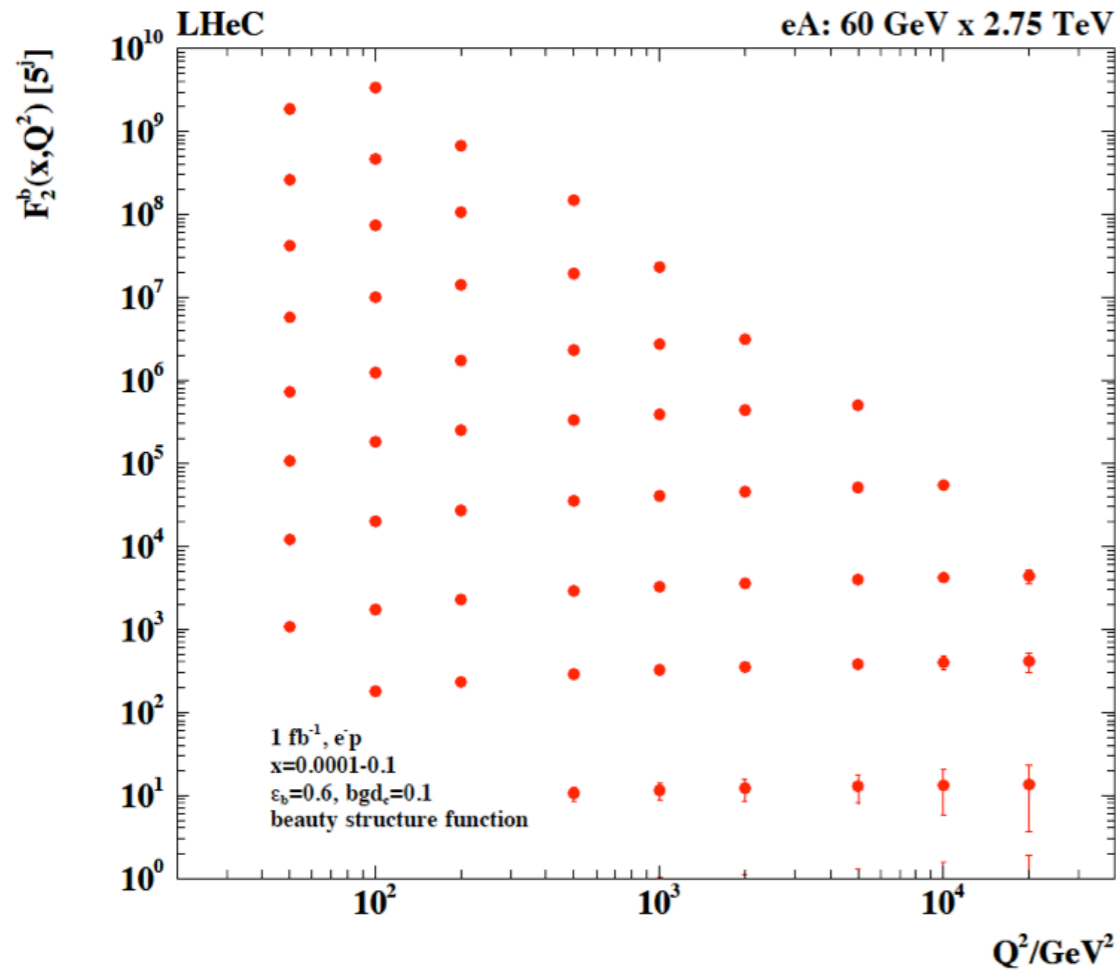
nPDFs after including LHeC constraints

Substantial constraint on the sea and gluon nPDFs from the LHeC simulated data.

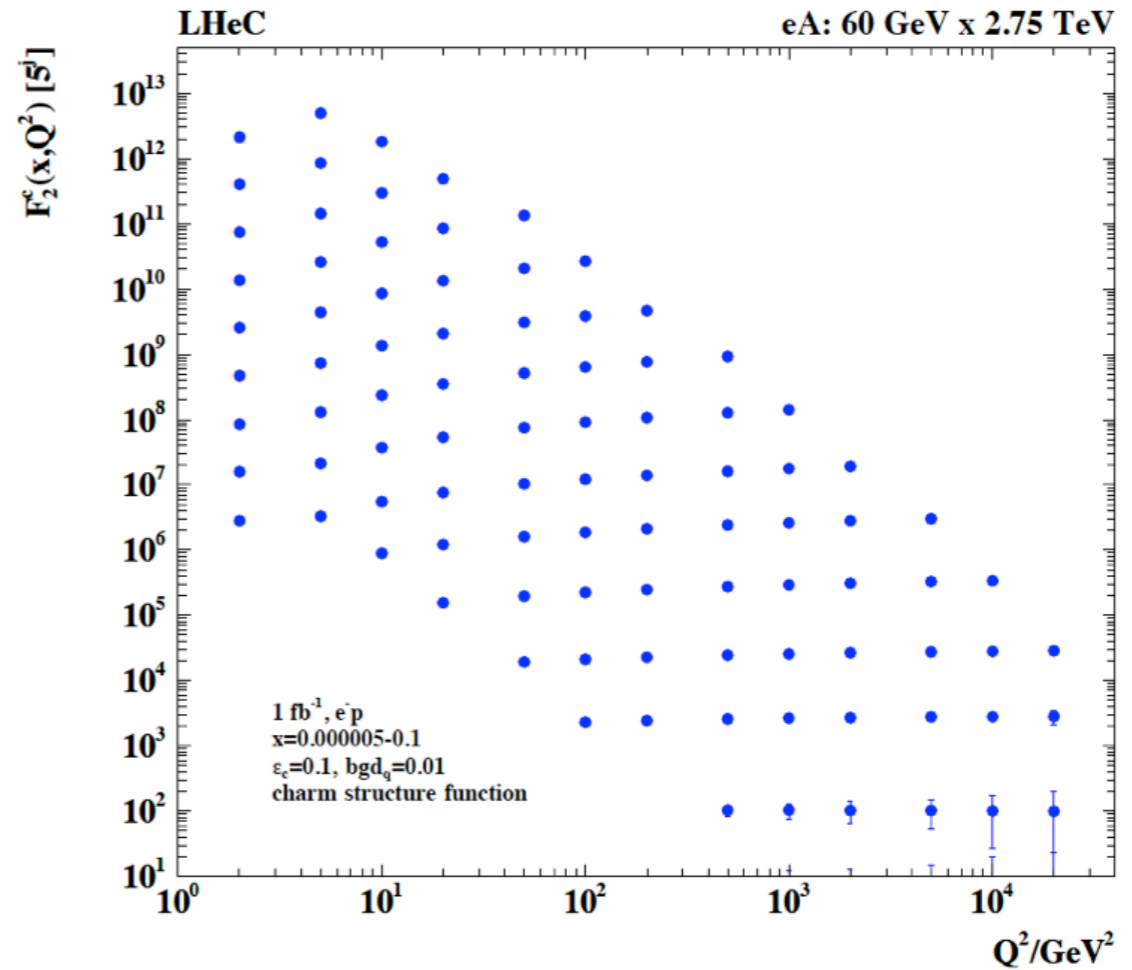


Heavy flavors: LHeC simulation

Heavy Flavour – Beauty in ePb - from NC



Heavy Flavour – Charm in eA - from NC



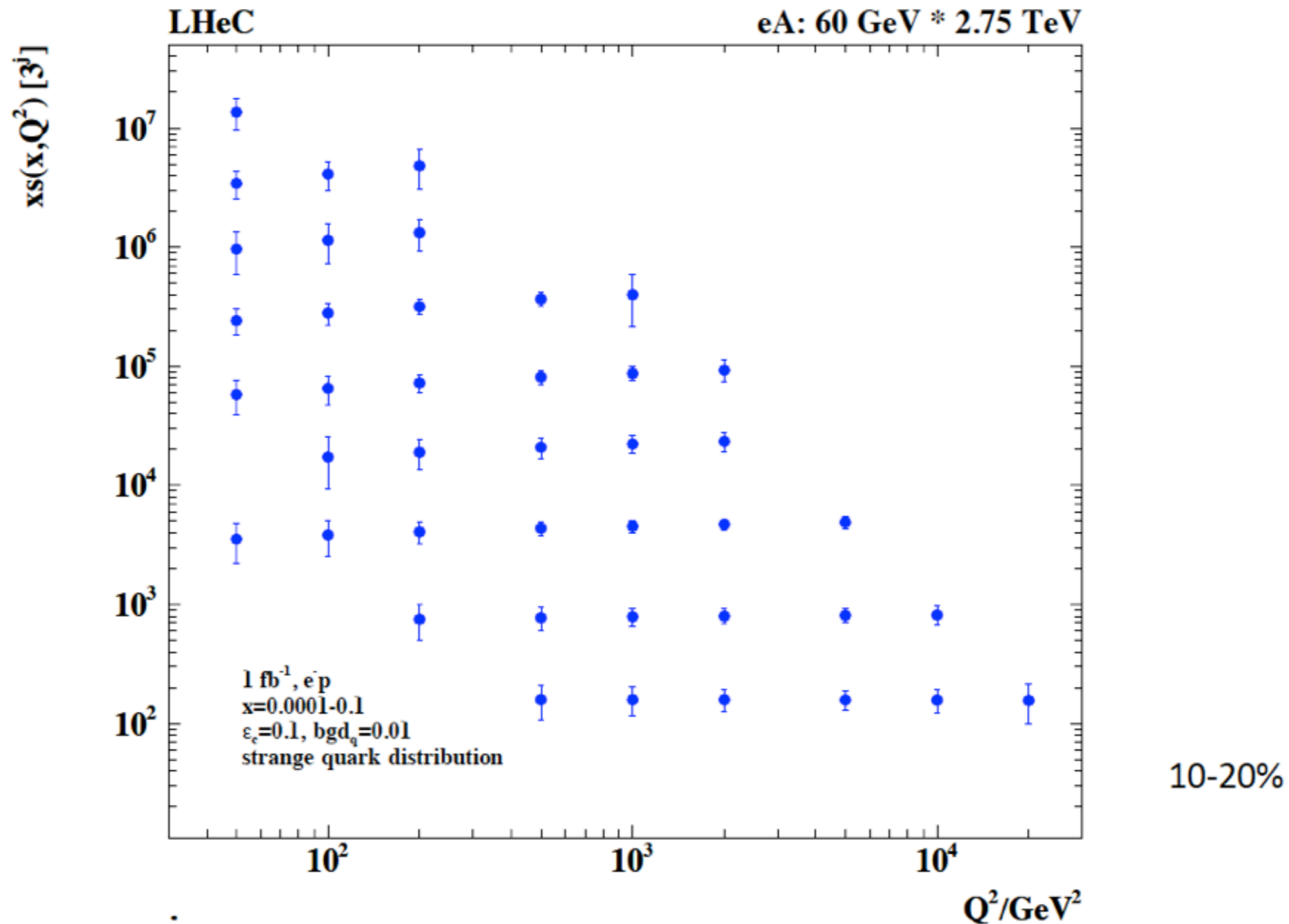
3-5%

Max Klein nPDFs with LHeC 10.9.2015 POETIC a PARIS

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

Heavy flavors: LHeC simulation

Heavy Flavour – Strange in ePb - from CC



Max Klein nPDFs with LHeC 10.9.2015 POETIC a PARIS

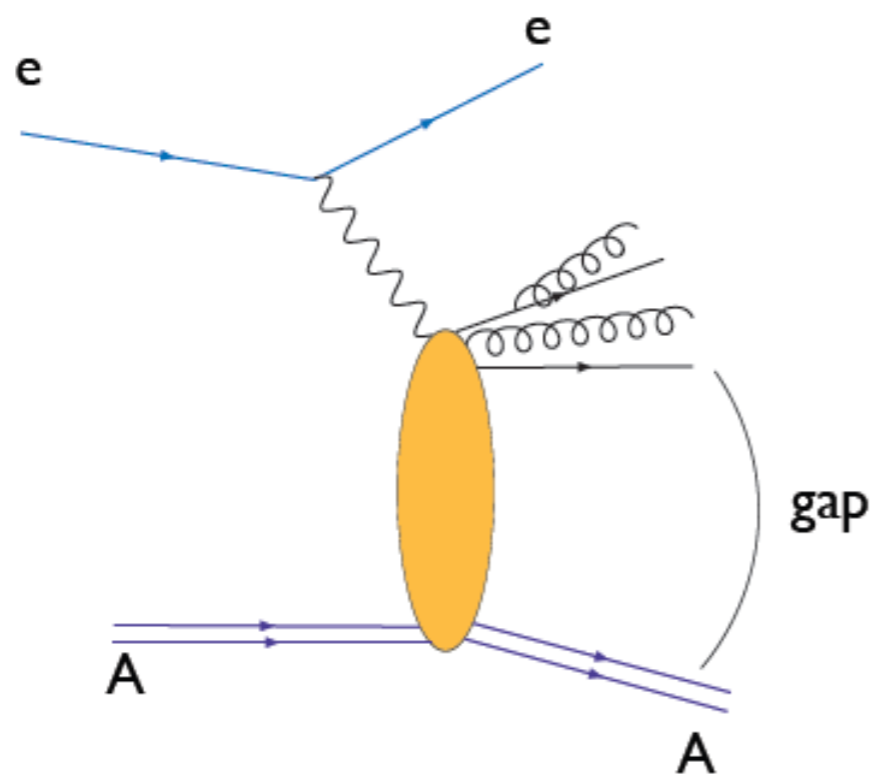
Extraction of strange quark distribution in eA through CC interaction.

Diffraction in eA

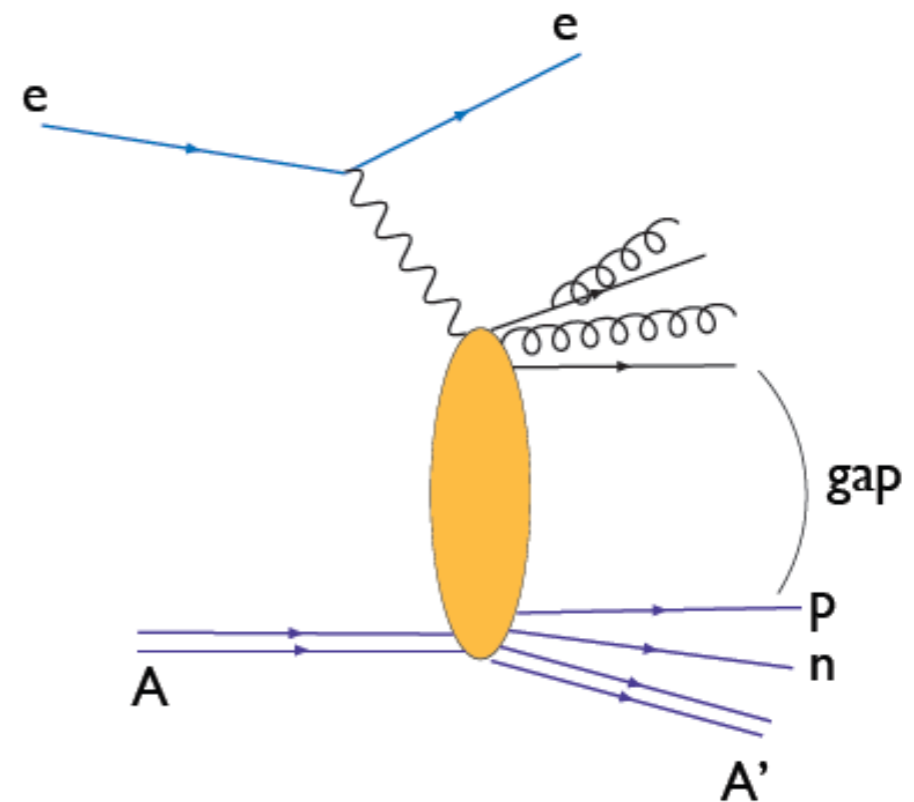
Diffraction: event in hadronic collisions characterized by the large rapidity gap, void of any activity

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)

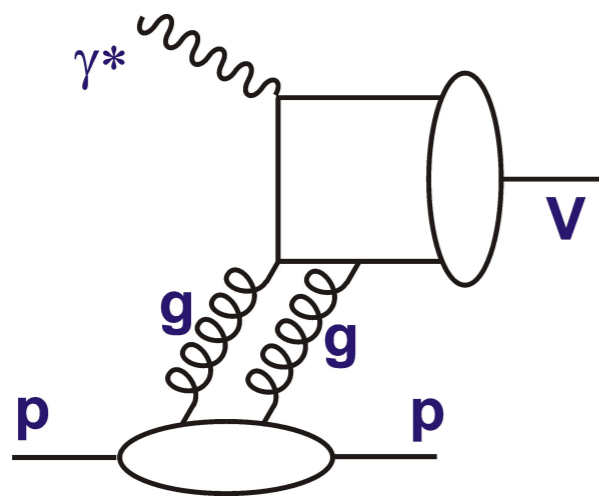


coherent



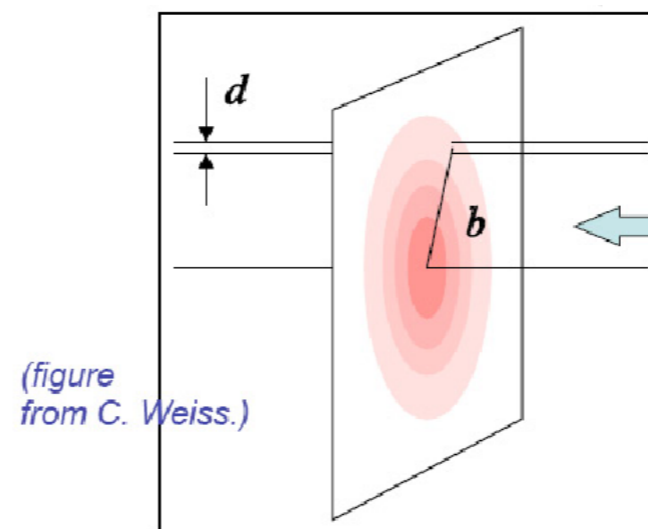
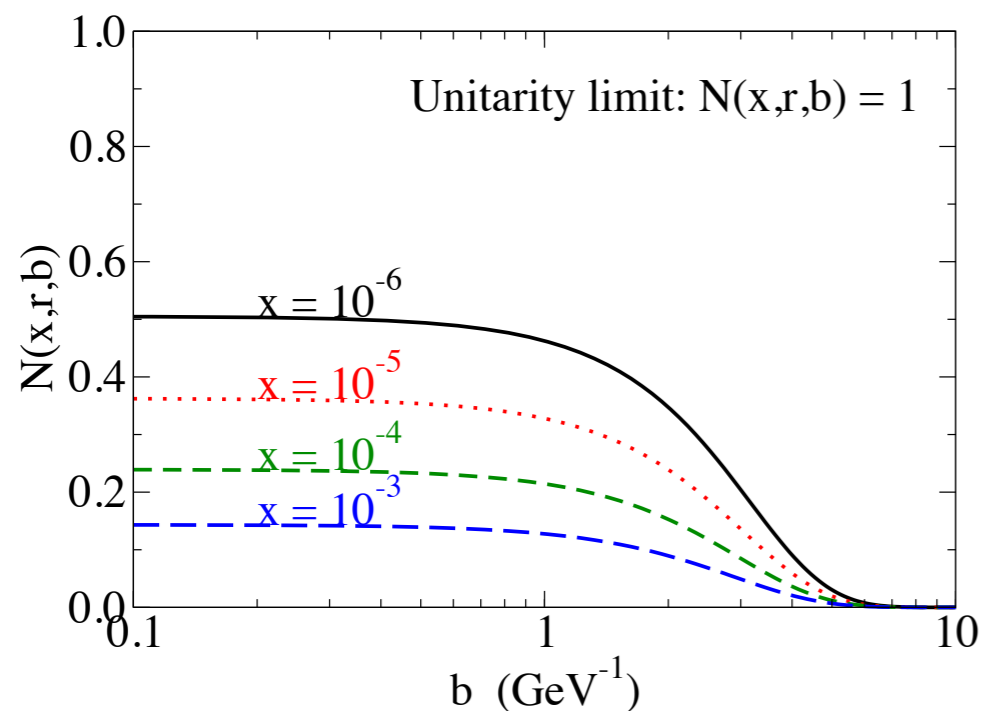
incoherent

Exclusive diffraction



- Exclusive diffractive production of VM is an excellent process for extracting the dipole amplitude and GPDs
- Suitable process for estimating the 'blackness' of the interaction.
- t -dependence provides an information about the impact parameter profile of the amplitude.

"b-Sat" dipole scattering amplitude with $r = 1 \text{ GeV}^{-1}$



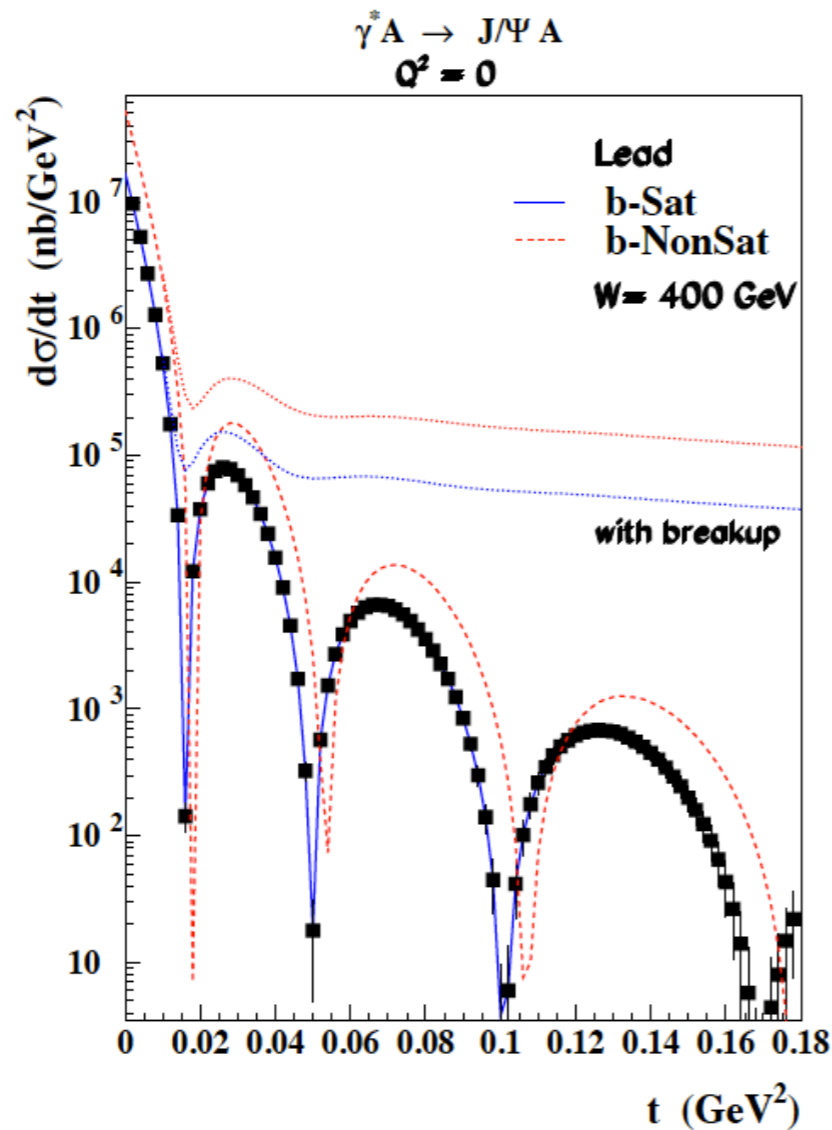
Central black region growing with decrease of x .

Large momentum transfer t probes small impact parameter where the density of interaction region is most dense.

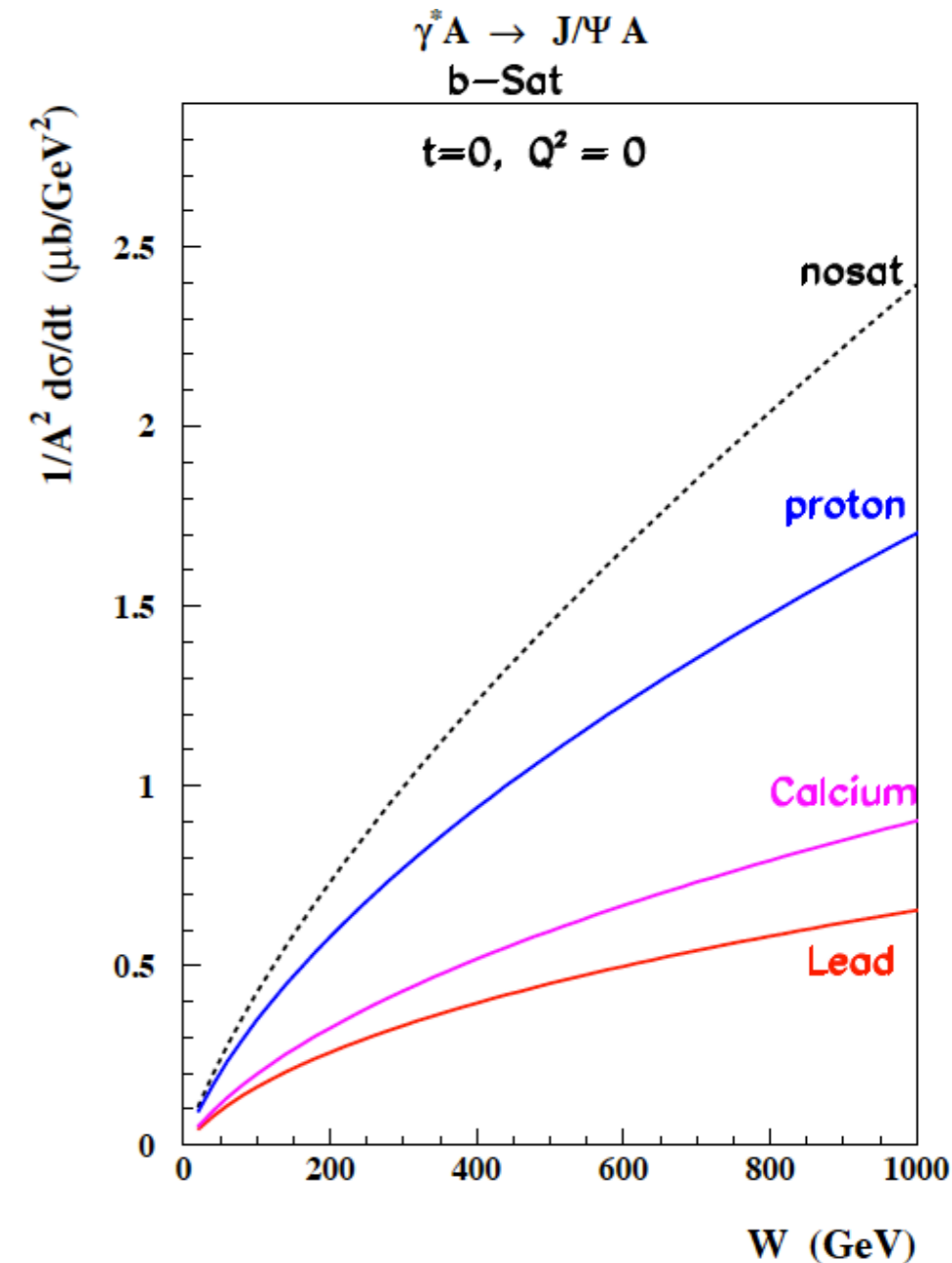
Exclusive diffraction on nuclei

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.



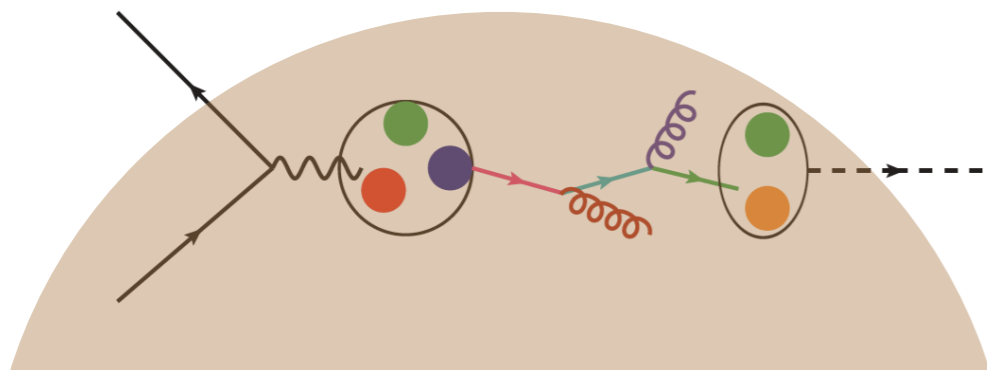
t -dependence: characteristic dips.

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

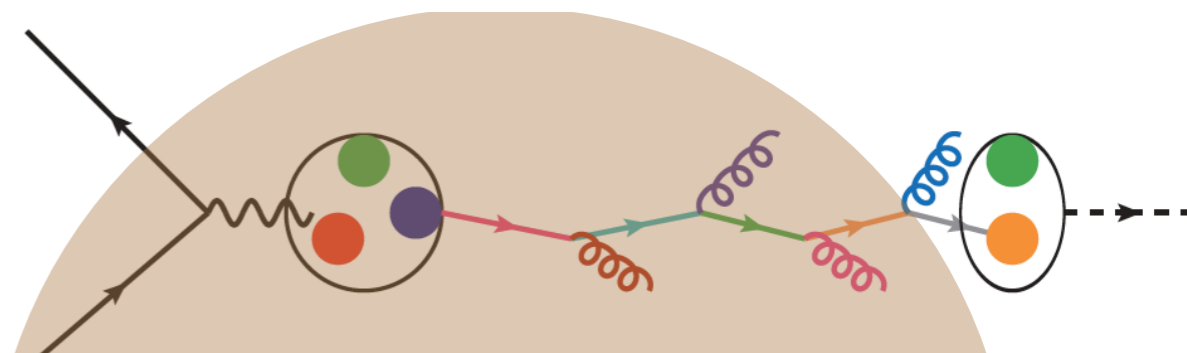
Radiation and Hadronization

- LHeC can provide information on radiation 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



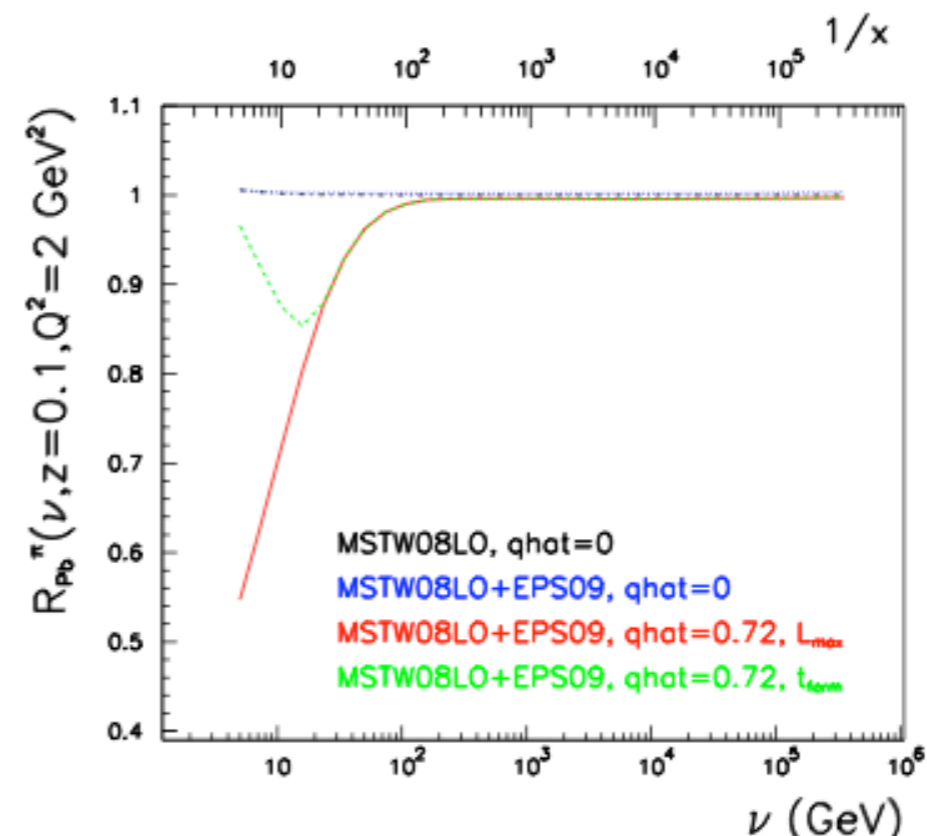
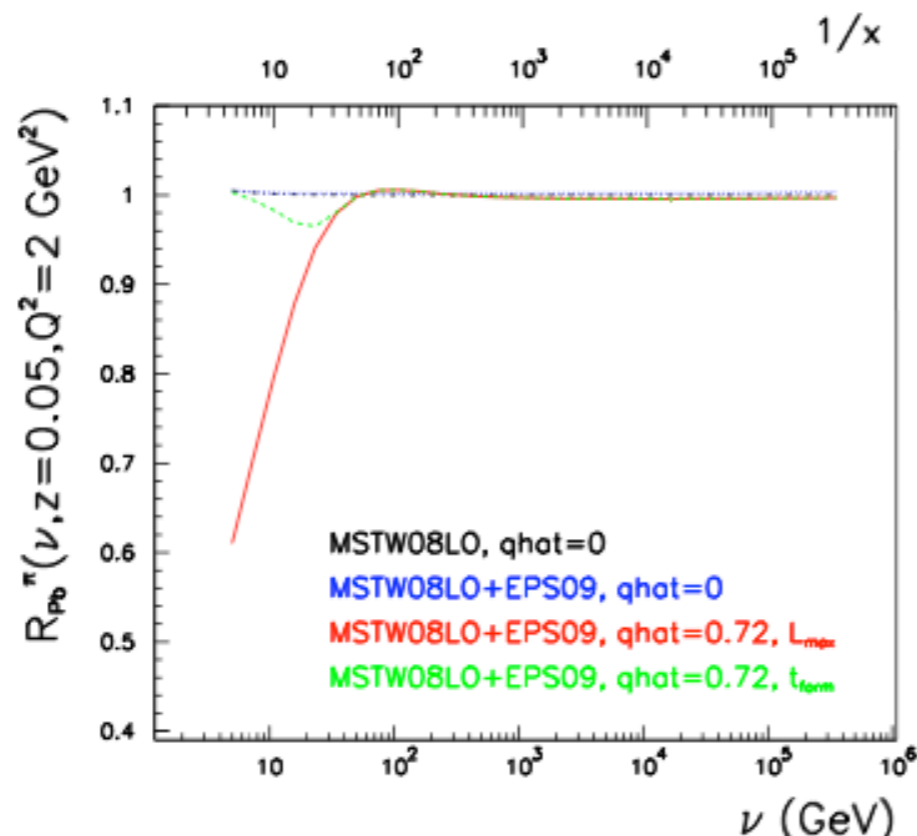
High energy: partonic evolution altered in nuclear medium



Radiation and Hadronization

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

- N^e number of scattered electrons at given photon energy and Q
- Ratio becomes sensitive to ratio of fragmentation functions in nucleus and proton
- Ratio is close to one for large energies as energy losses are becoming smaller.
- Suppression larger for larger z due to steepness of the fragmentation function.
- Formation time effects are non-negligible only at smallest energies.



Summary

- LHeC/FCC-ep has an unprecedented potential as a high luminosity, high energy DIS machine. Offering a unique window for small x physics and high parton density regime.
- eA at high energy essential to untangle the complex nuclear structure at low x and constrain the initial conditions for AA at the LHC. Complementary to pp/pA/AA.
- Precision measurements of nuclear pdfs, heavy flavor in nuclei.
- Inclusive diffraction, factorization, ratio of diffractive to total and transition to dense regime.
- Exclusive diffraction, impact parameter dependence, precise tomography of nucleus.
- Hadronization and fragmentation in medium, testing interplay of timescales, important for heavy ion collisions.