Electron-Ion Physics with the LHeC

DIS2015

Ilkka Helenius
on behalf of the LHeC Study Group

Lund University
Department of Astronomy
and Theoretical Physics

28.4.2015

Outline

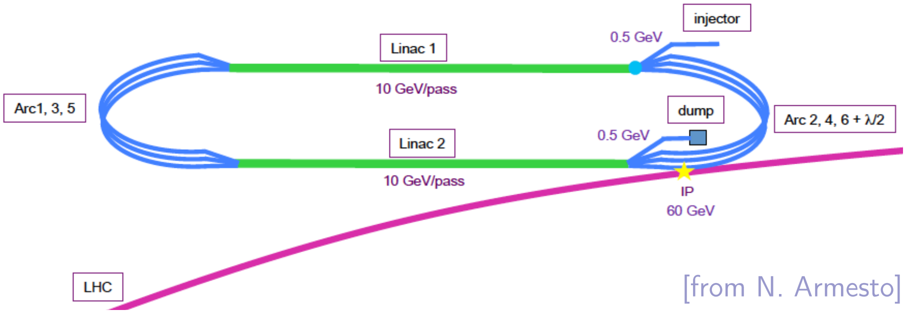
- Large Hadron Electron Collider
  - Kinematics
- Nuclear PDFs
  - Recent analyses
  - Current data constraints
  - Impact of LHeC data
- Other $\mathrm{e}+A$ physics
  - Small-x physics
  - Jet production and hadronization
- Summary & Outlook

Thanks to

- Nestor Armesto (Univ. of Santiago de Compostela)
- Hannu Paukkunen (Univ. of Jyväskylä)

Large Hadron Electron Collider (LHeC) [CDR: arXiv:1206.2913]

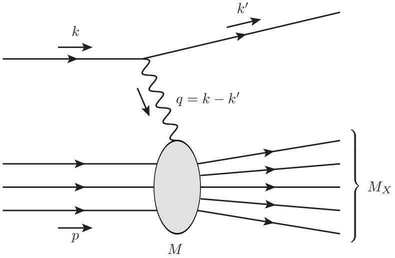
- LHC proton/ion beam + new $\mathrm{e}^{\pm}$ accelerator
  - $E_\mathrm{p} = 7\,\mathrm{TeV}$ (corresponds to $E_\mathrm{Pb} = 2.76\,\mathrm{TeV}$), $E_\mathrm{e} = 60\,\mathrm{GeV}$
  - Synchronous $\mathrm{p+p}$ and $\mathrm{e+p}$ (A+A and $\mathrm{e}+A$) operation
  - luminosity:
    - $\mathrm{e+p}$: $16 \cdot 10^{33}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ (post-CDR)
    - $\mathrm{e}+A$(per nucleon): $5 \cdot 10^{31}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ (updated: few $\cdot 10^{32}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$)
- Further in the future: FCC-he ($E_\mathrm{p} = 50\,\mathrm{TeV}, E_\mathrm{e} = 175\,\mathrm{GeV}$)



[from N. Armesto]

Kinematics

- Deep inelastic scattering (DIS):



Invariant variables

$$
\begin{aligned}
Q^2 &= -q^2 \\
x &= \frac{Q^2}{2\,p \cdot q} \\
y &= \frac{p \cdot q}{p \cdot k}
\end{aligned}
$$

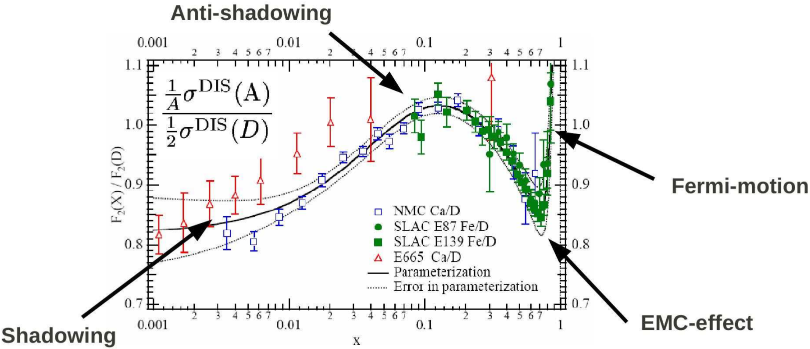
Cross section

$$
\frac{d\sigma^{\mathrm{DIS}}}{dx dQ^2} = \frac{4\pi\alpha_{\mathrm{EM}}^2}{Q^4}\frac{1}{x}\left[xy^2 F_1(x, Q^2) + (1-y)\, F_2(x, Q^2)\right]
$$

- Measured structure functions $F_i(x, Q^2)$ can be directly related to parton distribution functions (PDFs)
- Also other interesting (non-inclusive) measurements in $\mathrm{e} + \mathrm{p}/A$!

Nuclear PDFs

- Structure functions modified in nuclear collisions:



[from H. Paukkunen]

- Modifications absorbed into *process independent* nuclear PDFs:

$$f_i^A(x, Q^2) = R_i^A(x, Q^2) f_i(x, Q^2)$$

- Global DGLAP analyses
  - Provide the nuclear modifications $R_i^A(x, Q^2)$
  - Test factorization of nuclear effects

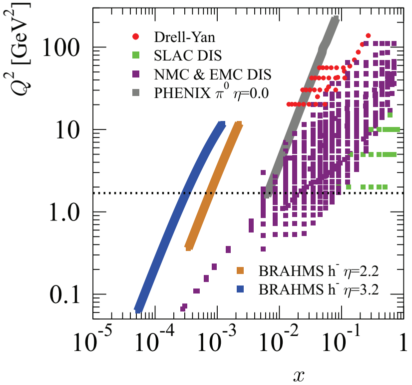
Recent nPDF analyses

	HKN07	EPS09	DSSZ	nCTEQ prelim.
Ref.	Phys. Rev. C76 (2007) 065207	JHEP 0904 (2009) 065	Phys.Rev. D85 (2012) 074028	arXiv:1307.3454
Order	LO & NLO	LO & NLO	NLO	NLO
Neutral current e+A / e+d DIS	√	√	√	√
Drell-Yan dileptons in p+A / p+d	√	√	√	√
RHIC pions in d+Au / p+p		√	√	
Neutrino-nucleus DIS			√	
Q^2 cut in DIS	1GeV	1.3GeV	1GeV	2GeV
# of data points	1241	929	1579	708
Free parameters	12	15	25	17
Error sets available		√	√	√
Error tolerance $\Delta\chi^2$	13.7	50	30	35
Baseline	MRST98	CTEQ6.1	MSTW2008	CTEQ6M
Heavy quark treatment	ZM_VFNS	ZM_VFNS	GM_VFNS	GM_VFNS

[from H. Paukkunen]

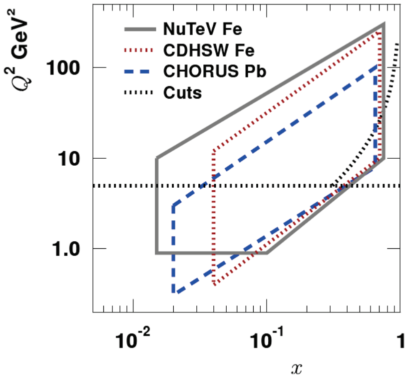
Kinematic coverage of data in current nPDF fits

- DIS, DY and inc. hadrons:



- Brahms data not included to fits
- Lower Q^2 cut varies between analyses (EPS09 cut shown)

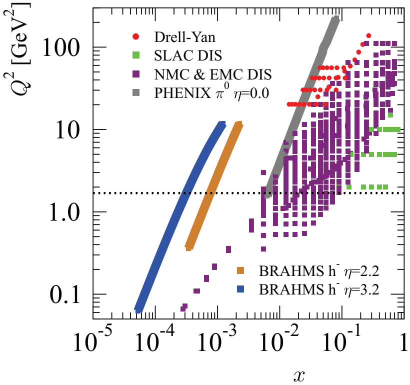
- Neutrino DIS:



- Included only to DSSZ so far
- Provides flavor separation

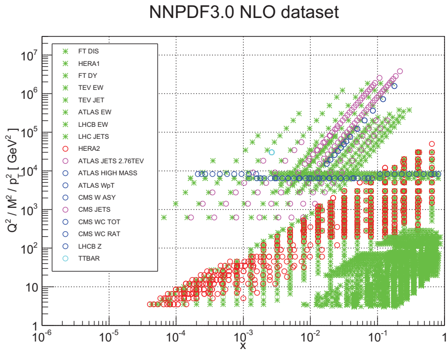
Kinematic coverage of data in current nPDF fits

- DIS, DY and inc. hadrons:



- Brahms data not included to fits
- Lower Q^2 cut varies between analyses (EPS09 cut shown)

- Comparison to proton PDF fits:

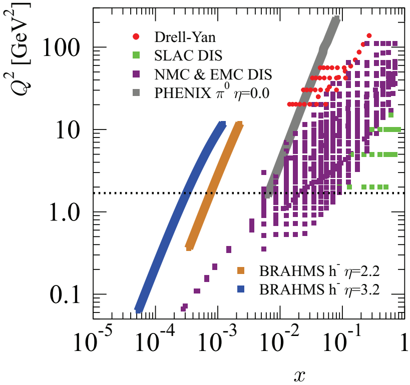


[arXiv:1410.8849]

- Much broader reach due to HERA and LHC data
- p+Pb data will improve kinematic reach of nPDF analyses

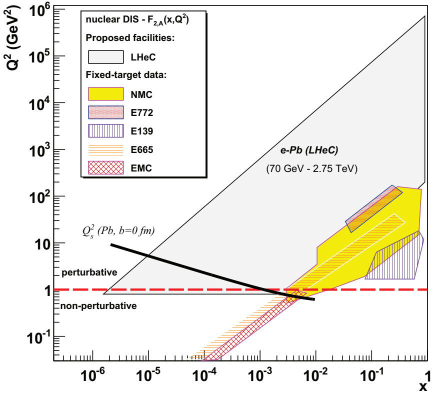
Kinematic coverage of data in current nPDF fits

- DIS, DY and inc. hadrons:



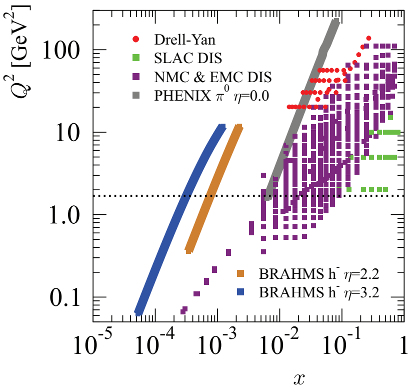
- Brahms data not included to fits
- Lower Q^2 cut varies between analyses (EPS09 cut shown)

- The expected coverage of LHeC:



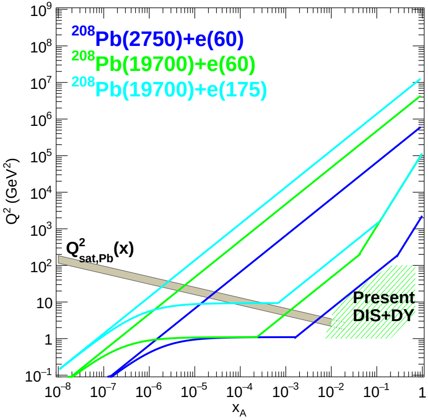
- LHeC data would provide a huge improve for the kinematic reach!
- $\mathrm{e}+A$ much cleaner measurement than $\mathrm{p}+A$

- DIS, DY and inc. hadrons:



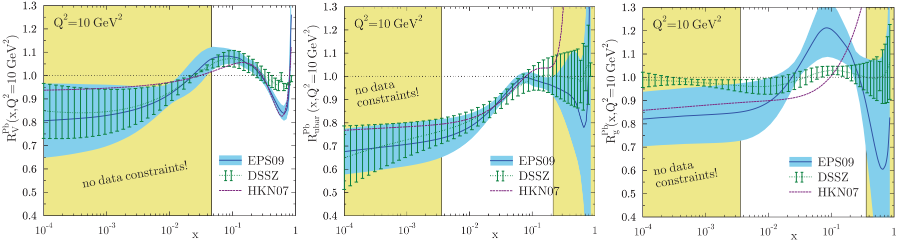
- Brahms data not included to fits
- Lower Q^2 cut varies between analyses (EPS09 cut shown)

The expected coverage of FCC-eA:



- Further extension of kinematics
- Large electron energy requires large acceptance

Comparison between different fits:



[Nucl.Phys.A926 (2014) 24-33]

- nCTEQ analysis provides somewhat larger uncertainties
  [Talk by A. Kusina at 14.00 (WG1)]
- Recent $\mathrm{p+Pb}$ data from LHC constrains nPDFs mostly at $x > 0.01$
  [Talk by I.H. at 14.25 (WG1)]
- Uncertainties remain large at small-x regions
  $\Rightarrow$ No accurate baseline for heavy-ion physics at LHC
- Impact of the LHeC?

Impact of LHeC data

How to study impact of new data

1. Generate "pseudodata" corresponding the expected measurement
2. Add the pseudodata to global analysis on top of existing data
3. Perform a re-analysis and compare the results

For the LHeC

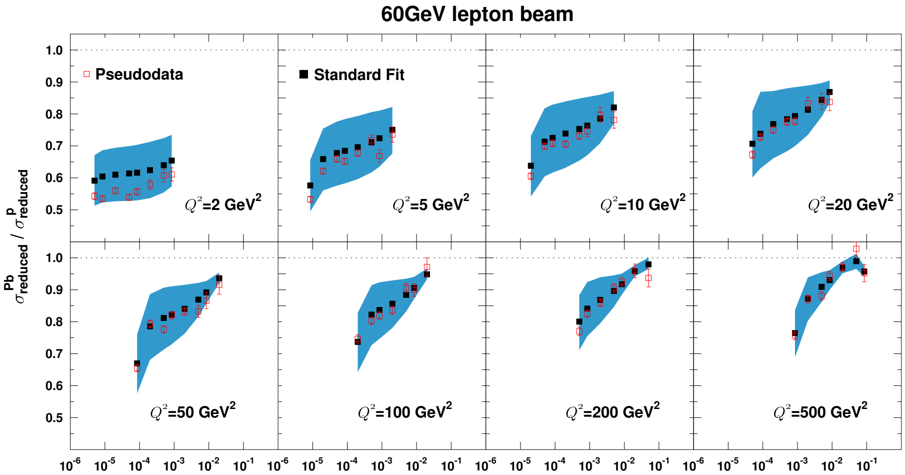
- Samples of neutral current DIS reduced cross section

$$\sigma_{\text{reduced}} = \frac{xQ^4}{2\pi\alpha_{\text{EM}}^2 Y_+}\frac{\mathrm{d}^2\sigma^{DIS}}{\mathrm{d}x\mathrm{d}Q^2} \quad \text{where} \quad Y_+ = 1 + (1-y)^2$$

  were generated in the kinematic window
  - $10^{-5} < x < 1$
  - $2 < Q^2 < 10^5\,\mathrm{GeV}^2$
- Nuclear modifications from EPS09

Impact of LHeC data

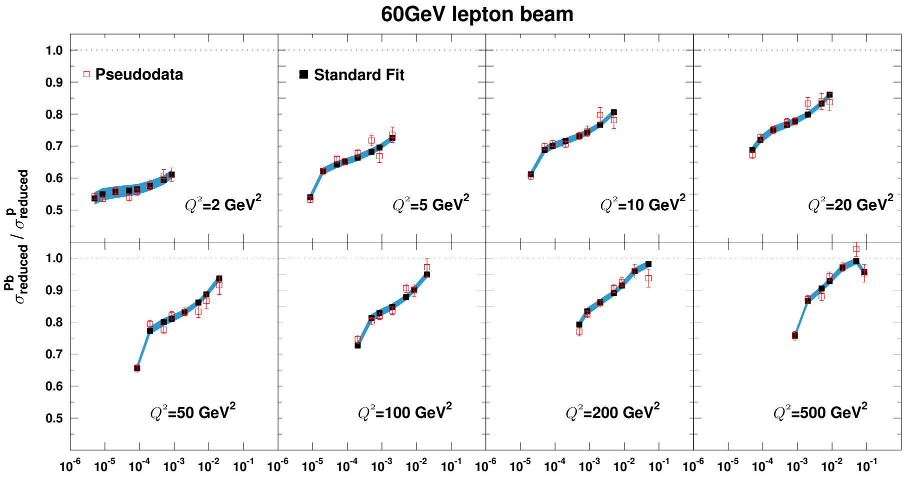
- Low-Q^2 pseudodata and prediction before the inclusion:



[H. Paukkunen, preliminary]

Impact of LHeC data

- Low-Q^2 pseudodata and prediction after the inclusion:

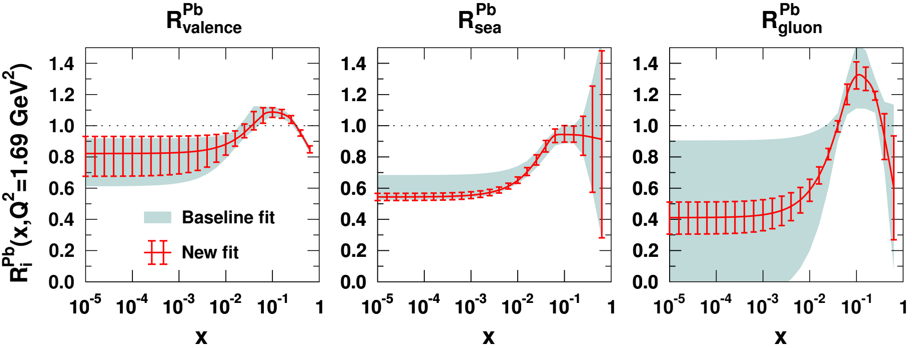


[H. Paukkunen, preliminary]

- Significant reduction of nPDF-originating uncertainties (blue bands)

Impact of LHeC data

- Impact to the nPDF uncertainties

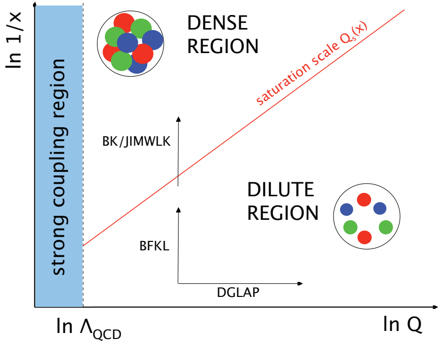


[H. Paukkunen, preliminary]

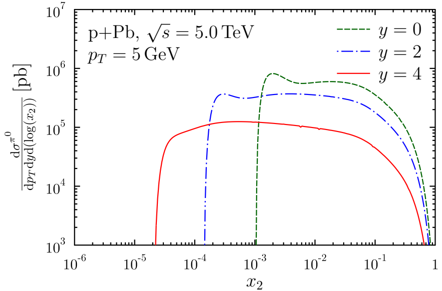
- Huge reduction of the small-x uncertainties for gluons and sea quarks
- Results still preliminary: the form of the fit function at low x might have impact also to size of the uncertainties
- Charged current (c and b) data should constrain flavor dependence (Currently unconstrained, some constraints from $\mathrm{W}^{\pm}$ in p+Pb)

Small-x physics

- Linear QCD-evolution leads to large number of gluons at small x
- Breakdown at high densities $\Rightarrow$ saturation?



Inclusive hadrons in p+Pb (NLO):

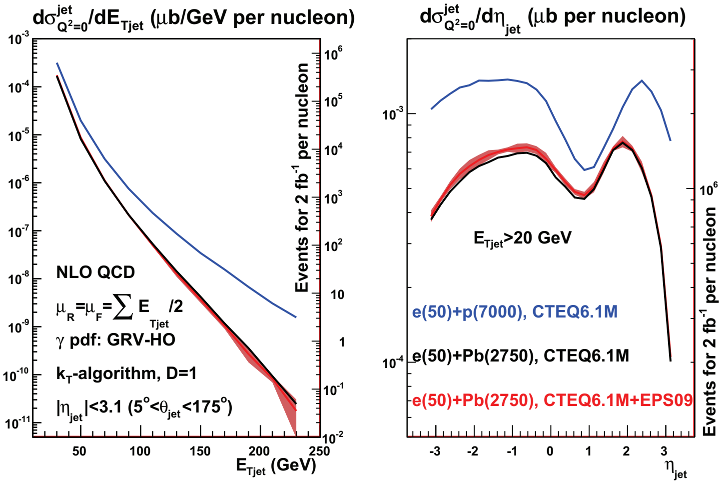


- $Q_s^2 \propto A^{1/3} x^{-0.3} \Rightarrow$ saturation more pronounced at large A
- Hard to be sensitive to small-x physics in p+Pb

$\Rightarrow$ LHeC should be sensitive to saturation physics especially with $\mathrm{e}+A$

Jets in $\mathrm{e}+A$

- Photoproduction of jets: direct and resolved (γ PDFs) processes

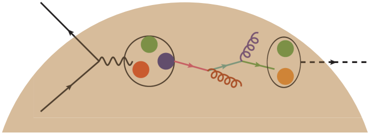


- Large E_T jets also in $\mathrm{e}+A$
- Useful to study parton dynamics and photon structure
- Not all theoretical uncertainties considered yet

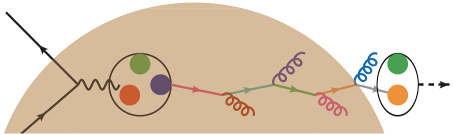
Hadronization in nuclear medium

- LHeC provides clean environment to study hadron production with nuclear target (''cold nuclear matter'')

- Low energy:
  - hadronization happens inside the nuclear medium
  - pre-hadronic absorbtion?



- High energy:
  - hadronization happens outside the nuclear medium
  - partonic evolution inside the medium



- Benchmark for hadron production in $A+A$ and $\mathrm{p}+A$
- See Phys.Rev. D81 (2010) 054001 for medium modified FF analysis

Summary

Nuclear PDFs

- Data constraining current nPDF fits quite limited in kinematics
- $\mathrm{p+Pb}$ data from LHC will improve fits at $x \gtrsim 0.01$
- LHeC would provide very precise data down to $x \sim 10^{-5}$
  $\Rightarrow$ Drastic reduction of the nPDF uncertainties!
  $\Rightarrow$ Flavor decomposition from charged current and heavy quark data

Other $\mathrm{e}+A$ physics

- Clean environment to study small-x phenomena such as saturation
- Photoproduction of jets can be used to study photon (nuclear) PDFs
- Cold nuclear matter effects to hadron production

\+ Topics not covered here (Diffraction, Vector Mesons, . . .)

Outlook

Theoretical improvements

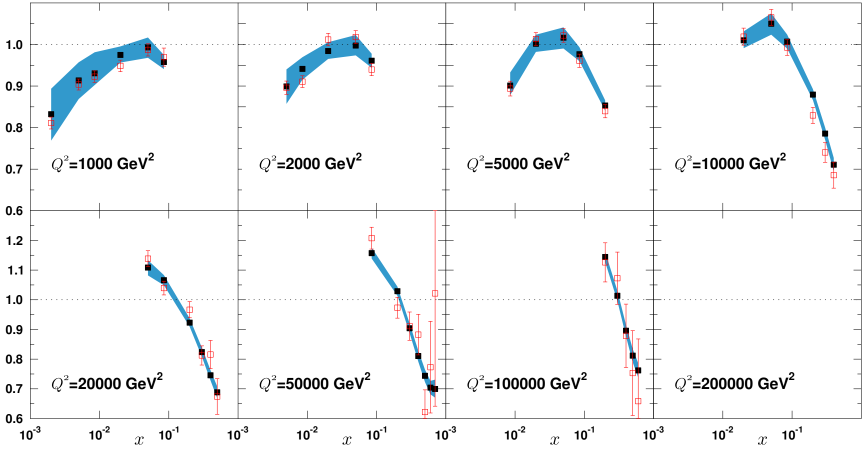
- Finalize the nPDF re-analysis with pseudodata
  - Include charged current data
    $\Rightarrow$ Relax the assumption of flavor symmetry
  - Chart the uncertainty due to the initial parametrization
- Details of jet production and reconstruction
- Monte Carlo generators for $\mathrm{e+p}/A$

TDR during this year

Backup

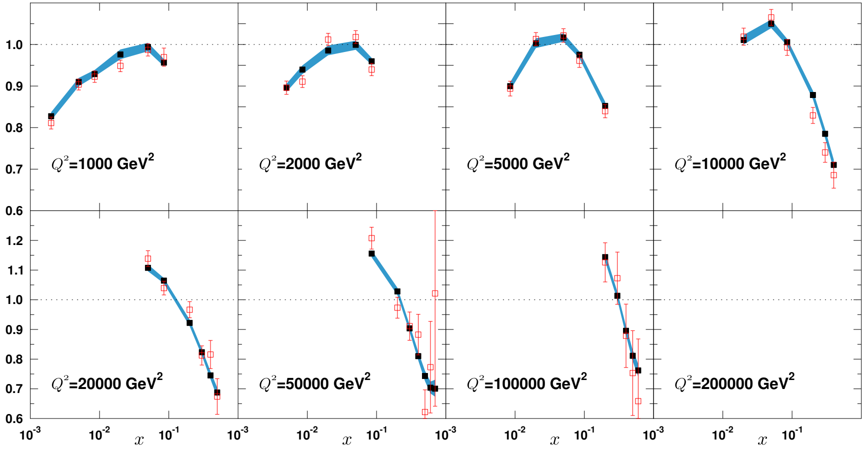
Impact of LHeC data

- High-Q^2 pseudodata and prediction before the inclusion:



Impact of LHeC data

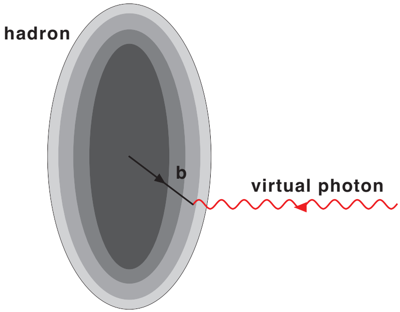
- High-Q^2 pseudodata and prediction after the inclusion:

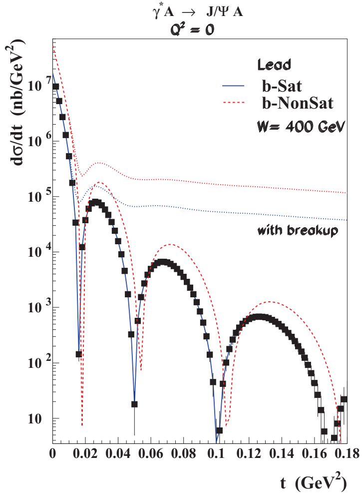


- the nPDF-originating uncertainties (blue bands) already rather small at high-Q^2

Vector Meson (VM) production

- The t-differential cross-section of exclusive diffractive VM production can be related to impact parameter
  $\Rightarrow$ Transverse profile of hadron/nucleus can be extracted

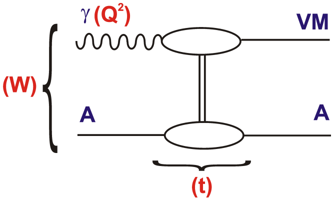




- Also sizable saturation effects expected

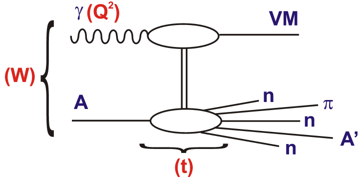
Elastic VM production

- Coherent VM production:

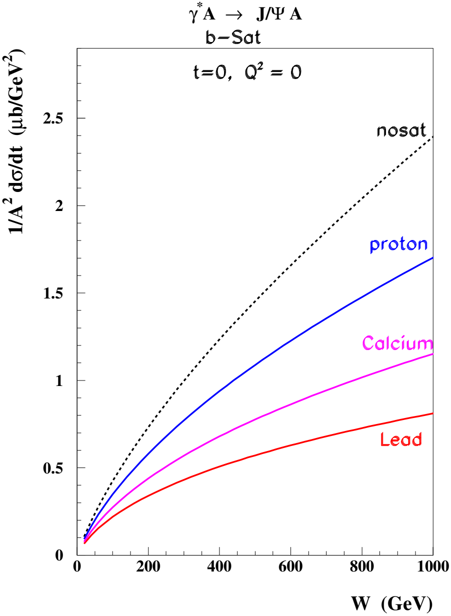


Predictions available showing large saturation ⇒

- Incoherent VM production:

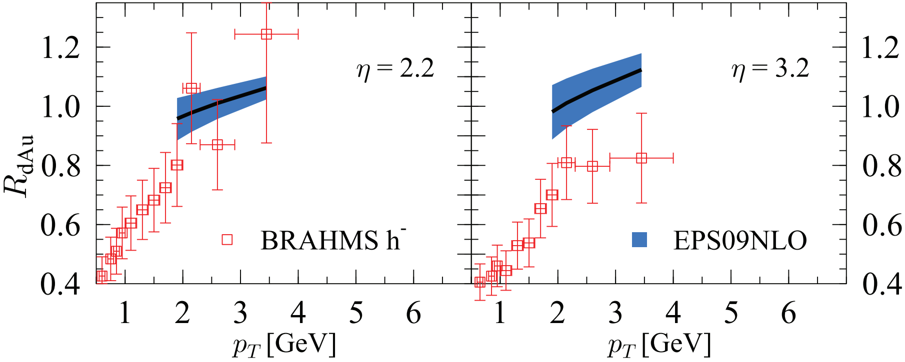


Energy denpendence of coherent VM



Charged hadron production

- Nuclear modification factor at forward rapidities for charged hadrons



- Data induces tension in global analysis
- NLO calculation agree with the d+Au spectra but not with the p+p baseline