eA physics at the LHeC

DIS2016

Ilkka Helenius
on behalf of the LHeC Study Group

Lund University
Department of Astronomy
and Theoretical Physics

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Outline

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

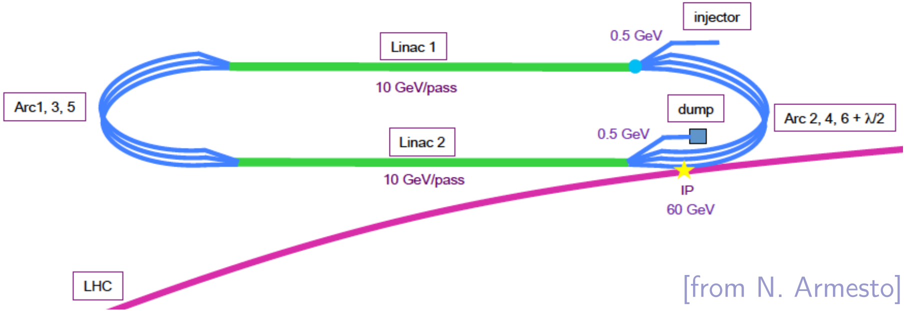
Thanks to

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

Introduction

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

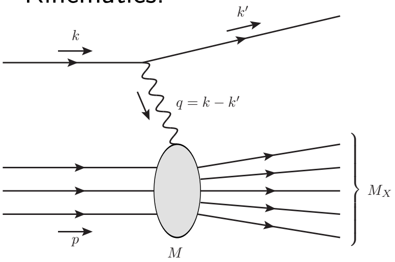
- LHC proton/ion beam + new $\mathrm{e}^{\pm}$ accelerator
  - $E_{\mathrm{p}} = 7\,\mathrm{TeV}$ (corresponds to $E_{\mathrm{Pb}} = 2.76\,\mathrm{TeV}$), $E_{\mathrm{e}} = 60\,\mathrm{GeV}$
  - Synchronous $\mathrm{p+p}$ and $\mathrm{e+p}$ (A+A and e+A) operation
    - $\mathrm{e+p}$: $16 \cdot 10^{33}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ (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 ($E_{\mathrm{p}} = 50\,\mathrm{TeV}, E_{\mathrm{e}} = 60\,\mathrm{GeV}$)
  - $\mathrm{e+p}$: $9 \cdot 10^{33}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$, $\mathrm{e+Pb}$: $9 \cdot 10^{32}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$



[from N. Armesto]

Deep inelastic scattering (DIS)

- Kinematics:



Invariant variables

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

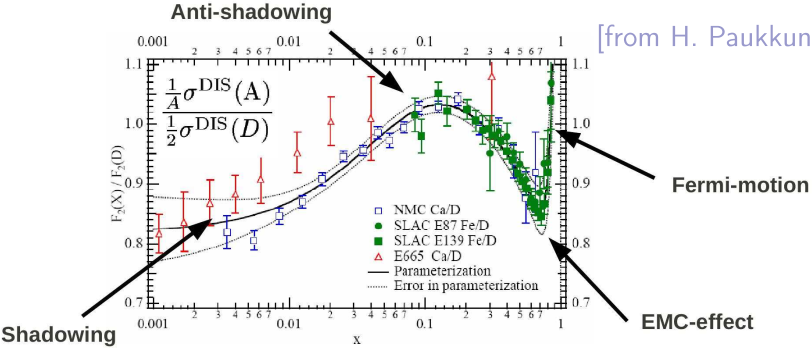
Cross section

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

- 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]

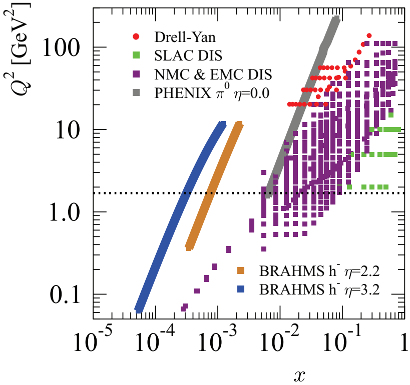
- Modifications absorbed into *process independent* nuclear PDFs:

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

- Global DGLAP analyses (EPS09, DSSZ, nCTEQ, HKN07)
  - Test factorization of nuclear effects
  - Provide the nuclear modifications $R_i^A(x,Q^2)$

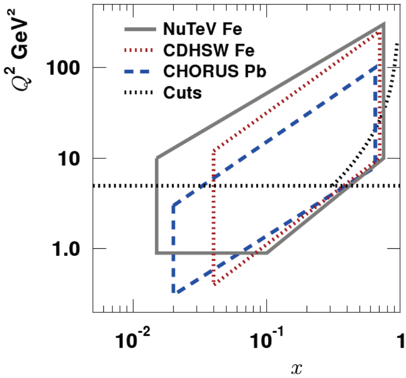
Kinematic coverage

- DIS, DY and inc. hadrons:



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

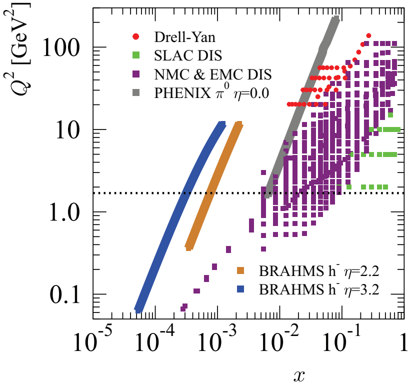
- Neutrino DIS:



- Included only to DSSZ so far
- Provides flavor separation

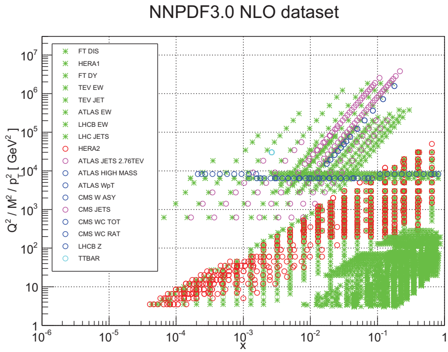
Kinematic coverage

- 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:

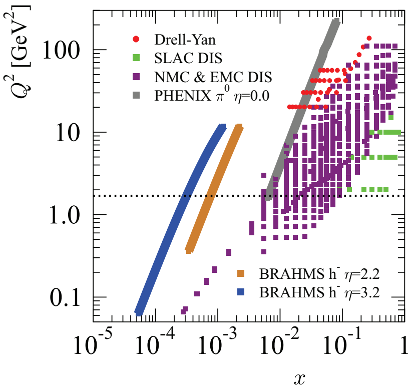


[arXiv:1410.8849]

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

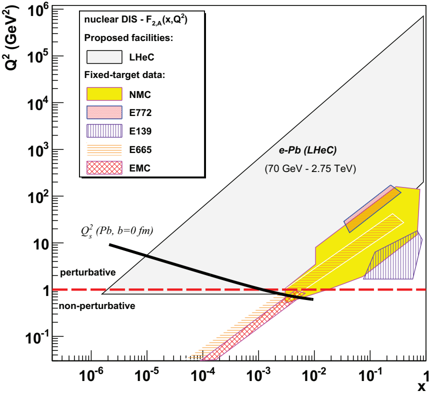
Kinematic coverage

- DIS, DY and inc. hadrons:



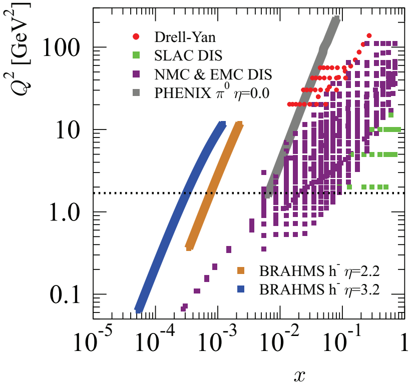
- Brahms data not included to fits
- Lower Q^2 cut varies between analyses (EPS09 cut shown)

- The expected coverage of LHeC:



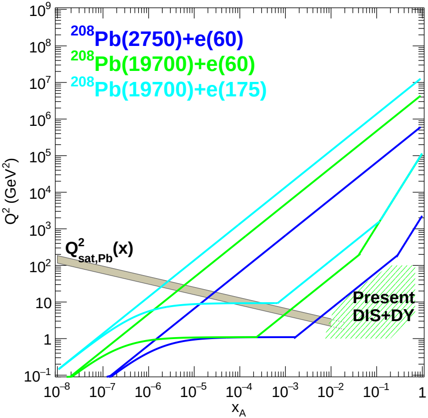
- LHeC data would provide a huge improve for the kinematic reach!
- $\mathrm{e}+A$ much cleaner measurement than $\mathrm{p}+A$

- DIS, DY and inc. hadrons:



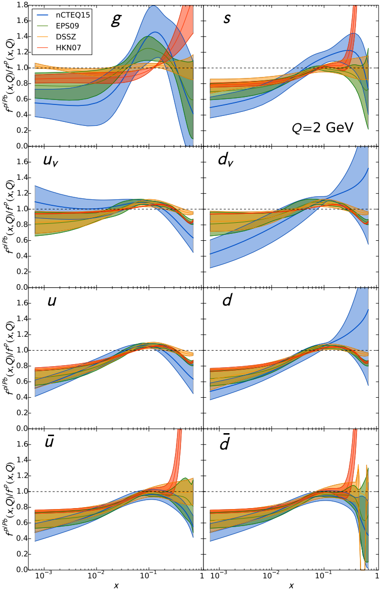
- Brahms data not included to fits
- Lower Q^2 cut varies between analyses (EPS09 cut shown)

The expected coverage of FCC-eA:



- Further extension of kinematics
- Large electron energy requires large acceptance (here 1° for the electron)

Uncertainties in the current nPDF fits



[nCTEQ arXiv:1509.00792 [hep-ph]]

- nCTEQ15 analysis provides somewhat larger uncertainties [A. Kusina on Wednesday at 11:40]
- Recent p+Pb data from LHC constrains nPDFs mostly at $x > 0.01$
  - See e.g. [arXiv:1512.01528 [hep-ph]]

$\Rightarrow$ No significant improvements at small-x from present LHC data

  - direct γ at large η would help [JHEP 1409 (2014) 138]

Questions

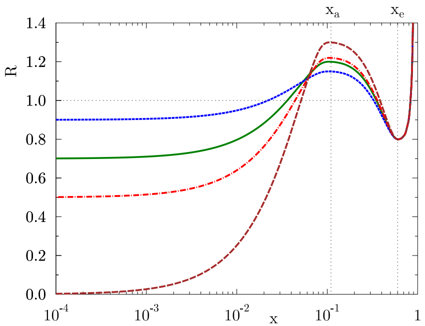
- Are the small-x uncertainties realistic (no direct constraints $x \lesssim 0.01$)?
- Impact of the LHeC data?

Functional forms

The fit function in EPS09:

$$R^{\mathrm{EPS09}}(x) = \begin{cases} a_0 + (a_1 + a_2 x)\left(e^{-x} - e^{-x_a}\right) & x \le x_a \\ b_0 + b_1 x + b_2 x^2 + b_3 x^3 & x_a \le x \le x_e \\ c_0 + (c_1 - c_2 x)(1-x)^{-\beta} & x_e \le x \le 1 \end{cases}$$

(power-law parametrization of A-dependence at x_a, x_e, and $x \to 0$)



[from H. Paukkunen]

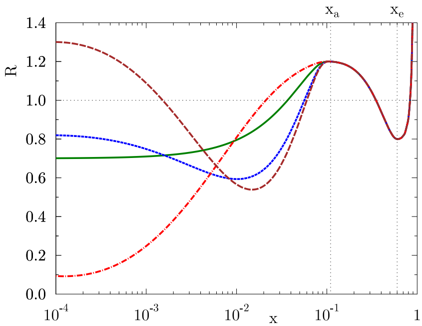
- Very little freedom at small x — need to extend this for LHeC

Functional forms

More flexible form

- Replace the small-x part with

$$R(x \leq x_a) = a_0 + a_1(x - x_a)^2$$
$$+ \sqrt{x}(x_a - x)\left[a_2 \log\left(\frac{x}{x_a}\right) + a_3 \log^2\left(\frac{x}{x_a}\right) + a_4 \log^3\left(\frac{x}{x_a}\right)\right]$$



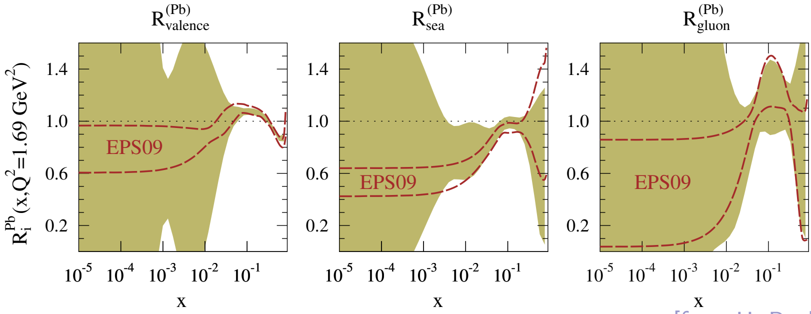
[from H. Paukkunen]

- The bias at small x should be significantly reduced

The fit framework

Baseline setup

- New, more flexible, small-x behaviour
- Same data as in EPS09 (DIS, DY, inclusive π^0)
- CTEQ 6.6 proton PDFs
- Flavour-independent nuclear modifications at $Q_0 = 1.3$ GeV
- NLO cross sections



[from H. Paukkunen]

- No control at small-x due to lack of data

The fit framework

Baseline setup

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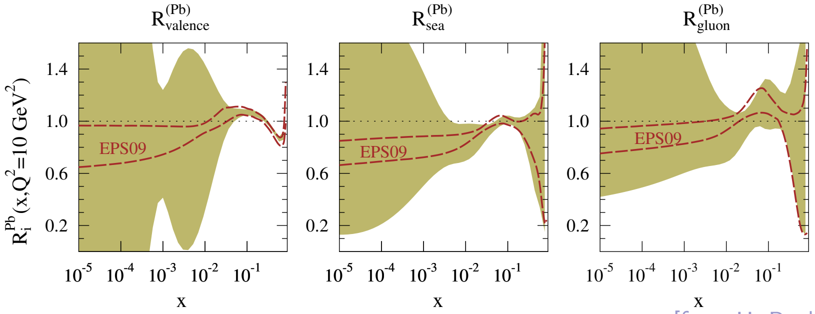


[from H. Paukkunen]

- Scale evolution decreases the uncertainties

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

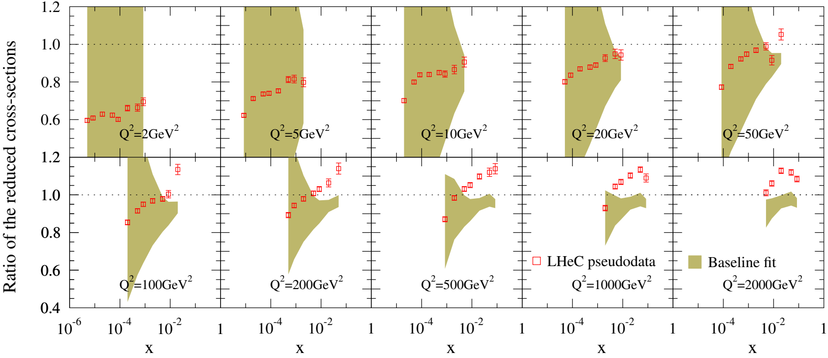
LHeC pseudodata [Max Klein]

- Samples of neutral current DIS reduced cross section in $\mathrm{e+p}$ & $\mathrm{e+Pb}$

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

  were generated in the kinematic window
  - $10^{-5} < x < 1$
  - $2 < Q^2 < 10^5\,\mathrm{GeV}^2$
- Nuclear modifications from EPS09
- Realistic fluctuations assuming $\mathcal{L}_{\mathrm{ep}} = 10\,\mathrm{fb}$, $\mathcal{L}_{\mathrm{ePb}} = 1\,\mathrm{fb}$ (per nucleon)

- The baseline fit without the LHeC data

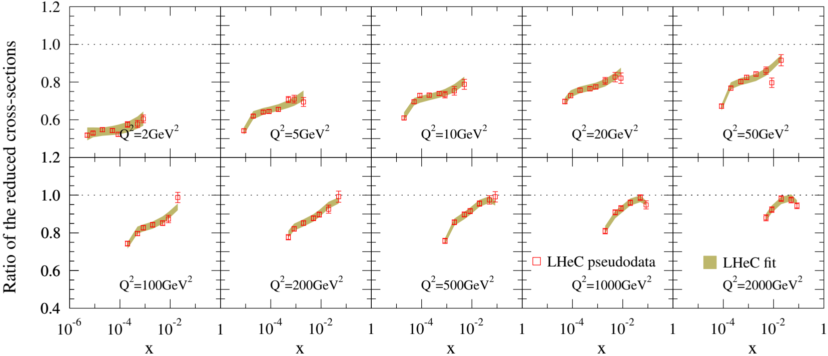


[H. Paukkunen, preliminary]

- The error bands hugely exceed the expected data uncertainties
- The offset between the data and fit at large-x due to "optimal" normalization factor $f \sim 1.1$ for the data (new baseline $\neq$ EPS09)

Impact of the LHeC data

- The fit with the LHeC data

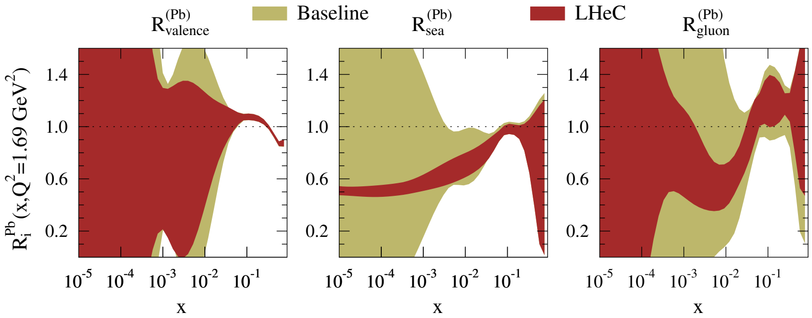


[H. Paukkunen, preliminary]

- Drastic reduction of nPDF-originating uncertainties when LHeC data is included!

Impact of the LHeC data

- Impact to the nPDF uncertainties

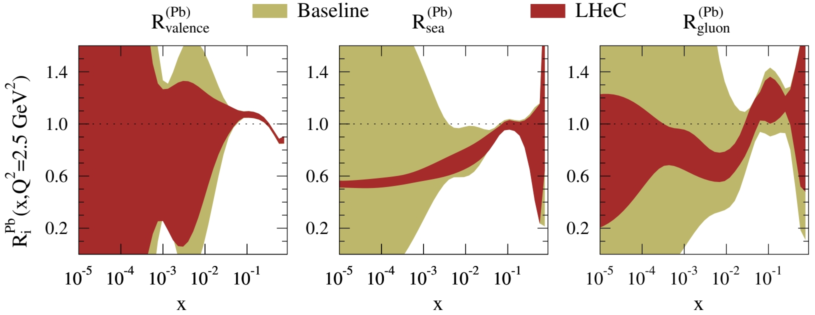


[H. Paukkunen, preliminary]

- Significant reduction of small-x uncertainties for gluons and sea quarks

Impact of the LHeC data

- Impact to the nPDF uncertainties

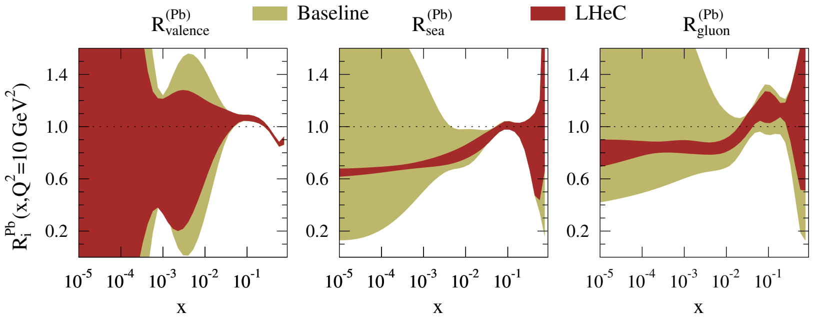


[H. Paukkunen, preliminary]

- Significant reduction of small-x uncertainties for gluons and sea quarks
- Scale evolution shrinks the gluon uncertainties further

Impact of the LHeC data

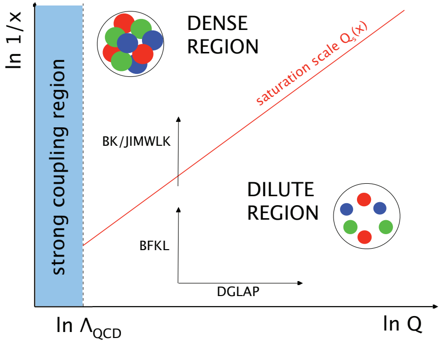
- Impact to the nPDF uncertainties



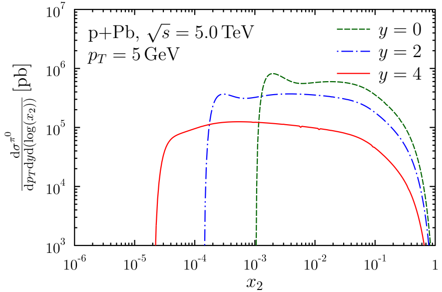
[H. Paukkunen, preliminary]

- Significant reduction of small-x uncertainties for gluons and sea quarks
- Scale evolution shrinks the gluon uncertainties further
- Estimated precision would substantially improve the accuracy of pQCD baseline for LHC and FCC heavy-ion physics at $p_T \gtrsim 3$ GeV/c

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



Inclusive hadrons in p+Pb (NLO):

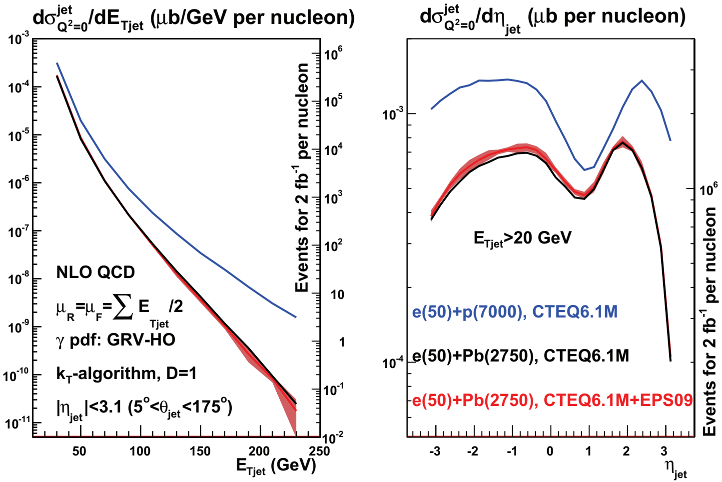


- $Q_s^2 \propto A^{1/3} x^{-0.3} \Rightarrow$ saturation more pronounced at large A
- Hard to be sensitive to small-x physics in p+Pb (direct γ at $\eta > 3$ should help)

$\Rightarrow$ 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

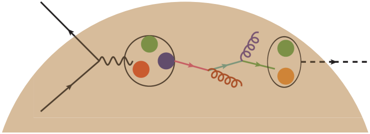


- Large E_T jets also in $\mathrm{e}+A$
- Useful to study parton dynamics and photon structure
- Not all theoretical uncertainties considered yet

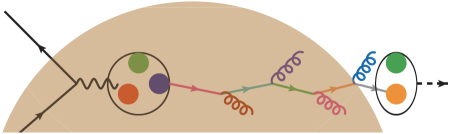
Hadronization in nuclear medium

- 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 kinematic reach
- Small-x uncertainties much larger than in the current parametrization
  - Small-x enhancement allowed by the data (theoretically unfavored)
  - Global analyses should reflect the data, not fitters physical intuition!
- Recent $\mathrm{p+Pb}$ data from LHC will improve fits at $x \gtrsim 0.01$
- LHeC would provide very precise data down to $x \sim 10^{-5}$
- Study constraints for flavor dependence from charged-current 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, . . .) that would be useful to unravel saturation and to determine nuclear GPDs

Backup

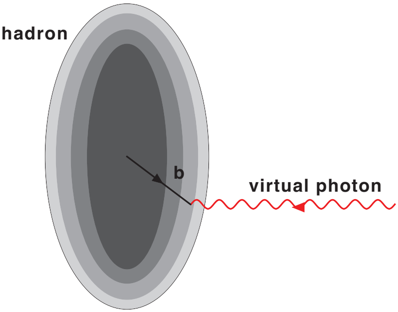
Recent nPDF analyses

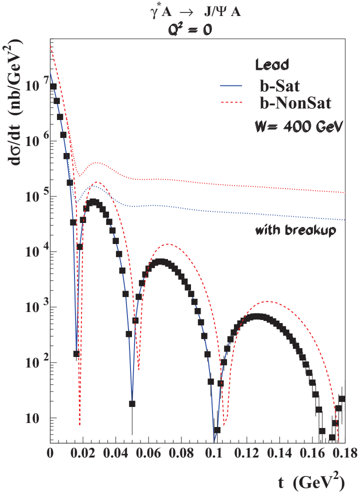
	HKN07	EPS09	DSSZ	nCTEQ prelim.
Ref.	Phys. Rev. C76 (2007) 065207	JHEP 0904 (2009) 065	Phys.Rev. D85 (2012) 074028	arXiv:1307.3454
Order	LO & NLO	LO & NLO	NLO	NLO
Neutral current e+A / e+d DIS	√	√	√	√
Drell-Yan dileptons in p+A / p+d	√	√	√	√
RHIC pions in d+Au / p+p		√	√	
Neutrino-nucleus DIS			√	
Q^2 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]

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

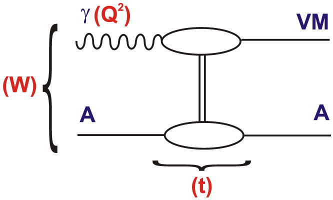




- Also sizable saturation effects expected

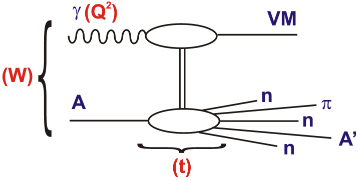
Elastic VM production

- Coherent VM production:

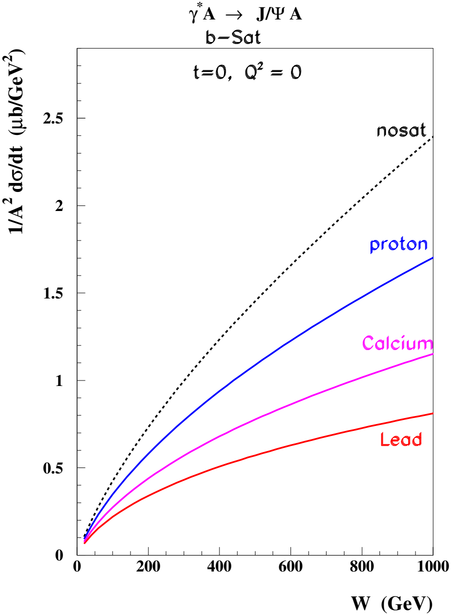


Predictions available showing large saturation ⇒

- Incoherent VM production:

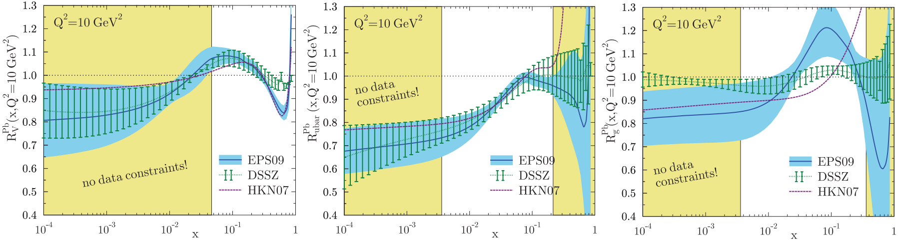


Energy denpendence of coherent VM



Uncertainties in the current nPDF fits

Comparison between different fits:



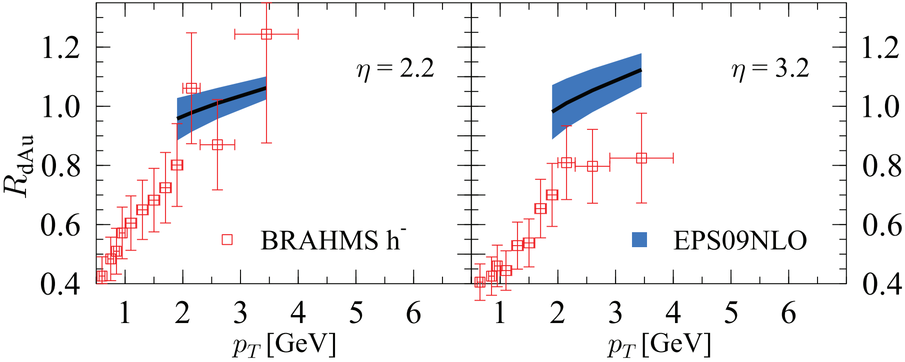
[Nucl.Phys.A926 (2014) 24-33]

- nCTEQ analysis provides somewhat larger uncertainties
  [Talk by A. Kusina on Wednesday at 11:40 (WG1)]
- Recent $\mathrm{p+Pb}$ data from LHC constrains nPDFs mostly at $x > 0.01$
  - e.g. high-p_T jets [Nucl.Phys. A931 (2014) 331-336]

  $\Rightarrow$ No significant improvement at small values of x
- Fairly small uncertainties in the unconstrained region
- Impact of the LHeC data?

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