Current status of nPDFs and future facilities

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QCD evolution 2017, Jefferson Lab

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

Unión Europea

Fondo Europeo
de Desarrollo Regional
"Una manera de hacer Europa"

Outline

- Introduction
- Pre-LHC global analysis
- Post-LHC run I
- Where are we going?
- Conclusions

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Collinear factorization

- Factorization

Parton distribution functions (PDFs)

$$d\sigma = \sum_{i,j} f_i(Q_f^2) \otimes d\sigma_{ij}(Q_f^2, Q_r^2) \otimes f_j(Q_f^2) + \mathcal{O}\left(Q_f^{-2n}\right)$$

Coefficient functions (calculable by perturbative methods)

- DGLAP equations

$$Q^2 \frac{\partial f_i(x, Q^2)}{\partial Q^2} = \sum_j P_{ij}(Q^2) \otimes f_j(x, Q^2)$$

Splitting functions (calculable by perturbative methods)

Global Analysis

- Choose data
- Parametrize the PDFs at the initial scale
- DGLAP evolution
- Compute the cross sections
- Evaluate χ^2
- Minimize $\chi^2 \Rightarrow$ Best fit $\Rightarrow$ Hessian analysis for uncertainties.

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What is parametrized?

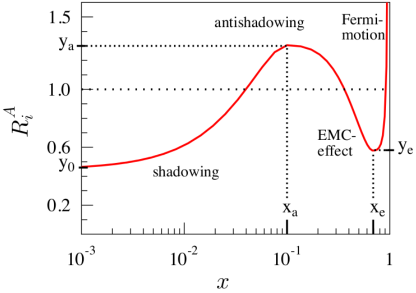
- Free proton baseline

$$f_i^{p/A}(x, Q_0) = f_i^p(x, Q_0) R_i(x, A)$$

- Data are of the form

$$F_2^A(x, Q^2)/F_2^p(x, Q^2)$$

nPDFs always relative to proton-free PDFs.



Flavor decomposition

- Free proton baseline

$$f_i^{p/A}(x, Q_0) = f_i^p(x, Q_0) R_i(x, A)$$

- Usually flavor independence (FI) is assumed at Q_0:

$$R_{u_V}(x, Q_0^2) = R_{d_V}(x, Q_0^2)$$

$$R_{\overline{u}}(x, Q_0^2) = R_{\overline{d}}(x, Q_0^2) = R_{\overline{s}}(x, Q_0^2)$$

- DGLAP destroyes flavor independence
- Flavor separation should be considered

nCTEQ15: No FI for valence quarks.

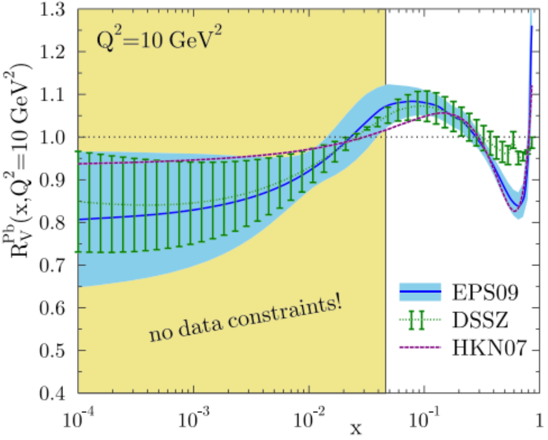
EPPS16: No FI for sea and valence quarks.

Before LHC run I

	EPS09	DSSZ12	KA15	NCTEQ15
Order in α_s	LO & NLO	NLO	NNLO	NLO
Neutral current DIS ℓ+A/ℓ+d	✓	✓	✓	✓
Drell-Yan dilepton p+A/p+d	✓	✓	✓	✓
RHIC pions d+Au/p+p	✓	✓		✓
Neutrino-nucleus DIS		✓		
Q cut in DIS	$1.3\,\mathrm{GeV}$	$1\,\mathrm{GeV}$	$1\,\mathrm{GeV}$	$2\,\mathrm{GeV}$
datapoints	929	1579	1479	708
free parameters	15	25	16	17
error analysis	Hessian	Hessian	Hessian	Hessian
error tolerance $\Delta\chi^2$	50	30	N.N	35
Free proton baseline PDFs	CTEQ6.1	MSTW2008	JR09	CTEQ6M-like
Heavy-quark effects		✓		✓
Flavour separation	none	none	none	some
Reference	[JHEP 0904 065]	[PR D85 074028]	[PRD 93, 014026]	[PR D93 085037]

Paukkunen, Nucl. Phys. **A** 926 (2014) 24

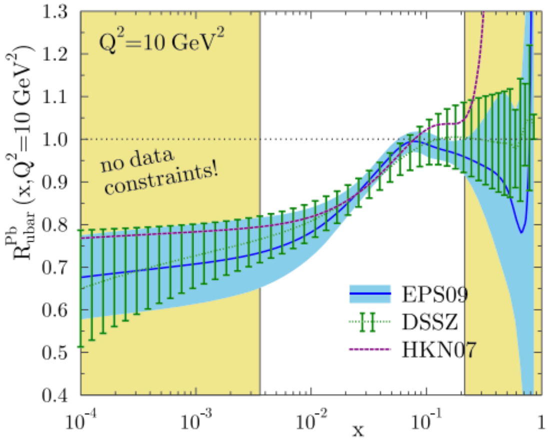
Valence



$$R_{u_v} = R_{d_v}$$

Paukkunen, Nucl. Phys. **A** 926 (2014) 24

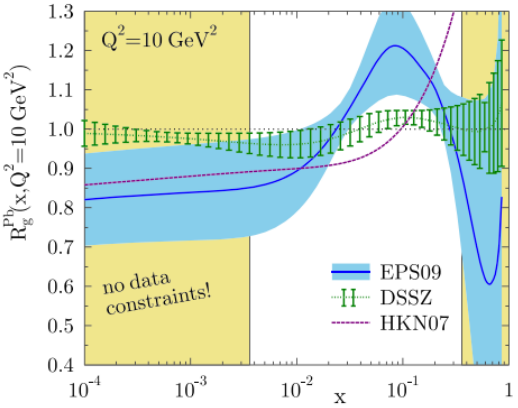
Sea



Agreement in the data-constrained region

Paukkunen, Nucl. Phys. **A** 926 (2014) 24

Gluon



- No constraints from DIS and Drell-Yan
- nCTEQ15, EPS09 and DSSZ: some constraints from inclusive pion production

Where were we?

- Extrapolations not completely reliable:
    - Depend on the initial parametrization (model-dependent)
- Low x: extrapolations
- High x: no constraints
- **Gluon**: **no** sensitivity at **low** and **high x**
- **No** flavor decomposition

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Where are we?

LHC run I

LHC Run I: data

- Charged hadrons (ALICE, CMS) and pions (ALICE)
- Jets (ATLAS)
- **Di-jets** (CMS) ⇒ **Gluon** constraints at **high** x**!**
- **W**$^{\pm}$(ALICE, CMS) and **Z**^{0} (ATLAS, CMS) bosons ⇒ Flavor separation?
- Only last two included in EPPS16

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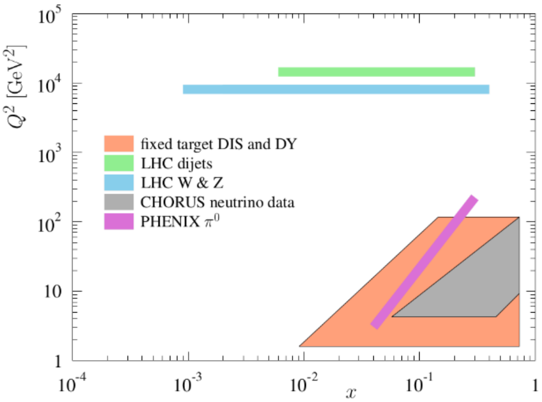
Kinematic region

- Much higher Q^2 and lower x.



EPPS16, arXiv:1612.05741

The LHC opens an unexplored kinematic region!

Global analysis

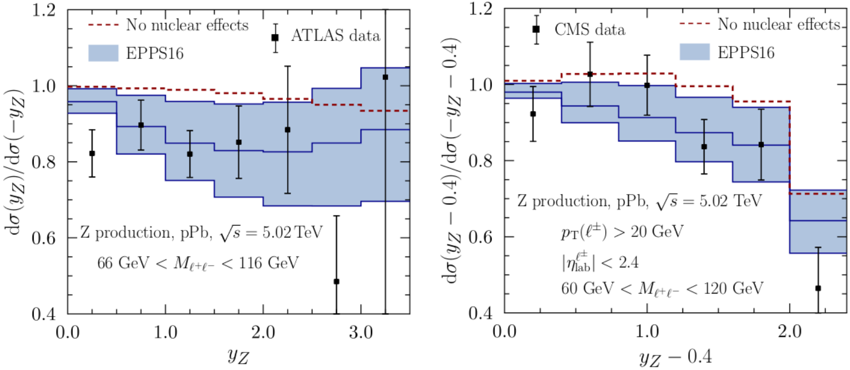
Thanks to Paukkunen QM2017

	EPPS16	DSSZ12	KA15	NCTEQ15
Order in α_s	NLO	NLO	NNLO	NLO
Neutral current DIS ℓ+A/ℓ+d	✓	✓	✓	✓
Drell-Yan dilepton p+A/p+d	✓	✓	✓	✓
RHIC pions d+Au/p+p	✓	✓		✓
Neutrino-nucleus DIS	✓	✓		
Drell-Yan dilepton $\pi+A^1$	✓			
LHC p+Pb jet data	✓			
LHC p+Pb W, Z data	✓			
Q cut in DIS	$1.3\,\mathrm{GeV}$	$1\,\mathrm{GeV}$	$1\,\mathrm{GeV}$	$2\,\mathrm{GeV}$
datapoints	1811	1579	1479	708
free parameters	20	25	16	17
error analysis	Hessian	Hessian	Hessian	Hessian
error tolerance $\Delta\chi^2$	52	30	N.N	35
Free proton baseline PDFs	CT14NLO	MSTW2008	JR09	CTEQ6M-like
Heavy-quark effects	✓	✓		✓
Flavour separation	full	none	none	some
Reference	[ARXIV:1612.05741	[PR D85 074028]	[PRD 93, 014026]	[PR D93 085037]

Z^0 production in p-Pb

EPPS16, arXiv:1612.05741

$$x \approx \frac{M_z}{\sqrt{s}} e^{-y_z}$$

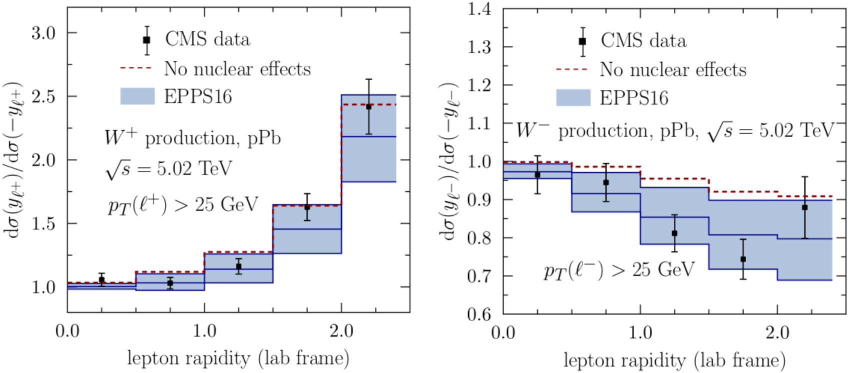


- Data deviates from unity for non-symmetric acceptance
- Shadowing for $y_z > 0 \Rightarrow$ Suppression

$W^{\pm}$ production in p-Pb

EPPS16, arXiv:1612.05741

$$x \approx \frac{M_z}{\sqrt{s}} e^{-y_l}$$

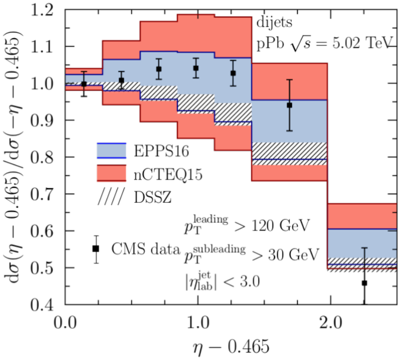


- Isospin effects $\Rightarrow$ Baseline suppression
- Shadowing for $y_{l\pm} > 0 \Rightarrow$ Suppression

Di-jets production in p-Pb

EPPS16, arXiv:1612.05741

Di-jets to constrain large-x gluons!



- Antishadowing for $\eta_{\text{dijet}} > 0$ and EMC for $\eta_{\text{dijet}} < 0 \Rightarrow$ Enhancement
- Data deviates from unity for non-symmetric acceptance

Di-jets production in p-Pb

EPPS16, arXiv:1612.05741

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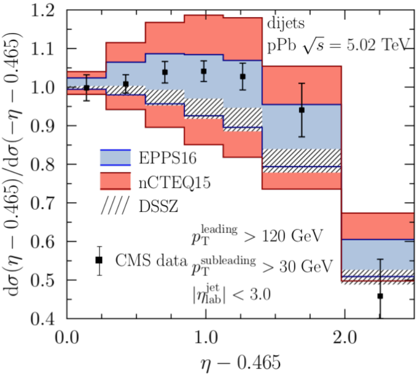
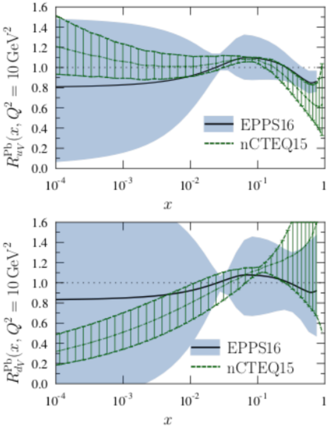
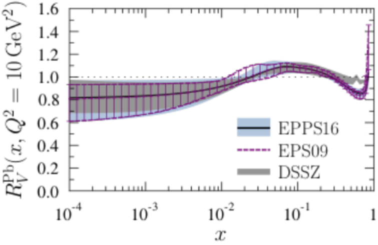


- nCTEQ15: large di-jet uncertainty band
- DSSZ: similar to no nuclear effects

$R_{valence}$

EPPS16, arXiv:1612.05741

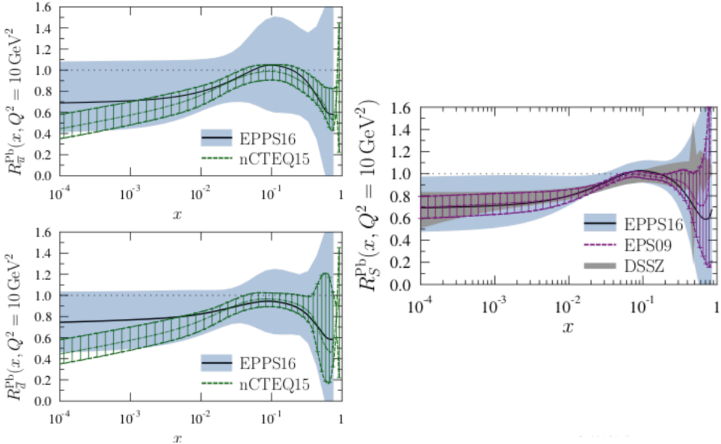




- $R_V \equiv \frac{u_v^{Pb/p}+d_v^{Pb/p}}{u_v^p+d_v^p}$
- nCTEQ15: partly flavor dependence

R_{sea}

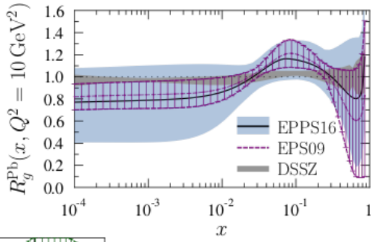
EPPS16, arXiv:1612.05741

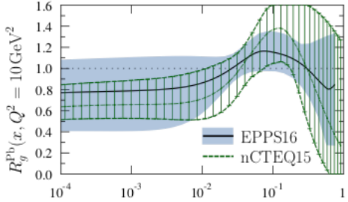


- $R_S \equiv \frac{\bar{u}^{Pb/p}+\bar{d}^{Pb/p}+\bar{s}^{Pb/p}}{\bar{u}^{p}+\bar{d}^{p}+\bar{s}^{p}}$
- EPPS16: more freedom for sea quarks ⇒ Larger uncertainties

R_{gluon}

EPPS16, arXiv:1612.05741





- EPPS16 more parameters ⇒ larger uncertainties. Except: large-x (di-jet data)
- DSSZ almost no suppression

Summary

- LHC run I: **novel constraints!**
- Larger uncertainties, but lower bias
- **Flavor separation** possible with ν-DIS data $\Rightarrow R_{u_v} \sim R_{d_v}$
- Di-jets: **gluons** more constrained at **large** x
- **Correlated systematics** missing!
- Accurate FFs needed
- **Symmetric acceptances in the c.m frame!**

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Where are we going?

LHC: run I and run II

- LHC run I: p-p reference at $\sqrt{s} = 5$ GeV measured $\Rightarrow R_{\mathrm{pPb}}$ $\Rightarrow$ Other observables possible
- LHC run II: already a p-p reference at $\sqrt{s} = 8$ GeV $\Rightarrow$ Drell-Yan at LHCb
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- It would be better: same phase space for p-p and p-Pb

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A-Z NNLO nPDFS

- First NNLO nPDF set within a GM-VFNS
- Charged lepton and neutrino DIS data already included
- Drell-Yan to come
- Nuclear effects in deuterium
- Flavor separation?
- When? 17xx.xxxx

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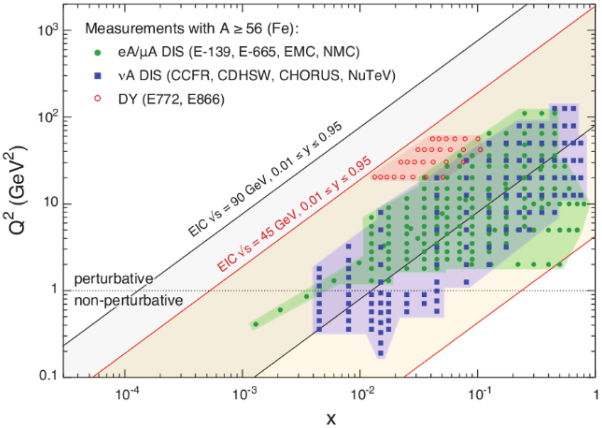
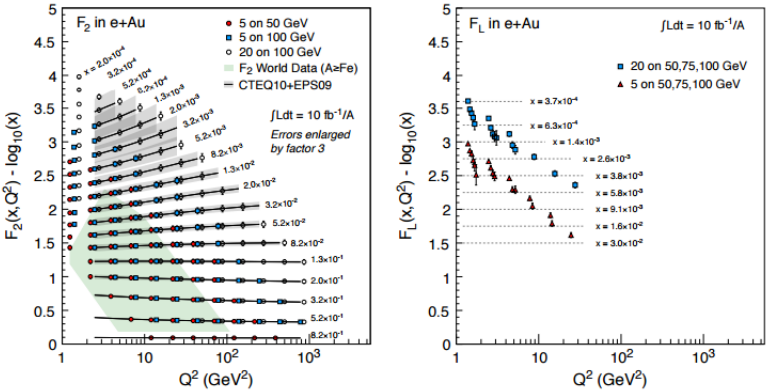
EIC: kinematics



Crucial to study the low-x region!!

Accardi *et al.*, Eur. Phys. J. **A52 (2016) no.9, 268**

EIC



Accardi *et al.*, Eur. Phys. J. **A52 (2016) no.9, 268**

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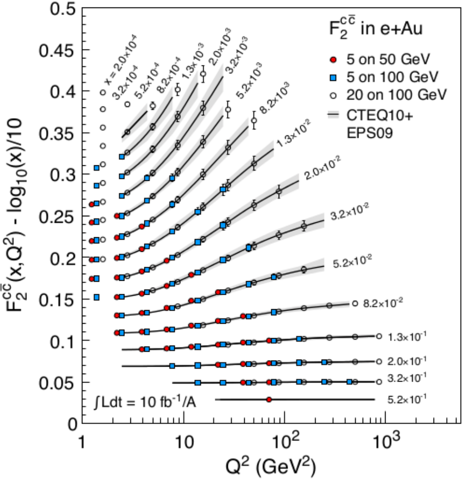
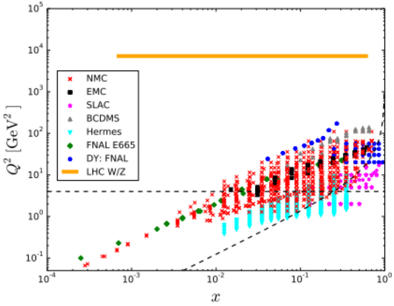
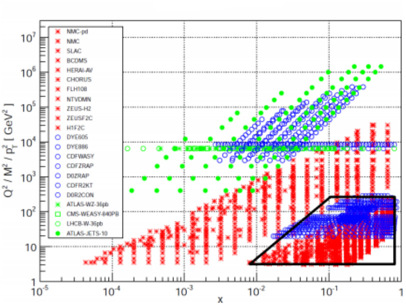


Never measured for e-A!!

Backup

nPDFs vs. PDFs kinematics





Hessian method

- χ^2 expanded around the minimum

$$\chi^2 = \chi_0^2 + \sum_{i,j} \left(a_i - a_i^0\right) H_{ij} \left(a_j - a_j^0\right) = \chi_0^2 + \sum_i z_i^2$$

$$(\delta X)^2 = \left(\frac{\partial X}{\partial z_i} \times \delta z_i\right)^2 , \quad \delta z_i = \frac{\delta z_i^+ + \delta z_i^-}{2}$$

- PDF uncetainty sets $S_i^\pm$:

$$S_1^\pm = \delta z_1^\pm (1, 0, ..., 0)$$
$$S_N^\pm = \delta z_N^\pm (0, 0, ..., N)$$

$$(\delta X)^2 = \frac{1}{4} \sum_i \left[X(S_i^+) - X(S_i^-)\right]^2$$

Hessian method

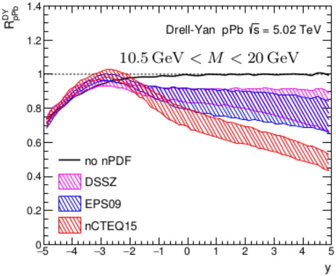
- $\delta z_i^{\pm}$ are defined to correspond to a fixed $\Delta\chi^2$
- Ideally $\Delta\chi^2 = 1$
- In practice: $\Delta\chi^2 >> 1$ due to the parametrization bias:

$$\text{EPPS16: } \Delta\chi^2 = 52$$
$$\text{DSSZ12: } \Delta\chi^2 = 30$$
$$\text{nCTEQ15: } \Delta\chi^2 = 35$$

EPJ C63 189

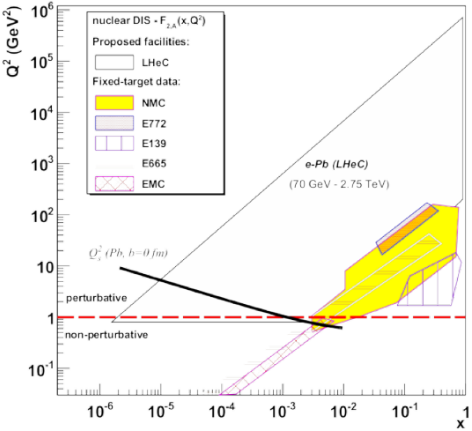
Drell-Yan

- Intermediate-mass Drell-Yan process at forward direction would provide a nice probe of small-x sea quarks [Arleo et.al, Phys.Rev. D95 (2017) 011502]



- Within the possibilities of e.g. LHCb with the Run-II luminosity [LHCb-PUB-2016-011].
- New low-mass Drell-Yan measurements expected from Fermilab SeaQuest experiment [FERMILAB-THESIS-2016-13].

LHeC



nuclear DIS - $F_{2,A}(x,Q^2)$
Proposed facilities:
LHeC
Fixed-target data:
NMC
E772
E139
E665
EMC
e-Pb (LHeC)
(70 GeV - 2.75 TeV)
Q_s^2 (Pb, b=0 fm)
perturbative
non-perturbative
Q^2 (GeV^2)
x