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Extraction of the strong coupling with HERA and EIC inclusive data

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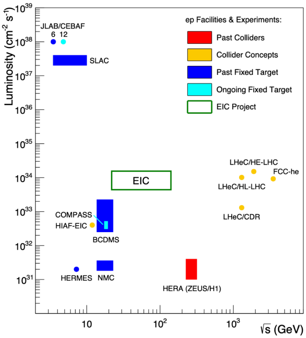
The Electron-Ion Collider

- A next-generation DIS collider, to be built at BNL. EIC will be unique and have un-precedented experimental capabilities;
  - High lumi ep Collider (50×HERA), Polarised target collider, First ever high energy eA collider, First ever fully polarized collider
- Flexible center-of-mass energy ($30 < \sqrt{s} < 140$ GeV), accessing moderate-to-large x values by comparison with HERA.
- Physics targets include:
  - 3D proton structure, Proton mass, Proton spin, Dense partonic systems in nuclei



Motivation

- Physics scopes of HERA and EIC differ but have significant overlap.
  - Inclusive DIS cross sections will be measured to high precision in a phase space region that will be complementary to HERA.
- The strong coupling, α_s, is the least well constrained.
  - Essential ingredient of SM cross section calculations, as well as constraints on new physics and grand unification scenarios.
- Inclusive NC DIS cross section is sensitive to α_s through F_2 and F_L.

$$\frac{d^2\sigma}{dx dQ^2} = \frac{2\pi\alpha^2}{xQ^4}\left[Y_+ F_2(x,Q^2) - y^2 F_L(x,Q^2) \mp Y_- x F_3(x,Q^2)\right]$$

Input HERA Data (ep)

- Final combined H1 and ZEUS inclusive DIS NC and CC cross sections [EPJC(2015)75:580]
  - $\sqrt{s} = 320, 300, 251, 225$ GeV
  - Total integrated luminosity: 1fb^{-1}
  - NC: $0.045 \leq Q^2 \leq 50000$ GeV^2, $6{\cdot}10^{-7} \leq x_{B_j} \leq 0.65$, $0.005 \leq y \leq 0.95$
  - CC: $200 \leq Q^2 \leq 50000$ GeV^2, $1.3{\cdot}10^{-2} \leq x_{B_j} \leq 0.40$, $0.037 \leq y \leq 0.76$
  - H1 and ZEUS inclusive and dijet measurements included [EPJC(2022)82:243]

Data set	Taken From to	Q^2[GeV^2] range From	To	$\mathcal{L}$ pb^{-1}	e^+/e^-	$\sqrt{s}$ GeV	Normalised	All points	Used points
H1 HERA I normalised jets	1999–2000	150	15,000	65.4	e^+p	319	Yes	24	24
H1 HERA I jets at low Q^2	1999–2000	5	100	43.5	e^+p	319	No	28	20
H1 normalised inclusive jets at high Q^2	2003–2007	150	15,000	351	e^+p/e^-p	319	Yes	30	30
H1 normalised dijets at high Q^2	2003–2007	150	15,000	351	e^+p/e^-p	319	Yes	24	24
H1 normalised inclusive jets at low Q^2	2005–2007	5.5	80	290	e^+p/e^-p	319	Yes	48	37
H1 normalised dijets at low Q^2	2005–2007	5.5	80	290	e^+p/e^-p	319	Yes	48	37
ZEUS inclusive jets	1996–1997	125	10,000	38.6	e^+p	301	No	30	30
ZEUS dijets	1998–2000 and 2004–2007	125	20,000	374	e^+p/e^-p	318	No	22	16

- Trijets from HERAPDF2Jets NLO excluded → no NNLO predictions
- H1 low Q^2 data added - particularly sensitive to α_s

The simulated EIC data (ep)

- EIC pseudodata are produced by considering the studies performed in the ATHENA framework(JINST 17 P10019).
  - Detailed simulation work to optimise resolutions throughout phase-space
    - 5 bins per decade in x and Q^2
  - NC pseudodata are produced for five different CMEs.

e-beam energy (GeV)	p-beam energy (GeV)	$\sqrt{s}$ (GeV)	Integrated lumi (fb^{-1})
18	275	141	15.4
10	275	105	100
10	100	63	79.0
5	100	45	61.0
5	41	29	4.4

  - CC pseudodata are produced for only $\sqrt{s}$ = 141 GeV.
  - Kinematic coverage:
    - $Q^2 > 1$ GeV^2
    - 0.001 $< y = \frac{Q^2}{sx} <$ 0.95
    - $W^2 = \frac{Q^2(1-x)}{x} > 10$ GeV^2

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Systematic Precision

- Dominant sources at HERA were
  - Electron energy scale (intermediate y)
  - Photoproduction background (high y)
  - Hadronic energy scale / noise (low y)
- EIC will improve in all areas (e.g. dedicated particle ID detectors suppress π/e contamination to below 10^{-6} level at low momenta)
- Assumed systematic precision conservative compared with Yellow report:
  - 1.9$\%$ point-to-point uncorrelated (growing to 2.75$\%$ at low y)
  - 3.4$\%$ normalisation (uncorrelated between different $\sqrt{s}$)

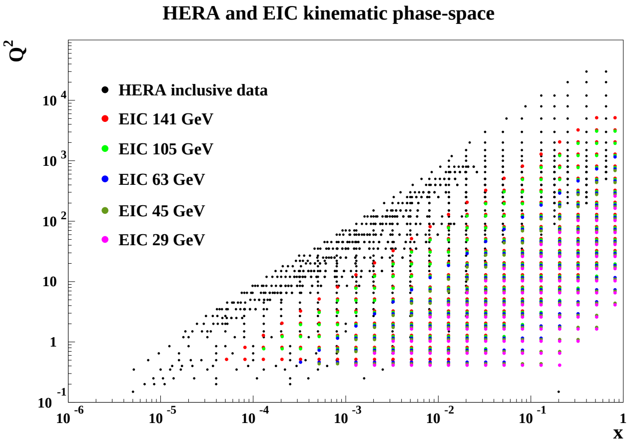
Fit settings for $\alpha_s(M_Z^2)$ fit

- Based on the QCD fit → the HERAPDF theoretical framework, PDF parameterisations and model parameter choices.
- Used HERAPDF20_NNLO_ALPHAS_116 LHAPDF set.
- The xFitter framework is used.
- The PDF parameterisation (following the HERAPDF2.0 approach):

$$
\begin{aligned}
xg(x) &= A_g x^{B_g}(1-x)^{C_g} - A'_g x^{B'_g}(1-x)^{25};\\
xu_v(x) &= A_{u_v} x^{B_{u_v}}(1-x)^{C_{u_v}}\left(1+E_{u_v}x^2\right);\\
xd_v(x) &= A_{d_v} x^{B_{d_v}}(1-x)^{C_{d_v}};\\
x\bar{U}(x) &= A_{\bar{U}} x^{B_{\bar{U}}}(1-x)^{C_{\bar{U}}}\left(1+D_{\bar{U}}x\right);\\
x\bar{D}(x) &= A_{\bar{D}} x^{B_{\bar{D}}}(1-x)^{C_{\bar{D}}}.
\end{aligned}
$$

- PDFs are parameterised at a starting scale for QCD evolution of $\mu_{f0} = 1.9$ GeV^2.
- Strangeness fraction: $f_s = x\bar{s}/(x\bar{d} + x\bar{s}) = 0.4$
- The theory settings and their variations:
  - Central scales: $\mu_r^2 = \mu_f^2 = Q^2$ for the inclusive DIS data, $\mu_r^2 = \mu_f^2 = Q^2 + p_T^2$ for inclusive jet data and $\mu_r^2 = \mu_f^2 = Q^2 + <p_T>_2^2$ for dijets.
  - Scale variations: μ_r, μ_f scales are varied up and down by a factor of 2.

Kinematic phase-space



- HERA data have limited high-x sensitivity due to kinematic correlation between x and Q^2 and $1/Q^4$ factor in cross section.
- EIC data fills in large-x, modest Q^2 region with high precision.

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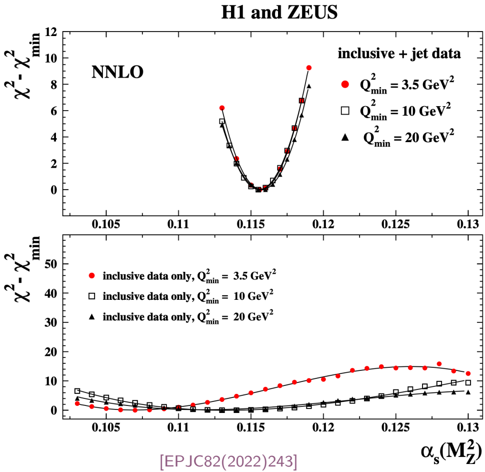
Taking α_s as an additional free parameter

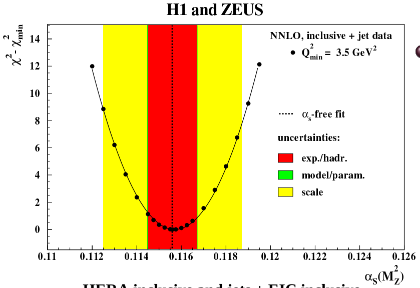


[EPJC82(2022)243]

- When using HERA data only
  - HERAPDF2.0 shows only limited sensitivity when fitting inclusive data only.
  - Including jet data allows simultaneous α_s extractions to competitive precision without significant impact on PDFs.
- What happens when fitting HERA+EIC data together?

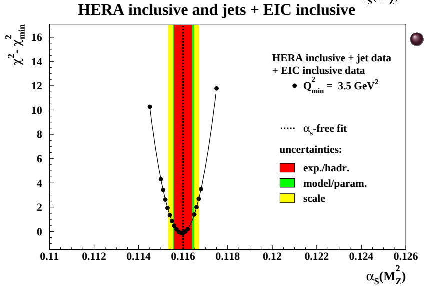
QCD fits with EIC inclusive and HERA inclusive+jet data

- A simultaneous NNLO fit is performed to extract the PDFs and $\alpha_s(M_Z^2)$ from HERA inclusive and jet data and EIC inclusive data.



- **HERA inclusive + jet data, NNLO:** (EPJC82(2022)243)

$$\alpha_s(M_Z^2) = 0.1156 \pm 0.0011\ (\text{exp})\ {}^{+0.0001}_{-0.0002}\ (\text{model} + \text{param}) \pm 0.0029\ (\text{scale})$$

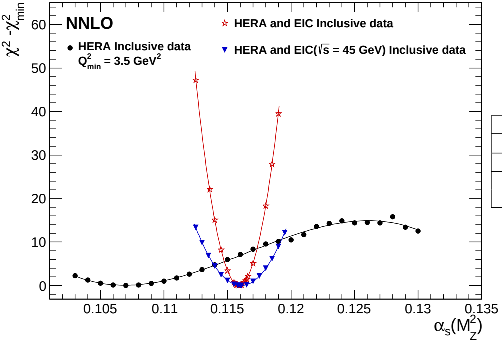


- **EIC inclusive data and HERA inclusive + jet data, NNLO:**

$$\alpha_s(M_Z^2) = 0.1160 \pm 0.0004\ (\text{exp})\ {}^{+0.0003}_{-0.0002}\ (\text{model} + \text{param}) \pm 0.0005\ (\text{scale})$$

QCD fits with HERA and EIC inclusive data only

- A simultaneous NNLO fit is performed to extract the PDFs and $\alpha_s(M_Z^2)$ from HERA and EIC inclusive data.



Central values of model input parameters and their one-sigma variations.

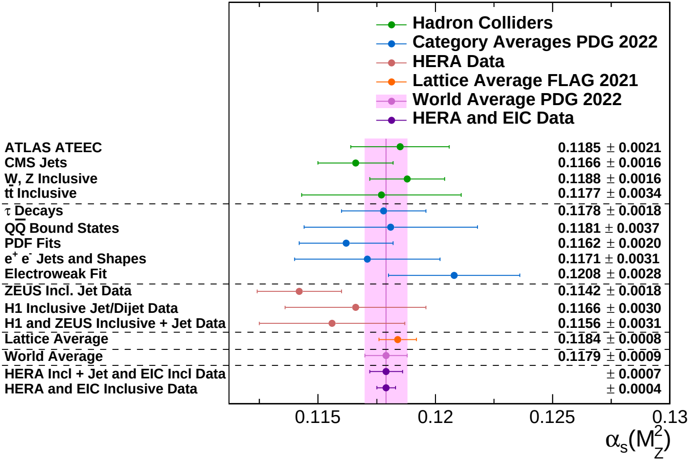
Parameter	Central val.	Downwards var.	Upwards var.
$Q^2_{\rm min}$ [GeV^2]	3.5	2.5	5.0
f_s	0.4	0.3	0.5
M_c [GeV]	1.41	1.37	1.45
M_b [GeV]	4.20	4.10	4.30

No scale variations are made for the inclusive data

- **EIC and HERA inclusive data, NNLO:**

$$\alpha_s(M_Z^2) = 0.1159 \pm 0.0004\ (\text{exp})\ ^{+0.0002}_{-0.0001}\ (\text{model} + \text{param})$$

Comparison to other $\alpha_s(M_Z^2)$ results



- With using only inclusive DIS data from HERA and EIC, we are able to determine the $\alpha_s(M_Z^2)$ with potentially world-leading precision in a simultaneous fit of PDFs and $\alpha_s(M_Z^2)$ at NNLO.

Comments on Scale Uncertainties

- 'Scale' uncertainties express uncertainties due to missing higher orders beyond NNLO in the theory.
- Expected to be small for inclusive data, and covariances with other uncertainties have to be considered (hence generally omitted in global fits) - Moving the machinery to N^3LO will make them even smaller.
- Ongoing work by global fitting groups (e.g. NNPDF arXiv:1906.10698) to develop a consistent framework.
  - outcomes eagerly awaited
  - may become very important in EIC era!

Comment on Origin of EIC Impact

- Restricting data range by imposing Q^2_{min} (or x_{min}) cuts has only very small impact on the result.
  - EIC impact traceable to the large x, moderate Q^2 region.
- There is, however some sensitivity to the W^2 cut:
  - Default ($> 10\ GeV^2$) yields experimental precision 0.0004.
  - Switching to $> 15\ GeV^2$ leads to experimental precision 0.0006.
- Important to avoid sensitivity to higher twist or resummation effects.

Conclusion

- The estimated total uncertainty on $\alpha_s(M_Z^2)$ when including EIC DIS pseudodata is better than 0.4% → Improves the precision of the present world experimental and lattice averages.
- We are working with global fitting experts to assign a meaningful scale uncertainty to our result, due to missing higher order contributions beyond NNLO in the theory.
- Adding inclusive jet and dijet EIC pseudodata to the QCD analysis can improve the $\alpha_s(M_Z^2)$ precision.

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Acknowledgements

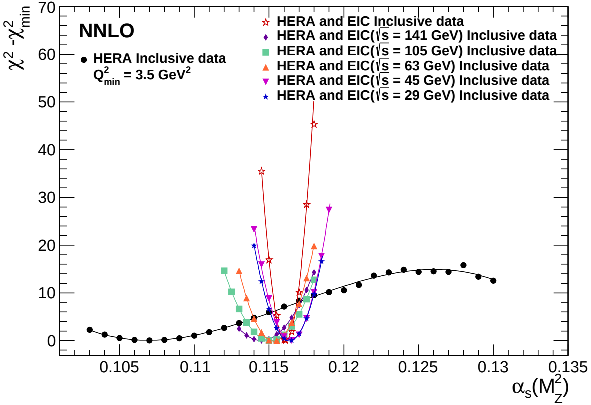
- We are very grateful to
  - many colleagues in the EIC experimental community for their immense effort in working on all aspects of the project over many years.
  - Néstor Armesto, Andrea Barontini, Thomas Cridge, Stefano Forte, Lucian Harland-Lang, Anna M. Staśto and Robert S. Thorne for their very valuable discussions about the theory uncertainties.
  - Valerio Bertone and Francesco Giuli for their help with the `APFEL` program.
  - Christopher Schwan for his help with the `PineAPPL` tool.

THANK YOU!

Backup

QCD fits with HERA and EIC inclusive data only

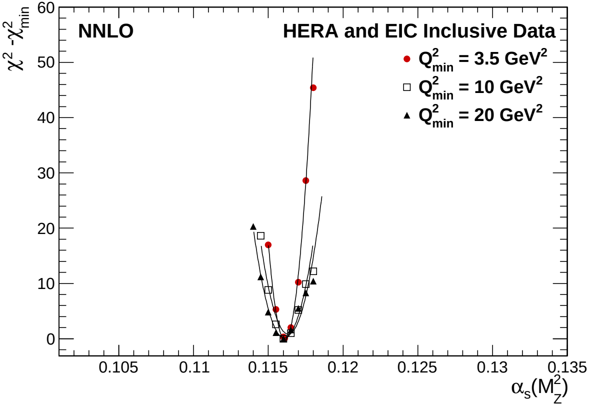
- A simultaneous NNLO fit is performed to extract the PDFs and $\alpha_s(M_Z^2)$ from HERA and EIC inclusive data.



$\Delta\chi^2 = \chi^2 - \chi^2_{min}$ vs. $\alpha_s(M_Z^2)$ for the NNLO fits to HERA data on inclusive ep scattering only (black), and also with the addition of simulated EIC inclusive data for all five $\sqrt{s}$ values together (red) or for only one $\sqrt{s}$ value.

Sensitivity to minimum Q^2 cut

- The analysis is repeated with the Q^2_{min} cut increased from 3.5 GeV^2 to 10 GeV^2 or 20 GeV^2.
- The distinct minima still observed, with only a small dependence on Q^2_{min} (below 0.1%).



$\Delta\chi^2 = \chi^2 - \chi^2_{min}$ vs. $\alpha_s(M_Z^2)$