Strong Coupling Measurements at EIC

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on behalf of the authors of Eur. Phys. J. C 83, 1011 (2023)

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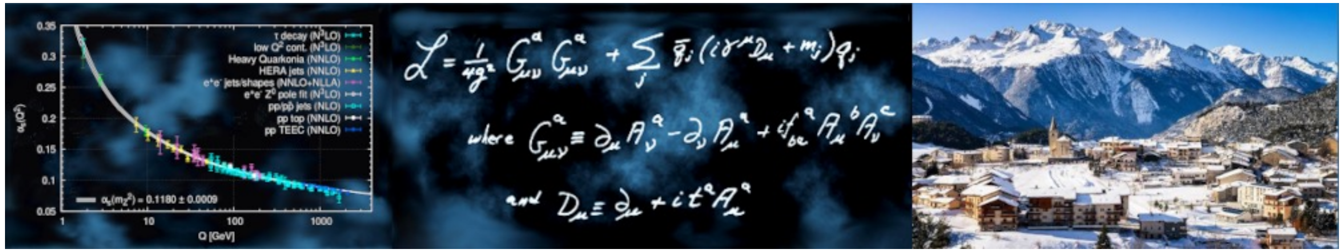


alphas-2025: Workshop on Precision Measurements of the Strong Coupling Constant

Stony Brook University

Center for Frontiers in Nuclear Science

Extracting α_s

- The strong coupling is the least precisely measured of the fundamental couplings.
  - Critical input for SM precision tests and BSM sensitivity.
- PDG: χ^2- combine six ≥ NNLO pre-averages (τ, quarkonium, PDF fits, e^+e^- shapes/jets, hadron collider, EW)
  - merge with lattice via an unweighted average

$$\alpha_s(m_Z^2) = 0.1180 \pm 0.0009\ (\pm 0.8\%)$$

$\delta\alpha_s = 1.4\ \%$

$\delta\alpha_s = 3.3\ \%$

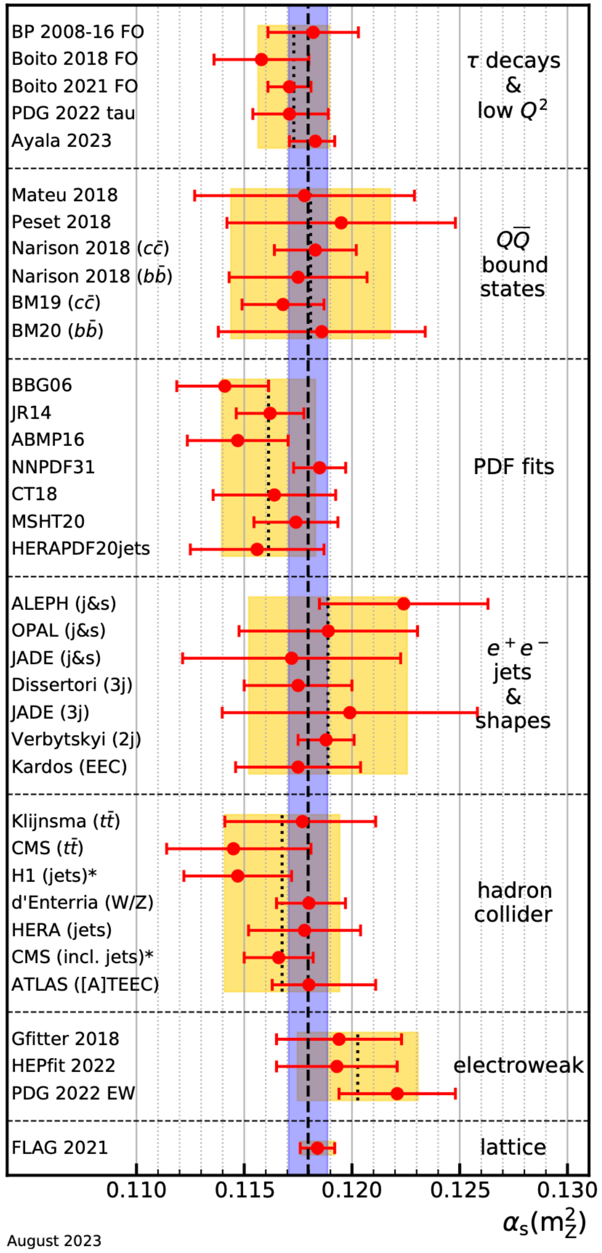
$\delta\alpha_s = 1.9\ \%$

$\delta\alpha_s = 3.1\ \%$

$\delta\alpha_s = 2.3\ \%$

$\delta\alpha_s = 2.3\ \%$

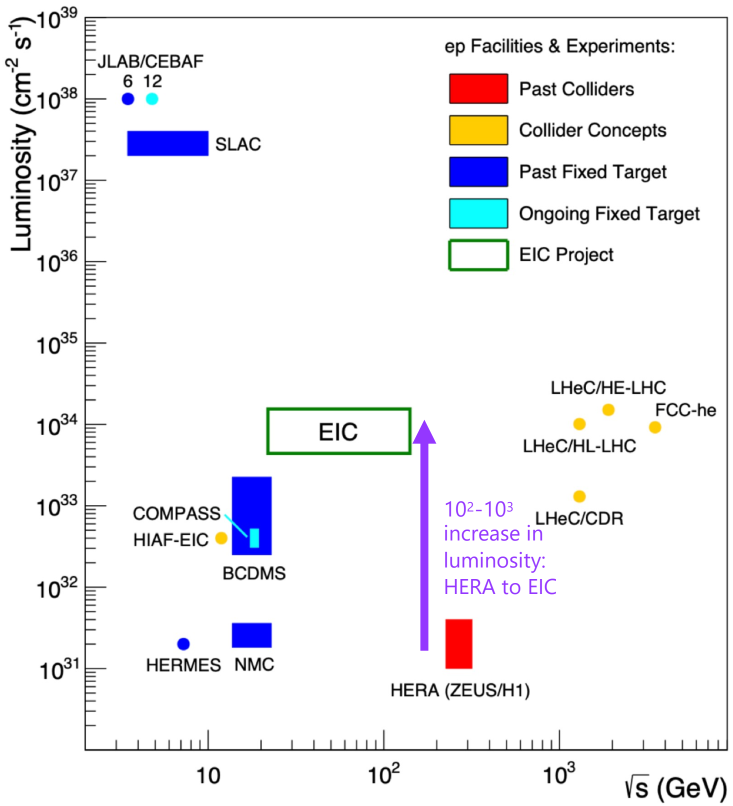
$\delta\alpha_s = 0.7\ \%$



PDG 2024

Why EIC?

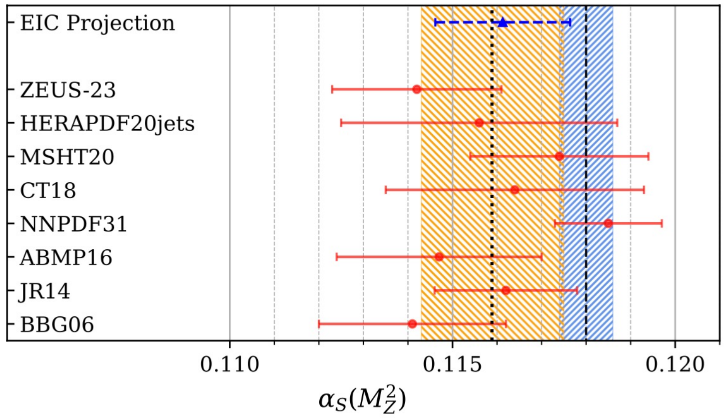
- EIC will allow us to probe the non-linear, non-perturbative regime of QCD where mass, spin, and confinement emerge.
- Exploration of gluon saturation at small-*x*, especially in nuclei, where universal behavior is expected.
- EIC covers high-*x*, moderate-Q^2 phase space — crucial for strong coupling studies.
- Unique facility:
  - Polarized lepton and hadron beams
  - Broad range of beam energies and ion species
  - High luminosity: $\mathcal{L} = 10^{33} - 10^{34}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$



Potential α_s measurements at EIC

- **Inclusive DIS (PDF fits):**
  - Extraction of the strong coupling with HERA and EIC inclusive data
    - Eur. Phys. J. C (2023) 83: 1011
  - Impact of inclusive Electron Ion Collider data on collinear parton distributions
    - Phys. Rev. D 109, 054019
- **Polarized DIS (Bjorken sum rule):**
  - High precision measurements of α_s at the future EIC
    - Phys. Rev. D 110, 074004
- **DIS event shapes:**
  - Precision DIS thrust predictions for HERA and EIC
    - arXiv: 2504.05234

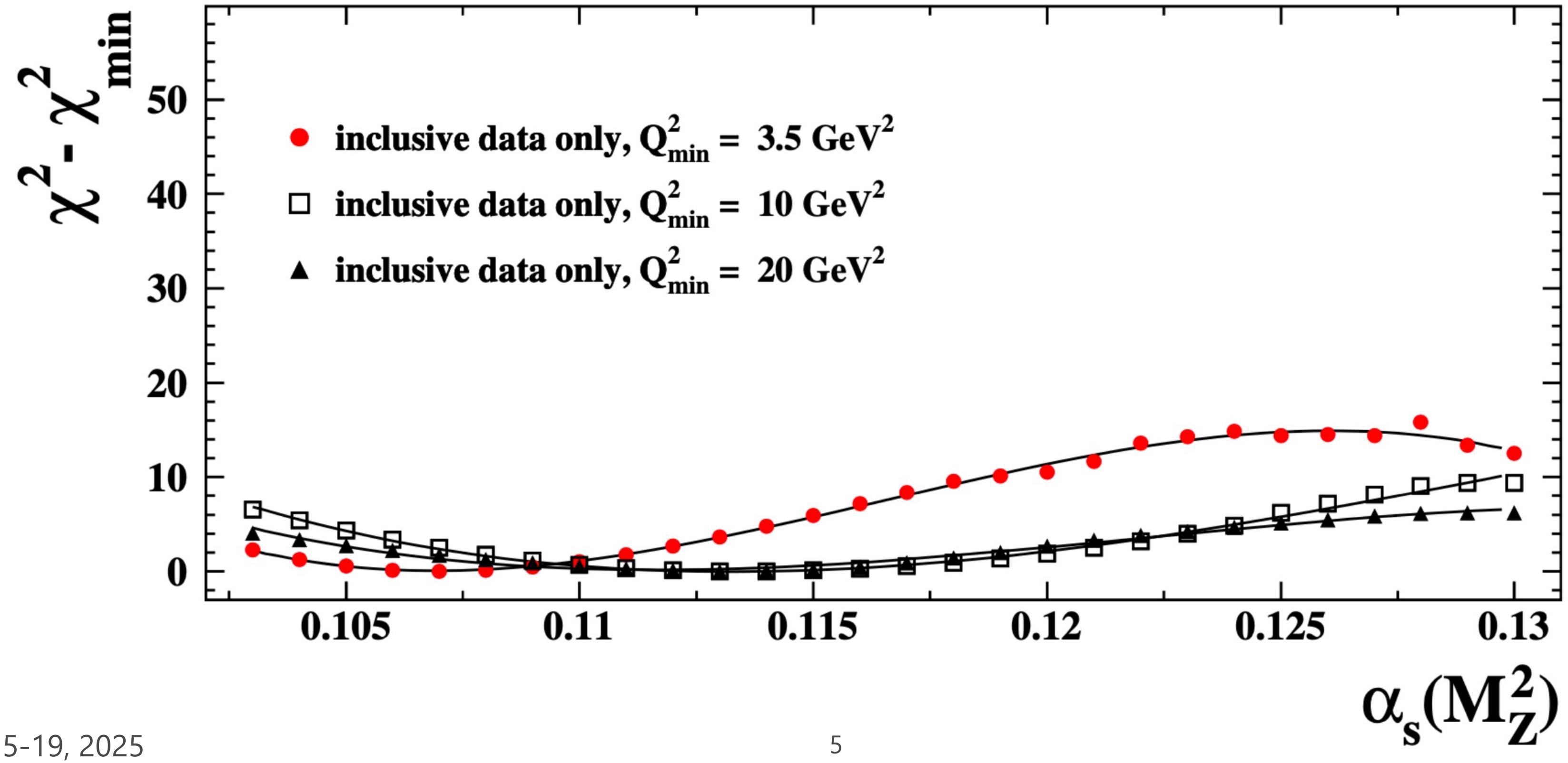
PRD 110, 074004 (2024)



Determining α_s from DIS

- DIS-based extractions: limited by scale uncertainties and limited phase space.
  - HERA data alone not sufficient for sub-permille precision.

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



Datasets

HERA data

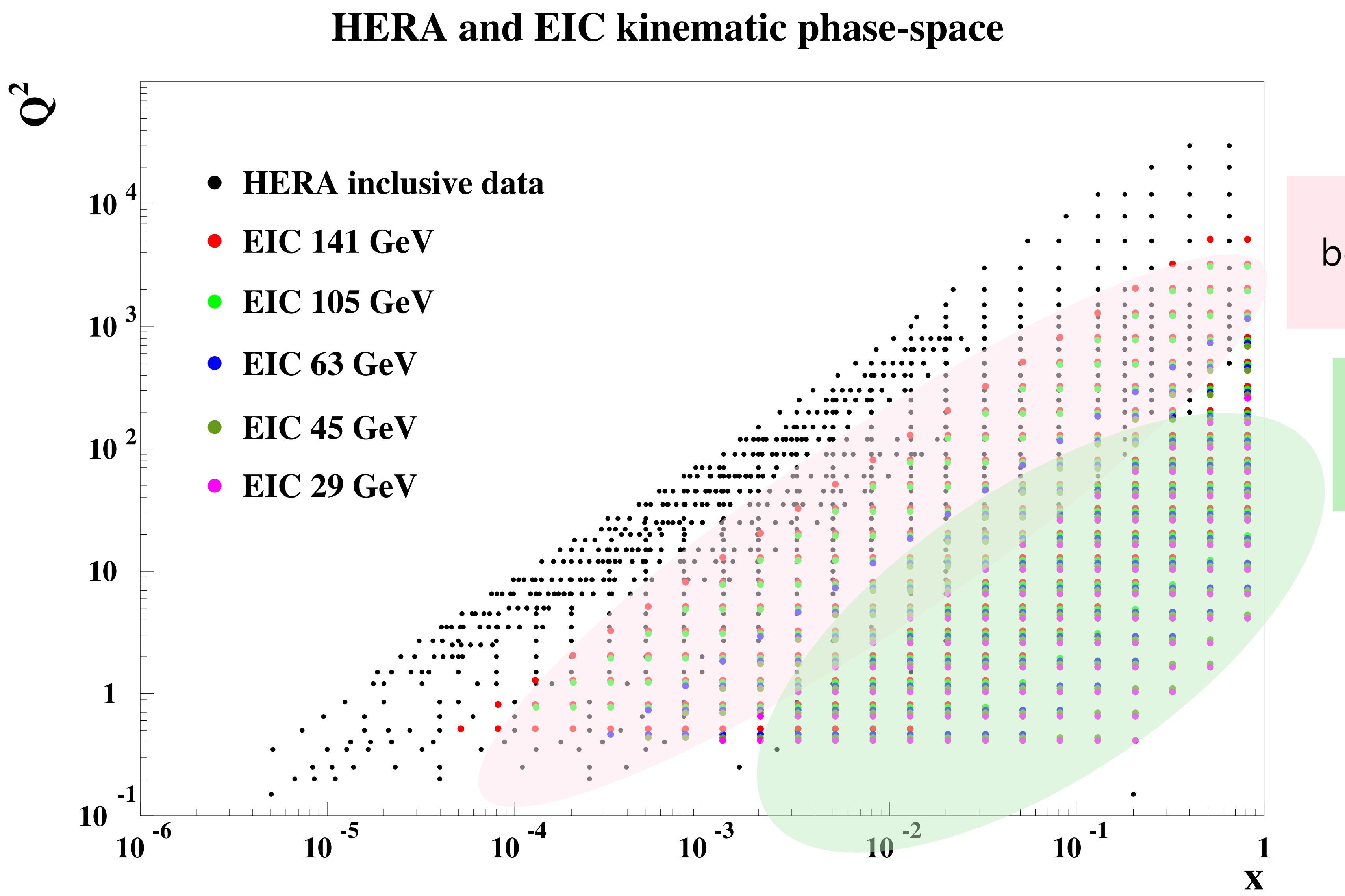
- H1 and ZEUS combined
  - inclusive DIS NC, CC cross sections [EPJC(2015)75:580]
  - Inclusive jet and dijets measurements [EPJC(2022)82:243]
- Integrated luminosity of 1 fb^{-1}.

EIC (Projected data)

- Simulated data with HERAPDF2.0 NNLO, uncertainties from ATHENA detector proposal [JINST17P10019]
- 1 year of data taking. Uncertainties:
  - uncorrelated 1.9% - 2.75%,
  - fully correlated normalization 3.4%.

Experiment	Q^2 (GeV²)	$y = Q^2/sx$ range	$\sqrt{s}$ (GeV)
HERA (NC)	0.045 – 50000	0.005 – 0.95	225, 251, 301, 319
HERA (CC)	200 – 50000	0.037 – 0.76	319
EIC (NC)	≥ 1	0.001 – 0.95	29, 45, 63, 105, 141
EIC (CC)	≥ 1	0.001 – 0.95	141

Kinematic Coverage



Overlap between HERA and EIC

EIC extend to high-*x* and moderate Q^2

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

- Used HERAPDF20_NNLO_ALPHAS_116 LHAPDF set
- Simultaneous proton PDF and strong coupling fit using xFitter, with minimization provided by MINUIT.
- $Q^2 > 3.5\ \mathrm{GeV}^2$ ($\ln 1/x$ resummation issue), $W^2 = Q^2(1-x)/x > 10\ \mathrm{GeV}^2$ (higher twist effects)
- 14 free parameters in the PDF parameterization (HERAPDF2.0 approach)

$$xg(x) = A_g x^{B_g}(1-x)^{C_g} - A'_g x^{B'_g}(1-x)^{25}$$

$$xu_v(x) = A_{u_v} x^{B_{u_v}}(1-x)^{C_{u_v}}\left[1 + E_{u_v} x^2\right]$$

$$xd_v(x) = A_{d_v} x^{B_{d_v}}(1-x)^{C_{d_v}}$$

$$x\bar{U}(x) = A_{\bar{U}} x^{B_{\bar{U}}}(1-x)^{C_{\bar{U}}}(1 + D_{\bar{U}} x)$$

$$x\bar{D}(x) = A_{\bar{D}} x^{B_{\bar{D}}}(1-x)^{C_{\bar{D}}}$$

- PDFs are parameterized at a starting scale for QCD evolution of $\mu_{f,0}^2 = 1.9\ \mathrm{GeV}^2$
- Strangeness fraction: $f_s = \frac{x\bar{s}}{x\bar{d}+x\bar{s}} = 0.4$
- QCD fit;
  - α_s scan: Fix α_s, fit PDFs, and scan χ^2 vs α_s
  - Free α_s: simultaneously fit both PDFs and α_s

Uncertainties

Model Uncertainties

Parameter	Central Value	Downward variation	Upwards variation
Q^2_{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

Parametrization uncertainties

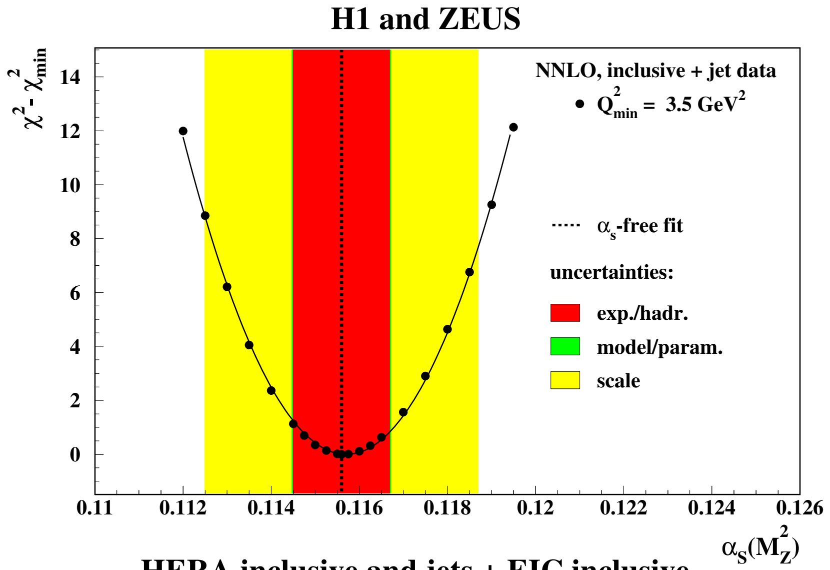
- Adding additional parameters
- Vary the starting scale, $\mu^2_{f,0}$, by $\pm 0.3\ \mathrm{GeV}^2$

Scale uncertainties

- Vary μ_F and μ_R by a factor of 2.
  - Central scale: $\mu_F^2 = \mu_R^2 = Q^2$ for inclusive DIS, $\mu_F^2 = \mu_R^2 = Q^2 + p_T^2$ for inclusive jet, $\mu_F^2 = \mu_R^2 = Q^2 + \langle p_T \rangle_2^2$ for dijets
- No scale variations for inclusive DIS only.

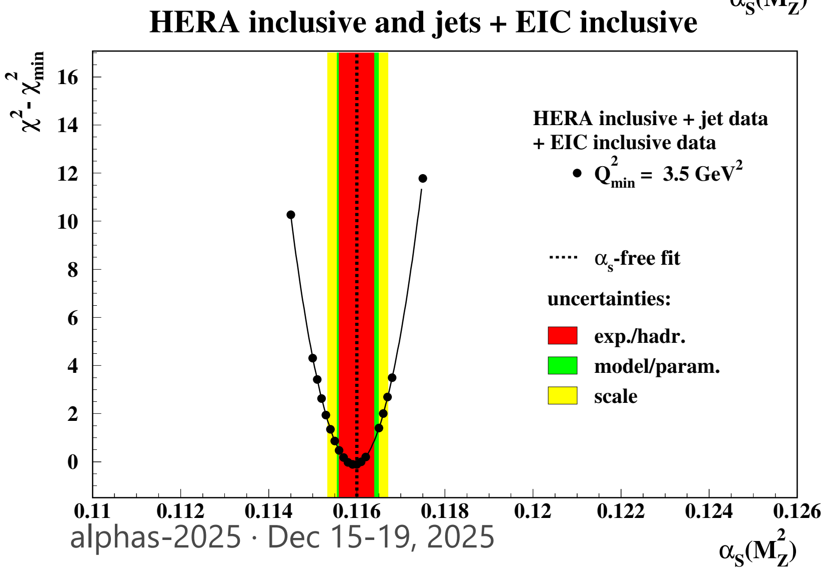
QCD fits with HERA inclusive DIS + jet data and EIC inclusive DIS

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



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

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

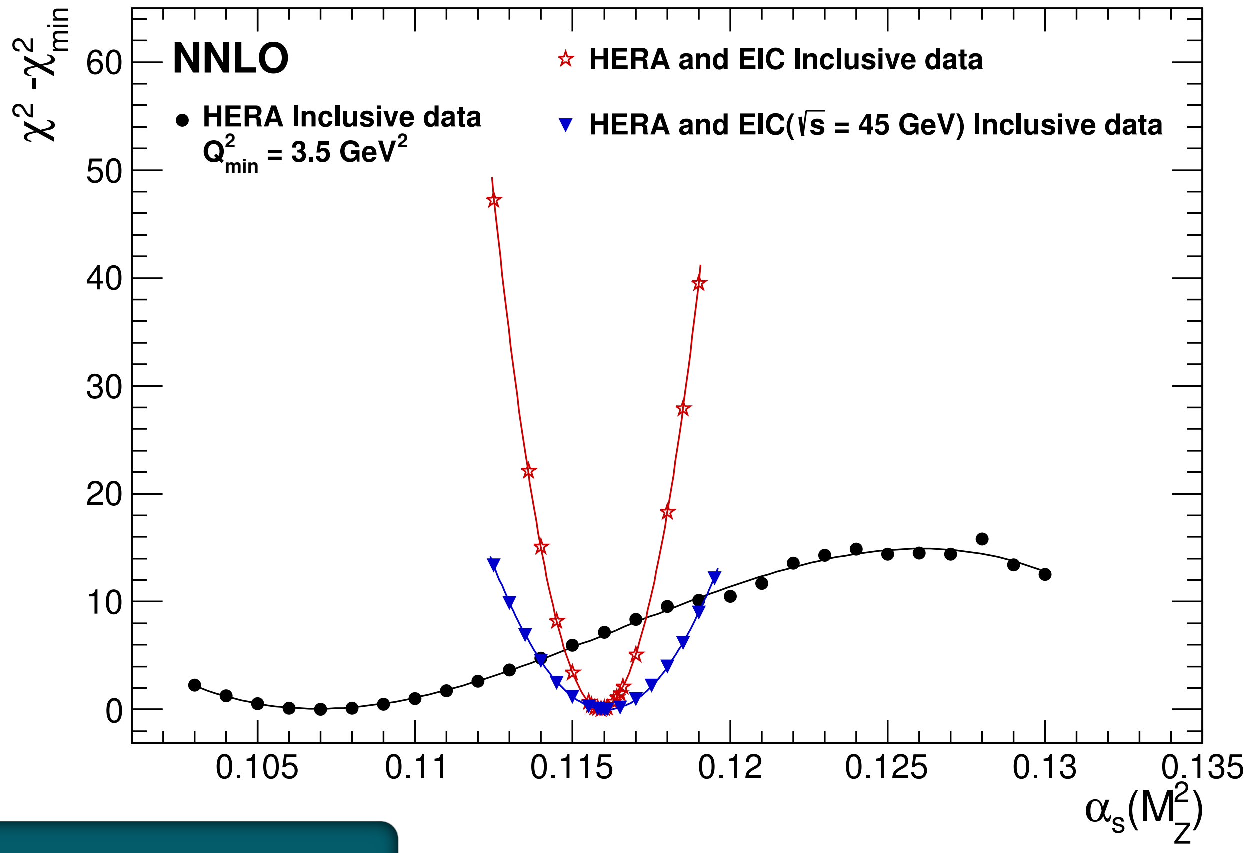


HERA inclusive DIS + jet data and EIC inclusive DIS, NNLO:

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

QCD Fit Using Inclusive DIS data from HERA and EIC

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



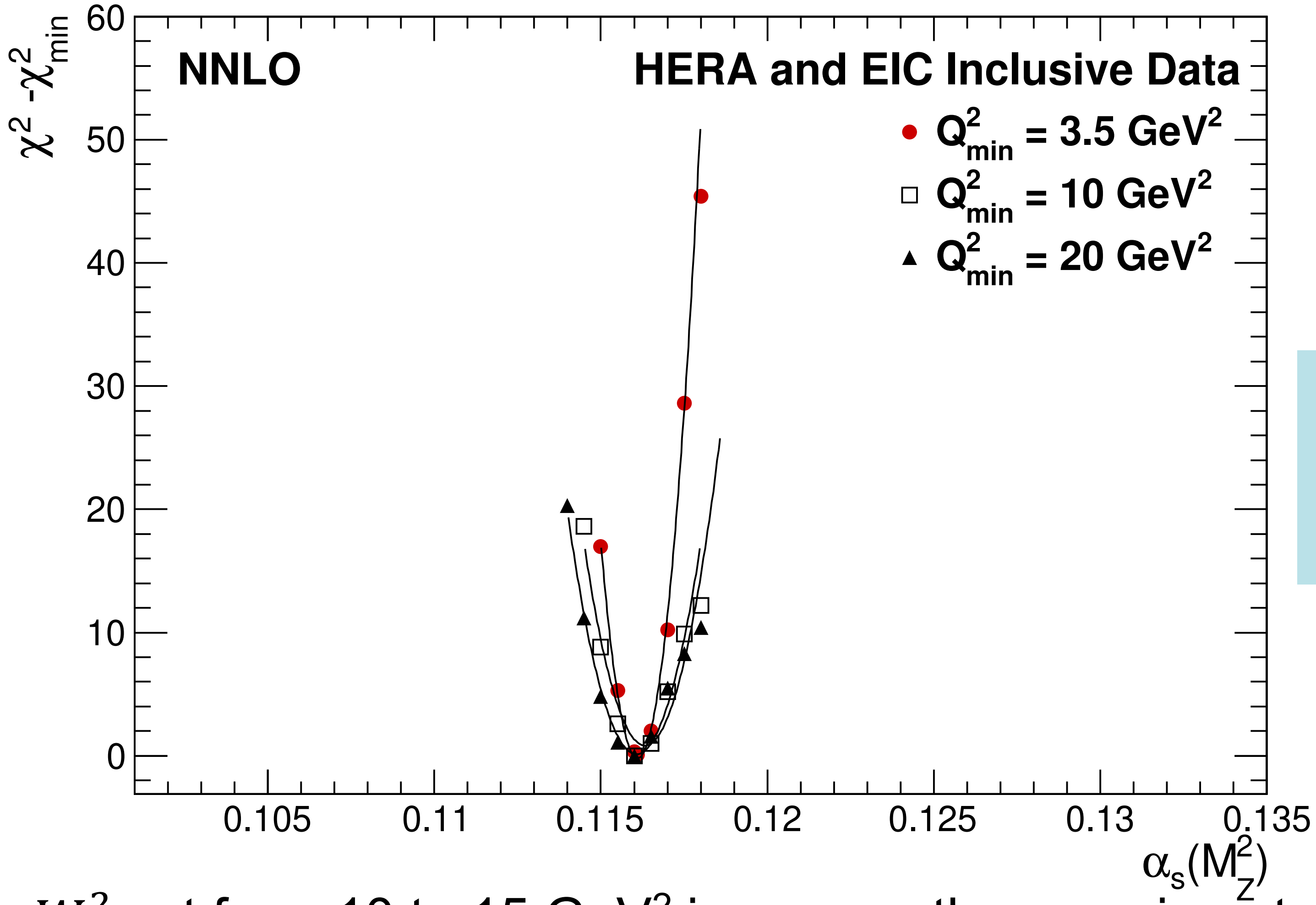
📌 No scale variations are made for the inclusive data

HERA and EIC inclusive DIS, NNLO:

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

Robustness of $\alpha_s(M_z^2)$ with respect to Q^2_{min} cuts

- Minimal variation in $\alpha_s(M_z^2)$ across a range of Q^2_{min} cuts.

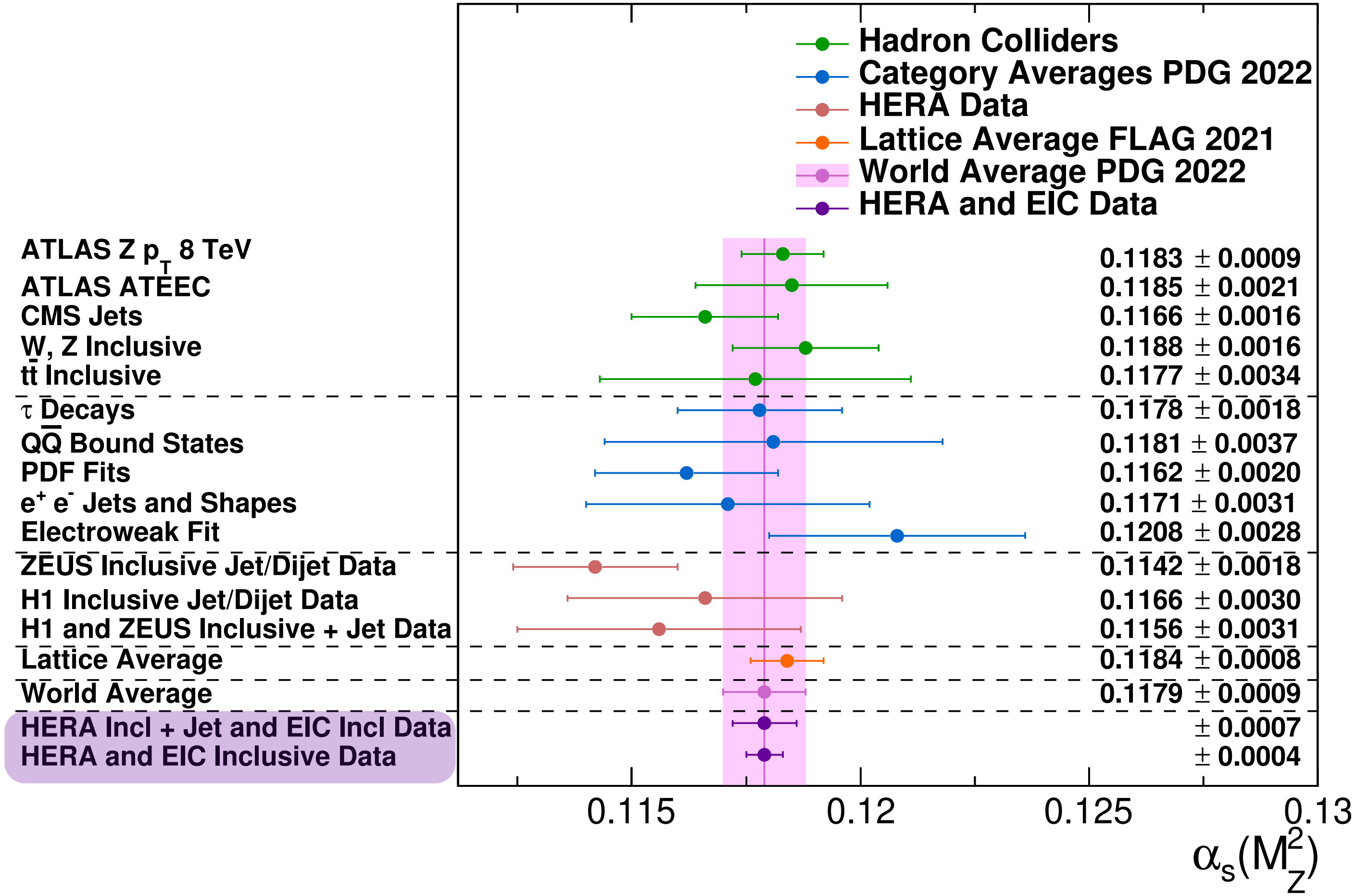


📌 Even when pushing Q^2_{min} from 3.5 to 20 GeV^2, the extracted $\alpha_s(M_z^2)$ remains extremely stable.

- Increasing the W^2 cut from 10 to 15 GeV^2 increases the experimental uncertainty from **0.34% to 0.52%.**

xFitter

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



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- Using only **inclusive DIS data from HERA and EIC**, we extract $\alpha_s(M_Z^2)$ with **potentially** world-leading precision in a simultaneous NNLO fit of PDFs and strong coupling.

Scale Uncertainties

- Scale uncertainties arise due to missing higher orders beyond NNLO.
- Expected to be small for inclusive data, generally omitted in global fits.
- Migration to N^3LO will reduce these further.
- Global PDF fitting groups (e.g. NNPDF collaboration, arXiv:1906.10698, arXiv:2401.10319) are actively developing systematic frameworks to incorporate MHOUs into global fits.
  - These methodologies are crucial for achieving precision extractions of $\alpha_s(M_Z^2)$ and PDFs.
- **Our current step: Implementing Theory Uncertainties in xFitter**
  - Generate theory predictions under scale variations (μ_F and μ_R)
  - Build a theory covariance matrix.

$$S_{ij} = \frac{1}{N} \sum_{m=1}^{N} (T_i^{(m)} - T_i^{(0)})\,(T_j^{(m)} - T_j^{(0)})$$

  - Add to experimental covariance matrix (NNPDF collaboration, arXiv:1002.4407)
  - Use in χ^2 minimization in xFitter.

Conclusion

- Including EIC inclusive DIS projected data leads to a total uncertainty of 0.4%.
  - This improves the precision of current world averages.
- We are working with global fitting experts to assign a meaningful scale uncertainty, accounting for missing higher order contributions beyond NNLO.
  - Properly including MHOU will be critical to match this high level of precision.

Thank You!

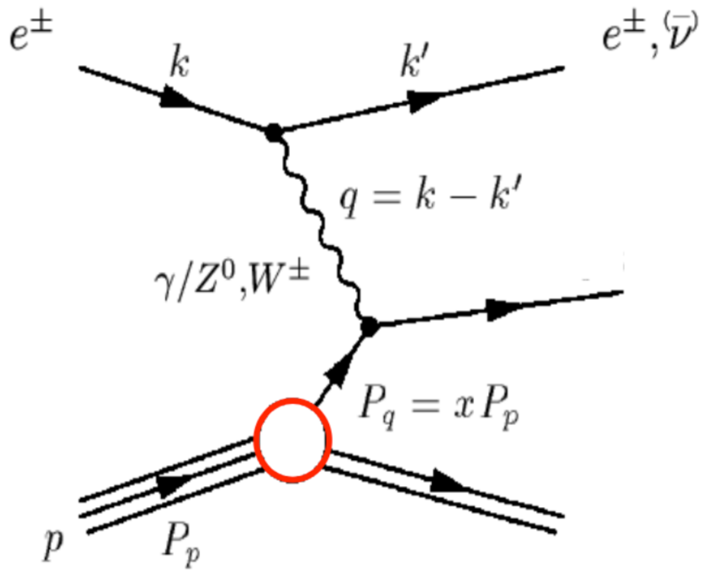
Acknowledgements

- 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.
  - Alexander Glazov for his help with the xFitter.

Backup

Proton PDFs and Structure Functions in DIS

PDFs extracted from structure function measurements in DIS



γ, Z Exchange: Neutral Current $ep \to eX$

$$\frac{d^2\sigma_{e^\pm p}}{dxdQ^2} = \frac{2\pi\alpha^2}{xQ^4}\left[Y_+F_2 \mp Y_-xF_3 - y^2F_L\right]$$

Contributions:

- LO: $F_2 \propto \sum_i (q_i(x) + \bar{q}_i(x))$ dominant contribution
- LO: $F_3 \propto \sum_i (q_i(x) - \bar{q}_i(x))$ γ/Z interference
- NLO: $F_L \propto x \cdot \alpha_s \cdot g(x, Q^2)$ contribution from gluon

$W^\pm$ Exchange: Charged Current $ep \to \nu X$

$$\sigma^{CC}_{e^+p} \propto x\left\{(\bar{u} + \bar{c}) + (1-y)^2(d+s)\right\}$$

$$\sigma^{CC}_{e^-p} \propto x\left\{(u + c) + (1-y)^2(\bar{d}+\bar{s})\right\}$$

Kinematic Variables:

- $Q^2 = -q^2$ (boson virtuality)
- $x = -\frac{q^2}{2p\cdot q}$ (Bjorken scaling variable)
- $s = (k+p)^2$ (center of mass energy)
- $y = \frac{q\cdot P}{k\cdot P}$, (transferred energy fraction)
- $Y_\pm = 1 \pm (1-y)^2$

The role of F_2 and F_L in gluon distribution

The NLO expression for the logarithmic derivative of $F_2(x, Q^2)$ is:

$$\frac{dF_2(x, Q^2)}{d\ln Q^2} = \frac{\alpha_s(Q^2)}{2\pi} \int_x^1 \frac{dz}{z} \left[P_{qq}^{(0)}\left(\frac{x}{z}\right) q(z, Q^2) + P_{qg}^{(0)}\left(\frac{x}{z}\right) g(z, Q^2) \right]$$

The longitudinal structure function $F_L(x, Q^2)$ is related to the gluon distribution as:

$$F_L(x, Q^2) \propto \alpha_s(Q^2) \int_x^1 \frac{dz}{z} P_{qg}\left(\frac{x}{z}\right) g(z, Q^2)$$

Luminosity @ EIC

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Table 1 Beam energies, centre-of-mass energies and integrated luminosities of the different configurations considered for the EIC

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