Extraction of the Strong Coupling from HERA and EIC inclusive data

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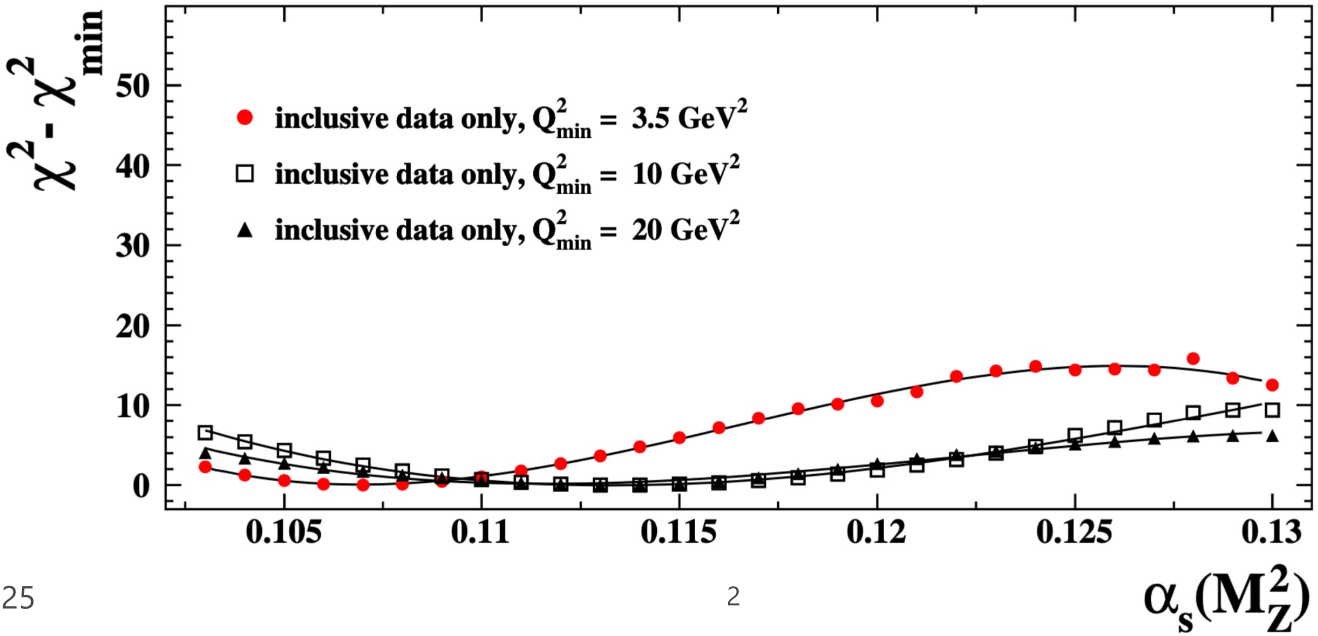
Extracting the Strong Coupling at the EIC and Other Future Colliders Workshop

Motivation

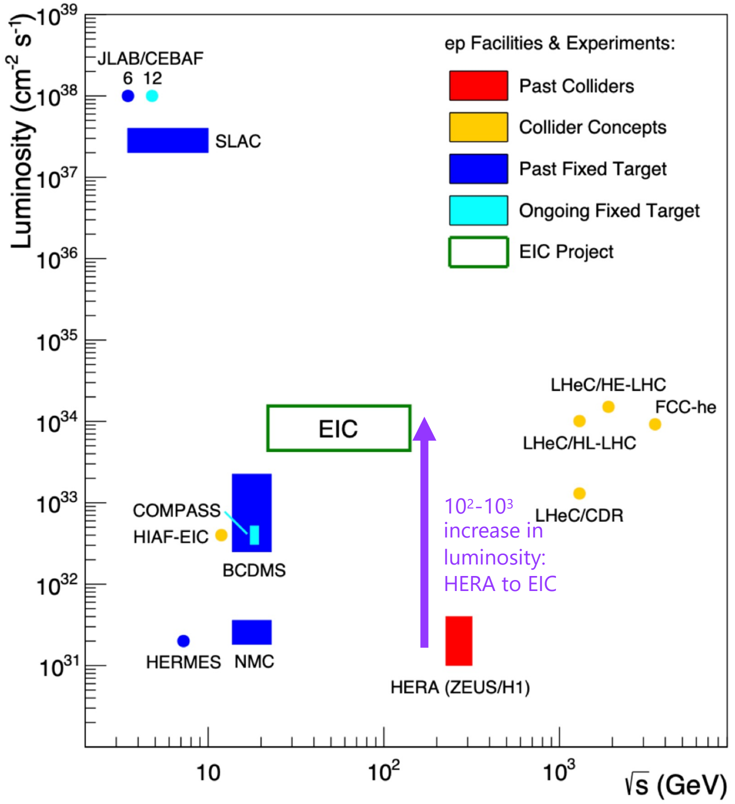
- The strong coupling is the least precisely known of the fundamental couplings.
    - Critical input for SM precision tests and BSM sensitivity.
    - Current uncertainty dominated by theory limitations, especially at low and moderate Q^2.
    - DIS-based extractions: limited by scale uncertainties and limited phase space.
        - HERA data alone not sufficient for sub-permille precision.

$$\frac{d^2\sigma}{dx\,dQ^2} = \frac{2\pi\alpha^2}{xQ^4}\left[Y_+ F_2(x,Q^2) - y^2 F_L(x,Q^2) \mp Y_- xF_3(x,Q^2)\right]$$



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: $\mathcal{L} = 10^{33} - 10^{34}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$



Datasets

HERA data

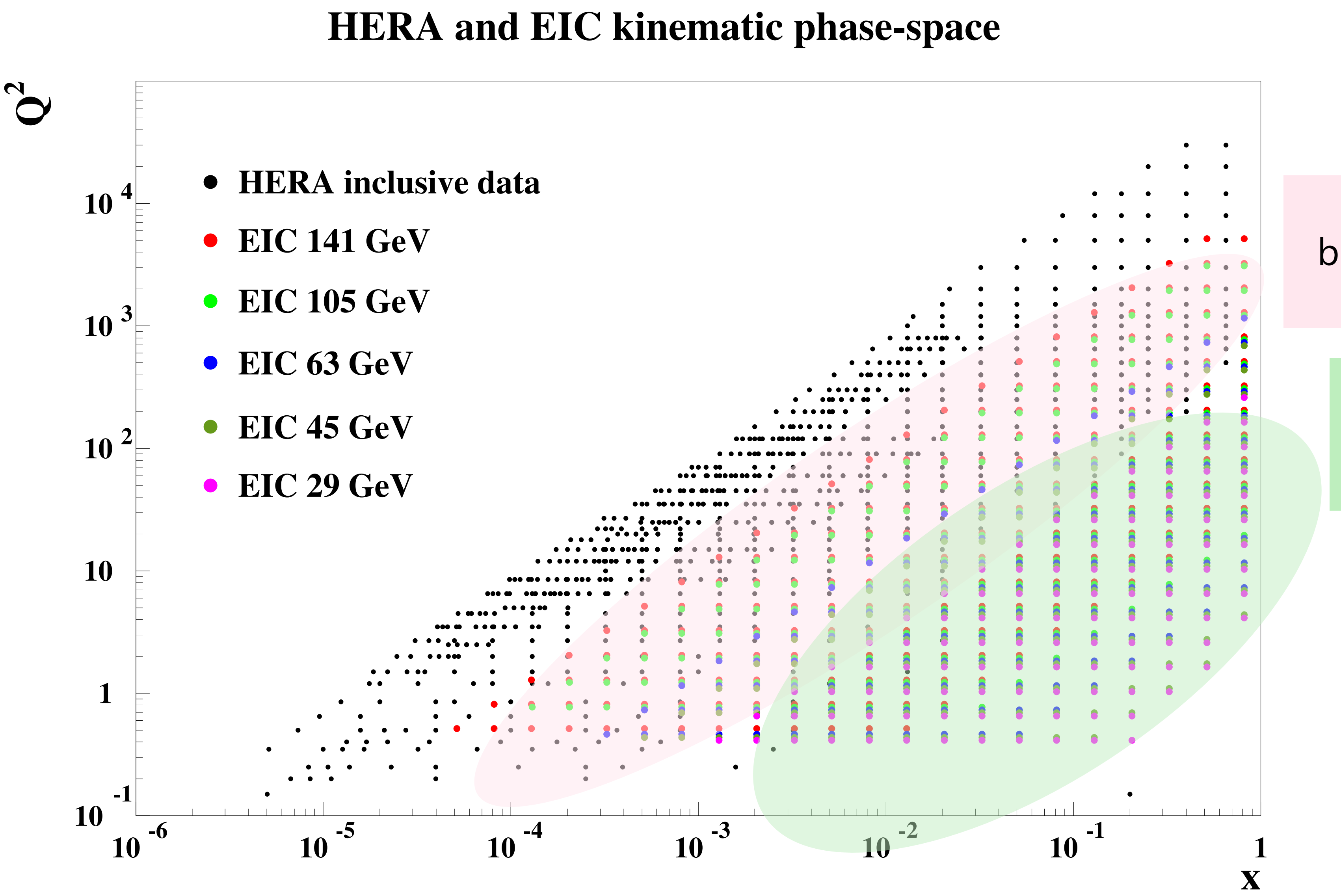
- H1 and ZEUS combined
  - inclusive DIS NC, CC cross sections [EPJC(2015)75:580]
  - Inclusive jet and dijets measurements [EPJC(2022)82:243]
- Integrated luminosity of 1 fb^{-1}.

EIC (Projected data)

- Simulated data with HERAPDF2.0 NNLO, uncertainties from ATHENA detector proposal [JINST 17 P10019]
- 1 year of data taking. Uncertainties:
  - uncorrelated 1.9% - 2.75%,
  - fully correlated normalization 3.4%.

Experiment	Q^2 (GeV^2)	$y = Q^2/sx$ 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)	100	0.001 – 0.95	29, 45, 63, 105, 141
EIC (CC)	100	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} $[\mathrm{GeV}^2]$	3.5	2.5	5.0
f_s	0.4	0.3	0.5
M_c $[\mathrm{GeV}]$	1.41	1.37	1.45
M_b $[\mathrm{GeV}]$	4.20	4.10	4.30

Parametrization uncertainties

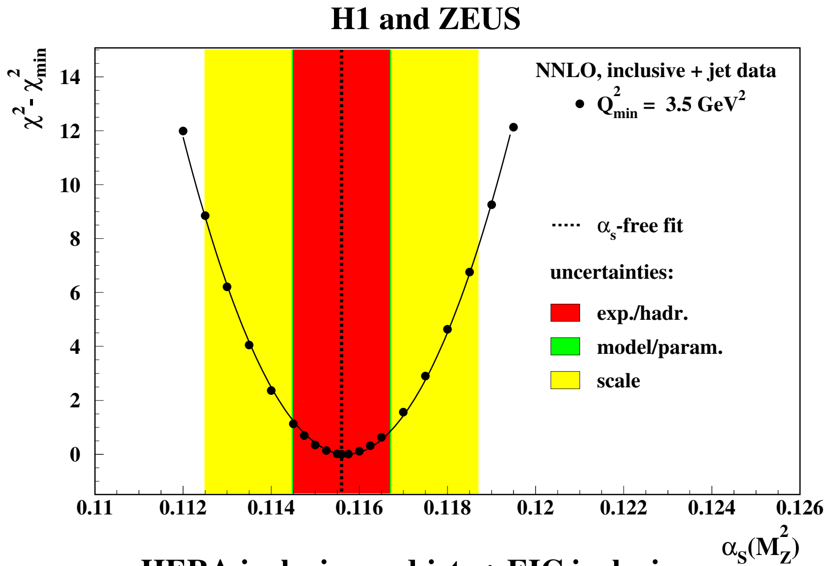
- Adding additional parameters
- Vary the starting scale, $\mu^2_{f,0}$, by $\pm 0.3\ \mathrm{GeV}^2$

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.

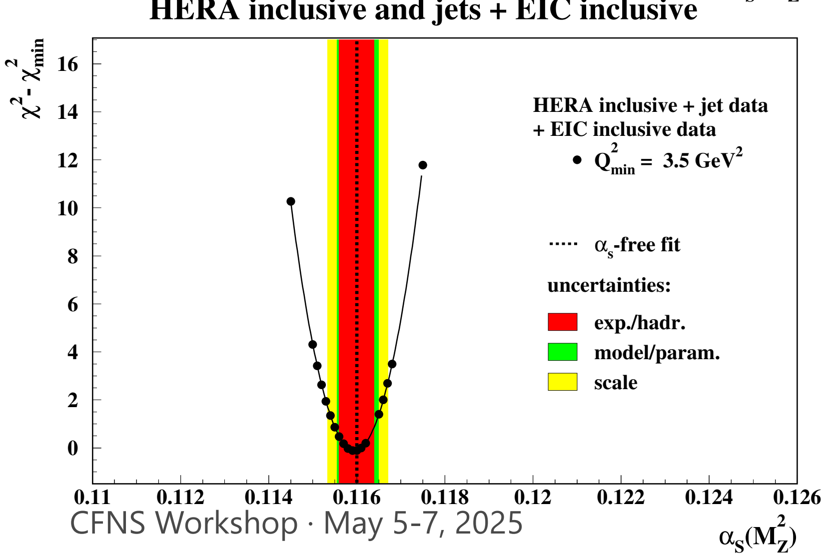
QCD fits with HERA inclusive DIS + jet data and EIC inclusive DIS

- 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:

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

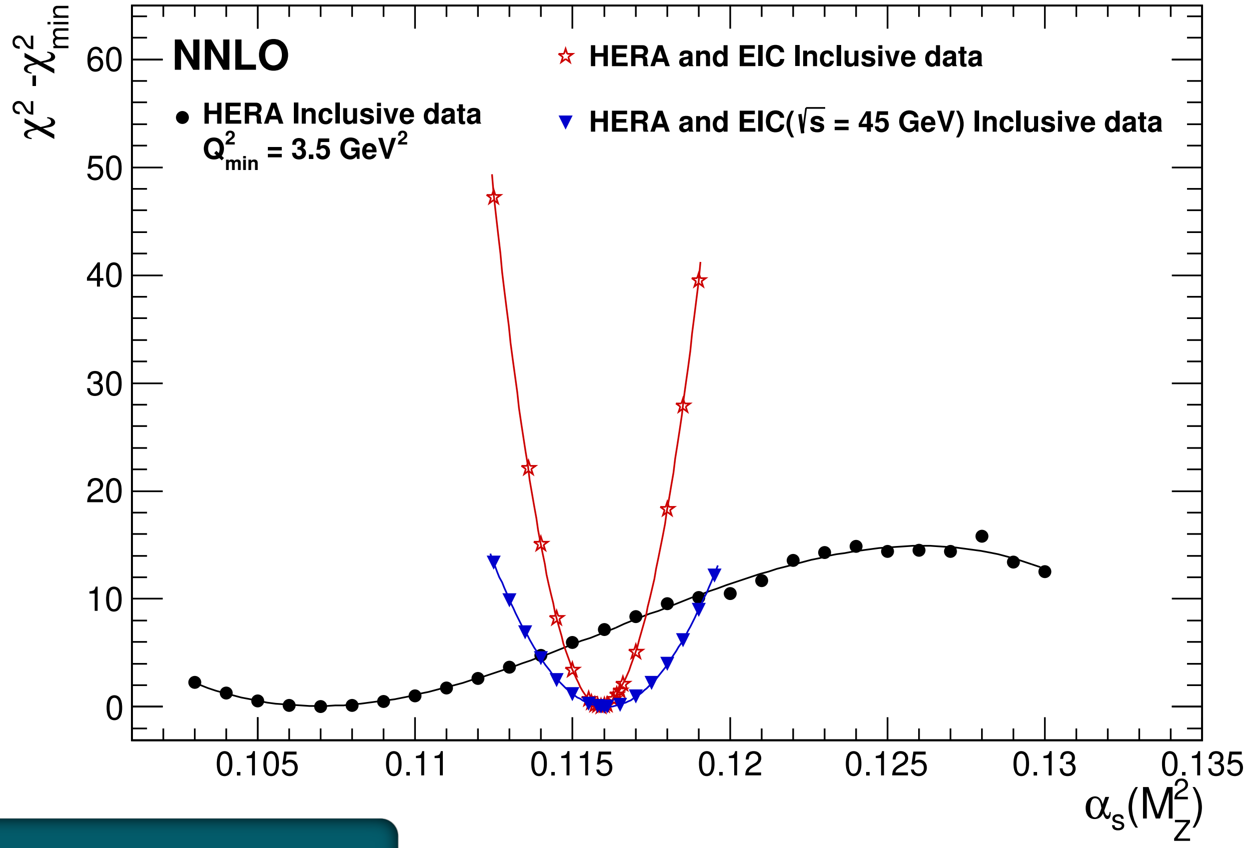


HERA inclusive DIS + jet data and EIC inclusive DIS, NNLO:

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

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 $\alpha_s(M_Z^2)$.



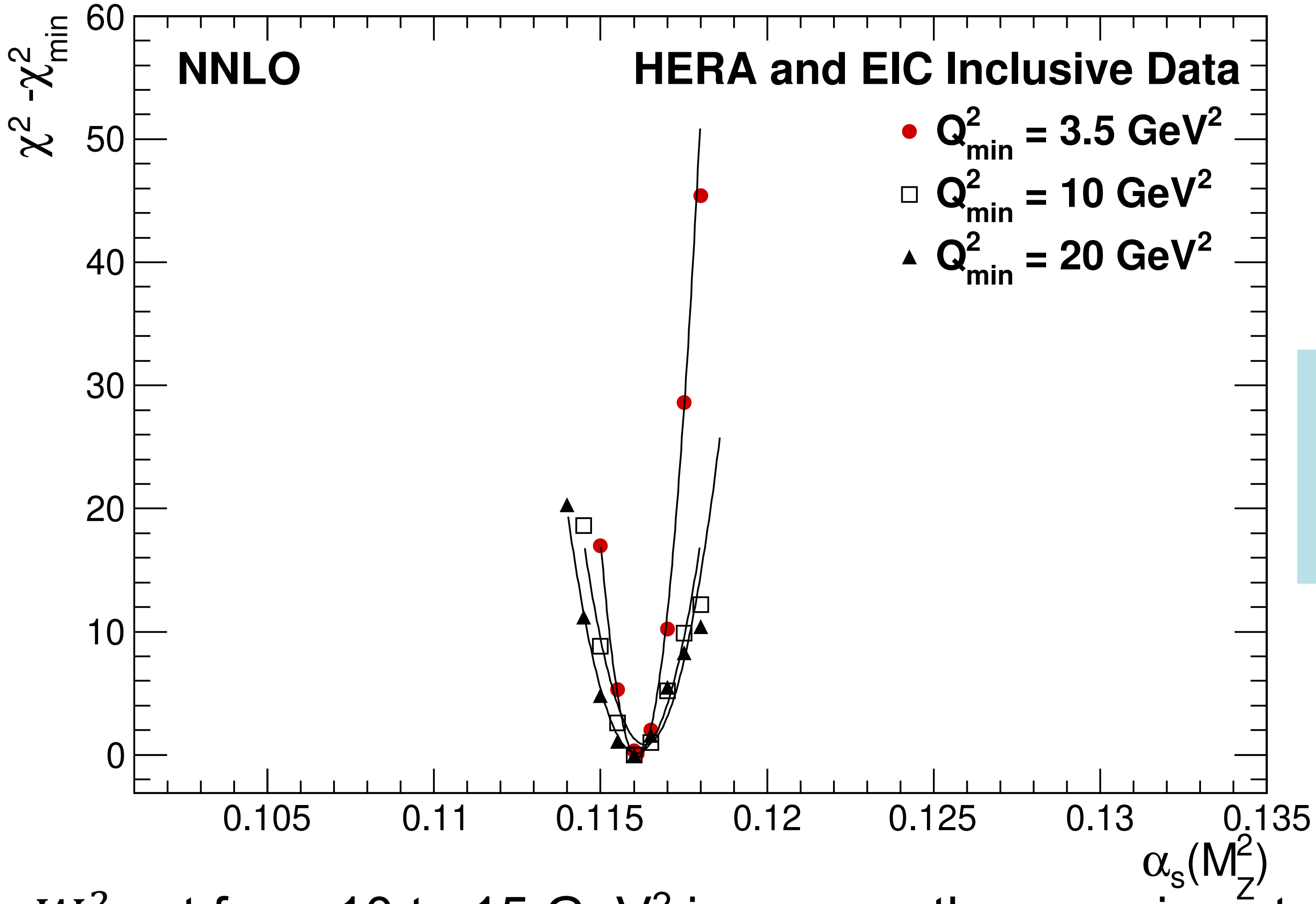
No scale variations are made for the inclusive data

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_{min}^2 cuts

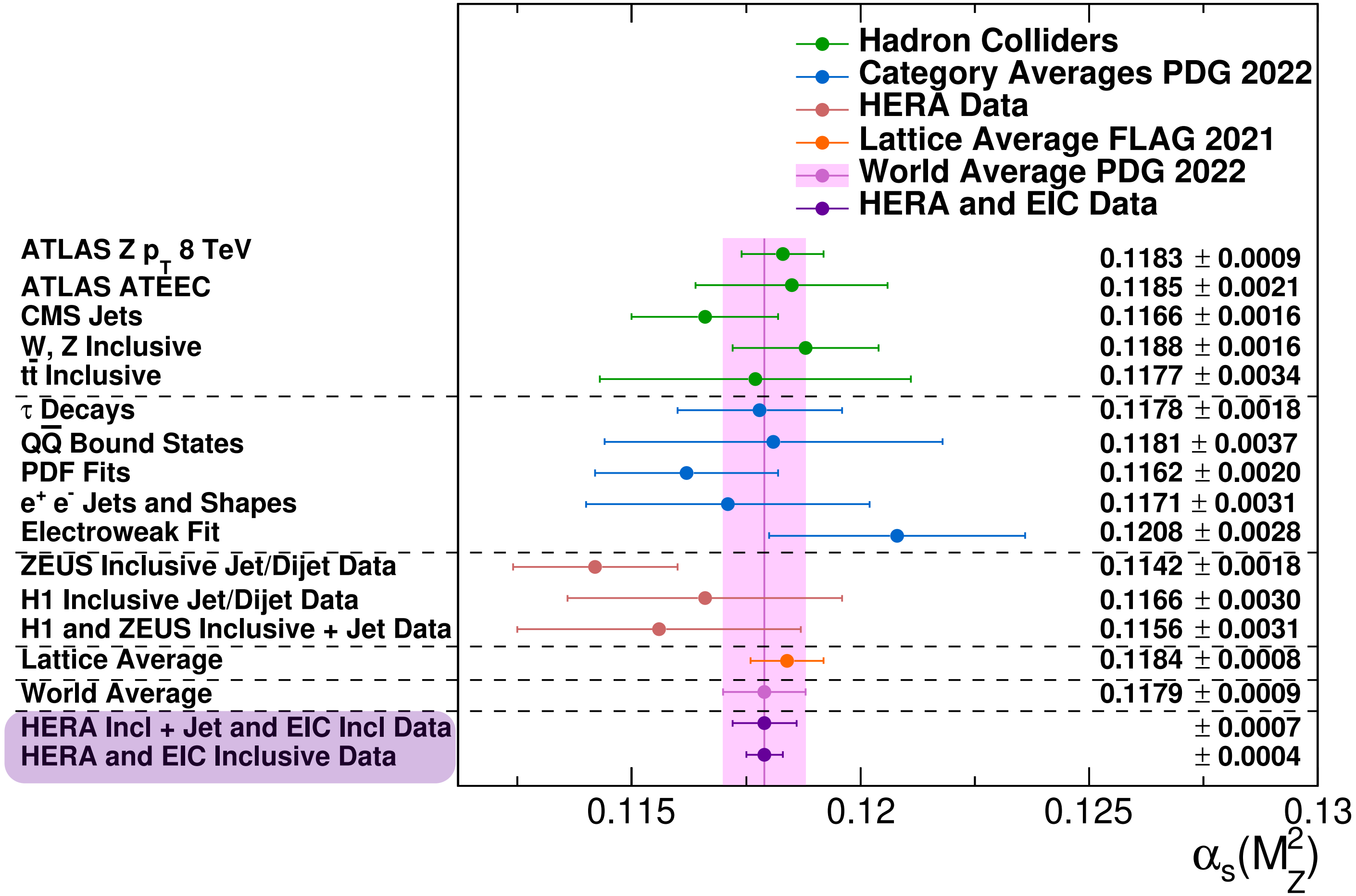
- Minimal variation in $\alpha_s(M_z^2)$ across a range of Q_{min}^2 cuts.



📌 Even when pushing Q_{min}^2 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%.**

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



- 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^{3}LO 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

- **Precision:**
  - Including EIC inclusive DIS projected data leads to a total uncertainty below 0.4%.
  - This improves the precision of current world averages (both experimental and lattice).
- **Theory:**
  - We are working with global fitting experts to assign a meaningful **scale uncertainty**, accounting for missing higher order contributions (MHOU) beyond NNLO.
  - Properly including MHOU will be critical to match this high level of precision.
- **Future:**
  - Adding EIC inclusive jet and dijet pseudodata to the QCD analysis has potential to further improve the strong coupling determination.

✧ Projected EIC data enables sub-0.4% precision in $\alpha_s(M_Z^2)$ – potentially world-leading

Acknowledgements

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  - Alexander Glazov for his help with the xFitter.

Thank You!

Backup