Istituto Nazionale di Fisica Nucleare

Extraction of the strong coupling with HERA and EIC inclusive data

Andrea Barontini on behalf of the authors of arXiv:2307.01183

alphas-2024: Workshop on precision measurements of the QCD coupling constant

Trento, 06/02/2024

UNIVERSITÀ DEGLI STUDI DI MILANO

Motivation.

- The strong coupling constant is the least well constrained of the coupling strength of the fundamental forces.
- It is however a fundamental ingredient for precision SM and for BSM constraints.

Limited sensitivity when using only inclusive DIS data

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Goal of this work:

Investigate sensitivity on $\alpha_s(M_z)$ with projected measurements from EIC

Missing higher order uncertainties (MHOU) is still leading source of uncertainties

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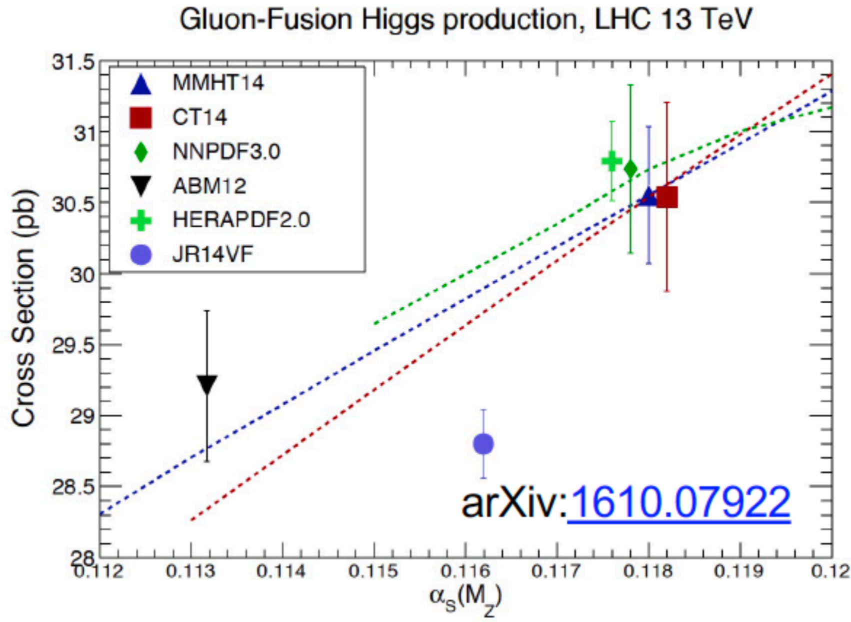
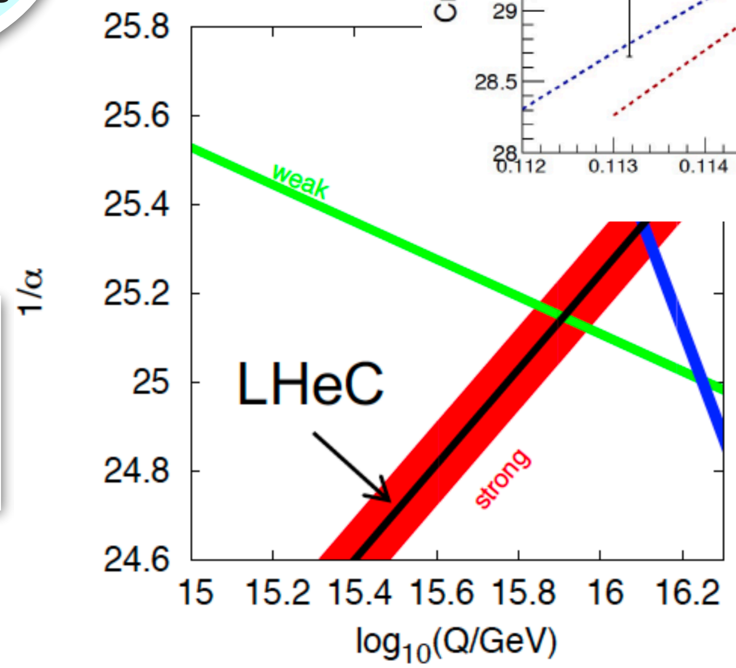
New idea:

Include MHOU using the NNPDF methodology

arXiv:1906.10698 arXiv:2401.10319





Electron Ion Collider (EIC).

arXiv:1212.1701

→ It will collide highly polarised electrons with highly polarised protons and light/heavy nuclei.

→ In ep mode, the expected luminosity is of order $10^{33} - 10^{34} cm^{-2} s^{-1}$ and the centre-of-mass energy $\sqrt{s}$ will range from $29 GeV$ to $141 GeV$.

Inclusive DIS cross sections will be measured to **high precision** in a phase space region that is **complementary** to HERA

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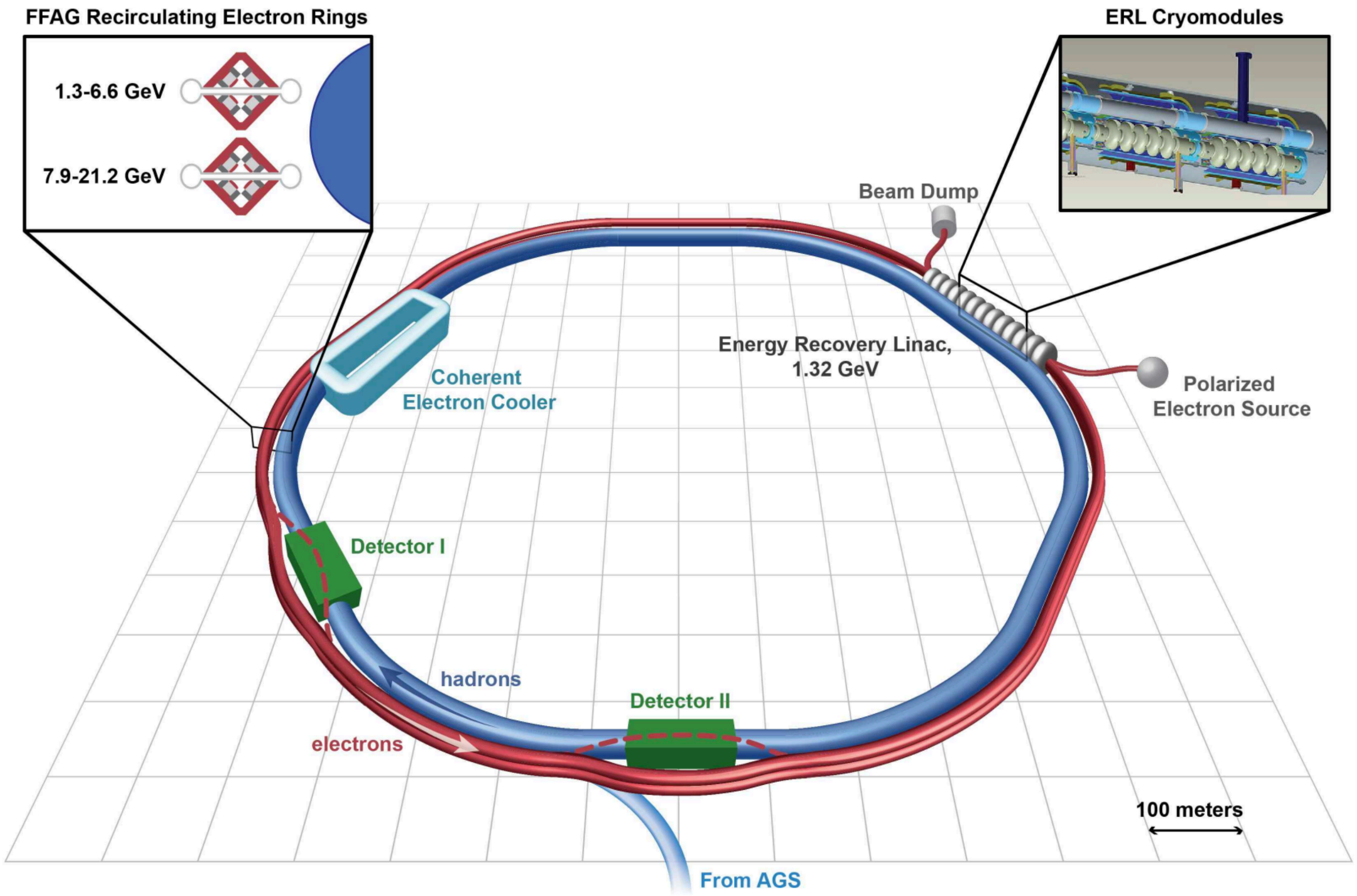
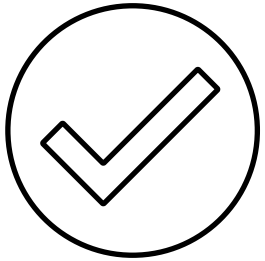
Large x

Can this have an impact on the sensitivity to the strong coupling?



Outline.

DATASET AND METHODOLOGY



RESULTS

MHOU

Outline.

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Description of the dataset.

HERA (real) data

- H1 and ZEUS **inclusive DIS** NC and CC cross sections.
  arXiv:1506.06042
- H1 and ZEUS inclusive and **dijets measurements**.
  arXiv:2112.01120
- Integrated luminosity of about $1\,fb^{-1}$.

e-beam energy (GeV)	p-beam energy (GeV)
27.5	460
27.5	575
27.5	820
27.5	920

EIC (projected) data

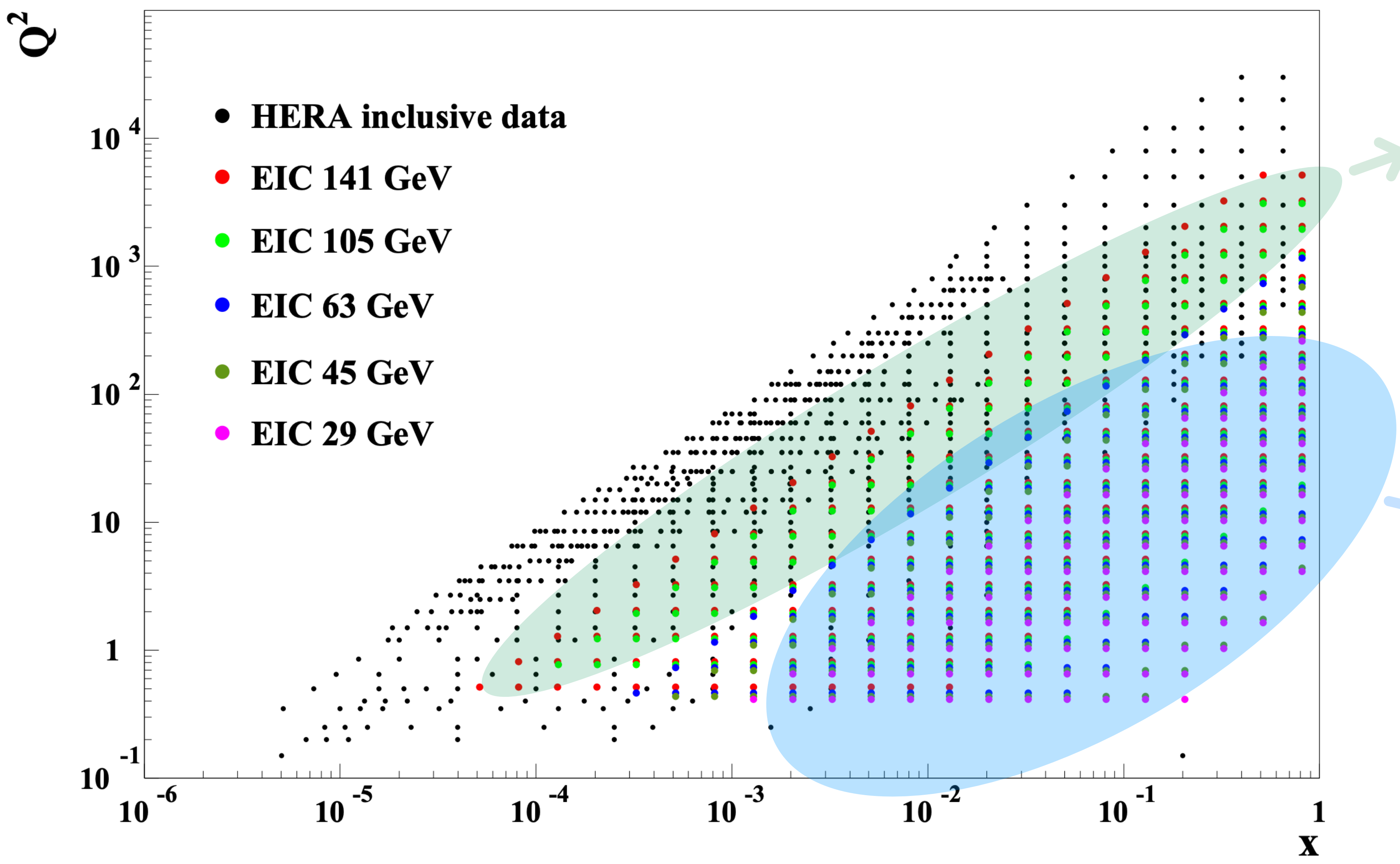
- Central values produced using HERAPDF2.0NNLO…
- … and smeared based on Gaussian distribution with standard deviations taken from ATHENA detector proposal.
  arXiv:2210.09048
- Integrated luminosity corresponding to 1 year of data taking.

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

Systematic uncertainties

- Uncorrelated uncertainty of $1.9\,\%$ to $2.75\,\%$.
- Fully correlated (between data with same $\sqrt{s}$) normalization uncertainty of $3.4\,\%$.

Kinematic coverage.



Overlap between HERA and EIC data

EIC data extend to high-x, moderate Q^2

Theory framework.

- Simultaneous proton PDF and strong coupling fit using xFitter, with minimization provided by MINUIT.
- Light coefficient functions obtained with QCDNUM. Mass effects described by a **General-mass VFNS**.
- **Cuts:** $Q^2 > 3.5\,GeV^2$ (ln $1/x$ resummation problem); $W^2 = Q^2(1-x)/x > 10\,GeV^2$ (higher twist).

Unphysical scales

Inclusive DIS	$\mu_R = \mu_F = \sqrt{Q^2}$
Inclusive jets	$\mu_R^2 = \mu_F^2 = Q^2 + p_t^2$
Dijets	$\mu_R^2 = \mu_F^2 = Q^2 + \langle pt \rangle_2^2$

PDFs parametrization

- $\mu_{f,0}^2 = 1.9\,GeV^2$

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

- 14 free parameters after imposition of **quark counting rule** and **momentum sum rule**
- $x\bar{s} = f_s x\bar{D}$, $f_s = 0.4$

Uncertainties.

Parameter	Central value	Downwards 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

Model uncertainties

+

Parametrization uncertainties

→ Adding additional D and E parameters.

→ Vary $\mu^2_{f,0}$ by $\pm 0.3\ GeV^2$.

Scale uncertainties

→ Vary μ_F and μ_R by a factor of 2, excluding $(0.5{,}2)$ and $(2{,}0.5)$.

→ No scale variations for inclusive DIS → **discussed later.**

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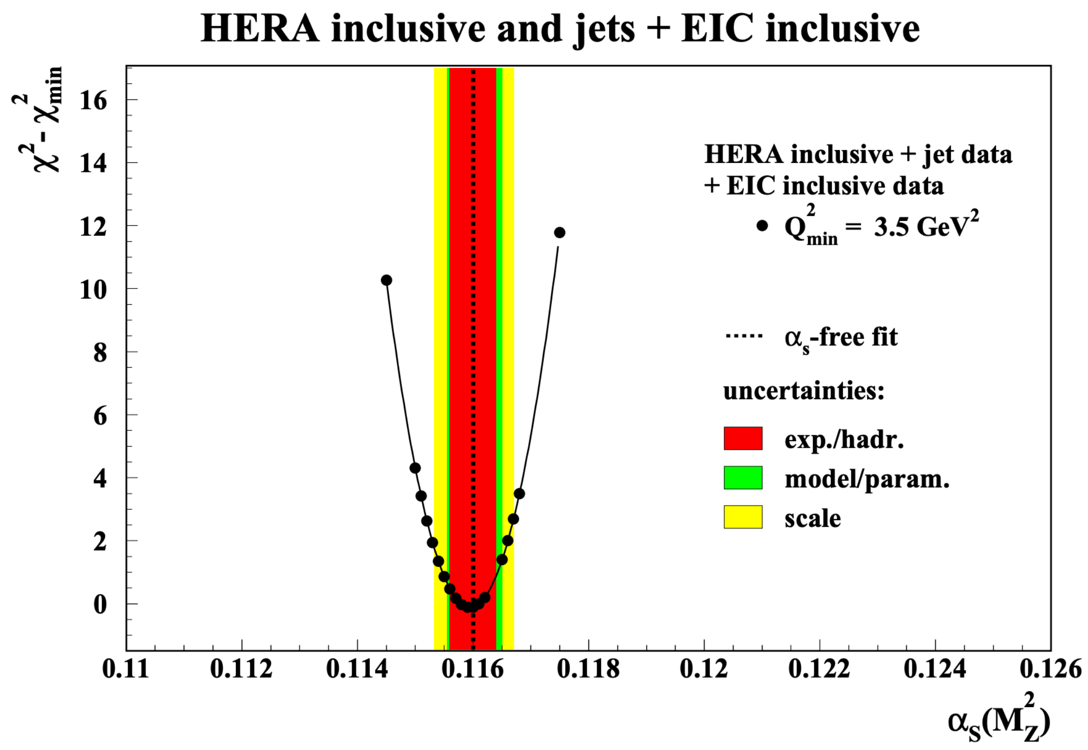
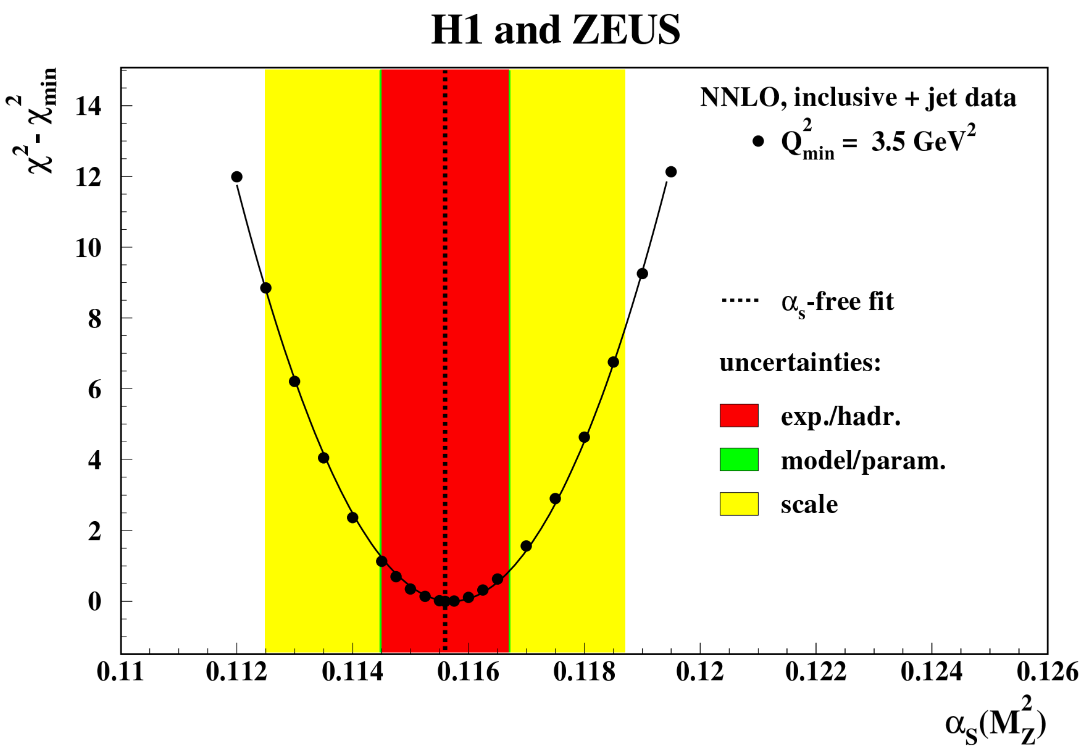
Impact of EIC data on global fit.

→ Stunning reduction of the uncertainties, mostly due to reduction of scale uncertainties → The fit depends less on jet data

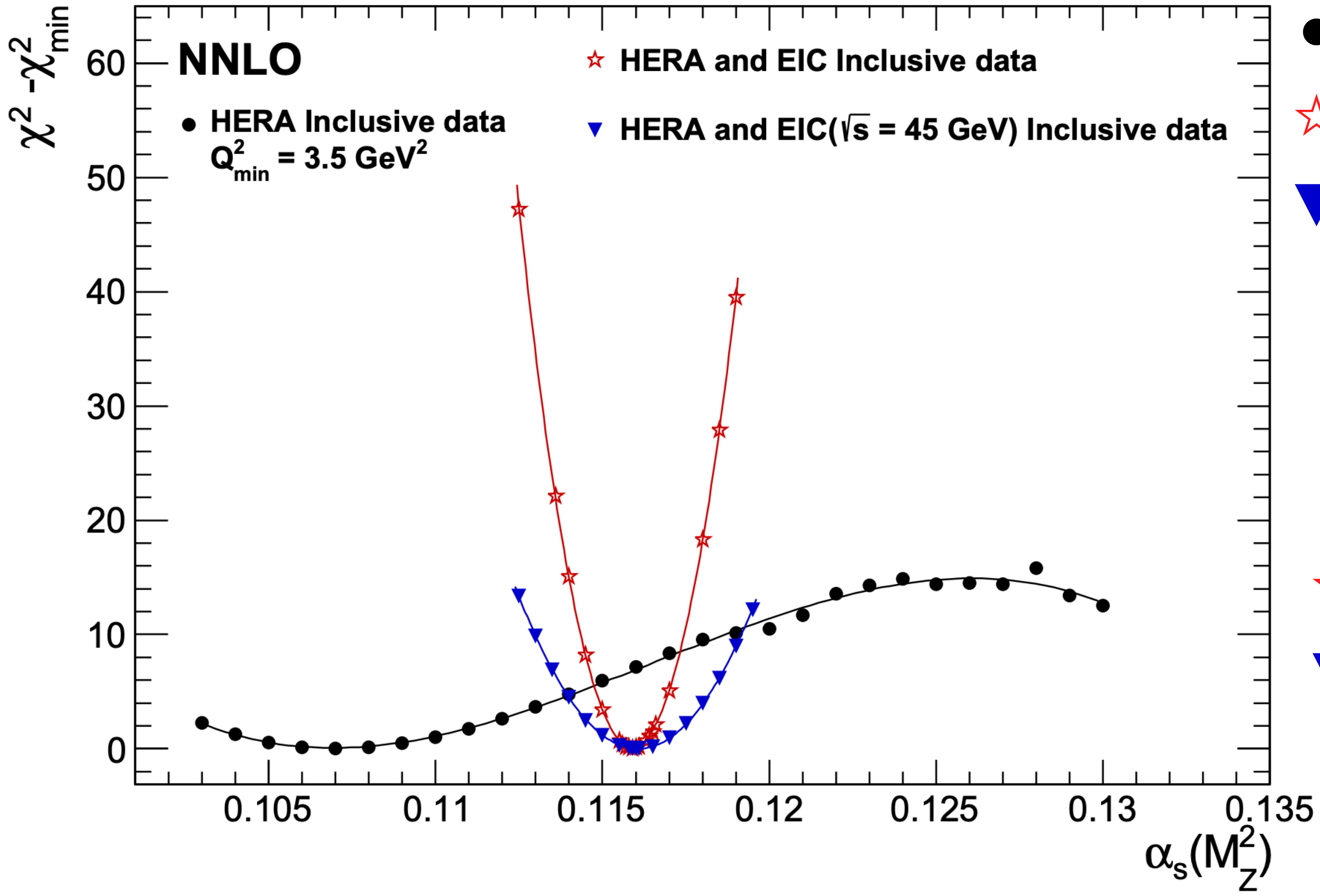




$\alpha_s(M_z^2) = 0.1160 \pm 0.0004(\text{exp})\,{}^{+0.0003}_{-0.0002}(\text{mod}+\text{para}) \pm 0.0005(\text{scale})$

$\alpha_s(M_z^2) = 0.1156 \pm 0.0011(\text{exp})\,{}^{+0.0001}_{-0.0002}(\text{mod}+\text{para}) \pm 0.0029(\text{scale})$

Dependence on HERA jets data.



- ● Only inclusive DIS data.
- ☆ Inclusive DIS data + EIC simulated data.
- ▼ Inclusive DIS data + EIC simulated data only for $\sqrt{s} = 45\ GeV$.

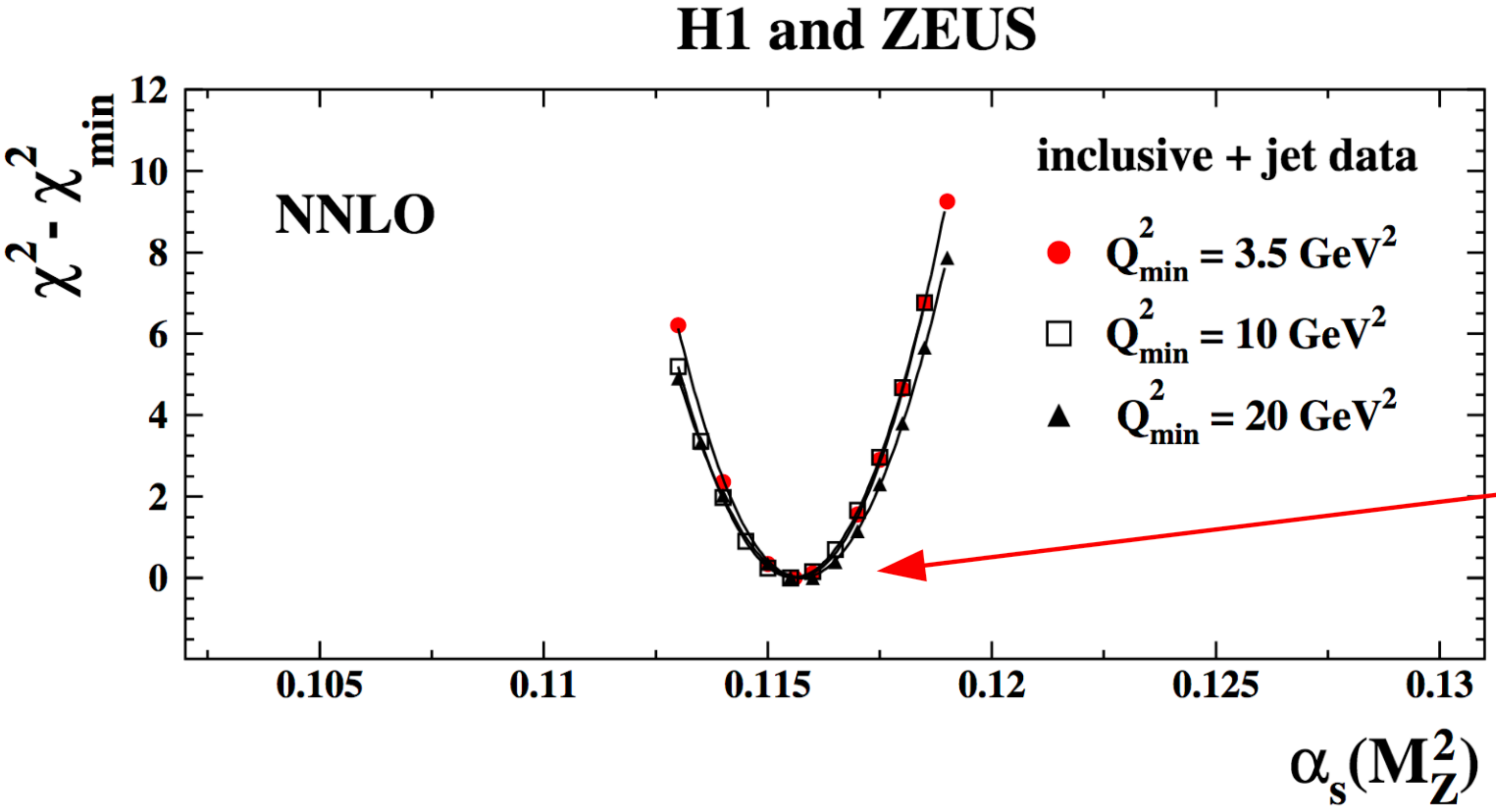
↓

- ● Almost insensitive to α_s.
- ☆ Very pronounced minimum. Best result.
- ▼ Only limited deterioration with respect to ☆

☆ $\alpha_s(M_z^2) = 0.1159 \pm 0.0004(\text{exp})^{+0.0002}_{-0.0001}(\text{mod} + \text{para})$ → No scale variations for inclusive DIS → **discussed later.**

Robustness of the determination.

→ Q^2 cut have basically no effect on the result.

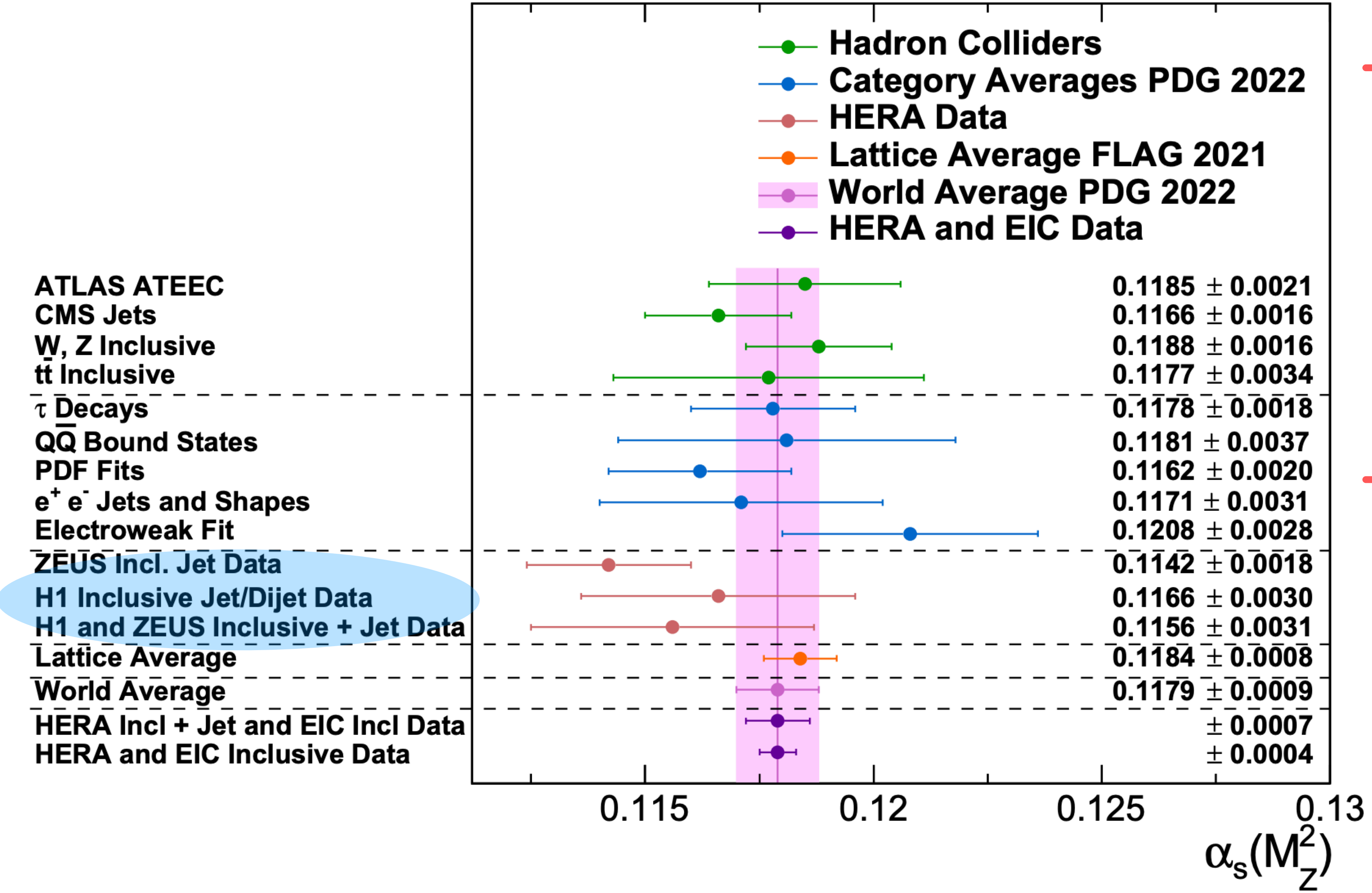


Q^2 cuts do not result in any significant change to the value of $\alpha_s(M_Z)$

→ When moving the W^2 cut to $W^2 > 15\,GeV^2$, the experimental uncertainty increase from $0.34\,\%$ to $0.52\,\%$.

Small W^2 region very important for α_s determination.

Comparison to world average.



→ Stunning improvement with respect to other HERA measurements and even world average.

→ However no scale uncertainties for inclusive DIS data are included.

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Further studies are required

See next slides…

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MHOU in a PDF fit: the *theory covmat*.

The NNPDF4.0MHOU PDFs set
arXiv:2401.10319

NNPDF

How to use it

→ Experimental and theoretical uncertainties enter in a symmetric way in the figure of merit used for PDF determination.

→ The theory covariance matrix S describes theoretical uncertainties and correlations.

→ Include it in figure of merit.

FIT WITHOUT THEORY ERRORS

$$\chi^2 \propto (D_i - T_i) C_{ij}^{-1} (D_j - T_j)$$

→

FIT WITH THEORY ERRORS

$$\chi^2 \propto (D_i - T_i)(C + S)_{ij}^{-1} (D_j - T_j)$$

MHOU in a PDF fit: the *theory covmat*.

How to construct it

$$S_{ij} = n_m \sum_{V_m} \left(\overline{F}(\kappa_f, \kappa_{r_a}) - F \right)_{i_a} \left(\overline{F}(\kappa_f, \kappa_{r_b}) - F \right)_{j_b}$$

→ *Factorization scale* **correlates** all the points

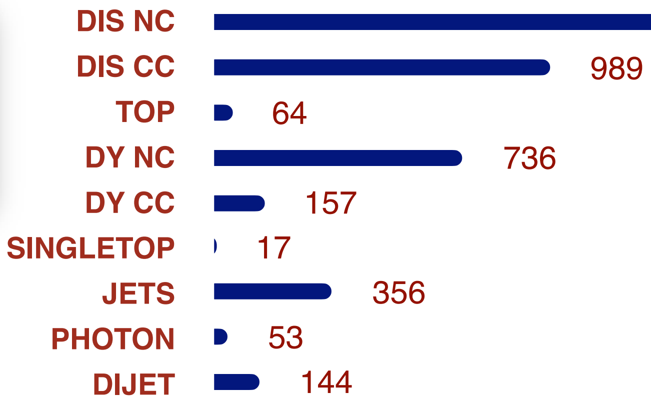
→ *Renormalization scale* **correlates** points belonging to the same process

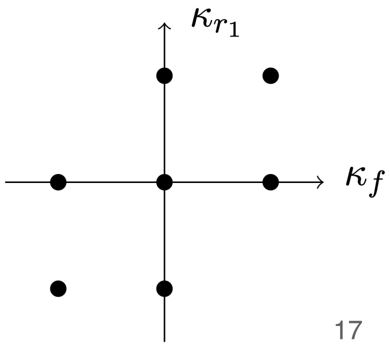
Scale Variations

$$\overline{F}^{NLO}(\mu_f = \kappa_f Q, \mu_r = \kappa_r Q) - F^{NLO}(\mu_f = Q, \mu_r = Q) = \mathcal{O}(NNLO)$$

↓

MHOU



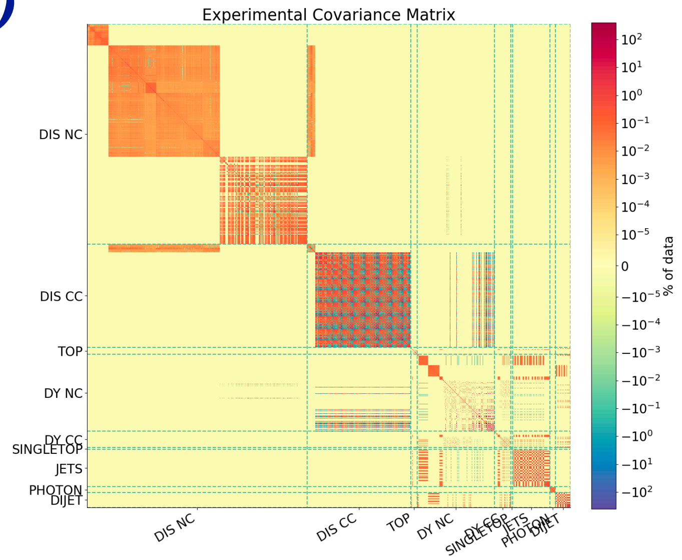


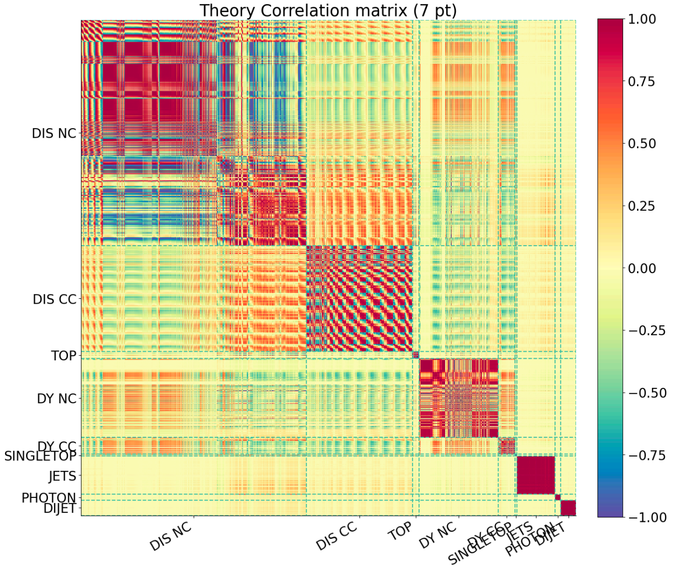
How do they look like?

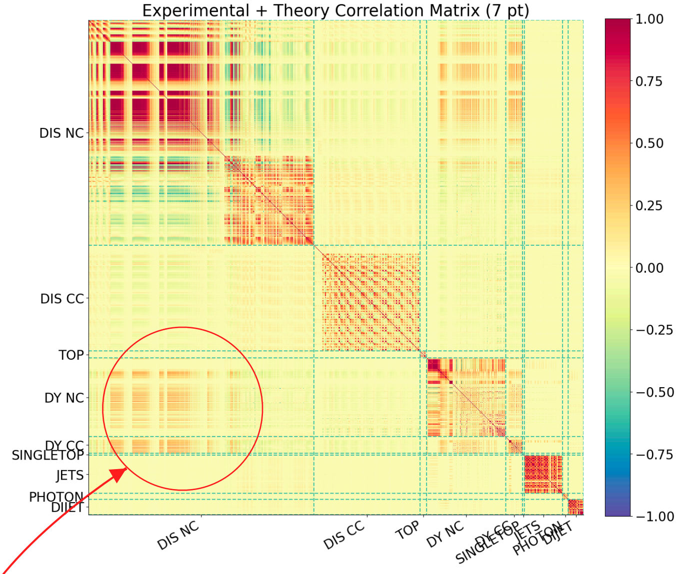
C $\quad$ S $\quad$ $C+S$

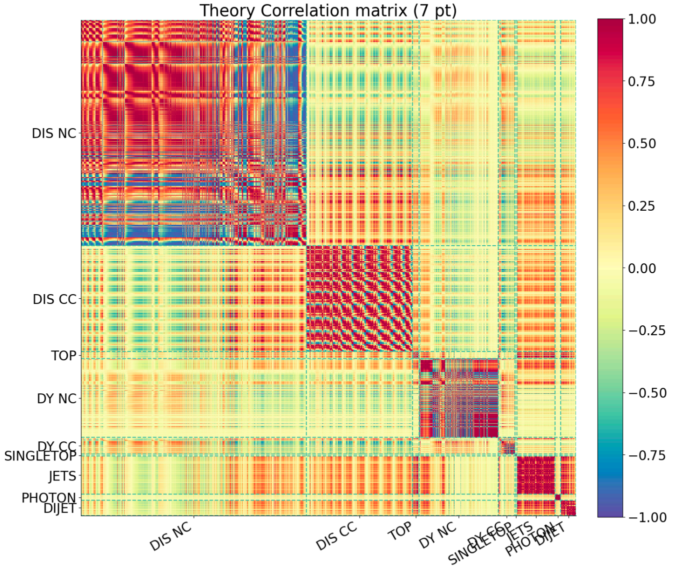
→ *NLO*

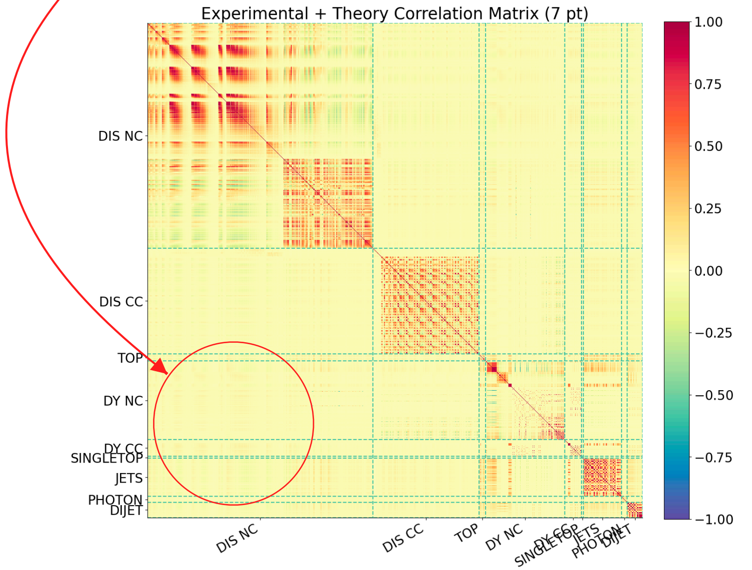
→ *NNLO*











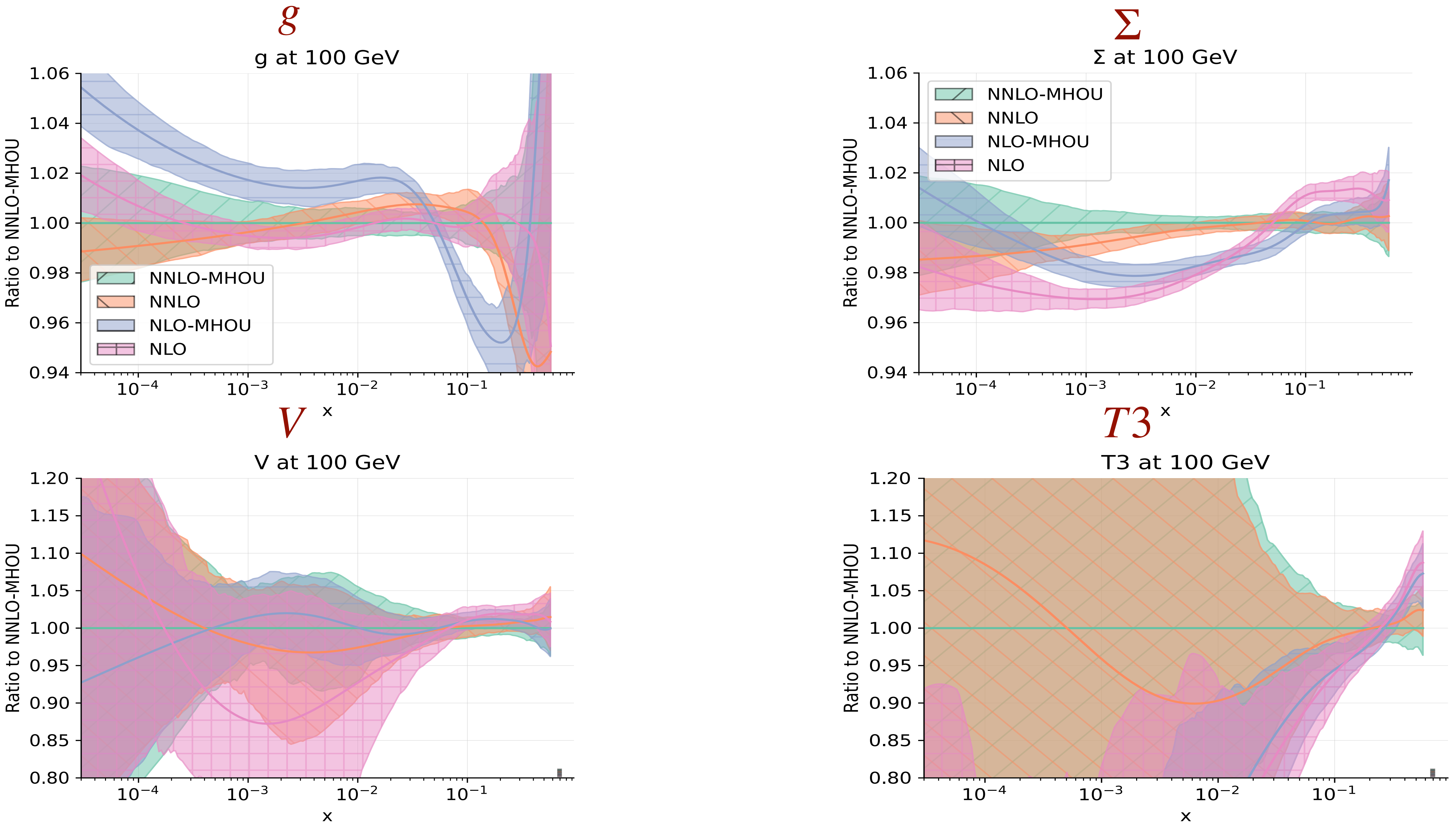
Fit quality.

χ^2

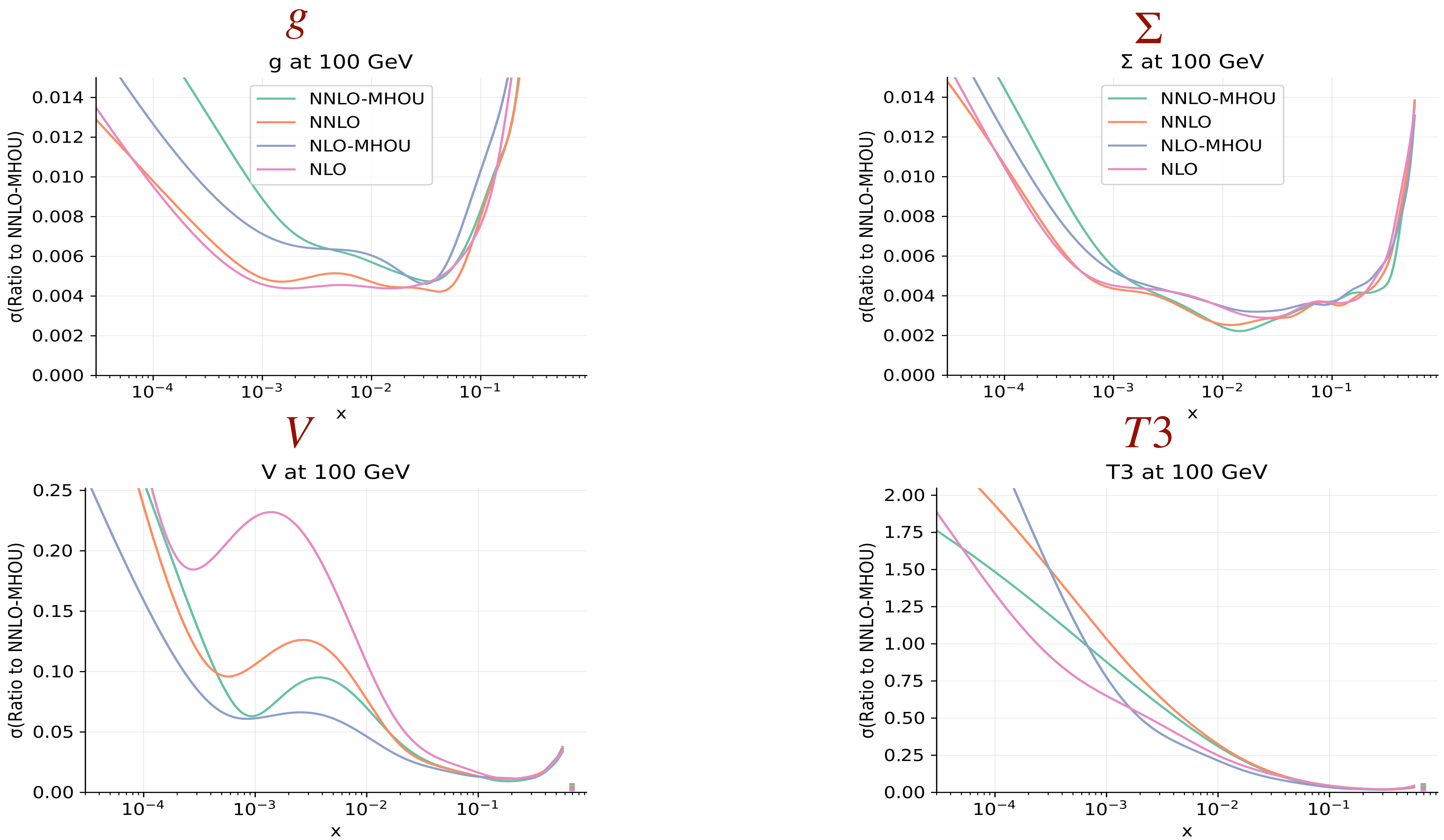
Dataset	N_{dat}	NLO $C+S^{(\mathrm{nucl})}$	NLO $C+S^{(\mathrm{nucl})}+S^{(7\mathrm{pt})}$	NNLO $C+S^{(\mathrm{nucl})}$	NNLO $C+S^{(\mathrm{nucl})}+S^{(7\mathrm{pt})}$
DIS NC	2100	1.30	1.22	1.23	1.20
DIS CC	989	0.92	0.87	0.90	0.90
DY NC	736	2.01	1.71	1.20	1.15
DY CC	157	1.48	1.42	1.48	1.37
Top pairs	64	2.08	1.24	1.21	1.43
Single-inclusive jets	356	0.84	0.82	0.96	0.81
Dijets	144	1.52	1.84	2.04	1.71
Prompt photons	53	0.59	0.49	0.75	0.67
Single top	17	0.36	0.35	0.36	0.38
Total	4616	1.34	1.23	1.17	1.13

- The total χ^2 **decreases** upon inclusion of MHOU for both NLO and NNLO.
- For most of the **process groups** the NLO theory covariance matrix correctly accounts for the missing NNLO terms.

PDF comparison.



PDF uncertainties.



Conclusions

- A faithful and precise determination of the strong coupling is required for SM precision physics and to constrain GUT.
- Thanks to the EIC data, it will be possible to determine the strong coupling with a stunning reduction of the uncertainties.
- It will be important to include MHOU in a proper way to match such level of precision with the same level of accuracy.

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