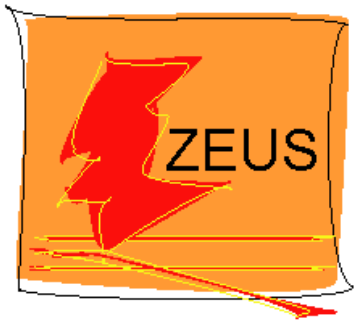
Measurement and QCD analysis of inclusive jet production in deep inelastic scattering at HERA

DESY-23-129, arxiv:2309.02889



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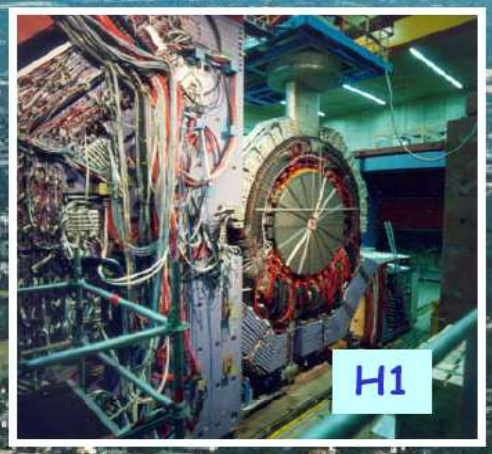
on behalf of the ZEUS collaboration

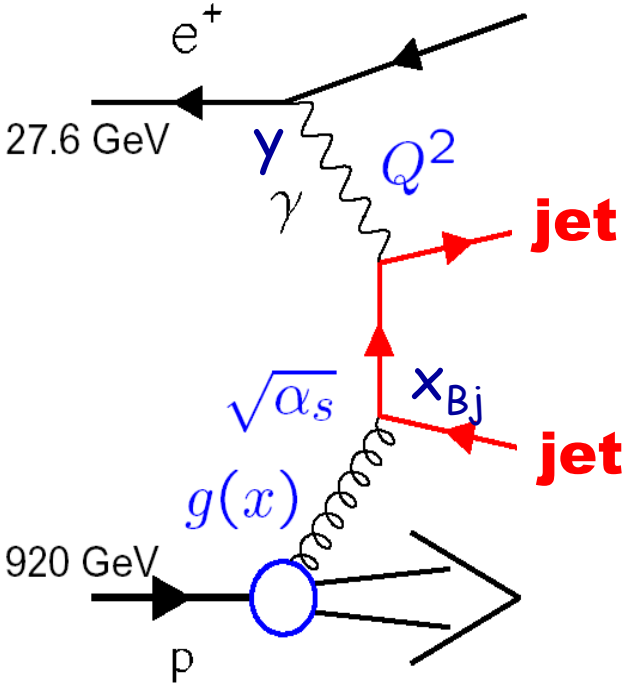
Low-x workshop 2023
Leros Island, Greece
7 September 2023

- Introduction
- Jet production in DIS at HERA
- ZEUS inclusive jet cross sections
- QCD fit, NNLO α_s + PDF determination
- NNLO running of α_s
- Note on QED corrections
- Conclusions

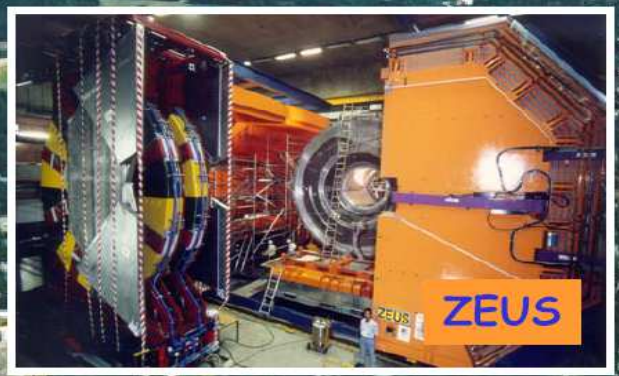
The HERA ep collider and experiments

DESY, Hamburg
~ 2007





e.g. copious source of
jets, dijets, ...



HERA I: ~ 130 pb^{-1} (physics)

HERA II: ~ 380 pb^{-1} (physics)

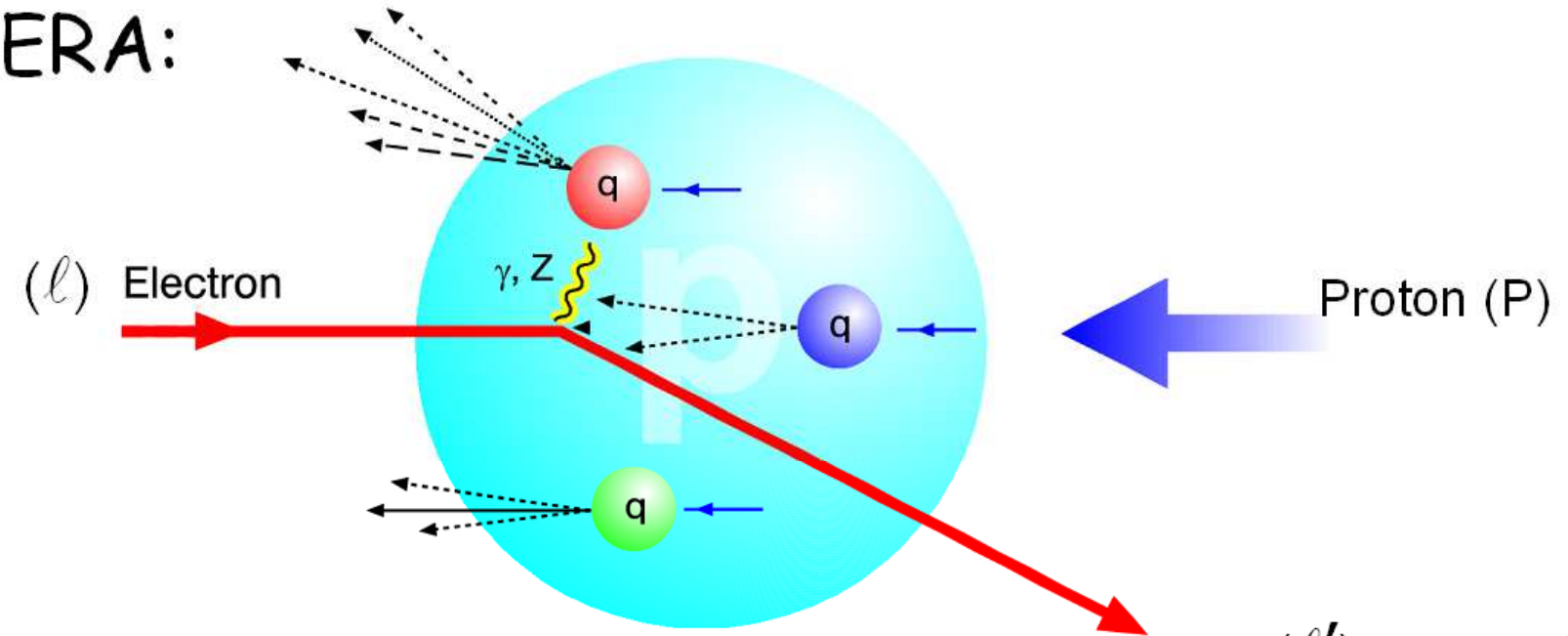
combined: ~ 0.5 fb^{-1}

HERA:

p (920 GeV) e (27.6 GeV)

Deep Inelastic ep Scattering at HERA

HERA:



kinematic variables:

$Q^2 = -q^2$ photon (or Z) virtuality, squared momentum transfer

$x_{Bj} = \frac{Q^2}{2Pq}$ Bjorken scaling variable

for $Q^2 \gg (2m_q)^2$: momentum fraction of p constituent

(equivalent in LO QPM only)

$y = \frac{qP}{\ell P}$ inelasticity,

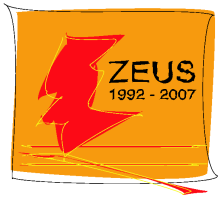
γ momentum fraction (of e)

$Q^2 \lesssim 1$ GeV^2: photoproduction

$Q^2 \gtrsim 1$ GeV^2: DIS

Why continue studying jet production in HERA data?

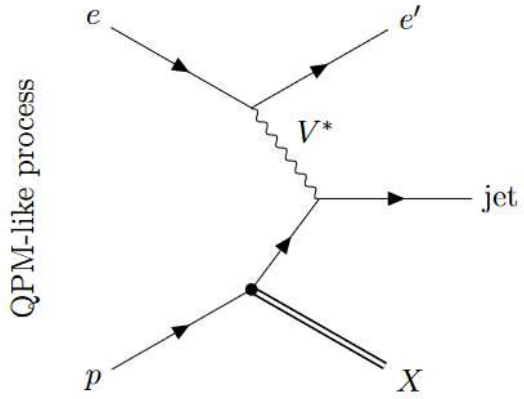
- HERA still only ep collider -> data remain unique
- still not all data fully analyzed (person power)
  -> example today (more to come, open for anybody to join)
- new theory developments (e.g. NNLO QCD)
  and improved experimental and theoretical procedures allow extraction of world-class results
- here: final results on inclusive jet production in high Q^2 DIS at ZEUS with full HERA II statistics and combined NNLO QCD analysis with previous measurements



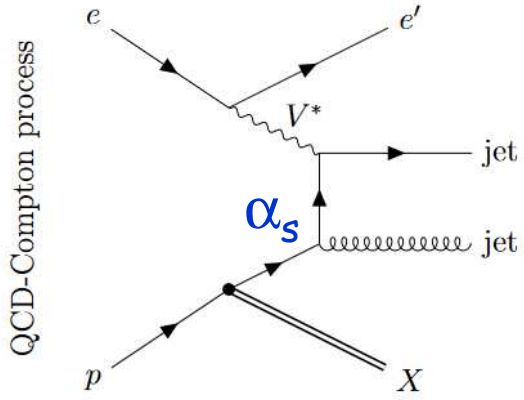
Jet production in DIS at HERA

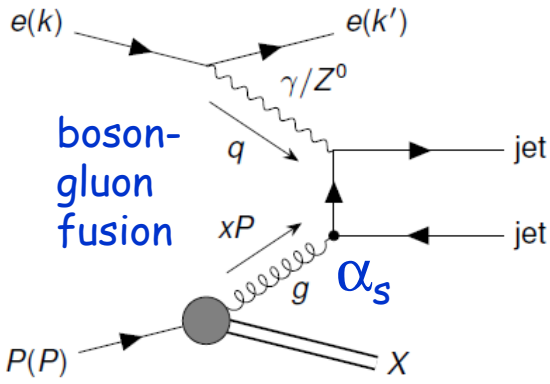
- Not all jets at HERA are a priori of QCD origin
- Quark-Parton Model

  no QCD in matrix elements



- LO QCD





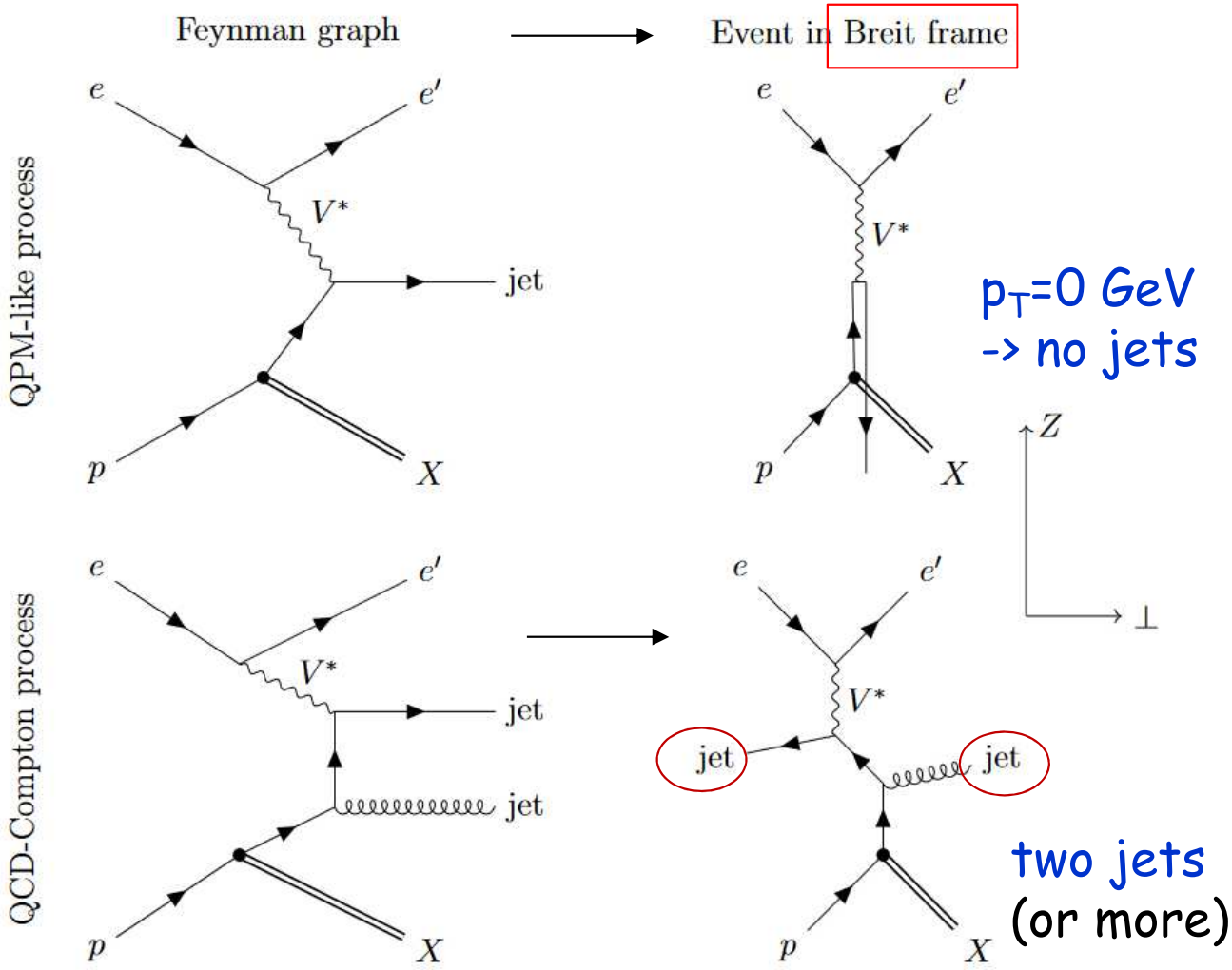
disentangles sensitivity to α_s and gluon distribution

Studying QCD jet contributions: Breit frame

- Breit frame = frame in which parton and virtual photon collide head-on.

QPM

LO QCD
(or higher)



p_T=0 GeV
-> no jets

two jets
(or more)

Measurement: inclusive jets in Breit frame

ZEUS, final result, DESY-23-129, arxiv:2309.02889 replaces ZEUS-prel-22-001

- full ZEUS HERA II data, 347 pb^{-1}

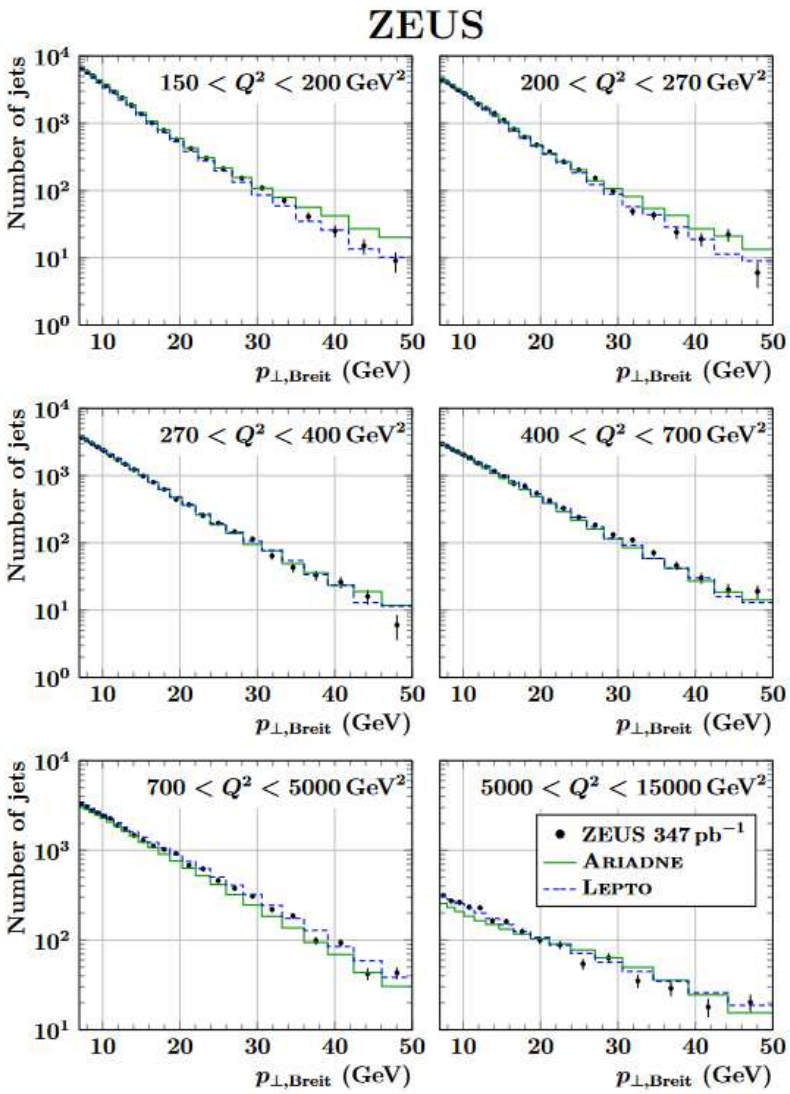
Event level phase space (Born level):

- $150 < Q^2 < 15000$ GeV^2
- $0.2 < y < 0.7$ (mom. transf. fraction)

Jet level phase space (hadron jets):

- 7 GeV $< p_{\perp,\mathrm{Breit}} < 50$ GeV
- $-1 < \eta_{\mathrm{lab}} < 2.5$

detector level comparison with LO+PS MC predictions

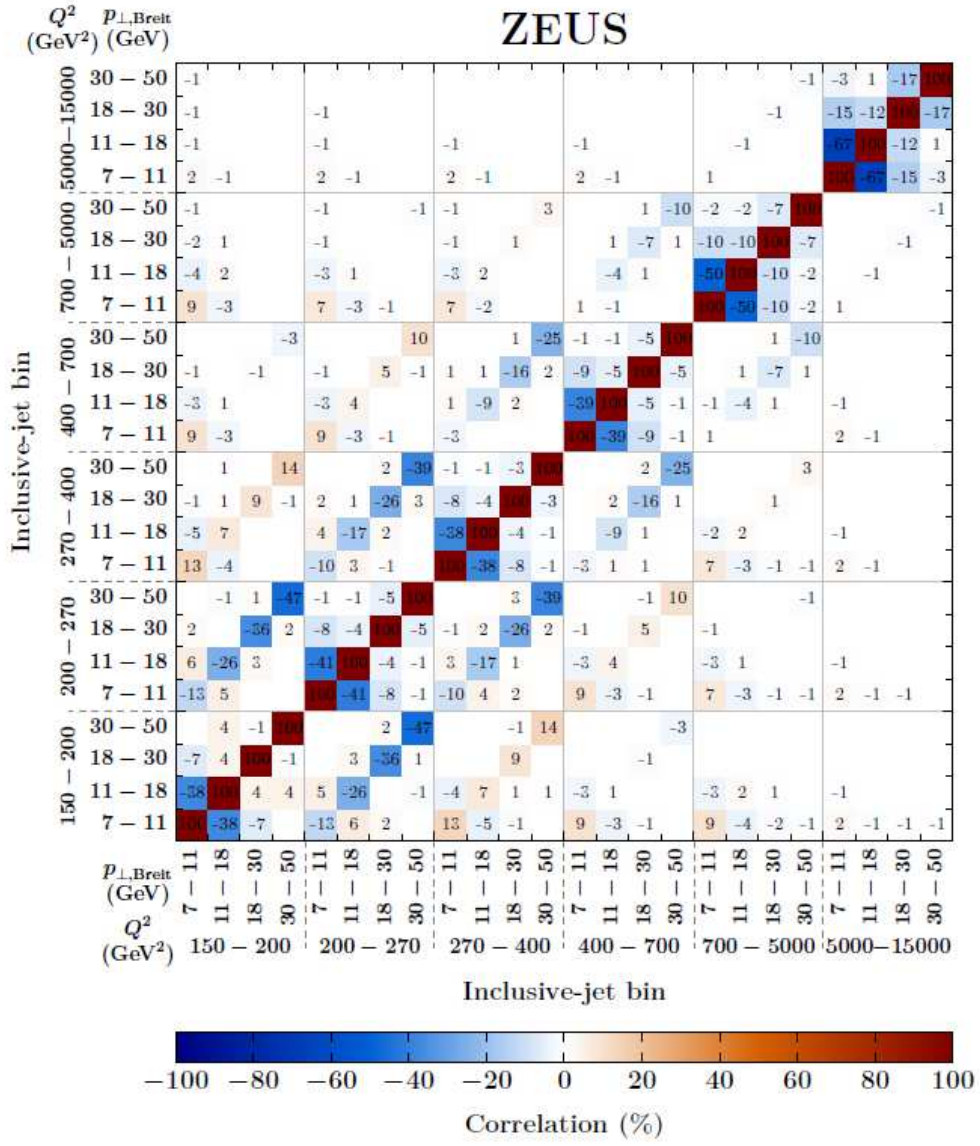


Ok to use for efficiency corrections (difference=uncertainty)

Matrix unfolding to hadron level

ZEUS, final result, DESY-23-129, arxiv:2309.02889 replaces ZEUS-prel-22-001

- 6 Q^2 and 4 p_{Tjet} bins, with correlations (in %):



- (alternatively also use bin-to-bin unfolding as for preliminary result and earlier ZEUS results;
- results in very good agreement

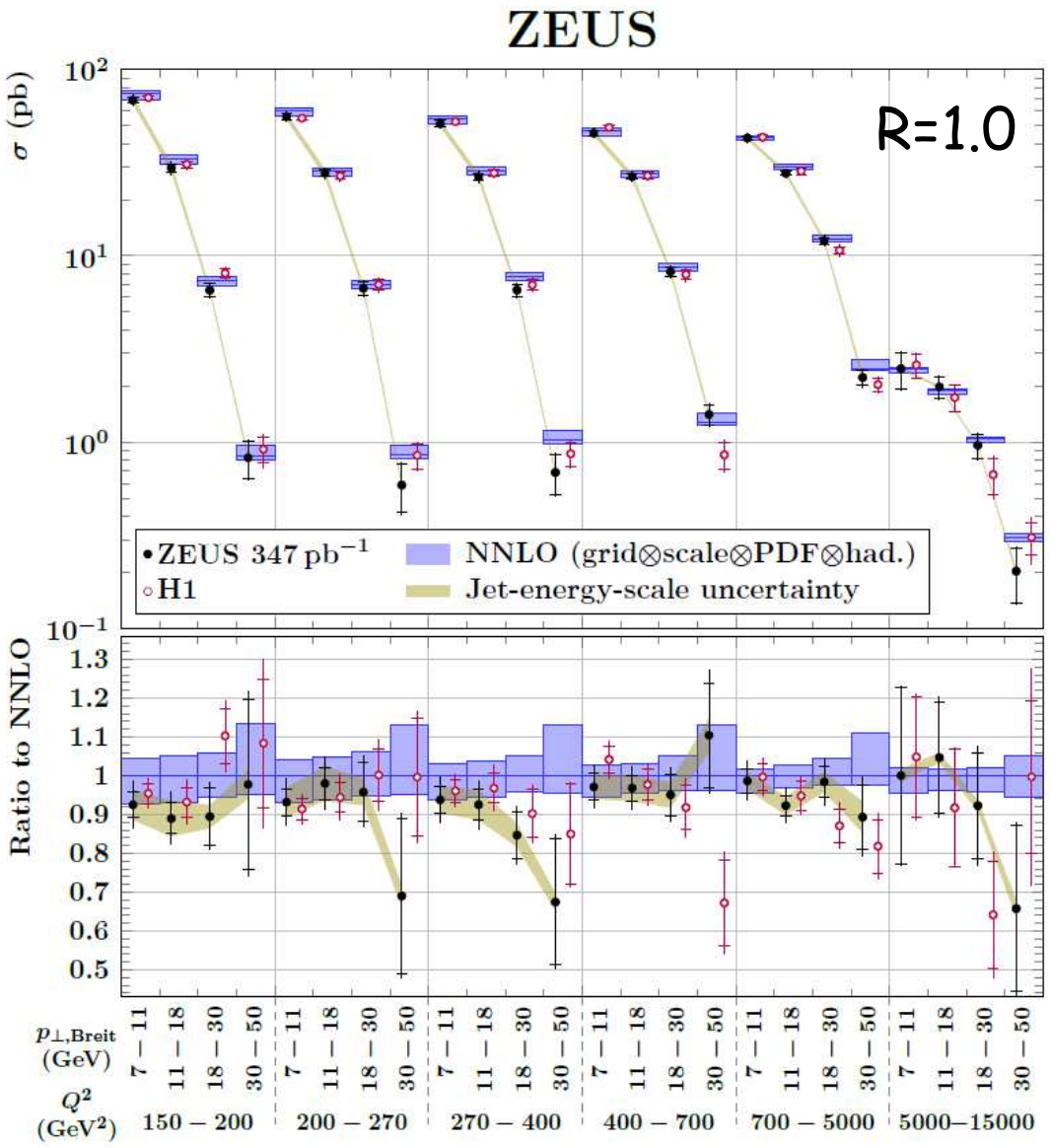
-> also validates earlier results)

Double differential inclusive jet cross sections

ZEUS, final result, DESY-23-129, arxiv:2309.02889 replaces ZEUS-prel-22-001

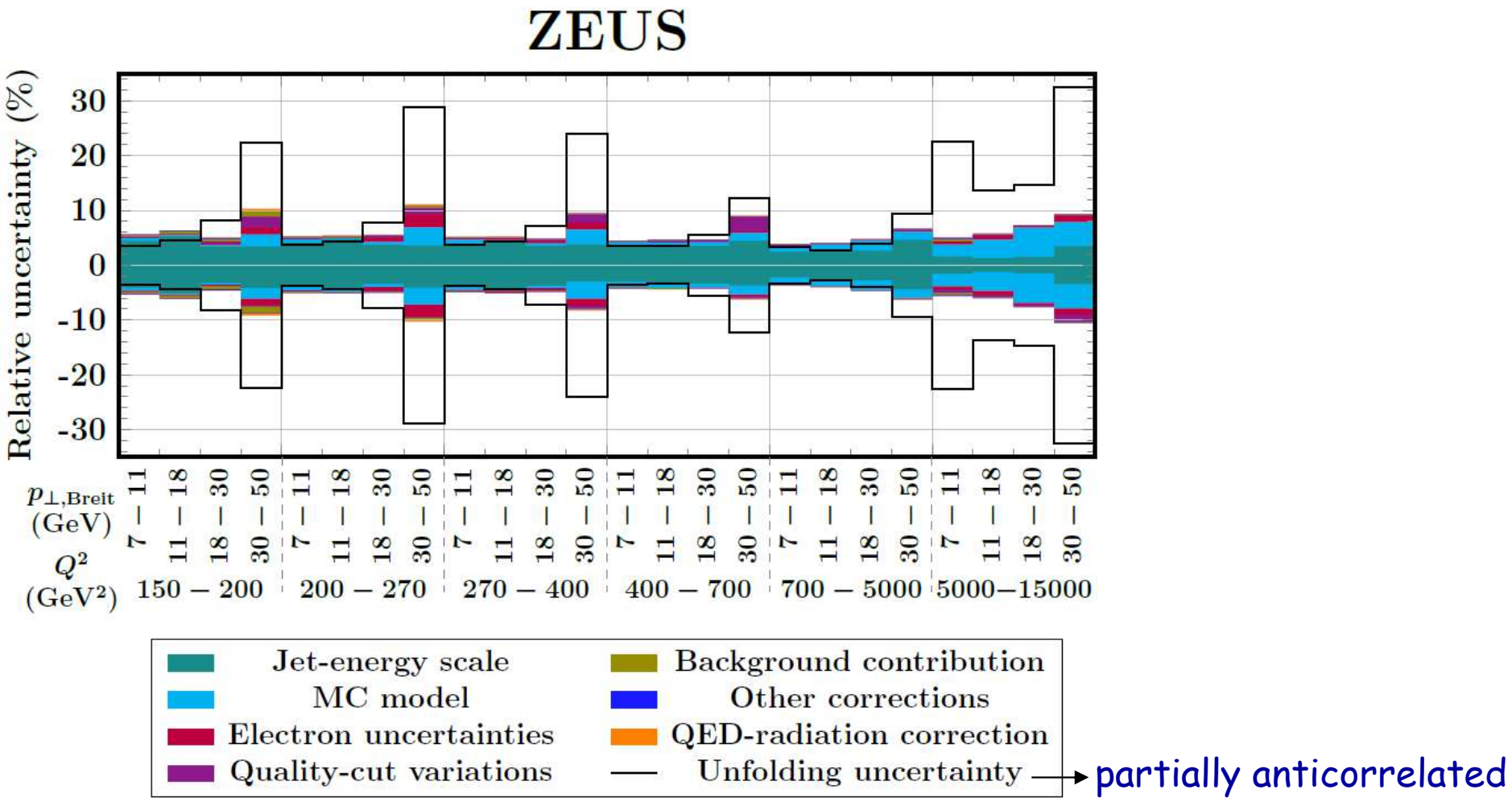
- corrected to QED Born level
- good agreement between ZEUS and H1 cross sections
- reasonably described by NNLO QCD ⊗ hadr..
- Currie et al., JHEP 07 (2017) 018, JHEP 12 (2020) 042, also NNLOjet

  FastNLO, arXiv:1208.3641
  ApplFast, M. Sutton et al.,



breakdown of cross section uncertainties

ZEUS, final result, DESY-23-129, arxiv:2309.02889 replaces ZEUS-prel-22-001



→ partially anticorrelated

Breakdown of uncertainties and corrections

ZEUS, final result, DESY-23-129, arxiv:2309.02889 replaces ZEUS-prel-22-001

large (partial LO, Heracles)

QED corrections -> Born

Q^2 (GeV^2)	$p_{\perp,\mathrm{Breit}}$ (GeV)	σ (pb)	δ_{unf} (%)	δ_{uncor} (%)	δ_{JES} (%)	δ_{model} (%)	δ_{fake} (%)	$\delta_{\text{Low-}Q^2}$ (%)	δ_{E-p_z} (%)	δ_{TME} (%)	c_{QED}	c_Z	c_{Had}	δ_{Had} (%)
150–200	7–11	68.4	3.6	1.7	$^{+4.4}_{-4.1}$	2.0	1.7	0.3	$^{+0.9}_{-0.0}$	1.4	0.69	1.00	0.93	0.8
150–200	11–18	29.6	4.5	1.8	$^{+5.3}_{-5.1}$	1.0	2.1	1.1	$^{+0.8}_{-0.2}$	1.4	0.87	1.00	0.97	0.9
150–200	18–30	6.55	8.3	1.7	$^{+3.4}_{-3.2}$	1.4	1.2	1.7	$^{+1.8}_{-0.3}$	1.3	0.95	1.00	0.97	0.4
150–200	30–50	0.828	22.4	5.3	$^{+3.4}_{-4.2}$	4.2	1.1	4.2	$^{+5.3}_{+0.0}$	1.2	0.90	1.00	0.96	0.3
200–270	7–11	55.9	3.7	1.6	$^{+4.1}_{-3.9}$	2.3	1.3	0.2	$^{+0.7}_{-0.2}$	1.0	0.68	1.00	0.94	1.2
200–270	11–18	27.8	4.3	1.3	$^{+4.7}_{-4.5}$	0.9	1.5	0.1	$^{+1.1}_{-0.2}$	1.0	0.80	1.00	0.96	0.2
200–270	18–30	6.70	7.8	2.8	$^{+3.7}_{-3.4}$	-2.0	1.0	-0.1	$^{+2.0}_{-0.3}$	1.0	0.95	1.00	0.98	0.2
200–270	30–50	0.590	28.9	7.1	$^{+3.6}_{-4.1}$	5.5	1.4	-2.3	$^{+4.5}_{-1.2}$	0.9	0.95	1.00	0.98	0.8
270–400	7–11	51.2	3.7	1.7	$^{+3.9}_{-3.6}$	2.5	1.3	0.1	$^{+0.8}_{+0.1}$	0.7	0.70	1.00	0.93	1.6
270–400	11–18	26.6	4.3	2.3	$^{+4.2}_{-4.3}$	0.9	1.4	0.2	$^{+1.0}_{-0.0}$	0.8	0.69	1.00	0.97	0.1
270–400	18–30	6.56	7.2	2.2	$^{+3.6}_{-3.7}$	1.7	1.0	0.2	$^{+1.4}_{-0.5}$	0.7	0.92	1.00	0.97	0.2
270–400	30–50	0.690	24.0	5.0	$^{+3.8}_{-2.9}$	-5.2	1.1	1.0	$^{+5.0}_{-1.6}$	0.7	0.96	1.00	0.98	0.4
400–700	7–11	45.5	3.5	1.1	$^{+3.3}_{-3.0}$	2.4	1.2	0.2	$^{+0.9}_{-0.2}$	0.6	0.75	1.01	0.92	1.4
400–700	11–18	26.7	3.4	1.2	$^{+3.5}_{-3.6}$	1.8	1.2	-0.1	$^{+1.7}_{-0.0}$	0.6	0.63	1.01	0.97	0.2
400–700	18–30	8.23	5.6	1.0	$^{+3.5}_{-3.3}$	2.2	0.9	-0.0	$^{+1.7}_{-0.2}$	0.6	0.85	1.01	0.97	0.3
400–700	30–50	1.41	12.2	3.2	$^{+4.5}_{-3.7}$	3.5	0.8	-0.2	$^{+6.3}_{-0.1}$	0.6	0.98	1.01	0.97	0.5
700–5000	7–11	42.9	3.3	1.3	$^{+2.5}_{-2.2}$	2.4	1.1	0.1	$^{+0.4}_{-0.2}$	0.5	0.83	1.03	0.90	0.6
700–5000	11–18	27.8	2.8	1.8	$^{+2.5}_{-2.5}$	2.2	0.9	-0.0	$^{+0.9}_{-0.2}$	0.5	0.70	1.03	0.97	0.7
700–5000	18–30	12.1	4.0	0.9	$^{+2.7}_{-2.7}$	3.5	0.9	-0.0	$^{+1.2}_{-0.0}$	0.5	0.57	1.03	0.97	0.0
700–5000	30–50	2.23	9.4	1.6	$^{+4.6}_{-4.4}$	4.0	1.4	0.1	$^{-0.7}_{-0.4}$	0.5	0.71	1.03	0.96	0.4
5000–15000	7–11	2.48	22.6	2.9	$^{+1.6}_{-1.6}$	-3.4	2.0	0.1	$^{-1.0}_{-0.5}$	0.3	0.93	1.16	0.89	0.6
5000–15000	11–18	1.99	13.6	3.5	$^{+1.3}_{-1.2}$	4.3	1.4	-0.1	$^{-0.6}_{+0.0}$	0.3	0.87	1.16	0.95	0.3
5000–15000	18–30	0.965	14.8	3.1	$^{+1.5}_{-1.5}$	6.4	0.8	-0.0	$^{-2.4}_{-1.6}$	0.3	0.72	1.16	0.98	0.1
5000–15000	30–50	0.204	32.5	4.9	$^{+3.5}_{-3.4}$	6.9	1.7	-0.1	$^{-5.0}_{-4.1}$	0.3	0.43	1.16	0.98	0.9

moderate hadronization corrections

ZEUS NNLO QCD fit

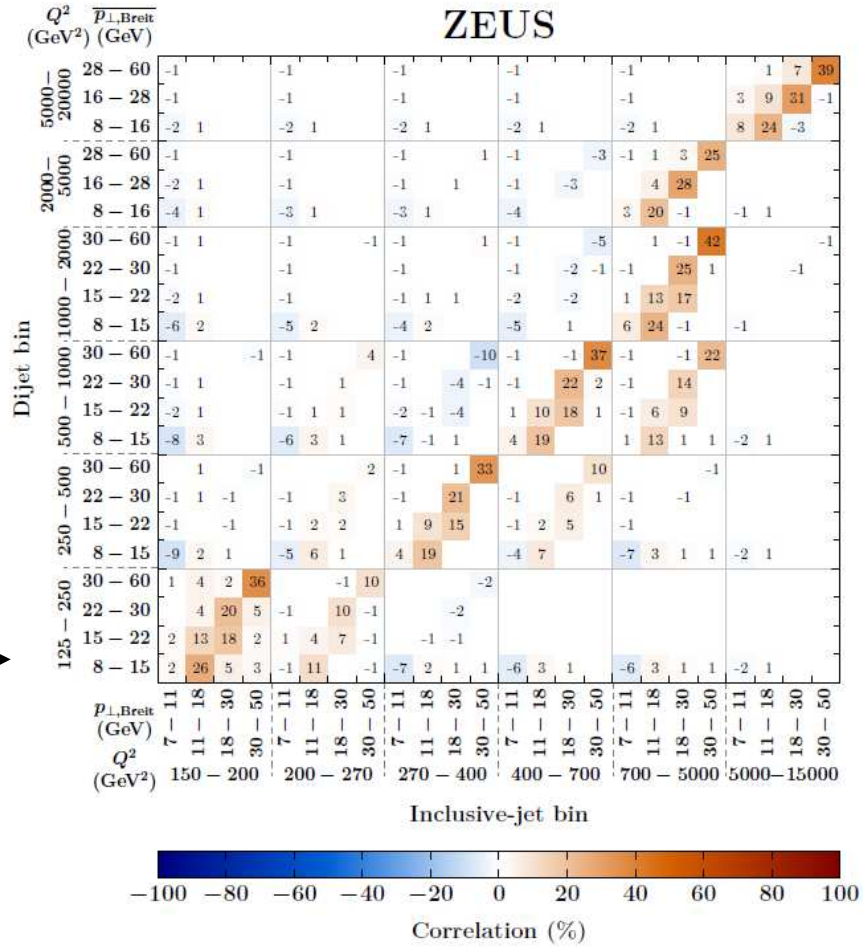
ZEUS, final result, DESY-23-129, arxiv:2309.02889 replaces ZEUS-prel-22-001

- combined PDF + α_s fit, input:

- combined inclusive HERA DIS data (as for essentially any recent PDF fit)

- ZEUS HERA II inclusive jet data (this report)
  + corresponding HERA I data
  (still need to add reference)

- ZEUS HERA I+II dijet data
  + correlations
  to inclusive jets



ZEUS NNLO QCD fit, standard approach

ZEUS, final result, DESY-23-129, arxiv:2309.02889 replaces ZEUS-prel-22-001

$$\text{NNLO: } \alpha_s(M_Z^2) = 0.1143 \pm 0.0017\ (\text{exp./fit})\ ^{+0.0006}_{-0.0007}\ (\text{model/param.})\ ^{+0.0012}_{-0.0005}\ (\text{scale}),$$

$$\text{NLO: } \alpha_s(M_Z^2) = 0.1160 \pm 0.0017\ (\text{exp./fit})\ ^{+0.0007}_{-0.0009}\ (\text{model/param.})\ ^{+0.0026}_{-0.0014}\ (\text{scale}),$$

NNLO:

(thesis F. Lorkowski)

Dataset	Partial χ^2/Number of points
HERA NC e^+p DIS, $E_P = 920$ GeV	447.65/377
HERA NC e^+p DIS, $E_P = 820$ GeV	64.99/70
HERA NC e^+p DIS, $E_P = 575$ GeV	219.16/254
HERA NC e^+p DIS, $E_P = 460$ GeV	216.58/204
HERA NC e^-p DIS, $E_P = 920$ GeV	219.88/159
HERA CC e^+p DIS, $E_P = 920$ GeV	47.52/39
HERA CC e^-p DIS, $E_P = 920$ GeV	51.73/42
HERA I inclusive jets	26.38/30
HERA I/II dijets	14.65/16
HERA II inclusive jets	14.98/24
Shifts of correlated systematics	96.24
Global χ^2 per degree of freedom	1418.93/1200

good fit

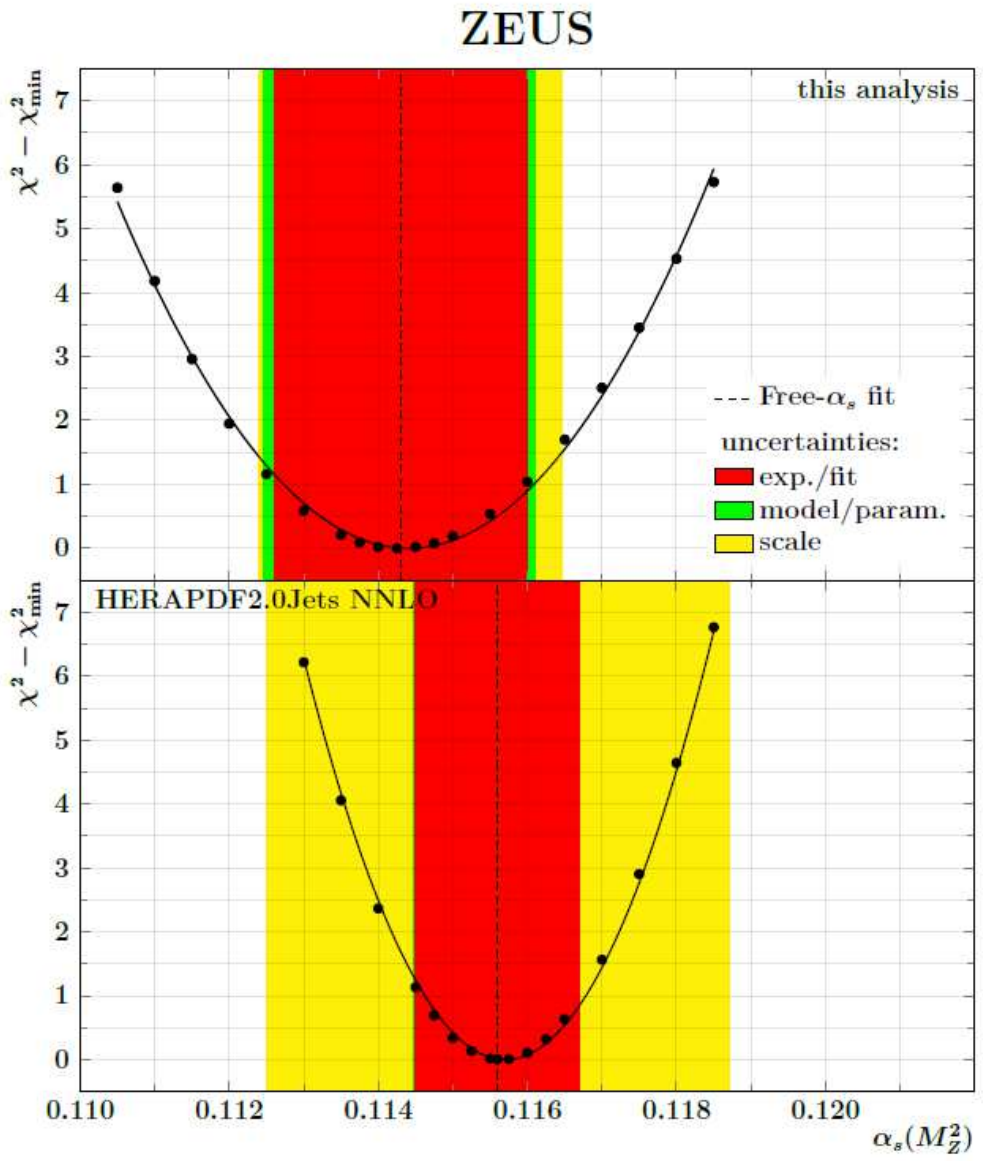
Comparison to HERAPDF2.0Jets NNLO

ZEUS, final result, DESY-23-129, arxiv:2309.02889 replaces ZEUS-prel-22-001

HERA inclusive DIS data plus:

- ZEUS high Q^2 (di)jets only (this work)
- all suitable HERA jet data except new inclusive ZEUS jets

-> significant potential for further improvement



treatment of correlations in scale variations

ZEUS, final result, DESY-23-129, arxiv:2309.02889 replaces ZEUS-prel-22-001

standard treatment: treat QCD scale variations as fully correlated between

- Low Q^2 and high Q^2 jet data -> HERAPDF2.0Jets only
- Low p_{Tjet} and high p_{Tjet} -> both ZEUS and HERAPDF2.0Jets
- Inclusive jets and dijets -> both ZEUS and HERAPDF2.0Jets

while at least sometimes they could be uncorrelated or even anticorrelated

-> including more data can lead to increased uncertainty!

Partially mitigate this by treating scale variations as half correlated and half uncorrelated for all jet data: **final result**

$$\text{NNLO: } \alpha_s(M_Z^2) = 0.1142 \pm 0.0017\ (\text{exp./fit})\ ^{+0.0006}_{-0.0007}\ (\text{model/param.})\ ^{+0.0006}_{-0.0004}\ (\text{scale}),$$
$$\text{NLO: } \alpha_s(M_Z^2) = 0.1159 \pm 0.0017\ (\text{exp./fit})\ ^{+0.0007}_{-0.0009}\ (\text{model/param.})\ ^{+0.0012}_{-0.0009}\ (\text{scale}).$$

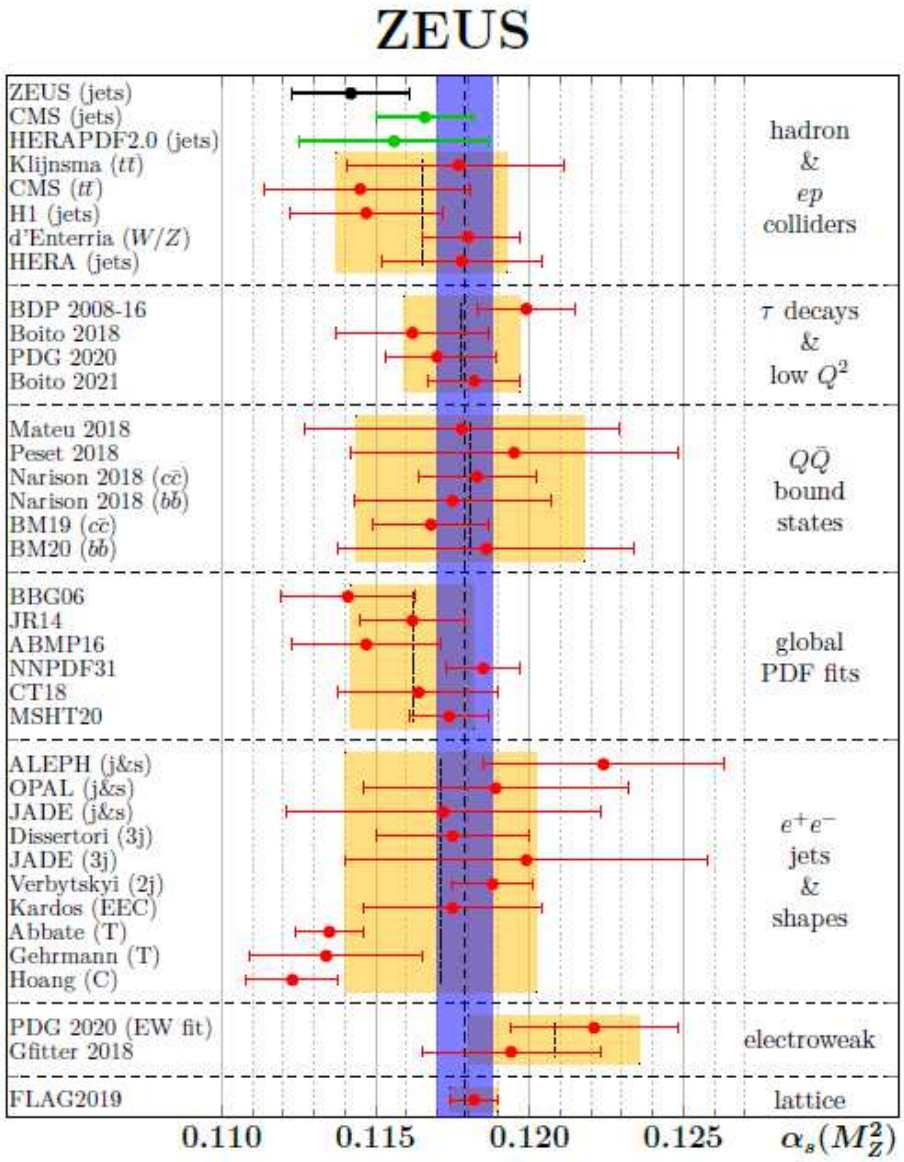
Comparison to PDG and selected other results

ZEUS, final result, DESY-23-129, arxiv:2309.02889 replaces ZEUS-prel-22-001

$\alpha_s(m_Z) = 0.1142 \pm 0.0019$

one of most precise α_s measurements from colliders

CMS inclusive jet measurement presented on monday

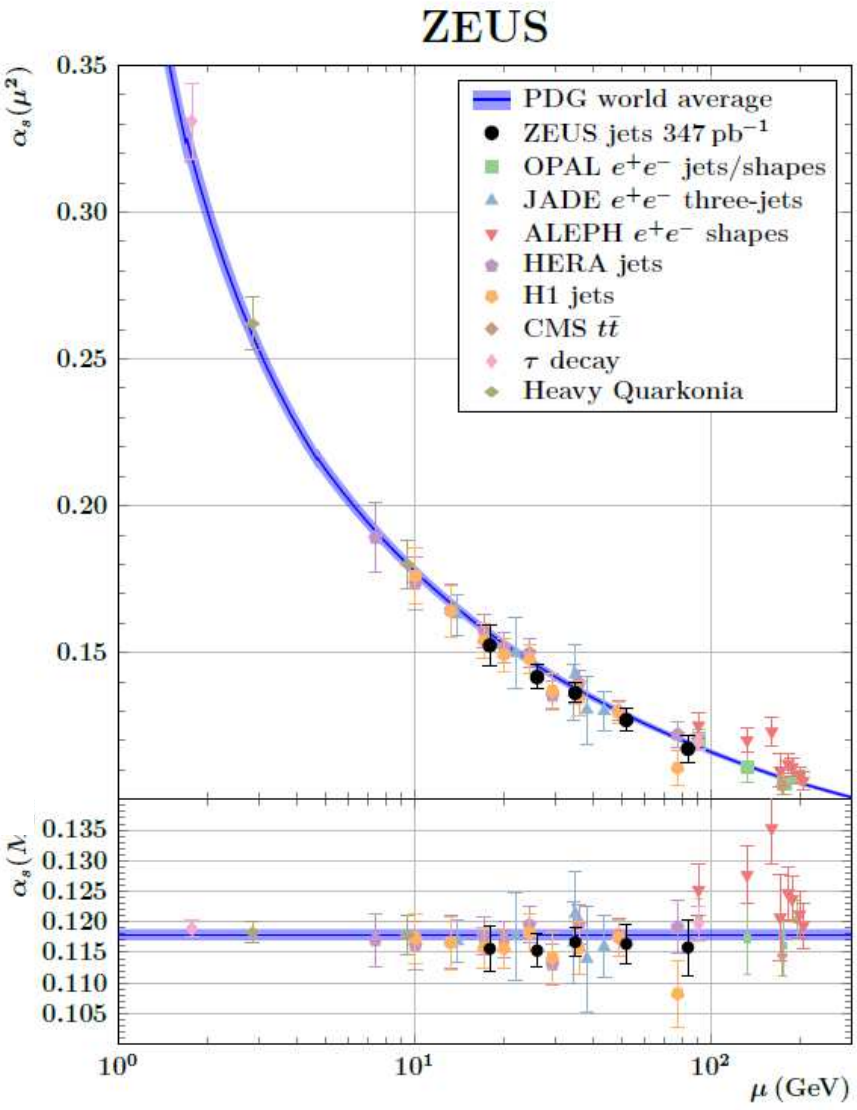


NNLO running of α_s from ZEUS jets

ZEUS, final result, DESY-23-129, arxiv:2309.02889 replaces ZEUS-prel-22-001

- Repeat α_s determination for 5 different data subsets and PDFs fixed to DIS only (apart from consistent α_s)

Number of jet cross sections	$\langle\mu\rangle$ (GeV)	$\alpha_s(M_Z^2)$	$\pm\delta_{\text{exp./fit}}$	$\pm\delta_{\text{mod./par.}}$	$\pm\delta_{\text{scale}}$	$\alpha_s(\langle\mu\rangle^2)$	$\pm\delta_{\text{total}}$
12	18	0.1156	±0.0037	±0.0008	$^{+0.0035}_{-0.0025}$	0.1525	±0.0086
16	26	0.1153	±0.0026	±0.0006	$^{+0.0028}_{-0.0017}$	0.1417	±0.0054
19	35	0.1167	±0.0024	±0.0003	$^{+0.0018}_{-0.0010}$	0.1363	±0.0039
12	52	0.1164	±0.0032	±0.0002	$^{+0.0011}_{-0.0003}$	0.1271	±0.0040
11	84	0.1158	±0.0045	±0.0003	$^{+0.0014}_{-0.0004}$	0.1172	±0.0047



-> α_s running consistent with NNLO QCD expectation

Addendum: Cross sections with reduced QED corrections

- Actual measurement at detector level includes final state QED radiation and rejects events with hard collinear initial state photon radiation off the electron.

- QCD theory calculations only exist at QED Born level (no photon radiation at either initial nor final state)
  -> measured DIS cross sections at HERA are by default extrapolated to and (only) quoted at this level
  -> large QED corrections, calculated to LO only.

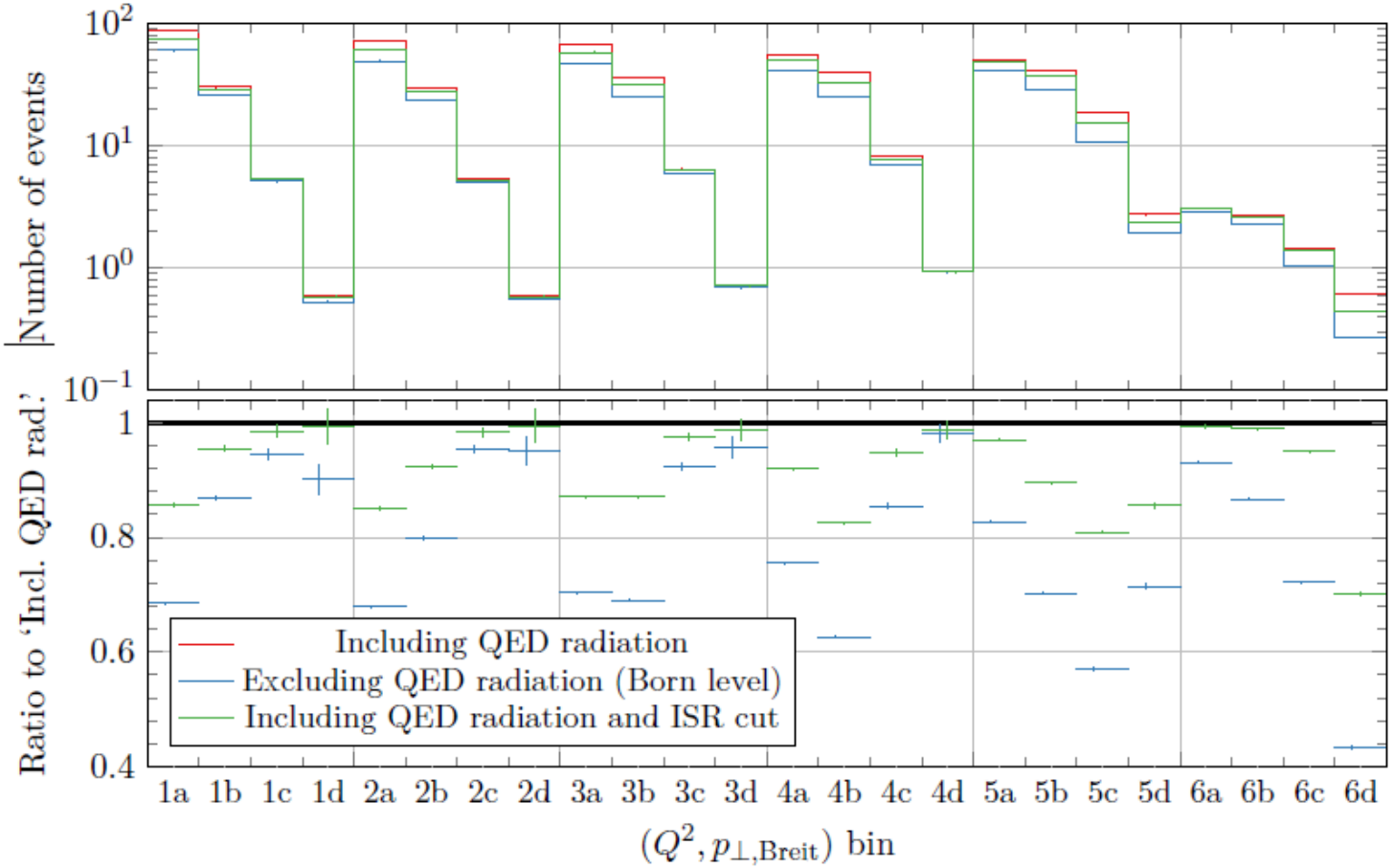
  Such cross sections can not be used for later full NNLO QCD + NLO EW comparisons.

  -> also provide cross sections closer to phase space actually being measured.

Addendum: Cross sections with reduced QED corrections

- Additional cross section including QED radiation apart from cut on hard initial state radiation.

(thesis
F. Lorkowski)



Addendum: Cross sections with reduced QED corrections

default

Q^2 (GeV^2)	$p_{\perp,\mathrm{Breit}}$ (GeV)	σ (pb)	δ_{unf} (%)	δ_{uncor} (%)	δ_{JES} (%)	δ_{model} (%)	δ_{fake} (%)	$\delta_{\text{Low-}Q^2}$ (%)	δ_{E-p_z} (%)	δ_{TME} (%)	c_{QED}	c_Z	c_{Had}	δ_{Had} (%)
150–200	7–11	68.4	3.6	1.7	$^{+4.4}_{-4.1}$	2.0	1.7	0.3	$^{+0.9}_{-0.0}$	1.4	0.69	1.00	0.93	0.8
150–200	11–18	29.6	4.5	1.8	$^{+5.3}_{-5.1}$	1.0	2.1	1.1	$^{+0.8}_{-0.2}$	1.4	0.87	1.00	0.97	0.9
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150–200	30–50	0.828	22.4	5.3	$^{+3.4}_{-4.2}$	4.2	1.1	4.2	$^{+5.3}_{+0.0}$	1.2	0.90	1.00	0.96	0.3
200–270	7–11	55.9	3.7	1.6	$^{+4.1}_{-3.9}$	2.3	1.3	0.2	$^{+0.7}_{-0.2}$	1.0	0.68	1.00	0.94	1.2
200–270	11–18	27.8	4.3	1.3	$^{+4.7}_{-4.5}$	0.9	1.5	0.1	$^{+1.1}_{-0.2}$	1.0	0.80	1.00	0.96	0.2
200–270	18–30	6.70	7.8	2.8	$^{+3.7}_{-3.4}$	-2.0	1.0	-0.1	$^{+2.0}_{-0.3}$	1.0	0.95	1.00	0.98	0.2
200–270	30–50	0.590	28.9	7.1	$^{+3.6}_{-4.1}$	5.5	1.4	-2.3	$^{+4.5}_{-1.2}$	0.9	0.95	1.00	0.98	0.8
270–400	7–11	51.2	3.7	1.7	$^{+3.9}_{-3.6}$	2.5	1.3	0.1	$^{+0.8}_{+0.1}$	0.7	0.70	1.00	0.93	1.6
270–400	11–18	26.6	4.3	2.3	$^{+4.2}_{-4.3}$	0.9	1.4	0.2	$^{+1.0}_{-0.0}$	0.8	0.69	1.00	0.97	0.1
270–400	18–30	6.56	7.2	2.2	$^{+3.6}_{-3.7}$	1.7	1.0	0.2	$^{+1.4}_{-0.5}$	0.7	0.92	1.00	0.97	0.2
270–400	30–50	0.690	24.0	5.0	$^{+3.8}_{-2.9}$	-5.2	1.1	1.0	$^{+5.0}_{-1.6}$	0.7	0.96	1.00	0.98	0.4
400–700	7–11	45.5	3.5	1.1	$^{+3.3}_{-3.0}$	2.4	1.2	0.2	$^{+0.9}_{-0.2}$	0.6	0.75	1.01	0.92	1.4
400–700	11–18	26.7	3.4	1.2	$^{+3.5}_{-3.6}$	1.8	1.2	-0.1	$^{+1.7}_{-0.0}$	0.6	0.63	1.01	0.97	0.2
400–700	18–30	8.23	5.6	1.0	$^{+3.5}_{-3.3}$	2.2	0.9	-0.0	$^{+1.7}_{-0.2}$	0.6	0.85	1.01	0.97	0.3
400–700	30–50	1.41	12.2	3.2	$^{+4.5}_{-3.7}$	3.5	0.8	-0.2	$^{+6.3}_{-0.1}$	0.6	0.98	1.01	0.97	0.5
700–5000	7–11	42.9	3.3	1.3	$^{+2.5}_{-2.2}$	2.4	1.1	0.1	$^{+0.4}_{-0.2}$	0.5	0.83	1.03	0.90	0.6
700–5000	11–18	27.8	2.8	1.8	$^{+2.5}_{-2.5}$	2.2	0.9	-0.0	$^{+0.9}_{-0.2}$	0.5	0.70	1.03	0.97	0.7
700–5000	18–30	12.1	4.0	0.9	$^{+2.7}_{-2.7}$	3.5	0.9	-0.0	$^{+1.2}_{-0.0}$	0.5	0.57	1.03	0.97	0.0
700–5000	30–50	2.23	9.4	1.6	$^{+4.6}_{-4.4}$	4.0	1.4	0.1	$^{-0.7}_{-0.4}$	0.5	0.71	1.03	0.96	0.4
5000–15000	7–11	2.48	22.6	2.9	$^{+1.6}_{-1.6}$	-3.4	2.0	0.1	$^{-1.0}_{-0.5}$	0.3	0.93	1.16	0.89	0.6
5000–15000	11–18	1.99	13.6	3.5	$^{+1.3}_{-1.2}$	4.3	1.4	-0.1	$^{-0.6}_{+0.0}$	0.3	0.87	1.16	0.95	0.3
5000–15000	18–30	0.965	14.8	3.1	$^{+1.5}_{-1.5}$	6.4	0.8	-0.0	$^{-2.4}_{-1.6}$	0.3	0.72	1.16	0.98	0.1
5000–15000	30–50	0.204	32.5	4.9	$^{+3.5}_{-3.4}$	6.9	1.7	-0.1	$^{-5.0}_{-4.1}$	0.3	0.43	1.16	0.98	0.9

extra (thesis F. Lorkowski)

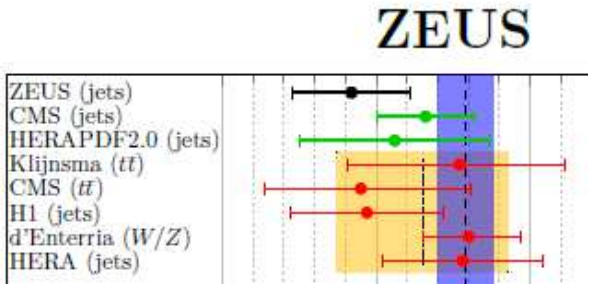
Q^2 [GeV^2]	$p_{\perp,\mathrm{Breit}}$ [GeV]	σ [pb]	δ_{uncor} [%]	c'_{QED}	δ'_{QED} [%]
150–200	7–11	85.4	1.7	0.86	0.2
150–200	11–18	32.6	1.8	0.95	0.4
150–200	18–30	6.82	1.8	0.99	1.0
150–200	30–50	0.913	5.6	0.99	3.0
200–270	7–11	70.0	1.6	0.85	0.2
200–270	11–18	32.1	1.3	0.92	0.3
200–270	18–30	6.91	2.8	0.98	0.8
200–270	30–50	0.617	7.3	0.99	3.0
270–400	7–11	63.4	1.7	0.87	0.2
270–400	11–18	33.5	2.3	0.87	0.3
270–400	18–30	6.93	2.2	0.98	0.6
270–400	30–50	0.712	5.0	0.99	1.8
400–700	7–11	55.4	1.1	0.92	0.2
400–700	11–18	35.2	1.2	0.83	0.2
400–700	18–30	9.13	1.1	0.95	0.5
400–700	30–50	1.42	3.3	0.99	1.5
700–5000	7–11	50.3	1.3	0.97	0.1
700–5000	11–18	35.4	1.8	0.90	0.1
700–5000	18–30	17.1	0.9	0.81	0.2
700–5000	30–50	2.67	1.5	0.85	0.5
5000–15000	7–11	2.65	2.9	0.99	0.2
5000–15000	11–18	2.27	3.5	0.99	0.2
5000–15000	18–30	1.270	3.1	0.95	0.2
5000–15000	30–50	0.330	4.9	0.70	0.2

will hopefully carry fruit when NNLO QCD + full NLO EW predictions (including PDFs) will become available.

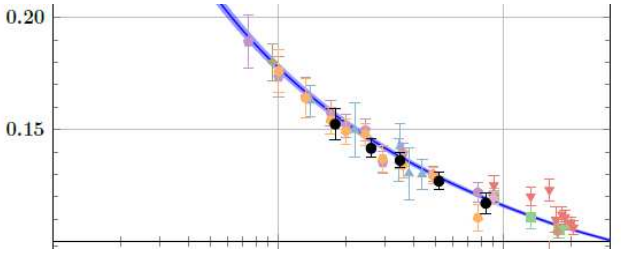
Summary and conclusions

ZEUS, final result, DESY-23-129, arxiv:2309.02889

- inclusive Breit frame jet cross sections in high Q^2 DIS at HERA have been measured with the ZEUS detector
- very good agreement with similar H1 measurements
- cross sections corrected to QED Born level well described by NNLO QCD + partial LO EW calculations
- NNLO QCD PDF+α_s fit together with inclusive HERA DIS and other ZEUS jet data gives $\alpha_s(m_Z) = 0.1142 \pm 0.0019$, one of the most precise measurements from colliders



- running of α_s consistent with QCD expectations



- cross sections with strongly reduced LO QED extrapolation are being provided for later comparison to full NNLO QCD + NLO EW predictions.

Backup slides

Comparison of pre- and post-fit results