Jets, α_s and QCD measurements at HERA

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on behalf of the H1 and ZEUS Collaborations

QCD@LHC 2013 - DESY
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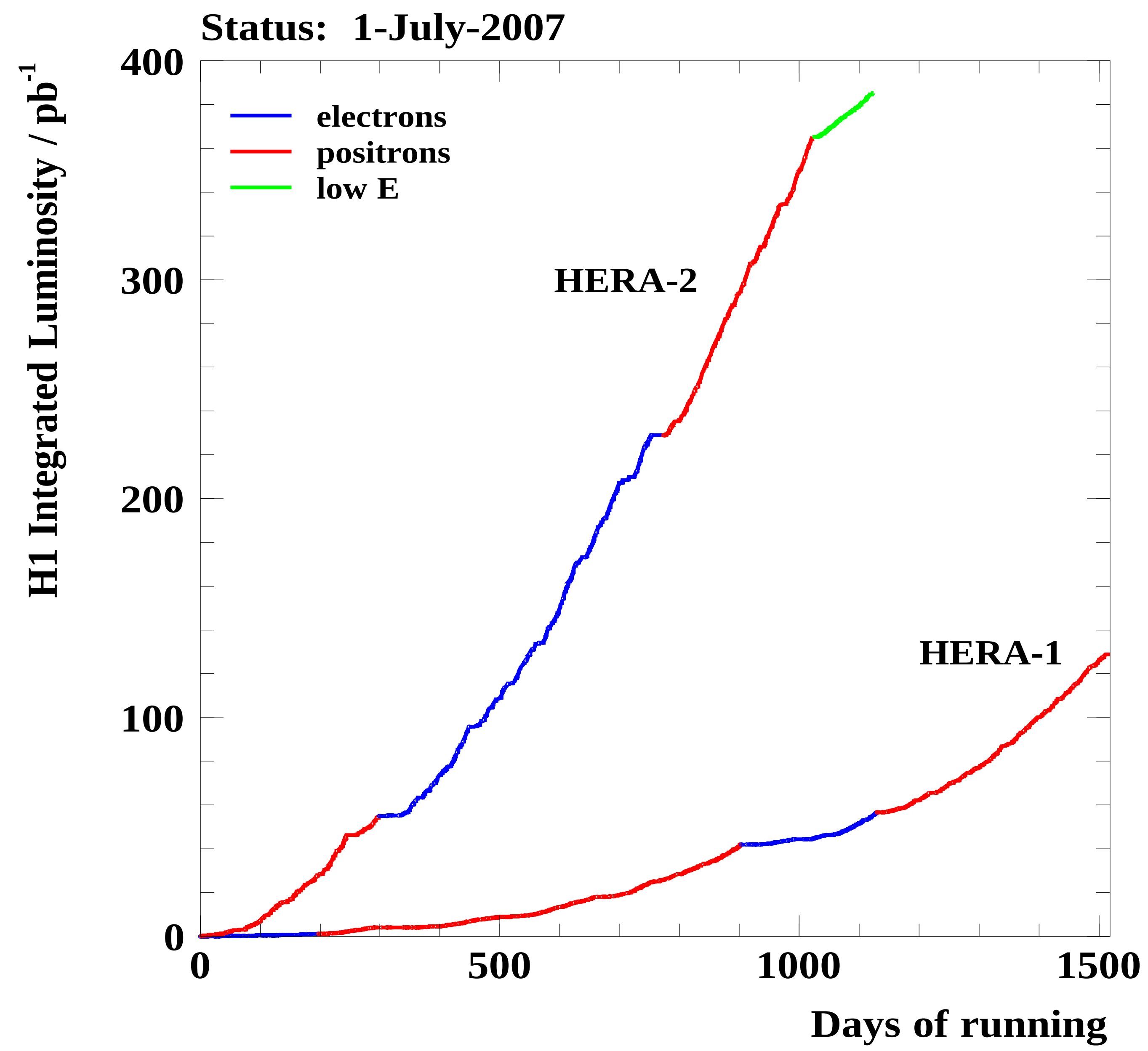
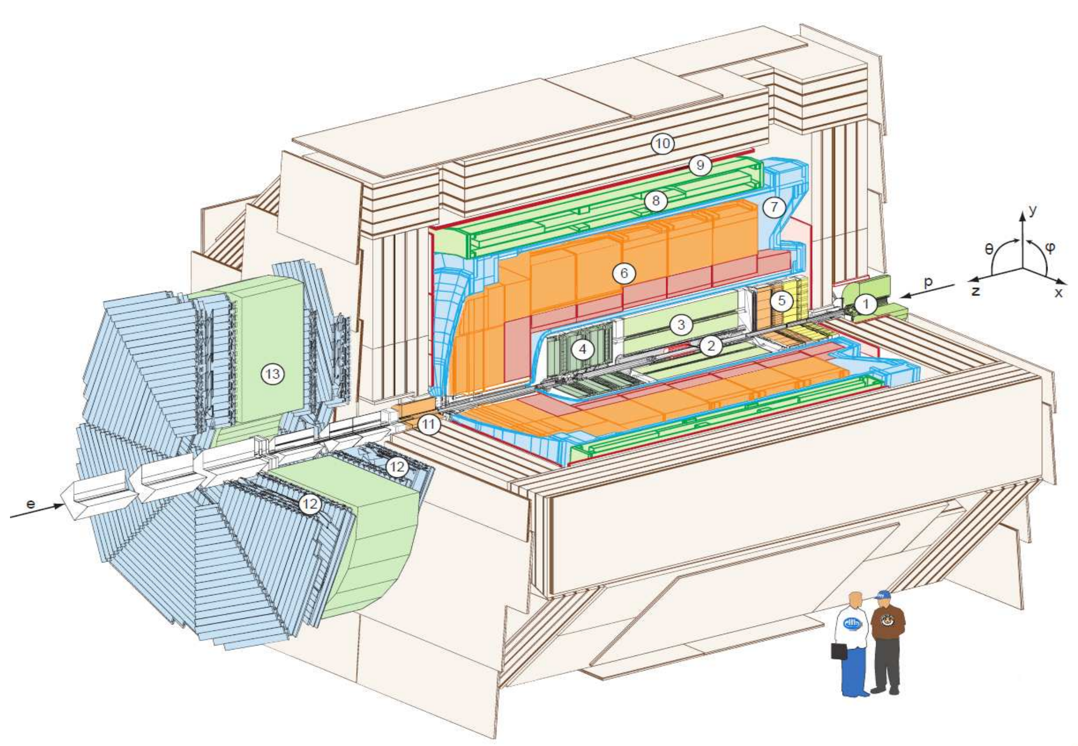
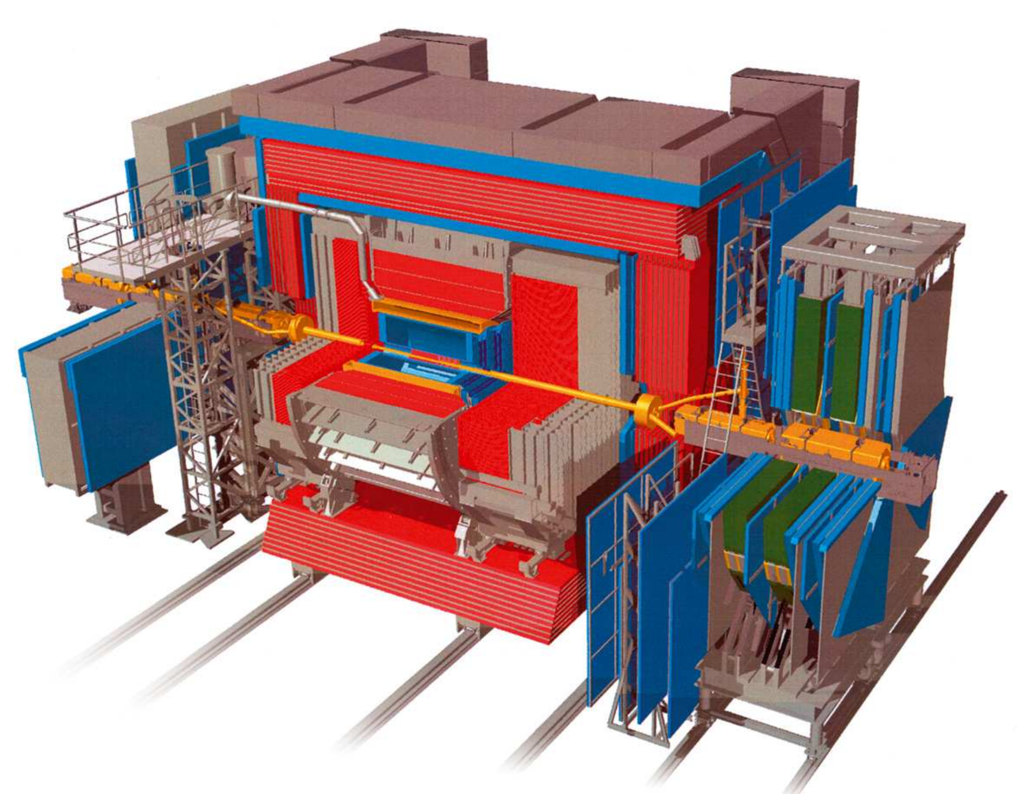
HERA with the H1 and ZEUS detectors

HERA $e^{\pm}p$ collider

- $\sqrt{s}$ = 319 GeV
  - E_e = 27.6 GeV
  - E_p = 920 GeV
- Operational until 2007







Two multi-purpose experiments: H1 and ZEUS

- Luminosity: ~ 0.5 fb^{-1} per experiment
- Excellent control over experimental uncertainties
  - Overconstraint system in DIS
  - Electron measurement: 0.5 – 1% scale uncertainty
  - Jet energy scale: 1%
  - Trigger and normalization uncertainties: 1-2 %
  - Luminosity: 1.8 – 2.5%

Inclusive deep-inelastic *ep* scattering (DIS)

ep **scattering:** $e^{\pm}p \rightarrow e^{\pm} + X$

- Center-of-mass energy

$$\sqrt{s} = \sqrt{(k+p)^2}$$

- Virtuality of exchanged boson

$$Q^2 = -q^2 = -(k-k')^2$$

- Bjorken scaling variable

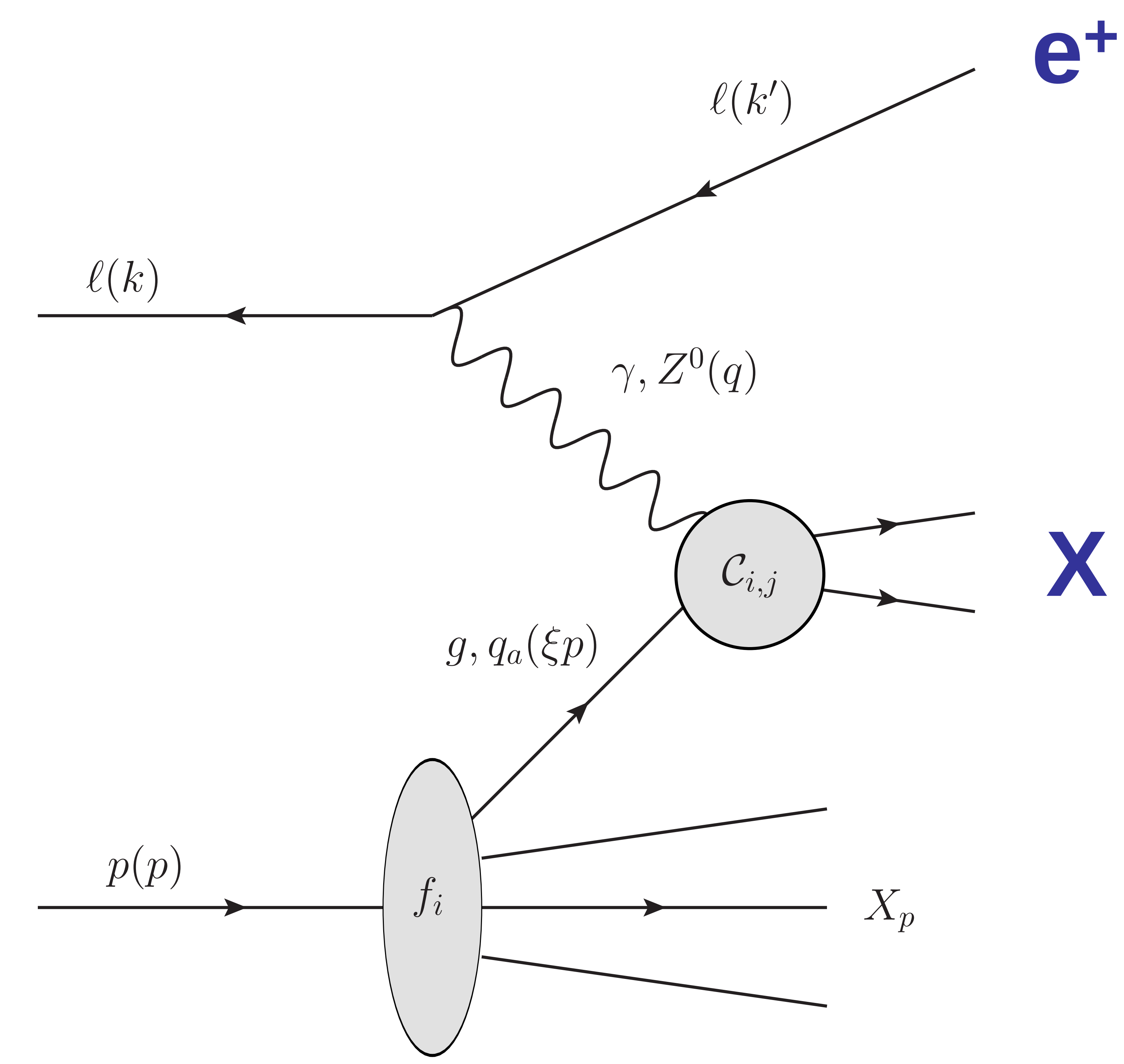
$$x_{\mathrm{Bj}} = \frac{Q^2}{2p \cdot q}$$

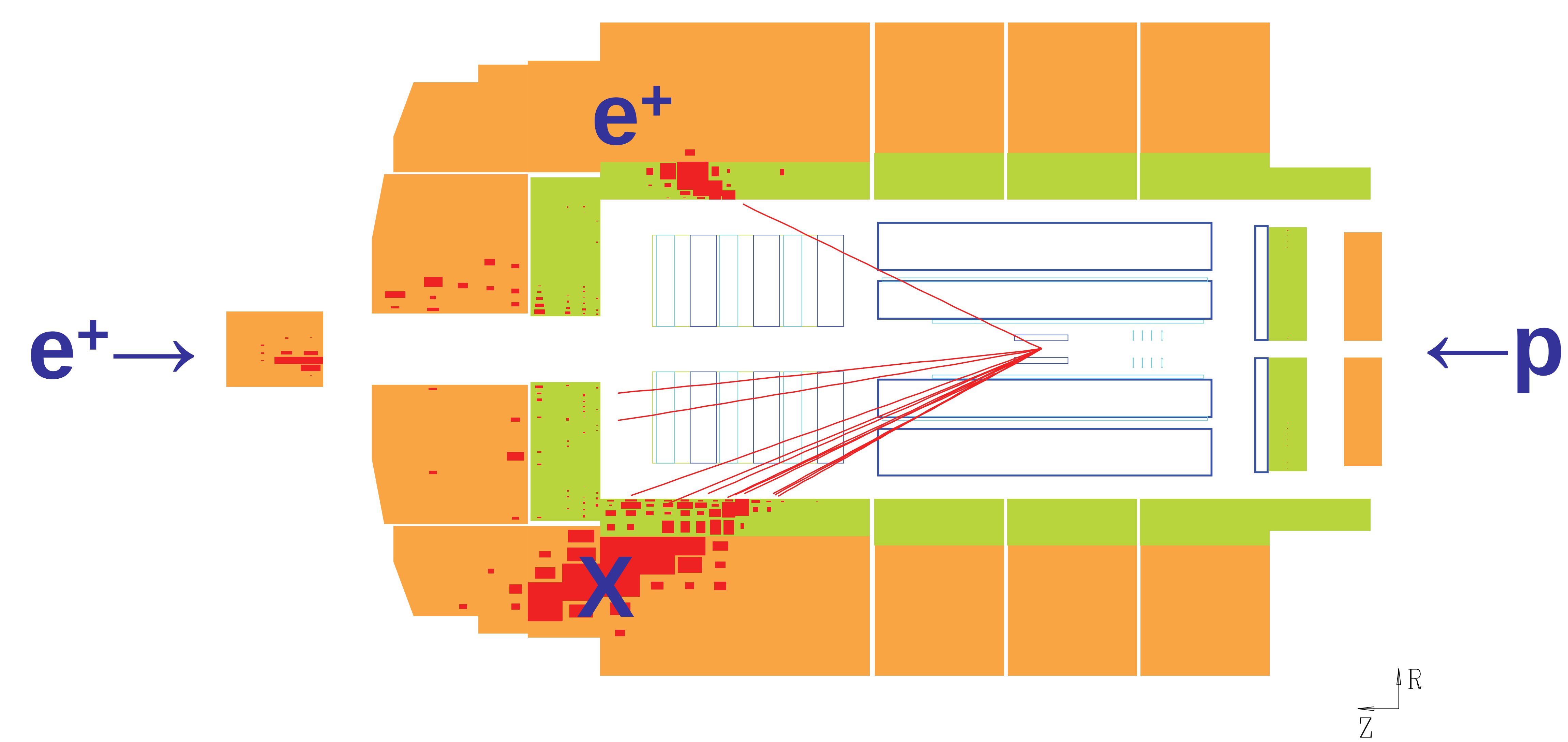
- Inealsticity

$$y = \frac{p \cdot q}{p \cdot k}$$

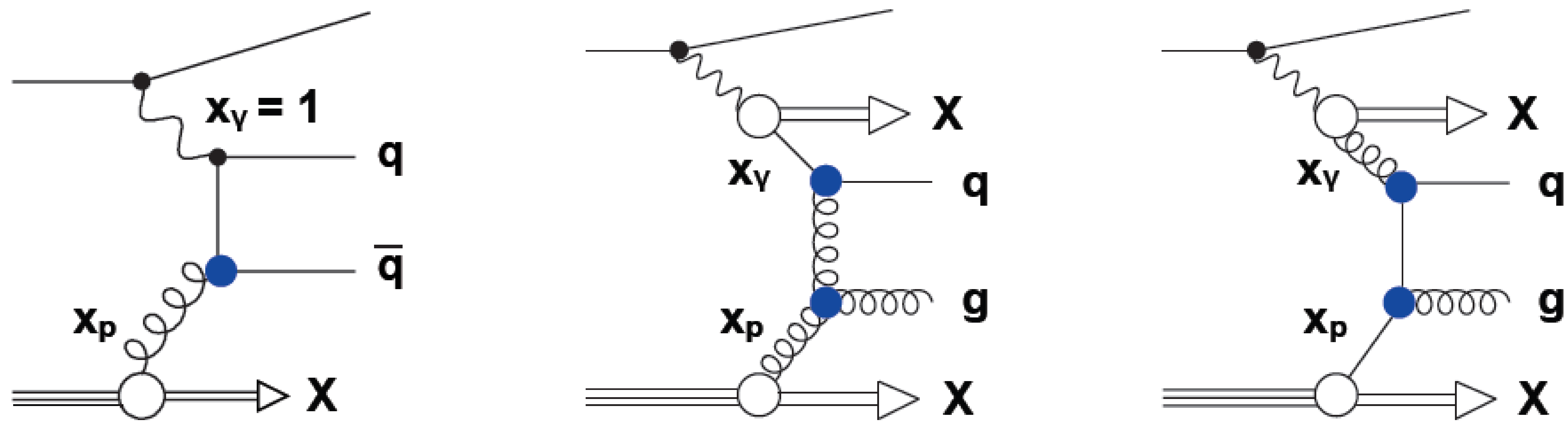
Cross section calculation

- Collinear factorization
- Hard scattering calculable in QCD (pQCD)
  - Calculable up to NNLO for inclusive NC DIS
- PDFs have to be determined from experiment





Jet production in photoproduction γp



direct photoproduction　　　　resolved photoproduction

When $Q^2 \rightarrow 0$ GeV^2: Two processes contribute

Direct photoproduction $x_\gamma^{obs} \rightarrow 1$: order of α_s

Resolved photoproduction: $x_\gamma^{obs} <$ ~0.8

- Leading order of $O(\alpha_s^2)$
- Two hadrons are involved
  -> sensitive to multi-parton interactions

Expect ≥ 2 jets in the final state

Partonic momentum fraction of the photon

$$x_\gamma^{\mathrm{obs}} = \frac{E_T^{\mathrm{jet1}} e^{-\eta^{\mathrm{jet1}}} + E_T^{\mathrm{jet2}} e^{-\eta^{\mathrm{jet2}}}}{2yE_e}$$

Analysis performed in laboratory rest frame

Inclusive jets in photoproduction: ep → e + jet + X

Nucl. Phys. B 864 (2012) 1-37

Double-differential measurements in E_T and η

- $Q^2 < 1$ GeV^2
- $142 < W_{\gamma p} < 293$ GeV
- Cross sections include every jet $E_T^{jet} > 17$ GeV, $-1 < \eta_{jet} < 2.5$
- Energy scale: 1% -> 5-10 % uncertainty

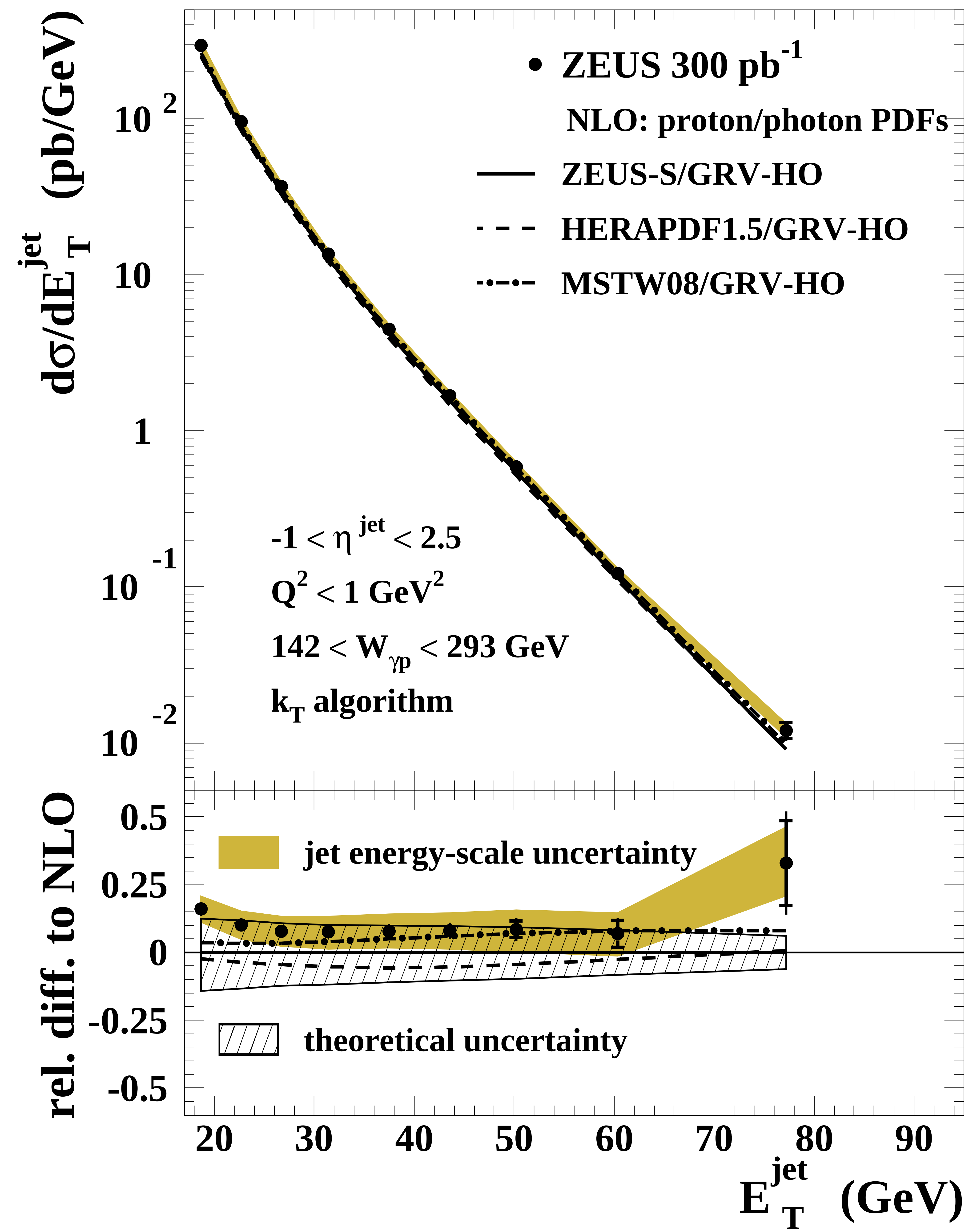
Comparison to NLO predictions

The data are well described by NLO QCD

- Klasen et al.
- ZEUS-S/GRV-HO
- $\mu_r = \mu_f = E_T^{jet}$

Disagreement at η_{jet}>2

from $17 < E_T^{jet} < 21$ GeV



Inclusive jets in photoproduction: $ep \to e + jet + X$

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Comparison of jet algorithms

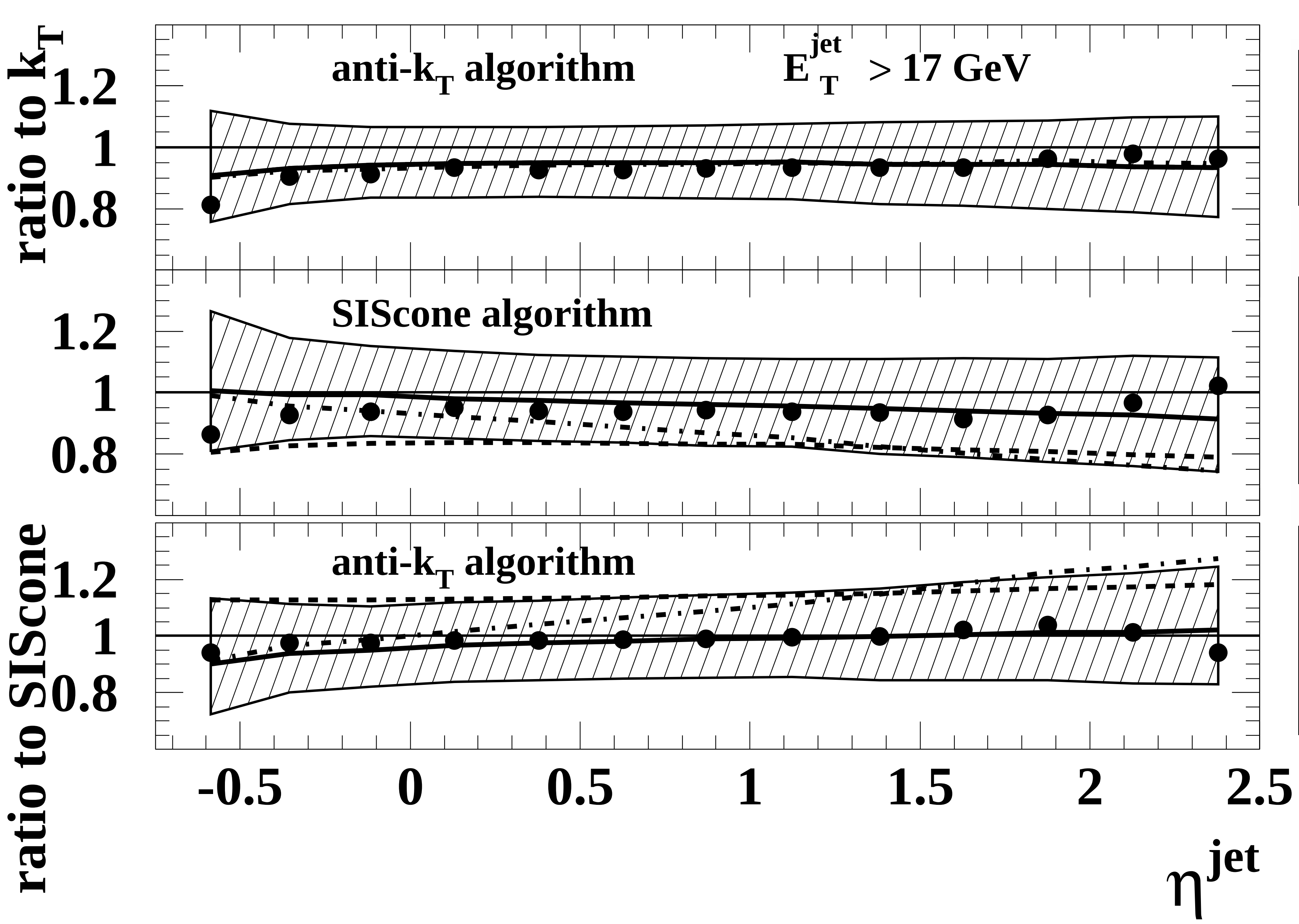
k_T, anti-k_T and *SISCone*

Hadronization corrections are largest for SISCone

Similar size for k_T and anti-k_T

Ratios of cross sections with different jet algorithm

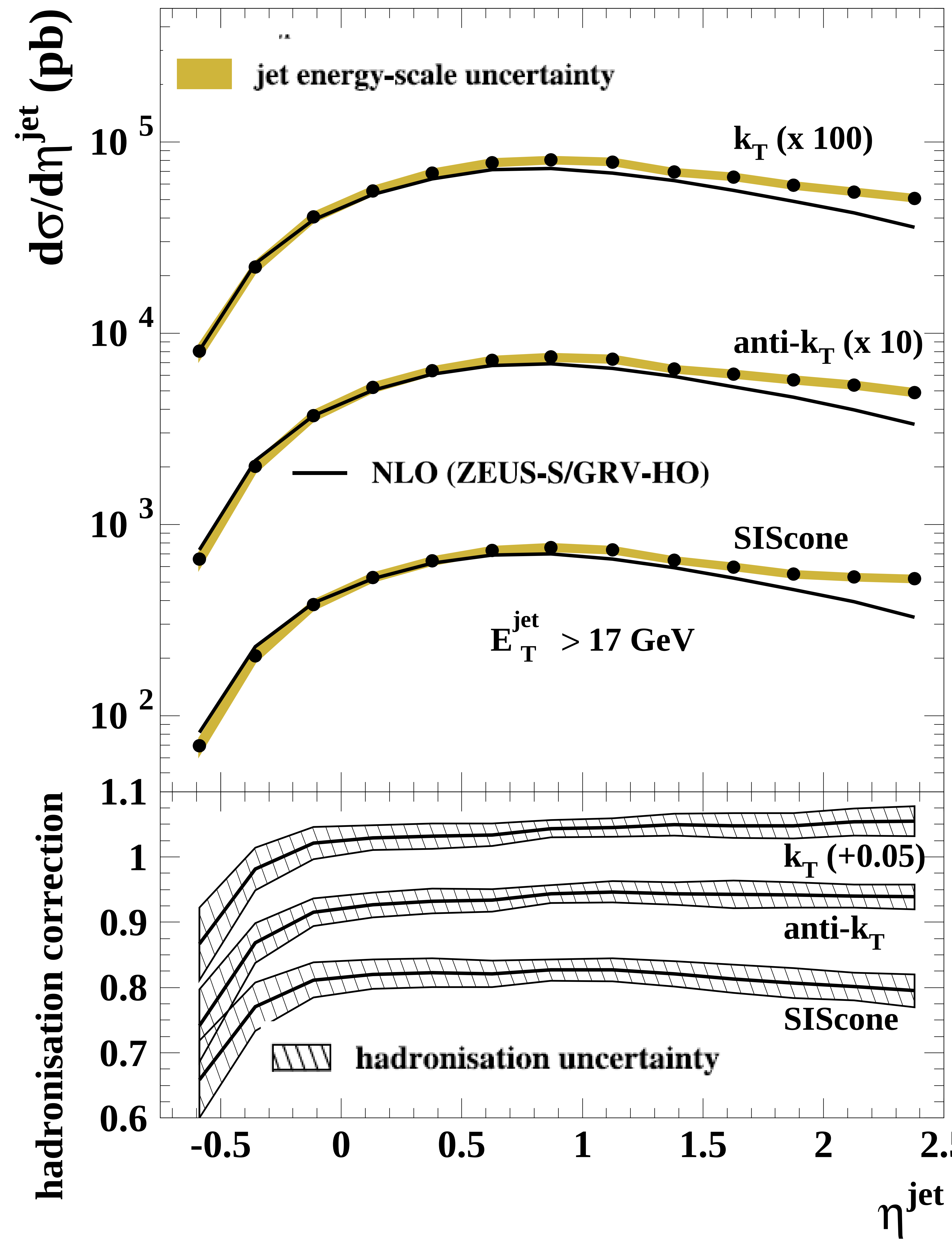
- Partial cancelletion of uncertainties (e.g. en. scale)
- anti-k_T 6% smaller cross section than k_T
- SIScone differs in shape



anti-k_t / k_t

SIS cone / k_t

anti-k_t / SIS cone



Inclusive jets in photoproduction: ep → e + jet + X

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Photoproduction: two 'hadrons' for resolved processes

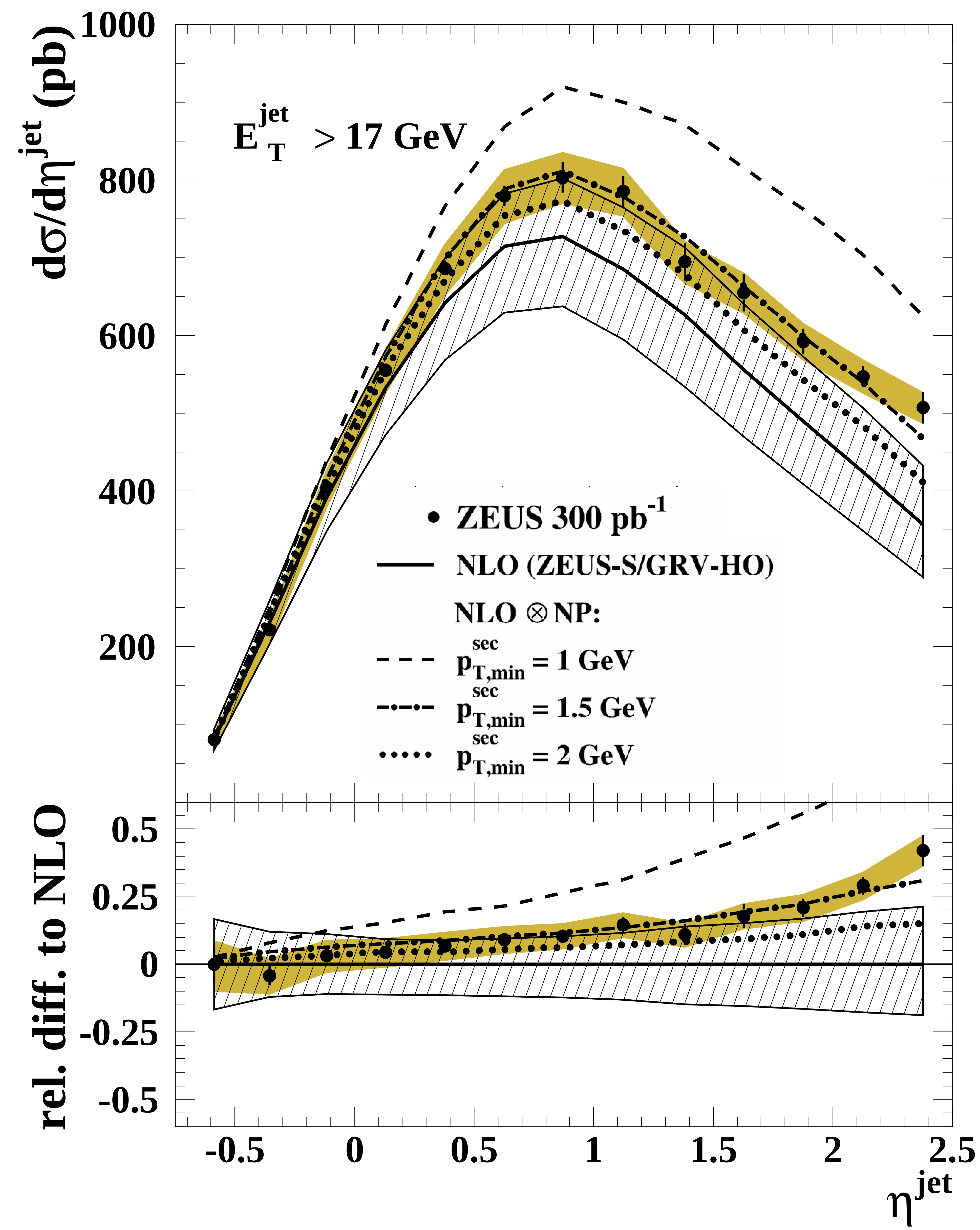
Sensitivity to **proton PDF**

Sensitivity to **photon PDF**

-> Measurements have the potential to **constrain** photon and proton **PDFs**

Sensitivity to multi parton interactions (MPI)

- Use NLO ⊗ NP
- NP simulated using Pythia
- MPI increase the predictions at low E_T jet and large η_{jet}
- Data description is improved
- Best description of data for $p_{T,min}^{sec}$ = 1.5 GeV
- Effect of MPI is reduced for E_T^{jet} > 21 GeV



Inclusive jets in photoproduction: $ep \rightarrow e + jet + X$

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Fit of NLO QCD to single differential cross sections $d\sigma / dE_T^{jet}$

Use only $21 < E_t^{jet} < 71$ GeV

$\alpha_s(M_Z)$ dependence is parameterized

ZEUS-S proton PDF at various values of $\alpha_s(M_Z)$

GRV-HO photon PDF

Consistent results for all three jet algorithms

1.8% Experimental

3.3% Theory

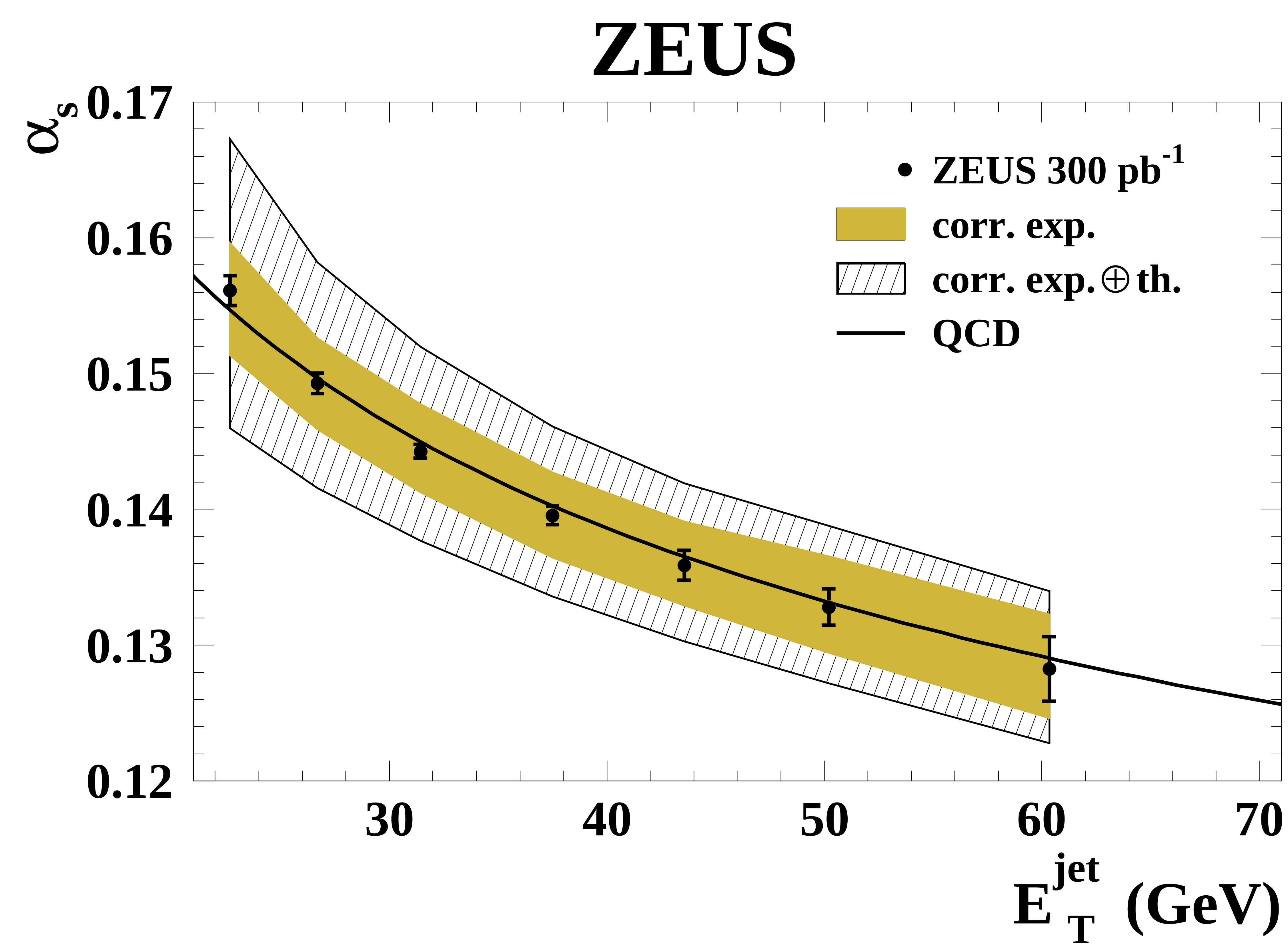
Data confirms running of α_s over a wide range of E_T

Good agreement with two-loop QCD prediction

$$\alpha_s(M_Z)|_{k_T} = 0.1206\,^{+0.0023}_{-0.0022}\,(\text{exp.})\,^{+0.0042}_{-0.0035}\,(\text{th.})$$

$$\alpha_s(M_Z)|_{\text{anti-}k_T} = 0.1198\,^{+0.0023}_{-0.0022}\,(\text{exp.})\,^{+0.0041}_{-0.0034}\,(\text{th.})$$

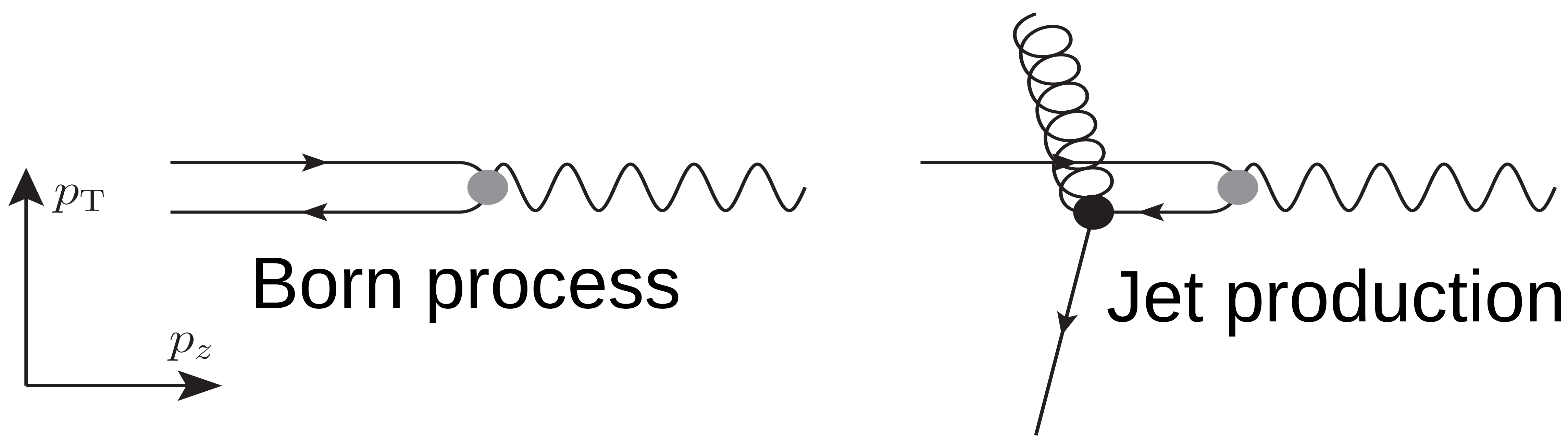
$$\alpha_s(M_Z)|_{\text{SIScone}} = 0.1196\,^{+0.0022}_{-0.0021}\,(\text{exp.})\,^{+0.0046}_{-0.0043}\,(\text{th.})$$



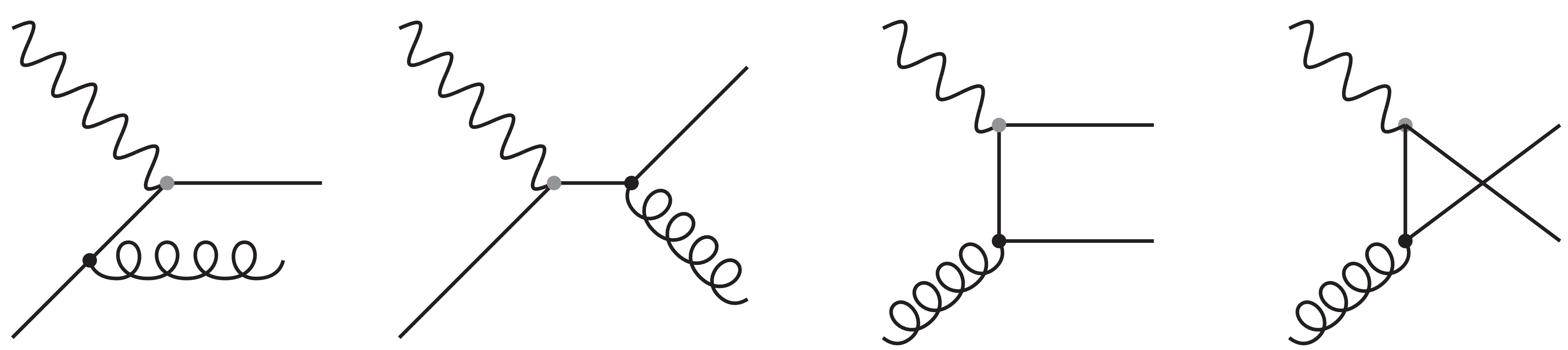
Jet production in neutral current DIS

Jet measurements performed in 'Breit frame'

Breit frame fullfils equation $2x_{\mathrm{Bj}}p + k = 0$



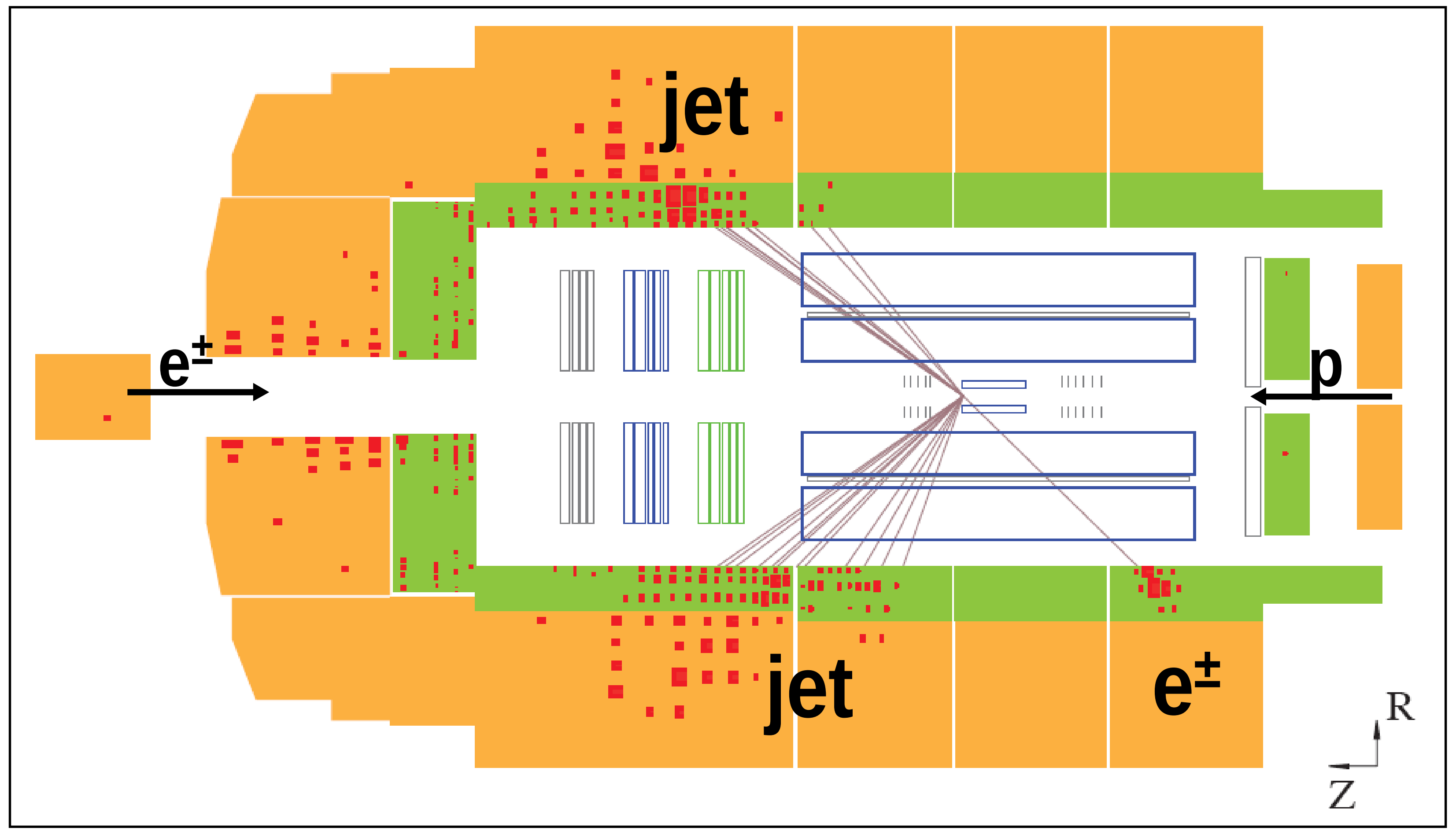
Jet production in leading-order pQCD



QCD compton | QCD compton | Boson – gluon fusion | Boson – gluon fusion

Jet production is directly sensitive to α_s

Events show two-jet topology



Inclusive jet

Count every single jet with transverse momentum

Dijet and trijet observable

Average of two/three leading jets

$$\langle p_{\mathrm{T}} \rangle_2 = (p_{\mathrm{T}}^{\mathrm{jet1}} + p_{\mathrm{T}}^{\mathrm{jet2}})/2$$

Multijet at high Q^2 – Incl. jet, Dijet, Trijet (H1)

H1prelim-12-031

Simulataneous measurement of normalized inclusive jet, dijet and trijet cross sections

- Normalization w.r.t. inclusive NC DIS
- Cancellation of normalization uncertainties
- Partly cancellation of other exp. uncertainties

Neutral current phase space

$150 < Q^2 < 15000$ GeV^2

$0.2 < y < 0.7$

Jet acceptance

$-1.0 < \eta_{lab} < 2.5$

Inclusive Jet

$7 < p_T^{jet} < 50$ GeV

Dijet and Trijet

$5 < p_T^{jet} < 50$ GeV

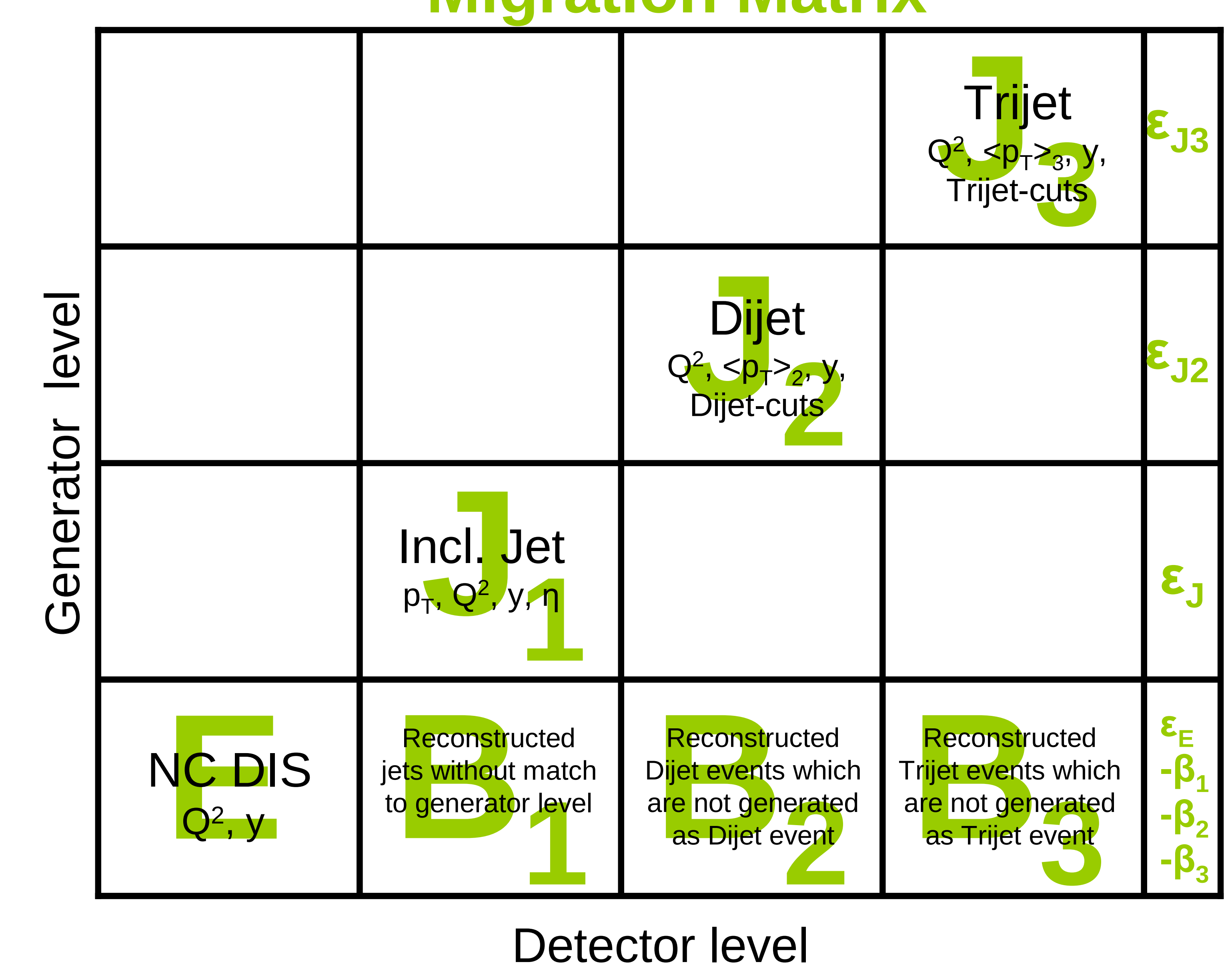
$M_{12} > 16$ GeV

$7 < \langle p_T \rangle < 50$ GeV

Multidimensional regularized unfolding

- Four double-differential measurements are unfolded simultaneously
  - NC DIS, inclusive jet, dijet and trijet
- Using TUnfold
- Statistical correlations considered
- Enlarged phase space
- Up to 6 observables are considered for migrations

Migration Matrix



Multijet at high Q^2 – Incl. jet, Dijet, Trijet (H1)

H1prelim-12-031

Jet energy scale 1%

-> 3 - 7% effect on cross sections

NLO predictions

nlojet++, fastNLO and QCDNUM

CT10, α_s=0.118, $\mu_r^2 = (Q^2+p_T^2)/2$

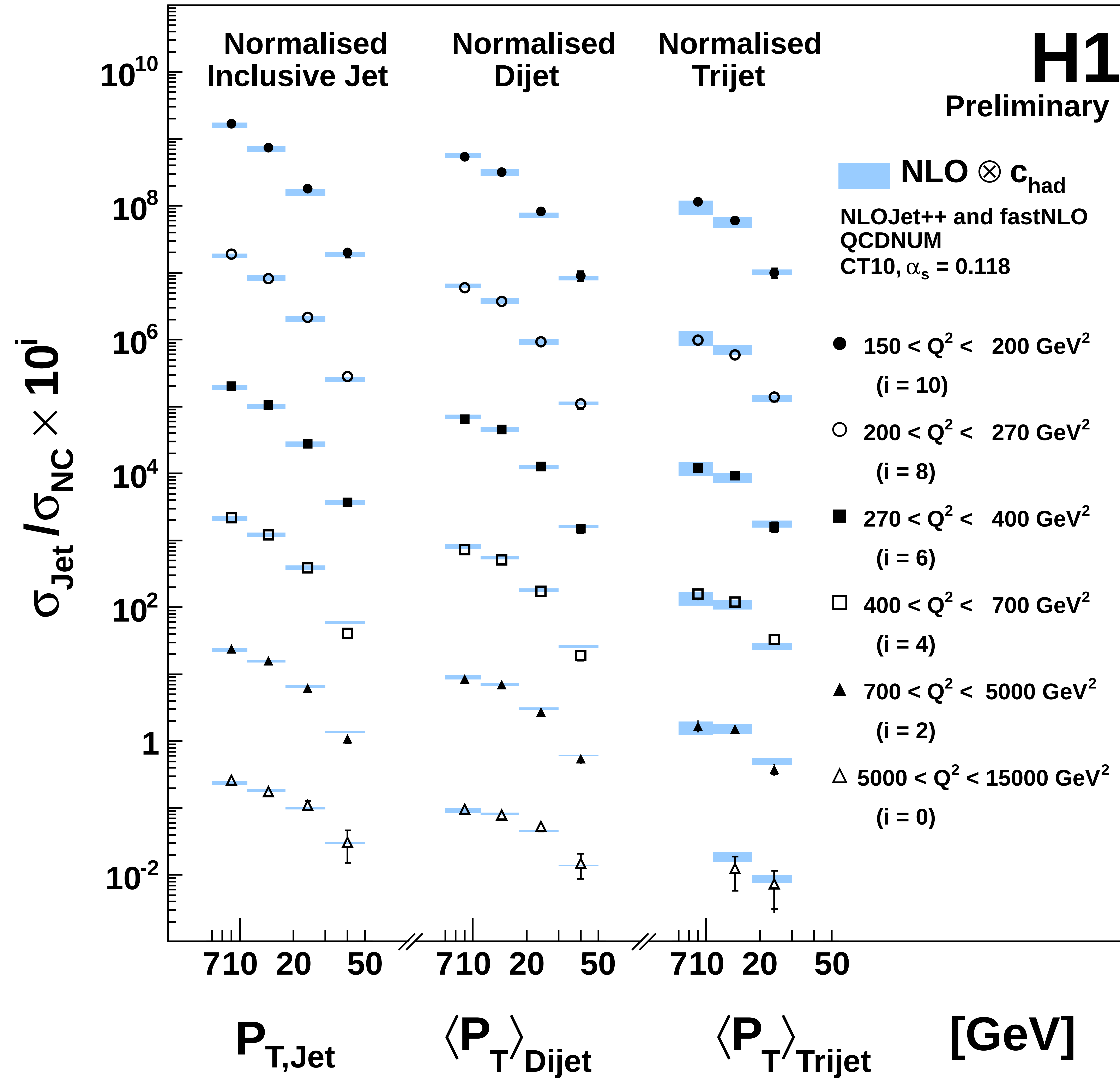
Trijet (NLO) is of leading order $O(\alpha_s^2)$

Data well described by theory

PDF uncertainty ~ 1%

Correlations between observables are known

-> Can be used together in fit



Multijet at high Q^2 – Incl. jet, Dijet, Trijet (H1)

H1prelim-12-031

Statistical correlations available

All data points can be used together in a fit

Normalization uncertainties have been canceled out

$\alpha_s(M_Z)$ from inclusive jet: 0.1197 ± 0.0008(exp) ± 0.0057 (theo)

$\alpha_s(M_Z)$ from dijet: 0.1142 ± 0.0008(exp) ± 0.0052 (theo)

$\alpha_s(M_Z)$ from trijet: 0.1185 ± 0.0018(exp) ± 0.0047 (theo)

Hessian method for α_s determination

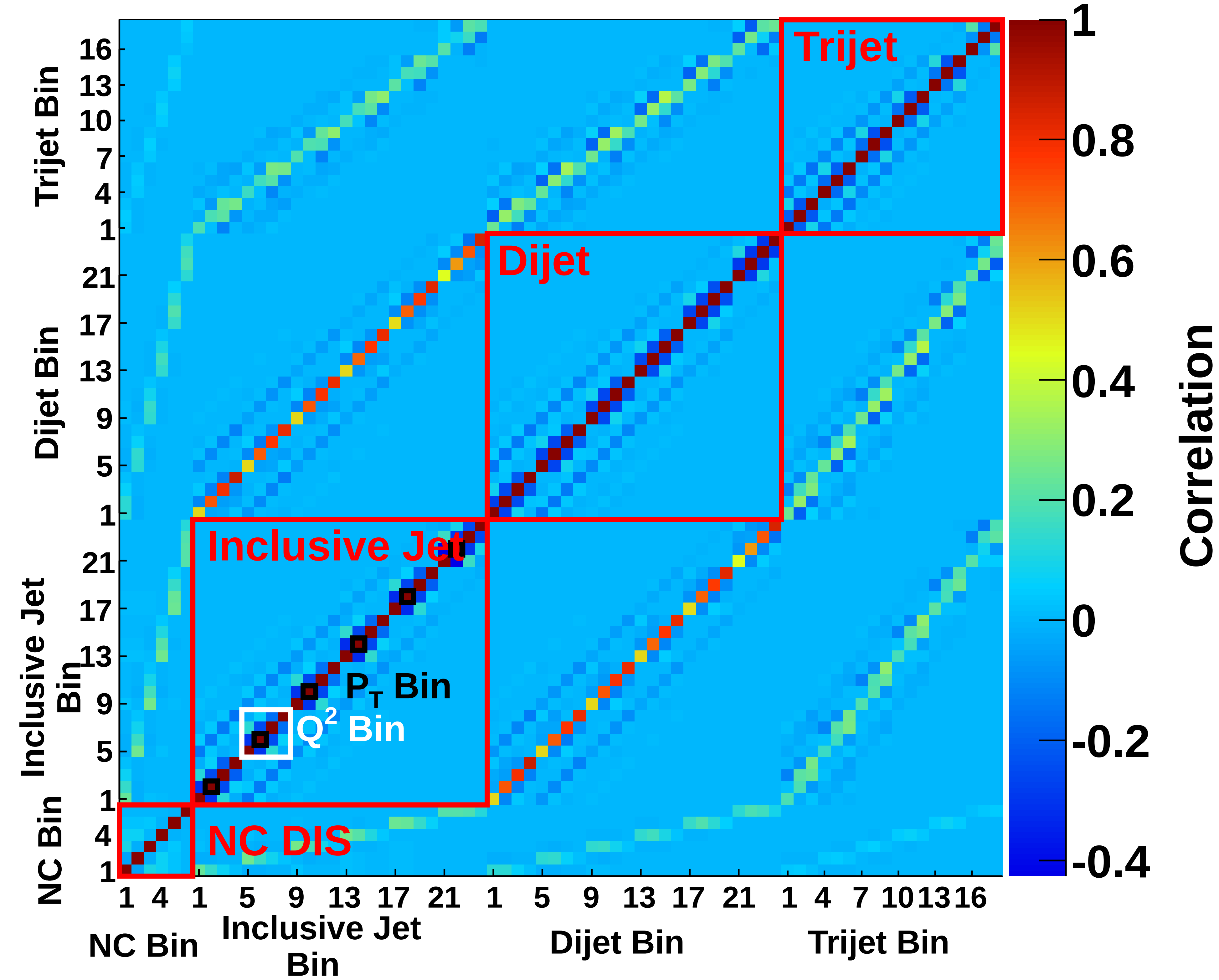
Constrain k-factor: require k < 1.3

Uncertainty

1% experimental

3.6% theory and PDF

Correlation matrix



Normalized Multijet (k < 1.3)

$$\alpha_s(M_Z) = 0.1163 \pm 0.0011(\text{exp}) \pm 0.0014\ (\text{PDF}) \pm 0.0008\ (\text{had}) \pm 0.0040\ (\text{theo})$$

$$\chi^2 / \text{ndf} = 53.3 / 41 = 1.30$$

$\alpha_s(M_Z)$ from inclusive DIS & inclusive jet in DIS

H1prelim-11-034, ZEUS-prel-11-001

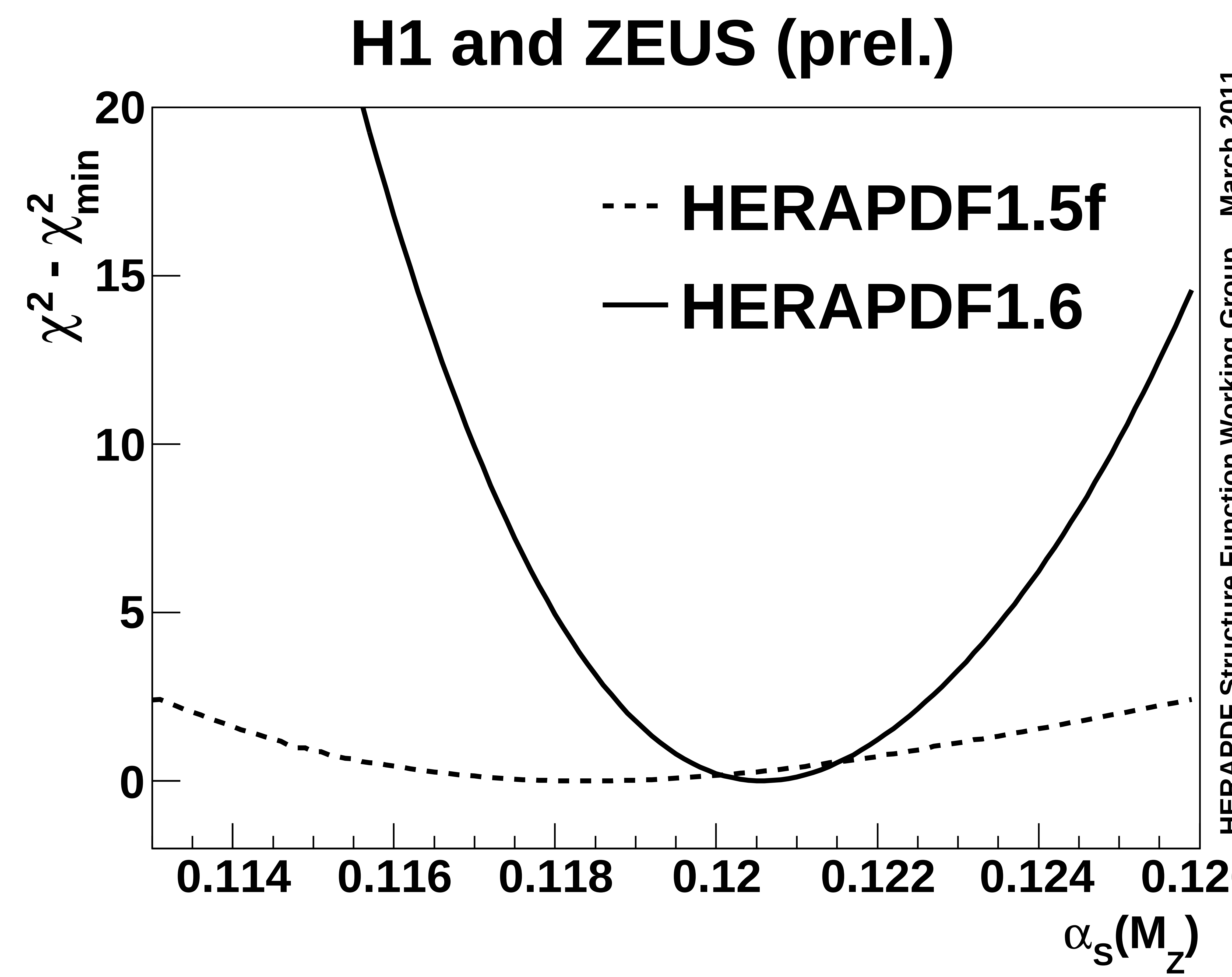
Combined fit of PDF and $\alpha_s(M_Z)$ to inclusive DIS data and inclusive jet data

HERAPDF1.5f: incl. DIS only

HERAPDF1.6: incl. DIS and jet data

Jet data is capable of reducing correlation between α_s and gluon

Scale uncertainty from variation of renormalization and factorization scale



$\alpha_s(M_Z)$ from combined fit with PDFs from incl. DIS and jet data in NLO

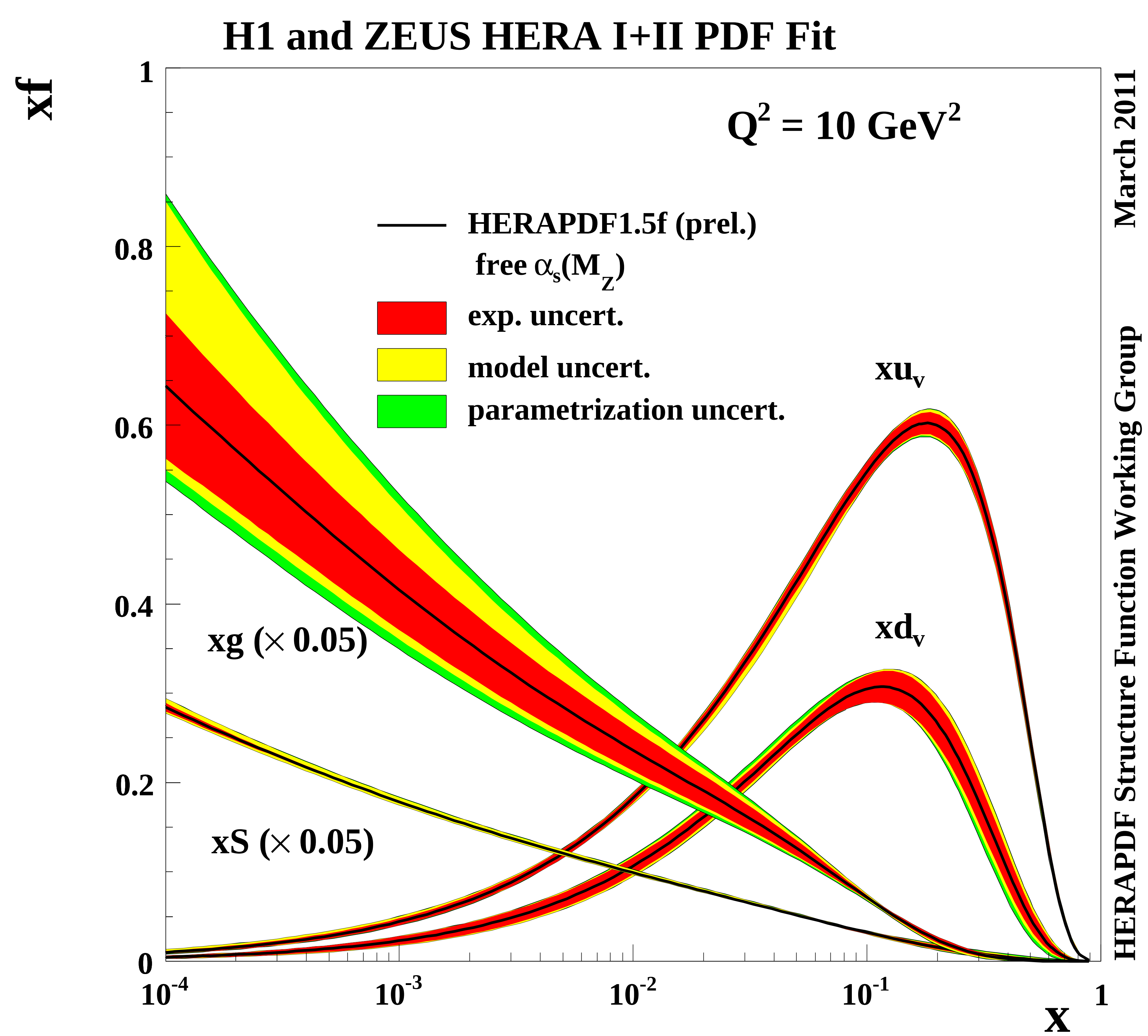
$$\alpha_s(M_Z) = 0.1202 \pm 0.0019(\text{exp/model/param/had.}) \pm^{0.0045}_{0.0036}(\text{scale})$$

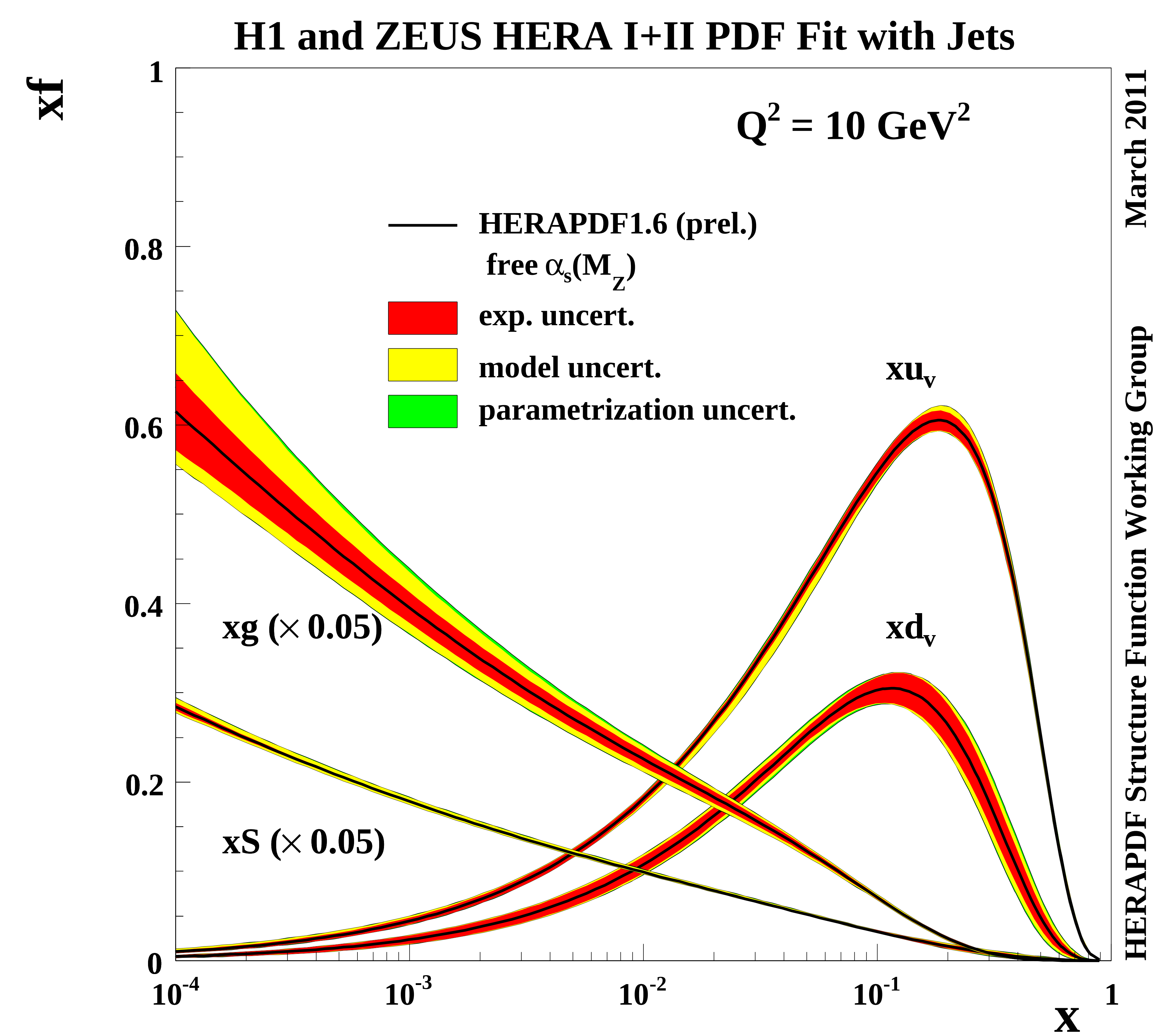
Inclusive jets in PDF fits

H1prelim-11-034, ZEUS-prel-11-001

Double-differential inclusive jet data from H1 and ZEUS are added to the PDF fit

DIS jets have high sensitivity to gluon density through boson-gluon fusion: $\sigma \sim \alpha_s \times g$





PDF fit of inclusive data (without jets)

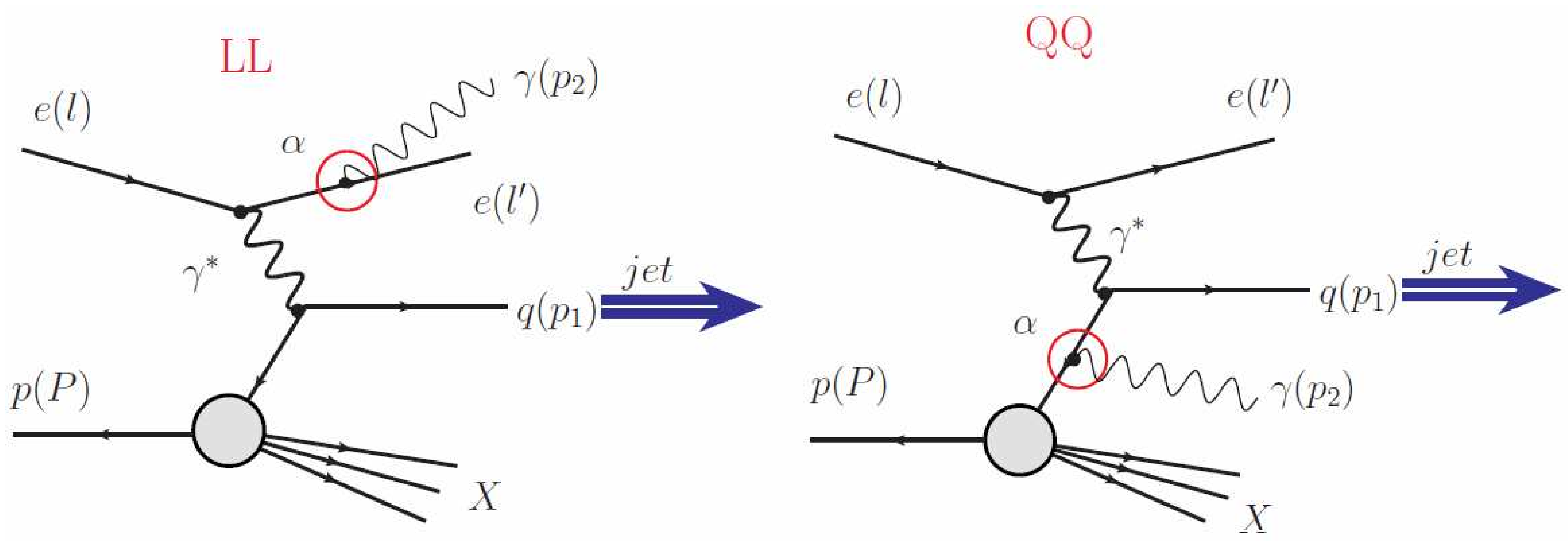
gluon uncertainty blows up at small x

PDF fit of inclsuive data and inclusive jet data

- Dramatically decreases the low-x gluon uncertainty
- Also model and parametrization uncert. reduced

Prompt photon plus jets in DIS: ep → e+γ+j+X

Phys Lett B 715 (2012) 88-97



Photon radiation unaffected by parton hadronization

-> Direct probe of underlying partonic process

-> Allows to test QCD 'matrix elements'

Phase space

DIS: $10<Q^2<350$ GeV^2, $E_e>10$ GeV, $\theta_e>140°$

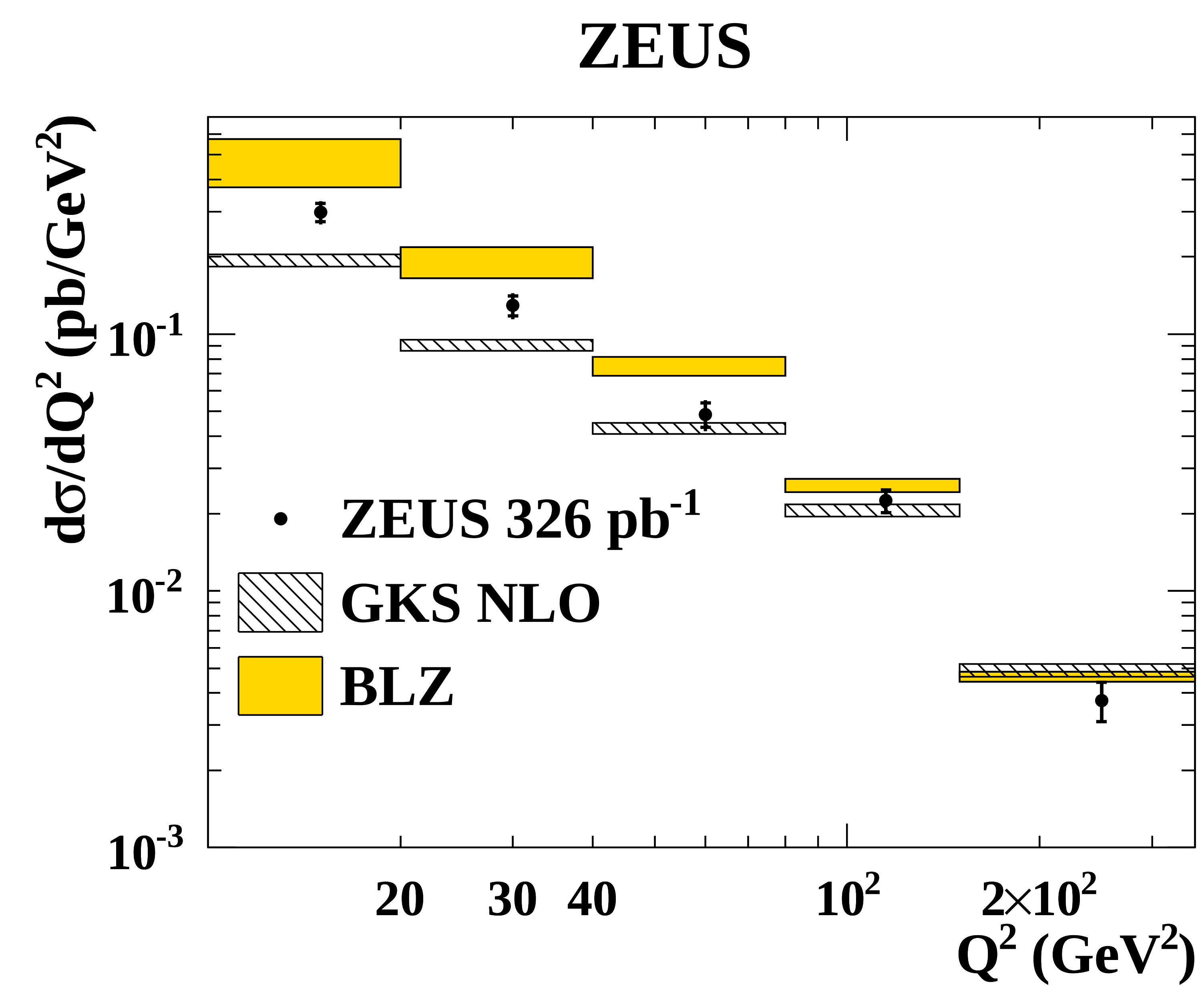
photon: $4<E_T^\gamma<15$ GeV, $-0.7<\eta_\gamma<0.9$, $E_T^\gamma/E_T^{\gamma\text{-jet}}>0.9$

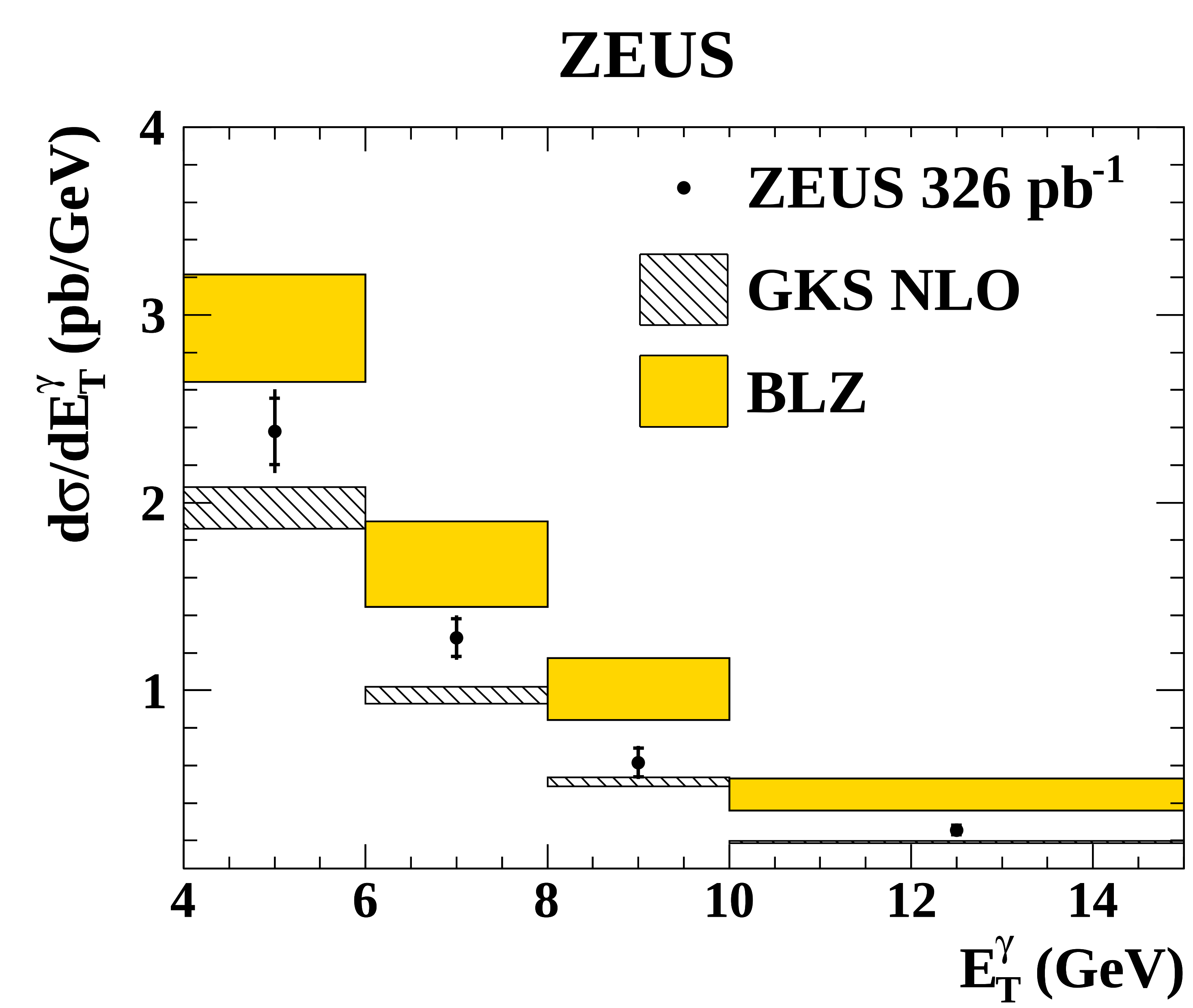
jet: $E_T^{jet}>2.5$ GeV, $-1.5<\eta_{jet}<1.8$

Theory

- GKS: NLO ($O(\alpha^3\alpha_s)$) with BFG parton-photon frag. functions
- BLZ: k_T factorization approach

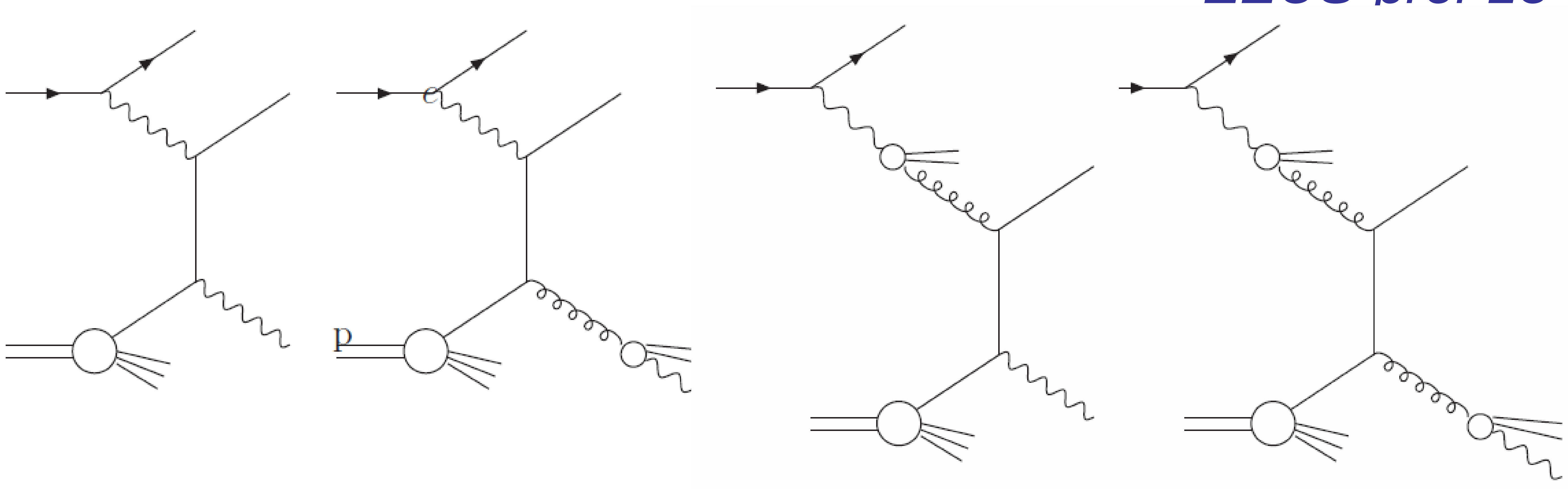
Photon and jet E_T: shape well described by GKS and BLZ
GKS: Low-x and low Q^2 unerestimated

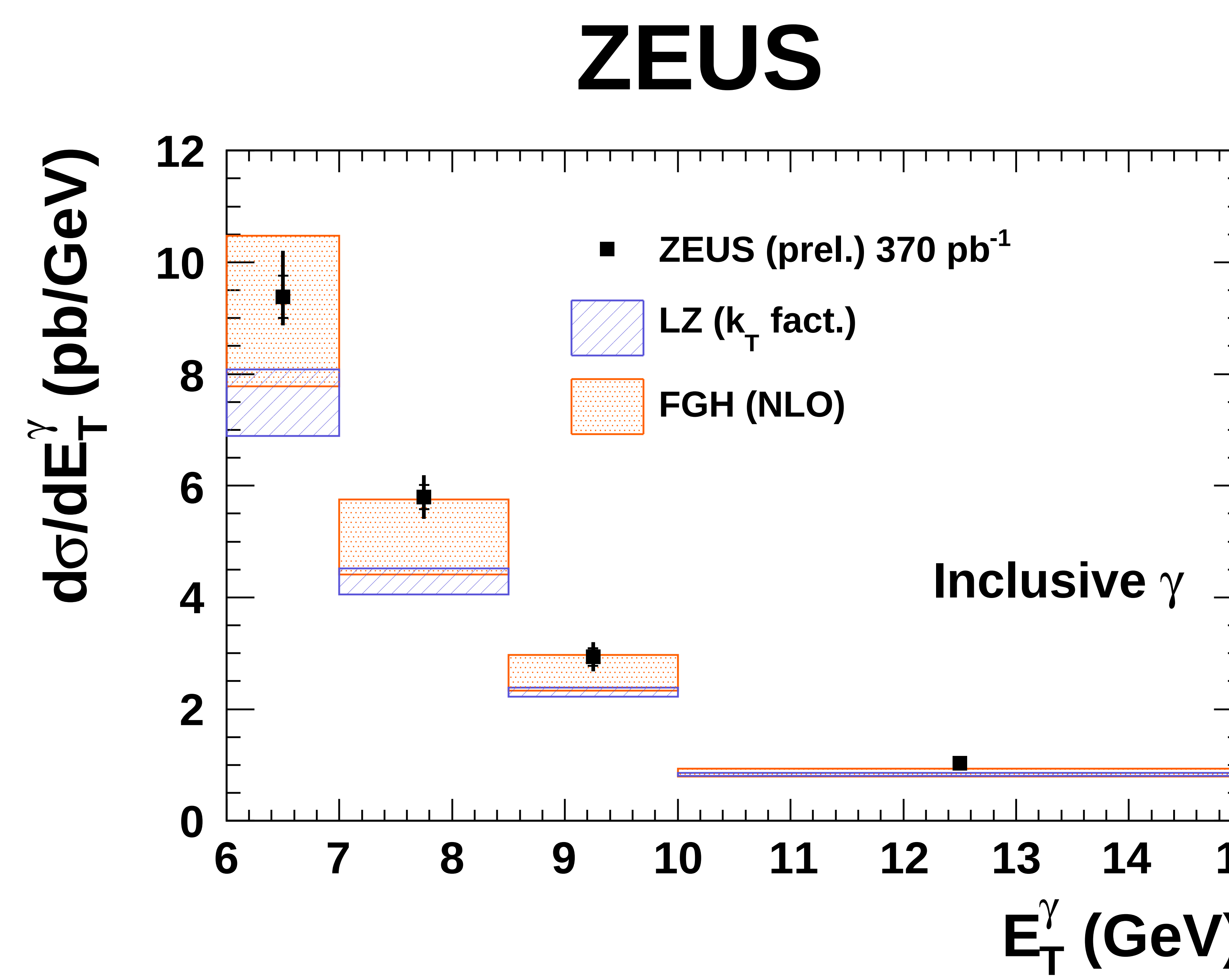


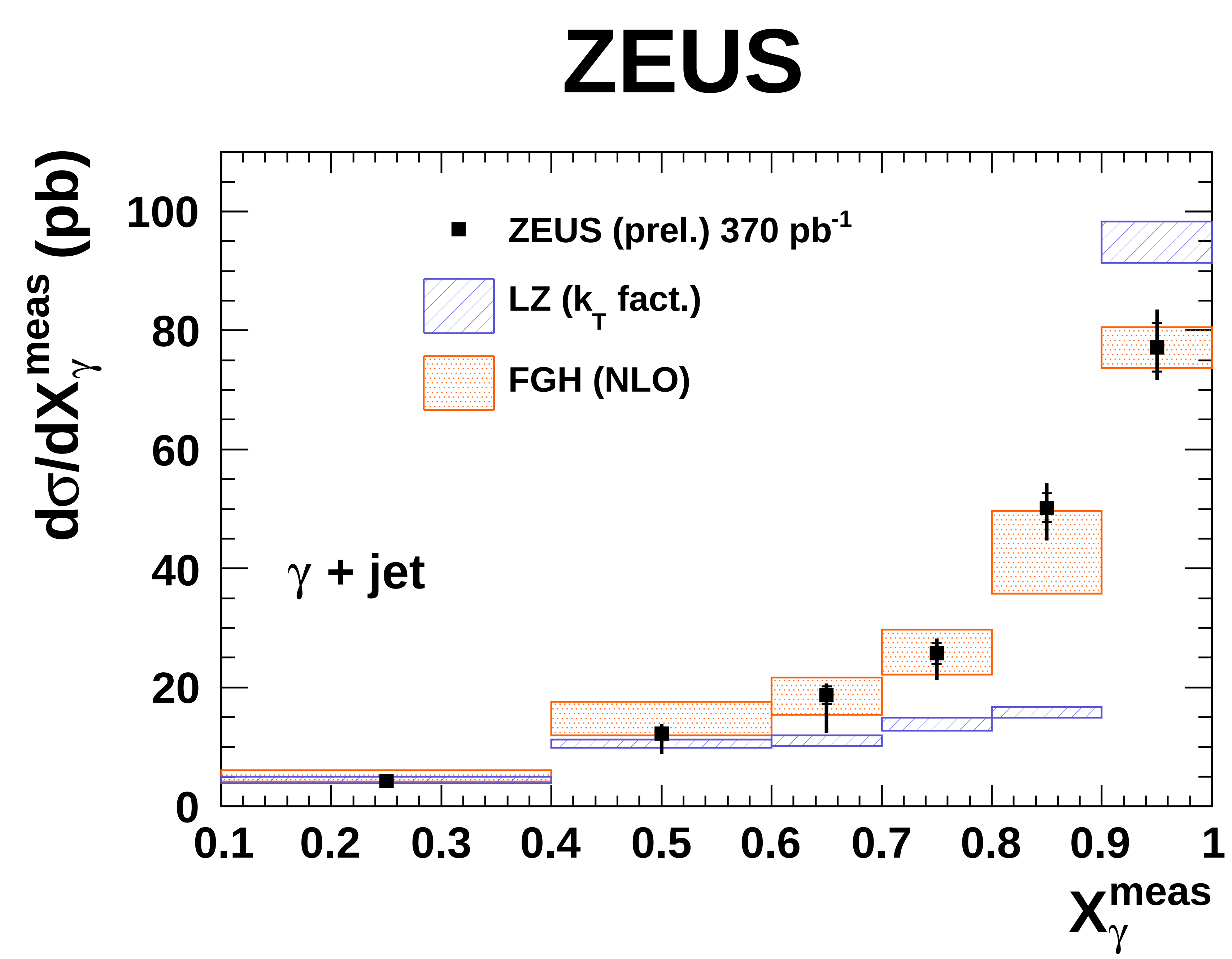


Prompt photons in γp: ep → γ+X (+j) [+e] (ZEUS)

ZEUS-prel-13-001







Prompt photons in photoproduction $Q^2<1$ GeV^2

Direct and resolved processes

Prompt radiation and fragmentation

Measured with and without accompanying jet

Theory

FGH: NLO with fragmentation functions ($O(\alpha^3\alpha_s^2)$)

- Shape well descibed; tend to be lower

BLZ: k_T factorization with unintegrated parton densities

- Most data well described
- problems at direct peak in γ+jet ($x_\gamma^{meas} \to 1$)

Comparison of $\alpha_s(M_Z)$ values

HERA jet cross sections

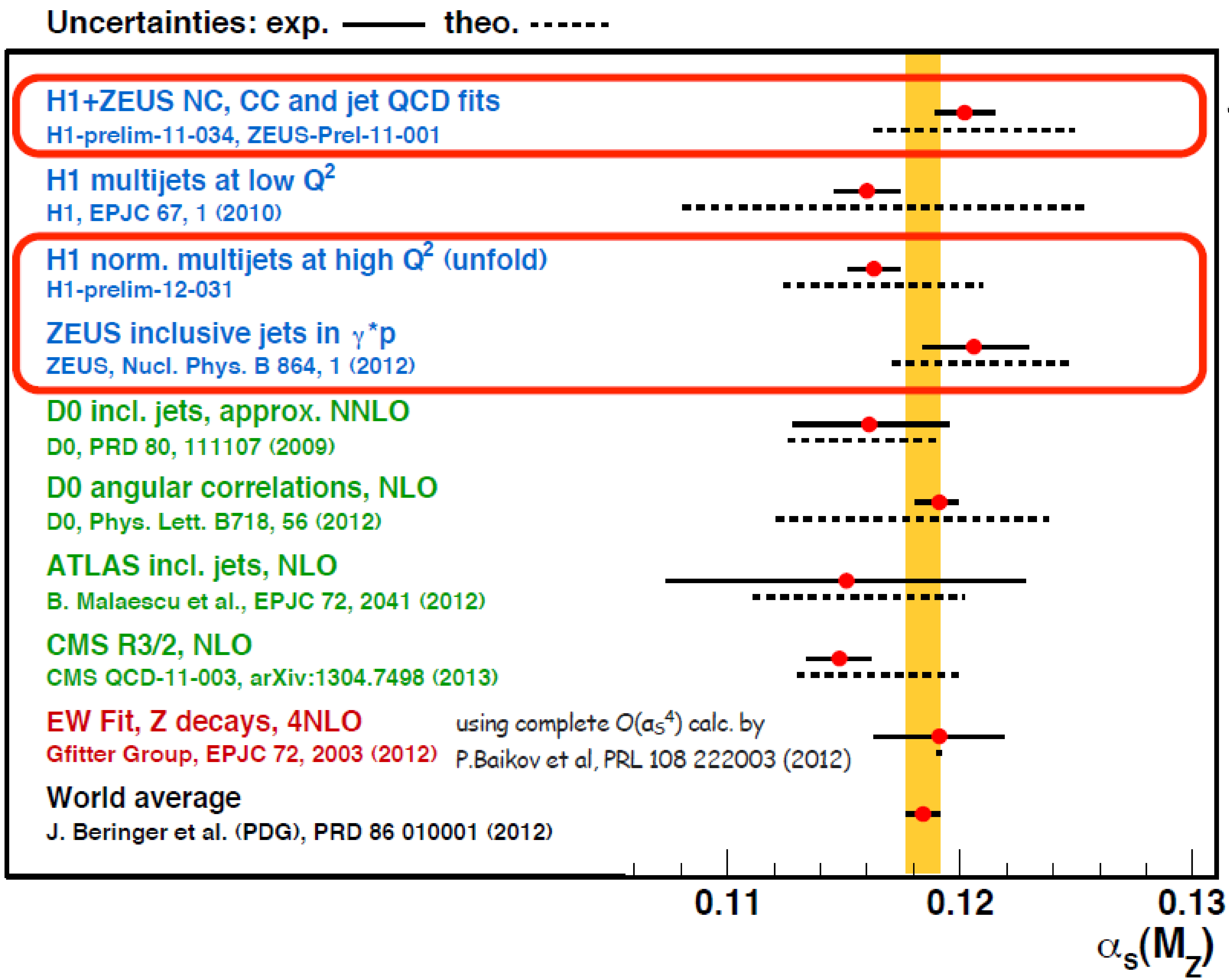
High experimental sensitivity to $\alpha_s(M_Z)$

Complementary methods and processes

Consistent results

Theory uncerainty from missing higher order dominate

NNLO precision is needed



Summary

Very active physics analyses at HERA ongoing

Experiments provide measurements with final precision

- Jet energy scale ~1%; final calibration of data!
- Highly ambitious analyses techniques (e.g. 6-dimensional reg. unfolding)

Rich variety of QCD physics with high precision

- Jets in DIS and photoproduction
- Studying hard QCD interactions
- Sensitivity to multi parton interactions in γp

Including DIS jet data in PDF fits shows high sensitivity to gluon density and $\alpha_s(M_Z)$ in PDF fits

$\alpha_s(M_Z)$ values from jets at HERA reach experimental precision of <1%

However: limited by theory with 3-4 % precision -> We need NNLO for jets (also in DIS)

Inclusive jets in photoproduction: ep → e + jet + X

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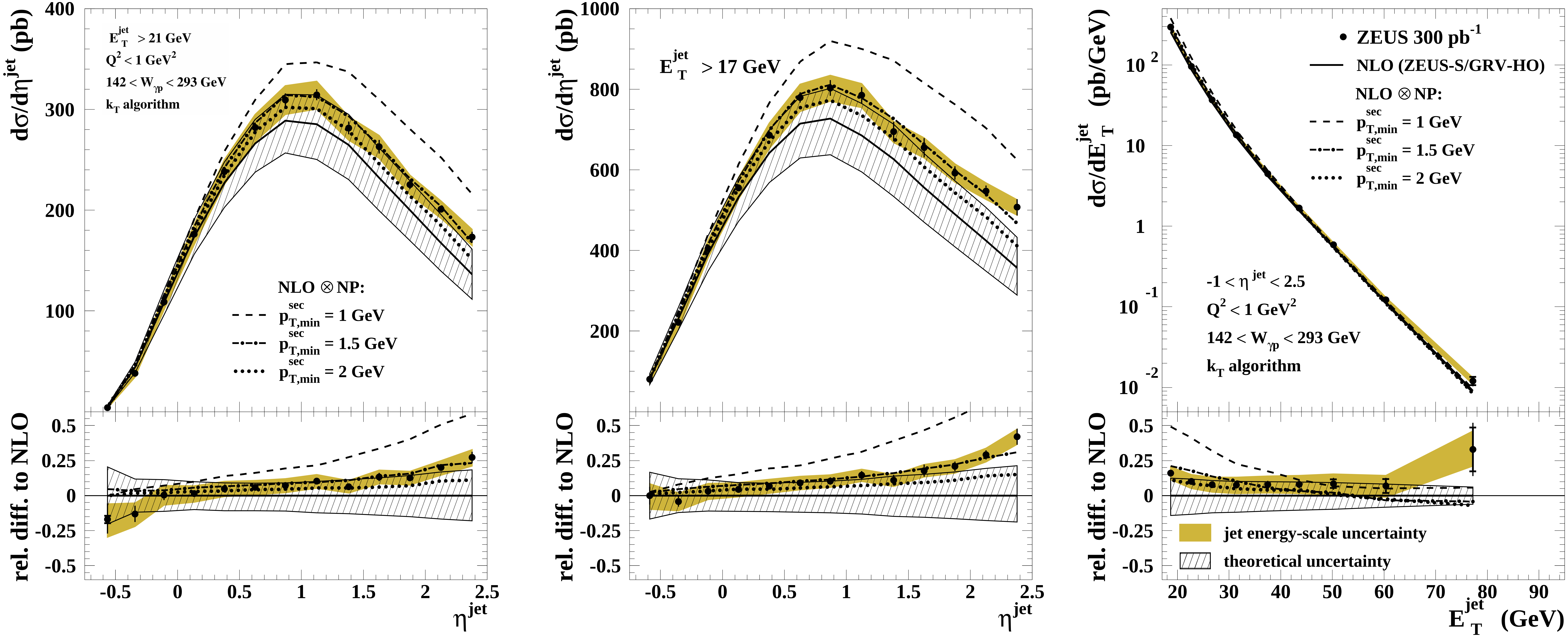
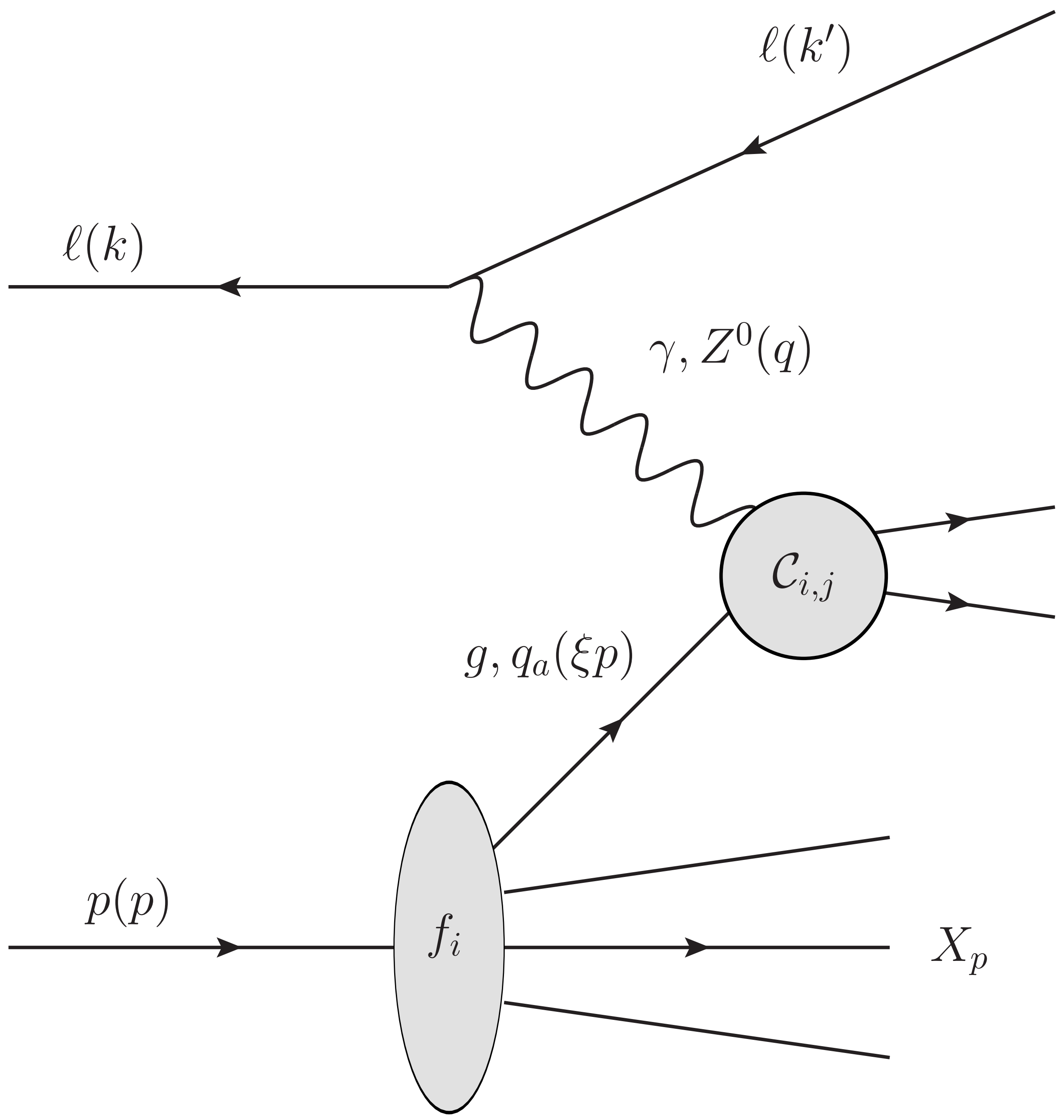


Jet production in *ep* scattering

Deep-inelastic *ep* scattering



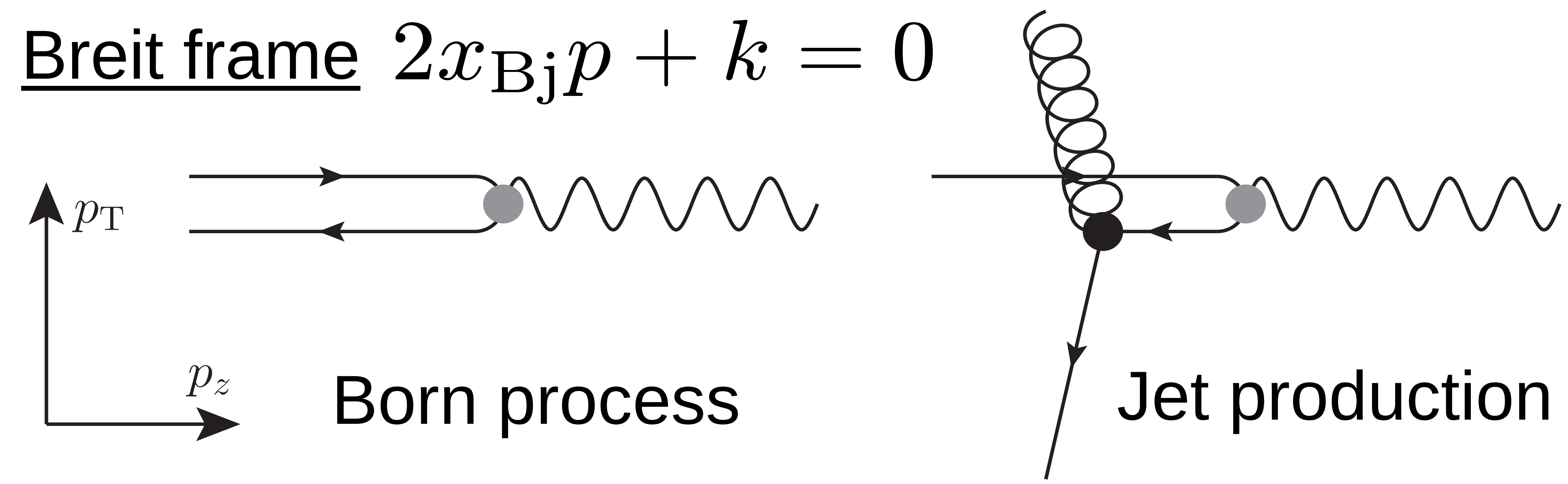
Boson virtuality $Q^2 = -q^2 = -(k-k')^2$

Inelasticity $y = \dfrac{p \cdot q}{p \cdot k}$

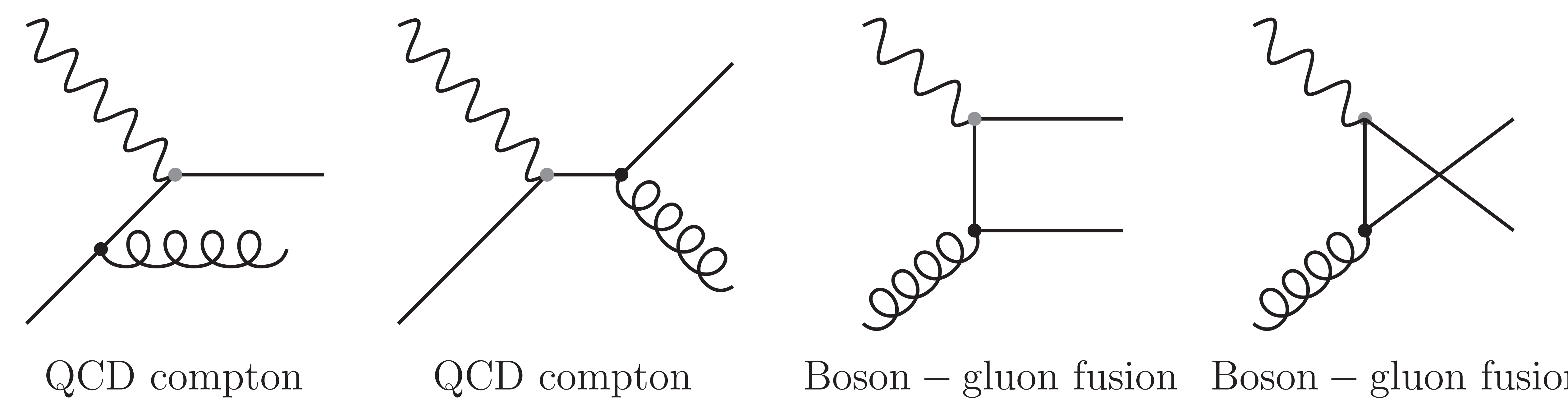
Bjorken variable $x_{\mathrm{Bj}} = \dfrac{Q^2}{2p \cdot q}$

Jet measurements performed in 'Breit frame'

<u>Breit frame</u> $2x_{\mathrm{Bj}}p + k = 0$

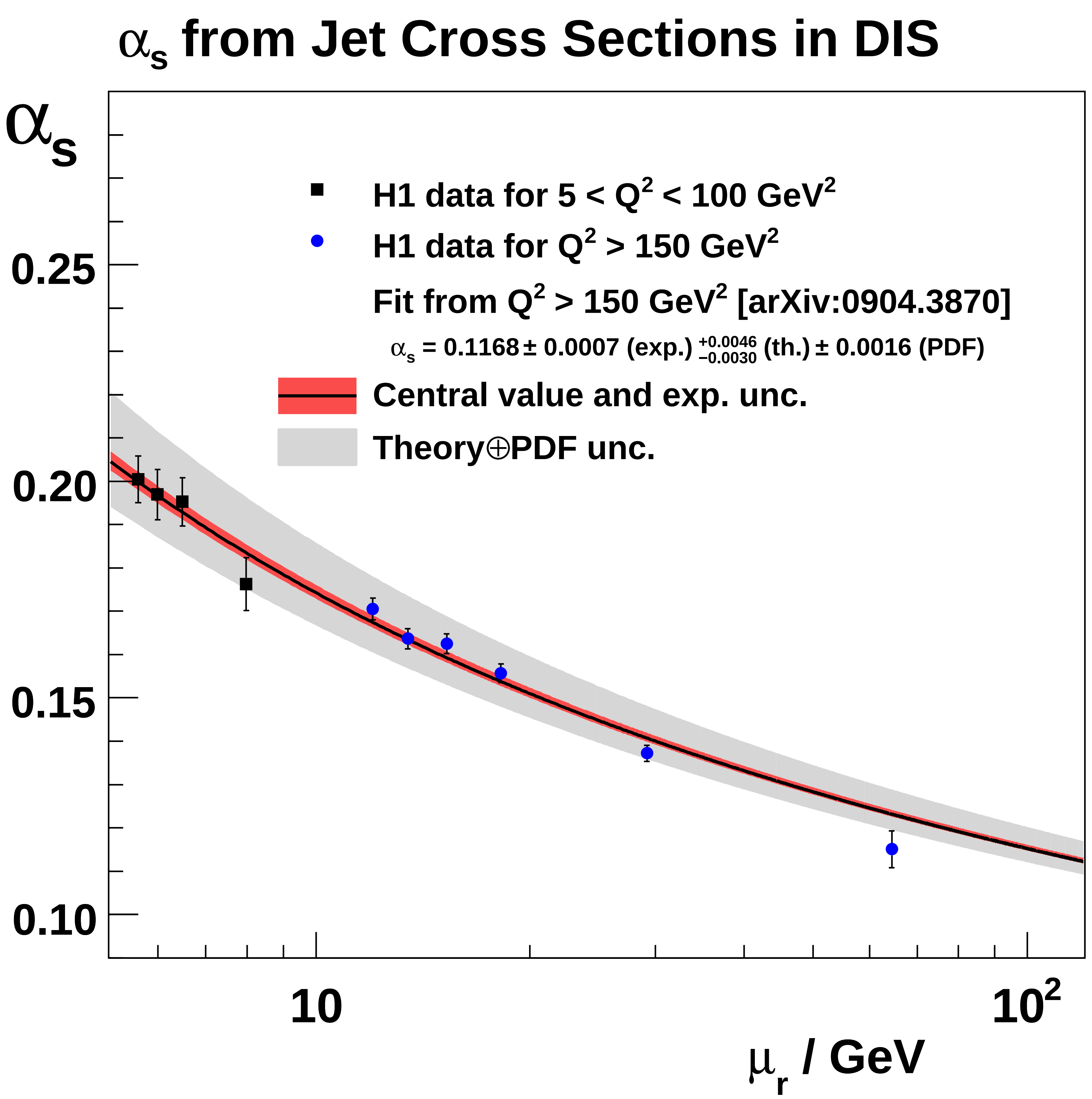


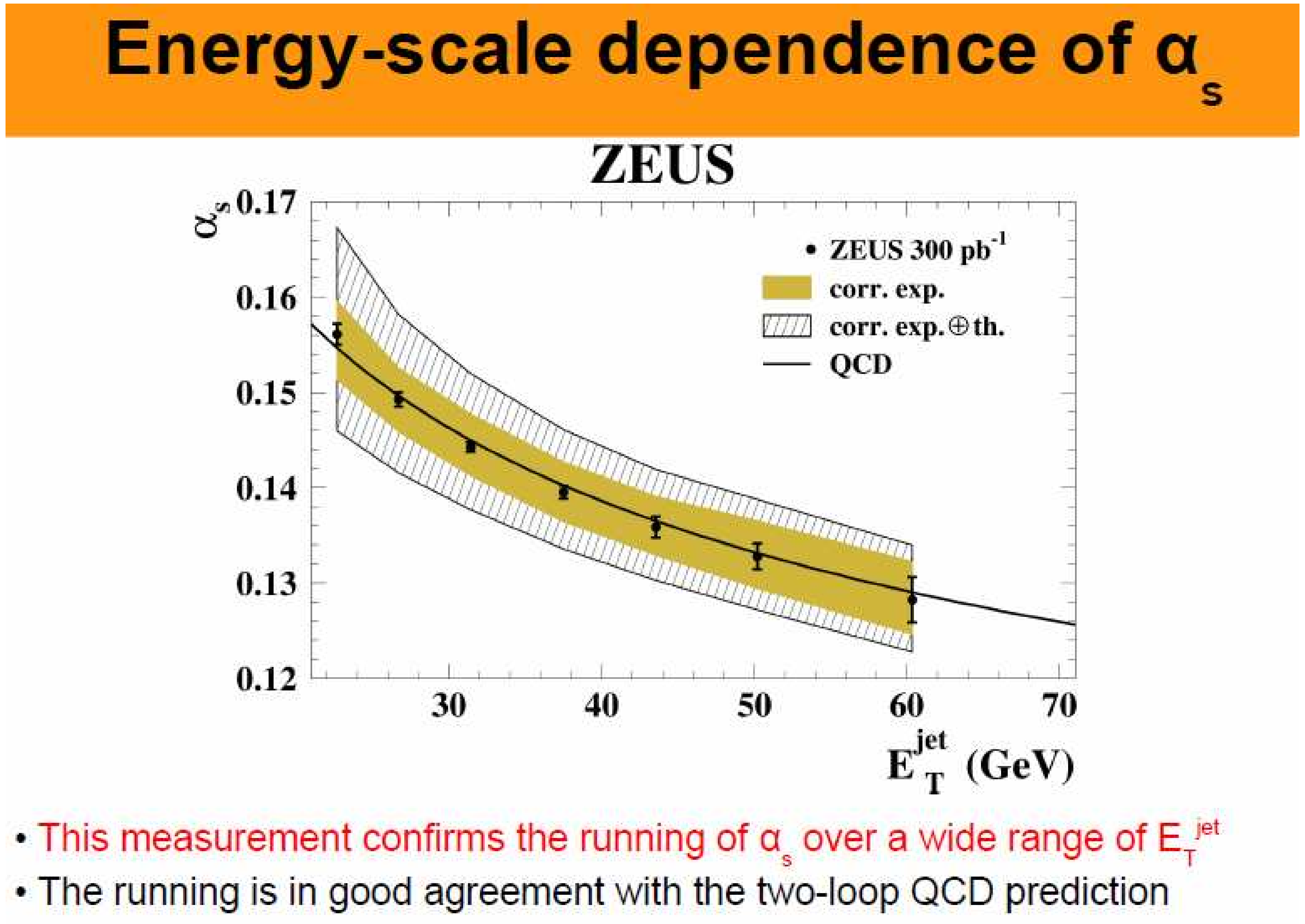
Jet production in leading-order pQCD



Jet production is directly sensitive to α_s

Probe running of alpha_s





Inclusive Jets in photoproduction: ep → e + jet + X

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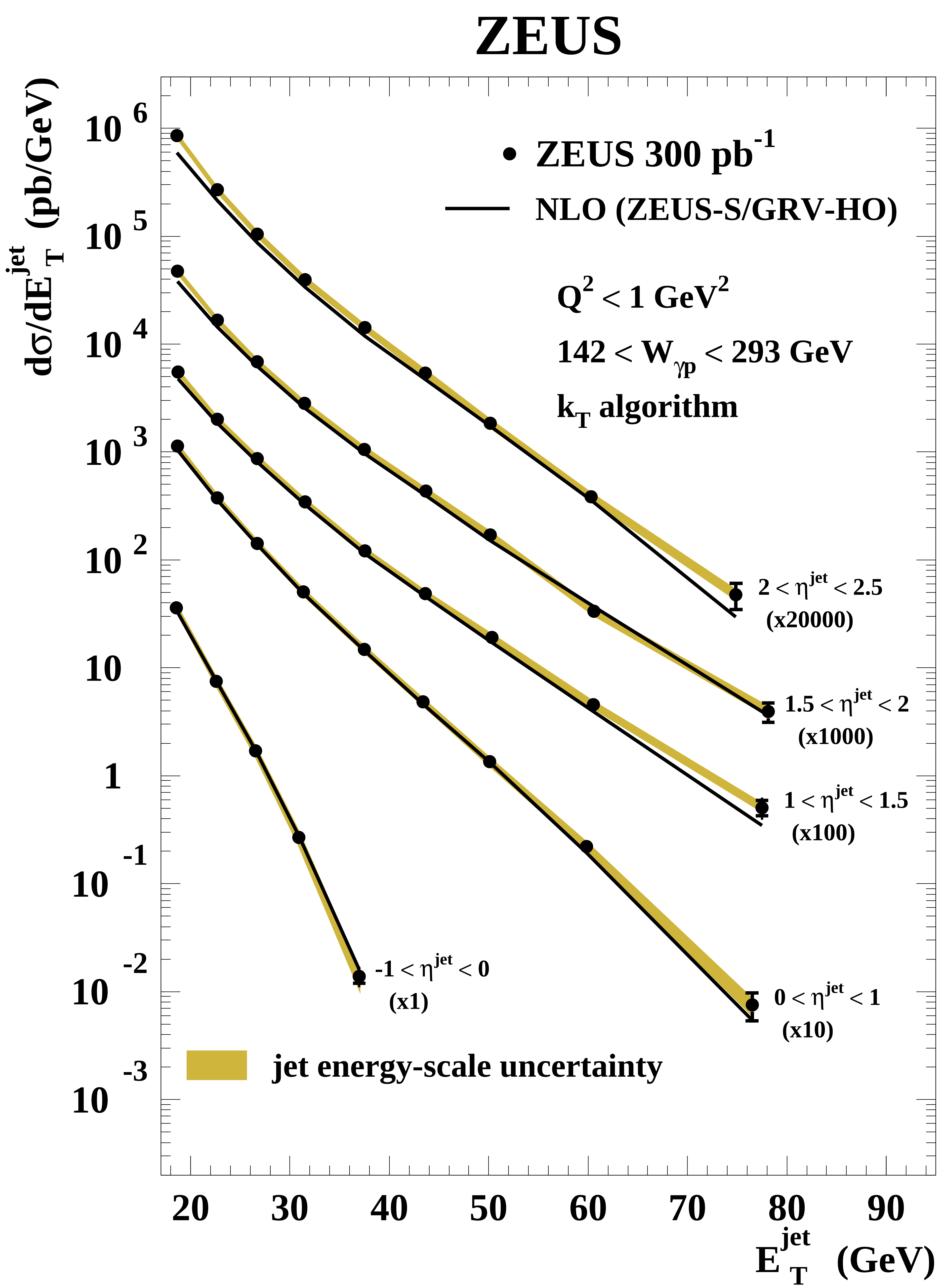

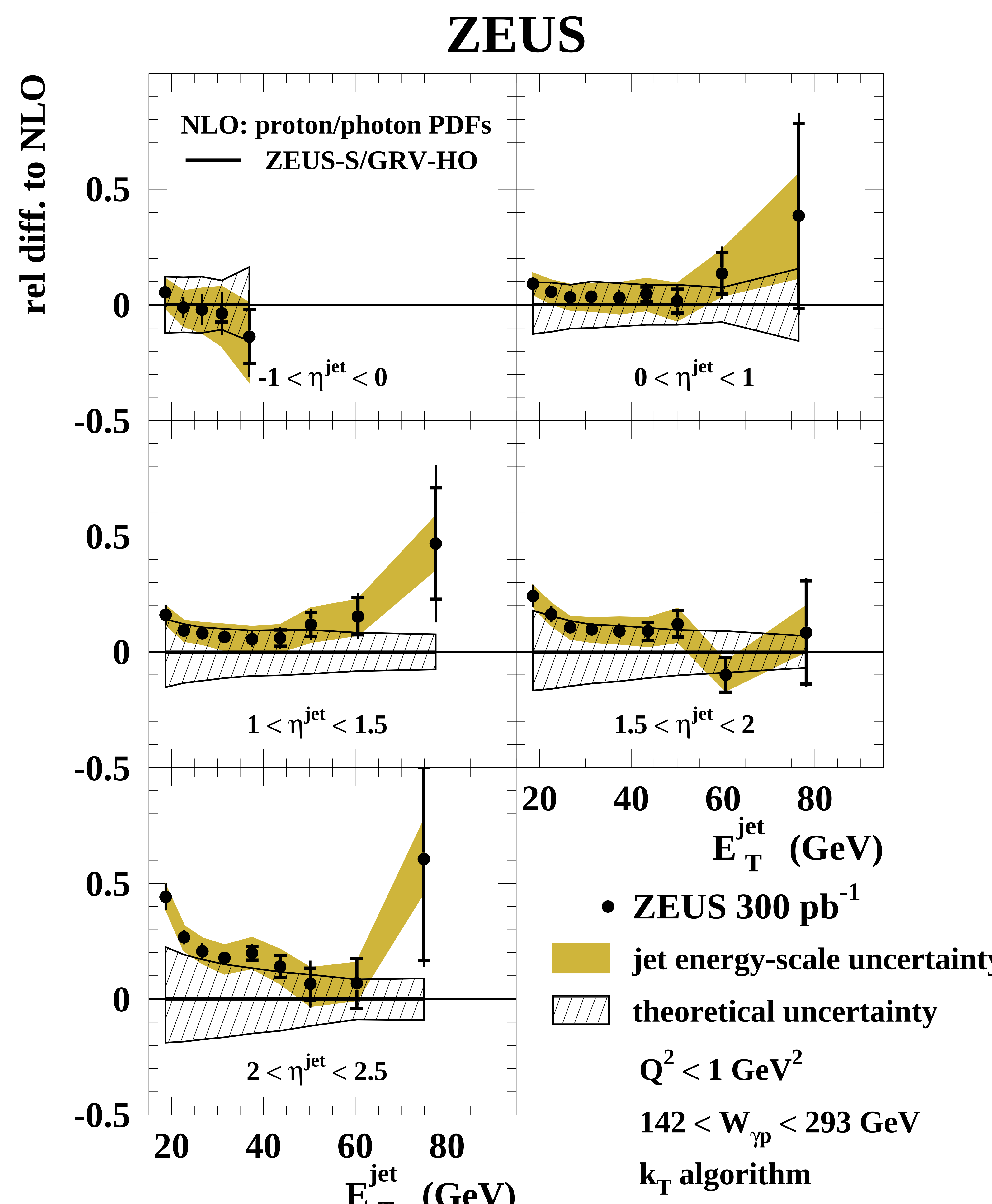

Inclusive jet, Dijet and Trijet at low Q^2

Eur.Phys.J. C67 (2010) 1

Inclusive Jet, 2-Jet and 3-Jet Cross Sections