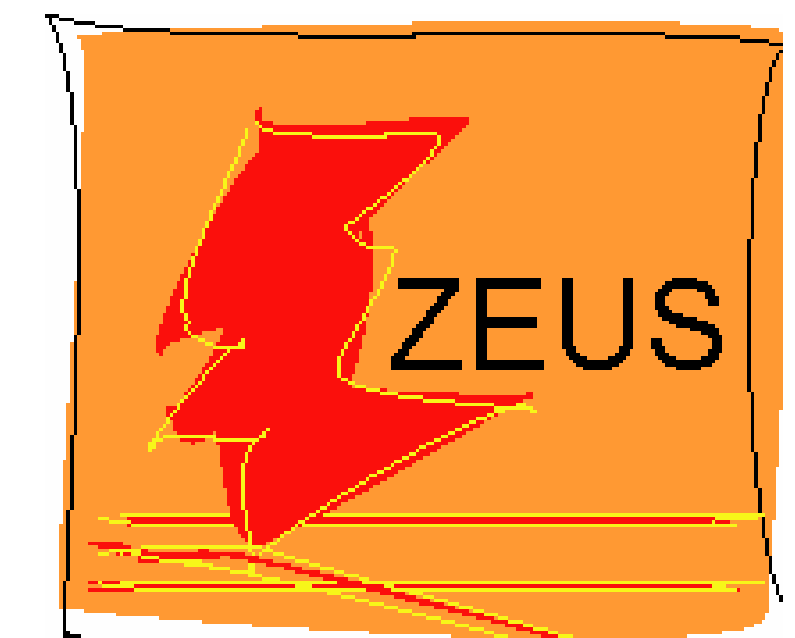


Precise QCD measurements at HERA

Krzysztof Nowak
on behalf of
H1 and ZEUS
collaborations

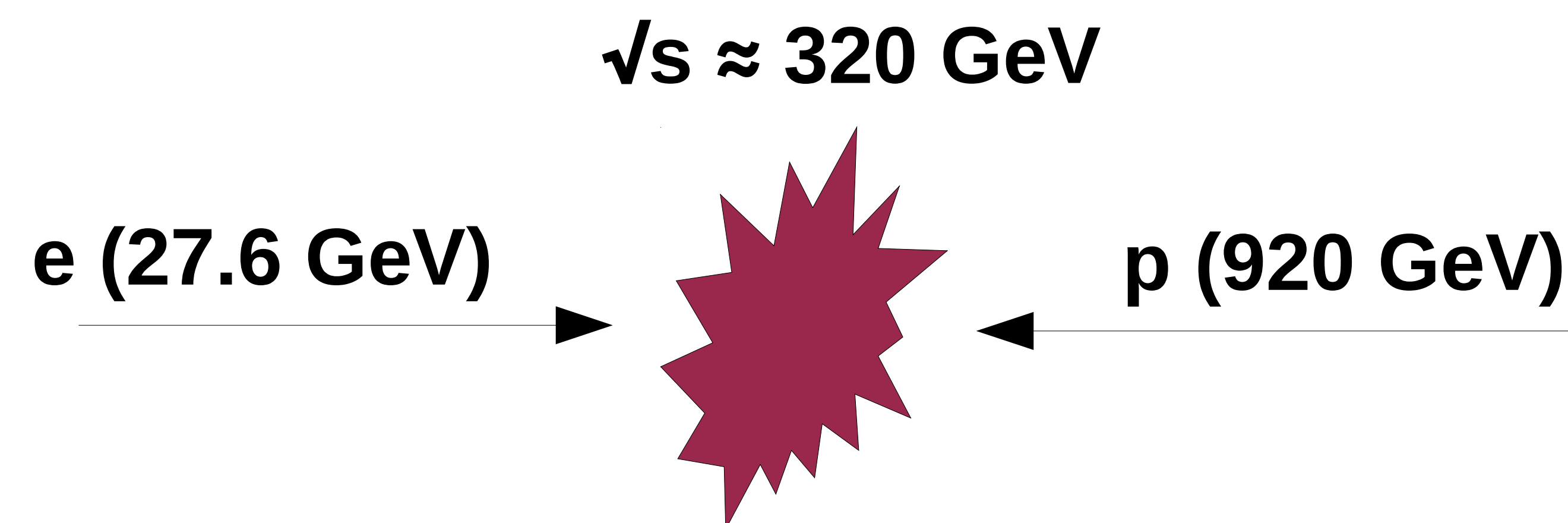


- ✓ *Introduction to jets at HERA*
- ✓ *H1 and ZEUS jet measurements*
- ✓ *Strong coupling constant α_s determination*

QCD at HERA

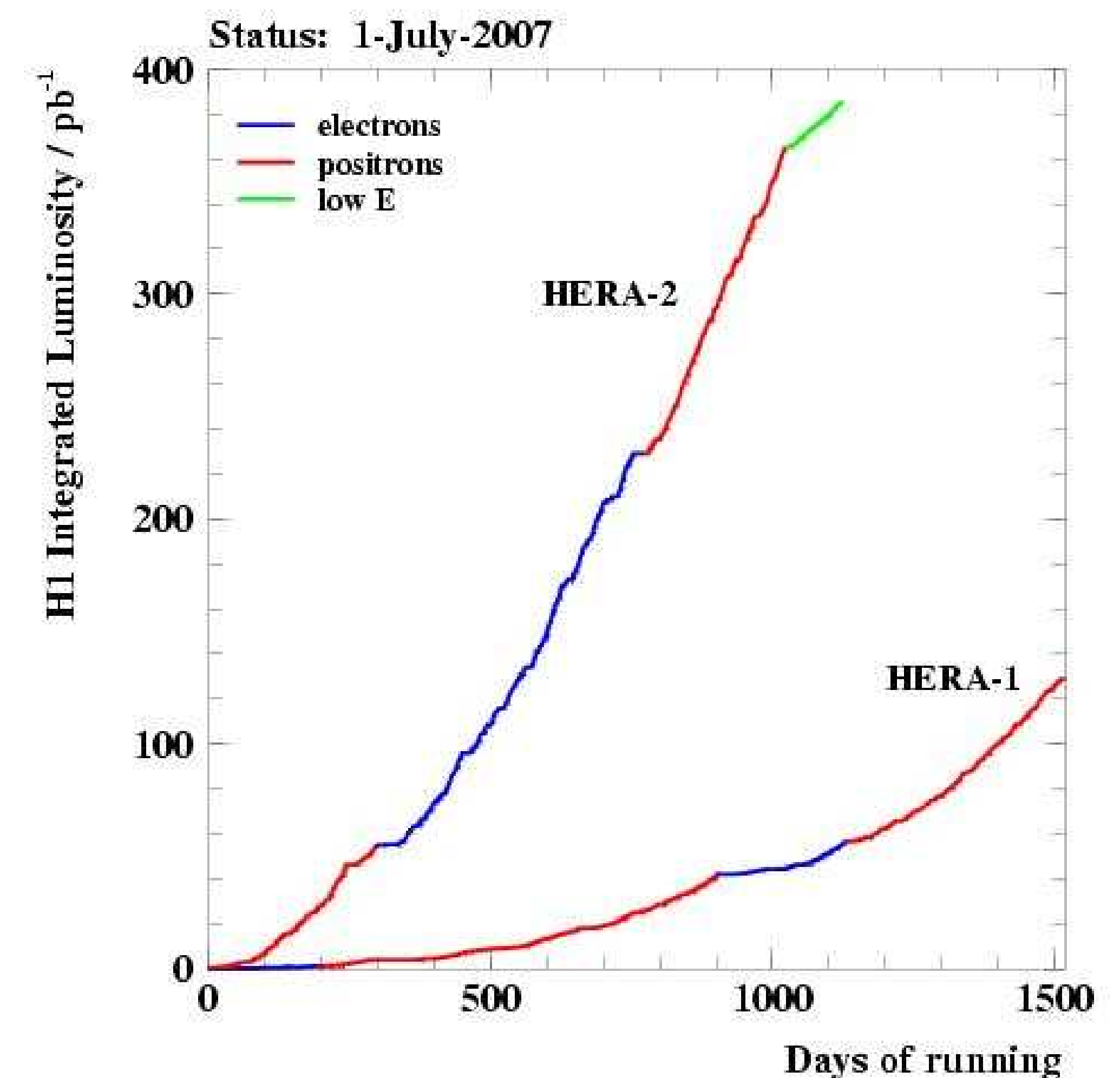
HERA ep collisions great for precise QCD studies

- ✓ *Interacting hadron (as opposed to ee)*
- ✓ *Relatively clean environment (as opposed to pp)*
- ✓ *Lasting legacy in understanding of the proton dynamics*



Collected $\sim 0.5 \text{ fb}^{-1}$ of luminosity per experiment

Work ongoing to provide final measurements using all available data

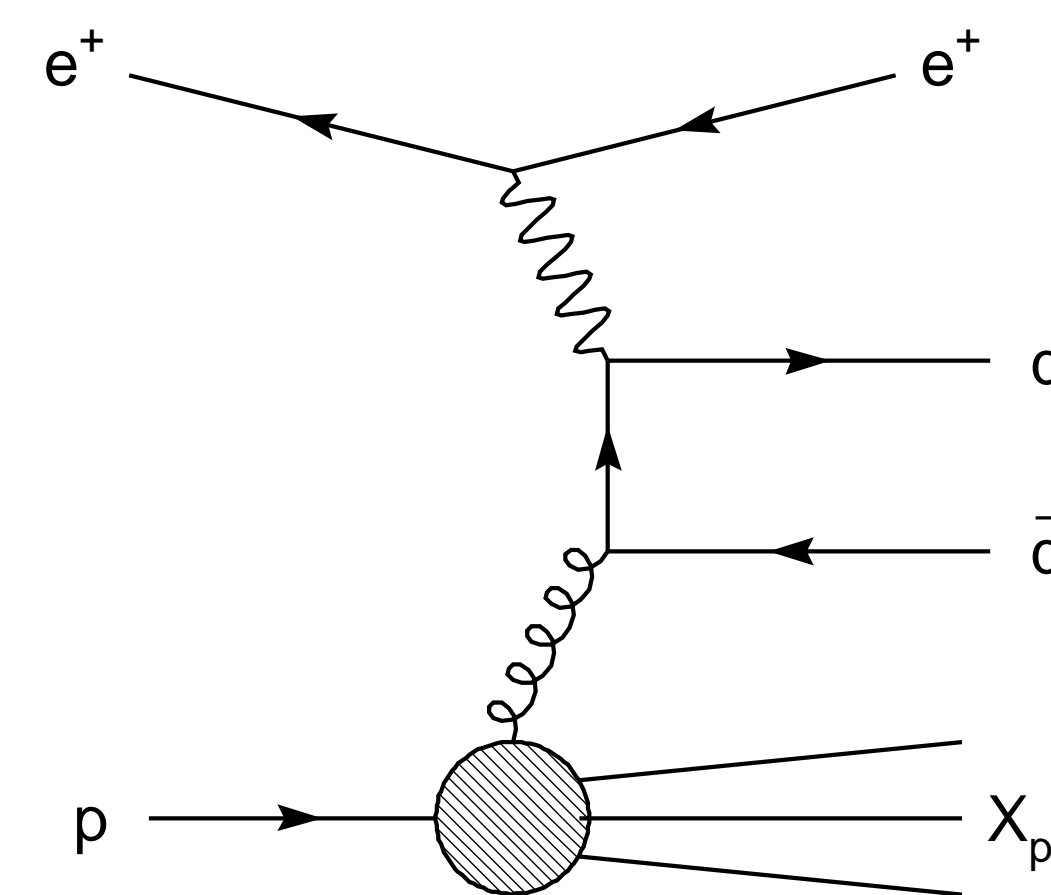


Electron – proton collisions

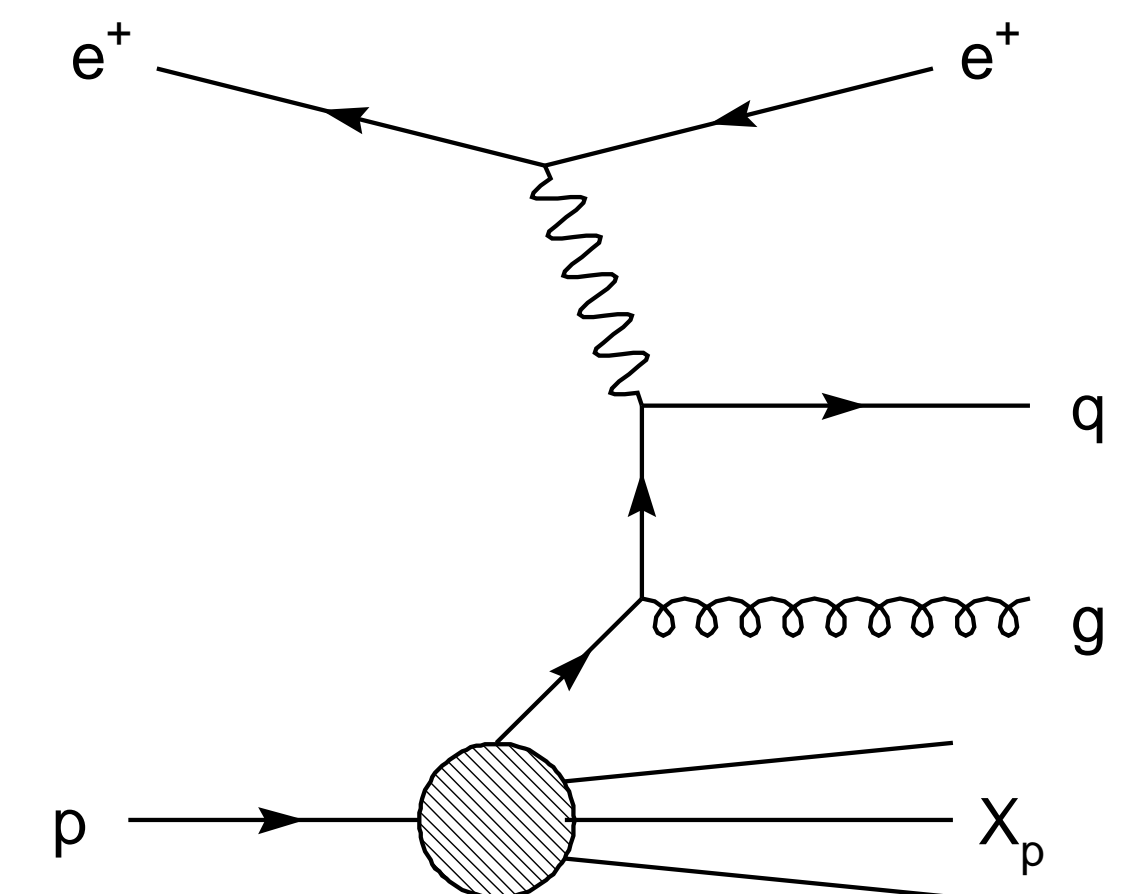
Two kinematic regions depending the virtuality of the mediating boson Q^2 :

1. Deep Inelastic Scattering (DIS)

- ✓ $Q^2 \gg \Lambda_{QCD}$
- ✓ *Hard scale always present*



Boson-gluon fusion



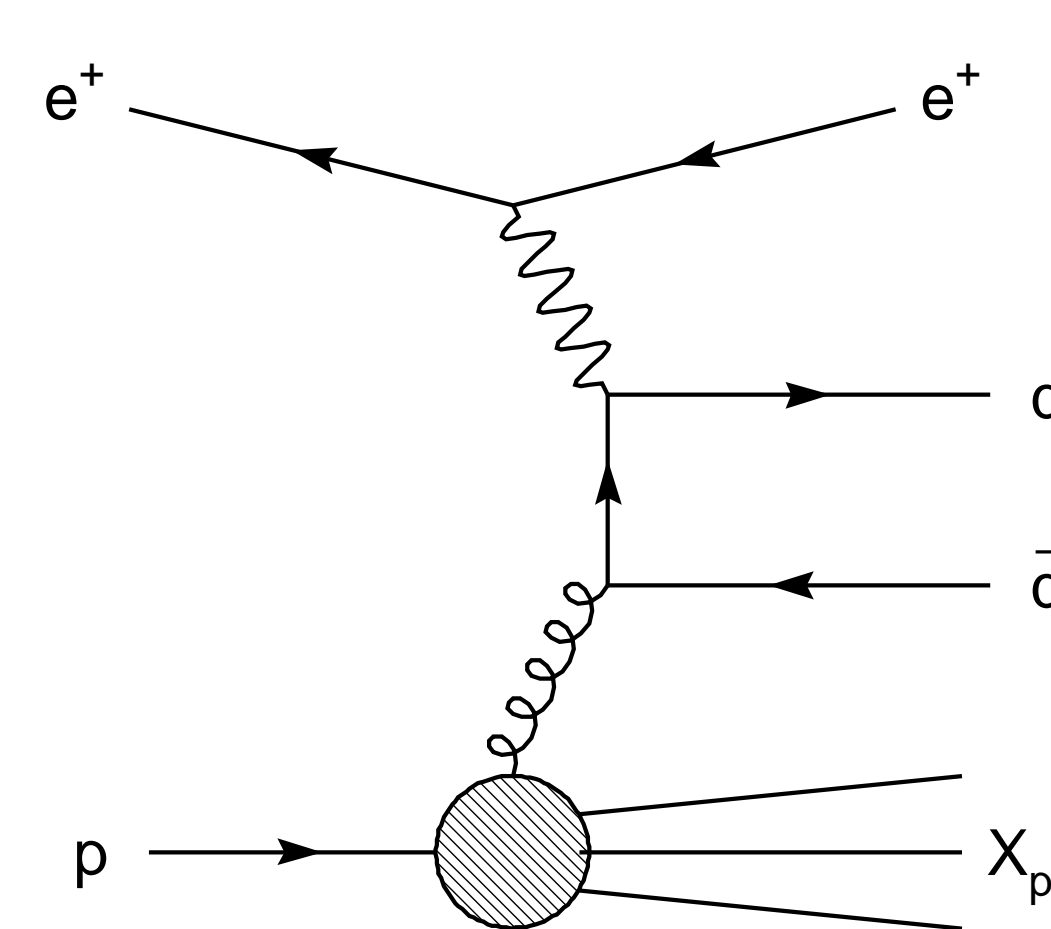
QCD Compton

Electron – proton collisions

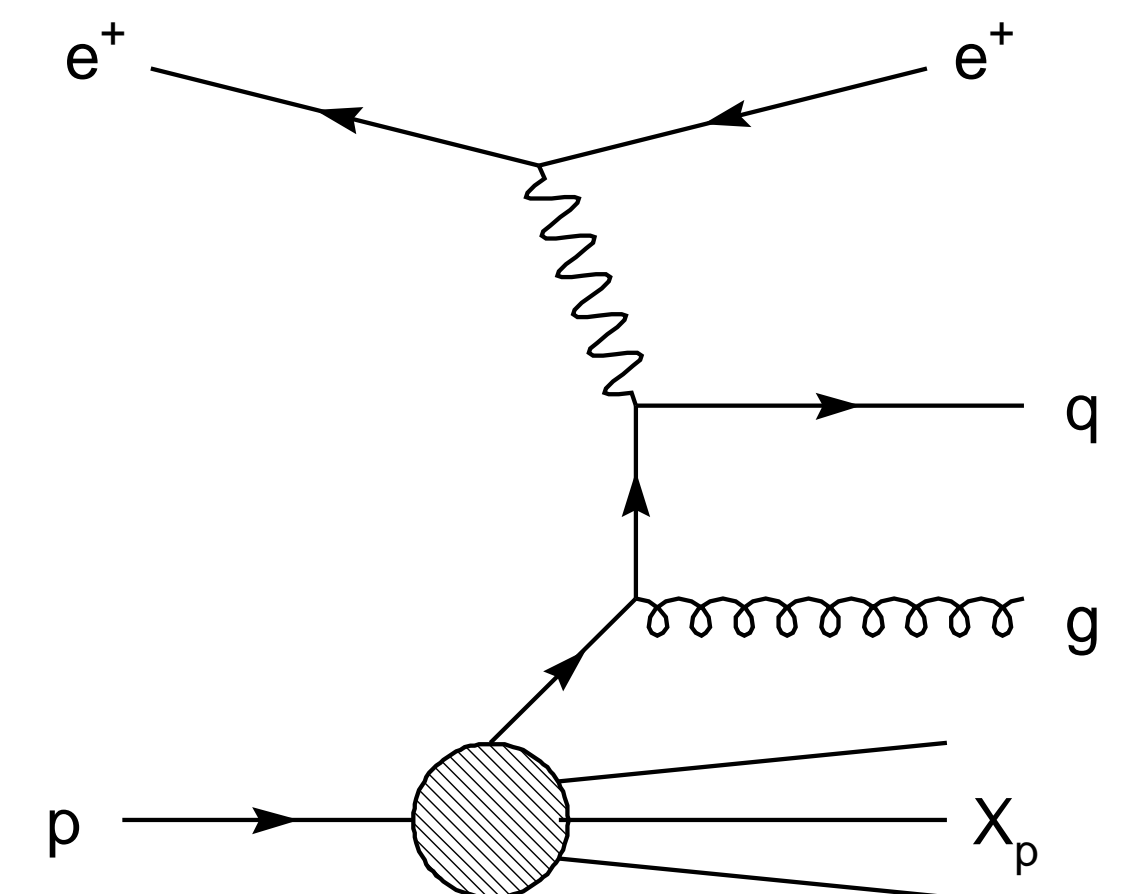
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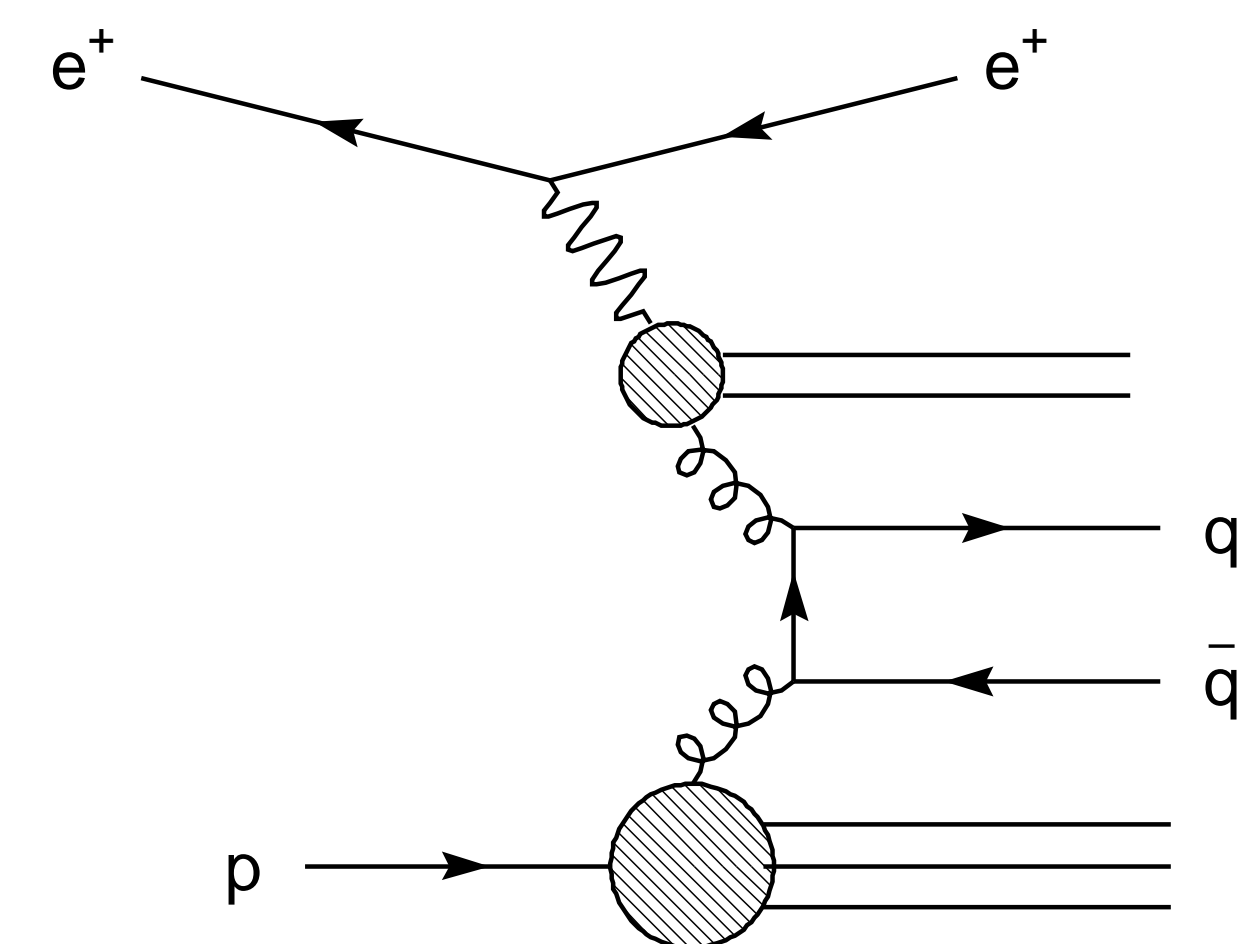
Boson-gluon fusion



QCD Compton

2. Photoproduction (PHP)

- ✓ $Q^2 \approx 0 \text{ GeV}$
- ✓ *Mediating photon may fluctuate into partons (resolved events) – similarity to hadron-hadron collisions*



Resolved photoproduction

Jet physics at HERA

Jet cross section:

$$d\sigma_{jet} \sim \sum_{j=q,\bar{q},g} \int dx \underbrace{f_{j/p}(x, \mu_F)}_{\text{proton content}} \underbrace{d\hat{\sigma}_j(x, \alpha_s(\mu_R), \mu_R, \mu_F)}_{\text{pQCD matrix element}}$$

x - Bjorken x
 f - PDFs
 μ_R - renormalization scale
 μ_F - factorization scale
 α_s - strong coupling const.

Jet physics at HERA

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 f - PDFs
 μ_R - renormalization scale
 μ_F - factorization scale
 α_s - strong coupling const.

In the resolved case:

$$d\sigma_{jet} \sim \sum_{i,j=q,\bar{q},g} \int dx_p \int dx_\gamma \underbrace{f_{j/p}(x_p, \mu_{Fp})}_{\text{proton content}} \underbrace{f_{i/\gamma}(x_\gamma, \mu_{F\gamma})}_{\text{photon content}} \underbrace{d\hat{\sigma}_{ij}(x_p, x_\gamma, \alpha_s, \mu_R, \mu_F)}_{\text{pQCD matrix element}}$$

Jet physics at HERA

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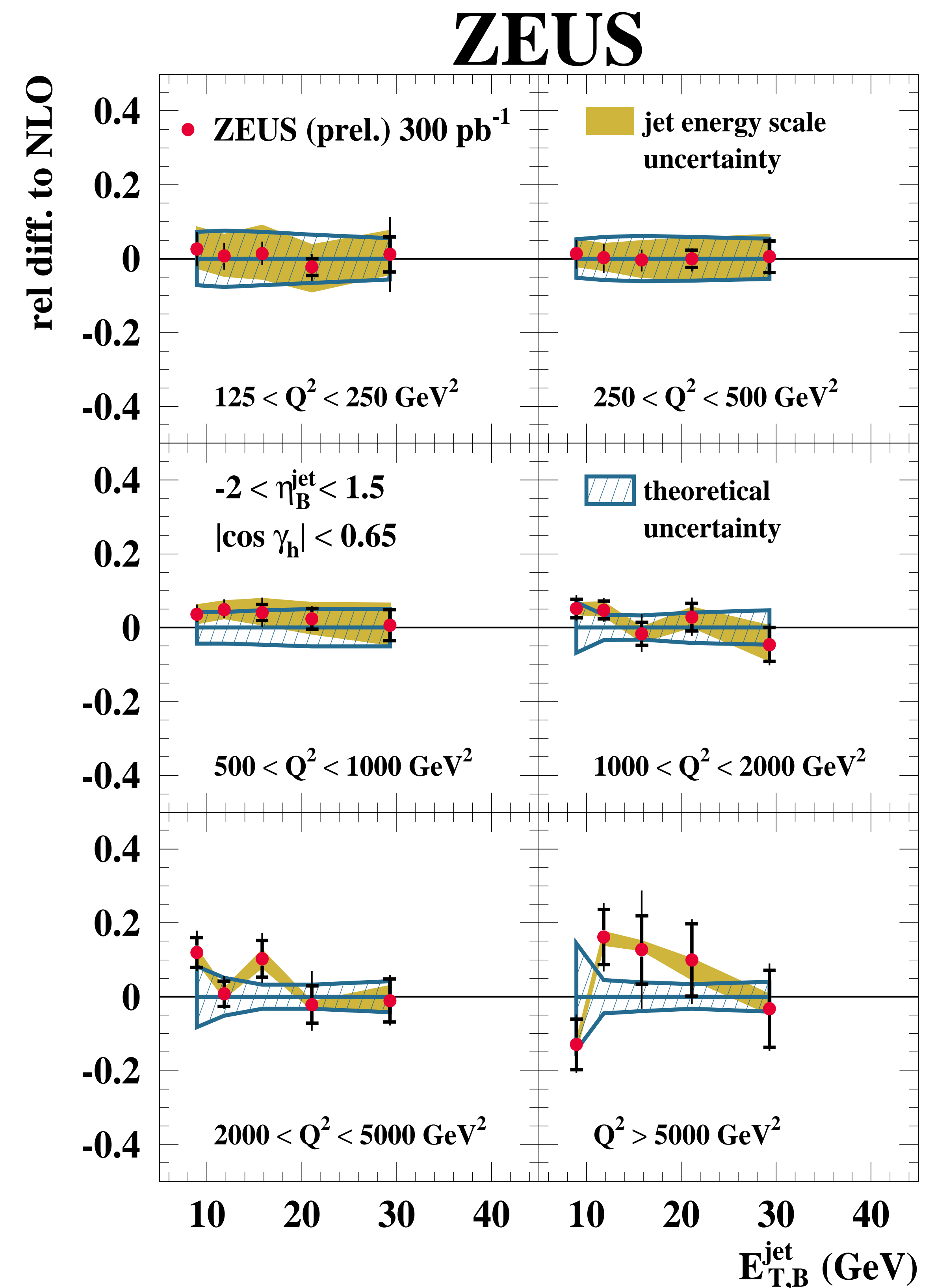
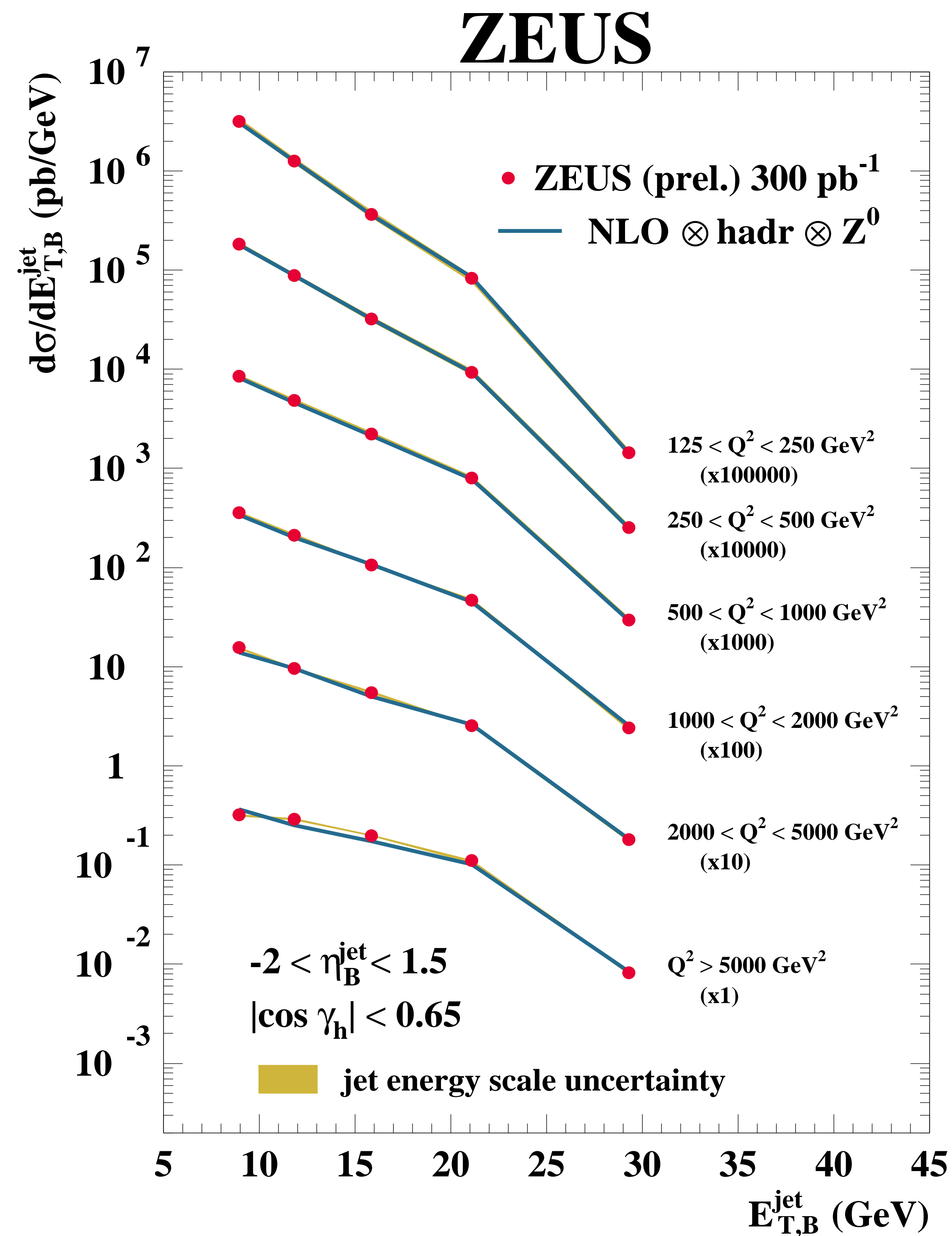
Use of jets:

- ✓ sensitivity to the structure of both proton and photon
- ✓ extensive pQCD tests
- ✓ determination of α_s



High Q^2 DIS inclusive jets

$$\begin{aligned} \mathcal{L} &= 300 \text{ pb}^{-1} \\ Q^2 &> 125 \text{ GeV}^2 \\ |\cos \gamma_h| &< 0.65 \\ P_{T,B}^{JET} &> 8 \text{ GeV} \\ -2.0 < \eta_B^{JET} &< 1.5 \end{aligned}$$





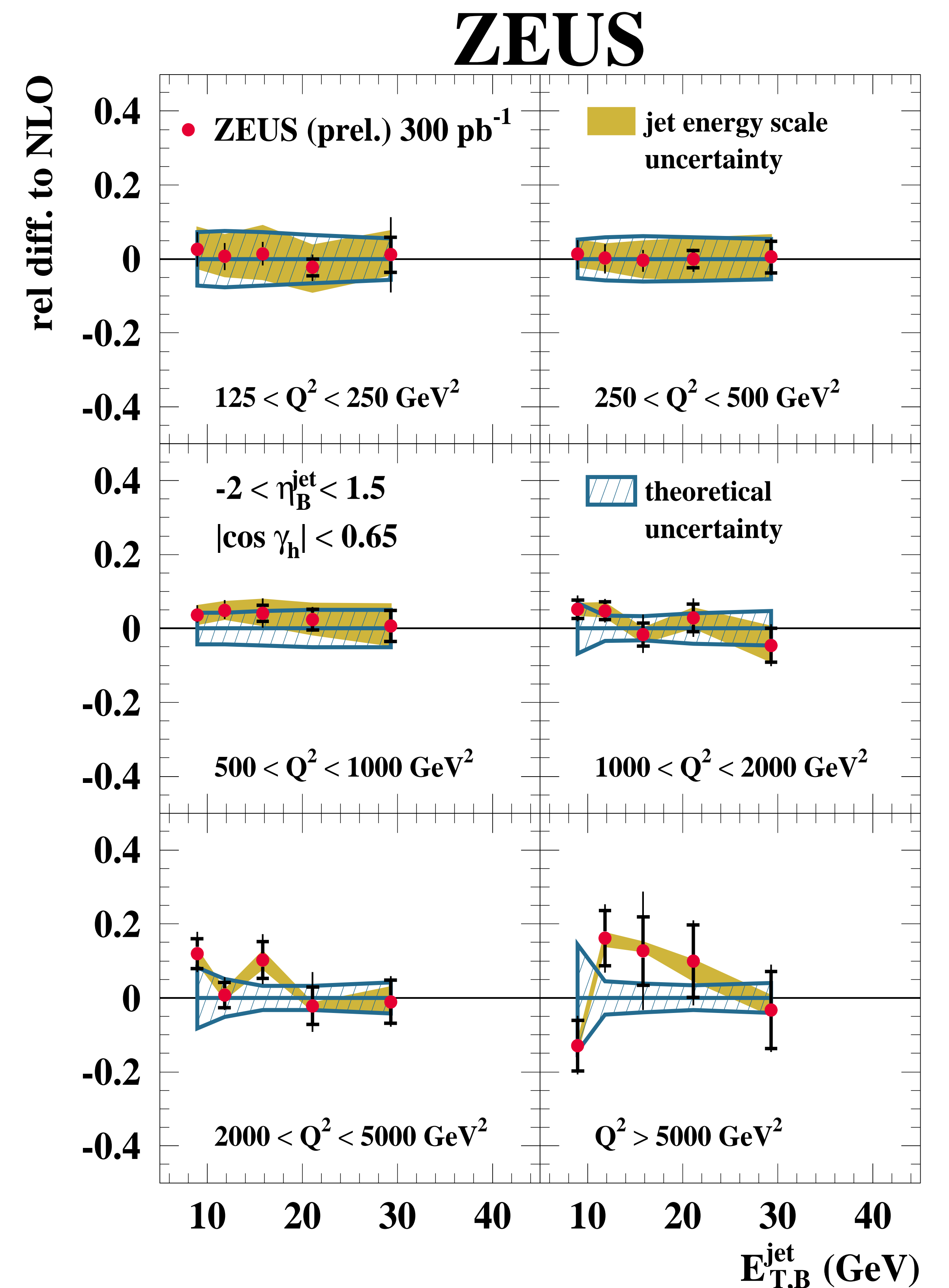
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Dominant experimental error – jet energy scale

Comparably high theoretical uncertainty (estimated terms beyond NLO)

Measurement well described by NLO prediction

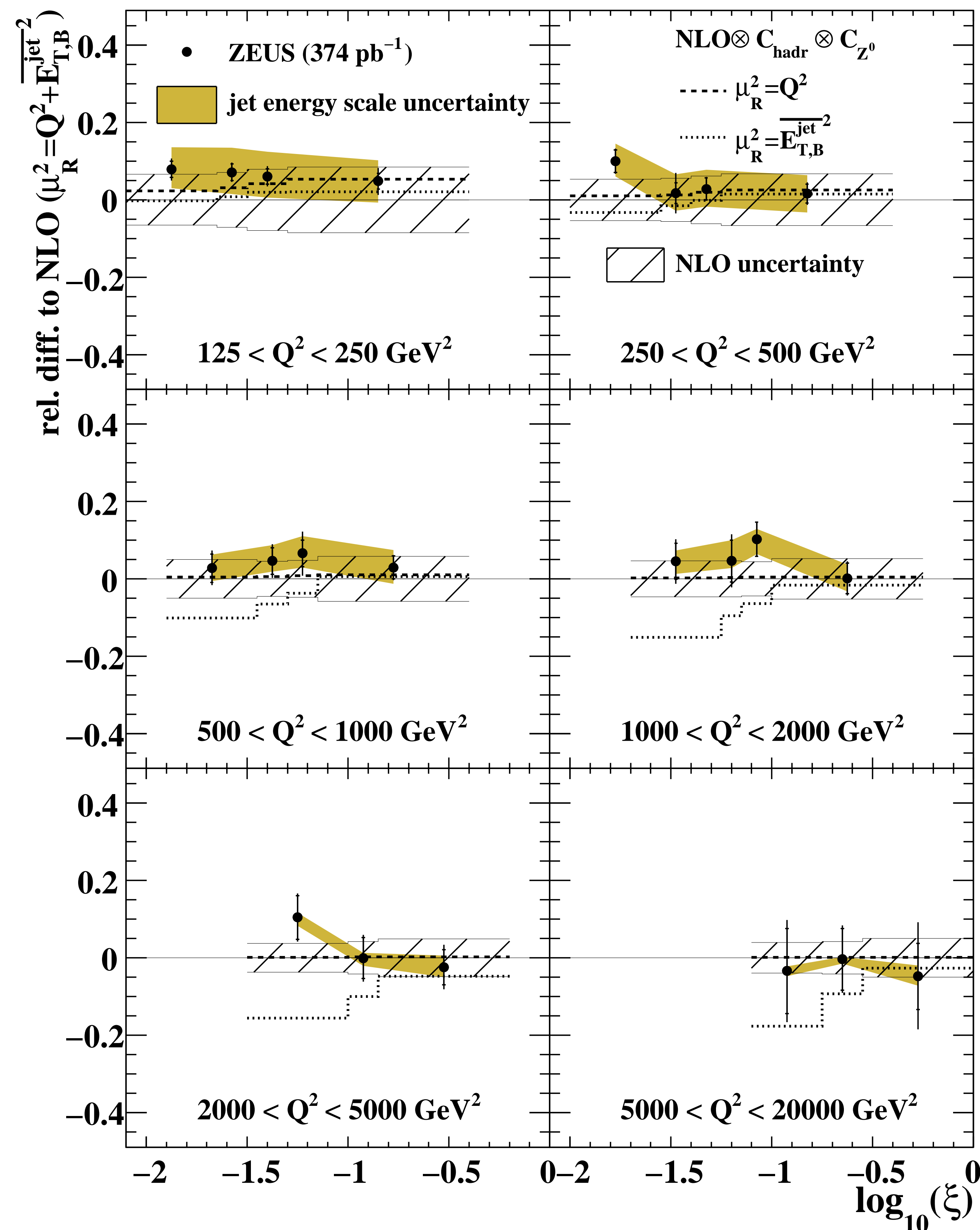




High Q^2 DIS dijets

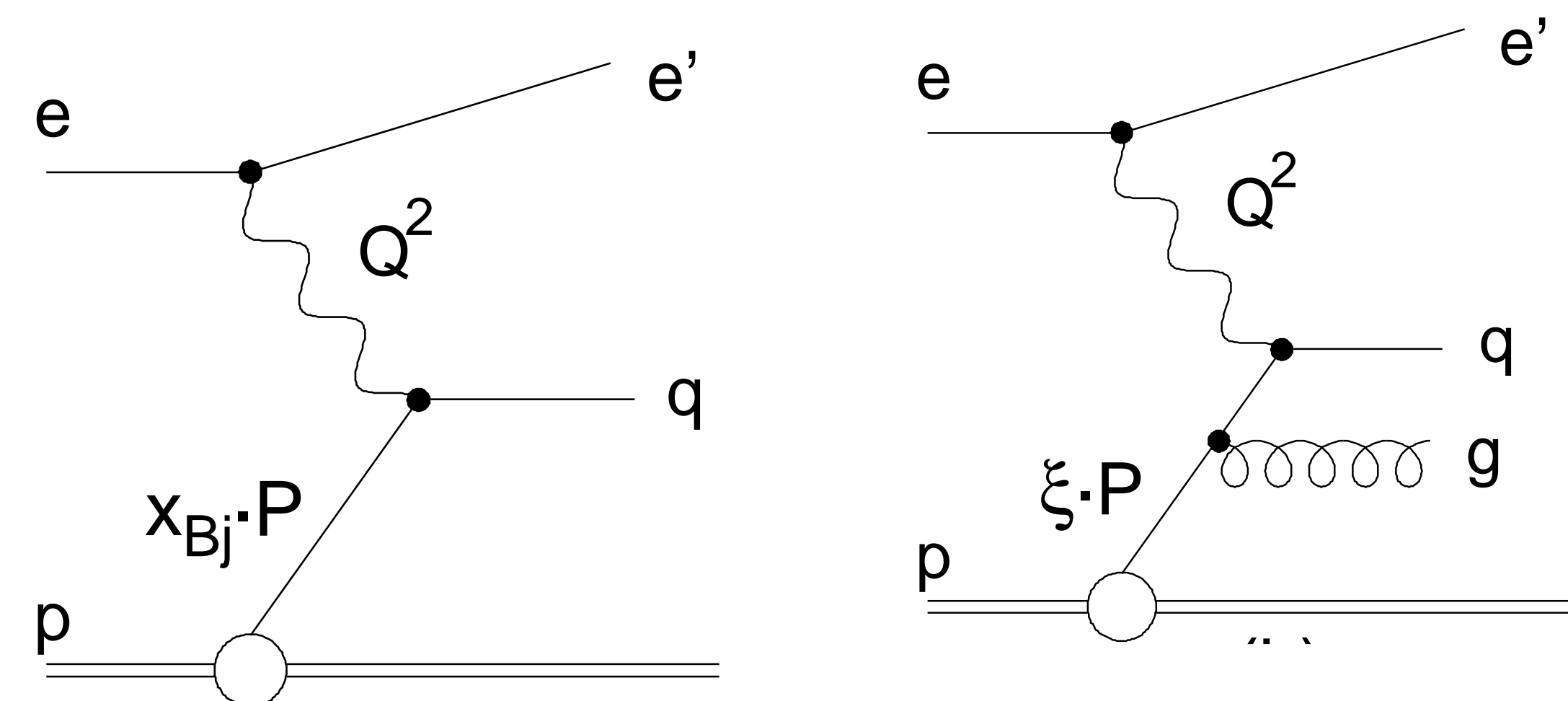
ZEUS

$$\begin{aligned} \mathcal{L} &= 374 \text{ pb}^{-1} \\ 125 < Q^2 < 20000 \text{ GeV}^2 \\ 0.2 < y < 0.6 \\ P_{T,B}^{JET} &> 8 \text{ GeV} \\ -1.0 < \eta_{lab}^{JET} < 2.5 \end{aligned}$$



Estimator of the fraction of the proton momentum taken by the interacting parton (ξ) possible

$$\xi = x_{Bj} (1 + M_{jj}^2 / Q^2)$$



Measurement sensitive to proton PDF

Measurement well described by the NLO calculation

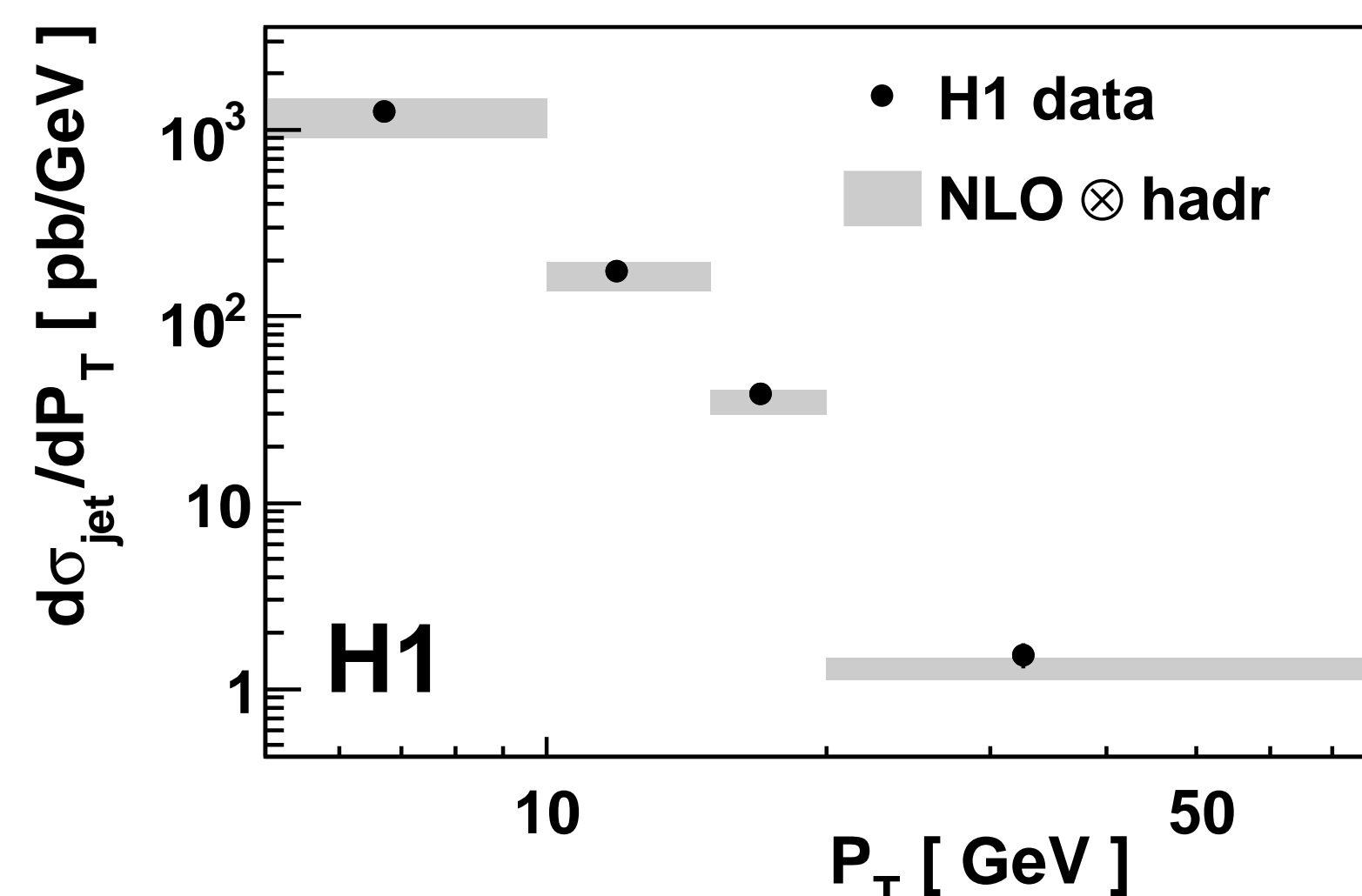
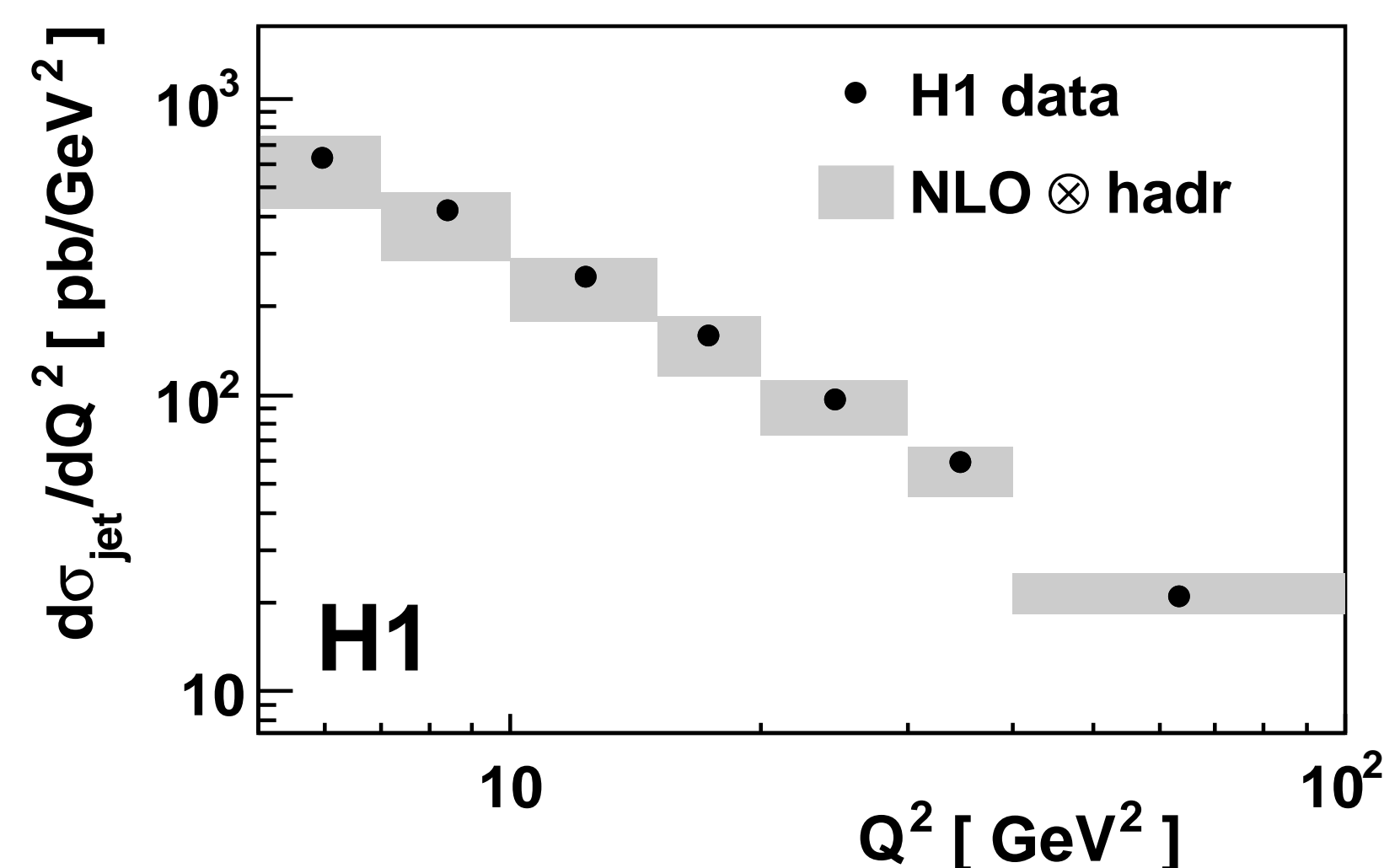


Low Q^2 DIS jets

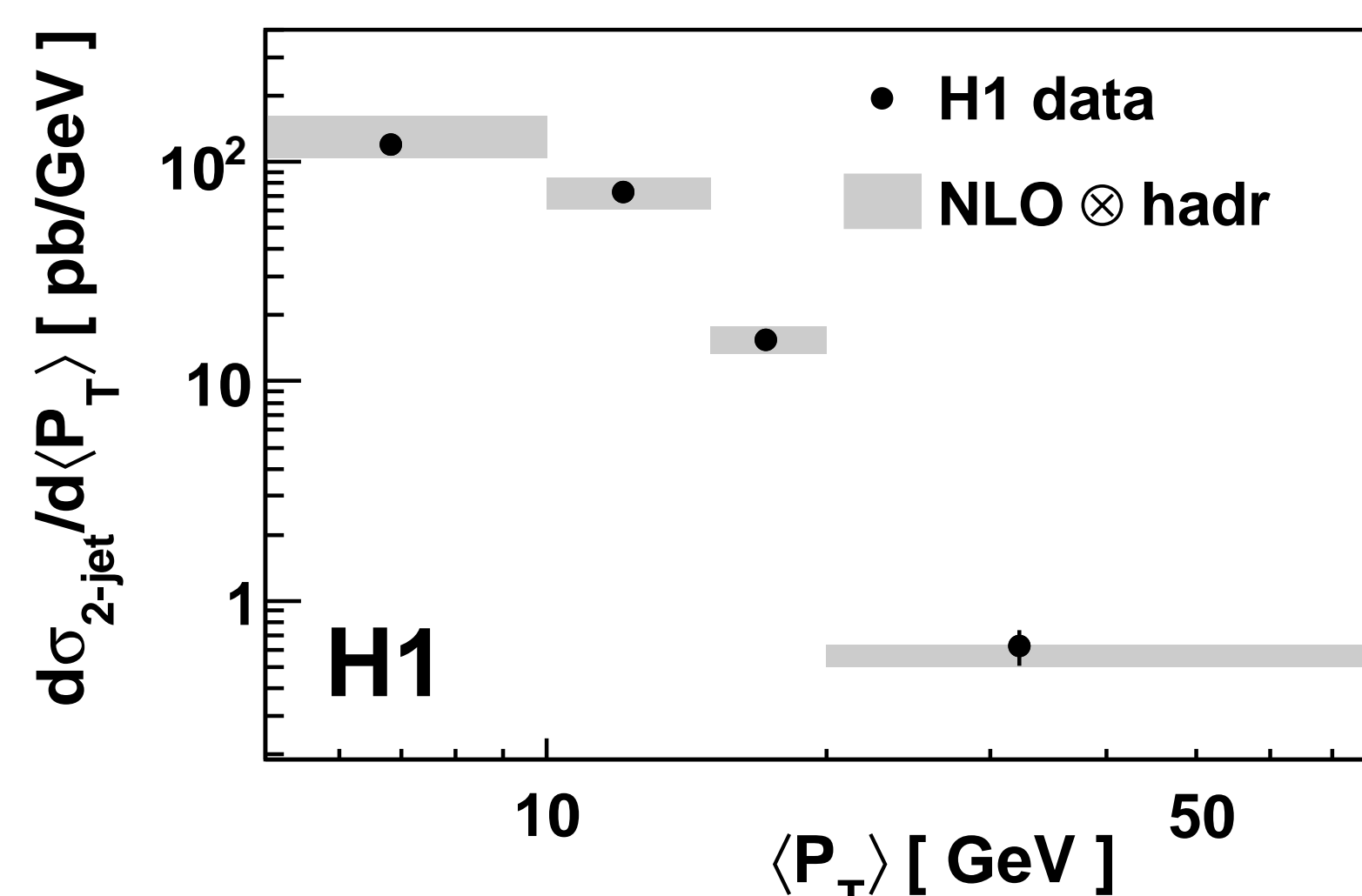
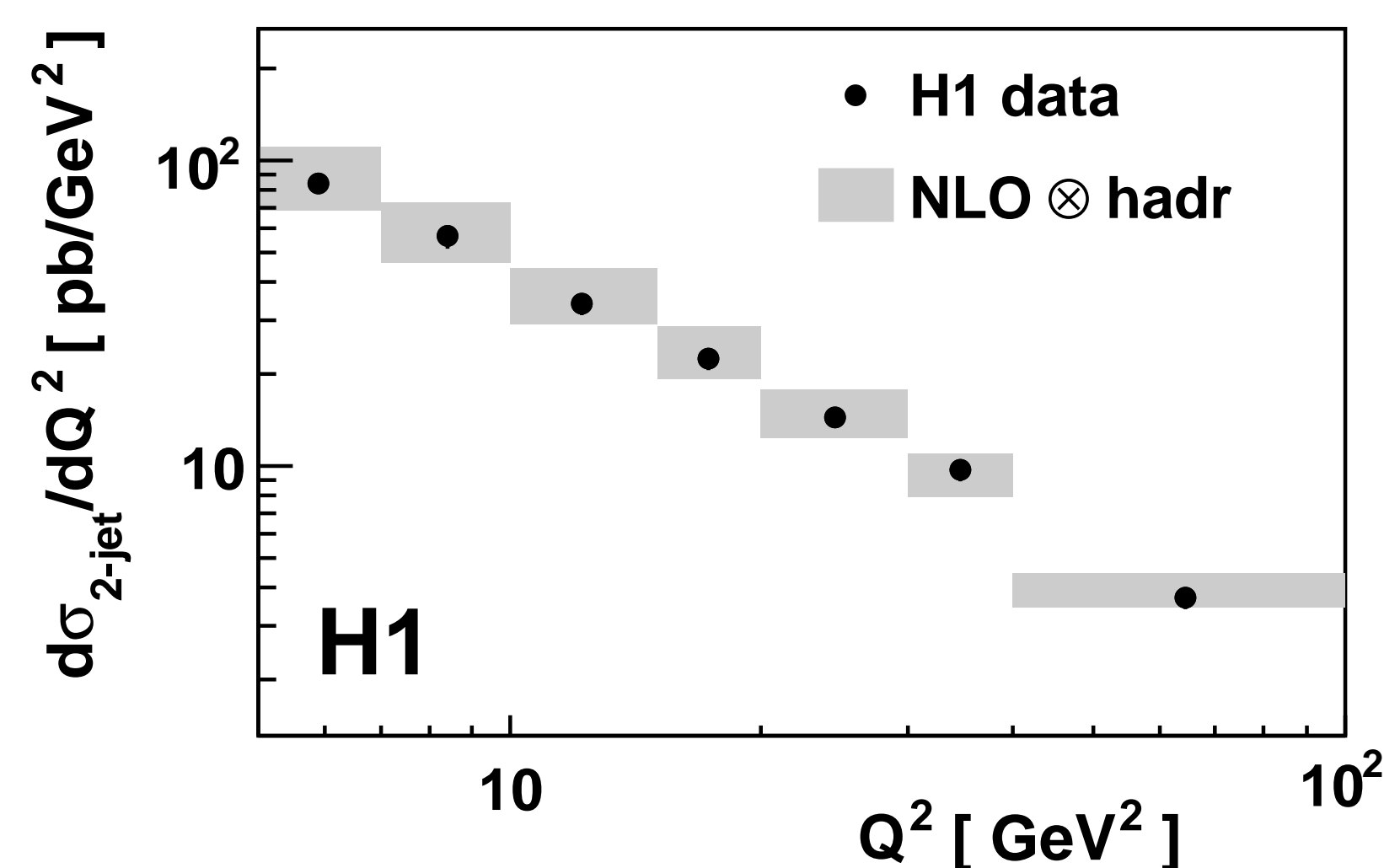
$$\begin{aligned} \mathcal{L} &= 43.5 \text{ pb}^{-1} \\ 5 < Q^2 < 100 \text{ GeV}^2 \\ 0.2 < y < 0.7 \\ P_{T,B}^{JET} &> 5 \text{ GeV} \\ -1.0 < \eta_{lab}^{JET} < 2.5 \end{aligned}$$

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

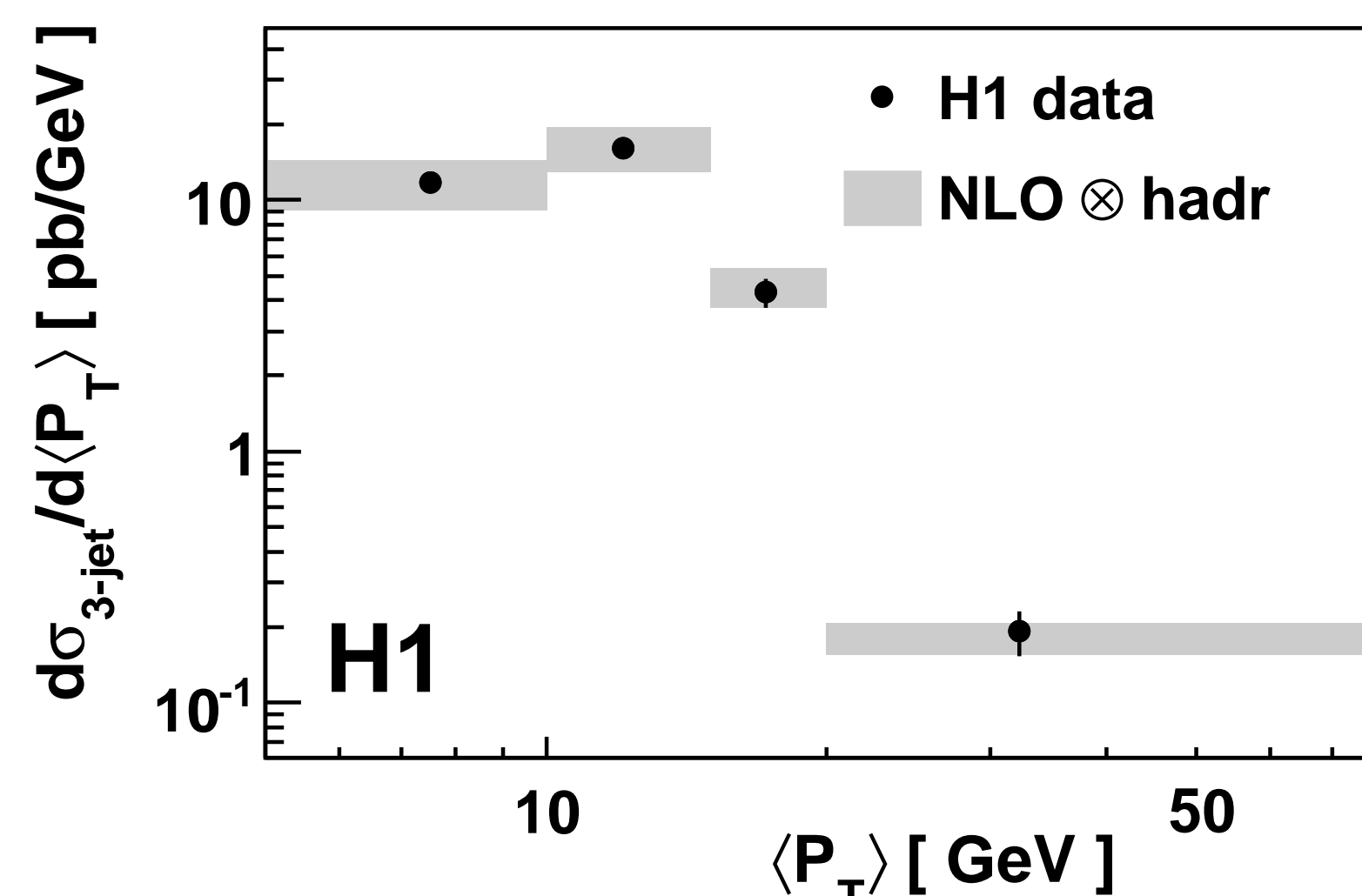
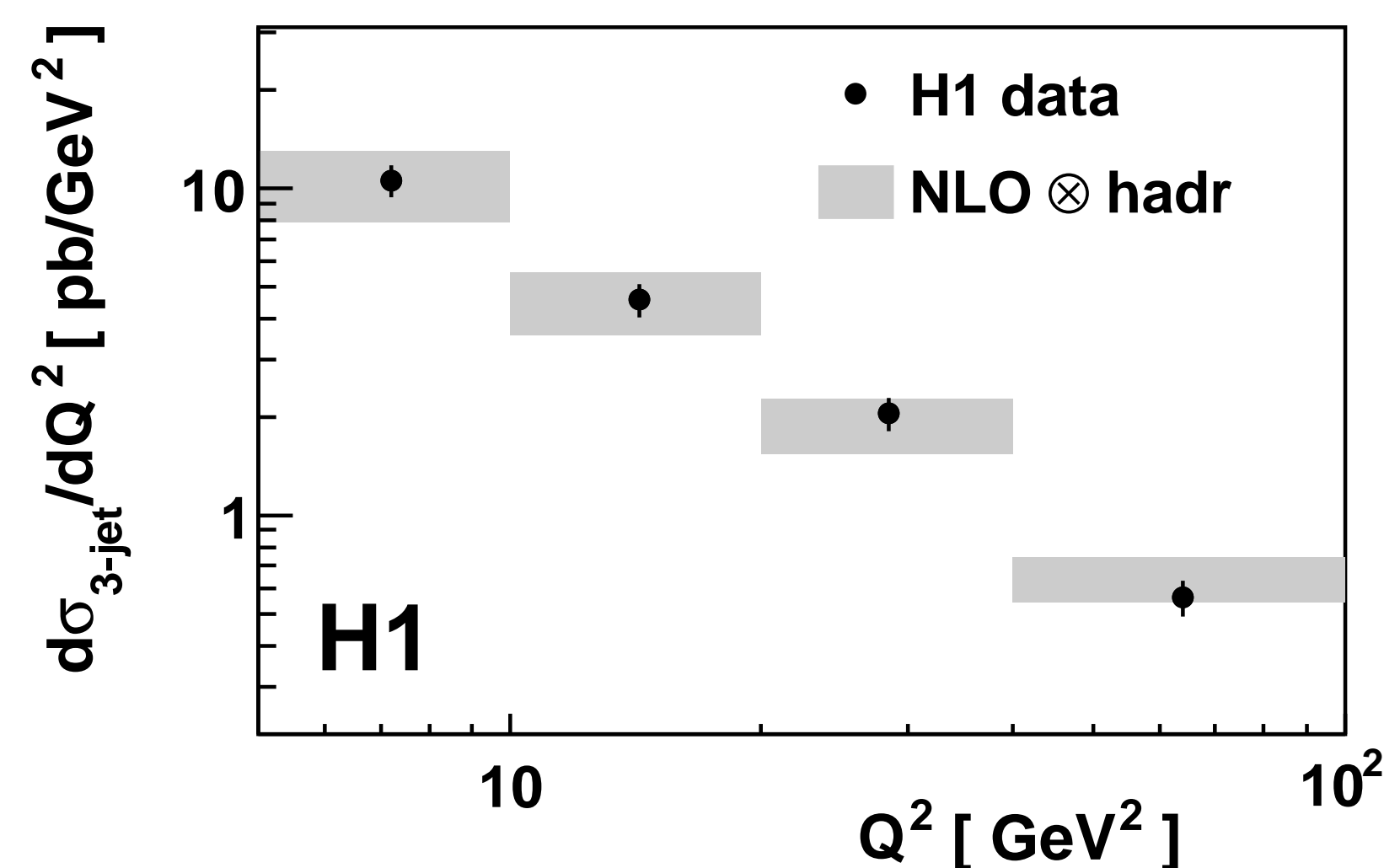
Inclusive



Dijet



Trijet



Inclusive and multijet cross section measured

Large theoretical uncertainty (10-30%) especially at lower Q^2

Mostly due to missing higher orders in the calculations

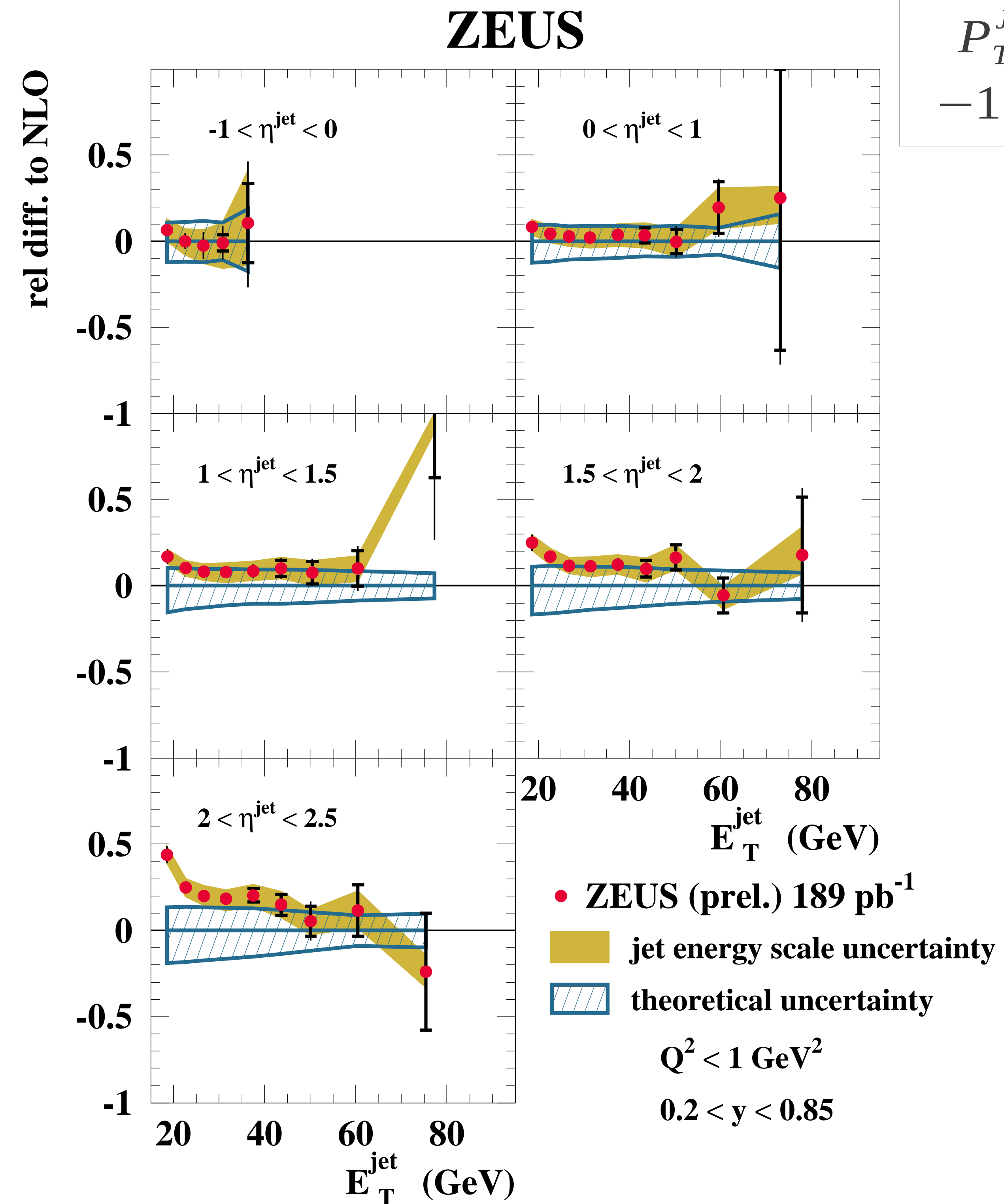
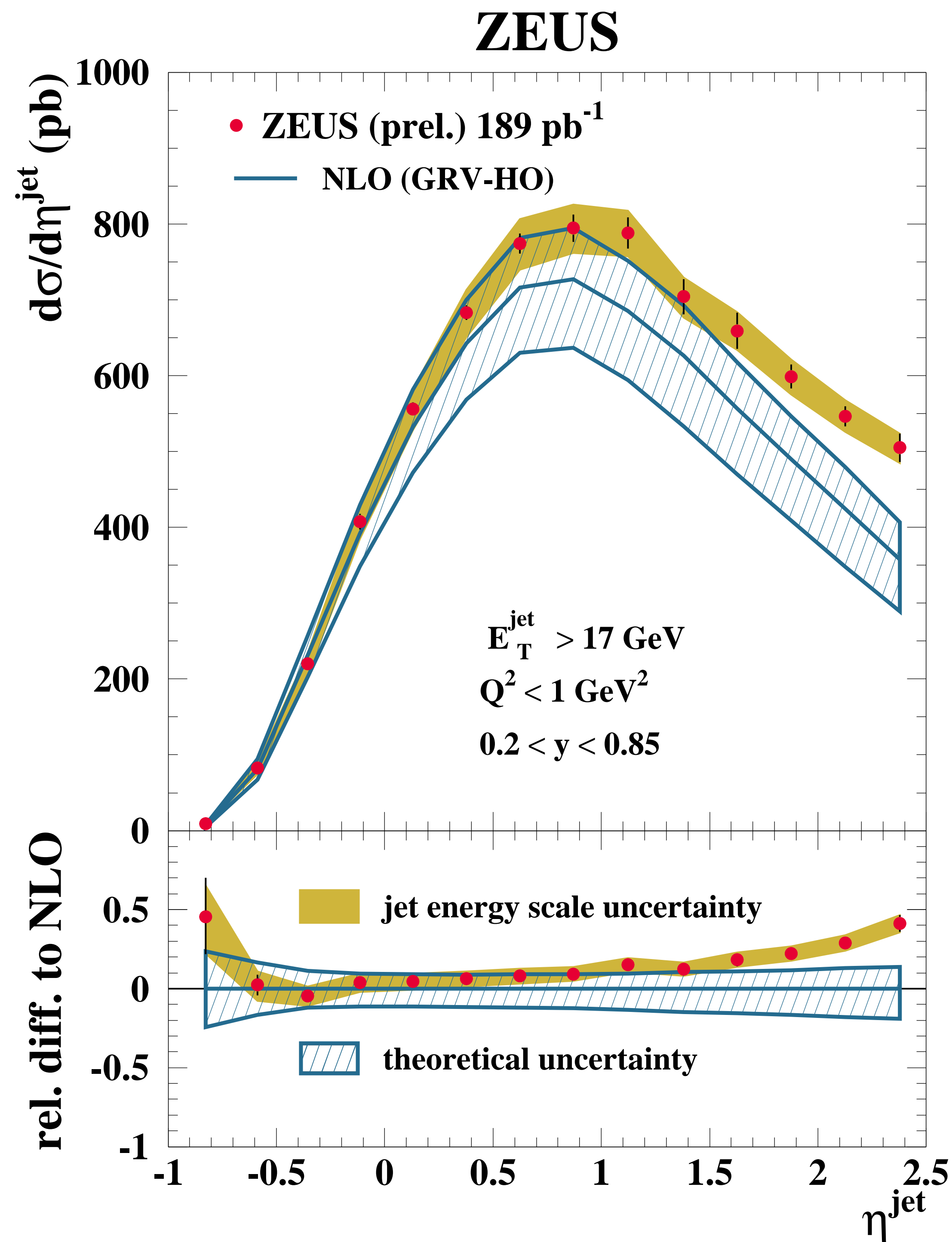
Measurement well described by the NLO calculation

NNLO calculation needed to take full advantage of the precise data



Jets in photoproduction

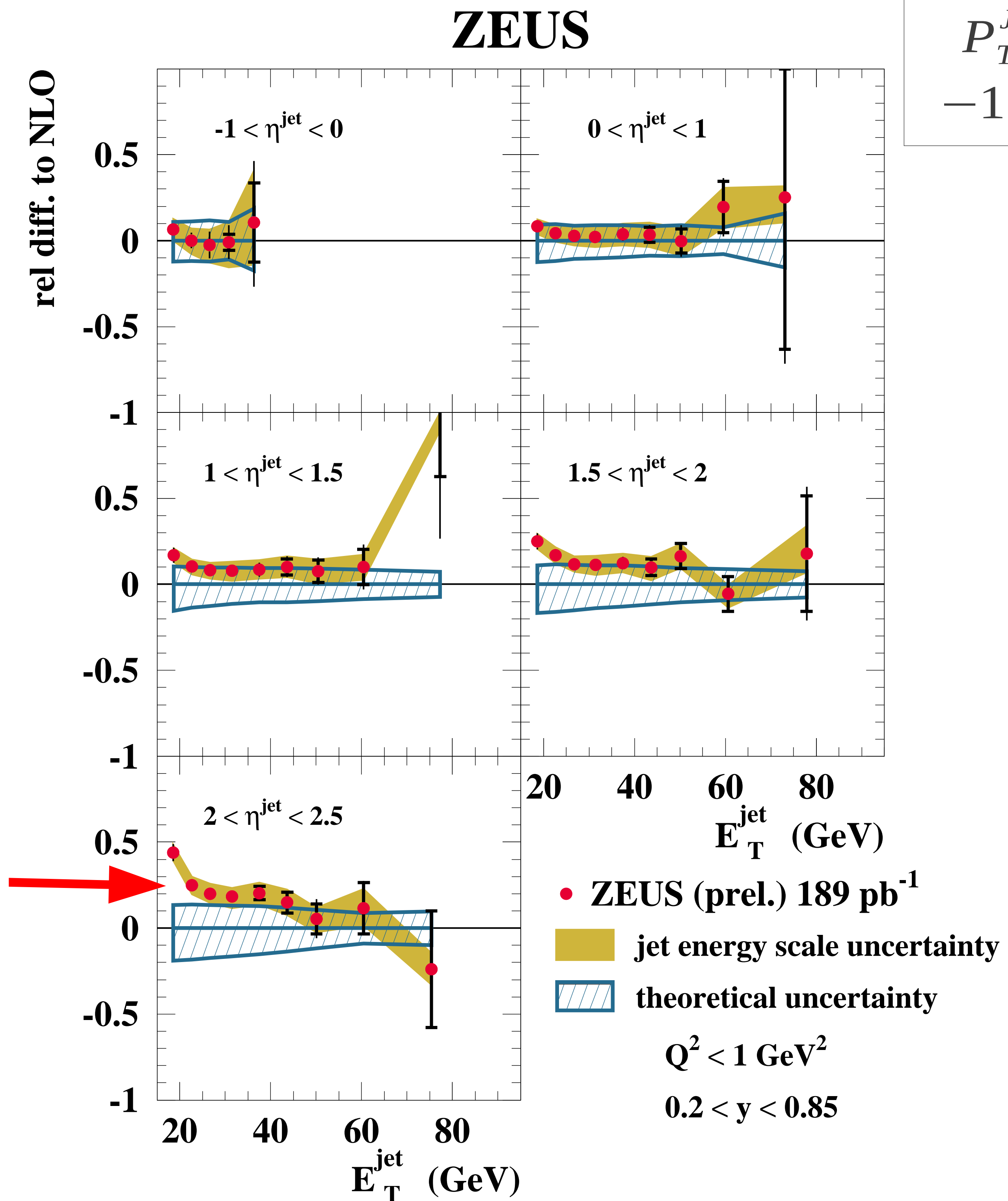
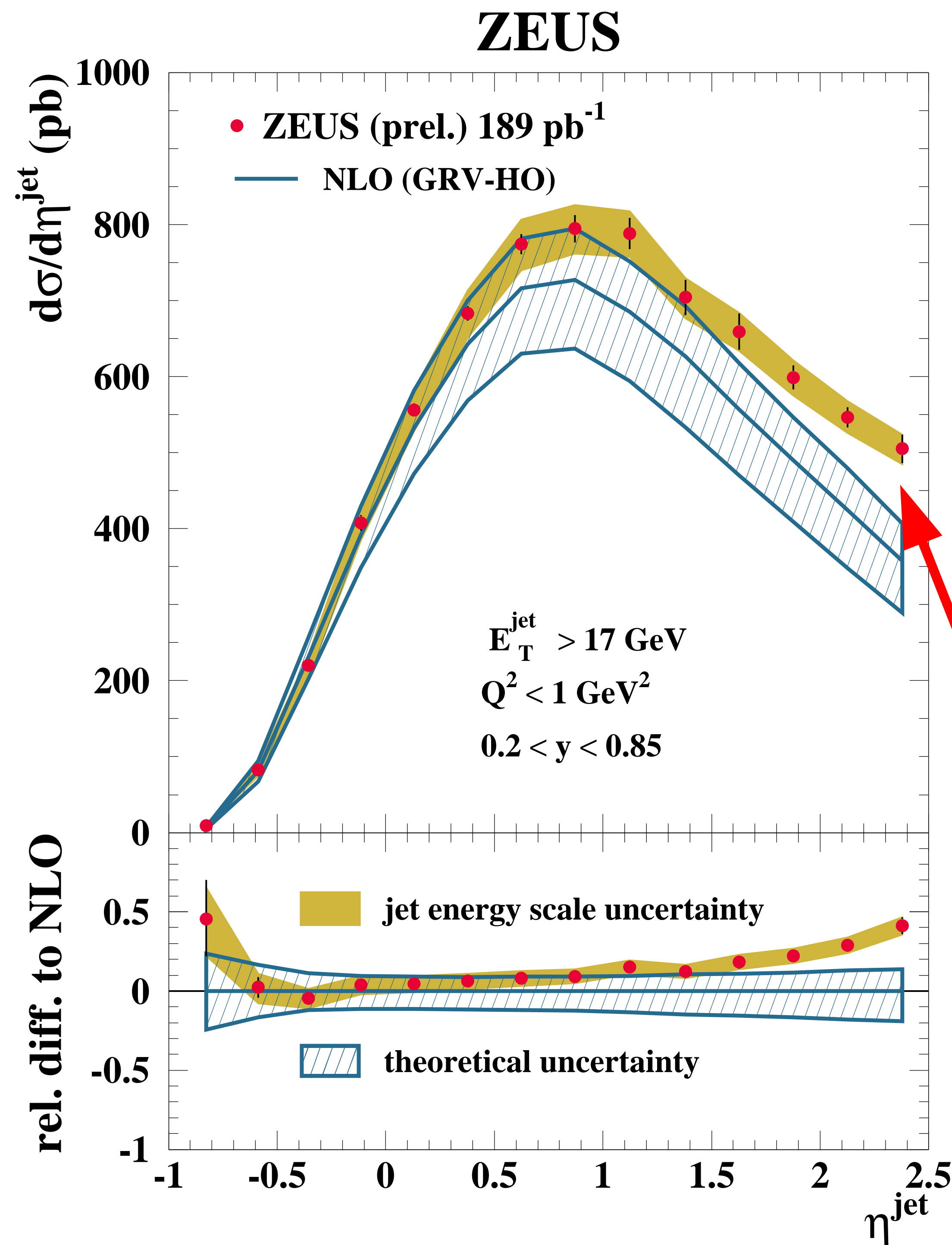
$\mathcal{L} = 189 \text{ pb}^{-1}$
 $Q^2 < 1 \text{ GeV}^2$
 $0.2 < y < 0.85$
 $P_T^{JET} > 17 \text{ GeV}$
 $-1.0 < \eta_{lab}^{JET} < 2.5$





Jets in photoproduction

$\mathcal{L} = 189 \text{ pb}^{-1}$
 $Q^2 < 1 \text{ GeV}^2$
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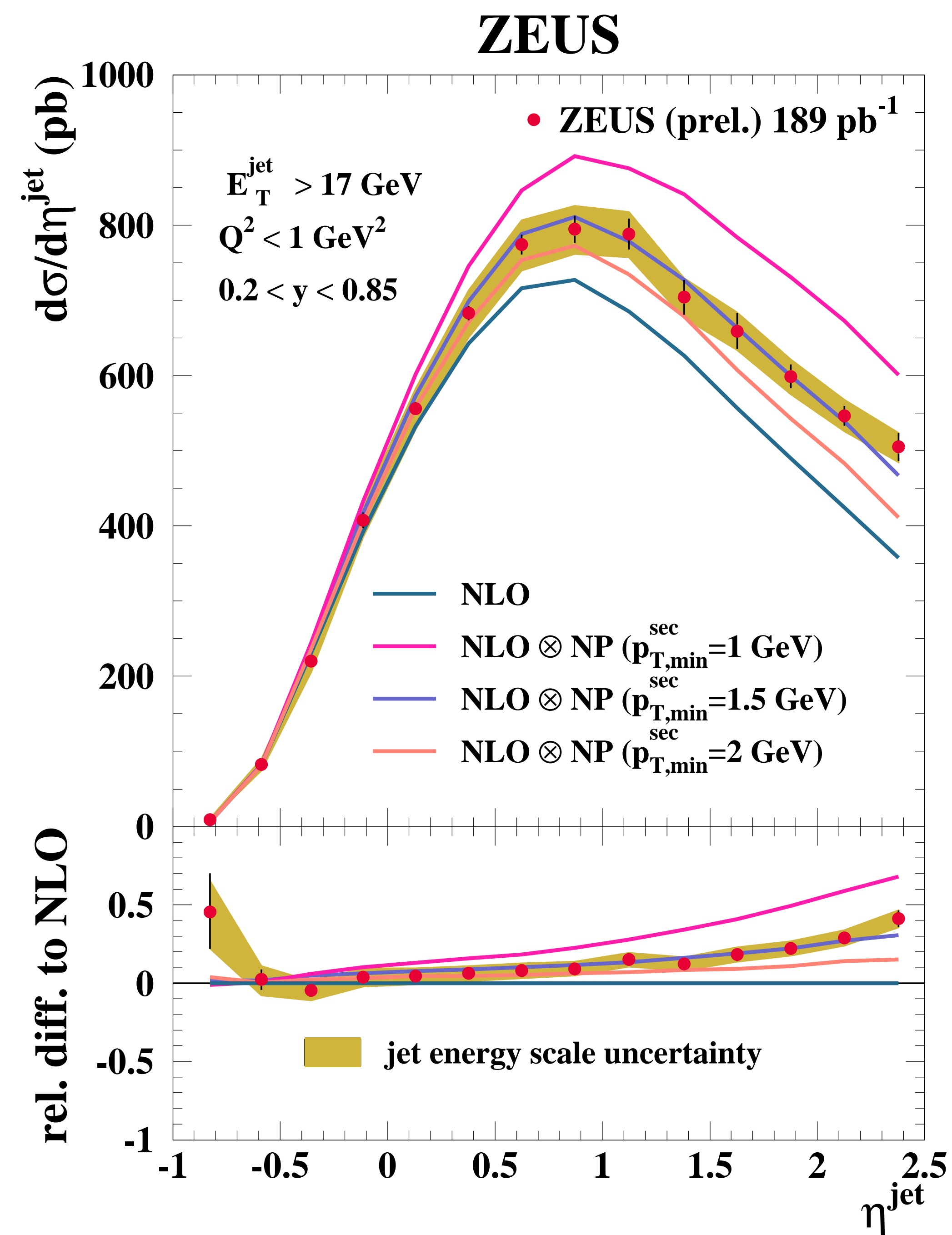
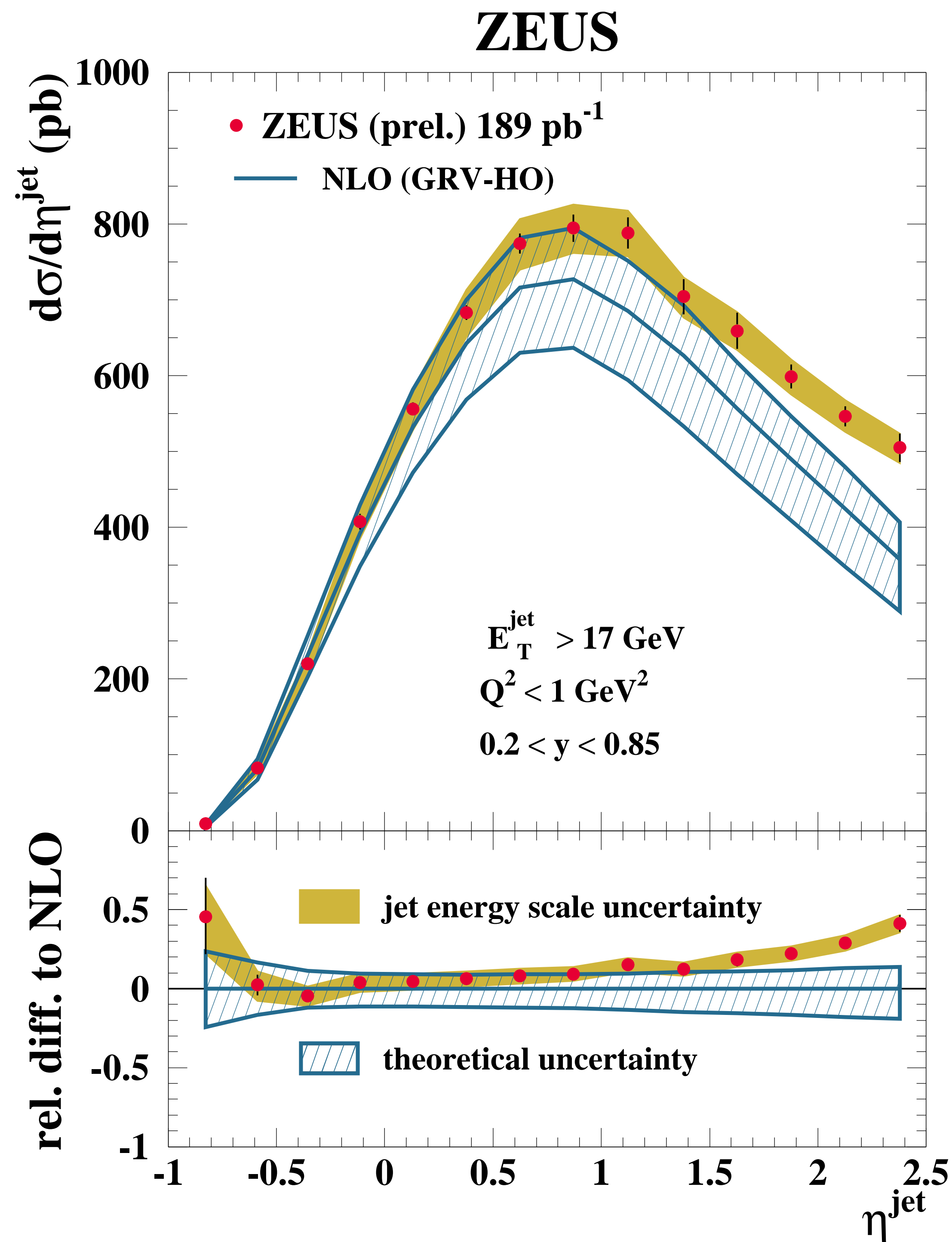


Everything well described except of forward region (low P_T)



Jets in photoproduction

$\mathcal{L} = 189 \text{ pb}^{-1}$
 $Q^2 < 1 \text{ GeV}^2$
 $0.2 < y < 0.85$
 $P_T^{JET} > 17 \text{ GeV}$
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One of possible explanations: Multiparton Interactions

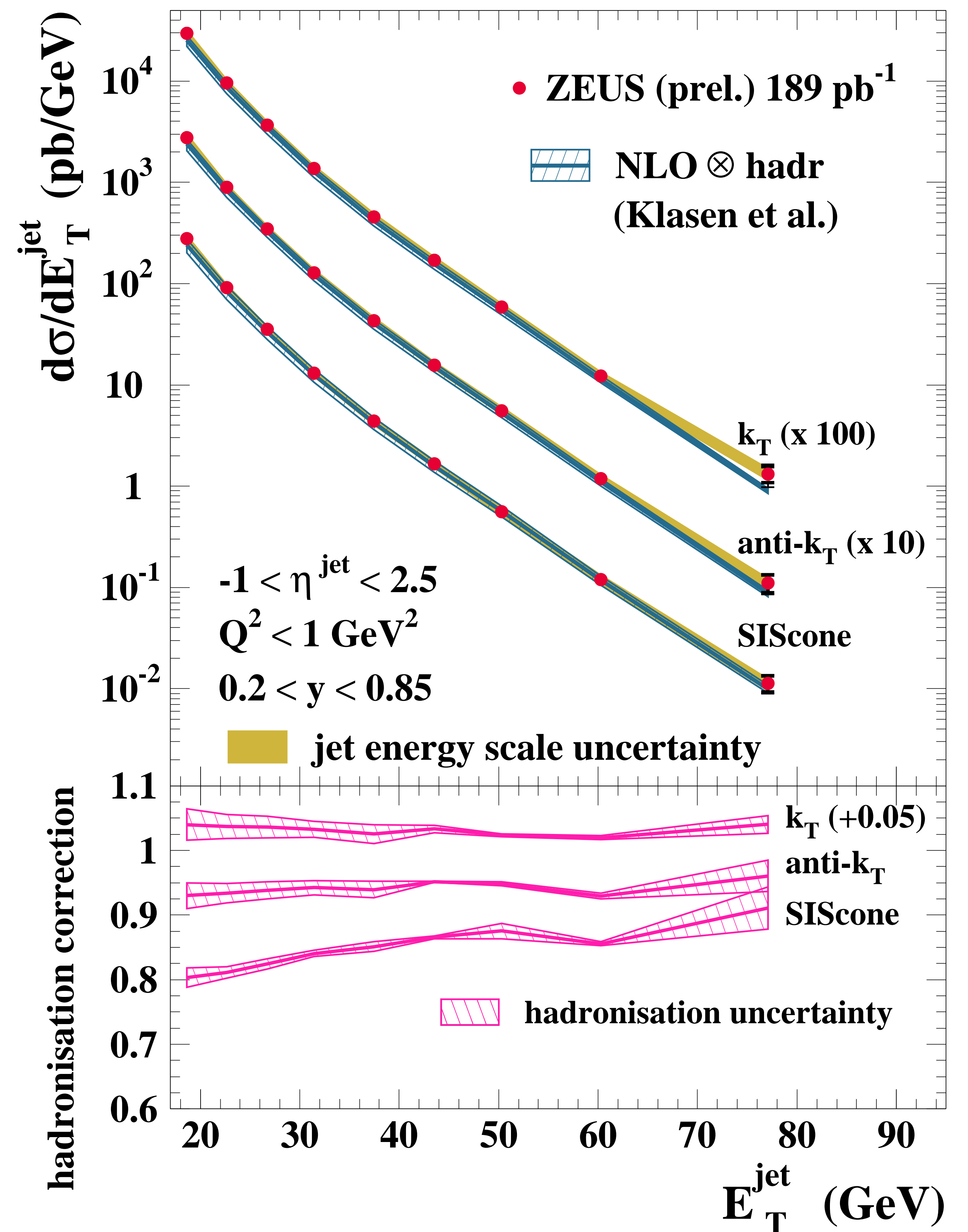


Jet algorithms comparison

Performance test for new algorithms developed for LHC ($\text{anti-}k_T$, SIScone) using DIS and PHP data

ZEUS

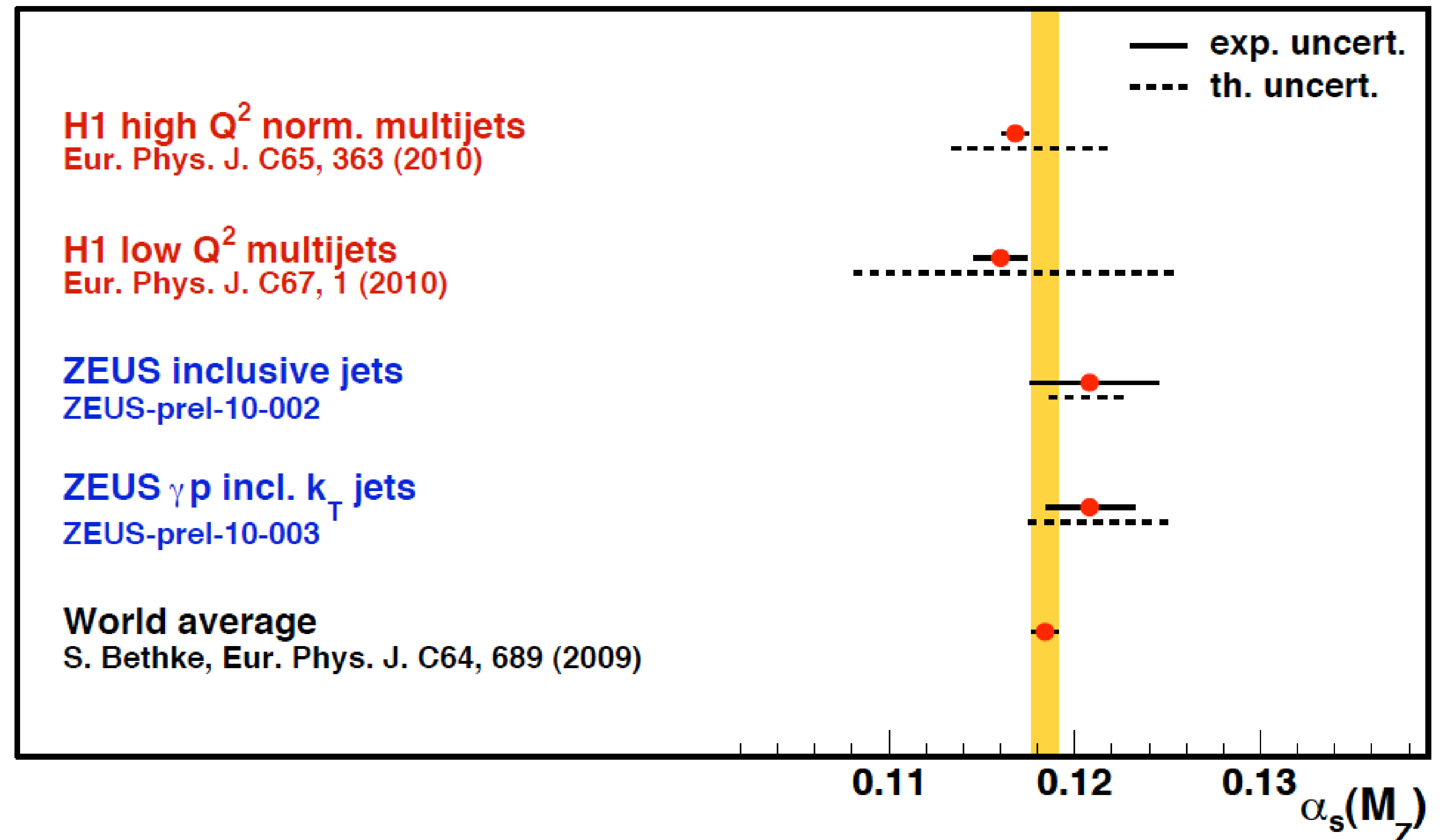
- ✓ k_T and $\text{anti-}k_T$ exhibit similar performance
- ✓ SIScone hadronization correction somewhat higher
- ✓ SIScone slightly higher missing terms uncertainty



Determination of α_s

Both experiments use their data to determine the strong coupling constant $\alpha_s(M_Z)$

All determined couplings consistent with the world average

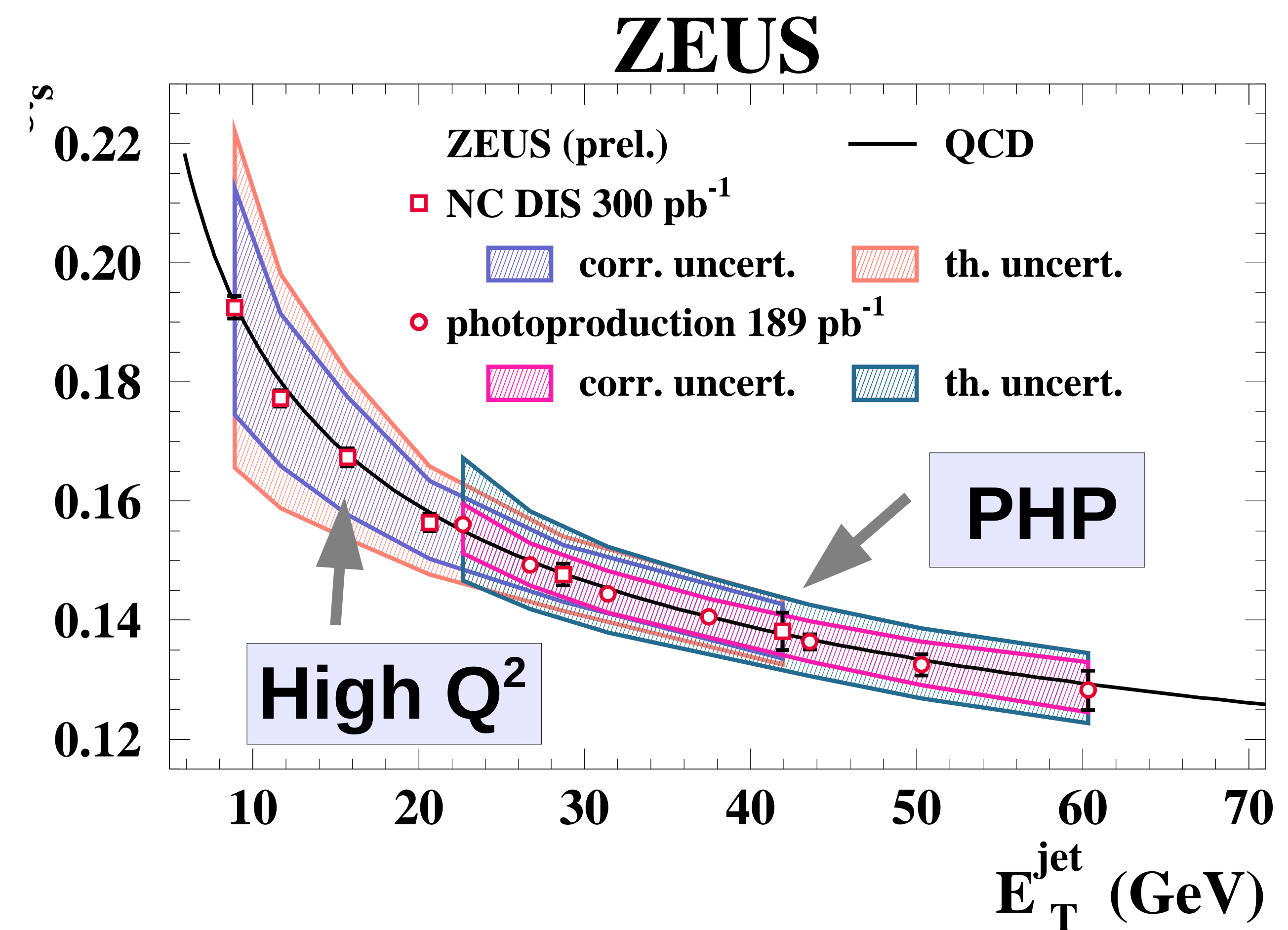
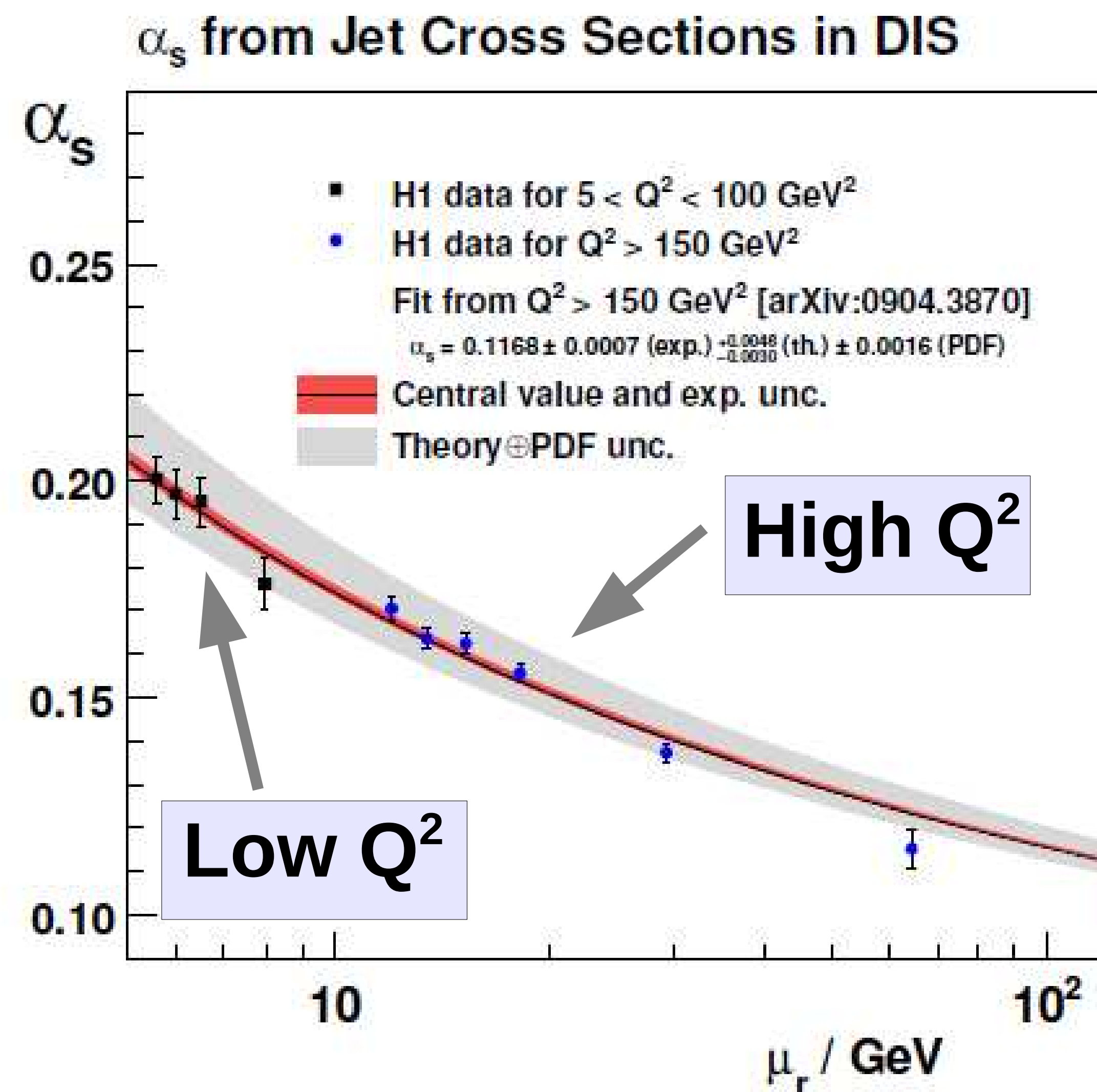


Couplings extracted from simultaneous fit to inclusive, dijet and trijet has reduced experimental uncertainty

Precision limited by the NLO calculation

Running of α_s test

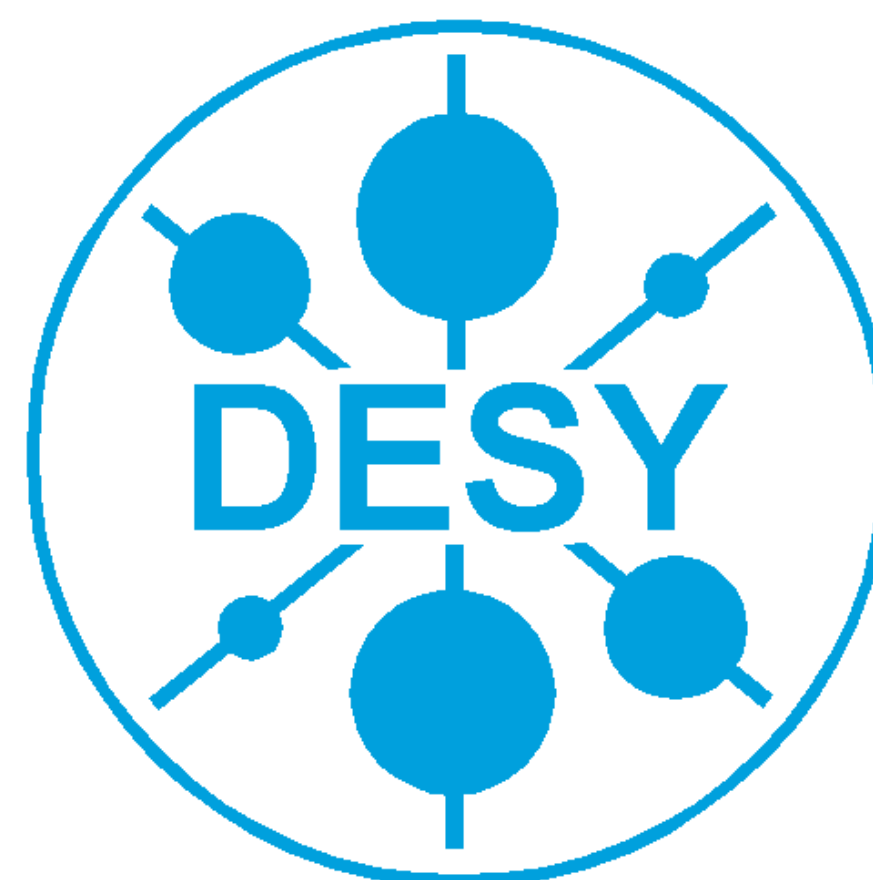
Both experiments perform tests of the running α_s



Tests show high level of consistency in our understanding of QCD

Conclusions

- ✓ *Jet measurements from HERA as important tool for*
 - ✓ *understanding of QCD*
 - ✓ *precise determination of strong coupling constant $\alpha_s(M_Z)$*
 - ✓ *test of the running of α_s over wide range of the scale*





High Q^2 DIS normalized jets

$$\mathcal{L} = 395 \text{ pb}^{-1}$$

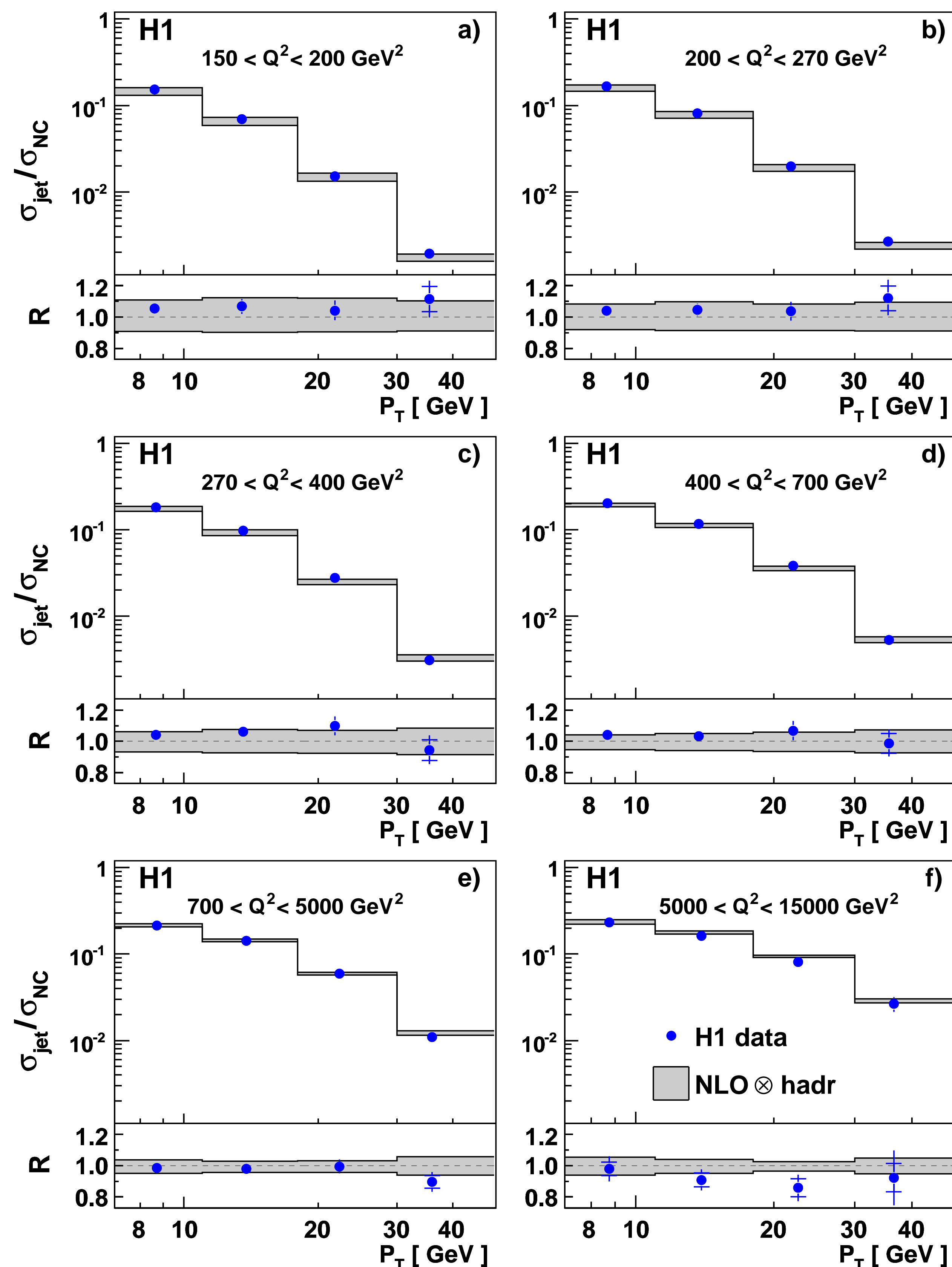
$$150 < Q^2 < 15000 \text{ GeV}^2$$

$$0.2 < y < 0.7$$

$$7(5) < P_T^{JET} < 50 \text{ GeV}$$

$$-0.8 < \eta^{JET} < 2.0$$

Normalised Inclusive Jet Cross Section



Inclusive, dijets and trijets cross sections normalized to inclusive DIS cross sections

Normalization allows to decrease experimental error

Theory error dominating, mostly renormalization scale uncertainty (up to 30%) - NNLO needed

Data well described by NLO calculations (DISENT, NLOJET++, FastNLO)

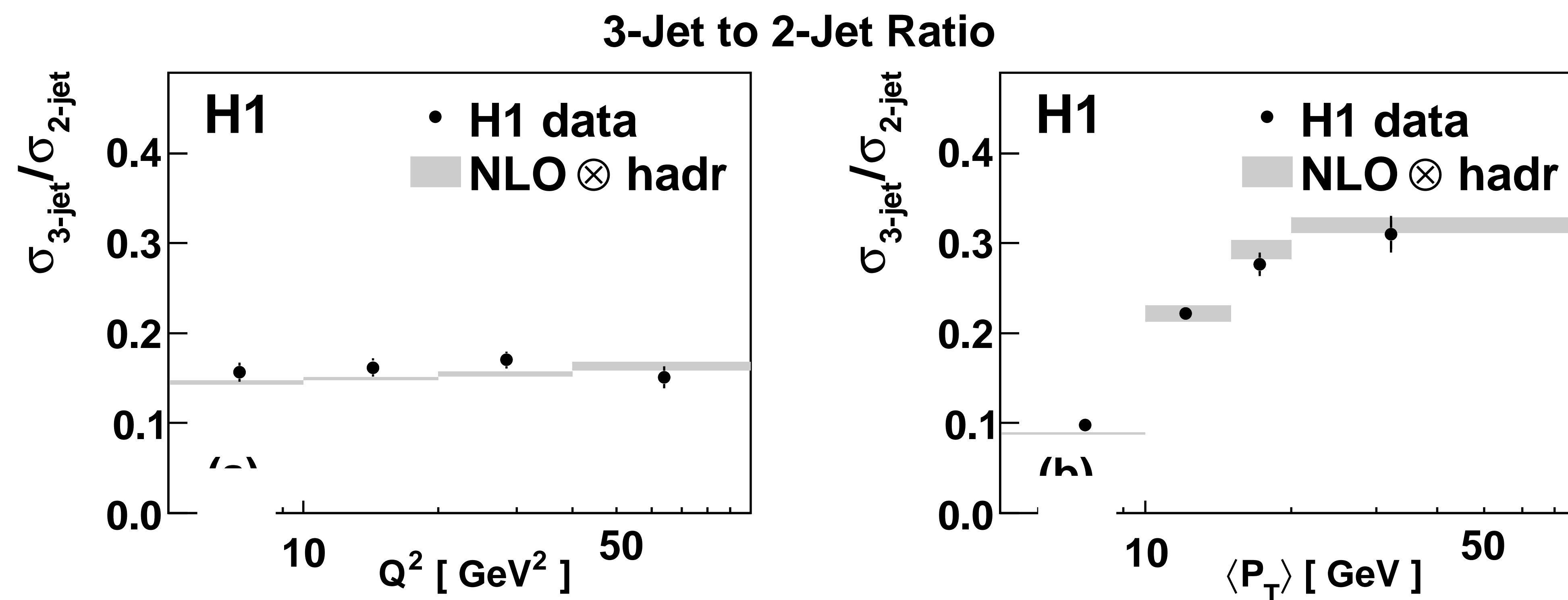


Low Q^2 DIS jets

$$\begin{aligned} \mathcal{L} &= 43.5 \text{ pb}^{-1} \\ 5 &< Q^2 < 100 \text{ GeV}^2 \\ 0.2 &< y < 0.7 \\ P_{T,B}^{JET} &> 5 \text{ GeV} \\ -1.0 &< \eta_{lab}^{JET} < 2.5 \end{aligned}$$

Improvement on the uncertainty can be achieved by measuring trijet to dijet ratio:

- ✓ Cancellation of some systematic uncertainties (by 50%)
- ✓ Strong reduction of missing higher orders influence

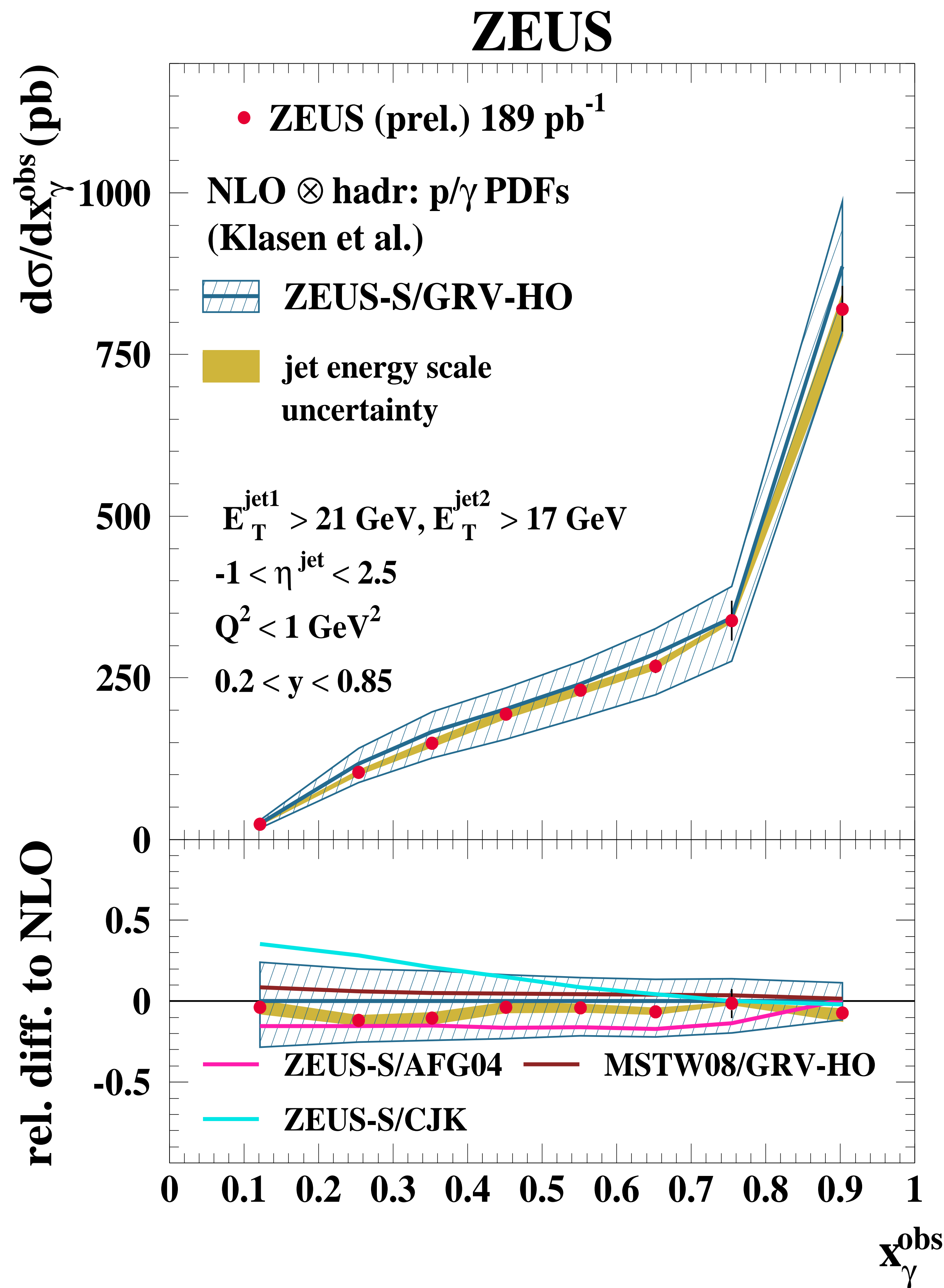


No discrepancy between theory and data observed

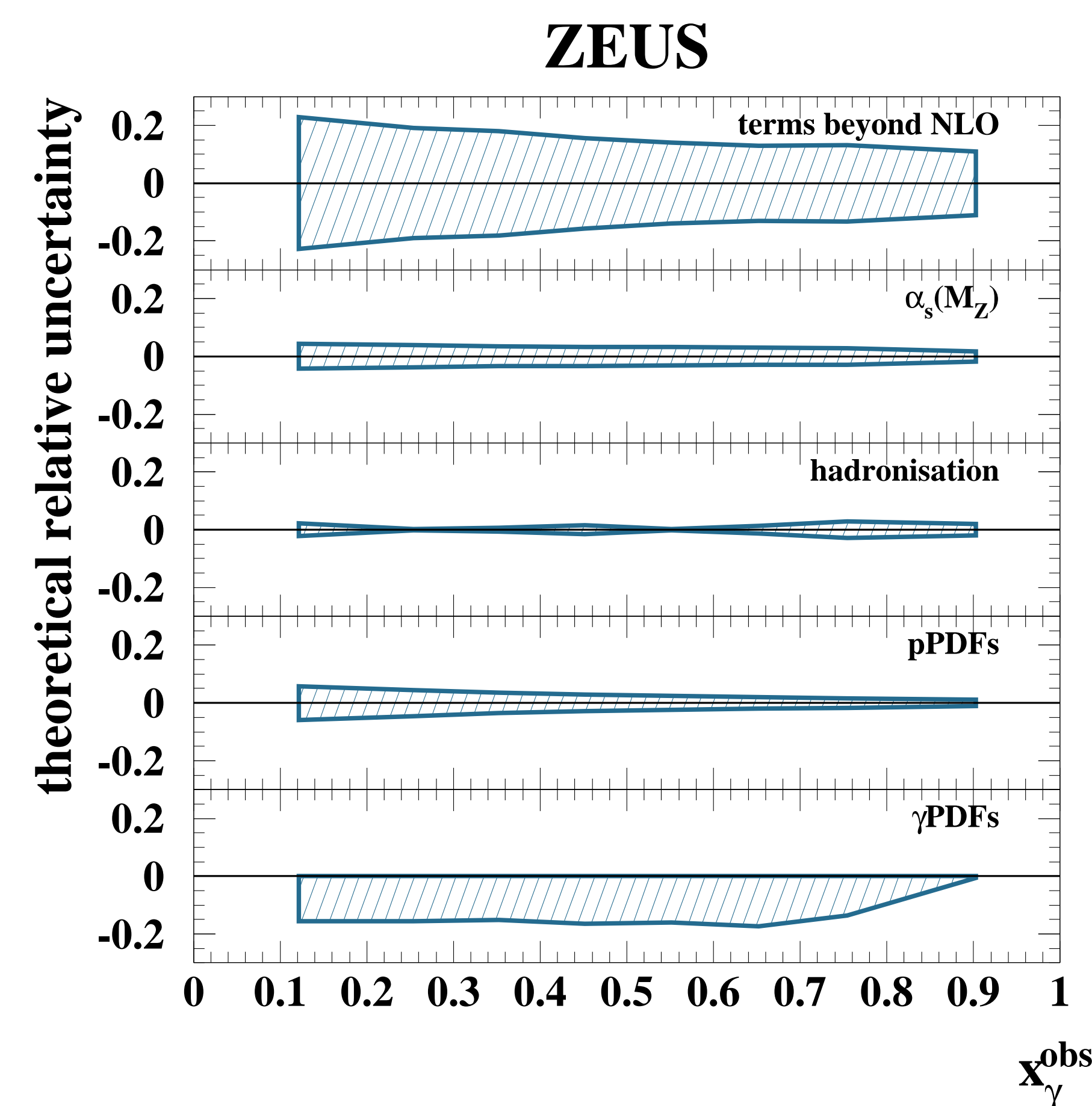


Dijets in photoproduction

$$\begin{aligned}\mathcal{L} &= 189 \text{ pb}^{-1} \\ Q^2 &< 1 \text{ GeV}^2 \\ 0.2 &< y < 0.85 \\ P_{T,B}^{JET} &> 21 (17) \text{ GeV} \\ -1.0 &< \eta_{lab}^{JET} < 2.5\end{aligned}$$



*Large theoretical uncertainty
(missing higher orders)*



- ✓ Sensitivity to photon PDF at low x_γ^{obs}
- ✓ High x_γ^{obs} better known, more suitable to be used in fits



Jet algorithms comparison

Performance test for new algorithms developed for LHC (anti- k_T , SIScone) using DIS and PHP data

- ✓ k_T and anti- k_T exhibit similar performance
- ✓ SIScone hadronization correction somewhat higher
- ✓ SIScone beyond NLO uncertainty slightly higher

