



Jets and α_s Measurements at HERA

Voica Radescu
(DESY)

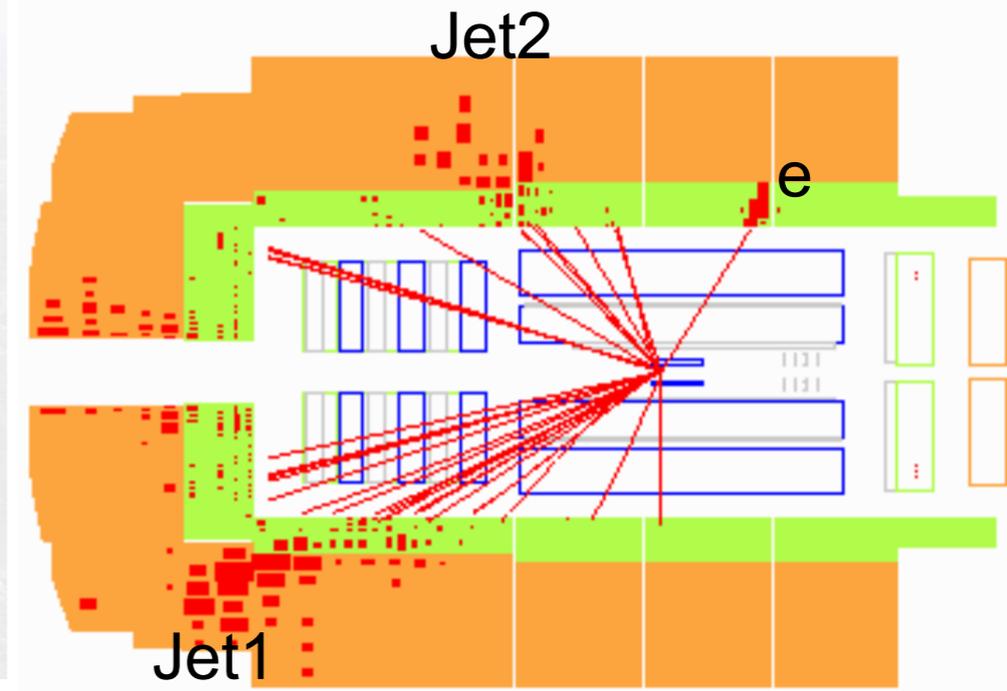
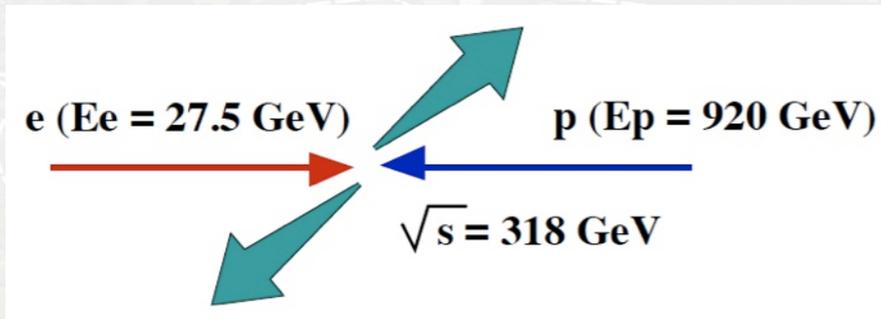
on behalf of the H1 and ZEUS collaborations

Outline

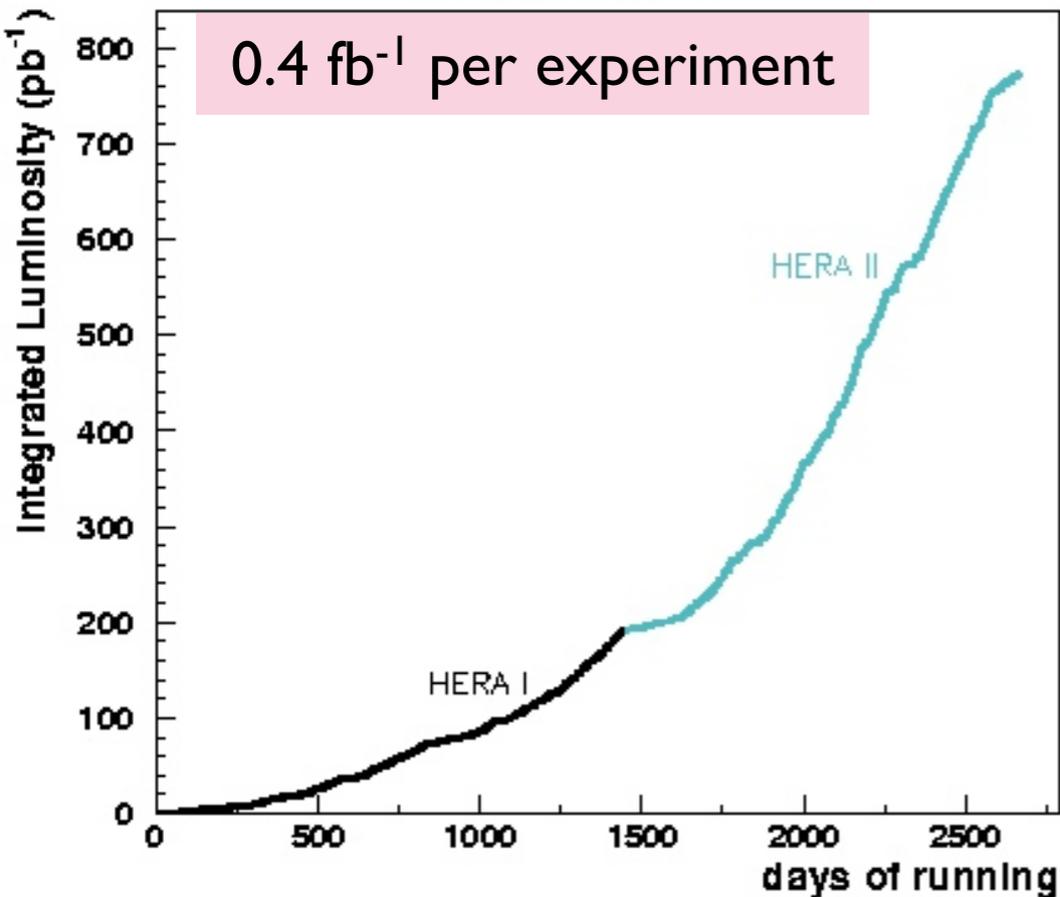
- Introduction
 - Jet Production at HERA
- Recent Measurements at HERA
 - Inclusive Jets in Photoproduction
 - Inclusive Jets in DIS at low and high Q^2
 - Multi Jets in CC DIS
- Results
- Summary



- HERA is an ep collider at DESY
- In operation for 15 years (1992-2007)
- H1 and ZEUS are collider experiments
 - general purpose detectors



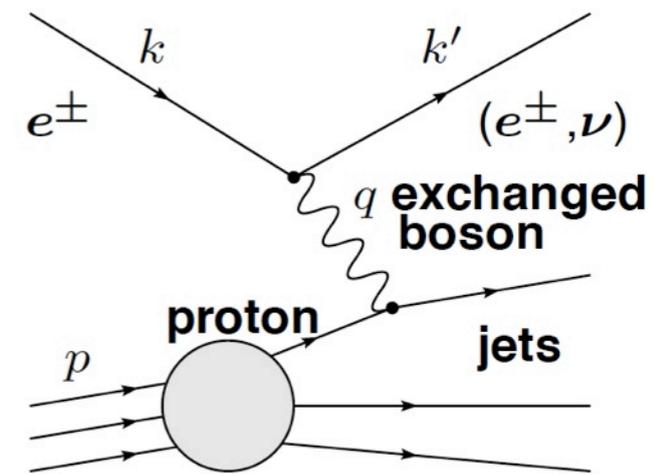
HERA delivered



Kinematic Variables:

- virtuality of exchanged boson:
 $Q^2 = -(k-k')^2$
- Bjorken scaling variable
 $x = Q^2/2pq$
- Inelasticity parameter
 $y = pq/pk$

$$Q^2 = sxy$$





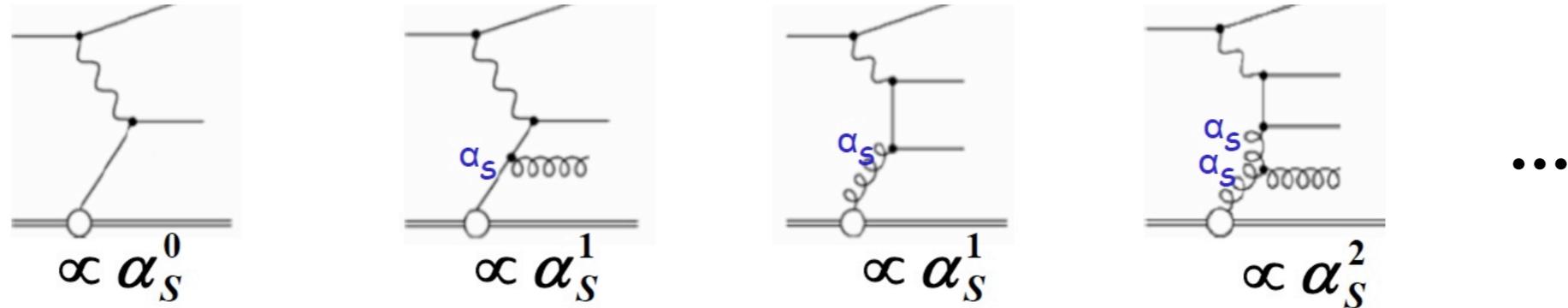
New Physics Results with Jets at HERA

- Jet production has been intensively studied at HERA
- Measurements of jets in DIS ($Q^2 > 1 \text{ GeV}^2$) and photo-production ($Q^2 \sim 0$) provide a powerful ground to:
 - test pQCD, factorization, determine alphas and test universality of PDFs
 - Inclusive Jets in Photoproduction [ZEUS-prel-08-008]
 - Inclusive Jets at low Q^2 [H1prelim-08-032]
 - Inclusive- and Multi-Jets at high Q^2 [ZEUS-prel-09-006][H1 DESY-09-032]
 - Multi Jets in CC DIS [ZEUS DESY-08-024]
- Jet substructure is a powerful tool to test the underlying colour dynamics, the pattern of parton radiation, the splitting functions
 - [DESY-08-100, DESY-08-178, ZEUS-prel-09-007]

} this talk

Jet Production at HERA

- Jet Cross Section in pQCD: Series Expansion in powers of α_s

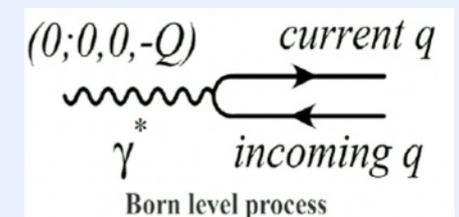


$$d\sigma_{\text{jet}} = \sum_{a=q,\bar{q},g} \int dx f_a(x, \mu_F) d\hat{\sigma}_a(x, \alpha_s(\mu_R), \mu_R, \mu_F)$$

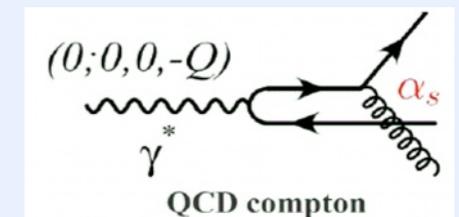
- f_a : parton a density, determined from experiment
- $\hat{\sigma}_a$: subprocess cross section, calculable in pQCD

- Jet finding is usually performed in the Breit Frame:

- Quark Parton Model diagram: no transverse momentum (E_T)
 - virtual boson and proton collide head-on



- Diagrams with α_s contributions: significant E_T produced by:
 - QCD Compton
 - Boson-gluon fusion



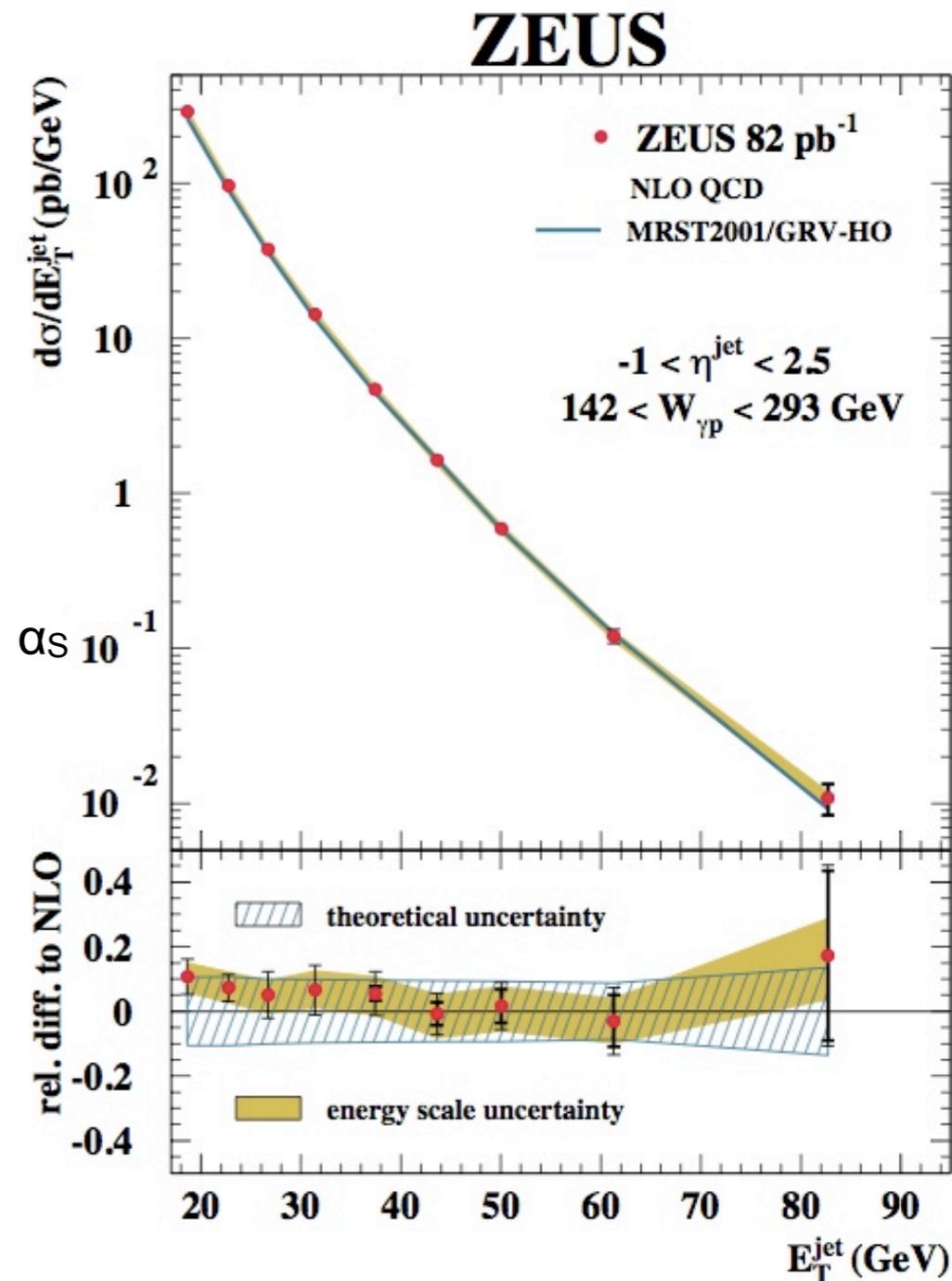
- two high E_T jets well separated from p-remnant

- Jets are reconstructed using the k_T cluster algorithm:
 - collinear and infrared safe



Inclusive Jets in Photoproduction [ZEUS-prel-08-008]

- QCD analysis from previous publication
 - [ZEUS Phys. Lett. B 560 (2003)]
 - Data 98-00 with Lumi=82 pb⁻¹
 - α_s extracted from $d\sigma/dE_T$
- $$\alpha_s(M_Z) = 0.1224 \pm 0.0001 \text{ (stat.) } \begin{matrix} +0.0022 \\ -0.0019 \end{matrix} \text{ (exp.) } \begin{matrix} +0.0054 \\ -0.0042 \end{matrix} \text{ (th.)}$$
- theory uncertainty clearly dominates!
- Re-analysis of the same data with NLO ($O(\alpha_s^2)$) QCD calculations [Klasen, Kleinwort, Kramer] using:
 - MRST2001 PDF set for proton for different values of α_s
 - GRV-HO PDFs for photon
 - $\mu_r = \mu_f = E_T^{\text{jet}}$ for each jet
 - new estimate for the theoretical uncertainties using method of Jones et al. [JHEP 0312, 007 (2003)]
- New calculations result in better description of the data
- The extraction of α_s results in a very precise determination with a reduced total uncert: 3.1%
 - exp. unc: 1.8 %, PDF unc: <1%, had. corr <0.5%



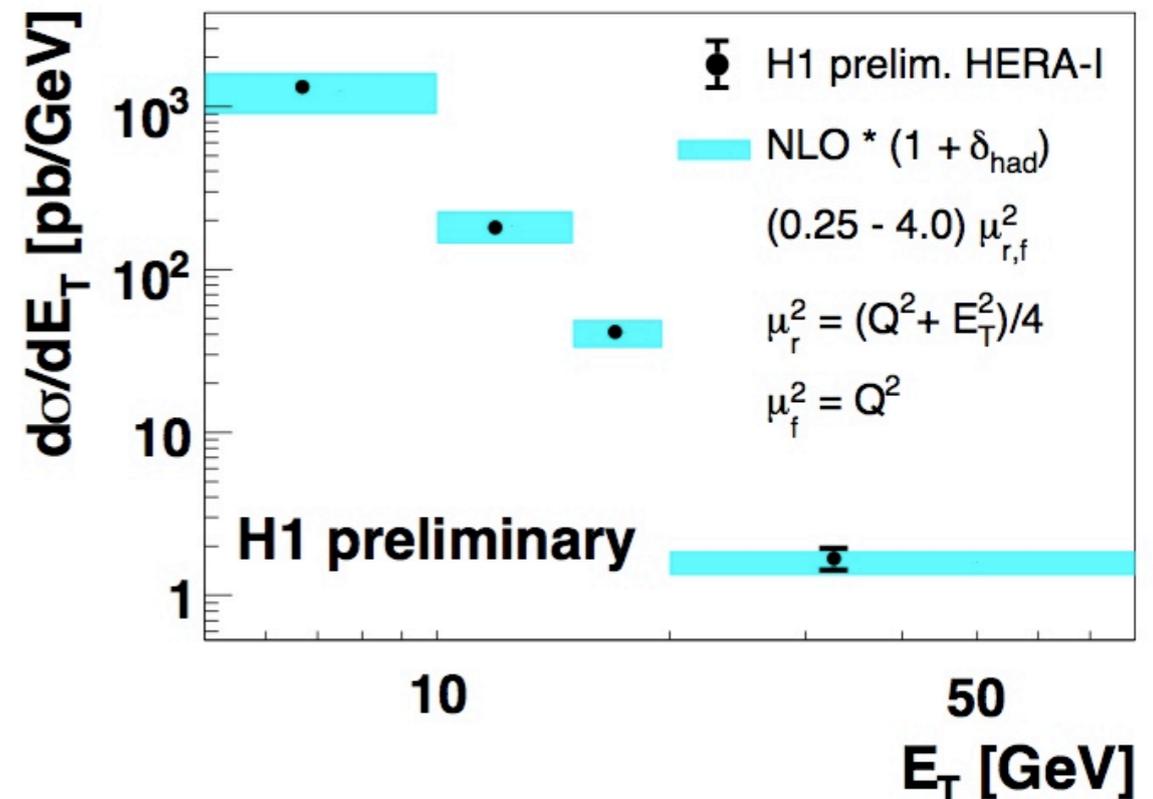
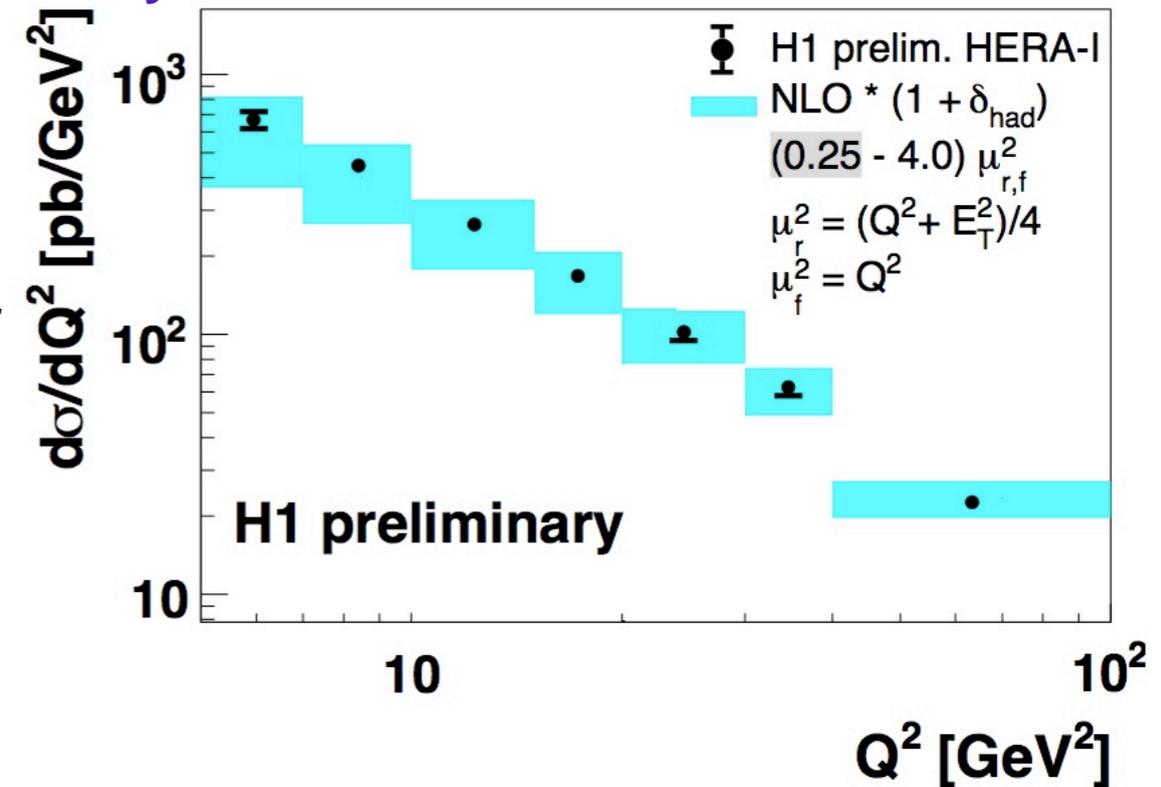
$$\alpha_s(M_Z) = 0.1223 \pm 0.0001 \text{ (stat.) } \begin{matrix} +0.0023 \\ -0.0021 \end{matrix} \text{ (syst.) } \pm 0.0030 \text{ (th.)}$$



Inclusive Jet Production at low Q^2 [H1 prelim-08-032]

- Data H1: 99-00 with Lumi = 43.5 pb⁻¹
 - Kinematic range:
 - $5 < Q^2 < 100 \text{ GeV}^2$
 - $0.2 < y < 0.7$
- Cross sections are measured as function of Q^2, P_{T}^{jet} for
 - single inclusive jets → every jet with $P_T > 5 \text{ GeV}$
 - Main Experimental uncertainties:
 - 2% hadronic energy scale: $\Delta\sigma/\sigma = 4\text{-}10\%$
 - uncertainty of acceptance and QED rad. correction: $\Delta\sigma/\sigma = 2\text{-}15\%$
- Data compared to NLO predictions
 - MS scheme for 5 massive quarks
 - CTEQ6 PDFs
 - $\mu_F^2 = Q^2$ and $\mu_R^2 = Q^2 + E_T^2/4$

Inclusive Jet Cross Sections $d\sigma/dQ^2$ and $d\sigma/dE_T$

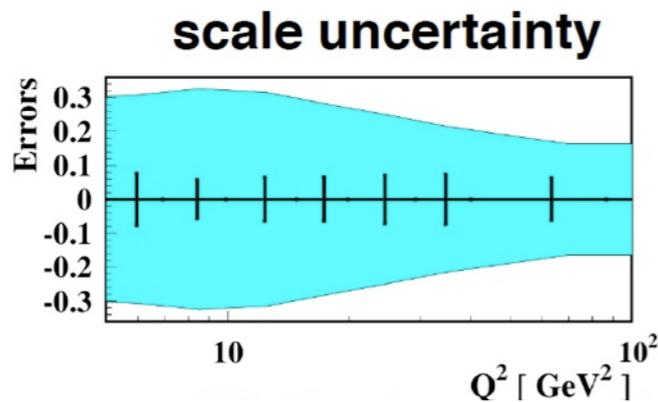




Inclusive Jet Production at low Q^2 [H1 prelim-08-032]

• Accurate measurement well described by NLO QCD:

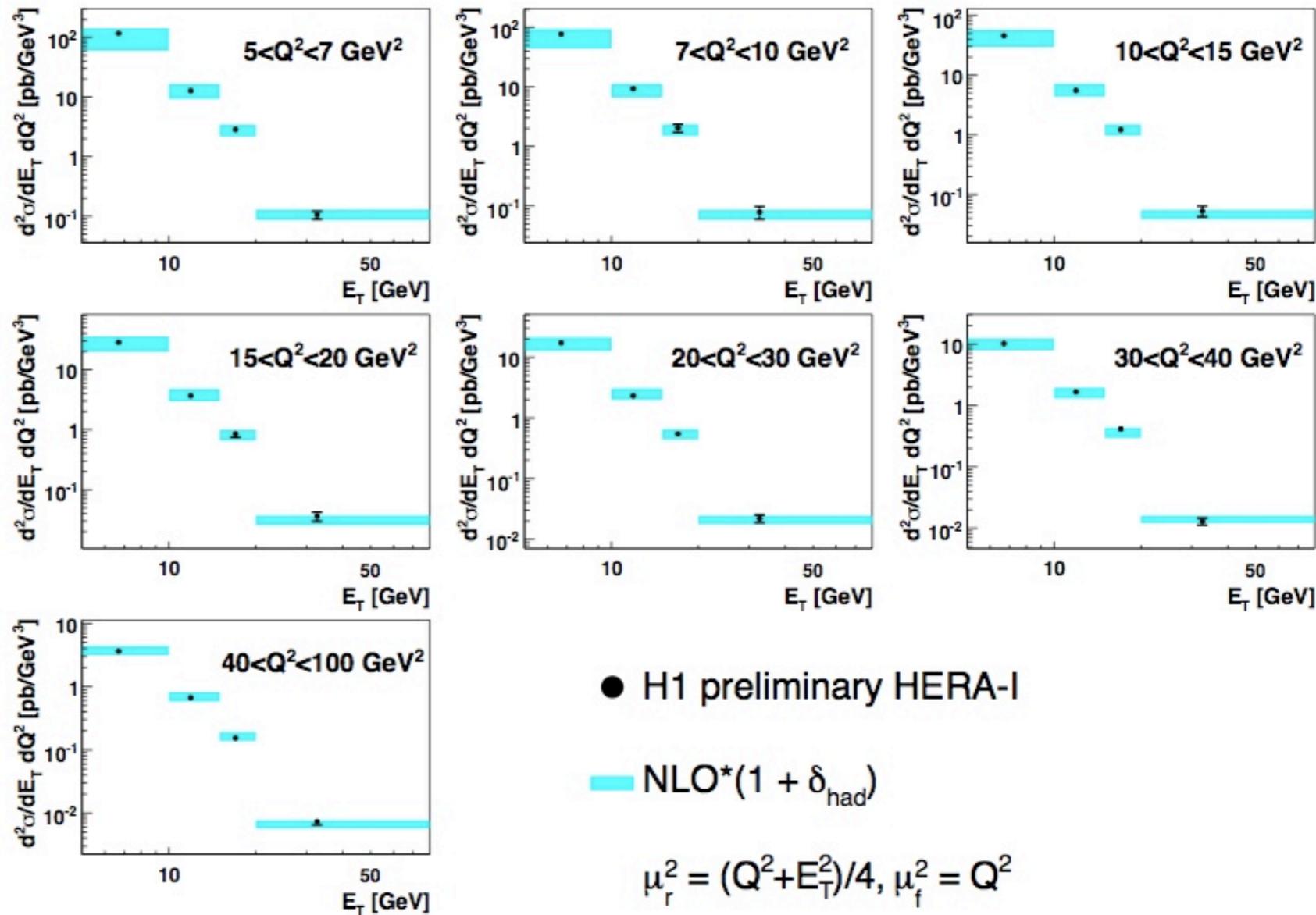
- **exper. uncer: 5-10%**
- **theory uncer: 15-30%**
 - renorm. scale uncert. dominates and increases with decreasing Q^2



- **small predictive power of NLO calculations at low Q^2 or E_T**

• Orders beyond NLO are needed in theoretical predictions!

H1 Inclusive Jet Cross Sections $\frac{d^2\sigma}{dQ^2 dE_T}$





Running of α_s from low Q^2 [H1 prelim-08-032]

- Extraction of α_s from low Q^2 double differential inclusive jet cross section produces

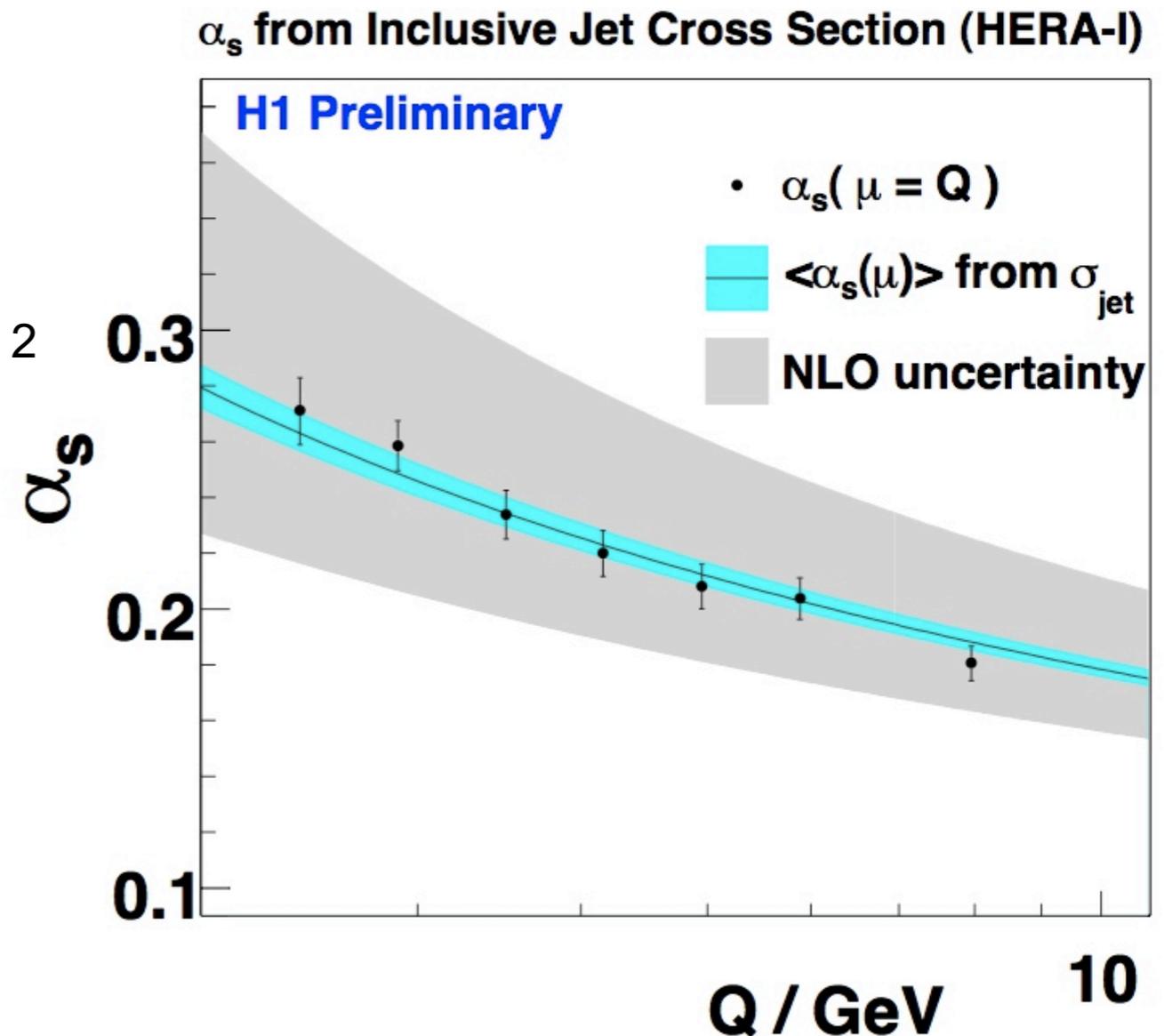
$$\alpha_s(M_Z) = 0.1186 \pm 0.0014(\text{exp})_{-0.0101}^{+0.0132}(\text{theory}) \pm 0.0021(\text{pdf}),$$

correlated experimental uncertainties ($\sim 1\%$)

theoretical uncertainty ($\sim 10\%$):

- variation of **renormalisation** and factorisation scales separately by 1/2 and 2
- PDF uncertainty
- hadronisation corrections

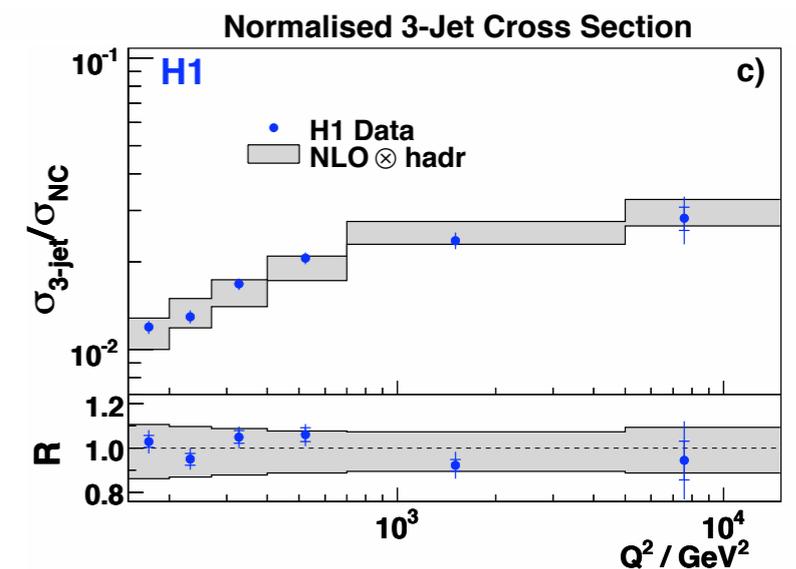
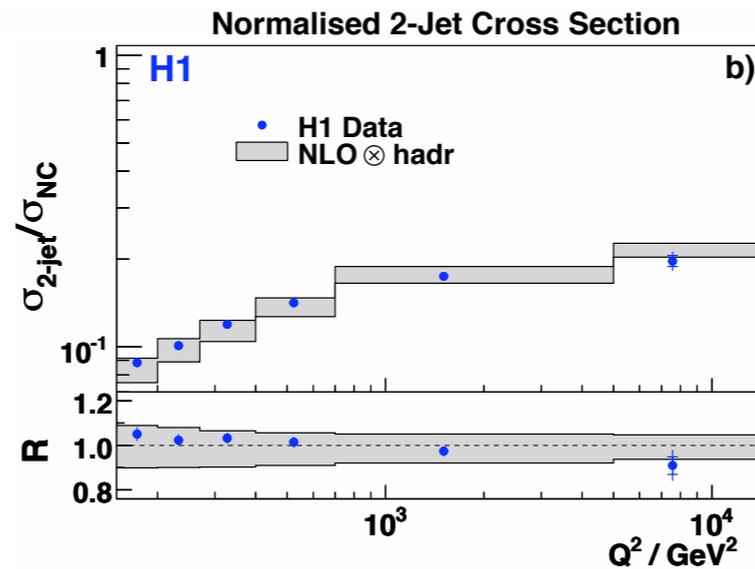
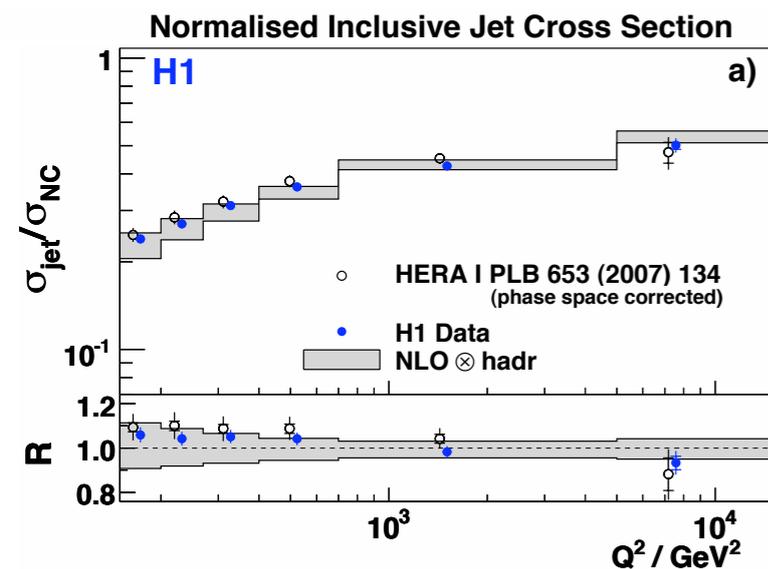
- **Small predictive power of NLO calculations!**





Inclusive Jet Production at high Q^2 [H1 DESY-09-032]

- Data H1: 1999-2007 with Lumi = 395 pb⁻¹ and kinematic range:
 - 150 < Q^2 < 15000 GeV²
 - 0.2 < y < 0.7
- Cross sections are measured as function of Q^2 , P_T^{jet} , $\xi = x(1+M_{12}^2/Q^2)$ for
 - single inclusive jets → every jet with 7 < P_T < 50 GeV
 - 2(3)-jets → events with at least 2(3) jets with 5 < P_T < 50 GeV and M_{12} > 16 GeV
- Measurements are normalised to the inclusive NC DIS cross section
 - partial cancellations of experimental and theoretical uncertainties:
 - lumi, trigger efficiencies, QED effects, ...
- Experimental uncertainties:
 - hadronic energy scale dominates (1-5% effect on cross section)
 - overall experimental uncert. ranges between 3%-6%, reaching 15% at highest P_T
- Jet multiplicity increases with Q^2 and is well described by NLO QCD





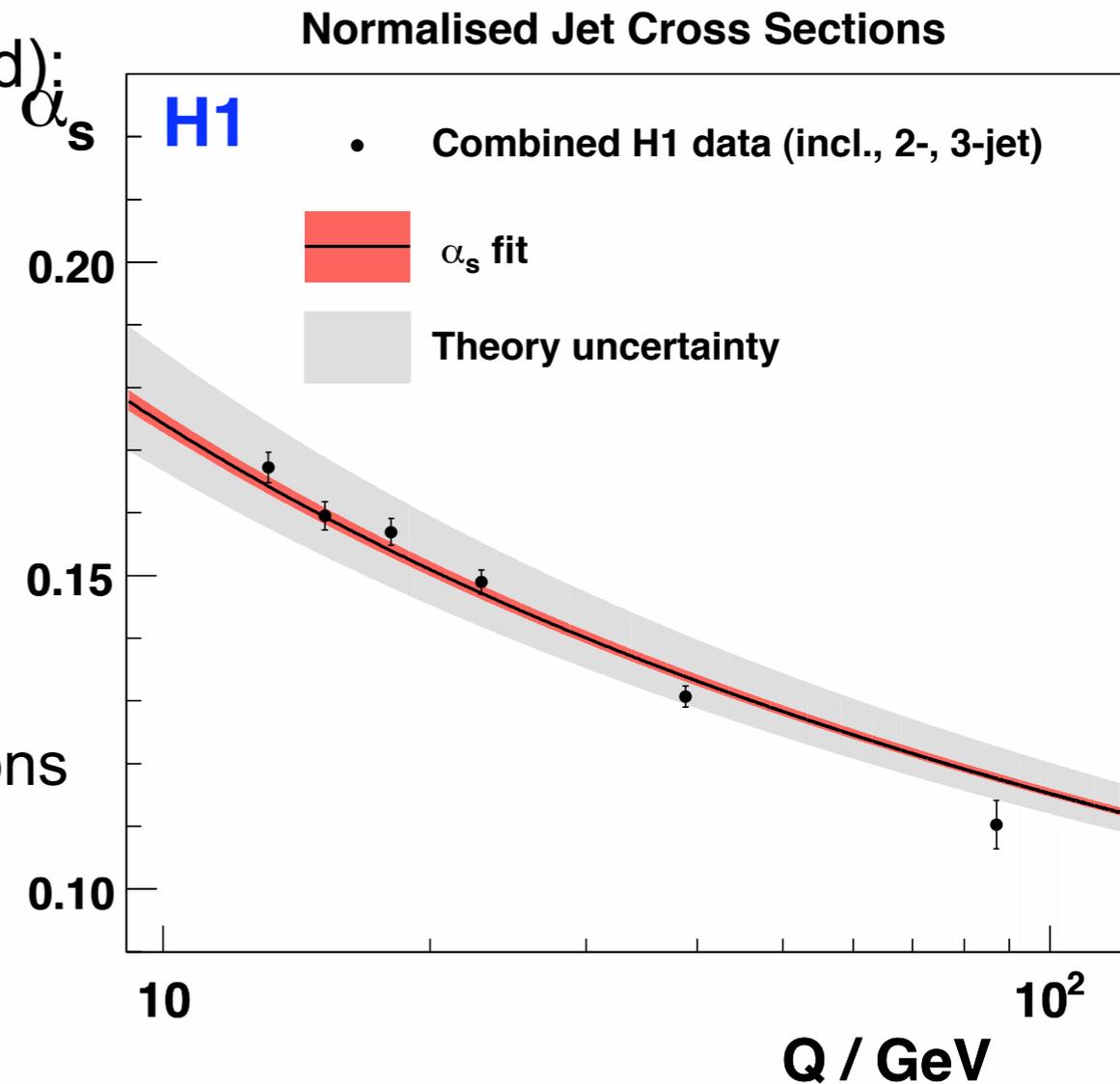
Inclusive Jet Production at high Q^2 [H1 DESY-09-032]

- Extraction of the strong coupling:
 - determined from the measured normalised jet cross sections as function of Q^2 and E_T^{jet} using the PDFs from global analyses
 - determination performed from individual observables and from their combination

- Result of simultaneous fit (Hessian method):
 - for $Q^2 > 150 \text{ GeV}^2$

$$\alpha_s(M_Z) = 0.1168 \pm 0.0007 (\text{exp.}) \begin{matrix} +0.0046 \\ -0.0030 \end{matrix} (\text{th.}) \pm 0.0016 (\text{PDF})$$

- Experimental uncertainty: **0.6 %**
- result with best experimental precision!
- Total uncertainty: **3.6%**
- Running of α_s agrees with QCD expectations





Running of α_s from low and high Q^2 [H1 prelim-08-032]

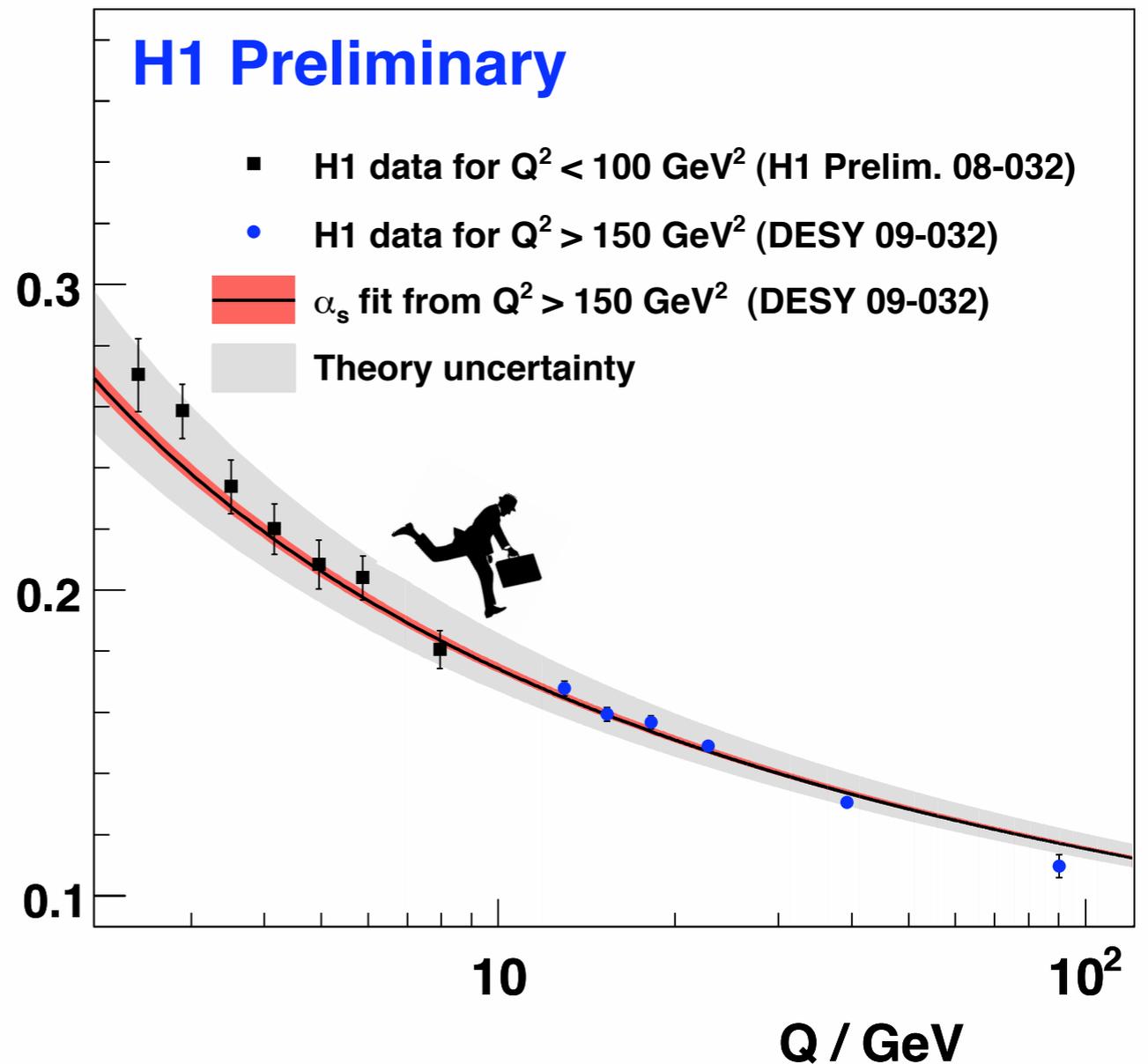
- α_s from low Q^2 added to high Q^2 curve:
- very good agreement between low and high Q^2 extractions
- low Q^2 data lie within the theory uncertainty of the high Q^2 fit

low Q^2

$$\alpha_s(M_Z) = 0.1186 \pm 0.0014(\text{exp})^{+0.0132}_{-0.0101}(\text{theory}) \pm 0.0021(\text{pdf}),$$

high Q^2

$$\alpha_s(M_Z) = 0.1168 \pm 0.0007(\text{exp.})^{+0.0046}_{-0.0030}(\text{th.}) \pm 0.0016(\text{PDF})$$





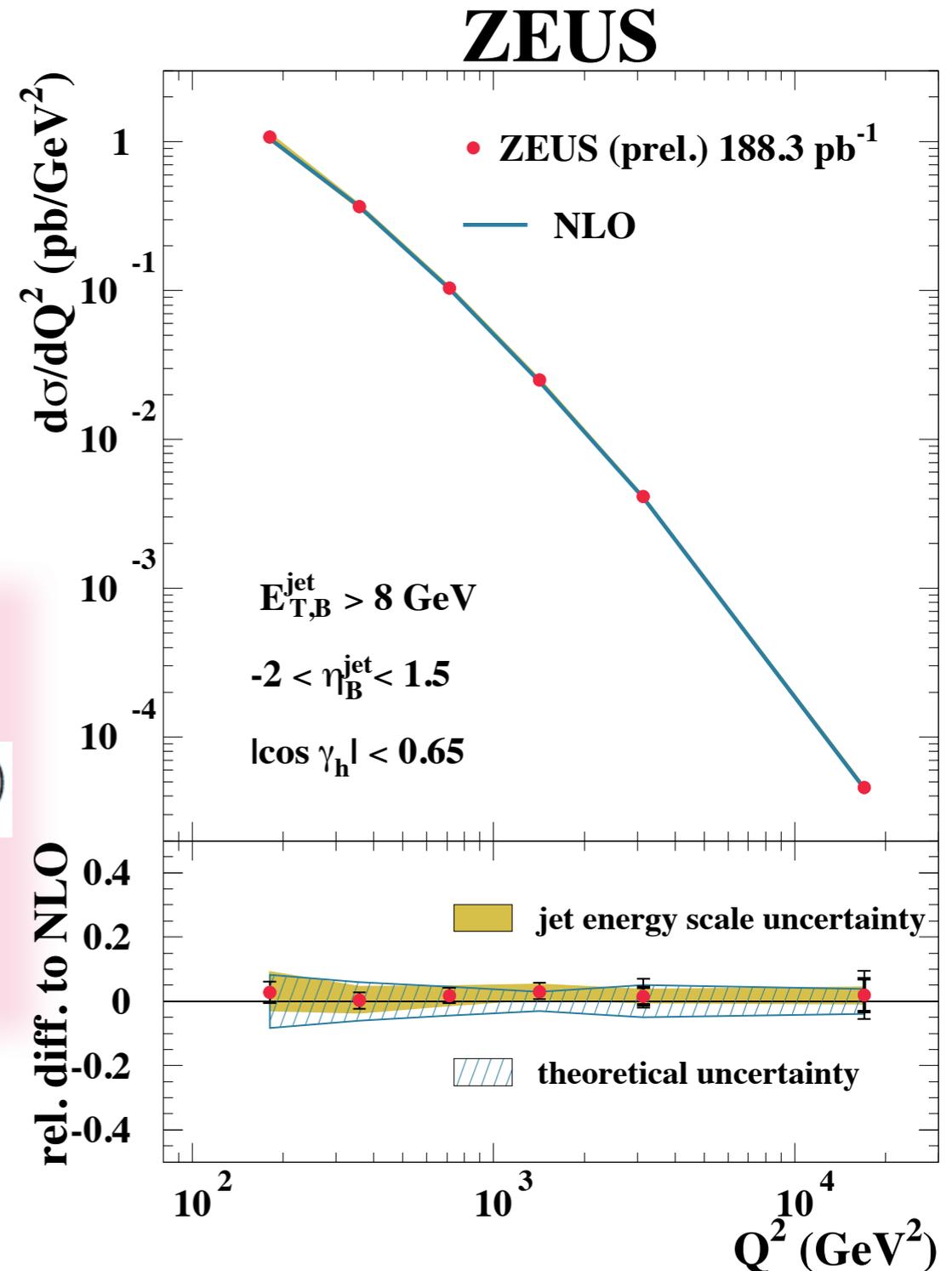
Inclusive Jet Production at high Q^2 [ZEUS-prel-09-006]

- Data: ZEUS HERA II with Lumi = 188 pb⁻¹
- Kinematic range:
 - $Q^2 > 125 \text{ GeV}^2$
- Measurements:
 - single differential cross sections as function of Q^2 or E_T or η^{jet}
 - Main uncertainties for cross section:
 - hadron energy scale
 - theoretical uncert. dominates over exper.
 - to minimize total uncertainty, α_s extracted for $Q^2 > 500 \text{ GeV}^2$

$$\alpha_s(M_Z) = 0.1192 \pm 0.0009 \text{ (stat.) } \begin{matrix} +0.0035 \\ -0.0032 \end{matrix} \text{ (exp.) } \begin{matrix} +0.0020 \\ -0.0021 \end{matrix} \text{ (th.)}$$

- 2.9% experimental uncertainty
- 3.5% total uncertainty.

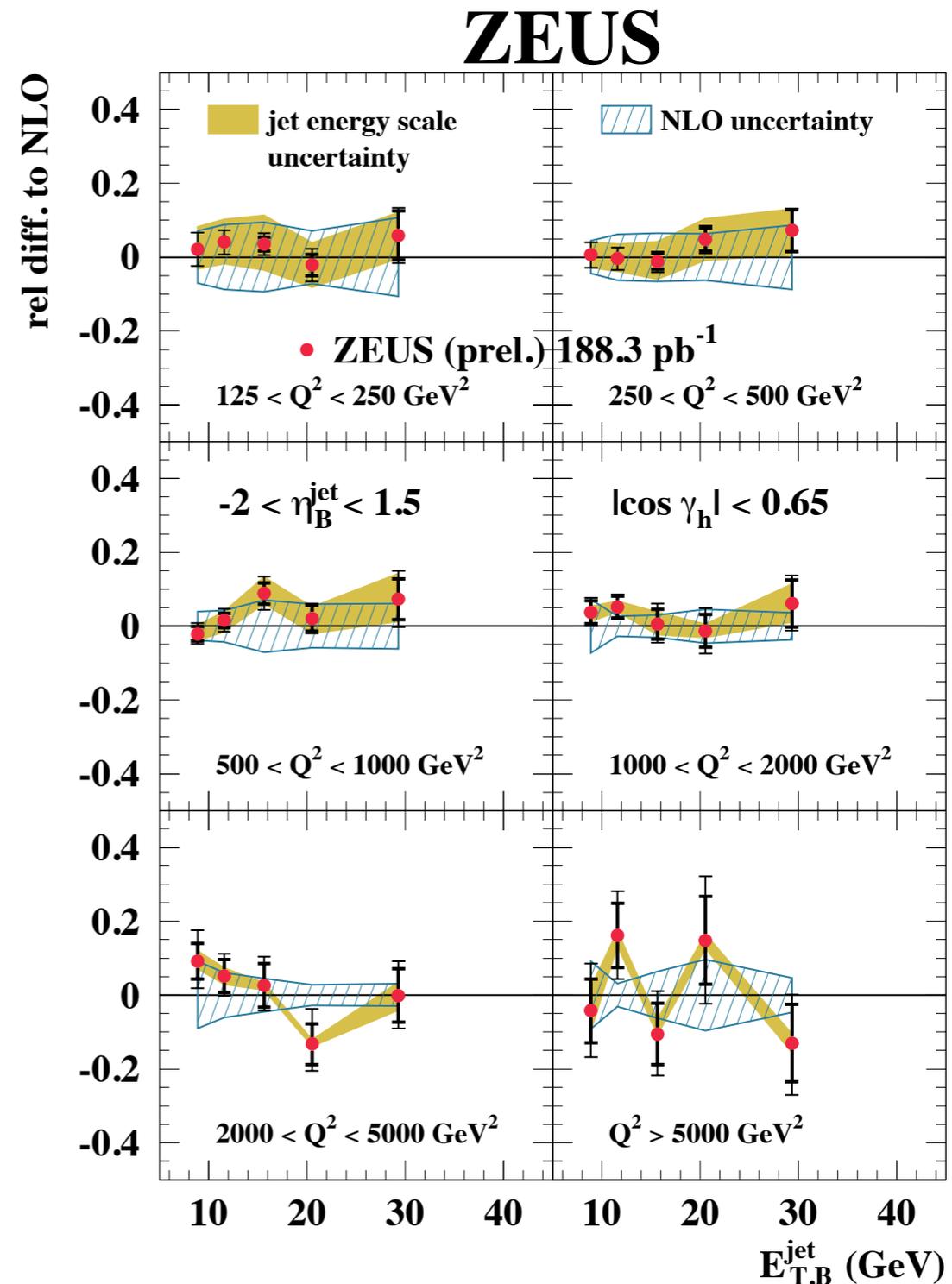
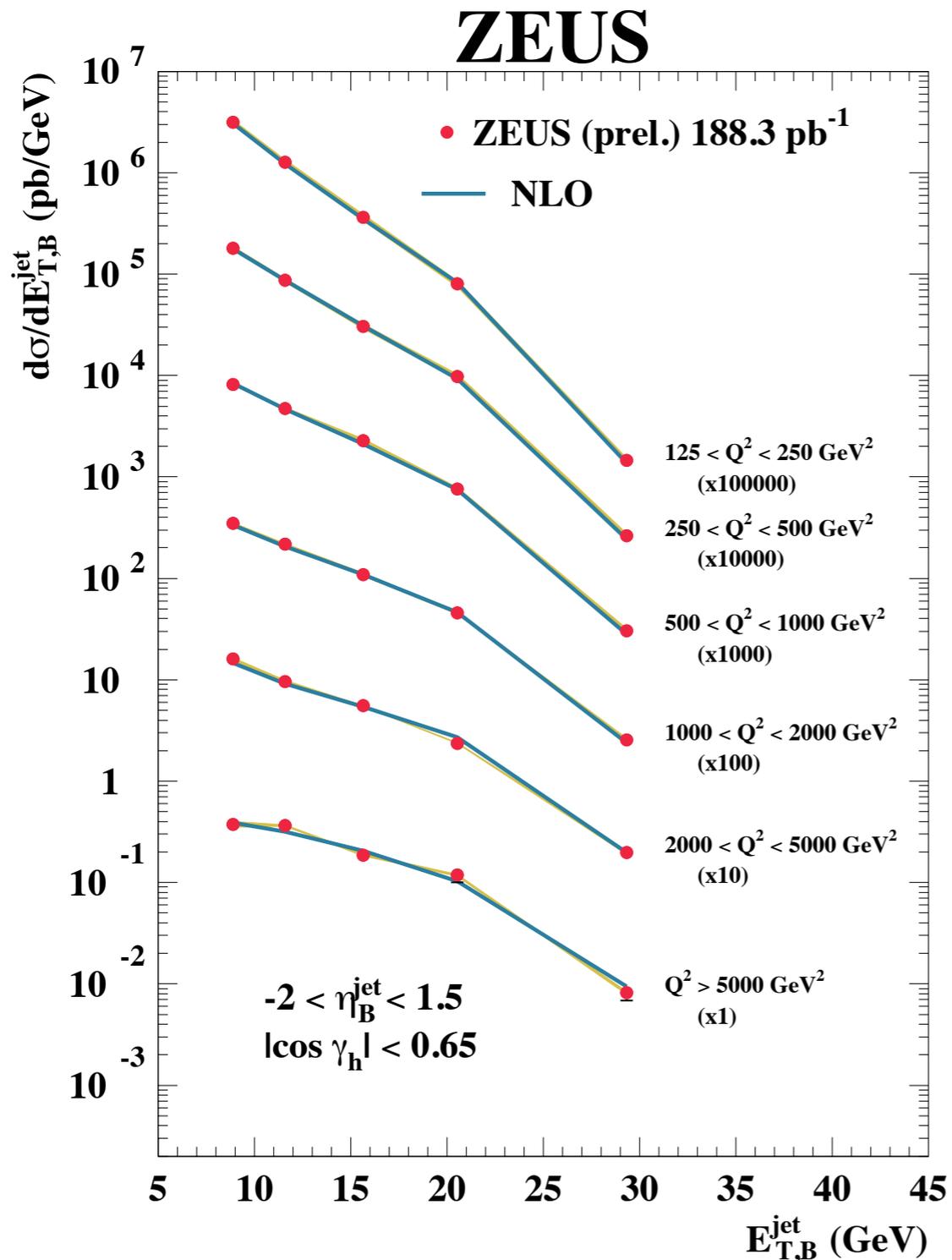
- double differential cross sections as function of E_T and Q^2
 - have potential to constrain gluon at high x





Inclusive Jet Production at high Q^2 [ZEUS-prel-09-006]

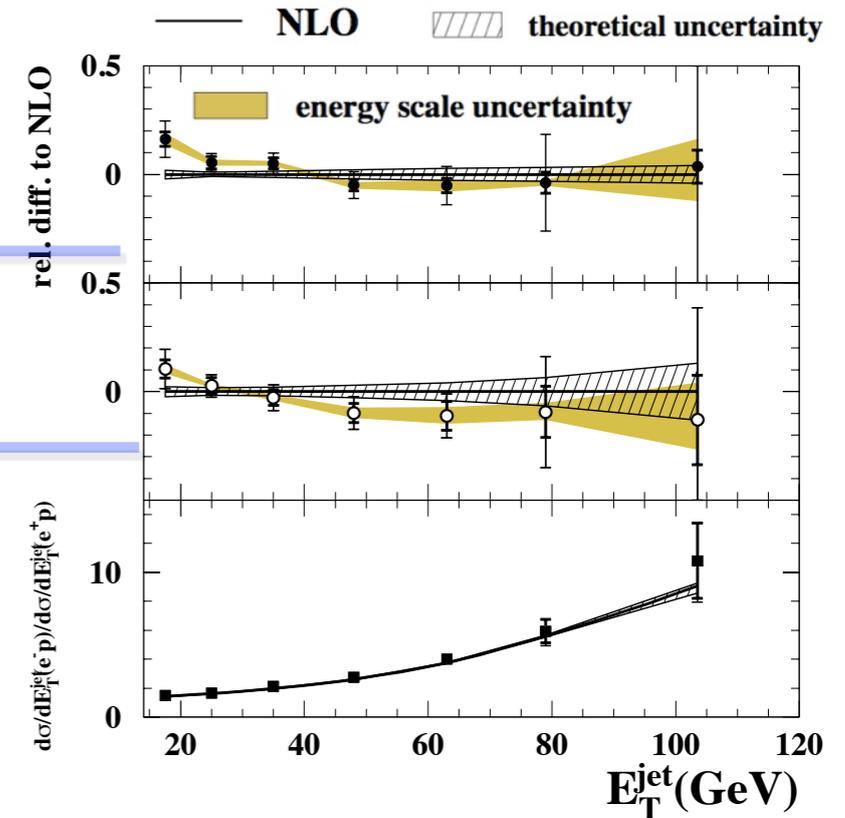
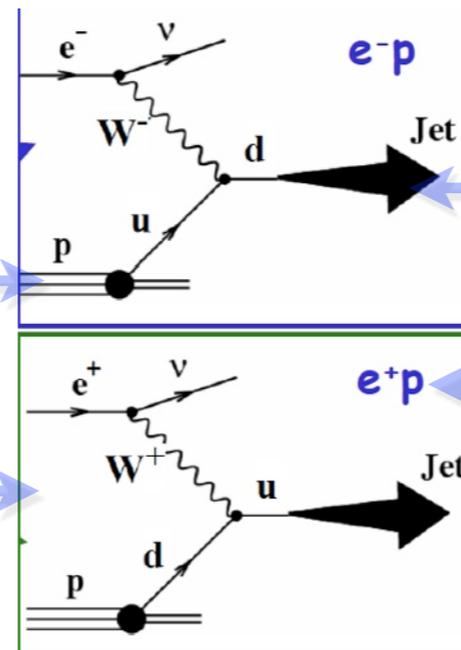
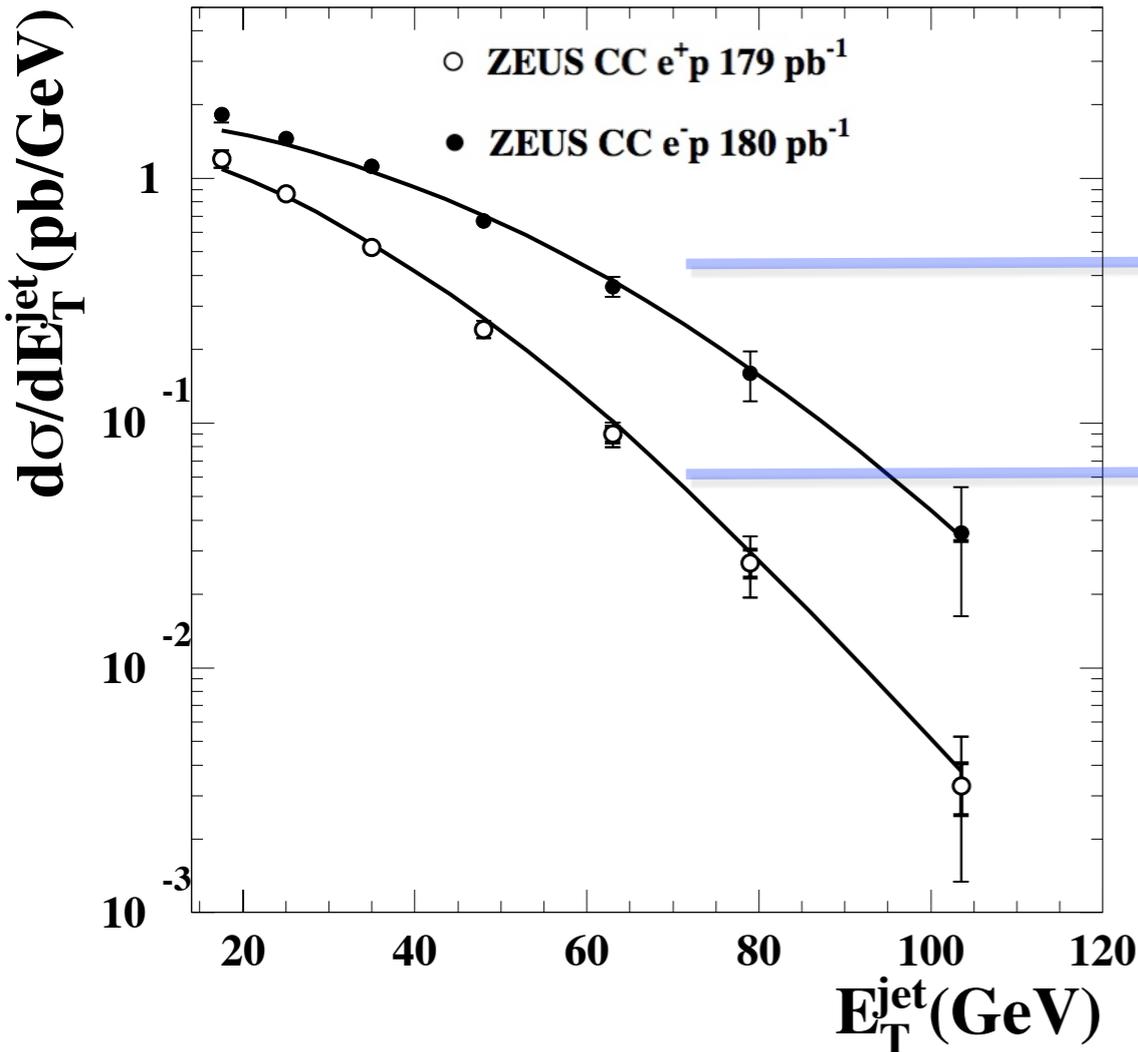
- Double differential inclusive jet cross sections as function of E_T and Q^2 shows good description of all data by NLO QCD





Inclusive Jet Production in CC DIS [ZEUS-DESY-08-024]

- Data: ZEUS HERA II with Lumi=0.36 fb⁻¹ (e⁺p/e⁻p data)
- Kinematic range:
 - Q² > 200 GeV²
 - y < 0.9
- Measurements of polarized and unpolarized integrated and differential multi-jet cross sections in CC DIS were performed.
 - E_T > 14 GeV and -1 < η^{jet} < 2.5

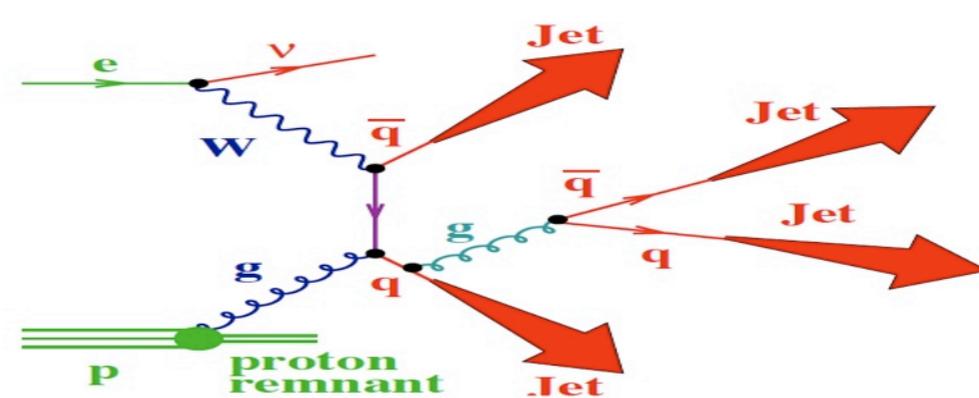
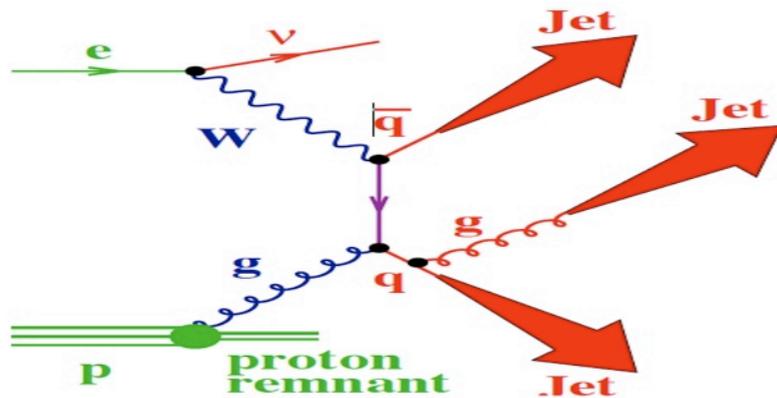


- Measured cross section for e⁺p decreases more rapidly than for e⁻p data:
- Comparison to NLO QCD predictions:
 - the shape and magnitude are reasonable well described

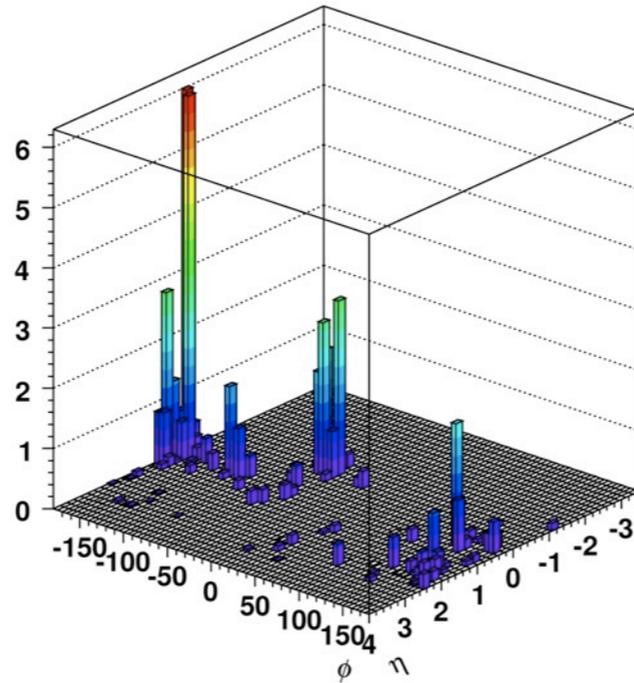
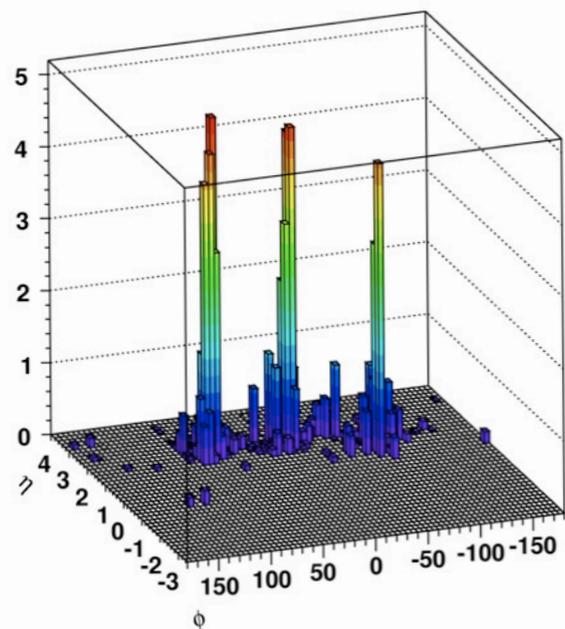
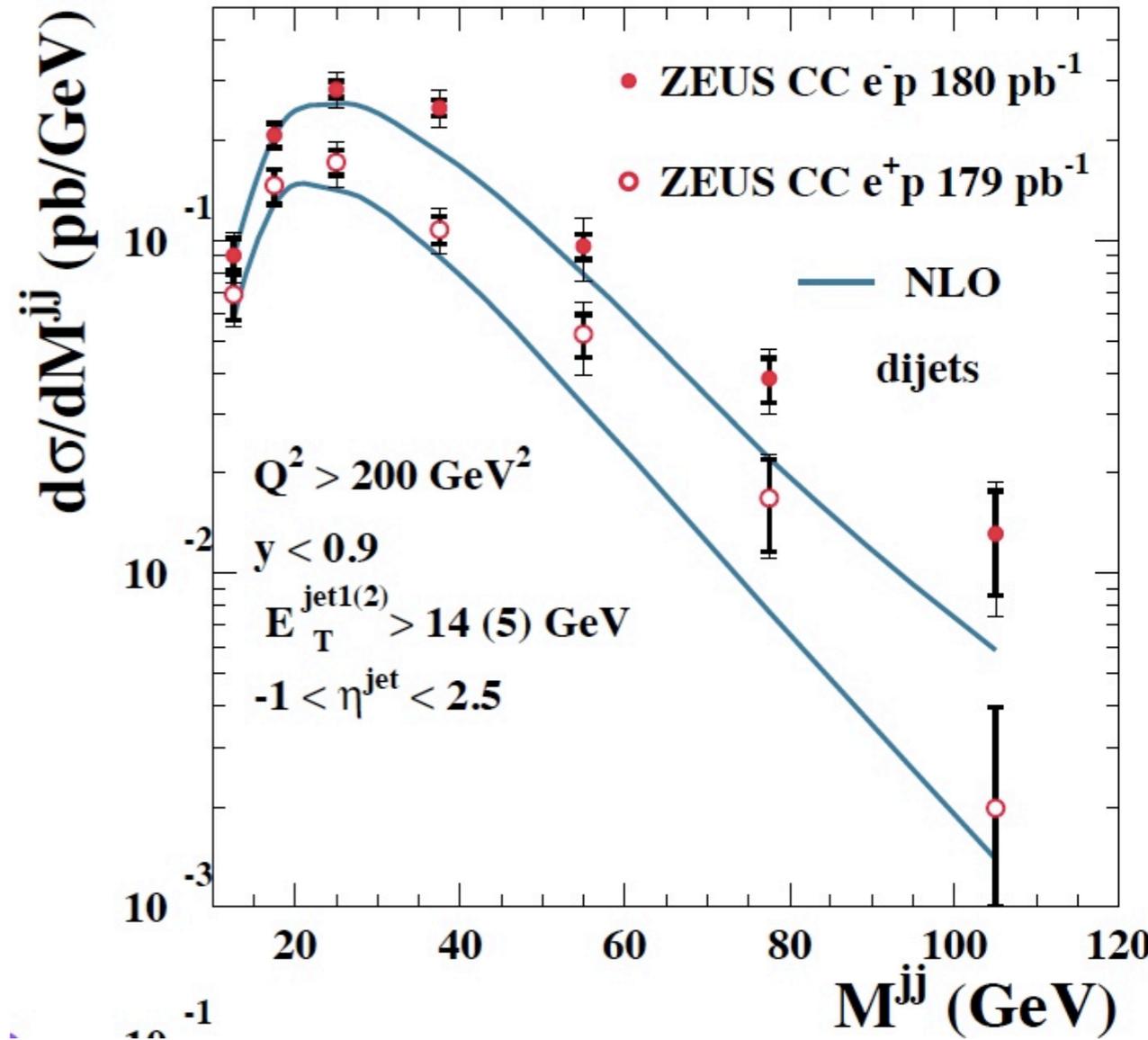


Multi-Jet Production in CC DIS [ZEUS-DESY-08-024]

- Additional jets with $E_T^{\text{jet}} > 5 \text{ GeV}$



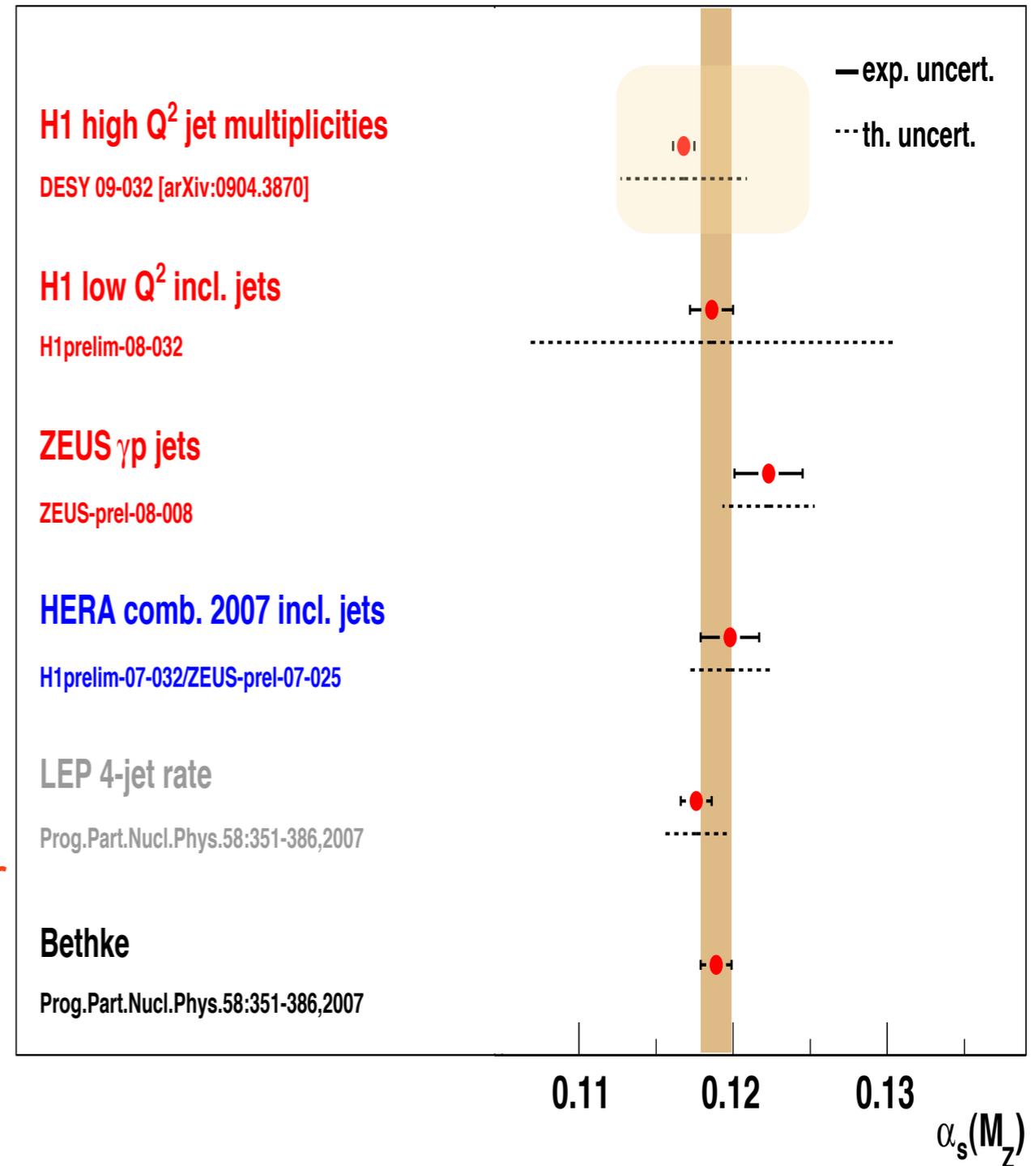
- Measured dijet cross sections are NOT well described by NLO
- First observations of 3- and 4-jet production in CC DIS





Summary

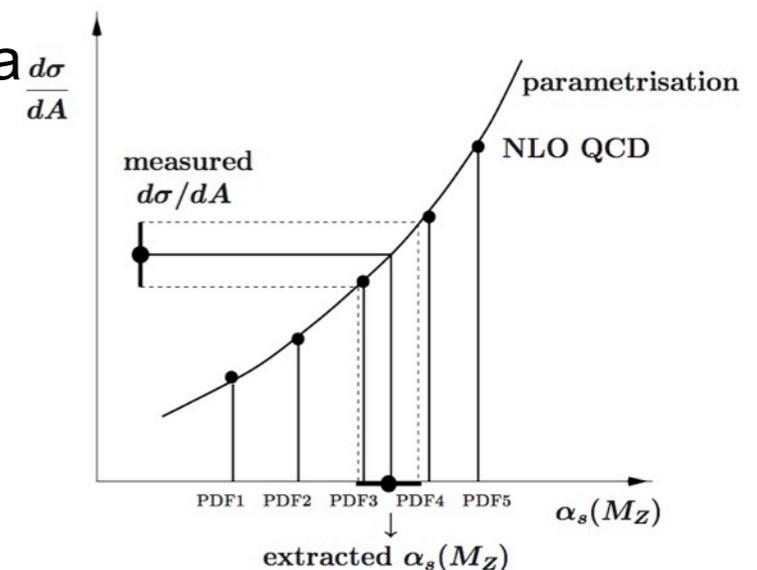
- Have presented a wealth of high precision experimental measurements of cross sections of inclusive jet production in
 - photoproduction
 - low Q^2 NC DIS
 - high Q^2 NC DIS
 - CC DIS
- New precise and consistent α_s extraction in photoproduction and DIS
 - compatible with world average and LEP
 - very high experimental precision
 - running of the coupling verified over large range $5 < Q^2 < 10\,000 \text{ GeV}^2$
 - very good agreement between low and high Q^2 measurements
- Data are well described by NLO QCD
 - Theory scale uncertainties dominate over the experimental uncertainties
 - Higher order calculations necessary to take full advantage of the data



- The extraction of α_s :
 - Predicted cross sections are a convolution of the proton/photon PDFs and the matrix elements
 - ingredients highly correlated concerning dependence on α_s
- Method is based on the full dependence of the calculations on α_s and the correlation with the PDFs:
 - perform NLO calculations using various PDF sets extracted assuming different $\alpha_s(M_Z)$
 - parametrise $\alpha_s(M_Z)$ dependence of observable $d\sigma/dA$ as

$$\frac{d\sigma}{dA}(\alpha_s(M_Z)) = C_1 \alpha_s(M_Z) + C_2 \alpha_s^2(M_Z)$$

- ★ C_1 and C_2 are the free parameters of the fit
- ★ extract $\alpha_s(M_Z)$ by mapping $d\sigma/dA$ to x axis



- Method preserves the α_s dependence of the calculation and PDFs!
- It results in a very precise determination with a reduced total uncert: 3.1%

$$\alpha_s(M_Z) = 0.1223 \pm 0.0001 \text{ (stat.)}^{+0.0023}_{-0.0021} \text{ (syst.)} \pm 0.0030 \text{ (th.)}$$

- experimental uncert: 1.8 %, PDF uncert: <1%, hadronisation correction: <0.5 %