QCD and Hadronic final states at HERA

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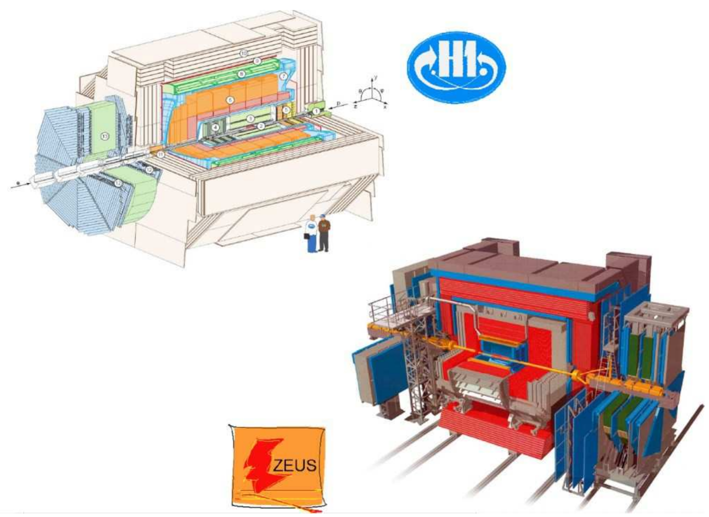
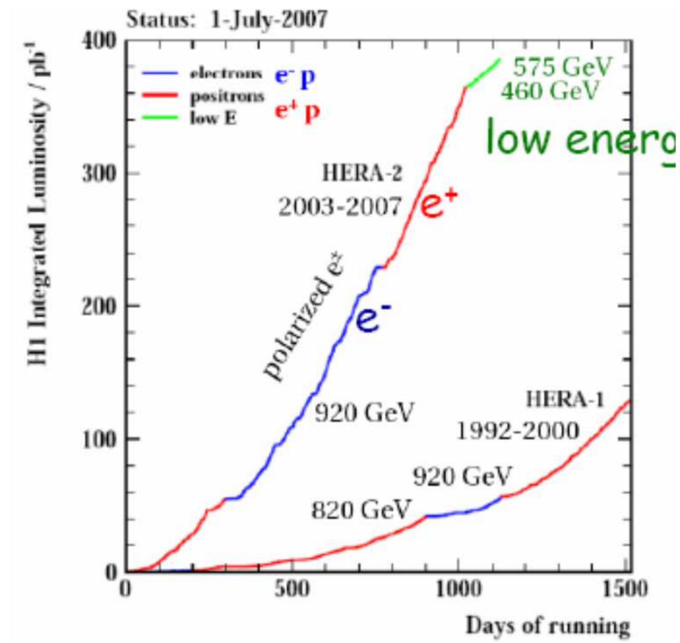
(on behalf of the H1 and ZEUS Collaborations)

Gatchina, Russia, June 30 – July 4, 2014

HERA with two general purpose detectors H1 and ZEUS





Collected ~0.5 fb^{-1} of integrated luminosity by each experiment;

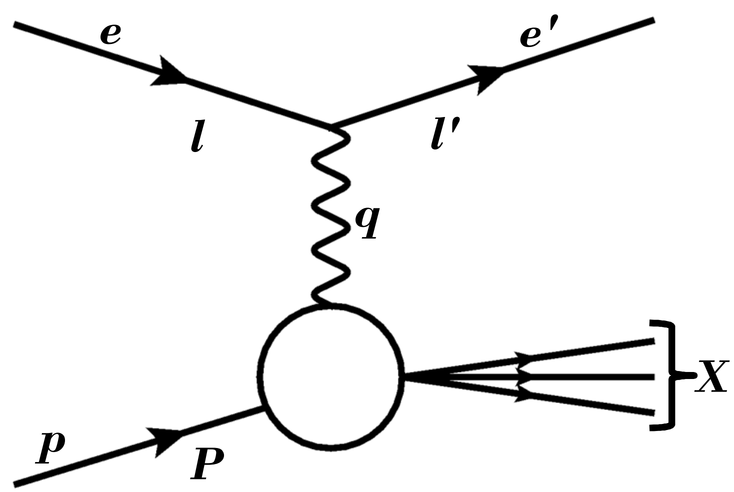
Inelastic *ep*-scattering at HERA

Kinematics:

- Centre-of-mass energy
  $$\sqrt{s} = \sqrt{(l+p)^2}$$
- Momentum transfer
  $$Q^2 = -q^2 = -(l - l')^2$$
- Bjorken x
  $$x = Q^2/2P\cdot q$$
- Inelasticity
  $$y = P\cdot q/P\cdot l$$

Any two of the variables (Q^2, x, y) define kinematics.

$Q^2 > 1$ GeV^2 deep inelastic scattering (DIS)
$Q^2 < 1$ GeV^2 photoproduction (PHP)

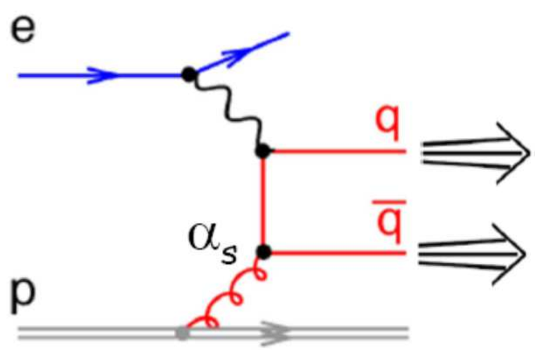


HERA experiments ZEUS & H1 - one of the best QCD laboratories, good job for LHC and future QCD initiatives (EIC, eRICH and LHeC);

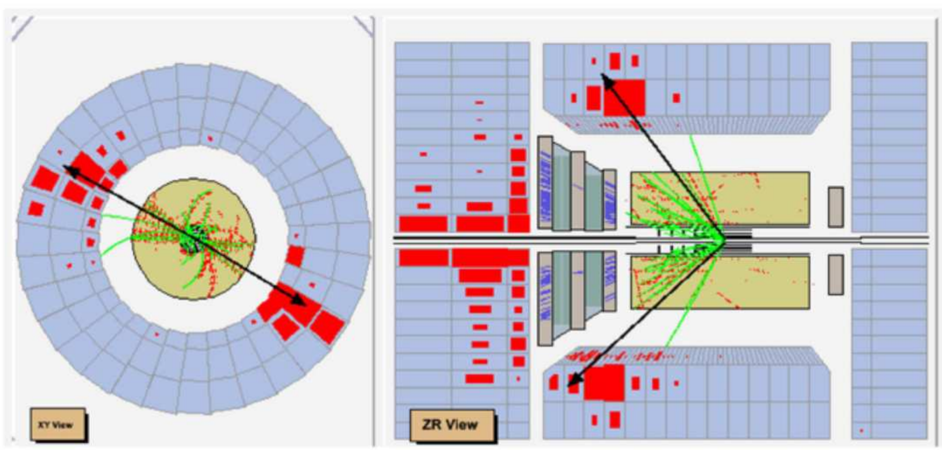
Jets and strong coupling constant α_s

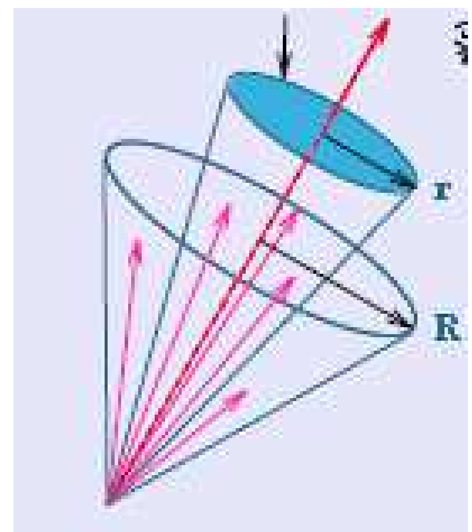
Jets and α_s

Quantum Chromodynamics (QCD)



Jet: narrow cone of hadrons produced by the hadronization of quarks or gluons





Jet cross sections provided precise determinations of the strong coupling constant α_s and testing perturbative QCD (pQCD).

Used k_T algorithm

H1 Collaboration

DESY-14-089

June 2014

submitted to Eur. Phys. J.

Paper is at arXiv:1406.4709 since a couple of weeks ago

New results:

MEASUREMENT OF MULTIJET PRODUCTION IN ELECTRON-PROTON COLLISIONS AT HIGH Q^2 AND DETERMINATION OF THE STRONG COUPLING ALPHA_S

Jet production in neutral current deep-inelastic ep scattering at HERA: important process to study the strong interaction -> allows for a direct measurement of the strong coupling α_s.

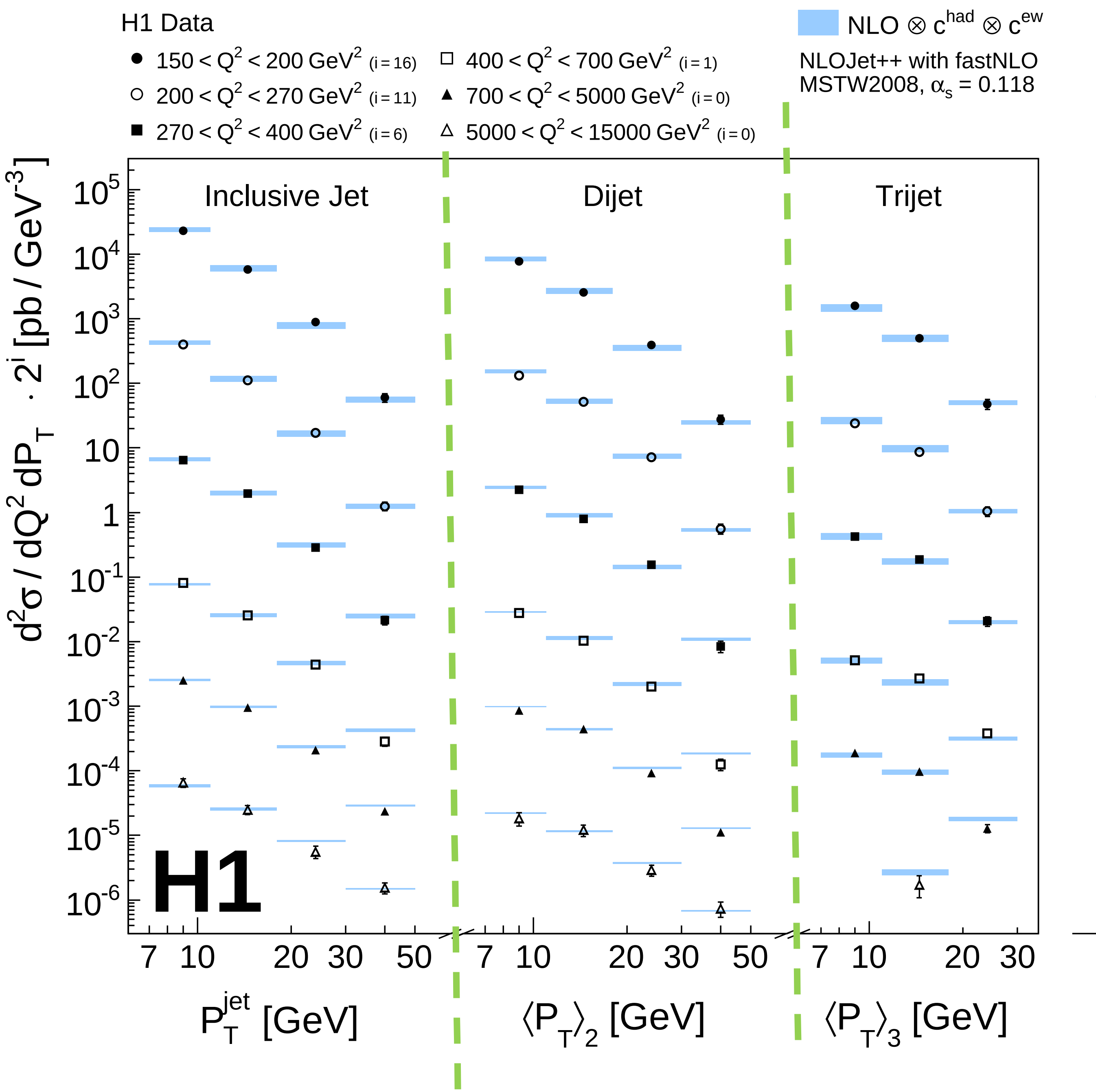
Inclusive jet, dijet and trijet differential cross sections are measured in neutral current deep-inelastic scattering for:

integrated luminosity of 351 pb^{-1}

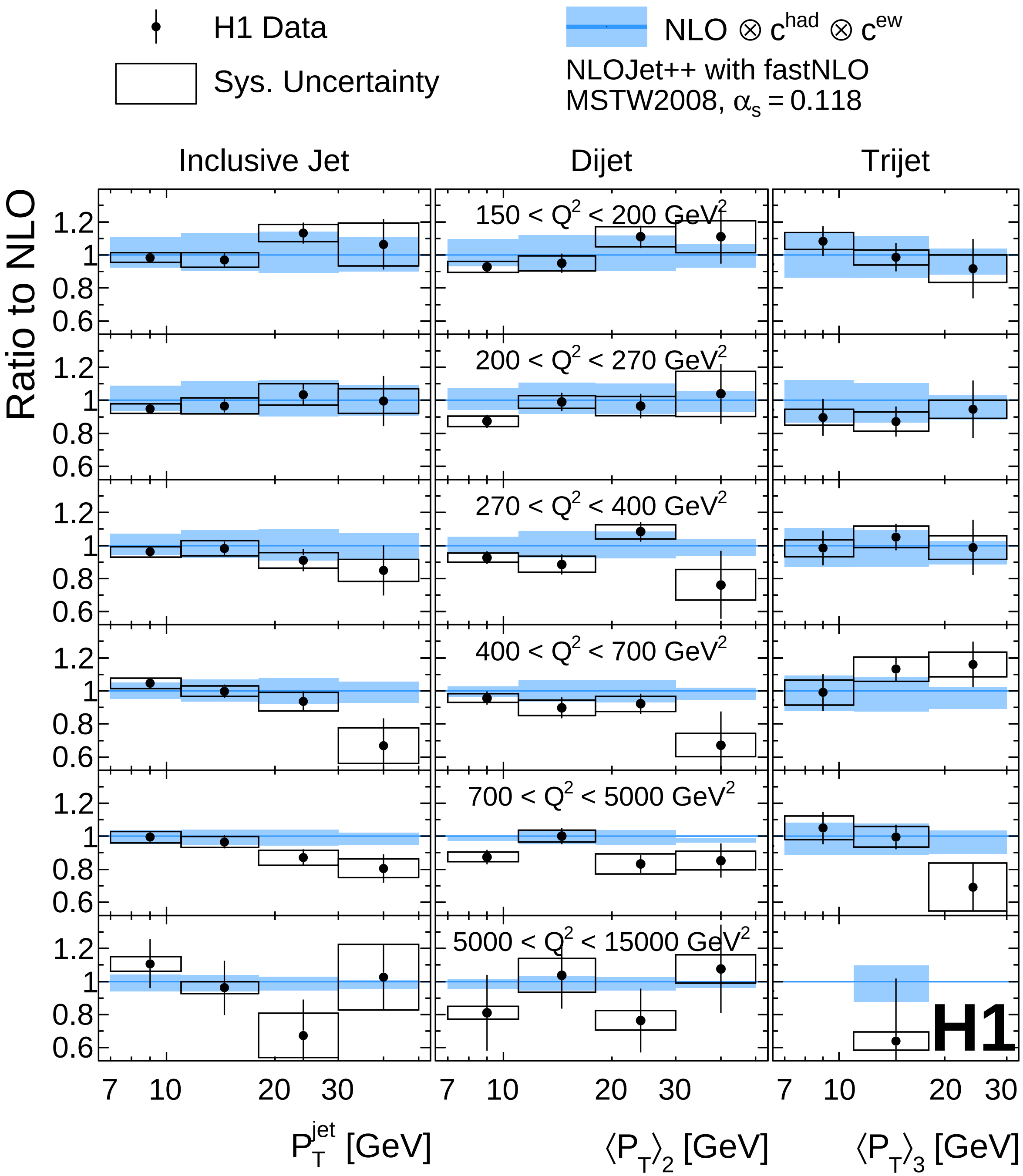
exchanged boson virtuality $150 < Q^2 < 15\,000 GeV^2$

$45 < E - P_z < 65$ GeV

	Extended analysis phase space	Measurement phase space for jet cross sections
NC DIS phase space	$100 < Q^2 < 40\,000\,\mathrm{GeV}^2$ $0.08 < y < 0.7$	$150 < Q^2 < 15\,000\,\mathrm{GeV}^2$ $0.2 < y < 0.7$
Jet polar angular range	$-1.5 < \eta^{\mathrm{jet}}_{\mathrm{lab}} < 2.75$	$-1.0 < \eta^{\mathrm{jet}}_{\mathrm{lab}} < 2.5$
Inclusive jets	$P^{\mathrm{jet}}_{\mathrm{T}} > 3\,\mathrm{GeV}$	$7 < P^{\mathrm{jet}}_{\mathrm{T}} < 50\,\mathrm{GeV}$
Dijets and trijets	$3 < P^{\mathrm{jet}}_{\mathrm{T}} < 50\,\mathrm{GeV}$	$5 < P^{\mathrm{jet}}_{\mathrm{T}} < 50\,\mathrm{GeV}$ $M_{12} > 16\,\mathrm{GeV}$



Measured cross sections for the k_T jet algorithm as a function of P_T in different Q^2 bins.

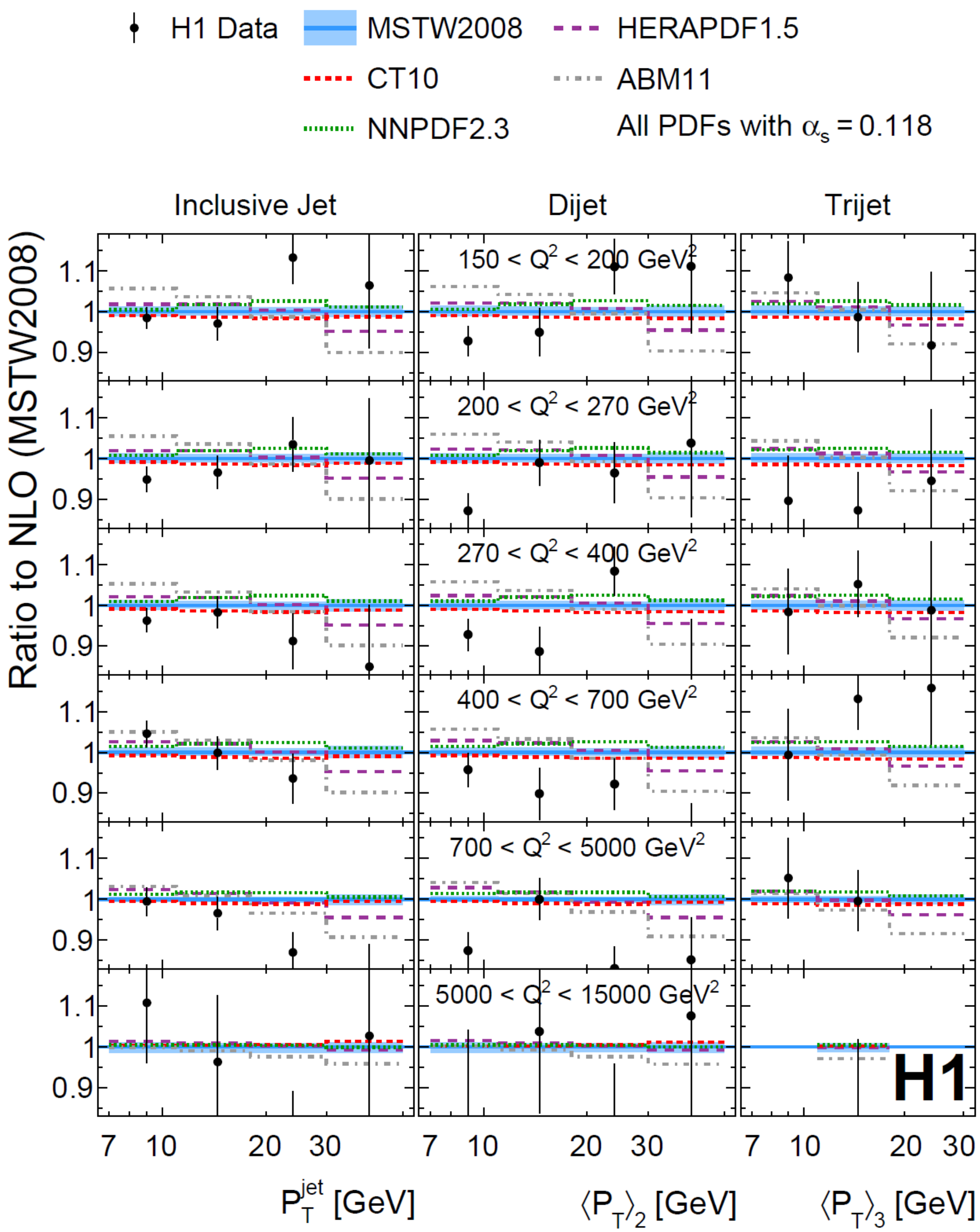


Ratio of data to NLO:

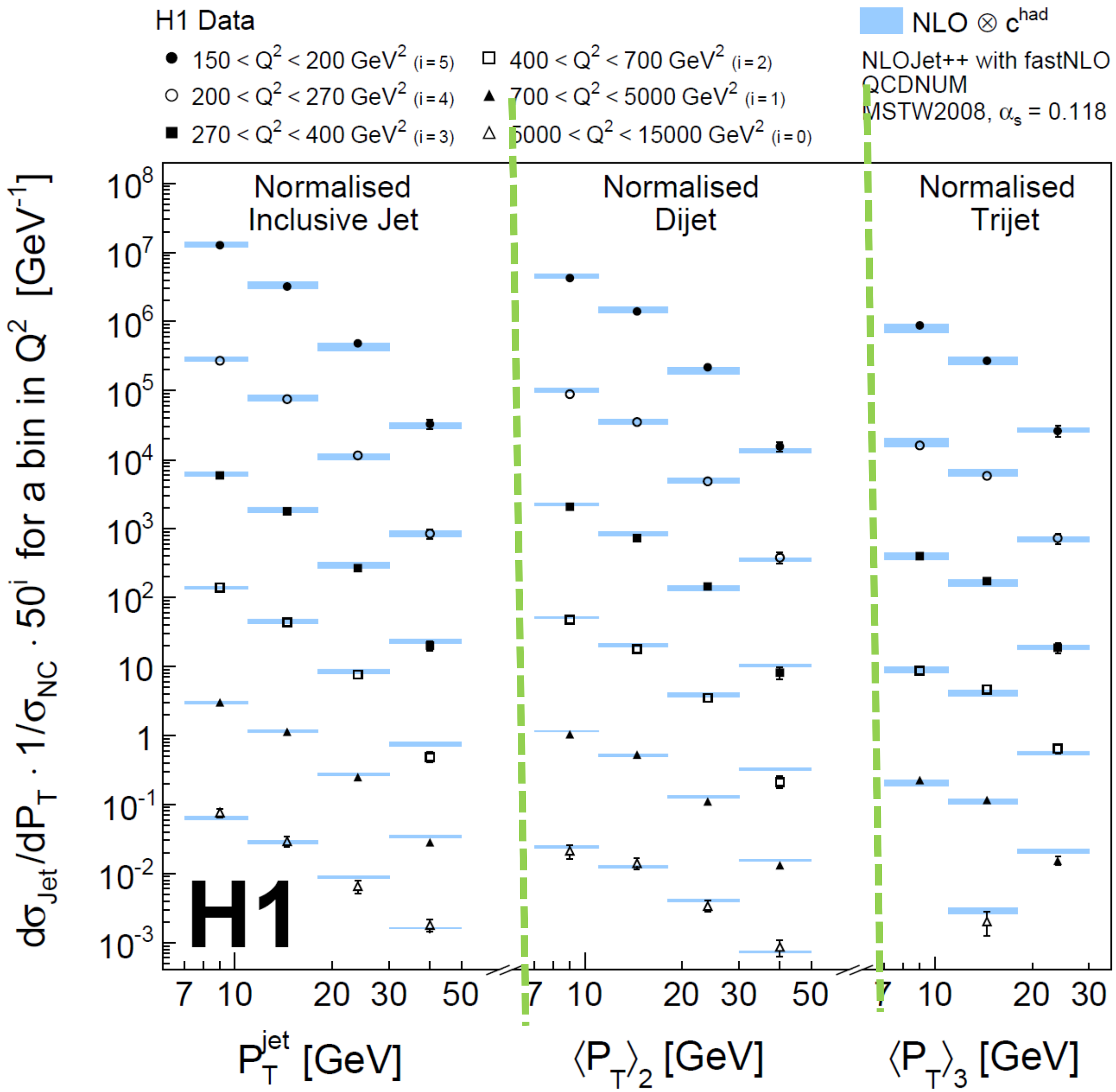
(detailed comparison of the predictions to the measured cross sections)

- theory uncertainties from scale variations dominate over the sum of experimental uncertainties in most bins;

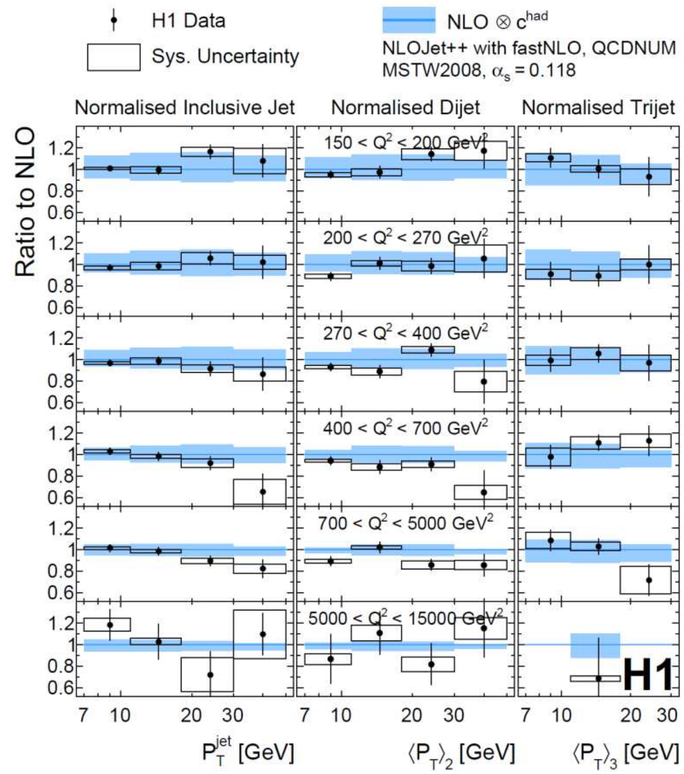
- NLO in good agreement with data within uncertainties;

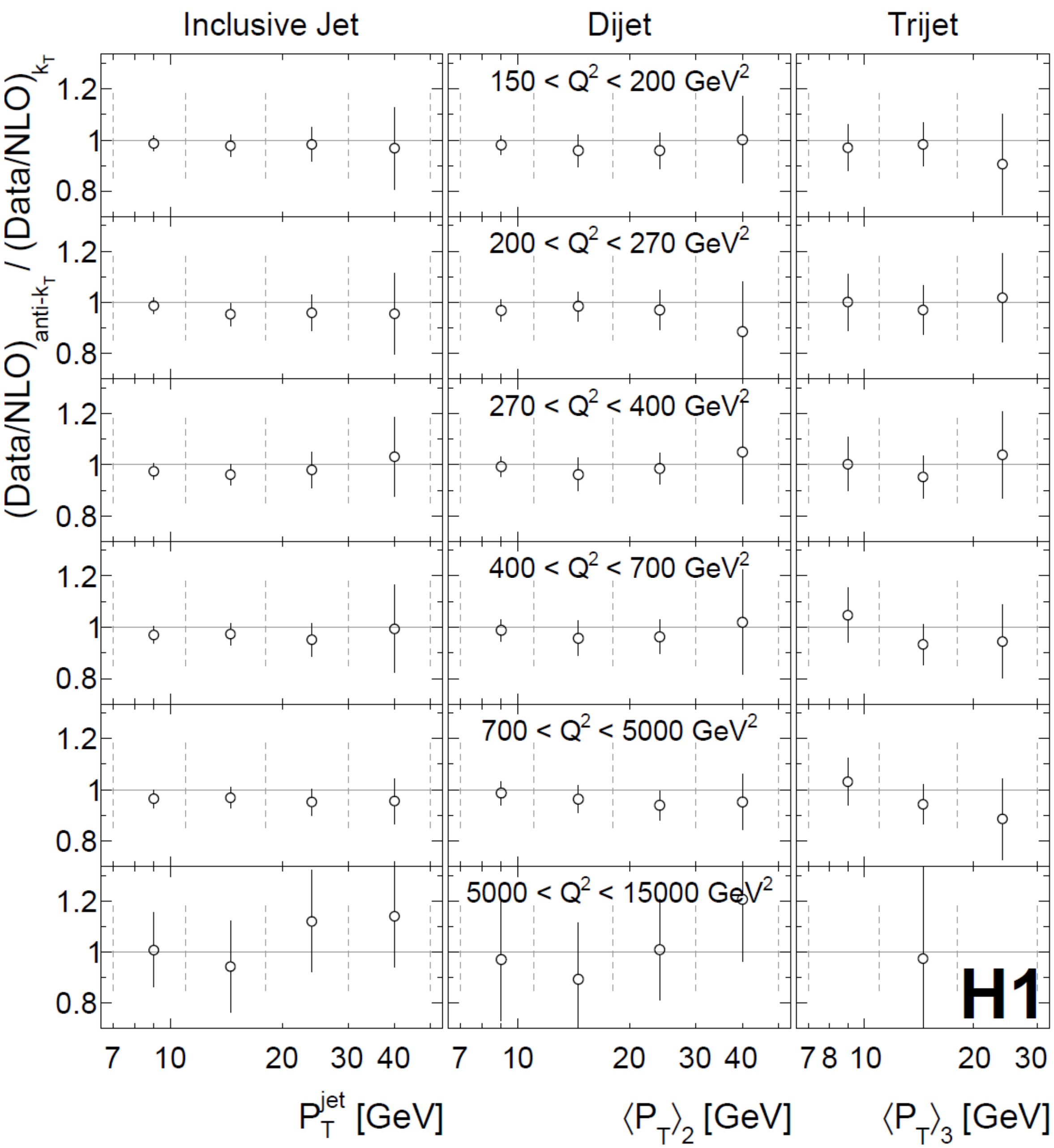


Ratio of NLO predictions with various PDF sets to predictions using the MSTW2008 PDF set as a function of Q^2 and P_T.



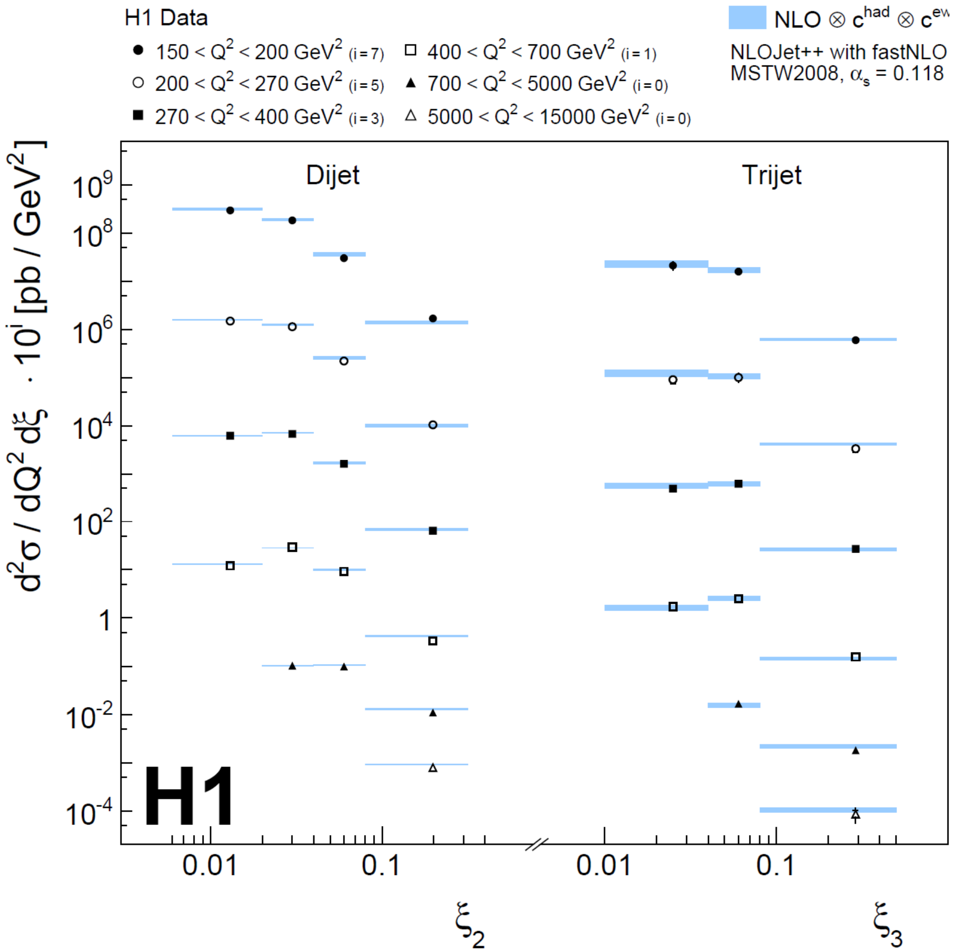
Double-differential normalized cross sections for jet production in DIS as a function of Q^2 and P_T.



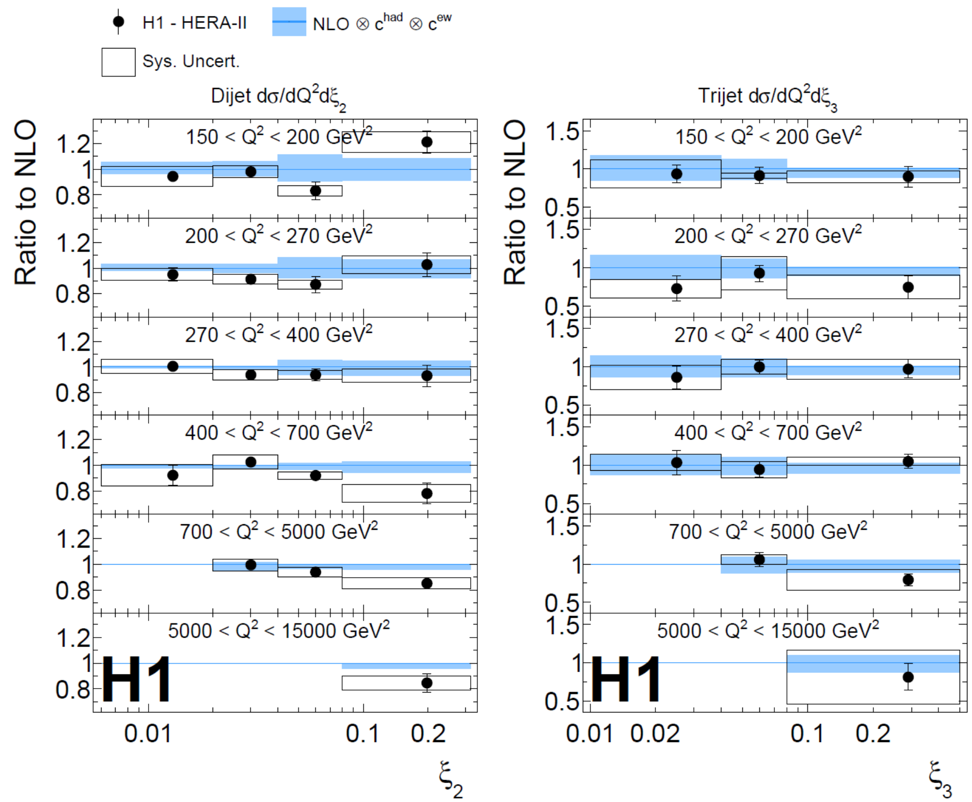


Comparison of cross section measured using the k_T cluster algorithm and the anti−k_T

No systematic differences are observed for the inclusive jet and dijet cross sections.



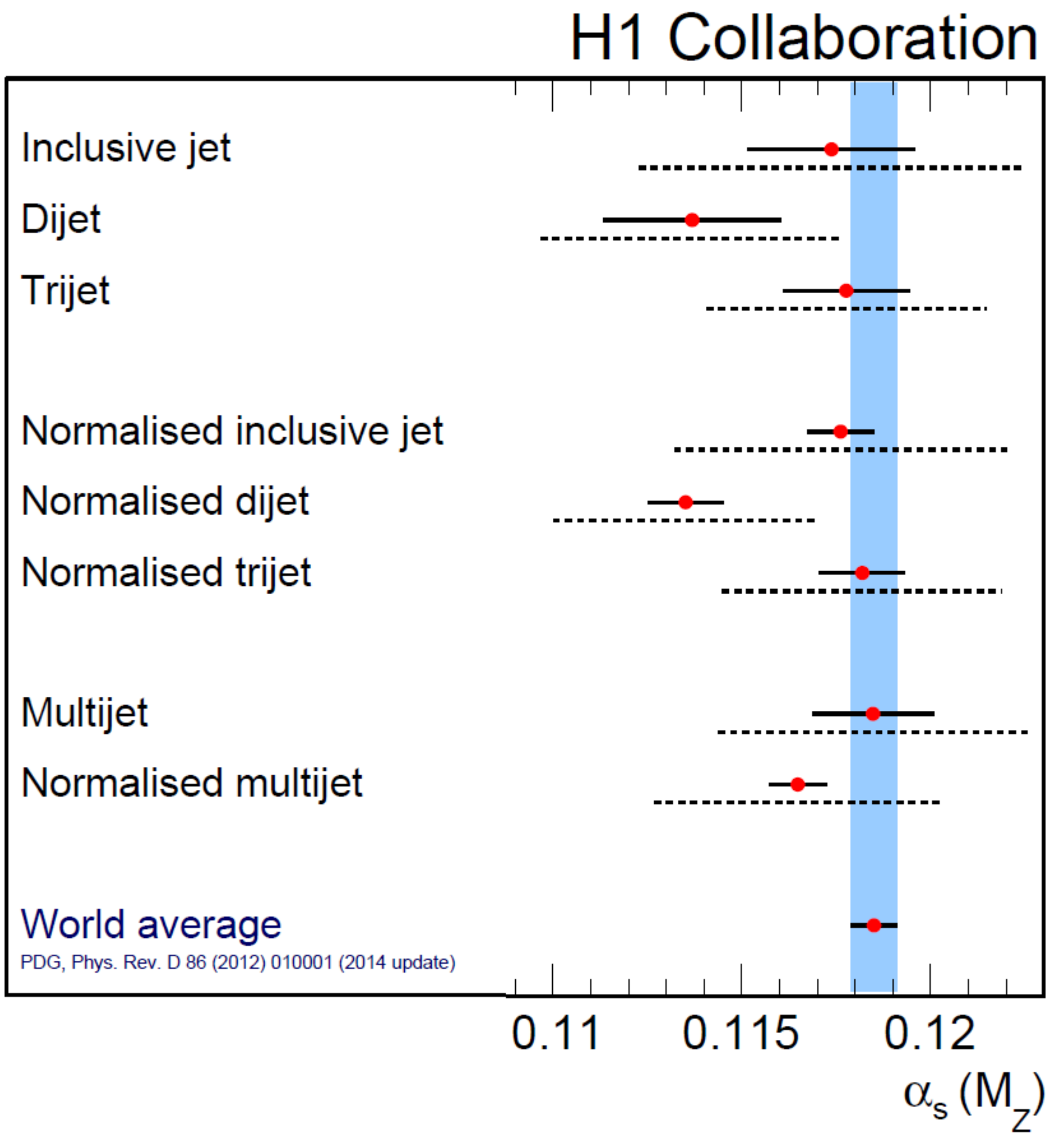
Ratio of the dijet and trijet cross sections as function of Q^2 and ξ



The fraction of the proton momentum carried by the parton that enters the hard subprocess $\xi = x_{Bj}(1 + M_{12}^2 / Q^2)$

Boost to Breit frame, $2xP + q = 0$

Extraction of $\alpha_s(M_Z)$



Method: fit NLO QCD calculations with $\alpha_s(M_Z)$ as free parameter to absolute and normalized inclusive, dijet and trijet cross sections (both individually and simultaneously);

- **Results are consistent with the world average;**
- **Dijet results give smaller values, but within experimental uncertainties;**
- **Results gain in precision when using normalised multijet cross sections**
- **Need NNLO calculations to match experimental precision (0.7%)**

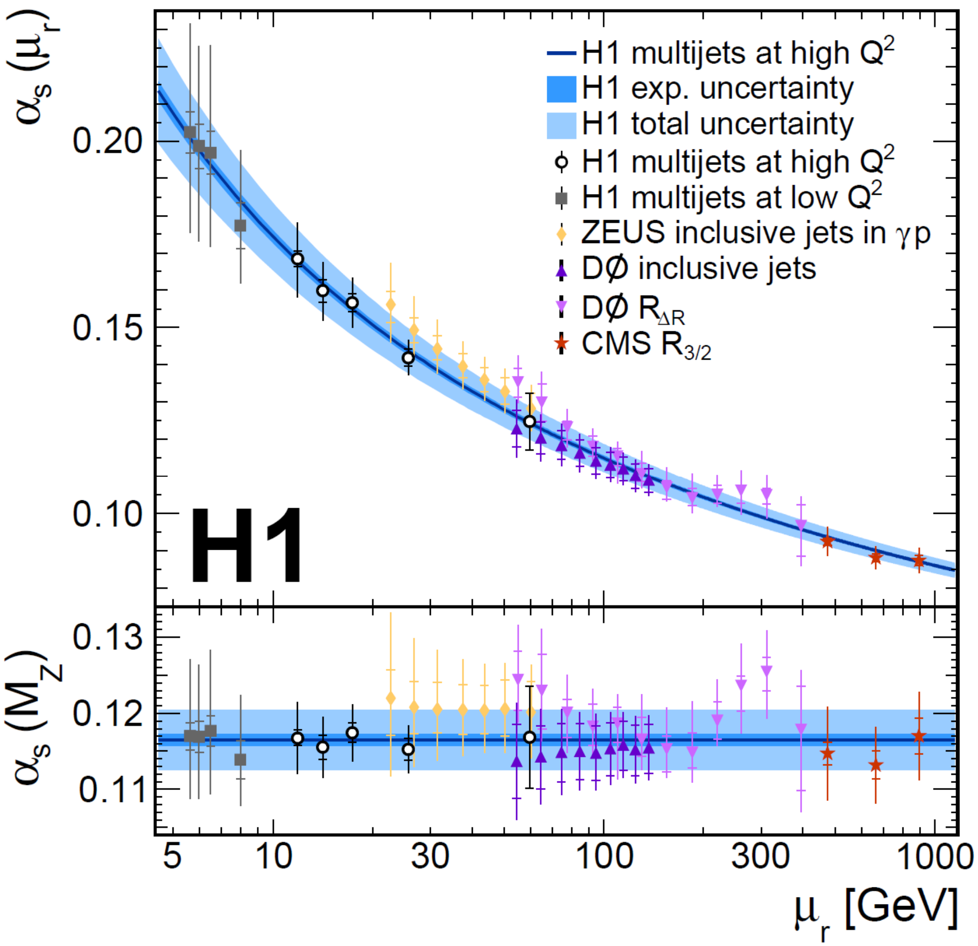
The smallest **total** uncertainty on the extracted $\alpha_s(M_Z)$ is found for Q^2>400GeV

$\boldsymbol{\alpha_s(M_Z)|_{kT} = 0.1160\ (11)_{exp}\ (32)_{pdf,theo}}$

Running of $\alpha_s(\mu_r)$

The simultaneous extraction of the strong coupling constant $\alpha_s(M_Z)$ from the normalized inclusive jet, the dijet and the trijet samples using the k_T jet algorithm yields:

$$\alpha_s(M_Z)|_{kT} = 0.1165\ (8)_{exp}\ (38)_{pdf,theo}$$



$\alpha_s(M_Z)$-values are found to be consistent and independent of μ_r

Good agreement with H1 data at lower scales and other data at higher scales;

The extracted $\alpha_s(M_Z)$-values are compatible within uncertainties with the world average value of $\alpha_s(M_Z)$ = 0.1185 (6) and with α_s-values from other jet data.

Brand new ZEUS preliminary results:

ZEUS-prel-14-008

25th June 2014

TRIJET PRODUCTION IN DIS AT HERA

- ***Selected events:*** **with at least three jets passing kinematic cuts. Each event was counted using the leading three jets of the event.**
- ***Measured:*** **bin-averaged differential trijet production cross sections as function of various event- and trijet-kinematic observables;**
- ***Other ZEUS dijet paper:*** **in the same kinematic region,** EPJ C 70 (2010) 965-982

Cross section determination and theoretical calculations

Phase space:

$125 < Q^2 < 20000$ GeV^2
$0.2 < y < 0.6$
jets with $E_{T,B}^{jet} > 8$ GeV,
$-1 < \eta_{lab}^{jet} < 2.5$
$M_{jj} > 20$ GeV
Integrated luminosity 295 pb^{-1}

Prediction: NLOJet++

- **pPDF: HERAPDF1.5**
- **$\mu_R^2 = Q^2 + (E_T^{jet})^2$**
- **$\mu_F^2 = Q^2$**

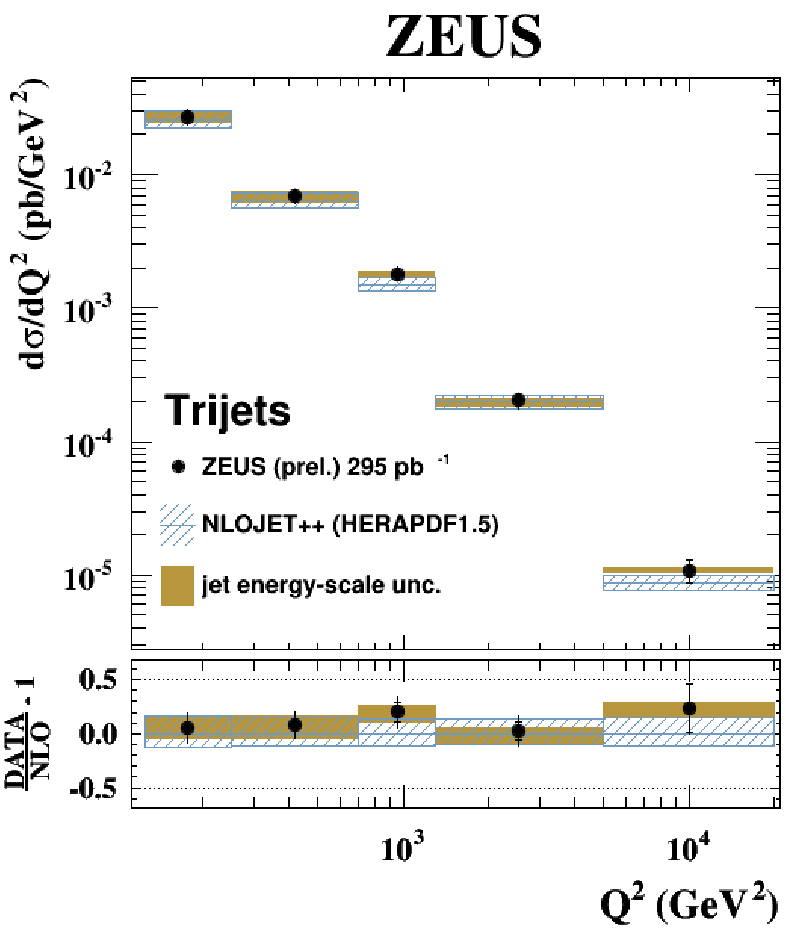
- $C_i^A = \frac{N_i^{HAD}}{N_i^{DET}}$ acceptance correction factor
- $C_i^{QED} = \frac{\sigma_i^{BORN}}{\sigma_i^{QED}}$ QED correction factor (accounts for higher-order QED effects)
- $\frac{d\sigma_i}{dX} = \frac{N_i^{DATA}}{Lk_i} \times C_i^A \times C_i^{QED}$ cross section value
- L- integrated luminosity
- k_i – bin width

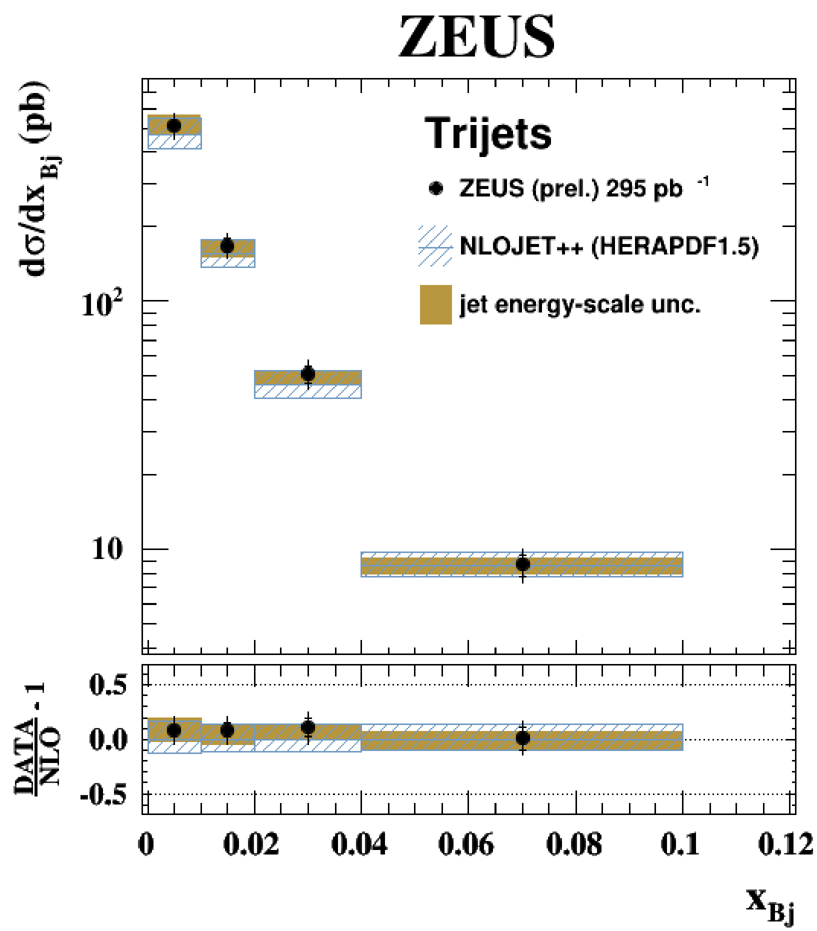
ξ *is defined as* $x_{Bj} \cdot (1 + m_{jjj}^2/Q^2)$

$\overline{E_{T,B}^{jet}}$ *denotes the average transverse momentum of the three leading jets*

- **Selected 2199 events with at least three jets passing kinematic cuts and invariant mass two leading jets $M_{jj} > 20$ GeV**

Trijet cross section vs. Q^2 and x_{Bj}

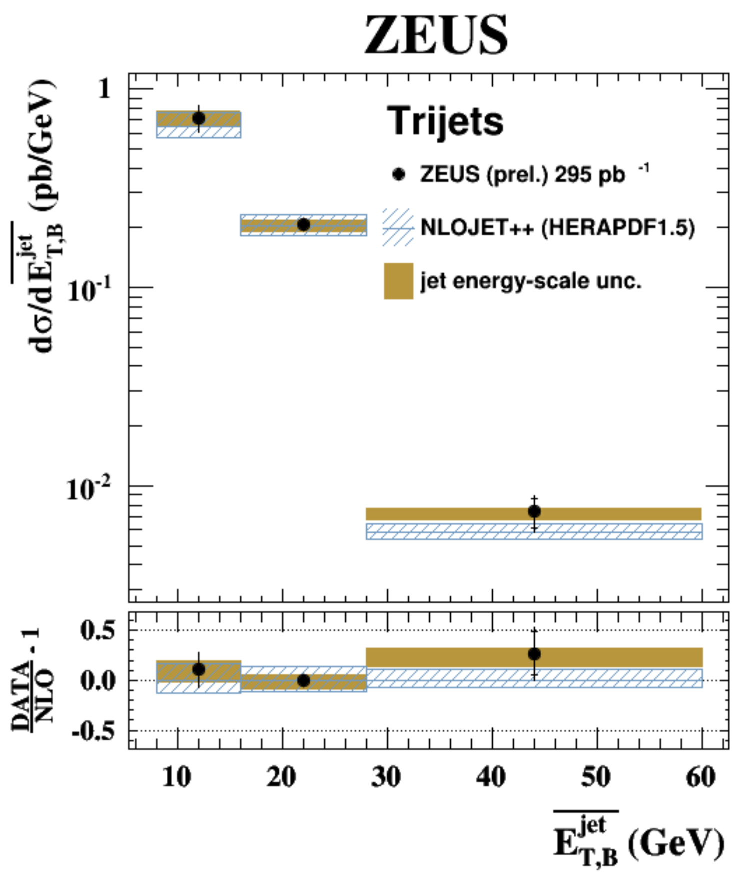


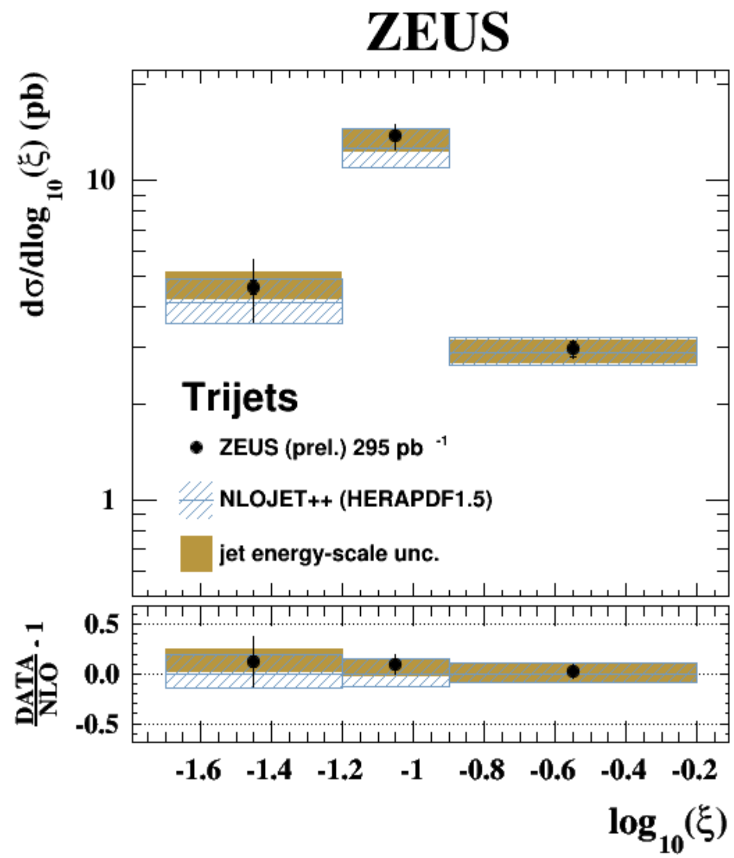


- NLO QCD calculations describe data well in shape and normalization.
- Measured cross sections are sensitive to the nature of partons taking part in hard interaction

Trijet cross sections vs. log(ξ) and E_{TB}^{jet}

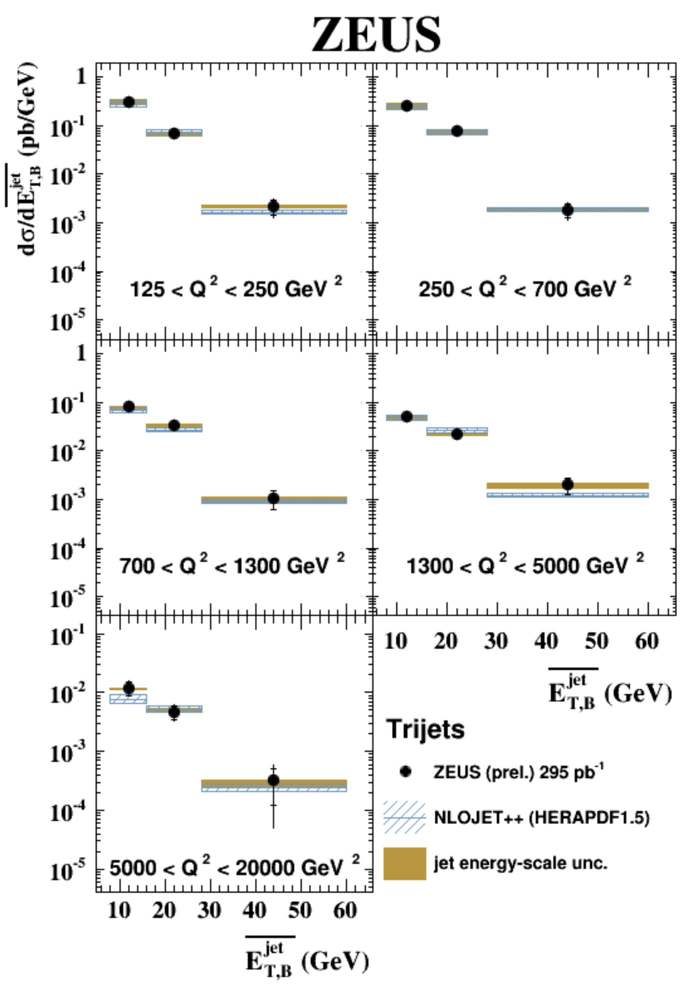
(i.e. average transfers momentum of the three leading jets in the Breit frame)

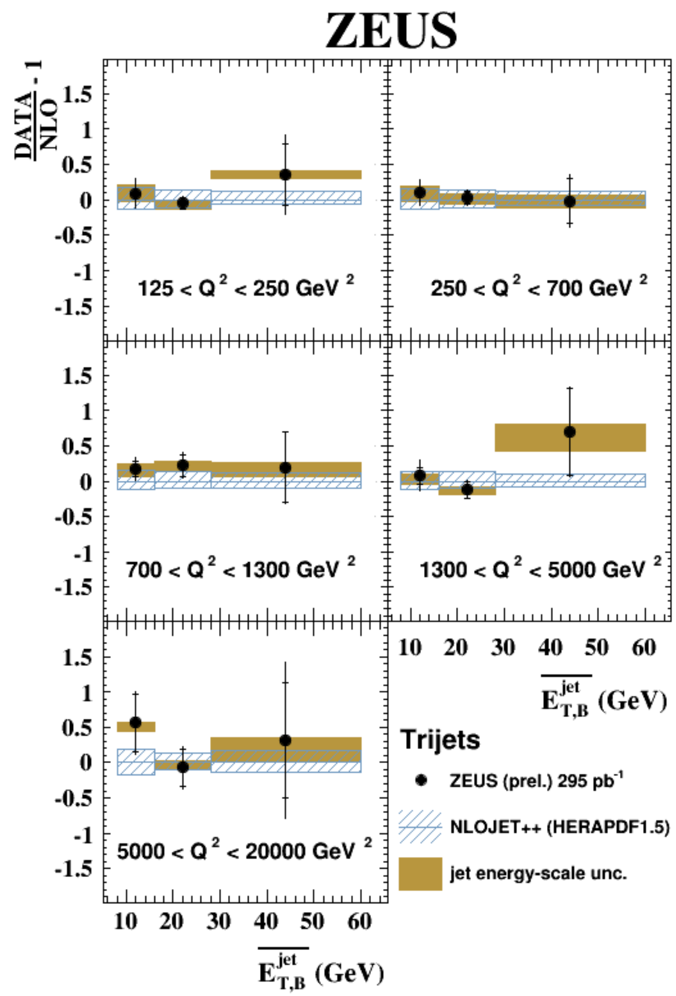




- Perturbative QCD predictions reasonably well describe measured cross sections.
- Precise measurements are sensitive to the dynamics of hard scattering and to longitudinal momentum fraction taking part in the interaction

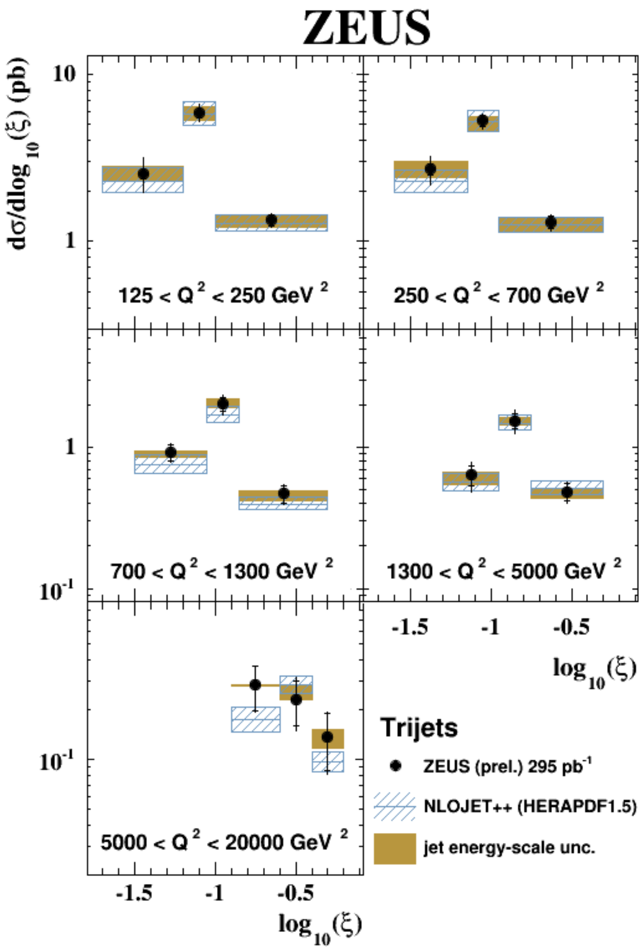
Trijet cross sections as function of E_{TB}^{jet} in regions of Q^2

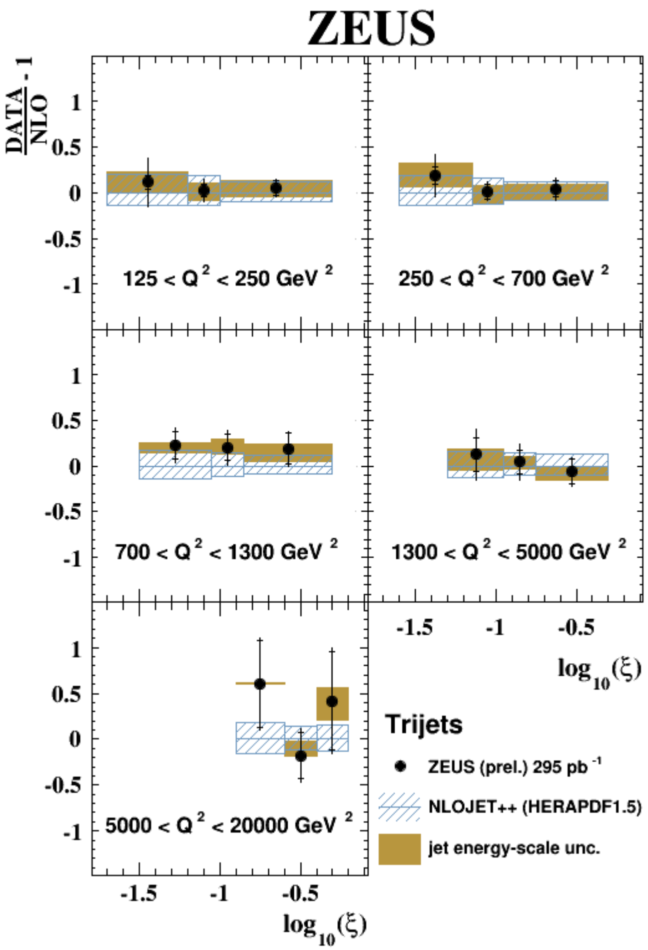




Measured cross sections probe the details of the strong interaction and can be used for extraction of the value of the strong coupling

Trijet cross sections as function of log(ξ) in regions of Q^2





Double-differential cross sections are sensitive to the parton distribution in the proton and can be used to constrain PDFs.

Studies of the photoproduction of isolated photons with a jet at HERA

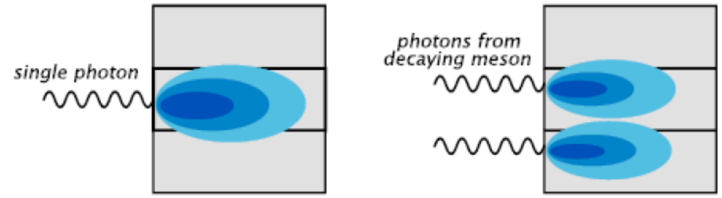
DESY–14–086
May 2014

Motivation:

- **isolated or prompt photons emerge directly from the hard scattering process and give a particular view of this;**
- **prompt photons allow tests of specific QCD models;**
- **important: as potential background to "new physics", should be well understood;**

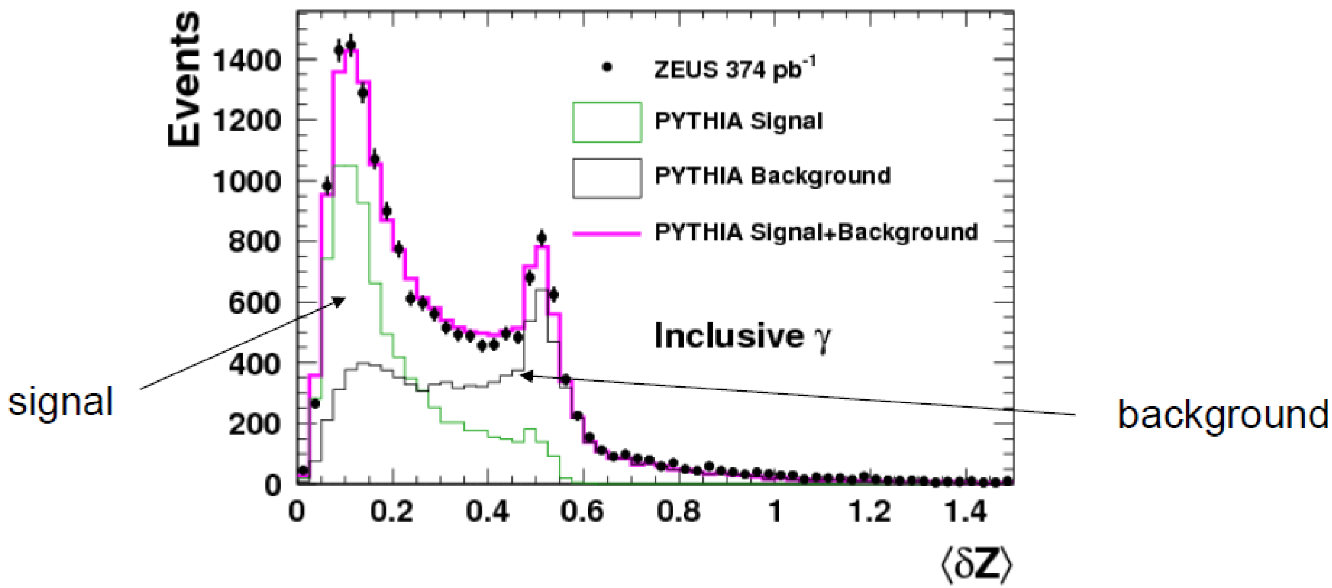
✓ **measured:** photoproduction of isolated photons together with a jet for different ranges of the fractional photon energy contributing to the photon-jet final state.
✓ **phase space:** photon transverse-energy and pseudorapidity ranges $6 < E_T < 15$ GeV and $-0.7 < \eta^{\gamma} < 0.9$, and for jet transverse-energy and pseudorapidity ranges $4 < E_{jetT} < 35$ GeV and $-1.5 < \eta^{jet} < 1.8$;
✓ integrated luminosity of 374 pb^{-1}

Calorimeter: signal/background:



Photon candidates: groups of signals in BEMC cells.

Challenge: separate photons from backgrounds from decays of neutral mesons.



E_T-weighted mean of Z_{CELL} is Z_{Mean}.

<dZ> = E_T-weighted mean of $|Z_{CELL} - Z_{Mean}|$.

Peaks from photon and π^0, other background is η + multi-π^0.
Fit performed In each bin of each measured quantity.

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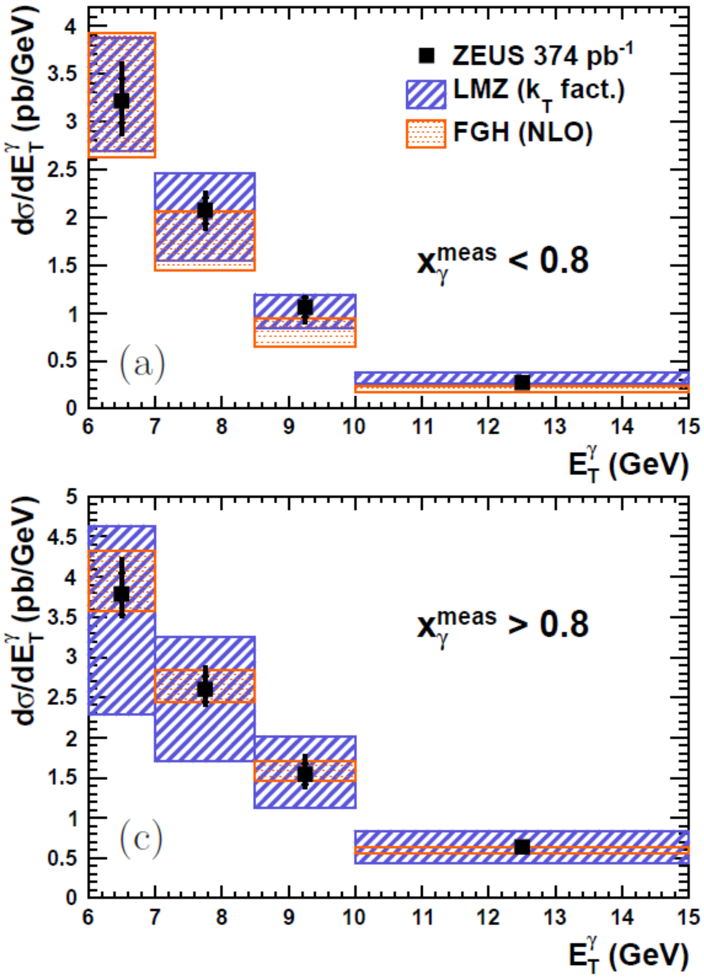
Theories:

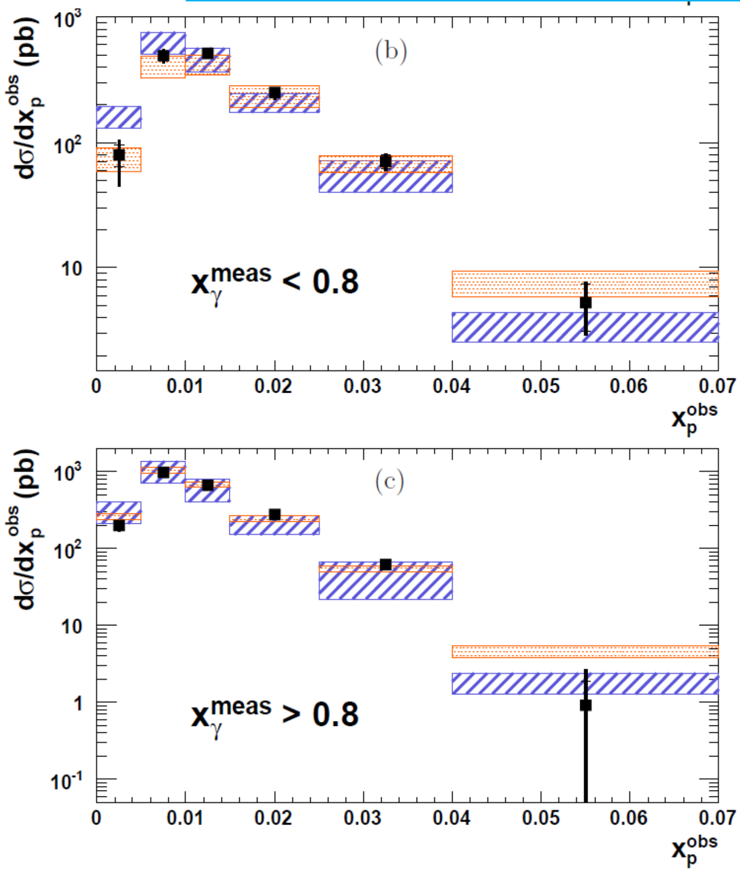
1) Fontennaz, Guillet and Heinrich (FGH, EPHOX): NLO + box diagram and a contribution from fragmentation.

2) Lipatov, Malyshev, Zotov (LMZ): k$_T$-factorisation with unintegrated parton distributions and initial-state parton cascade. Upgraded for second ZEUS analysis.

$$x_\gamma^{\rm meas} = \frac{E^\gamma + E^{\rm jet} - p_Z^\gamma - p_Z^{\rm jet}}{E^{\rm all} - p_Z^{\rm all}}$$

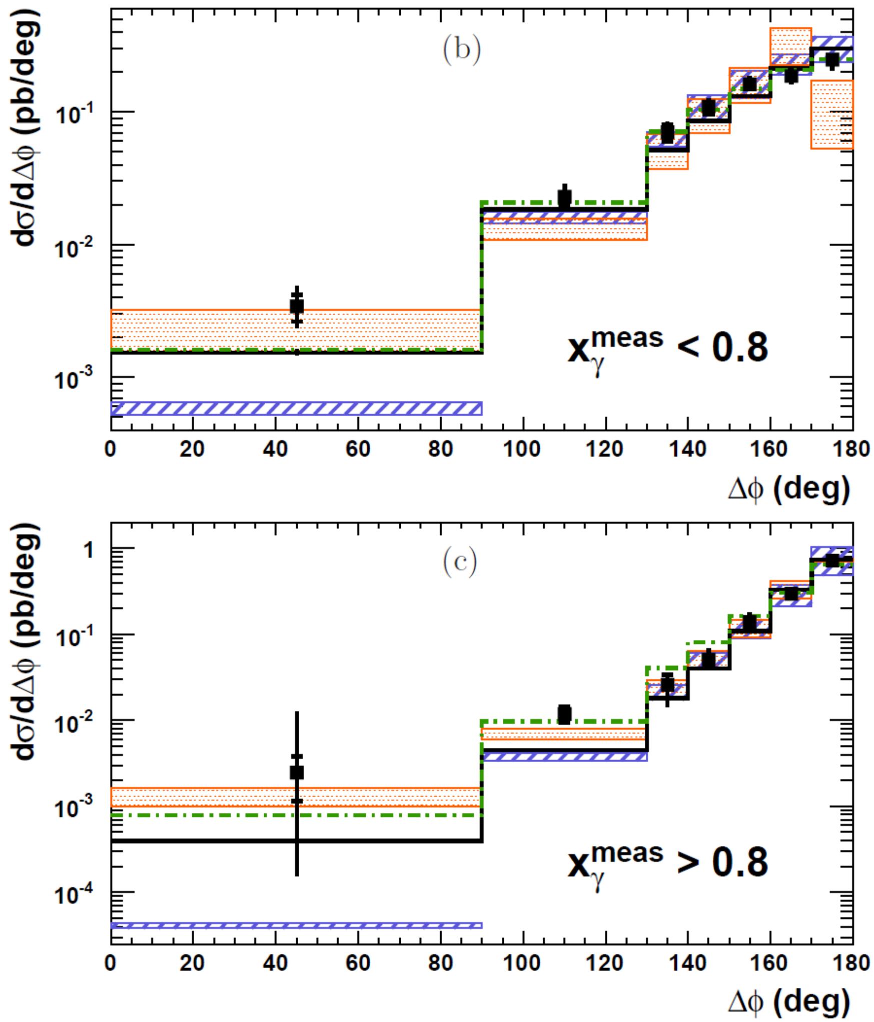
$$x_p^{\rm obs} = (E_T^\gamma \exp\eta^\gamma + E_T^{\rm jet}\exp\eta^{\rm jet})/2E_p$$





Fraction of proton energy taken by the parton that interacts with the photon; **its distribution is sensitive to the proton's partonic structure.**

Δφ - absolute difference between the azimuths of the photon and the high-E_T jet; sensitive to the presence of higher-order gluon radiation in the event, especially relative to the outgoing quark, which can generate non-collinearity between the photon and the leading jet.



Overall:

- **The kinematic observables studied comprise the transverse energy and pseudorapidity of the photon and the jet, the azimuthal difference between them, the fraction of proton energy taking part in the interaction, and the difference between the pseudorapidities of the photon and the jet.**
- **Higher-order theoretical calculations are compared to the results.**

Conclusions

- ***ZEUS jet measurement:*** **bin-averaged differential trijet production cross sections as function of various event- and trijet-kinematic observables have been measured using the ZEUS detector for jets with $E_{T,B}^{jet} > 8$ GeV and events with $125 < Q^2 < 20000$ GeV^2. QCD predictions at next-to-leading-order (NLO) reasonably well describe measured cross sections;**
- ***H1 jet measurement:*** **data are in general well described by the theoretical predictions and precision of the measurement is better than that of NLO calculations. Most precise $\alpha_S(M_Z)$ is extracted from fit to the normalized multijet cross section, yielding: $\alpha_s(M_Z)|_{k_T} = 0.1160\ (11)_{exp}\ (32)_{pdf,theo}$**
- **Prompt photon photoproduction measured in many variables by ZEUS.**