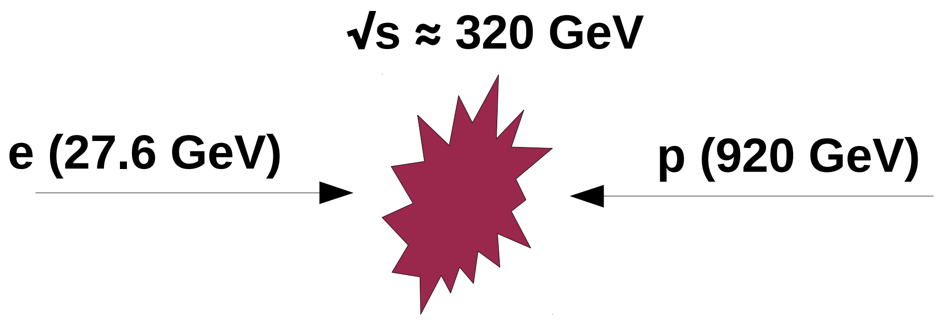
QCD measurements with jets and α_s determination at HERA

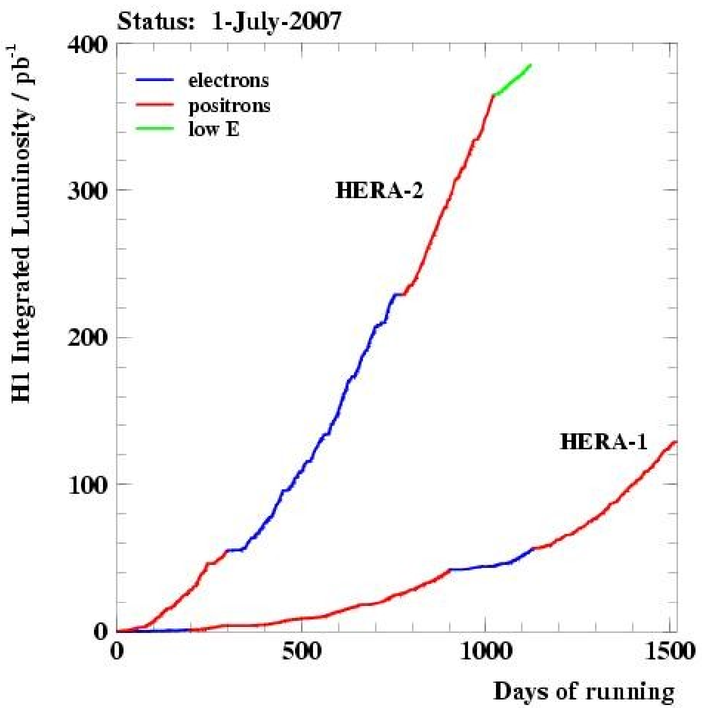
Krzysztof Nowak
on behalf of
H1 and **ZEUS**
collaborations

- *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





Collected ~0.5 fb^{-1} of luminosity per experiment

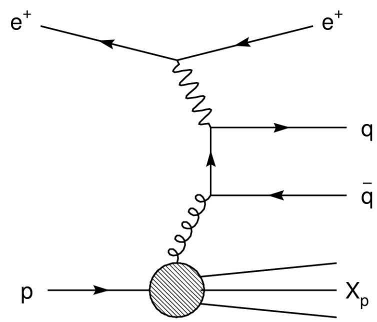
Work ongoing to provide final measurements using all available data

Jet production at HERA

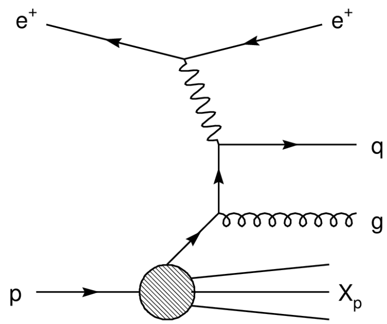
Two kinematic regions depending on the virtuality of the mediating boson Q^2:

1. Deep Inelastic Scattering (DIS)

- ✓ $Q^2 \gg \Lambda_{QCD}$
- ✓ *Two scale present, Q^2, P_T*



Boson-gluon fusion



QCD Compton

Jet production at HERA

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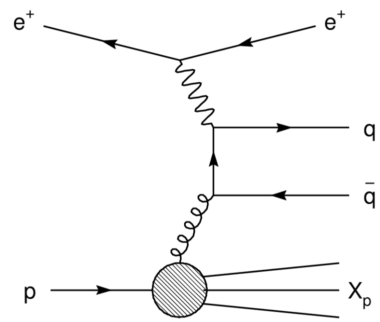

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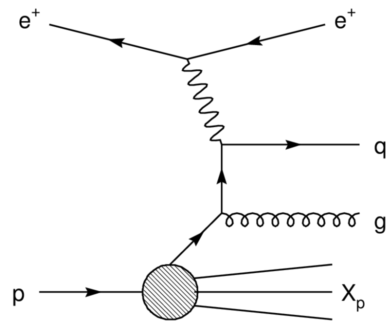
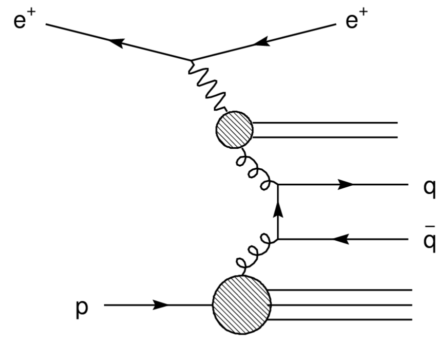


QCD Compton

2. Photoproduction (PHP)

- $Q^2 \approx 0\, GeV$
- *In addition to B-G fusion and QCD Compton: Resolved photoproduction*
- *Similarity to hadron-hadron collisions*



Resolved photoproduction

Jet production at HERA

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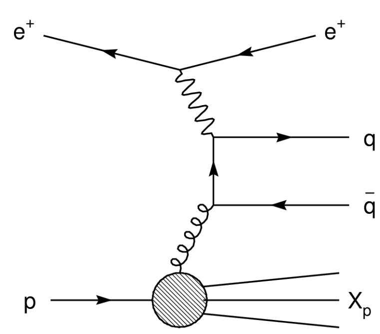
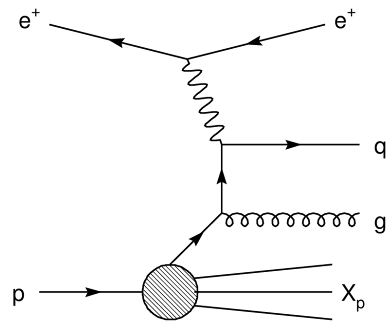


Boson-gluon fusion



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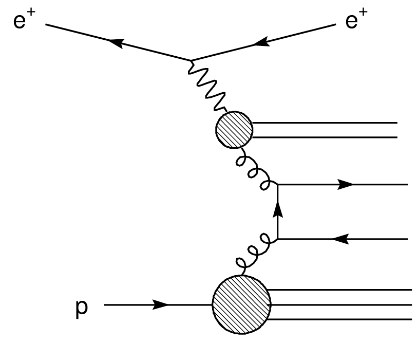

Resolved photoproduction

Remark: *Breit frame = no QPM events*

Jet physics at HERA

Jet cross section:

$$d\sigma_{jet} \sim \sum_{j=q,\bar{q},g} \int dx\, f_{j/p}(x,\mu_F)\, d\hat{\sigma}_j(x,\alpha_s(\mu_R),\mu_R,\mu_F)$$

proton content | **pQCD matrix element**

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

Programs used to compute NLO jet cross sections:

- ***DIS****: DISENT, NLOJET++*
- ***PHP****: Frixione-Ridolfi, Klasen-Kleinwort-Kramer*

Calculations corrected for hadronization and Z^0 *exchange*

Theoretical uncertainty estimated by variation of the scale

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In the resolved case:

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

proton content **photon content** **pQCD matrix element**

Jet physics at HERA

Jet cross section:

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proton content — **photon content** — **pQCD matrix element**

Use of jets:

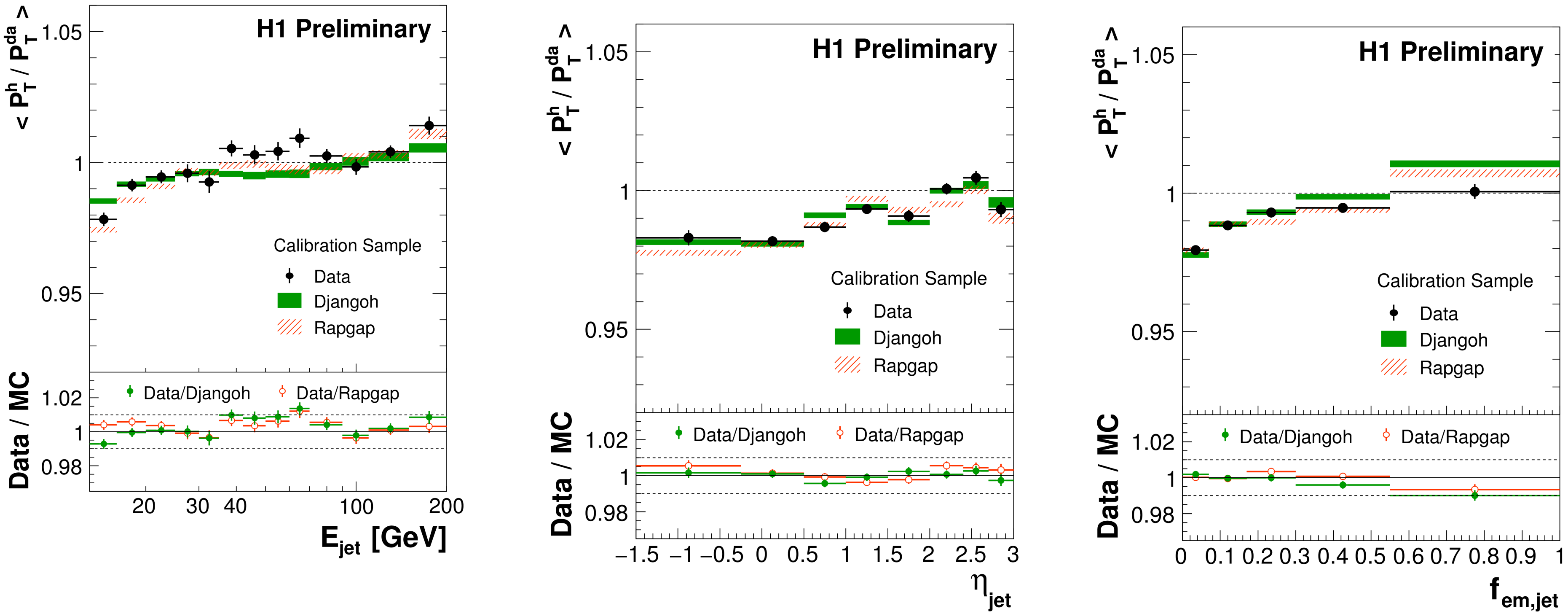
- ✓ *sensitivity to the structure of both proton and photon*
- ✓ *extensive pQCD tests*
- ✓ *determination of* α_s

Jet calibration

High control over the jet energy scale at HERA (leading experimental uncertainty source for jet measurements)

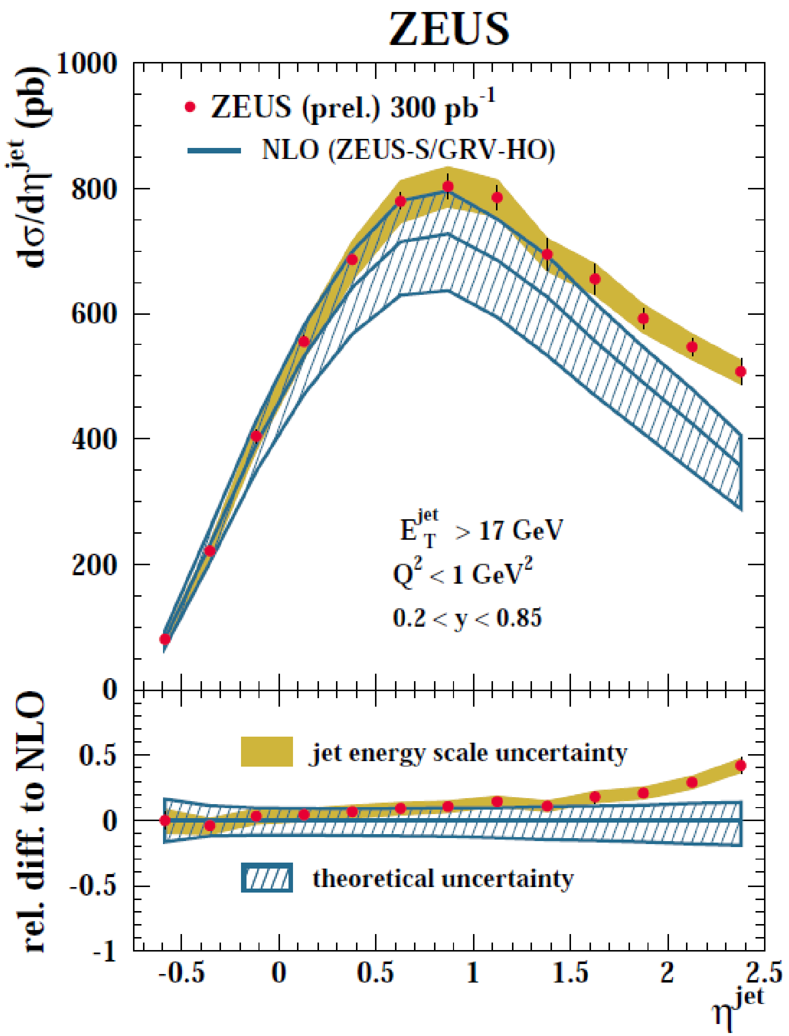
Well measured scattered electron used to calibrate jet energy

1% precision level on the jet energy scale



Jets in photoproduction

$\mathcal{L} = 300\text{pb}^{-1}$
$Q^2 < 1\,GeV^2$
$0.2 < y < 0.85$
$P_T^{JET} > 17\,GeV$
$-1.0 < \eta_{lab}^{JET} < 2.5$



High statistics in photoproduction

More complex analysis (no detected electron, resolved photon, photon PDF uncertainty, etc.)

Great potential but understanding of the photon needed

Theory underestimates jet production in forward region (low P_T^{jet})

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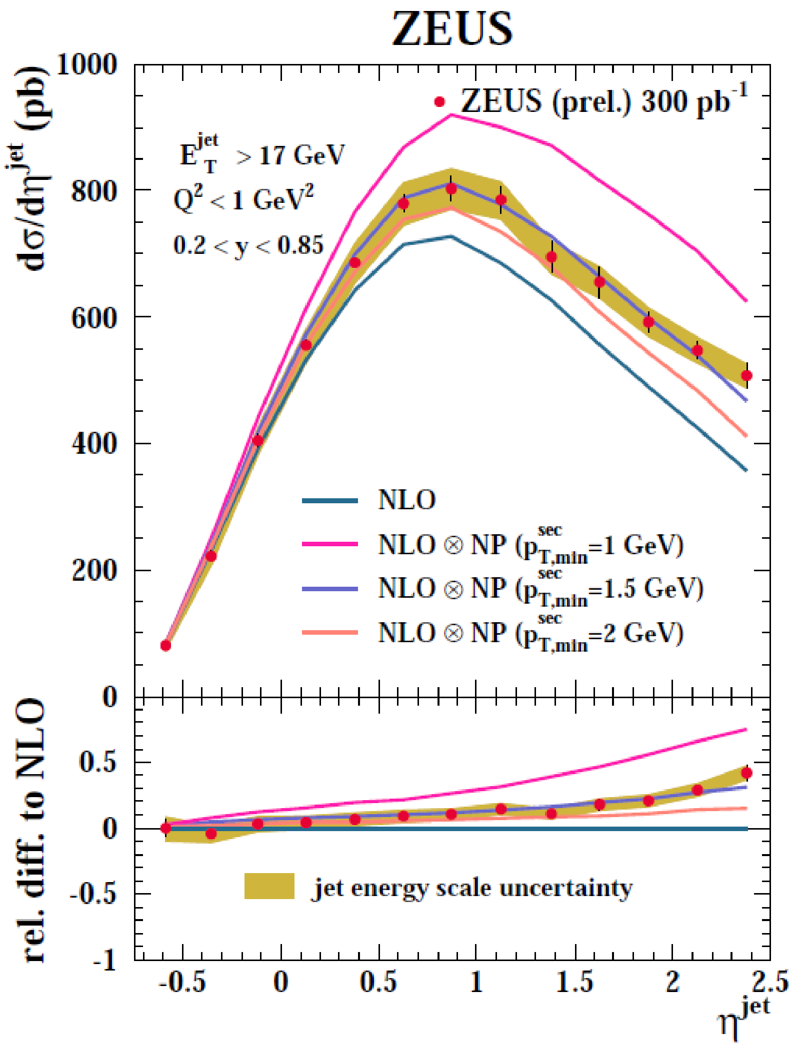

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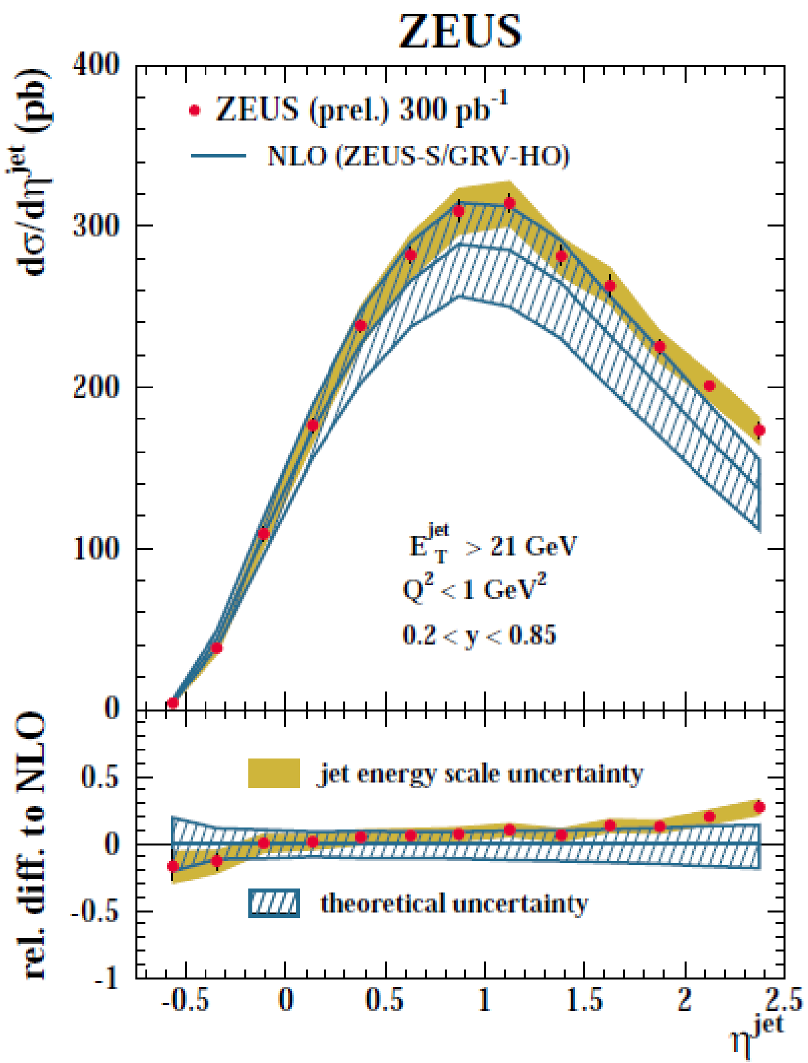

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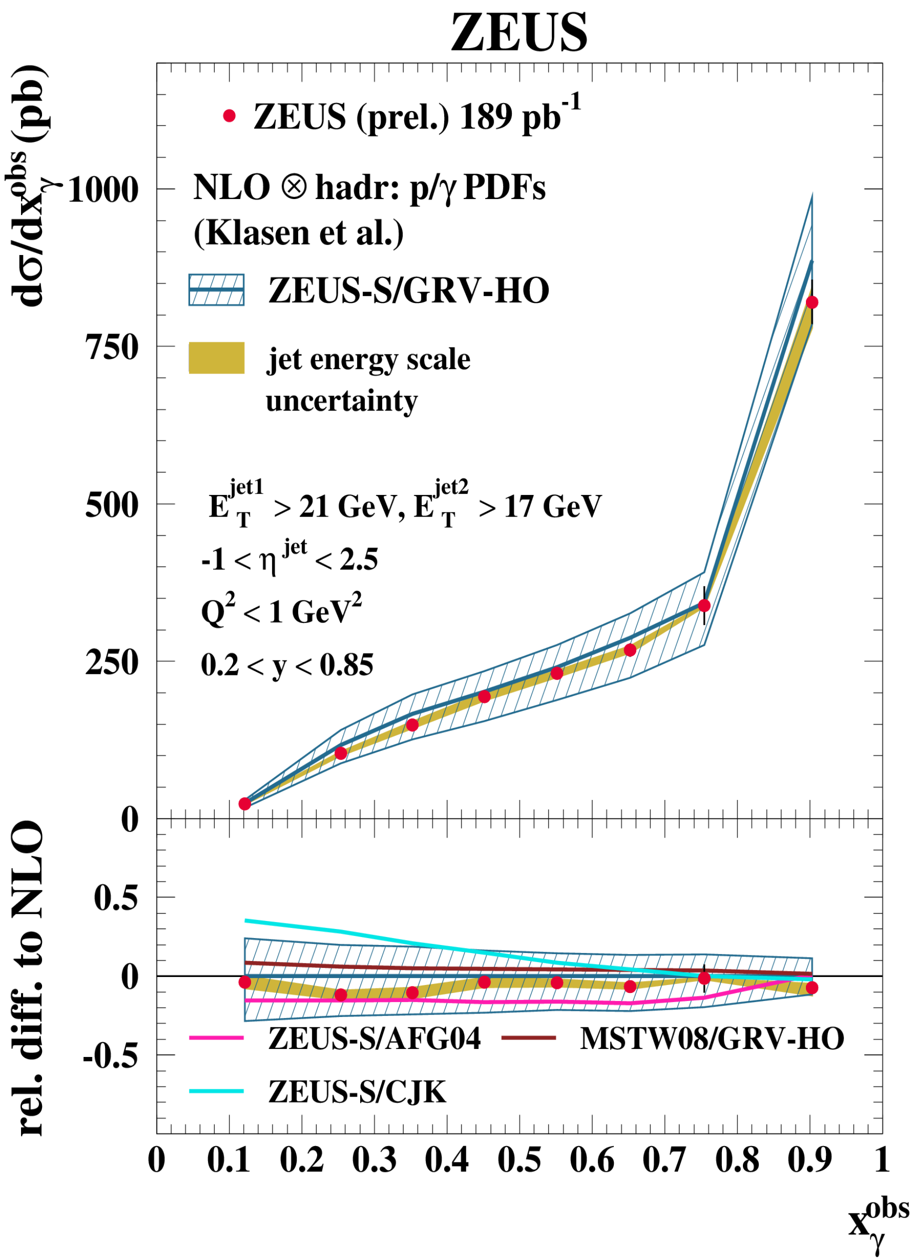
For α_s *fits* P_T^{jet} *restricted to described region* $P_T^{jet} > 21$ *GeV*

Dijets in photoproduction

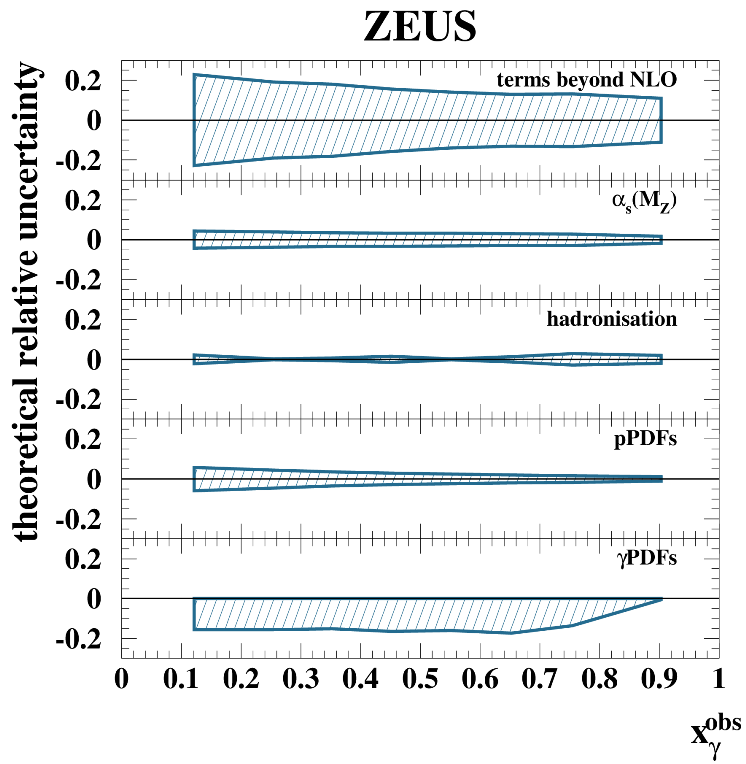
$\mathscr{L} = 189\,\text{pb}^{-1}$
$Q^2 < 1\,GeV^2$
$0.2 < y < 0.85$
$P_{T,B}^{JET} > 21\,(17)\,GeV$
$-1.0 < \eta_{lab}^{JET} < 2.5$



Sensitivity to photon PDF at low x_γ^{obs}

$$x_\gamma^{LO} = \left(E_T^{jet1} e^{-\eta^{jet1}} + E_T^{jet2} e^{-\eta^{jet2}}\right)/2yE_e$$

Large theoretical uncertainty



scale

α_s

hadr.

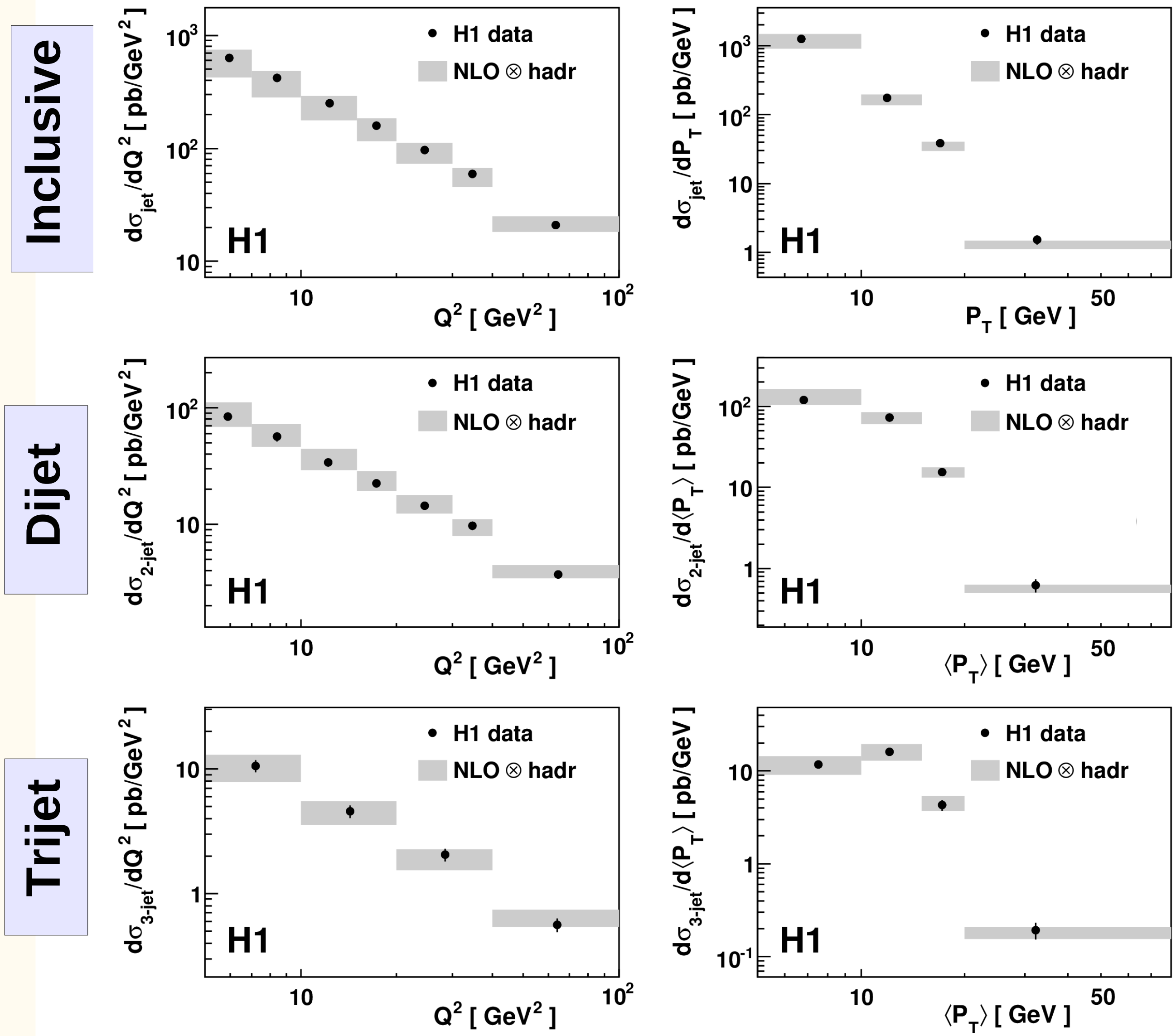
pPDF

γPDF

Low Q^2 DIS jets

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

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



Inclusive jet and multijet cross section measured

Triggering on scat. electron – measurement lower in P_T

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

For α_s fit using only points with

$$k = \sigma_{NLO} / \sigma_{LO} < 2$$

$$\alpha_s = 0.1160 \pm 0.0014(\exp)^{+0.094}_{-0.079}(th)$$

Measurement well described by the NLO calculation

NNLO calculation needed to take full advantage of the precise data

Low Q^2 DIS jets

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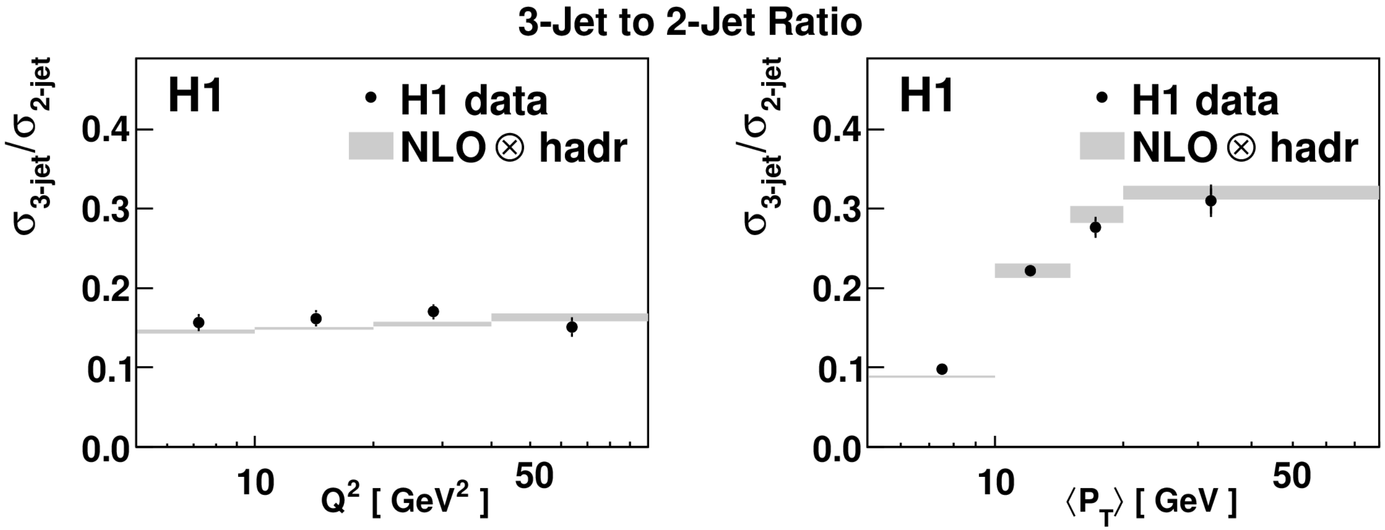
$0.2 < y < 0.7$
$P_{T,B}^{JET} > 5\, GeV$
$-1.0 < \eta_{lab}^{JET} < 2.5$

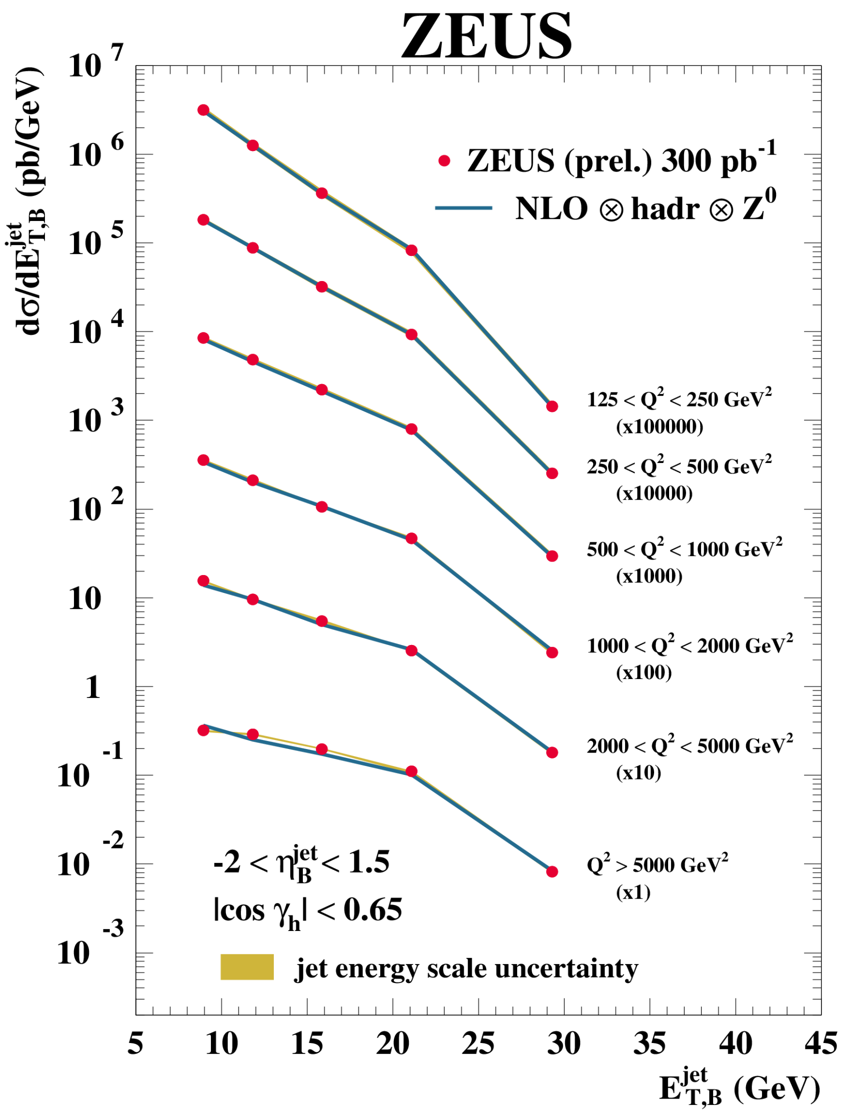
Improvement on the uncertainty can be achieved by measuring trijet to dijet ratio:

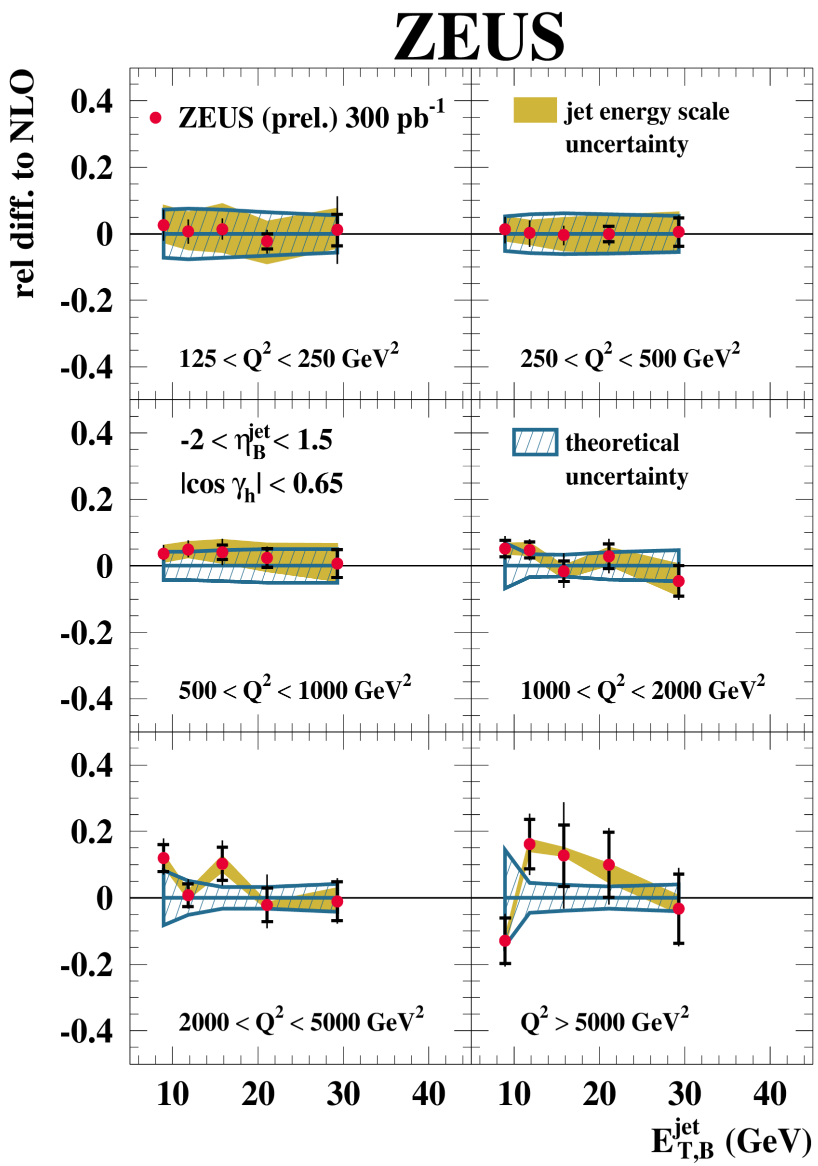
- ✔ *Cancellation of some systematic uncertainties*
- ✔ *Strong reduction of theoretical uncertainty*
- ✔ $\alpha_s \sim \sigma_{3\text{-}jet} / \sigma_{2\text{-}jet}$



High Q^2 DIS inclusive jets

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





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$$P_{T,B}^{JET} > 8\,GeV$$
$$-2.0 < \eta_B^{JET} < 1.5$$

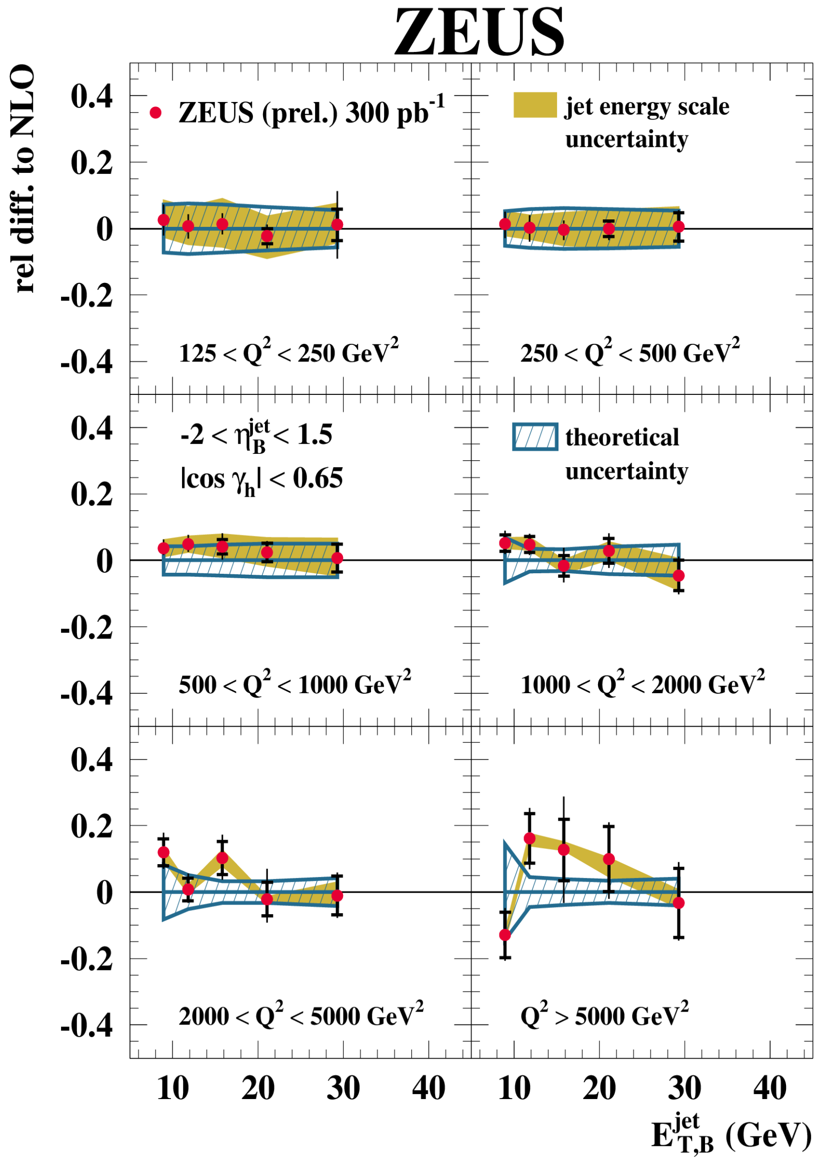
Dominant experimental error – jet energy scale

Comparably high theoretical uncertainty (estimated terms beyond NLO)

Using only points with $Q^2 > 500\ GeV^2$:

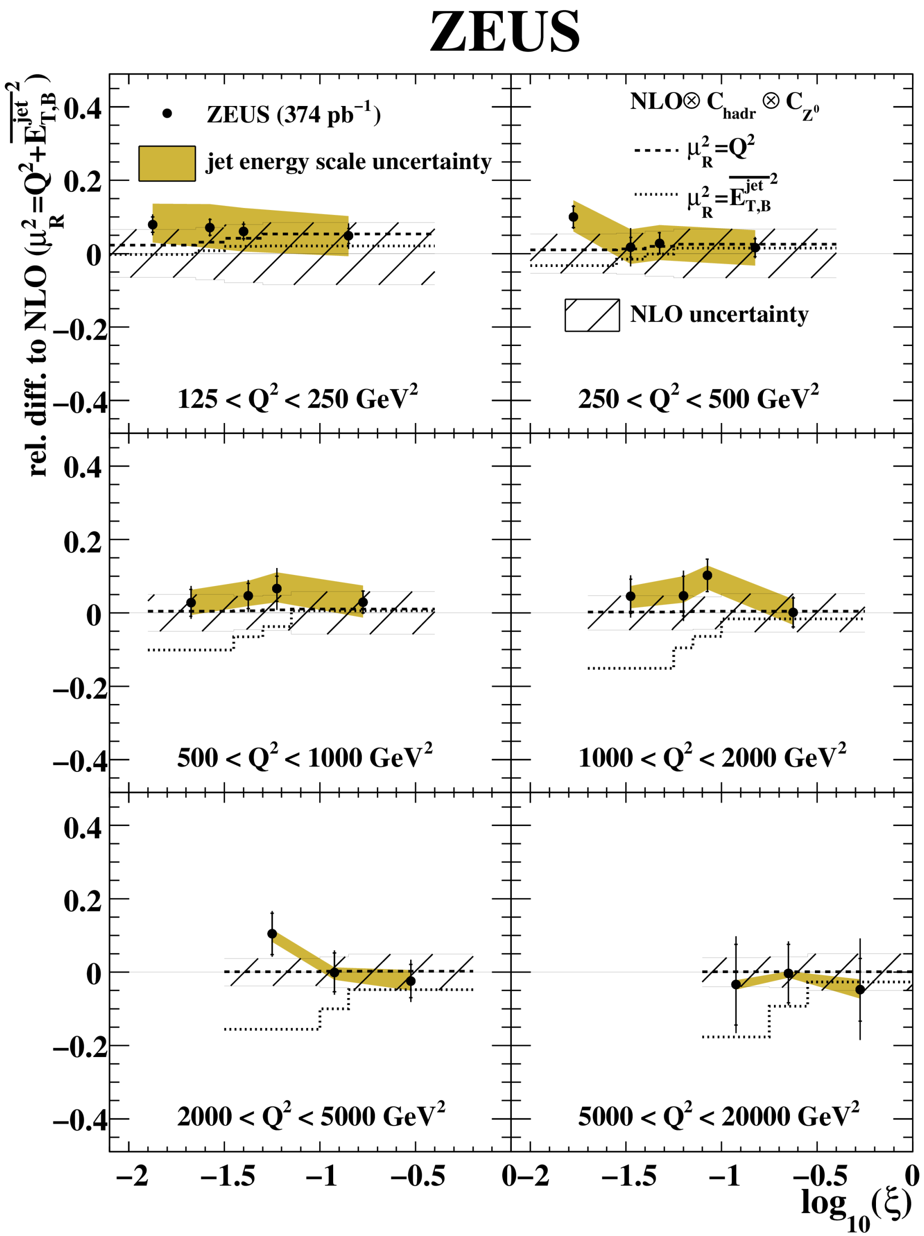
$$\alpha_s = 0.1208^{+0.0032}_{-0.0037}(exp.)^{+0.0022}_{-0.0022}(th.)$$

Measurement well described by NLO prediction



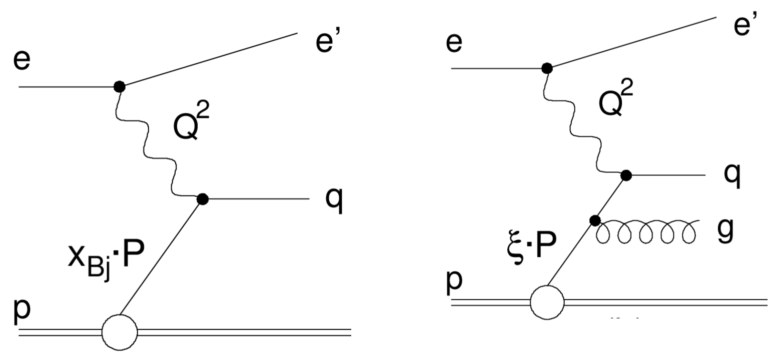
High Q^2 DIS dijets

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



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

High Q^2 DIS jets

$\mathscr{L} = 350 \mathrm{pb}^{-1}$
$150 < Q^2 < 15000\, GeV^2$
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$7 > P_{T,B}^{JET} > 50\, GeV$
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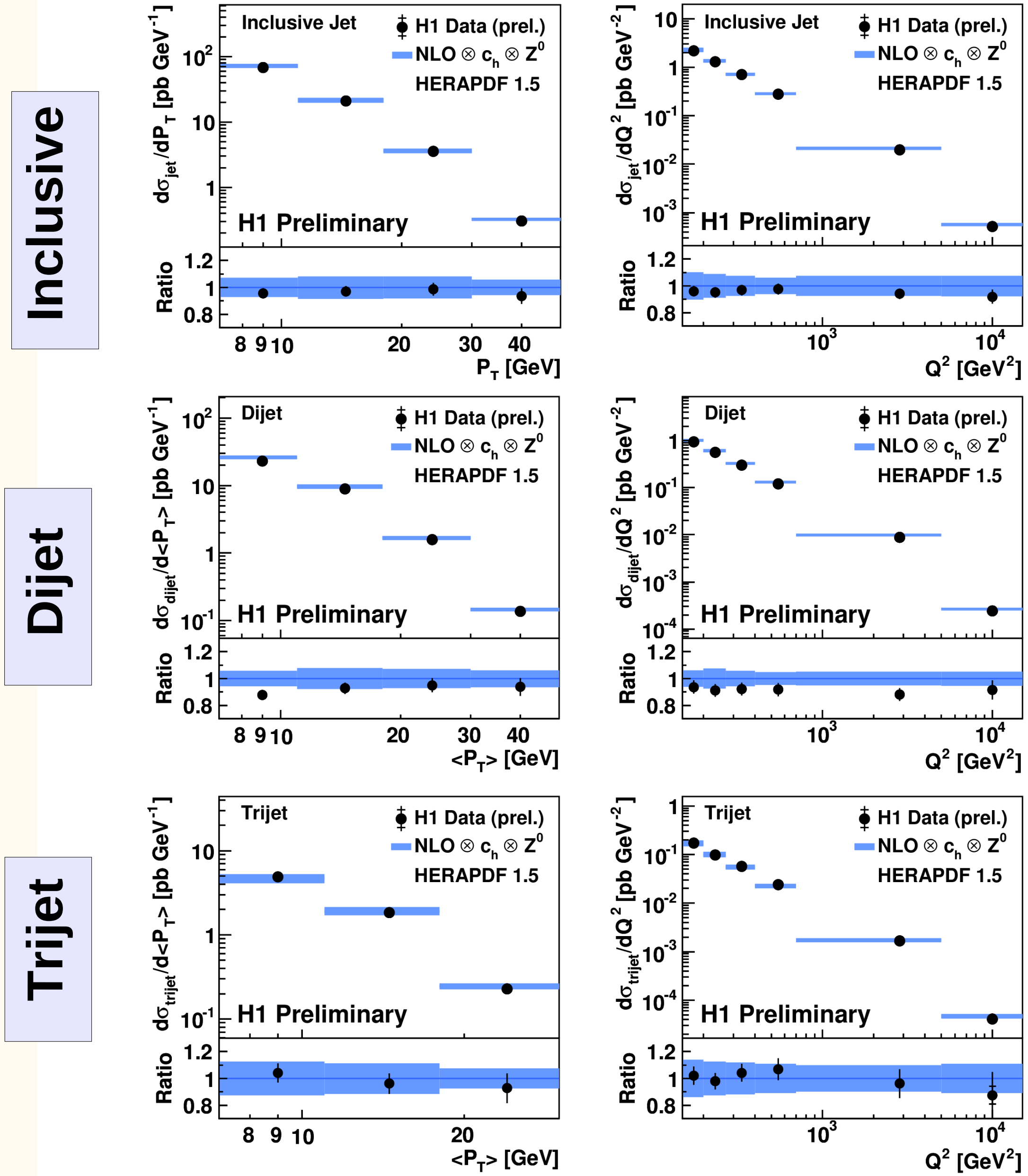

Inclusive jet, dijet and trijet cross section measured

First ever double differential trijet cross section at HERA

Measurement well described by the NLO calculation

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Strong coupling constant determined using inclusive jet, dijet and trijet cross sections independently:

Inclusive jets:

$$\alpha_s(M_Z) = 0.1190 \pm 0.0021(exp.) \pm 0.0020(pdf)^{+0.0050}_{-0.0056}(th.)$$

Dijets:

$$\alpha_s(M_Z) = 0.1146 \pm 0.0022(exp.) \pm 0.0021(pdf)^{+0.0044}_{-0.0045}(th.)$$

Trijets:

$$\alpha_s(M_Z) = 0.1196 \pm 0.0016(exp.) \pm 0.0010(pdf)^{+0.0055}_{-0.0039}(th.)$$

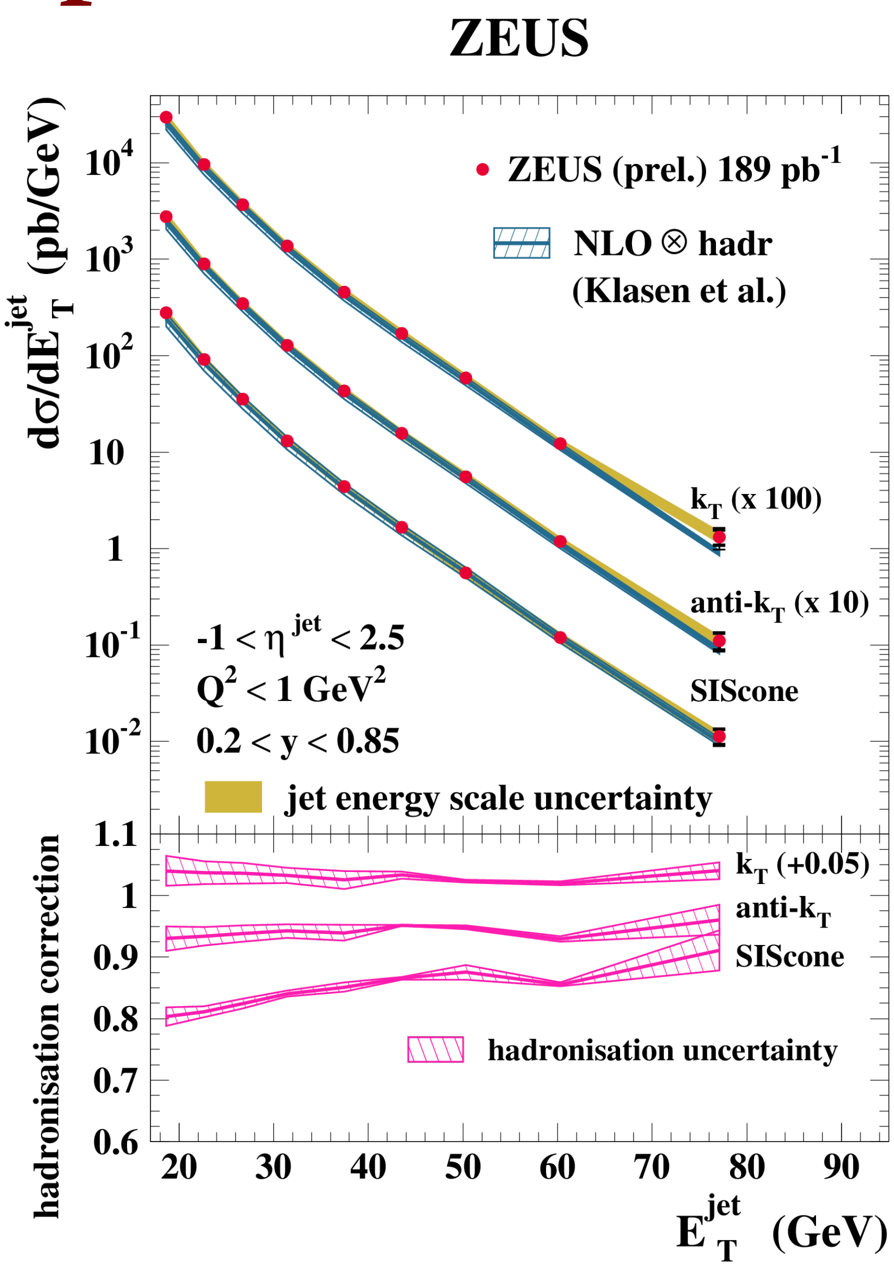
Theoretical uncertainty dominates

Trijet cross sections give experimentally the most precise result

Jet algorithms comparison

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

- *k_T and anti-k_T exhibit similar performance*
- *SIScone hadronization correction somewhat higher*



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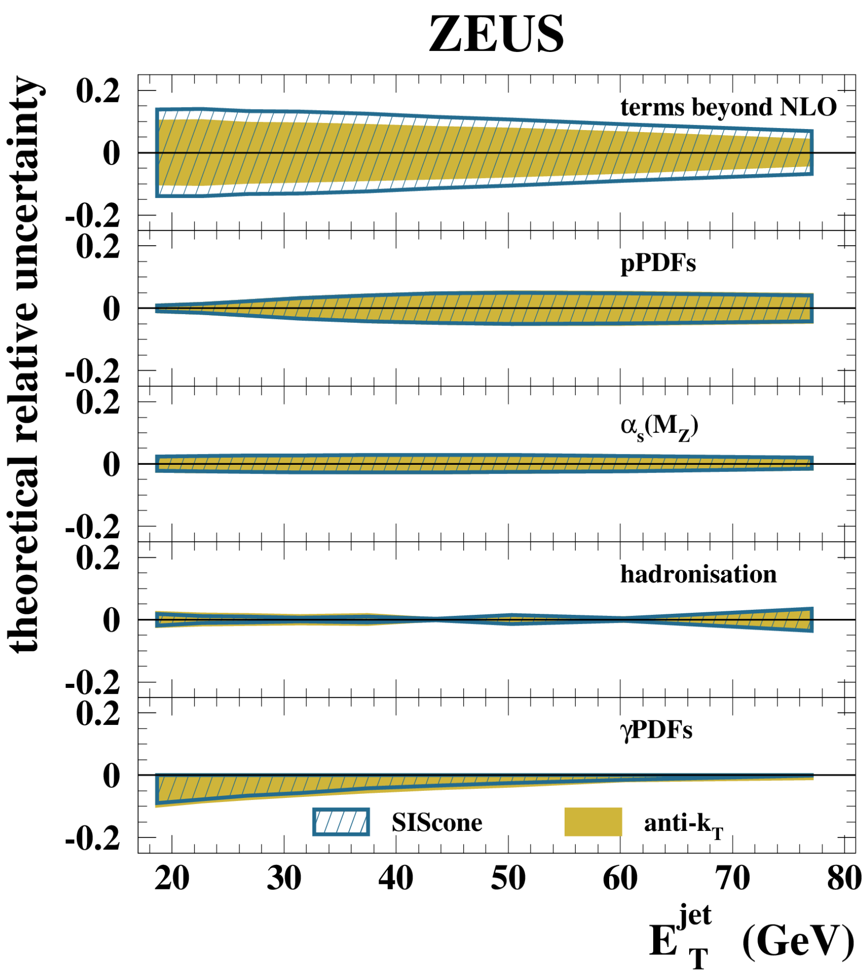
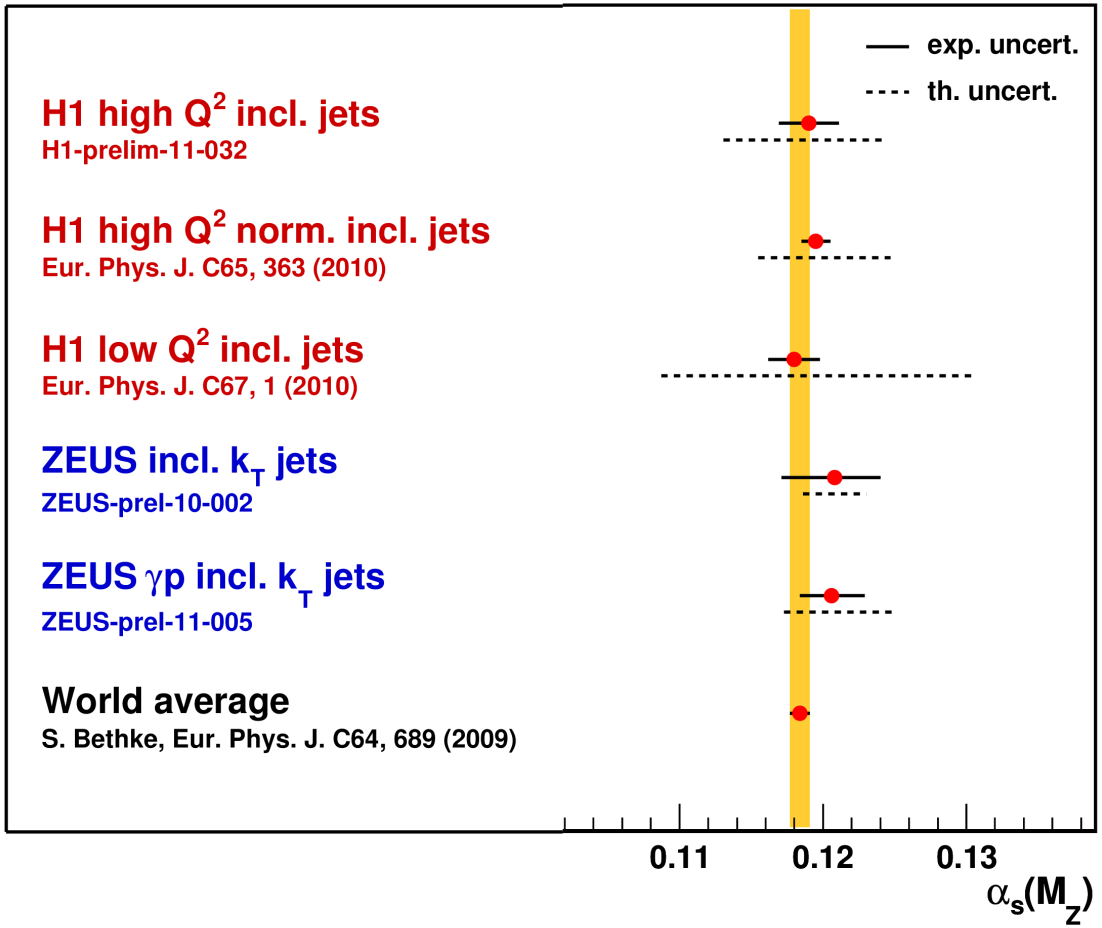


- *k_T and anti-k_T exhibit similar performance*
- *SIScone hadronization correction somewhat higher*
- *SIScone beyond NLO uncertainty slightly higher*

Determination of α_s

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

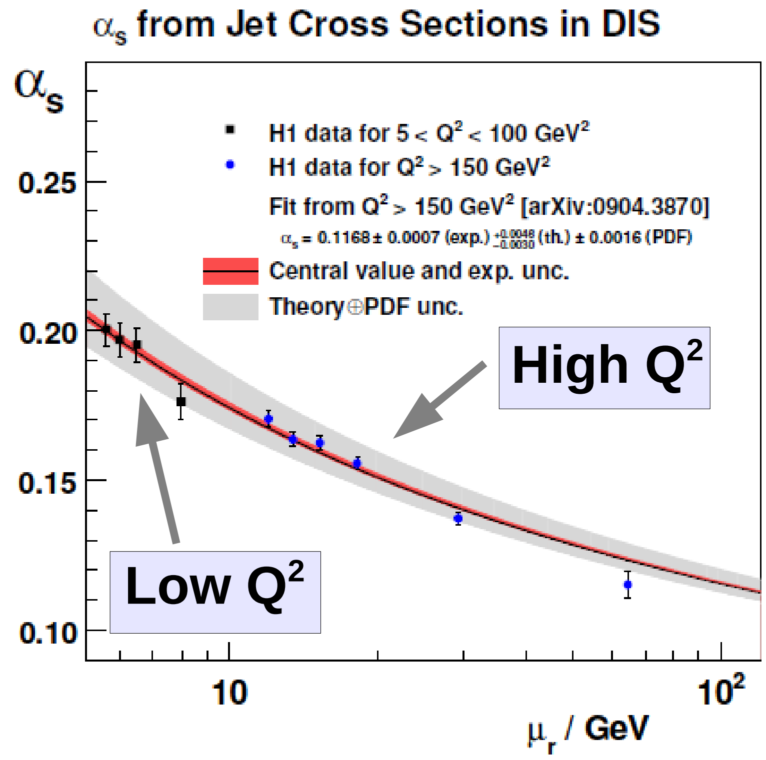
All determined couplings consistent with the world average

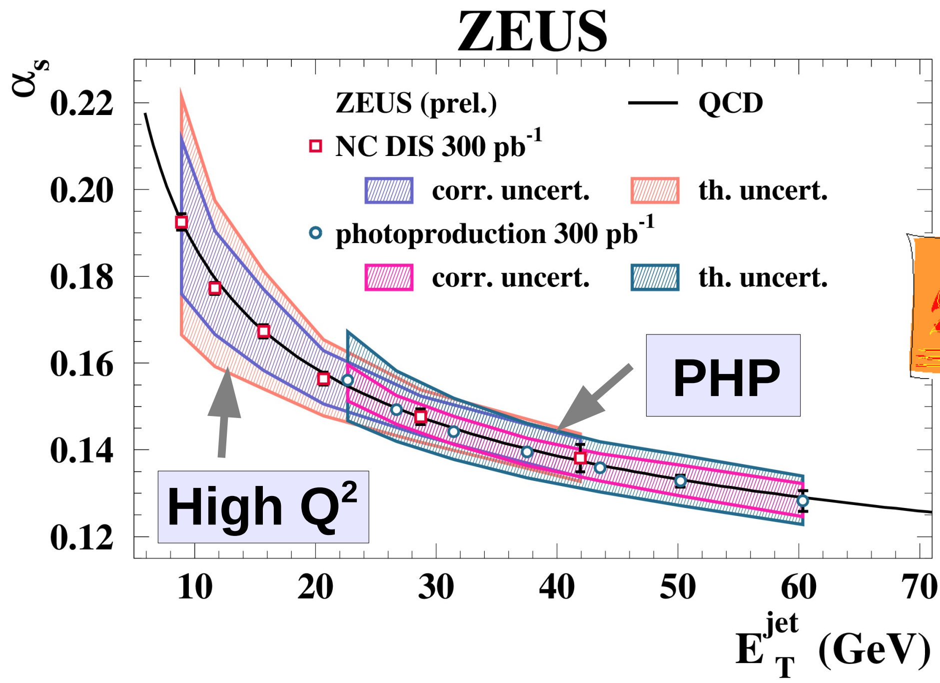


NNLO calculations needed to take advantage of the available experimental precision!

Running of α_s test

Both experiments perform tests of the running of the α_s





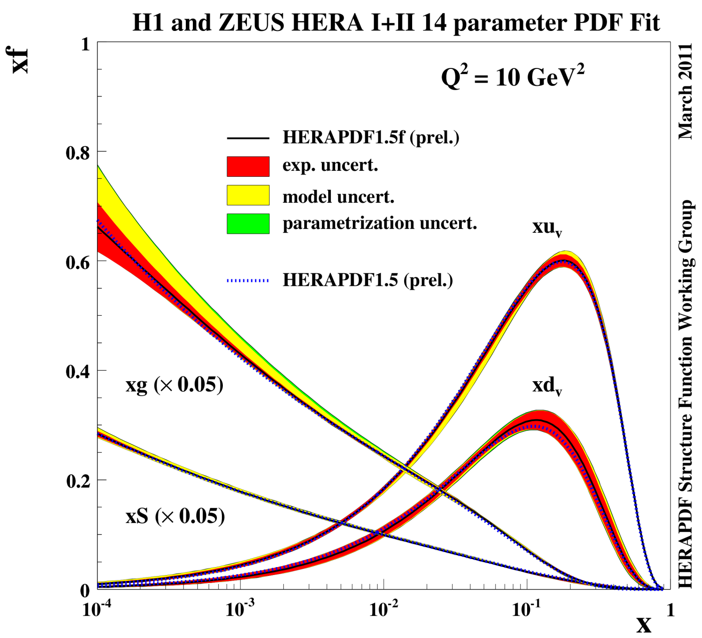
Tests show high level of consistency in our understanding of QCD

Simultaneous PDF and α_s fit

HERA QCD analysis (talk by E. Rizvi) determine proton PDF using fixed α_s

HERA jet measurements determine α_s using PDF determined elsewhere

Inclusion of inclusive jet data into QCD analysis and simultaneous fit of the $\alpha_s(M_Z)$ and PDFs



no jets, fixed α_s

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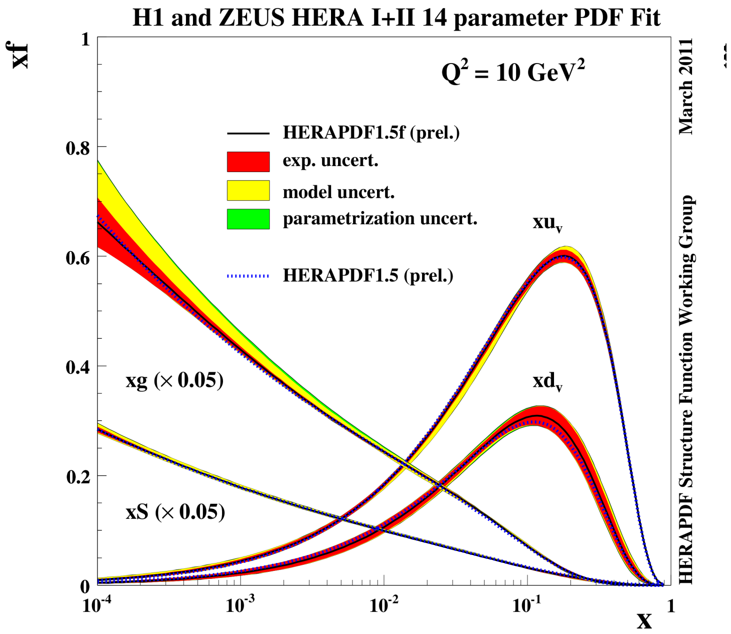
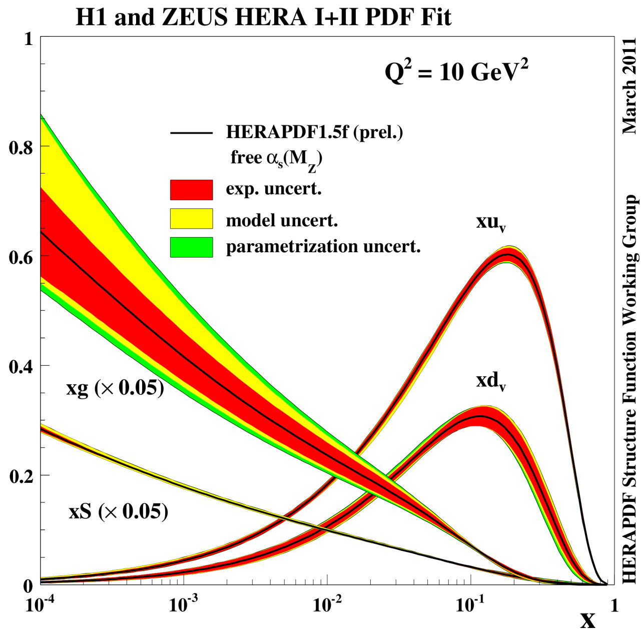


no jets, fixed α_s



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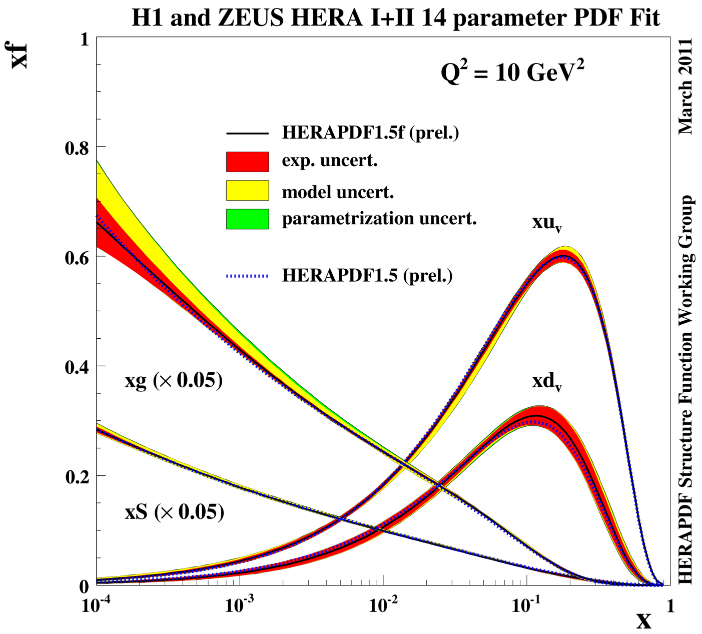
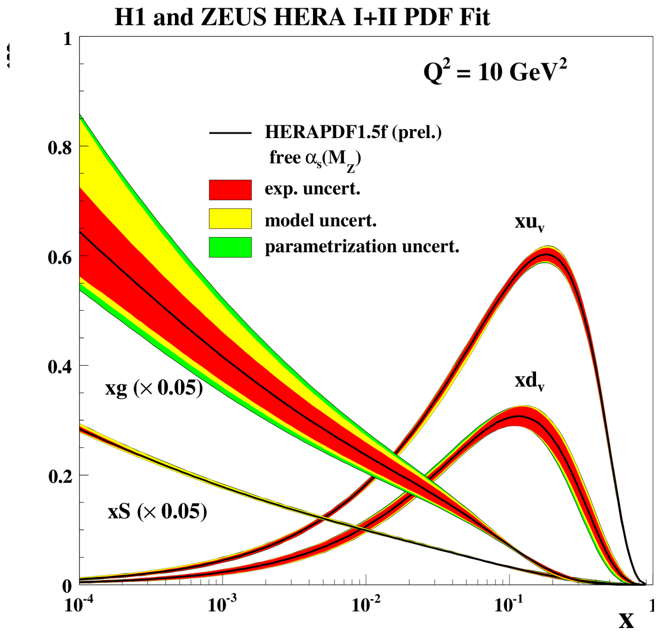
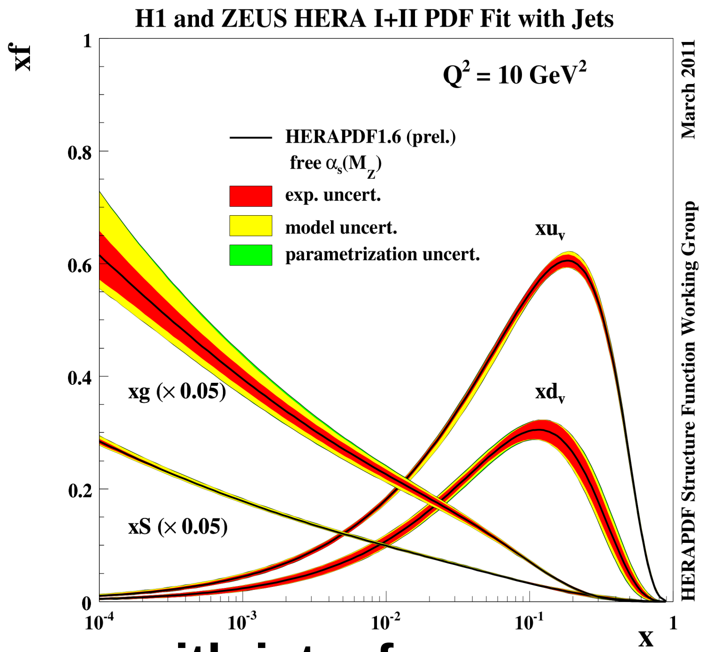


no jets, fixed α_s



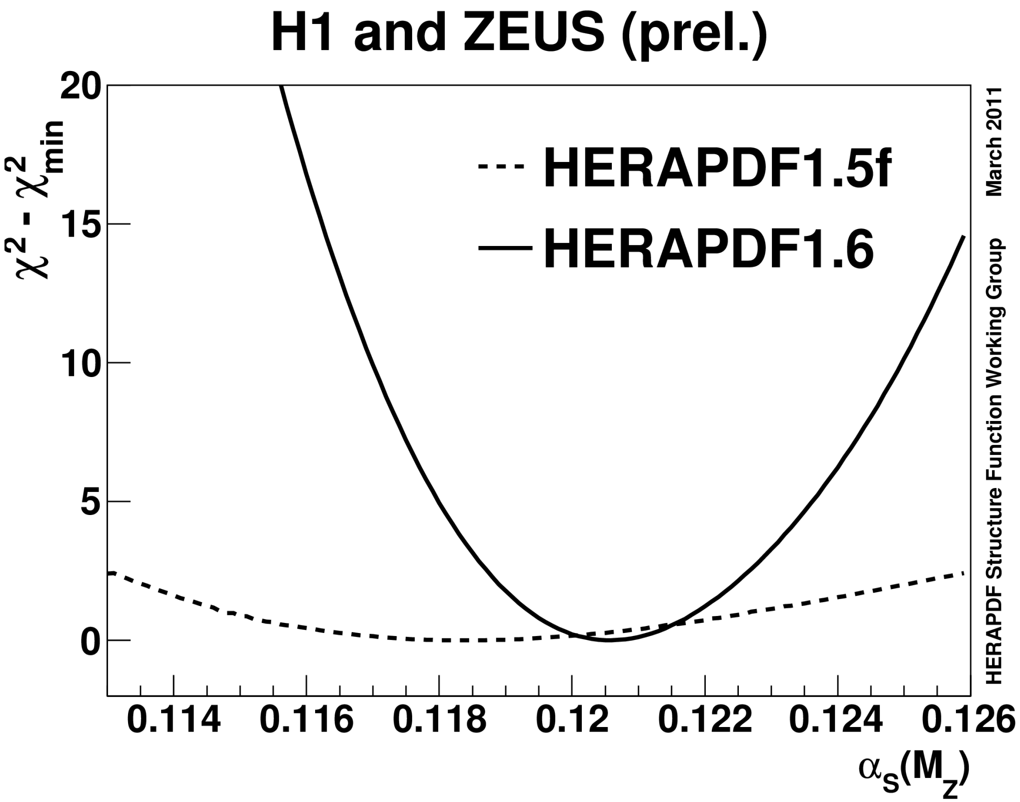
no jets, free α_s



with jets, free α_s

Jet data needed to disentangle gluon and α_s

Simultaneous PDF and α_s fit



Without jet data (HERAPDF1.5f) χ^2 scan exhibits very shallow minimum

With jets (HERAPDF1.6) narrow minimum of the χ^2 scan

HERA jet data sufficient to determine the strong coupling constant:

$$\alpha_s = 0.1202 \pm 0.0013(exp) \pm 0.0007(mod/par) \pm 0.0012(hadr) {}^{+0.0045}_{-0.0036}(scale)$$

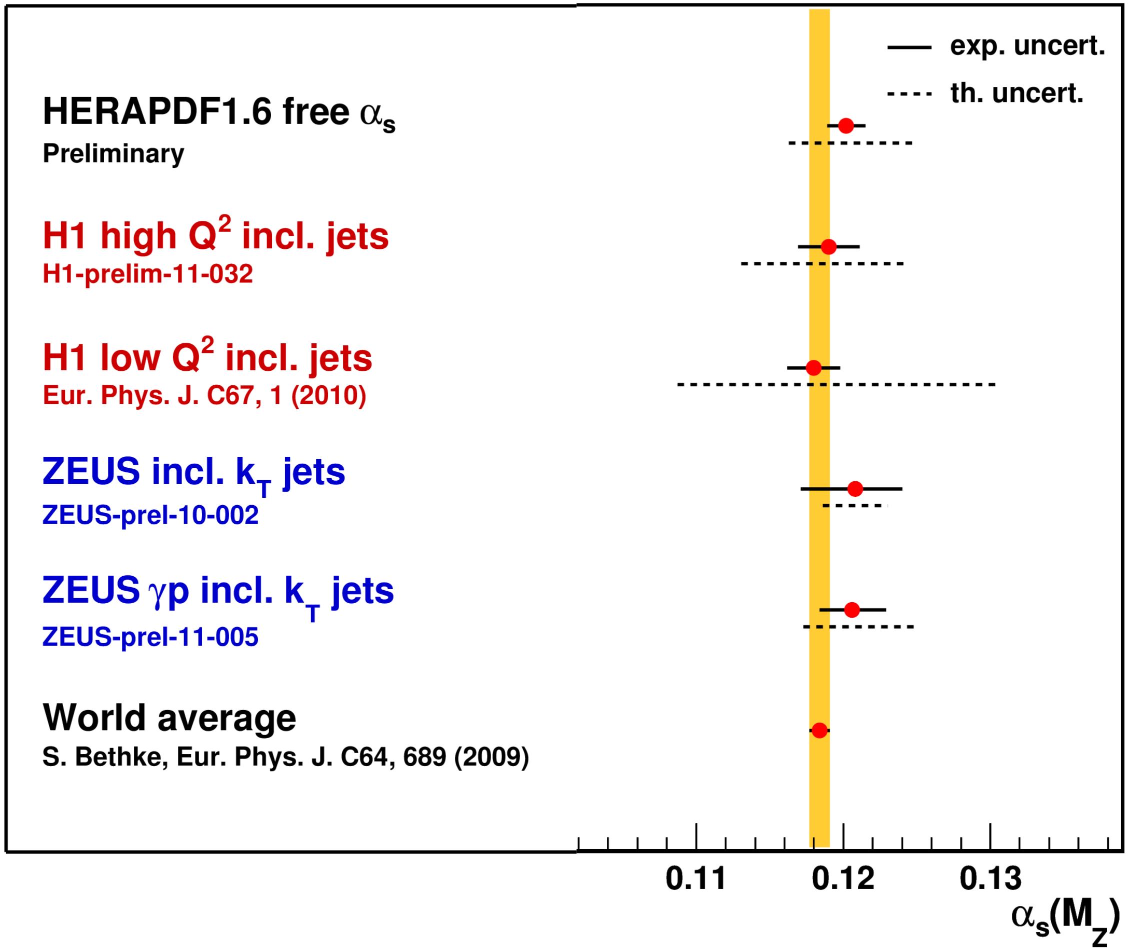
Similarly to the situation before, the α_s precision limited by the theoretical uncertainty

Determination of α_s

Fit is not using the most recent preliminary jet results

Only inclusive jet data used

Obtained $\alpha_s(M_Z)$ compatible with world average and has already competitive precision



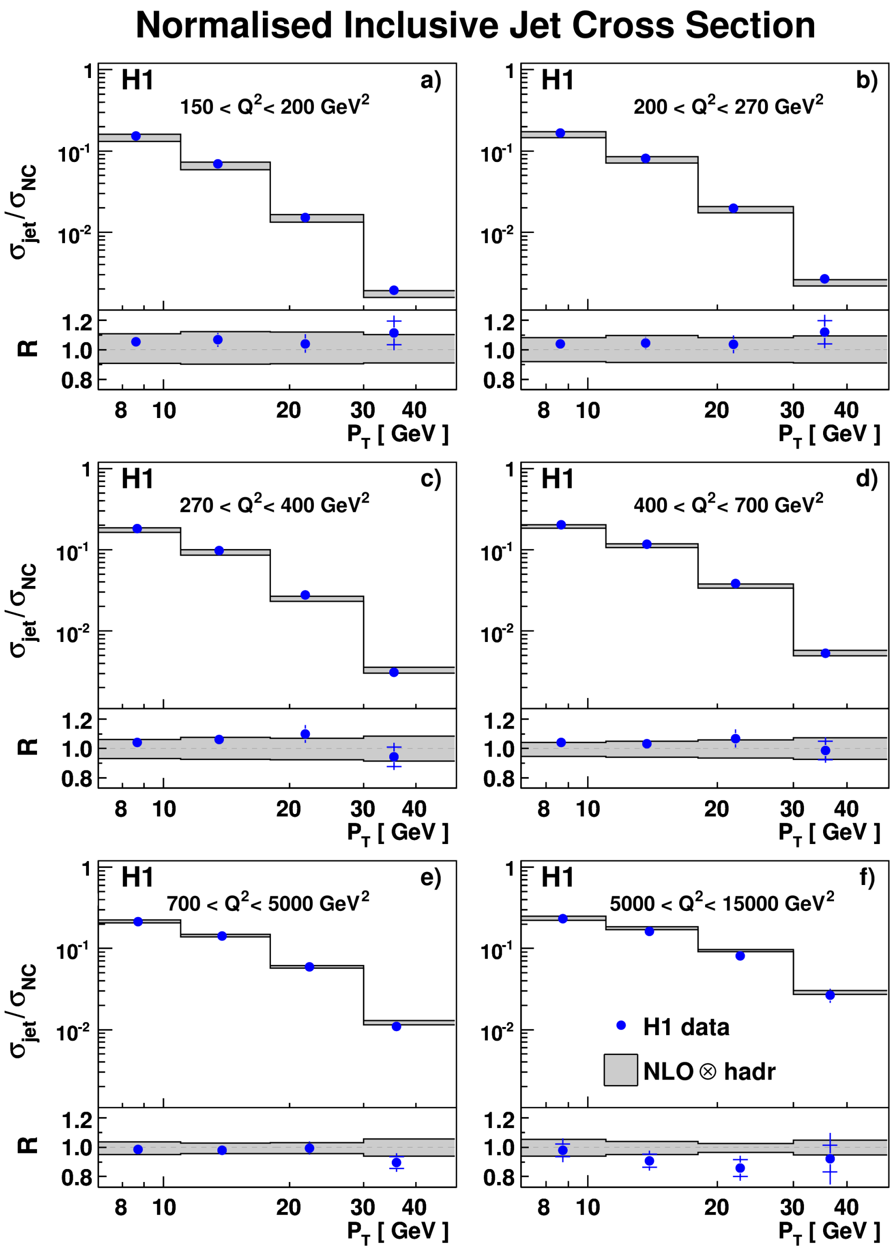
Conclusions

Jet measurements from HERA

- *important for understanding of QCD*
- *possibly sensitive to non-perturbative effects*
- *allowing 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

$\mathscr{L} = 395 \mathrm{pb}^{-1}$
$150 < Q^2 < 15000\, GeV^2$
$0.2 < y < 0.7$
$7(5) < P_T^{JET} < 50\, GeV$
$-0.8 < \eta^{JET} < 2.0$



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)