Jet physics at HERA and extraction of α_s

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on behalf of the H1 and ZEUS Collaborations

New Trends in HEP

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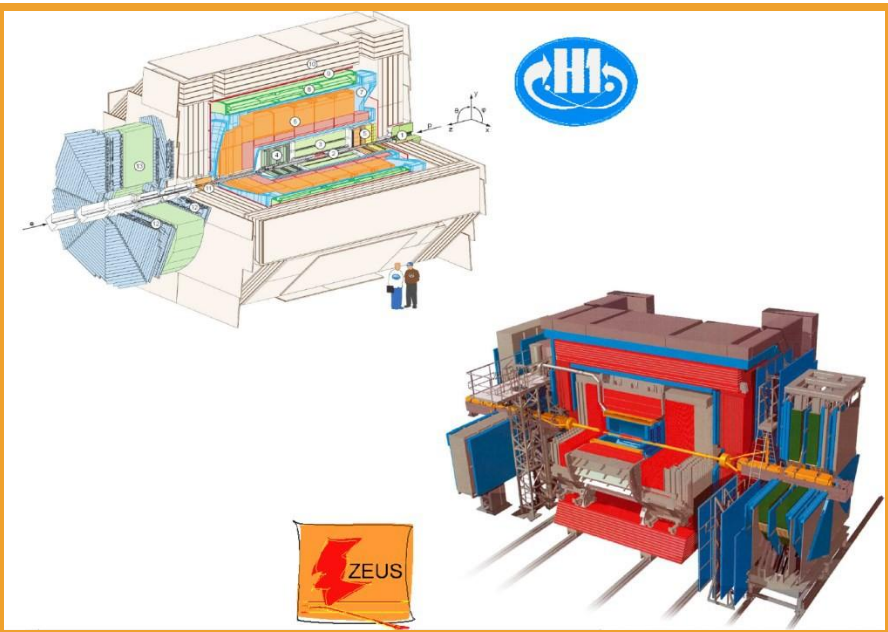
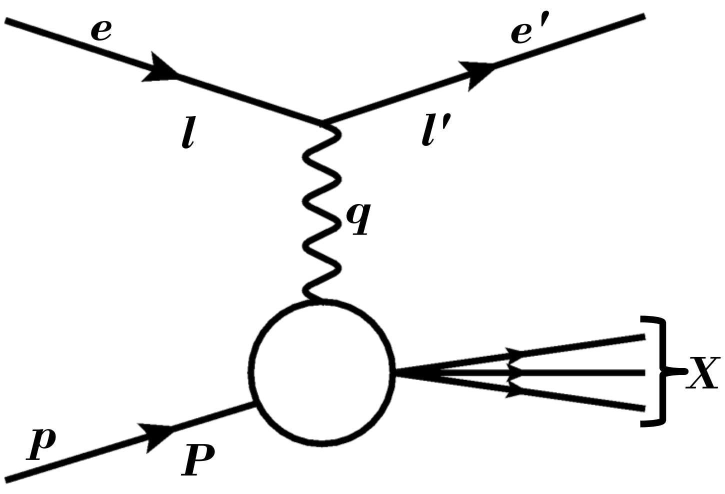
HERA collider: H1 and ZEUS experiments.

HERA is a unique $e^{\pm}$ collider:
- located at Hamburg, Germany;
- operated during 1992-2007;
- $\sqrt{s}$ = 318 GeV



H1 and ZEUS collider experiments:
- general purpose detectors;
- 4π geometry;
- collected ~0.5 fb^{-1} of integrated luminosity by each experiment

Jet physics 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
  $y = P\cdot q/P\cdot l$

- Photoproduction:
  - $Q^2 < 1\mathrm{GeV}^2$
- DIS:
  - $Q^2 > 1\mathrm{GeV}^2$

$$d\sigma_{jet} = \sum_{i,j} \int dy\ f_{\gamma/e}(y) \int dx_p\ f_{j/p}(x_p, \mu_{F_p}) \int dx_\gamma\ f_{i/\gamma}(x_\gamma, \mu_{F_\gamma})\, d\hat{\sigma}_{i(\gamma)j}$$

f : parton density, determined from experiment

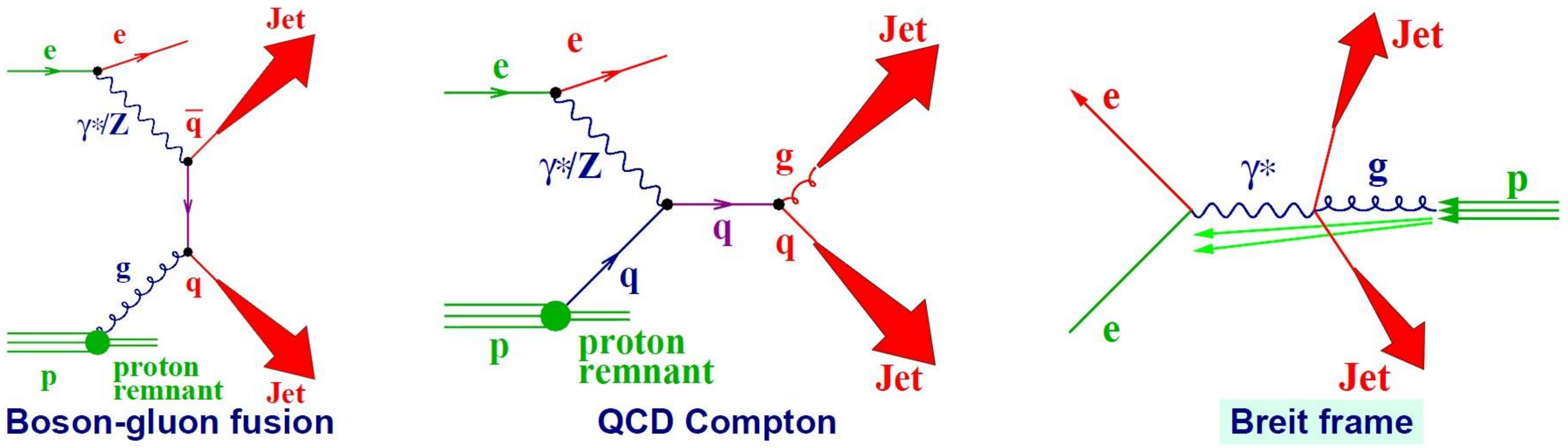
$\hat{\sigma}$: subprocess cross section, calculable in pQCD

Jet cross sections at HERA provide a testing ground for pQCD:

- **precise extraction of $\alpha_s(M_Z)$ and test of the running of α_s;**
- **constraints on the proton PDFs**

Jets in NC DIS at HERA

- Jet production in neutral current deep inelastic ep scattering at $\mathcal{O}(\alpha_s)$ in the Breit frame:

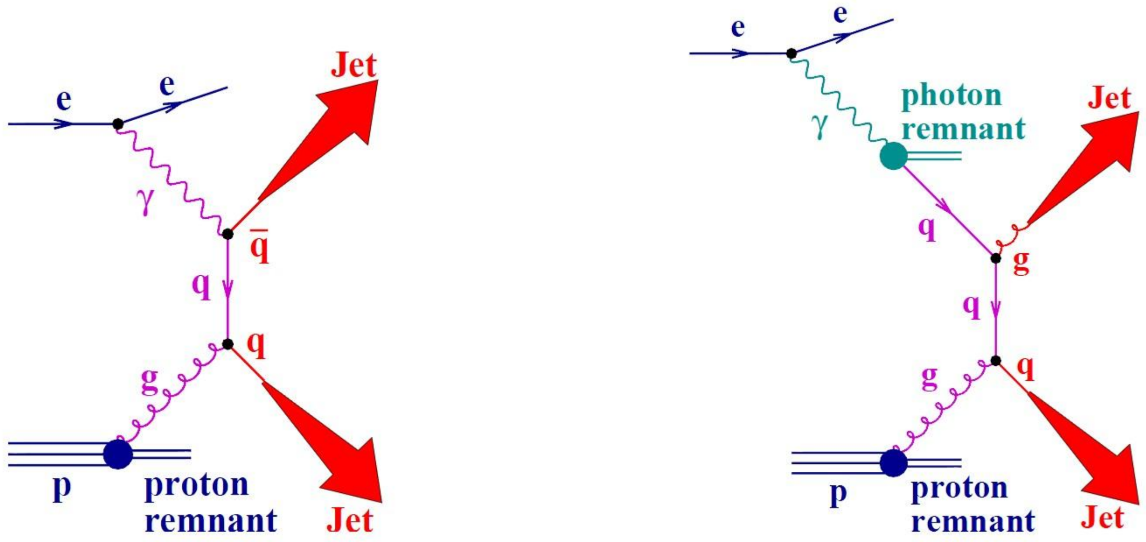


<u>Jet searched using the k⊥ cluster algorithm in the Breit frame</u>

Measurements of jet production in NC DIS at HERA provide a clean hadron-induced reaction

Jets in PHP at HERA

- Jet production in photoproduction at $\mathcal{O}(\alpha_s)$:



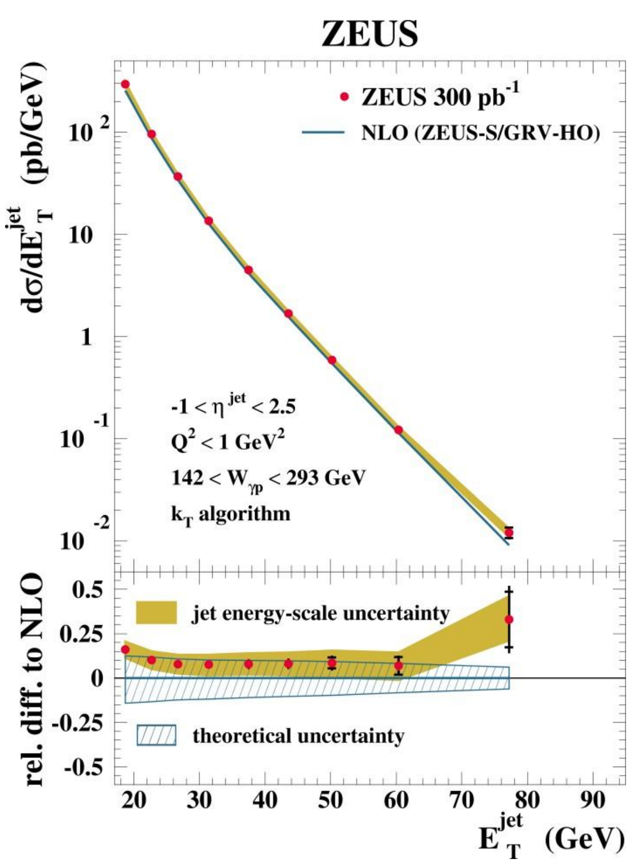
direct photoproduction resolved photoproduction

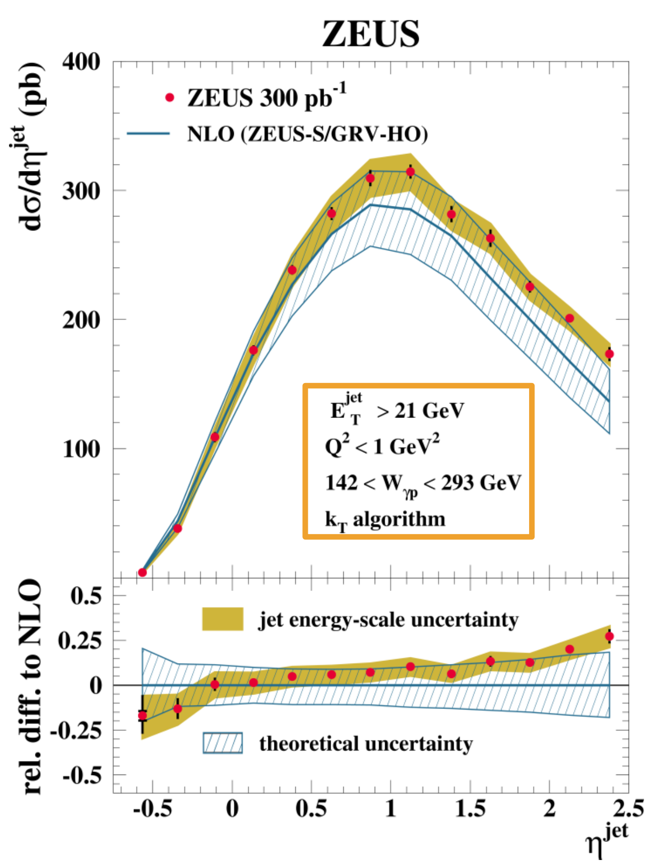
Jets were identified using the k⊥, anti-k⊥ or SIScone jet algorithms in the laboratory frame

Photoproduction is the main source of jets at HERA

Single-differential inclusive-jet photoproduction cross sections as functions of E_T^{jet} and η^{jet}

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





Fixed-order QCD calculations

Using program by
M. Klasen, T. Kleinwort, G. Kramer

- pPDFs: ZEUS-S
- γPDFs: GRV-HO
- Renormalisation and factorisation scales: $\mu_R = \mu_F = E_T{}^{jet}$
- Calculations corrected for hadronisation effects

→Dominant source of the theoretical uncertainty is due to terms beyond NLO

Small experimental uncertainties

Reasonable description of data in shape and normalisation by NLO QCD

Extraction of $\alpha_s(M_Z)$. Test of energy-scale dependence of α_s.

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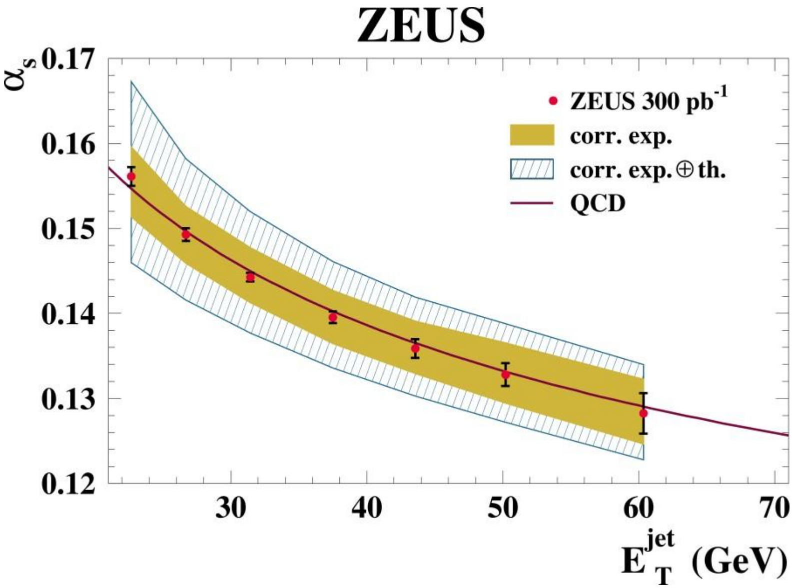
- Values of $\alpha_s(M_Z)$ were determined from the measured cross sections to quantify the performance of the jet algorithms:

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

- $\alpha_s(M_Z)$ from inclusive-jet cross sections in PHP with different jet algorithms are consistent with each other and have similar precision

- Extracting α_s from the measured $\frac{d\sigma}{dE_T^{jet}}$ at different E_T^{jet} values
- **The results are in good agreement with the predicted running of α_s over a wide range in E_T^{jet} from a single experiment**



Normalised multijet-jet cross sections at high-Q^2 NC DIS

- **Simultaneous measurement of normalized* inclusive jet, dijet and trijet cross sections**

* Normalization w.r.t. inclusive NC DIS:
- ✓ cancellation of normalisation unc.
- ✓ partly cancellation of other exp. unc.

Correction of detector effects using regularised unfolding

- **Detector effects**
  - Acceptance and efficiency
  - Migrations due to limited resolution
- **Aim**
  - Cross section on hadron level
  - Direct detector response matrix inversion often not possible

→ **Using TUnfold**

NC DIS phase space:
$150 < Q^2 < 15000$ GeV^2
$0.2 < y < 0.7$

Jet acceptance:
$-1.0 < \eta^{lab} < 2.5$

Inclusive Jet:
count every single jet with transverse momentum $7 < p_T^{jet} < 50$ GeV

Dijet and **Trijet:**

average of two/three leading jets

$$<p_T> = \frac{p_T^1 + p_T^2}{2}$$

$5 < p_T^{jet} < 50$ GeV
$M_{12} > 16$ GeV
$7 < <p_T^{jet}> < 50$ GeV

NC DIS, inclusive jet, dijet and trijet are unfolded simultaneously: stat. correlations are considered

Normalised multijet-jet cross sections at high-Q^2 NC DIS

H1prelim-12-031

NLO predictions

Using programs
nlojet++, fastNLO and QCDNUM

- pPDFs: CT10
- $\alpha_s(M_Z) = 0.118$
- Renormalisation and factorisation

scales: $\mu_r = \mu_F = \frac{\sqrt{p_T^2 + Q^2}}{2}$

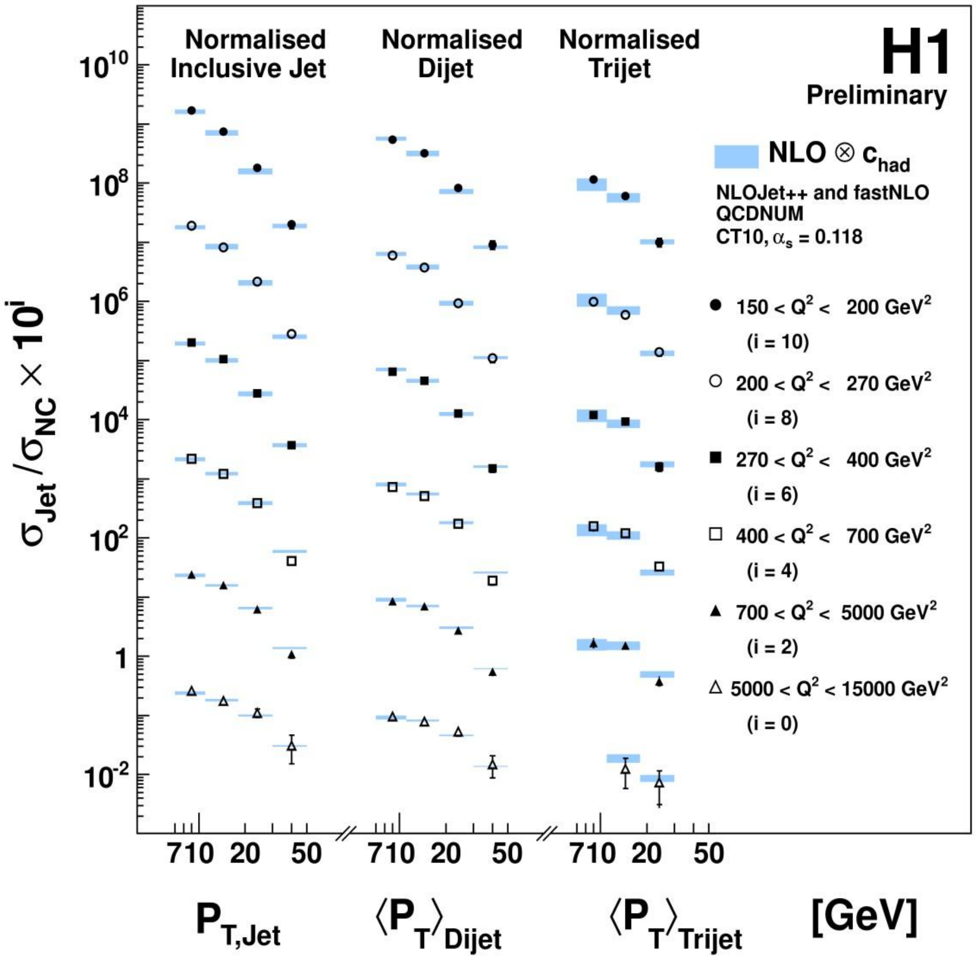
$< p_T >$ instead of p_T for dijet and trijet

- Calculations corrected for hadronisation effects

→Dominant source of the theoretical uncertainty is due to terms beyond NLO

Jet energy scale 1%

→ 3 - 7% effect on cross sections



- ✓ **NLO QCD calculations provide a good description of the measurements**
- ✓ **All three normalised jet measurements can be used together in a fit since the correlation matrix is known**

Extraction of $\alpha_s(M_Z)$

- **α_s fit to individual measurements**

H1prelim-12-031

Normalised inclusive jet

$\alpha_s(M_Z) = 0.1197 \pm 0.0008\ (\text{exp}) \pm 0.0014\ (\text{PDF}) \pm 0.0012\ (\text{had}) \pm 0.0054\ (\text{theo})$

χ^2 / ndf = 28.7/23 = 1.25

Normalised dijet

$\alpha_s(M_Z) = 0.1142 \pm 0.0010\ (\text{exp}) \pm 0.0017\ (\text{PDF}) \pm 0.0009\ (\text{had}) \pm 0.0048\ (\text{theo})$

χ^2 / ndf = 27.0/23 = 1.18

Normalised trijet

$\alpha_s(M_Z) = 0.1185 \pm 0.0018\ (\text{exp}) \pm 0.0013\ (\text{PDF}) \pm 0.0016\ (\text{had}) \pm 0.0043\ (\text{theo})$

χ^2 / ndf = 12.0/16 = 0.75

Results

- High experimental precision
- Reasonable $\chi 2$/ndf for each fit

Tension between inclusive jet and dijet *(observed also in previous H1 and ZEUS analyses)*

- **α_s simultaneous fit to normalised inclusive jet, dijet and trijet cross sections**

Normalized Multijet (k < 1.3)

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

χ^2 / ndf = 53.3 / 41 = 1.30

✓ **Value consistent with world average**

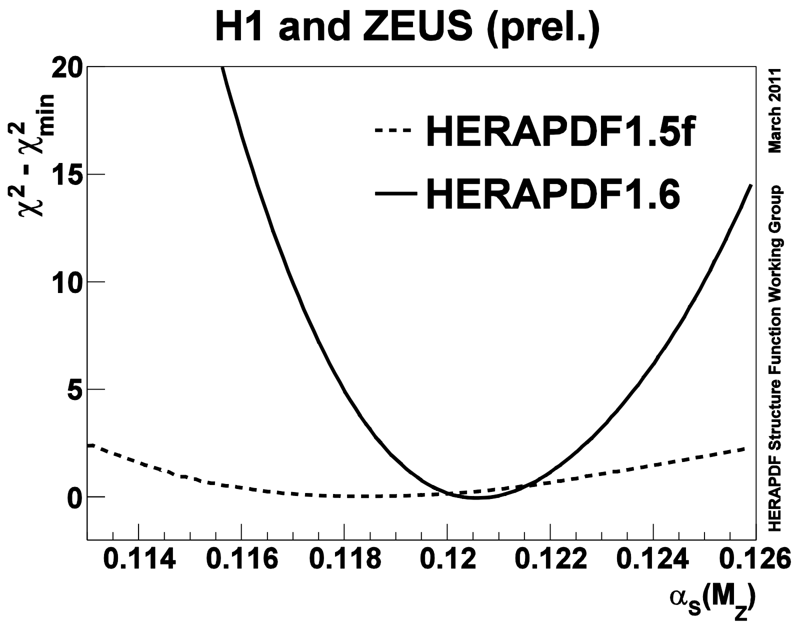
$\alpha_s(M_Z)$ from inclusive DIS & inclusive jet data. Comparison of $\alpha_s(M_Z)$ values.

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

Combined fit of PDF and αs(MZ) 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 PDF



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

✓Scale uncertainty from variation of renormalization and factorization scale

Summary

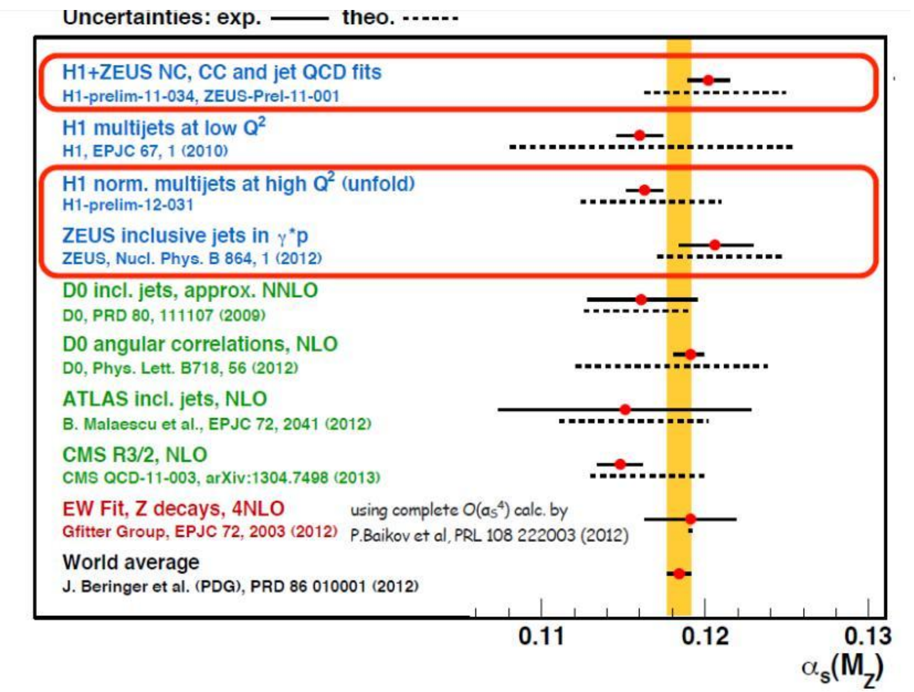
- **Jet physics at HERA continues providing precision measurements towards understanding QCD and improving the determination of the pPDFs**

→ The measured jet cross sections are well described by the NLO predictions in the whole measured range

→Precise new jet measurements will help to constrain further the proton PDFs

→Precise values of $\alpha_s(M_Z)$ extracted from jet production in different regimes

→Precise determination of the running of α_s over a wide range of the scale



HERA jet cross sections
→ High experimental sensitivity to $\alpha_s(M_Z)$
Complementary methods and processes
→ Consistent results
Theory uncertainty from missing higher order dominates

Study of the influence of non-perturbative effects and γPDF at high η^{jet}

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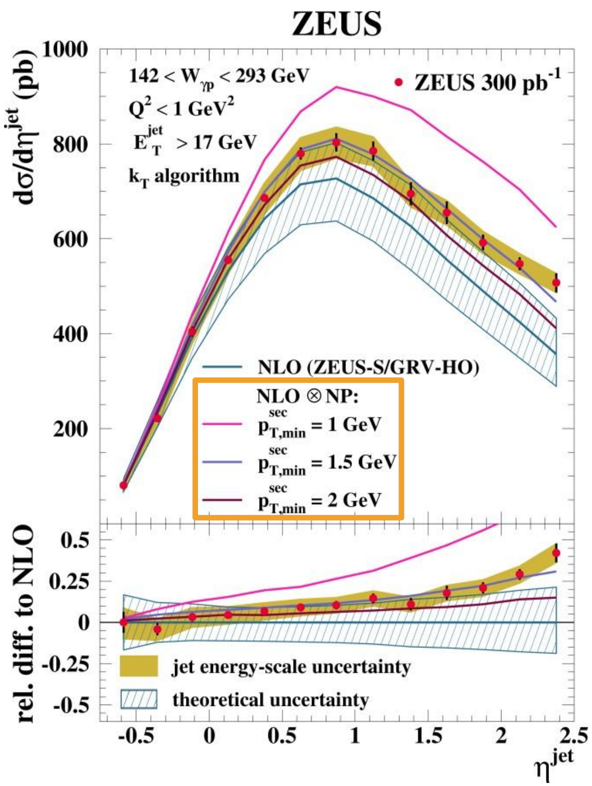

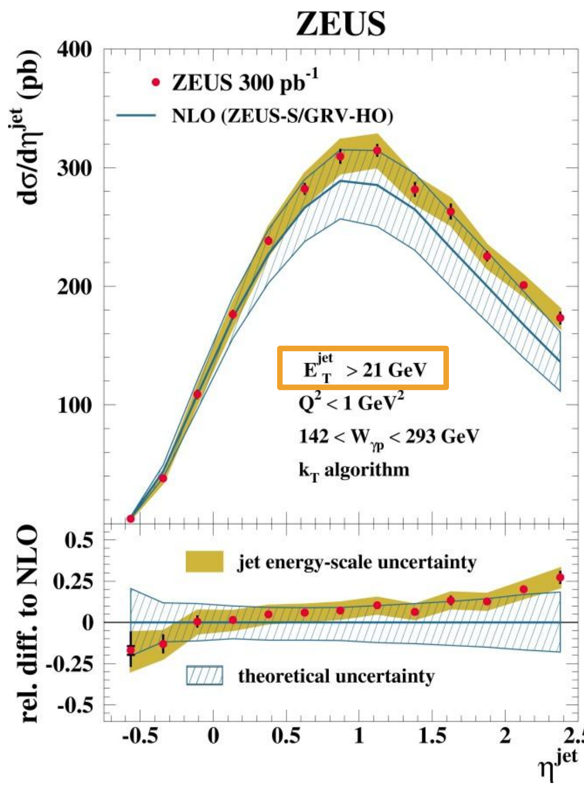

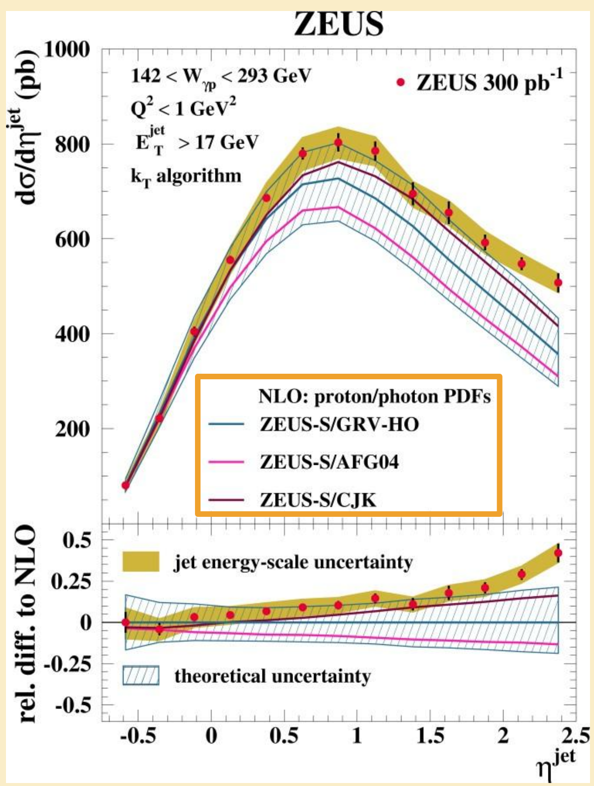

- Non-perturbative contribution increases the jet rate in the regions where discrepancies between data and NLO are observed
- Disagreement between data and NLO decreases when increasing $E_T{}^{jet}$ threshold to 21 GeV

- CJK (AFG04) gives higher (lower) prediction than GRV-HO at high η^{jet}

Inclusive-jet cross sections in PHP for k⊥, anti-k⊥ and SIScone

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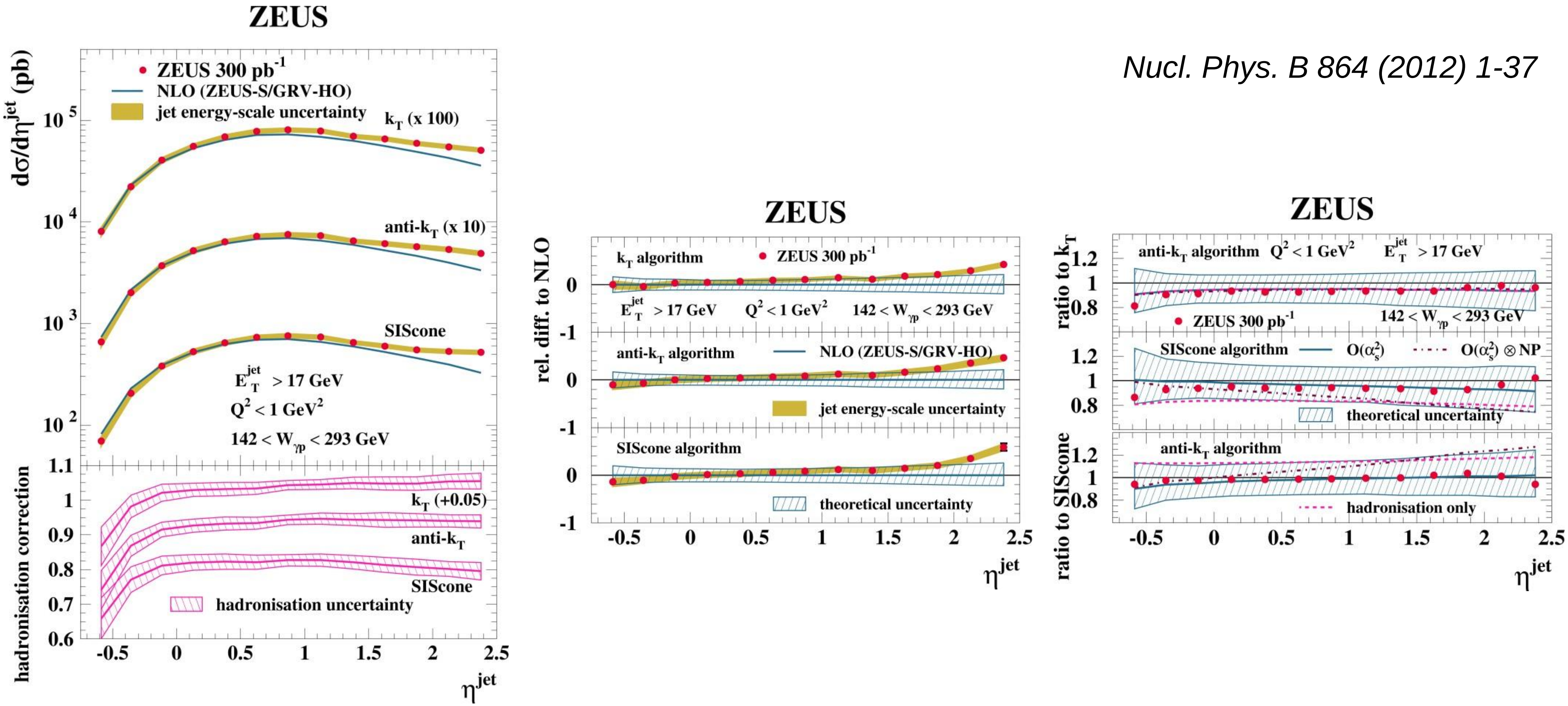


- Good description of data in shape and normalisation by NLO QCD
- Bigger hadronisation corrections for SIScone than anti-k⊥ (similar to k⊥)
- anti-k⊥ has same shape and is 6% smaller than k⊥
- SIScone has slightly different shape than k⊥ and anti-k⊥

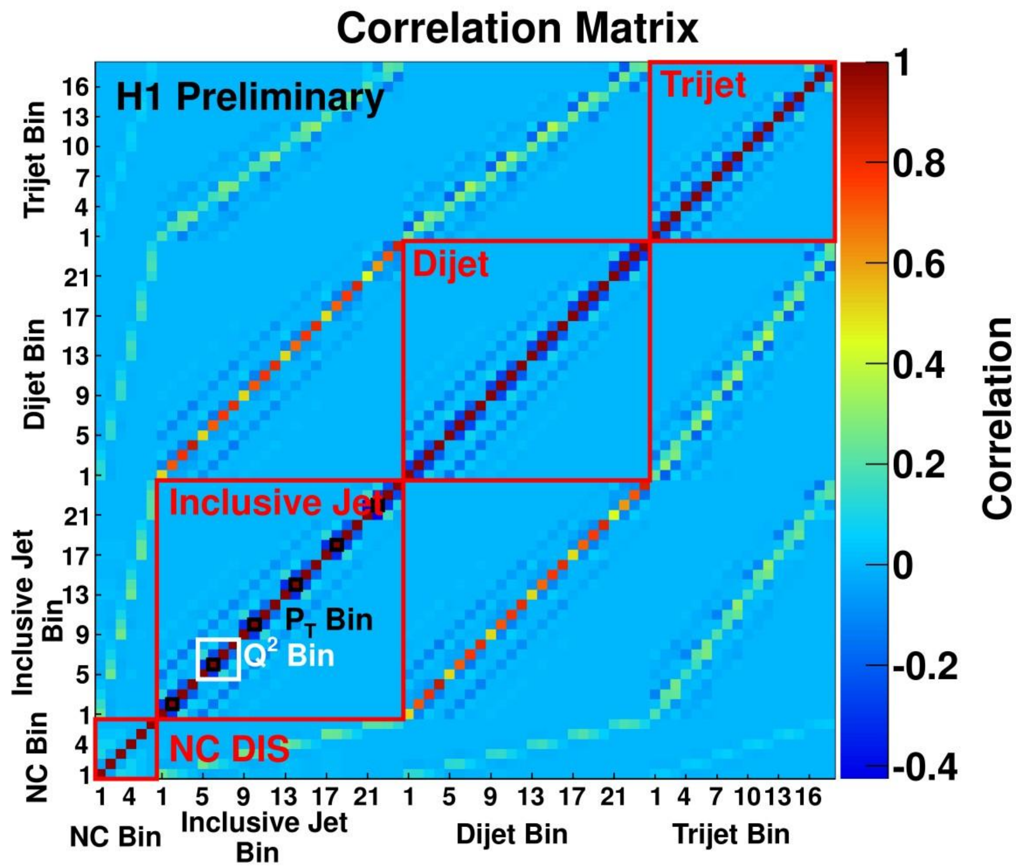
Correlation matrix for all four measurements

H1prelim-12-031

Covariance matrix
Obtained through linear error propagation of statistical uncertainties

Useful for
- Cross section ratios
- Combined fits
- Normalised cross sections

All three normalised jet measurements can be used together in a fit since the correlation matrix is known



Correlation matrix is employed for correct error propagation for norm. cross sections