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Jet physics at HERA

from
ZEUS Collab.
H1 Collab.

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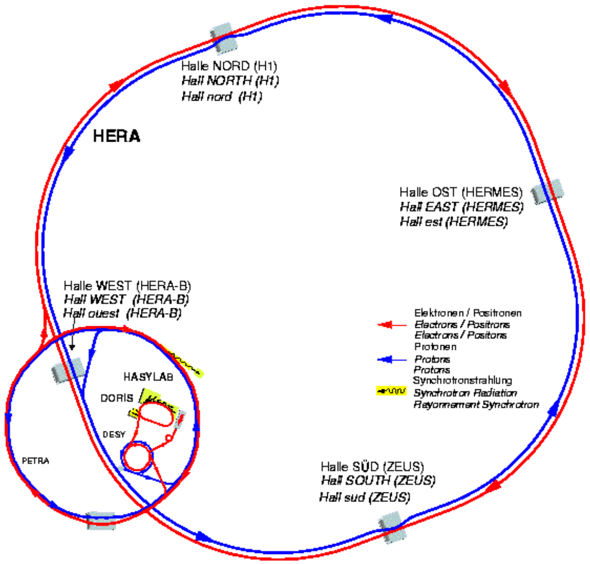
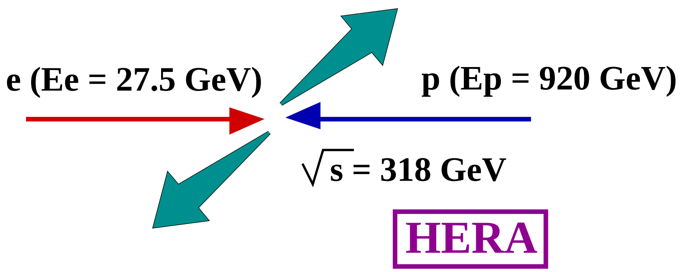


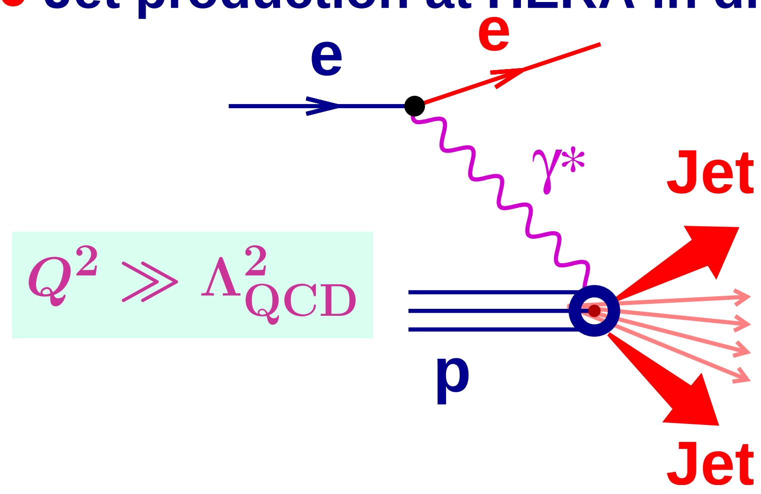


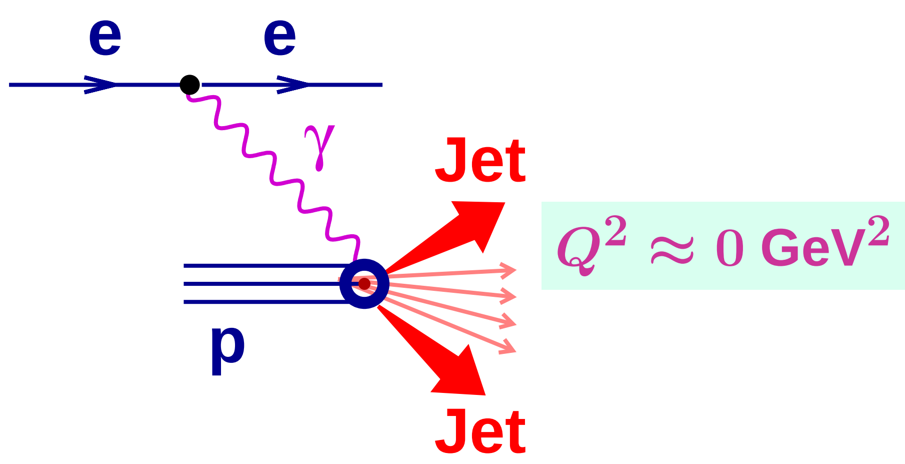
Jet physics at HERA

- ep collider HERA: very suitable environment to do precision studies of QCD
  - $\longrightarrow$ tests of QCD in hadronic-induced reactions (as opposed to e^+e^- at LEP)
  - $\longrightarrow$ but cleaner than $p\bar{p}$ at TeVatron or pp at LHC
- Jet physics at HERA
  - — tests of pQCD and precision measurements of QCD parameters (α_s)
  - — constraints on PDFs (especially, gluon density in the proton at medium to high x)

$\longrightarrow$ input to understand QCD background and make cross-section predictions at LHC

- Jet production at HERA in different kinematic regimes:





NC deep inelastic scattering (DIS)

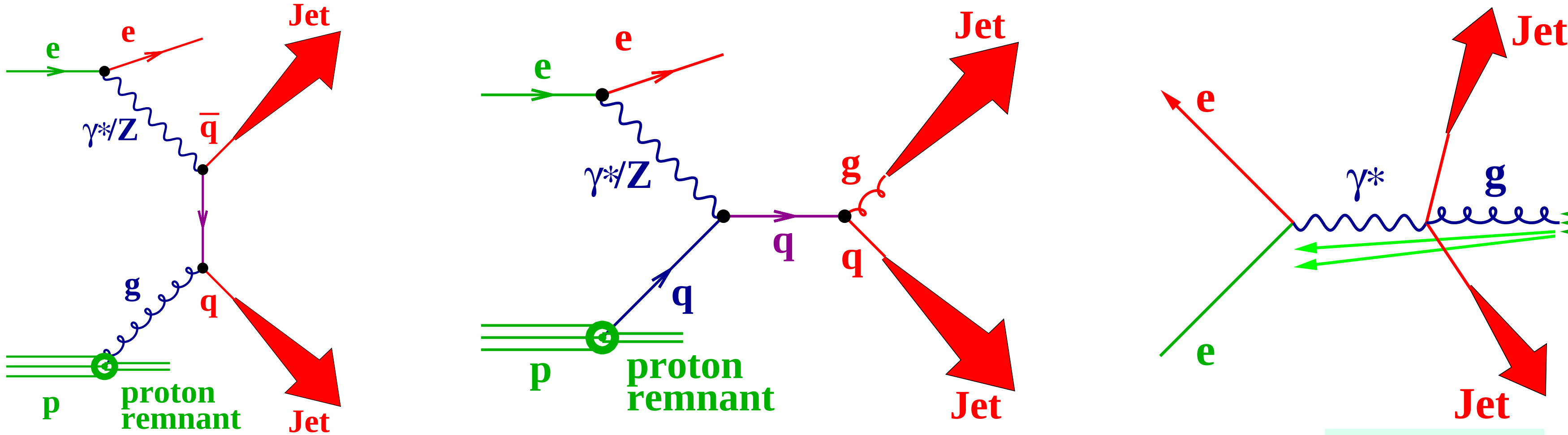
$$ep \longrightarrow e + \mathrm{Jet}\ (+\mathrm{Jets}) + X$$

Photoproduction (PHP)

$$ep \longrightarrow e + \mathrm{Jet}\ (+\mathrm{Jets}) + X$$

Jets in NC DIS at HERA

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



- Jet production cross section in NC DIS is given in pQCD by:

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

– f_a: parton a density, determined from experiment
  → long-distance structure of the target

– $\hat{\sigma}_a$: subprocess cross section, calculable in pQCD
  → short-distance structure of the interaction

Kinematics:

– momentum transfer: $Q^2 = -q^2 = -(k-k')^2$

– Bjorken x: $x = \frac{Q^2}{2P\cdot q}$

– inelasticity: $y = \frac{P\cdot q}{P\cdot k} = 1 - \frac{E'_e(1-\cos\theta_e)}{2E_e}$

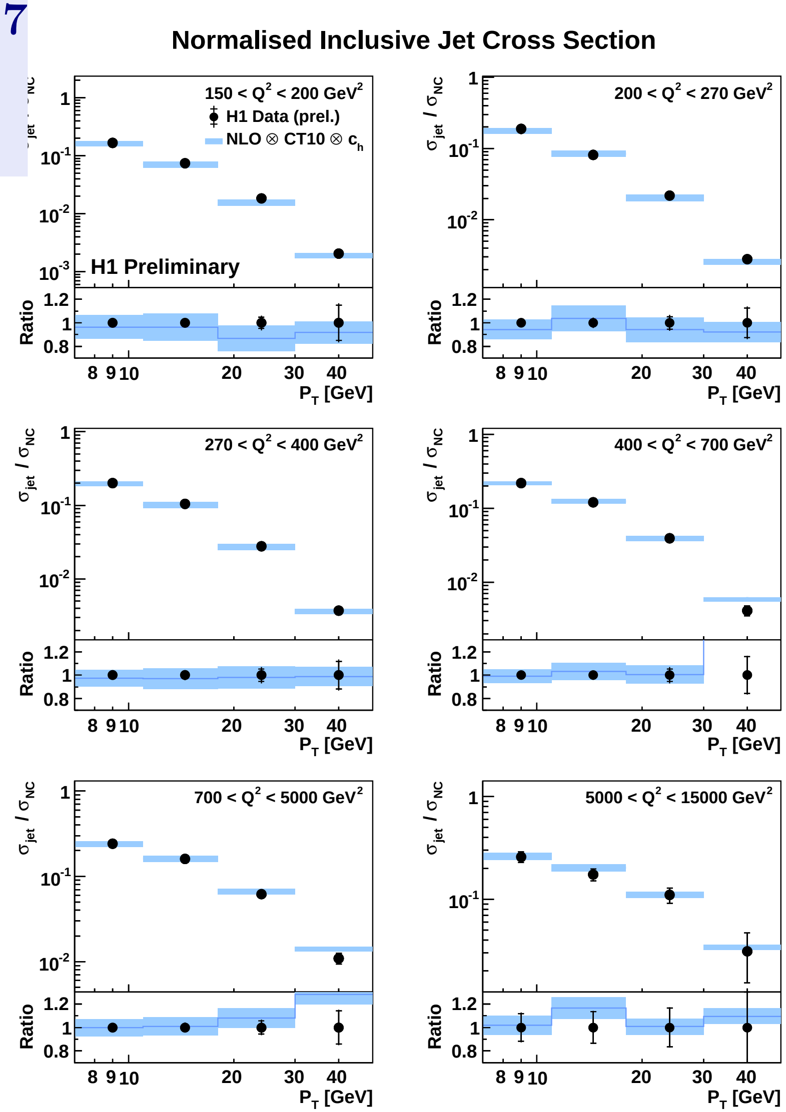
Jet cross sections in NC DIS

$ep \to e + \text{jet} + X$: **normalised inclusive-jet cross sections**

$\mathcal{L} = 0.36$ fb^{-1}

- **Kinematic region:** $150 < Q^2 < 15000$ GeV^2 and $0.2 < y < 0.7$
- **Jet search:** k_T cluster algorithm in Breit frame
- **Jets with** $7 < P_T^{\text{jet}} < 50$ GeV and $-1 < \eta_{\text{LAB}}^{\text{jet}} < 2.5$ selected
- Jet cross sections normalised to inclusive NC DIS cross section in each Q^2 region
- **Comparison to NLO predictions:**
  - $\longrightarrow$ calculations using NLOJET++ and QCDNUM
  - $\longrightarrow$ good description of data by NLO prediction
    - $\longrightarrow$ validity of the description of the dynamics of jet production in NC DIS at $\mathcal{O}(\alpha_s^2)$
- **Theoretical uncertainties:**
  - $\longrightarrow$ higher orders

$\longrightarrow$ Measurements provide **direct** sensitivity to $\alpha_s(M_Z)$



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Jet cross sections in NC DIS

- Correction for detector effects was performed using the multidimensional regularised unfolding (MRU) method: $\vec{m} = A \cdot \vec{x}$

$\vec{m}$: measured distribution (detector level), A: migration matrix describing detector response,
$\vec{x}$: true distribution (particle level)

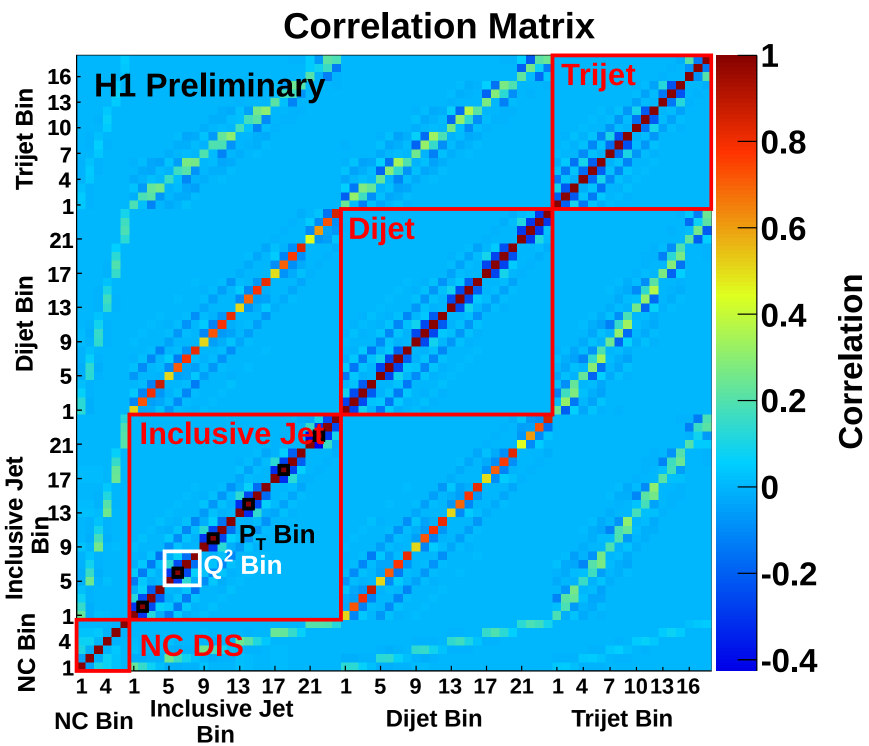
- Find particle level x by analytic minimisation of χ^2 as function of x

$$\chi^2(\vec{x}) = \frac{1}{2}(\vec{m} - A\vec{x})^T V^{-1}(\vec{m} - A\vec{x}) + \tau^2 \cdot L$$

τ: regularisation parameter, L: regularisation condition,
V: covariance matrix

- The MRU method takes into account correlations and migrations when unfolding
  - $\longrightarrow$ different bins within a given distribution
  - $\longrightarrow$ simultaneously different measurements

- The MRU method especially suited when
  - $\longrightarrow$ measuring normalised cross sections
  - $\longrightarrow$ performing combined fits to all jet data



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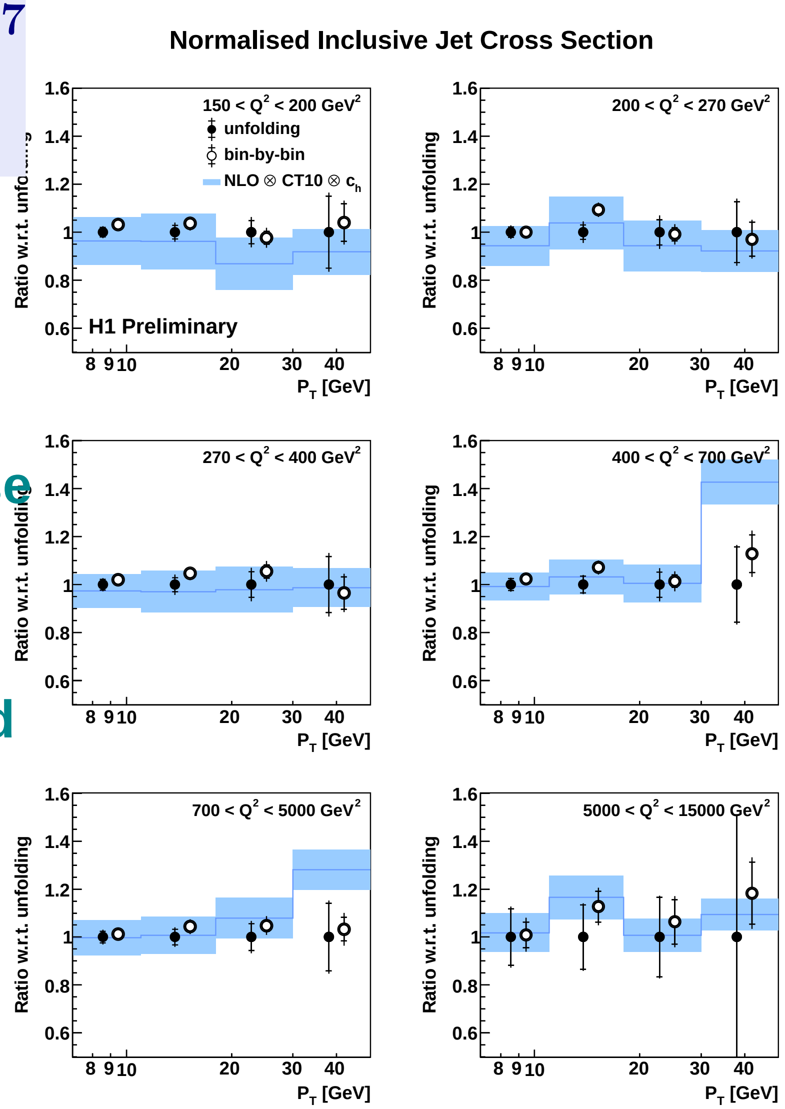
Jet cross sections in NC DIS

$\mathcal{L} = 0.36\ \text{fb}^{-1}$

$ep \rightarrow e + \text{jet} + X$: **normalised inclusive-jet cross sections**

- Kinematic region: $150 < Q^2 < 15000$ GeV^2 and $0.2 < y < 0.7$
- Jet search: k_T cluster algorithm in Breit frame
- Jets with $7 < P_T^{\text{jet}} < 50$ GeV and $-1 < \eta_{\text{LAB}}^{\text{jet}} < 2.5$ selected
- Jet cross sections normalised to inclusive NC DIS cross section in each Q^2 region



- **Comparison of bin-by-bin and MRU results:**
  - $\longrightarrow$ bin-by-bin results tend to be higher than those from MRU method, but within uncertainties
  - $\longrightarrow$ full knowledge of correlations in MRU results
  - $\longrightarrow$ possibility to apply error propagation coupled with correlations in MRU (not possible to do correlation of errors in bin-by-bin method)
  - $\longrightarrow$ smaller model bias in MRU results

$\Rightarrow$ **MRU method provides more reliable and less model-dependent results**

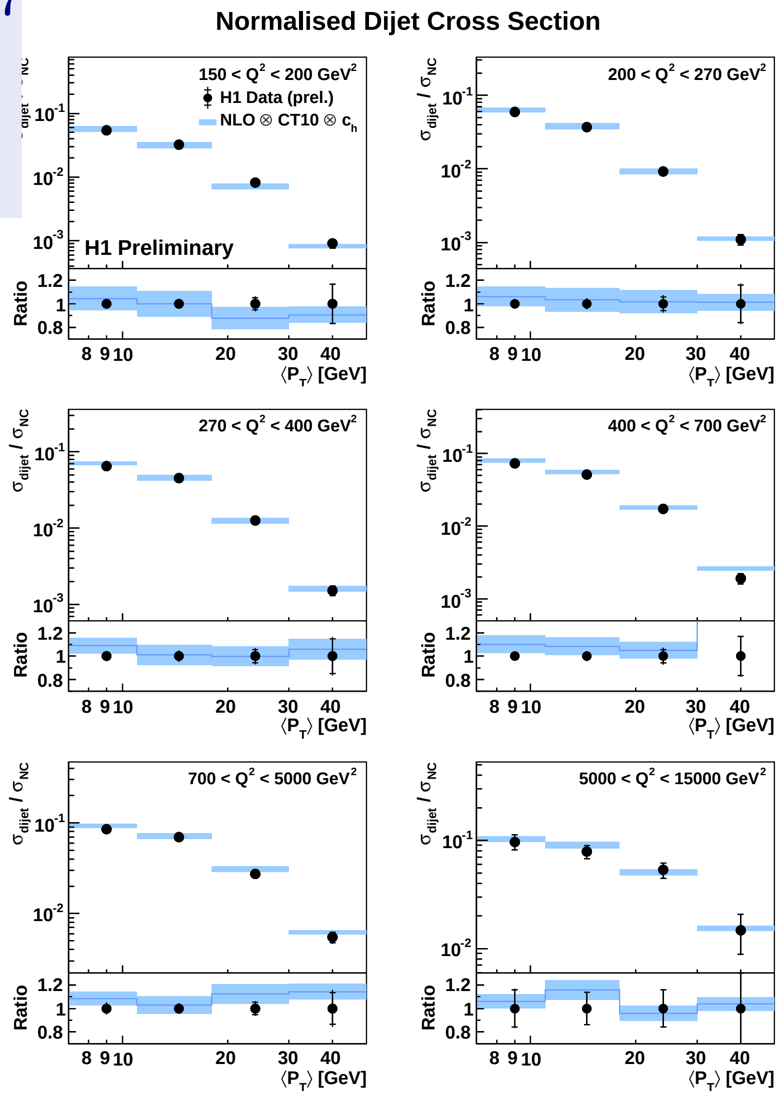
H1 Collab, H1prelim-12-031

Jet cross sections in NC DIS

$ep \to e + 2\text{jets} + X$: **normalised dijet cross sections**

$\mathcal{L} = 0.36$ fb^{-1}

- Kinematic region: $150 < Q^2 < 15000$ GeV^2 and $0.2 < y < 0.7$
- Jet search: k_T cluster algorithm in Breit frame
- Two jets with $5 < P_T^{\text{jet}} < 50$ GeV and $-1 < \eta_{\text{LAB}}^{\text{jet}} < 2.5$
- $M^{\text{jj}} > 16$ GeV



- **Comparison to NLO predictions:**
  - $\longrightarrow$ calculations using NLOJET++ and QCDNUM
  - $\longrightarrow$ the measured dijet cross sections are well described by the NLO predictions
- **Processes initiated by gluons expected to have a large contribution in this kinematic range**
  - $\longrightarrow$ measurements can provide further constraints to gluon density in proton
  - $\longrightarrow$ theoretical uncertainty dominated by terms beyond NLO
    - $\longrightarrow$ NNLO predictions needed to take full advantage of high-precision data

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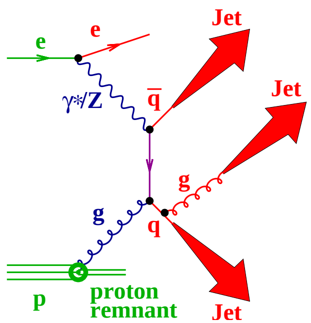
Jet cross sections in NC DIS

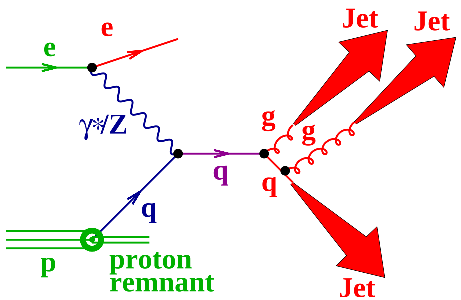
$ep \to e + 3\text{jets} + X$: normalised trijet cross sections

$\mathcal{L} = 0.36\ \text{fb}^{-1}$

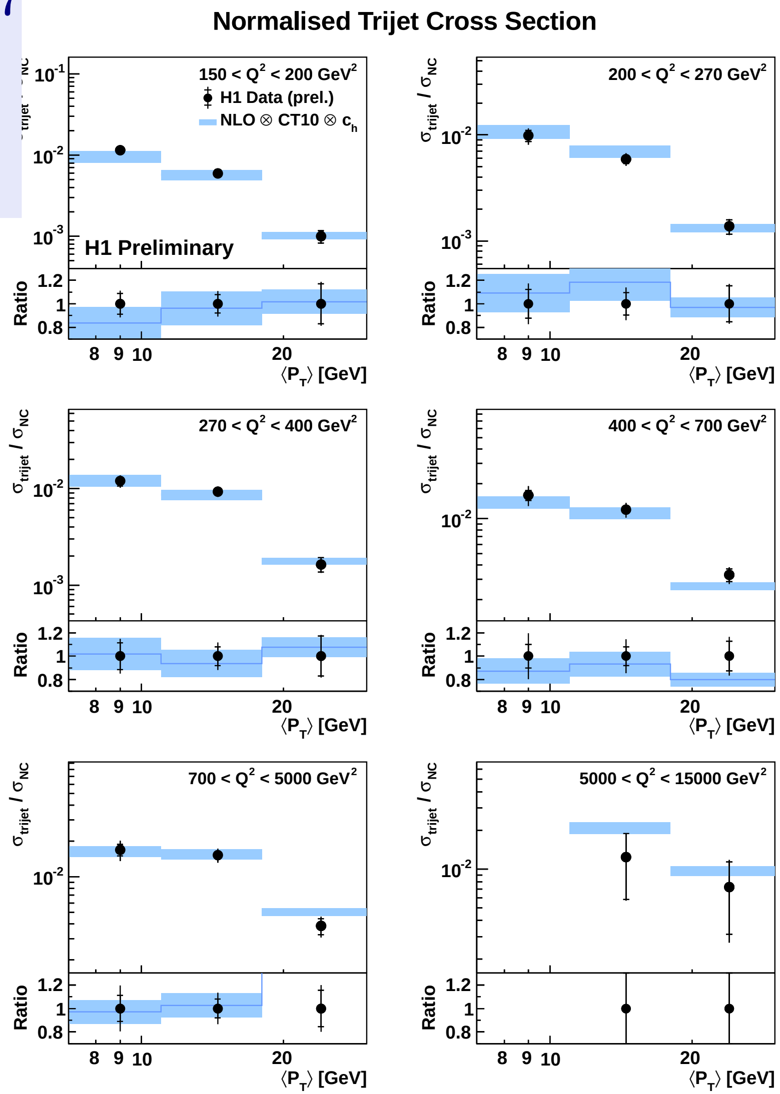
- Kinematic region: $150 < Q^2 < 15000$ GeV^2 and $0.2 < y < 0.7$
- Jet search: k_T cluster algorithm in Breit frame
- Three jets with $5 < P_T^{\text{jet}} < 50$ GeV and $-1 < \eta_{\text{LAB}}^{\text{jet}} < 2.5$
- $M^{\text{jj}} > 16$ GeV

- Three-jet events provide tests of QCD directly beyond LO: $\sigma_{3\text{jet}} \propto \alpha_s^2$ at lowest order
- Three-jet production at $\mathcal{O}(\alpha_s^2)$:





- Comparison to NLO predictions ($\mathcal{O}(\alpha_s^3)$):
  $\longrightarrow$ the measured trijet cross sections are well described by the NLO predictions



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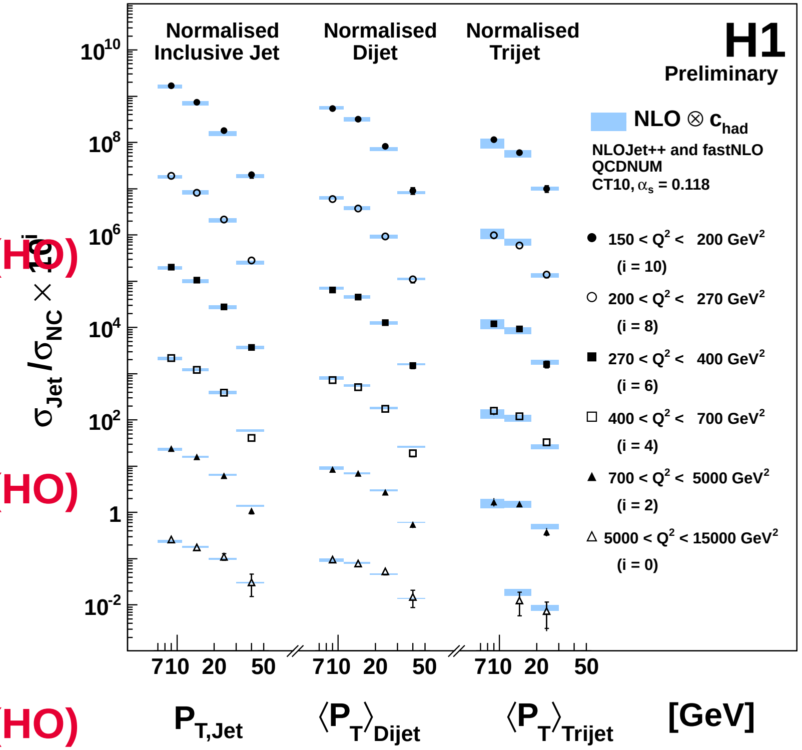
Tests of pQCD: determination of α_s

- Values of $\alpha_s(M_Z)$ were extracted from the measured normalised cross sections using the Hessian method



- Normalised inclusive-jet cross sections:

$$\alpha_s(M_Z) = 0.1197 \pm 0.0008\ (\text{exp}) \pm 0.0056\ (\text{th})$$

uncert: $\pm 0.7\%$ (exp), $\pm 1.2\%$ (PDFs), $\pm 0.9\%$ (hadr), $\pm 4.4\%$ (HO)

- Normalised dijet cross sections:

$$\alpha_s(M_Z) = 0.1142 \pm 0.0010\ (\text{exp}) \pm 0.0051\ (\text{th})$$

uncert: $\pm 0.9\%$ (exp), $\pm 1.4\%$ (PDFs), $\pm 0.8\%$ (hadr), $\pm 4.2\%$ (HO)

- Normalised trijet cross sections:

$$\alpha_s(M_Z) = 0.1185 \pm 0.0018\ (\text{exp}) \pm 0.0047\ (\text{th})$$

uncert: $\pm 1.5\%$ (exp), $\pm 1.1\%$ (PDFs), $\pm 1.4\%$ (hadr), $\pm 3.5\%$ (HO)

★ Simultaneous fit to cross-section measurements in region of phase space with NLO corrections below $\pm 30\%$ to avoid tension between inclusive-jet and dijet data: 42 points out of 65 kept

$$\alpha_s(M_Z) = 0.1163 \pm 0.0011\ (\text{exp}) \pm 0.0042\ (\text{th})$$

uncertainties: $\pm 0.9\%$ (exp), $\pm 1.2\%$ (PDFs), $\pm 0.7\%$ (hadr), $\pm 3.4\%$ (HO), $\pm 3.8\%$ (total)

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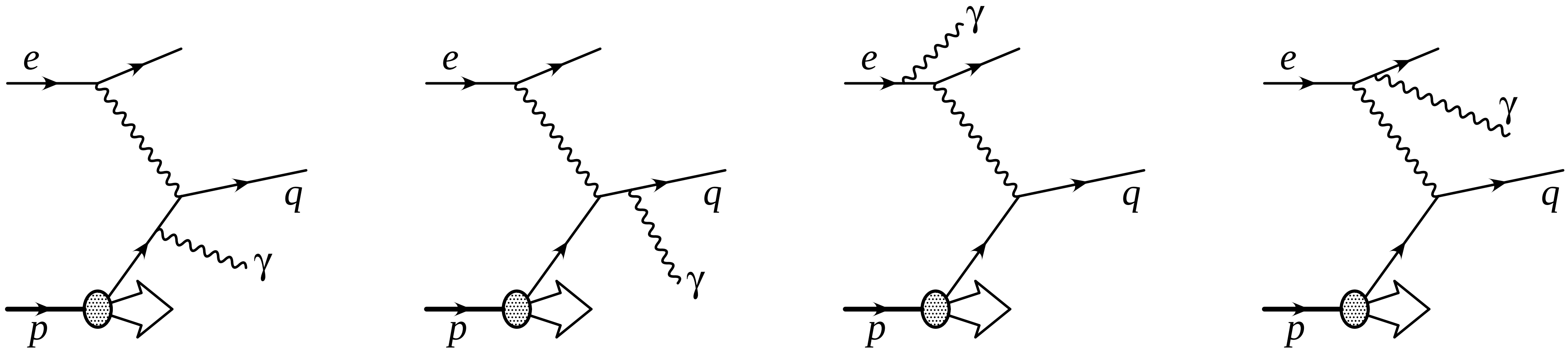
Isolated-photon plus jet in NC DIS at HERA

- **Isolated-photon production in NC DIS at $\mathcal{O}(\alpha^3)$:**



photon radiated from quark line (QQ) **photon radiated from lepton line (LL)**

- **Isolated-photon plus jet production**
  - $\longrightarrow$ direct probe of underlying partonic process less affected by hadronisation than pure jet production
  - $\longrightarrow$ QQ contribution provides stringent test of pQCD in a kinematic region with two hard scales: Q and $E_T^{\rm jet}$
  - $\longrightarrow$ measurements sensitive to underlying dynamics mediated by quark exchange
  - $\longrightarrow$ more detailed test of pQCD compared to inclusive-photon measurements
  - $\longrightarrow$ smaller background than in inclusive-photon measurements

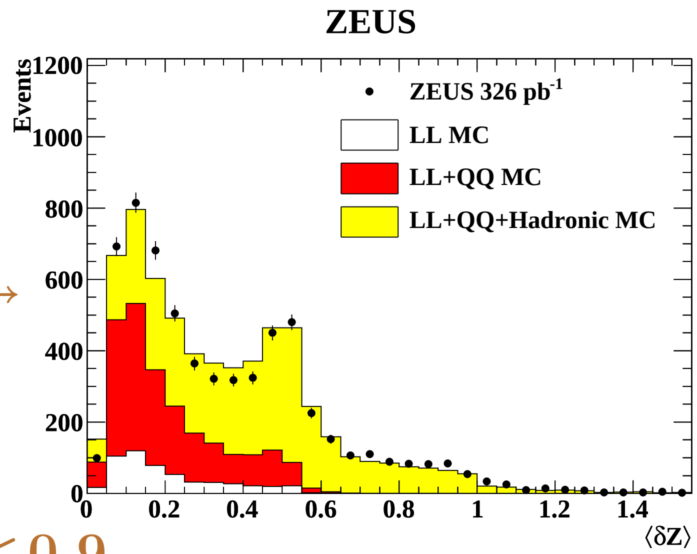
Isolated-photon plus jet in NC DIS at HERA

$ep \to e + \gamma + \text{jet} + X$: isolated-photon plus jet cross sections

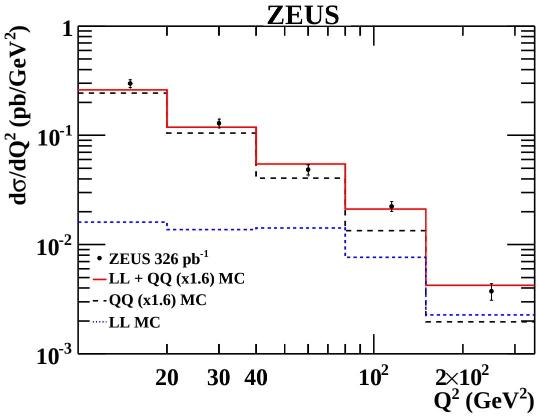
$\mathcal{L} = 0.33$ fb^{-1}

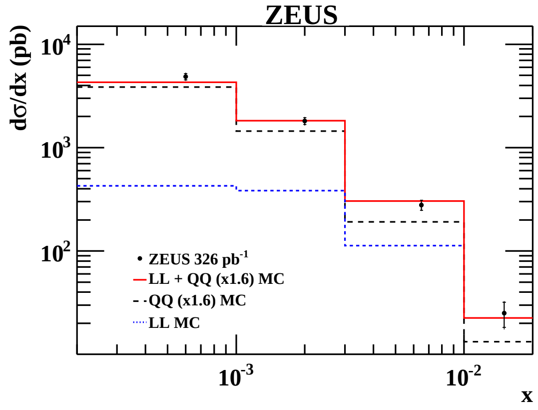
- Jet search: k_T cluster algorithm in Laboratory frame
- At least one jet with $E_T^{\text{jet}} > 2.5$ GeV and $-1.5 < \eta^{\text{jet}} < 1.8$
- Kinematic region: $10 < Q^2 < 350$ GeV^2, $E_e > 10$ GeV and $\theta_e > 140°$

- Photon identification: shower shapes ($\langle \delta Z \rangle < 0.8$)
  lateral width of EM energy-cluster associated to γ candidate $\to$



- Photon isolation: $\to$ no track within $\Delta R = 0.2$ of γ
  $\to \frac{E^{\gamma}}{E^{\text{jet containing } \gamma}} > 0.9$
- Photon selection: $4 < E_T^{\gamma} < 15$ GeV and $-0.7 < \eta^{\gamma} < 0.9$
- Experimental uncertainties:
  - $\to$ E_e scale uncertainty ($\pm 2\%$): $< \pm 5\%$
  - $\to$ E^{γ} scale uncertainty ($\pm 2\%$): $< \pm 5\%$
  - $\to$ jet energy scale uncertainty ($\pm 4, 2.5, 1.5\%$): $\pm 2 - 10\%$
  - $\to$ photon identification: typically $\pm 5\%$





$\to$ **Good description of data by LL+QQ(x1.6) Monte Carlo predictions**

ZEUS Collab, DESY-12-089

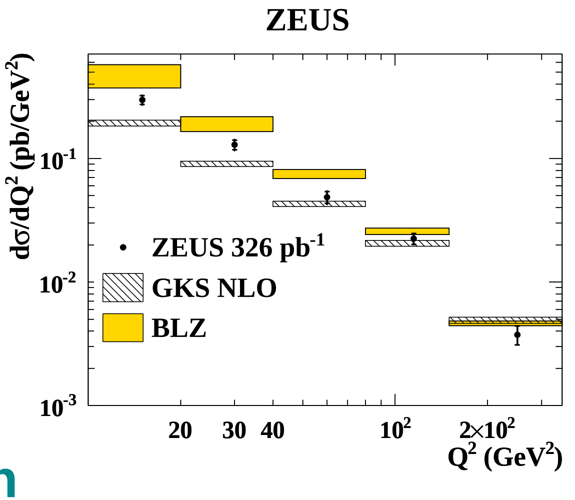
Tests of pQCD: comparison to theoretical calculations

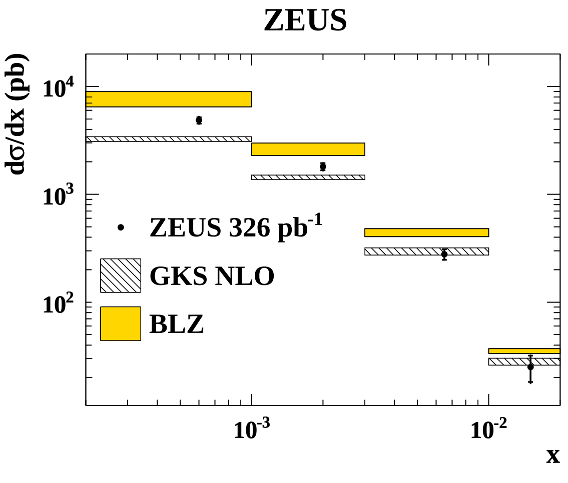
$ep \to e + \gamma + \text{jet} + X$: isolated-photon plus jet cross sections $\mathcal{L} = 0.33$ fb^{-1}

- Theoretical predictions:
  - $\longrightarrow$ A Gehrmann-De Ridder, G Kramer and H Spiesberger (GKS)
    - LO(α^3) and NLO($\alpha^3\alpha_s$) calculations with QQ (including photon from jet fragmentation), LL and interference (LQ, very small for isolated photons) terms
    - uncertainties of NLO calculations: $^{+4.3}_{-5.2}\%$ (integrated cross section) rising to $\pm 10\%$ for $\eta^{\rm jet} < 0$ from higher orders; $< \pm 5\%$ from pPDFs
  - $\longrightarrow$ SP Baranov, AV Lipatov and NP Zotov (BLZ)
    - k_T factorisation method with LL and QQ terms and using unintegrated PDFs
      $\longrightarrow$ quark-radiated contribution enhanced wrt LO collinear approximation
    - uncertainties: 20%, due to procedure of selecting jets in the evolution cascade

$\longrightarrow$ GKS calculations describe shape of measurements but underestimate rise at low Q^2 and low x

$\longrightarrow$ BLZ calculations describe shape of measurements but the predicted overall rate is too high





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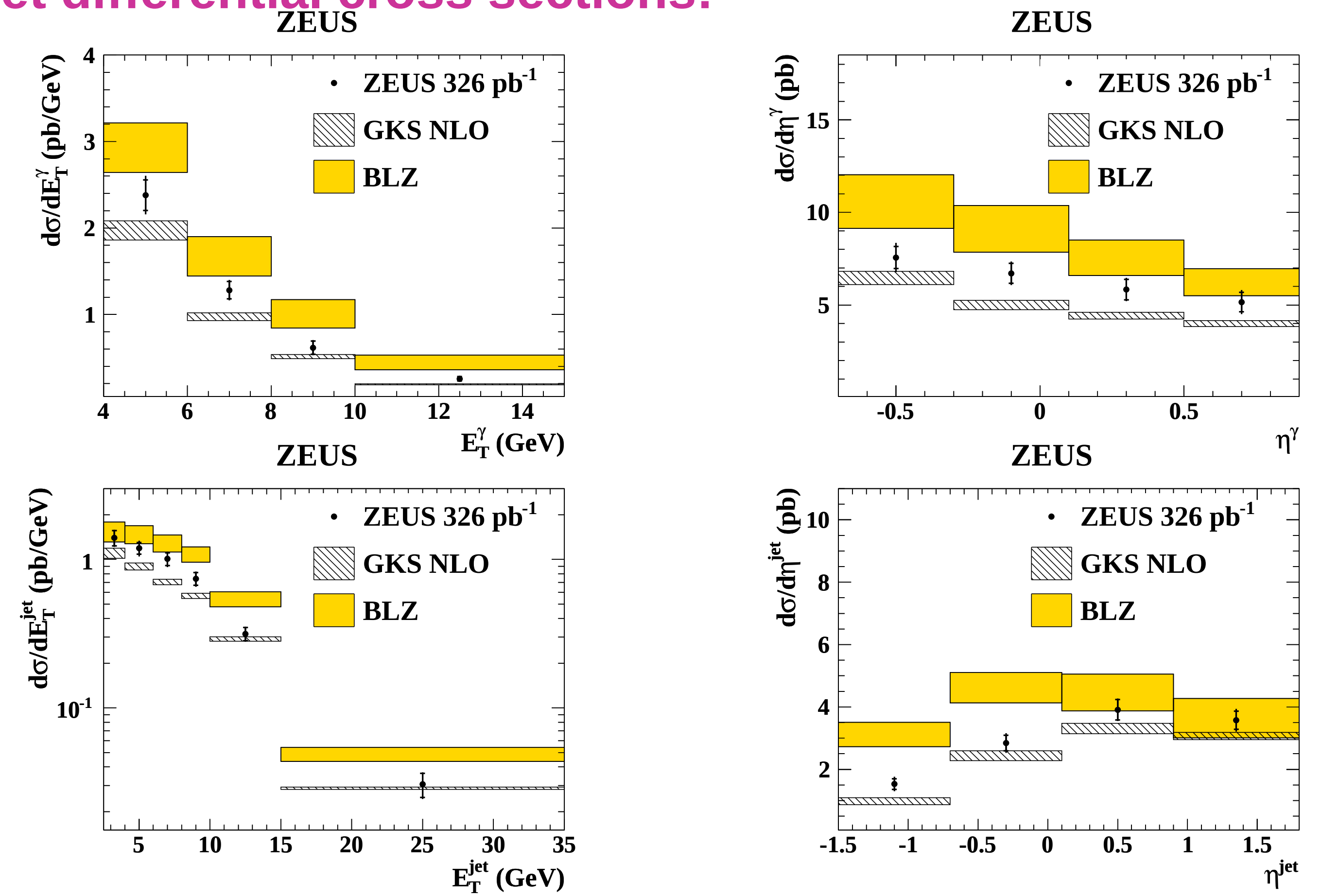
Tests of pQCD: comparison to theoretical calculations

$ep \rightarrow e + \gamma + \text{jet} + X$: **isolated-photon plus jet cross sections** $\mathcal{L} = 0.33$ fb^{-1}

- **Photon and jet differential cross sections:**



→ **Both calculations describe the shape of the measurements, but GKS (BLZ) calculations underestimate (overestimate) the normalisation**

→ **an improved theoretical description of $\gamma + \text{jet}$ production is needed**

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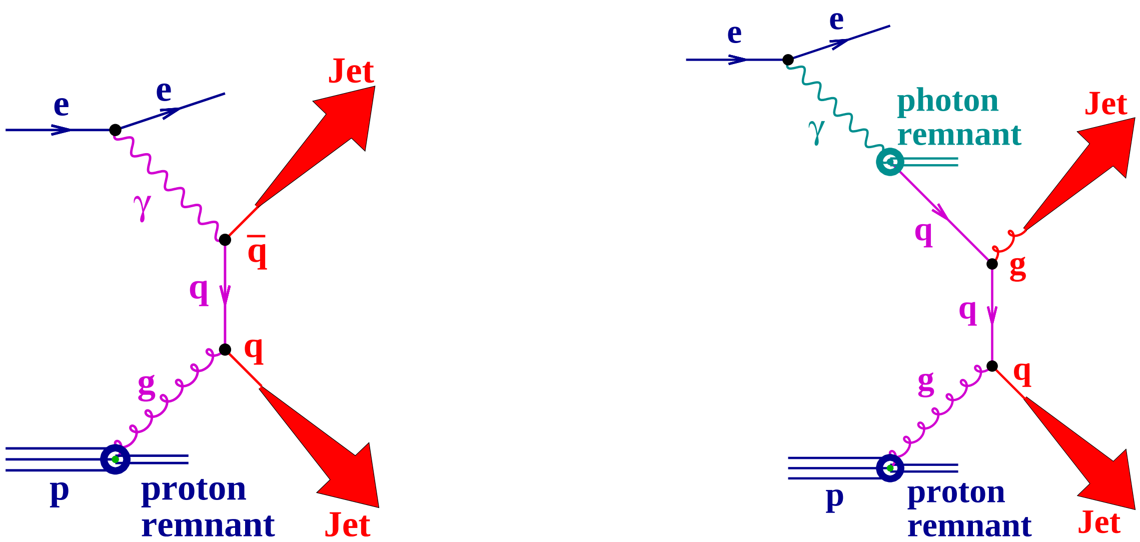
Jets in PHP at HERA

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

$Q^2 \approx 0$: γ virtuality
W: γp cms energy
y: inelasticity
$x_{\gamma(p)}$: parton momentum fraction from $\gamma(p)$



direct photoproduction **resolved photoproduction**

- **Jet production cross section in photoproduction is given in pQCD by:**

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

$\longrightarrow$ **Measurements of jet cross sections in photoproduction allow tests of:**

structure of the photon **pQCD** **structure of the proton**

and determination of α_s

Jet algorithms

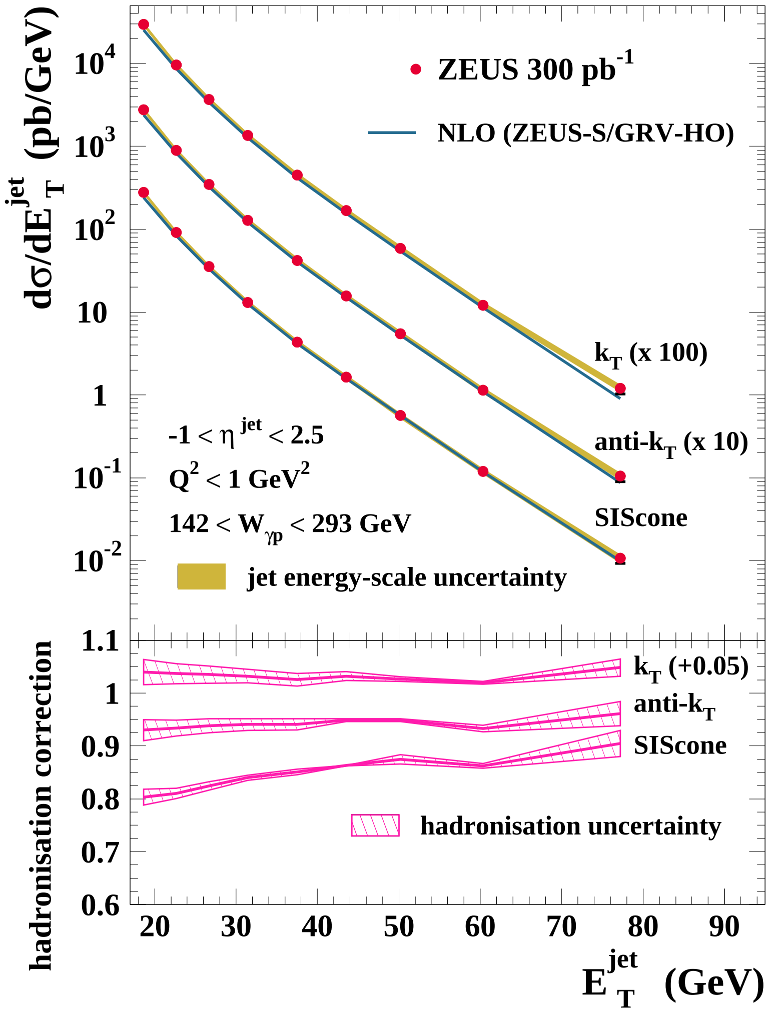
- Tests of pQCD with jets require infrared- and collinear-safe jet algorithms:
  - → performance of k_T cluster algorithm in longitudinally invariant inclusive mode (S Catani, S Ellis & D Soper) tested extensively at HERA:
  - → stringent tests of pQCD: good description of data for different jet radii
  - → good performance of algorithm: small theoretical uncertainties / hadronisation corrections
  - → new measurements in photoproduction presented here
- New infrared- and collinear-safe jet algorithms:
  - → anti-k_T (M Cacciari, G Salam & G Soyez) provides ≈ circular jets
    - ⋆ experimentally desirable
  - → SIScone (G Salam & G Soyez) seedless cone algorithm provides infrared- and collinear-safe calculations
    - ⋆ theoretically necessary
- New studies at HERA:
  - → test performance of anti-k_T and SIScone in well-understood hadron-induced reaction:
    - ∗ comparison to measurements based on k_T
    - ∗ comparison of measurements and NLO QCD calculations
    - ∗ study of theoretical uncertainties and hadronisation corrections

Jet cross sections in PHP

$ep \rightarrow e + \text{jet} + X$: inclusive-jet cross sections

- Kinematic region: $Q^2 < 1$ GeV^2 and $0.2 < y < 0.85$
- Jet search: k_T, anti-k_T and SIScone in laboratory frame
- At least one jet with $E_T^{\text{jet}} > 17$ GeV and $-1 < \eta^{\text{jet}} < 2.5$

$\mathcal{L} = 0.3$ fb^{-1}



- Experimental uncertainties:
  - $\rightarrow$ systematic: typically below $\pm 5\%$
  - $\rightarrow$ energy scale $\pm 1\%$ (!): $\sim \pm 5\ (10)\%$ at low (high) E_T^{jet}
- Comparison to NLO predictions (Klasen et al):
  - $\rightarrow$ good description of data by NLO prediction
    - $\rightarrow$ validity of the description of the dynamics of jet photoproduction at $\mathcal{O}(\alpha_s^2)$
- Theoretical uncertainties:
  - $\rightarrow$ higher orders: $\pm 10\ (4)\%$ at low (high) E_T^{jet} (k_T/anti-k_T)
    $\pm 14\ (7)\%$ at low (high) E_T^{jet} (SIScone)
  - $\rightarrow$ proton PDFs: $\pm 1\ (5)\%$ at low (high) E_T^{jet}
  - $\rightarrow$ hadronisation: $< \pm 3\%$; $\alpha_s(M_Z)$: $< \pm 2\%$
  - $\rightarrow$ photon PDFs: $\pm 9 - 10\ (1 - 3)\%$ at low (high) E_T^{jet}

$\rightarrow$ Measurements provide direct sensitivity to α_s and gluon density with small experimental and theoretical uncertainties

ZEUS Collab, DESY-12-045

Jet cross sections in PHP

$ep \rightarrow e + \text{jet} + X$: inclusive-jet cross sections

$\mathcal{L} = 0.3$ fb^{-1}

- Kinematic region: $Q^2 < 1$ GeV^2 and $0.2 < y < 0.85$
- Jet search: k_T, anti-k_T and SIScone in laboratory frame
- At least one jet with $E_T^{\text{jet}} > 17$ GeV and $-1 < \eta^{\text{jet}} < 2.5$

- **Experimental uncertainties:**
  - $\rightarrow$ systematic: typically below $\pm 5\%$
  - $\rightarrow$ energy scale $\pm 1\%$ (!): $\sim \pm 5\ (10)\%$ at low (high) E_T^{jet}
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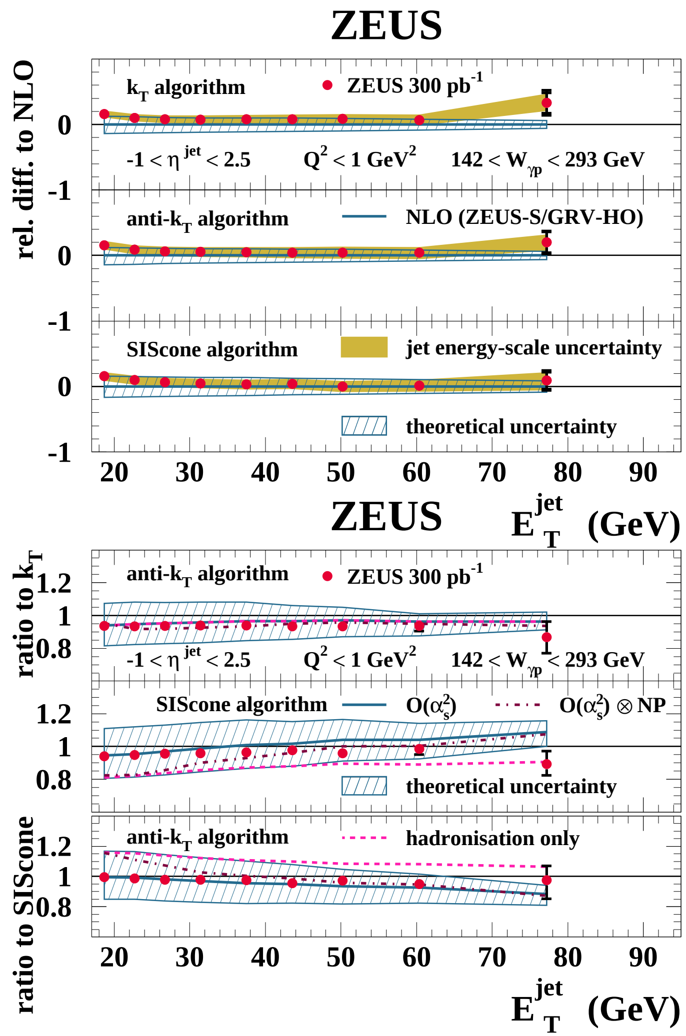


$\rightarrow$ Measurements provide direct sensitivity to α_s and gluon density with small experimental and theoretical uncertainties

ZEUS Collab, DESY-12-045

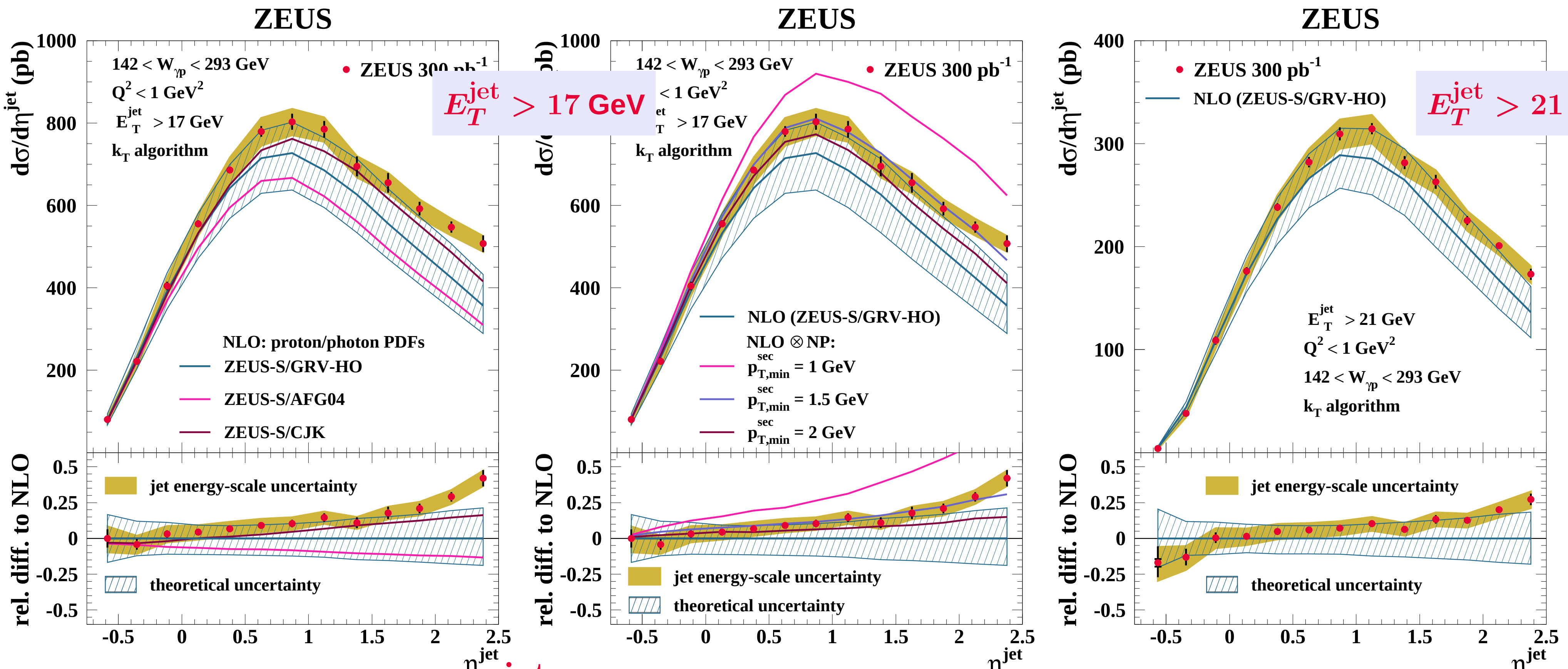
Jet cross sections in PHP

$ep \rightarrow e + \text{jet} + X$: inclusive-jet cross sections

$\mathcal{L} = 0.3$ fb^{-1}

$E_T^{jet} > 17$ GeV

$E_T^{jet} > 21$ GeV



- Discrepancies at high η^{jet} might be due to γPDFs or non-perturbative effects
  - $\rightarrow$ γPDFs: AFG04 (CJK) gives lower (higher) prediction than GRV-HO at high η^{jet}
  - $\rightarrow$ non-perturbative effects: jet rate increases at high η^{jet}
  - $\rightarrow$ disagreement between data and NLO disappears when increasing E_T^{jet}

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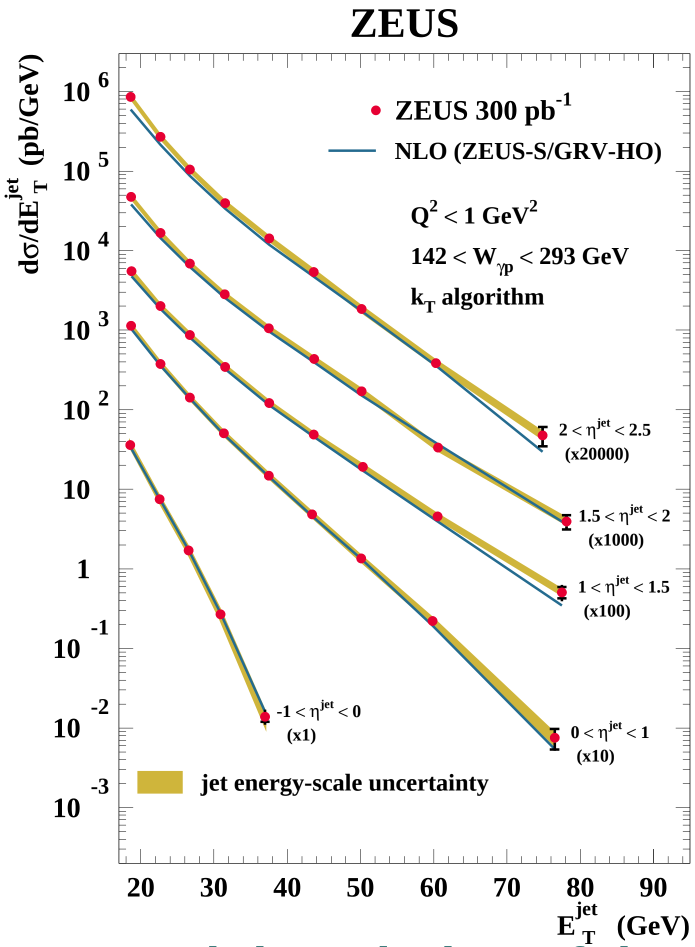
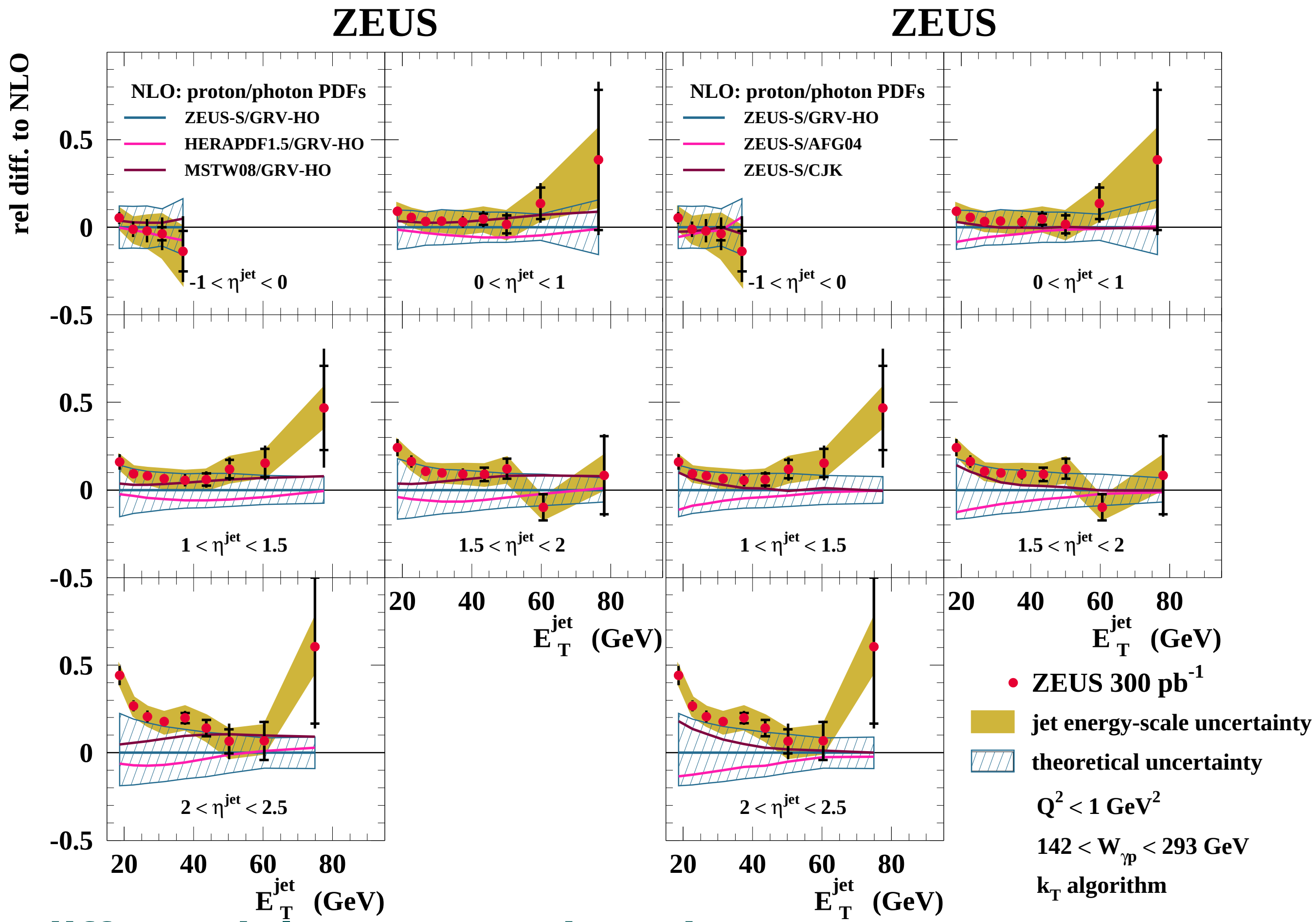
Jet cross sections in PHP

$ep \rightarrow e + \text{jet} + X$: inclusive-jet cross sections

$\mathcal{L} = 0.3\ \text{fb}^{-1}$





→ **Good description of double-differential cross sections by NLO QCD, except at low E_T^{jet} and high η^{jet}**

→ **Sensitivity to proton (high E_T^{jet}/low η^{jet}) and photon (low E_T^{jet}/high η^{jet}) PDFs**

ZEUS Collab, DESY-12-045

Tests of pQCD: determination of α_s

- The energy-scale dependence of the coupling was determined from the data $\longrightarrow$ results in good agreement with predicted running of α_s over a wide range in $E_T^{\rm jet}$
- Values of $\alpha_s(M_Z)$ were extracted from the measured cross sections for $21 < E_T^{\rm jet} < 71$ GeV:

anti-k_T:

$$\alpha_s(M_Z) = 0.1198^{+0.0023}_{-0.0022}\,(\text{exp})^{+0.0041}_{-0.0034}\,(\text{th})$$

uncert: $^{+1.9}_{-1.8}\%$ (exp), $\pm1.0\%$ (pPDFs), $\pm0.4\%$ (hadr), $^{+2.3}_{-2.4}\%$ (HO), $^{+2.2}_{-0.9}\%$ (γPDFs), $^{+3.9}_{-3.4}\%$ (total)

SIScone:

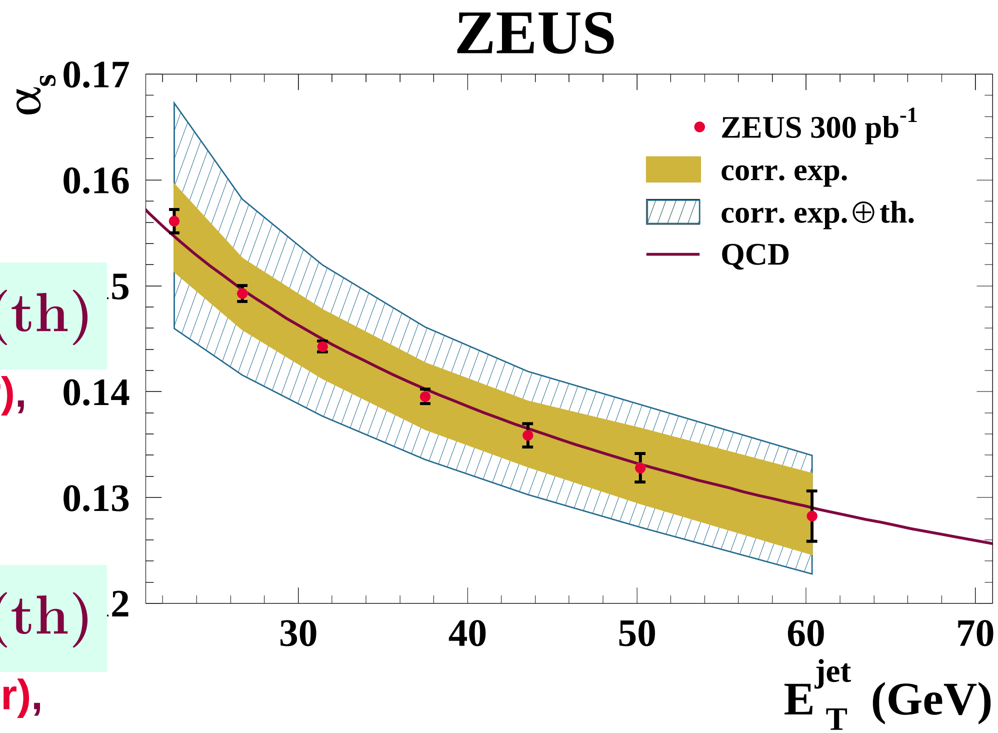
$$\alpha_s(M_Z) = 0.1196^{+0.0022}_{-0.0021}\,(\text{exp})^{+0.0046}_{-0.0043}\,(\text{th})$$

uncert: $\pm1.8\%$ (exp), $\pm1.0\%$ (pPDFs), $\pm0.2\%$ (hadr), $^{+3.2}_{-3.3}\%$ (HO), $^{+1.9}_{-0.9}\%$ (γPDFs), $^{+4.3}_{-4.0}\%$ (total)

k_T:

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

uncert: $^{+1.9}_{-1.8}\%$ (exp), $\pm1.0\%$ (pPDFs), $\pm0.4\%$ (hadr), $^{+2.4}_{-2.5}\%$ (HO), $^{+2.3}_{-0.9}\%$ (γPDFs), $^{+4.0}_{-3.4}\%$ (total)



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

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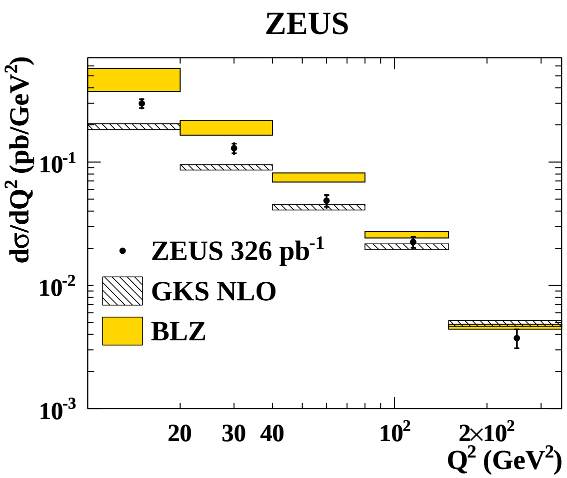
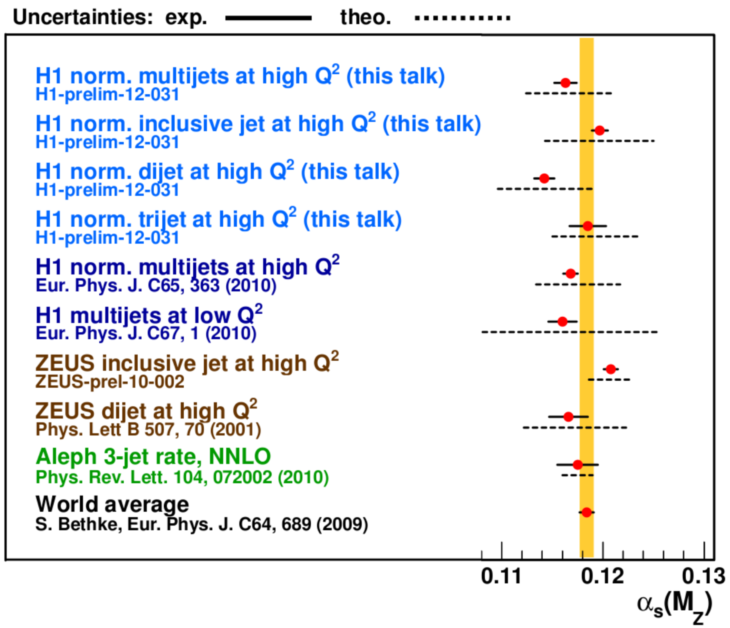
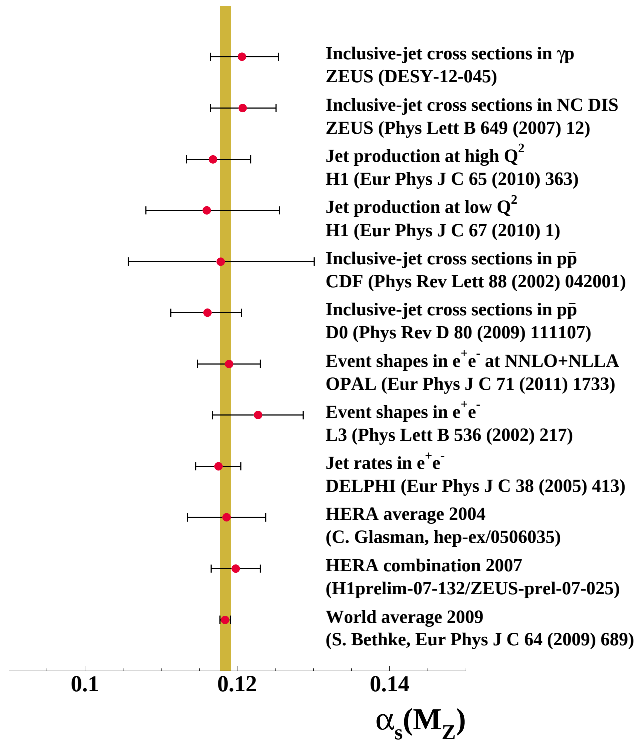
Conclusions

- **Jet physics at HERA continues providing precision measurements towards understanding QCD and improving the determination of the p/γPDFs**
  - $\longrightarrow$ **precise new jet measurements will help to constrain further the p/γPDFs**
  - $\longrightarrow$ **precise tests of the performance of new jet algorithms**
  - $\longrightarrow$ **precise values of $\alpha_s(M_Z)$ extracted from jet production in different regimes**
  - $\longrightarrow$ **precise determination of the running of α_s over a wide range of the scale**
  - $\longrightarrow$ **precise measurements of isolated-photon plus jet cross sections will help to improve the theoretical description**



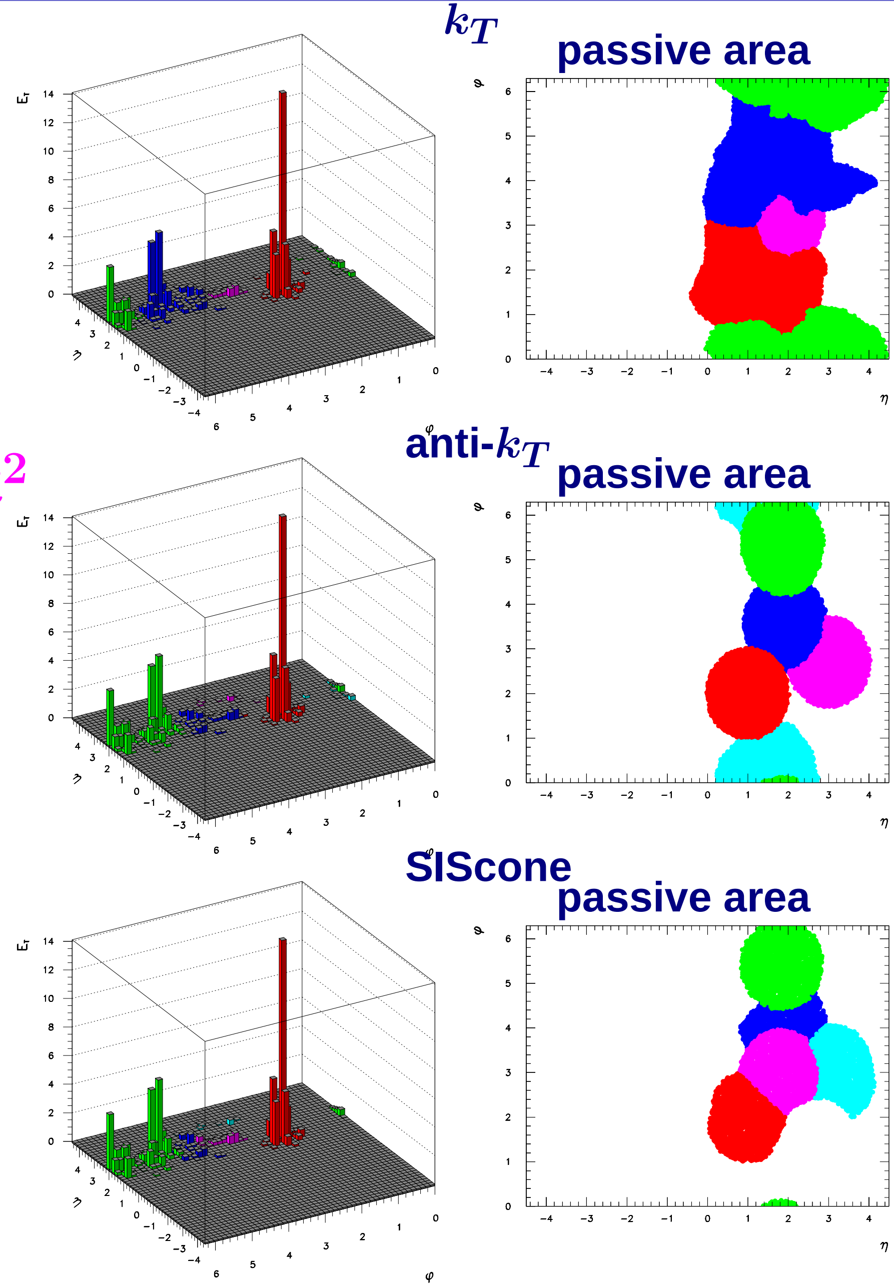




Back-up slides

k_T vs anti-k_T vs SIScone

- New infrared- and collinear-safe jet algorithms:
  - → anti-k_T (M Cacciari, G Salam & G Soyez) and SIScone (G Salam & G Soyez)
- Cluster algorithms:
  - → $d_{ij} = \min[(E^i_{T,\mathrm{B}})^{2p}, (E^j_{T,\mathrm{B}})^{2p}] \cdot \Delta R^2/R^2$ with $p = 1$ (-1) for k_T (anti-k_T)
  - → anti-k_T keeps infrared and collinear safety and provides ≈ circular jets (experimentally desirable)
- Cone algorithms:
  - → seedless cone algorithm produces also jets with well-defined area and is infrared and collinear safe (theoretically necessary)



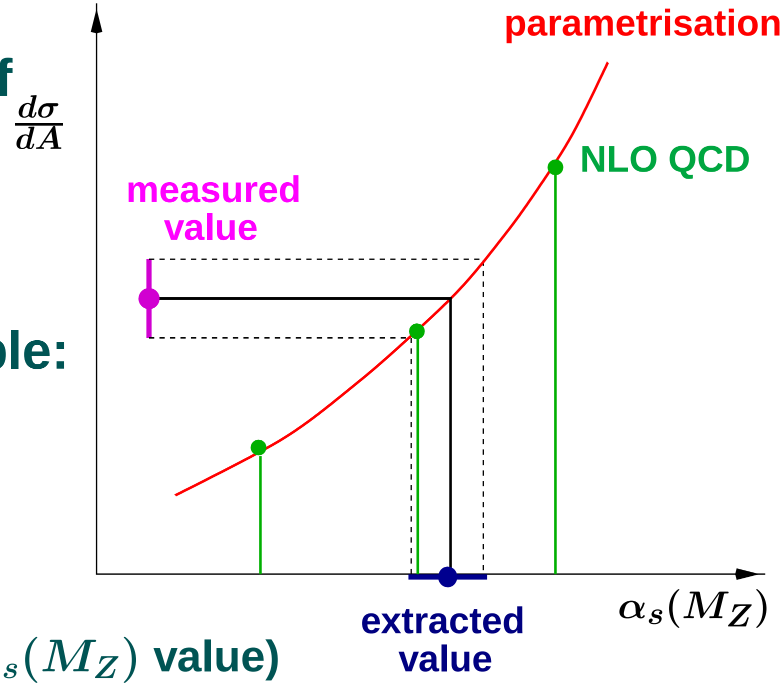
The method to determine α_s from jet observables

- The procedure to determine α_s from jet observables used by ZEUS is based on the α_s dependence of the pQCD calculations, taking into account the correlation with the PDFs:
  - perform NLO calculations using different sets of proton PDFs
  - use as input in each calculation the value of $\alpha_s(M_Z)$ assumed in each PDF set
  - parametrise the α_s dependence of the observable:

$$A^i(\alpha_s(M_Z)) = A_1^i\,\alpha_s(M_Z) + A_2^i\,\alpha_s(M_Z)^2$$

  - determine $\alpha_s(M_Z)$ from the measured value using the NLO parametrisation

    (MINUIT is used to determine $A_j^i,\ j = 1, 2$ and the final $\alpha_s(M_Z)$ value)



- This procedure handles correctly the complete α_s-dependence of the NLO calculations (explicit dependence in the partonic cross section and implicit dependence from the PDFs) in the fit, while preserving the correlation between α_s and the PDFs

The method to determine α_s from jet observables

NLO calculations depend on PDF and α_s

- Keep PDF fixed and determine $\alpha_s(M_Z)$

Jet cross sections

- NLOJET++, FastNLO v2.0
- $\mu_r^2 = (Q^2 + E_T^2)/2$
- $\mu_f^2 = Q^2$

NC-DIS cross sections

- QCDNUM
- $\mu_f^2 = \mu_r^2 = Q^2$

NLO × Had. corrections

PDF: CT10

Hessian Method

- Minimise χ^2
- TMinuit
- Comparable to Eur. Phys. J. C65, 363

$$\chi^2(\alpha_s, \varepsilon_k) = \vec{\tilde{\sigma}}^T \cdot V^{-1} \cdot \vec{\tilde{\sigma}} + \sum_k^{SysErr} \varepsilon_k^2$$

$$\vec{\tilde{\sigma}}_i = \sigma_i^{Data} - \sigma_i^{Theo}(\alpha_s, f(\alpha_{s,fix})) \cdot \left(1 - \sum_k^{SysErr} \Delta_{i,k}(\varepsilon_k)\right)$$

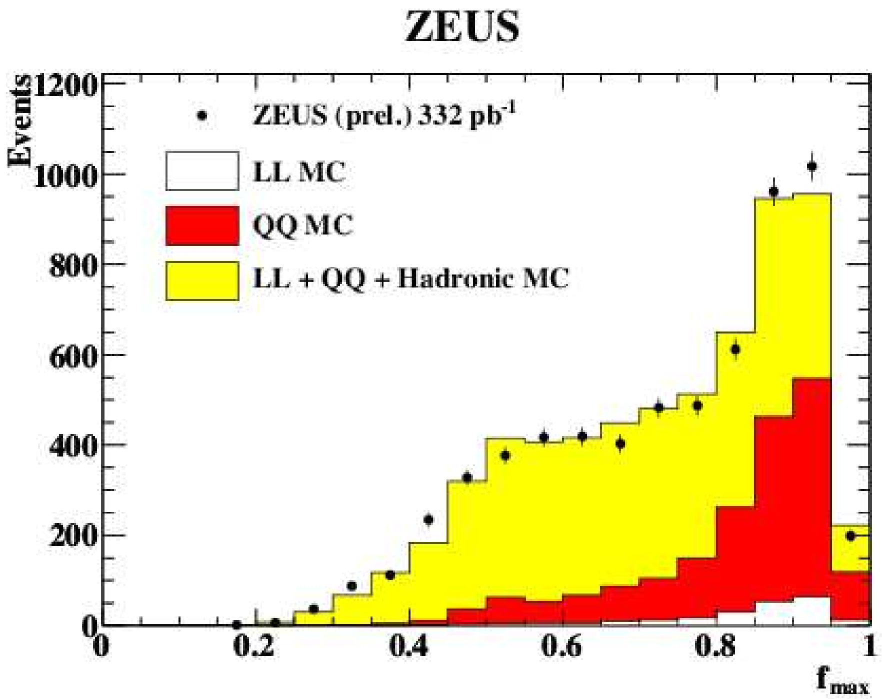
Usage of full covariance matrix V from unfolding

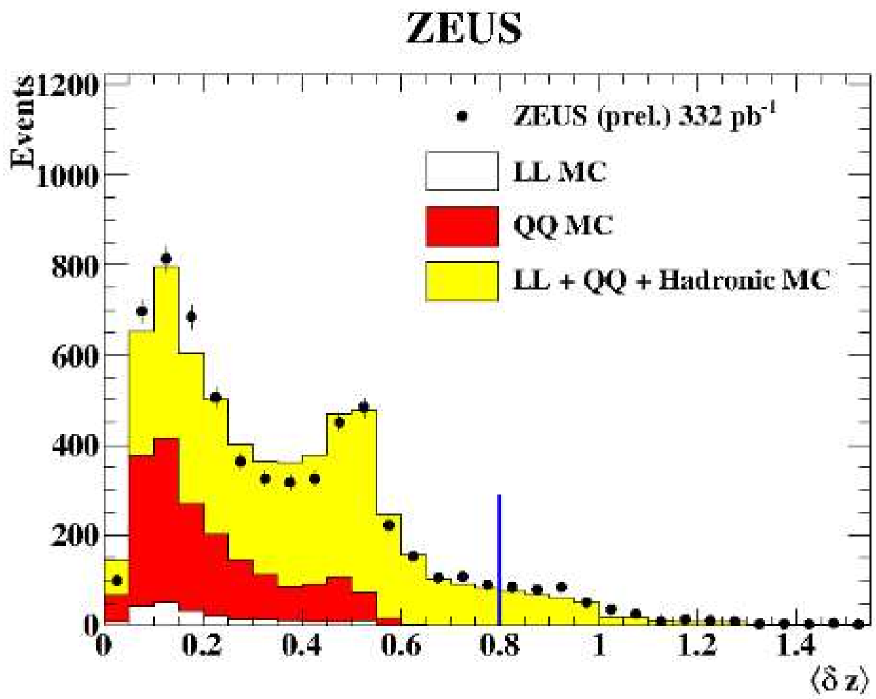
- All correlations are respected in fit

Systematic errors as penalty terms

Extraction of isolated-photon signal

Following variables are using to describe the shower shape:



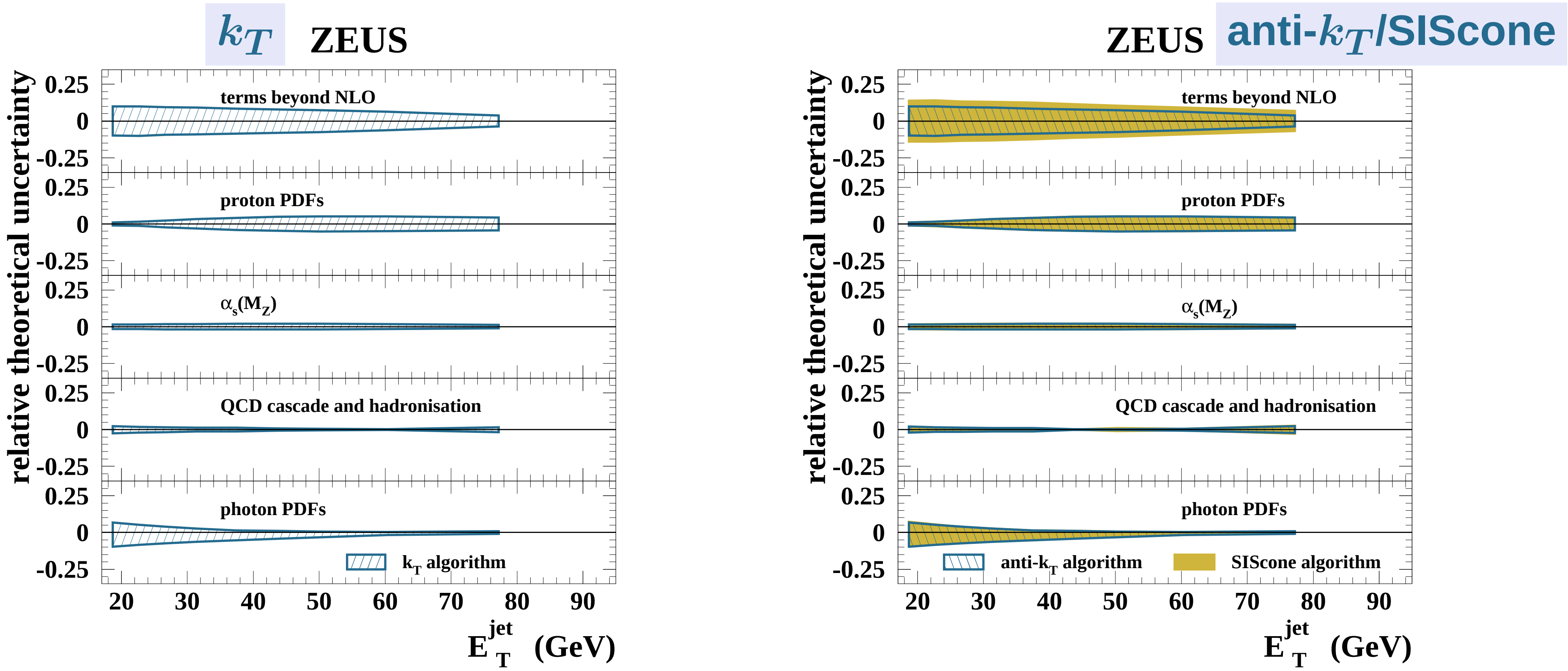


$$f_{max} = \frac{\text{Energy in the most energetic BEMC cell}}{\text{Total energy of the cluster}} \qquad \langle \delta z \rangle = \frac{\Sigma |z_i - z_{cluster}| \cdot E_i}{l_{cell} \Sigma \mathrm{E_i}}$$

→ mixture of different type Monte Carlo events is used to fit the data distribution
→ $\langle \delta z \rangle$ variable is used for the signal extraction, because it carries more information

Tests of pQCD: jet algorithms

- **Theoretical uncertainties:**
  - $\longrightarrow$ PDFs and $\alpha_s(M_Z)$:
    - $\longrightarrow$ very similar for all three jet algorithms
  - $\longrightarrow$ terms beyond NLO and QCD cascade/hadronisation modelling:
    - $\longrightarrow$ very similar for k_T and anti-k_T; somewhat larger for SIScone



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Tests of pQCD: jet algorithms

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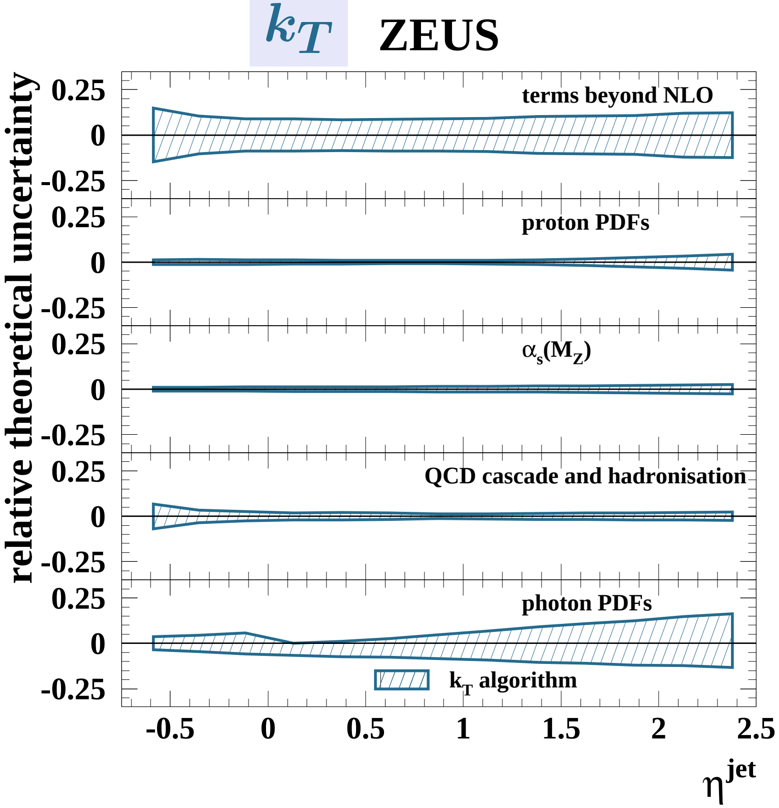
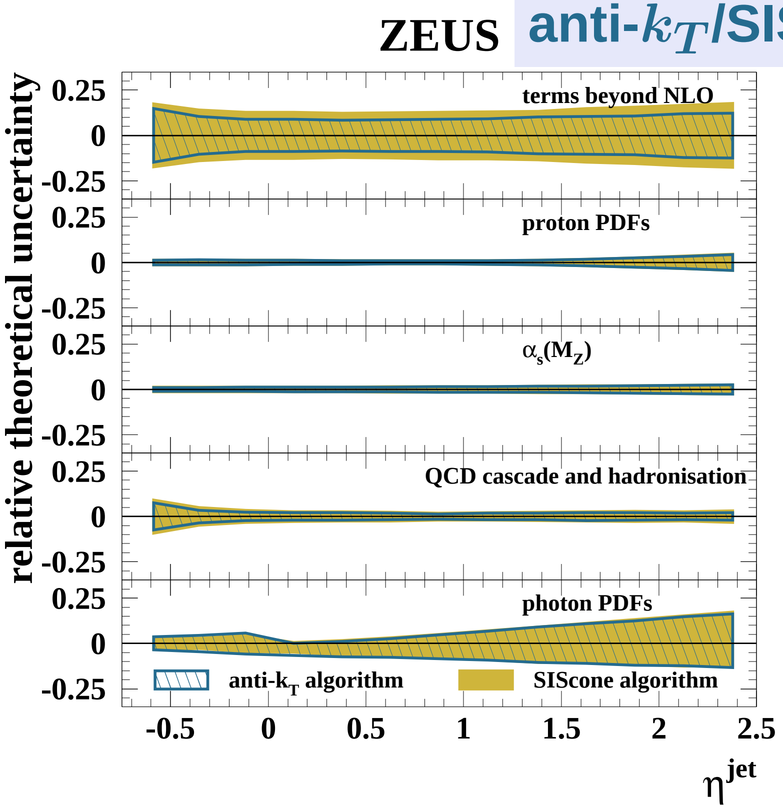
k_T



anti-k_T/SIScone



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