Jet Production at HERA with ZEUS

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Outline:

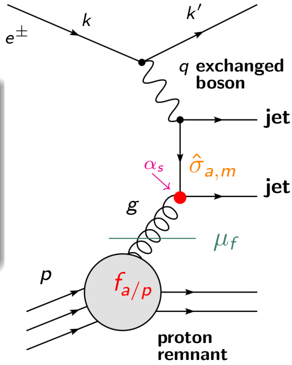
1. Jet Production at HERA
2. Inclusive Jets and Dijets in Photoproduction
3. Inclusive Jets and Dijets in Deep-Inelastic Scattering
4. Extraction of the Strong Coupling α_s
5. Summary

Jets at HERA: Deep-Inelastic Scattering

$\rightarrow$ deep inelastic scattering (**DIS**) $\rightarrow Q^2 > \Lambda^2_{\mathrm{QCD}}$

Kinematics:

- centre-of-mass energy: $\sqrt{s} = 318\ \mathrm{GeV}$
- momentum transfer: $Q^2 = -q^2 = -(k - k')^2$
- Bjorken x: $x = \frac{Q^2}{2p \cdot q}$
- inelasticity: $y = \frac{Q^2}{s \cdot x}$



Jet cross section in pQCD: Series expansion in powers of α_s

$$\sigma_{\mathrm{jet}} = \sum_m \alpha_s{}^m(\mu_R) \sum_{a=q,\bar{q},g} f_{a/p}(x, \mu_F) \otimes \hat{\sigma}_{a,m}(x, \mu_R, \mu_F) \ldots$$

Coefficients are convolutions of:

$\Rightarrow$ parton distribution functions (PDFs): $f_{a/p} \leftarrow$ long-distance structure (proton)

$\Rightarrow$ lepton-parton cross section: $\hat{\sigma} \leftarrow$ short-distance structure of the interaction

Jets at HERA: Photoproduction

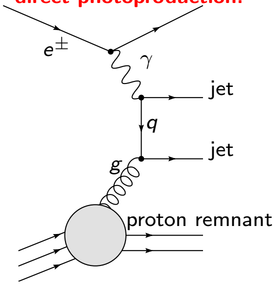
→ photoproduction (γp) → $Q^2 \approx 0\ \mathrm{GeV}^2$

In lowest order two types of processes:

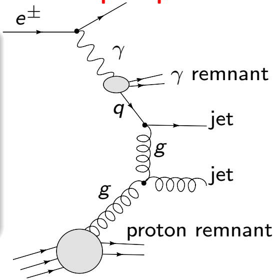
1. direct process: photon interacts directly with parton
2. resolved process: photon acts as source of partons
   ↪ final state closer to that encountered in hadron-hadron collisions

- jet cross section in pQCD incorporates photon structure function

direct photoproduction:



resolved photoproduction:



Observables (used in this talk):

- momentum fraction carried by gluon: $\xi = x_{Bj}\left(1 + \frac{M_{jj}^2}{Q^2}\right)$
- CMS scattering angle: θ^*
- transverse energy and invariant mass: E_T^{jet}, M_{jj}
- pseudorapidity: $\eta_{\mathrm{lab}}^{\mathrm{jet}}$

Inclusive Jet Production in PHP (1/2)

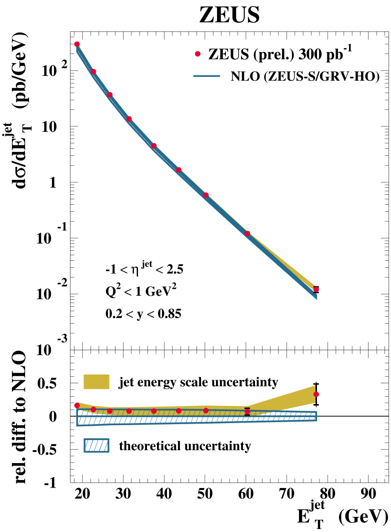
- at least one jet with in the range $-1 < \eta^{\text{jet}} < 2.5$ with $E_T^{\text{jet}} > 17$ GeV

Experimental Uncertainties:

- uncorrelated: mostly $< 4\%$
- correlated (jet energy scale):
  - uncertainty $\pm 1\%$
  - $\approx \pm 5 - 10\%$ effect on cross section

Theoretical Uncertainties:

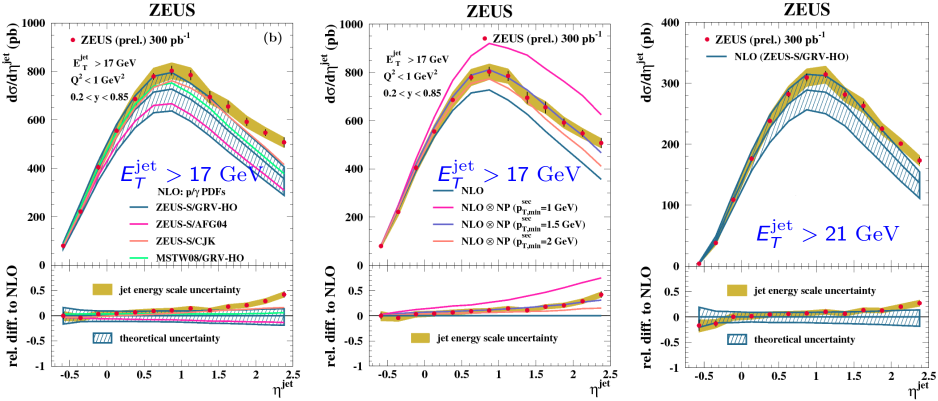
- higher orders: $< \pm 10\,(< 7)\,\%$ at low (high) E_T^{jet}
- γ PDFs: $-10\,(-2)\,\%$ at low (high) E_T^{jet}
- proton PDFs: $\pm 1\,(5)\,\%$ at low (high) E_T^{jet}
- hadronisation: mostly $< 2.5\%$
- $\alpha_s\,(M_Z)$: typically $< \pm 3.7\%$



$\Rightarrow$ **Good description of data by NLO calculations**

Measurement suited for $\alpha_s\,(M_Z)$ extraction with small uncertainties

Inclusive Jet Production in PHP (2/2)



- proton PDFs ZEUS-S and MSTW08 provide roughly similar predictions
- non-perturbative effects or the γ PDFs at high η^{jet} could cause observed discrepancy between data and the theory
  - → γ PDFs: predictions for AFG04 and CJK significantly differ from GRV-HO
  - → contributions from non-perturbative effects significantly depend on η^{jet}
  - → after increasing the E_T^{jet} cut the theory agrees with the data

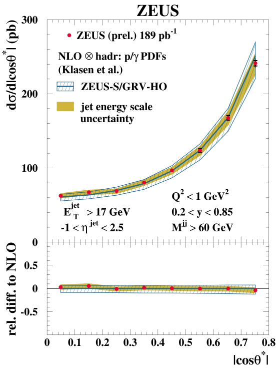
Dijet Production in PHP

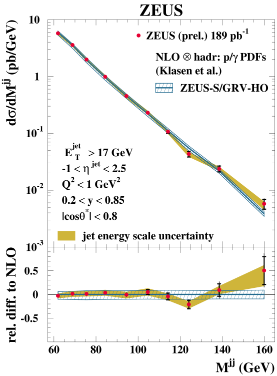
CMS Scattering Angle:

- $\theta^* \rightarrow \cos\theta^* = \tanh\frac{\eta_1 - \eta_2}{2}$

QCD Dynamics:

- study underlying dynamics by measuring differentially in M^{jj} and θ^*
- expectation from QCD: different shape of $d\sigma/d\left|\cos\theta^*\right|$ for resolved and direct processes due to different nature of propagator





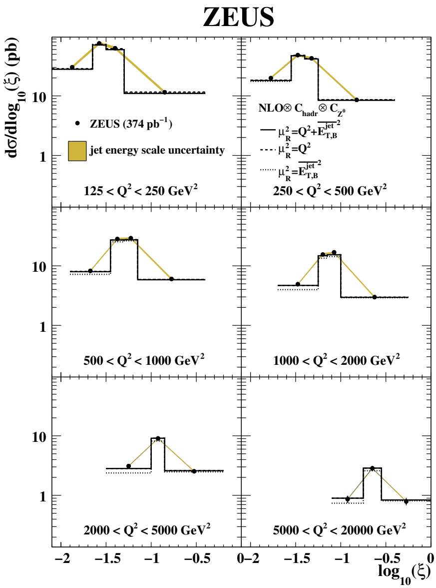
→ **good description of data by NLO predictions at $O\left(\alpha_s^2\right)$**

→ **concept of resolved photons holds**

Dijets in DIS at High Q^2 (1/2)

- jets produced in the boson-gluon-fusion process are sensitive to the gluon density
- gluon fractional contribution:
  - $125 < Q^2 < 500\ \mathrm{GeV}^2$: $> 60\%$
  - $500 < Q^2 < 2000\ \mathrm{GeV}^2$: $> 40\%$
- PDFs depend on ξ and $\mu_F^2 = Q^2$

→ possibility to constrain gluon PDF with dijet measurement:
  - at least two jets with $E_{T,B}^{\mathrm{jet}} > 8\ \mathrm{GeV}$ and $-1 < \eta_{\mathrm{lab}} < 2.5$
  - $M^{jj} > 20\ \mathrm{GeV}$



Dijets in DIS at High Q^2 (2/2)

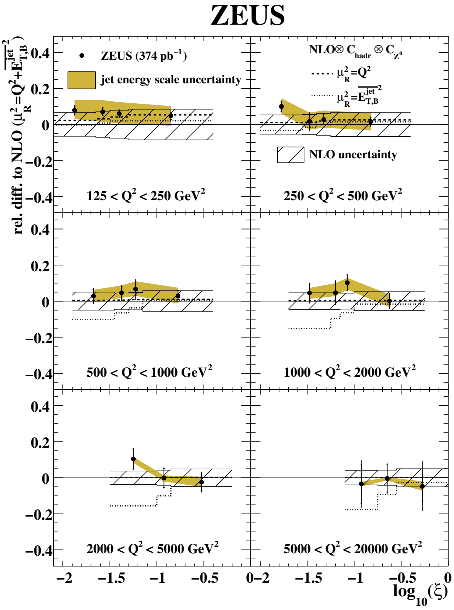
Experimental Uncertainties:

- uncorrelated: $\pm 2\,(6)\,\%$ at low (high) Q^2
- correlated: $\approx 5\,(3)\,\%$ at low (high) Q^2

Theoretical Uncertainties:

- missing higher orders: $\approx 3-6\%$
- PDF: $\approx 4\%$
  - $\rightarrow$ in some regions larger than μ_R uncertainty
- $\alpha_s\,(M_Z)$: $< 3\%$
- hadronisation: $\approx 2\%$
- choice of μ_F: negligible

Dijet cross sections have potential to constrain PDFs in global QCD fits!



Inclusive Jets at High Q^2

- at least one jet with $E_{T,B}^{\text{jet}} > 8$ GeV and $-2 < \eta_{\text{B}} < 1.5$

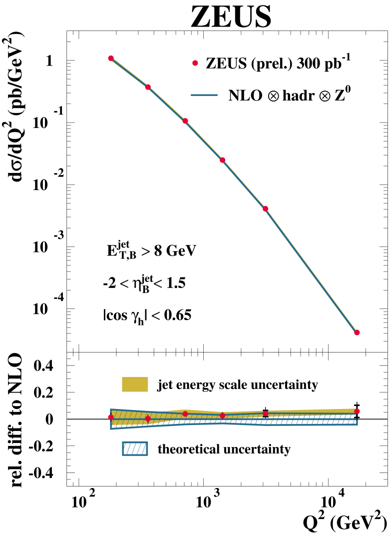
Experimental Uncertainties:

- uncorrelated: $\pm 3\,(7)\,\%$ at low (high) Q^2
- correlated: $\approx 5\,(2)\,\%$ at low (high) Q^2

Theory Uncertainties:

- dominated by choice of μ_R ($\approx \pm 5\%$) and PDF (typically $< 3\%$)

- **NLO pQCD describes the data very well in the whole measured range**



→ **Due to small uncertainties α_s can be extracted with high precision**

Extraction of $\alpha_s\,(M_Z)$

Inclusive Jets in ...	NC DIS	PHP
phase space:	$Q^2 > 500$ GeV yields smaller α_s uncertainty	$21 < E_T^{\mathrm{jet}} < 71$ GeV
theoretical uncertainty dominated by terms beyond NLO:	$\pm 1.5\%$	$\pm 2.5\%$
experimental uncertainty ruled by jet energy scale:	$\pm 1.9\%$	$\pm 1.8\%$

NC DIS:

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

$\rightarrow$ **total uncertainty:** $\pm 3.5\%$

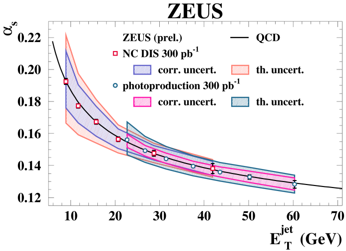
PHP:

$\alpha_s\,(M_Z) = 0.1206^{+0.0023}_{-0.0022}(\mathrm{exp.})^{+0.0042}_{-0.0033}(\mathrm{th.})$

$\rightarrow$ **total uncertainty:** $\pm 4.0\%$

- world average (2009):
  $\alpha_s\,(M_Z) = 0.1184 \pm 0.0007$

- **predicted running of α_s agrees very well with the data**

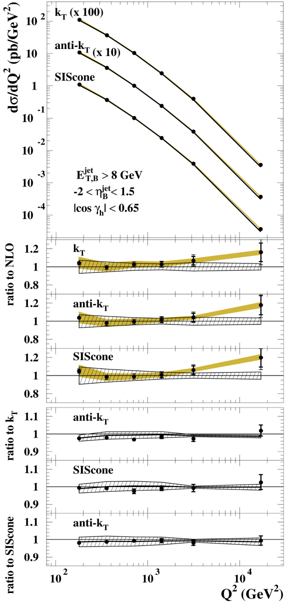


Jet Algorithms

- study of pQCD with jets require infrared- and collinear safe jet algorithms
- cross check of the influence of the choice of jet algorithms (k_T, anti-k_T and SIScone)
- differences of jet cross sections between these jet algorithms can be calculated with NLOJet++ up to $O\left(\alpha_s^3\right)$

⇒ **QCD calculations with up to four final state partons agree very well with the data**

⇒ **algorithms can be used in hadron-hadron collisions (e.g. LHC) with theoretically reliable performance**



Summary

Measurement of jet production allow detailed tests of QCD dynamics!

- Recently, at ZEUS stringent tests of pQCD were performed using ...
  - → inclusive jets and dijets in photoproduction
  - → inclusive jets and dijets in deep-inelastic scattering
- The strong coupling constant α_s was extracted from
  - → inclusive jets in photoproduction and deep-inelastic scattering

Conclusion:

→ pQCD calculations describe the data over a wide range of phase space!

→ theoretical uncertainties are often larger than experimental uncertainties.

→ α_s extractions are competitive!

Backup

Technicalities

Technicalities:

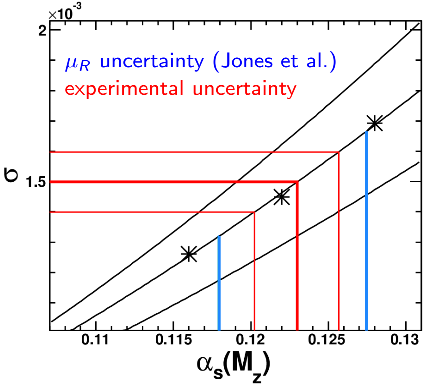
- jet search performed with the k_T cluster algorithm in ...
  1. DIS: ... in boson-quark collinear frame (Breit frame).
     $\hookrightarrow$ directly sensitive to hard QCD processes, E_T can be used for identification
  2. Photoproduction: ... laboratory frame.
- data are corrected for detector and higher-order QED effects
- theory is corrected with LO MC $\otimes$ parton shower $\otimes$ hadronisation model $\otimes$ electro-weak effects

α_s Extraction:

- pQCD calculations depend on α_s via the partonic cross section and the PDFs
- NLO calculations using various sets of PDFs with different assumed α_s were performed
- parametrize $\alpha_s\,(M_Z)$ dependence of observable $d\sigma/dA$ in bin i according to

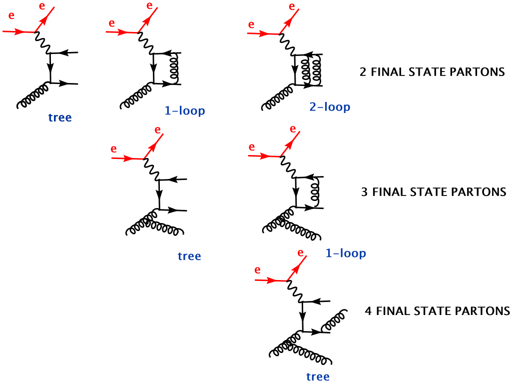
$$\frac{d\sigma_i}{dA} = C_1 \cdot \alpha_s\,(M_Z) + C_2 \cdot \alpha_s^2\,(M_Z)$$

- map measured $d\sigma/dA$ to x-axis and extract $\alpha_s\,(M_Z)$



$\Rightarrow$ complete α_s dependence of the calculations and the PDFs is preserved! (matrix elements and PDF evolution)

Jet Algorithms



$$\frac{d\sigma_{\mathrm{SIScone}}/dX}{d\sigma_{k_T}/dX} = 1 + \frac{d\sigma_{\mathrm{SIScone}}/dX - d\sigma_{k_T}/dX}{d\sigma_{k_T}/dX} = 1 + \frac{E_2 \cdot \alpha_s^2 + E_3 \cdot \alpha_s^3}{A_1 \cdot \alpha_s + A_2 \cdot \alpha_s^2}$$

$$\frac{d\sigma_{\mathrm{anti-k_T}}/dX}{d\sigma_{k_T}/dX} = 1 + \frac{d\sigma_{\mathrm{anti-k_T}}/dX - d\sigma_{k_T}/dX}{d\sigma_{k_T}/dX} = 1 + \frac{F_3 \cdot \alpha_s^3}{A_1 \cdot \alpha_s + A_2 \cdot \alpha_s^2}$$