

**Workshop on the LHeC**  
**September 1 - 3, 2009**  
**Divonne, France**



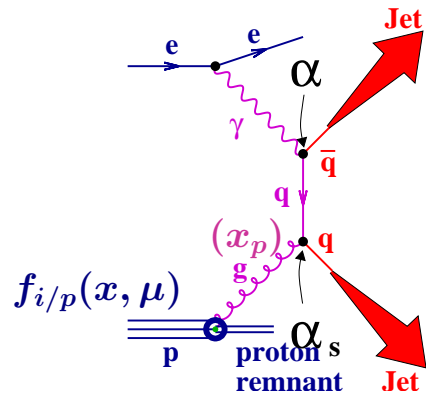
**Jets in photoproduction at LHeC**

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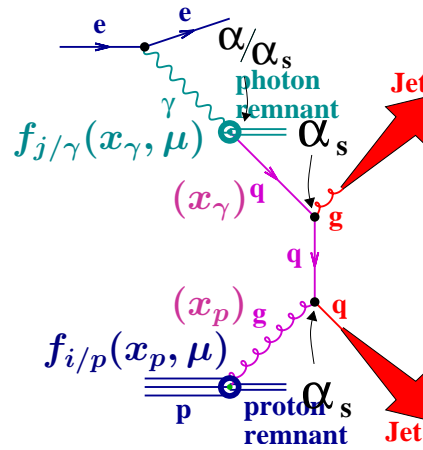
# Jets in photoproduction

- Jet production in photoproduction up to  $\mathcal{O}(\alpha\alpha_s)$ :



$$\gamma p \rightarrow e + \text{jet} + \text{jet} + X$$

(direct photoproduction)



$$\gamma p \rightarrow e + \text{jet} + \text{jet} + X$$

(resolved photoproduction)

- $Q^2$ :  $\gamma$  virtuality
- $W$ :  $\gamma p$  cms energy
- $y$ : inelasticity
- $x_{\gamma(p)}$ : parton momentum fraction from  $\gamma(p)$
- $\alpha_s$ : strong coupling constant
- $\mu_{F_{\gamma(p)}}$ :  $\gamma(p)$  factorisation scale
- $\mu_R$ : renormalisation scale

- Jet production cross section for photoproduction is given in QCD by:

$$d\sigma(ep \rightarrow e + \text{jet} + \text{jet} + X) = \sum_{i,j} \int_0^1 dy f_{\gamma/e}(y) \int_0^1 dx_p \int_0^1 dx_\gamma f_{i/\gamma}(x_\gamma, \mu_{F_\gamma}) \left[ d\hat{\sigma}_{i(\gamma)j(i(\gamma)j \rightarrow \text{jet jet})} \right] f_{j/p}(x_p, \mu_{F_p})$$

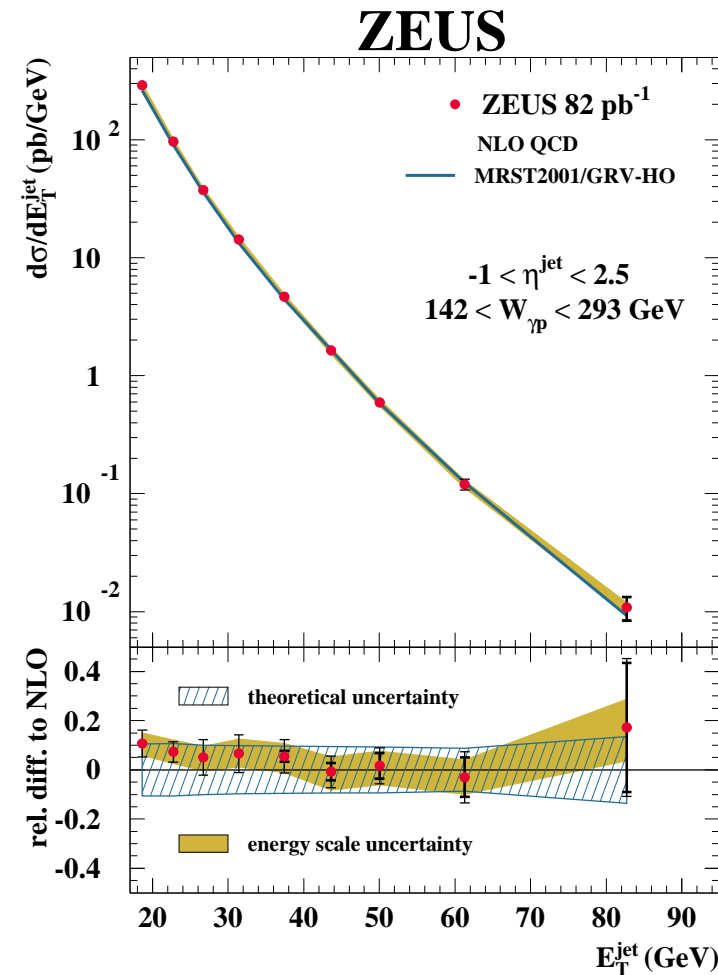
→ Measurements of jet cross sections in photoproduction allow tests of:

- structure of the photon
- pQCD,  $\alpha_s$
- structure of the proton
- search for new physics

# Measurement of $d\sigma/dE_T^{\text{jet}}$ in inclusive-jet photoproduction

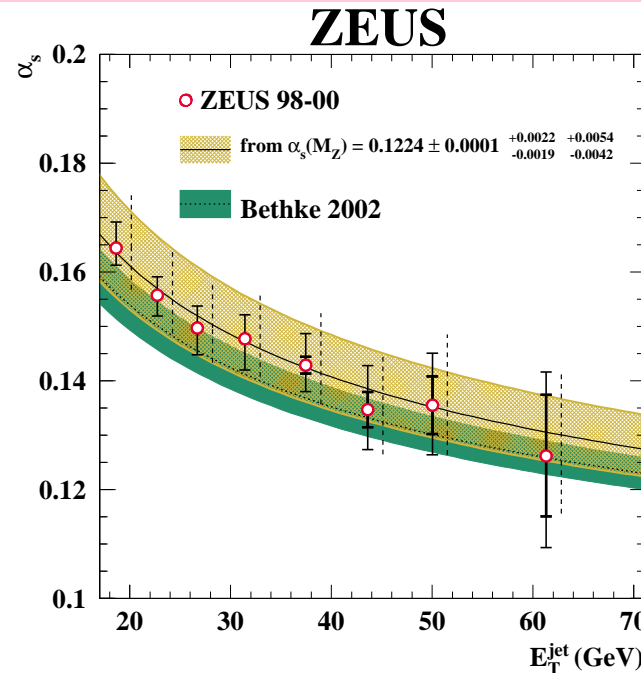


- At least one jet of  $E_T^{\text{jet}} > 17$  GeV and  $-1 < \eta^{\text{jet}} < 2.5$  ( $k_T$  cluster algorithm)
- Kinematic region:  $0.2 < y < 0.85$  and  $Q^2 \leq 1$  GeV<sup>2</sup>



- From the measured  $d\sigma/dE_T^{\text{jet}}$  a value of  $\alpha_s(M_Z)$  was extracted:

$$\alpha_s(M_Z) = 0.1223 \pm 0.0001 \text{ (stat.) } \begin{matrix} +0.0023 \\ -0.0021 \end{matrix} \text{ (exp.) } \begin{matrix} +0.0029 \\ -0.0030 \end{matrix} \text{ (th.)}$$



Total uncertainty:  $\pm 3.0\%$

→ Test of the running of  $\alpha_s$  over a wide range in  $E_T^{\text{jet}}$  from a single measurement

→ For improvement:

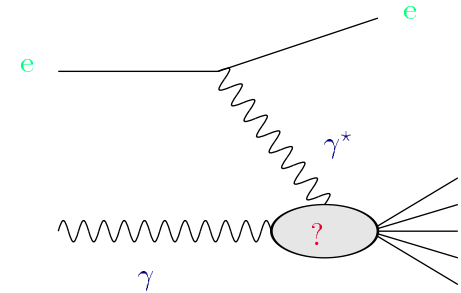
- NNLO calculations
- decrease jet energy scale uncertainty

- NLO QCD gives good description of data over whole  $E_T^{\text{jet}}$  range

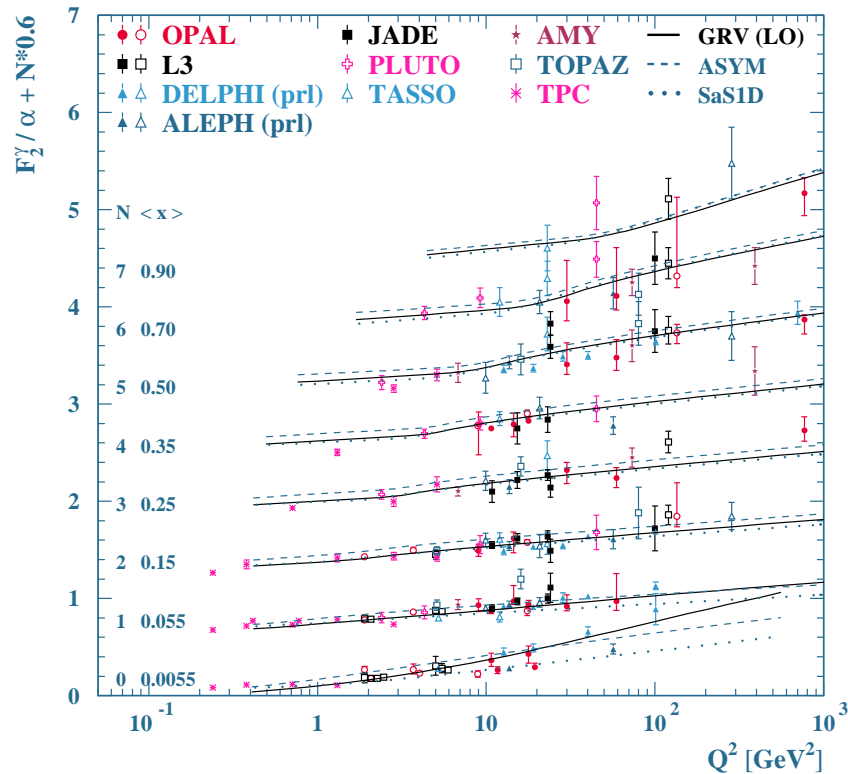
ZEUS Collab, Phys Lett B 560 (2003) 7  
ZEUS Collab, ZEUS-prel-08-008

# Photon structure

- The structure of a quasi-real photon  $\gamma$  ( $P^2 \approx 0$ ) can be probed by a highly virtual photon  $\gamma^*$  ( $Q^2 \gg 0$ ) emitted by the electron in deep inelastic  $e\gamma$  scattering



- Compilation of  $F_2^\gamma$  measurements from deep inelastic  $e\gamma$  scattering:



- Fits to the data to obtain the  $\gamma$ PDFs is not as “easy” as for the proton:
  - no momentum sum rule applies to the  $\gamma$ PDFs
  - gluon PDF determination from  $F_2^\gamma$  very difficult
  - cross section very small and falls rapidly with  $Q^2$  → large statistical errors
  - photon energy determined from hadronic system → large systematic errors
- However, there exist several parametrisations
- The parametrisations obtained in DIS  $e\gamma$  can be used in other experiments, (HERA, LHeC), to test the universality of the photon structure and its scale evolution

# Measurement of $d\sigma/dx_\gamma^{\text{obs}}$ in dijet photoproduction



- At least two jets of  $E_T^{\text{jet}1} > 20 \text{ GeV}$ ,  $E_T^{\text{jet}2} > 15 \text{ GeV}$  and  $-1 < \eta^{\text{jet}} < 3$  ( $k_T$  cluster algorithm)
- Kinematic region:  $0.2 < y < 0.85$  and  $Q^2 \leq 1 \text{ GeV}^2$

## ZEUS

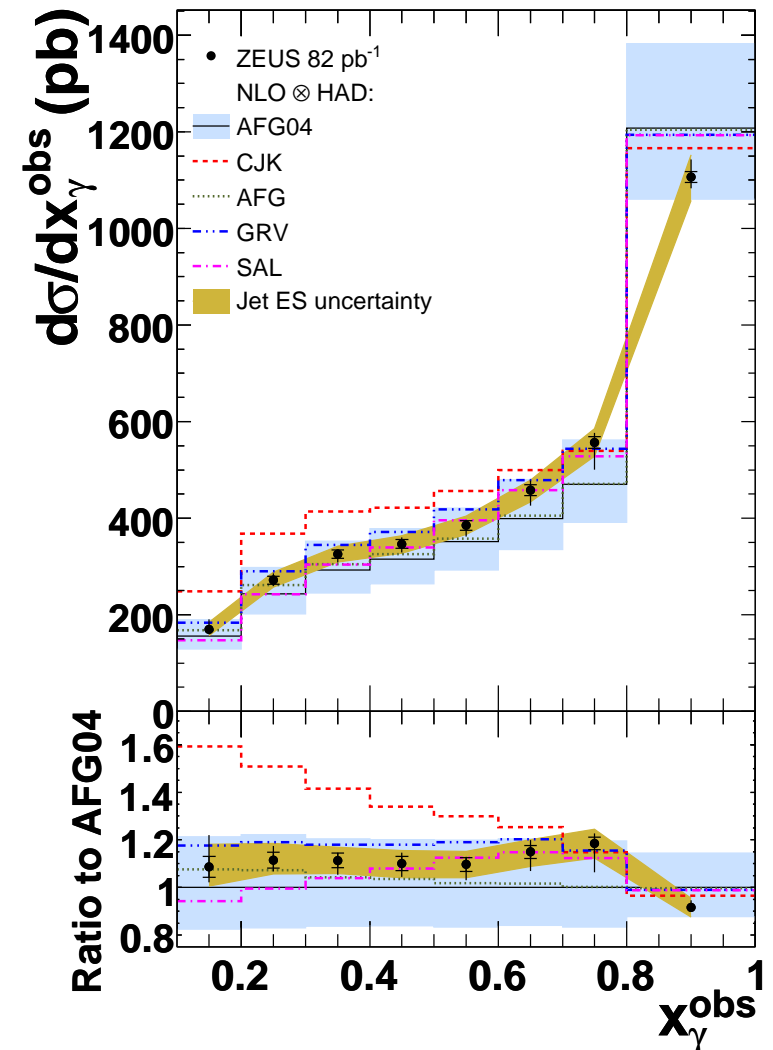
→ The data show sensitivity to the  $\gamma$ PDFs at low  $x_\gamma^{\text{obs}}$

→ The predictions based on AFG, GRV and SAL differ by up to 25% and describe the data within the uncertainties

→ CJK: different gluon PDF; differs by  $\sim 60\%$  at low  $x_\gamma^{\text{obs}}$

- The data have the potential to constrain the gluon PDF (insufficiently constrained by  $F_2^\gamma$  data alone)

→ Large room for improvement



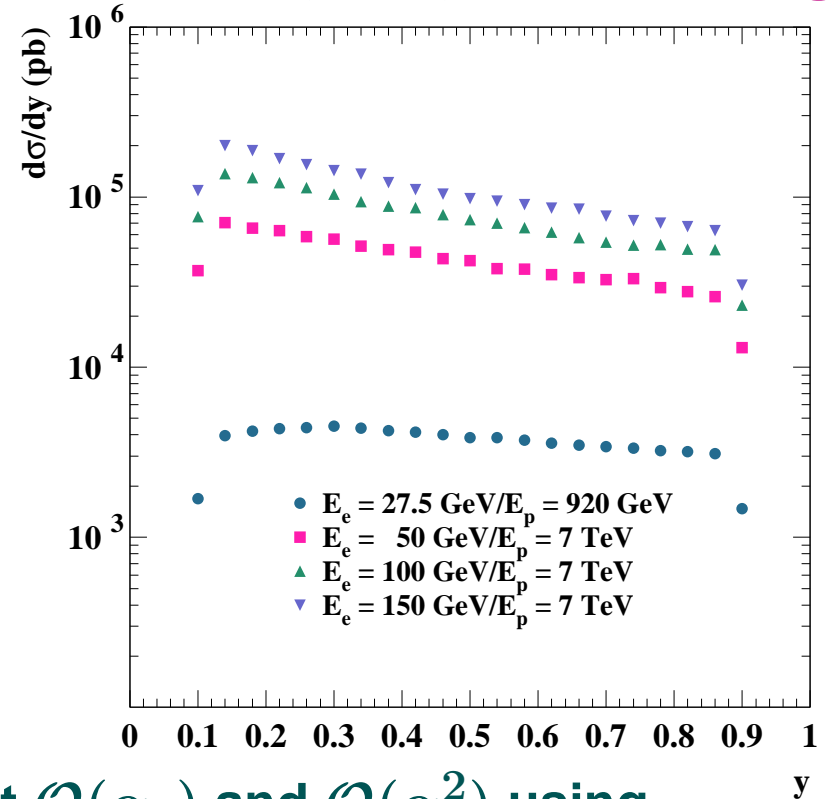
ZEUS Collab, Phys Rev D 76 (2007) 072011

# Photoproduction studies at LHeC energies

- Three  $E_e$  scenarios were studied for  $E_p = 7$  GeV:  $E_e = 50, 100, 150$  GeV using PYTHIA MC (resolved and direct processes)

$$ep \rightarrow e + \text{jet} + X$$

- Jets searched using the  $k_T$  cluster algorithm
- Kinematic region:  $0.1 < y < 0.9$  and  $Q^2 \leq 1$  GeV<sup>2</sup>
- At least one jet of  $E_T^{\text{jet}} > 15$  GeV and  $-3 < \eta^{\text{jet}} < 3$



- Fixed-order QCD calculations:

→ differential cross sections were calculated at  $\mathcal{O}(\alpha_s)$  and  $\mathcal{O}(\alpha_s^2)$  using

Klasen et al. program with:

– pPDFs: CTEQ6.1 sets

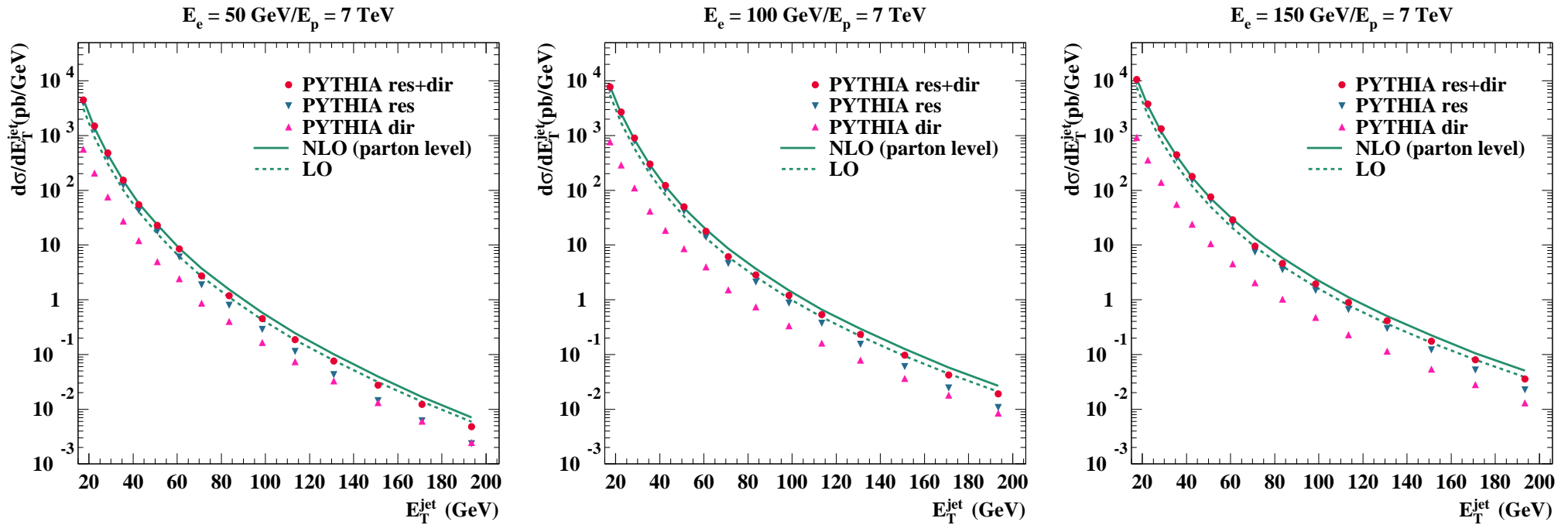
–  $\gamma$ PDFs: GRV-HO set

–  $\alpha_s$  was calculated at two loops with  $\alpha_s(M_Z) = 0.119$  as default input

– renormalisation and factorisation scales  $\mu_R = \mu_F = E_T^{\text{jet}}$  of each jet

# Inclusive-jet cross sections at LHeC

- $d\sigma/dE_T^{\text{jet}}$  at parton level for PYTHIA and QCD calculations:

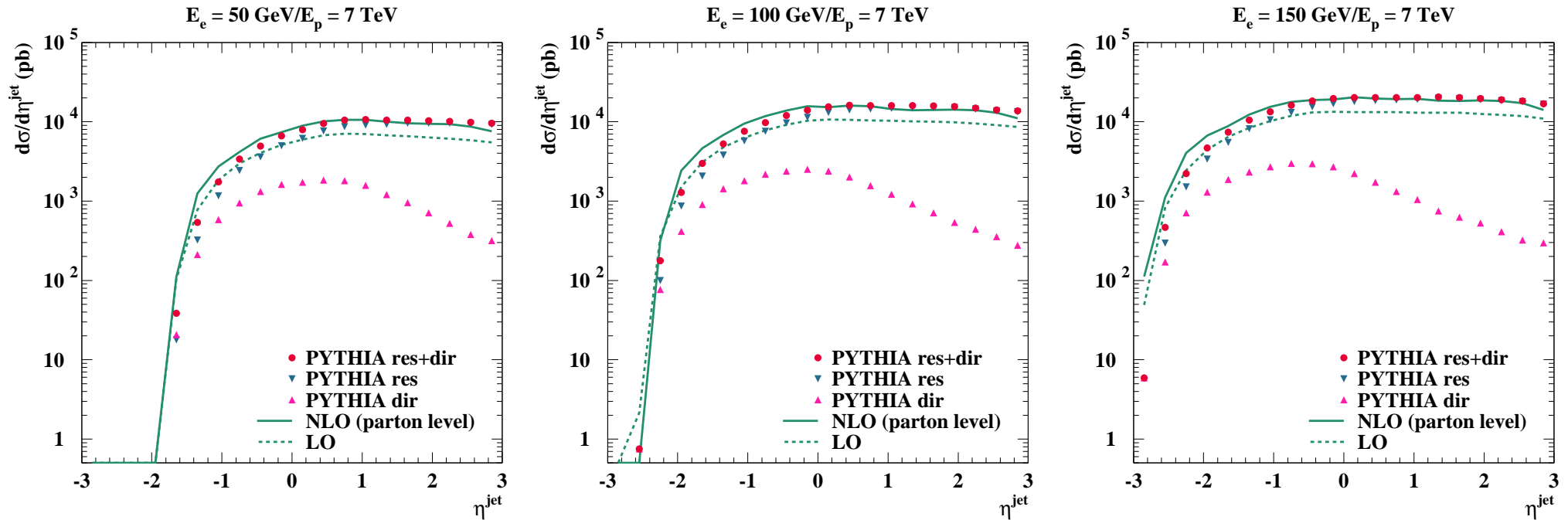


- Calculations predict a sizeable rate for  $E_T^{\text{jet}}$  at least up to 200 GeV
- Resolved processes dominate at low  $E_T^{\text{jet}}$ , but direct processes become increasingly more important as  $E_T^{\text{jet}}$  increases
- PYTHIA MC (normalised) agrees well in shape with the NLO calculations



# Inclusive-jet cross sections at LHeC

- $d\sigma/d\eta^{\text{jet}}$  at parton level for PYTHIA and QCD calculations:

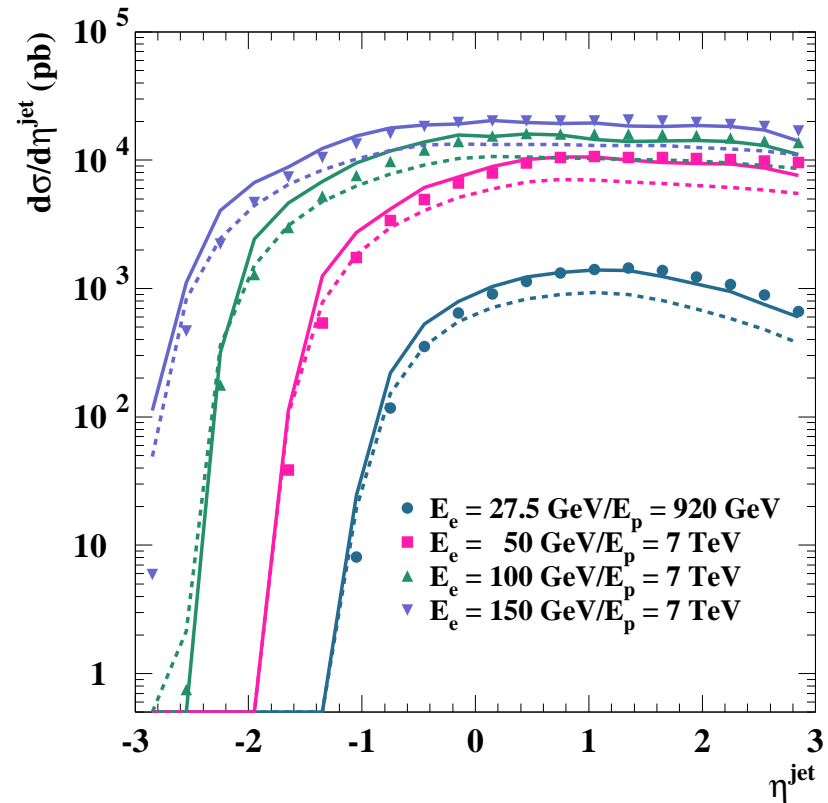
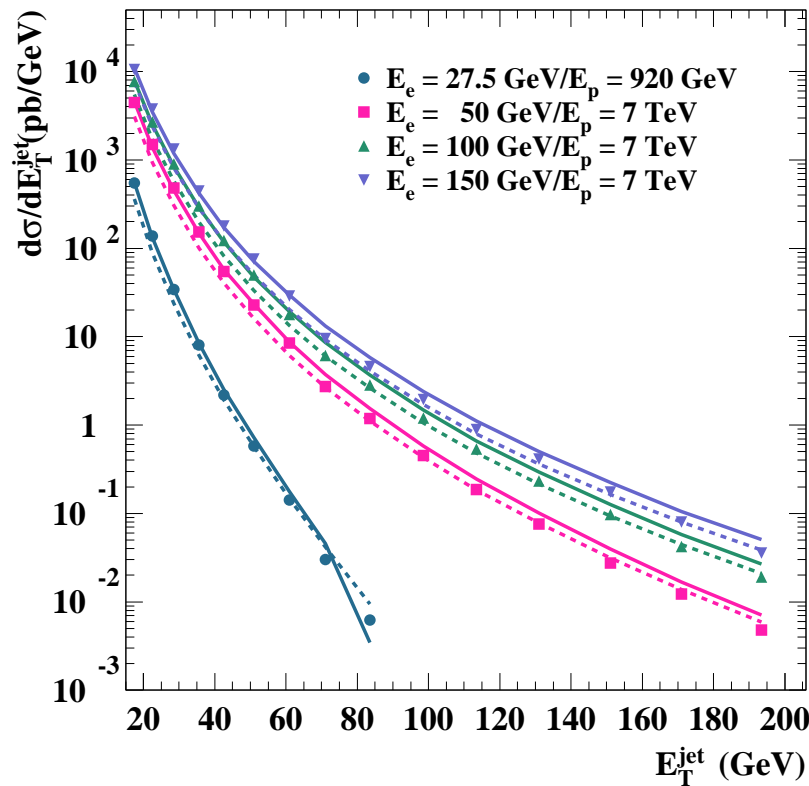


- Calculations predict a sizeable rate for very forward  $\eta^{\text{jet}}$
- Resolved processes dominate at high  $\eta^{\text{jet}}$ , but direct processes produce more central jets
- PYTHIA MC (normalised) agrees well in shape with the NLO calculations



# Inclusive-jet cross sections at LHeC

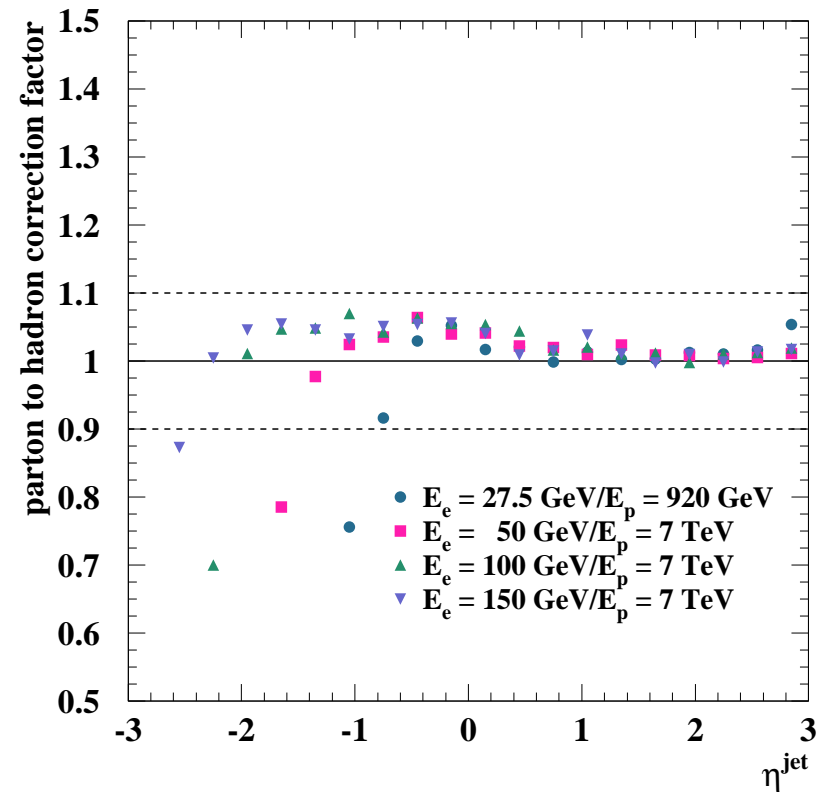
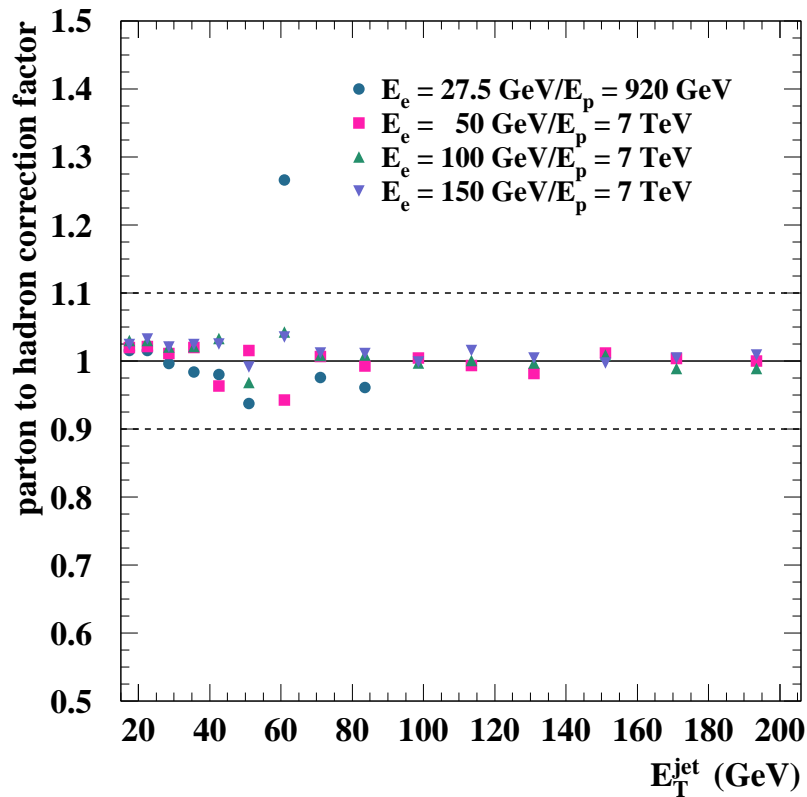
- $d\sigma/dE_T^{\text{jet}}$  and  $d\sigma/d\eta^{\text{jet}}$  at parton level for different LHeC scenarios:



- Cross sections at fixed  $E_T^{\text{jet}}$  increase with increasing  $\sqrt{s}$
- Jets tend to go more backward as  $\sqrt{s}$  increases
- Much wider reach in  $E_T^{\text{jet}}$  and  $\eta^{\text{jet}}$  compared to HERA

# Inclusive-jet cross sections at LHeC

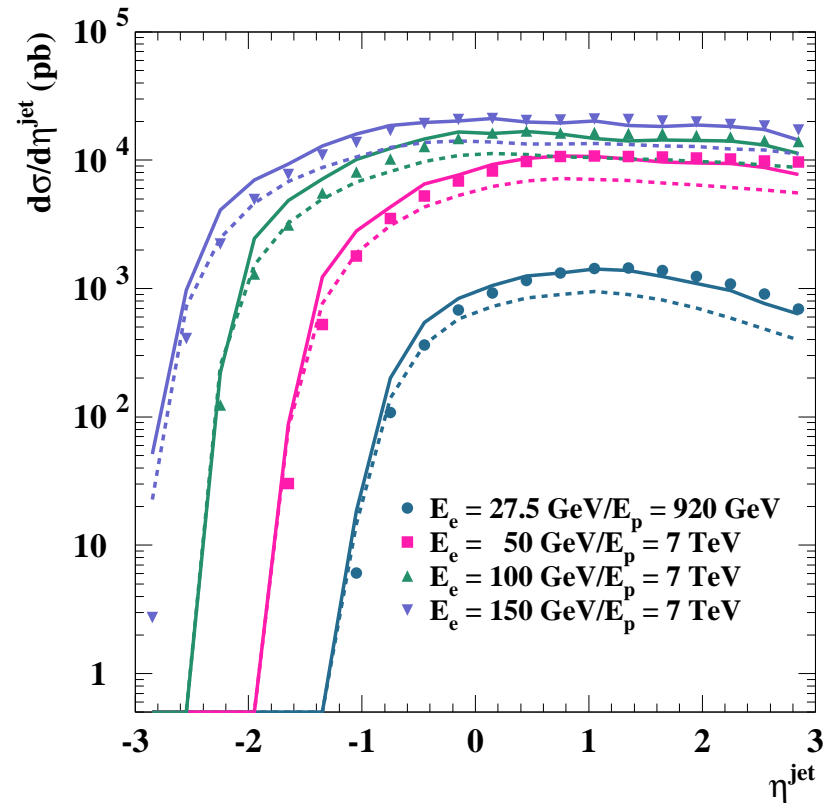
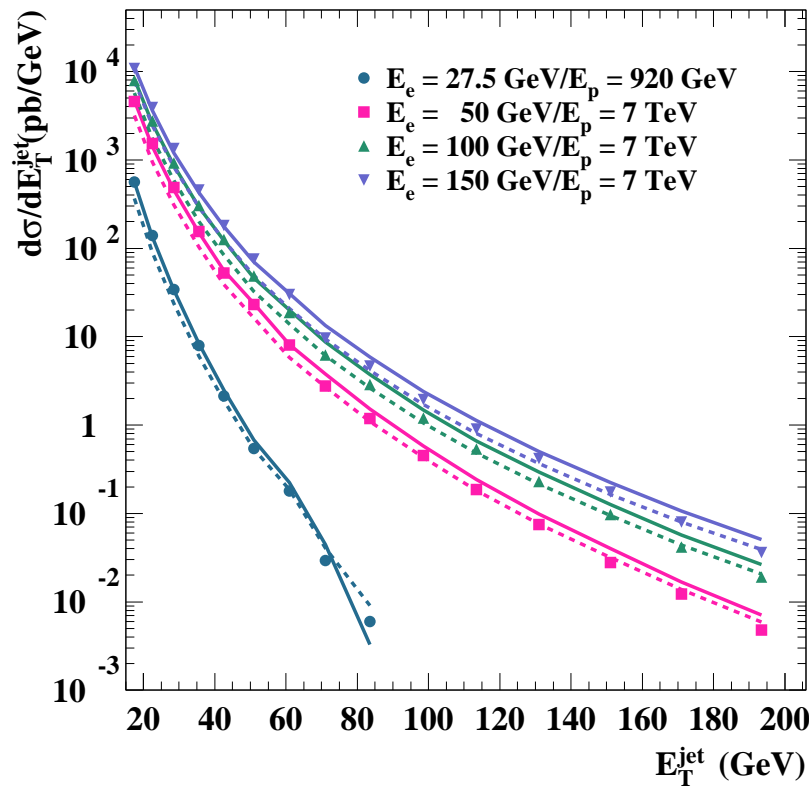
- Hadronisation corrections for  $d\sigma/dE_T^{\text{jet}}$  and  $d\sigma/d\eta^{\text{jet}}$  for different scenarios:



- Parton to hadron corrections are predicted to be very small (below  $\pm 5\%$ ) for the chosen scenarios
- Effects for  $40 < E_T^{\text{jet}} < 60 \text{ GeV}$  and  $\eta^{\text{jet}} < -1$  are statistical fluctuations of the Monte Carlo samples used

# Inclusive-jet cross sections at LHeC

- $d\sigma/dE_T^{\text{jet}}$  and  $d\sigma/d\eta^{\text{jet}}$  at hadron level for different LHeC scenarios:



- Cross sections at fixed  $E_T^{\text{jet}}$  increase with increasing  $\sqrt{s}$
- Jets tend to go more backward as  $\sqrt{s}$  increases
- Much wider reach in  $E_T^{\text{jet}}$  and  $\eta^{\text{jet}}$  compared to HERA

## Summary and conclusions

- **Inclusive-jet cross sections in photoproduction were investigated for several energy scenarios of the LHeC:  $E_p = 7$  TeV with  $E_e = 50, 100$  or  $150$  GeV**
  - **Parton to hadron corrections are predicted to be very small (below  $\pm 5\%$ ) for the chosen scenarios**
  - **Cross sections at fixed  $E_T^{\text{jet}}$  increase with increasing  $\sqrt{s}$**
  - **Calculations predict a sizeable rate for  $E_T^{\text{jet}}$  at least up to  $200$  GeV**
  - **Jets tend to go more backward as  $\sqrt{s}$  increases**
  - **Much wider reach in  $E_T^{\text{jet}}$  and  $\eta^{\text{jet}}$  compared to HERA**
- ↪ **Wide detector coverage and good calibration will be essential for precise tests of pQCD/extraction of  $\alpha_s$ /constraints on  $\gamma/p$  PDFs in photoproduction at LHeC**
- **Outlook:**
  - **Other possible scenarios under consideration?**
  - **Still to be done: theoretical uncertainties**
  - **Still to be done: investigate effect of multiparton interactions at LHeC energies**