



# High-Et di-jet & three- & four-jet events in photoproduction, at HERA

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# HERA

- Stands for “Hadron-Elektron-Ringanlage”
- (Was) an (electron-proton)  $ep$ -collider
- Located in Hamburg, Germany
- 6.3 Km long
- 10-25m underground
- Hosted H1, HERMES, HERA-B & ZEUS
- Operation started in 1992
- Final run on 30th June, 2007
- Max  $p$ -beam energy,  $E_p$  : 920GeV
- Max  $e$ -beam energy,  $E_e$  : 27.5GeV
- (Max  $ep$  COM energy: 318GeV)



# Photoproduction

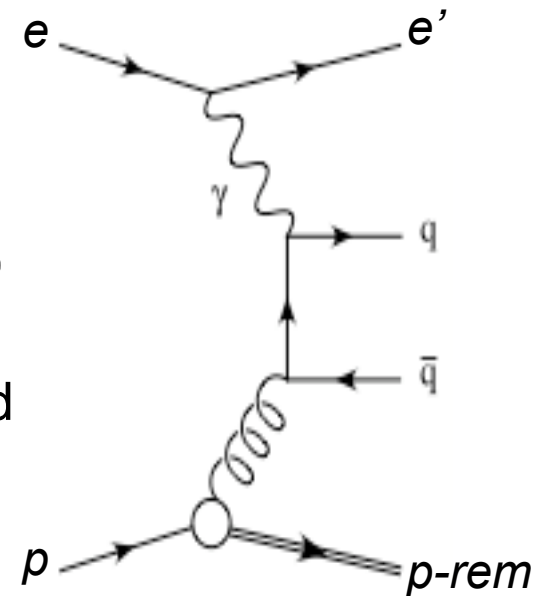
- In contrast to DIS, photoproduction is an  $ep$  interaction mediated by a quasi-real photon ( $\gamma$ ) - i.e. the virtuality,  $Q^2 = -(q_\gamma^2) \approx 0$

- Unlike DIS:

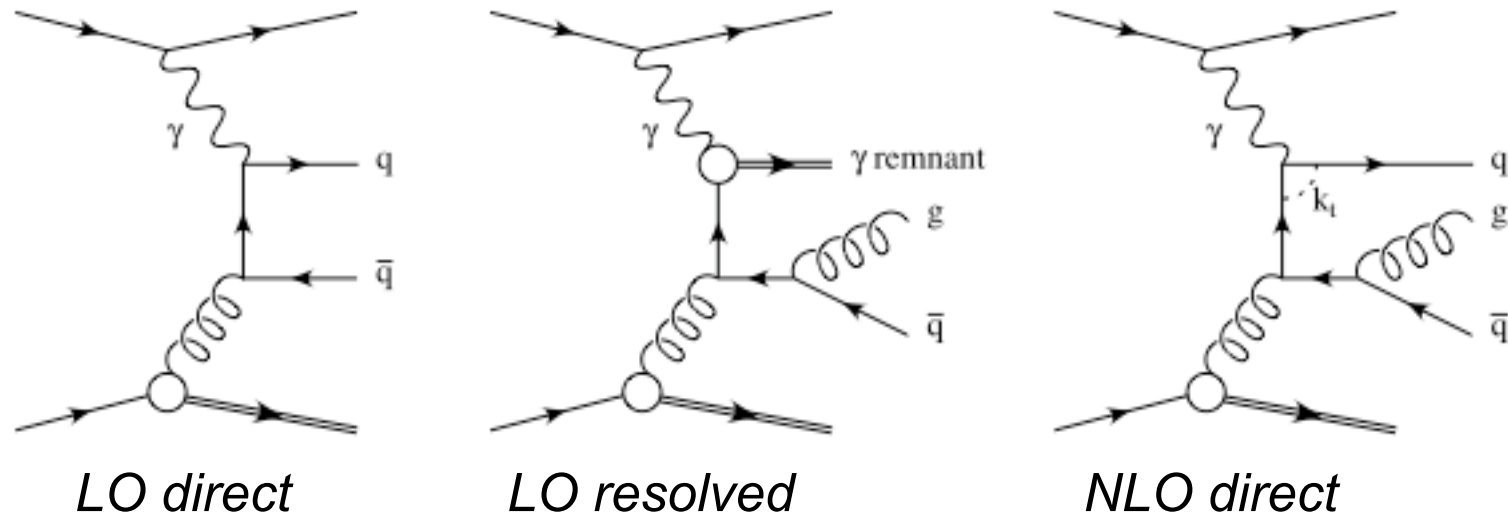
- the “scattered” electron develops very little  $E_T$
- $Q^2$  not a pQCD hard-scale (use e.g. jet- $E_T$  instead)

- Low- $Q^2$  (i.e. almost on-mass-shell) means  $\gamma$  long-lived w.r.t. characteristic interaction time-scale, therefore:

- valid to view collision as a  $\gamma p$  interaction
- $\gamma$  may fluctuate into a partonic or meson-like system



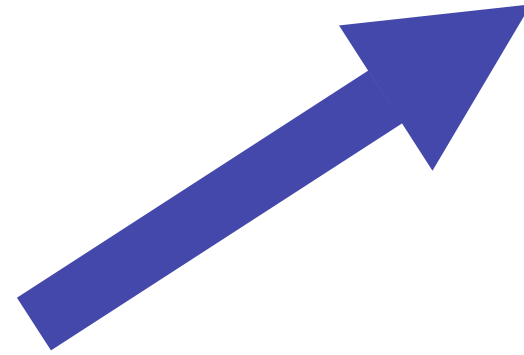
# Direct & resolved photoproduction



- The photon may interact as a:
  - point-like electromagnetic object: **direct photoproduction**
  - partonic or meson-like system: **resolved photoproduction**
- This distinction is only unambiguous at leading order (LO)
- pQCD photoproduction calculations require both a **proton** and **photon PDF**



# High-Et di-jets in photoproduction



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# Motivation

- Data used to fit photon PDFs is relatively sparse, the most important being the photon structure function,  $F_2^\gamma$
- Proton PDF fits include a wider range of data but have a common feature that the gluon PDF is poorly constrained at (Bjorken)  $x_p > 0.1$
- **Motivation 1)** To produce a data set that could be used to **test** and hopefully **constrain parameterisations of both the photon and proton PDFs**
- Di-jets in photoproduction have been measured before by ZEUS but never:
  - with such a high integrated luminosity
  - including jets with such a large pseudorapidity,  $\eta$
  - at such high-Et
- high-Et data good for PDF fitting as minimal pQCD scale uncertainty

} *see next  
slide for  
details*

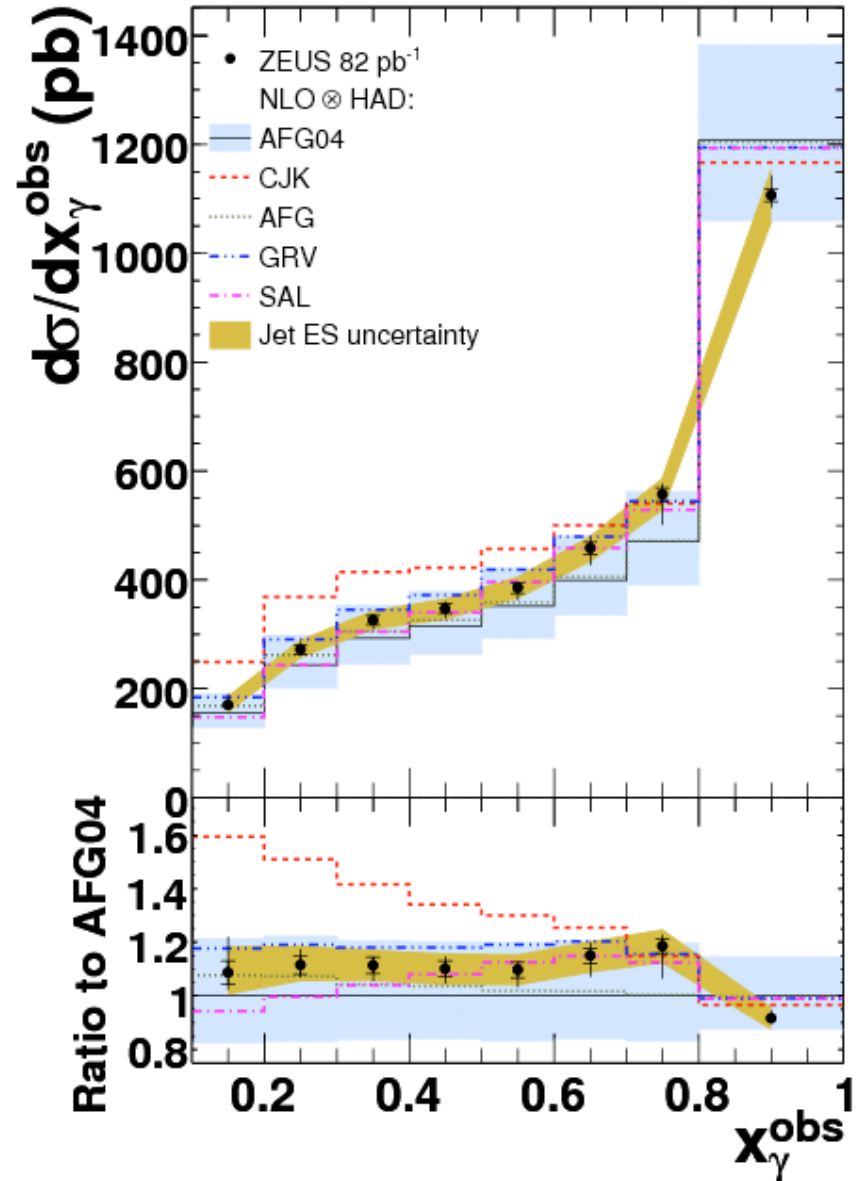
# Analysis strategy

- Jets were found using the Kt-algorithm and an event was selected if it had:
  - at least two jets (ordered in  $E_T$ ) with *(integrated lumi: 81.8 pb-1)*
  - $E_T^{jet1} > 20 \text{ GeV}$  &  $E_T^{jet2} > 15 \text{ GeV}$
  - in the pseudorapidity range  $-1 < \eta^{jet} < 3$
  - with at least one jet in  $-1 < \eta^{jet} < 2.5$
- Look in direct- and resolved-photoproduction enriched regions.
- Look in “optimised” regions where gluon PDF uncertainties are largest
- Compare to NLO pQCD using various photon PDFs to distinguish between fits
- Photon PDFs Considered: CJK, AFG04, SAL, GRV-HO, AFG
- CJK assume **more strongly rising gluon** & treats heavy flavours thoroughly
- Proton PDF used: CTEQ5M1

# Photon PDF sensitivity

- define:  $x_\gamma^{obs} = \frac{1}{2yE_e} \sum^{jets} E_T^{jet} \exp[-\eta^{jet}] \approx x_\gamma$   
 $y$  is the fraction of  $E_e$  carried by the  $\gamma$   
 $x_\gamma$  is the fraction of the  $\gamma$  momentum transferred to final state

- Direct-enriched:  $x_\gamma^{obs} > 0.75$
- Resolved-enriched:  $x_\gamma^{obs} \leq 0.75$
- Direct region insensitive to  $\gamma$ -PDF. All give a similar & OK description  $> 0.8$
- Larger discrepancies in resolved region
- CJK gives much larger prediction
- Others describe data reasonably well



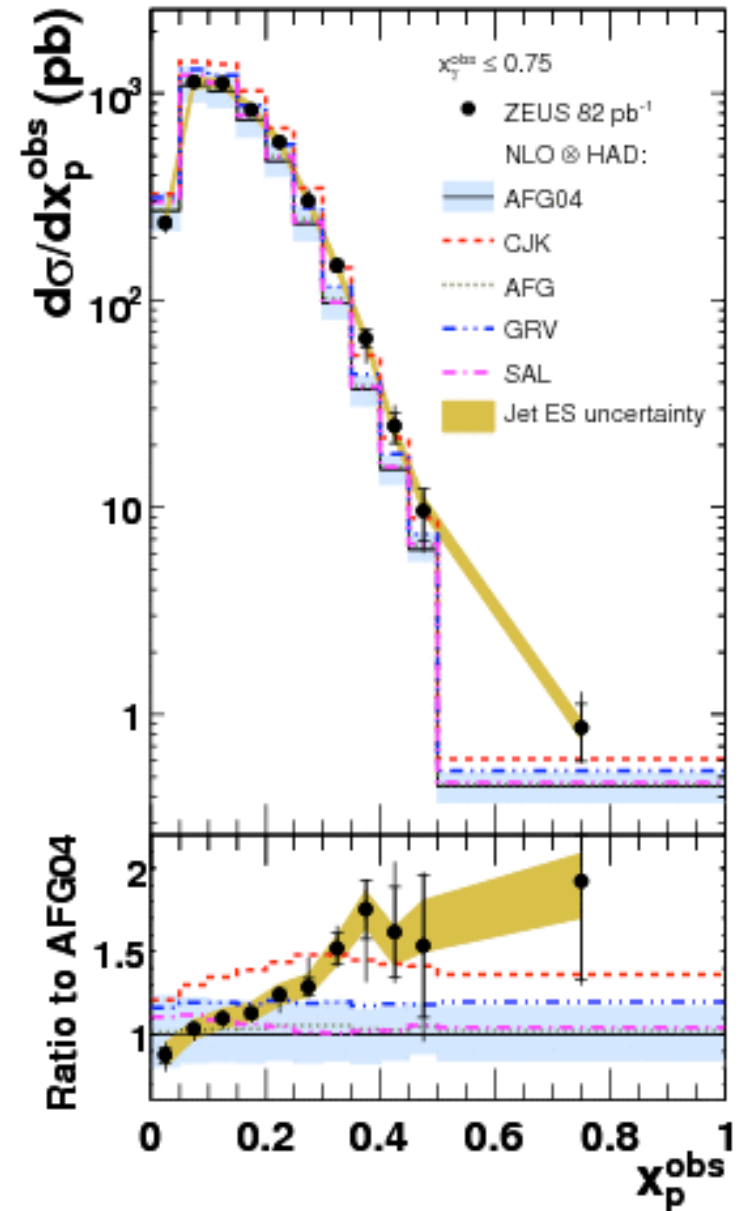


# Photon PDF sensitivity

- Resolved-enriched:  $x_\gamma^{obs} \leq 0.75$

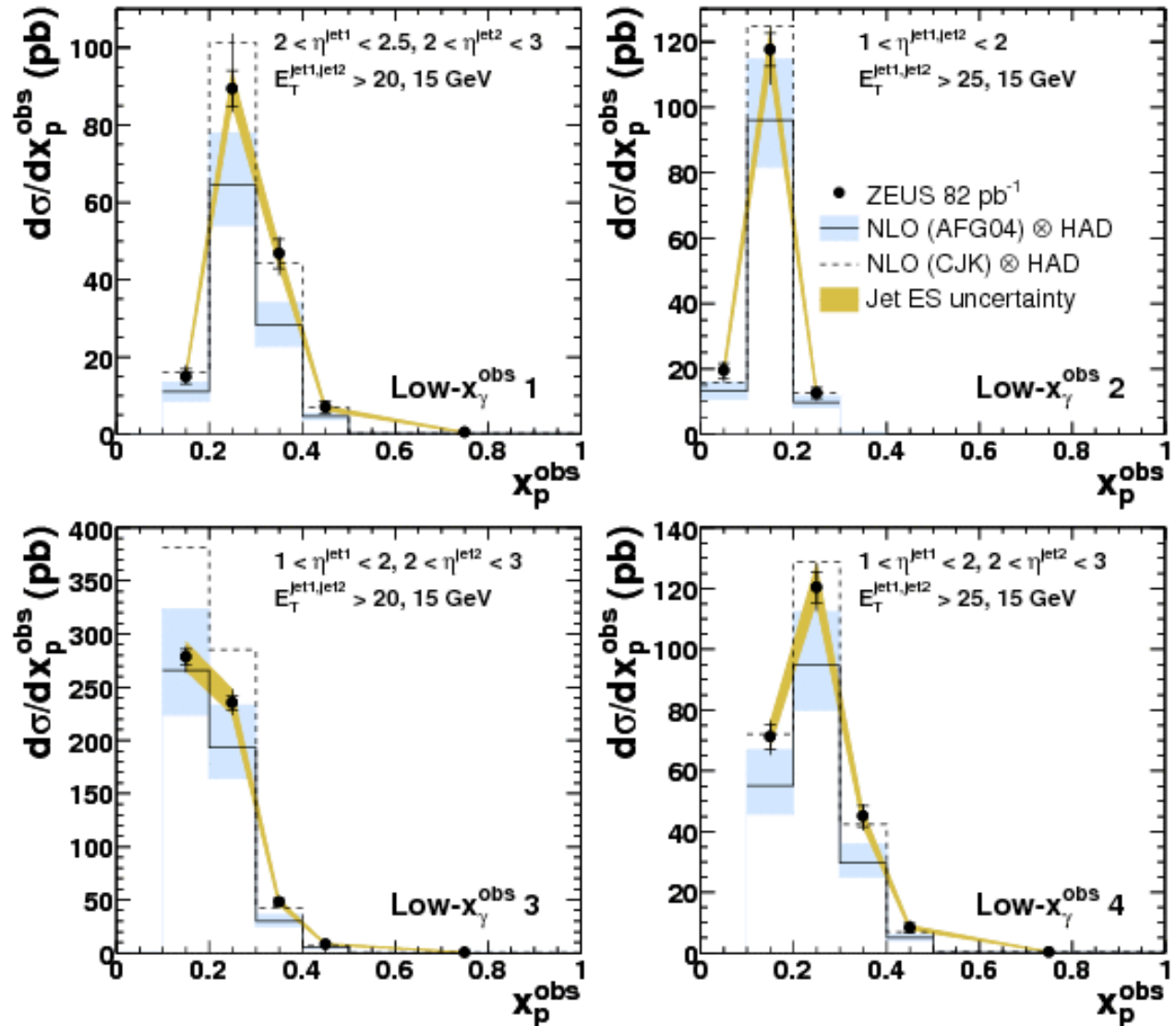
- define: 
$$x_p^{obs} = \frac{1}{2E_p} \sum^{jets} E_T^{jet} \exp[\eta^{jet}] \approx x_p$$

- All predict too steep a distribution (CJK less so)
- CJK is reasonable for  $x_p^{obs} > 0.3$  and predicts a markedly shallower curve (inline with data)
- But CJK significantly overestimates the cross section ( $\sim 40\%$ ) between  $0.1 < x_p^{obs} < 0.3$



# Proton PDF sensitivity

- The  $x_p^{obs}$  cross section in 4 optimised regions defined with different jet  $E_T$  and  $\eta$  criteria
- Here, the gluon PDF uncertainty dominates (not shown on figure)
- All are direct-enriched (insensitive to  $\gamma$ -PDF)
- It is hoped these data will help constrain the gluon PDF for  $x_p > 0.1$

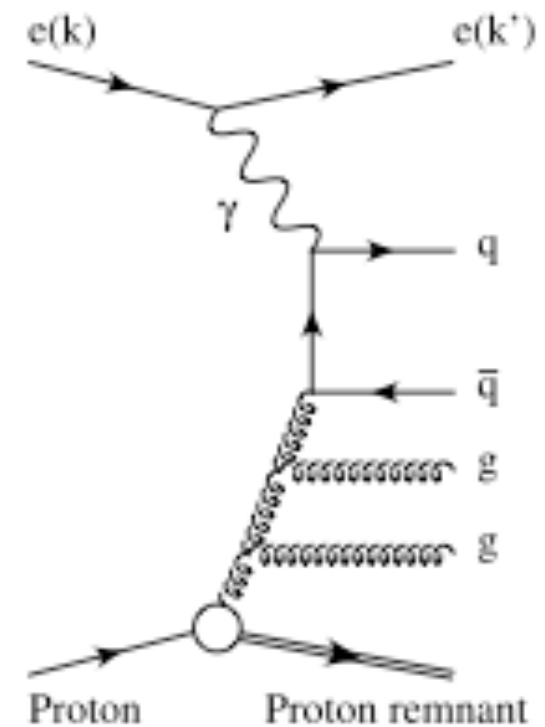




# Three- & four-jets in photoproduction

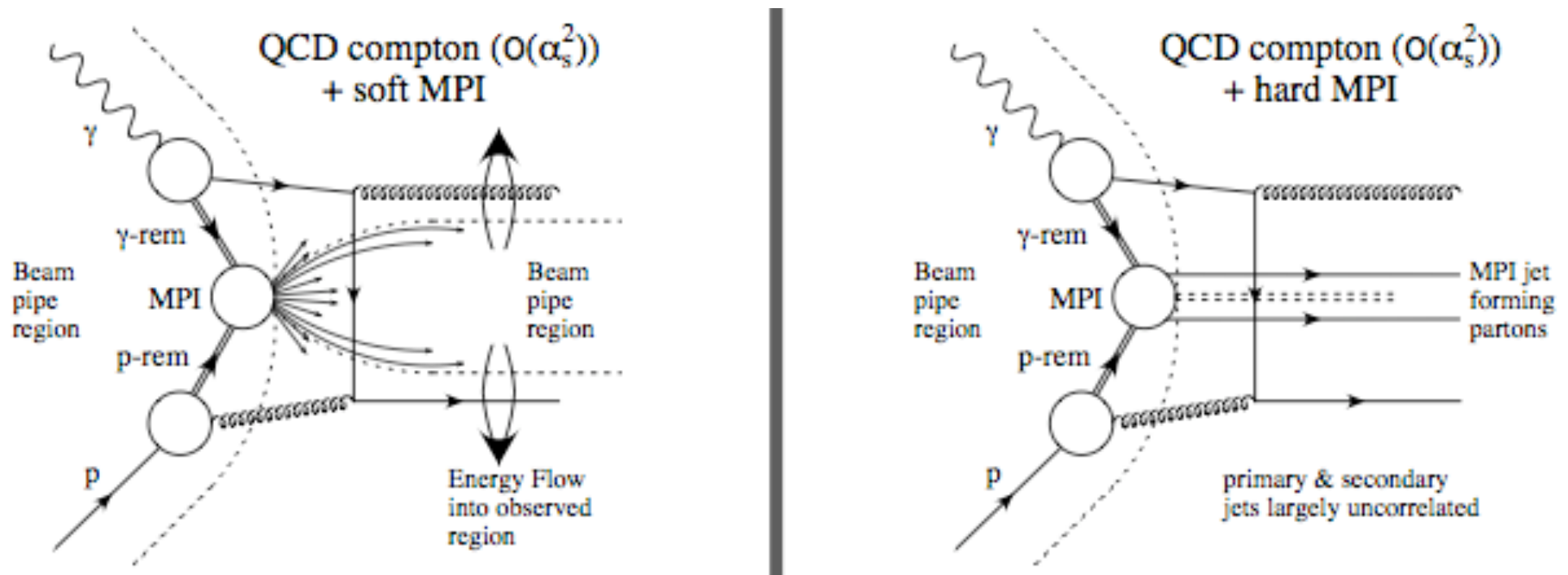
# Multi-jet processes in photoproduction

- Multi-jet final states (three or more jets) can be produced by:
  - Beyond LO photoproduction processes
  - LO process with a hard MPI (see next slide)
- Ignoring MPIs, an  $n$ -jet:
  - direct process is  $O(\alpha\alpha_s^{n-1})$
  - resolved processes is  $O(\alpha_s^n)$



4-jet direct process

# Multi-parton interactions



- Roughly speaking, MPIs occur when the  $\gamma$  & p-remnants interact
- Only present in resolved photoproduction - i.e. ( $x_\gamma < 1$ )
- The resulting energy flow will tend to have low-Pt: **soft MPI**
- Feasibly, an MPI may be “hard” enough to produce extra jets: **hard MPI**
- MPIs are not in pQCD calculations and only ad-hoc in MCs

# Motivation

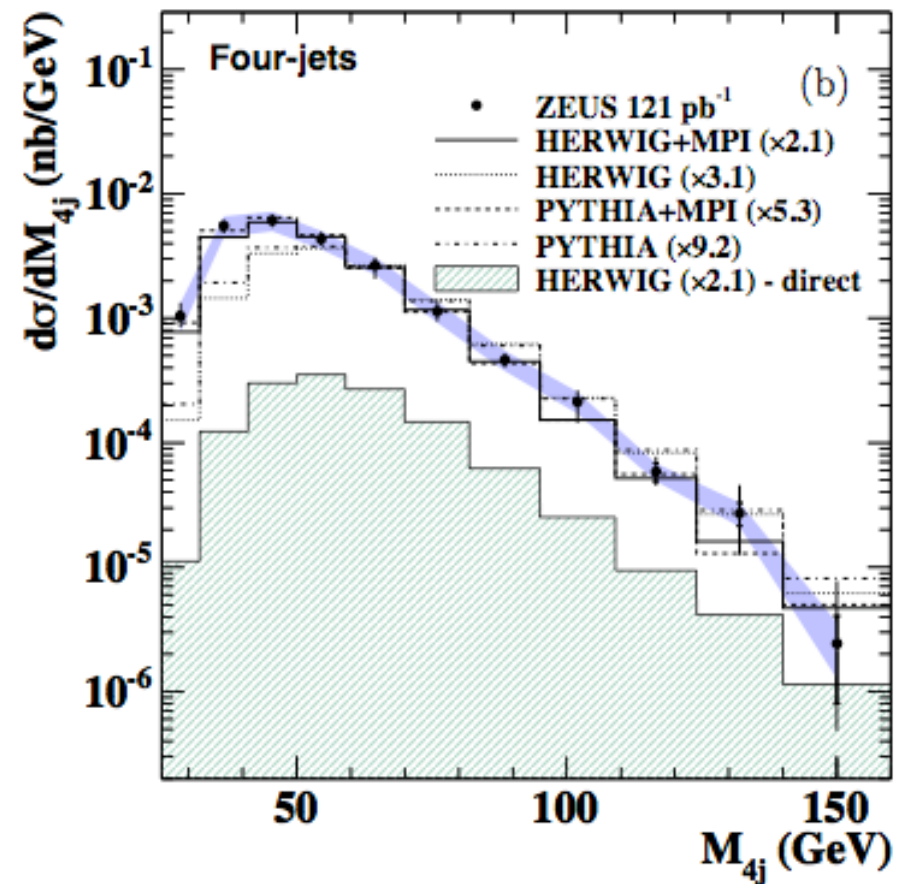
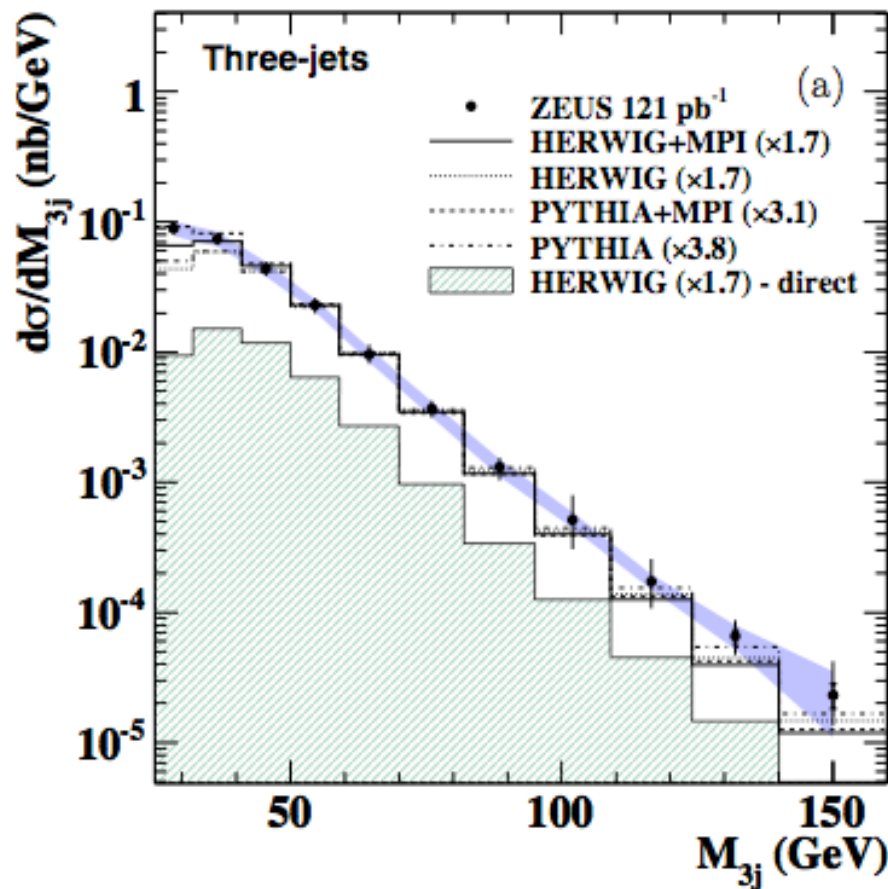
- **Motivation 1)** produce data set to test high-order pQCD
  - four-jet process shown here is the highest studied at HERA
  - PHP complicated - direct & resolved, proton and photon PDFs
- Multi-jet final states can be simulated in MC by using parton shower approximation - hard (high-Et) branching leads to additional hadronic jet
- **Motivation 2)** test this use of parton showers (only strictly valid collinearly)
- Plus, since MC predicts some influence from MPIs
- **Motivation 3)** test magnitude of predicted MPI influence on cross sections
- **Motivation 4)** look for evidence of hard MPI scattering (i.e. MPI jets)

# Analysis strategy

- Photoproduction events were selected that had: *(lumi: 121.2 pb<sup>-1</sup>)*
  - 3+ or 4+ (Kt) jets in with  $E_T^{jet} > 6$  GeV and  $|\eta^{jet}| < 2.4$
- And were subdivided into low- and high-mass samples with:
  - $25 \leq M_{nj} < 50$  GeV and  $M_{nj} \geq 50$  GeV *(invariant n-jet mass)*
- Cross sections were measured and compared to:
  - (HERWIG & PYTHIA) MC predictions with and without MPIs
  - A LO pQCD calculation (3-jet data only)
- MPIs were simulated in:
  - HERWIG using JIMMY (tuned to the data shown)
  - PYTHIA using the “simple model” in the default setting

# Comparison with Monte Carlo

- The cross sections binned differentially in the invariant 3- & 4-jet mass
- Compared to various MC cross sections (scaled as indicated in the legends)

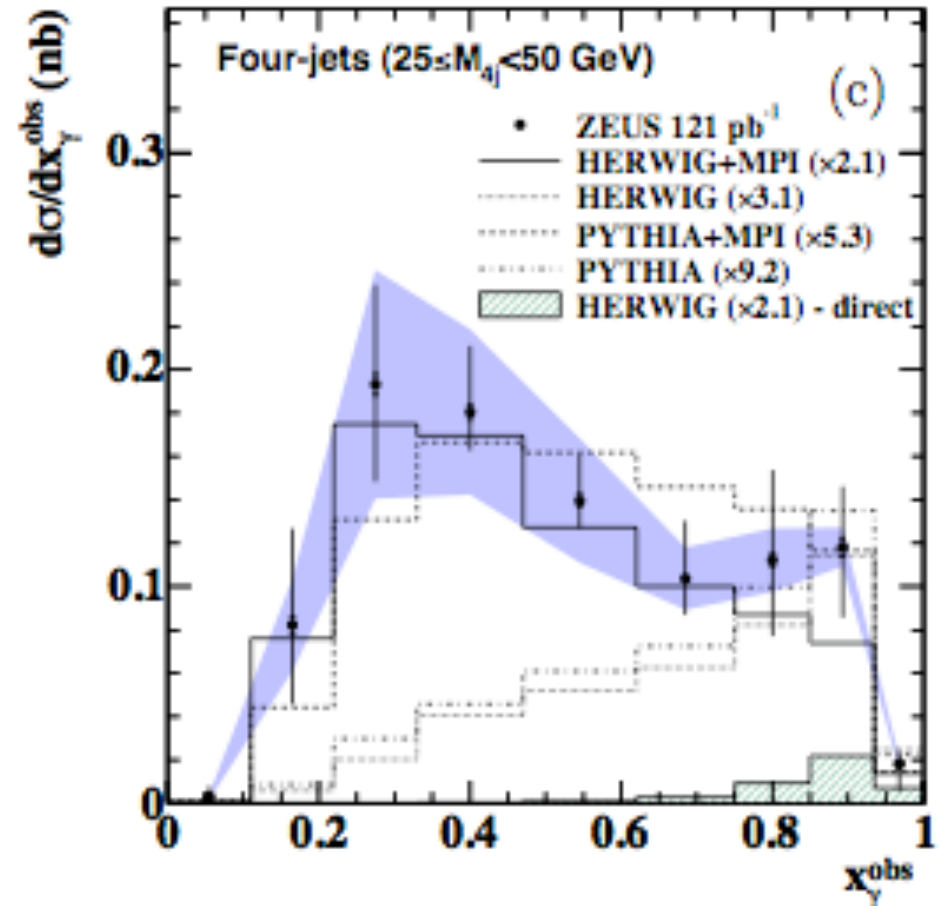
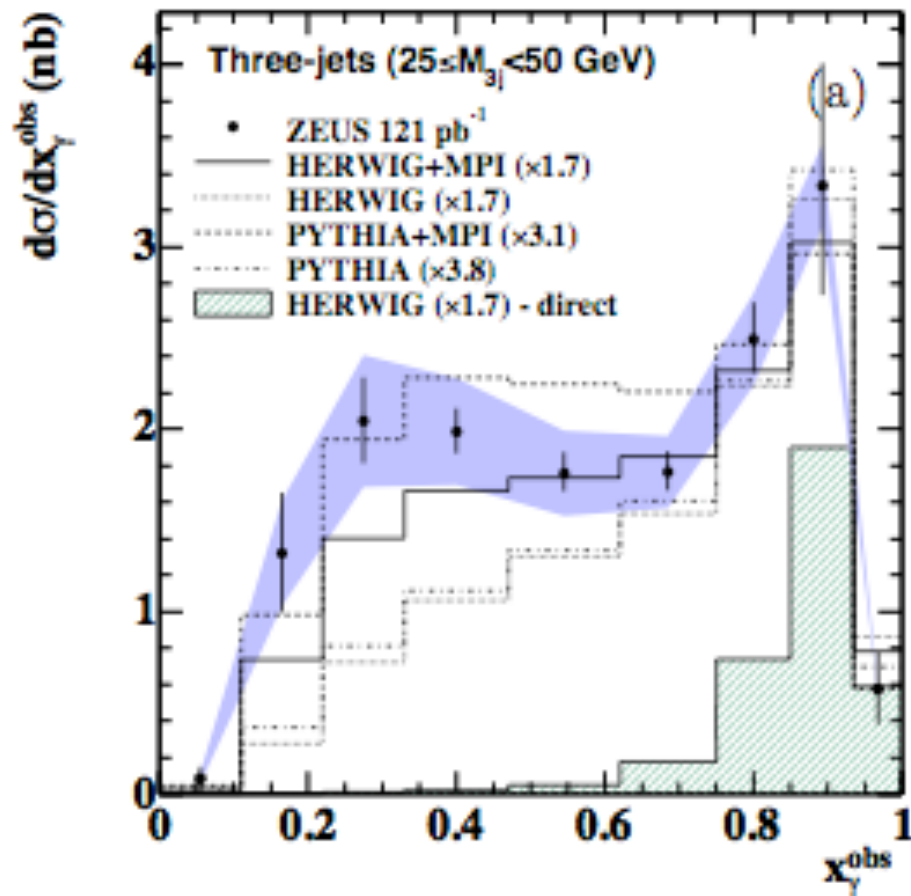


- Generally a good description by all models at high- $M_{nj}$
- Low- $M_{nj}$  only described once MPIs are introduced



# Comparison with Monte Carlo

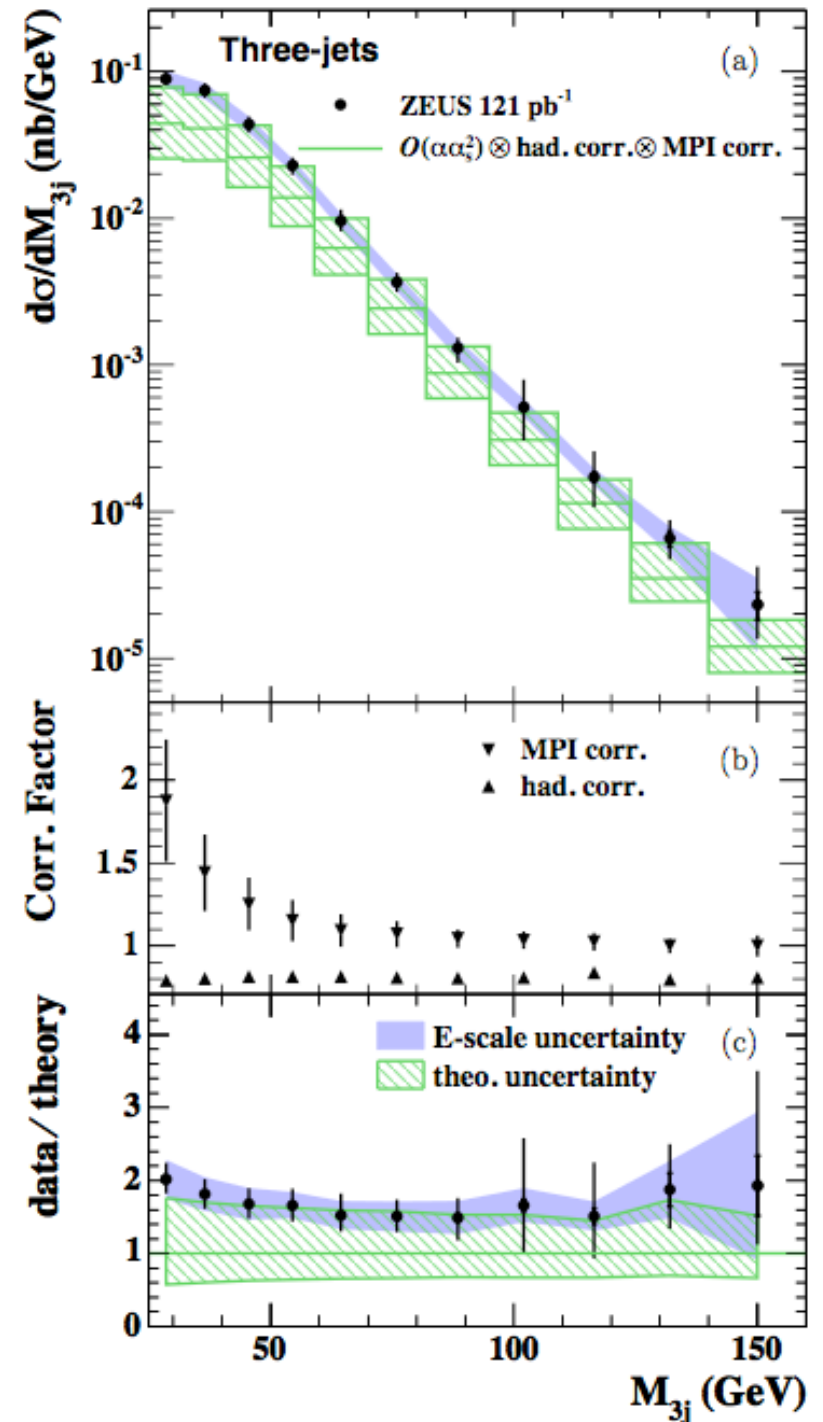
- The low- $M_{nj}$  cross sections binned differentially in  $x_\gamma^{obs}$



- High- $x_\gamma^{obs}$  (direct enriched) region described by all models
- Low- $x_\gamma^{obs}$  (resolved enriched) region requires significant MPI influence

# Comparison with LO pQCD

- $M_{3j}$  cross section compared to LO pQCD
- corrected for hadronisation & MPI effects
- Theory describes data within uncertainties
- very large MPI corrections at low- $M_{3j}$
- More evidence for MPIs but only LO pQCD
- Could it be purely due to higher orders?
- Would be nice to see a comparison with NLO pQCD - *now available (nlojet++)*
- Would be the highest order comparison in photoproduction to date
- if MPI corrections still needed at NLO that would be strong(er) evidence for MPIs



Just to summarise...

# High-Et di-jets summary

- High- $E_T$  di-jet cross sections have been measured in photoproduction
- The cross sections are sensitive to the paramterisation of the photon PDFs
- The data have been compare to NLO with 5 different photon PDFs
- The behaviour of the NLO was similar with 4 of the PDFs but the set from CJK, which incorporates a more strongly rising gluon, was markedly different
- CJK gave a poorer description of the  $x_\gamma^{obs}$  distribution but a better description of the features of the  $x_p^{obs}$  distribution. None worked throughout.
- Cross sections were measured in regions where the dominant uncertainty was in the gluon PDF. It is hoped such data will further constrain the gluon.

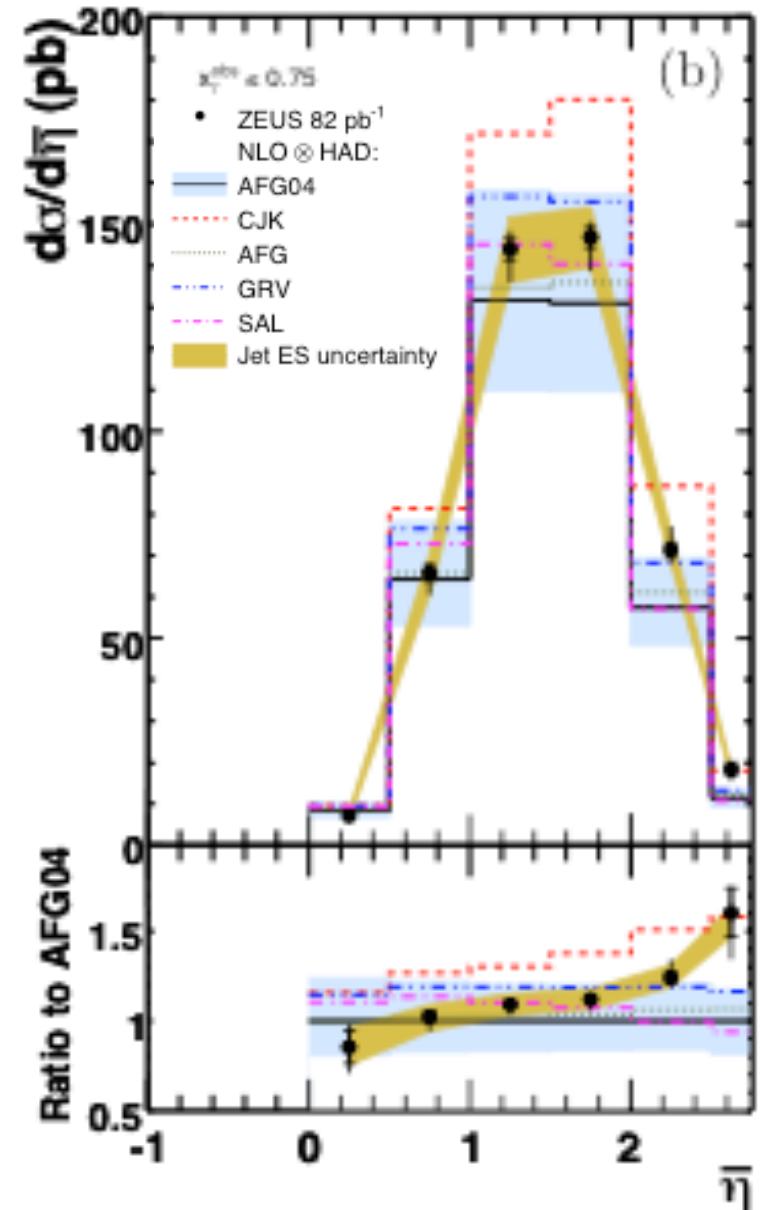
# Three- & four-jet summary

- Inclusive three- and four-jet cross sections have been measured in PHP
- They have been compared to MC with parton showers and LO pQCD
- Both require augmentation at low-  $M_{3j}$  and low-  $x_\gamma^{obs}$
- MC was use to show MPIs are a possible mechanism to explain observation
- At high- $M_{nj}$ , both LO pQCD and (scaled) MC describe the cross sections indicating minimal NLO corrections and the validity of using PS to simulate high jet multiplicities (in this region)
- The data will provide an interesting test of higher order pQCD

Back-up slides

# Photon PDF sensitivity

- Resolved-enriched:  $x_\gamma^{obs} \leq 0.75$
- define:  $\bar{\eta} = 1/2(\eta^{jet1} + \eta^{jet2})$
- All but CJK give a reasonable description for  $\bar{\eta} < 2.5$  but are too low at higher values
- Conversely, CJK is too large for  $0.5 < \bar{\eta} < 2.5$  but recreates the high- $\bar{\eta}$  cross section



# Higher order sensitivity

- Define:  $|\Delta\phi^{jj}| = |\phi^{jet1} - \phi^{jet2}|$  - (at LO:  $|\Delta\phi^{jj}| \equiv \pi$  so if  $|\Delta\phi^{jj}| < \pi$  NLO is LO)
- $|\Delta\phi^{jj}|$  data is very sensitive to higher orders away from peak at  $|\Delta\phi^{jj}| = \pi$

- can compare to “NLO”
- or MC in which higher orders are simulated using parton showers
- NLO describes peak where it really is NLO
- But underestimates the data elsewhere
- More so in resolved-enriched region
- (area normalised) MC does a much better job describing shape

