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

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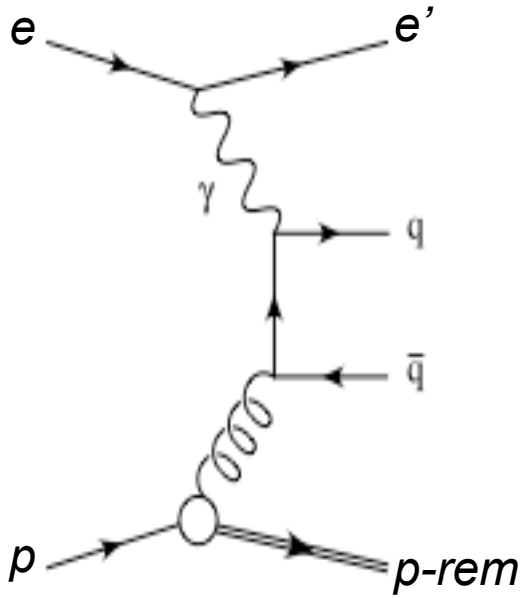
HERA

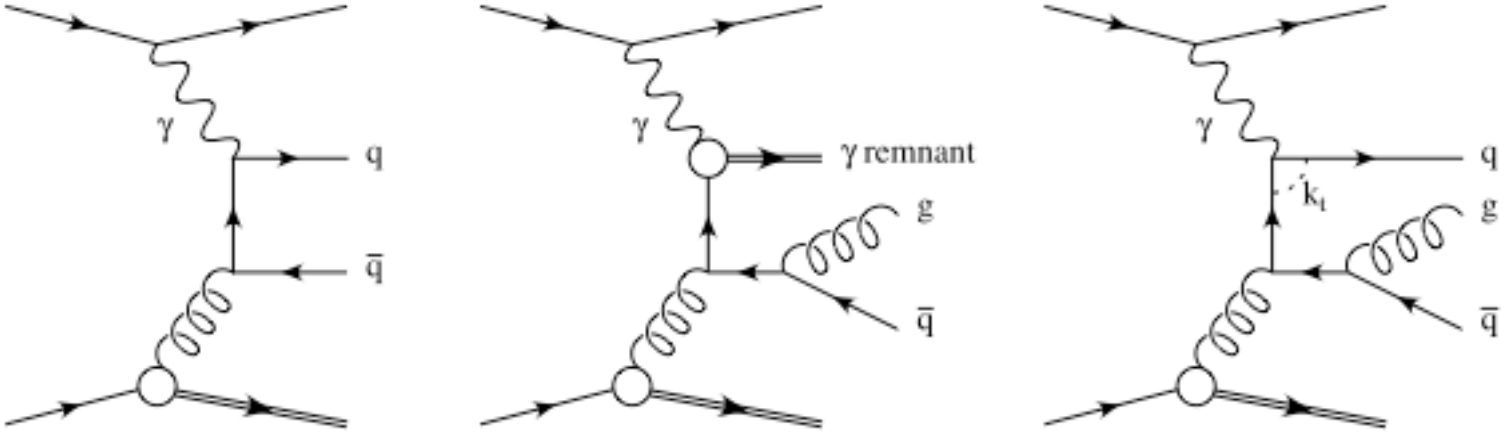
- Stands for “Hadron-Elektron-Ringanlage”
- (Was) an (electron-proton) *ep*-collider
- Located in Hamburg, Germany
- 6.3 Km long
- 10-25m underground
- Hosted H1, HERMES, HERA-B & ZEUS
- Operation started in 1992
- Final run on 30th June, 2007
- Max *p*-beam energy, E_p: 920GeV
- Max *e*-beam energy, 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 (γ) - i.e. the virtuality, $Q^2 = -\left(q_\gamma^2\right) \approx 0$
- 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 γ long-lived w.r.t. characteristic interaction time-scale, therefore:
  - valid to view collision as a γp interaction
  - γ may fluctuate into a partonic or meson-like system



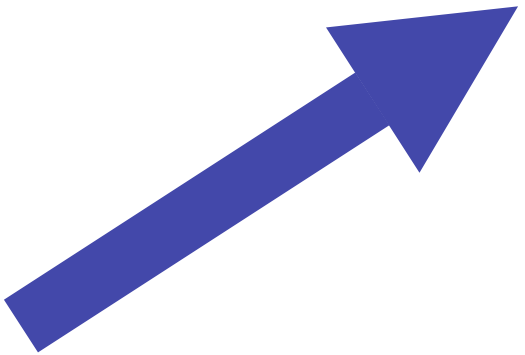
Direct & resolved photoproduction



LO direct *LO resolved* *NLO direct*

- The photon may interact as a:
  - point-like electromagnetic object: ***direct photproduction***
  - 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^γ
- 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, η
  - at such high-Et

} *see next slide for details*

- high-Et data good for PDF fitting as minimal pQCD scale uncertainty

Analysis strategy

•Jets were found using the Kt-algorithm and an event was selected if it had:

- at least two jets (ordered in Et) with
- $E_T^{jet1} > 20$ GeV & $E_T^{jet2} > 15$ GeV

(integrated lumi: 81.8 pb-1)

- 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

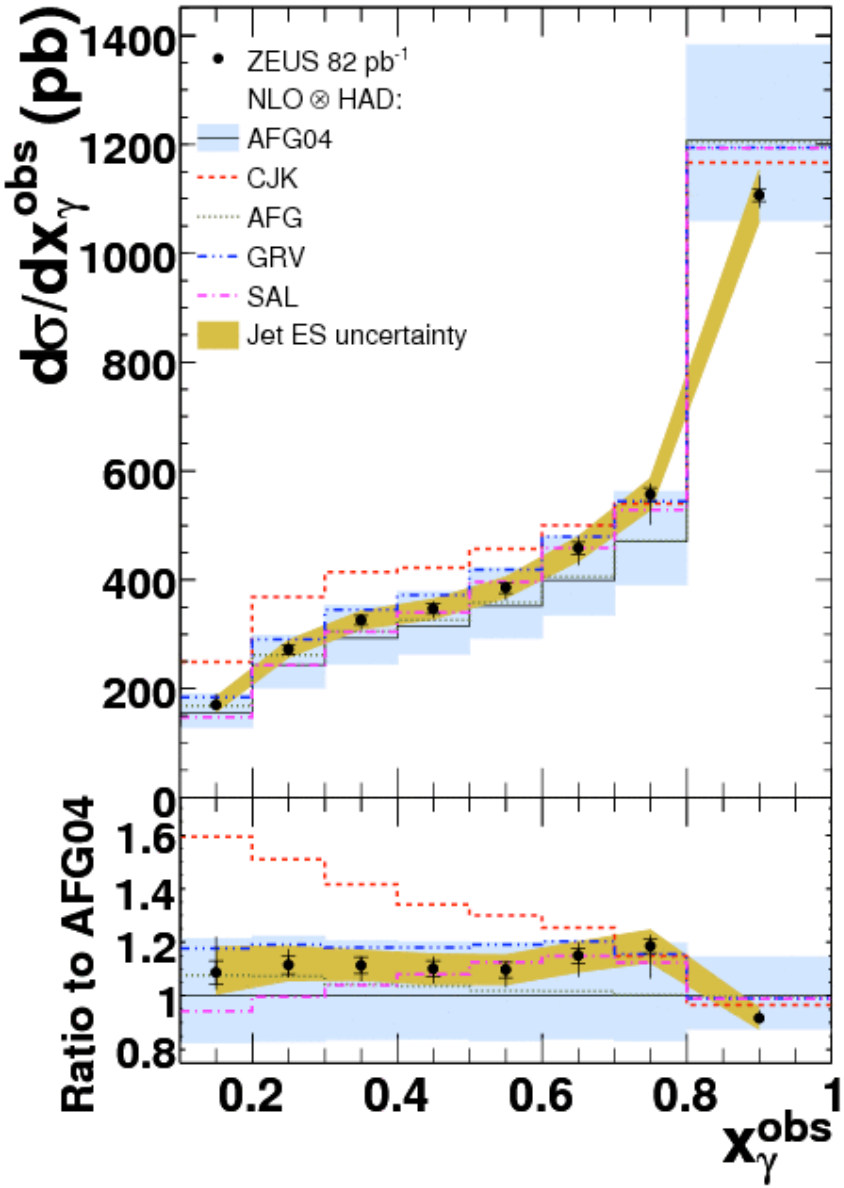
Photon PDF sensitivity

- define: $x_\gamma^{obs} = \frac{1}{2yE_e}\sum^{jets} E_T^{jet}\exp\left[-\eta^{jet}\right] \approx x_\gamma$

  y is the fraction of E_e carried by the γ

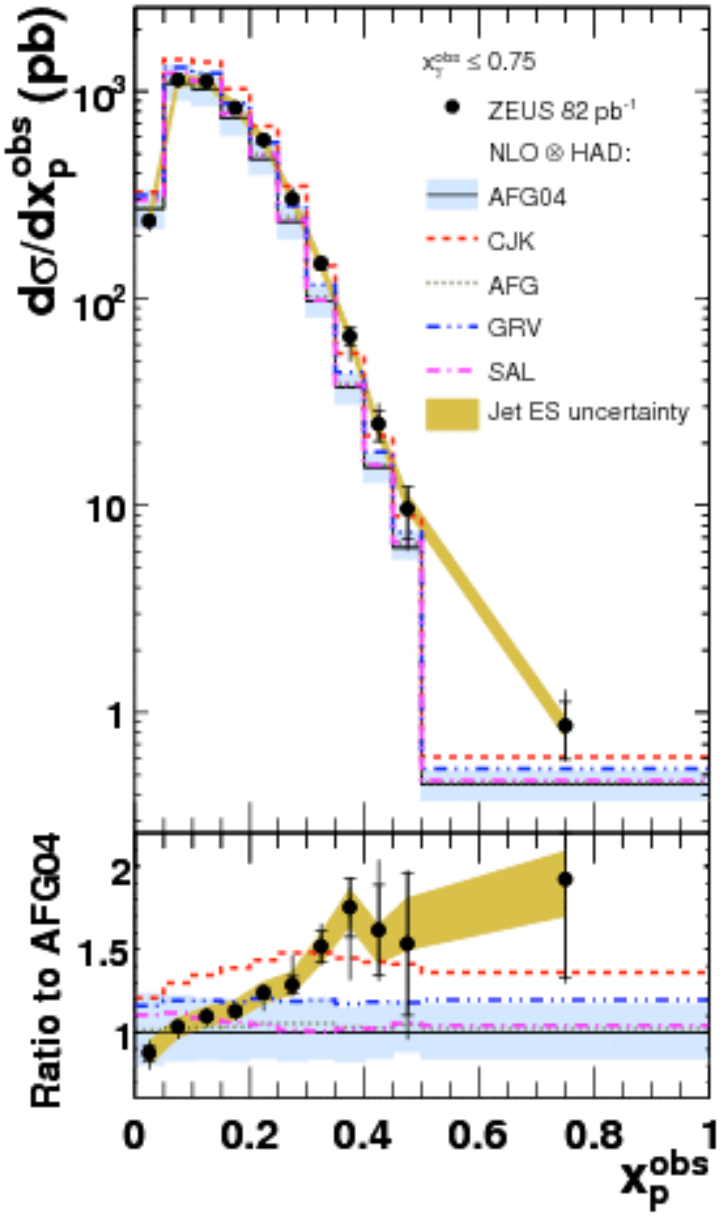
  x_γ is the fraction of the γ momentum transferred to final state

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



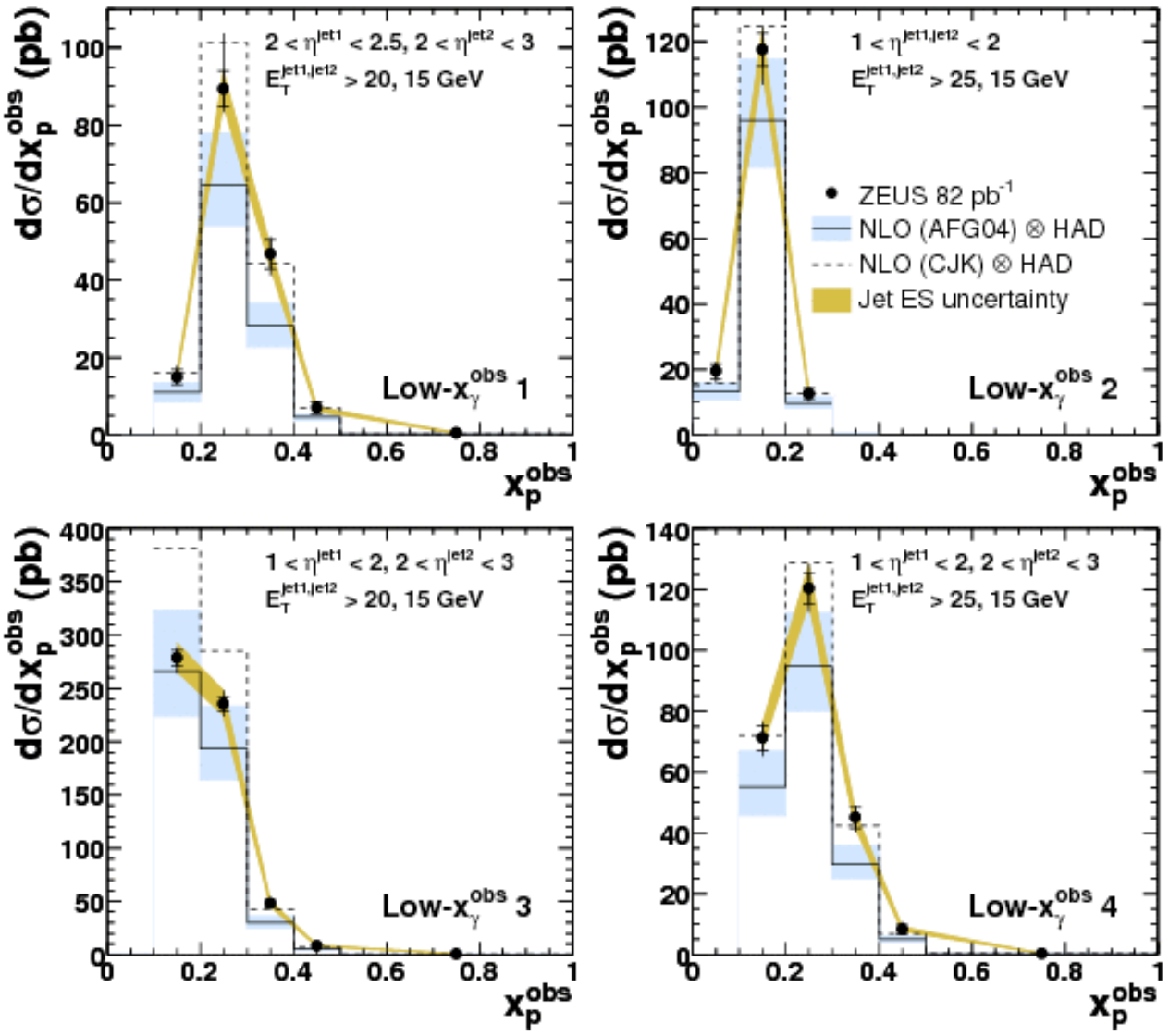
Photon PDF sensitivity

- Resolved-enriched: $x_\gamma^{obs} \leq 0.75$
- define: $x_p^{obs} = \frac{1}{2E_p} \sum^{jets} E_T^{jet} \exp\left[\eta^{jet}\right] \approx x_p$
- 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 (~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 η criteria
- Here, the gluon PDF uncertainty dominates (not shown on figure)
- All are direct-enriched (insensitive to γ-PDF)
- It is hoped these data will help constrain the gluon PDF for $x_p > 0.1$



Three- & four-jets in photoproduction

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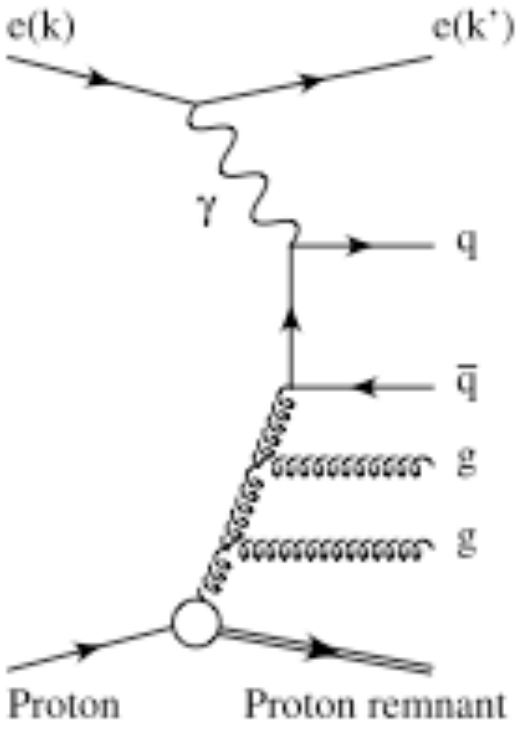
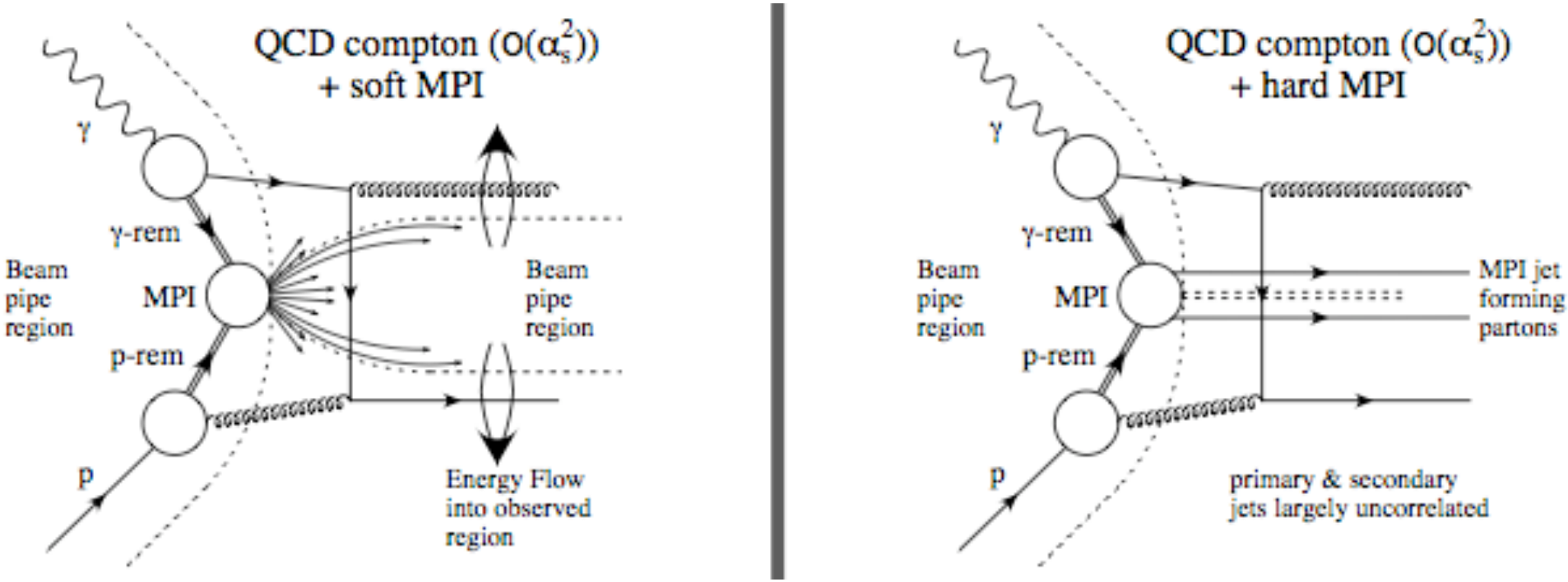
Multi-jet processes in photoproduction

- 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 $O\left(\alpha\alpha_s^{n-1}\right)$
  - resolved processes is $O\left(\alpha_s^n\right)$



4-jet direct process

Multi-parton interactions



- Roughly speaking, MPIs occur when the γ- & p-remnants interact
- Only present in resolved photoproduction - i.e. $\left(x_\gamma < 1\right)$
- 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)

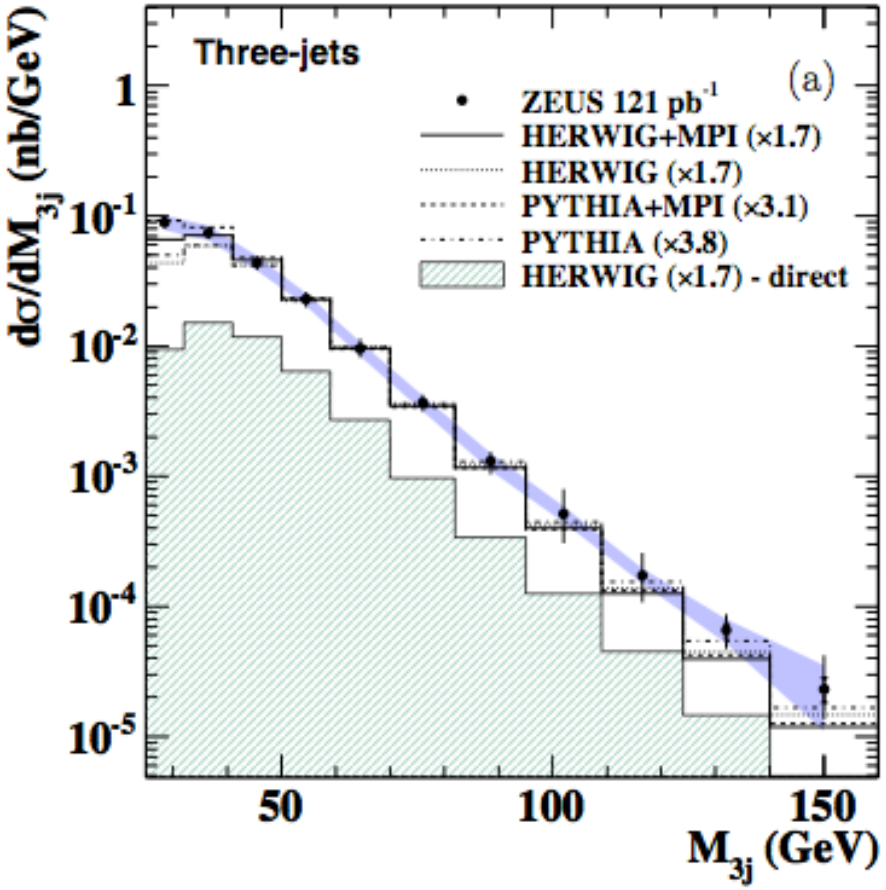
- Plus, since MC predicts some influence from MPIs
- **Motivation 3)** test magnitude of predicted MPI influence on cross sections
- **Motivation 4)** look for evidence of hard MPI scattering (i.e. MPI jets)

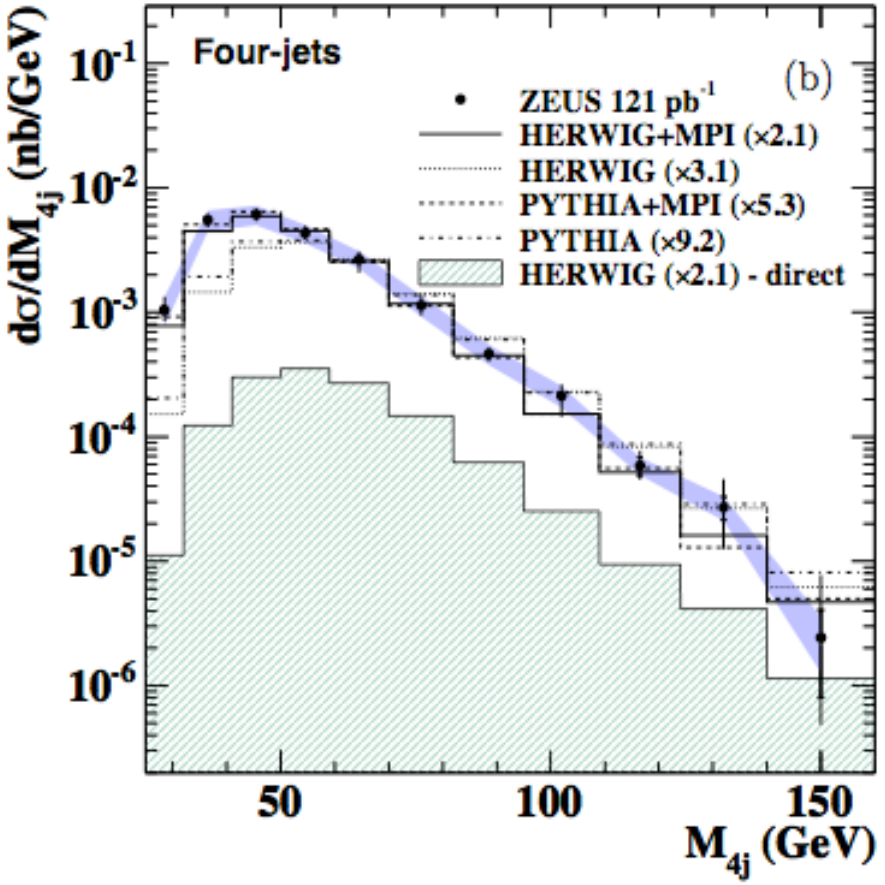
Analysis strategy

- Photoproduction events were selected that had: *(lumi: 121.2 pb-1)*
  - 3+ or 4+ (Kt) jets in with $E_T^{jet} > 6$ GeV and $\left|\eta^{jet}\right| < 2.4$
- 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)

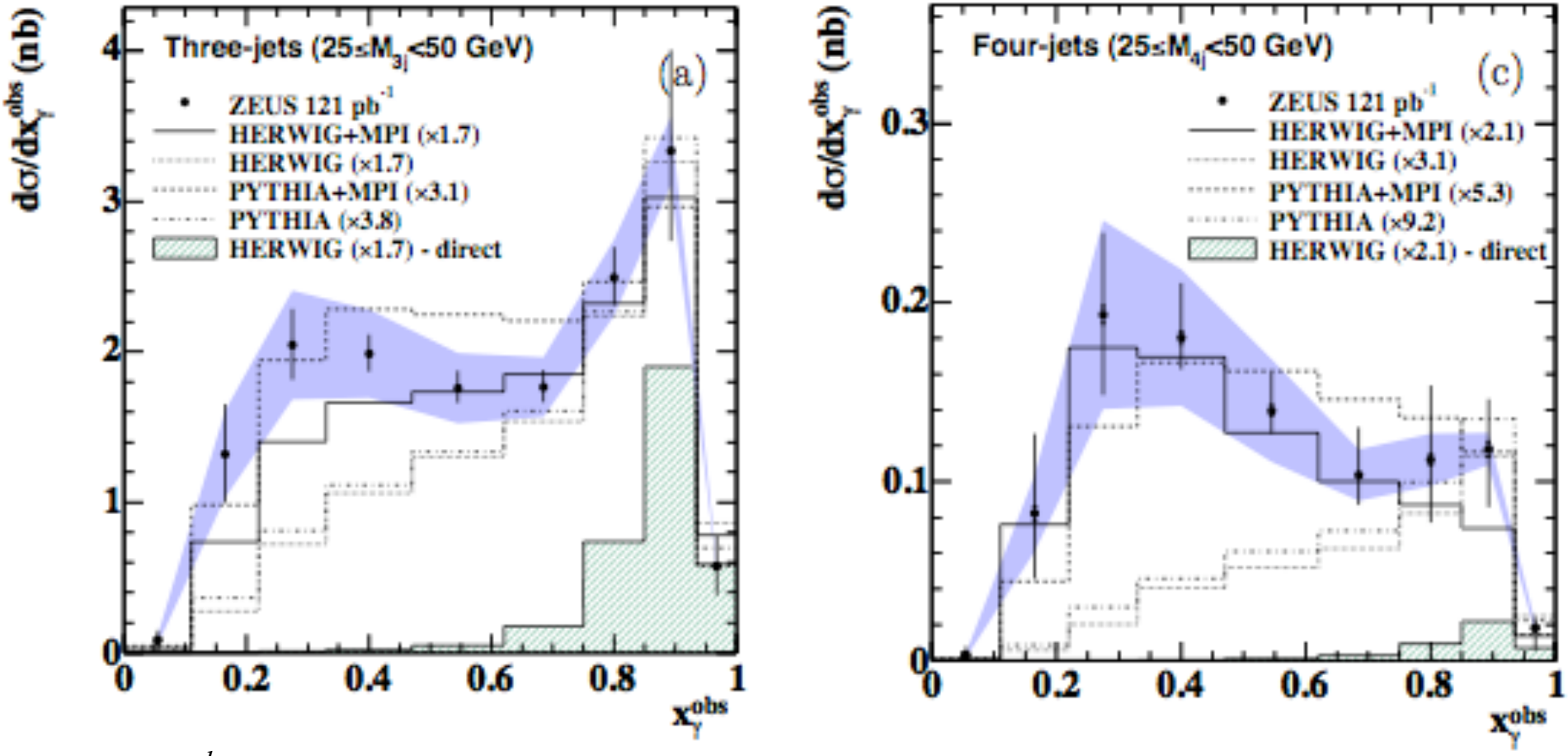




- Generally a good description by all models at high-M_{nj}
- Low-M_{nj} only described once MPIs are introduced

Comparison with Monte Carlo

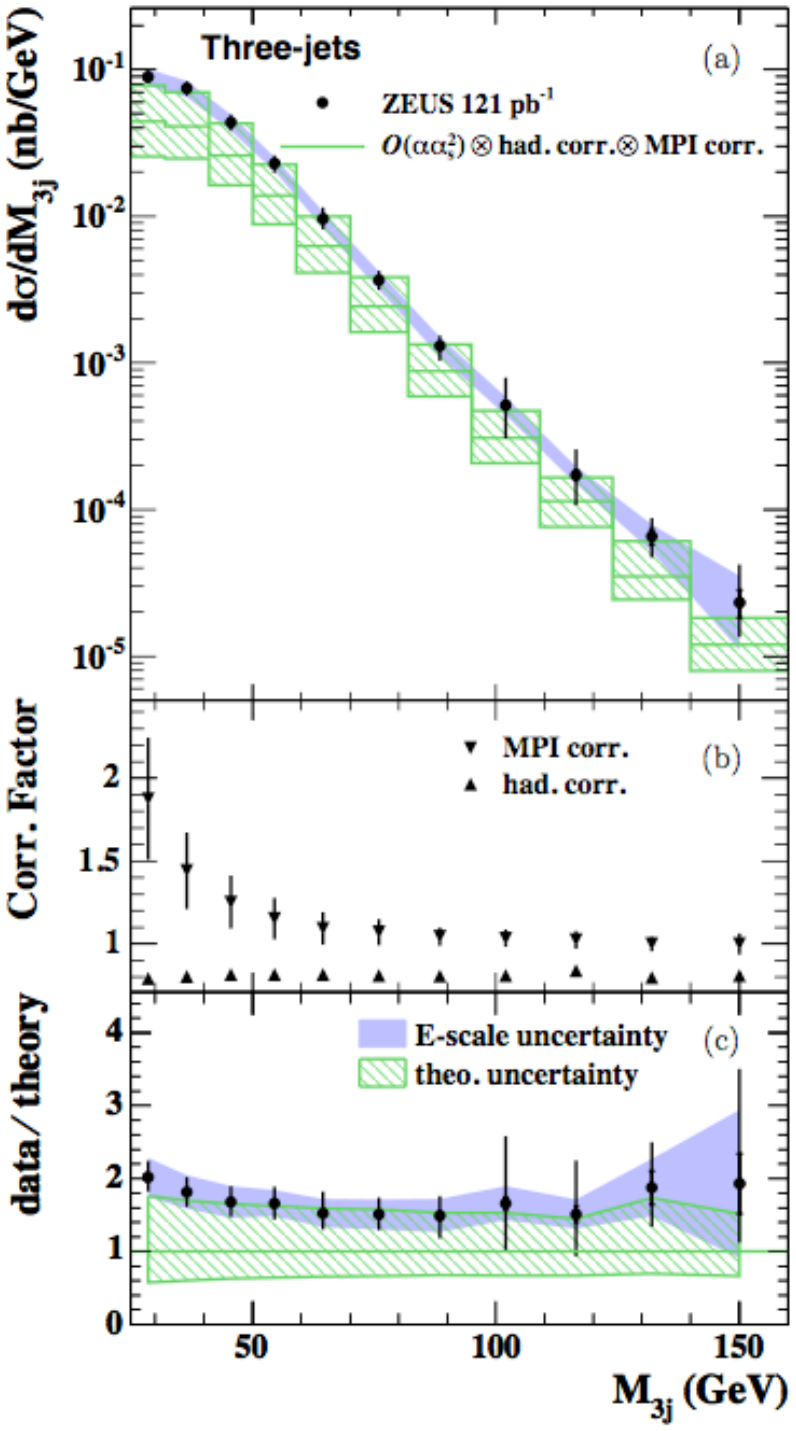
- The low-M_{nj} cross sections binned differentially in x_γ^{obs}



- High-x_γ^{obs} (direct enriched) region described by all models
- Low-x_γ^{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_γ^{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- $M_{3\,j}$ and low- x_{γ}^{obs}
- MC was use to show MPIs are a possible mechanism to explain observation
- At high-Mnj, 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: $x_\gamma^{obs} \leq 0.75$

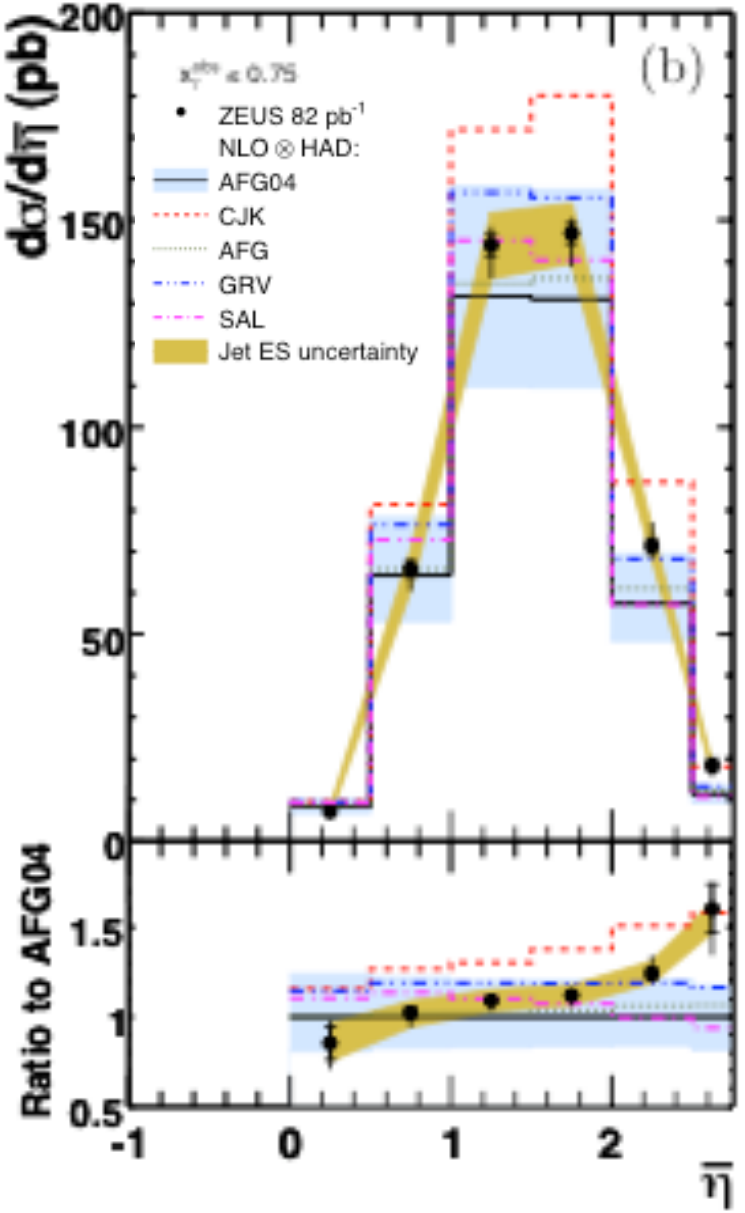
- define: $\overline{\eta} = 1/2\left(\eta^{jet1} + \eta^{jet2}\right)$

- All but CJK give a reasonable description for

  $\overline{\eta} < 2.5$ but are too low at higher values

- Conversely, CJK is too large for $0.5 < \overline{\eta} < 2.5$

  but recreates the high-$\overline{\eta}$ cross section



Higher order sensitivity

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