

# High- $p_T$ Processes and the Photon Structure

## (Jet) Photoproduction Results from HERA

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on behalf of the H1 and ZEUS Collaborations

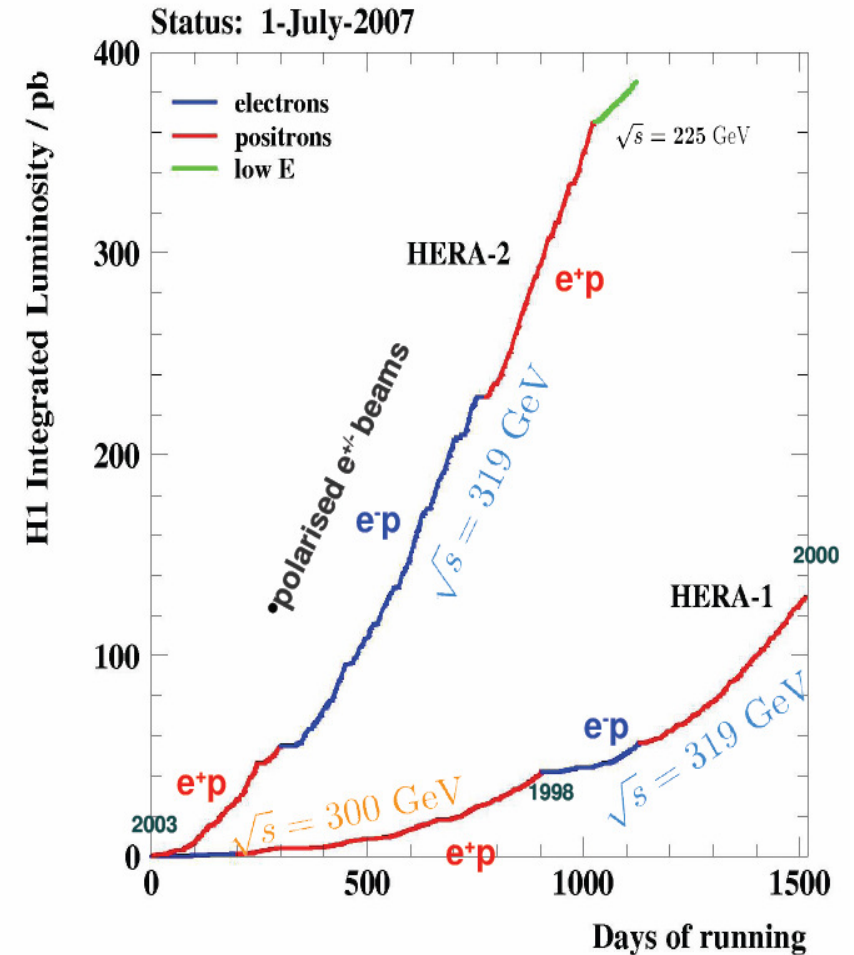
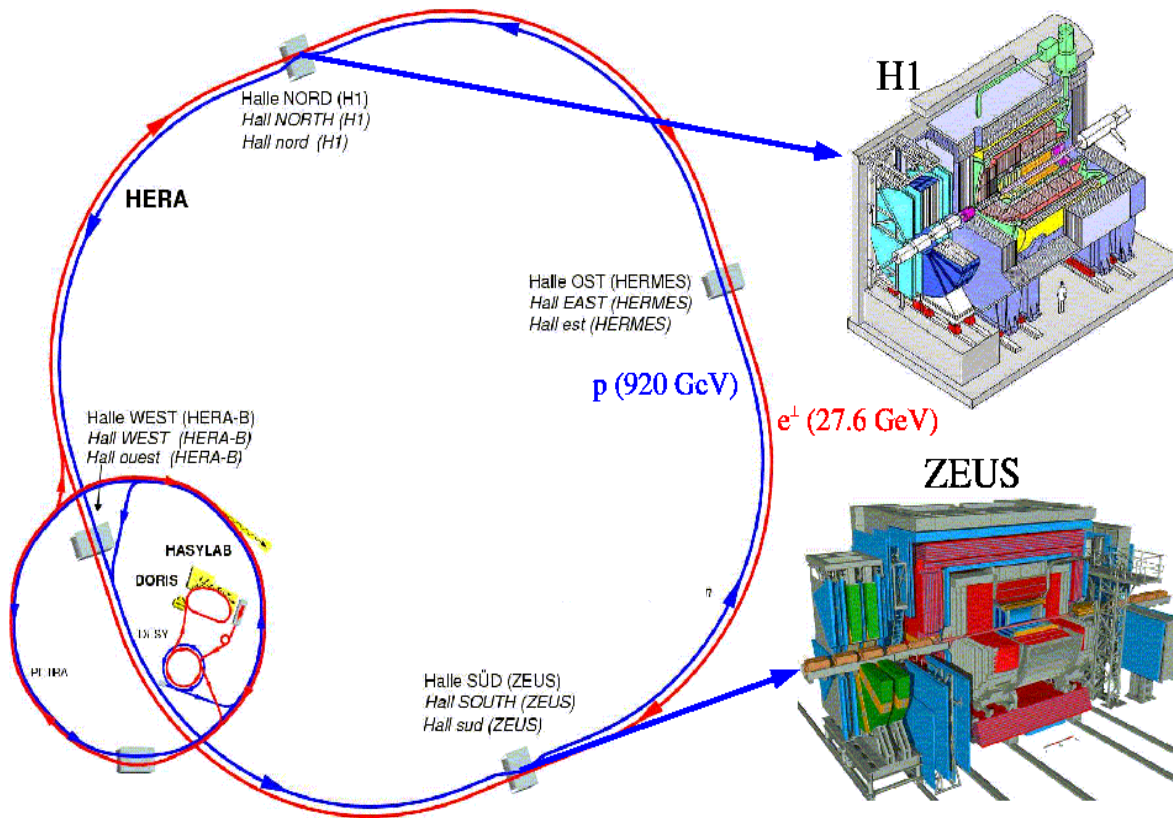


Workshop on  
High-Energy Photon Collisions  
CERN, 22 April 2008

- Introduction
- The resolved photon
- Jet cross sections
- PDF sensitivity
- Prompt photon production
- Underlying event and MPI

# HERA, H1, ZEUS

- operation from 1992-2007
- world's largest electron microscope ( $\lambda \sim 1/Q$ ).
- 820/920 GeV protons on 27.5 GeV electrons.

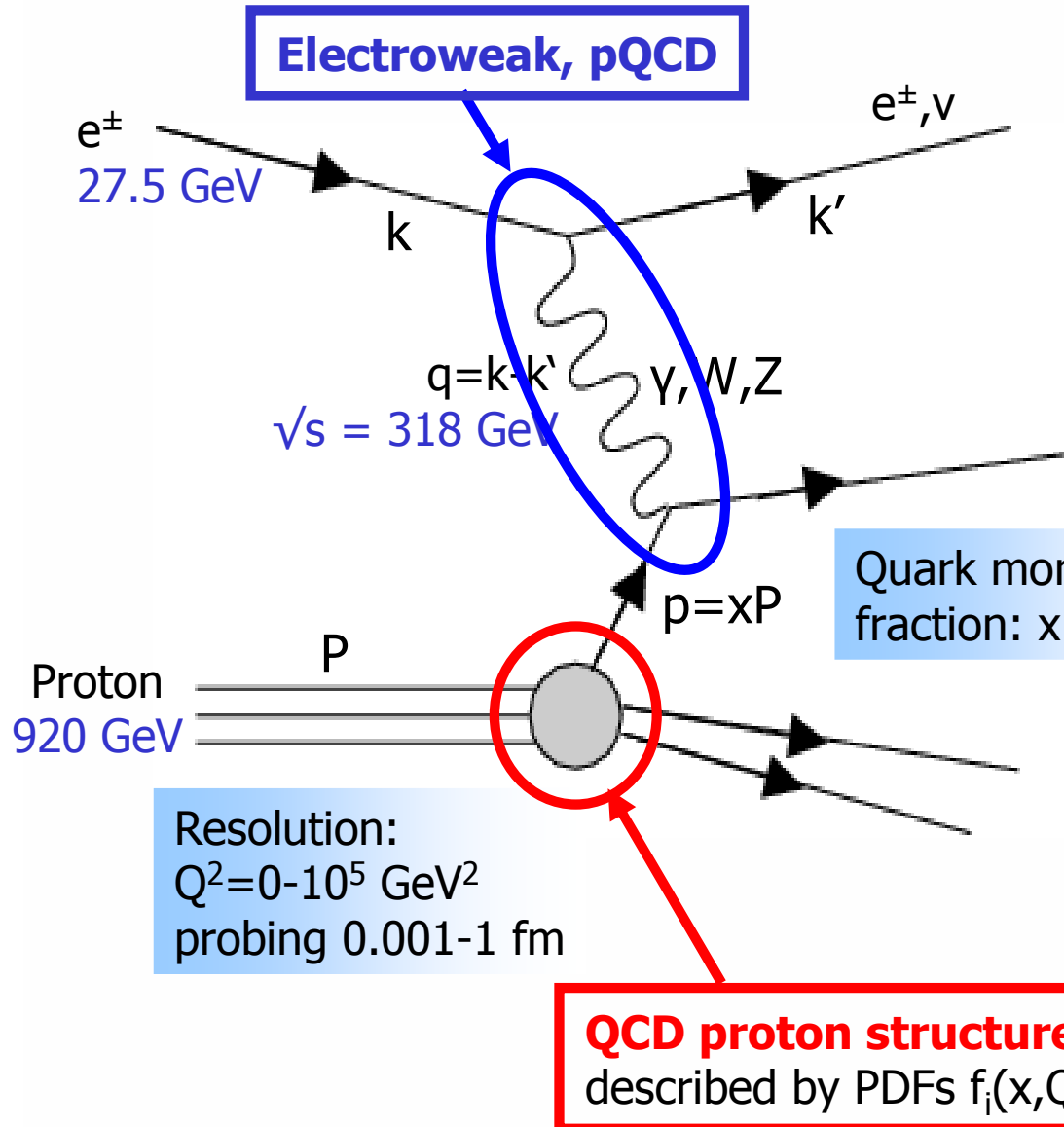


- H1:**
- LAr calorimeter with 45000 cells.
  - $e^\pm$ :  $\sigma/E = 12\%/\sqrt{E[\text{GeV}]} + 1\%$
- ZEUS:**
- comp. U/scint., 12k cells.
  - hadrons:  $\sigma/E = 35\%/\sqrt{E[\text{GeV}]}$
- Silicon tracking; lumi from  $ep \rightarrow e\gamma$ .

	$E_p$ (GeV)	HERA ( $\text{pb}^{-1}$ )	ZEUS ( $\text{pb}^{-1}$ )
HERA-I	820 / 920	193	143
HERA-II	920	562	407
LER/MER	460 / 575	16 / 9	13 / 8

# PHYSICS AT HERA

## The electron as a probe for the proton structure



Kinematic variables:

- $Q^2 = -q^2 = -(k - k')^2 \sim 1/\lambda^2$  (resolution)
- $y = qp/kp = 1 - E'/E$  (in p rest frame)
- $x = Q^2/(2pq)$ :  $10^{-6} < x < 1$

Related by  $Q^2 = sxy$ ; determined from scattered e or from HFS.

$$\sigma(ep) \sim \sigma(eq) \otimes PDF$$

Quark momentum fraction:  $x = 10^{-6} - 1$

Resolution:  
 $Q^2 = 0 - 10^5 \text{ GeV}^2$   
probing 0.001-1 fm

Distinguish:

- Neutral and charged current
- DIS and photoproduction

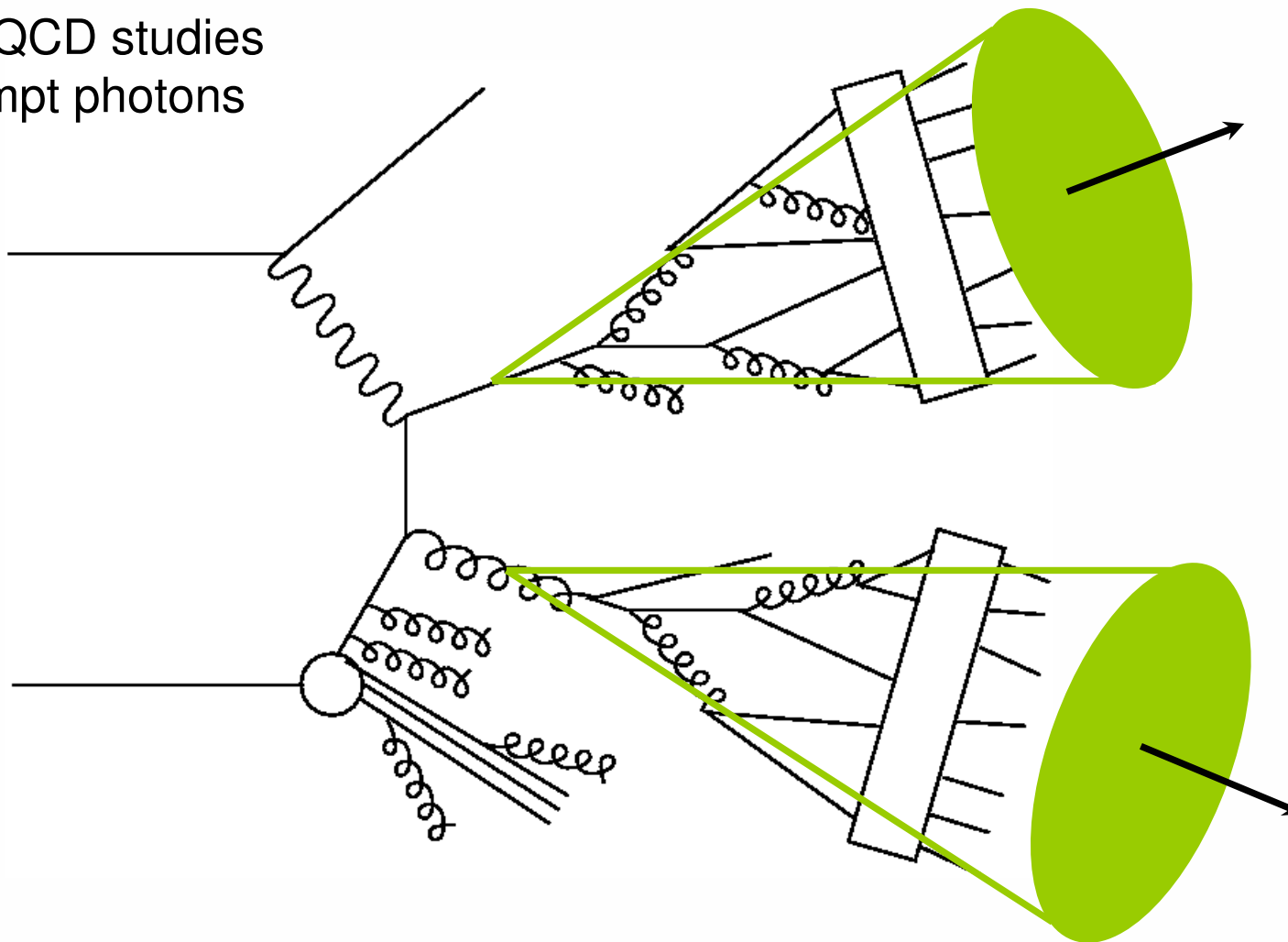
DIS @ HERA:

- 1) super-microscope to study PDFs
- 2) Sensitivity to EW physics!

# JETS: WHY AND WHAT?

HERA: rich hadronic final state

- detailed QCD studies
- jets, prompt photons

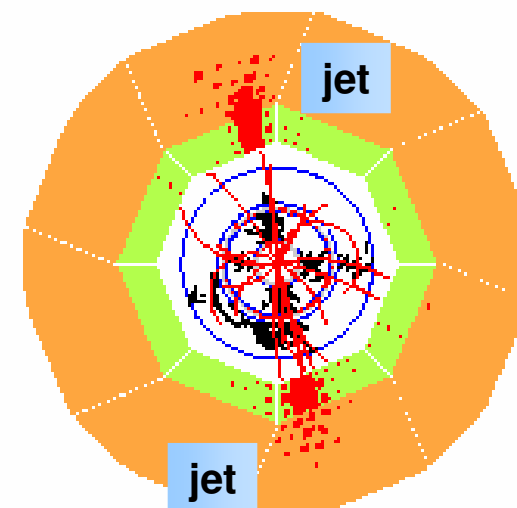


$$\sigma_{jet} = \sum_n \alpha_S^n(\mu_R^2) \cdot \sum_{a=q,\bar{q},g} \int dx_p dx_\gamma f_{a/p}(x_p, \mu_F^2) \cdot \hat{\sigma}_{n,ab}(\mu_R^2, \mu_F^2, x_p, x_\gamma) \cdot f_{b/\gamma}(x_\gamma, \mu_F^2)$$

# JETS IN PHOTOPRODUCTION

## Jet technicalities:

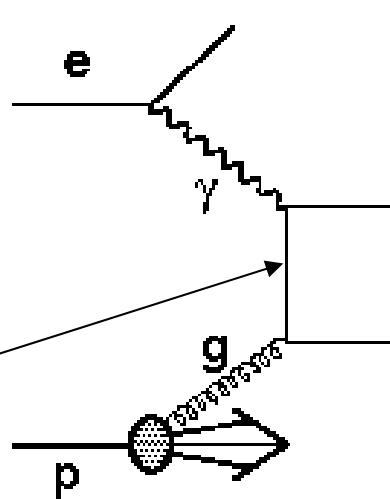
- longitudinally invariant  $k_T$  algorithm in inclusive mode
- Run on calorimeter cells or “energy flow objects”.
- Hard jets selected using cuts on transverse energy  $E_T$ ,
- Detector acceptances  $-1 < \eta < 2.5$ , with  $\eta = -\ln \tan(\theta/2)$ .
- (Jet energy scale and jet  $E_T$  corrections.)



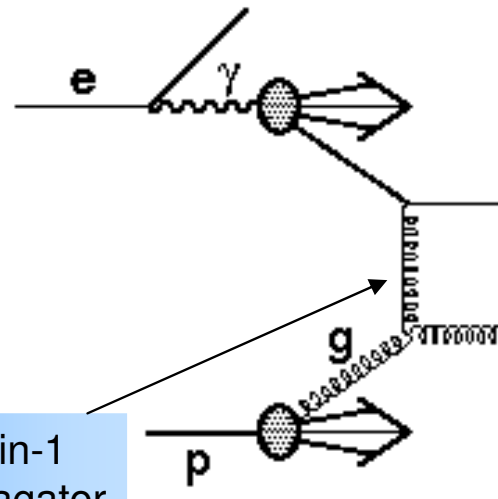
## Direct versus resolved photoproduction:

- Quasi-real photon can fluctuate into hadronic system before undergoing the hard scattering: “resolved” interactions.
- Proton and photon momentum fractions  $x_p$  and  $x_\gamma$ :

$$x_p = \frac{E_{T,1}e^{\eta_1} + E_{T,2}e^{\eta_2}}{2E_p}$$



Spin-1/2  
propagator



Spin-1  
propagator

$$x_\gamma = \frac{E_{T,1}e^{-\eta_1} + E_{T,2}e^{-\eta_2}}{2yE_e}$$

$x_\gamma > 0.8$ : direct

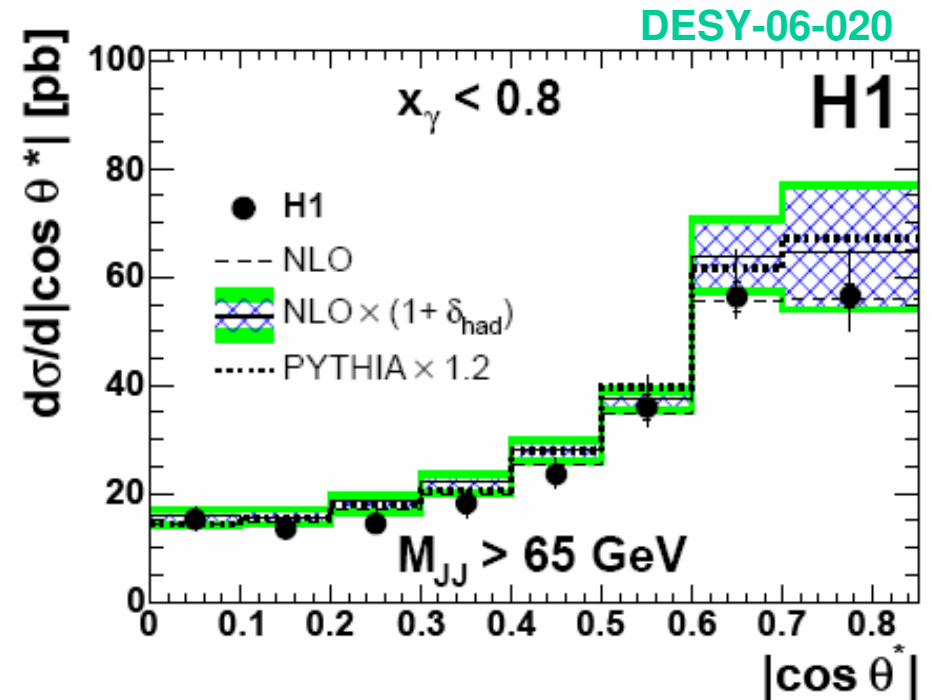
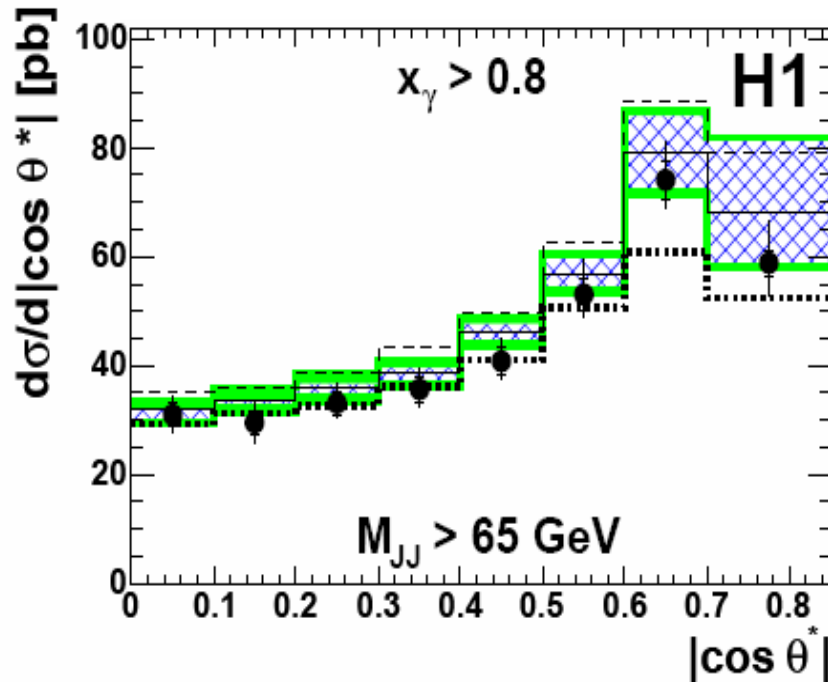
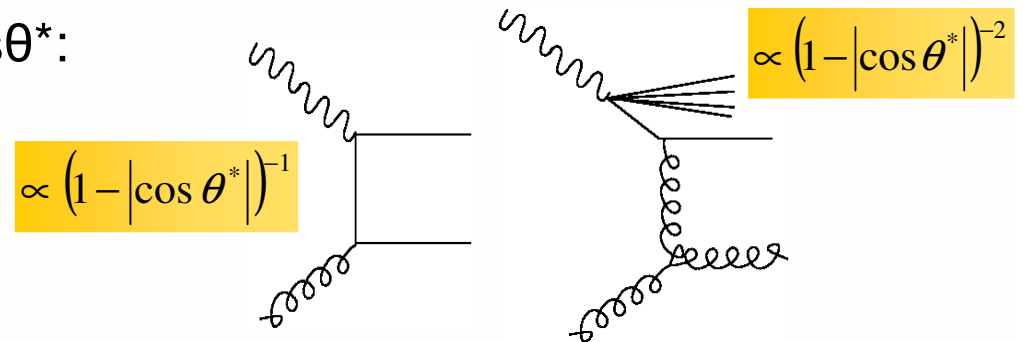
$x_\gamma < 0.8$ : resolved

# CONFIRMATION: RESOLVED CONCEPT

Observable: CMS scattering angle:  $\cos\theta^*$ :

$$\cos\theta^* = \tanh\left(\frac{\eta^{(1)} - \eta^{(2)}}{2}\right)$$

→ Resolved should rise more rapidly due to different nature of propagator:



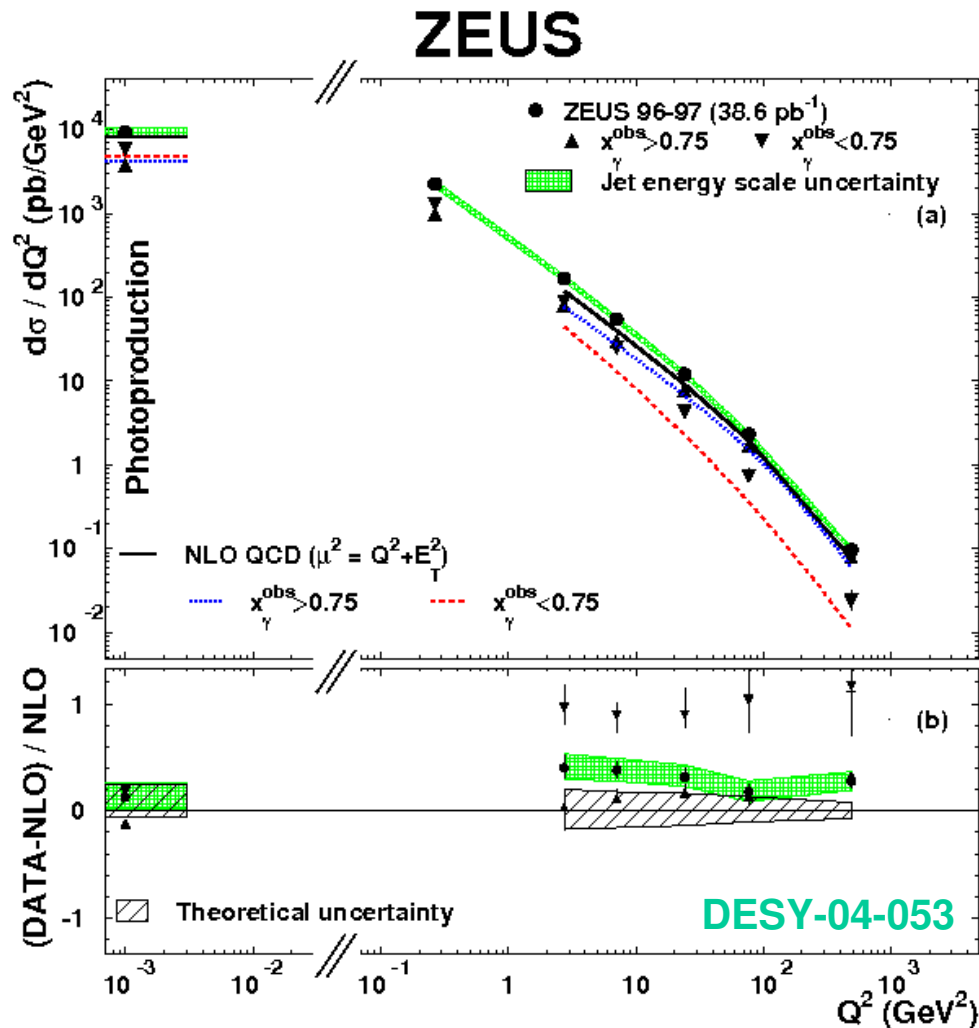
[ H1 data,  $66.6 \text{ pb}^{-1}$ ,  $0.1 < y < 0.9$   
 Dijets;  $E_T > 25 \text{ GeV}$ ,  $-0.5 < \eta < 2.75$  ]

→ Beautiful confirmation of “resolved” concept.  
 → similar results from ZEUS (DESY-01-220)

# AMOUNT OF RESOLVED (PHP AND DIS)?

## Single-differential dijet cross section $d\sigma/dQ^2$ :

- For photoproduction  $Q^2 = 0$  and DIS (here for  $Q^2 < 1000 \text{ GeV}^2$ ).
- Separately for direct and resolved events ( $x_\gamma < > 0.75$ ).

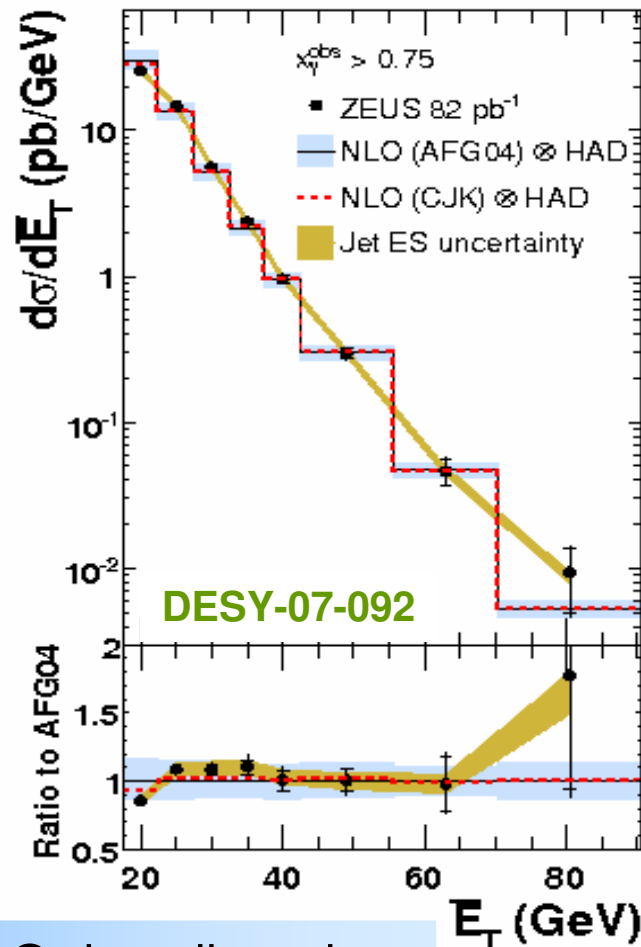
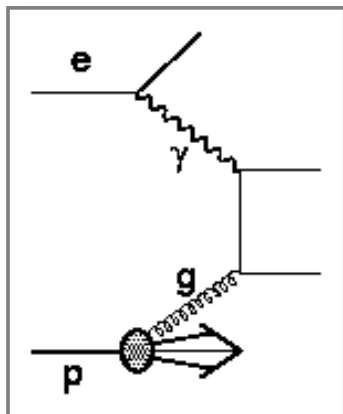


- Even at  $Q^2 = 500 \text{ GeV}^2$  about 24% “resolved” events!
- NLO QCD  $\sim 30\%$  too low.
- Resolved contribution in DIS not described by NLO QCD (not included in DISASTER++)
- LO MC models can describe the data.
- For  $Q^2 = 0$  data in agreement with NLO.

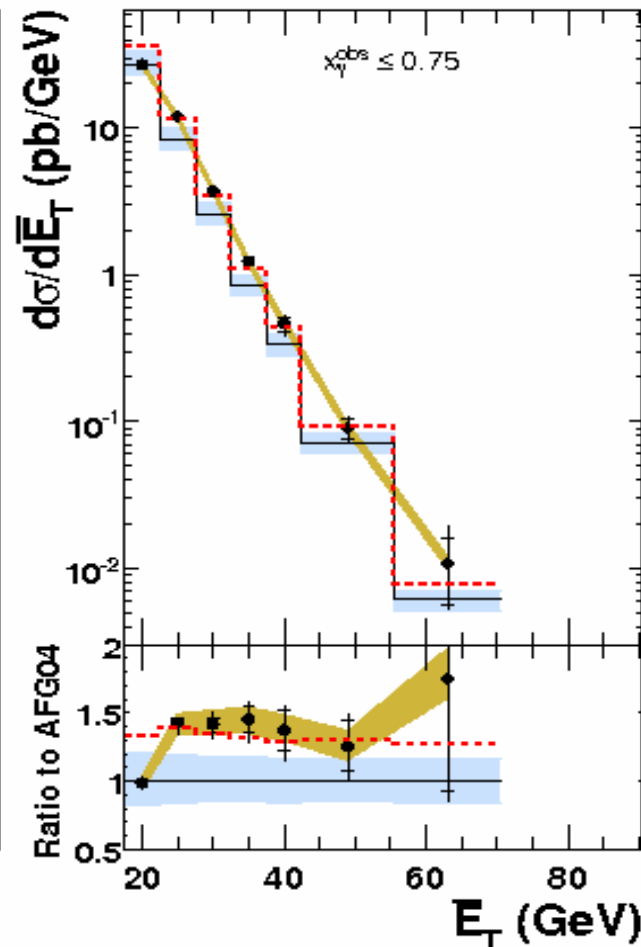
[ ZEUS data,  $38.6 \text{ pb}^{-1}$ ,  $0.2 < y < 0.55$   
 Dijets;  $E_T > 7.5/6.5 \text{ GeV}$ ,  $-3 < \eta_{\text{yp}} < 0$  ]

# JETS IN PHOTOPRODUCTION

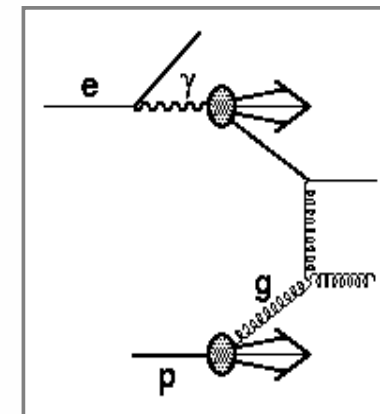
Cross-sections in direct and resolved:



Direct: NLO describes data on the level of about 10%.



Resolved: large influence of photon PDF (up to 50%)  
→ potential to constrain?

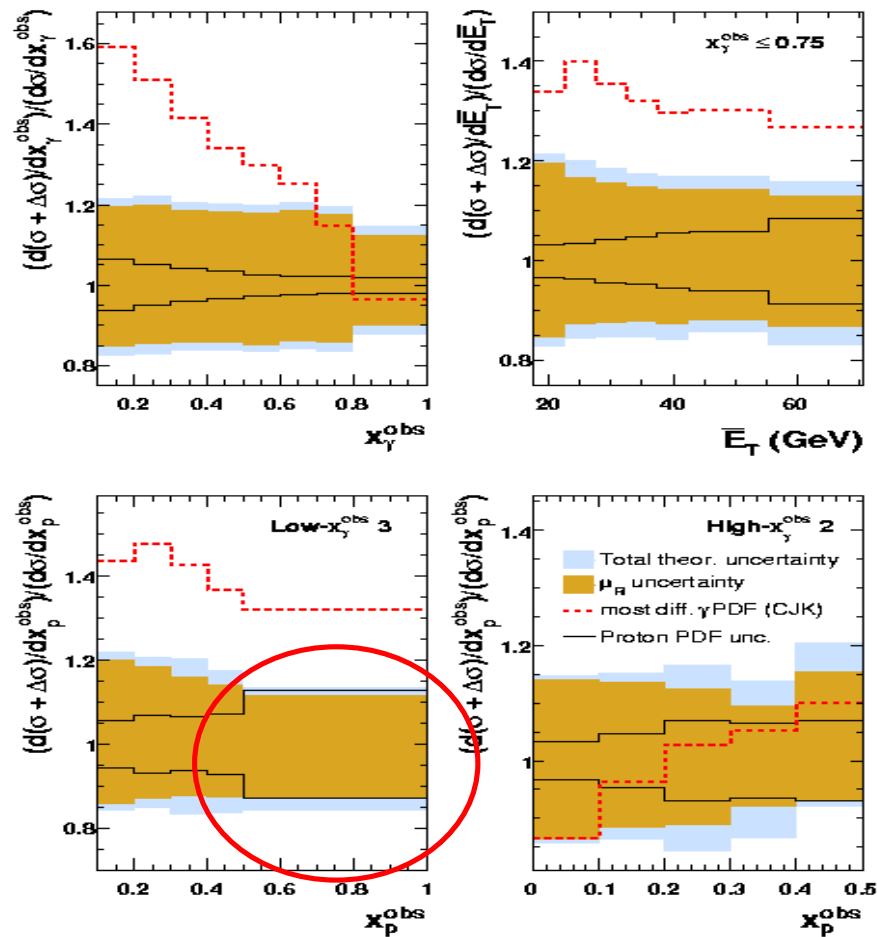


[ ZEUS data, 81.8 pb<sup>-1</sup>, 0.15 < y < 0.7  
Dijets; E<sub>T</sub> > 20/15 GeV, -1 < η < 3 ]

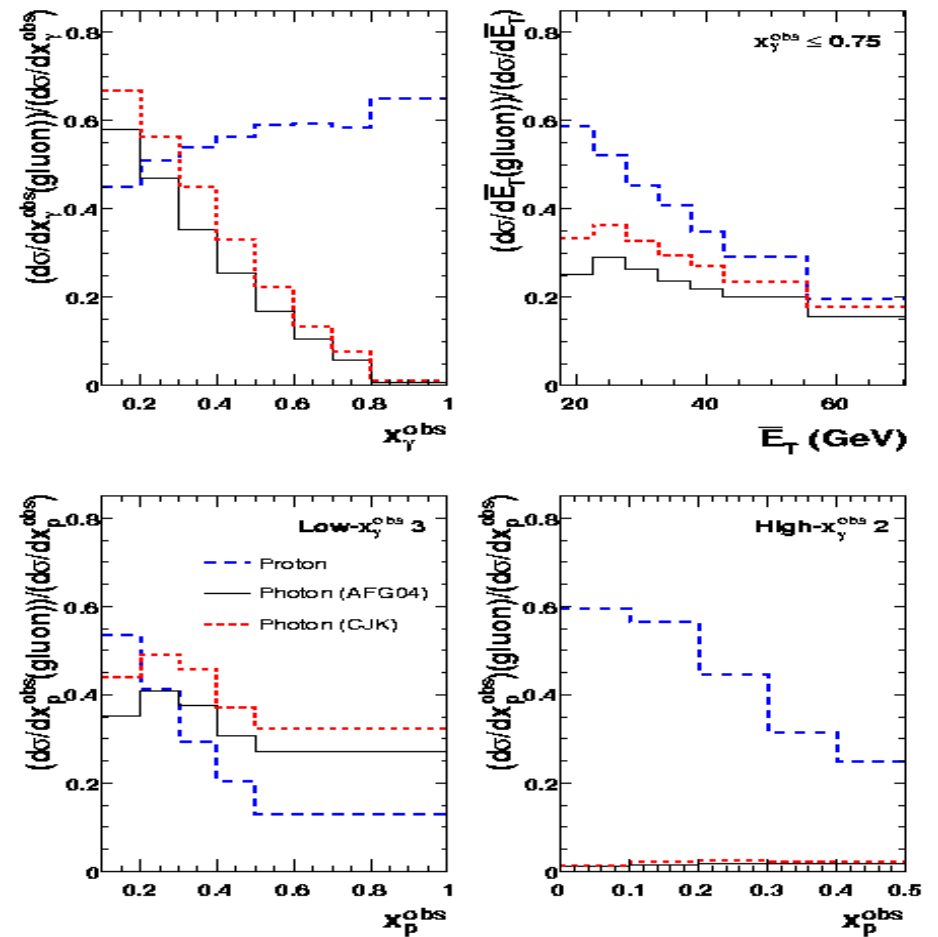


# PDF SENSITIVITY

Theoretical uncertainties ...  
... for different kinematic regions.



In addition: partly large gluon contributions from p and/or  $\gamma$ :

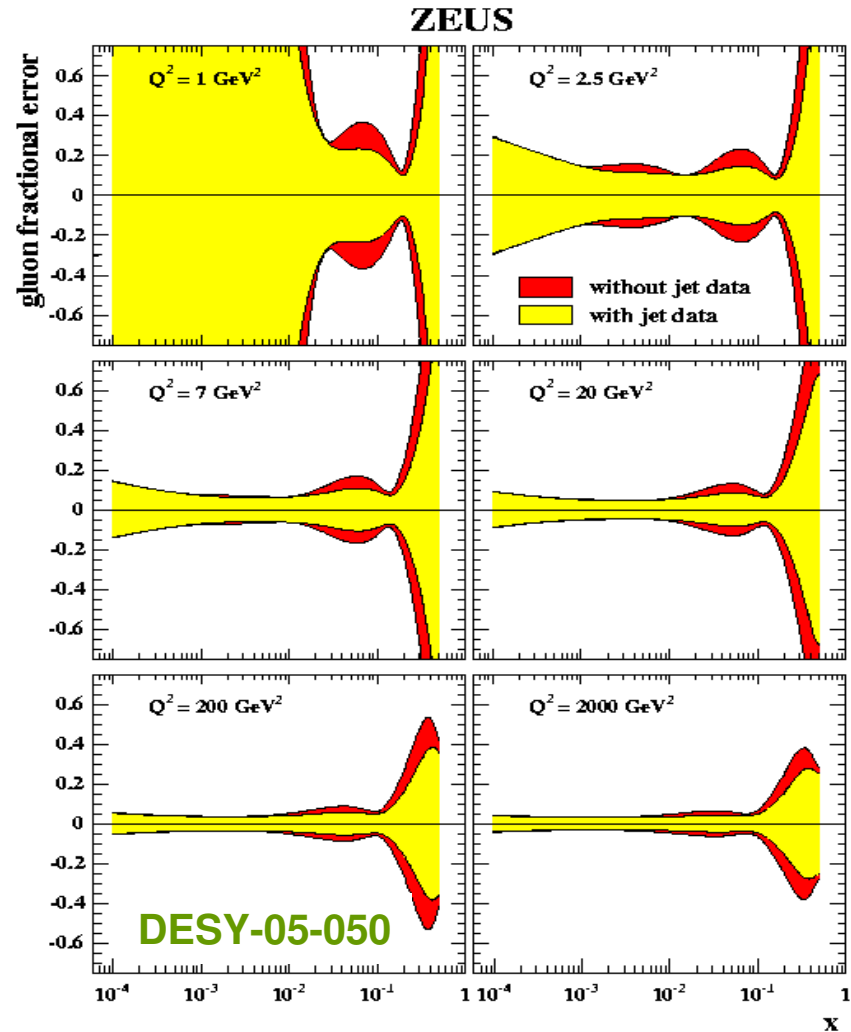
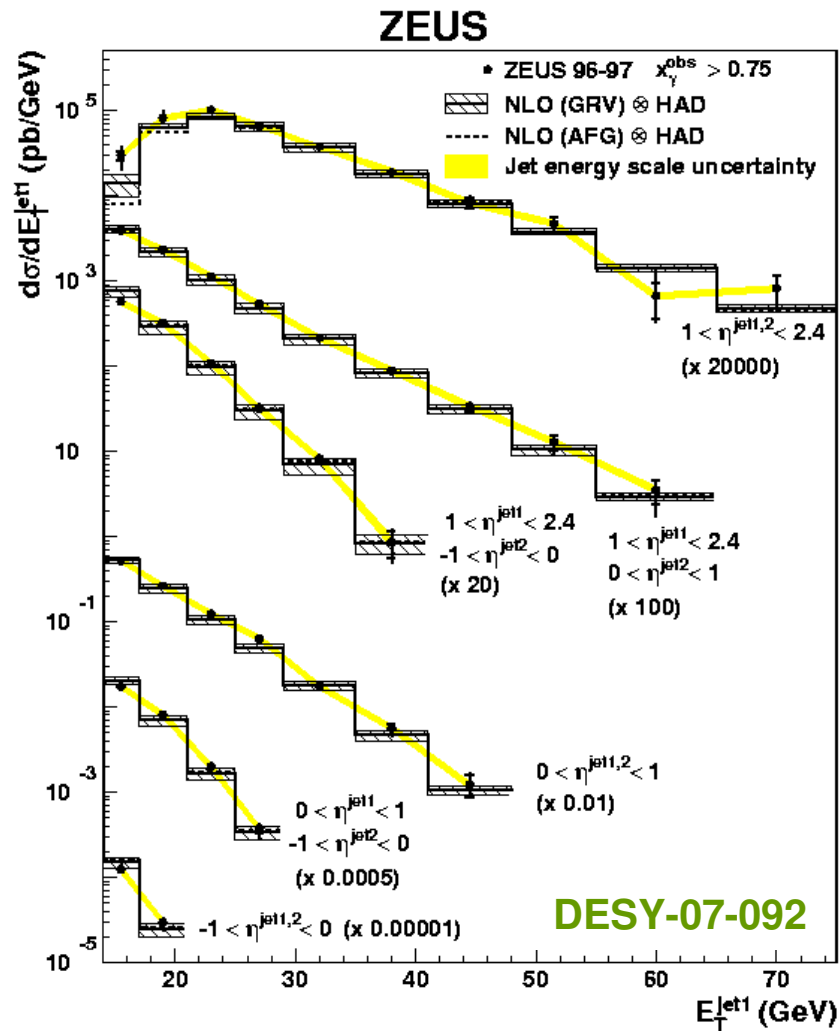


Proton PDF: Sometimes dominant!  
Photon PDF: Large effect!

➔ Potential to constrain both photon + proton PDFs using high- $E_T$  PHP!

# IMPROVING THE PROTON PDF

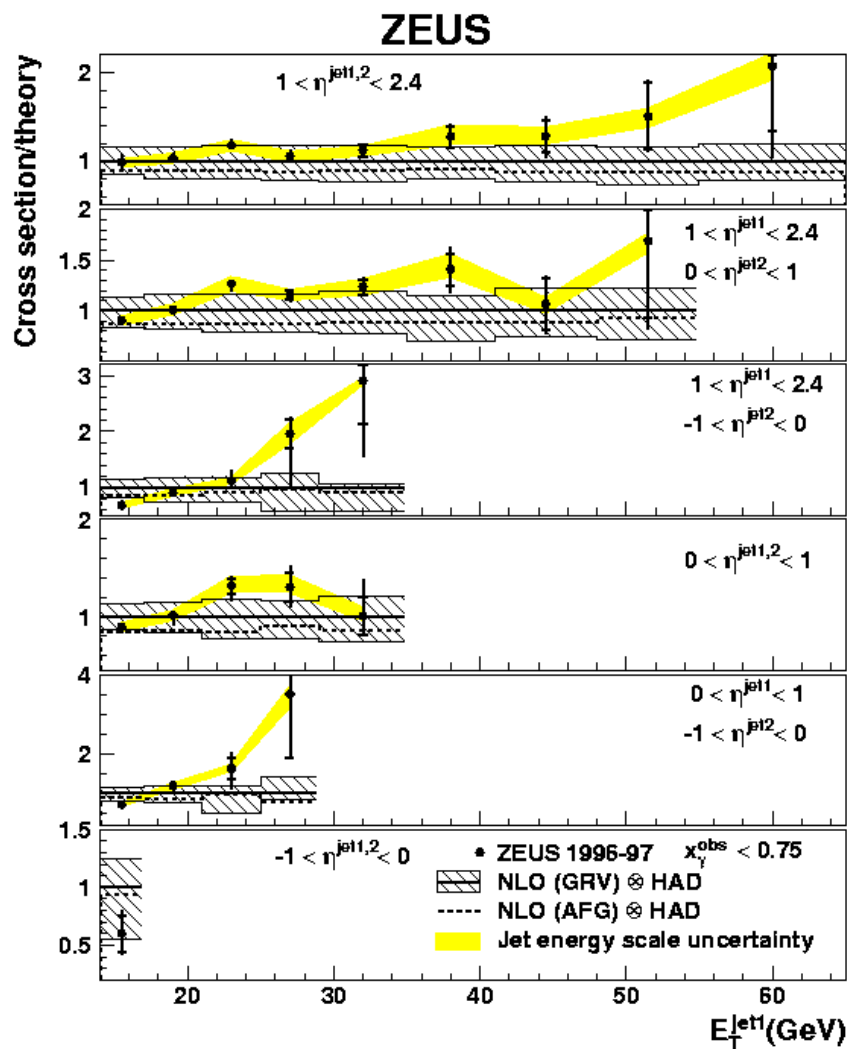
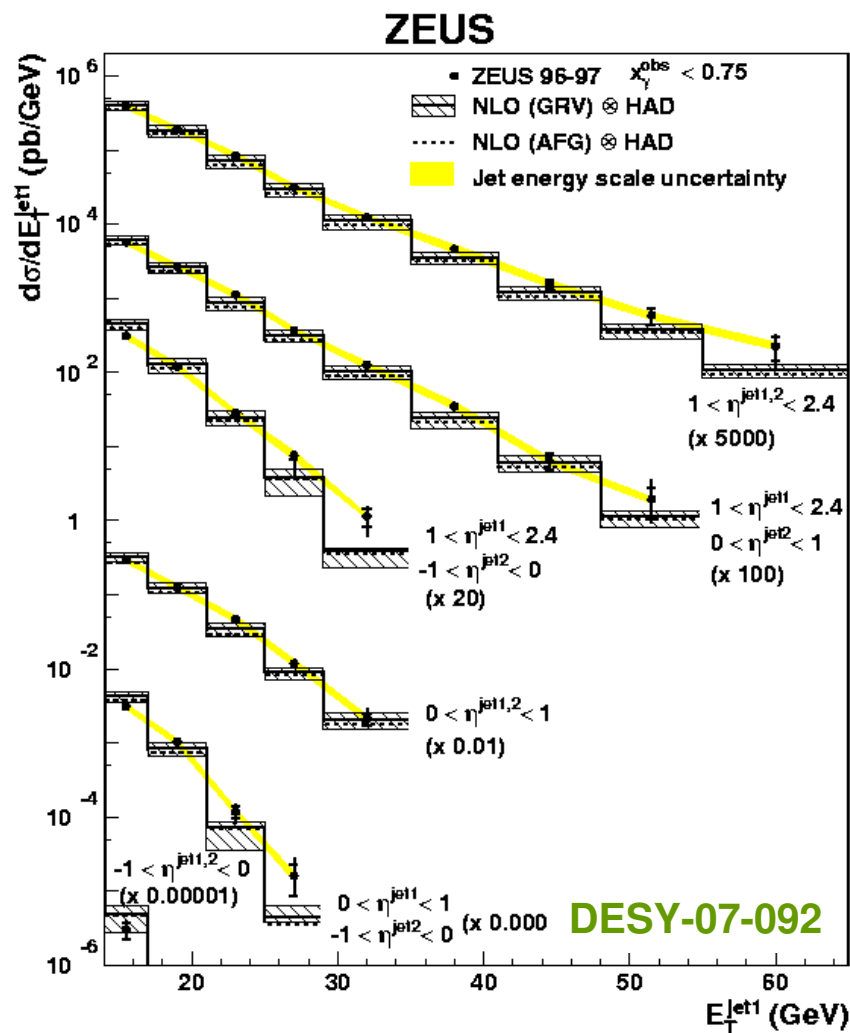
Use of double-differential direct dijet cross sections in NLO QCD fits together with DIS jet data ...



Reduction of proton gluon density uncertainty by up to 40% or so!

# JETS IN PHP: RESOLVED

... the corresponding resolved data:



- Data not described over all phase-space.
- Systematic differences between GRV and AFG photon PDFs (15%).

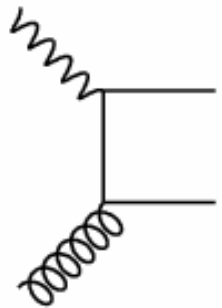
# JETS IN PHP: $x_\gamma$ , $x_p$

$$x_p = \frac{E_{T,1}e^{\eta_1} + E_{T,2}e^{\eta_2}}{2E_p}$$

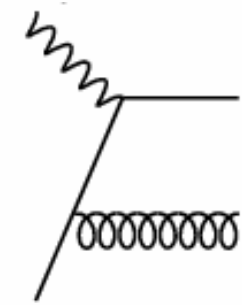
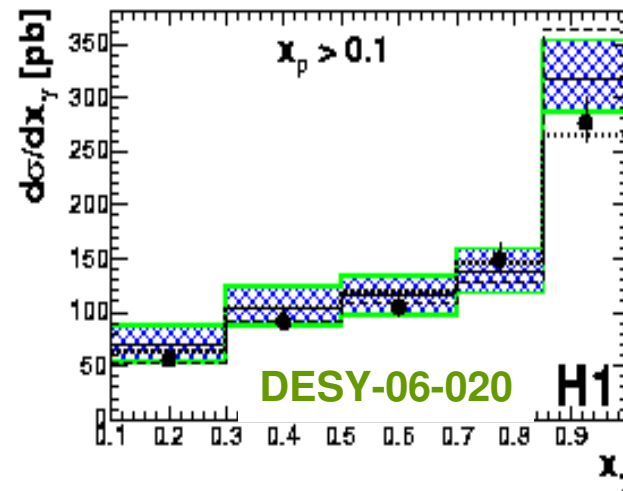
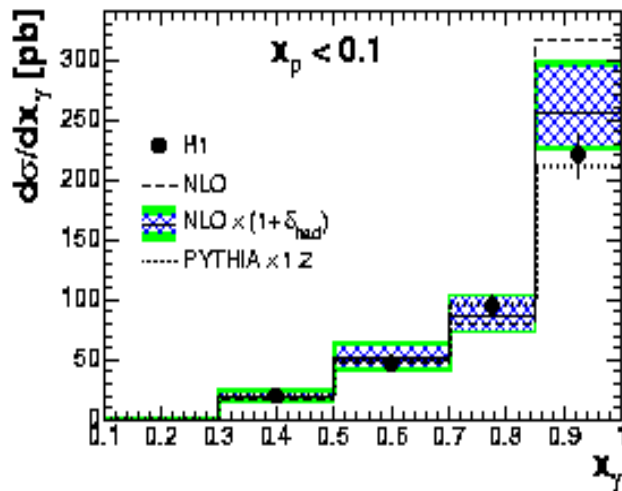
$$x_\gamma = \frac{E_{T,1}e^{-\eta_1} + E_{T,2}e^{-\eta_2}}{2yE_e}$$

Interest in photon (and proton) structure  
 → measure  $x_\gamma$  (and  $x_p$ )!

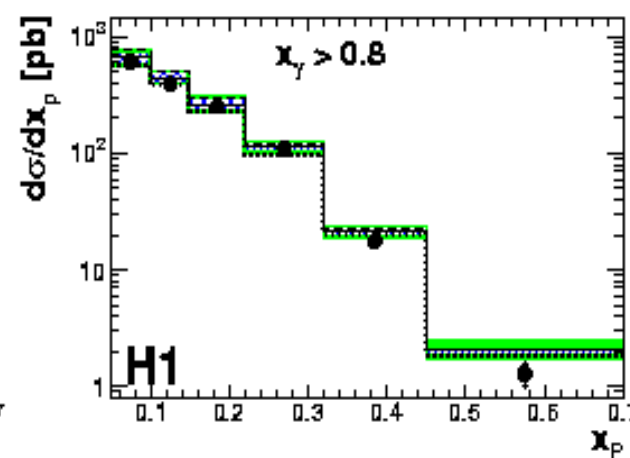
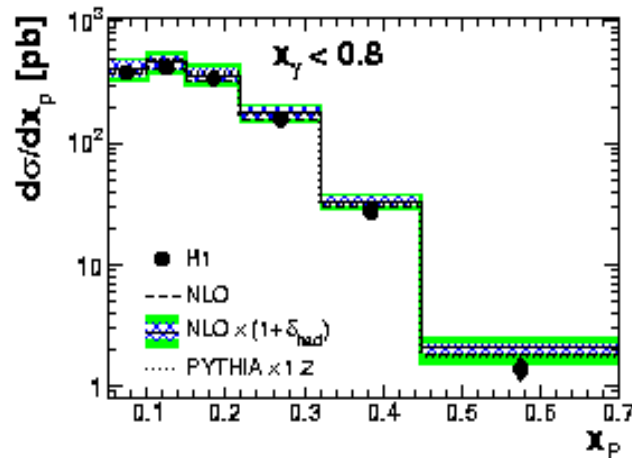
[ H1 data, 66.6 pb<sup>-1</sup>, 0.1 < y < 0.9  
 Dijets; E<sub>T</sub> > 25 GeV, -0.5 < η < 2.75 ]



Boson-gluon fusion (70%)



QCD-Compton (15%)

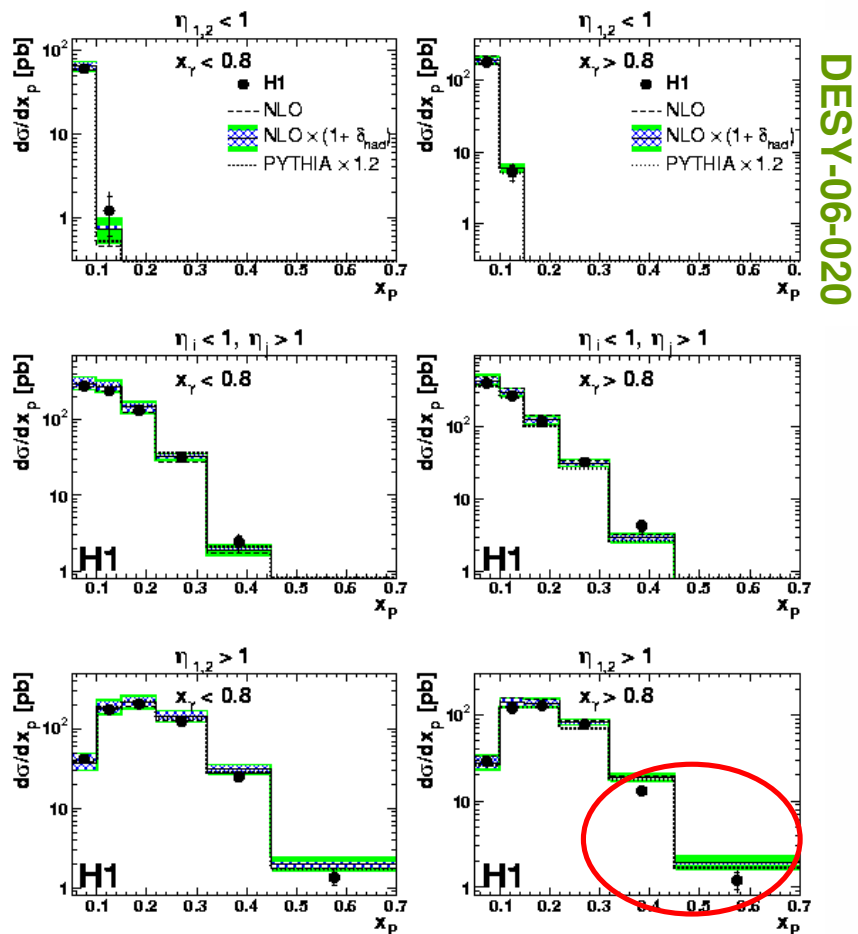


- NLO describes data over basically all phase space within errors (jet scale!).
- PYTHIA with GRV-LO, NLO with GRV-HO as photon PDF.

# JETS IN PHP: PSEUDORAPIDITIES etc.

## Jet pseudorapidities:

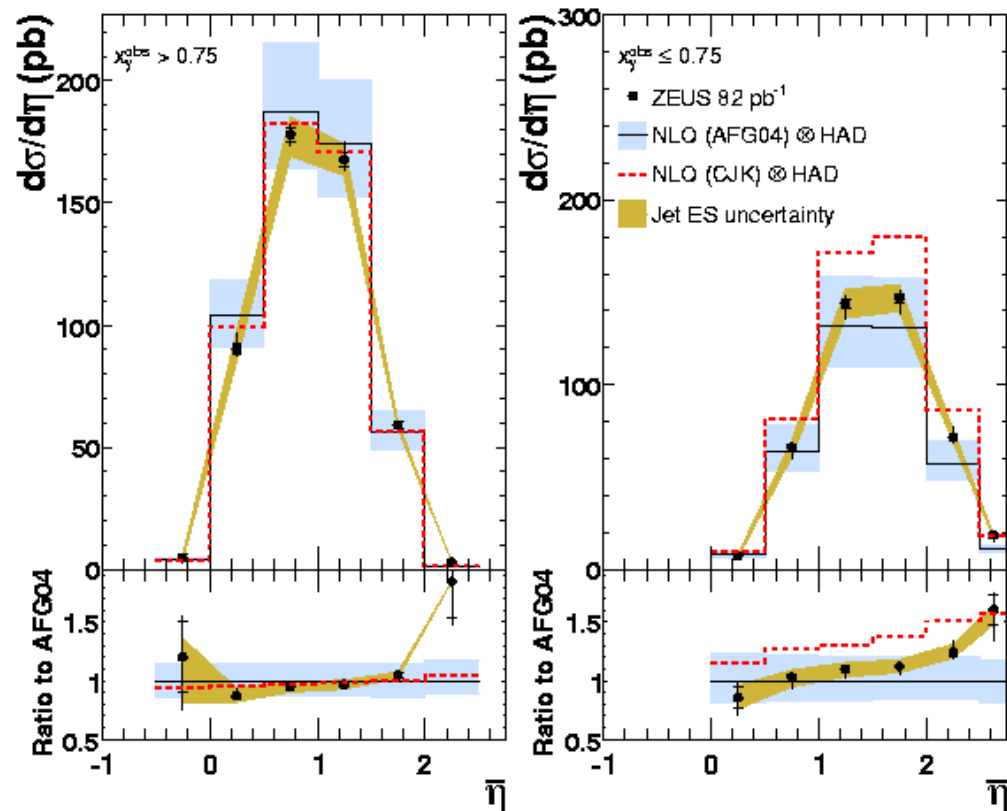
- Sensitivity to momentum distributions of incoming hadrons.
- (double-differential) measurements in  $\eta$ ,  $E_T$  (or  $x_p$ ).



NLO describes data well (small discrepancies in direct with both jets forward).

**ZEUS**

**DESY-07-092**

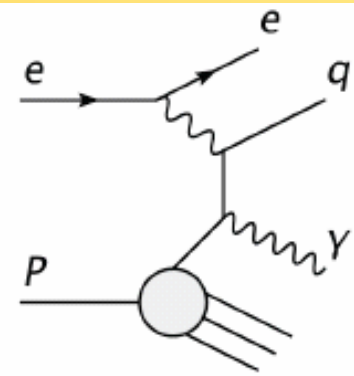


- Potential to constrain  $p$  and  $\gamma$  PDF.
- Often CJK  $\gamma$  PDF best (in shape).
- Differences between  $\gamma$  PDFs up to 50%  
→ constrain photon structure!

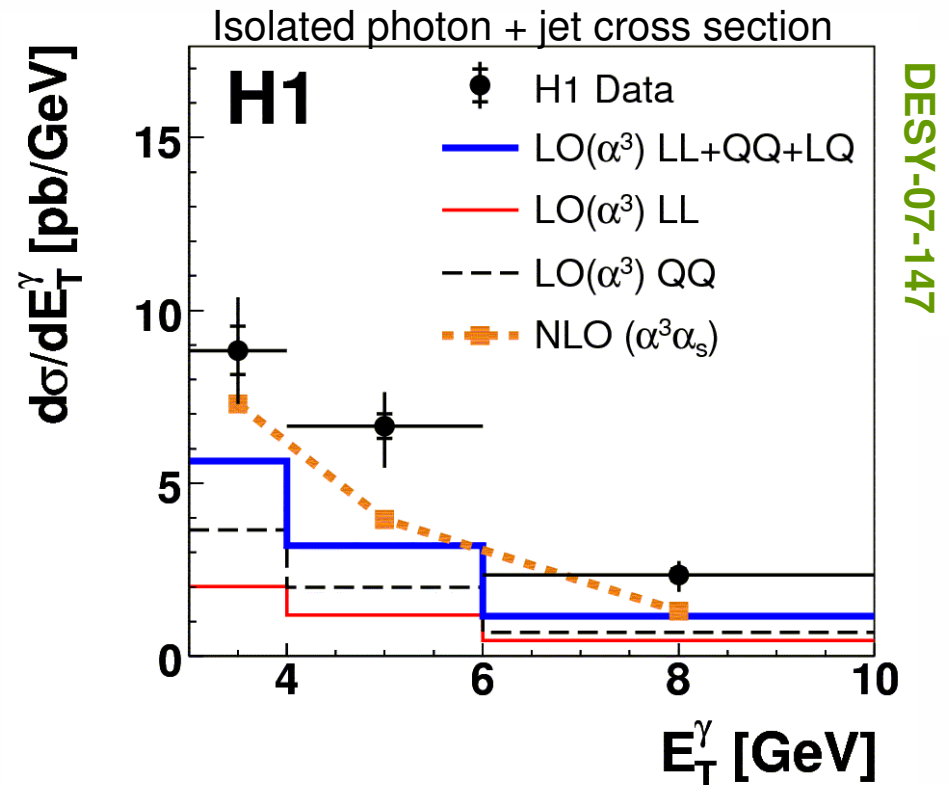
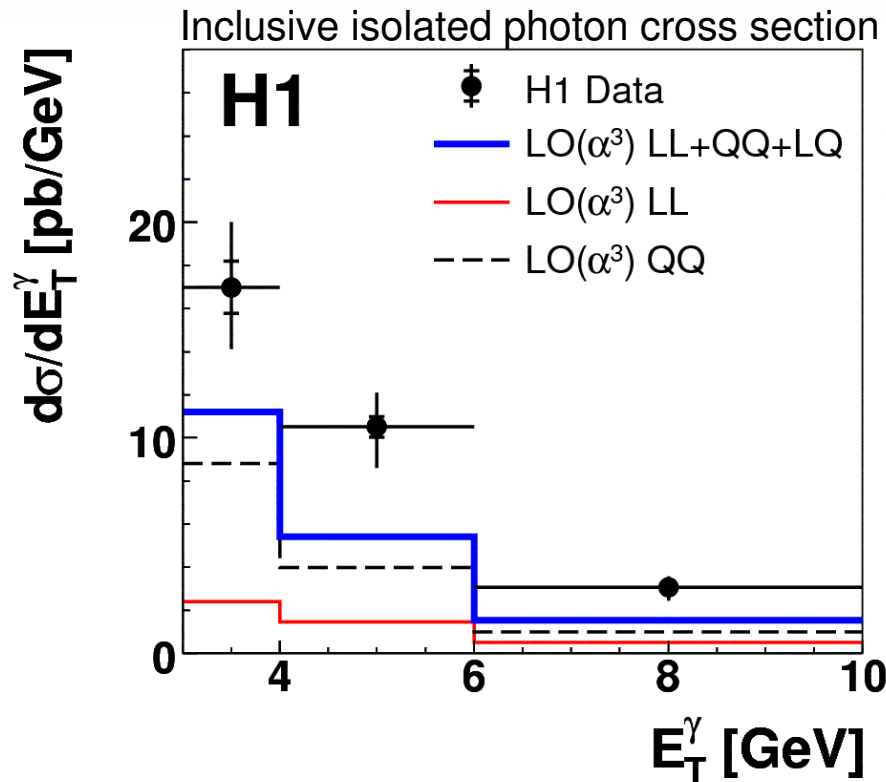
# PROMPT PHOTONS: DIS

Alternative access to QCD issues:

- Different systematics.
  - Smaller hadronisation corrections.
- In addition importance for new-physics searches.



Photon from lepton (LL), quark (QQ) or interference (LQ).

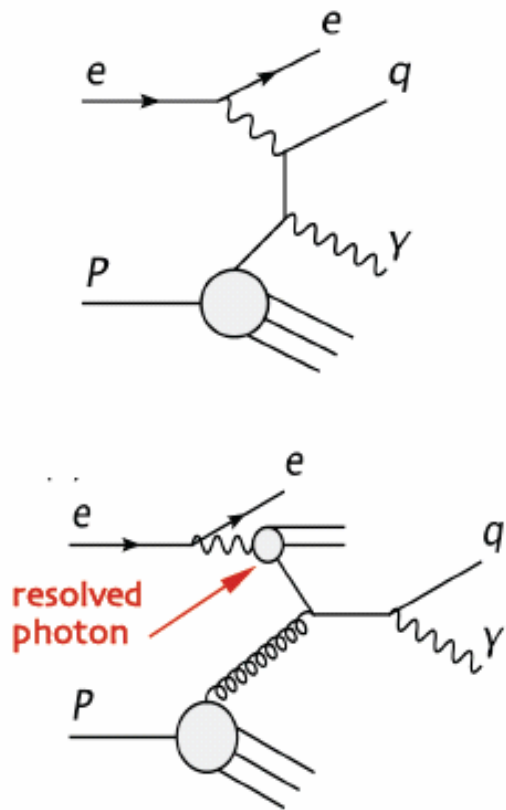


[ H1, 227 pb<sup>-1</sup>, 4 < Q<sup>2</sup> < 150 GeV<sup>2</sup>  
3 < E<sub>Tγ</sub> < 10 GeV, y > 0.05 ]

Without jet requirement (LO) theory factor 2 below data, shapes agree. With jet requirement (NLO) theory better.

# PROMPT PHOTONS: PHP

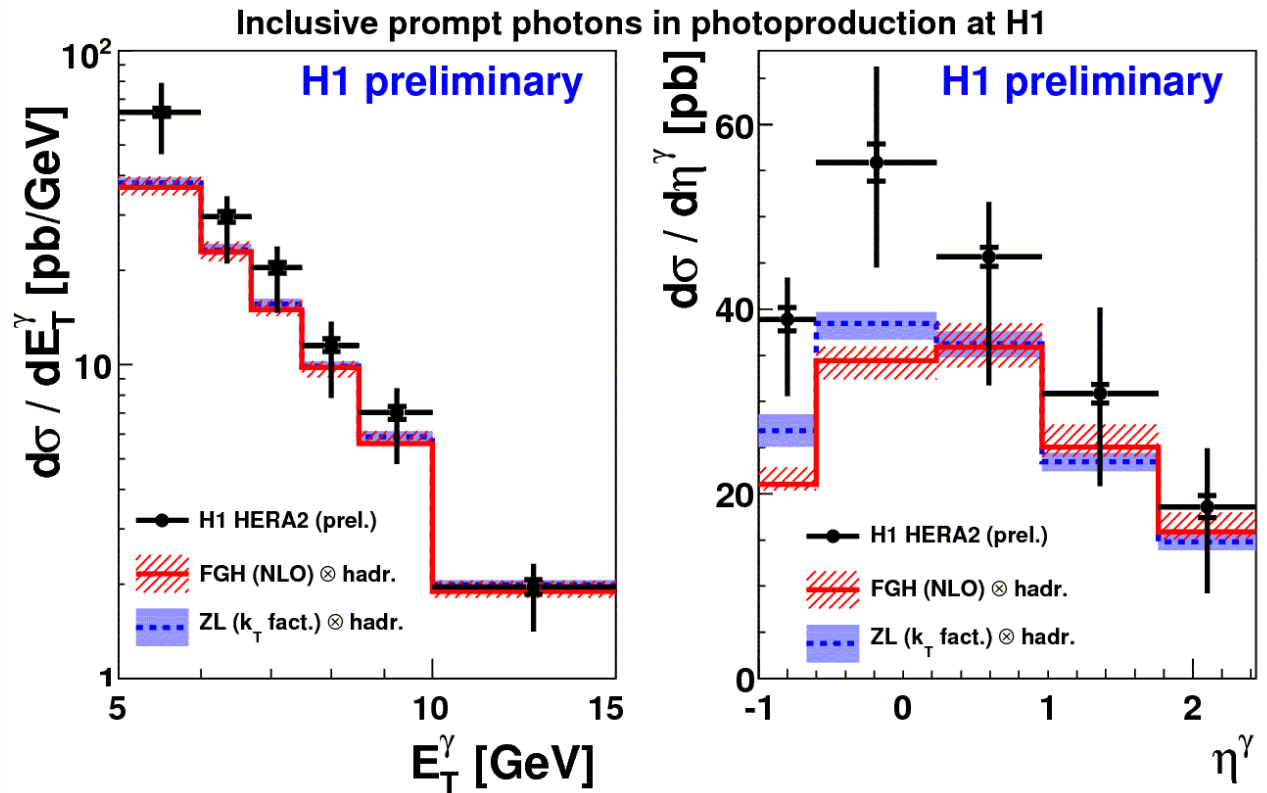
... after the problems in DIS, how about PHP?  
 direct+resolved contribution.  
 → access to p and  $\gamma$  PDFs.



[ H1, 340 pb<sup>-1</sup>, 2004-2007 data  
 5 < E<sub>T $\gamma$</sub>  < 15 GeV, 0.1 < y < 0.7 ]

## Comparison of data

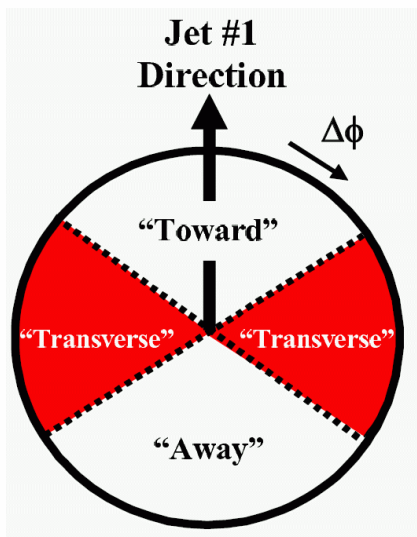
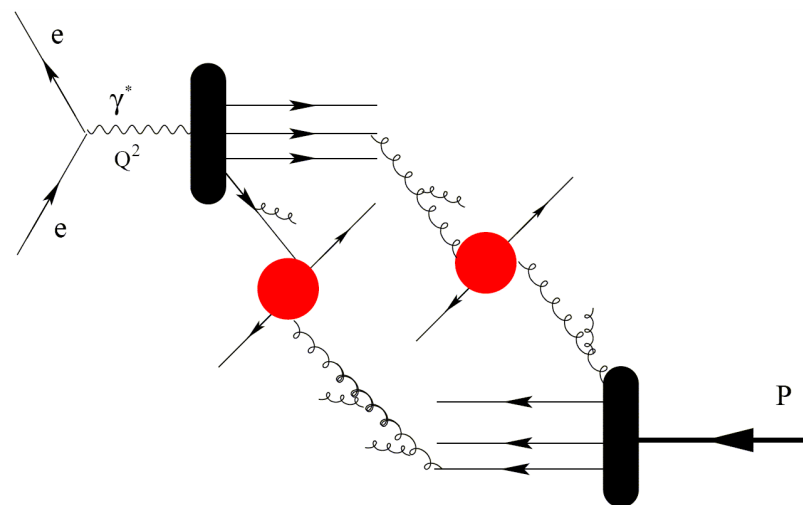
- to NLO (DGLAP) calculation (Fontannaz et al.)
- to k<sub>T</sub> factorisation approach (Zotov et al.)



Both calculations undershoot data. Slightly improved situation for photon+jet requirement (like in DIS).

# THE UNDERLYING EVENT

- Resolved PHP: hadron-hadron-like  
 → phenomenon of underlying event!
- (soft) beam remnant interactions
  - additional (semi)hard constituent scatterings (multi-parton interactions, MPI)
  - initial and final state radiation etc.

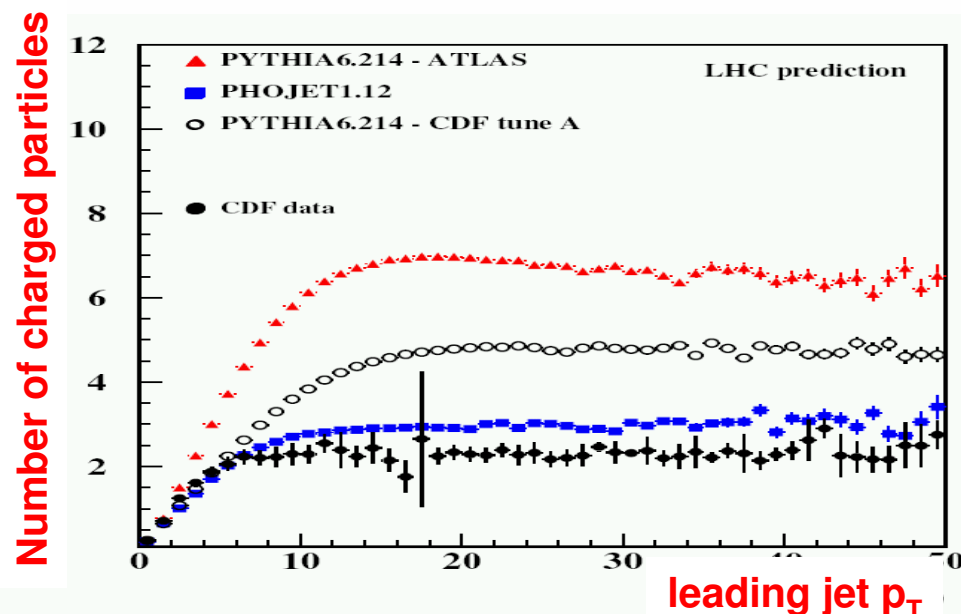


Quantify: “Activity in transverse regions”  
 Regions away from hard scattering products (jets) should be most sensitive to UE effects.

## CDF experience:

- MPI models can be tuned to CDF data!
- But extrapolation to LHC not meaningful!

→ Important + theoretically challenging!





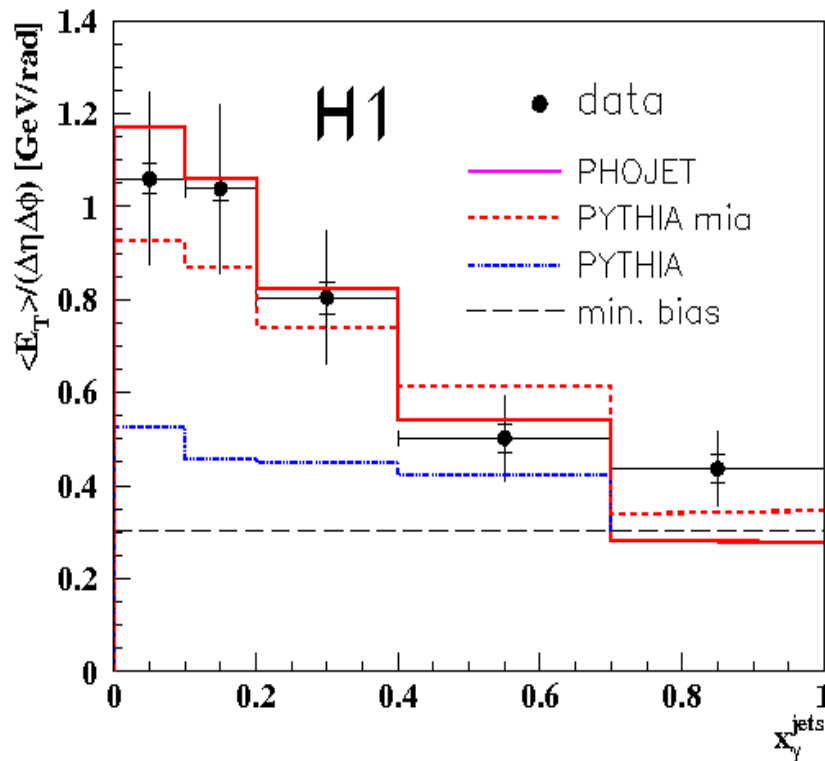
# UE/MPI NECESSITY

## ¶ HERA measurements demonstrate necessity of UE/MPI

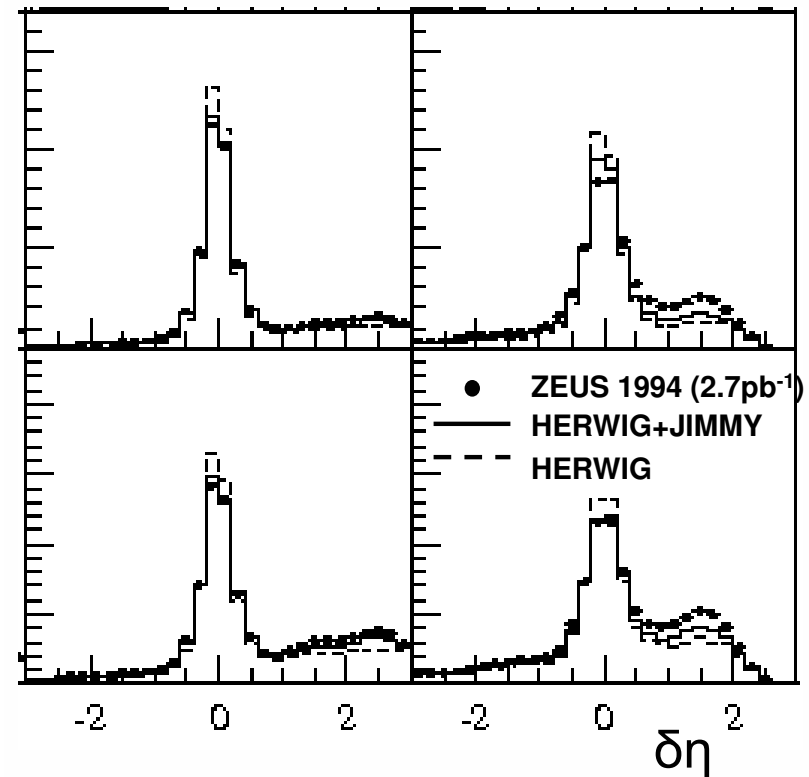
– Photoproduction dijets at HERA,

- H1: ZP C70 (1996) 17

- ZEUS: EPJ C1 (1998) 109



$$x_\gamma = \frac{E_{T,1}e^{-\eta_1} + E_{T,2}e^{-\eta_2}}{2E_\gamma}$$



Jet profiles: energy flow relative to jet axis in different  $\eta$  regions

# UE MODEL IMPLEMENTATIONS

## ¶ PYTHIA + MPI

- Various models (old / intermediate / new): differ wrt color flow, remnant treatment, showering initiators, shower mode, interleaving of ISR and MPI, ...
- simple overlap of hadrons or impact-parameter dependence
- Average number of interactions per event derived from regularised  $2 \rightarrow 2$  cross-section and total cross-section; secondary interactions Sudakov-suppressed.

## ¶ HERWIG + JIMMY

- Based on eikonal model assuming matter distributions in colliding particles and an overlap function  $A(b)$ .
- Assign  $2 \rightarrow 2$  cross-section to all events, choose number of interactions according to precalculated probability distribution.

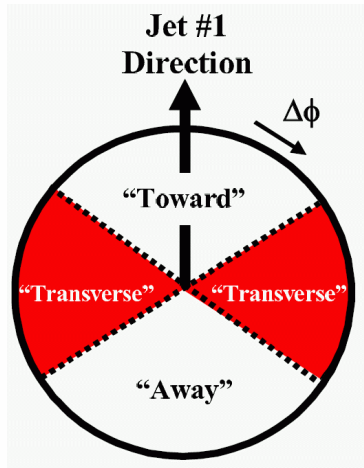
## ¶ More models:

- Sherpa: similar assumptions as in PYTHIA, module AMISIC++ for MPIs.
- Phojet: Not part of general purpose generator, limited use for HEP.

# H1 ANALYSIS: MINIJETTS IN DIS

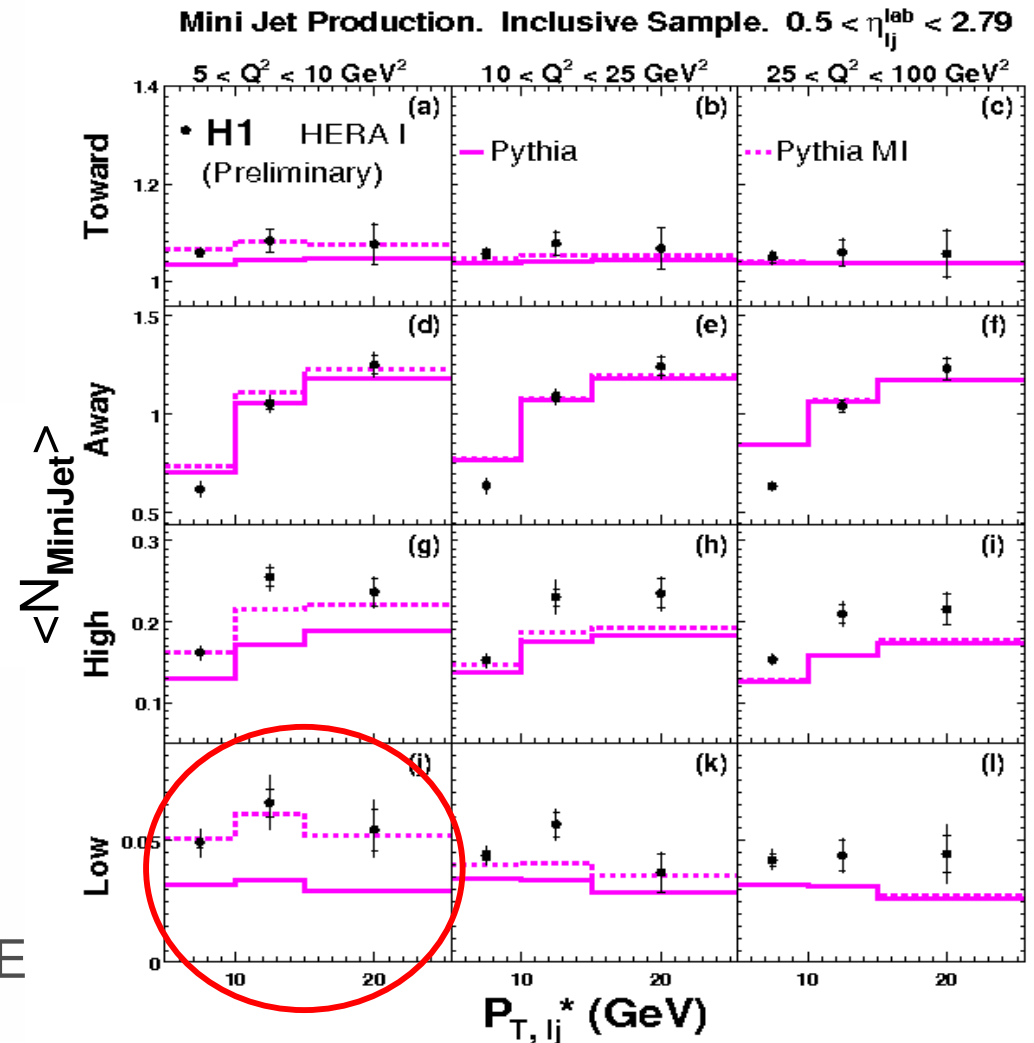
## Measure for UE

- average number of low- $p_T$  “mini” jets in different azimuthal regions as function of  $p_{T,lead}$



- Inclusive (dijet) sample in regions of  $Q^2$  and  $\eta^{lab}$  ( $x_V$ ).
- Data compared to PYTHIA, ARIADNE RAPGAP, ...

[ H1 data,  $57.4\text{pb}^{-1}$ ,  $5 < Q^2 < 100 \text{ GeV}^2$ .  
 Jets:  $p_T > 5 \text{ GeV}$ , minijets:  $p_T > 3 \text{ GeV}$ .  
 Dijets Azimuthal separation:  $> 140^\circ$ . ]



H1-prelim-07-032

Jet regions: PYTHIA (no MPI) okay!  
 Transverse regions: MPI needed!

# H1: DIJET SAMPLE

## ¶ Jet regions:

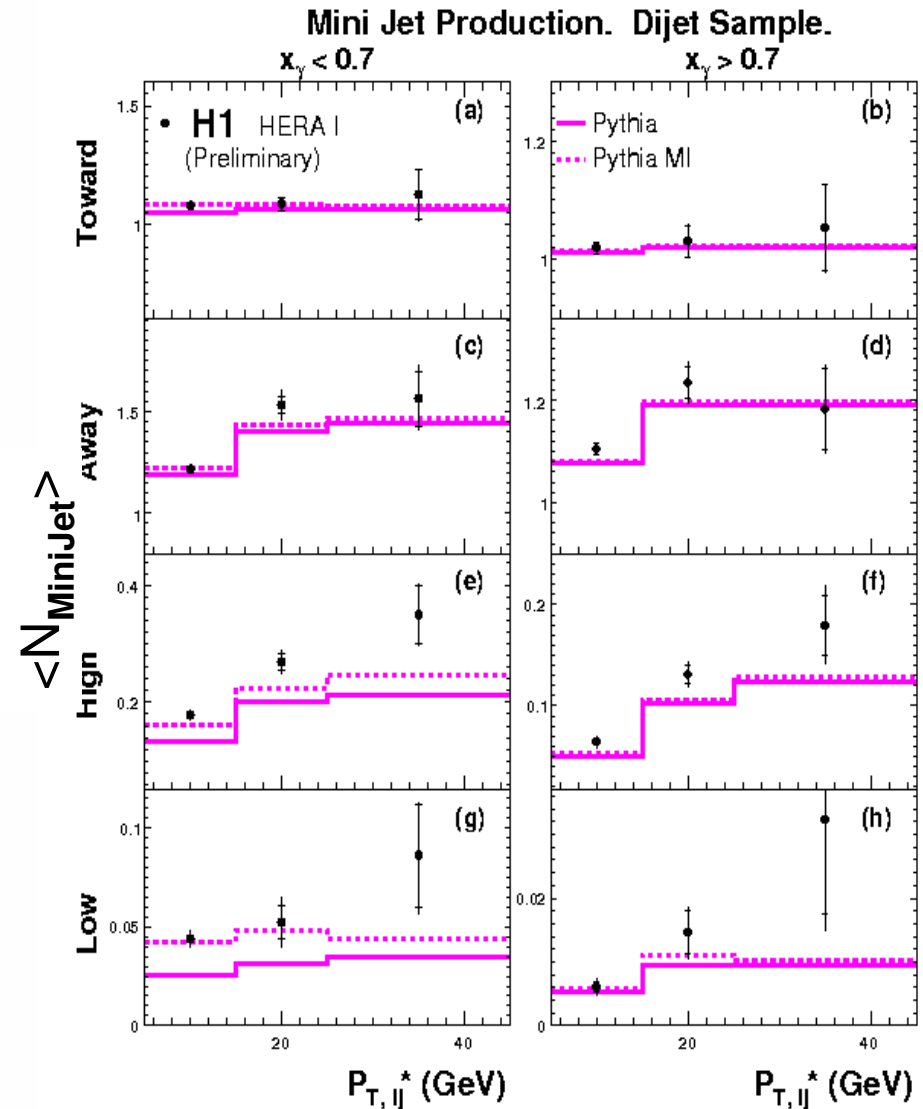
- all models with and without UE/MPI describe data.

## ¶ Transverse regions

- data generally above the models.
- Some UE influence; MPI again needed to describe data.

Influence of MPI / necessity of its modelling demonstrated.

Underlying effects not very well understood. Pin down mechanism with data like these? Energy evolution?



H1-prelim-07-032

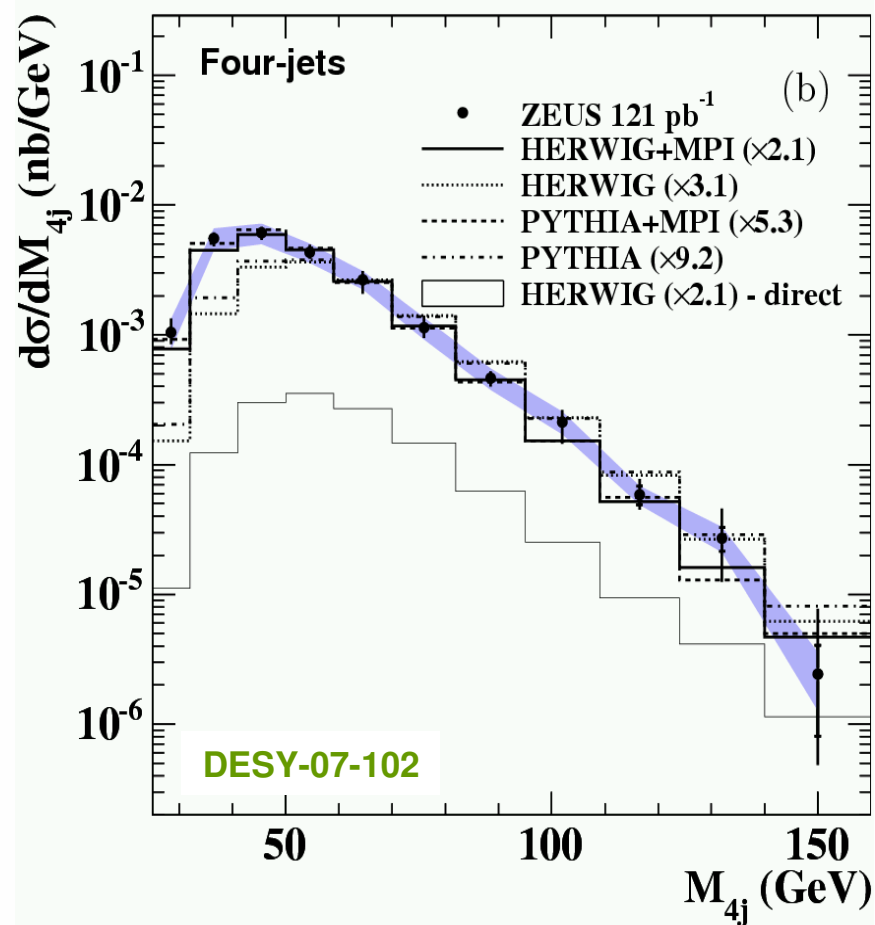
# ZEUS: MULTIJETS IN $\gamma^*p$

## ¶ Measure for UE:

- 3- and 4-jet cross-sections.
- Jets 3, 4 generated by hard QCD radiation? MPI?

## ¶ Models for comparison:

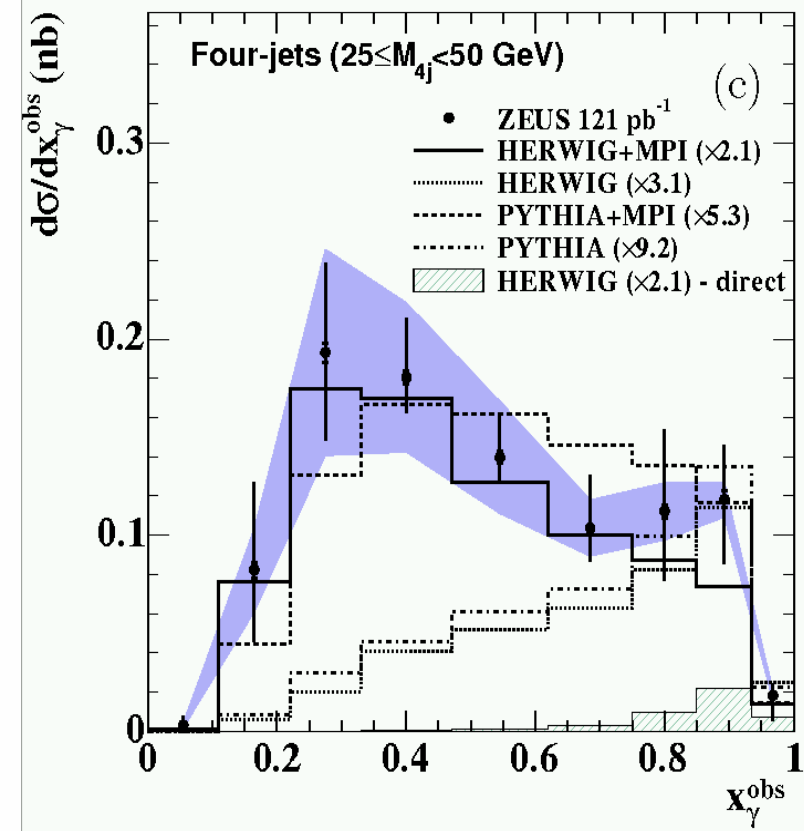
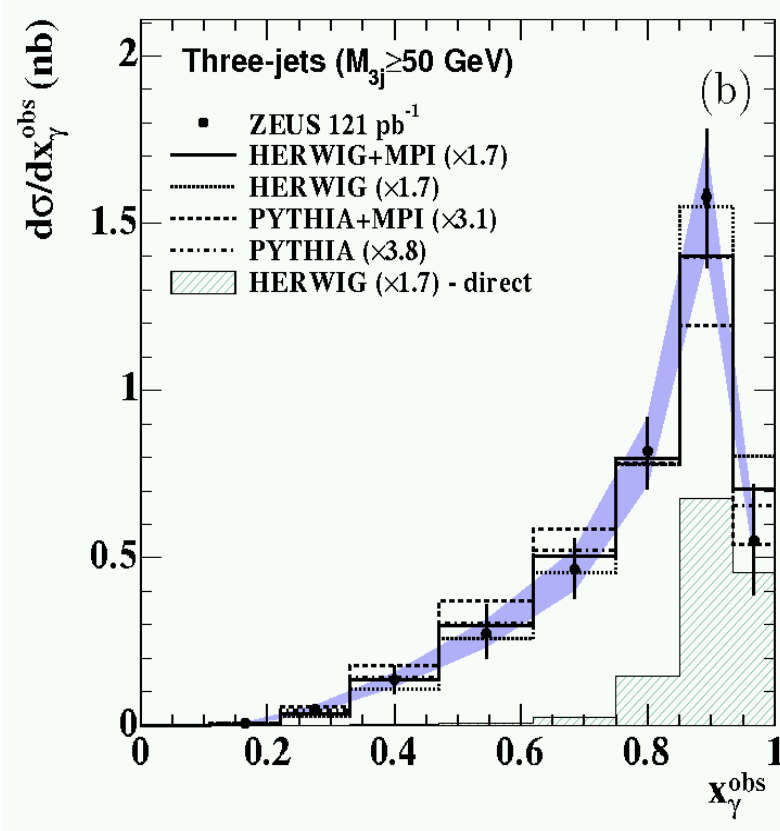
- HERWIG 6.505 + JIMMY 4.0
- PYTHIA 6.206 + “simple” MPI model
- Also: NLO calculation (Klasen et al.) for 3jet case (effectively LO!)



[ ZEUS data, 121pb<sup>-1</sup>, 0.2 < y < 0.85.  
Jets: E<sub>T</sub> > 6 GeV, |η| < 2.4.  
High/low-mass region: M<sub>nj</sub> <> 50 GeV ]

Need MPI/UE simulations to correctly describe the data:  
HERWIG and PYTHIA without UE / MPI fail to describe data at low M<sub>nj</sub>.

# ZEUS 3- AND 4-JETS: $d\sigma/dx_\gamma$



- Models without MPI suggest decreasing cross-sections with decreasing  $x_\gamma$ .
- But for low masses large discrepancy with INCREASING data
  - mechanism beyond direct+resolved as modelled in MC necessary.
- Even “direct” region ( $x_\gamma > 0.75$ ) dominated by resolved events ( $\leftrightarrow$  dijets!).
- Especially HERWIG+JIMMY describes data well.
- Note large systematic uncertainties: Model dependence

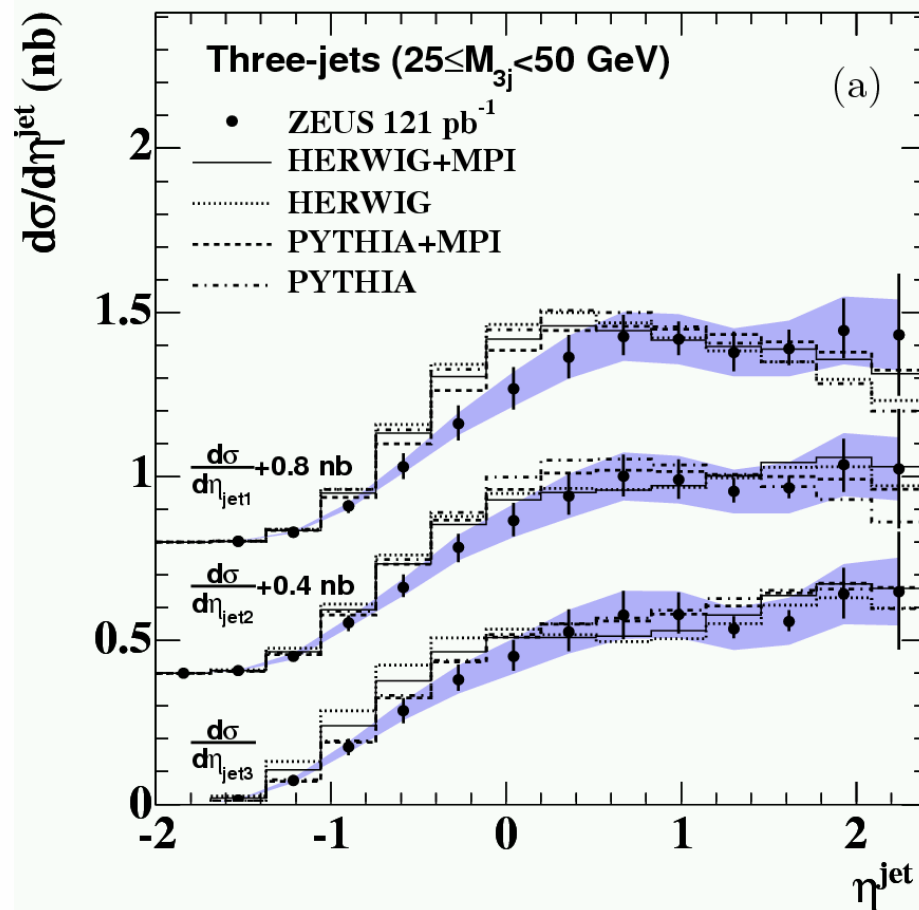
# ZEUS MULTIJETS

## ¶ $d\sigma/d\eta$ versus LO models:

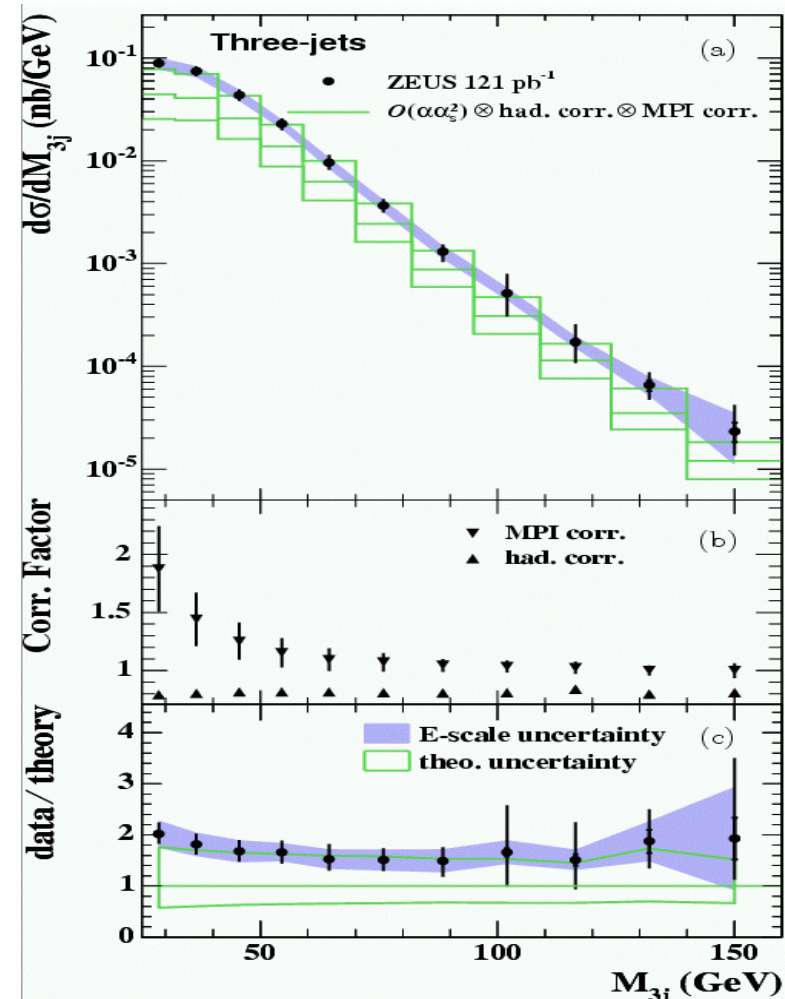
- High-mass data described by all models.
- Best description of low-M data: HERWIG.
- MPI improve description at high  $\eta$ .

## ¶ $d\sigma/dM_{3j}$ versus “NLO”:

- Large MPI corrections (from models) at low masses! Large theo. uncertainties.



Similar message for  $E_T$  spectra.



# SUMMARY

## ¶ Jets in photoproduction:

- Possibility of many QCD tests (coupling, factorisation, perturbation theory, ...)
- Sensitivity to both photon and proton PDFs!
  - pPDF already improved using jet data (ZEUS-JET proton PDF).
- Direct part of data typically well described by NLO QCD calculations / LO models.
- Large (50%) differences between different  $\gamma$  PDFs → potential to constrain?

## ¶ Prompt photon production:

- Alternative access to QCD issues; different systematics (hadronisation!)
- DIS: Models and (LO) calculations tend to undershoot data (factor 2).
- Photoproduction: Similar as in DIS. Photon+jet requirement helps a bit.

## ¶ Multi-parton interactions:

- Resolved photoproduction: Multiple parton Interactions possible!
- HERA data clearly indicate necessity for MPI contributions to models.
- HERA (low-energy) points helpful in identifying the underlying mechanism?

## ¶ Many HERA-II results to come!

- So far most results with limited HERA-I statistics!
- Many measurements limited by renorm. scale uncertainty! Need theoretical input!

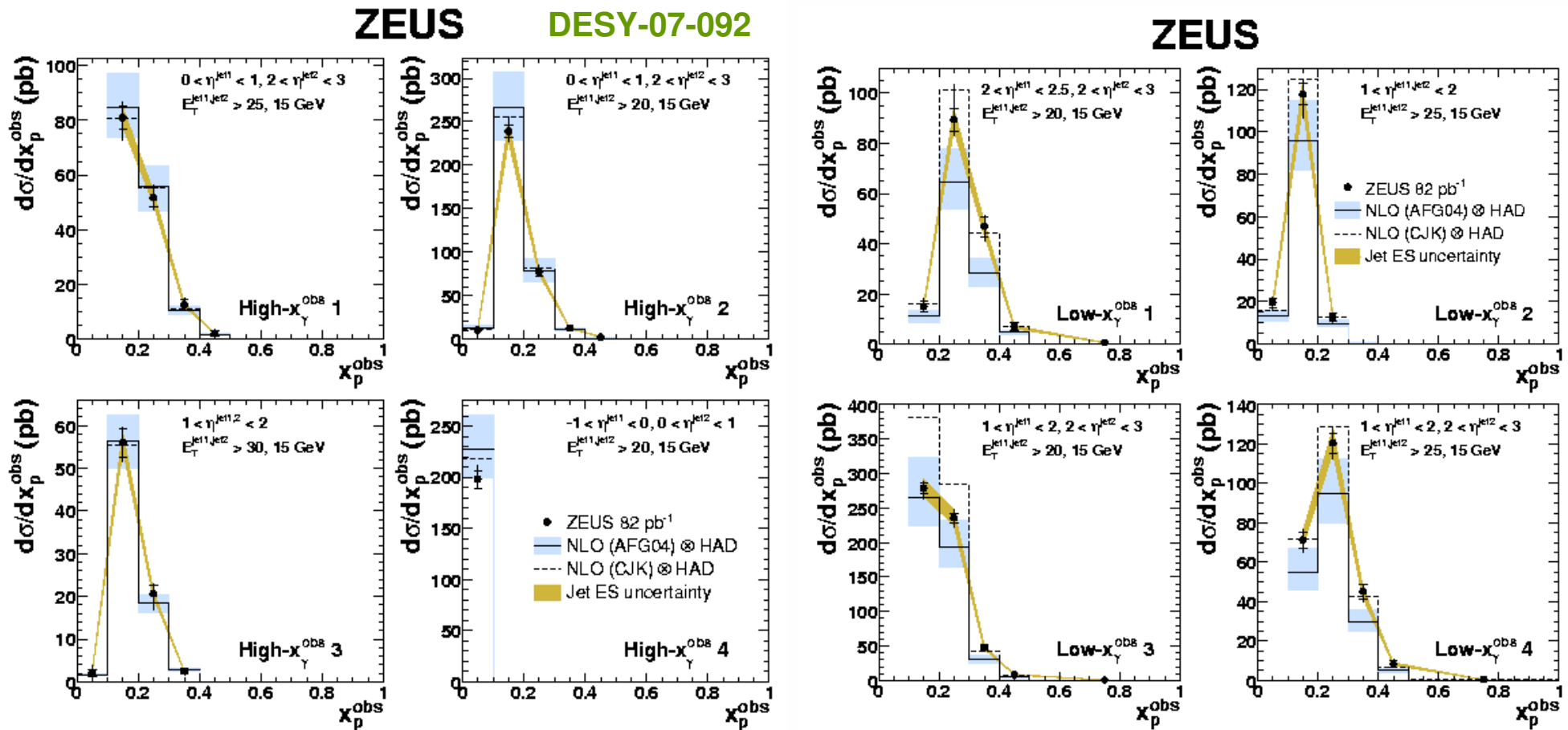


# JETS IN PHP: "OPTIMIZED" REGIONS

Regions of phase-space with particular sensitivity to PDFs (gluon):

→ Isolate regions with large gluon contributions.

→ direct / resolved to isolated influence of photon / proton PDFs.

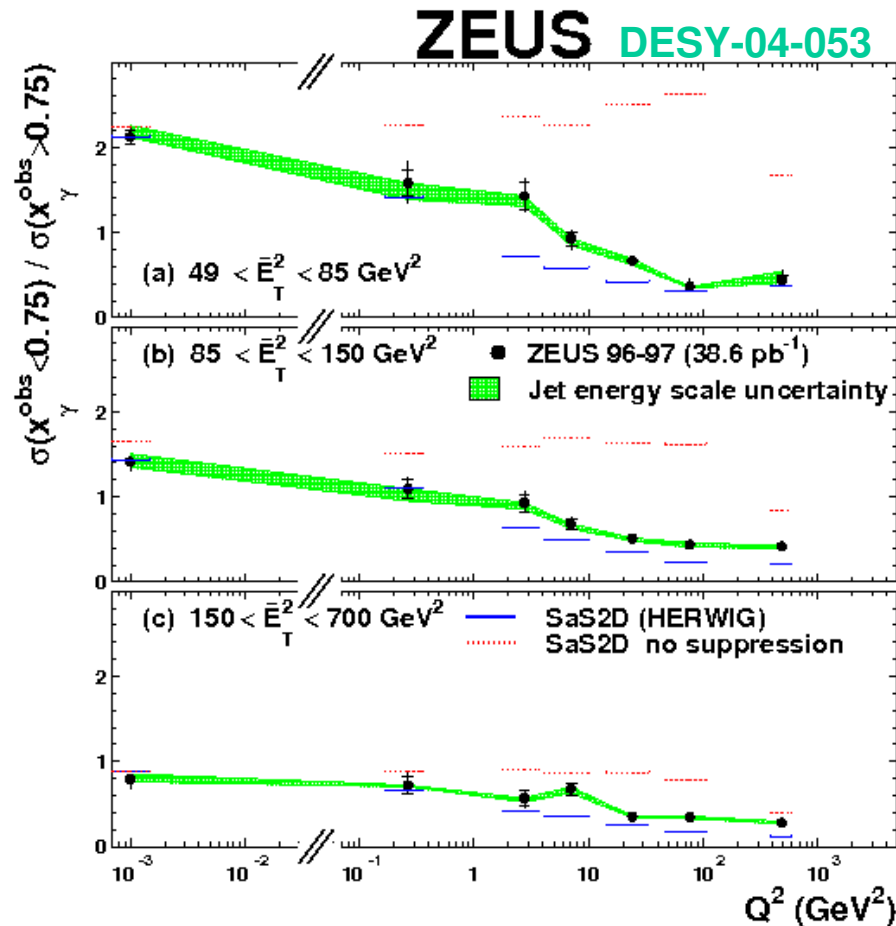


Potential of these and similar data to further constrain the photon!

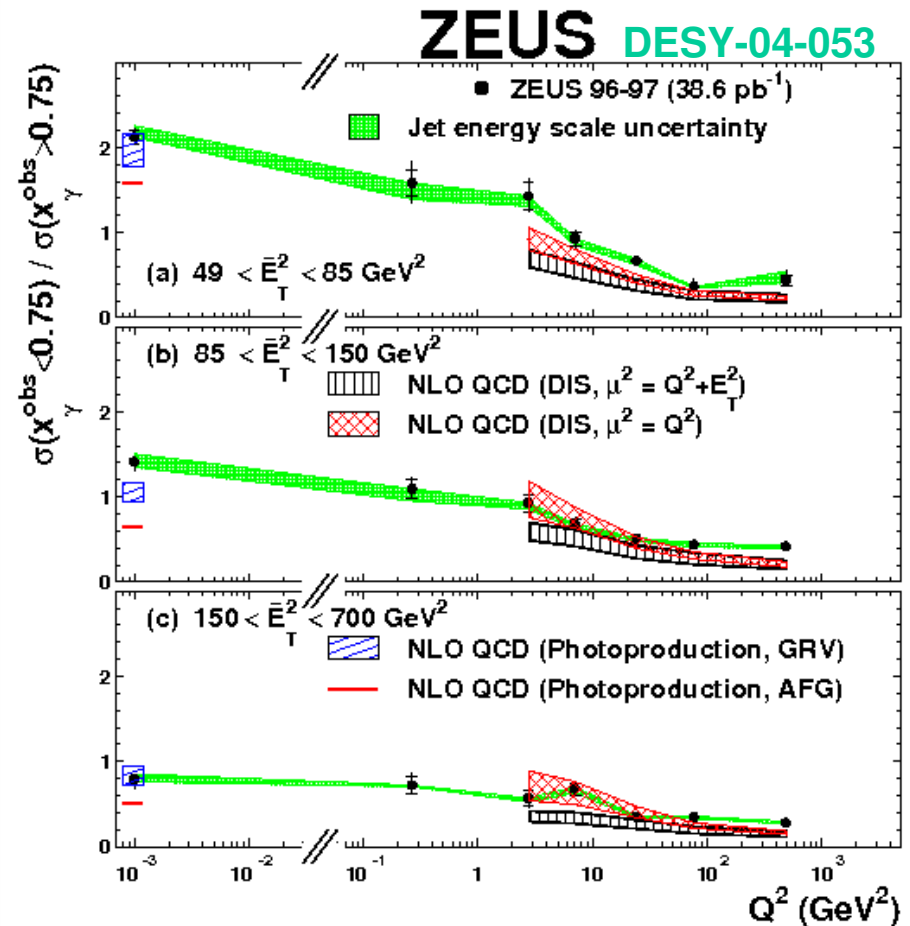
# RESOLVED VERSUS DIRECT

Ratio  $R = \sigma(\text{resolved}) / \sigma(\text{direct})$  as fct of  $Q^2$  in regions of mean  $E_T$ :

- Better understanding of resolved component at  $Q^2 > 1 \text{ GeV}^2$ ?
- Data compared to HERWIG LO MC with two different photon PDFs, and to NLO.



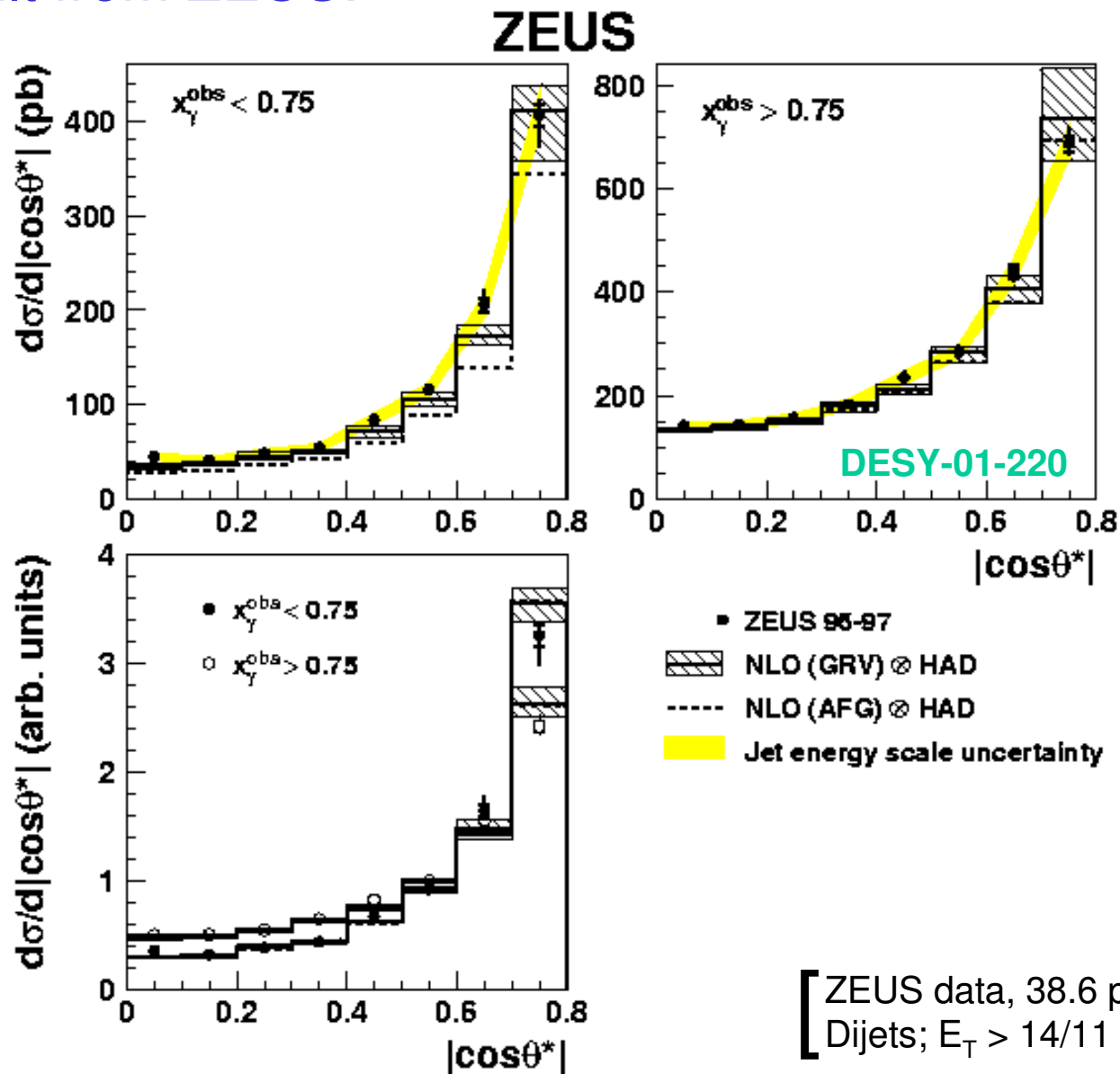
SaS2d with  $\gamma$  PDF suppression reproduces the data!



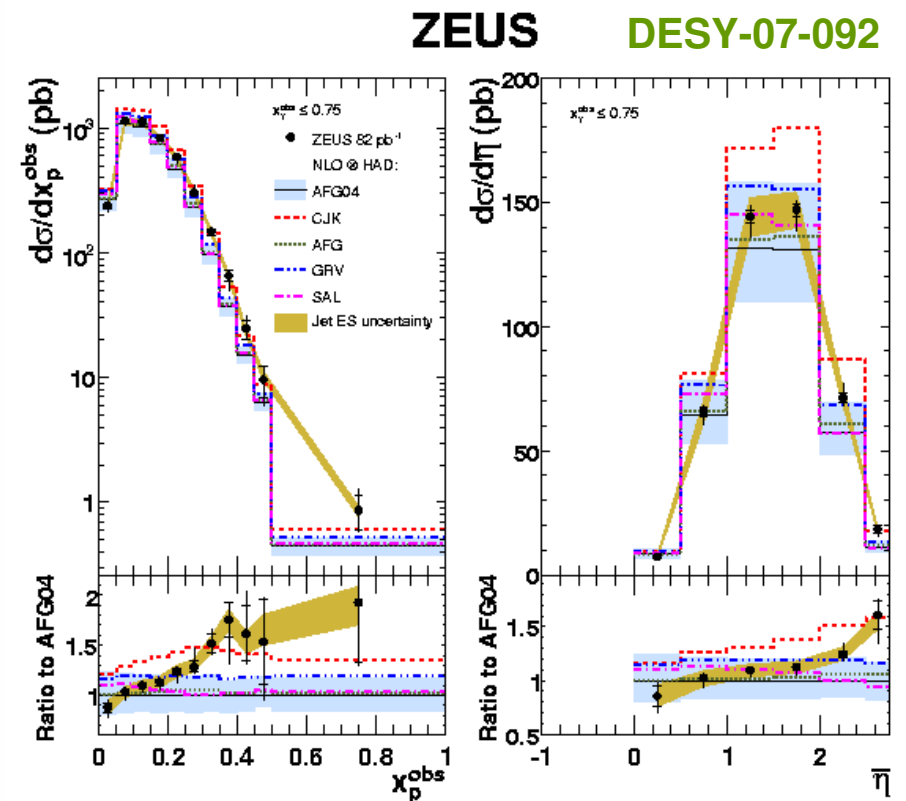
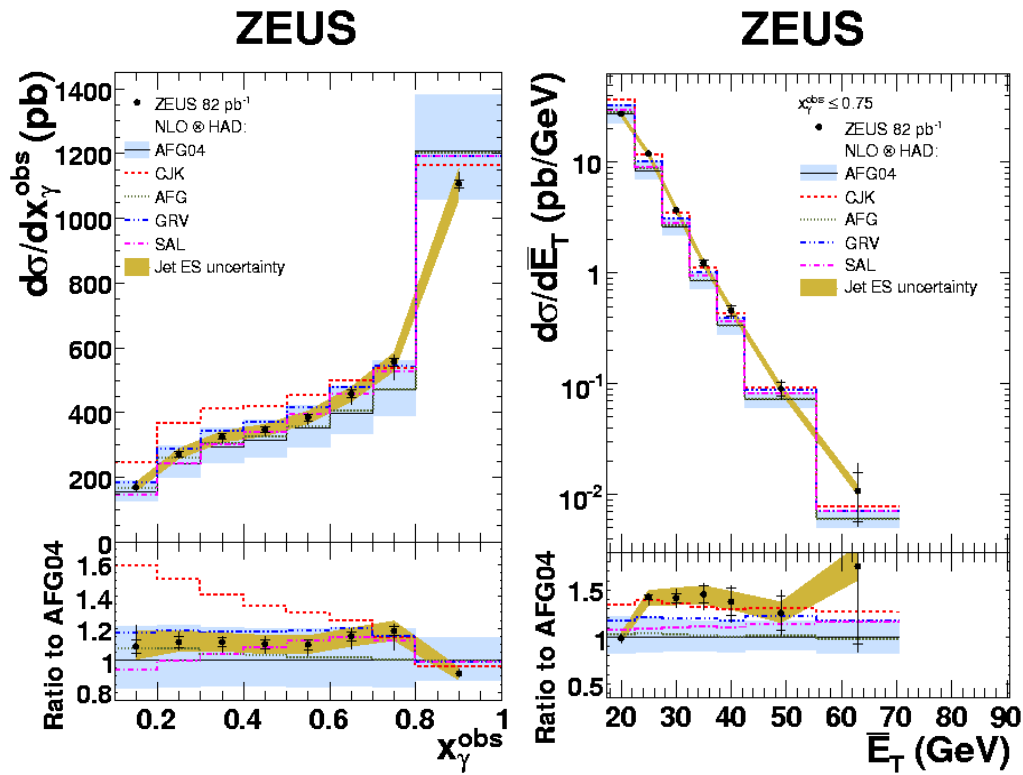
PHP Description depends on photon PDF used! Some  $Q^2$  suppression.

# CONFIRMATION: RESOLVED CONCEPT

Similar result from ZEUS:



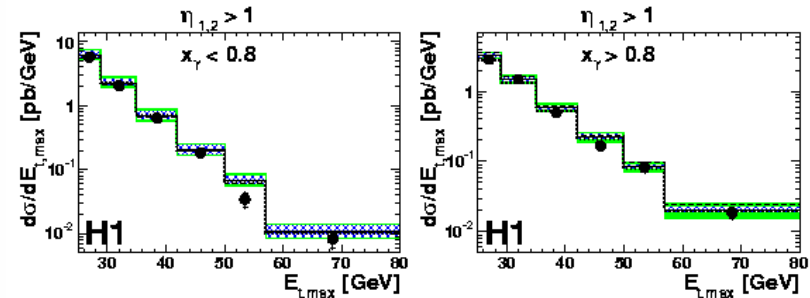
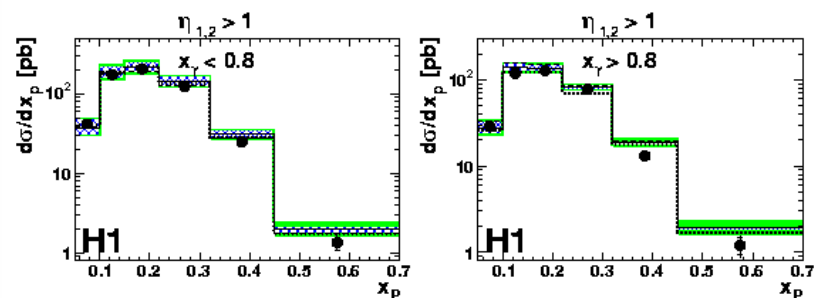
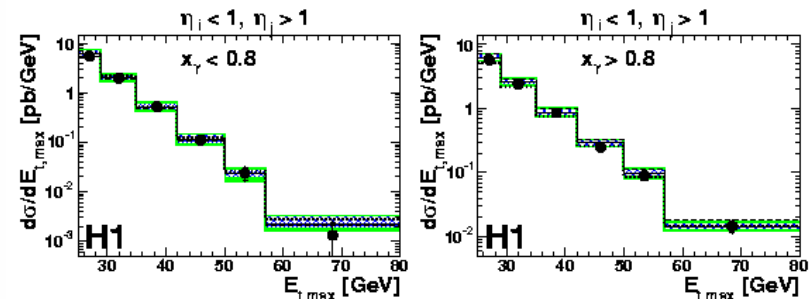
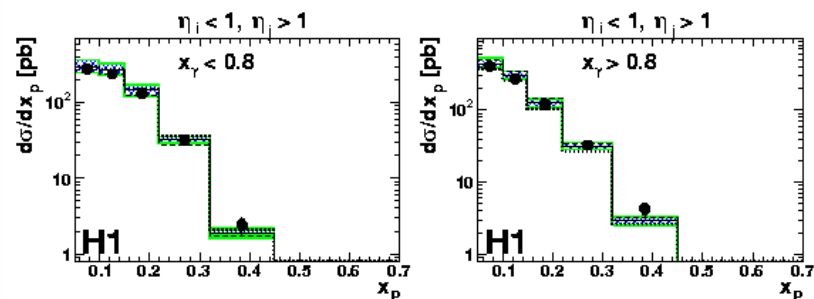
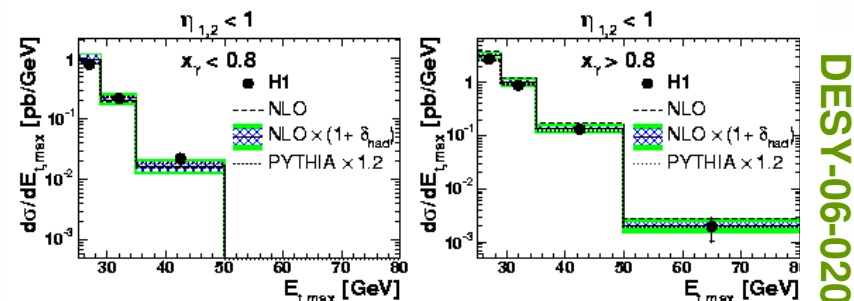
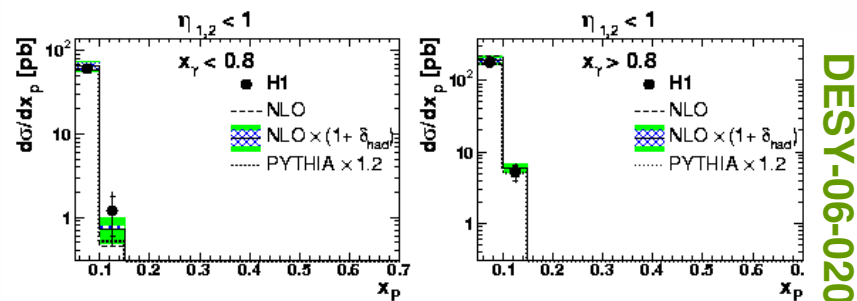
# JETS IN PHOTOPRODUCTION



# JETS IN PHOTOPRODUCTION

## Jet pseudorapidities:

- Sensitivity to momentum distributions of incoming hadrons.
- double-differential measurements in  $\eta$ ,  $E_T$  (or  $x_p$ ).



- NLO describes data well (small discrepancies in direct with both jets forward).
- Detailed ZEUS study: Large potential of data to constrain  $p$  and  $\gamma$  PDF.

# JETS IN PHOTOPRODUCTION

Similar findings at ZEUS:

- Large influence of photon PDF in use; often CJK describes best the trend of the data (but normalisation).
- Differences between different parametrisations up to 50%!

