High-p_T Processes and the Photon Structure

(Jet) Photoproduction Results from HERA

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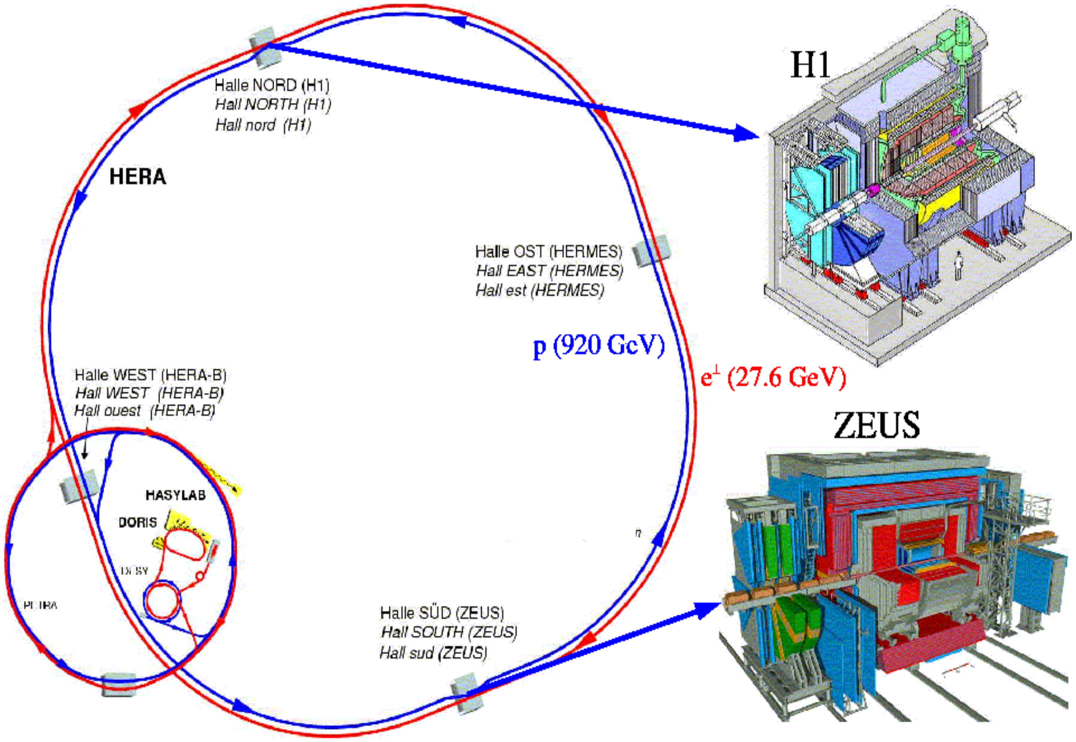
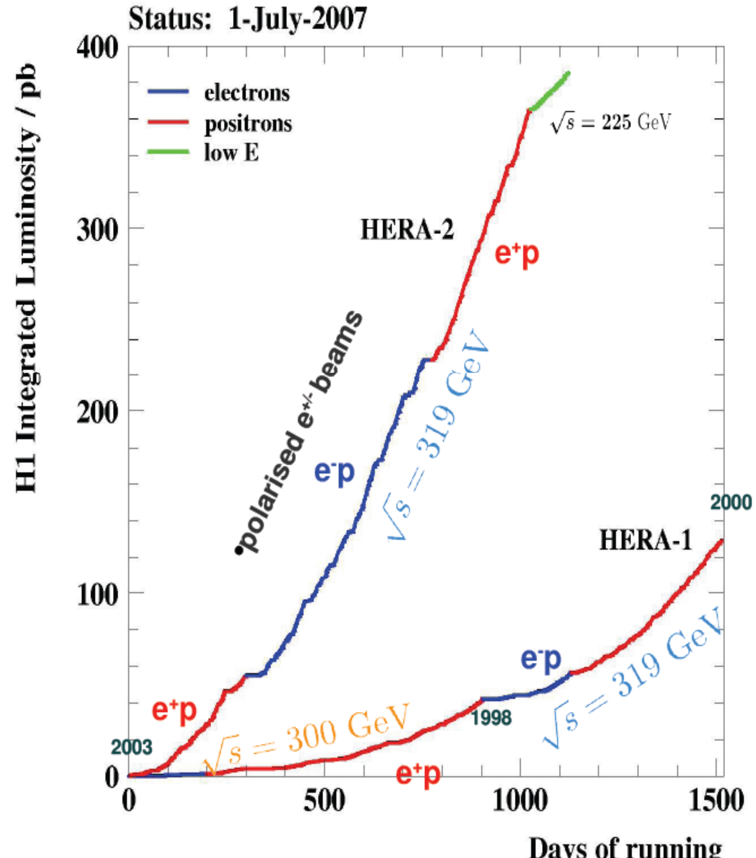
Workshop on
High-Energy Photon Collisions
CERN, 22 April 2008

- 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 (λ~1/Q).
– 820/920 GeV protons on 27.5 GeV electrons.





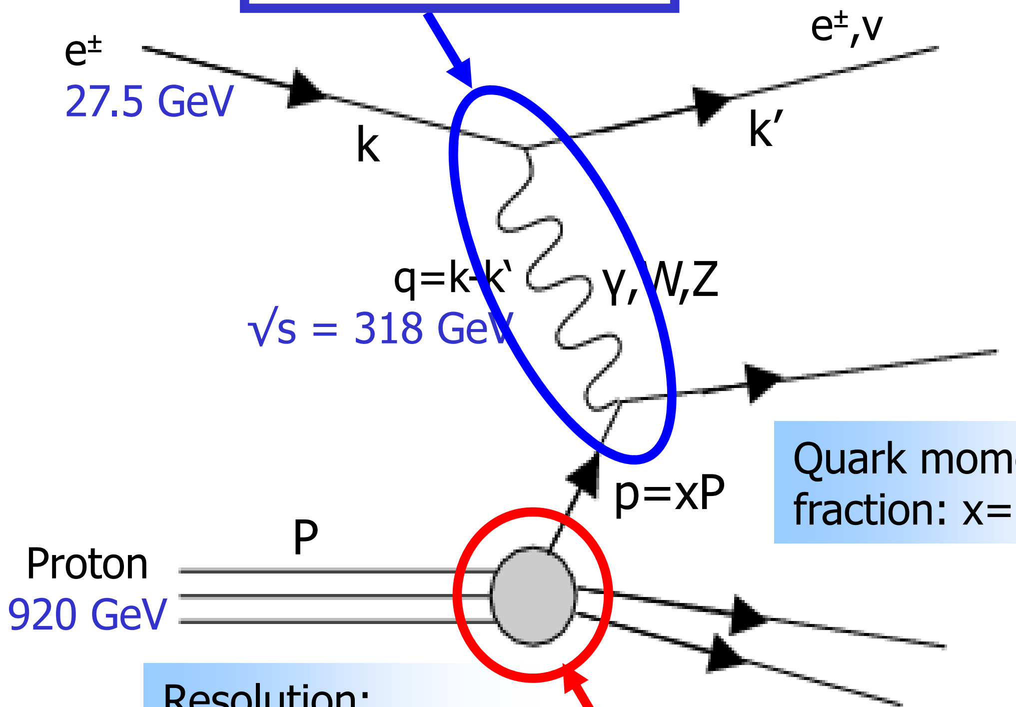
H1: – LAr calorimeter with 45000 cells.
– $e^{\pm}$: $\sigma/E = 12\%/\sqrt{E[GeV]}+1\%$
ZEUS: – comp. U/scint., 12k cells.
– hadrons: $\sigma/E = 35\%/\sqrt{E[GeV]}$
Silicon tracking; lumi from ep→ epγ.

	E_p (GeV)	HERA (pb^{-1})	ZEUS (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

Electroweak, pQCD



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

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

QCD proton structure
described by PDFs $f_i(x,Q^2)$

Kinematic variables:

- $Q^2=-q^2=-(k-k')^2\sim1/\lambda^2$ (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.

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

Distinguish:
– Neutral and charged current
– DIS and photoproduction

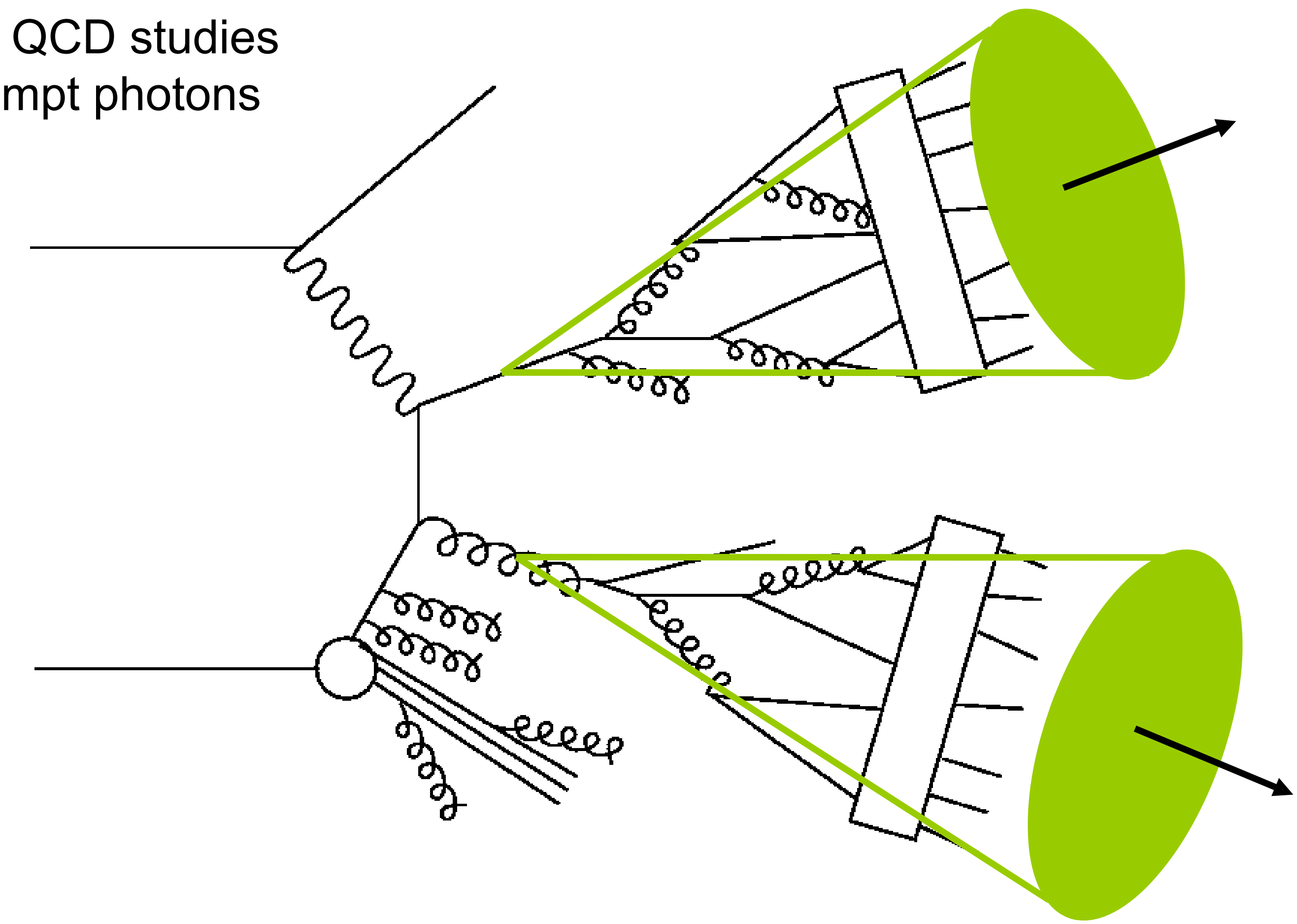
DIS @ HERA:
1) super-microscope to study PDFs
2) Sensitivity to EW physics!

JETS: WHY AND WHAT?

HERA: rich hadronic final state

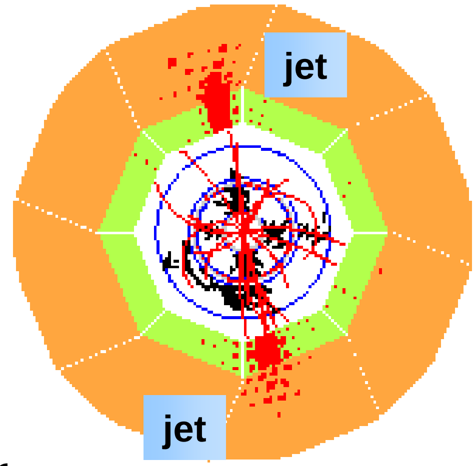
→ detailed QCD studies

→ 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



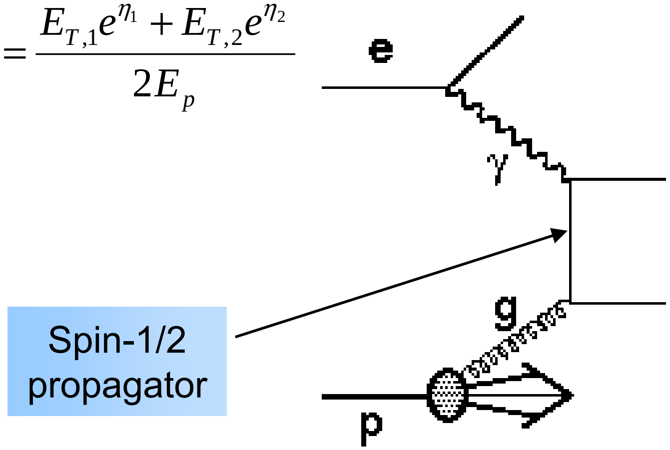
Jet technicalities:

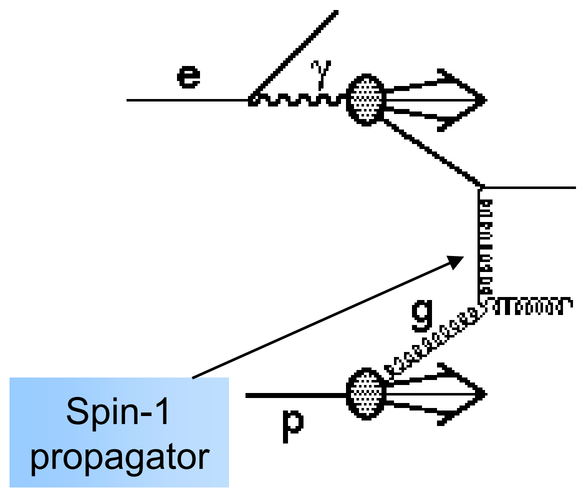
– longitudinally invariant k_T algorithm in inclusive mode
– Run on calorimeter cells or “energy flow objects”.
– Hard jets selected using cuts on transverse energy $E_{T;}$,
– Detector acceptances $-1 < \eta < 2.5$, with $\eta = -\ln \tan(\theta/2)$.
– (Jet energy scale and jet E_T corrections.)

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_γ:

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





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

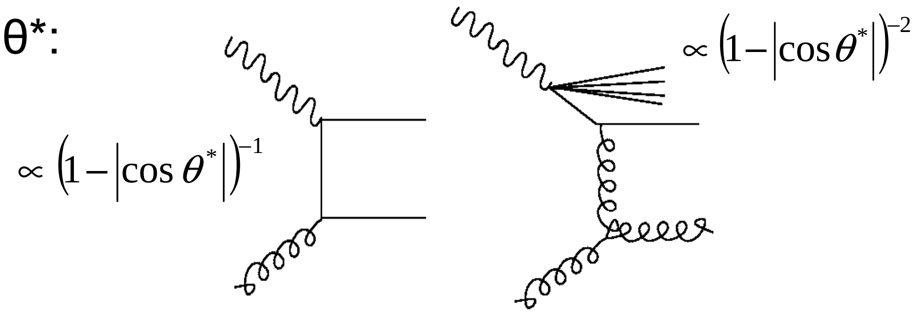
$x_\gamma > 0.8$: direct
$x_\gamma < 0.8$: resolved

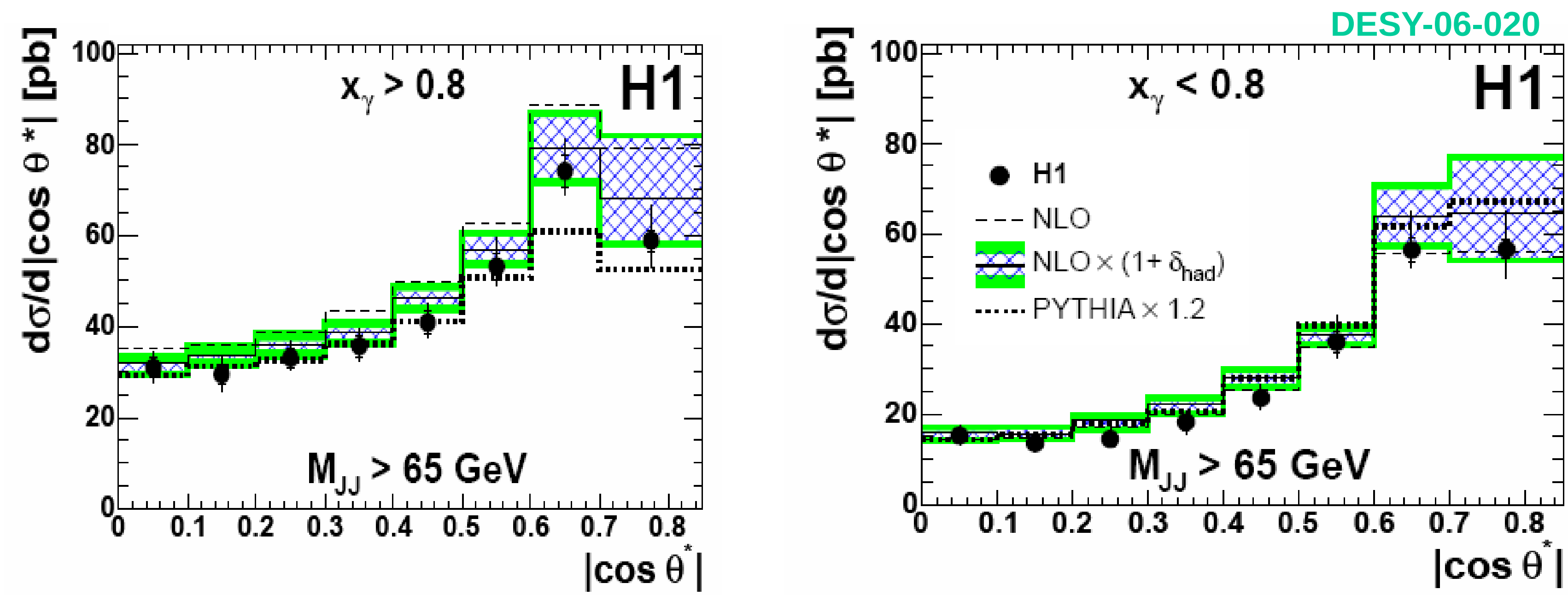
CONFIRMATION: RESOLVED CONCEPT

Observable: CMS scattering angle: cosθ*:

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

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





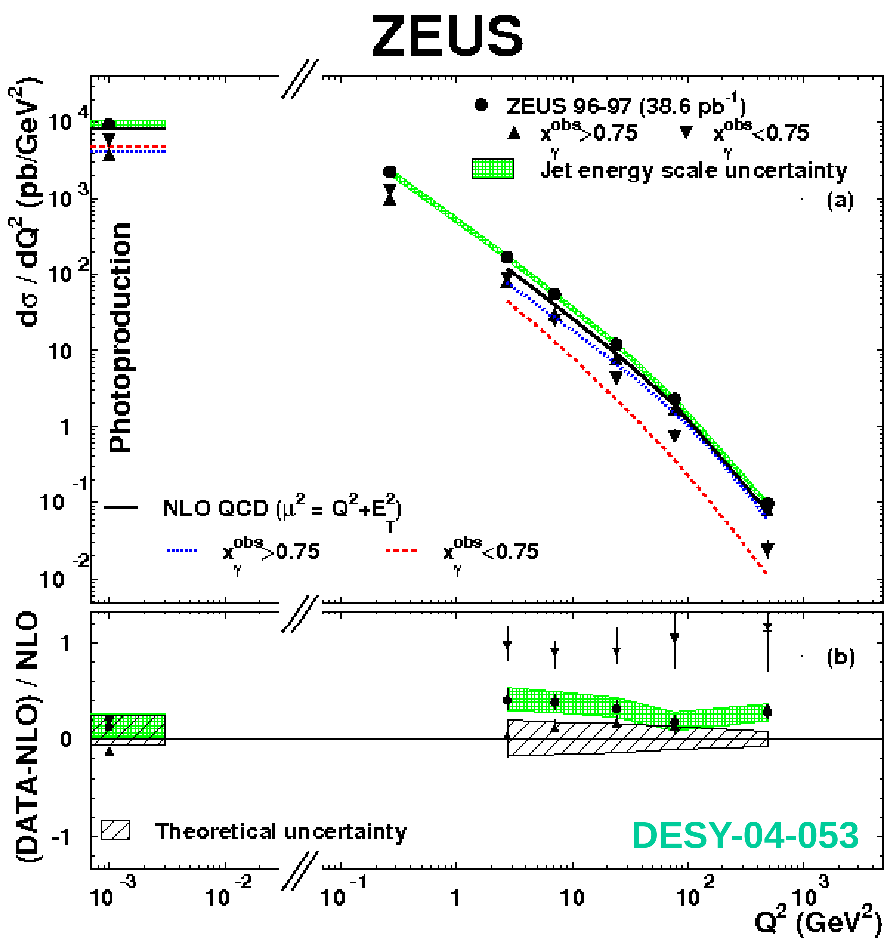
[H1 data, 66.6 pb^{-1}, 0.1 < y < 0.9
Dijets; E_T > 25 GeV, -0.5 < η < 2.75]

→ 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 $Q^2 < 1000$ GeV^2).
– Separately for direct and resolved events (x_γ<>0.75).



→ Even at $Q^2 = 500$ GeV^2 about 24% “resolved” events!

→ NLO QCD ~30% too low.

→ Resolved contribution in DIS not described by NLO QCD (not included in DISASTER++)

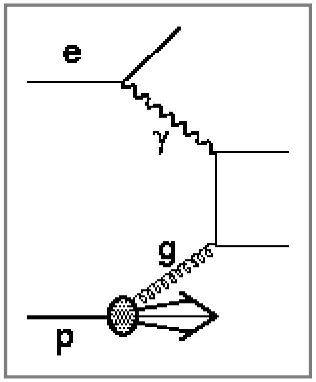
→ LO MC models can describe the data.

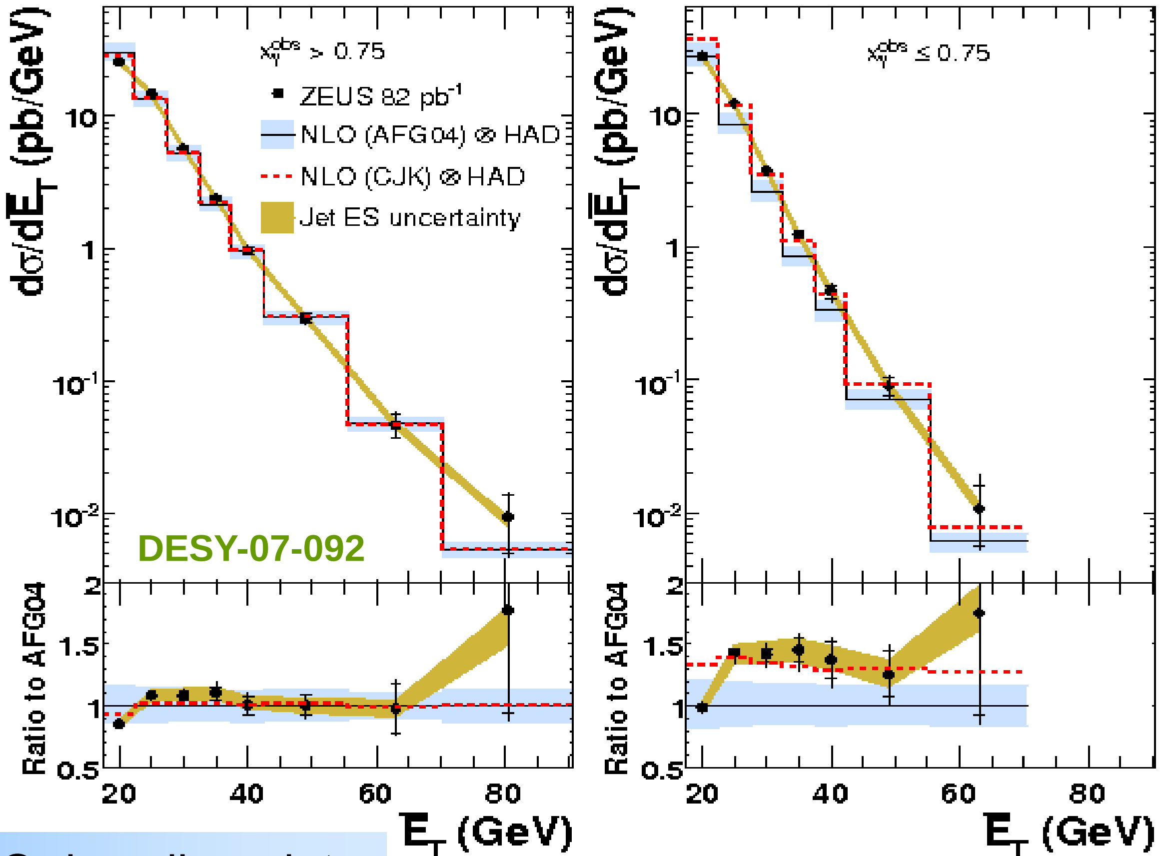
→ For $Q^2 = 0$ data in agreement with NLO.

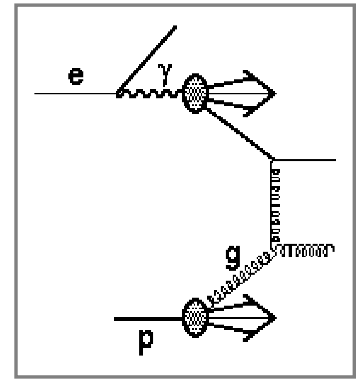
[ZEUS data, 38.6 pb^{-1}, $0.2 < y < 0.55$
Dijets; $E_T > 7.5/6.5$ GeV, $-3 < \eta_{\gamma p} < 0$]

JETS IN PHOTOPRODUCTION

Cross-sections in direct and resolved:







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

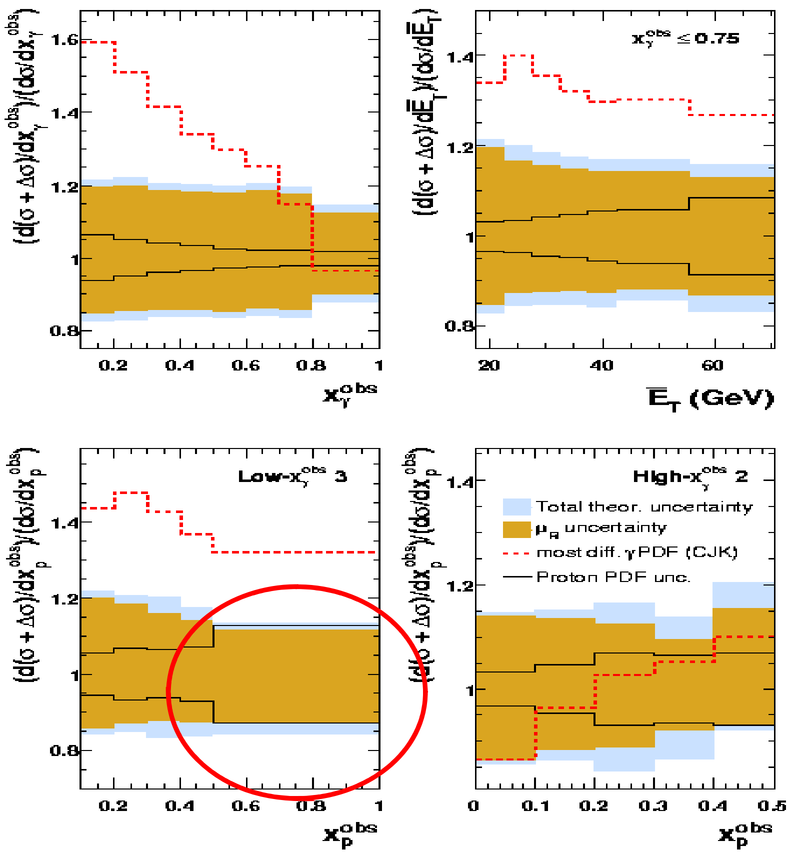
Resolved: large influence of photon PDF (up to 50%)
→ potential to constrain?

[ZEUS data, 81.8 pb^{-1}, $0.15 < y < 0.7$
Dijets; $E_T > 20/15$ GeV, $-1 < \eta < 3$]

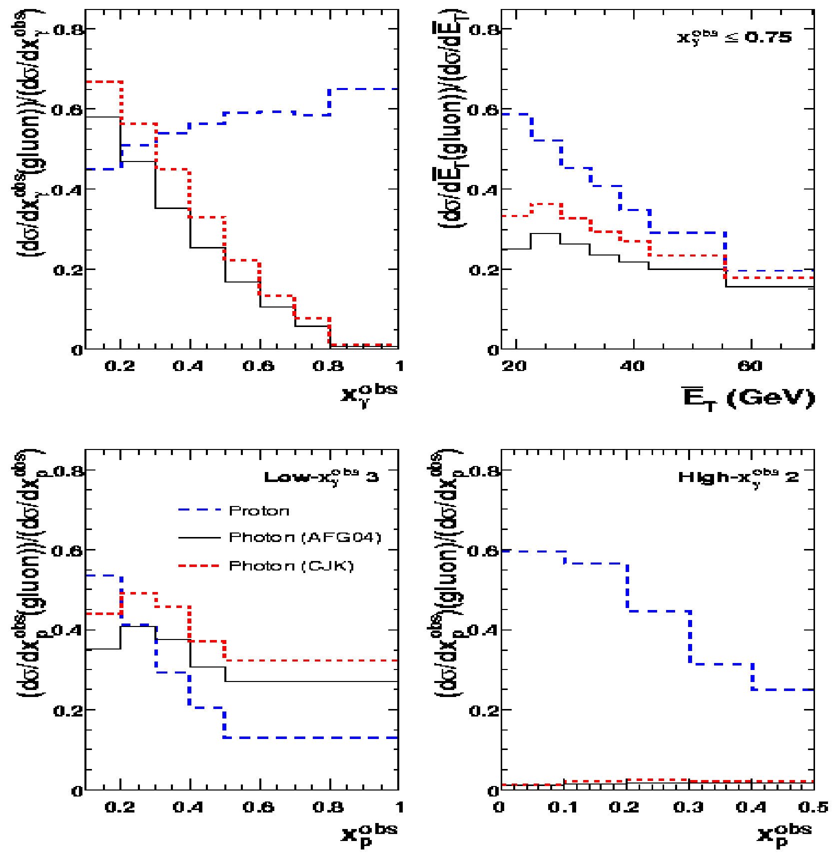
PDF SENSITIVITY

Theoretical uncertainties …

… for different kinematic regions.



In addition: partly large gluon contributions from p and/or γ:

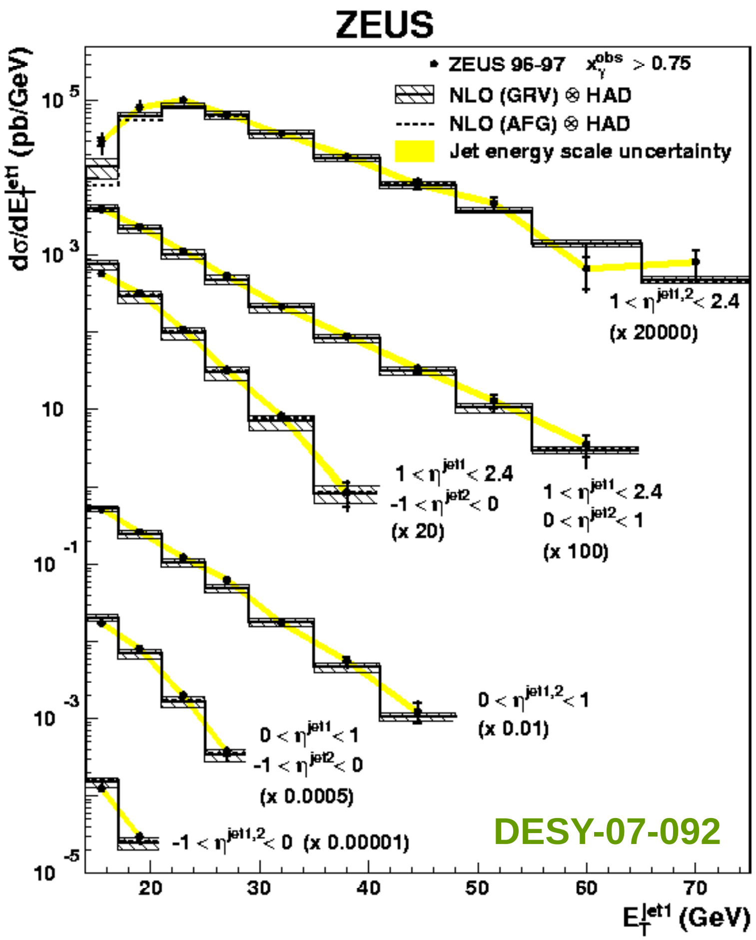


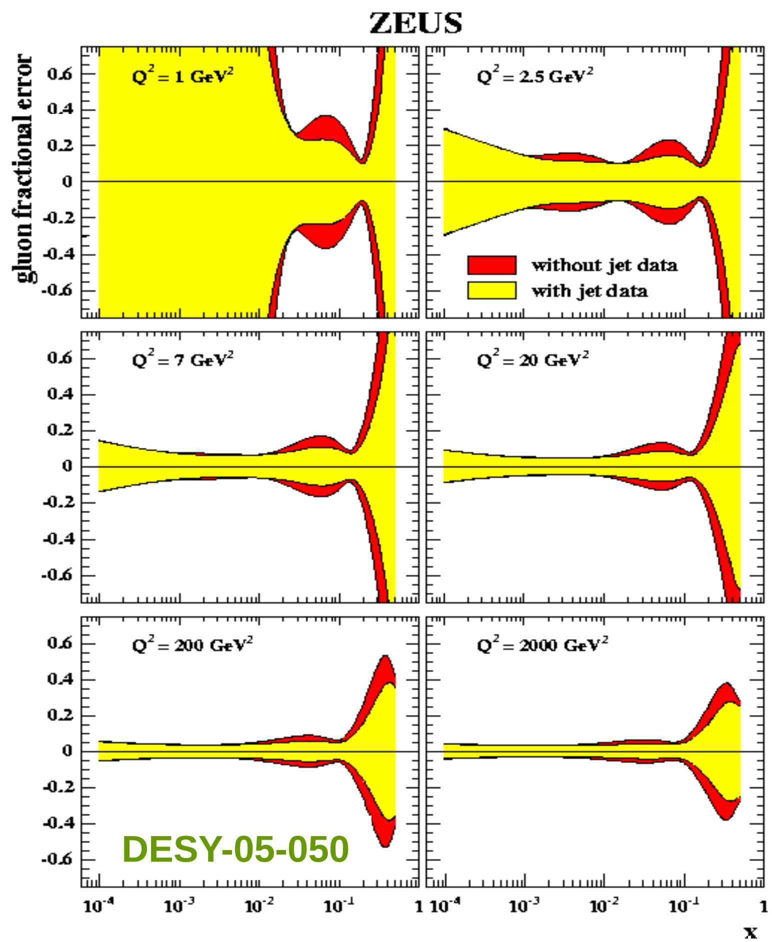
Proton PDF: Sometimes dominant!
Photon PDF: Large effect!

➔ 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 …

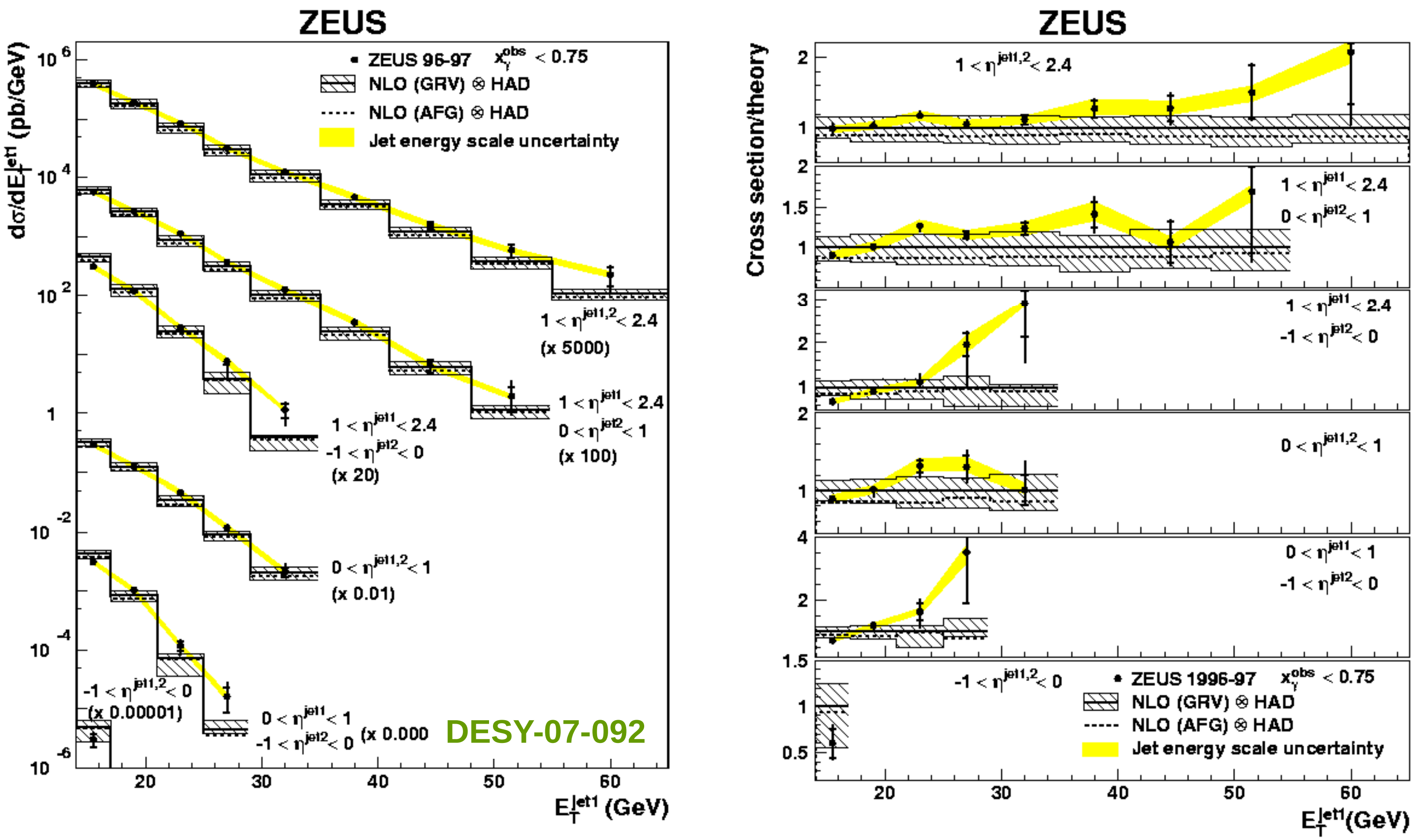




Reduction of proton gluon density uncertainty by up to 40% or so!

JETS IN PHP: RESOLVED

… the corresponding resolved data:



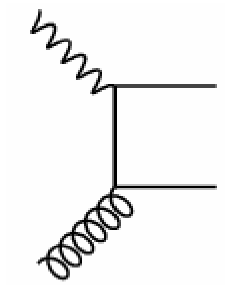
– Data not described over all phase-space.
– Systematic differences between GRV and AFG photon PDFs (15%).

JETS IN PHP: x_γ, x_p

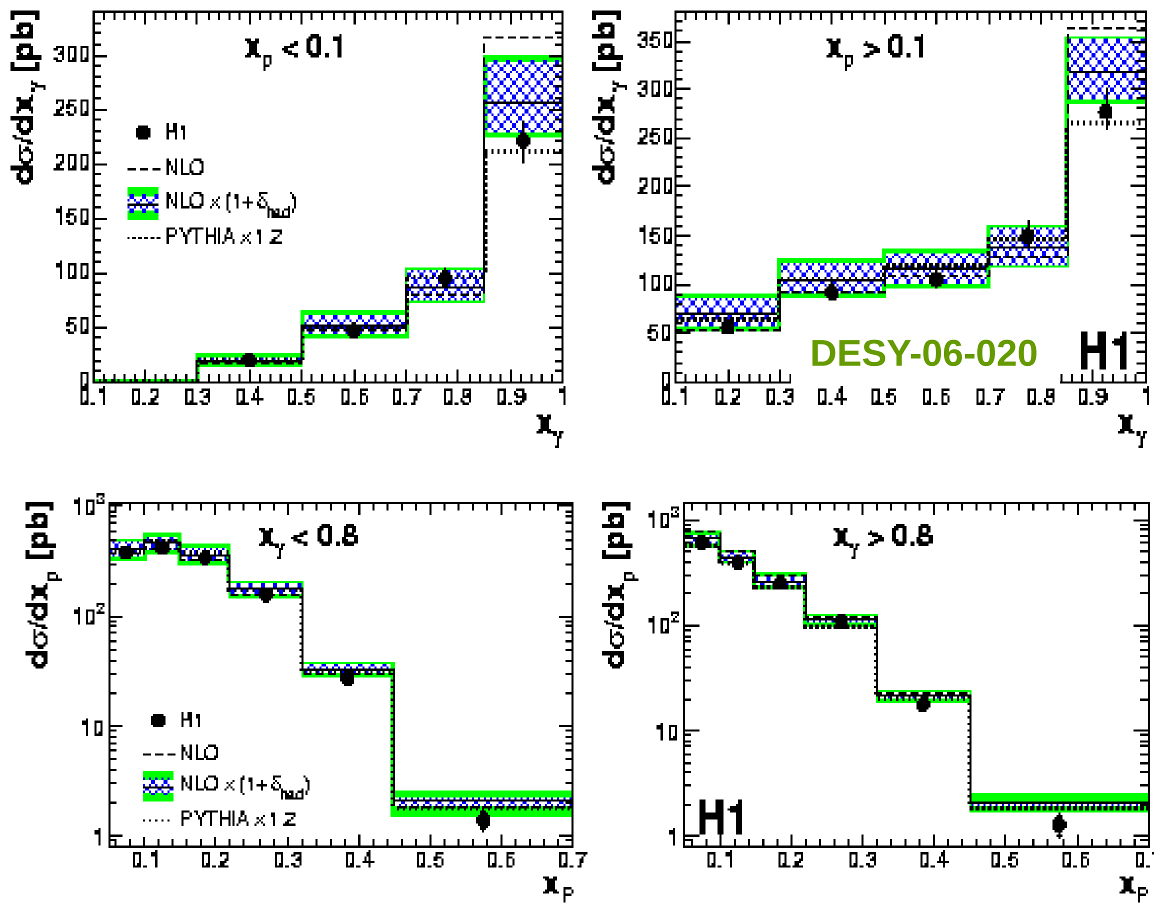
$$x_p = \frac{E_{T,1}e^{\eta_1} + E_{T,2}e^{\eta_2}}{2E_p} \qquad x_\gamma = \frac{E_{T,1}e^{-\eta_1} + E_{T,2}e^{-\eta_2}}{2yE_e}$$

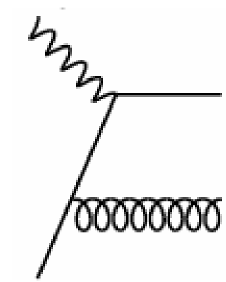
Interest in photon (and proton) structure
→ measure x_γ (and x_p)!

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



Boson-gluon fusion (70%)





QCD-Compton (15%)

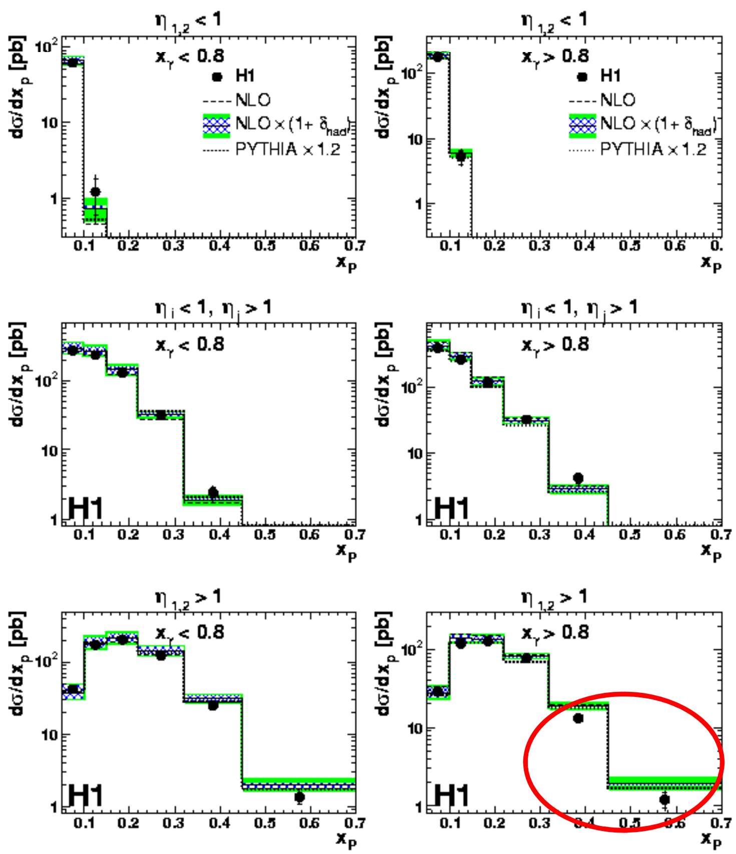
– NLO describes data over basically all phase space within errors (jet scale!).
– PYTHIA with GRV-LO, NLO with GRV-HO as photon PDF.

JETS IN PHP: PSEUDORAPIDITIES etc.

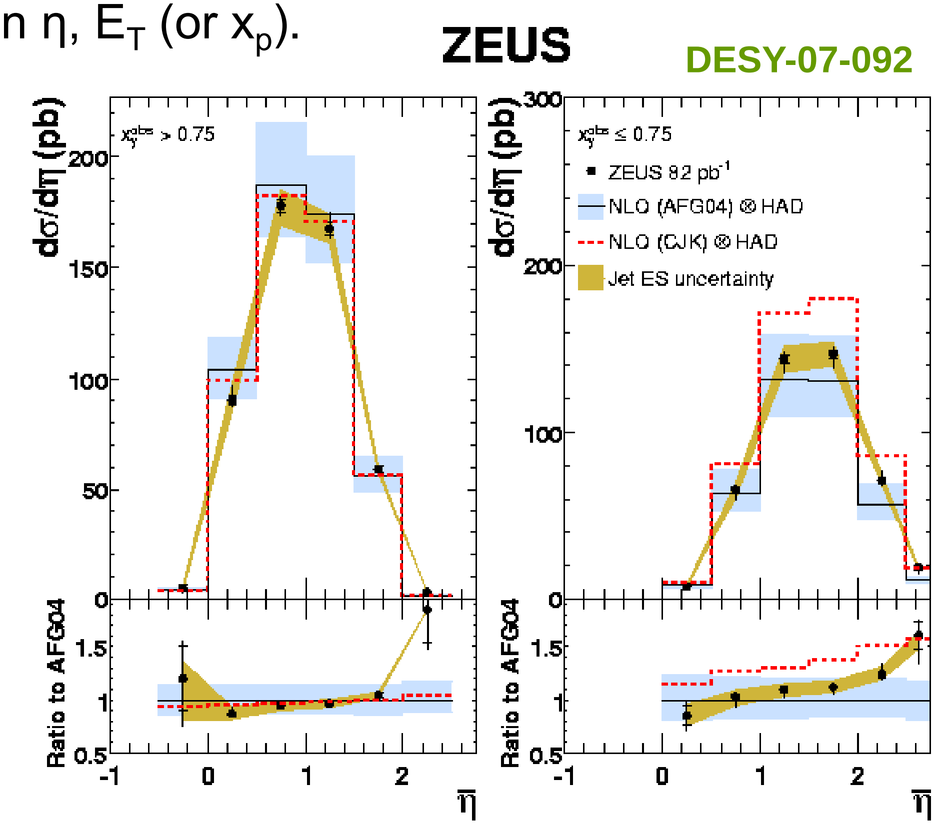
Jet pseudorapidities:

→ Sensitivity to momentum distributions of incoming hadrons.

→ (double-differential) measurements in η, E_T (or x_p).



DESY-06-020

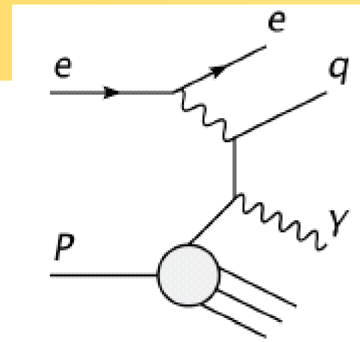


DESY-07-092

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

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

PROMPT PHOTONS: DIS



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

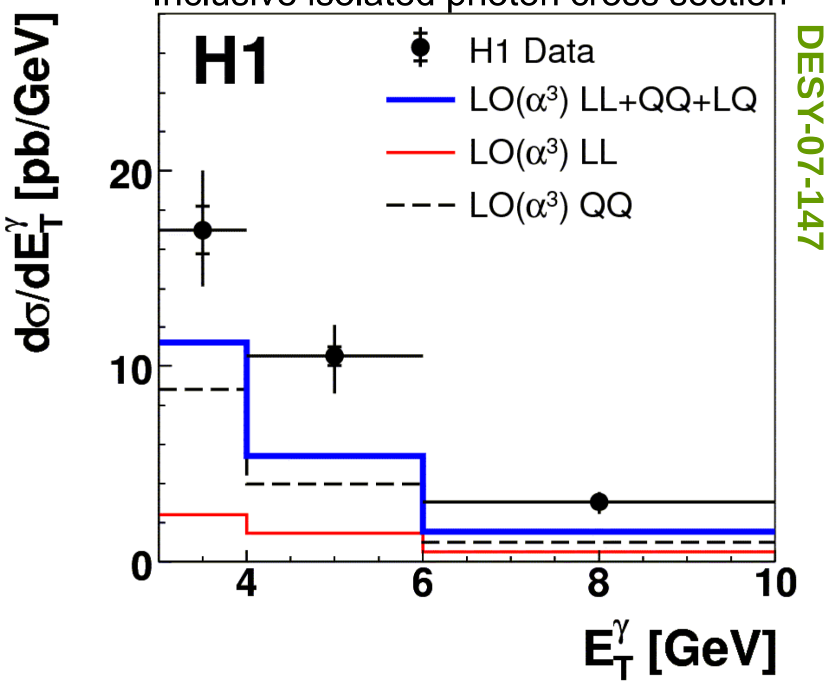
Alternative access to QCD issues:

→ Different systematics.

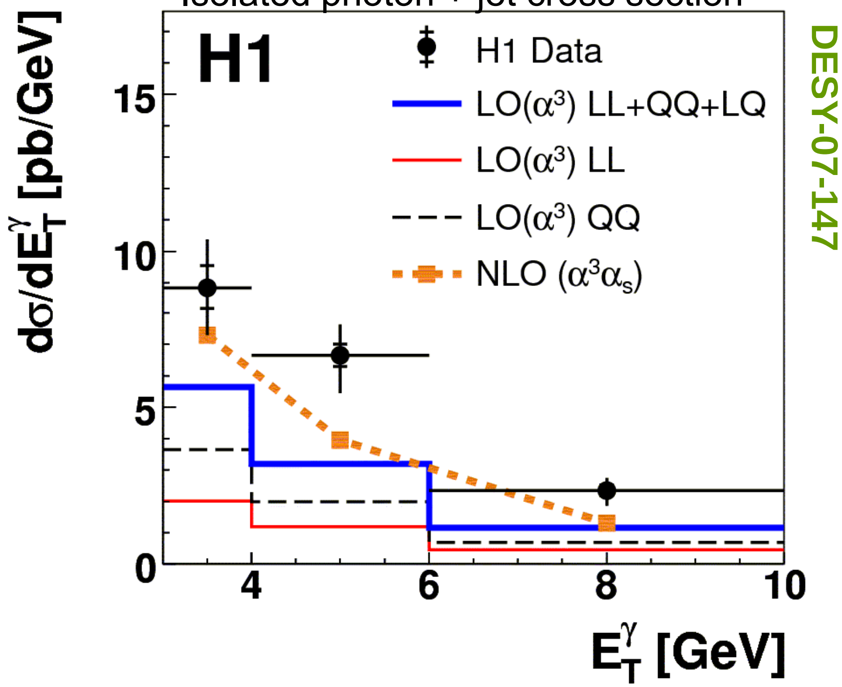
→ Smaller hadronisation corrections.

In addition importance for new-physics searches.

Inclusive isolated photon cross section



Isolated photon + jet cross section



[H1, 227 pb^{-1}, $4 < Q^2 < 150$ GeV^2
$3 < E_{T\gamma} < 10$ GeV, $y > 0.05$]

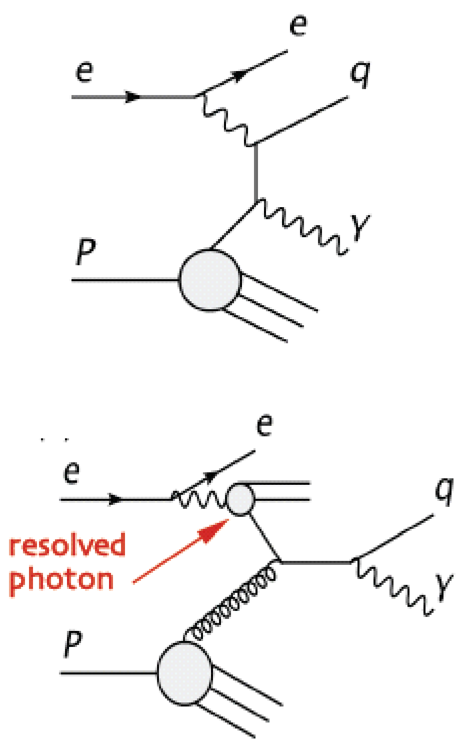
Without jet requirement (LO) theory factor 2 below data, shapes agree. With jet requirement (NLO) theory better.

PROMPT PHOTONS: PHP

… after the problems in DIS, how about PHP?

direct+resolved contribution.

→ access to p and γ PDFs.

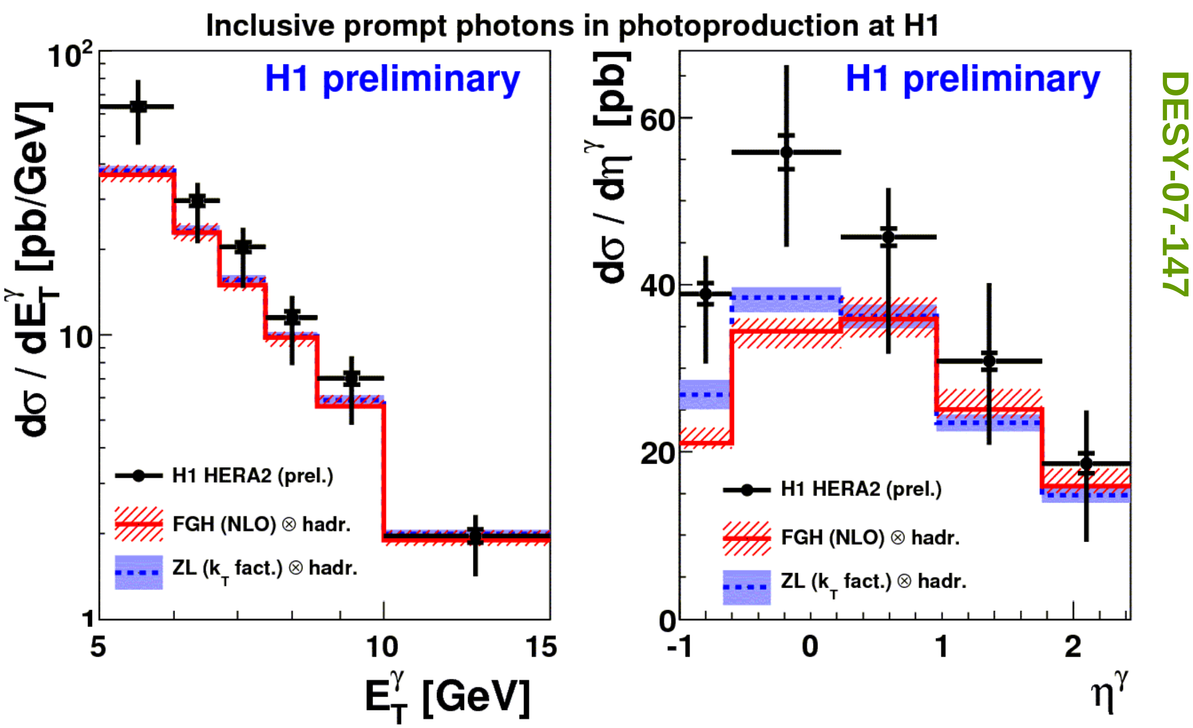


[H1, 340 pb^{-1}, 2004-2007 data
5 < $E_{T\gamma}$ < 15 GeV, 0.1 < y < 0.7]

Comparison of data

– to NLO (DGLAP) calculation (Fontannaz et al.)

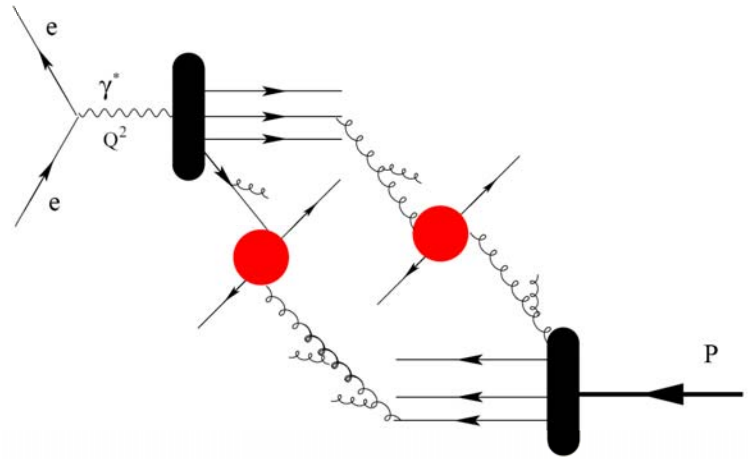
– to k_T factorisation approach (Zotov et al.)

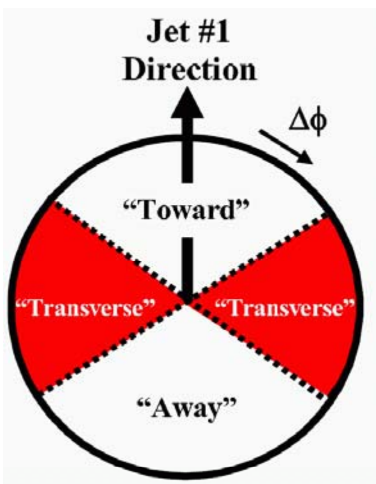


Both calculations undershoot data. Slightly improved situation for photon+jet requirement (like in DIS).

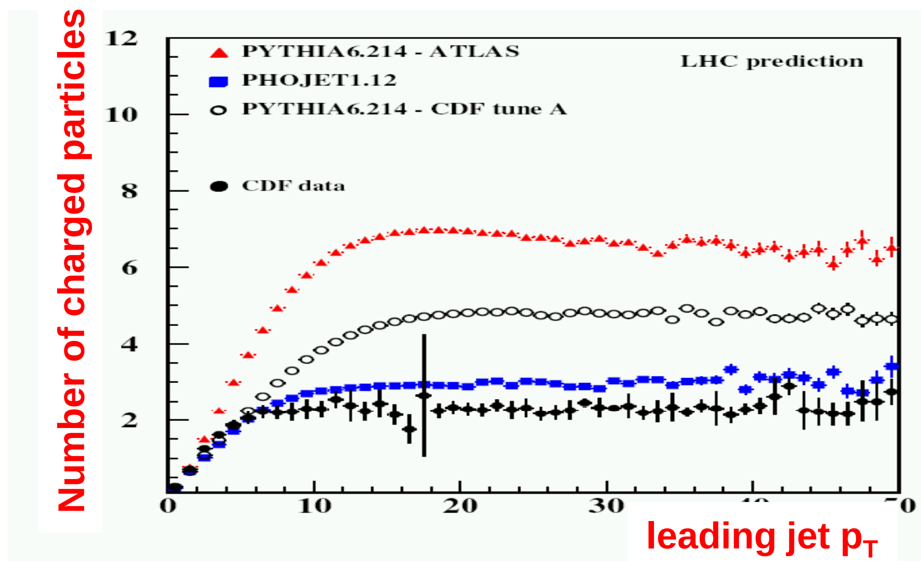
THE UNDERLYING EVENT

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.



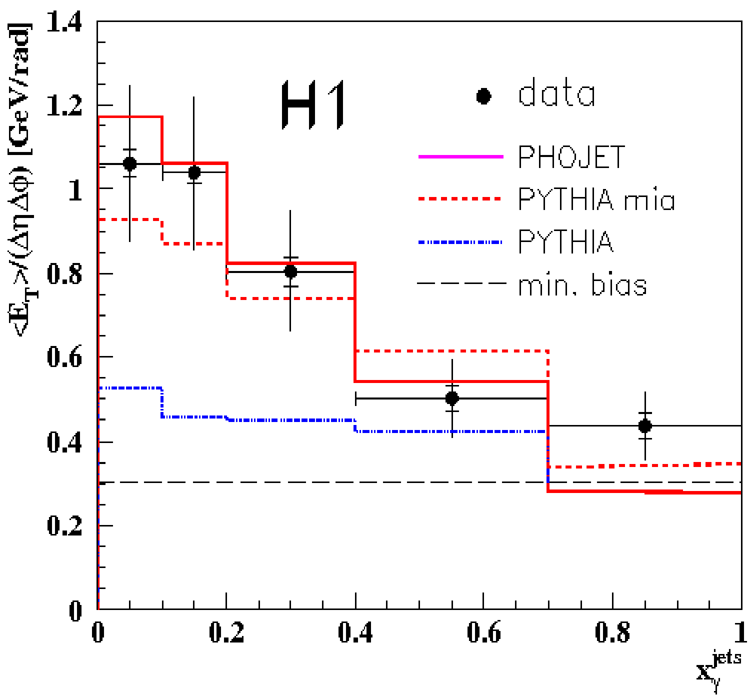
CDF experience:
– MPI models can be tuned to CDF data!
– But extrapolation to LHC not meaningful!

→ Important + theoretically challenging!

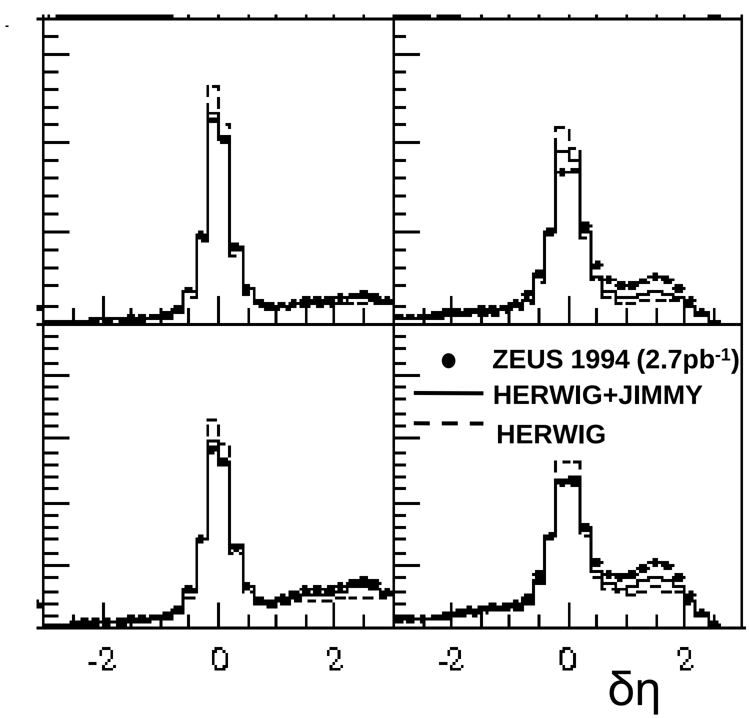
UE/MPI NECESSITY

¶ 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 η 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→2 cross-section and total cross-section; secondary interactions Sudakov-suppressed.

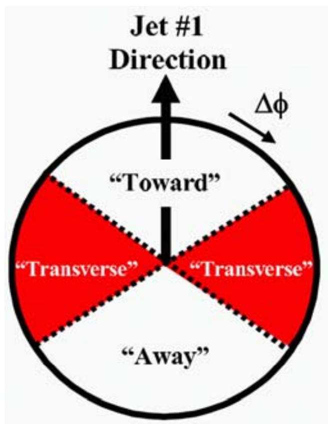
¶ HERWIG + JIMMY
- Based on eikonal model assuming matter distributions in colliding particles and an overlap function A(b).
- Assign 2→2 cross-section to all events, choose number of interactions according toprecalcuted probability distribution.

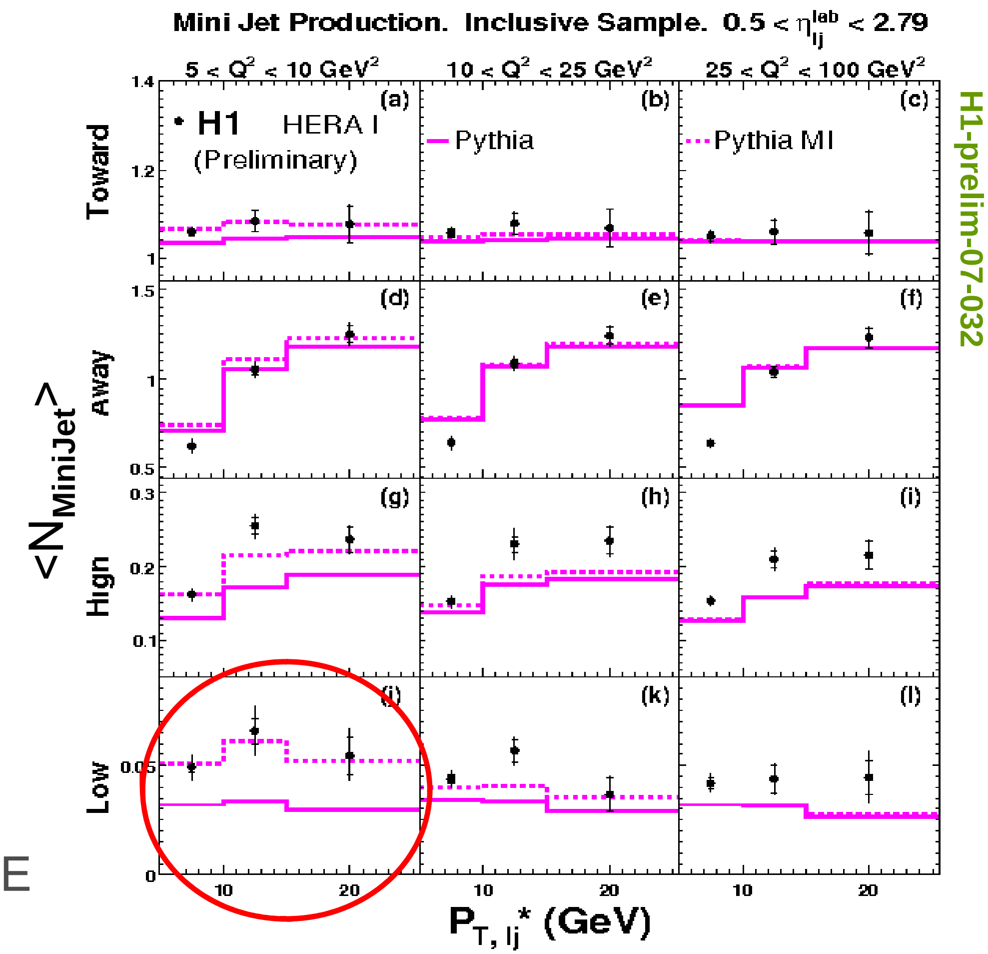
¶ More models:
- Sherpa: similar assumptions as in PYTHIA, module AMISIC++ for MPIs.
- Phojet: Not part of general purpose generator, limited use for HEP.

H1 ANALYSIS: MINIJETS 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 η^{lab} (x_γ).
- Data compared to PYTHIA, ARIADNE RAPGAP, …

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

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

H1: DIJET SAMPLE

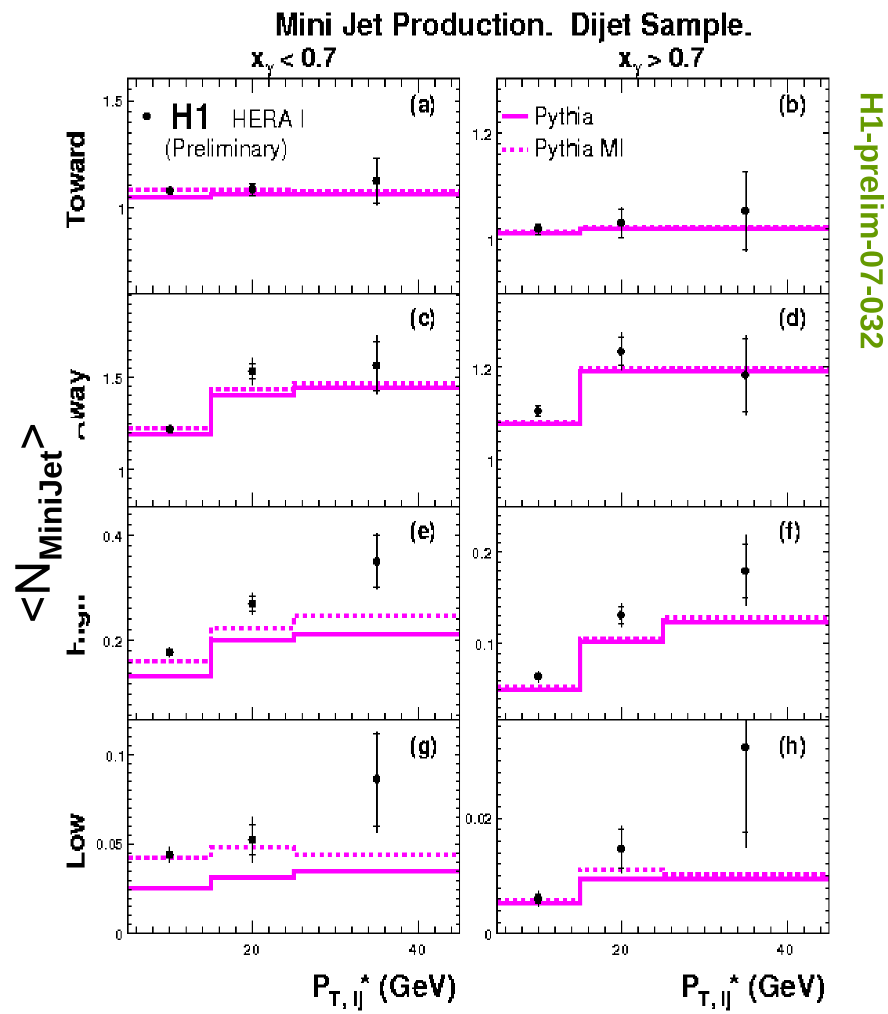
¶ Jet regions:

– 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.



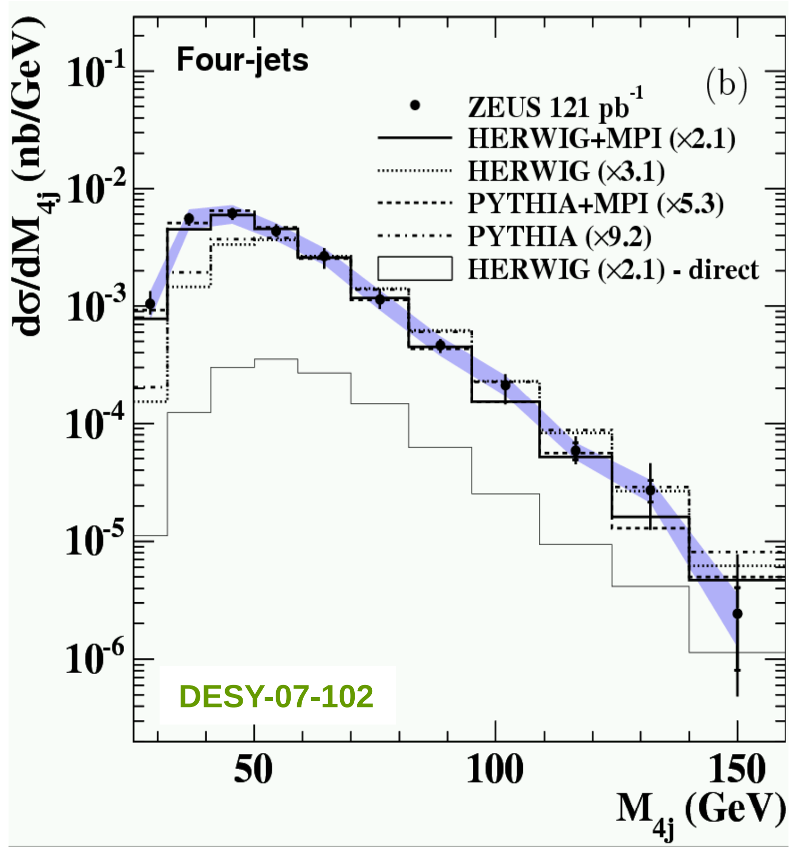
Influence of MPI / necessity of its modelling demonstrated.

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

ZEUS: MULTIJETS IN γ*p

¶ Measure for UE:
- 3- and 4-jet cross-sections.
- Jets 3, 4 generated by hard QCD radiation? MPI?

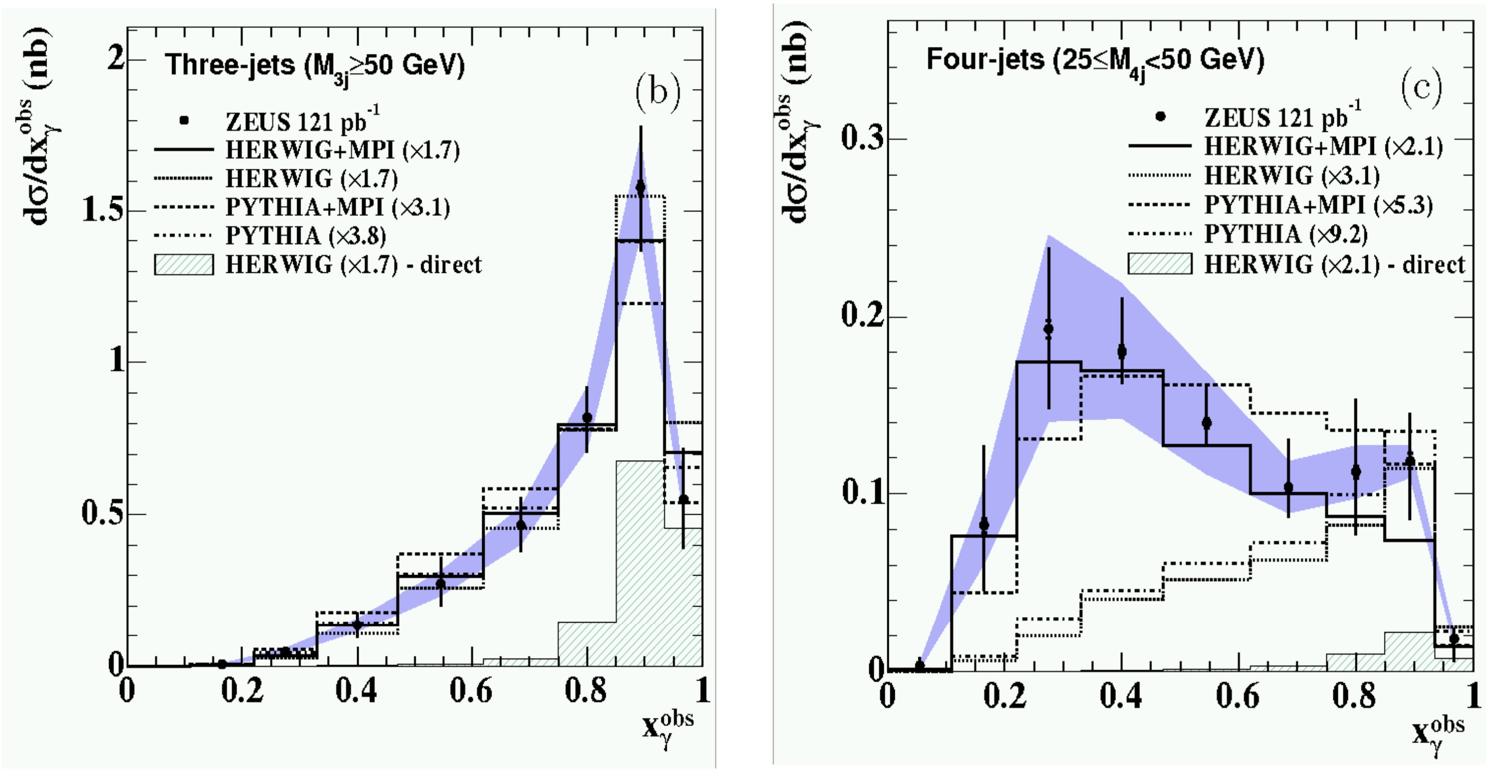
¶ Models for comparison:
- HERWIG 6.505 + JIMMY 4.0
- PYTHIA 6.206 + "simple" MPI model
- Also: NLO calculation (Klasen et al.) for 3jet case (effectively LO!)



[ZEUS data, $121 pb^{-1}$, $0.2 < y < 0.85$.
Jets: $E_T > 6$ GeV, $|\eta| < 2.4$.
High/low-mass region: M_{nj} <> 50 GeV]

Need MPI/UE simulations to correctly describe the data:
HERWIG and PYTHIA without UE / MPI fail to describe data at low M_{nj}.

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

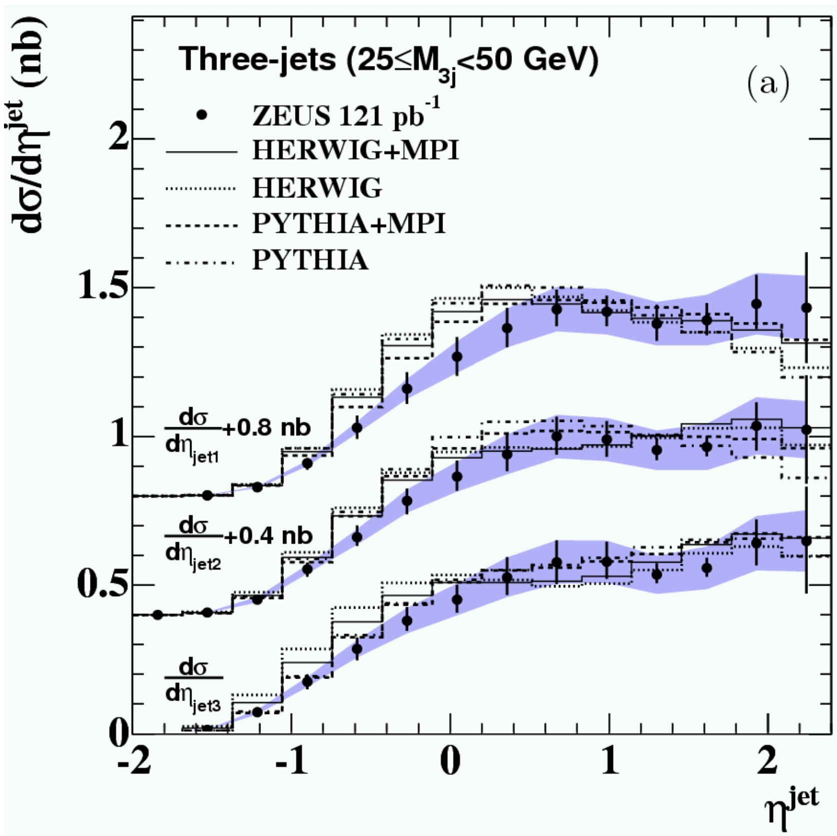


- Models without MPI suggest decreasing cross-sections with decreasing x_γ.
- But for low masses large discrepancy with INCREASING data
  → mechanism beyond direct+resolved as modelled in MC necessary.
- Even “direct” region ($x_\gamma > 0.75$) dominated by resolved events (↔dijets!).
- Especially HERWIG+JIMMY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

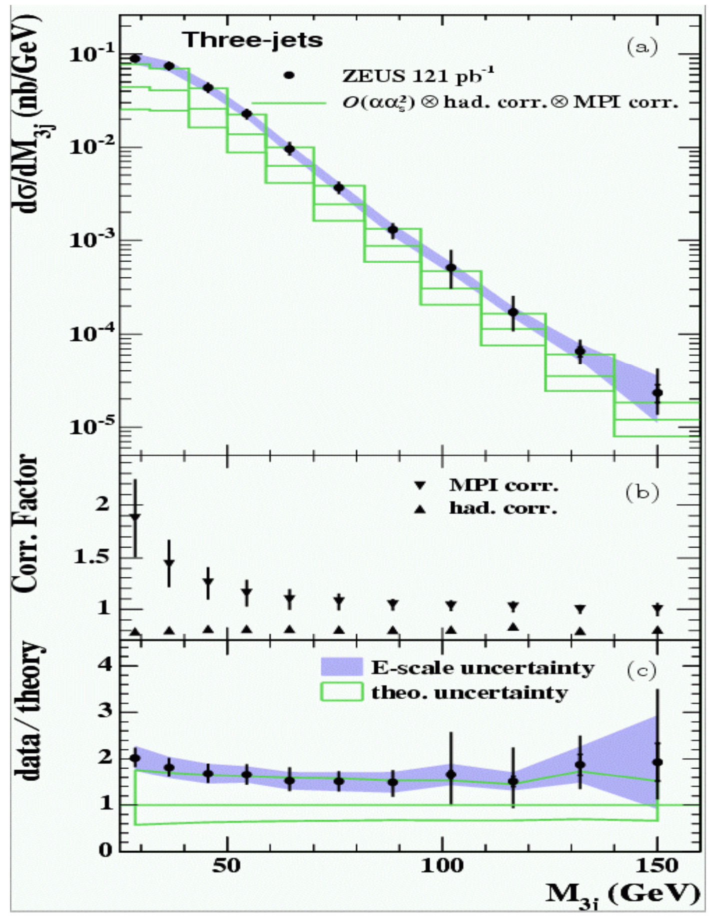
ZEUS MULTIJETS

¶ dσ/dη versus LO models:
- High-mass data described by all models.
- Best description of low-M data: HERWIG.
- MPI improve description at high η.

¶ dσ/dM3$_j$ 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 γ 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?

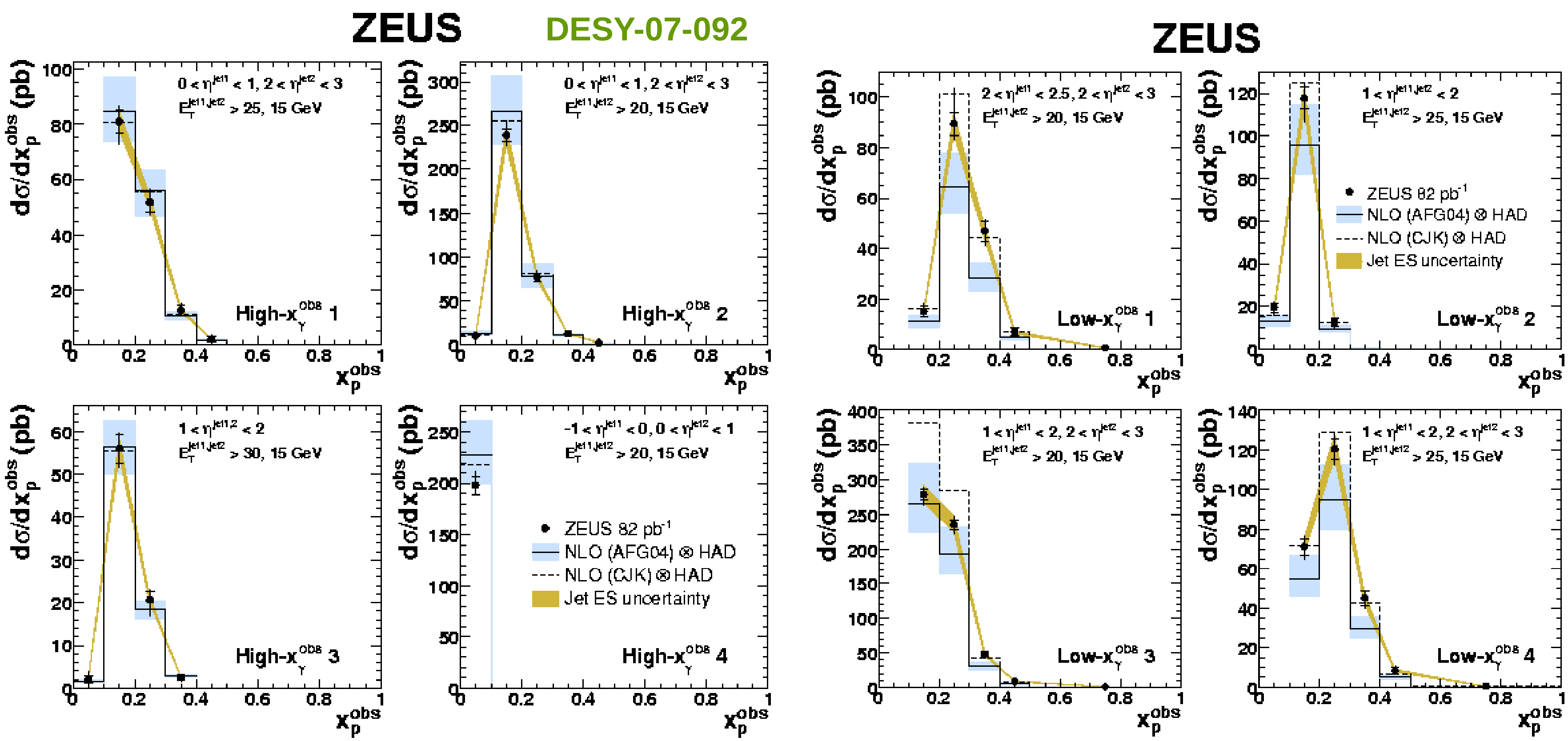
¶ Many HERA-II results to come!
– So far most results with limited HERA-I statistics!
– Many measurements limited by renorm. scale uncertainty! Need theoretical input!

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.



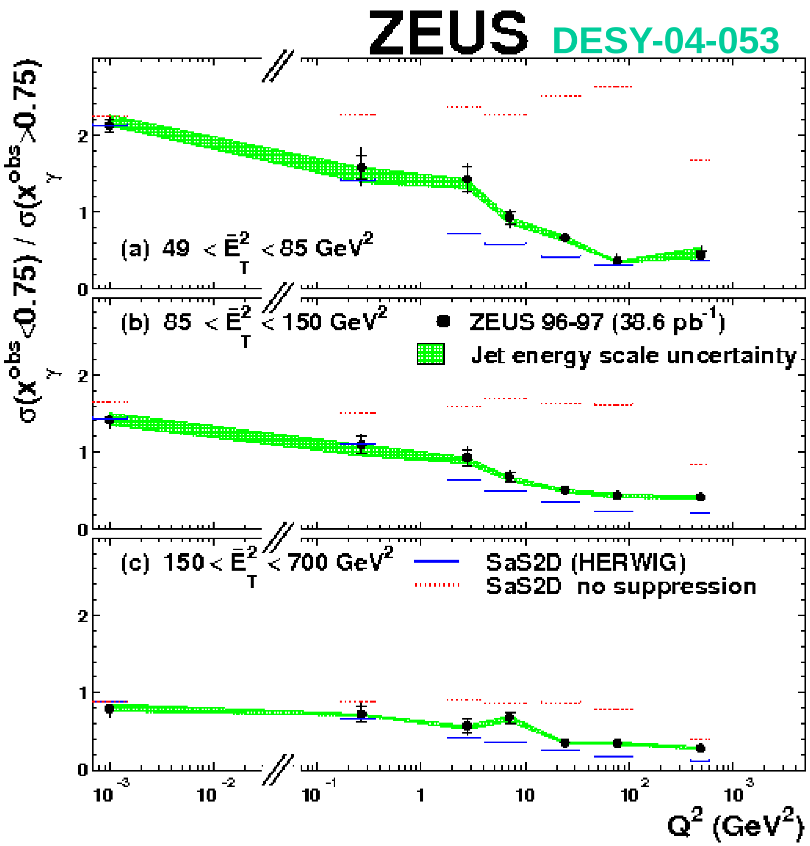
Potential of these and similar data to further constrain the photon!

RESOLVED VERSUS DIRECT

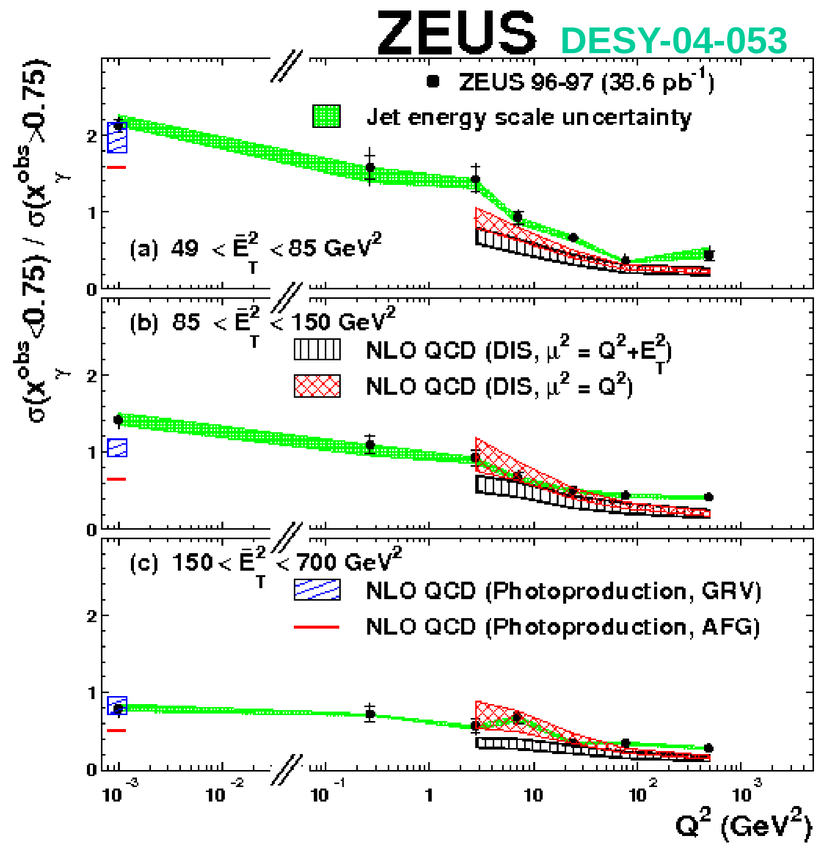
Ratio R=σ(resolved)/σ(direct) as fct of Q^2 in regions of mean E_T:

– Better understanding of resolved component at $Q^2 > 1\ GeV^2$?

– Data compared to HERWIG LO MC with two different photon PDFs, and to NLO.



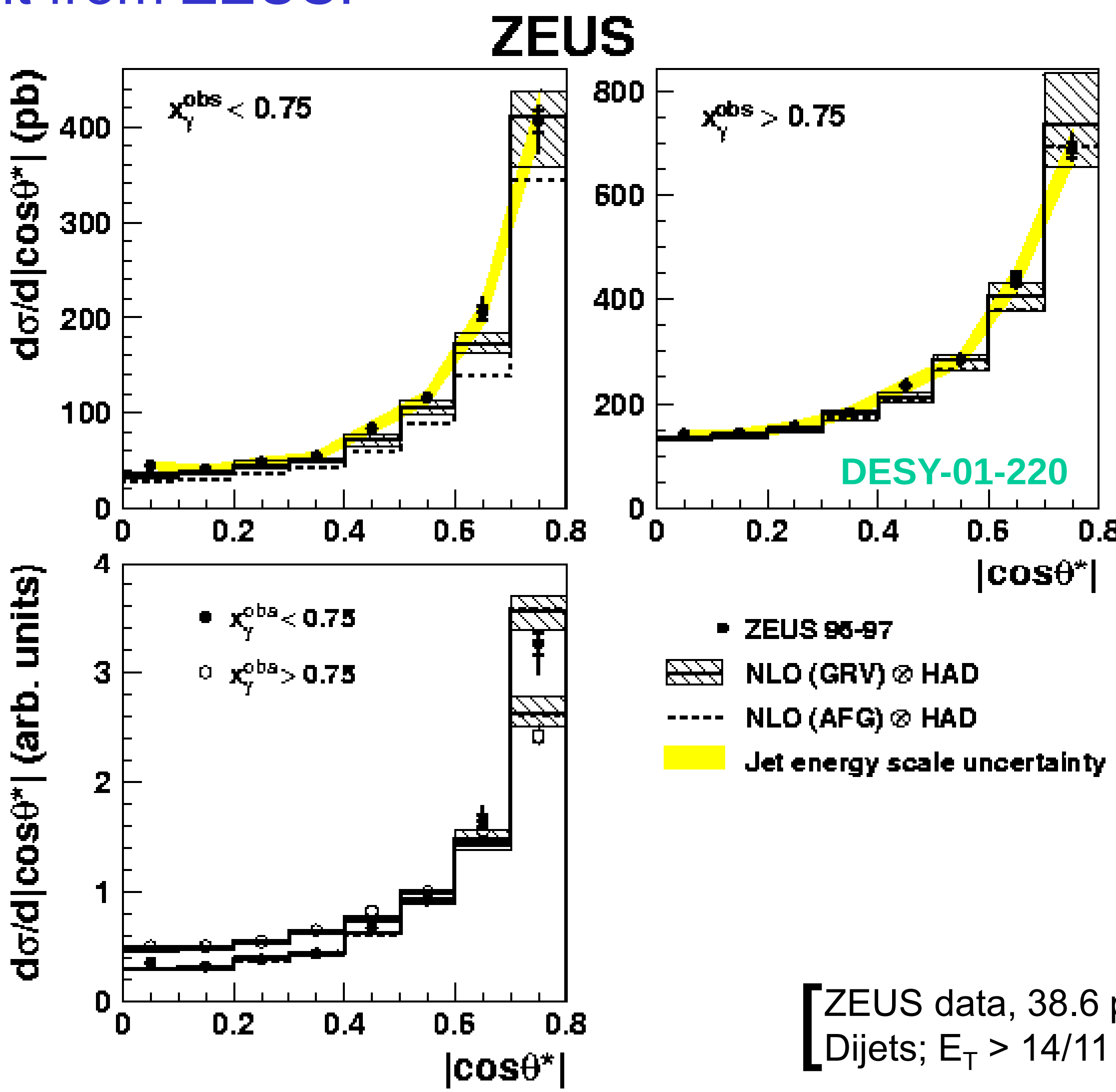
SaS2d with γ PDF suppression reproduces the data!



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

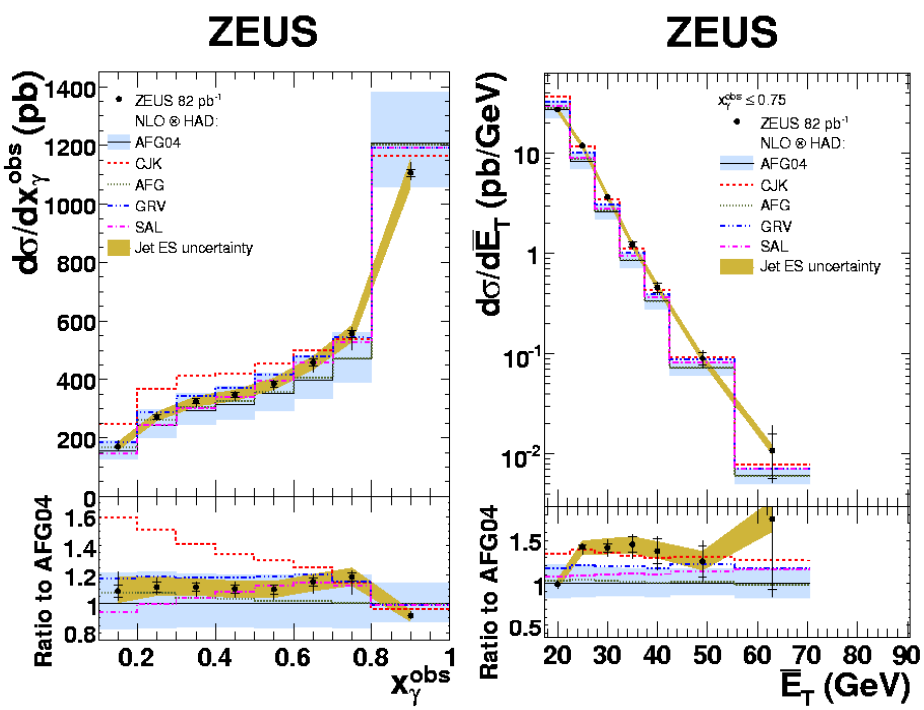
CONFIRMATION: RESOLVED CONCEPT

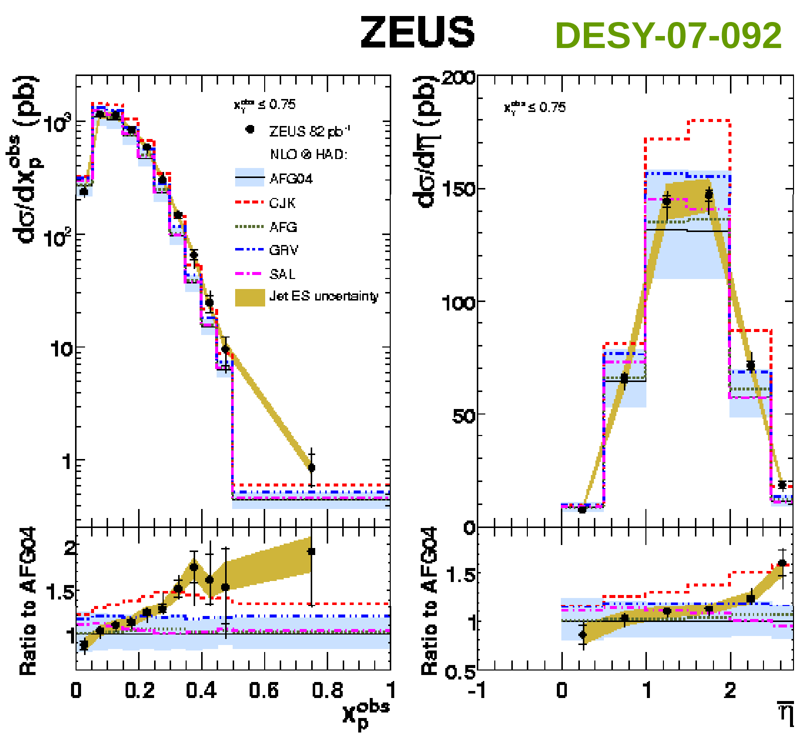
Similar result from ZEUS:



[ZEUS data, 38.6 pb^{-1}, $0.2 < y < 0.85$
Dijets; $E_T > 14/11$ GeV, $-1 < \eta < 2.4$]

JETS IN PHOTOPRODUCTION





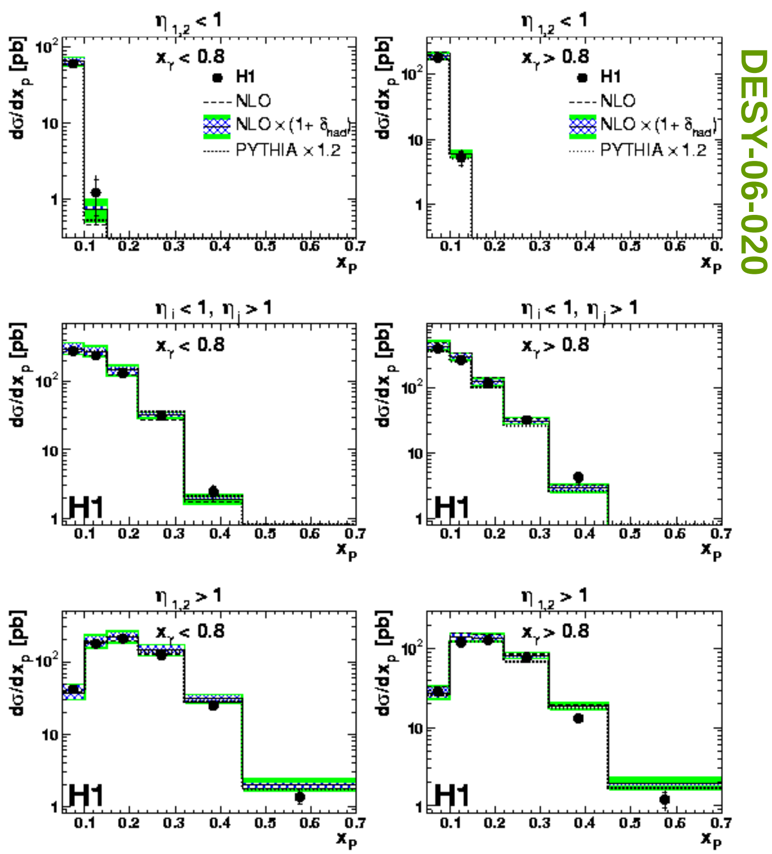
DESY-07-092

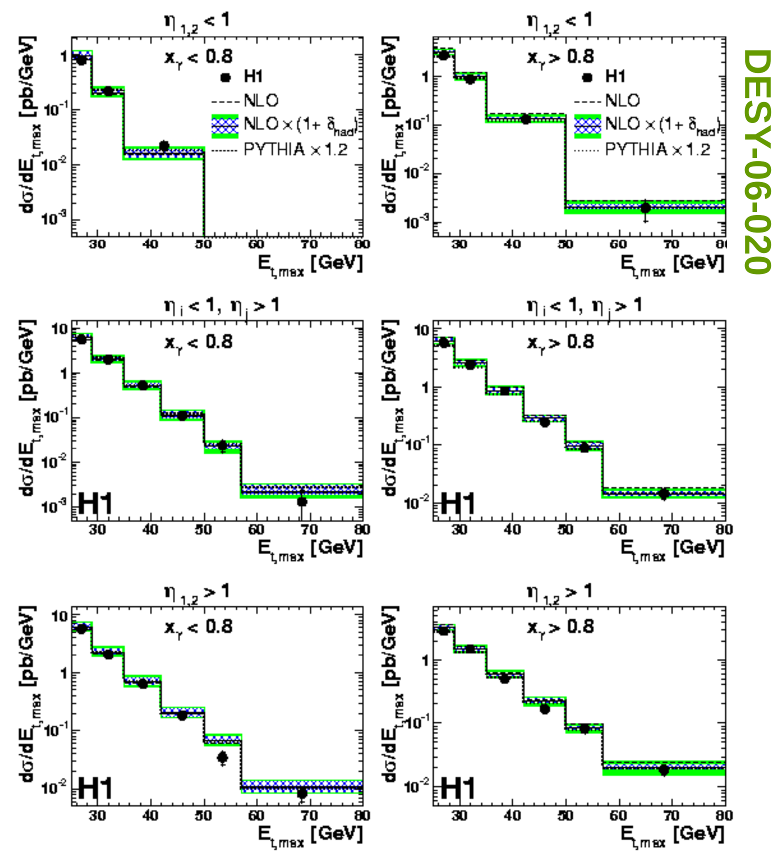
JETS IN PHOTOPRODUCTION

Jet pseudorapidities:

→ Sensitivity to momentum distributions of incoming hadrons.

→ double-differential measurements in η, 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 γ 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%!