Photoproduction of jets and prompt photons

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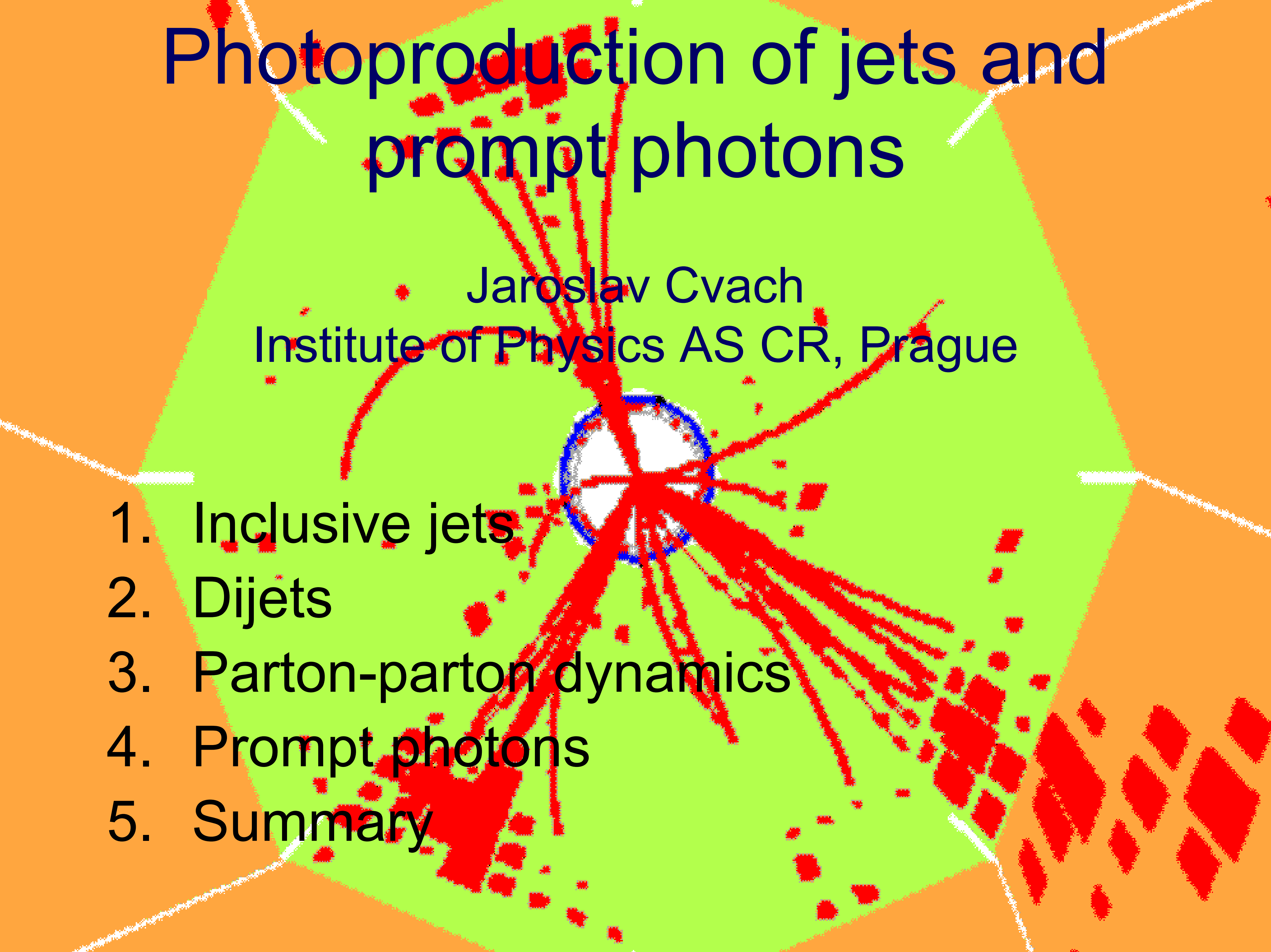
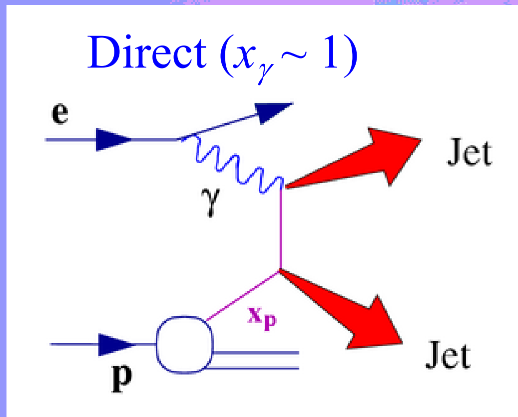
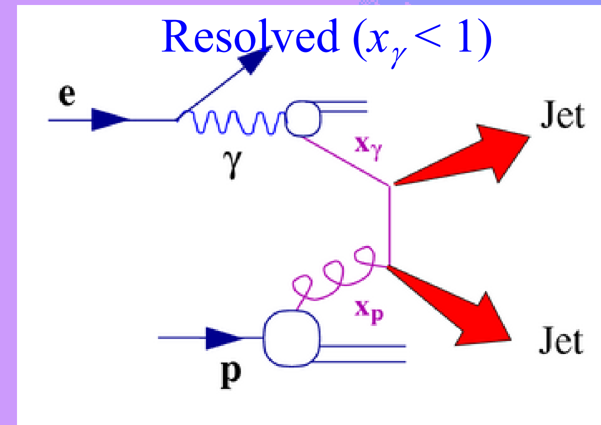
1. Inclusive jets
2. Dijets
3. Parton-parton dynamics
4. Prompt photons
5. Summary



Parton level (photo)production





$$\sigma^{\text{direct}}_{\text{ep}\to\text{e+jets+X}} = f_{i/p} \otimes \hat{\sigma}_{ei\to\text{jets}}$$

$$\sigma^{\text{resolved}}_{\text{ep}\to\text{e+jets+X}} = f_{\gamma/e} \otimes f_{j/\gamma} \otimes f_{i/p} \otimes \hat{\sigma}_{ij\to\text{jets}}$$

$$x_\gamma = \frac{\sum_{\text{jets}} E_T^{\text{jet}} \mathrm{e}^{-\eta^{\text{jet}}}}{2\mathrm{E}_\gamma} = \frac{\sum_{\text{jets}} (E_i - p_{z,i})}{\sum_{\text{had}} (E_h - p_{z,h})}$$

Resolved/direct processes:

- resolved photons are meaningful when $Q^2 \ll E_T^2$
- distinction can only clearly be made in LO
- use x_γ to separate resolved and direct enhanced samples

QCD calculations:

- renormalisation and factorisation scales in parton cross sections and PDF f_{ij} lead to an uncertainty
- different NLO calculation differ in their treatment of infrared and collinear divergences

Motivation

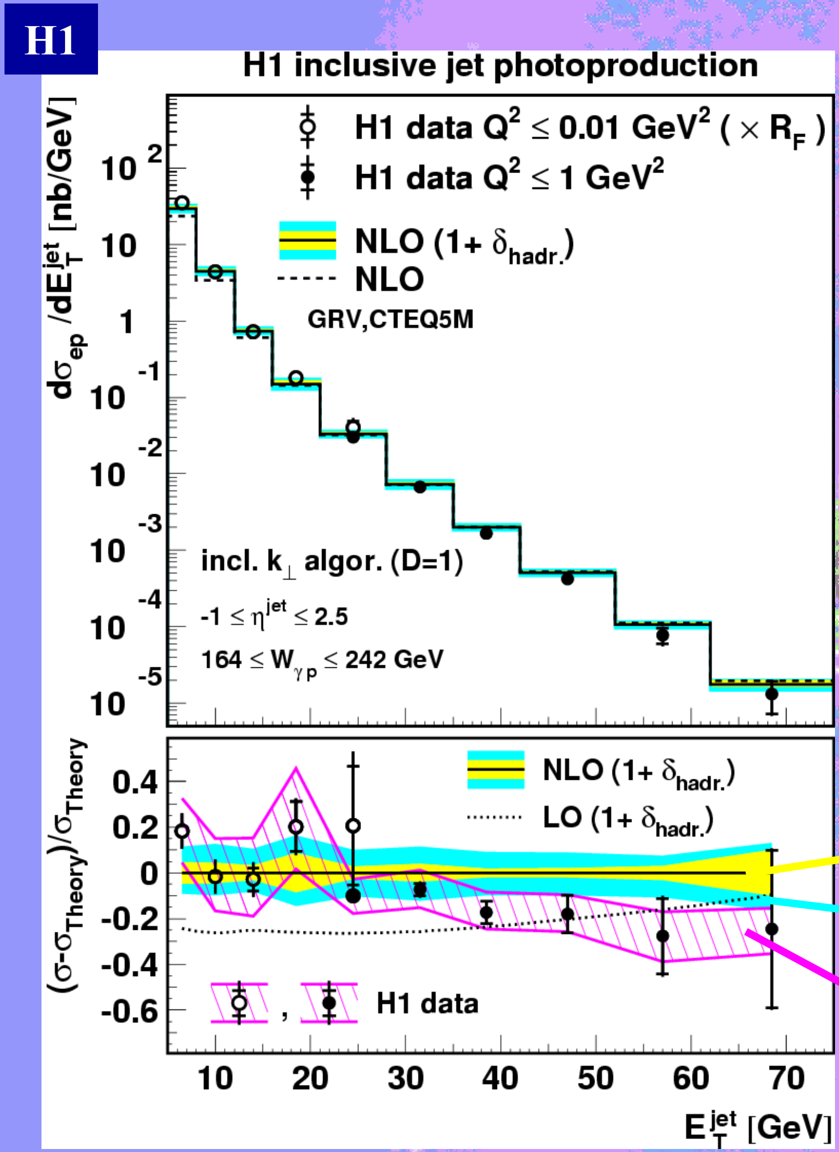
- **High E_T jets**
  - ⇨ Precise tests of perturbative QCD predictions
  - ⇨ Constrain photon and proton PDFs
  - ⇨ Direct insight into parton-parton dynamics
  - ⇨ Search for new physics
- **Low E_T jets** (non-perturbative effects and scale uncertainty important)
  - ⇨ Test phenomenological models of underlying event + fragmentation
  - ⇨ Test limits of pQCD applicability
  - ⇨ Investigation of resolved photon processes
- **Inclusive vs dijet**
  - \+ More statistics, extended kinematic range
  - – No direct reconstruction of x_γ, x_p
  - \+ No infrared sensitivity w.r.t. kinematical cuts as for dijet
- **Prompt photons**
  - \+ Direct insight into the hard process not biased by fragmentation
  - – Low cross section

NLO QCD calculations and Monte Carlo

- NLO weighted parton MC - Frixione, NP B507 (1997) 295
  (H1 - inclusive and dijets, ZEUS – dijets)
  - photon & proton PDFs: GRV & CTEQ5M
  - Other choice : photon: AFG, proton: MRST99, CTEQ5HJ (g↑ at ↑ x_p)
- Klasen, Kleinwort, Kramer, EPJ Direct C1 (1998) 1, (ZEUS – inclusive jets)
  - photon & proton PDFs: GRV & MRST99
- Fontannaz, Guillet, Heinrich, hep-ph/0105121 (H1-prompt photons)
  - photon: AFG, proton: MRST2
- LO QCD Monte Carlo event generators to correct data and calculations to hadron level:
  - Fragmentation: LUND String (PYTHIA, PHOJET) or cluster (HERWIG)

Underlying event: {
Multiple Interactions (PYTHIA) p_T^{mia} =1.2 GeV
Dual Parton Model (PHOJET)
Soft Underlying Event (HERWIG) 35% resolved

Inclusive jets: E_T



- cross section falls by more than 6 orders of magnitude from E_T^{jet} = 5 to 75 GeV
- LO QCD underestimates the cross section (less so at high E_T^{jet})
- NLO QCD reproduces the data well, but needs hadronisation corrections at low E_T
- different choices of photon and proton pdf's describe the data within errors (variations at the level of 5-10%)

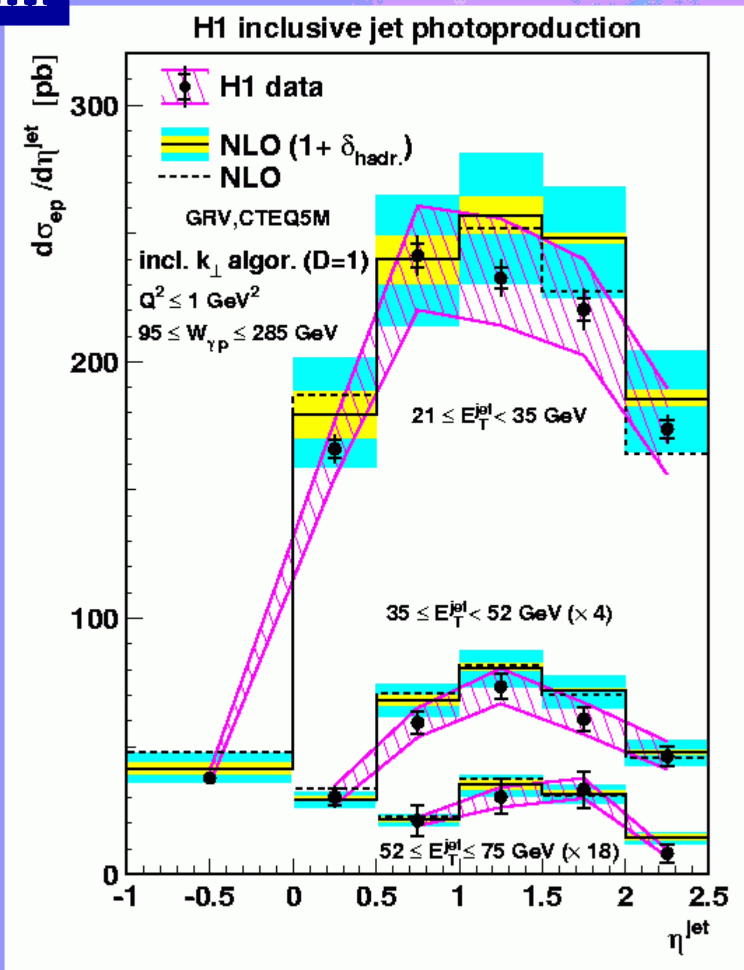
hadronisation correction uncertainty

renormalisation and factorisation scale uncertainty

calorimeter energy scale uncertainty

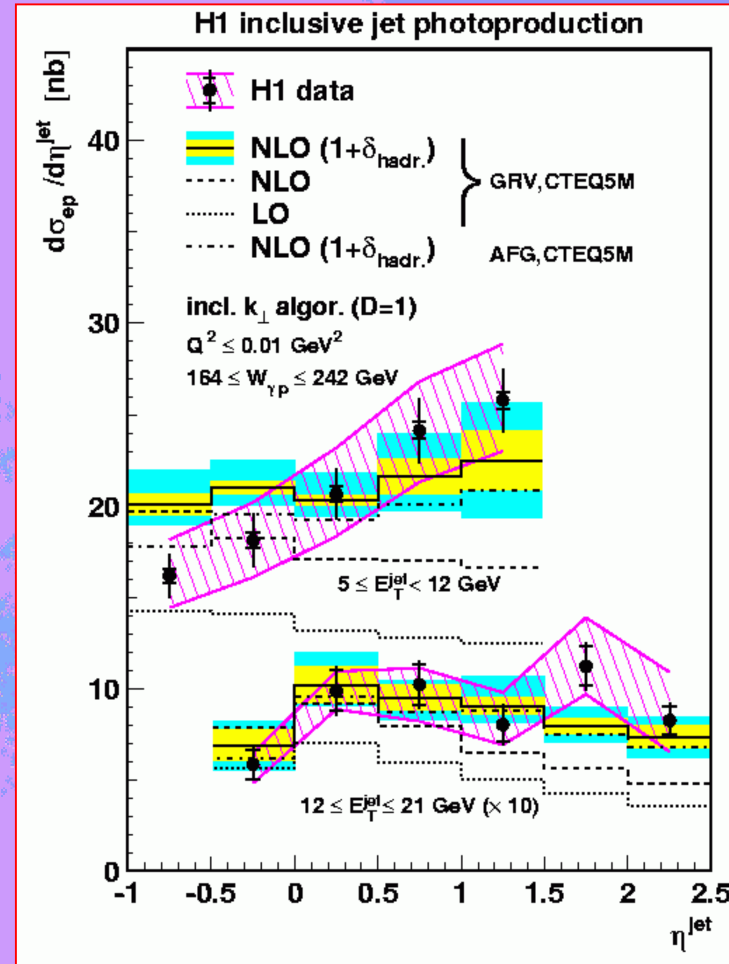
η distribution

high E_T



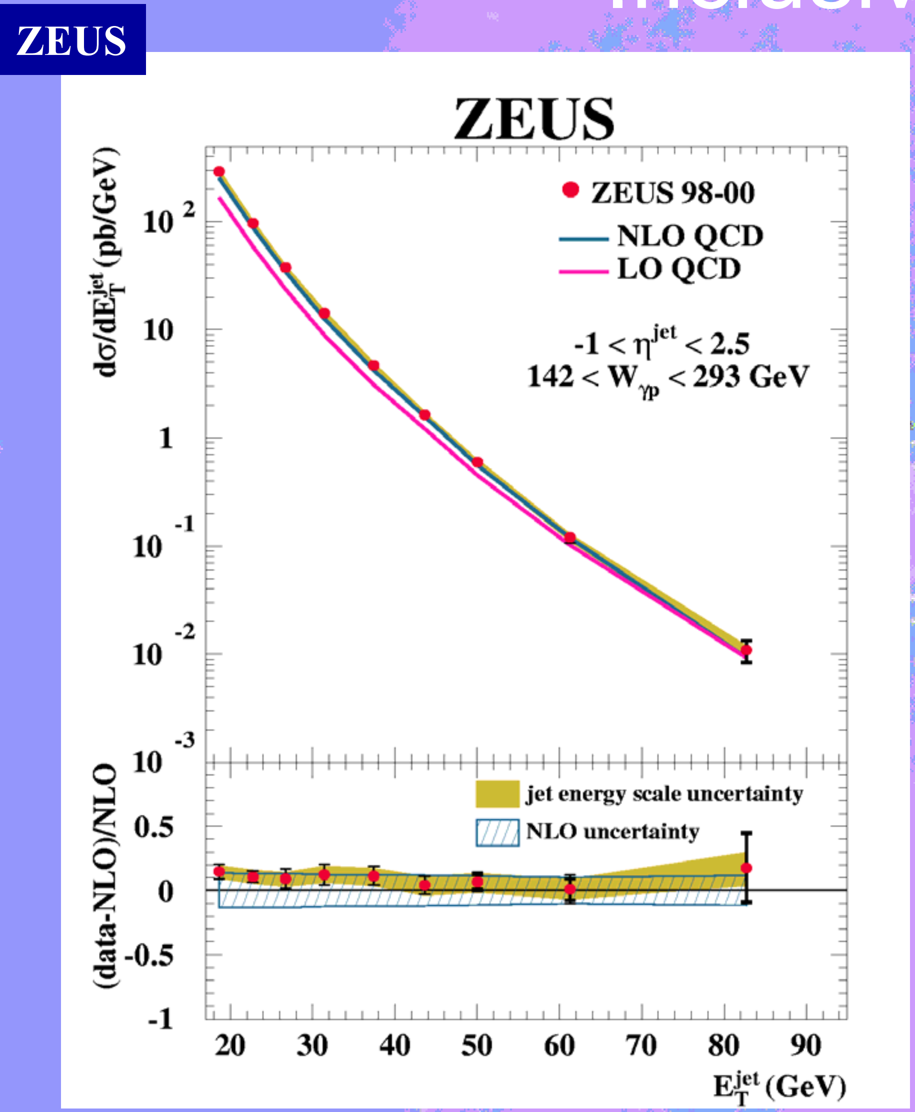
trend different from calculation ➡➡➡

low E_T



⇨ inadequacy of photon PDFs? ⇨ higher-order terms needed?

Inclusive jets: E_T



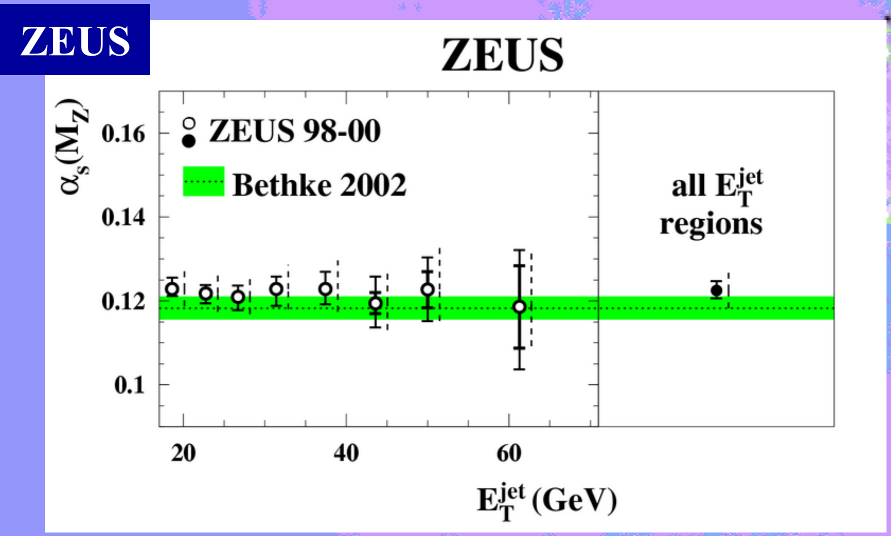
- cross section falls by more than 5 orders of magnitude from E_T^{jet} = 17 to 95 GeV
- NLO QCD gives excellent description
- corrections to hadron level applied to NLO < 2.5%

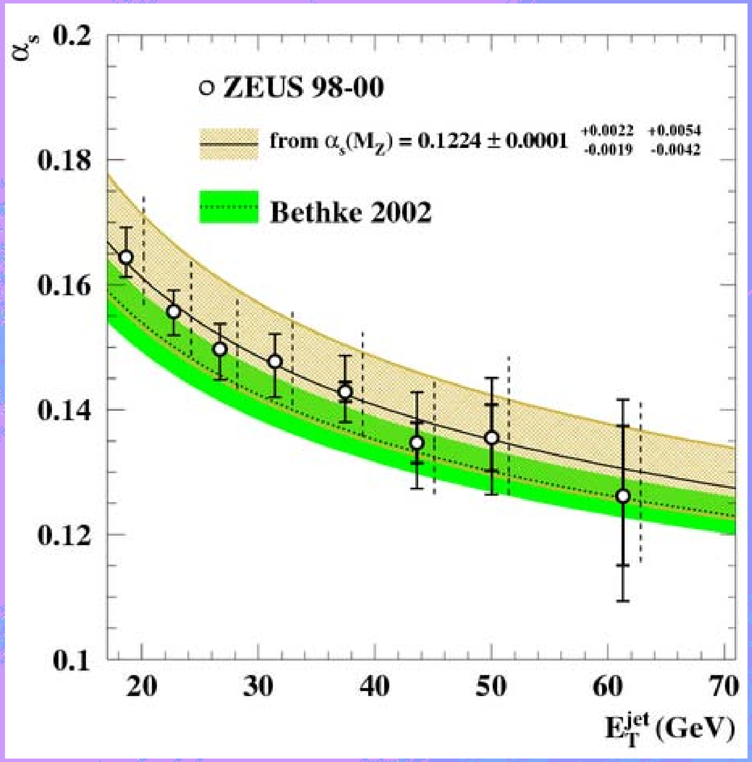
Data used:

- To test the scaling hypothesis
- For α_S extraction

Jet photoproduction: α_S *extraction*

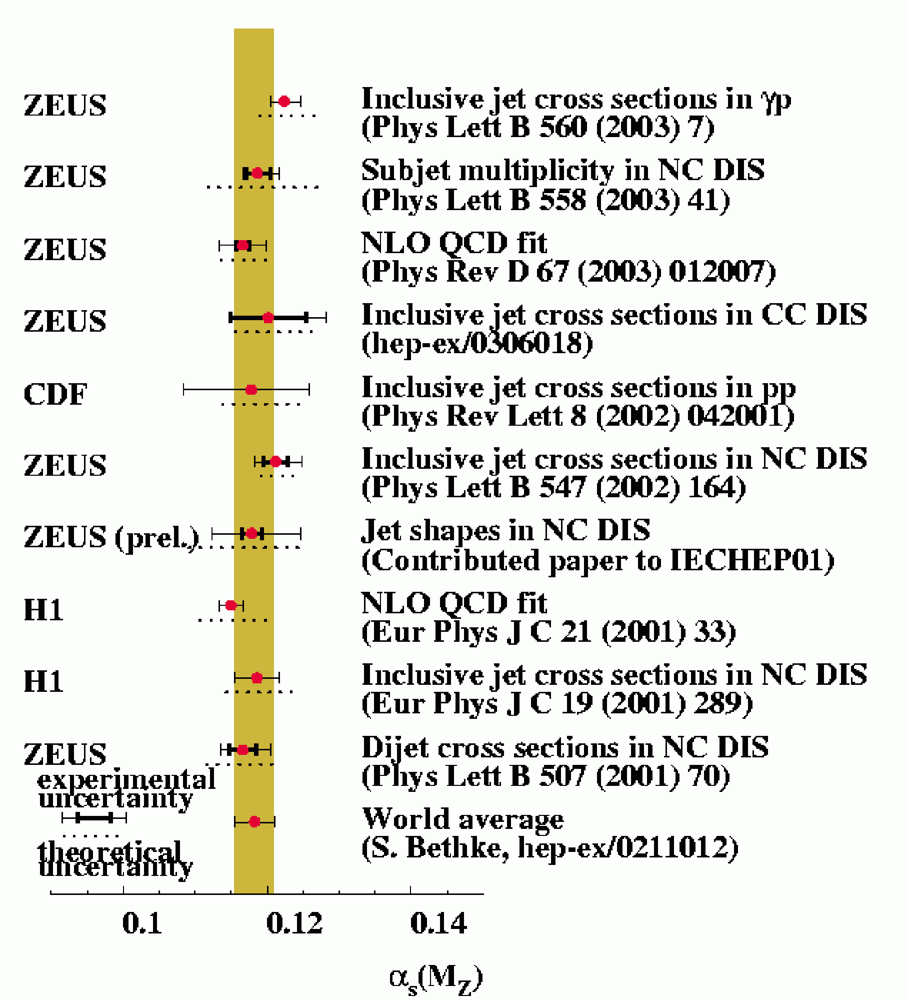
- fit of $\left[d\sigma / dE_T^{jet} \right]_i$ to formula: $C_1^i \alpha_S(\mu) + C_2^i \alpha_S^2(\mu)$, in each bin i
- constants C_j^i from NLO calculat-ions
- Fit of the E-scale dependence of measured α_S^{jet} to renormalization group equation





$$\alpha_S(M_Z) = 0.1224 \pm 0.0001^{+.0022}_{-.0019}(\text{exp})^{+.0054}_{-.0042}(\text{th})$$

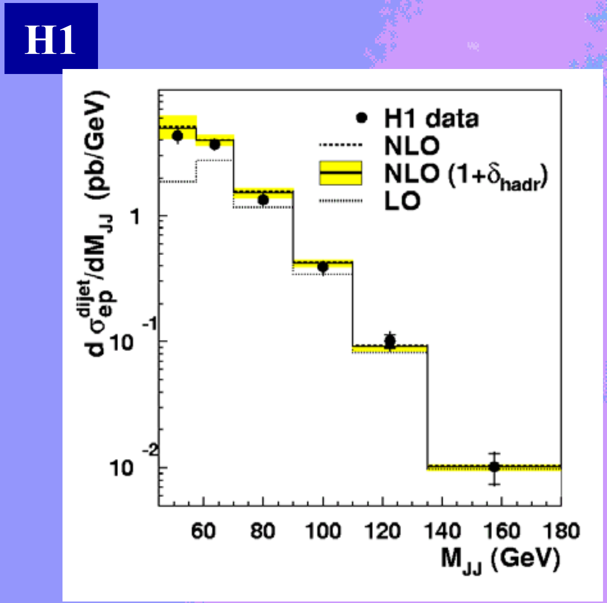
α_S summary

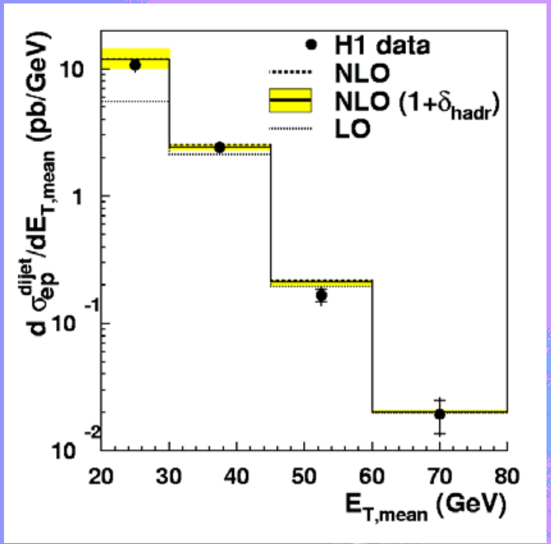


⇦ this measurement **ZEUS**

- α_S value consistent with the current world average 0.1183+-0.0027
- Similar accuracy obtained from subjet multiplicity in DIS and
- and NLO QCD fits to F_2
- HERA is very competitive in determining α_S

Dijets: M_{JJ}, $E_{T,\mathrm{mean}}$ cross sections





$E_{T,max} > 25$ GeV, $E_{T,sec} > 15$ GeV, $-0.5 < \eta < 2.5$

- NLO QCD calculations describe the shape and normalization of M_{jj} cross section well
- Similar statement from ZEUS measuments

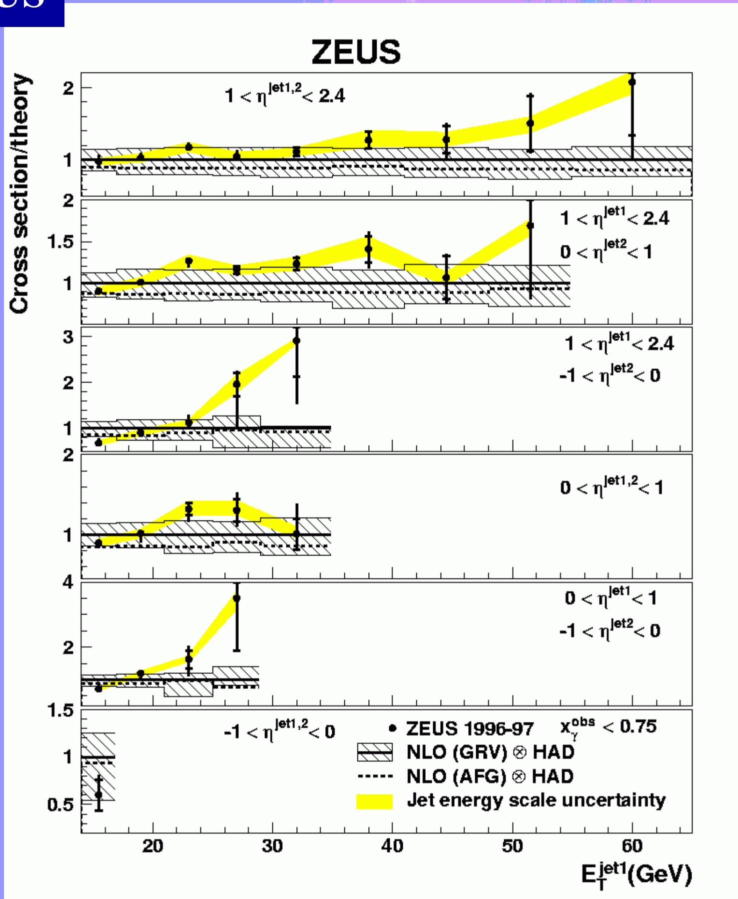
- In the dijet cross sections $d\sigma / dE_{T,\mathrm{mean}}$ the scale uncertainties are reduced to ~ 5% for $E_{T,\mathrm{mean}} > 30$ GeV, hadr. corrections < 5%.
- NLO describes also well $d\sigma / dE_{T,\max}$ cross section

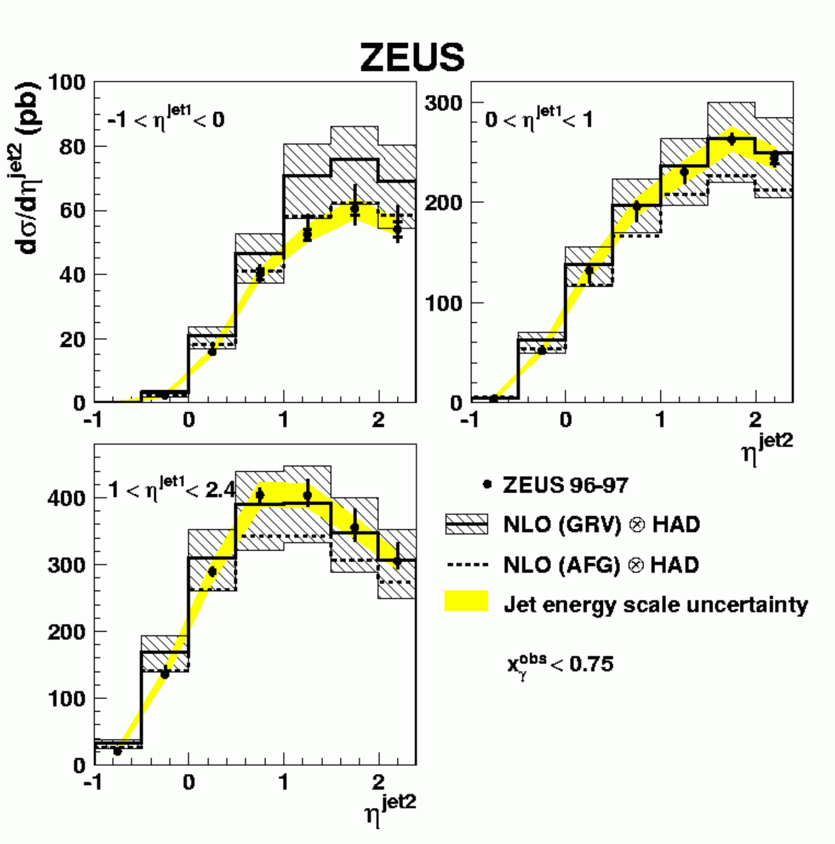
➢ Validity of pQCD description of parton - parton and γ - parton interactions in photoproduction

E_T, η jet cross sections

$x_\gamma < 0.75$

ZEUS

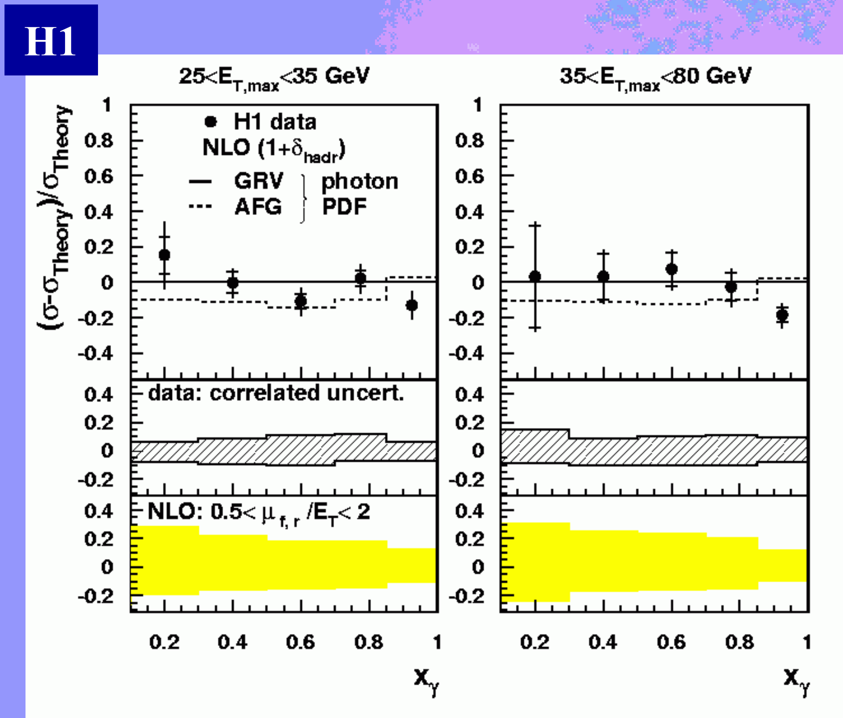


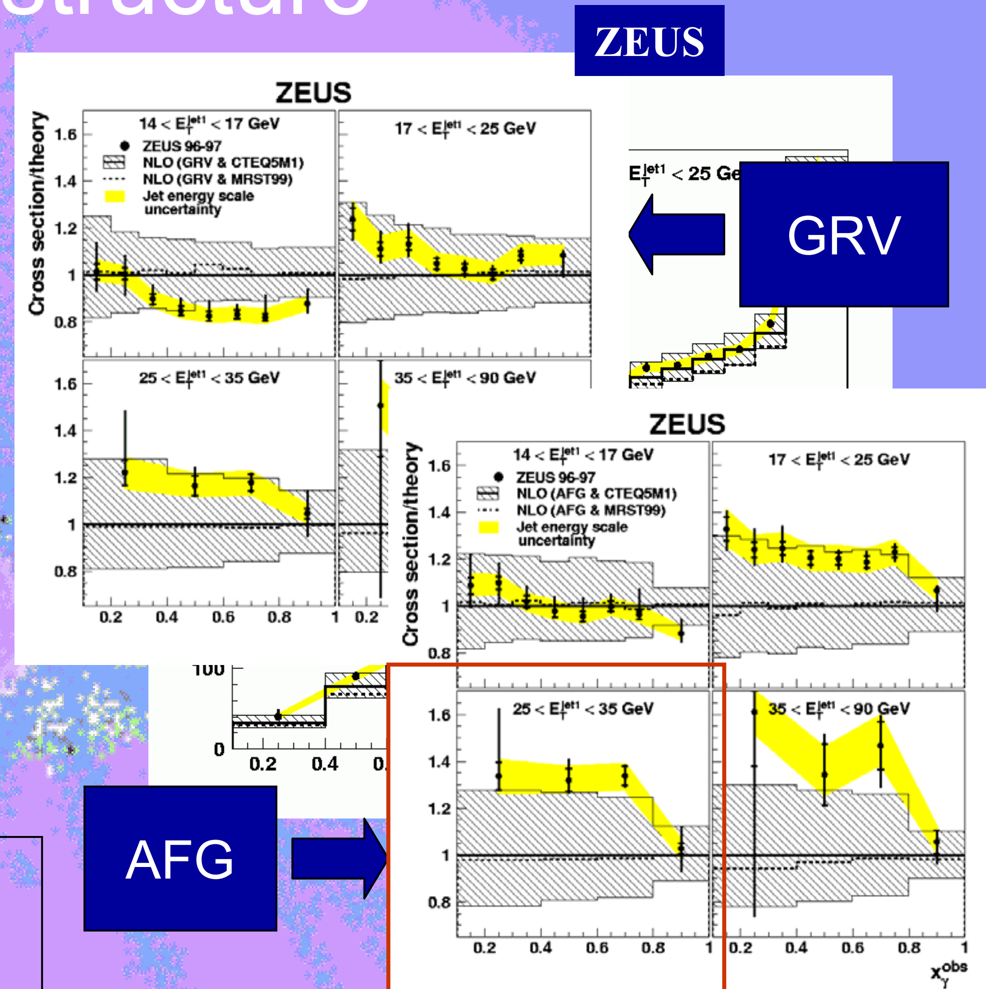


When both jets in $1 < \eta^{jet1,2} < 2.4$, NLO lies below data at high E_T^{jet}

- The NLO gives good description except for $-1 < \eta^{jet1} < 0$
- Good agreement with NLO for $x_\gamma > 0.75$

Photon structure



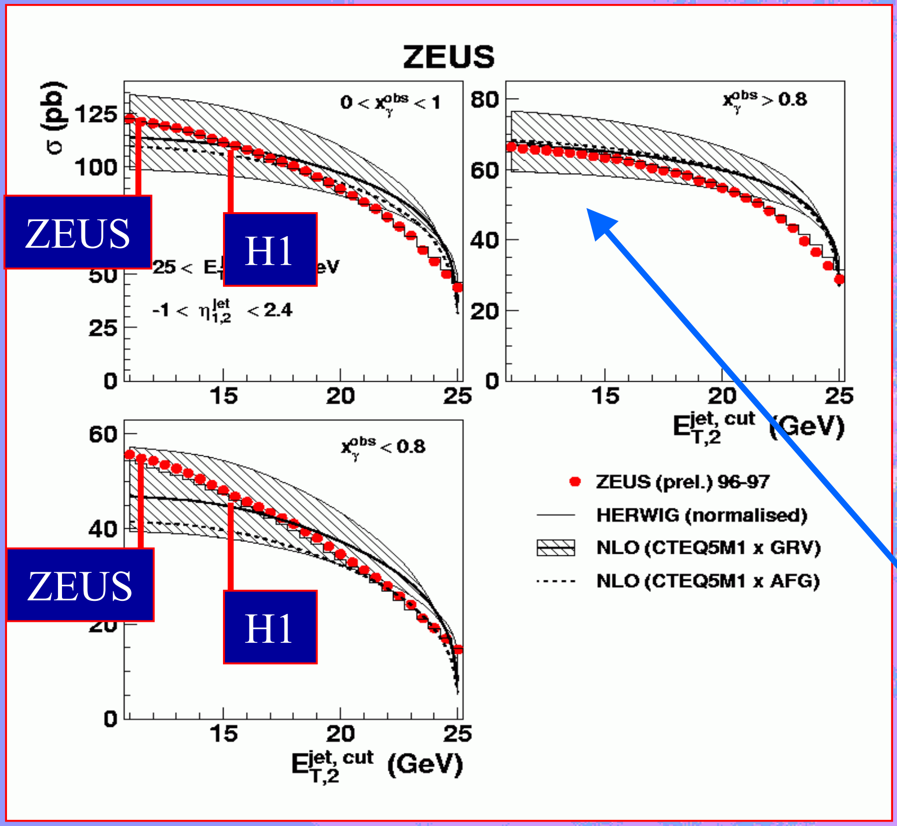


- uncorrelated syst. errors shown by hatched histogram
- Calo energy scale uncertainty
- Prediction agrees well with the data

neither GRV nor AFG pdf's provide a perfect description everywhere

Sensitivity of NLO calculation on E_T^{jet}

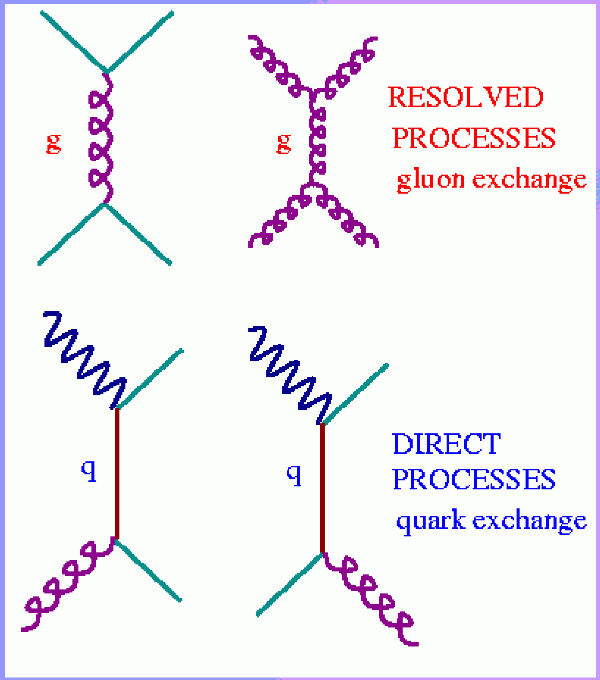
$25 < E_T^{jet1} < 35$ GeV



- Differences between ZEUS and H1 appear to be due to the different cuts on E_{T2}
- Comparison of data vs NLO depends on the cut value!
- E_{T2} dependence significantly different for data and NLO
- HERWIG describes dependence very well
- For $x_\gamma > 0.8$ converges to the data as E_{T2} cut is decreased; the cross section is less sensitive to the E_{T2} cut value

Theoretical work on improving the dijet calculations is needed!

Dynamics of resolved and direct processes

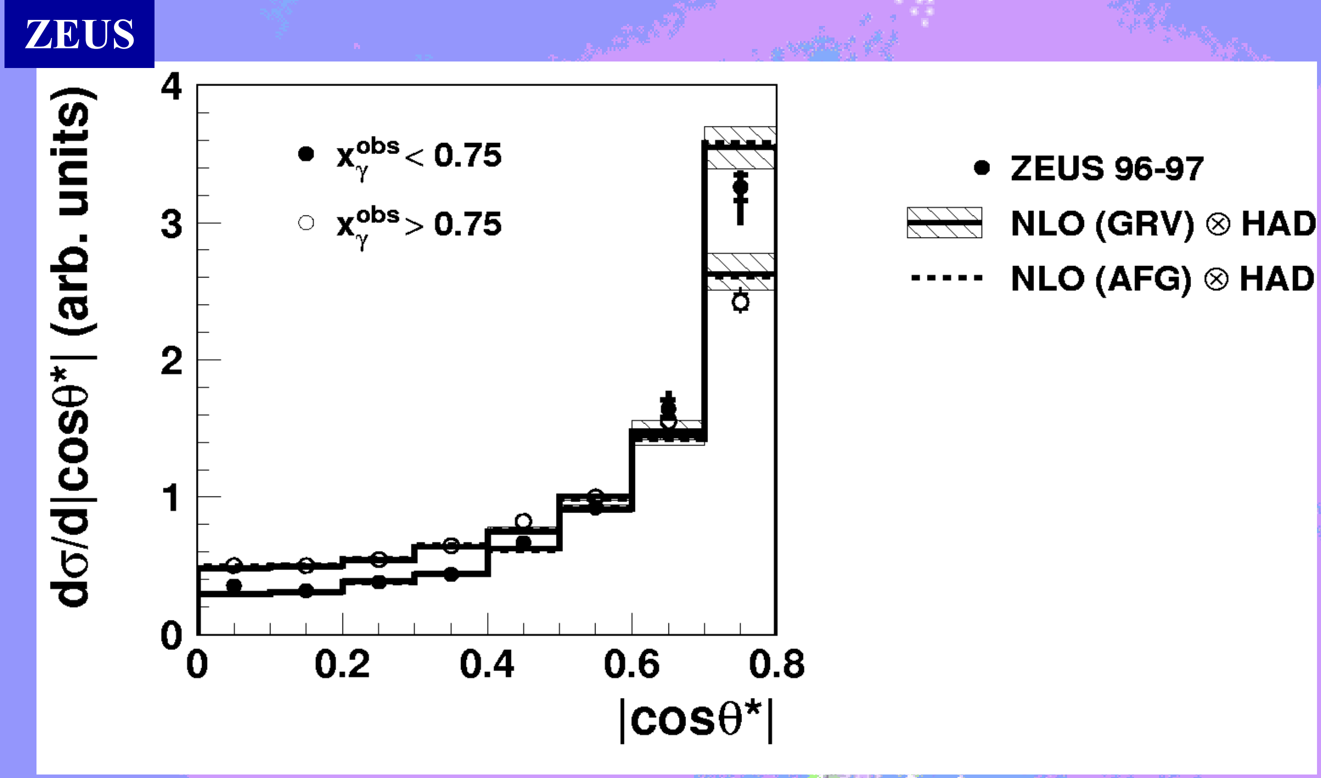


- Scatering angle θ^* of 2→2 parton scattering coincides with scattering angle in dijet CMS

$$\cos\theta^* = \tanh\left[\frac{1}{2}\left(\eta_1^{jet} - \eta_2^{jet}\right)\right]$$

- Small angle jet angular distribution given by the spin of the exchanged particle
  - Resolved (gluon dominant) $\frac{d\sigma}{d|\cos\theta^*|} \sim \left(1-|\cos\theta^*|\right)^{-2}$
  - Direct (quark exchange) $\frac{d\sigma}{d|\cos\theta^*|} \sim \left(1-|\cos\theta^*|\right)^{-1}$

Dijet θ^* distribution should be steeper for resolved processes ($x_\gamma < 0.75$) compared to direct ones ($x_\gamma > 0.75$) as $|\cos\theta^*| \to 1$



cos θ*

- To study cos θ^* without bias at small angles→ cut on low mass dijet mass M_{jj} is applied (this cut eliminates bias from low E_T^{jet} cut)
- Cut on $\eta_{mean} = (\eta_1^{jet} + \eta_2^{jet})/2$ ensures the PS uniformity in cosθ^*
- **Dijet angular resolution is steeper for the resolved sample**
- NLO describes the shape and normalization of data both for direct and resolved parts (using GRV-HO for the photon PDF)
- H1 analysis brings the same conclusion

Jet shapes

- The dominant mechanism for high E_T production in γp goes via
  - $q_\gamma g_p \rightarrow qg$ (resolved)
  - $\gamma p \rightarrow q\bar{q}$ (direct)
- Majority of quark jets in γ (e) direction $\eta_{jet} < 0$
- Increasing fraction of gluon jets with increasing η_{jet}
- Tagging quark and gluon jets can disentangle the underlying hard process

➢ gluon – "thick" jet:

$\Psi(r = 0.3) < 0.6$ and $n_{sbj} \geq 6$

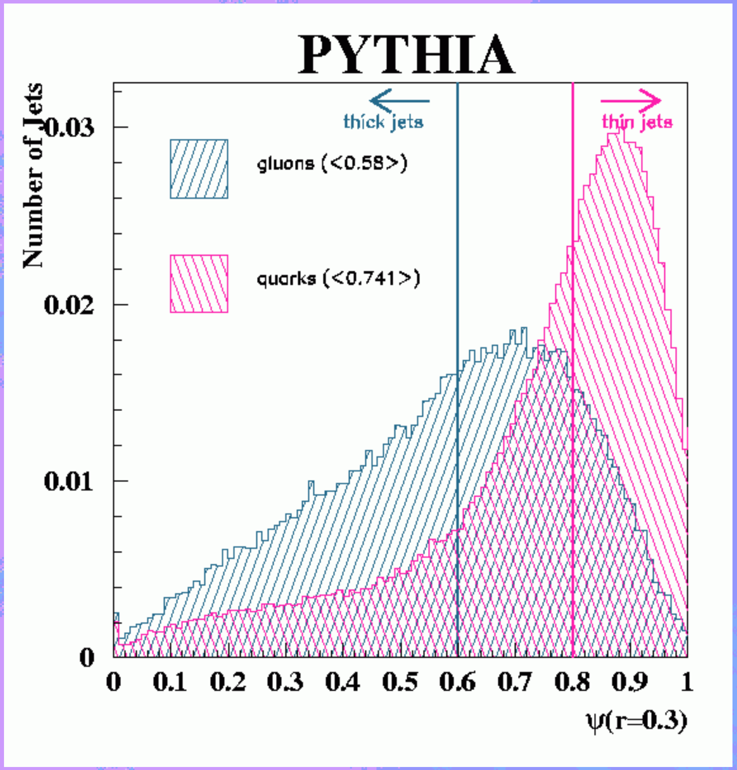
➢ quark - "thin" jet:

$\Psi(r = 0.3) < 0.8$ and $n_{sbj} < 4$

for $y_{cut} = 0.0005$ in k_t cluster algorithm

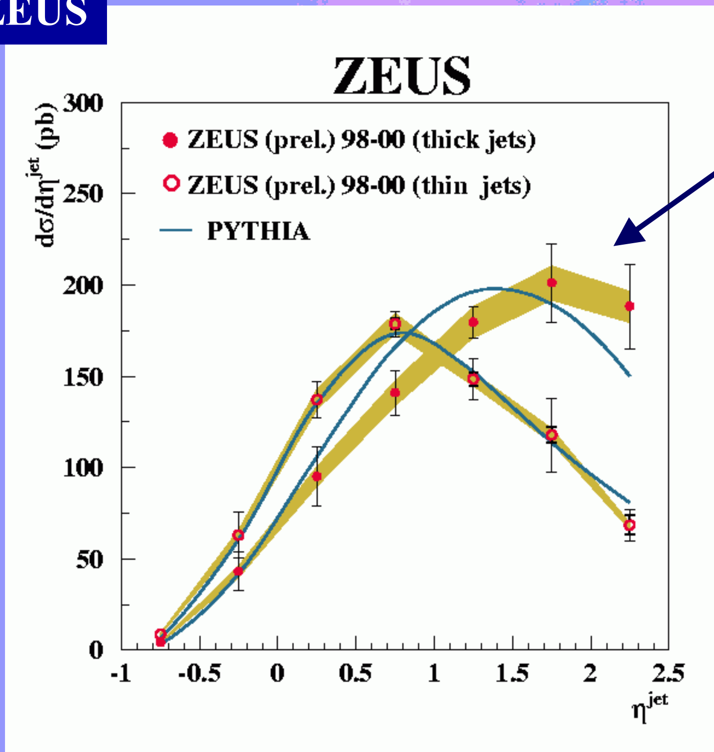
Integrated jet shape in θ-φ plane of radius r

$$\Psi(r) = E_T(r) / E_T^{jet}$$



Inclusive sample

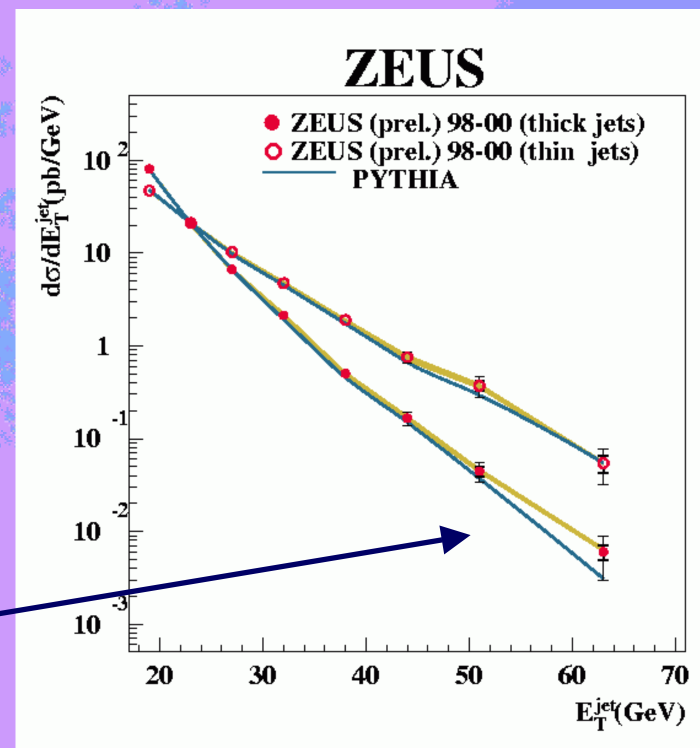
ZEUS



- Inclusive cross sections for jets with

$$E_T^{jet} > 17 \text{ GeV} \quad , \quad -1 < \eta^{jet} < 2.5$$

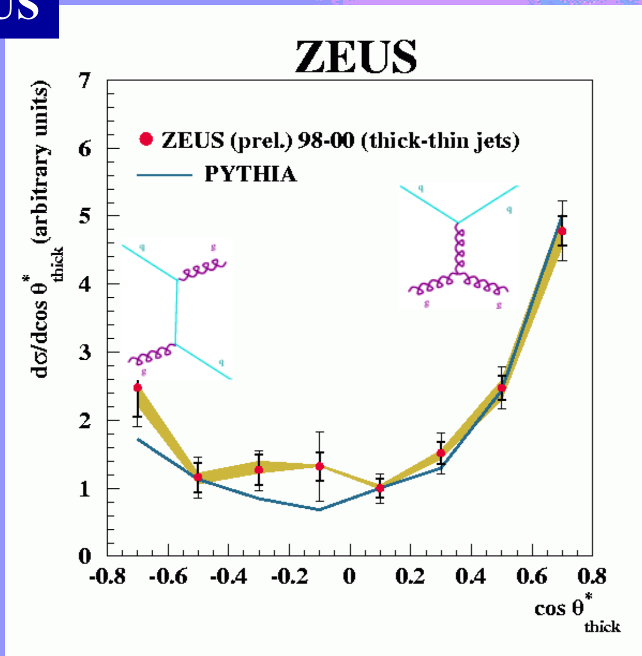
- Thick jets peak in forward direction
- PYTHIA normalized to the total no. of events
- Good description of thin jets



- Thick jets reasonably well described by PYTHIA (MI), HERWIG fails
- Thick jets exhibit a softer spectrum than thin jets

Dijet sample

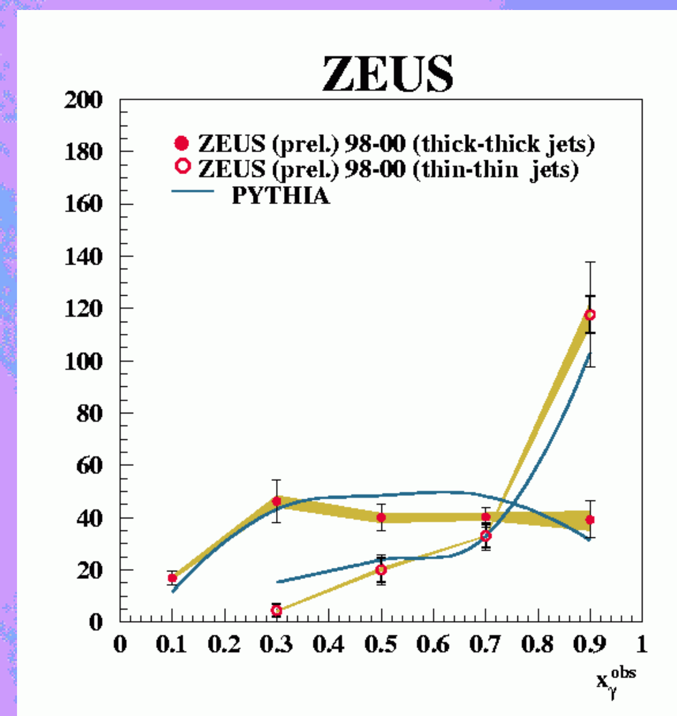
ZEUS



$E_T^{jet,1} > 17$ GeV, $E_T^{jet,2} > 14$ GeV, $-1 < \eta < 2.5$

- Cross sections normalized at $|\cos\theta^*|=0.1$
- Asymmetry of $|\cos\theta^*_{thick}|$ is due to different dominant diagrams:
  - g exchange → +1,
  - q exchange → -1

- PYTHIA gives the best description of data
- The difference between 2 samples:
  - Thick - thick: resolved $qg \rightarrow qg$
  - Thin - thin: direct $\gamma g \rightarrow q\bar{q}$



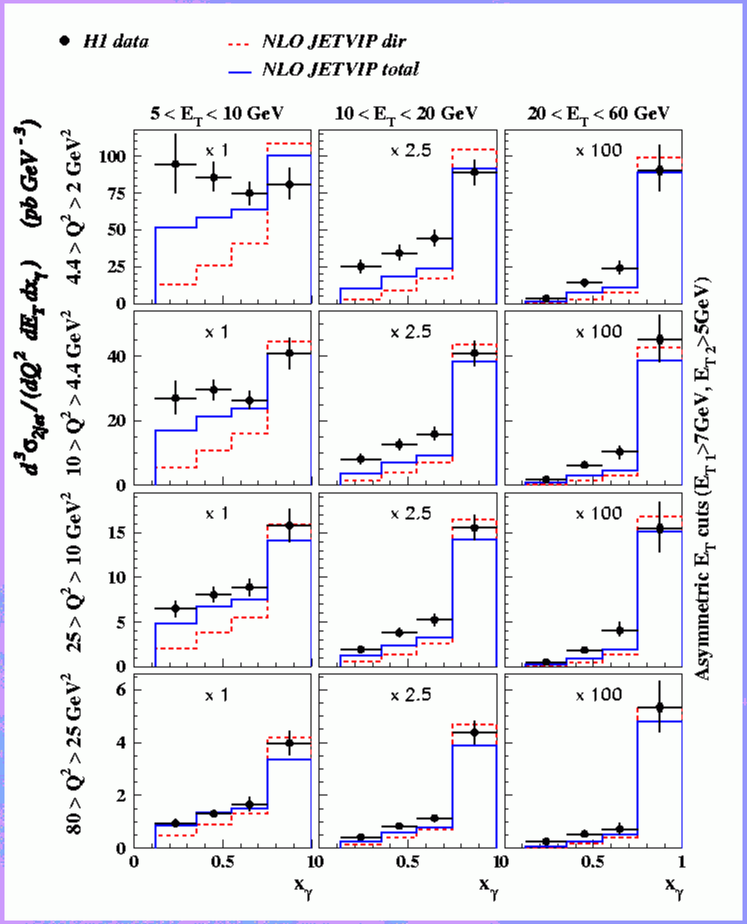
Jet shapes give a powerful handle on dynamics

Dijets at low Q^2

- H1 new analysis of 58 pb^{-1} data with e^+ in Spacal → $2 < Q^2 < 80$ GeV^2
- Large $0.1 < y < 0.85$ range to study contribution from longitudinal photon
- Comparison with NLO in environment with two hard scales: Q^2 and jet E_T when neither of scales is large
- For $E_T^2 \gg Q^2$ virtual photon behaves as both direct and resolved similar to photoproduction
- No collinear divergencies in NLO for virtual photon ☺
- PDF for virtual photon is perturbatively calculable, multiple parton interactions small ☺

E_T →

Q^2 ↓

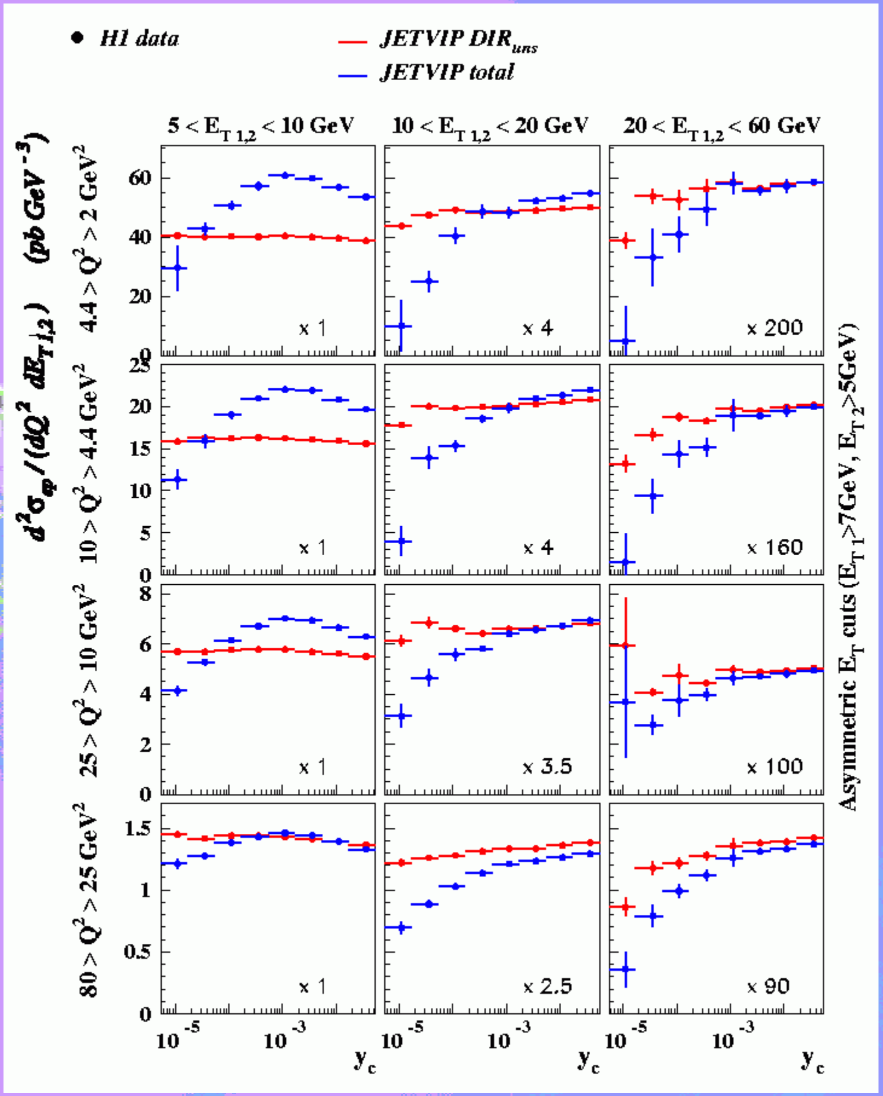


x_γ →

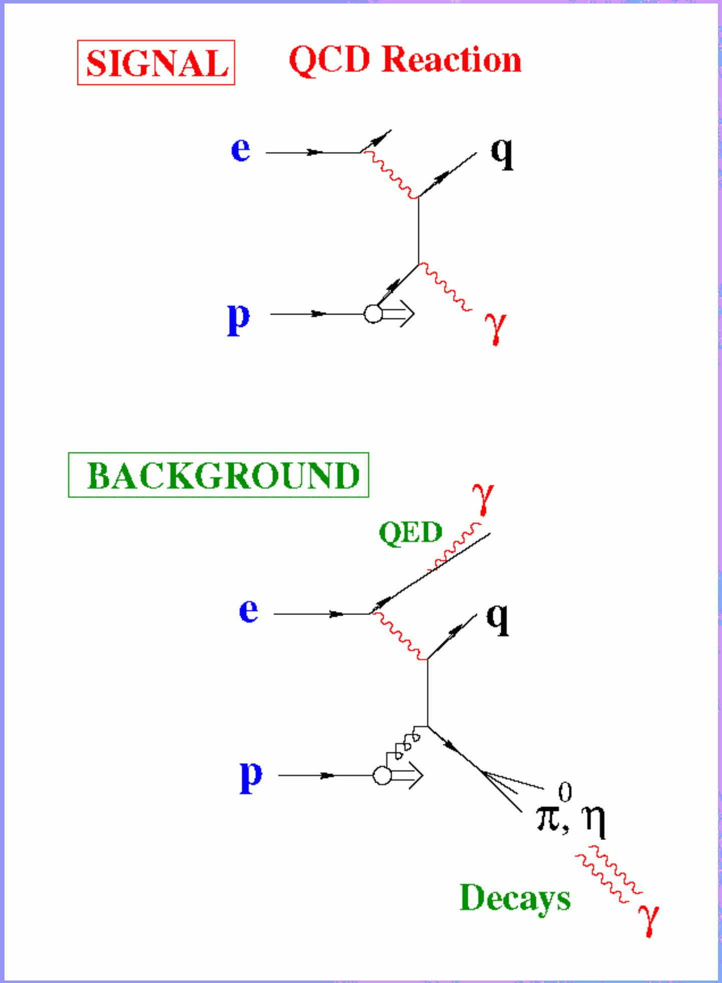
Tripple differential dijet cross section of x_γ in bins (Q^2, E_T) compared to the NLO calculation by Jetvip

Stability of Jetvip calculations

- Jetvip uses phase space slicing method to integrate the NLO QCD equations
- Detailed investigations of cross section dependence on parameter y_c
- Small dependence for the direct processes – calculation are stable
- Sizable dependence for the resolved processes
- As there are not any other NLO calculations for resolved we used $y_c = 3.10^{-3}$ (value which ~maximizes cross section and is recommended by the author (B. Pötter)



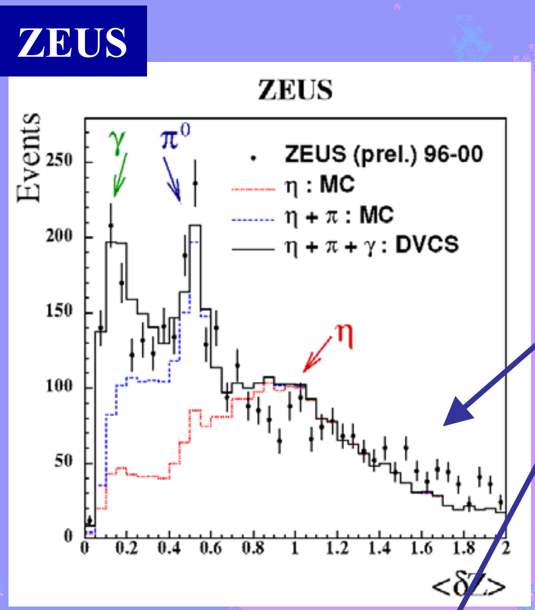
Prompt photons



- High E_T photon in the final state
- ***Signature*: well isolated compact elmg. shower and track veto**
- Difficult: background from π^0, η^0
- Prompt photons produced both in direct and resolved processes

➢ Tests of pQCD calculations:
  – NLO matrix element
  – PDFs of the photon and the proton

γ,π^0,η separation



Shower shape variables:

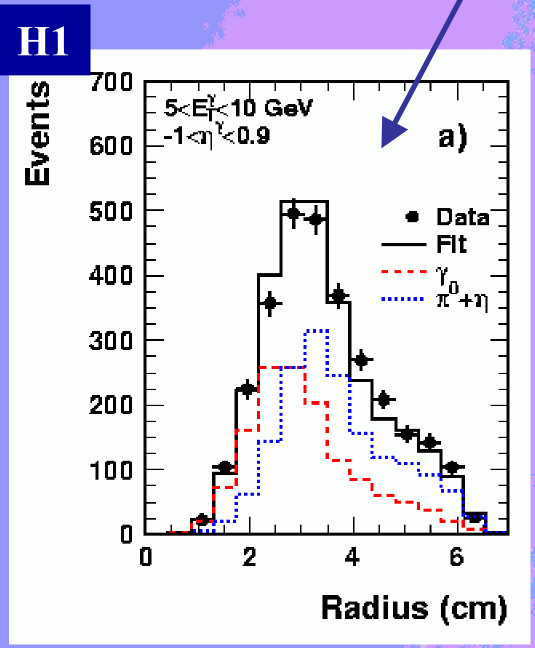
ZEUS: longitudinal shape $\langle \delta Z \rangle = \sum E_i * |Z_i - \langle Z \rangle| / \sum E_i$

H1: radial shape radius = $\sum r_i \varepsilon_i / \sum \varepsilon_i$

Distribution of energy in shower:

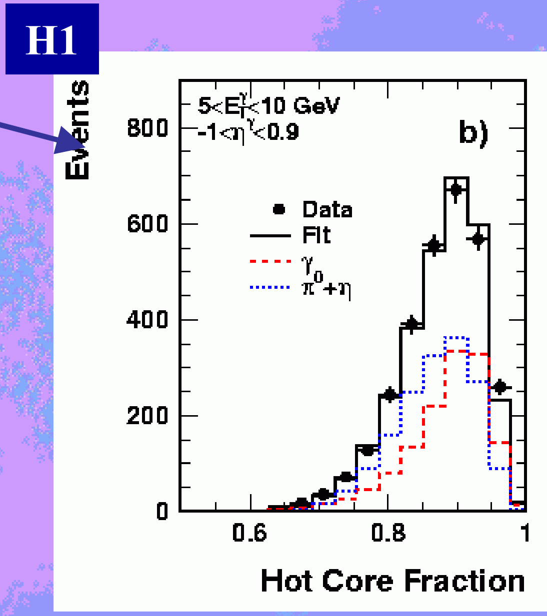
ZEUS: f_{max} fraction of energy of the most energetic cell

H1: hot core fraction = energy in core / cluster energy



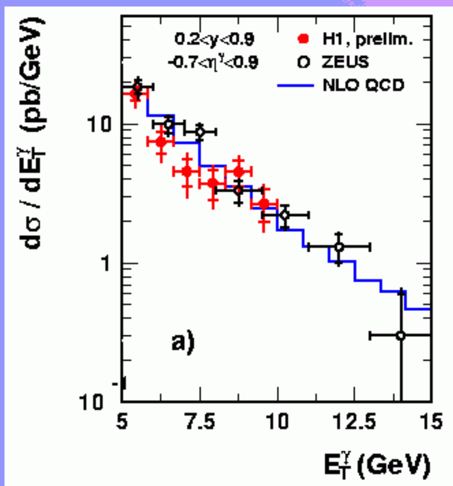
Signal extracted by fit:

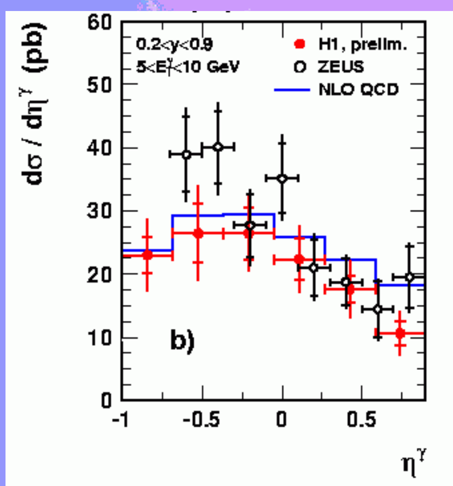
H1: likelihood discriminators in (E_T, η)



Discriminating variables are well described by the fit

Inclusive prompt photons





- New H1 results presented as *ep* cross sections for $5 < E_T < 10$ GeV, $-1 < \eta < 0.9$ at $0.2<y<0.7$

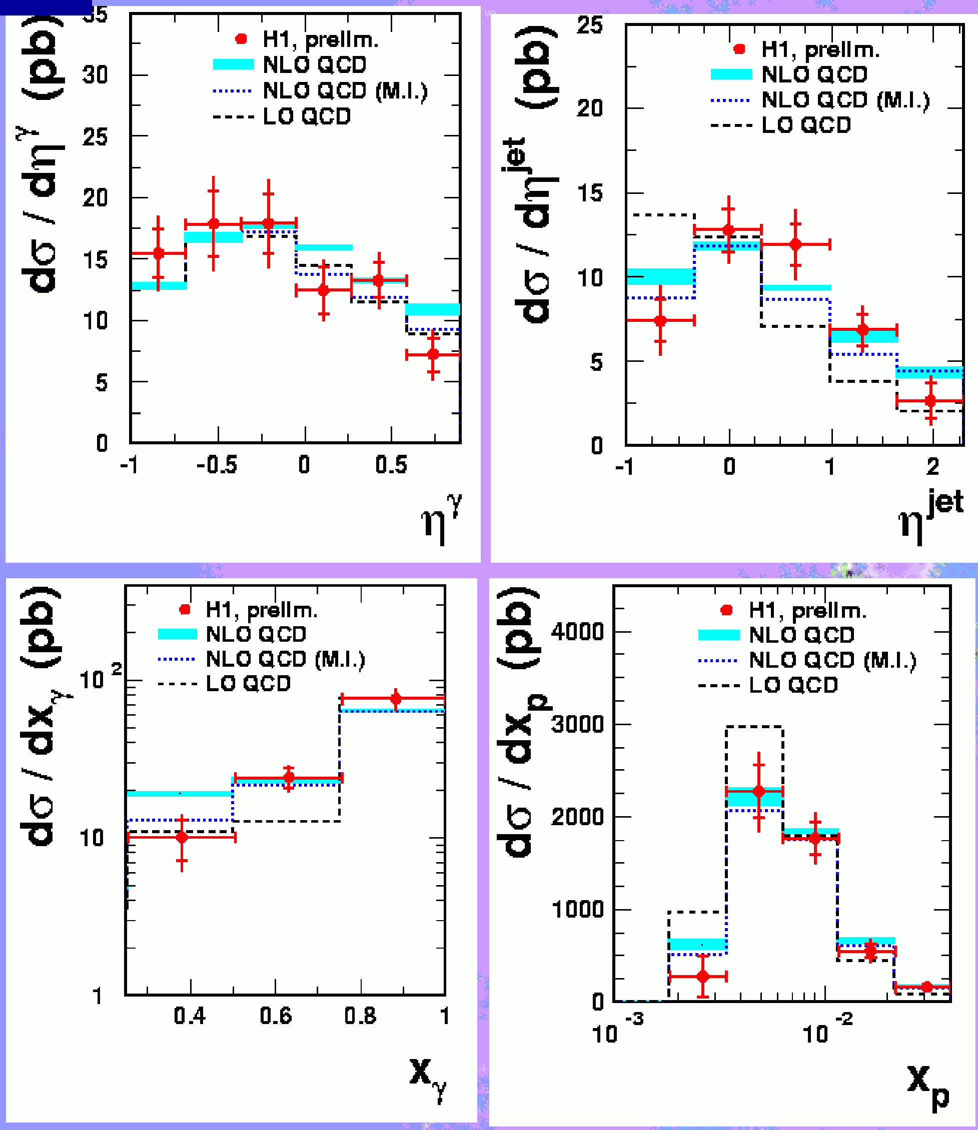
- Inclusive cross sections compared to the NLO QCD calculations of Fontannaz, Guillet, Heinrich
- *photon PDF*: AFG *proton PDF*: MRST2
- NLO describes data quite well with tendency to overshoot data at large rapidities

- PYTHIA (not shown) describes data well in shape but is low by 30% in normalization

- **ZEUS 1997 data above H1 data**

Prompt photon and jet cross sections

H1



- New H1 results presented as *ep* cross sections for
  $E_T^{jet} < 4.5$ GeV,
  $-1 < \eta^{jet} < 2.3$
- Avoid symmetric E_T cuts for NLO comparison!
- NLO describes data within errors
- Substantial and negative NLO corrections at $\eta^{jet} < 0$
- NLO describes well also cross sections in x_γ and x_p variables
- Correction for MI calculated by PYTHIA → improvement of description at large η^γ, small x_γ

Summary

- HERA measures jets in large kinematic domain and large dynamic range, e.g. jet E_T cross section spans over 6 orders of magnitude
- Inclusive single jet cross section are in agreement with NLO QCD and can be used to extract very precise α_S value
- Dijet cross sections are accurately measured but comparison with NLO QCD is often difficult due to theoretical uncertainties in the treatment of infrared and collinear divergencies. Comparison of data with calculations is for experimentalists often more tedious than the data analysis itself.

Theoretical progress in this field is needed!

- At HERA II a 'classical' photoproduction of jets will step down in favour of jet production in diffraction and with jets heavy flavours