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Hadronic final states at HERA

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for the H1 and ZEUS Collaborations

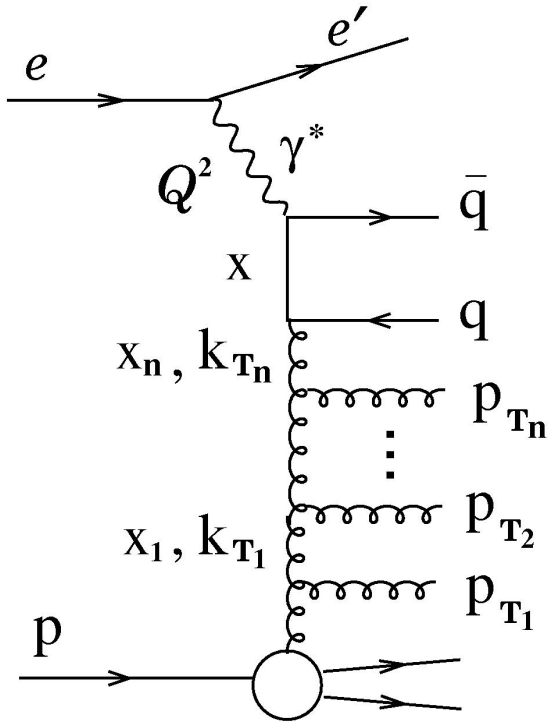
Contents

H1: Measurement of charged particle spectra in deep-inelastic *ep* scattering at HERA.
Eur. Phys. J C73 (2013) 2406

H1: Measurement of Feynman-*x* spectra of photons and neutrons in the very forward direction in deep-inelastic scattering at HERA. ArXiv 1404.0201

ZEUS: Photoproduction of isolated photons, inclusively and with a jet, at HERA. Phys. Lett. B730 (2014) 293

ZEUS: Further studies of the photoproduction of isolated photons with a jet at HERA. ArXiv 1405.7127



Q^2 = 4-momentum transfer to virtual photon.

y = fractional energy loss of lepton in proton rest frame.

$x = Q^2/sy$

Charged particle spectra in DIS

As Q^2 and x decrease, evolution should change from DGLAP to BFKL.

CCFM is a combination.

Ordering of partons in p_T is different in the different models.

Models tested (all LO QCD matrix elements.)

RAPGAP : DGLAP

DJANGOH: uses colour dipole model (ARIADNE), BFKL-like

CASCADE: CCFM

HERWIG: with POWHEG option, HO corrections, different ordering.

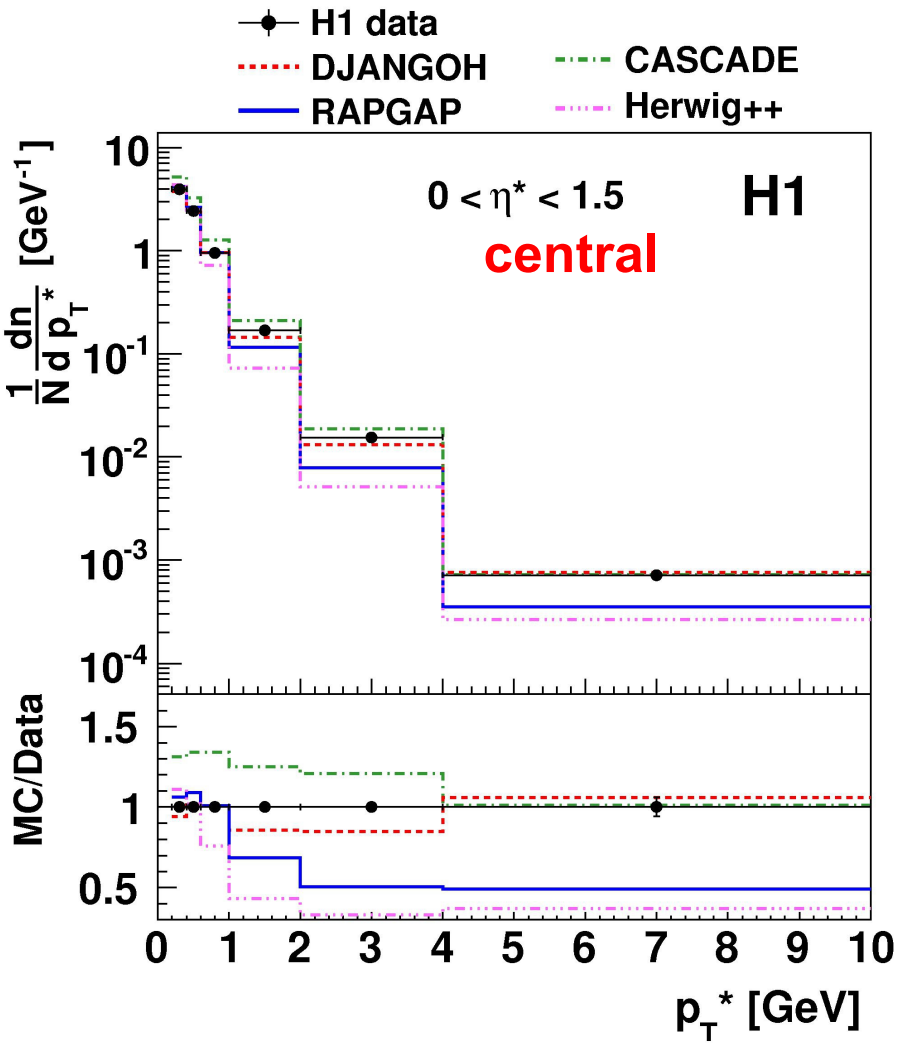
H1 experimental observables

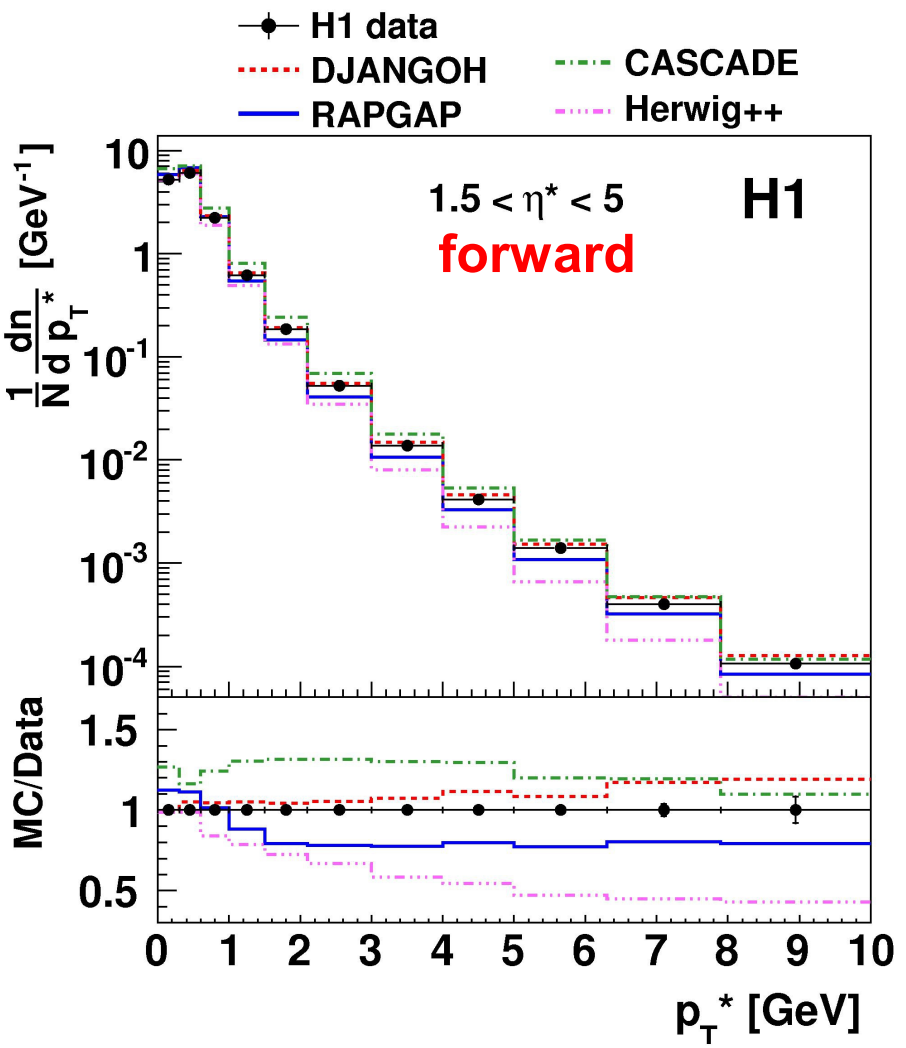
Variables defined in hadronic CM frame, using Q^2 and y.

+z* axis in direction of virtual photon.

Measure charged particle densities in η^* and p_T^* in this frame
integrated over $5 < Q^2 < 100\ GeV^2$.

Results





Most of the models fail over p_T^* range: DJANGOH is best.

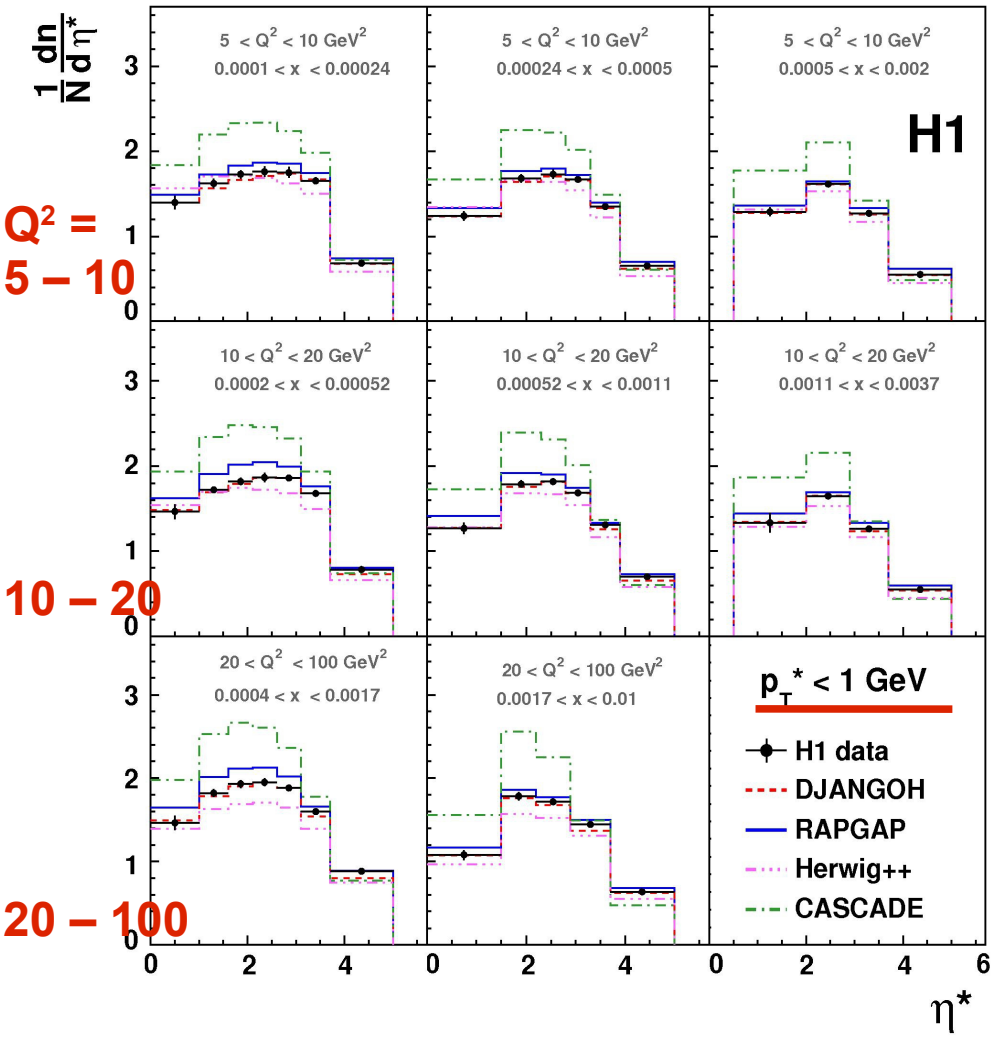
Bins in Q^2 and x, for low and high p_T^*

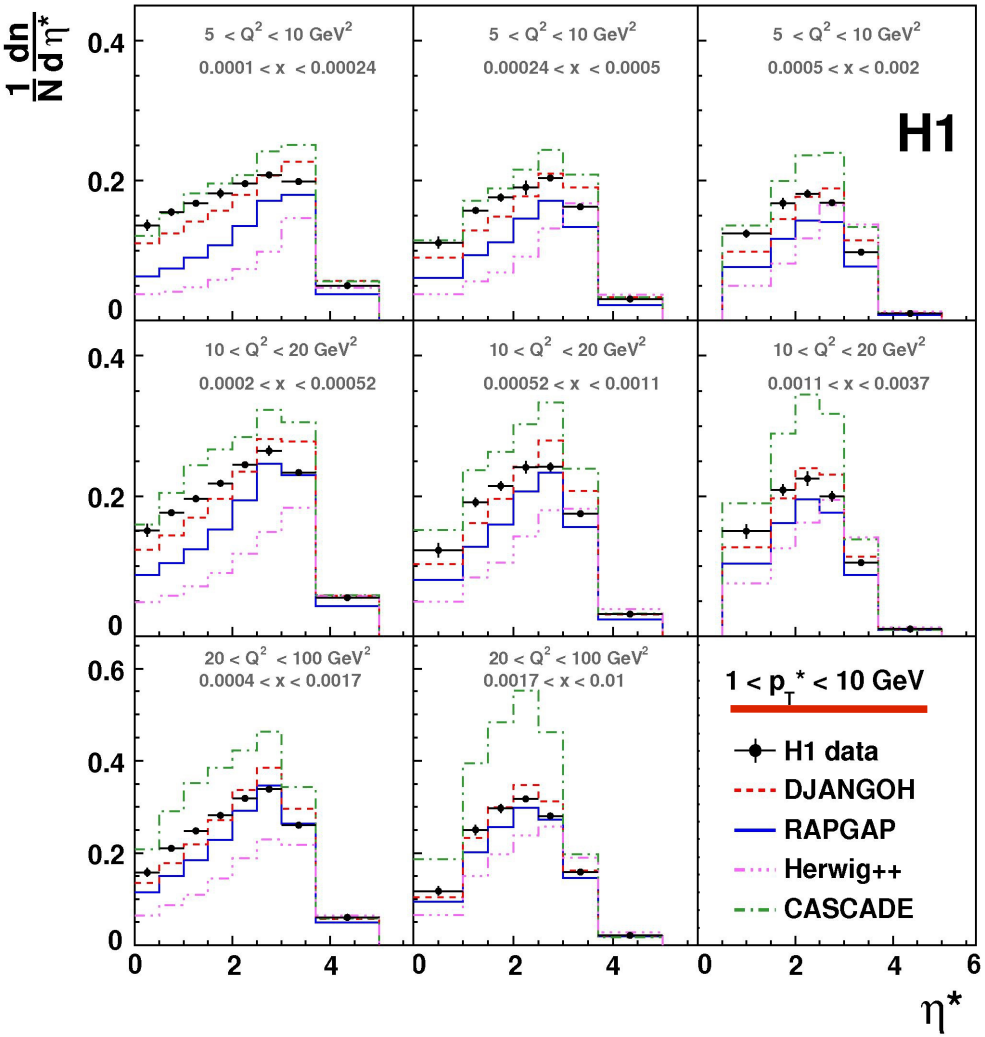
x = 0.0001 – 0.00024 … 0.0005 … 0.002

Q^2 = 5 – 10

10 – 20

20 – 100





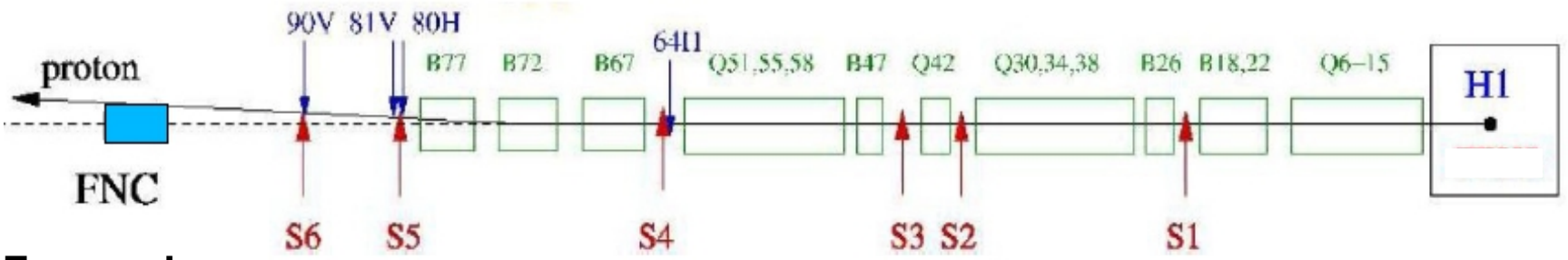
p_T^* < 1 GeV: apart from CASCADE, distributions in η* are OK .

p_T^* > 1 GeV: DJANGOH OK, others poor especially at low Q^2 and x.

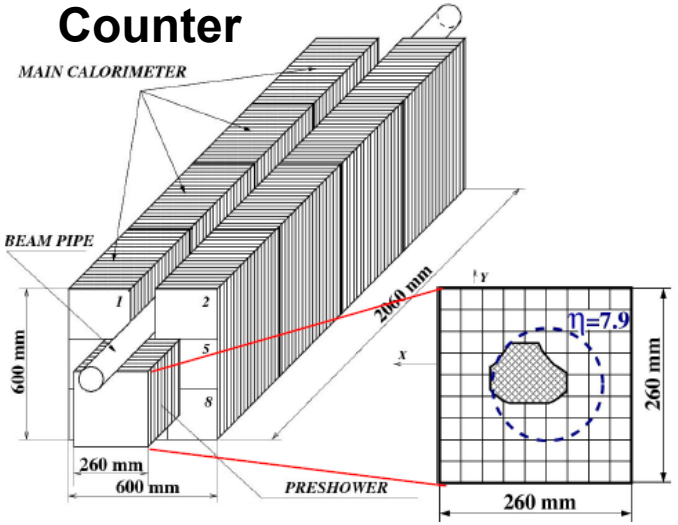
Conclusions

- Charged hadrons measured by H1 in DIS,
  for Q^2 range 5 – 100 GeV^2 . 89 pb^{-1} HERA data taken in 2006.
- Shapes of distributions compared to various MC models.
- DJANGOH best,
  RAPGAP also satisfactory at low p_T but not at high p_T.
- CASCADE (based on CCFM) is the least successful model.

Forward measurements in H1



Forward Neutron Counter



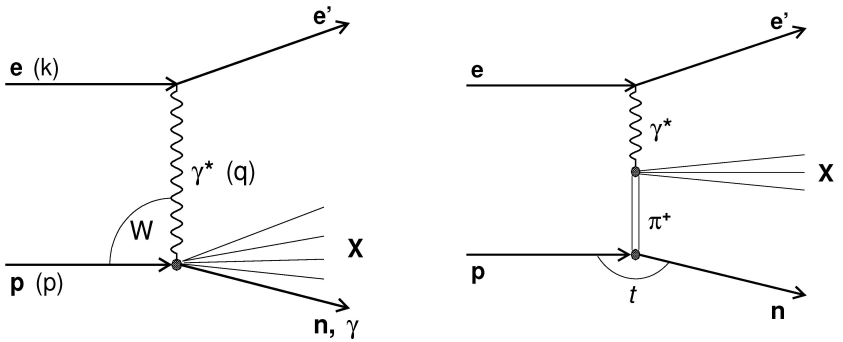
Can measure

- photons and neutrons from decay of excited proton.
- neutrons also from colour singlet exchange process.

Feynman scaling:

distribution in $x_F = 2p_\parallel^*/ W$

- independent of c.m. energy W ?



Models tested

ep based: (Lund string) LEPTO, RAPGAP + ARIADNE (colour dipole, CDM)

Cosmic ray based, adapted for ep:

SIBYLL, QGSJET: reggeon-based, interfaced using PHOJET.

EPOS LHC: parton constitutents, modified treatment of central diffraction based on LHC measurements.

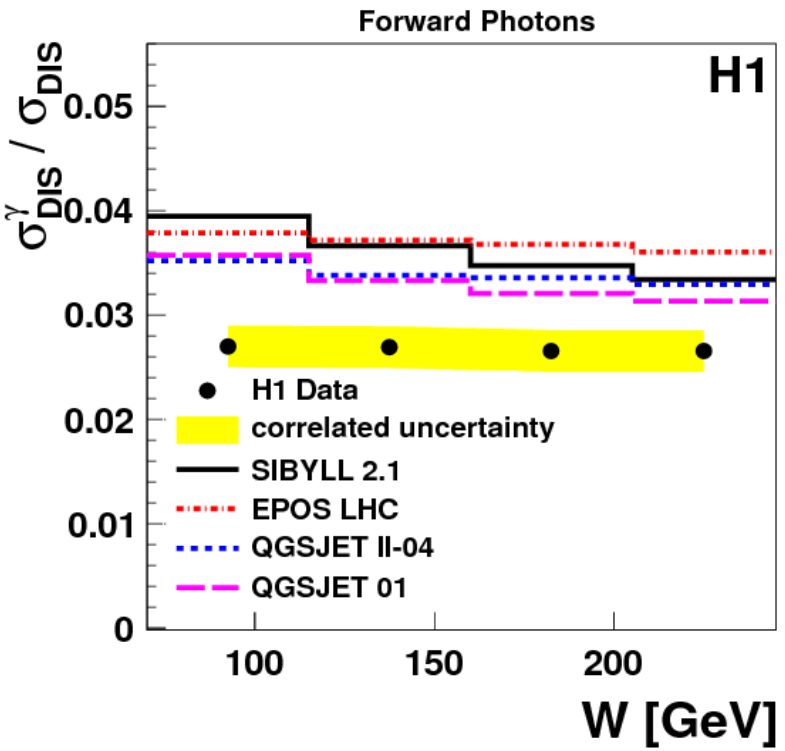
Experimental method

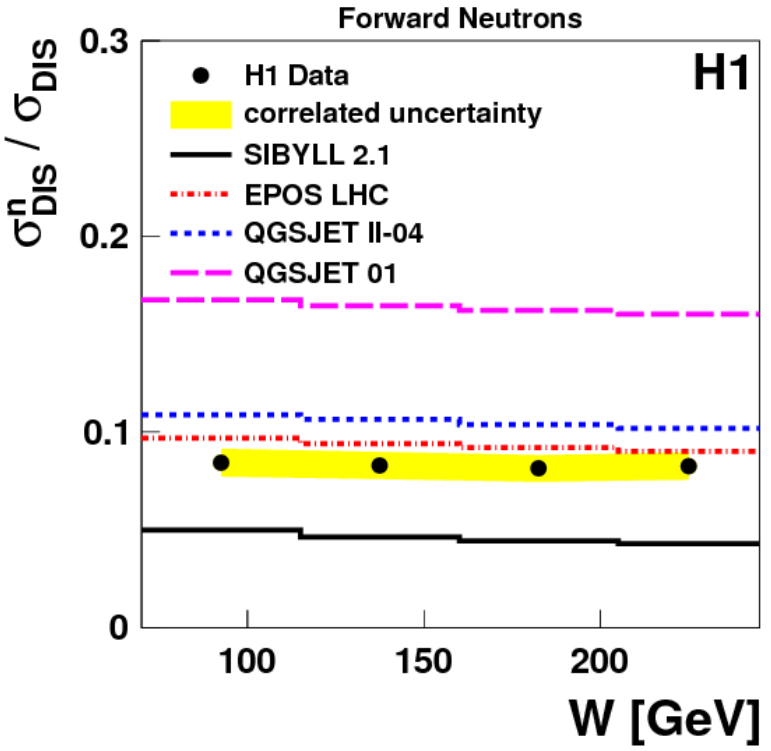
Variables defined in lab frame.

$W = \sqrt{(ys - Q^2)}$

Photons, neutrons with $\eta > 7.9$ measured in forward neutron detector.

Normalised W distributions for photons and neutrons



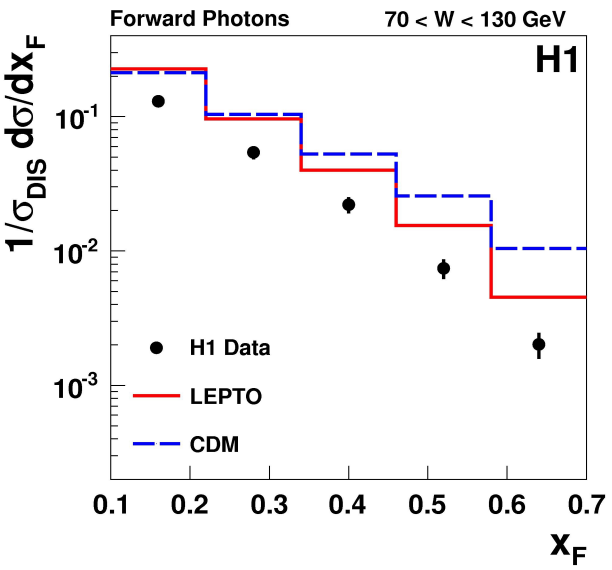


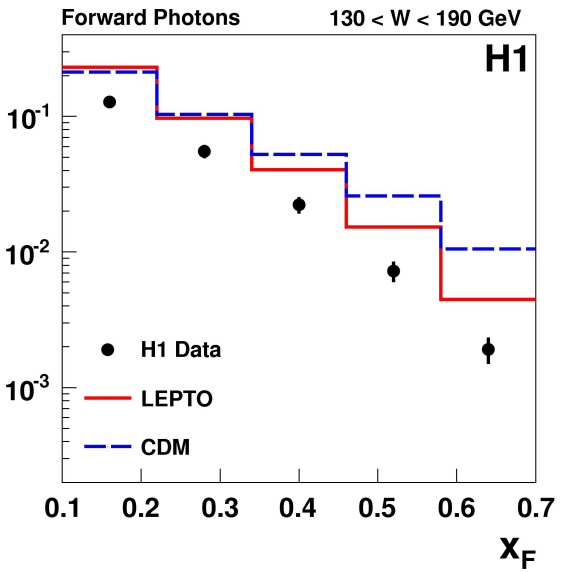
Photons: cosmic ray models all similar, all too high.

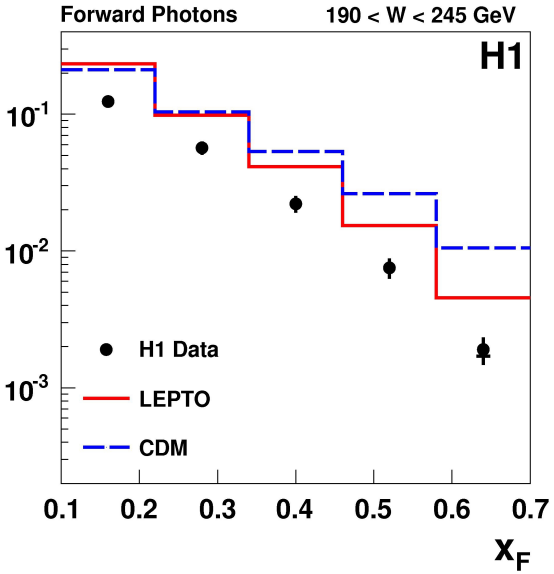
Neutrons: very variable. EPOS LHC best.

Relative rate of photons/neutrons /DIS is independent of W.

Results in x_F for photons



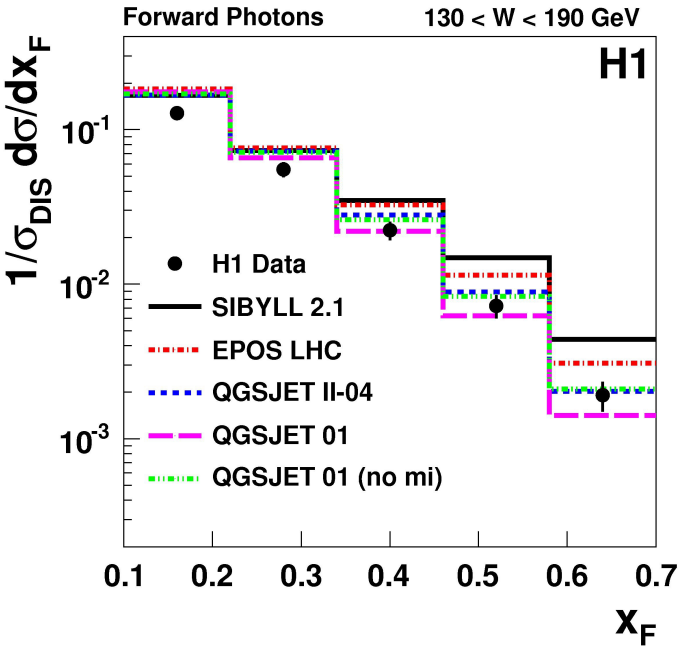




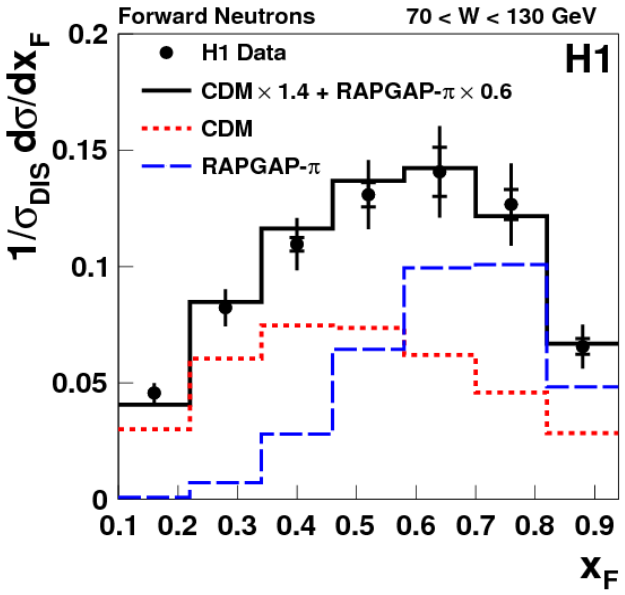
Normalised x_F distributions very similar in different W ranges.

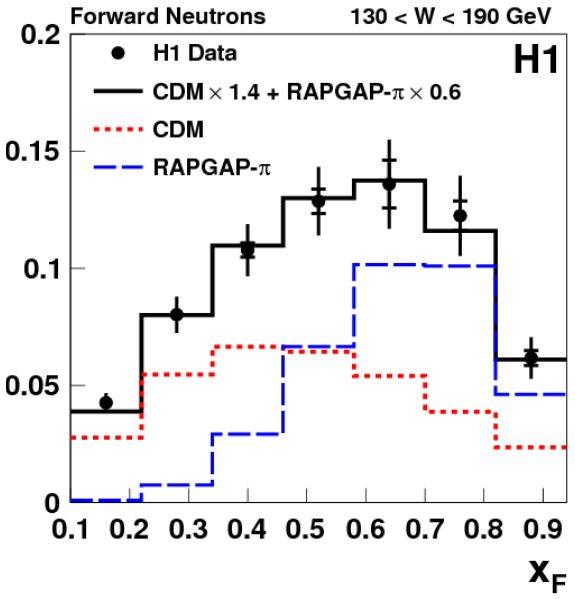
LEPTO and most cosmic ray models reproduce data shape fairly well.

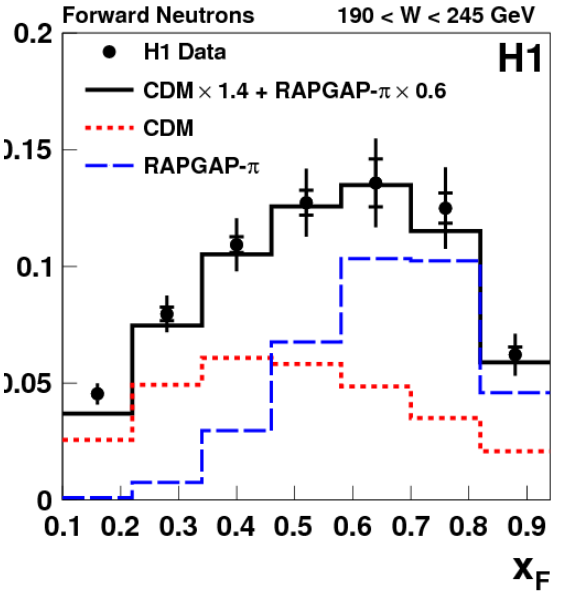
CDM and SIBYLL fail.



Results in x_F for neutrons



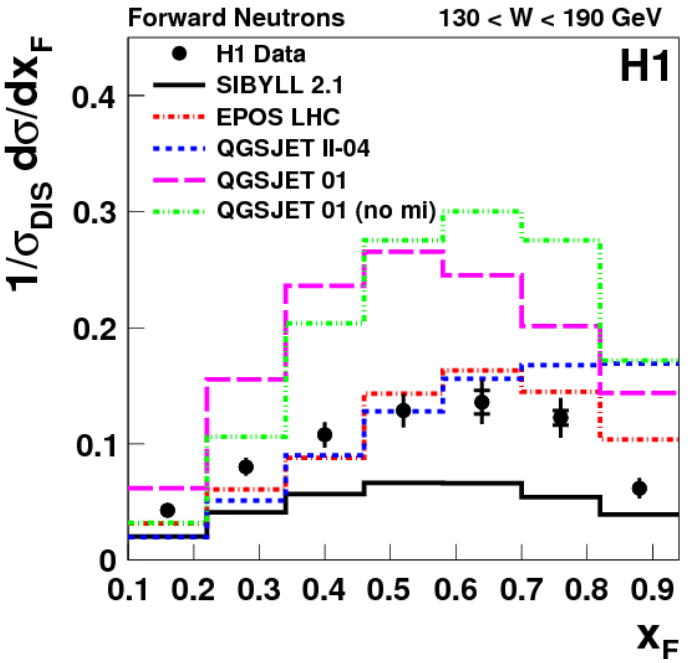




Again similar in different W ranges,
confirming x_F scaling.

RAPGAP (diffractive) and CDM (central):
a combination works well.

EPOS LHC OK,
other cosmic ray models fail.



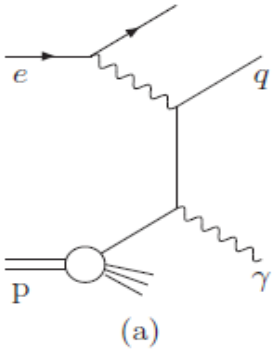
Conclusions

- Very forward photons and neutrons measured by H1 for Q^2 range 6 – 100 GeV^2 , 0.05 < y < 0.6. 131 pb^{-1} HERA data in 2006-7.
- Relative rate of photons/neutrons / DIS independent of W, consistent with limiting fragmentation hypothesis.
- Feynman-x scaling confirmed in measured range.
- MC models overestimate the photon rate, but are mostly reasonable.
- Neutron distributions described well by RAPGAP+CDM or by EPOS LHC.

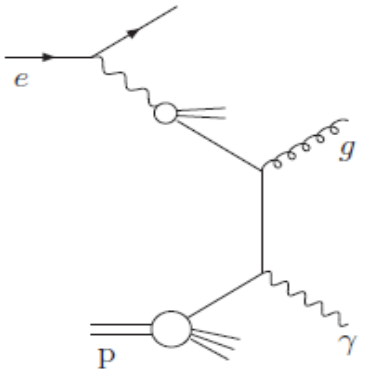
Prompt photons in photoproduction.

- "Prompt" photons emerge directly from the hard scattering process and give a particular view of this.
- Tests of specific QCD models.
- As potential background to "new physics", should be well understood.

direct



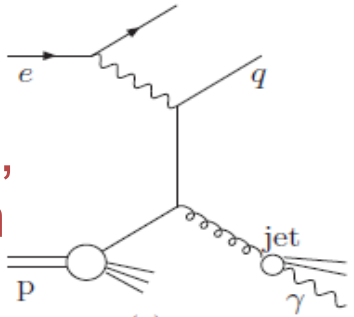
(a)



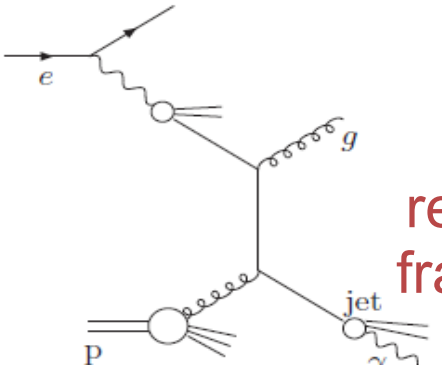
(b)

resolved

direct, fragmentation



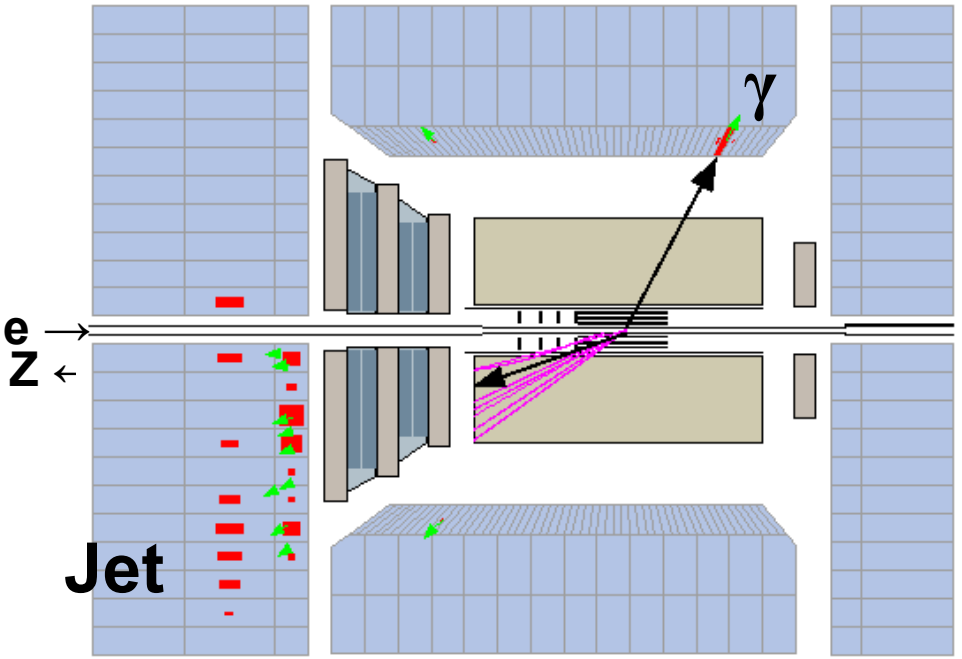
(c)

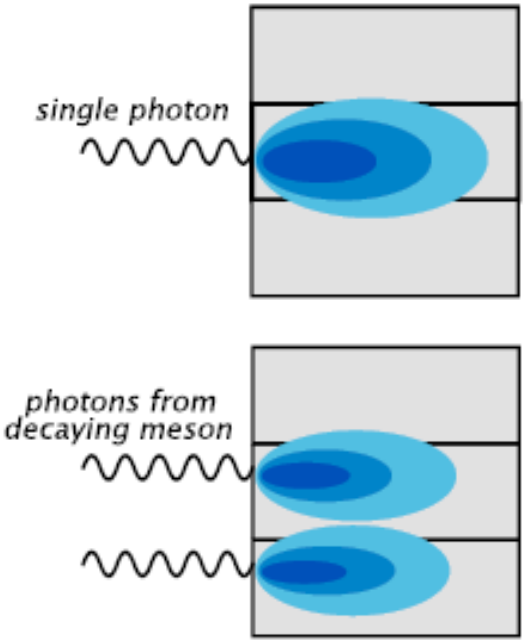


(d)

resolved, fragmentation

Hard photons in finely segmented central ZEUS calorimeter

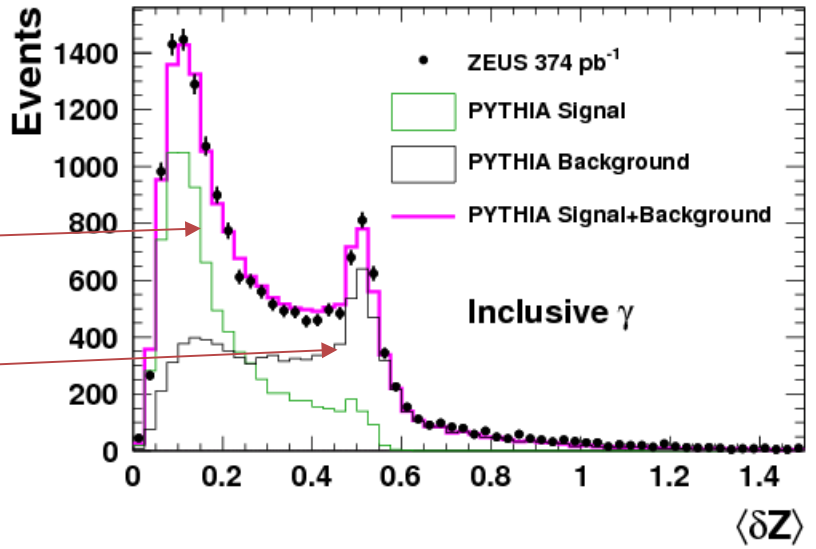




Width of shower is evaluated.

Fit to narrow photon peak

+ broader mesonic background:



Models tested

Fontannaz, Guillet and Heinrich (FGH, EPHOX):

NLO + box diagram and a contribution from fragmentation.

Lipatov, Malyshev, Zotov (LMZ): k_T-factorisation with unintegrated parton distributions and initial-state parton cascade. Upgraded for second ZEUS analysis.

Experimental quantities:

Photons: $E_T > 6$ GeV central: $-0.7 < \eta^\gamma < 0.9$

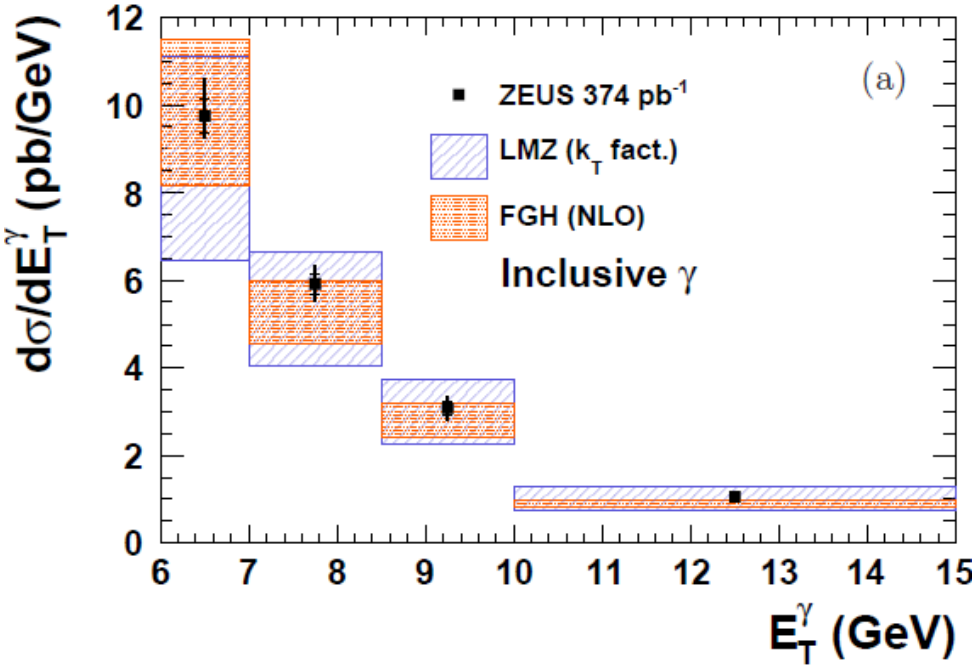
Isolated: to reduce fragmentation component and backgrounds, E > 0.9* energy of jet-like object containing photon.

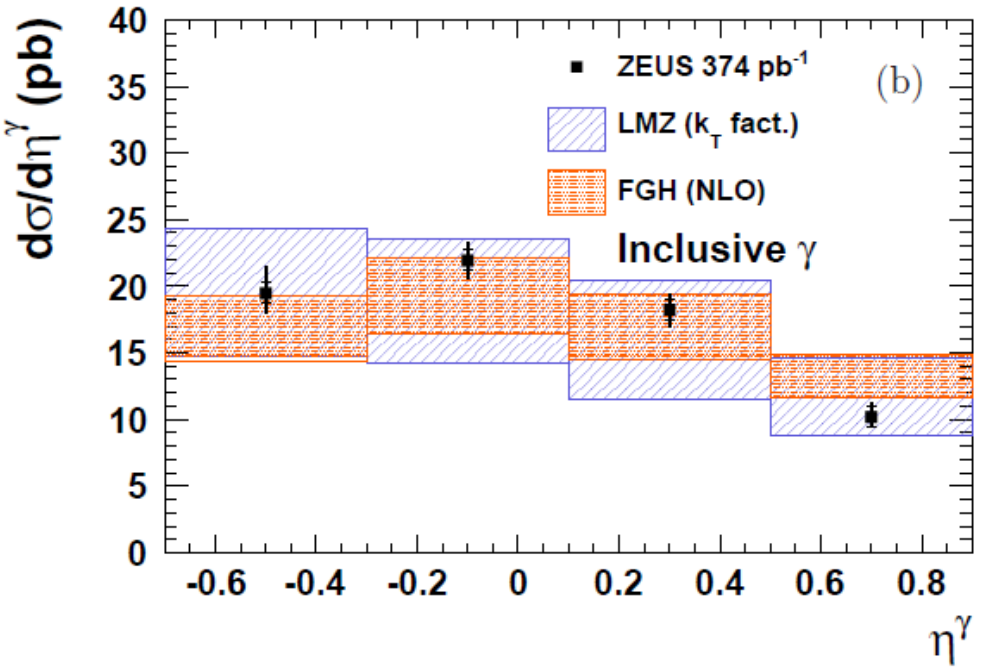
Jets: use k_T clustering algorithm. $E_T > 4$ GeV

Make use of $x_\gamma^{meas} = \Sigma_{photon+jet}(E - p_z) / \Sigma_{all\ final\text{-}state\ hadrons}(E - p_z)$

Results

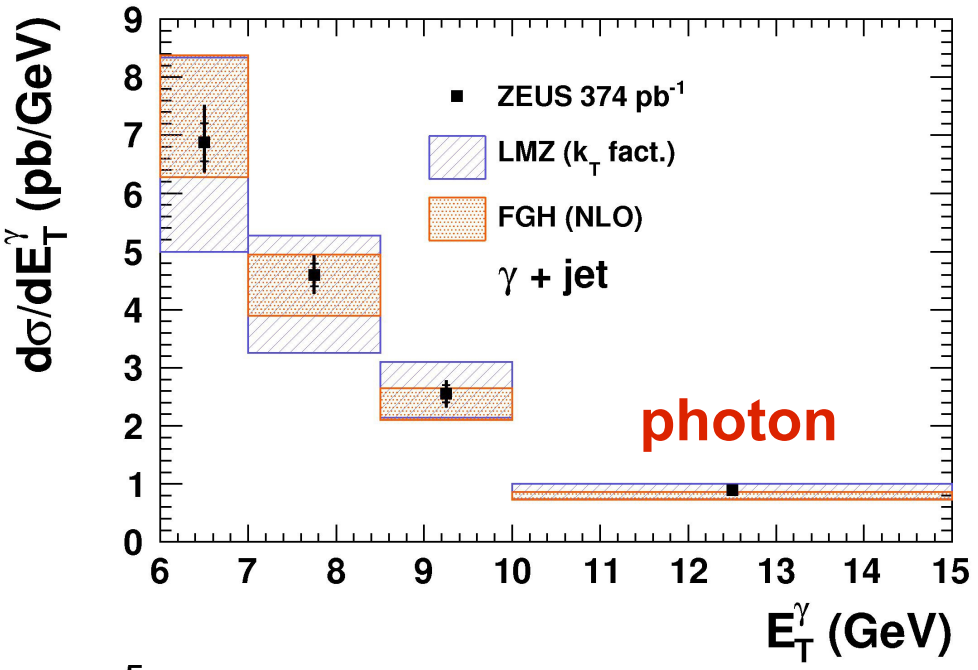
Inclusive isolated photon cross sections

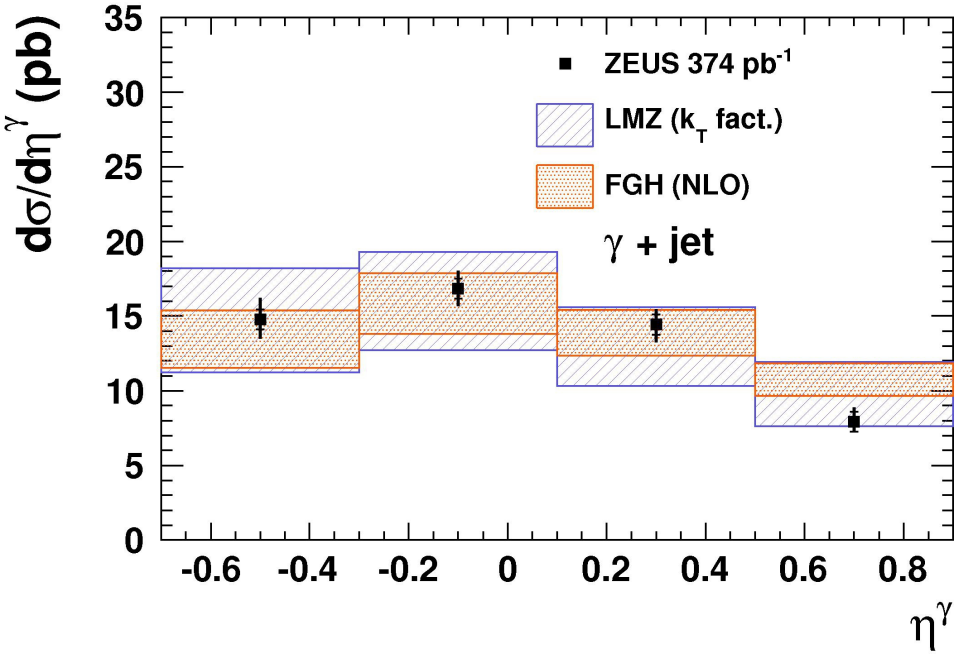


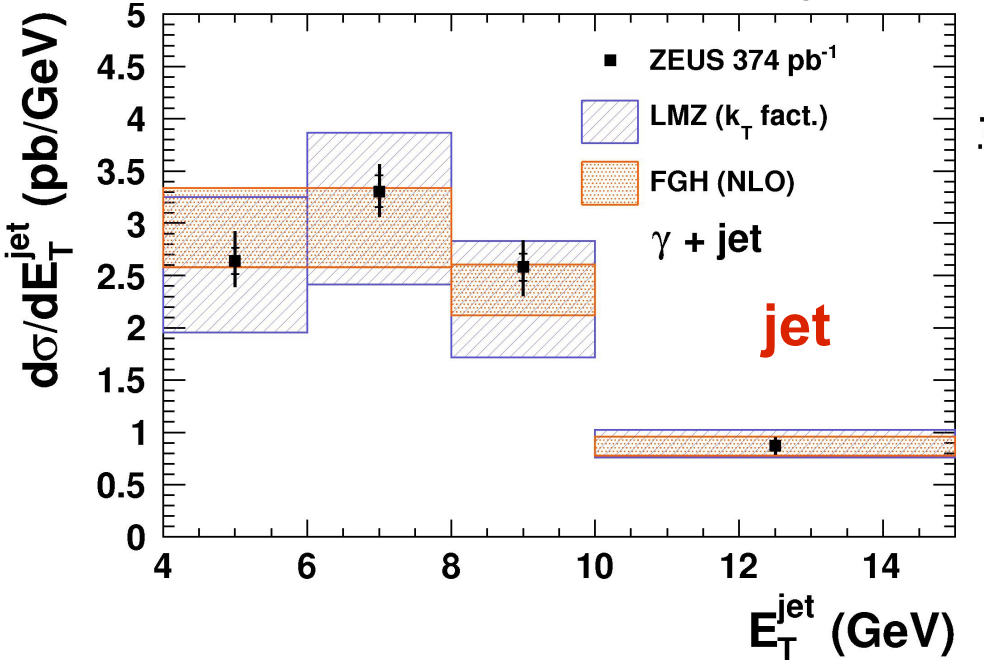


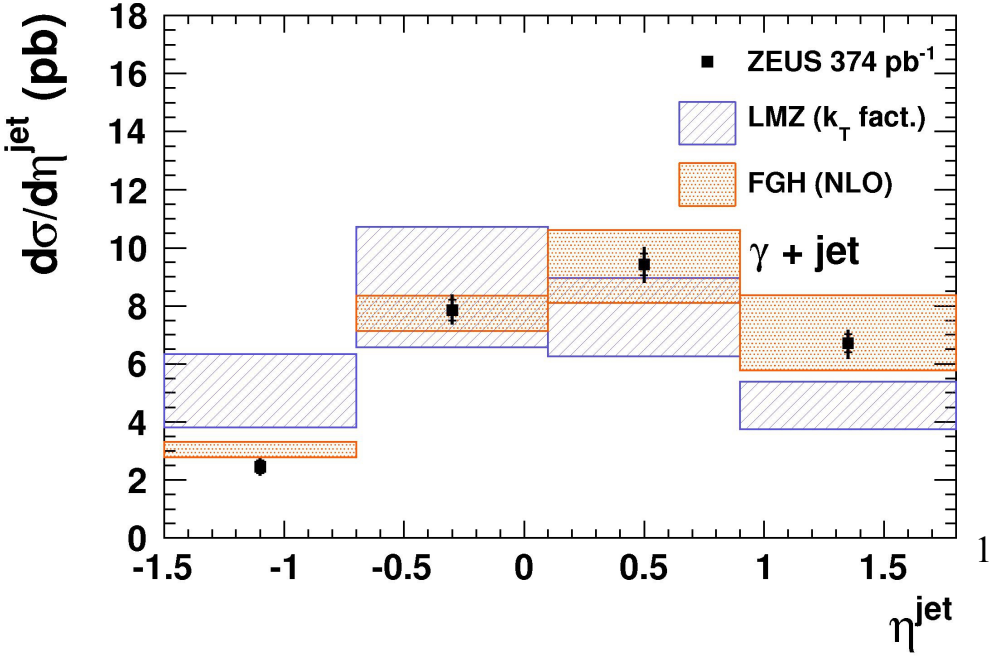
Both **FGH** and **LMZ** give a satisfactory description.
But large theory uncertainties.

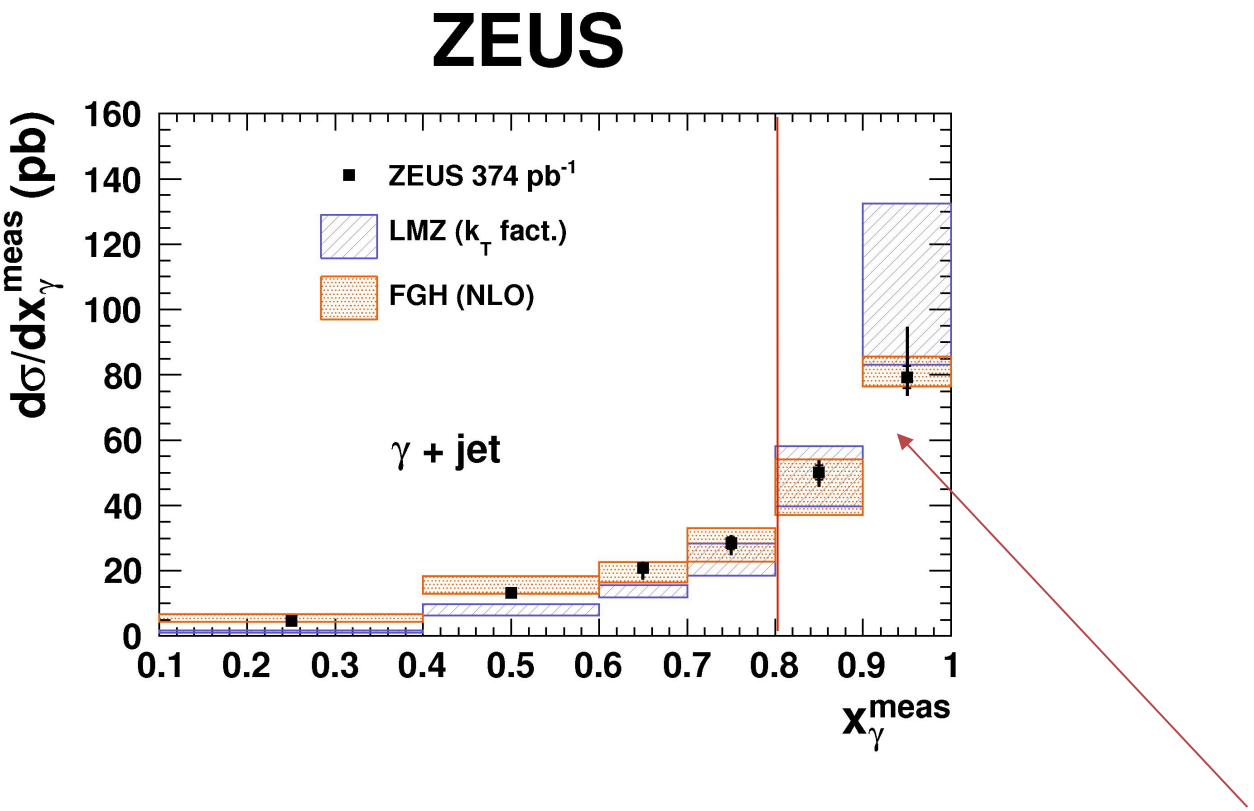
Photon plus jet.









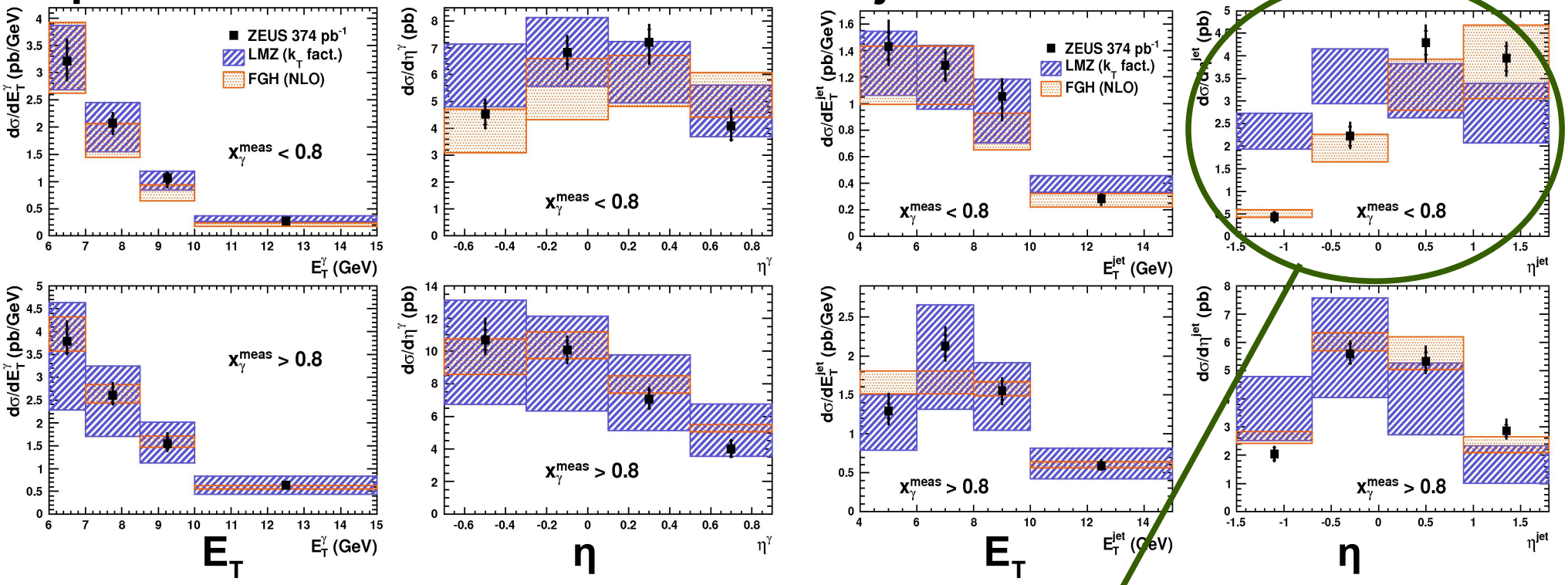


The x_γ^{meas} distribution shows a peak near unity corresponding to the direct process.

To investigate resolved-enhanced and direct-enhanced regions further,
apply selections $x_\gamma^{meas} < 0.8$ **and** $x_\gamma^{meas} > 0.8$

$x_\gamma^{meas} < 0.8$ **(upper)** $x_\gamma^{meas} > 0.8$ **(lower)**

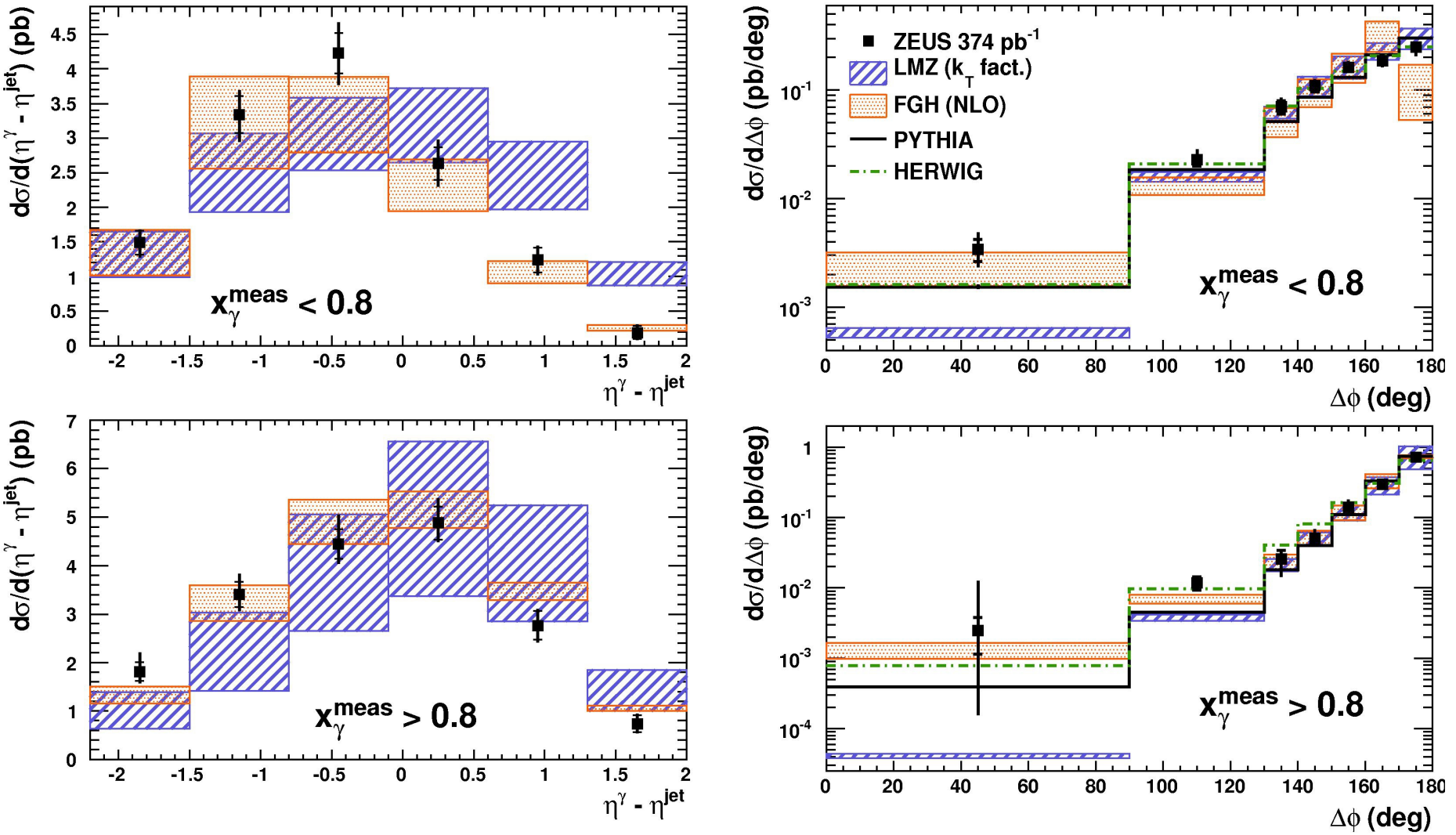
photon **jet**



All distributions good for both models, except η(jet) for LMZ, $x_\gamma^{meas} < 0.8$.

Perhaps due to mismodelling of initial-state cascade.

Further variables: $\eta^{\gamma} - \eta^{jet}$ and $|\varphi^{\gamma} - \varphi^{jet}|$



FGH is again fine, LMZ poorer on pseudorapidity difference.

PYTHIA and HERWIG also do well in the azimuth difference.

Conclusions:

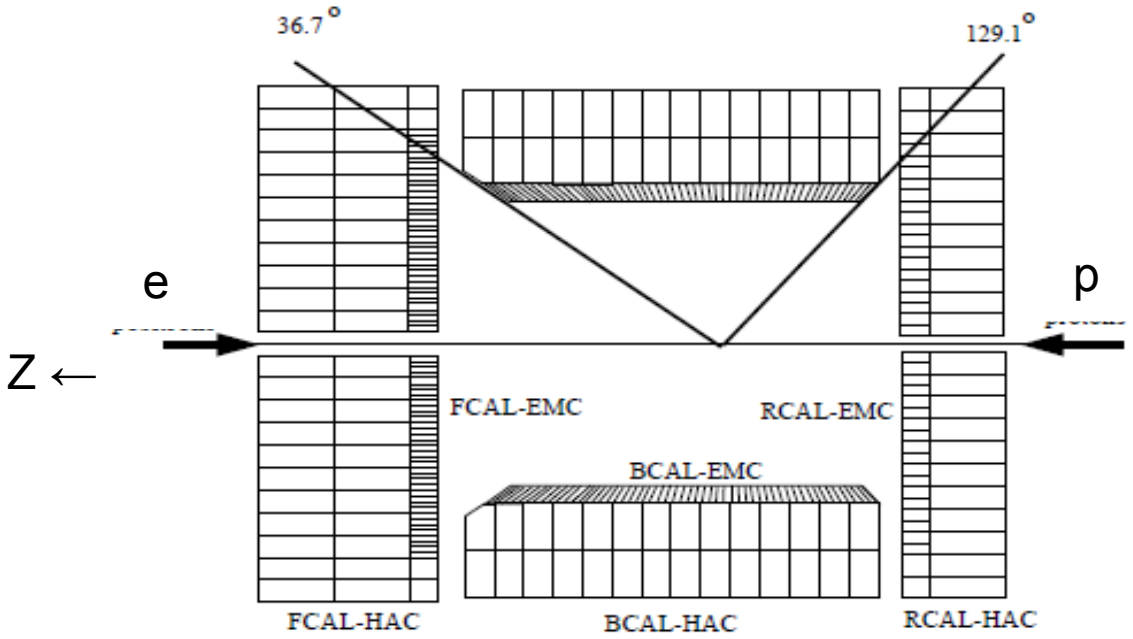
- Prompt photon photoproduction measured in many variables by ZEUS.
- The FGH (EPHOX) program gives the better account of the physics, but LMZ is satisfactory for most variables.

Overall summary

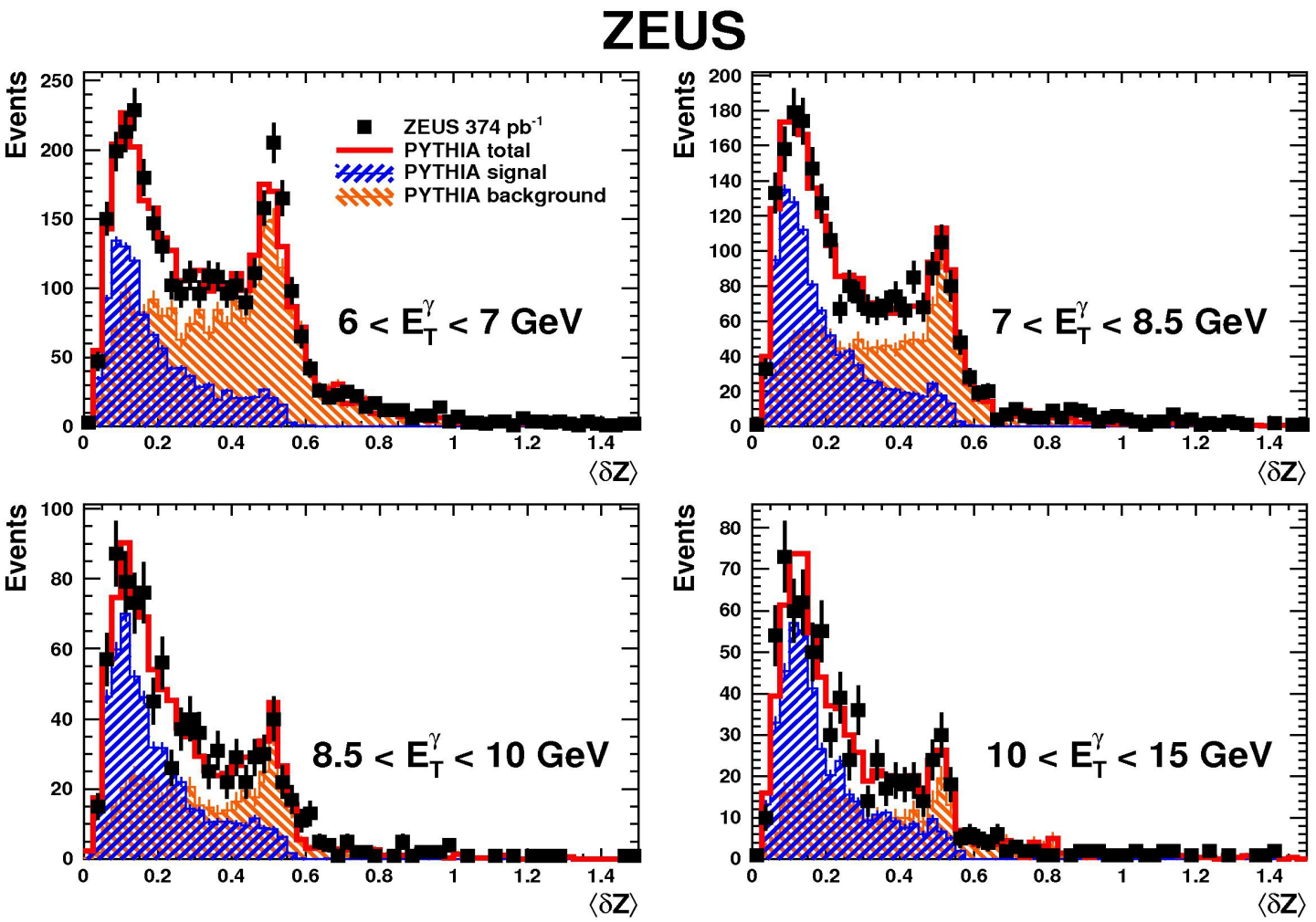
H1 and ZEUS at HERA continue to bear fruitful analyses of ep physics to test QCD models!

Backup

ZEUS calorimeter



Hard scattered photons measured in the BCAL (finely segmented in the Z direction).


ZEUS
Events
ZEUS 374 pb-1
PYTHIA total
PYTHIA signal
PYTHIA background
6 < E_T^γ < 7 GeV
7 < E_T^γ < 8.5 GeV
8.5 < E_T^γ < 10 GeV
10 < E_T^γ < 15 GeV
⟨δZ⟩

Summary:

- Measurements of prompt photons with jets in photoproduction have been made by ZEUS using the full HERA II data sample.

- Results are well described by
- NLO theories next.