# Hard QCD and Hadronic Final State at HERA

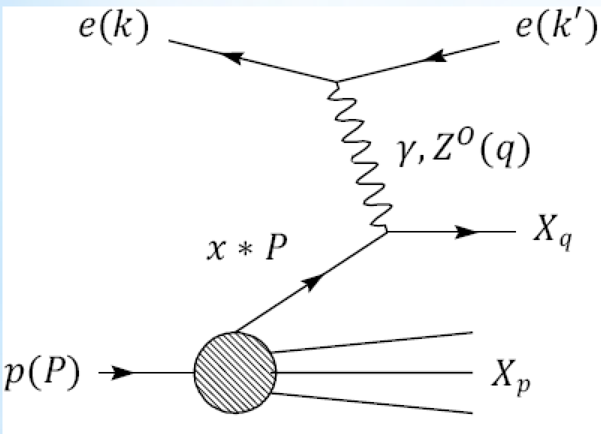
Alice Valkárová, on behalf of H1 and ZEUS Collaborations

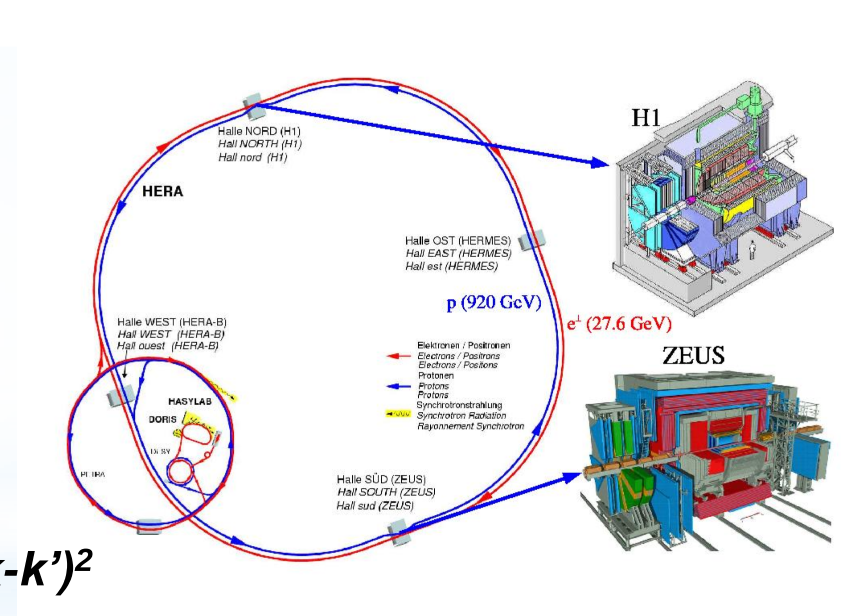
Diffraction 2016, Acireale, Sicily

4.9.2016

# HERA collider experiments

- 27.5 GeV electrons/positrons on 920 GeV protons →√s=318 GeV
- data taken in 1992-2007
- HERA I,II: ~ 500 $pb^{-1}$ per experiment
- H 1 & ZEUS - 4π detectors


**Virtuality** of exchanged boson $Q^2 = -q^2 = -(k-k')^2$

**Inelasticity** $y = Pq/Pk$

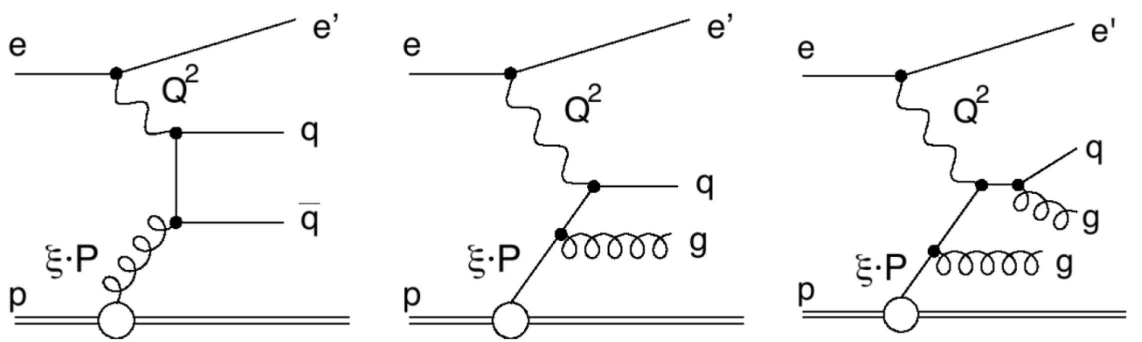
**Bjorken scaling variable** $x = Q^2/2qP$

**Two regimes:**

**$Q^2 <$ 1 $GeV^2$ photoproduction ($\gamma p$)**

**$Q^2 \gg$ 1 $GeV^2$ Deep Inelastic Scattering (*DIS*)**

# Jets in DIS ep collisions




Boson-gluon fusion | QCD Compton | Trijet leading-order

Jet measurements in **Breit reference frame →**

exchanged virtual boson collides head on with parton from proton

**Dijet measurement**: boson-gluon fusion & QCD Compton sensitive to $O(\alpha_s)$ already at LO

**Trijet measurement**: calculations in pQCD in LO already at $O(\alpha_s^2)$

| Process | | H1 | | ZEUS | |
|---|---|---|---|---|---|
| | | HERA I | HERAII | HERA I | HERA II |
| Low $Q^2$ | inclusive | | This analysis | | |
| | dijets | EPJC 67 (2010) 1 | H1prelim 16-061 | Nucl.Ph.B 765 (2007) 1 | |
| | trijets | | H1prelim 16-062 | | |
| High $Q^2$ ($Q^2>150$ GeV$^2$) | inclusive | EPJC 65 (2010) 363 | EPJC 75 (2015) 2 | PL B 691 (2010) 127 | EPJC 70 (2010) 945 |
| | dijets | | This analysis | | |
| | trijets | | H1prelim 16-062 | | |

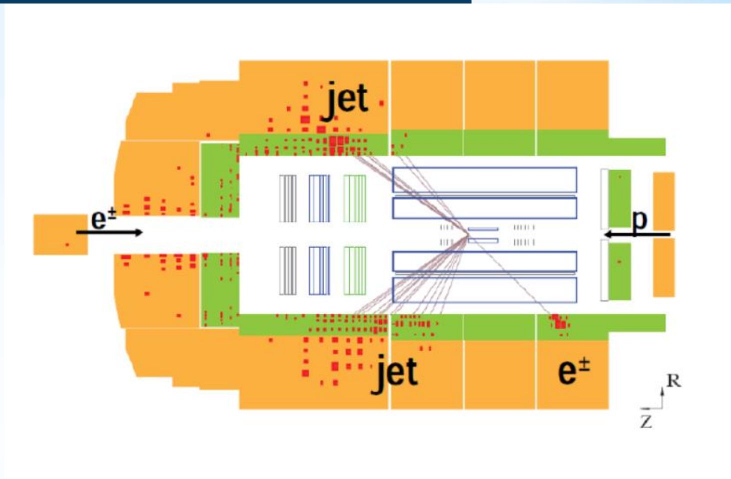
# Jets in DIS ep collisions

**Data:** HERA II period 2006-2007
Integrated luminosity $L$=184 $pb^{-1}$

**Regularised unfolding procedure**
S.Schmitt,JINST 7(2012)T10003
Takes into account kinematic migration by considering an 'extended phase space' → describes accurately migrations into and out of final 'measurement phase space'

H1prelim-16-061,H1prelim-16-062
included also high $Q^2$ data from Eur.Phys.J.C75 (2015) 2, 65

- Inclusive $k_t$ algorithm with R=1
- Jet energy calibration using neural networks




$-1.5<\eta^{jet}_{lab} < 2.5$

| | Phase space low $Q^2$ | Phase space high $Q^2$ |
|---|---|---|
| NC DIS phase space | $5.5<Q^2<80$ $GeV^2$<br>$0.2<y<0.6$ | $150<Q^2<15000$ $GeV^2$<br>$0.2<y<0.7$ |
| Inclusive jets | $4.5 <p_T^{jet}<50$ GeV | $5 <p_T^{jet}<50$ GeV |
| Dijets Njet ≥ 2 | $5 <\langle p_T\rangle_2 < 50$ GeV | |
| Trijets Njet ≥ 3 | $5.5 <\langle p_T\rangle_3 < 40$ GeV | |

# MC models and NLO QCD

**Monte Carlo generators:**

RAPGAP: LO matrix elements +PS

DJANGOH:Color-dipole model -Ariadne

Lund string fragmentation for hadronisation

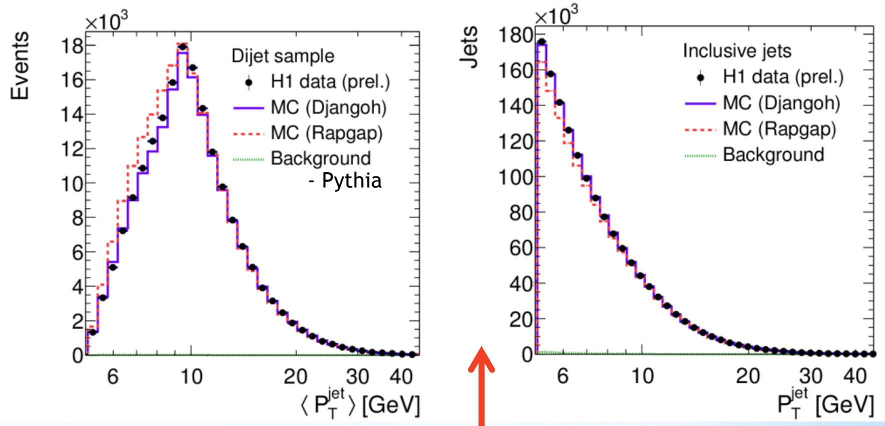
**NLO calculations:**

- nlojet++ (Z.Nagy et al.), 5 quarks
- with NNPDF 3.0
  (includes full H1&ZEUS HERAII DIS data)
- $\alpha_s$ = 0.118 (as in PDF)
- renormalisation and factorisation
  scales: $\mu_r = \mu_f = \sqrt{(P_T^2 + Q^2)/2}$

**aNNLO and NNLO calculations:**

**Normalised with NC DIS NNLO predictions (APFEL)**

- aNNLO –**JetViP,** approximate NNLO using threshold resummation , PR D 92 (2015) 074037
- NNLO - **NNLOJET**
  J.Currie at al, PRL, 117 (2016) 042001




MCs weighted to achieve a better description of data

**Hadronisation corrections to NLO,NNLO:**

- the average of corrections from RAPGAP and DJANGOH
- multiplicative factors, typically 0.86-0.97 for trijet at low $<P_T>$ up to 0.73
- uncertainty defined as difference between (RAPGAP – DJANGOH)/2

**Correction applied to data:** Data are corrected for **QED radiative effects**

# Inclusive x-sections & NLO and NNLO

**Inclusive jets**:

-count each jet with $P_T^{jet}$ >4.5 GeV in NC DIS event

**Systematic uncertainties** dominated by jet and cluster energy, scale and model uncertainty

**NNLO predictions:**

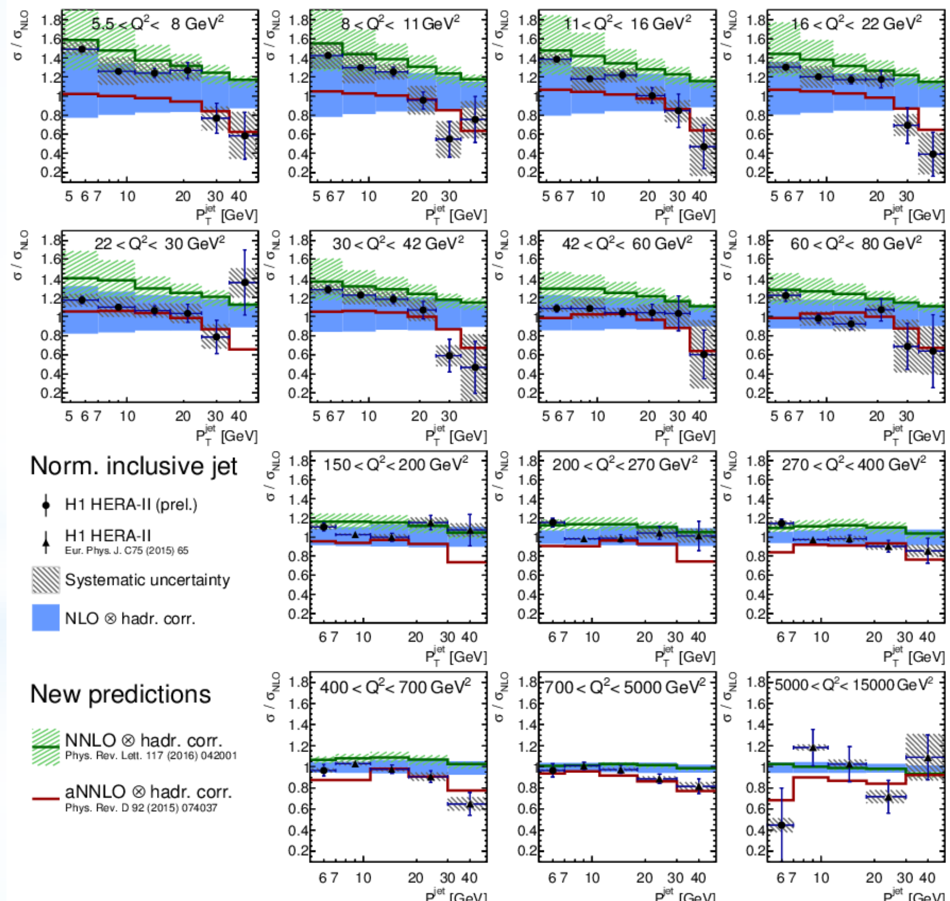
-the description of the data improved in comparison with NLO predictions (mainly for low $P_T^{jet}$ and low $Q^2$)

**aNNLO predictions:**

-the description of the data improved at higher values of $P_T^{jet}$ as compared to NLO predictions

$\sigma_i = \sigma_i^{jet} / \sigma_{iQ2}$

Inclusive jets - normalised to NC DIS x-sections
Ratio $\sigma_i / \sigma_{iNLO}$



# Dijets - NLO and NNLO

Dijets - normalised to NC DIS x-sections
Ratio $\sigma/\sigma_{NLO}$

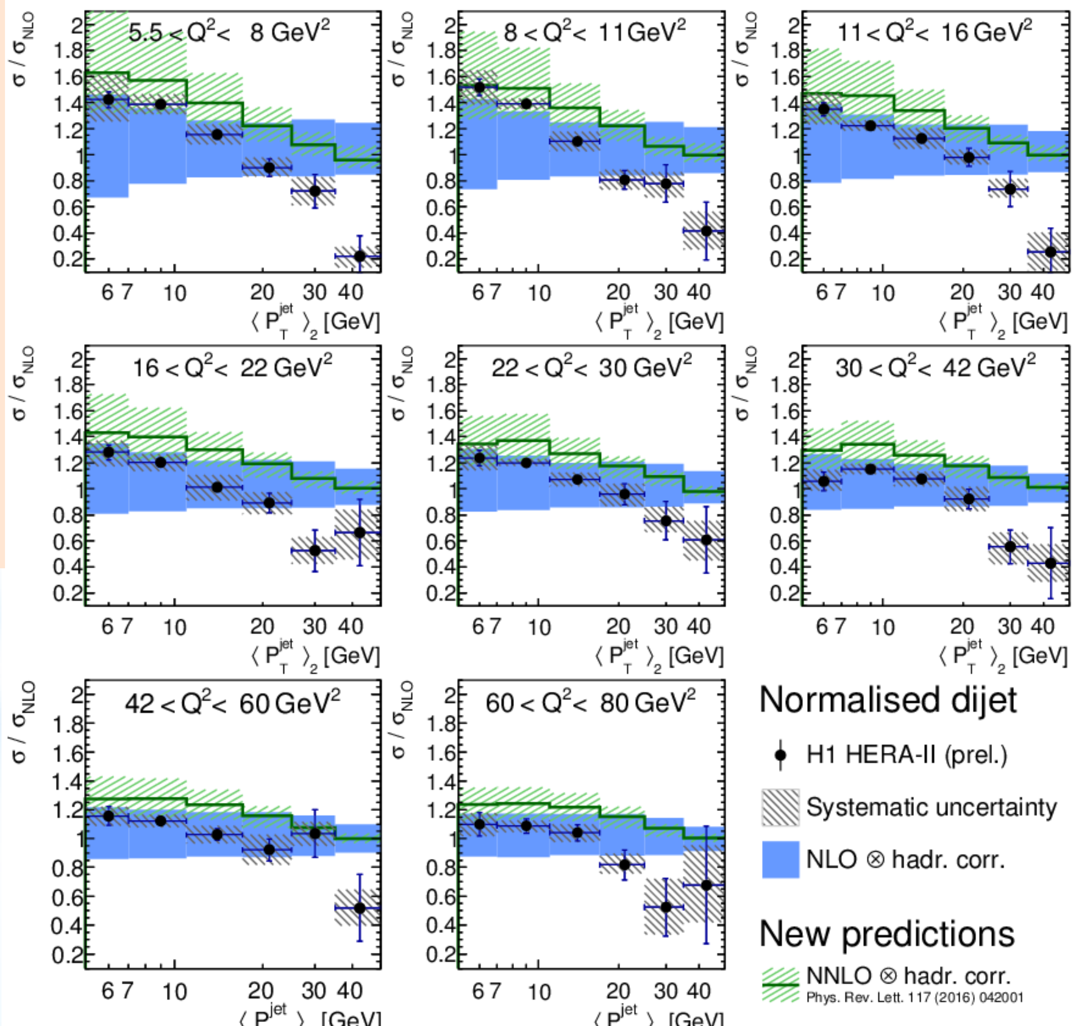
$<P_T^{jet}>_2 = ½ (P_T^{jet1} + P_T^{jet2})$

**NNLO predictions:**

-the description of the data improved in comparison with NLO predictions (mainly for low $P_T^{jet}$ and low $Q^2$)

-significant improvement of the shape description

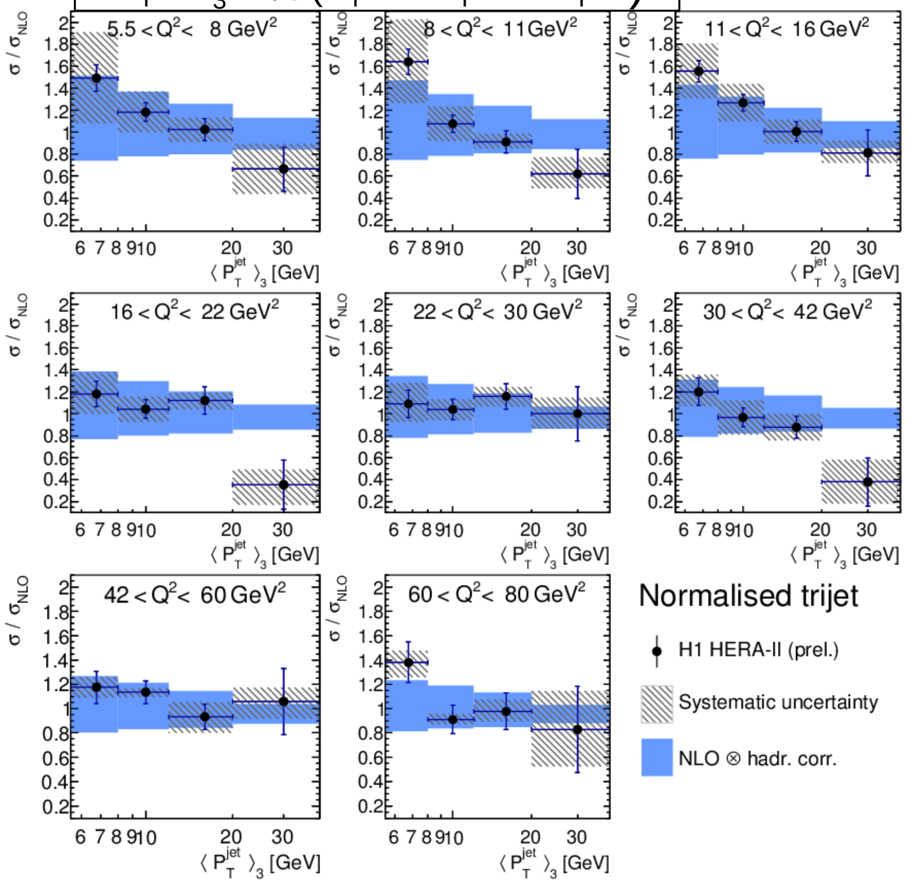
-slightly higher in normalisation (partially due to the normalisation to NC DIS cross sections)



# Trijet cross sections & NLO

Trijets - normalised to NC DIS x-sections
Ratio $\sigma/\sigma_{NLO}$

$\langle P_T^{jet} \rangle_3 = ⅓ (P_T^{jet1} + P_T^{jet2} + P_T^{jet3})$

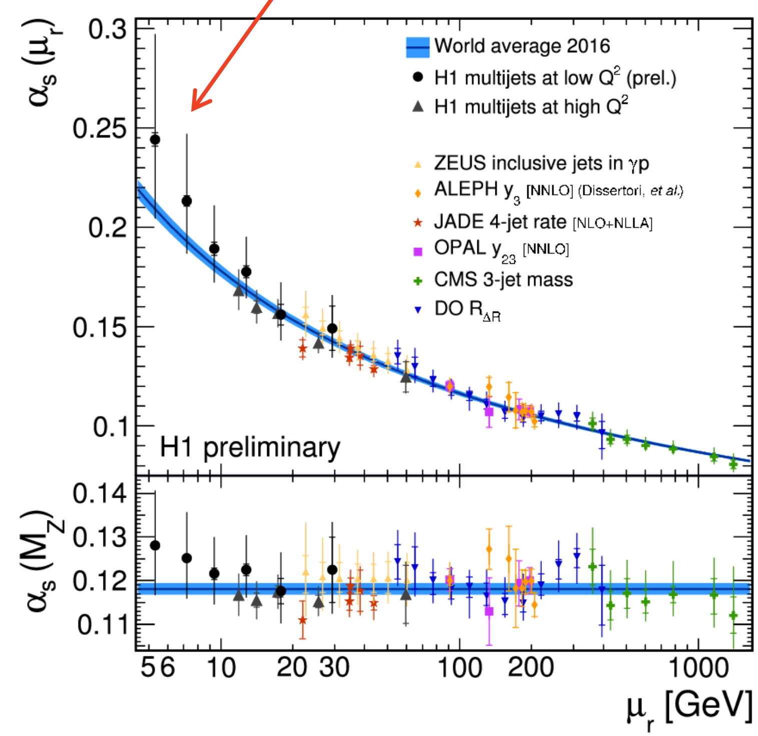



-Data well described by NLO within large experimental and theoretical uncertainties

$\alpha_s(m_Z)$ from normalised low-$Q^2$ multijets & NLO
- probe running of $\alpha_s(\mu)$ in range $6<\mu<30$ GeV

- Normalised low-$Q^2$ and high-$Q^2$ multijets experimental precision about 0.4%

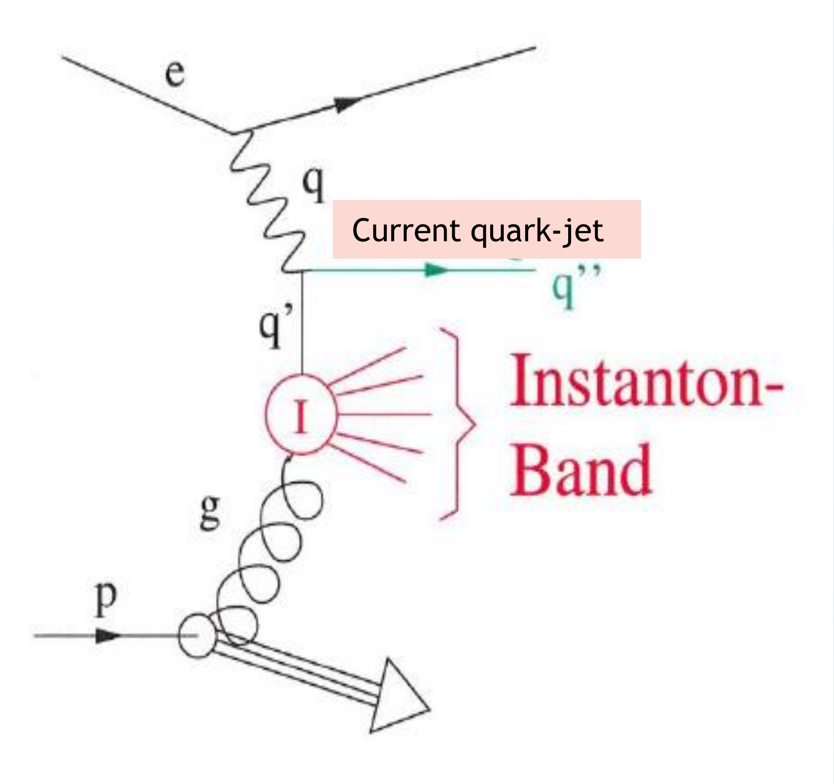
The deviation in low $\mu_r$ in accordance with observed enhancement of NNLO vs NLO and data jets!



# Search for Instantons

Confirmation of non-perturbative QCD of SM?

Signature:
- Hard current jet
- Instanton band – high multiplicity
- Isotropy in I rest frame
- Parton (u,d,s) democracy



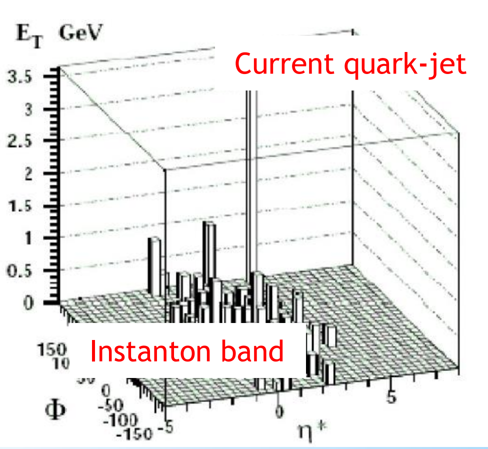

Theory: for HERA σ ~ 10-100 pb
A.Ringwald,F.Schrempp a.o.

HERA I data – not observed by H1 and ZEUS, upper limits compatible with theory

HERA II : data sample ~ 351 $pb^{-1}$

Predicted x-section in studied phase space:

$150 < Q^2 < 15000$ GeV$^2$, $0.2 < y < 0.7$
$Q'^2 = -q'^2 > 109$ GeV$^2$, $x' = Q'^2/(2g \cdot q') > 0.35$
$\sigma(I) = 10 \pm 3$ pb



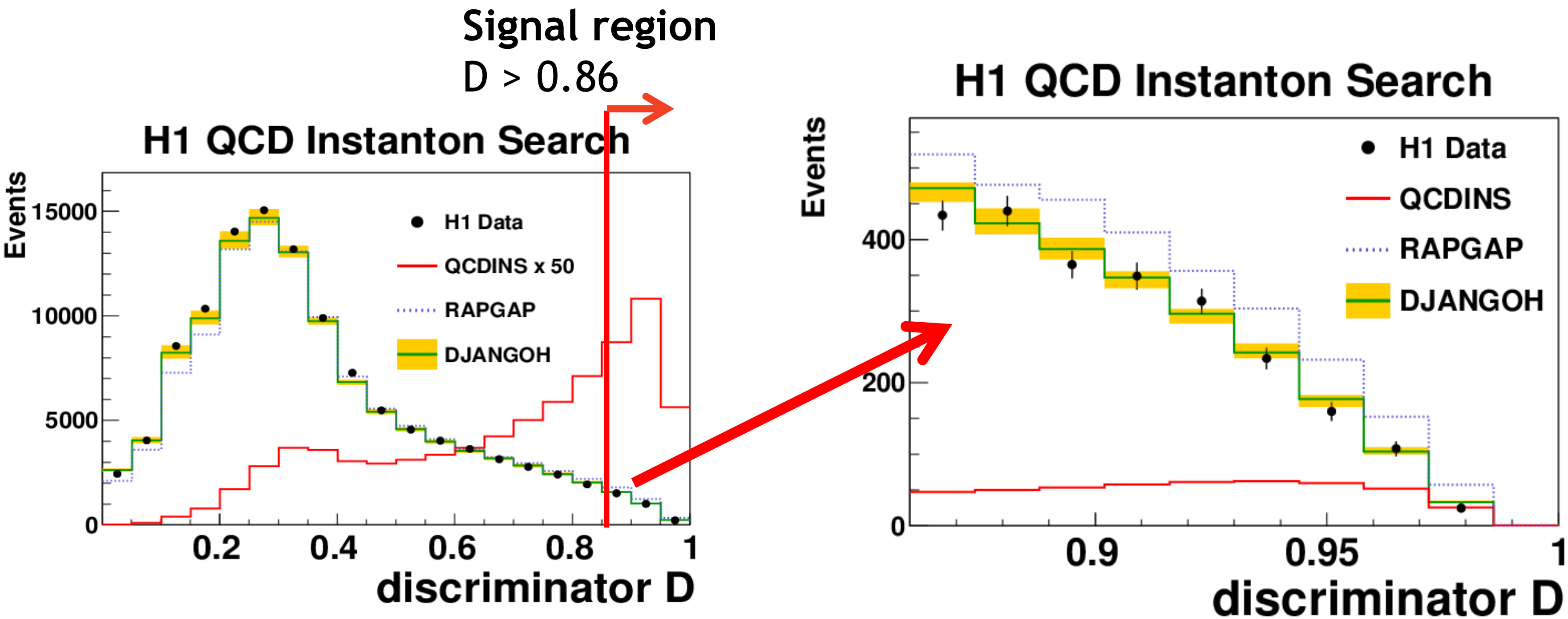
# Search for Instantons

Background needs to be reduced by at least 2 orders of magnitude

**MultiVariate analysis**

→ 5 variables as input to MVA (number of particles, transverse energy of the band, sphericity, Fox-Wolfram moments) – PDERS method (ROOT TMVA package)

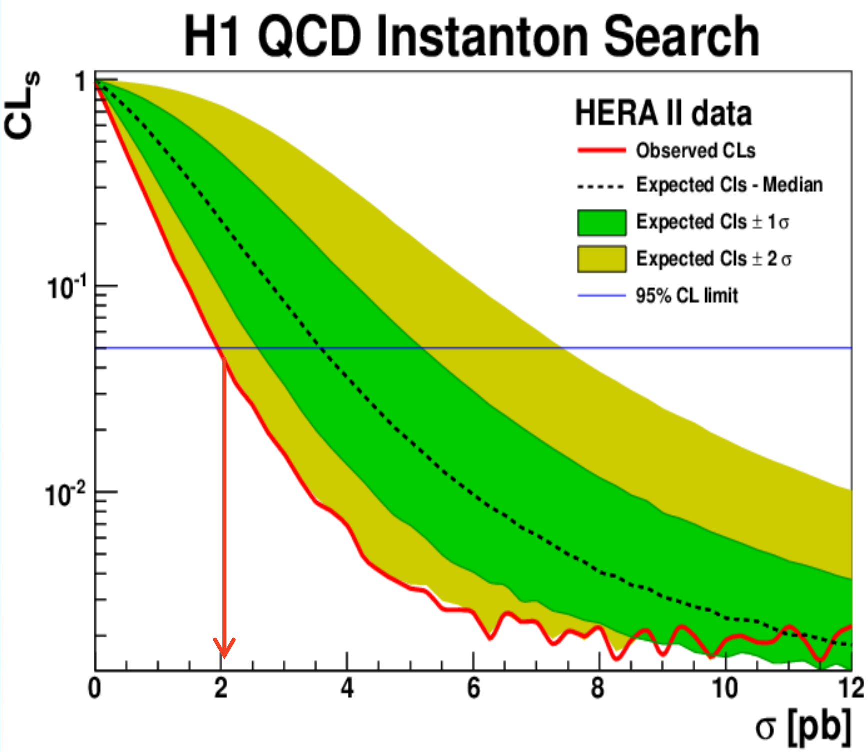
- training with RAPGAP/DJANGOH as background and QCDINS as signal MC
- good signal/background separation
- reasonable background description




Good description by DJANGOH in signal-background region

**NO SIGNAL OBSERVED IN DATA!**

# Search for Instantons




- CLs method
- Using full range discriminator
- Background is DJANGOH

Observed Upper Limit:

2pb at 95 % CL

Published in Eur.Phys.J.C76 (2016) 7

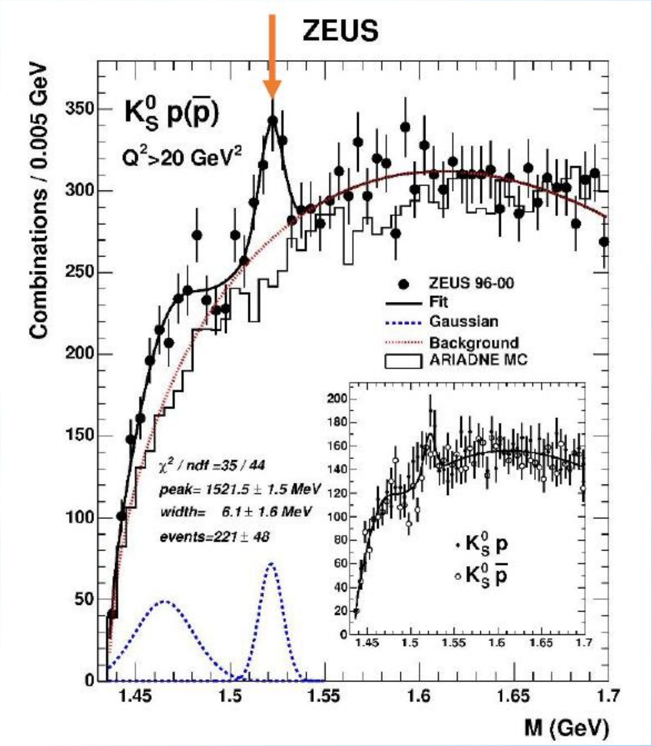
# Pentaquarks

In 2015 LHCb -: possible discovery of two pentaquark states at 4.38 and 4.45 GeV corresponding to $uudc\bar{c}$.

**Pentaquarks are topical again!**

Early 2000's reported exotic objects consisting with 5 quarks.

ZEUS: evidence for a peak in $pK^0_s$ ($\bar{p}K^0_s$) corresponding to $uudd\bar{s}$ state at 1.52 GeV (HERA I) , Θ state ?
Phys.Lett.B 591 (2004) 7




H1 - **No such a signal seen,** Phys.Lett B 639 (2006) 202

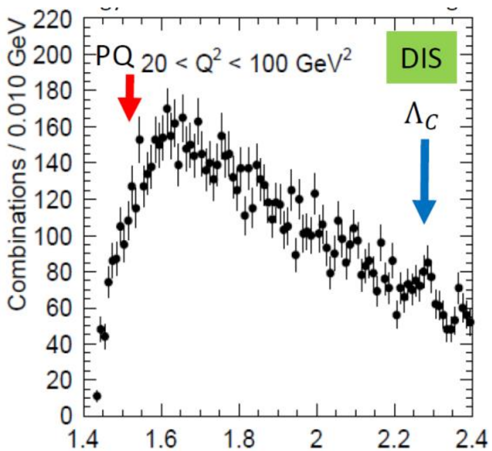
H1 analysis HERA I – peak in D*p spectrum at 3.1 GeV - $uudd\bar{c}$ (2004)

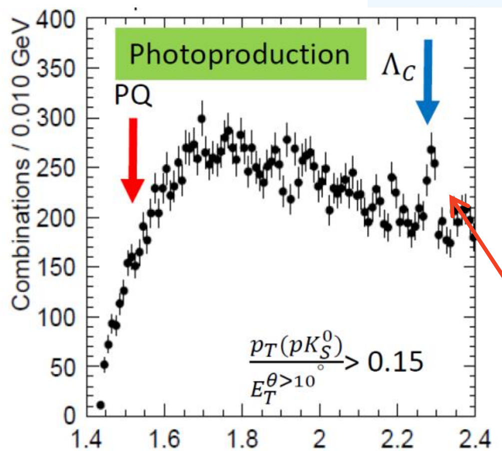
**Not confirmed by ZEUS and with HERA II data!** (2008)

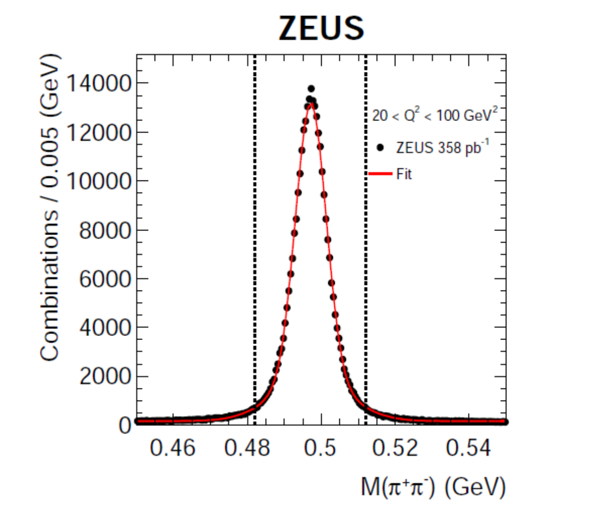
# Pentaquarks

Now HERA II, 3x larger luminosity

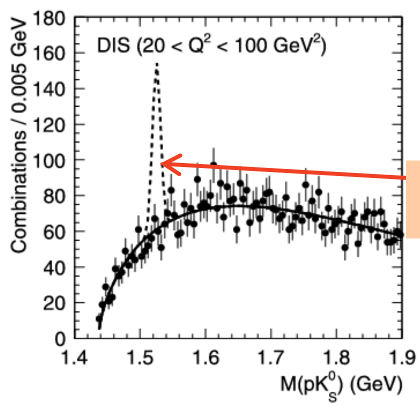
The $pK^0_S$ invariant-mass distribution




A clear $\Lambda_c$ (2286) peak observed in photoproduction and DIS sample



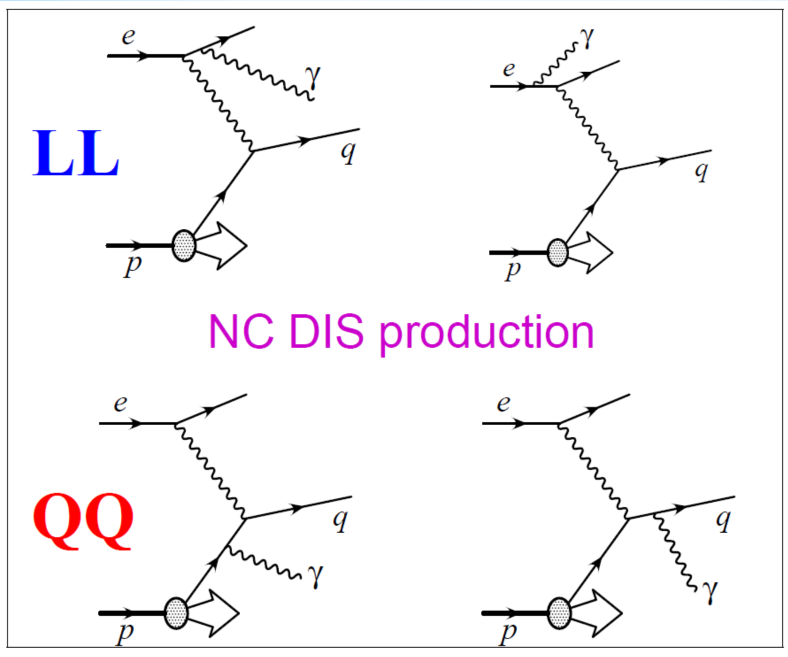

286 events expected

**A peak at 1.52 GeV observed in a previous ZEUS analysis, based on HERA I data, is not confirmed.**

Published in Phys.Lett. B759 (2016), 446

The dashed line represents the signal corresponding to the ZEUS HERA I result

# Prompt photons in DIS

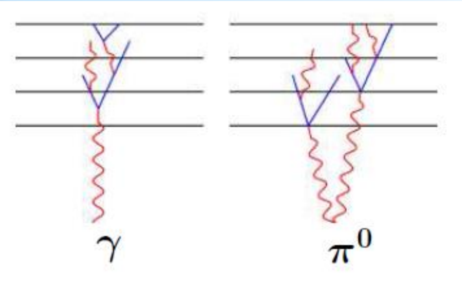



LL-photons are emitted from incoming or outgoing lepton

QQ- photons are emitted from a quark as a part of hard process

Test of QCD, unaffected by hadronisation

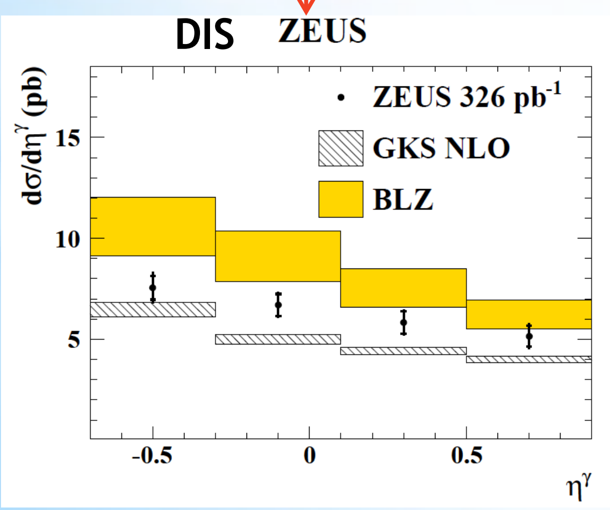
- Free of hadronisation corr. for photon -> direct link to parton level
- Sensitivity to parton and photon PDFs
- Important SM background to possible New physics




- Low statistics as compared to jets
- Difficult background from π/η/ decays -> systematics ~5-10%

# HERA II publications on isolated photons in DIS

| Publication | | L/pb-1 | DIS |
|---|---|---|---|
| 2008 (H1) | EPJC 54 | 227 | incl γ, γ+jet |
| 2010 (ZEUS) | PLB 687 | 320 | incl γ |
| 2012 (ZEUS) | PLB 715 | 326 | γ+jet |
| 2015 (ZEUS) | prelim. | 326 | γ+jet |




**Messages from previous measurements:**

- NLO QCD calculations in collinear approximations underestimate cross sections
- Predictions using $k_t$ factorisation approach lower than data
- Prompt photons production remains a challenge for theory

# Models used for comparison

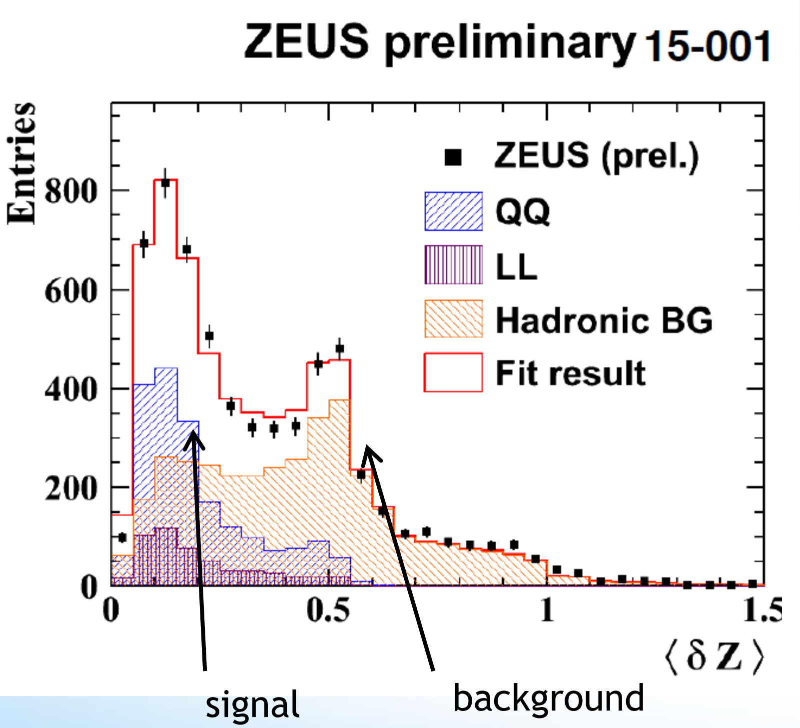
**Signal:** **QQ photons** – **MC PYTHIA**, DIS events with additional radiation from the quark line
**LL photons** – **MC HERACLES & DJANGOH**, higher QCD effects included using color-dipole model as implemented in **ARIADNE**

**Background:** Photonic decays of neutral mesons produced in DIS - **DJANGOH**

## Theoretical calculations (BLZ):

**$k_t$ - factorization QCD approach**
Baranov, Lipatov and Zotov, Phys. Rev. D 81 (2010) 094034
Photon radiation from the quarks as well as from the lepton is taken into account

# Extraction of the photon signal




Method to distinguish the signal from hadronic background based on MC fit of δZ distribution

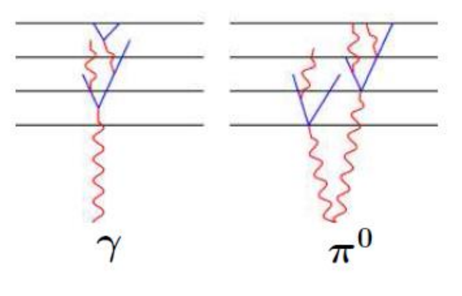
Energy-weighted mean width of the electromagnetic shower(cluster) in calorimeter relative to its centroid:

$$\langle \delta Z \rangle = \frac{\sum_i |z_i - z_{cluster}| \cdot E_i}{l_{cell} \sum E_i}$$

$Z_i$, ($Z_{cluster}$) Z position of the *i-th* cell (centroid of the electromag. cluster),
$l_{cell}$ - width of the cell ,
$E_i$- energy recorded in the cell

In each bin of each measured physical quantity, photon signal + hadronic background is fitted

This fit allows to **separate statisticaly prompt photon signal** (left peak) from **background** dominated by photons from $\pi^0$ decay (right peak)



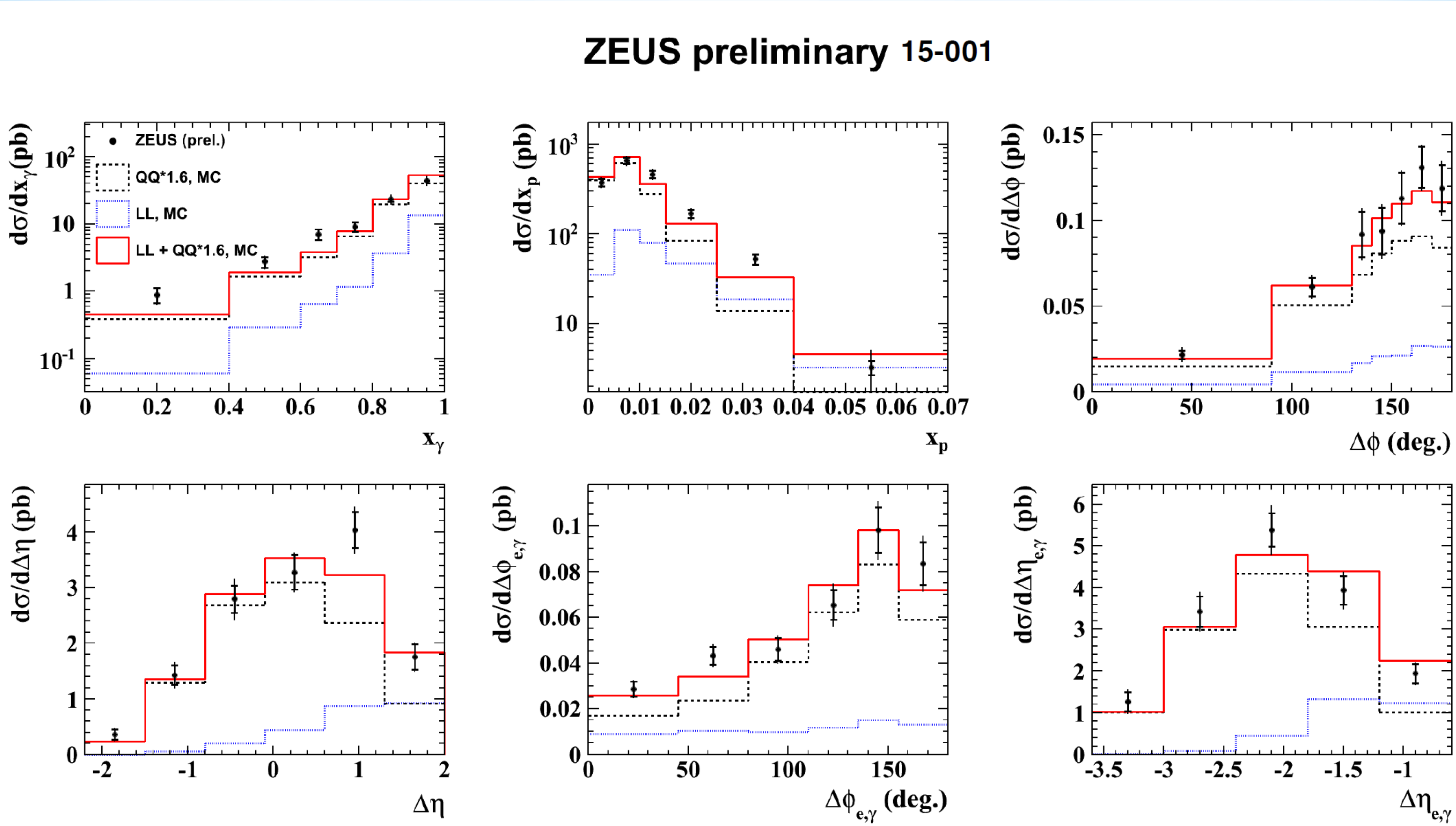
# Cross sections compared to weigthed LO MC

- $x_\gamma = \frac{\sum_{jet,\gamma}(E-p_z)}{2y_{JB}E_e}$
- $x_p = \frac{\sum_{jet,\gamma}(E+p_z)}{2E_p}$

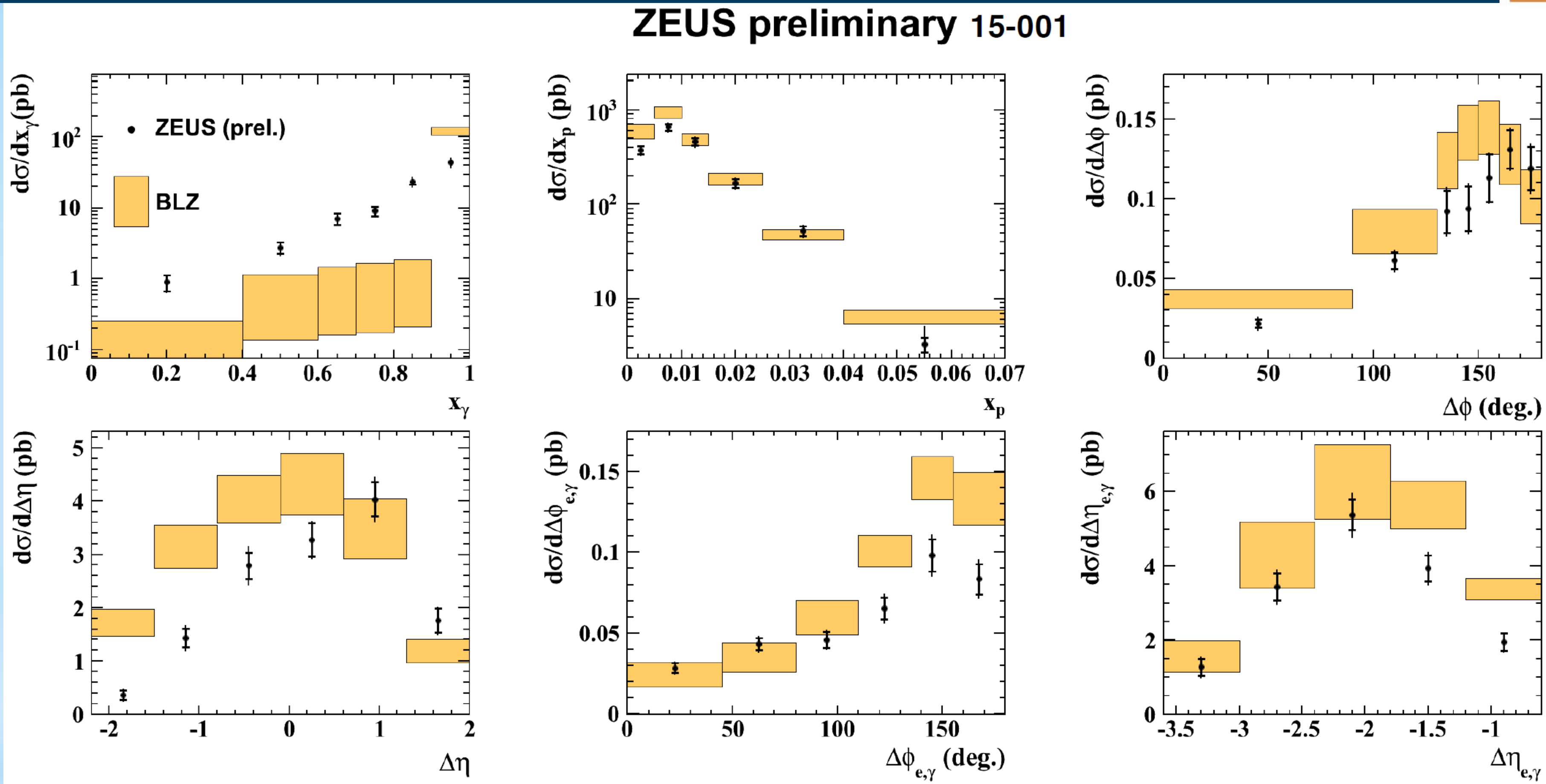
- $\Delta\eta = \eta_{jet} - \eta_\gamma$
  $\Delta\Phi = \varphi_{jet} - \varphi_\gamma$
  $\Delta\Phi_{e\gamma} = \varphi_e - \varphi_\gamma$
- $\Delta\eta_{e,\gamma} = \eta_e - \eta_\gamma$

Cross sections compared to
LL(DJANGOHH) + QQ(PYTHIA) *1.6

**Shapes** are fairly decribed



# Cross sections compared to $k_T$ factorisation model




**Theoretical calculations, $k_t$ - factorization QCD approach (BLZ)**

Baranov, Lipatov and Zotov, Phys. Rev. D 81 (2010) 094034

Photon radiation from the quarks as well as from the lepton is taken into account

BLZ calculations describe shapes of data distributions not so well (mainly $x_\gamma$ and η)

# Conclusions

- New double-differential inclusive jet,dijet and trijet cross sections in DIS obtained, inclusive and dijet data compared for the first time with NNLO predictions. NNLO predictions improve the description of the normalised inclusive and dijet experimental double-differential x-sections compared to NLO.

- Instantos at HERA not found, upper limit 2pb at 95% CL, predicted cross section 10 pb excluded. Exclusion limits improved by an order of magnitude.

- A resonance in the $pK^0_s$ ($pK^0_s$ ) (pentaquark) at 1.52 GeV from previous ZEUS measurement not confirmed , limits for production cross section established.

- Prompt photons in DIS measured. The predictions for the sum of the expected LL contributions (DJANGOH) and QQ contributions (PYTHIA) rescaled by factor 1.6 → good description of the shapes of the kinematic variables. The calculations of BLZ based on $k_t$-factorisation method describe the data not so well.