Hard QCD probes at DIS

- HERA kinematics
- Prompt Photon Production at HERA (ZEUS)

  Summary I
- Jet Production at Low Momentum Transfer at HERA (H1)

  Summary II

Low-x Meeting 6-11 June 2016 Gyöngyös, Hungary

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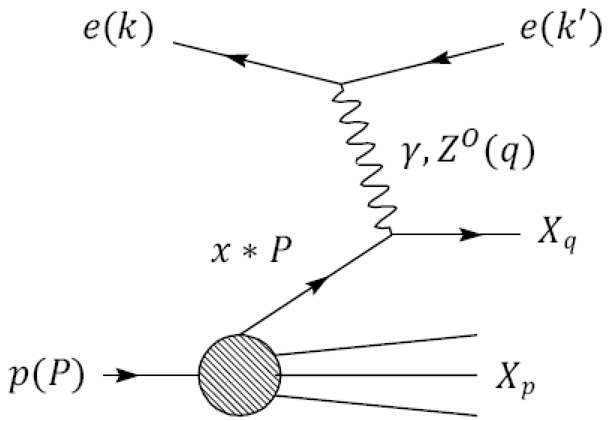
representing the H1 and ZEUS Collaborations

H1 & ZEUS colliding experiments at *ep* collider HERA

E(e)=27.5 GeV, E(p)=920 GeV (820 GeV before 1998) sqrt(s) ~320 GeV

HERA-I: 1994-2000
Upgrade: 2000-2002
HERA-II: 2003-2007
$e^{\pm}p$, lepton beam polarisation
total luminosity ~ 1 fb^{-1} (H1+ZEUS)

Kinematics



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

Inelasticity $y = Pq/Pk$

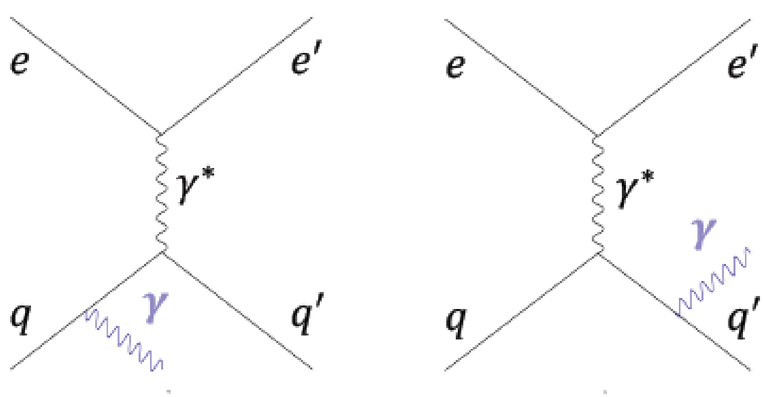
Bjorken scaling variable $x = Q^2/2qP$

Two regimes:
$Q^2 < 1$ GeV^2 photoproduction (γp)
$Q^2 > 1$ GeV^2 Deep Inelastic Scattering (*DIS*)

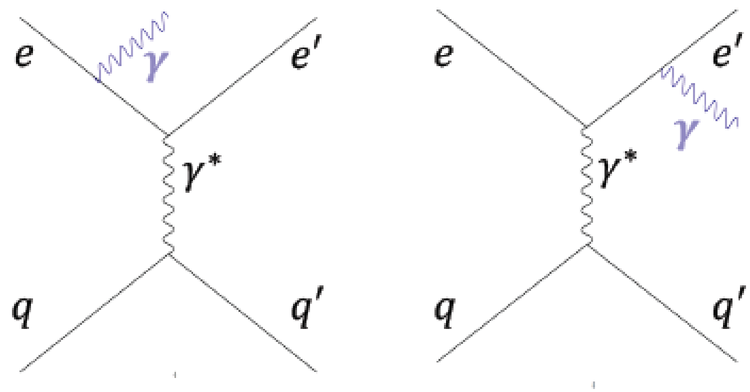
High p_T isolated photons

The lowest-order tree-level diagram for high-energy photon production in DIS

QQ - photons



LL - photons



Prompt **photons** are radiated directly **from partons** of the hard interaction

↓

emission unaffected by parton hadronisation → direct probe of the underlying partonic process in high-energy collisions involving hadrons, **test of perturbative QCD**

possible **background to new physics** processes

photons from the incoming or outgoing **lepton**

Event selection

NC ev. with **an electron, a photon candidate and at least one hadronic jet ->** increase of the fraction of prompt photon processes relative to lepton-radiated contrib.

Exchanged photon virtualities Q^2

$$10 < Q^2 < 350 \text{ GeV}^2$$

Prompt γ measured in Barrel Calorim.

$$E_{EMC}/(E_{EMC}+E_{HAD}) > 0.9$$

$$4 < E_T^{\gamma} < 15 \text{ GeV}$$

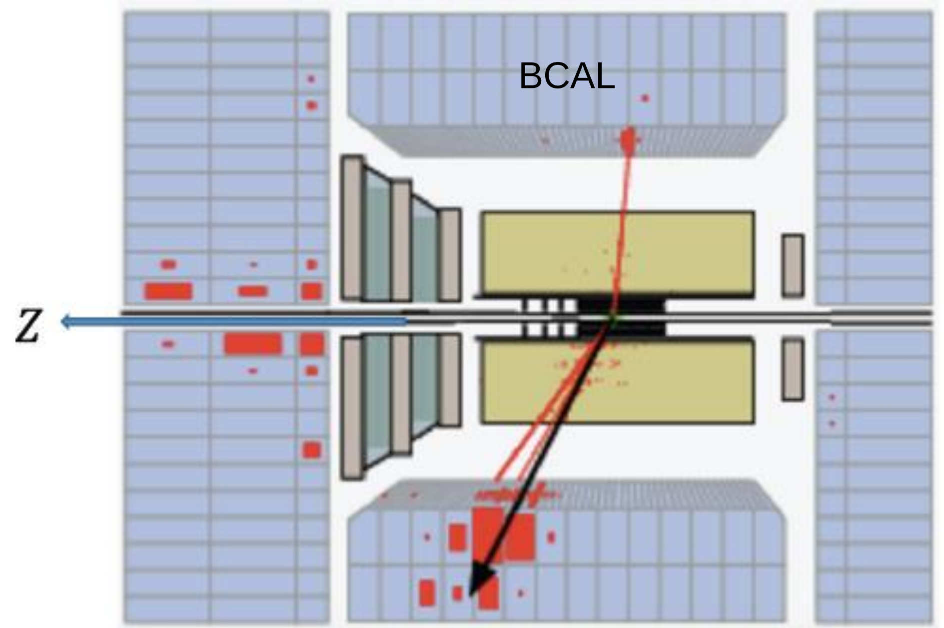
$$-0.7 < \eta^{\gamma} < 0.9 \text{ (in BCAL)}$$

Jet reconstruction: k_T clustering algorithm

$$E_T^{jet} > 2.5 \text{ GeV}$$

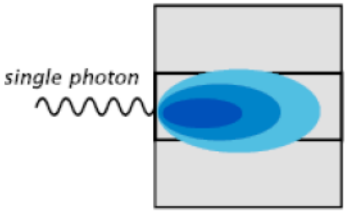
$$-1.5 < \eta^{jet} < 1.8$$

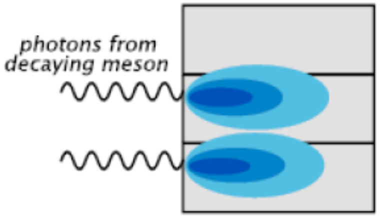
jet with the highest E_T^{jet}



BCAL is finely segmented in the Z direction

use shower-shape distributions to distinguish isolated photons from products of neutral meson decays (π^0, $\eta \rightarrow \gamma\gamma$)





photon isolation from tracks and other hadronic activity

$\Delta R(\eta,\varphi) > 0.2$
(distance to the nearest reconstructed track)

$E^{\gamma}/E^{jet\ with\ \gamma} > 0.9$

Data, Monte Carlo simulations and theory

Data: HERA II 2004-2007

- Analysed integrated luminosity L = 326 pb^{-1}

Monte Carlo event simulations: LO MC programs

signal

- **PYTHIA** : simulation of DIS events with additional radiation from the quark line → **QQ photons**
- **LL photons: HERACLES + generator DJANGOH**: higher QCD effects included using colour-dipole model as implemented in **ARIADNE**

background

- **DJANGOH:photonic decays** of neutral mesons produced in general DIS processes

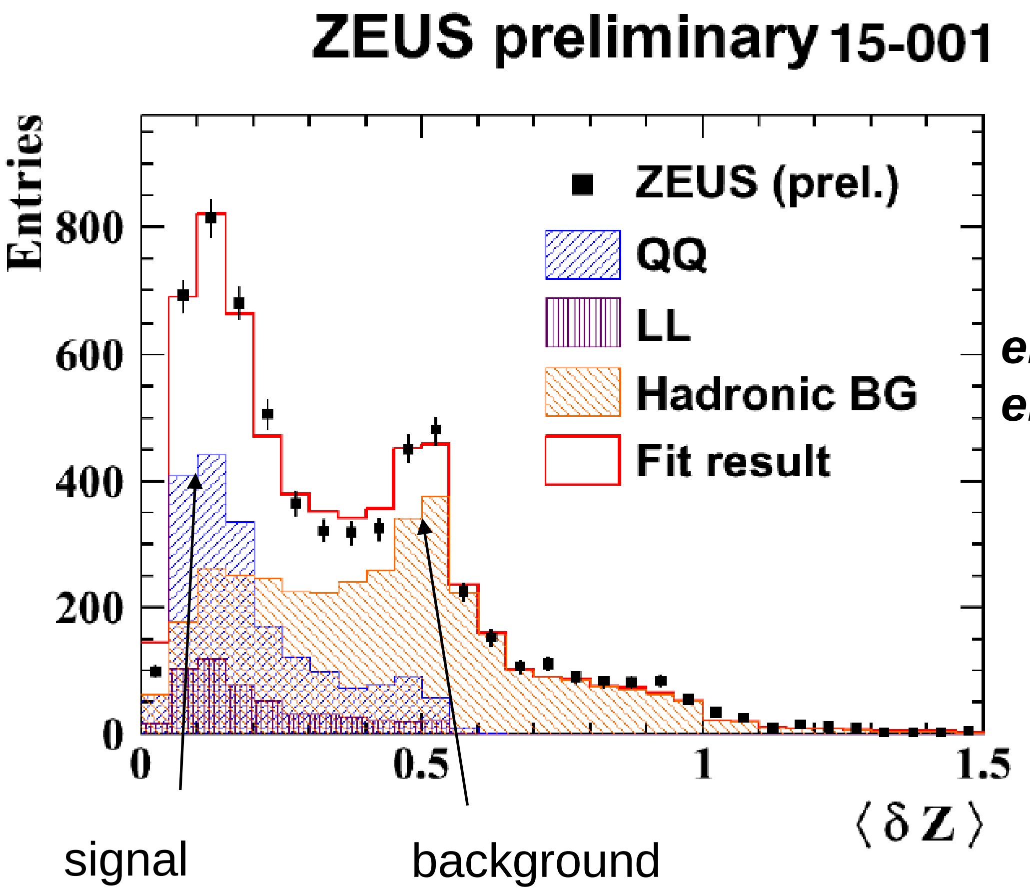
- **Lund string fragmentation** for hadronisation

Theoretical predictions:

- a calculation based on the 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 is based on **MC fit of the δZ distribution**

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

energy weighted mean width of the electromagnetic cluster in Z direction

$Z_{i,}$ (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 **statistically separate prompt photon signal** (left peak) from **background** dominated by photons from π^0 decay (right peak)

Determination of the production cross-section

For a given observable Y the production cross-section is determined using

$$\frac{d\sigma}{dY} = \frac{N(\gamma_{QQ})}{A_{QQ} \cdot \mathcal{L} \cdot \Delta Y} + \frac{d\sigma_{LL}^{MC}}{dY}$$

$N(\gamma_{QQ})$ - the number of QQ photons extracted from the fit

ΔY - the bin width

$\frac{d\sigma_{LL}^{MC}}{dY}$ - the predicted cross section for LL photons from DJANGOH

A_{QQ} - the acceptance correction for QQ photons

$\mathcal{L}$ - the total integrated luminosity

Uncertainties

ΔN – statistical errors on QQ and LL MC samples

ΔA_{cc} – acceptance uncertainty, ~3-4 % (maximum ~22% at high x_p)

Δa – fit parameter uncertainty ~1%

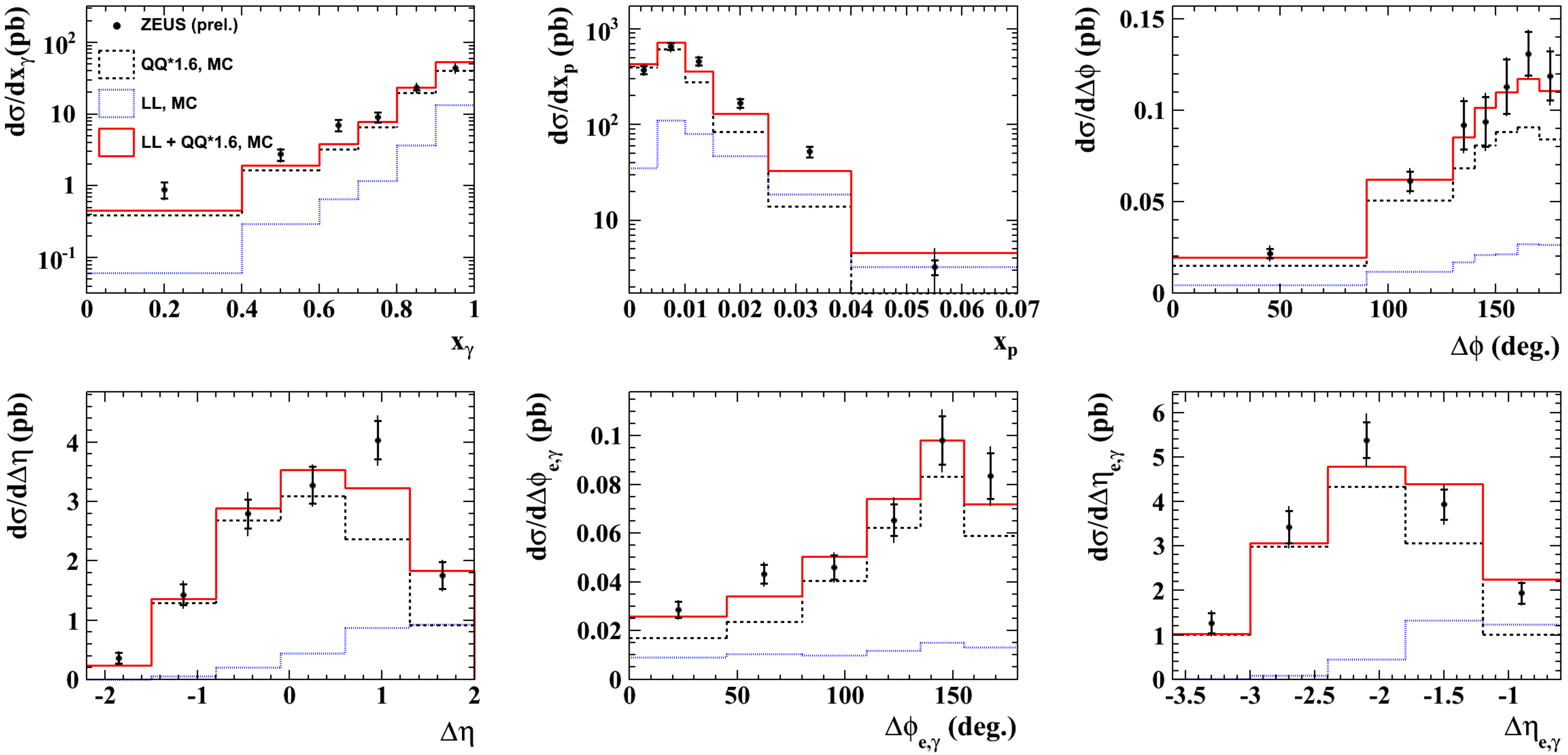
ΔL – the common uncertainty on luminosity measurement not included

- typical mean statistical uncertainty is 13% with maximum 26% in the first bin of x_γ and the last bin of x_p
- typical mean systematic uncertainty is 10% with maximum 50% in last bin of x_p

In figures: the inner error bars show statistical uncertainty
the outer error bars show statistical and systematic uncertainties added in quadrature

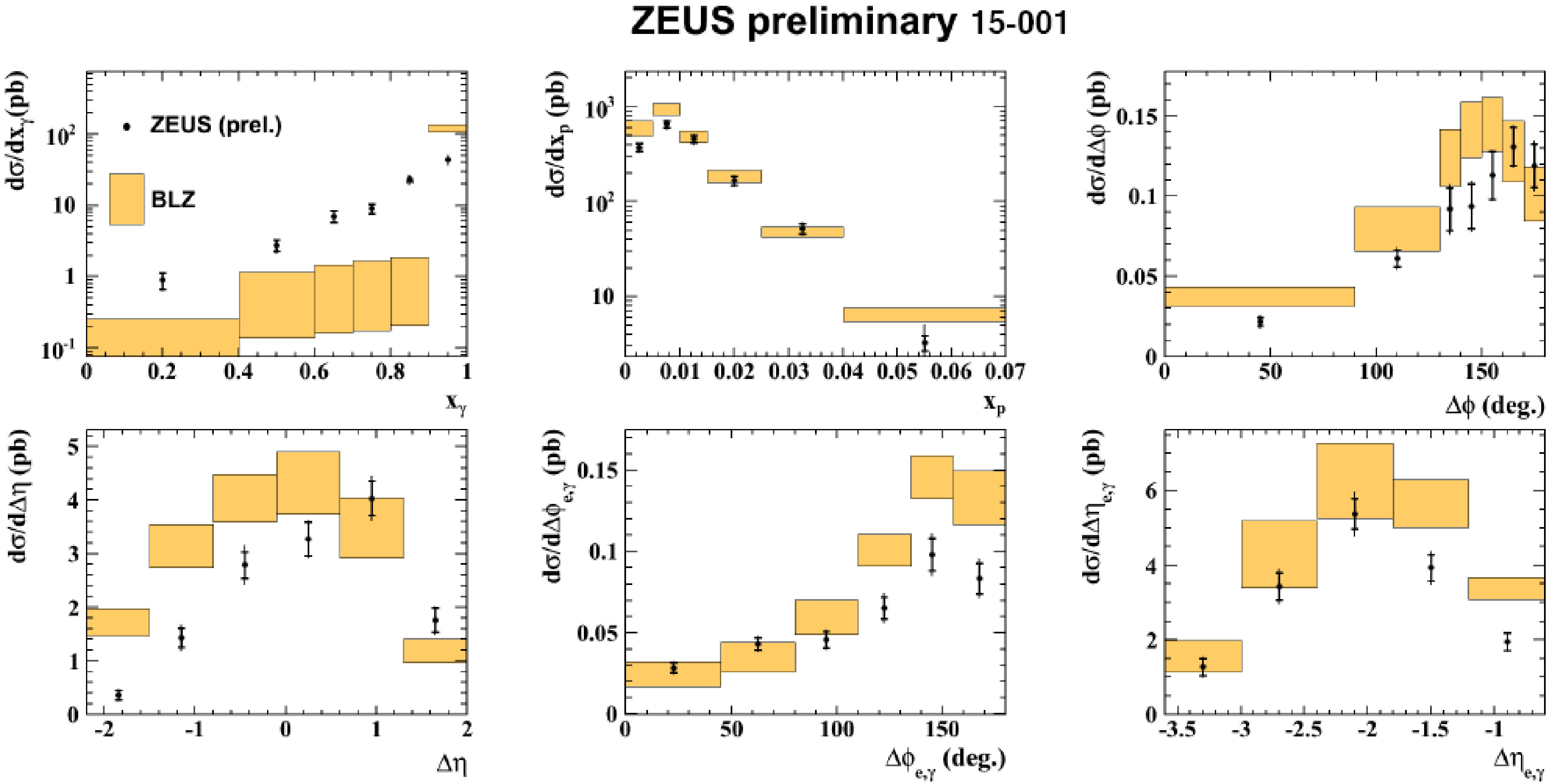
x-sections compared to weighted LO MC

- $x_\gamma = \frac{\sum_{jet,\gamma}(E-p_z)}{2y_{JB}E_e}$
- $x_p = \frac{\sum_{jet,\gamma}(E+p_z)}{2E_p}$
- $\Delta\eta = \eta_{jet} - \eta_\gamma$
- $\Delta\varphi = \varphi_{jet} - \varphi_\gamma$
- $\Delta\varphi_{e,\gamma} = \varphi_e - \varphi_\gamma$
- $\Delta\eta_{e,\gamma} = \eta_e - \eta_\gamma$



shape of distributions are fairly well described by the sum of the expected LL contributions from DJANGOH and a factor of 1.6 times the expected QQ contributions from PYTHIA

x-sections compared to predictions from k_T factorisation method (BLZ)



The calculations describe the shape of the data reasonably with exception of x_γ, $\Delta\eta$ distrib.

Summary of high P_T photon production

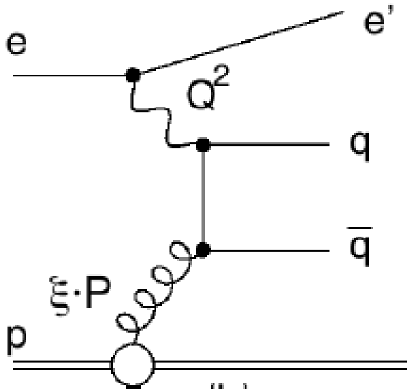
Prompt photons accompanied by jets in ep DIS have been measured

- Differential x-section as functions of (x_γ, x_p, $\Delta\eta$, $\Delta\varphi$, $\Delta\eta_{e\gamma}$, $\Delta\varphi_{e\gamma}$) for a region defined by kinematic cuts are shown

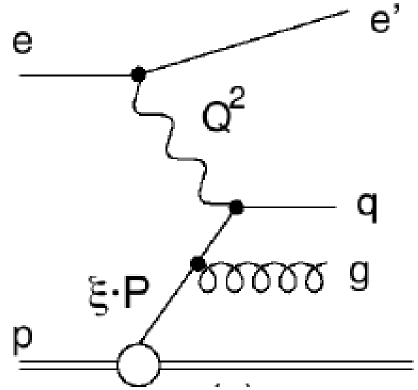
- The predictions for the sum of the expected LL contributions from DJANGOH and the expected QQ contributions from PYTHIA rescaled by factor 1.6 provide a good description of the shapes of the kinematic variables

- The calculations of BLZ based on k_t-factorisation method describe the data with exception of x_γ and $\Delta\eta$ distributions

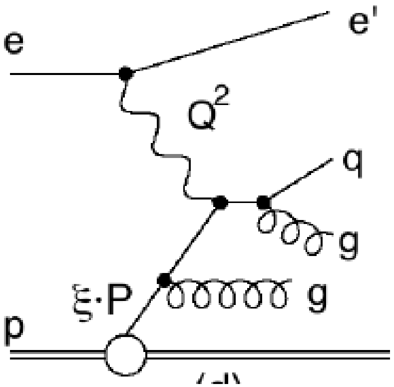
Jet Production in *ep* Scattering at low Q^2



Boson-gluon fusion



QCD Compton



Trijet leading-order

jets are measured in Breit reference frame

(exchanged virtual boson coliides 'head-on' with a parton from proton)

- using the inclusive k_T cluster algorithm

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)

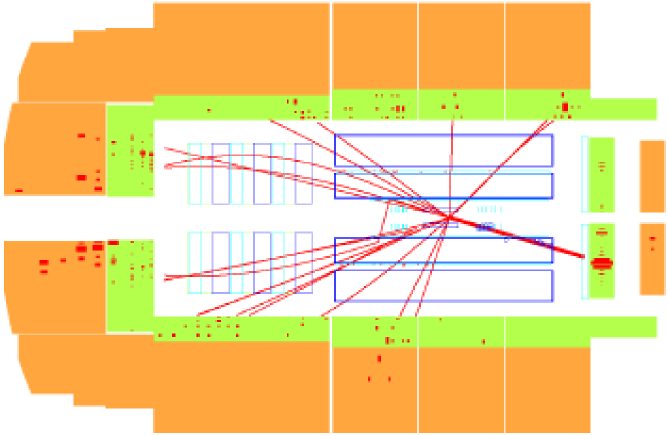
Data and analysis strategy

Data: HERA II period 2006-2007

Analysed integrated luminosity *L*=184 pb-1

Data are corrected for acceptance and efficiency effects and kinematic migrations using **a regularised unfolding procedure.**

Typical event display



Matrix based unfolding method

Describe kinematic migration

Consider an 'extended phase space'

Describe accurately migrations into and out of final 'measurement phase space'

Extended phase space for unfolding	
NC DIS	$Q^2 > 3$ GeV^2
	$y > 0.08$
(inclusive) Jets	$P_T^{jet} > 3$ GeV
	$-1.5 < \eta^{lab} < 2.75$
Dijet and Trijet	
	$\langle P_T^{jet} \rangle > 3$ GeV

Phase space of cross sections	
NC DIS	$5 < Q^2 < 100$ GeV^2
	$0.2 < y < 0.65$
(inclusive) Jets	$P_T^{jet} > 5$ GeV
	$-1.0 < \eta^{lab} < 2.5$
Dijet and Trijet	$M_{jj} > 16$ GeV
	$\langle P_T^{jet} \rangle > 5$ GeV

Monte Carlo simulations and control distributions

simulated NC events needed for unfolding procedure

Monte Carlo generators:

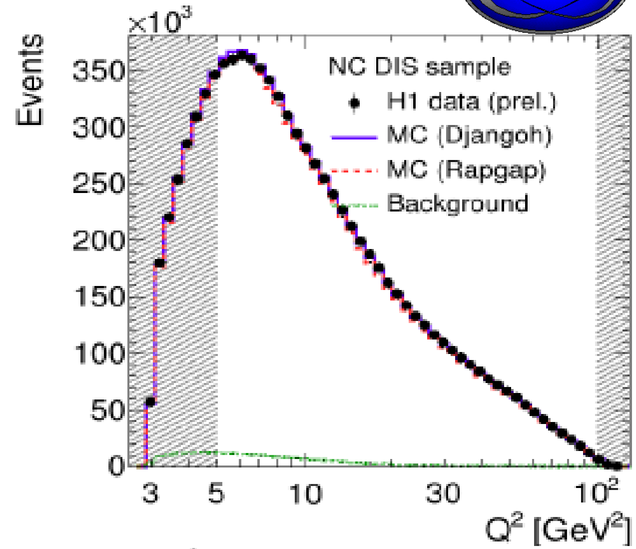
RAPGAP: LO matrix elements +PS

DJANGOH:Color-dipole model as implemented in Ariadne

Lund string fragmentation for hadronisation

NC DIS sample:

- scattered lepton in backward EMC SpaCal
- lepton energy E_e>11 GeV
- selection based on un-prescaled triggers

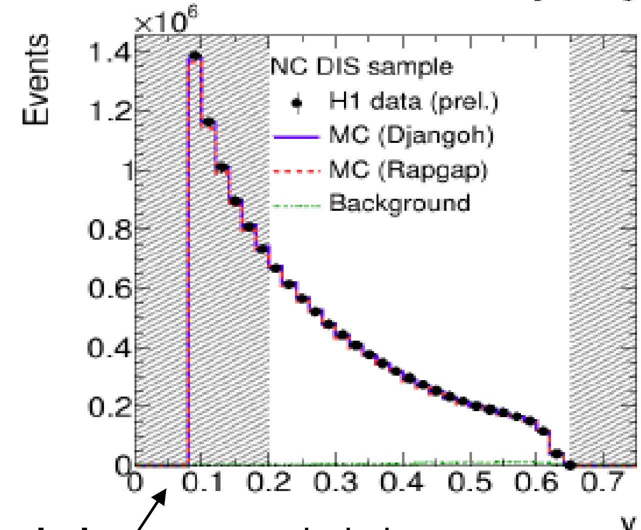


Monte Carlo simulations:

MC doesn't reproduce well the observed spectra and jet multiplicities:

- DJANGO: p_T^{jet} spectra too hard
- RAPGAP: jet multiplicity underestimated
- both generators: too few jets in forward direction

→ **MC generators are weighted** to achieve a better description of the data



shaded area: extended phase space for unfolding procedure

Detector-level distributions for jets

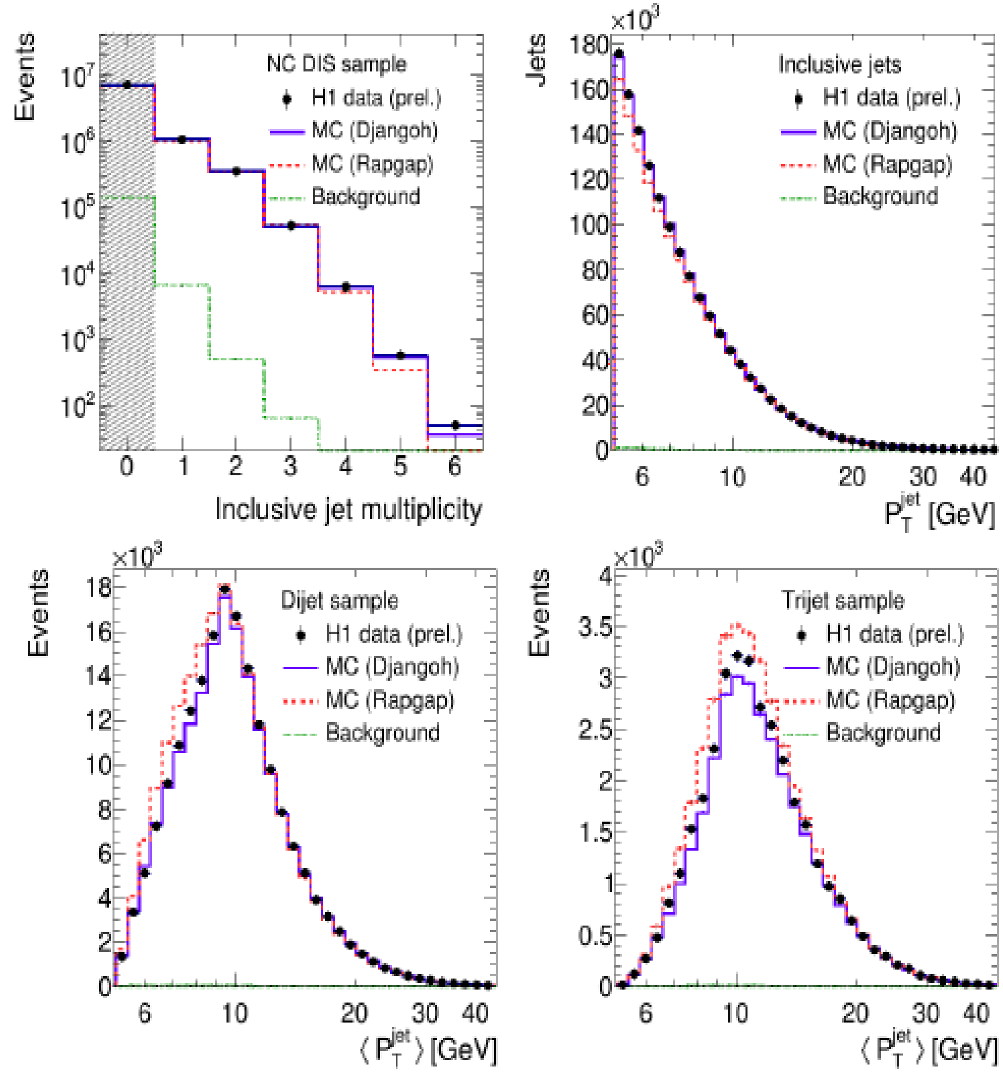
Weighted MC simulations:
detector-level data well described

Background:
- simulated photoproduction events using PYTHIA MC
- normalisation to data using dedicated event sample

-> **background almost negligible** for jet quantities

Dijet and trijet data:
- distributions of $\langle P_T^{jet} \rangle$ on detector level for the measured phase space
- observed a steep rise due to cut on $P_T^{jet} > 5$ GeV

-> **extended phase space important for migration**



Comparison to pQCD predictions in NLO accuracy

NLO calculations

- based on **nlojet++** (Z.Nagy et al.)
- with NNPDF 3.0 (R.D. Ball et al., includes full H1&ZEUS HERAII DIS data)
- Alpha_s = 0.118 (as in PDF)
- renormalisation and factorisation scales:

$$\mu_r^2 = \mu_f^2 = \text{sqrt}\,((P_T^2 + Q^2)/2)$$

Uncertainty estimated from the so-called 'asymmetric 6-point' scale variation:

- the largest deviations taken as uncertainty

k-factor = NLO/LO between 0.9 -3.8

Corrections to NLO predictions:

hadronisation effects are not part of the QCD predictions -> correction factors derived from MC:

- the average of corrections from RAPGAP and DJANGOH
- multiplicative factors, typically 0.88-0.95 for trijet at low <P_T> up to 0.75
- uncertainty defined as difference between (RAPGAP – DJANGOH)/2

Correction applied to data:

Data are corrected for **QED radiative effects**

Regularised unfolding

S.Schmitt,
JINST 7 (2012) T10003
X hadron level
Y detector level
A Migration Matrix
τL^2 Regularisation term

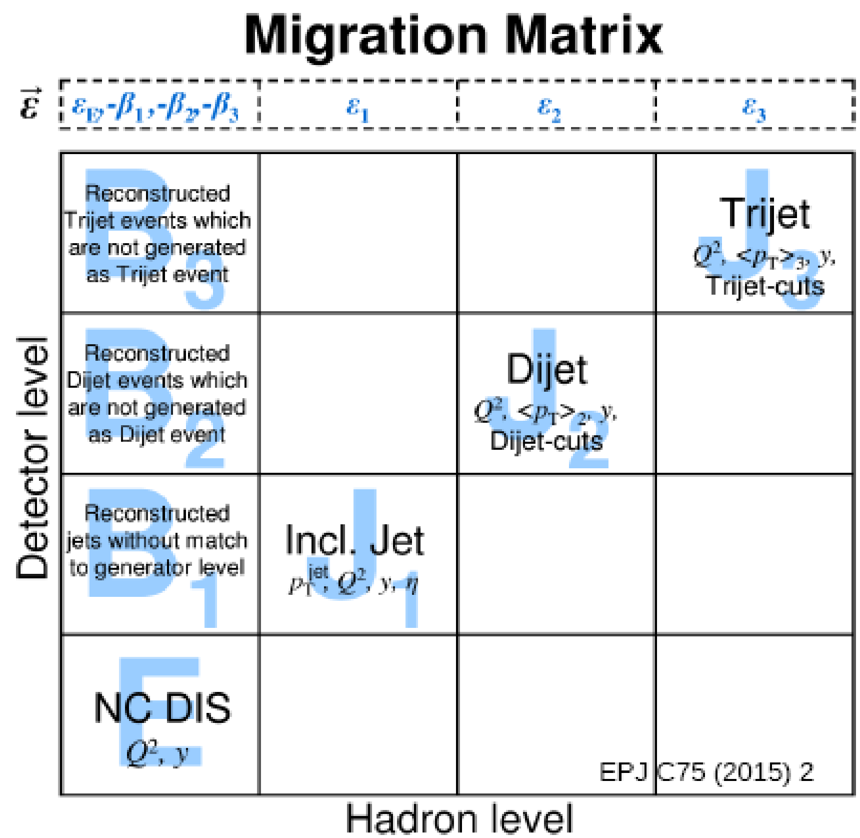
Regularised unfolding using ROOT::TUnfold package

Calculate minimum for unfolded distribution ***x***

$$\chi^2(x,\tau) = (y - Ax)^T V_y^{-1} (y - Ax) + \tau L^2$$

-Linear method including regularisation term
-Linear uncertainties propagation
-Covariance matrix V_y on detector level
 accounts for statistical correlations

Migration matrix consists of measurements of:
NC DIS, Inclusive jet, dijet, trijet
and bins to constrained 'detector level-only' jet contributions with NC DIS data



Simultaneous unfolding -> one measurement of multiple observables
- **similarly as in high Q^2 analysis (V.Andreev et al., EPJ C75 (2015) 2)**
- huge migration matrix ($O(10^6)$ entries)
- up to 6 variables considered for migration
- typically 2-times more bins on det-level than on gen-level -> system of linear equations becomes overconstrained

Double-diff. x- sections for **inclusive jet** production as a function of Q^2 and P_T^{jet}

Inclusive jets:

-count each jet with $P_T^{jet} > 5$ GeV in an NC DIS event

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

Statistical uncertainties and correlations are measured

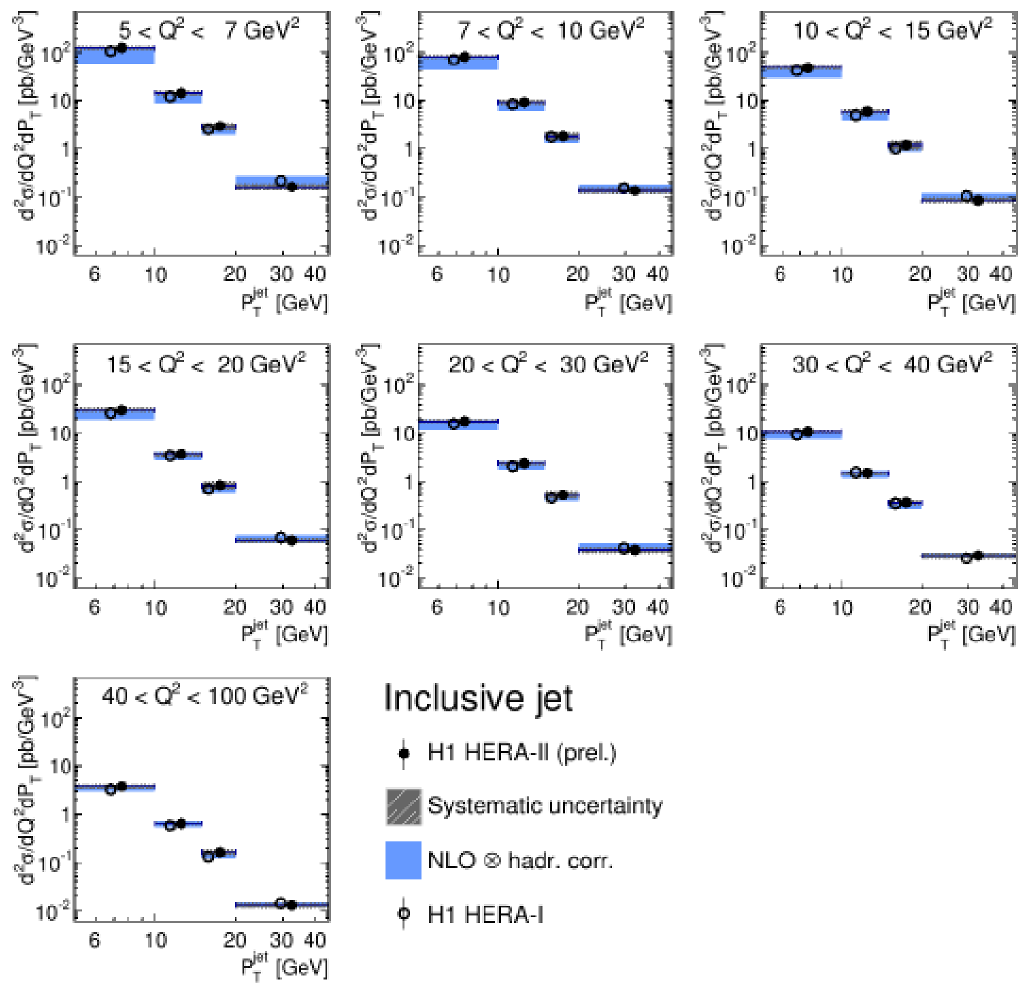
Comparison to NLO predictions:

-data and theory **consistent** within uncertainties for all data points

Comparison to HERA-I data:

- HERA-II data compatible with HERA-I

-statistical uncertainty reduced for high P_T and high Q^2

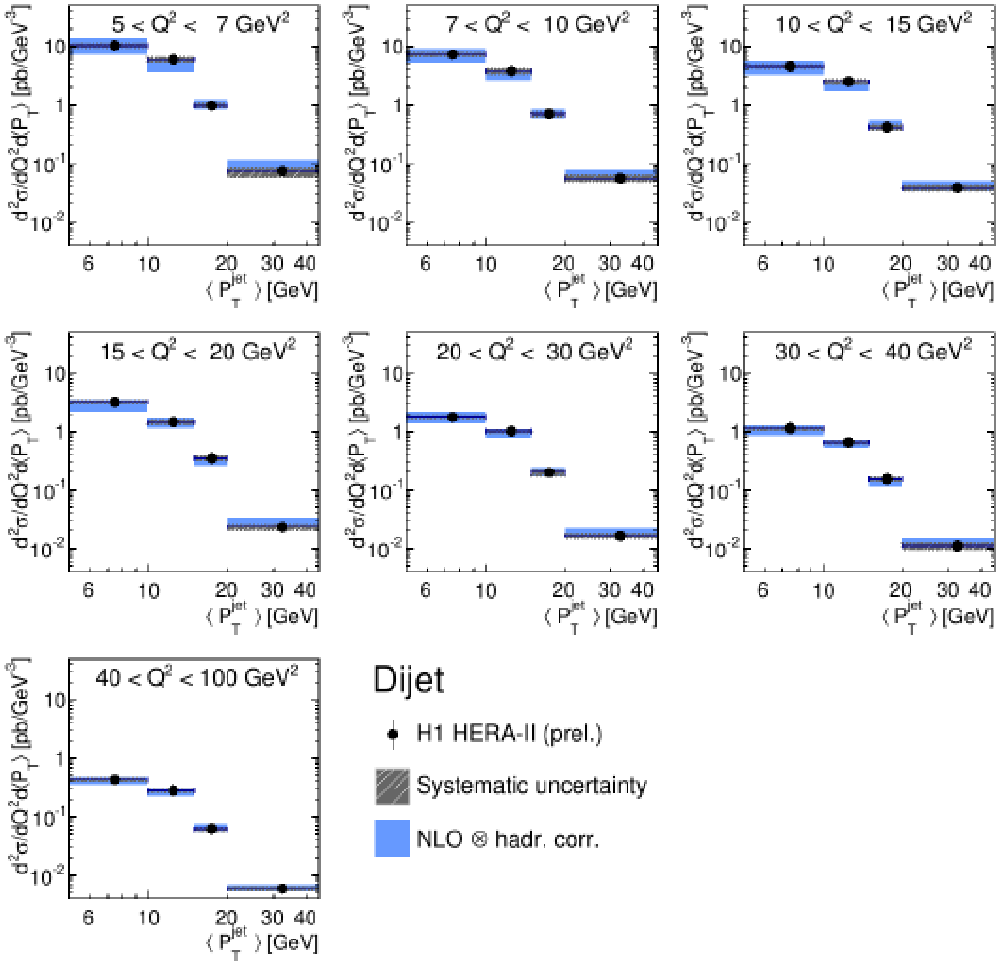


Double-differential x- sections for **dijet** production as a function of Q^2 and P_T^{jet}

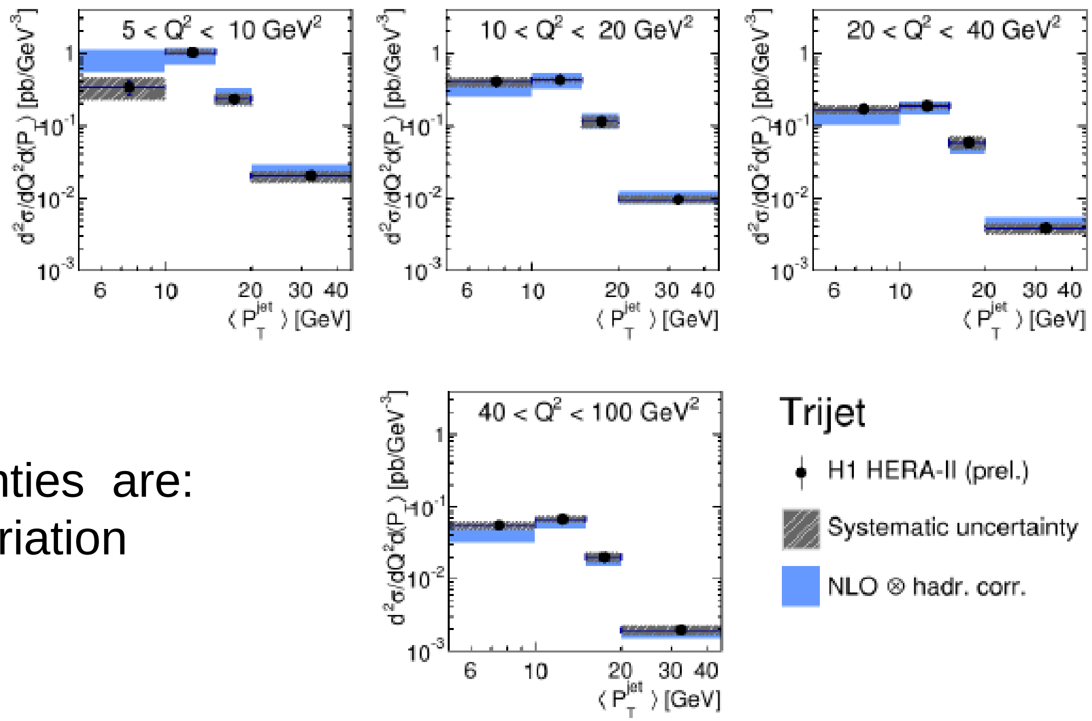
$\langle P_T^{jet} \rangle = \frac{1}{2}(P_T^{jet\,1} + P_T^{jet2})$

Comparison to NLO calculations:
- good description of the data for the measured phase space
- large uncertainty from the variation of renormalisation and factorisation scales
- large k-factors may point to the NNLO contributions

Data are much **more precise than theory** predictions



Double-differential x- sections for **trijet** production as a function of Q^2 and P_T^{jet}



Large systematic uncertainties over full kinematic range **limit** precision of measurement.

The largest systematic uncertainties are:
- jet and cluster energy scale variation
- model uncertainty.

Data precision overshoots theory precision at low Q2

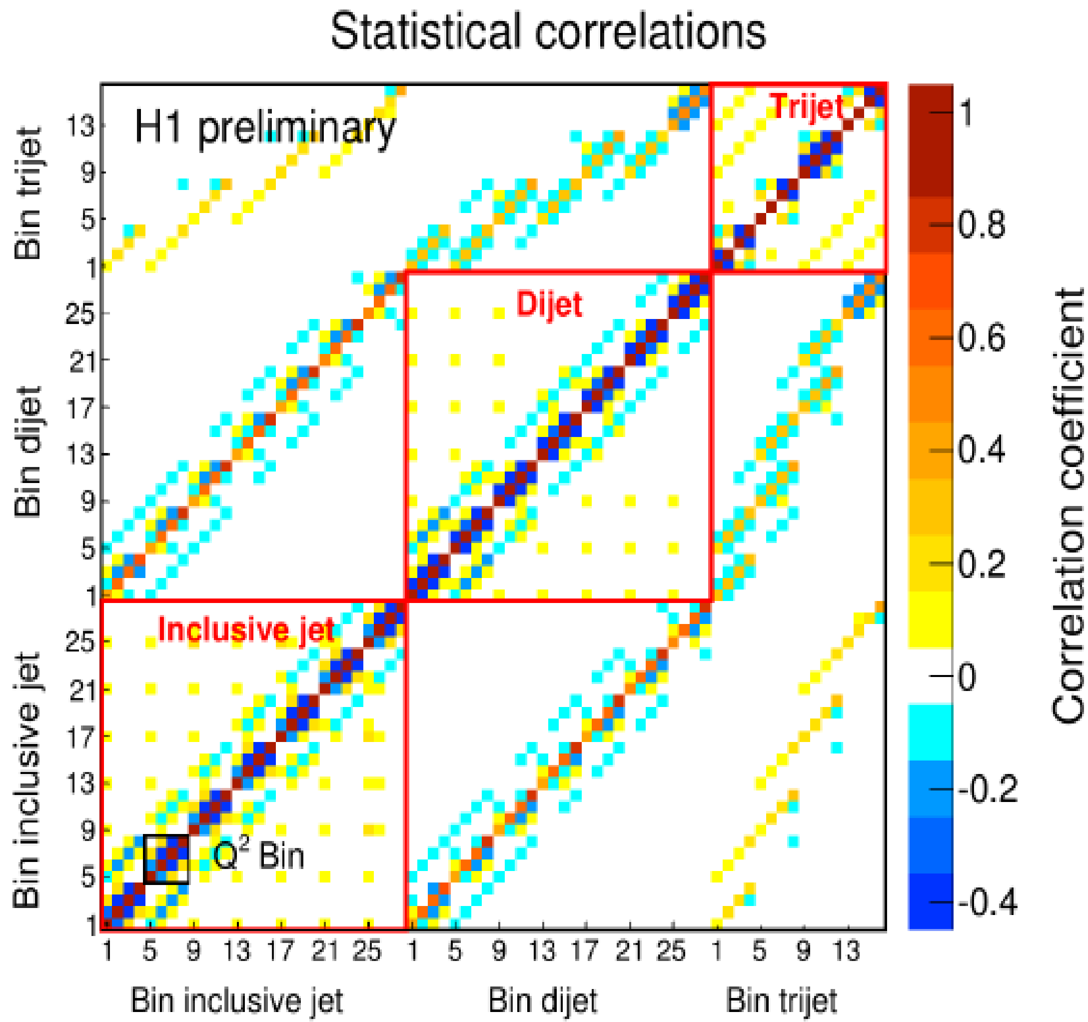
$<P_T^{jet}> = ⅓ (P_T^{jet1} + P_T^{jet2} + P_T^{jet3})$

Statistical correlations

Covariance matrix:
- correlation coefficients of the statistical uncertainty of the three unfolded cross section measurements
- obtained through linear error propagation

Correlations come from:
- unfolding
- statistical correlations between different measurements
- correlations of inclusive jets

Used in :
- calculations of cross-section ratios
- normalised cross-sections
- combined fits



Summary of jet production at low Q^2

New measurements of double differential inclusive jet, dijet and trijet cross sections at low Q^2 are presented with high statistical and experimental precision

- large HERA-II H1 data with final re-processing and precise calibration are used
- sofisticated unfolding allows simultaneous usage of all data in future fits
- NLO predictions describe data within large theoretical uncertainties

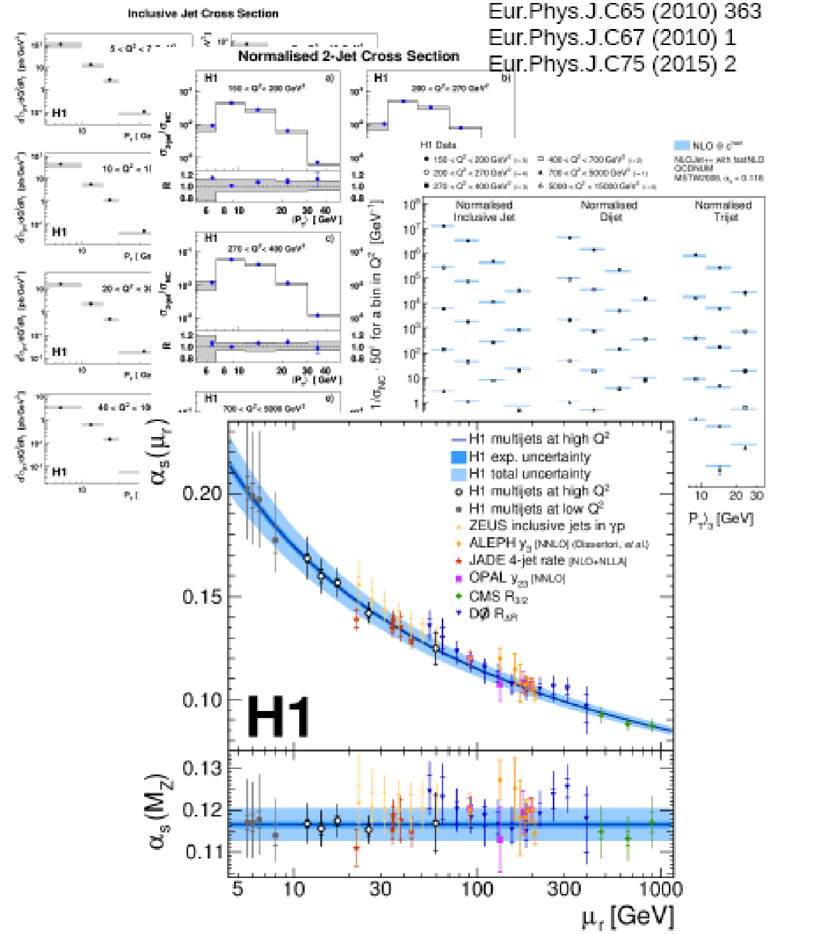
Backup

History and Outlook

Last missing piece of H1 jet legacy

Process		HERA-I	HERA-II
Low Q^2	Inclusive jet Dijet Trijet	EPJ C 67 (2010) 1	This analysis H1prelim 16-061
High Q^2	Inclusive jet Dijet Trijet	EPJ C 65 (2010) 363	EPJ C 75 (2015) 2

Eur.Phys.J.C65 (2010) 363
Eur.Phys.J.C67 (2010) 1
Eur.Phys.J.C75 (2015) 2



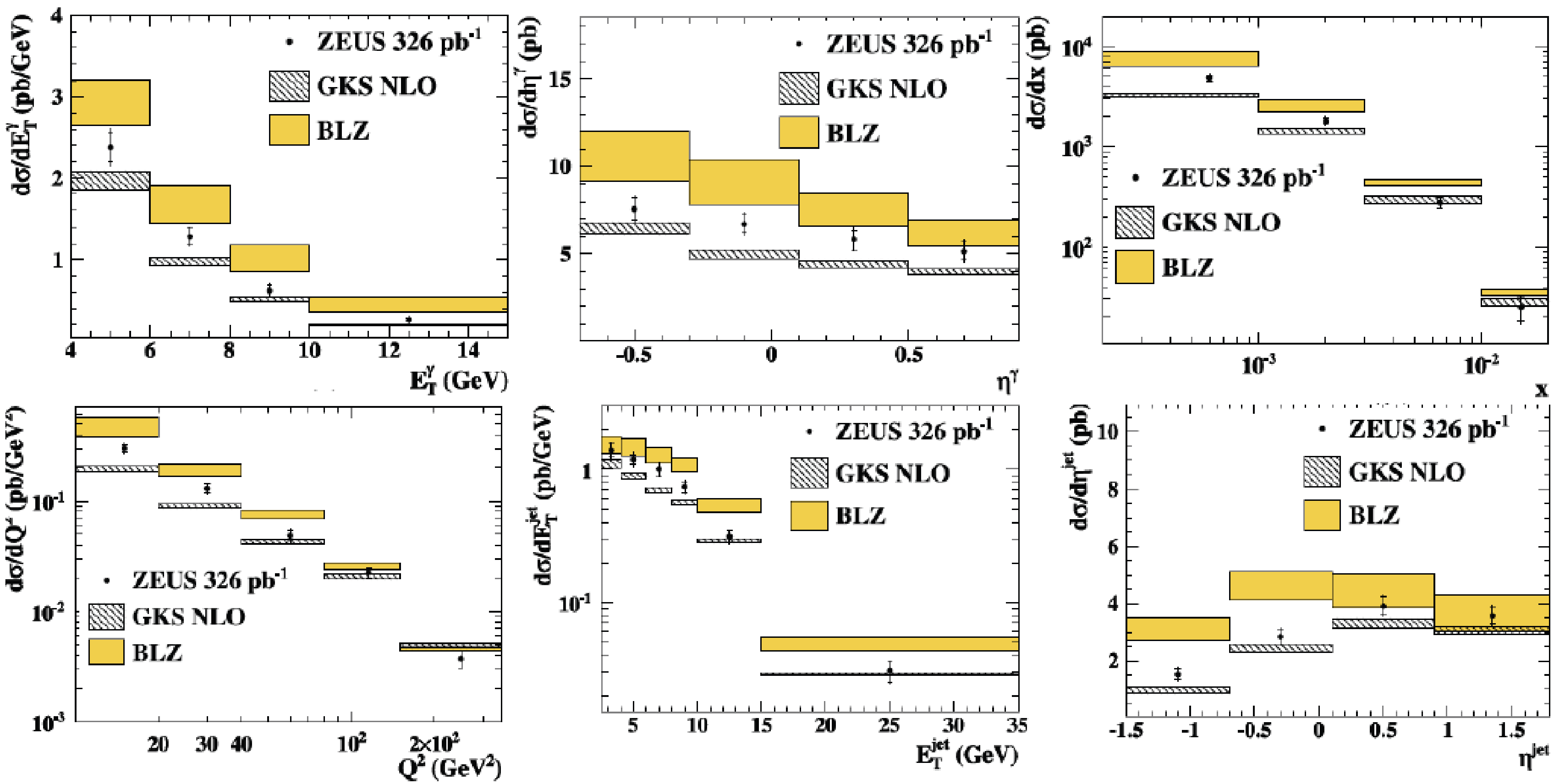
Probe running of α_s over one order of magnitude with all H1 jet data

- Very high experimental precision on $\alpha_s(M_Z)$
  Expect experimental precision of ~5.5%
- Looking forward for theory enhancement
  - aNNLO for low-Q^2 regime
    (Biekötter, Klasen, Kramer, Phys.Rev. D92 (2015) 7, 074037)
  - full NNLO predictions
    (Gehrmann et al., see plenary contribution on monday)

Earlier studies in DIS

H.Abramowicz et al.,
Phys.Lett. B715 (2012)

differential cross-sections as a function of ***x, Q^2, E_T^γ, η^γ, E_T^{jet}, η^{jet}***



shaded areas show the theoretical uncertainties

GKS (A.Gehrmann-De Ridder et al.) and BLZ predictions describe the shape of all the distributions reasonably well

Similar studies in photoproduction

"Further studies of the photoproduction of isolated photons with a jet at HERA", DESY-14-086, arXiv:1405.7127v2[hep-ex]

Photon-jet and photon-electron variables

- $x_\gamma = \frac{\Sigma_{jet,\gamma}(E-p_z)}{2y_{JB}E_e}$
- $x_p = \frac{\Sigma_{jet,\gamma}(E+p_z)}{2E_p}$
- $\Delta\eta = \eta_{jet} - \eta_\gamma$
- $\Delta\varphi = \varphi_{jet} - \varphi_\gamma$
- $\Delta\varphi_{e,\gamma} = \varphi_e - \varphi_\gamma$
- $\Delta\eta_{e,\gamma} = \eta_e - \eta_\gamma$