Multi-Jet Cross Sections in
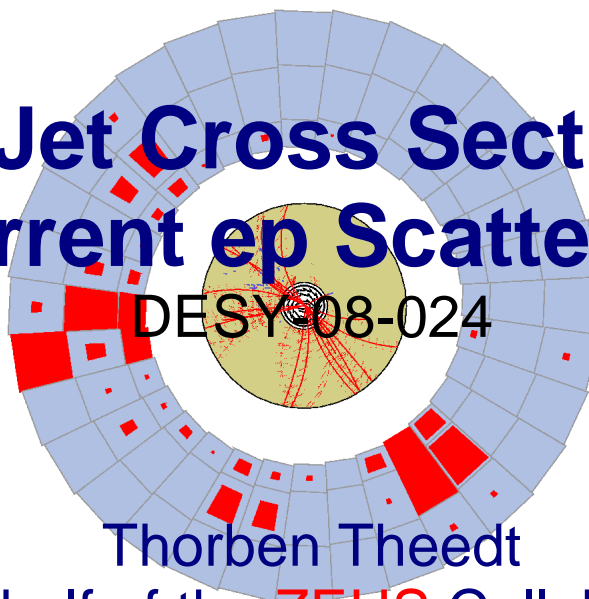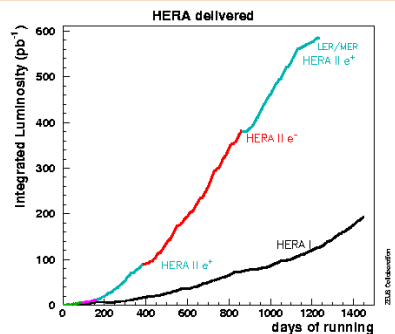# Charged Current ep Scattering at HERA
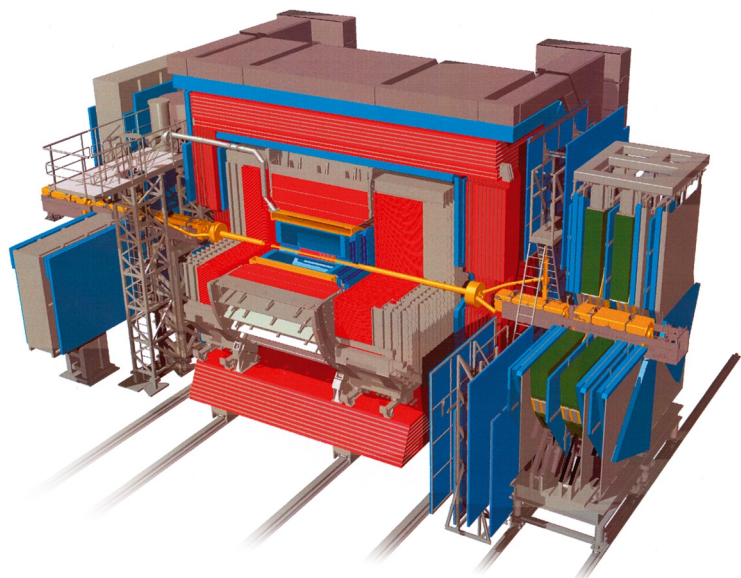
DESY 08-024

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on Behalf of the ZEUS Collaboration

Outline

- **Experimental setup**

- **Physics at HERA**

  - DIS events in HERA

  - Charged current DIS: Why are we interested in multi-jets in CC DIS?

- **Measurement**

  - Data selection and jet reconstruction

  - Systematic uncertainties

- **Fixed order QCD calculation**

  - Determination of theoretical errors

- **Results**

  - Polarized inclusive-jet cross sections

  - Unpolarized inclusive-jet cross sections

  - Dijet cross sections

  - Three-jet cross sections

HERA

- E_e = 27.5 GeV , E_p = 920 GeV
- $\sqrt{s}$ = 318 GeV
- HERA 1 (93-00) L= 143 pb^{-1}
- HERA 2 (02-07) L= 358 pb^{-1}
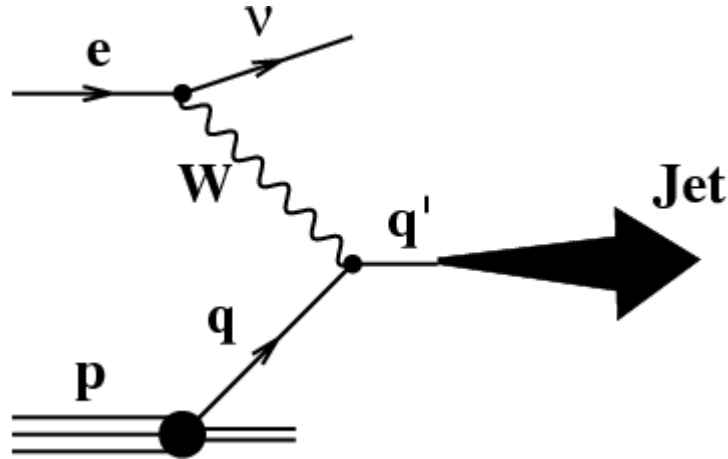 longitudinally-polarized electron beam

ZEUS: Multipurpose detector
Central Tracking Detector
- Drift chamber

- Polar angle $15^o<\Theta<164^o$
Uranium -Calorimeter
- Covers 99.7% of solid angle
- $\dfrac{\sigma(E)}{E} = \dfrac{0.18(0.35)}{\sqrt{E}}$ for electrons (hadrons)

QPM process:

Kinematic variables:

- Q^2 ... virtuality of the exchanged boson
- x_{Bj}...fraction of proton momentum carried by struck quark
- y...inelasticity, energy transfer from electron into hard scattering process

$$Q^2 = x_{Bj}\, y\, s$$

Charged current DIS:

- No electron in the final state
- Signature: large missing p_T and large E_T
- Kinematic variables are calculated from hadronic final state

Jacquet-Blondel method

$$y_{jb} = \frac{\sum_i (E_i - p_{zi})}{2 E_e} \qquad Q^2_{jb} = \frac{\left(\sum_i p_{xi}\right)^2 + \left(\sum_i p_{yi}\right)^2}{1 - y_{jb}} \qquad x_{jb} = \frac{Q^2_{jb}}{s\, y_{jb}}$$

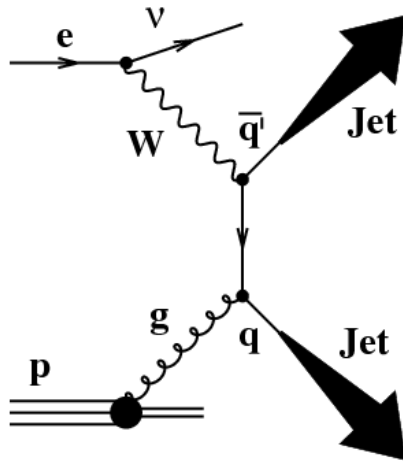**CC DIS cross section in QPM:**

$$\frac{d^2\sigma_{CC}^{e^- p}}{dx\,dQ^2} = \frac{G_F^2}{2\pi}\frac{M_W^4}{(M_W^2+Q^2)^2}\sum_{i=1}^{2}[u_i(x,Q^2)+(1-y)^2\bar{d}_i(x,Q^2)]\times(1-P_{e^-})$$ electron
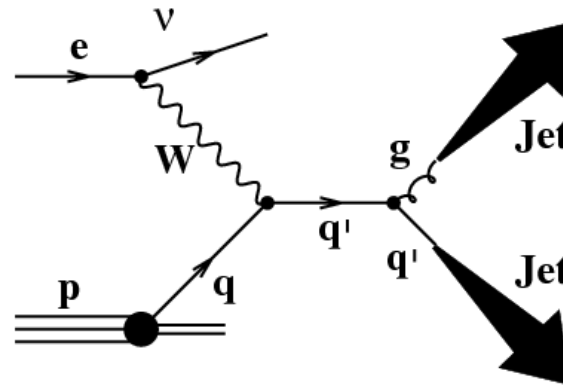
$$\frac{d^2\sigma_{CC}^{e^+ p}}{dx\,dQ^2} = \frac{G_F^2}{2\pi}\frac{M_W^4}{(M_W^2+Q^2)^2}\sum_{i=1}^{2}[\bar{u}_i(x,Q^2)+(1-y)^2 d_i(x,Q^2)]\times(1+P_{e^+})$$ positron

Sensitive to M_W and to u-type and d-type quark (anti-quark) densities, polarization

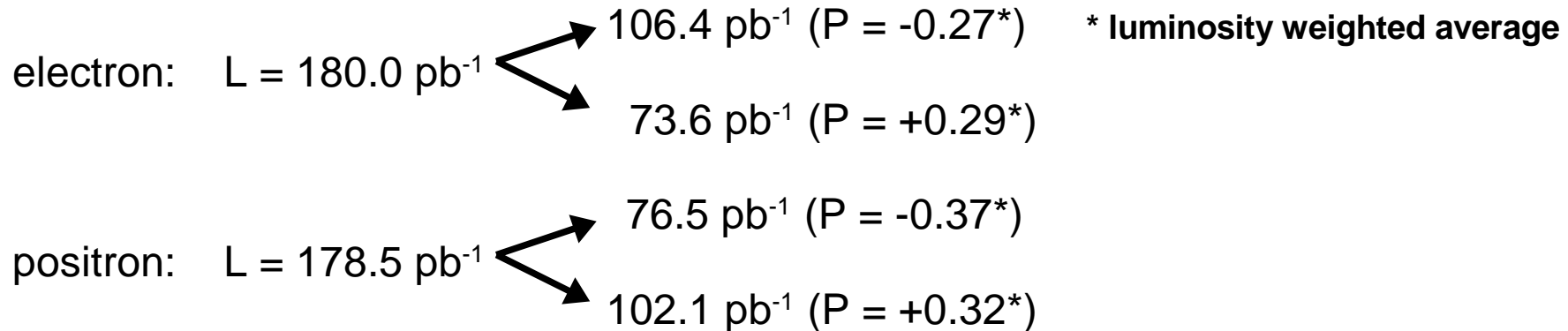**Higher order processes O(α_s):**

Boson(W) -gluon fusion process

QCD -Compton process

Sensitive to α_s
and
gluon density

Data:
ZEUS 2004-2007 L = 358 pb^{-1}
polarized electron and positron data

electron: L = 180.0 pb^{-1}

106.4 pb^{-1} (P = -0.27*)   * **luminosity weighted average**

73.6 pb^{-1} (P = +0.29*)

positron: L = 178.5 pb^{-1}

76.5 pb^{-1} (P = -0.37*)

102.1 pb^{-1} (P = +0.32*)

Phase Space: $Q^2 > 200$ GeV^2 and $y < 0.9$

Jet reconstruction: k$_T$ cluster algorithm in longitudinally invariant mode in LAB frame

incl. jet sample: $-1 < \eta^{jet} < 2.5$ and $E_T^{jet} > 14$ GeV ,   (10611 events)

dijet sample: $-1 < \eta^{jet} < 2.5$ and $E_T^{jet1(jet2)} > 14$ (5) GeV ,   (1581 events)

three-jet sample: $-1 < \eta^{jet} < 2.5$ and $E_T^{jet1(jet2)(jet3)} > 14$ (5)(5) GeV ,   (139 events)

Acceptance correction:
- bin-by-bin method
- ARIADNE MC using CDM for QCD cascade

Systematic uncertainties:

Systematic	Variation	Error (incl, dijet, trijet)
Jet energy scale	$\pm 1\%$ $E_T < 75$ GeV	0.5%, 2%, 4%
	$\pm 2\%$ $E_T > 75$ GeV	
Energy scale CAL	$\pm 1\%$ $p_{T,miss} < 75$ GeV	0.2%, 0.3%, 0.4%
	$+3(-1)\%$ $p_{T,miss} > 75$ GeV	
Parton shower model	CDM / MEPS	0.7%, 7%, 6%
Cut on missing pT	± 1 GeV	0.2%, 0.1%, < 0.1%
Cut on Z_{VTX}	± 11 cm	2%, 2%, 2%
Trigger	additional jet $E_T > 8$ GeV	Negligible

- Experimental uncertainties dominated by statistical uncertainty (1.5% ,4%, 15%)
- Exception: incl. jet cross sections at high E_T and high Q^2
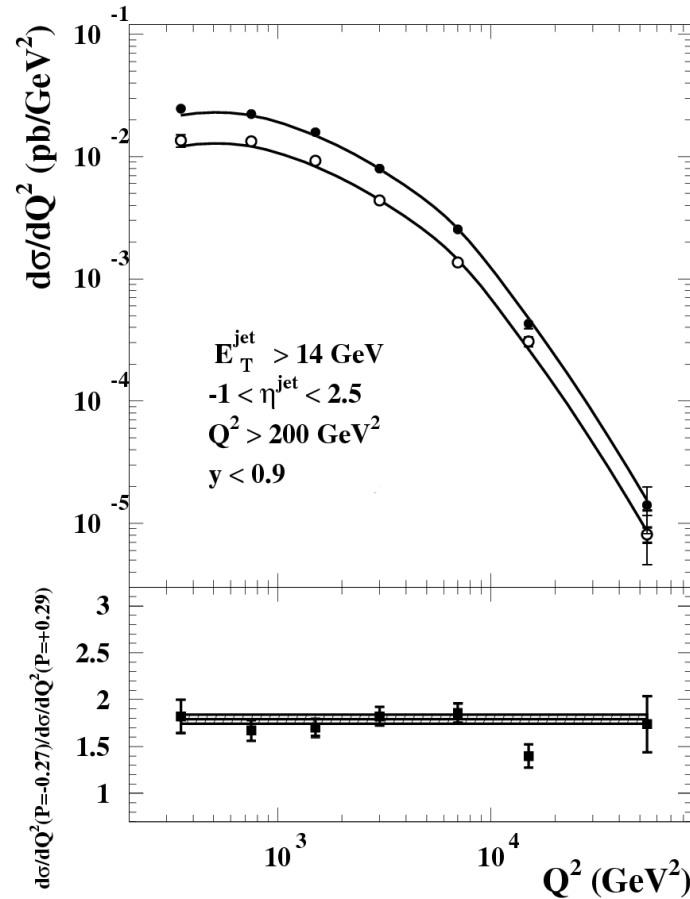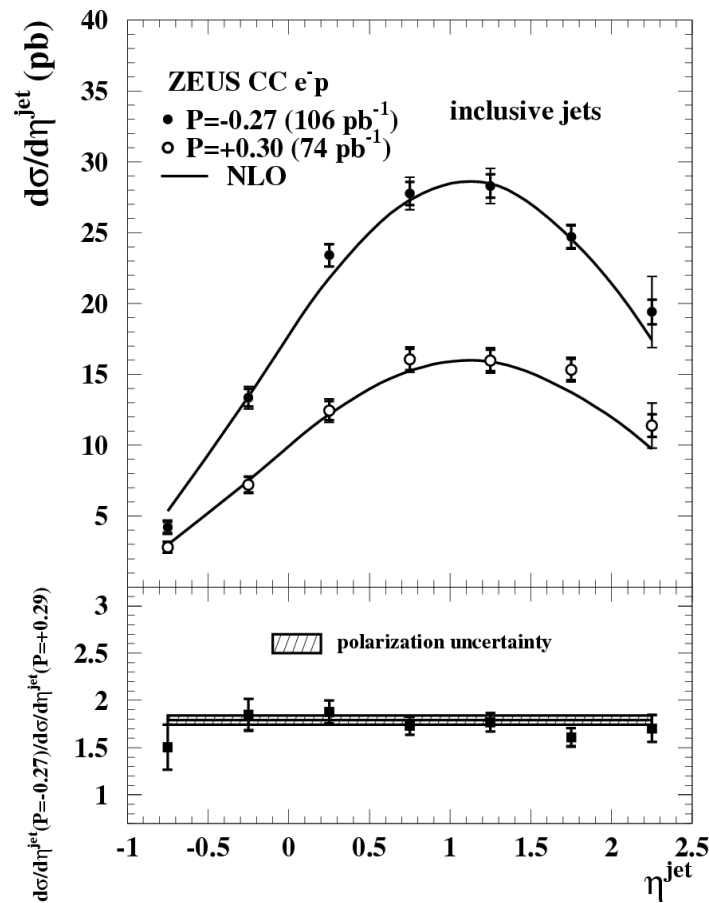 where uncertainty from modeling of QCD cascades is large

Fixed-order QCD calculation

- MEPJET: employs phase-space slicing method, calculations in $\overline{MS}$ scheme
- $O(\alpha_s^2)$: NLO for incl. jet and dijets, LO for three-jets
- Number of flavours: 5
- $\mu_R = \mu_f = Q$, $M_W = 80.40$ GeV, $M_Z = 91.188$ GeV, $\alpha_s(MZ) = 0.118$ (two loop accuracy)
- PDFs: ZEUS-S parametrisation (CTEQ6 / MRST2001)
- Calculated cross sections corrected for hadronisation with bin-by-bin method

Theoretical uncertainties:

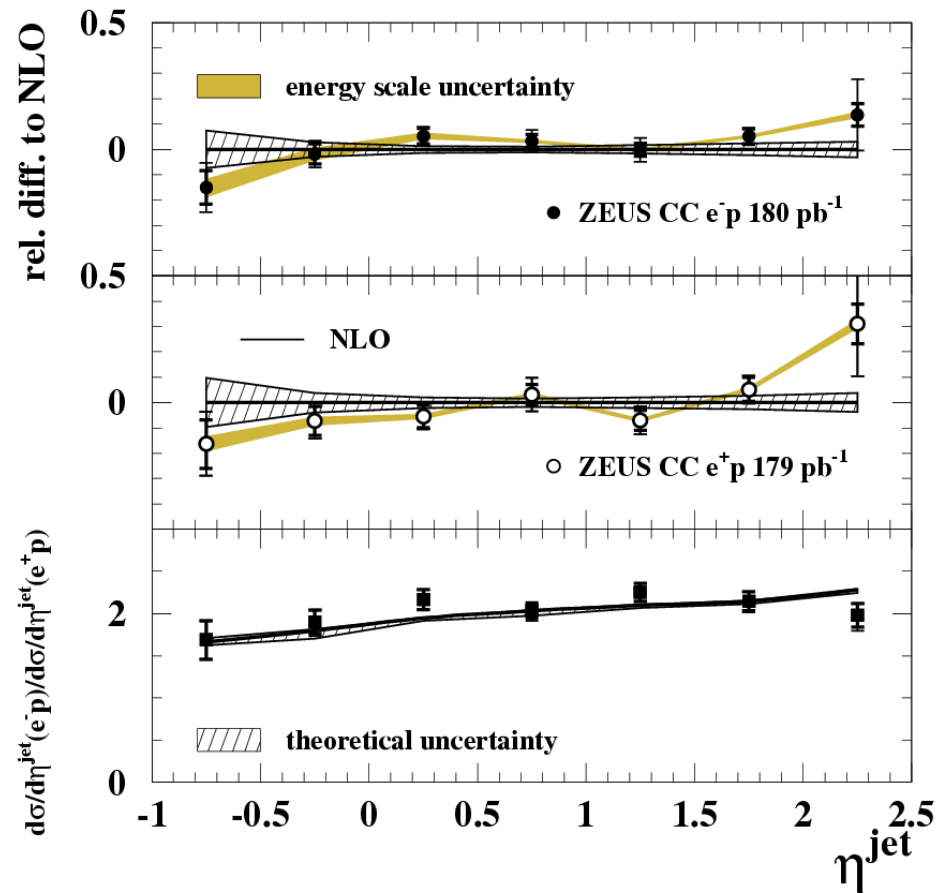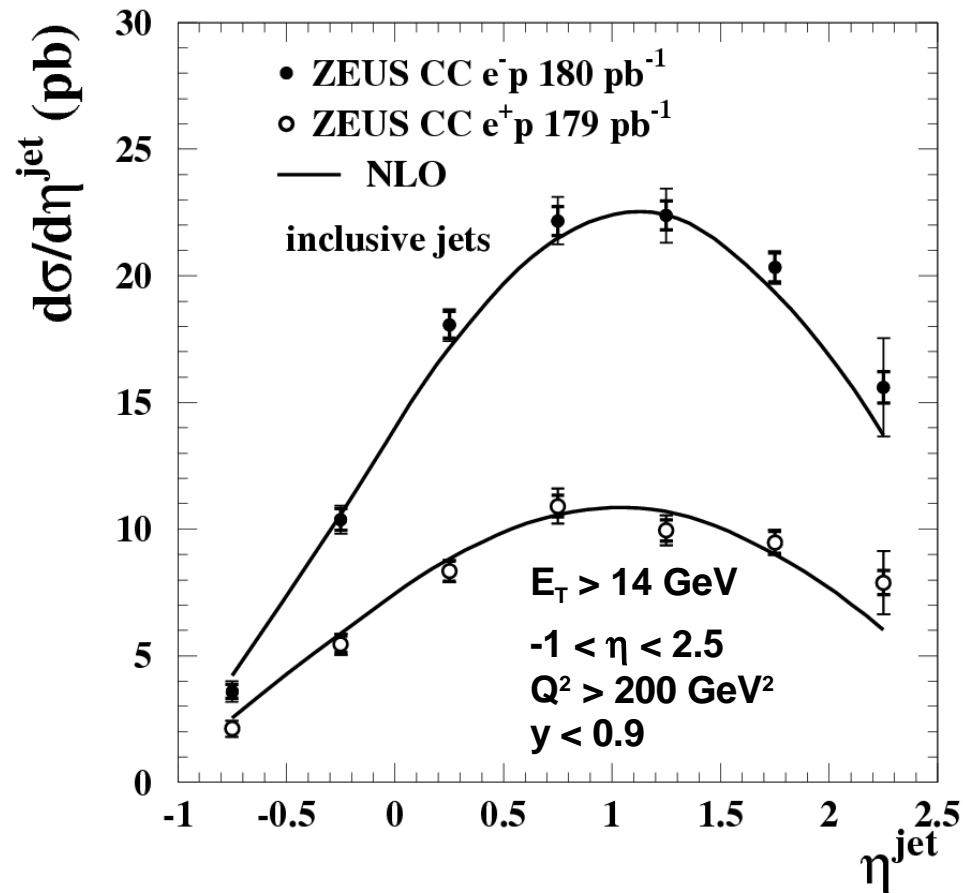| Systematic	Variation	Error (incl, dijet, trijet)
Higher orders	$\mu_R = Q/2$, $\mu_R = 2Q$	< 2%, <5%, 30%
Uncertainty on PDFs	22 additional sets from ZEUS-S	< 4%, <5%, - - - (10%, 15% , - - -)*
Uncertainty on α_s	Two additional sets of PDFs	< 1% ,<1%, - - -
QCD cascade	CDM / MEPS	< 1% ,<1%, - - -
Factorisation scale	$\mu_F = Q/2$, $\mu_F = 2Q$	Negligible

* in high-Q^2, high-E_T and high-x region

- For inclusive-jet and dijet cross sections dominated by uncertainty on PDFs

The figures show ZEUS CC e^-p inclusive jets data:
- $P = -0.27$ (106 pb^{-1})
- $P = +0.30$ (74 pb^{-1})
- — NLO

Kinematic conditions:
$E_T^{jet} > 14$ GeV
$-1 < \eta^{jet} < 2.5$
$Q^2 > 200$ GeV^2
$y < 0.9$

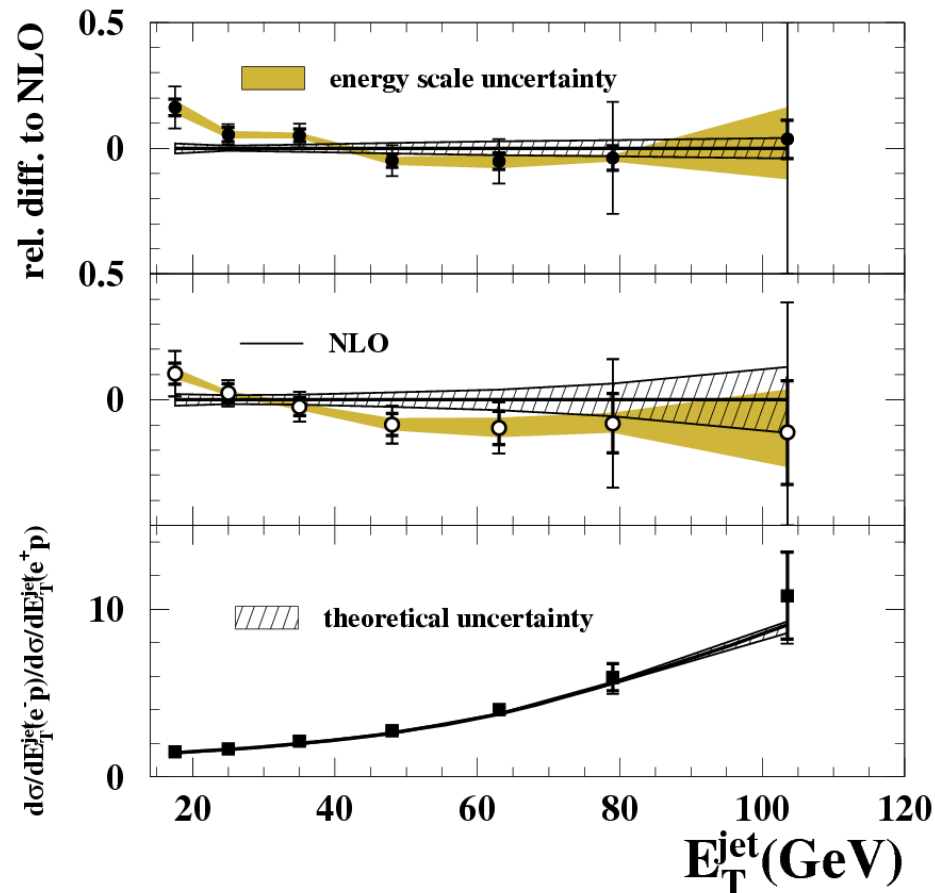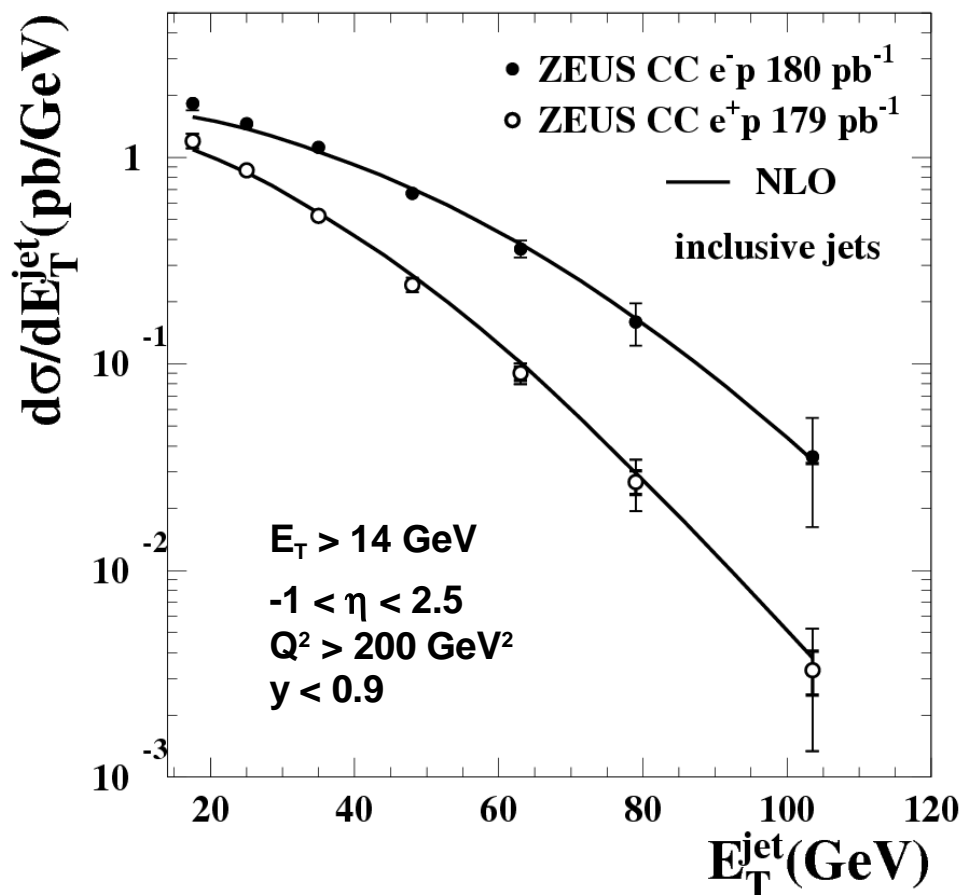$$\frac{(1-P_{e^-}^{neg})}{(1-P_{e^-}^{pos})} = \frac{(1+0.27)}{(1-0.3)} = 1.79$$

- Good agreement between data and NLO calculation (3 orders of magnitude for Q^2)
- Ratio between negatively and positively polarized cross sections in good agreement with measured polarizations

- Reasonable description by the NLO calculation
- Ratio between electron and positron data is ~2 over whole eta range, well described by NLO calculation
- Electron (positron) data probing u-type (d-type) quark density

- Values of E_T^{jet} of more than 100 GeV accessible with present statistic
- Fall-off of two (three) orders of magnitude in electron (positron) sample
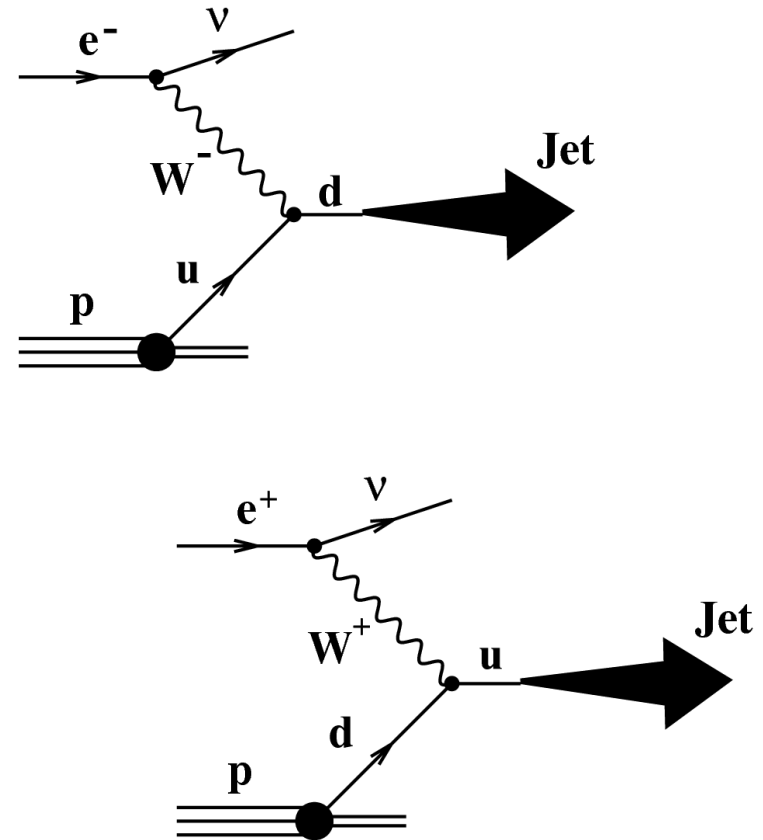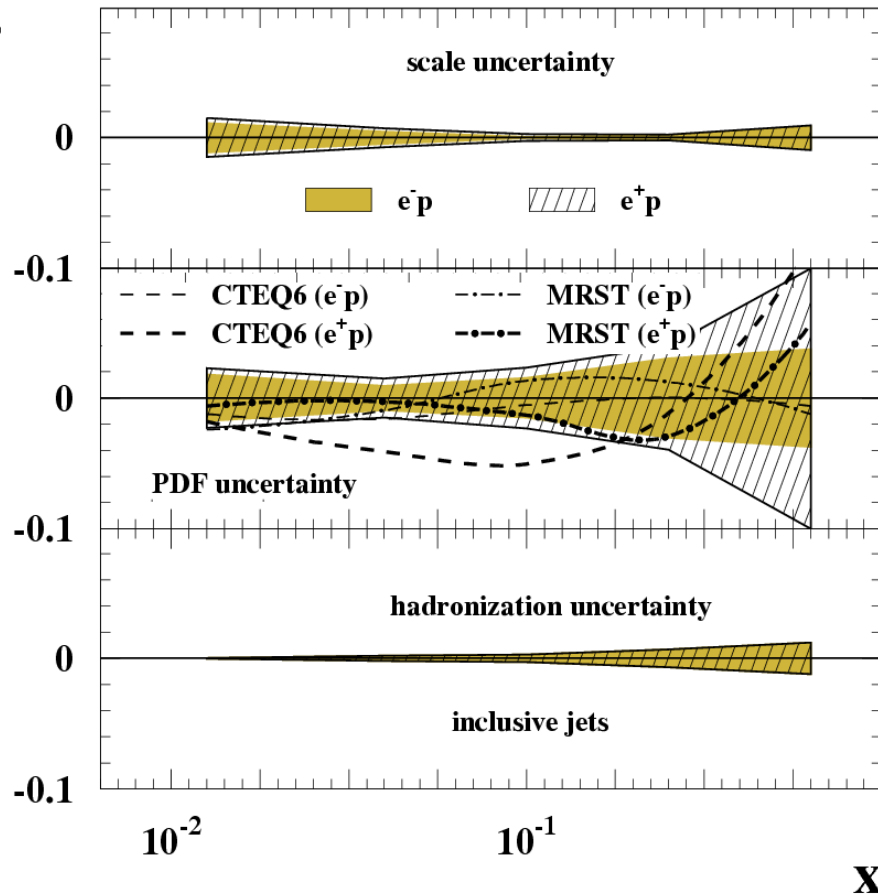- Reasonable description of shape and normalization

- The values in *x* accessible by the data are within the range 0.013 < *x* < 0.63
- Reasonable description by NLO calculation
- At high *x* large theoretical uncertainty especially for positron data
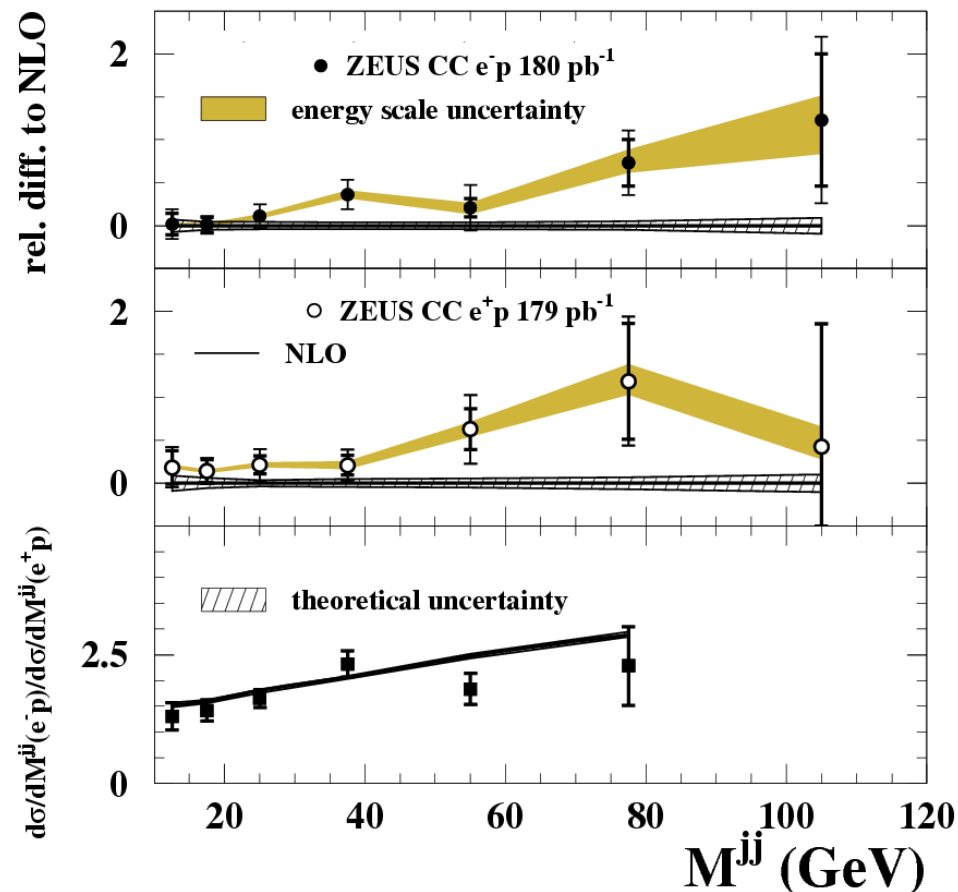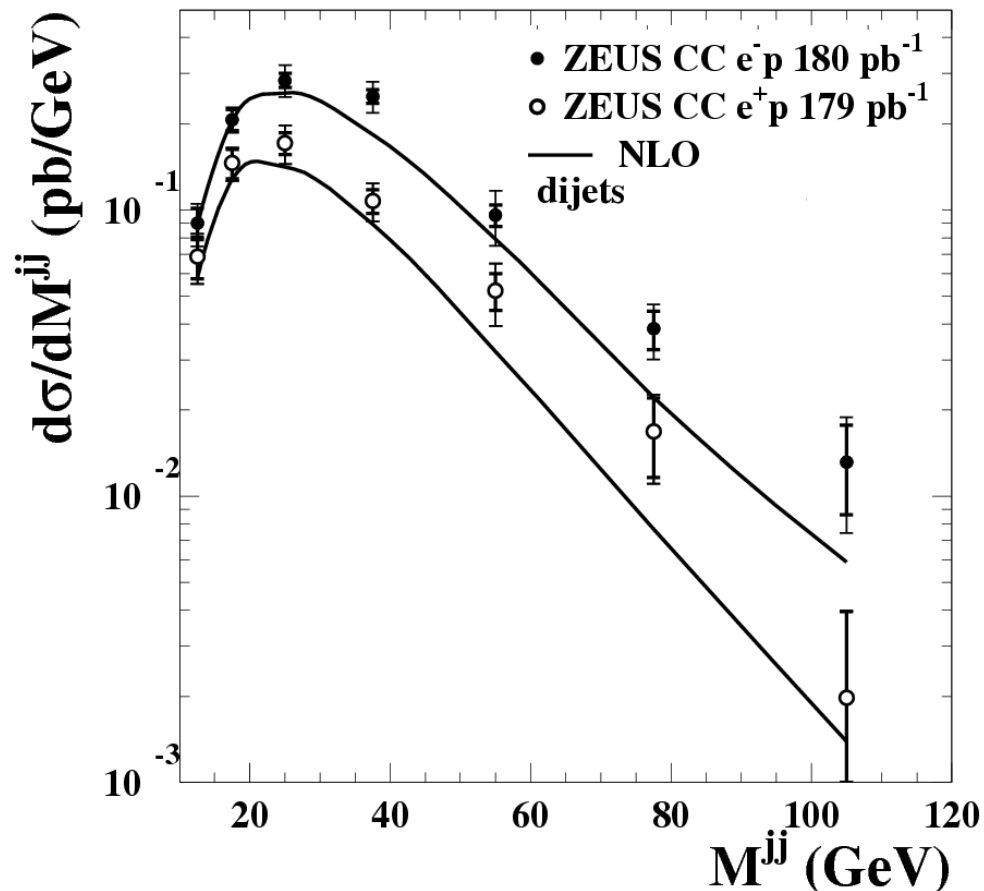
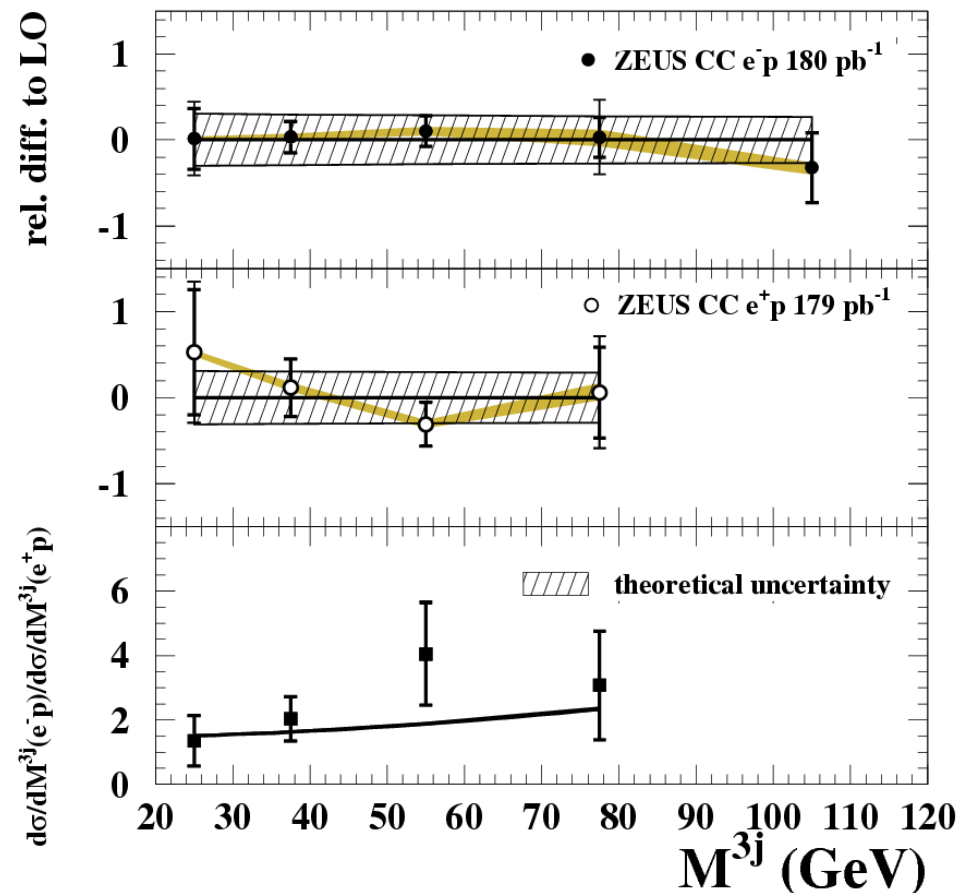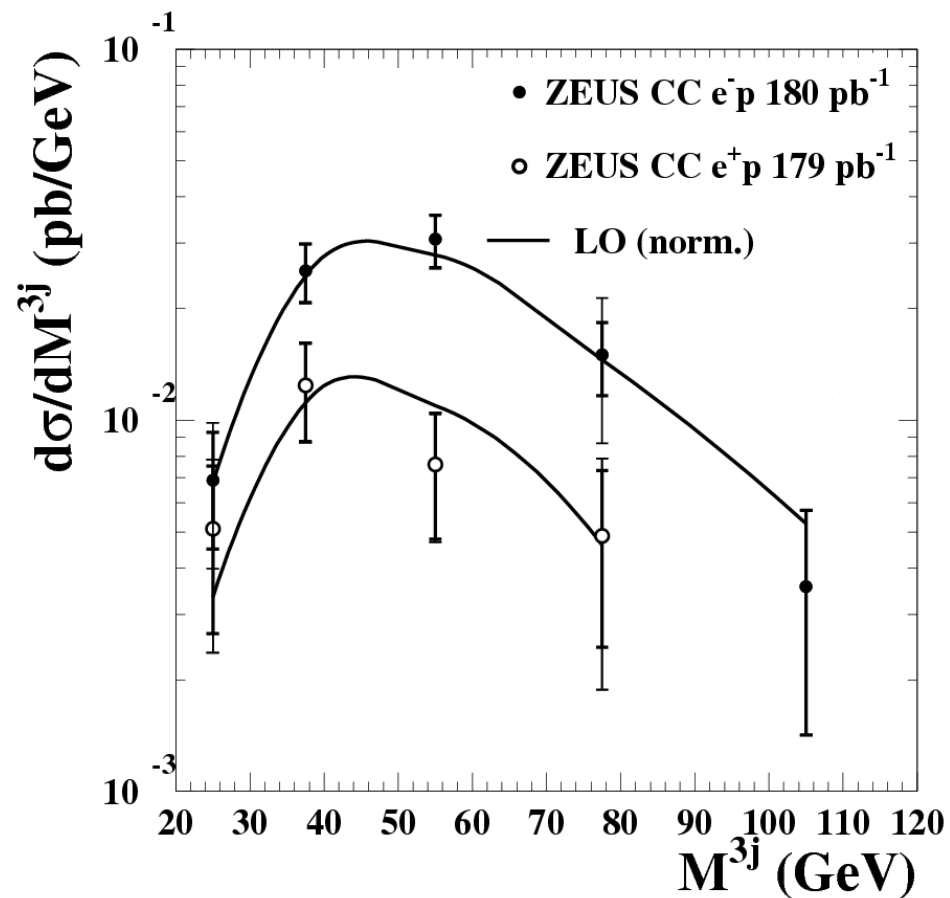- Theoretical uncertainties dominated by uncertainty on proton PDFs
- Largest uncertainty for positron data at high x: large uncertainty on d-quark density
- Other theoretical uncertainties are small and well under control
- Cross sections have the potential to constrain flavour content of the proton at high *x*

- Reasonable description of ratio between *e⁻p* and *e⁺p* cross sections by the NLO but:
- NLO does not give an adequate description in shape and normalization
- Jet cross sections in NC DIS calculated with MEPJET differ by 5-8% from results of other NLO programs but for CC no alternative to MEPJET
- New implementations of theory needed to use CC dijet cross sections in PDF fits

- First measurement of three-jet events in CC DIS ep collisions
- QCD calculations are LO and can not predict the normalization
- QCD predictions are scaled to reproduce the integrated three-jet cross sections
- Scaled LO calculations give a good description of the shape

Summary

Polarized and unpolarized multi-jet cross sections have been measured in charged current $e^{\pm}$ p DIS using 0.36 fb^{-1} of HERA II data

Polarized incl.-jet cross sections have been measured differentially in η^{jet}, E_t^{jet}, Q^2, and x

- Cross sections are in good agreement with SM predictions
- Ratios of differential cross sections for neg. and pos. longitudinally- polarized lepton beams are well described by the predictions

Inclusive-jet cross sections have been measured differentially in η^{jet}, E_T^{jet}, Q^2 and x
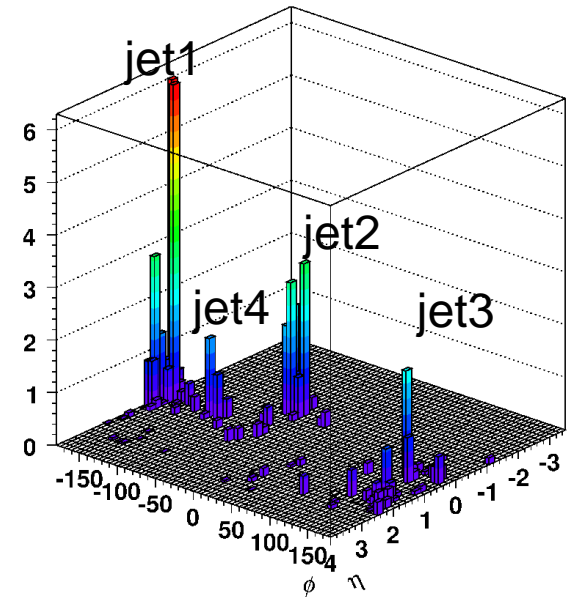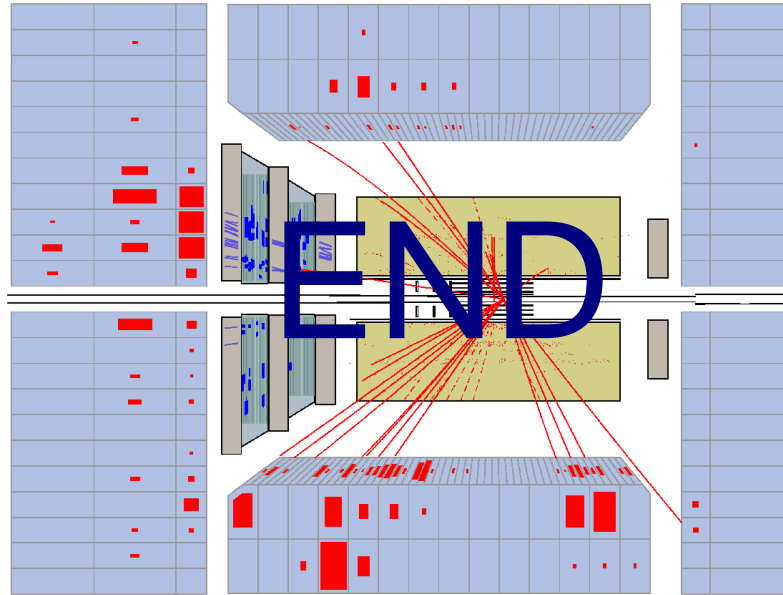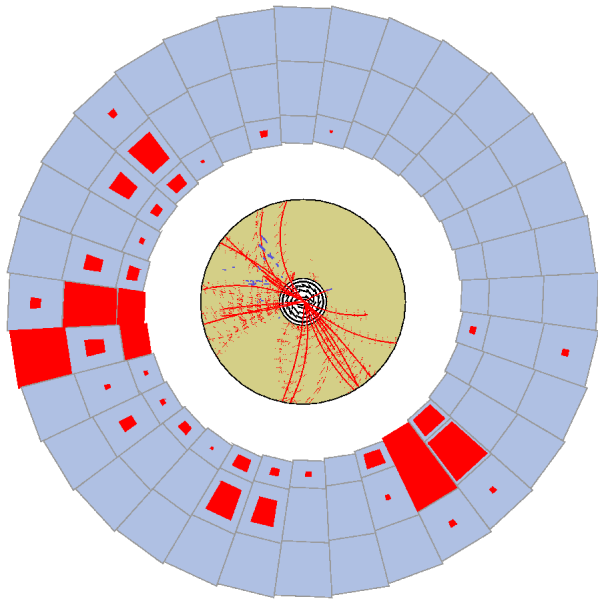
- NLO QCD predictions give a good description of the measured cross sections
- Ratio of cross sections for e$^-$p and e$^+$p collision is well described
- Theoretical uncertainties are dominated by contribution from PDFs
- Cross sections have the potential to constrain flavor content of the proton at high x
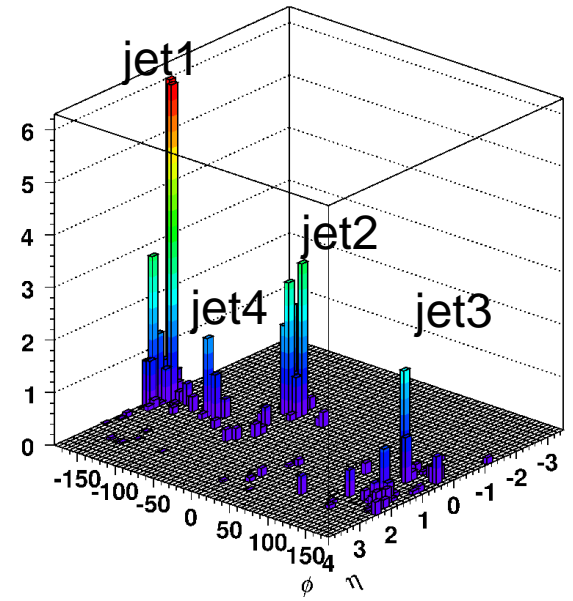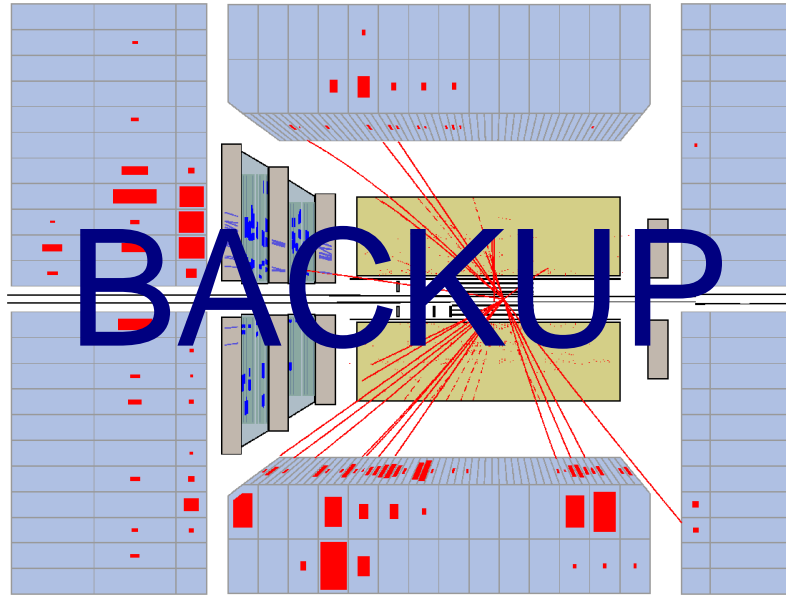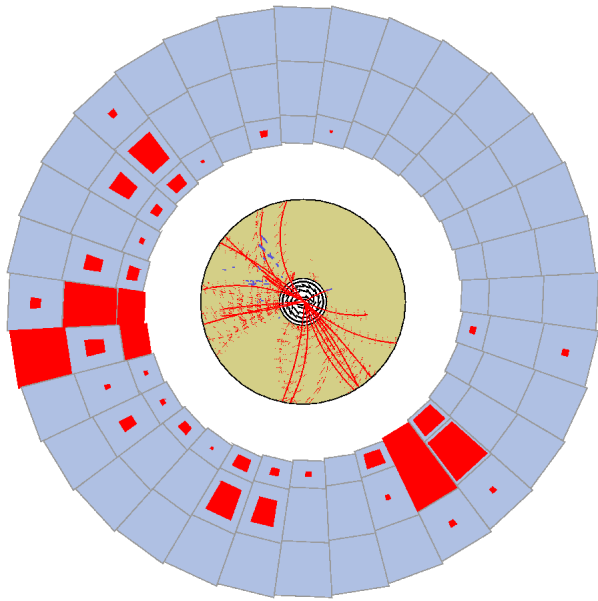
Dijet cross sections have been measured differentially in $\overline{\eta},\ \overline{E}_T^{jet},\ M^{jj},$ and Q^2

- NLO calculation by MEPJET provides poor description of shape and normalization
- Improved implementations of theory are crucially needed to use dijet cross sections in QCD fits to constrain the proton PDFs

Three-jet cross sections have been measured differentially in $\overline{\eta},\ \overline{E}_T^{jet},\ M^{3j},$ and Q^2

- First measurement of three-jet cross sections in CC ep DIS
- LO QCD calculation by MEPJET gives good description of shape
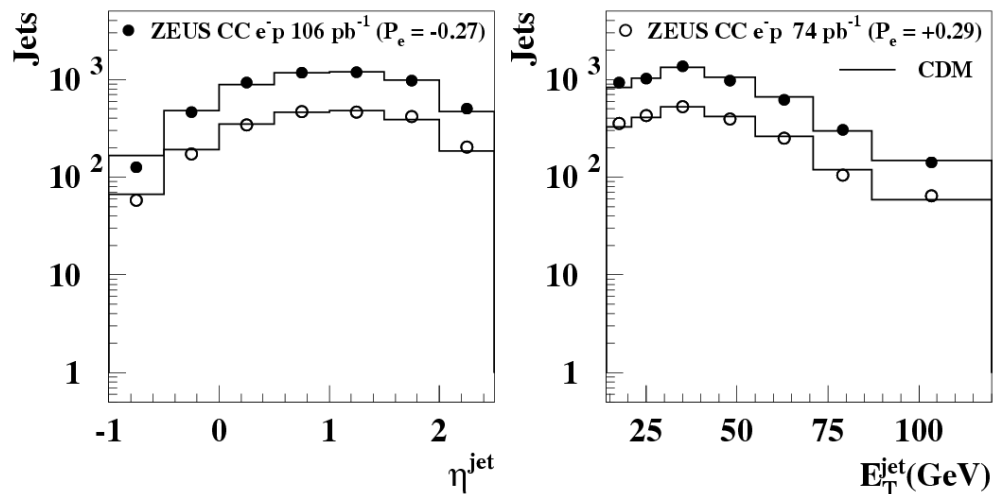- 11 three-jet candidates do have 4th jet with $E_T > 5$ GeV

END

jet1

jet2

jet4

jet3

BACKUP

jet1
jet2
jet4
jet3

- $p_{T,miss} > 11$ GeV

- $p_{T,miss} / E_T > 0.5$: reject photoproduction and beam-gas background

- $-35 < Z_{VTX} < 33$ cm

- At least one track associated with the vertex: reject non ep background

- $\Delta\varphi < 1$ rad (difference between azimuth of net transverse momentum measured by tracks and azimuth measured by CAL): reject random coincidences of cosmic rays and ep interactions

- $\mathbf{p_{T,tracks} / p_{T,miss}} > 0.1$: reject events with additional energy not related to ep events

- No electron candidate with $E' > 10$ GeV: reject NC DIS

- $E_{BHAC2} / E_{BCAL} > 0.5$ for $E_{BCAL} > 2$ GeV and

  $E_{BHAC1} / E_{BCAL} > 0.85$ for $E_{BCAL} > 8$ GeV : reject beam related backgrounds

- No tracking requirement if highest E_T jet had an $\eta > 2$, $p_{T,miss}$ cut raised to 20 GeV

- $Q^2 > 200$ GeV

- $y < 0.9$: poor resolution for large values of y

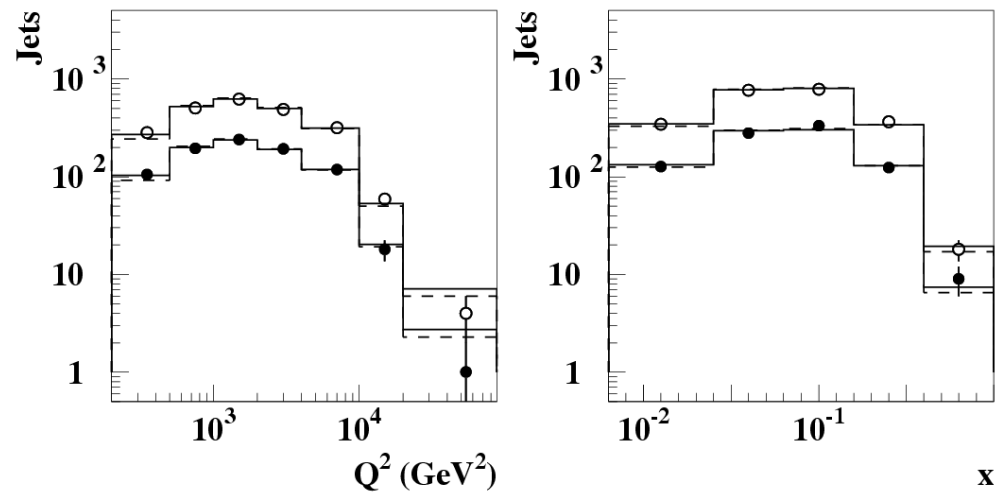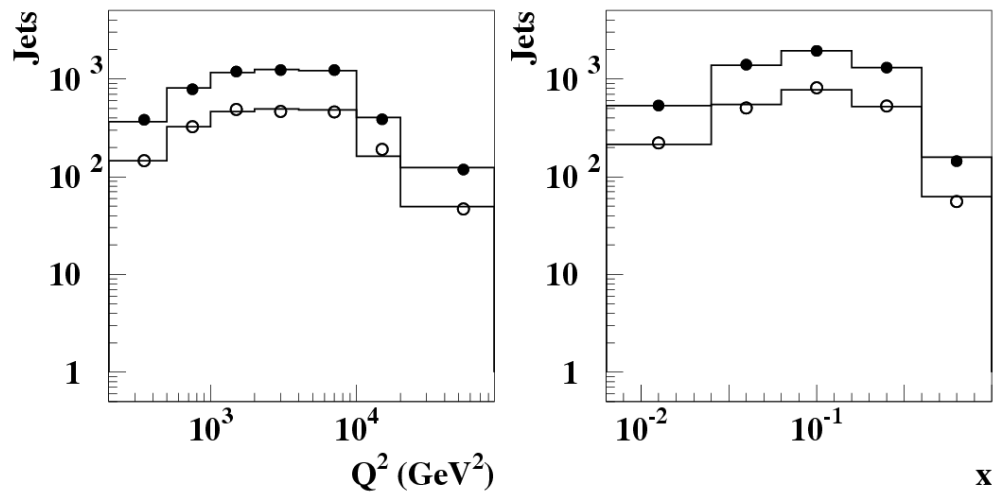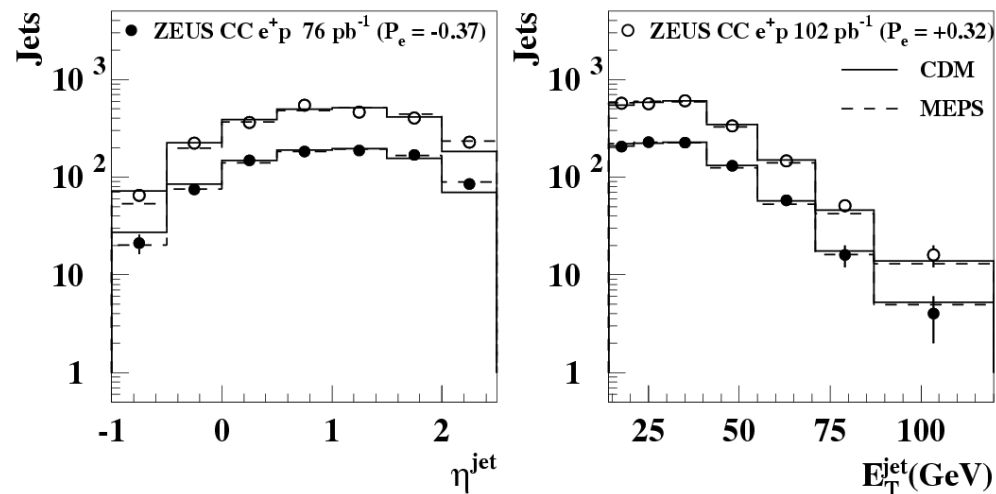## Polarized inclusive-jet electron data

Polarized inclusive-jet positron data

Unpolarized inclusive-jet electron and positron data