Jet Production at Low Momentum Transfer at HERA

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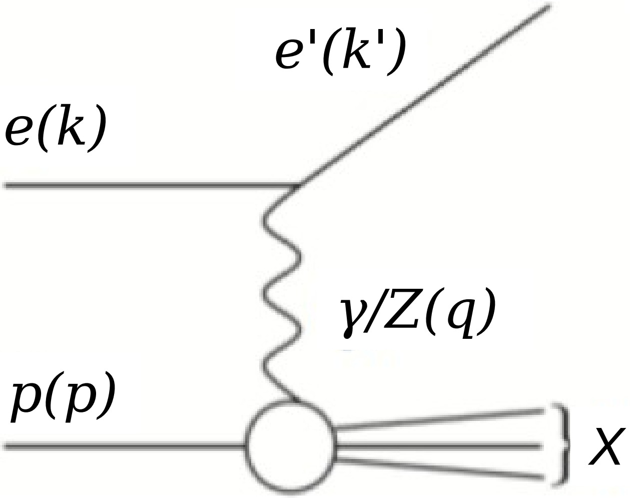
Deep-inelastic scattering

Neutral current deep-inelastic scattering

Process: $ep \rightarrow e'X$

Electron or positron



Kinematic variables

Virtuality of exchanged boson Q^2

$$Q^2 = -q^2 = -(k-k')^2$$

Inelasticity

$$y = \frac{p \cdot q}{p \cdot k}$$

Factorisation in ep collisions

Hard scattering coefficients and parton distribution functions (PDFs)

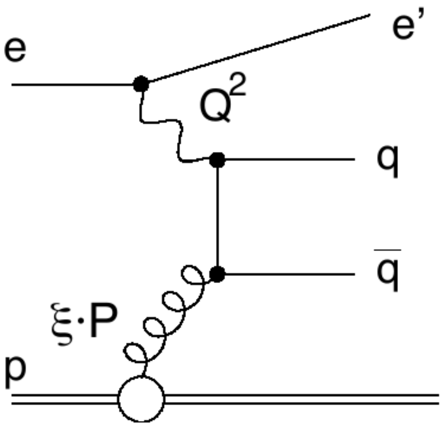
$$\sigma_{ep\rightarrow eX} = f_{p\rightarrow i} \otimes \hat{\sigma}_{ei\rightarrow eX}$$

Predictions in perturbative QCD

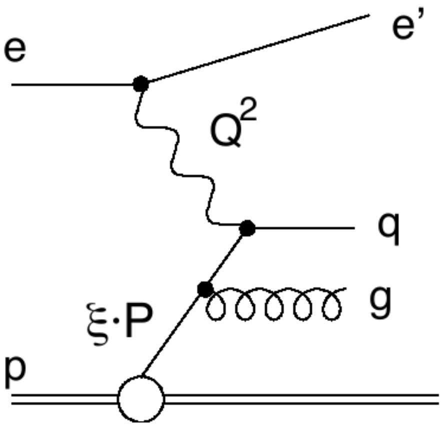
Hard scattering is calculated perturbatively

PDFs have to be determined from experimental data (usage of DGLAP)

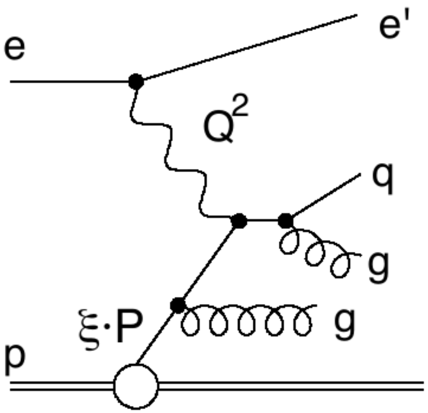
Jet production in *ep* scattering



Boson-gluon fusion



QCD Compton



Trijet leading-order

Jet measurements are performed in Breit reference frame

- Exchanged virtual boson collides 'head-on' with parton from proton

Jet measurement sensitive to α_s already at leading-order

- Boson-gluon fusion
- QCD compton

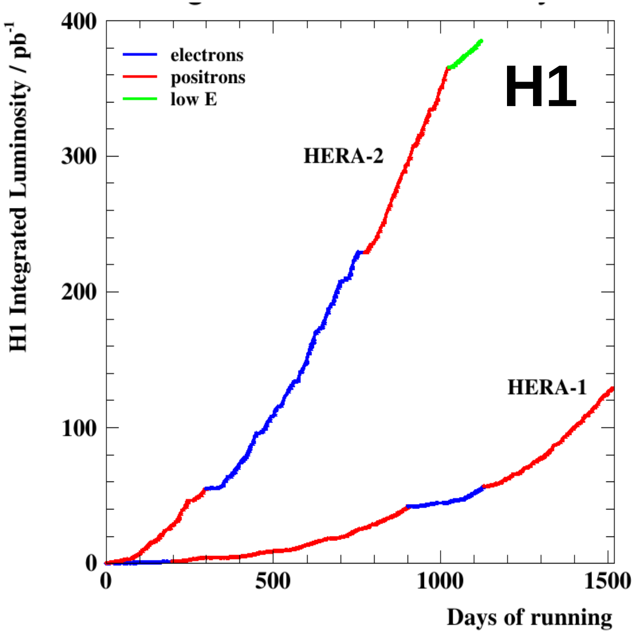
Trijet measurement

- More than three jets with significant transverse momenta
- Leading-order already at $O(\alpha_s^2)$

The HERA ep collider

HERA *ep* collider

Integrated luminosity



HERA ep collider in Hamburg

- Data taking periods
  - HERA I: 1994 – 2000
  - HERA II: 2003 – 2007
  - Special runs with reduced E_p in 2007
- Delivered integrated luminosity ~ 0.5 fb^{-1}

HERA-II period

- Electron and positron runs
- $\sqrt{s}$ = 319 GeV
  - E_e = 27.6 GeV
  - E_p = 920 GeV
- Analysed int. Luminosity: L = 184 pb^{-1}

The H1 experiment

H1 multi-purpose detector

Asymmetric design

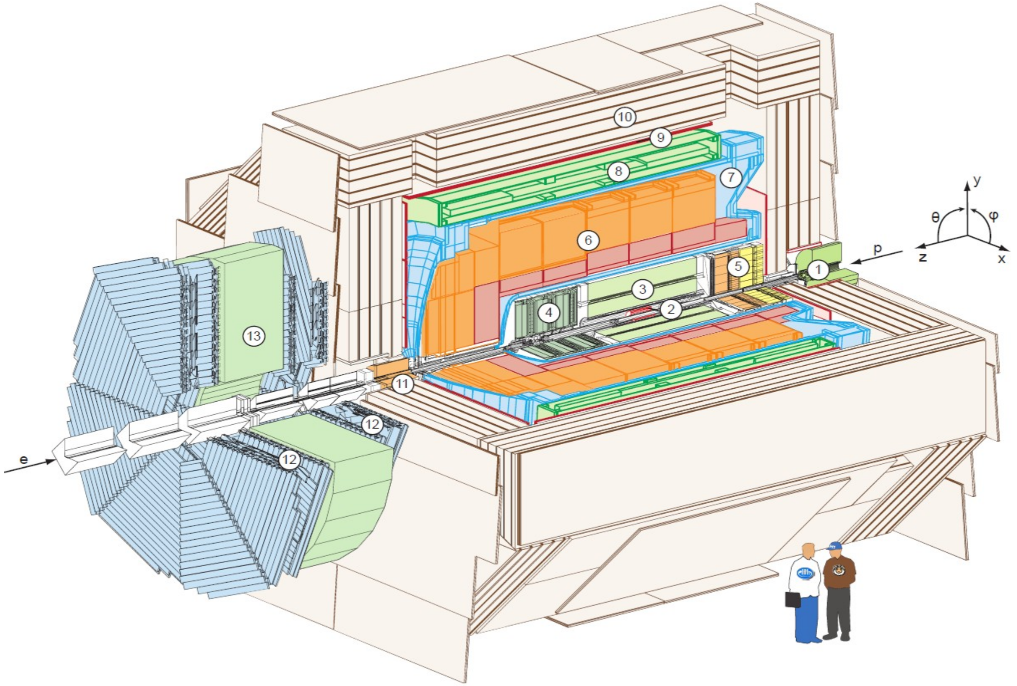
Trackers
- Silicon tracker
- Jet chambers
- Proportional chambers

Calorimeters
- Liquid Argon sampling calorimeter
- SpaCal: scintillating fiber calorimeter

Superconducting solenoid
- 1.15T magnetic field

Muon detectors

Drawing of the H1 experiment



Excellent control over experimental uncertainties
- Overconstrained system in NC DIS
- Electron measurement: 0.5 – 1% scale uncertainty
- Jet energy scale: 1%
- Luminosity: 2.5%

Analysis strategy and kinematic range

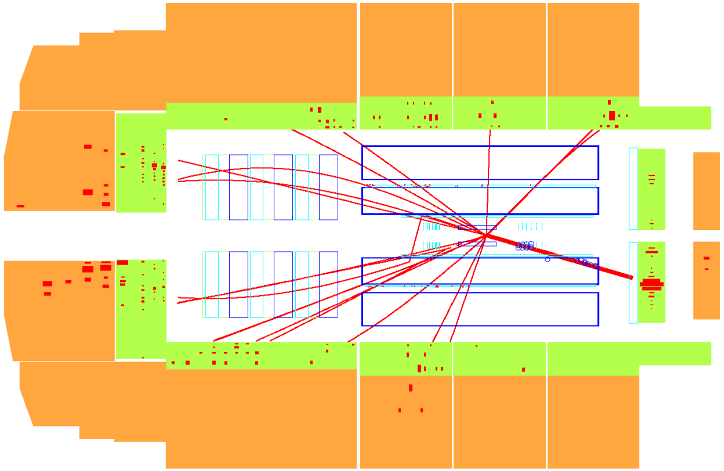
Data must be corrected for detector effects

- Kinematic migrations
- Acceptance and efficiency effects

Regularised unfolding

- Matrix based unfolding method
- Consider an '*extended phase space*' for accurate description of migrations into and out of 'measurement phase space'

Typical event display



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

Phase space of cross sections	
NC DIS	$5 < Q^2 < 100\ \mathrm{GeV}^2$
	$0.2 < y < 0.65$
(inclusive) Jets	$P_T^{jet} > 5\ \mathrm{GeV}$
	$-1.0 < \eta^{lab} < 2.5$
Dijet and Trijet	$M_{jj} > 18\ \mathrm{GeV}$
	$\langle P_T^{jet} \rangle > 5\ \mathrm{GeV}$

Control distributions

Acceptance of NC DIS events

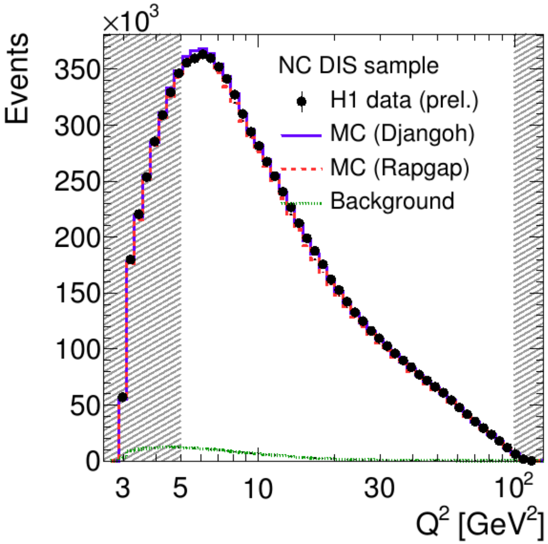
- Scattered lepton is found in SpaCal
- Lepton energy E_e > 11 GeV
- Selection based on un-prescaled SpaCal electron trigger

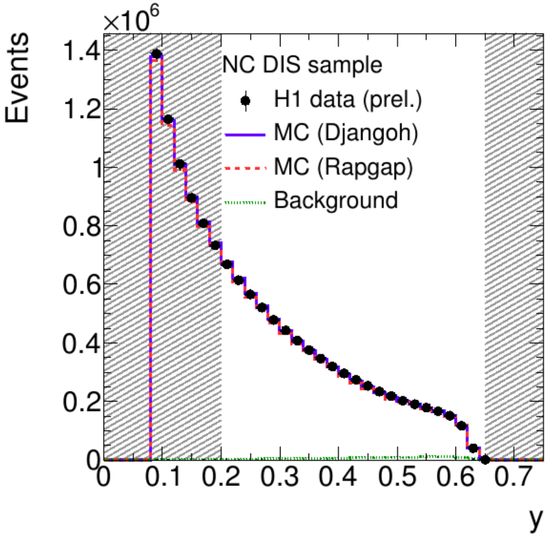
Monte Carlo generators

- Rapgap: LO matrix elements + PS
- Djangoh: Color-dipole model
- String fragmentation for hadronisation

Background

- Photoproduction simulation using Pythia
- Normalised to data using dedicated event selection
- Background for jet quantities almost negligible





Detector-level distributions for jets

Jet reconstruction

- k_T jet algorithm with R=1
- Jets built from tracks and clusters
- Jet energy calibration using neural networks

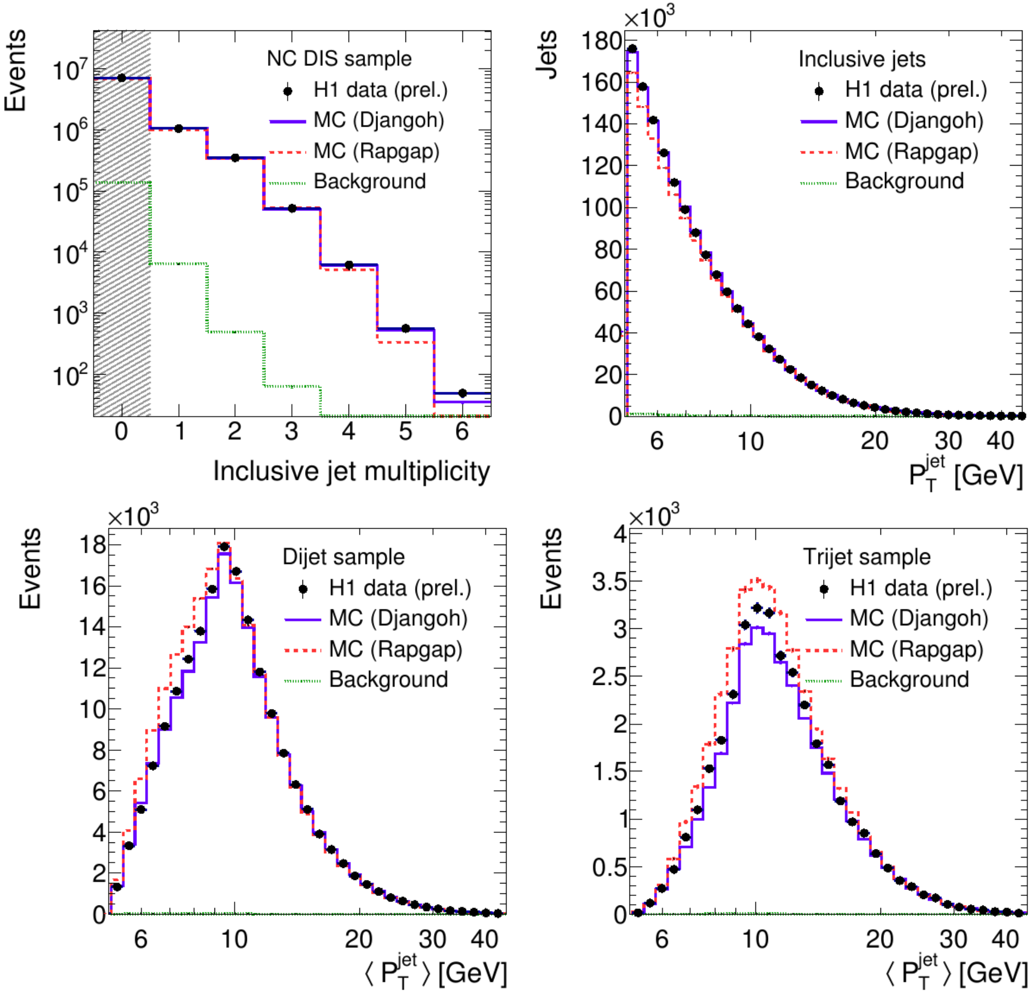
Monte Carlo predictions

- MC simulations used for unfolding procedure
- Jet multiplicities and spectra not well modelled
  - Djangoh: p_T^{jet} spectra too hard
  - Rapgap: Jet multiplicity underestimated
  - Both generators tend to have too few jets in forward direction
  - -> MC generators are weighted to describe data
- Weighted MC predictions

Dijet and Trijet

- Distributions raise steeply due to p_T^{jet} > 5 GeV requirement

-> Extended phase space important for migrations



Regularised unfolding

Regularised unfolding using ROOT::TUnfold

- Calculate unfolded distribution *x* by minimising

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

- Linear analytic solution
- Linear propagation of all uncertainties
- Statistical correlations are considered in V_y

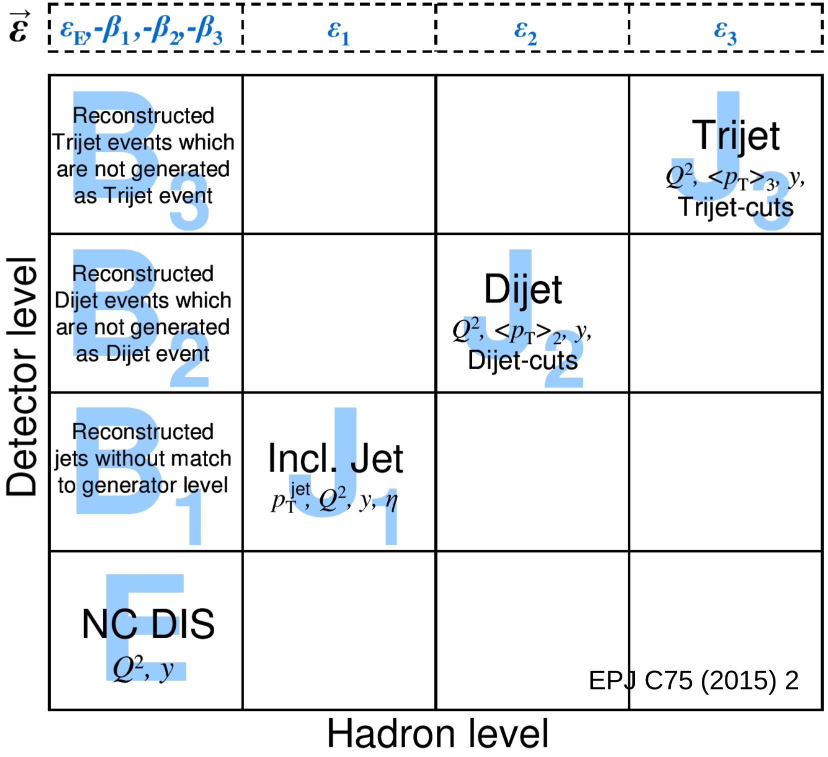
Simultaneous unfolding of Inclusive jet, Dijet, Trijet, NC DIS

- Similar to EPJ C75 (2015) 2
  -> One measurement of multiple observables
- Matrix constituted from O(10^6) entries
- Migrations in up to 6 variables considered for a single measurement
- 'detector-level-only' jets/events are contrained with NC DIS data
- System of linear equation becomes overconstrained when using more bins on detector than on generator level

JINST 7 (2012) T10003

x	Hadron level
y	Detector level
V_y	Covariance matrix
A	Migration matrix
τL^2	Regularisation term

Migration Matrix



EPJ C75 (2015) 2

Data to theory comparisons

Data is compared to predictions based on next-to-leading order QCD calculations

NLO calculations

nlojet++ (Z. Nagy et al.) with NNPDF 3.0

ep → *2 jets* for inclusive jet and dijet

ep → *3 jets* for trijets

Scale choices

$$\mu_r^2 = \mu_f^2 = \frac{1}{2}\left(P_T^2 + Q^2\right)$$

Estimated uncertainty

6-point asymmetric scale variations

k-factors: 0.9 < NLO/LO < 3.8

Hadronisation corrections to NLO predictions

Lund string model

- Average of correction factors from the two MC models

Multiplicative factors

- typically 0.88 – 0.95
- up to 0.75 for trijets at low $\langle P_T \rangle$

Corrections to data

Bin-wise correction factors for QED radiative effects

Dijet cross sections

Double-differential Dijet cross sections

$$\langle P_T \rangle = \frac{P_{T,1}+P_{T,2}}{2}$$

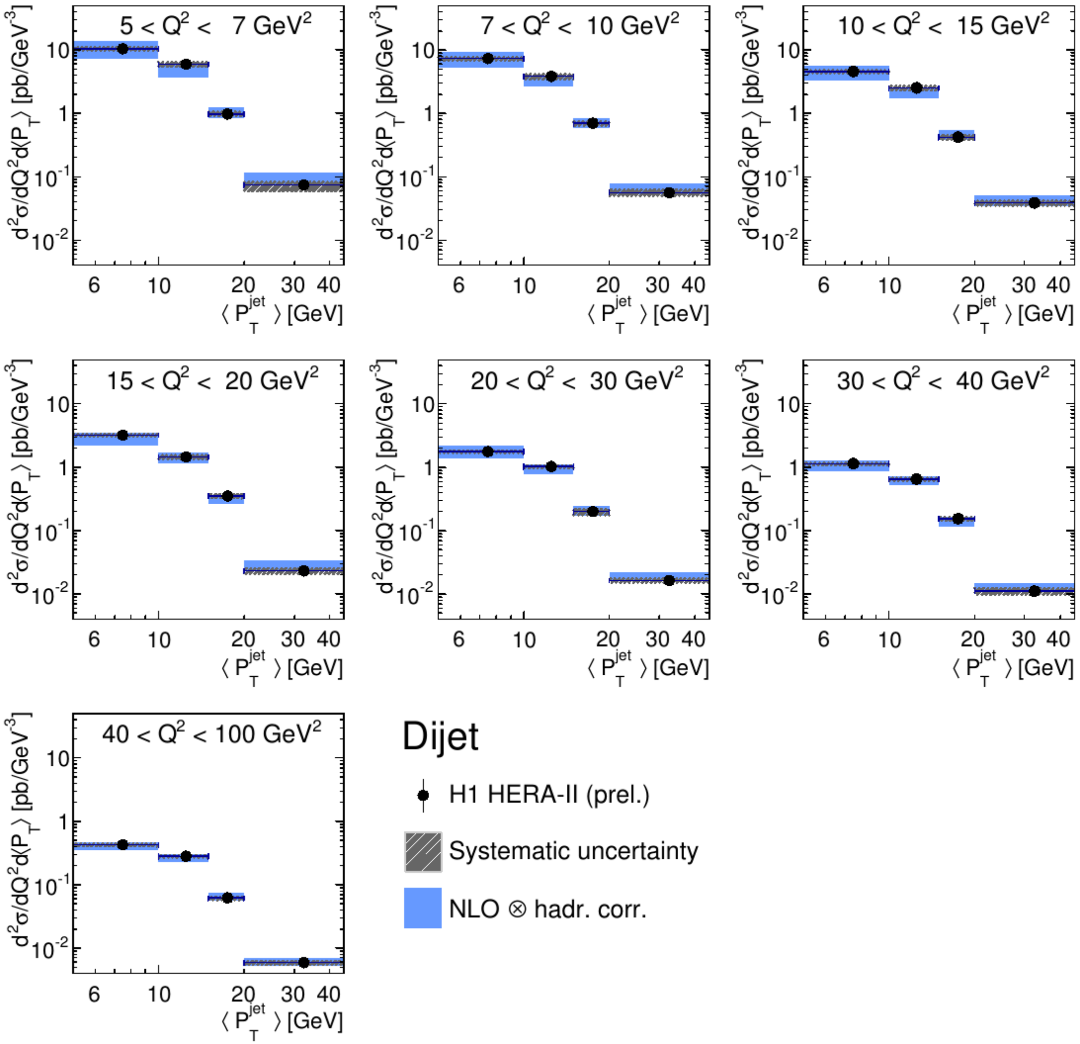
High precision

- Exp. uncertainty dominated by jet energy scale and model uncertainty

Compared with NLO

- NLO gives reasonable description over full kinematic range
- Large k-factors may indicate relevant contributions beyond NLO
- Large uncertainties from scale variation

Data precision overshoots significantly theory precision



Inclusive jet cross sections

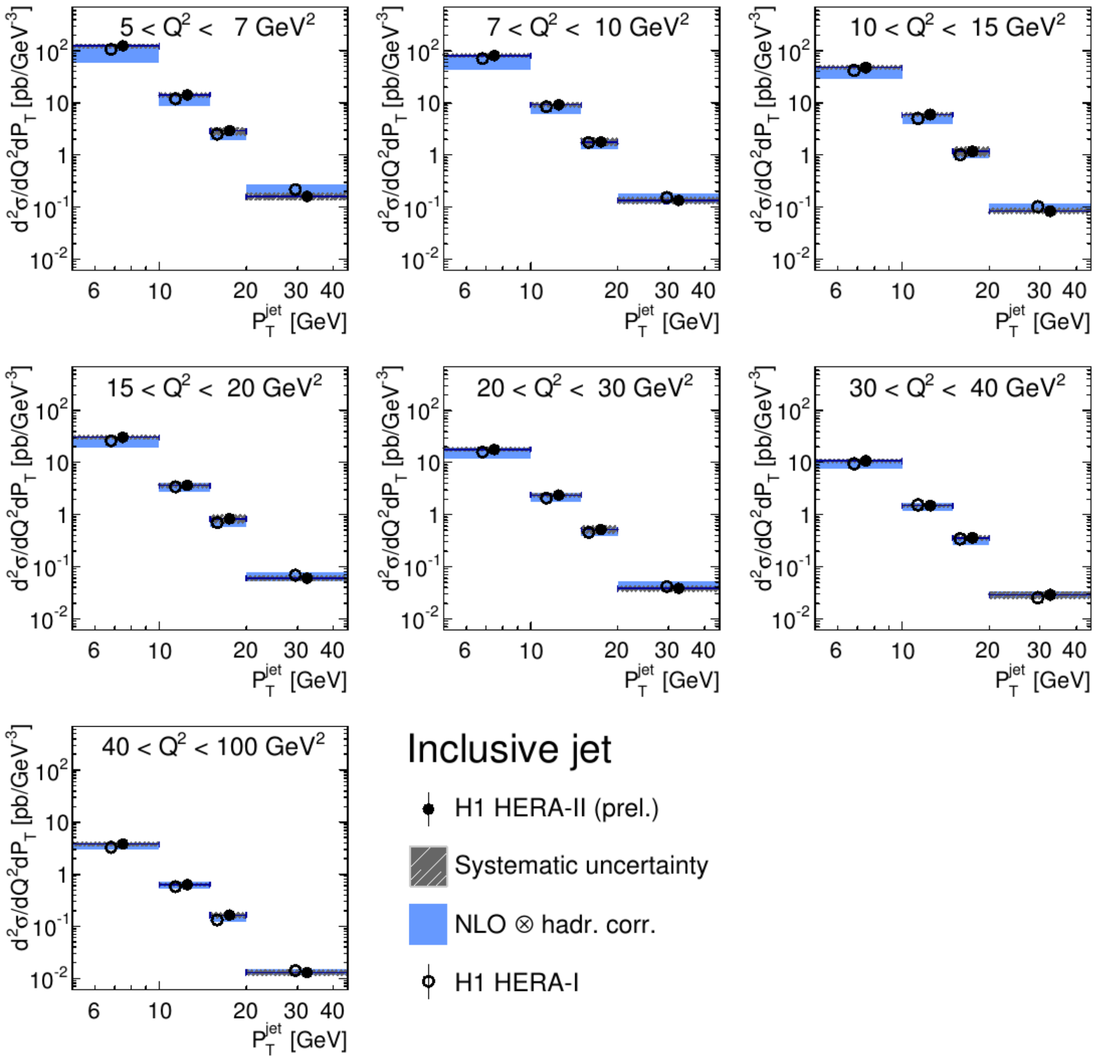
Double-differential inclusive jet cross sections

Inclusive jets

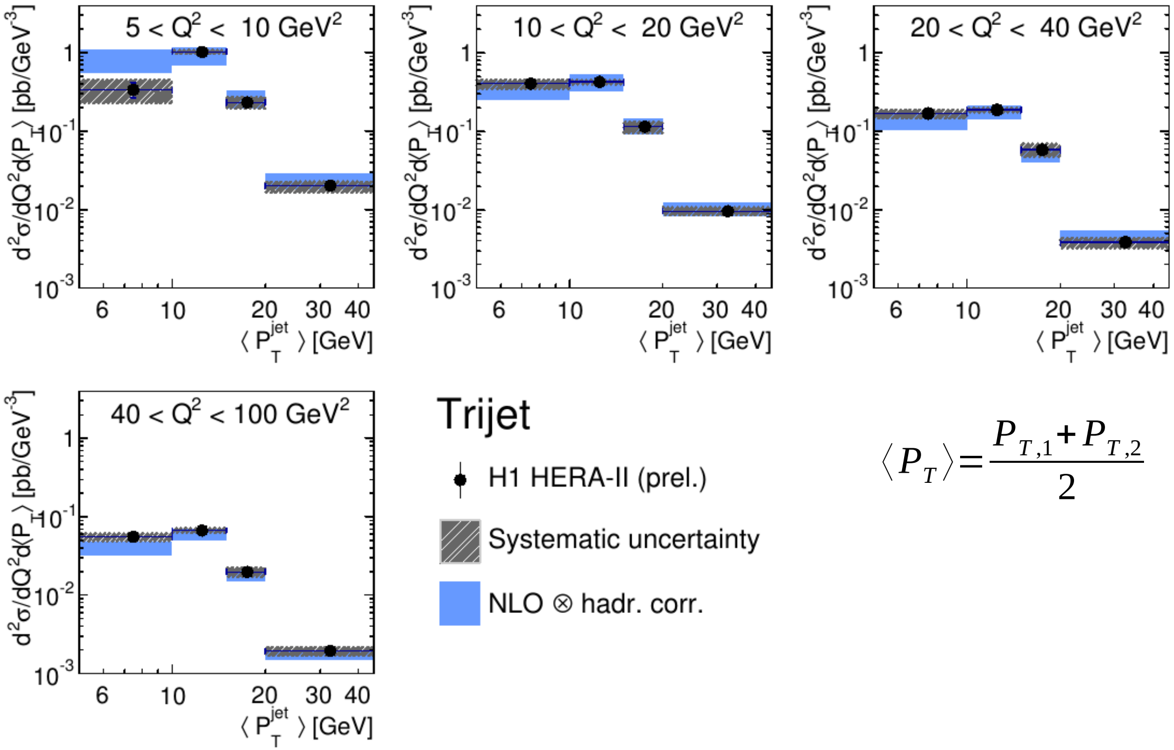
- Count each jet in an NC DIS event
- Stat. uncertainty and correlations are measured
- Well described by NLO

Compared to H1 HERA-I

- Largely independent measurement
- HERA-II data with comparable precision
- Benefit from refined experimental methods
- Statistical uncertainty reduced for high P_T and high Q^2



Trijet cross sections



$$\langle P_T\rangle = \frac{P_{T,1}+P_{T,2}}{2}$$

Double-differential Trijet cross sections

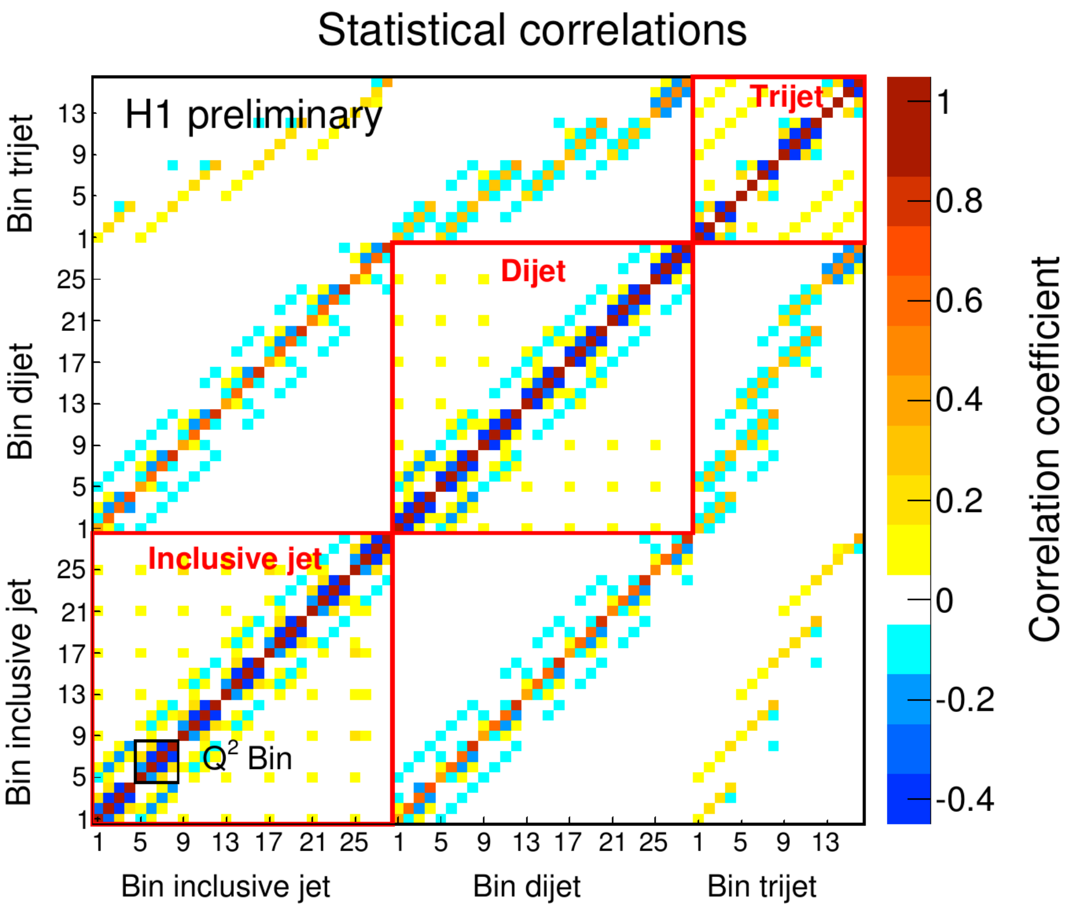
- Precision limited by systematic uncertainties over whole kinematic range
- dominated by: Jet energy scale and model uncertainty
- At low values of Q^2:
  Data precision significantly overshoots NLO precision

Correlation matrix of multijets

Covariance matrix
- Correlations beteween all data points are measured
- Obtained through linear error propagation of statistical uncertainties

Correlations
- Resulting from unfolding
- Physical correlations
  - Between measurements
  - Within inclusive jet

Useful for
- Cross section ratios
- Combined fits
- Normalised cross sections

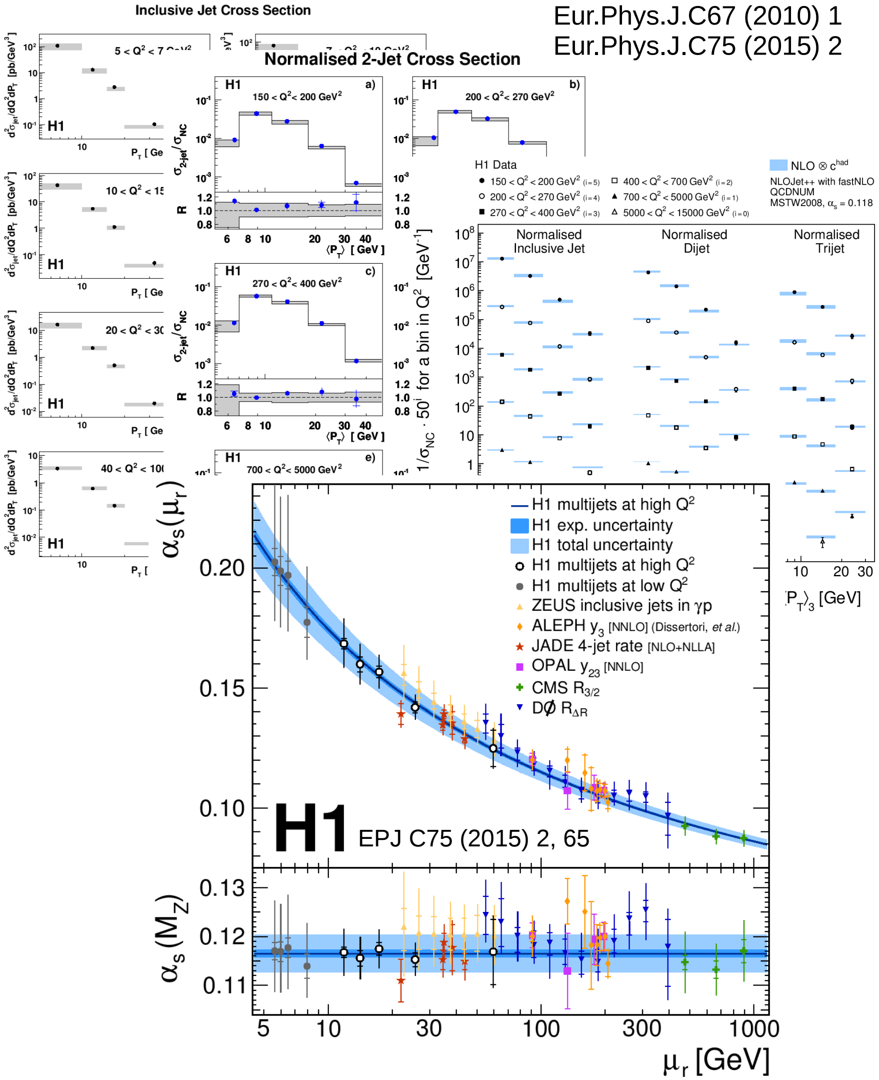


History and Outlook

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

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



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 developements
  - aNNLO for low-Q^2 regime
    (Biekötter, Klasen, Kramer, Phys.Rev. D92 (2015) 7, 074037)
  - full NNLO predictions
    (Currie, Niehues, Gehrmann et al., see plenary on monday)

Summary

New double-differential inclusive jet, dijet and trijet cross sections

- New measurements of multijet cross sections at low Q^2 presented
- Large HERA-II dataset analysed
- High statistical and experimental precision
- Analysis uses final H1 data re-processing and precise calibration of the H1 detector
- Sophisticated unfolding allows simultaneous usage of all data in future fits
- Data well described by NLO predictions within large theoretical uncertainties

Outlook

- Data will be valuable input for α_s extractions
  -> Use HERA-I and HERA-II, low- and high-Q^2 jet data
- Looking forward for confrontation with aNNLO and NNLO predictions