Jets in DIS

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for the H1 Collaboration

PDF4LHC, September 2016
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Deep-inelastic scattering

Neutral current deep-inelastic scattering

Process: $ep \rightarrow e'X$

Electron or positron

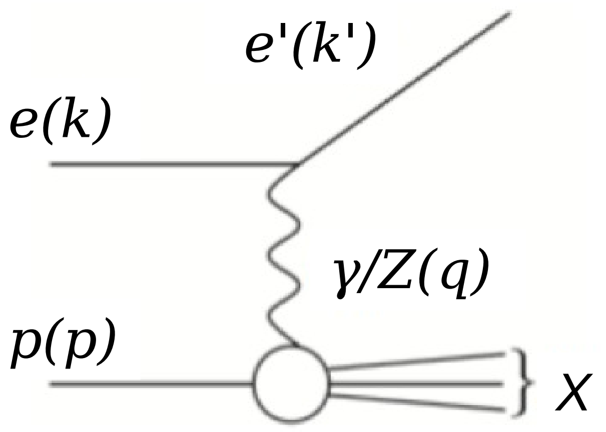
Kinematic variables

Virtuality of exchanged boson Q^2

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

Inelasticity

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



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

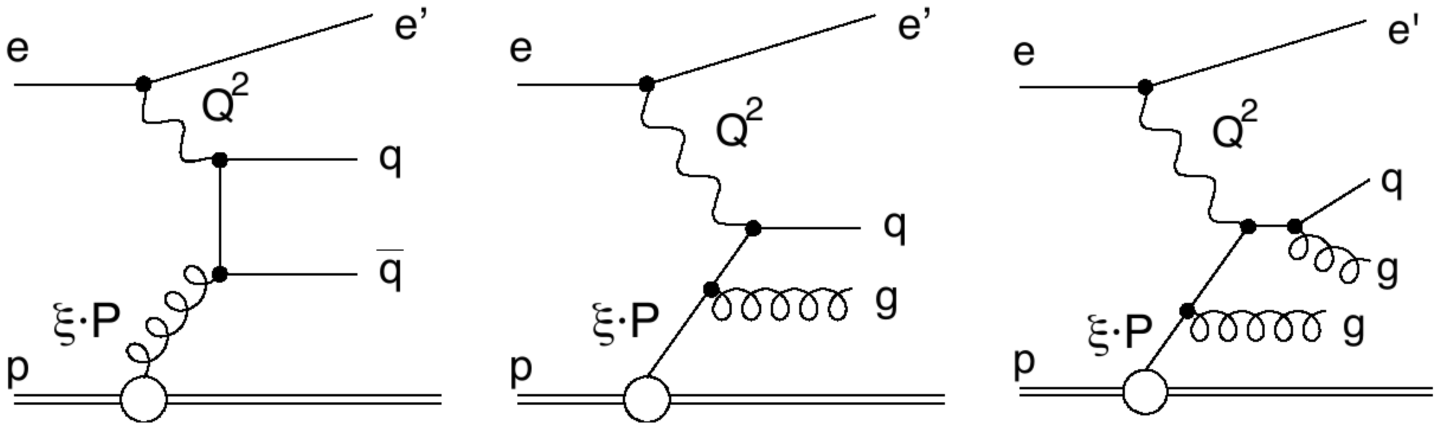
NC and CC DIS cross sections (HERA-II) are mandatory ingredients for PDF fits

- Only one proton involved
  -> lepton directly probes (charged) constitutents of proton

Gluon is mainly indirectly constrained by DGLAP and sum-rules

-> Measurement of *ep -> 2j+X* will allow direct access of gluon content

Jet production in *ep* scattering



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

Jet measurements are performed in Breit reference frame

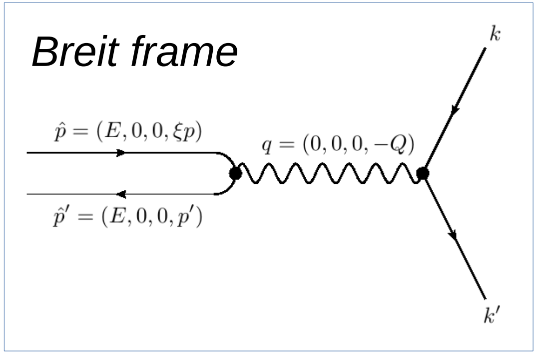
- Exchanged virtual boson collides 'head-on' with parton from proton ('brick-wall' frame)

Jet measurements directly sensitive

- to α_s already at leading-order
- to gluon content of proton

Trijet measurement

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



New H1 jet cross sections @ low-Q2

H1prelim-16-061

- inclusive jet, dijet and trijet cross sections in NC DIS
- preliminary results in identical phase space as HERA-I analysis
  - $5 < Q^2 < 100$ GeV^2
  - $0.2 < y < 0.65$

H1prelim-16-062

- 'normalised' inclusive jet, normalised dijet and normalised trjet cross sections i.e. normalised to NC DIS cross section in respective Q2 range
- optimized NC DIS phase space
  - $5.5 < Q^2 < 80$ GeV^2
  - $0.2 < y < 0.6$
- optimised jet-binning
- optimised dijet and trijet defintion
  - No cut on invariant mass of the 2-leading jets
  - (implicit) asymmetric cuts on jet-pT to avoid infrared sensitive regions of pQCD calculations

Analysis strategy and kinematic range

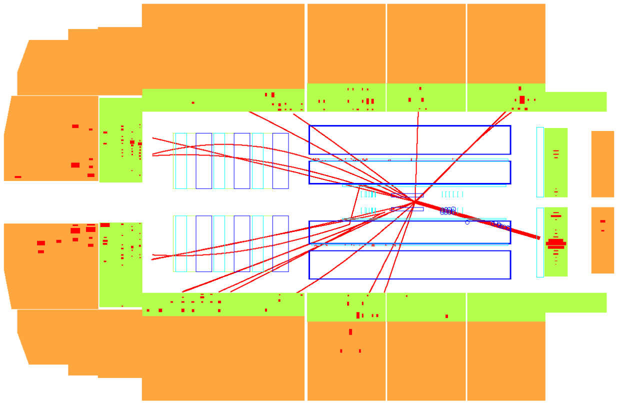
Data must be corrected for detector effects

- Kinematic migrations
- Acceptance and efficiency effects

Regularised unfolding

- Matrix based unfolding method (TUnfold)
- 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	$Q^2 > 3$ 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		
	H1prelim-16-061	**H1prelim-16-062**
NC DIS	$5 < Q^2 < 100$ GeV^2	$5.5 < Q^2 < 80$ GeV^2
	$0.2 < y < 0.65$	$0.2 < y < 0.6$
(inclusive) Jets	$P_T^{jet} > 5$ GeV	$P_T^{jet} > 4.5$ GeV
	$-1.0 < \eta^{lab} < 2.5$	$-1.0 < \eta^{lab} < 2.5$
Dijet and Trijet	$M_{jj} > 18$ GeV	$P_T^{jet} > 4$ GeV
	$\langle P_T^{jet}\rangle > 5$ GeV	$\langle P_T^{jet}\rangle > 5$ [5.5] GeV

Control distributions

H1prelim-16-061

Acceptance of NC DIS events

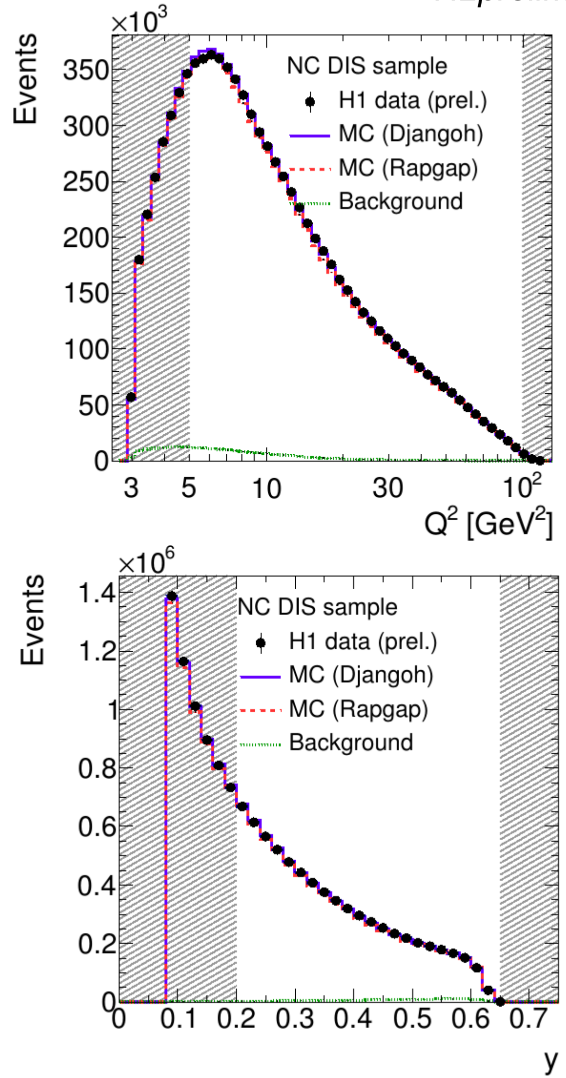
- Scattered lepton is found in SpaCal
- Lepton energy E_e > 11 GeV
- Selection based on un-prescaled SpaCal electron trigger

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
  Approx. 1% Jet energy scale uncertainty

Monte Carlo predictions

- MC simulations used for unfolding
- 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

Dijet and Trijet

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

-> Extended phase space important for migrations

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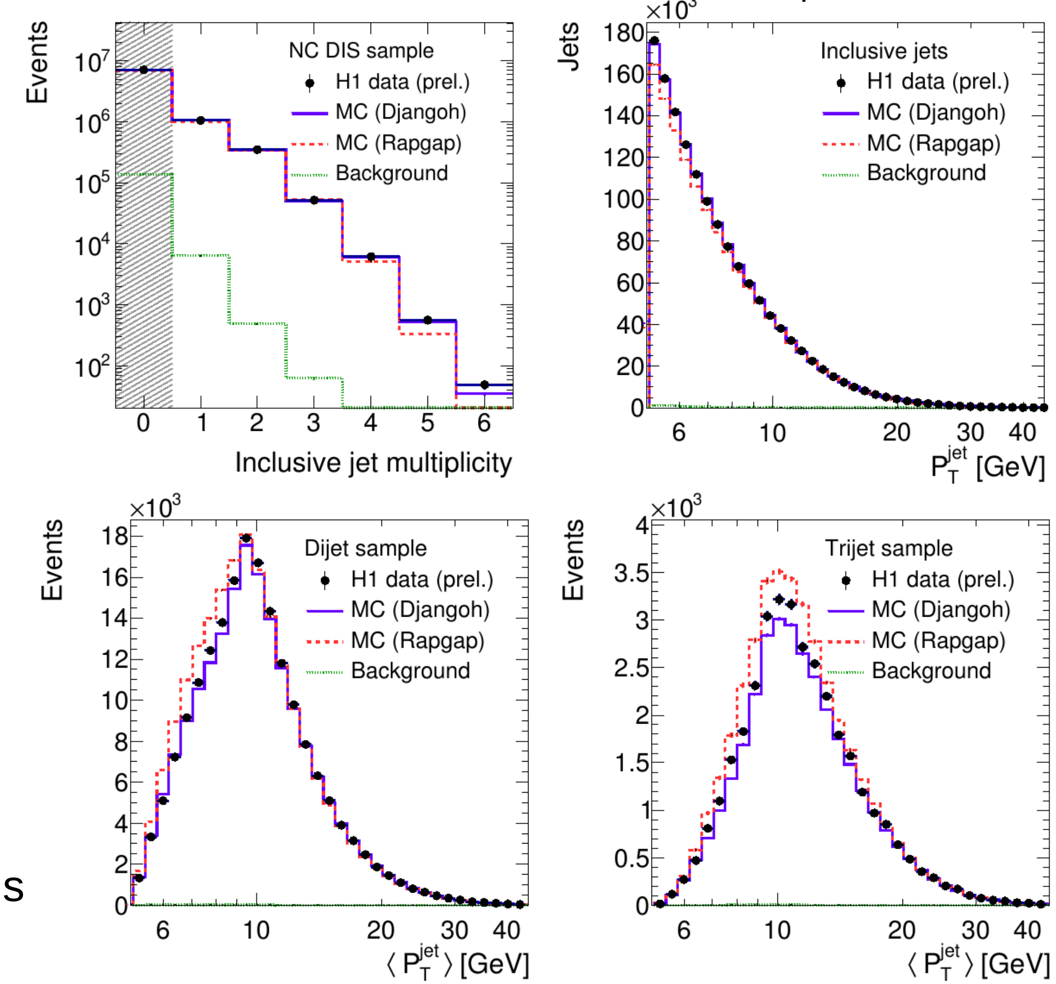


Inclusive jet cross sections

H1prelim-16-061

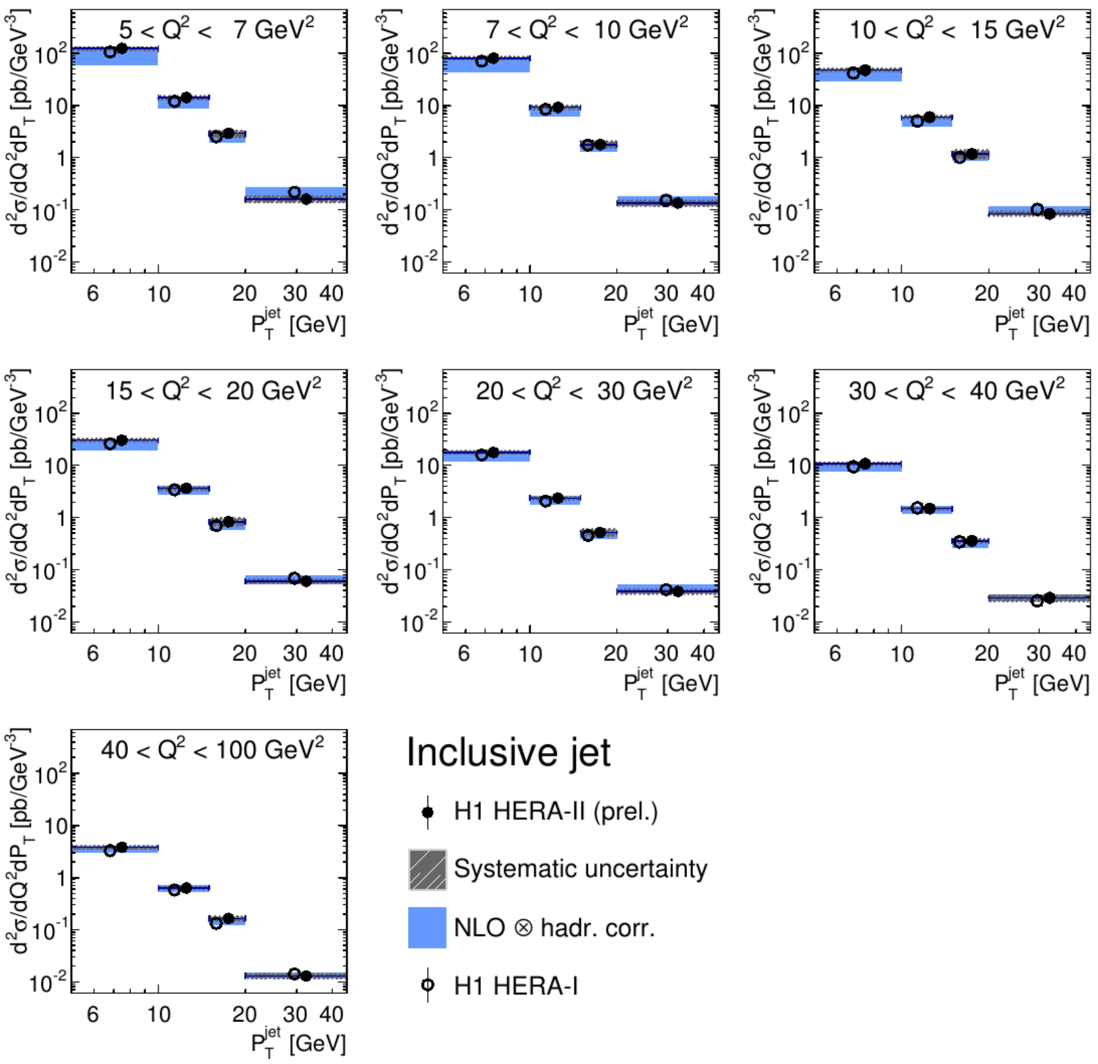
Double-differential inclusive jet cross sections as function of Q^2 and p_T^{jet}

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



Reminder: inclusive jets @ high-Q^2

Eur. Phys. J. C75 (2015) 2

- H1 HERA-II jet cross sections at high-Q^2

Jet cross sections at 'high-Q^2'

- Inclusive jet, dijet and trijet cross sections
- $150 < Q^2 < 15000 \text{GeV}^2$

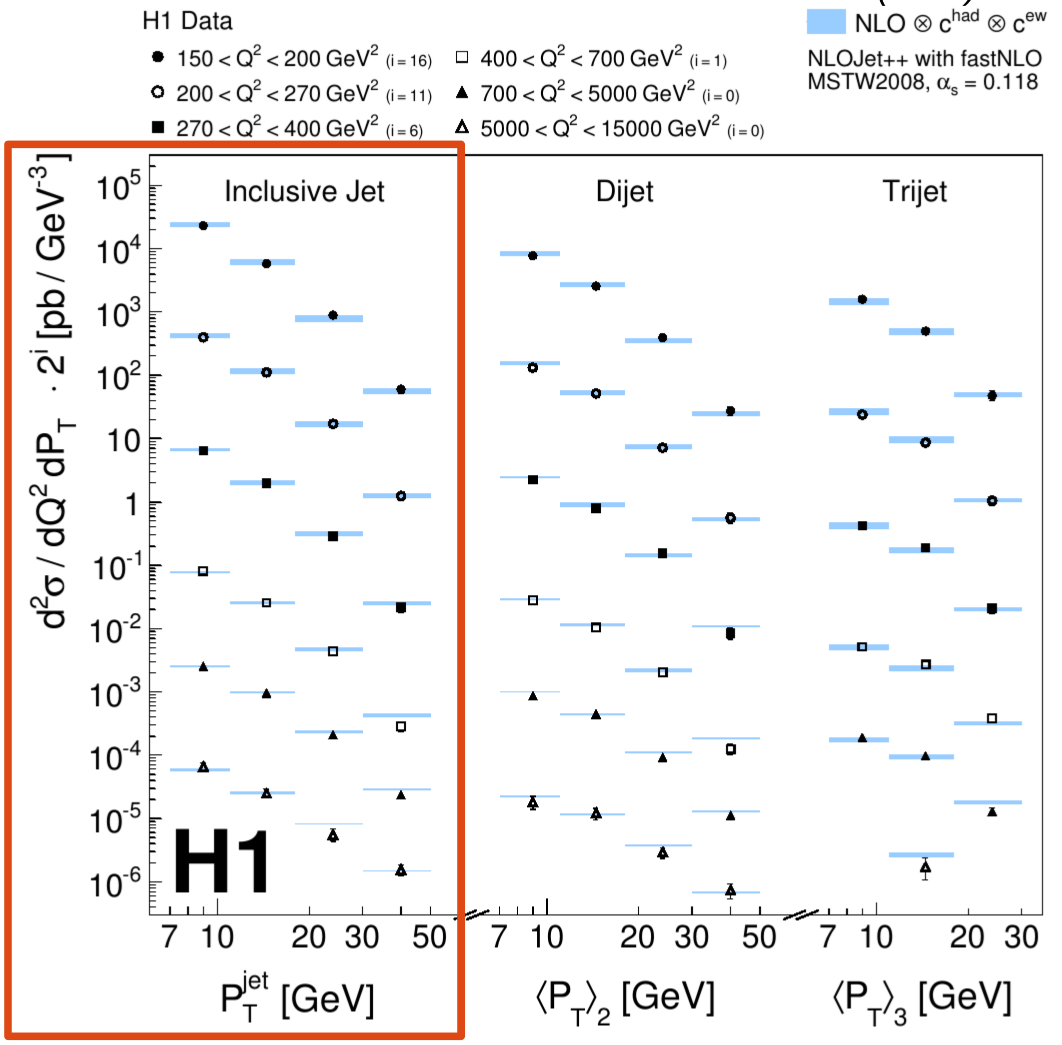
Inclusive jets published for

- $7 < p_T < 50$ GeV

Recent studies

- Inclusive jets are well measurable down to $p_T = 5$ GeV
- The original 'high-Q2 '-analysis contained a cross section bin for inclusive jets for
  - $5 < p_T < 7$ GeV
- These additional bins (for each Q2 range) are now provided
  - Absolute and normalised cross sections

EPJ C75 (2015) 2



Inclusive jets production in NC DIS

'Normalised' jet cross sections

- H1prelim-16-062
- Normalise jet cross sections w.r.t. inclusive NC DIS cross section
  - Full/partial cancellation of uncertainties

<u>New Data</u>

HERA-II low-Q^2

HERA-II high-Q^2, $5 < p_T < 7$GeV

Inclusive jets for major part of HERA NC DIS phase space

<u>New predictions</u>

aNNLO from JetViP

- Approximate NNLO using threshold resummation

  PR D 92 (2015) 074037 & work in progress

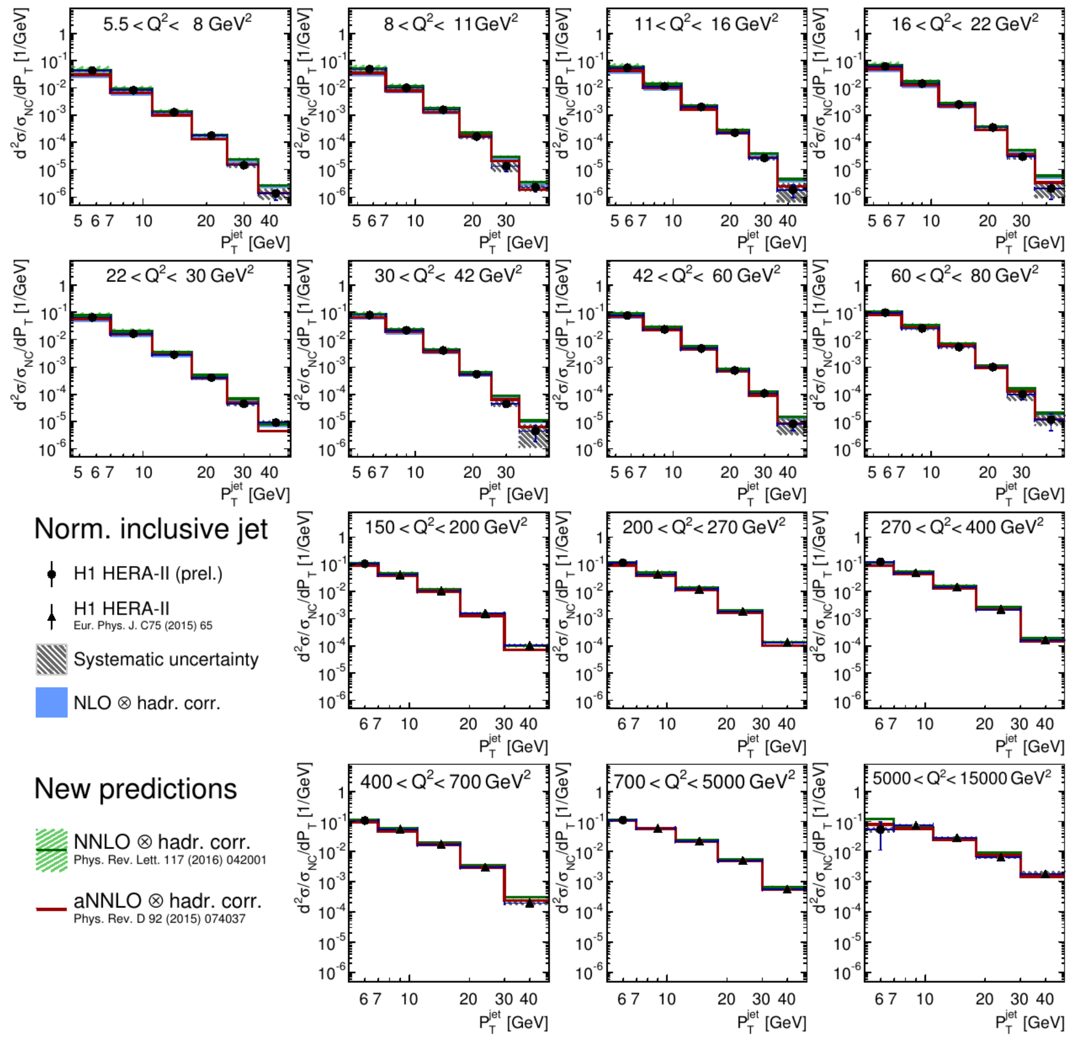
NNLO

- Full NNLO

  PRL 117 (2016) 042001 & work in progress

  See talk by J. Currie @ QCD@LHC2016
- Improved description of data by NNLO

H1prelim-16-062



Normalised Inclusive Jets

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Detailed ratio to NLO prediction

- Data reasonably described by NLO theory, but NLO scale uncertainty large

Normalisation w.r.t. NC DIS for predictions

- NNLO & aNNLO predictions normalised with NC DIS predictions from APFEL using FONLL-C [V. Bertone et al.]
- NLO predictions normalised with ZM-VFNS using QCDNUM

PDF: *NNPDF30_(n)nlo_0118*

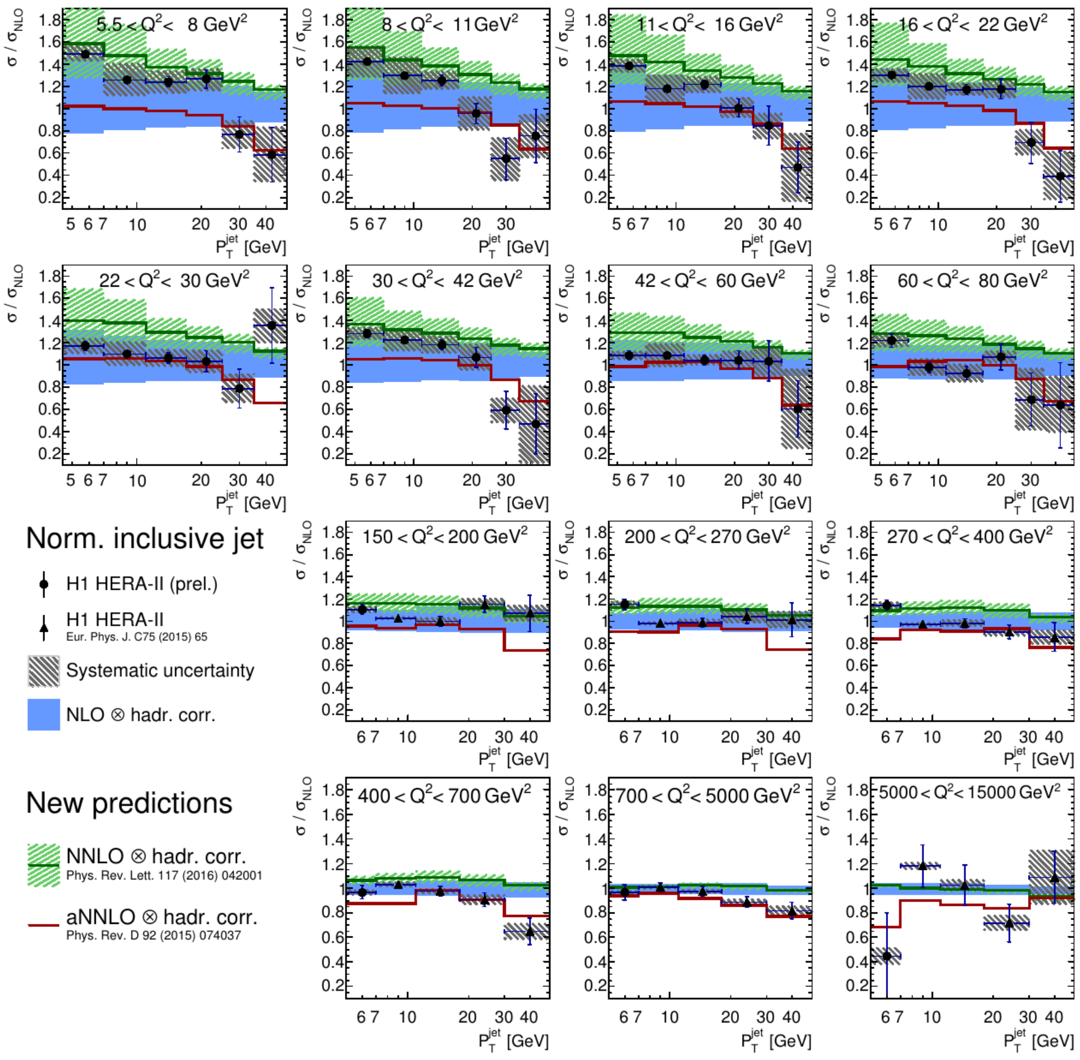
Scale $\mu_r = \mu_f = (Q^2+P_T^2)/2$

aNNLO

- Improved data description at high-pT
- At low-pT aNNLO similar to NLO

NNLO

- Improved description of data by NNLO
- Significantly reduced scale uncertainty (particularly for higher scales)



Normalised dijets

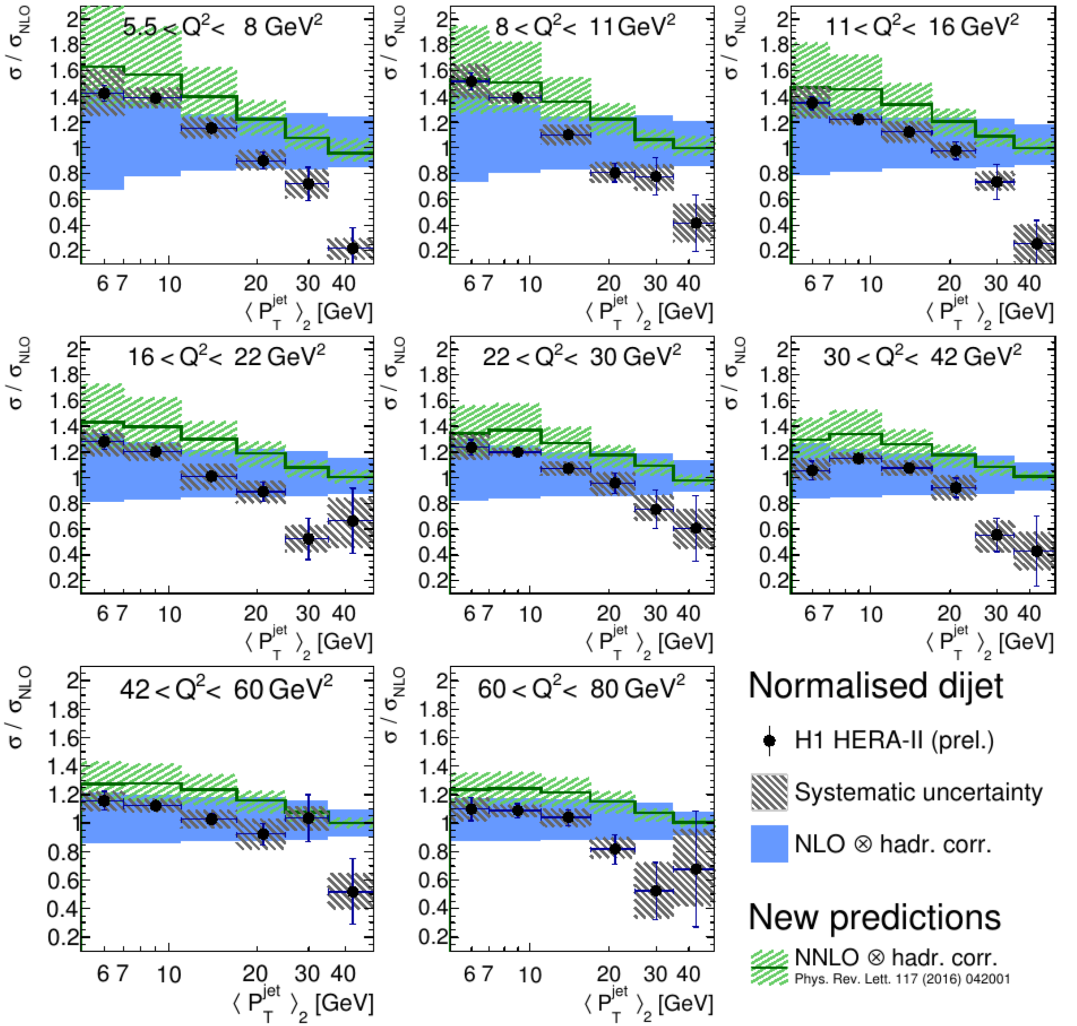
H1prelim-16-062

Normalised dijet cross sections in NC DIS as a function of Q^2 and $<p_T>_2$

- $<P_T>_2 = (P_T^{jet1} + P_T^{jet2})/2$
  with: $P_T^{jet} > 4$ GeV

Comparison to NLO and <u>NNLO</u> predictions

- NLO give reasonable descriptions within large scale uncertainties ('6-point' variation)
- NNLO improves shape dependence
- NNLO slightly overshoots data -> partially caused by normalisation w.r.t. NC DIS
- high-pT region difficult to describe



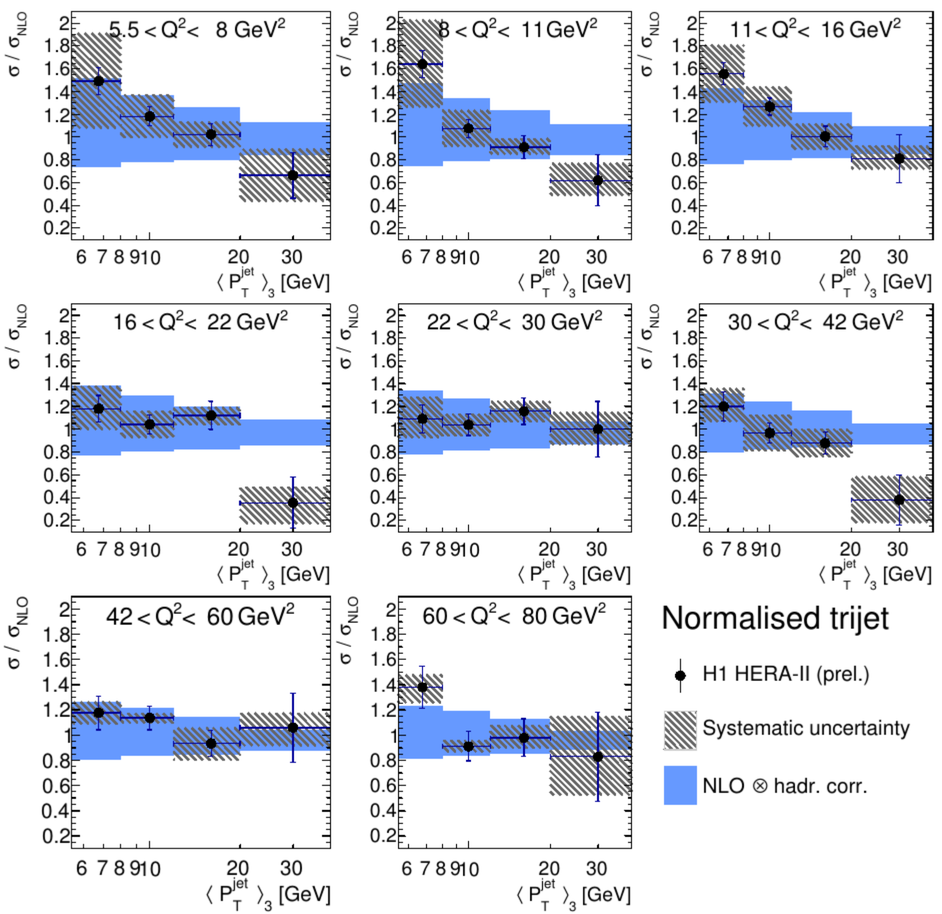
Trijet cross sections

H1prelim-16-062

Double-differential (normalised) Trijet cross sections as a function of Q^2 and $\langle p_T \rangle_3$

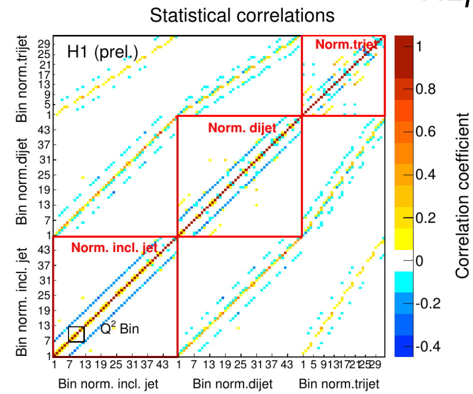
- Precision limited by systematic uncertainties over whole kinematic range
- 4 x 8 data points
  -> Excellent measurement of shape and dependence
- dominated by: Jet energy scale and model uncertainty
- Data precision overshoots NLO precision
- NLO has similar problems in describing the shape at low-Q2 as for dijet cross sections

No NNLO calculations available yet



Fits to H1 jet cross sections

H1prelim-16-062



All statistical (and syst.) correlations are known

- Low and high-Q^2 data can be fitted together
- Inclusive jet, dijet and trijet cross sections can be fitted together
  -> Basically two quadruple-differential cross section measurement (Q^2, p_T^{jet}, $\langle P_T\rangle_2$,$\langle P_T\rangle_3$)

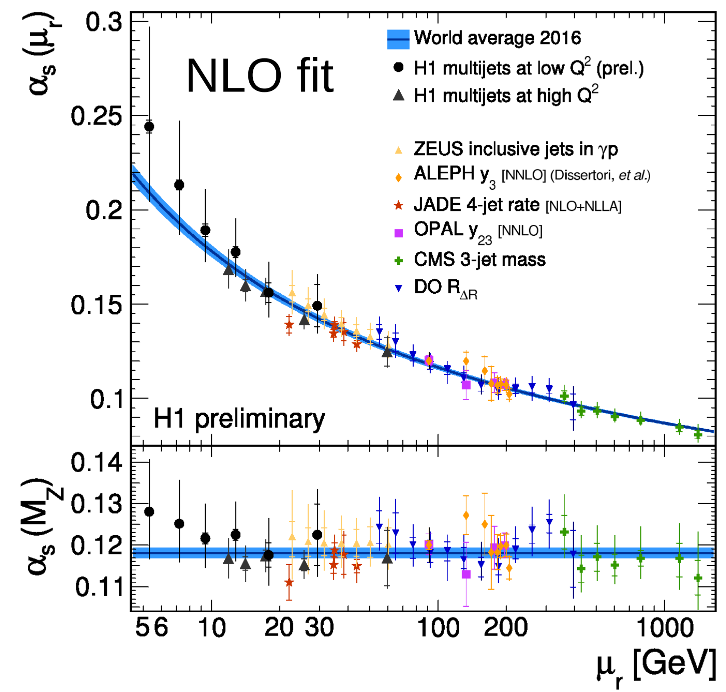
Template for usage of H1 jet data for (PDF-)fits provided

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

Very high experimental precision on $\alpha_s(m_Z)$

- Use normalised *low-Q^2* and *high-Q^2* H1-multijets
- Experimental precision about ***0.4%***

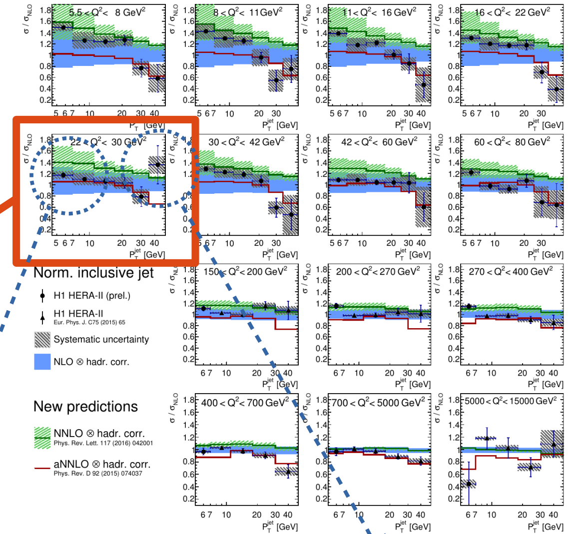
-> Data already prepared for use in PDF fits !

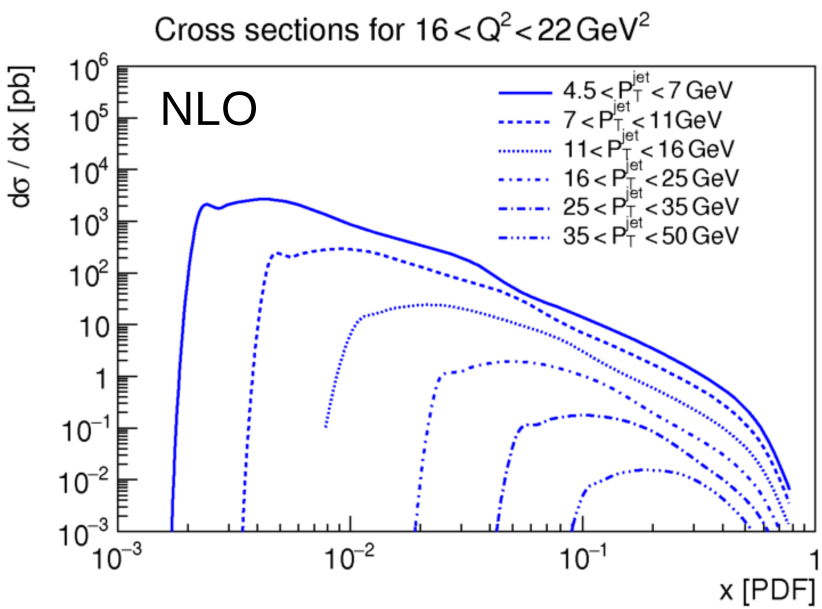


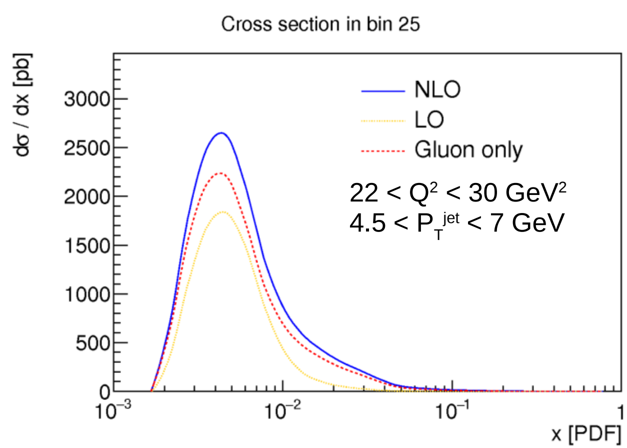
PDF dependence of jet cross sections

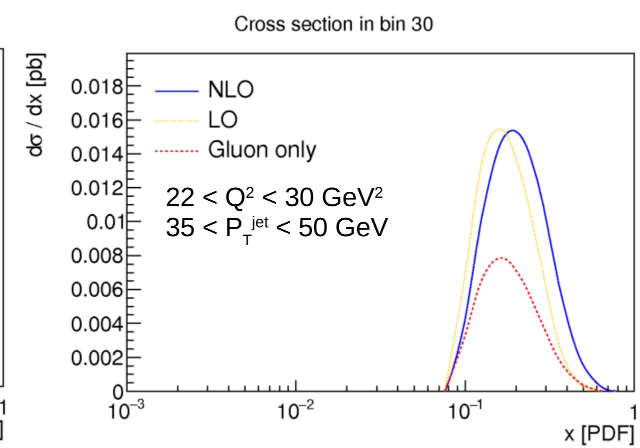
PDF dependence of <u>inclusive jet</u> cross sections

- Cross sections of single data points as a function of x(PDF)
- P_T-binning probes different x-regions
- Lowest x-values: $x \sim 10^{-3}$
- High-P_T cross sections: $x > 10^{-1}$
  -> H1 Jets may become important for high-x gluon
  No convolution with second hadron in DIS
- x-dependence shows little dependence on Q^2







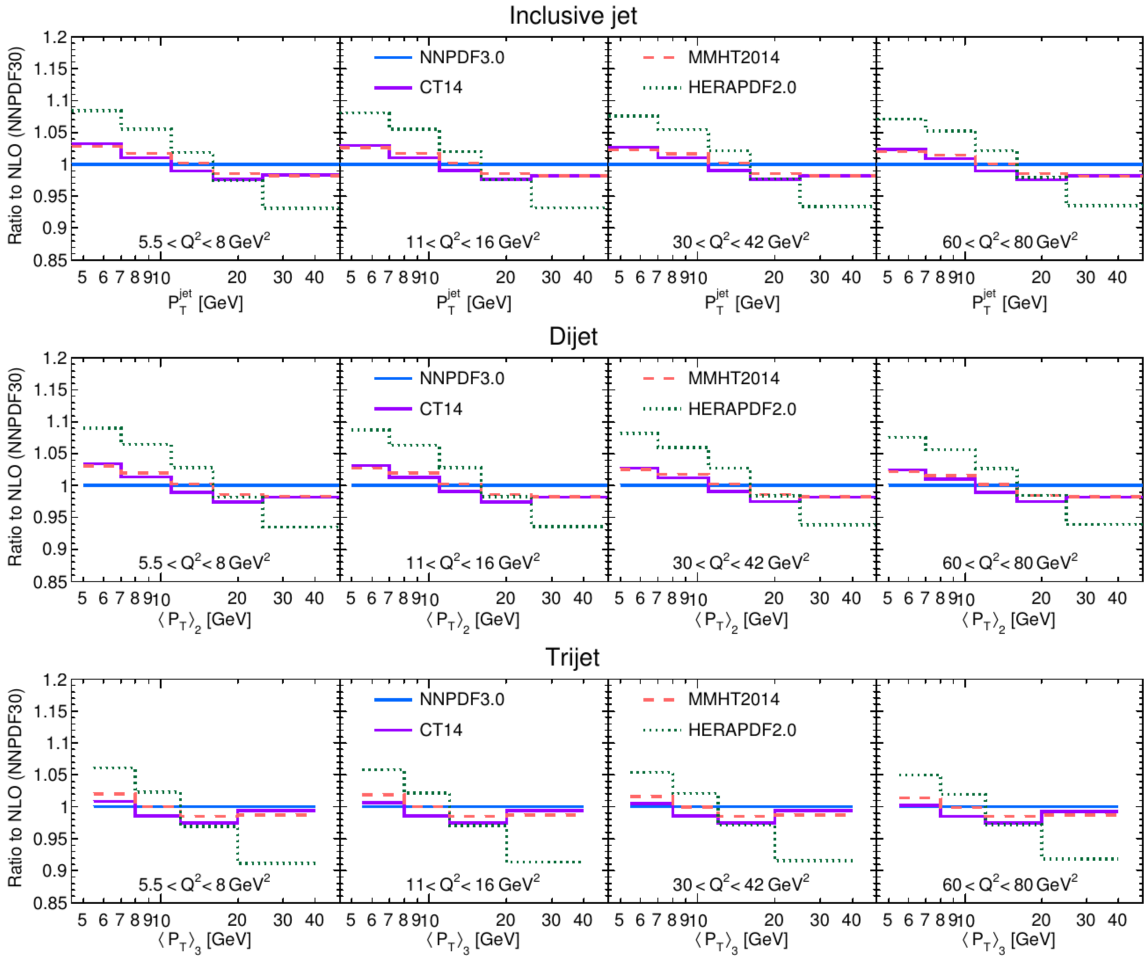


Expected sensitivity to PDFs

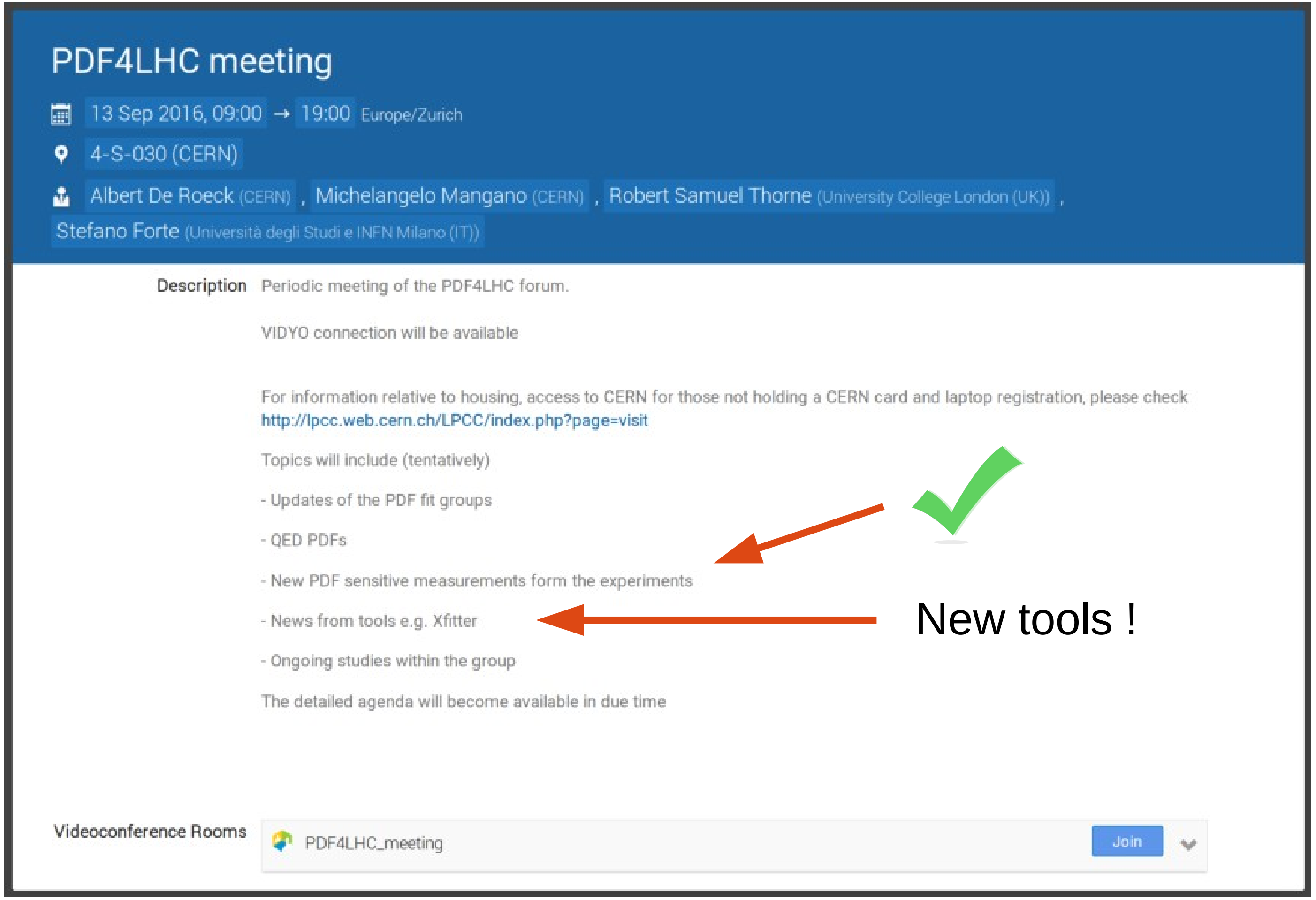
Predictions using different PDFs
- NLO predictions
- NNPDF30, CT14, MMHT, HERAPDF2.0

Comparison
- Agreement of CT14 and MMHT
- NNPDF3.0 predicts harder spectra
- HERAPDF2.0 predicts softer spectra as preferred by data

- High-pT cross sections refer to high-x gluon densities (at low μ_f)



PDF4LHC workshop topics



PDF4LHC meeting

13 Sep 2016, 09:00 → 19:00 Europe/Zurich

4-S-030 (CERN)

Albert De Roeck (CERN) , Michelangelo Mangano (CERN) , Robert Samuel Thorne (University College London (UK)) , Stefano Forte (Università degli Studi e INFN Milano (IT))

Description Periodic meeting of the PDF4LHC forum.

VIDYO connection will be available

For information relative to housing, access to CERN for those not holding a CERN card and laptop registration, please check http://lpcc.web.cern.ch/LPCC/index.php?page=visit

Topics will include (tentatively)

- Updates of the PDF fit groups

- QED PDFs

- New PDF sensitive measurements form the experiments

- News from tools e.g. Xfitter

- Ongoing studies within the group

The detailed agenda will become available in due time

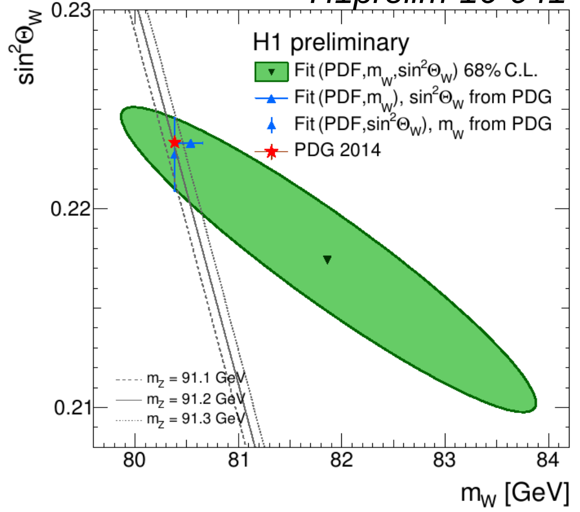
Videoconference Rooms PDF4LHC_meeting Join

H1 electroweak fit and new PDF fitting code

H1 combined QCD + electroweak fit

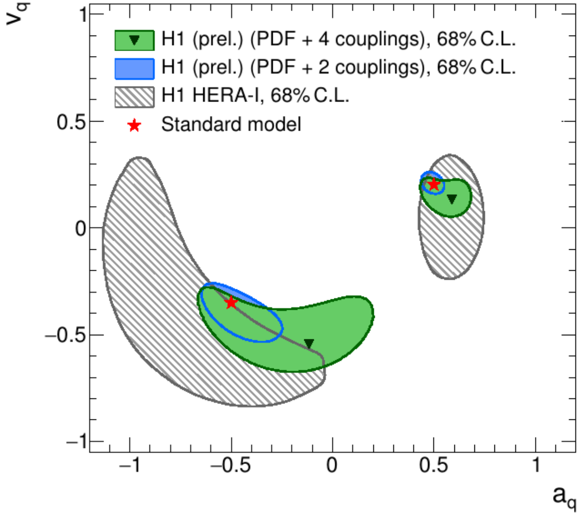
- *H1prelim-16-041*
- Fit of <u>electroweak parameters</u> (weak couplings of quarks, m_W, m_Z, $\sin^2\theta_W$, G_F, ...) and <u>PDFs</u> to all H1 structure function data

H1prelim-16-041



New (public) fitting framework for PDF and SM fits
<u>Alpos</u>

- C++ object-oriented framework
- Well-defined interfaces for new...
  - Data
  - Theoretical predictions (<- Input to those predictions are specified in steering and are not hard-coded)
  - Tasks (e.g. minimizers) or χ^2 functions
- Applicable for <u>PDF fits</u> (H1), <u>α_s</u> (H1, CMS), <u>SM parameters</u> (H1,ATLAS), ...
- Interfaces to fastNLO, Applgrid, QCDNUM, Apfel, EPRC, TMinuit, APC, LHAPDF, CRunDec, various PDF parameterisations, ...
- Exact reproduction of
  - HERAPDF1.0 and 2.0 PDF fits
  - H1, CMS and D0 α_s fits



New fitting-framework very well suited for fits of PDF and studies involving PDF fits

- Alpos is publicly available on request

Conclusions

New jet cross section measurements from H1

- Jet cross sections measured by H1 from HERA-I and HERA-II data in NC DIS for major kinematic range of HERA
- HERA-II jet cross sections at low and high-Q^2 with high experimental precision
- H1 jet data is already employed for $\alpha_s(M_Z)$ fits
  -> Template how to use our data in fits is provided

Sensitivity to PDFs

- High sensitivity to high-x gluon
- Disentangling gluon-α_s correlation, by providing precise measurement of α_s itself

New predictions

- Approx. NNLO predictions for inclusive jets available
- Full NNLO predictions available for inclusive jet and dijet cross sections
  -> Interface to fastNLO in progress

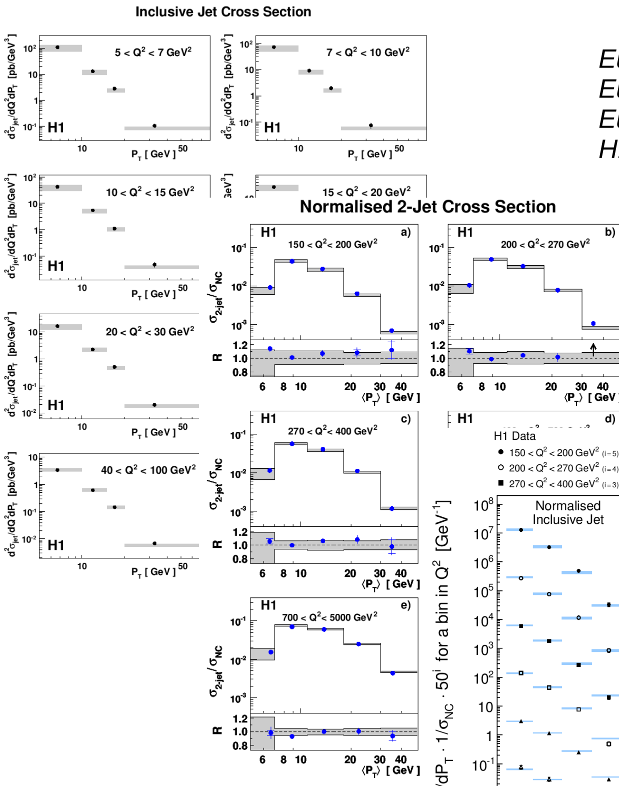
Outlook

- New H1 HERA-II jet data (@ low-Q^2) published by end of this year
- NNLO predictions available as fastNLO-tables by end of this year

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	H1prelim 16-061 H1prelim 16-062
High Q^2	Inclusive jet Dijet Trijet	EPJ C 65 (2010) 363	EPJ C 75 (2015) 2



Eur.Phys.J.C65 (2010) 363
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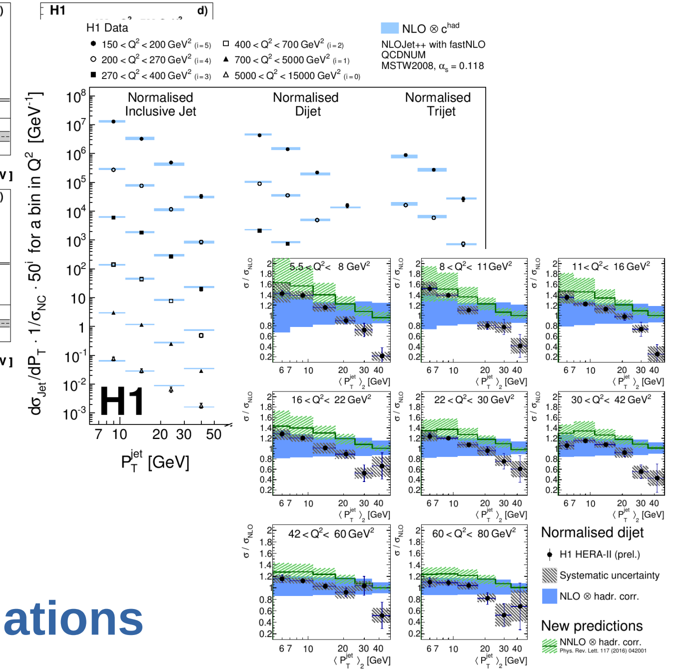
Eur.Phys.J.C75 (2015) 2
H1prelim-16-061 & H1prelim-16-062



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

- Very high experimental precision on $\alpha_s(M_Z)$

Contrain PDFs with H1 jet data

- Very high sensitivy to gluon density
  Particularly at low μ_f

HERA-I and HERA-II data can be used together for PDF fits

Finally we arrived: High-precision jet data and NNLO calculations

Backup

Predictions	**NLO**	**aNNLO**	**NNLO**
Jet cross sections			
Program	nlojet++	JetViP	NNLOJET
pQCD order	NLO [8]	approximate NNLO [12]	NNLO [15]
Calculation detail	Dipole subtraction	NLO plus NNLO contributions from unified threshold resummation formalism	Antenna subtraction
NC DIS cross sections			
Program	QCDNUM	APFEL	APFEL
Heavy quark scheme	ZM-VFNS	FONLL-C	FONLL-C
Order	NLO	NNLO	NNLO
PDF	NNPDF3.0_NLO	NNPDF3.0_NNLO	NNPDF3.0_NNLO
$\alpha_s(M_Z)$	0.118	0.118	0.118
Hadronisation corrections	Djangoh and Rapgap		
Available for			
Normalised inclusive jet	✓	✓	✓
Normalised dijet	✓		✓
Normalised trijet	✓		

Table 2: Summary of the theory predictions for the normalised jet cross sections. All predictions are corrected for hadronisation effects with multiplicative corrections factors obtained from Djangoh and Rapgap.

Regularised unfolding

Regularised unfolding using ROOT::TUnfold

- Calculate unfolded distribution *x* by minimising

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

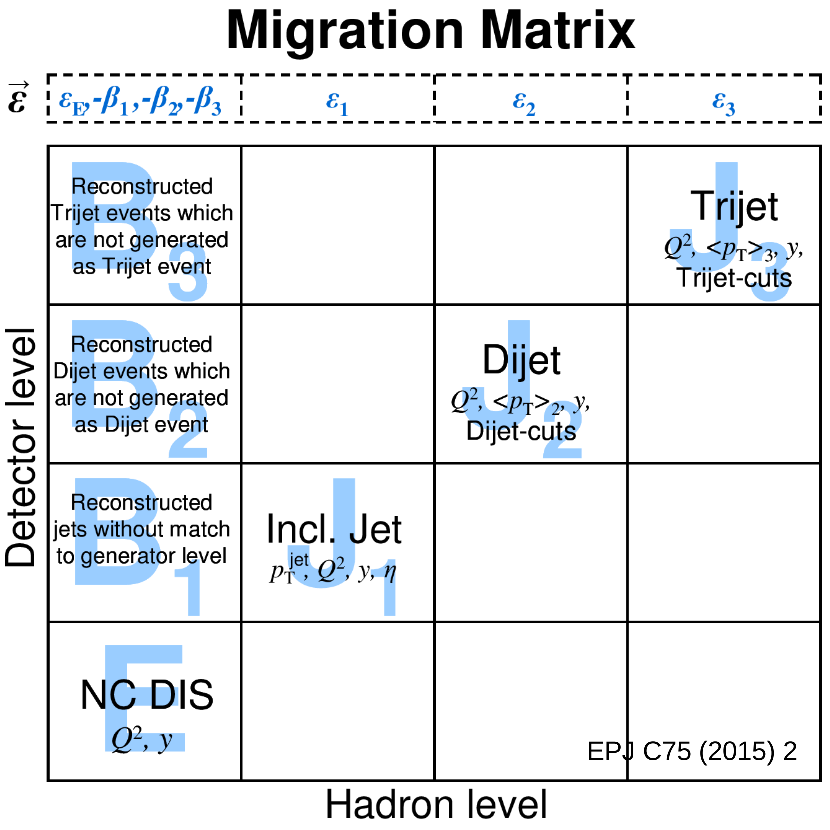
- Linear analytic solution
- Linear propagation of all uncertainties
- Statistical correlations are considered in V_y

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



The H1 experiment

H1 multi-purpose detector

Asymmetric design

Trackers

- Silicon tracker
- Jet chambers
- Proportional chambers

Calorimeters

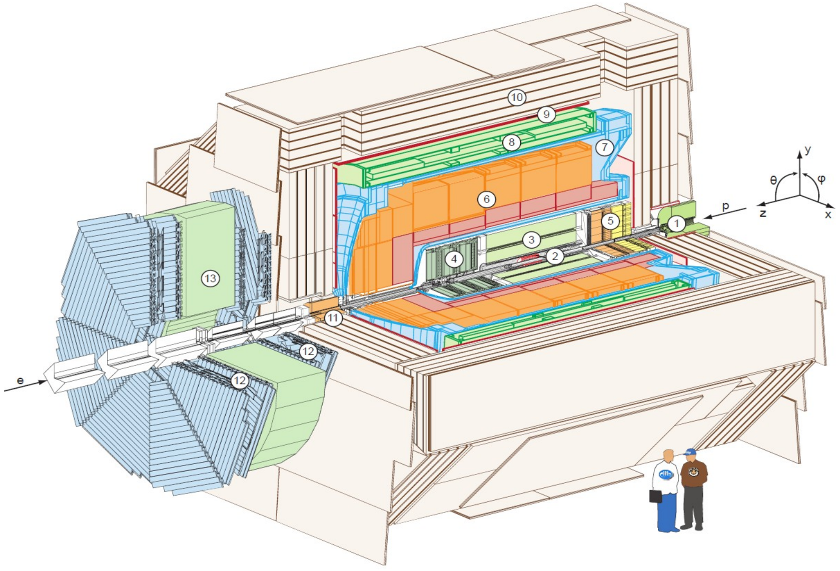
- Liquid Argon sampling calorimeter
- SpaCal: scintillating fiber calorimeter

Superconducting solenoid

- 1.15T magnetic field

Muon detectors

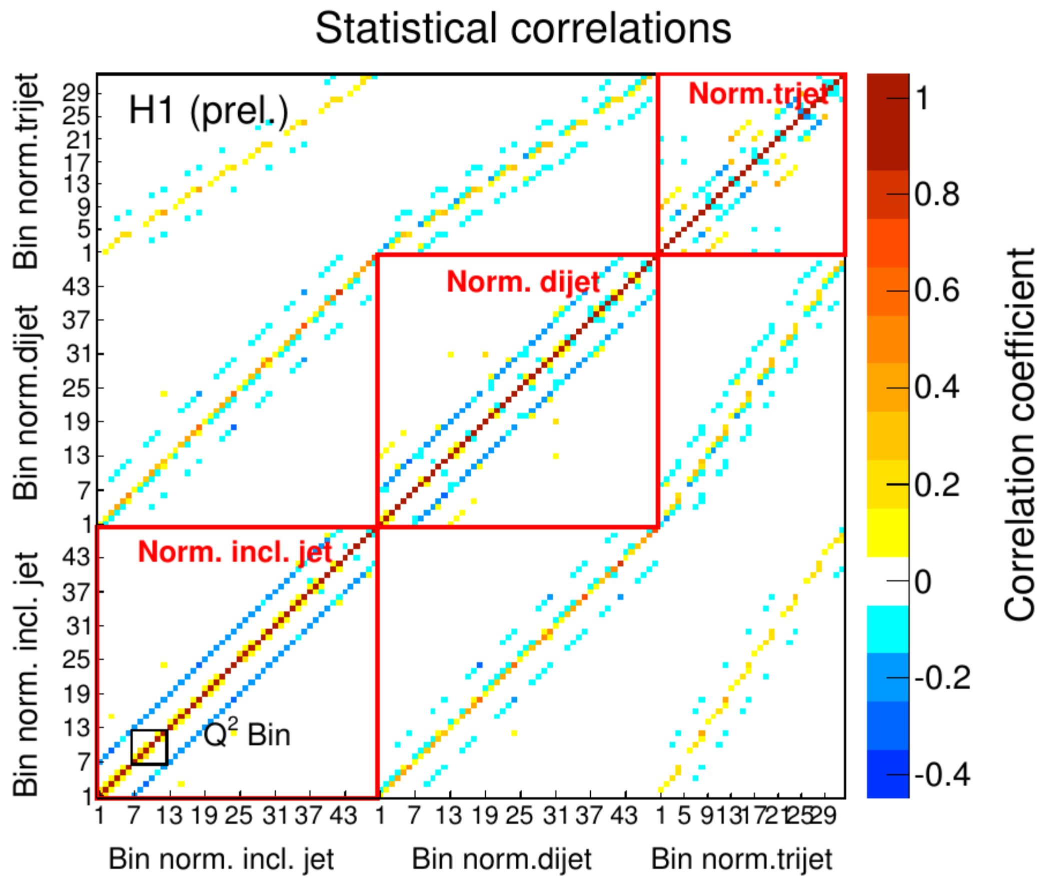
Drawing of the H1 experiment



Excellent control over experimental uncertainties

- Overconstrained system in NC DIS
- Electron measurement: 0.5 – 1% scale uncertainty
- Jet-calibration with neural networks as functions of η and p_T
  - Jet energy scale: 1%
- Luminosity: 2.5%

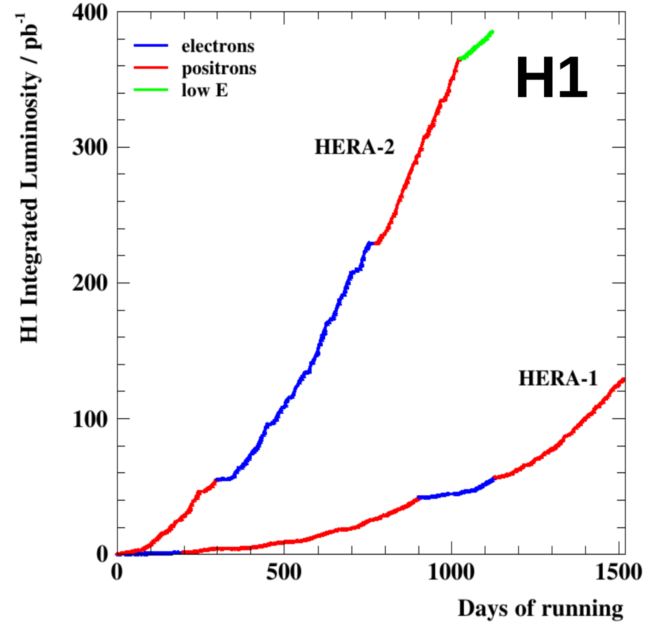
Stat. correlations of H1 low-Q^2 multijets



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}

H1 EW-fit: methology II

New C++-based fitting code for PDF and more general fits developed (Alpos)

- DGLAP evolution of PDFs in NNLO QCD (QCDNUM with ZMVFNS)
- PDFs are parameterised at starting scale $Q_0^2 = 1.9\,\text{GeV}^2$ (similar to HERAPDF2.0)

xg	xg
xu_v	$xU = xu + xc$
xd_v	$xD = xd + xs$
$x\bar{U}$	$x\bar{U} = x\bar{u} + x\bar{c}$
$x\bar{D}$	$x\bar{D} = x\bar{d} + x\bar{s}$

→

$$
\begin{aligned}
xg(x) &= A_g x^{B_g}(1-x)^{C_g} - A'_g x^{B'_g}(1-x)^{C'_g},\\
xu_v(x) &= A_{u_v} x^{B_{u_v}}(1-x)^{C_{u_v}}\left(1 + E_{u_v}x^2\right),\\
xd_v(x) &= A_{d_v} x^{B_{d_v}}(1-x)^{C_{d_v}},\\
x\bar{U}(x) &= A_{\bar{U}} x^{B_{\bar{U}}}(1-x)^{C_{\bar{U}}}\left(1 + D_{\bar{U}}x\right),\\
x\bar{D}(x) &= A_{\bar{D}} x^{B_{\bar{D}}}(1-x)^{C_{\bar{D}}}.
\end{aligned}
$$

fixed or constrained by sum-rules
parameters set equal but free

- Use only data with $Q^2 >= 12\,\text{GeV}^2$

χ^2 Definition

- Uncertainties on cross sections are assumed to be 'log-normal' distributed (relative uncertainties)
- Uncertainties on polarisation measurements are assumed to be 'normal' distributed
- Correlations of syst. uncertainties between different datasets are considered

$$\chi^2 = \left(\log(d) - \log(t)\right)^T V_R^{-1} \left(\log(d) - \log(t)\right) + (d-t)^T V_A^{-1} (d-t)$$

Fit parameters

- 13 PDF parameters
- 4 polarisation values
- 4 Light-quark couplings (or other SM parameters)
- More general also 'nuisance parameters' of syst. uncertainties