The 7th Joint International HADRON STRUCTURE'13 Conference
30 June – 4 July, Tatranské Maltiare, Slovakia

Precision QCD measurments at HERA:

Jet production and α_s determination

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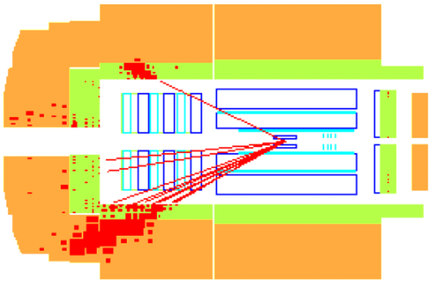
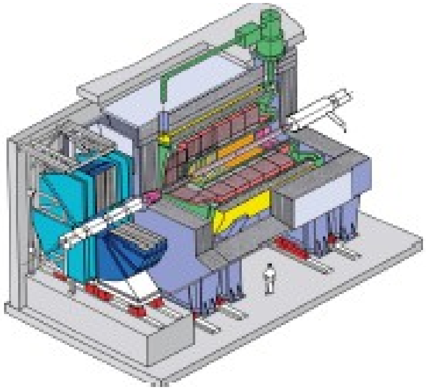
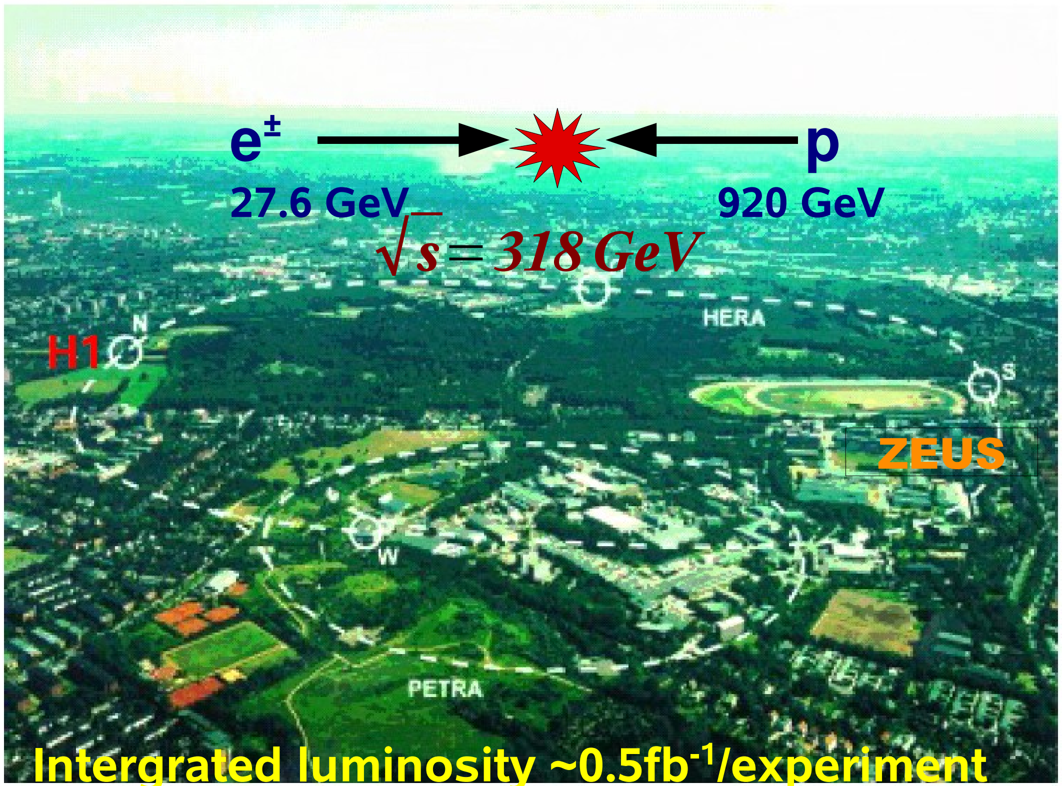
on behalf of the H1 and ZEUS collaborations

HERA Experiments

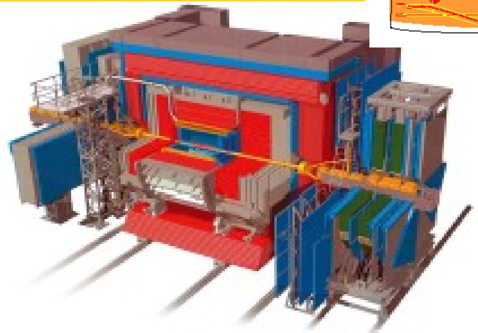


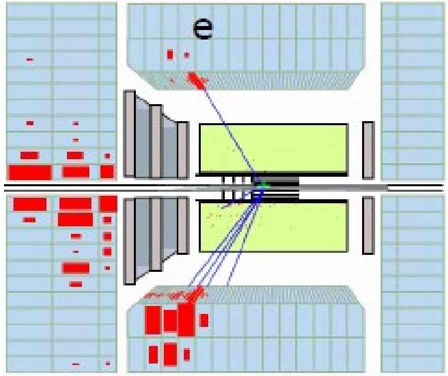


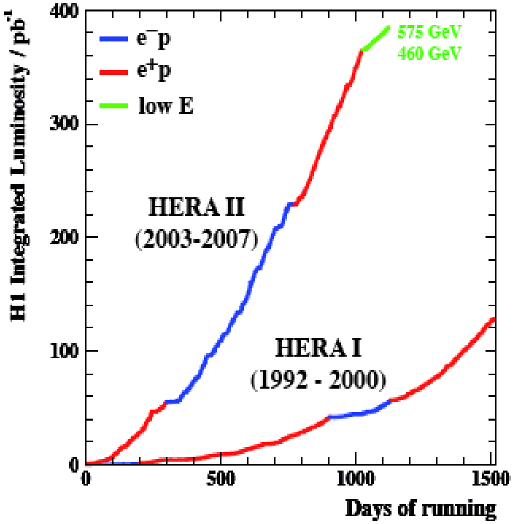


$\sqrt{s} = 318\,GeV$

Intergrated luminosity ~0.5fb^{-1}/experiment







Standard DIS variables :

Q^2 virtuality of the exchanged boson

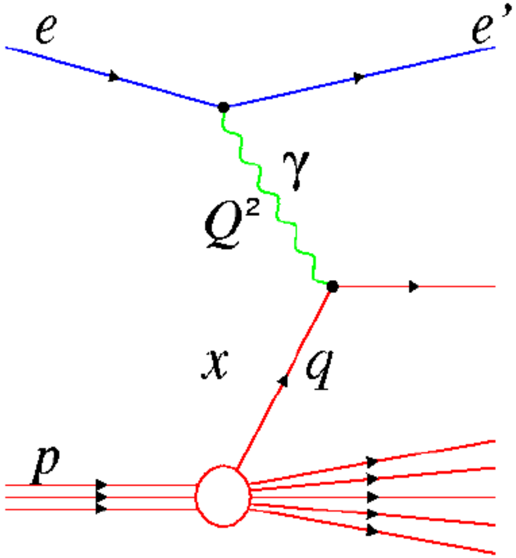
x in QPM fraction of proton momentum carried by struck quark

$y = Q^2 / xs$ inelasticity

Kinematics regimes:

$Q^2 \approx 0\ GeV^2$ – Photoproduction (γp)

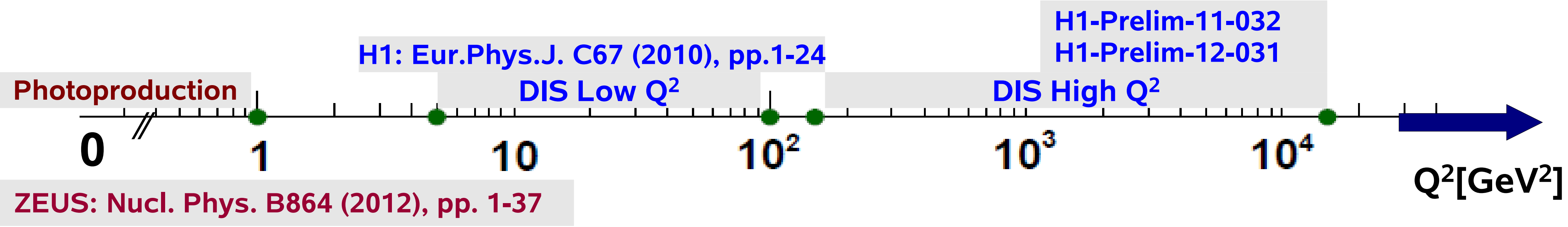
$Q^2 > 1 GeV^2$ - DIS



Overview

Part I

- jets production in large range of Q^2: inclusive jets(PHP) and multijets(DIS)
- measurements of the cross sections and extraction of $\alpha_s(M_z)$
- comparison with NLO prediction



H1: Eur.Phys.J. C67 (2010), pp.1-24

H1-Prelim-11-032
H1-Prelim-12-031

Photoproduction

DIS Low Q^2

DIS High Q^2

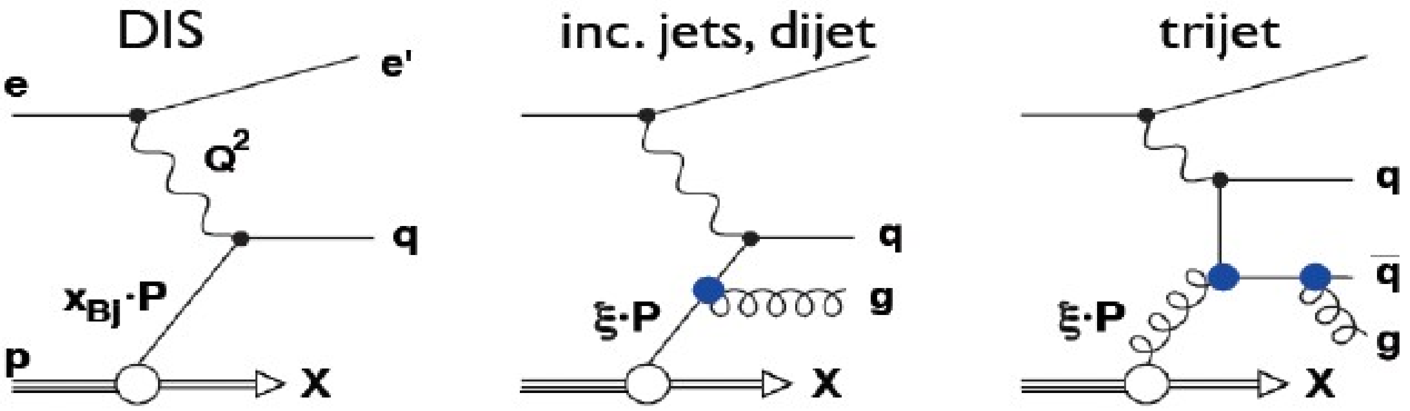
ZEUS: Nucl. Phys. B864 (2012), pp. 1-37

Part II

H1:Eur. Phys. J. C72 (2012) 1910

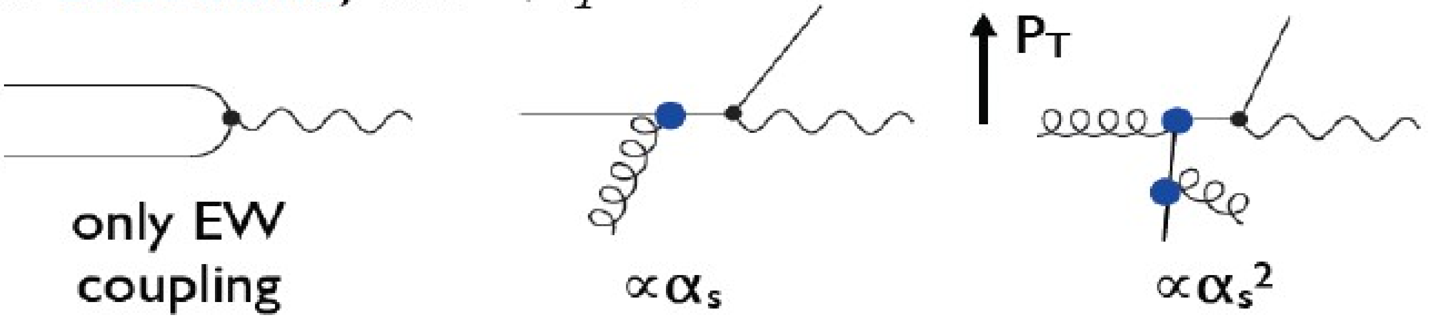
Test of QCD evolution mechanisms (*DGLAP / BFKL / CCFM*)
using azimuthal correlation
between the most forward jet and the scattered positron in DIS

Jet Production in DIS



The momentum fraction of the proton carried by the parton entering the hard subprocess : $\xi = x_{Bj}(1 + M_{12}^2 / Q^2)$

Boost to Breit frame, $2xP + q = 0$



Only hard QCD process generates significant P_T in Breit frame
Direct sensitivity to α_s and gluon PDF

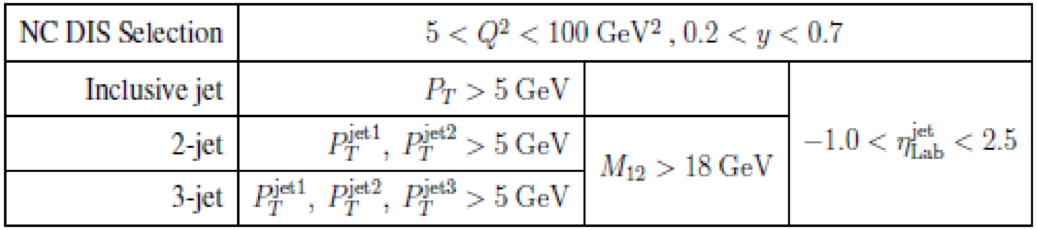
Multi-Jet Production in DIS

Low Q^2

High Q^2

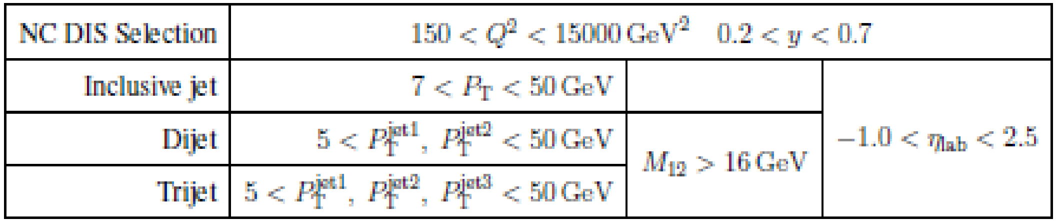
NC DIS and Jet selections

HERA-1 data 44pb^{-1}



NC DIS Selection	$5 < Q^2 < 100\ \mathrm{GeV}^2$, $0.2 < y < 0.7$		
Inclusive jet	$P_T > 5\ \mathrm{GeV}$		$-1.0 < \eta^{\mathrm{jet}}_{\mathrm{Lab}} < 2.5$
2-jet	$P_T^{\mathrm{jet1}},\ P_T^{\mathrm{jet2}} > 5\ \mathrm{GeV}$	$M_{12} > 18\ \mathrm{GeV}$	
3-jet	$P_T^{\mathrm{jet1}},\ P_T^{\mathrm{jet2}},\ P_T^{\mathrm{jet3}} > 5\ \mathrm{GeV}$		

HERA-2 data 350pb^{-1}



NC DIS Selection	$150 < Q^2 < 15000\ \mathrm{GeV}^2$ $0.2 < y < 0.7$		
Inclusive jet	$7 < P_T < 50\ \mathrm{GeV}$		$-1.0 < \eta_{\mathrm{lab}} < 2.5$
Dijet	$5 < P_T^{\mathrm{jet1}},\ P_T^{\mathrm{jet2}} < 50\ \mathrm{GeV}$	$M_{12} > 16\ \mathrm{GeV}$	
Trijet	$5 < P_T^{\mathrm{jet1}},\ P_T^{\mathrm{jet2}},\ P_T^{\mathrm{jet3}} < 50\ \mathrm{GeV}$		

- Cross sections are measure as function of Q^2, p_T($<p_T>$) and ξ
- main experimental uncertainties
  - jet energy scale 2% → $\Delta\sigma/\sigma$ = 4-10%
  - uncertainty in acceptance → $\Delta\sigma/\sigma$= 2-15%
- NLO calculation: NLOJET++
  - MSbar scheme for 5 massless quark flavors
  - PDFs: CTEQ6.5M

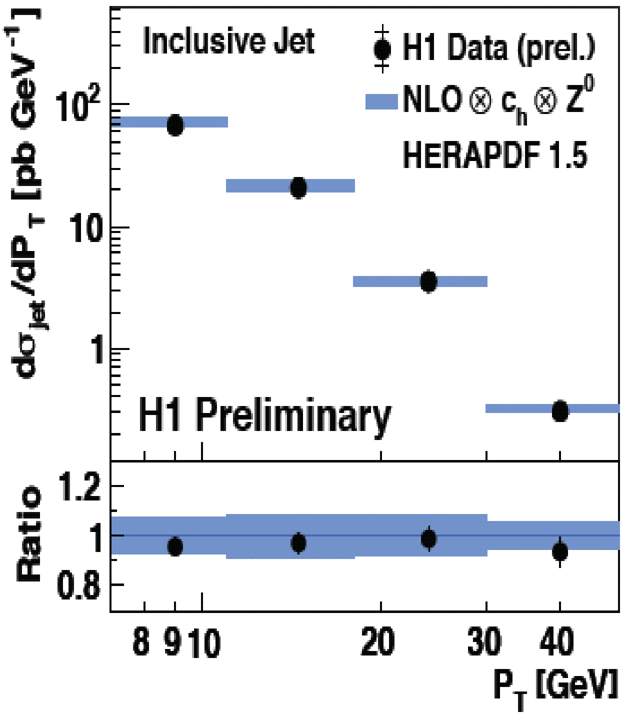
- Cross sections are measure as function of Q^2, p_T($<p_T>$) and ξ
- main experimental uncertainties
  - jet energy scale 1% → $\Delta\sigma/\sigma$ = 3-10%
  - uncertainty in acceptance → $\Delta\sigma/\sigma$= 4-5%
- NLO calculation: NLOJET++
  - MSbar scheme for 5 massless quark flavors
  - PDFs: HERAPDF1.5, CT10

Multi-Jet Cross Sections at High Q^2

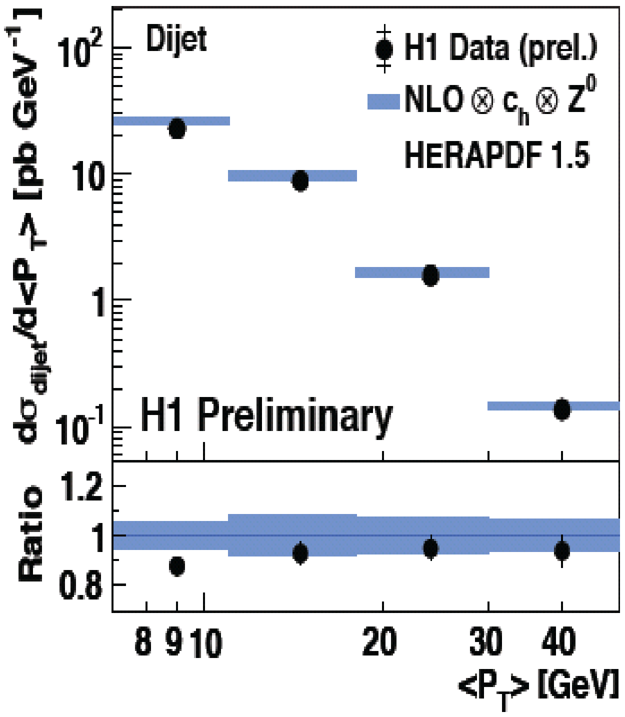
H1-Prelim-11-032

Single Differential Cross Sections

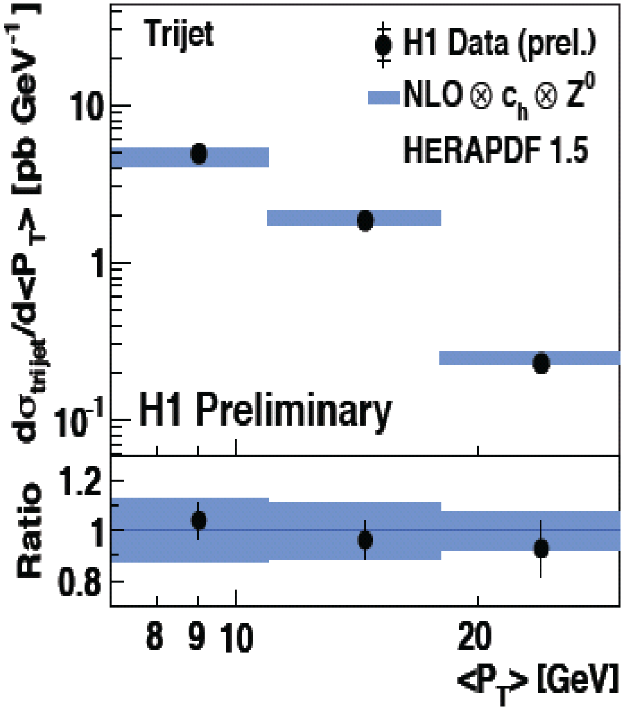
Incl. Jet



2- Jet



3- Jet

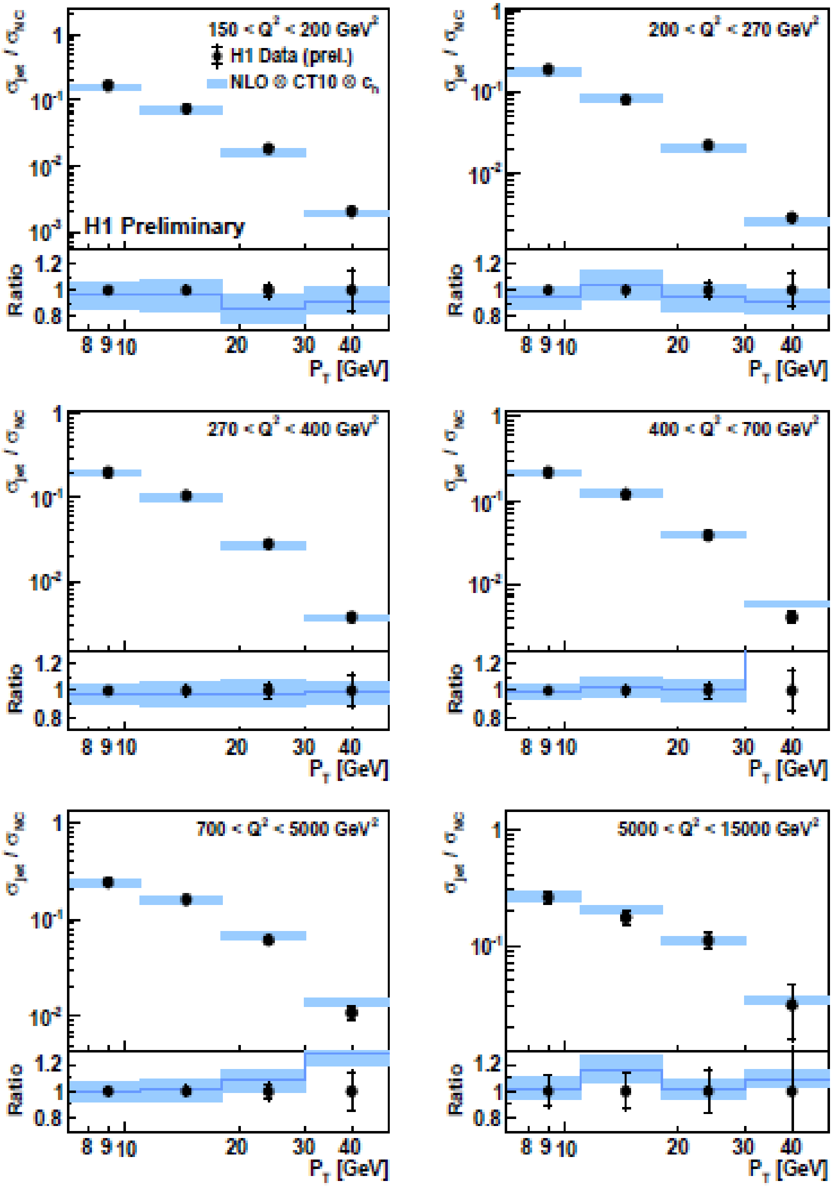


NLO QCD with $\mu_r = \sqrt{(Q^2 + P_T^2)/2}$ and HERAPDF 1.5 describes well inclusive jet, dijet and trijet single differential cross sections

Normalised Multi-Jet Cross Sections at High Q^2

H1-Prelim-12-031

Double Differential Inclusive Jet Cross Sections



Benefit:

partial cancellation of experimental and theoretical uncertainties

Comparison with

NLOJet++ and QCDNUM corrected to hadronisation effects

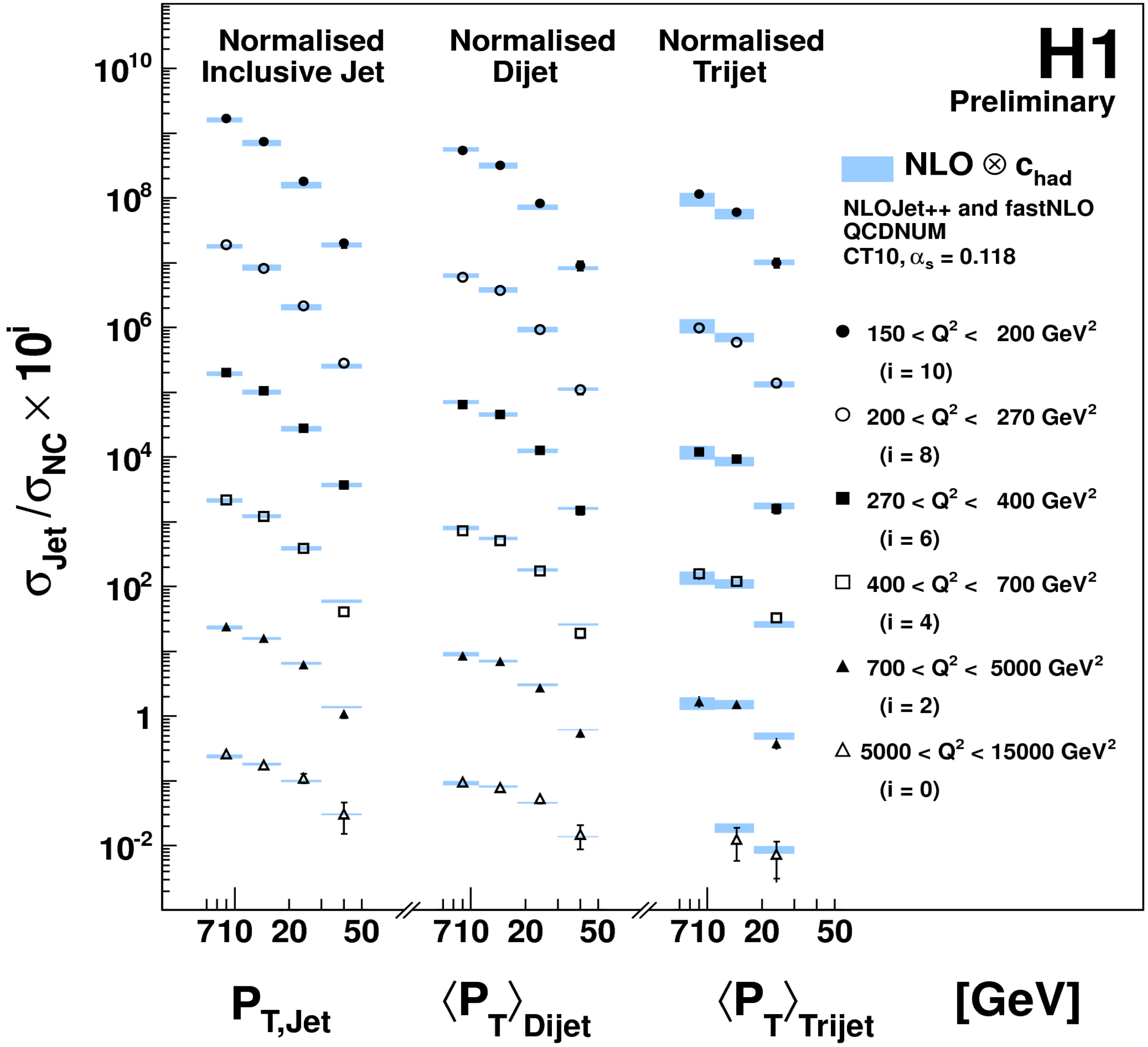
Scale choice:

$\mu^2_f = Q^2$,

$\mu^2_r = (Q^2+P_T^2)/2$

In all bins (besides the highest Q^2 and highest P_T)
the experimental uncertainties are smaller than the theoretical uncertainties

Normalized Multi-Jet Cross Sections at High Q^2



NLO Calculation:

NLOJet++ and QCDNUM corrected for hadronisation effects

Scale Choice:

$\mu_f^2 = Q^2$

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

- **Small experimental uncertainties**
- **Good NLO description of the data**

$\alpha_s(M_Z)$ from Normalized Multi-Jet Cross Sections at High Q^2

$\alpha_s(M_z)$ Combined Fit

Largest benefit is from a combined fit

simultaneous fit to normalised inclusive jet, dijet and trijet cross sections (all correlations are included)

Sensitive to higher orders

Theoretical uncertainties estimated by variation of scale, k-factor ($k = \sigma_{NLO}/\sigma_{LO}$) – an estimator of higher order contributions reaches values up to 1.45

Restrict analysis to k < 1.3

faster convergence of perturbative series

trade-off between number of data points and smaller theoretical uncertainties

Normalised Multijets with k < 1.3

χ^2/ndf: 53.2/41 = 1.30

$$\alpha_s(M_Z) = 0.1163 \pm 0.0011(exp.) \pm 0.0008(had)^{+0.0044}_{-0.0035}(th.) \pm 0.0014(PDF)$$

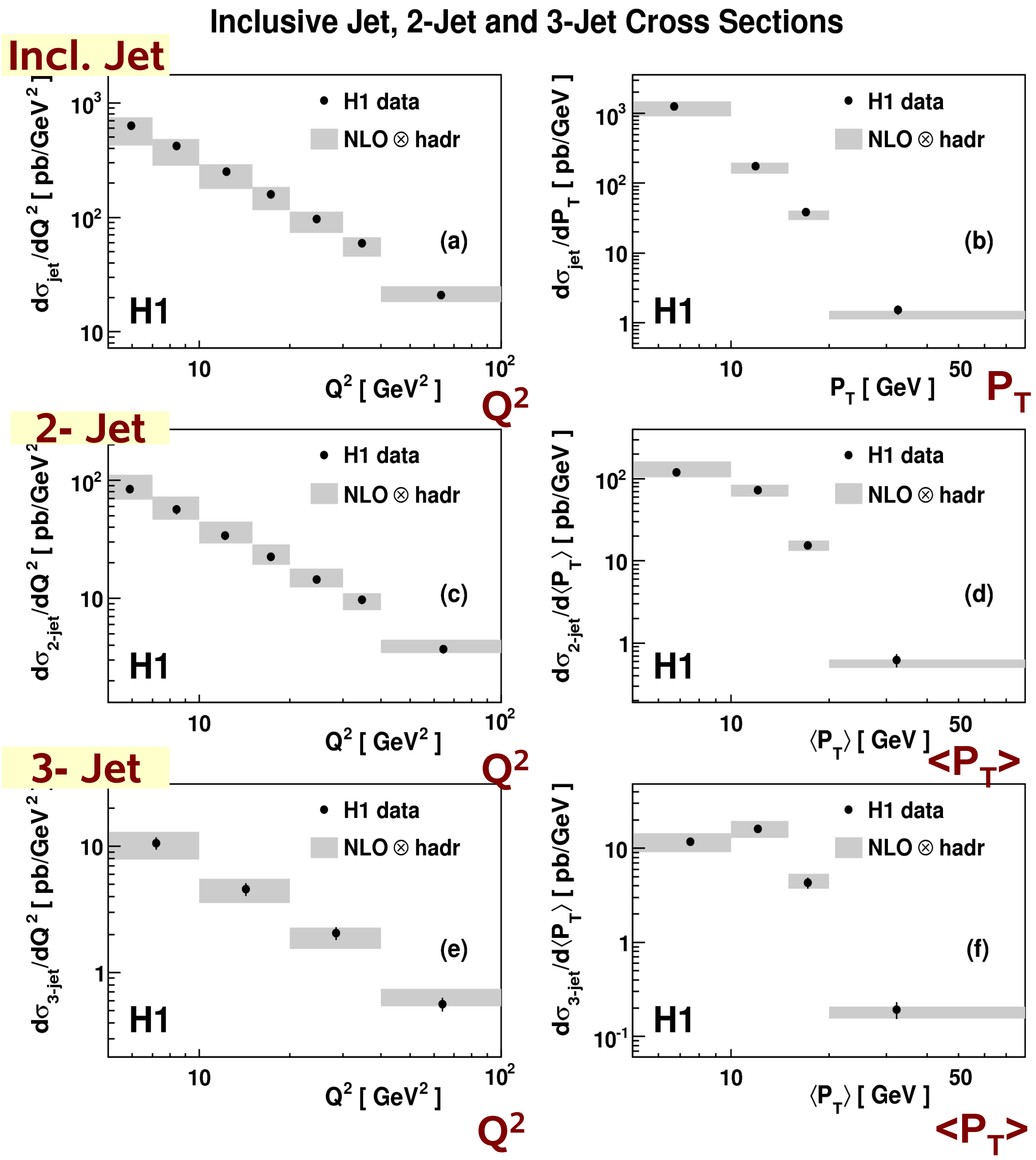
Consistent with other $\alpha_s(M_Z)$ measurements

Small experimental uncertainties

Theoretical uncertainties are larger than the experimental

Multi-Jet Cross Sections at Low Q^2

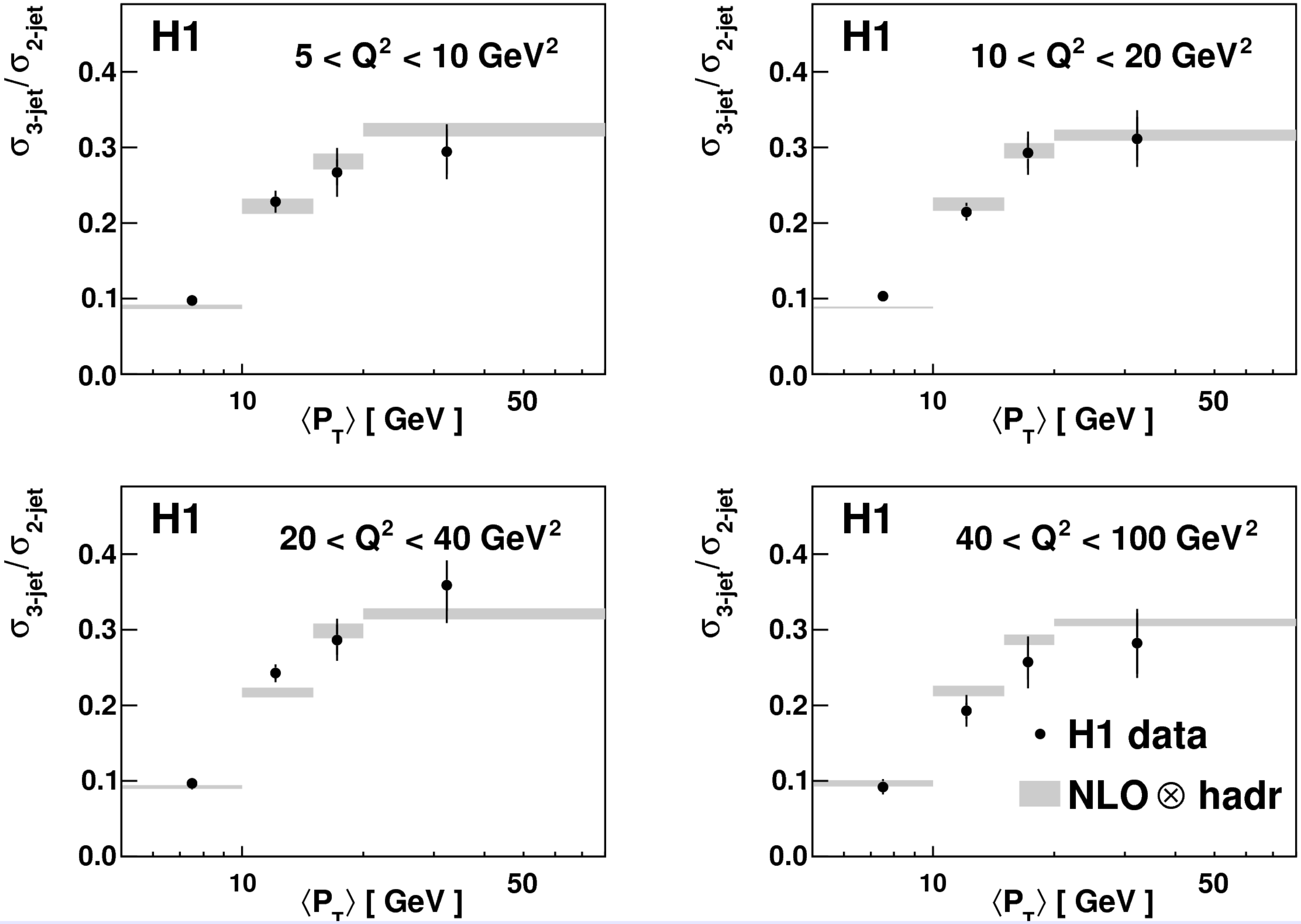
Eur.Phys.J. C67 (2010), pp.1-24



- measurements are well discribed by NLO
- Experimental uncertainty 6-11%
- theory uncertainty dominated by renorm. scale uncertainty: 10%(highest Q^2 and P_T) to 30%(lowest Q^2 and P_T)
- pdf uncertainty 2-6%
- low predictive power of NLO at low Q^2 and/or low P_T
- orders beyond NLO are needed to match the precision of data

Multi-Jet Cross Sections at Low Q^2

3-Jet to 2-Jet Ratio

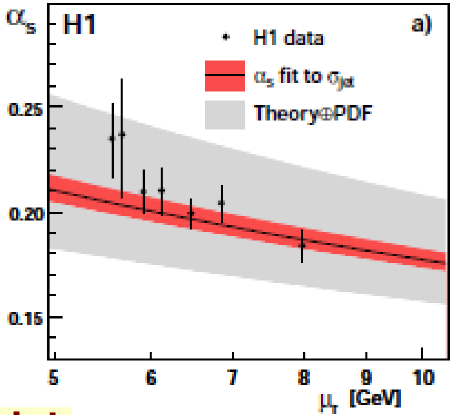


- in ratio normalisation errors cancel and other syst. Uncertainties reduced by 50%
- reduced sensitivity to renormalisation scale variation in theory
- good description of ratio by NLOjet++

α_s from Multi-Jet Cross Sections at Low Q^2

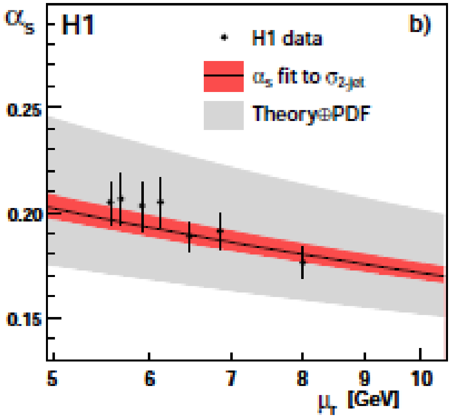
Incl. Jet

α_s from Inclusive Jet Cross Sections



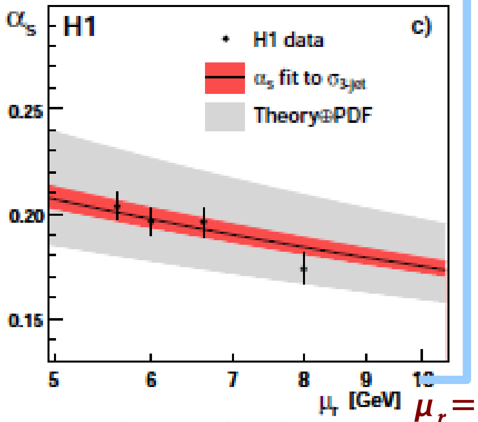
2- Jet

α_s from 2-Jet Cross Sections



3- Jet

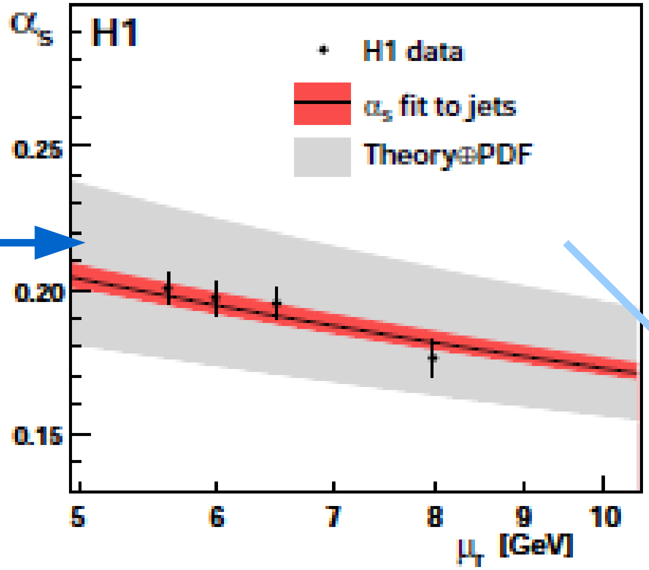
α_s from 3-Jet Cross Sections



$$\mu_r = \mu_f = \sqrt{(Q^2 + p_{T,jet}^2)/2}$$

Combined Fit Incl.Jet+2-jet+3-jet :

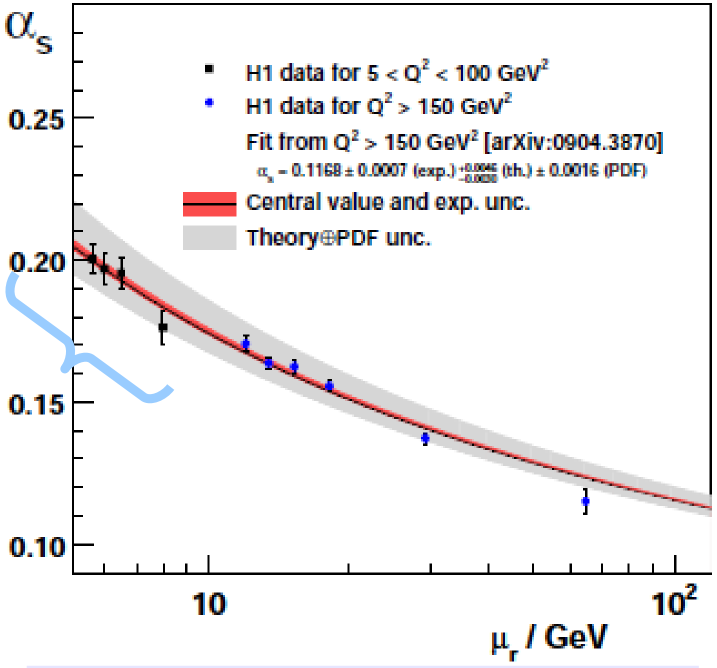
$$\alpha_S(M_Z) = 0.1160 \pm 0.0014\,(exp.)^{+0.0093}_{-0.0077}\,(th.) \pm 0.0016\,(PDF)$$



Experimental uncertainties reduced significantly wrt individual α_s extraction

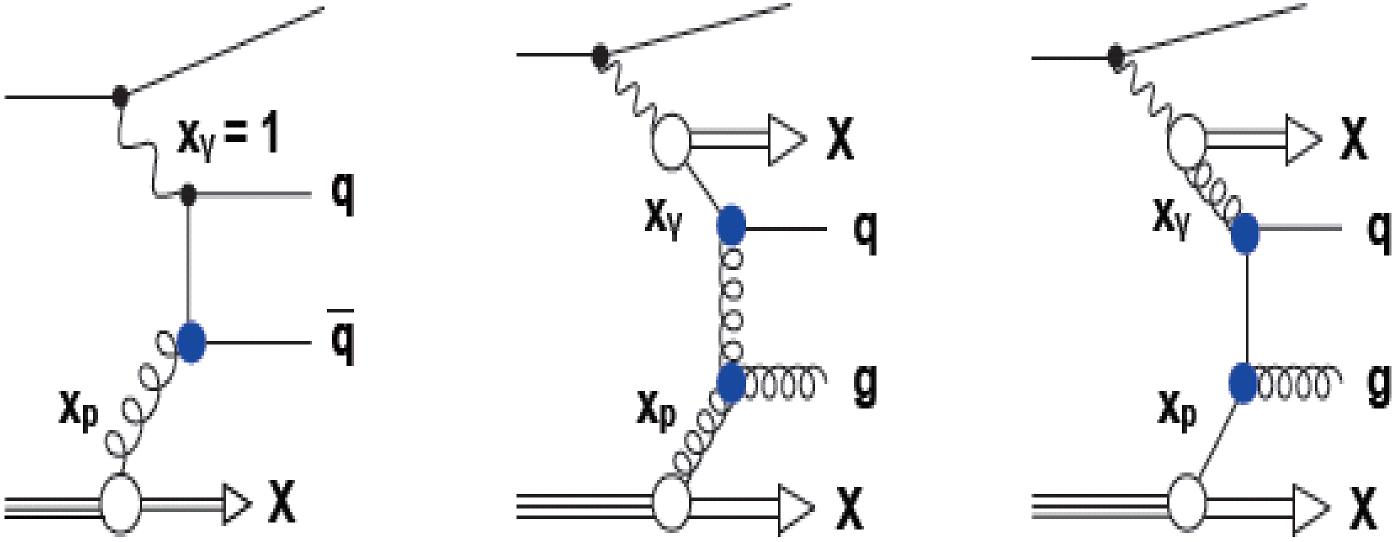
α_s from Jet Cross Sections in DIS

(High Q2 results: Eur.Phys.J.C65 (2010) 363), *not this talk*)



Remarkable agreement between low, high Q^2 α_s extraction and QCD expectations

Jet Production in Photoproduction



direct photoproduction

resolved photoproduction

Direct sensitivity to α_S, gluon and photon PDFs

Jet Production in Photoproduction

Data: ~300pb^{-1} (HERA-2)

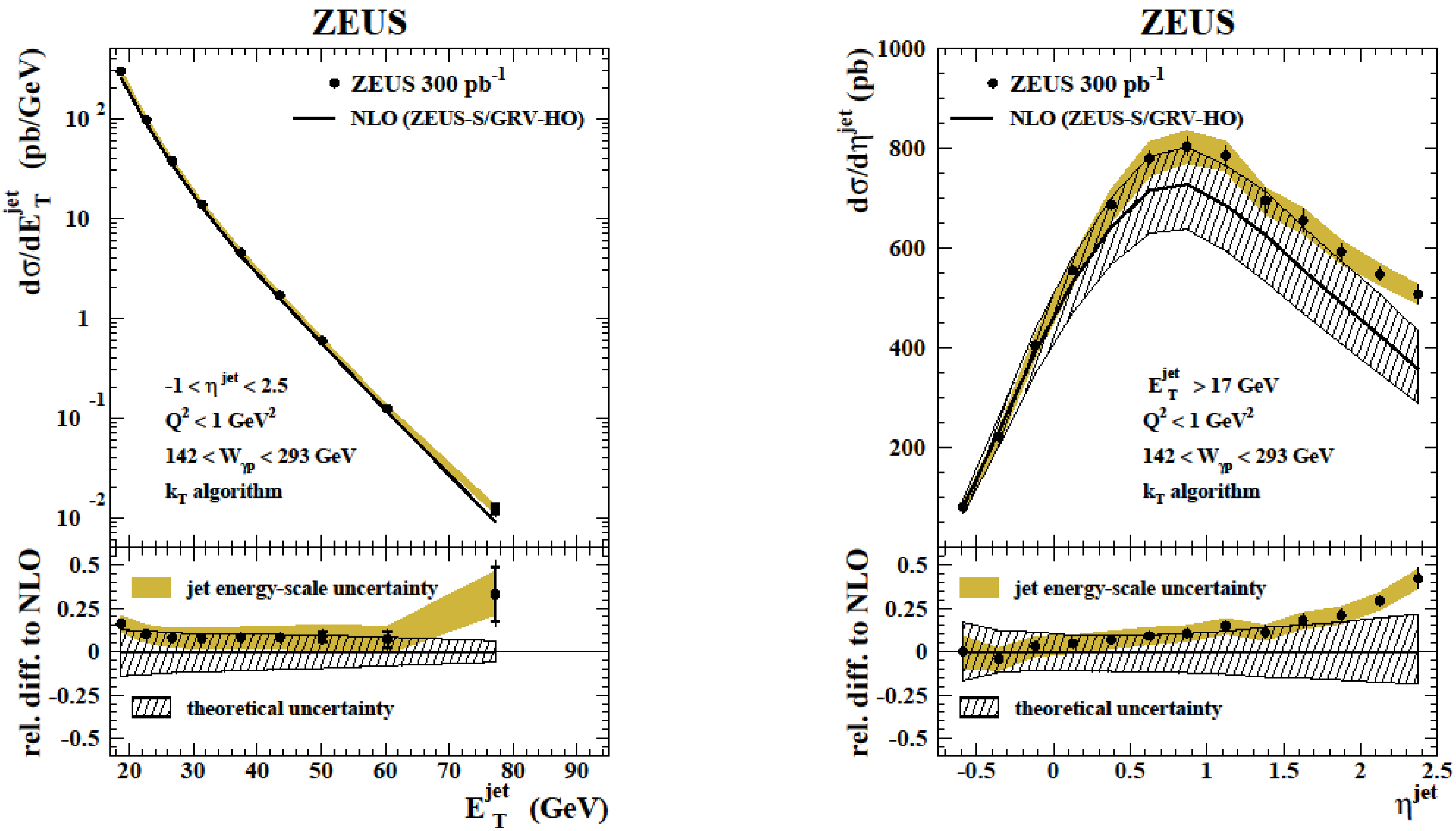
Single and double differential inclusive jet cross sections are measured as functions of jet transverse energy E_T^{jet} and pseudorapidity η^{jet} for

photon virtuality: $Q^2 < 1$ GeV^2
γp centre-of-mass energies: $142 < W_{\gamma p} < 293$ GeV
Jets in lab frame:
$E_T^{jet} > 17$ GeV
$-1 < \eta^{jet} < 2.5$

Jets were identified using the k_T, anti-k_T and SIScone jet algorithms in laboratory frame.

Inclusive Jets in Photoproduction

Nucl. Phys. B864 (2012) 1



Data compared to NLO QCD ($O(\alpha_s^2)$):

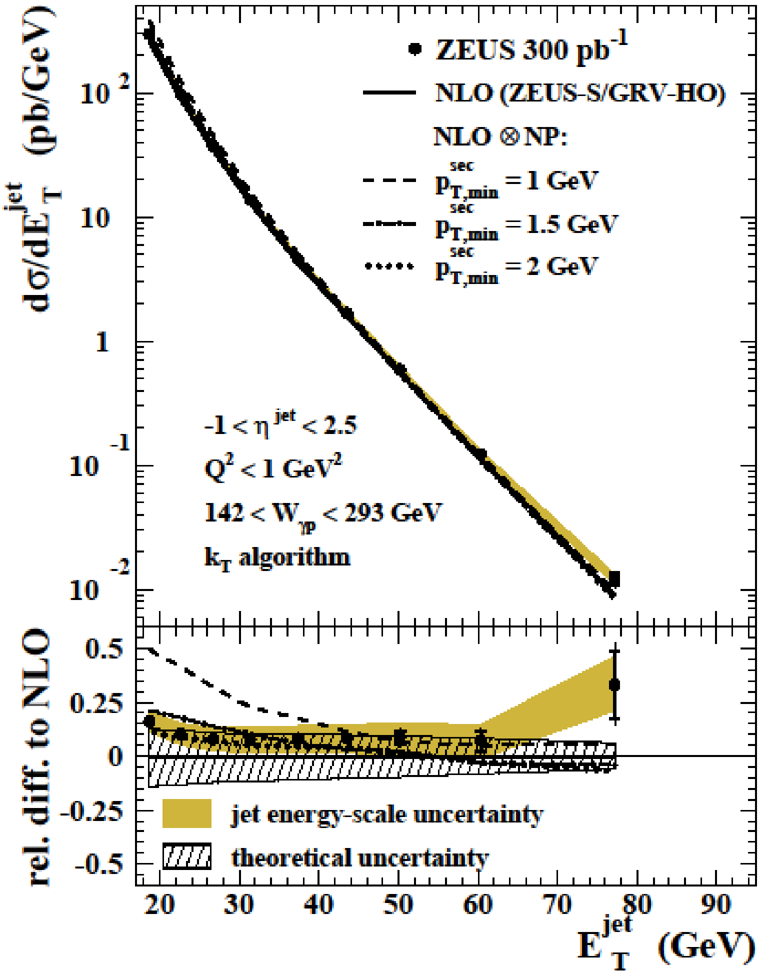
$\mu_R = \mu_F = \mu = E_T^{jet}$

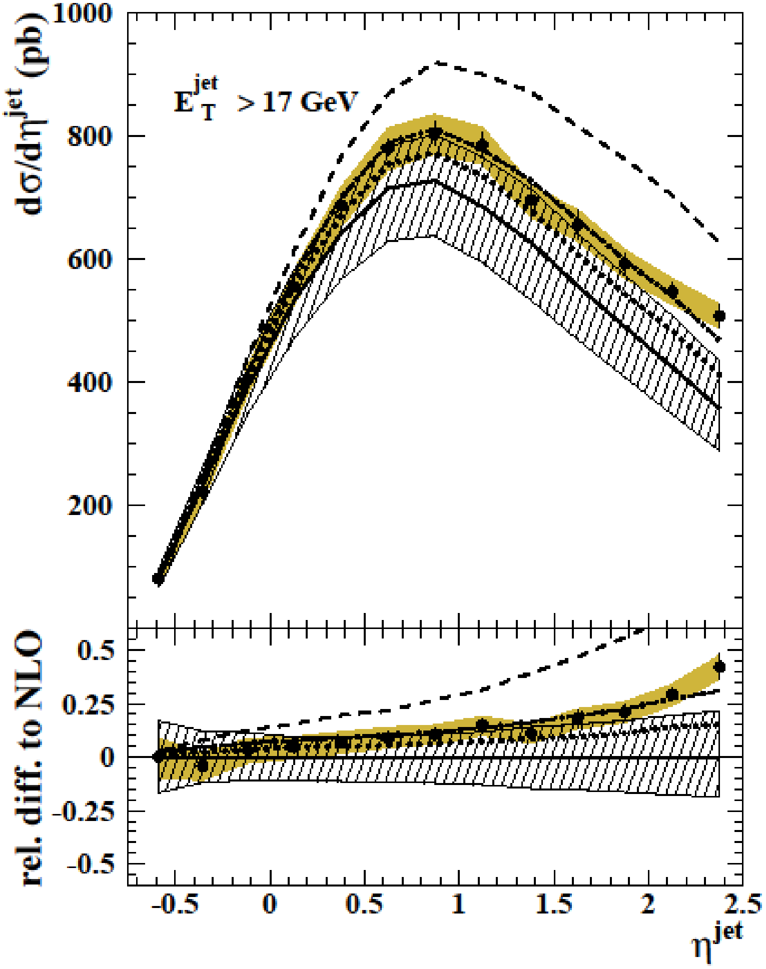
PDFs: proton PDF -ZEUS-s, photon PDF – GRV-HO, $\alpha_s = 0.118$

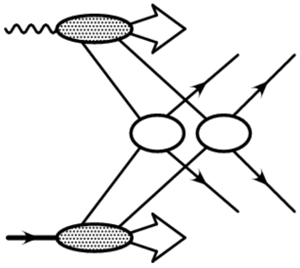
The NLO QCD calculation reproduce $d\sigma/dE_T^{jet}$ well, $d\sigma/d\eta^{jet}$ is well described for $\eta^{jet} < 2$

Inclusive Jets in Photoproduction

Non-perturbative Effects







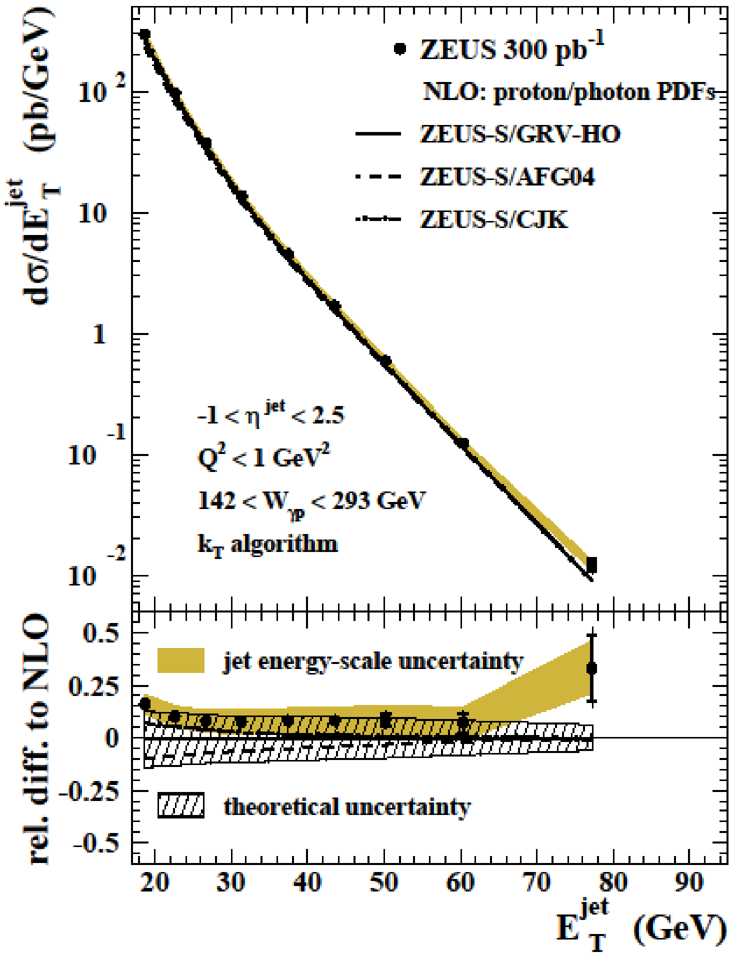
Multi-parton interactions not includeed in NLO calculation

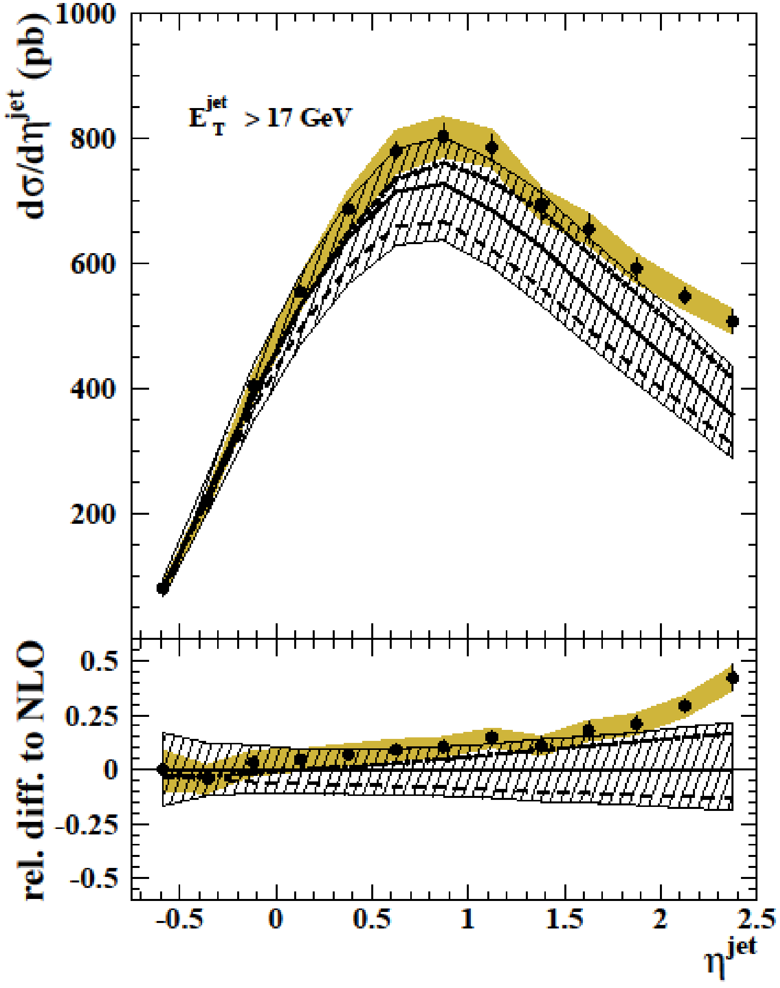
Data comparison to the NLO QCD calculation including an estimation of non-perturbative effects from underlying events (not related to hadronisation)

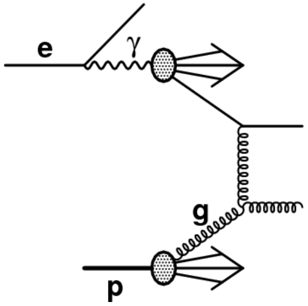
Possible presence of effects in the data, which are not included in the NLO QCD calculation

Inclusive Jets in Photoproduction

Dependence on photon PDFs





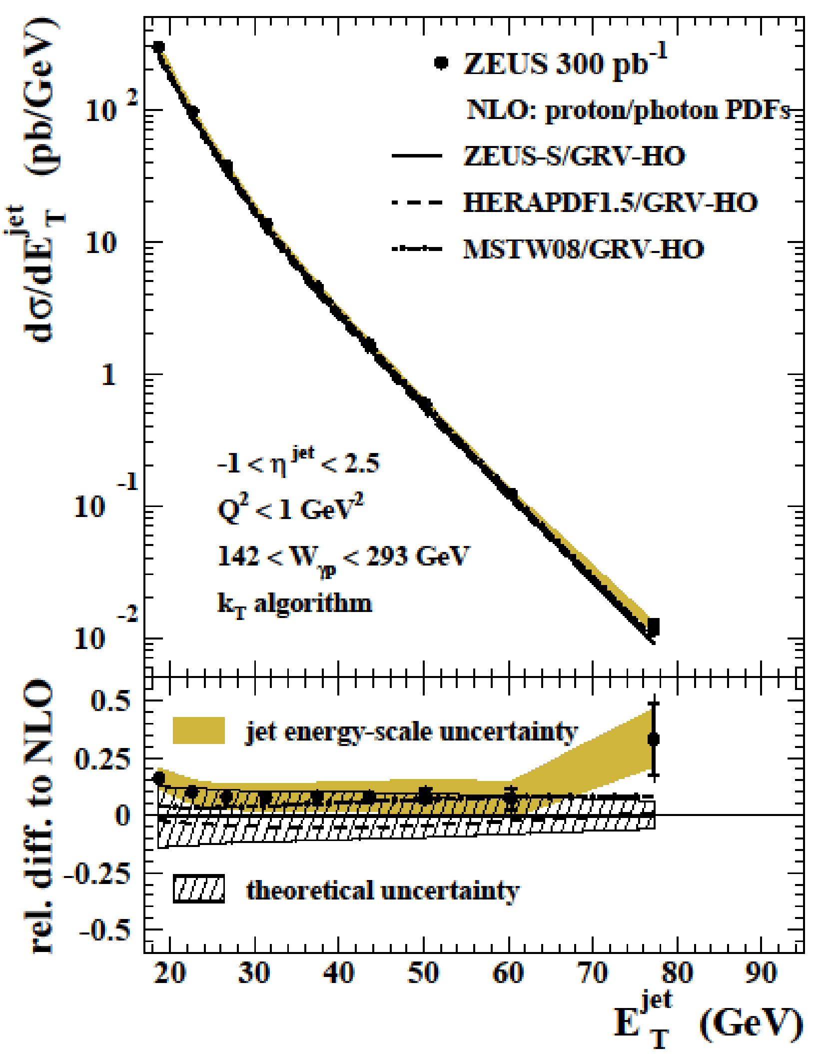


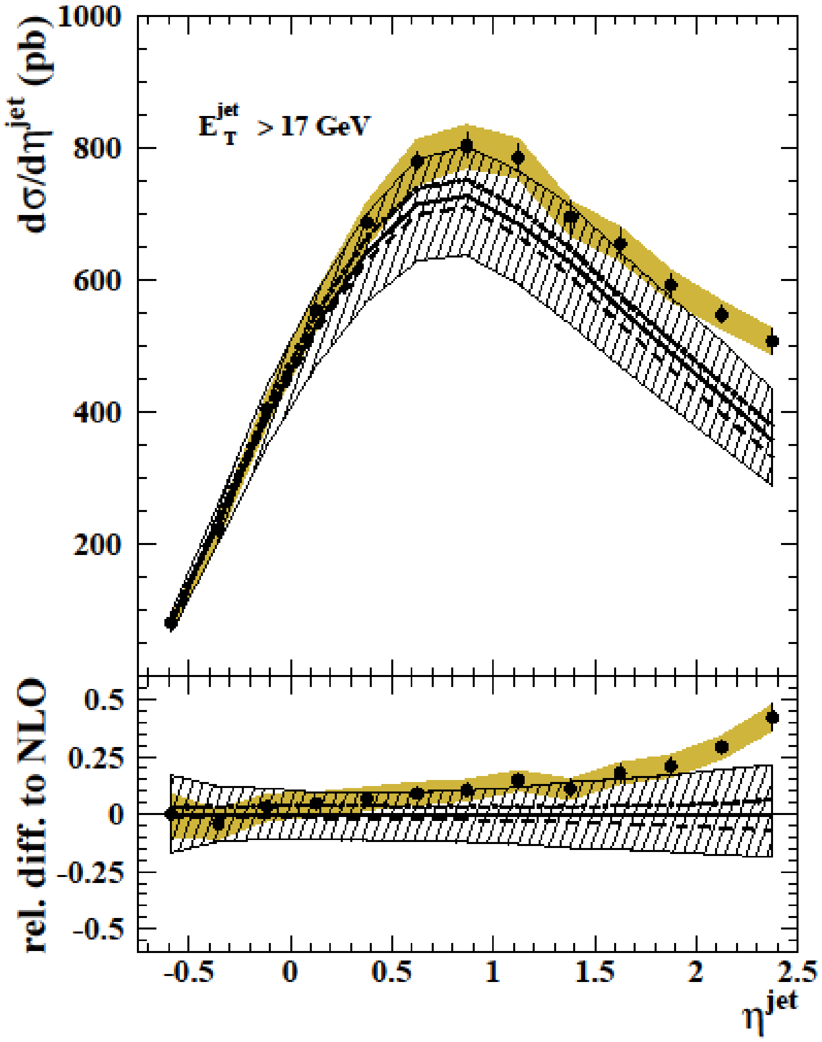
Some difference between three predictions, especially at low E^{jet}_T and high η^{jet}

Potential to constrain photon PDFs

Inclusive Jets in Photoproduction

Dependence on proton PDFs

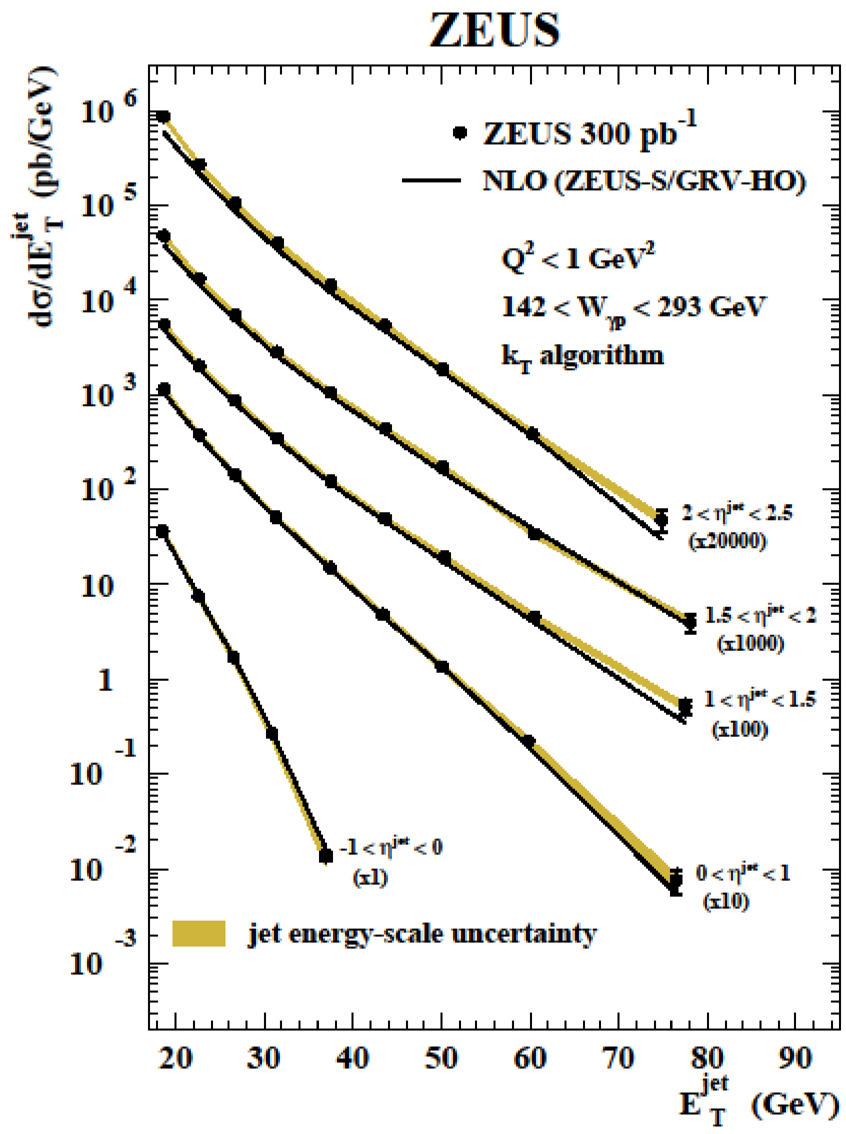




Small difference between three predictions

Low sensitivity to proton PDFs

Inclusive Jets in Photoproduction



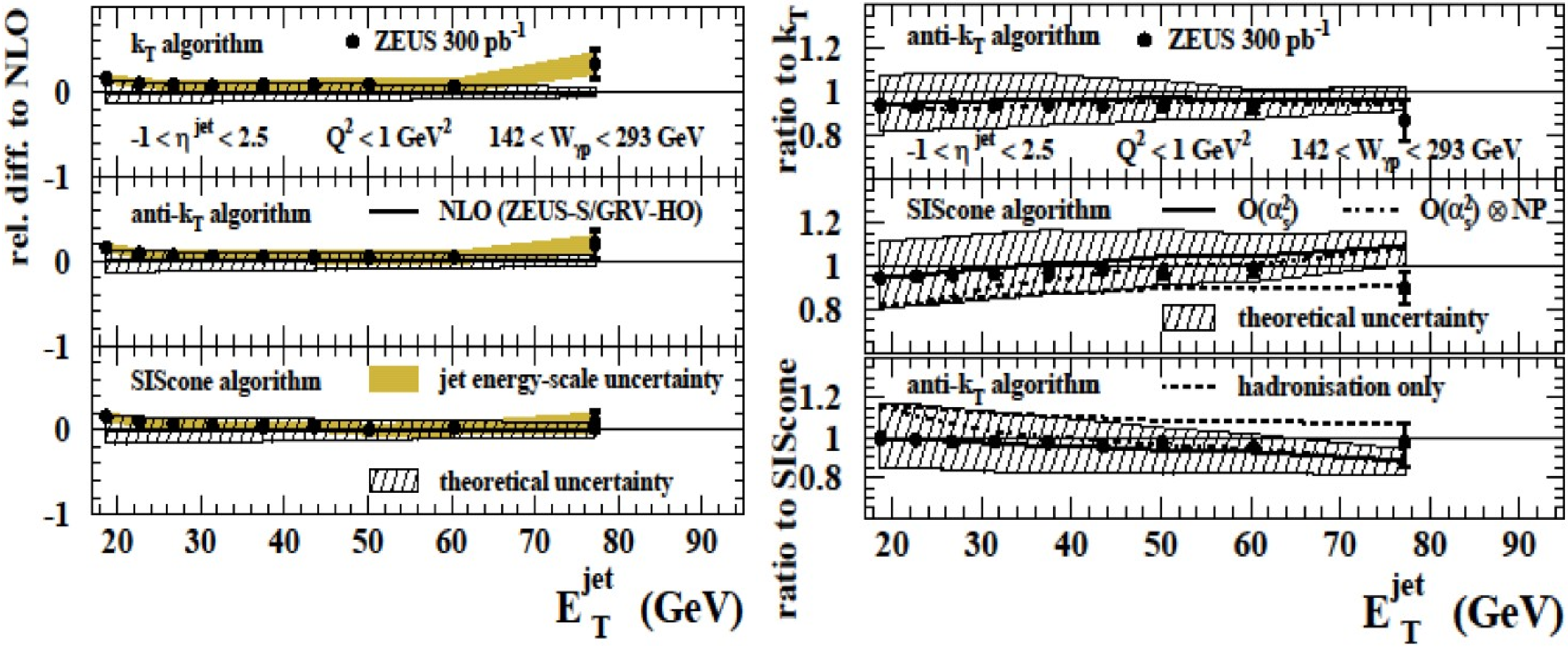
Differential cross section based on k_T jet algorithm for inclusive jet photoproduction with E^{jet}_T >17 GeV in different η^{jet} regions.

Difference between data and NLO at large η^{jet} and low E^{jet}_T could be from photon PDFs or non-perturbative effects

The NLO QCD predictions give a good description of the data , except at (low E_T^{jet} and high η^{jet})

Inclusive Jets in Photoproduction

NLO QCD and Jet Algorithms Comparison



- the agreement of the data to the NLO prediction is the same for all three jet algorithms
- no sensitivity of the result on the choice of the jet algorithm used

Inclusive Jets in Photoproduction

Determination of $\alpha_s(M_z)$ and Energy scale dependence

The measured single differential cross sections based on the three jet algorithms were used to determine $\alpha_s(M_Z)$ values.

To minimise the effects of a non-perturbative contributions and reduce uncertainties coming from proton PDFs only the measurements for $21 < E^{jet}_T < 71$ GeV were used in the fit.

$\alpha_s(M_Z)$ obtained from presented data are:

$$\alpha_s(M_Z)|_{k_T} = 0.1206\,^{+0.0023}_{-0.0022}\,(\text{exp.})\,^{+0.0042}_{-0.0035}\,(\text{th.}),$$

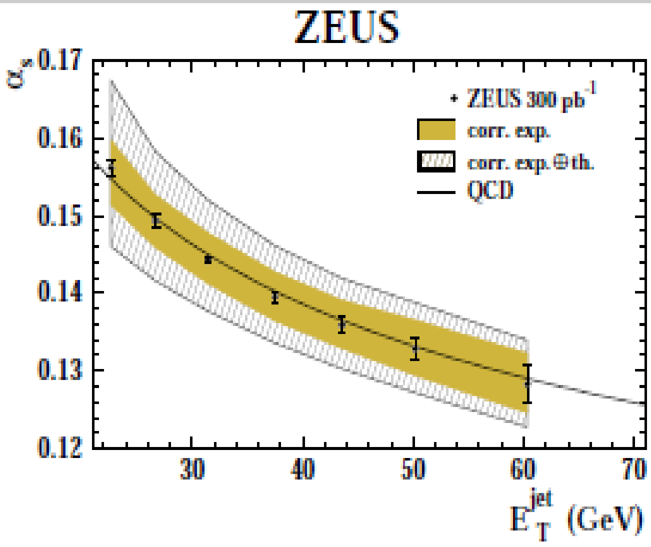
$$\alpha_s(M_Z)|_{\text{anti-}k_T} = 0.1198\,^{+0.0023}_{-0.0022}\,(\text{exp.})\,^{+0.0041}_{-0.0034}\,(\text{th.}),$$

$$\alpha_s(M_Z)|_{\text{SIScone}} = 0.1196\,^{+0.0022}_{-0.0021}\,(\text{exp.})\,^{+0.0046}_{-0.0043}\,(\text{th.}).$$

The value of $\alpha_s(M_Z)$ determined from the k_T, anti-k_T and SIScone measurements are nicely agreeing

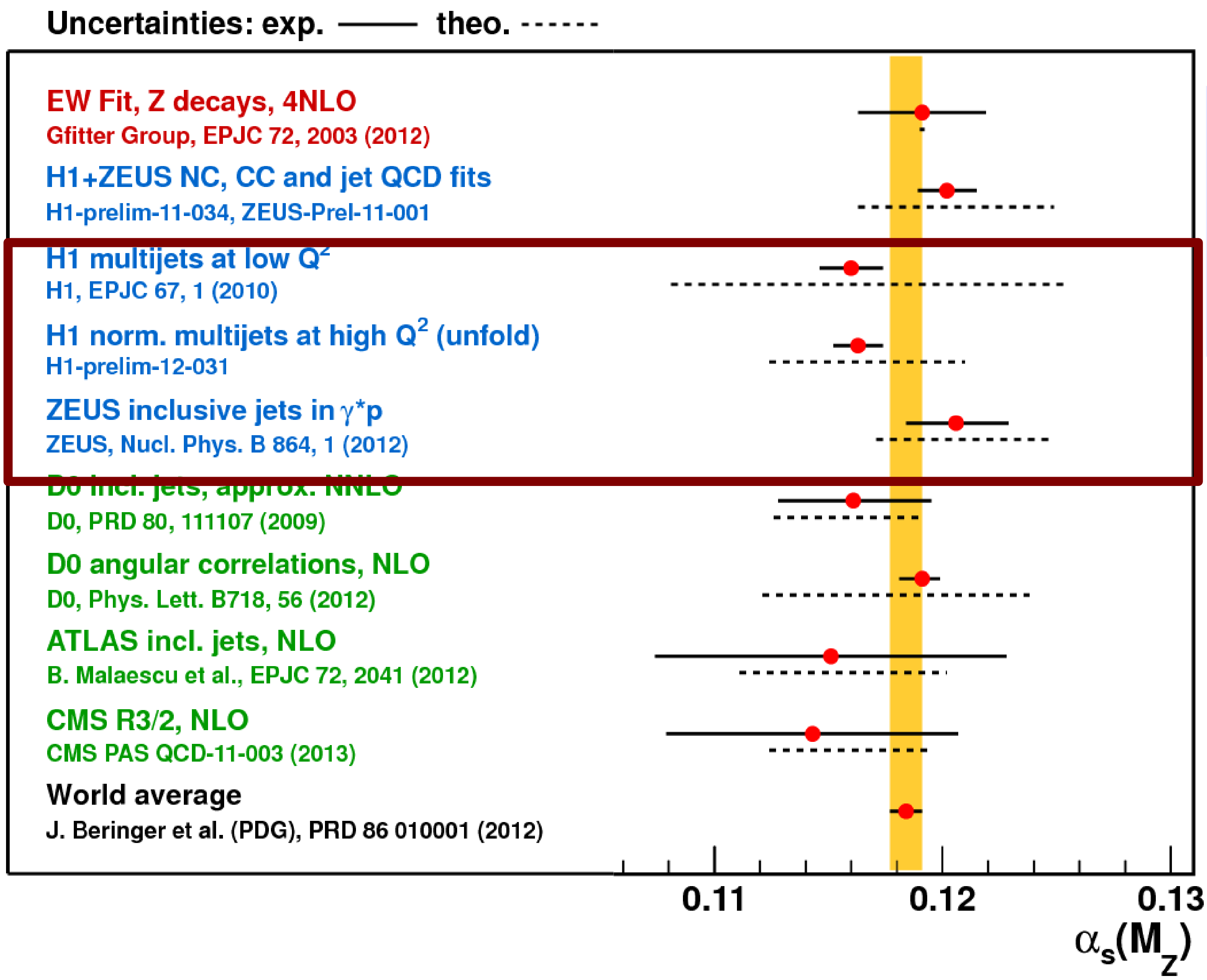
These determinations are consistent with previous determinations of $\alpha_s(M_Z)$ and have a precision comparable to those obtained from e^+e^- experiments

Energy-scale dependence of α_s



Running of α_s in single experiment in good agreement with Renormalisation Group Equations prediction at 2-loops

Comparison of $\alpha_S(M_Z)$ values



Experimental precision as good as or better than others measurements

Theory uncertainty dominates and NNLO is needed

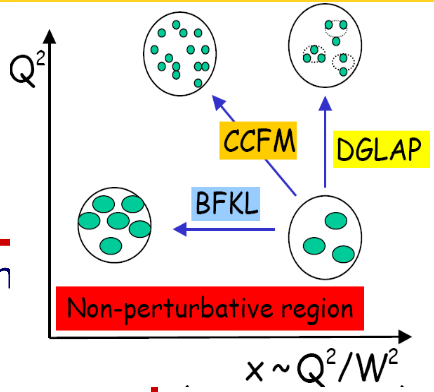
Part II

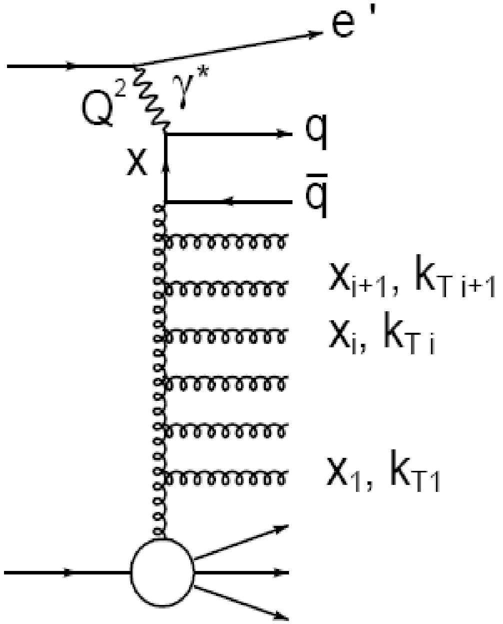
Test of QCD evolution mechanisms (*DGLAP / BFKL / CCFM*) using azimuthal correlation between the most forward jet and the scattered positron in DIS

QCD dynamics at low Bjorken-x

HERA : DIS at low Bjorken-x down to 10^{-5} → energy in γ^*p cms is large ($W_{\gamma^*p} \approx Q^2 / x$)

- long gluon cascades exchanged between the proton and the photon
- pQCD – multiparton emissions described only with approximations :





- **DGLAP** (Dokshitzer-Gribov-Lipatov-Altarelli-Parisi) evolution

  resums terms $\sim (\alpha_S \ln Q^2)^n$

  Assumes strong ordering of parton k_T

- **BFKL** (Balitsky-Fadin-Kuraev-Lipatov) evolution:

  resums terms $\sim (\alpha_S \ln(1/x))^n$

  No ordering in k_T, strong ordering in x_i

  Transition from DGLAP to BFKL scheme expected at low x

- **CCFM** (Ciafaloni-Catani-Fiorani-Marchesini) evolution:

  emitted partons are ordered in angles

  reproduces DGLAP at large x and BFKL at x → 0

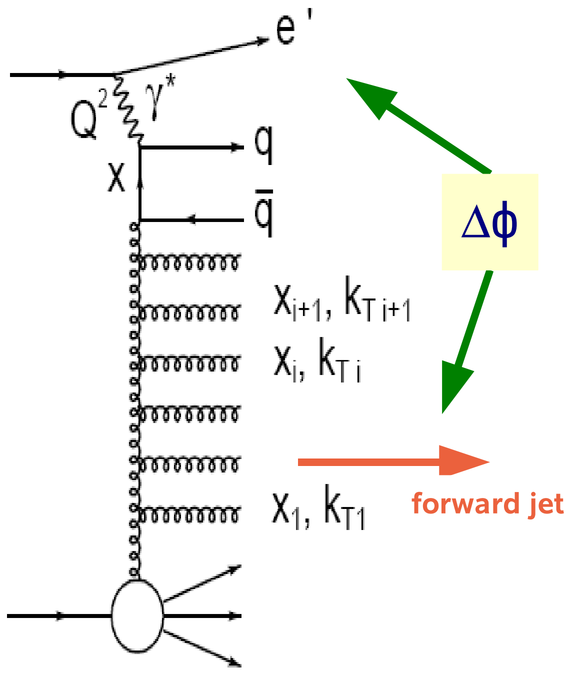
Search at HERA for effects of parton dynamics beyond the standard DGLAP approach

- Strong rise of the proton structure function $F_2(x, Q^2)$ with decreasing x
  - well described by NLO DGLAP over a large range of Q^2

  F_2 measurement too inclusive to discriminate between different QCD evolution schemes

- Look at hadronic final states – reflecting kinematics, structure of gluon emissions

Forward Jet Azimuthal Correlations



Forward Jets in DIS (*Mueller – Navelet jets*) :

BFKL – more hard partons emitted close to the proton

Study high transverse momentum and high energy jets produced close to the proton (forward region in LAB)

Suppress standard DGLAP evolution in Q^2 :

$p^2_{T,\mathrm{fwdjet}} \approx Q^2$

Enhance BFKL evolution in x :

$x_{\mathrm{fwdjet}} = E_{\mathrm{fwdjet}} / E_p >> x_{\mathrm{Bjorken}}$

Data:H1, L=38.2 pb^{-1}

DIS selection

$0.1 < y < 0.7$

$5 < Q^2 < 85\ \mathrm{GeV}^2$

$0.0001 < x < 0.004$

Jets reconstructed in the Breit frame and boosted to LAB, all cuts in LAB

$p_{T,\ \mathrm{fwdjet}} > 6\ \mathrm{GeV}$,

$1.73 < \eta_{\mathrm{fwdjet}} < 2.79$

$x_{\mathrm{fwdjet}} = E_{\mathrm{fwdjet}} / E_p > 0.035$

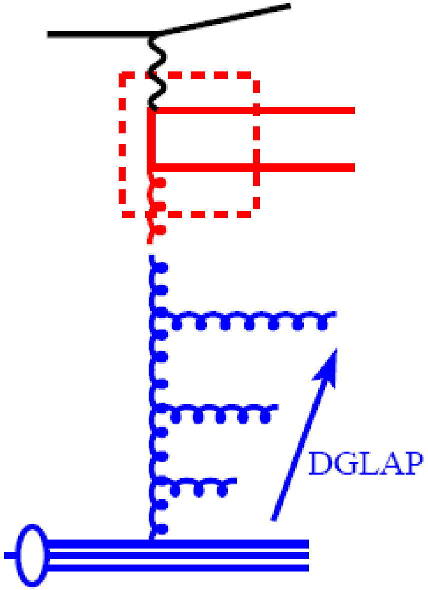
$0.5 < p_{T,\mathrm{fwdjet}}^2 / Q^2 < 6.0$

Measurement of the azimuthal angle difference $\Delta\phi$ between the scattered positron and the forward jet as a function of the rapidity distance Y between them.

Monte Carlo models with different QCD dynamics

RAPGAP - DGLAP

LO QCD matrix elements + HO modelled by leading log parton showers

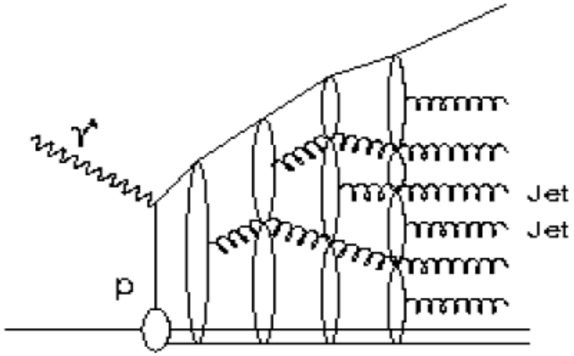


Single DGLAP ladder with
strong ordering in k_T

ARIADNE Colour Dipole Model

CDM: QCD radiation from the colour dipole formed by the struck quark and
the proton remnant.

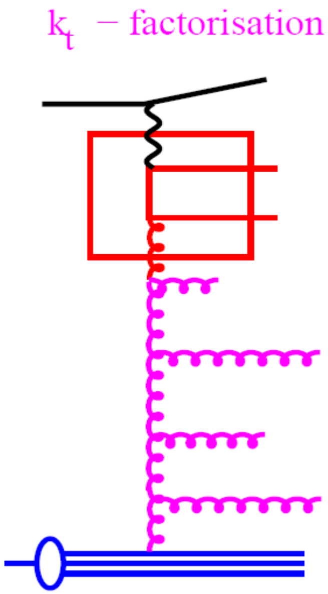
Chain of independently radiating dipoles formed by the emitted gluons.



BFKL- like Monte Carlo :
random walk in k_T

CASCADE - CCFM

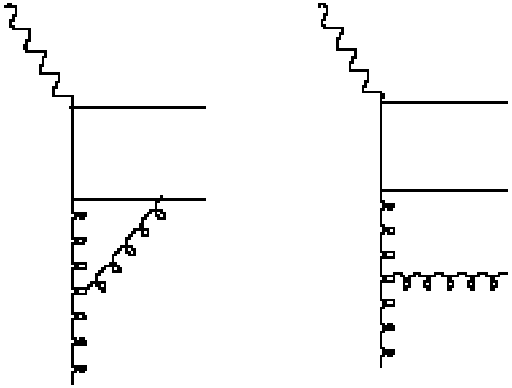
Off-shell QCD ME + parton emissions based on the CCFM equation



Angular ordering of parton emissions

Fixed order NLO DGLAP predictions

Forward jet cross sections – comparison with the predictions of pQCD at NLO (α_s^2) accuracy



- **Forward jet analysis – reconstruction of jets in the Breit frame → at least dijet topology**

NLOJET ++ program (Nagy & Trocsanyi, 2001) :
dijet production at parton level in DIS at NLO (α_s^2)

- **PDF : CTEQ6.6, $\alpha_s(M_Z) = 0.118$**
- **parton level cross sections corrected for hadronistaion effects using the RAPGAP model**

Forward Jet Azimuthal Correlations

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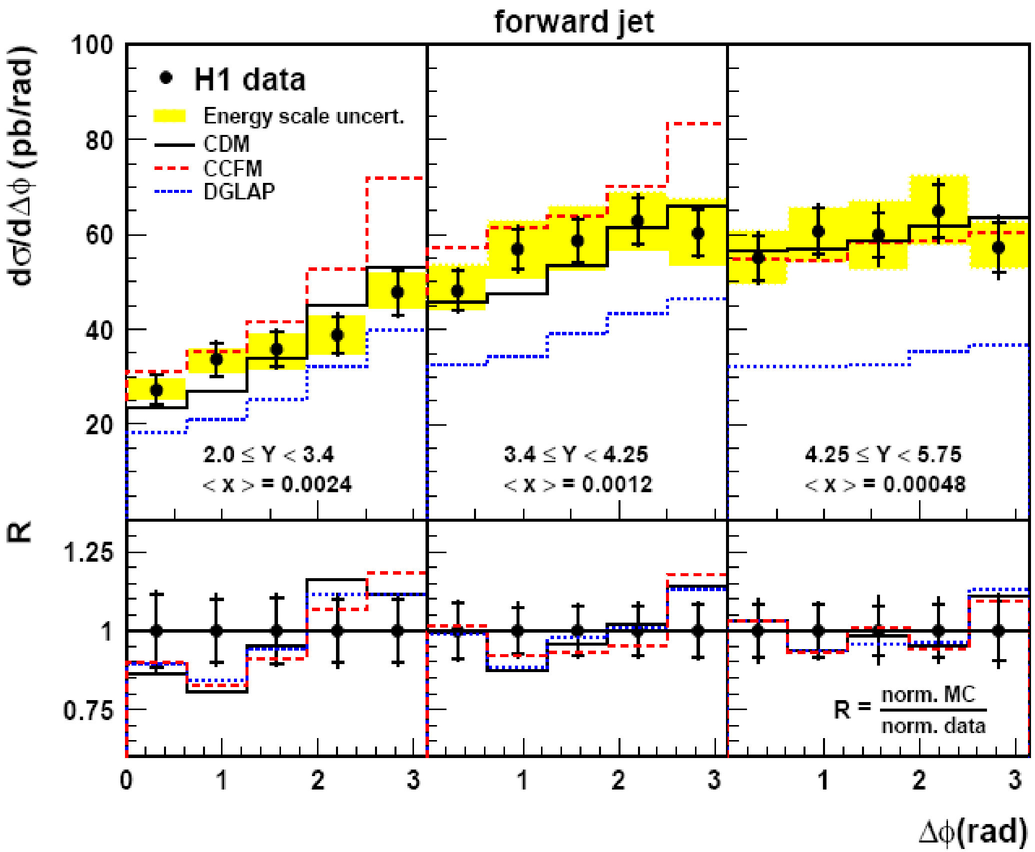
At higher Y correspondig to lower x the forward jet is more decorrelated from the scattered positron



Cross sections best described by BFKL-like model CDM

- **DGLAP predictions below the data**
- **CCFM (set A0) as good description as CDM at large Y**

The shape of $\Delta\phi$ distributions are similarly well described by all MC models

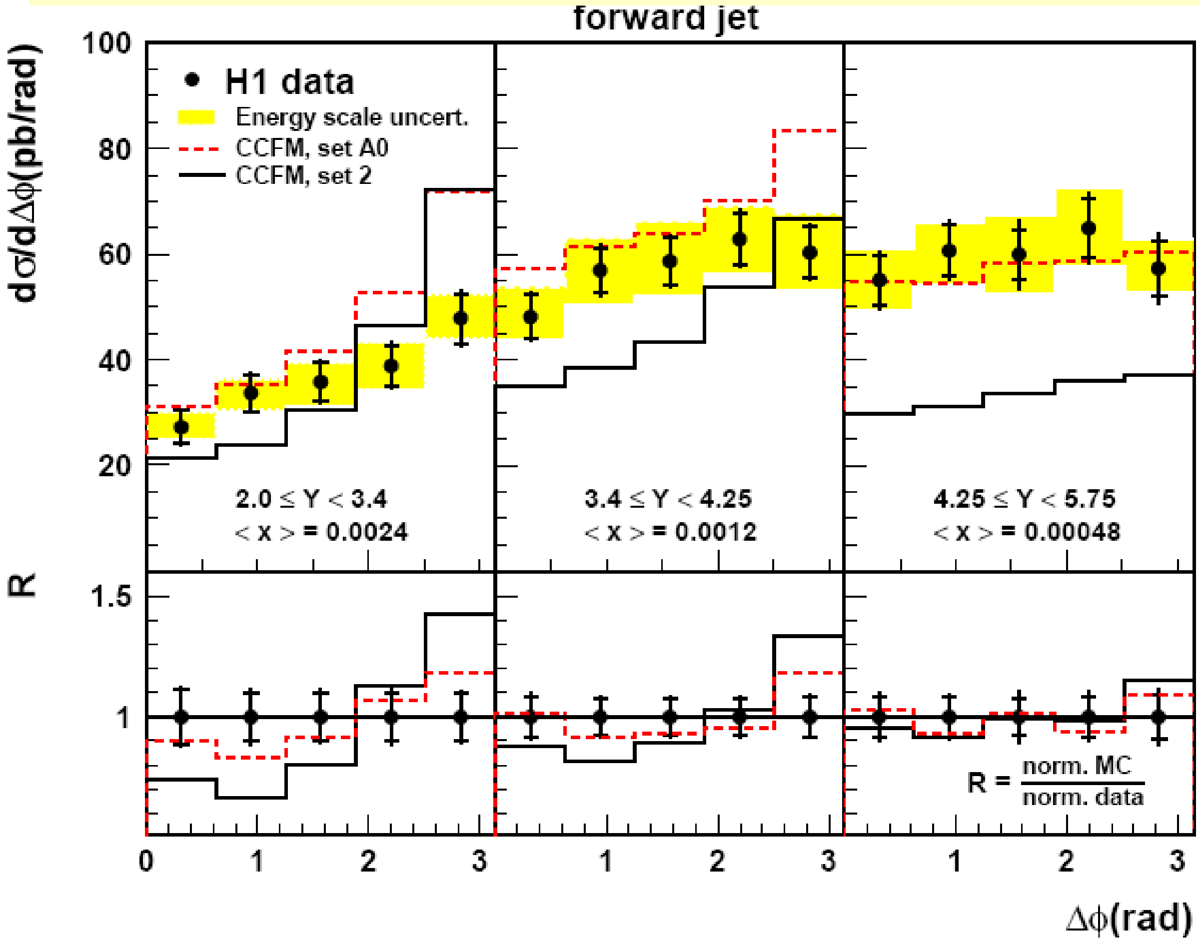
$Y = \ln(x_{fwdjet} / x)$ rapidity distance between the most forward jet and the scattered positron

$$R = \left(\frac{1}{\sigma^{\mathrm{MC}}}\frac{d\sigma^{\mathrm{MC}}}{d\Delta\phi}\right) \Big/ \left(\frac{1}{\sigma^{\mathrm{data}}}\frac{d\sigma^{\mathrm{data}}}{d\Delta\phi}\right)$$

Forward Jet Azimuthal Correlations

Different splitting functions used in unintegrated gluon density function (uPDF):

set A0 – only singular terms of the gluon splitting function
set 2 – includes also non-singular terms

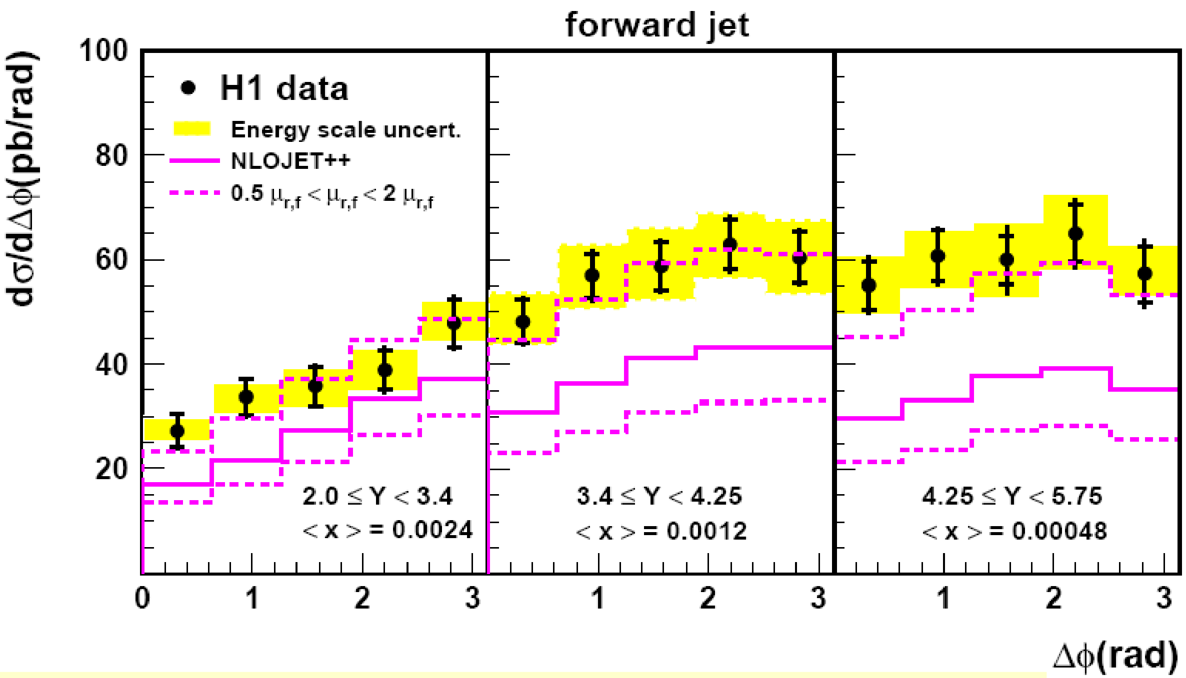


- **Cross sections strongly depend on uPDF**
- **Shape of Δφ distributions**
  - **at low Y shows sensitivity to uPDF**
  - **well described by the set A0**

Predictions of the CCFM model depend on the choice of uPDF

Forward Jet Azimuthal Correlations

Comparison to NLO ($O(\alpha_s^2)$) predictions



NLO predictions

- shape of $\Delta\phi$ distributions described, but central value too low
- large scale uncertainty (of up to 50%) indicates importance of higher orders

NLOJET++

PDF : CTEQ6.6, $\alpha_S(M_Z)=0.118$

Renormalisation and factorisation scales :

$$\mu_f=\mu_r=\sqrt{\frac{p^2_{T,fwdjet}+Q^2}{2}}$$

Theoretical uncertainty :

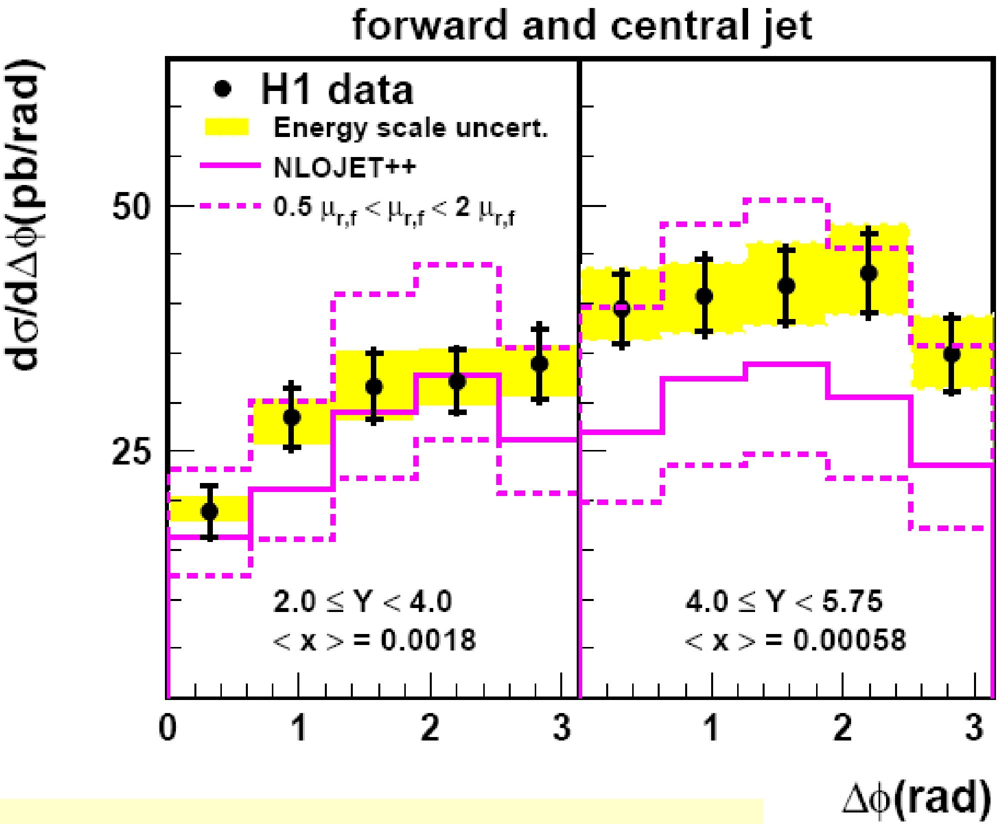
factor 2 or ½ applied to μ_r and μ_f scales simultaneously

Forward Jet Azimuthal Correlations (+*central jet*)

- **Subsample of events with <u>forward jet + additional central jet</u>**

  $p_{T,\mathrm{centet}} > 4$ GeV, $-1 < \eta_{\mathrm{centet}} < 1$

  $\Delta\eta = \eta_{\mathrm{fwdjet}} - \eta_{\mathrm{centjet}} > 2$ (enhance radiation between the forward and central jet)
- $\Delta\phi$ still between the forward jet and the scattered positron



<u>NLO ($O(\alpha_s^2)$) predictions</u>

- **at low Y reasonable description of the data**
- **at high Y, central value to small but still within theory uncertainty**
- **large scale uncertainty (of up to 40%) indicates importance of higher order contributions**

<u>NLOJET++</u>

PDF : CTEQ6.6, $\alpha_S(M_Z)=0.118$

$$\mu_f=\mu_r=\sqrt{\frac{\langle p_T\rangle^2+Q^2}{2}}, \quad \langle p_T\rangle=\frac{(p_{T,fwdjet}+p_{T,centjet})}{2}$$

Summary

Jets & α_s

HERA jet data among the most precise data for precision test of QCD
Perturbative QCD NLO calculations in general describe the data

Precision Measurement of Jet Production in DIS
- inclusive jets, dijets and trijets measurements
- absolute and normalised single and double differential cross sections
- multi-dimentional unfolding of various measurements simultaneously

Precision Measurement of Inclusive Jet Production in Photoproduction
- single and double differential cross sections based on the three jet algorithms (k_T , anti- k_T, SIScone)
- the three jet algorithms give very similar results

Extracted values of $\alpha_s(M_z)$ from jet production in different regimes competitve with other measurements, precision dominated by theoretical uncertaintes

Running of α_s determination over a wide range of scale

Theory: Missing higher orders calculation (NNLO) often is dominated source of uncertainty

Azimuthal correlation of forward jets in DIS

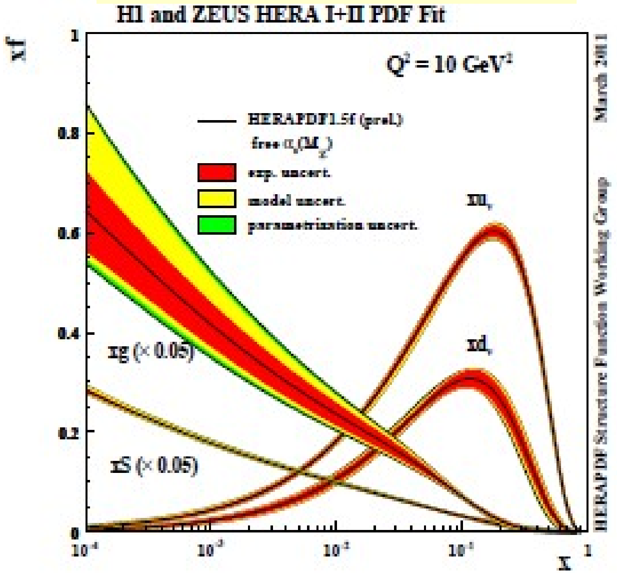
Cross sections as a function of $\Delta\phi$ and rapidity separation between the forward jet and the scattered positron are best described by the BFKL – like model CDM

The shape of $\Delta\phi$ distributions are well described by LO MC models with different QCD evolution schemes

NLO DGLAP predictions are in general below the data, but still in agreement within the large theoretical uncertainties

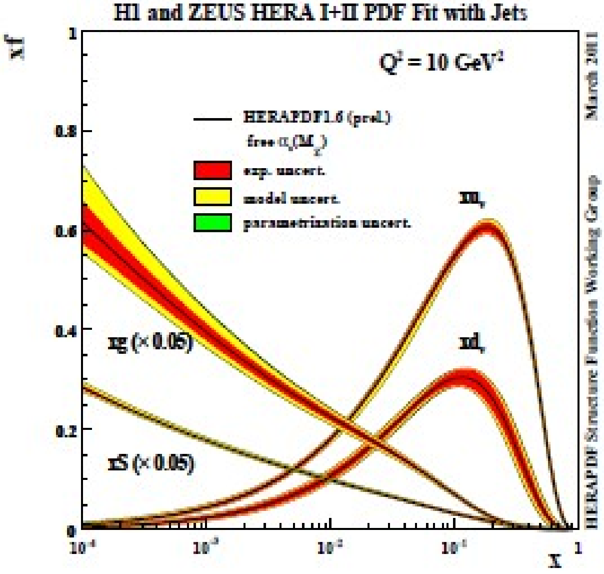
Snapshot: Jets in PDFs fits

No Jets, $\alpha_s(M_z)$ free



Adding jets

+ Jets, $\alpha_s(M_z)$ free



Adding jet data dramatically decreases the low-x gluon uncertainty, not only the experimental but also the model and parametrization uncertainties

See Achim Geiser's Wednsday talk