Jets at HERA

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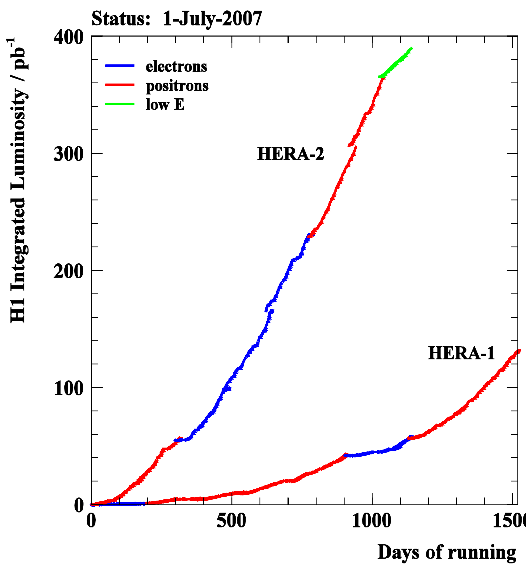
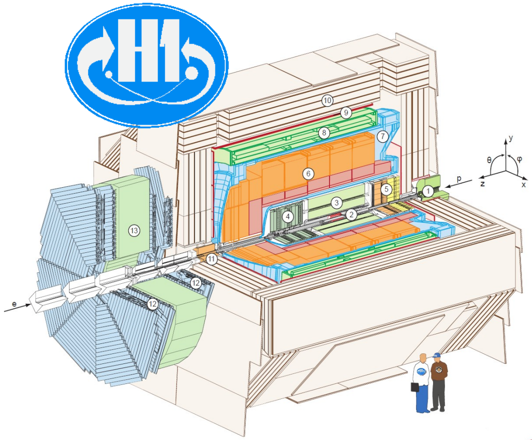
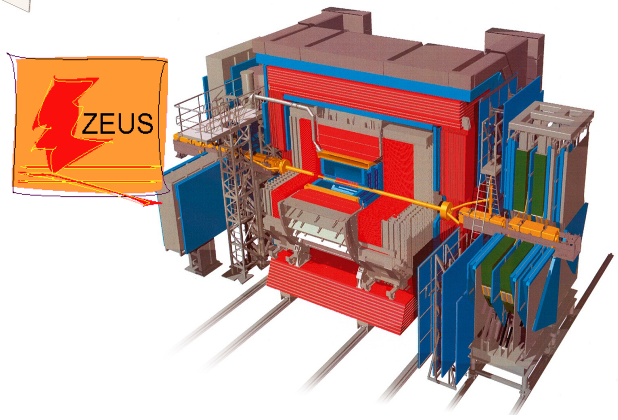
HERA with the H1 and ZEUS Detectors

HERA *e*±*p* collider
- $\sqrt{s}$ = 319 GeV
- E_e = 27.6 GeV
- E_p = 920 GeV
- Operational until 2007







Two multi-purpose experiments: H1 and ZEUS
- Luminosity: ~0.5 fb^{-1} per experiment
- Excellent control over experimental uncertainties
  - Overconstrained system in DIS
  - Electron measurement: 0.5 – 1% scale uncertainty
  - Jet energy scale: 1%
  - Trigger and normalisation uncertainties: 1-2 %
  - Luminosity: 1.8 – 2.5%

Inclusive deep-inelastic *ep* scattering (DIS)

ep scattering: $e^{\pm}p = e^{\pm} + X$

- Centre-of-mass energy

$$\sqrt{s} = \frac{p}{(k+p)^2}$$

- Virtuality of exchanged boson

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

- Bjorken scaling variable

$$x_{\mathrm{Bj}} = \frac{Q^2}{2p \cdot q}$$

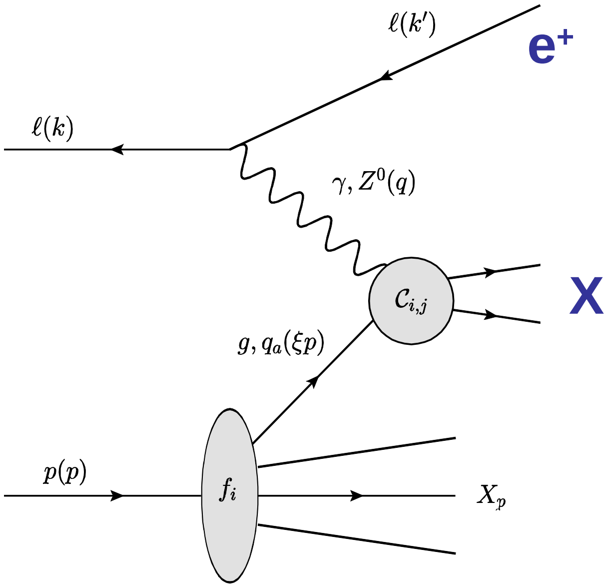
- Inealsticity

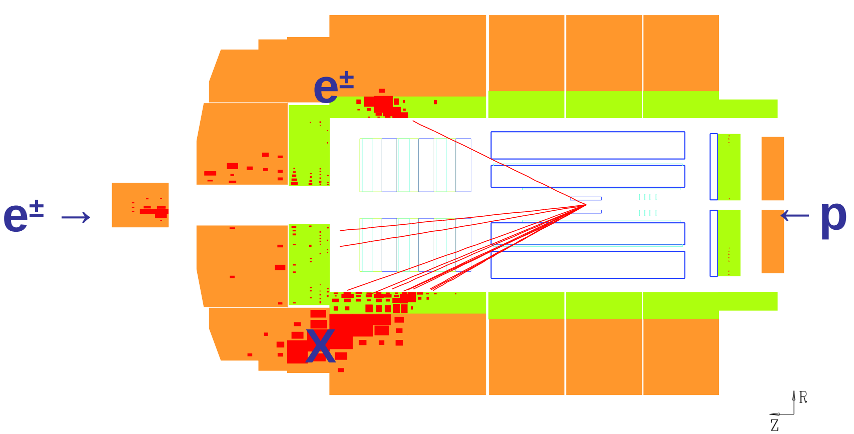
$$y = \frac{p \cdot q}{p \cdot k}$$

Cross section calculation

- Collinear factorisation
- Hard scattering calculable in pQCD
- PDFs have to be determined from experiment

Neutral current DIS





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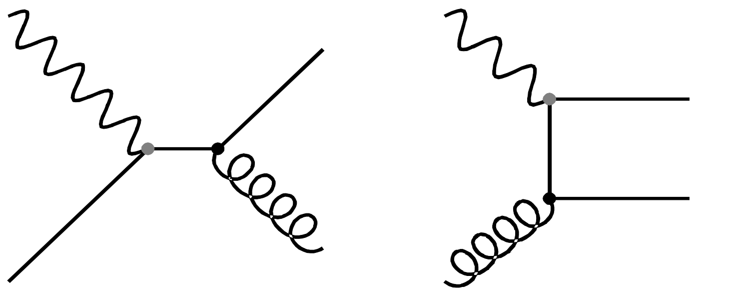
Multijet at high Q^2 – Inclusive Jet, Dijet, Trijet (H1)

DIS jet production in Breit frame



QCD compton   Boson – gluon fusion

Neutral current phase space

$150 < Q^2 < 15000$ GeV^2

$0.2 < y < 0.7$

Jet acceptance

$-1.0 < \eta_{lab} < 2.5$

Inclusive Jet

$7 < p_T^{jet} < 50$ GeV

Dijet and Trijet

$5 < p_T^{jet} < 50$ GeV

$M_{12} > 16$ GeV

$7 < \langle p_T \rangle < 50$ GeV

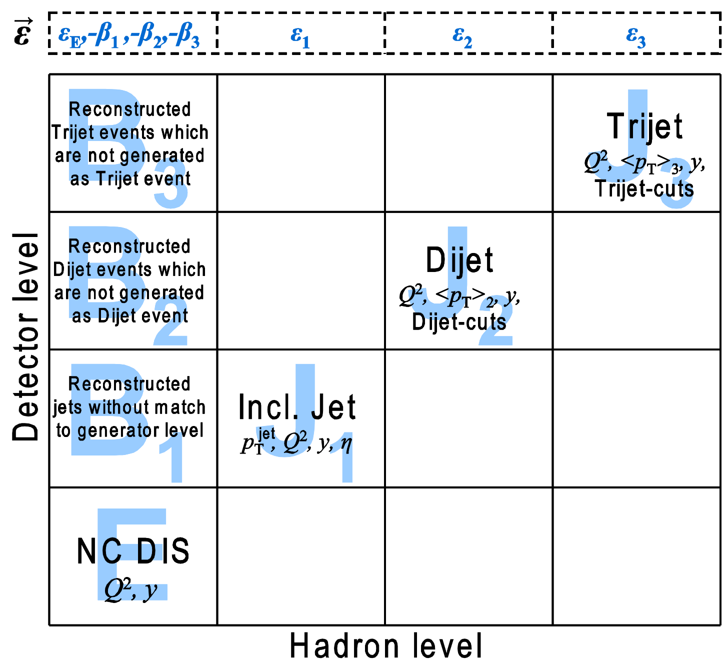
Simultaneous Measurement of

- inclusive jet, dijet and trijet cross sections
- normalised inclusive jet, dijet and trijet CS
  - Normalisation w.r.t. inclusive NC DIS

Multidimensional Unfolding using TUnfold

- The 4 double-differential measurements are unfolded simultaneously

Migration Matrix



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Multijet at high Q² – Inclusive Jet, Dijet, Trijet (H1)

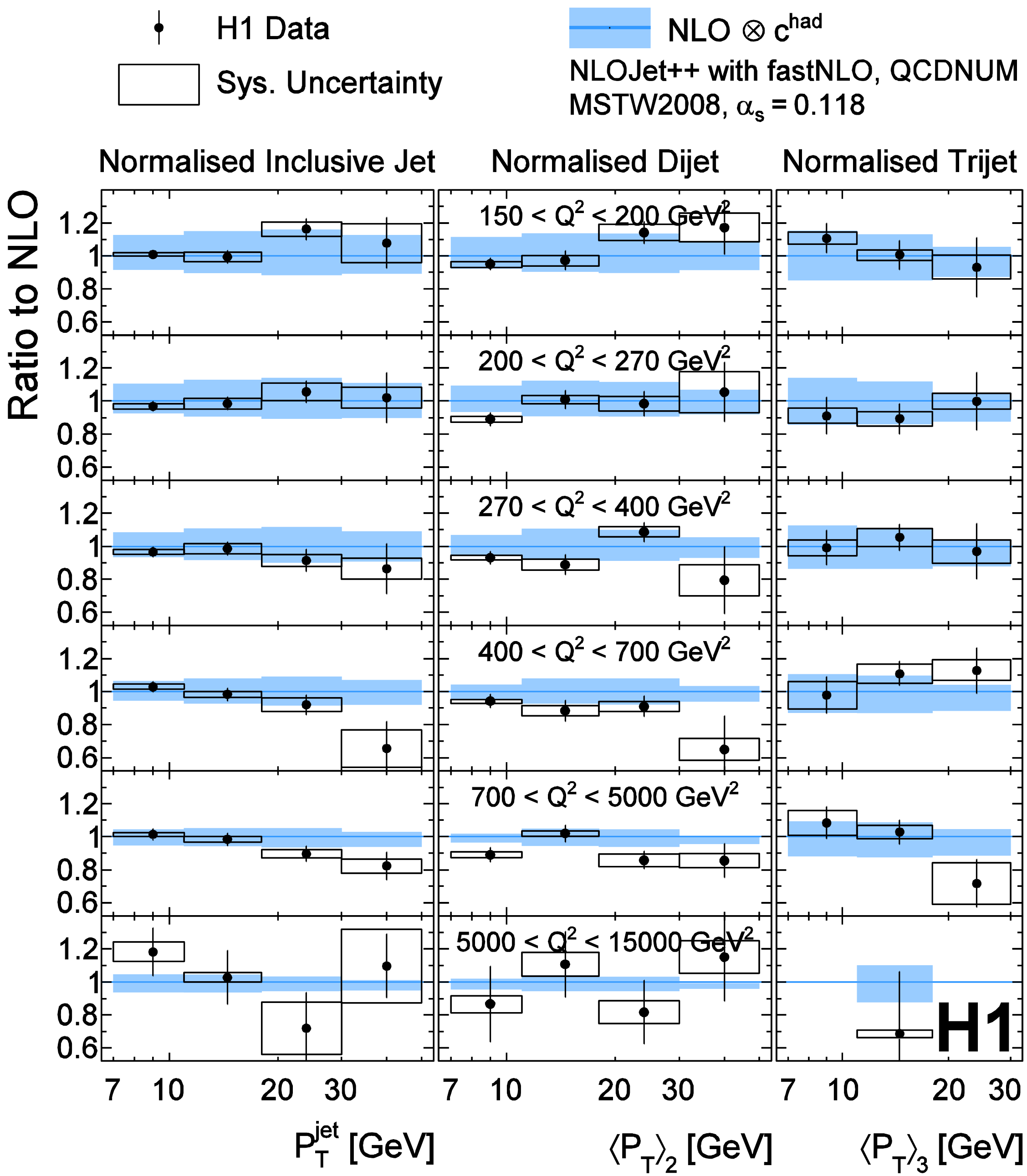
Ratio to NLO calculations from nlojet++ and QCDNUM

Normalised Multijets

- Cancellation of experimental uncertainties
- Normalisation uncertainties cancel
- Other exp. uncertainties cancel partially

Experimental precision higher than theory uncertainty from scale variations

Overall good description of data by theory in NLO



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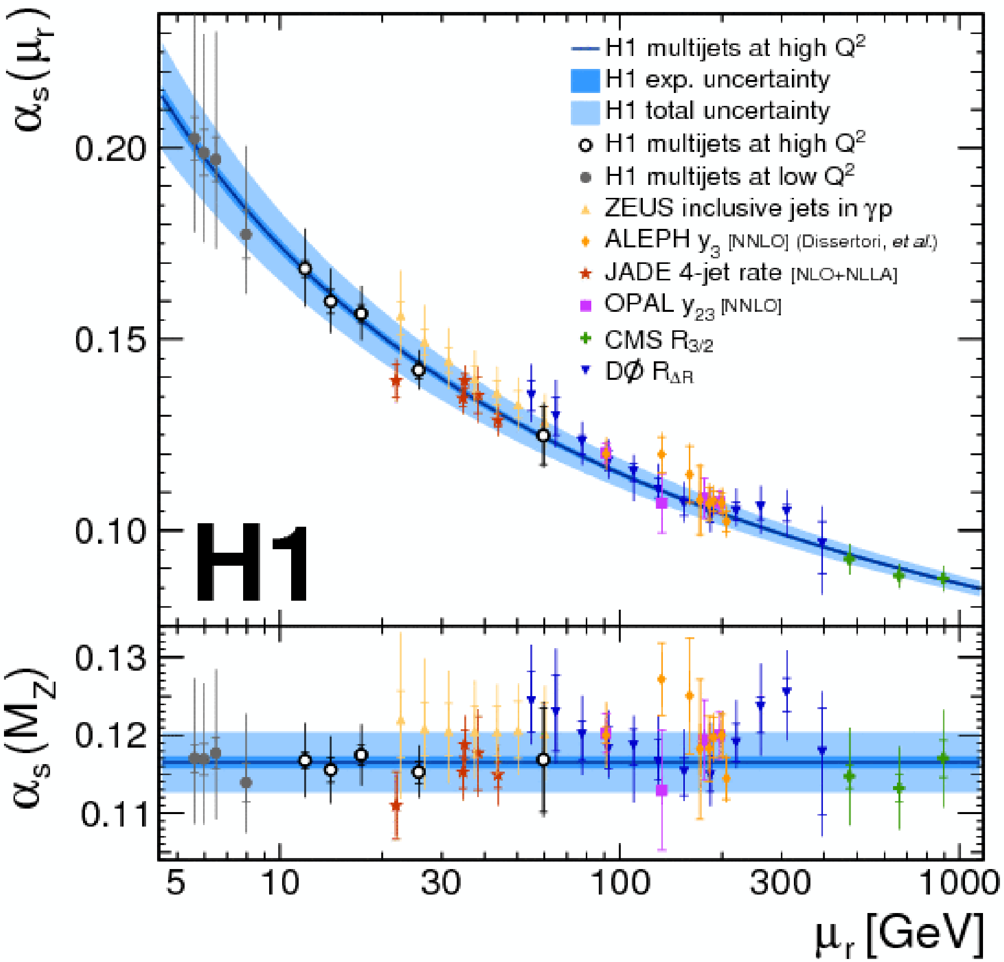
Extraction of strong coupling constant α_s

Simultaneous χ^2-fit to normalised inclusive jet, dijet and trijet cross section



Determination of $\alpha_s(M_Z)$ at various scales

- H1 Multijet cross sections with superior experimental precision
- Consistency with other jet data
- Confirmation of prediction by SU(3) over more than two orders of magnitude

Extraction from all measurements

- Experimental uncertainty significantly smaller than theoretical one
- Value consistent with other extractions

Most precise value of $\alpha_s(M_Z)$ from jet cross sections

$$\alpha_s(M_Z)|_{k_T} = 0.1165\ (8)_{\rm exp}\ (5)_{\rm PDF}\ (7)_{\rm PDFset}\ (3)_{{\rm PDF}(\alpha_s)}\ (8)_{\rm had}\ (36)_{\mu_r}\ (5)_{\mu_f}$$
$$= 0.1165\ (8)_{\rm exp}\ (38)_{\rm pdf,theo}\ .$$

Trijet measurement in DIS (ZEUS)

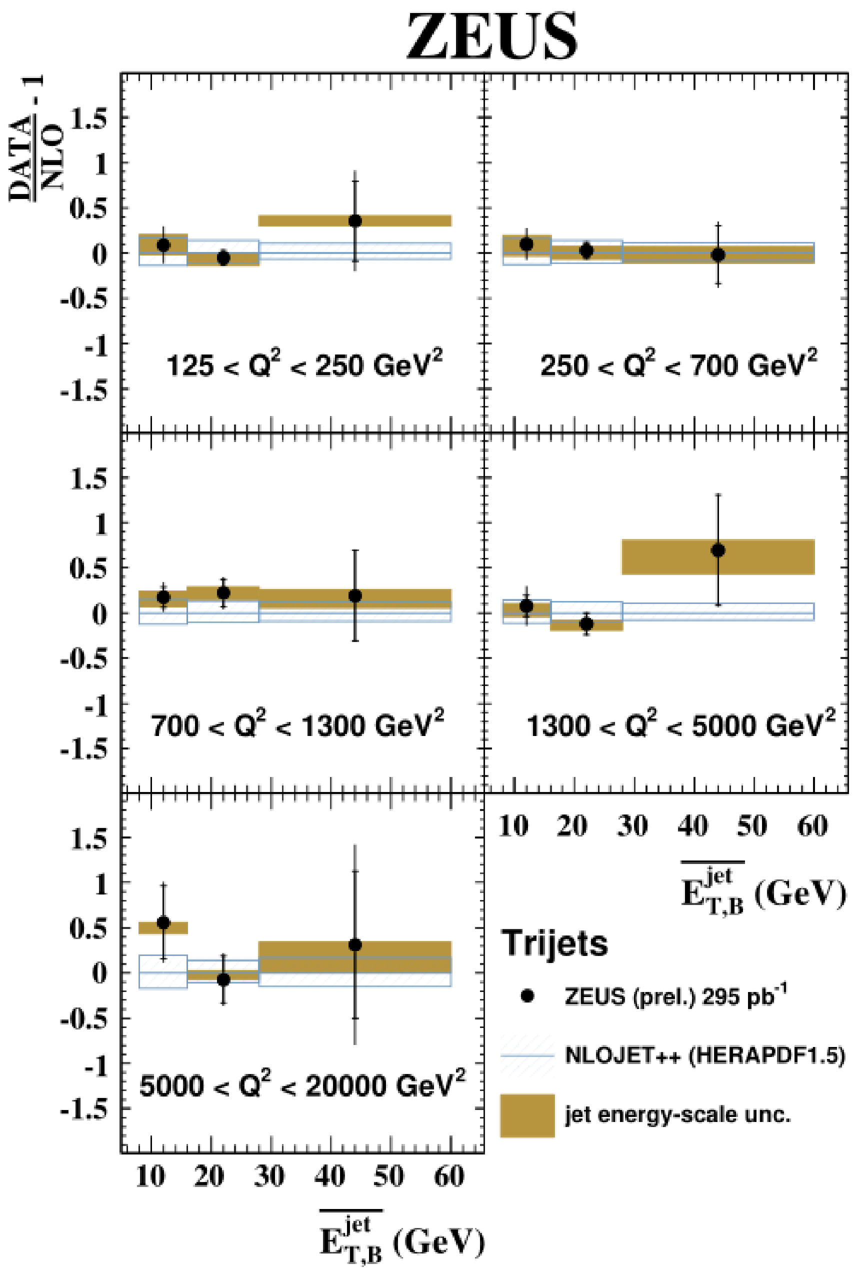
Trijet production in neutral current DIS
- Photon virtuality $125 < Q^2 < 20000$ GeV^2
- Inelasticity: $0.2 < y < 0.6$
- Jet transverse momentum $E^{jet}_{T,B} > 8$ GeV

Statistics
- L =295pb^{-1}

Major source of systematic uncertainties:
- Jet energy scale ~1% (3%), for jets with $E^{jet}_{T,L}$ >10GeV (<10GeV)

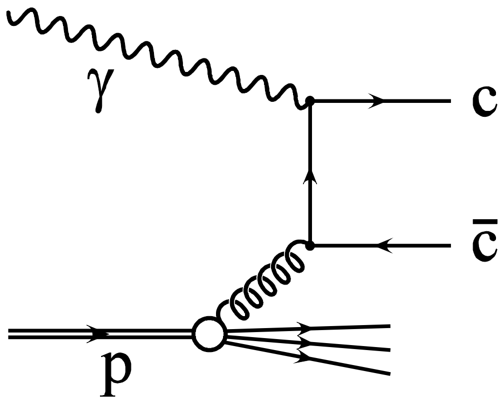
NLO Calculation

NLOJet++ corrected for hadronisation effects using HERAPDF1.5



D* production in DIS (H1+ZEUS)

$D^{*\pm}$ production in DIS



$D^{*+} \rightarrow D^0\pi^+_s \rightarrow (K^-\pi^+)\pi^+_s$

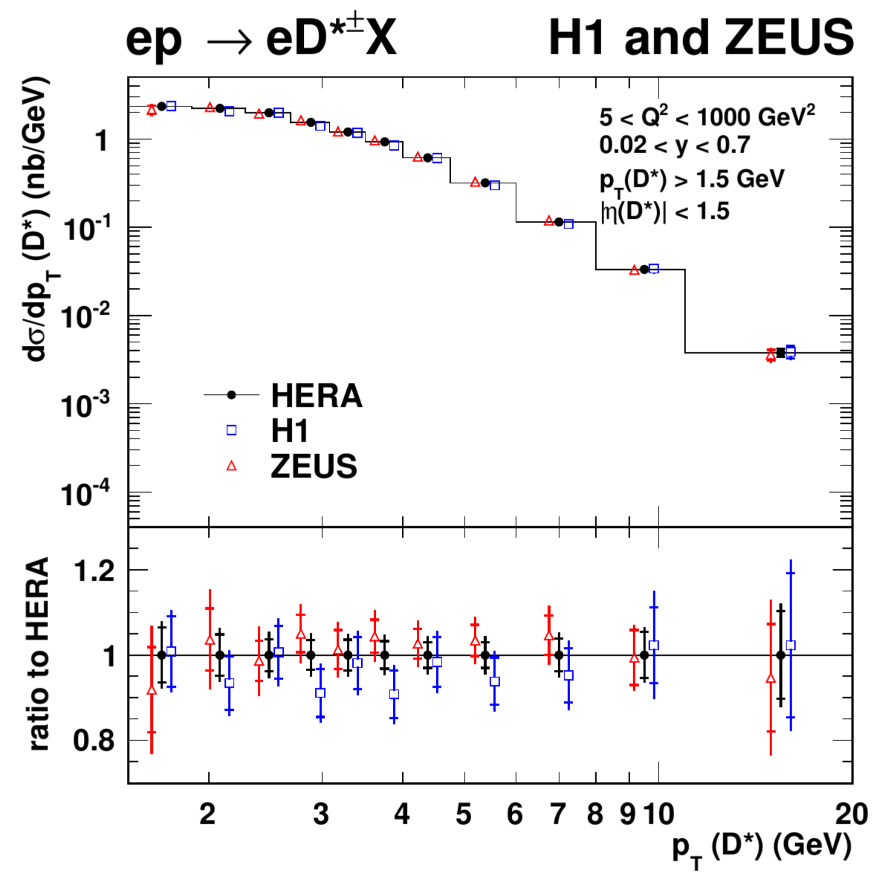
Clean D^{*+} signal in $M(K^-\pi^+\pi^+_s)$ - $M(K^-\pi^+)$

D^{*+} differential cross sections in

- differential in Q^2, y, $p_T(D^*)$, $\eta(D^*)$, $z(D^*)$
- Kinematic region
  - $5 < Q^2 < 1000\ \mathrm{GeV}^2$,
  - $1.5 < p_T(D^*) < 20$ GeV
  - $|\eta(D^{\pm})| < 1.5$
  - $0.02 < y < 0.7$

Combination of precise H1 and ZEUS data

- Full HERA-II data sets (354 pb^{-1})



Data of H1 and ZEUS consistent

Great benefit from combination

D* production in DIS (H1+ZEUS)

Double-differential data combination extends to HERA-I data

- Increased range to lower values of Q^2

Negligible swimming corrections

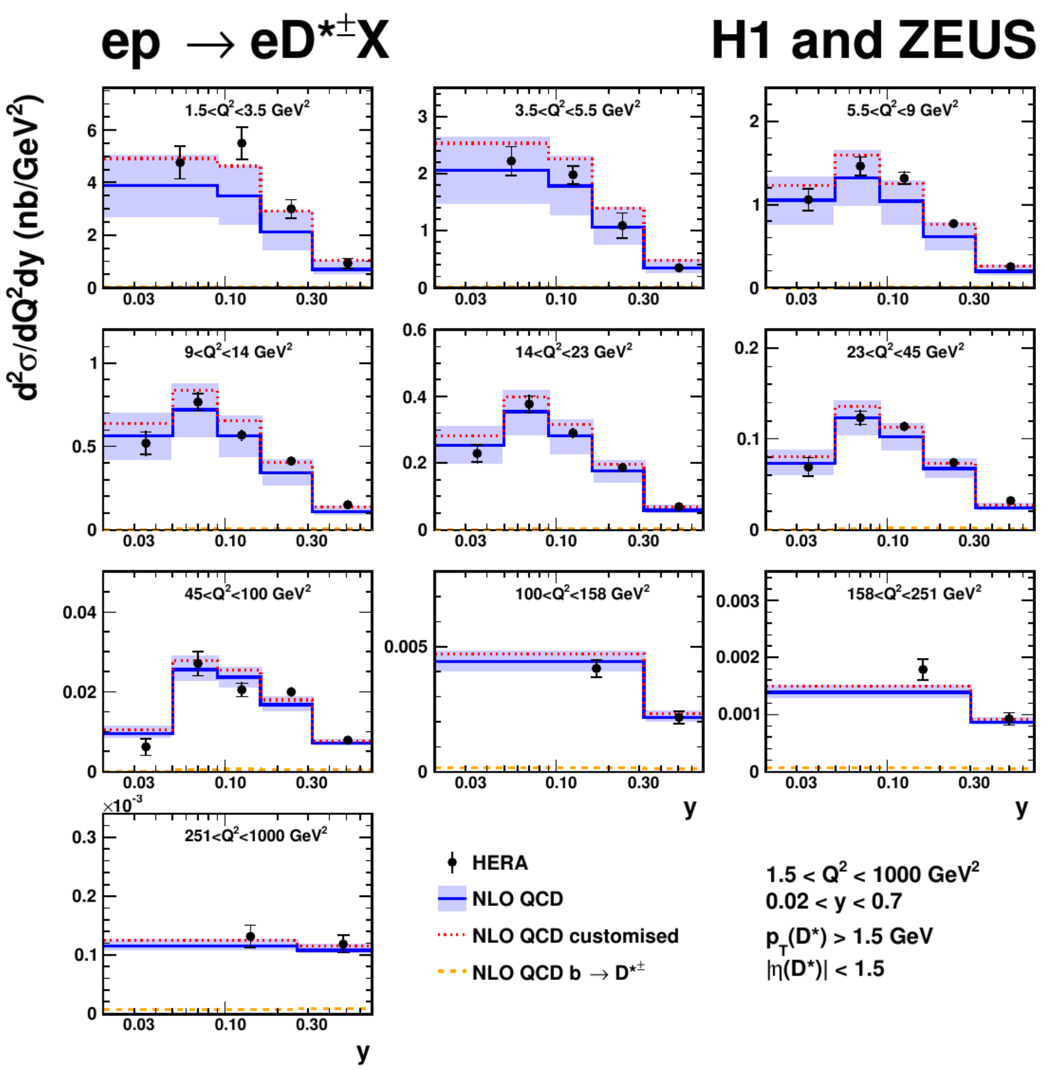
- Data free from swimming corrections

Double-differential cross sections

- Further increase in precision

Compared to NLO calculations

- HVQDIS with 3-flavor FFNS PDF



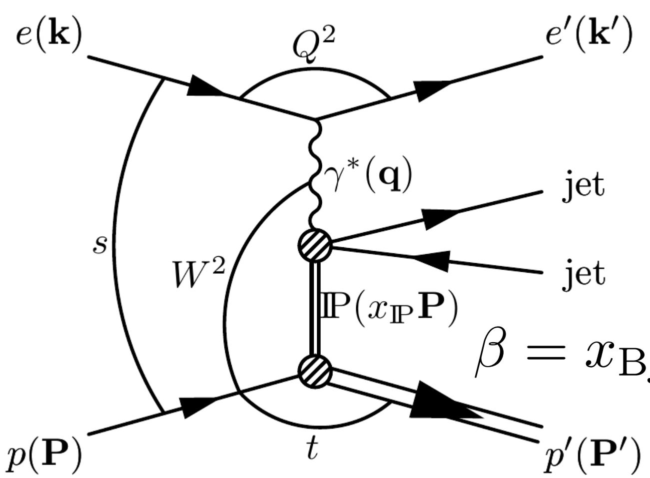
NLO theory describes data well

Data yields much higher precision than theory

Exlusive dijets in diffractive DIS (ZEUS)

Exclusive dijets sensitive to the nature of exchanged object:

- Single or double gluon exchange ?



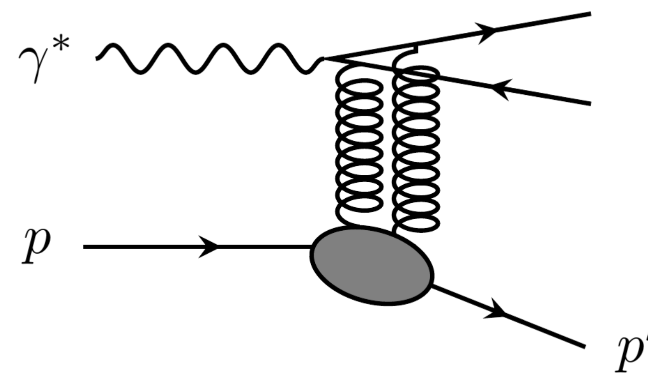
$\beta = x_{\mathrm{Bj}}/x_{IP}$

Dijet events identified using 'large rapidity gap'
Exclusive Durham jet algorithm in phase space

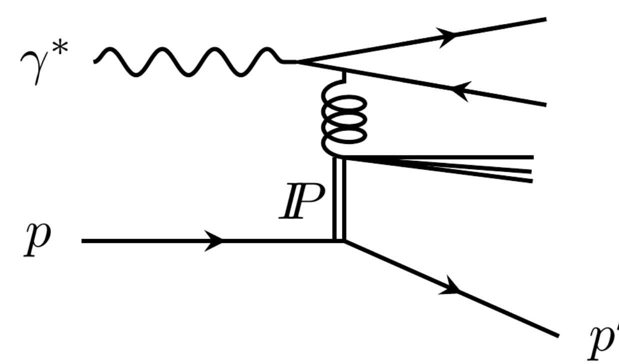
$$\mathrm{Q}^2 > 25\mathrm{GeV}^2$$
$$90 < W < 250\mathrm{GeV}$$
$$\mathrm{x}_{IP} < 0.01$$
$$\mathrm{M}_X > 5\mathrm{GeV}$$
$$\mathrm{p}_T^{\mathrm{jet}} > 2GeV$$

Compare different models

- Two-gluon exchange model



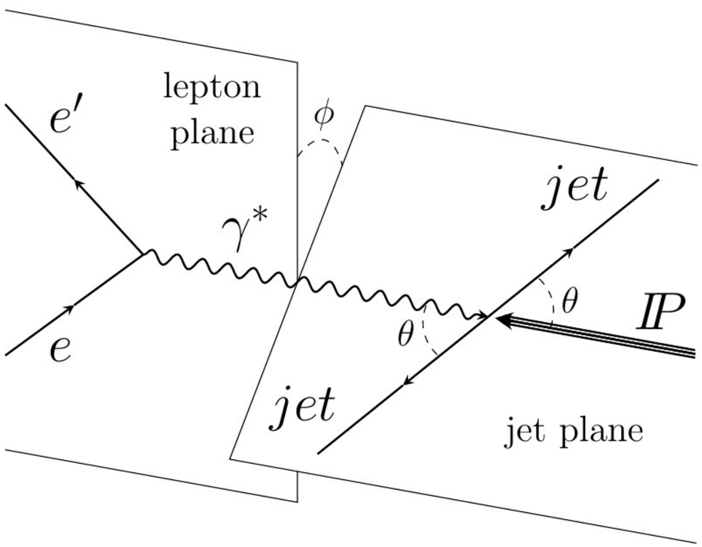
- Resolved Pomeron model



Exlusive dijets in diffractive DIS (ZEUS)

Normalised single differential cross sections in φ

- Angle between two planes



Fit function

$$\frac{1}{\sigma}\frac{\mathrm{d}\sigma}{\mathrm{d}\phi} \propto 1 + A\cos 2\phi$$

Parameter *A* distiguishes between the two models

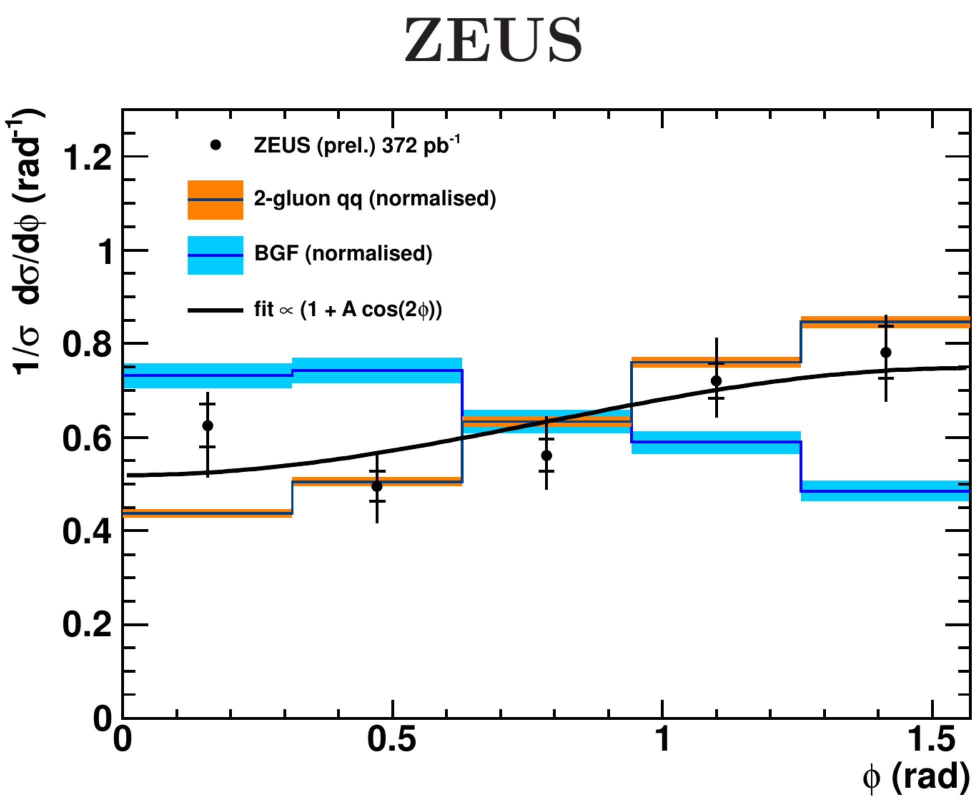
- Positive A for single gluon
- Negative A for two gluon

Fit with stat. uncertainties to yields

$A = -0.18 \pm 0.06\ ^{+0.08}_{-0.11}$

Compares to:

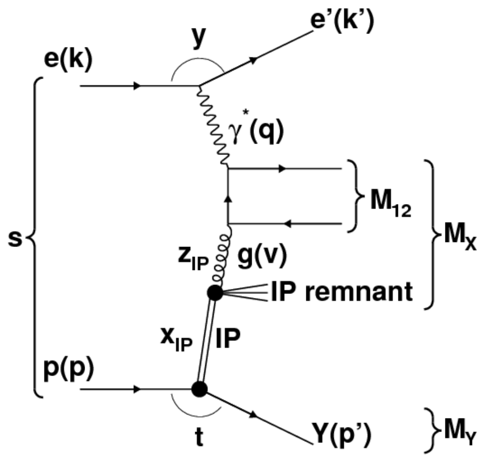
Two-gluon exchange model: A = -0.2
Resolved pomeron model: A = +0.34



Fit prefers two-gluon exchange model

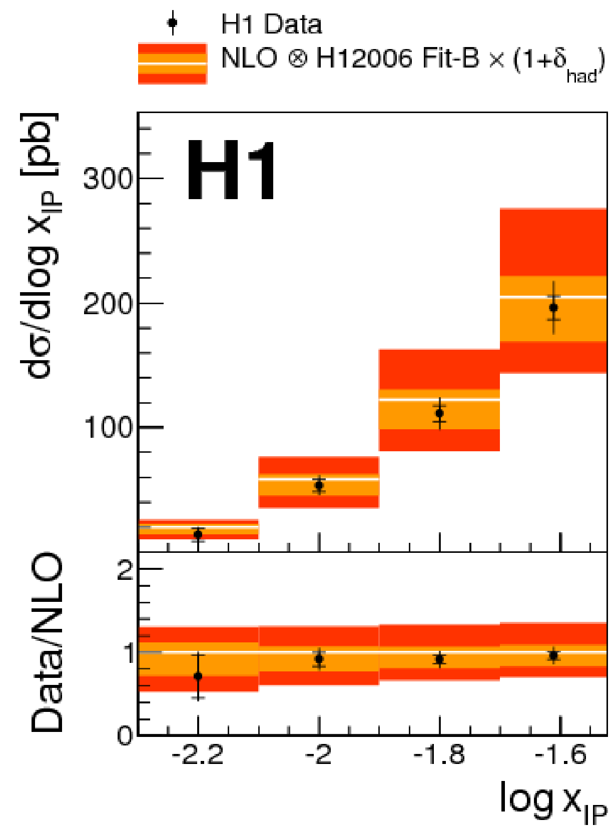
Dijets in diffractive DIS (LRG) (H1)

(Inclusive) Dijet production in diffractive DIS



Diffractive events identified by
'large rapidity gap' (LRG)
Jets identified using k_T jet algorithm

Measurement Cross Section Phase Space
$4 < Q^2 < 100$ GeV^2
$0.1 < y < 0.7$
$x_P < 0.03$
$\|t\| < 1$ GeV^2
$M_Y < 1.6$ GeV
$p^*_{T,1} > 5.5$ GeV
$p^*_{T,2} > 4.0$ GeV
$-1 < \eta^{lab}_{1,2} < 2$



Data well described by NLO predictions

- nlojet++ (adapted to diff. DIS)
- H1PDF2006 FitB

Large PDF and theory uncertainties

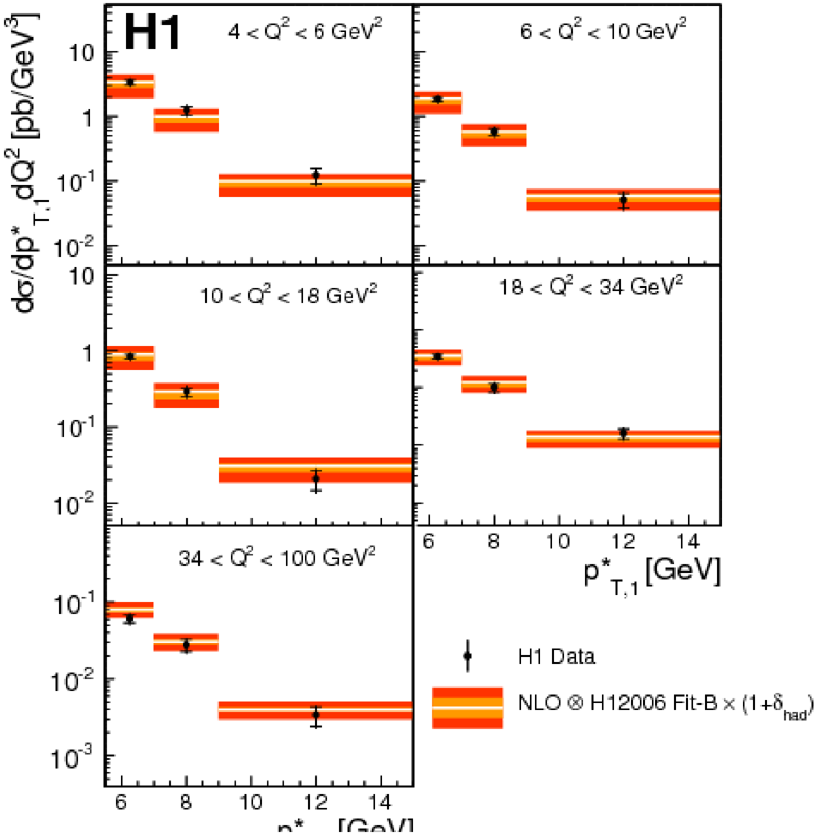
Dijets in diffractive DIS (LRG) (H1)

Double differential measurement (p^*_{T1}, Q^2) employed for extraction of strong coupling constant $\alpha_s(M_Z)$

$$\alpha_s(M_Z) = 0.119 \pm 0.004\,(\text{exp}) \pm 0.002\,(\text{had}) \pm 0.005\,(\text{DPDF}) \pm 0.010\,(\mu_r) \pm 0.004\,(\mu_f)$$
$$= 0.119 \pm 0.004\,(\text{exp}) \pm 0.012\,(\text{DPDF, theo})$$

- Fit yields good χ^2/ndf = 16.7/14
- Fit limited by theoretical precision
- Experimenal precision limited by normalisation uncertainty (including LRG selection)
- Result supports concept of perturbative QCD calculations for diffractive dijets.

Although uncertainty is not competitive with other determinations, the extraction supports the concept of dijet calculations in pQCD



arXiv:1502.01683
(subm. to JHEP)

Diffractive Dijets in Photoproduction and DIS (VFPS) (H1)

History

- 'Suppression' w.r.t. to NLO observed by H1
- No indication observed by ZEUS

Simultaneous measurement of dijets

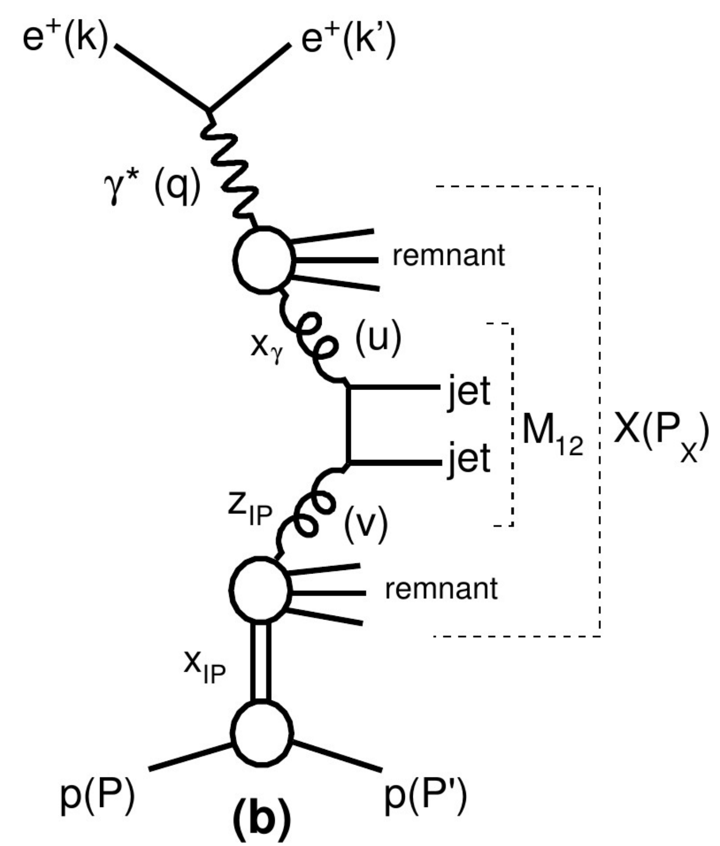
- in DIS
- in Photoproduction (γp): $Q^2 \rightarrow 0\ \mathrm{GeV}^2$

Data corrected to hadron level using TUnfold

PHP	DIS
$Q^2 < 2\,\mathrm{GeV}^2$	$4\,\mathrm{GeV}^2 < Q^2 < 80\,\mathrm{GeV}^2$
Common Cuts	
$0.2 < y < 0.7$	
$E_T^{*\mathrm{jet1}} > 5.5\,\mathrm{GeV}$	$E_T^{*\mathrm{jet2}} > 4.0\,\mathrm{GeV}$
$-1 < \eta^{\mathrm{jet1}} < 2.5$	$-1 < \eta^{\mathrm{jet2}} < 2.5$
$\lvert t \rvert < 0.6\,\mathrm{GeV}^2$	$0.010 < x_{I\!P} < 0.024$
$z_{I\!P} < 0.8$	

Measure scattered proton in VFPS (Very Forward Spectrometer)

- VFPS is 220m from interatction point
- Complementary method to LRG method



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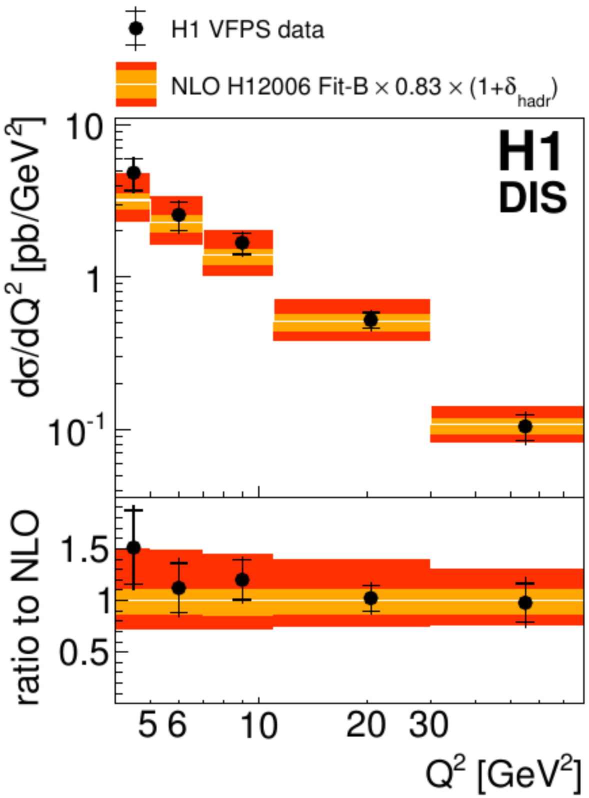
Diffractive Dijets in Photoproduction and DIS (VFPS) (H1)

Dijets in **DIS**

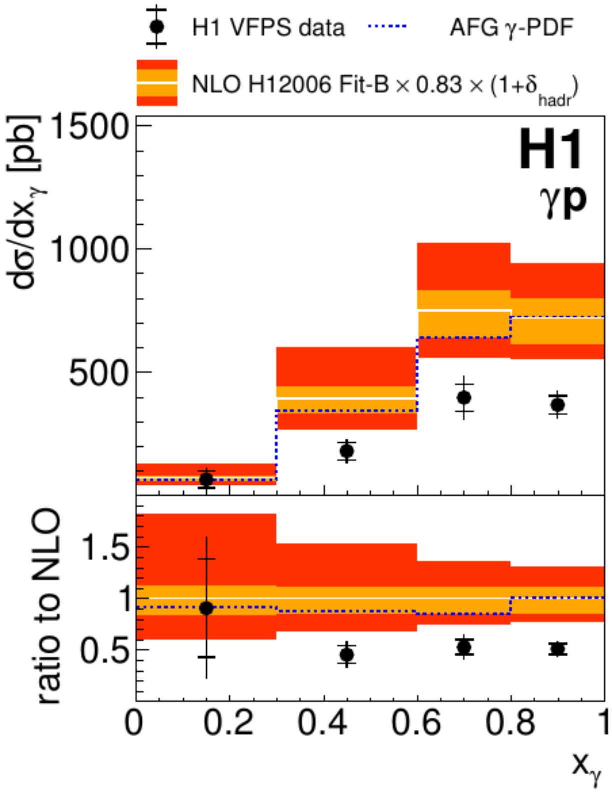
- Single diff. cross sections
- NLO by nlojet++
- H12006 Fit-B



Shape and normalisation well described by NLO

Dijets in **γp**

- Single diff. cross sections
- NLO by FKS (Frixione et al.)
- H12006 Fit-B
- GRV and AFG γ-PDF

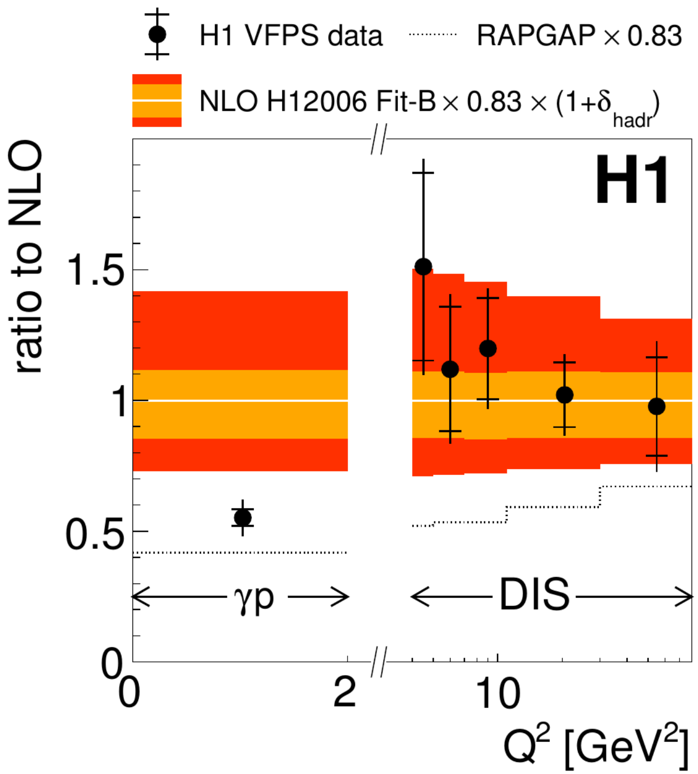


Shape well described by NLO, but normalisation is overestimated

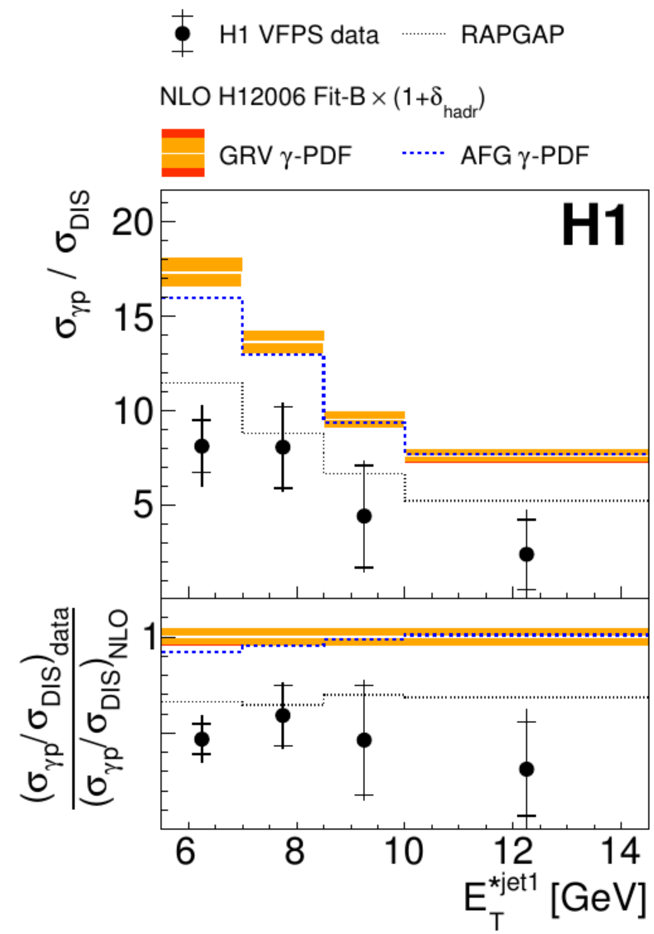
arXiv:1502.01683
(subm. to JHEP)

Diffractive Dijets in Photoproduction and DIS (VFPS) (H1)

Direct comparison of DIS and γp data with NLO and RAPGAP



Double-ratio γp/DIS of single-differential cross sections



New analysis confirms previous results from H1 with complementary experimental method

No hint for 'suppression' as function of x_γ or E_T^{jet1}

Summary

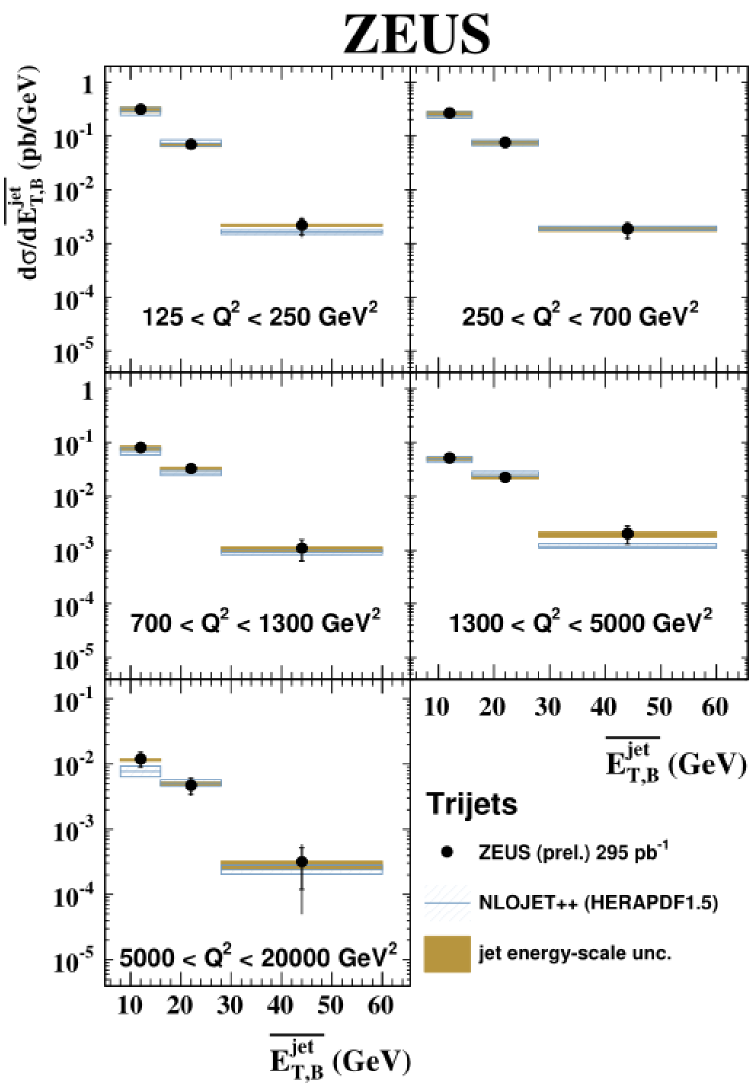
New QCD results from HERA experiments with final data precision

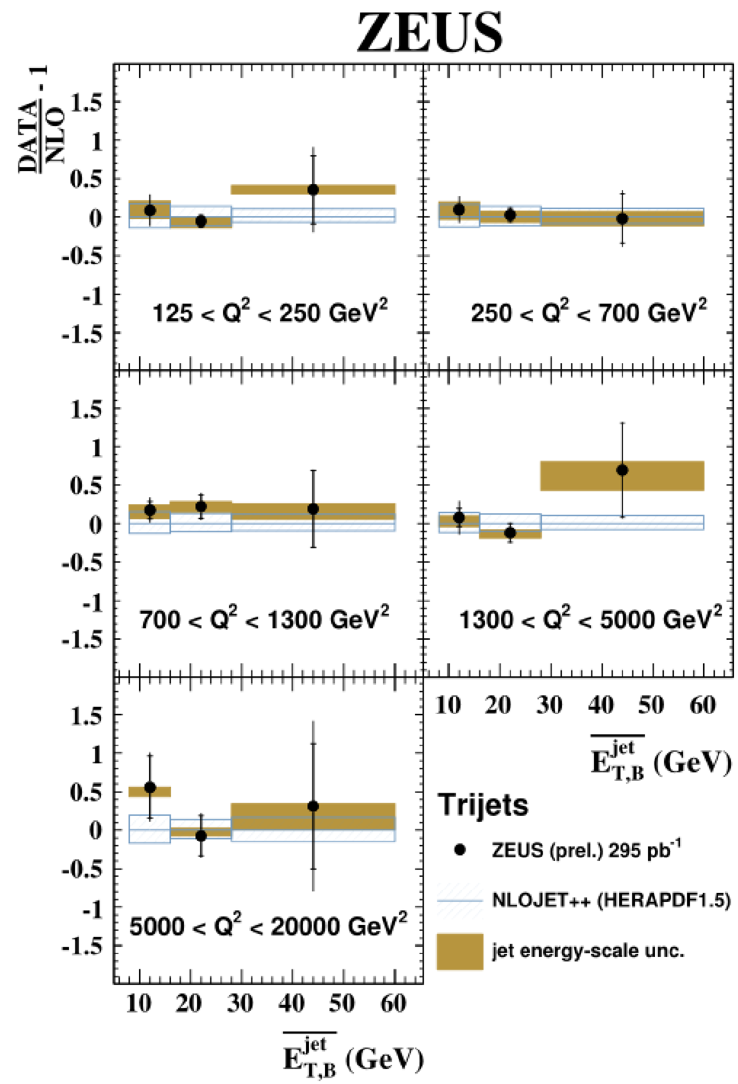
Combined D* cross sections	Data precision surpasses NLO precision
Trijet cross sections in DIS	Cross sections well described in NLO
Multijet cross sections in DIS	Inclusive jets, dijets and trijets simultaneously Highest precision on α_s from jet measurements
Exclusive dijets in diffractive DIS	Data prefers two-gluon exchange model
Inclusive dijets in diffractive DIS	Data well described in NLO α_s extraction feasible ($\Delta^{theo} > \Delta^{data}$)
Inclusive dijets in γp (and DIS)	Complementary measurements using VFPS NLO overshoots γp cross sections

Outlook

H1 and ZEUS are still active
More measurements to come
HERAPDF2.0 together with final inclusive cross sections very soon

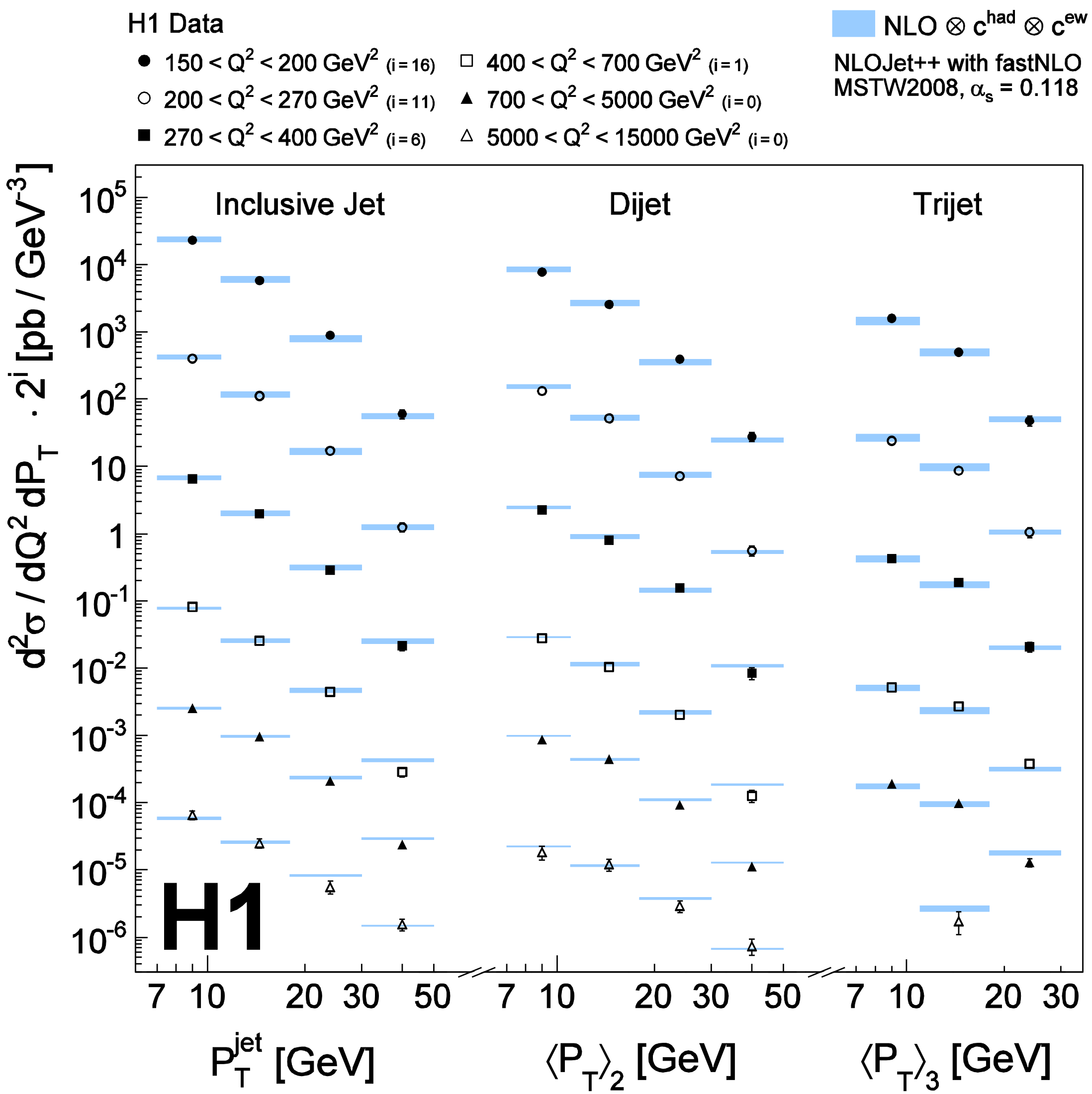
Double differential trijet cross sections





Good agreement between data and NLO calculations

Multijet at high Q^2 – Inclusive Jet, Dijet, Trijet



NLO Calculations

- NLOJet++ corrected for
  - hadronisation effects
- Scale Choice:
  - $\mu_f^2 = Q^2$
  - $\mu_r^2 = (Q^2 + P_T^2)/2$
- Theory uncertainty
  - Vary scales by factor 2

NLO QCD with MSTW2008 describes well inclusive jet, dijet and trijet differential cross sections

Correlation matrix of all data points

Covariance matrix

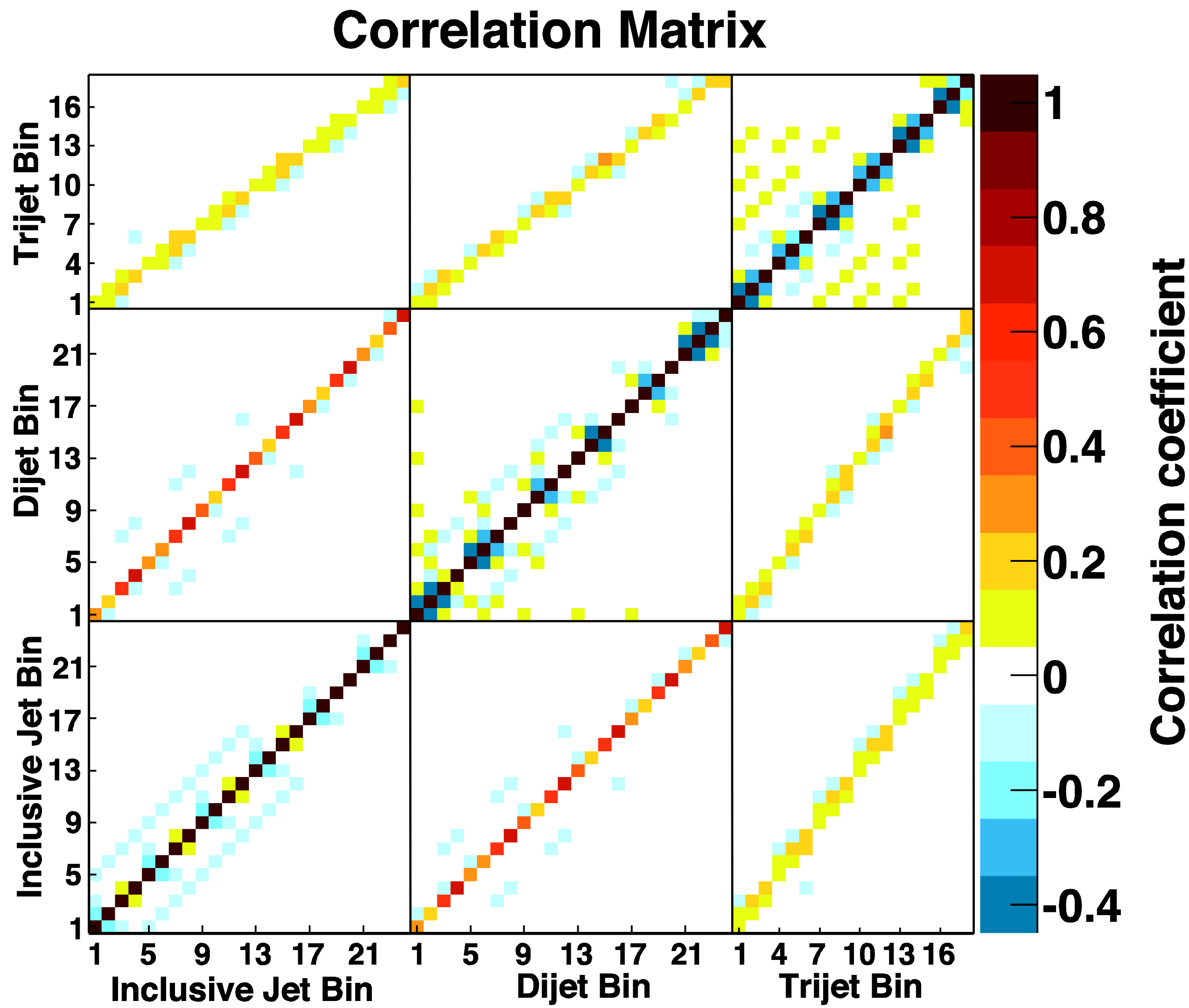
Obtained through linear error propagation of statistical uncertainties

Correlations

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

Useful for

- Cross section ratios
- Combined fits
- Normalised cross sections



Correlation matrix is employed for correct error propagation for norm. cross sections