Precision QCD (jets and α_s) measurements at HERA

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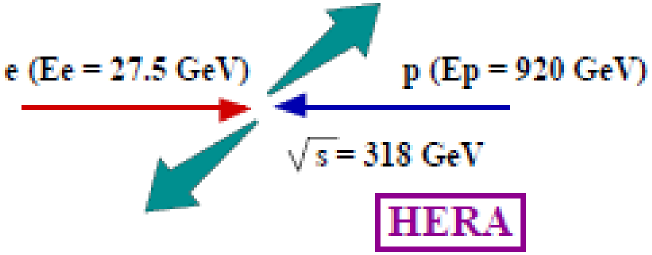
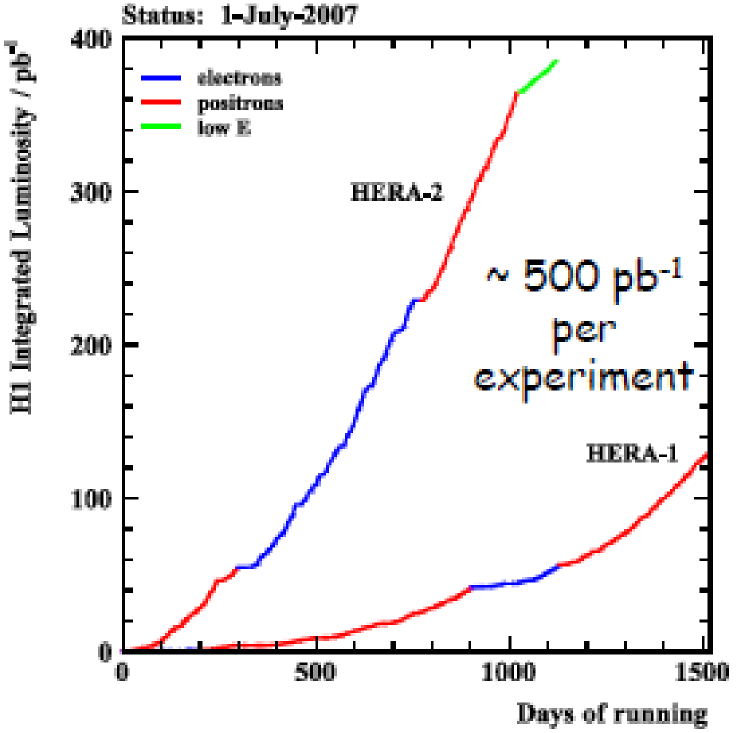
On behalf of H1 and ZEUS Collaborations

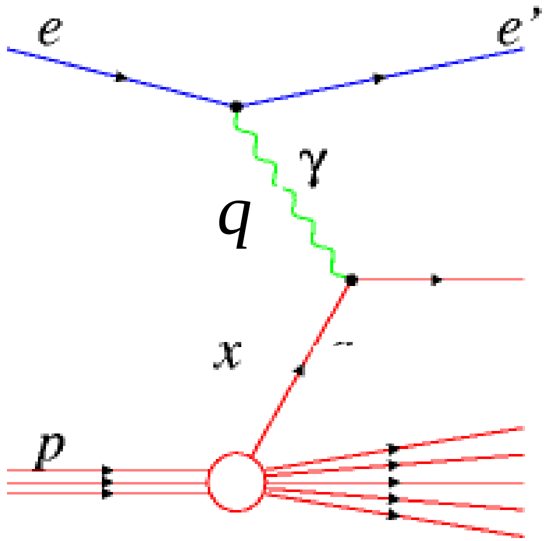
- Jet measurements at HERA
- Multijet measurement in DIS – unfolding
- Jet measurement in photoproduction
- Extraction of α_s : H1 and ZEUS methods
- Comparison of the extracted values of α_s
- Summary

ep – scattering at HERA





~ 500 pb^{-1} per experiment



$Q^2 = -q^2$ exchanged boson virtuality

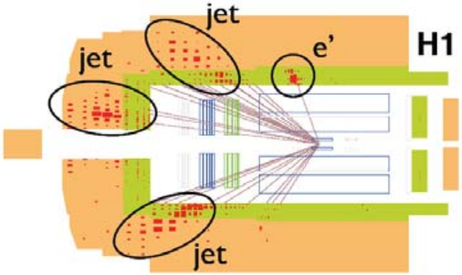
x Bjorken scaling variable

Two kinematic regimes:

- $Q^2 \approx 0$ GeV^2 : Photoproduction
- $Q^2 > 1$ GeV^2 : DIS

Precision jet measurements at HERA

❑ Data sets 300 – 500 pb^{-1} → High statistics → small statistical uncertainties even at high Q^2 and high jet transverse momentum



H1 DIS multijets:

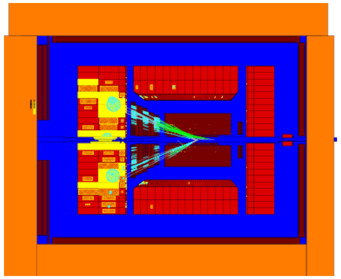
≈ 104000 events

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

$0.2 < y < 0.$

$-1 < \eta_{lab} < 2.5$

$5(7) < p_T < 50$ GeV



ZEUS photoproduction

≈ 450000 events

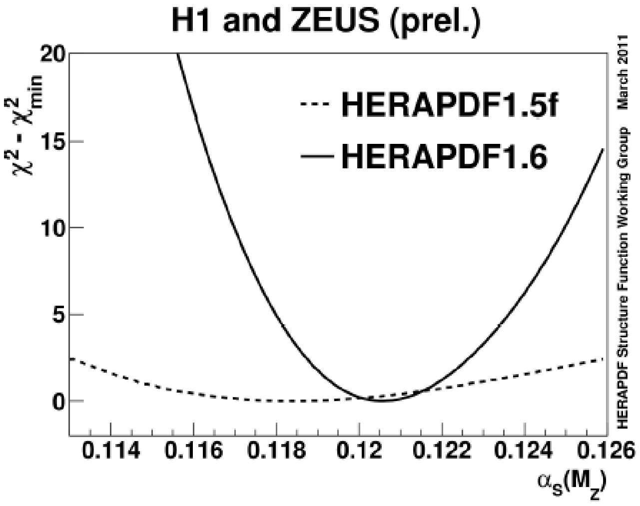
- $Q^2 <1$ GeV^2
- $0.2 < y_{JB} < 0.85$
- $E_T > 17$ GeV
- $-1 < \eta^{jet} < 2.5$

❑ Excellent control of systematic uncertainties

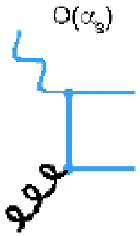
- ➢ Electron measurement : 0.5 – 1% scale uncertainty
- ➢ **Jet energy scale : 1% !** (effect on jet cross section 3-10 %)

Jets: key to precise determination of α_s

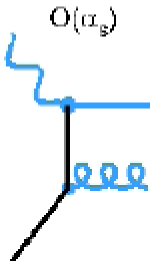
Breit frame inclusive jet cross section proportional to α_s in LO. Its inclusion to global QCD fit (HERAPDF1.5→1.6) increases immensly sensitivity to $\alpha_s(M_Z)$



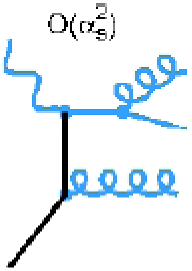
BGF: strong correlation
α_s – gluon density

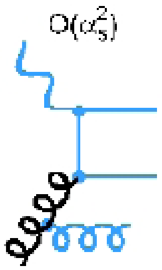


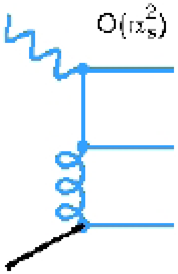
Due to high statistics of events with $Q^2 > 1000$ GeV and increased sensitivity to QCDC (valence quark distributions) gluon – α_s correlation diminished



Trijets: α_s^2 term in LO diminishes experimental uncertainty in extraction of $\alpha_s(M_Z)$







Multijet measurements - unfolding

- ☐ Detector resolution introduces migrations between jet samples
- ☐ Correlations between samples ex definitione: inclusive dijet (trijet) is a subsample of inclusive jet (dijet)...

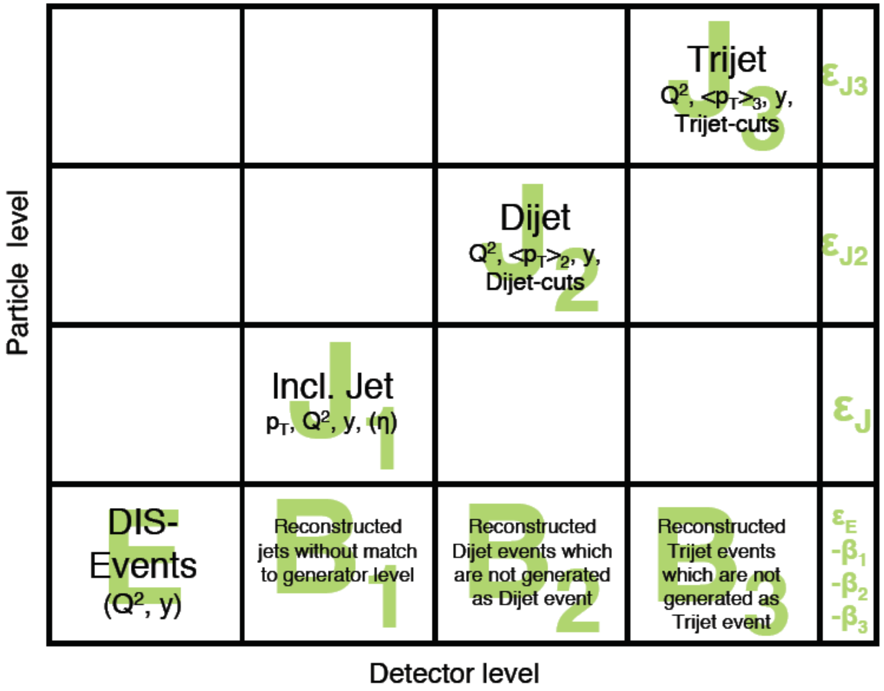
m - measured distribution at the detector level

x **-** true particle level

A – detector response

Unfolding solves equaution **m = A·x**

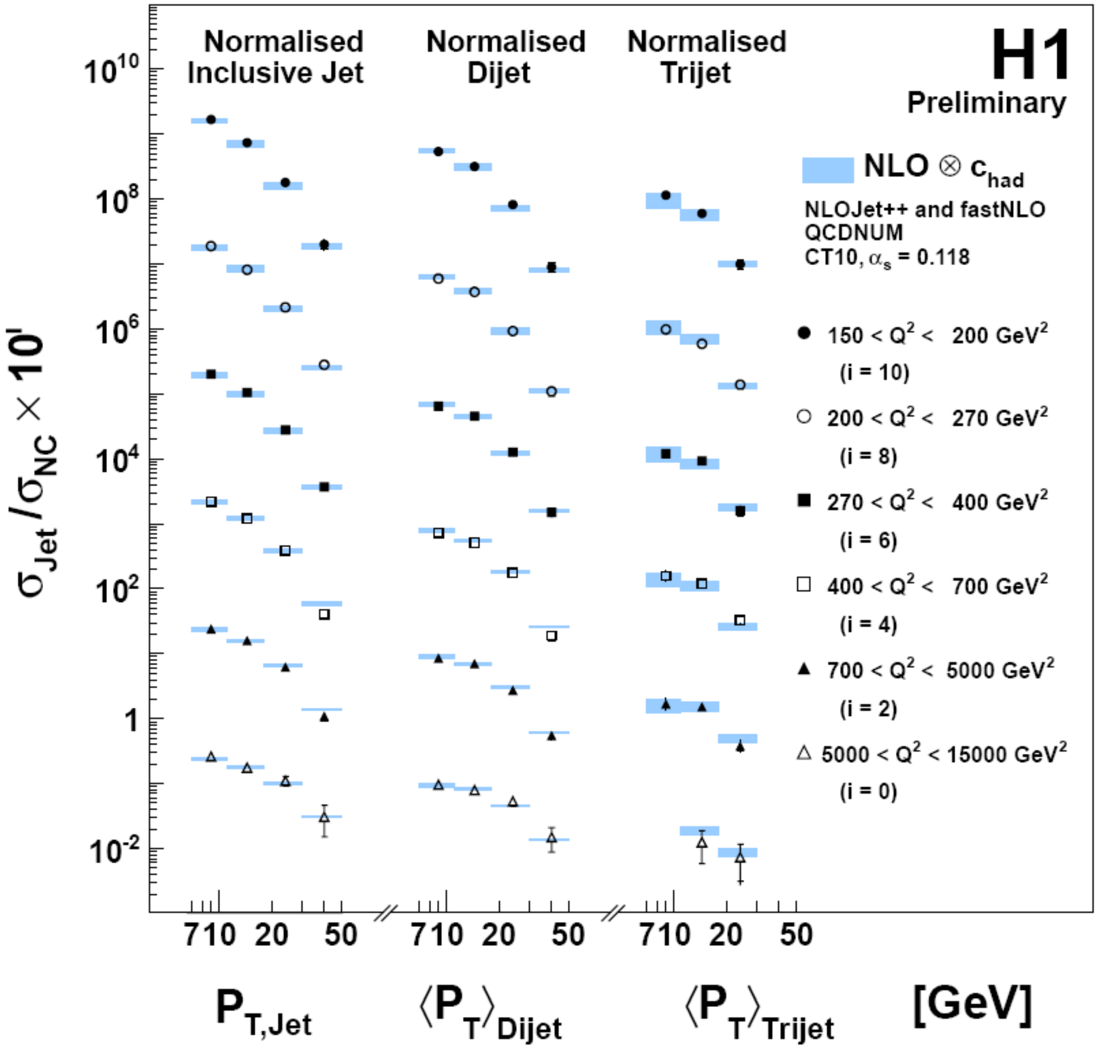
Method: TUnfold, regularized unfolding Root application (S. Schmitt, arXiv:1205.6201)



			Trijet Q^2, $<p_T>_3$, y, Trijet-cuts J_3	ε_{J3}
		Dijet Q^2, $<p_T>_2$, y, Dijet-cuts J_2		ε_{J2}
	Incl. Jet p_T, Q^2, y, (η) J_1			ε_J
DIS-Events (Q^2, y) E	Reconstructed jets without match to generator level B_1	Reconstructed Dijet events which are not generated as Dijet event B_2	Reconstructed Trijet events which are not generated as Trijet event B_3	ε_E $-\beta_1$ $-\beta_2$ $-\beta_3$

600 X 2200 bins

Normalized multijet cross sections



H1-Prel-12-031

NLO Calculation:

PDF: CT10,α_s = 0.118

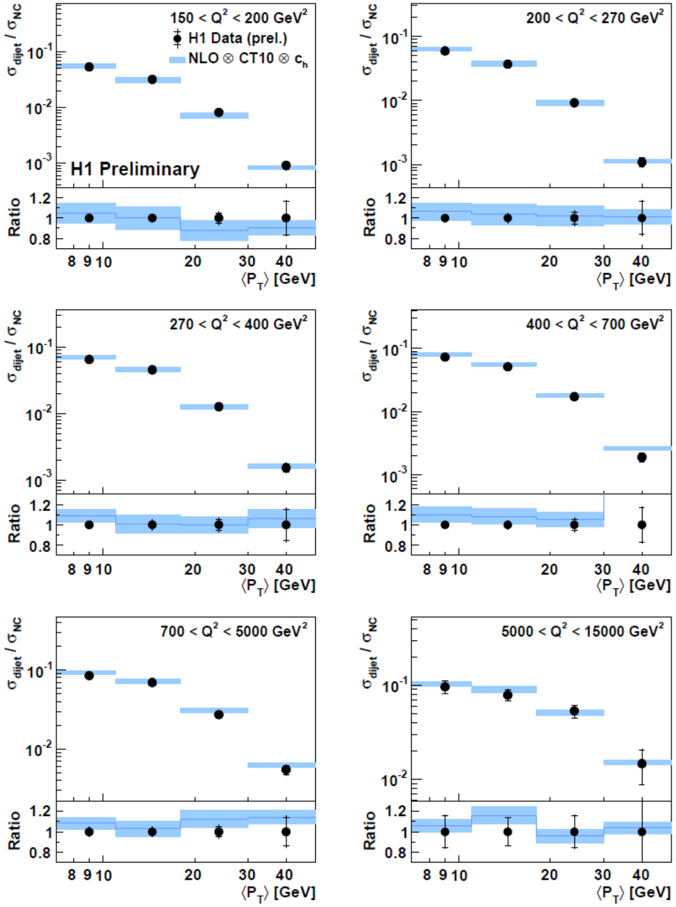
NLOJet++

FastNLO QCDNUM

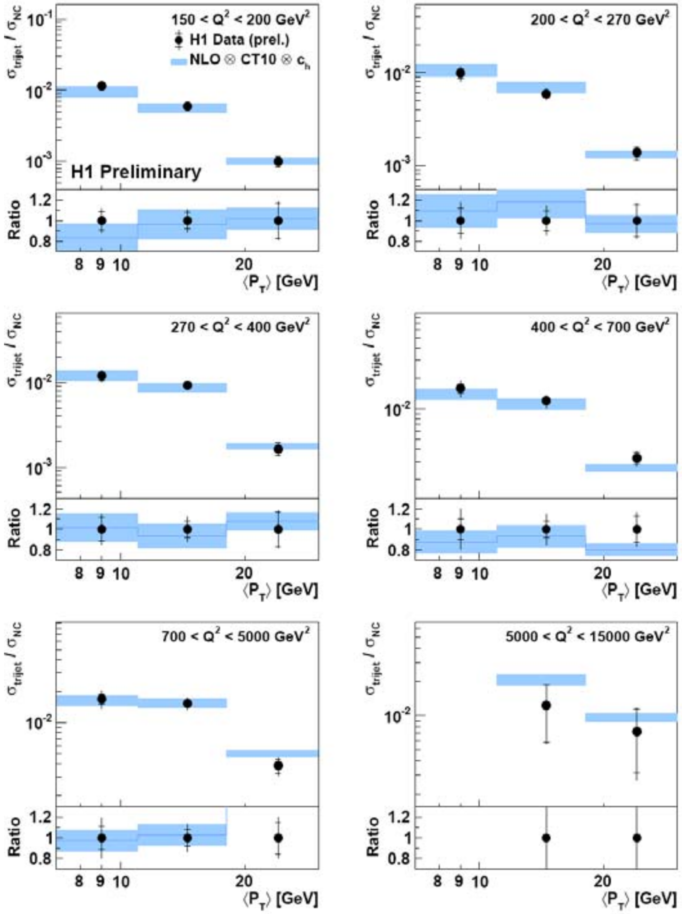
Corrected for hadronisation

- **Trijets for the first time**
- **Small experimental errors**
- **Very good NLO and LO (trijets) description of the data**

Normalized dijet and trijet cross sections



Normalised Dijet Cross Section



Normalised Trijet Cross Section

Except for highest Q^2 bins experimental uncertainty much smaller than theoretical

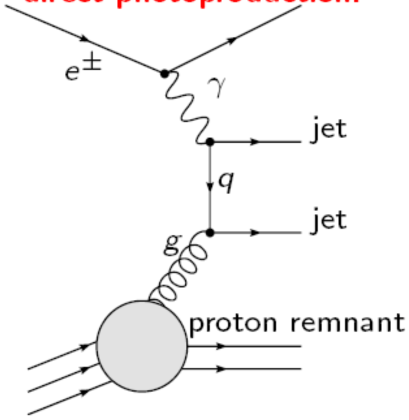
Jets in photoproduction ($Q^2 \approx 0$)

- Large cross section → large statistics of jets with very high transverse momentum
- Single hard scale : jet p_T

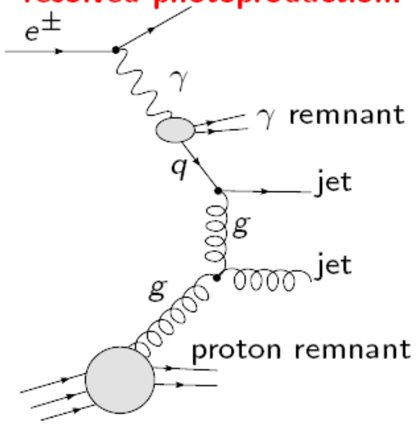
Excellent for extraction of α_s

But...

direct photoproduction:



resolved photoproduction:



Multiple parton interactions and significant spread between photon structure functions (γPDF) - possible source of ambiguities

Inclusive jet measurement in photoproduction

DESY-12-045 (March 2012) Nucl. Phys. B864 (2012), pp. 1-37

Phase space

- $Q^2 < 1$ GeV^2
- $0.2 < y_{JB} < 0.85$
- $E_T > 17$ GeV
- $-1 < \eta^{jet} < 2.5$

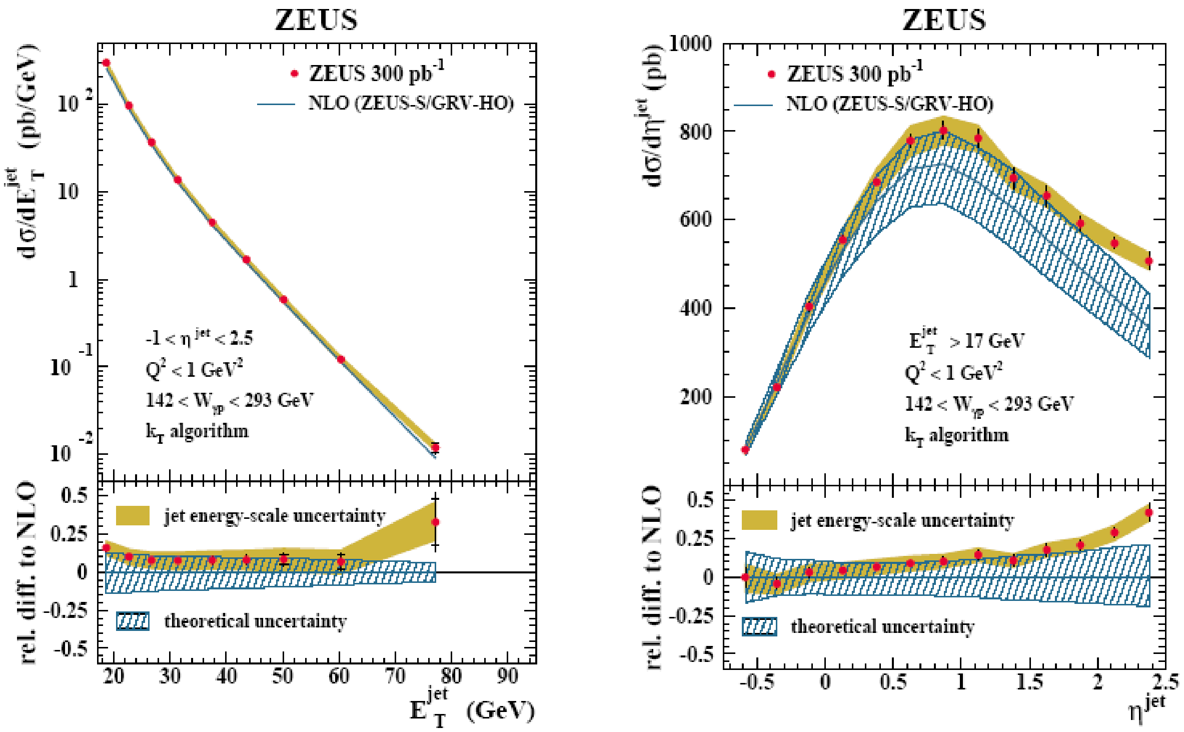
NLO QCD

Klasen,Kleinwort,Kramer

pPDF: ZEUS-S

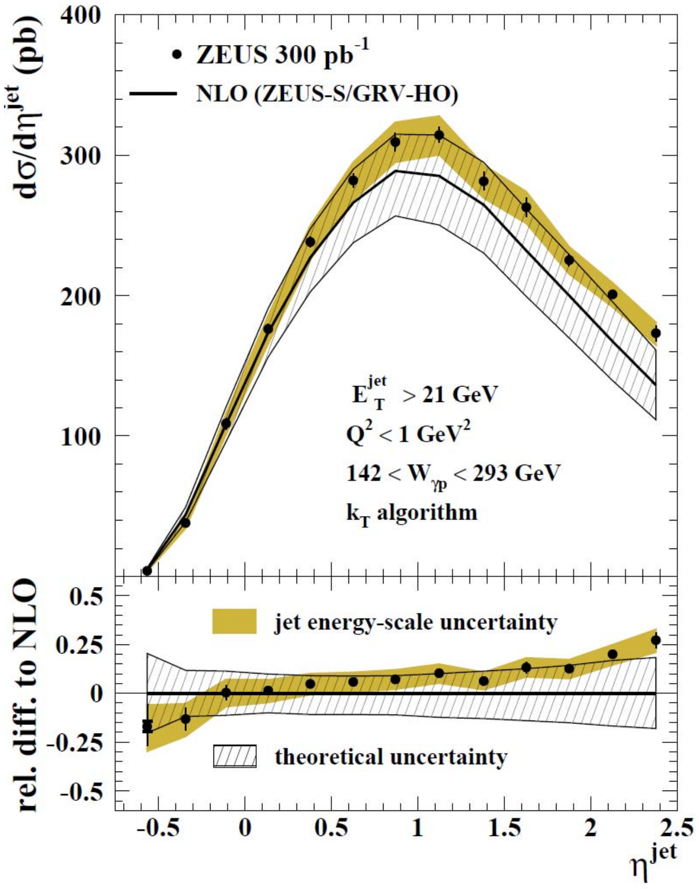
γPDF: GRV-HO

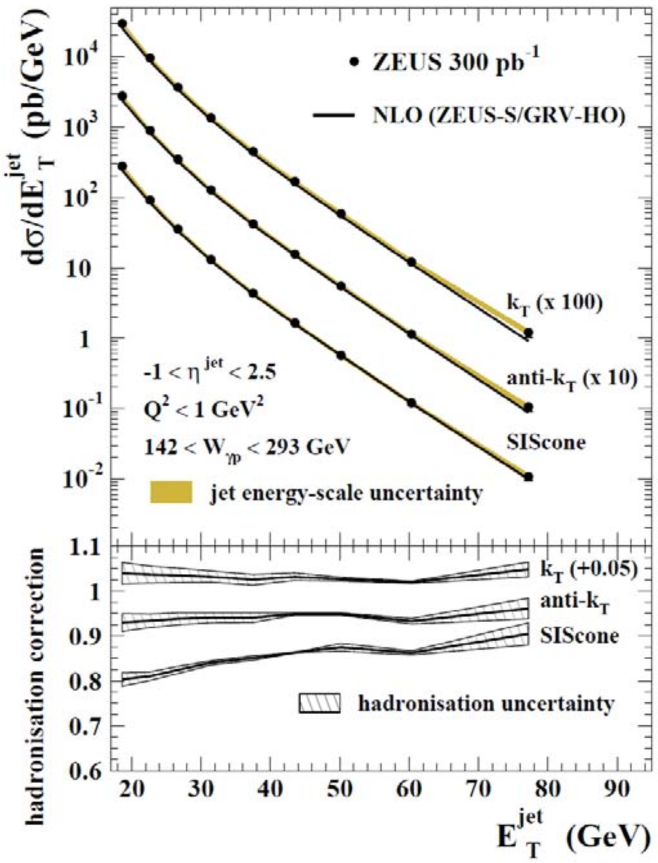
$\mu_r = \mu_f = E_T^{jet}$



- experimental uncertainty smaller than theoretical
- good description by NLO calculation except for $\eta^{jet} > 2.0$
- MI and/or γPDF possible source of discrepances

Inclusive jet measurement in photoproduction





- Good description in the whole η^{jet} range after raising threshold to E_T > 21 GeV
- Stringent test of jet algorithms

Determination of $\alpha_s(M_Z)$

H1: Hessian method: Minimise $\chi^2(\alpha_s)$

$$\chi^2 = \sum_{i=1}^{N} \frac{[d_i - t_i(1 - \sum_k \epsilon_k \Delta_{ik})]^2}{\sigma^2_{i,\mathrm{stat}} + \sigma^2_{i,\mathrm{uncorr}}} + \sum_k \epsilon_k^2$$

- Keep PDF (CT10) fixed and fit α_s

•Theoretical uncertainty obtained by offset method : repeat fit with μ_r and μ_f varied by factor ½ and 2

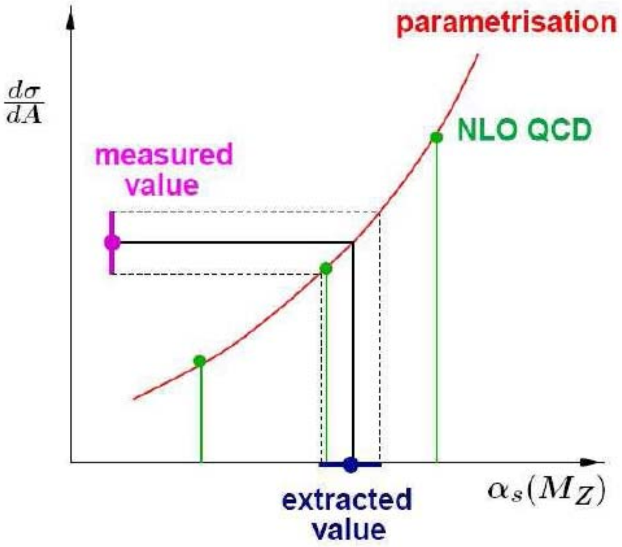
ZEUS:

•Parametrise theory using NLO calculations with PDF sets obtained for different α_s.

•Measured value and its uncertainty is projected on the parametrization

•Theory uncertainty by band method (more sophisticated version of offset method → 30-50% smaller uncertainty

•ZEUS method unlike H1 takes into account α_s – PDF (gluon) correlation



Extracted $\alpha_s(M_Z)$

$$\sigma^{jet} \rightarrow \sigma^{parton} \rightarrow \alpha_s(M_Z)$$

Normalized multijets (k-factor < 1.3)

$\alpha_s = 0.1163 \pm 0.0011$ (exp)	Measurement of jet cross section	
± 0.0014 (PDF)	Dependence on proton PDF	theory
± 0.0008 (had)	Hadron→parton level	
± 0.0045 (scale)	μ_r and μ_f dependence	

Theory uncertainty dominated by scale and >> experimental uncertainty

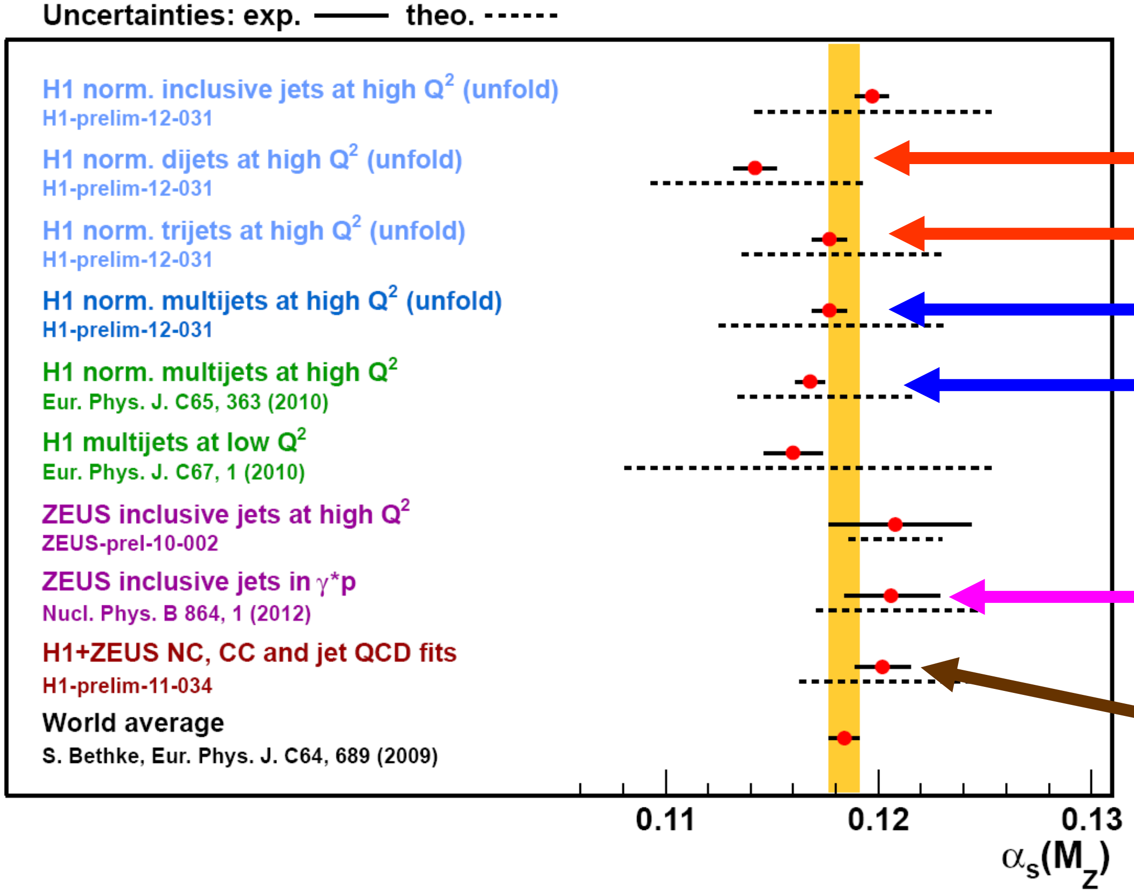
Photoproduction inclusive jets E_T > 21 GeV

$\alpha_s = 0.1206 \pm 0.002$ (exp)

± 0.004 (theory)

γPDF **and scale contribute equally to theory uncertainty**

Comparison of extracted $\alpha_s(M_Z)$ values



Tension between dijets and trijets

multijets with very small exp. uncertainty

Trade-off theoretical for experimental uncertainty (only Q^2>500 points)

Potential to decrease exp. uncertainty including multijets into global fit

Experimental uncertainty much smaller than theoretical, dominated by missing NNLO

All results compatible with world average within uncertainties

Summary

☐ Recent precision jet measurements at high Q^2 (H1) and in photoproduction (ZEUS)

☐ Inclusive jet, dijet and trijet measurements at high Q^2 using multidimensional unfolding, very small experimental uncertainties, good description of the data by NLO (jet, dijet) and LO (trijet) calculation

☐ Inclusive jet measurement in photoproduction, good descrption of the data by NLO calculation for $E_T > 21$ GeV

☐ **In general, the data are more precise than QCD predictions**

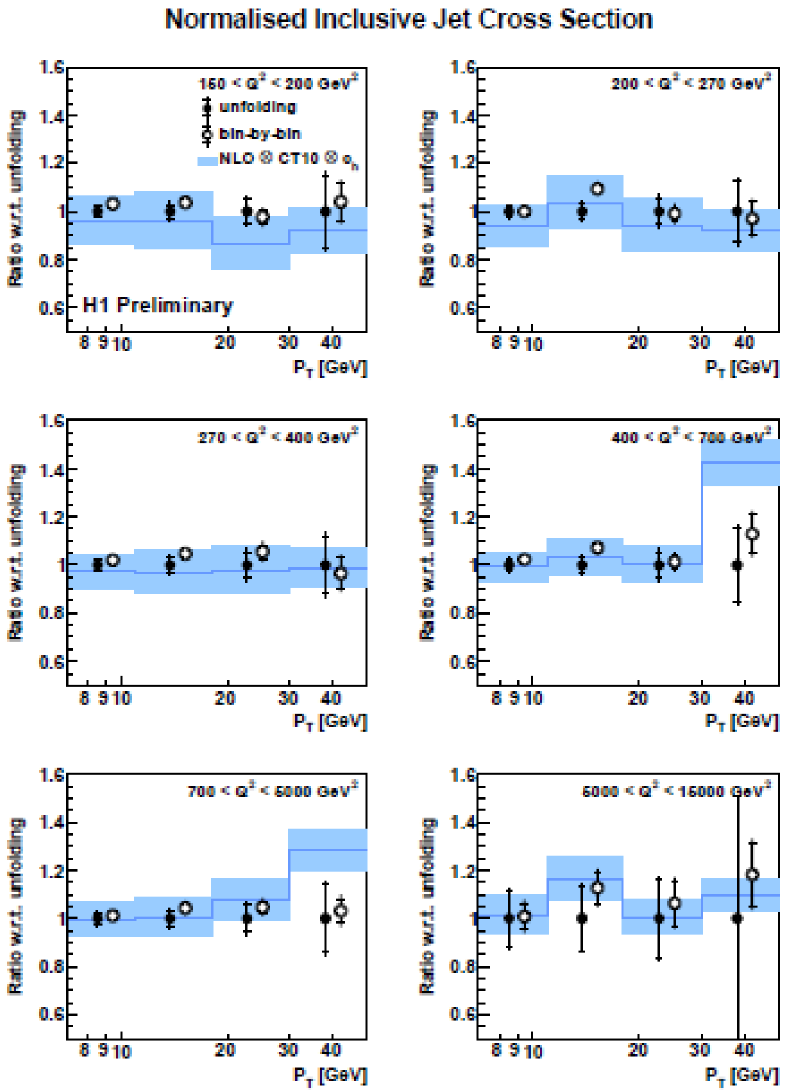
☐ **Extracted values of α_s are consistent with world average and their experimental uncertainties are much smaller than theoretical**

☐ In the inclusive multijet measurement, theoretical α_s uncertainty is dominated by missing NNLO terms of the perturbative expansion

☐ In the inclusive photoproduction jet measurement terms beyond NLO and γPDF contribute similarly to theoretical α_s uncertainty

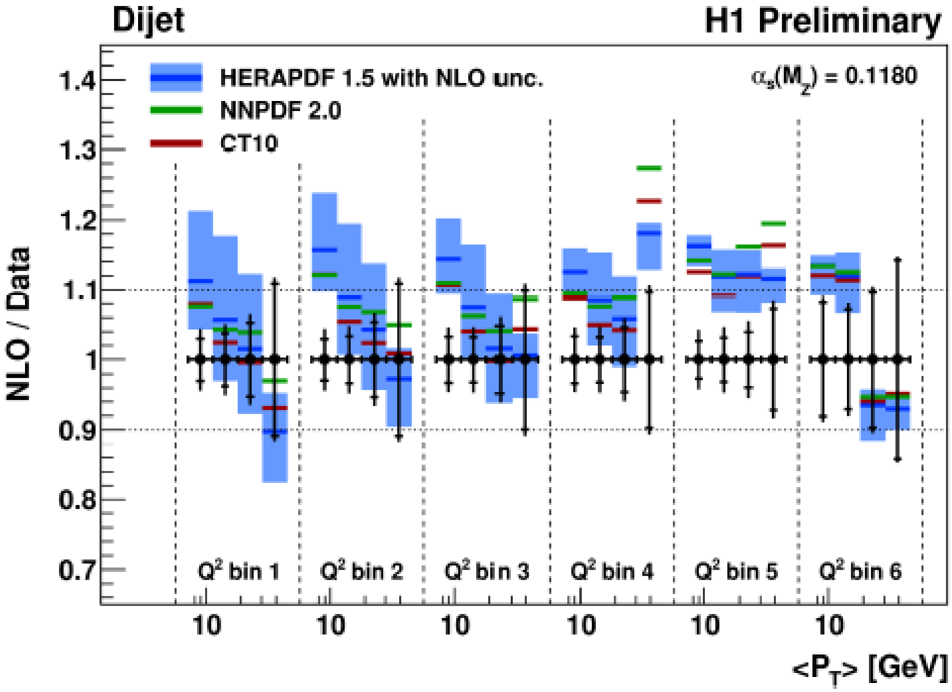
Backup slides

Unfolding vs. Bin-by-bin

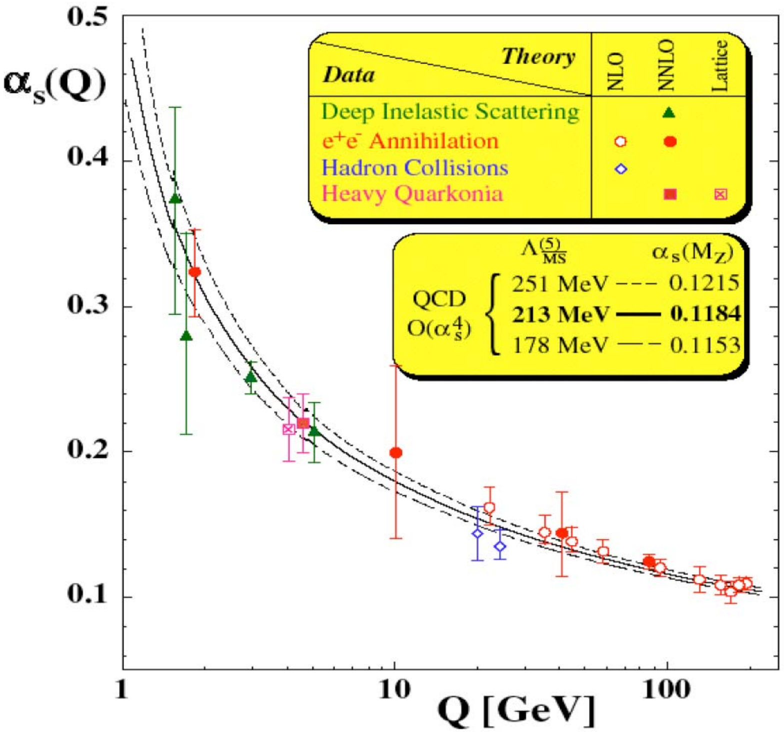

Normalised Inclusive Jet Cross Section

PDF dependence

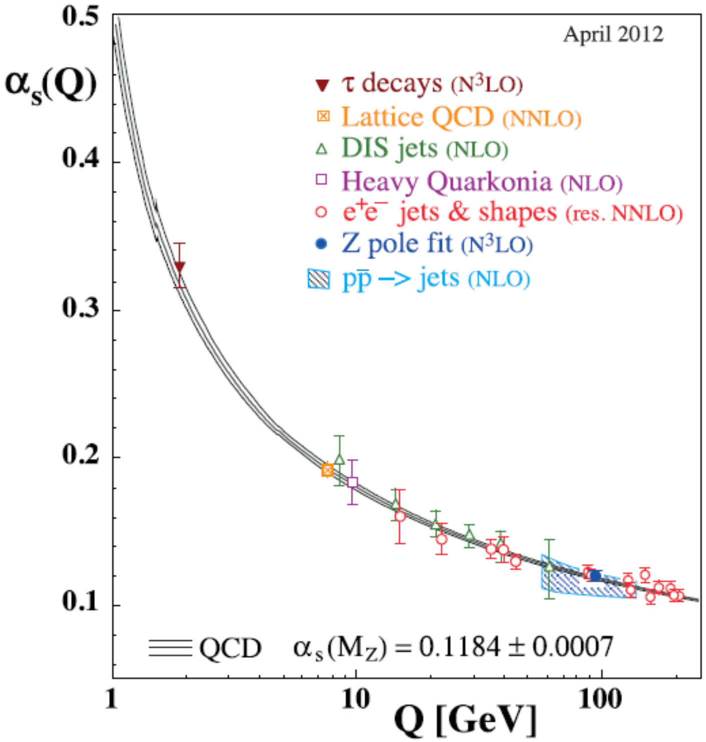
4 – 6%



$\alpha_s(M_Z)$ – fundamental constant



Copied from slide of prof. Frank Wilczek Nobel Lecture **2004**

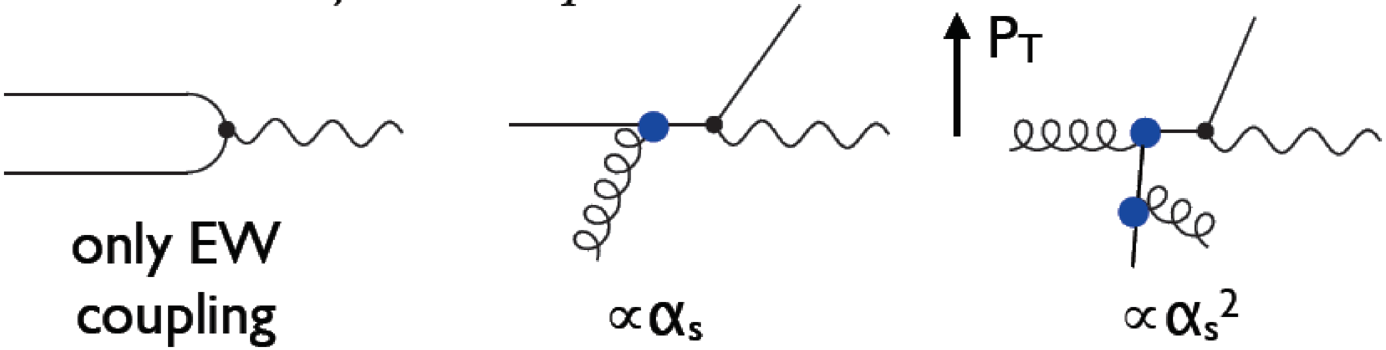


Running α_s compilation from **2012** PDG QCD review

$\alpha_s(M_Z)$ is a fundamental constant of the nature, it is not possible to exaggerate in efforts to increase the accuracy of the measurements

Jet production in DIS

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



- In Breit frame only hard QCD processes generate considerable p_T
- Inclusive jets,dijets, trijets...: at least one, two three.. jet above certain threshold in p_T
- n-jet production in LO proportional to α_s^{n-1}