Precision QCD (jets and α_s) measurements at HERA

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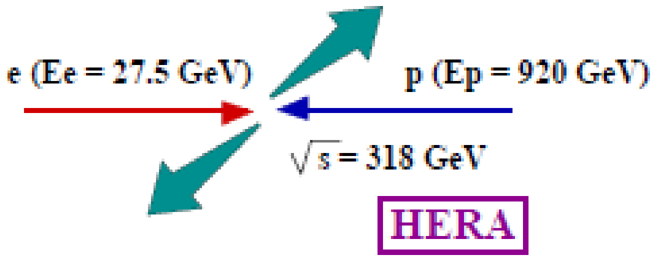
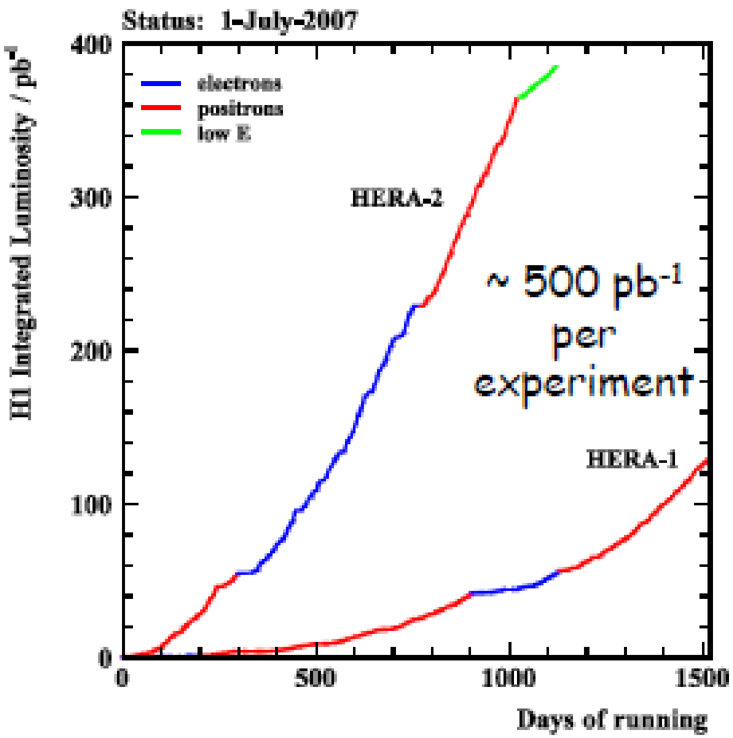
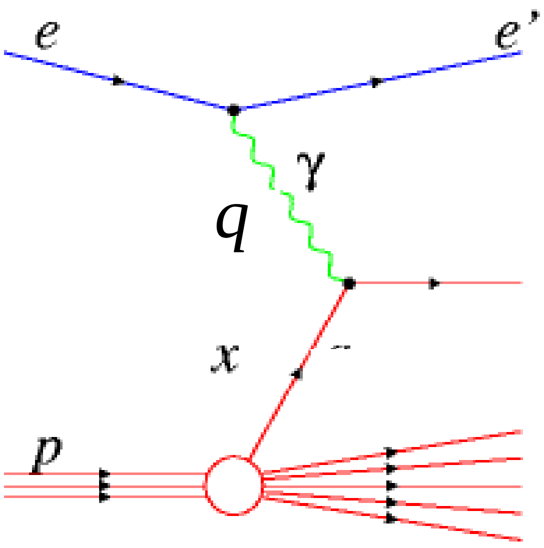
On behalf of H1 and ZEUS Collaborations

- 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







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

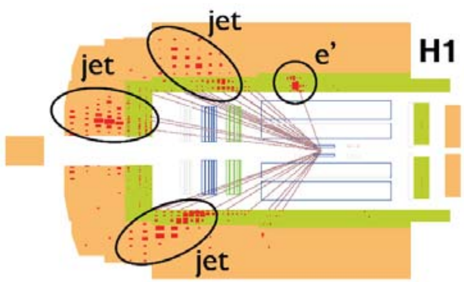
x Bjorken scaling variable

Two kinematic regimes:

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

Precision jet measurements at HERA

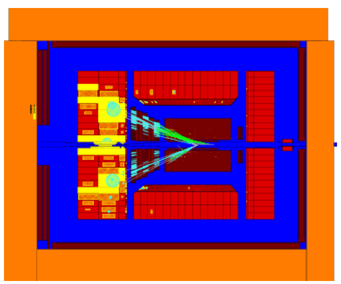
❑ Data sets 300 – 500 pb^{-1} → High statistics → small statistical uncertainties even at high Q^2 and high jet transverse momentum



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

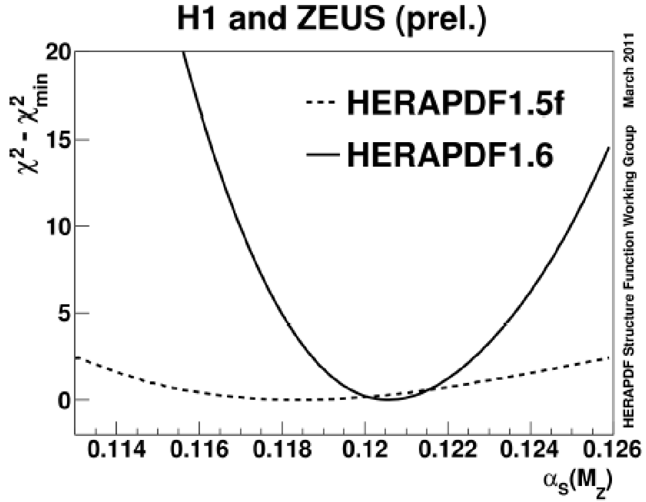
≈ 450000 events

•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

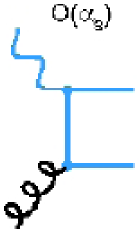
- ➢ Electron measurement : 0.5 – 1% scale uncertainty
- ➢ **Jet energy scale : 1% !** (effect on jet cross section 3-10 %)

Jets: key to precise determination of α_s

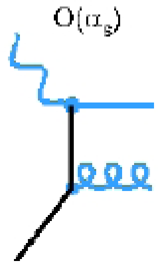


Breit frame inclusive jet cross section proportional to α_s in LO. Its inclusion to global QCD fit (HERAPDF1.5→1.6) increases immensly sensitivity to $\alpha_s(M_Z)$

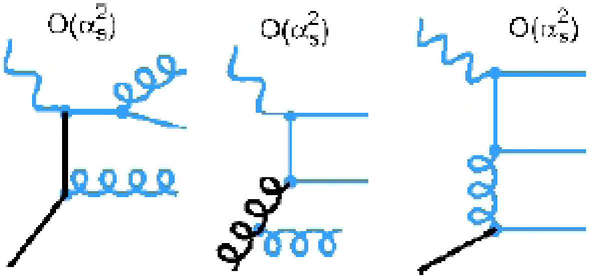
BGF: strong correlation α_s – gluon density



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)...

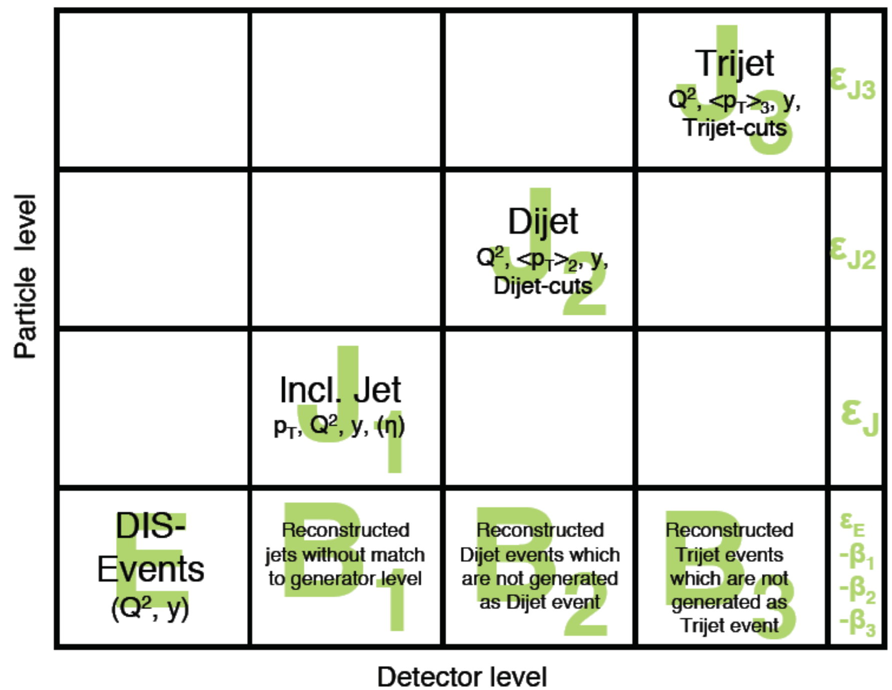
m - measured distribution at the detector level

x **-** true particle level

A – detector response

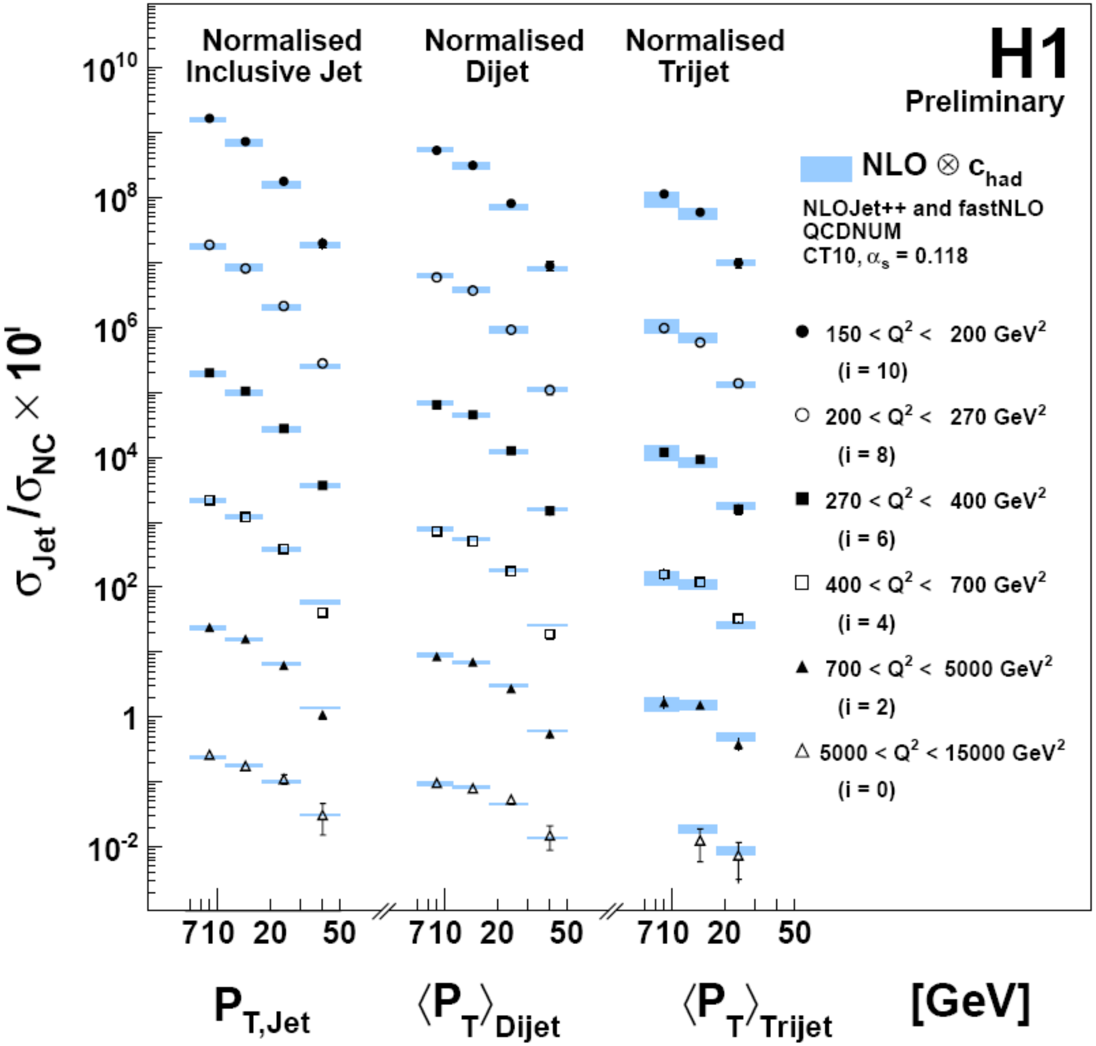
Unfolding solves equaution **m = A·x**

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



600 X 2200 bins

Normalized multijet cross sections



H1-Prel-12-031

NLO Calculation:

PDF: CT10,α_s = 0.118

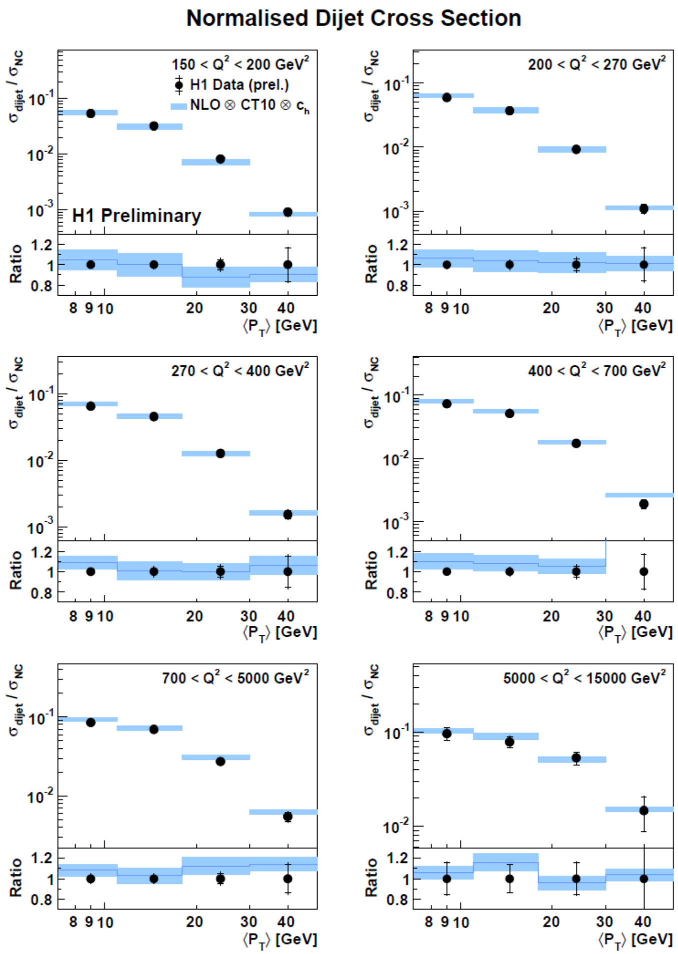
NLOJet++

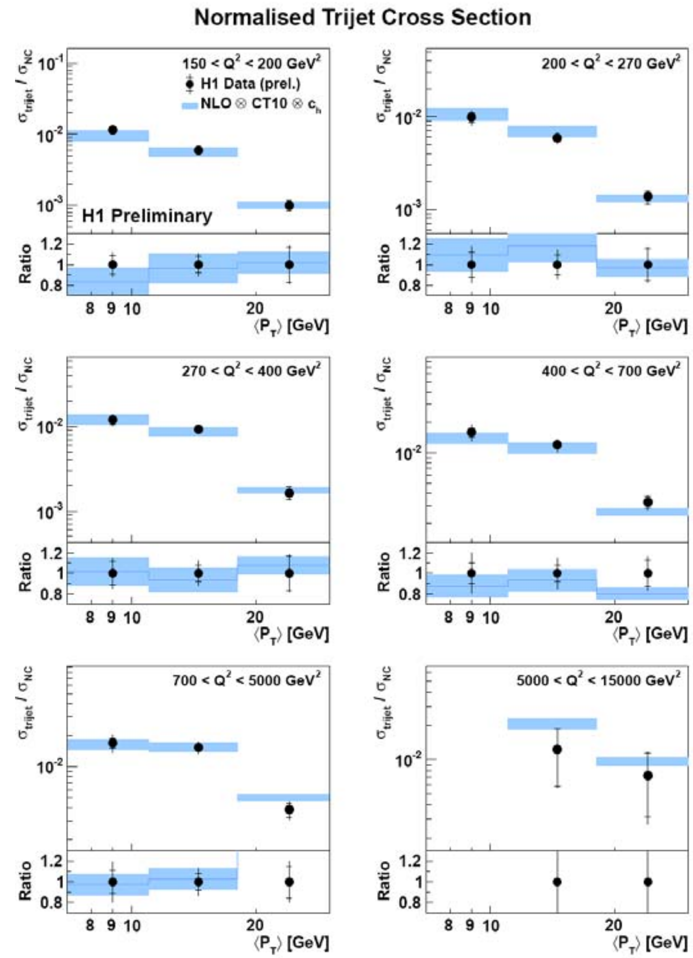
FastNLO QCDNUM

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





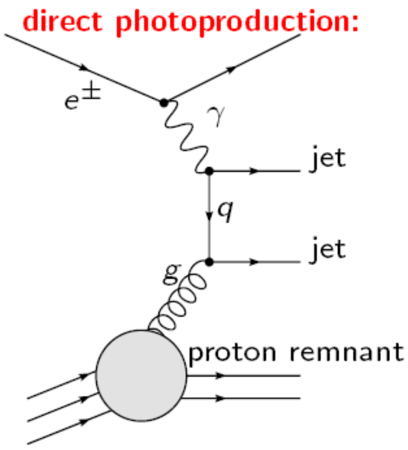
Except for highest Q^2 bins experimental uncertainty much smaller than theoretical

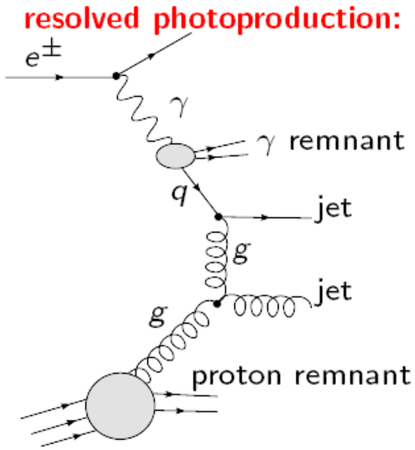
Jets in photoproduction ($Q^2 \approx 0$)

- 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...





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
- $-1 < \eta^{jet} < 2.5$

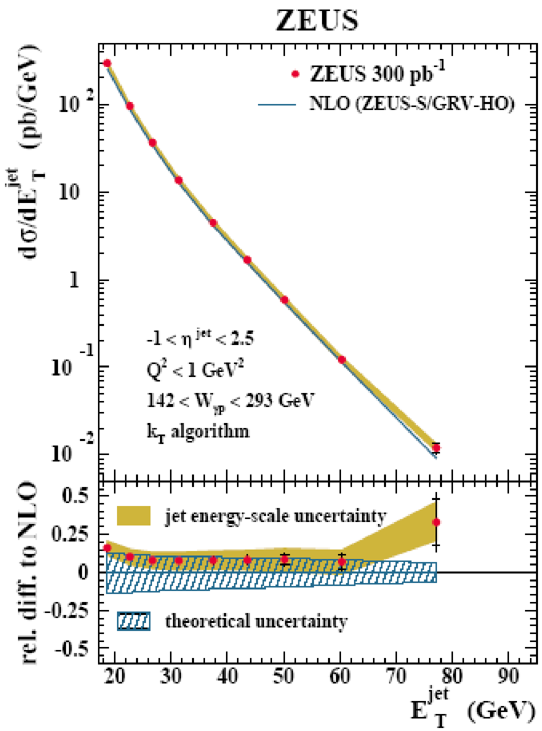
NLO QCD

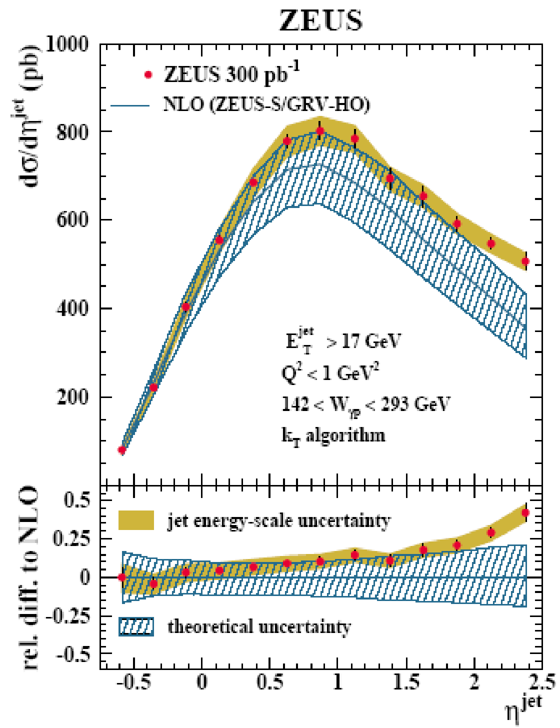
Klasen,Kleinwort,Kramer

pPDF: ZEUS-S

γPDF: GRV-HO

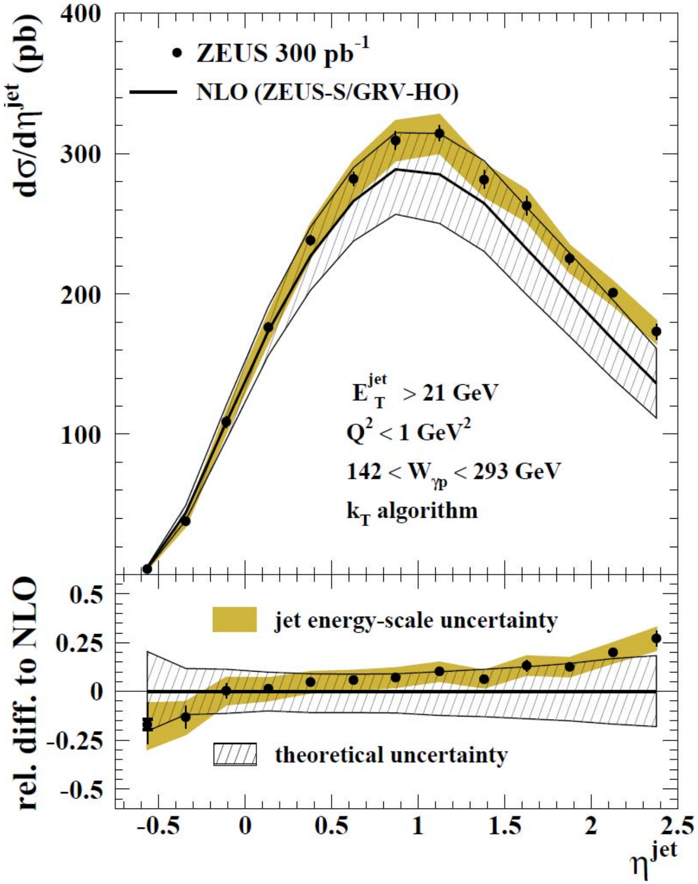
$\mu_r = \mu_f = E_T^{jet}$

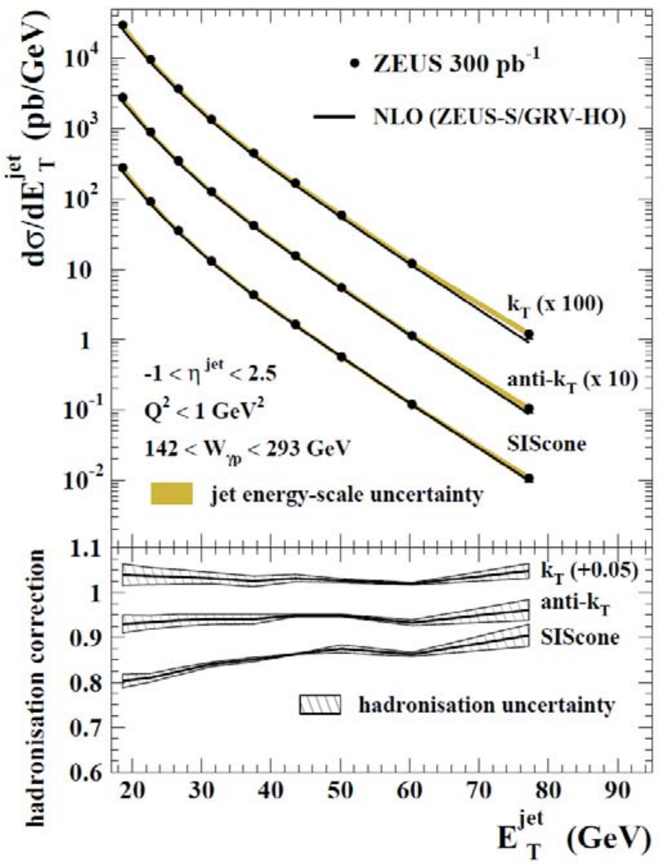




- experimental uncertainty smaller than theoretical
- good description by NLO calculation except for $\eta^{jet} > 2.0$
- MI and/or γPDF possible source of discrepances

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 $\alpha_s(M_Z)$

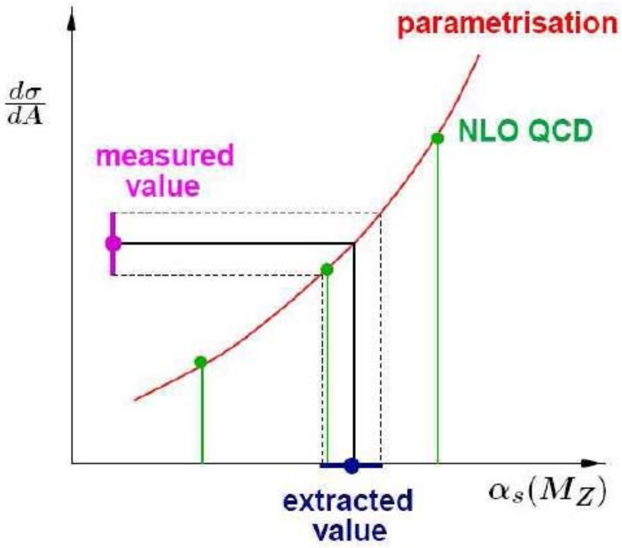
H1: Hessian method: Minimise $\chi^2(\alpha_s)$

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

- 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	
$\pm\ 0.0014$ (PDF)	Dependence on proton PDF	theory
$\pm\ 0.0008$ (had)	Hadron→parton level	theory
$\pm\ 0.0045$ (scale)	μ_r and μ_f dependence	theory

Theory uncertainty dominated by scale and >> experimental uncertainty

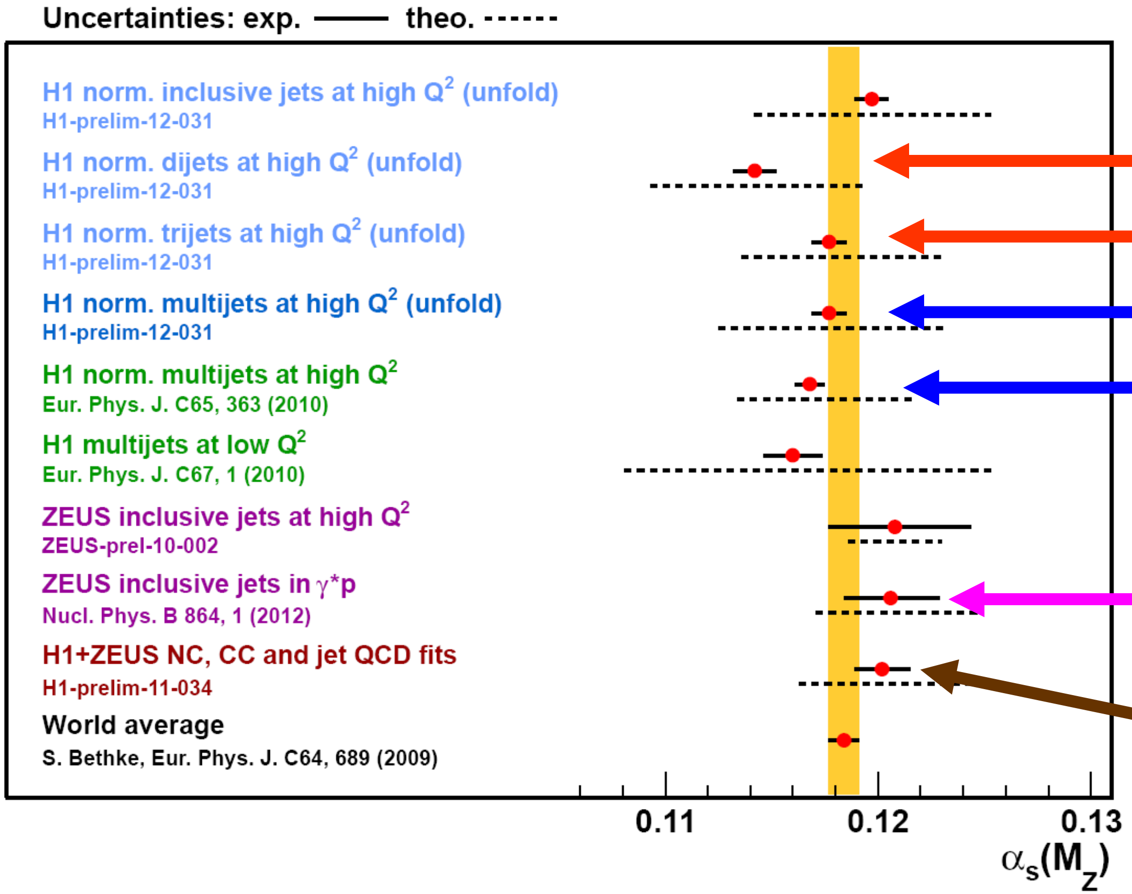
Photoproduction inclusive jets E_T > 21 GeV

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

$\pm\ 0.004$ (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

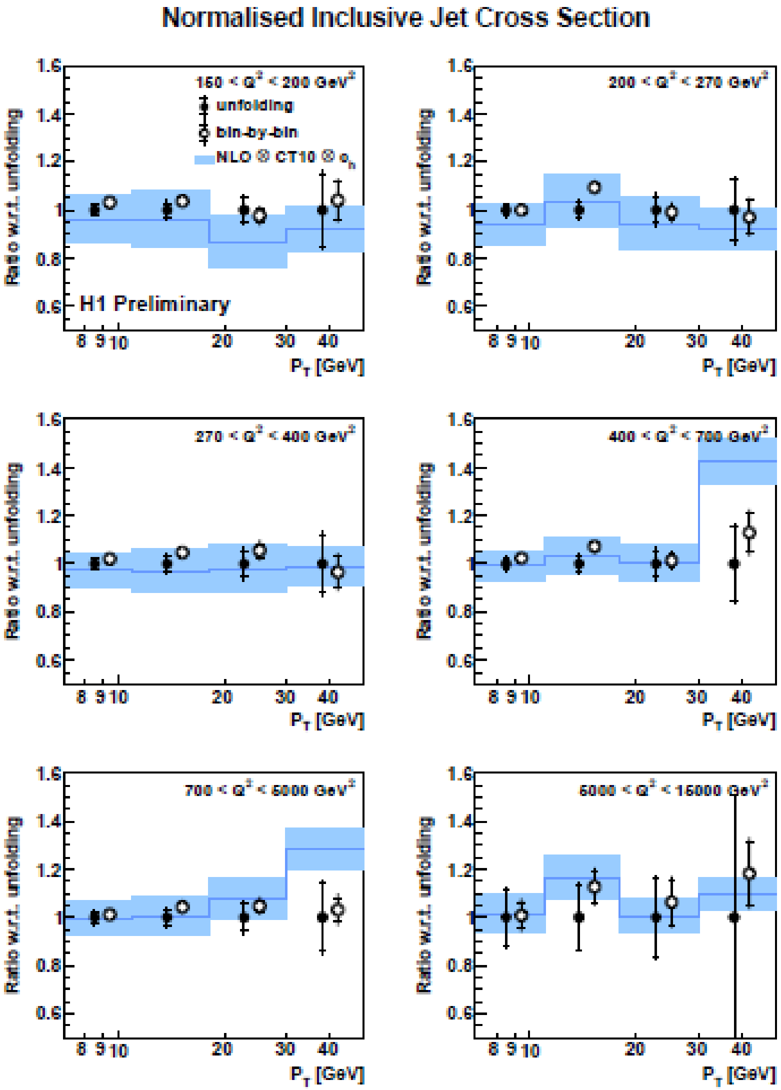
All results compatible with world average within uncertainties

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

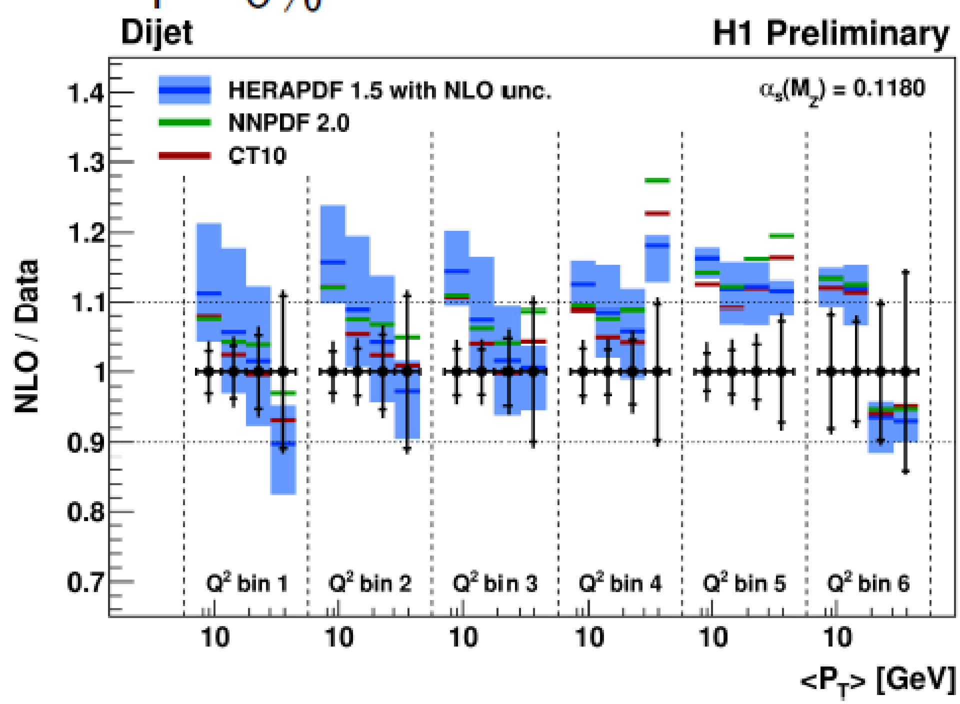
Backup slides

Unfolding vs. Bin-by-bin

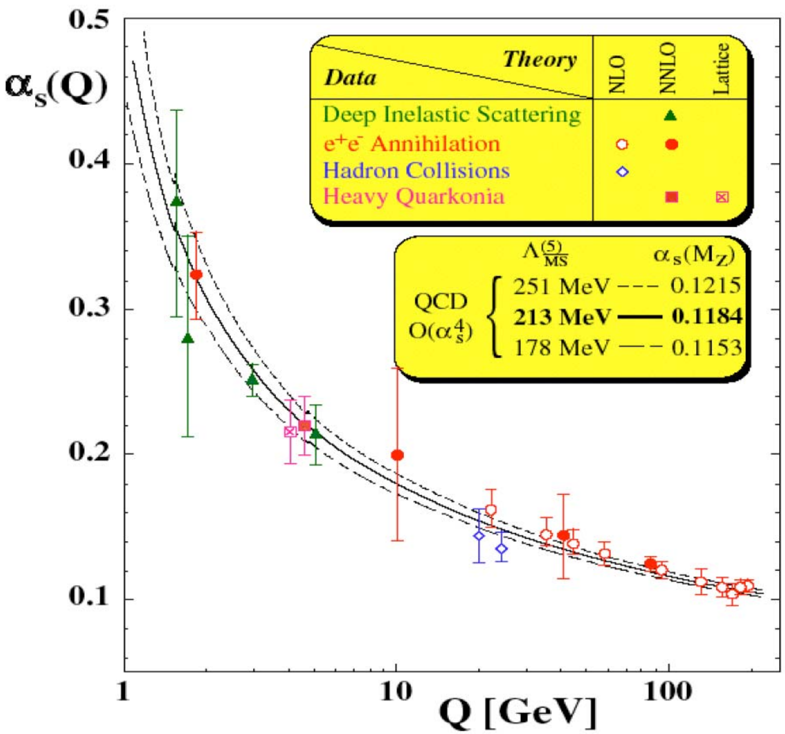


PDF dependence

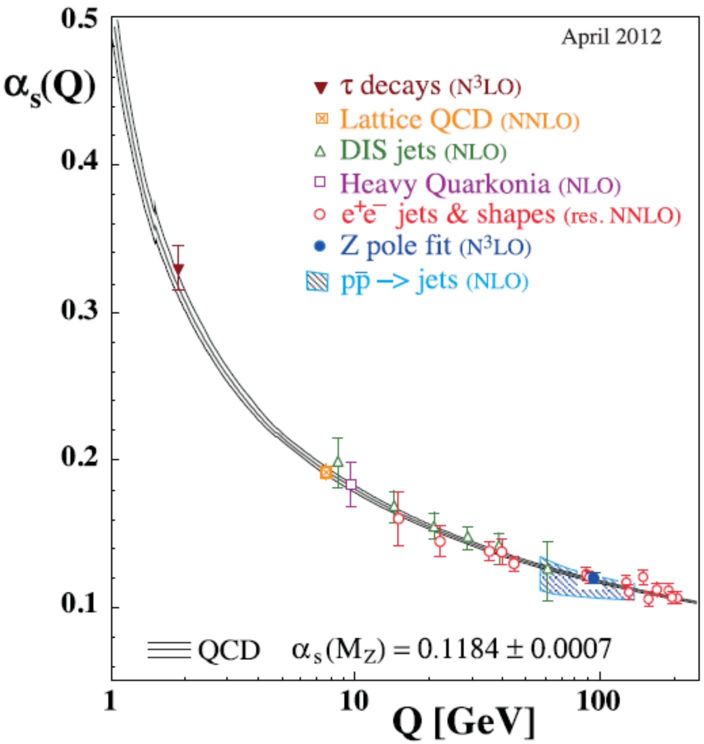
$4 - 6\%$



$\alpha_s(M_Z)$ – fundamental constant



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

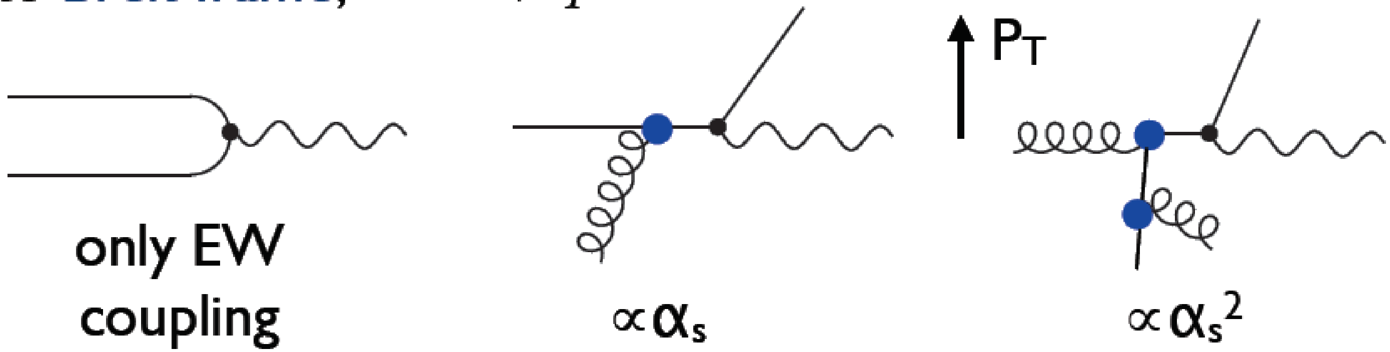


Running α_s compilation from **2012** PDG QCD review

$\alpha_s(M_Z)$ 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}