Jet physics and strong coupling at HERA

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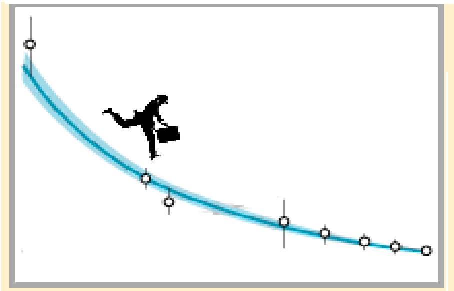
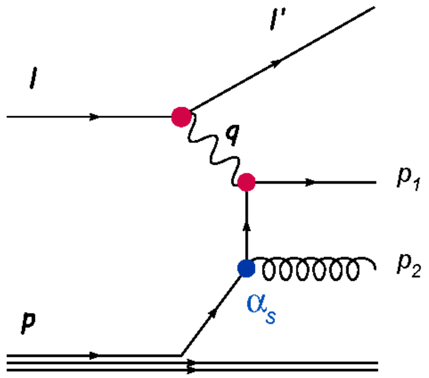


Overview of latest results on the QCD gauge structure from jets in DIS at HERA

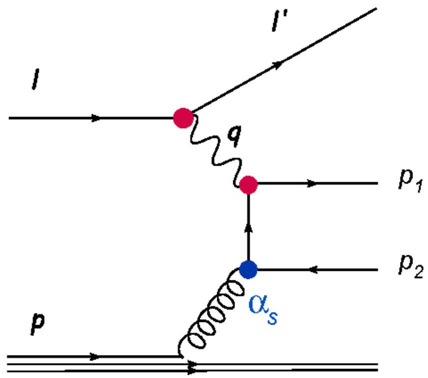
On behalf of the H1 and ZEUS collaborations

Multi-jet production in DIS NC at HERA

e (27.6 GeV) + p (920 GeV) → X + e

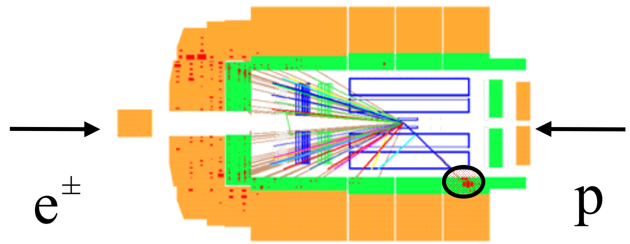


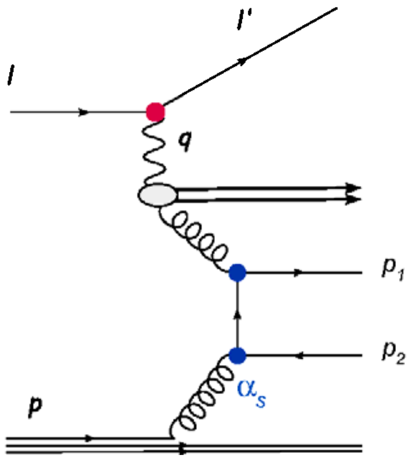
QCD Compton



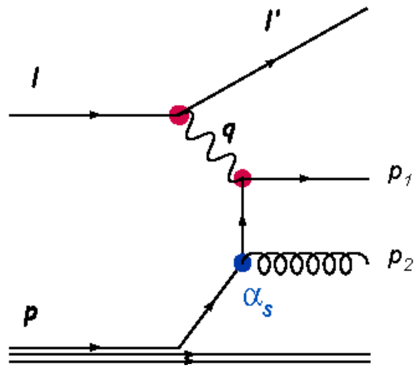
BOSON GLUON Fusion

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

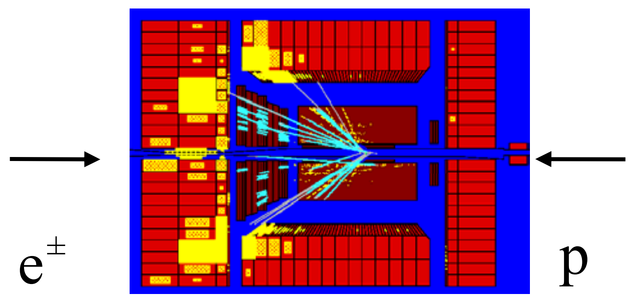




RESOLVED



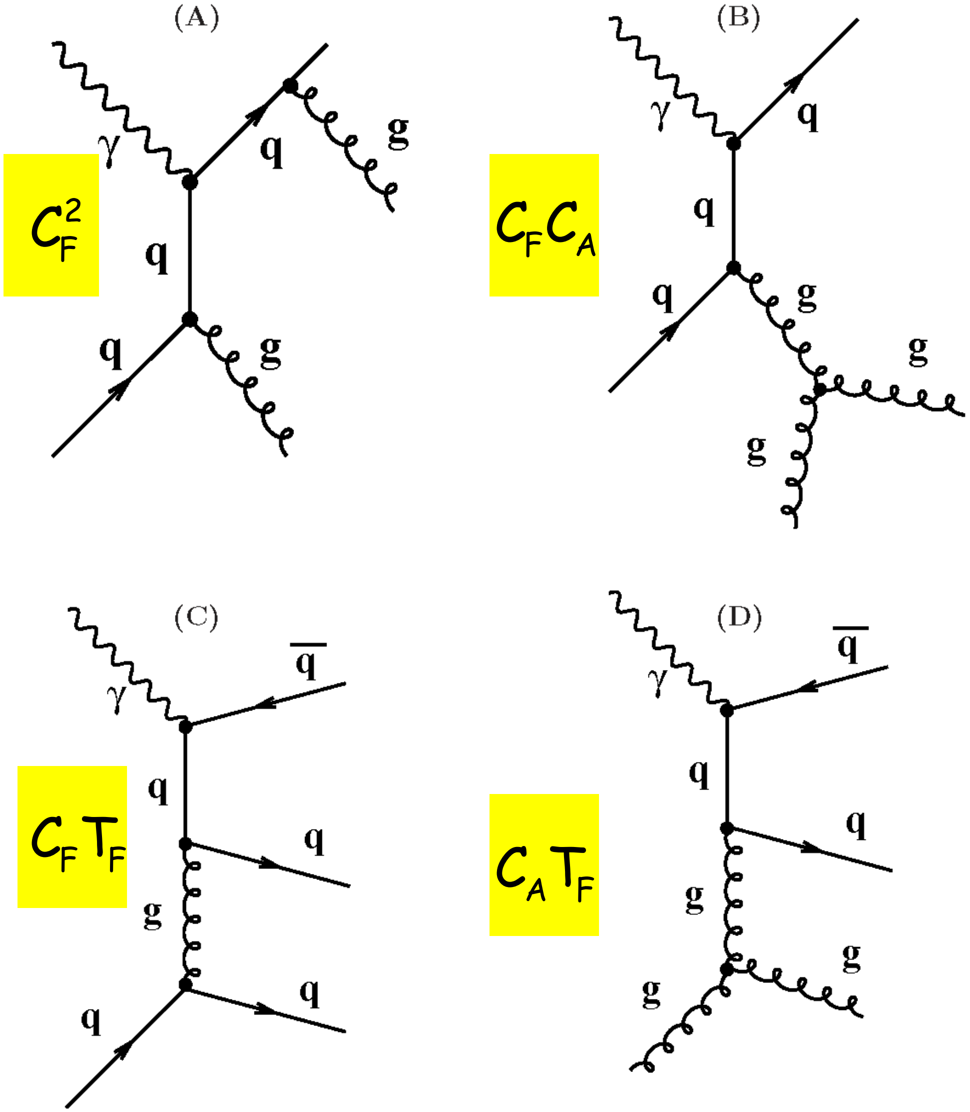
DIRECT



$\gamma p \quad Q^2 \sim 0$

Colour factors from 3-jets (ZEUS)

$$\sigma = C_F^2 \cdot \sigma_A + C_F C_A \cdot \sigma_B + C_F T_F \cdot \sigma_C + C_A T_F \cdot \sigma_D$$



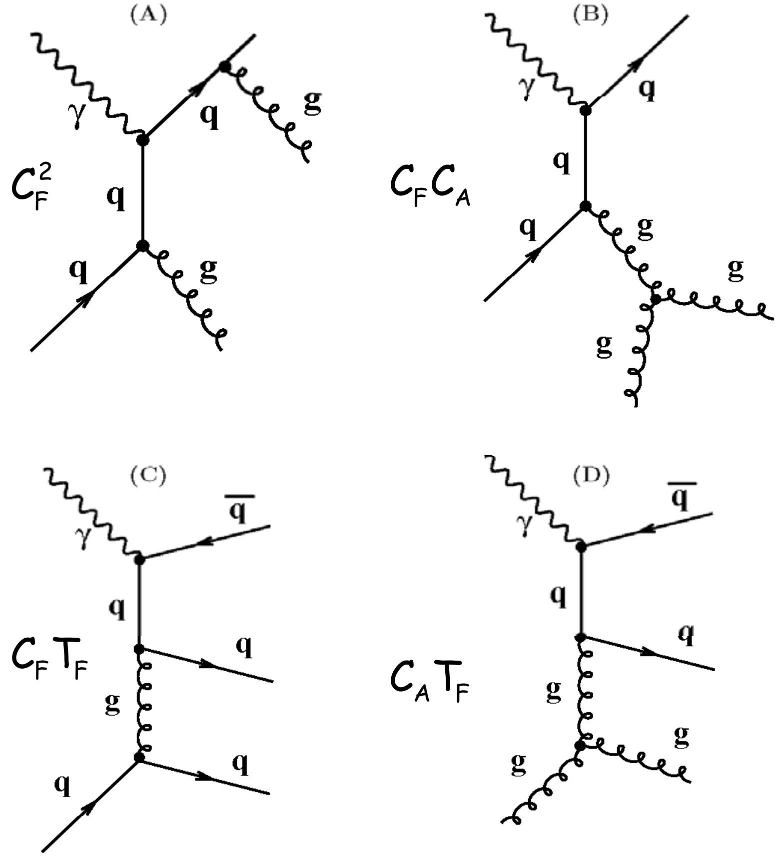
- 3-jet in *ep* sensitive to underlying gauge structure of QCD (like 4-jets in e^+e^-)
- Values of the colour factors are proper to each gauge group

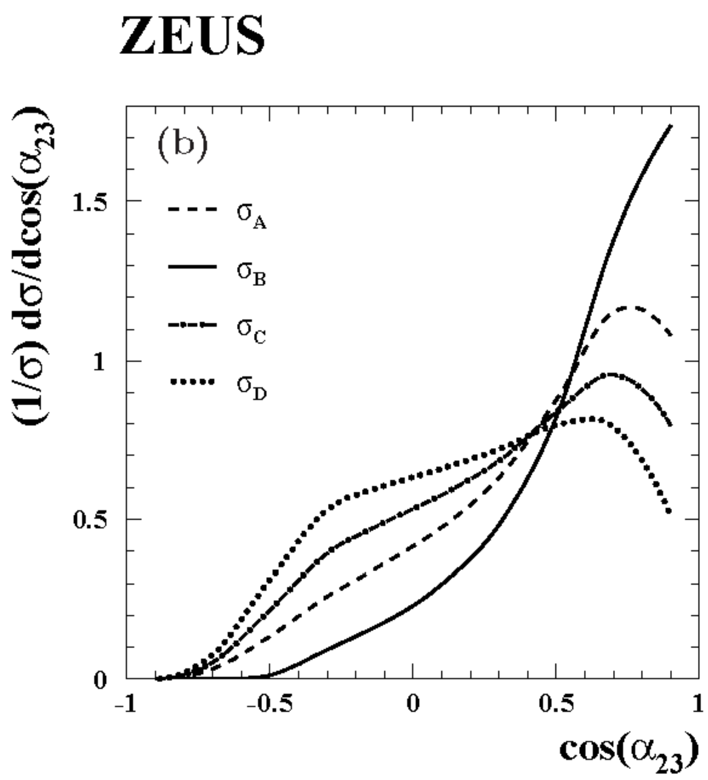
$$C_F : q \to qg$$
$$C_A : g \to gg$$
$$T_F : g \to qq$$

- Matrix elements A,B,C (also in e^+e^-) D (specific *ep*)

Colour factors from 3-jets (ZEUS)

Angular correlations between jets related to angular momentum conservation: sensitive to different processes and thus give handle to the colour factors





-Example: γp cos of angle between jet 2 and 3 jet in P_T

- Sensitive to processes with 3-gluon vertex present in SU(3) not in $U(1)^3$

Colour factors from 3-jets (ZEUS)

DESY-08-100

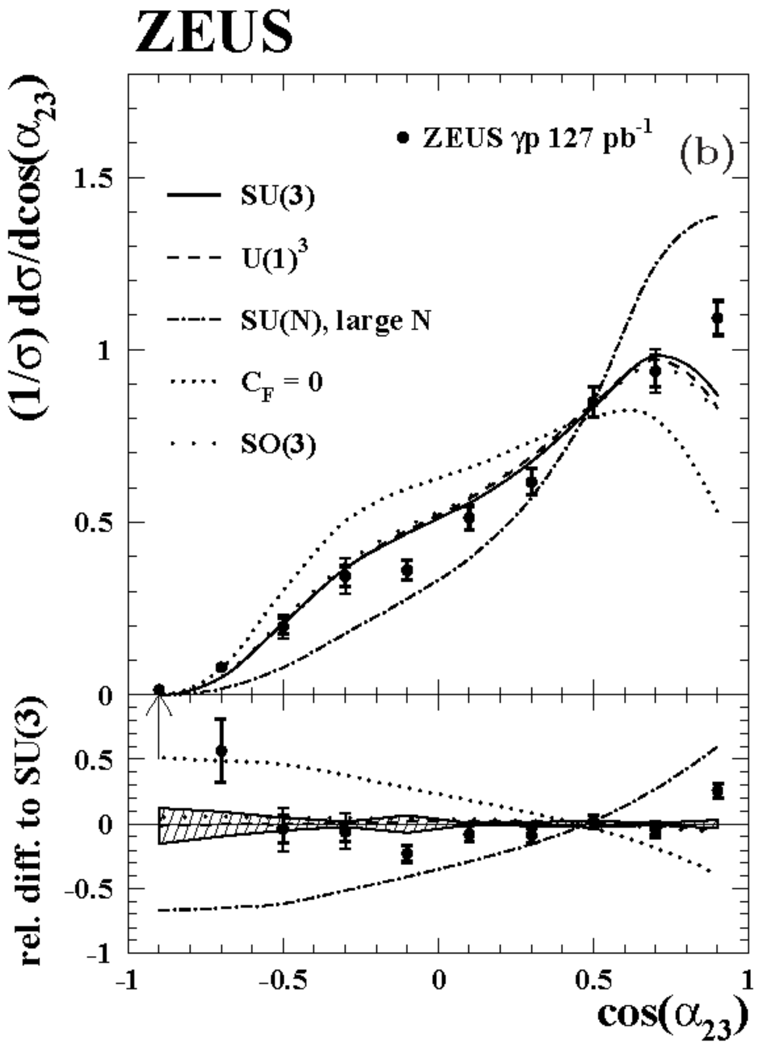
- Measured in γp and DIS with 130 pb^{-1}

- Shape normalised to reduce sensitivity to α_S running

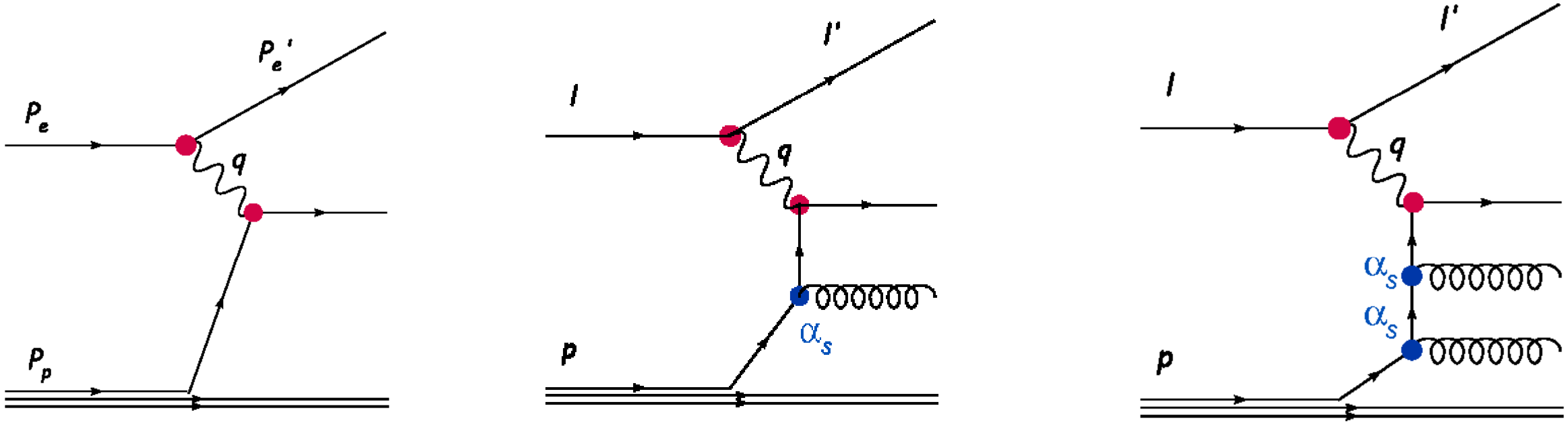
- Experimental and theoretical uncertainties dominated by parton shower and hadronisation model dependence

- The measurements discard limit symmetry groups like SU(N) or $C_F = 0$

- Further improvements are ongoing to perform an explicit determination of color factors. May be performed together with α_S



Sensitivity of jet observables to α_s



DIS Born $\propto \alpha_S^0$

2-jets $\propto \alpha_S^1$

Inclusive jets $\propto \alpha_S^1$

3-jets $\propto \alpha_S^2$

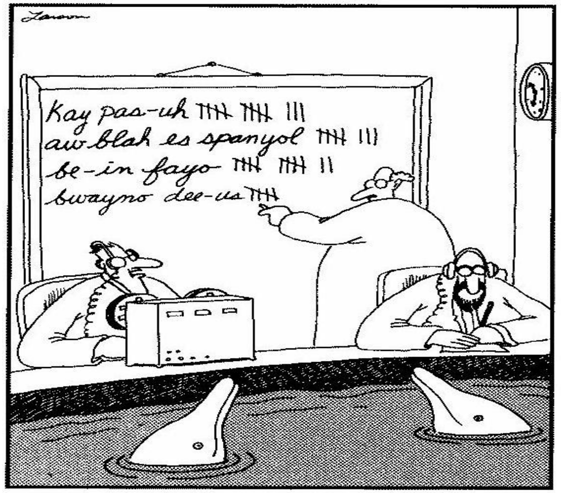
- Number of jets is proportional to α_S
- 2-jet and inclusive jets cross sections sensitive to the proton gluon PDF

Sensitivity of jet observables to α_s

Counted number of jets or jet events

- normalised to the luminosity
- corrected for detector acceptance and resolution with LO MC (LEPTO, ARIADNE …) simulated using GEANT 3

Scientists often learn the most when they look for patterns in data



"Matthews... we're getting another one of those strange 'aw blah es span yol' sounds."

Theory fitted to data with α_S (M_Z) only free parameter

PDFs
- proton
- photon

NLO QCD (SU3) calculations corrected for hadronisation with LO MC model (Lund string – JETSET or cluster fragmentation - HERWIG)

Inclusive jets in photoproduction (ZEUS)

ZEUS-prel-08-008

- 1998-2000 data (82 pb^{-1})

  Inclusive jets in γp above $p_T > 17$ GeV

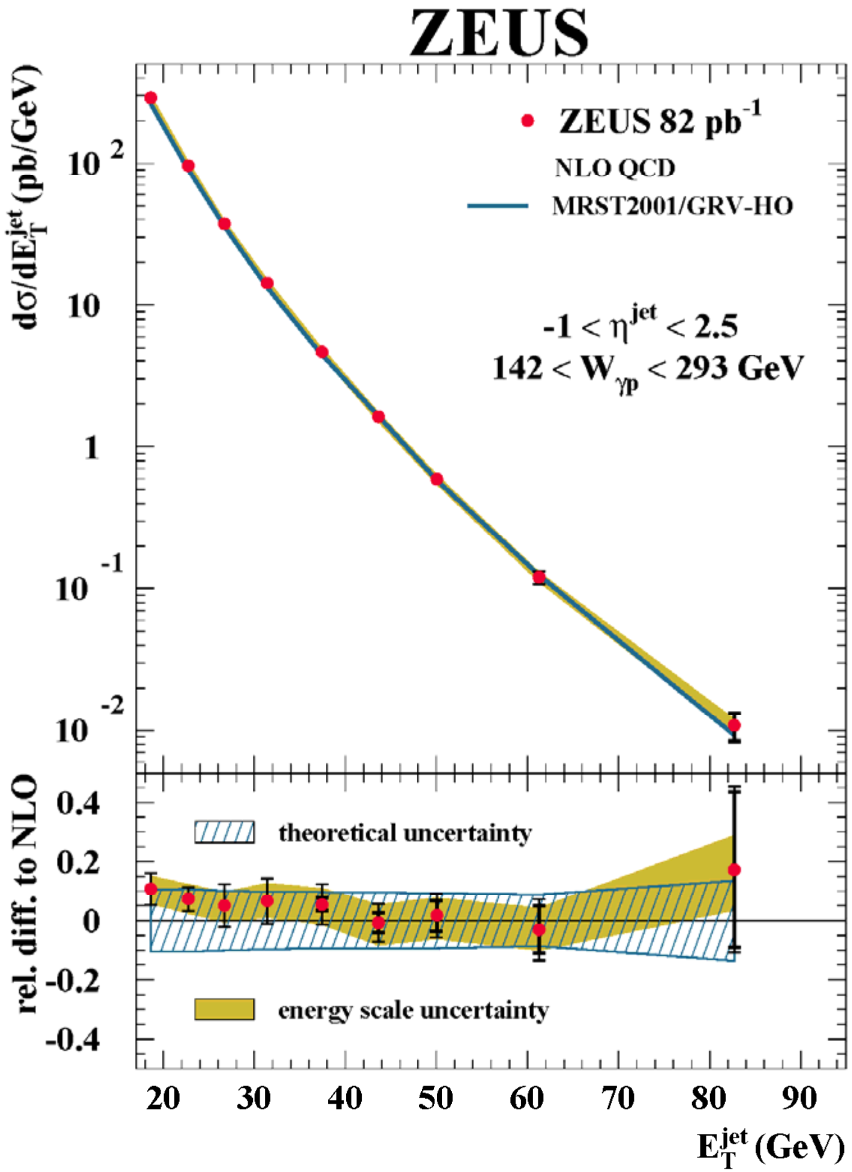
- Accurate measurement: experimental uncertainty ~ 5-10% on cross sections

- Well described by NLO QCD calculations

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

proton PDF = MRST2001

photon PDF = GRV-HO



α_S from photoproduction jets (ZEUS)

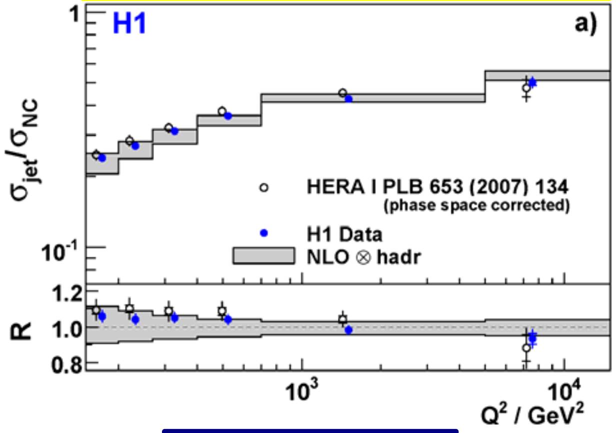
$$\alpha_S(M_Z) = 0.1223 \pm 0.0001\ (\text{stat.})^{+0.0023}_{-0.0021}(\text{exp.})^{+0.0029}_{-0.0030}(\text{th.})$$

- Experimental uncertainty on α_S : dominated by hadronic energy calibration $\pm 1.5\%$
- Theoretical uncertainties on α_S :
  - Terms beyond NLO: no clear indication how to estimate their size
    Prescription used to provide an estimate: μ_r, μ_f variation by factors 0.5 and 2
  - PDFs uncertainties : < 1%
  - hadronisation (HERWIG and Pythia) : < 0.5%

Jets multiplicities in DIS (H1)

Paper in preparation

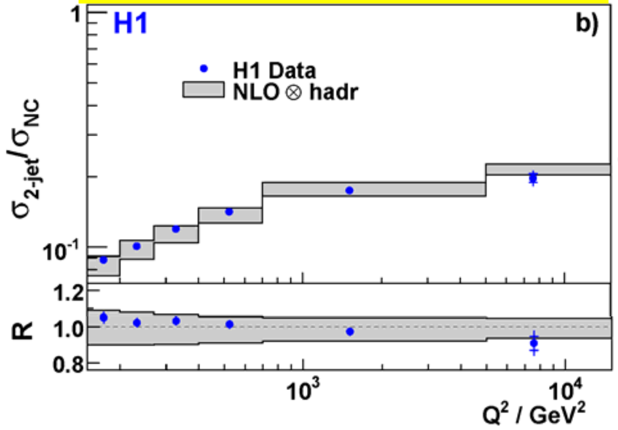
Inclusive jets



$P_T^{jet} > 7$ GeV

$-0.8 < \eta_{jet} < 2.0$

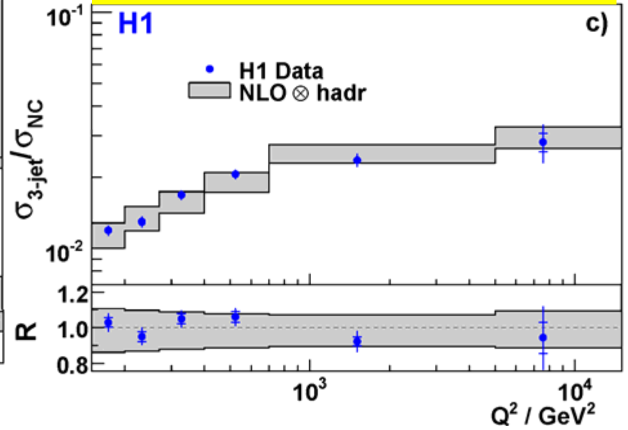
2-jets



$P_T^{jet1,\,jet2} > 5$ GeV $\quad M_{12} > 16$ GeV

$-0.8 < \eta_{jet} < 2.0$

3-jets



$P_T^{jet1,\,jet2,\,jet3} > 5$ GeV $\quad M_{12} > 16$ GeV

$-0.8 < \eta_{jet} < 2.0$

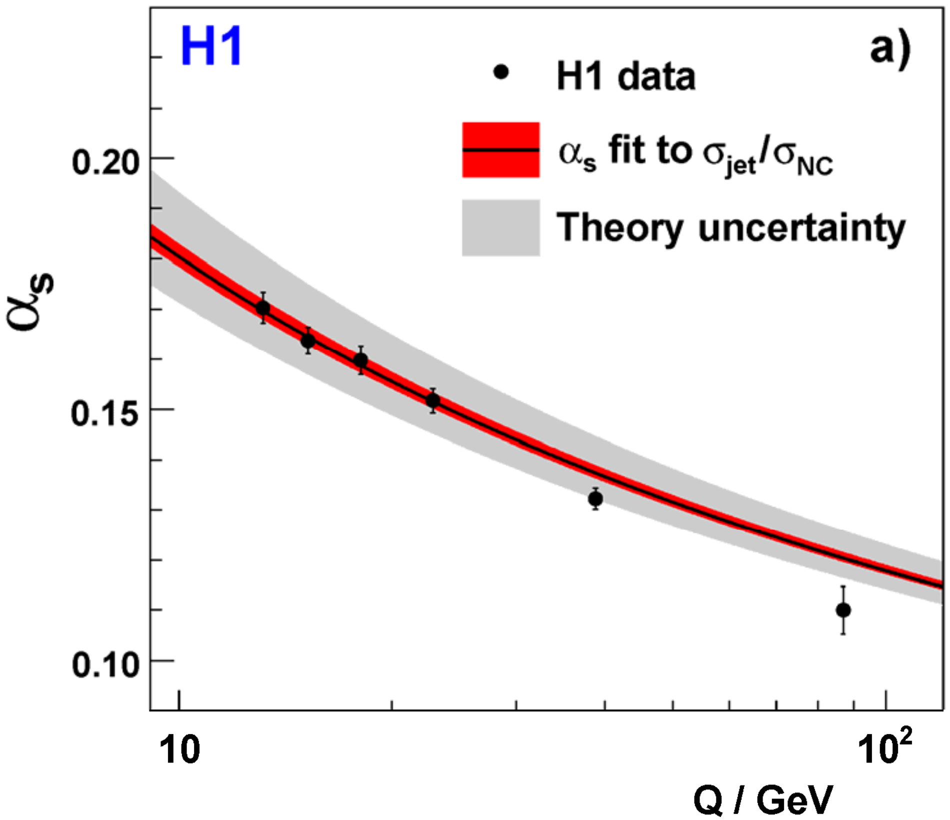
- Data sample 1999-2007: 395 pb^{-1}
- Accurate measurement improved by normalising to the total DIS NC cross section : experimental uncertainty ~ 3 % on cross sections
Uncertainty dominated by hadronic energy calibration known within 1.5% : ~ 2 % effect on cross sections
- Jet multiplicity increases with Q and well described by NLO QCD

$$\mu_r = \sqrt{Q^2 + P_T^2/2};\ \mu_f = Q$$

PDF = CTEQ6.5 M

α_s from jets in DIS (H1)

Normalised Inclusive Jet Cross Section



$\alpha_S(M_Z)$

Incl. jets

$0.1195 \pm 0.0010(\text{exp.})^{+0.0049}_{-0.0036}(\text{th.}) \pm 0.0018(\text{PDF})$

2-jets

$0.1155 \pm 0.0009(\text{exp.})^{+0.0042}_{-0.0031}(\text{th.}) \pm 0.0017(\text{PDF})$

3-jets

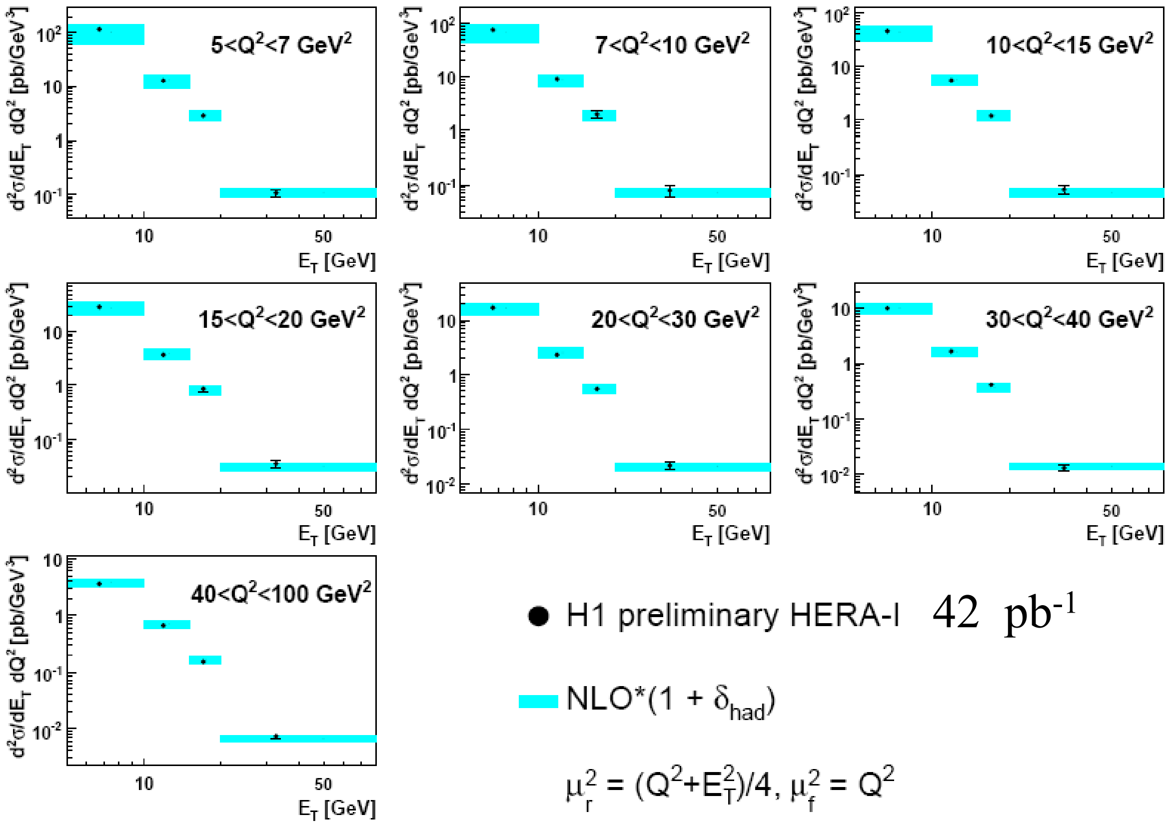
$0.1172 \pm 0.0013(\text{exp.})^{+0.0052}_{-0.0031}(\text{th.}) \pm 0.0009(\text{PDF})$

Jets (Q^2>150 GeV^2): $\alpha_S(M_Z) = 0.1168 \pm 0.0007(\text{exp.})^{+0.0046}_{-0.0030}(\text{th.}) \pm 0.0016(\text{PDF})$

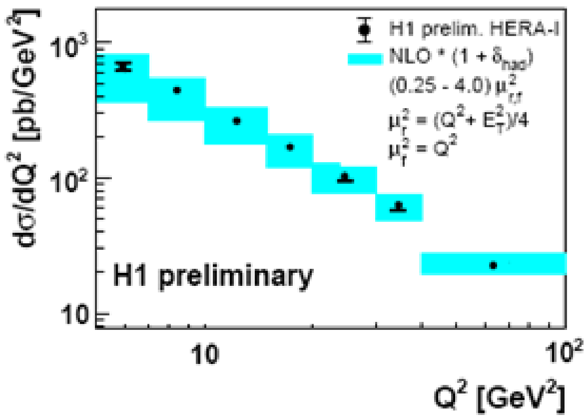
Inclusive jets in DIS (H1): low Q

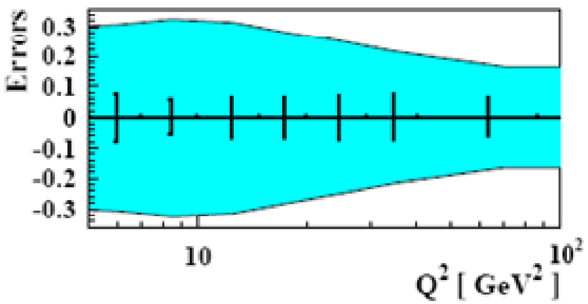
H1prelim-08-032

H1 Inclusive Jet Cross Sections $\frac{d^2\sigma}{dQ^2 dE_T}$



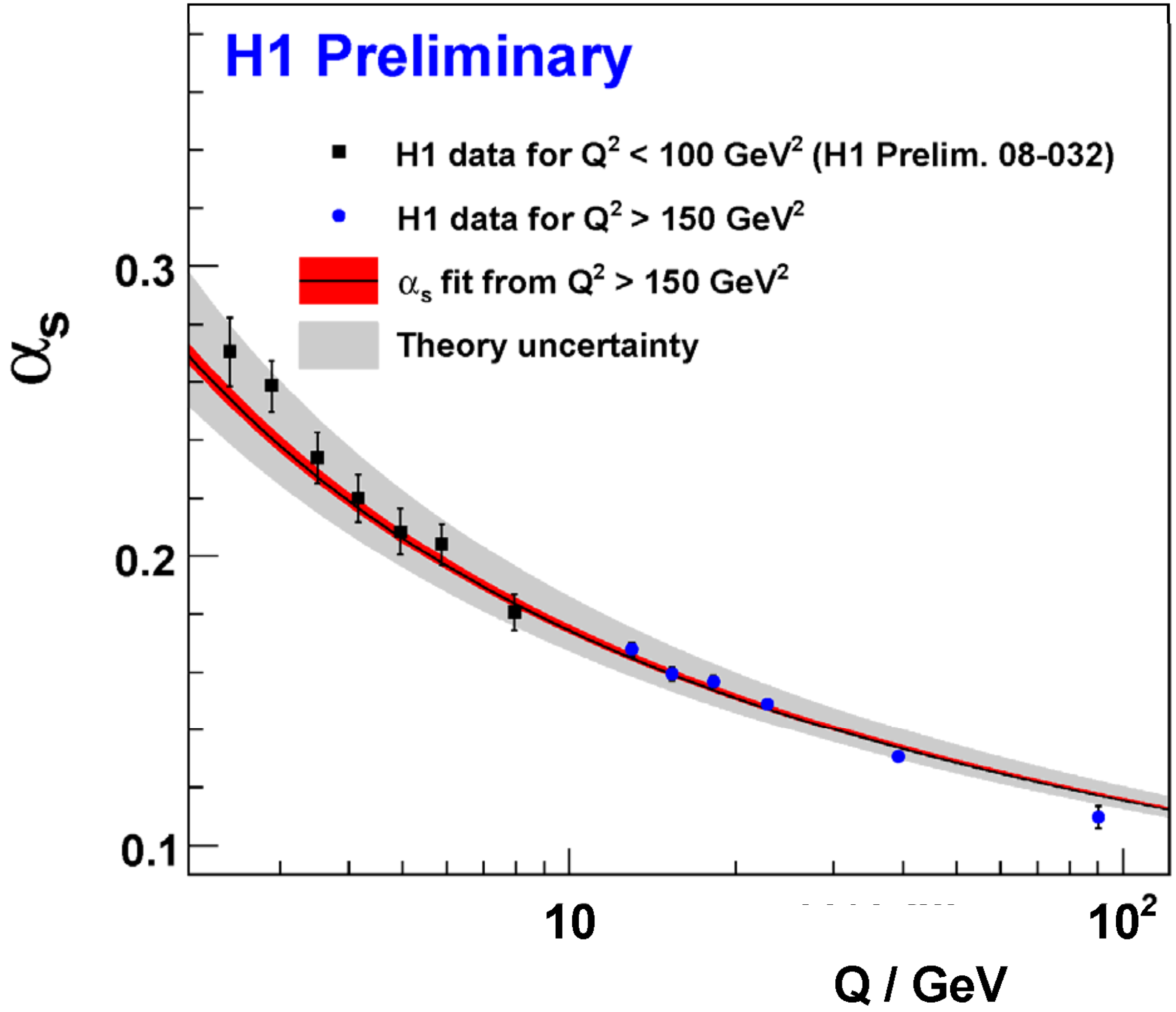
Inclusive Jet Cross Sections $\frac{d\sigma}{dQ^2}$





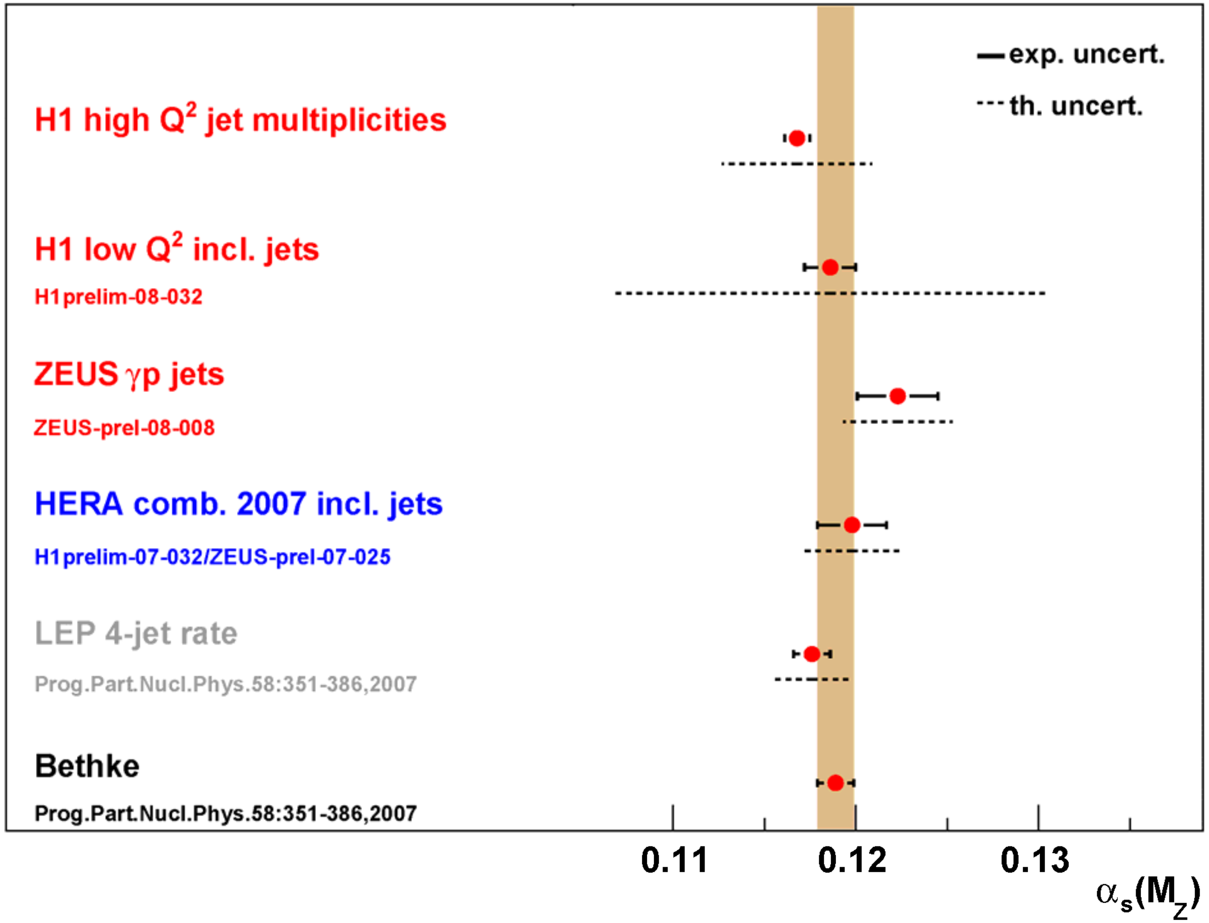
- Accurate measurement well described by QCD NLO: experimental uncertainty ~ 5-10 % on cross sections
- But small predictive power of NLO calculations : Missing orders uncertainty ~ 15-30% on cross sections

α_s from jets in DIS (H1)



$$\textbf{Jets } (\mathbf{Q^2<100\ GeV^2}): \alpha_S(M_Z) = 0.1186 \pm 0.0014(\text{exp.})^{+0.0132}_{-0.0101}(\text{th.}) \pm 0.0021(\text{PDF})$$

Summary of α_s extractions



- New measurements in γp, low and high Q^2 compatible with LEP and the world average
- High experimental precision (0.6-2%)
- Dominated by NLO uncertainty
- H1-ZEUS combination is promising:
  - 2 times more data
  - inter-calibration of hadronic energy scales

Summary and outlook

Jet production in ep collisions is sensitive to the structure of the underlying QCD gauge symmetry

➢ Angular correlations in 3-jet events was shown to be sensitive to the colour factors. More data will be analysed to extract colour factors.

➢ Inclusive jet and 2(3)-jet production allows a precise test of coupling running over 2 orders of magnitude in energy. Precise determination of $\alpha_S(M_Z)$:

Jets in DIS (Q^2>150 GeV^2 - H1):

$$\alpha_S(M_Z) = 0.1168 \pm 0.0007(\text{exp.})^{+0.0046}_{-0.0030}(\text{th.}) \pm 0.0016(\text{PDF})$$

Jets in γp (ZEUS):

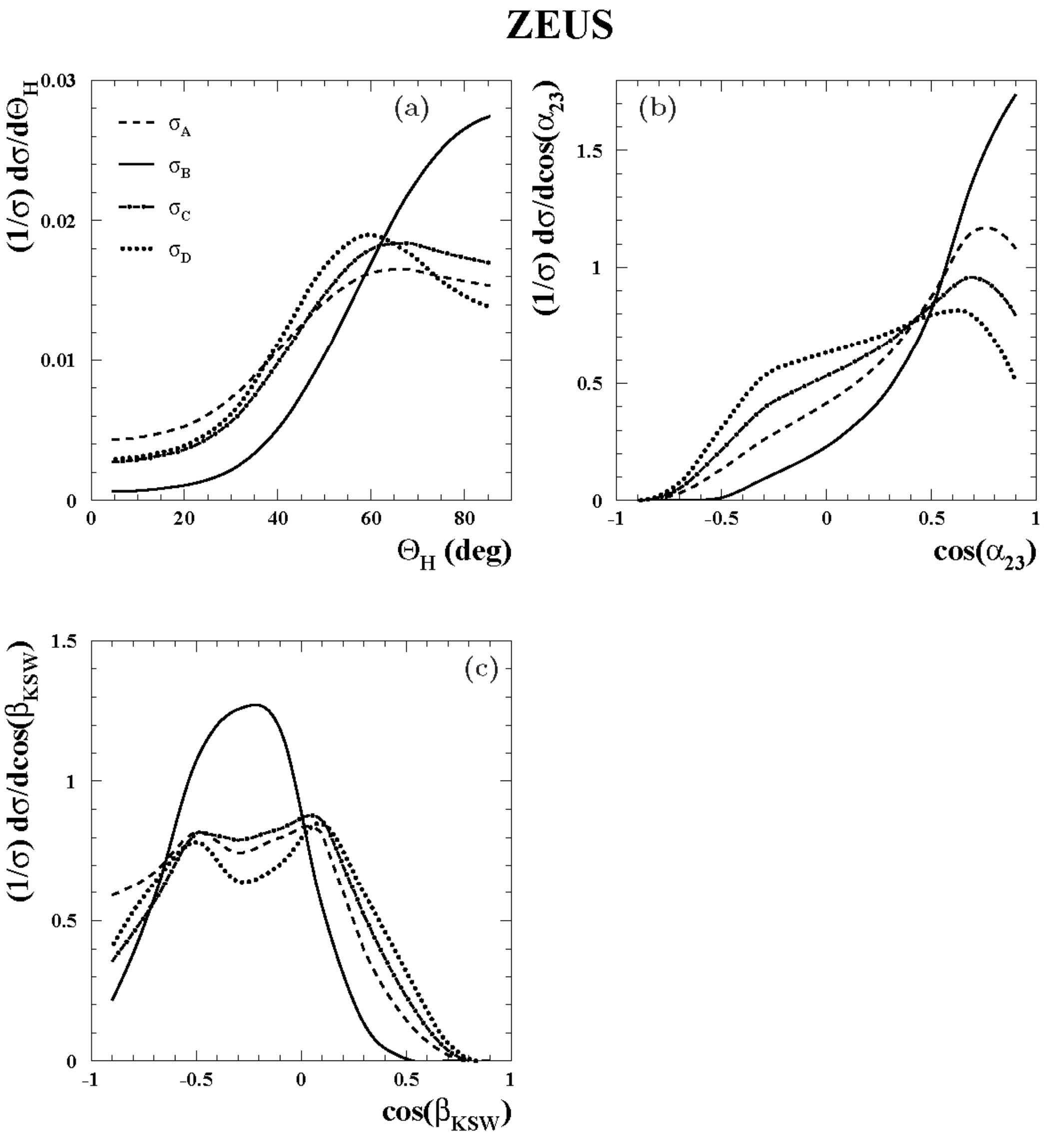
$$\alpha_S(M_Z) = 0.1223 \pm 0.0022\ (\text{exp.}) \pm 0.0030(\text{th.})$$

Still room for improvement in experimental precision of $\alpha_S(M_Z)$: more data on tape, improvement of jet calibrations, combination of experiments. Possibility of simultaneous extraction with colour factors.

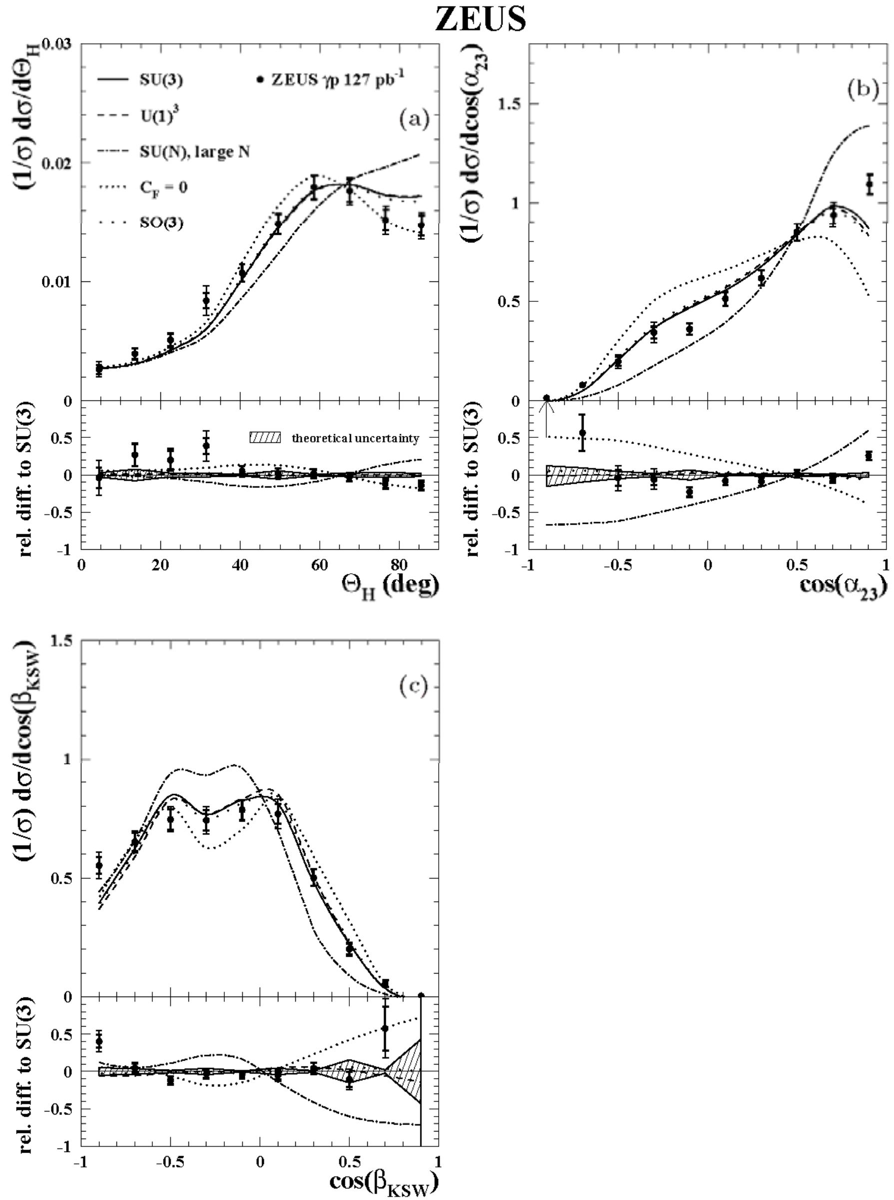
➢ NNLO necessary to take full advantage of the data.

BACKUP

Colour factors from 3-jets (ZEUS)

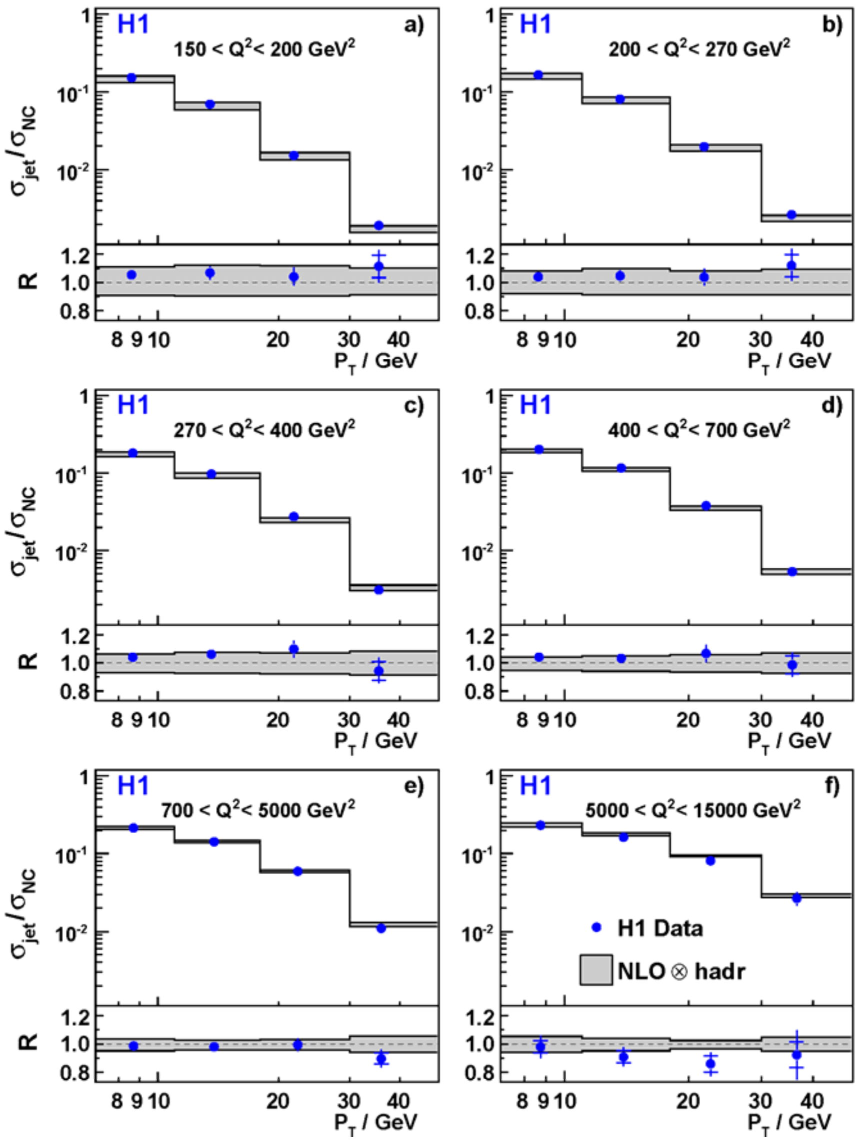


Colour factors from 3-jets (ZEUS)



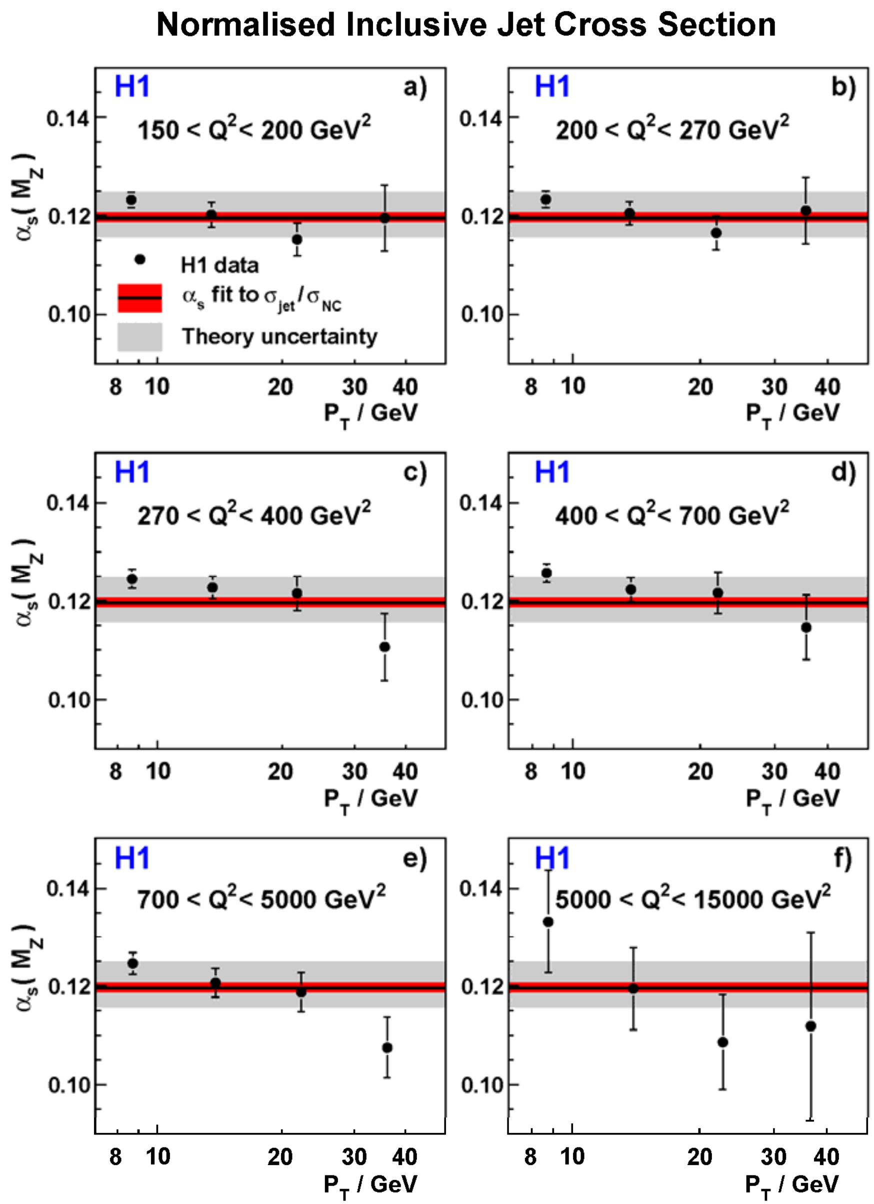
Jet multiplicities in DIS (H1) : high Q

Normalised Inclusive Jet Cross Section



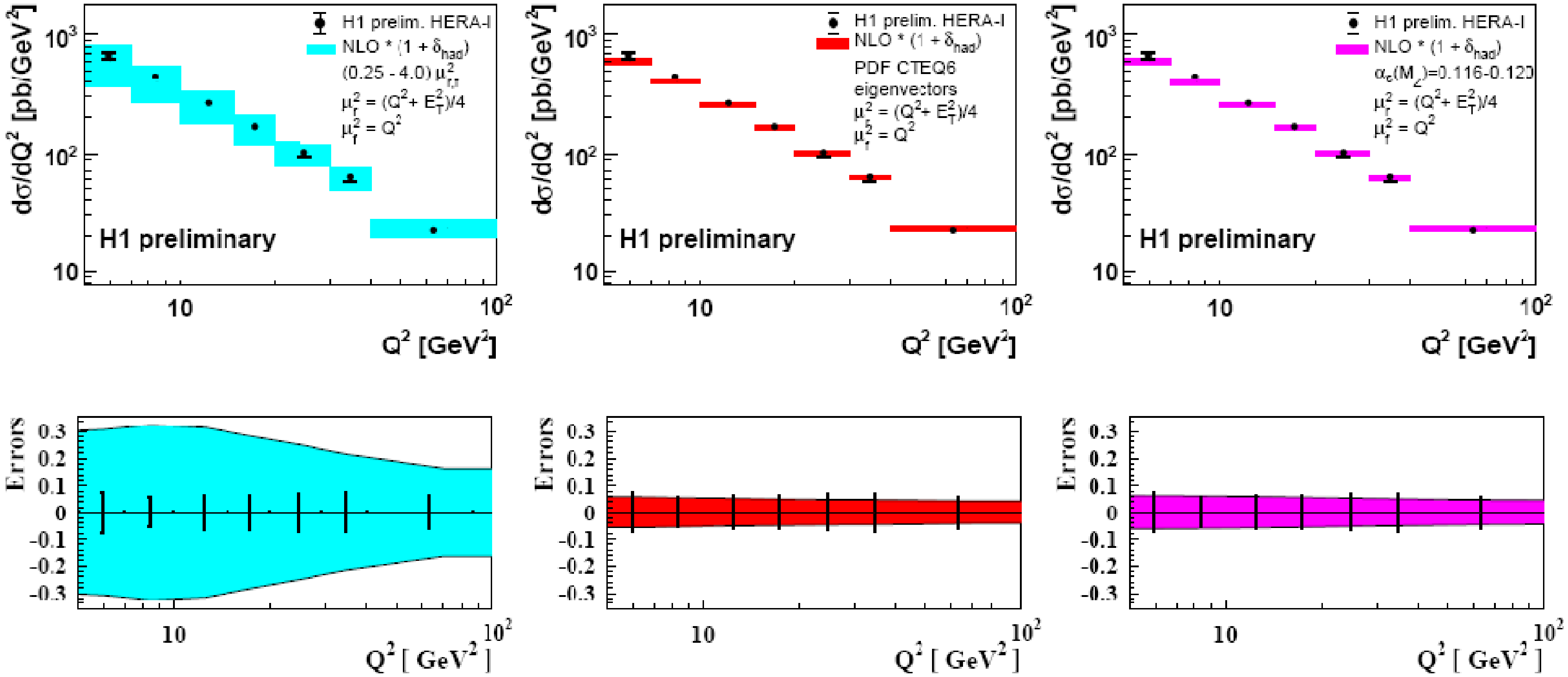
- Accurate measurement (3-6 %) well described by NLO QCD prediction.
- Experimental uncertainty smaller than the theoretical (5-10 %).
- Jet spectrum becomes harder when phase-space opens.

α^{S} from inclusive jets at high Q (H1)



- Minimal χ fit with experimental correlations of NLO QCD with $\alpha S(MZ)$ free
- Theoretical uncertainties (offset method more conservative than Jones *et al.*): scales, hadronisation, PDF are varied and $\alpha S(MZ)$ refitted.

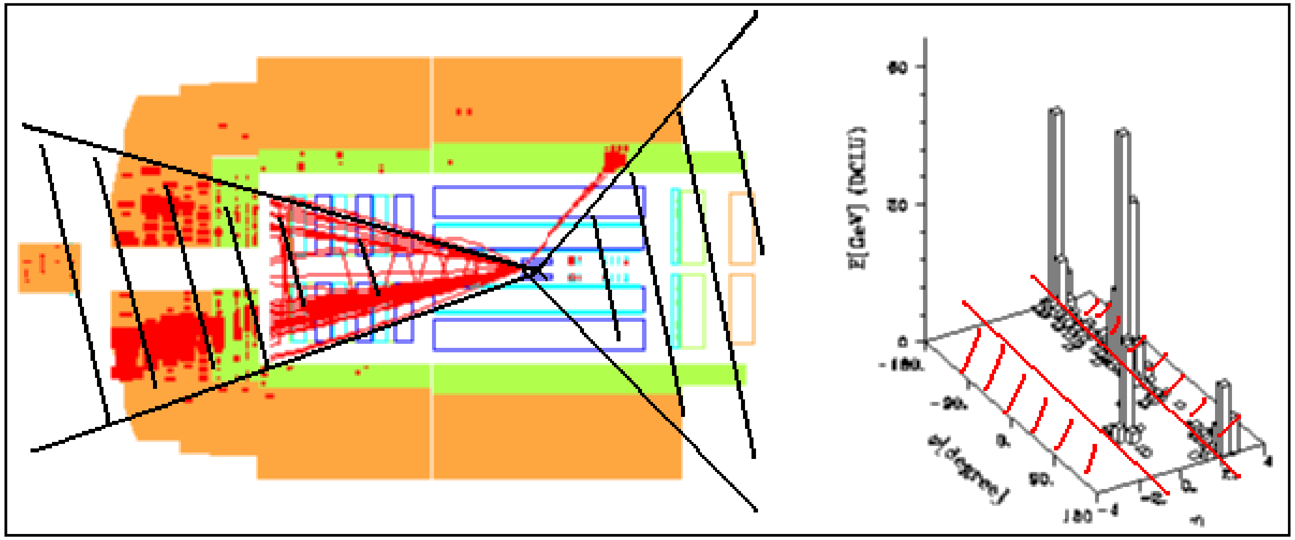
Inclusive Jet Cross Sections $\frac{d\sigma}{dQ^2}$



μ_R, μ_F dependance | PDF param. sensitivity | α_S sensitivity

- Scale dependence is the most important source of theoretical uncertainty at low Q2
- The sensitivity to the PDF and to αS parameterizations are comparable

JET fiducial cuts



JET OBSERVABLES

Inclusive jets: Individual jet counting for all events.
Hypothesis: Independent Individual parton emission.

Low Q $E_T > 5\,\mathrm{GeV}$, $-1.0 < \eta^{Lab} < 2.5$

High Q $E_T > 7\,\mathrm{GeV}$, $-0.8 < \eta^{Lab} < 2.0$

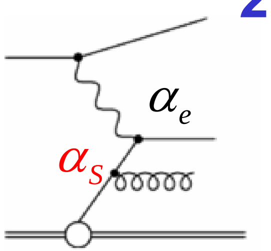
Multi-jets: Event counting with more than *n* jets. Sensitive to α_S.

$E_T > 5\,\mathrm{GeV}$

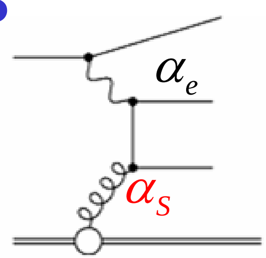
$-0.8 < \eta^{Lab} < 2.0$

$M_{12} > 16\,\mathrm{GeV}$

2-JETS

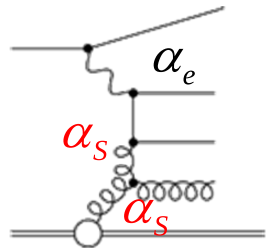


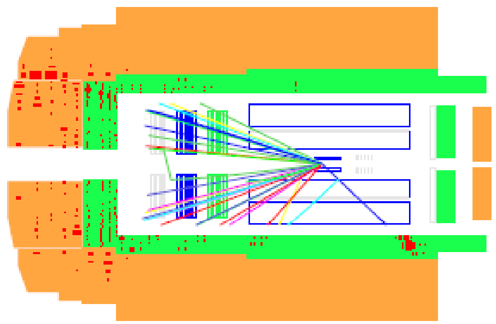
Boson Gluon Fusion

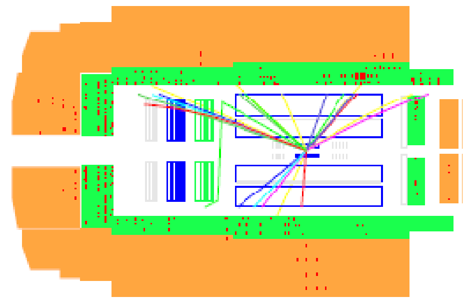


QCD Compton

3-JETS







Measurement of the cross sections

Low Q $\sigma_{Incl.\,jets} = f\left(Q^2, E_T^{Breit}\right)$

High Q

Jet multiplicity

$$\frac{\sigma_{Incl.\,jets}}{\sigma_{NC}} = f\left(Q^2, E_T^{Breit}\right)$$

Multi-jet rates

$$\frac{\sigma_{2\,jets}}{\sigma_{NC}} = f\left(Q^2, E_T^{Breit}\right) \qquad \frac{\sigma_{3\,jet}}{\sigma_{NC}} = f\left(Q^2\right)$$

DATA CORRECTION

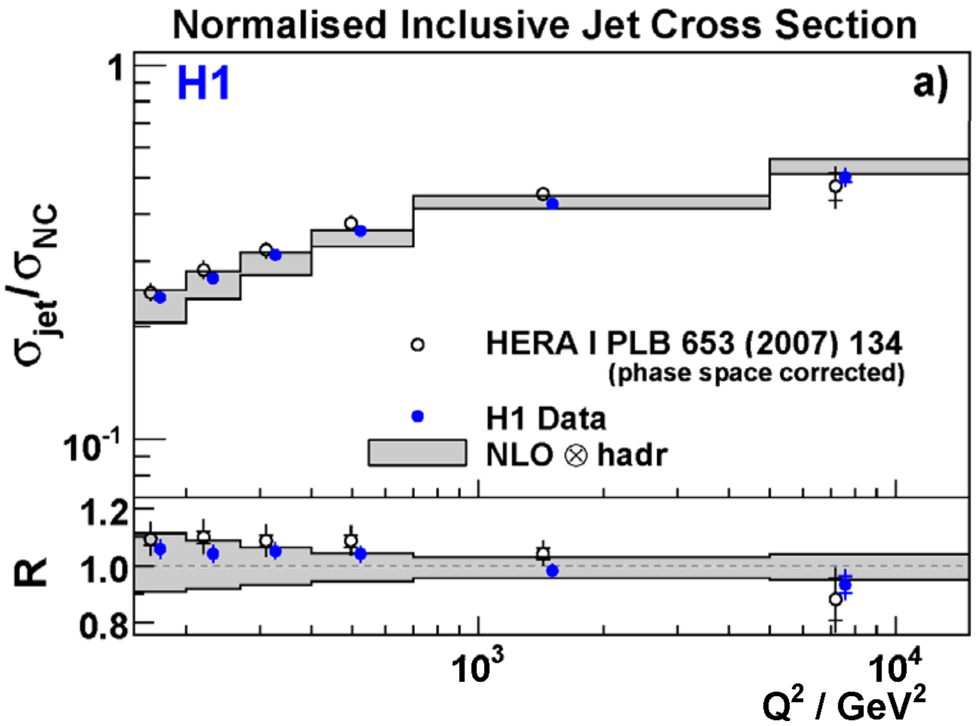
- **Acceptance correction**: < 20 % bin by bin acceptance with DJANGO-CDM and RAPGAP-MEPS
- **QED radiative correction**: 5-10 % with HERACLES
- **Z exchange**: significant at High Q with LEPTO

Normalized cross sections at high Q ⇨

- Normalization errors – cancel completely
- Correlated errors – cancel partially

Jets multiplicities in DIS (H1)

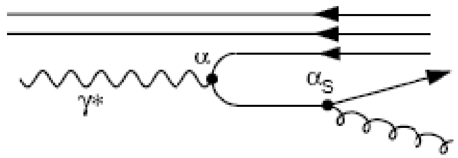
Paper in preparation



Uncertainty	HERA I → HERA I+II	Impact normalised cross section
Statistics	64 pb-1 → 395 pb-1	1-3%
Hadronic energy calibration	2% → 1.5%	2-4%

Jets reconstruction

Reconstructed in boson-proton collinear frame



Photoproduction – laboratory frame

DIS – Breit frame

Longitudinally invariant kT algorithm

- Collinear and infrared safe
- Iterative clustering:

$$d_{i,j} = \min(P_{T,i}^2, P_{T,j}^2) \cdot R_{ij}$$

$$R_{ij} = (\eta_i - \eta_j)^2 + (\varphi_i - \varphi_j)^2$$

- pT-weighted masseless recombination scheme

Resulting jets: Njets with $R_{ij} > R = 1$