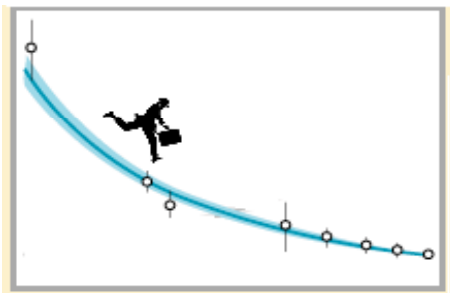


# Jet physics and strong coupling at HERA



Maxime GOUZEVITCH  
DESY, Germany



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

On behalf of the



and

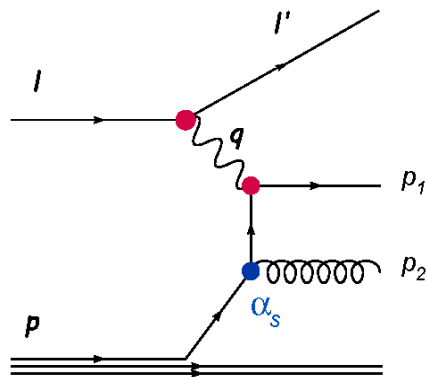


collaborations

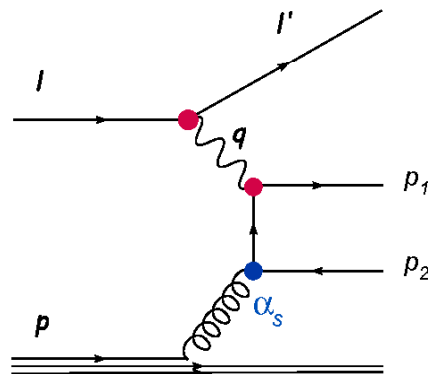
# Multi-jet production in DIS NC at HERA



$$e (27.6 \text{ GeV}) + p (920 \text{ GeV}) \rightarrow X + e$$

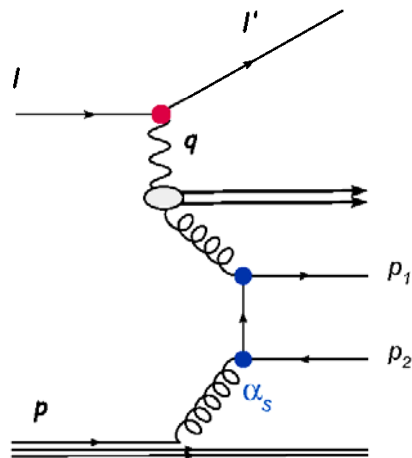
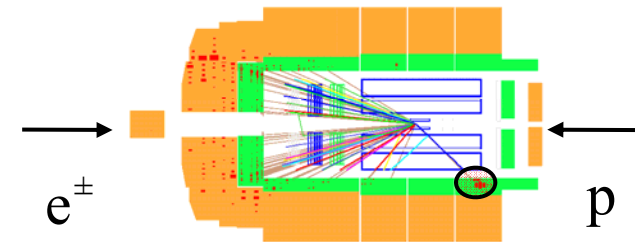


**QCD Compton**

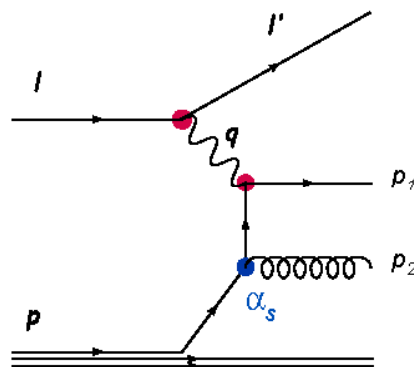


**BOSON GLUON Fusion**

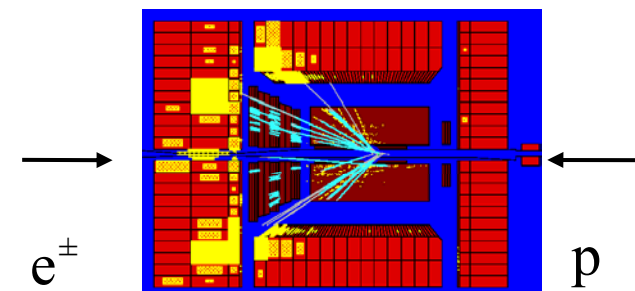
$$\text{DIS } Q^2 > 1 \text{ GeV}^2$$



**RESOLVED**



**DIRECT**

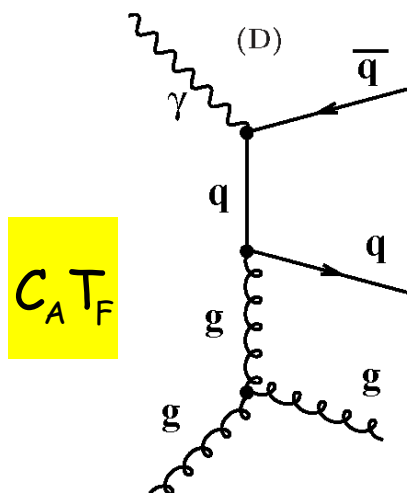
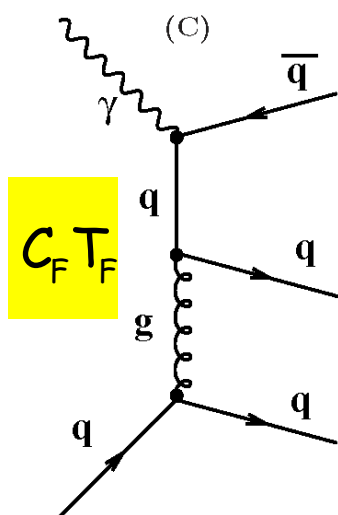
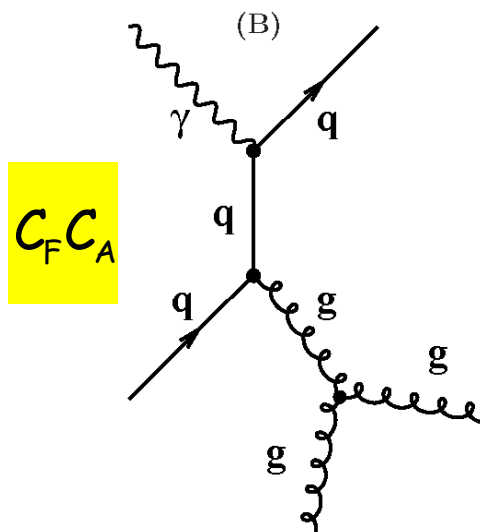
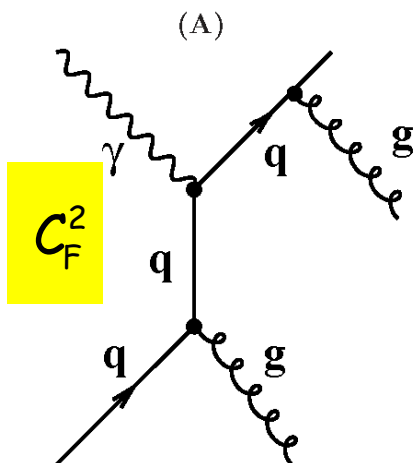


$$\gamma p \quad Q^2 \sim 0$$

# 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

$$C_F : q \rightarrow qg$$

$$C_A : g \rightarrow gg$$

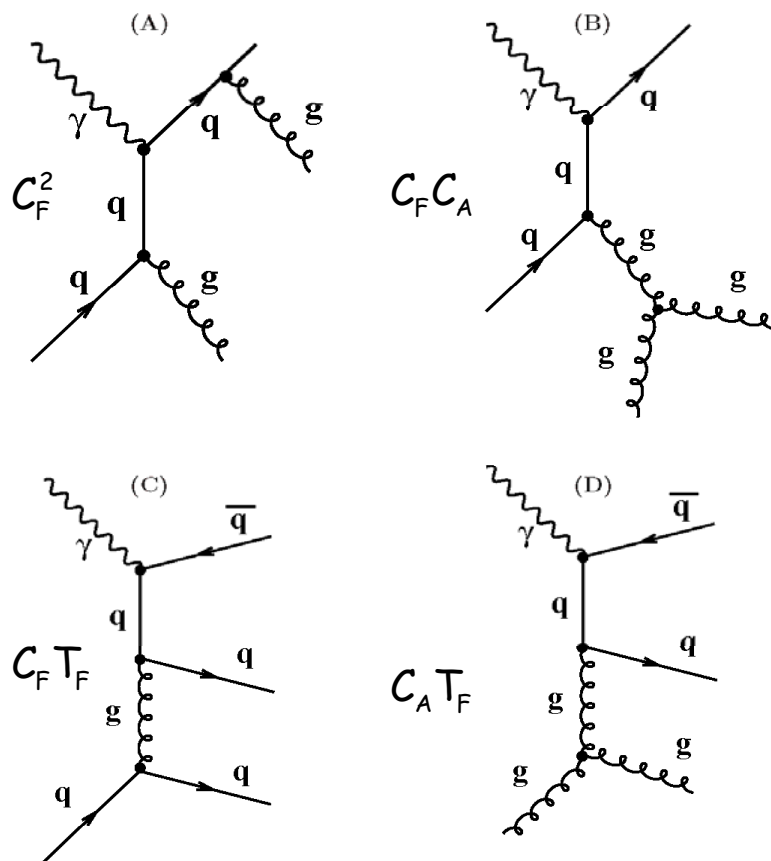
$$T_F : g \rightarrow qq$$

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

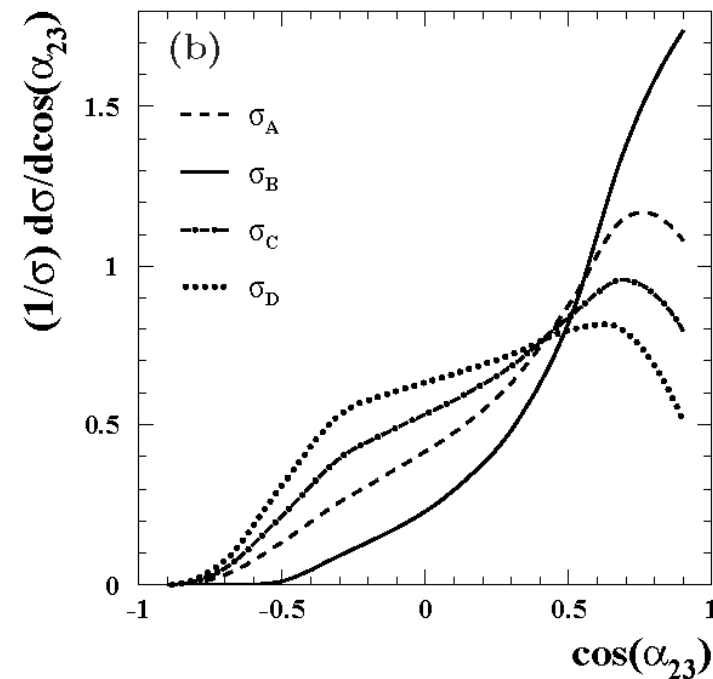
# Colour factors from 3-jets (ZEUS)



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



## ZEUS



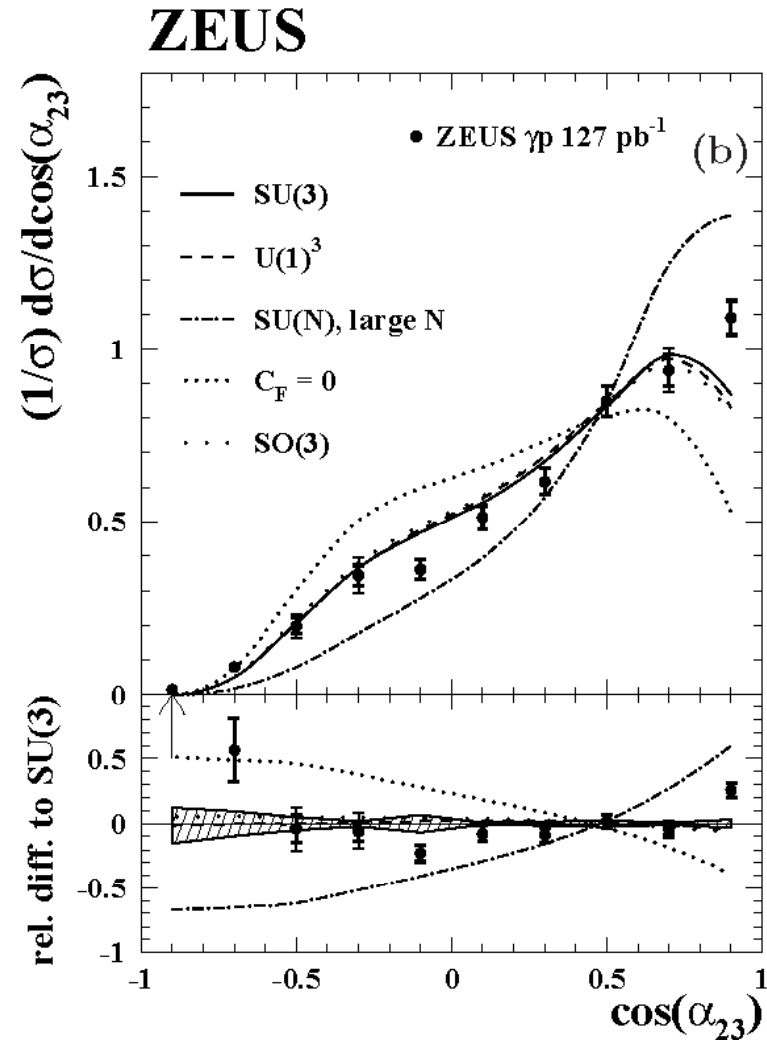
- Example:  $\gamma p$   $\cos$  of angle between jet 2 and 3 jet in  $P_T$
- Sensitive to processes with 3-gluon vertex present in  $SU(3)$  not in  $U(1)^3$

# Colour factors from 3-jets (ZEUS)

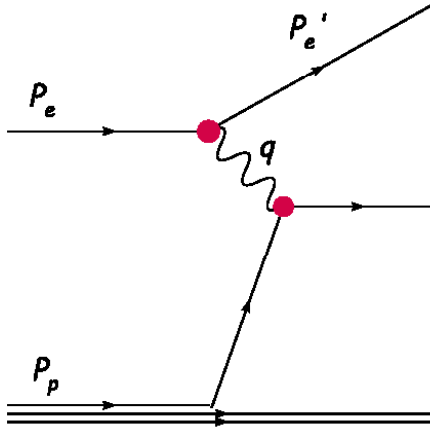
DESY-08-100



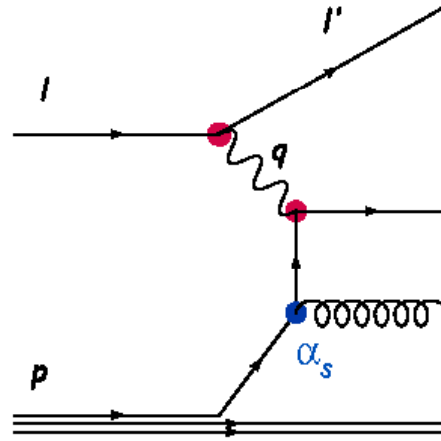
- Measured in  $\gamma p$  and DIS with  $130 \text{ pb}^{-1}$
- Shape normalised to reduce sensitivity to  $\alpha_S$  running
- Experimental and theoretical uncertainties dominated by parton shower and hadronisation model dependence
- The measurements discard limit symmetry groups like  $SU(N)$  or  $C_F = 0$
- Further improvements are ongoing to perform an explicit determination of color factors. May be performed together with  $\alpha_S$



# Sensitivity of jet observables to $\alpha_s$

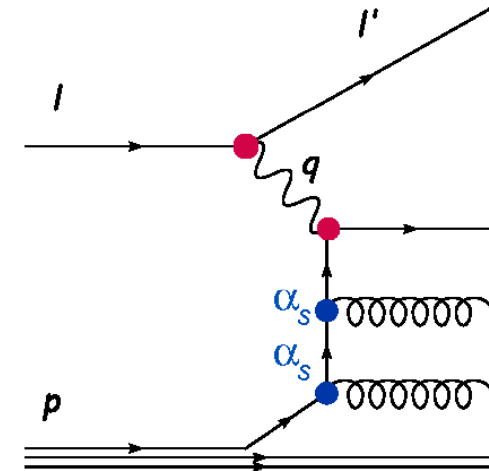


DIS Born  $\propto \alpha_s^0$



2-jets  $\propto \alpha_s^1$

Inclusive jets  $\propto \alpha_s^1$



3-jets  $\propto \alpha_s^2$

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

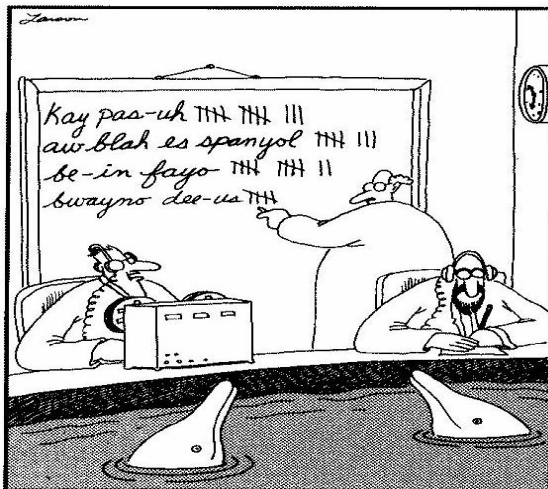
# Sensitivity of jet observables to $\alpha_s$



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  $\alpha_s(M_Z)$  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<sup>-1</sup>)

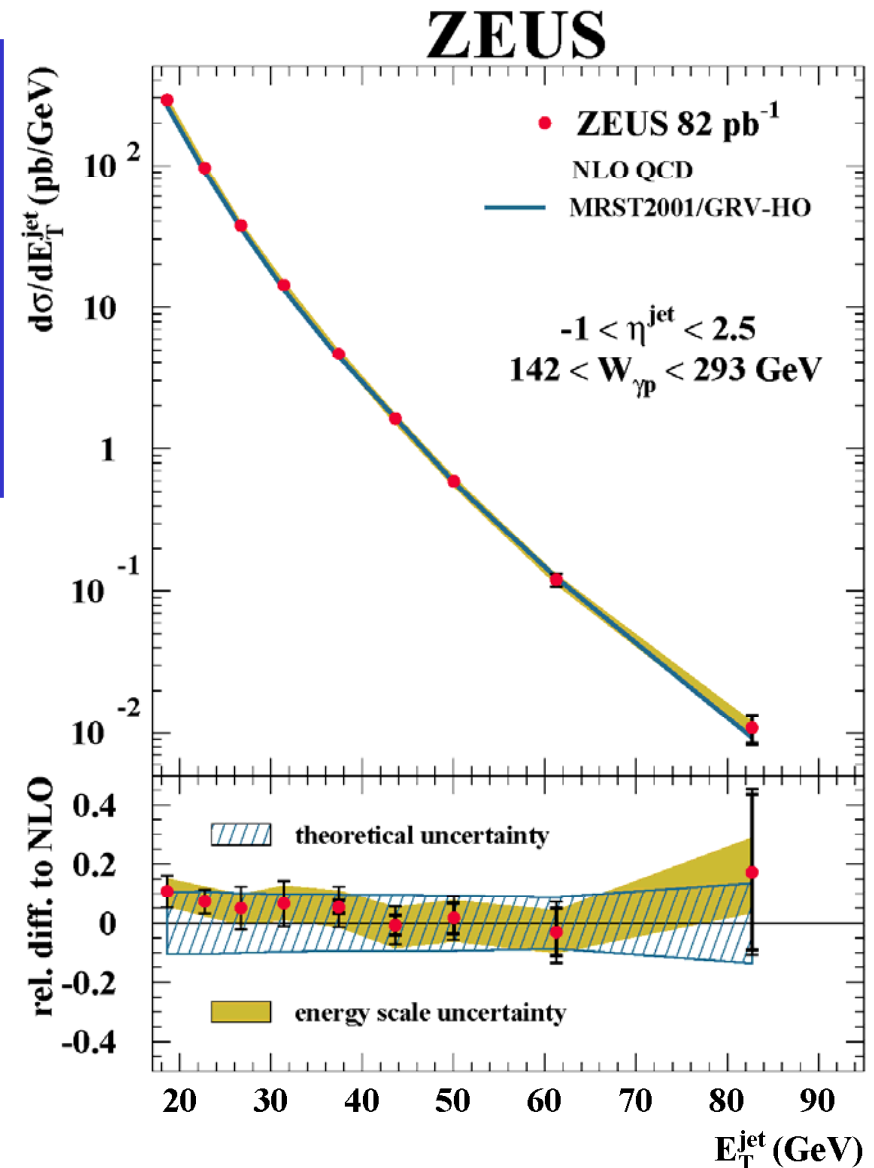
Inclusive jets in  $\gamma p$  above  $p_T > 17$  GeV

- Accurate measurement: experimental uncertainty  $\sim 5$ -10% on cross sections
- Well described by NLO QCD calculations

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

proton PDF = MRST2001

photon PDF = GRV-HO



## $\alpha_s$ from photoproduction jets (ZEUS)

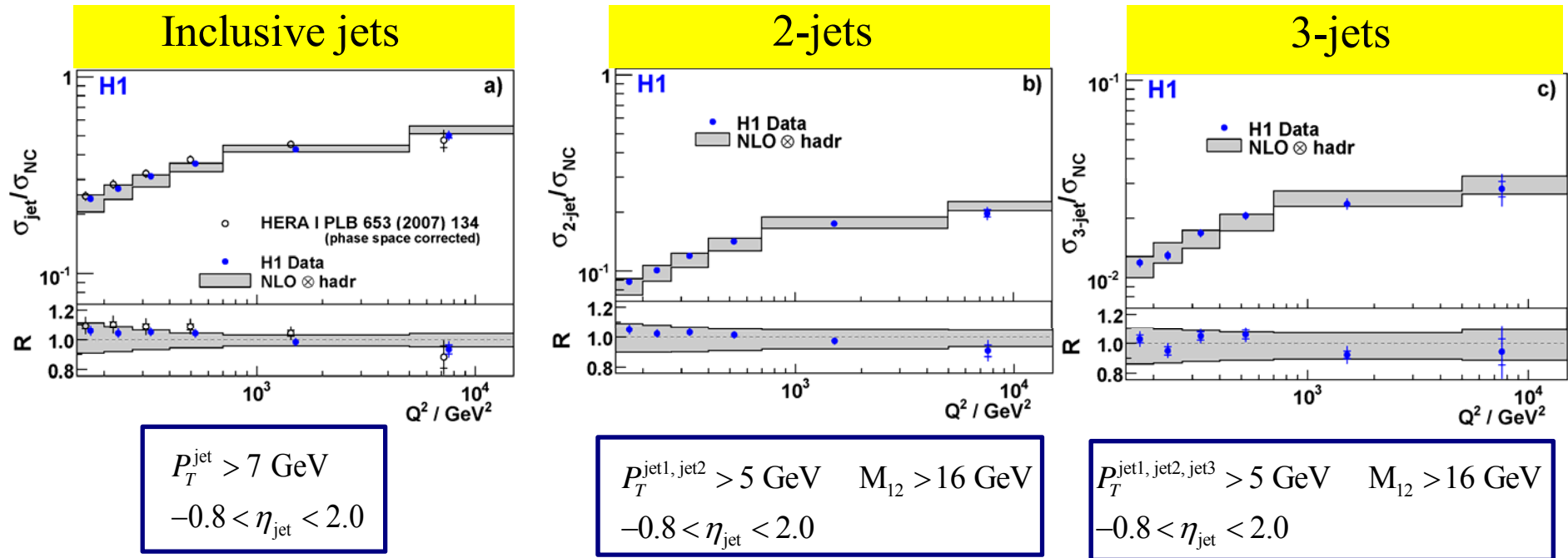


$$\alpha_s (M_Z) = 0.1223 \pm 0.0001 \text{ (stat.)}_{-0.0021}^{+0.0023} \text{ (exp.)}_{-0.0030}^{+0.0029} \text{ (th.)}$$

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

# Jets multiplicities in DIS (H1)

Paper in preparation



- Data sample 1999-2007: 395 pb<sup>-1</sup>
- 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

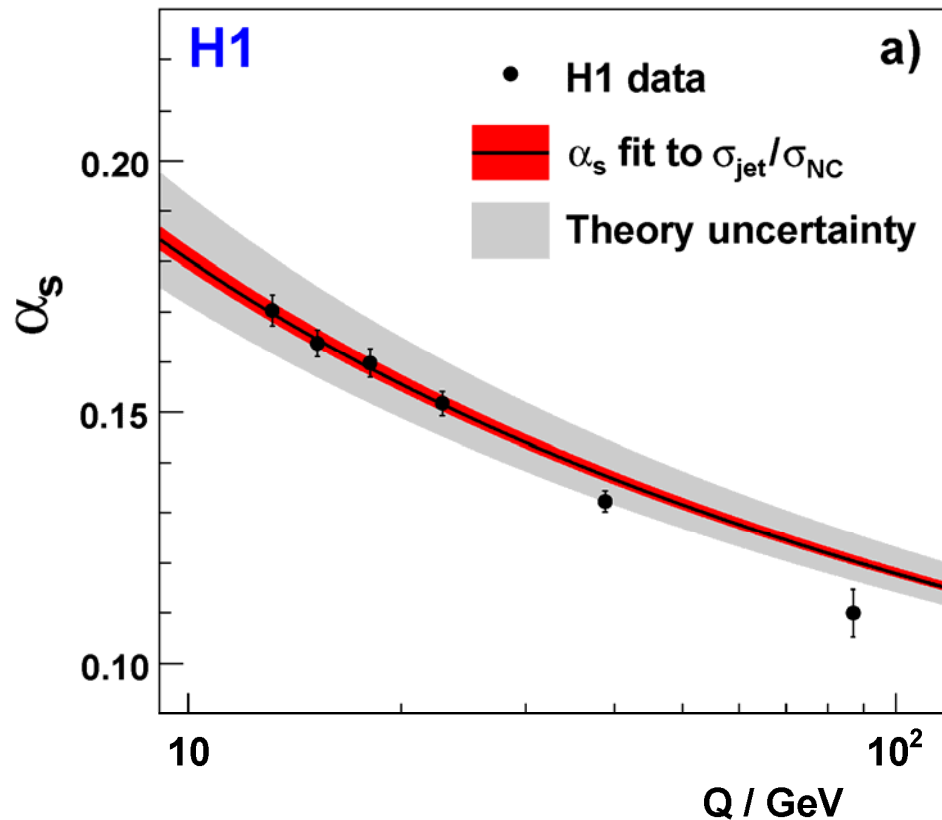
$$\mu_r = \sqrt{Q^2 + P_T^2/2}; \mu_f = Q$$

$$\text{PDF} = \text{CTEQ6.5 M}$$

# $\alpha_s$ 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**

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

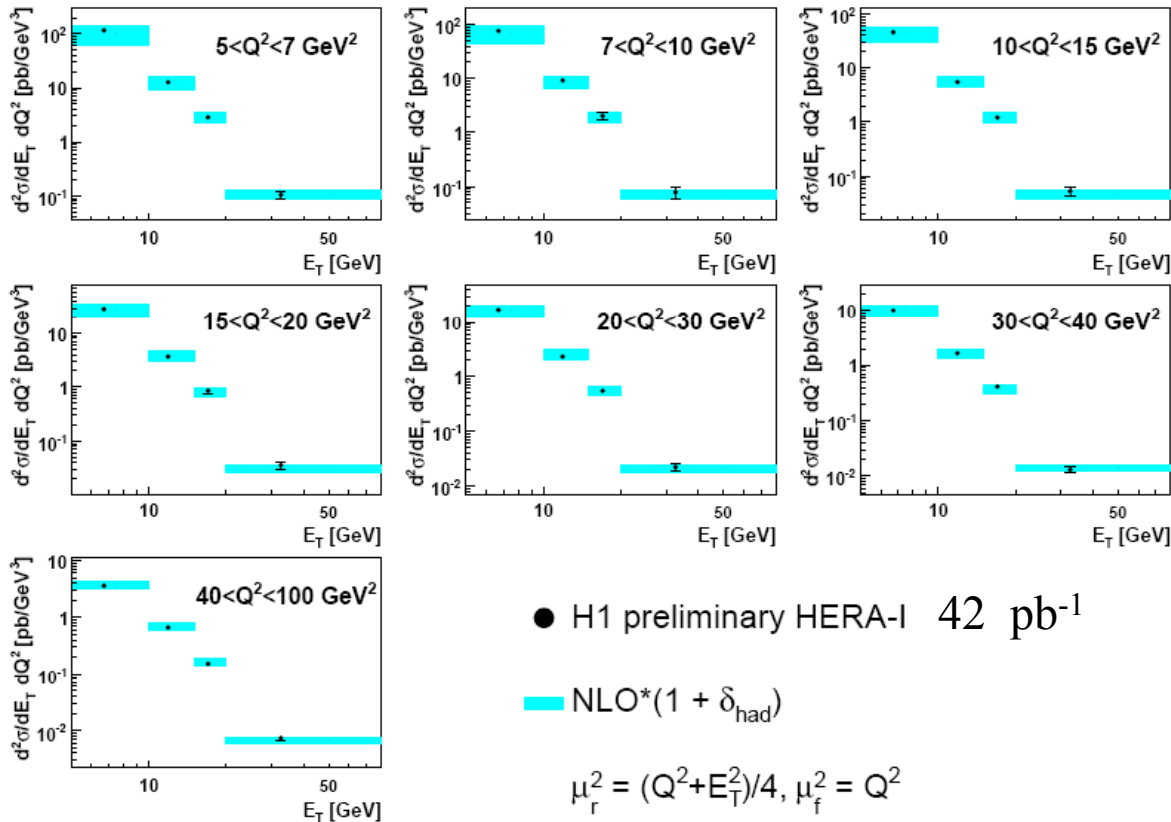
$$\text{Jets } (Q^2 > 150 \text{ GeV}^2): \alpha_s(M_Z) = 0.1168 \pm 0.0007(\text{exp.})^{+0.0046}_{-0.0030}(\text{th.}) \pm 0.0016(\text{PDF})$$

# Inclusive jets in DIS (H1): low Q

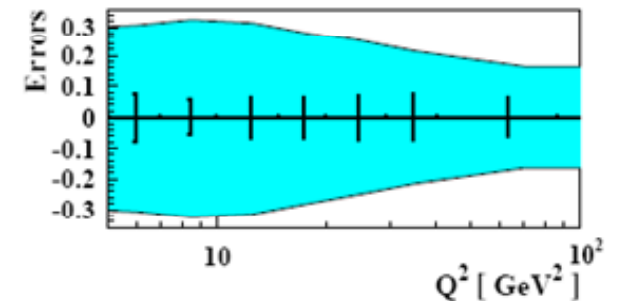
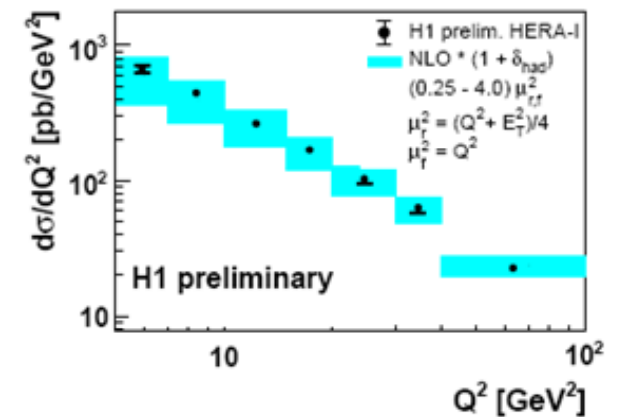
H1prelim-08-032



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

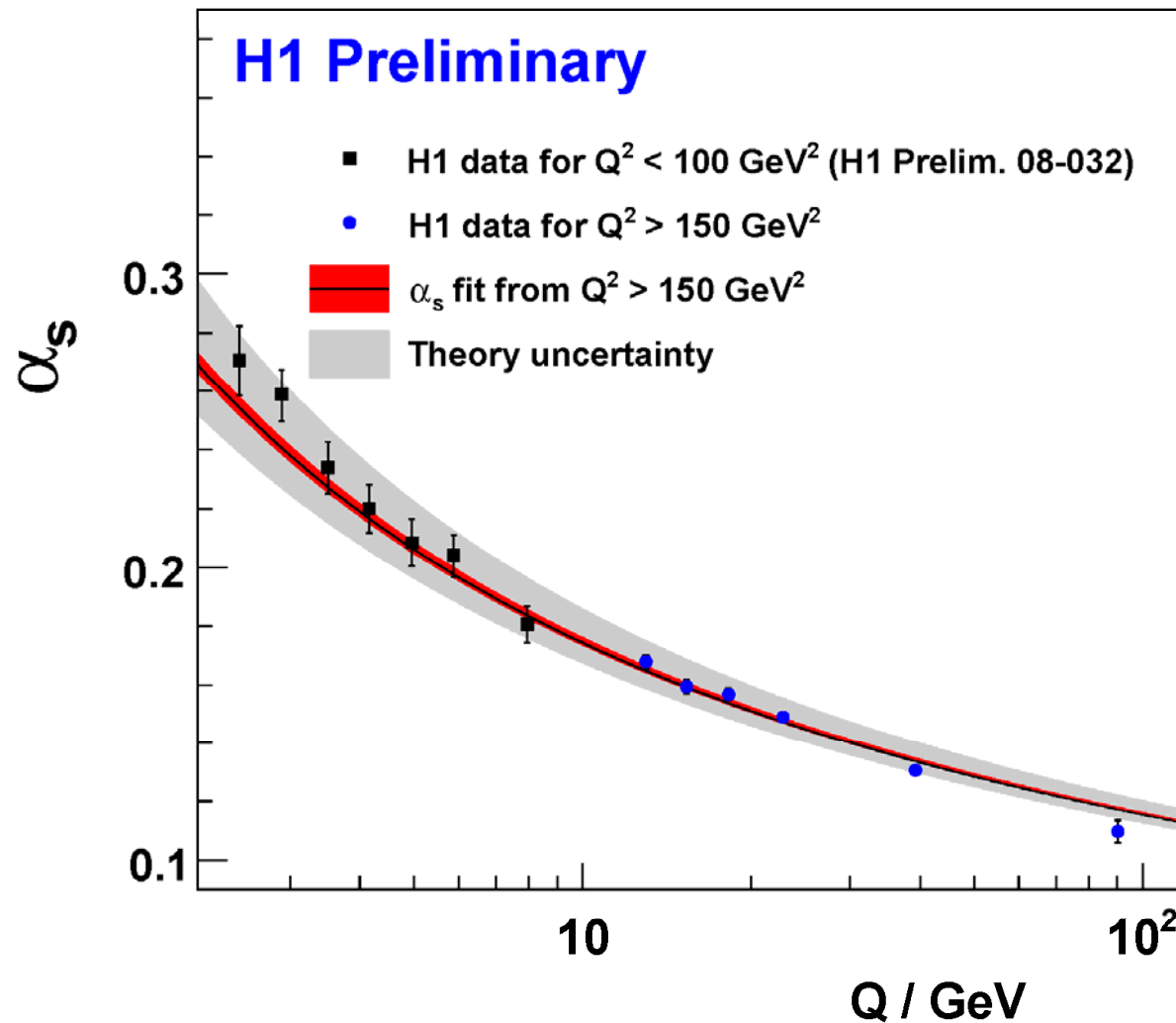


## Inclusive Jet Cross Sections $\frac{d\sigma}{dQ^2}$



- 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

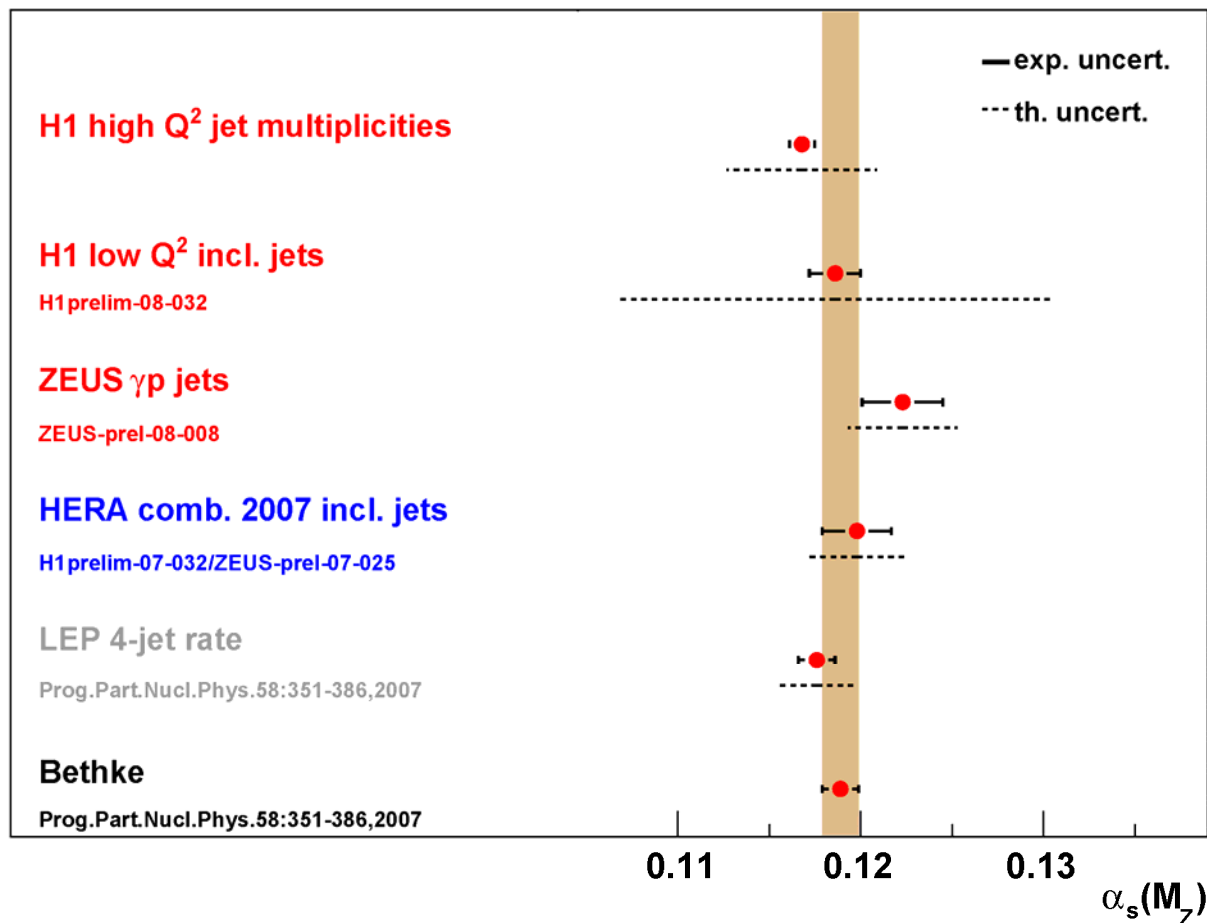
# $\alpha_s$ from jets in DIS (H1)



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



# Summary of $\alpha_s$ extractions



- New measurements in  $\gamma p$ , 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 ( $Q^2 > 150 \text{ GeV}^2$  - 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  $\gamma p$  (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.

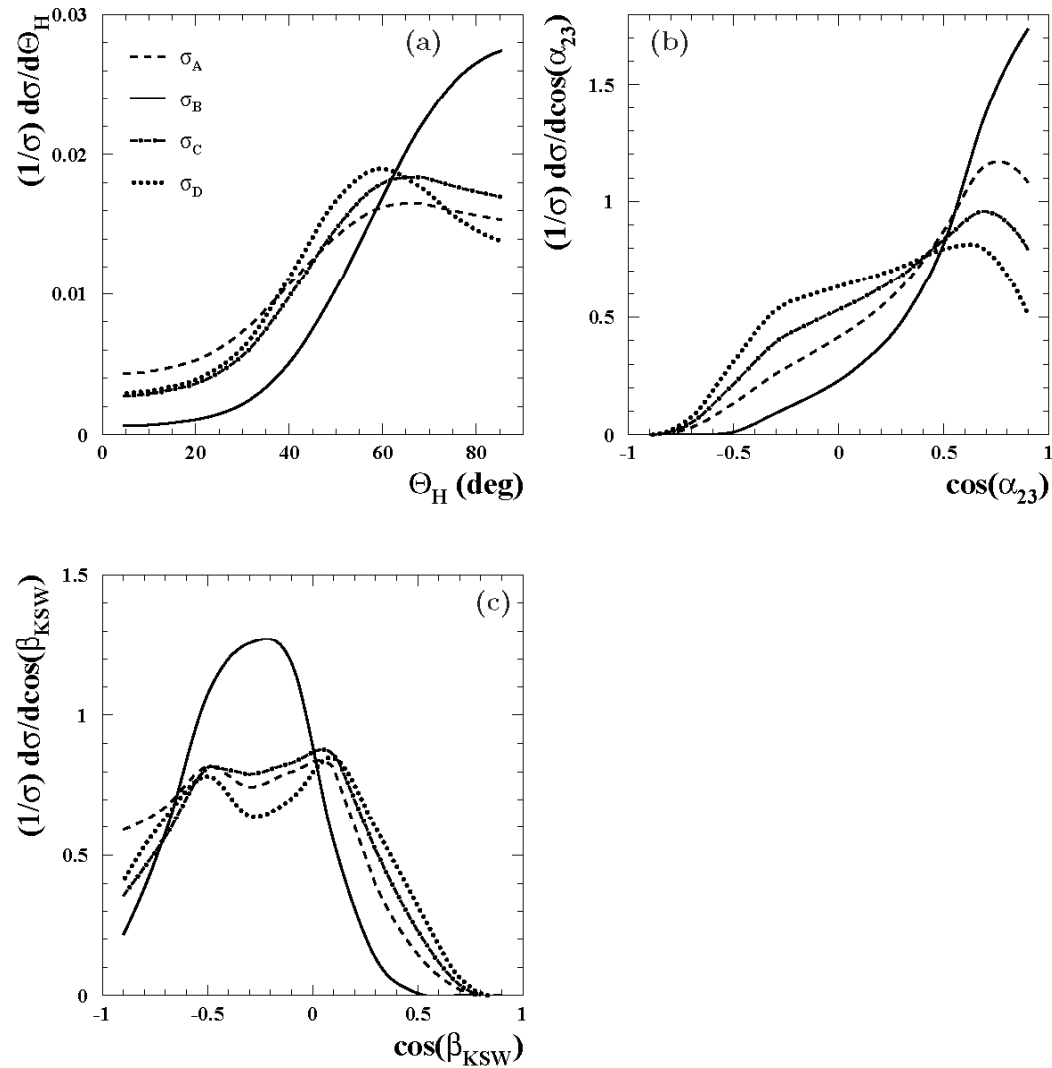
- NNLO necessary to take full advantage of the data.

# BACKUP

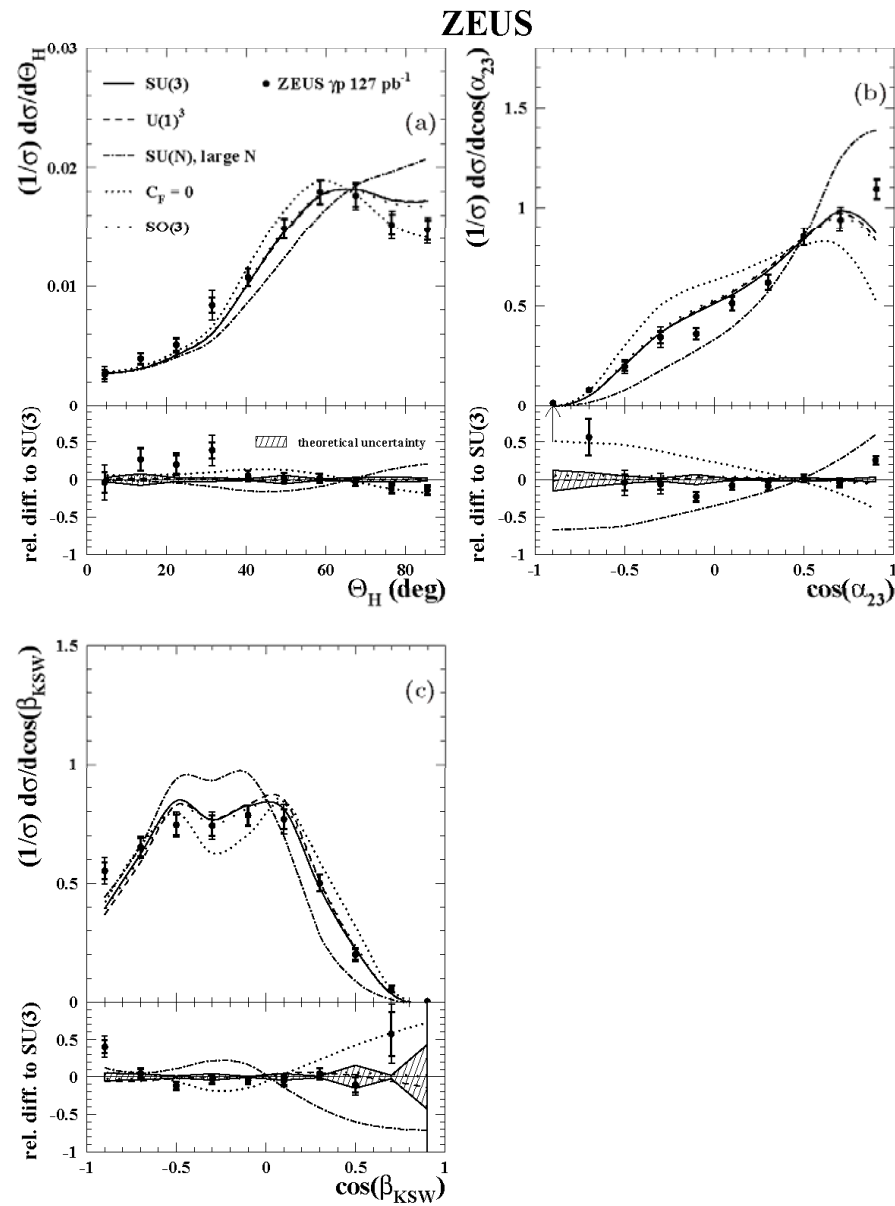
# Colour factors from 3-jets (ZEUS)



ZEUS



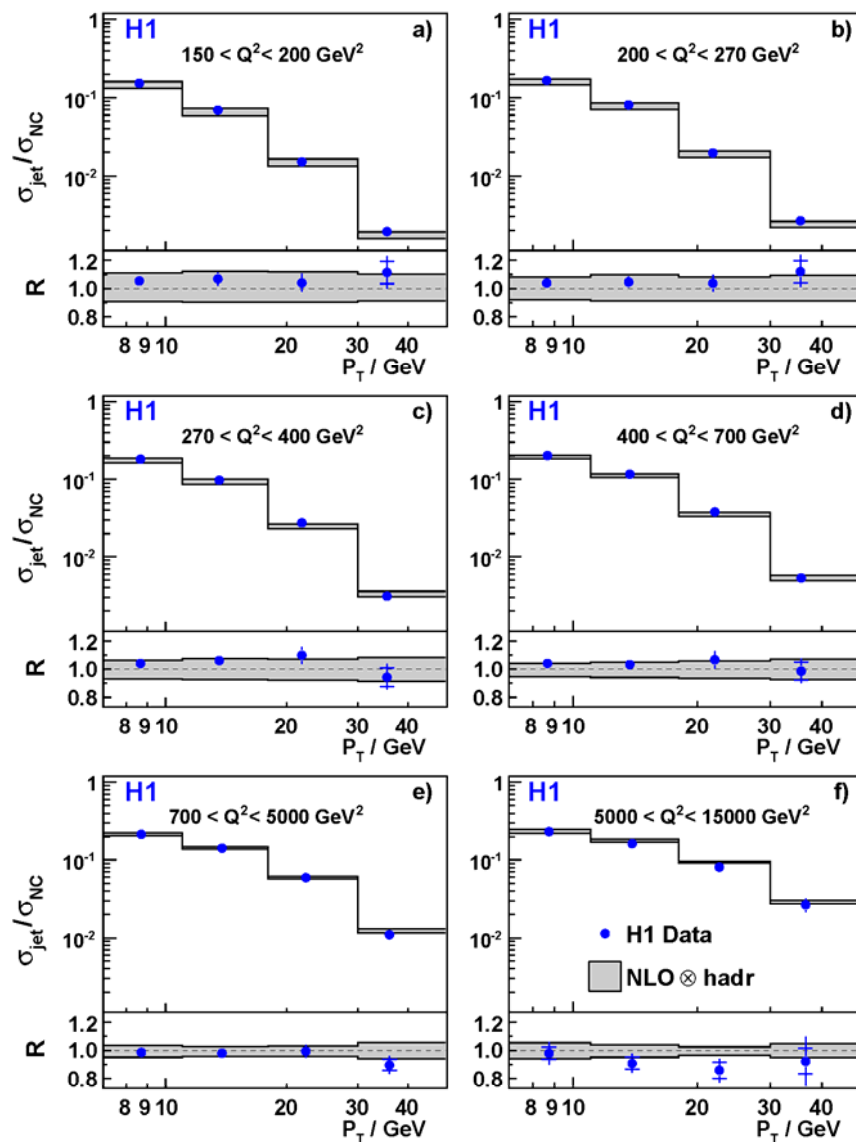
# Colour factors from 3-jets (ZEUS)



# Jet multiplicities in DIS (H1) : high Q



## Normalised Inclusive Jet Cross Section

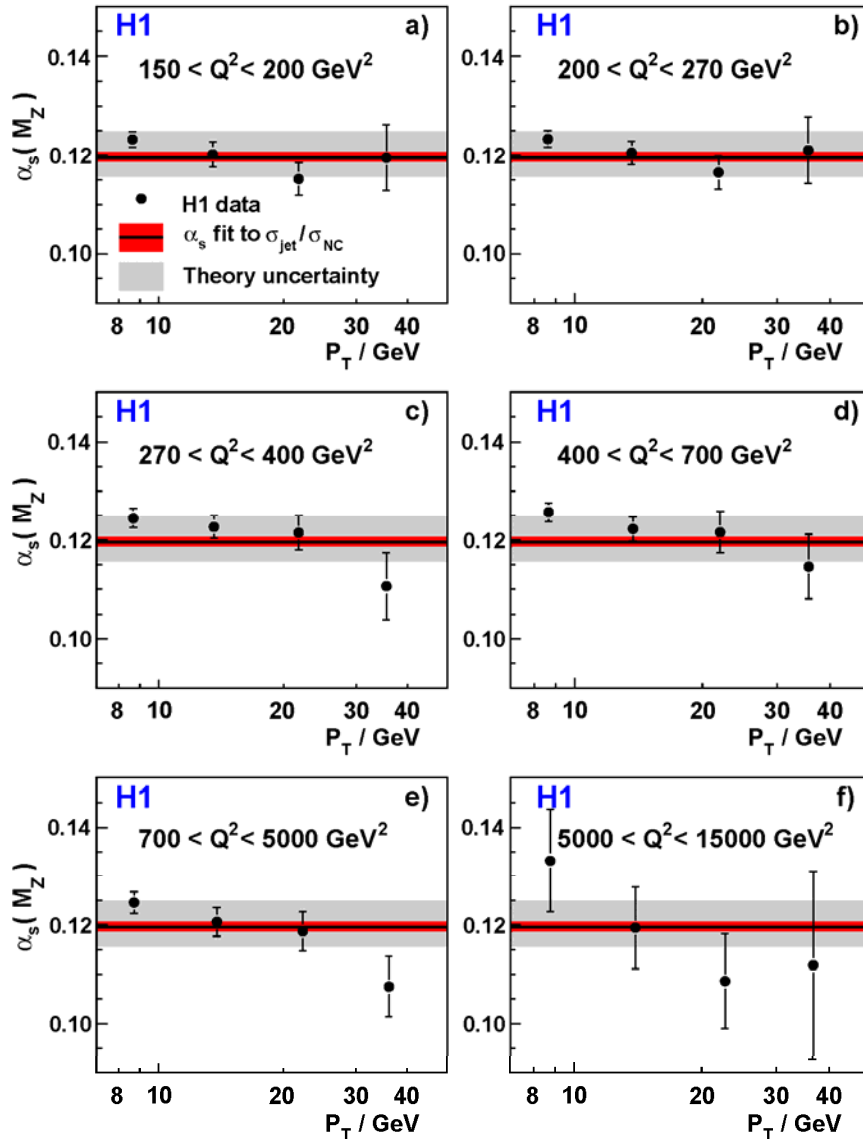


- Accurate measurement (3-6 %) well described by NLO QCD prediction.
- Experimental uncertainty smaller than the theoretical (5-10 %).
- Jet spectrum becomes harder when phase-space opens.

# $\alpha_s$ from inclusive jets at high $Q$ (H1)

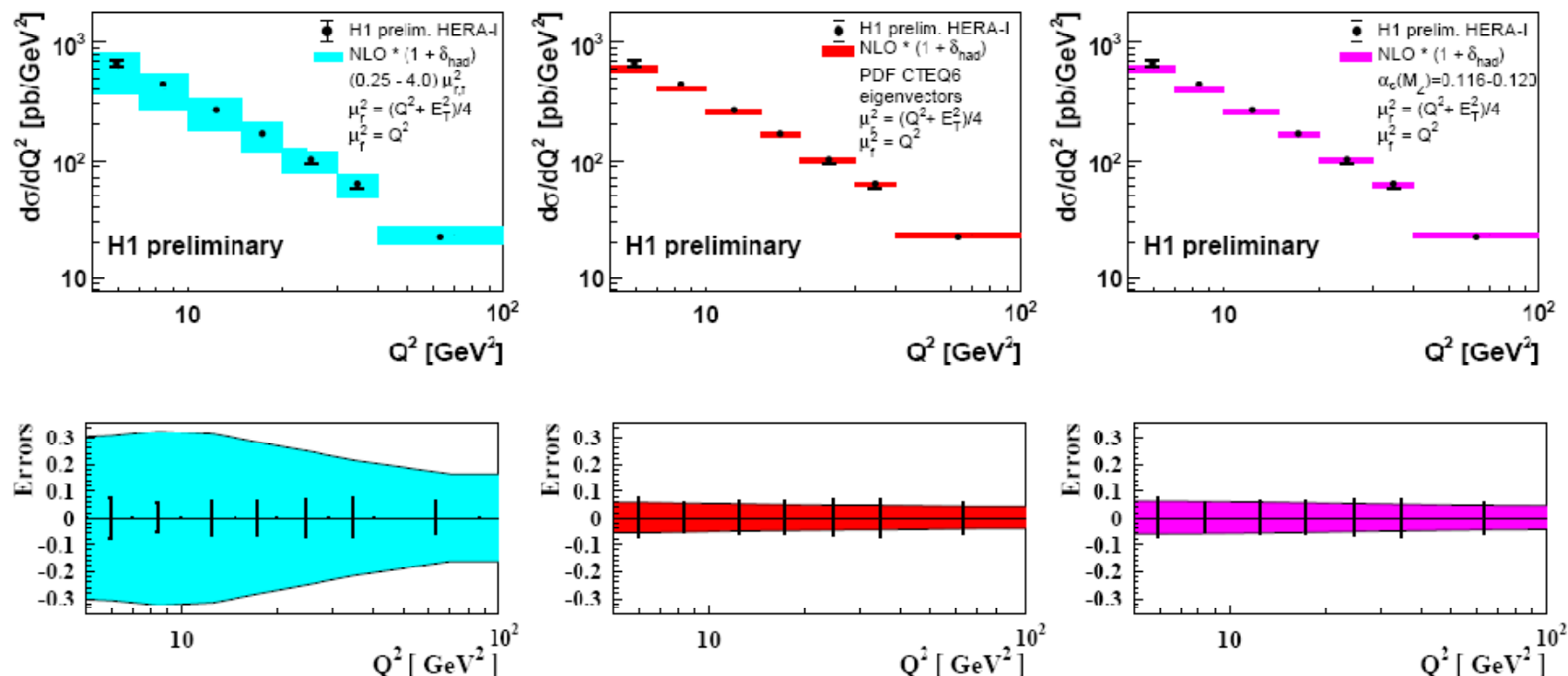


Normalised Inclusive Jet Cross Section



- Minimal  $\chi^2$  fit with experimental correlations of NLO QCD with  $\alpha_s(M_Z)$  free
- Theoretical uncertainties (offset method more conservative than Jones *et al.*): scales, hadronisation, PDF are varied and  $\alpha_s(M_Z)$  refitted.

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



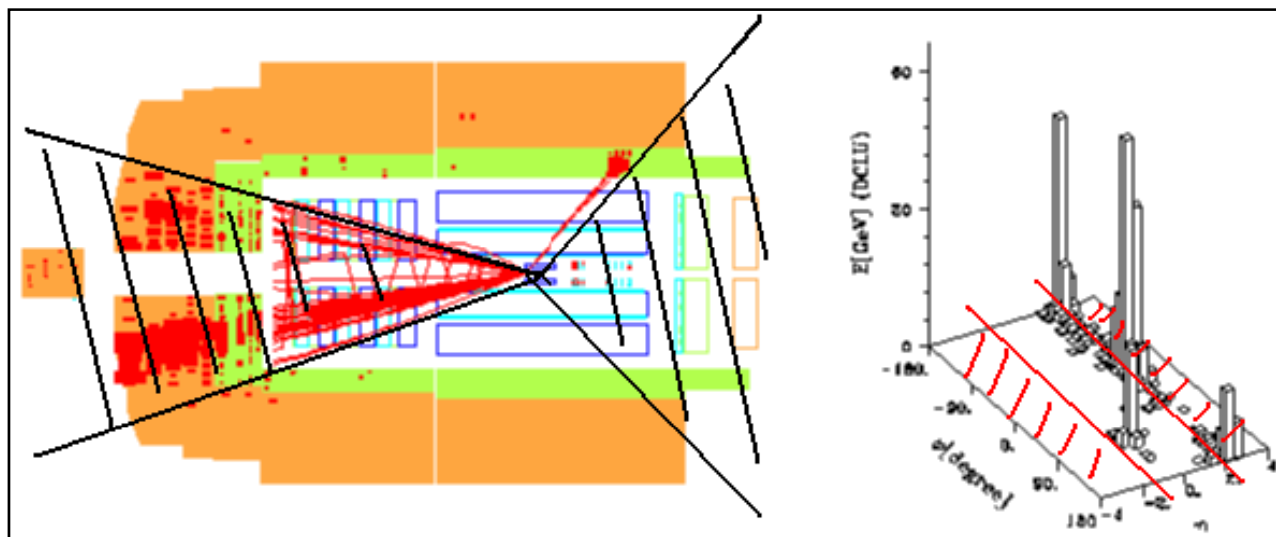
$\mu_R, \mu_F$  dependance

PDF param. sensitivity

$\alpha_s$  sensitivity

- Scale dependence is the most important source of theoretical uncertainty at low  $Q^2$
- The sensitivity to the PDF and to  $\alpha_s$  parameterizations are comparable

# JET fiducial cuts



# JET OBSERVABLES



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

**Low Q**

$$E_T > 5 \text{ GeV}$$

$$-1.0 < \eta^{\text{Lab}} < 2.5$$

**High Q**

$$E_T > 7 \text{ GeV}$$

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

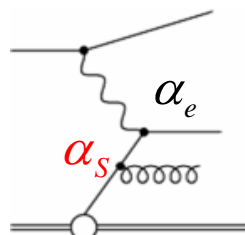
**Multi-jets:** Event counting with more than  $n$  jets. Sensitive to  $\alpha_S$

$$E_T > 5 \text{ GeV}$$

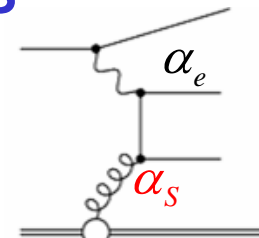
$$-0.8 < \eta^{\text{Lab}} < 2.0$$

$$M_{12} > 16 \text{ GeV}$$

**2-JETS**

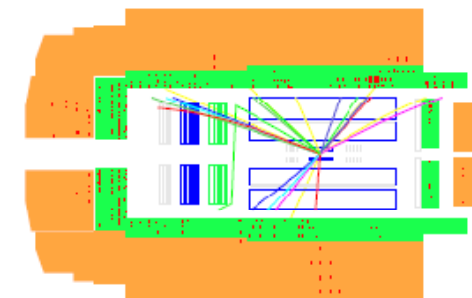
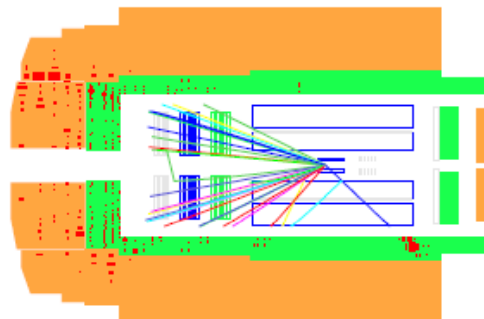
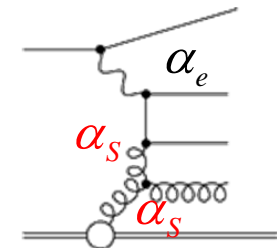


**Boson Gluon Fusion**



**QCD Compton**

**3-JETS**



# Measurement of the cross sections



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

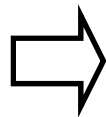
**High Q Jet multiplicity**

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

**Multi-jet rates**

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

Normalized cross  
sections at high Q



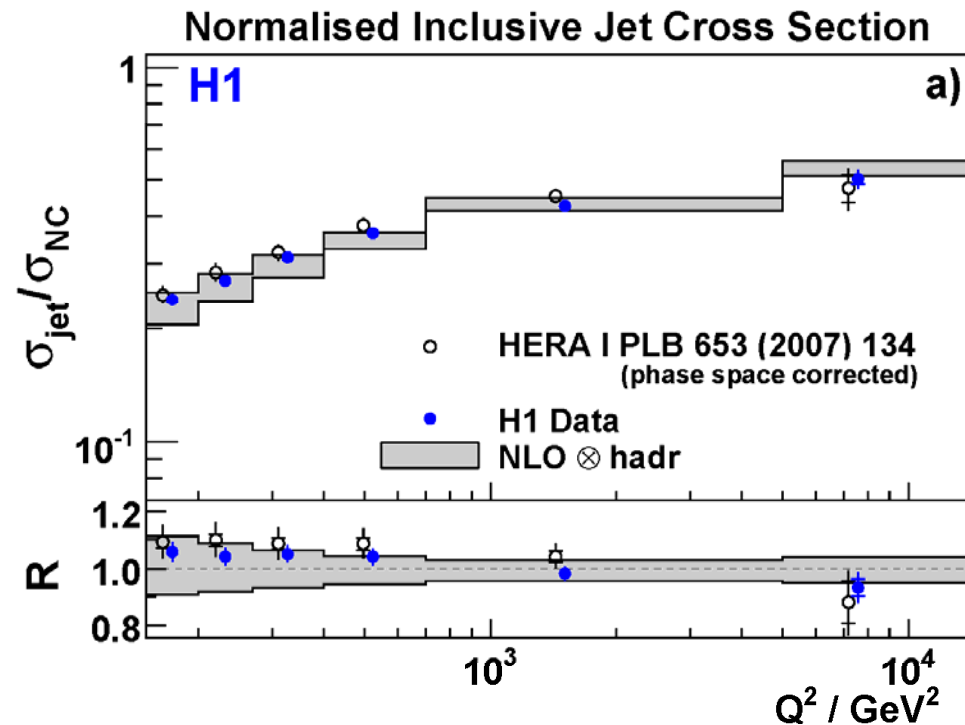
- Normalization errors – cancel completely
- Correlated errors – cancel partially

## 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

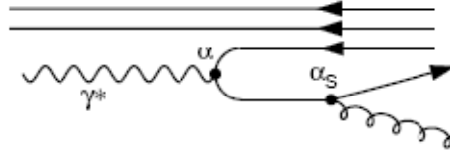
# Jets multiplicities in DIS (H1)

Paper in preparation



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

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 massless recombination scheme

Resulting jets:  $N_{\text{jets}}$  with  $R_{ij} > R = 1$