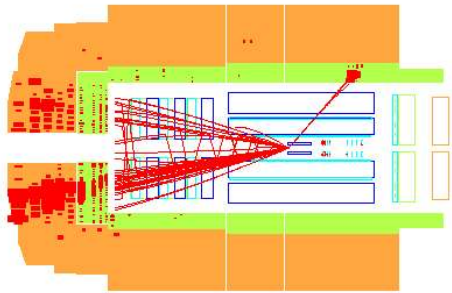


# Jet Measurements and Determination of $\alpha_s$

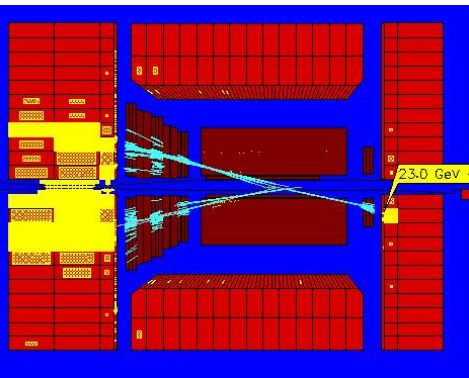
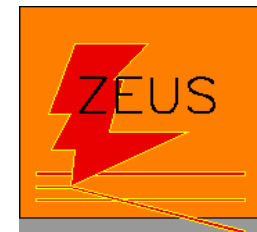
40<sup>th</sup> anniversary  
rencontres de  
Moriond

## at HERA

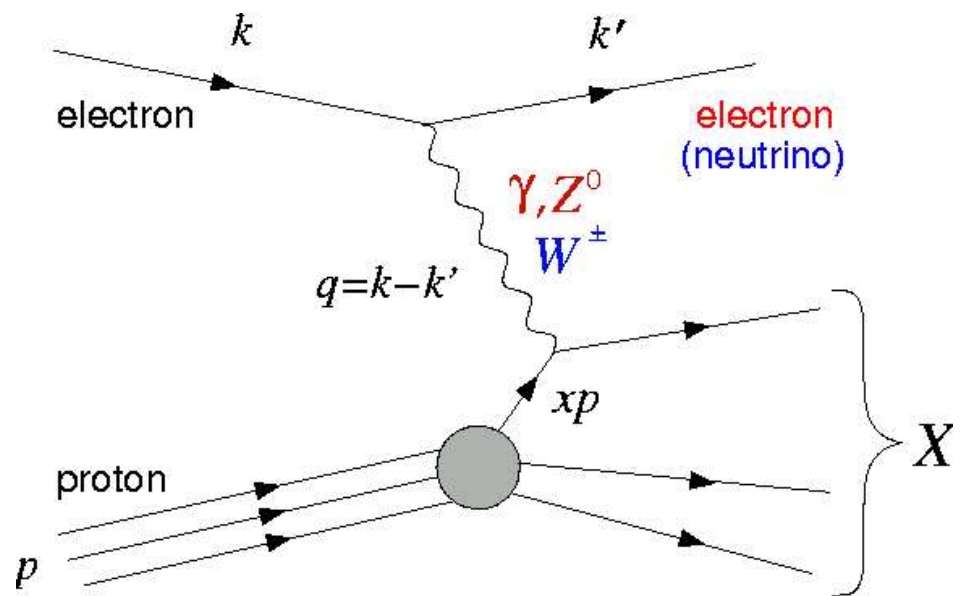
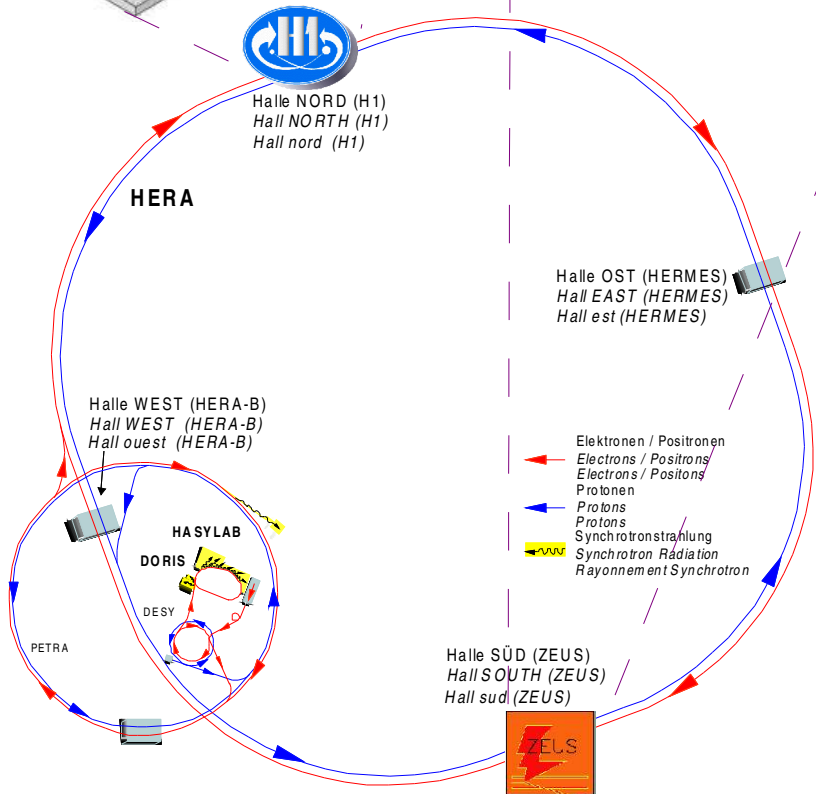
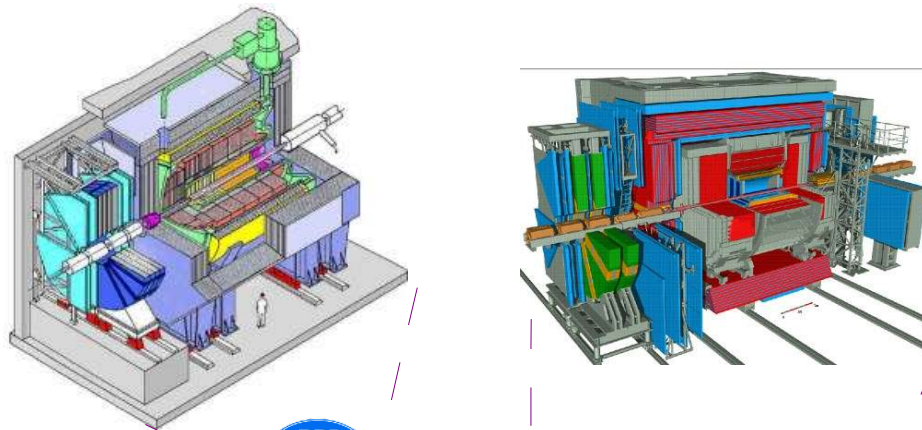
Christoph Wissing



On behalf of the collaborations H1 and ZEUS



# Deep Inelastic Scattering at HERA

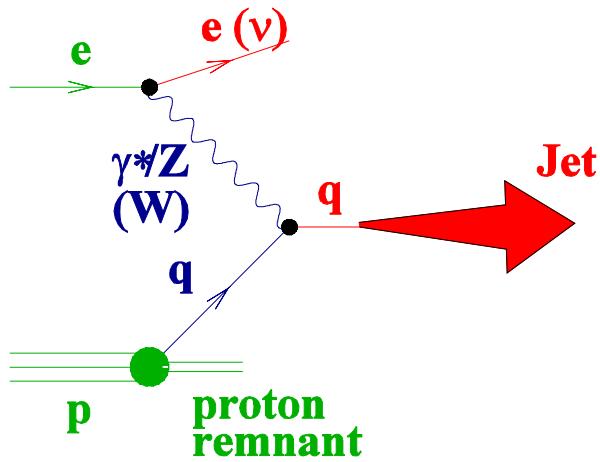


**Kinematics:**

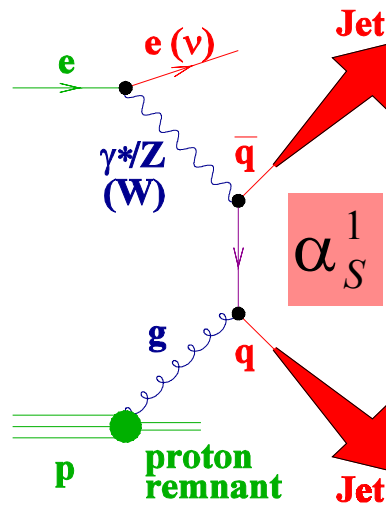
CMS energy $s = (p + k)^2$	Momentum transfer $Q^2 = -q^2$
Bjorken x $x = \frac{Q^2}{2q \cdot p}$	Inelasticity $y = \frac{q \cdot p}{k \cdot p}$

# Jet Production in DIS

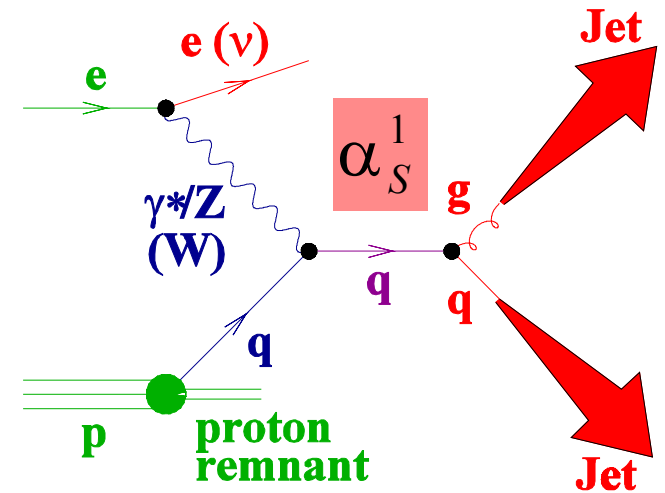
Quark Parton Model  
 $E_{t,lab}$  balanced by  $e$



Boson Gluon Fusion

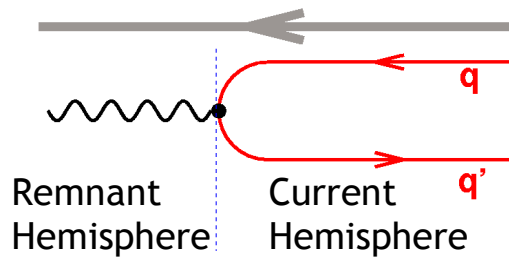


QCD Compton

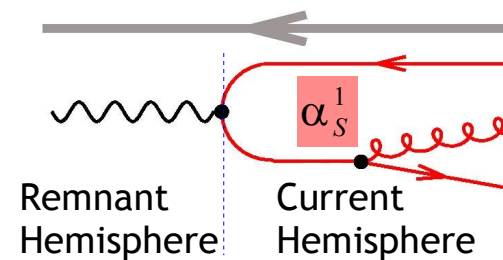


Breit Frame:  $2x\vec{p} + \vec{q} = 0$

No intrinsic  $p_t$

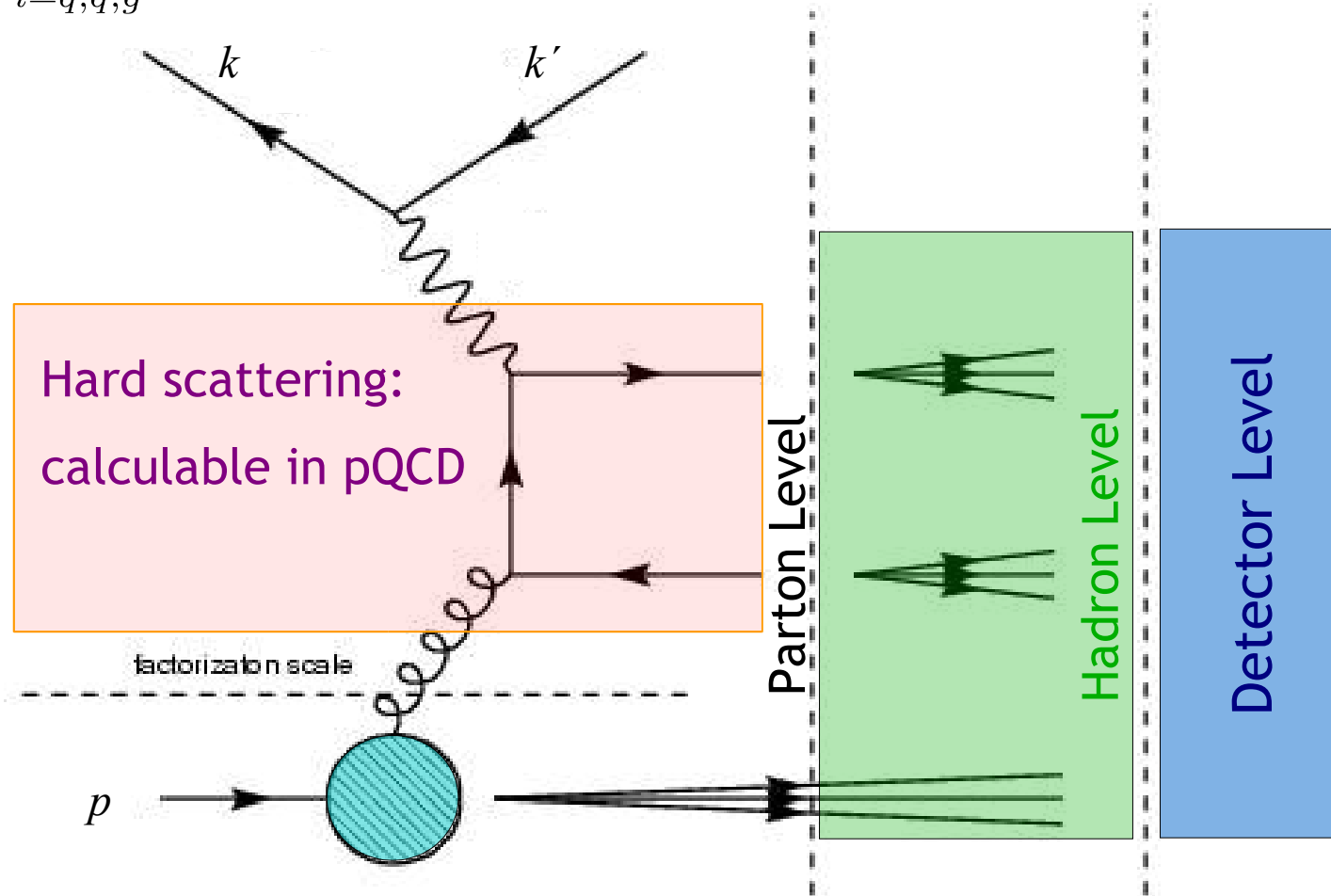


$p_t$  from QCD effects



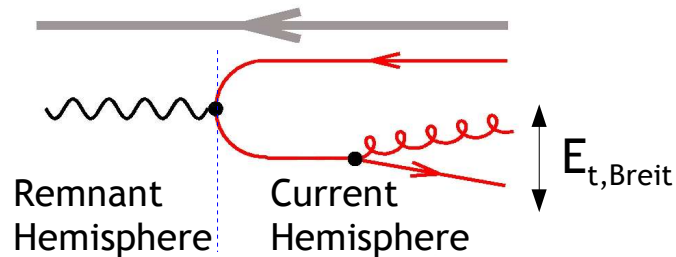
# Jet Cross Section

$$\sigma_{jet} = \sum_{i=q,\bar{q},g} \int dx f_i(x, \mu_F, \alpha_s) \cdot \hat{\sigma}_{QCD}(x, \mu_F, \mu_R, \alpha_S) \cdot (1 + \delta_{had})$$



# Inclusive Jets in DIS (1)

Select Jet(s) in the Breit Frame:



At least one Jet with  $E_{t,Breit} > 8 \text{ GeV}$

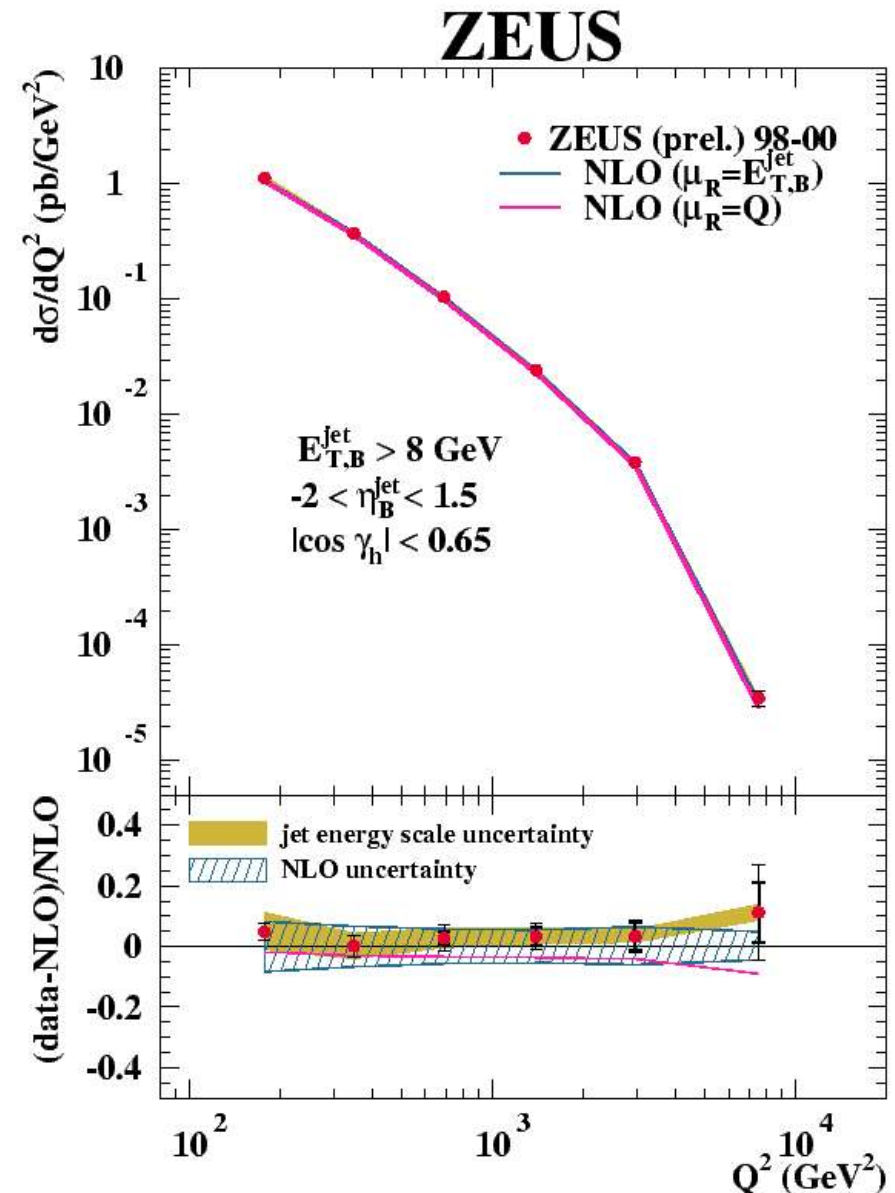
Luminosity:  $81.7 \text{ pb}^{-1}$   
(HERA I 1998-2000)

$$Q^2 > 125 \text{ GeV}^2$$

NLO pQCD: DISINT

Scales:  $\mu_F = Q$ ,  $\mu_R = E_t$  (or  $Q$ )

PDFs: MRST99



# Inclusive Jets in DIS (2)

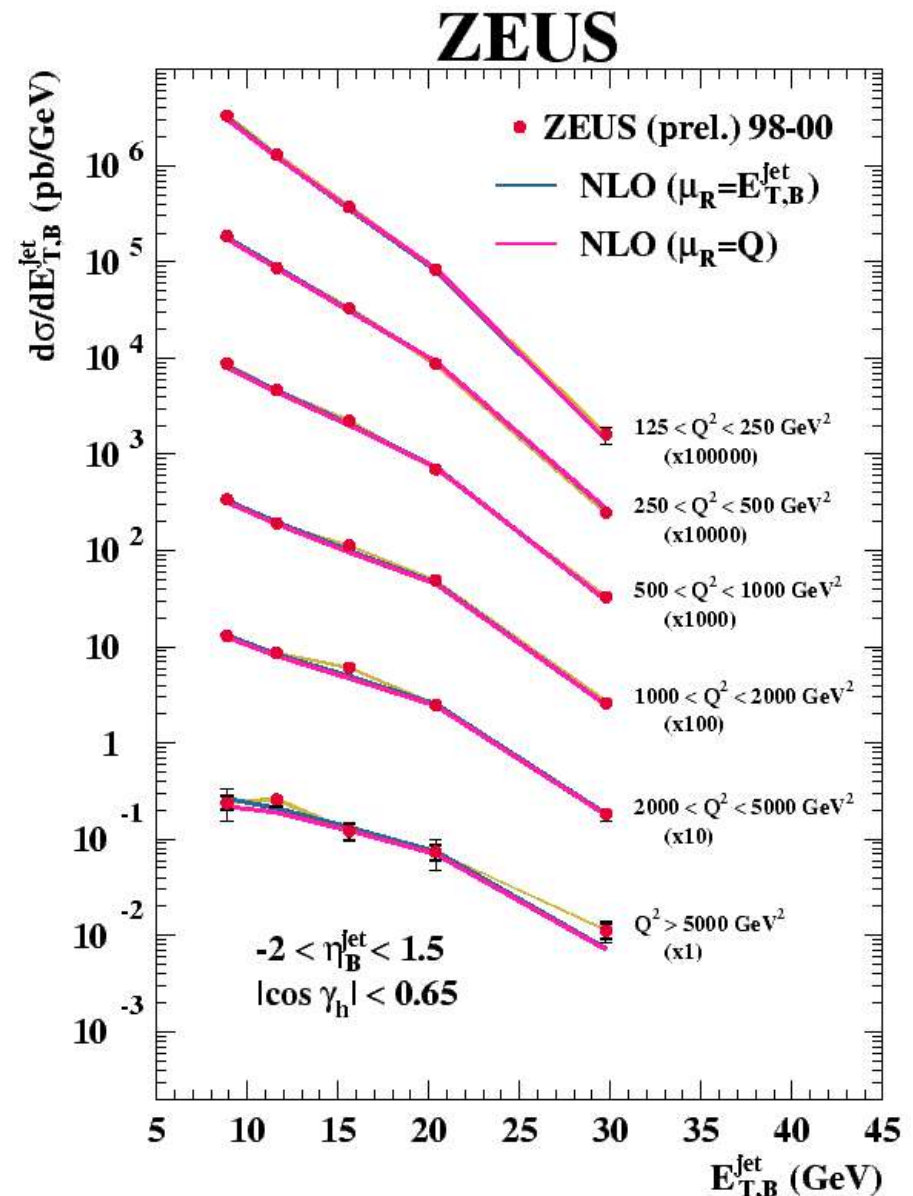
Good agreement data  $\leftrightarrow$  theory  
in all differential distributions

$d\sigma_{\text{jet}}/dE_t$ ,  $d\sigma_{\text{jet}}/dQ^2$  and  $d\sigma_{\text{jet}}/d\eta_B$

Main uncertainties:

Exp: Calorimeter energy scale

Theo: Missing higher orders, PDFs



# Extraction of $\alpha_s$

1.

Generate  $\sigma_{\text{jet}}$  for various  $\alpha_s$

2.

Fit  $\alpha_s$  dependence in each bin:

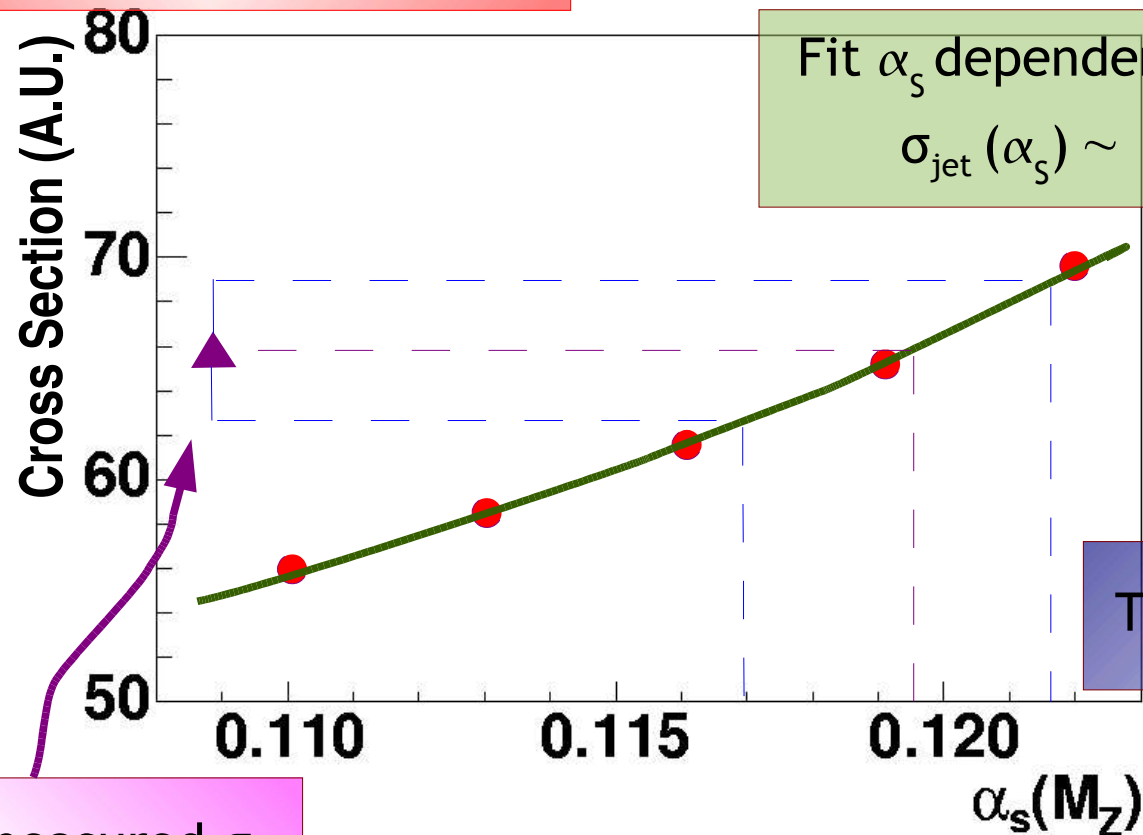
$$\sigma_{\text{jet}}(\alpha_s) \sim A \cdot \alpha_s + B \cdot \alpha_s^2$$

4.

Treat uncertainties

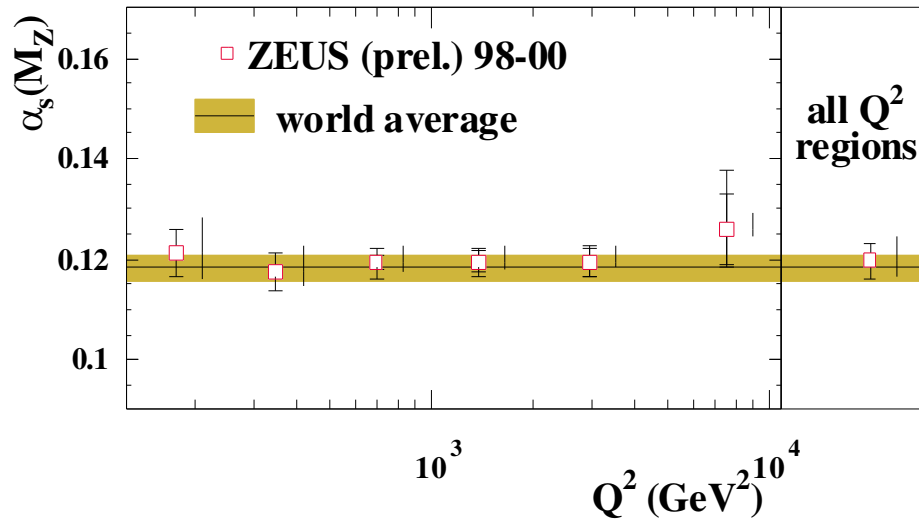
3.

“Compare” to measured  $\sigma_{\text{jet}}$



# $\alpha_s$ from Inclusive Jets

ZEUS



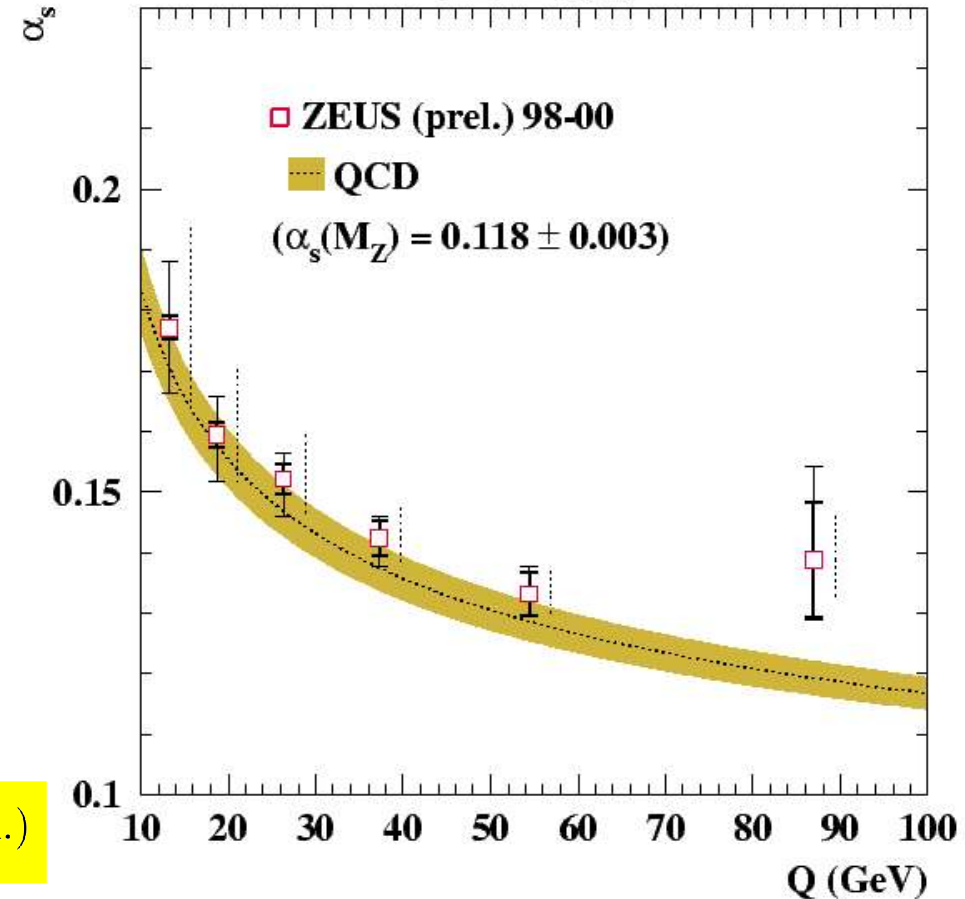
Fits to  $d\sigma_{\text{jet}}/dE_t$  and  $d\sigma_{\text{jet}}/dQ^2$

Best result for  $Q^2 > 500 \text{ GeV}^2$

$$\alpha_s(M_Z) = 0.1196 \pm 0.0011(\text{stat.})_{-0.0025}^{+0.0019}(\text{exp.})_{-0.0017}^{+0.0029}(\text{th.})$$

Good agreement with  
world average  $\alpha_s$   
Small Errors

ZEUS

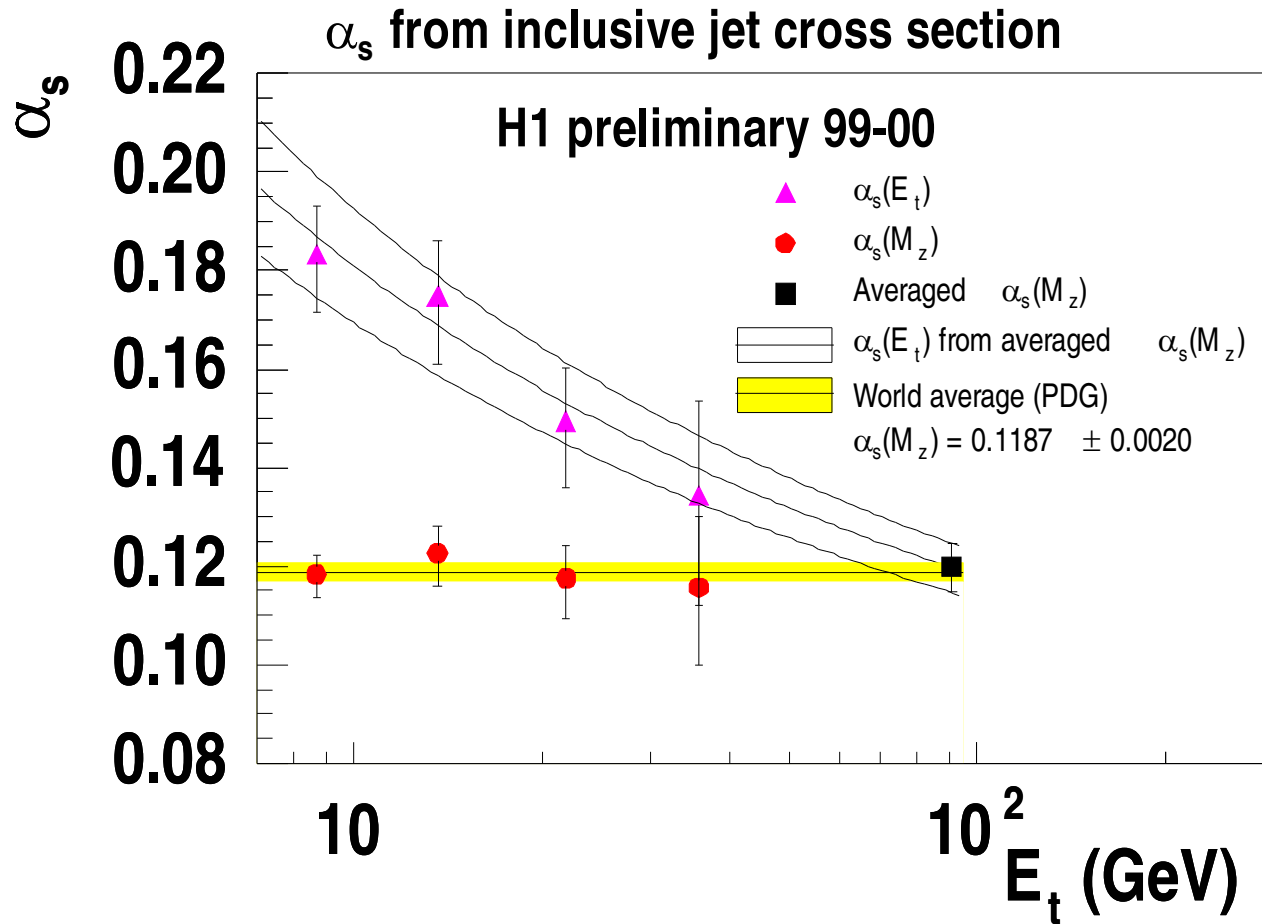


Running of  $\alpha_s$ :

Fit  $\alpha_s(\langle E_t \rangle)$  or  $\alpha_s(\langle Q \rangle)$  parametrized pQCD



# $\alpha_s$ from Inclusive Jets



Luminosity:  $61.25 \text{ pb}^{-1}$   
(HERA 1999-2000)

$150 < Q^2 < 5000 \text{ GeV}^2$

$E_{t,\text{Breit}} > 7 \text{ GeV}$

NLO pQCD: **NLOJET++**

Scales:  $\mu_R^2 = E_t^2, \mu_F^2 = Q^2$

PDFs: CTEQ5M1

Running of  $\alpha_s$ :

Evolution to  $\alpha_s(E_t)$  by

Renormalization Group Equation

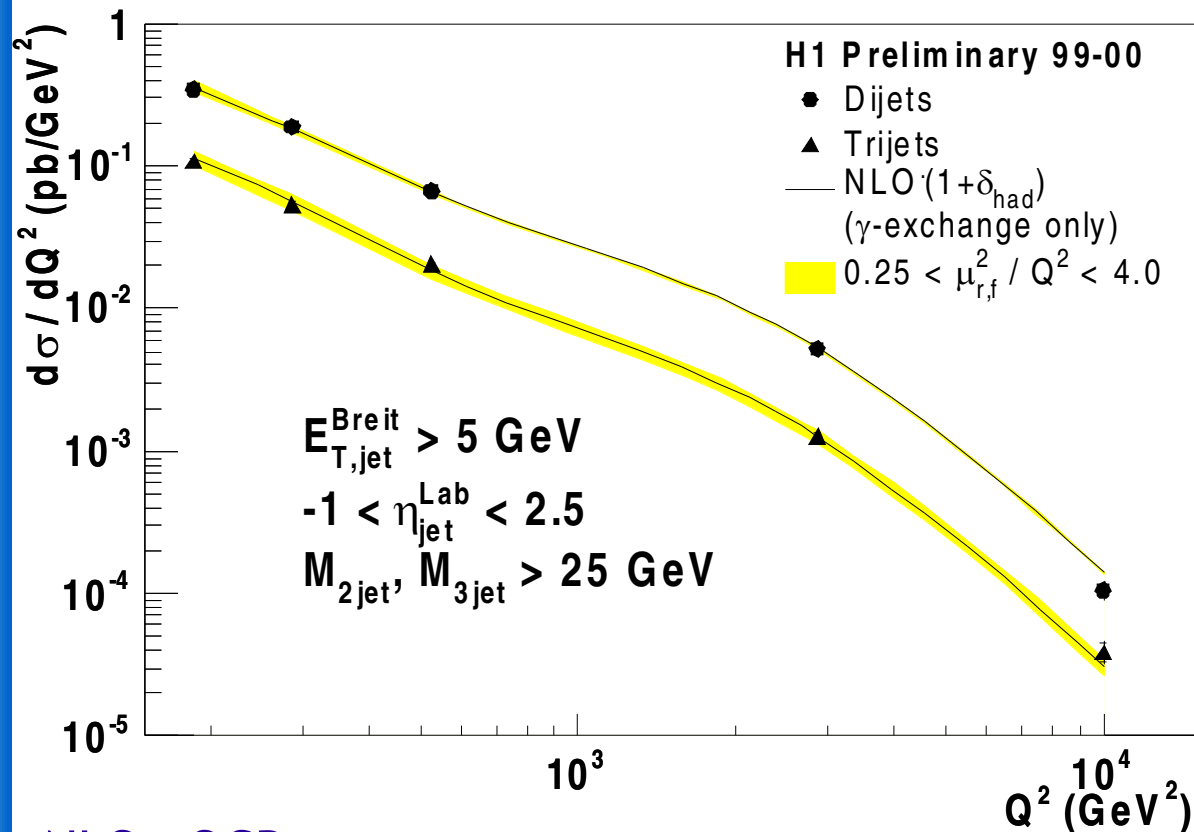
$$\alpha_s(M_Z) = 0.1197 \pm 0.0016(\text{exp.})_{-0.0048}^{+0.0046}(\text{th.})$$

Error dominated  
by theory

# Multi Jet Cross Sections

Disadvantage: Less statistics

Advantage:  $\sigma_{3jet}/\sigma_{2jet}$  many uncertainties cancel

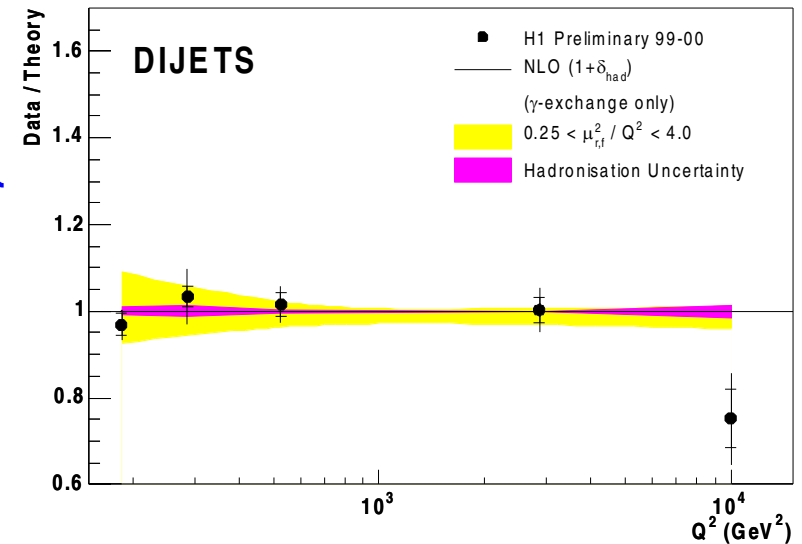


NLO pQCD: **NLOJET++**

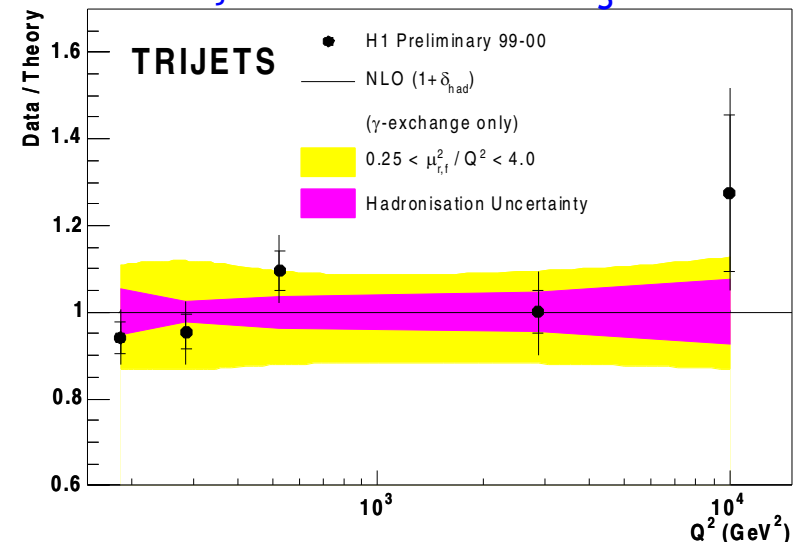
Scales:  $\mu_R^2 = Q^2, \mu_F^2 = Q^2$

PDFs: CTEQ5M (CTEQ4A)

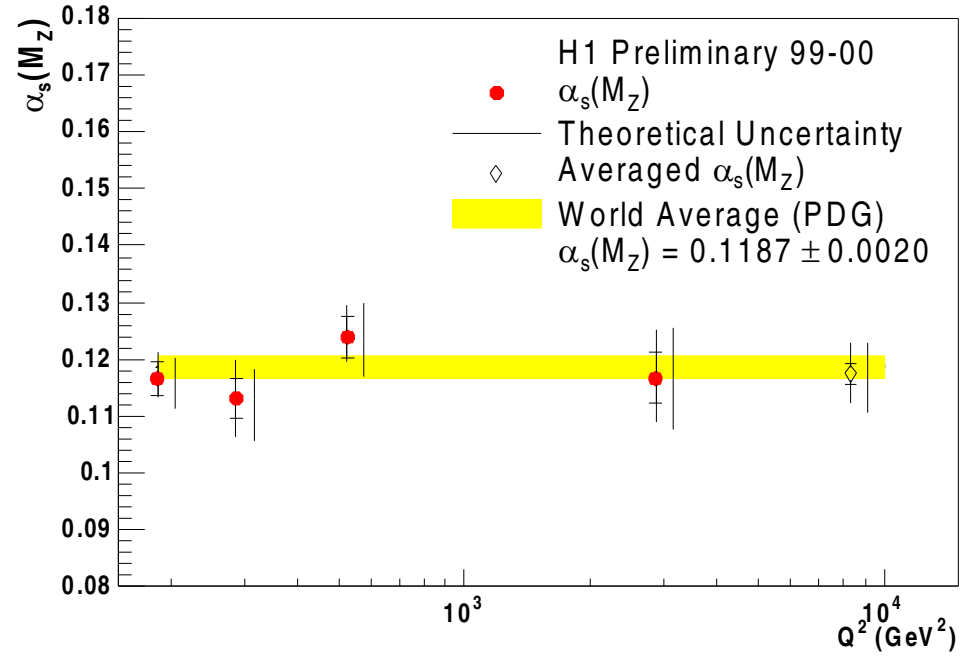
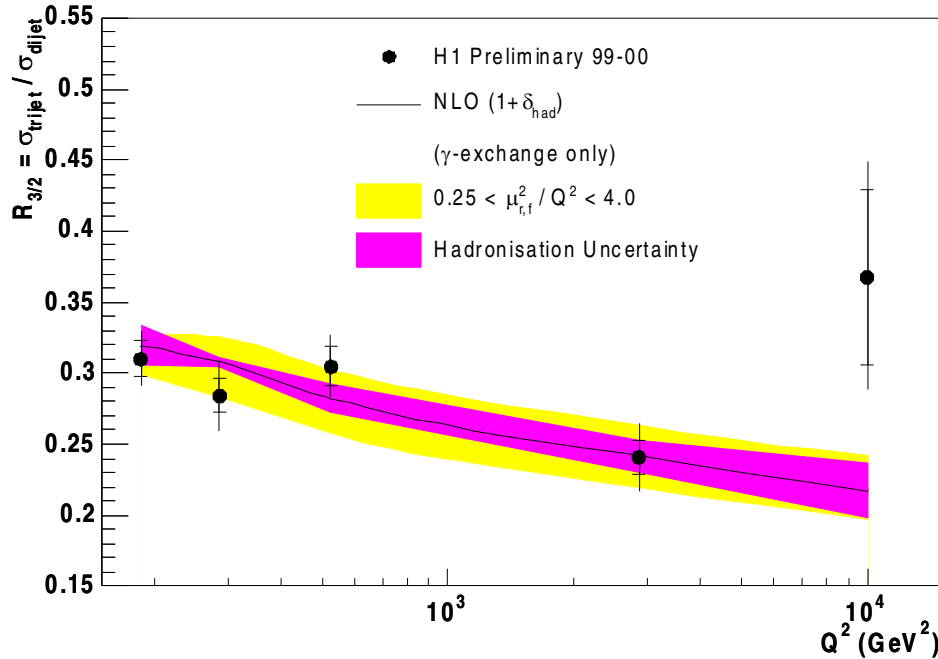
Issues @high  $Q^2$   
(missing  $Z^0$  in NLO calc)



$\sigma_{3jet}$  sensitive to  $\alpha_s^2$



# $\alpha_s$ from the Trijet to Dijet Ratio $R_{3/2}$



Highest  $Q^2$  bin has large uncertainty  $\rightarrow$  **exclude** from  $\alpha_s$  fit

$$\alpha_s(M_Z) = 0.1175 \pm 0.0017(\text{stat.}) \pm 0.0050(\text{sys.})_{-0.0068}^{+0.0054}(\text{th.})$$

# Event Shape Variables

Investigate particle flow in final state → sensitivity to hadronisation

Breit frame: Maximal separation between current jet and remnant

Thrust: (“Longitudinal momenta”)

$$\tau = 1 - T \quad T = \frac{\sum_i |\vec{p}_{z,i}|}{\sum_i |\vec{p}_i|}$$

$$\tau_C = 1 - T_C \quad T_C = \max(\vec{n}_T) \frac{\sum_i |\vec{p}_i \cdot \vec{n}_T|}{\sum_i |\vec{p}_i|}$$

Broadening: (“Transverse momenta”)

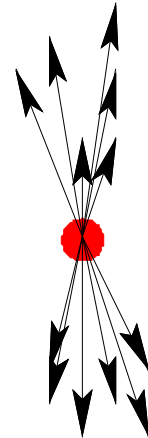
$$B = \frac{\sum_i |\vec{p}_{t,i}|}{2 \sum_i |\vec{p}_i|}$$

Squared Jet Mass:

$$\rho = \frac{(\sum_i E_i)^2 - |\sum_i \vec{p}_i|^2}{2(\sum_i E_i)^2}$$

“C-Parameter”

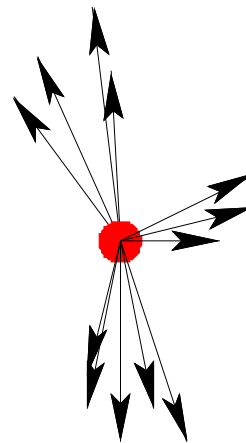
$$C = \frac{3 \sum_{ij} |\vec{p}_i| |\vec{p}_j| \cos^2(\theta_{ij})}{2(\sum_i |\vec{p}_i|)^2}$$



“Narrow Events”:

$$F \rightarrow 0$$

[QPM: 1 collimated jets]



“Broader Events”:

$$F > 0$$

[QCD: Gluon radiation]

# Power Corrections

Hadronisation (non-perturbative):

- “Usually” phenomenological models (many parameters)
- **Power corrections** (Dokshitzer & Webber) analytic approach

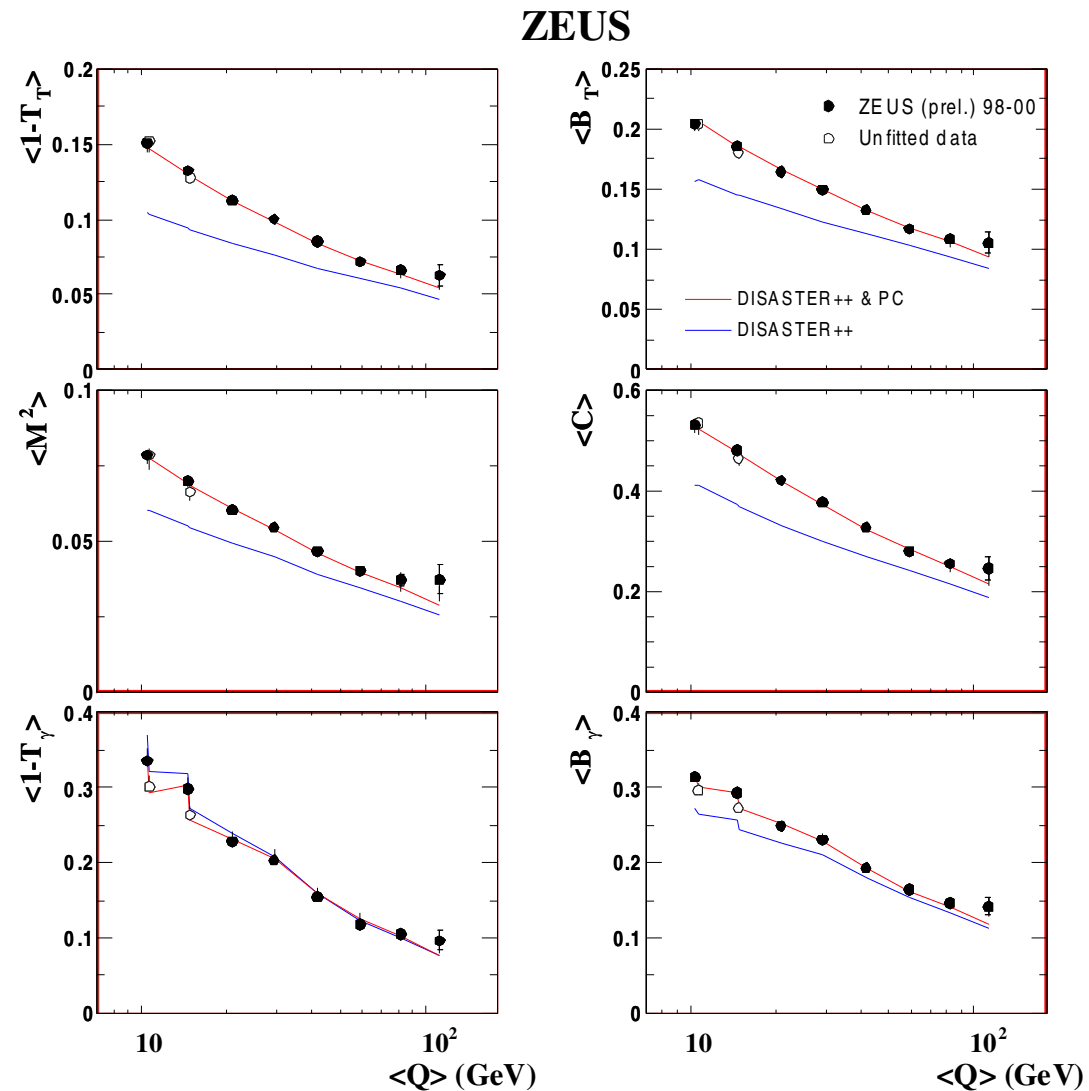
Mean or differential distribution of event shape variable  $F$

$$\langle F \rangle = \langle F \rangle^{pQCD} + a_F \mathcal{P}$$

$$\mathcal{P} \sim \frac{A(\alpha_0, \alpha_S)}{Q}$$

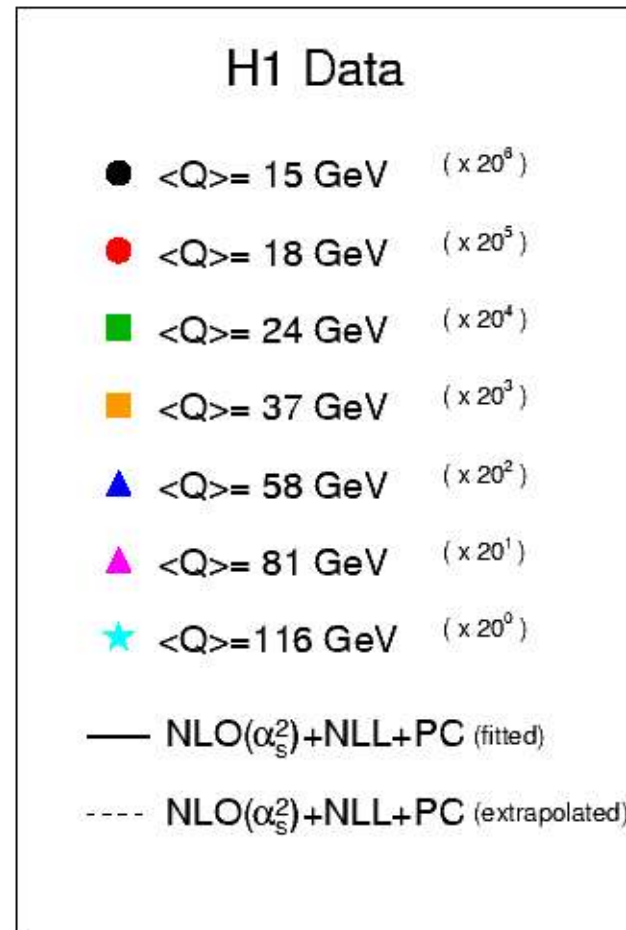
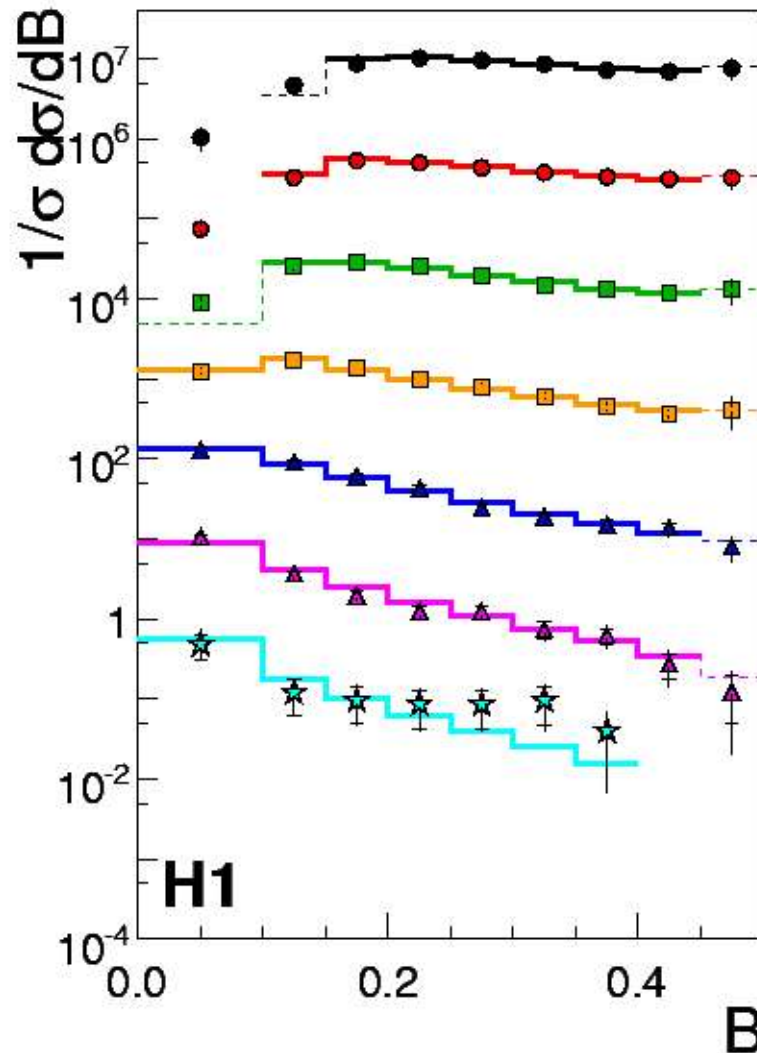
$\alpha_0$ : Universal Parameter

(Expected to be  $\approx 0.5$ )



Data well described by NLO+PC+Fit

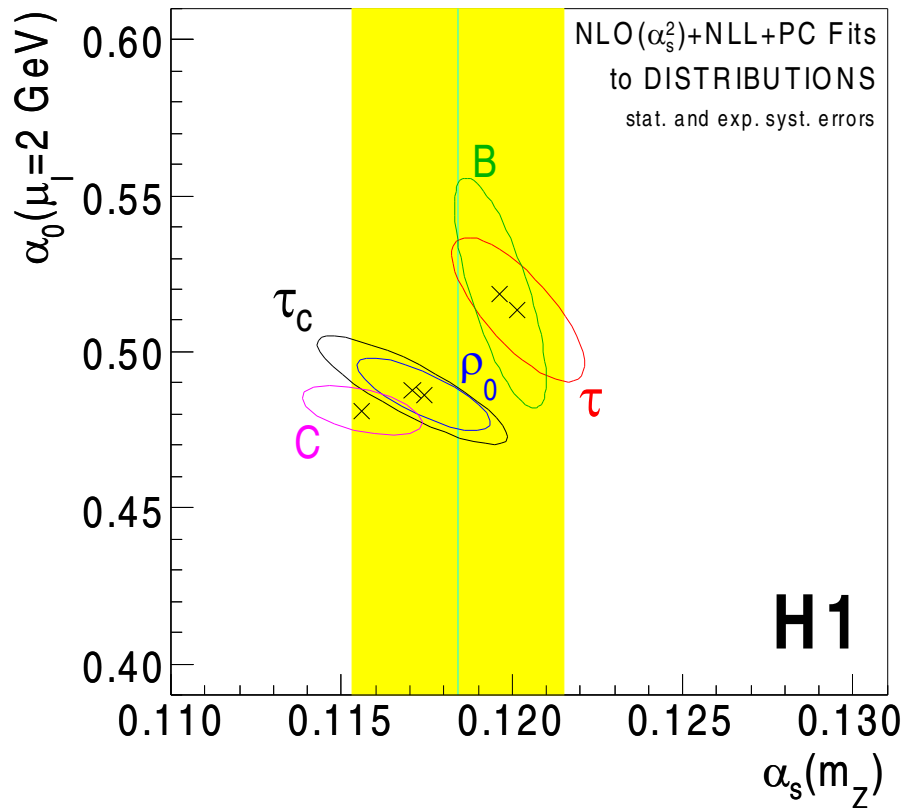
# Event Shape Distributions



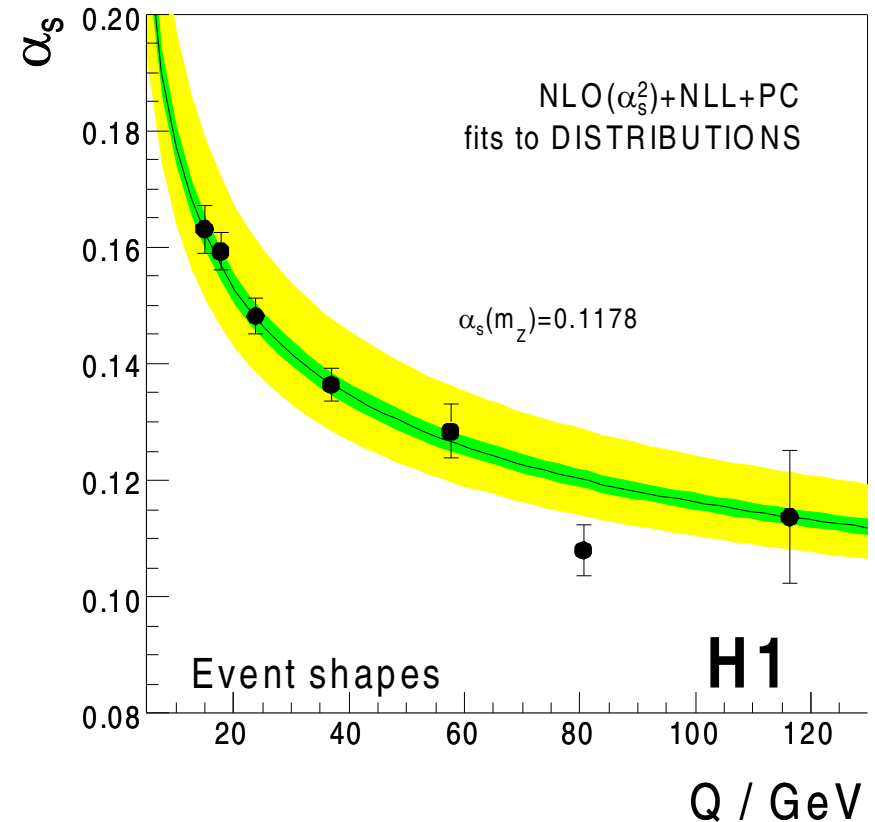
Luminosity:  $106 \text{ pb}^{-1}$   
(HERA I 1995-2000)

$196 < Q^2 < 40,000 \text{ GeV}^2$   
 $0.1 < y < 0.7$

# $\alpha_s$ from Event Shapes



Fit each  $F$  in all bins:  $m_i - t_i(\alpha_0, \alpha_s)$   
Measurement     Theorie



Fit for each  $F$ :  $\{ \alpha_s(Q=Q_i), \alpha_0 \}$

Running nicely described

Consistent with  $\alpha_s$  from jets  
with comparable precision

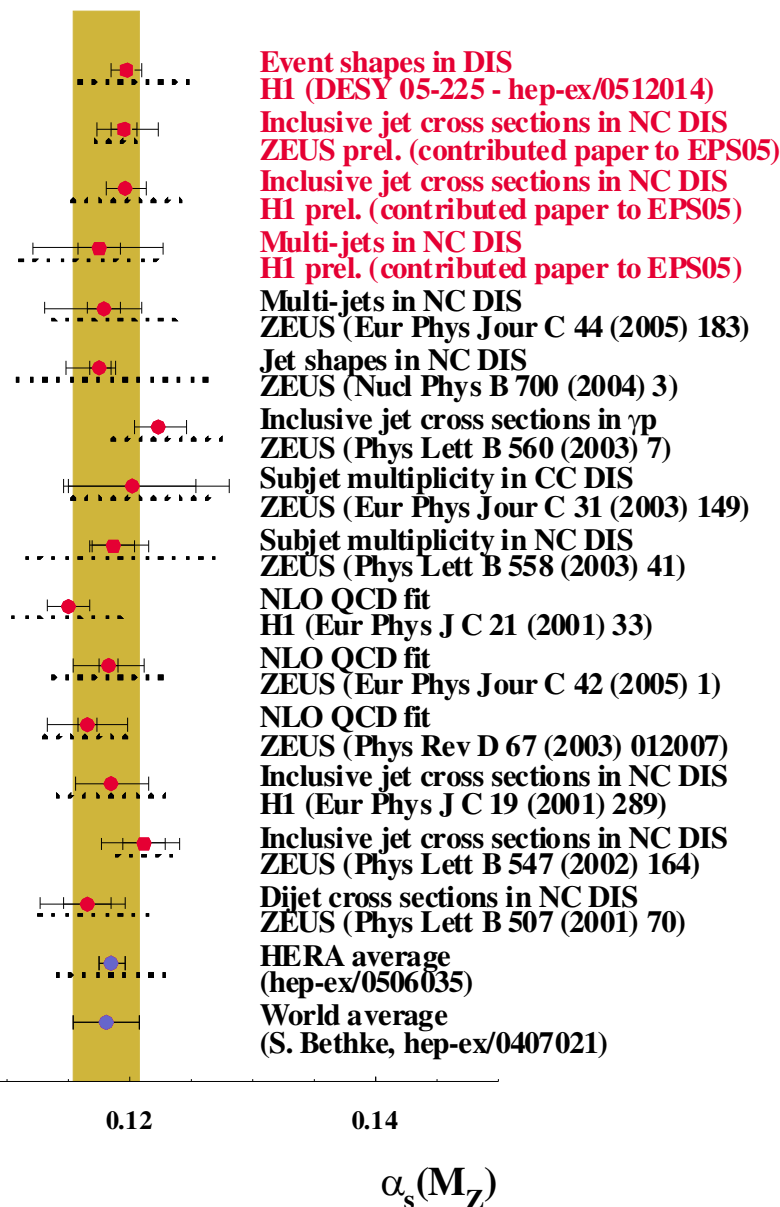
$$\alpha_0 = 0.476 \pm 0.008(\text{exp})_{-0.059}^{+0.018}(\text{theo}) \quad \checkmark$$

$$\alpha_s(m_Z) = 0.1198 \pm 0.0013(\text{exp})_{-0.0043}^{+0.0056}(\text{theo})$$



# Summary

th. uncert.  
exp. uncert.



- ◆  $\alpha_s$  precision measurements by HERA Experiments
  - Dominating error: Theory
  - Well compatible with world average
- ◆ More data with HERA II
  - Increased statistics @high  $Q^2$  &  $E_+$
  - Improved detector understanding
- ◆ Expected progress in theory
  - NNLO
  - EW effects