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Jet Production in Deep Inelastic *e-p* Collisions at High Q^2 and Determination of α_s

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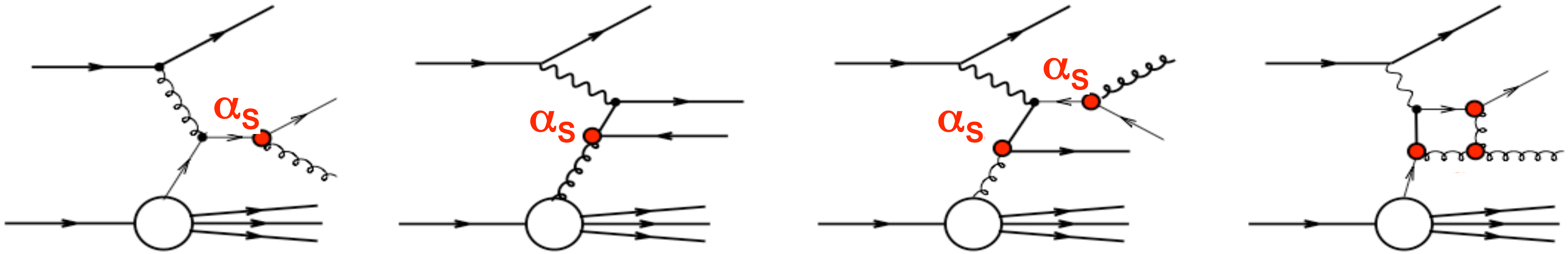
on behalf of the H1 Collaboration

Jet production in deep-inelastic *e-p* scattering

- **multi-jet states (> 1+1) = direct manifestation of QCD**



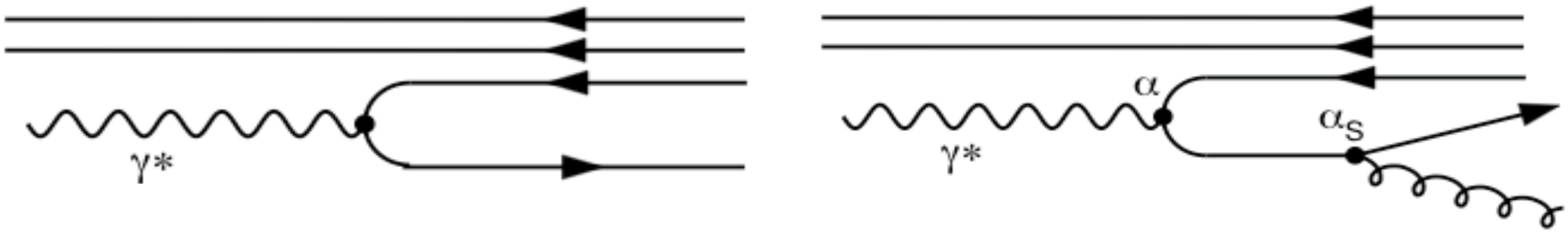
QCD Compton **Boson Gluon Fusion** **higher order corrections**

- **comparison with & fit to pQCD predictions ⇒ access to:**
  - parton distribution functions (gluon)
  - **precision measurement of strong coupling α_s**
- **e^+-*p* and e^--*p* DIS data from HERA (1999-2007) : 395 pb^{-1}**
- **high Q^2 neutral current (NC) DIS selection :**

$$150 < Q^2 < 15000 \text{ GeV}^2$$
$$0.2 < y < 0.7$$

} **from scattered electron**

Jet Finding: inclusive k_T Algorithm in the Breit Frame



- **Breit frame: proton and virtual photon collide head-on,** in the naïve quark parton model the quark bounces off from the photon like from a "brick wall"
- **transverse momentum in Breit frame stems mainly from QCD process**
- **longitudinally invariant k_T jet-algorithm in the Breit frame**
  - collinear and infrared safe
  - iterative clustering: $d^2_{i,j} = min(p^2_{T,i}, p^2_{T,j}) \cdot \left[(\eta_i - \eta_j)^2 + (\varphi_i - \varphi_j)^2\right]$
  - result: *n* jets with $d_{i,j} > R$ where $R = 1$
- **jet selection:**

	$n_{Jet} \geq 1$	$n_{Jet} \geq 2$	
	$p_T > 7$ GeV	$p_T > 5$ GeV	
jets invariant mass		$m_{12} > 16$ GeV	*accuracy of pQCD prediction*
lab. pseudorapidity	$-0.8 < \eta_{Jet,Lab} < 2$		*jet containment in detector*

Jet observables : Normalized Multi-Jet Cross-Sections

Inclusive, 2-jet and 3-jet cross-sections normalized by NC DIS cross-section

- ➤ experimental normalization uncertainty cancels completely
- ➤ correlated experimental and theoretical uncertainties cancel partially

inclusive jet rate
(= average jet multiplicity)

$$\frac{\sigma_{Jet}}{\sigma_{NC}}(Q^2)$$

$$\frac{\sigma_{Jet}}{\sigma_{NC}}(Q^2, p_T)$$

2-jet rate

$$\frac{\sigma_{2Jet}}{\sigma_{NC}}(Q^2)$$

$$\frac{\sigma_{2Jet}}{\sigma_{NC}}(Q^2, \langle p_T \rangle) \text{ with } \langle p_T \rangle = \frac{1}{2}\left(p_T^{(1)} + p_T^{(2)}\right)$$

$$\frac{\sigma_{2Jet}}{\sigma_{NC}}(Q^2, \xi) \text{ with } \xi = x_B\left(1 + \frac{m_{12}^2}{Q^2}\right)$$

3-jet rate

$$\frac{\sigma_{3Jet}}{\sigma_{NC}}(Q^2)$$

3-jet to 2-jet ratio

$$\frac{\sigma_{3Jet}}{\sigma_{2Jet}}(Q^2)$$

QCD Predictions of Jet Production Cross-Sections

- **Calculation of multi-jet X-sections at parton level : NLOJET++**
  NLO QCD matrix elements for up to 3+1 final state partons
- **Calculation of DIS NC cross-section at NLO: DISENT**
- **FastNLO : Interface for fast PDF convolution and α_S evolution**
- **Hadronization corrections: leading order MC event generators**
  DJANGO (color dipole model) and RAPGAP (parton showers)
  cross-checked with soft gluon power corrections [arXiv:0903.2187]
- **THEORETICAL UNCERTAINTIES:**
  - Scale (μ_R,μ_F) uncertainties : variation by factors 0.5 … 2
  - PDF parameterization dependence with CTEQ65M set (eigenvector method)

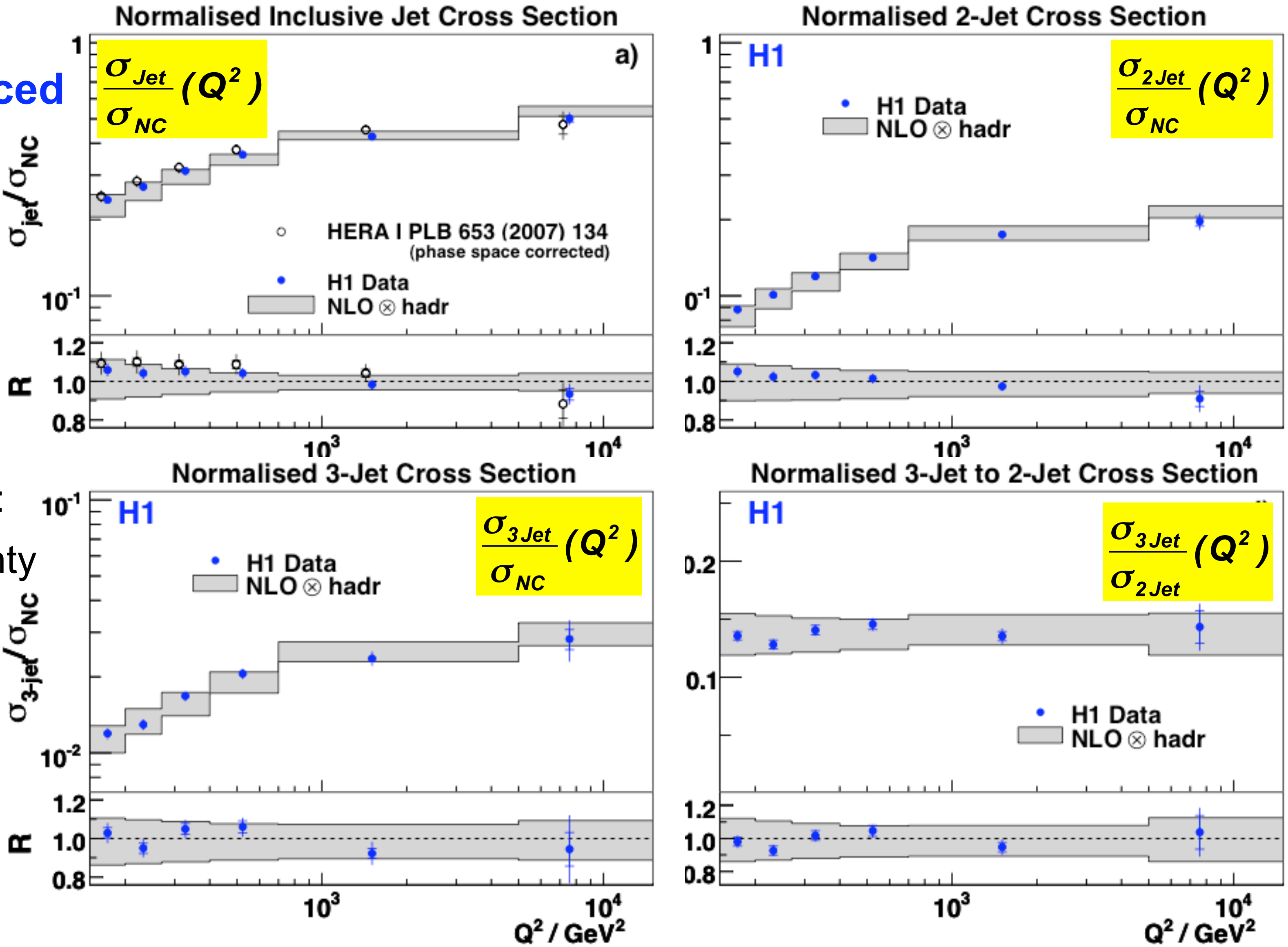
Observable	μ_R	μ_F	PDF	α_S
Inclusive jets	$\sqrt{(Q^2 + p_T^2)/2}$	Q	CTEQ65M	0.1168
2-, 3-jets	$\sqrt{(Q^2 + \langle p_T \rangle^2)/2}$			

Multi-Jet Rates as Function of Q^2

exp. uncertainties significantly reduced
compared to previous HERA-I analysis ($65 pb^{-1}$) :

➤statistical errors: mostly negligible

➤systematical errors: reduction of uncertainty on had. energy scale

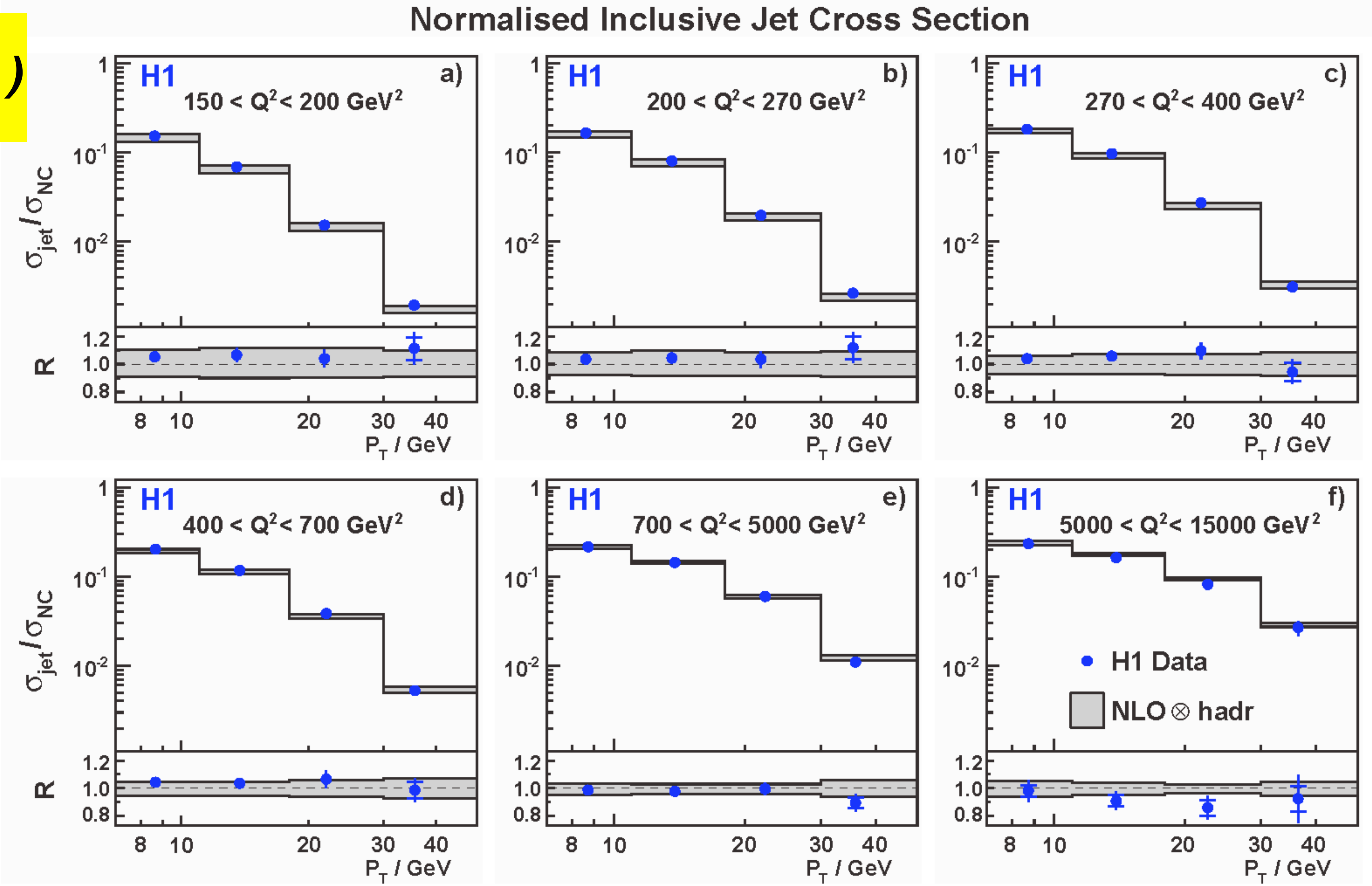


R=data/NLO

data well described by NLO perturbative QCD

Average Jet Multiplicity, double - differential

$$\frac{\sigma_{Jet}}{\sigma_{NC}}(Q^2, p_T)$$



R=data/NLO

- data well described by NLO pQCD within exp. uncertainties (2–6%)
- theory error (5-10%) dominates: missing higher orders ⇒ μ_R dependency

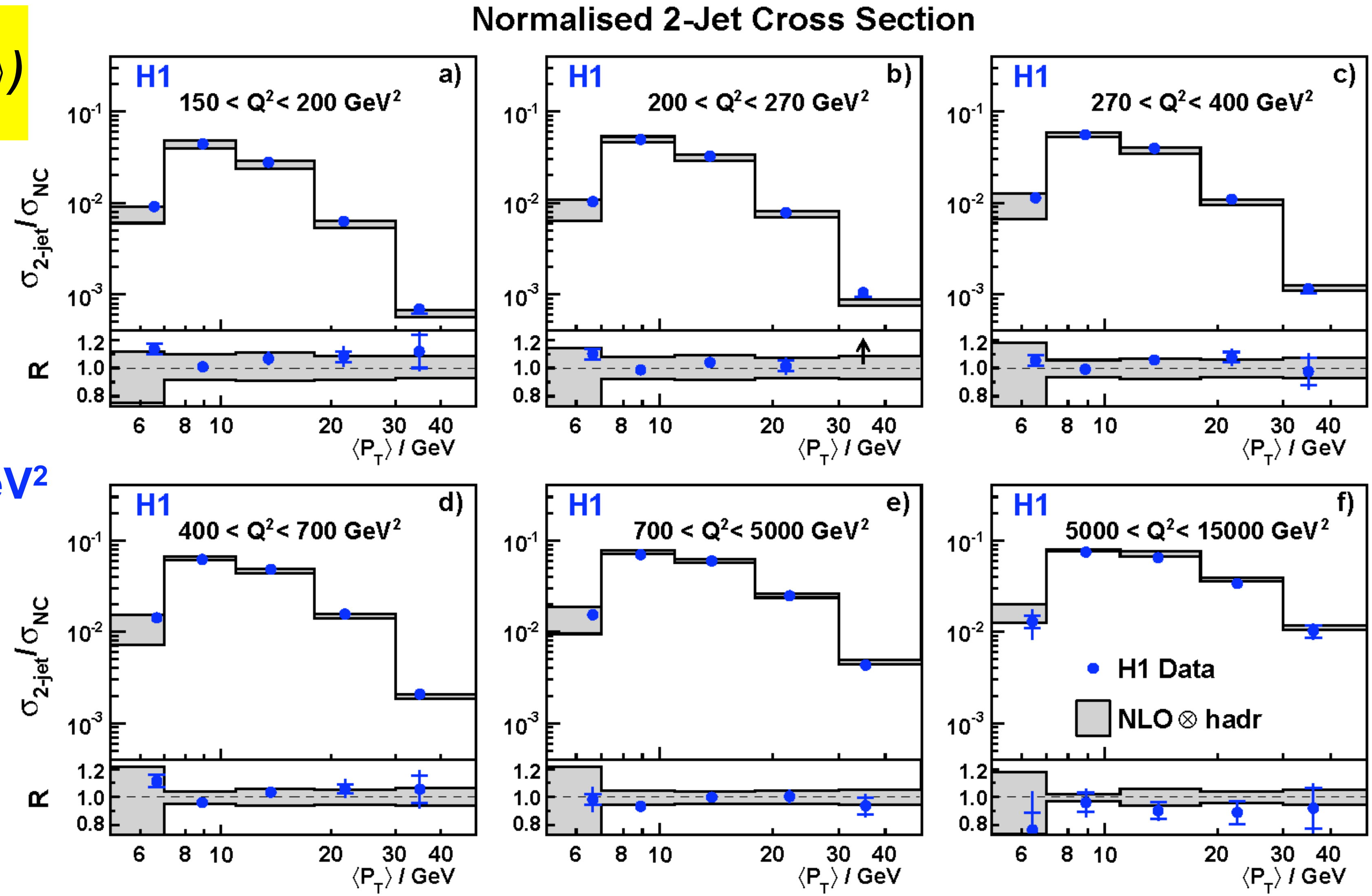
Two Jet Rate, double differential in Q^2 and $\langle p_T \rangle$

$$\frac{\sigma_{2\,Jet}}{\sigma_{NC}}\left(Q^2, \langle p_T \rangle\right)$$

$$\langle p_T \rangle = \frac{p_T^{(1)} + p_T^{(2)}}{2}$$

$m_{12} > 16$ GeV²

R=data/NLO



- low E_T bin strongly suppressed by invariant mass cut
- data well described by NLO pQCD within exp. uncertainties

Two Jet Rate, double differential in Q^2 and ξ

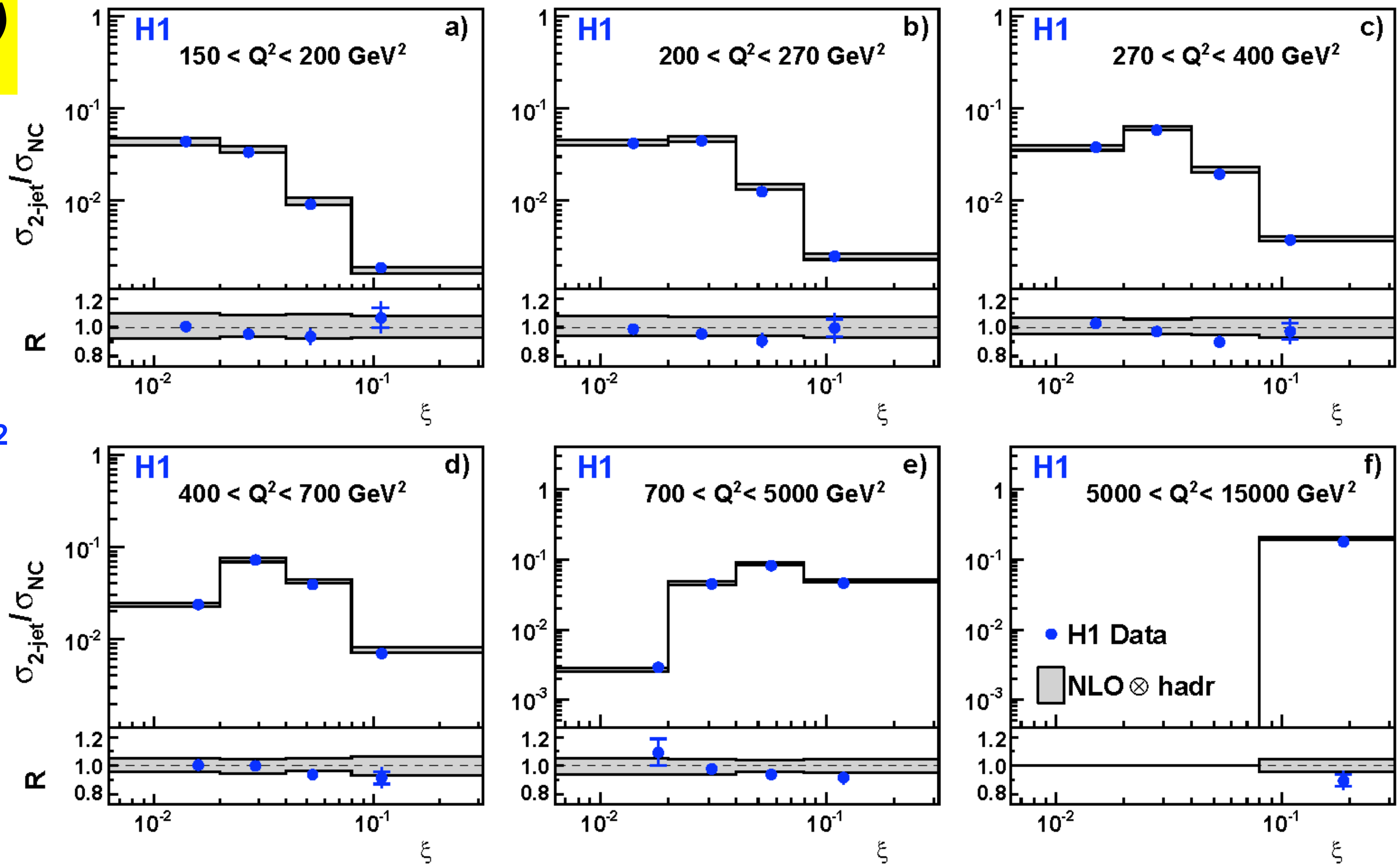
$$\frac{\sigma_{2\,Jet}}{\sigma_{NC}}(Q^2,\xi)$$

$$\xi = x_B\left(1+\frac{m_{12}^2}{Q^2}\right)$$

$m_{12} > 16\text{GeV}^2$

R=data/NLO

Normalised 2-Jet Cross Section



data well described by NLO pQCD within exp. uncertainties

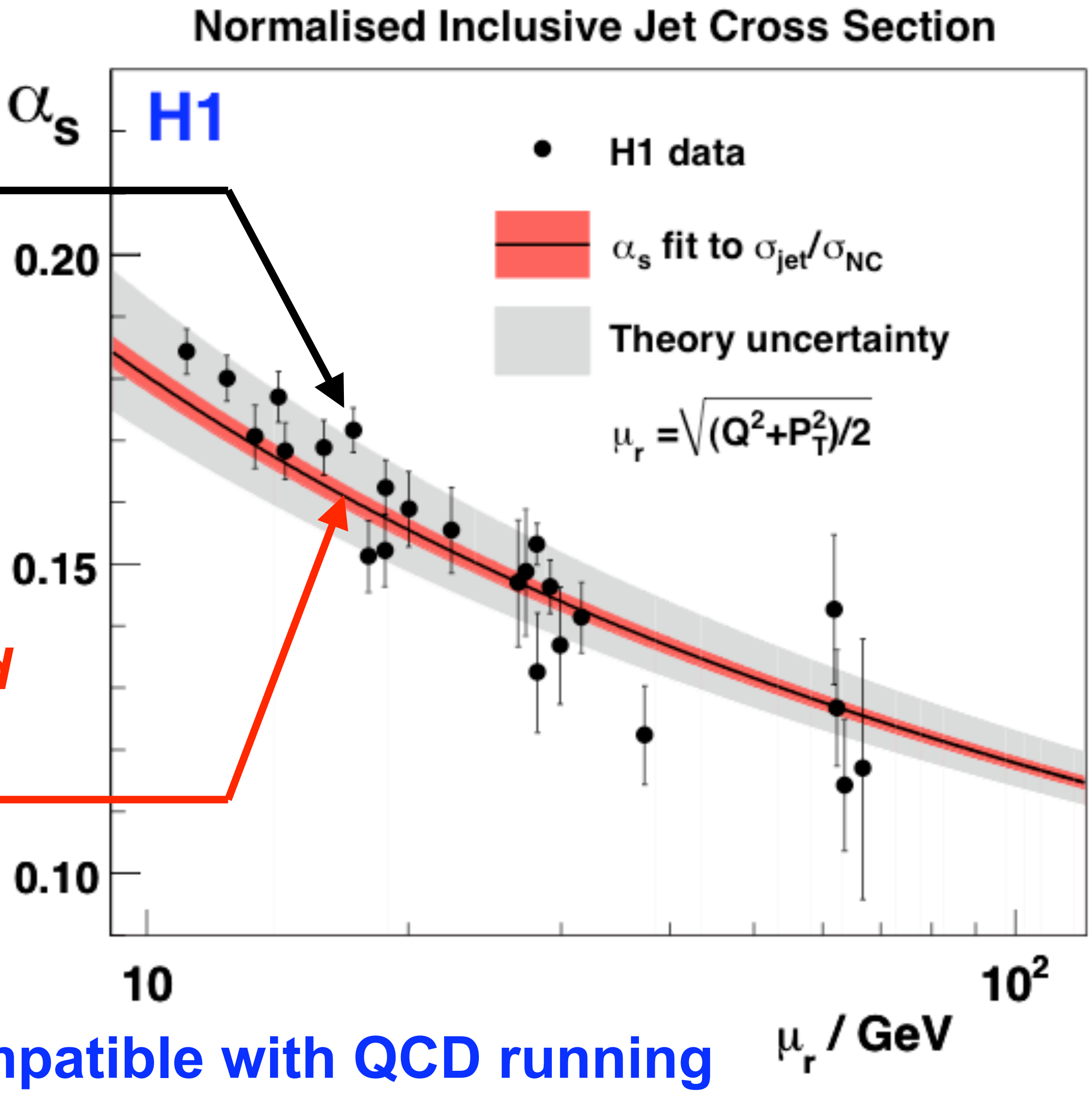
Determination of α_S from jet rates

- **consistency check: individual fits**
  - ➤adjust α_S in NLO QCD prediction to match each data point
  - ➤evolve α_S from scale μ_R associated to each point to a common scale M_Z
- **extraction of strong coupling: combined fits**
  - ➤ χ^2 fit of NLO QCD predictions to data with $\alpha_S(M_Z)$ as free parameter.
  - ➤correlated systematical errors (e.g. jet energy scale) taken into account by "Hessian procedure" (common shift of data point in the χ^2-fit, compatible with a priori error estimate). Statistical correlations are taken in account.
  - ➤ error on theory prediction taken in account by offset method:
    - scales, hadronization corrections and PDF parameterizations are varied and $\alpha_S(M_Z)$ refitted.
    - resulting variations are added in quadrature.

Check of α_S running (here: in inclusive jet rates)

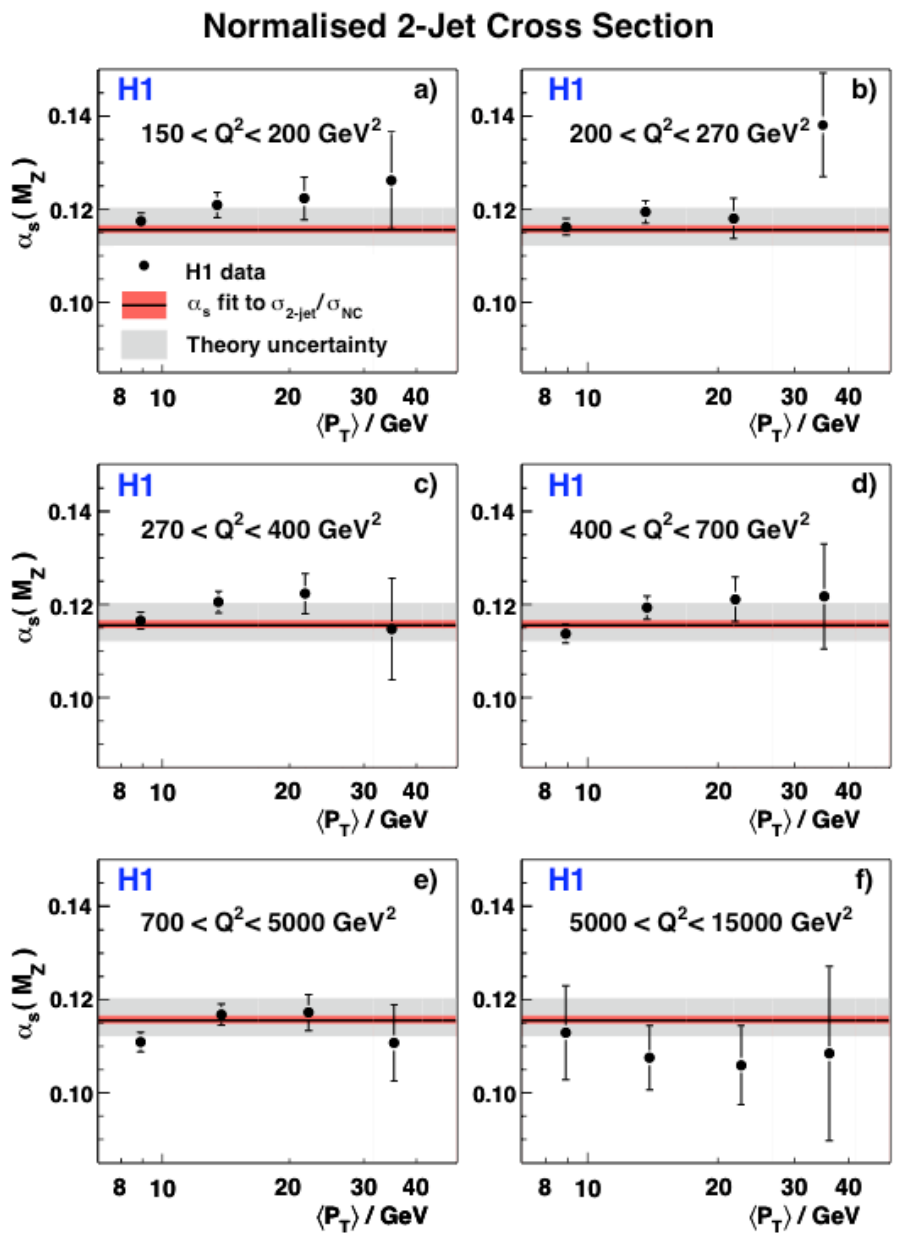
α_S fitted in each bin

$\alpha_S(M_Z) = 0.1168$ evolved to μ_R with 2-loop RGE



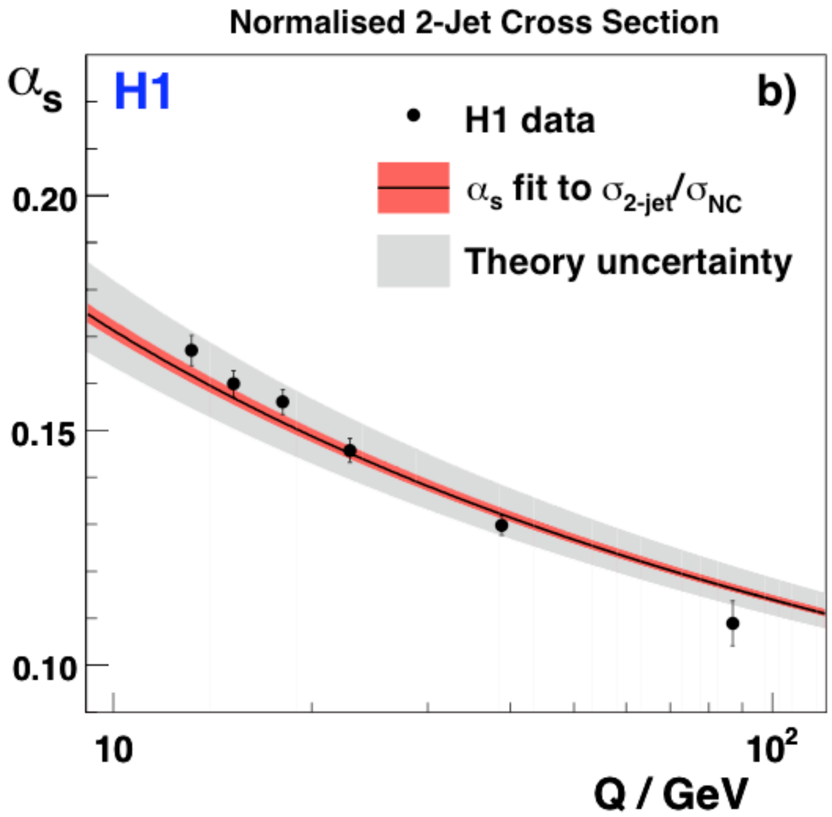
individually fitted α_S compatible with QCD running

Combined α_s fits for one observable (here: 2-jet rates)



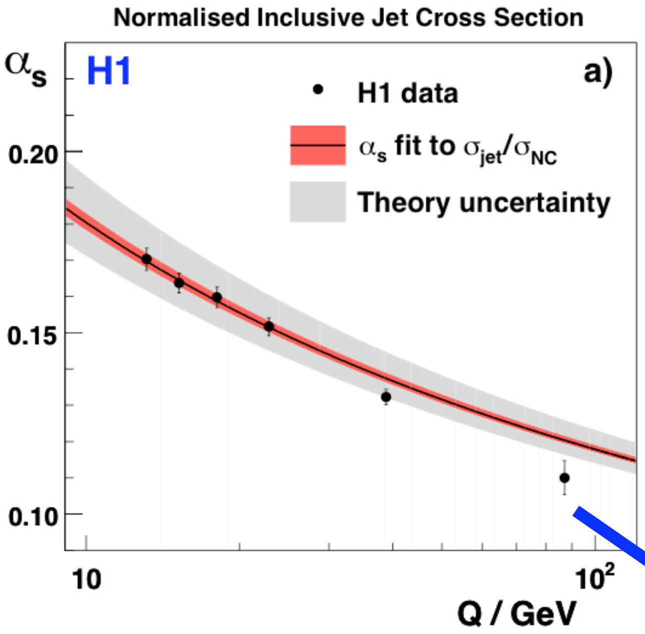
- **individual fit of $\alpha_S(M_Z)$ at each (Q^2, $\langle p_T \rangle$) point**
  → check running of $\alpha_S(\langle p_T \rangle)$ for "fixed " Q^2

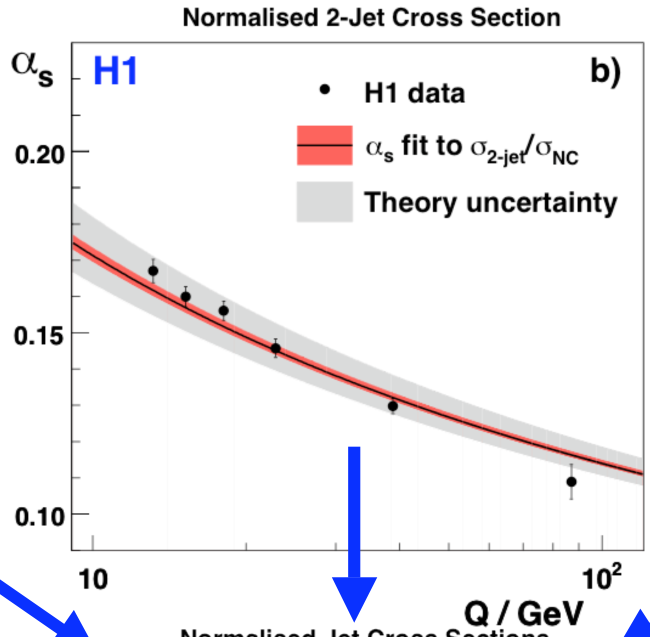
- **combined fit of $\alpha_S(M_Z)$ inside each Q^2 range**
  → test of $\alpha_S(Q)$ running for each observable

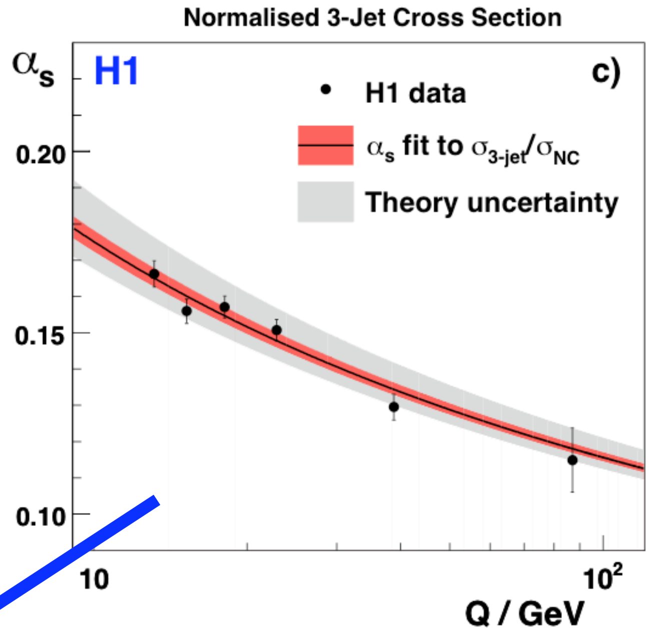


- **combined fit of $\alpha_S(M_Z)$ to all 24 points**
  → error correlation between bins from MC

α_s from multi-jet rates: combined fit to all observables

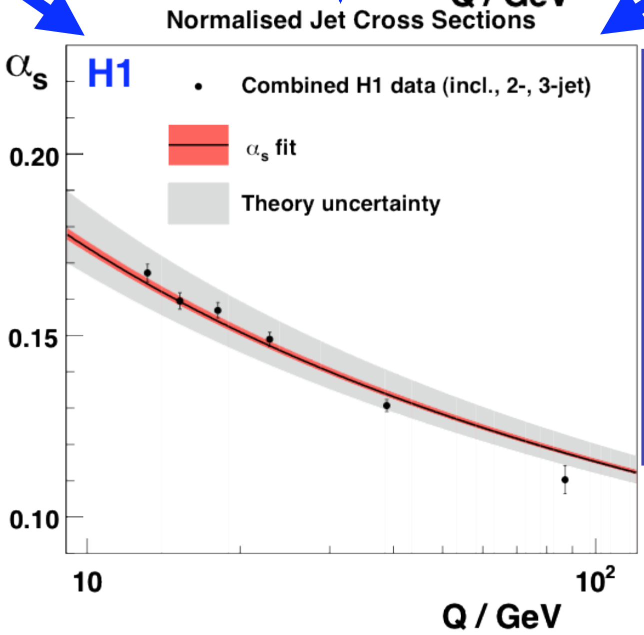






1 - individual fit for each point of each jet observable

2 - $\alpha_s(Q^2)$ running verified for each observable



3 - Combined fit to 54 (=24+24+6) data points

- **observable correlation taken into account**
- **χ^2/NDF = 65.0/53**

Synopsis of α_s extractions

Observable	α_s	exp. error	theory err.		χ^2/NDF
			Scales	PDF	
$\frac{\sigma_{Jet}}{\sigma_{NC}}(Q^2, p_T)$	0.1195	0.0010	+0.0049 - 0.0036	0.0018	24.7/23
$\frac{\sigma_{2Jet}}{\sigma_{NC}}(Q^2, \langle p_T \rangle)$	0.1155	0.0009	+0.0042 - 0.0031	0.0017	30.4/23
$\frac{\sigma_{3Jet}}{\sigma_{NC}}(Q^2)$	0.1172	0.0013	+0.0052 - 0.0031	0.0009	7.0/5
$\frac{\sigma_{Jet}}{\sigma_{NC}} \cup \frac{\sigma_{2Jet}}{\sigma_{NC}} \cup \frac{\sigma_{3Jet}}{\sigma_{NC}}$	0.1168	0.0007	+0.0046 - 0.0030	0.0016	65.0/53
low Q^2 (incl. jets)* $\sigma_{Jet}(Q^2, p_T)$	0.1186	0.0014	+0.0132 - 0.0101	0.0021	20.5/27

* H1-Prelim. 08-032

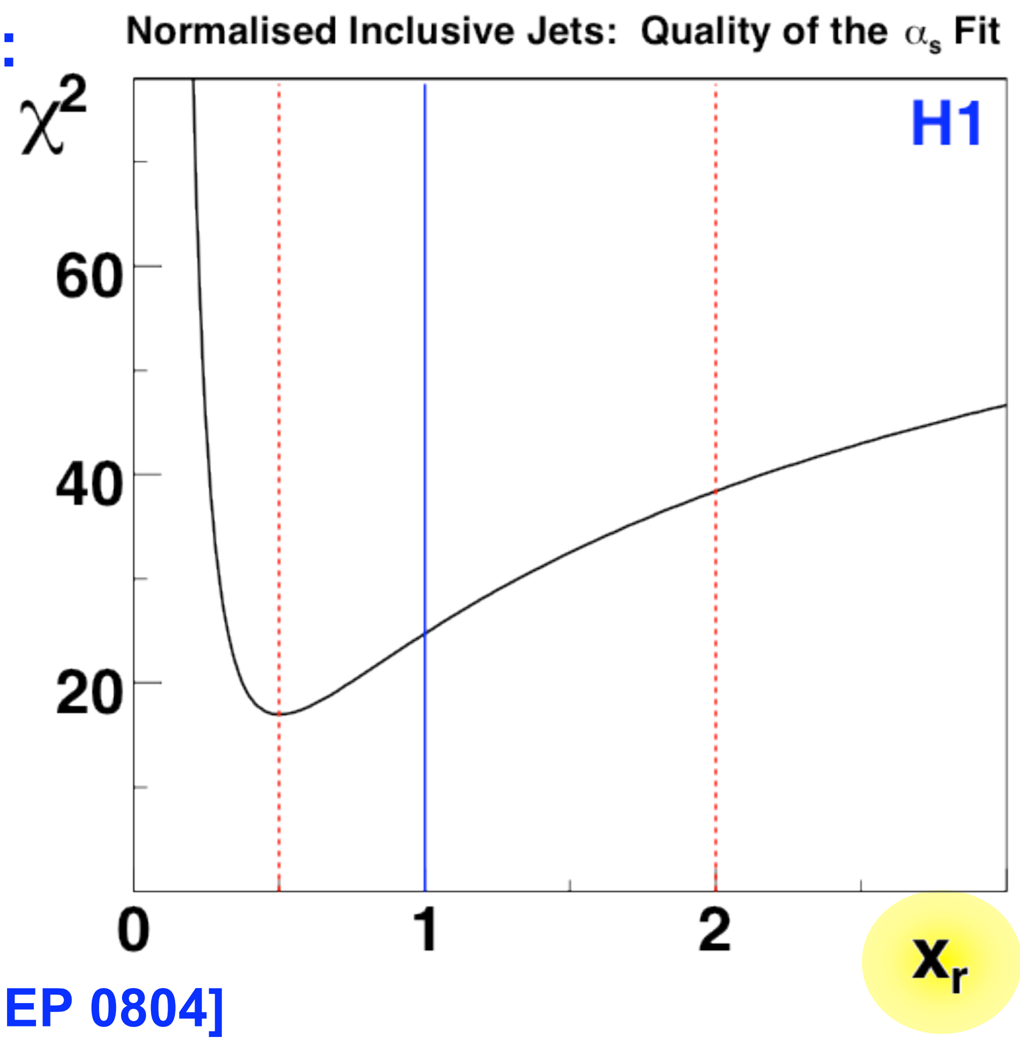
Robustness of combined fit result

- **choice of renormalization scale:**
  (normalized inclusive jets)
  - **nominal scale :**

    $$\mu_R = \sqrt{(Q^2 + p_T^2)/2}$$

  - $\mu_R = p_T$ $\Rightarrow \alpha_S \downarrow$ **0.7%**
  - $\mu_R = Q$ $\Rightarrow \alpha_S \uparrow$ **1.5%**
  - **similar for 2- and 3-jet rates**
- **fit quality v/s renorm. scale**
  - **variation of nominal scale:**

    $$\mu_R = x_r \sqrt{(Q^2 + p_T^2)/2}$$



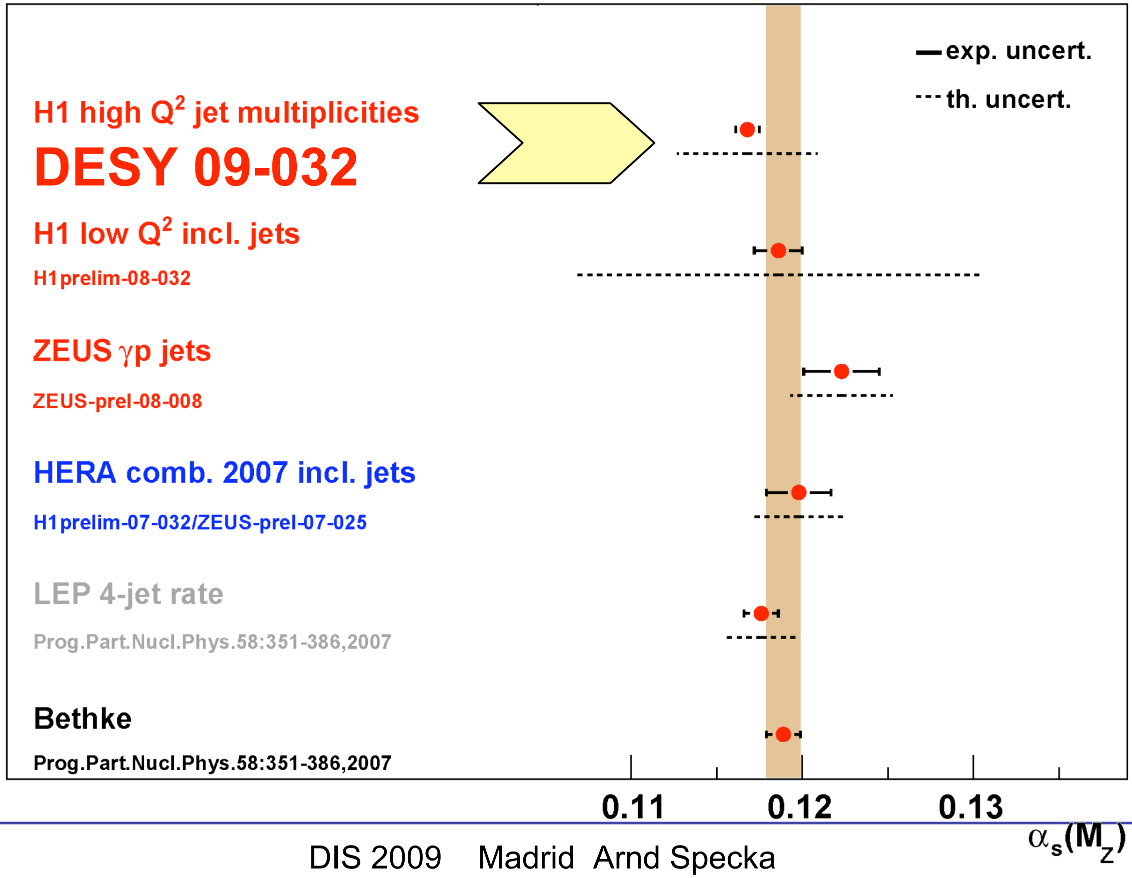
- **jet algorithm**
  (normalized inclusive jets and 2-jet rate))
  cross-check with anti-k_T algorithm [JHEP 0804]

$$d_{i,j}^2 = \min\left(\frac{1}{p_{T,i}^2}, \frac{1}{p_{T,j}^2}\right) \cdot \left[\Delta\eta^2 + \Delta\varphi^2\right]$$

$\Rightarrow \alpha_S$ **changes by less than 0.6%**

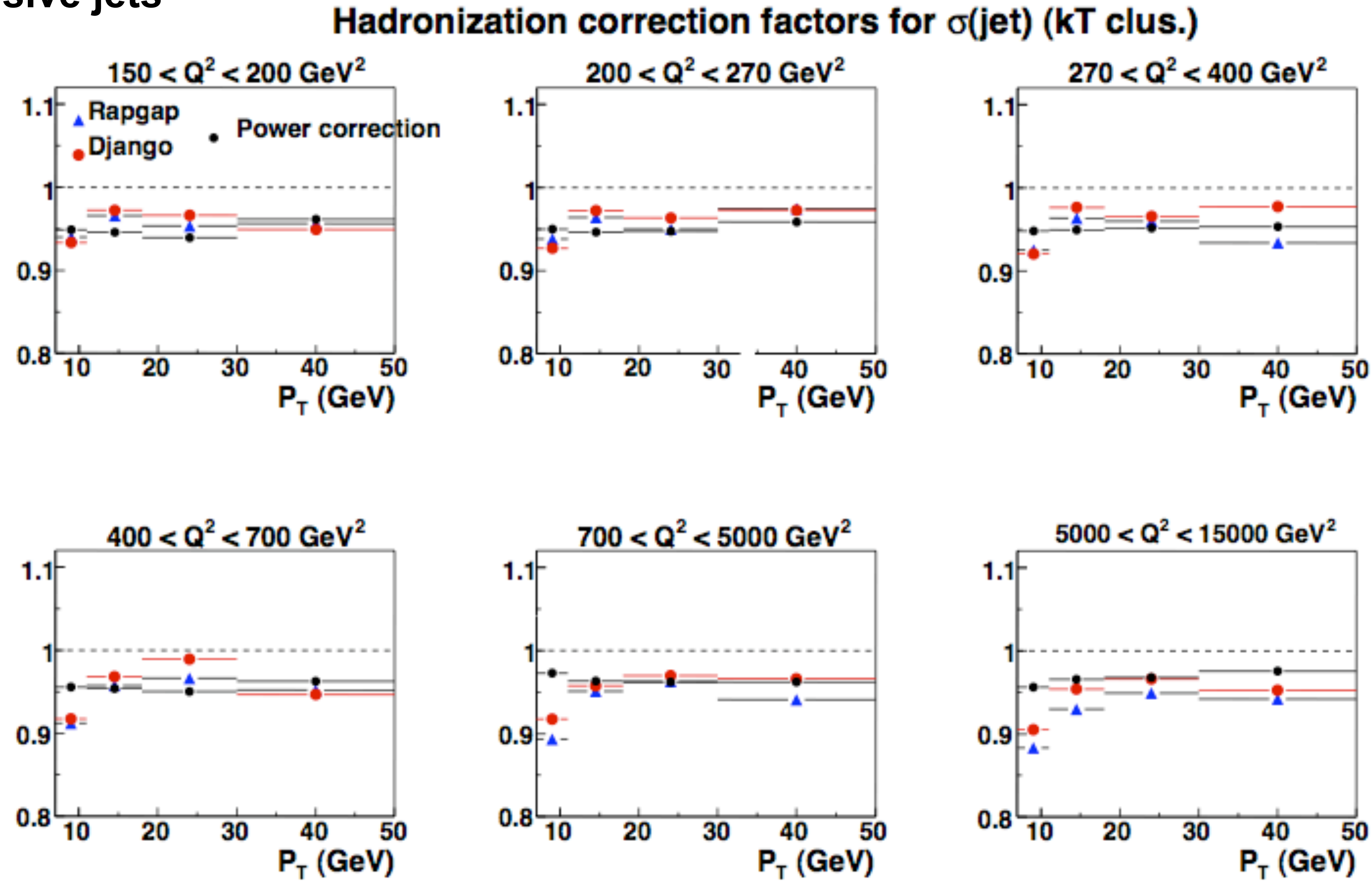
Summary

- multi-jet production in DIS measured with unequalled experimental accuracy
- Inclusive, 2-jet and 3-jet rates well described by NLO QCD
- theory error much higher than experimental uncertainties
  NNLO calculation necessary to take full advantage of data
- α_S from combined fit: $\alpha_S(M_Z) = 0.1168 \pm 0.0007\ (exp)\ ^{+0.0046}_{-0.0030}\ (th) \pm 0.0016\ (PDF)$



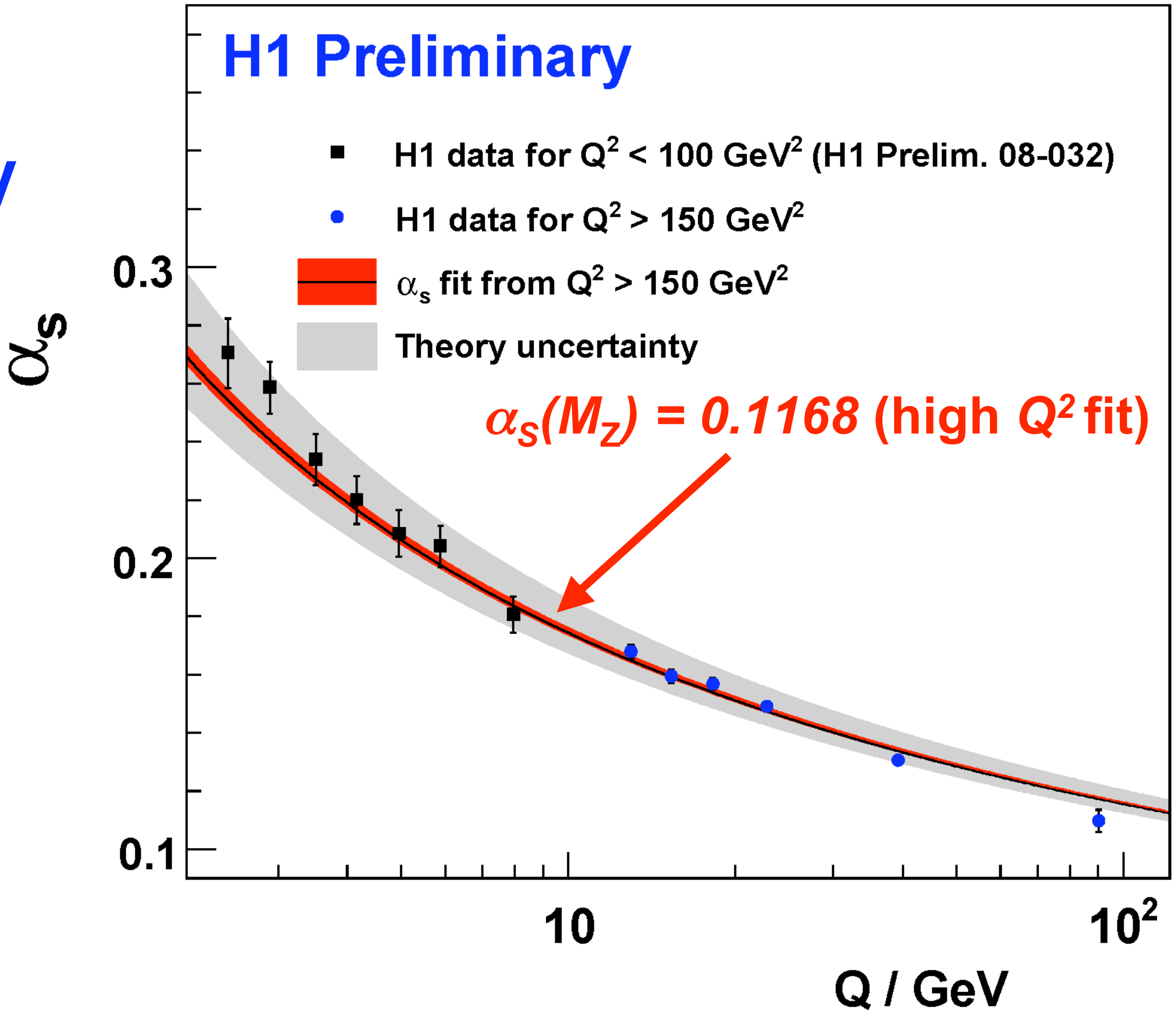
Hadronization corrections to NLO prediction

inclusive jets



Comparison to low Q2 inclusive jets (HERA-I)

- HERA-1 data: 43.5 pb $^{-1}$
- inclusive jets $p_T > 5$ GeV
- absolute cross-section (not normalized by σ_{NC})
- individual fits of $\alpha_S(M_Z)$ in good agreement with $\alpha_S(M_Z)$ from high Q^2 fit
- result of fit to low Q^2 inclusive jets alone:



$$\alpha_S(M_Z) = 0.1186 \pm 0.0014\ (\text{exp})\ ^{+0.0132}_{-0.0101}\ (\text{th}) \pm 0.0021\ (\text{PDF})$$