k_T, anti-k_T & SIScone jets and α_s @ HERA

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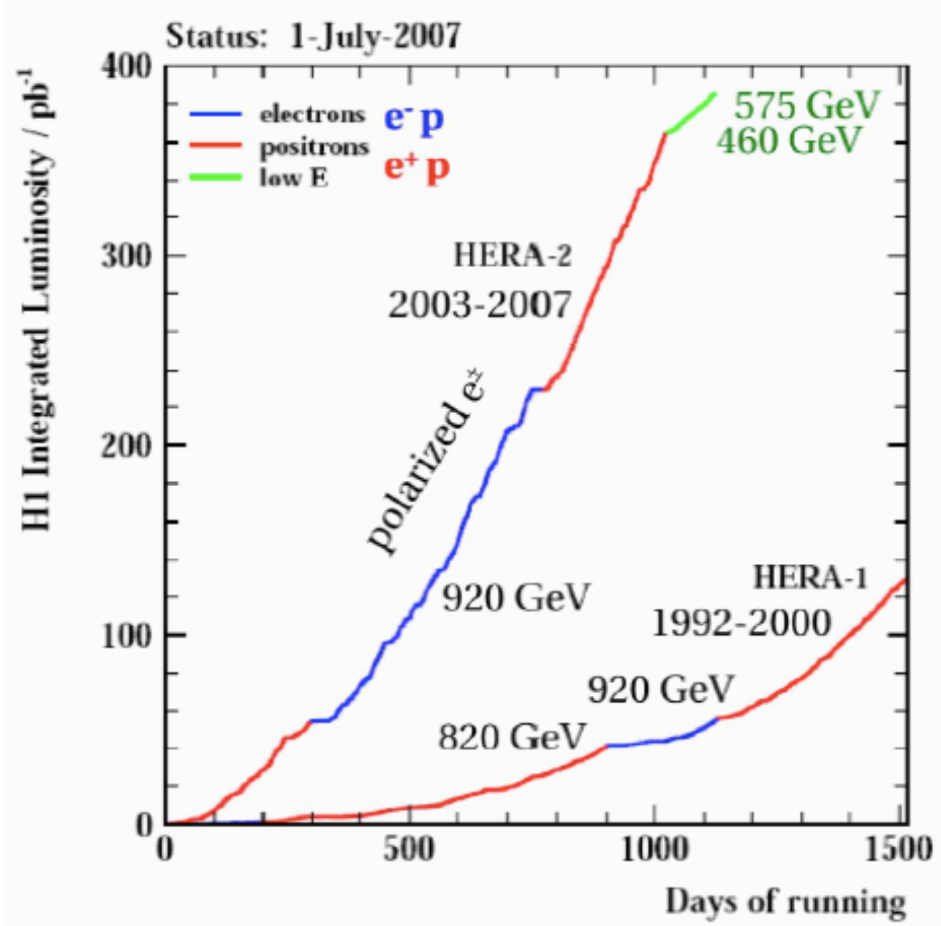
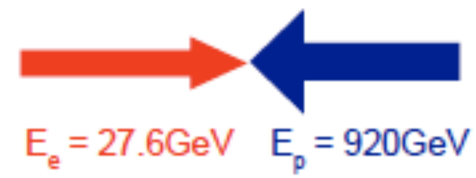
on behalf of the H1 and ZEUS collaborations

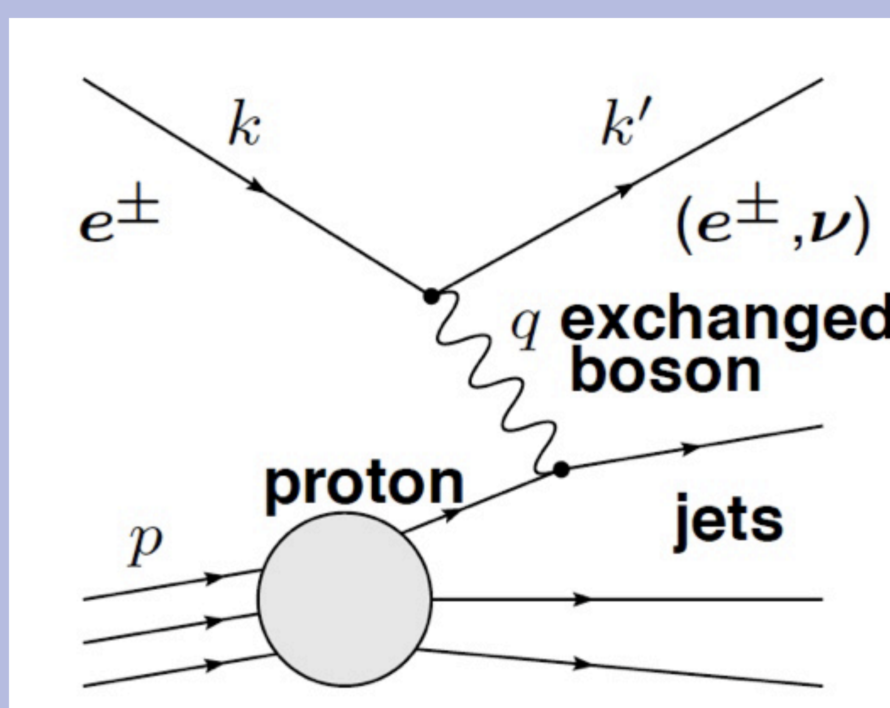
- introduction
- measurements of k_T multijets at low Q^2
- measurement of inclusive k_T, anti-k_T and SIScone jets at high Q^2
- comparison of data to NLO
- running α_s and $\alpha_s(M_Z)$ from jets

HERA: ep collider, basic kinematics



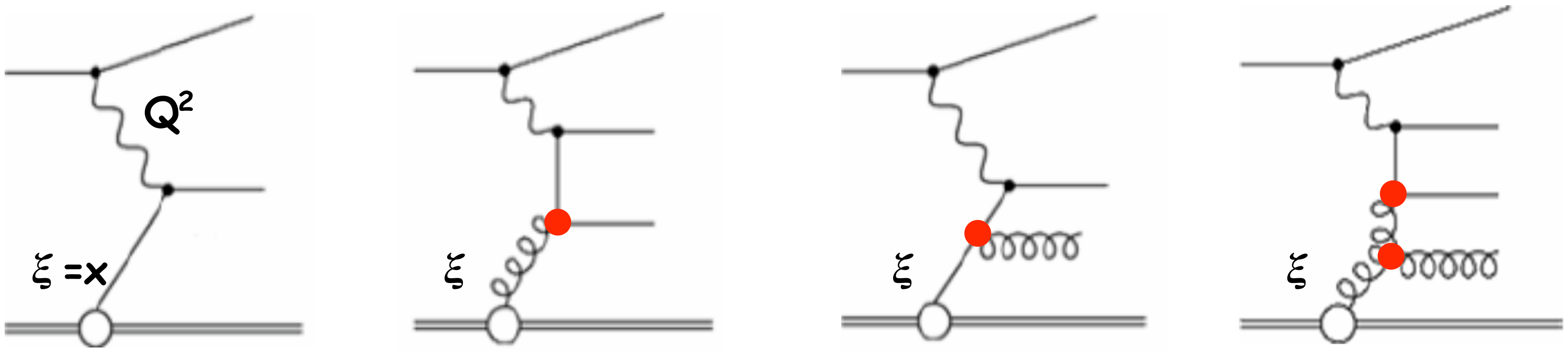
- 1992 - 2007
- 

  $\sqrt{s}$ = 318 GeV
- 2001/2002 luminosity upgrade → HERA-2
- ~ 0.5 fb^{-1} of data collected per experiment



- virtuality of the exchanged boson: $Q^2 = -q^2 = -(k-k')^2 = sxy$
- Bjorken scaling variable: $x = Q^2/2p \cdot q$
- inelasticity: $y = p \cdot q / p \cdot k$

Jet production in DIS @ HERA



$\propto \alpha_s^1$ $\propto \alpha_s^1$ $\propto \alpha_s^2$ . . .

$$d\sigma_{\rm njet} = \sum_{i=q,\bar{q},g} \int dx\, f_i(x,\mu_f)\, d\hat{\sigma}_i(x,\alpha_s^{n-1}(\mu_r),\mu_r,\mu_f) \;\; (1+\delta_{\rm had})$$

$-\ f_i$: pdf of parton i in proton

$-\ \hat{\sigma}_i$: matrix element i, calculable in pQCD

2 large scales in DIS: Q (2-125 GeV) & P_T^{jet} (5-80 GeV)

typical choices for pQCD calculations are:

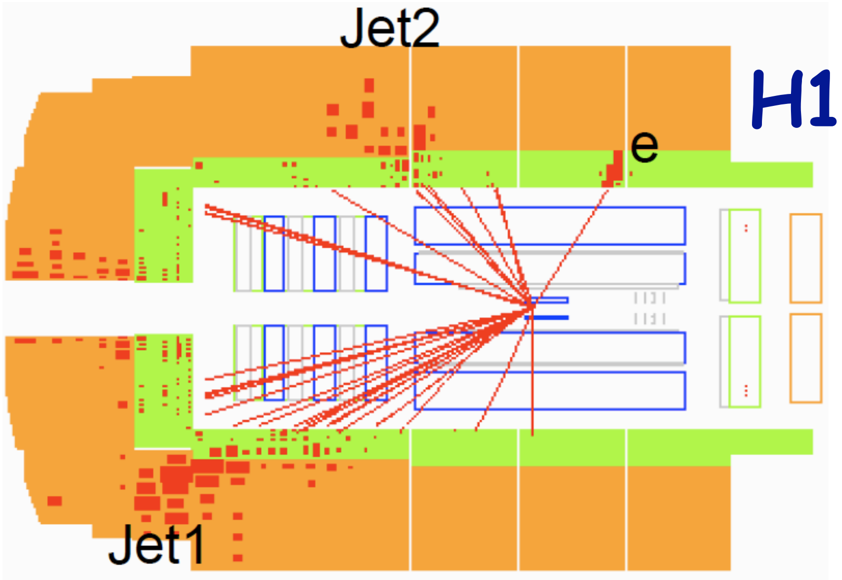
μ_f = Q

μ_r = Q or P_T^{jet} (ZEUS)

μ_r = $\sqrt{[(Q^2 + (P_T^{jet})^2)/2]}$ (H1)

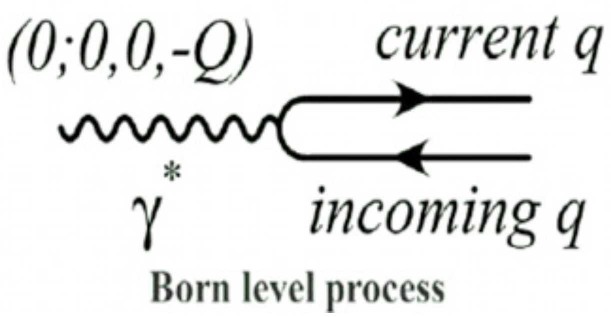
Jet production in DIS @ HERA

tracks and calorimetric energy deposits are measured in the laboratory

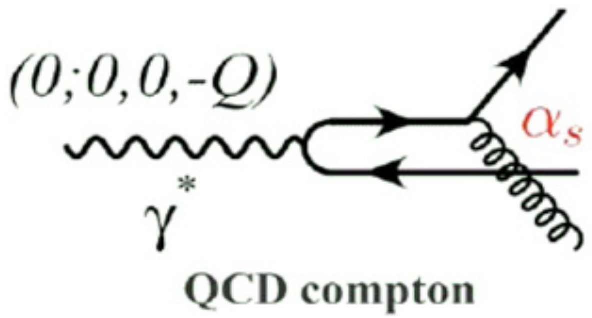


Jet finding is usually performed in the Breit frame (in analogy to e+e-)

QPM process generates no p_T



only QCD processes generate p_T



Jet finding: k_T, anti-k_T & SIScone

Requirements for comparing jet cross sections with pQCD:

- factorization $\Longrightarrow$ in DIS perform measurement in Breit frame
- collinear & infrared safe jet algorithm $\Longrightarrow$ k_T, anti-k_T & SIScone

G.Salam & G.Soyez

S.Catani, S.Ellis & D.Soper

M.Cacciari, G.Salam & G.Soyez)

Sequential recombination algorithms:

$$\mathrm{d}_{ij} = \min(k_{\mathrm{T}i}, k_{\mathrm{T}j})^{2p}\, \Delta R^2/R^2 \text{ and } \mathrm{d}_{iB} = k_{\mathrm{T}i}^{2p}$$

$$\text{with } \Delta R^2 = (\eta_i - \eta_j)^2 + (\phi_i - \phi_j)^2$$

p = 1 → k_T

p = -1 → anti-k_T

at HERA typically R=1.0

SIScone:

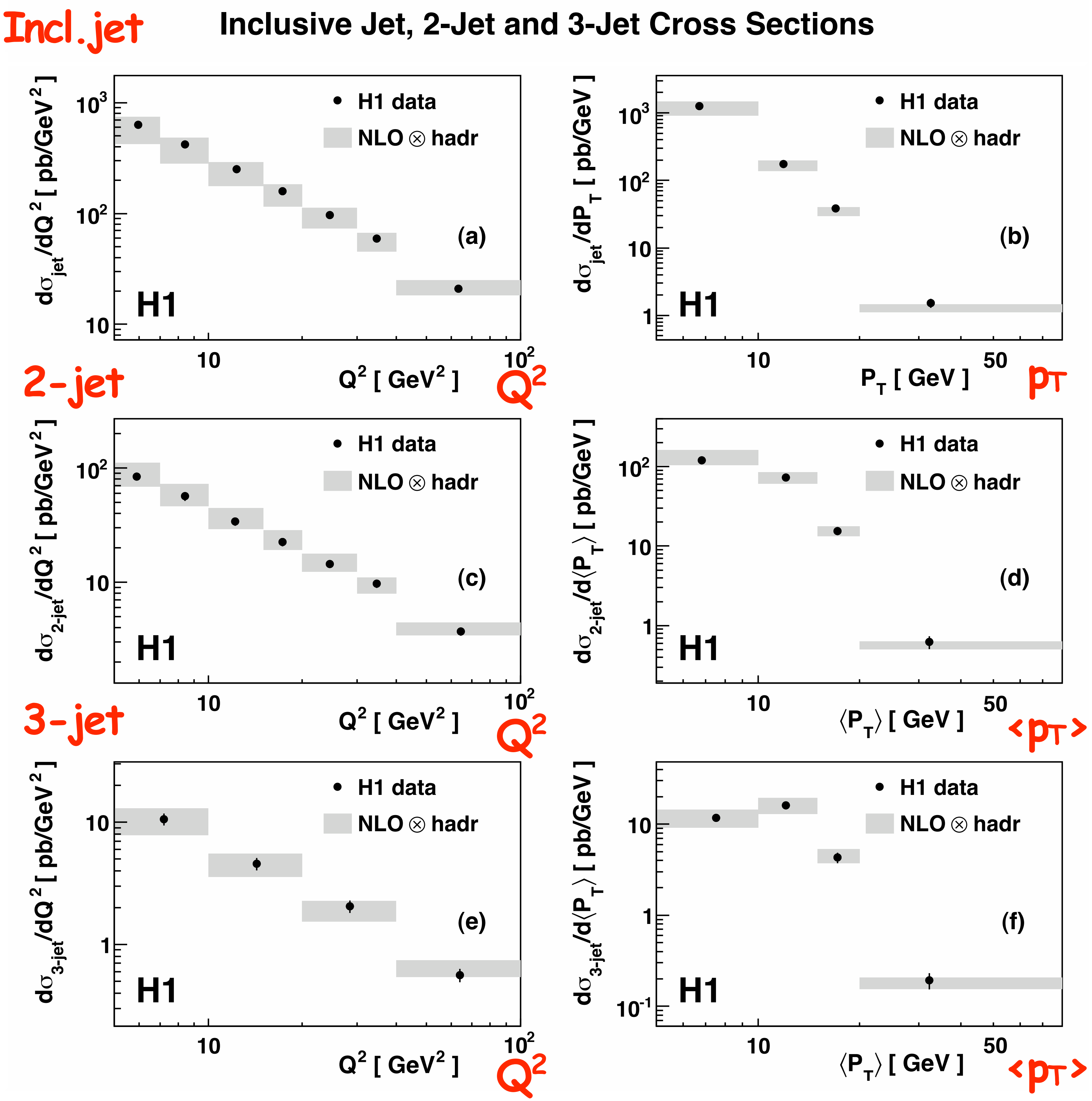
seedless iterative cone with split merge (0.75)

finds stable cones, i.e. cone axis = momentum sum of particles

H1: Multijet cross sections at low Q^2

- arXiv:0911.5678, HERA-1 data, 44 pb^{-1}
- DIS phase space: $5 < Q^2 < 100$ GeV^2, $0.2 < y < 0.7$
- jet phase space: $-1.0 < \eta_{jet,lab} < 2.5$
  - incl. jets, 2-jet, 3-jet: $p_T > 5$ GeV (Breit)
  - 2-jet & 3-jet: $M_{1,2} > 18$ GeV
- cross sections are measured as function of Q^2, p_T ($\langle p_T \rangle$) and ξ
- main experimental uncertainties:
  - jet energy scale 2% $\Longrightarrow \Delta\sigma/\sigma$ = 4-10%
  - uncertainty in acceptance $\Longrightarrow \Delta\sigma/\sigma$ = 2-15%
- NLO calculation: NLOJET++
  - MSbar scheme for 5 massless quark flavors,
  - $\mu_{\rm f} = \mu_{\rm r} = \sqrt{(Q^2 + p^2_{\rm T,jet})/2}$
  - PDFs: CTEQ6.5M

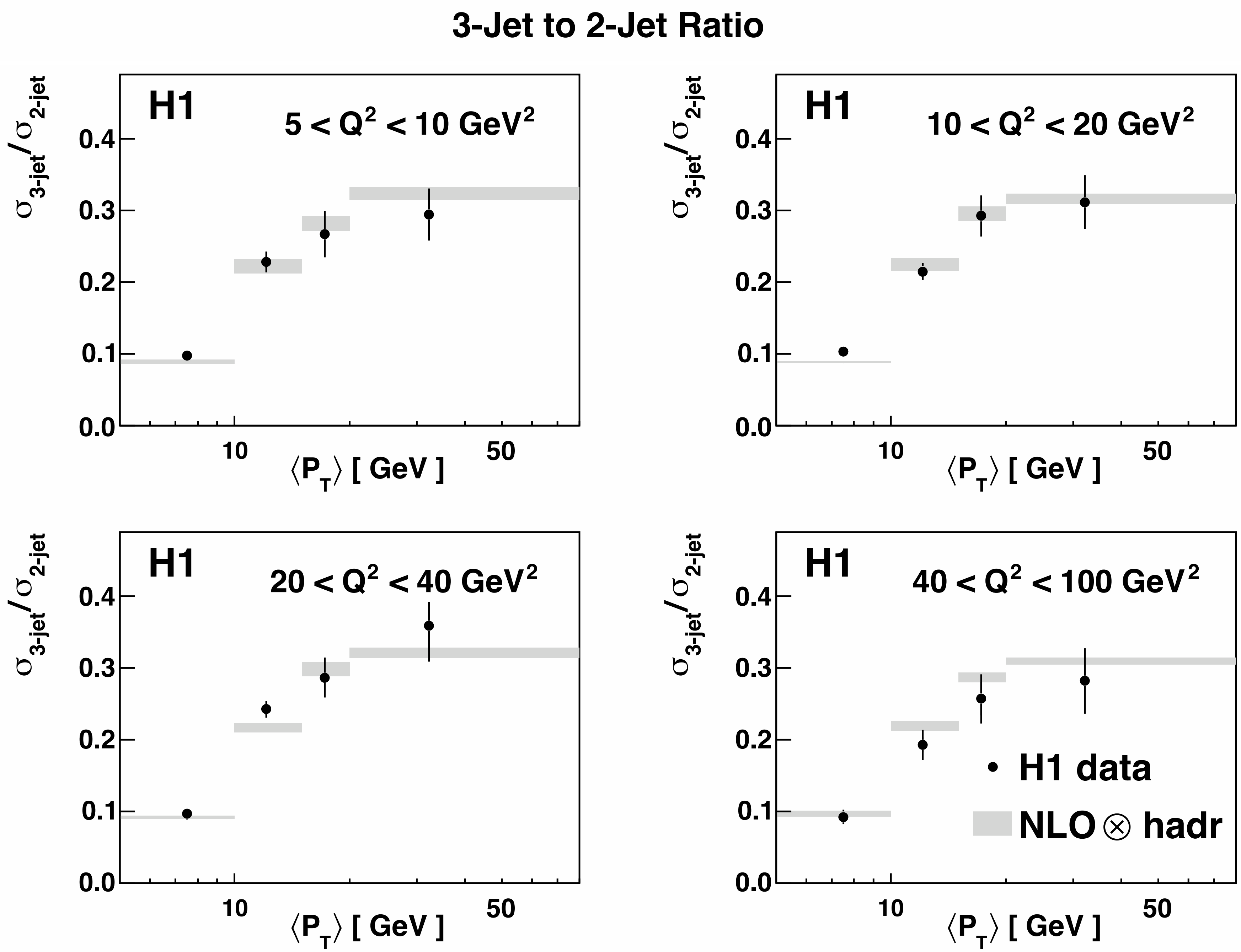
H1: Multijet cross sections at low Q^2



- measurements are well described by NLO
- exp. uncertainty 6-11%
- theo. uncert., dominated by renorm. scale uncertainty: 30% (lowest Q^2 and p_T) to 10% (highest Q^2 and p_T)
- pdf uncertainty: 6 to 2%

- low predictive power of NLO at low Q^2 and/or low p_T $\Longrightarrow$ orders beyond NLO are needed to match the precision of the data

H1: 3-jet/2-jet ratio in Q^2, $\langle p_T \rangle$



- in ratio norm. errors cancel & other syst. uncertainties reduced by 50%
- reduced sensitivity to renorm. scale variation in theory
- good description of ratio by NLOjet++

analysis on 9 x stats of HERA-2 in progress

H1: α_S from low & high Q^2 jets

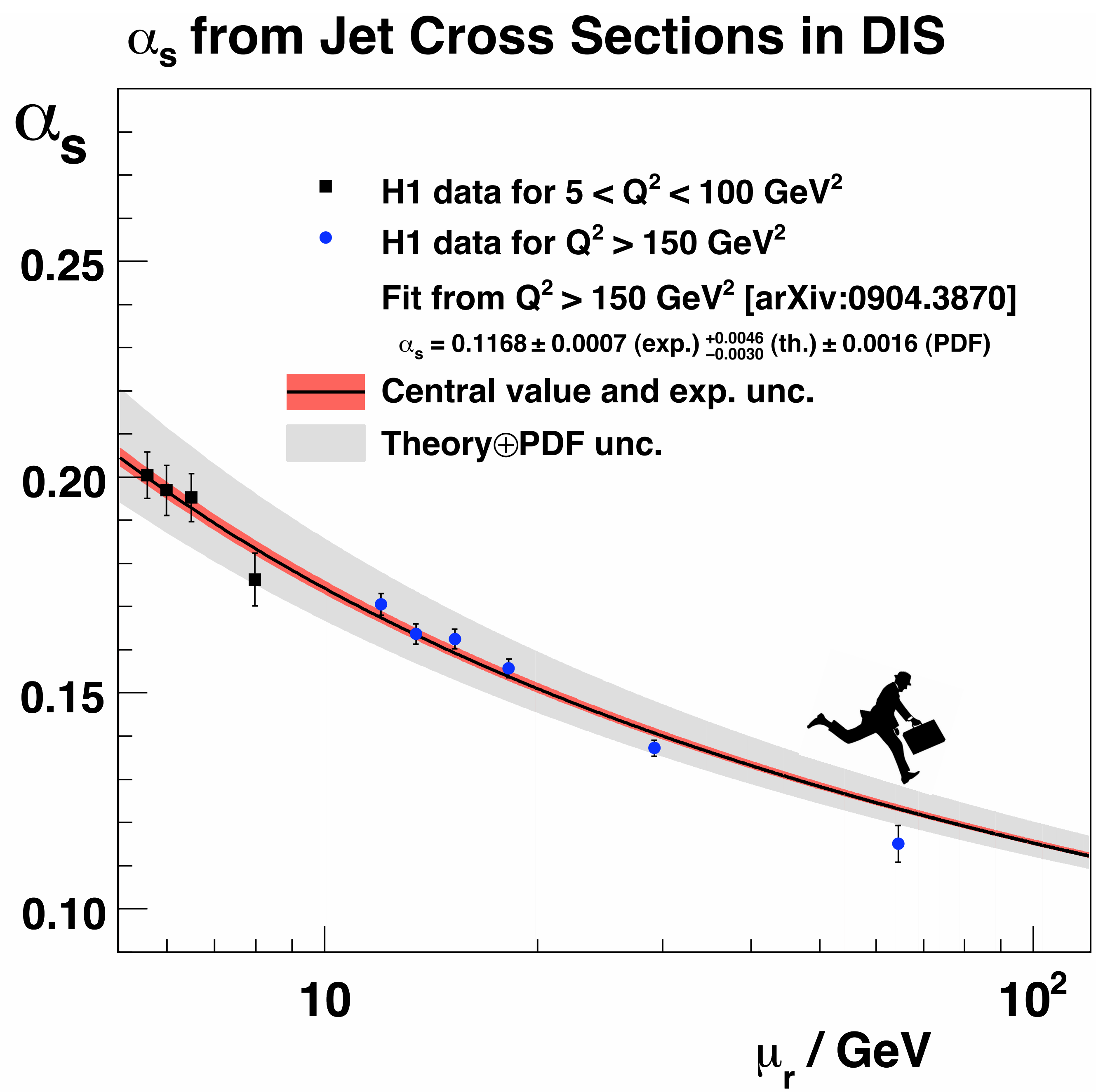
- at low Q^2, extraction of $\alpha_S(M_Z)$ from double diff. incl. jet, 2 and 3-jet cross sections using the k_T jet finder: $\alpha_s(M_Z) = 0.1160 \pm 0.0014\,(\text{exp.})\,^{+0.0093}_{-0.0077}\,(\text{th.}) \pm 0.0016(\text{pdfs})$

- at high Q^2, extraction of $\alpha_S(M_Z)$ from double diff. normalized incl. jet, 2 and 3-jet cross sections using the k_T jet finder:

$$\alpha_s(M_Z) = 0.1168 \pm 0.0007\,(\text{exp.})$$

$$^{+0.0046}_{-0.0030}\,(\text{th.}) \pm 0.0016\,(\text{pdfs})$$

central value of $\alpha_S(M_Z)$ using anti-k_T is within 0.6%



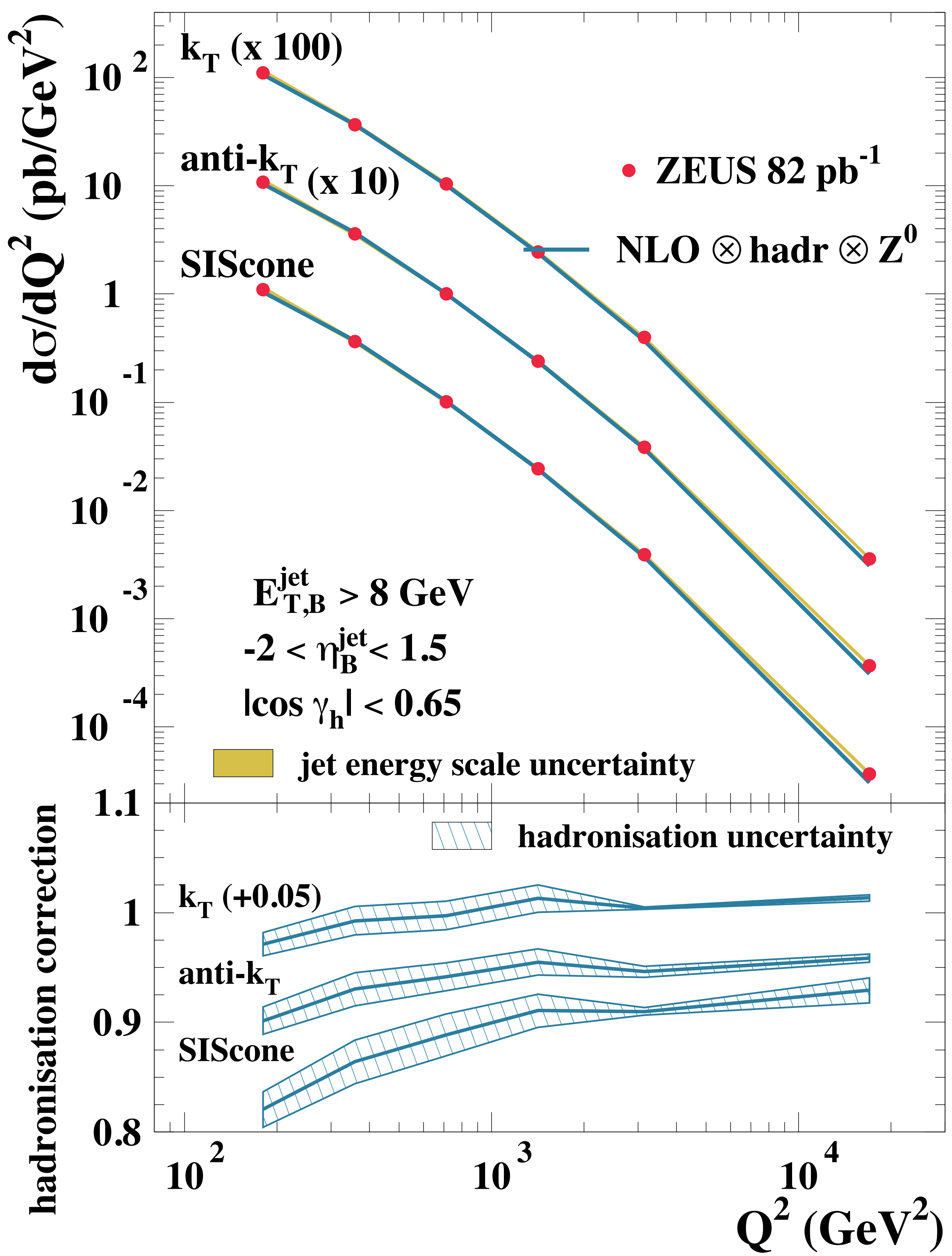
remarkable agreement between low and high Q^2 extraction & with QCD expectations

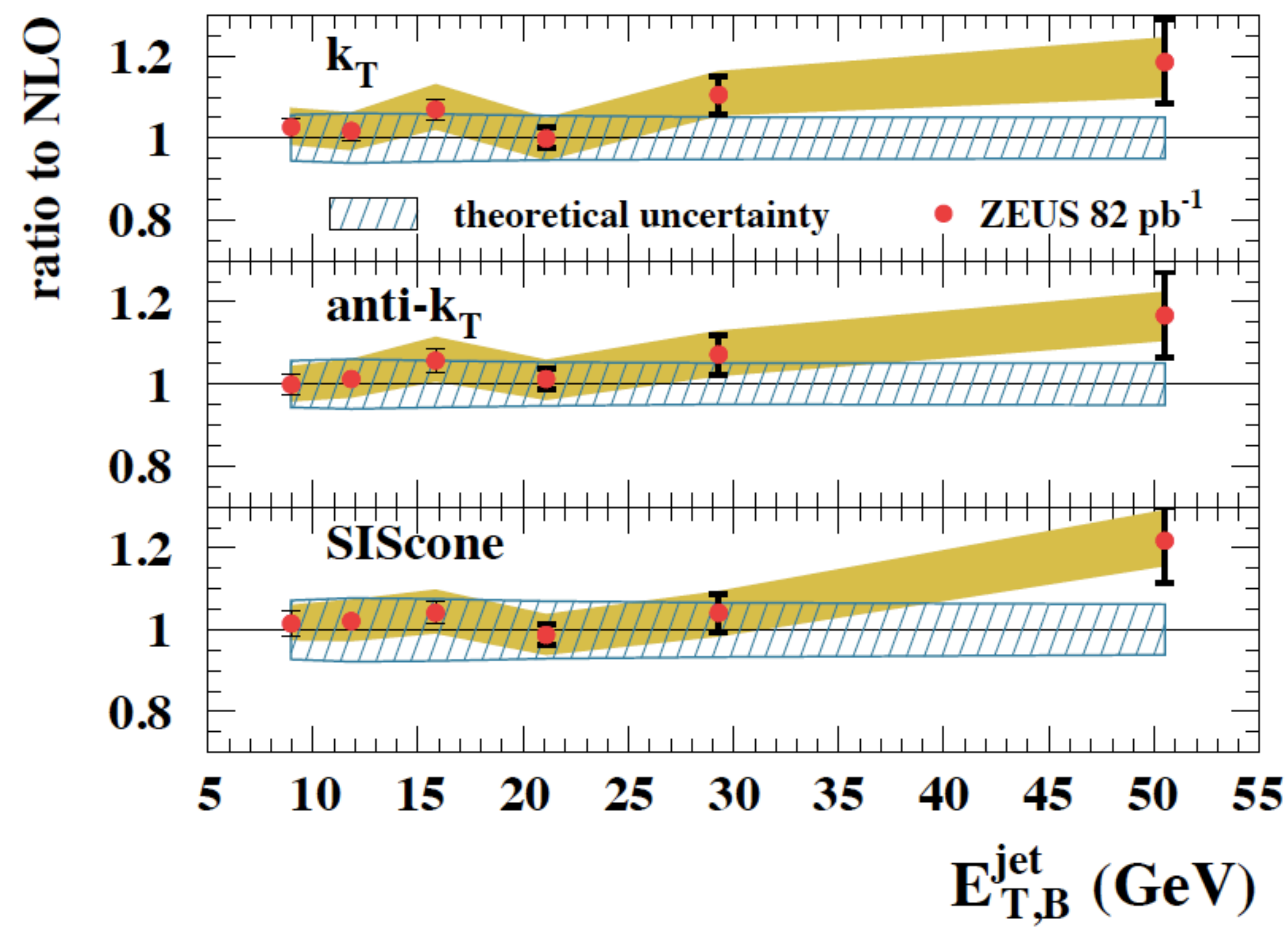
for high Q2 results see Moriond 2009 and Eur.Phys.J. C 65 (2010) 363

ZEUS: Incl. k_T, anti-k_T, SIScone jets

- HERA-1 data, 82 pb^{-1}, DESY-10-034, arXiv:1003.2923
- DIS phase space: $Q^2 > 125$ GeV^2, $|\cos\gamma_h| < 0.65$
- jets are found in the Breit frame using anti-k_T and SIScone
- jet phase space: at least one jet with $-2 < \eta < 1.5$, $E_T > 8$ GeV in Breit frame
- incl. jet cross sections are measured as a function of Q^2 and E_T
- results using k_T from same data, published in Phys.Lett. B 649 (2007) 12
- main experimental uncertainties:
  - jet energy scale 1% ($E_{T,lab} > 10$ GeV) to 3% for lower $E_{T,lab} \Longrightarrow \Delta\sigma/\sigma \approx 5\%$
  - uncertainty in acceptance $\Longrightarrow \Delta\sigma/\sigma \approx 4\%$
- NLO calculations: DISENT & NLOjet++
  - MSbar scheme for 5 massless quark flavors
  - $\mu_f = Q$ and $\mu_r = E_T$
  - PDFs: ZEUS-S parametrization

ZEUS: Incl. k_T, anti-k_T, SIScone jets

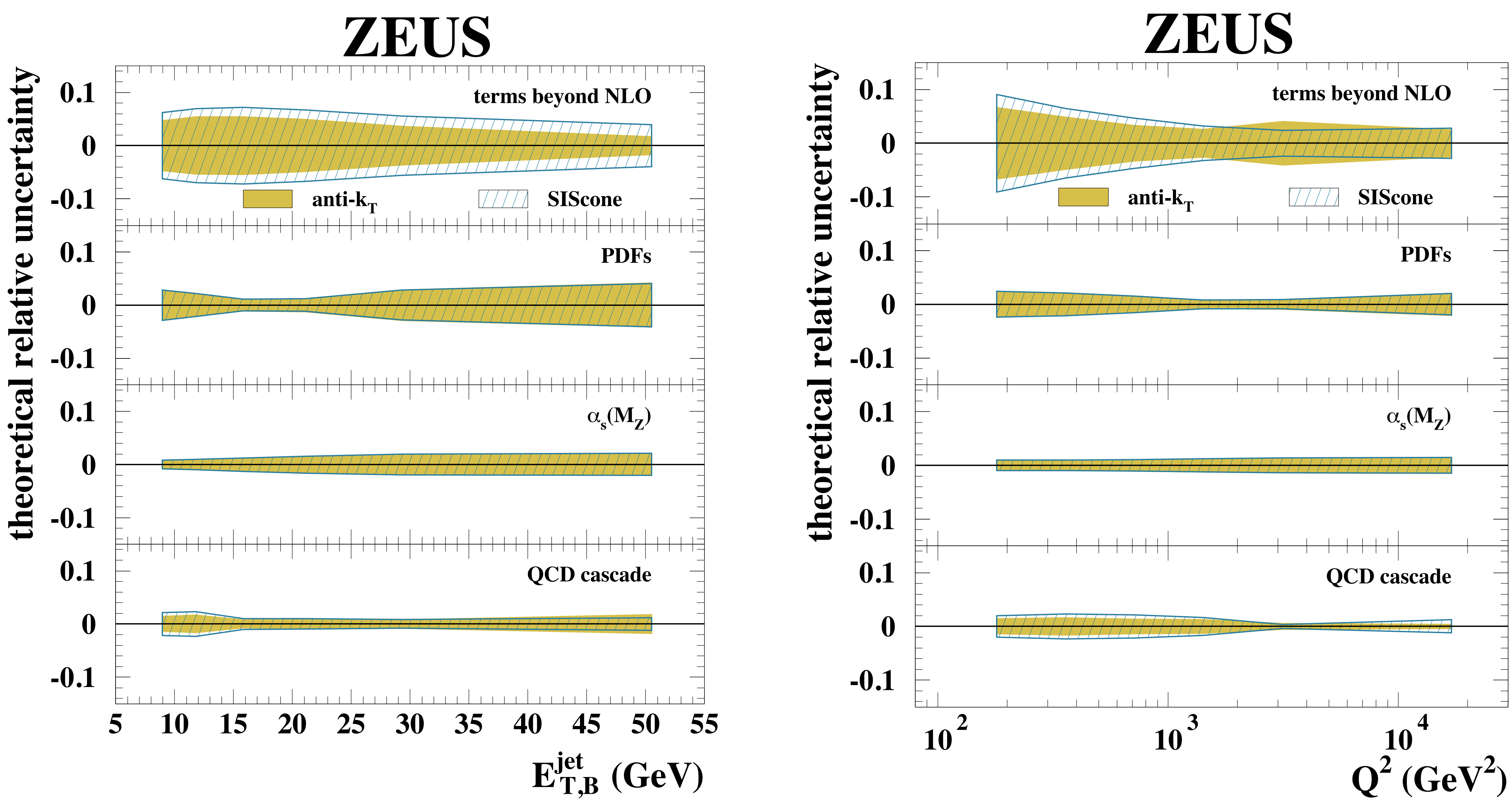




- data and NLO are in good agreement
- hadronization corrections are smallest for k_T and largest for SIScone

ZEUS: Incl. k_T, anti-k_T, SIScone jets

- theoretical relative uncertainties



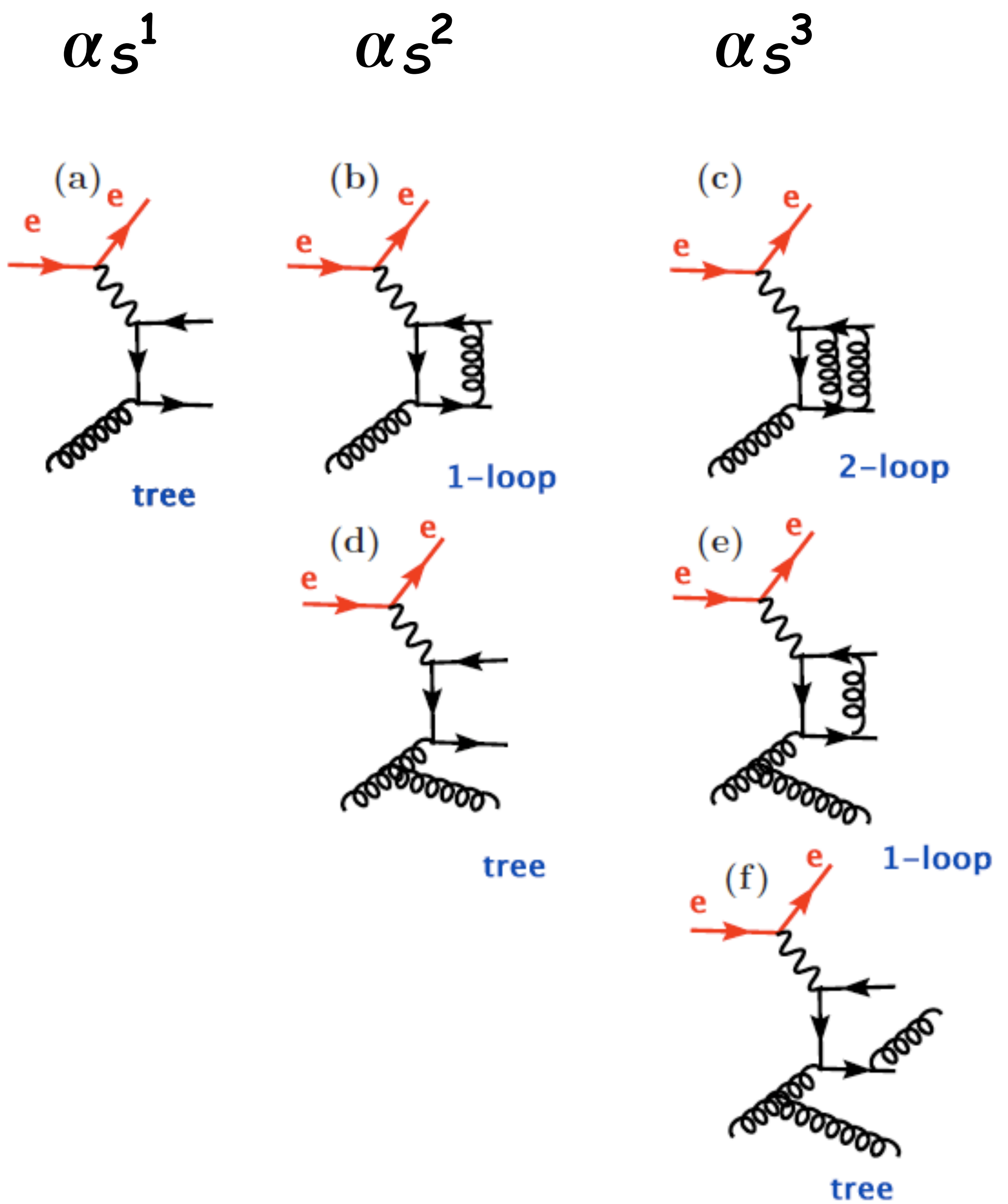
- theory uncert. as a funct. of Q^2 varies from 3-7% (3-10%) for the anti-k_T (SIScone)
- NLO using k_T and anti-k_T have similar precision, with SIScone slightly less precise

ZEUS: xsect ratios of data & of NLO

Ratio of incl. jet cross sections based on different jet algorithms:

- incl. jet cross sections currently calculated up to O(α_s^2)
- differences of incl. jet cross sections using different jet algorithms can however be predicted up to O(α_s^3) using NLOjet++

Examples of diagrams contributing to incl. jets in Breit frame

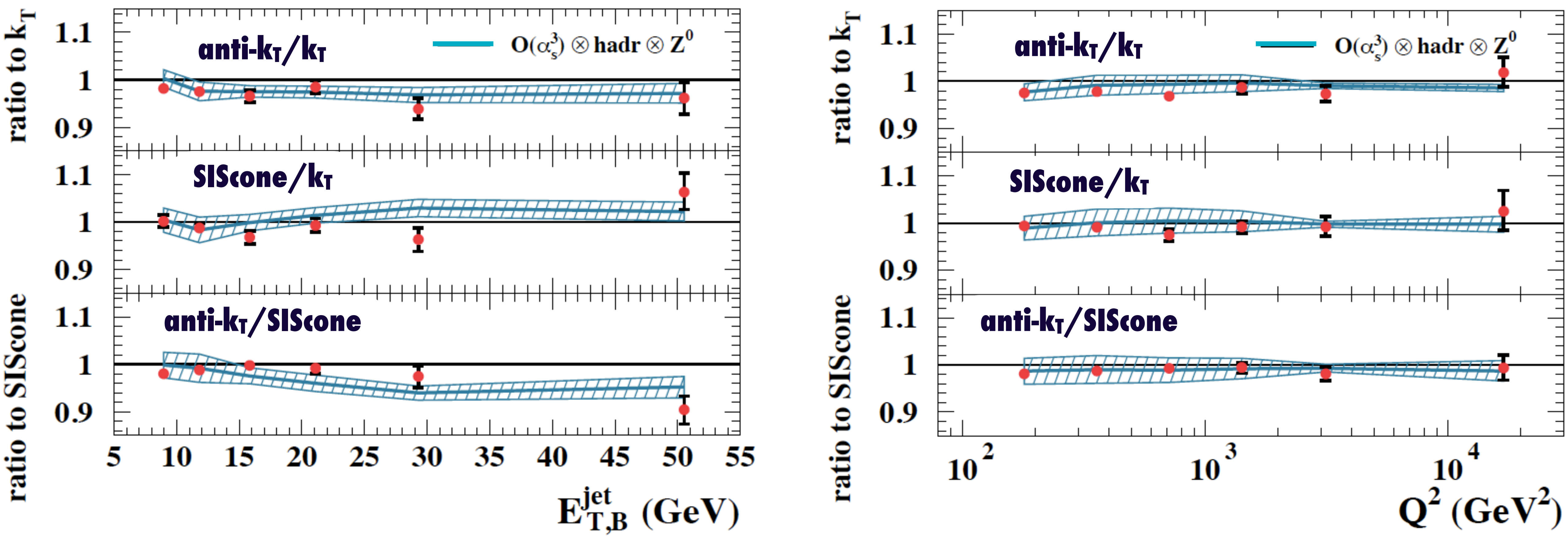


$$\frac{d\sigma_{\mathrm{anti-k_T}}/dX}{d\sigma_{\mathrm{k_T}}/dX} = 1 + \frac{d\sigma_{\mathrm{anti-k_T}}/dX - d\sigma_{\mathrm{k_T}}/dX}{d\sigma_{\mathrm{k_T}}/dX} \simeq 1 + \frac{C\alpha_s^3}{A\alpha_s + B\alpha_s^2}$$

$$\frac{d\sigma_{\mathrm{SIScone}}/dX}{d\sigma_{\mathrm{k_T}}/dX} = 1 + \frac{d\sigma_{\mathrm{SIScone}}/dX - d\sigma_{\mathrm{k_T}}/dX}{d\sigma_{\mathrm{k_T}}/dX} \simeq 1 + \frac{D\alpha_s^2 + E\alpha_s^3}{A\alpha_s + B\alpha_s^2}$$

note: for the cancellations to work, the differences are calculated on an event by event basis

ZEUS: xsect ratios of data & of NLO



- in E_T the ratios differ from unity by < 3.6%, except at highest E_T (10%)
- in Q^2 they differ by < 3.2 %

➤ data ratios are well described by predictions up to $O(\alpha_s{}^3)$

- in ratio, theoretical uncertainty mainly due to hadronization uncertainty

ZEUS: determination of $\alpha_s(M_Z)$

- use data on $d\sigma/dQ^2$ for $Q^2 > 500$ GeV^2 (to minimize error on $\alpha_s(M_Z)$)
- NLO calculation using DISENT
- PDFs: ZEUS-S parametrizations for five different values of $\alpha_s(M_Z)$
- main uncertainties on $\alpha_s(M_Z)$
  - jet energy scale → 1.9 to 2%
  - terms beyond NLO → 1.5% (method by Jones et al.)
  - pdfs → 0.7 to 0.8%
  - hadronization → 0.8% (k_T), 0.9% (anti-k_T), 1.2% (SIScone)

$$k_T: \alpha_s(M_Z) = 0.1207 \pm 0.0014\,(\text{stat.})\,^{+0.0035}_{-0.0033}\,(\text{exp.})\,^{+0.0022}_{-0.0023}\,(\text{th.})$$

$$\text{anti}-k_T: \alpha_s(M_Z) = 0.1188 \pm 0.0014\,(\text{stat.})\,^{+0.0033}_{-0.0032}\,(\text{exp.})\,^{+0.0022}_{-0.0022}\,(\text{th.})$$

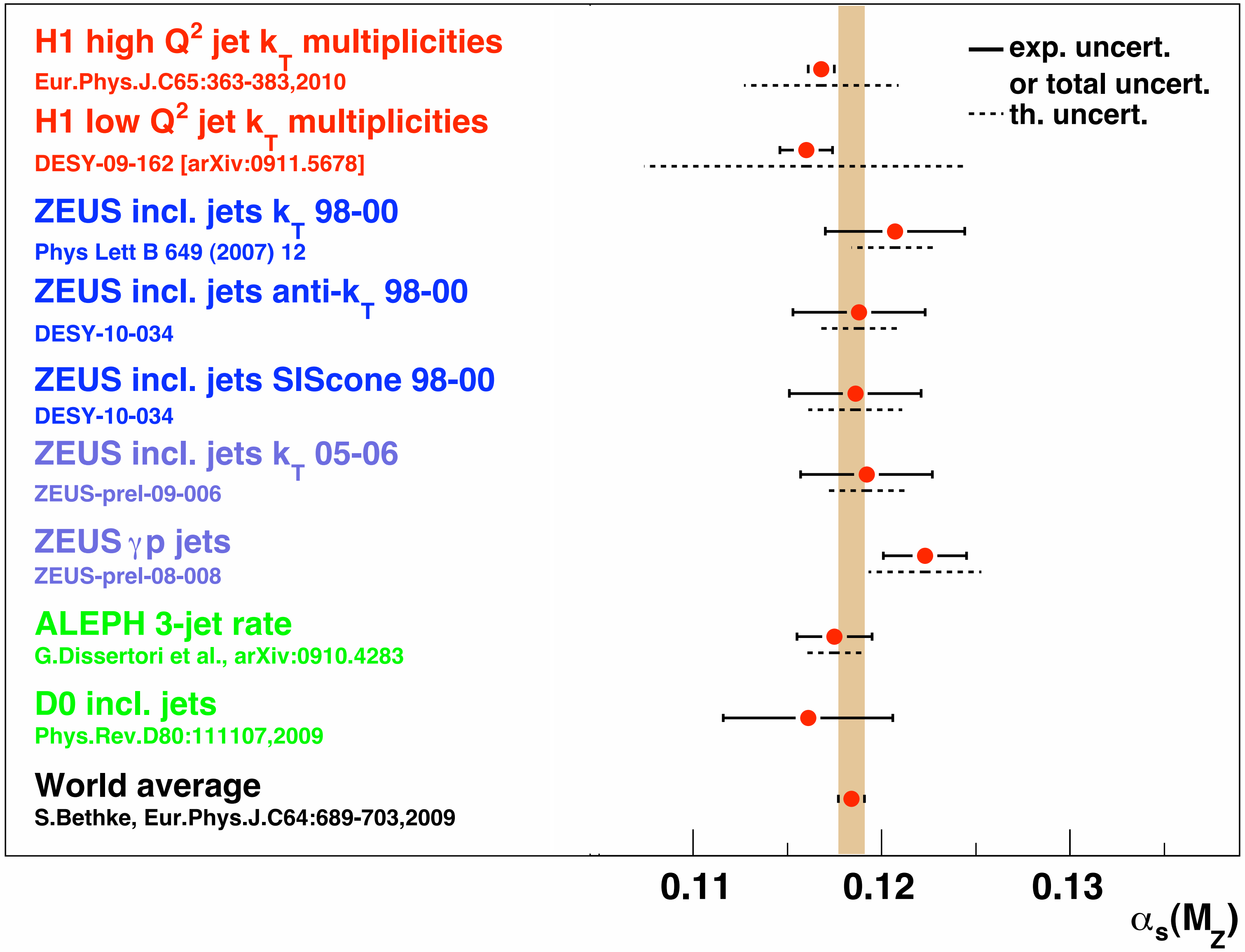
$$\text{SIScone}: \alpha_s(M_Z) = 0.1186 \pm 0.0013\,(\text{stat.})\,^{+0.0034}_{-0.0032}\,(\text{exp.})\,^{+0.0025}_{-0.0025}\,(\text{th.})$$

The values are very similar, differences comparable to terms beyond NLO

Summary

- Multijet cross sections for $Q^2 < 100$ GeV^2 in good agreement with expectations from NLO
- consistent $\alpha_S(M_Z)$ & running from low and high Q^2 multijet cross sections

- first measurements of incl. jet cross sections using anti-k_T and SIScone
- the measured cross sections have similar shapes & normalization, and they agree well with NLO
- calculations have similar precision, only SIScone is slightly less precise
- k_T, anti-k_T and SIScone lead to similar values of $\alpha_S(M_Z)$ with similar precision.



calculations beyond NLO in DIS are needed !

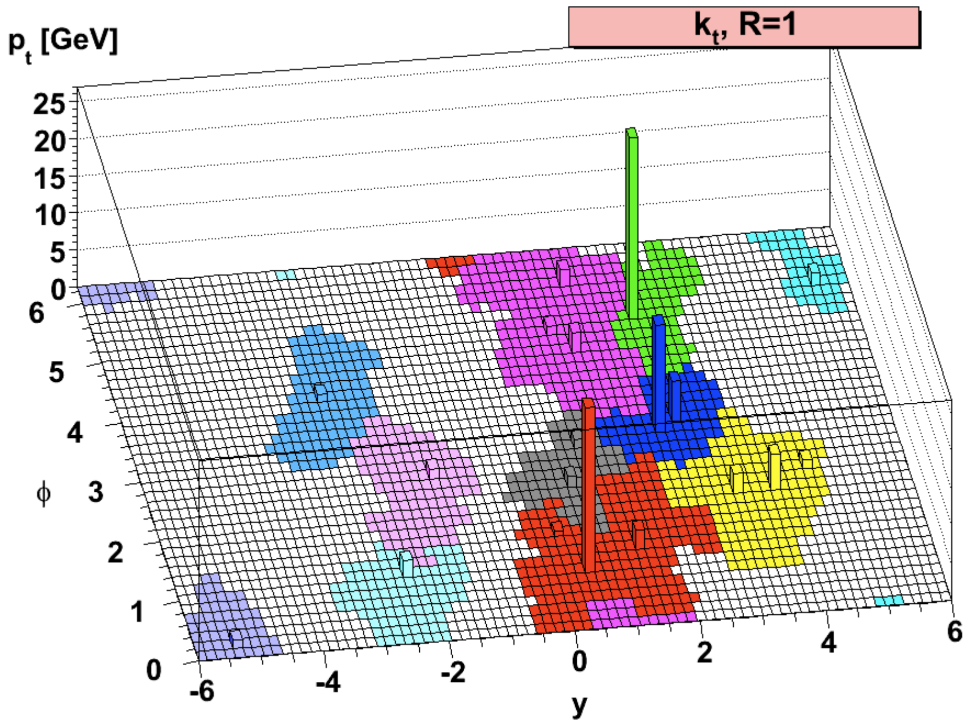
Thank you !

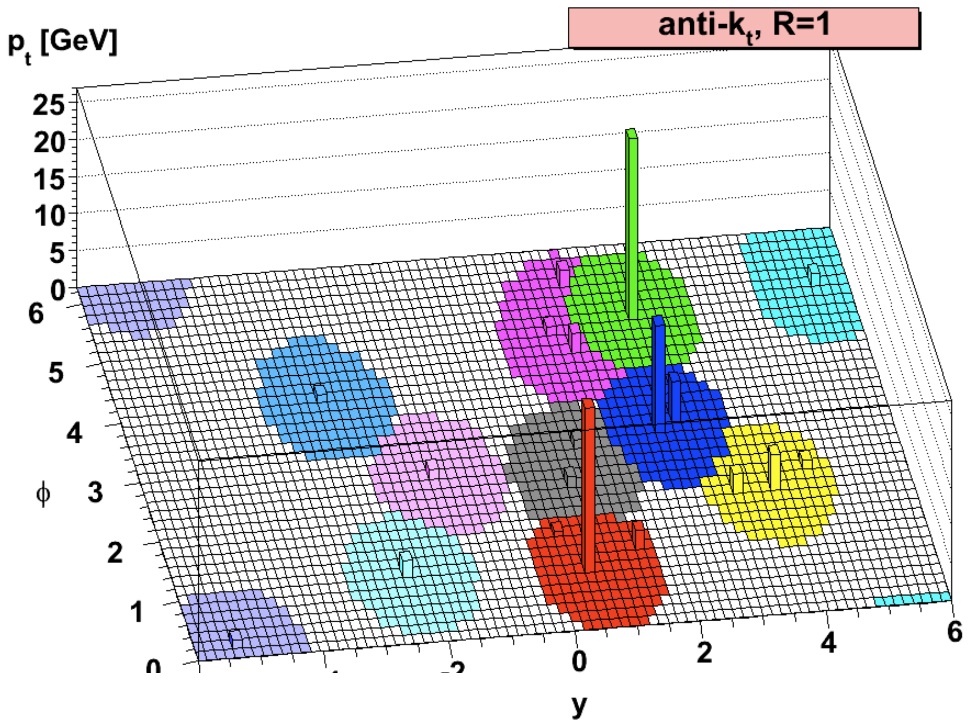
Further results from H1 & ZEUS:

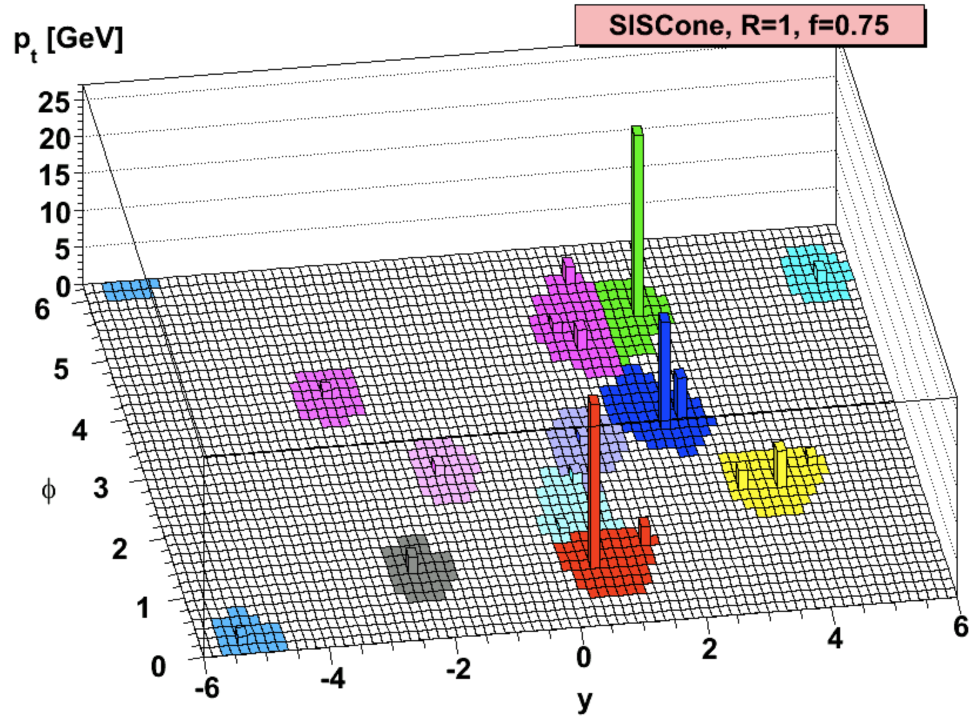
http://www-h1.desy.de/publications/H1_sci_results.shtml

http://www-zeus.desy.de/zeus_papers/zeus_papers.html

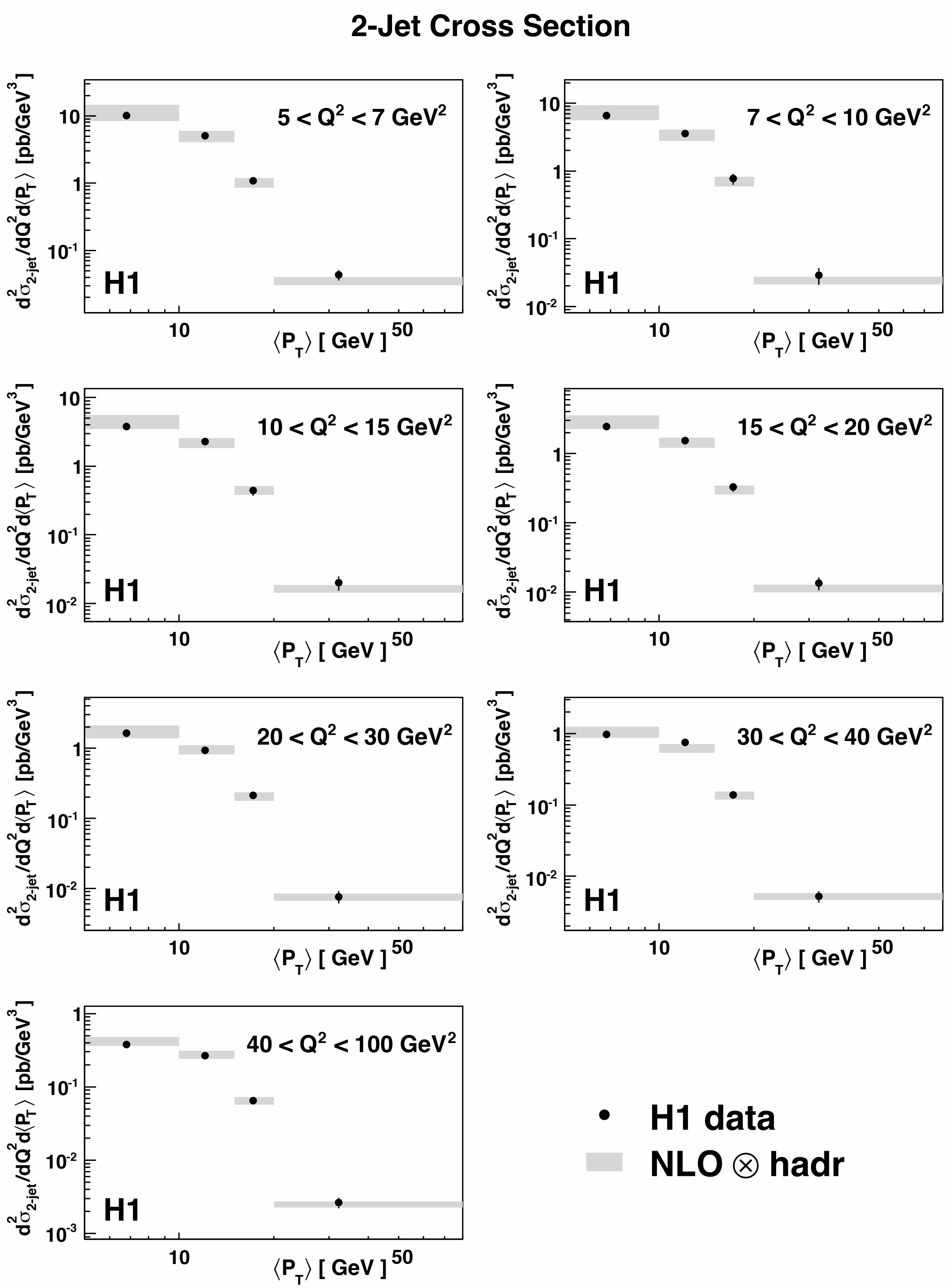
Jet finding: kT, anti-kT & SIScone

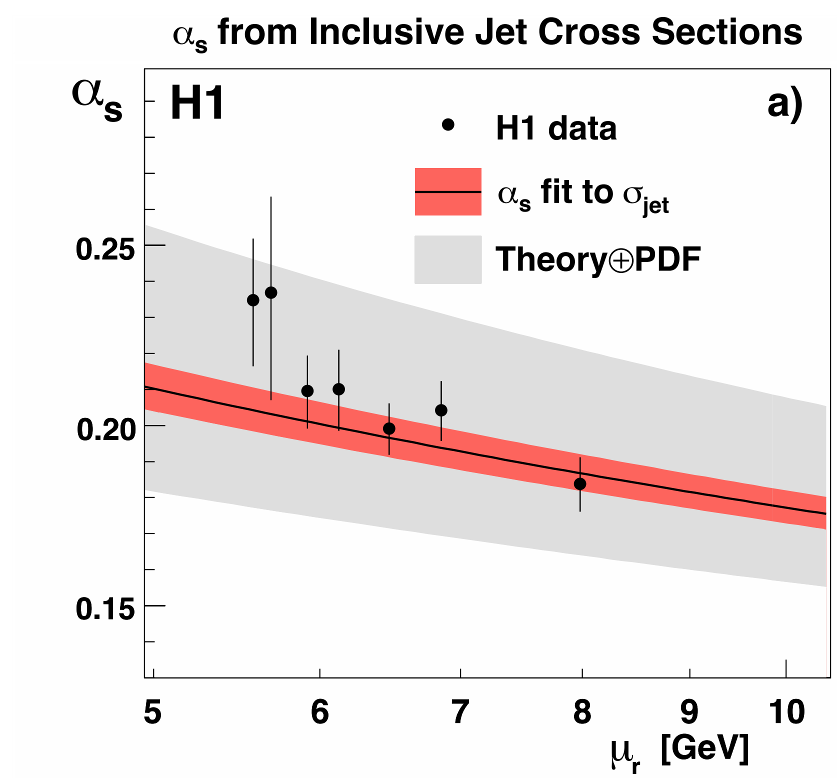


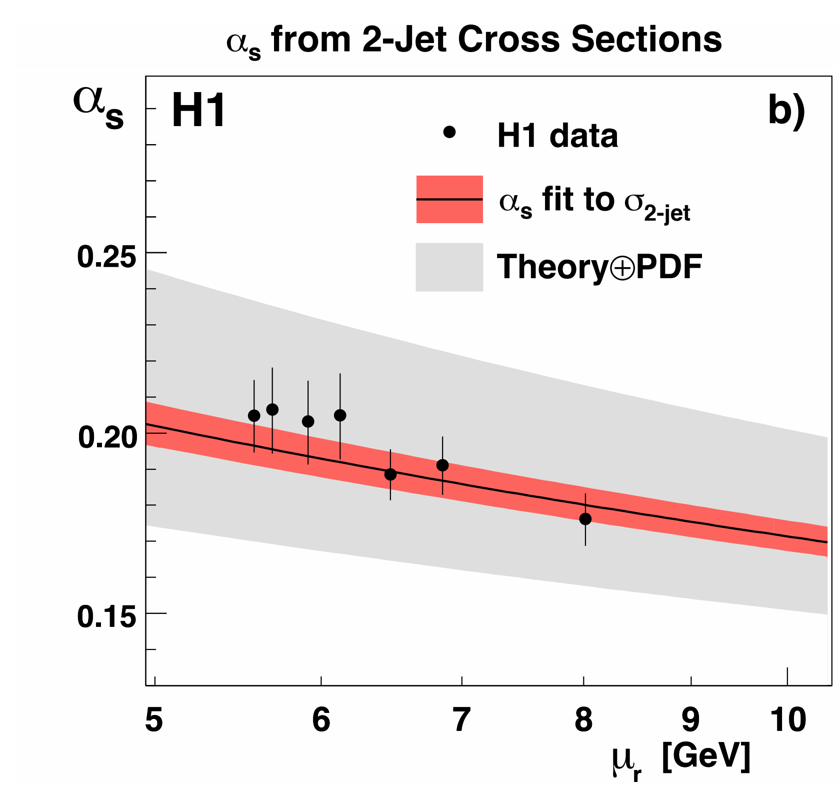




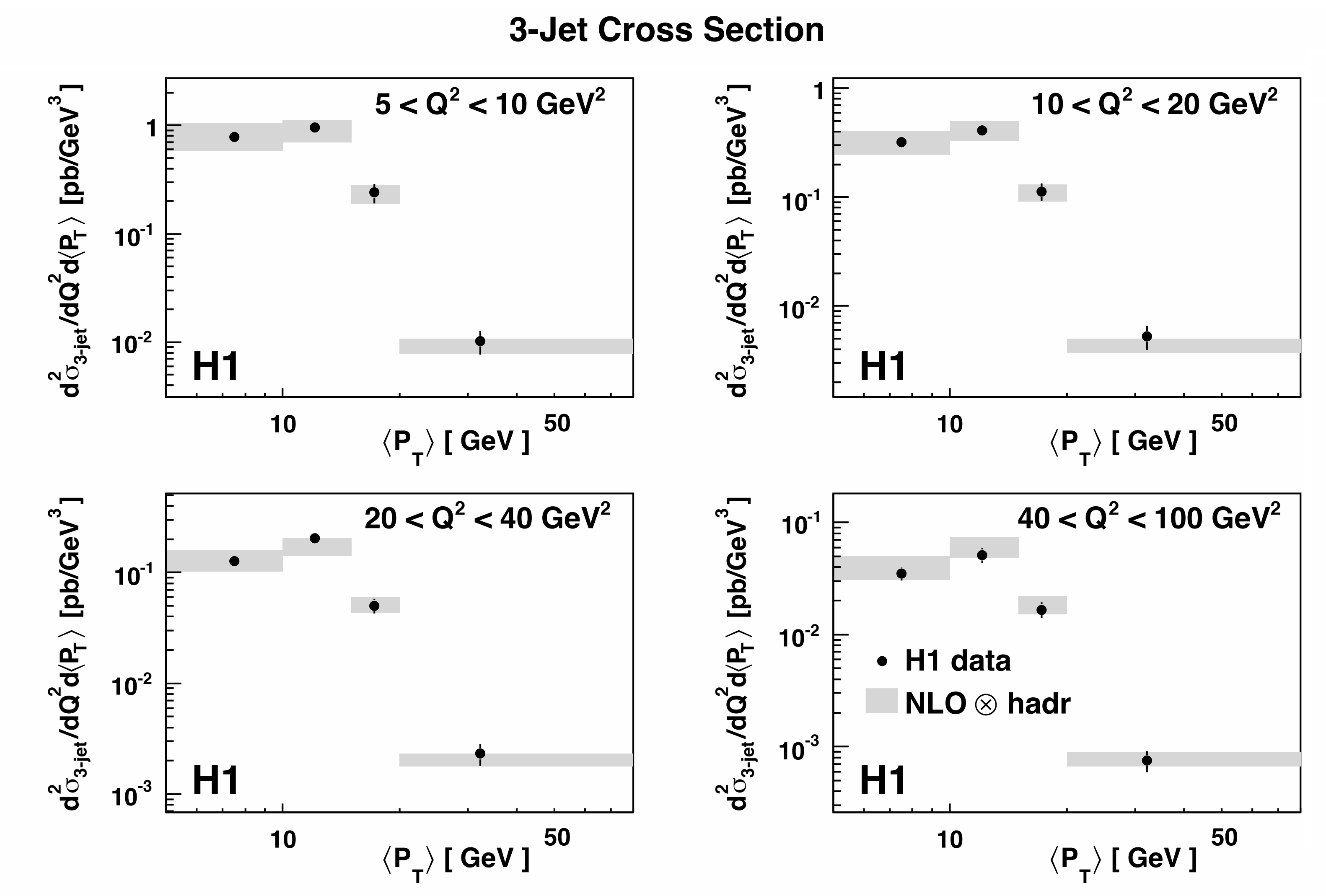
H1: 2-jets & α_s

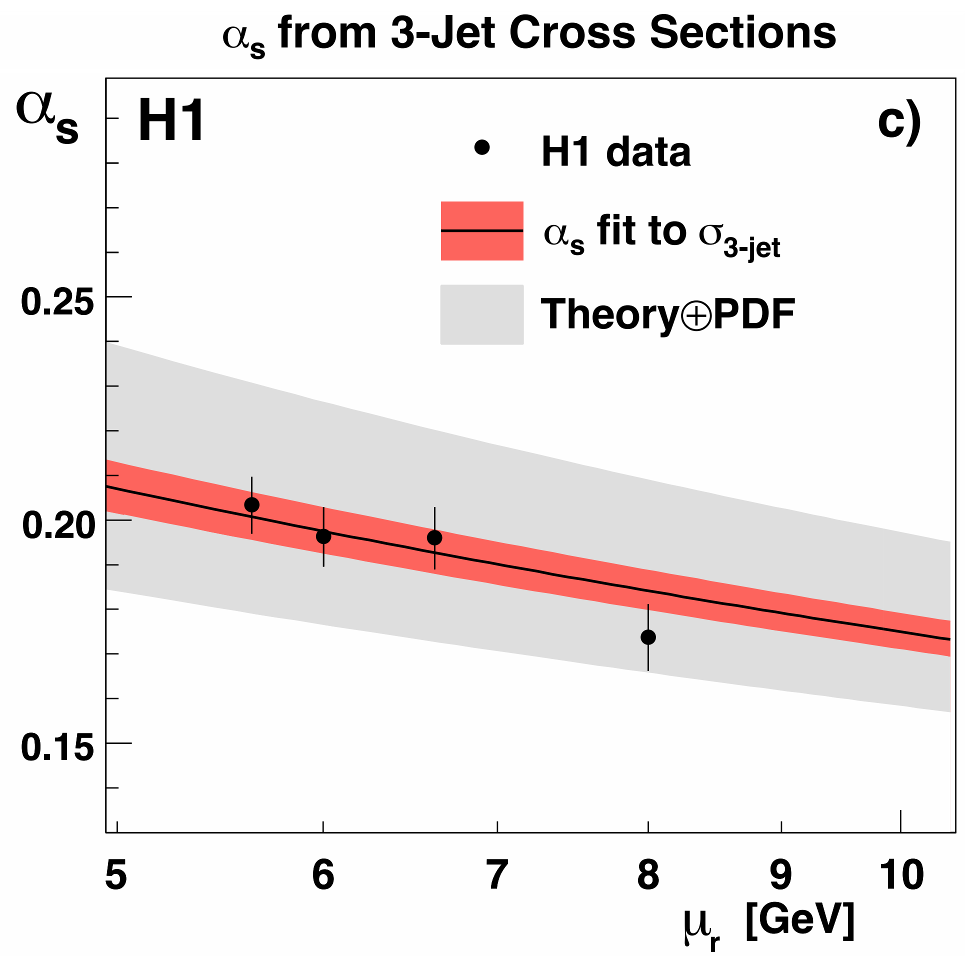






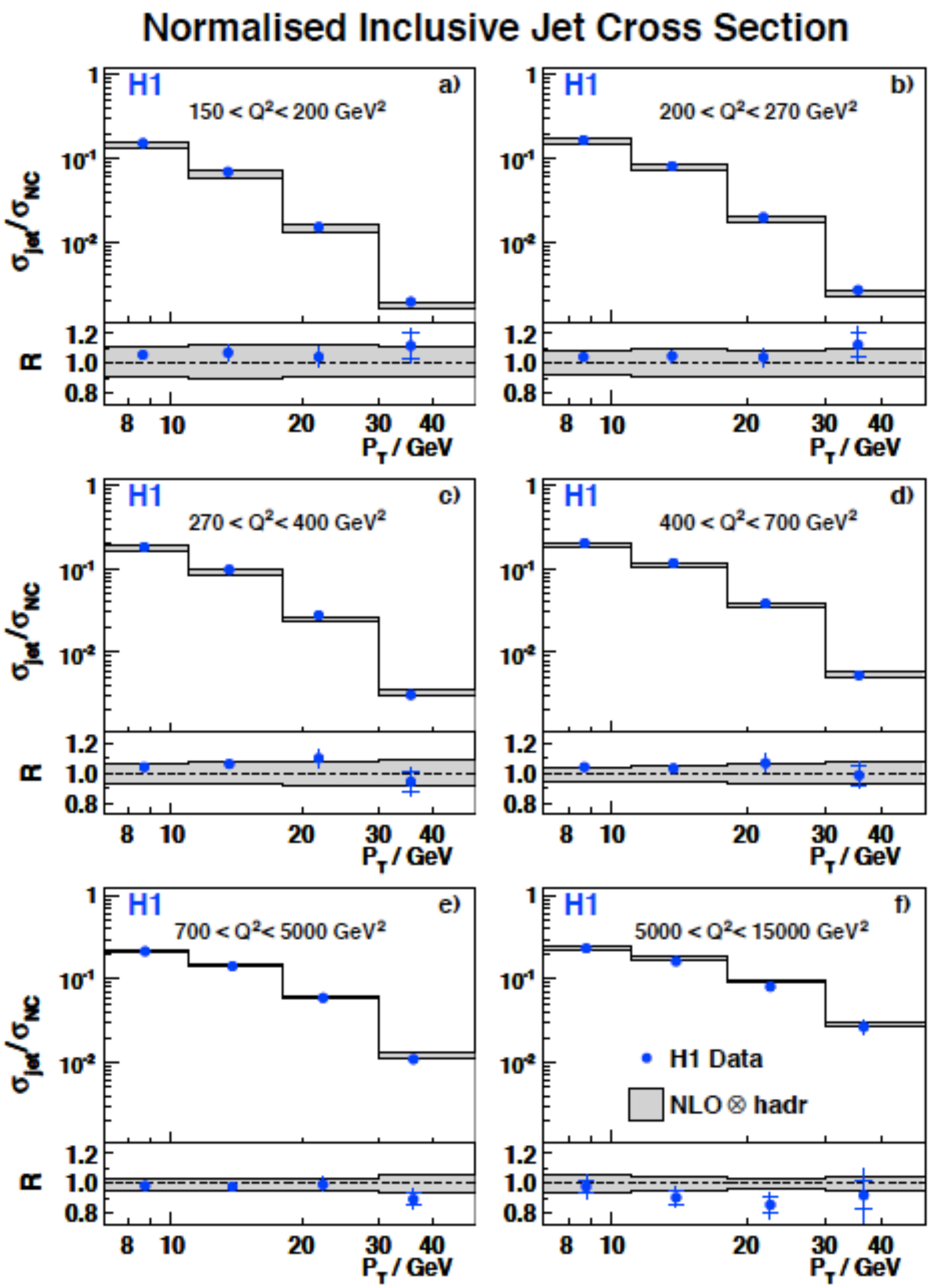
H1: 3-jets & α_s

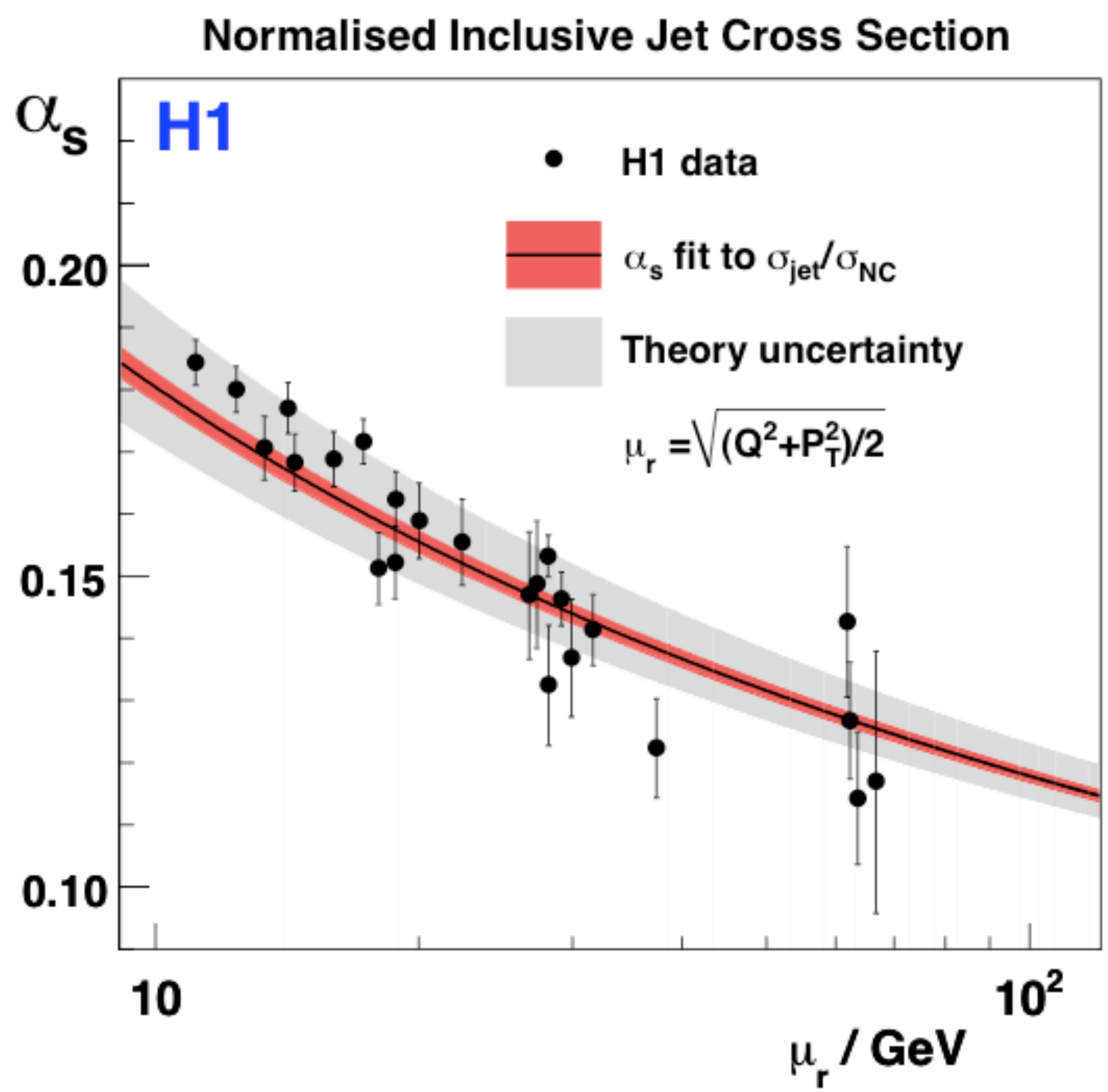




- NLOjet++ provides also a good description of the 3-jet cross section in NLO, i.e. $O(\alpha_s^3)$.

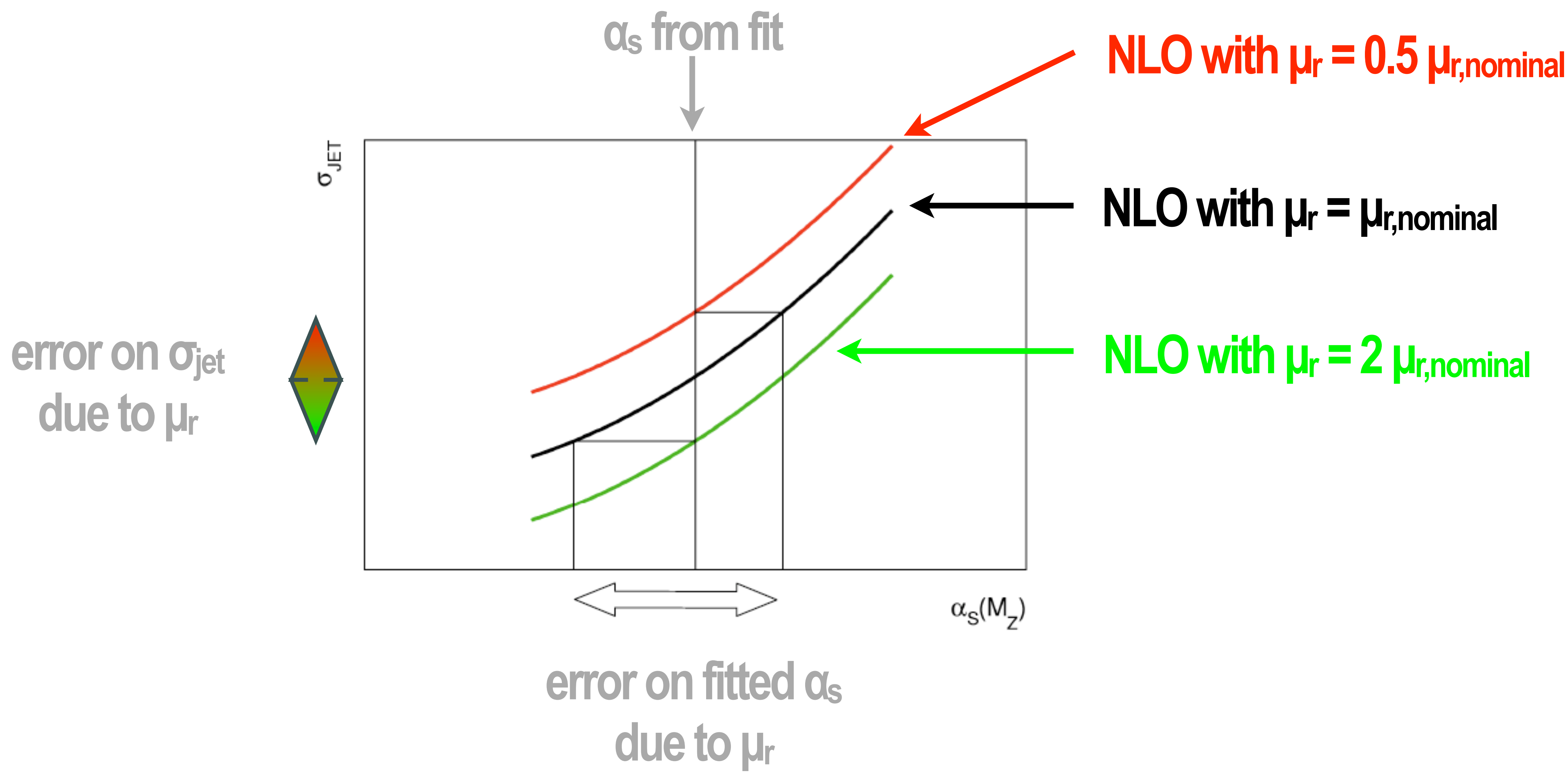
Jet multiplicity & Running α_s



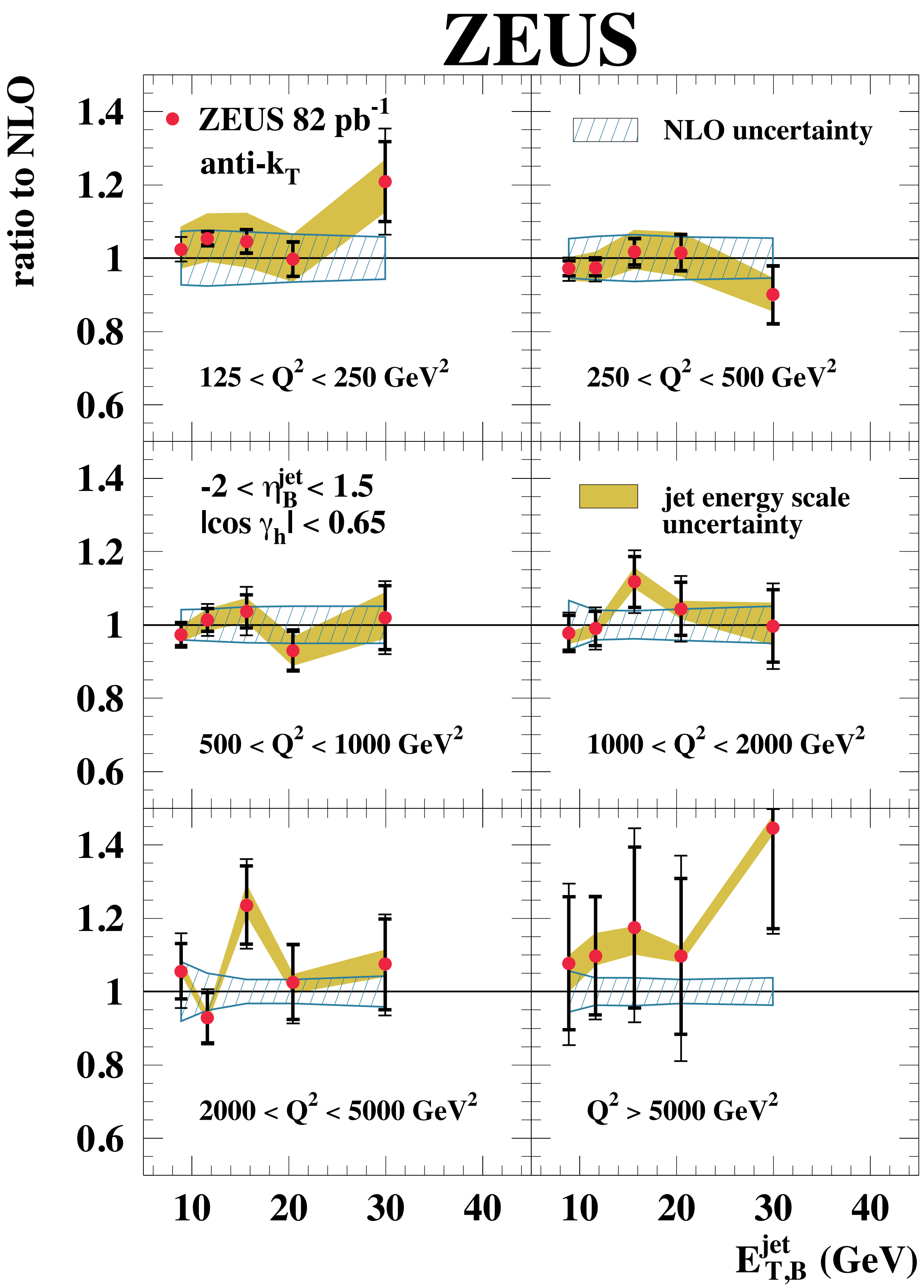


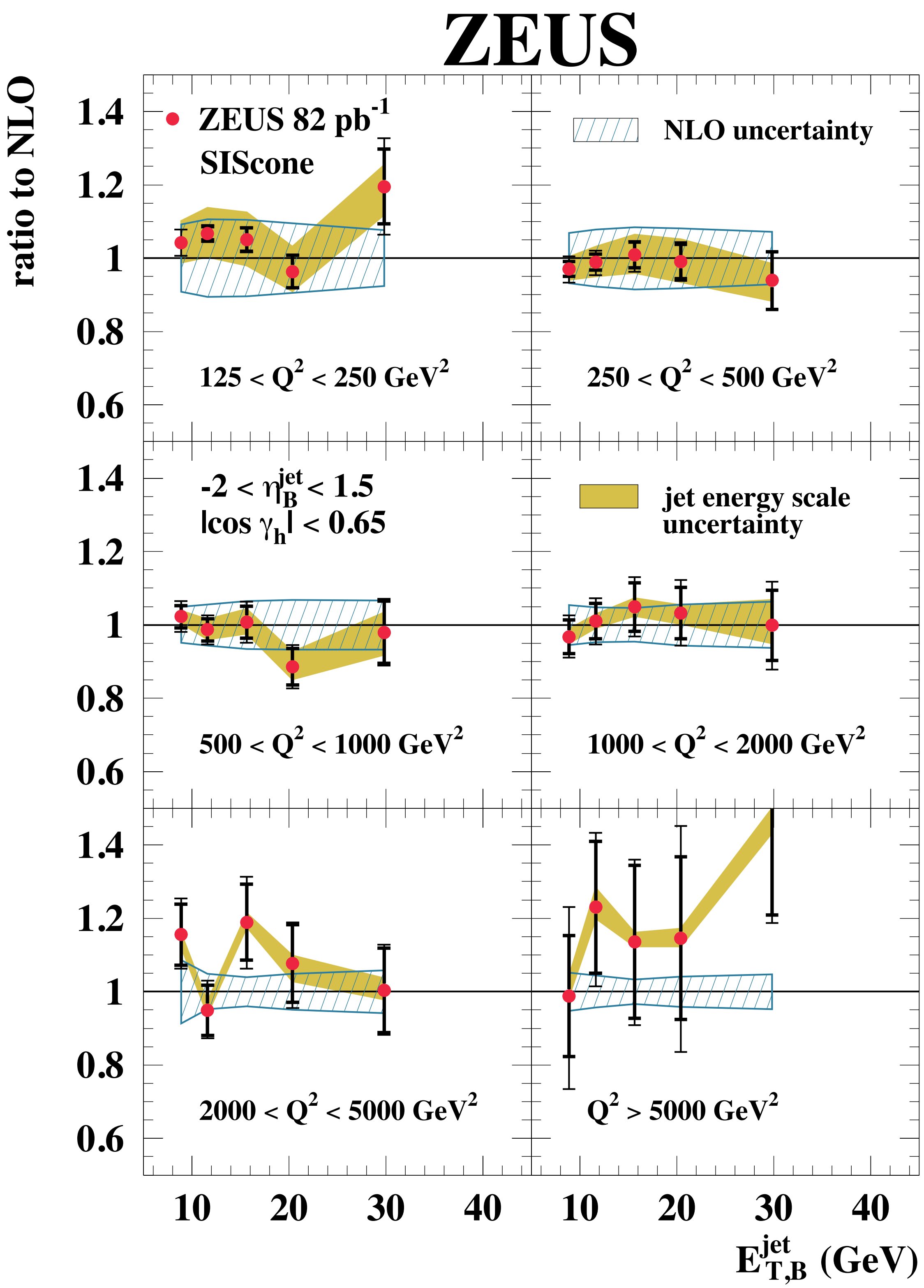
Theory uncertainty on $\alpha_s(M_Z)$

- method 1: the fit of $\alpha_s(M_Z)$ to the data is repeated with μ_r scaled by 0.5 and 2 in the NLO calc.; the difference to the result with the nominal scale is taken as uncertainty.
  ➡ the theory uncertainty depends on the data
- method 2: only theory is used (Jones et al., JHEP 122003007), no refit to data



ZEUS: data/NLO for k_T & SIScone





Fitting $\alpha_S(M_Z)$: χ^2

Minimise $\chi^2(\alpha_s(M_Z))$ defined as:

$$\chi^2 = \vec{V}^T \cdot M^{-1} \cdot \vec{V} + \sum_k \varepsilon_k^2$$

correlated version of $\sum$(difference/error)^2

penalty term for fitted systematics "Hessian" method

$$M = M^{\mathrm{stat.}} + M^{\mathrm{uncor.}}$$

correlated for some bins

uncorrelated systematics

$$V_i = \sigma_i^{\mathrm{exp.}} - \sigma_i^{\mathrm{theo.}} \left(1 - \sum_k \Delta_{ik} \varepsilon_k\right)$$

bin #

correlated systematical error #k

parameter in fit, pull "Hessian" method

Exp. uncertainty of fit defined as α_s interval upto minimum χ^2+1