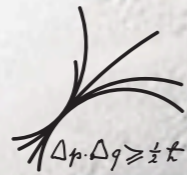


k_T , anti- k_T & SIScone jets and α_s @ HERA



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MPI für Physik, München

Rencontres de Moriond, La Thuile, March 13-20, 2010

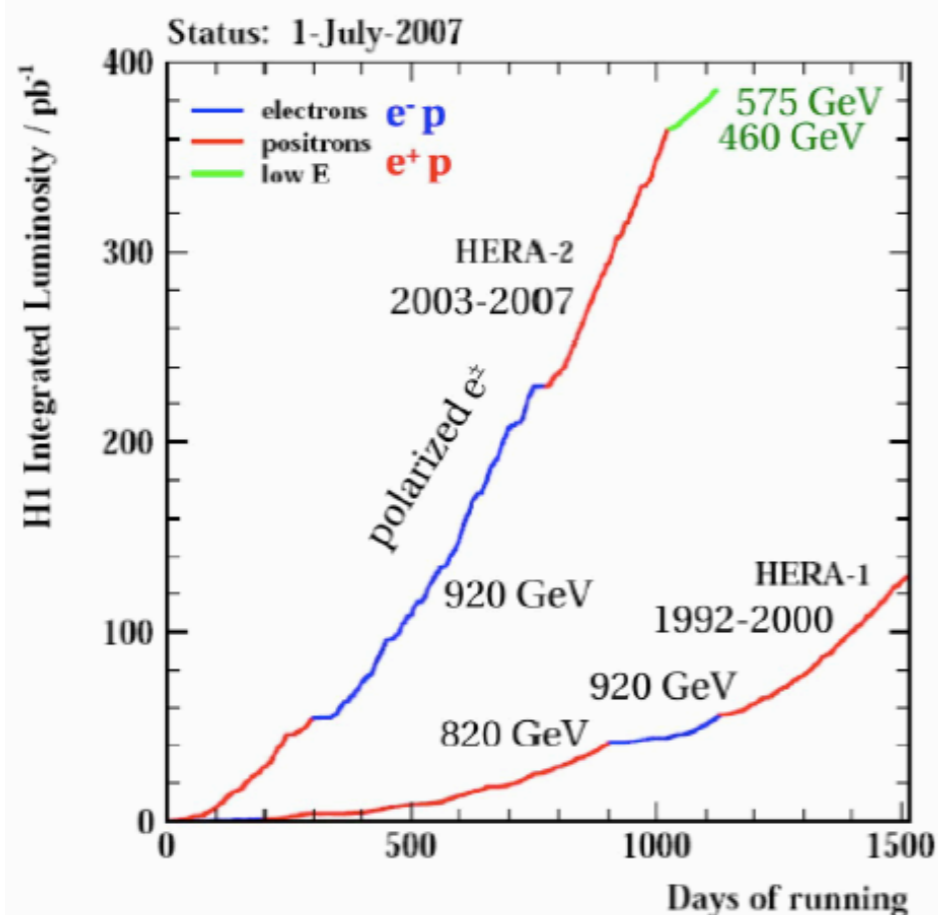


on behalf of the H1 and ZEUS collaborations



- 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

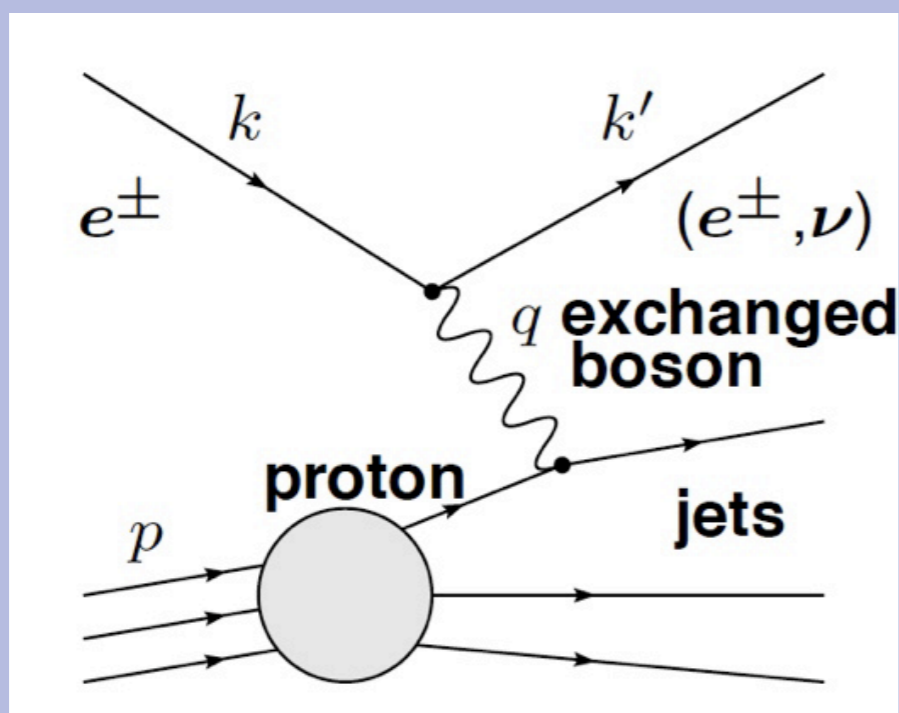


- 1992 - 2007

- $\sqrt{s} = 318 \text{ GeV}$
 $E_e = 27.6 \text{ GeV}$ $E_p = 920 \text{ GeV}$

- 2001/2002 luminosity upgrade \rightarrow HERA-2

- $\sim 0.5 \text{ fb}^{-1}$ of data collected per experiment

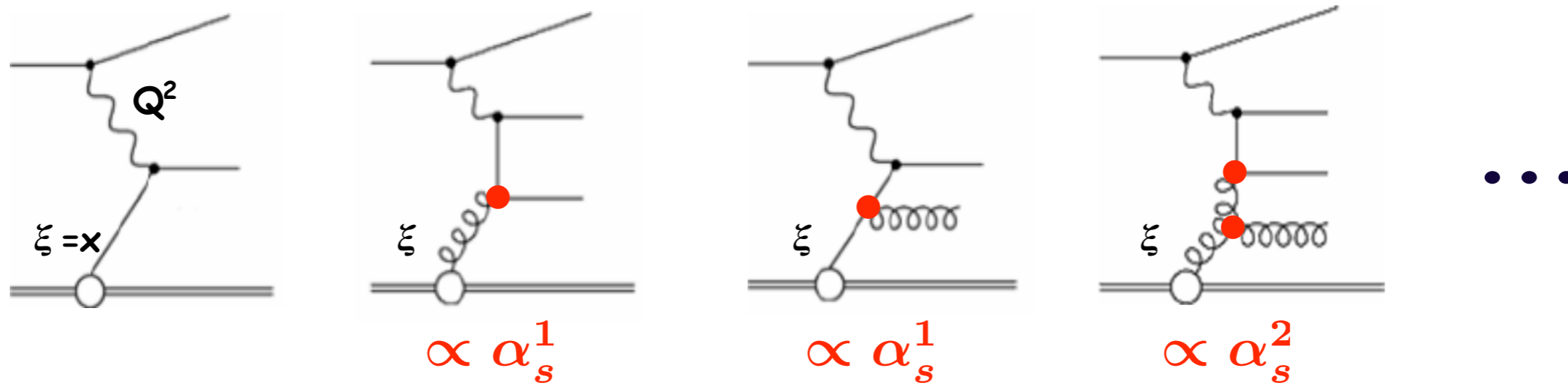


- virtuality of the exchanged boson:
 $Q^2 = -q^2 = -(k-k')^2 = sxy$

- Bjorken scaling variable:
 $x = Q^2/2p \cdot q$

- inelasticity: $y = p \cdot q/p \cdot k$

Jet production in DIS @ HERA



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

- 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) & $P_{\text{T}}^{\text{jet}}$ (5-80 GeV)

typical choices for pQCD calculations are:

$$\mu_f = Q$$

$$\mu_r = Q \text{ or } P_{\text{T}}^{\text{jet}} \text{ (ZEUS)}$$

$$\mu_r = \sqrt{[(Q^2 + (P_{\text{T}}^{\text{jet}})^2)/2]} \text{ (H1)}$$

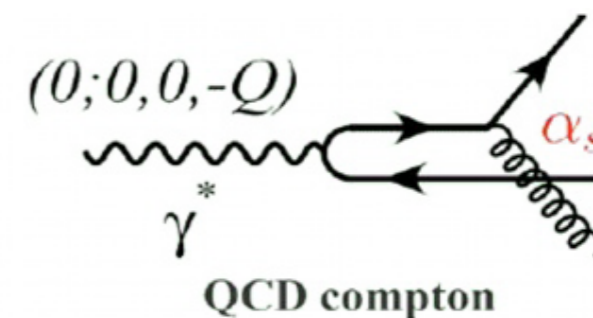
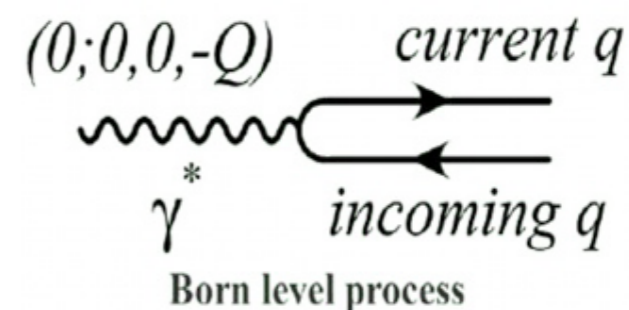
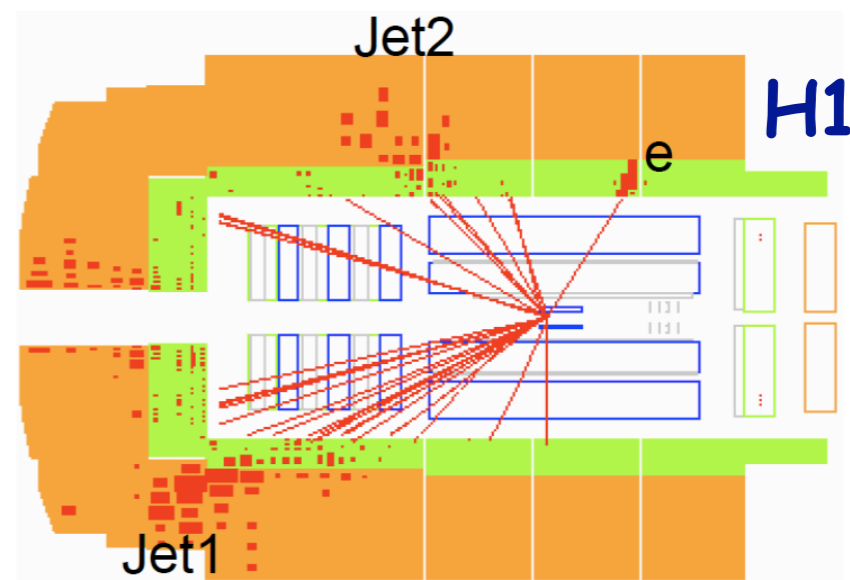
Jet production in DIS @ HERA

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

G.Salam & G.Soyez

Sequential recombination algorithms:

$$d_{ij} = \min(k_{Ti}, k_{Tj})^{2p} \Delta R^2 / R^2 \text{ and } d_{iB} = k_{Ti}^{2p}$$

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

$$p = 1 \rightarrow k_T$$

$$p = -1 \rightarrow \text{anti-}k_T$$

at HERA typically

$$R=1.0$$

S.Catani, M.Cacciari, G.Salam & G.Soyez
S.Ellis & D.Soper

SIScone:

seedless iterative cone with split merge (0.75)

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

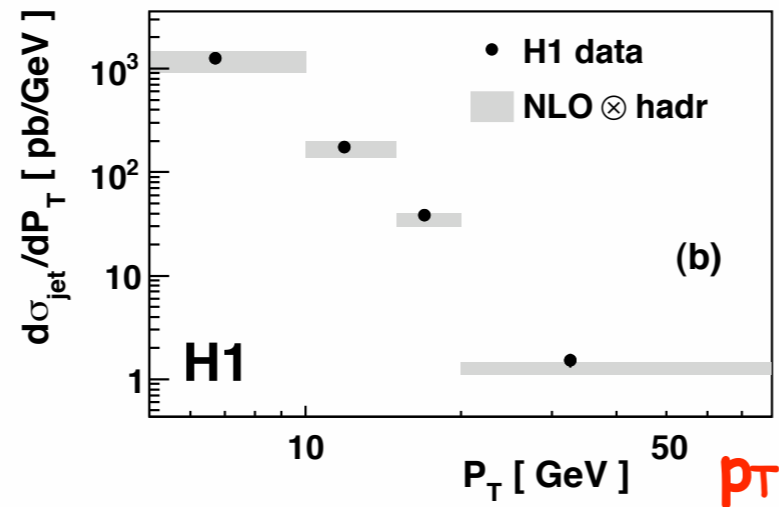
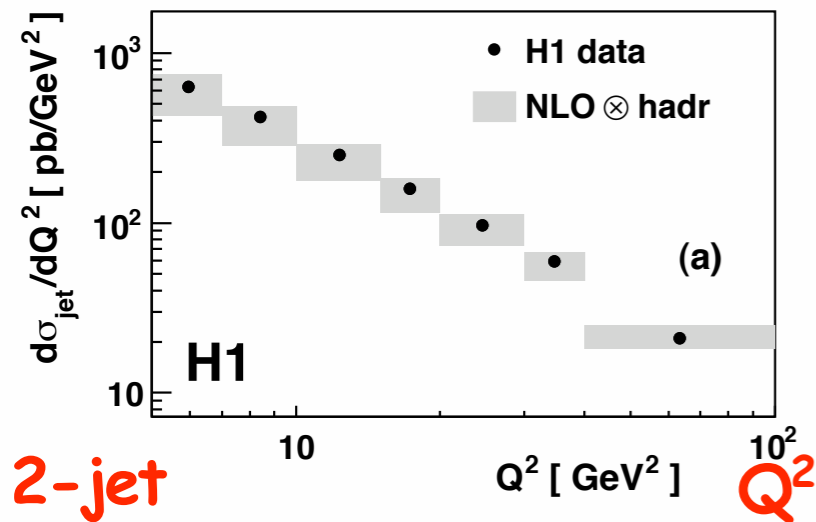
H1: Multijet cross sections at low Q^2

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

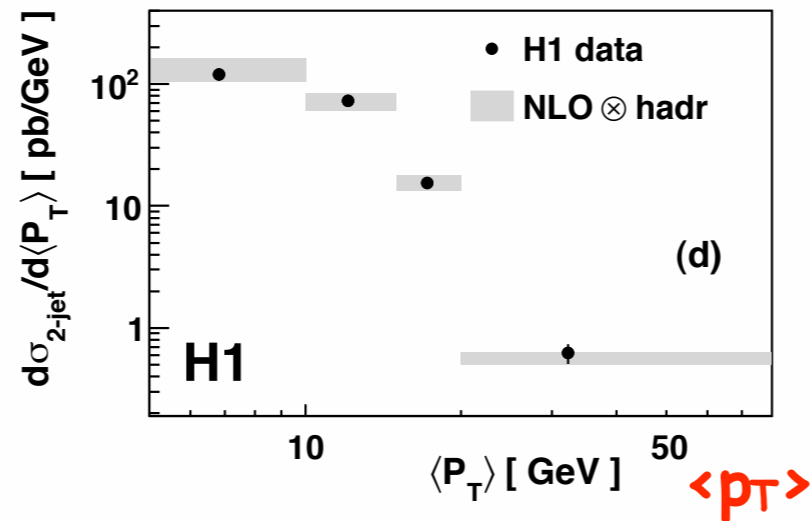
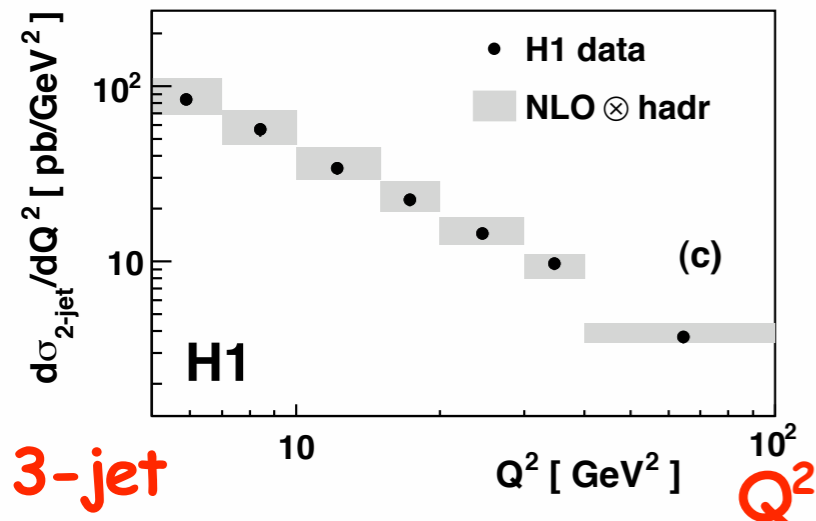
H1: Multijet cross sections at low Q^2

Incl. jet

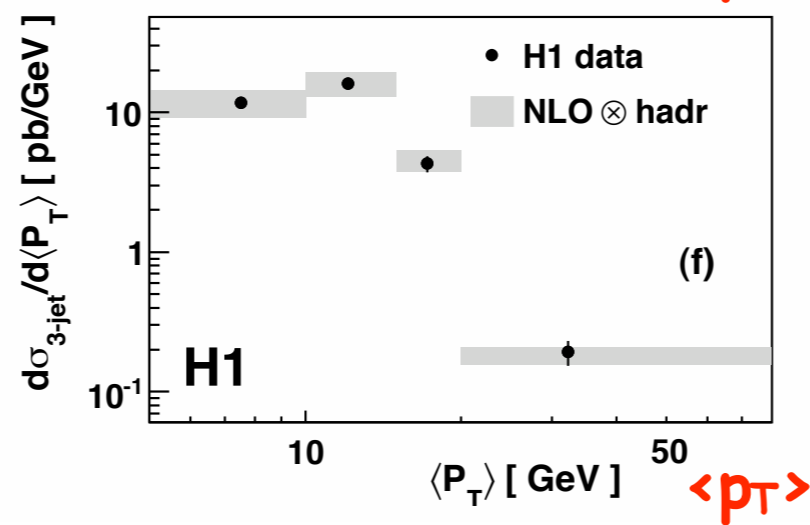
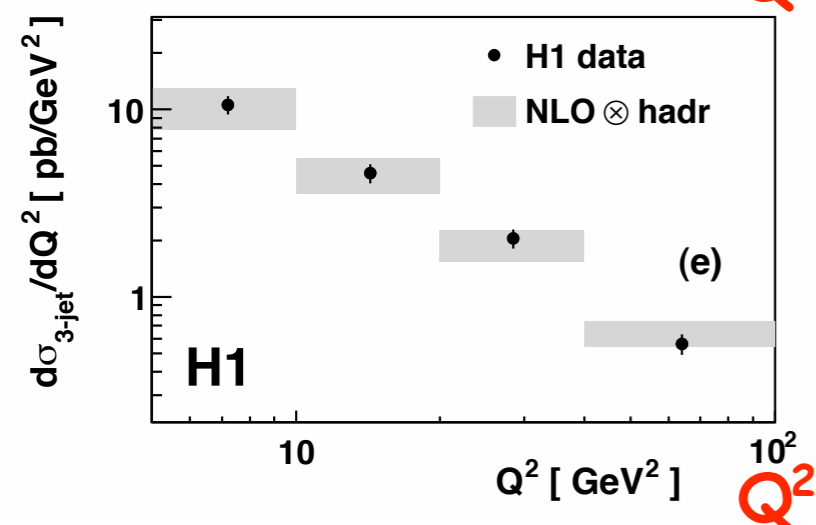
Inclusive Jet, 2-Jet and 3-Jet Cross Sections



2-jet



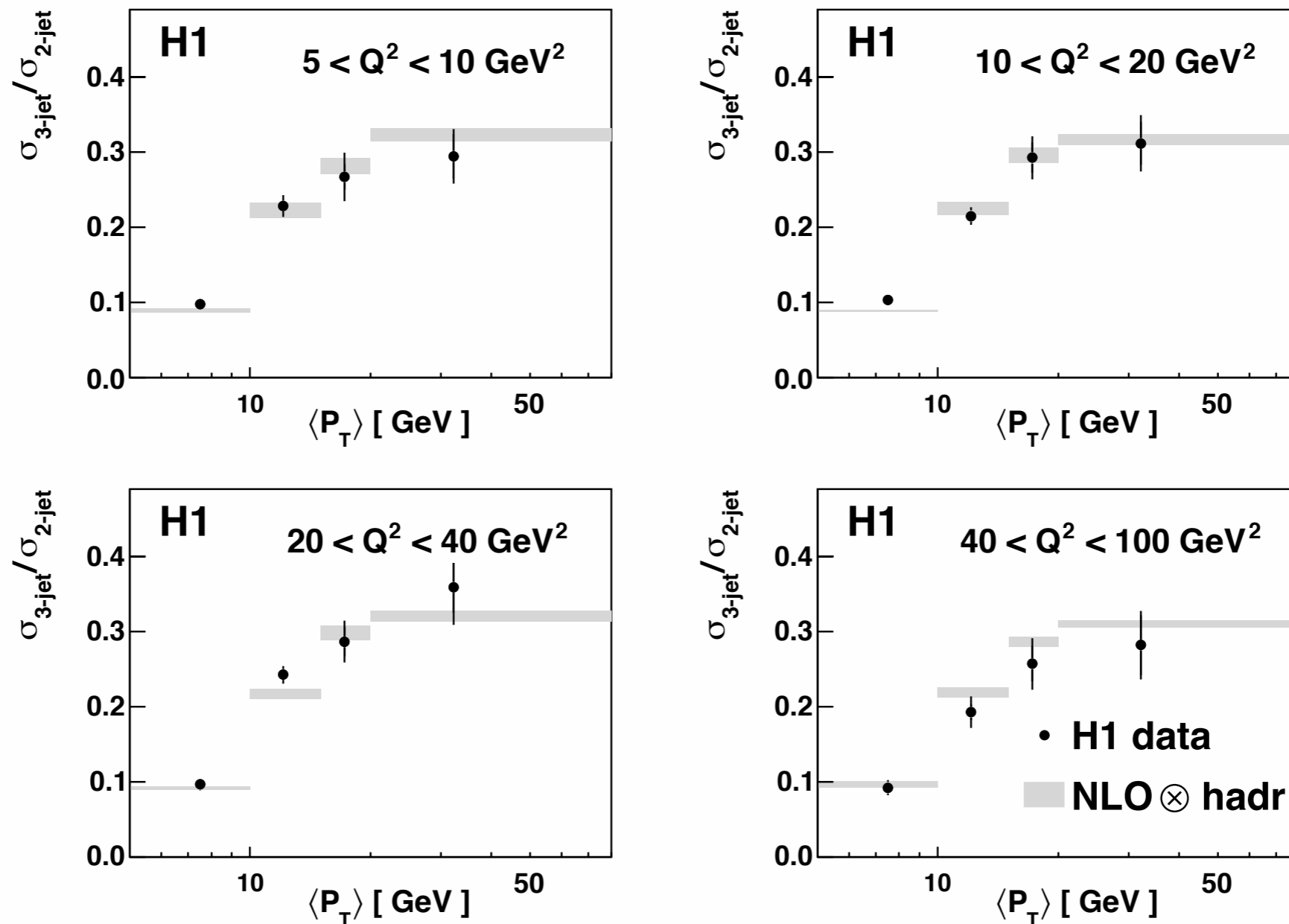
3-jet



- 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 ⇒ orders beyond NLO are needed to match the precision of the data

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

3-Jet to 2-Jet Ratio



- 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: $\alpha_s(M_Z) = 0.1160 \pm 0.0014$ (exp.) $^{+0.0093}_{-0.0077}$ (th.) ± 0.0016 (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:

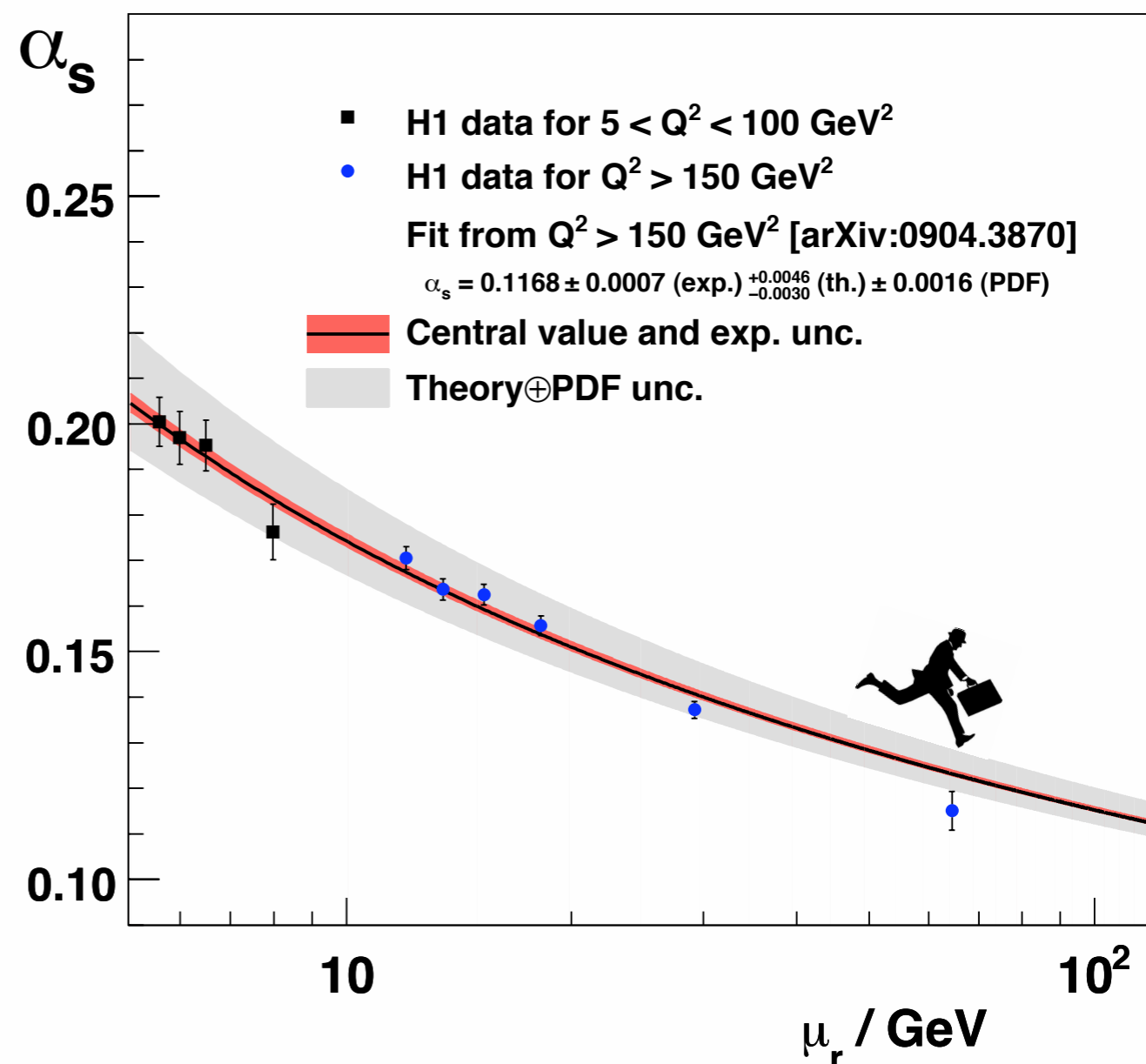
$$\alpha_s(M_Z) = 0.1168 \pm 0.0007 \text{ (exp.)}$$

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

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

α_s from Jet Cross Sections in DIS

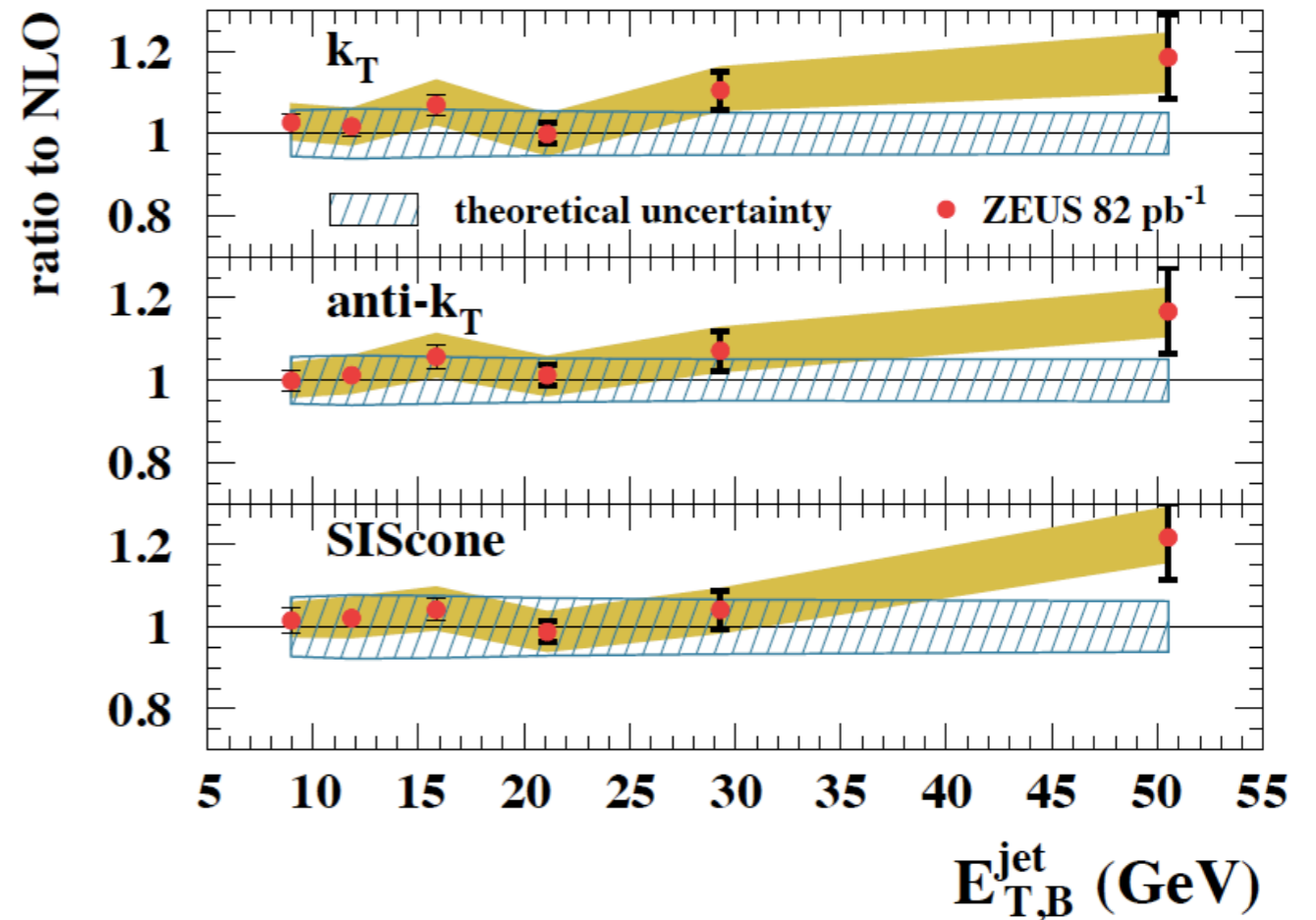
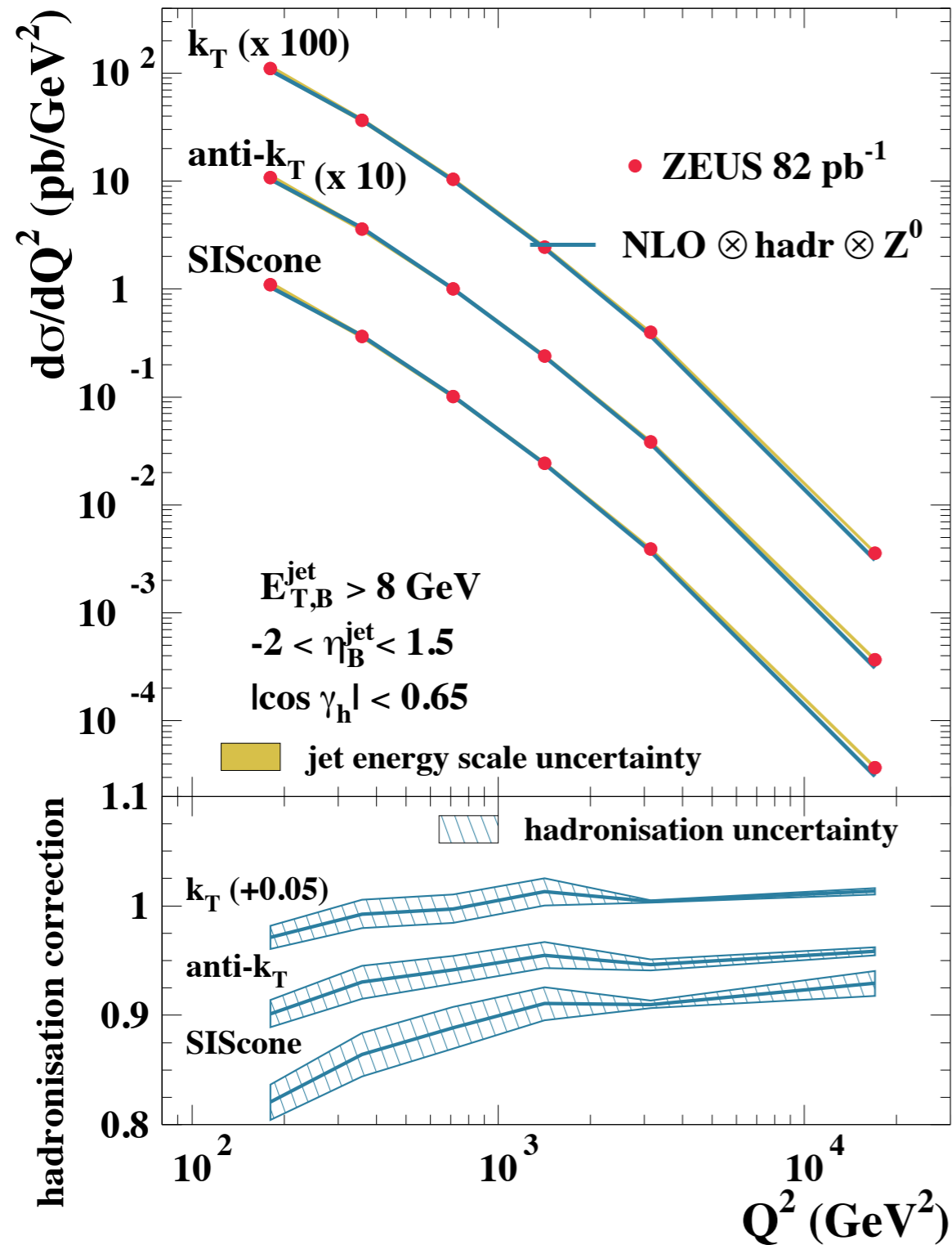


for high Q^2 results see Moriond 2009 and Eur.Phys.J. C 65 (2010) 363

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

- HERA-1 data, 82 pb^{-1} , DESY-10-034, arXiv:1003.2923
- DIS phase space: $Q^2 > 125 \text{ GeV}^2$, $|\cos \gamma_h| < 0.65$
- jets are found in the Breit frame using anti- k_T and SIScone
- jet phase space: at least one jet with $-2 < \eta < 1.5$, $E_T > 8 \text{ GeV}$ 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% ($E_{T,\text{lab}} > 10 \text{ GeV}$) to 3% for lower $E_{T,\text{lab}} \Rightarrow \Delta \sigma / \sigma \approx 5\%$
 - uncertainty in acceptance $\Rightarrow \Delta \sigma / \sigma \approx 4\%$
- NLO calculations: DISENT & NLOjet++
 - $\overline{\text{MS}}$ scheme for 5 massless quark flavors
 - $\mu_f = Q$ and $\mu_r = E_T$
 - PDFs: ZEUS-S parametrization

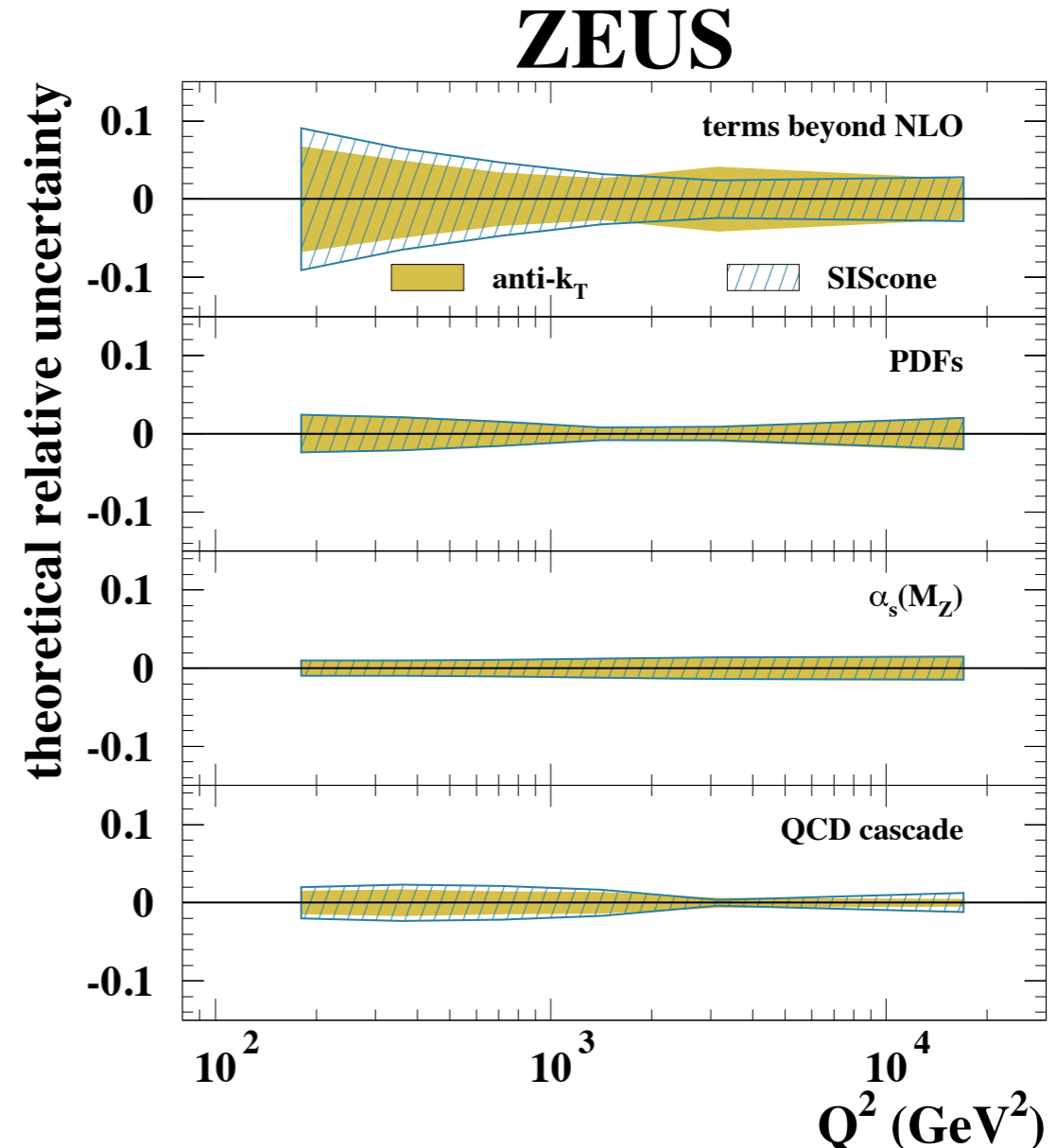
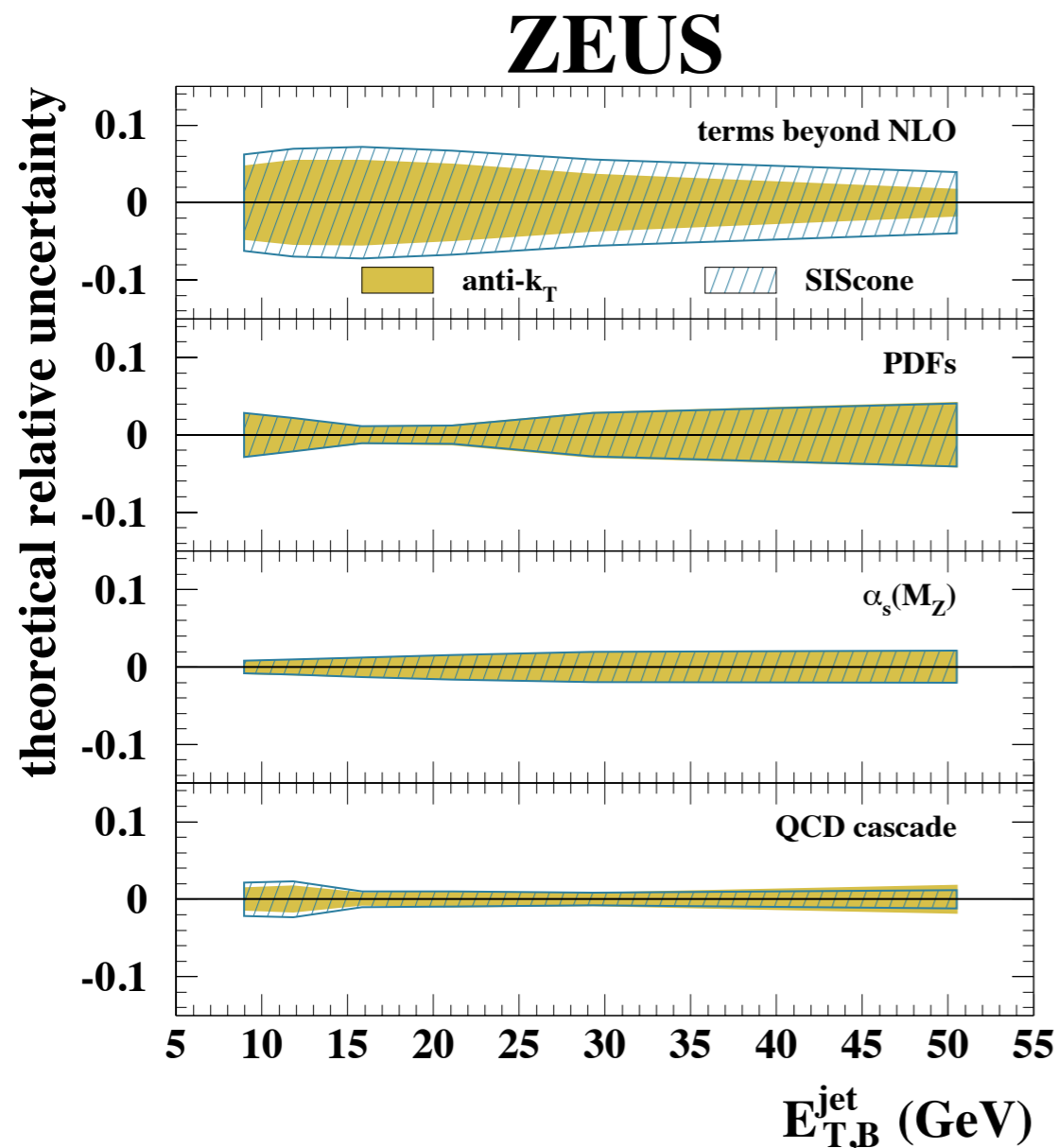
ZEUS: Incl. k_T , anti- k_T , SIScone jets



- 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:

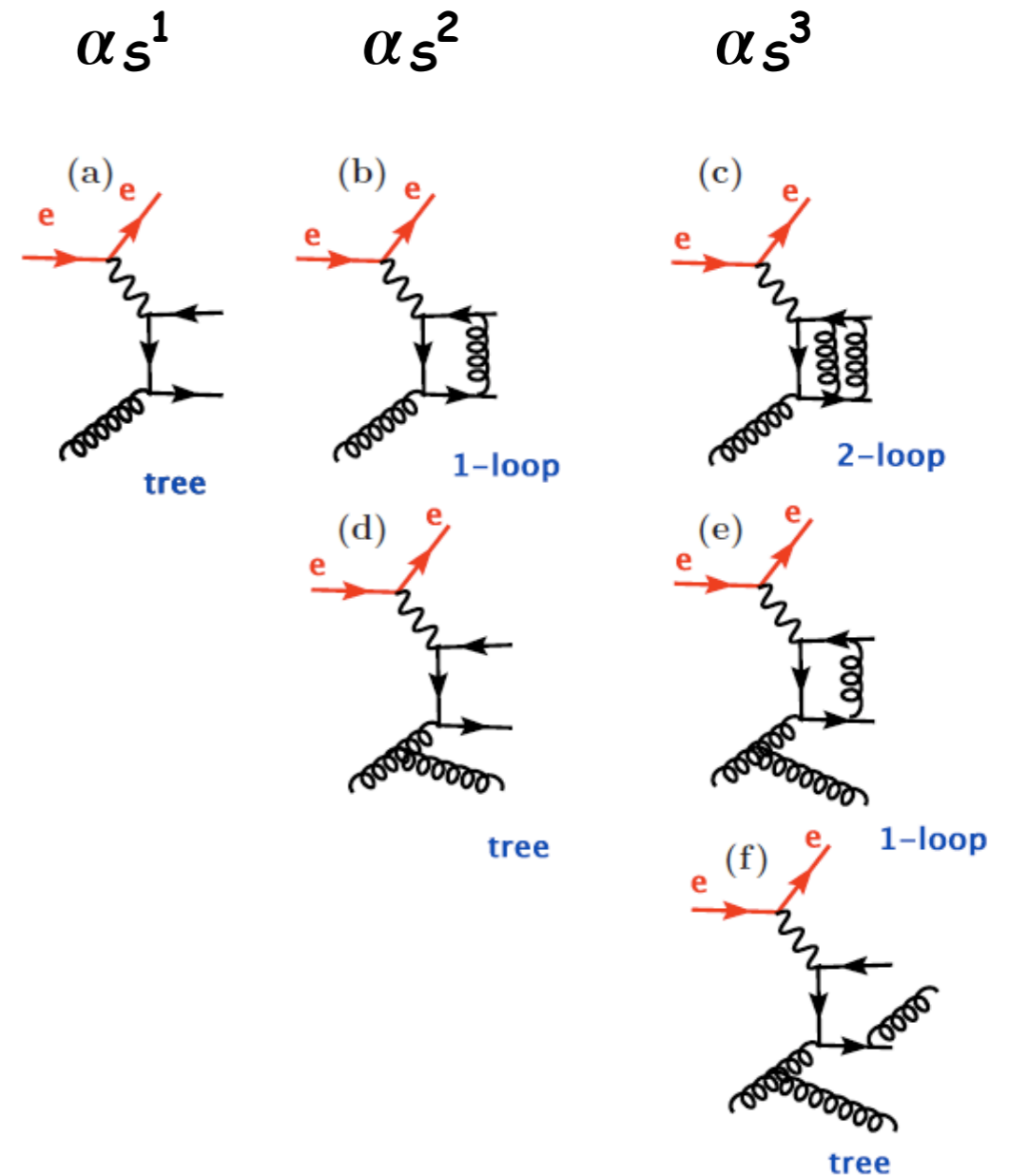
- incl. jet cross sections currently calculated up to $O(\alpha_s^2)$
- differences of incl. jet cross sections using different jet algorithms can however be predicted up to $O(\alpha_s^3)$ using NLOjet++

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

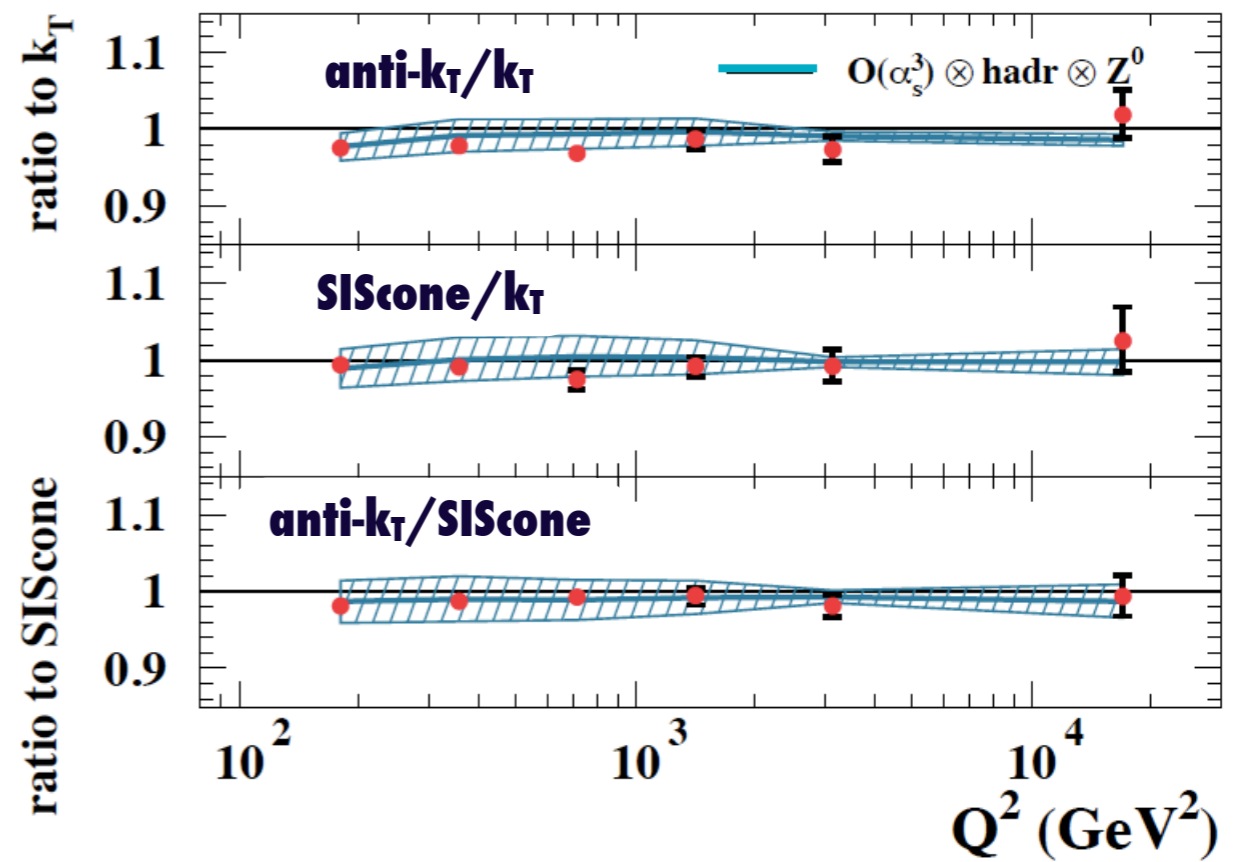
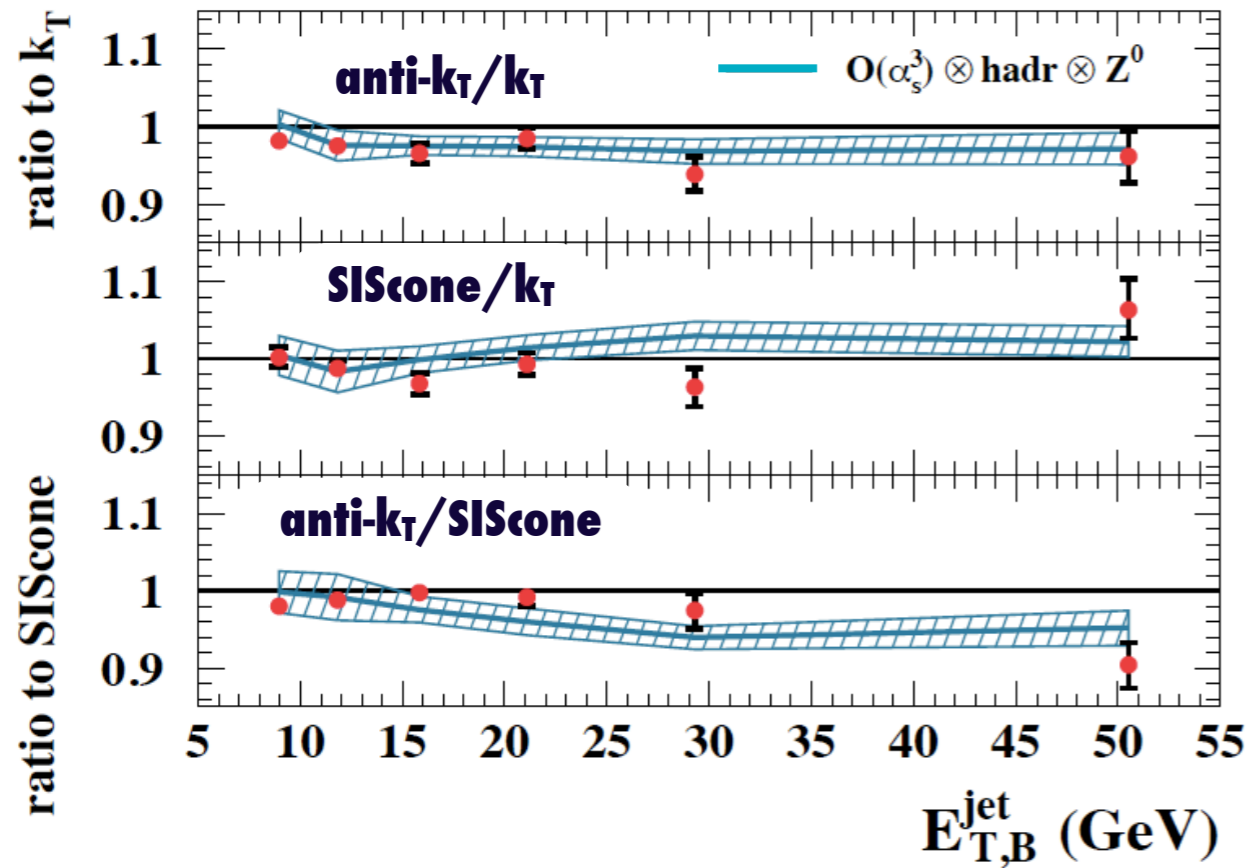
$$\frac{d\sigma_{\text{SIScone}}/dX}{d\sigma_{k_T}/dX} = 1 + \frac{d\sigma_{\text{SIScone}}/dX - d\sigma_{k_T}/dX}{d\sigma_{k_T}/dX} \simeq 1 + \frac{D\alpha_s^2 + E\alpha_s^3}{A\alpha_s + B\alpha_s^2}$$

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

Examples of diagrams contributing to incl. jets in Breit frame



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

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

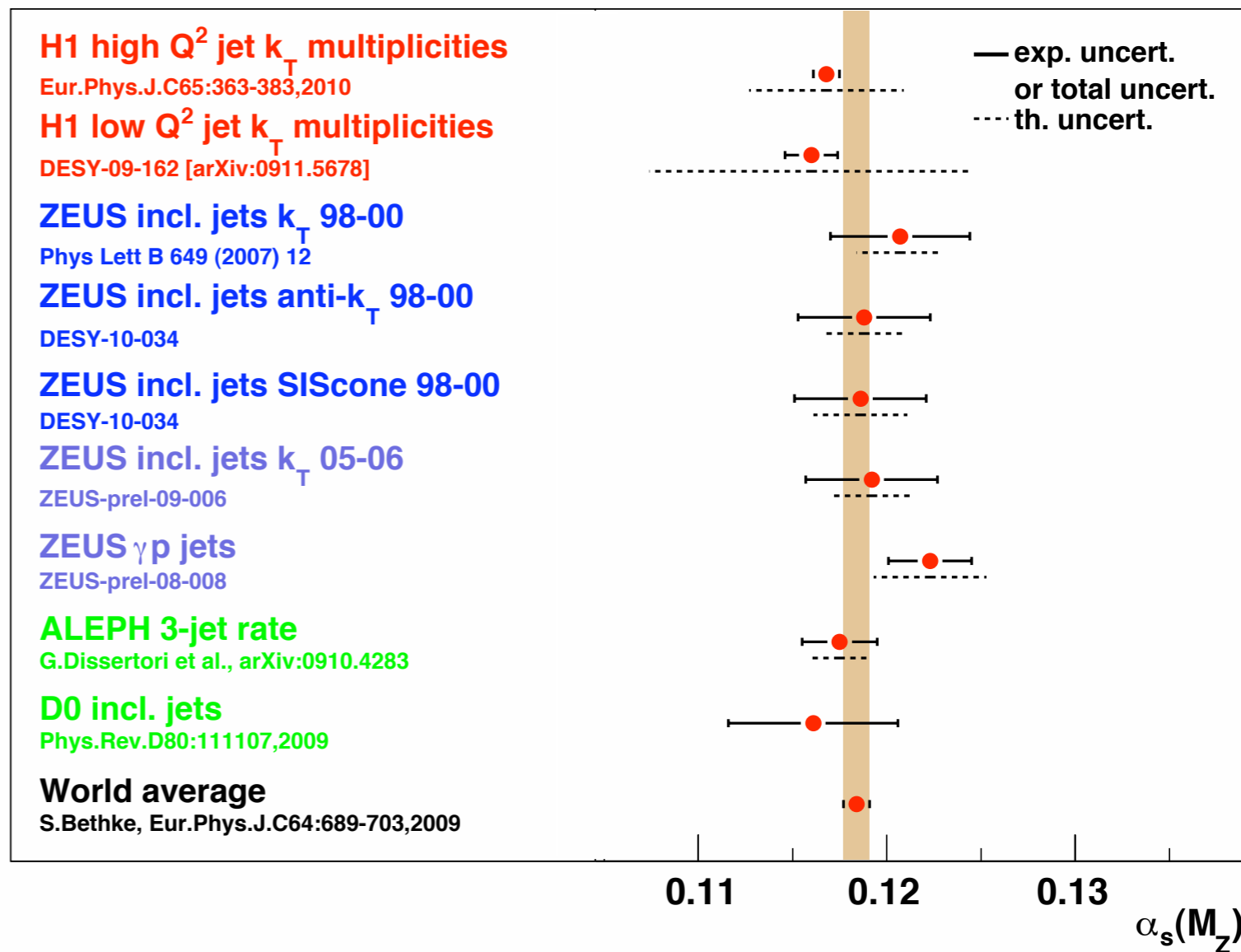
$$\text{anti-}k_T : \alpha_s(M_Z) = 0.1188 \pm 0.0014 \text{ (stat.) } \begin{matrix} +0.0033 \\ -0.0032 \end{matrix} \text{ (exp.) } \begin{matrix} +0.0022 \\ -0.0022 \end{matrix} \text{ (th.)}$$

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

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

Summary

- Multijet cross sections for $Q^2 < 100 \text{ GeV}^2$ 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 !

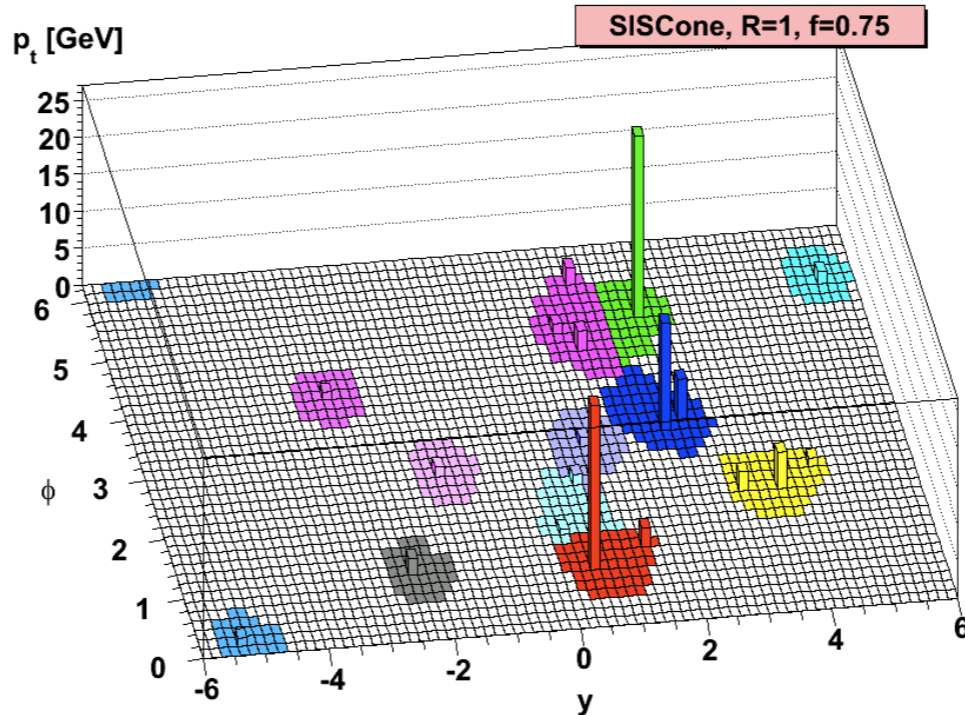
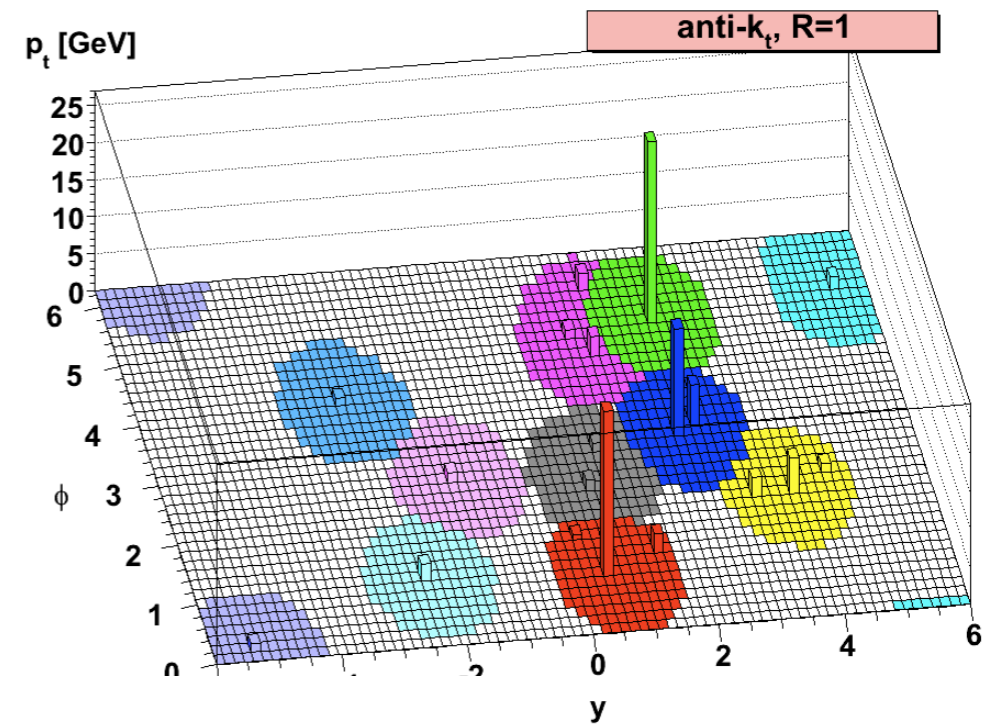
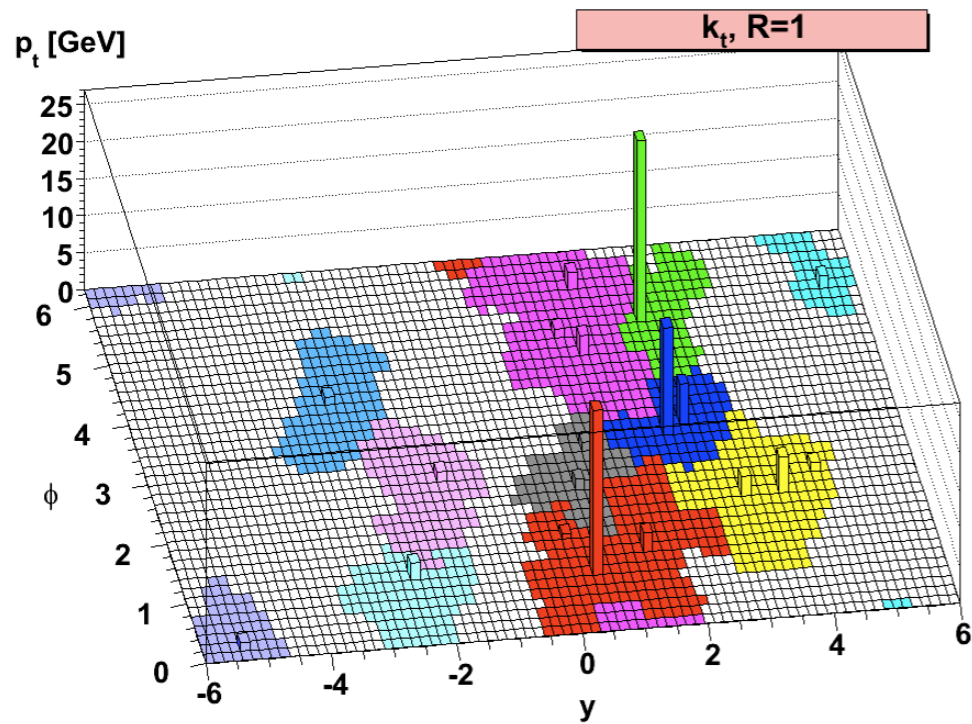
Further results from H1 & ZEUS:

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

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

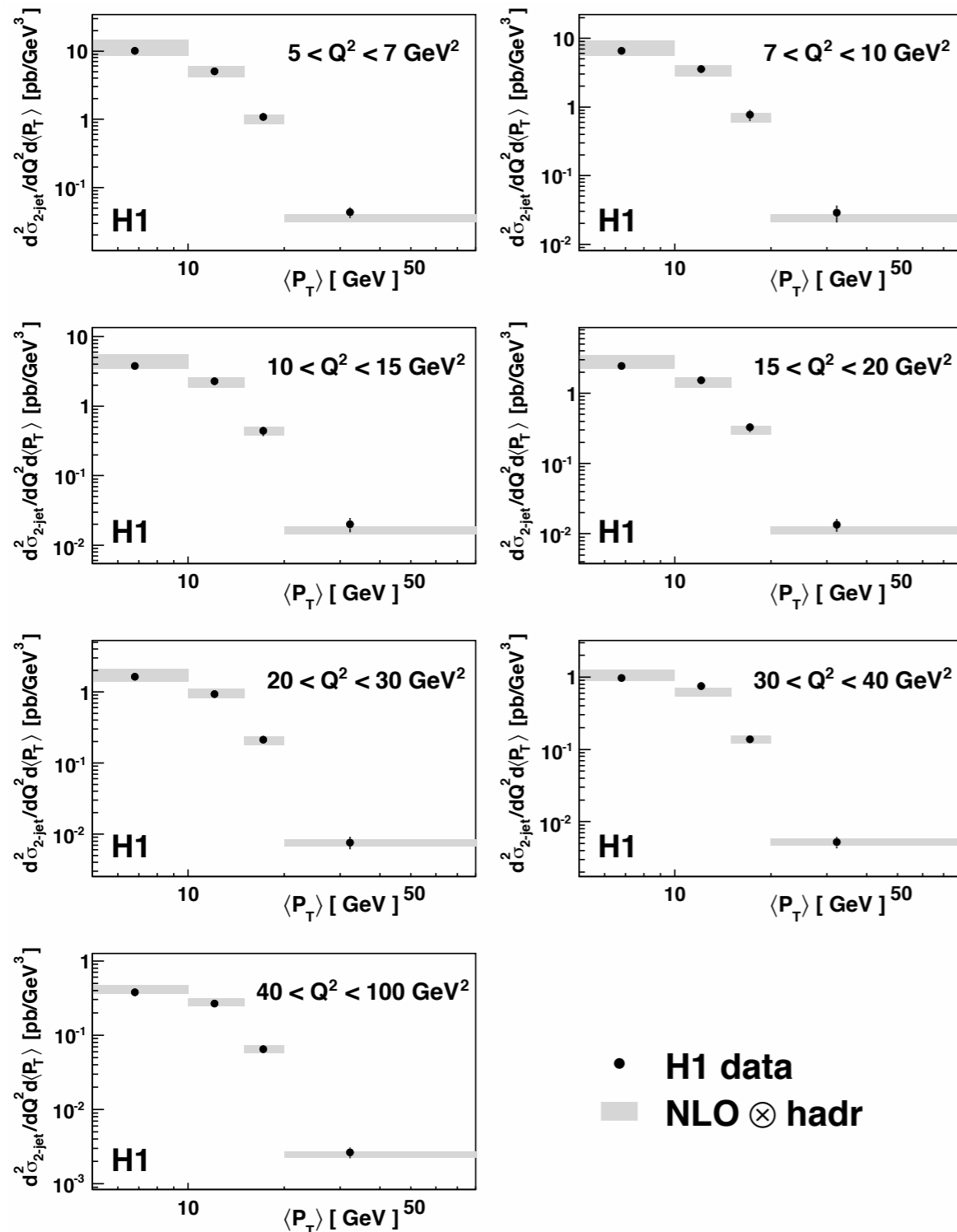


Jet finding: k_T , anti- k_T & SIScone

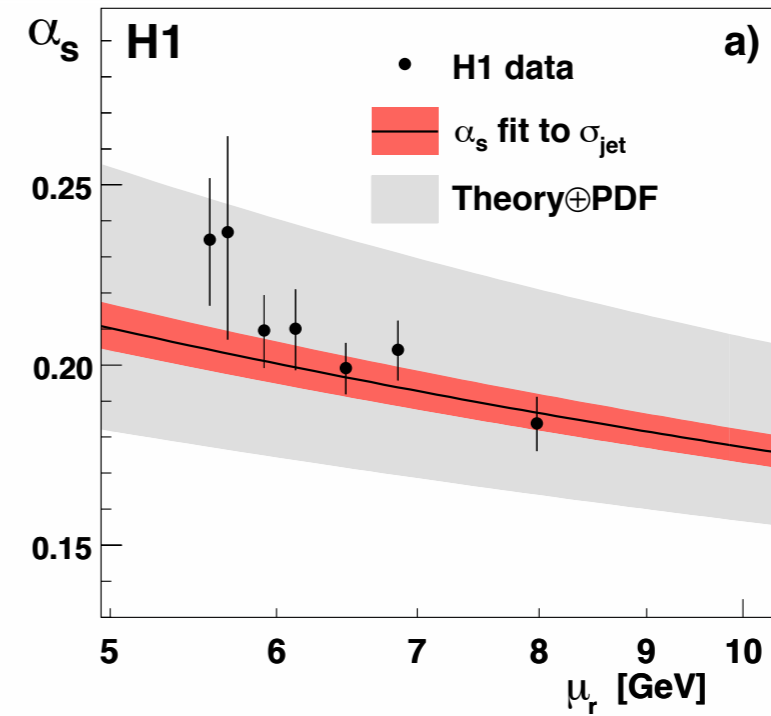


H1: 2-jets & α_s

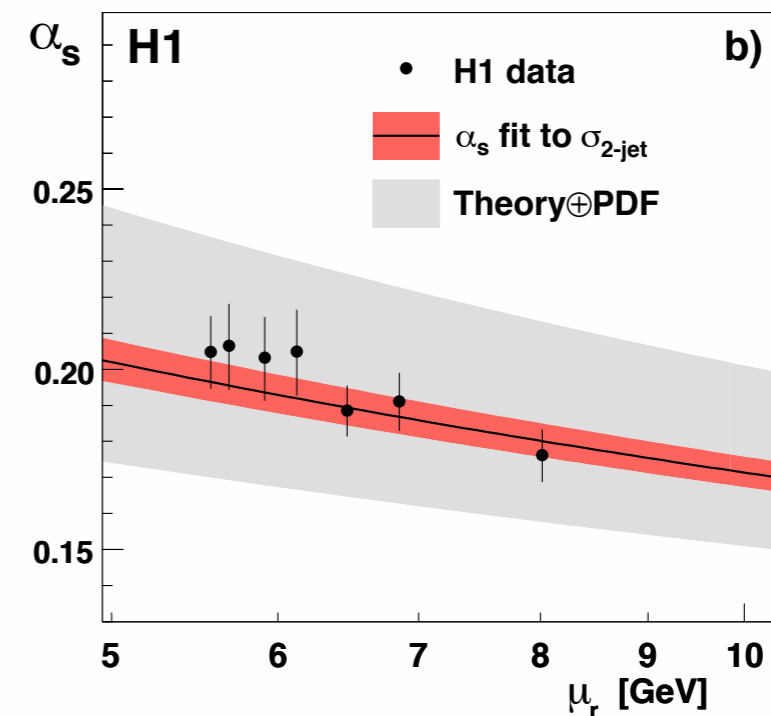
2-Jet Cross Section



α_s from Inclusive Jet Cross Sections

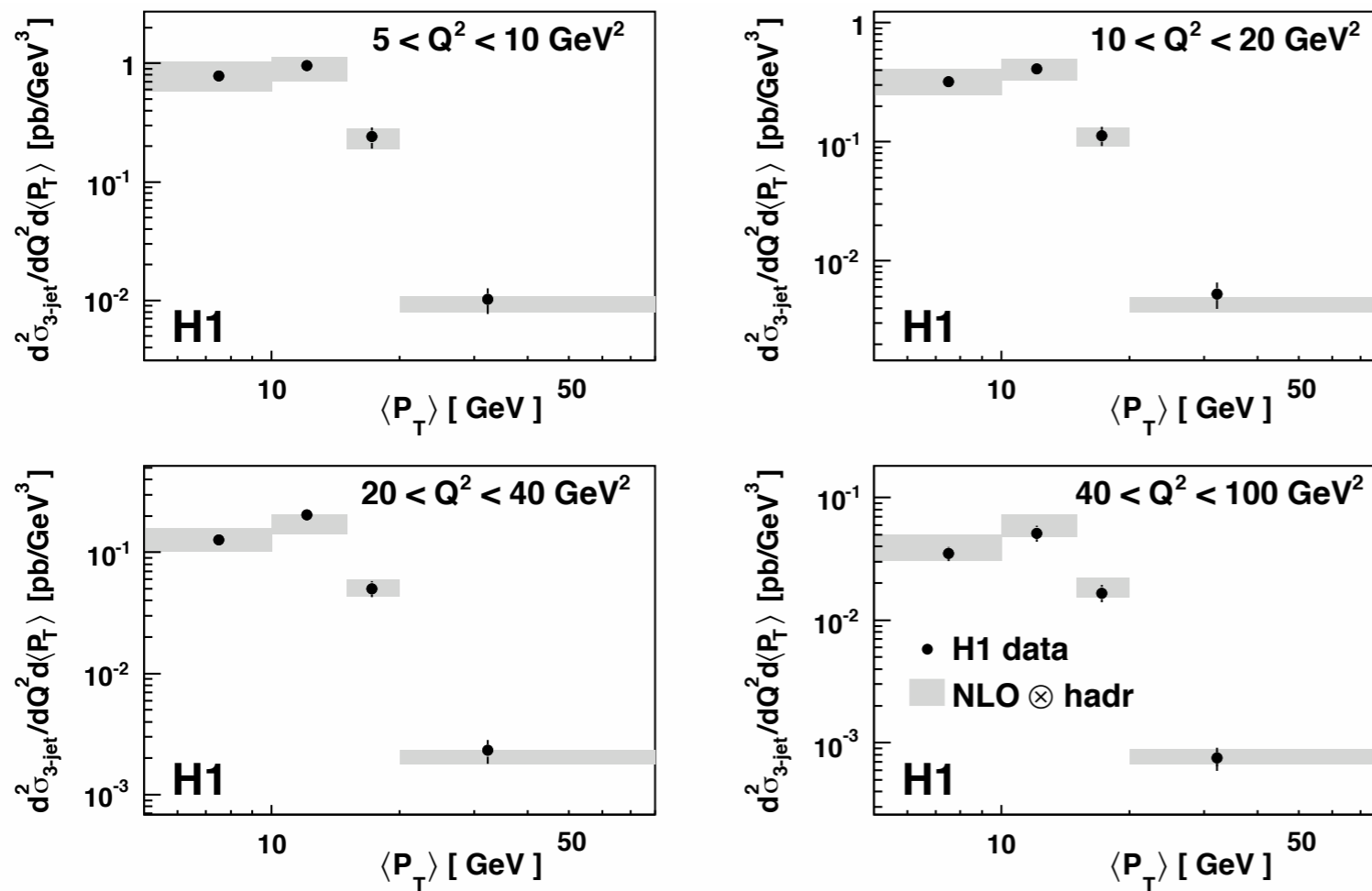


α_s from 2-Jet Cross Sections

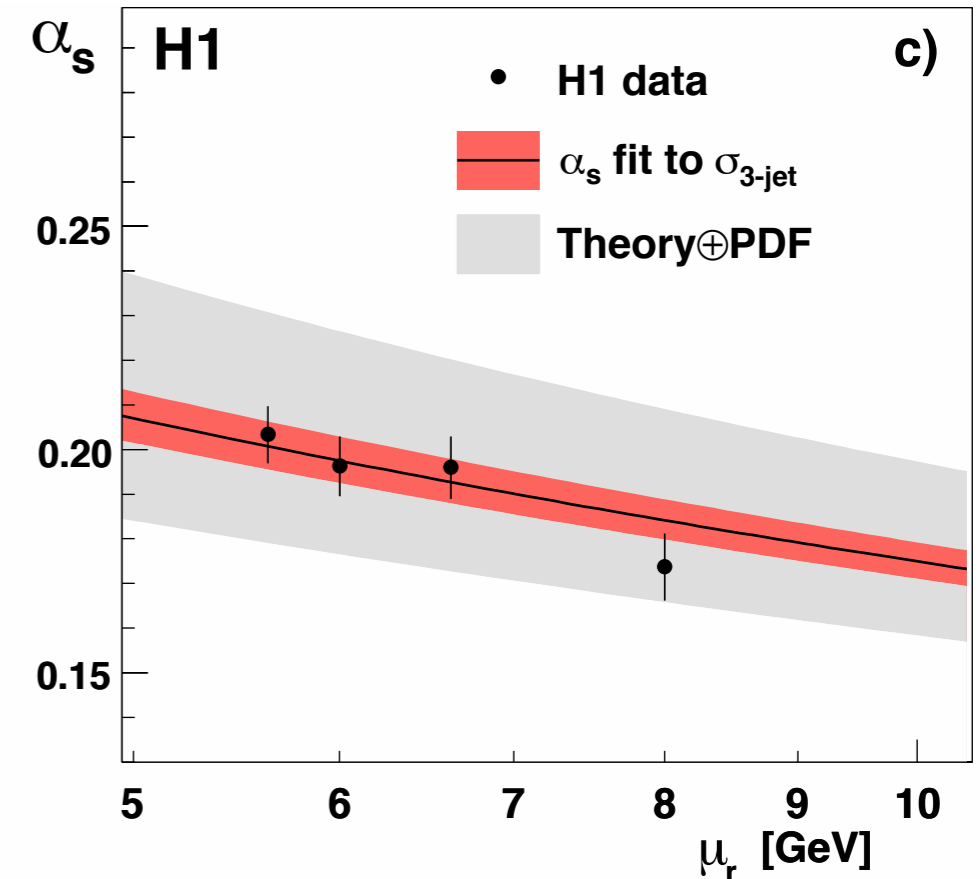


H1: 3-jets & α_s

3-Jet Cross Section

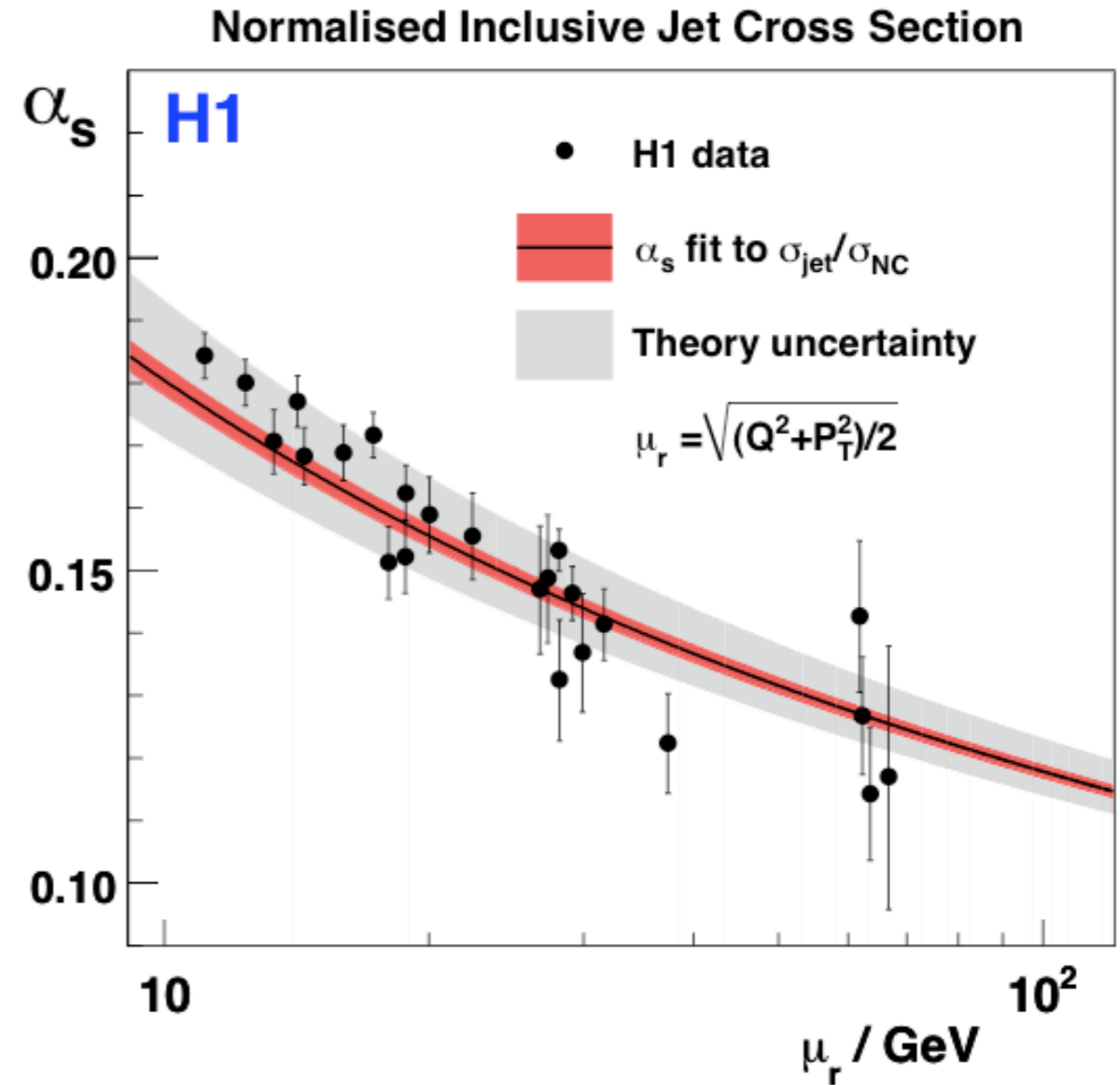
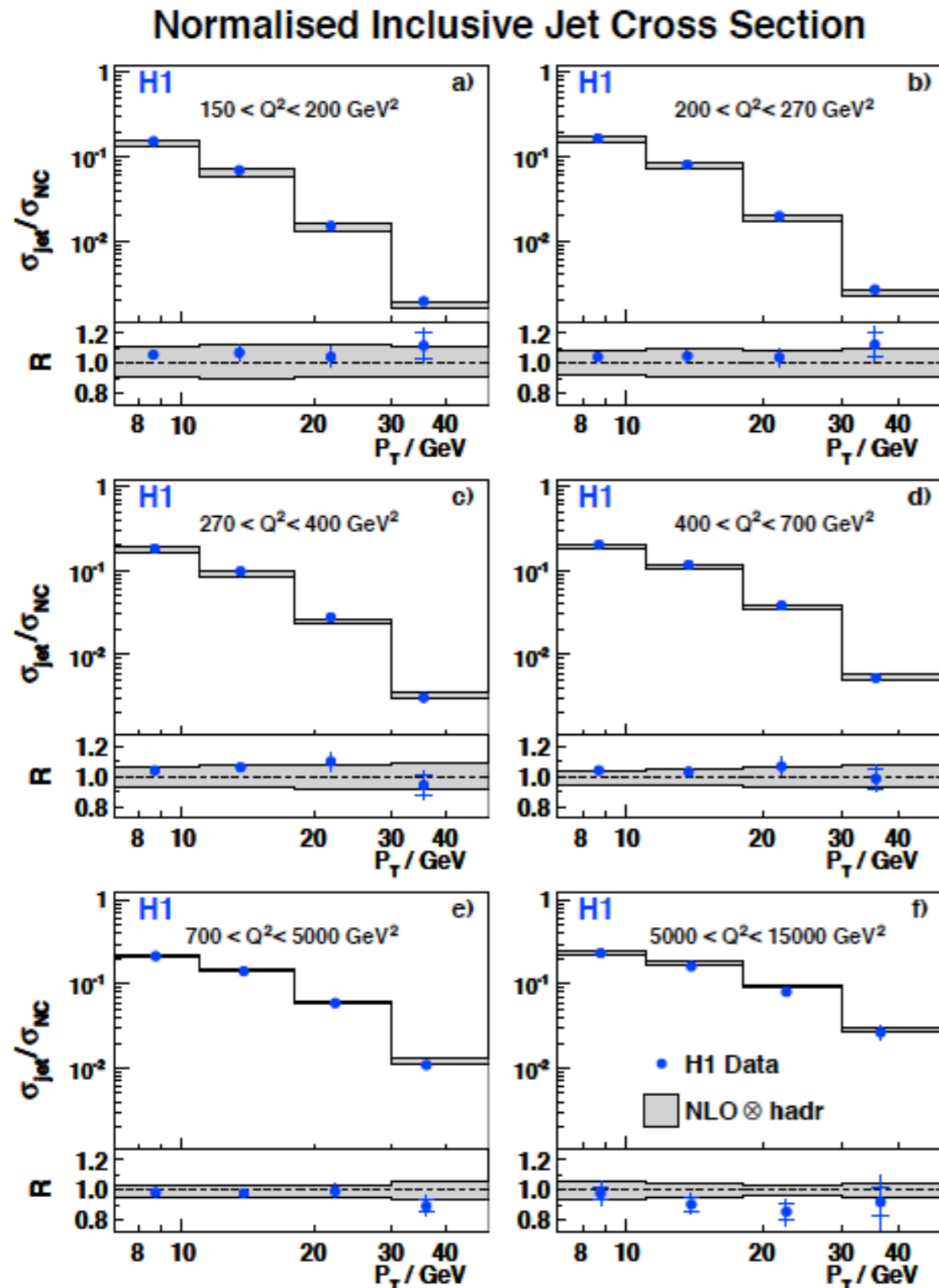


α_s from 3-Jet Cross Sections



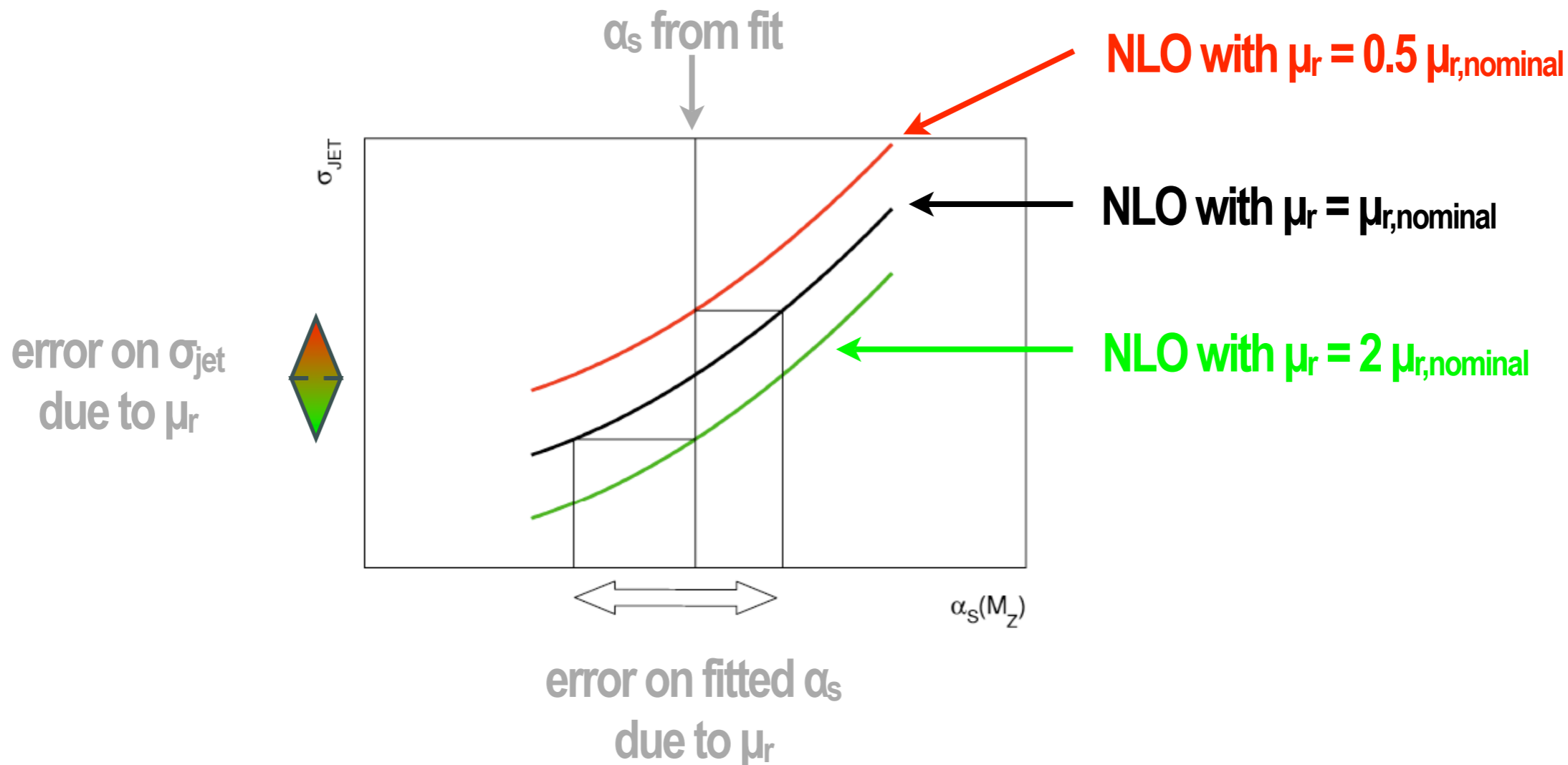
- NLOjet++ provides also a good description of the 3-jet cross section in NLO, i.e. $O(\alpha_s^3)$.

Jet multiplicity & Running α_s



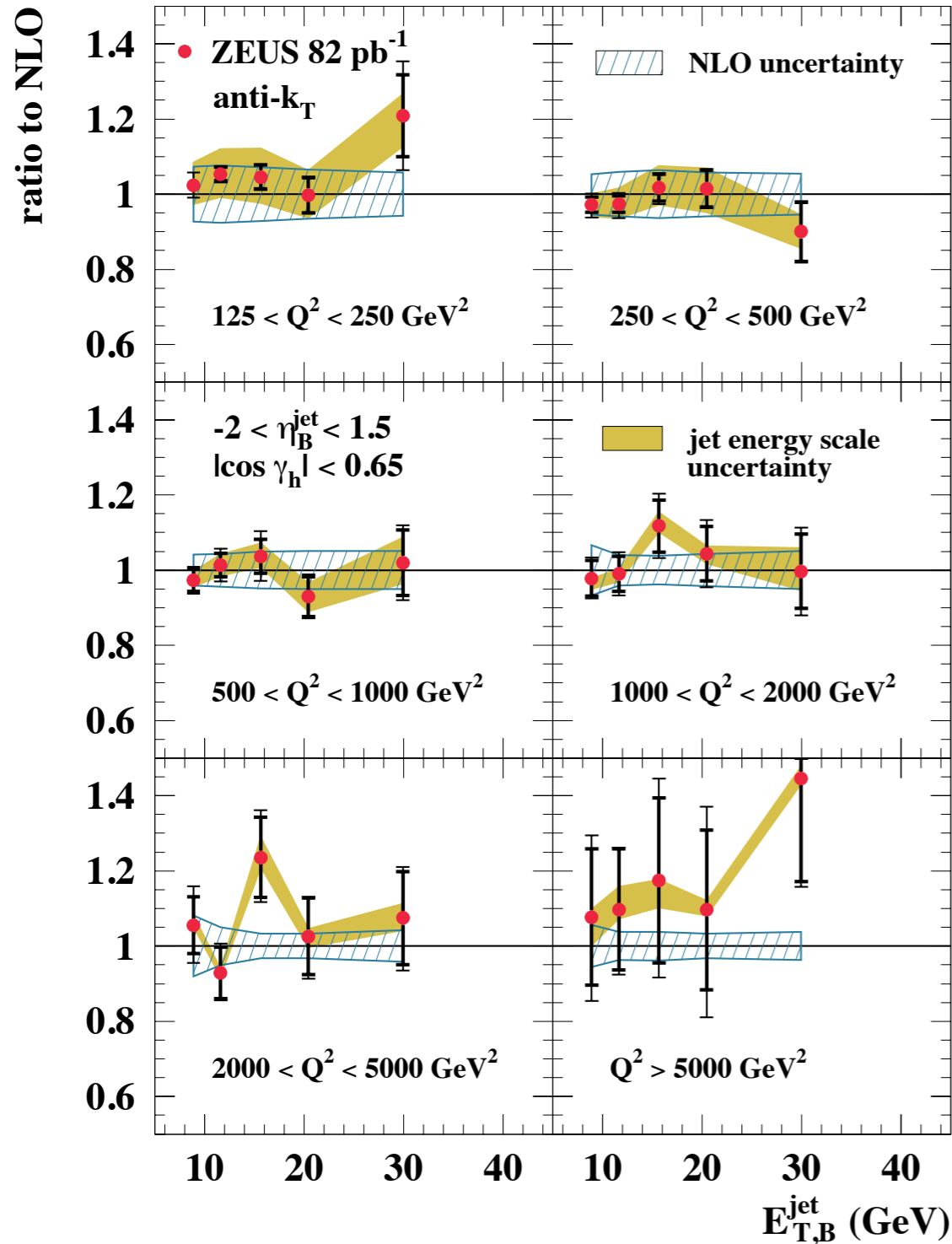
Theory uncertainty on $\alpha_s(M_Z)$

- 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

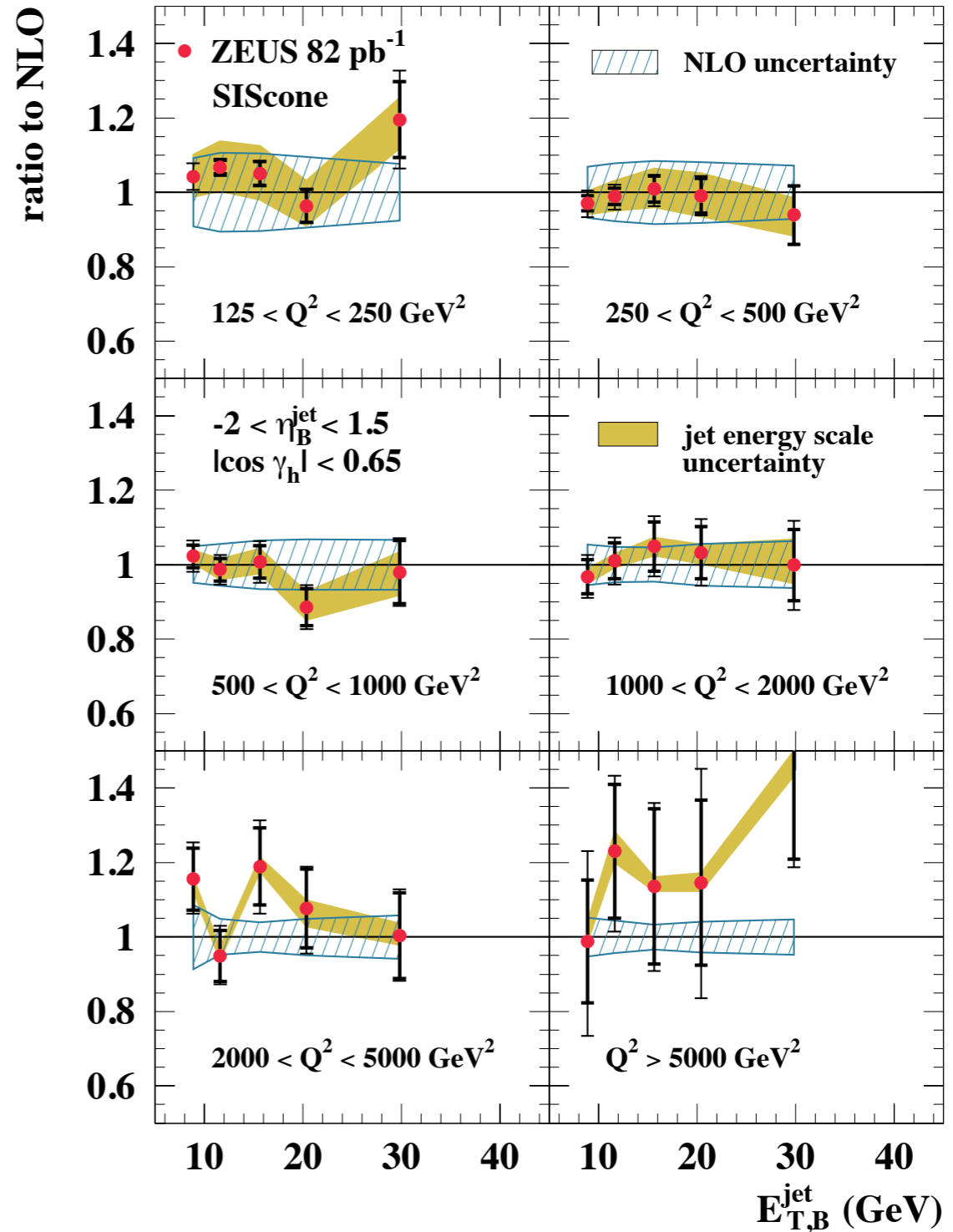


ZEUS: data/NLO for k_T & SIScone

ZEUS



ZEUS



Fitting $\alpha_s(M_Z)$: χ^2

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

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

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

*penalty term for fitted systematics
"Hessian" method*

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

correlated for some bins *uncorrelated systematics*

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

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