Jet measurements and α_s @ HERA

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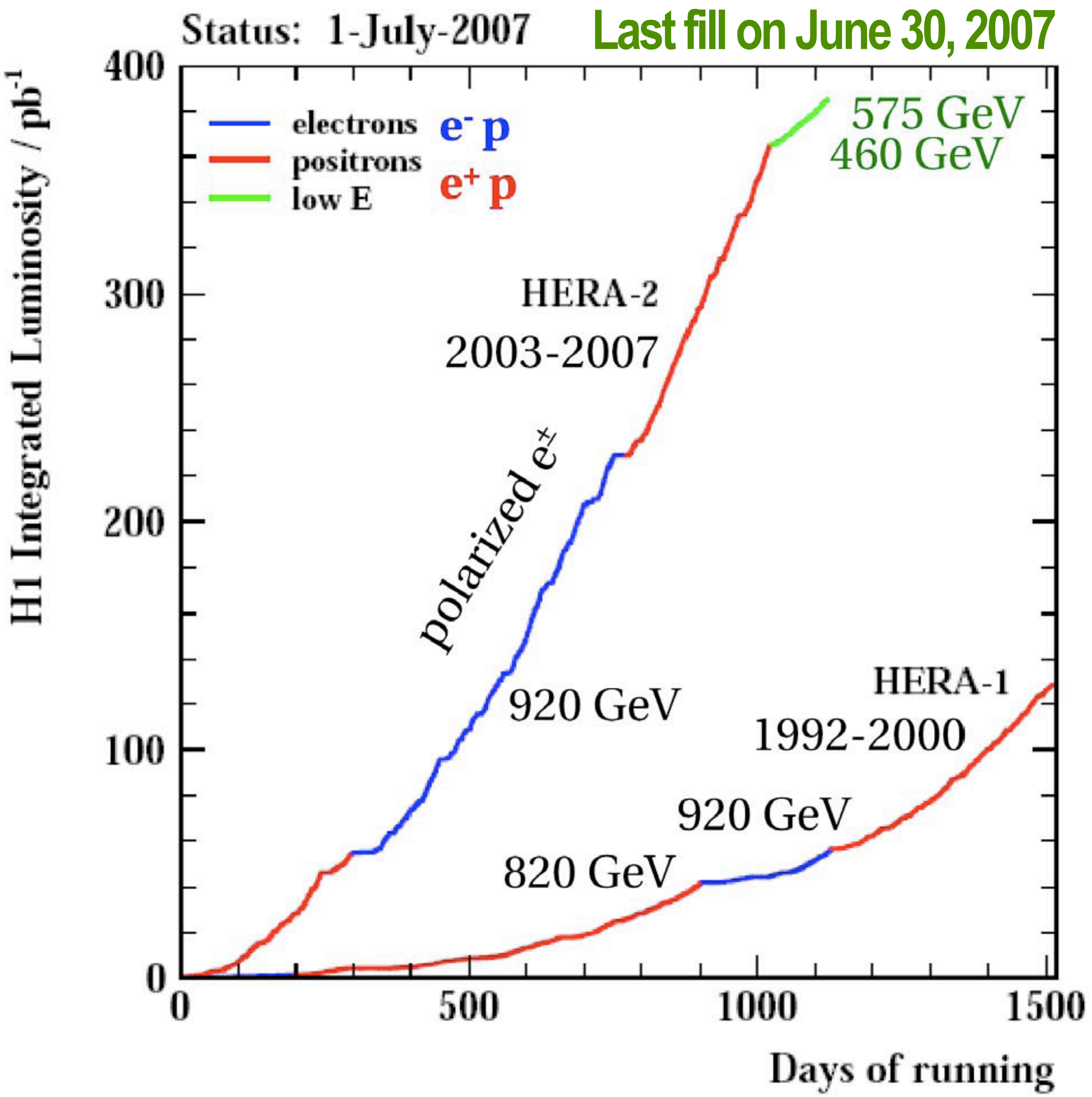
on behalf of H1 and ZEUS

June 30 - July 4 , Gatchina

- jet production in NC and CC
- jet structure
- pQCD, $\alpha_s(M_Z)$, pdfs

The ep collider HERA

HERA Luminosity



- HERA-1: 1992 - 2000
- HERA-2: 2003 - 2007
  - lumi upgrade
  - longitudinal polarisation of the lepton beams $< P_e > \approx$ 30 - 40 %
  - detector upgrades

➡ total lumi: 0.5 fb^{-1} per experiment

What can we study with jets ?

- Measurements of jets in DIS and PHP have provided rich results on:
  - parton dynamics
  - proton and photon pdfs
  - precise determinations of the strong coupling $\alpha_s(M_Z)$ and of its running

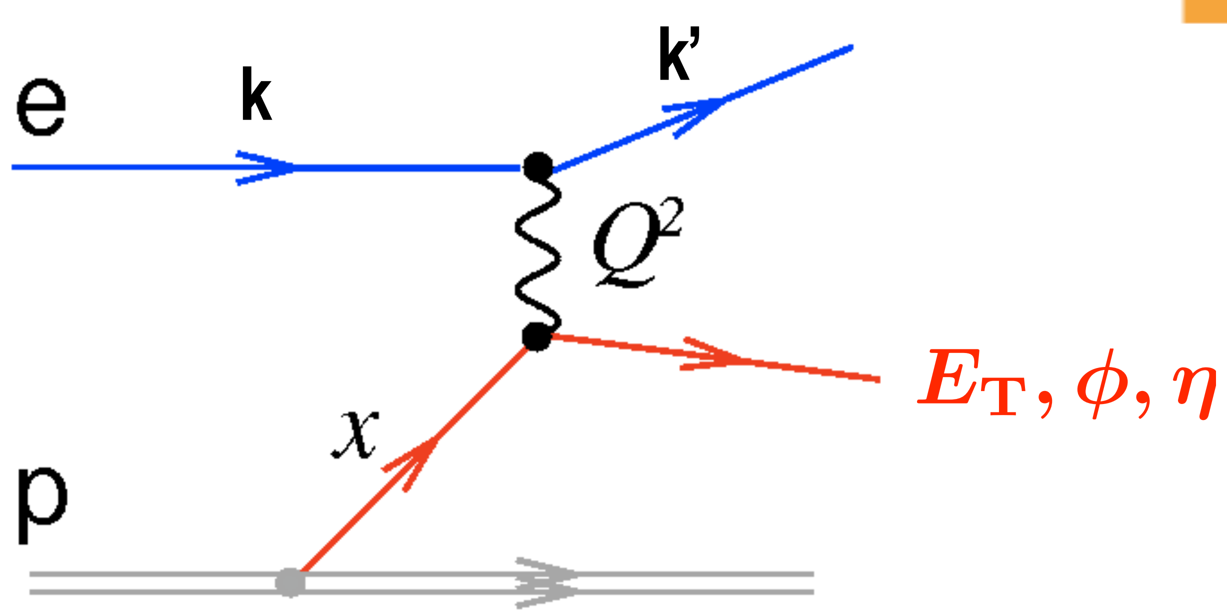
➡ In general these measurements are in excellent agreement with pQCD when hard scales (Q^2, $E_{T,jet}$, ...) are involved. Minor problems have appeared in special regions of phase space (low x_{Bj}), which may require the calculation of higher orders in DGLAP or evolution a la BFKL and un-integrated parton density functions

- Measurements of jet structure have provided insights on:
  - the differences between quark and gluon jets and heavy flavor jets
  - the transition from a parton produced in a hard process and the experimentally observed jet
  - These measurements have been shown to be reasonably well described by either pQCD calculations alone or by QCD based models including fragmentation

Here, we will review only some of the latest results from HERA in both areas

DIS & jet kinematics

- at fixed ep center-of-mass energy $\sqrt{s}$, the fully inclusive process can be described by only two independent kinematic variables, usually chosen among the following:
  - photon virtuality $Q^2 = -(k-k')^2$
  - inelasticity $y = (P\cdot q) / (P\cdot k)$
  - scaling variable $x_{Bj} = Q^2 / (2P\cdot q) = Q^2 / ys$

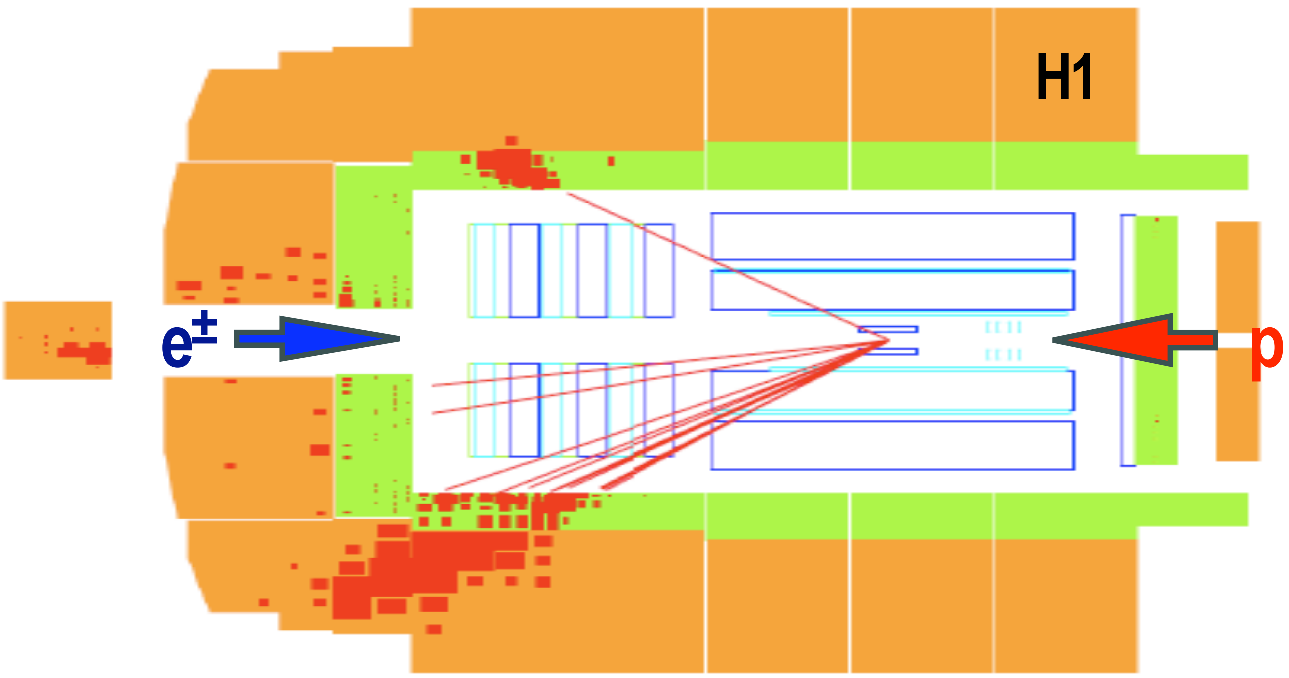


$(\eta = -\ln\tan(\theta/2))$

NC

$$\mathbf{Q_e^2 = 2E_eE_e'(1+\cos\theta_e')}$$

$$\mathbf{y = 1-(E'/2E_e)(1-\cos\theta_e')}$$

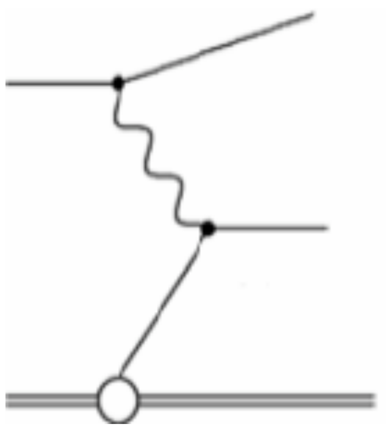
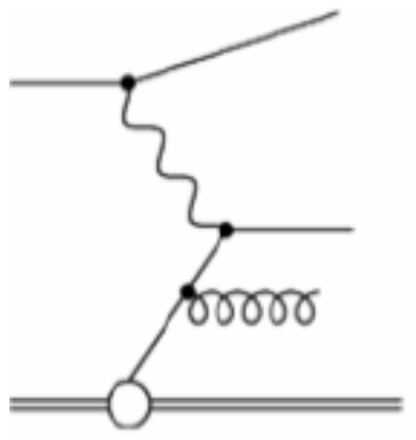
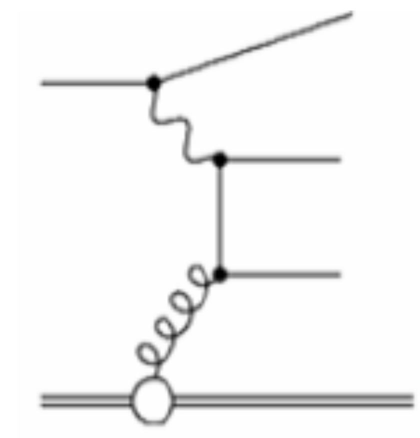
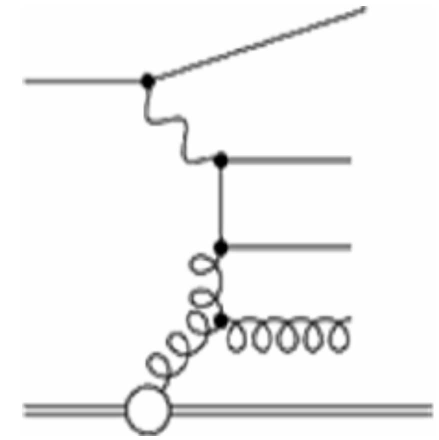


CC

$$\mathbf{Q_h^2 = p_{T,h}^2/(1-y_h)}$$

$$\mathbf{y_h = (E-p_z)_h/(2E_e)}$$

Jet production processes

QPM	QCDC	BGF	BGF+	
				…
$\mathcal{O}(\alpha)$	$\mathcal{O}(\alpha\alpha_s)$	$\mathcal{O}(\alpha\alpha_s)$	$\mathcal{O}(\alpha\alpha_s^2)$	

$$d\sigma_{\mathrm{n-jet}} = \sum_{i=q,\bar{q},g} \int dx\, f_i(x,\mu_f^2)\, d\hat{\sigma}_i(x,\alpha_s^{n-1}(\mu_r),\mu_r^2,\mu_f^2)$$

- to study pQCD in jet production in DIS, jet finding is usually done in the Breit frame in order to get rid of QPM jets, which have no E_T in that frame.
- to study the structure of jets one may want to also use QPM jets, and therefore such analyses are done in the Lab frame

Incl. jet cross sections $d^2\sigma/dQ^2dE_T$ (low Q^2)

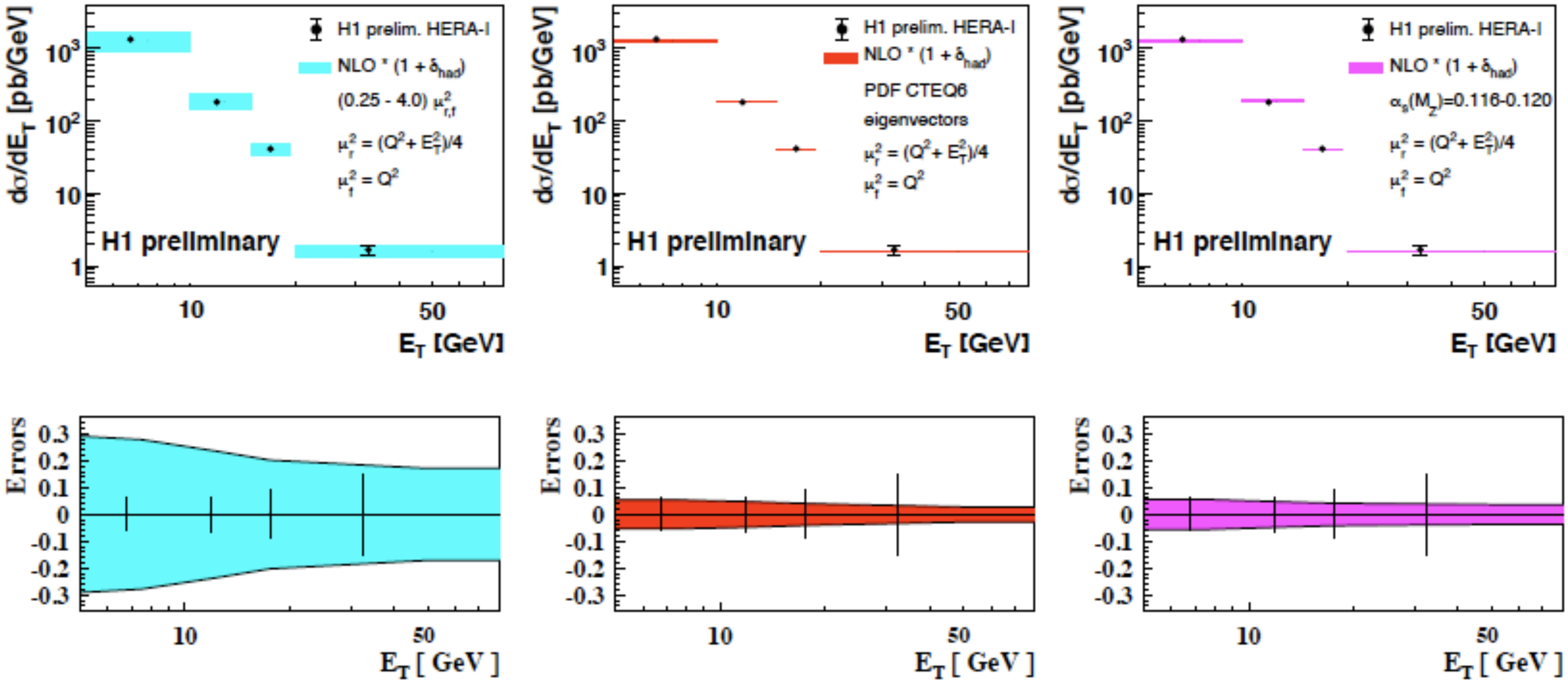
H1prelim-08-032

- H1 preliminary results from HERA I with luminosity of 43.5 pb^{-1}
- DIS phase space: $5 < Q^2 < 100$ GeV^2, $0.2 < y < 0.7$
- Jets are found in the Breit frame using the longitudinally invariant inclusive k_T cluster algorithm
  - $E_{T,jet} > 5$ GeV, $-1 < \eta_{lab} < 2.5$
  - largest syst. error due to 2% uncertainty on the hadronic energy scale, leading to 4 to 10% uncertainty on the cross section
  - measured are double differential cross sections in Q^2 and jet E_T

- NLO calculations: NLOJET++ and fastNLO, theory uncertainties and $\alpha_s(M_Z)$
  - $\mu_F^2 = Q^2$ and $\mu_R^2 = (Q^2+E_T^2)/4$
  - CTEQ6 proton pdfs, including their uncertainties
  - higher orders: $\mu_{R,F}$ varied between (0.5 - 2) $\mu_{R,F}$ separately
  - $\alpha_s(M_Z) = 0.118$, varied between 0.116 and 0.120

Incl. jet cross sections $d\sigma/dE_T$ $5 < Q^2 < 100$ GeV^2

▸ theory uncertainty ▸ pdf uncertainty ▸ $\alpha_s(M_Z)$ uncertainty

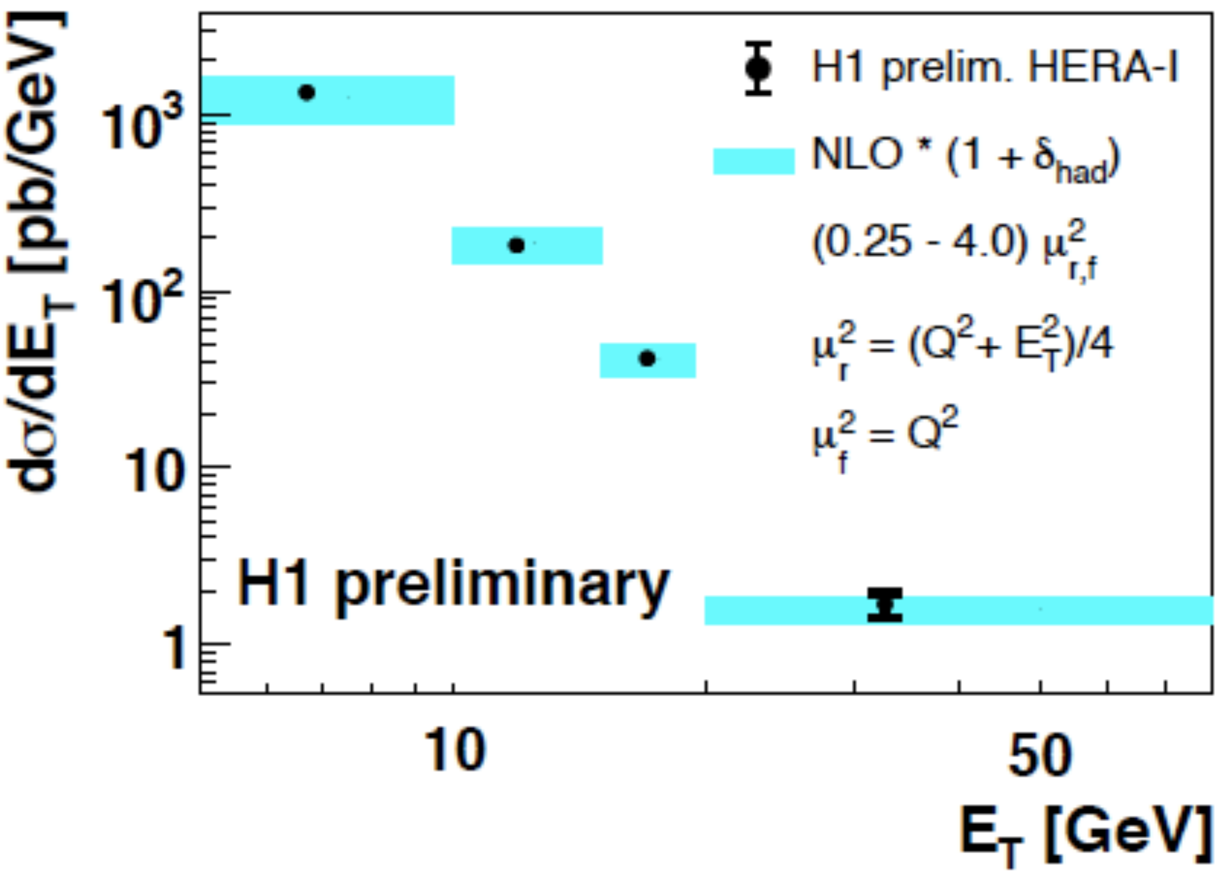


- uncertainty due to missing higher orders (ren. scale) dominates and increases with decreasing Q^2 and E_T ➔ need NNLO calculations
- uncertainties due to pdfs and $\alpha_s(M_Z)$ are of similar size

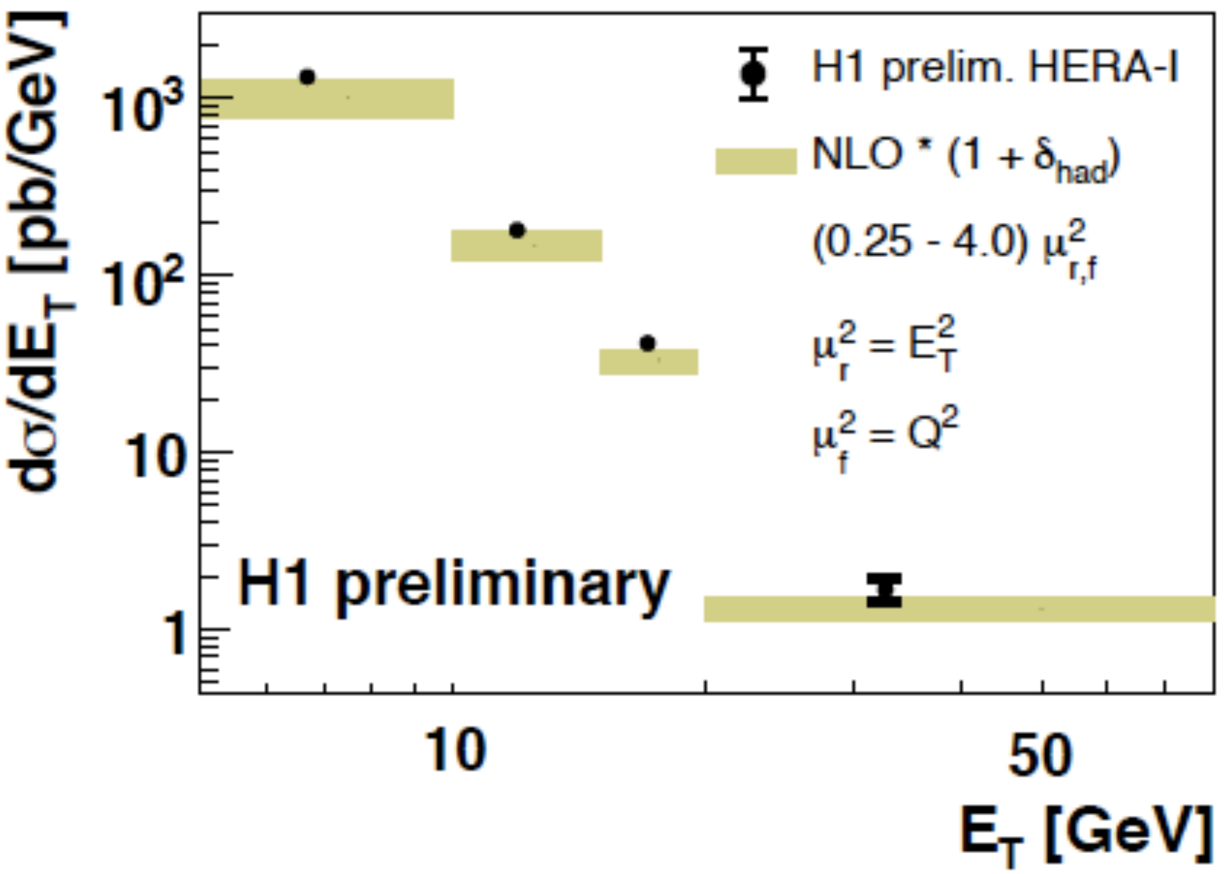
Incl. jet cross sections $d\sigma/dE_T$

- **sensivity to the choice of renormalization scale**

- $\mu_R^2 = (Q^2+E_T^2)/4$

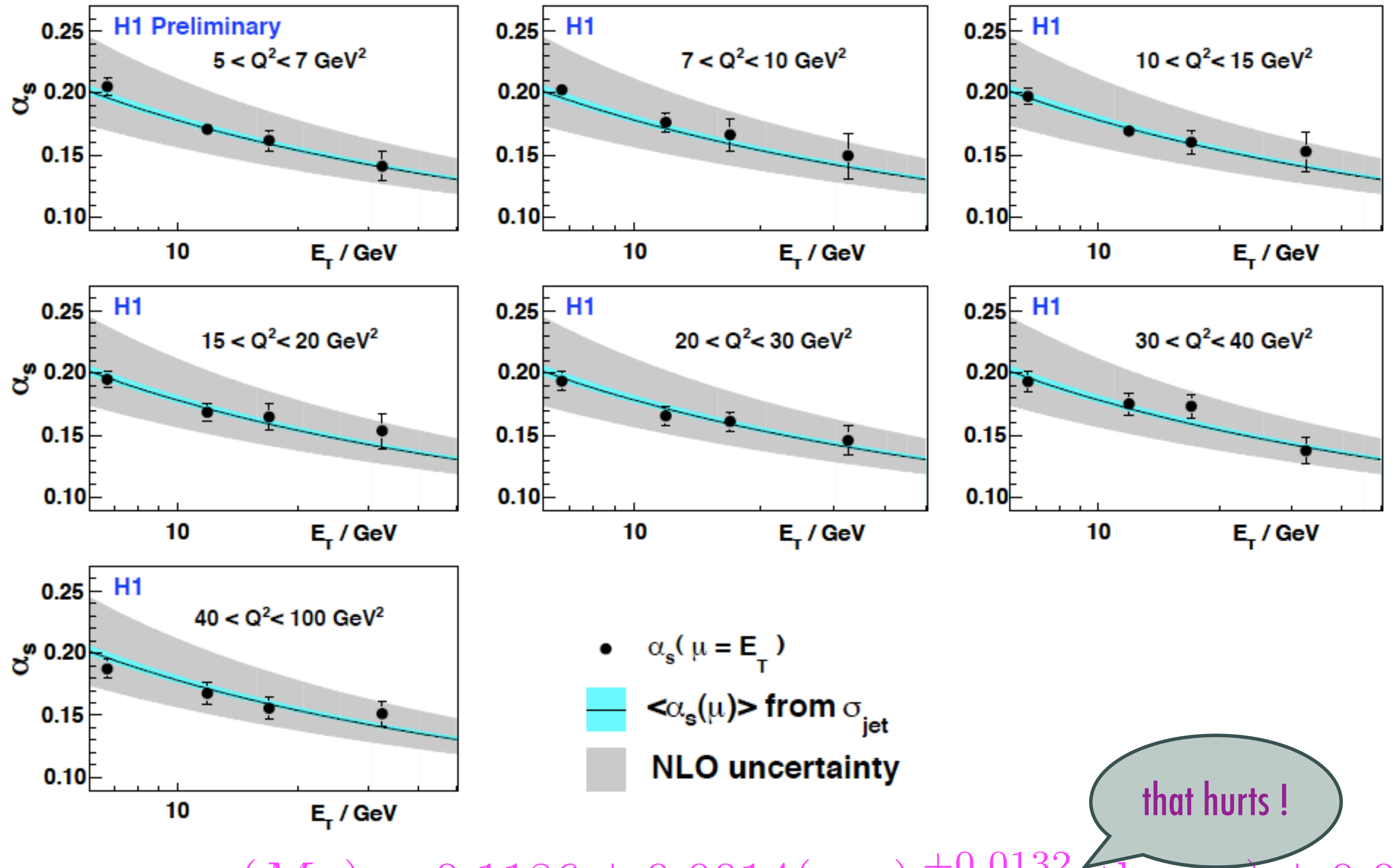


- $\mu_R^2 = E_T^2$



$\alpha_s(E_T)$ & $\alpha_s(M_Z)$ fitted to $d^2\sigma/dQ^2dE_T$ (low Q^2)

fitted values of $\alpha_s(E_T)$ & black line showing RGE evolved α_s from fit of $\alpha_s(M_Z)$ to the 28 measurements of $d^2\sigma/dQ^2dE_T$



$$\alpha_s(M_Z) = 0.1186 \pm 0.0014(\text{exp}) {}^{+0.0132}_{-0.0101}(\text{theory}) \pm 0.0021(\text{pdfs})$$

Norm. n-jet cross sections $\sigma_{n\text{-jet}}/\sigma_{NC}$ (high Q^2)

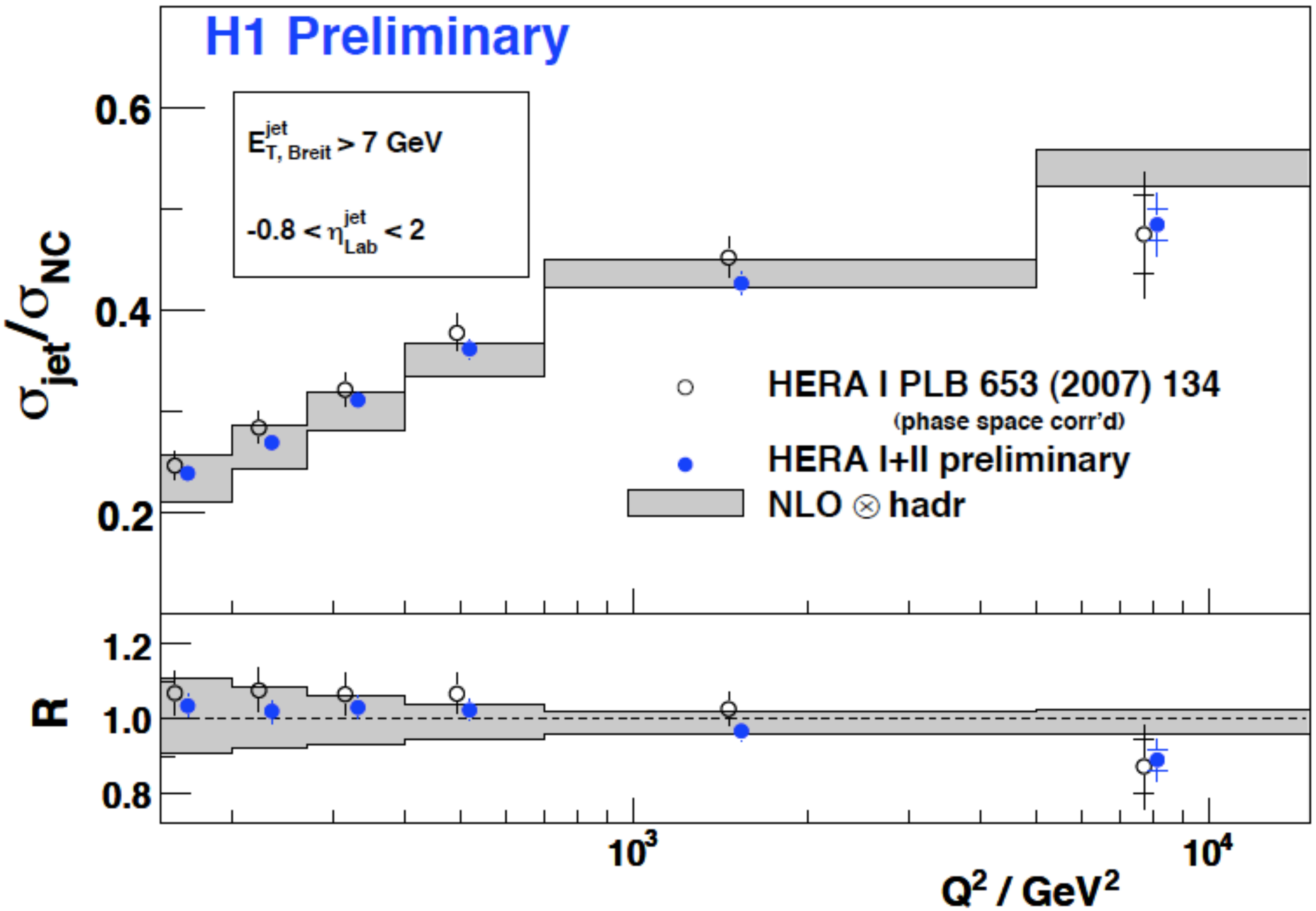
H1prelim-08-031

- H1 preliminary results from HERA I + II with luminosity of 395 pb^{-1}
- DIS phase space: $150 < Q^2 < 15000$ GeV^2, $0.2 < y < 0.7$
- jets in Breit frame using the longitudinally invariant inclusive k_T cluster algorithm
  - $E_{T,jet} > 7$ GeV, $-0.8 < \eta_{lab} < 2.0$, for 2 (3) - jets in addition: $M_{12} > 16$ GeV
  - normalized cross sections $\sigma_{n\text{-jet}}/\sigma_{NC}$ as function of Q^2 and jet E_T or mean jet E_T
    ➜ luminosity uncertainty cancels completely and correlated errors partially
  - largest syst. uncertainty: 1.5% uncertainty on jet energy ➜ 1 to 3% on the normalized cross section

- NLO calculations: NLOJET++ and fastNLO, theory uncertainties and $\alpha_s(M_Z)$
  - for inclusive jets: $\mu_F^2 = Q^2$ and $\mu_R^2 = (Q^2 + E_T^2)/4$; for 2 (3) - jets: $\mu_R^2 = \mu_F^2 = Q^2$
  - proton pdfs: CTEQ65M including uncertainties
  - uncertainty du to higher orders: $\mu_{R,F}$ varied between (0.5 - 2) $\mu_{R,F}$
  - $\alpha_s(M_Z) = 0.118$, varied between 0.116 and 0.120

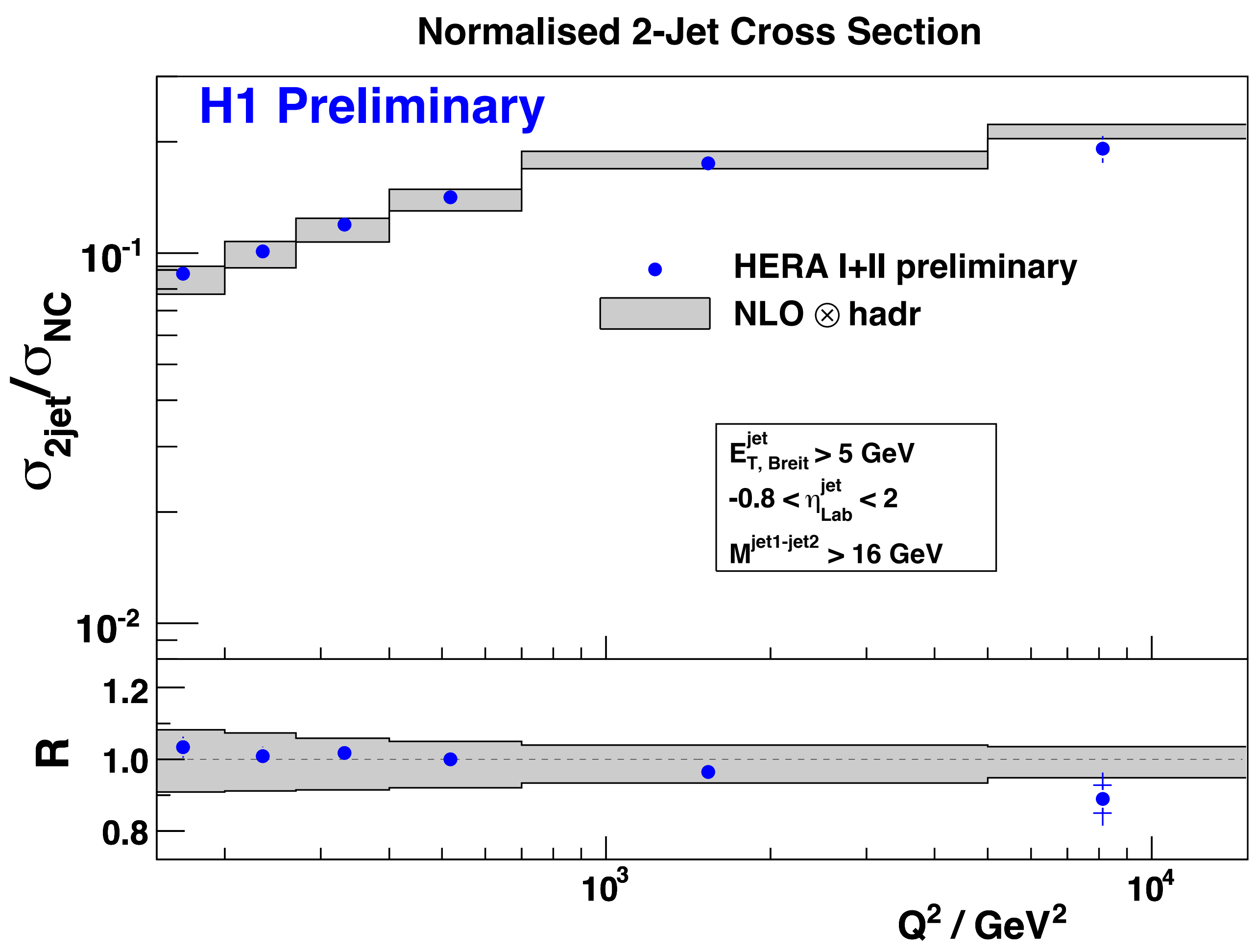
For lack of time the normalized cross sections will only be shown as a function of Q^2

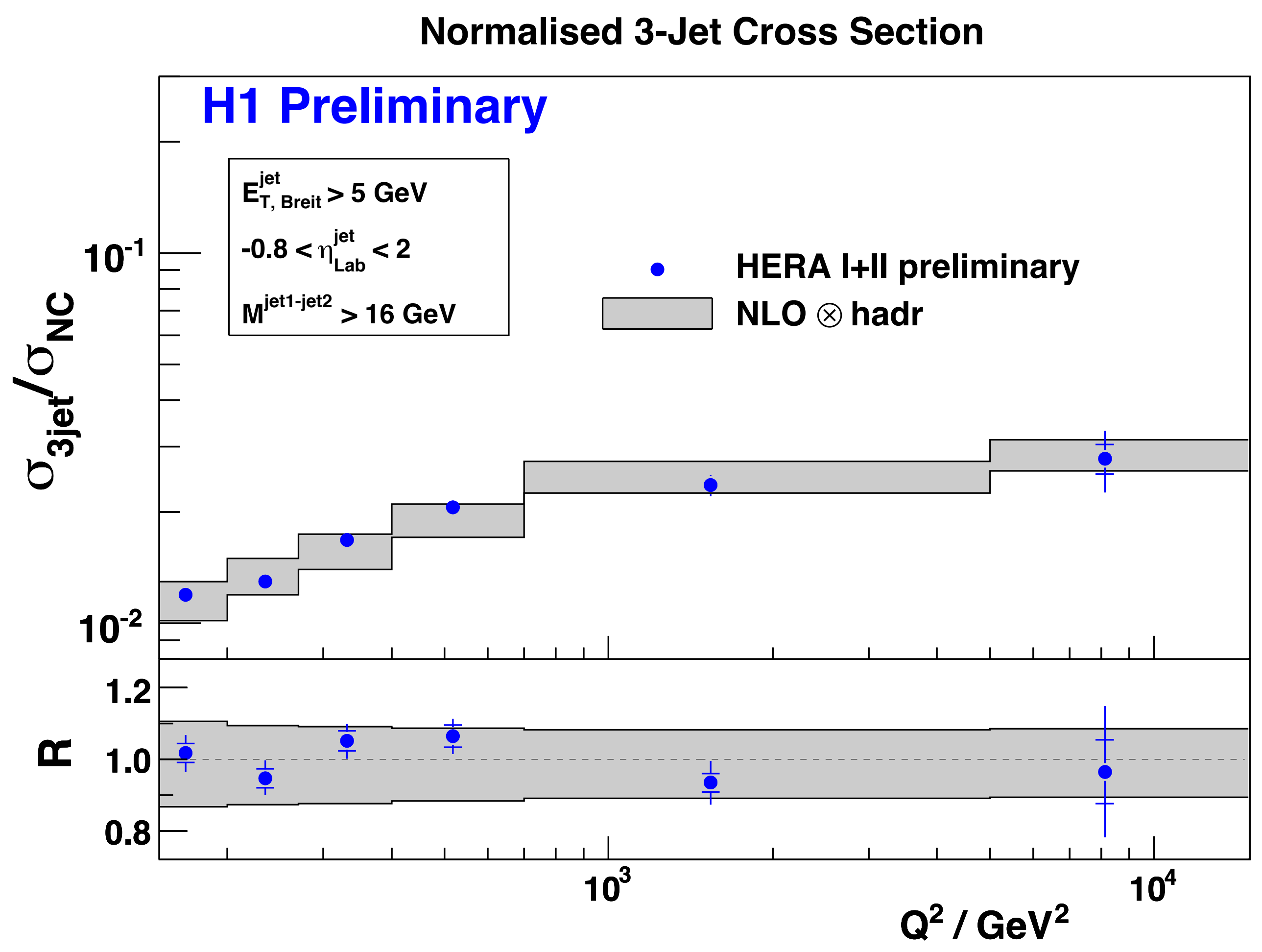
Normalized inclusive jet cross section



- HERA I+II prel. results consistent with published HERA I results, but significantly reduced uncertainty due to increased statistics and reduced jet energy scale uncertainty
- the data are well described by NLO QCD predictions
- “conventional” theory uncertainty > experimental uncertainty

Normalized 2 (3) - jet cross sections





- Measured normalized 2 (3) - jet cross sections well described by NLO
- Measurement errors in all cases < theory uncertainty

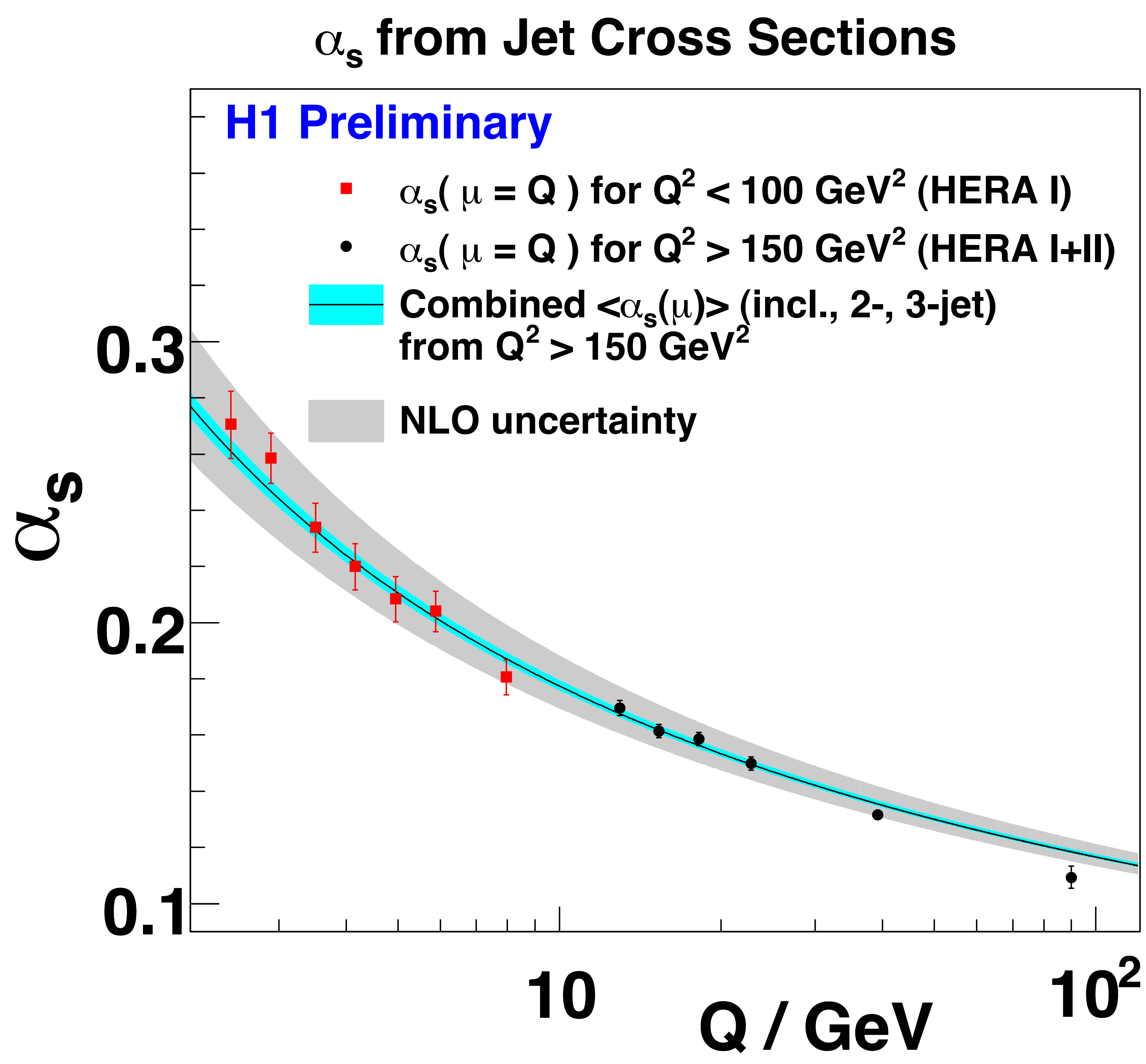
Extractions of α_s

- NLO with $\alpha_s(M_Z)$ as free parameter is fitted to normalized jet cross sections
- $\chi^2(\alpha_s)$ is calculated from measurement and NLO with the Hessian method, with sources of correlated systematic uncertainties, for example the jet energy scale, left free in the fit, allowing to check consistency with expectations. Statistical correlations are also taken into account.
- theoretical uncertainties: offset method is used, i.e. renormalization and factorization scales, hadronization corrections and pdfs are varied within their uncertainties and $\alpha_s(M_Z)$ is refitted. The resulting variations, added in quadrature, provide the total theoretical error.

Measurement	$\alpha_S(M_Z)$	exp.error	scale error		PDF error	χ^2/ndf
$\sigma_{Incl.JET}/\sigma_{DIS} = f(Q^2, E_T)$	0.1196	0.0010	+0.0049	-0.0036	0.0019	26.8/23
$\sigma_{2JET}/\sigma_{DIS} = f(Q^2, < E_T >)$	0.1171	0.0010	+0.0048	-0.0036	0.0018	28.1/23
$\sigma_{3JET}/\sigma_{DIS} = f(Q^2)$	0.1179	0.0014	+0.0056	-0.0034	0.0009	4.53/5
$\sigma_{Incl.JET}/\sigma_{DIS}, \sigma_{2JET}/\sigma_{DIS}, \sigma_{3JET}/\sigma_{DIS}$	0.1182	0.0008	+0.0041	-0.0031	0.0018	55.8/53

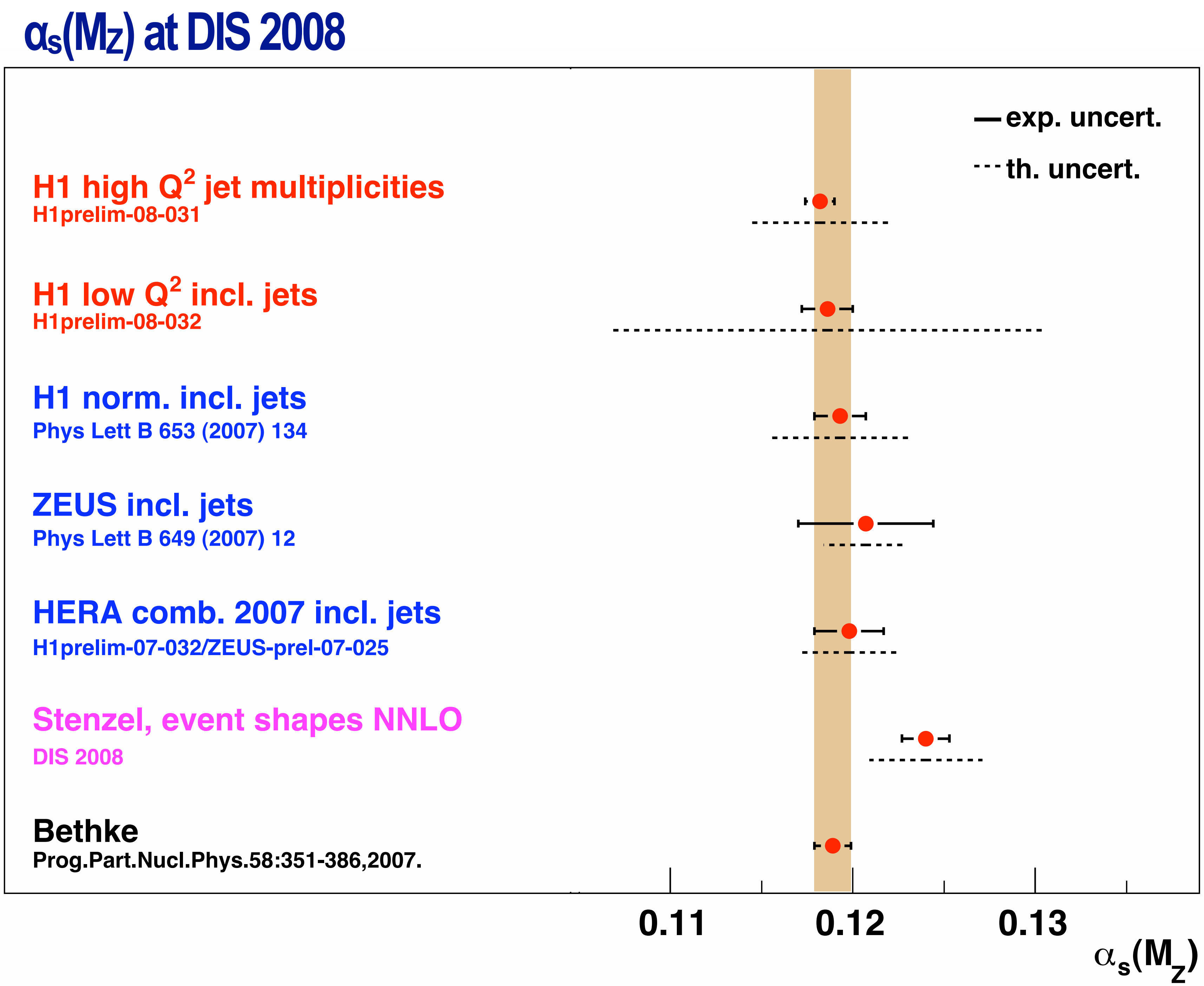
- precise and consistent result: small exp. error (0.7%), theory error (3.5%) mainly due to μ_R
- in good agreement with the result at low Q^2
- exp. error as small as best results from LEP
- looking forward to NNLO calculations !

Running of α_s



- $\alpha_s(Q)$ from low and high Q^2
- $\alpha_s(M_Z)$ from fit to high Q^2 data, evolved down to low Q^2 data
- good consistency from high to low Q^2

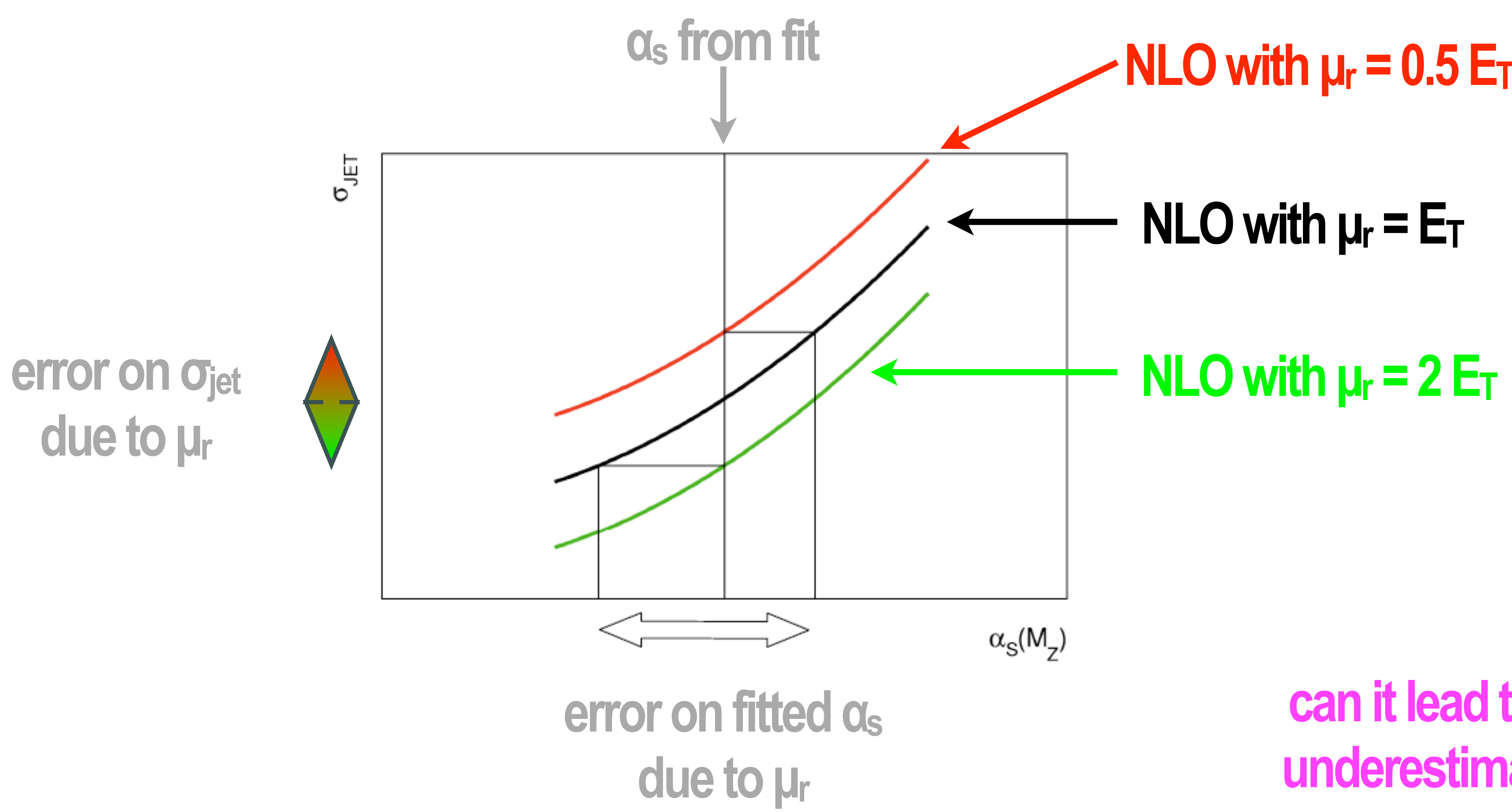
Summary of various extractions of $\alpha_s(M_Z)$



- excellent experimental precision has been reached
- HERA comb. 2007
  - used latest published inclusive jet cross sections from H1 and ZEUS in a combined fit.
  - alternative method used to estimate theoretical uncertainty

Theory error (renormalization scale)

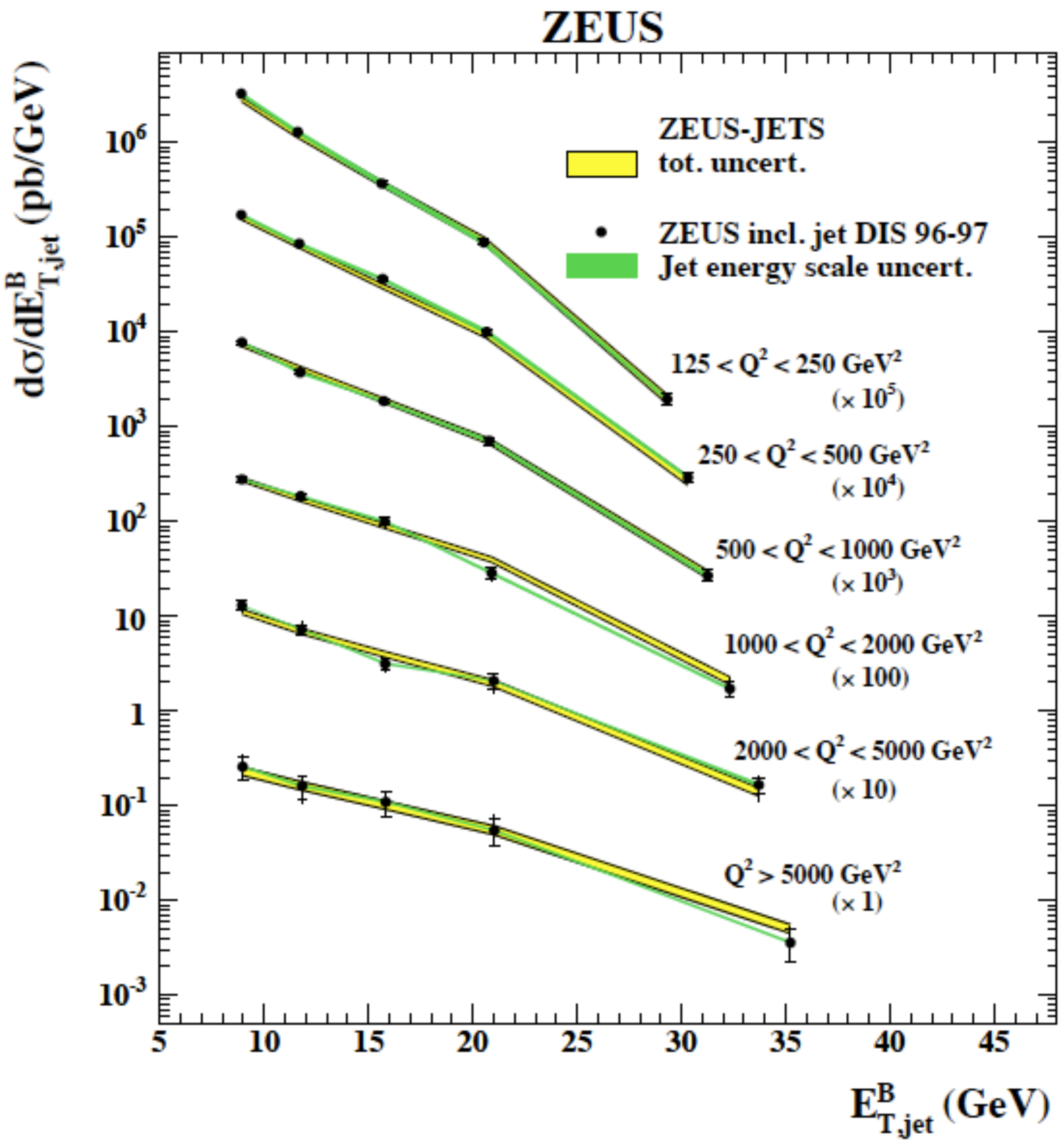
- method 1: the fit of $\alpha_s(M_Z)$ to the data is repeated with μ_R scaled by 0.5 and 2 in the NLO calculation, and the difference to the result with the nominal scale is taken as error.
  - ➡ the theory error depends on the data
  - ➡ due to limited statistics and fluctuations in the data, this method may lead to an overestimate
- method 2: only theory is used (a la Jones et al., JHEP 122003007), no refit to data

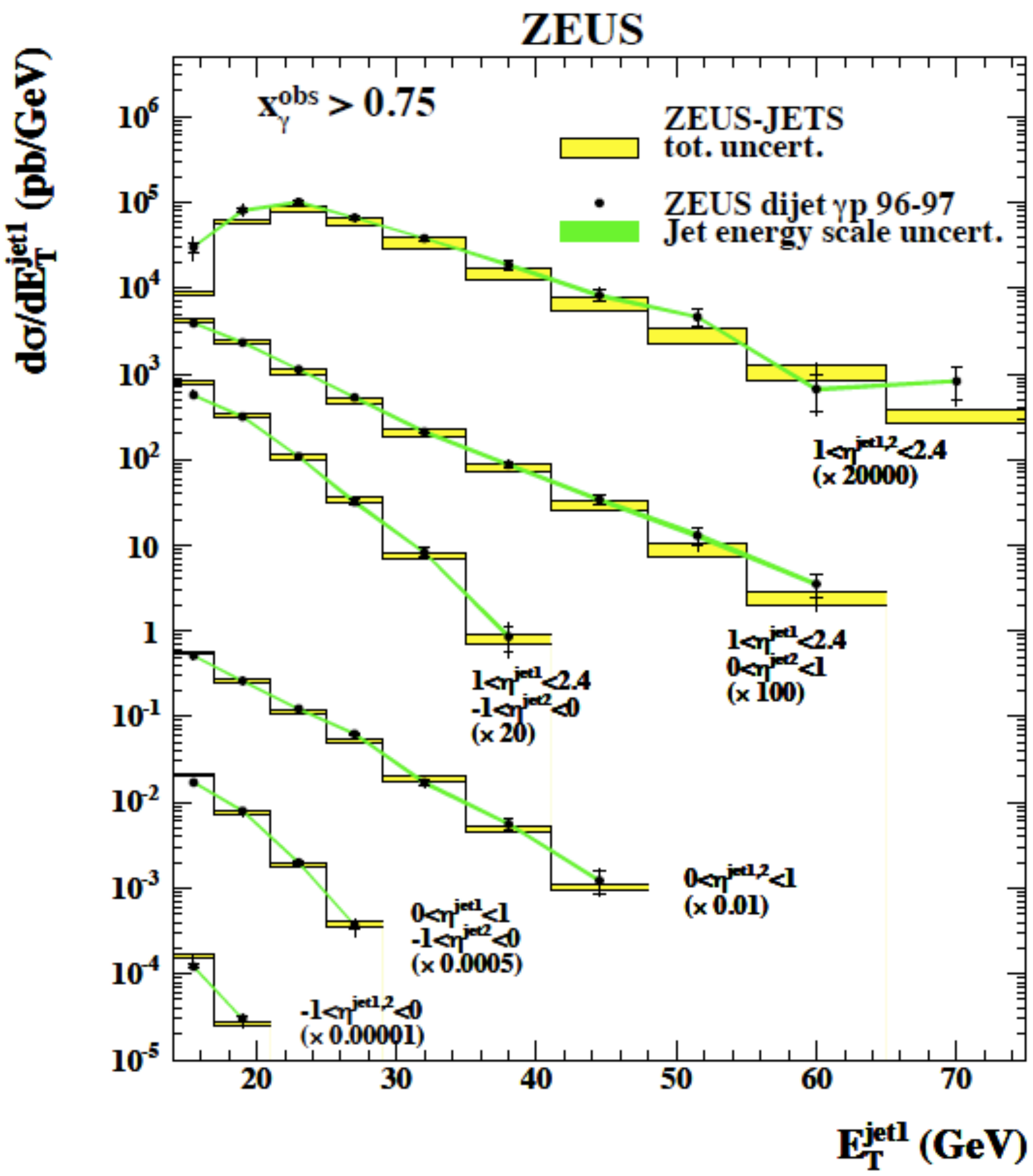


can it lead to an underestimate ?

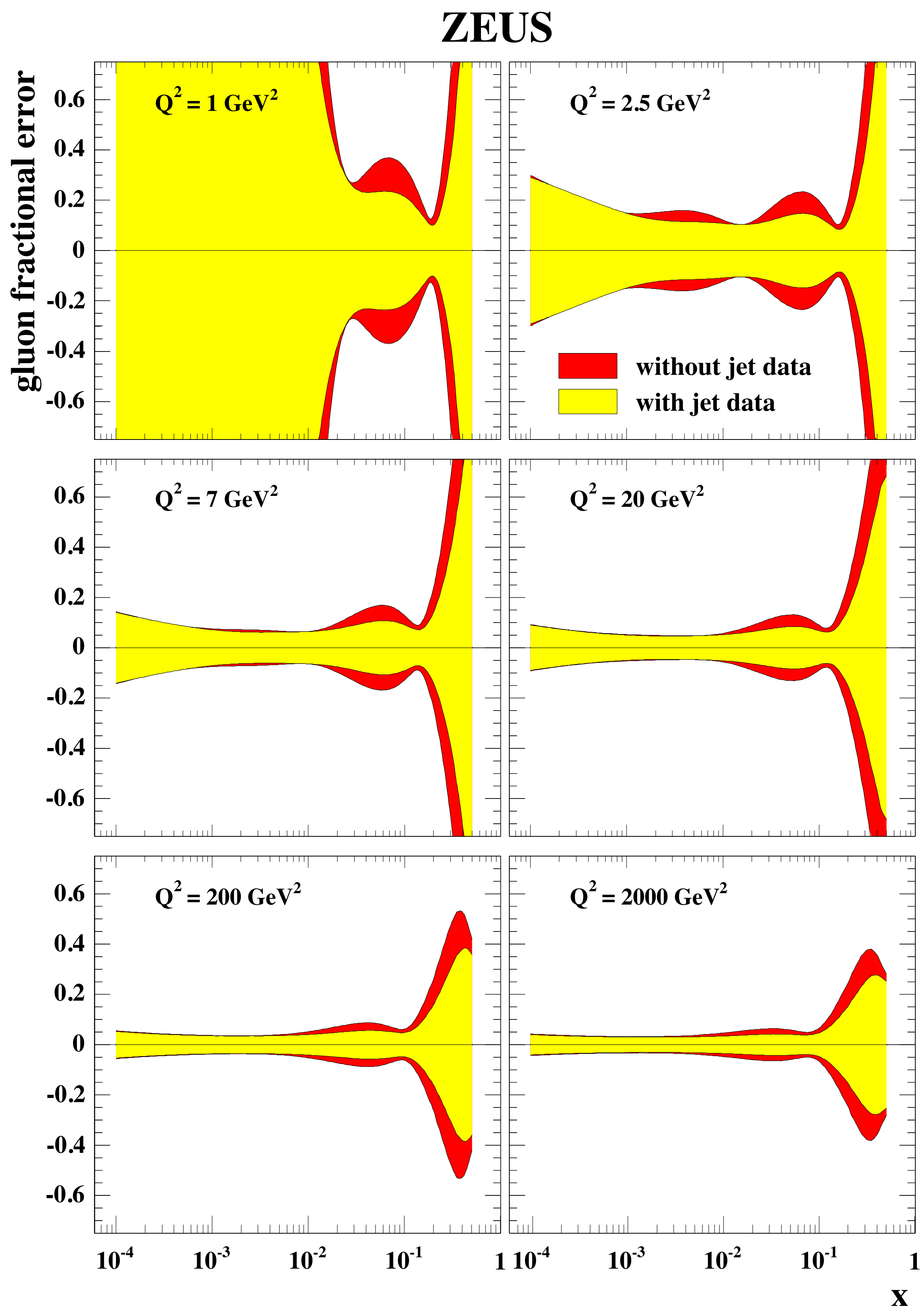
Impact of ‘96-’97 jet data on pdfs (ZEUS)

- The following HERA I data from ZEUS were used:
  - e+/e- NC and CC inclusive data
  - e+p inclusive jet data in DIS
  - dijet data in direct PHP





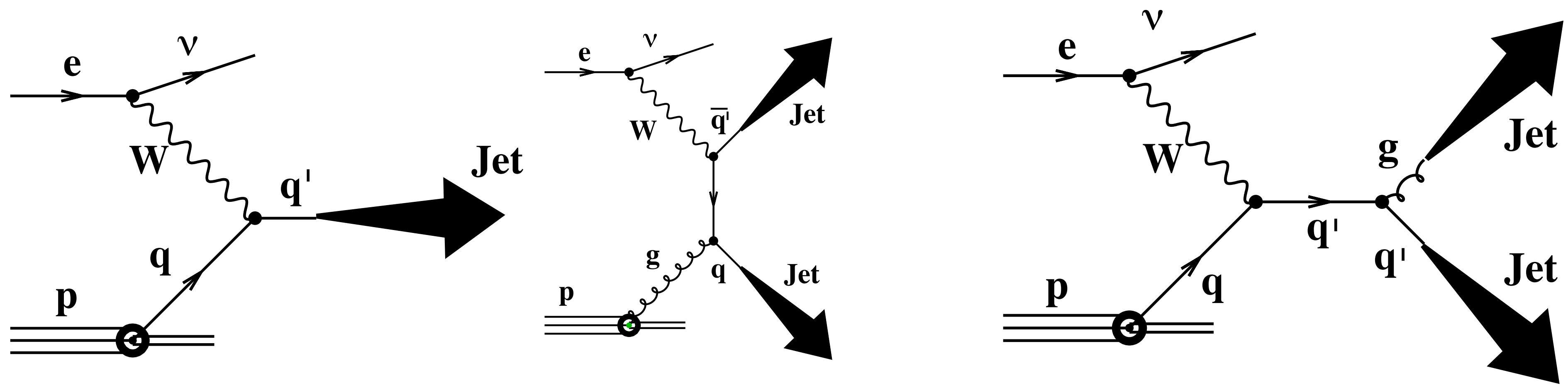
Impact of jet data from '96-'97 on pdfs



- pdf fit
  - without jet data
  - with jet data
    - ➡ most significant improvement for the gluon density in the range $0.01 < x < 0.4$

Multijet cross sections in CC DIS $e^{\pm}p$ scattering

Jets in CC DIS allow to test pQCD as well as the electroweak sector of the SM

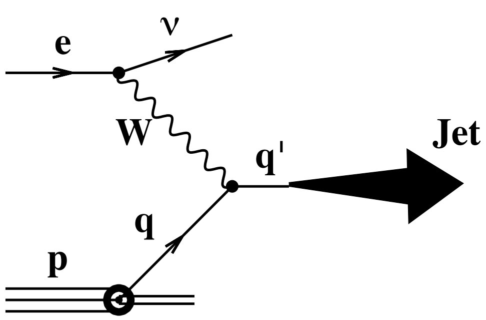


- sensitive to W propagator and in LO
  - in e^-p mainly to $u(x,Q^2)\,(1-P_{e-})$
  - in e^+p mainly to $(1-y)\,d(x,Q^2)\,(1+P_{e+})$
- ➡ jet measurements using the pos. and neg. longitudinal lepton beam polarizations are in good agreement with the SM (and will not be discussed here)
- ➡ the photon predominantly probes u density and u jets, W^- u density and d jets, and W^+ d density and u jets
- in NLO sensitive to α_s and the gluon density

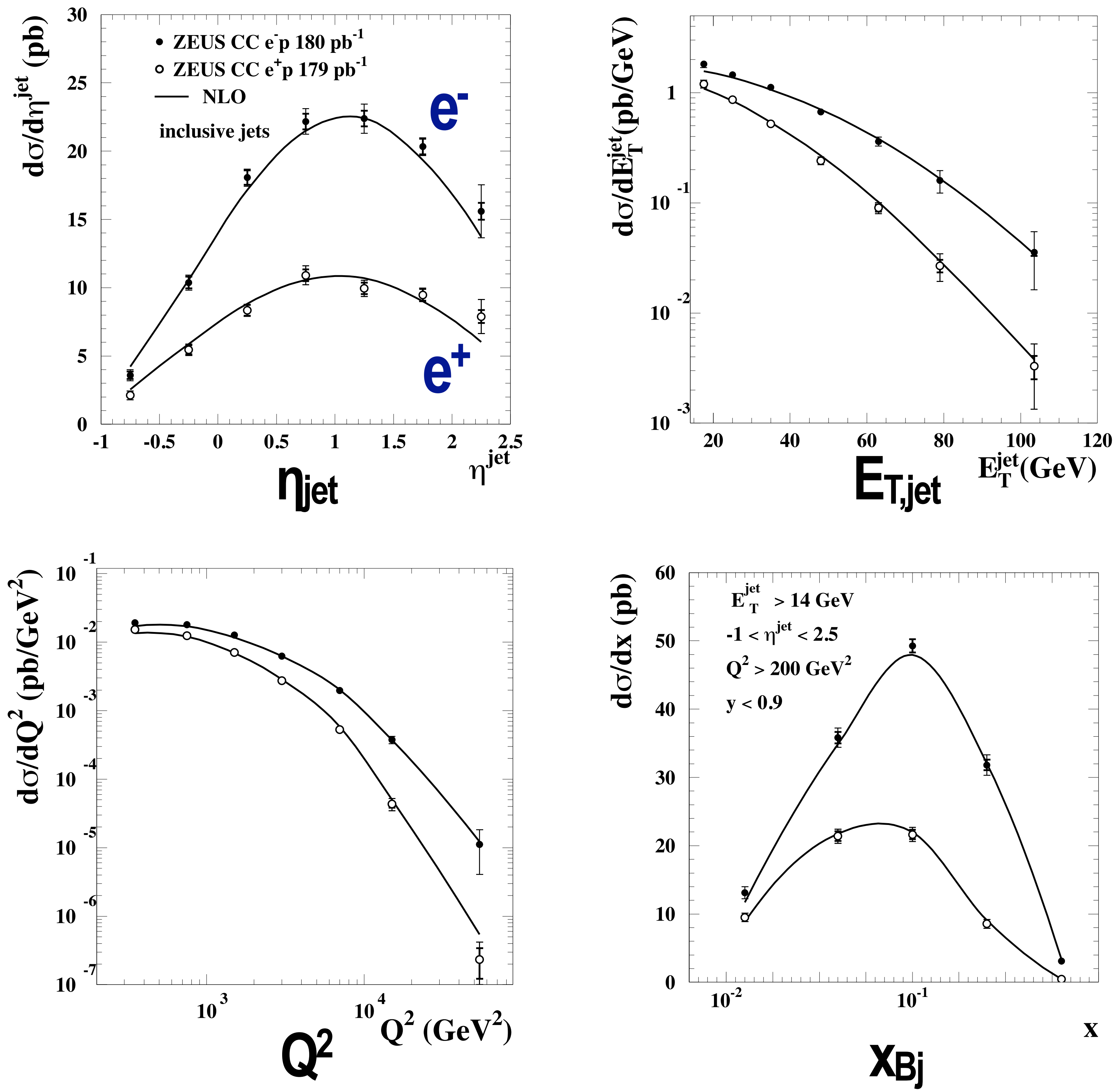
Multijet cross sections in CC DIS e±p scattering

arXiv:0802.3955v2

- ZEUS measurements of inclusive, dijet and three-jet cross sections using full HERA II data
- luminosity 358.5 pb^{-1}, 180 pb^{-1} (178.5 pb^{-1}) with polarized e^- (e^+) data
- DIS phase space: $Q^2 > 200$ GeV^2 and $y < 0.9$
- signature: no scattered electron, large missing P_T and large E_T
- jets found using the longitudinally invariant inclusive k_T cluster algorithm in the Lab frame
- jet phase space: for all jets $-1 < \eta_{jet} < 2.5$
  - inclusive jets: $E_{T,jet} > 14$ GeV
  - dijets: $E_{T,jet1} > 14$ GeV, $E_{T,jet2} > 5$ GeV
  - tree-jets: $E_{T,jet1} > 14$ GeV, $E_{T,jet2,jet3} > 5$ GeV
- largest uncertainties on data: stat. errors and model uncertainties (CDM and MEPS)
- NLO calculations: MEPJET, $\mu_R = \mu_F = Q$, $\alpha_s(M_Z) = 0.118$, scale uncertainty $\mu_R = 2^{\pm1}$ Q
- proton pdfs: ZEUS-S pdfs including their uncertainty
- dominating theory uncertainty: pdf uncertainty

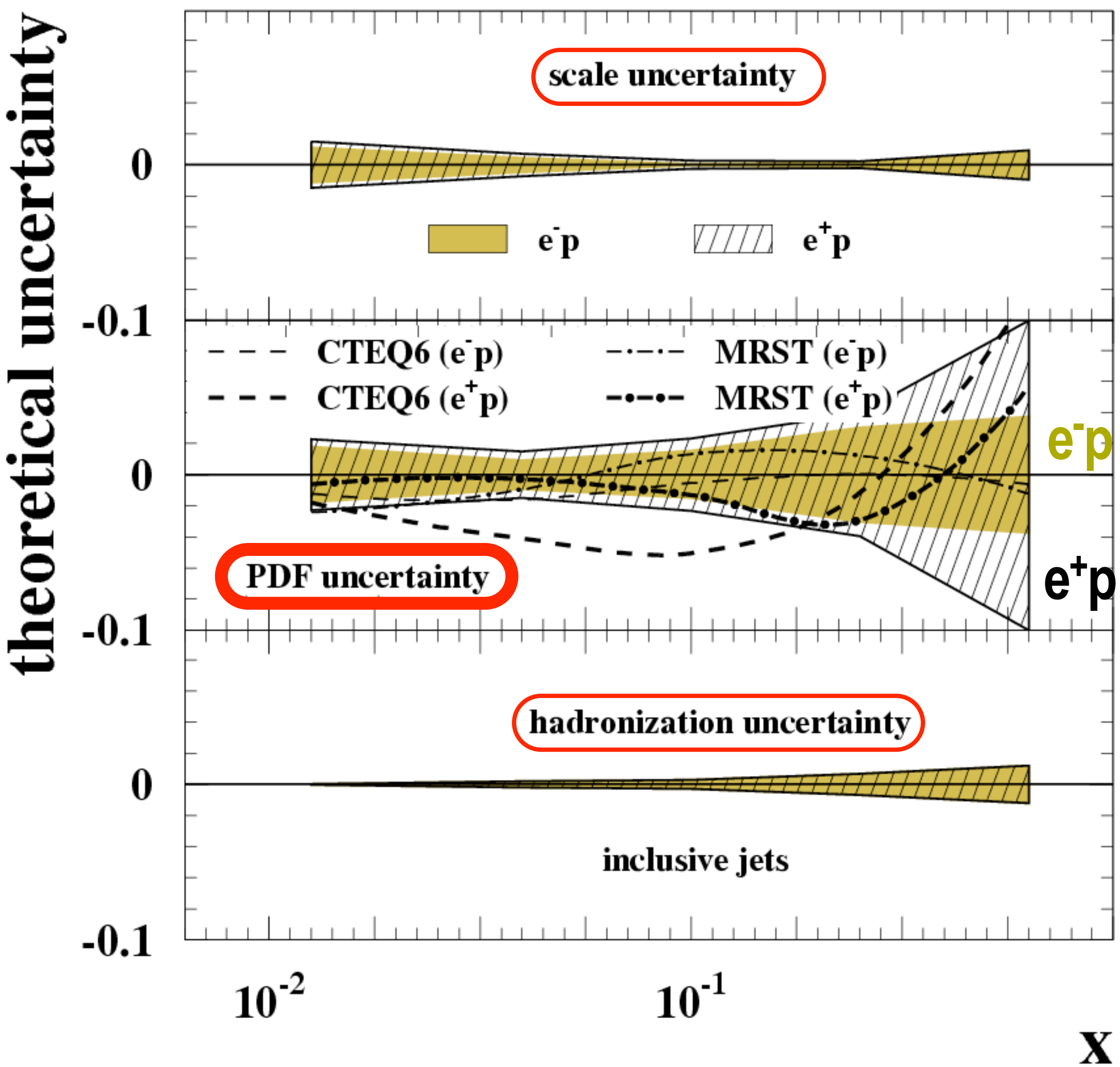


Unpolarized CC inclusive jet cross sections



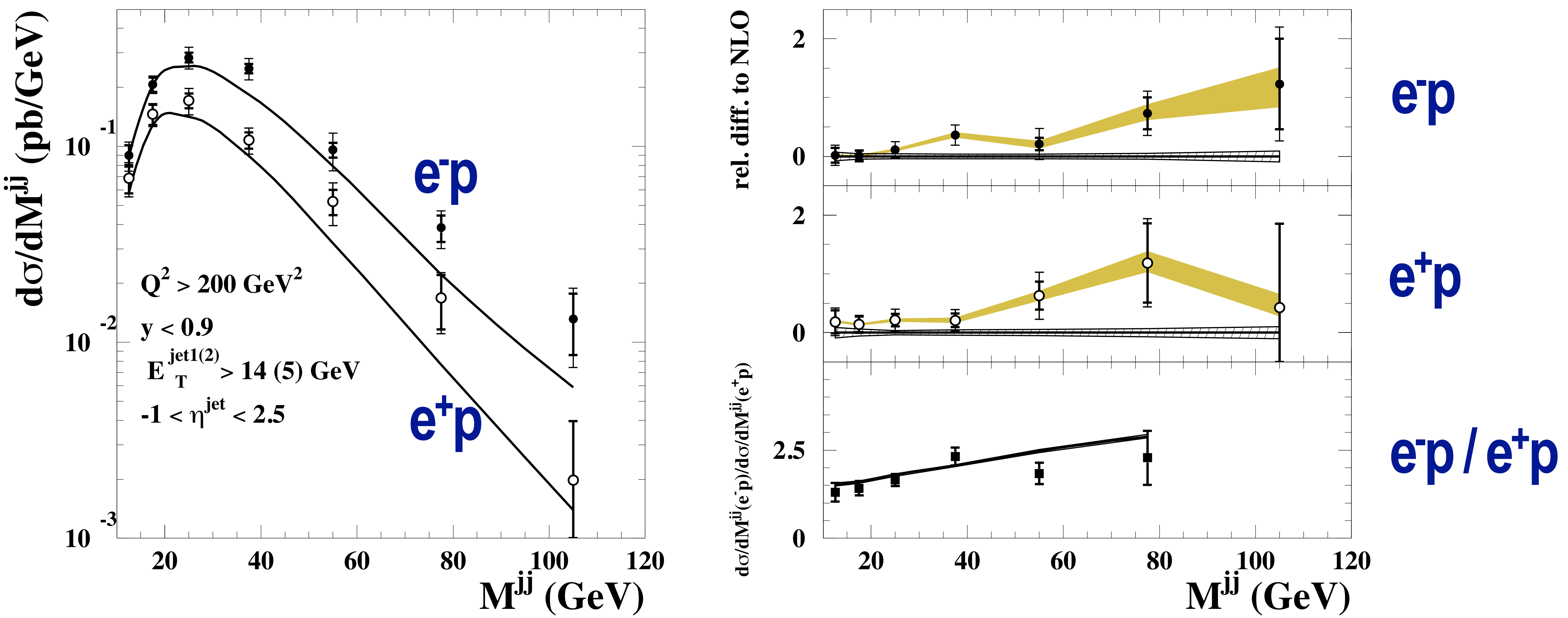
- less strong fall-off with Q^2 and $E_{T,jet}$ than for NC due to W propagator
- good description of data by NLO (MEPJET)

CC incl. jets: theoretical uncertainties



- theoretical uncertainties for e^-p and e^+p are dominated by pdfs (bands are from the ZEUS-S fit)
- pdf uncertainty for e^+p > e^-p at large x (d pdf less well known than u pdf)
- spread in predictions from CTEQ6 and MRST w.r.t. ZEUS-S pdfs
- CC data have the potential to constrain u/d content of the proton in x-range 0.013 to 0.63

Unpolarized CC dijet cross section $d\sigma/dM_{jj}$

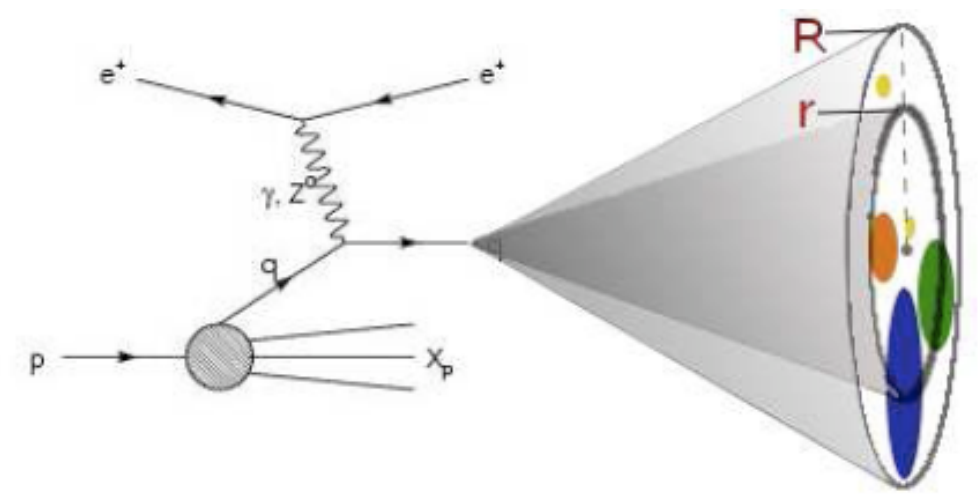


- for dijets NLO appears to have problems with normalization and shape
- can one trust the NLO calculation ?
  - NC jet cross sections differ between MEPJET and other programs by 5 to 8%, for CC only MEPJET is available so far
  - 2nd NLO program for CC would be welcome
- ratio of e^-p / e^+p reasonably well described by NLO

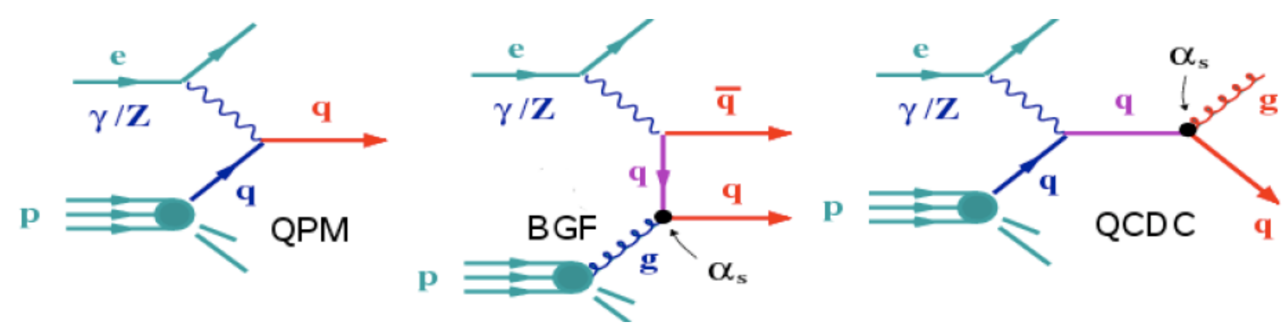
Mean integrated jet shape $<\psi(r)>$

ZEUS-prel-07-013

- at sufficiently high jet E_T ➜ jet substructure mainly due to parton radiation and not fragmentation
  - ➡ can be tested by comparing measured $<\psi(r)>$ to NLO prediction
- ZEUS prel. results with 368 pb^{-1} of luminosity
- $Q^2 > 125$ GeV^2, $y < 0.95$
- jets found in the lab-frame using the longitudinally invariant inclusive k_T cluster algorithm
- 2 samples are studied:
  - 1 jet sample with $E_T > 14$ GeV and $-1 < \eta_{jet} < 2.5$ ➜ enriched in quark jets
  - 2 jet sample with $E_{T1,2} > 14$ GeV and $-1 < \eta_{1,2} < 2.5$ and $D = 2.0$ or 2.5, using lower E_T jet ➜ enriched in gluon jets

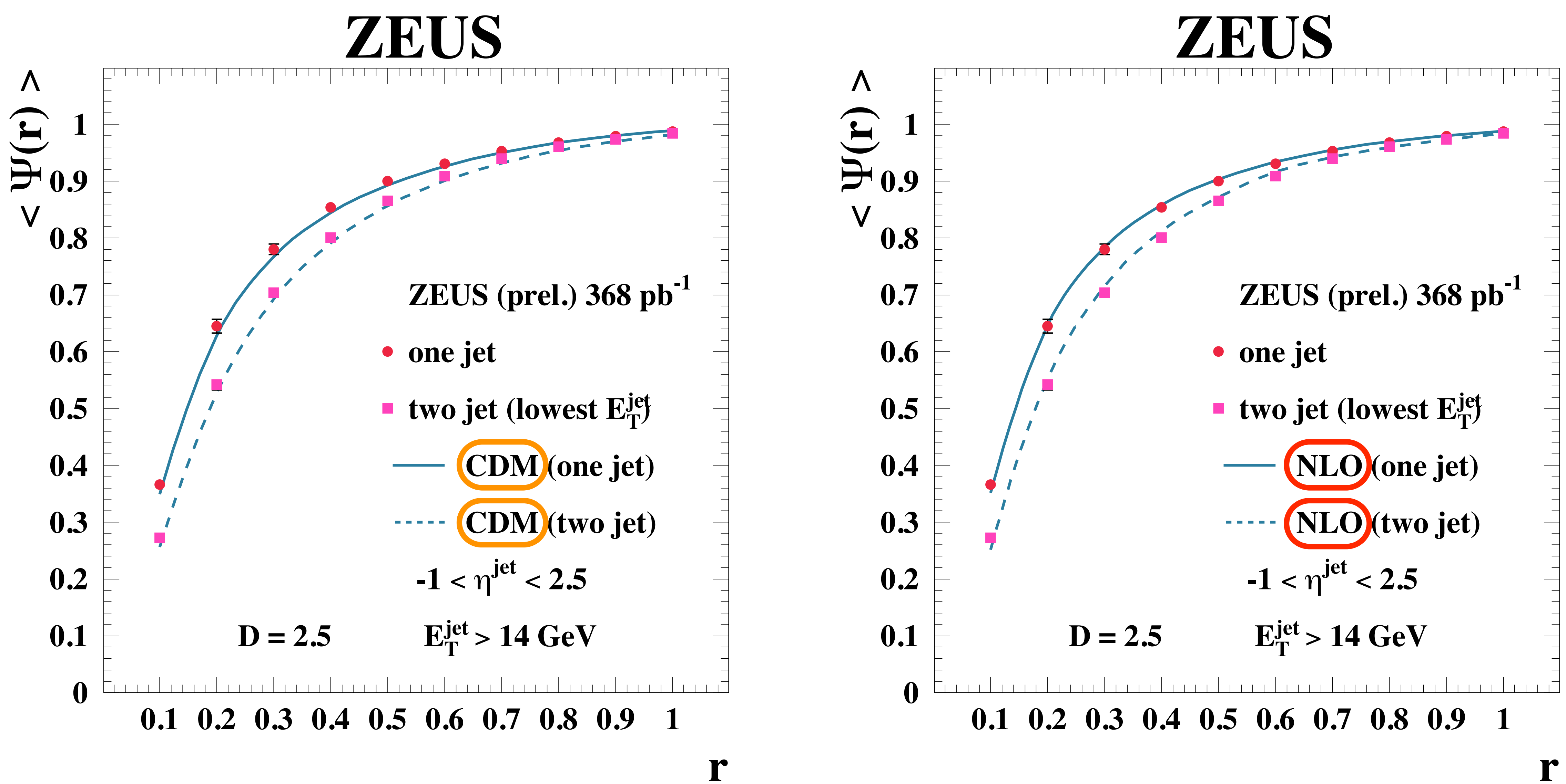


$$<\Psi(r,R)>=\frac{1}{N_{\text{jets}}}\sum^{N_{\text{jets}}}\frac{E_T^{\text{jet}}(r)}{E_T^{\text{jet}}(r=R)}$$



$$d_{12}=\sqrt{(\eta_{\text{jet1}}-\eta_{\text{jet2}})^2+(\phi_{\text{jet1}}-\phi_{\text{jet2}})^2}\leq \text{D}$$

Mean integrated jet shape < ψ(r) >



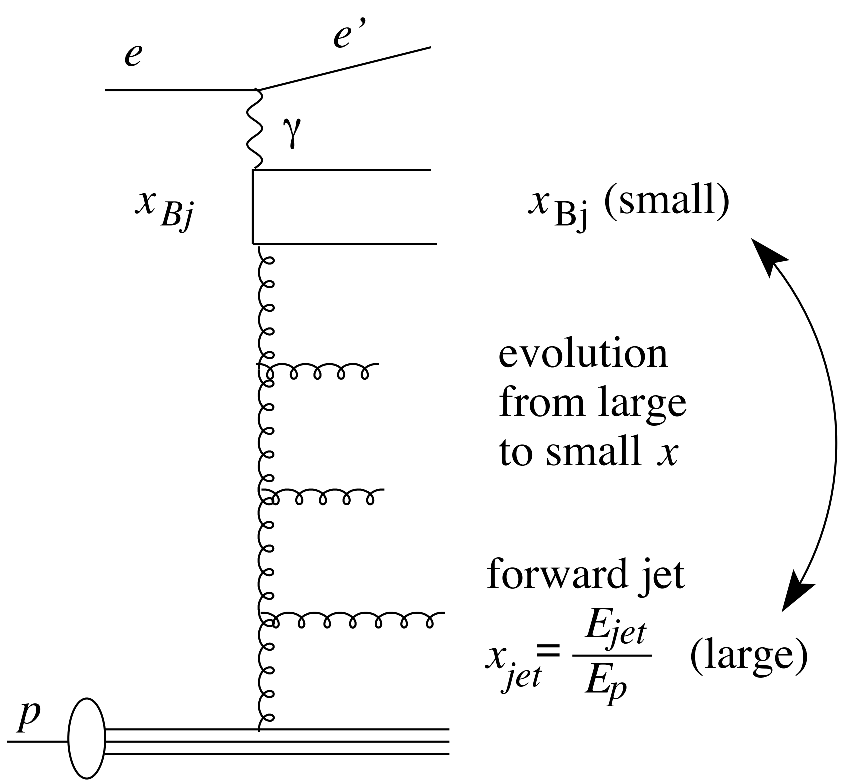
- 2nd jet with lowest E_T is broader than one jet as expected
- both distributions are well described by CDM (ARIADNE) and NLO calculations (DISENT and NLOJET++) using $\alpha_s(M_Z) = 0.118$, CTEQ6 and $\mu_r = \mu_f = Q$; the NLO calc. have been corrected for hadronization effects

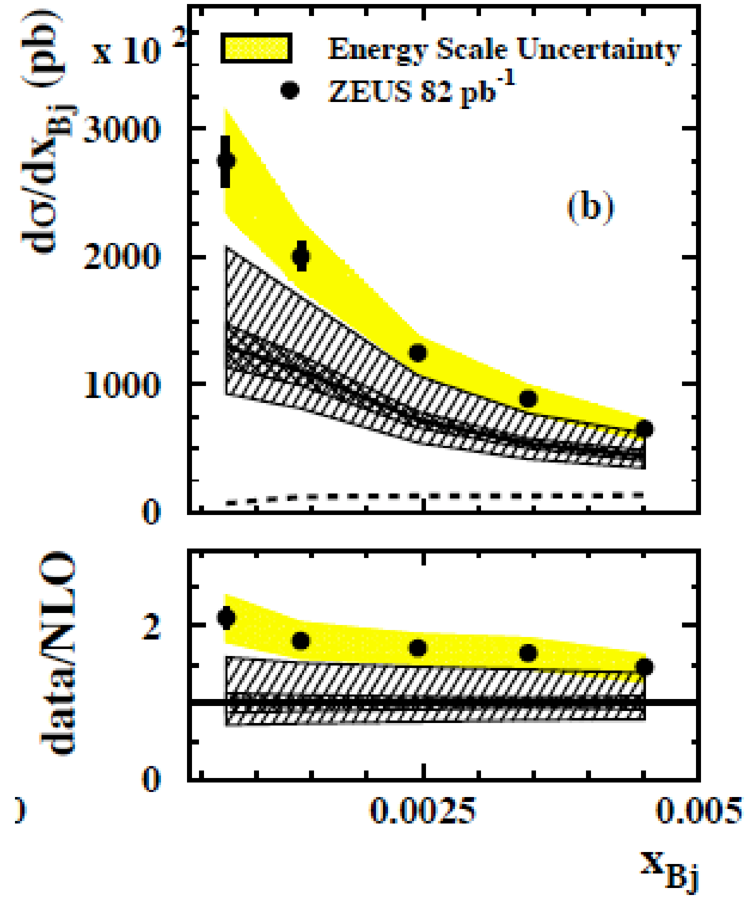
Summary

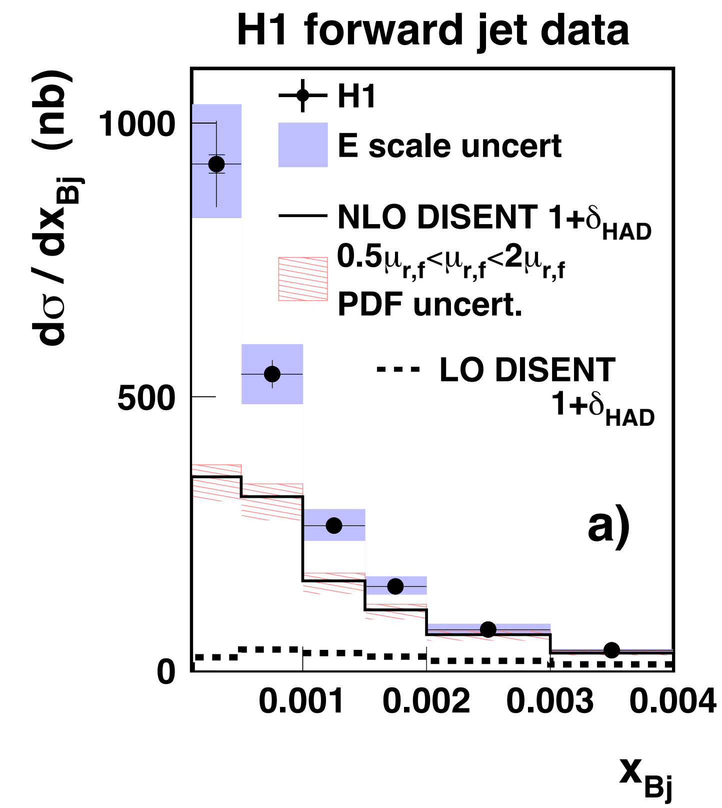
- Precise measurements of multijet production in NC and CC have been made, some with the full HERA statistics and jet energy scale uncertainties of 1 to 2%
- The data on jet production are in general very well described by NLO calculations with theory uncertainty > exp. errors
- Jet shapes are well described by NLO and by CDM as implemented in ARIADNE
- The precise jet production data allow a precise determination of $\alpha_s(M_Z)$ at NLO, with an exp. uncertainty of 0.7% and a much larger theory uncertainty between 2 and 3.5%
- An NNLO calculation of jet production has the potential of significantly shrinking the total error on $\alpha_s(M_Z)$
- The high statistics and precision of the HERA II jet data has the potential of further improving the precision of the proton pdfs when used in global fits
- This will provide obvious benefits to the LHC physics program
- The final analysis of inclusive and jet data from HERA I+II with further improved precision is in progress

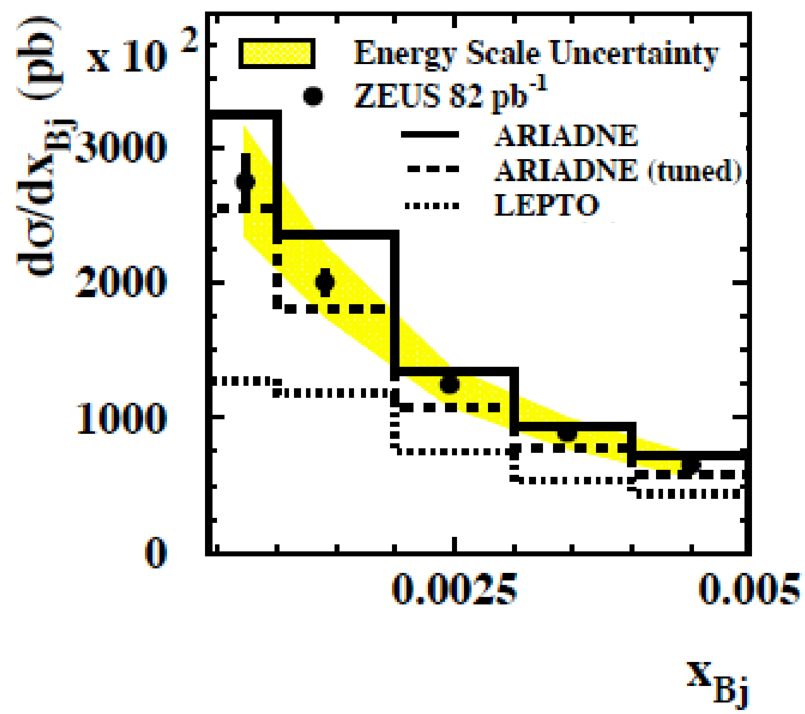
Extras

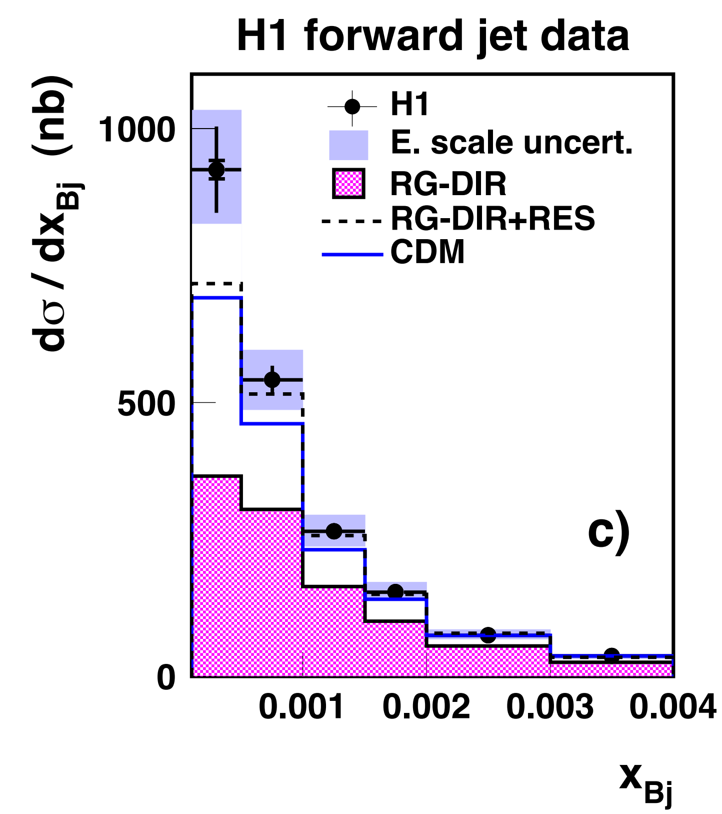
Low x jets





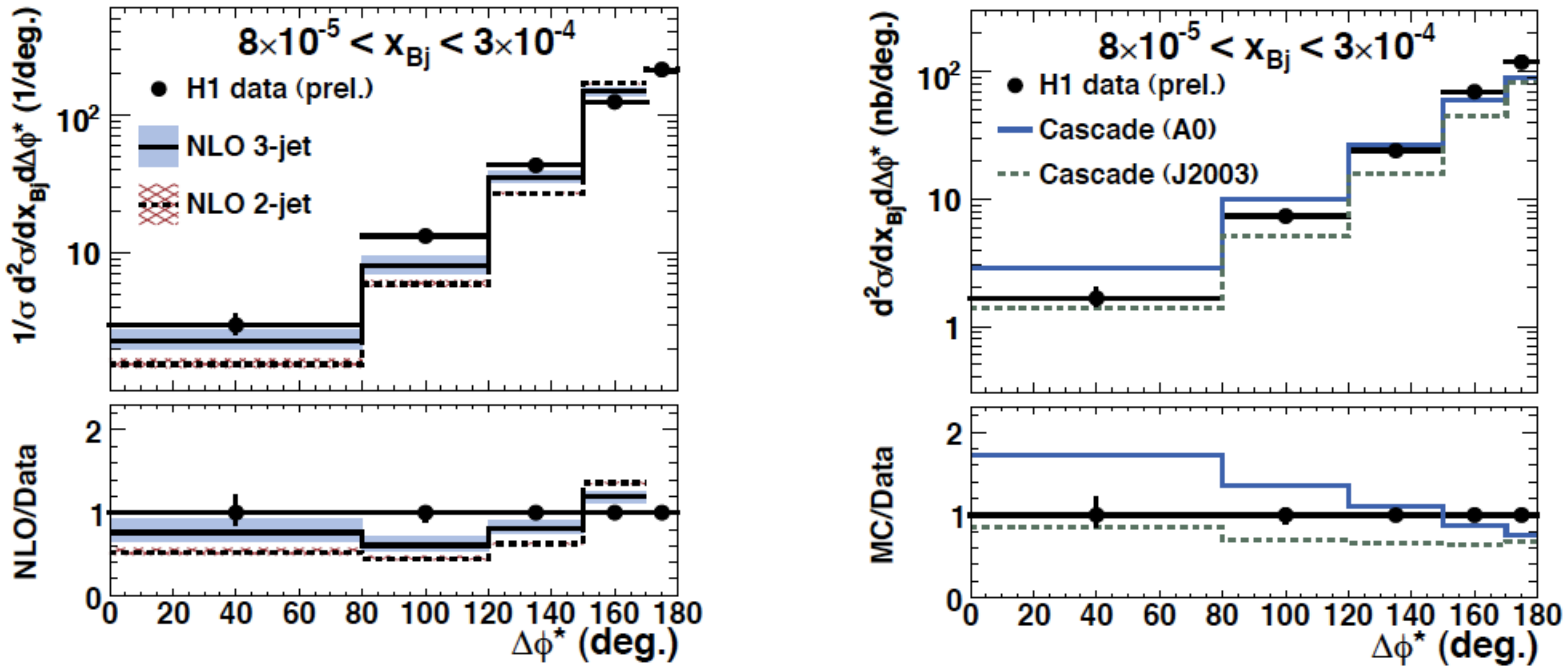






- Forward jet cross sections from H1 and ZEUS (note: DIS phase space not identical)
- not described by DGLAP based NLO
- only CDM (ARIADNE) is able to describe the fully differential H1data

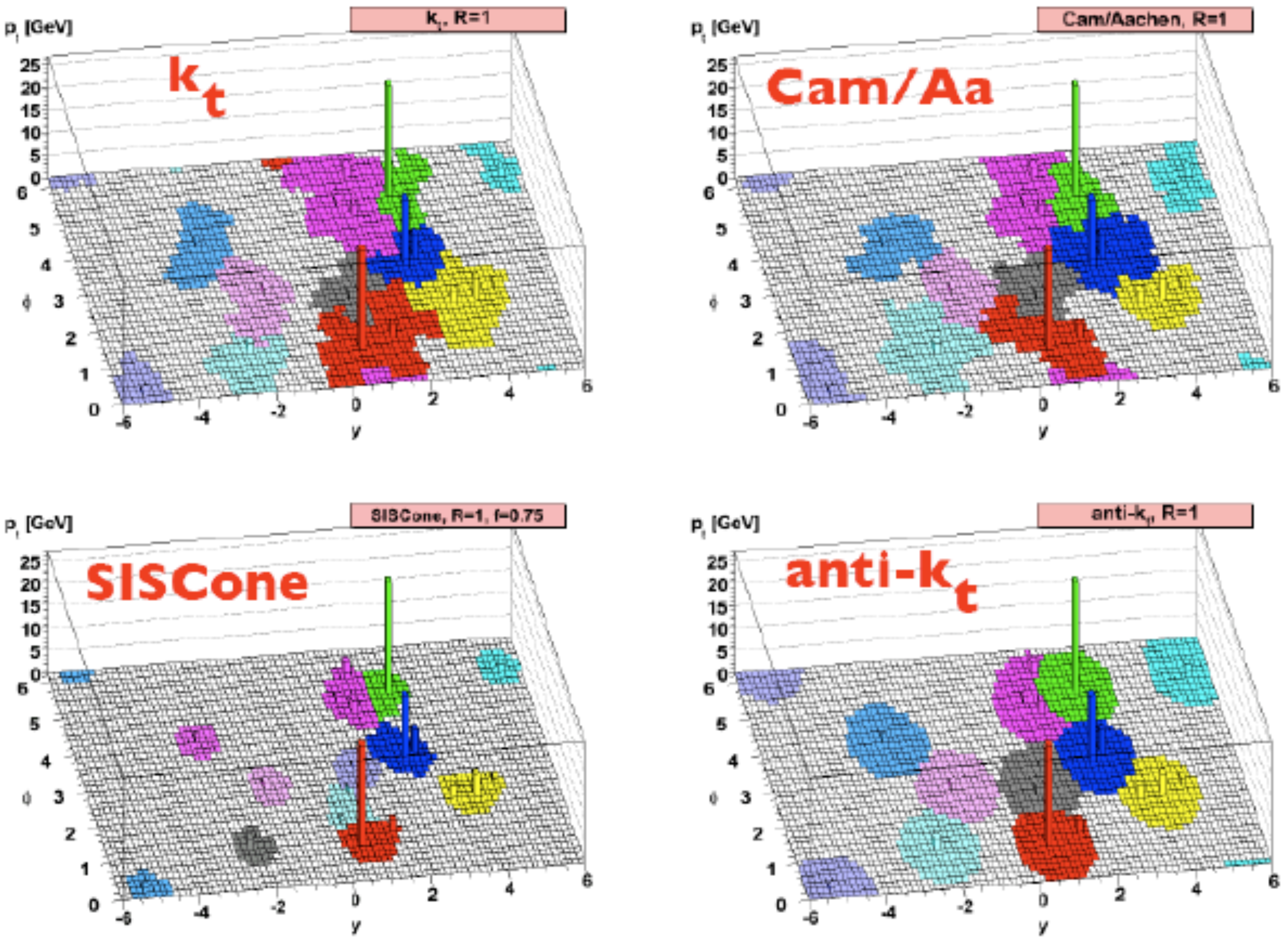
Azimuthal decorrelation of jets at low x



- DGLAP based NLO slightly below the data away from back to back region
- CASCADE indicates data are sensitive to un-integrated gluon distribution

Improved jet algorithms

- Improved jet algorithms and jet area (M. Cacciari, G. Salam, G. Soyez)
- ensure infrared safety
- good speed
- for area introduce zero energy ghost particles in clustering



$$d_{ij} = min(k_{t,i}, k_{t,j})^{2p}(\Delta\phi_{ij}^2 + \Delta\eta_{ij}^2)$$

k_t : p = 1 and
anti-k_t: p = -1