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Jet Production in Deep Inelastic ep Scattering at HERA: extraction of α_S and the gluon density in the proton

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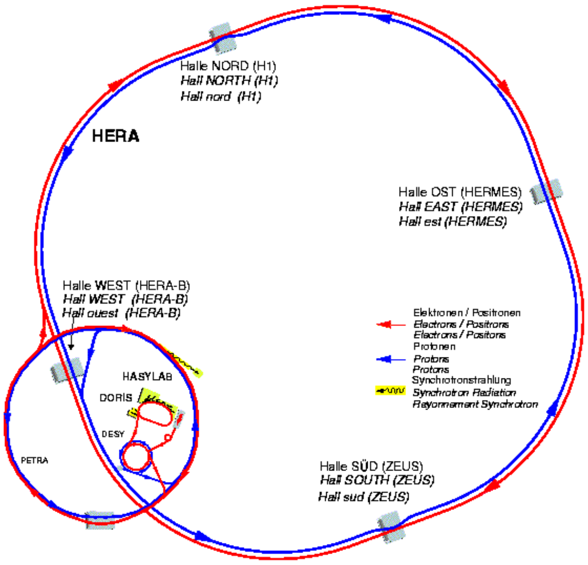
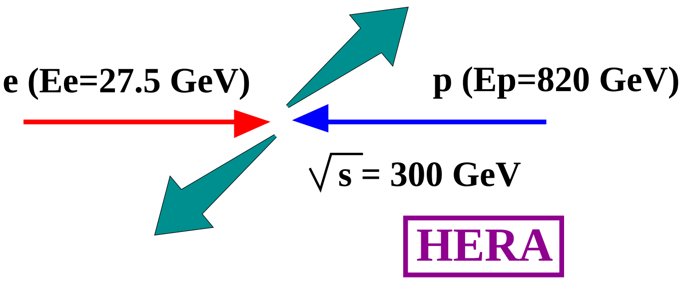
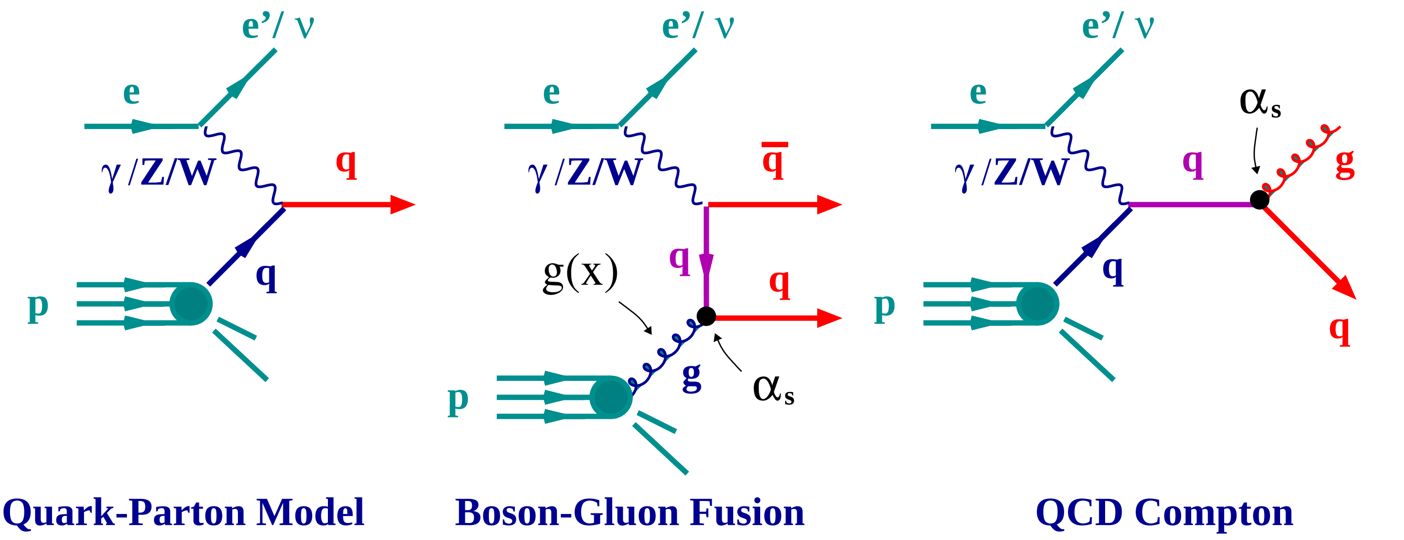




Introduction:

- Jet production in neutral and charged current interactions up to $\mathcal{O}(\alpha_S)$:

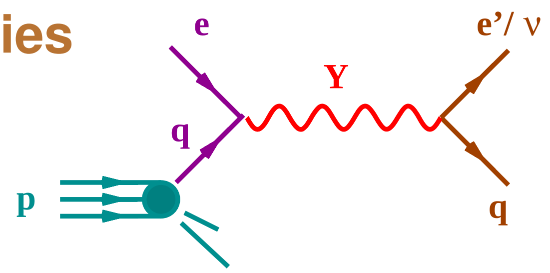


- Jet production cross section:

$$d\sigma_{jet} = \sum_{a=q,\bar{q},g} \int dx\ f_a(x, \mu_F^2)\ d\hat{\sigma}_a(x, \alpha_S(\mu_R^2), \mu_R^2, \mu_F^2)$$

  – f_a: parton a density in the proton, determined from experiment; long-distance structure of the target
  – $\hat{\sigma}_a$: subprocess cross section, calculable in pQCD; short-distance structure of the interaction

- Jet cross sections in NC and CC interactions provide a test of pQCD calculations, measurements of α_S, constrain parton densities and are sensitive to the production of new particles and new interactions



Introduction:

- Jet production in DIS is a testing ground of pQCD and allows a direct determination of α_S and the pPDFs

$\ast$ To do a QCD analysis:

- Extraction of α_S depends on the PDFs $\rightarrow$ need to assume PDFs and determination should be made from observables that have a small dependence on the PDFs (eg ratios of observables)

  $\rightarrow$ For a precise measurements of α_S need small experimental uncertainties (eg ratios) and small theoretical uncertainties (need NLO calculations)

- The PDFs depend on α_S $\rightarrow$ need to assume a value of $\alpha_S(M_Z)$

  $\rightarrow$ The gluon density can be determined from scaling violations in inclusive DIS cross sections

  $\rightarrow$ Direct measurements of the gluon density can be performed with dijet cross sections

  $\rightarrow$ And a combined fit of inclusive data and dijet cross sections reduces the uncertainties

. . . or perform a simultaneous determination of α_S and the PDFs

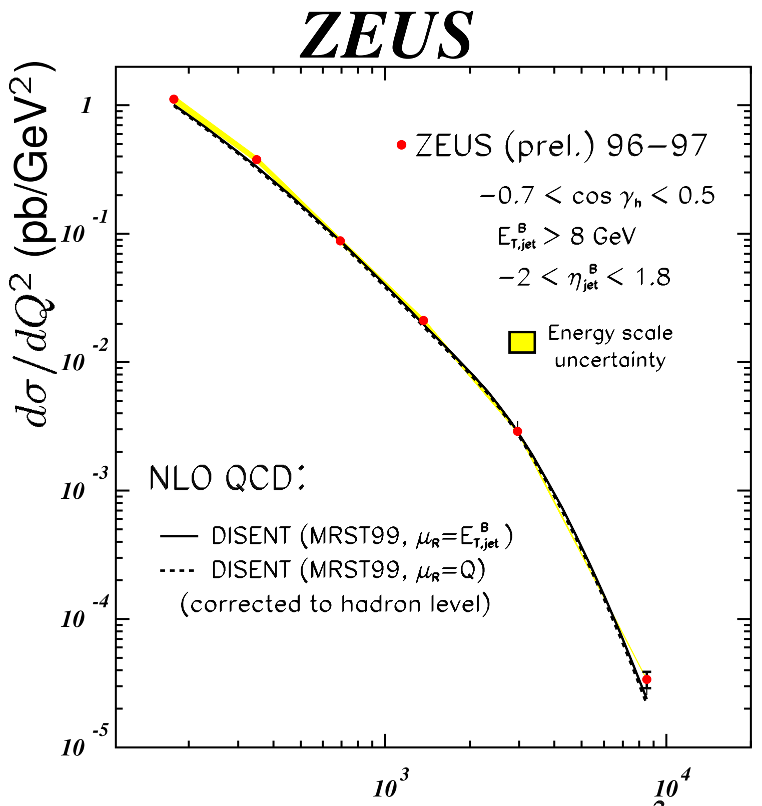
NLO calculations in DIS:

- Several NLO ($\mathcal{O}(\alpha_S^2)$) programs are available for performing jet cross sections calculations:
  $\rightarrow$ DISENT, MEPJET, DISASTER++, NLOJET
- NLO corrections:
  $\rightarrow$ virtual corrections with internal particle loops
  $\rightarrow$ real corrections with a third parton in the final state
- Different methods to calculate real corrections:
  $\rightarrow$ phase space slicing method (M)
  $\rightarrow$ subtraction method (D, D++, NJ)
- Since there are two hard scales in jet production, the renormalisation and factorisation scales can be chosen as one of the two, $\mu_R,\ \mu_F = Q$ or E_T^{jet}
- The calculations are for jets of partons and the measurements are done at the hadron level $\rightarrow$ need to correct the calculations for hadronisation effects
- Theoretical uncertainties:
  $\rightarrow$ terms beyond NLO, which are usually estimated by varying μ_R by factors between 1/2 and 2; it amounts to $5-10\%$
  $\rightarrow$ the uncertainties on $\alpha_S(M_Z)$ and the PDFs have to be considered; they amount to $\sim 5\%$
  $\rightarrow$ uncertainty coming from the hadronisation corrections; the correction factor varies from 5% to 20%, depending on the analysis, and the uncertainty is of the order of 2%

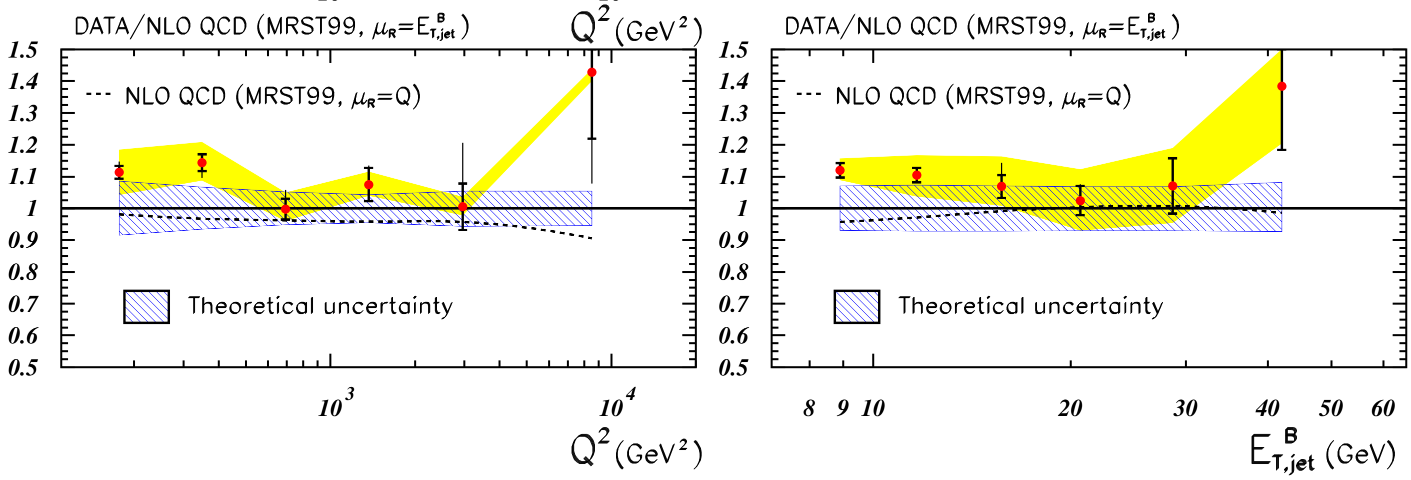
Inclusive jet cross sections in NC DIS:

$ep \to e$ + jet + X in the Breit frame

- Jets searched using the k_T cluster algorithm
- Kinematic region: $Q^2 > 125$ GeV^2 and $-0.7 < \gamma < 0.5$
  (γ, direction of scattered quark in the QPM)
- At least one jet with $E_{T,\mathrm{B}}^{jet} > 8$ GeV and $-2 < \eta_{\mathrm{B}}^{jet} < 1.8$



- **Advantages of inclusive jet cross sections in a QCD analysis:**
  – **infrared insensitivity**
  – **better suited to test resummed calculations**
  – **smaller theoretical uncertainties than in dijet cross sections**

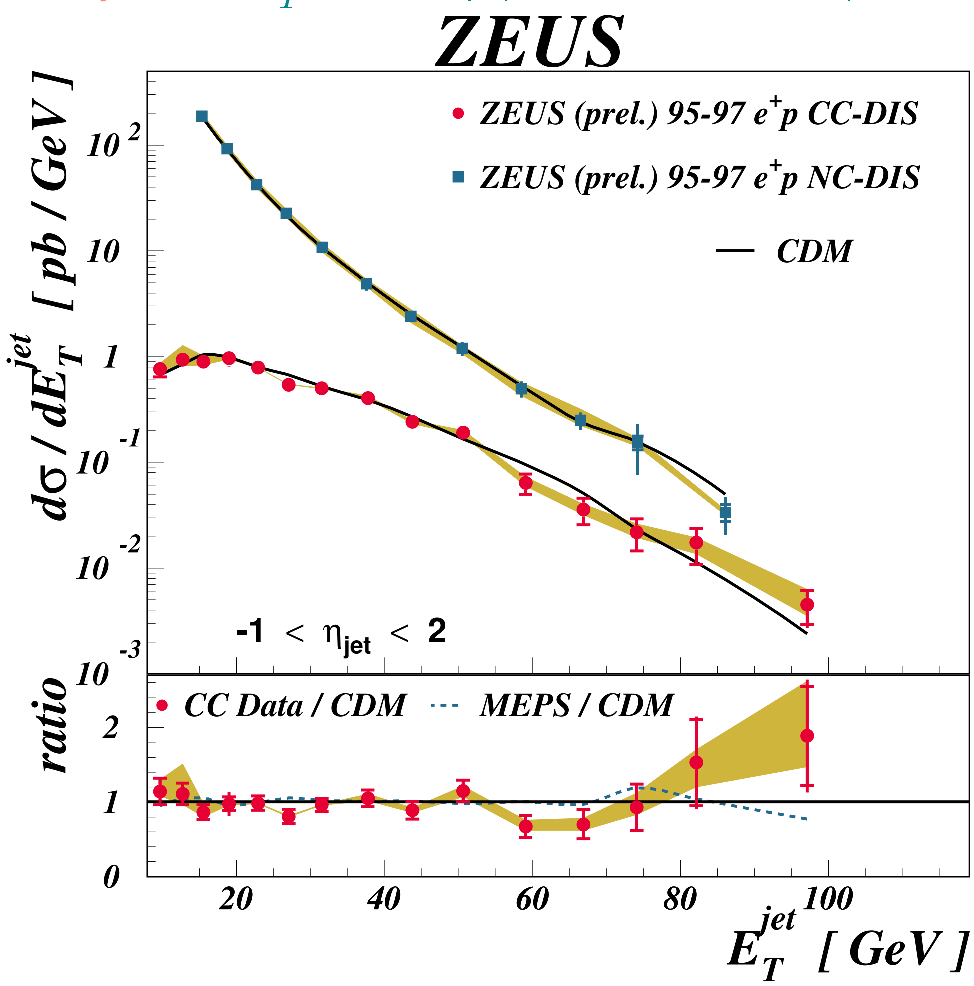


$\to$ **The NLO calculations describe reasonably well the measured cross sections for $Q^2 > 500$ GeV^2 and $E_{T,\mathrm{B}}^{jet} > 15$ GeV**

Inclusive jet cross sections in NC and CC DIS:

$ep \to e\ (\nu)\ +$ jet $+$ X in the LAB frame

- Jets searched using the k_T cluster algorithm
- Kinematic region: $Q^2 > 125\ (200)$ GeV^2 and $y < 0.9$
- At least one jet with $E_T^{jet} > 14\ (8)$ GeV and $-1 < \eta^{jet} < 2$



- **The behaviour in CC is very different than in NC: the distribution in CC falls less rapidly and approaches the NC cross section for $E_T^{jet} \sim 80$ GeV, interpreted as due to the presence of a massive propagator in CC events**

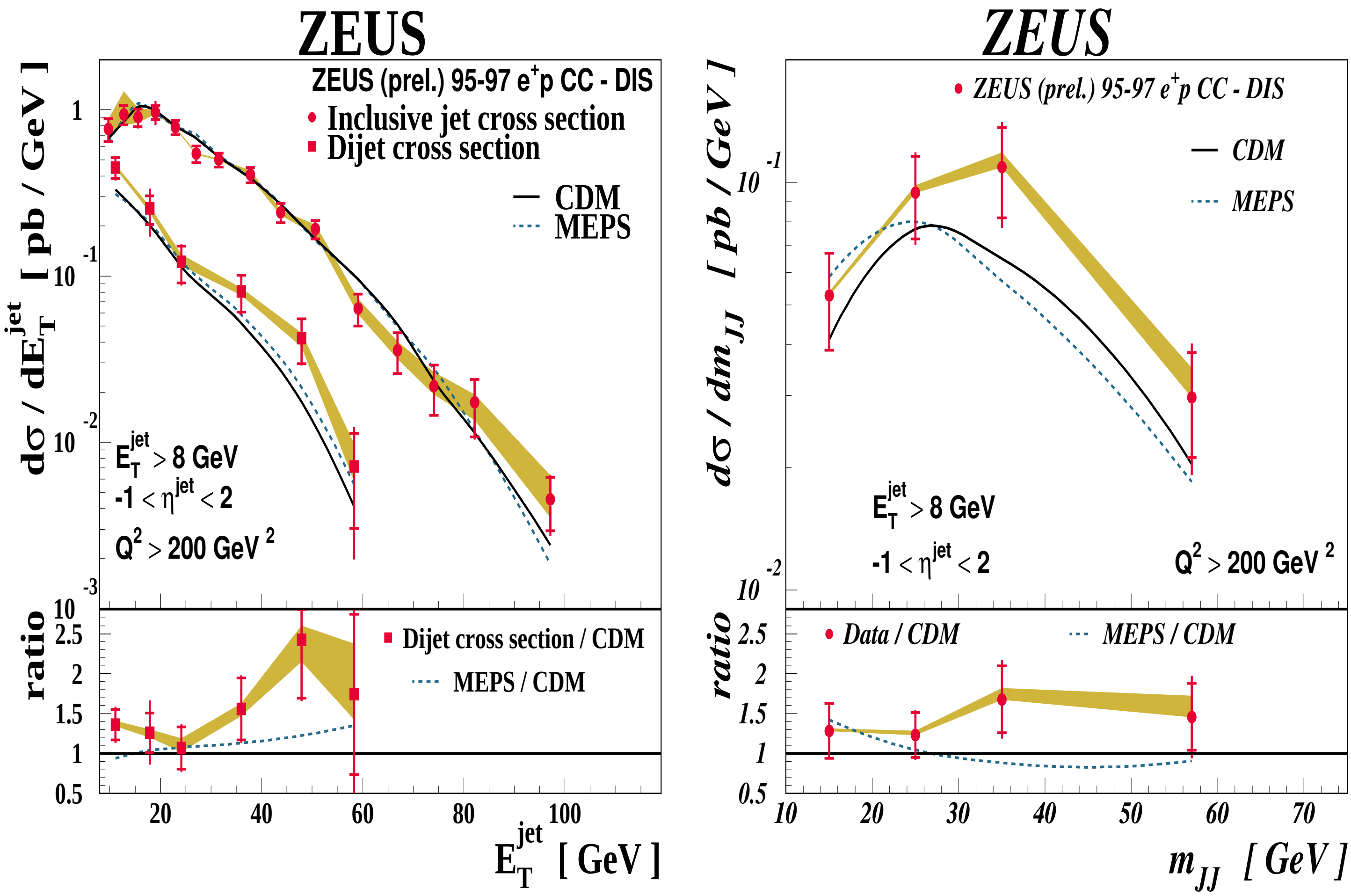
$\to$ **Leading-logarithm parton-shower MC models describe reasonably well the measured cross section**

$\to$ **No significant deviation from the Standard Model is observed up to $E_T^{jet} \sim 100$ GeV**

Dijet cross sections in CC DIS:

$ep \rightarrow \nu$ + jet + jet + X in the LAB frame

- Jets searched using the k_T cluster algorithm
- Kinematic region: $Q^2 > 200$ GeV^2 and $y < 0.9$
- At least one jet with $E_T^{jet} > 8$ GeV and $-1 < \eta^{jet} < 2$



- **The shape of the E_T^{jet} distribution in dijets is very different than the one in the inclusive jets: the inclusive jet cross section is governed by EW and M_W whereas the dijet cross section is governed by QCD**

$\rightarrow$ **Leading-logarithm parton-shower MC models describe reasonably well the shape of the measured cross sections, but underestimate the normalisation by $\sim 50\%$**

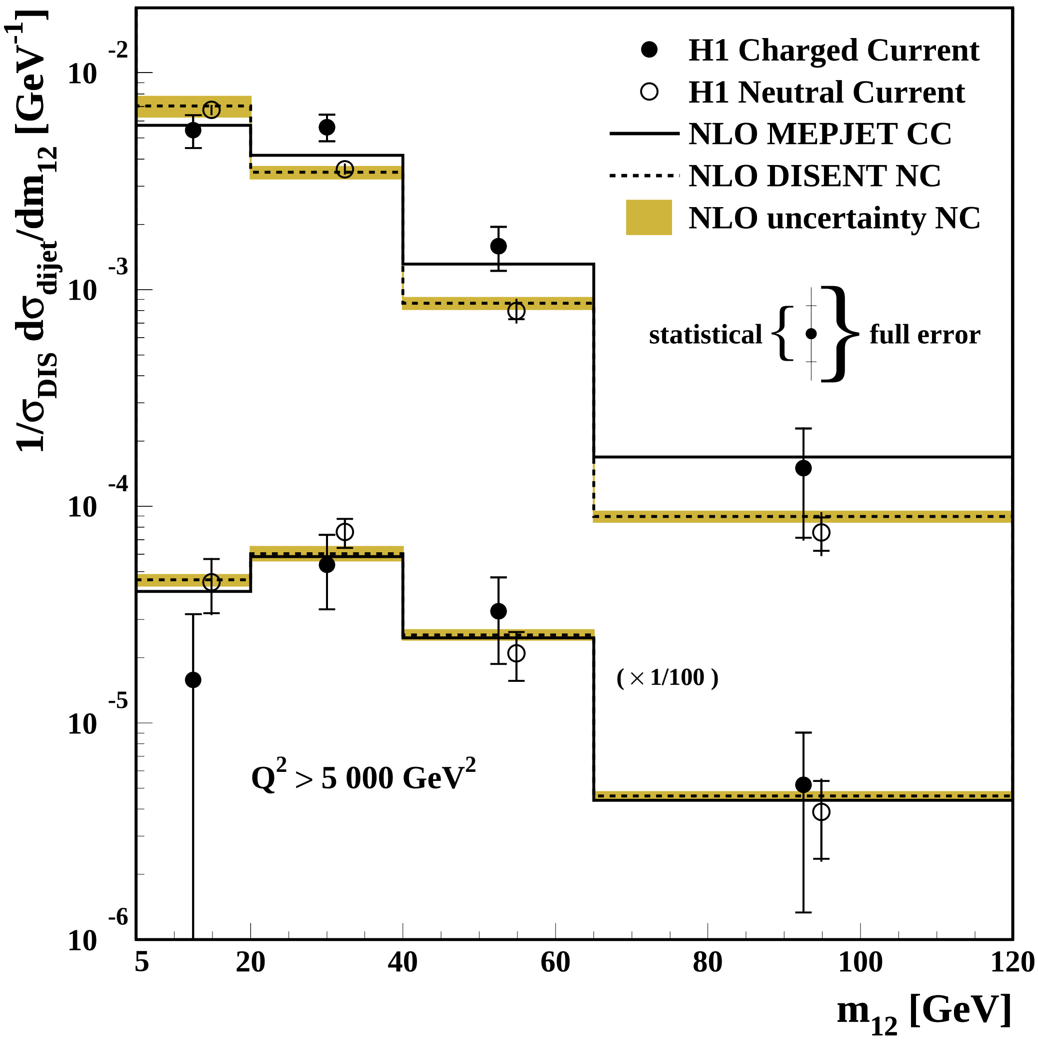
Dijet cross sections in NC and CC DIS:

$ep \to e\ (\nu)$ + jet + jet + X in the LAB frame

- Jets searched using a modified Durham jet algorithm
- Kinematic region: $Q^2 > 640$ and 5000 GeV^2
- Dijet events are defined with $y_{cut} > 0.002$

(y_{cut}, resolution parameter)

NLO calculations using H1 collab pPDFs extracted from inclusive DIS data



→ **Using parton densities derived from NLO QCD fits to inclusive DIS data, perturbative calculations based on the EW and QCD ($\mathcal{O}(\alpha_S^2)$) matrix elements give a consistent description of NC and CC jet cross sections at the highest invariant masses and Q^2**

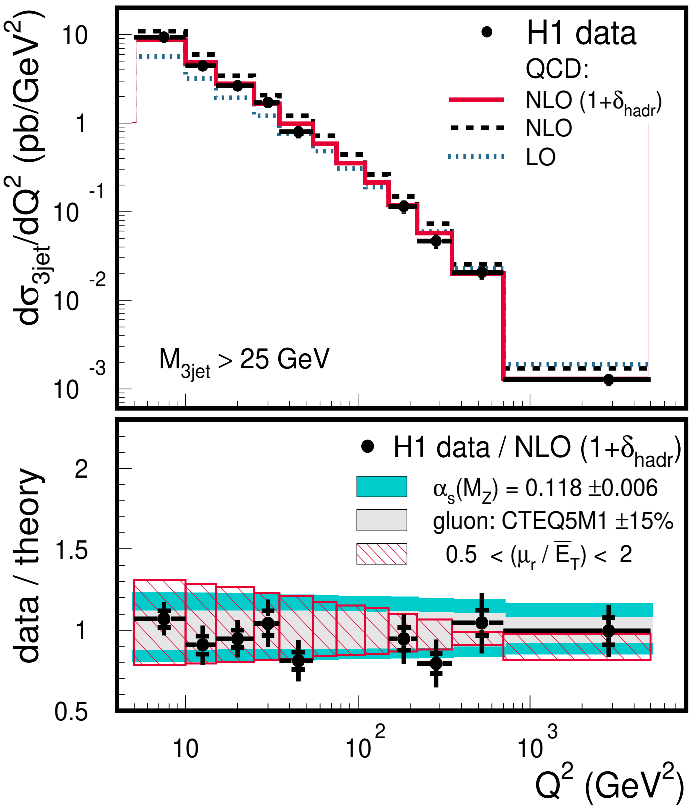
Three-jet cross sections in NC DIS:

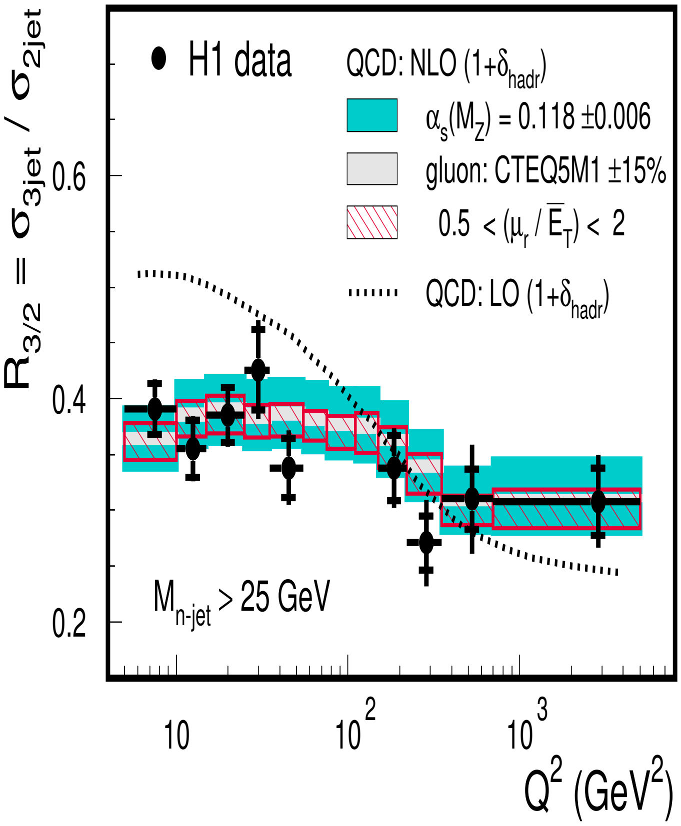
$ep \rightarrow e$ + jet + jet + jet + X in the Breit frame

- Jets searched using the k_T cluster algorithm
- At least three jets with $E_{T,B}^{jet} > 5$ GeV and $-1 < \eta_{LAB}^{jet} < 2.5$
- Kinematic region: $M^{3J} > 25$ GeV, $X_3 < 0.95$ and $|\cos\theta_3| < 0.8$

- **Three-jet cross sections test QCD beyond LO directly**

$$\sigma_{3jet} \propto \alpha_S^2$$



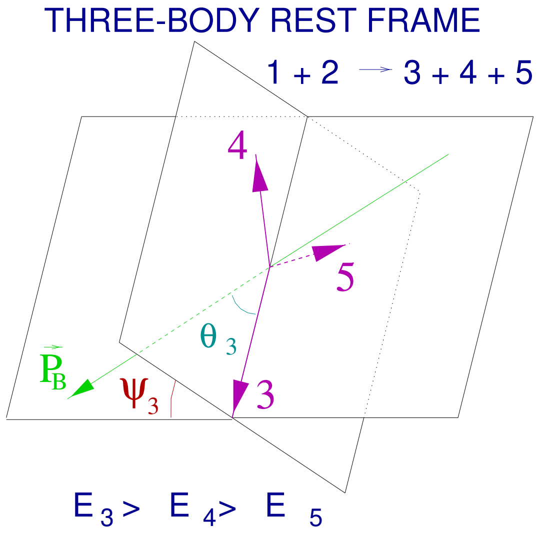


→ **The NLO calculations give a good description of the data over the whole Q^2 range**

- **Theoretical uncertainties from PDFs and higher order terms reduced in the three-jet to dijet ratio but large hadronisation corrections ($\sim 20\%$)**

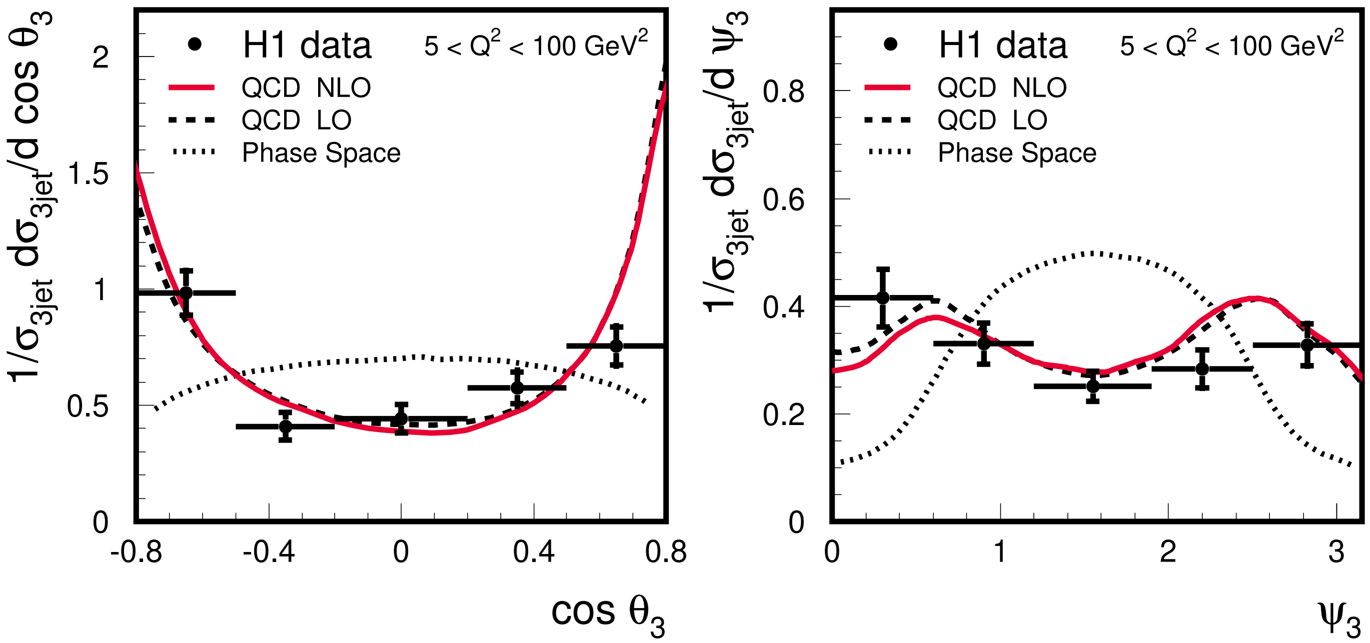
  → **more accurate determination of α_S could be possible from these measurements when corrections get under control**

Three-jet cross sections in NC DIS:



— θ_3 is sensitive to the spin of the exchanged particle

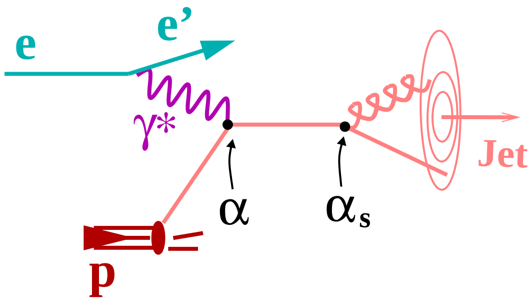
— ψ_3 reflects the orientation of the lowest energy jet



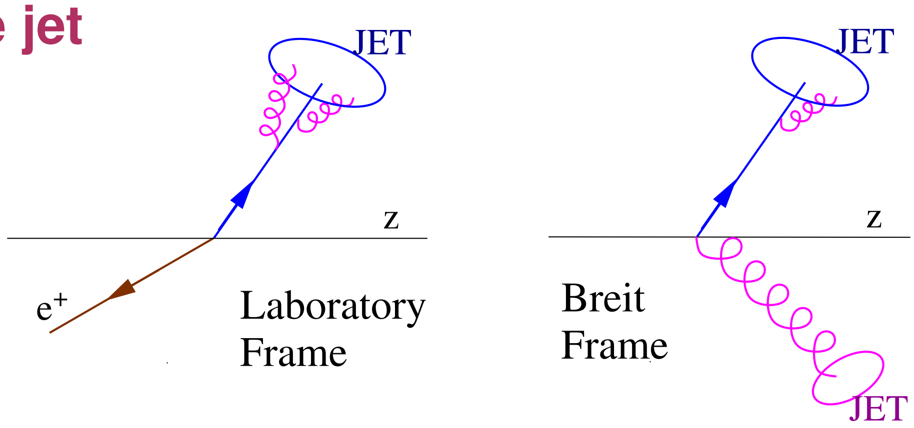
- The $\cos\theta_3$ distribution indicates that the highest energy jet tends to go either towards the proton or towards the photon directions
- The ψ_3 distribution probes the dynamics beyond LO directly
- The measured angular distributions are drastically different from phase space and in good agreement with QCD

Jet substructure:

- The investigation of the internal structure of jets gives insight into the transition between a parton produced in a hard process and the experimentally observable spray of hadrons
- At sufficiently high E_T^{jet}, where fragmentation effects become negligible, the jet structure is expected to be calculable by pQCD
- The dependence of the pQCD calculations on the knowledge of the pPDF is reduced
- The lowest non-trivial-order contribution to the measurements is given by $\mathcal{O}(\alpha\alpha_S)$ pQCD calculations



- Thus, measurements of jet substructure provide a stringent test of pQCD calculations beyond LO and allow a determination of α_S by comparing NLO calculations of jet subtructure to the measurements since in the LAB frame it is possible to have 3 partons inside one jet

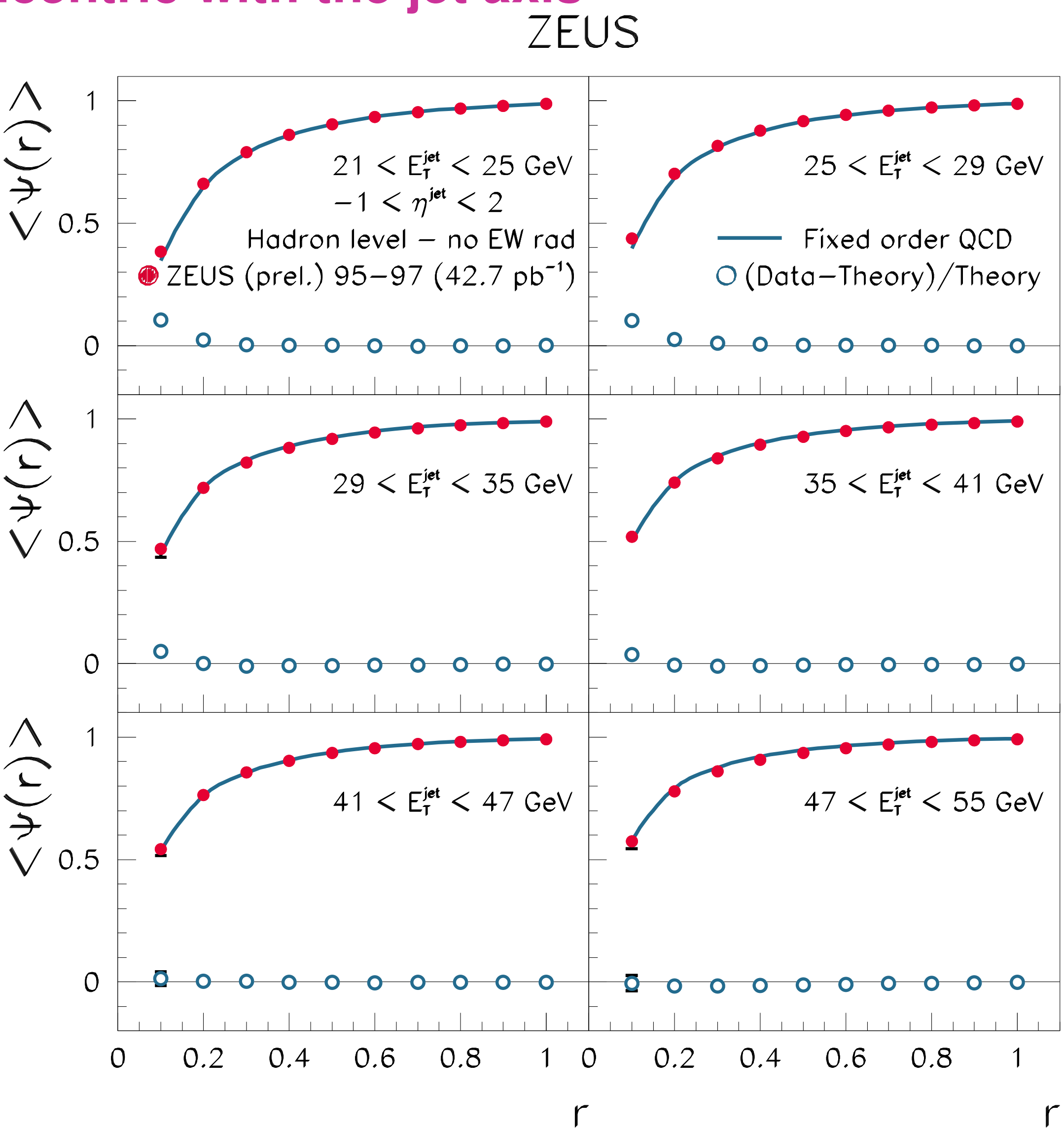


Jet substructure in NC DIS:

$ep \to e$ + jet + X in the LAB frame

- Jets searched using the k_T cluster algorithm
- Kinematic region: $Q^2 > 125$ GeV^2
- At least one jet with $E_T^{jet} > 21$ GeV and $-1 < \eta^{jet} < 2$

- **Integrated jet shape ($\psi(r)$): Average fraction of the jet's transverse energy that lies inside a cone in the $\eta - \varphi$ plane of radius $r = \sqrt{(\Delta\eta)^2 + (\Delta\varphi)^2}$ concentric with the jet axis**



→ **The NLO calculations give a very good description of the data**

Jet substructure in NC DIS:

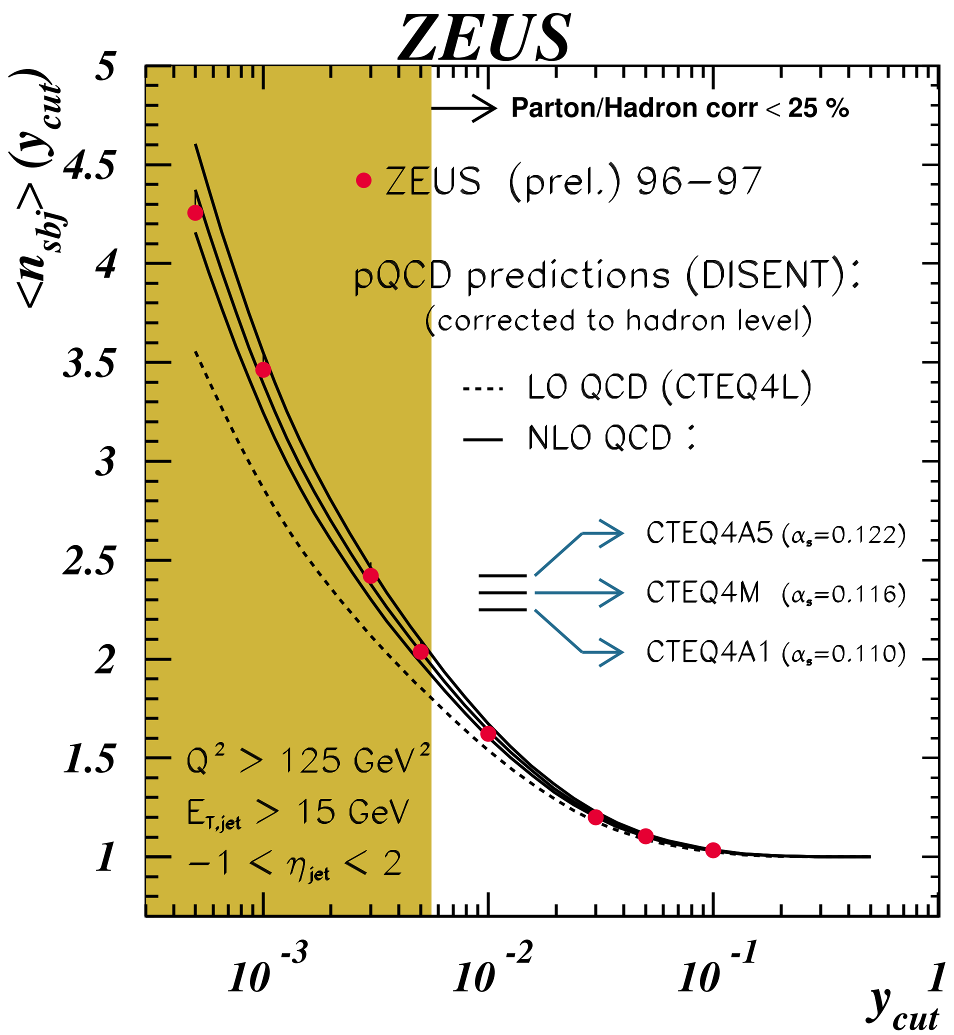
$ep \to e$ + jet + X in the LAB frame

- Jets searched using the k_T cluster algorithm
- Kinematic region: $Q^2 > 125$ GeV^2
- At least one jet with $E_T^{jet} > 15$ GeV and $-1 < \eta^{jet} < 2$

- **Subjet multiplicity (n_{subjet}): Subjets are resolved within a jet by reapplying the k_T algorithm until for every pair of particles the quantity**

$$d_{ij} = min(E_{Ti}, E_{Tj})^2[(\eta_i - \eta_j)^2 + (\varphi_i - \varphi_j)^2]$$

is above $y_{cut} \cdot (E_T^{jet})^2$

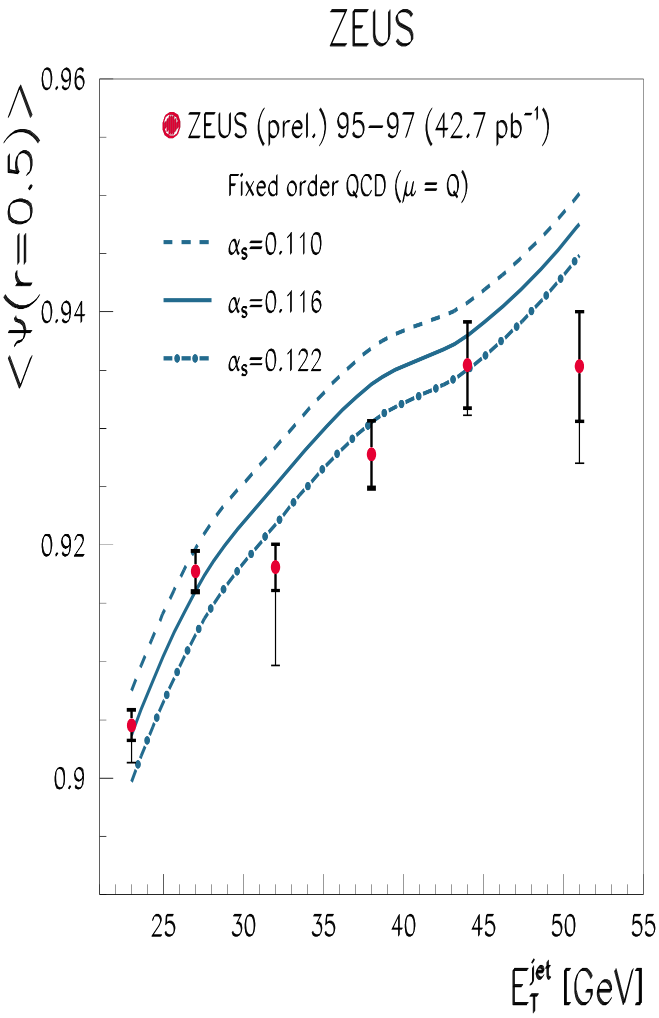


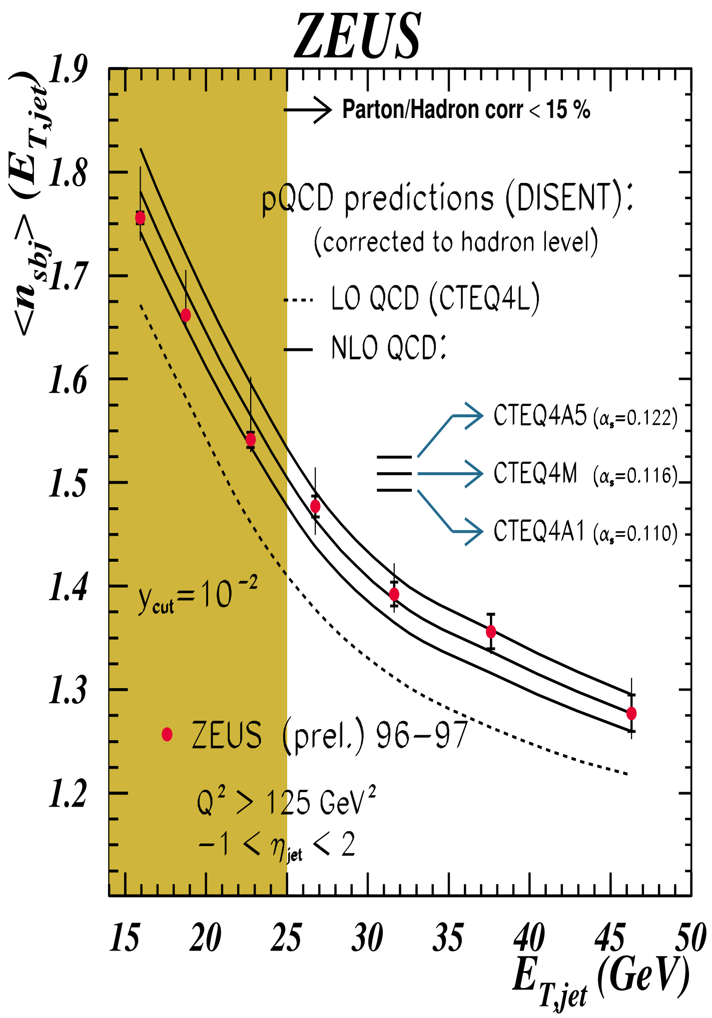
→ **The NLO calculations give a very good description of the data**

E_T^{jet} dependence of the jet substructure:

$ep \rightarrow e$ + jet + X in the LAB frame

- Jets searched using the k_T cluster algorithm
- Kinematic region: $Q^2 > 125$ GeV^2
- At least one jet with $E_T^{jet} > 15$ GeV and $-1 < \eta^{jet} < 2$



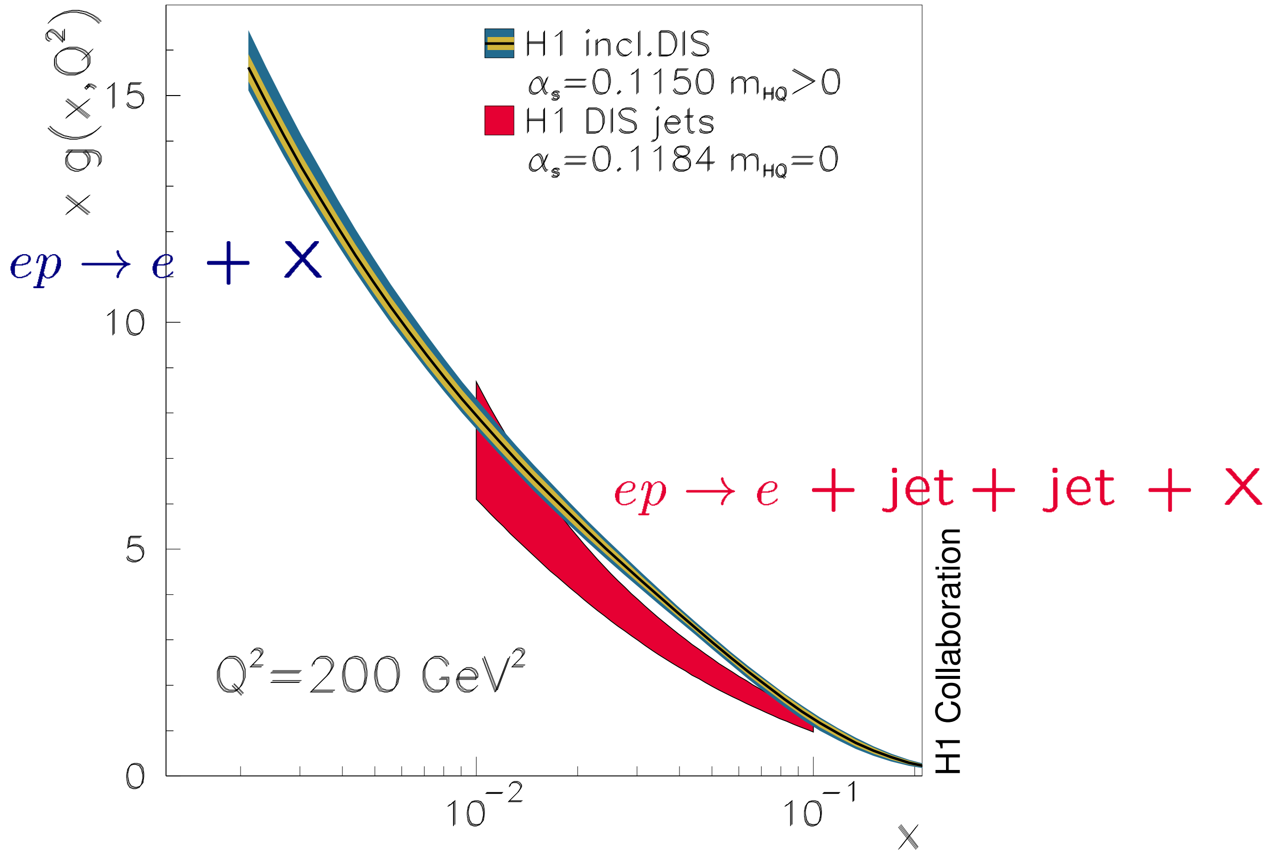


- The jet shape increases and the subjet multiplicity decreases as E_T^{jet} increases $\rightarrow$ jets get narrower

$\rightarrow$ **The NLO calculations give a good description of the data $\rightarrow$ Use the comparison of measurements and theory of $< \psi(r = 0.5) >$ and $< n_{subjet} >$ at $y_{cut} = 10^{-2}$ as a function of E_T^{jet} to extract α_S**

Extraction of the gluon density: using inclusive DIS data and dijet cross sections in NC DIS

- The gluon density in the proton is extracted from fits to measurements of the double differential dijet cross section $d^2\sigma/dQ^2dx$ (BGF process) and the inclusive DIS cross section (scaling violations) in the kinematic region $200 < Q^2 < 5000$ GeV^2



→ **The gluon density extracted from dijet cross sections in NC DIS is consistent with that extracted from scaling violations in inclusive data, but it has more uncertainties**

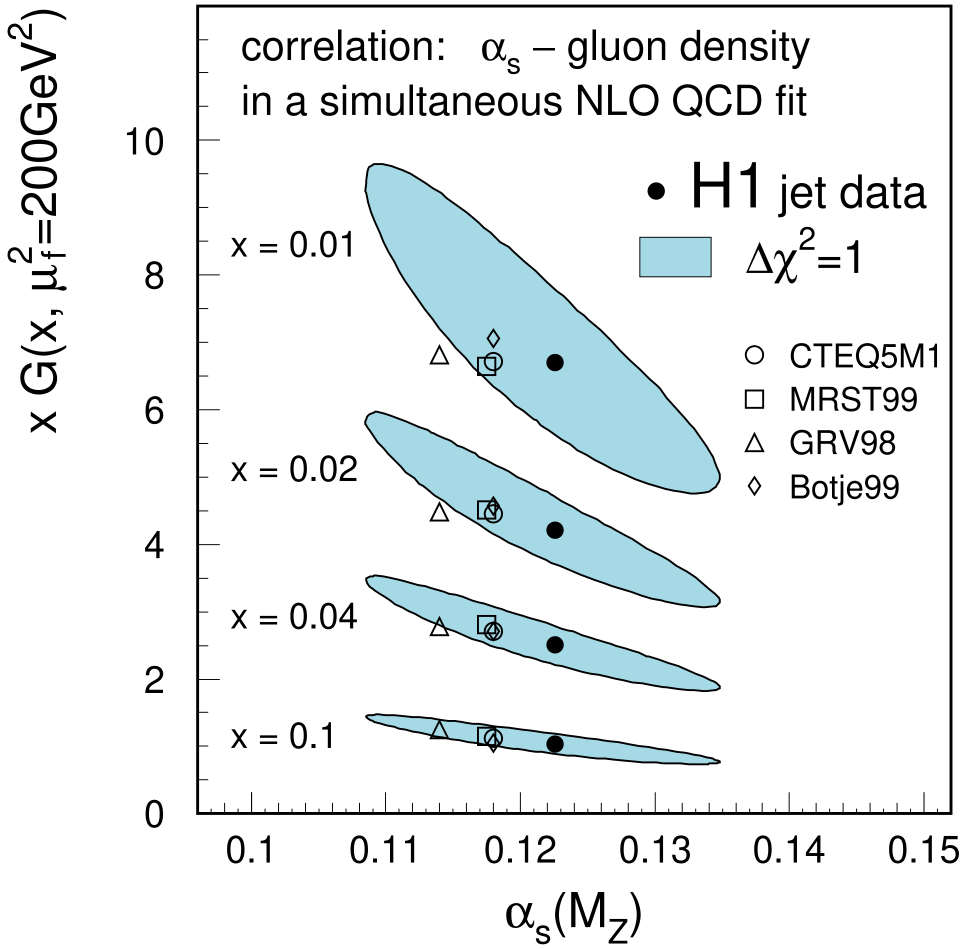
→ **The inclusion of the dijet data in a combined fit, improves the stability of the extraction at high x wrt to the fit using only inclusive data**

Simultaneous QCD fit of $\alpha_S(M_Z)$ and $xg(x)$:

→ **Using inclusive DIS cross sections, inclusive jet and dijet cross sections, a simultaneous extraction of α_S and the gluon density in the proton has been performed**

$$\sigma_{incl} \propto q$$

$$\sigma_{incl\ jet} \propto \alpha_S \cdot (c_g\, g + c_q\, q) \qquad \sigma_{dijet} \propto \alpha_S \cdot (c'_g\, g + c'_q\, q)$$



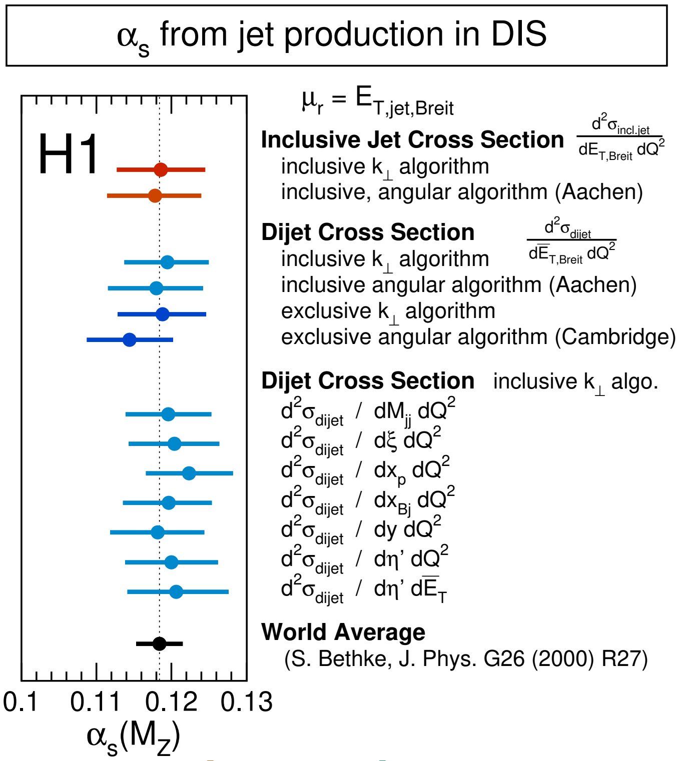
→ **Extracted $\alpha_S(M_Z)$ and gluon density compatible with the world average and results from global fits**

→ **$\alpha_S(M_Z)$-gluon density anti-correlation → data sensitive to $\alpha_S \cdot g(x)$**

→ **But present uncertainties do not allow a simultaneous determination of α_S and the gluon with high accuracy**

Extraction of α_S:

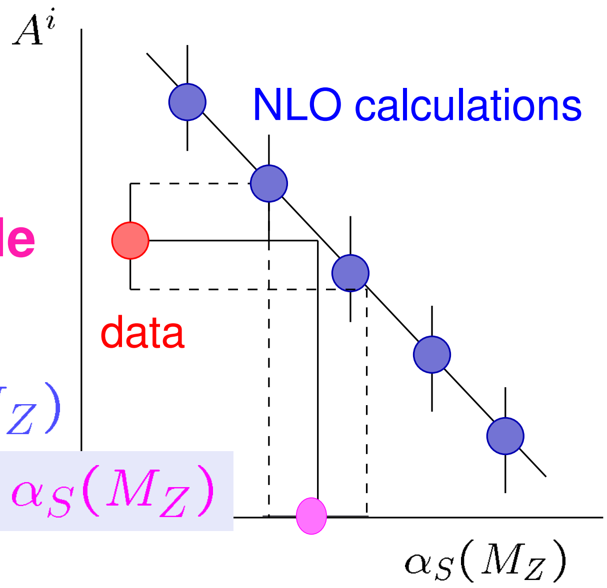
H1:



ZEUS:

- **The measurements of $d\sigma/dQ^2$ for $Q^2 > 500$ GeV^2, $<\psi(r=0.5)>$ for $E_T^{jet} > 21$ GeV and $<n_{subjet}>$ at $y_{cut} = 10^{-2}$ for $E_T^{jet} > 25$ GeV were used to determine $\alpha_S(M_Z)$**
- **NLO calculations for each observable are performed using the five CTEQ4 sets of the "A-series" and then they are corrected for hadronisation effects**
  $\rightarrow$ **the value of $\alpha_S(M_Z)$ in each calculation is that of each set of PDFs**
- **The calculations are used to parametrise the $\alpha_S(M_Z)$ dependence of each observable according to a linear fit**

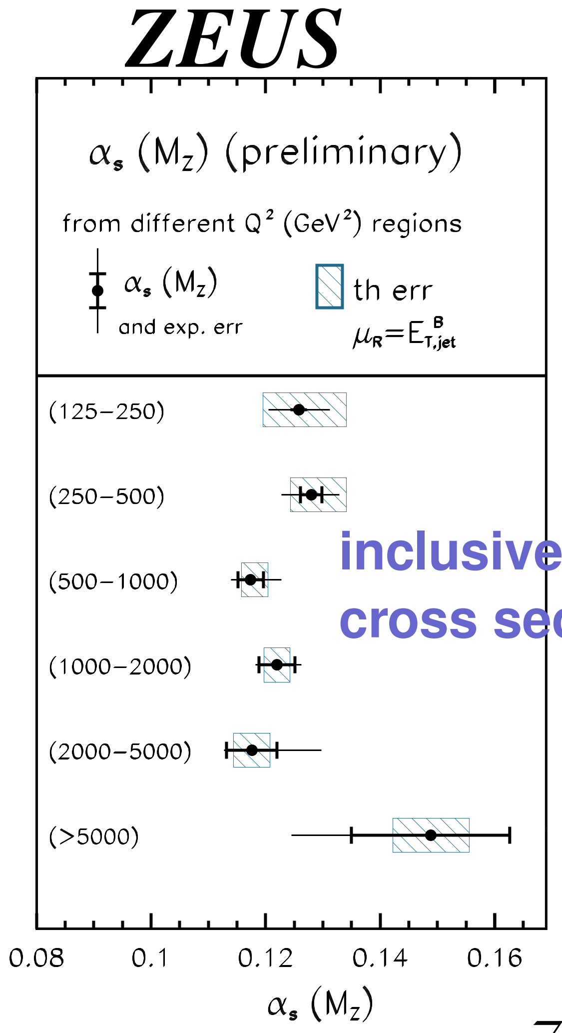
$$A^i(\alpha_S(M_Z)) = B_1^i + B_2^i \cdot \alpha_S(M_Z)$$



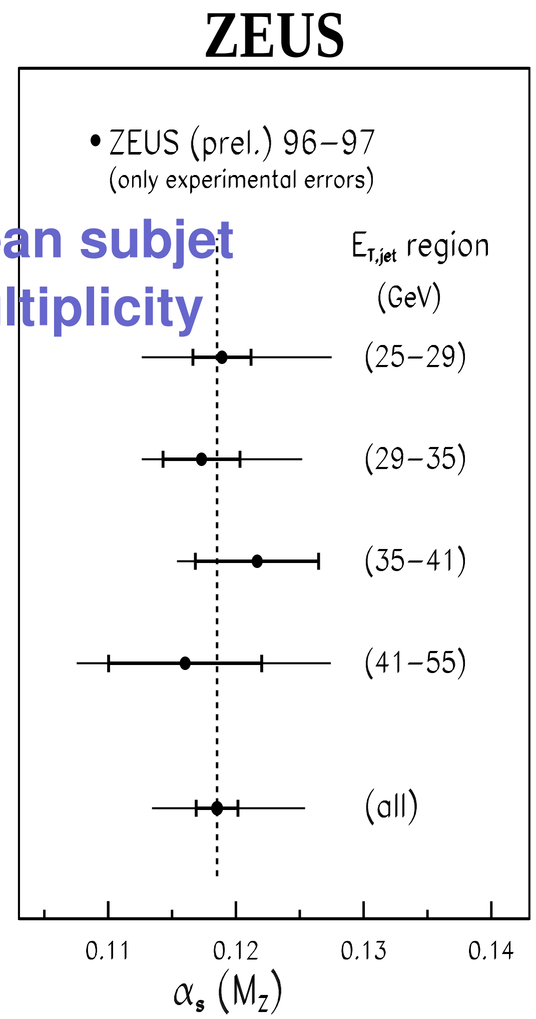
extracted value of $\alpha_S(M_Z)$

Extracted values of α_S from each Q^2 and E_T^{jet} range:

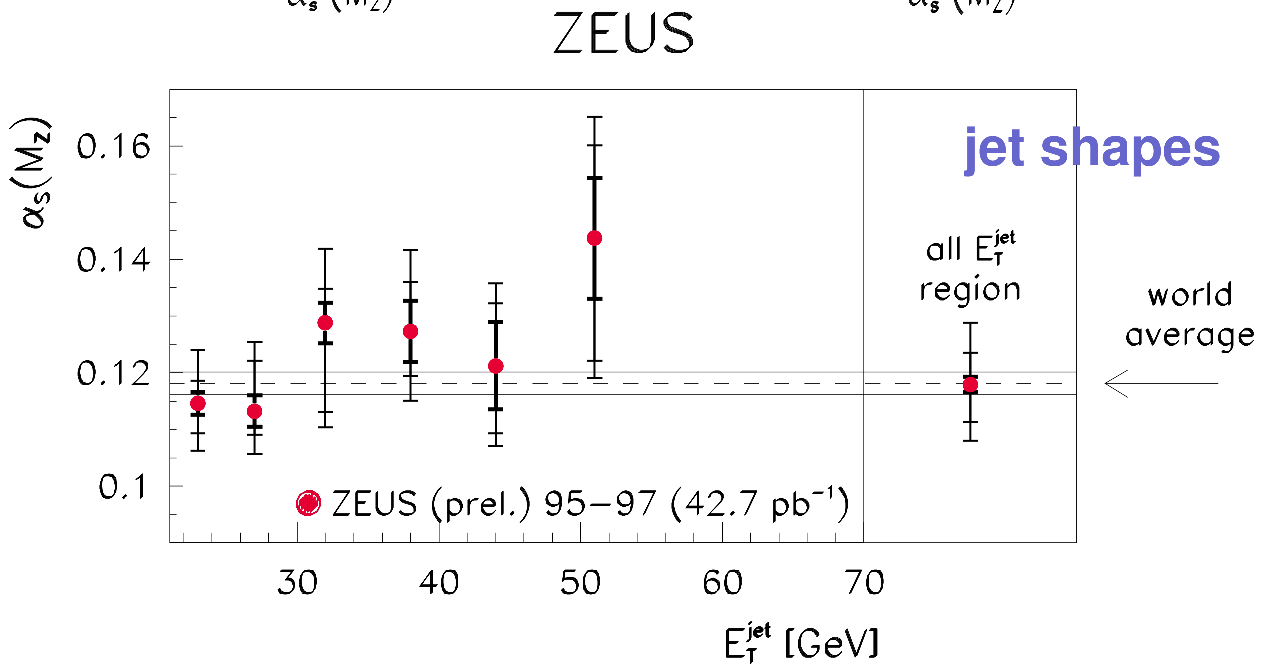
inclusive jet cross sections



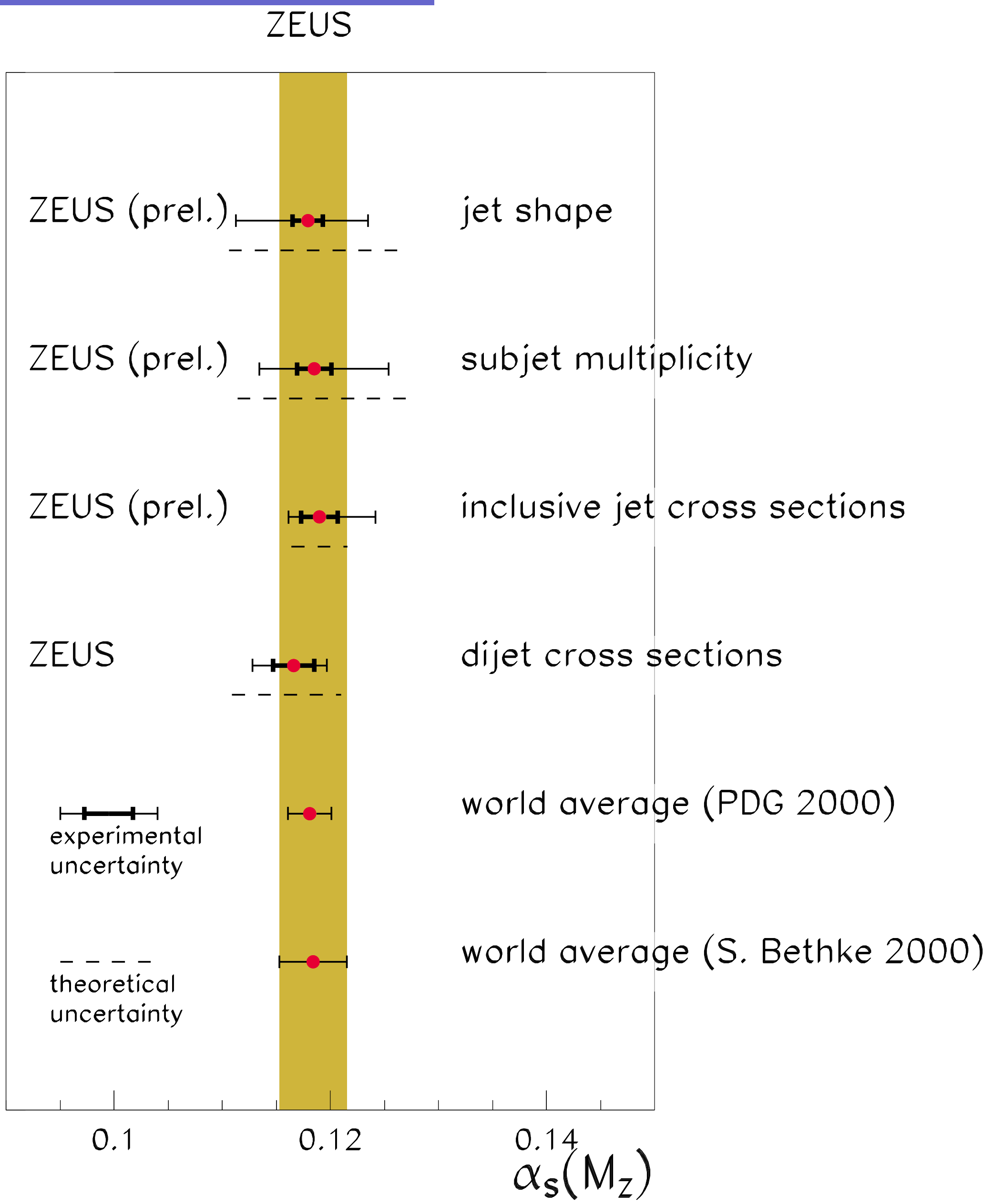
mean subjet multiplicity



jet shapes



Extracted values of α_S:



$\rightarrow$ Inclusive jet cross section $d\sigma/dQ^2$ for $Q^2 > 500$ GeV^2:

$\alpha_S(M_Z) = 0.1190 \pm 0.0017\,(\text{stat})^{+0.0049}_{-0.0023}\,(\text{exp})^{+0.0026}_{-0.0026}\,(\text{th})$

$\rightarrow < \psi(r = 0.5) >$ for $E_T^{jet} > 21$ GeV:

$\alpha_S(M_Z) = 0.1179 \pm 0.0014\,(\text{stat})^{+0.0054}_{-0.0065}\,(\text{exp})^{+0.0094}_{-0.0073}\,(\text{th})$

$\rightarrow < n_{subjet} >$ at $y_{cut} = 10^{-2}$ for $E_T^{jet} > 25$ GeV:

$\alpha_S(M_Z) = 0.1185 \pm 0.0016\,(\text{stat})^{+0.0067}_{-0.0048}\,(\text{exp})^{+0.0089}_{-0.0071}\,(\text{th})$

Conclusions:

- New measurements of jet cross sections in NC and CC DIS have been presented

- New determinations of $\alpha_S(M_Z)$ and the gluon density and a simultaneous QCD fit of $\alpha_S(M_Z)$ and the gluon density have been presented; the results are consistent with the world average on $\alpha_S(M_Z)$ and the gluon density from global fits:

  $\rightarrow$ Experimental uncertainties are small
  $\rightarrow$ determinations are precise

- But the determinations of $\alpha_S(M_Z)$ and the gluon density are not accurate since the NLO calculations used in the QCD analyses have large uncertainties:

  $\rightarrow$ need better QCD calculations: higher orders, inclusion of EW effects, Z° couplings and heavy quark masses, turn on of active flavours as a function of the scale, more choices of μ_F, $\ldots$