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The Internal Structure of Jets at HERA

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- Introduction, definition of the observables
- Jet substructure in neutral current DIS, determination of α_s
- Comparison to charged current results
- Jet substructure in photoproduction
- Extracting the internal structure of gluon jets
- Conclusions

Introduction

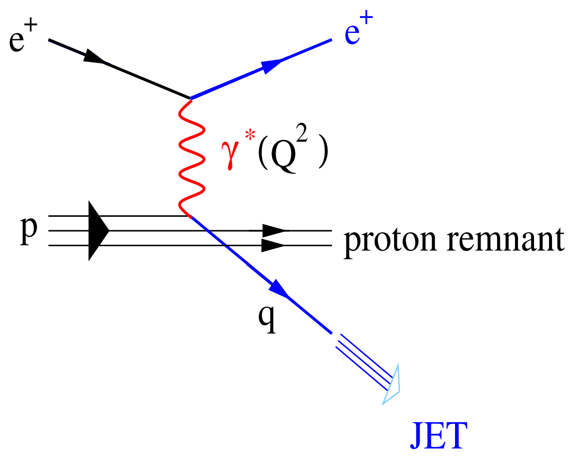
- Jet production in e^+p deep-inelastic scattering (DIS) and photoproduction provides a rich testing ground of perturbative QCD (pQCD).
- The internal structure of jets gives insight into the transition from partons to the experimentally observable spray of hadrons.
- Measurements of the jet structure in neutral current (NC) DIS allow an experimentally precise determination of the strong coupling α_s.
- The type of the primary parton (quark or gluon) influences the jet substructure. In photoproduction q and g-jets can be disentangled.
- The internal structure of jets can be characterised by the integrated and the differential jet shape and by the mean subjet multiplicity.
- In this talk, measurements of these variables taken with the ZEUS detector in the years 1996-2000 will be presented.

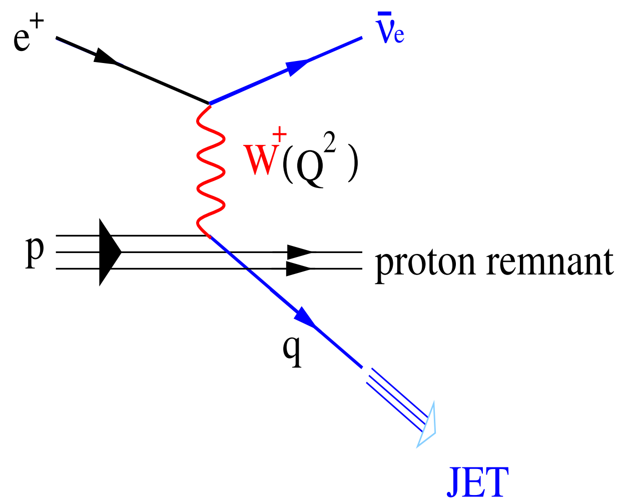
  Jets are selected in the laboratory frame applying the longitudinally invariant k_T-cluster algorithm. The jet axis is defined according to the Snowmass convention.

Deep inelastic scattering, α_s

- Deep inelastic scattering at HERA is characterised by a high virtuality $Q^2 \gg \Lambda^2_{\mathrm{QCD}}$ of the exchanged boson.

- One distinguishes between neutral current (NC) and charged current (CC) events.

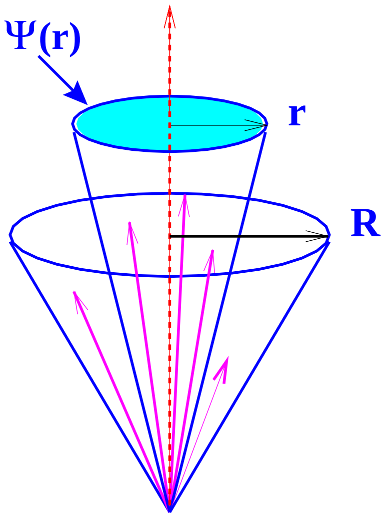




- In inclusive jet NC DIS, the strong coupling α_s can be determined from the internal jet structure.

- For this type of variable, the dependence of perturbative QCD calculations on the parton distribution functions (PDFs) is reduced.

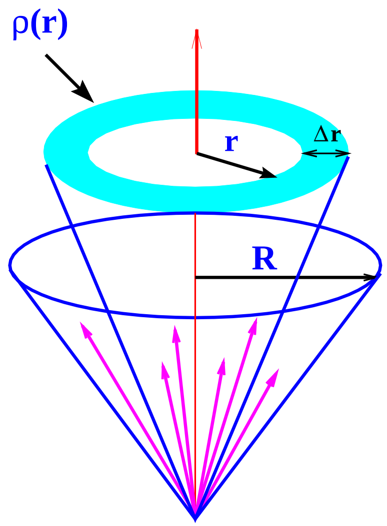
Jet shape variables



- The integrated jet shape is defined as the average fraction $E_T(r)/E_T^{\text{Jet}}$ of the jet transverse energy that lies inside a cone of radius $r = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$ in the η-ϕ plane

  concentric with the jet axis: $\langle\psi(r)\rangle = \frac{1}{N_{\text{Jets}}} \sum_{\text{Jets}} \frac{E_T(r)}{E_T^{\text{Jet}}}$

- Narrower jets are characterised by larger values of $\langle\psi(r)\rangle$.



- The differential jet shape is given by the average fraction of the jet's transverse energy that lies between two cones of radius r and $r + \Delta r$ respectively:

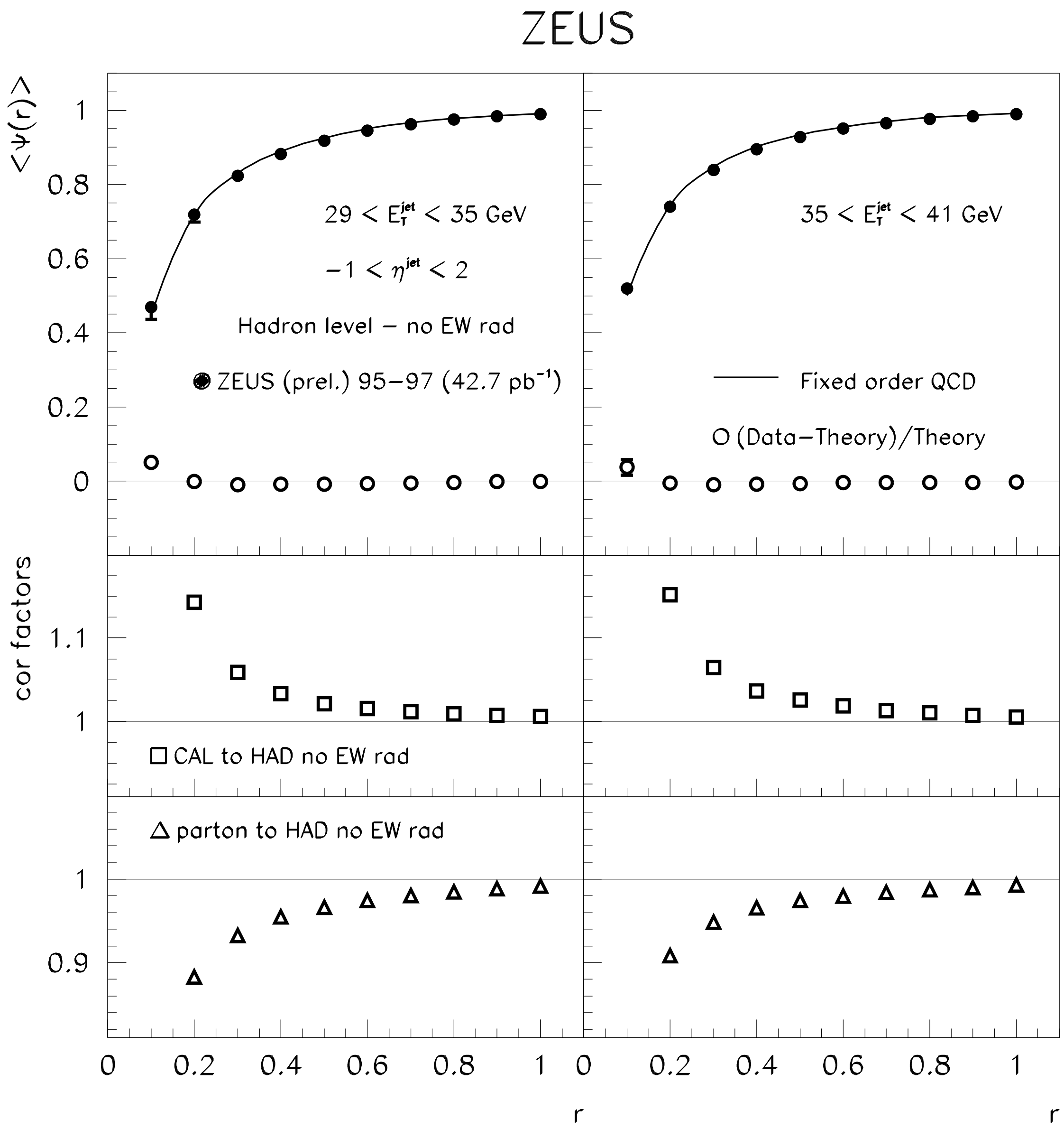
$$\rho(r) = \frac{d\psi}{dr} = \frac{1}{N_{\text{Jets}}} \sum_{\text{Jets}} \frac{E_T^{\text{Jet}}(r, r+\Delta r)}{E_T^{\text{Jet}}}$$

Integrated Jet Shape in NC DIS ($Q^2 > 125$ GeV^2)

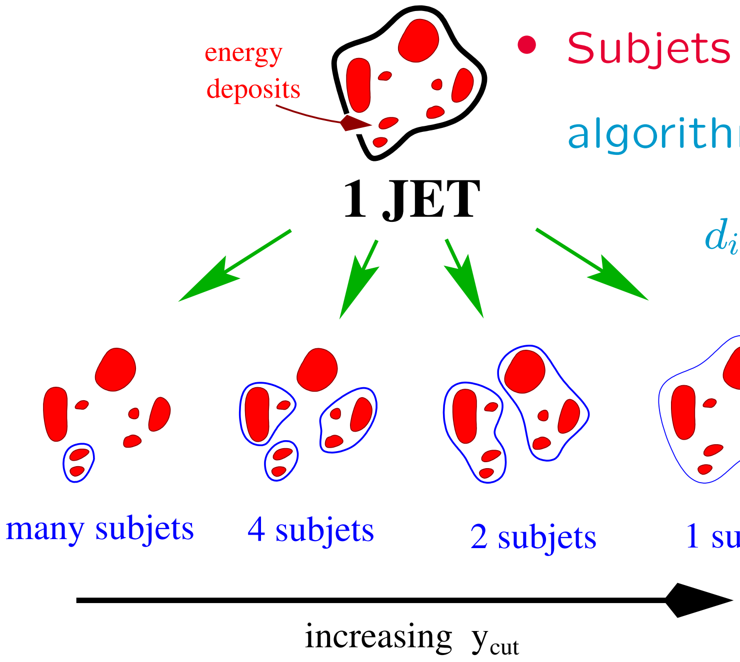
- Data & NLO QCD calculations are corrected to hadron level and then compared.

- Correction factors are obtained from Monte Carlo (MC).

- The measured jet shapes are well described by NLO QCD calculations: fractional differences are below 1.3% for $r \geq 0.5$.

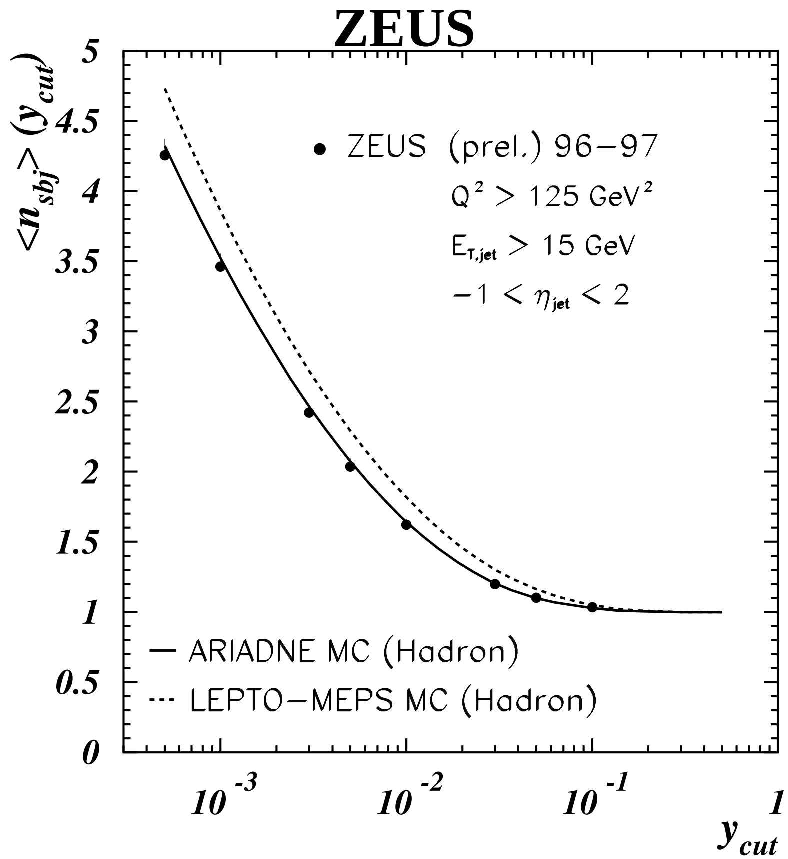


The Mean Subjet Multiplicity $\langle n_{sbj} \rangle$



- Subjets are resolved within a jet by reapplying the k_T-cluster algorithm to all particles in the jet until for every i, j:

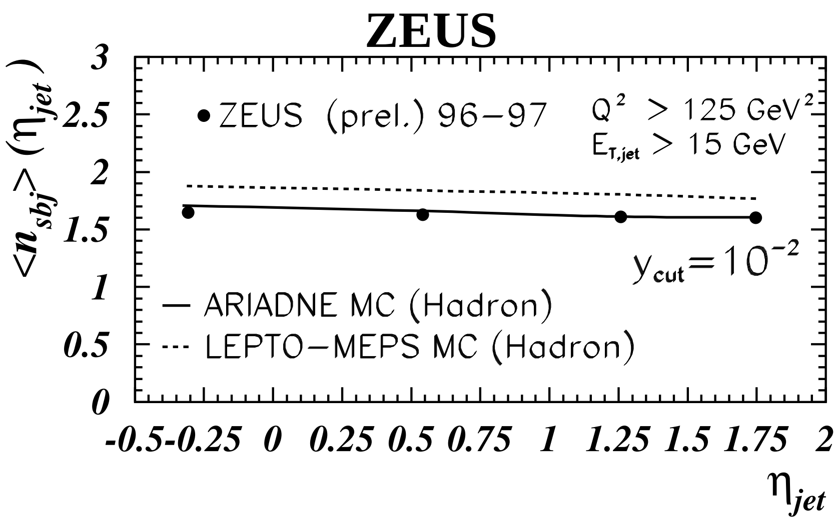
  $d_{i,j} > d_{\text{cut}} = y_{\text{cut}} \left(E_T^{\text{Jet}}\right)^2$. All remaining clusters are subjets.



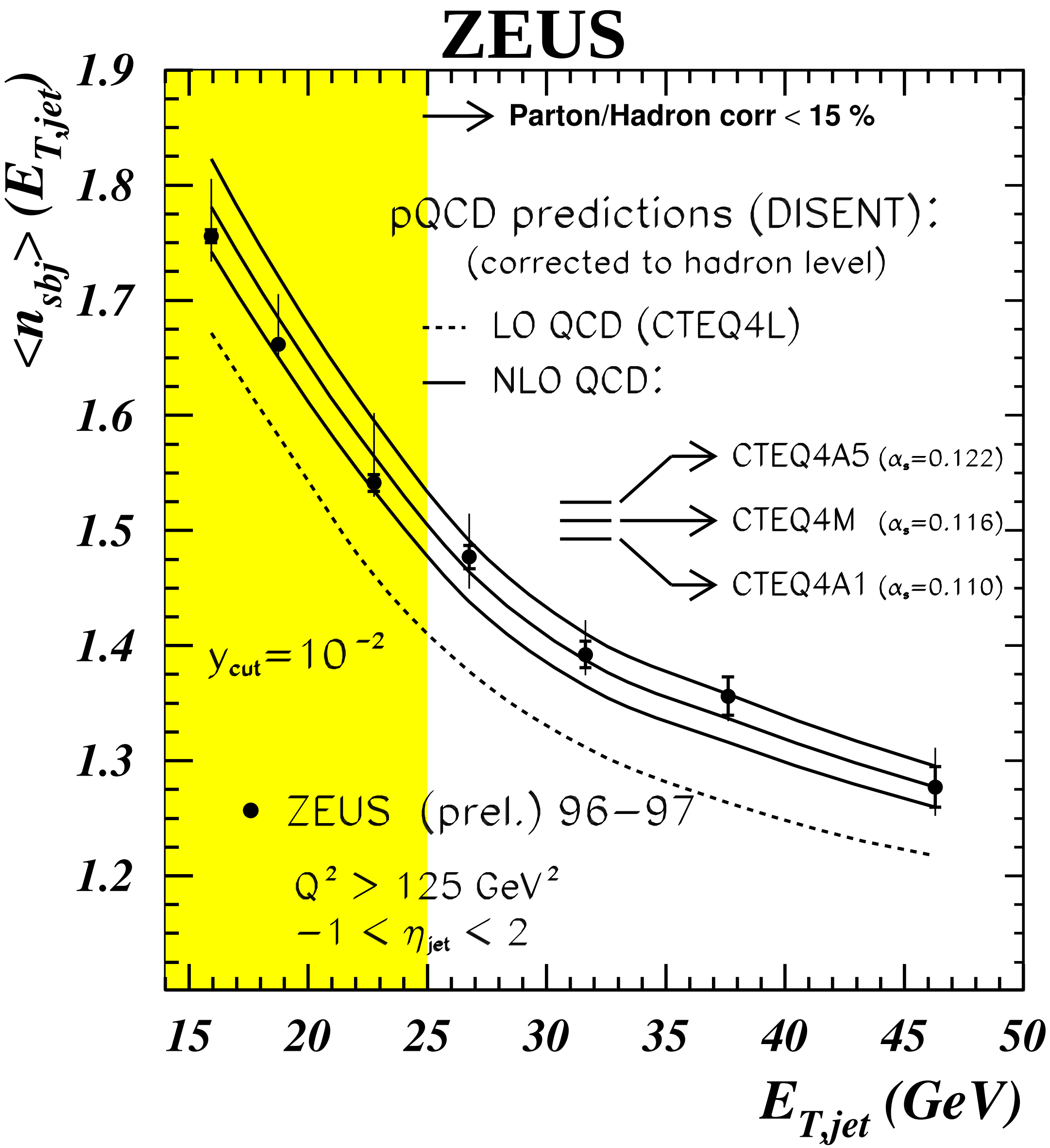
- The mean subjet multiplicity, averaged over all jets in the sample, depends on the resolution parameter y_{cut}.

$\langle n_{sbj} \rangle$ as a function of η^{Jet} and E_T^{Jet}

- $\langle n_{\rm sbj} \rangle$ at $y_{\rm cut} = 10^{-2}$ shows no significant dependence on $\eta_{\rm Jet}$ and decreases as $E_T^{\rm Jet}$ increases.



- NLO QCD calculations provide a good description of the data.
  $\Rightarrow$ used to extract $\alpha_s(M_Z)$ from measurements at $E_T^{\rm Jet} > 25$ GeV



Determination of α_s (NC)

$\alpha_s(M_Z)$ from $A = \langle n_{\mathsf{sbj}} \rangle \left(y_{\mathsf{cut}} = 10^{-2}\right)$ for $E_T^{\mathsf{Jet}} > 25\,\mathrm{GeV}$, $\langle \psi(r = 0.5) \rangle$ for $E_T^{\mathsf{Jet}} > 21\,\mathrm{GeV}$:

- NLO QCD calculations of A performed for "A"-series of CTEQ4 (5 sets), using same α_s in partonic cross section calculation and in PDFs
- one α_s value per E_T^{Jet}-bin and combined value (χ^2-fit to all bins) determined

Result from $\langle n_{\mathsf{sbj}} \rangle (y_{\mathsf{cut}})$:

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

to be compared with PDG value $\alpha_s(M_Z) = 0.1181 \pm 0.0020$

$\alpha_s(M_Z)$: Comparison with other Measurements

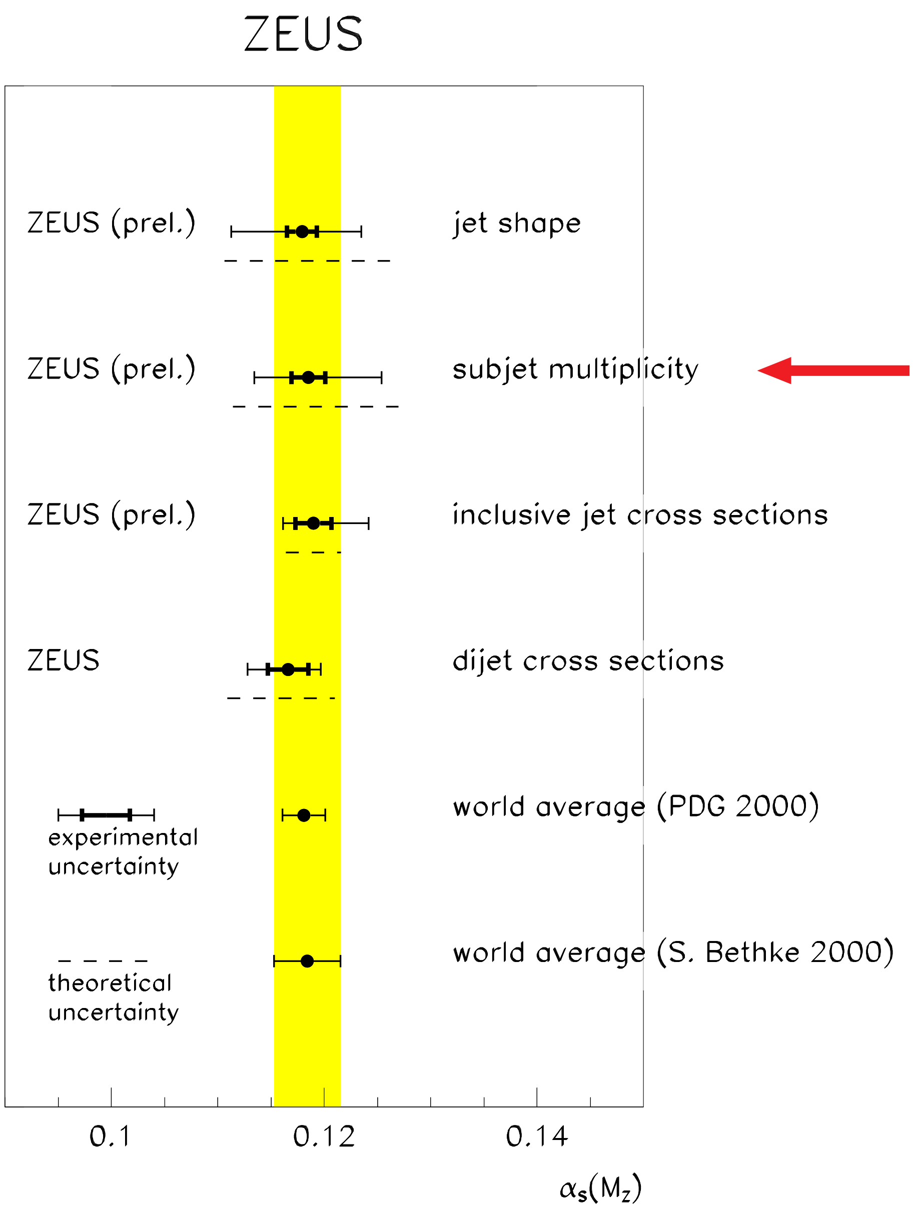
$\alpha_s(M_Z)$ from jet substructure consistent

with recent determinations by ZEUS and

with the current PDG world average

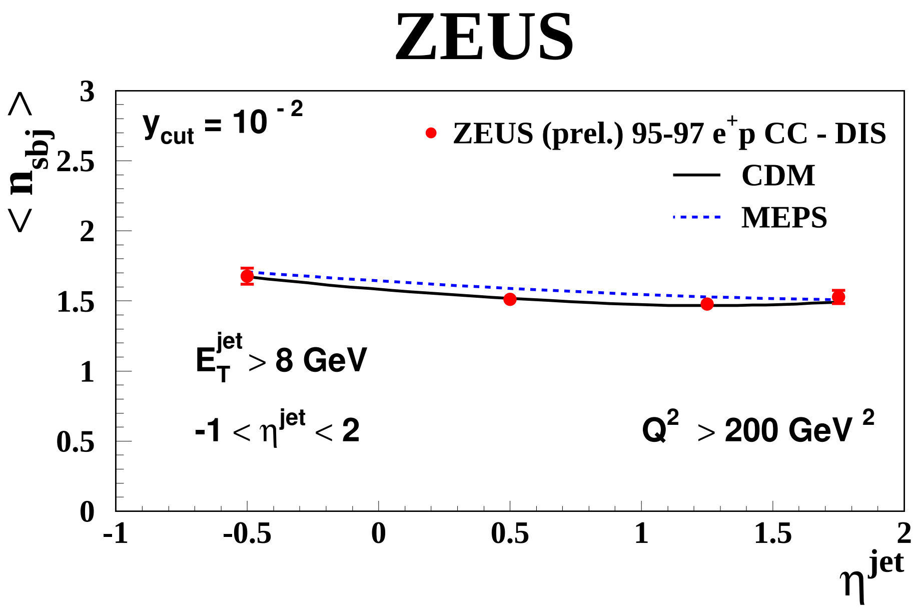
The error is dominated by the

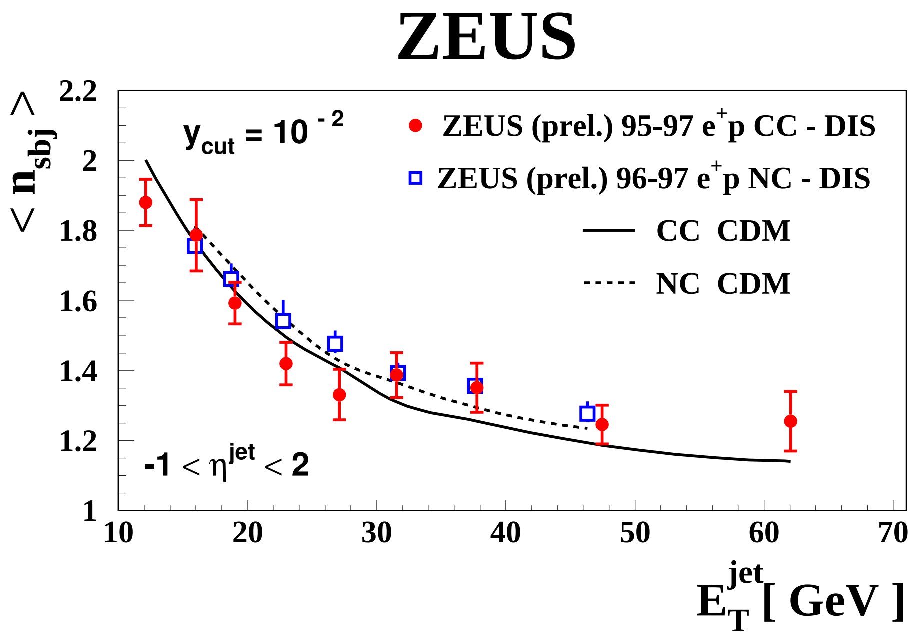
theoretical uncertainty.



Mean Subjet Multiplicity in CC DIS

The jet substructure in charged current (CC) DIS is very similar to the one observed in NC reactions.

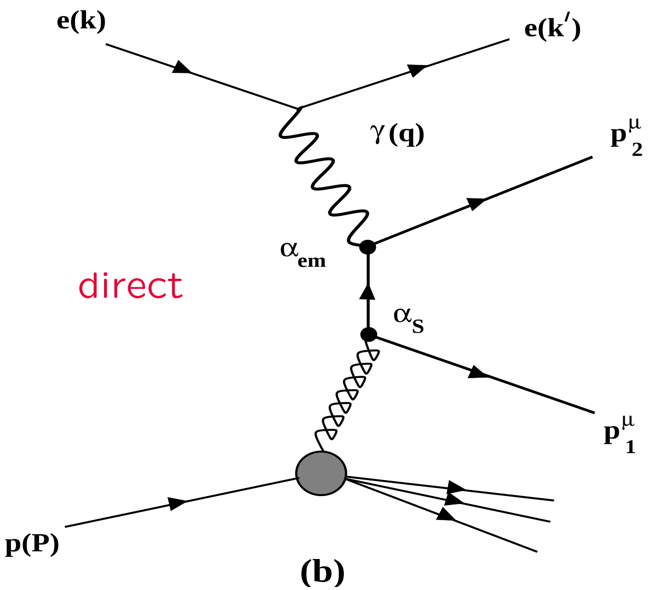


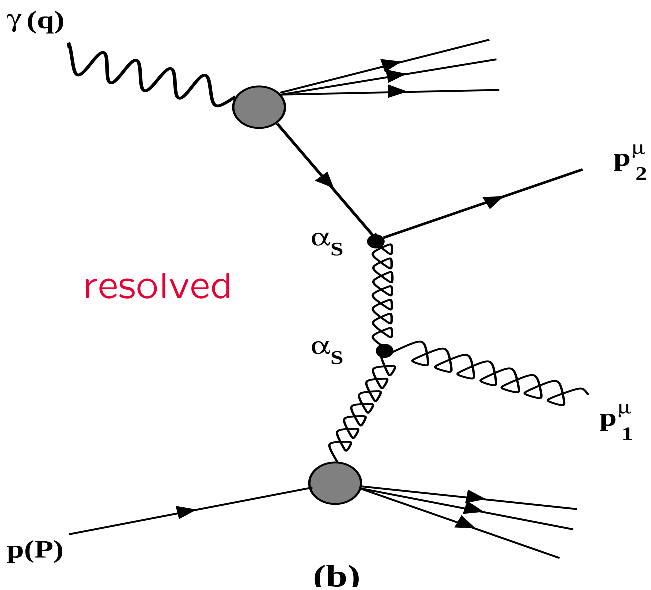


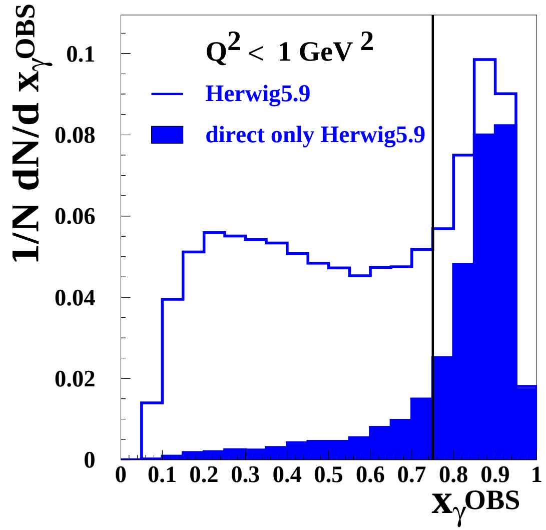
- The similarity between CC and NC jets is attributed to a similarly large content of quark jets in these two processes.
- Thus the pattern of QCD radiation close to a primary quark is to a large extent independent of the hard scattering process.

Jets in Photoproduction

- In photoproduction at HERA ($Q^2 \approx 0$), two types of QCD processes contribute to jet production at leading order:







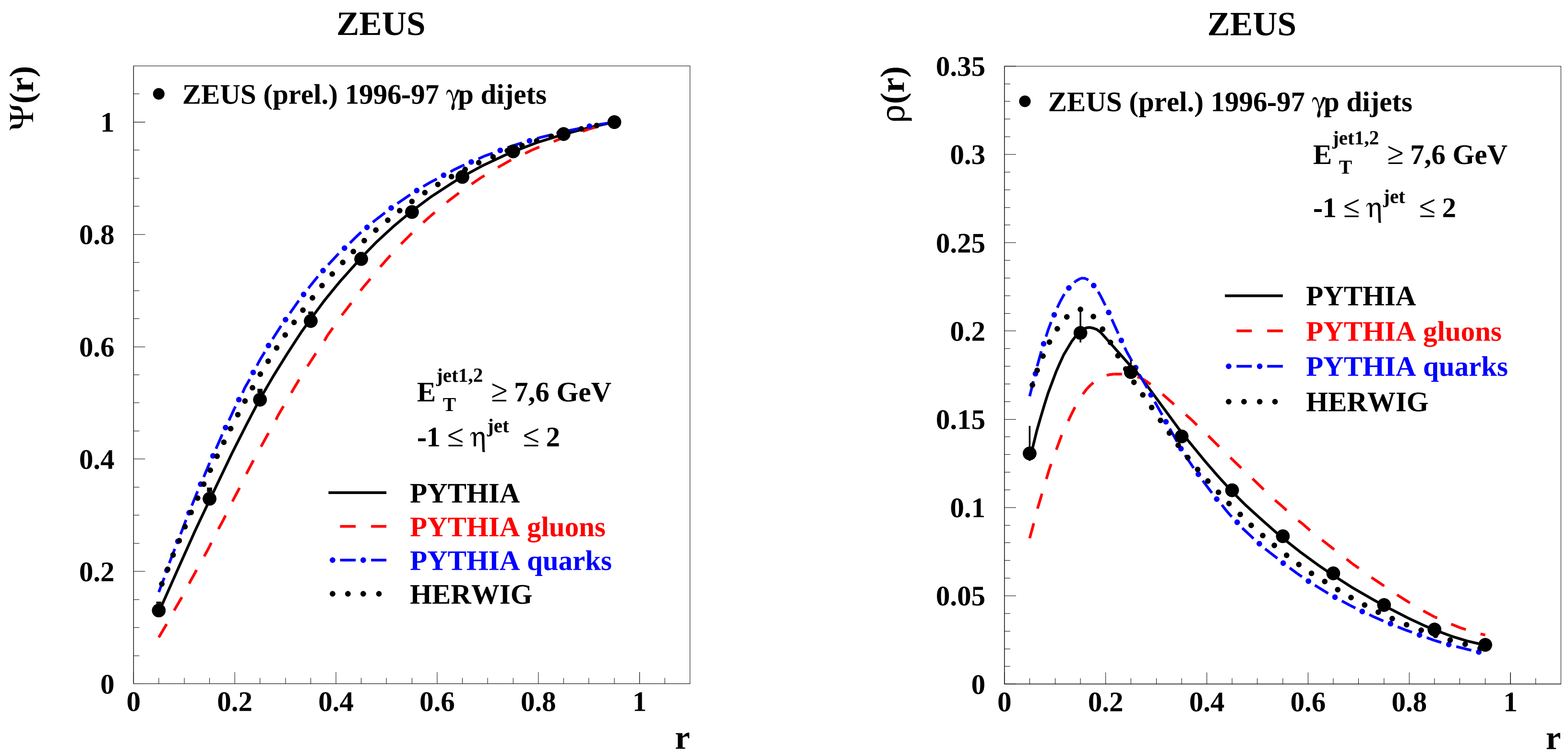
$$x_\gamma^{\text{OBS}} = \sum_{\text{jets}} \frac{E_T e^{-\eta}}{2yE_e}$$

- The majority of the jets for $\eta^{\text{Jet}} < 0$ are predicted to originate from quarks, while the fraction of gluon-initiated jets increases as η^{Jet} increases.

- Gluon jets are predicted to be broader than quark jets due to the larger colour charge of the gluon.

Jet Shapes in Photoproduction

- The integrated jet shape $\psi(r)$ and the differential jet shape $\rho(r)$ have been measured. They are well described by the PYTHIA prediction.



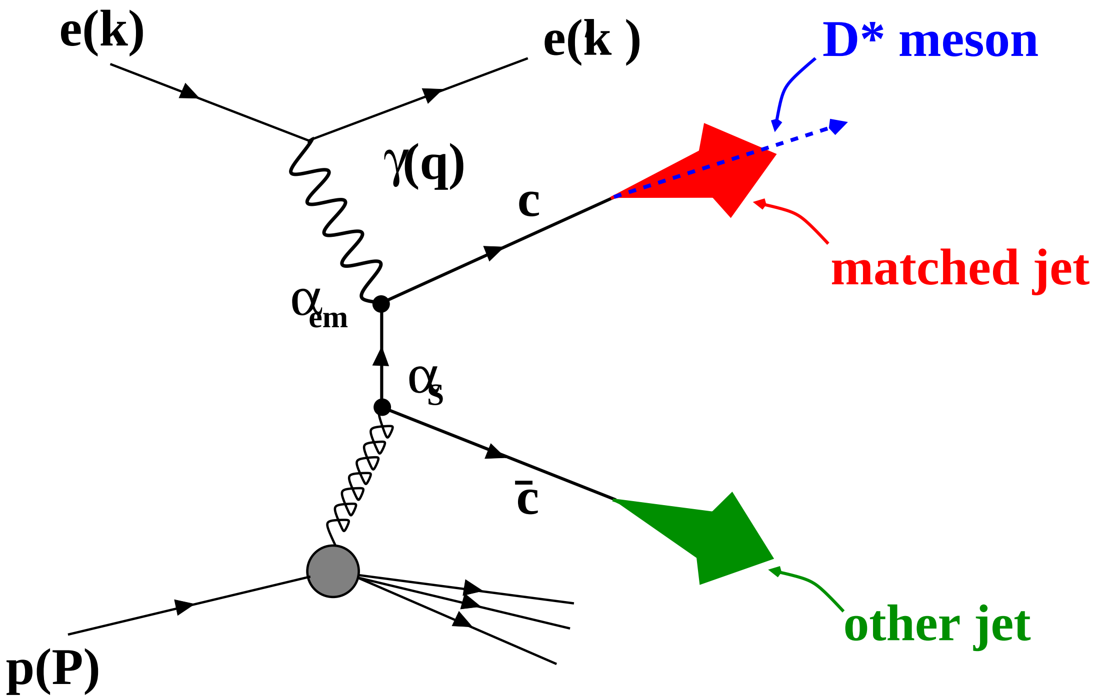
- MC predictions for pure samples of q-jets and g-jets show that gluon jets are expected to be broader than quark-initiated jets.

Charm-Induced Jets in Photoproduction

- D^* mesons were reconstructed from their decay products:

  $D^{*+} \longrightarrow D^0 + \pi_S^+ \longrightarrow (K^- + \pi^+) + \pi_S^+$

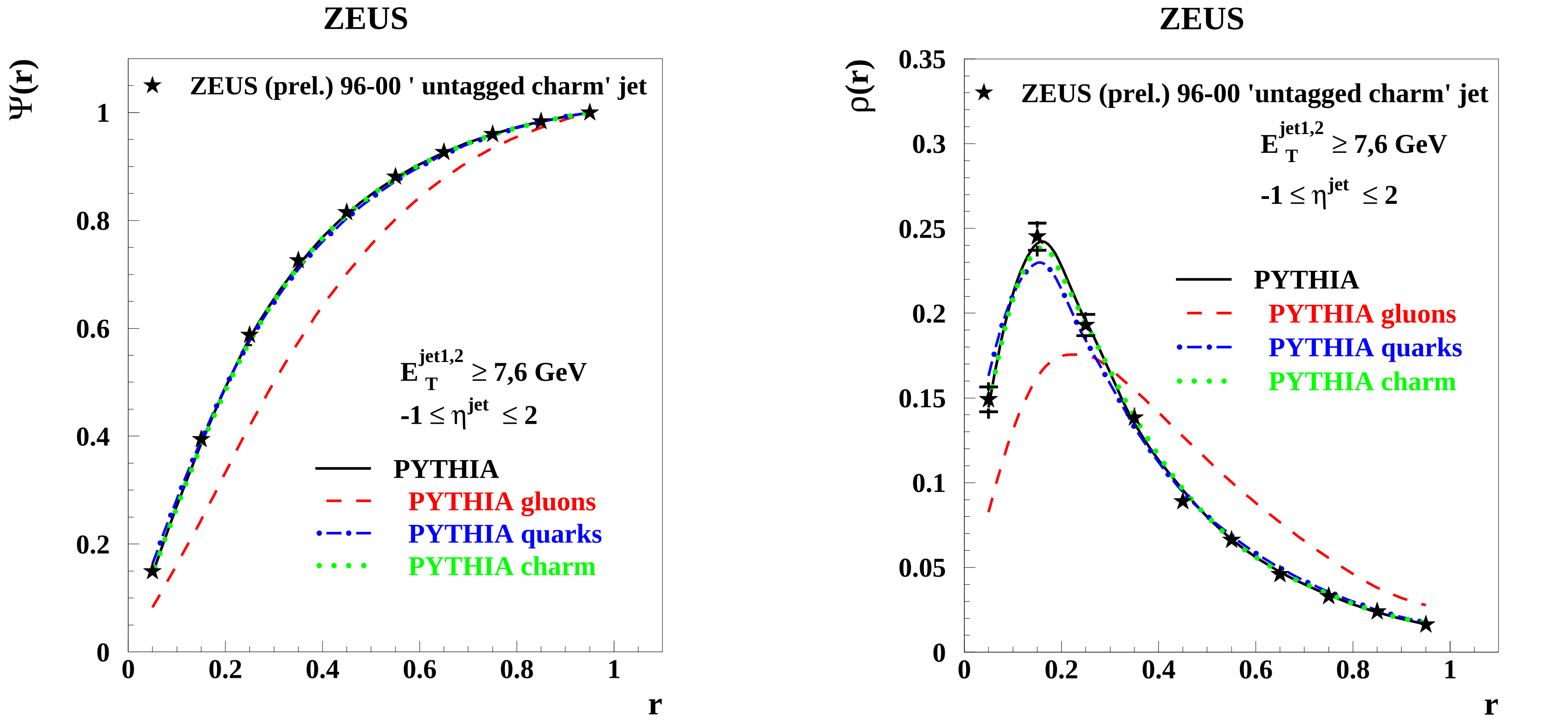
- The jet closest to the D^* in ϕ was associated to the charm meson.



- The other jet ("untagged-charm jet") represents an unbiased jet candidate, whose internal properties were investigated.

Jet Shapes for "untagged-charm" jets

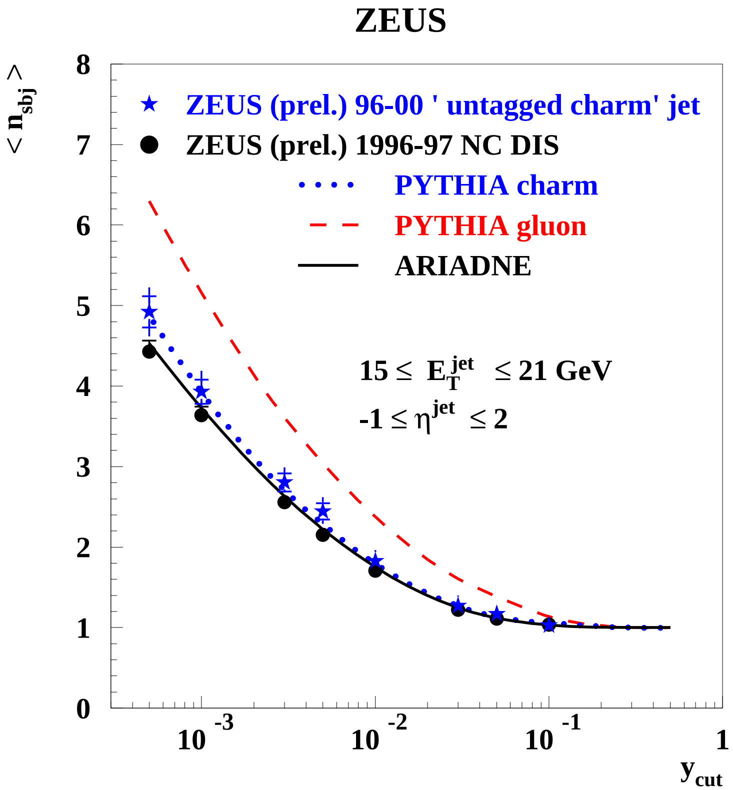
- Integrated and differential jet shape of the "untagged-charm" jet in the D^*-tagged dijet sample have been measured and compared to PYTHIA MC.

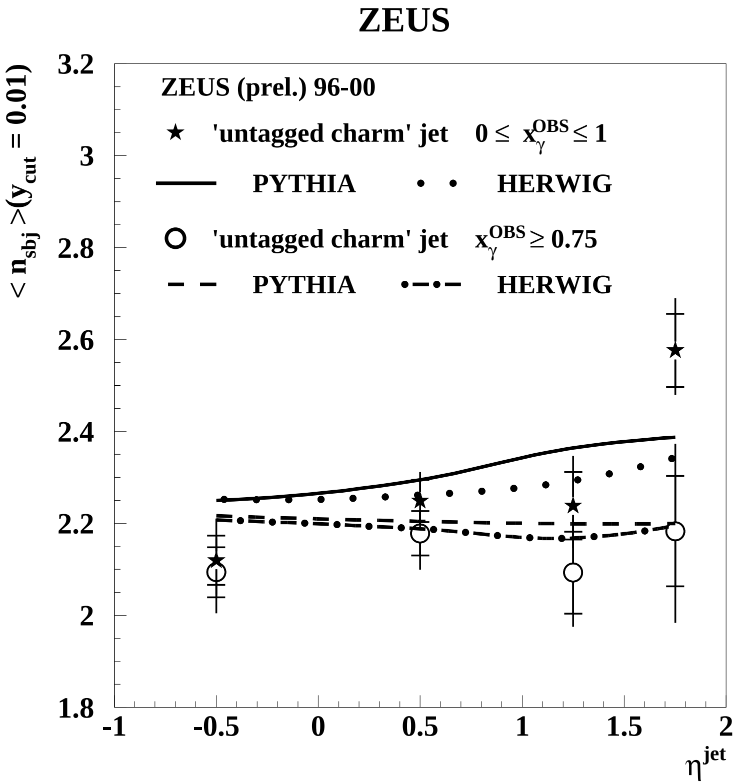


- The agreement between data and Monte Carlo is very good and the predictions for charm-initiated jets are consistent with the measurements.

$\langle n_{sbj} \rangle$ for “untagged-charm” jets

- Charm-initiated jets are very similar to light quark jets observed in NC and CC DIS in the region, where charm-mass effects can be neglected ($y_{\text{cut}} \geq (m_c/E_T^{\text{jet}})^2 \approx 10^{-2}$).





large η_{Jet}: untagged-c-jets broader due to increased fraction of g-jets from resolved processes

- A direct-enriched D^*-tagged sample at high E_T^{Jet} ($x_\gamma^{\text{OBS}} > 0.75$, $E_T^{\text{Jet}} \geq 15\,\text{GeV}$) can be considered as pure quark-jet sample.

Extracting the internal structure of gluon-jets

- The dijet photoproduction sample consists of a mixture of q- and g-jets:

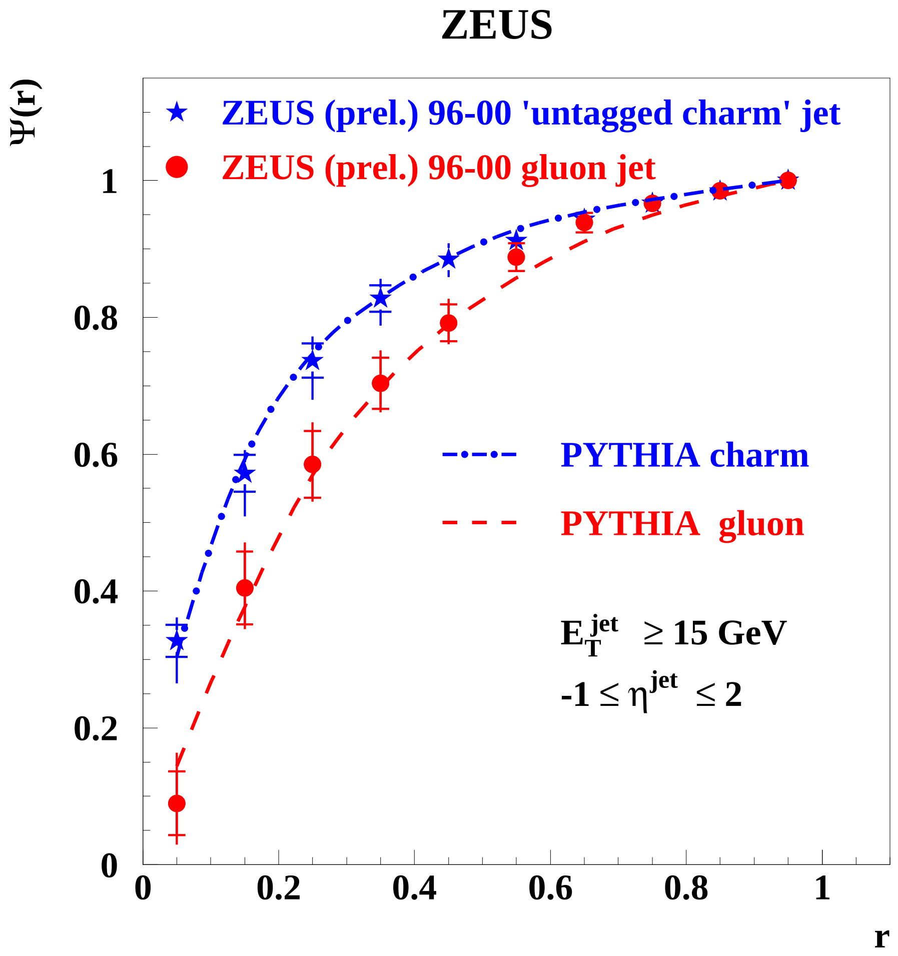
$$\mathcal{O}_{\text{dijet}} = f_q \cdot \mathcal{O}_{\text{quark}} + f_g \cdot \mathcal{O}_{\text{gluon}}$$

- $\mathcal{O}_{\text{dijet}}$ known from dijet photoproduction sample

  $\mathcal{O}_{\text{quark}}$ constrained by direct enriched D^*-tagged sample

  f_q and f_g taken from LO MC

- pQCD predictions are in good agreement with measurements in both the "untagged-charm" jets and in the extracted gluon jets.



Conclusion

- In DIS, jets are predominantly initiated by quarks. Jets become narrower as E_T^{Jet} increases and exhibit no significant dependence on η^{Jet}.
- Next-to-leading order QCD calculations reproduce the measured observables well showing the validity of the description of the internal jet structure by QCD.
- Measurements of the internal jet structure in NC events allow a precise determination of the strong coupling. The value of α_s obtained from these measurements is in good agreement with the world average.
- The sample of jets obtained from photoproduction dijet events represents a mixture of quark- and gluon-initiated jets. Based on D^*-tagging a sample of charm-initiated jets has been isolated and used to disentangle the quark and gluon contributions. While the quark-jets resemble those found in DIS, the "gluon" jets are broader due to the larger colour charge of the gluon.