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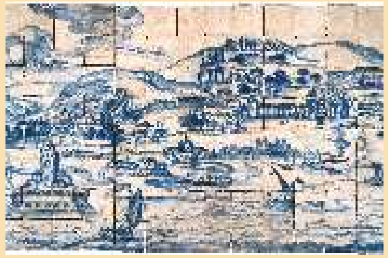

Event shapes and subjet distributions at HERA

Claudia Glasman

Universidad Autónoma de Madrid

from

ZEUS Collab.

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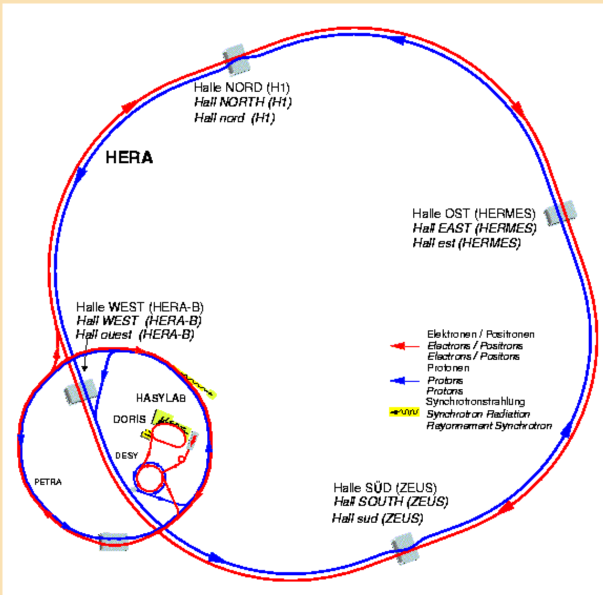
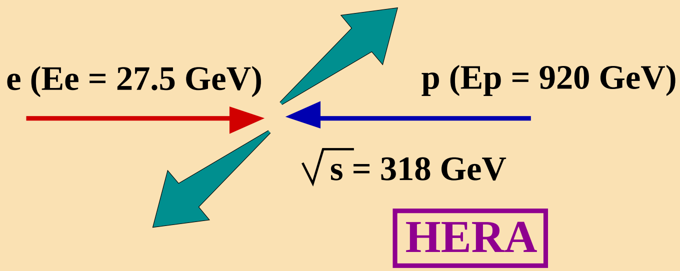
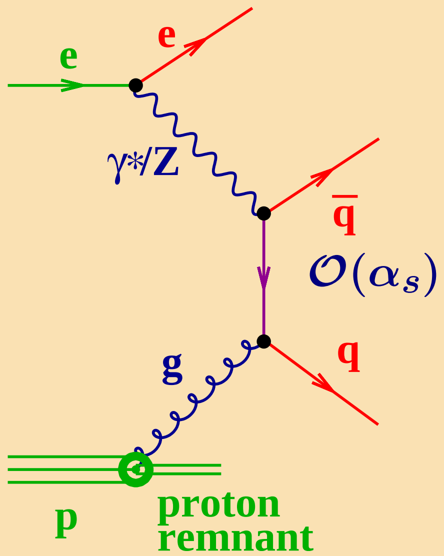
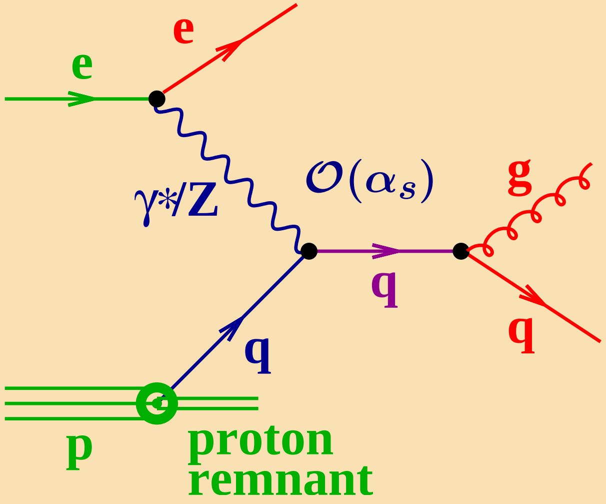
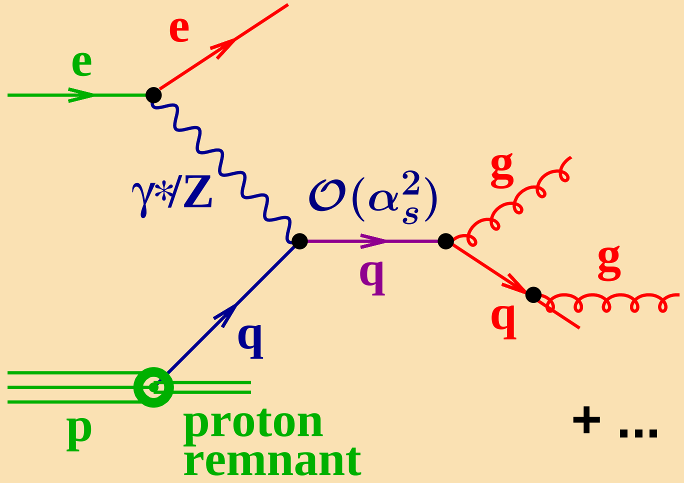




The hadronic final state in NC DIS







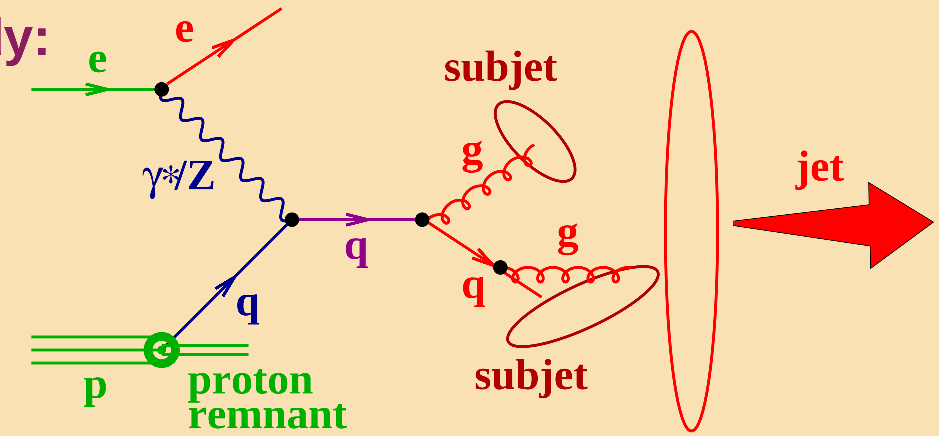
Observable = $\sum_a f_a(x, \mu_F) \otimes$ Matrix Element

- The HFS in NC DIS can also be used to study:

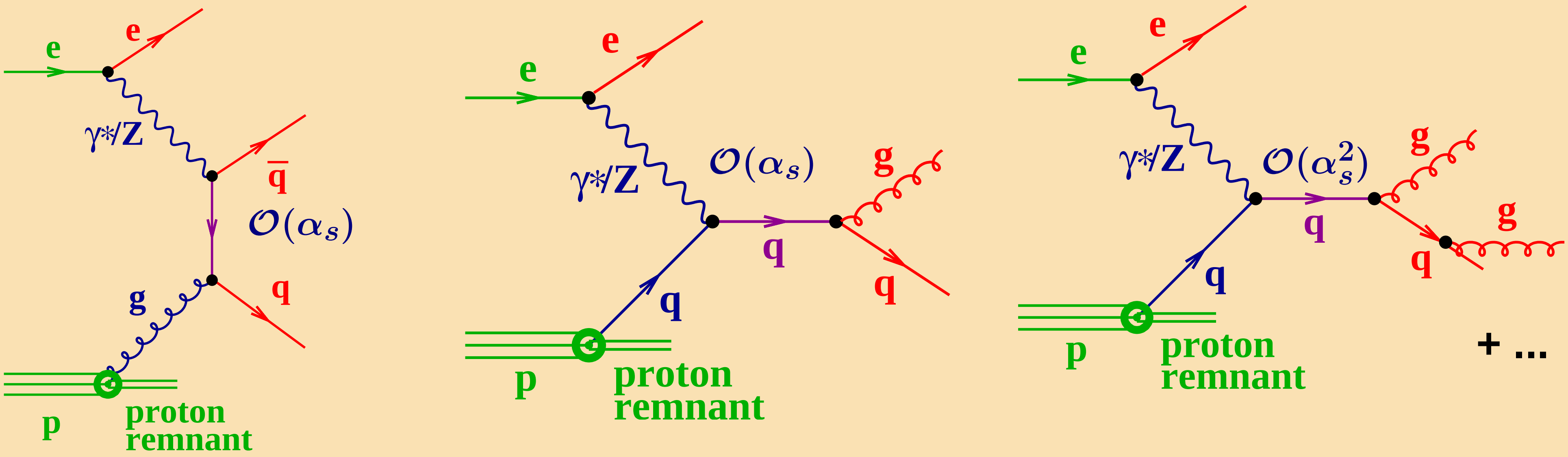
  $\longrightarrow$ pattern of parton radiation: subjets

  $\longrightarrow$ calculable in pQCD

  $\longrightarrow$ stringent test of pQCD



The hadronic final state in NC DIS



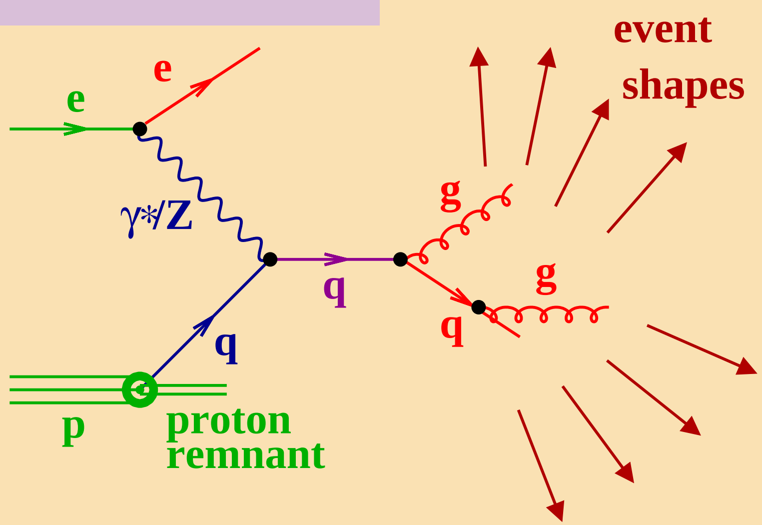
Observable = $\sum_a f_a(x, \mu_F) \otimes$ Matrix Element

- The HFS in NC DIS can also be used to study:

  $\longrightarrow$ hadronisation process: event shapes

  $\longrightarrow$ non-perturbative effect

  $\longrightarrow$ test of power-correction model

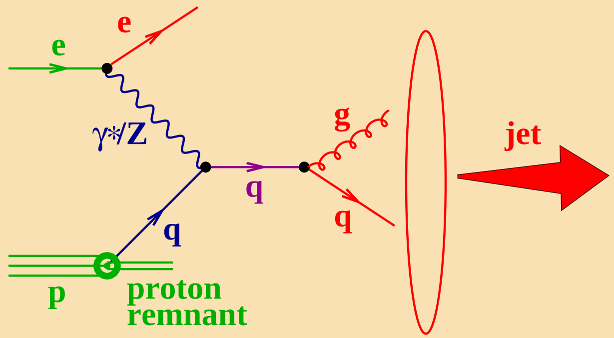


Internal structure of jets

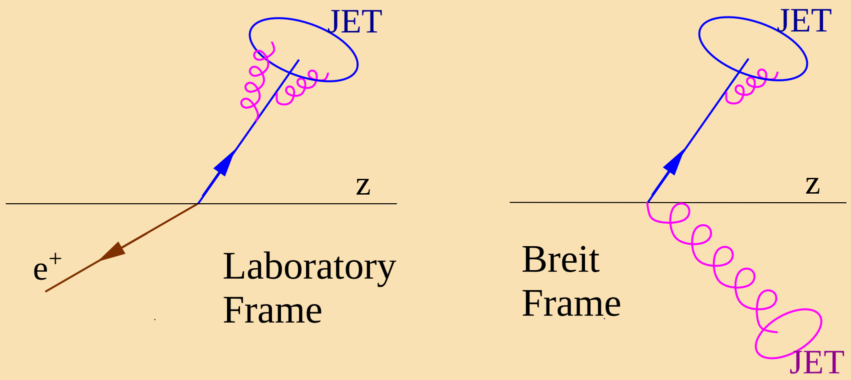
- The investigation of the internal structure of jets gives insight into the transition between a parton produced in a hard process and the experimentally observable jet of hadrons

- At sufficiently high $E_T^{\rm jet}$, where fragmentation effects become negligible, the jet structure can be calculated perturbatively

- The lowest non-trivial-order contribution to the jet substructure is given by $\mathcal{O}(\alpha_s)$ calculations for NC DIS in LAB frame



- NLO calculations of jet substructure can be obtained in the LAB frame since it is possible to have three partons inside one jet

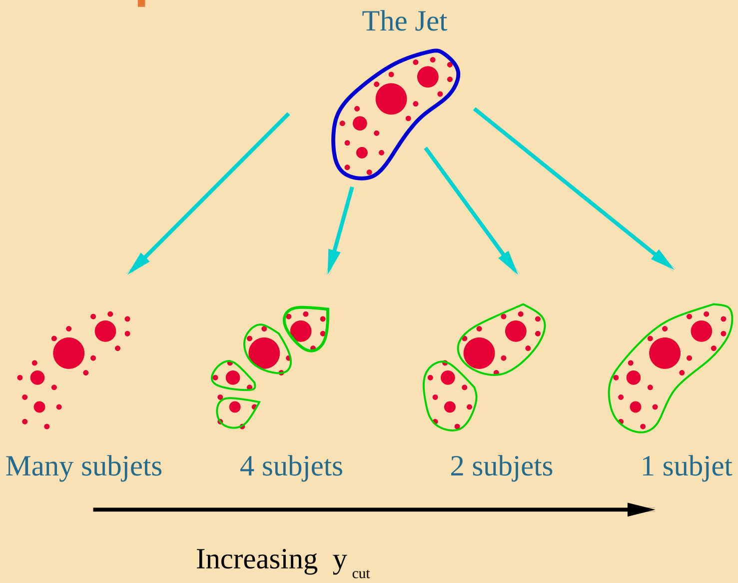


Internal structure of jets: subjets

- The internal structure of the jets can be studied by using the subjet topology

- Subjets are resolved within a jet by reapplying the k_T cluster algorithm on all the particles belonging to the jet until for every pair of particles the distance between clusters is above

$$d_{\rm cut} = y_{\rm cut} \cdot (E_T^{\rm jet})^2$$



- All remaining clusters are called subjets

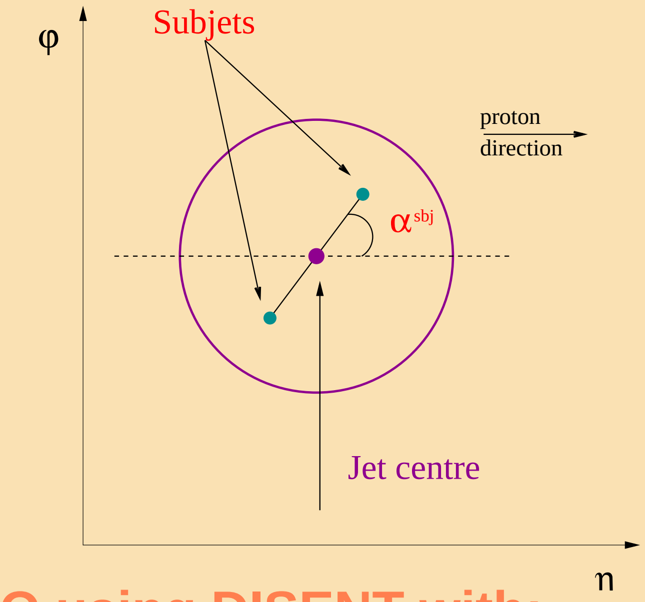
- The subjets multiplicity depends upon the value chosen for the resolution parameter $y_{\rm cut}$

- The study of subjets:
  — is sensitive to the pattern of parton radiation

Subjet distributions

- The pattern of QCD radiation from a primary parton has been studied by measuring normalised cross sections as a function of the subjet observables:

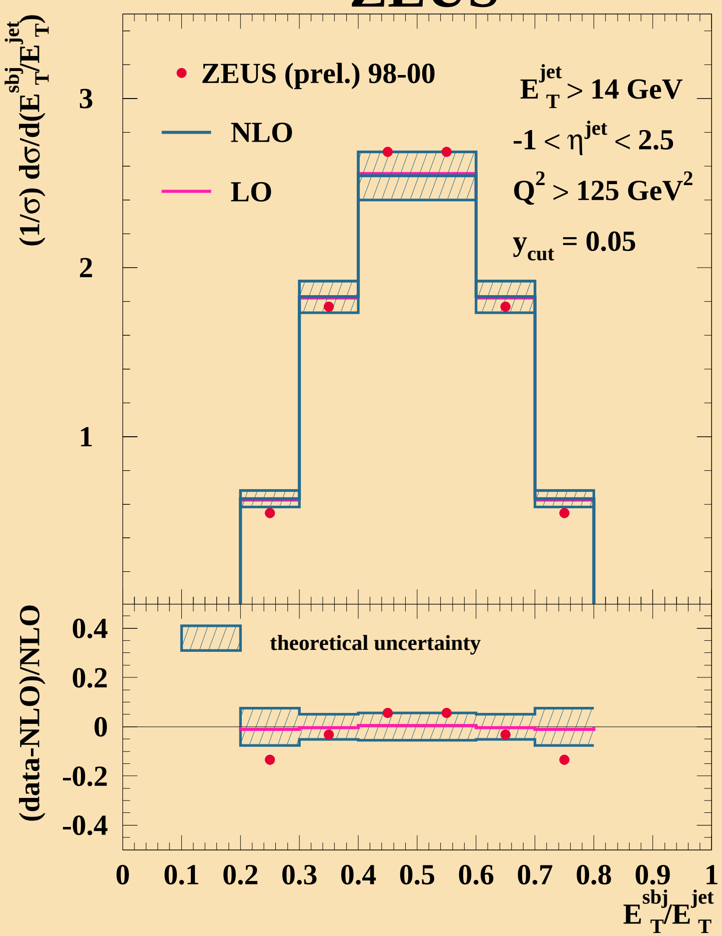
$$E_T^{\rm sbj}/E_T^{\rm jet},\ \eta^{\rm sbj}-\eta^{\rm jet},\ |\phi^{\rm sbj}-\phi^{\rm jet}| \text{ and } \alpha^{\rm sbj}$$

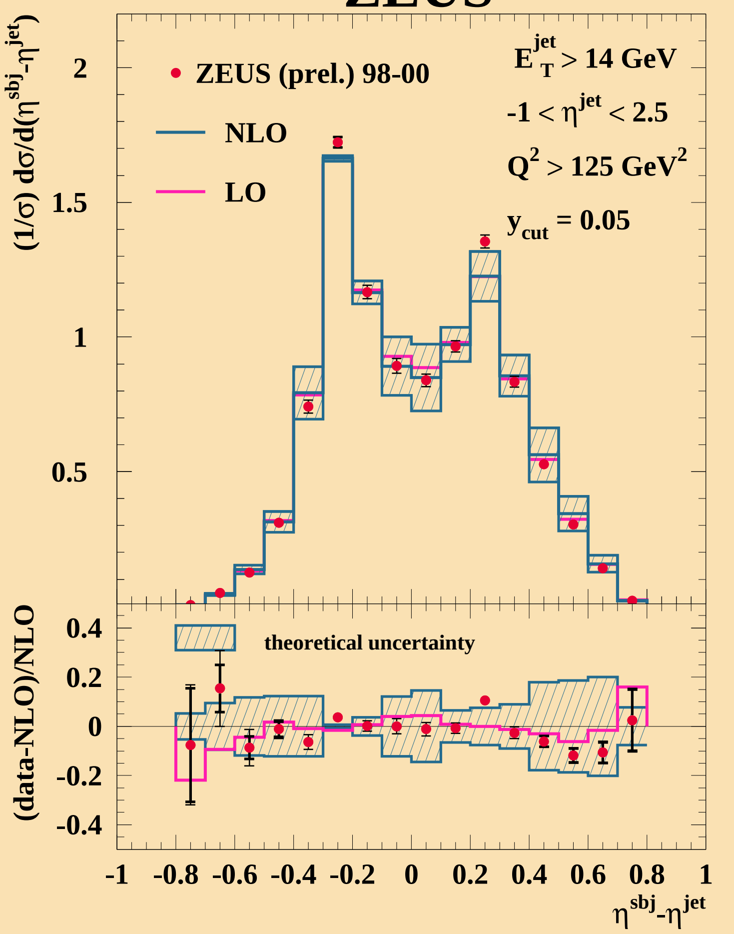


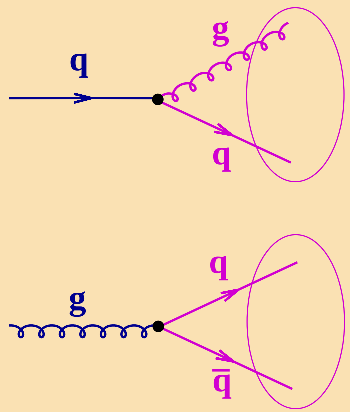
- Measurements of the normalised cross sections were done for $Q^2 > 125$ GeV^2:
  - the k_T cluster algorithm was used in the LAB frame and at least one jet of $E_T^{\rm jet} > 14$ GeV and $-1 < \eta^{\rm jet} < 2.5$ was required
  - Final sample: jets that have two subjets for $y_{\rm cut} = 0.05$
- Fixed-order QCD predictions were calculated at NLO using DISENT with:
  - pPDFs: MRST99 sets
  - calculations are at $\mathcal{O}(\alpha_s^2)$
  - α_s was calculated at two loops with $\alpha_s(M_Z) = 0.1175$
  - renormalisation and factorisation scales: $\mu_R = \mu_F = Q$
  - calculations were corrected to hadron level to compare with the data

Measurements of subjet distributions

- $E_T^{\rm sbj}/E_T^{\rm jet}$ and $\eta^{\rm sbj}-\eta^{\rm jet}$ measured normalised cross sections for $E_T^{\rm jet} > 14$ GeV compared with fixed-order pQCD calculations:







$\longrightarrow$ The NLO predictions describe the data within $\pm 10\%$

Measurements of subjet distributions

- $|\phi^{\rm sbj}-\phi^{\rm jet}|$ and $\alpha^{\rm sbj}$ measured normalised cross sections for $E_T^{\rm jet}>14$ GeV compared with fixed-order pQCD calculations:

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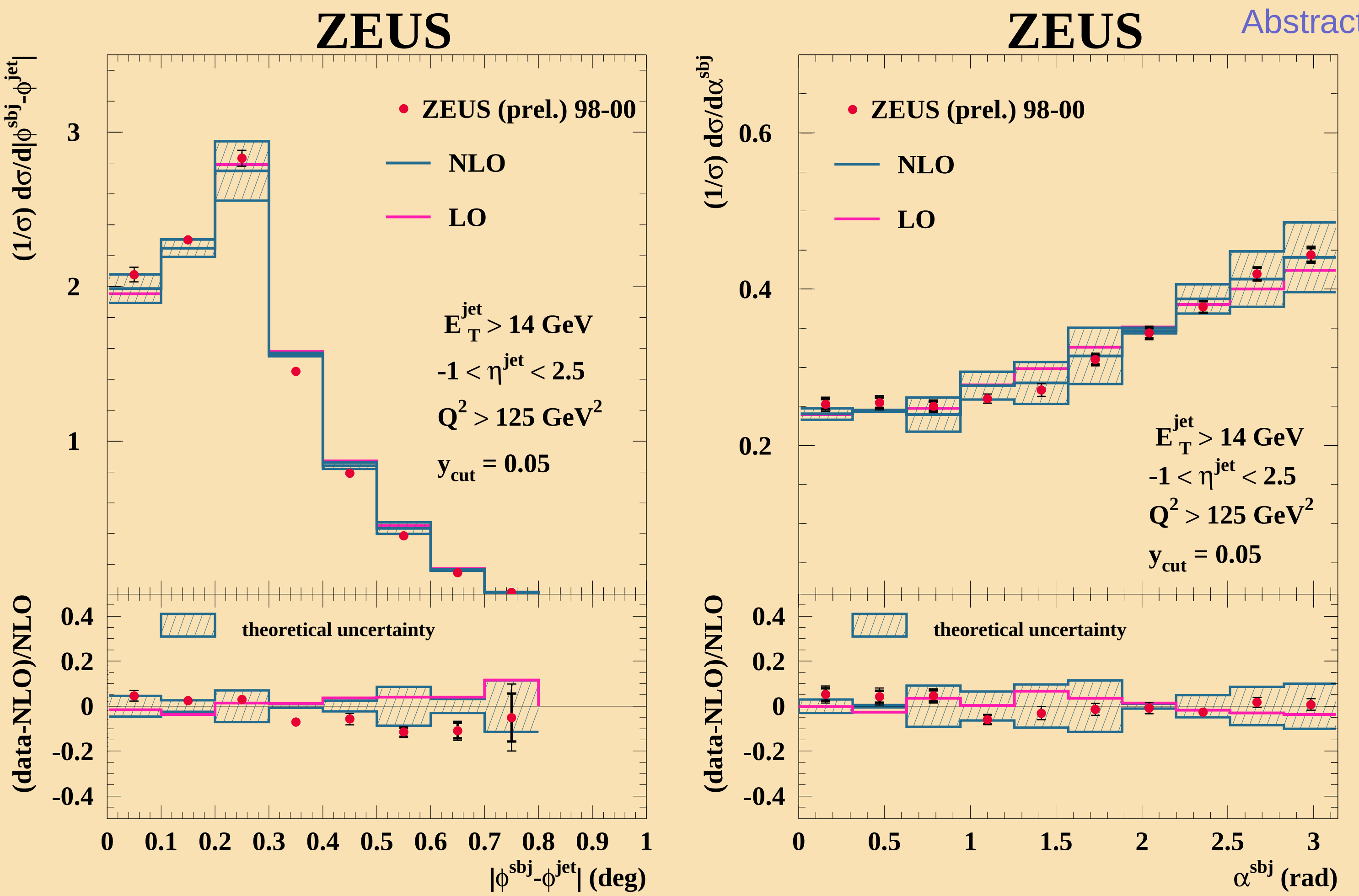
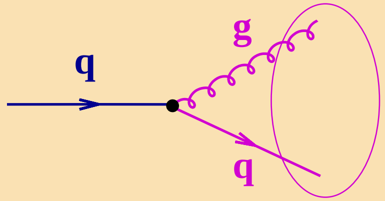
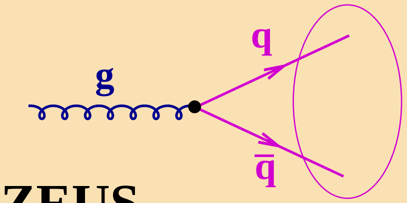


$\longrightarrow$ The NLO predictions describe the data within $\pm 10\%$

Measurements of subjet distributions

- $E_T^{\rm sbj}/E_T^{\rm jet}$, $\eta^{\rm sbj}-\eta^{\rm jet}$ and $|\phi^{\rm sbj}-\phi^{\rm jet}|$ measured normalised cross sections for $E_T^{\rm jet} > 14$ GeV compared with quark- and gluon-induced calculations:
  $\longrightarrow$ NLO prediction: 82% of q-induced and 18% of g-induced





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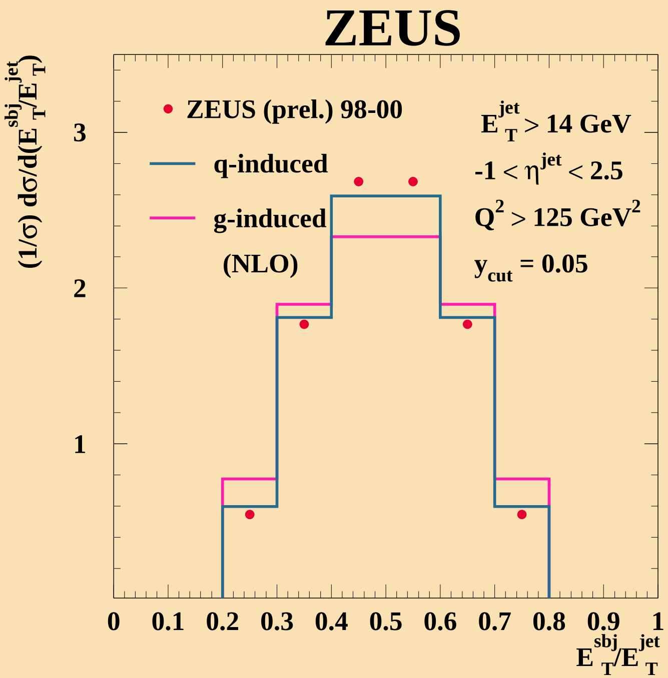
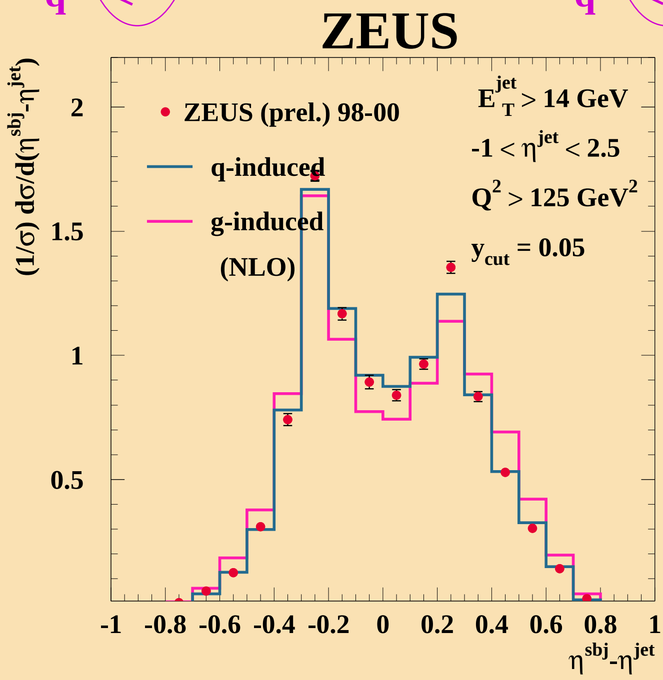
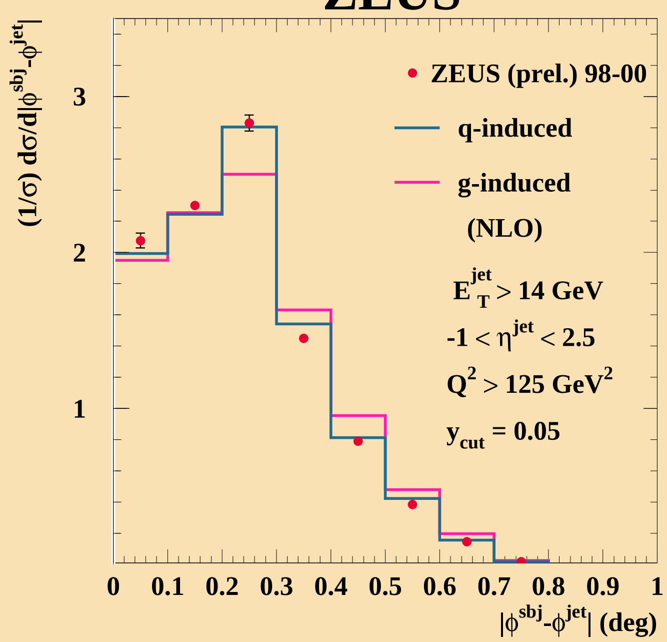






$\longrightarrow$ **The data are well described by the calculations for jets arising from the splitting of a quark into a quark-gluon pair**

Event shapes

- Event-shape variables are particularly sensitive to the details of the non-perturbative effect of hadronisation
- In this type of analysis, the data are compared to a model prediction which consists of a combination of NLO QCD calculations and the expectations of the power corrections, characterised by an effective coupling $\bar{\alpha}_0$:

$$F = F_{\text{perturbative}} + F_{\text{power correction}}$$

where F is an event-shape mean or distribution (NLO + matched NLL)

Event-shape variables:

- Axis-dependent variables: thrust or broadening wrt thrust or photon axis

Thrust: $T = \frac{\sum_i |\vec{p}_i \cdot \hat{n}|}{\sum_i |\vec{p}_i|}$ Broadening: $B = \frac{\sum_i |\vec{p}_i \times \hat{n}|}{\sum_i |\vec{p}_i|}$

- Axis-independent variables:

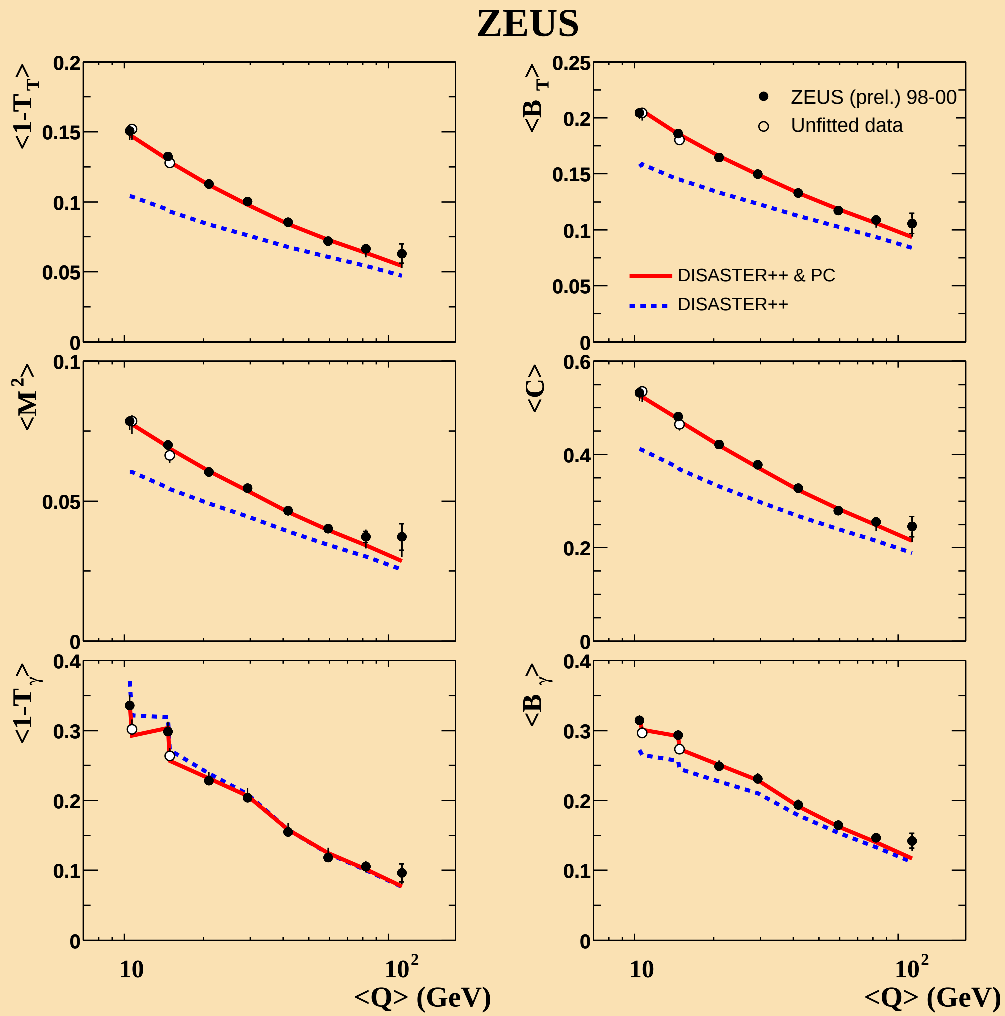
C parameter: $C = \frac{3 \sum_{ij} |\vec{p}_i||\vec{p}_j| \sin^2(\theta_{ij})}{2(\sum_i |\vec{p}_i|)^2}$ Jet mass: $M^2 = \frac{(\sum_i E_i)^2 - |\sum_i \vec{p}_i|^2}{(2\sum_i E_i)^2}$

- A suitable frame in which to study event shapes at HERA is the Breit frame $\longrightarrow$ the separation between the current jet and the proton remnant is maximal

Event-shape means

- Measurement of event-shape means for $80 < Q^2 < 2 \cdot 10^4$ GeV^2 and $0.0024 < x < 0.6$:
- Fitting procedure:
  - → NLO + PC predictions fitted to measured event-shape means
  - → fitting parameters: $\alpha_s(M_Z)$ and $\bar{\alpha}_0$
  - → Hessian method (including statistical and systematic uncertainties of data)
  - → each observable fitted separately
- Calculations:
  - → DISASTER++ (CTEQ4M or MRST99 pPDFs) for fixed-order predictions

→ Reasonable fits are obtained for all event-shape observables within the Q^2 range studied



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Event-shape differential distributions

- Event-shape distributions for $9 < Q < 141$ GeV and $0.0024 < x < 0.6$:
- Two-parameter $(\alpha_s, \bar{\alpha}_0)$ fit using NLO + NLL + PC:
  - range of fit restricted to region where predictions of PC are valid
  - each observable fitted separately
  - DISRESUM used for PC and matched NLL resummation predictions

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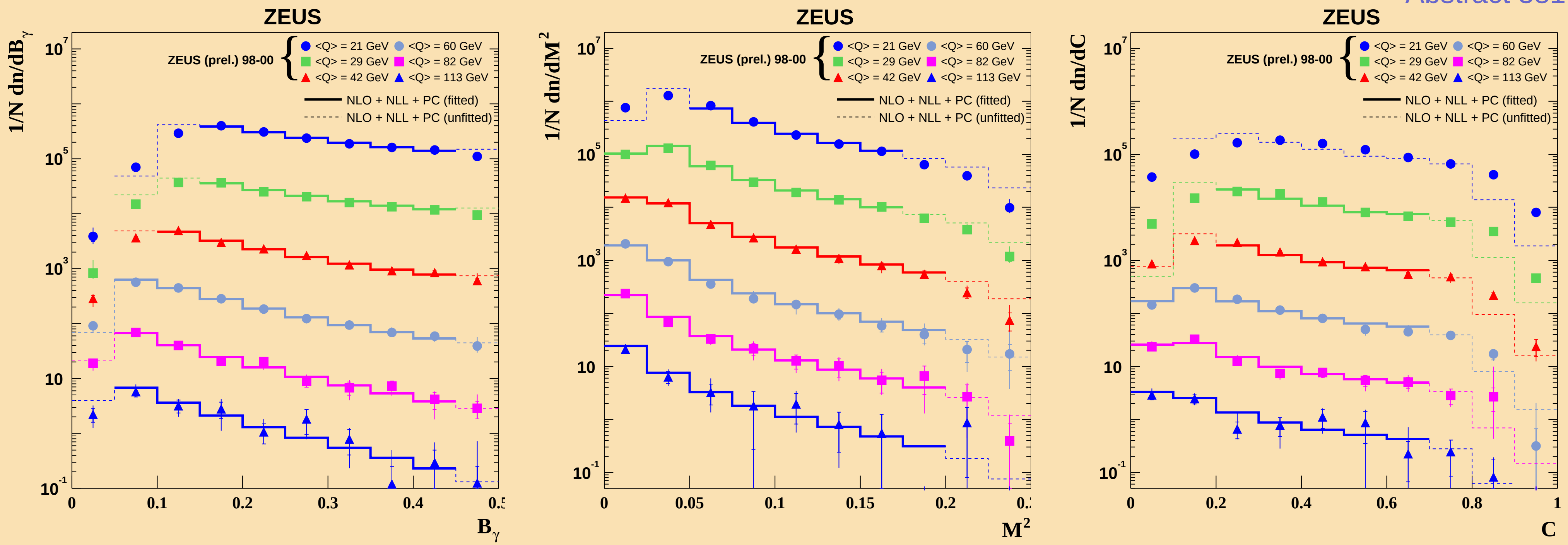

$\longrightarrow$ Reasonable fits are obtained for all event-shape observables within the restricted ranges studied

Test of the power-correction model

- **Extracted $\bar{\alpha}_0$ and $\alpha_s(M_Z)$ values for each event-shape observable:**

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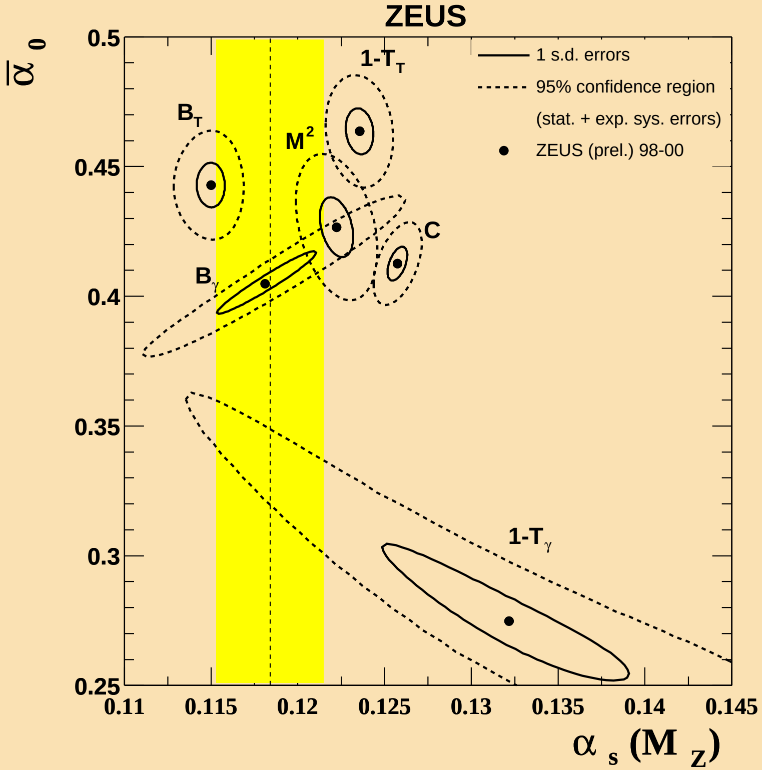
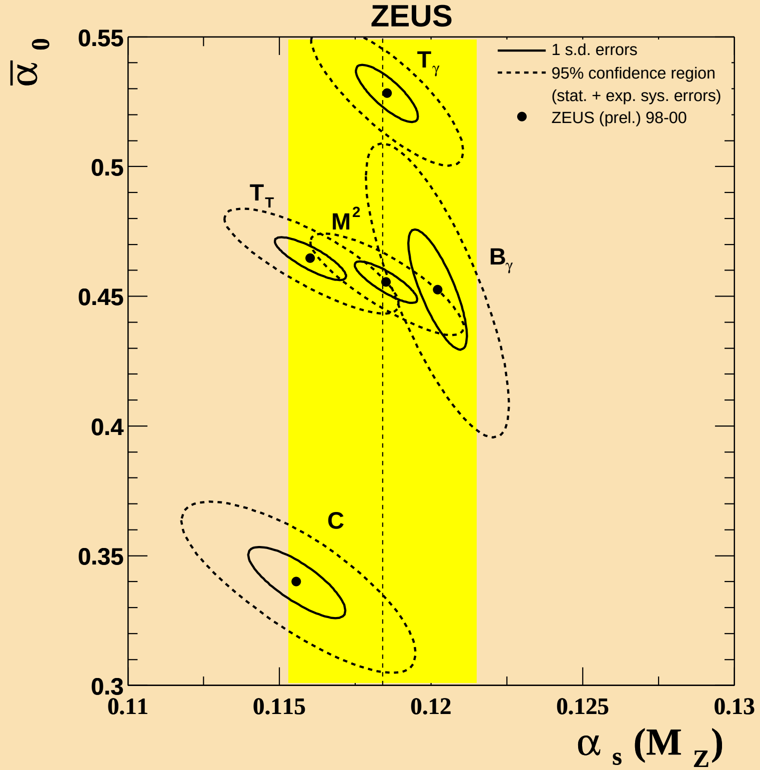
From means





From distributions

$\rightarrow$ **Universal non-perturbative parameter $\bar{\alpha}_0 = 0.45 \pm 10\%$, except for T_γ and C parameter (distributions)**

$\rightarrow$ **Extracted value of $\alpha_s(M_Z)$ consistent for all observables to within 5% (means)**

$\rightarrow$ **The dispersion of the extracted values could be due to higher-order terms**

$\rightarrow$ **Extracted values of $\alpha_s(M_Z)$ consistent with world average (distributions)**

Event shapes with jets

- **Out-of-plane momentum:** $K_{\rm out} = \sum_i |\overrightarrow{p_i^{\rm out}}|$
- **Energy flow out of event plane defined by proton direction and thrust major axis**
  - $\longrightarrow$ **sensitive to perturbative and non-perturbative contributions**
  - $\longrightarrow$ **lowest non-trivial contribution to $K_{\rm out}$ from non-perturbative effects or NLO pQCD dijet contributions**
- **Measurement of $K_{\rm out}/Q$ for $100 < Q^2 < 500$ GeV^2 and $500 < Q^2 < 800$ GeV^2:**

$\longrightarrow$ **Data well described by LEPTO and ARIADNE models**

$\longrightarrow$ **First comparison of LO+NLL+PC (using $\alpha_s = 0.118$ and $\bar{\alpha}_0 = 0.52$) with data in high-Q^2 range only**

$\longrightarrow$ **more precise test of the model needs $\mathcal{O}(\alpha_s^3)$ calculations**

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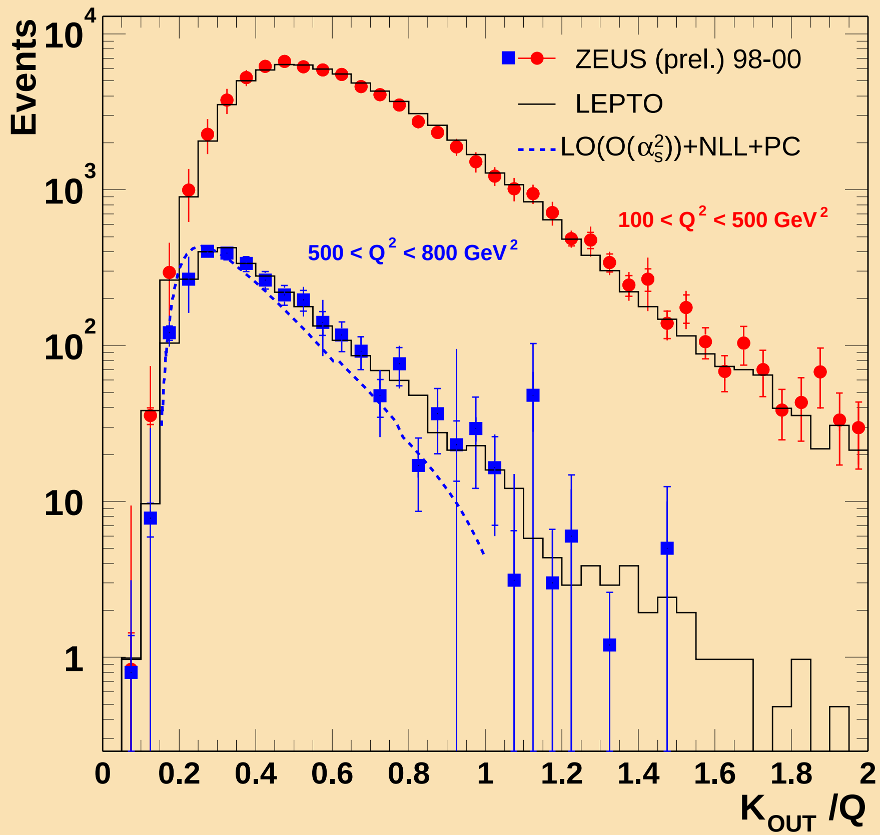

Conclusions

- Subjet normalised cross sections have been measured in NC DIS in the LAB frame

→ Reasonable description of the data by NLO pQCD calculations:

  – the pattern of QCD radiation as implemented in the NLO calculations reproduces the behaviour of the data

  – the data are well described by the calculations for jets arising from the splitting of a quark into a quark-gluon pair

- Event-shape means and distributions have been measured in NC DIS in the Breit frame

→ NLO (+ NLL) + PC calculations give a reasonable description of the means (distributions):

  – extracted values of PC parameter $\bar{\alpha}_0$ are consistent within 10% (except T_γ, C)

  – extracted values of the strong coupling contant $\alpha_s(M_Z)$ are consistent with the world average (except T_γ)

  – more theoretical input is needed to fully exploit the potential of these measurements