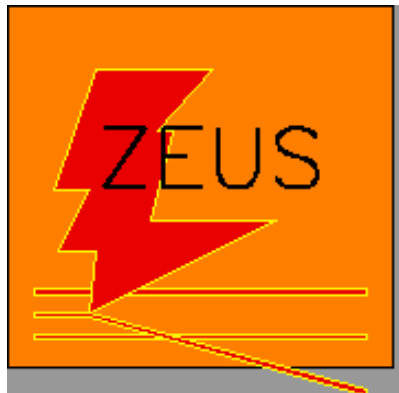
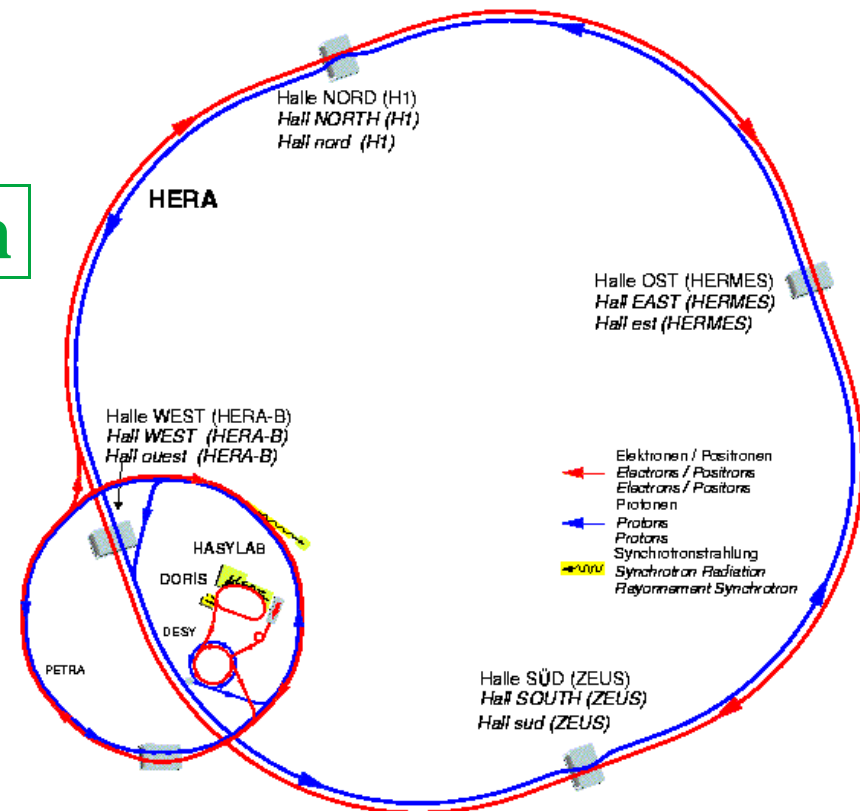
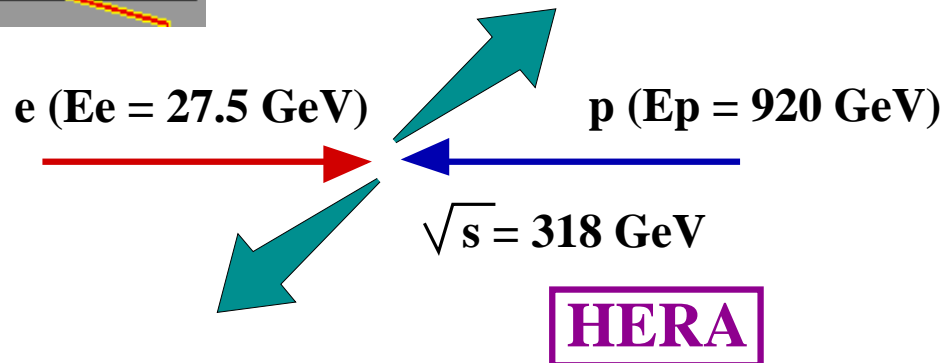


Substructure of jets in NC DIS

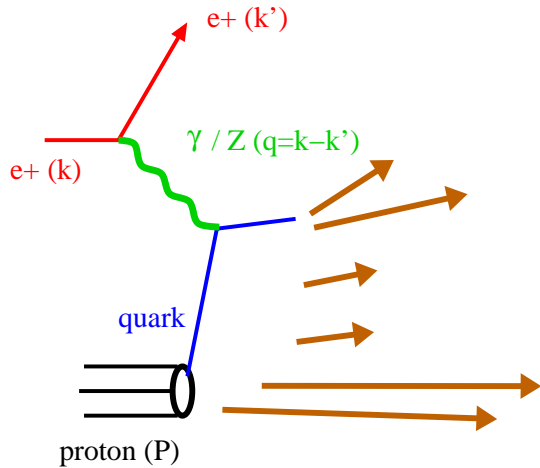
Juan Terrón (Universidad Autónoma de Madrid, Spain)



ZEUS Collaboration



Neutral Current Deep Inelastic Scattering

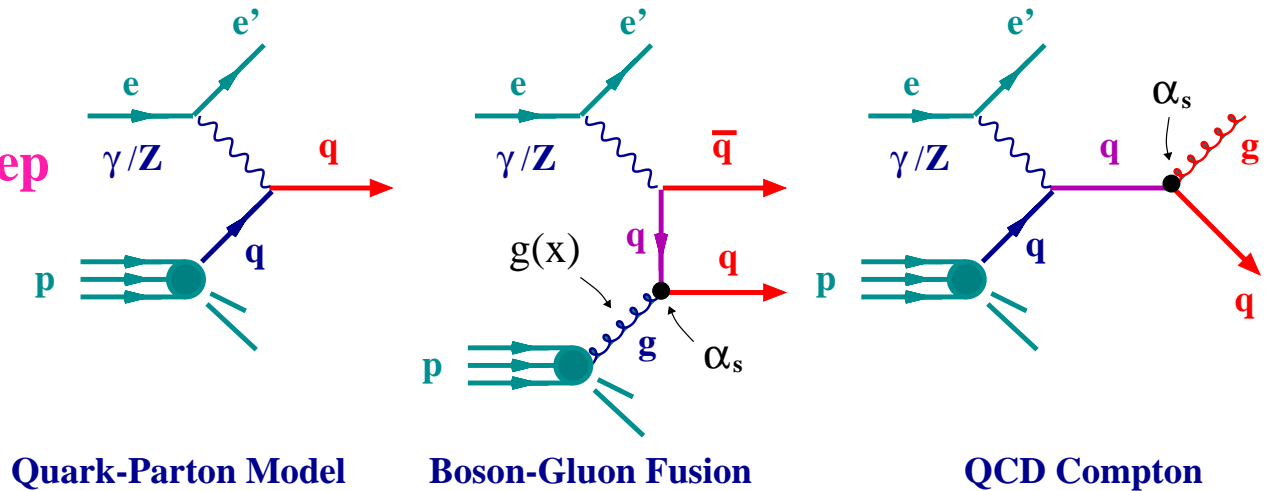


For a given ep centre-of-mass energy, \sqrt{s} , the fully inclusive cross section for $ep \rightarrow e + X$ can be described by two independent kinematic variables, e.g.

$$Q^2 = -(k - k')^2 \text{ and } x_{Bj} = Q^2 / (2P \cdot q)$$

Jet production in neutral current deep inelastic scattering up to $\mathcal{O}(\alpha_s) \rightarrow$

Measurements of jet cross sections in NC DIS at high Q^2 have allowed precise tests of the pQCD calculations



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

as well as precise determinations of α_s

NOW: Let's test pQCD to the extreme... \rightarrow

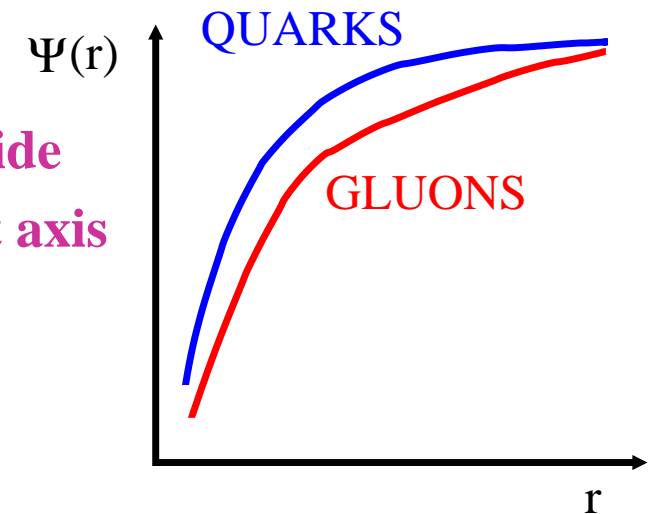
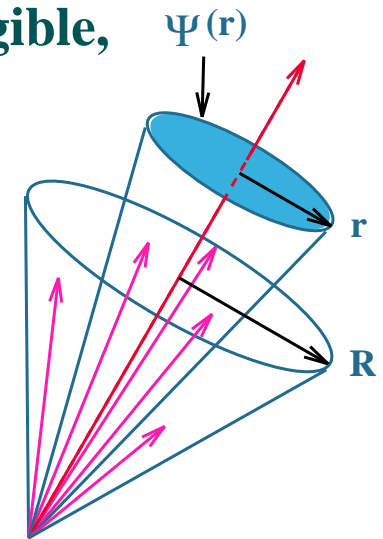
Jet Substructure in Neutral Current Deep Inelastic Scattering

- At sufficiently **high** E_T^{jet} , where fragmentation effects become negligible, the jet substructure is expected to be calculable by pQCD
- **Measurements of jet substructure allow investigations on**
 - the differences between quark- and gluon-initiated jets and
 - the dynamics of the different partonic final states,
 - as well as determinations of α_s

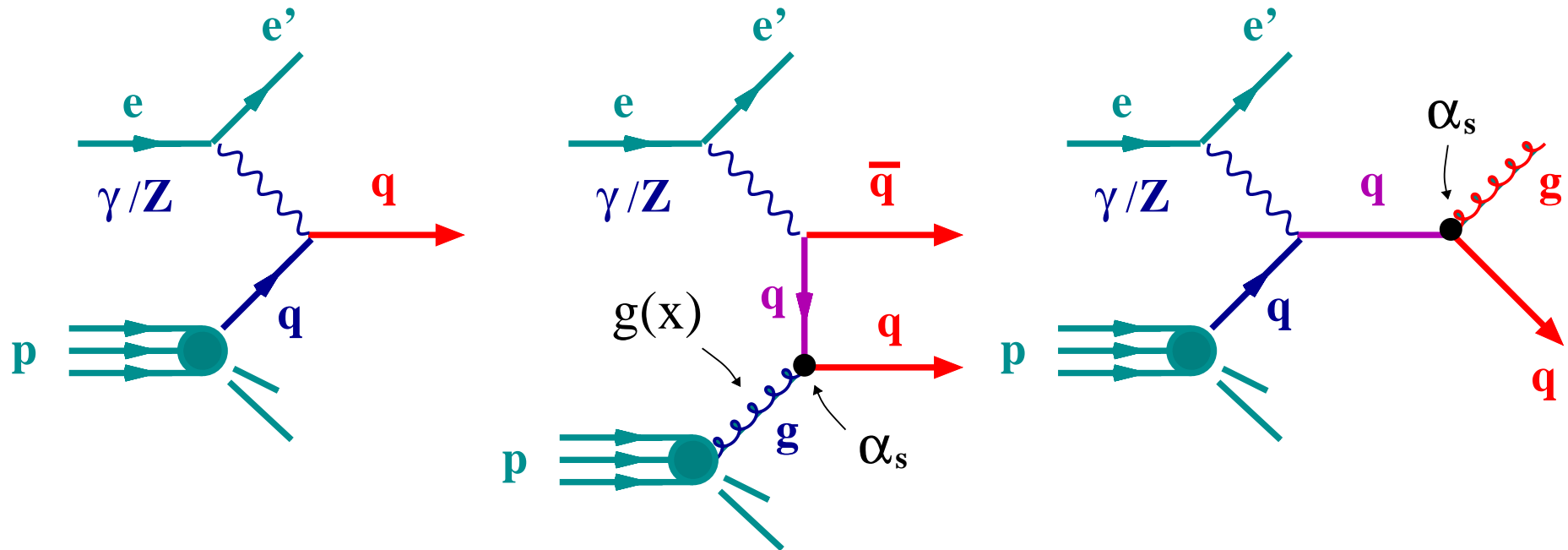
- **Integrated jet shape:**
$$\langle \Psi(r) \rangle = \frac{1}{N_{jets}} \sum_{jets} \frac{E_T(r)}{E_T^{jet}}$$

Average fraction of the jet's transverse energy that lies inside a circle in the η - ϕ plane of radius r concentric with the jet axis

- QCD predicts that gluon jets are broader than quark jets
 $\Rightarrow \Psi_{QUARKS}(r) > \Psi_{GLUONS}(r)$



Jet Substructure in Neutral Current Deep Inelastic Scattering



Quark-Parton Model

Boson-Gluon Fusion

QCD Compton

One-jet events

Enriched in quark jets

Two-jet events

Higher content of gluon jets

Jet Substructure in Neutral Current Deep Inelastic Scattering

- **Comparison with calculations:**

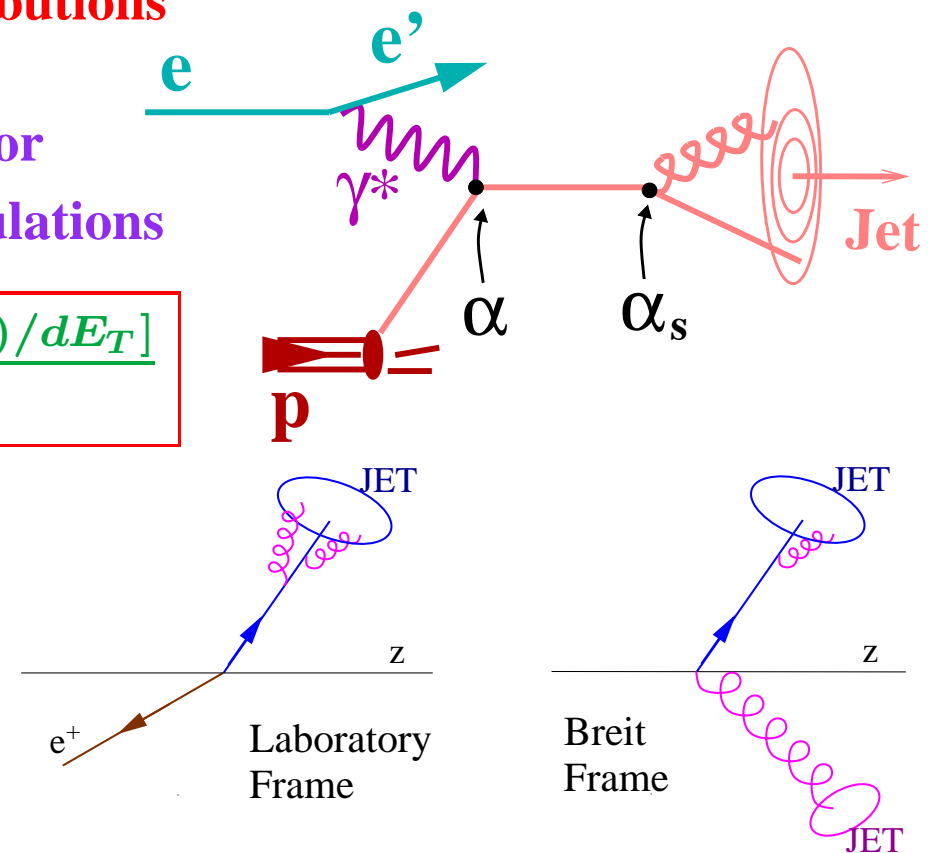
→ **Monte Carlo generators** (ARIADNE-CDM, LEPTO-MEPS) approximate the substructure of jets with **parton showers**

→ **Fixed-order QCD calculations:** at lowest order a jet consists of one parton (no structure); higher-order terms give **the non-trivial contributions**

- **E.g. the lowest non-trivial-order contribution for one-jet events** is given by $\mathcal{O}(\alpha\alpha_s)$ pQCD calculations

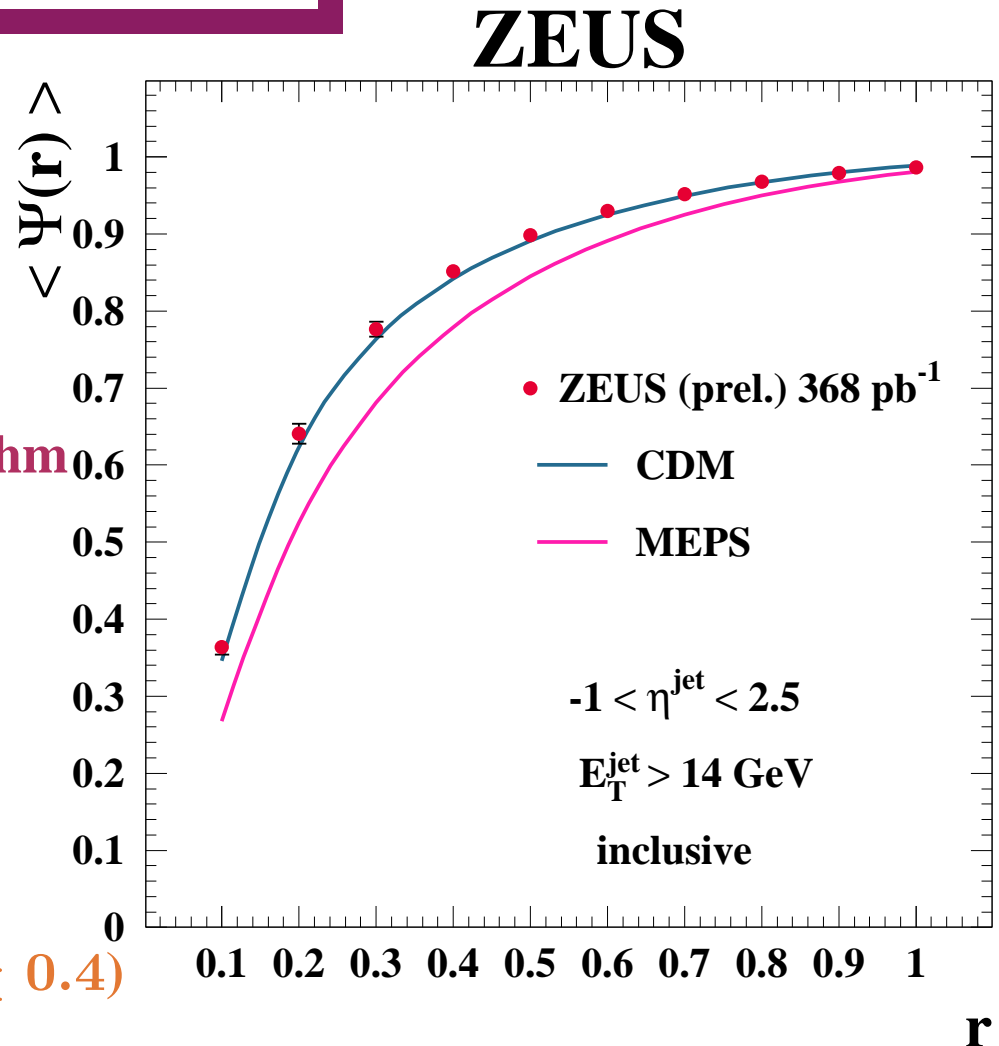
$$\langle 1 - \Psi(r) \rangle = \frac{\int dE_T E_T [d\sigma(ep \rightarrow 2\text{partons})/dE_T]}{E_T^{jet} \sigma_{jet}(E_T^{jet})}$$

- **NLO QCD calculations of jet substructure can be made in the laboratory frame** since it is possible to have **3 partons in the same jet** (not possible in the Breit frame)



Measurements of Jet Substructure in NC DIS

- Measurement of $\langle \Psi(r) \rangle$ for an **inclusive sample of jets** in NC DIS with $Q^2 > 125 \text{ GeV}^2$ using HERA II data: $\mathcal{L} = 368 \text{ pb}^{-1}$
- Jets are defined using the k_T -cluster algorithm (longitudinally invariant mode) in the laboratory frame and required to have $E_T^{\text{jet}}(\text{Lab}) > 14 \text{ GeV}$ and $-1 < \eta^{\text{jet}}(\text{Lab}) < 2.5$
- The measurements of $\langle \Psi(r) \rangle$ have been corrected for detector effects ($< 10\%$ for $r \geq 0.4$)
- Comparison to QCD-inspired Monte models:
 - the colour-dipole model (CDM, ARIADNE) reproduces the data well
 - matrix-elements plus parton-showers (MEPS, LEPTO) predict too-broad jets



Measurements of Jet Substructure in NC DIS

- Measurement of $\langle \Psi(r) \rangle$ in NC DIS with $Q^2 > 125 \text{ GeV}^2$ using $\mathcal{L} = 368 \text{ pb}^{-1}$ for two samples of jets:

One-jet events

$$E_T^{\text{jet}} > 14 \text{ GeV}, -1 < \eta^{\text{jet}} < 2.5$$

Two-jet events

both jets are required to have

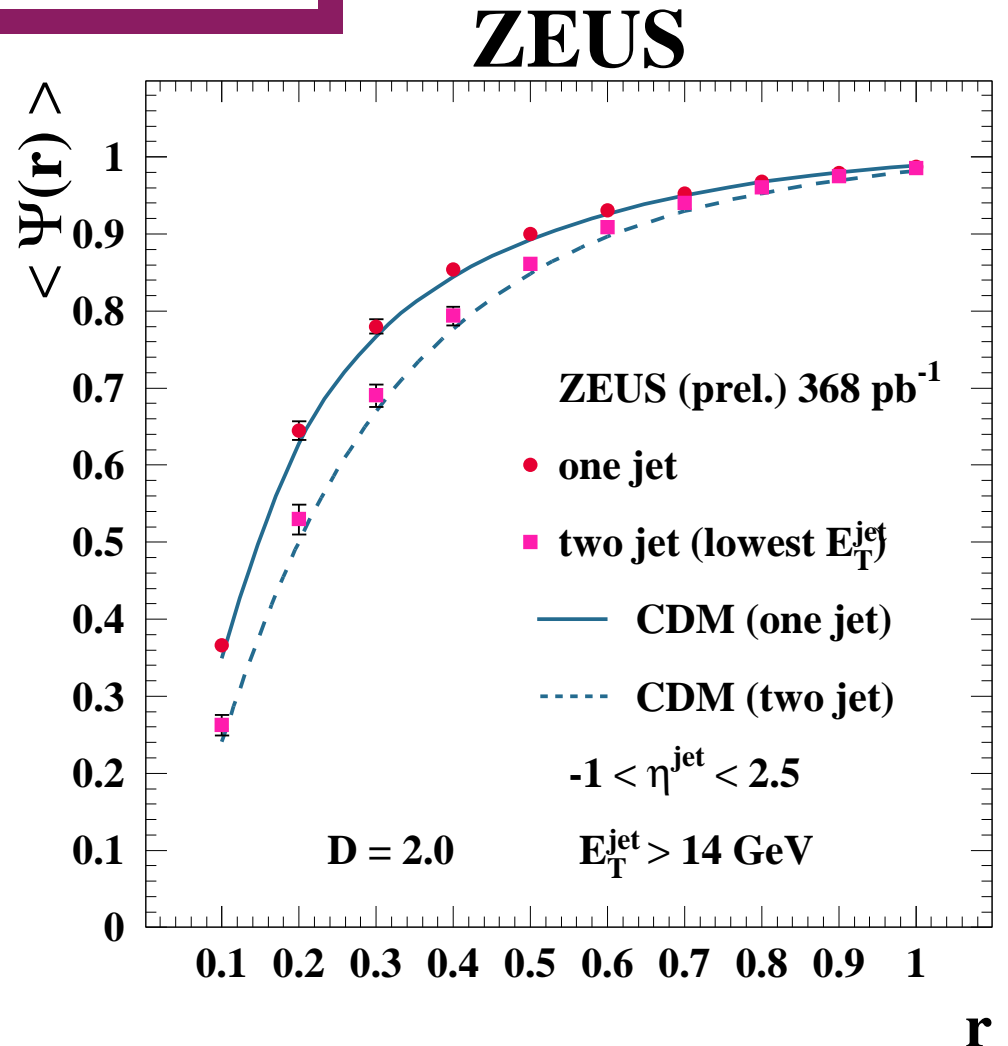
$$E_T^{\text{jet}} > 14 \text{ GeV}, -1 < \eta^{\text{jet}} < 2.5$$

and to be close to each other in the η - ϕ plane

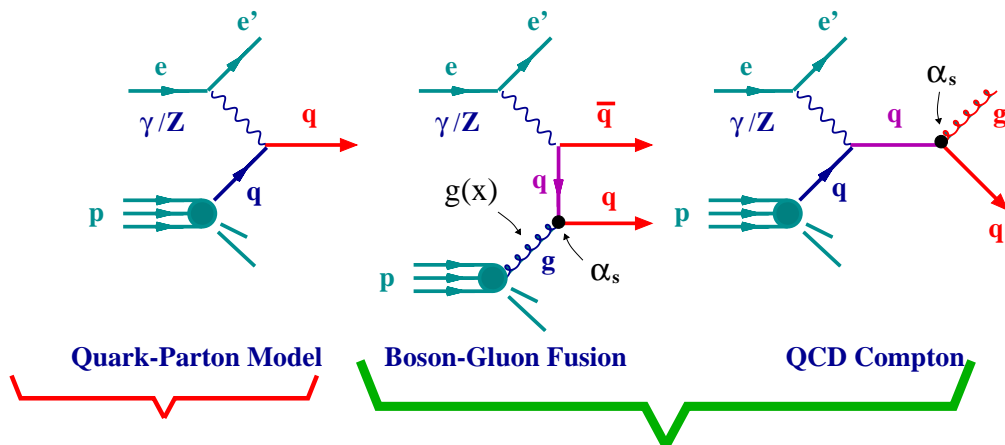
$$\text{distance jet-jet} = \sqrt{\Delta\eta^2 + \Delta\phi^2} \leq D = 2$$

→ the jet with lowest E_T^{jet} is considered

- The lowest- E_T^{jet} jet in the two-jet event sample is **BROADER**



Measurements of Jet Substructure in NC DIS



One-jet events

- Enriched in quark jets

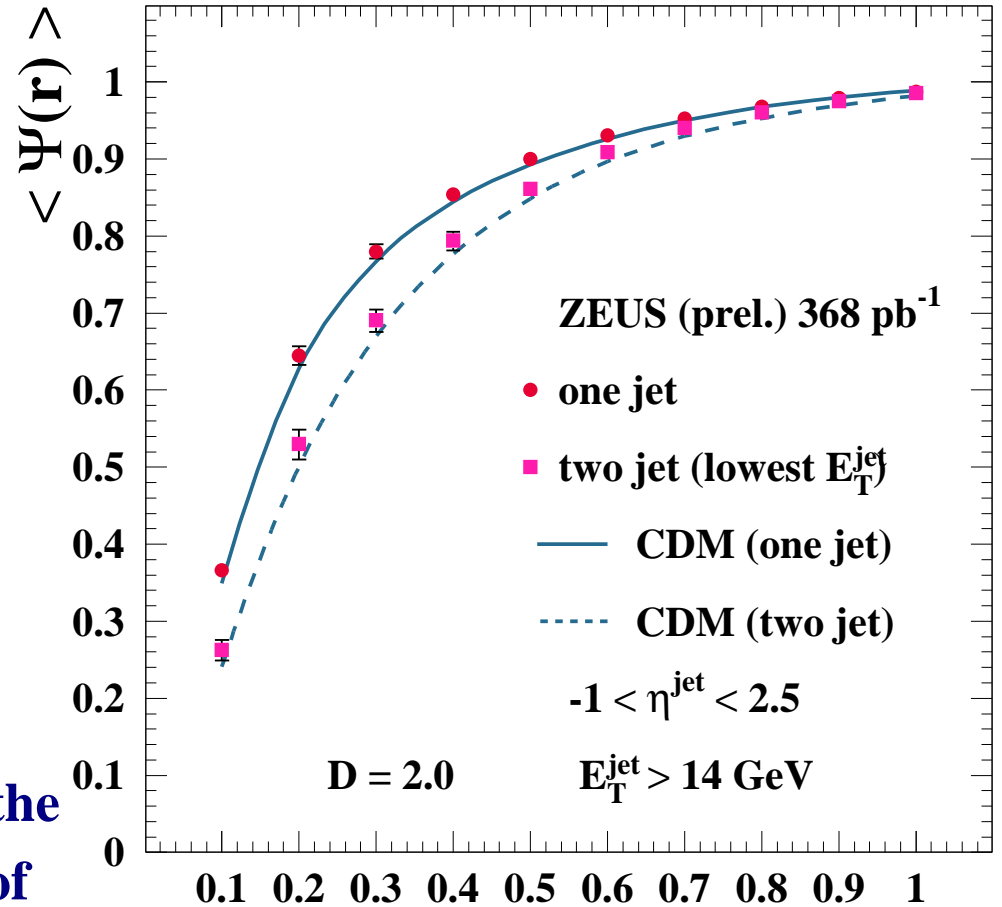
Two-jet events

- Higher content of gluon jets

● The observation that the lowest- E_T^{jet} jet in the two-jet event sample is **BROADER** than that of the one-jet sample is consistent with a **higher gluon content in two-jet events**

→ The colour-dipole model (CDM, ARIADNE) reproduces the data reasonably well; in particular, the difference in jet shape between the two samples

ZEUS



Measurements of Jet Substructure in NC DIS: $14 < E_T^{jet} < 17 \text{ GeV}$

- Measurement of $\langle \Psi(r) \rangle$ in NC DIS with $Q^2 > 125 \text{ GeV}^2$ using $\mathcal{L} = 368 \text{ pb}^{-1}$ for two samples of jets:

One-jet events

$$14 < E_T^{jet} < 17 \text{ GeV}, -1 < \eta^{jet} < 2.5$$

Two-jet events

both jets are required to have

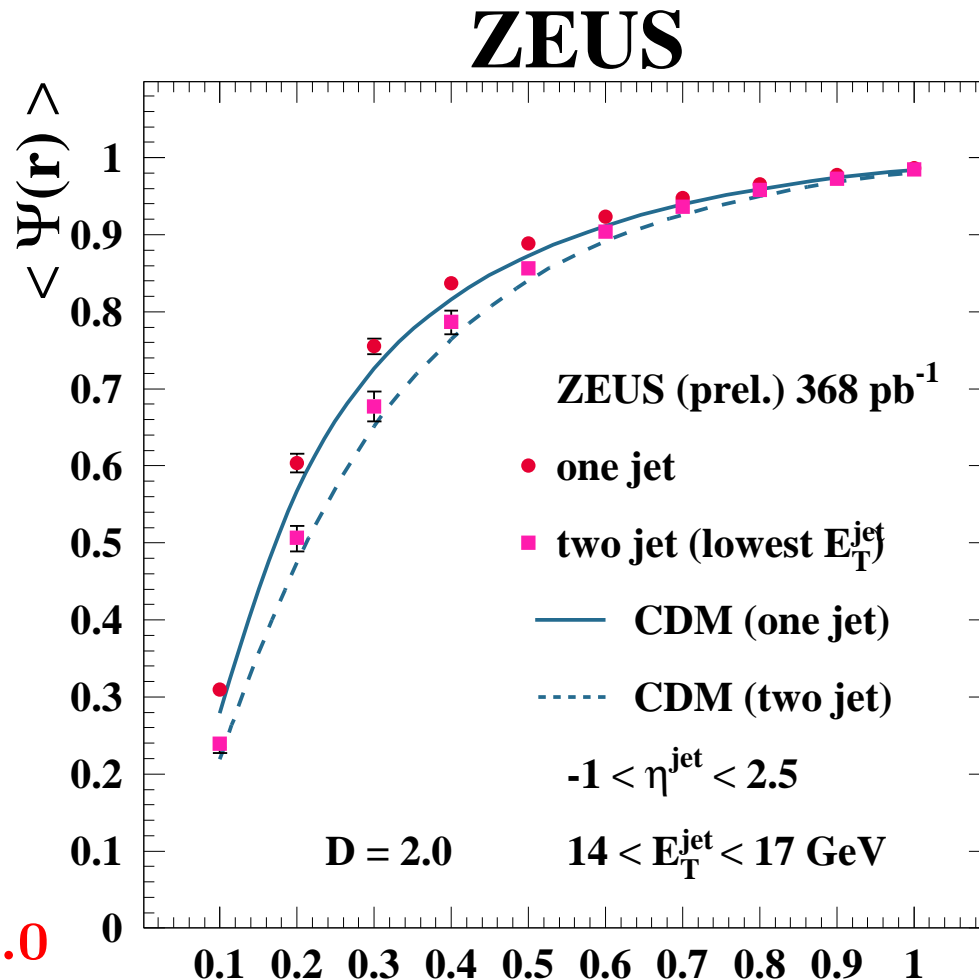
$$E_T^{jet} > 14 \text{ GeV}, -1 < \eta^{jet} < 2.5$$

and to be close to each other in the η - ϕ plane

$$\text{distance jet-jet} = \sqrt{\Delta\eta^2 + \Delta\phi^2} \leq D = 2.0$$

→ the jet with lowest E_T^{jet} (and $14 < E_T^{jet} < 17 \text{ GeV}$) is considered

- The lowest- E_T^{jet} jet in the two-jet event sample is **BROADER**



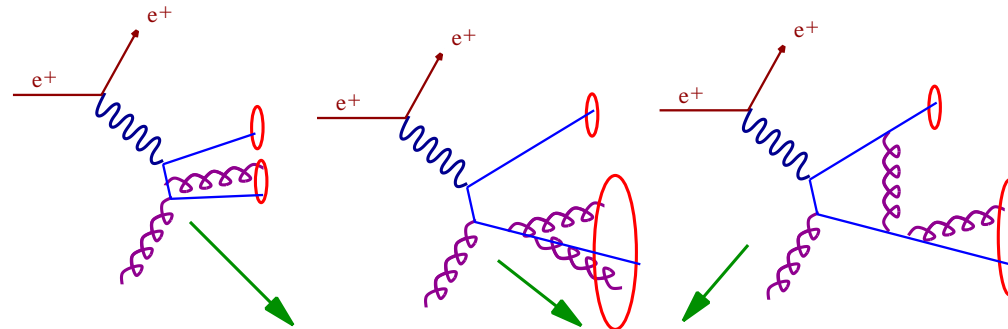
NLO QCD calculations for **inclusive/one-jet production**

$$\langle 1 - \Psi(r) \rangle = \frac{b_1 \cdot \alpha_s^1 + b_2 \cdot \alpha_s^2}{a_0 \cdot \alpha_s^0 + a_1 \cdot \alpha_s^1}$$

DISENT program
S. Catani and M.H. Seymour
Nucl. Phys. B485 (1997) 291

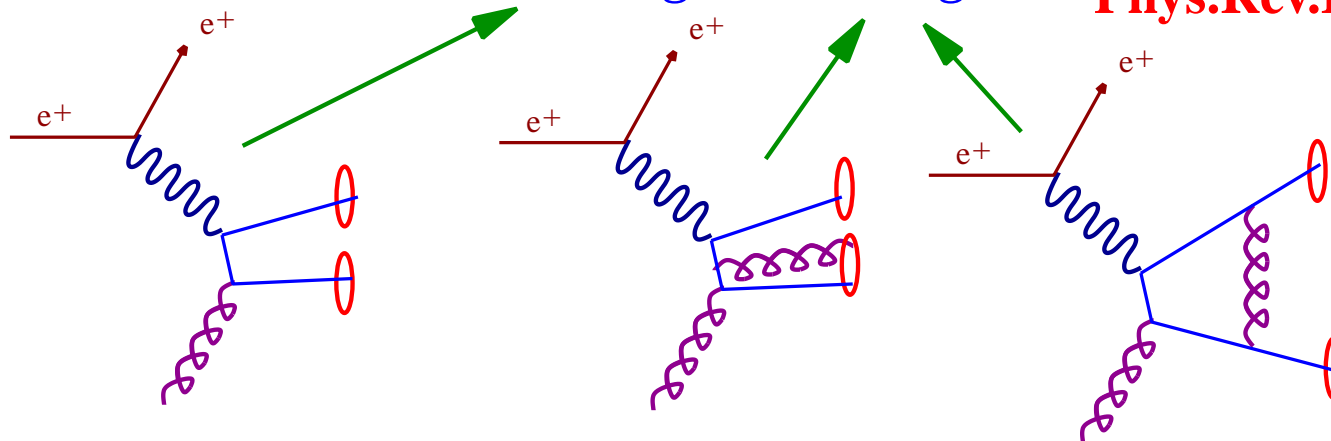
- **DISENT program:** $\alpha_s(M_Z) = 0.118$; $\mu_R = \mu_F = Q$; CTEQ6 proton PDFs
 → **Dominant theoretical uncertainty: terms beyond NLO, < 5% for $r \geq 0.2$**

NLO QCD calculations for **two-jet production**



$$\langle 1 - \Psi(r) \rangle = \frac{d_2 \cdot \alpha_s^2 + d_3 \cdot \alpha_s^3}{c_1 \cdot \alpha_s^1 + c_2 \cdot \alpha_s^2}$$

NLOJET++ program
Z. Nagy and Z. Trocsanyi
Phys.Rev.Lett. 87 (2001) 082001



- **NLOJET++ program:** $\alpha_s(M_Z) = 0.118$; $\mu_R = \mu_F = Q$; CTEQ6 proton PDFs

Measurements of Jet Substructure in NC DIS vs NLO QCD

- Measurement of $\langle \Psi(r) \rangle$ in NC DIS with $Q^2 > 125 \text{ GeV}^2$ using $\mathcal{L} = 368 \text{ pb}^{-1}$ for two samples of jets:

One-jet events

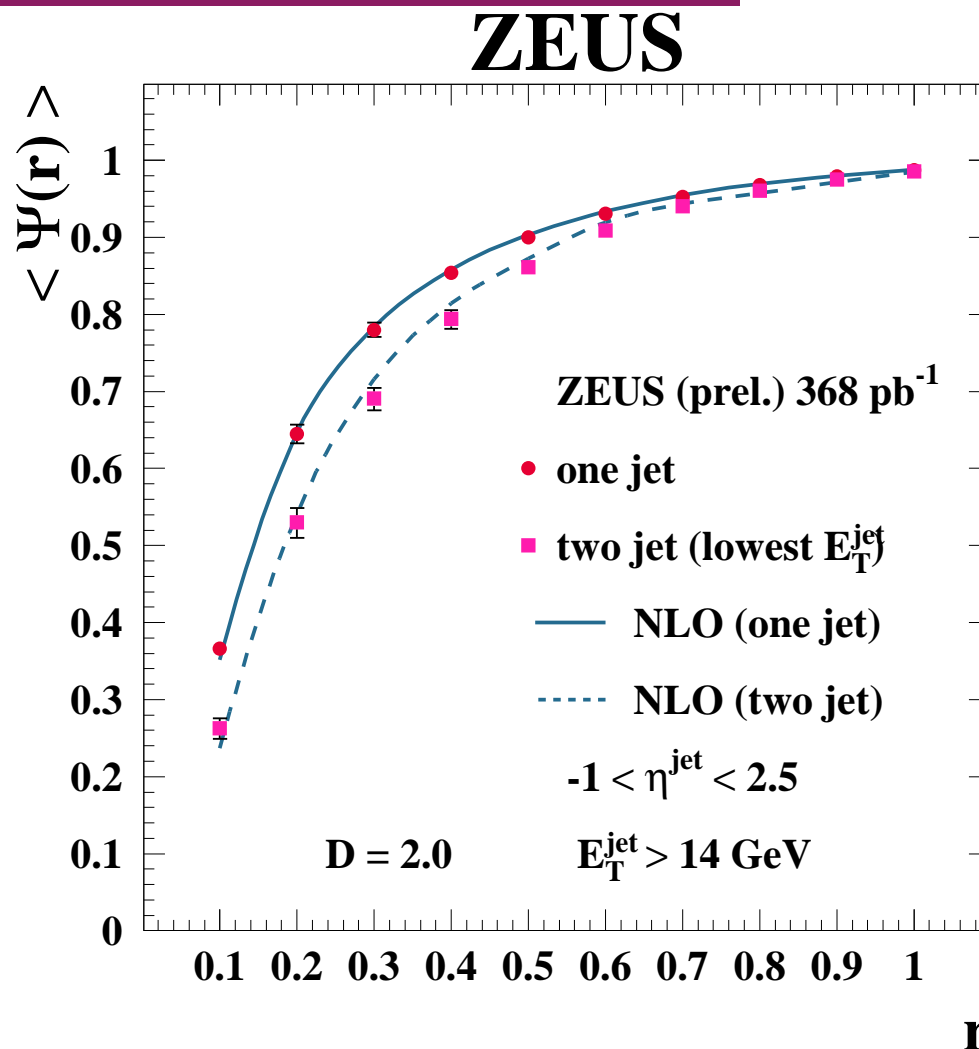
$$E_T^{\text{jet}} > 14 \text{ GeV}, -1 < \eta^{\text{jet}} < 2.5$$

Two-jet events

$$E_T^{\text{jet}} > 14 \text{ GeV}, -1 < \eta^{\text{jet}} < 2.5$$

$$\text{distance jet-jet} = \sqrt{\Delta\eta^2 + \Delta\phi^2} \leq D = 2$$

→ the jet with lowest E_T^{jet} is considered



NLO QCD calculations corrected for hadronisation effects ($< 10\%$ for $r \geq 0.4$) reproduce the data reasonably well; in particular, the difference in jet shape between the two samples

Measurements of Jet Substructure in NC DIS vs NLO QCD

- Measurement of $\langle \Psi(r) \rangle$ in NC DIS with $Q^2 > 125 \text{ GeV}^2$ using $\mathcal{L} = 368 \text{ pb}^{-1}$ for two samples of jets:

One-jet events

$$14 < E_T^{\text{jet}} < 17 \text{ GeV}, -1 < \eta^{\text{jet}} < 2.5$$

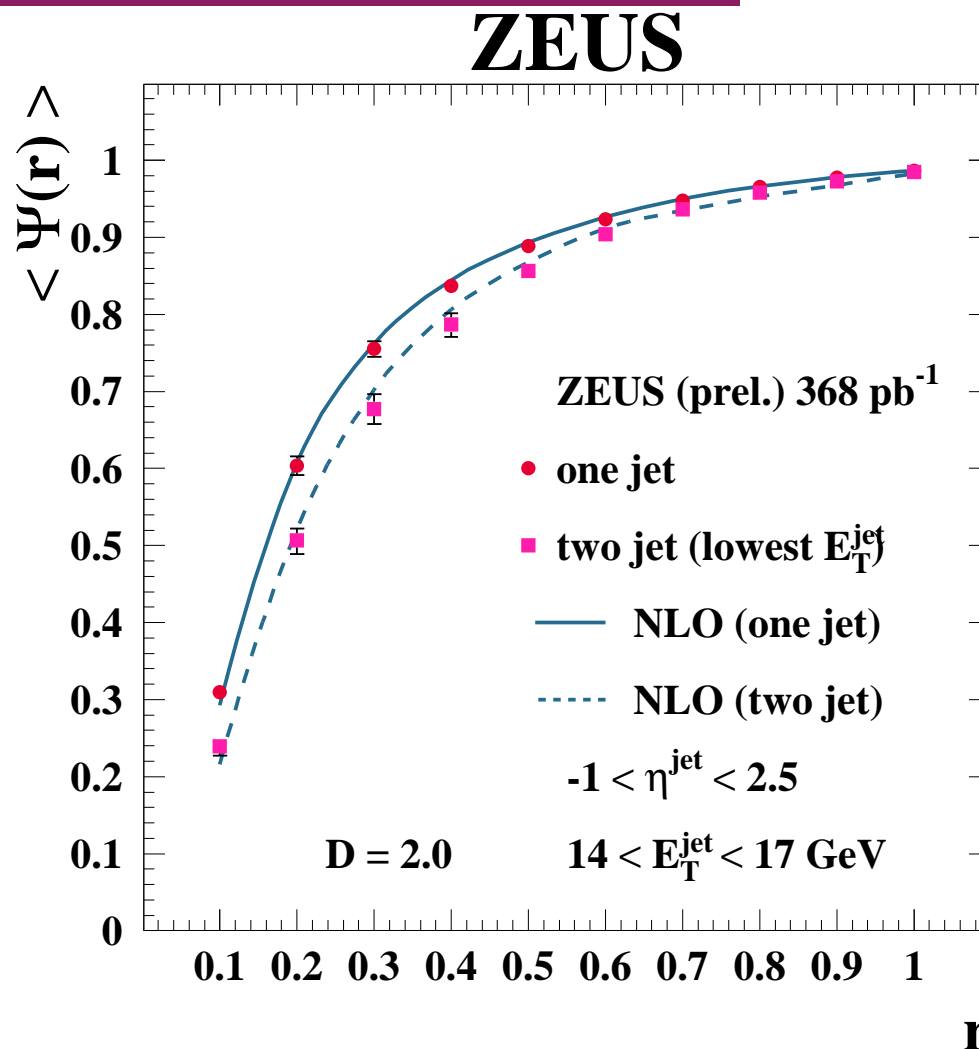
Two-jet events

$$E_T^{\text{jet}} > 14 \text{ GeV}, -1 < \eta^{\text{jet}} < 2.5$$

$$\text{distance jet-jet} = \sqrt{\Delta\eta^2 + \Delta\phi^2} \leq D = 2$$

→ the jet with lowest E_T^{jet} (and

$14 < E_T^{\text{jet}} < 17 \text{ GeV}$) is considered



NLO QCD calculations corrected for hadronisation effects ($< 10\%$ for $r \geq 0.4$) reproduce the data reasonably well; in particular, the difference in jet shape between the two samples

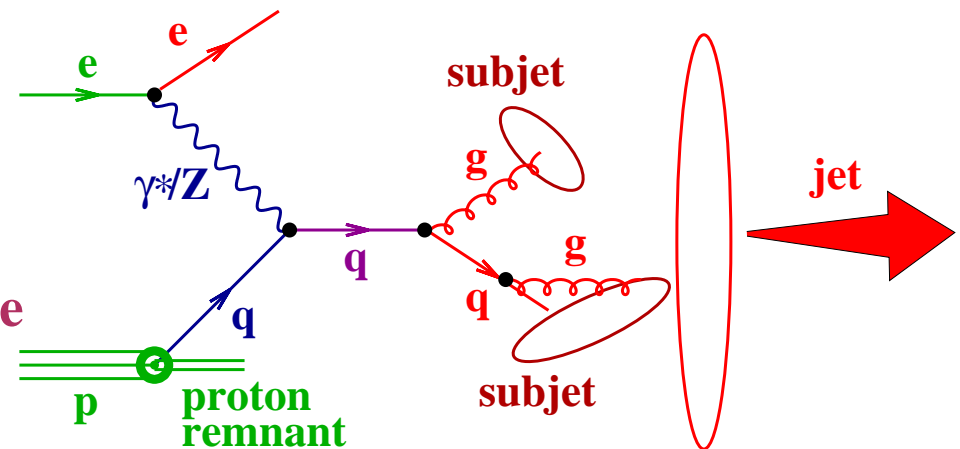
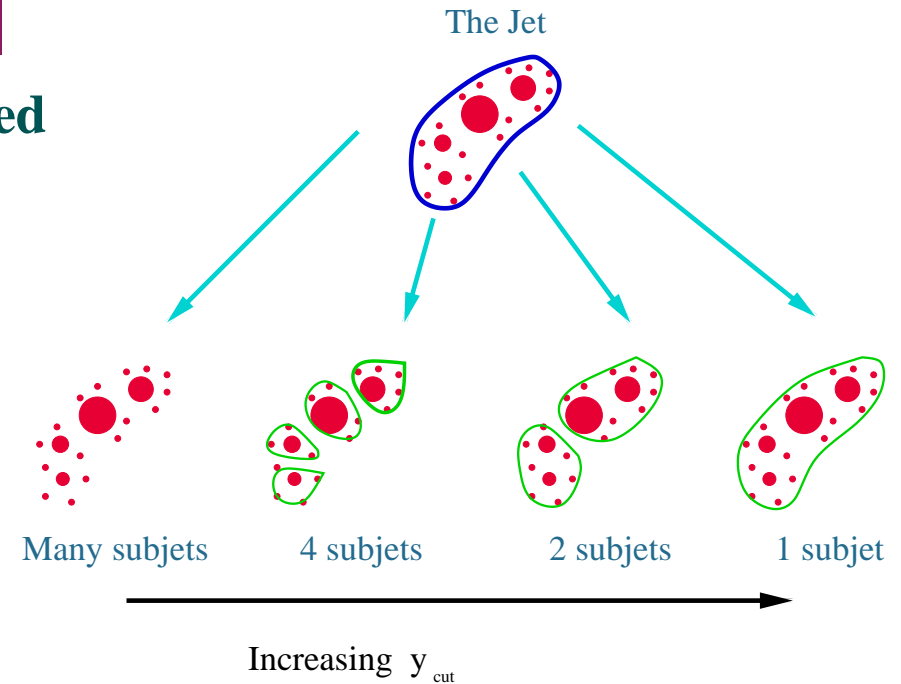
Jet Substructure in NC DIS: subjets

- The internal structure of jets has also been studied 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

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

- all remaining clusters are called **subjets**
- the **subjet multiplicity** depends upon the resolution parameter y_{cut}

- The distributions of subjets are sensitive to the pattern of parton radiation



Measurements of Subjet Distributions in NC DIS

- The pattern of QCD radiation from a primary parton has been studied by measuring normalised cross sections as functions of subjet variables

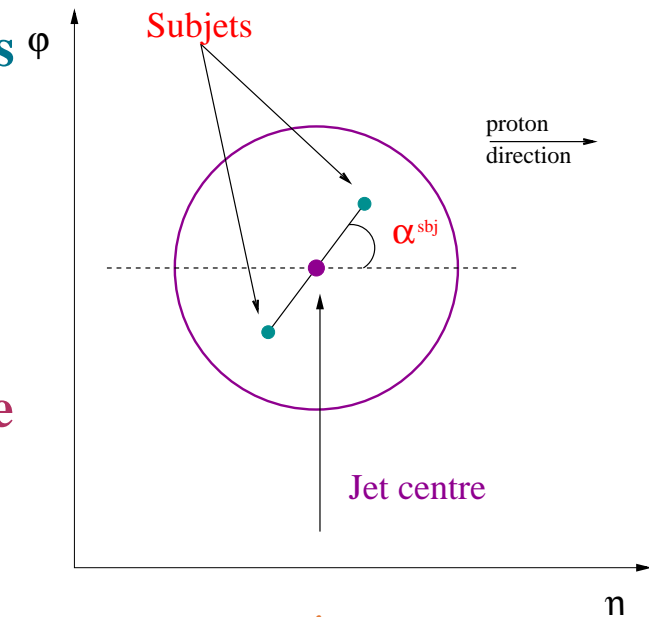
$$E_T^{sbj} / E_T^{jet}, \eta^{sbj} - \eta^{jet}, \phi^{sbj} - \phi^{jet} \text{ and } \alpha^{sbj}$$

- Measurements of the normalised cross sections were done in NC DIS for $Q^2 > 125 \text{ GeV}^2$:

- Jets are defined using the k_T -cluster algorithm in the laboratory frame; at least one jet with $E_T^{jet} > 14 \text{ GeV}$ and $-1 < \eta^{jet} < 2.5$
- Selected sample of jets: jets with exactly **TWO** subjets at $y_{cut} = 0.05$

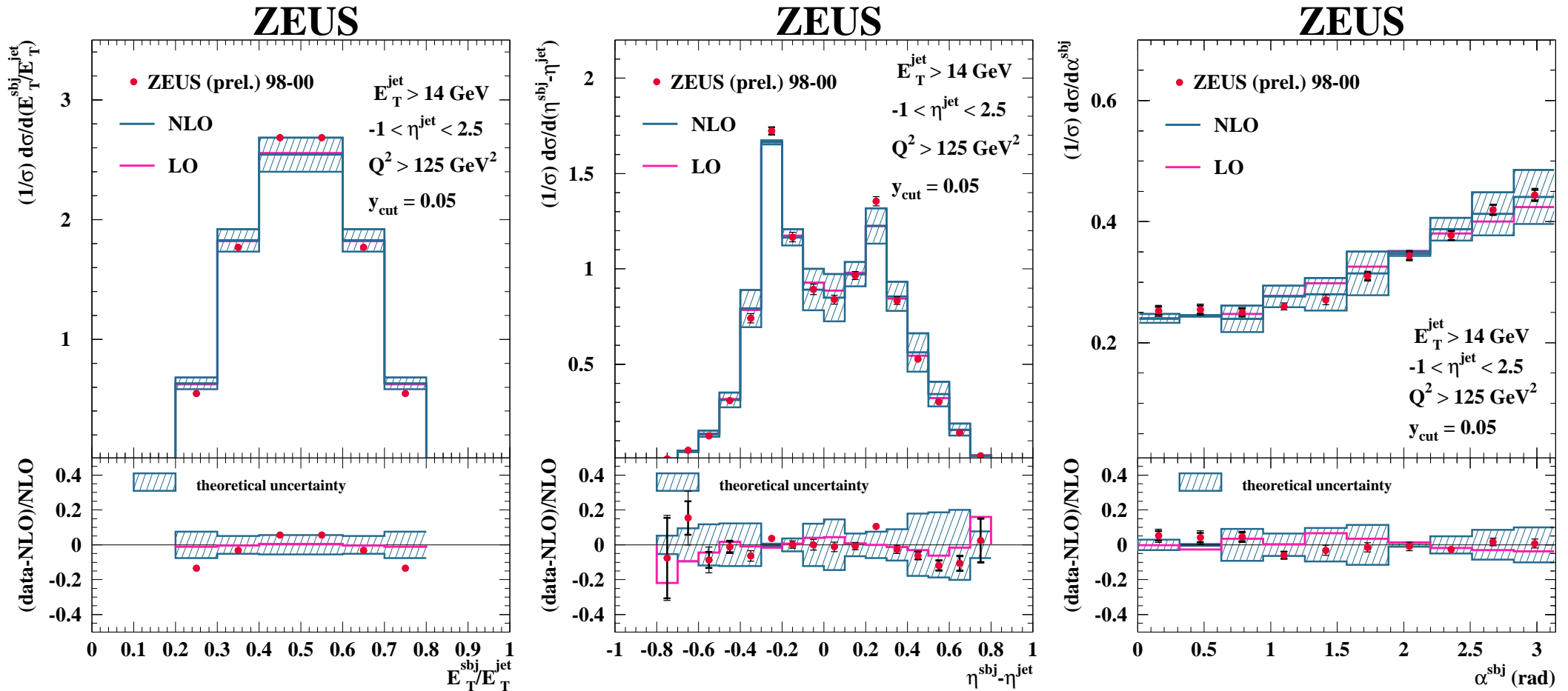
- Comparison to LO ($\mathcal{O}(\alpha_s)$) and NLO ($\mathcal{O}(\alpha_s^2)$) QCD calculations using DISENT:

- MRST99 set of proton PDFs
- $\alpha_s(M_Z) = 0.1175$
- renormalisation and factorisation scales, $\mu_R = \mu_F = Q$
- corrected for hadronisation effects



Measurements of Subjet Distributions in NC DIS vs NLO

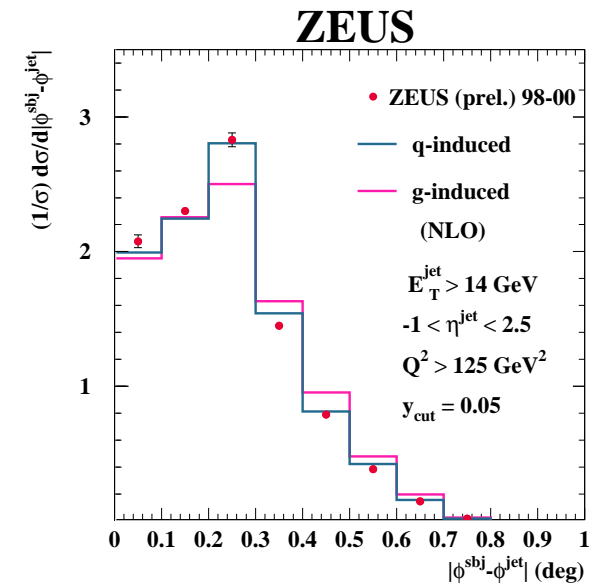
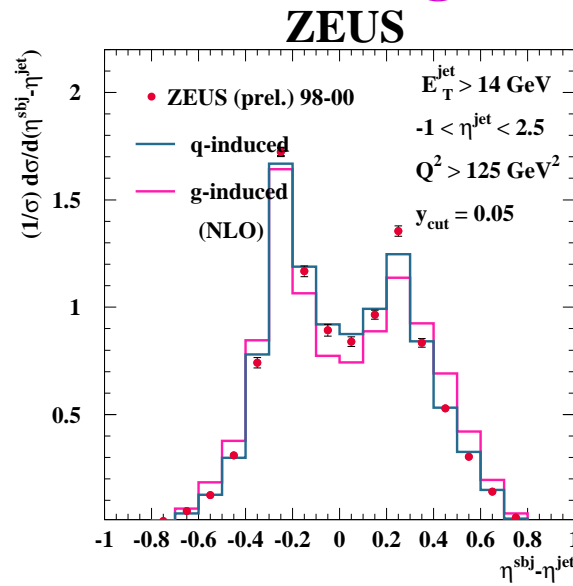
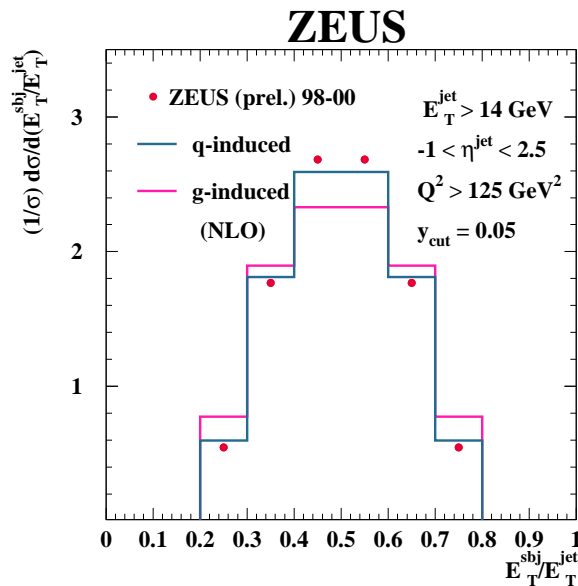
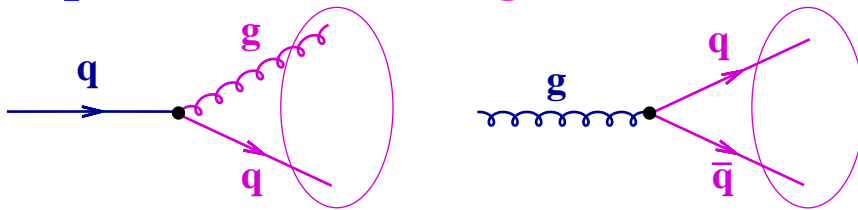
- Measurements of the normalised cross sections for subjet production as functions of E_T^{sbj} / E_T^{jet} , $\eta^{sbj} - \eta^{jet}$ and α^{sbj} vs LO and NLO QCD calculations



→ NLO QCD calculations describe the data within $\pm 10\%$

Measurements of Subjet Distributions in NC DIS

- Measurements of the normalised cross sections for subjet production as functions of E_T^{sbj} / E_T^{jet} , $\eta^{sbj} - \eta^{jet}$ and $|\phi^{sbj} - \phi^{jet}|$ vs QCD calculations for quark- (82%) and gluon-induced (18%) contributions (NLO predictions)



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

Summary

- **Measurements of the integrated jet shape in NC DIS** ($Q^2 > 125 \text{ GeV}^2$) for jets with $E_T^{\text{jet}} > 14 \text{ GeV}$ using HERA II data ($\mathcal{L} = 368 \text{ pb}^{-1}$)
 - The jet with lowest E_T^{jet} in two-jet events is **broader** than that of a sample of one-jet events for the same range in E_T^{jet}
 - NLO QCD calculations (**with up to three partons in a jet!**) describe the data reasonably well
- **Measurements of the normalised cross sections for subjet production in NC DIS** ($Q^2 > 125 \text{ GeV}^2$)
 - the **pattern of QCD radiation** as implemented in the NLO calculations reproduces the measured **subjet distributions**¹
 - the subjet distributions are well described by the calculations for jet arising from **the splitting of a quark into a quark-gluon pair**

