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Jet Substructure at HERA

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from

ZEUS

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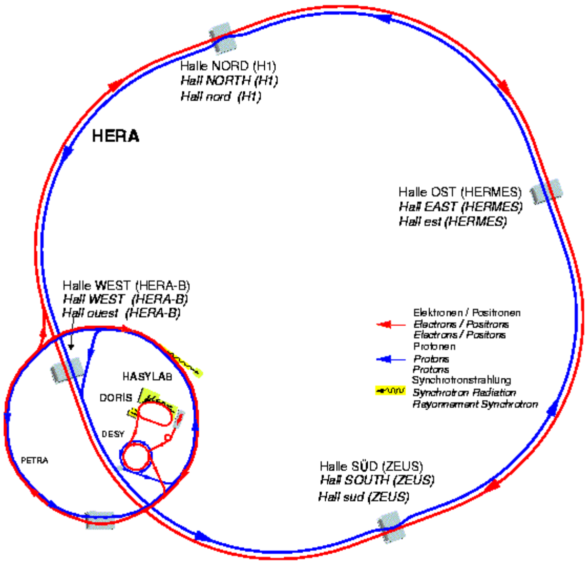
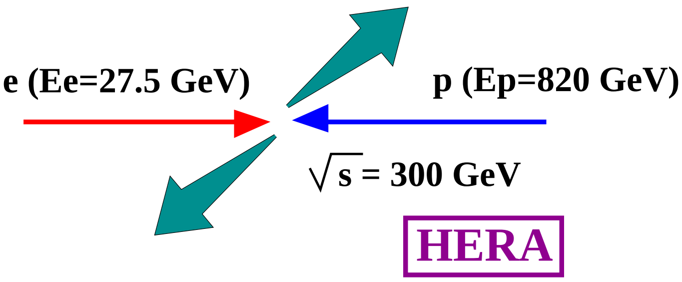




Jet substructure

- 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 jet of hadrons

- The internal structure of a jet is expected to depend mainly on the type of primary parton, quark or gluon, from which it originated and to a lesser extent on the particular hard scattering process

- QCD predictions:

  $\rightarrow$ At sufficiently high E_T^{jet}, where fragmentation effects become negligible, the jet structure is expected to be driven by gluon emission off the primary parton, and therefore, calculable by pQCD.

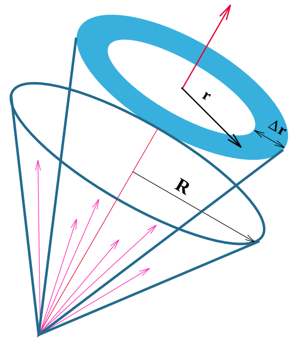
  $\rightarrow$ Gluon jets are predicted to be broader than quark jets due to the larger colour charge of the gluon

- The lowest non-trivial-order contribution to the jet substructure is given by $O(\alpha\alpha_S^2)$ calculations

  $\rightarrow$ Measurements of jet substructure provide a stringent test of pQCD calculations beyond LO

Jet substructure: jet shape

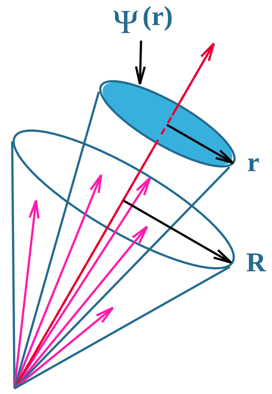
- **Differential jet shape ($\rho(r)$):**
  Average fraction of the jet's transverse energy that lies inside an annulus in the $\eta - \varphi$ plane of radii $r \pm \Delta r/2$ concentric with the jet axis



$$\rho(r) = \frac{1}{N_{jets}} \frac{1}{\Delta r} \sum_{jets} \frac{E_T(r - \Delta r/2, r + \Delta r/2)}{E_T(0, r = 1)}$$

$$\rightarrow r = \sqrt{(\Delta\eta)^2 + (\Delta\varphi)^2}$$

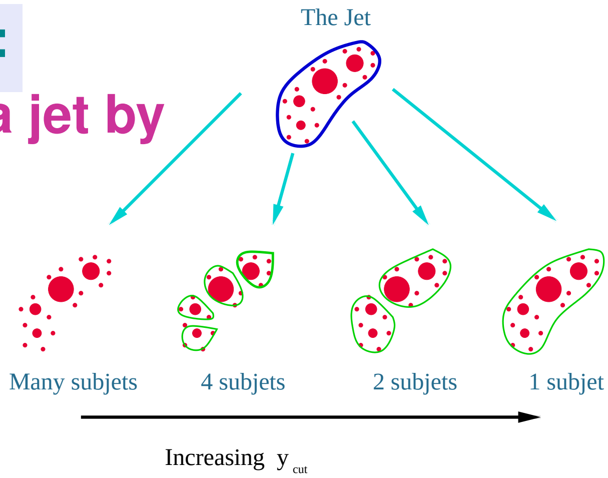
- **Integrated jet shape ($\psi(r)$):**
  Average fraction of the jet's transverse energy that lies inside a cone in the $\eta - \varphi$ plane of radius r concentric with the jet axis



$$\psi(r) = \frac{1}{N_{jets}} \sum_{jets} \frac{E_T(r)}{E_T(r = 1)}$$

Jet substructure: subjet multiplicity

- **Subjet multiplicity (n_{subjet}):** Subjets are resolved within a jet by reapplying the k_T cluster algorithm until for every pair of particles the quantity d_{ij} is above $y_{cut} \cdot (E_T^{jet})^2$



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

- **Theoretical advantadges:**

  $\longrightarrow$ "safe" observables can be defined at any order in pQCD

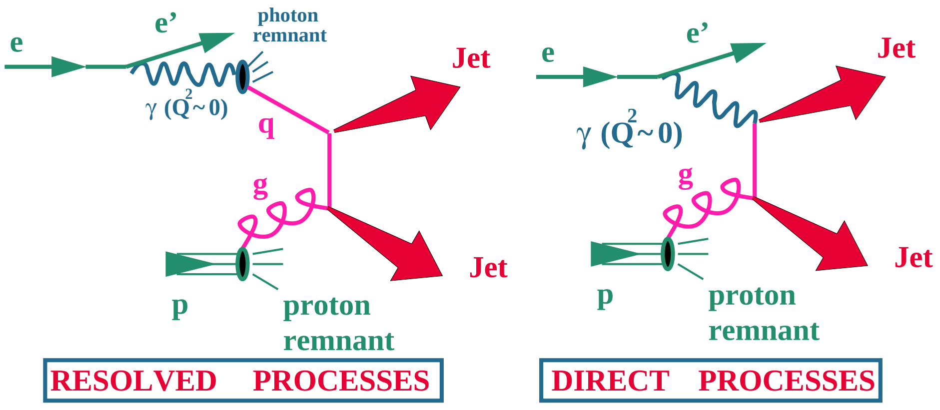
  $\longrightarrow$ allowance for "resummed" calculations

  $\longrightarrow$ useful tool to investigate colour dynamics (e.g. quark/gluon differences)

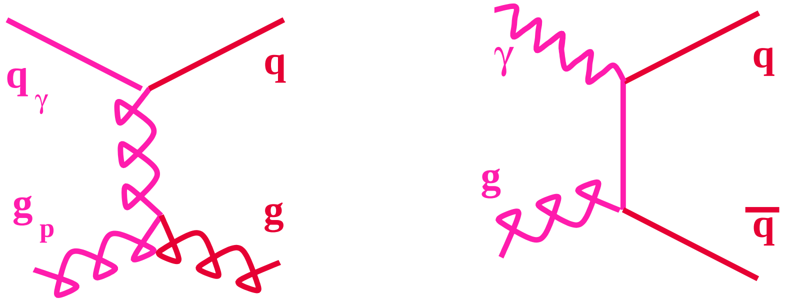
  $\longrightarrow$ small hadronisation corrections (for not too low y_{cut})

Jet production at LO QCD in photoproduction

$$ep \to e + \text{jet}\ (+\text{jet}) + X$$



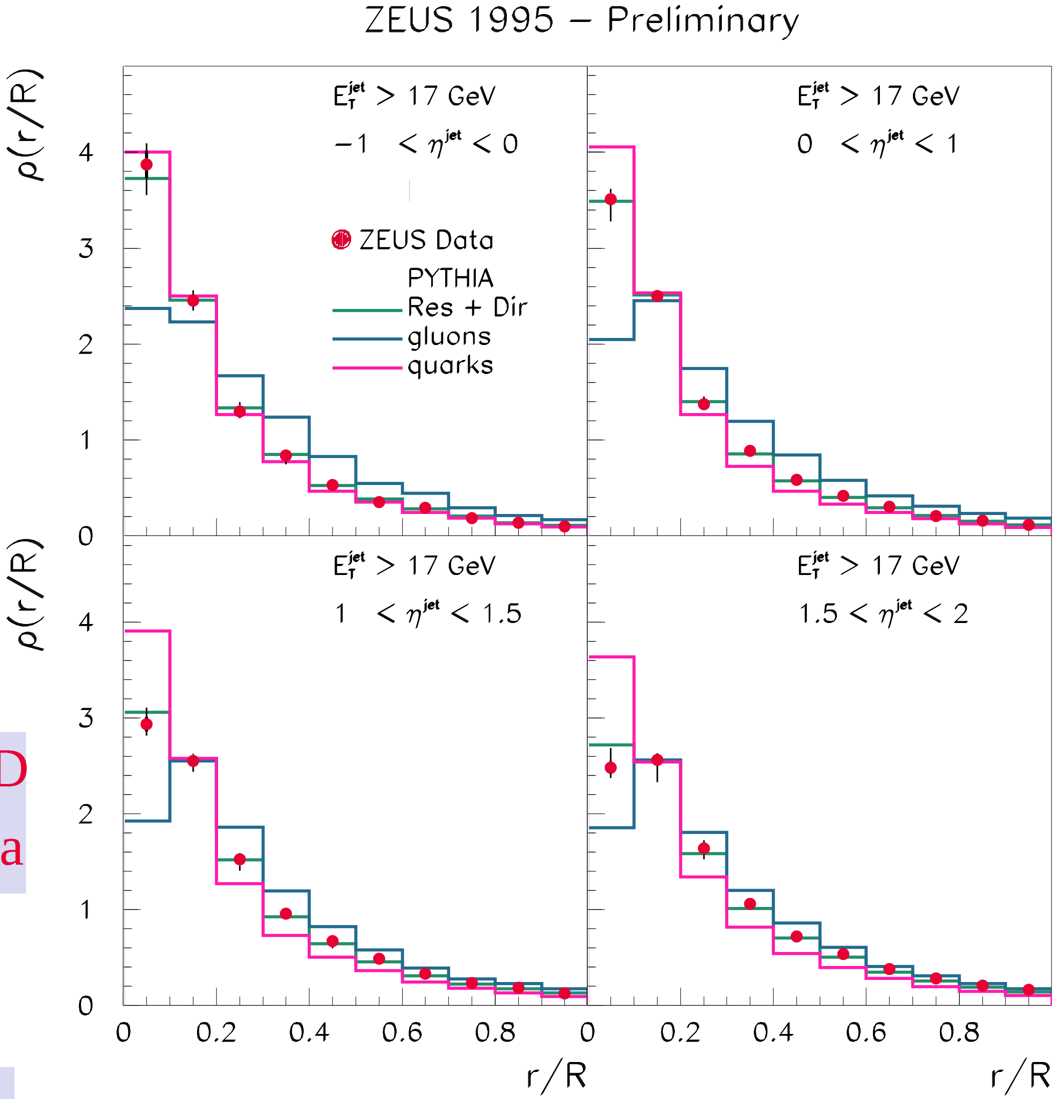
- **Dominant partonic subprocesses:**
  $q_\gamma g_p \to qg$ **and** $\gamma g \to q\bar{q}$



- **The kinematic of these subprocesses are such that the majority of the jets in $\eta^{jet} < 0$ originate from quarks and the fraction of gluon-initiated jets increases as η^{jet} increases**

Measurement of $\rho(r)$: η^{jet} dependence

- Jets searched using the longitudinally invariant k_T cluster algorithm in the inclusive mode
- Kinematic region: $0.2 < y < 0.85$ and $Q^2 \leq 1$ GeV^2
- At least one jet with $E_T^{jet} > 17$ GeV and $-1 < \eta^{jet} < 2$



→ $\rho(r)$ in different η^{jet} regions: jets become broader as η^{jet} increases

→ Models including initial and final state QCD radiation give a good description of the data

→ The measured jets are:
→ quark-like for $-1 < \eta^{jet} < 0$
→ more gluon-like for $1.5 < \eta^{jet} < 2$

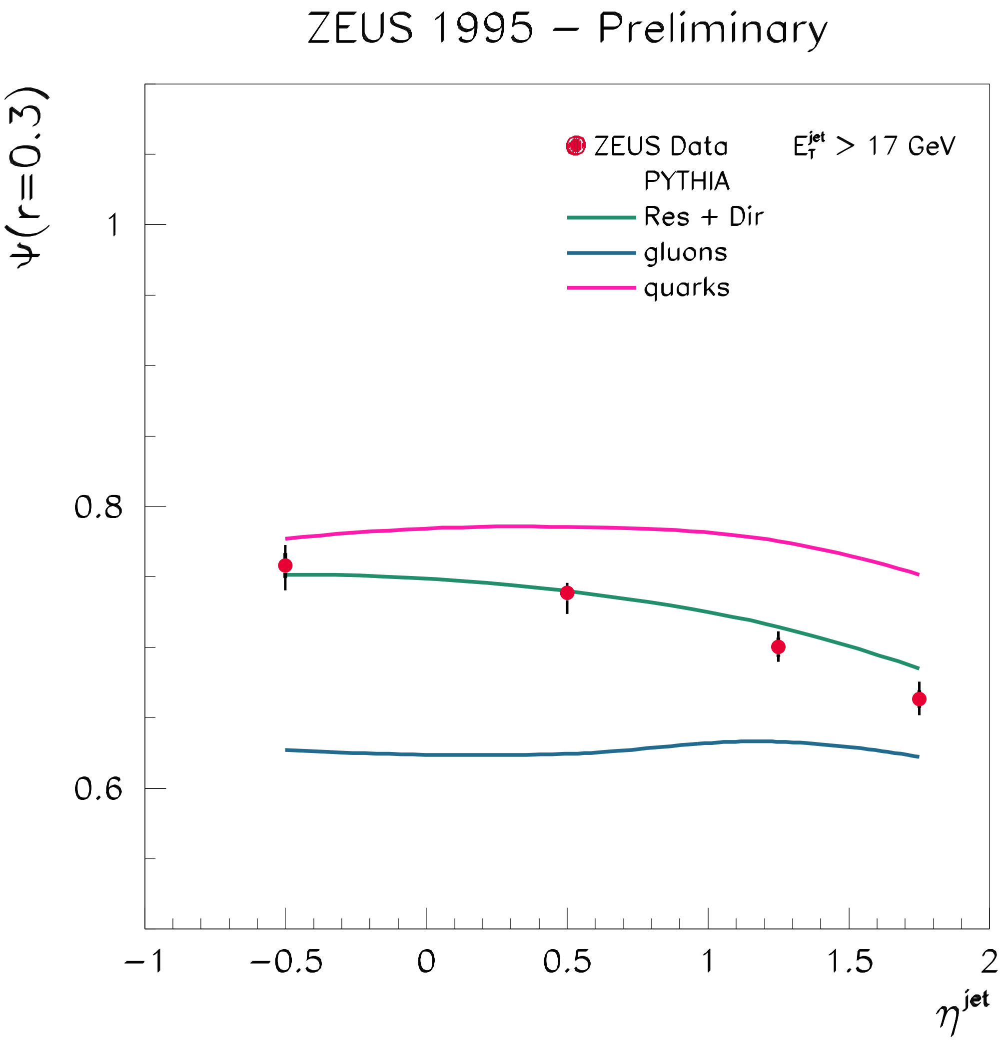
→ Challenge for NLO QCD calculations

Measurement of $\psi(r)$: η^{jet} dependence at fixed r

→ **The measured jet shape $\psi(r = 0.3)$ decreases with η^{jet} : the jets become broader as η^{jet} increases**

- **Comparison with the predictions for quark and gluon jets:**

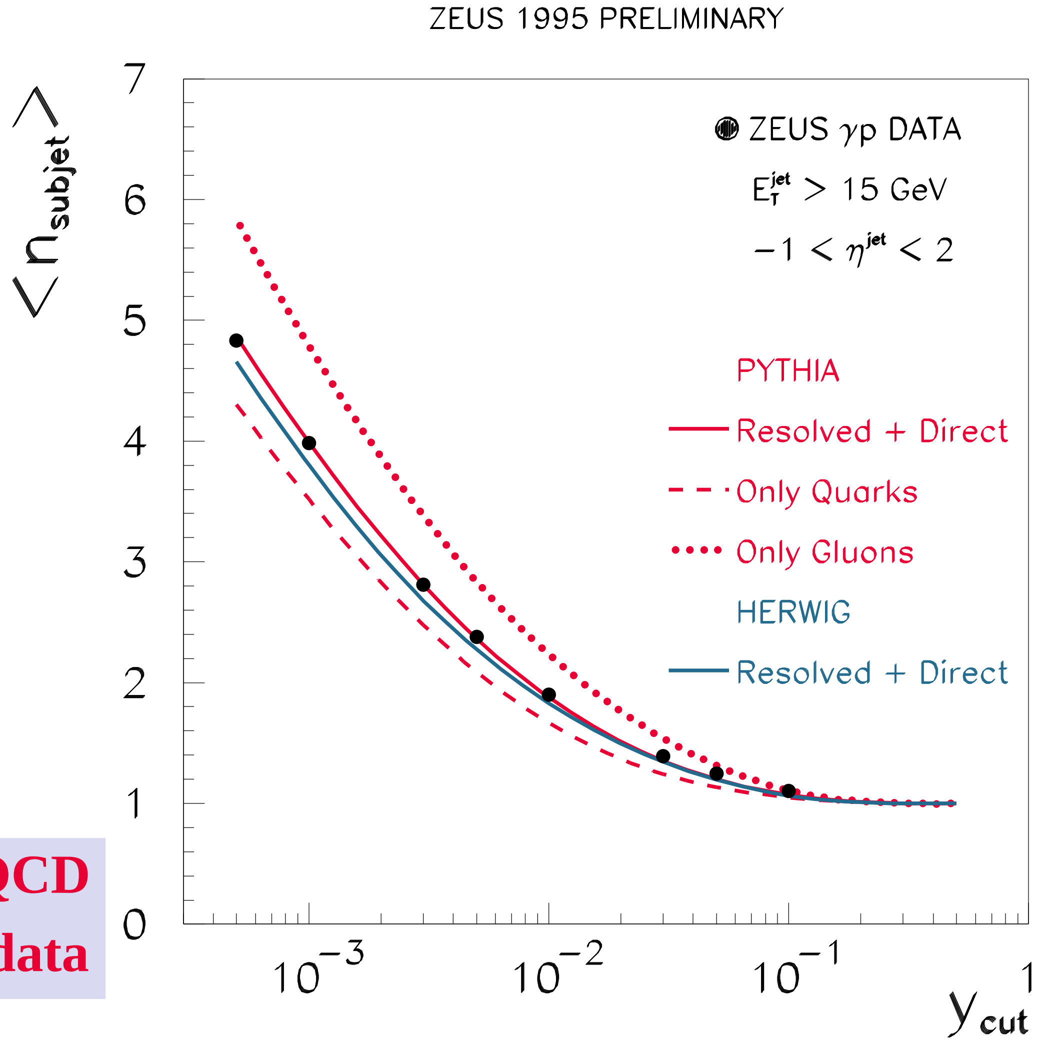
→ **The broadening of the jets is consistent with an increasing fraction of gluon-initiated jets as η^{jet} increases**



Measurement of $< n_{subjet} >$: y_{cut} dependence

- Jets searched using the longitudinally invariant k_T cluster algorithm in the inclusive mode
- Kinematic region: $0.2 < y < 0.85$ and $Q^2 \leq 1$ GeV^2
- At least one jet with $E_T^{jet} > 15$ GeV and $-1 < \eta^{jet} < 2$

→ Models including initial and final state QCD radiation give a good description of the data

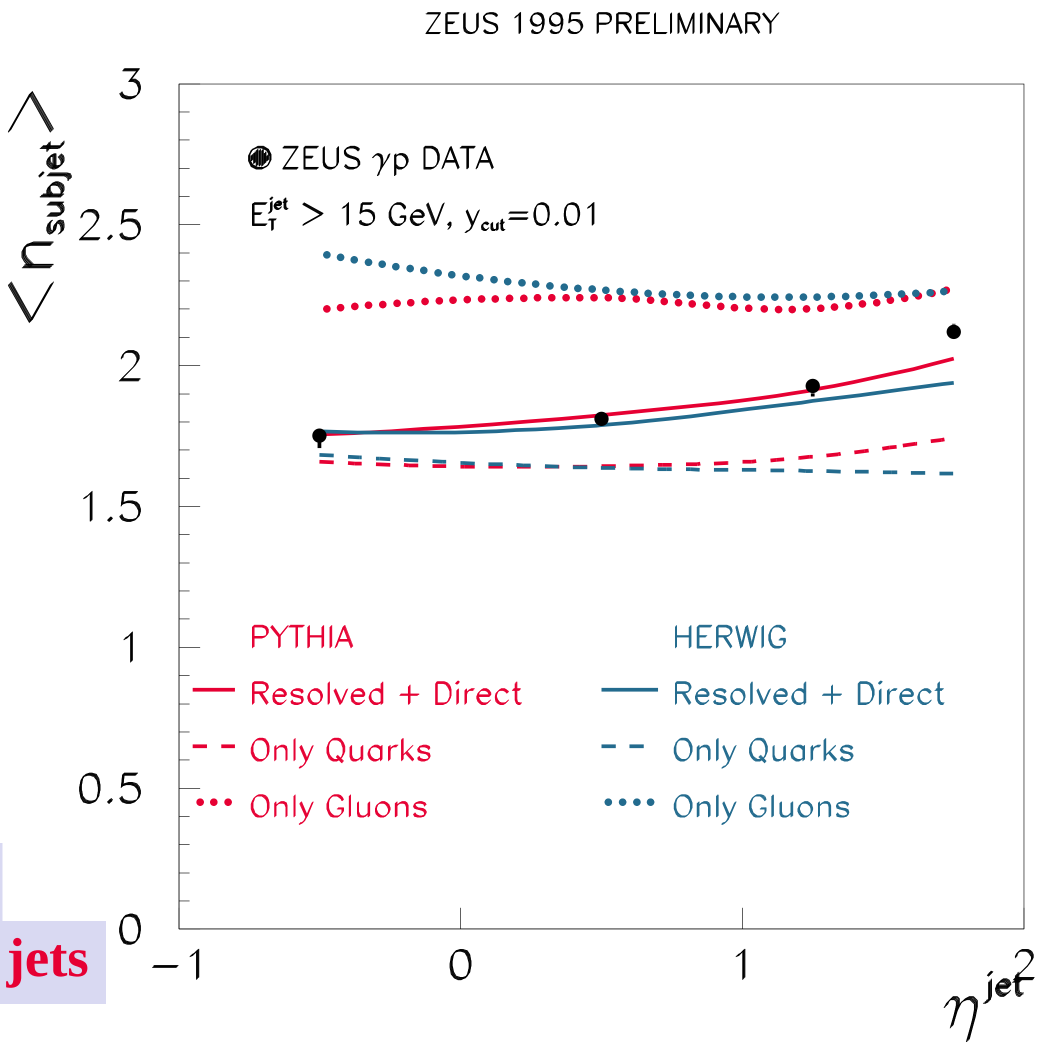


Measurement of $< n_{subjet} >$: η^{jet} dependence at fixed y_{cut}

→ **The measured mean subjet multiplicity $< n_{subjet}(y_{cut} = 10^{-2}) >$ increases as η^{jet} increases**

- **Comparison with the predictions for quark and gluon jets:**

→ **The increase in $< n_{subjet} >$ as η^{jet} increases is consistent with the predicted increase in the fraction of gluon-initiated jets**

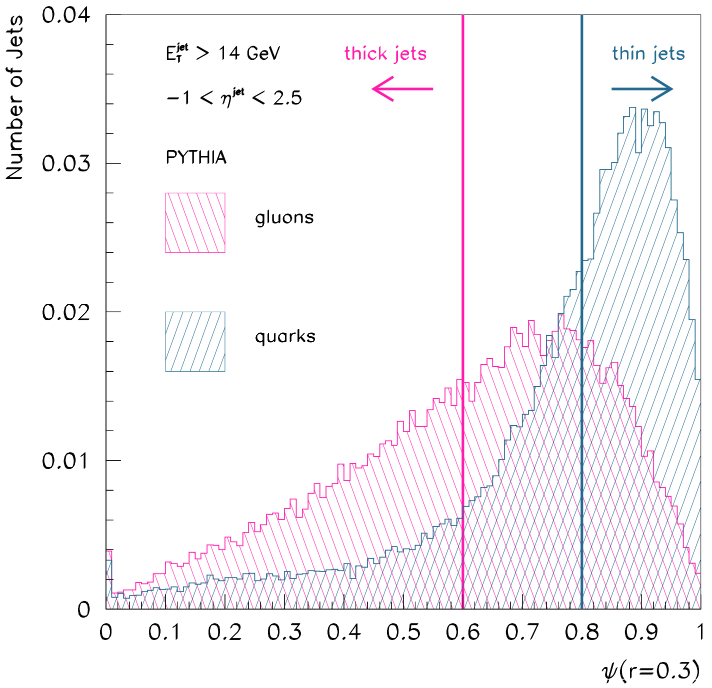


Selection of quark and gluon jets

- Monte Carlo predictions of $\psi(r)$ and n_{subjet} for quark- and gluon-initiated jets show clear differences $\rightarrow$ handle to study subprocesses ?

- Separation of quark and gluon jets assuming:

gluon jets $\leftrightarrow$ “thick” jets   quark jets $\leftrightarrow$ “thin” jets

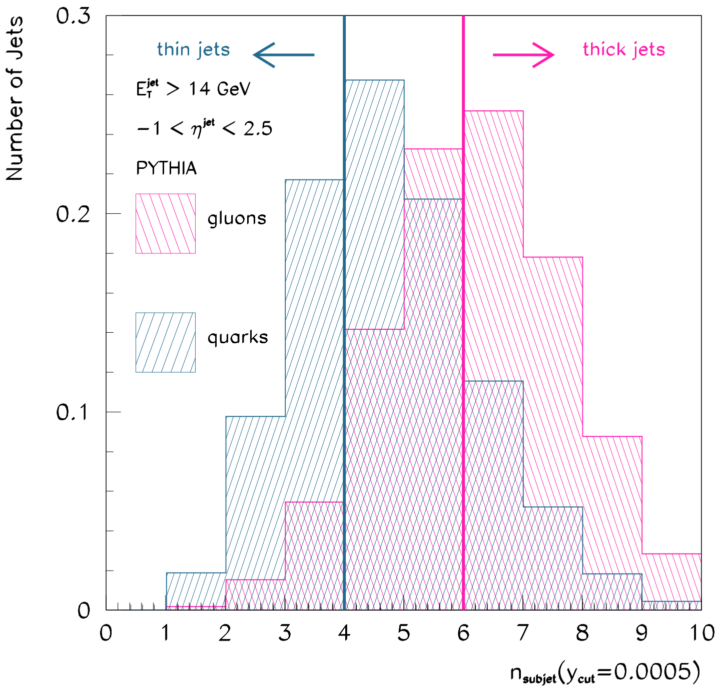


samples enriched in

gluon-like (“thick”) jets:

$* \ \psi(r = 0.3) < 0.6$

$* \ n_{subjet}(y_{cut} = 5.10^{-3}) \geq 6$



quark-like (“thin”) jets:

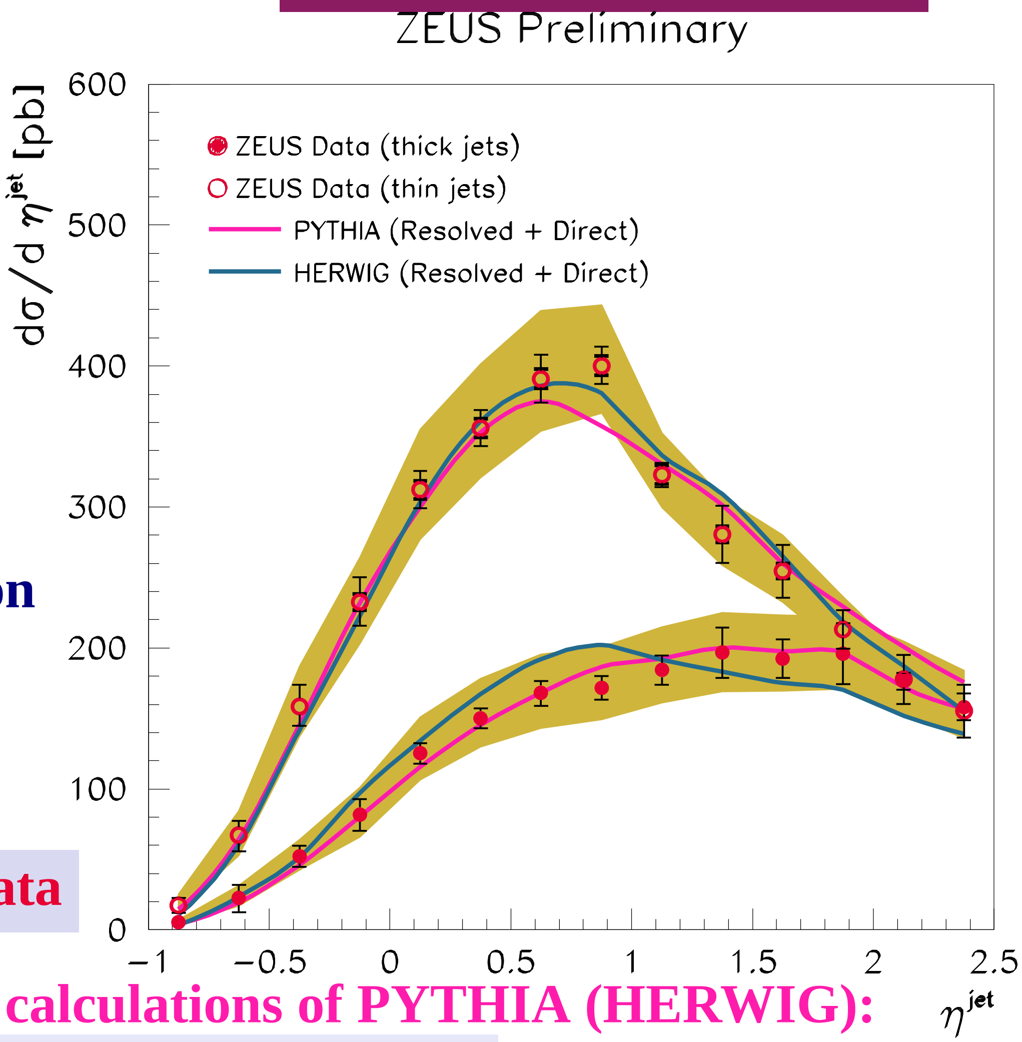
$* \ \psi(r = 0.3) > 0.8$

$* \ n_{subjet}(y_{cut} = 5.10^{-3}) < 4$

Measurement of $\frac{d\sigma}{d\eta^{jet}}$

- Jets searched using the k_T cluster algorithm
- Kinematic region:
  $0.2 < y < 0.85$ and $Q^2 \leq 1$ GeV^2
- At least two jets with
  $E_T^{jet} > 14$ GeV and $-1 < \eta^{jet} < 2.5$
- $d\sigma/d\eta^{jet}$ for "thick" and "thin" jets show different shape
- Comparison with leading-logarithm parton shower MC calculations:
  * same jet shape cuts as the data
  * MC area-normalised to data

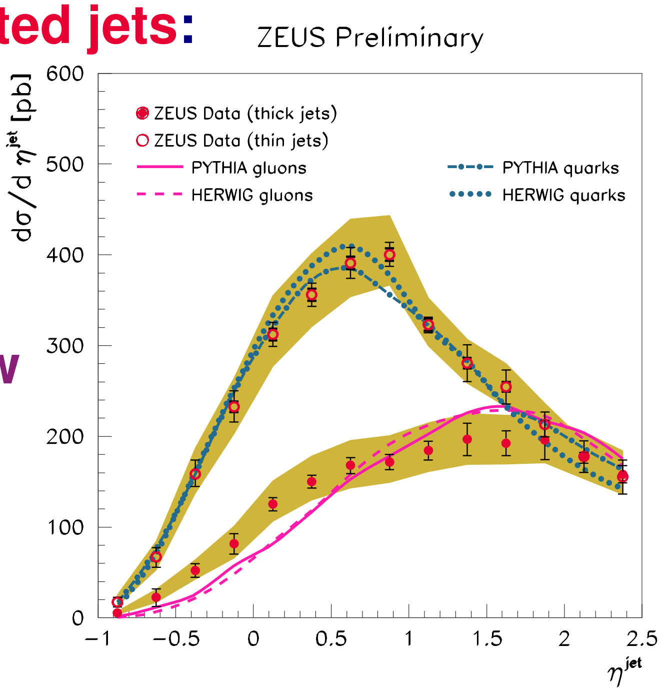
  $\rightarrow$ good description of the shape of the data



- Parton content of the final state from MC calculations of PYTHIA (HERWIG):
  $\rightarrow$ "thick" jets: $17(15)\%$ gg, $58(54)\%$ gq and $25(31)\%$ qq
  $\rightarrow$ "thin" jets: $54(56)\%$ qq, $41(41)\%$ qg and $5(3)\%$ gg

Measurement of $\frac{d\sigma}{d\eta^{jet}}$

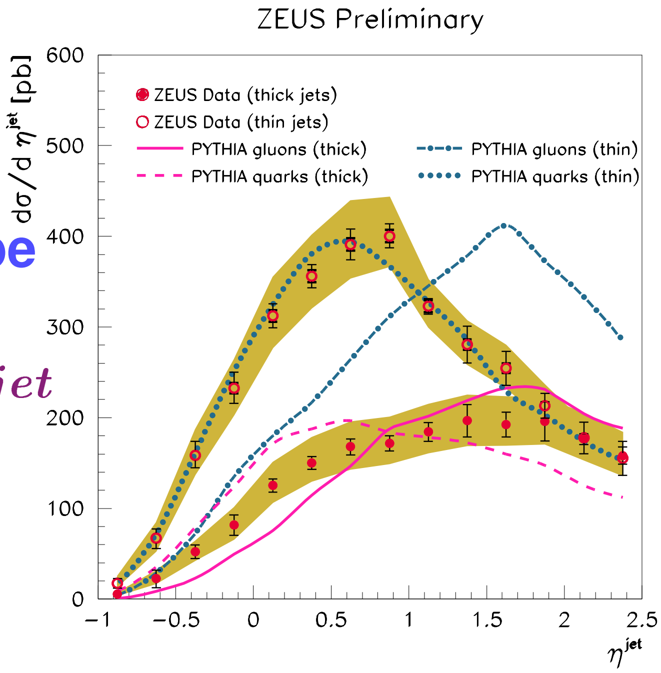
- **Comparison with MC calculations of quark- and gluon-initiated jets:**



∗ **No jet shape cuts applied to MC**

→ **"thick" ("thin") jets show similar η^{jet} shape to gluon (quark) jets**

MC area-normalised to data



∗ **Same jet shape cuts as data applied to MC**

→ **"thin" quark jets describe the data whereas "thin" gluon jets peak at higher η^{jet}**

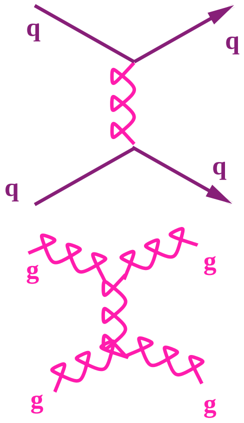
→ **quark jets alone do not describe the measured "thick"-η^{jet} distribution**

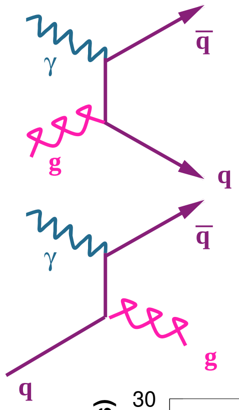
→ **a large content of gluon jets is needed to describe the data**

The $\cos\theta^*$ distribution

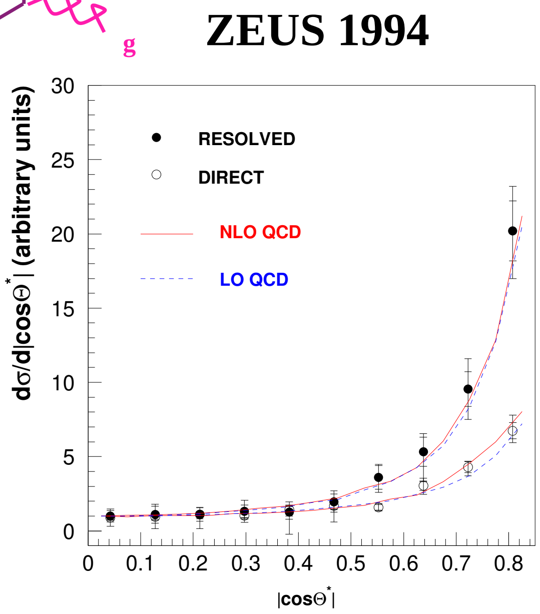
- The $\cos\theta^*$ distribution reflects the underlying parton dynamics $\rightarrow$ sensitive to the spin of the exchanged particle in two-body processes:

gluon exchange $\rightarrow (1-|\cos\theta^*|)^{-2}$ quark exchange $\rightarrow (1-|\cos\theta^*|)^{-1}$





- The $|\cos\theta^*|$ distribution for resolved processes (gluon exchange) rises more steeply than that of direct processes (quark exchange) for $|\cos\theta^*| \rightarrow 1$
- Resolved and direct separated according to x_γ^{OBS}



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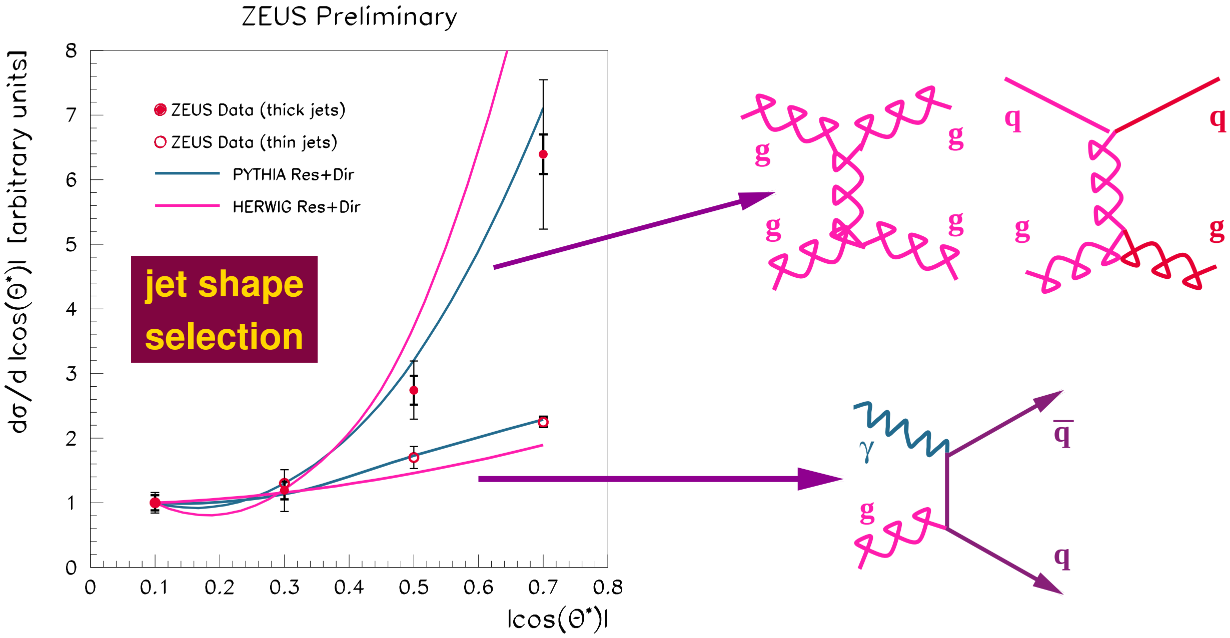
Measurement of $\frac{d\sigma}{d|\cos\theta^*|}$

- $d\sigma/d|\cos\theta^*|$ for $M^{JJ} > 47$ GeV for samples of two "thick"-jet events and two "thin"-jet events exhibit a different slope:



$*$ Data and MC normalised to unity at $|\cos\theta^*| = 0.1$

$\rightarrow$ $d\sigma/d|\cos\theta^*|$ at 0.7 for two "thick (thin)" jets is more than five (only two) times larger than at 0.1

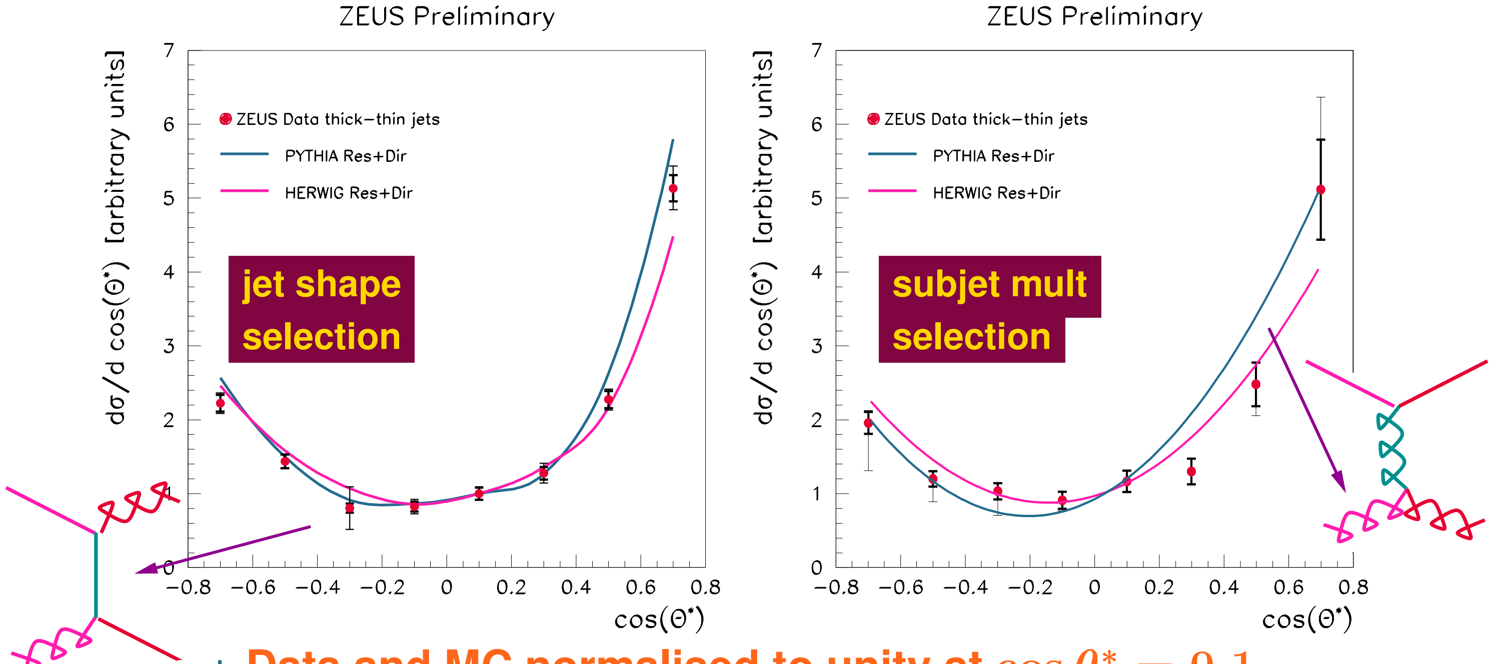
- Comparison with MC:
  - $*$ same selection cuts as the data for "thick"/"thin" sample

  $\rightarrow$ PYTHIA gives a reasonable description of the shape of the data

$\rightarrow$ Different slope understood in terms of the dominant two-body processes: $qg \rightarrow qg$ (dominant in "thick"-jet sample) rises more steeply than $\gamma g \rightarrow q\bar{q}$ (dominant in "thin"-jet sample) due to different spin of the exchanged particle

Measurement of $\frac{d\sigma}{d\cos\theta^*}$

- $d\sigma/d\cos\theta^*$ for a sample of events with one "thick" jet and one "thin" jet measured wrt the "thick" jet shows different behaviour on the negative and positive sides:



$*$ Data and MC normalised to unity at $\cos\theta^* = 0.1$

$\rightarrow$ $d\sigma/d\cos\theta^*$ at 0.7 is more than two times larger than at -0.7

- **Comparison with MC:**
  - $*$ same selection cuts as the data for "thick"/"thin" sample
  - $\rightarrow$ PYTHIA gives a reasonable description of the shape of the data

$\rightarrow$ Observed asymmetry understood in terms of the dominant resolved subprocess: $q_\gamma g_p \rightarrow qg$

$\rightarrow$ The asymmetry is due to the different dominant diagrams for $\cos\theta^* \rightarrow \pm 1$:
- $*$ $t-$channel gluon exchange at $\cos\theta^* = +1$
- $*$ $u-$channel quark exchange at $\cos\theta^* = -1$

CONCLUSIONS

- The jet shape and the mean subjet multiplicity have been measured as a function of η^{jet} for inclusive jets with $E_T^{jet} > 15$ GeV and $-1 < \eta^{jet} < 2$, $Q^2 \leq 1$ GeV^2 and 134 $< W <$ 277 GeV

- The jet shape broadens and the mean subjet multiplicity increases as η^{jet} increases

- Leading-logarithm parton shower MC models give a good description of the data

- The observed broadening of the jet shape and the increase of the mean subjet multiplicity as η^{jet} increases is consistent with an increase of the fraction of gluon jets

CONCLUSIONS

- $\psi(r)$ and n_{subjet} have been measured for dijet events with $E_T^{jet} > 14$ GeV and $-1 < \eta^{jet} < 2.5$, $Q^2 \leq 1$ GeV^2 and $134 < W < 277$ GeV
- The MC models display the expected differences for quark- and gluon-initiated jet samples and allow the use of $\psi(r)$ and n_{subjet} to select samples enriched in quark- ("thin") and gluon-initiated ("thick") jets:

→ $d\sigma/d\eta^{jet}$ for "thick" and "thin" jet samples shows the expected behaviour for samples enriched in gluon- and quark-initiated jets

→ $d\sigma/d|\cos\theta^*|$ for the two "thick (thin)"-jet sample displays a similar behaviour to the one expected for a sample enriched in processes mediated by gluon (quark) exchange

→ $d\sigma/d\cos\theta^*$ for a sample of events with one "thick" jet and one "thin" jet exhibits a large asymmetry consistent with the expected dominance of gluon (quark) exchange as $\cos\theta^* \to +1$ ($\cos\theta^* \to -1$)