Florence, DIS 2010

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Three-subjet distributions in NC DIS

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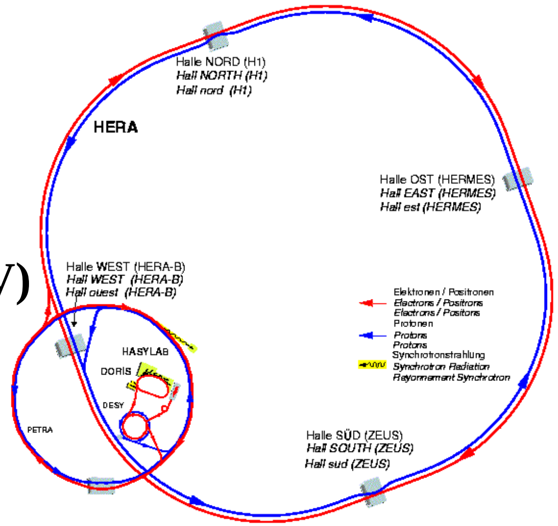
ZEUS Collaboration

e (Ee = 27.5 GeV)   p (Ep = 920 GeV)

$\sqrt{s}$ = 318 GeV

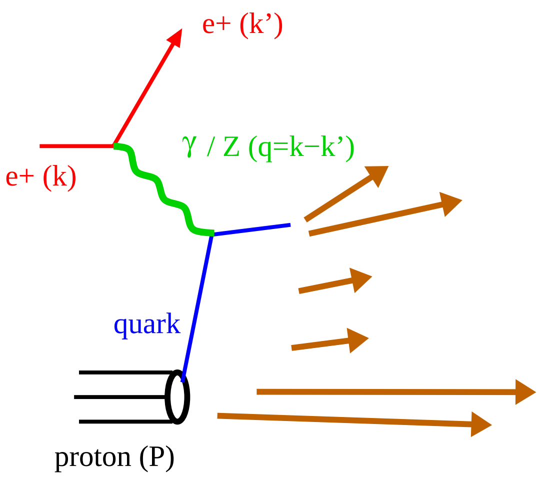
HERA



⇒ **Understanding jet substructure is becoming more and more relevant for boosted systems such as hadronic top decays, Higgs and supersymmetric final states at the LHC**

⇒ **NC DIS provides a more controlled hadronic-type environment than that of hadron-hadron colliders in which to assess the validity of the description of the subjet topology by QCD calculations**

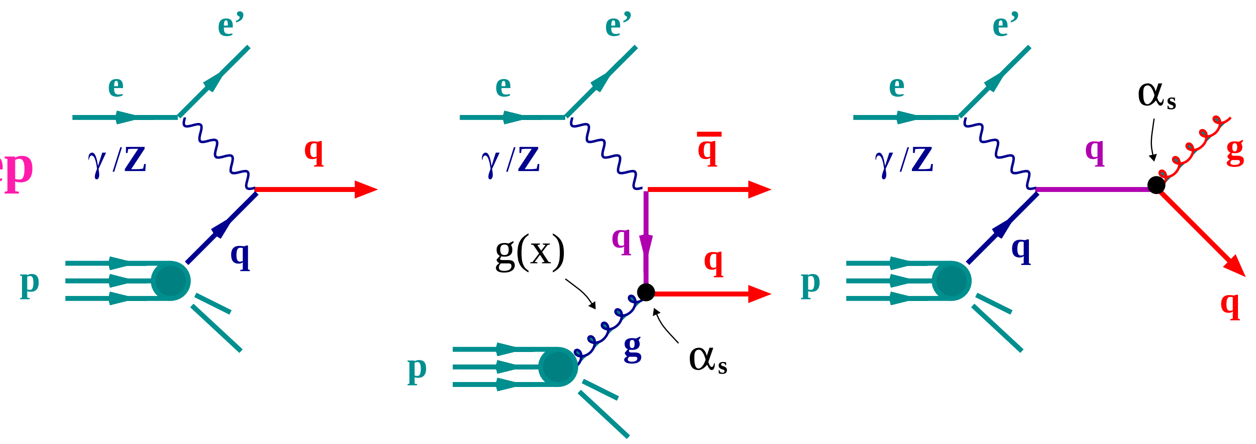
Neutral Current Deep Inelastic Scattering



For a given ep centre-of-mass energy, $\sqrt{s}$, the fully inclusive cross section for $ep \to e + X$ 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 $\mathcal{O}(\alpha_s) \to$



Quark-Parton Model Boson-Gluon Fusion QCD Compton

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... $\to$

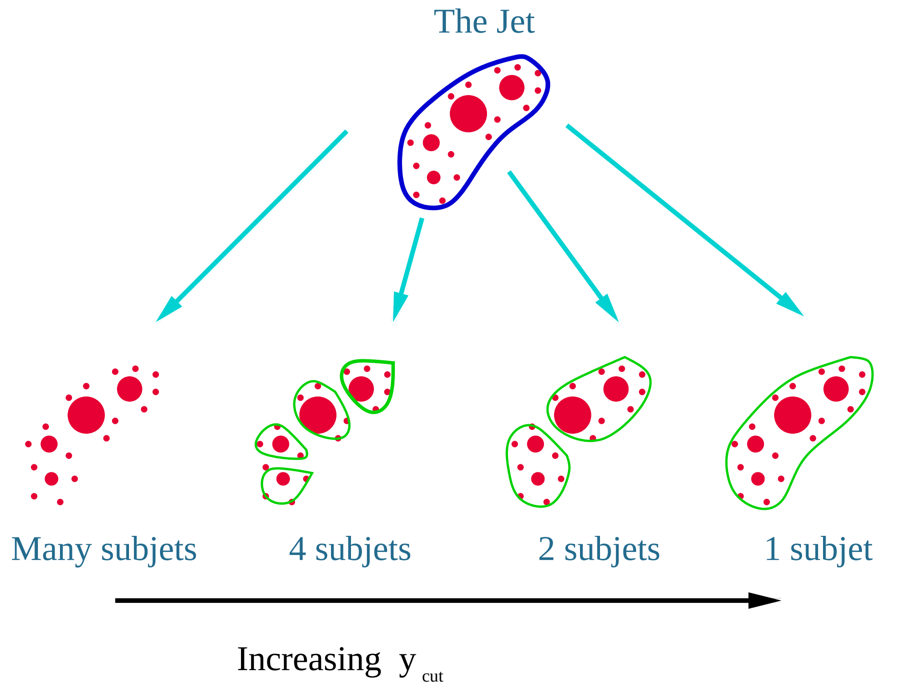
Subjets

- 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 betwen clusters is above

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

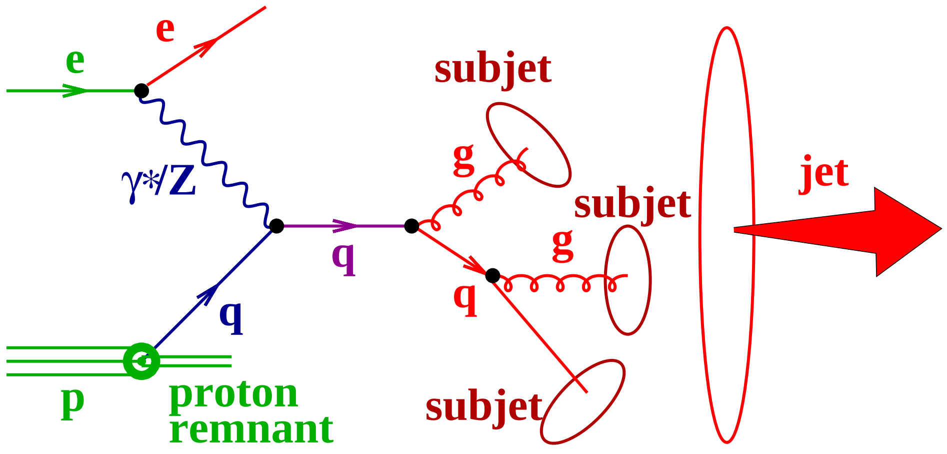
→ all remaining clusters are called subjets

→ the subjet multiplicity depends upon the resolution parameter y_{cut}



- At sufficiently high E_T^{jet}, where fragmentation effects become negligible, the subjet topology (at y_{cut} not too low) is expected to be calculable in pQCD

→ the distributions of subjets are sensitive to the pattern of parton radiation



Three-Subjet Variables in NC DIS

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

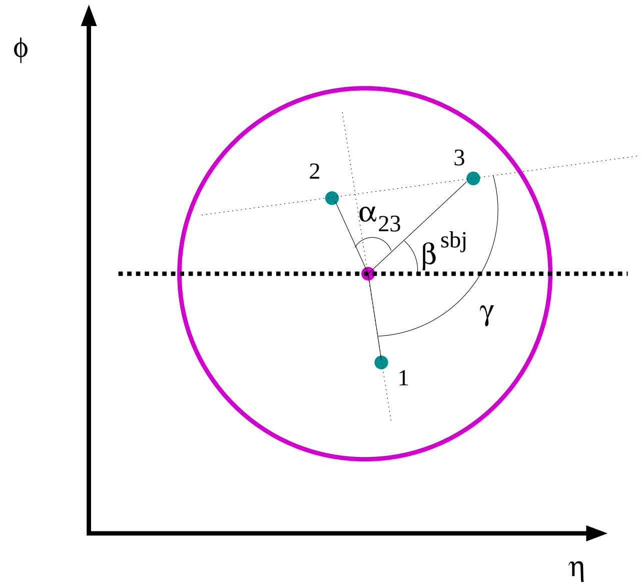
$$E_T^{sbj}/E_T^{jet} \quad , \quad \eta^{sbj} - \eta^{jet} \quad , \quad |\phi^{sbj} - \phi^{jet}|$$

and the angles in the η-ϕ plane of the laboratory frame

$\rightarrow \beta^{sbj}$, the angle, as viewed from the jet centre, between the subjet with lowest E_T and the proton beam direction

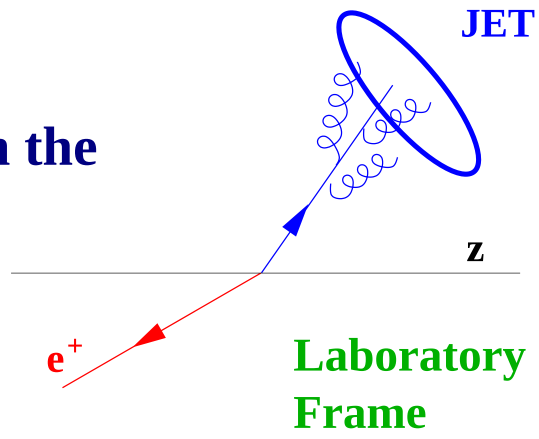
$\rightarrow \alpha_{23}$, the angle between the two lowest-E_T subjets as seen from the jet centre

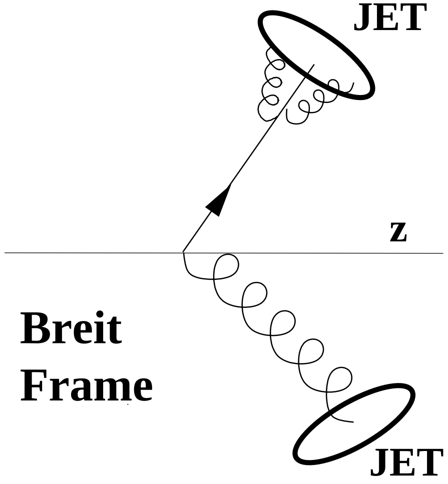
$\rightarrow \gamma$



- Jets (and subjets) are reconstructed in the laboratory frame since NLO QCD calculations are possible.

At $\mathcal{O}(\alpha_s^3)$, up to 4 partons can be in the same jet (not possible in the Breit frame)





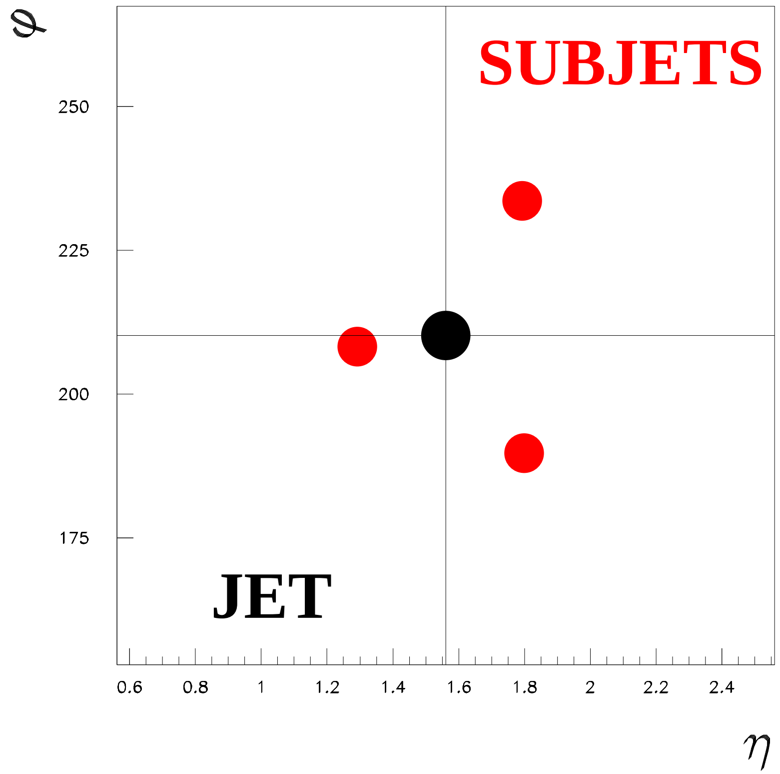
Measurements of Three-Subjet Distributions in NC DIS

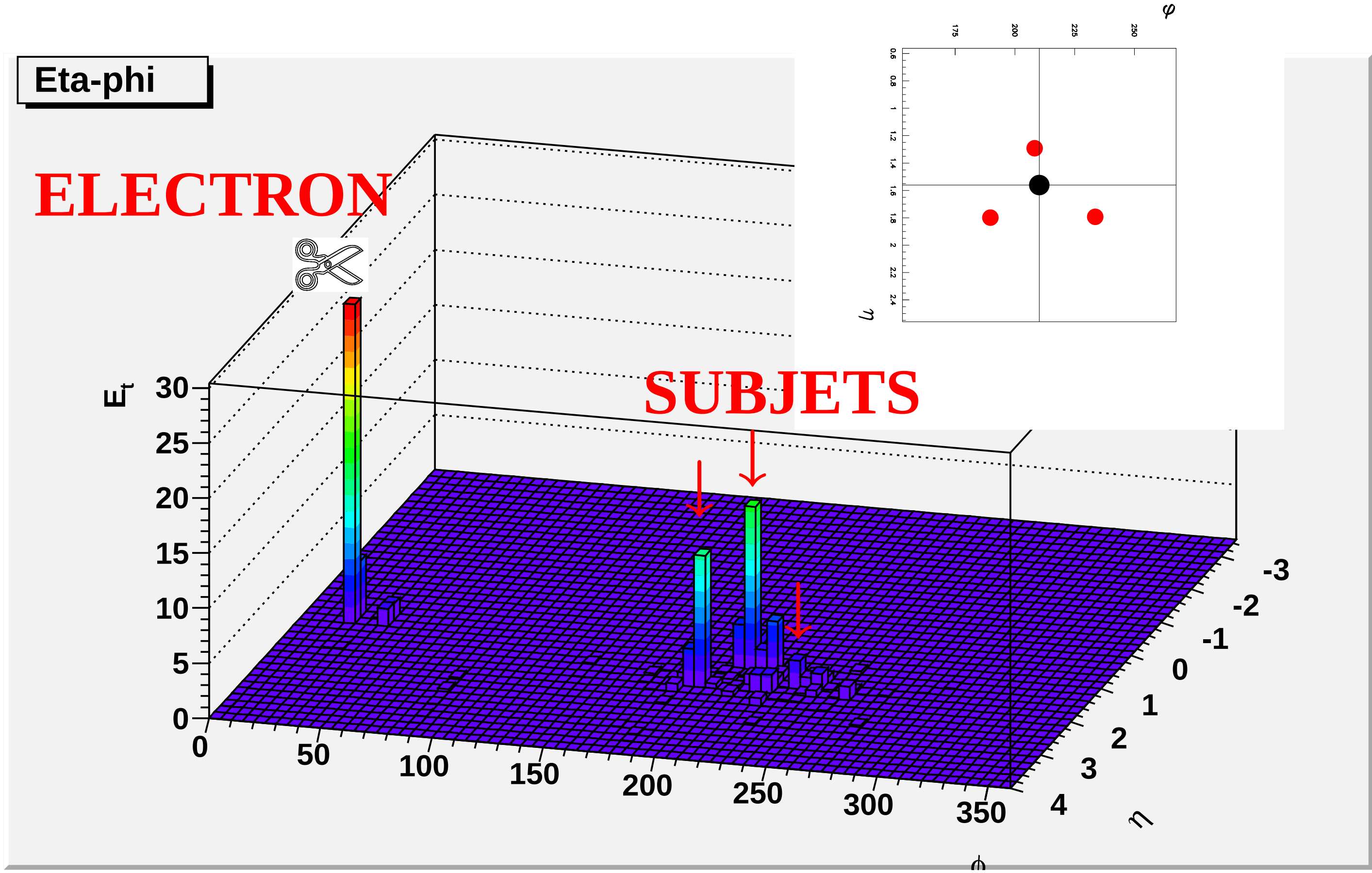
- **Measurements of the normalised cross sections in NC DIS for $Q^2 > 125$ GeV^2:**

$\longrightarrow$ **Jets with $E_T^{jet} > 14$ GeV and $-1 < \eta^{jet} < 2.5$**

$\longrightarrow$ **Selected sample of jets: jets with exactly THREE subjets at $y_{cut} = 0.01$**

$\longrightarrow$ **$\mathcal{L} = 299$ pb^{-1} $\Rightarrow$ 80 000 jets**





Three-Subjet Distributions in NC DIS

- **Subjets are reconstructed using the ZEUS calorimeter with resolutions:**

  $\sigma(E_T^{sbj}/E_T^{jet}) \approx 0.1$, $\sigma(\eta^{sbj} - \eta^{jet}) \approx 0.1$ and $\sigma(|\phi^{sbj} - \phi^{jet}|) \approx 0.12$

  $\sigma(\beta^{sbj}) \approx 0.16$ and $\sigma(\eta_{low}^{sbj} - \eta^{jet}) \approx 0.10$ for $(E_{T,mid}^{sbj} - E_{T,low}^{sbj})/E_T^{jet} > 0.2$

  $\sigma(\alpha_{23}) \approx 0.29$ and $\sigma(\gamma) \approx 0.33$ for $(E_{T,high}^{sbj} - E_{T,mid}^{sbj})/E_T^{jet} > 0.2$

- **Experimental uncertainties (below 10%):**

$\longrightarrow$ **modelling of the parton shower in the simulation of the hadronic final state**

$\longrightarrow$ **calorimeter response to low-energy particles**

- **Comparison to LO ($\mathcal{O}(\alpha_s^2)$) and NLO ($\mathcal{O}(\alpha_s^3)$) QCD calculations using the program NLOJET++ (Z. Nagy and Z. Trocsanyi, Phys.Rev.Lett. 87 (2001) 082001)**

$\longrightarrow$ **ZEUS-S set of proton PDFs; $\alpha_s(M_Z) = 0.118$**

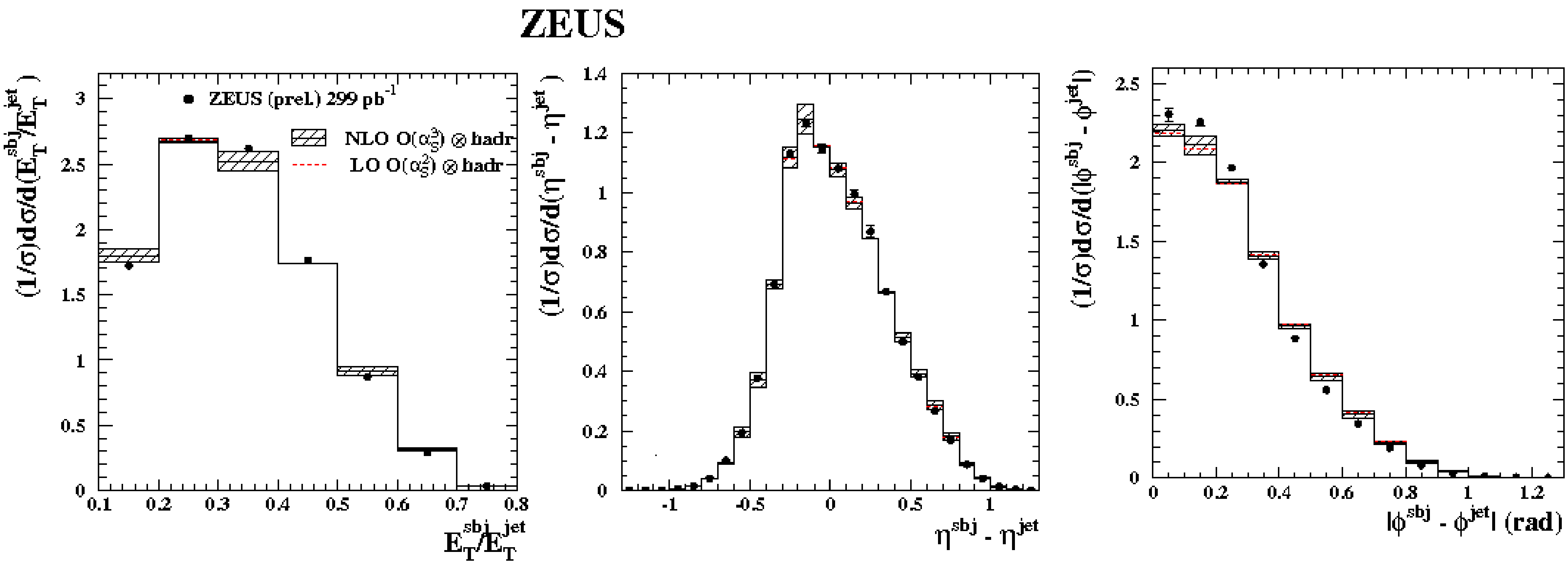
$\longrightarrow$ **renormalisation and factorisation scales, $\mu_R = \mu_F = Q$**

$\longrightarrow$ **corrected for hadronisation effects (change in shape typically below $\pm 20\%$)**

$\longrightarrow$ **theoretical uncertainties dominated by hadronisation correction (below 10%)**

Measurements of Three-Subjet Distributions in NC DIS

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

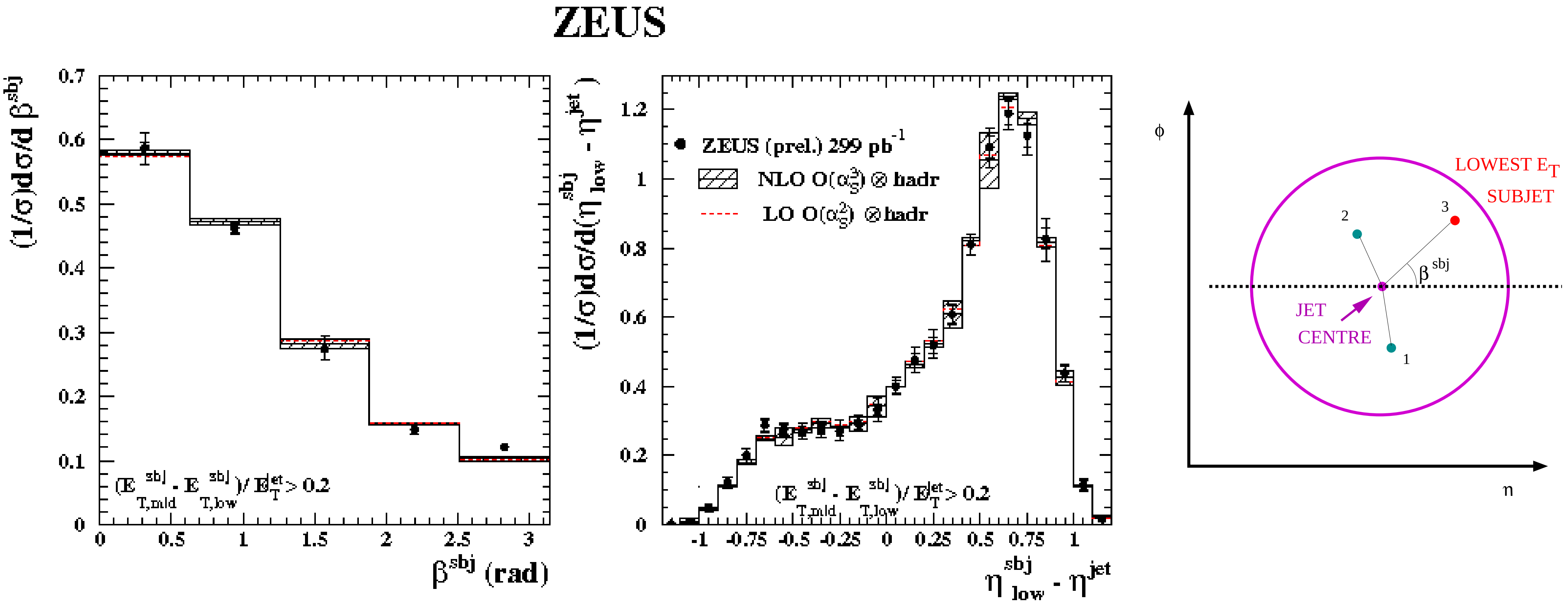


→ Good description of the measured distributions in E_T^{sbj}/E_T^{jet} and $\eta^{sbj} - \eta^{jet}$ by NLO

→ Reasonable description of the measured distribution in $|\phi^{sbj} - \phi^{jet}|$ by NLO

Measurements of Three-Subjet Distributions in NC DIS

- **Measurements of the normalised cross sections for three-subjet production as functions of β^{sbj} and $\eta^{sbj}_{low} - \eta^{jet}$ vs LO and NLO QCD calculations**
  - **→ Additional cut to "separate" lowest-E_T subjet: $(E^{sbj}_{T,mid} - E^{sbj}_{T,low})/E^{jet}_T > 0.2$**

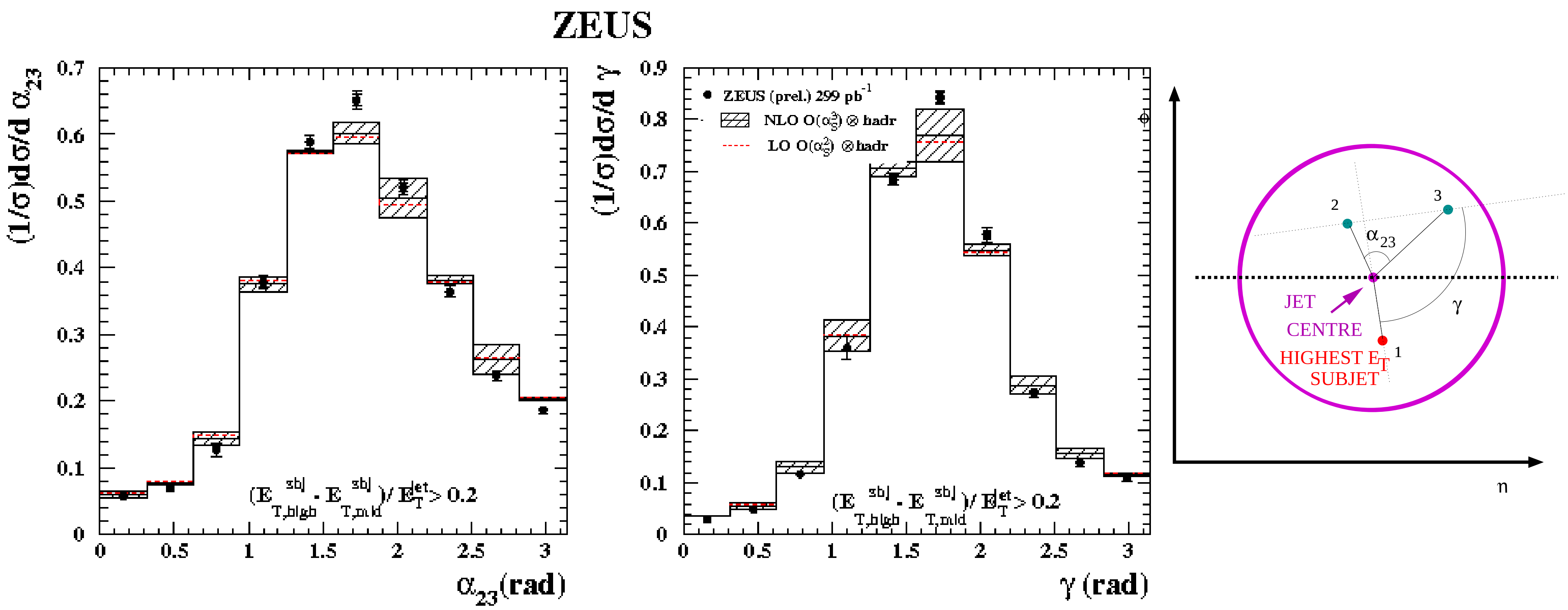


→ Good description of the measured distributions by NLO QCD

Measurements of Three-Subjet Distributions in NC DIS

- Measurements of the normalised cross sections for three-subjet production as functions of α_{23} and γ vs LO and NLO QCD calculations

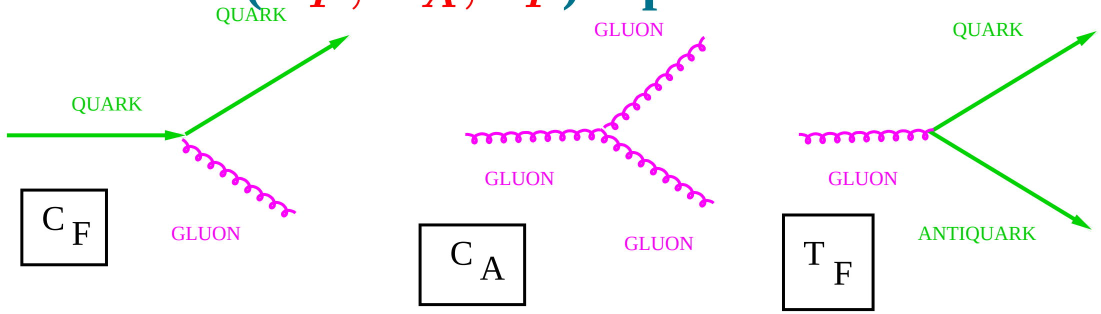
  → Additional cut to "separate" highest-E_T subjet: $(E^{sbj}_{T,high} - E^{sbj}_{T,mid})/E^{jet}_T > 0.2$



→ Reasonable description of the measured distributions by NLO QCD

Three-Subjet Distributions in NC DIS: colour factors

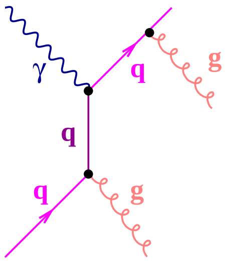
- The color factors (C_F, C_A, T_F) represent the relative strength of the processes



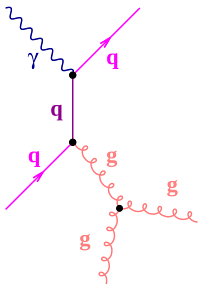
- Their values are predicted by the underlying gauge-group structure
  $\rightarrow$ for $SU(N)$: $C_F = (N^2 - 1)/2N, C_A = N, T_F = 1/2$
- Predicted cross section at $\mathcal{O}(\alpha_s^2)$ for three-subjet production

$$\sigma_{ep\rightarrow 3\,\text{subjets}} = C_F^2 \cdot \sigma_A + C_F C_A \cdot \sigma_B + C_F T_F \cdot \sigma_C + T_F C_A \cdot \sigma_D$$

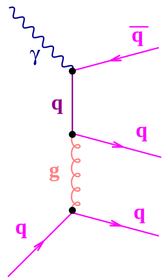
C_F^2



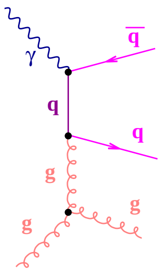
$C_F \cdot C_A$



$C_F \cdot T_F$



$T_F \cdot C_A$

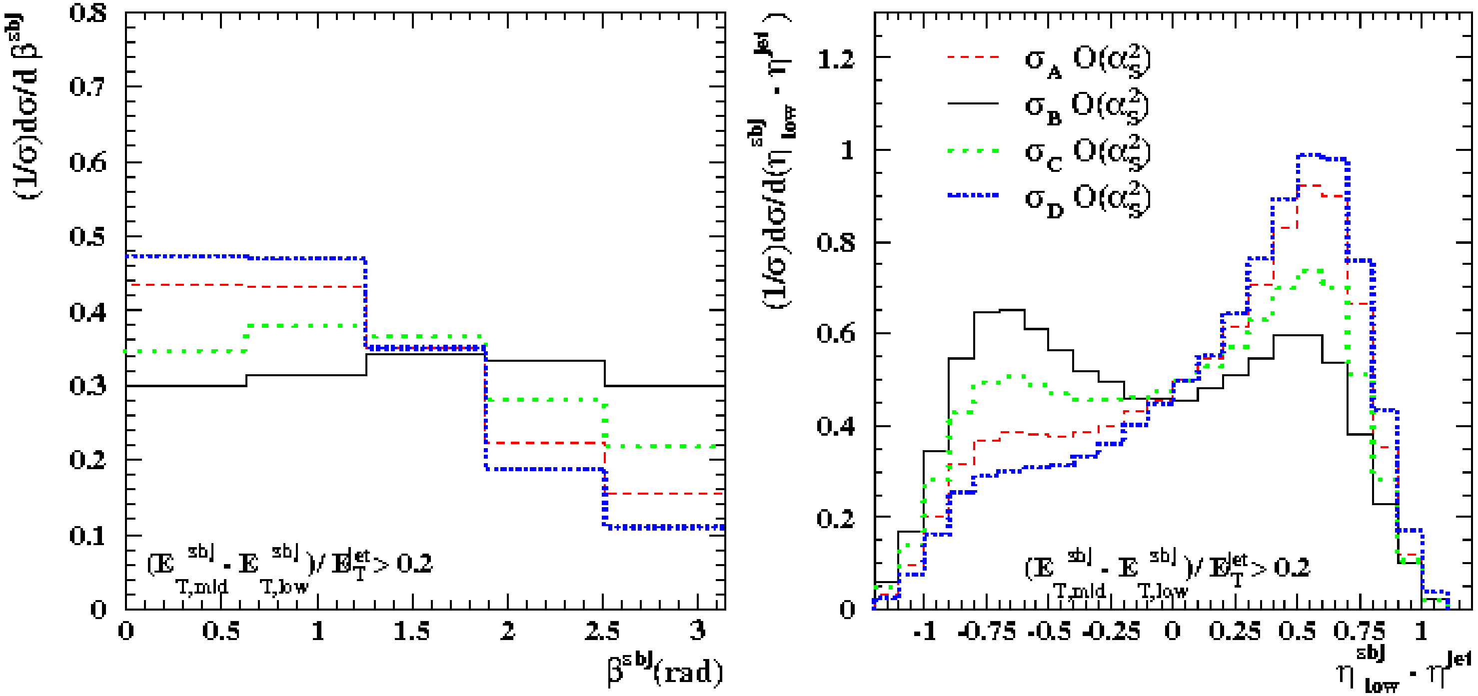


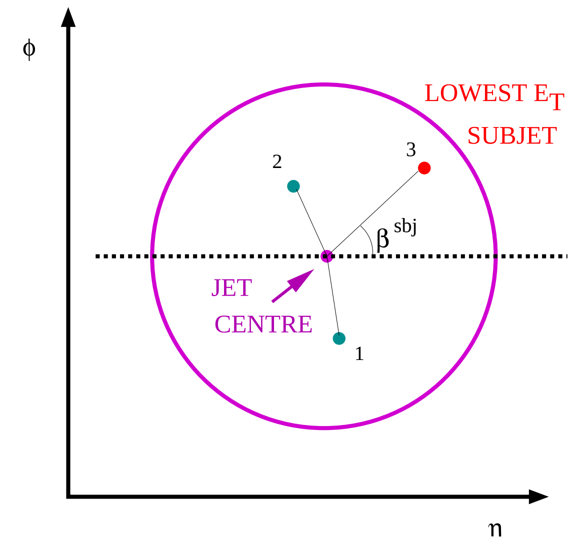
- Since the couplings qqg and ggg have different spin structures, the color factors give rise to **a specific pattern of angular correlations between the subjets**

Predictions of Three-Subjet Distributions in NC DIS

- **Predictions of the normalised cross sections for three-subjet production as functions of β^{sbj} and $\eta^{sbj}_{low} - \eta^{jet}$ at LO for different colour configurations**

ZEUS





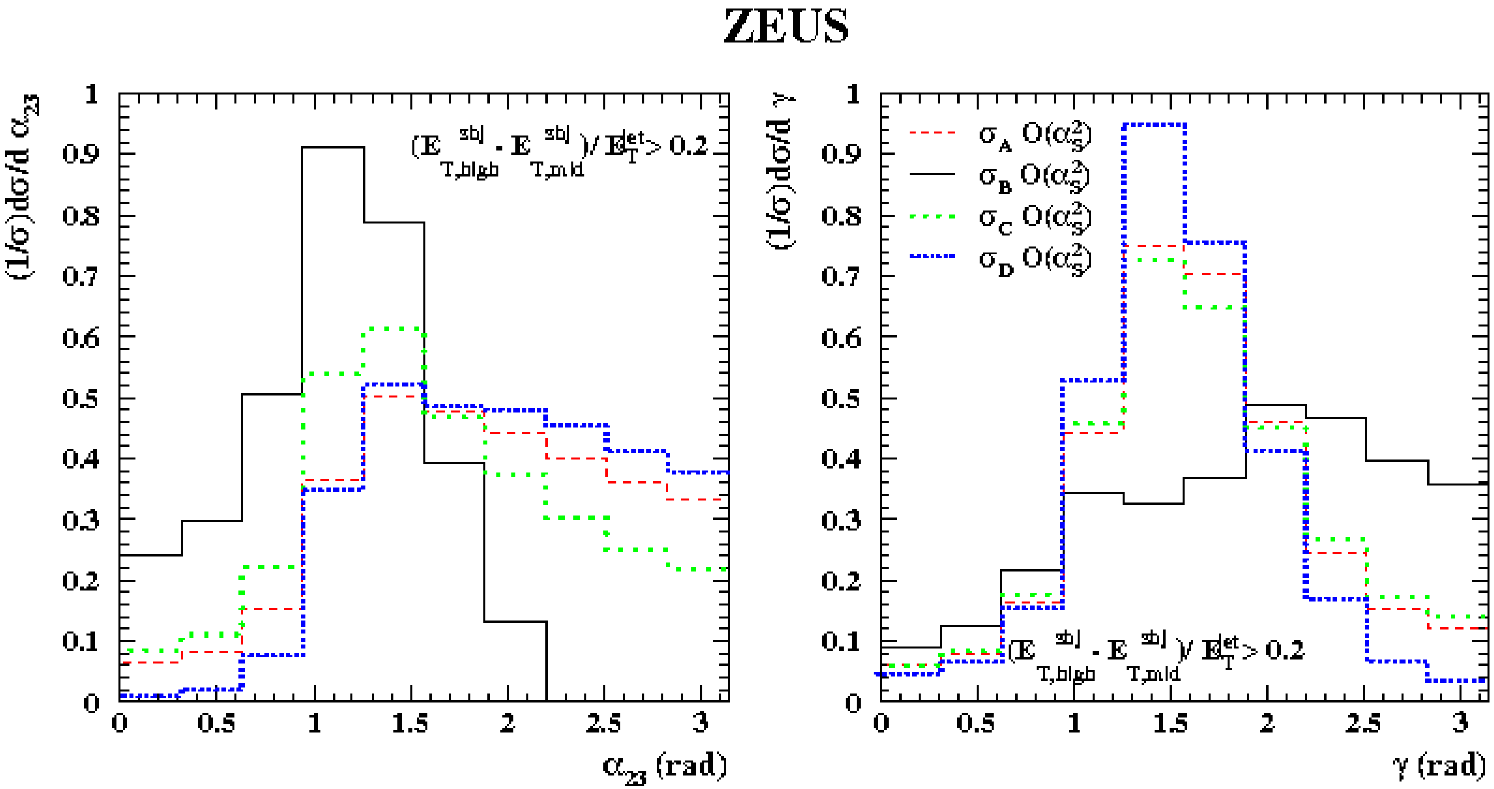
→ **The four colour configurations exhibit different behaviour in the distributions**

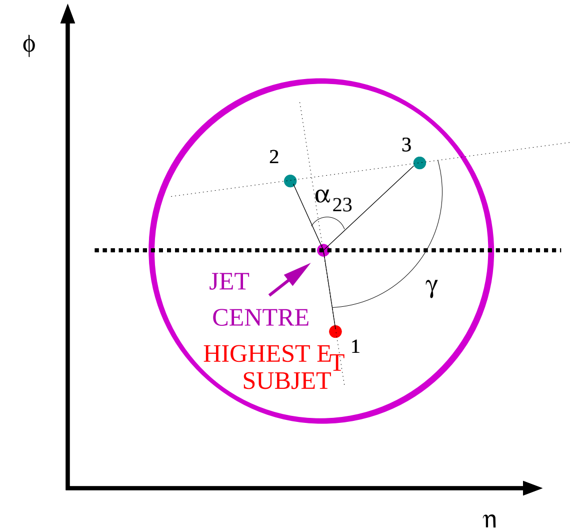
→ **Relative contributions predicted by SU(3):**

A(C_F^2): 54-57%, B($C_F C_A$): 14-15%, C($C_F T_F$): 21-23%, D($T_F C_A$): 8-9%

Predictions of Three-Subjet Distributions in NC DIS

- **Predictions of the normalised cross sections for three-subjet production as functions of α_{23} and γ at LO for different colour configurations**





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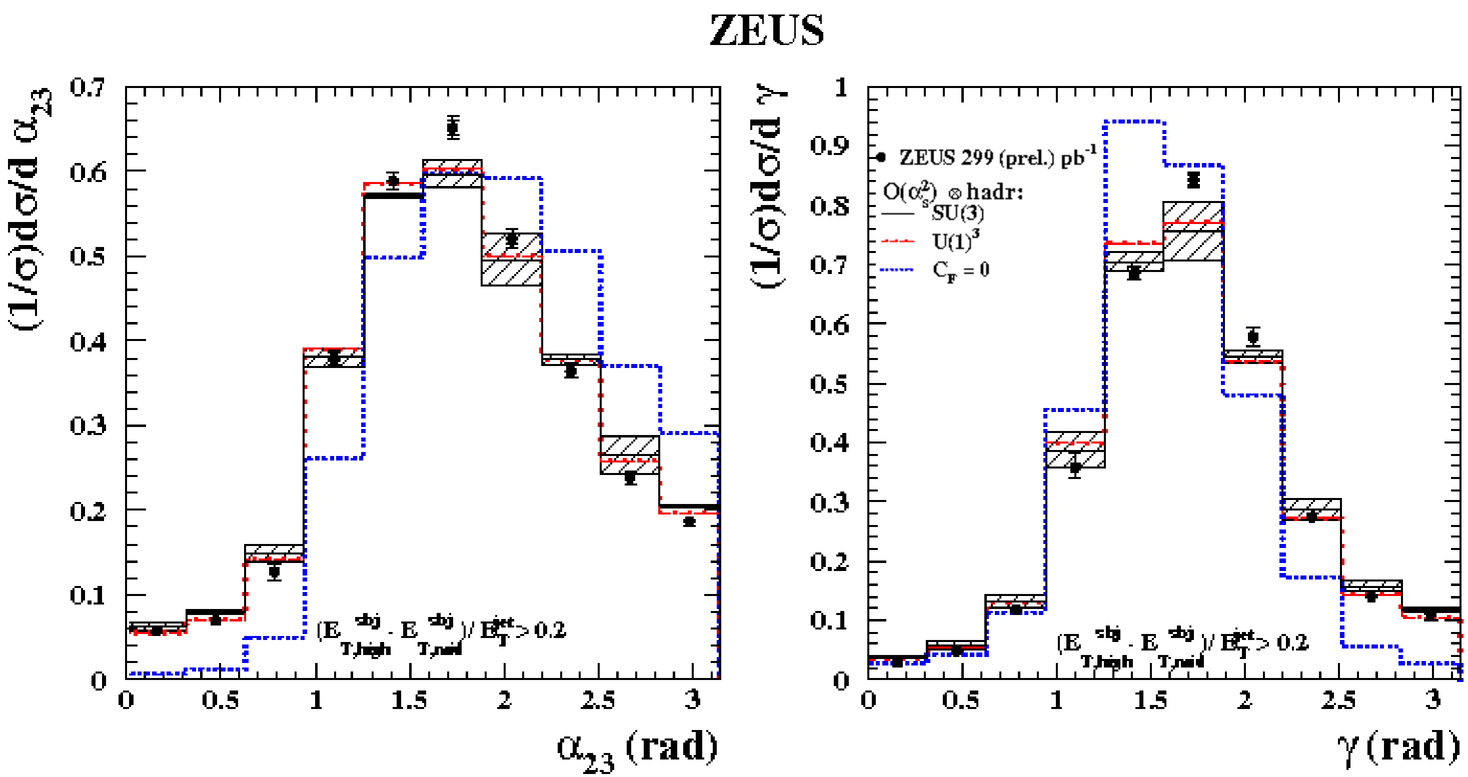
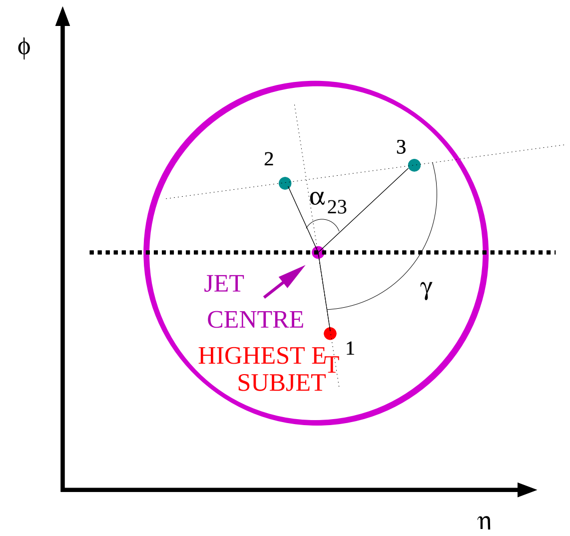
Measurements of Three-Subjet Distributions in NC DIS

- Measurements of the normalised cross sections for three-subjet production as functions of α_{23} and γ vs LO calculations assuming different gauge symmetry groups





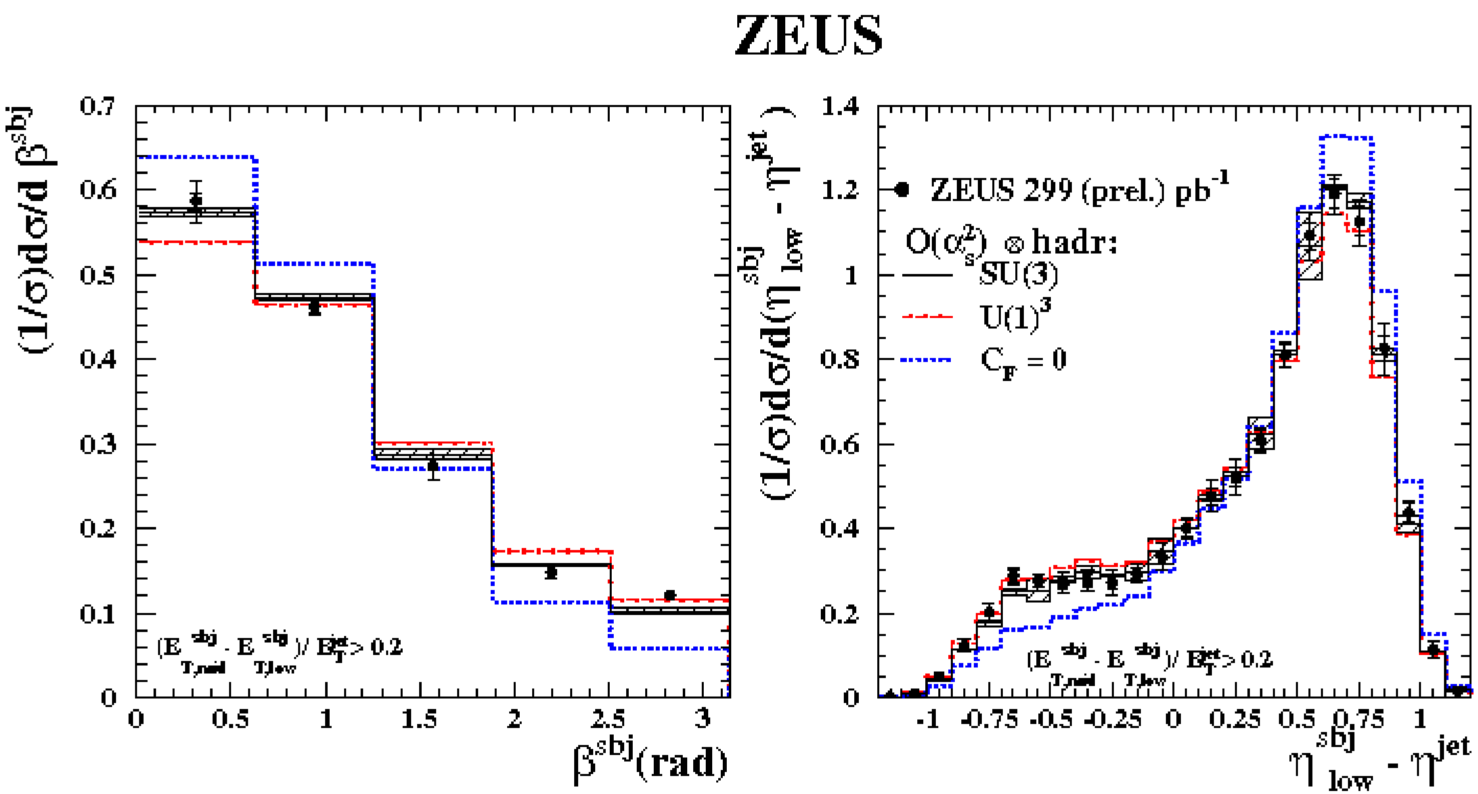
$\longrightarrow$ The data disfavours the predictions based on $C_F = 0$

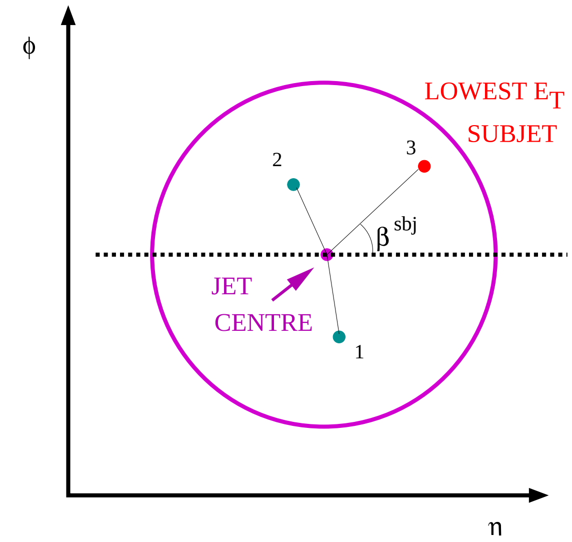
$\longrightarrow$ U(1)^3 vs SU(3): similar shapes due to smallness of σ_B and σ_D

$\longrightarrow$ The predictions of SU(3) describe reasonably well the data

Measurements of Three-Subjet Distributions in NC DIS

- Measurements of the normalised cross sections for three-subjet production as functions of β^{sbj} and $\eta^{sbj}_{low} - \eta^{jet}$ vs LO calculations assuming different gauge symmetry groups





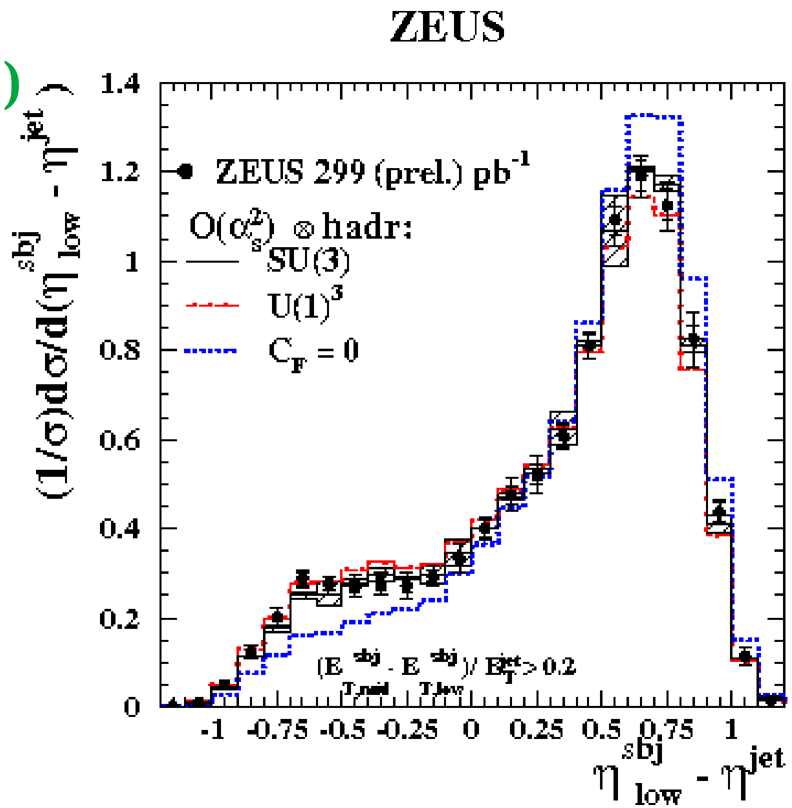
→ The data disfavours the predictions based on $C_F = 0$

→ U(1)^3 vs SU(3): some differences are observed in the β^{sbj} distribution

→ The predictions of SU(3) describe reasonably well the data

Summary

- Measurements of the normalised cross sections of **three-subjet production** in NC DIS ($Q^2 > 125$ GeV^2) for jets with $E_T^{jet} > 14$ GeV using $\mathcal{L} = 299$ pb^{-1}



$\longrightarrow$ the **pattern of QCD radiation** as implemented in the NLO calculations reproduces the measured **subjet distributions**

$\longrightarrow$ the subjet distributions are **sensitive to the colour configurations** and are found to be consistent with the predictions of SU(3)