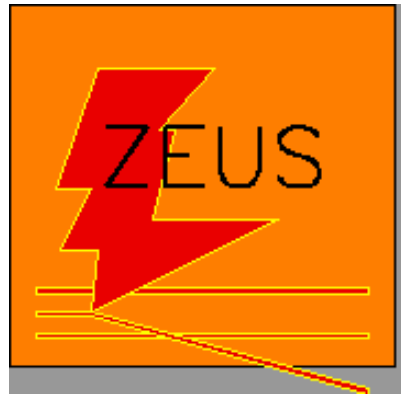


Three-subjet distributions in NC DIS

Juan Terrón (Universidad Autónoma de Madrid, Spain)



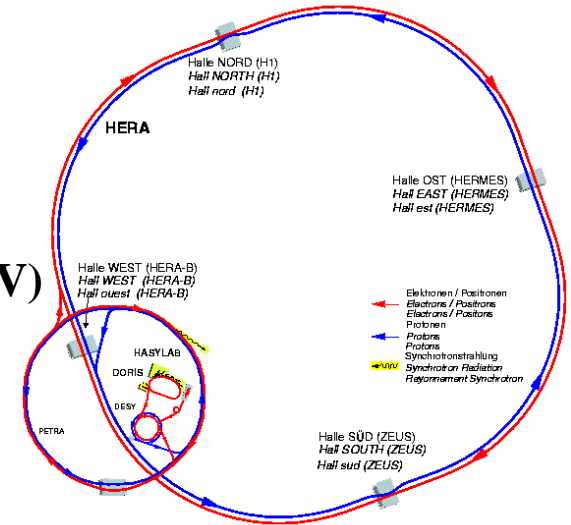
ZEUS Collaboration

e ($E_e = 27.5$ GeV)

p ($E_p = 920$ GeV)

$\sqrt{s} = 318$ GeV

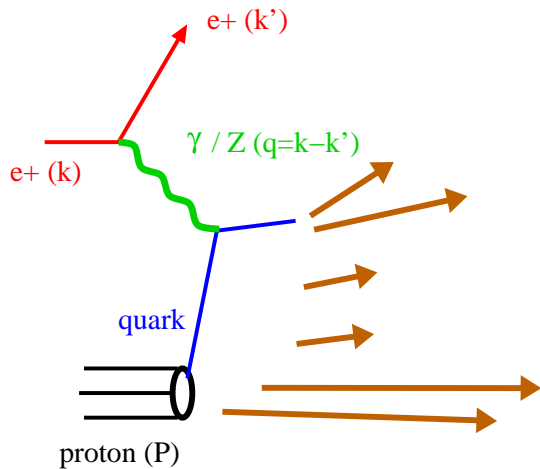
HERA



⇒ 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

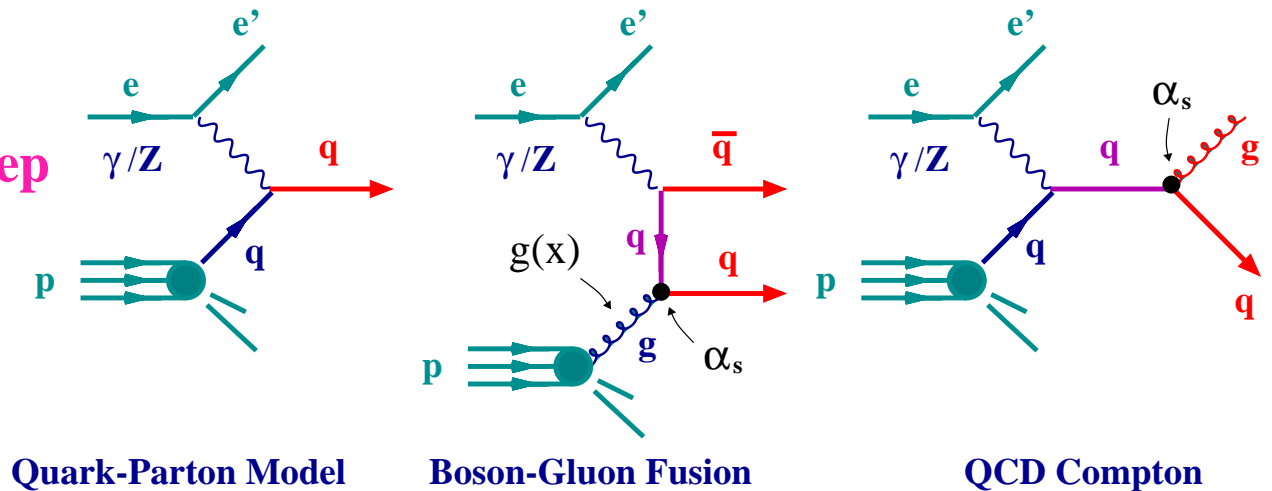


For a given ep centre-of-mass energy, \sqrt{s} , the fully inclusive cross section for $ep \rightarrow e + X$ can be described by two independent kinematic variables, e.g.

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

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

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 between clusters is above

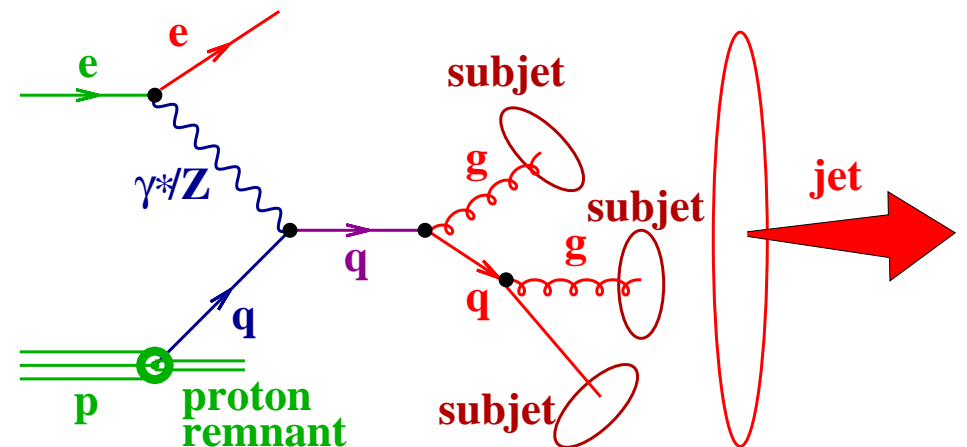
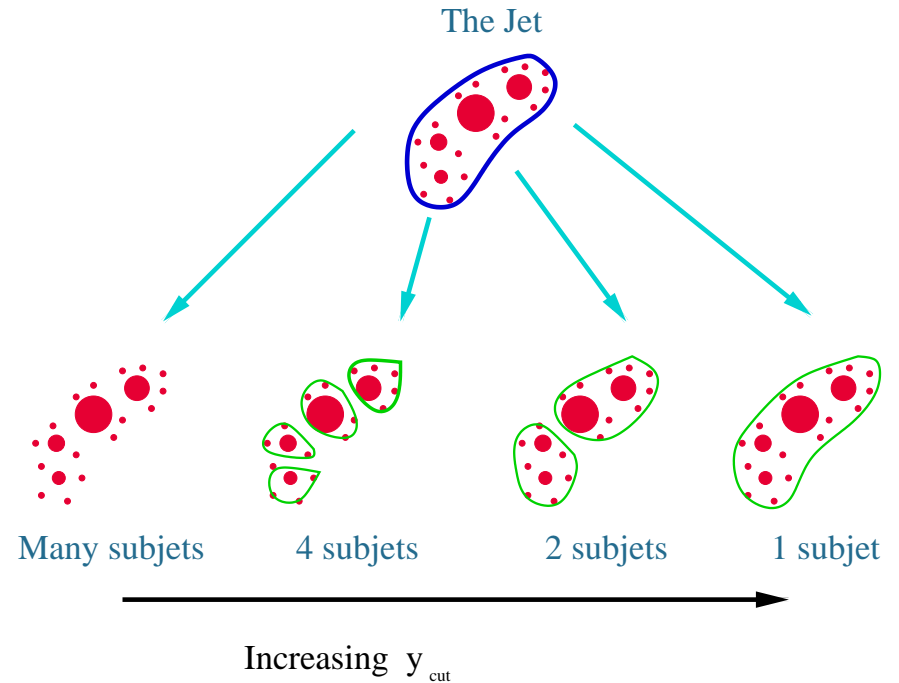
$$d_{cut} = y_{cut} \cdot (E_T^{jet})^2$$

→ all remaining clusters are called **subjets**

→ the **subjett multiplicity depends upon the resolution parameter y_{cut}**

- At sufficiently **high E_T^{jet}** , where fragmentation effects become negligible, **the subjett 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

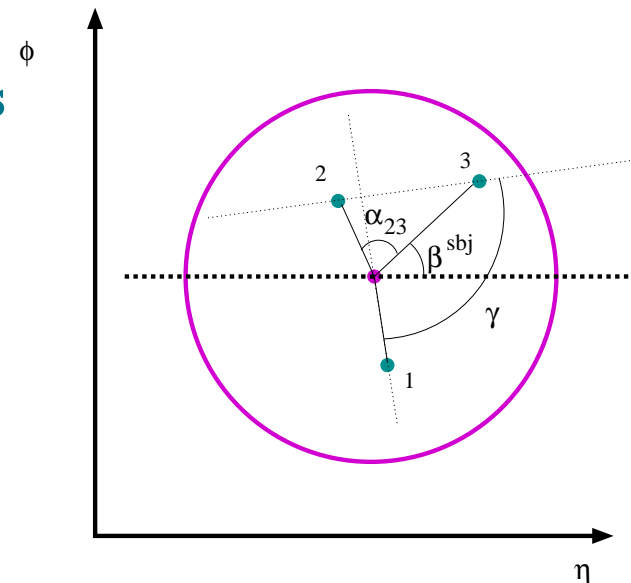
$$E_T^{sbj} / E_T^{jet} , \quad \eta^{sbj} - \eta^{jet} , \quad |\phi^{sbj} - \phi^{jet}|$$

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

→ β^{sbj} , the angle, as viewed from the jet centre, between the subjet with lowest E_T and the proton beam direction

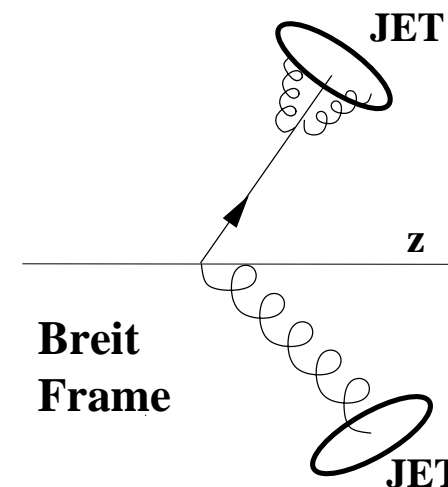
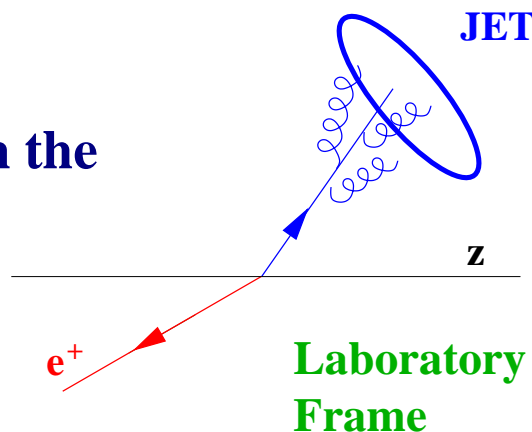
→ α_{23} , the angle between the two lowest- E_T subjets as seen from the jet centre

→ γ



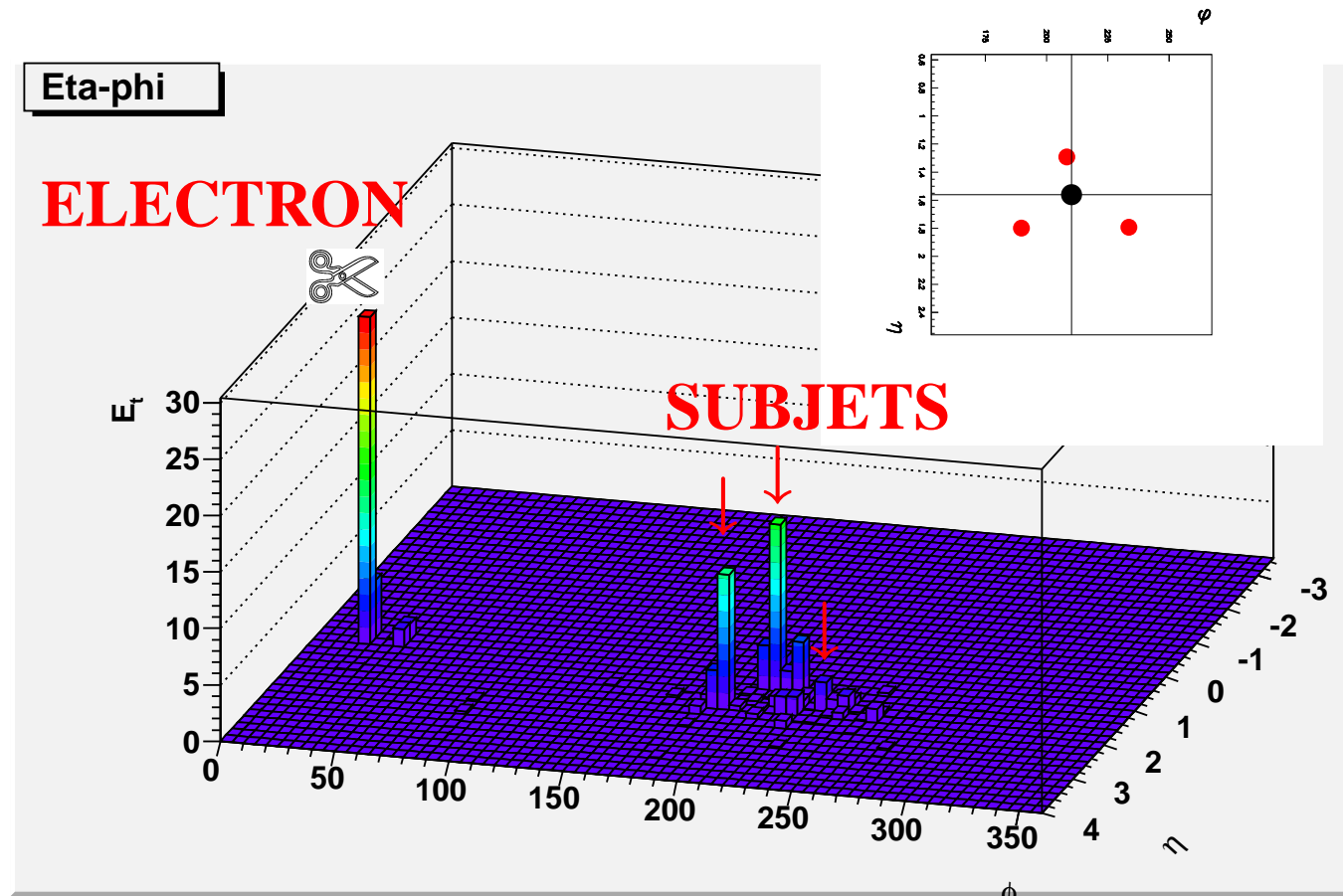
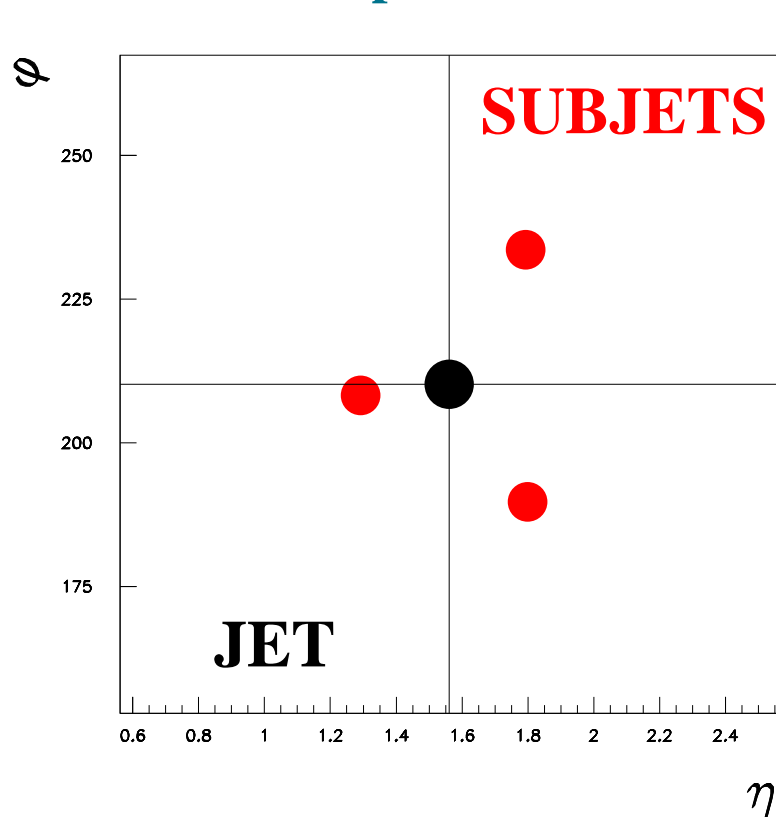
- Jets (and subjets) are reconstructed in the laboratory frame since NLO QCD calculations are possible.

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 $Q^2 > 125 \text{ GeV}^2$:
 - Jets with $E_T^{jet} > 14 \text{ GeV}$ and $-1 < \eta^{jet} < 2.5$
 - Selected sample of jets: jets with **exactly THREE** subjets at $y_{cut} = 0.01$
 - $\mathcal{L} = 299 \text{ pb}^{-1} \Rightarrow 80\,000 \text{ jets}$



Three-Subjet Distributions in NC DIS

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

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

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

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

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

- modelling of the parton shower in the simulation of the hadronic final state
- calorimeter response to low-energy particles

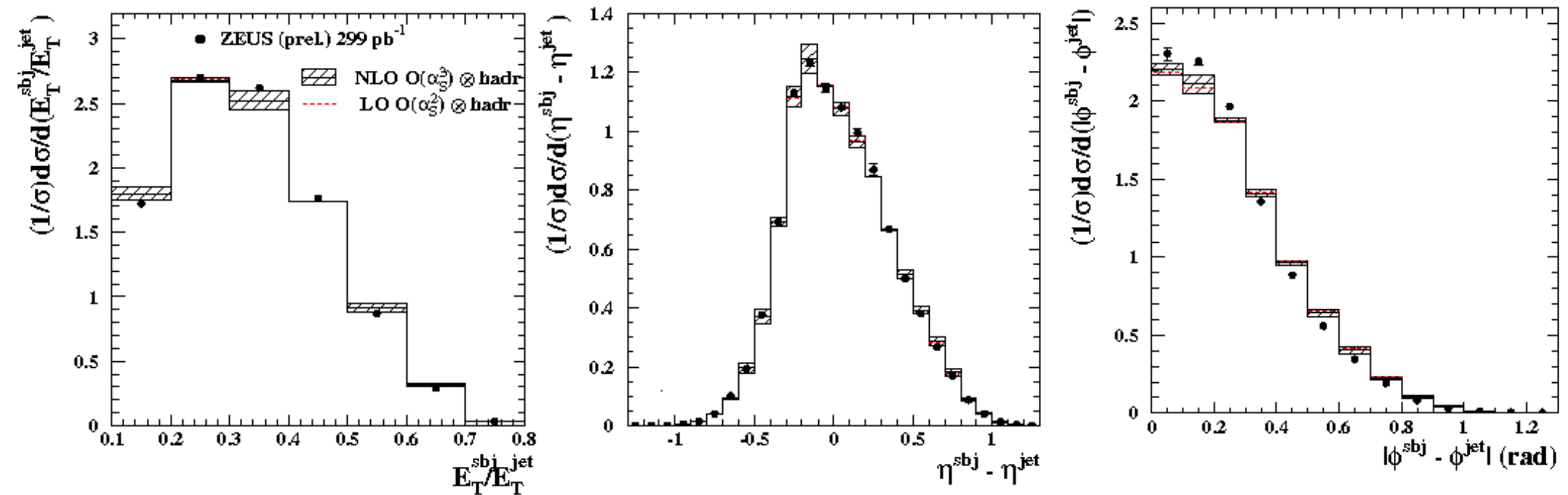
- **Comparison to LO ($\mathcal{O}(\alpha_s^2)$) and NLO ($\mathcal{O}(\alpha_s^3)$) QCD calculations using the program NLOJET++ (Z. Nagy and Z. Trocsanyi, Phys.Rev.Lett. 87 (2001) 082001)**

- ZEUS-S set of proton PDFs; $\alpha_s(M_Z) = 0.118$
- renormalisation and factorisation scales, $\mu_R = \mu_F = Q$
- corrected for hadronisation effects (change in shape typically below $\pm 20\%$)
- 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

ZEUS



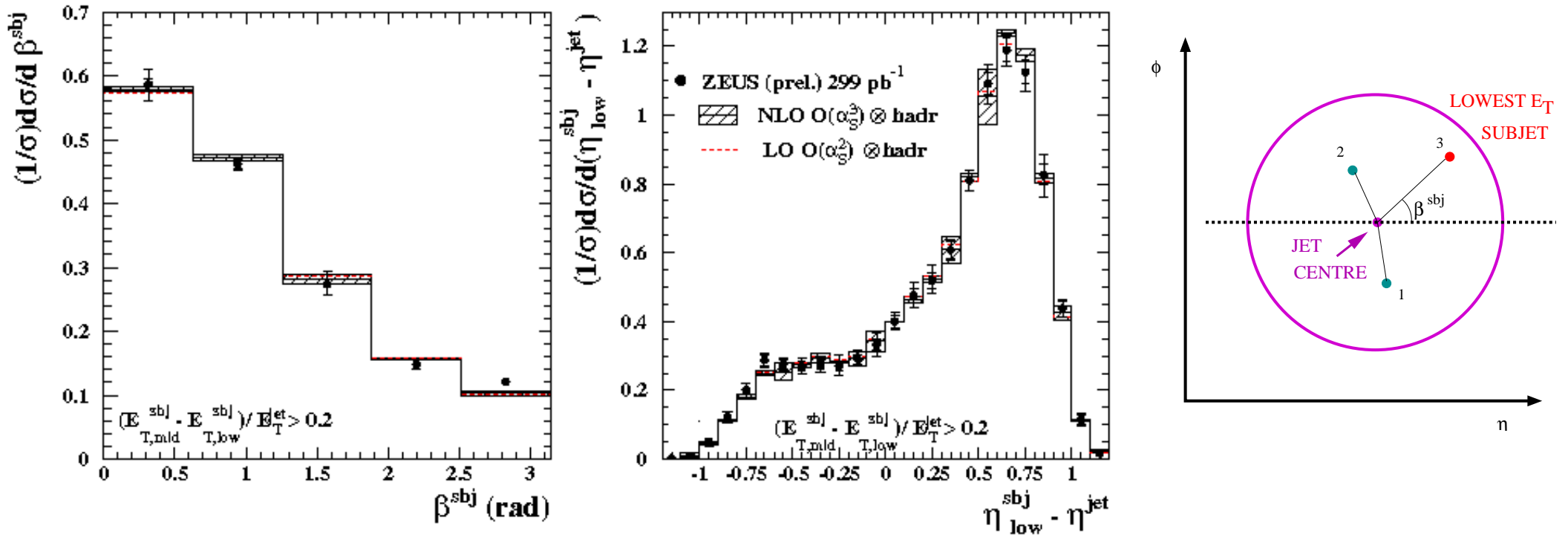
→ Good description of the measured distributions in E_T^{sbj} / E_T^{jet} and $\eta^{sbj} - \eta^{jet}$ by NLO

→ 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 $\eta_{low}^{sbj} - \eta^{jet}$ vs LO and NLO QCD calculations
 - Additional cut to “separate” lowest- E_T subjet: $(E_{T,mid}^{sbj} - E_{T,low}^{sbj})/E_T^{jet} > 0.2$

ZEUS

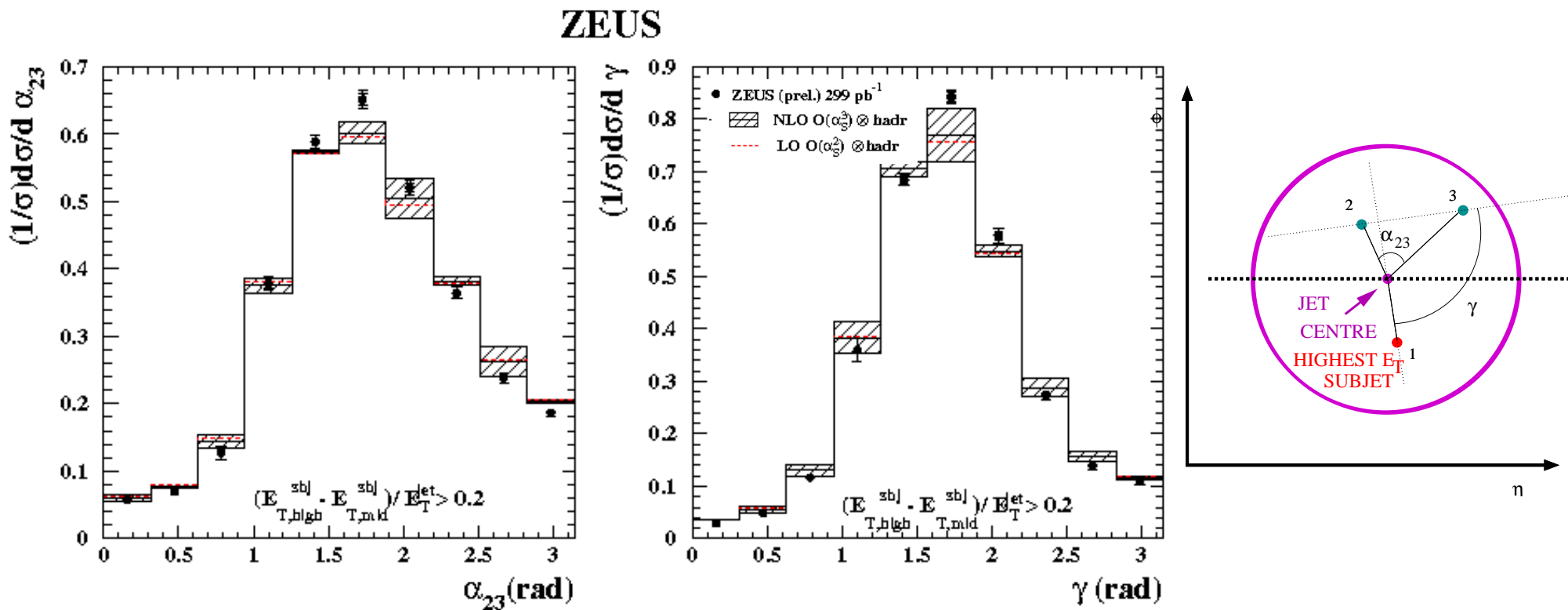


→ Good description of the measured distributions by NLO QCD

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

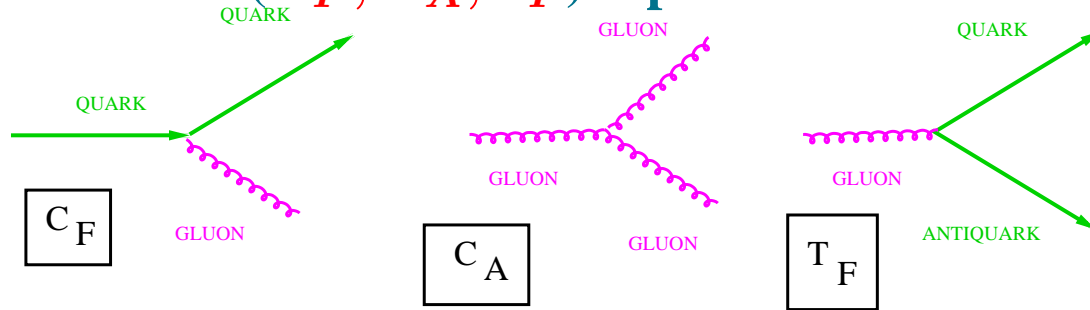
→ Additional cut to “separate” highest- E_T subjet: $(E_{T,high}^{sbj} - E_{T,mid}^{sbj}) / E_T^{jet} > 0.2$



→ 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

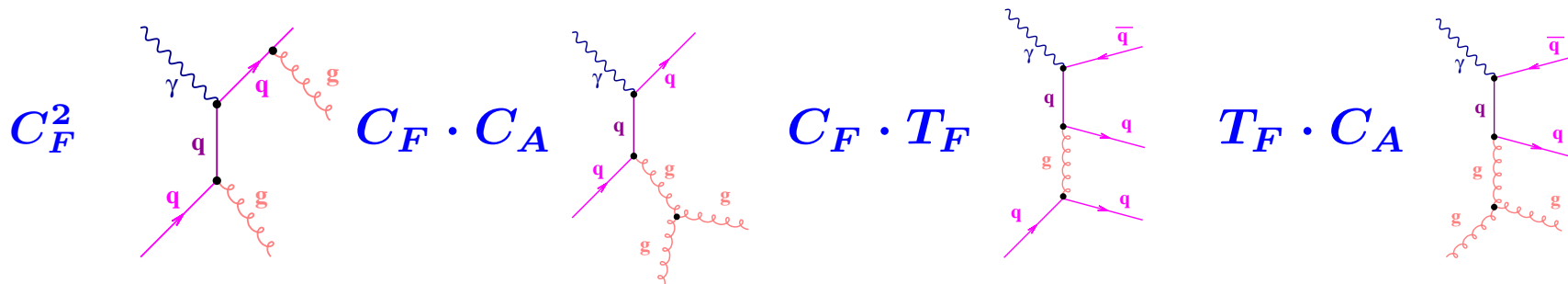


- Their values are predicted by the underlying gauge-group structure

→ 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

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

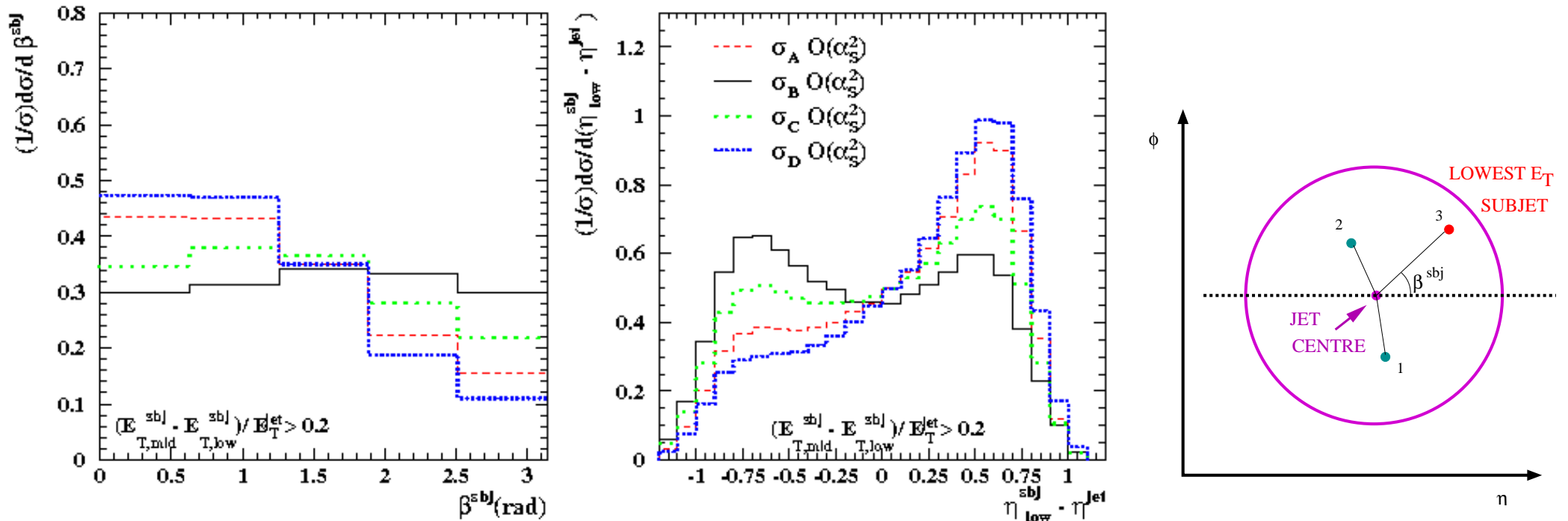


- Since the couplings qqg and ggg have different spin structures, the color factors give rise to a specific pattern of angular correlations between the subjets

Predictions of Three-Subjet Distributions in NC DIS

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

ZEUS



→ The four colour configurations exhibit different behaviour in the distributions

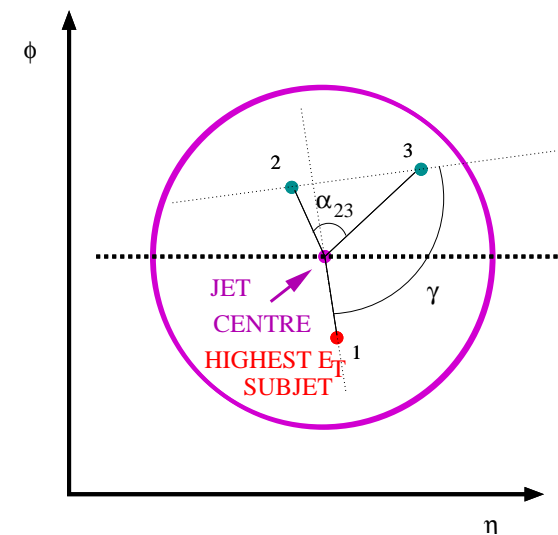
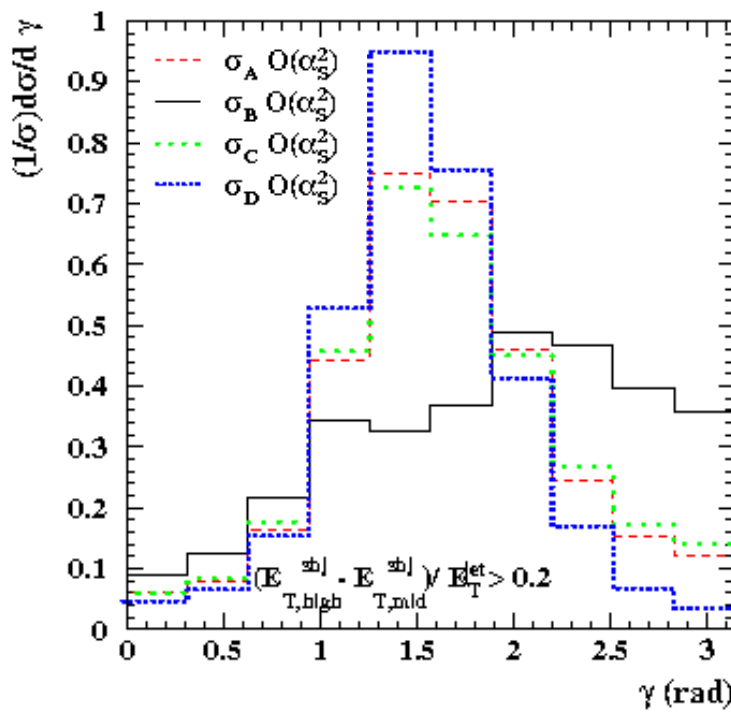
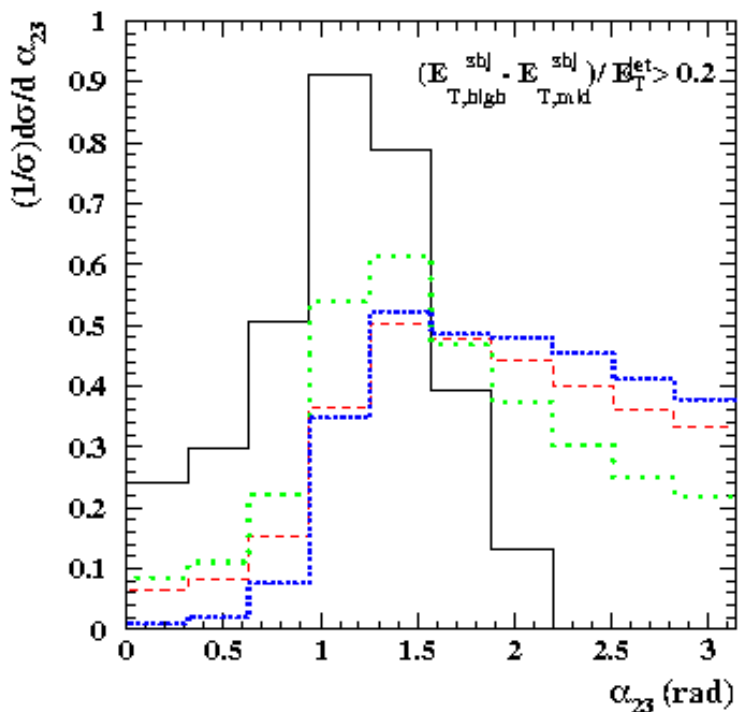
→ Relative contributions predicted by SU(3):

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

ZEUS



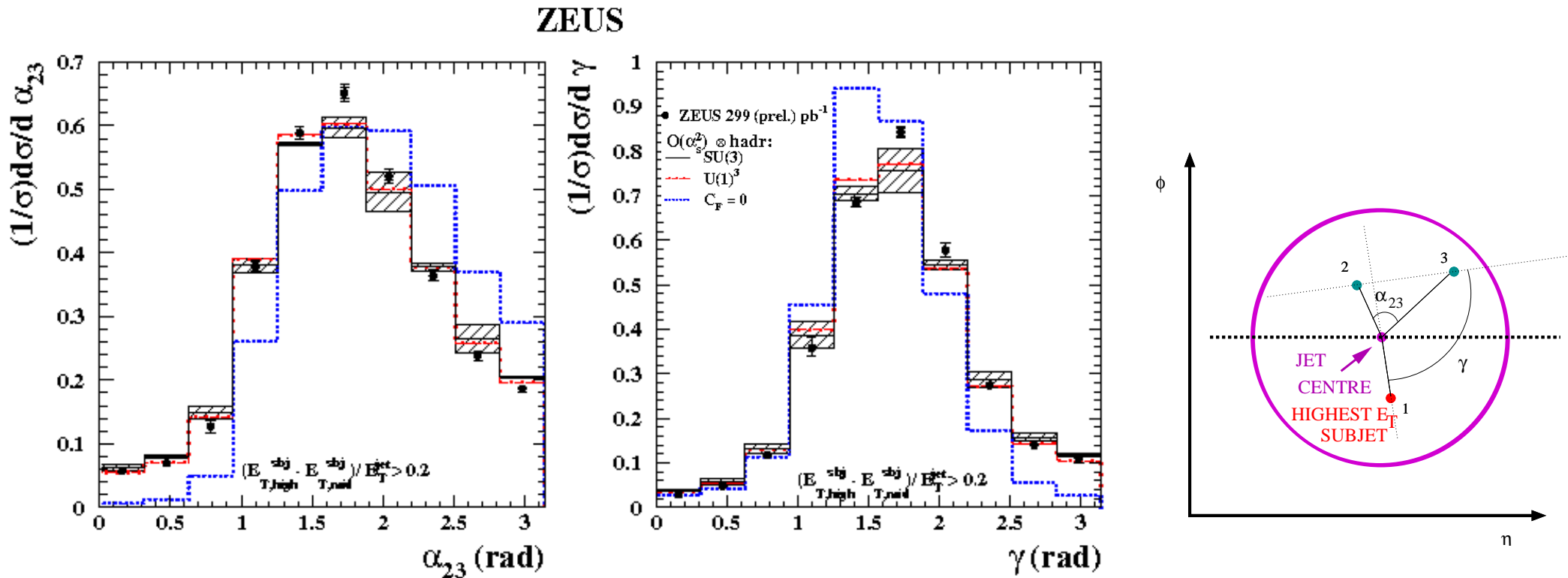
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Measurements of Three-Subjet Distributions in NC DIS

- 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

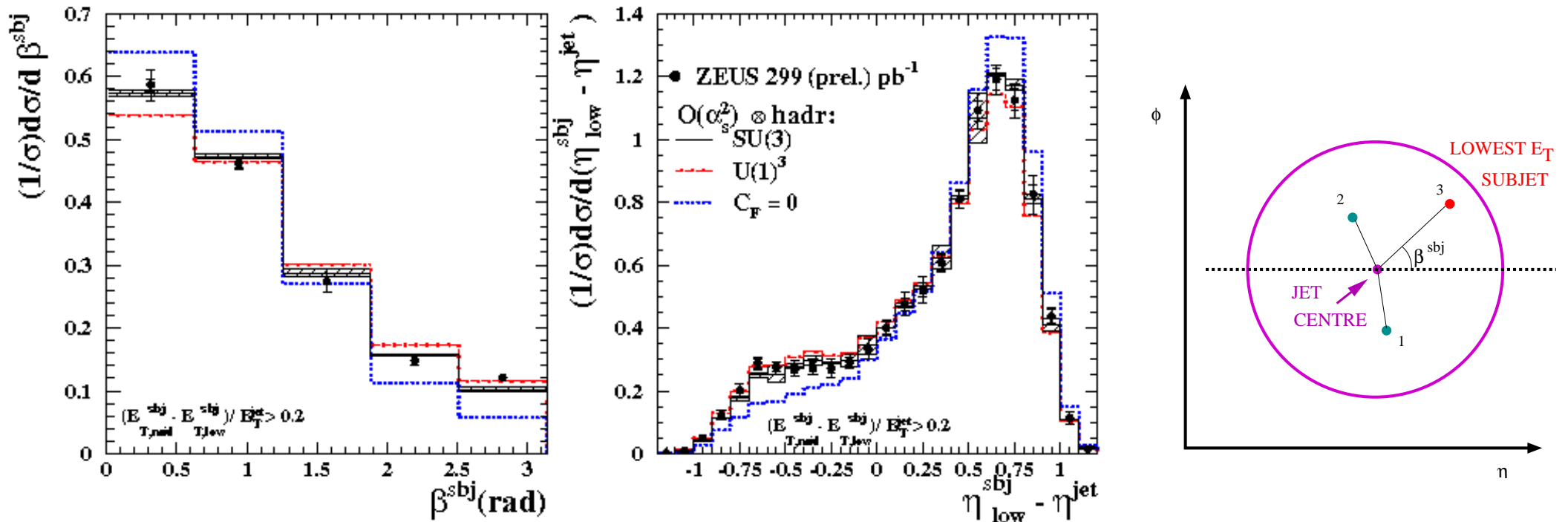


- The data disfavours the predictions based on $C_F = 0$
- U(1)³ vs SU(3): similar shapes due to smallness of σ_B and σ_D
- The predictions of SU(3) describe reasonably well the data

Measurements of Three-Subjet Distributions in NC DIS

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

ZEUS



- The data disfavors 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 ($Q^2 > 125 \text{ GeV}^2$) for jets with $E_T^{jet} > 14 \text{ GeV}$ using $\mathcal{L} = 299 \text{ pb}^{-1}$

→ the **pattern of QCD radiation** as implemented in the NLO calculations reproduces the measured **subject distributions**

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

