HEP 2009

2009 Europhysics Conference on High Energy Physics

July 16 - 22, 2009

Krakow, Poland

Jets and subjets at HERA

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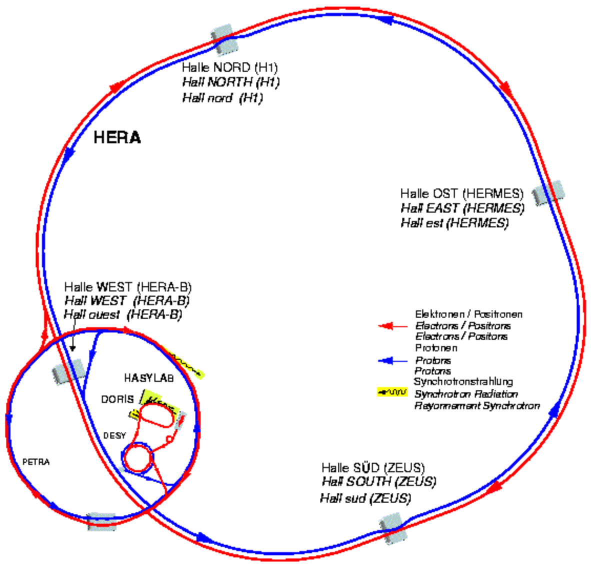
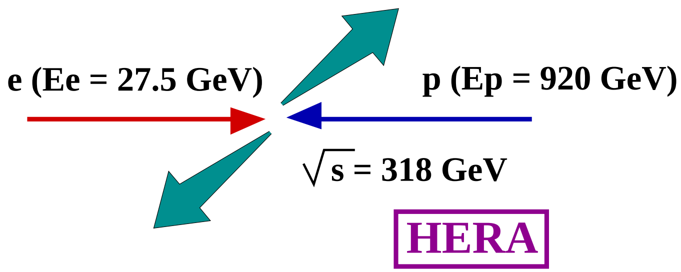
from

ZEUS Collaboration



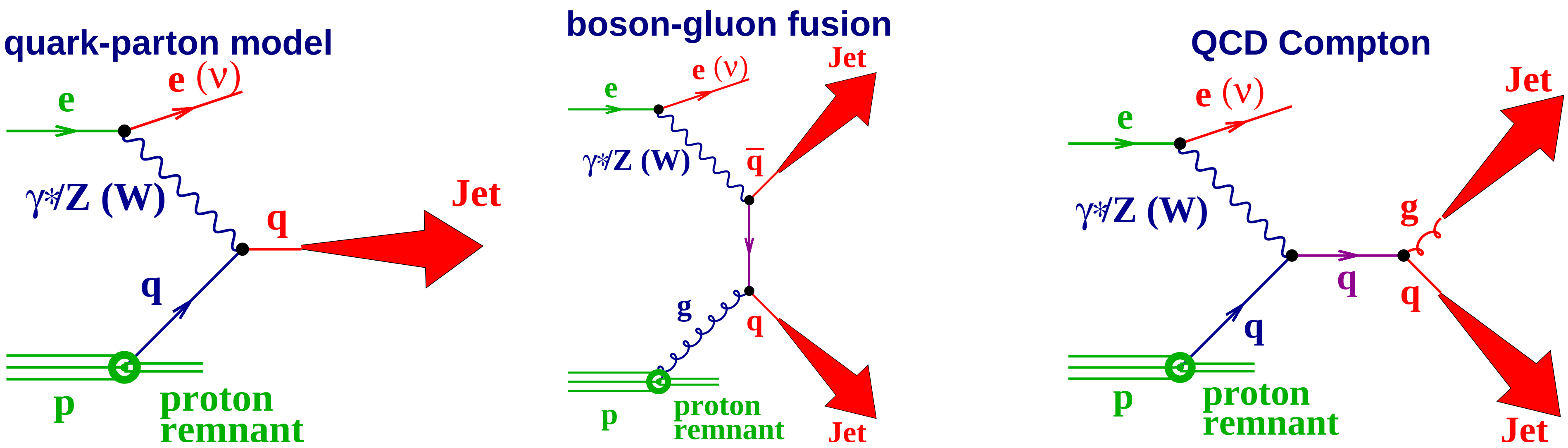


Jets and subjets at HERA

- Jet production and jet substructure has been extensively studied at HERA
- Jet cross sections have proven to be a powerful tool
  - → to test pQCD and the SM
    - → Multi-jet cross sections in CC DIS (ZEUS Collab, PRD 78 (2008) 032004)
  - → to constrain the gluon pPDFs
    - → see Juan Terrón's talk
  - → to determine α_s
    - → see Joerg Behr's talk
  - → to test the underlying colour dynamics
    - → Angular correlations in three-jet events (ZEUS Collab, DESY-08-100)
- Jet substructure has been proven to be a powerful tool
  - → to test the pattern of parton radiation
  - → to test splitting functions
  - → to study colour-coherence effects
  - → to test underlying colour dynamics
    - → Subjet distributions in DIS (ZEUS Collab, DESY-08-178)
    - → Three-subjet distributions in DIS (ZEUS Collab, ZEUS-prel-09-007)

Jet production in DIS at HERA

- Jet production in NC and CC deep inelastic ep scattering up to $\mathcal{O}(\alpha_s)$:



- Jet production cross section for DIS is given in QCD by:

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

Kinematics:

- momentum transfer: $Q^2 = -q^2 = -(k-k')^2$
- Bjorken x: $x = \frac{Q^2}{2P\cdot q}$
- inelasticity: $y = \frac{P\cdot q}{P\cdot k} = 1 - \frac{E'_e(1-\cos\theta_e)}{2E_e}$

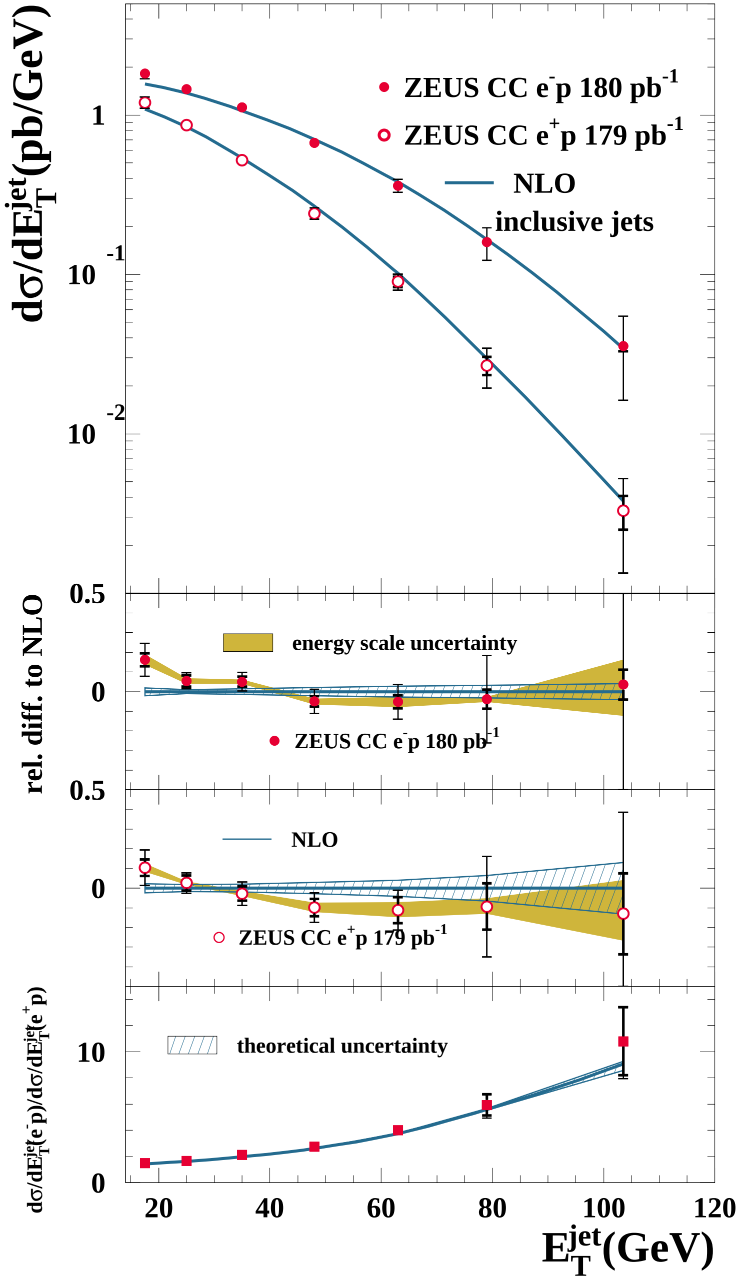
- f_a: parton a density, determined from experiment
  $\longrightarrow$ long-distance structure of the target
- $\hat{\sigma}_a$: subprocess cross section, calculable in pQCD
  $\longrightarrow$ short-distance structure of the interaction

CC DIS and QCD

$e^{\pm}p \rightarrow \nu + \text{jet} + X$ (inclusive jets)

- Jets searched using the k_T cluster algorithm in LAB frame
- Kinematic region: $Q^2 > 200$ GeV^2 and $y < 0.9$
- At least one jet with $E_T^{\text{jet}} > 14$ GeV and $-1 < \eta^{\text{jet}} < 2.5$
- $\mathcal{L} = 359$ pb^{-1} !!!

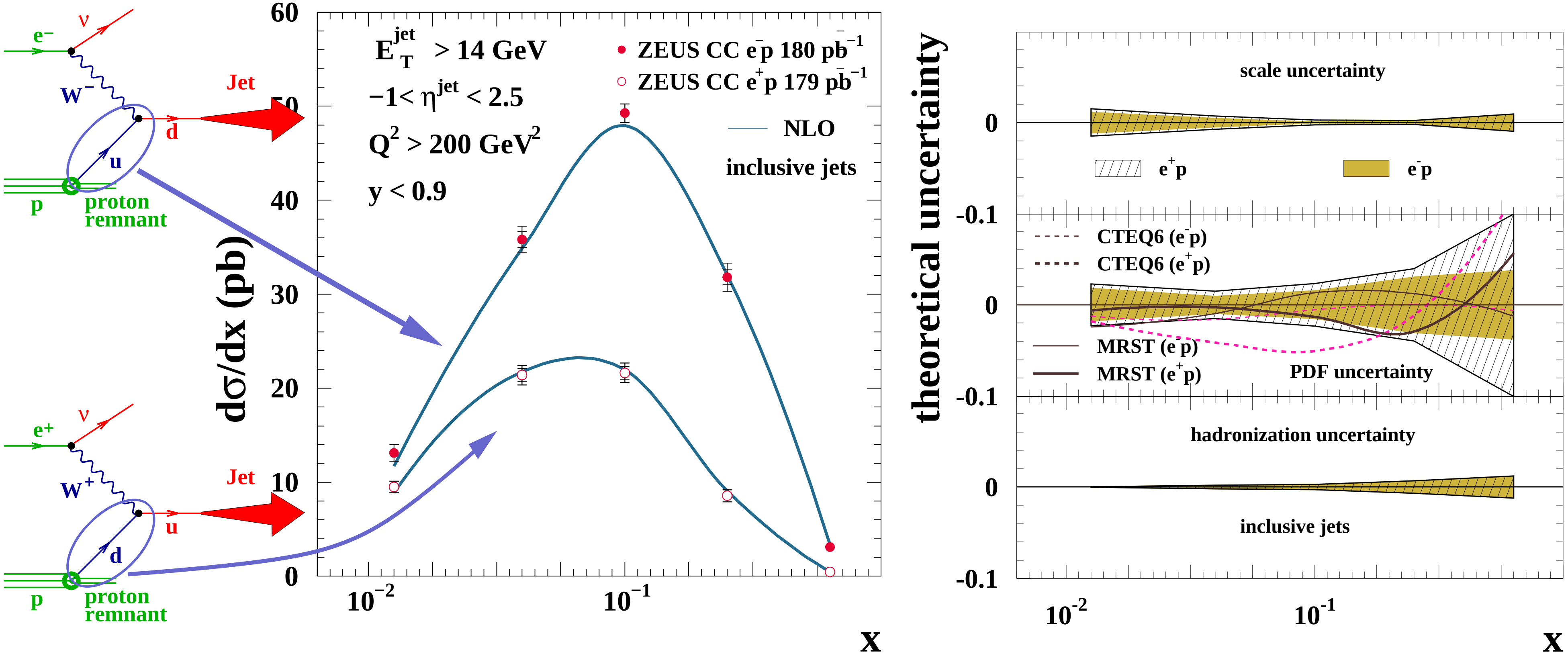
- The measured cross section for the e^+p sample decreases more rapidly than for the e^-p sample
- Comparison to NLO QCD predictions:
  $\longrightarrow$ the shape and magnitude of the measured cross sections are reasonably well described by the predictions
- Ratio of e^-p to e^+p cross sections expected to be ≈ 2
  $\longrightarrow$ increase at high E_T^{jet} values expected due to increasing contribution from valence-quark densities at high x
  $\longrightarrow$ both reactions are sensitive to different quark flavours



ZEUS Collab, Phys Rev D 78 (2008) 032004

CC DIS and the proton PDFs

- **Inclusive-jet cross sections in charged-current deep inelastic $e^{\pm}p$ scattering:**



→ Good description of data by NLO QCD calculations

→ Theoretical uncertainties dominated by PDF uncertainty

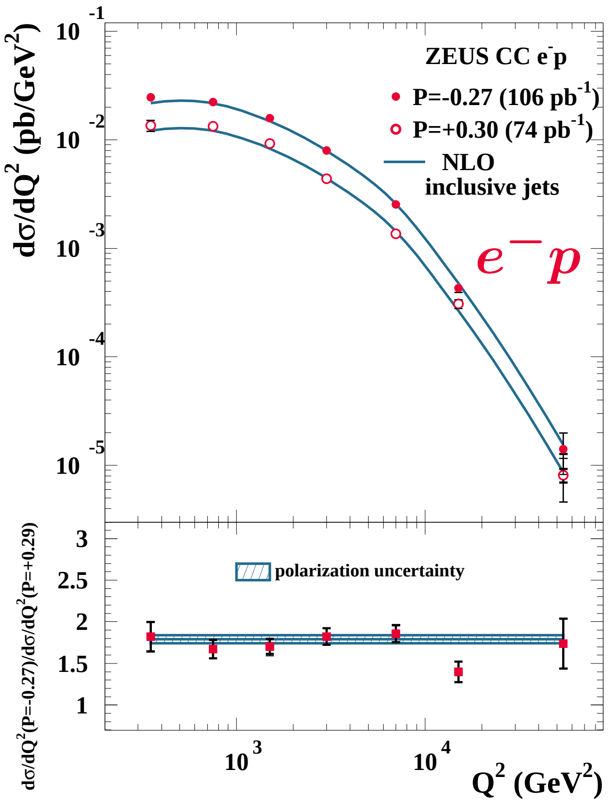
→ measured cross sections can help to constrain further u and d PDFs

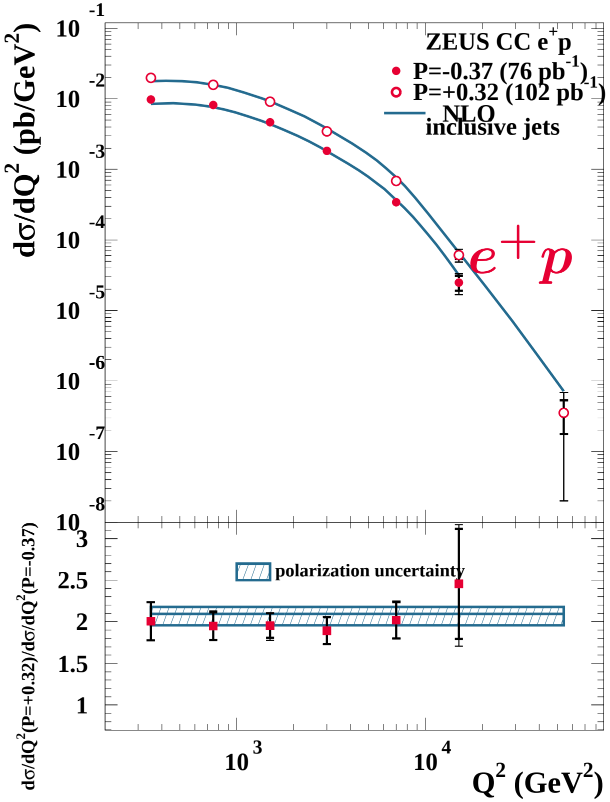
ZEUS Collab, Phys Rev D 78 (2008) 032004

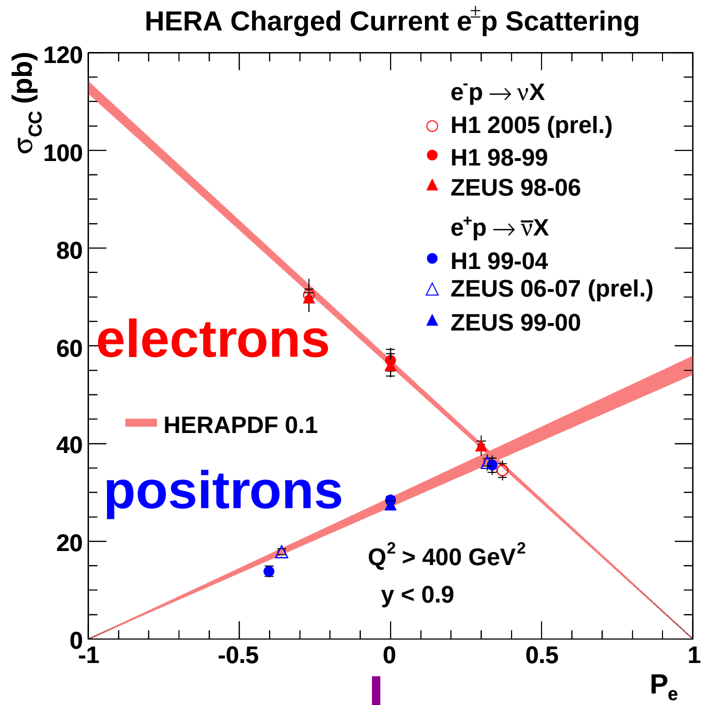
CC DIS and polarisation

- **Inclusive-jet cross sections in charged current DIS with longitudinally-polarised $e^{\pm}$ beams**
- **SM prediction for polarisation dependence:**

$$\sigma^{\pm}_{CC}(P_e) = (1 \pm P_e)\sigma^{0}_{CC}$$







“total” CC $e^{\pm}$ cross section vs P_e

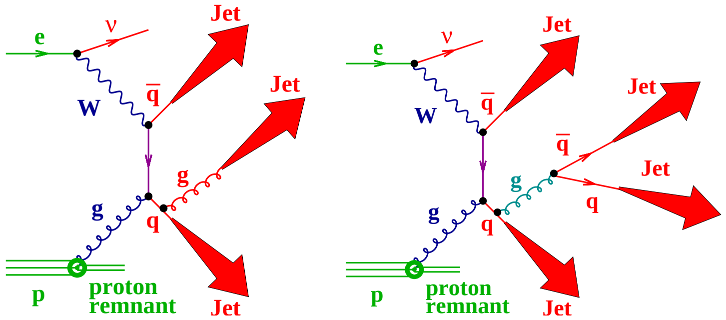
→ **jet cross sections in CC $e^{\pm}$ for different P_e**

⇒ **Good agreement with SM predictions**

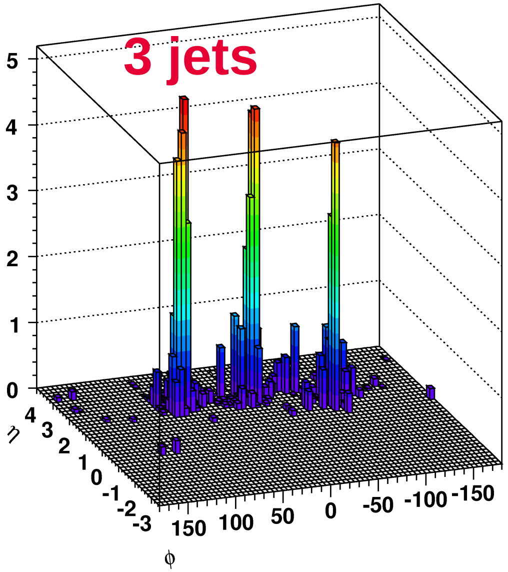
ZEUS Collab, Phys Rev D 78 (2008) 032004

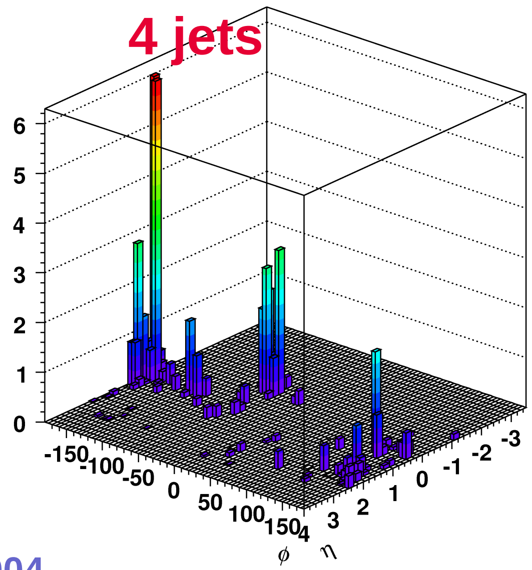
Multi-jet production in CC DIS and QCD

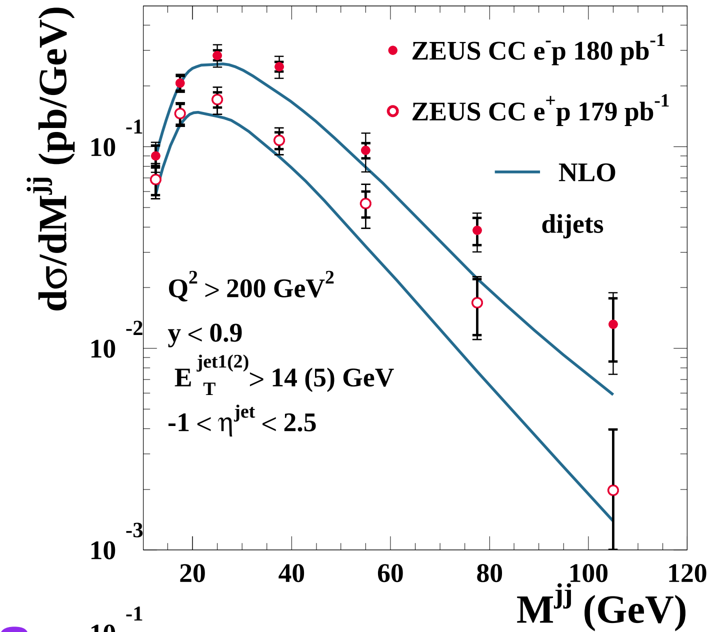
- **Additional jets with $E_T^{jet} > 5$ GeV**

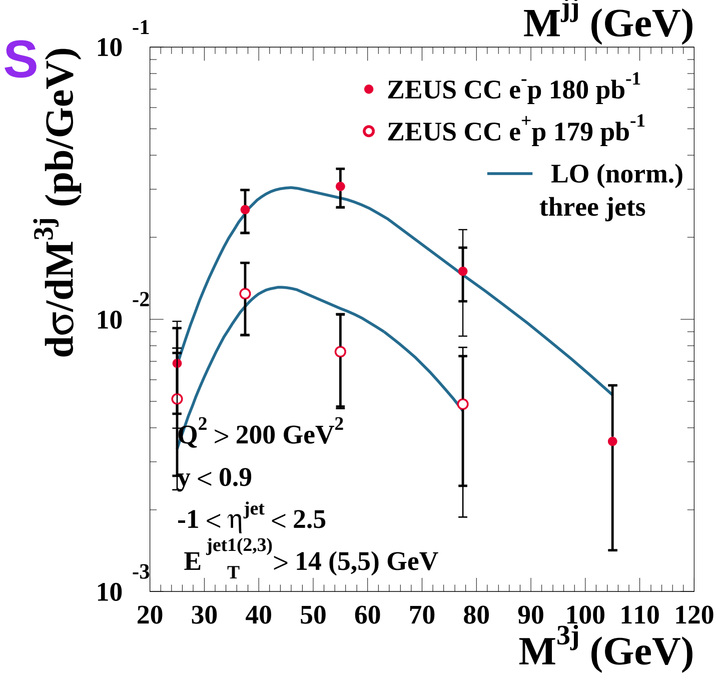


- **The measured dijet cross sections are not well described by NLO**
- **The shape of the measured three-jet cross sections are well described by LO**
- **First observation of 3- and 4-jet production in CC DIS**









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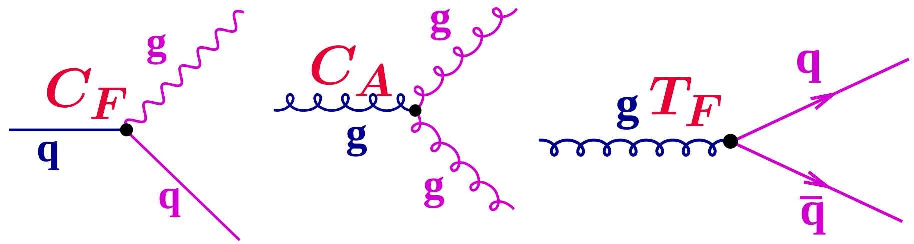
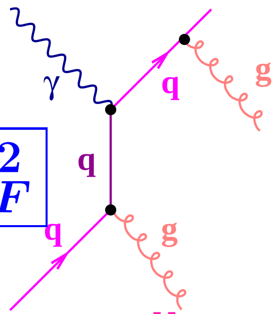
Underlying group symmetry and colour factors

- The colour factors represent the relative strength of the processes and their relative contributions

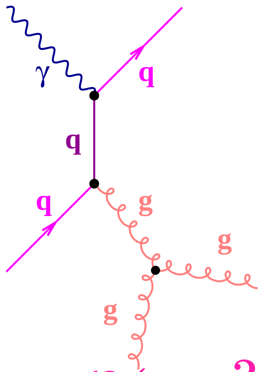


- Their values are predicted by the underlying gauge-group structure
  $\rightarrow$ for $SU(N)$: $C_F = (N^2-1)/2N$, $C_A = N$, $T_F = 1/2$
- Since the couplings qqg and ggg have different spin structures, the colour factors give rise to a specific pattern of angular correlations between the final-state jets
- Colour factors extensively studied at LEP by measuring angular correlations between final-state jets in $e^+e^- \rightarrow 4$ jets and C_A/C_F and T_F/C_F determined
- In ep collisions at HERA, colour factors are studied using angular correlations in three-jet events

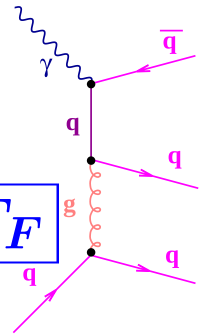
C_F^2



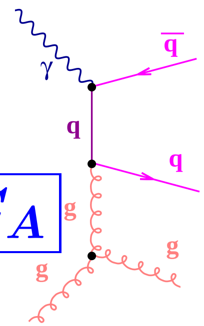
$C_F \cdot C_A$



$C_F \cdot T_F$



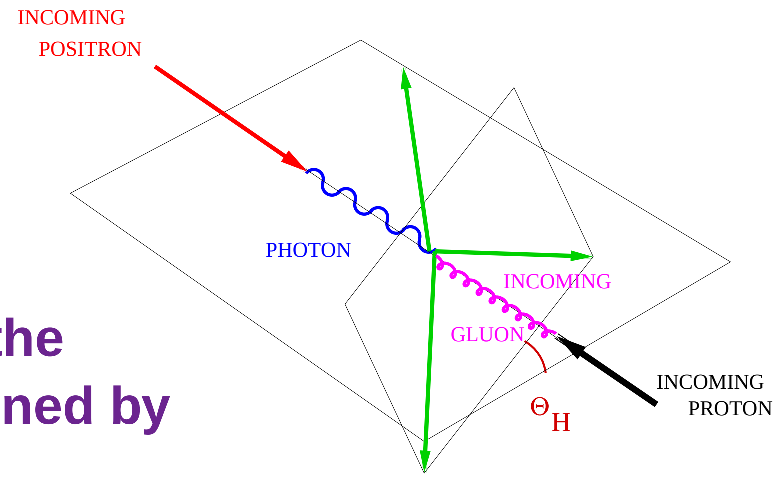
$T_F \cdot C_A$



- The predicted cross section at $\mathcal{O}(\alpha\alpha_s^2)$ can be written as

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

Angular correlations in three-jet events



- Variables to highlight the contributions from the different colour configurations
  $\longrightarrow$ angular correlations between the three jets

$\longrightarrow$ θ_H: the angle between the plane determined by the highest $E_T^{\rm jet}$ and the beam and the plane determined by the two lowest $E_T^{\rm jet}$ jets (Muñoz-Tapia, Stirling)

$\longrightarrow$ α_{23}: the angle between the two lowest $E_T^{\rm jet}$ jets (inspired by the variable $\alpha_{34}^{e^+e^-}$ for $e^+e^- \longrightarrow 4{\rm jets}$)

$\longrightarrow$ β_{KSW}: defined by

$$\cos\beta_{KSW} = \cos\frac{1}{2}[\angle[(\vec{p}_1 \times \vec{p}_3), (\vec{p}_2 \times \vec{p}_B)] + \angle[(\vec{p}_1 \times \vec{p}_B), (\vec{p}_2 \times \vec{p}_3)]],$$

where $\vec{p}_i$ is the momentum of jet i (ordered according to decreasing $E_T^{\rm jet}$) and $\vec{p}_B$ is a unit vector in the direction of the proton beam (inspired by the Körner-Schierholz-Willrodt angle $\Phi_{KSW}^{e^+e^-}$ for $e^+e^- \longrightarrow 4{\rm jets}$)

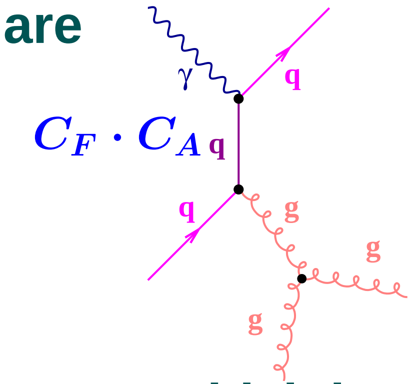
$\longrightarrow$ $\eta_{\rm max}^{\rm jet}$: pseudorapidity of the most forward jet

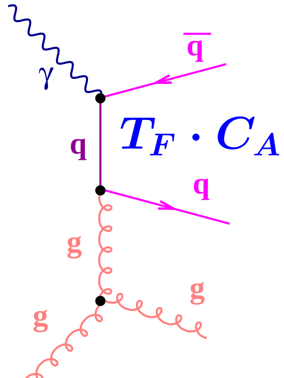
ZEUS Collab, DESY-08-100

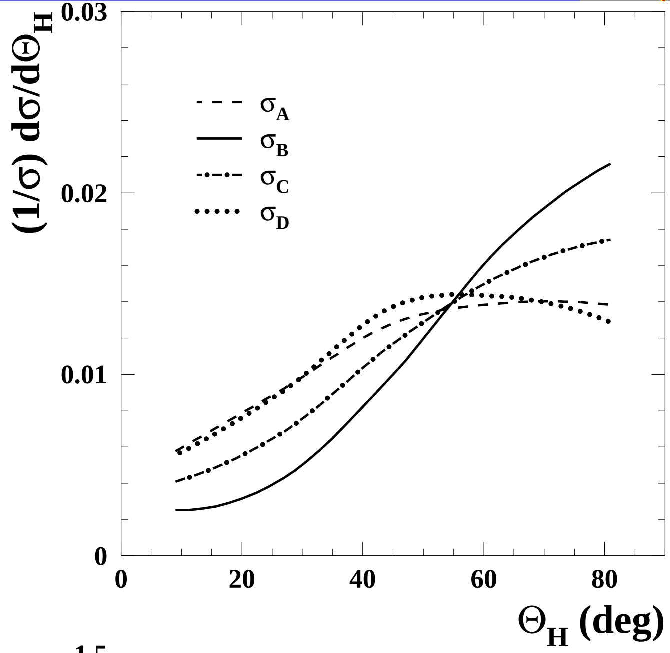
Three-jet events in NC DIS and colour configurations

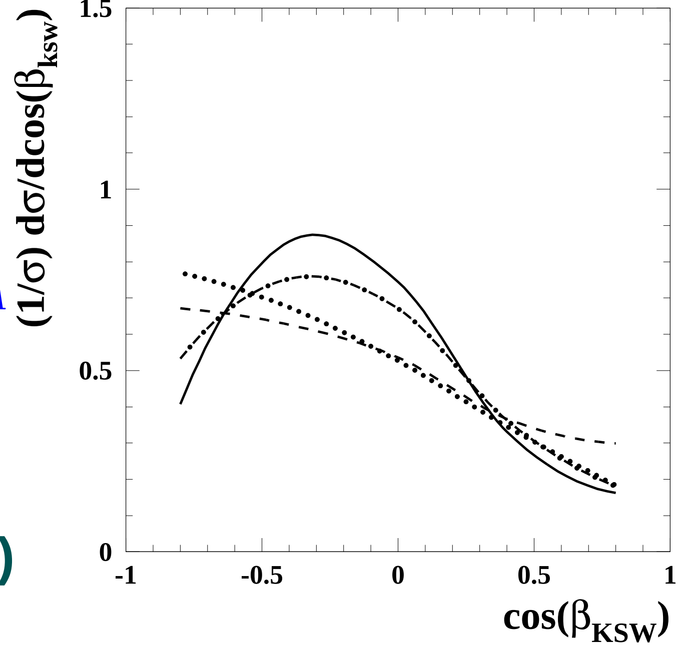
$$ep \rightarrow e + 3\text{jet} + X$$

- Jets searched using the k_T cluster algorithm in Breit frame
- Kinematic region: $Q^2 > 125$ GeV^2 and $|\cos\gamma_h| < 0.65$
- Three jets with $E^{\rm jet}_{T,{\rm B}} > 8(5)$ GeV and $-2 < \eta^{\rm jet}_{\rm B} < 1.5$
- Predictions for the angular correlations show sensitivity to the different colour configurations
- The distribution for σ_B has a very different shape than the others in all variables
- The distribution for σ_D has a different shape than the others in $\eta^{\rm jet}_{\rm max}$
- The predicted relative contributions of each colour configuration in SU(3) are
  - $\rightarrow \sigma_A$ (C_F^2): 23%
  - $\rightarrow \sigma_B$ ($C_F C_A$): 13%
  - $\rightarrow \sigma_C$ ($C_F T_F$): 39%
  - $\rightarrow \sigma_D$ ($T_F C_A$): 25%







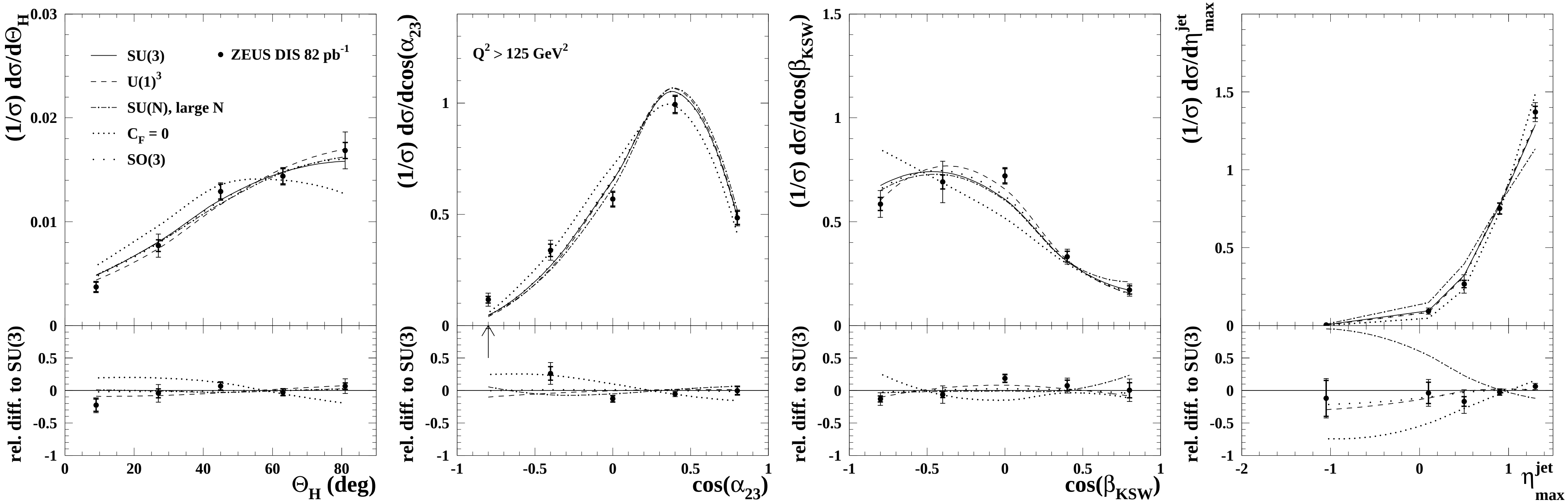


$\rightarrow$ A total of 38% for diagrams which involve C_A (TGV)

ZEUS Collab, DESY-08-100

Angular correlations and underlying gauge symmetry

- Measured normalised three-jet cross sections in NC DIS vs $\mathcal{O}(\alpha_s^2)$ predictions based on different symmetry groups

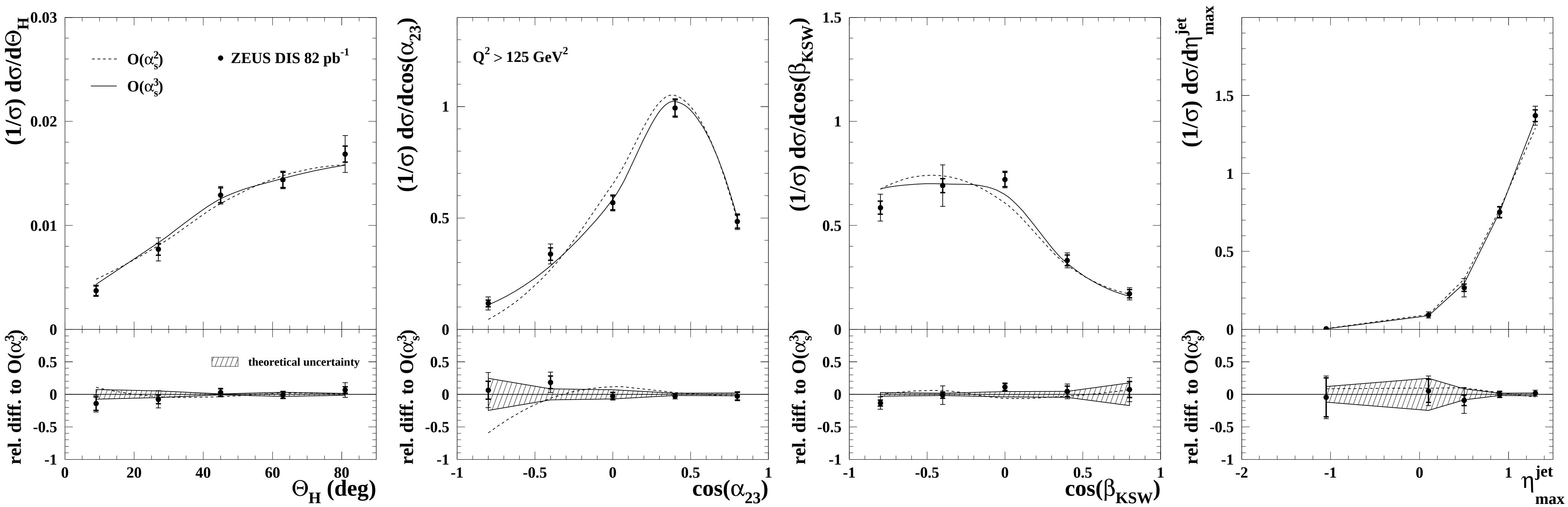


- The data disfavour SU(N) in the limit of large N and $C_F = 0$ symmetry groups
- The measurements are consistent with the admixture of colour configurations as predicted by SU(3)
  $\longrightarrow$ the discrepancies observed can be attributed to higher orders $\longrightarrow$

ZEUS Collab, DESY-08-100

Angular correlations and underlying gauge symmetry

- **Measured normalised three-jet cross sections in NC DIS vs $\mathcal{O}(\alpha_s^3)$ predictions based on SU(3) symmetry group**

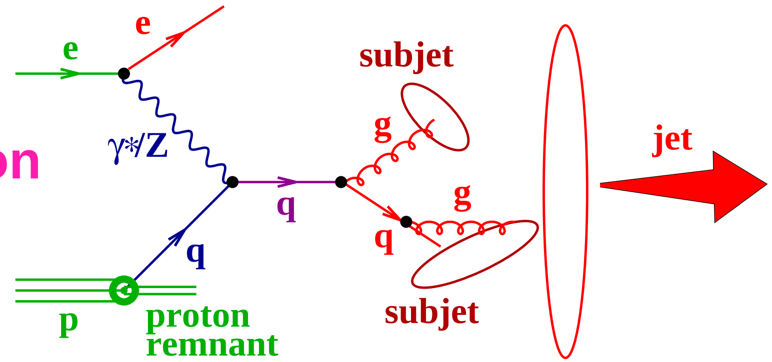


- **Very good description of data by SU(3) at $\mathcal{O}(\alpha_s^3)$**
- **Potential to extract the colour factors from these measurements**
  $\longrightarrow$ **NLO analysis and more statistics to be able to distinguish SU(3) and U(1)^3 are required**

ZEUS Collab, DESY-08-100

Two-subjet distributions

- **Subjets:** jet-like substructures identified by reapplying the k_T algorithm at smaller values of the resolution parameter $y_{\rm cut}$

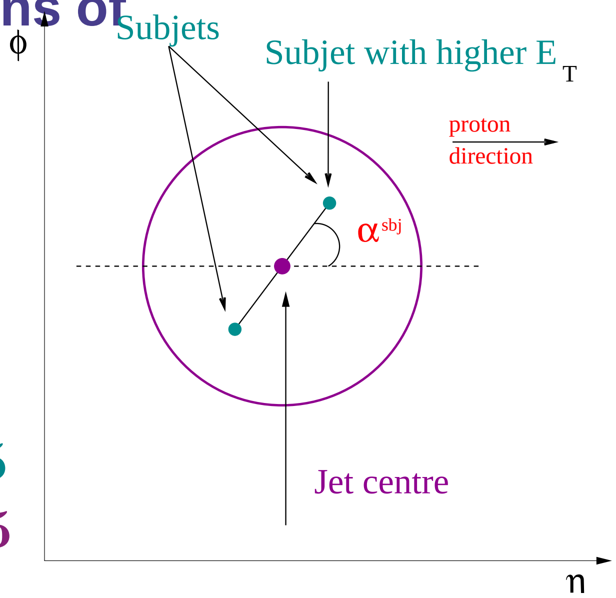


- Subjet distributions can be used to study:
  - → pattern of parton radiation from a primary parton
    - → direct test of splitting functions $P_{ab}(z, \mu)$ and their scale dependence
  - → colour coherence
    - → soft gluon radiation tends to be emitted towards proton direction

- Measurements of normalised cross sections as functions of

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

and their dependence with $E_T^{\rm jet}$, Q^2 and x



— Jets searched using the k_T cluster algorithm in LAB frame

— Kinematic region: $Q^2 > 125$ GeV^2

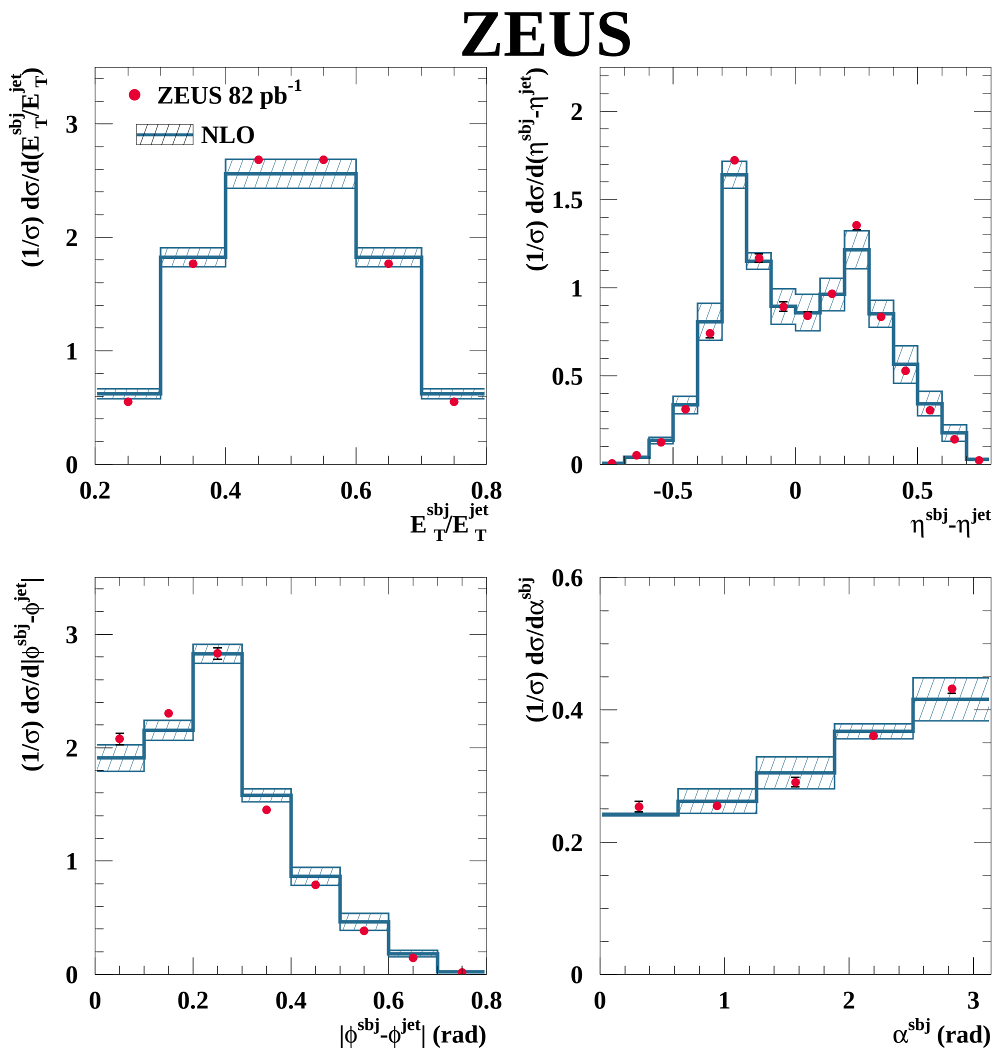
— At least one jet with $E_T^{\rm jet} > 14$ GeV and $-1 < \eta^{\rm jet} < 2.5$

— Final sample: jets that have two subjets for $y_{\rm cut} = 0.05$

ZEUS Collab, DESY-08-178

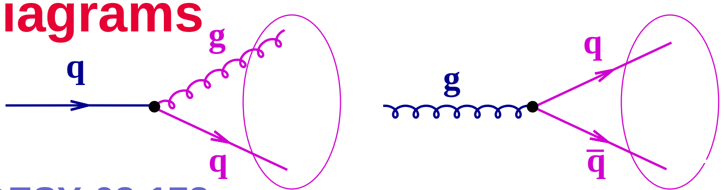
Two-subjet distributions and pattern of parton radiation

- **Normalised subjet cross sections compared with NLO calculations:**



- $E_T^{\rm sbj}/E_T^{\rm jet}$: the two subjets tend to have similar $E_T^{\rm sbj}$
- $\eta^{\rm sbj}-\eta^{\rm jet}$: asymmetric two-peak structure
- $|\phi^{\rm sbj}-\phi^{\rm jet}|$: suppression around 0 because the two subjets cannot be resolved when close
- $\alpha^{\rm sbj}$: higher $E_T^{\rm sbj}$ subjet tends to be in rear direction
  $\longrightarrow$ consistent with asymmetric peaks of $\eta^{\rm sbj}-\eta^{\rm jet}$

$\longrightarrow$ The NLO predictions, which contain these diagrams

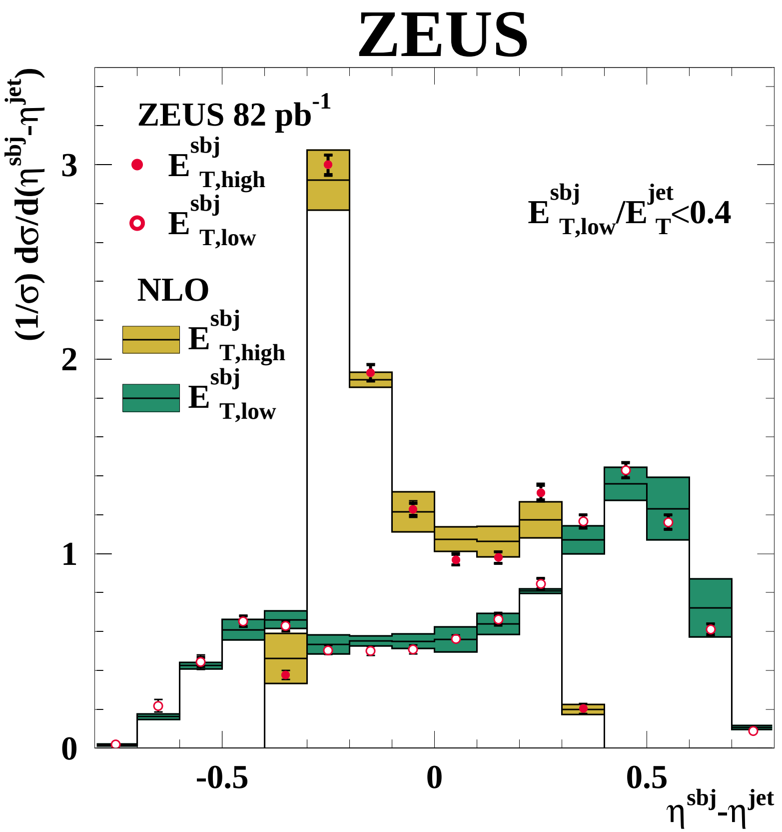


describe the data adequately

ZEUS Collab, DESY-08-178

Two-subjet distributions and colour coherence

- $\eta^{\rm sbj} - \eta^{\rm jet}$ normalised cross section for $E_{T,\rm low}^{\rm sbj}/E_T^{\rm jet} < 0.4$



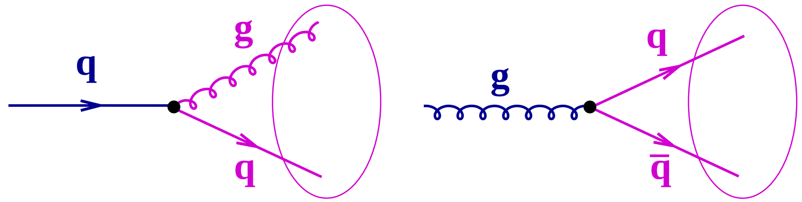
→ The higher (lower) $E_T^{\rm sbj}$ subjet tends to be in the rear (forward) direction

→ colour-coherence effects between the initial and final states

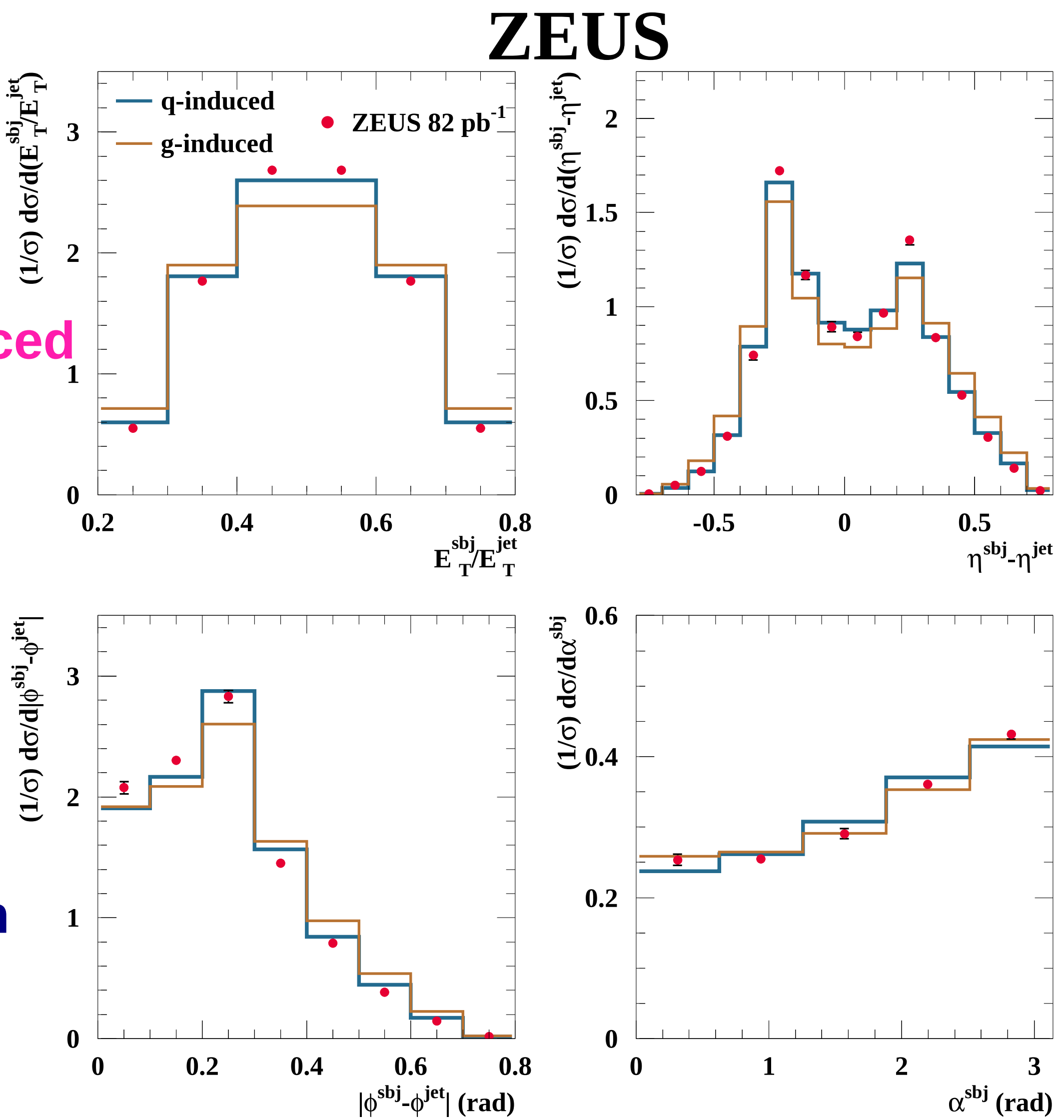
ZEUS Collab, DESY-08-178

Two-subjet distributions and parton splitting

- Comparison with predictions for quark- and gluon-induced processes



→ NLO prediction:
81% of q-induced and 19% of g-induced



- Predictions for these two types of processes are different:
  — the two subjets in q-induced have more similar $E_T^{\rm sbj}$ and are closer to each other than in g-induced

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

ZEUS Collab, DESY-08-178

Three-subjet distributions

- **Subjet distributions can be used to study:**
  - $\longrightarrow$ **pattern of parton radiation from a primary parton**
    - $\longrightarrow$ **direct test of splitting functions $P_{ab}(z, \mu)$ and their scale dependence**
  - $\longrightarrow$ **colour coherence**
    - $\longrightarrow$ **soft gluon radiation tends to be emitted towards proton direction**
  - $\longrightarrow$ **underlying group symmetry**
    - $\longrightarrow$ **angular correlations between three subjets should show sensitivity to the colour configurations**
- **Measurements of normalised cross sections as functions of**

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

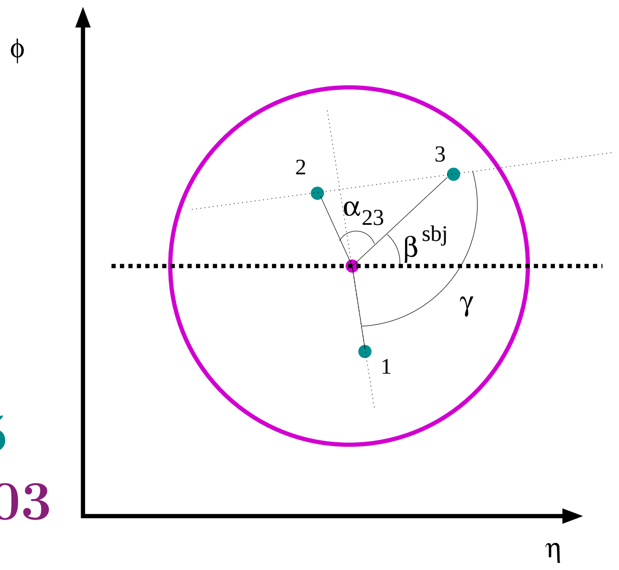
$$\theta_H,\ \alpha_{23} \text{ and } \gamma$$

— **Jets searched using the k_T cluster algorithm in LAB frame**

— **Kinematic region: $Q^2 > 125$ GeV^2**

— **At least one jet with $E_T^{\rm jet} > 14$ GeV and $-1 < \eta^{\rm jet} < 2.5$**

— **Final sample: jets that have three subjets for $y_{\rm cut} = 0.03$**



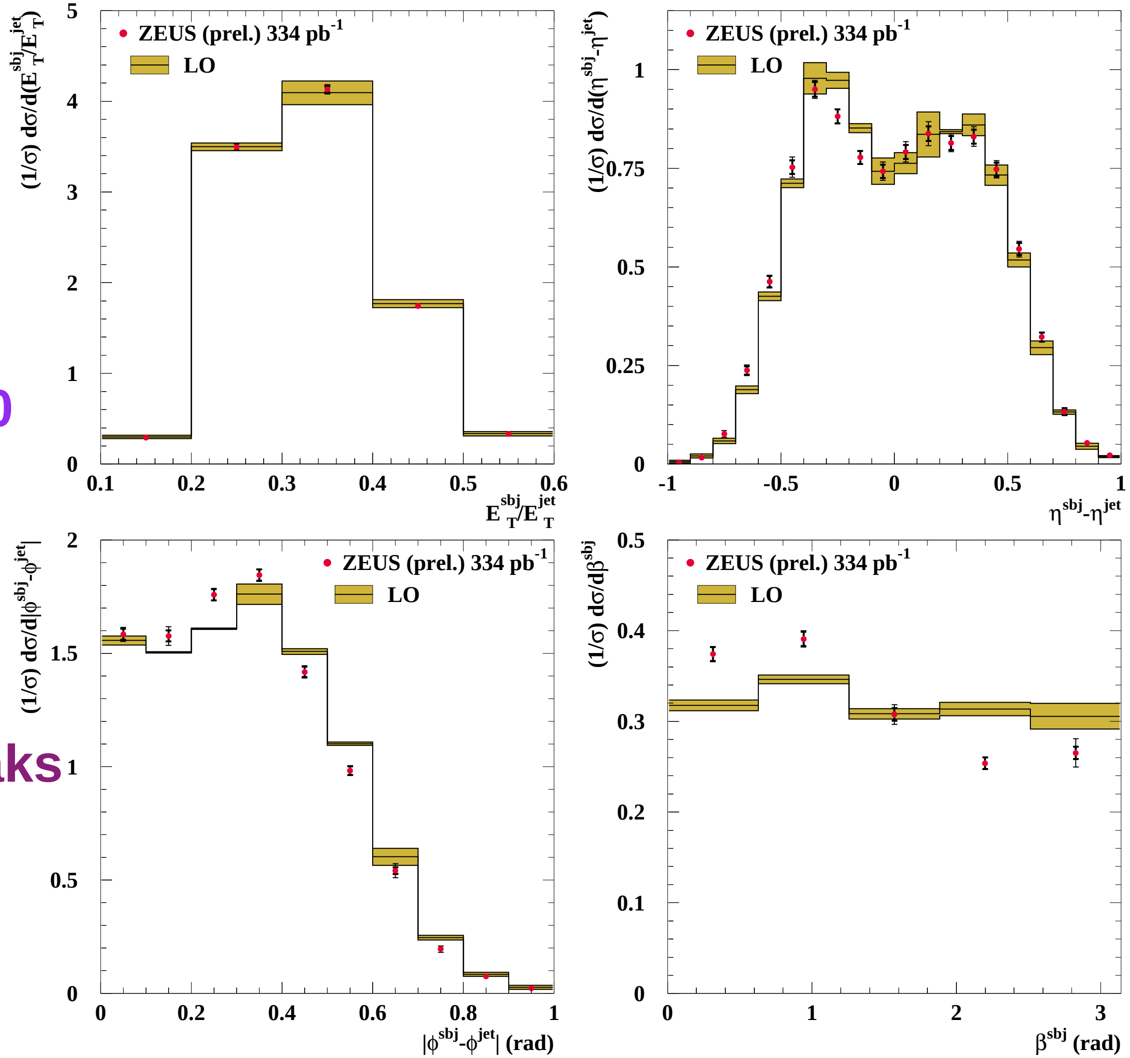
ZEUS Collab, ZEUS-prel-09-007

Three-subjet distributions and pattern of parton radiation

- **Normalised subjet cross sections compared with LO calculations:**

- $E_T^{\rm sbj}/E_T^{\rm jet}$: the three subjets tend to have similar $E_T^{\rm sbj}$
- $\eta^{\rm sbj} - \eta^{\rm jet}$: asymmetric two-peak structure
- $|\phi^{\rm sbj} - \phi^{\rm jet}|$: suppression around 0 because the subjets cannot be resolved when close
- $\beta^{\rm sbj}$: lowest $E_T^{\rm sbj}$ subjet tends to be in forward direction
  $\longrightarrow$ consistent with asymmetric peaks of $\eta^{\rm sbj} - \eta^{\rm jet}$

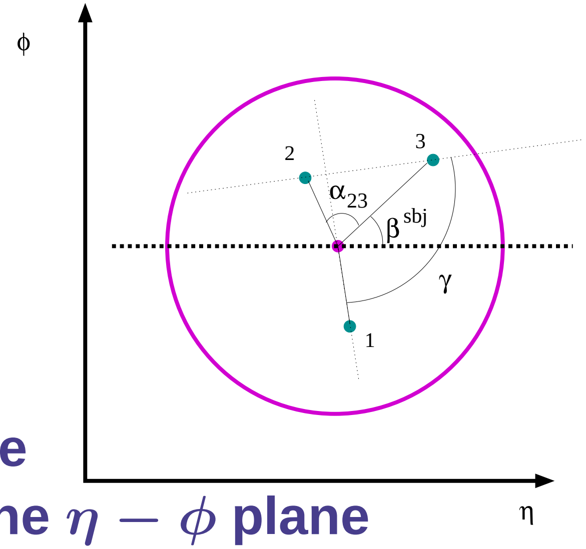
$\longrightarrow$ The LO predictions describe the data adequately, except for $\beta^{\rm sbj}$ (higher orders?)

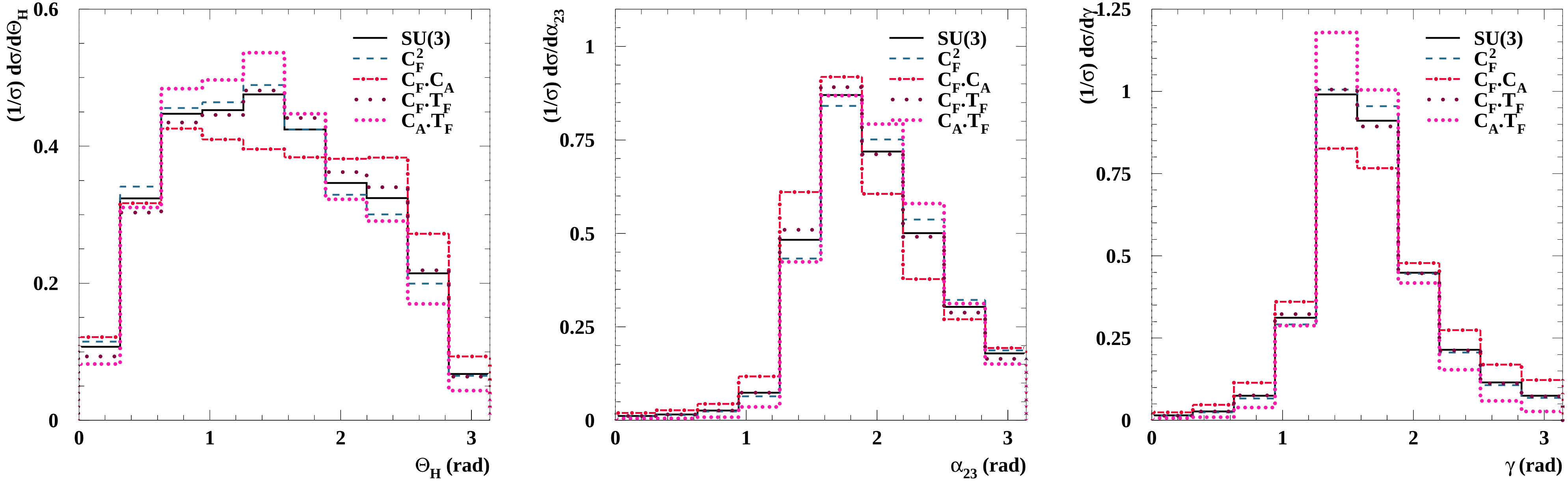


ZEUS Collab, ZEUS-prel-09-007

Angular correlations in three-subjet events

- **Three-subjet angular correlations**
  - $\longrightarrow$ θ_H: the angle between the planes determined by the highest-E_T subjet and the beam and the two lowest-E_T subjets
  - $\longrightarrow$ α_{23}: the angle between the two lowest-E_T subjets in the $\eta - \phi$ plane
  - $\longrightarrow$ γ: the angle between the highest-E_T subjet and the vector difference of the two lowest-E_T subjets in the $\eta - \phi$ plane



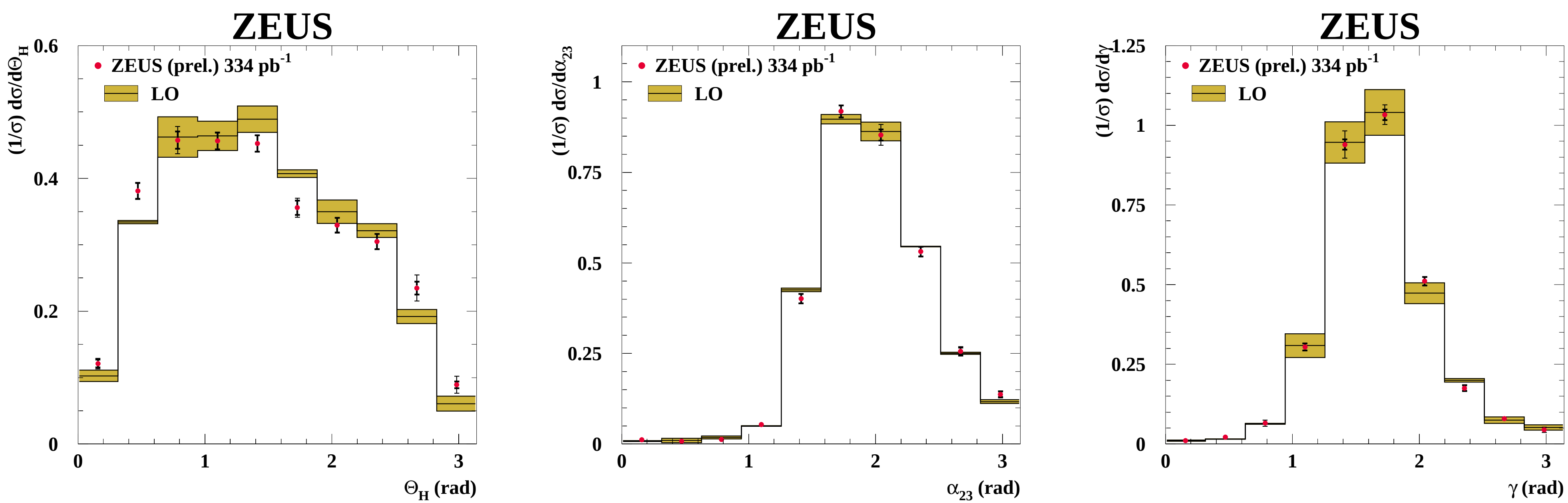


$\longrightarrow$ The $C_F \cdot C_A$ and $C_A \cdot T_F$ configurations display distinct behaviour

ZEUS Collab, ZEUS-prel-09-007

Angular correlations and underlying gauge symmetry

- **Measured normalised three-subjet cross sections in NC DIS vs $\mathcal{O}(\alpha_s^2)$ predictions based on SU(3)**



- **The measurements are consistent with the admixture of colour configurations as predicted by SU(3)**
- **SU(3) predicts: 47% (C_F^2), 17% ($C_F \cdot C_A$), 27% ($C_F \cdot T_F$) and 9% ($T_F \cdot C_A$) $\longrightarrow$ a total of 26% for the components which involve C_A (TGV)**
- **Potential to extract the colour factors from these measurements**

ZEUS Collab, ZEUS-prel-09-007

Conclusions

- Jet production and jet substructure are still being extensively studied at HERA

- Results shown:
  - Multi-jet cross sections in CC DIS
  - Angular correlations in three-jet events
  - Two-subjet distributions
  - Three-subjet distributions

- Measurements allow
  - ⇝ stringent tests of pQCD and the SM
  - ⇝ constraints on the proton PDFs
  - ⇝ test of the underlying gauge symmetry
  - ⇝ study of pattern of parton radiation
  - ⇝ study of colour coherence

↬ **Jet analysis at HERA:** a powerful tool that provides stringent tests of pQCD