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# COLOR DYNAMICS IN PHOTOPRODUCTION OF JETS AT HERA

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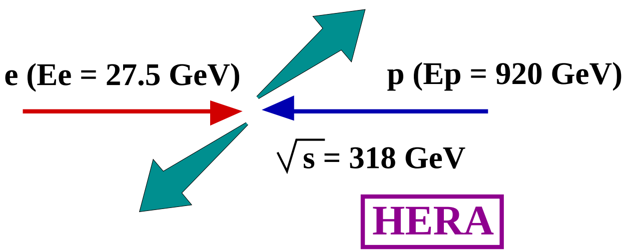
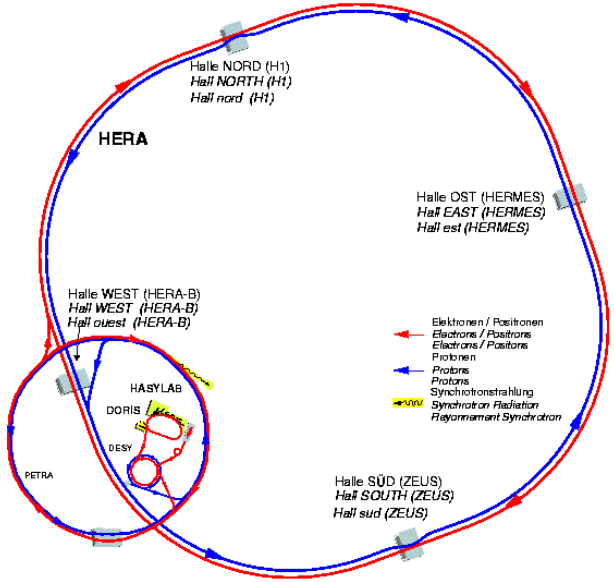
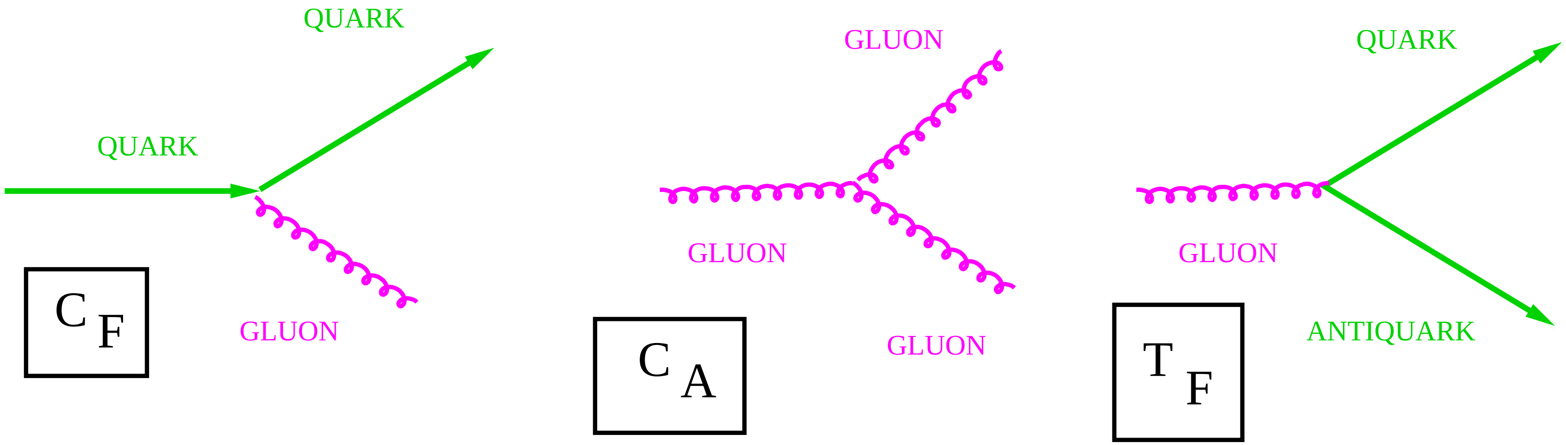



## ZEUS Collaboration

## Color 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
  $\longrightarrow$ for $SU(N)$: $C_F = (N^2 - 1)/2N, C_A = N, T_F = 1/2$
- The color factors determine the relative contributions of the various subprocesses
  $\longrightarrow$ e.g. in $e^+e^- \longrightarrow 4$ jets the contributions from $q\bar{q}gg$ and $q\bar{q}q'\bar{q}'$
- Since the couplings $qqg$ and $ggg$ have different spin structures, the color factors give rise to a specific pattern of angular correlations between the final-state jets

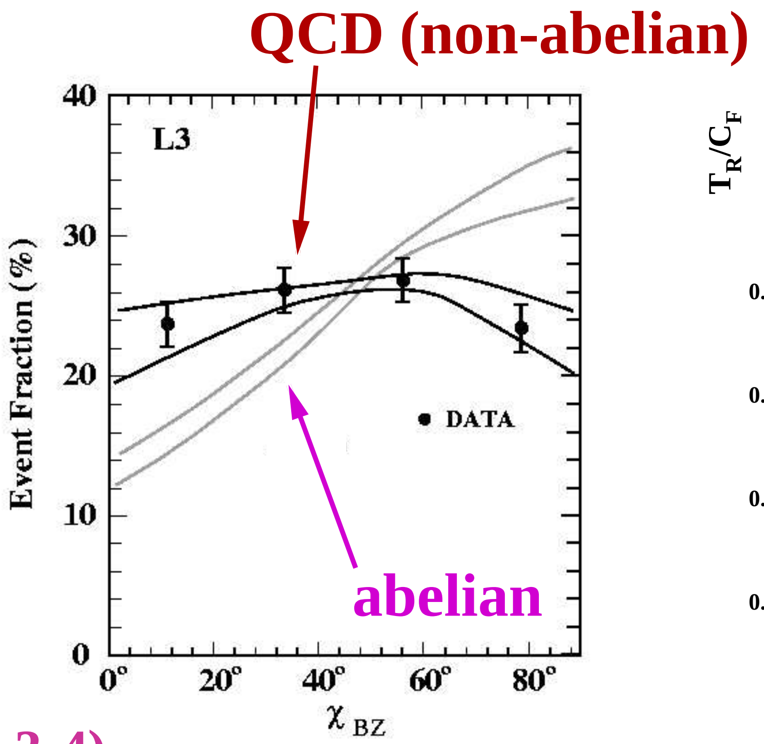
# Color Factors

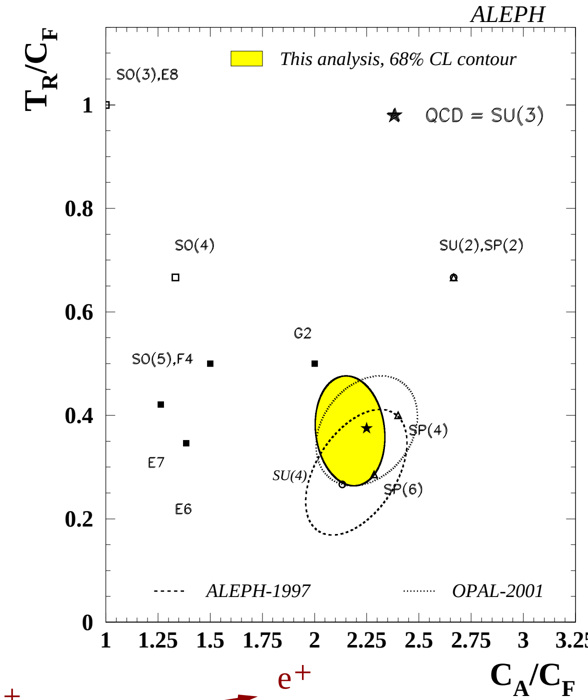
- **The effects of color factors have been extensively studied at LEP by measuring the angular correlations between the final state jets in**

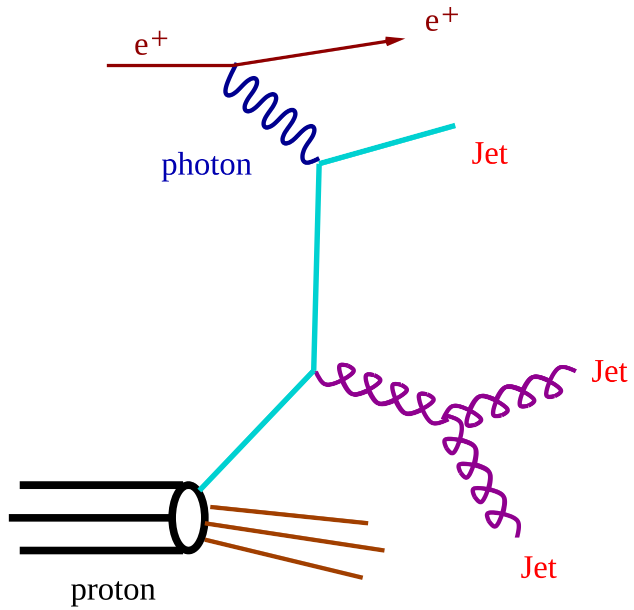
$$e^+e^- \rightarrow 4\ \text{jets}$$

**(e.g. using the Bengtsson-Zerwas variable $\chi_{BZ}$: angle between the plane of jets 1-2 and that of jets 3-4)**

**$\Rightarrow$ Determination of the ratios $C_A/C_F$ and $T_F/C_F$**

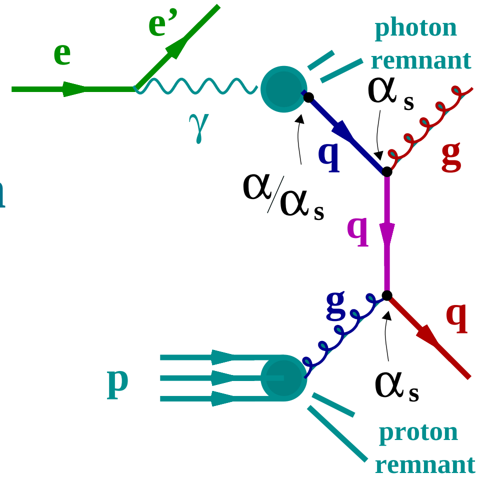


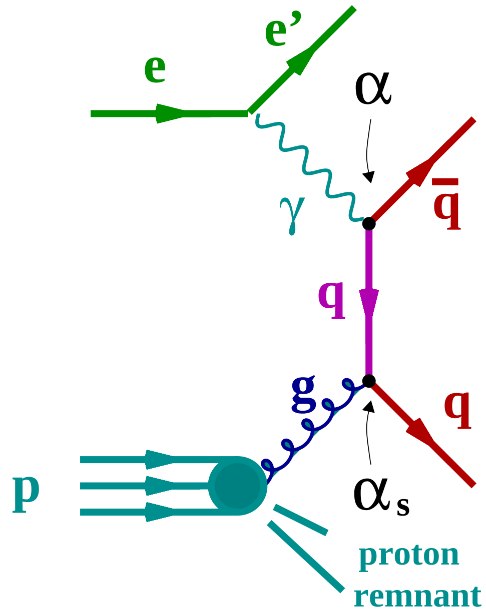




- **In $ep$ collisions at HERA, the effects of the color factors are expected in the photoproduction of three-jet events**

# Photoproduction of Jets




Resolved process




Direct process

- Production of jets in $\gamma p$ collisions has been measured via $ep$ scattering at $Q^2 \approx 0$
- At lowest order QCD, two hard scattering processes contribute to jet production ⇒
- pQCD calculations of jet cross sections

$$\sigma_{jet} = \sum_{a,b} \int_0^1 dy\, f_{\gamma/e}(y) \int_0^1 dx_\gamma\, f_{a/\gamma}(x_\gamma, \mu^2_{F\gamma}) \int_0^1 dx_p\, f_{b/p}(x_p, \mu^2_{Fp})\ \hat{\sigma}_{ab\to jj}$$

longitudinal momentum fraction of $\gamma/e^+$ ($y$), parton $a/\gamma$ ($x_\gamma$), parton $b$/proton ($x_p$)

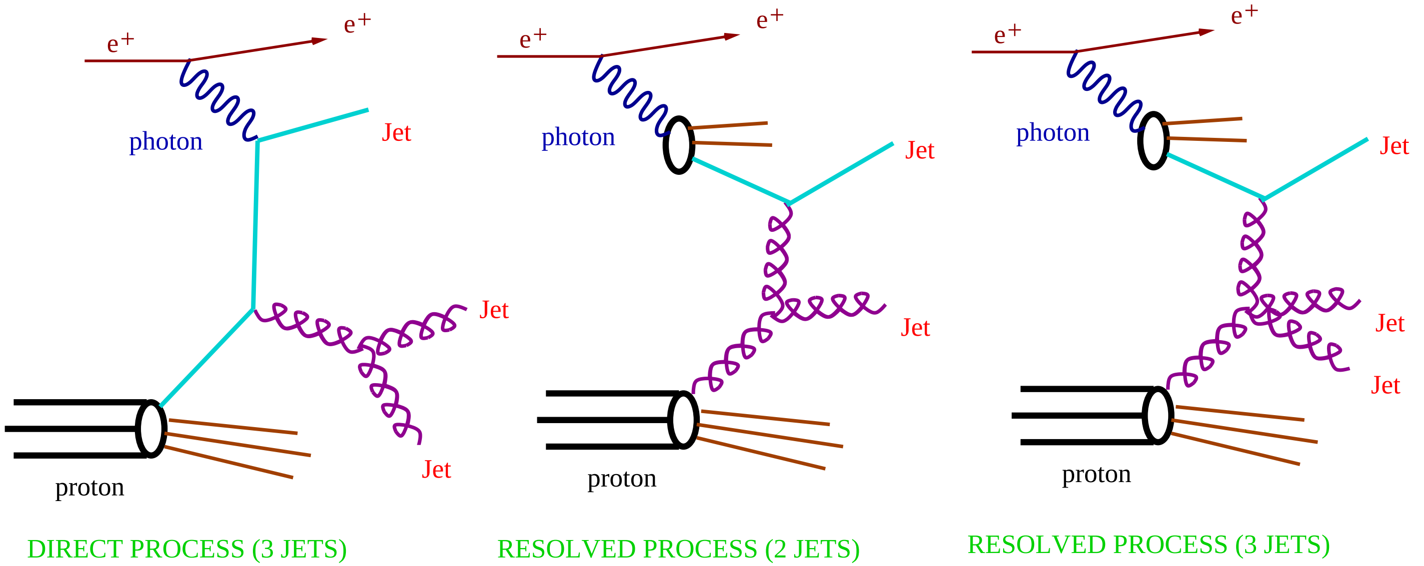
$\to f_{\gamma/e}(y) =$ flux of photons in the positron ($WW$ approximation)

$\to f_{a/\gamma}(x_\gamma, \mu^2_{F\gamma}) =$ parton densities in the photon (for direct processes $\delta(1-x_\gamma)$)

$\to f_{b/p}(x_p, \mu^2_{Fp}) =$ parton densities in the proton

$\to \sigma_{ab\to jj}$ subprocess cross section; short-distance structure of the interaction

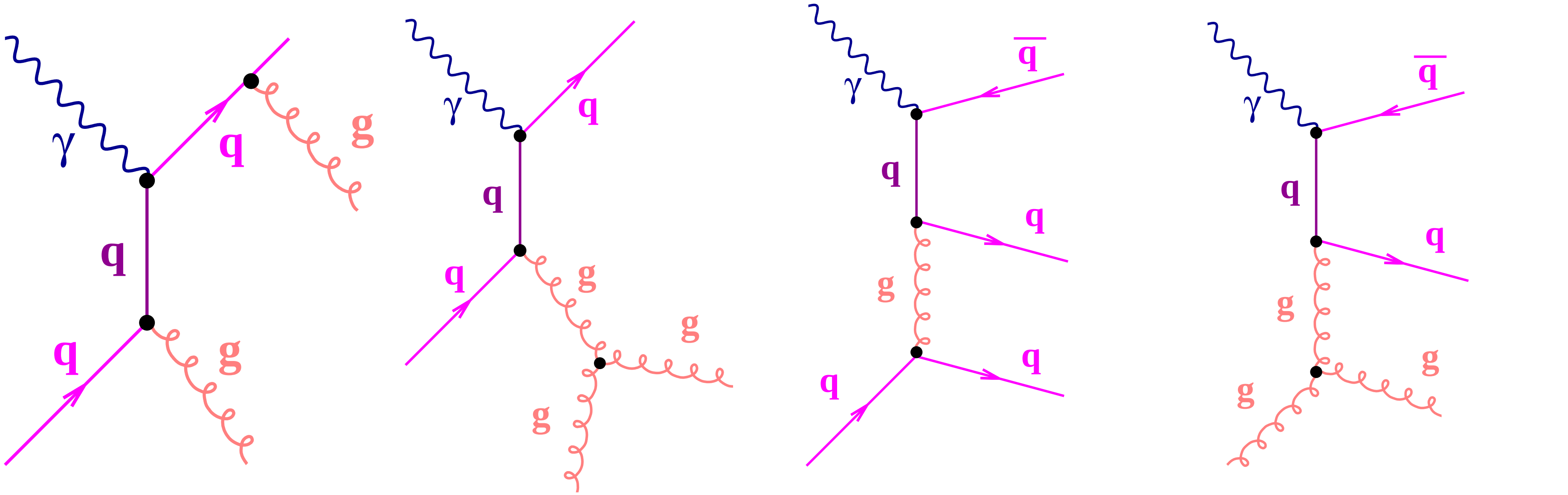
# Color Factors: Direct vs Resolved Processes




- **Resolved processes (dijet): the triple-gluon-vertex contribution already appears in the production of dijet events → not a distinct feature in the final state jets**
- **Resolved processes (trijet): new color factors contribute to the production of three-jet events → a rather complex situation to disentangle the effects of $C_F$, $C_A$, ...**
- **Direct processes (trijet): sensitive to the colour factors $C_F$, $C_A$ and $T_F$ through the angular correlations between the final-state jets (clean!)**
- **Observable to separate resolved/direct ⇒** $x_\gamma^{obs}(3\text{jets}) = \frac{1}{2E_\gamma}\sum_{i=1}^{3} E_T^{jet_i} e^{-\eta^{jet_i}}$

# Photoproduction of Three-Jet Events

- **Direct processes** provide a clean way to study the effects of the different color configurations

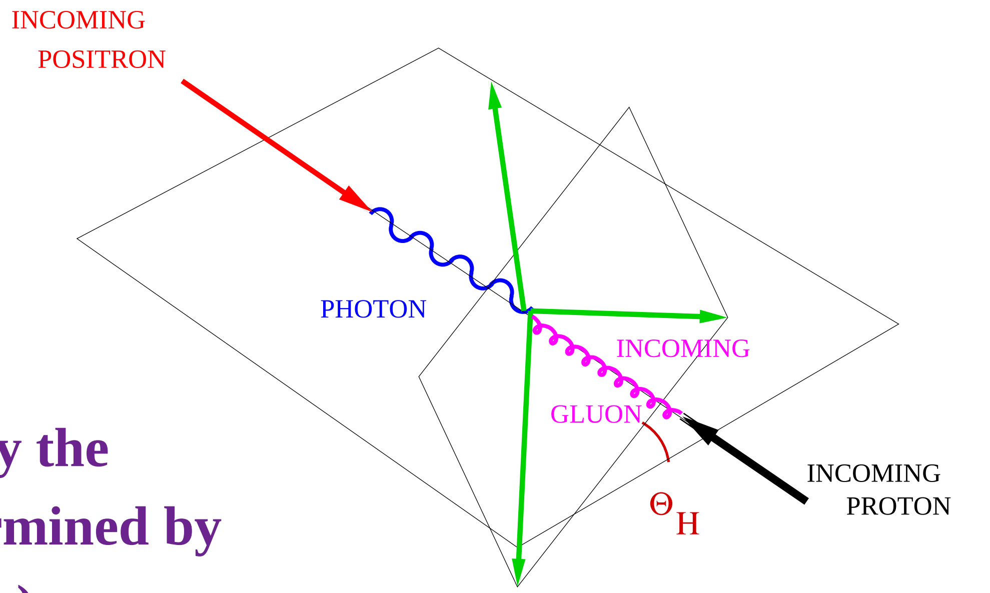



$C_F^2$ $\quad C_F \cdot C_A$ $\quad C_F \cdot T_F$ $\quad T_F \cdot C_A$

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

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

## Photoproduction of Three-Jet Events




- Variables to highlight the contributions from the different color configurations
  $\Rightarrow$ angular correlations between the jets

$\longrightarrow$ $\theta_H$, 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);

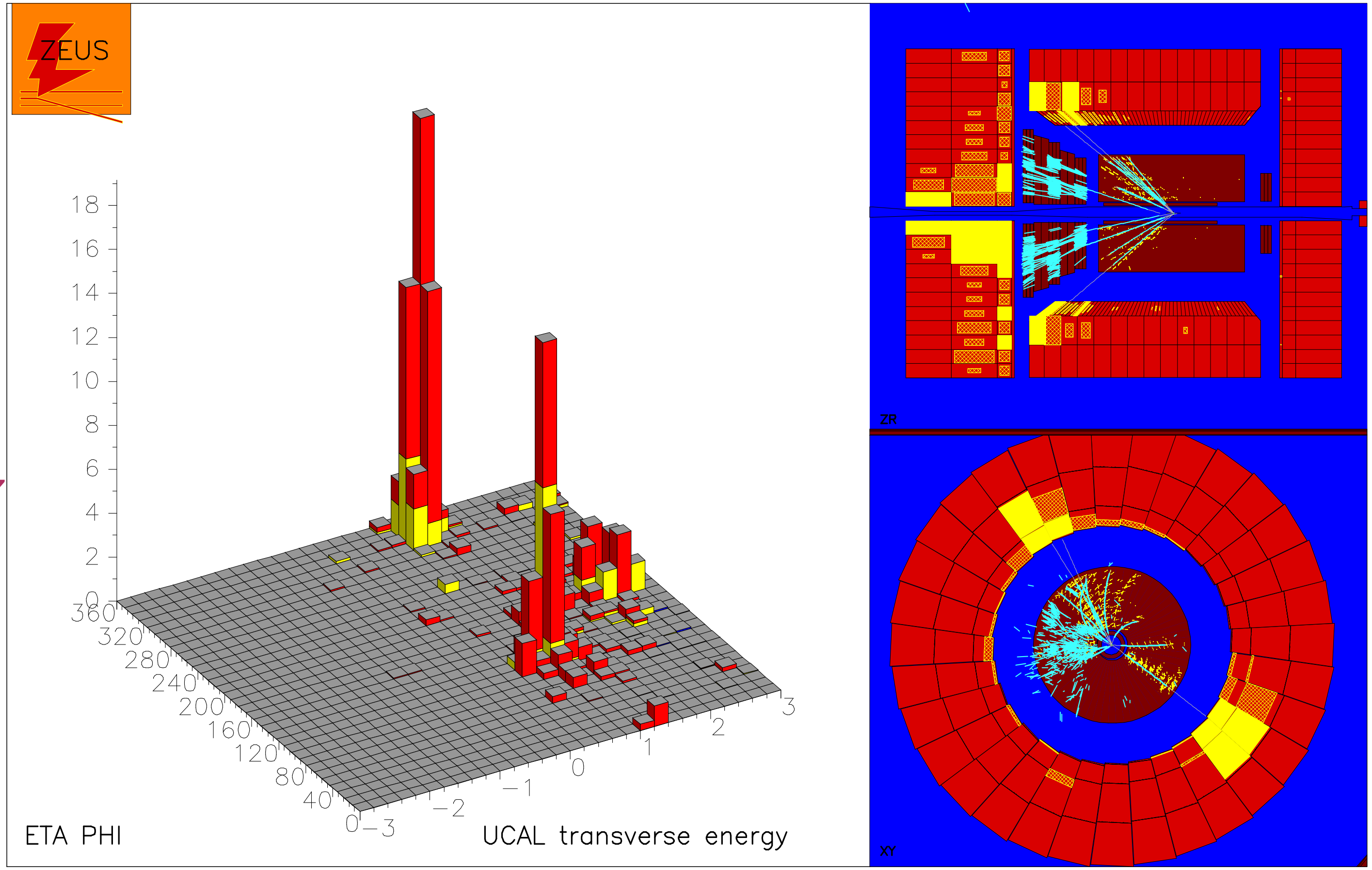
$\longrightarrow$ $\alpha_{23}$, the angle between the two lowest $E_T^{\rm jet}$ jets;
(inspired by the variable $\alpha_{34}^{e^+e^-}$ for $e^+e^- \rightarrow$ 4jets)

$\longrightarrow$ $\beta_{KSW}$, 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 $e^+e^- \rightarrow$ 4jets)

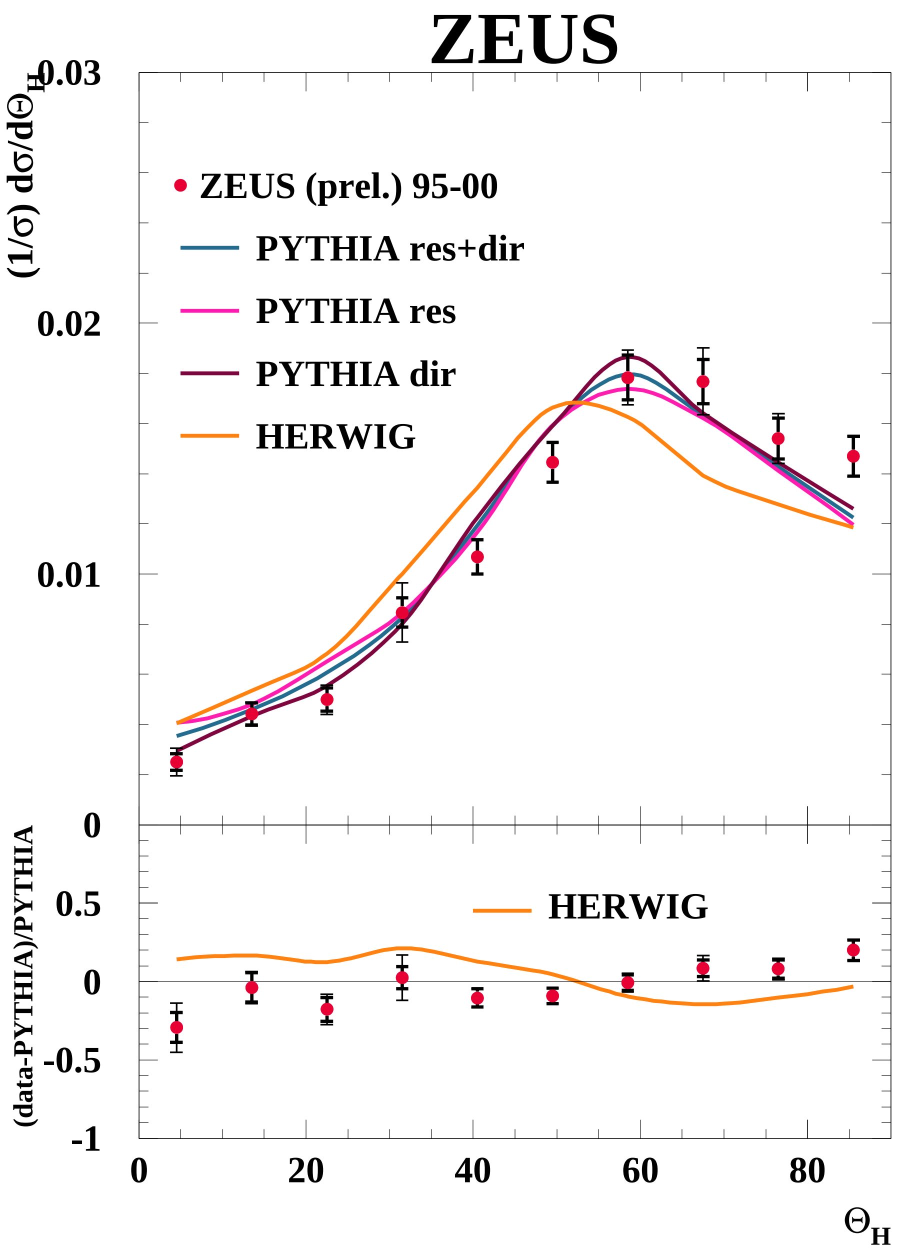
# Measurements of Three-Jet Events in Photoproduction

- Measurements using HERA I data: $\mathcal{L} = 127$ pb$^{-1}$
- Jets identified using the longitudinally invariant $k_T$ cluster algorithm in the laboratory frame: at least three jets with $E_T^{jet} > 14$ GeV, $-1 < \eta^{jet} < 2.5$
- Kinematic region: $Q^2 < 1$ GeV$^2$ and $0.2 < y < 0.85$

$\sim$ 2200 three-jet events satisfying $x_\gamma^{obs}(3\text{jets}) > 0.7$



# Measurement of the Distribution in $\theta_H$




- Measurement of the normalised cross section $1/\sigma\ d\sigma/d\theta_H$ for the production of events with three jets satisfying
  $E_T^{\rm jet} > 14$ GeV, $-1 < \eta^{\rm jet} < 2.5$
  and $x_\gamma^{\rm obs}(3{\rm jets}) > 0.7$
  in the kinematic region
  $Q^2 < 1$ GeV$^2$ and $0.2 < y < 0.85$

- Comparison to the predictions of PYTHIA and HERWIG (leading-logarithm parton-shower calculations based on SU(3))

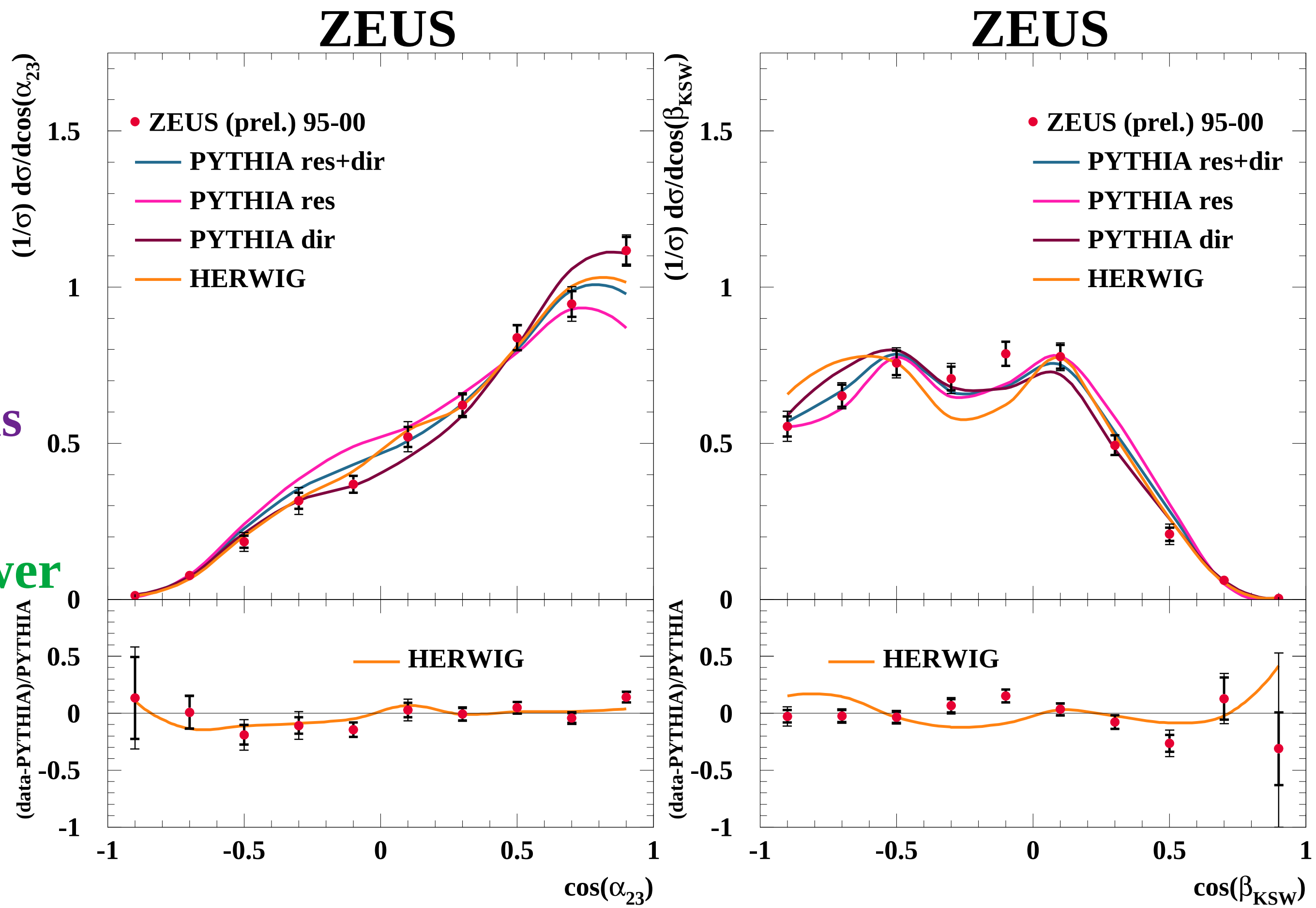
→ PYTHIA reproduces reasonably well the measured distribution

→ The distributions for direct and resolved processes ($\sim 34\%$) are very similar

# Measurement of the Distributions in $\alpha_{23}$ and $\beta_{KSW}$

- The distribution in $\alpha_{23}$ peaks at $\alpha_{23} \sim 0$
- The distribution in $\cos\beta_{KSW}$ has a broad peak between -0.5 and 0
- Comparison to the predictions of PYTHIA and HERWIG (leading-logarithm parton-shower calculations based on SU(3))

$\longrightarrow$ PYTHIA reproduces reasonably well the measured distribution




$\longrightarrow$ The distributions for direct and resolved processes are similar

- Experimental uncertainties: the statistical uncertainties are dominant

# Fixed-order Calculations for the Photoproduction of Three-Jet Events

- **Fixed-order ($\mathcal{O}(\alpha\alpha_s^2)$) calculations using the program by Klasen, Kleinwort and Kramer**

  → **direct processes only**

  → **choice of scales: $\mu_R = \mu_F = E_T^{max}$ (highest $E_T^{jet}$)**

  → **proton PDFs: MRST99 parametrisations**

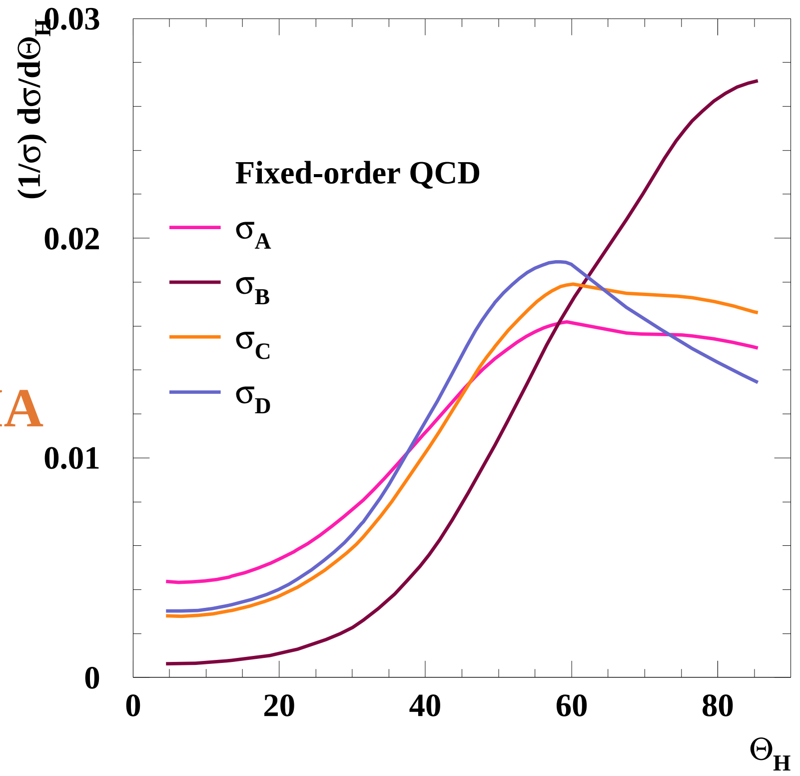
- **Parton-to-hadron corrections estimated with PYTHIA**

  ⇒ **small effect on the angular distributions ($< 5\%$)**

- **Small theoretical uncertainties**

  → **higher-order terms (by varying $\mu_R$)**

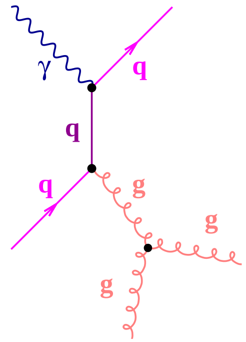
  → **uncertainties on the proton PDFs**



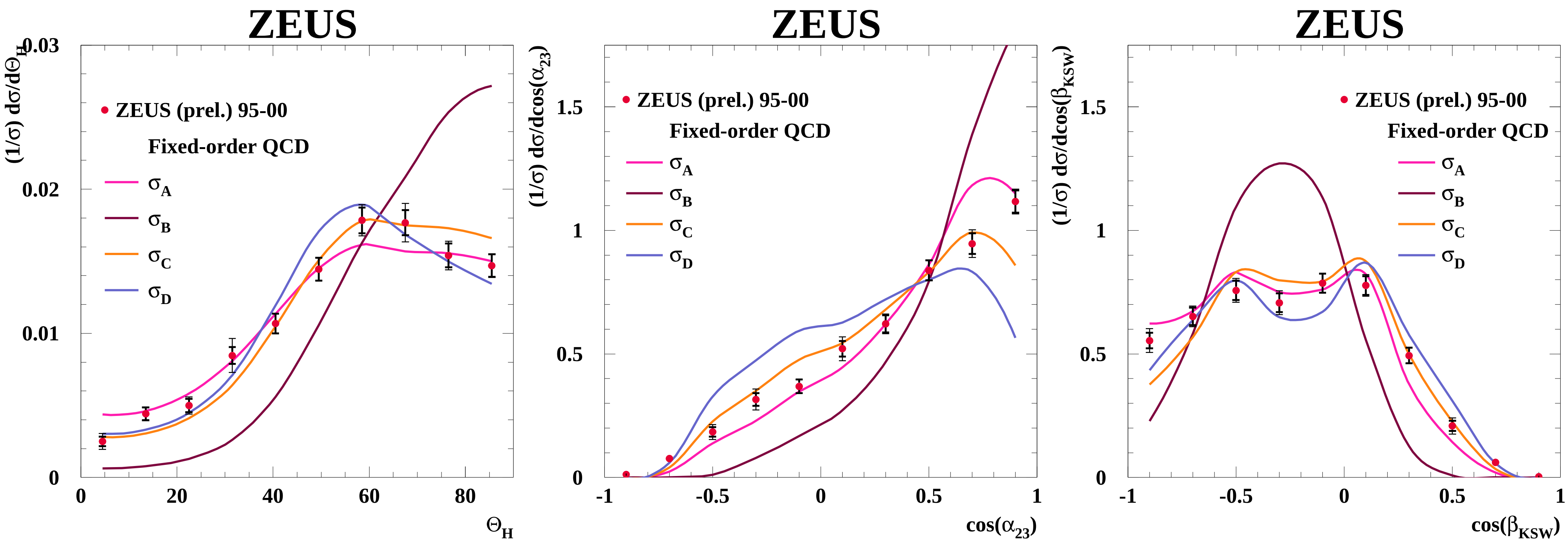

- **The program has been modified to allow the calculation for given input values of the color factors ($C_F, C_A, T_F$):**

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

- **Example: the distribution in $\theta_H$ for the contribution $\sigma_B$ (term with $C_F \cdot C_A$) is particularly distinct from the other color configurations due to diagrams →**



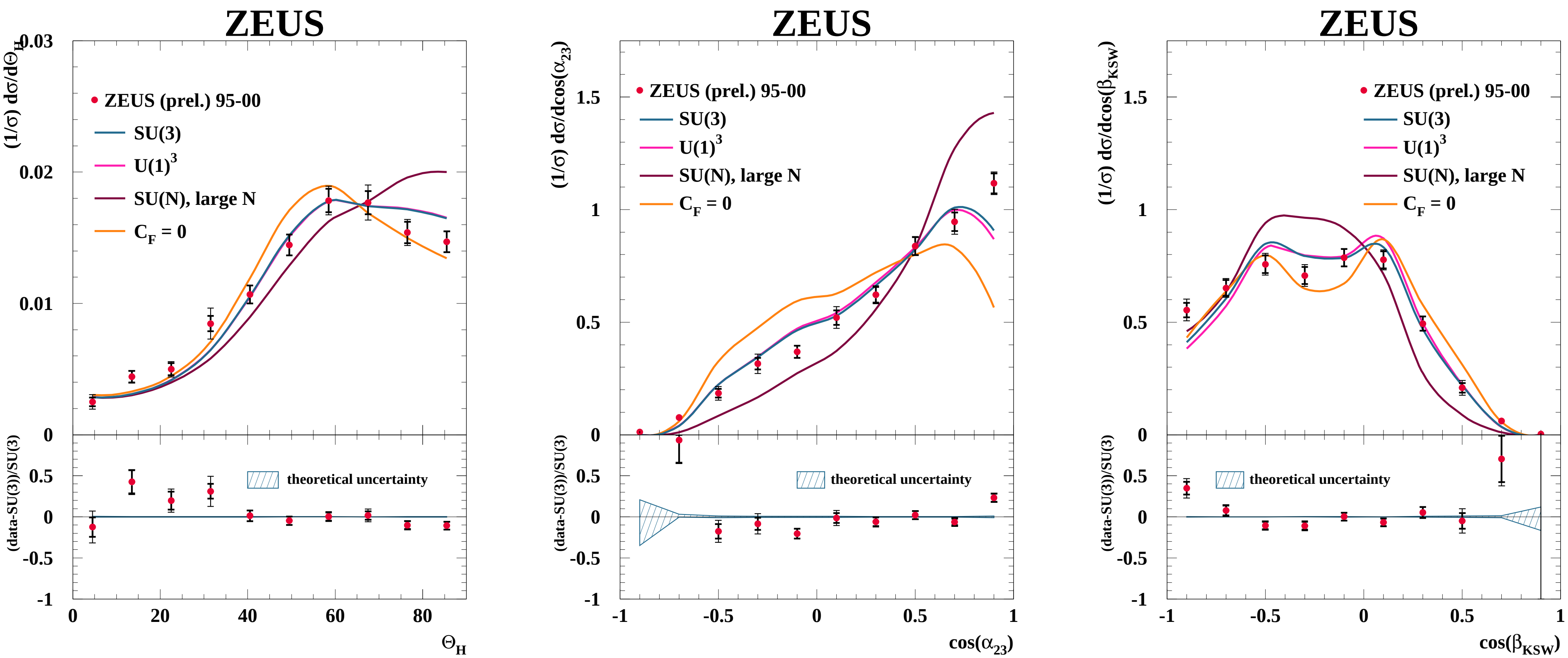
# Measurements vs Fixed-order Calculations (Contributions)




- The contribution $\sigma_B$ (term with $C_F \cdot C_A$) exhibits a very different shape than the other contributions in all three distributions ($\theta_H, \alpha_{23}, \beta_{KSW}$)
- The other contributions are better separated by the distribution of $\alpha_{23}$
- The predicted relative contributions for $SU(3)$:

  A ($C_F^2$) $\rightarrow$ 13%, B ($C_F C_A$) $\rightarrow$ 10%, C ($C_F T_F$) $\rightarrow$ 45%, D ($T_F C_A$) $\rightarrow$ 32%

# Measurements vs Fixed-order Calculations (Complete)




- **Comparison to fixed-order calculations based on differente symmetry groups $SU(3)$, $SU(N)$ with $N \gg 1$, $U(1)^3$ and the extreme choice $C_F = 0$**
- **$U(1)^3$ vs $SU(3)$: similar shapes due to the smallness of $\sigma_B$**
- **The data disfavour $T_F/C_F \approx 0$ ($SU(N \gg 1)$) or $C_F = 0$**
- **The predictions of $SU(3)$ describe reasonably well the data**

## Summary

- Measurements of angular correlations between the final-state jets (and the beam) in the photoproduction of three-jet events

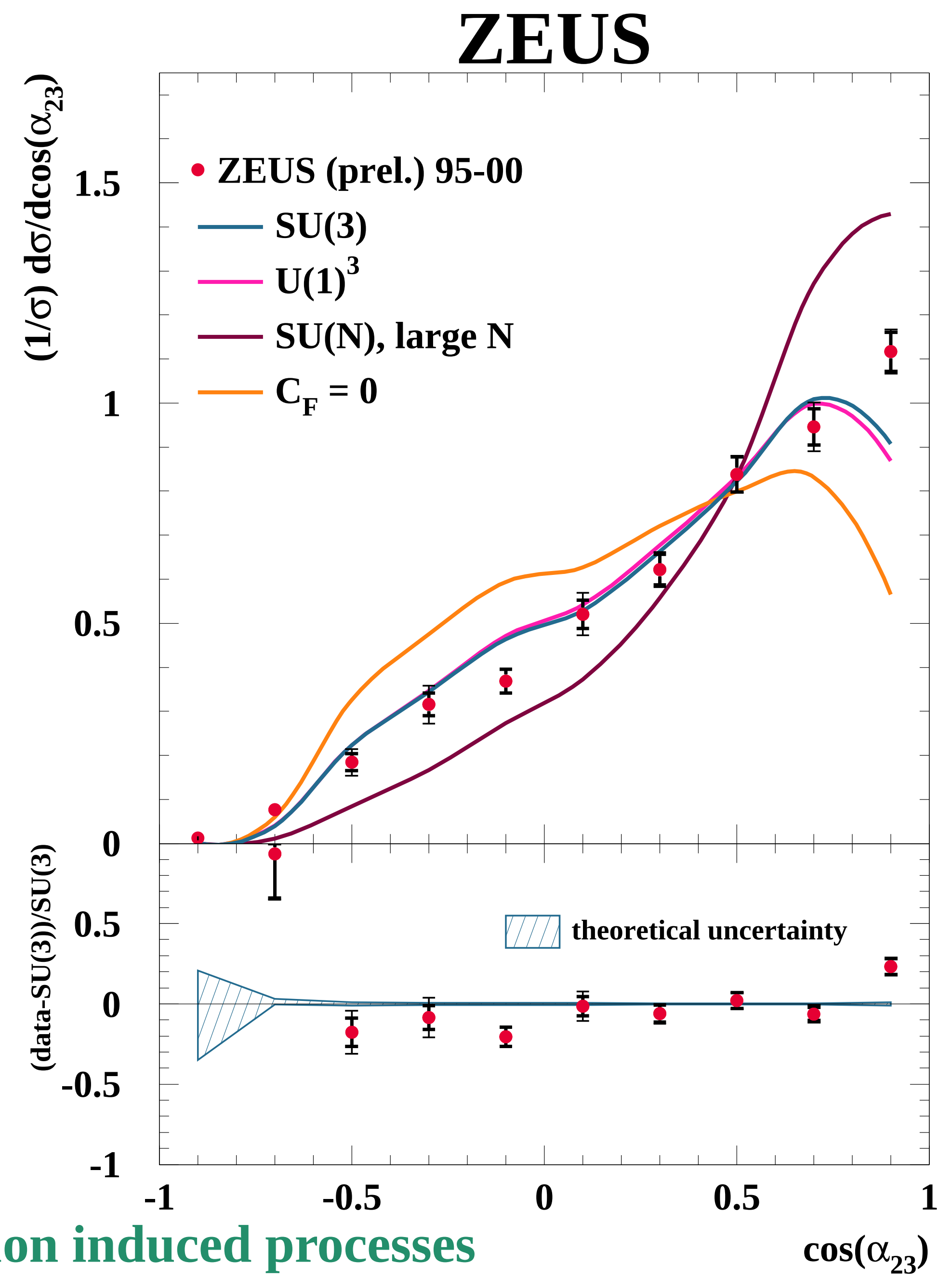
$\longrightarrow$ consistent with the admixture of color configurations predicted by $SU(3)$

- The measurements disfavour $T_F/C_F \approx 0$ as predicted by $SU(N)$ with large $N$ or the extreme choice $C_F = 0$

- The observables $\theta_H$, $\alpha_{23}$ and $\beta_{KSW}$

$\longrightarrow$ sensitivity to $C_F \cdot C_A$, but the predicted contribution is small (10%)

$\longrightarrow$ large contribution (32%) from $T_F \cdot C_A$, but not enough sensitivity




$\Rightarrow$ New variables are needed to enhance the contribution from the triple-gluon vertex in gluon induced processes