

Madison, DIS 2005

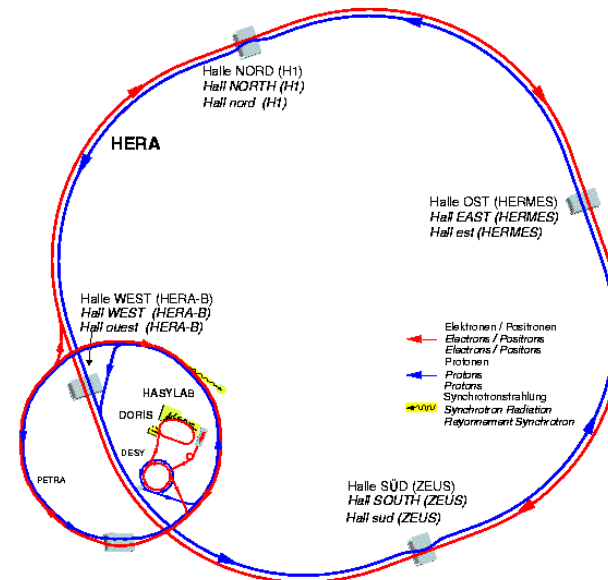
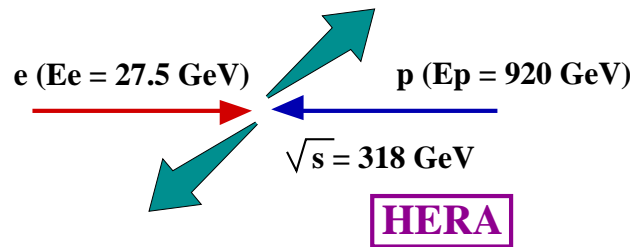
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# COLOR DYNAMICS IN PHOTOPRODUCTION OF JETS AT HERA

Juan Terrón (Universidad Autónoma de Madrid, Spain)

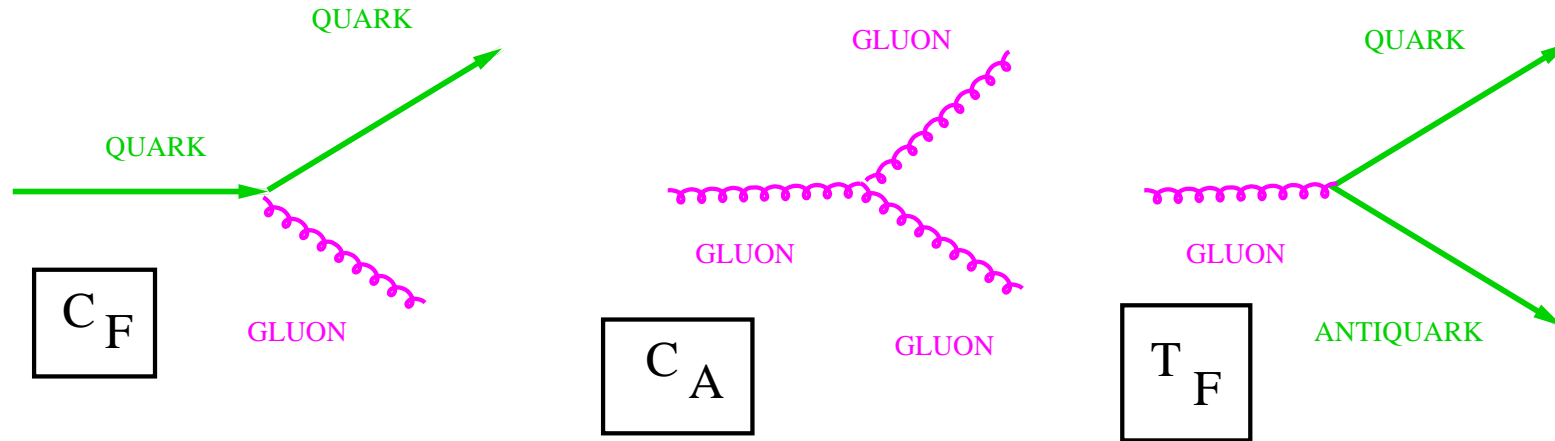


**ZEUS Collaboration**



## 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
  - 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
  - e.g. in  $e^+e^- \rightarrow 4$  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

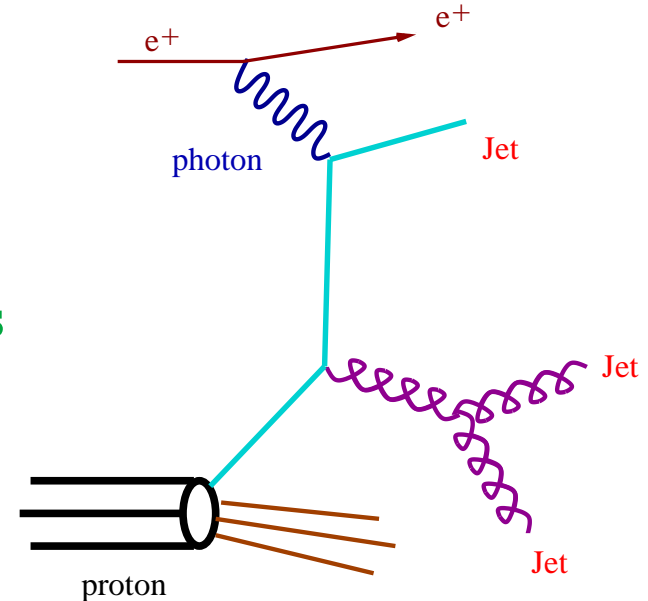
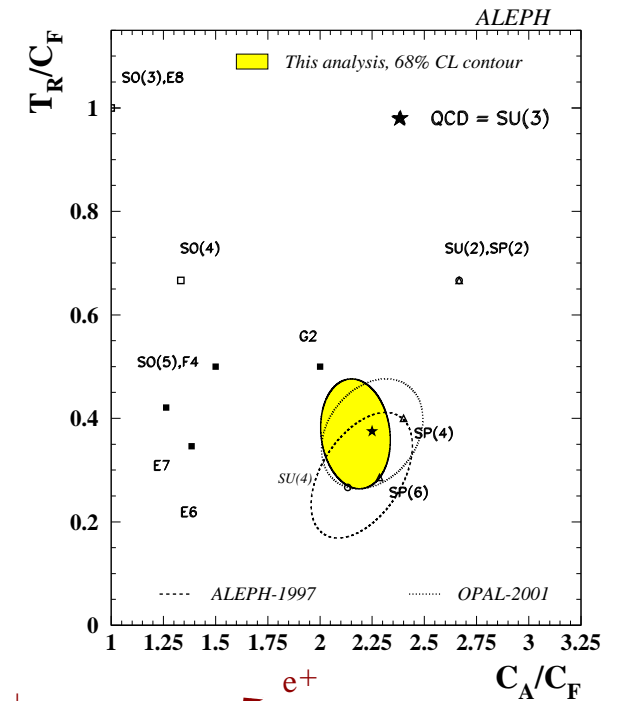
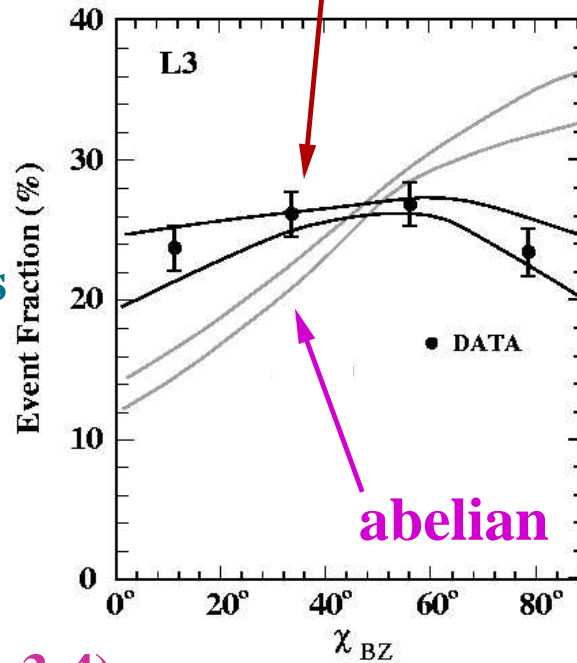
$$e^+ e^- \rightarrow 4 \text{ jets}$$

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

⇒ Determination of the ratios  $C_A/C_F$  and  $T_F/C_F$

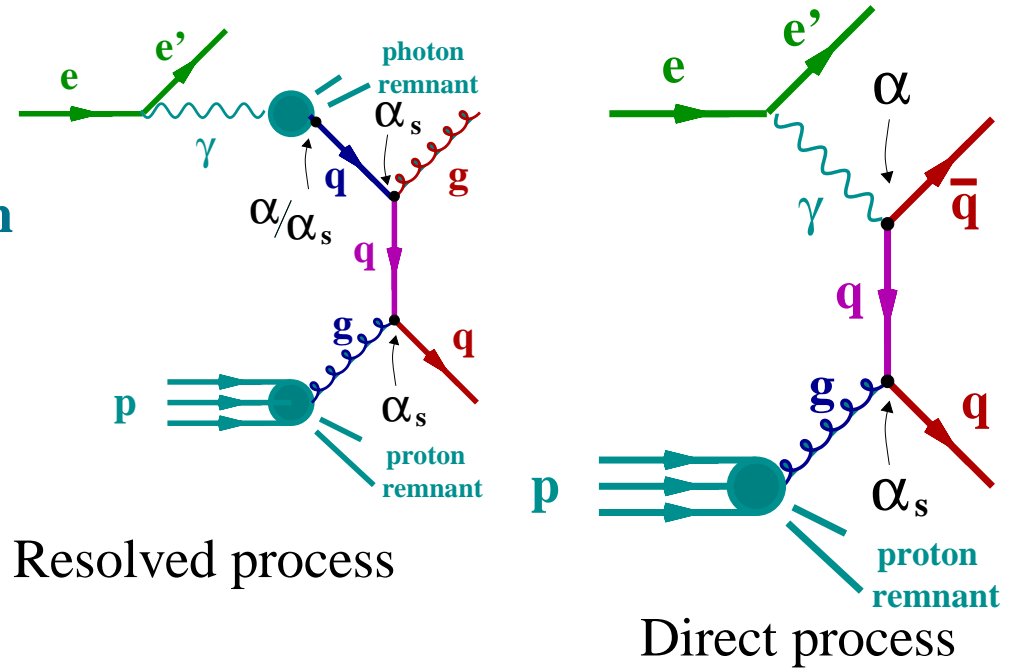
- In  $ep$  collisions at HERA, the effects of the color factors are expected in the photoproduction of three-jet events

**QCD (non-abelian)**



## Photoproduction of Jets

- 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  $\Rightarrow$
- pQCD calculations of jet cross sections



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

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

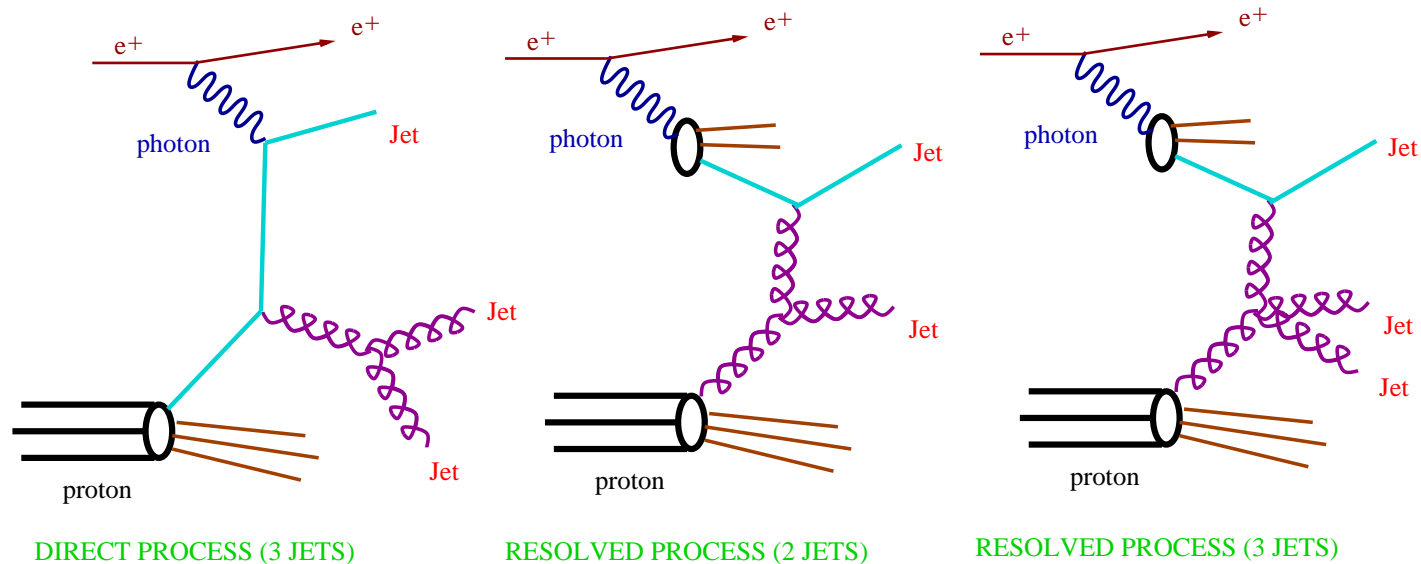
$\rightarrow f_{\gamma/e}(y)$  = flux of photons in the positron ( $WW$  approximation)

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

$\rightarrow f_{b/p}(x_p, \mu_{Fp}^2)$  = **parton densities in the proton**

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

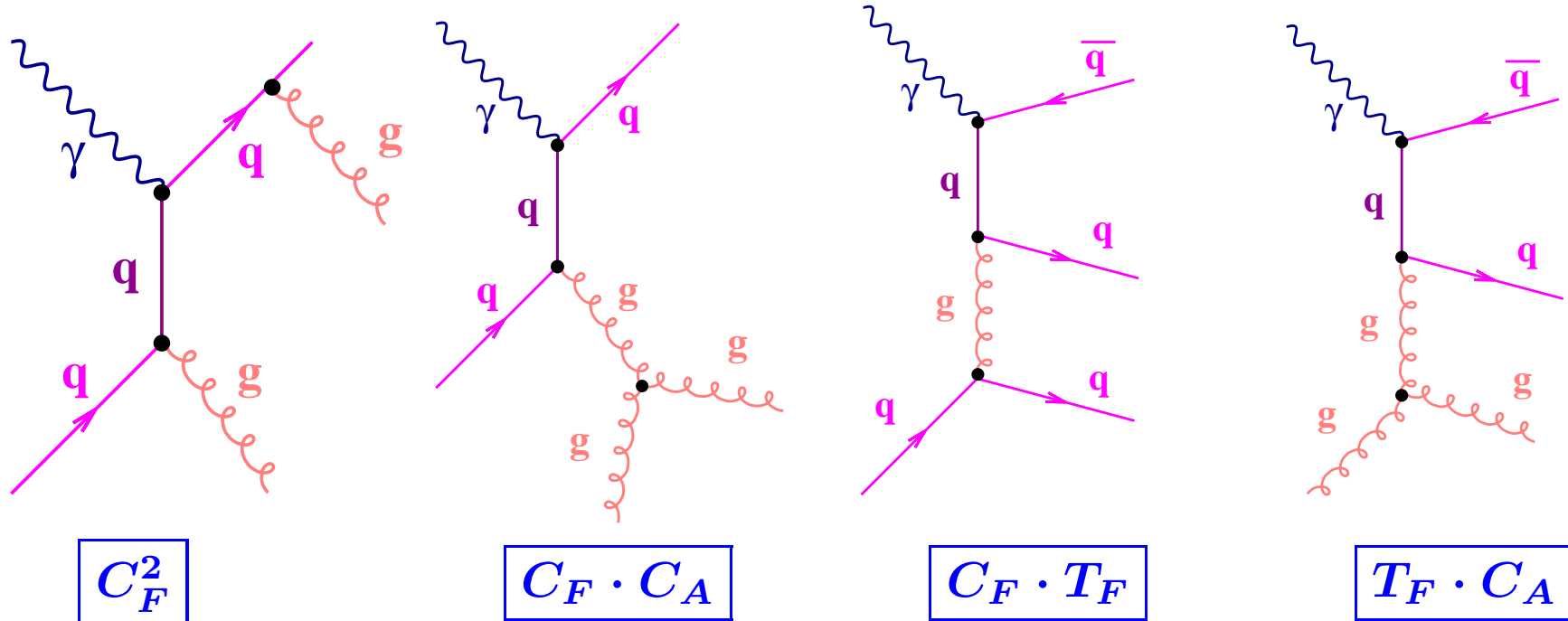
## Color Factors: Direct vs Resolved Processes



- 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 ⇒ 
$$x_\gamma^{obs}(3jets) = \frac{1}{2E_\gamma} \sum_{i=1}^3 E_T^{jet_i} e^{-\eta^{jet_i}}$$

## Photoproduction of Three-Jet Events

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



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

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

## Photoproduction of Three-Jet Events

- **Variables** to highlight the contributions from the different color configurations

⇒ **angular correlations between the jets**

→  $\theta_H$ , the angle between the plane determined by the highest  $E_T^{\text{jet}}$  and the beam and the plane determined by the two lowest  $E_T^{\text{jet}}$  jets (Muñoz-Tapia, Stirling);

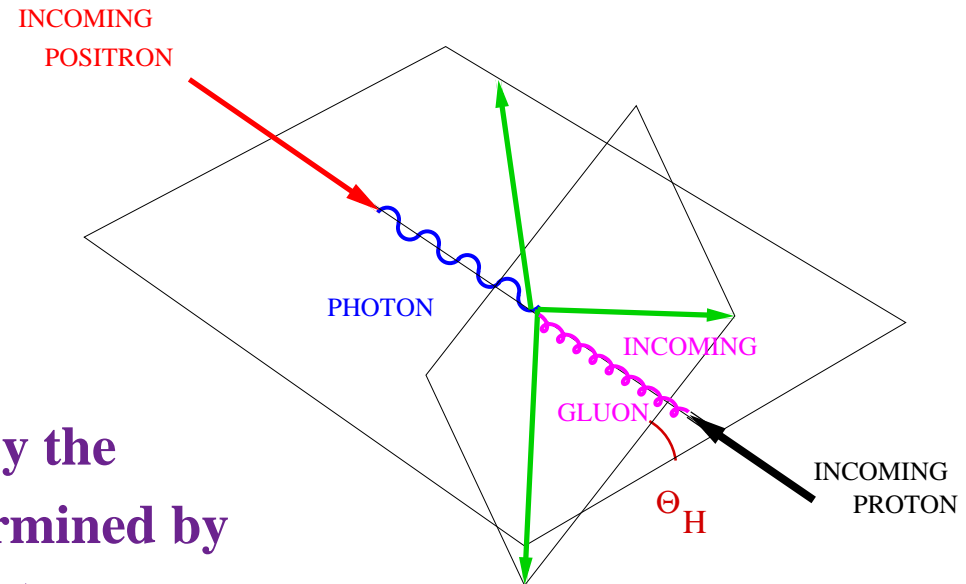
→  $\alpha_{23}$ , the angle between the two lowest  $E_T^{\text{jet}}$  jets;  
(inspired by the variable  $\alpha_{34}^{e^+e^-}$  for  $e^+e^- \rightarrow 4\text{jets}$ )

→  $\beta_{KSW}$ , 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  $E_T^{\text{jet}}$ ) and  $\vec{p}_B$  is a unit vector in the direction of the proton beam;

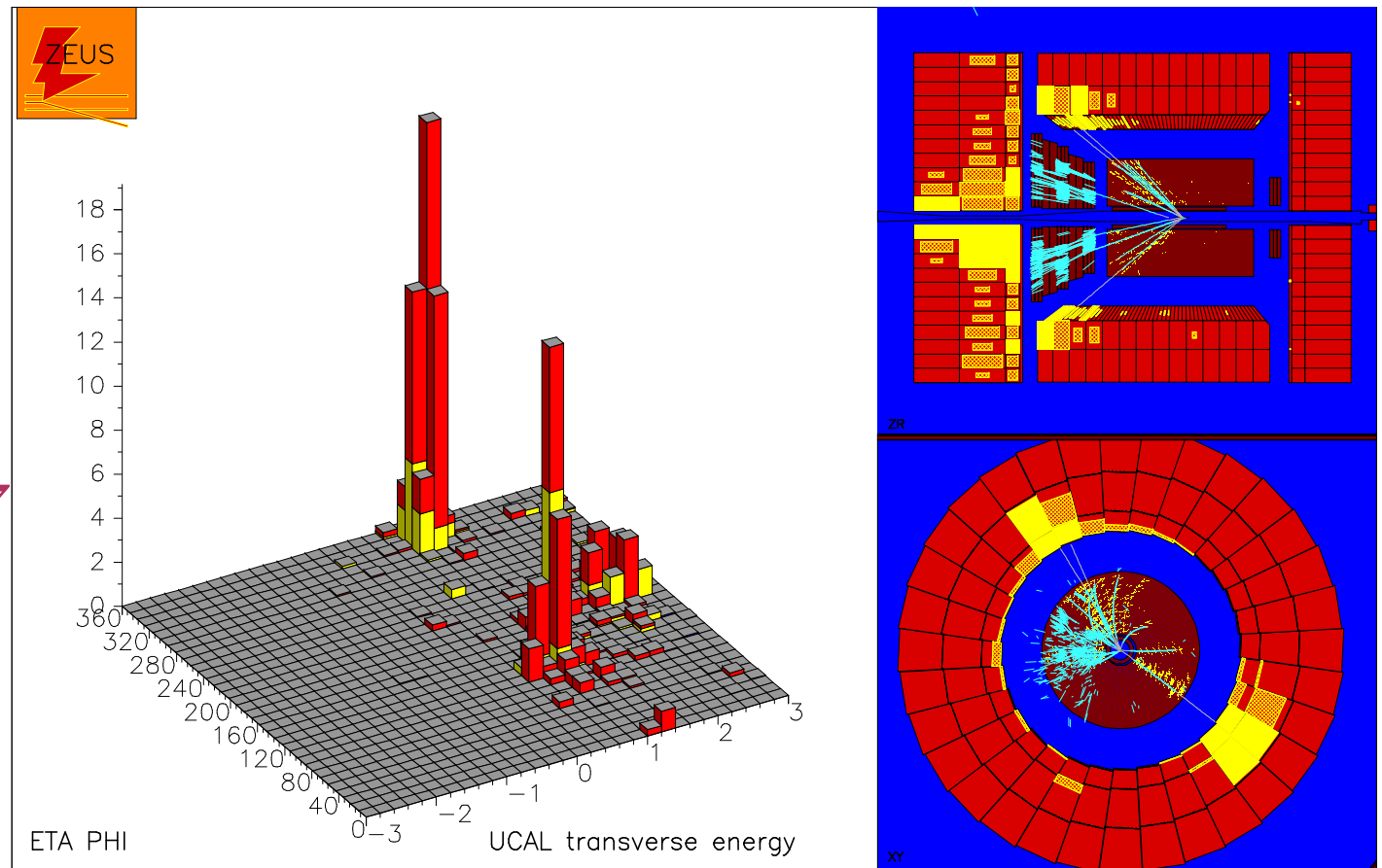
(inspired by the Körner-Schierholz-Willrodt angle  $\Phi_{KSW}^{e^+e^-}$  for  $e^+e^- \rightarrow 4\text{jets}$ )



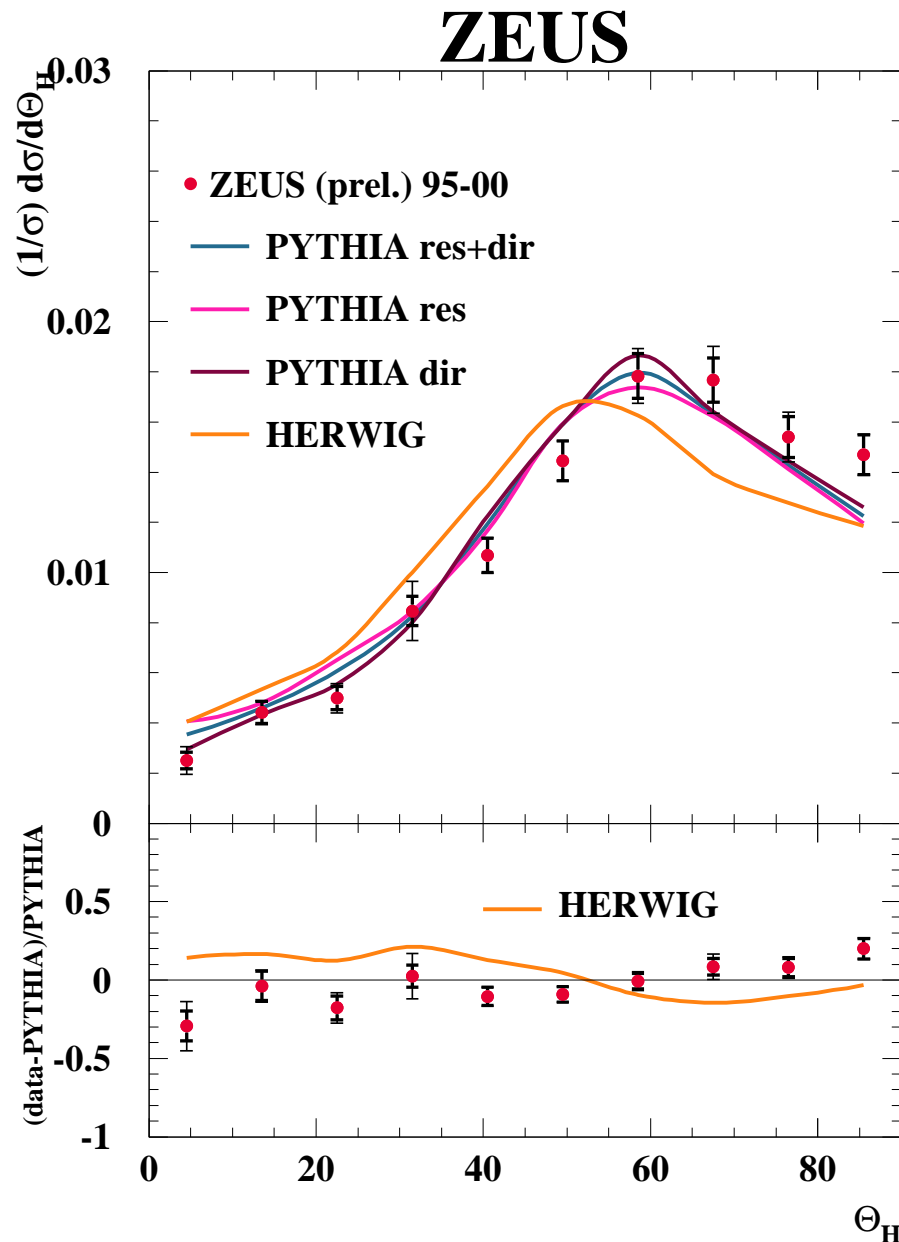
# Measurements of Three-Jet Events in Photoproduction

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

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



# 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

$$E_T^{\text{jet}} > 14 \text{ GeV}, -1 < \eta^{\text{jet}} < 2.5$$

$$\text{and } x_\gamma^{\text{obs}}(3\text{jets}) > 0.7$$

- in the kinematic region

$$Q^2 < 1 \text{ GeV}^2 \text{ and } 0.2 < y < 0.85$$

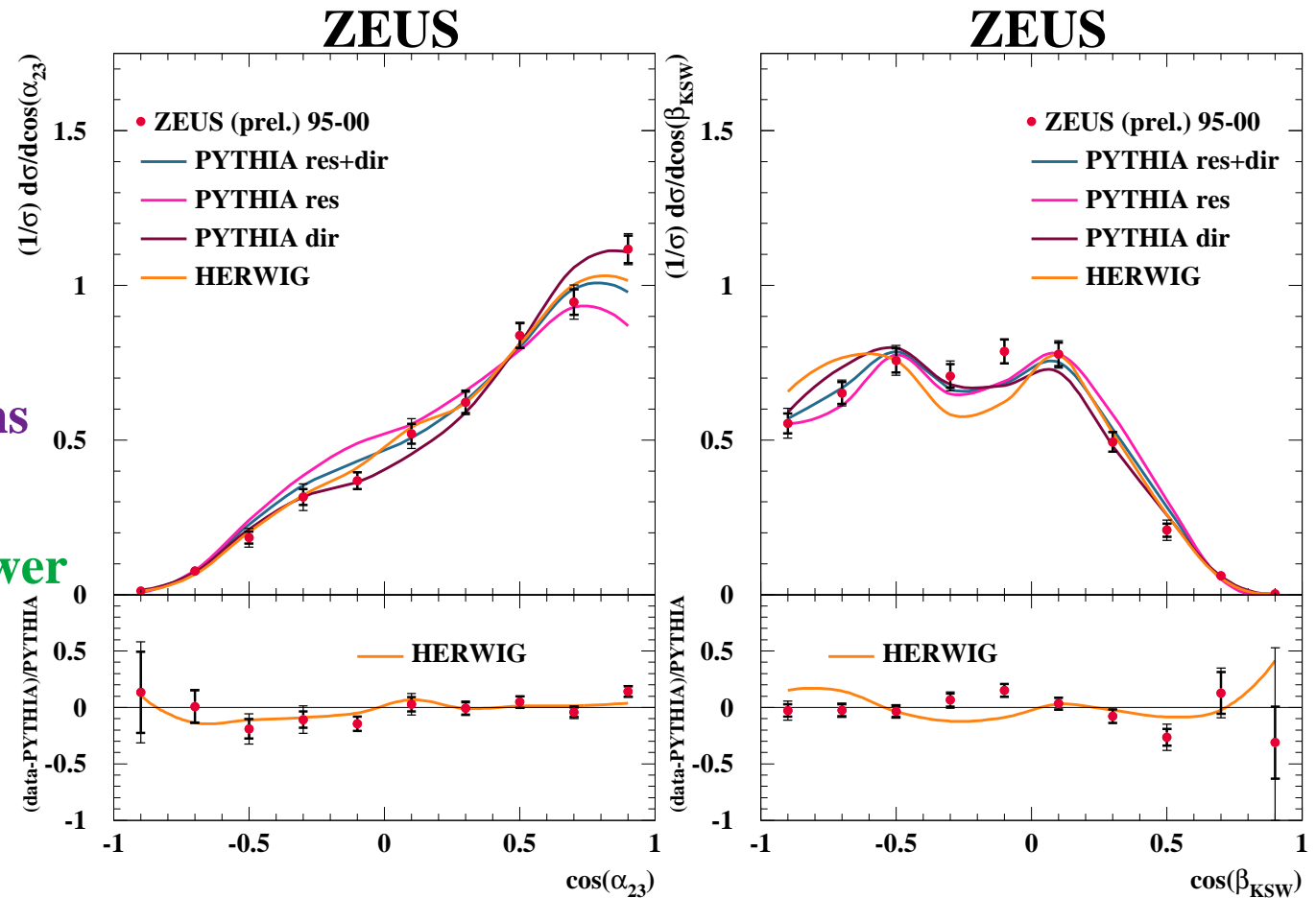
- Comparison to the predictions of PYTHIA and HERWIG (leading-logarithm parton-shower calculations based on SU(3))

→ 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))
- PYTHIA reproduces reasonably well the measured distribution



→ 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  $E_T^{\text{jet}}$ )

→ proton PDFs: MRST99 parametrisations

- Parton-to-hadron corrections estimated with PYTHIA

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

- Small theoretical uncertainties

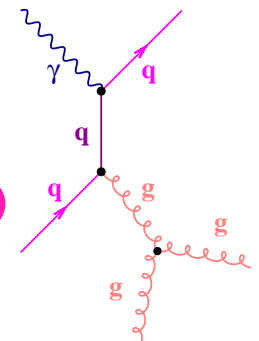
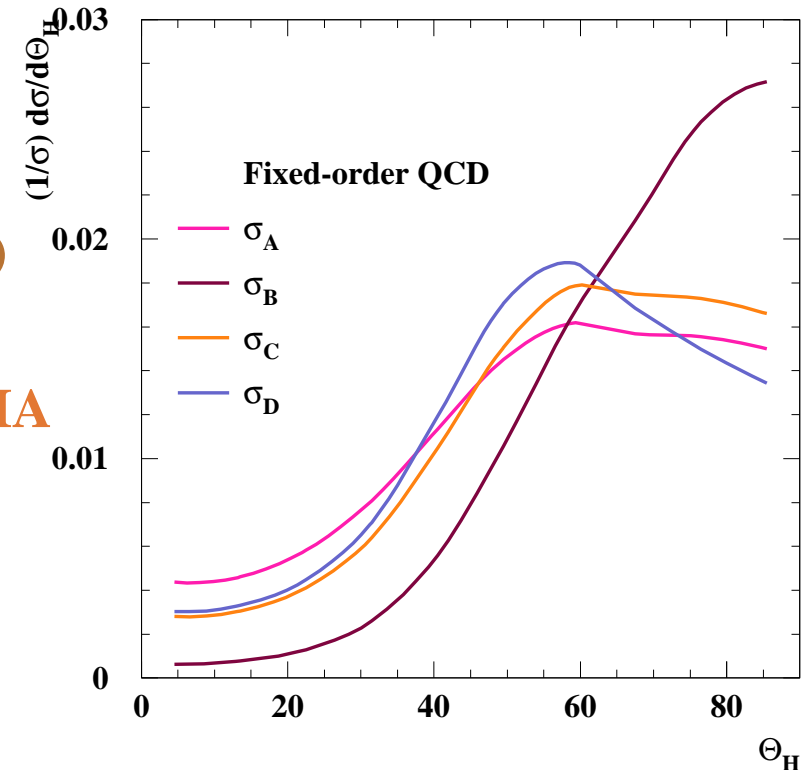
→ higher-order terms (by varying  $\mu_R$ )

→ uncertainties on the proton PDFs

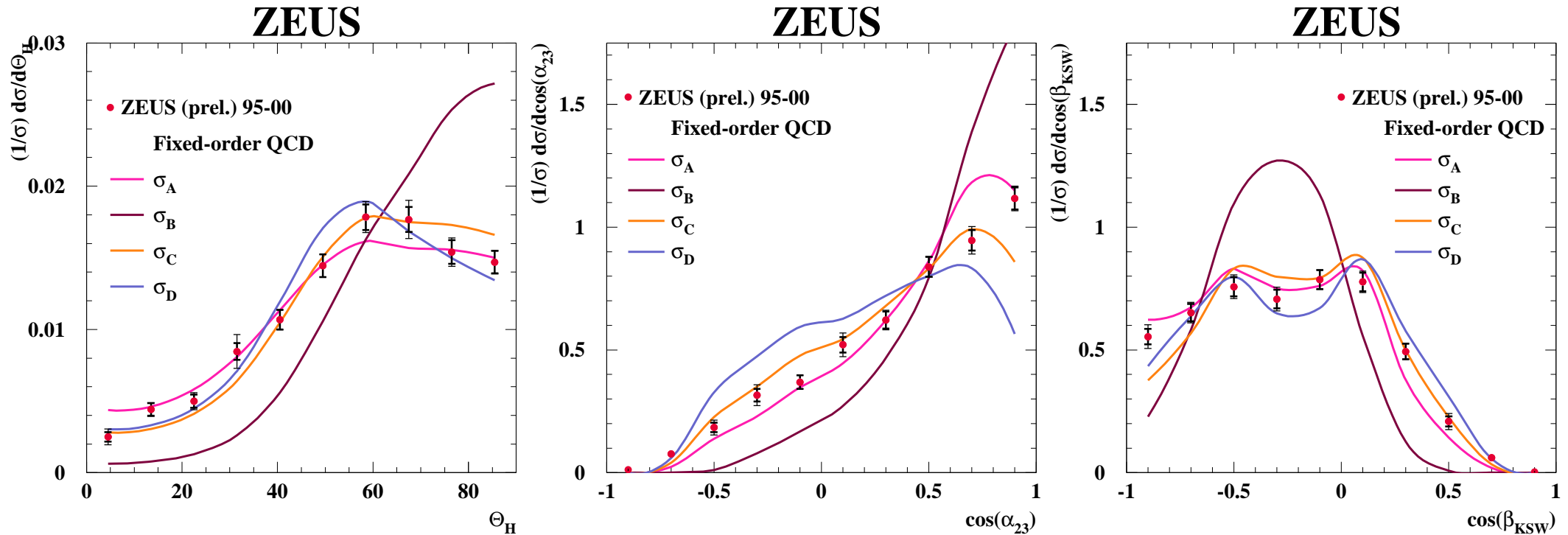
- The program has been modified to allow the calculation for given input values of the color factors ( $C_F, C_A, T_F$ ):

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

- 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 →



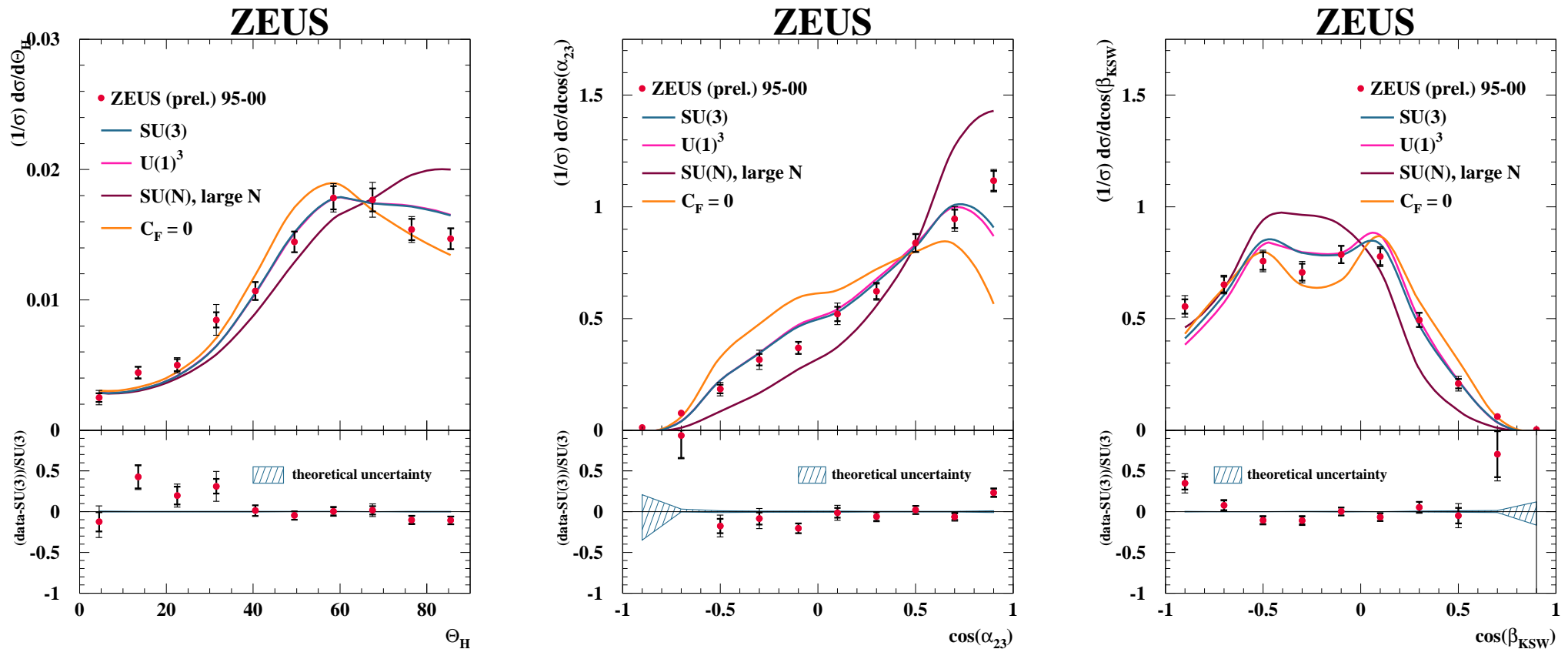
# Measurements vs Fixed-order Calculations (Contributions)



- 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 different 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 → 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  $\beta_{KSW}$  → sensitivity to  $C_F \cdot C_A$ , but the predicted contribution is small (10%) → large contribution (32%) from  $T_F \cdot C_A$ , but not enough sensitivity ⇒ New variables are needed to enhance the contribution from the triple-gluon vertex in gluon induced processes

