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COLOR DYNAMICS IN PHOTOPRODUCTION OF JETS AT HERA

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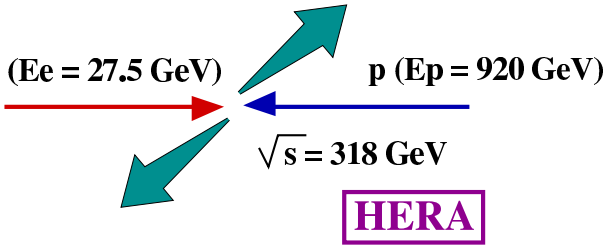
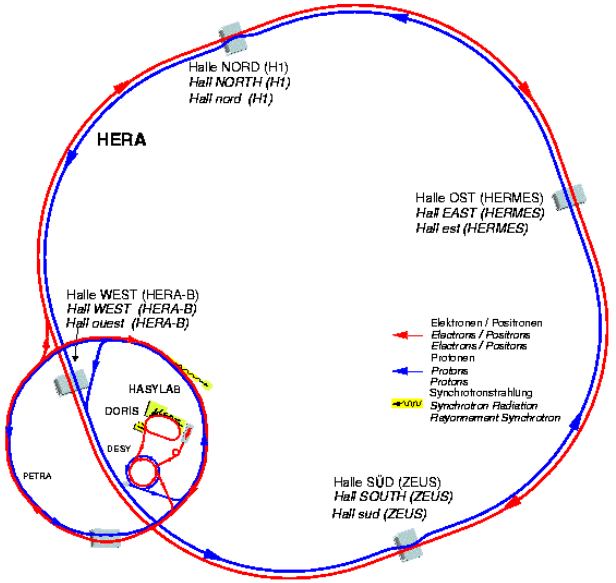
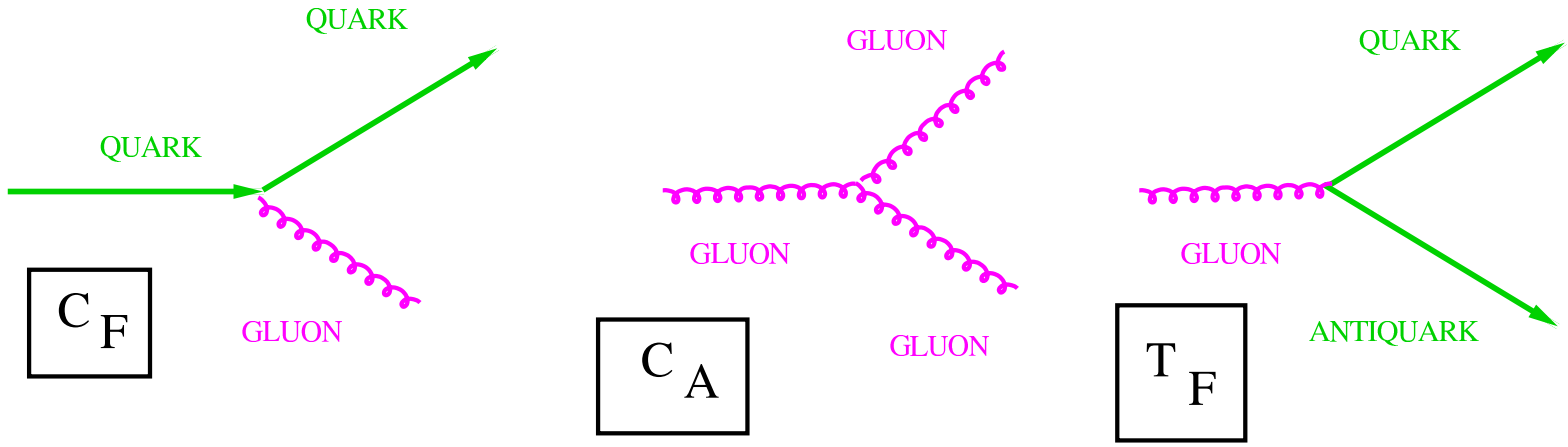




ZEUS Collaboration

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
  → 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 $e^+e^- \to 4$ 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

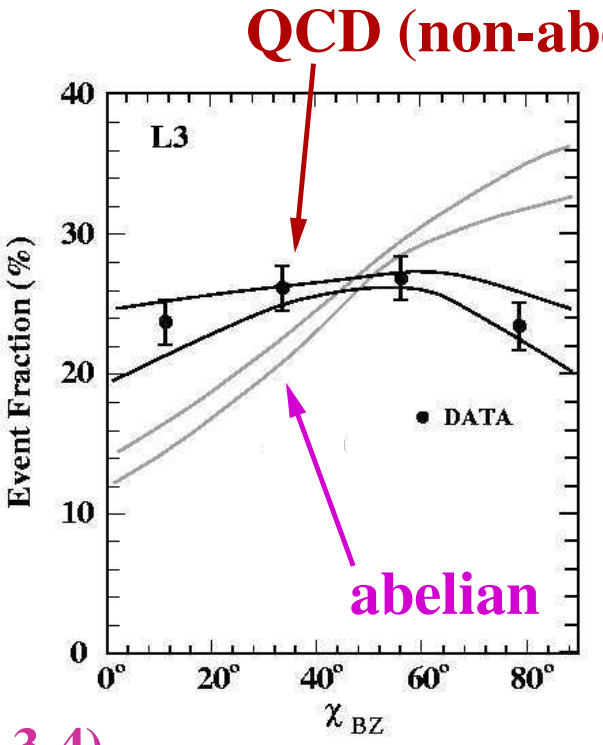
Color Factors

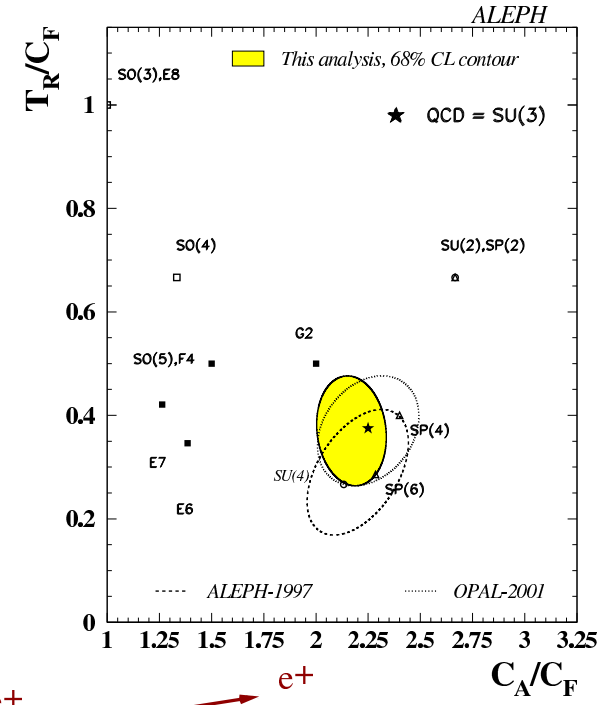
- The effects of color factors have been extensively studied at LEP by measuring the angular correlations between the final state jets in

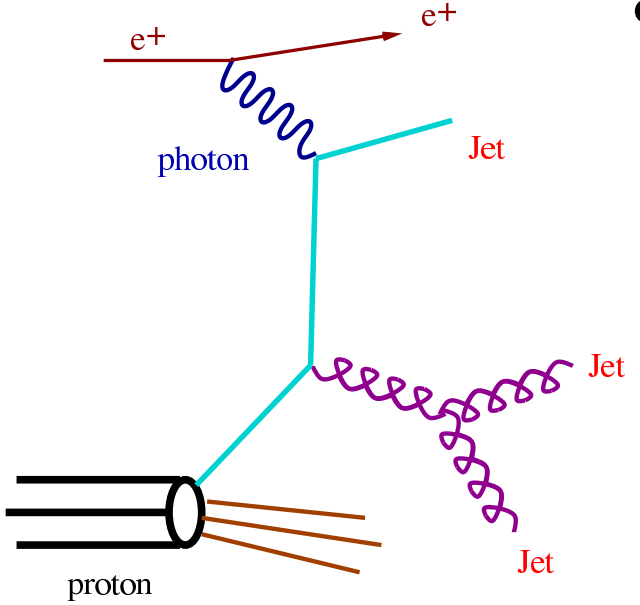
$$e^+e^- \rightarrow 4 \text{ jets}$$

(e.g. using the Bengtsson-Zerwas variable χ_{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



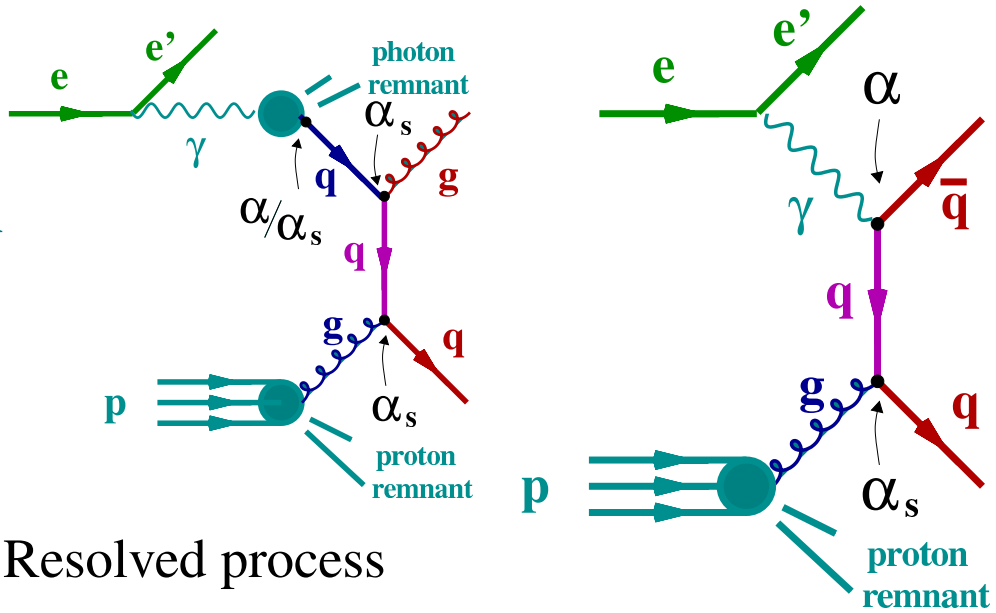




- In ep collisions at HERA, the effects of the color factors are expected in the photoproduction of three-jet events

Photoproduction of Jets

- Production of jets in γp 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



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

longitudinal momentum fraction of γ/e^+ (y), parton a/γ (x_γ), parton b/proton (x_p)

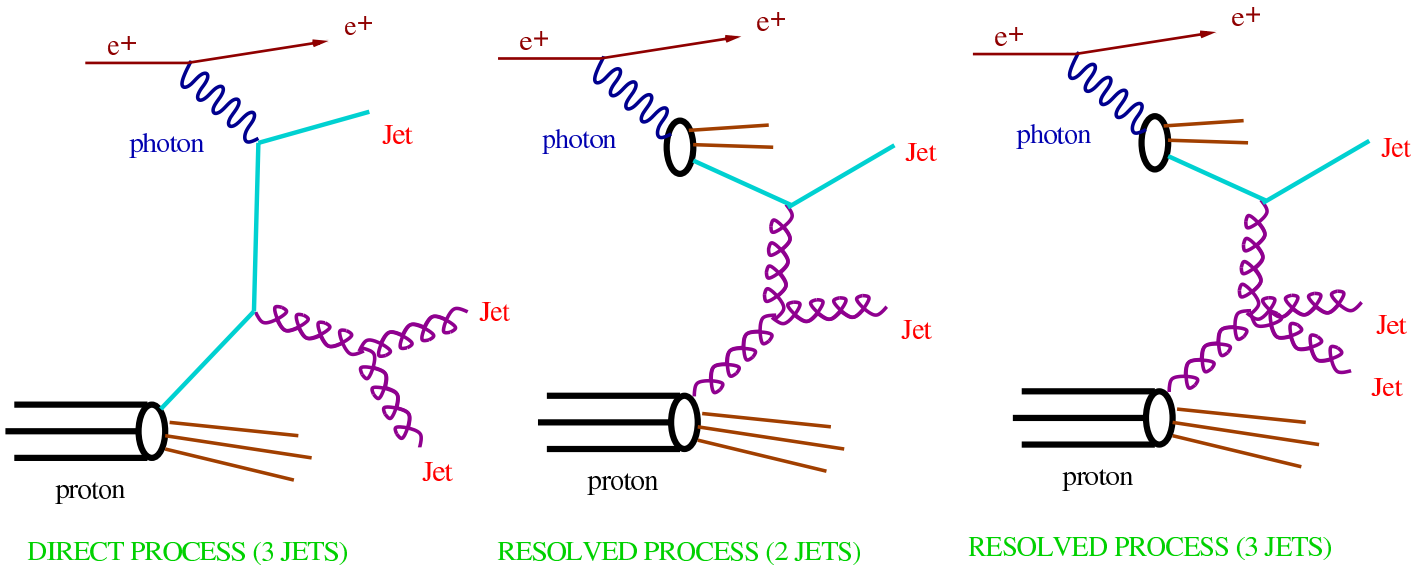
$\rightarrow$ $f_{\gamma/e}(y)$ = flux of photons in the positron (WW approximation)

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

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

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

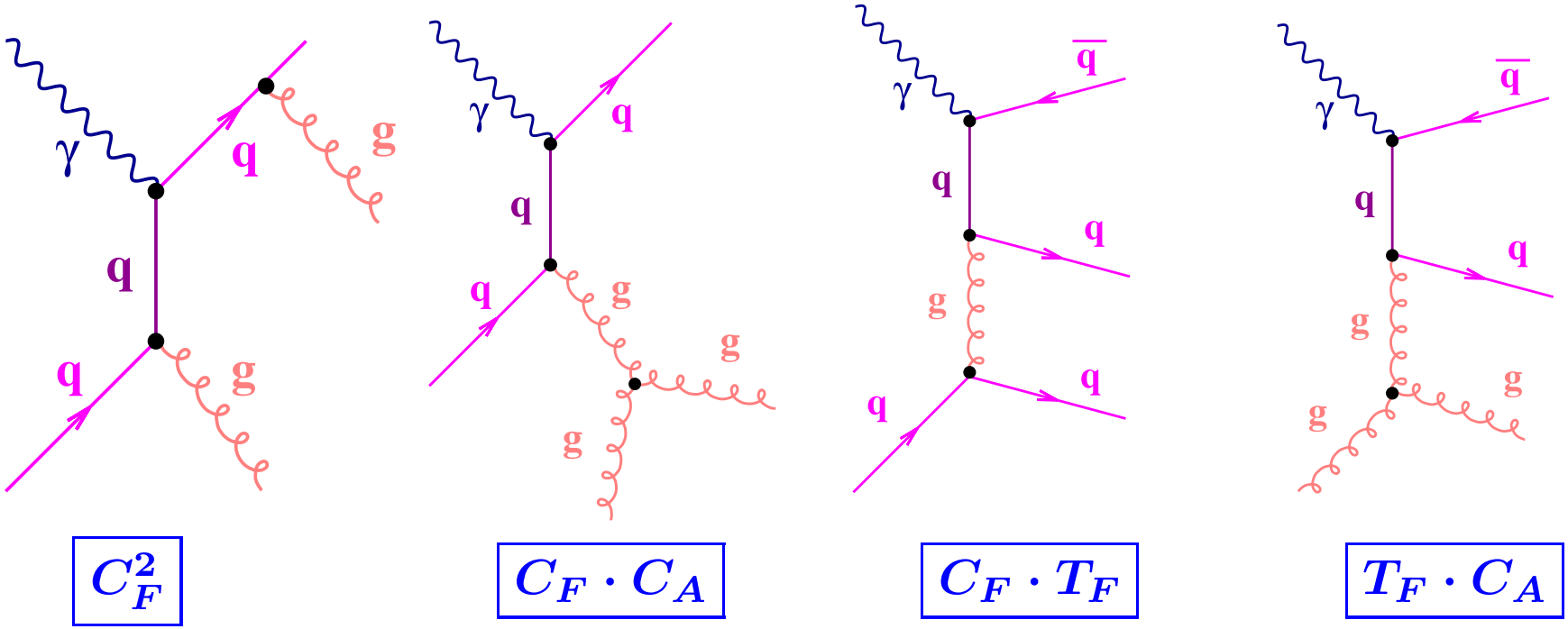
Color Factors: Direct vs Resolved Processes



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

Photoproduction of Three-Jet Events

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

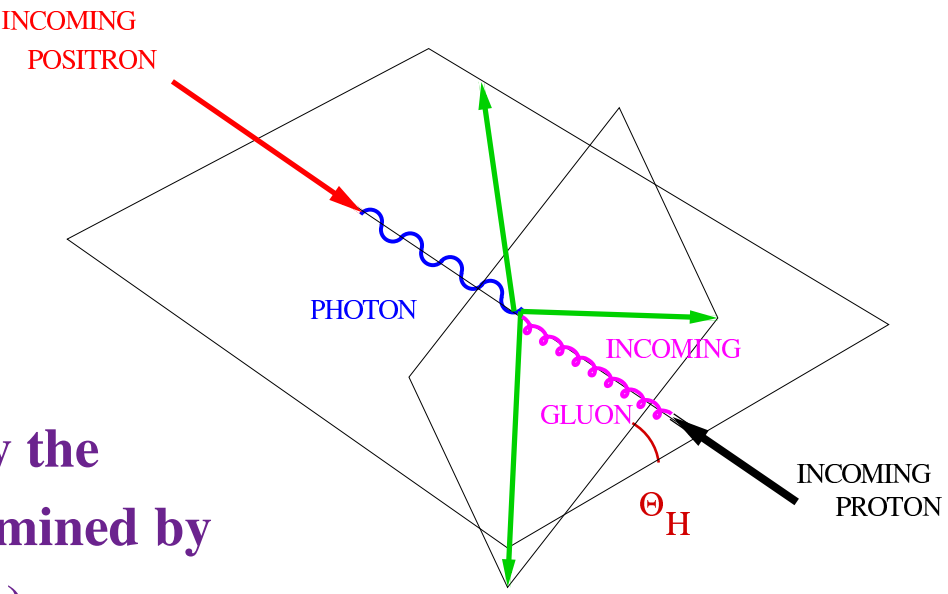


C_F^2 $C_F \cdot C_A$ $C_F \cdot T_F$ $T_F \cdot C_A$

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

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

Photoproduction of Three-Jet Events



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

$\rightarrow$ 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);

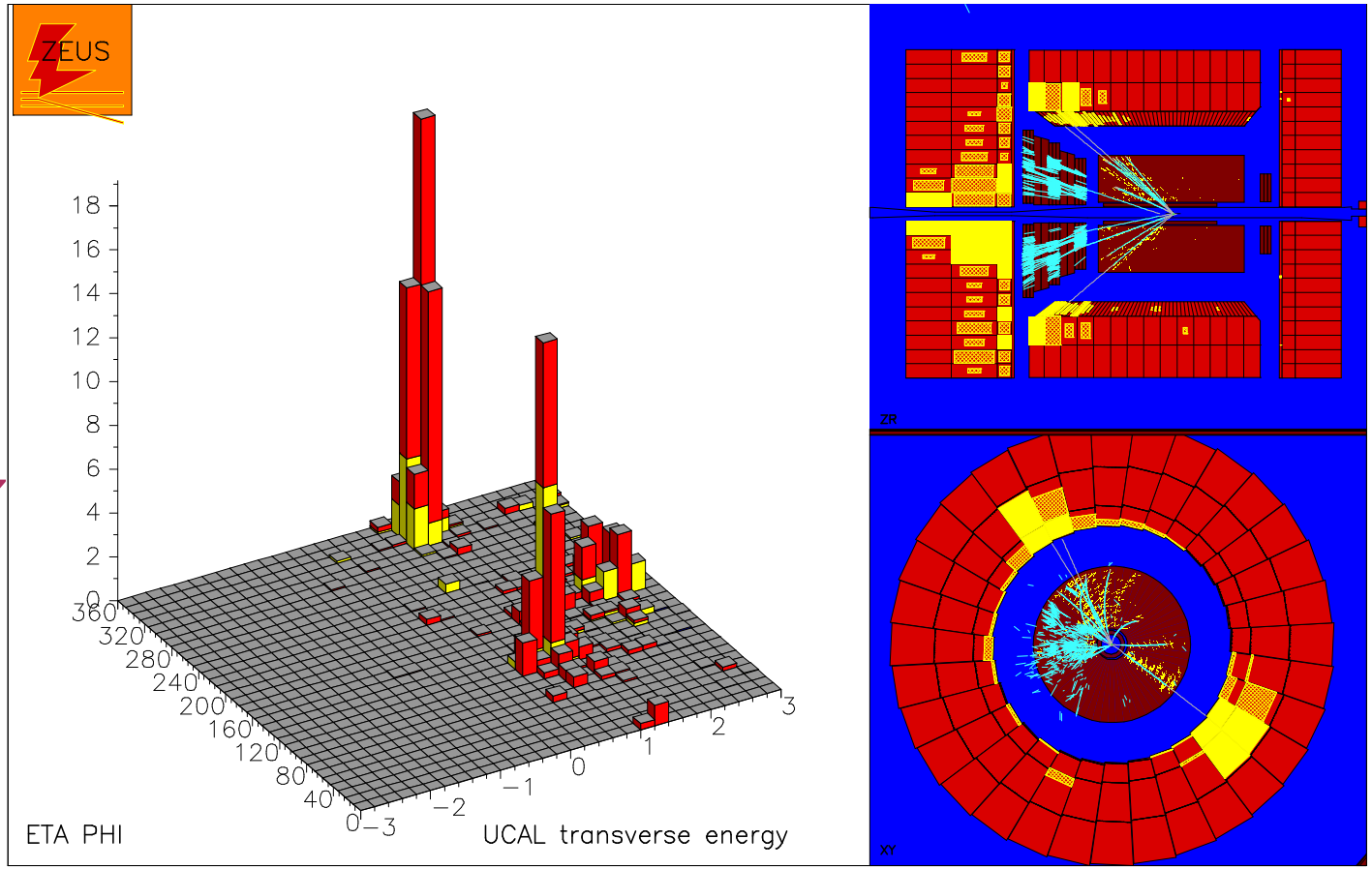
$\rightarrow$ α_{23}, the angle between the two lowest $E_T^{\rm jet}$ jets;
(inspired by the variable $\alpha_{34}^{e^+e^-}$ for $e^+e^- \rightarrow 4$jets)

$\rightarrow$ 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 $e^+e^- \rightarrow 4$jets)

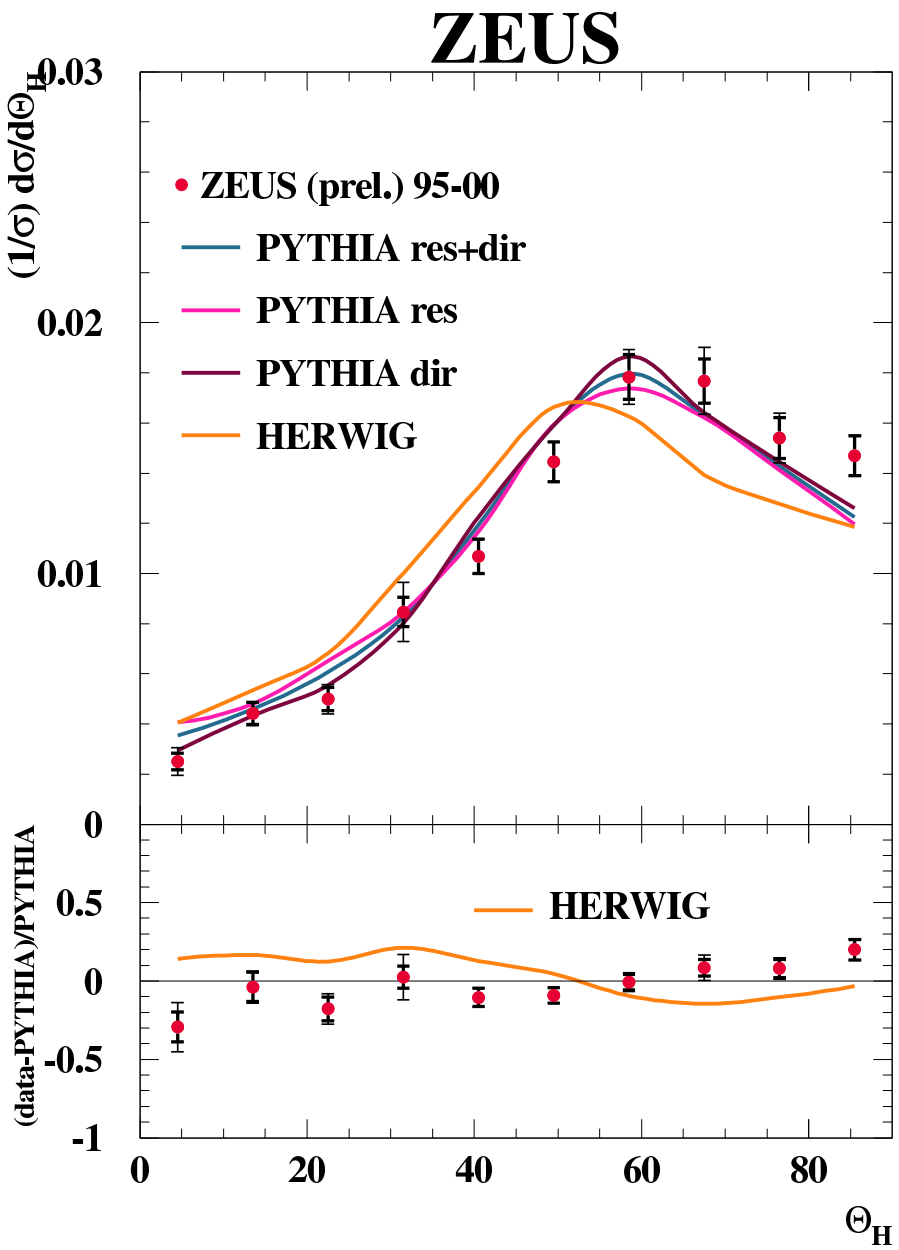
Measurements of Three-Jet Events in Photoproduction

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

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



Measurement of the Distribution in θ_H



- Measurement of the normalised cross section $1/\sigma \; d\sigma/d\theta_H$ for the production of events with three jets satisfying
  $E_T^{\text{jet}} > 14$ GeV, $-1 < \eta^{\text{jet}} < 2.5$
  and $x_\gamma^{\text{obs}}(3\text{jets}) > 0.7$
  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))

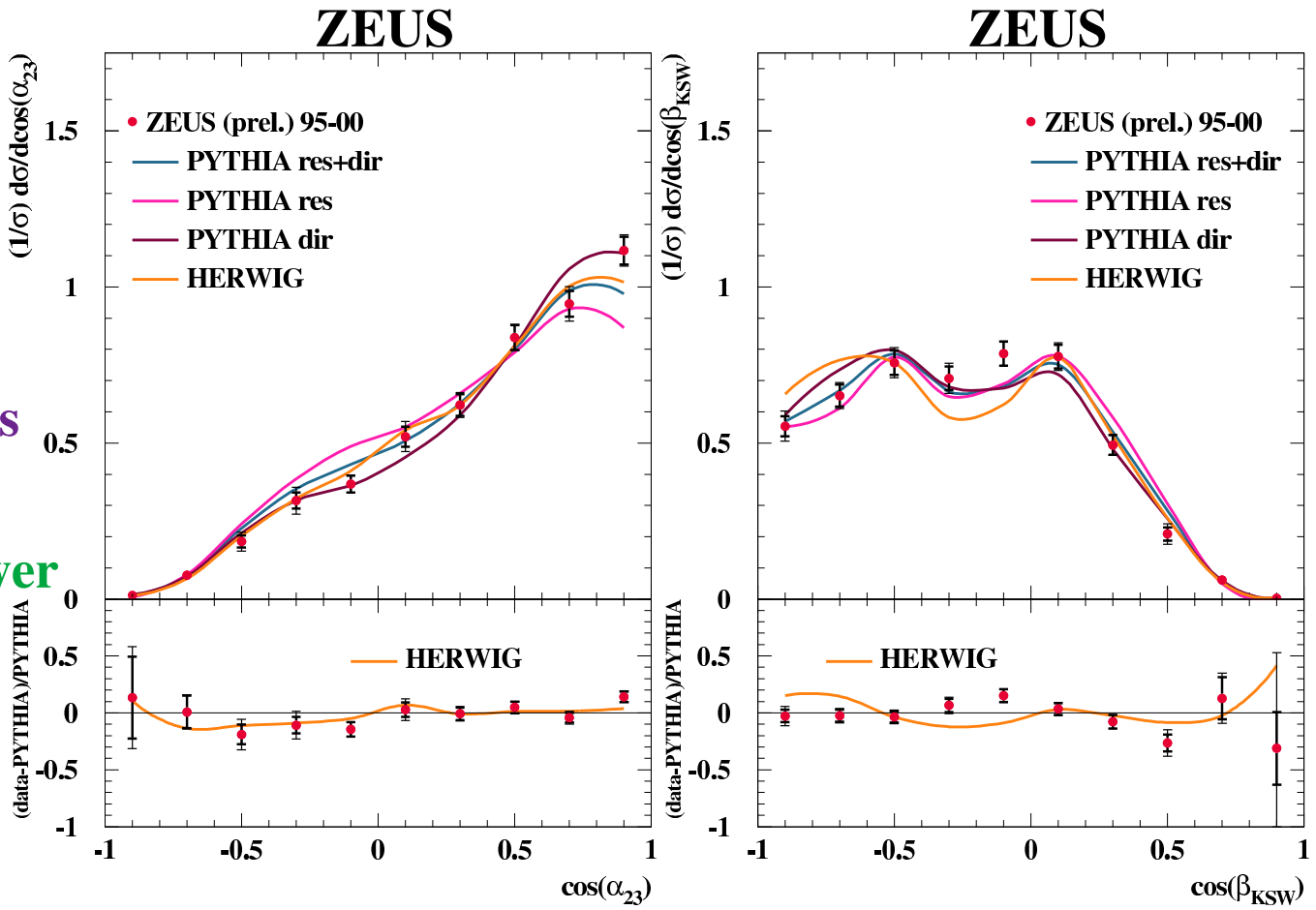
→ PYTHIA reproduces reasonably well the measured distribution

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

Measurement of the Distributions in α_{23} and β_{KSW}

- The distribution in α_{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^{jet})

→ proton PDFs: MRST99 parametrisations

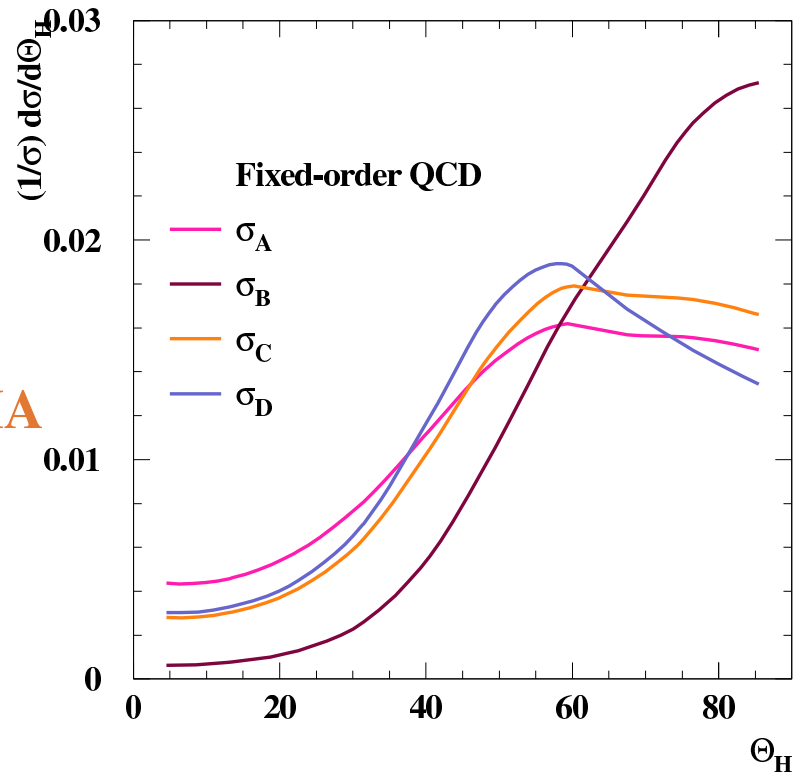
- Parton-to-hadron corrections estimated with PYTHIA

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

- Small theoretical uncertainties

→ higher-order terms (by varying μ_R)

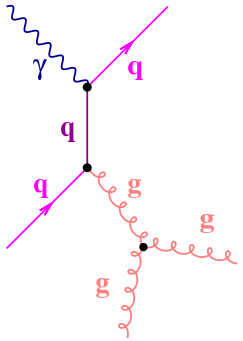
→ uncertainties on the proton PDFs



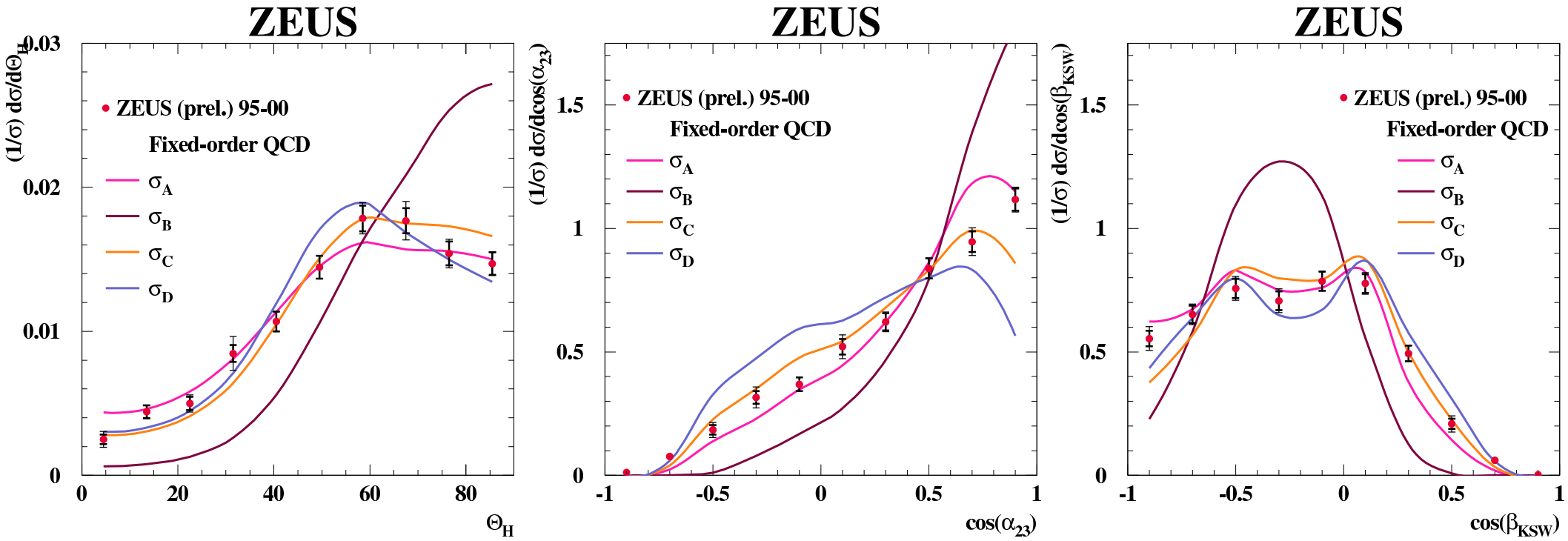
- The program has been modified to allow the calculation for given input values of the color factors (C_F, C_A, T_F):

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

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



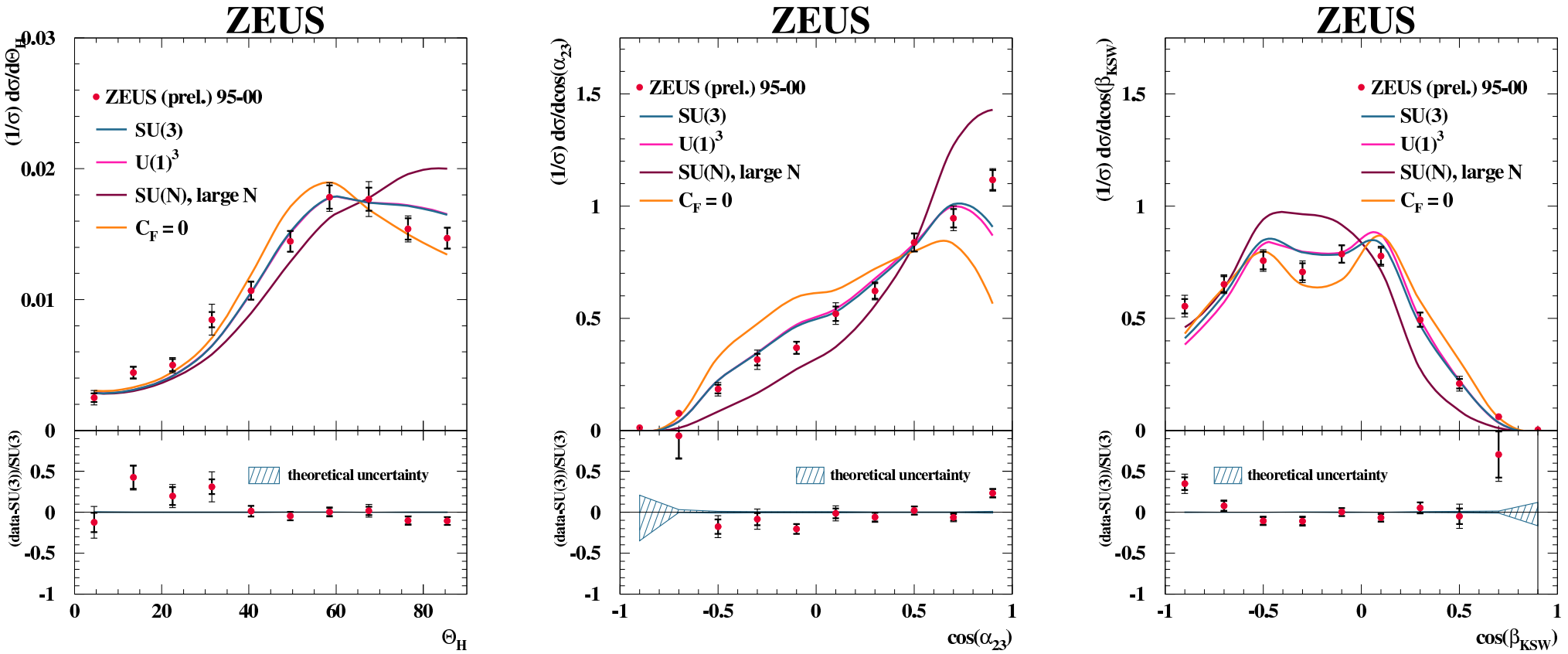
Measurements vs Fixed-order Calculations (Contributions)



- The contribution σ_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 α_{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%

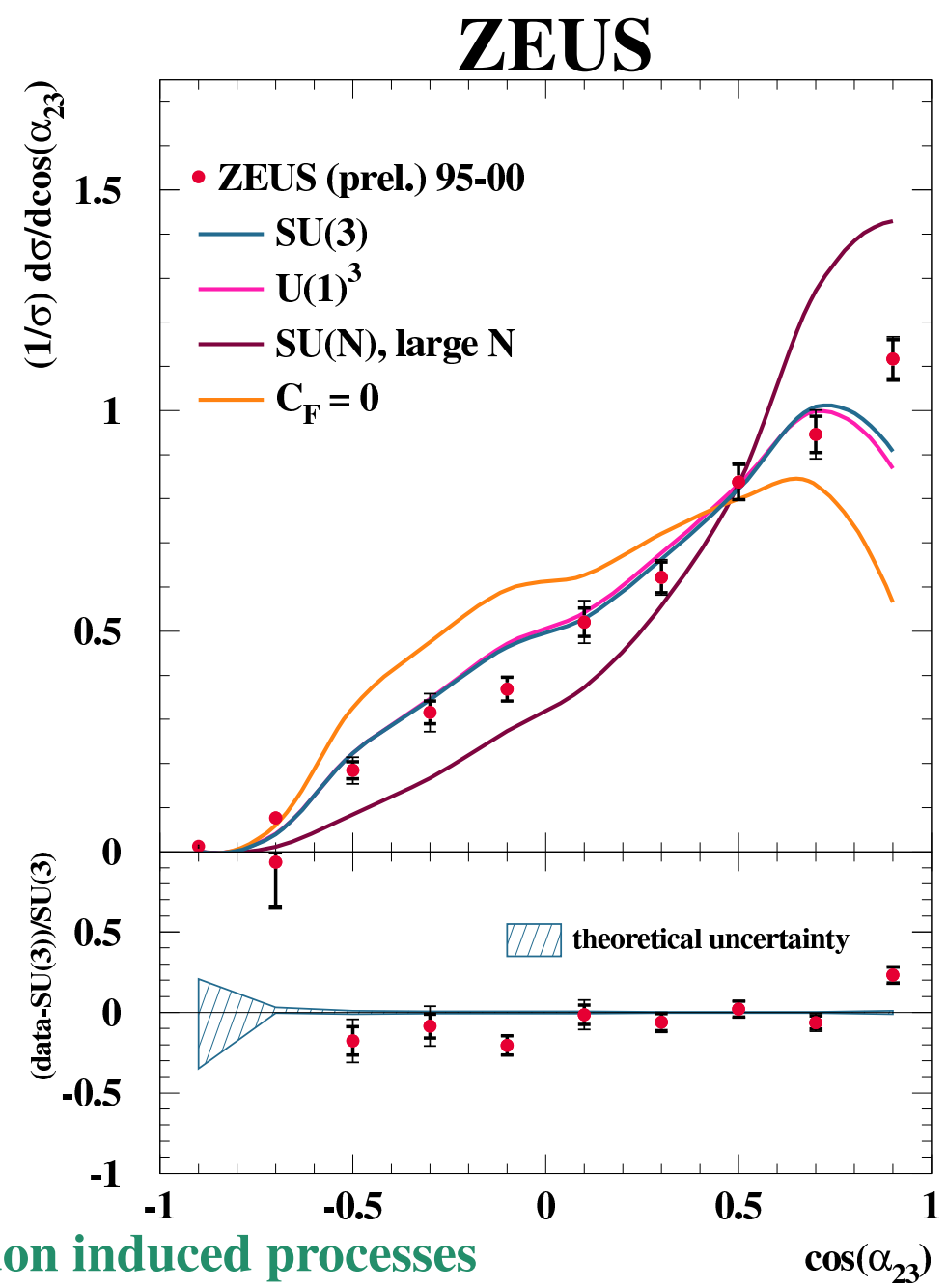
Measurements vs Fixed-order Calculations (Complete)



- 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 σ_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 θ_H, α_{23} and β_{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