COLOR DYNAMICS IN PHOTOPRODUCTION OF JETS AT HERA

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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:
  \(\text{for } SU(N): C_F = (N^2 - 1)/2N, C_A = N, T_F = 1/2\).
- The color factors determine the relative contributions of the various subprocesses:
  e.g. in \(e^+e^- \rightarrow 4 \text{ jets} \) 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 dynamics in photoproduction of jets at HERA

**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

- 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

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

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)

$\rightarrow f_{a/\gamma}(x_\gamma, \mu^2_{F\gamma})$ = 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

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

$$x^{obs}(3\text{jets}) = \frac{1}{2E_\gamma} \sum_{i=1}^{3} E_{T}^{jet_i} e^{-\eta^{jet_i}}$$
Photoproduction of Three-Jet Events

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

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

$$\sigma_{ep\rightarrow3jets} = C_F^2 \cdot \sigma_A + C_FC_A \cdot \sigma_B + C_FT_f \cdot \sigma_C + T_FCA \cdot \sigma_D$$
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 $e^+ e^- \to 4\text{jets}$)

→ $\beta_{KSW}$, defined by

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

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 $e^+ e^- \to 4\text{jets}$)
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 \( 0.2 < y < 0.85 \)

\(~ 2200 \text{ three-jet events satisfying } x^{\text{obs}}_{\gamma} (3\text{jets}) > 0.7 \)
Measurement of the Distribution in $\theta_H$

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

in the kinematic region $Q^2 < 1 \text{ GeV}^2$ 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))
  → 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 ($O(\alpha^2_s)$) calculations using the program by Klasen, Kleinwort and Kramer
  - direct processes only
  - choice of scales: $\mu_R = \mu_F = E_T^{\text{max}}$ (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 ($C_F, C_A, T_F$):
  $$\sigma_{ep\rightarrow3\text{jets}} = C_F^2 \cdot \sigma_A + C_FC_A \cdot \sigma_B + C_FT_F \cdot \sigma_C + T_F C_A \cdot \sigma_D$$
- 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
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 $SU(3)$:

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