Three-Jet Angular Correlations in ep Collisions

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for the ZEUS Collaboration
Tests of QCD at HERA

Jet cross sections vs fixed-order QCD

Strength of QCD interactions - $\alpha_s$

Evidence for spin1 gluon propagator

$\alpha_s(M_Z) = 0.118 \pm 0.003$

-> More fundamentals of QCD
Color effects
Gluon self-coupling
Gauge group structure
Color Factors in QCD

QED : $\gamma$ coupling between 2 charged particles
$\rightarrow e_1 e_2 \alpha$
Abelian – photon carries no charge

QCD : gluon coupling between 2 colored quarks
$\rightarrow \frac{1}{2} c_1 c_2 \alpha_s$
Non-Abelian – gluon is colored

Gluon emission/absorption by a quark

Gluon splitting into/forming from 2 gluons
Triple Gluon Vertex (TGV)

gluon splitting into/forming from 2 quarks

Color factors for some selected gauge groups

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<th>CF</th>
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<td>SU(N) Non-Abelian</td>
<td>$\frac{(N^2-1)}{2N}$</td>
<td>$2N/(N^2-1)$</td>
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<tr>
<td>SU(3) QCD Non-Abelian</td>
<td>$\frac{4}{3}$</td>
<td>$\frac{9}{4}$</td>
<td>$3$</td>
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Color Factors in 4-Jet Events at LEP

4-jet processes in $e^+e^-$ events at LEP

Color Factor ratio results:

- $C_A/C_F = 2.11 \pm 0.16\text{(stat.)} \pm 0.28\text{(syst.)}$
- $T_R/C_F = 2.01 \pm 0.54\text{(stat.)} \pm 0.68\text{(syst.)}$
- $T_F/C_F = 0.40 \pm 0.17$

~22K 4-jet events
Color Factors in 3-Jet Events at HERA

3-Jet events from Direct $\gamma p^*$ and DIS can be used to test the properties of the underlying gauge group, e.g. QCD as SU(3), determined by combinations of the appropriate color factors.

* Resolved $\gamma p$ with 2 jets has the TGV contribution, but it is difficult to distinguish these from 2-jet events with no TGV

Process diagram classes for DIS and Direct $\gamma p$:

3-Jet cross section at leading order ($\alpha_s^2$):

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

-> Angular variables can be defined which highlight the correlated jet structure of the events and provide sensitivity to the various color configurations.
Definition of Angular Variables

\( \theta_H \):
angle between plane of highest \( E_T \) jet and beam and plane of 2 lowest \( E_T \) jets
\( \rightarrow \) sensitive to TGV in \( C_F C_A \) process

\( \eta_{\text{jet max}} \):
pseudorapidity of most forward jet

\( \alpha_{23} \):
angle between 2 lowest \( E_T \) jets, based on \( \alpha_{34} \) defined for \( e^+e^- \rightarrow 4 \) jets
\( \rightarrow \) distinguishes between double-bremsstrahlung diagrams (\( C_F^2 \)) and those with a TGV (\( C_F C_A, T_F C_A \))

\( \beta_{KSW} \):
angle defined by \( \cos(\beta_{KSW}) = \cos\left[\frac{1}{2}(\angle[(p_1 \times p_3),(p_2 \times p_B)] + \angle[(p_1 \times p_B),(p_2 \times p_3)])\right] \),
based on the Körner-Schierholz-Willrodt angle \( \Phi_{KSW} \) for \( e^+e^- \rightarrow 4 \) jets
\( \rightarrow \) sensitive to differences in \( C_F C_A \) and \( C_F T_F \) processes
Normalized Differential 3-Jet X-Sections in $\gamma p$

$\sigma_B$, the quark-induced process containing a TGV ($C_F C_A$), has a different shape than others in all angular variables.

Best separation of all processes is in the variable $\cos(\alpha_{23})$ for $\gamma p$ interactions.
Again, $\sigma_B$, the quark-induced process with a TGV ($C_F C_A$), has a different shape than the others in most angular variables. $\sigma_D$, the gluon-induced process with a TGV ($T_F C_A$), seems to stand out in the high $Q^2$ DIS data.
Fixed Order Calculations of Direct $\gamma p$ Processes

Fixed order calculation:
Order ($\alpha_s^2$), # q flavors = 5, ZEUS-S proton pdfs, $\alpha_s$ @ 2 loops using $\Lambda_{\text{MS}}^{(5)}=226$ MeV -> $\alpha_s(M_Z)=0.118$

$\mu_R = \mu_F = E_T^{\text{max}} (E_T^{\text{jet1}})$

Compare to $\mu_R$, $\mu_F$ fixed

Order ($\alpha_s^3$) not yet available

Evolution of pdfs and running of $\alpha_s$ introduces additional dependencies on the color factors – using normalized cross section suppresses the pdf dependence.

$\mu_F$ variation (open dots) -> very small differences

$\mu_R$ variation (solid dots) -> sometimes large variations (especially DIS ->)
Fixed order calculations as in $\gamma p$:

$\mu_R = \mu_F = Q$, compare to $\mu_{R'}$, $\mu_{F'}$ fixed

$\mu_F$ variation (open dots) $\rightarrow$ again, very small differences

$\mu_R$ variation (solid dots) $\rightarrow$ large variations, especially in $\eta_{\text{max jet}}$, $\langle Q^2 \rangle \uparrow$ as $\eta_{\text{max jet}} \downarrow$

$\rightarrow$ Reduced effect at high $Q^2$ at $\alpha_s^2$ (running $\alpha_s$)

$\rightarrow$ Reduced effect at $\alpha_s^3$ $\rightarrow$ can extract color factors in entire region
Event Selection and Jet Definition in $\gamma p$

Lumi, ep parameters

~45 pb$^{-1}$ e$^+$p 1995-1997
$E_p=820$ GeV, $E_e=27.5$ GeV,
$\sqrt{s}=300$ GeV

~65 pb$^{-1}$ e$^+$p 1999-2000
~17 pb$^{-1}$ e-p 1998-1999
$E_p=920$ GeV, $E_e=27.5$ GeV,
$\sqrt{s}=318$ GeV

$Q^2<1$ GeV$^2$ (median $Q^2 \approx 10^{-3}$ GeV$^2$)

0.2<$y$<0.85

Jet Selection:

$\kappa_T$ cluster algorithm in longitudinally invariant inclusive mode from CAL cells

Jet search in $\eta$-$\phi$ plane of lab frame

Jets corrected in $E_T(\eta, E_T)$, at least 3 jets with $E_T^{\text{jet}}>14$ GeV and $-1<\eta^{\text{jet}}<2.5$

Direct $\gamma p$ events chosen with $x_\gamma^{\text{obs}}>0.8$ - from MC, direct process dominates

1888 3-jet events
Event Selection and Jet Definition in DIS

Lumi, ep parameters
~65 pb\(^{-1}\) e\(^+\)p 1999-2000
~17 pb\(^{-1}\) e\(^-\)p 1998-1999
\(E_p = 920\ \text{GeV},\ E_e = 27.5\ \text{GeV},\ \sqrt{s} = 318\ \text{GeV}\)

\(|\cos \gamma h| < 0.65\) (QPM struck quark angle)

Jet Selection:
\(k_T\) algorithm on CAL cells excluding scattered electron in Breit frame
Jets corrected in \(E_T\)
\(E_{T,B}^{\text{jet1}} > 8\ \text{GeV},\ E_{T,B}^{\text{jet2,3}} > 5\ \text{GeV}\)
\(-2 < \eta_{B}^{\text{jet}} < 1.5\)

\~1000 3-jet events
\~500 3-jet events
Gauge Group Comparison with Direct $\gamma p$ Data

Predictions based on the non-Abelian gauge group SU(3) describe the data for all angular variables.

The Abelian group U(1)$^3$ is also consistent with the $\gamma p$ data.

The non-Abelian group SO(3) is also consistent with the data.

Clearly disfavored are groups SU(N) where N is large and any group with $C_F=0$.

\[ SU(3) : \frac{C_A}{C_F} = 9/4, \frac{T_F}{C_F} = 3/8 \]
\[ U(1)^3 : \frac{C_A}{C_F} = 0, \frac{T_F}{C_F} = 3 \]
\[ SU(N) \text{ large } N : \frac{C_A}{C_F} = 2, \frac{T_F}{C_F} = 0 \]
\[ SO(3) : \frac{C_A}{C_F} = 1, \frac{T_F}{C_F} = 1 \]
Gauge Group Comparison with DIS Data

Again, predictions based on the non-Abelian gauge group SU(3) describe the data for all angular variables, as does the non-Abelian group SO(3) and the Abelian group U(1)^3.

However, in DIS, the U(1)^3 group shows differences of ~10% with respect to SU(3) (of the same order as the statistical uncertainties).

Clearly disfavored are groups SU(N) where N is large and any group with C_F=0.
Fixed Order ($\alpha_s^n$) Comparison with DIS Data

Very good $\alpha_s^3$ description of data – improvement over $\alpha_s^2$
Summary

• Measurements of 3-jet angular correlations in $\gamma p$ and NC DIS were done with the ZEUS detector on 127 pb$^{-1}$ of ep scattering data.

• Differential 3-jet cross sections were measured as functions of $\theta_H$, $\alpha_{23}$, $\beta_{KSW}$, and $\eta_{\text{max jet}}$, variables motivated by angles defined for 4-jet events in $e^+e^-$ scattering at LEP.

• Fixed-order ($\alpha_s^2$) calculations were separated according to color configurations and used to study the sensitivity of the angular correlations to underlying gauge group structures.

• The data clearly disfavor SU(N) in the limit of large N or any theory where $C_F=0$.

• Predictions based on SU(3) describe the data for all of the angular variables, while the predicted differences between SU(3) and U(1)$^3$ of ~10% are smaller than the current statistical uncertainties on the data.

• With complete $\alpha_s^3$ calculations, extraction of individual color factors may be possible with the full set of HERA data (~500 pb$^{-1}$).
Backup Slides
Data/MC Comparisons for $\gamma p$ 3-Jet Events

ZEUS

- $(a)$: ZEUS $\gamma p$ 127 pb$^{-1}$
- PYTHIA
- HERWIG
- $x^{BH} > 0.8$

- $(b)$: Events vs $\theta_H$ (deg)
- Events vs $\cos(\alpha_{23})$
- Events vs $\cos(\beta_{KSW})$

- $(c)$: Events vs $\cos(\beta_{KSW})$
Data/MC Comparisons for DIS 3-Jet Events

ZEUS

- ZEUS DIS 52 pb⁻¹
- MEPS
- CDM

Q² > 125 GeV²

\[ \Theta_H (\text{deg}) \]

\[ \cos(\alpha_{23}) \]

\[ \cos(\beta_{\text{KSW}}) \]

\[ \eta_{\text{jet max}} \]

500 < Q² < 5000 GeV²