Measurement of Event Shapes in Deep Inelastic Scattering with ZEUS at HERA

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Study of Partons

Particle Scattering

• Study charge & magnetic moment distributions
• Scattering via probe exchange
  • Wavelength \( \lambda = \frac{\hbar}{Q} \)

  \( \hbar \) : Plank’s Constant

  \( Q \) : related to momentum of photon

• Special Case : Deep Inelastic Scattering
  • High energy lepton transfers momentum to a nucleon via probe
Scattering on proton is sum of elastic scattering on all of the proton’s constituents (partons)

Point-like Partons

Structure Functions: quantify distribution of partons and their momentum

\[ F_2 = \sum_i e_i^2 x f_i(x) \quad F_i \rightarrow F_i(x) \]

Bjorken Scaling: Only \( x \) dependence
\( x \) related to fraction of momentum carried by quark

Parton Distribution Functions (PDF)

- Must be derived from experiment
Gluons: vector colored bosons carry strong force

- Gluons produce quark and gluon pairs
- Quarks gain transverse momentum

- Gluon-driven increase in $F_2$
  \( \Rightarrow \) Bjorken Scaling Violation:
  \[ F_i(x) \rightarrow F_i(x, Q^2) \]
  \( \Rightarrow \) Observation of QCD effects
Deep Inelastic Scattering

Center of Mass Energy of ep system squared:

\[ s = (p+k)^2 \sim 4E_p E_e \]

Photon Virtuality (4-momentum transfer squared at electron vertex):

\[ q^2 = -Q^2 = (k-k')^2 \]

Fraction of Proton’s Momentum carried by struck quark:

\[ x_{\text{Bjorken}} = \frac{Q^2}{2p \cdot q} \]

Fraction of e’s energy transferred to Proton in Proton’s rest frame:

\[ y = \frac{p \cdot q}{p \cdot k} \]
Perturbative and Non-Perturbative QCD

Lowest Order
no $\alpha_s$ vertex

Low energy scales $\Rightarrow$ Large distances

High energy scale $\Rightarrow$ Small distances

$\alpha_s$ soft scale

$\alpha_s$ hard scale

Perturbative: $Q^2$ large
Small $\alpha_s$ (hard scale)
Can expand with $\alpha_s$
High energy scale $\Rightarrow$ Small distances

Nonperturbative: $Q^2$ small
Large $\alpha_s$ (soft scale)
Can’t expand in $\alpha_s$
Low energy scales $\Rightarrow$ Large distances

Leading Order (LO)

QPM

QCD Compton (initial & final)

Boson gluon fusion

$A = A_0 + A_1 \alpha_s + A_2 \alpha_s^2 + \ldots$

Next to Leading Order (NLO)
Event Shapes, A. Everett, U. Wisconsin

From Partons to Hadrons

- Hard scattering: hard scale (short distance) perturbative process
- Parton showers: initial QCD radiation of partons from initial partons
- Hadronization: colorless hadrons produced from colored partons
  soft process (large distance) - not perturbatively calculable
  phenomenological models and experimental input
- Jets: colored partons evolve into ~collinear “spray” of colorless hadrons

We seek to penetrate this fog
• The hard scattering process determines the initial distribution of partons

• Parton Shower + Hadronization determine the final energy flow of the event
  • Event shape is energy flow carried by hadrons

• Universality of the hadronization process tested by comparison of measurements of energy flow dependence in reactions with different initial states
  • ep, e^+e^-

• Power Corrections (see next slide) offer an opportunity to analytically study hadronization

• Use Event Shapes to check the validity of Power Corrections
pQCD prediction $\rightarrow$ phenomenology $\rightarrow$ measured distribution

- **Correction factors for non-perturbative (soft) QCD effects**

Proposed theory*: Use power corrections to correct for non-perturbative effects in infrared and collinear safe event shape variable, $F$:

$$\langle F \rangle = \langle F \rangle_{\text{perturbative}} + \langle F \rangle_{\text{power correction}}$$

$$\langle F \rangle_{\text{pow}} = a_v \frac{3MA_1(\alpha_s, \bar{\alpha}_0)}{\pi Q}$$

**Power correction (PC)**

- Independent of any fragmentation assumptions

$$\bar{\alpha}_0 = \text{Universal "non-perturbative parameter"}$$

HERA Description

- 920 GeV $p^+$
- 27.5 GeV $e^-$ or $e^+$
- 318 GeV cms
- Equivalent to 50 TeV Fixed Target

Instantaneous luminosity max:
$1.8 \times 10^{31} \text{ cm}^{-2} \text{s}^{-1}$

- 220 bunches
- 96 ns crossing time

$I_p \sim 90 \text{mA} \ p$
$I_e \sim 40 \text{mA} \ e^+$

DESY Hamburg, Germany
Central Tracking Detector

Drift Chamber inside 1.43 T Solenoid
Can resolve up to 500 charged tracks
Average event has ~20-40 charged tracks
Determine interaction vertex of the event
Measure number of charged particles (tracks)
Region of good acceptance: -1.75 < $\eta$ < 1.75

$\eta = -\ln(\tan(\frac{\theta}{2}))$
Uranium-Scintillator Calorimeter (CAL)

- Alternating uranium and scintillator plates (sandwich calorimeter)
- Compensating - equal signal from hadrons and $\gamma / e^\pm$ particles of same energy - $e/h = 1$
- Energy resolution $\sigma_e/E_e = 18% / \sqrt{E}$, $\sigma_h/E_h = 35% / \sqrt{E}$, $E$ in GeV
- Covers 99.6% of the solid angle in the lab frame

$\eta = -\ln(\tan(\frac{\theta}{2}))$
10^7 Hz Crossing Rate, 10^5 Hz Background Rate, 10 Hz Physics Rate

**First Level**
- Dedicated custom hardware
- Pipelined without deadtime
- Global and regional energy sums
- Isolated $\mu$ and $e^+$ recognition
- Track quality information

**Second Level**
- “Commodity” Transputers
- Calorimeter timing cuts
- $E - p_z$ cuts
- Vertex information
- Simple physics filters

**Third Level**
- Commodity processor farm
- Full event info available
- Refined Jet and electron finding
- Advanced physics filters
$Q^2 = sxy$

$0.1 < Q^2 < 20000 \text{ GeV}^2$

$10^{-6} < x < 0.9$
Dijet Event
Extraction of $\alpha_0$ and $\alpha_s$

Two separate (but related) analyses:

**Apply Power Corrections to Event Shape Means vs. $Q^2$**
- Measure $<F>$ and compare to pQCD calculation (NLO) plus power correction (PC)
- Extract $\alpha_0$ and $\alpha_s$ from fits to means
  - Check consistency to test PC model

**Apply Power Corrections to Event Shape Distributions**
- Measure $F$ and compare to theoretical calculation plus power correction
- Extract $\alpha_0$ and $\alpha_s$ from fits to distributions
  - Check consistency to test PC model
Current Hemisphere of the Breit Frame

- **Current Target**

\[ 2xP + q = 0 \]

**Current region of Breit frame**
- equiv. to single hemisphere \( e^+e^- \)
- \( e^+e^- \): quarks produced back to back with \( E = \sqrt{s}/2 \)
- DIS: struck quark with \( E = Q/2 \)
- quark’s hadronization products in **current hemisphere**

- Breit frame great for identifying jets of particles
Three classes of event shapes studied in this analysis

• **Axis independent**
  - Analysis done in current region of Breit frame
  - Invariant jet mass: $M^2$
  - C-Parameter: $C$

• **Axis dependent**
  - Analysis done in current region of Breit frame
  - Thrust: $T_T$, $T_\gamma$
  - Broadening: $B_T$, $B_\gamma$

• **Multi-jet**
  - Analysis done in full Breit frame
  - Out-of-plane Momentum: $K_{out}$
  - Jet transition parameter: $y_n$
Sphericity: describes isotropy of energy flow

- Theoretical issue: *NOT* collinear and infrared safe
  - Unusable in DIS

C-Parameter:

- collinear and infrared safe combination of the sphericity eigenvalues

Invariant Jet Mass

\[
S = \frac{3}{2} (\lambda_2 + \lambda_3)
\]

\[
S^{\alpha\beta} = \frac{\sum_i p_i^\alpha p_i^\beta}{\sum_i |\vec{p}_i|^2}
\]

\[
0 \leq S \leq 1
\]

C Parameter

\[
C = \frac{3 \sum_{ij} |\vec{p}_i| |\vec{p}_j| \sin^2(\theta_{ij})}{2 \left( \sum_i |\vec{p}_i|^2 \right)^2}
\]

Jet Mass

\[
M^2 = \frac{\left( \sum_i p_i^\mu \right)^2}{2 \left( \sum_i E_i \right)^2}
\]
Linear collimation of hadronic system along a specified ("thrust") axis

T interpretation depends on choice of axis:

- Four Thrusts in DIS: $T_\gamma$, $T_M$, $T_m$, $T_T$

\[
T = \max_{\hat{n}_k} \frac{\sum_i |\vec{p}_i \cdot \hat{n}|}{\sum_i |\vec{p}_i|}
\]

\[
\frac{1}{2} \leq T_T \leq 1
\]

\[
0 \leq T_\gamma \leq 1
\]
Thrust and Sphericity

Collimated  Planar  Isotropic

$T_T=1$  Increase  $T_T=3/4$  Increase  $T_T=1/2$

$S=0$  Increase  $S=1/2$  Increase  $S=1$
Broadening of particles in transverse momentum wrt. thrust axis

\[ B = \frac{\sum_i |\vec{p}_i \times \vec{n}|}{\sum_i |\vec{p}_i|} \]

\[ 0 \leq B \leq \frac{1}{2} \]
In ep: $k_T$ is transverse momentum with respect to beamline

- **Algorithm**
  - For every object $i$ and every pair of objects $i$, $j$ compute
  - $d_i = E_{T,i}^2$ (distance to beamline in momentum space)
  - $d_{ij} = \min\{E_{T,i}^2, E_{T,j}^2\} [D_h^2 + D_f^2]$ (distance between objects)
  - Calculate $\min\{d_i, d_{ij}\}$ for all objects
  - If $(d_{ij}/R^2)$ is the smallest, combine objects $i$ and $j$ into a new object
    - $R$ is radius in $\eta - \phi$ space
    - If $d_i$ is the smallest, then object $i$ is a jet

- **Advantages:**
  - $k_T$ distributions can be predicted by QCD

**Jet Rate**

$$y_n \equiv \min\{d_i, d_j, d_{ij}\}$$
Event Shapes With Jets: $K_{out}$

Energy flow out of event plane defined by proton direction and thrust major axis

- Sensitive to perturbative & non-perturbative contributions
- Dijet event:
  - LO dijet pQCD calculation gives $K_{out} = 0$
  - First contribution to $K_{out}$ is from non-perturbative part or from NLO dijet pQCD calculation
Event generators use algorithms based on QCD and phenomenological models to simulate DIS events:

- Hard subprocess: pQCD
- Parton Cascade
- Hadronization
- Detector Simulation
  - correct for detector effects: finite efficiency, resolutions & acceptances

**Parton Cascades**
- LO Matrix Element + Parton Showers (MEPS)
- Color Dipole Model (CDM)

**Hadronization Models**
- String Fragmentation (Lund)
- Cluster Model

**PDFs**

**Parton Level** → **Hadron Level**

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NLO calculations stop here: $\mu_R$
Monte Carlo models: parton cascades and hadronization

Models for parton cascades:

Parton Shower Model:
- cascade of partons with decreasing virtuality continuing until a cut-off

Color Dipole Model:
- Gluons are emitted from the color field between quark-antiquark pairs, supplemented with BGF processes.

Hadronization models:

Lund String Model:
- color "string" stretched between q and q moving apart,
- string breaks to form 2 color singlet strings, and so on until only on-mass-shell hadrons.

Cluster Fragmentation Model:
- color-singlet clusters of neighboring partons formed
- Clusters decay into hadrons
Used well studied NC DIS sample of events taken in 1998-00 ~ 82.2 pb\(^{-1}\)

**Luminosity upgrade in 2003/2004: HERA II**

- 5x increase in Luminosity

### ZEUS Luminosities (pb\(^{-1}\))

<table>
<thead>
<tr>
<th>Year</th>
<th>HERA</th>
<th>ZEUS on-tape</th>
<th>Physics</th>
</tr>
</thead>
<tbody>
<tr>
<td>e(^-): 93-94, 98-99</td>
<td>27.37</td>
<td>18.77</td>
<td>32.01</td>
</tr>
<tr>
<td>e(^+): 94-97, 99-00</td>
<td>165.87</td>
<td>124.54</td>
<td>147.55</td>
</tr>
</tbody>
</table>
Inclusive Event Selection

ZEUS 98-00 (82.2 pb\(^{-1}\))

**General DIS cuts**
- \(Q^2_{DA} \geq 80 \ (100) \ \text{GeV}^2\)
- \(y_{JB} > 0.04\)
- \(y_{el} < 0.9\)
- Vertex with \(|z| < 40 \ \text{cm}\)
- \(38 < E-p_Z < 60 \ \text{GeV}\)
- Good positron
  - electron probability > 0.9
  - \(E_e > 10 \ \text{GeV}\)

**Additional Requirements**

**Global Shapes**
- \(|\eta_{lab}| < 1.75\)
- \(p_t > 0.15 \ \text{GeV}\)
  - Use the full tracking acceptance
- Current region multiplicity > 1
- \(E_C/Q > 0.25\)

**K\(_{out}\)**
- \(|\eta_{lab}| < 2.2\)
- \(p_t > 0.15 \ \text{GeV}\)
- \(\eta_{Breit} < 3\)
  - Select current region
- At least 2 jets in the Breit Frame
- \(y_2 > 0.1\)

**y\(_2\)**
- At least 1 particle in Breit frame
- \(p_t > 0.15 \ \text{GeV}\)
Apply Power Corrections to Event Shape Means vs. $Q^2$

- Measure $<F>$ and compare to pQCD calculation (NLO) plus power correction (PC)
  - NLO calculated with DISENT (Seymour and Catani) and DISASTER++ (Graudenz)

- Extract $\alpha_0$ and $\alpha_S$ from fits to means
  - Check consistency to test PC model
• Analysis conducted in 8 bins of $Q^2$
• Lowest two $Q^2$ bins are divided into two bins of $x$

Two studies:
• Means of each variable in each bin
• Differential distributions of each variable in each bin

NOTE: multiple $x$ bins at low $Q^2$
Add Power Correction to NLO in order to agree with data

2-parameter NLO + PC fit
- Simultaneous fit for $\alpha_s$ and $\alpha_0$
- Each shape fit separately

Fits use Hessian method for statistical and systematic errors
- Complete error matrix with error correlations

NLO calculation using DISASTER++
$T_\gamma$ illustrates PC limitations: x

Negative Power Correction
Studies systematic effect of cuts and analysis method on the event shape measurement

\[ \delta_{<F>} = \frac{<F>_{\text{systematic}} - <F>_{\text{central}}}{<F>_{\text{central}}} \]

Largest systematic uncertainties:

- Corrected particle energies (1-2%)
- Loosen the particle cuts (2-10%)
- Correct data with HERWIG (LEPTO) (2-10%)

Other systematic uncertainties smaller than the statistical uncertainties.
Extracted free parameters for each shape

- **Fitted $\alpha_s$ values consistent**
  - (excluding $B_T, T_\gamma$)

- **Fitted $\alpha_0$ consistent to ~10%**
  - (excluding $T_\gamma$)

Theory errors dominate, except for $\gamma$ axis shapes
Apply Power Corrections to Event Shape Distributions

- **Fit theory prediction to measured $F$**
  - Resummation of next-to-leading log (NLL) corrections for small $F$
    - Because perturbative radiation is suppressed
  - Match NLL to fixed-order results that are valid at large $F$
    - **Six choices for matching method:**
      - $M$, $M_2$, $\log R$, $M_{\text{mod}}$, $M_{2\text{mod}}$, $\log R_{\text{mod}}$
    - Fit sub-range where calculation is expected to be correct
      - Means were fitted to full range
    - Resummation, Matching, and PC calculated with DISRESUM

- **Extract $\alpha_0$ and $\alpha_S$ from fits to distributions**
  - Check consistency to test PC technique
Fit of ZEUS 98-00 differential distribution to NLO+NLL+PC

- NLO Calculated with DISPATCH
- Resummation is applied with DISRESUM
- Bins for which theoretical calculations are expected to be questionable are omitted from fit

Fit over this range gives a good $\chi^2$/dof
Fit to $T_\gamma$, $B_\gamma$ Differential Distributions

Fit of ZEUS 98-00 differential distribution to NLO+NLL+PC

- NLO Calculated with DISPATCH
- Resummation is applied with DISRESUM
- Bins for which theoretical calculations are expected to be questionable are omitted from fit

Fit over this range gives a good $\chi^2$/dof
Extracted free parameters for each shape

- Fitted $\alpha_s$ values consistent
- Fitted $\alpha_0$ consistent
  - (excluding C)

M2mod matching
Event Shapes: $y_2$

- Distributions and means measured in bins of $(x,Q^2)$

Compared to NLO (without PC) calculated by DISENT

- Theoretical mechanism for applying Power Correction not yet available

Conclusion: hadronization for $y_2$ is very small
New event shape variable: $K_{\text{out}}$
- Distribution and means measured in bins of $(x,Q^2)$

Compared to ARIADNE (LO): parton and hadron level
- Theoretical mechanism for applying Power Correction not yet available

Conclusion:
- Hadron level describes data well
- Hadronization effects are significant for $K_{\text{out}}$
Precise measurement of event shapes in DIS has been done

- **Means**
  - $\alpha_0$ and $\alpha_s$ still do not give a self-consistent results for all shapes

- **Differential distributions**
  - $\alpha_0$ are consistent within 10% (exclude C) in range 0.4-0.5
  - $\alpha_s$ are in good agreement with the world average

- $y_2$ and $K_{out}$ await theoretical input

**PC technique**

- Generally successful
- Suggests importance of higher-order processes
Universality of Power Corrections

- Higher energies
- Different kinematic regions
- Test validity in pp collisions