Scaled momentum distributions of charged particles in dijet photoproduction

ZEUS Collaboration

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Talk outline

1. Theoretical framework:
    - The MLLA and LPHD;
    - Physics motivation.
2. Physics Analysis:
    - Analysis strategy;
    - Data selection.
3. Results:
    - The measured ξ distributions;
    - Extraction of theoretical parameters;
    - Global comparisons.
4. Summary.

The MLLA + LPHD Theoretical Framework

The Modified Leading Log Approximation (MLLA)

- All orders pQCD resummation.
- Analytical description of parton evolution.
- Predicts parton multiplicity and momenta.
- MLLA describes fragmentation with 2 parameters:
  - Q_0 - A self-imposed cut-off energy scale.
  - Λ_{eff} - Absolute minimum cut-off of the theory.
- Predictions only physical with $Q_0 \geq \Lambda_{\text{eff}} > \Lambda_{\text{QCD}}$.
- Limiting spectrum defined such that, $Q_0 = \Lambda_{\text{eff}}$.
- Λ_{eff} predicted to be universal.
- We study MLLA within jets, where fragmentation is well defined.
- Assuming Local Parton Hadron Duality MLLA predictions are directly comparable to data.

The MLLA + LPHD Theoretical Framework

The Local Parton Hadron Duality (LPHD) Hypothesis

- Simple non-perturbative hypothesis.
- Assumes hadronisation is local and occurs at the end of the parton shower.
- Event topology is defined in the perturbative phase.
- Relates the observed hadron distributions to the calculated parton distributions via a single constant factor, κ_{ch}.

$$O(x_1, x_2, \ldots)|_{\text{hadrons}} = \kappa_{\text{ch}} O(x_1, x_2, \ldots, \Lambda_{\text{eff}})|_{\text{partons}}$$

What is κ_{ch} ?

- κ_{ch} is the ratio of the number of charged particles over the total number of partons produced during fragmentation.
- From isospin invariance, expect $\kappa_{\text{ch}} \approx 2/3$
- 2 free parameters in MLLA + LPHD: Λ_{eff} and κ_{ch}.

Physics Motivation

Investigating the limits of the MLLA

- $\Lambda_{\rm eff}$ and $\kappa_{\rm ch}$ have been measured using $359{\rm pb}^{-1}$ γP data collected using the ZEUS detector.
- The measurement was performed at various energy scales and within cones of various opening angles, θ_c, around the jet axis.

Is $\Lambda_{\rm eff}$ universal?

- $\Lambda_{\rm eff}$ previously measured for *ee*, *eP* & $P\bar{P}$. Never for γP.
- Is $\Lambda_{\rm eff}$ independent of interaction type? *ee*, *eP*, $P\bar{P}$, γP.
- Is $\Lambda_{\rm eff}$ independent of $E_{\rm Jet}$ and θ_c, as predicted?

How to measure Λ_{eff} and κ_{ch}

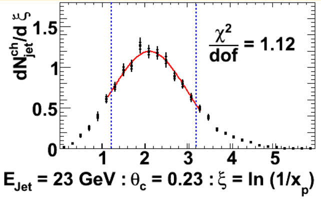
Outline of analysis

- Select dijet photoproduction events from $359\mathrm{pb}^{-1}$ ZEUS data.
- Measure scaled track momentum within jets, $x_p = \frac{P_{\mathrm{track}}}{P_{\mathrm{Jet}}}$.
- Plot scaled momentum distributions, $\xi = \ln\left(\frac{1}{x_p}\right)$, in bins of jet energy $E_{\mathrm{Jet}} = \frac{M_{2j}}{2}$ (the hard scale) and θ_c (the opening angle).

Fitting ξ distributions

- 2 methods:
  - Gaussian around mean;
  - MLLA + LPHD theory.
- ξ_{peak}, Λ_{eff} and κ_{ch} extracted from fits.

Sneak preview - a ξ distr.



Λ_{eff} dependence on jet opening angle, θ_c

MLLA predicts $E_{\text{Jet}} \sin(\theta_c)$ scaling

- Sequentially emitted partons are constrained to smaller angles due to enforced angular ordering.
- Scaling violations expected to occur at large θ_c as MLLA is only strictly valid in the collinear approximation.

Testing for scaling violations

- Calculate angle, θ_i, of each constituent particle from jet axis, working in the centre-of-mass frame, as θ_i not Lorentz invariant.
- Plot ξ distributions enforcing a maximum $\theta_i \leq \theta_c$ cut.
- The values of θ_c used are:
  - $\theta_c = 0.23$
  - $\theta_c = 0.28$
  - $\theta_c = 0.34$

Data Selection

Jet selection

- Jets were reconstructed using the k_T cluster algorithm in the longitudinally invariant inclusive mode.

- $E_T^{\mathrm{Jet1}} \geq 17$ GeV
- $E_T^{\mathrm{Jet2}} / E_T^{\mathrm{Jet1}} \geq 0.8$
- $0.9\pi \leq |\phi^{\mathrm{Jet1}} - \phi^{\mathrm{Jet2}}|$
- $|\eta^{\mathrm{Jet1,2}}| \leq 1.0$
- $E_T^{\mathrm{Jet3}} \leq 6$ GeV
- $|\eta^{\mathrm{Jet3}}| \leq 2.4$

Additional cuts

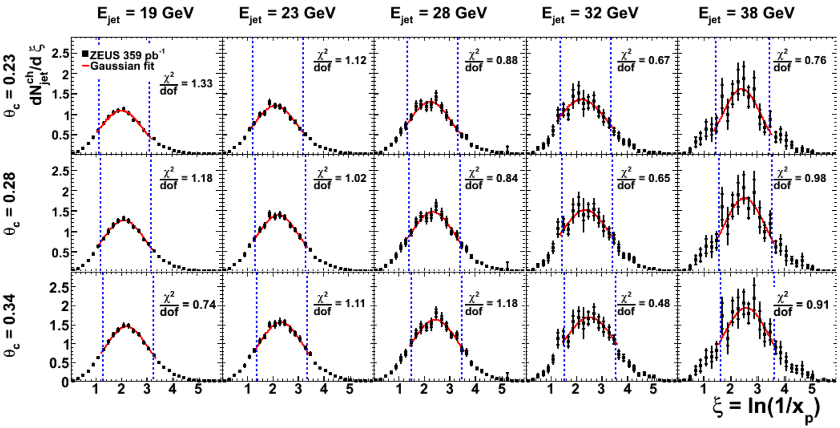
- $0.2 \leq y \leq 0.85$
- $Q^2 \leq 1\,\mathrm{GeV}^2$
- $x_\gamma^{\mathrm{OBS}} \geq 0.75$

Tracking cuts

- $p_T^{\mathrm{track}} \geq 150\,\mathrm{MeV}$
- $|\eta^{\mathrm{track}}| \leq 1.7$
- MC Truth lifetime $\geq 0.01 ns$

23,449 events were selected from $359\mathrm{pb}^{-1}$ of ZEUS data.

The measured ξ distributions



$359\mathrm{pb}^{-1}$ ZEUS data shown in bins of E_{Jet} and θ_c

- The Gaussian fits are shown. $0.48 \leq \chi^2/\mathrm{dof} \leq 1.33$
- Blue lines indicate fitted region, ± 1 around mean.

Determining $\xi_{\rm peak}$, $\Lambda_{\rm eff}$ and $\kappa_{\rm ch}$ - 2 methods:

1. The Gaussian fit method:

- Gives peak position of ξ distribution, $\xi_{\rm peak}$;
- $\xi_{\rm peak}$ gives $\Lambda_{\rm eff}$ - Only valid for Leading Order (LO).

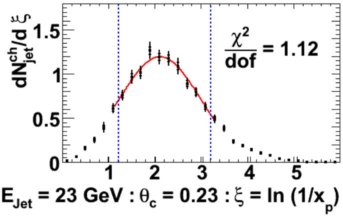
2. The MLLA+LPHD fit method:

- Gives $\Lambda_{\rm eff}$ and K (the normalisation) directly from fit;
- $\kappa_{\rm ch}$ is calculated from K;
- $\Lambda_{\rm eff}$ has strong dependence on ambiguous fit range;
- $\kappa_{\rm ch}$ only weakly dependant on the fitting range.

The results presented here use:

1. The Gaussian method for $\xi_{\rm peak}$ and $\Lambda_{\rm eff}$;
2. The MLLA+LPHD method for $\kappa_{\rm ch}$ and to cross check $\Lambda_{\rm eff}$.

The Gaussian fit method



Peak position, ξ_{peak}

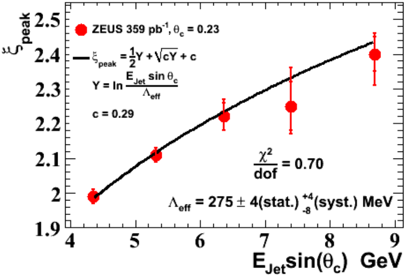
- Fit Gaussian ± 1 around mean.
- $\forall\ \xi$, independently measure ξ_{peak}.

$$\Lambda_{eff} = \frac{E_{Jet}\sin(\theta_c)}{e^{\left(\sqrt{0.87+2\xi_{peak}}-0.54\right)^2}} \qquad (@\ \text{LO})$$

Measuring Λ_{eff}

- Only use $\theta_c = 0.23$ energy points:
  - Different θ_c values are correlated;
  - MLLA looses validity at large θ_c.
- Fit equation to all 5 energy points.

$$\Lambda_{eff} = 275 \pm 4\,(\text{stat.})^{+4}_{-8}\,(\text{syst.})\ \text{MeV}$$



The MLLA + LPHD fit method

Momentum distribution of partons from a gluon is given by:

- $$\bar{D}^{\mathrm{lim}}_{\mathrm{g-Jet}}\left(\ln\left(\frac{1}{x_p}\right), Y\right) = \frac{4C_f}{b}\Gamma(B)\int_{-\frac{\pi}{2}}^{\frac{\pi}{2}} e^{-B\alpha}\left[\frac{\cosh\alpha+(1-2\zeta)\sinh\alpha}{\frac{4N_c}{b}Y\frac{\alpha}{\sinh\alpha}}\right]^{\frac{B}{2}} \cdot I_B\left(\sqrt{\frac{16N_c}{b}Y\frac{\alpha}{\sinh\alpha}[\cosh\alpha+(1-2\zeta)\sinh\alpha]}\right)\frac{d\tau}{\pi}$$
- Valid for: $\ln\left(\frac{1}{x_{p\ll 1}}\right) \leq \ln\left(\frac{1}{x_p}\right) \leq \ln\left(\frac{M_{2j}}{2P_0}\right)$ $\quad P_0 = \mathrm{Upper\ bound}$

For number of flavours, $N_f = 3$, and number of colours, $N_c = 3$

- $C_f = \frac{9}{4}$, $b = 9$, $B = 1.247$.
- I_B is the modified Bessel function of order B.
- $\alpha = \alpha_0 + i\tau$, where α_0 is determined by $\tanh\alpha_0 = 2\zeta - 1$
- $\zeta = 1 - \frac{\ln\left(\frac{1}{x_p}\right)}{Y}$ and $Y = \ln\left(\frac{E_{\mathrm{Jet}}\sin(\theta_c)}{\Lambda_{\mathrm{eff}}}\right)$ $\qquad \bar{D}^{\mathrm{lim}}_{\mathrm{q-Jet}} = \frac{1}{r}\bar{D}^{\mathrm{lim}}_{\mathrm{g-Jet}}$

Quarks, gluons and the next-to-MLLA predictions

Quark and gluon jet mixture

- In γP events there is a mix of quark and gluon jets.

$\bar{D}^{\text{lim}}_{\text{mix}} = \left(\epsilon_{\text{g}} + \frac{1-\epsilon_{\text{g}}}{r}\right) \bar{D}^{\text{lim}}_{\text{g-Jet}}$, where ϵ_{g} is the fraction of gluon jets.

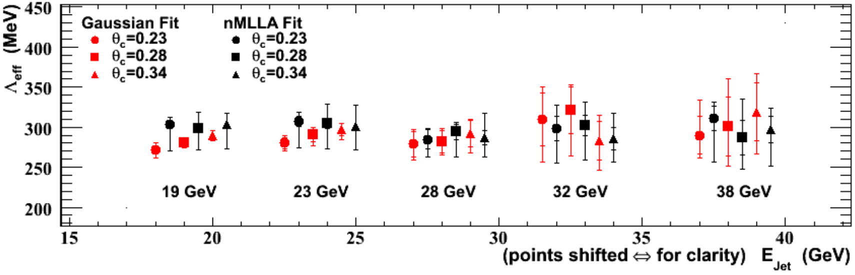
Energy (GeV)	19	23	28	32	38
ϵ_{g} (From PYTHIA)	0.203	0.213	0.211	0.227	0.242

The so called "next-to-MLLA" predictions

- Not actually higher order calculation, but a modification of MLLA.
- In nMLLA, $\bar{D}^{\text{lim}}_{\text{mix}} = F_{\text{nMLLA}} \left(\epsilon_{\text{g}} + \frac{1-\epsilon_{\text{g}}}{r}\right) \bar{D}^{\text{lim}}_{\text{g-Jet}}$
- Where $r = 1.6 \pm 0.2$ and $F_{\text{nMLLA}} = 1.3 \pm 0.2$ (from theory).
- When fitting to data the normalisation can be expressed as:

$$K = \kappa_{\text{ch}} F_{\text{nMLLA}} \left(\epsilon_{\text{g}} + \frac{1-\epsilon_{\text{g}}}{r}\right)$$

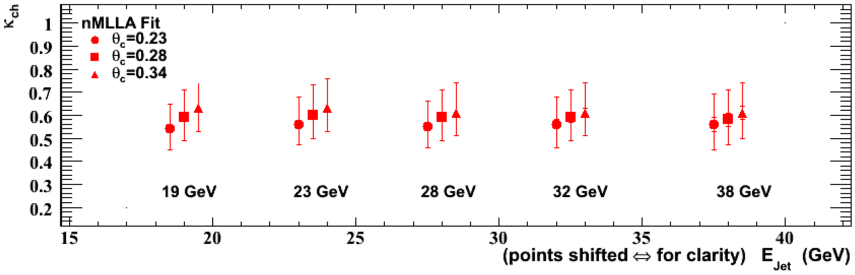
$\Lambda_{\rm eff}$ - Comparison of extraction methods



$\Lambda_{\rm eff}$ extracted from $359{\rm pb}^1$ ZEUS data via both methods

- $\forall\xi$, independently extract $\Lambda_{\rm eff}$: Red = Gaussian. Black = nMLLA.
- $\Lambda_{\rm eff}$ has a weak dependence on θ_c, no dependence on scale.
- nMLLA, $\theta_c = 0.23$: $\Lambda_{\rm eff} = 304 \pm 6\,({\rm stat.})^{+8}_{-32}\,({\rm syst.})$ MeV
- Large nMLLA systematics come from ambiguous fitting range.
- nMLLA regularisation scheme ⇒ Parton cut-off at $p_T^{\rm rel,pl} = \Lambda_{\rm eff}$

κ_{ch}

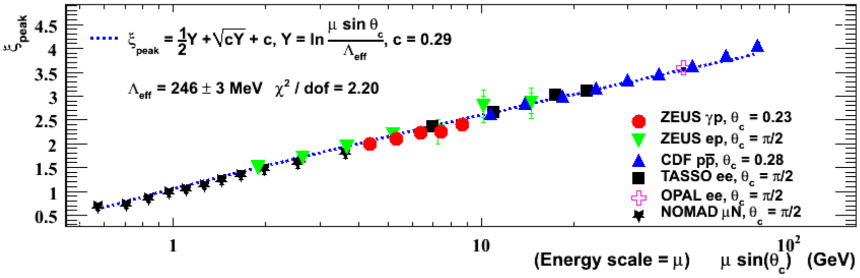


κ_{ch} extracted from 359pb[1] ZEUS data via nMLLA method

- κ_{ch} comes from the normalisation of ξ
- κ_{ch} is insensitive to the ambiguous fitting range.
- κ_{ch} has a weak dependence on θ_c, no dependence on scale.
- Theoretical uncertainties dominate the overall uncertainty.

$$\kappa_{\text{ch}} = 0.55 \pm 0.01\,(\text{stat.})^{+0.03}_{-0.02}\,(\text{syst.})^{+0.11}_{-0.09}\,(\text{theo.})$$

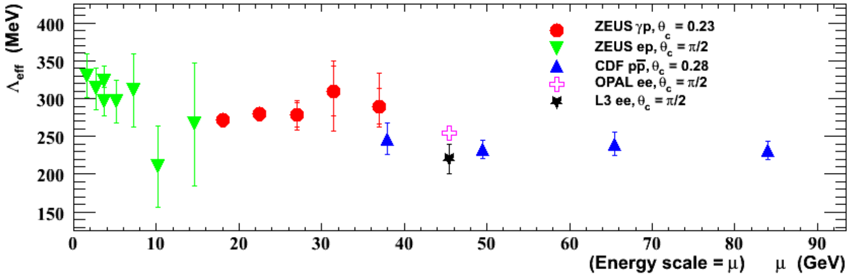
Global Comparisons - ξ_{peak}



Global fit gives $\Lambda_{eff} = 246 \pm 3$ MeV with $\chi^2/\mathrm{dof} = 2.20$

- The fit assumes that Λ_{eff} is independent of scale and θ_c.
- Both ZEUS and CDF observe a weak θ_c dependence.
- CDF also observe a weak scale dependence:
  - Λ_{eff} observed to decrease with increasing energy.
- May explain why this is inconsistent with ZEUS only fit result.

Global Comparisons - Λ_{eff}



Global results for Λ_{eff} as a function of energy scale.

- 359pb^{-1} ZEUS data fills the gap from $19 \rightarrow 38$ GeV.
- First measurement of Λ_{eff} from γp process.
- I will update this plot in a few years with LHC data to ~ 4 TeV.

Summary

Summary

- Scaled momentum distributions have been measured in dijet events in 359pb^{-1} γp ZEUS data.
- Λ_{eff} and κ_{ch} have been extracted at energy scales from $19 \rightarrow 38$ GeV.

$$\Lambda_{\text{eff}} = 275 \pm 4\,(\text{stat.})^{+4}_{-8}\,(\text{syst.})\ \text{MeV}$$

$$\kappa_{\text{ch}} = 0.55 \pm 0.01\,(\text{stat.})^{+0.03}_{-0.02}\,(\text{syst.})^{+0.11}_{-0.09}\,(\text{theo.})$$

Publication

- Pre-print on arXiv : hep-ex/0904.3466
- Submitted to JHEP.