Particle Spectra at ZEUS

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EPS 2009, Krakow
16-22 July 2009

Outline

- **Motivation**
- **Multiplicity studies in NC DIS:**
  - multiplicity distributions
  - KNO scaling
  - energy dependence of multiplicity with different energy scales
- **Scaled momentum distributions in dijet photoproduction:**
  - comparison with the MLLA predictions
  - Λ_{eff}, LPHD k_{ch}

Multiplicity Distributions in DIS

Data and motivation

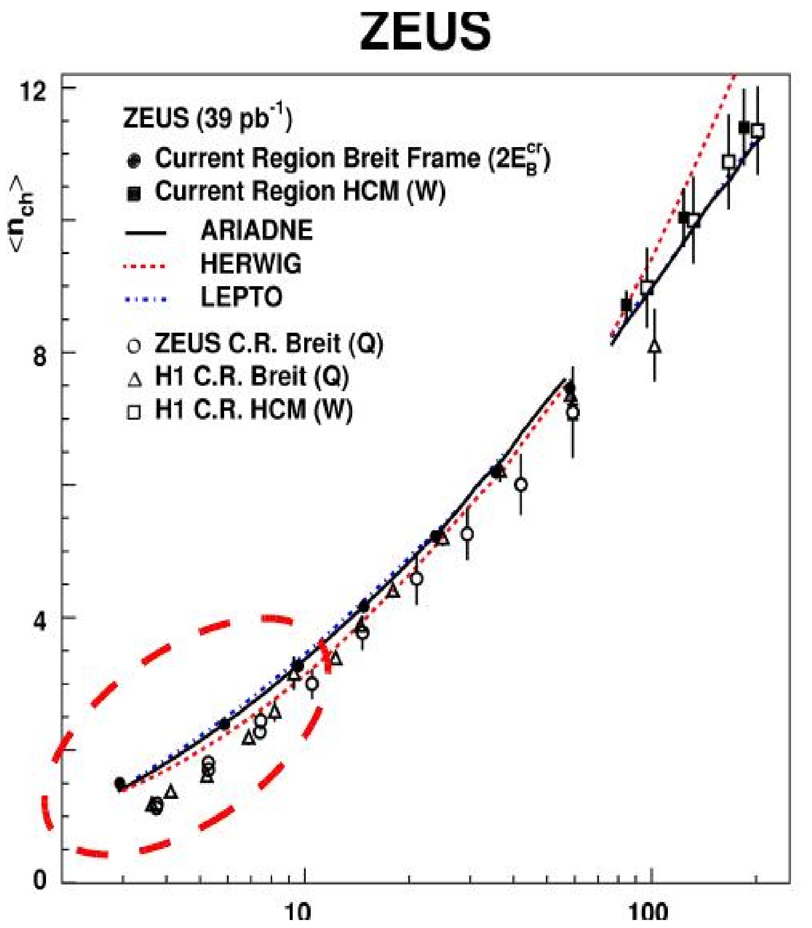
- **Luminosity 38.6 pb-1 collection in 1996-7 with E_{proton} = 820 GeV and E_{e+} = 27.5 GeV**
- **NC DIS events with** ***$Q^2 > 25\ GeV^2$*** ***$70 < W < 225$ GeV***

Comparison with e^+e^- in previous studies in Breit frame:

- a reasonable agreement at *Q>8 GeV*
- no agreement at *Q<8 GeV*
- explained by the asymmetric nature of γ*p

Alternative energy scales to *Q*:

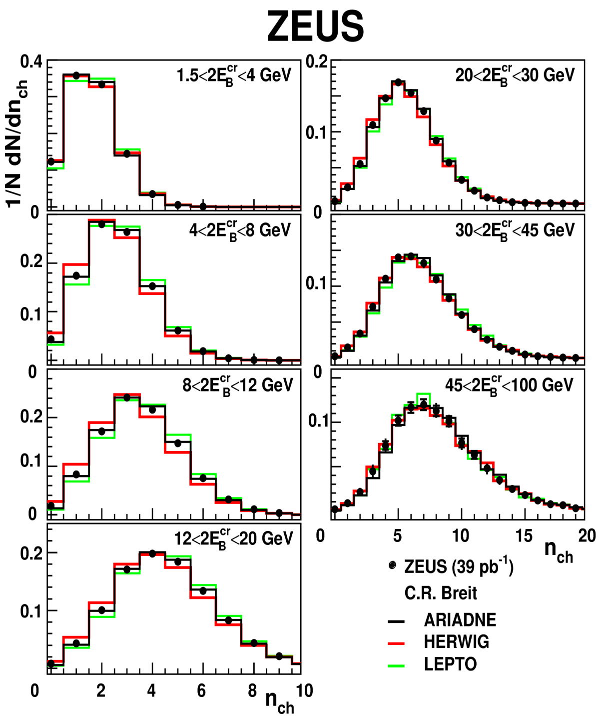
- the invariant mass of hadronic system M_{eff}^{Breit} and M_{eff}^{HCM}
- the available energy in the current region of Breit frame E_B^{Cr} or of HCM $E_{HCM}^{Cr} \approx W/2$

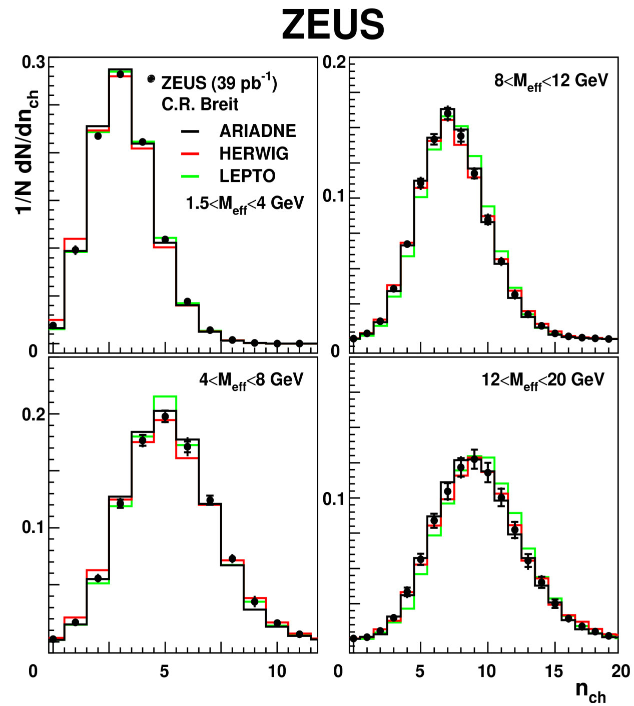


Q → *2E_BCr, W, Meff*

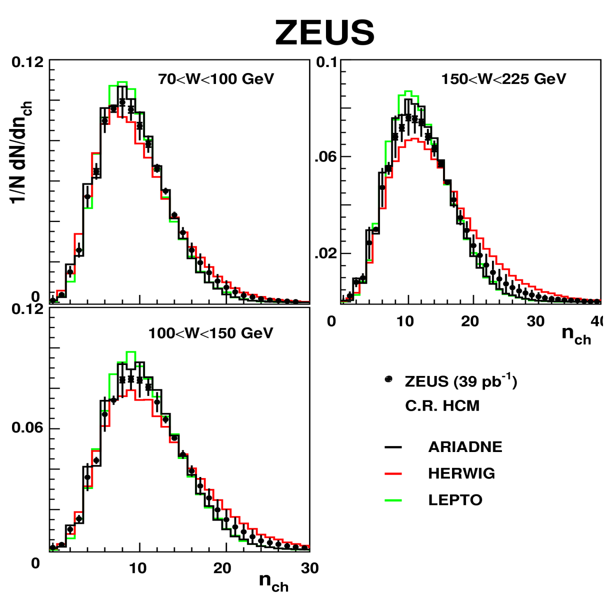
$$M_{eff}^2 = \Big(\sum_{i\neq e'} E^i\Big)^2 - \Big(\sum_{i\neq e'} p_x^i\Big)^2 - \Big(\sum_{i\neq e'} p_y^i\Big)^2 - \Big(\sum_{i\neq e'} p_z^i\Big)^2$$

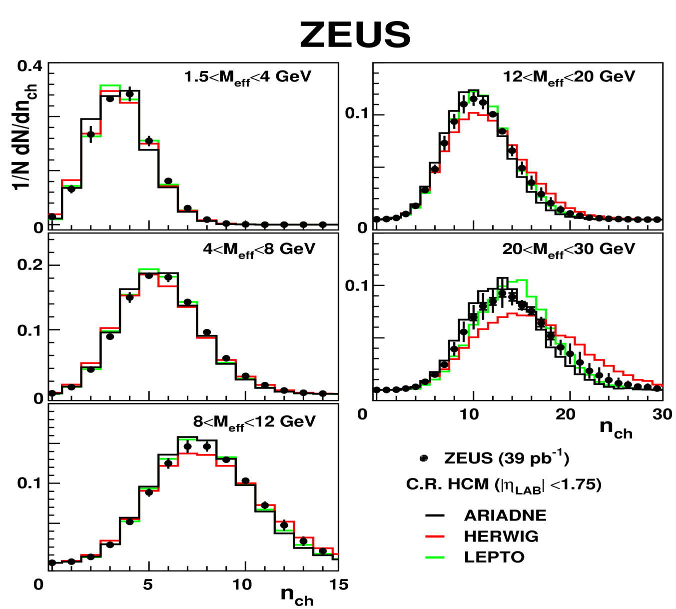
Multiplicity in





- 2 E_B^{cr} bins in the Breit frame
- W bins in HCM frame
- M_{eff} bins in the Breit frame
- M_{eff} bins in the CR of HCM frame





ARIADNE is the best

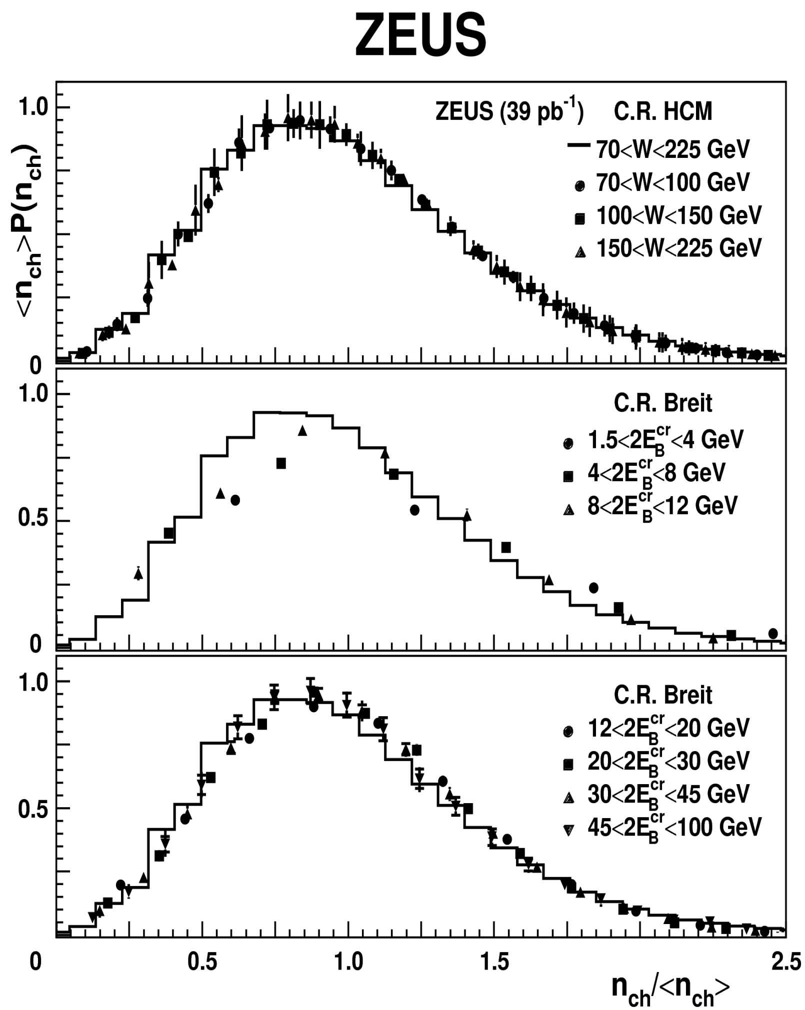
HERWIG −longer tails for multiplicities

→ increase of the systematic uncertainties

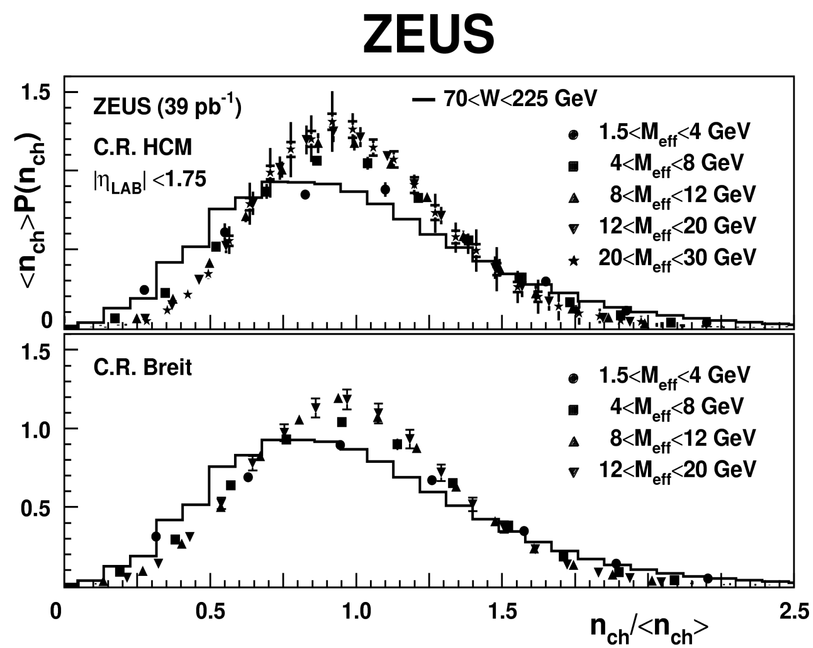
KNO SCALING

Koba, Z.H.B.Nielson, P.Olsen
N.P.B40(1972)317

W and 2 E_B^{cr} bins



M_{eff} bins

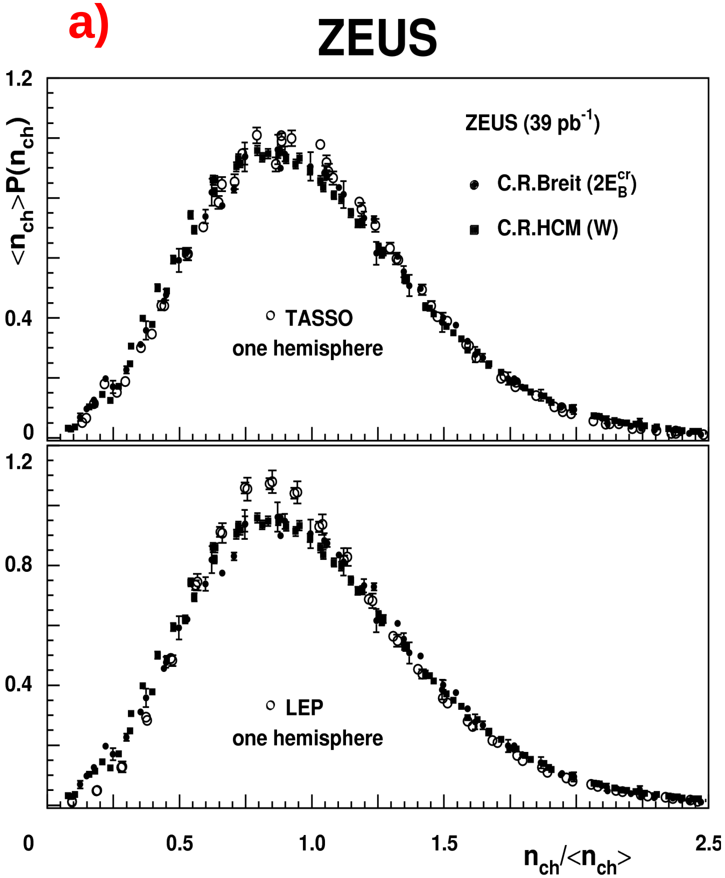


$$\langle n\rangle P(n_{ch})=\psi(n_{ch}/\langle n_{ch}\rangle)$$

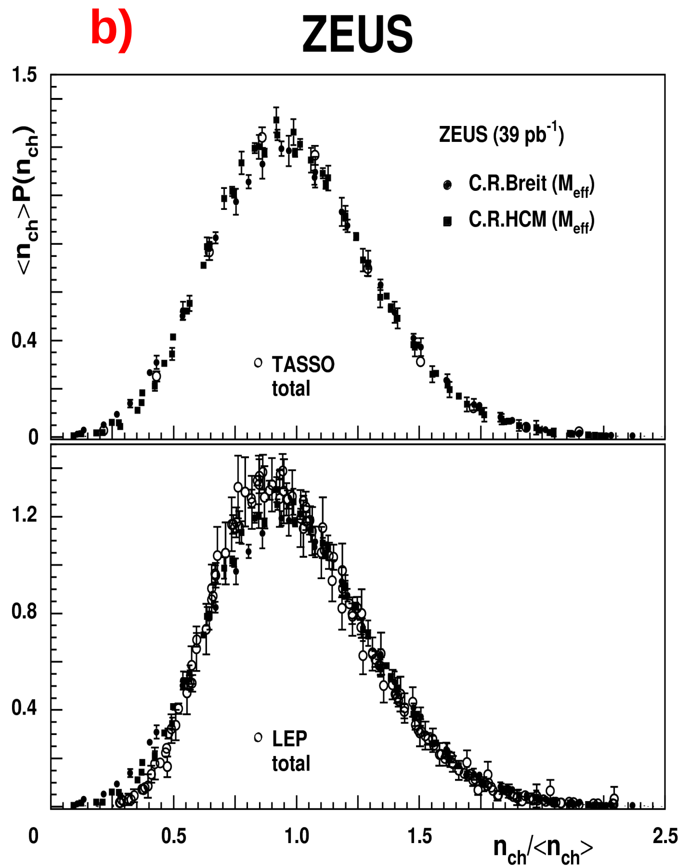
Scaling behaviour observed for HCM and Breit except M_{eff} less than 4 GeV

KNO scaling
comparison with e+e-

a)



b)



a) ep in bins $2E_B^{cr}$

W

$2E_B^{cr}>12$ GeV

b) in bins M_{eff}

$M_{eff}>8$ GeV

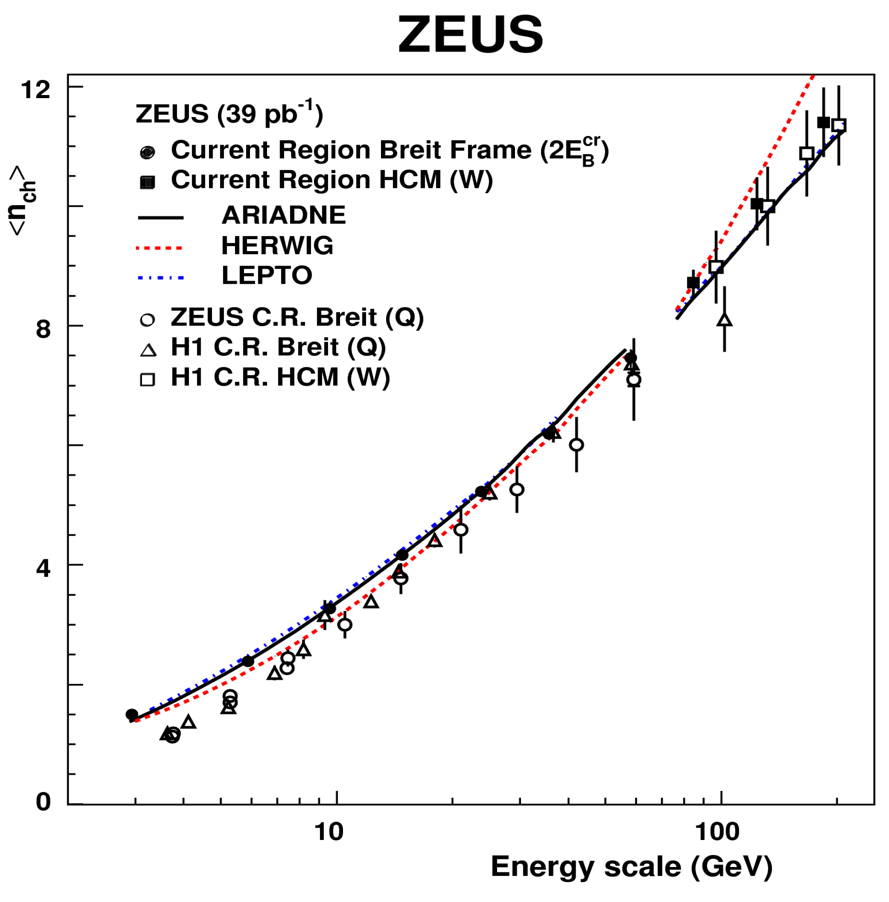
e+e− data from one hemisphere

LEP (DELPHI, OPAL) at Z^0
PETRA(TASSO)

e+e− data for 2 hemispheres

LEP(DELPHI, OPAL, L3, ALEPH)
PETRA(TASSO)

Energy dependence of average multiplicity



scales used:

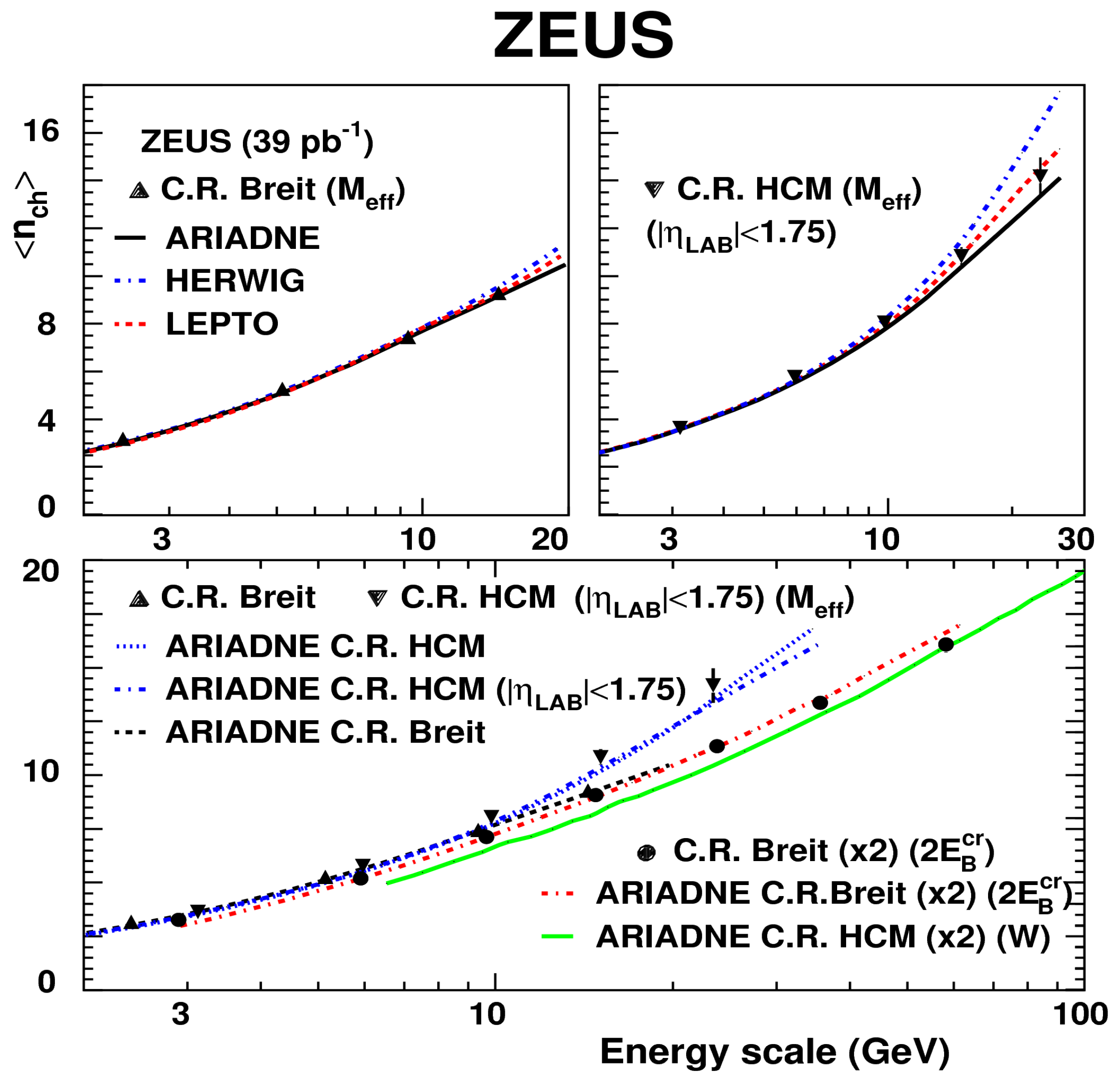
$2\,E_B^{cr}$

W

M_{eff}

At low energy scales : differences if $2E_B^{cr}$ or Q used

M_{eff} energy scale

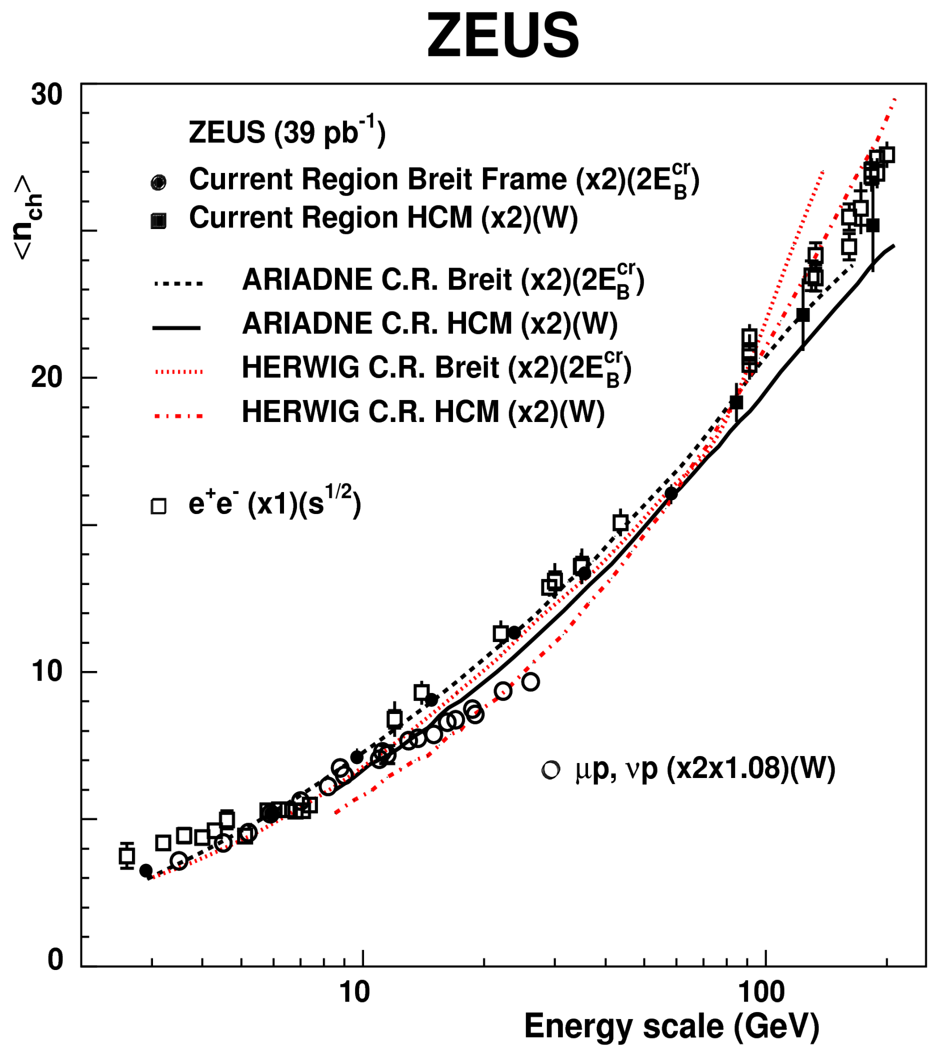


All three models describe the data reasonably well, in the last M_{eff} bin in C.R. HCM the Herwig prediction is too high

$<n_{ch}>$ vs M_{eff} in the C.R. of the Breit frame shows the same behaviour as $2<n_{ch}>$ vs $2E_B^{cr.}$

$<n_{ch}>$ vs M_{eff} rises faster in HCM than in the Breit frame

Summary plot



The measurements show good overall agreement with the those from other experiments. Exibit approximately the same dependence of the $<n_{ch}>$ on the respective energy scale.

– At low value of energy $<n_{ch}>$ vs $2\,E_B^{cr}$ agrees well with e+e- in contrast the previous measurements vs Q.
  – data in C.R. of HCM (W) agree with the LEP data, but systematically below them
  – when using these scales, ep DIS data can be consistently compared with data from e+e-, μP and νP collisions over a wide energy region

Scaled momentum distributions of charged particles in dijet photoproduction

Data and motivation

Luminosity 359 pb^{-1} collected in 2005-7
with E_{proton}= 920 GeV and E_e= 27.5 GeV

Photoproduction events (γp) were studied :

- required to have only two reconstructed jets
- energy scales in the range 19 to 38 GeV
- cones of various opening angles θ_c around the jet axis
- jets were reconstructed using the k_T cluster algorithm

Tests of MLLA predictions

- comparison of the scaled momentum distribution in jets with MLLA , LPHD is assumed
- extract MLLA scale Λ_{eff} and the LPHD parameter κ_{ch}
- Λ_{eff} previously measured for ee , eP,$P\bar{P}$, never for γP
- is Λ_{eff} independent of interraction type? ee, ep, $P\bar{P}$, γP
- is Λ_{eff} independent of E_{jet} and θ_c as predicted?

The MLLA+LPHD Theoretical Framework

The Modified Leading Log Approximation

- All orders pQCD resummation
- Analitical description of parton evolution
- Predicts parton multiplicity and momenta
- MLLA describes fragmentation with 2 parameters:
  Q_0 – self-imposed cut-off energy scale
  Λ_{eff} - QCD scale effective parameter
- We study MLLA within jets, where fragmentation is well drfined
- Λ_{eff} – predicted to be universal
- Assuming Local Parton Hadron Duality MLLA predictions are directly comparable to the data

The Local Parton Hadron Duality (LPHD)

- Assumes hadronization is local and occurs at the end of parton shower
- Relates the observed hadron distributions to calculated parton distributions via constant factor, κ_{ch}
- κ_{ch} is the ratio of the number of charged particles over the total number of partons produced during fragmentation
- 2 free parameters in MLLA + LPHD: Λ_{eff} and κ_{ch}

Measurement of Λ_{eff} and κ_{ch}

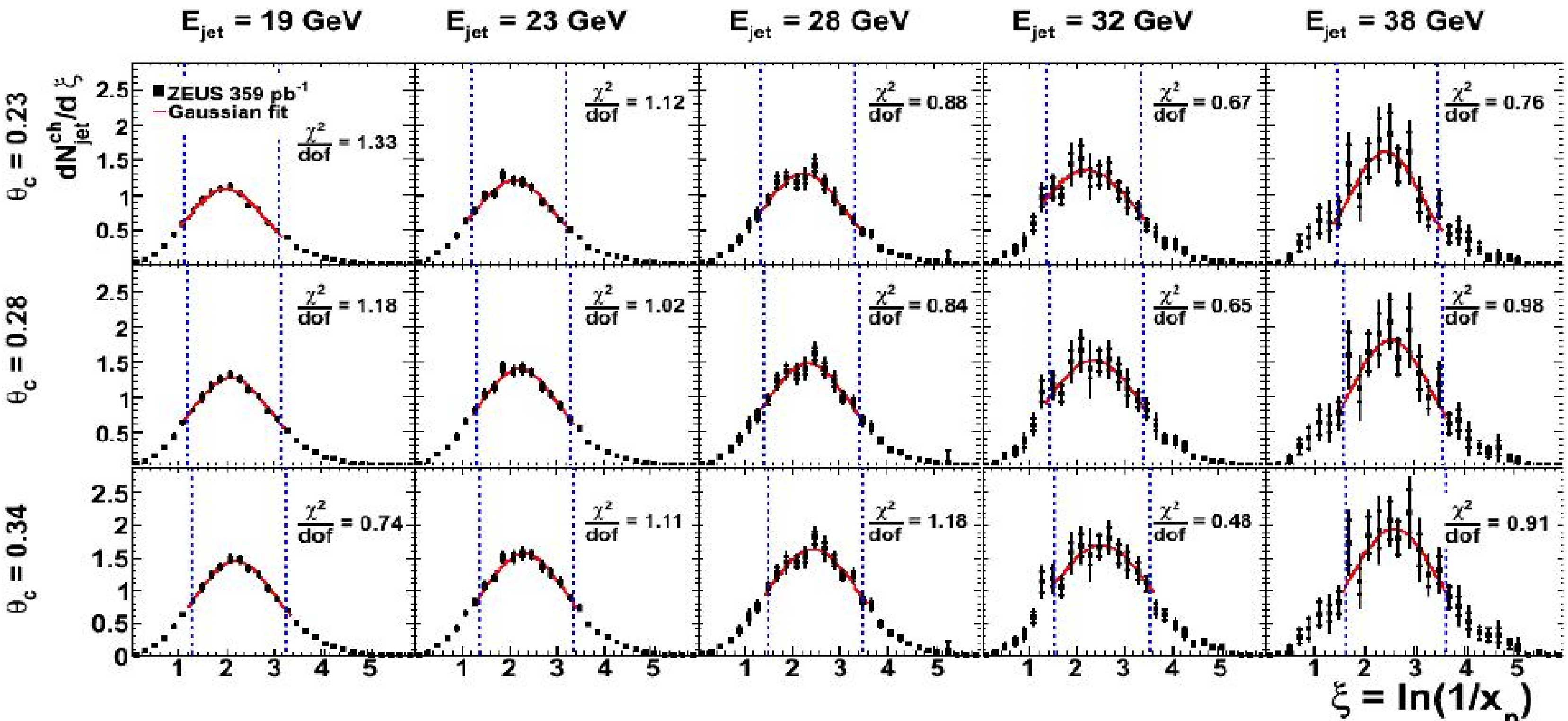
Strategy of the analysis

- Measure scaled track momentum within jets, $x_p = \frac{P_{\rm track}}{P_{\rm Jet}}$.
- Plot scaled momentum distributions, $\xi = \ln\left(\frac{1}{x_p}\right)$, in bins of jet energy $E_{\rm Jet} = \frac{M_{2j}}{2}$ (the hard scale) and θ_c (the opening angle).

To check the validity of the MLLA ptedictions fitting of the measured ξ distributions was done by

- 2 methods:
  - Gaussian around mean
  - MLLA +LPHD theory
- $\xi_{\rm peak}$, $\Lambda_{\rm eff}$ and $\kappa_{\rm ch}$ were extracted from fits

The measured ξ distributions



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

The Gaussian fit method

- Gives peak position of ξ distribution, ξ_{peak}
- ξ_{peak} gives Λ_{eff} - Only valid for Leading Order

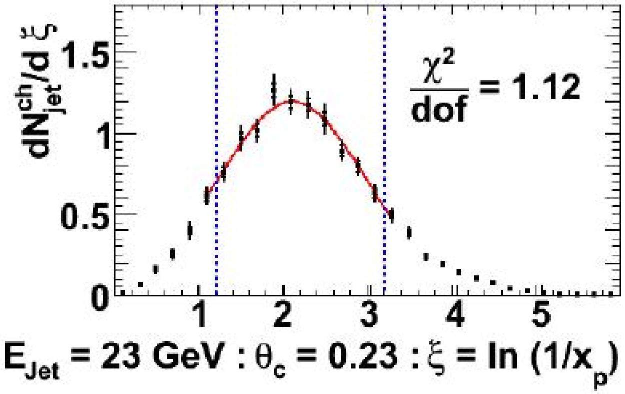
The MLLA +LPHD fit method

- Gives Λ_{eff} and K (the normalization) directly from fit
- κ_{ch} is calculated from K
- Λ_{eff} has strong dependence on ambiguous fit range
- κ_{ch} only weakly dependant on the fitting range

The results presented here use

- The Gaussian method for ξ_{peak} and Λ_{eff}
- The MLLA+LPHD method for κ_{ch} and to cross check Λ_{eff}

The Gaussian fit method



Peak position, ξ_{peak}

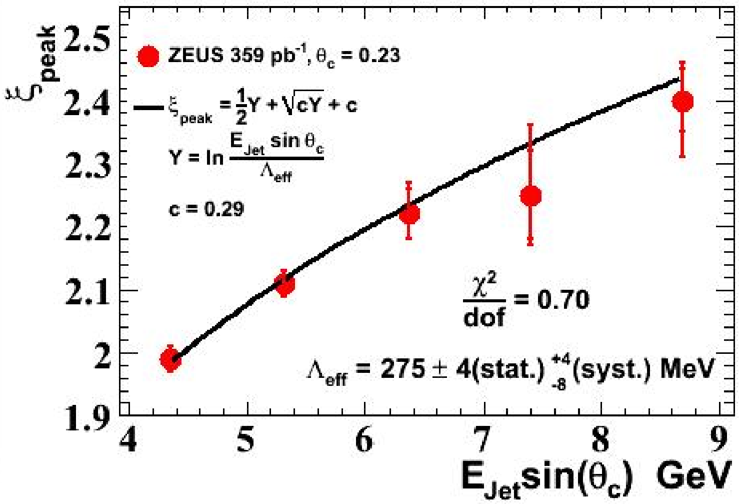
- Fit Gaussian ± 1 around mean.
- $\forall\ \xi$, independently measure ξ_{peak}.

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

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.

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



The MLLA+ LPHD fit method

Momentum distribution of partons from a gluon is given by:

- $\bar{D}^{\lim}_{\mathrm{g-Jet}}\left(\ln\left(\frac{1}{x_p}\right), Y\right) = \frac{4C_f}{b}\Gamma(B)\int_{-\frac{\pi}{2}}^{\frac{\pi}{2}} e^{-B\alpha}\left[\frac{\cosh\alpha+(1-2\zeta)\sinh\alpha}{\frac{4N_c}{b}Y\frac{\alpha}{\sinh\alpha}}\right]^{\frac{B}{2}}$
  $. \; I_B\left(\sqrt{\frac{16N_c}{b}Y\frac{\alpha}{\sinh\alpha}[\cosh\alpha+(1-2\zeta)\sinh\alpha]}\right)\frac{d\tau}{\pi}$
- 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 $Y = \ln\left(\frac{E_{\mathrm{Jet}}\sin(\theta_c)}{\Lambda_{\mathrm{eff}}}\right)$ $\qquad \bar{D}^{\lim}_{\mathrm{q-Jet}} = \frac{1}{r}\bar{D}^{\lim}_{\mathrm{g-Jet}}$

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.

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

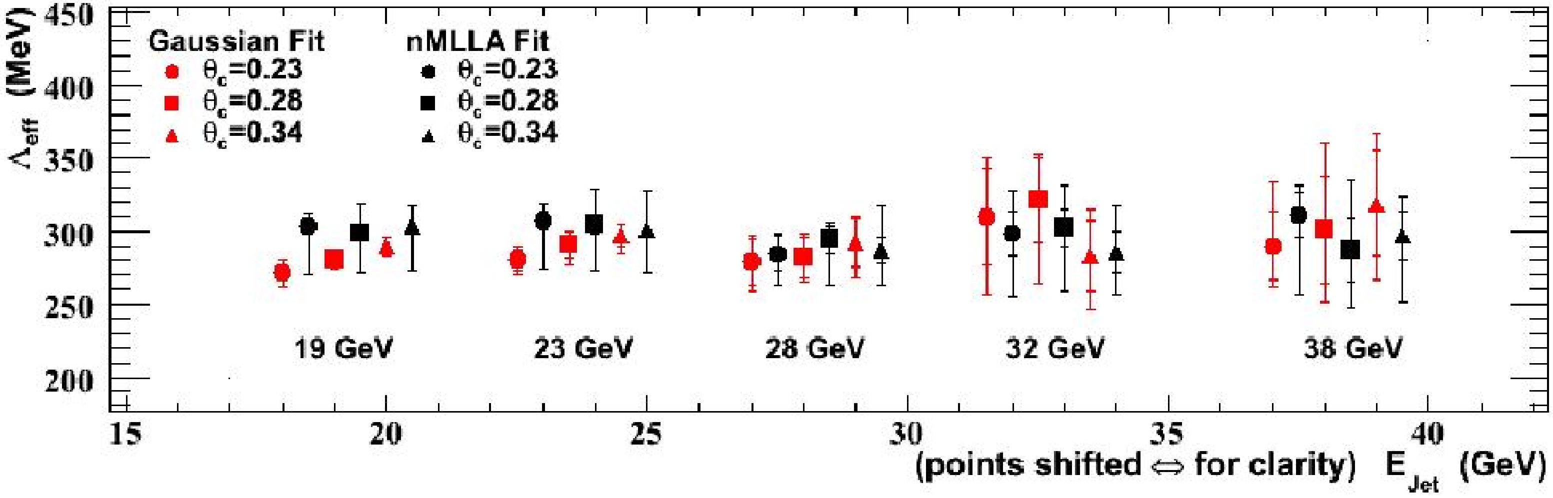
Energy (GeV)	19	23	28	32	38
ϵ_{g} (From PYTHIA)	0.203	0.213	0.211	0.227	0.242

The so called "next-to-MLLA" predictions

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

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

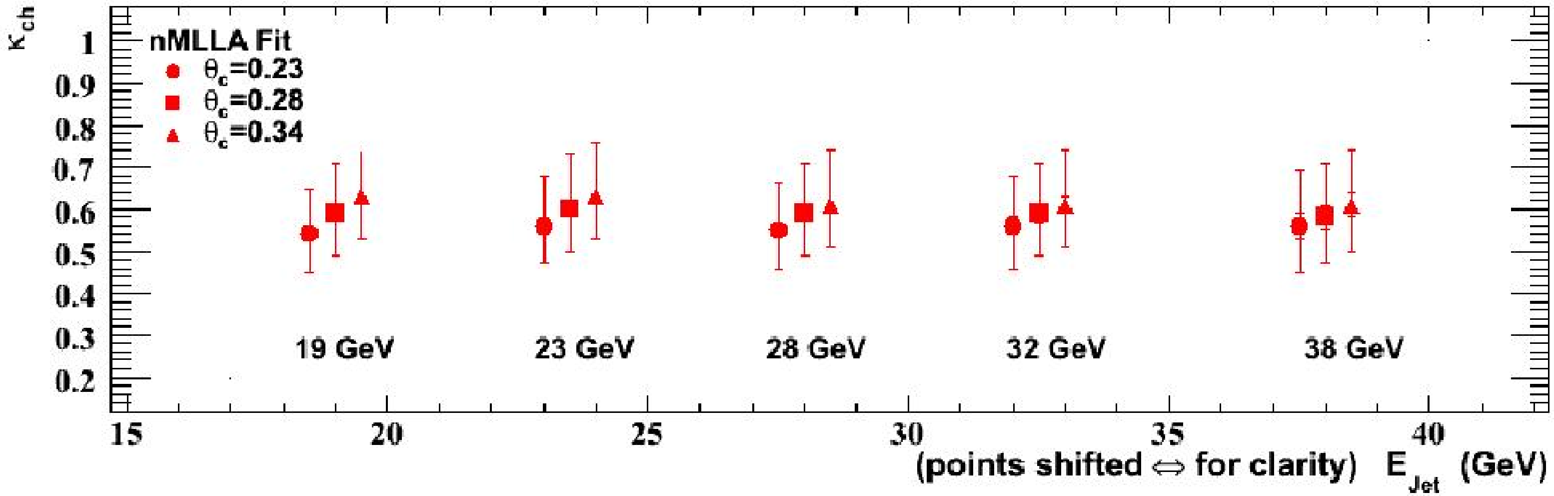
Λ_{eff} - Comparison of extraction methods



Λ_{eff} extracted from 359pb[1] ZEUS data via both methods

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

κ_{ch}

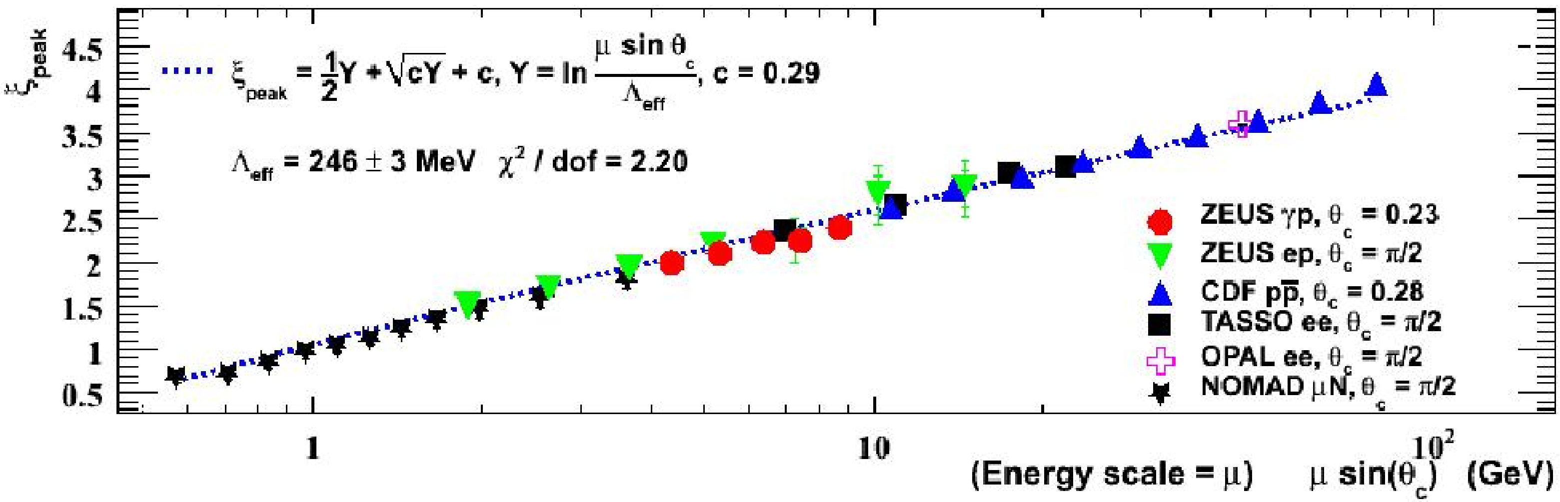


κ_{ch} extracted from 359pb[1] ZEUS data via nMLLA method

- 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.

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

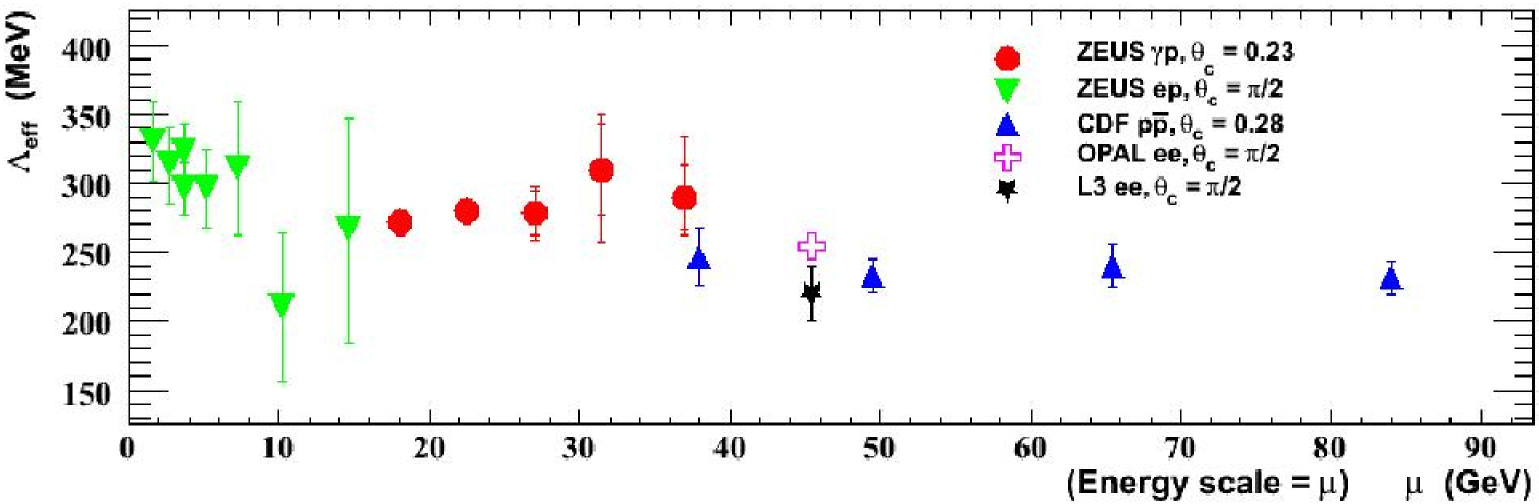
Global Comparisons - ξ_{peak}



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

- 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 - $\Lambda_{\rm eff}$



Λ_{eff} as a function of energy scale for different experiments

- $359\mathrm{pb}^{-1}$ ZEUS data fills the gap from 19 $\rightarrow$ 38 GeV.
- First measurement of $\Lambda_{\rm eff}$ from γp process.

Summary

Summary

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

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

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

Publication

- Pre-print on arXiv : hep-ex/0904.3466

Conclusions

Hadronic spectra proved to be a powerful tool for study of various aspects of the multiparticle dynamics:

Multiplicity studies in NC DIS:

– detailed comparison multiplicity distributions with MC models

– KNO scaling was studied with different energy scales

– energy dependence of multiplicity was investigated for different energy scales and detailed comparison with e+e- was done

Scaled momentun distribution:

– scaled momentum distributions were measured

– Λ_{eff} and LPHD and κ_{ch} were extracted

Still rich program of studies with ZEUS : many results not shown, many studies in progress...

Thank you for your attention!

Many thanks to Krakow for hospitality!