

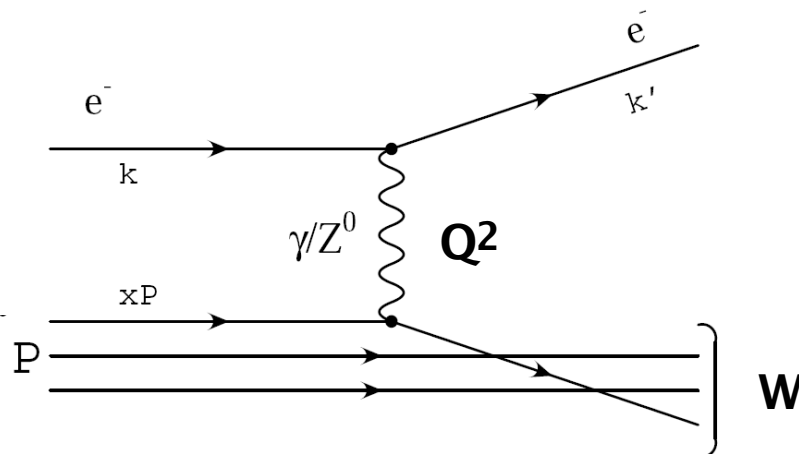


# Multiplicity and momentum distributions of hadrons in deep inelastic scattering at HERA energies

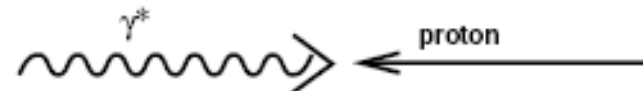
On behalf of the H1 and ZEUS Collaboration

Teresa Tymieniecka

University of Warsaw, Poland



- Energy of  $\sim 300$  GeV in ep CMS
- Neutral current (NC)





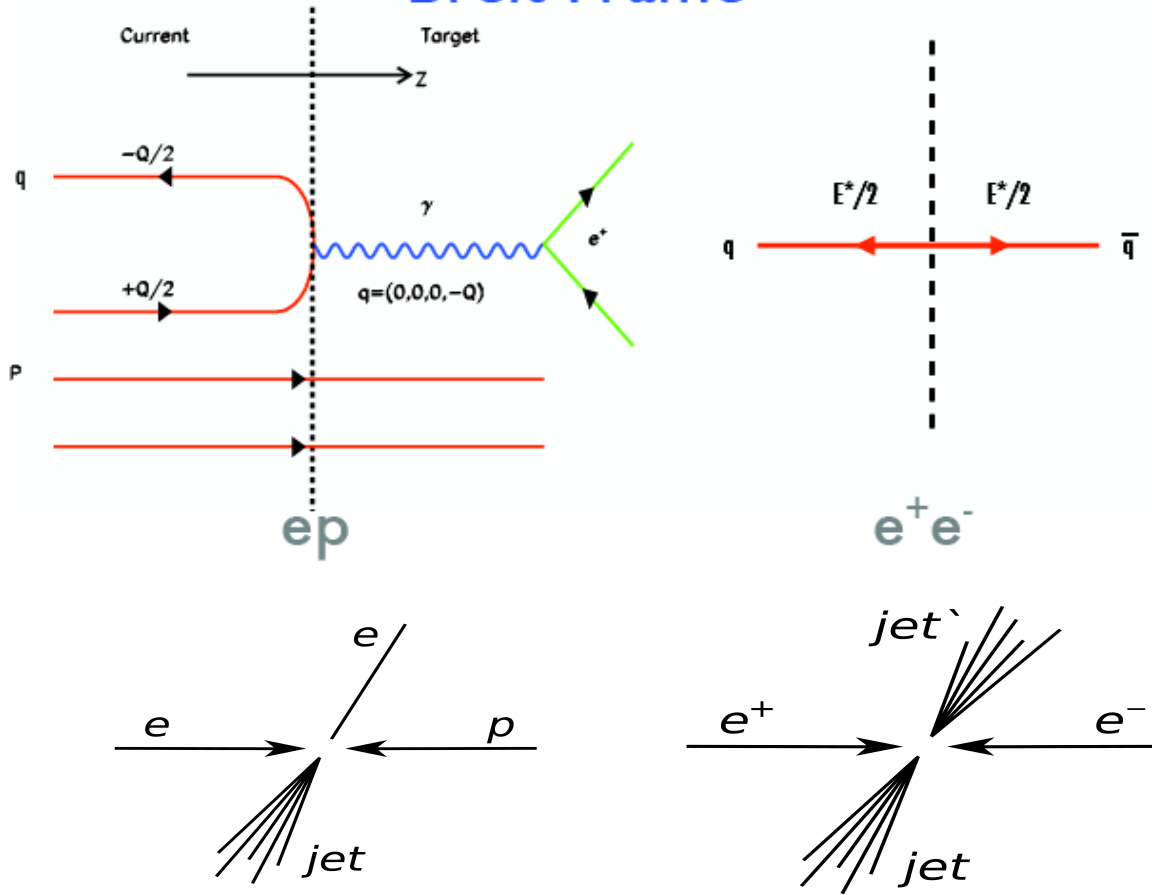
# **Multiplicity and momentum distributions of hadrons in deep inelastic scattering at HERA energies**

## **Outline**

- **Motivation:**
  - scaling with energy**
  - comparison with  $e^+ e^-$**
- **Multiplicity of charged hadrons**
- **Scaled momenta distributions of charged hadrons**
- **Summary and conclusions**

# Reference frames

## Breit Frame



## Hadronic Centre of Mass or CMS $\gamma p$

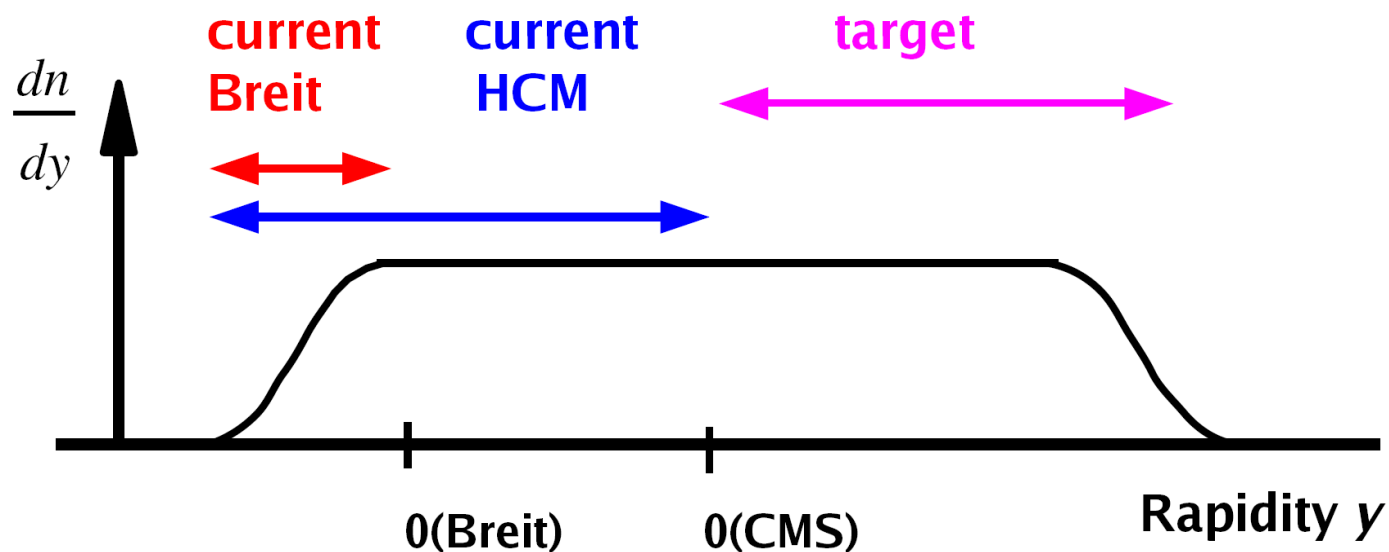
**Knowledge of particle rapidity is important for understanding of underlying processes and for comparison with  $e^+e^-$  or  $pp$ .**

**Photon virtuality,  $Q$ , is related to momentum of scattered quark.**



Rapidity of particles defines their expected features,

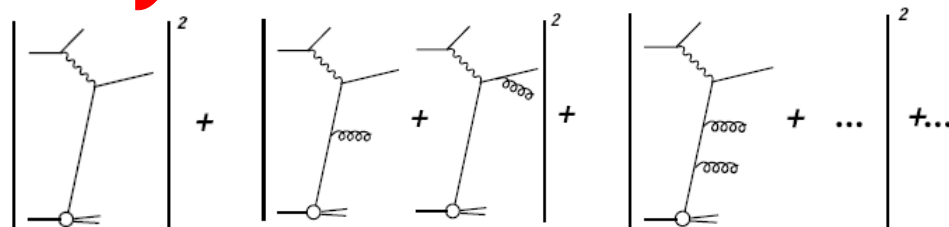
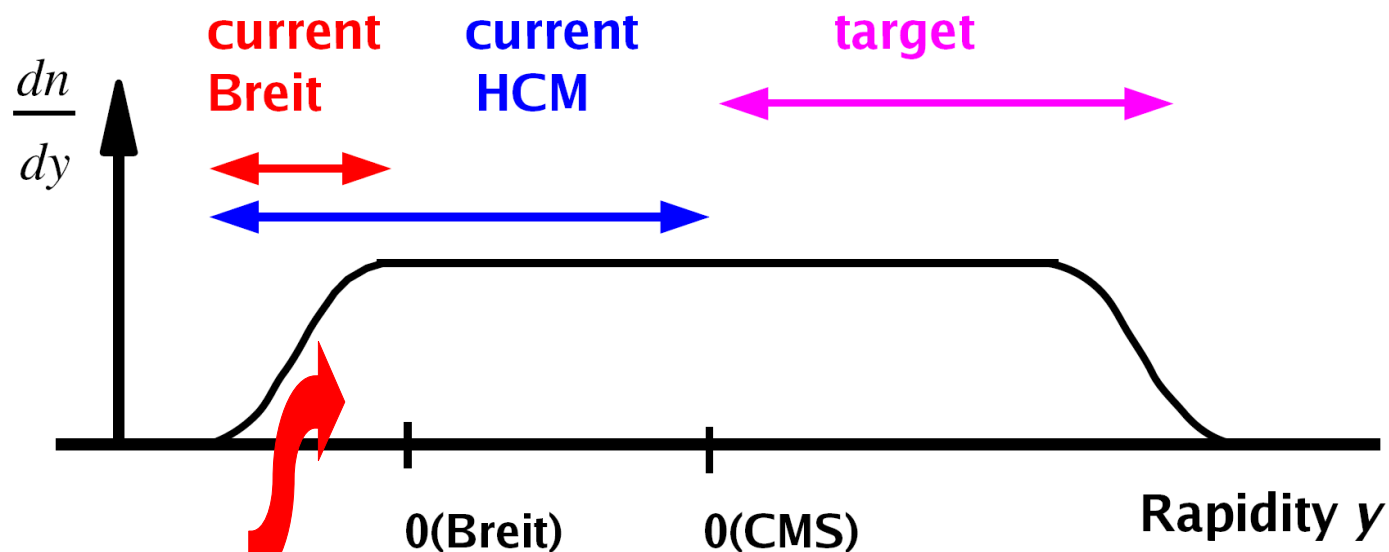
Similar to  $e^+e^-$





Rapidity of particles defines their expected features,

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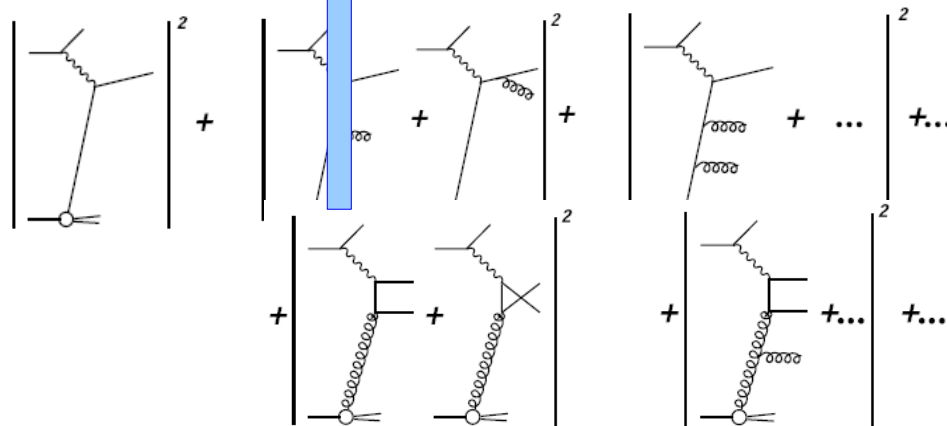
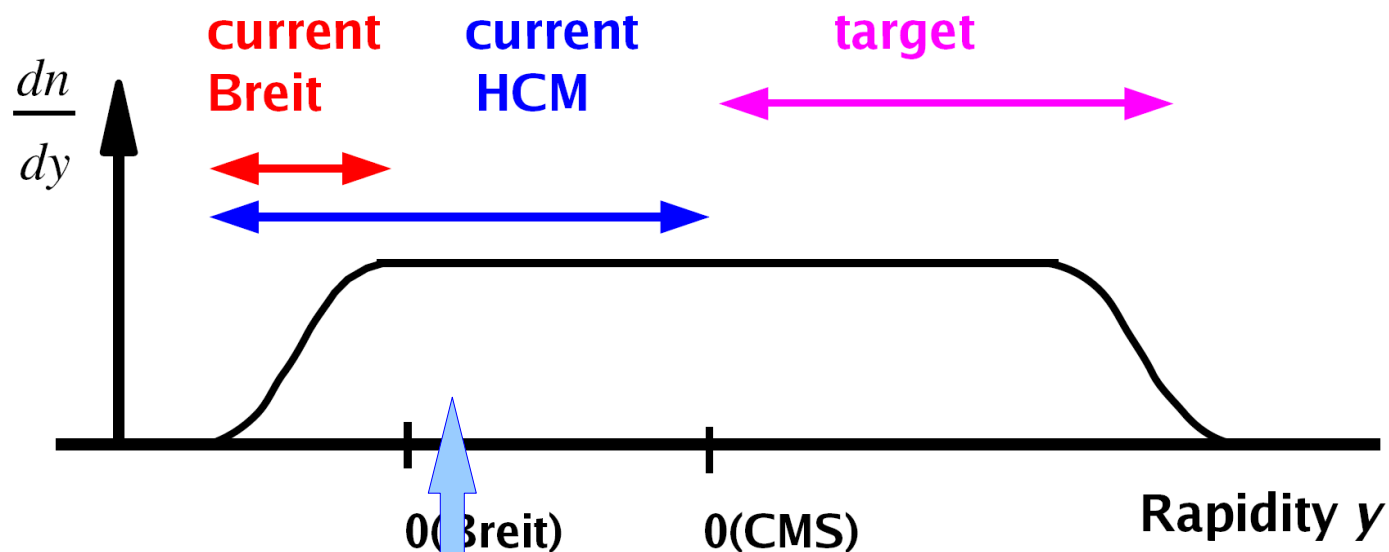


gluon emission



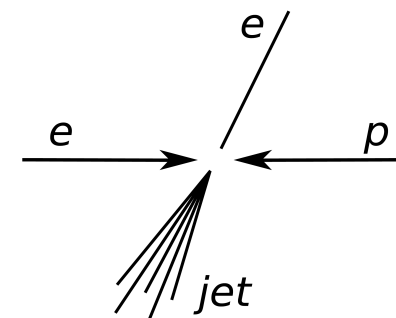
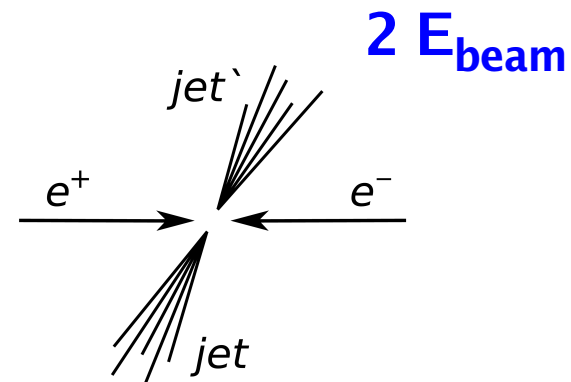
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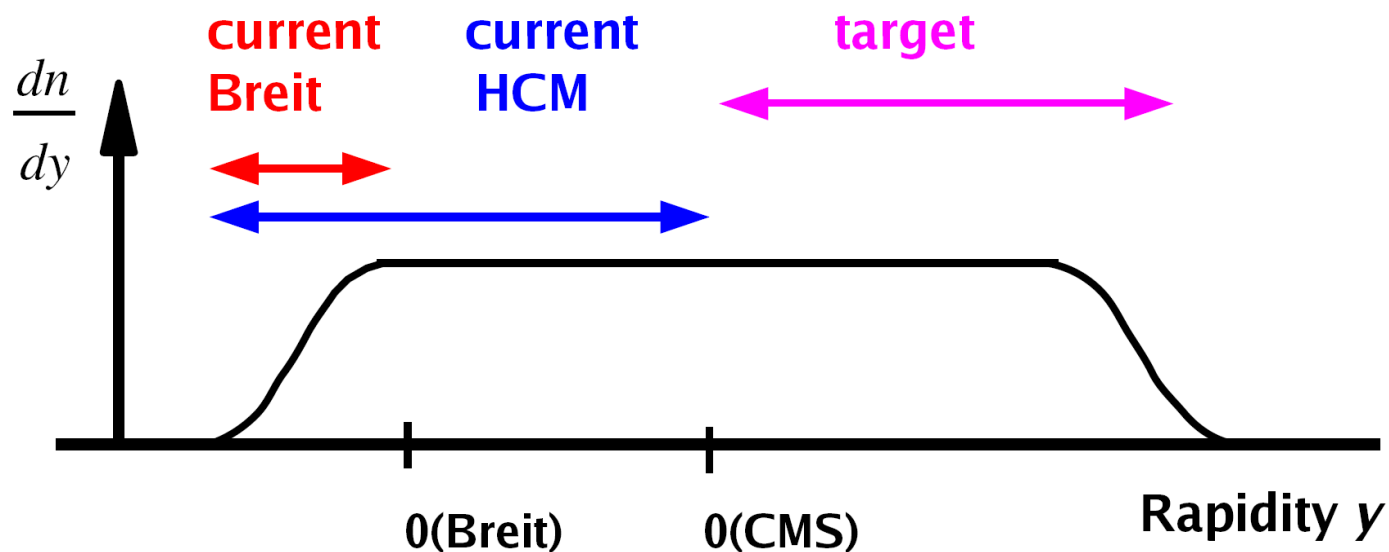


gluon emission

boson-gluon fusion



Similar to  $e^+e^-$



$Q, 2E_B^{cr}, M_{eff}$

$W, M_{eff}$

$$2E_B^{cr} = 2 \left( \sum_i^n E_i \right)$$

$$M_{eff}^2 = \left( \sum_i^n E_i \right)^2 - \left( \sum_i^n P_{Xi} \right)^2 - \left( \sum_i^n P_{Yi} \right)^2 - \left( \sum_i^n P_{Zi} \right)^2$$

# Discussed HERA DIS data

ZEUS Coll.,	Eur.Phys.J. C11(1999)251	(luminosity 38 pb <sup>-1</sup> )
H1 Coll.,	Phys.Lett. B654(2007)148	(luminosity 44 pb <sup>-1</sup> )
ZEUS Coll.,	JHEP06 (2008) 061	(luminosity 39 pb <sup>-1</sup> )
ZEUS Coll.,	Preliminary	(luminosity 0.5 fb <sup>-1</sup> )

## Predictions

### Monte Carlo models

ARIADNE 4.12	—	colour dipole model	
LEPTO MEPS	—	matrix element + parton shower	( <del>PS+SCI</del> )
fragmentation	—	the Lund string model	
HERWIG	—	cluster hadronisation model	

Charged hadrons taken with lifetime  $> 3 \cdot 10^{-11}$  s

stable particles include:  $\Lambda$ ,  $\Sigma^\pm$ ,  $\Omega$ ,  $K^0$

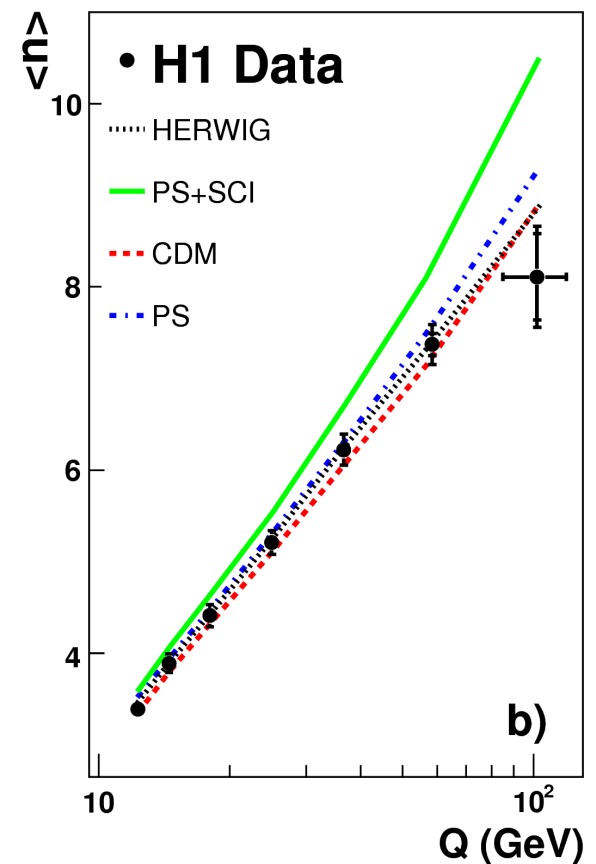
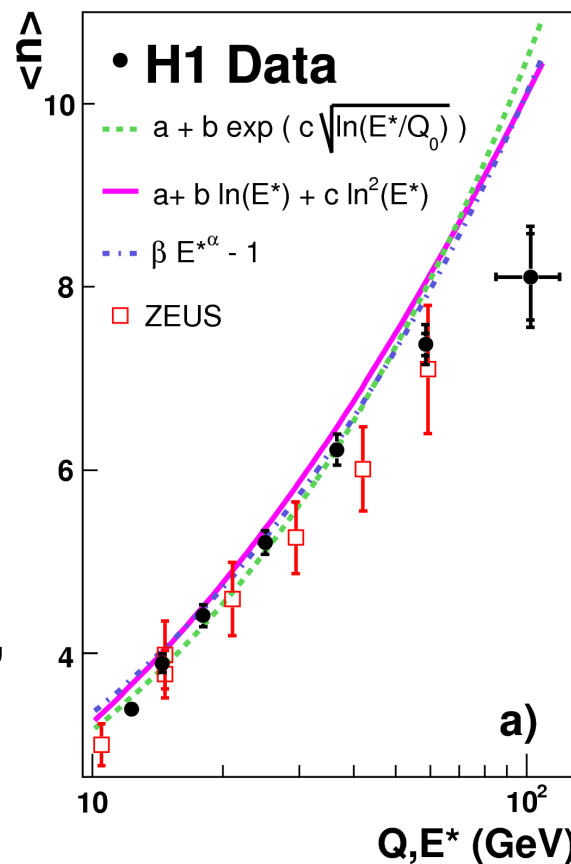


# Average multiplicity as f (Q) (e<sup>+</sup>e<sup>-</sup> vs ep)

Luminosity 44 pb<sup>-1</sup>  
collected in 2000  
with E<sub>proton</sub> = 920 GeV  
and E<sub>e+</sub> = 27.5 GeV

100 < Q<sup>2</sup> < 20000 GeV<sup>2</sup>  
0.05 < y < 0.6

e<sup>+</sup>e<sup>-</sup> is represented by  
parameterisations ,  
 $E^* = 2 E_{\text{beam}}$



## Conclusions:

- Good agreement with e<sup>+</sup>e<sup>-</sup> except at highest Q<sup>2</sup>
- Good agreement with predictions except at LEPTO (PS+SCI)

# Average multiplicity as $f(2E_B^{cr})$ and $f(W)$

$$2E_B^{cr} = 2 \left( \sum_i^n E_i \right)$$

Luminosity  $38.6 \text{ pb}^{-1}$   
collected in 1996-7  
with  $E_{\text{proton}} = 820 \text{ GeV}$   
and  $E_{e^+} = 27.5 \text{ GeV}$

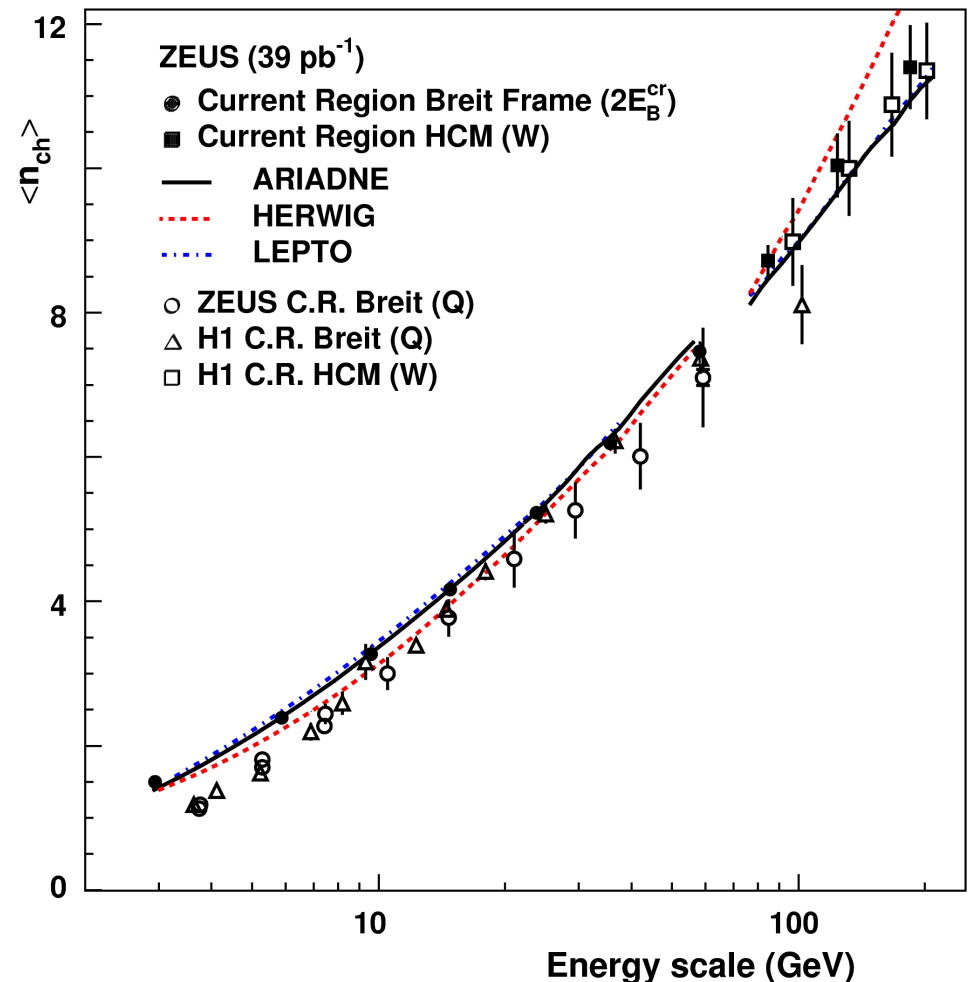
$Q^2 > 25 \text{ GeV}^2$   
 $70 < W < 225 \text{ GeV}$

Alternative energy scales to  $Q$

## Conclusions

- good agreement  
with LEPTO and ARIADNE  
not with HERWIG
- differences at low energy scales  
but not at high scales

ZEUS



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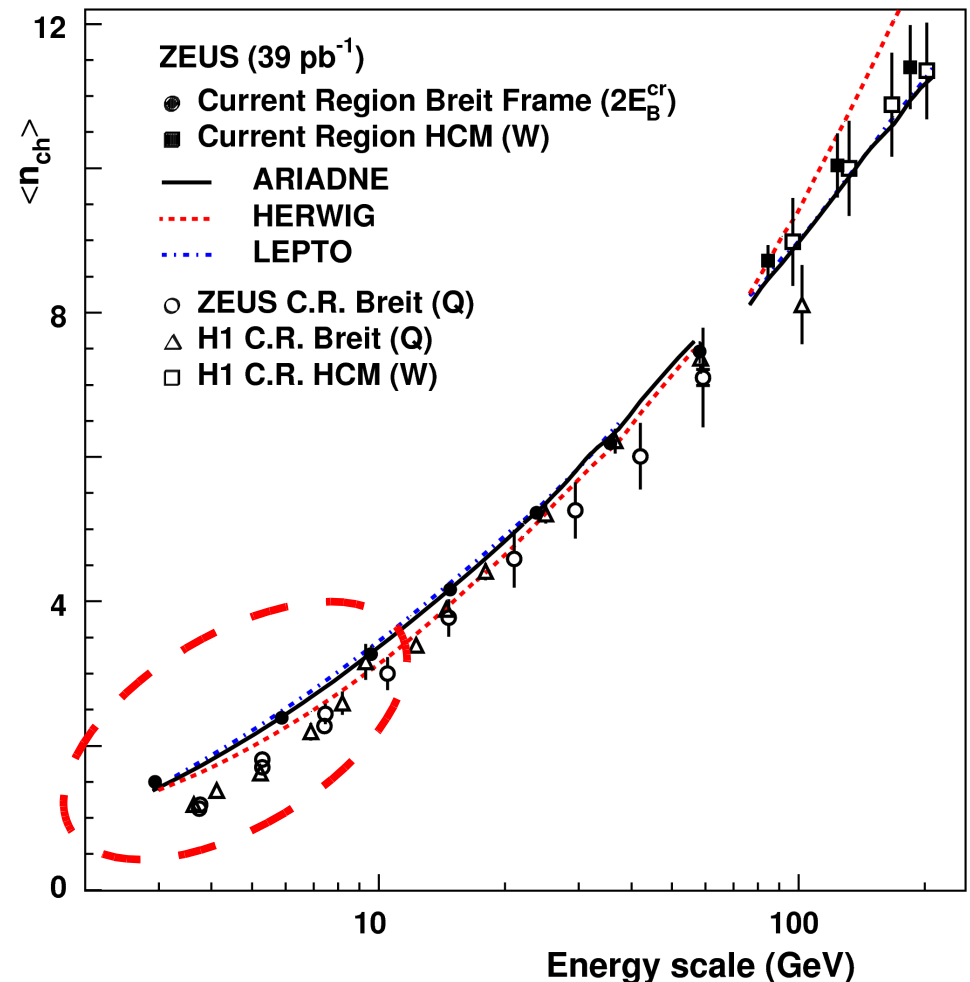
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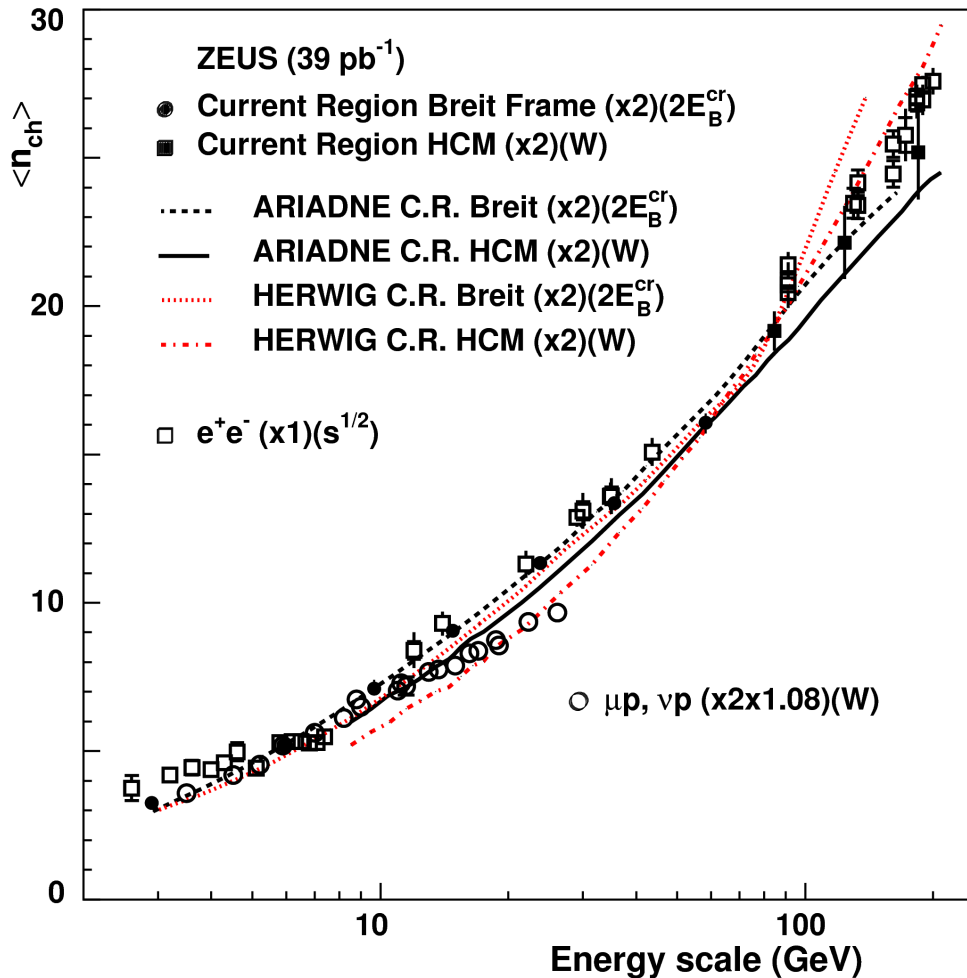
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ZEUS



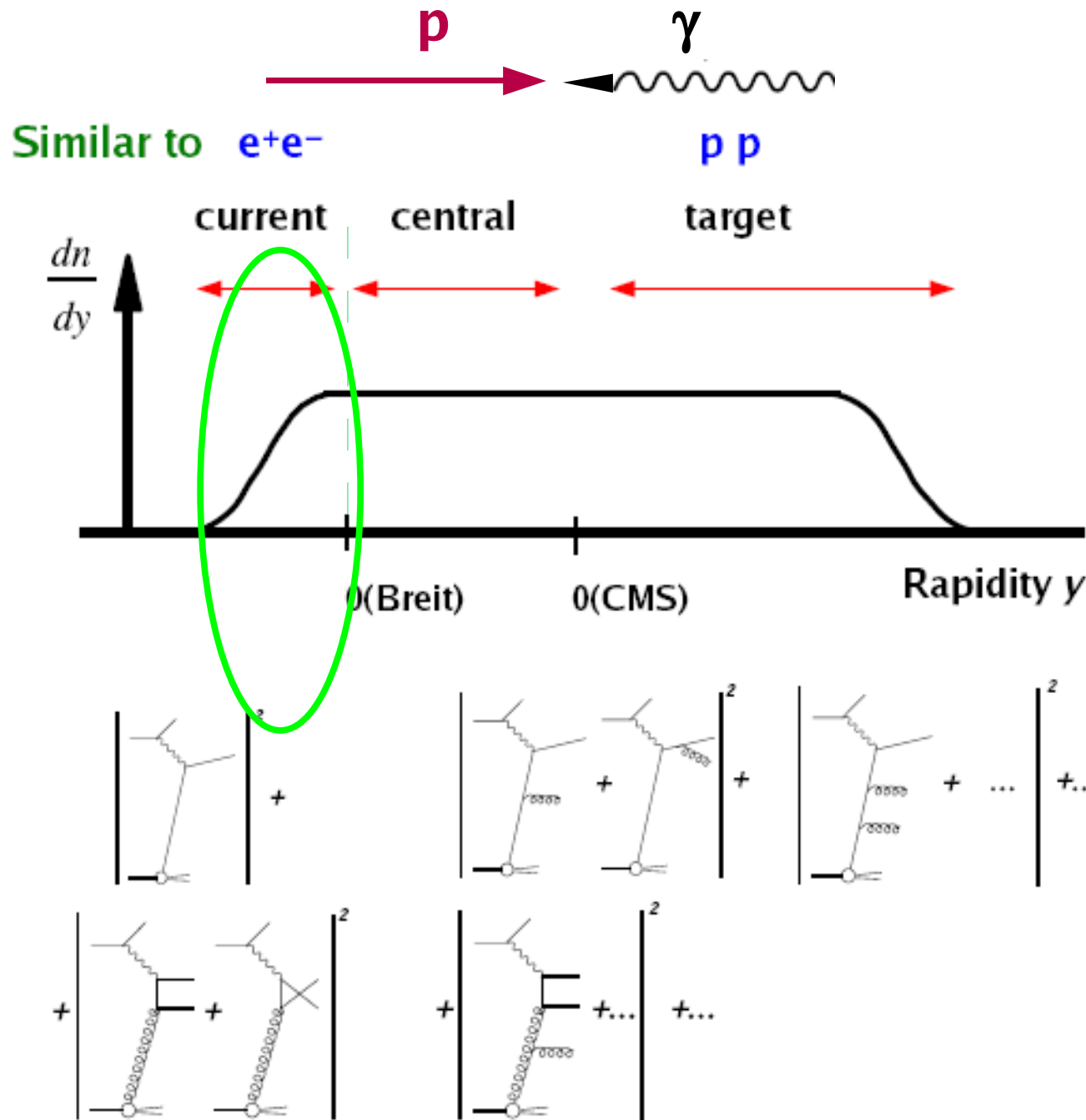
# Multiplicity ( $e^+e^-$ vs $ep$ & fixed target)

## ZEUS



- At low scales  $2E_B^{cr}$  gives better agreement with  $e^+e^-$  than  $Q$
- ARIADNE - the best description but data are systematically above predictions in HCM
- HERWIG deviates from data
- LEP data above  $ep$  data in HCM at scale  $>100$  GeV
- Fixed target data deviate from the observed energy dependence above 15 GeV

# Fragmentation in DIS



- hadron spectra in the Breit frame

# Fragmentation functions $D(z, Q^2)$

Hadron spectra in ep hard scattering

$$f(x, Q^2) \otimes \sigma(Q^2) \otimes D(z, Q^2)$$

Parton density

parton cross section (NLO,...)

probability for a parton to fragment into a hadron carrying a given fraction  $z$  of the parton energy

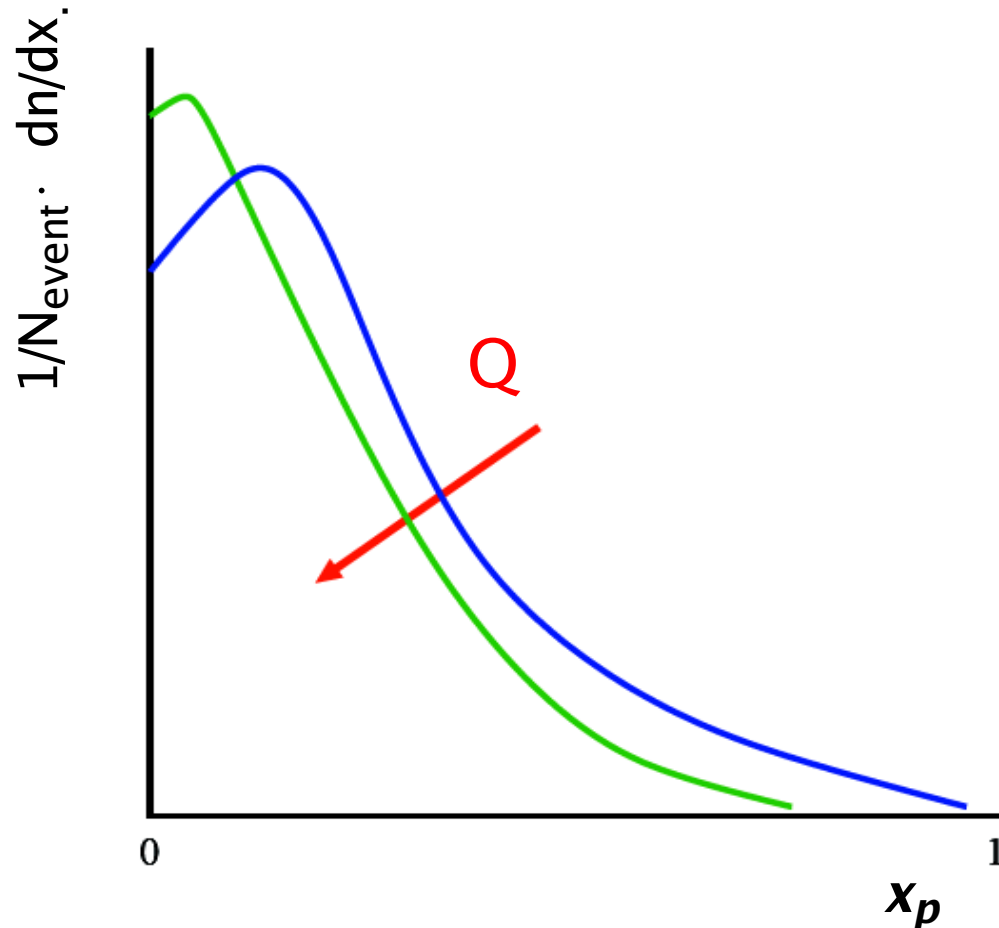
The diagram illustrates the factorization of hadron spectra in ep hard scattering. The equation  $f(x, Q^2) \otimes \sigma(Q^2) \otimes D(z, Q^2)$  is shown. Arrows point from the text labels below to the corresponding terms in the equation: 'Parton density' points to  $f(x, Q^2)$ , 'parton cross section (NLO,...)' points to  $\sigma(Q^2)$ , and 'probability for a parton to fragment into a hadron carrying a given fraction  $z$  of the parton energy' points to  $D(z, Q^2)$ . The fragmentation function  $D(z, Q^2)$  is highlighted in blue in the original image.

- Evolution of FF given by DGLAP
- FF are universal (from factorisation theorem)
- Scaling violation in the  $Q^2$  evolution permits to determine  $\alpha_s$

# Scaled momentum

$$x_p = \frac{(2 P_h)}{Q} = \frac{P_h}{E_{beam}}$$

For  $ep$  and  $e^+e^-$



$P_h$  – momentum of charged particles in current region of the Breit frame.

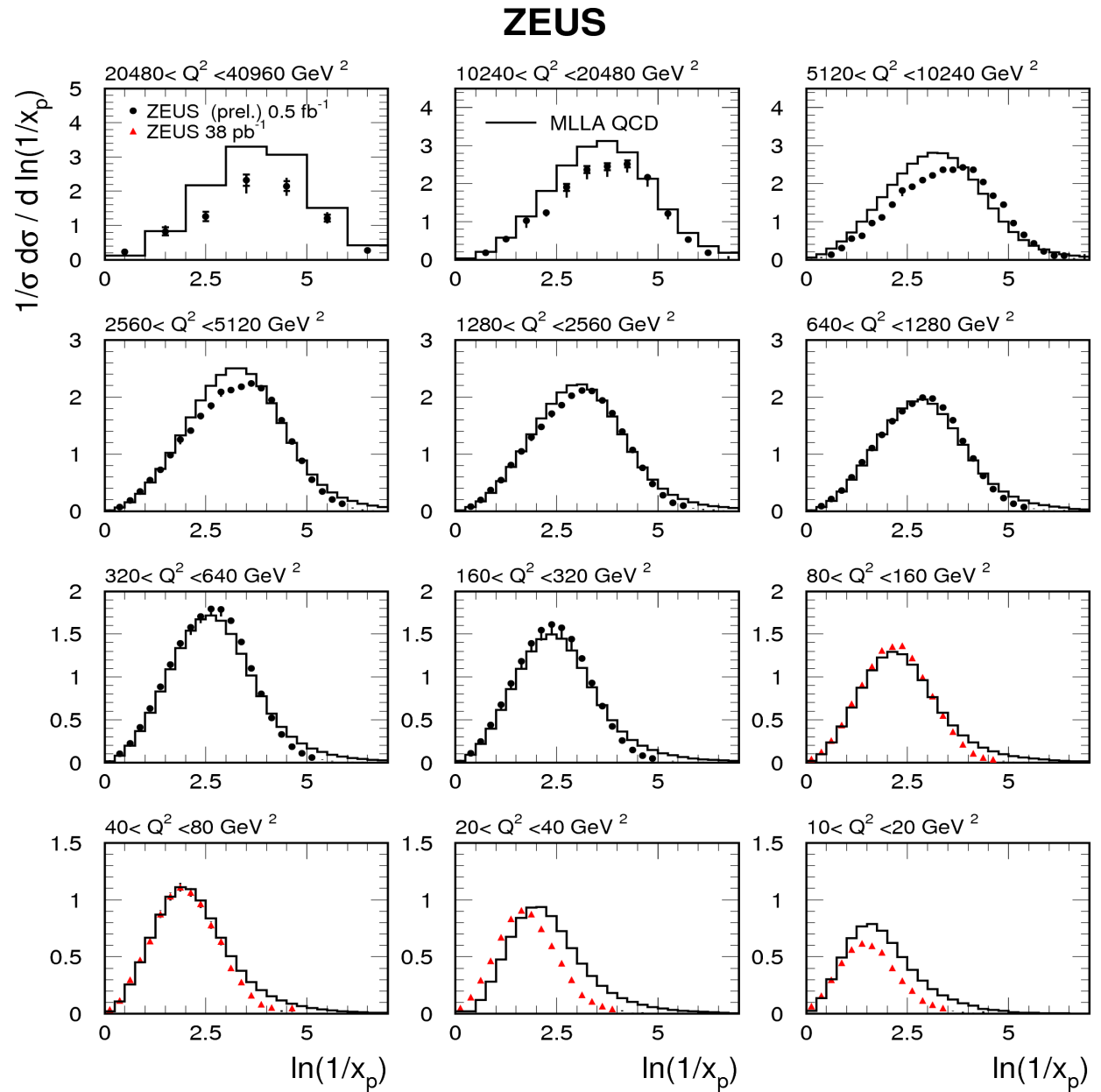
With  $Q$  increasing  $dn/dx_p$  is softer, i.e. more particles with smaller fraction of energy  $Q/2$ .

$\ln(1/x_p)$

# Modify Leading Log Approximation (MLLA)

The limiting spectra described by MLLA (+LHPD) are given  
 $\Lambda_{\text{QCD}}=270 \text{ MeV}$   
 $K_h=1.31$  (from  $e^+e^-$ ).

At low  $Q^2$   
migration from  
target region



$\ln(1/x_p)$



# Fragmentation functions (FF):

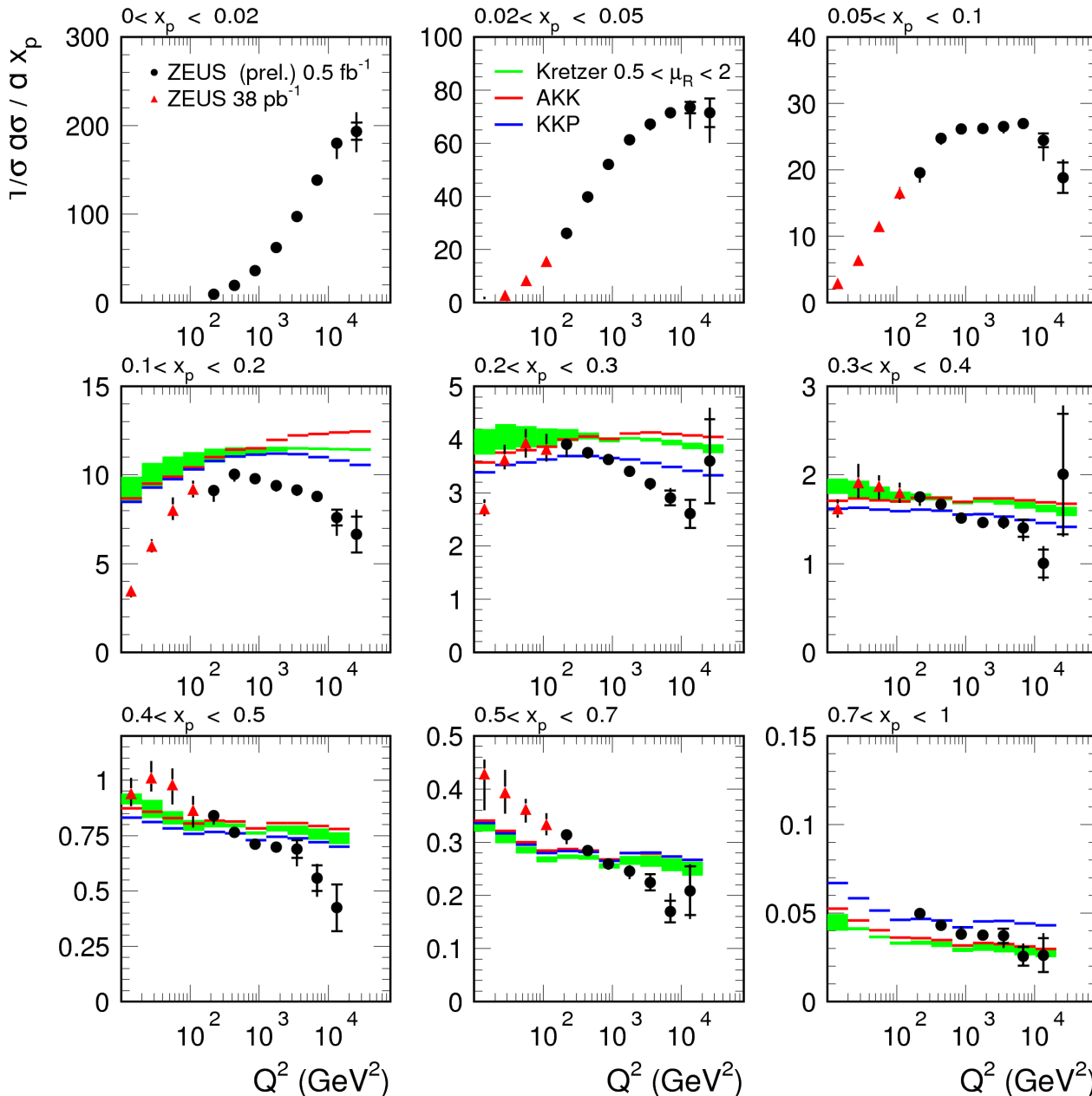
NLO QCD predictions  
implemented in **CYCLOPS**  
(PDF: CTEQ6M,  $\Lambda_{\overline{\text{MS}}}^{(5)}=266$

supported by S.Albino)

Full NLO matrix element  
+ partonic FF proposed by:

- **Kretzer** (2000) at  $Z^0$  pole data  
ALEPH, SLD, low-en. TPC
- **KKP** (Kniehl,Kramer,Poetter)  
(2000) at  $Z^0$  pole data  
... + DELPHI, 3jet OPAL
- **AKK** (Albino,Kniehl,Kramer)  
(2005) update of KKP (d,s)

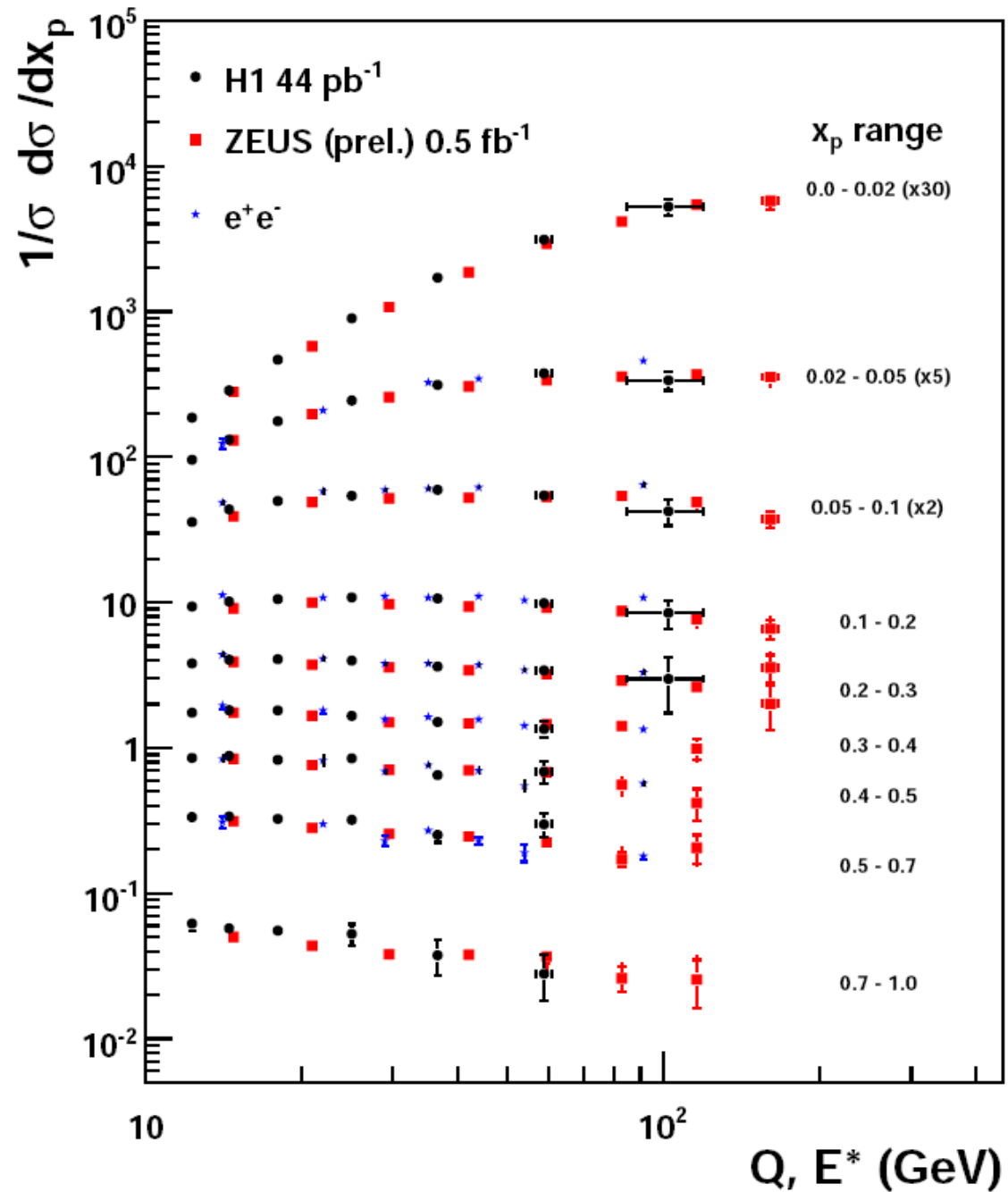
## ZEUS



## Comparison $ep$ with $e^+e^-$

- supports the concept of quark fragmentation universality.
- scaling violation is observed

ee data from TASSO, MARK II, AMY,  
DELPHI PL,B311(1993)408  
 $E^* = 2 E_{\text{beam}}$



# Summary and conclusions

- HERA provided a wealth of high precision hadronic data.

Charged hadron multiplicities were investigated in current region of Breit and HCM frames for different energy scales:  $2E_B^{\text{Cr}}$ ,  $W$ ,  $M_{\text{eff}}$ ,  $Q$ .

- Available energy for hadronisation defined by  $2E_B^{\text{Cr}}$  agrees better with e+e- than as  $Q$ .

Scaled momenta in current region of ep Breit frame compared with e+e-  
• general trends are the same — the scaling violation is observed for both  
but

- perturbative QCD calculations do not reproduce the ep data in entire range of  $Q^2$  and  $x_p$ .

Thank you for your attention.



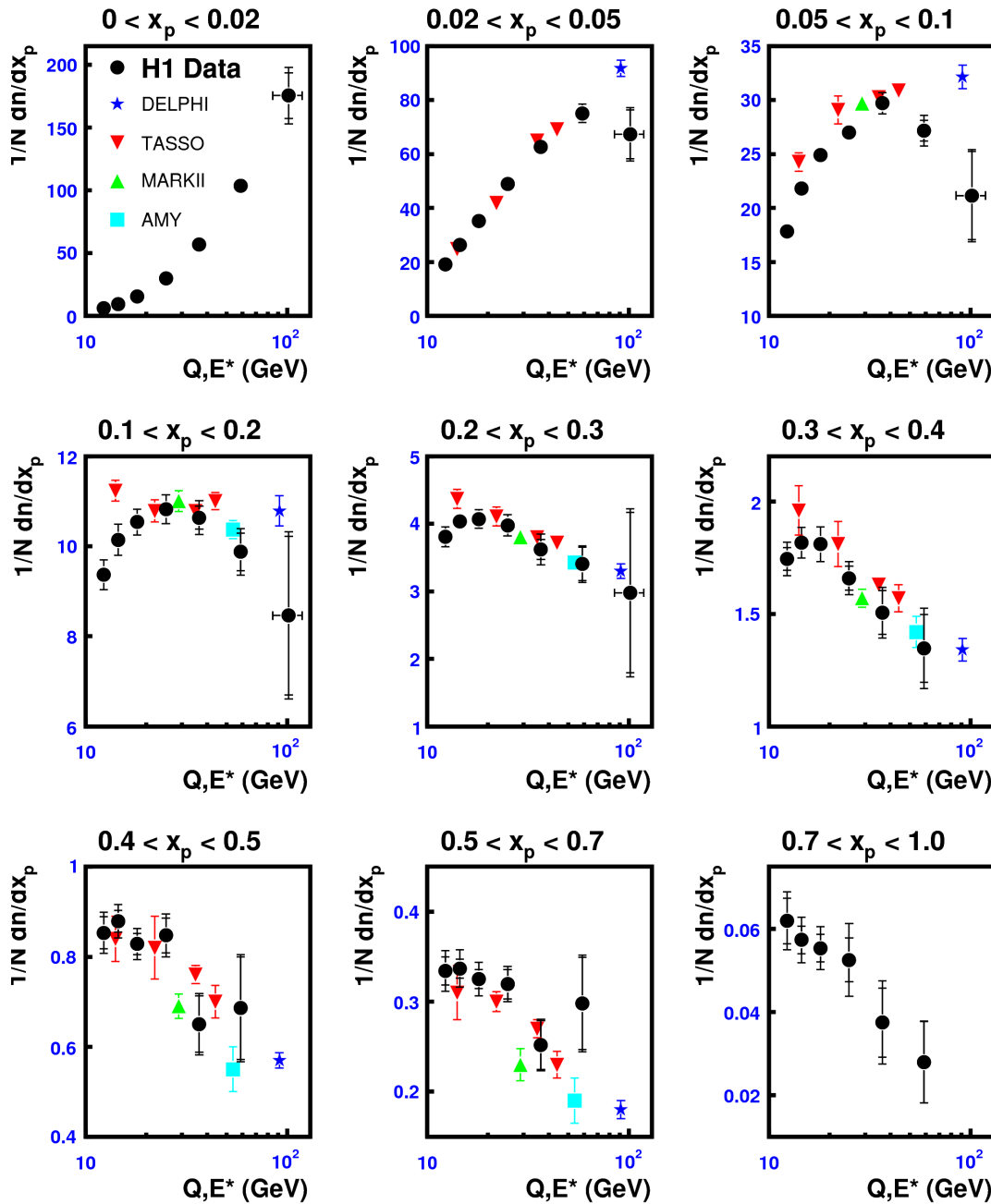
**Thank you for coming.**

**You could have been  
in a nicer place**



# Conclusions

- - MLLA+LPHD QCD calculations do not reproduce the **ep** data in entire range of  $Q^2$  and  $x_p$ ,
  - NLO + FF based on  $e^+e^-$  fail to describe  $x_p$  distribution as a function of  $Q^2$  (small differences between different FFs).



# Scaling violation in $x_p$ intervals

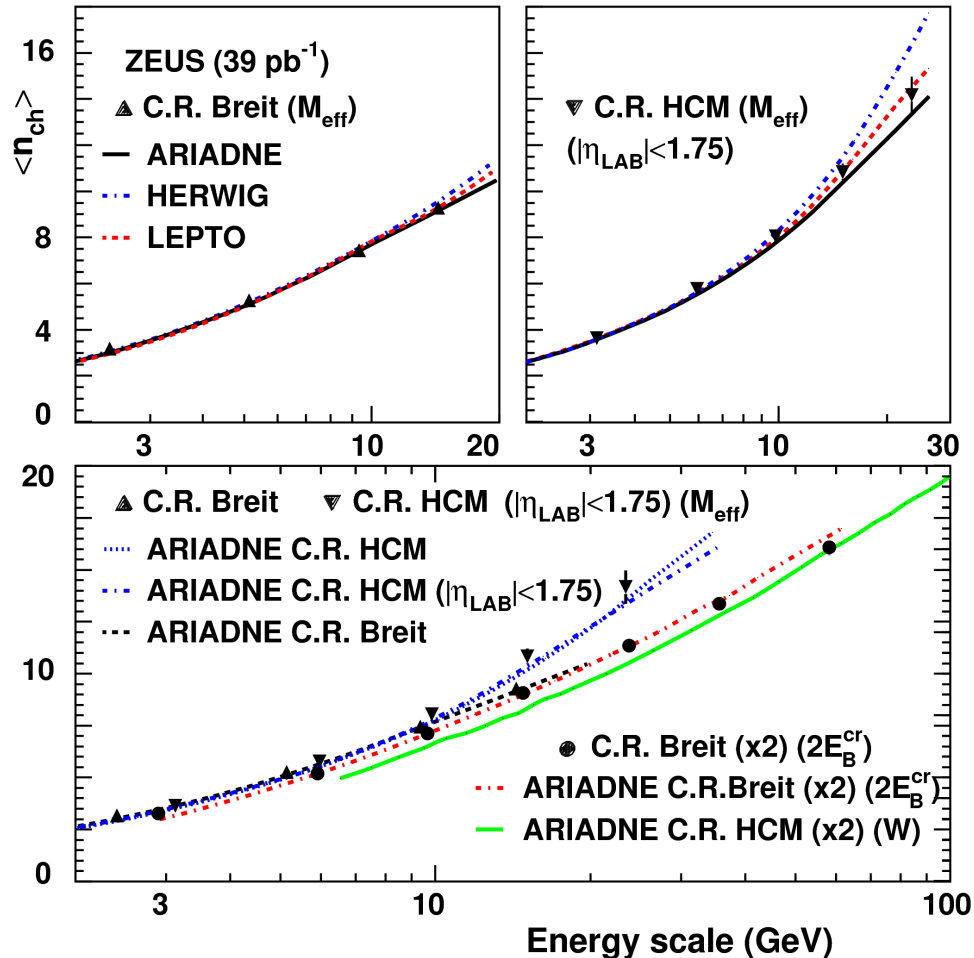
H1 data  
 **$e^+e^-$  data**

Good agreement between  
 $ep$  and  $e^+e^-$ , except:

- higher  $Q^2$  and small  $x_p$
- BGF contribution  
low  $Q^2$  and mid  $x_p$   
kinematics depopulates  
current region

# Average multiplicity as f ( $M_{\text{eff}}$ )

## ZEUS



Data agree with  
LEPTO and ARIADNE

At energy scales  $M_{\text{eff}} < 10 \text{ GeV}$   
 $\langle n_{\text{ch}} \rangle$  in Breit and HCM agree  
 at higher scales  
 $\langle n_{\text{ch}} \rangle$  rises faster in HCM