Jets in Lepton-Hadron Scattering

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• QCD in Lepton-Hadron Scattering

* QCD Processes in Deep Inelastic Scattering
* QCD Processes in Photoproduction

• Photoproduction Results from HERA

- *How well do pQCD jets match measured jets?*
- *NLO pQCD vs. parton showers : which approximation works best and where? Can they be reconciled?*

* Dijet Angular Distributions
* Jet Shapes
* Jet Cross Sections

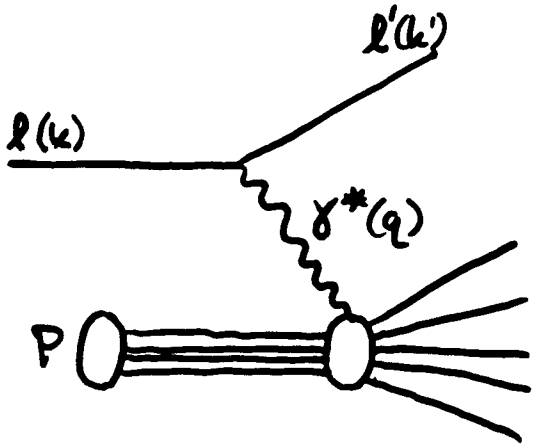
• DIS Results from HERA

- *Is there really an α_s problem?*
- *Will we recognize BFKL physics when we see it?*

* α_s Measurements
* BFKL Physics

• Conclusions

QCD Processes in Deep Inelastic Scattering



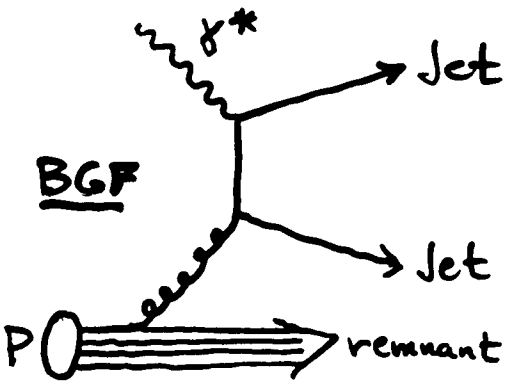
dominated by γ^* ($Q^2 < 10^4\,GeV^2$)

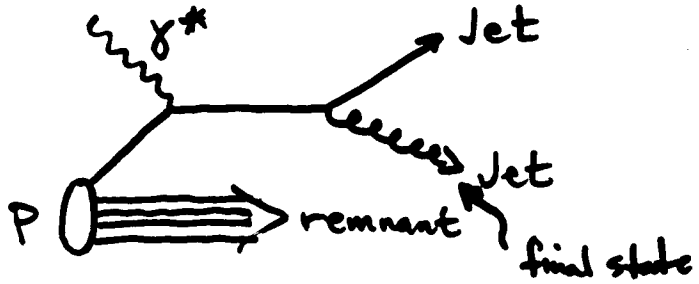
$$Q^2 = -q^2 = -(k-k')^2 > 0$$

$$y = E_{\gamma^*}/E_l = \frac{P\cdot q}{P\cdot k}$$

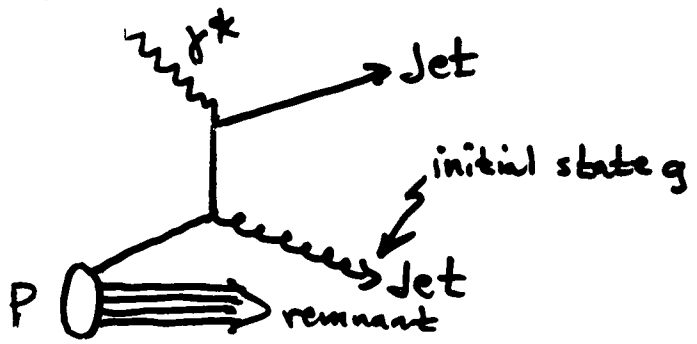
$$x = \frac{Q^2}{2P\cdot q} = \frac{Q^2}{sy}$$

LO QCD Processes



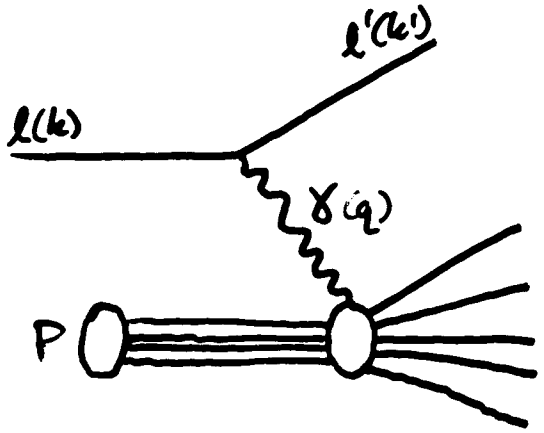


QCDC



Higher orders include additional q and g jets + virtual corrections

QCD Processes in Photoproduction



$Q^2 = 0$

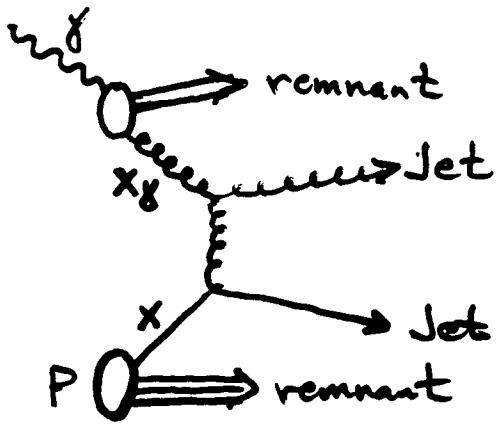
$(\langle Q^2_{obs} \rangle \sim 10^{-4}\,GeV^2$ @ HERA

$y = E_\gamma / E_l$

Real γ can interact pointlike (Direct Photoproduction) or hadron-like (Resolved Photoproduction)

Direct Processes : similar to DIS but $\gamma^* \to \gamma$

Resolved Processes : involve interactions between quarks and gluons in the γ and quarks and gluons in the P.



Two momentum fractions:

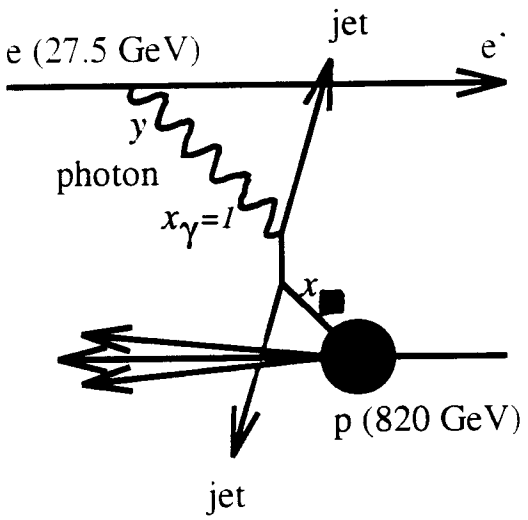
x_γ = momentum fraction of γ in hard scatter

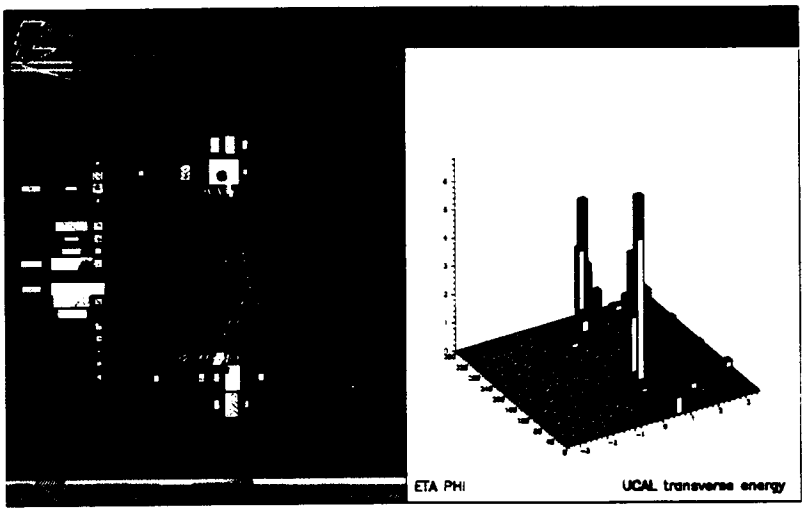
x = momentum fraction of parton in hard scatter

Jets in Photoproduction at HERA

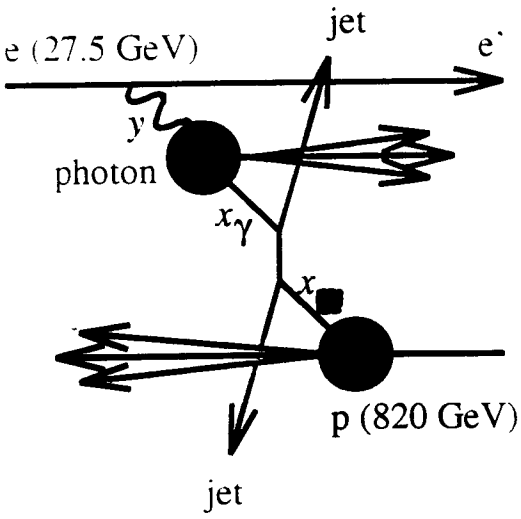
2 types of processes (at LO):

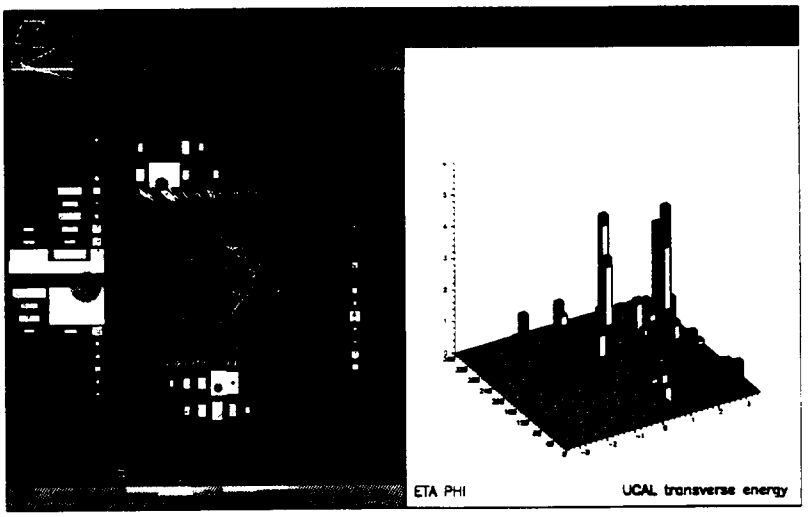
direct photon: $\gamma \equiv$ pointlike $\quad x_\gamma = 1$





resolved photon: $\gamma \equiv$ source of partons $\quad x_\gamma < 1$





$$x_\gamma^{OBS} = \frac{1}{2yE_e}\left(E_t^{jet1}e^{-\eta^{jet1}} + E_t^{jet2}e^{-\eta^{jet2}}\right)$$

Jet Definitions

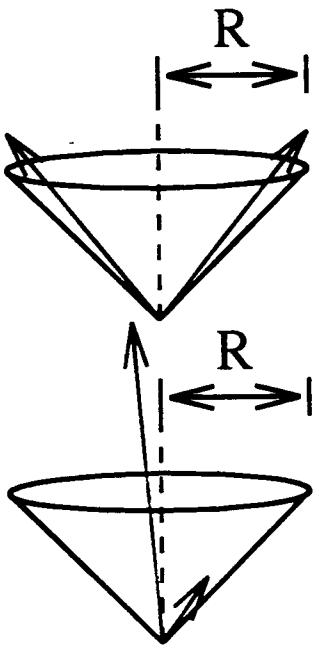
Standard in Hadron Physics: 'Snowmass' cone algorithms

We compare two algorithms using a cone radius $R = 1$:
PUCELL CDF type cone algorithm
EUCELL another cone algorithm used by ZEUS
Differences: seed finding and cone merging
(but both are in agreement with the Snowmass convention)

A new approach for Hadron Physics: cluster algorithm

KTCLUS (by M. Seymour)
using distance $d_{ij} = min({E_{ti}}^2, {E_{tj}}^2)[\Delta\eta_{ij}^2 + \Delta\phi_{ij}^2]$
There are no ambiguities in seed finding and merging.

Comparison with NLO Theory



→two or three parton final state
(no overlapping jets)

two partons are combined if

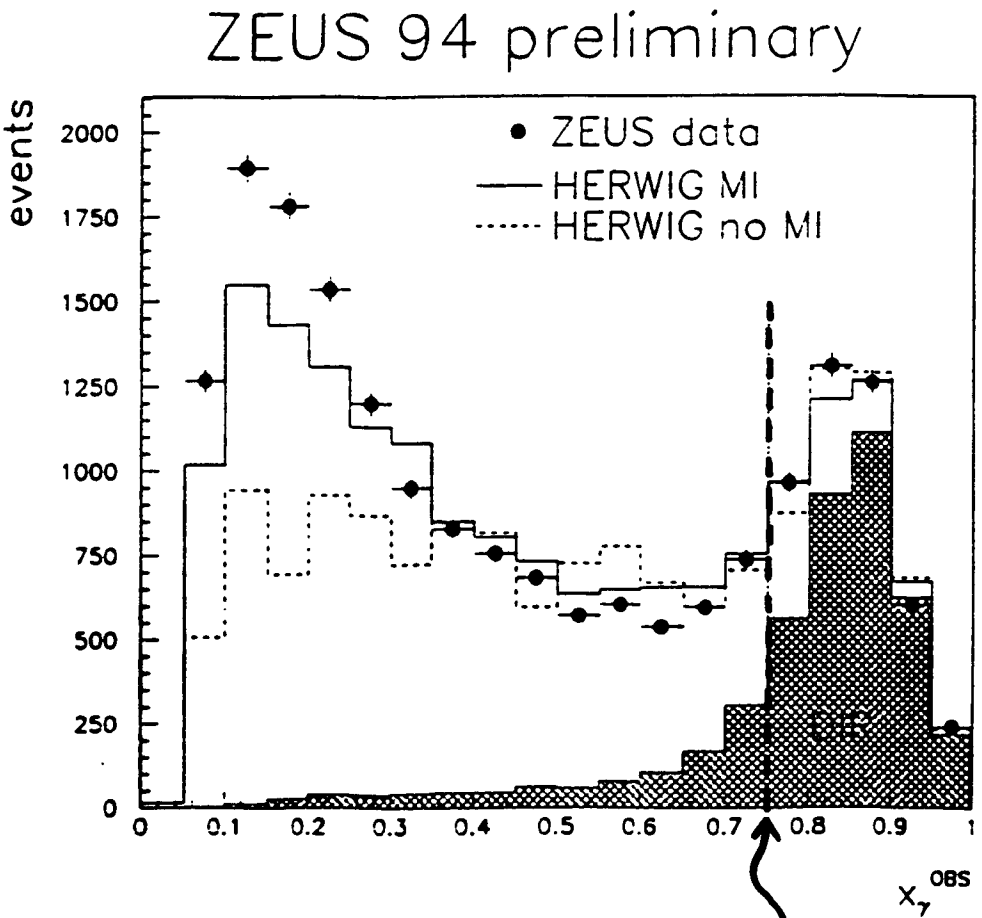
$$\Delta \equiv \sqrt{\Delta\eta_{ij}^2 + \Delta\phi_{ij}^2} < \frac{E_t^1 + E_t^2}{max\{E_t^1, E_t^2\}} R$$

with R_{sep} parameter (Ellis,Kunszt,Soper)

$$\Delta < min\left\{\frac{E_t^1 + E_t^2}{max\{E_t^1, E_t^2\}} R, R_{sep}\right\}$$

PUCELL $\longleftrightarrow R_{sep} = 1\ R$
EUCELL $\longleftrightarrow R_{sep} \approx 1.5 \ldots 2.0\ R$
KTCLUS $\longleftrightarrow R_{sep} = 1.$

X_γ Distribution – Separation of Direct and Resolved Photoproduction



$X_\gamma > 0.75 \Rightarrow$ Direct

$X_\gamma < 0.75 \Rightarrow$ Resolved

Comparison of data to HERWIG MC with and without MI (multiple interactions ≡ additional scattering of partons in γ, P remnant)

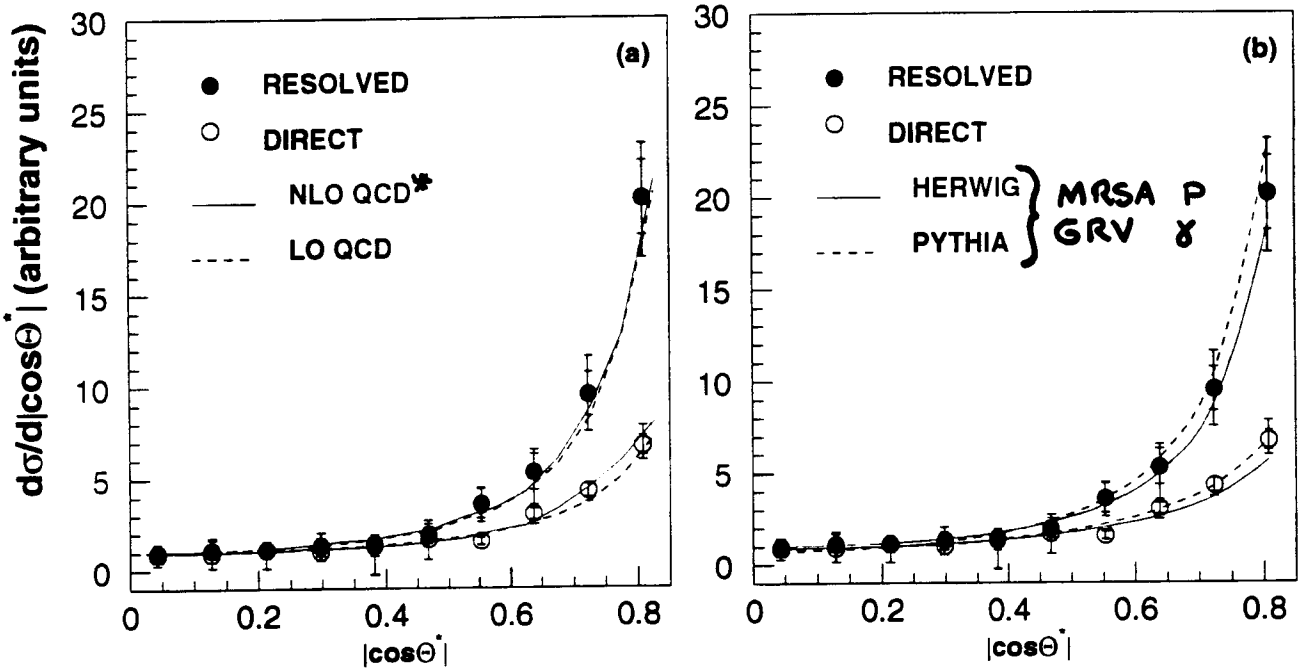
- better agreement with data when MI included

Shift in Direct peak from $X_\gamma = 1$:

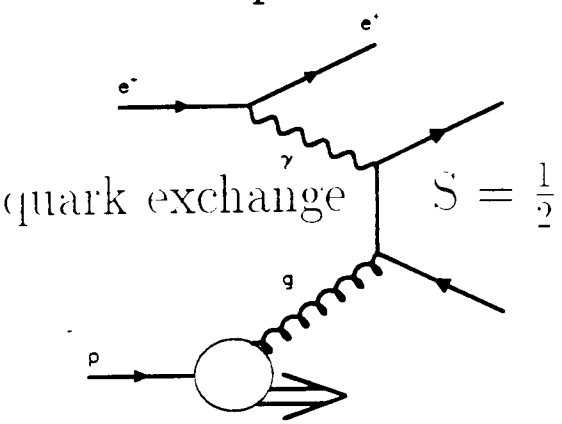
- energy losses (out-of-cone, energy scale, dead material)
- proton remnant in detector

Dijet Angular Distributions

ZEUS 1994



direct photon

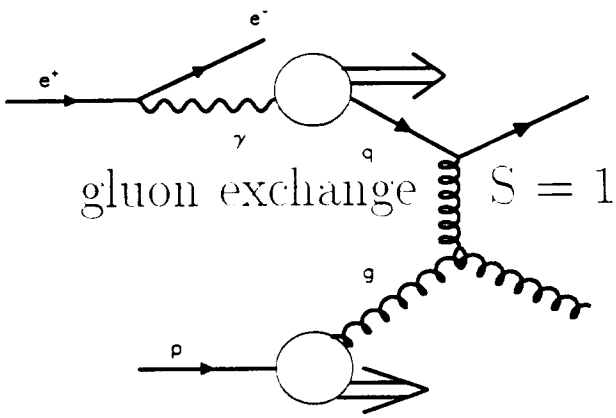


quark exchange $S = \frac{1}{2}$

$$\frac{d\sigma}{d|cos\theta^*|} \sim \frac{1}{(1-|cos\theta^*|)}$$

contribute to the "direct" sample $(x_\gamma > 0.75)$

resolved photon



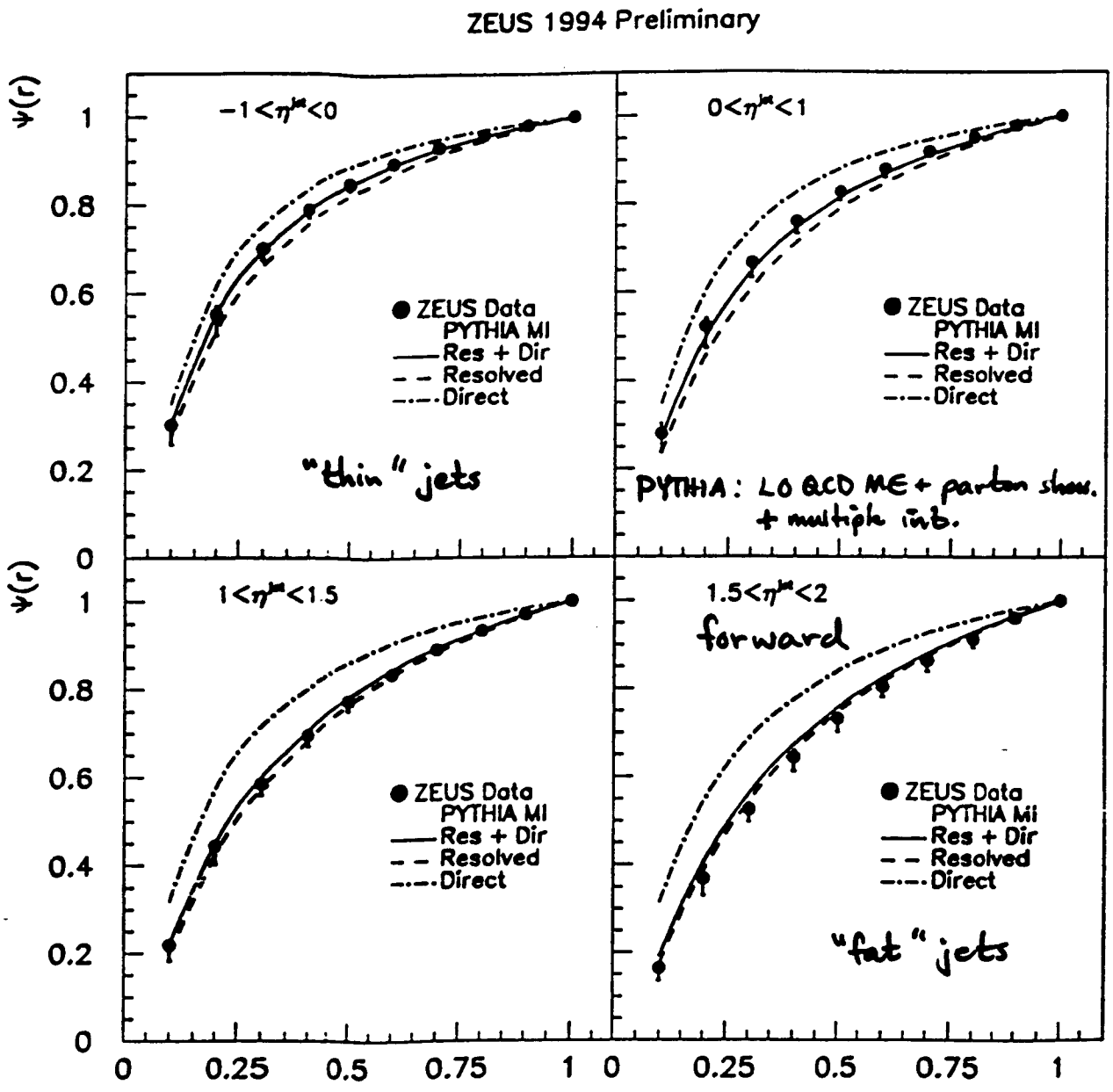
gluon exchange $S = 1$

$$\frac{d\sigma}{d|cos\theta^*|} \sim \frac{1}{(1-|cos\theta^*|)^2}$$

contribute to the "resolved" sample $(x_\gamma < 0.75)$

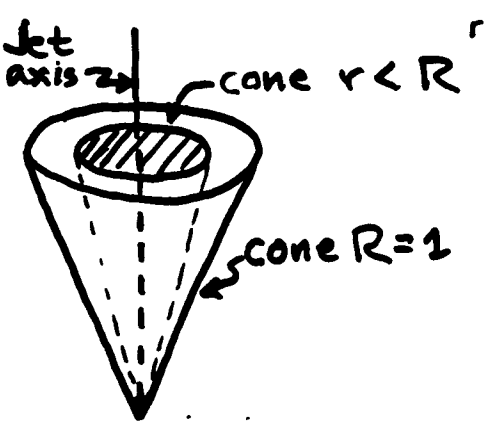
* H. Baer, J. Ohnemus, J.F. Owens, Phys. Rev. D40 (1989) 2844.

Jet Shapes in Photoproduction

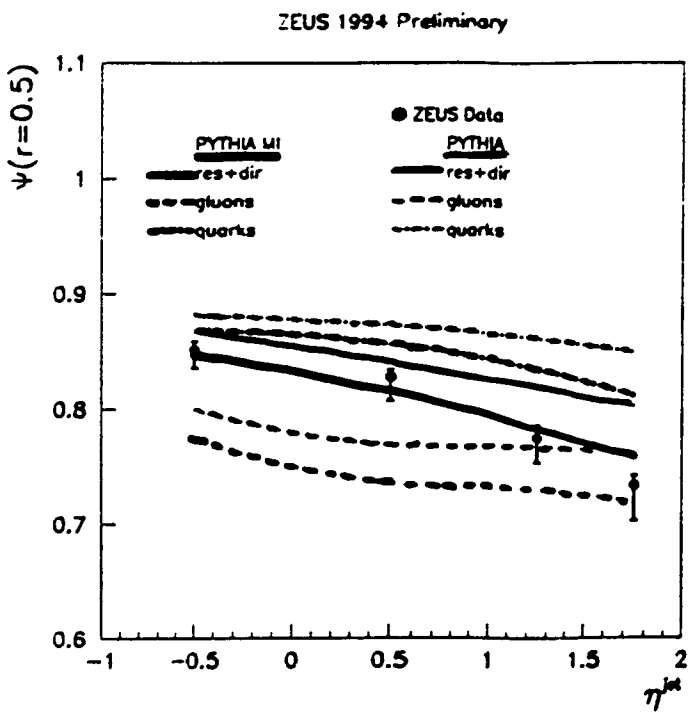


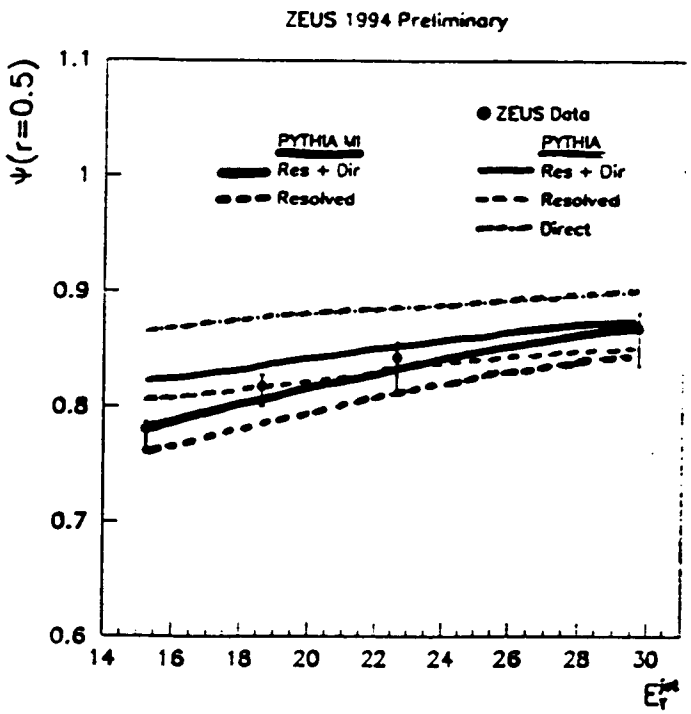
$$\Psi(r) = \frac{1}{N_{jets}} \sum_{jets} \frac{E_T^{jet}(r)}{E_T^{jet}(r=1)}$$

= fraction of E_T^{jet} in cone of radius $r < R$



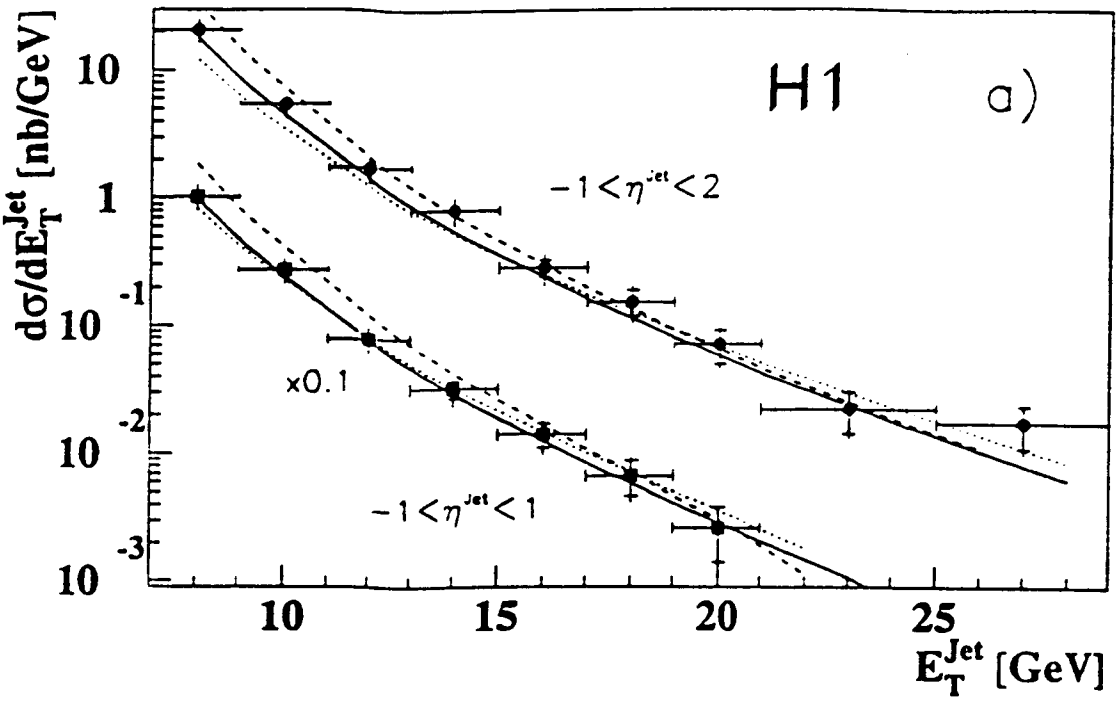
$\Psi(r=0.5)$ vs η^{jet}, E_T^{jet}





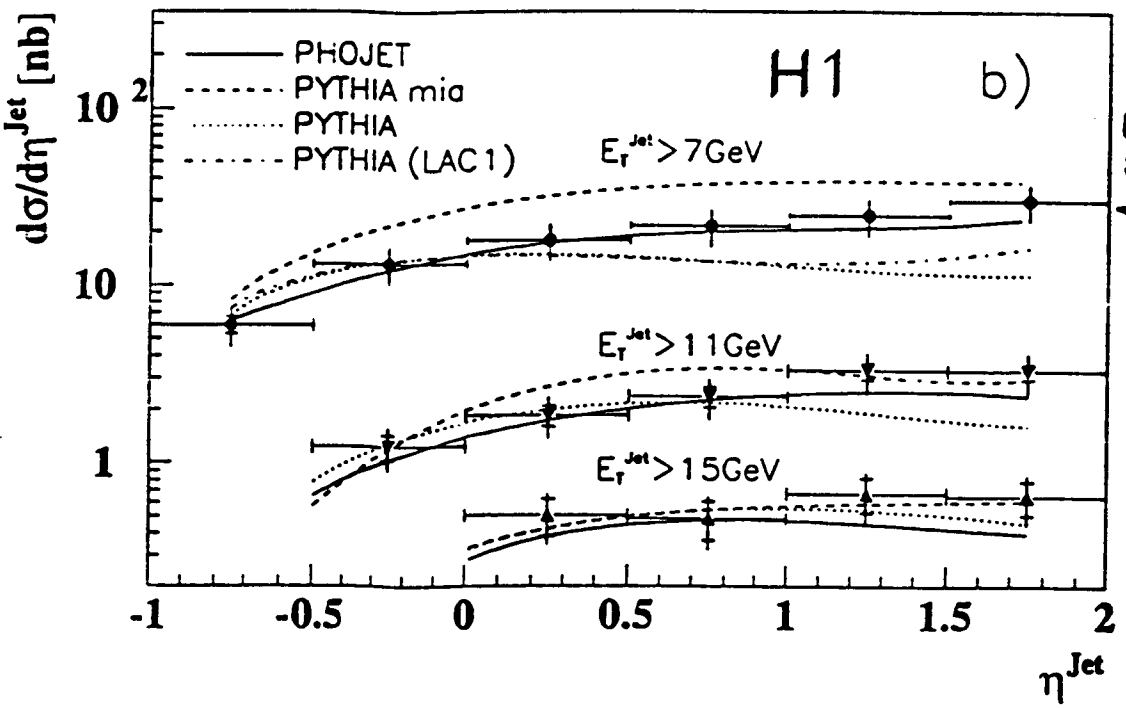
- MC (PYTHIA) including multiple parton interactions gives a better description of the data than MC without MI.
- MI are most important at large η^{jet} and low E_T^{jet}

Inclusive Jet Differential Cross Sections



$0.25 < y < 0.7$

$Q^2 < 0.01$ GeV



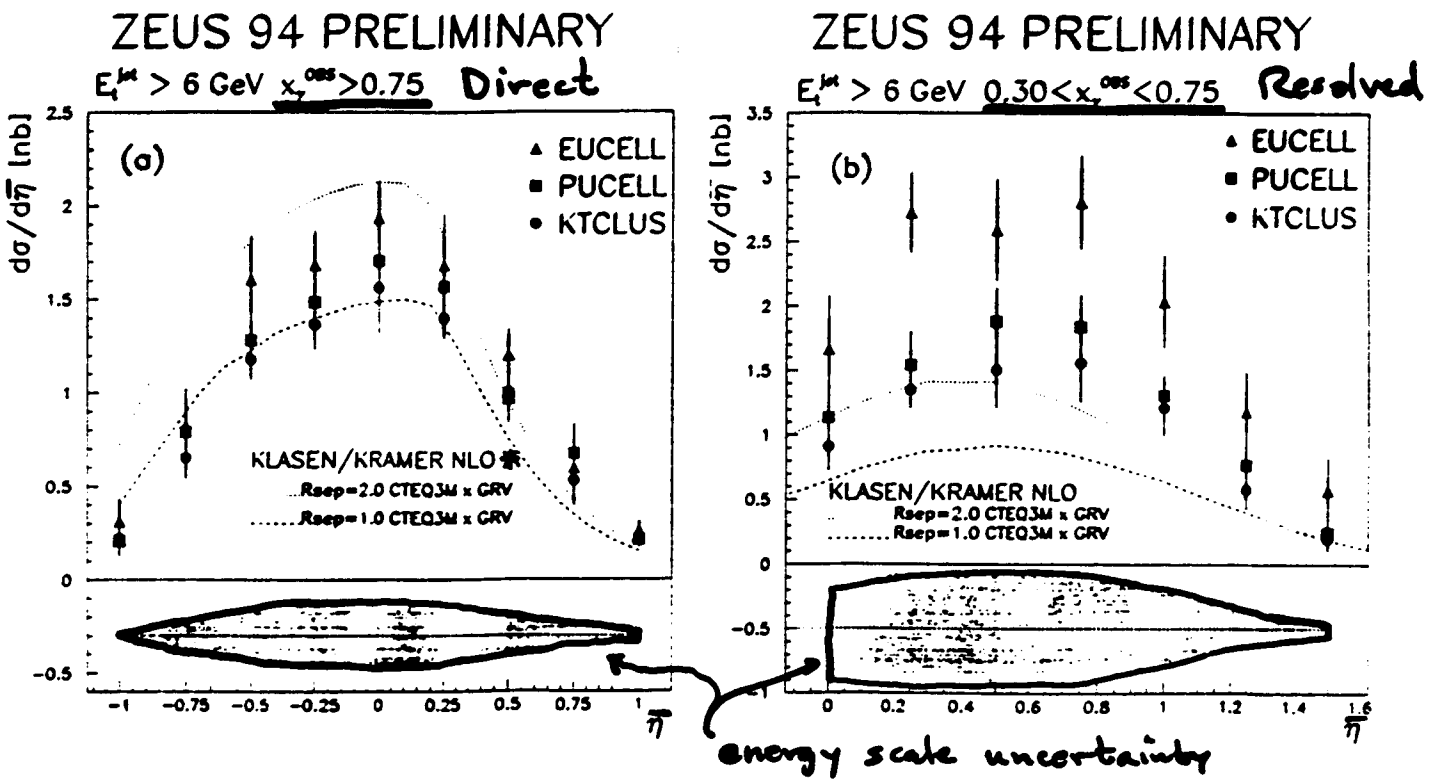
MC with multiple interactions favored

Monte Carlo Generators : LO QCD ME + parton showers
GRV-LO parton dist. for both γ, P

PHOJET : $p_T^{min} > 3$ GeV for hard scattering
multiple hard and soft interactions included

PYTHIA : $p_T^{min} > 2$ GeV for hard scattering
multiple interactions - LO QCD with $p_T^{mia} < p_T^{min}$
→ 1-3 additional interactions

Dijet Cross Sections for Direct and Resolved Photoproduction

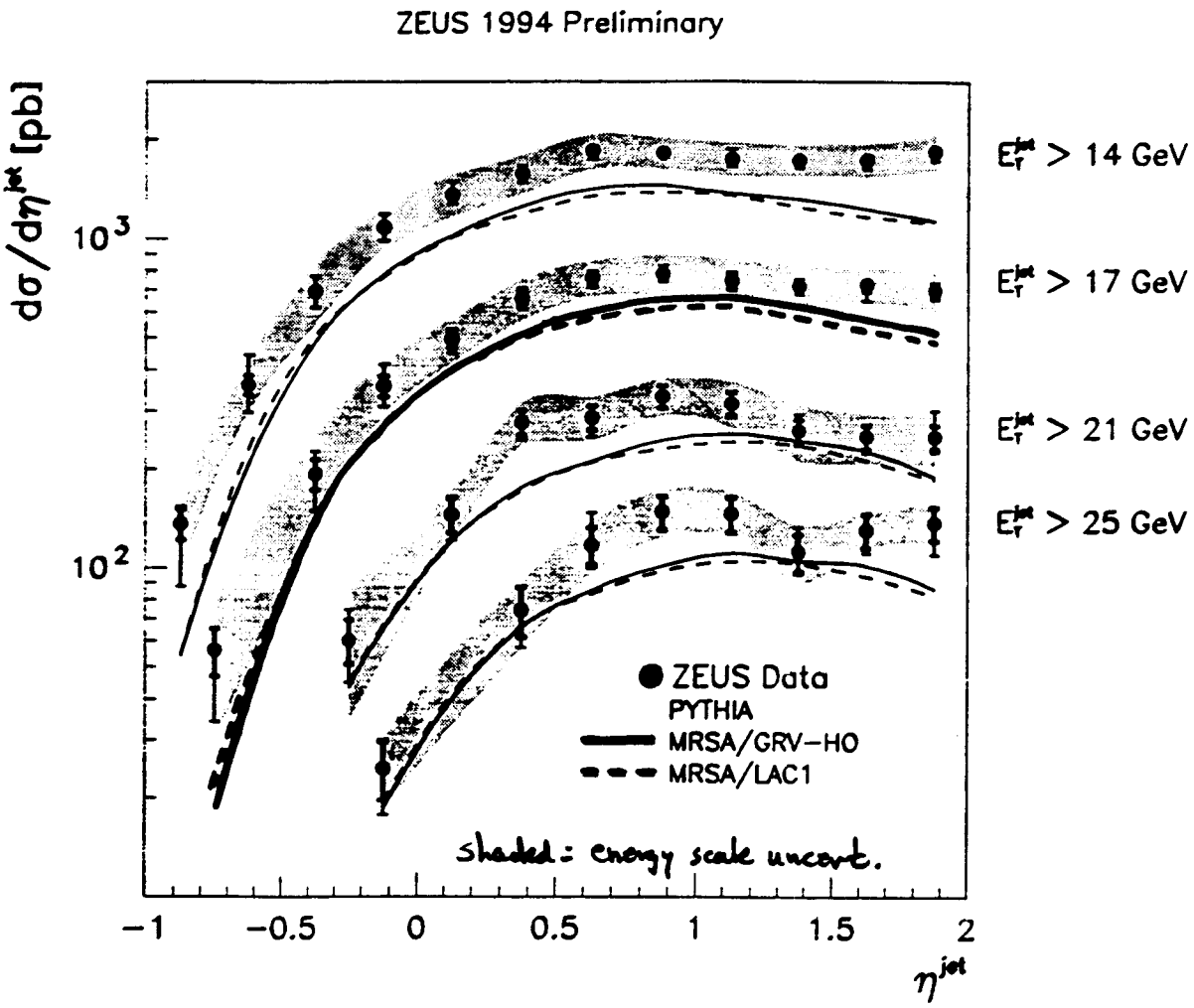


$\bar{\eta} = \frac{1}{2}(\eta_1 + \eta_2)$ where $-1.375 < \eta_{1,2} < 1.875$

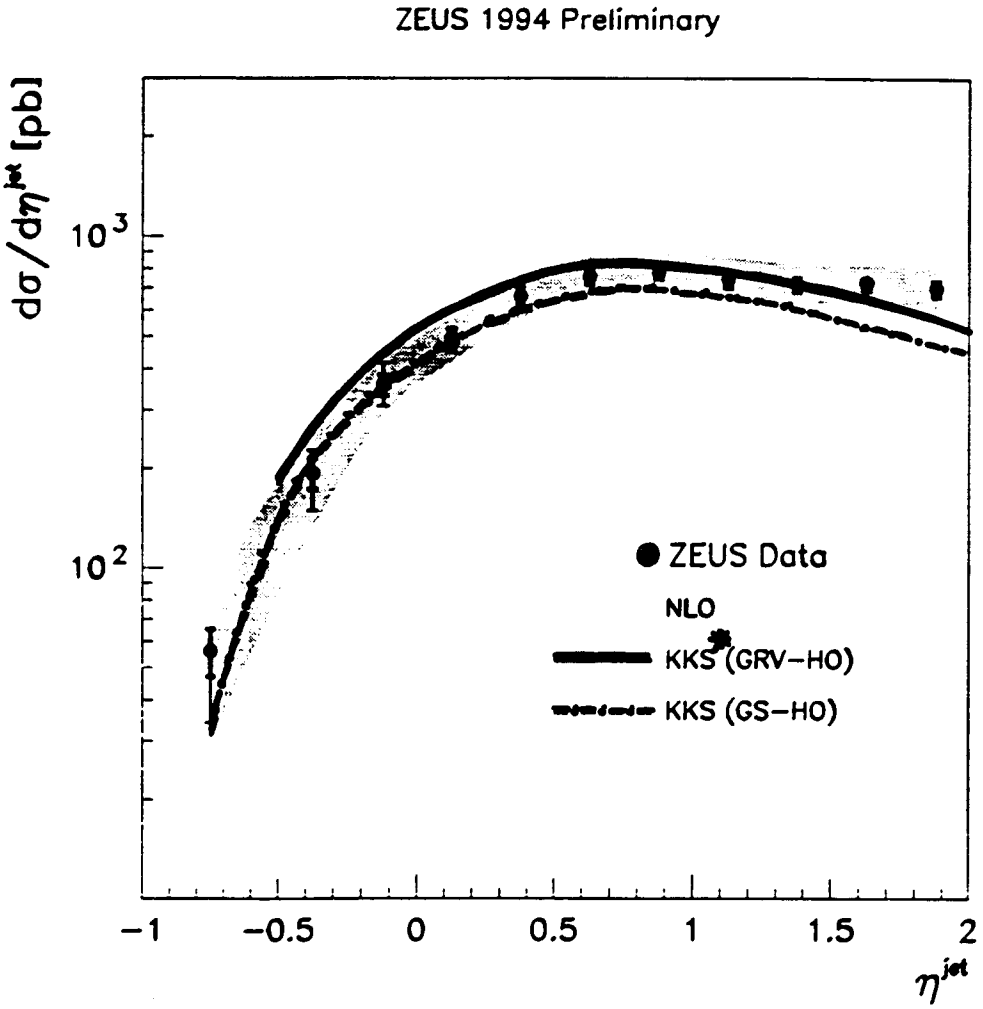
- Good agreement between data and NLO calcalation for Direct photoproduction (central rapidities)
- Resolved NLO calcalations lie below the data (forward rapidities)

* M. Klasen, G. Kramer, private communication

Inclusive Jet Differential Cross Sections



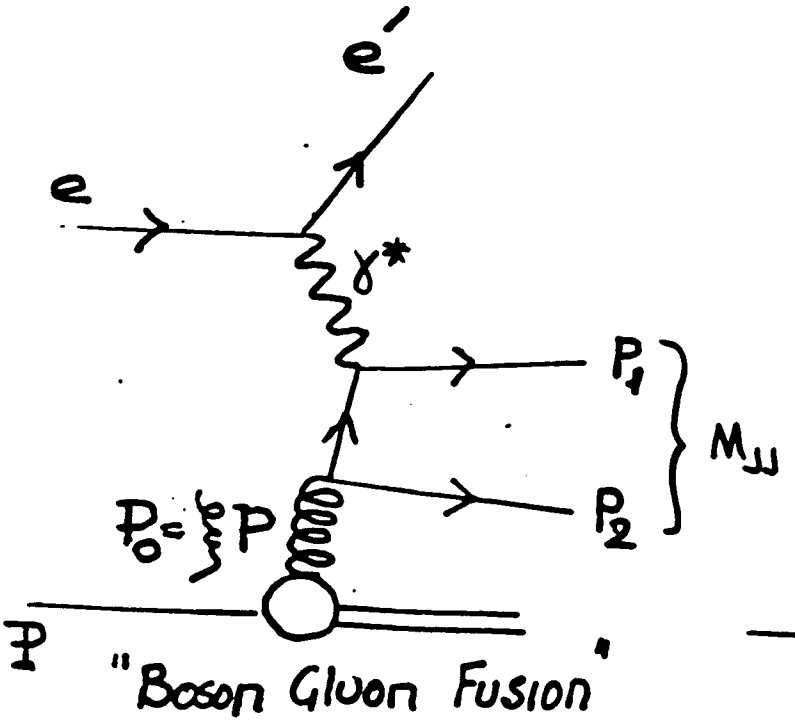
- MC (LO QCD + parton showers) gives a reasonable description of the shape of the data except for the lowest E_T^{jet}, high η^{jet} region.

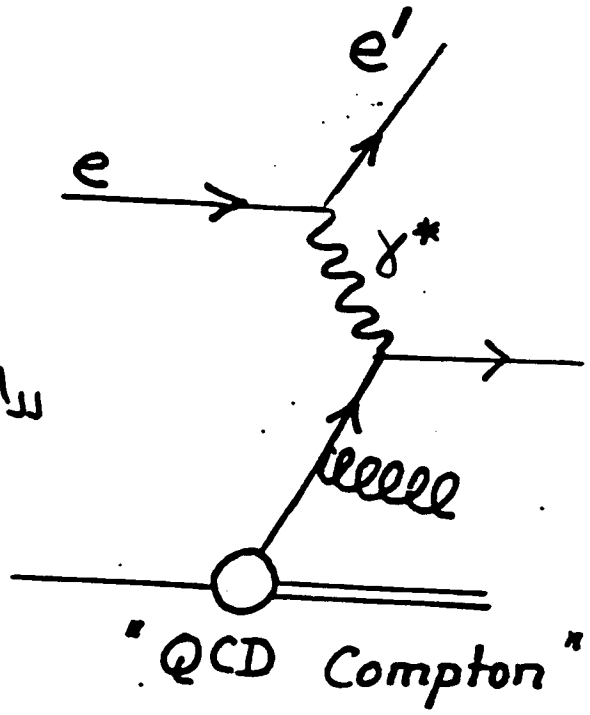


- NLO QCD calculations reasonably describe both the shape and magnitude of the data (possible difference appearing at large η_{jet}).

* M. Klasen, G. Kramer, S.G. Salesch, Zeit. f. Phys. C 68 (1995) 113.

DIS - TWO JET KINEMATICS





$$\frac{d\sigma_{2+1}}{dx\,dQ^2\,dx_p\,dz\,d\varphi^*} = f(x_p, z, x, Q^2, \varphi^*, \alpha_s)$$

additional variables for dijets

φ^* = ∠ between parton and lepton scattering planes in γ^*-parton CMS

Scaling variables

$$x_p = \frac{x_{Bj}}{\xi} = \frac{Q^2}{M_{JJ}^2 + Q^2}$$

$$z^{1,2} = \frac{P \cdot p^{1,2}}{P \cdot q} \approx \frac{(E - p_z)_{Jet_{1,2}}}{(E - p_z)Jet_1 + (E - p_z)_{Jet_2}}$$

$$z = \frac{1}{2}(1 - \cos\theta^*)\ \text{Angular Distribution in}\ \gamma^*\text{-parton CMS}$$

BGF:

$$d\sigma_{2+1}^{gq} \frac{[z^2 - (1-z)^2][x_p^2 + (1-x_p)^2]}{z(1-z)}$$

QCDC:

$$d\sigma_{2+1}^{gq} \propto \frac{1 + z^2 x_p^2}{(1-x_p)(1-z)}$$

CLUSTER ALGORITHMS

Jet Algorithm	JADE	$K_\perp$
Frame	LAB	BREIT CR ≡ ½ e^+e^- ph.sp.
Reference Mass	$W_{vis}^2 = s(1-x_{DA})y_{JB}$	Q_{DA}^2 (or constant $E_t^2 = 120GeV^2$)
Resolution	$2E_iE_j(1-\cos\theta_{ij})/W_{vis}^2$	$2\min(E_i^2, E_j^2)(1-\cos\theta_{ij})/Q_{DA}^2$
Resolution Parameter y-Cut	0.02	0.5
Z Cut	YES	NO
NLO Calculation	YES	YES (MEPJET)
Pseudo Particle	Put all missing longitudinal momentum in one pseudo particle	$2E_i^2(1-\cos\theta_{ip})/Q_{DA}^2$ *if* $y_{ip} < y_{ij}$ *Object* $\rightarrow$ *remnant jet*

Extraction of α_s:

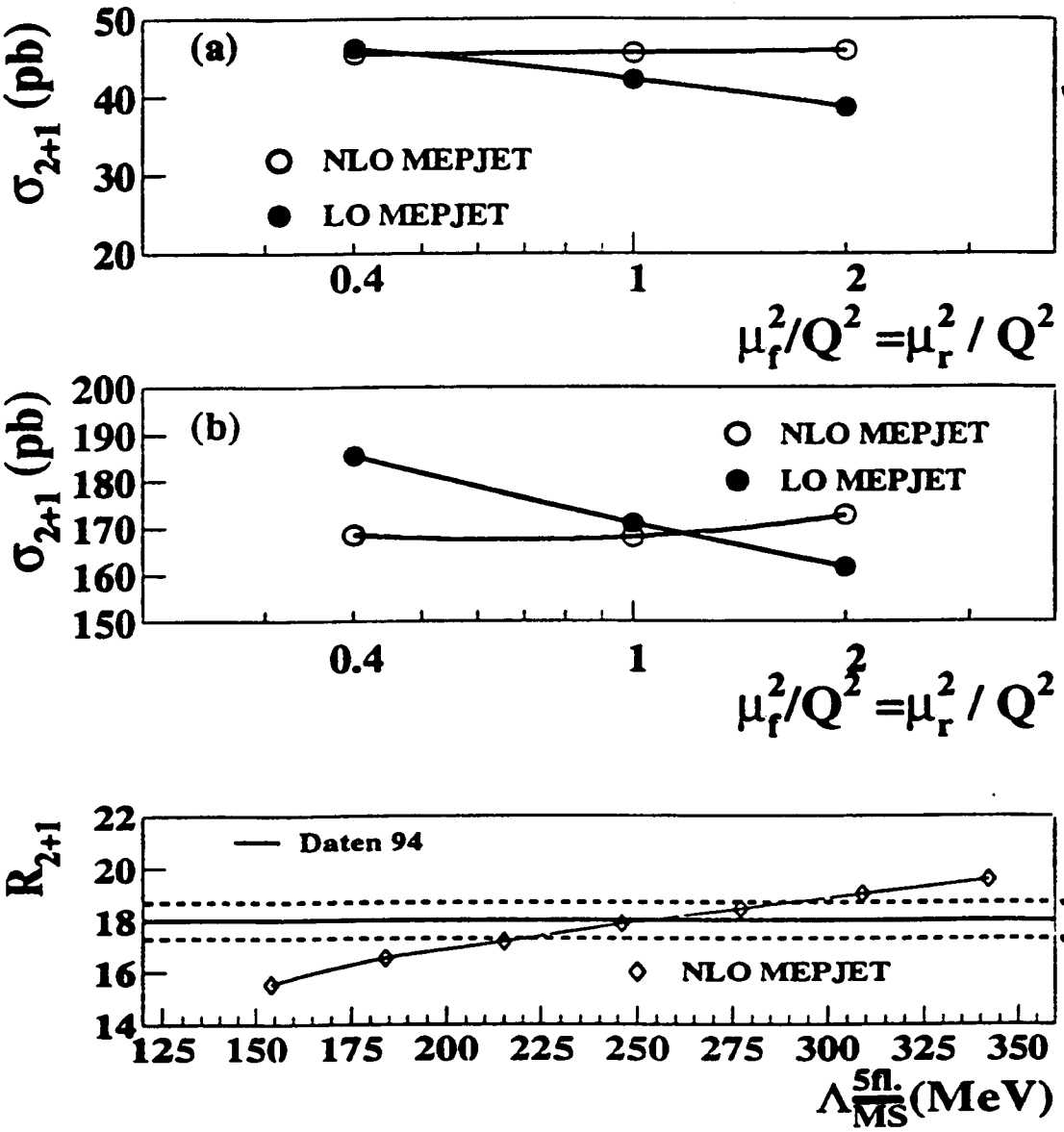
$$R_{2+1}(Q^2, y_cut) = C_1(Q^2, y_cut)\alpha_s(Q^2) + C_2(Q^2, y_cut)\alpha_s^2(Q^2) + \ldots$$

$$= \frac{\sigma_{2+1}(Q^2, \alpha_s, y_cut)}{\sigma_{tot}}$$

Use NLO calculation by MEPJET
(E. Mirkes and D. Zeppenfeld PL B380, 205 (1996).

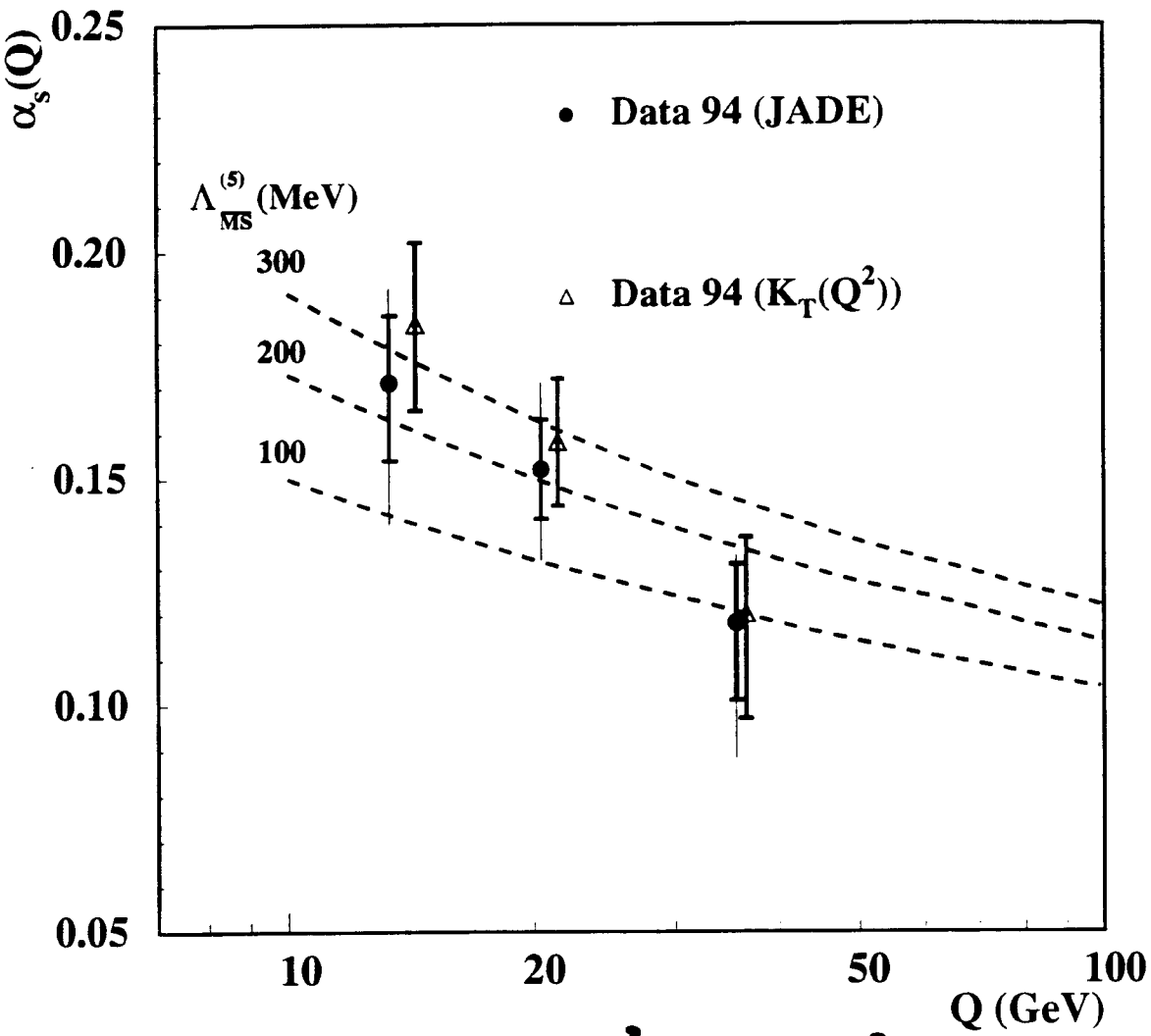
Note: Same jet algorithm in MEPJET as used for data and Monte Carlo.

Extraction of α_s - scale dependence and comparison to NLO QCD Calculation



- Less dependence on choice of scales for NLO compared to LO
- Data consistent with range of $\Lambda^5_{\overline{MS}}$ between 225 MeV - 275 MeV when compared with NLO QCD calculation

The Running of α_s at HERA:



Kinematic Cuts : $120\ GeV^2 < Q^2 < 3600\ GeV^2$
$0.01 < x < 0.1$
$0.1 < y < 0.95$

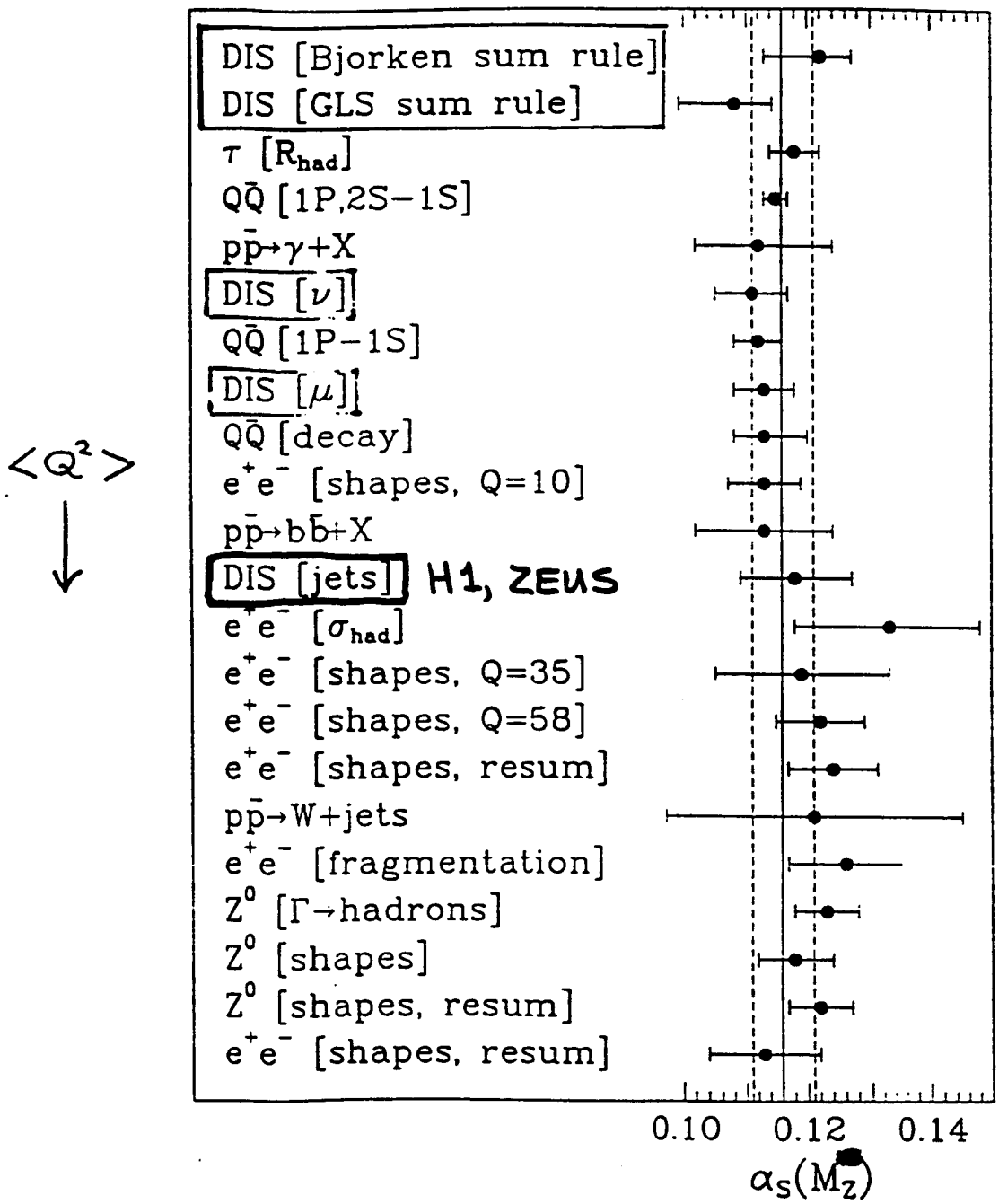
ZEUS preliminary (k_T result)

$\alpha_s(M_Z)$

$0.117 \pm .005\,(stat) \pm^{.004}_{.005}\,(syst_{exp}) \pm .007\,(syst._{theor})$ ZEUS

$0.123 \pm .018\,(stat. \oplus sysl.)$ H1

$\alpha_s(M_Z)$ vs. $\langle Q^2 \rangle$



- improvements in statistical, syst.$_{exp}$ errors
- syst.$_{theor.}$ dominated by scale uncertainty, hadronization corrs.

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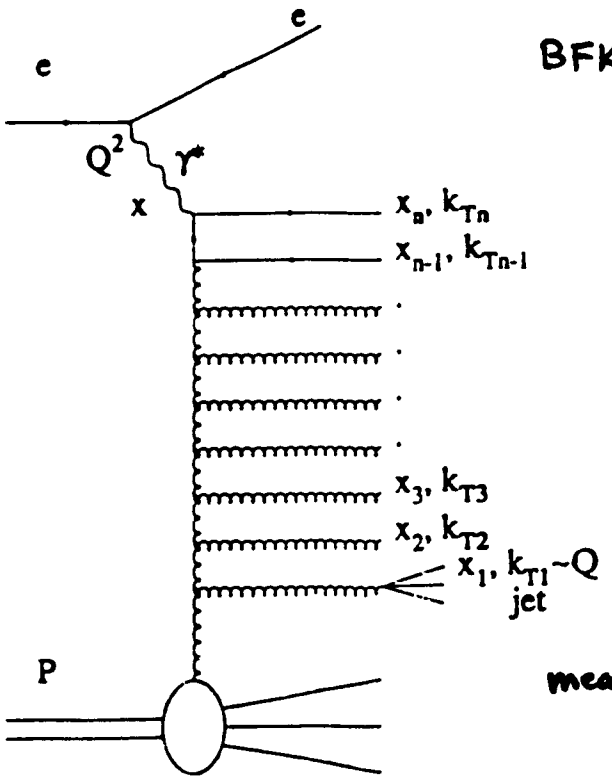
Search for BFKL Physics



BFKL Gluon Ladder Diagram

$$\Delta\eta = (\eta_1 - \eta_n) = \ln\left(\frac{x_1}{x}\right)$$

~4-5 max at HERA

measured jet : $x_{jet} = x_1 \gg x$

$k_T^{jet} \sim Q$

DGLAP

$k_{T_n}^2 \gg k_{T_{n-1}}^2 \gg \ldots \gg k_{T_1}^2$

$x_n < x_{n-1} < \ldots < x_1$

strong k_T ordering

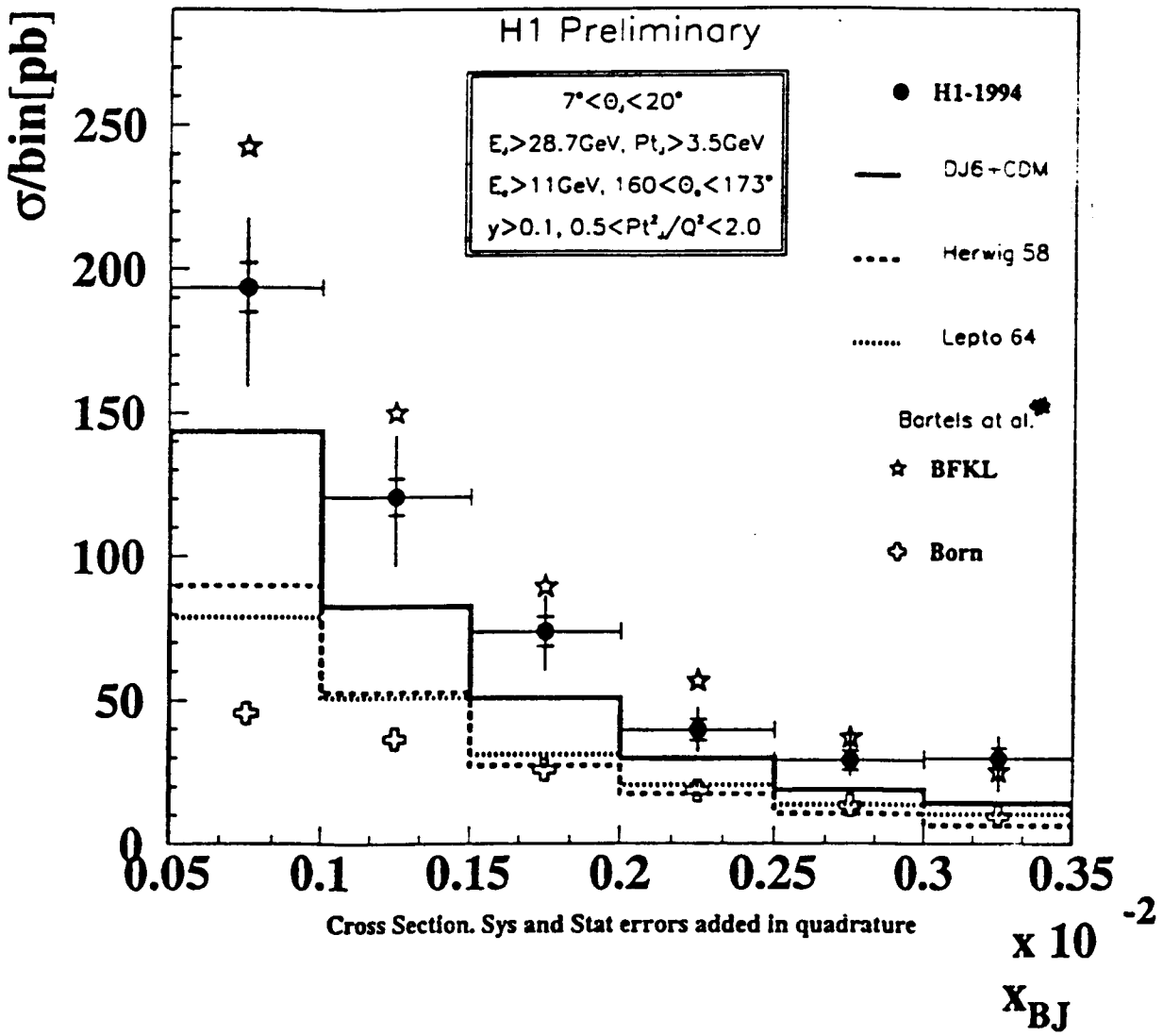
BFKL

no k_T ordering

$x_n \ll x_{n-1} \ll \ldots \ll x_1$

strong x_n ordering

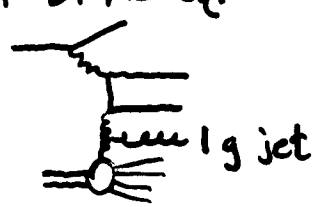
Forward Jet Cross Section vs x_{Bj}



Monte Carlos : LO QCD ME + parton showers

BFKL calculation : parton level evaluation of BFKL eq.

"Born" calculation : no gluons in ladder ⟹ ≡ NLO QCD (MEPJET)



- Data shape is steep ⇒ BFKL
  caution : hadronization effects not yet included

* J. Bartels et al., DESY 096-036 (1996).

Conclusions

- Jets at HERA in both Photoproduction and Deep Inelastic Scattering can be used to test QCD.

- From Photoproduction results, Monte Carlo models incorporating LO QCD matrix elements with parton showers give a reasonable description of the data when multiple interactions between the partons in the proton and photon remnant are also incorporated or added.

- NLO QCD calculations also reproduce the observed inclusive jet cross sections both in shape and magnitude, but there appears to be a discrepancy between NLO QCD and data for resolved photoproduction of dijets. This also appears in the inclusive jet cross section at low jet E_T and high η_{jet} (dominated by resolved processes).

- α_s has been measured at HERA from the dijet rate in DIS and has been found to be consistent with the world average.

- Increased forward jet cross sections in DIS have been reported which can be interpreted as the onset of BFKL dynamics. Calculations of DIS jet cross sections in NLO QCD and BFKL are now available for comparisons with data.