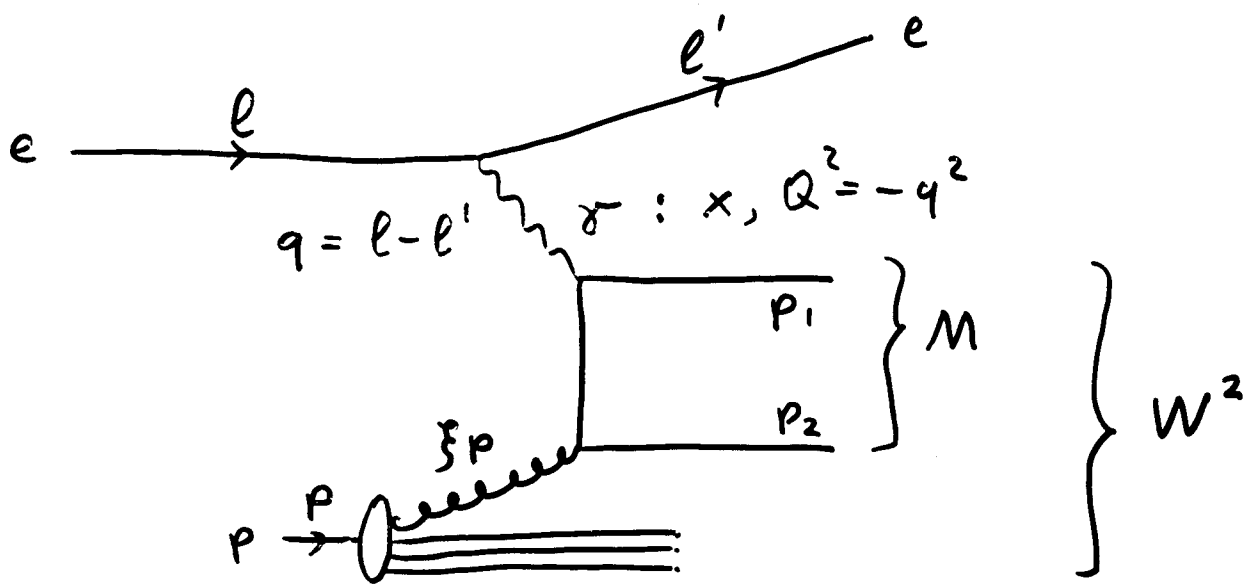
CTEQ 96

NLO calculation of jets in lepton-hadron processes

Dieter Zeppenfeld
UW - Madison

- Introduction: dijets at HERA
- NLO corrections to dijet production
- Comparison of jet algorithms and recombination schemes
- Forward jets and BFKL

Dijet Production in DIS



Scaling variables

$$x = \frac{Q^2}{2p\cdot q} \qquad \text{(Bjorken } x\text{)}$$

$$y = \frac{p\cdot q}{p\cdot \ell} = \frac{Q^2}{xs}$$

M : c.m. energy in γ^*-parton system

W : produced hadronic mass

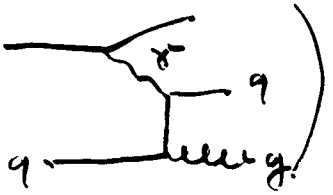
ξ : momentum fraction of incident parton

$$\xi = x\left(1 + \frac{M^2}{Q^2}\right)$$

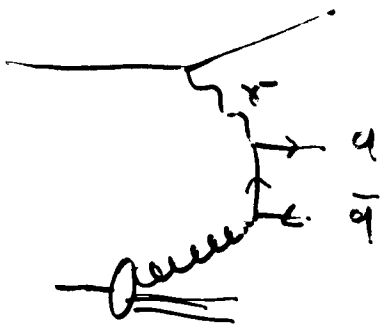
p_1, p_2 : jet momenta (at LO)

Topics to be studied

- Measure $\alpha_s(\mu_R^2)$

σ  $\sim \alpha_s$

- Directly measure gluon distribution fct

 $\sim g(\xi, \mu_F^2)$

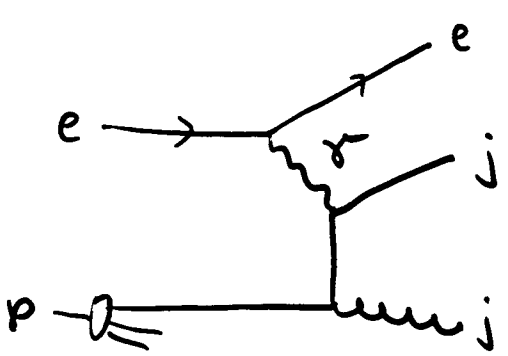
- Forward jets and BFKL dynamics
- polarized gluon pdf's ?

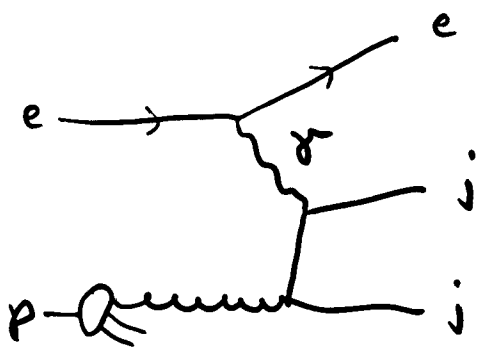
⋮

Need NLO QCD corrections

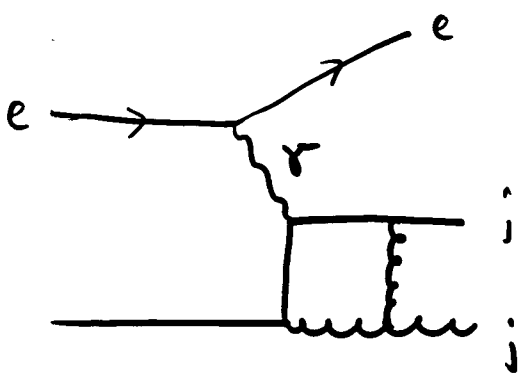
NLO corrections for $ep \to ejjX$ in DIS

LO:

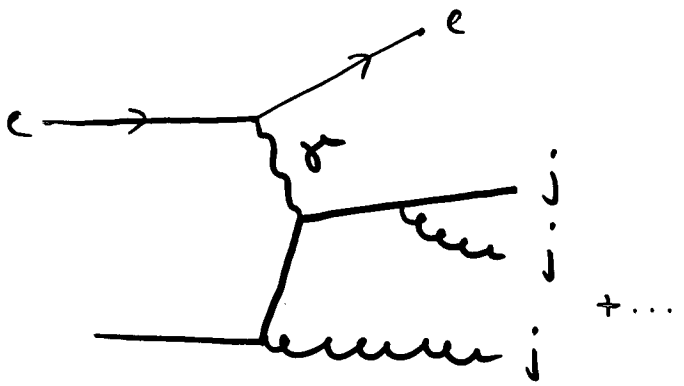




NLO:



virtual corr.



real emission

Previous calculations:

PROJET	Graudenz
DISJET	Brodkorb, Mirkes

semianalytic approach:

→ JADE jet definition scheme only

→ very restricted set of distributions & cuts

Two new calculations

Both as flexible NLO Monte Carlos

MEPJET Mirkes, Zeppenfeld

uses s_{min} method of Giele & Glover

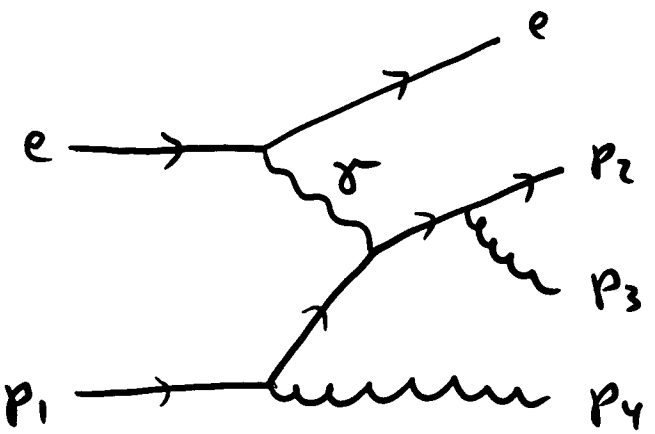
DISENT Catani, Seymour

uses subtraction method; available since Oct. 96

⇒ no detailed comparisons yet

Physics discussion below is based on MEPJET results.

Our approach: s_{min} phase space slicing method of Glover & Giele



$\sigma_3 = \infty$

(soft + collinear region)

3 parton cross section

$\sigma_3 (2 p_i \cdot p_j > s_{min})$ finite

"2 parton" cross section

structure function

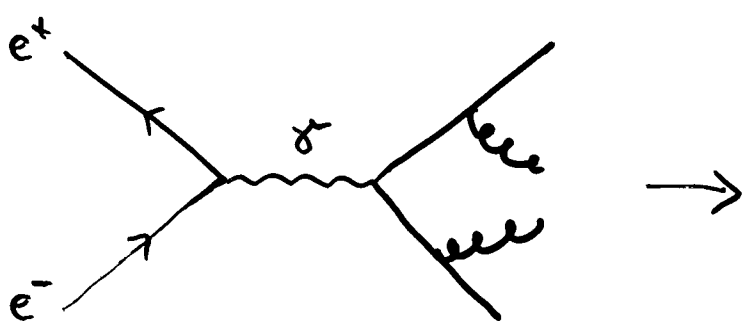
$$\sigma_2 = \sigma_{Born} + \underbrace{\sigma_{virtual} + \sigma_3 (2 p_i \cdot p_j < s_{min}) - \sigma_{factorize}}_{\text{finite}}$$

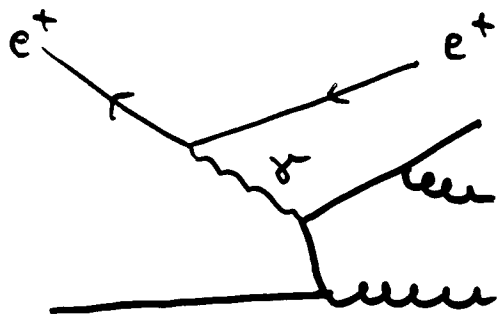
s_{min} small enough : soft + collinear approxim. allowed ; divergent terms

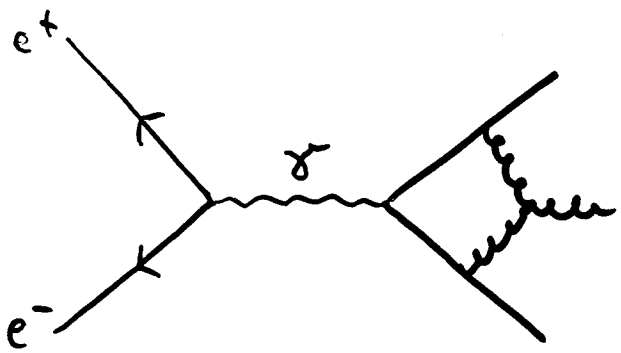
$$d\sigma/_{divergent} \sim d\sigma/_{Born} * \left(\frac{1}{\varepsilon}, \frac{1}{\varepsilon^2}\right)$$

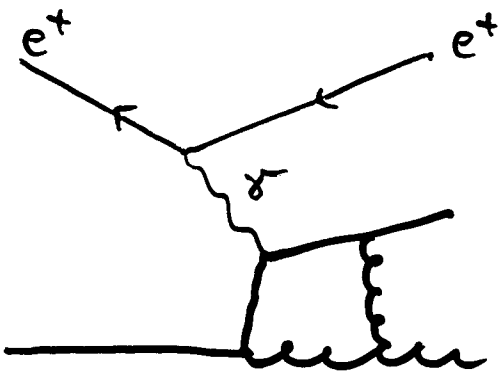
cancel divergencies at individual 2 parton phase space point

Analytic part of the calculation is straight forward: use known results for NLO QCD corrections to $e^+e^- \to 3$jets (e.g. Kramer et al.)









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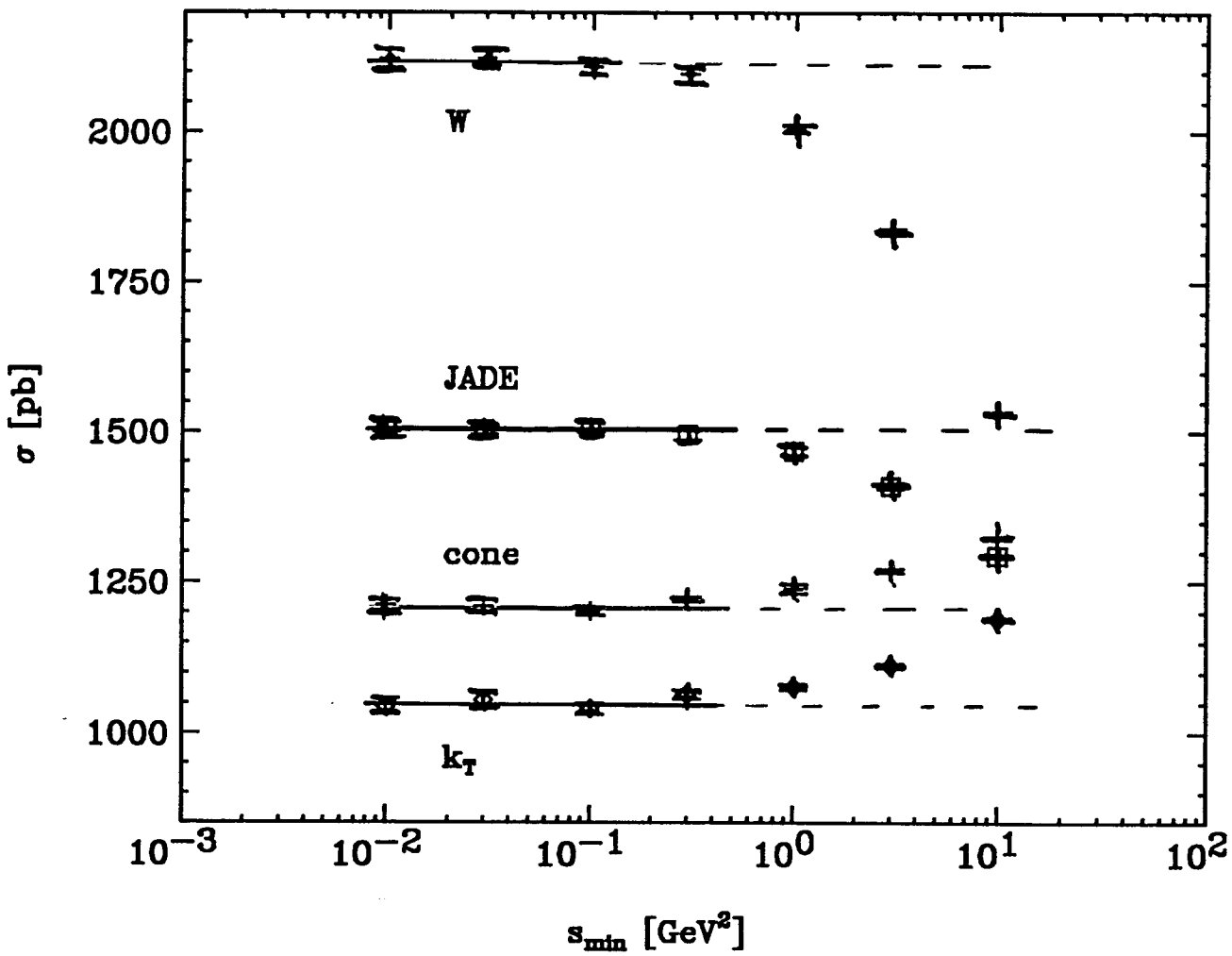
Crossing is performed by using NLO crossing functions of Giele, Glover, Kosower

Test of calculation :

s_{min} independence of result for small s_{min}



Jet definition schemes (parton level)

- cone scheme

  recombine partons/clusters with

  $$\Delta R < 1$$

  call recombined clusters jets if

  $$p_{Tj}^{lab} > 5\,GeV \quad , \quad |\eta_j| < 3.5$$

- K_T scheme

  defined in Breit frame, i.e frame in which

  $$\gamma^* : \quad q = (0, 0, 0, -2xE) \Rightarrow Q^2 = 4x^2E^2$$

  proton : $p = (E, 0, 0, E)$

  recombine partons i, j with

  $$M_{ij}^2 = 2 \min\{E_i^2, E_j^2\}(1 - \cos\theta_{ij}) < E_T^2$$

  recombine parton i with beam jet if

  $$2E_i^2(1 - \cos\theta_i) < E_T^2$$

Hard scattering scale for k_T-scheme

$$E_T^2 = 40 \text{ GeV}^2$$

Resulting clusters = jets

- W scheme

  Consider partons : p_i

  proton remnant: $p_r = (1-\xi)p$

  Recombine pair with smallest

  $$M_{ij}^2 \equiv (p_i + p_j)^2 < y_{cut} W^2$$

  Final clusters ($\neq$ remnant) = jets

  Here: $y_{cut} = 0.02$

- JADE scheme

  variant of W-scheme with

  $$M_{ij}^2 \equiv 2 E_i E_j (1 - \cos\theta_{ij}) < y_{cut} W^2$$

  i.e. neglect masses^2: p_i^2, p_j^2

  Here: $y_{cut} = 0.02$

Recombination schemes

Determine cluster 4-momentum p_{ij} from component 4-momenta p_i, p_j

- E-scheme

$$p_{ij}^{\mu} = p_i^{\mu} + p_j^{\mu}$$

- Eϕ-scheme

$$p_{ij} = (p_i^0 + p_j^0, \beta(\vec{p}_i + \vec{p}_j))$$

with β such that $p_{ij}^2 = 0$

- p-scheme

$$p_{ij} = (\frac{1}{\beta}(p_i^0 + p_j^0), \vec{p}_i + \vec{p}_j)$$

with β such that $p_{ij}^2 = 0$

Additional cuts:

$$40\ \text{GeV}^2 < Q^2 < 2500\ \text{GeV}^2$$

↑ eliminates Z-exchange

Final state lepton

$$E > 10\ \text{GeV}$$

$$y > 0.04$$

$$|\eta| < 3.5$$

Two-jet inclusive cross sections (in pb) for the four jet algorithms

	cone	k_T	W	JADE
LO	1107	1067	1020	1020
NLO (E)	1203	1038	2082	1507
NLO (EO)	1232	1014	1438	1387
NLO (p)	1208	944	1315	1265

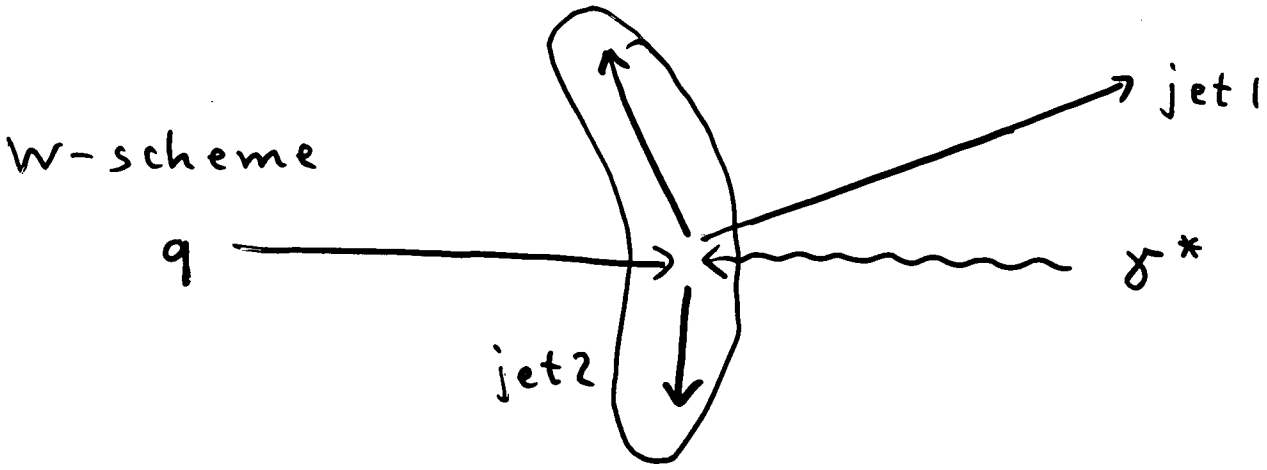
⇒ Large K-factor, strong recombination scheme dependence for W and JADE

Recombination scheme effects are only modeled at LO

⇒ Variation with recombination scheme is subject to large $O(\alpha_s^3)$ corrections

⇒ Large theory uncertainty for JADE & W

Source of recombination effects : mass of reconstructed jets



W and JADE scheme recombine relatively soft, well separated partons to jets

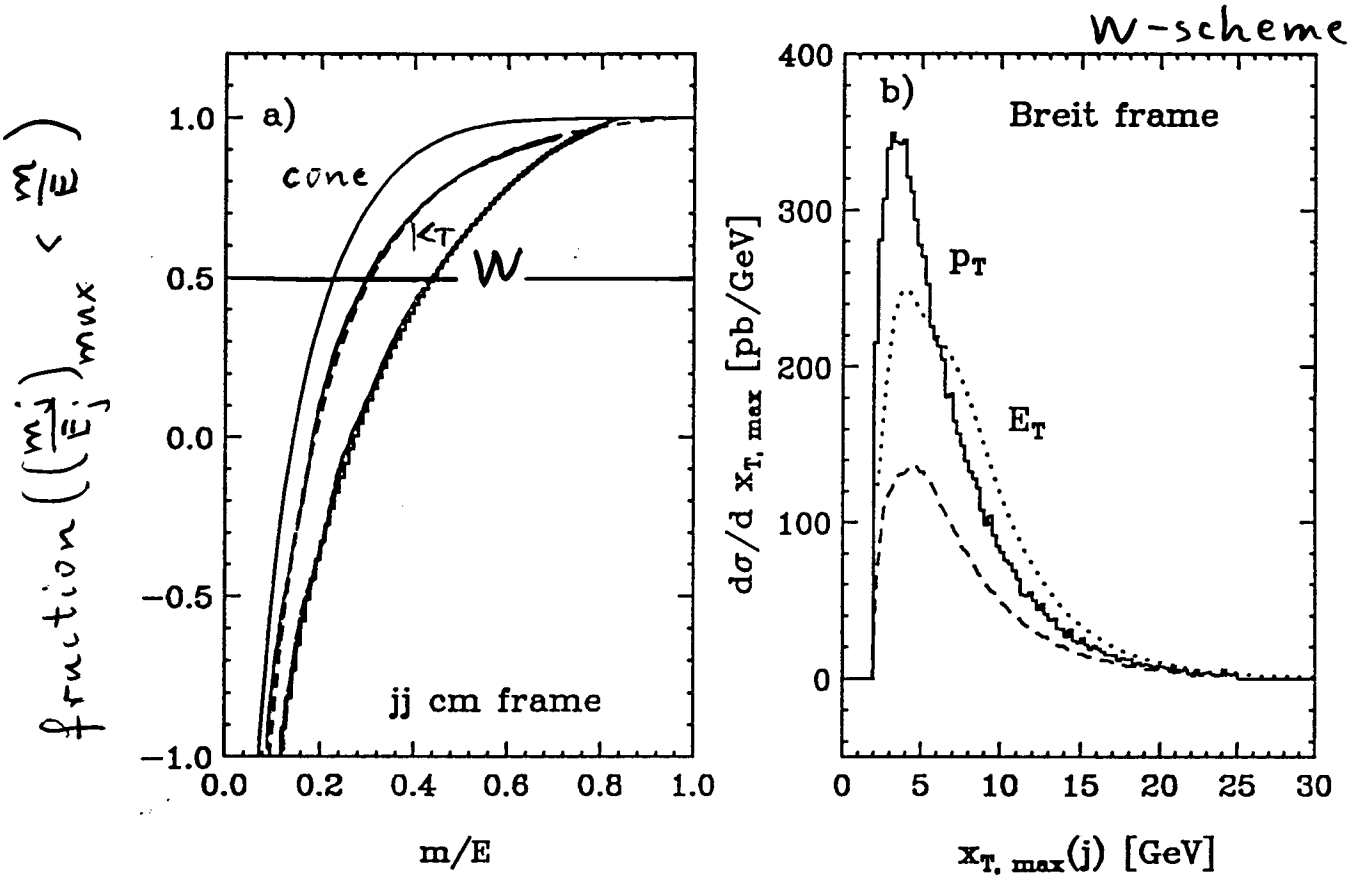
$\Rightarrow$ jet has sizable mass $\sqrt{p_2^2}$

Large mass helps to survive cut

$$(p_1 + p_2)^2 = 2p_1 \cdot p_2 + p_2^2 > y_{cut} W^2$$

Problem: NLO jets <u>do not</u> correspond to hard parton with some soft and colinear gluon radiation.

Importance of mass effects



median $(m_j/E_j)_{max}$:

cone scheme : 0.22

k_T scheme : 0.30

W scheme : 0.44

Scale dependence

Dependence of NLO cross section on

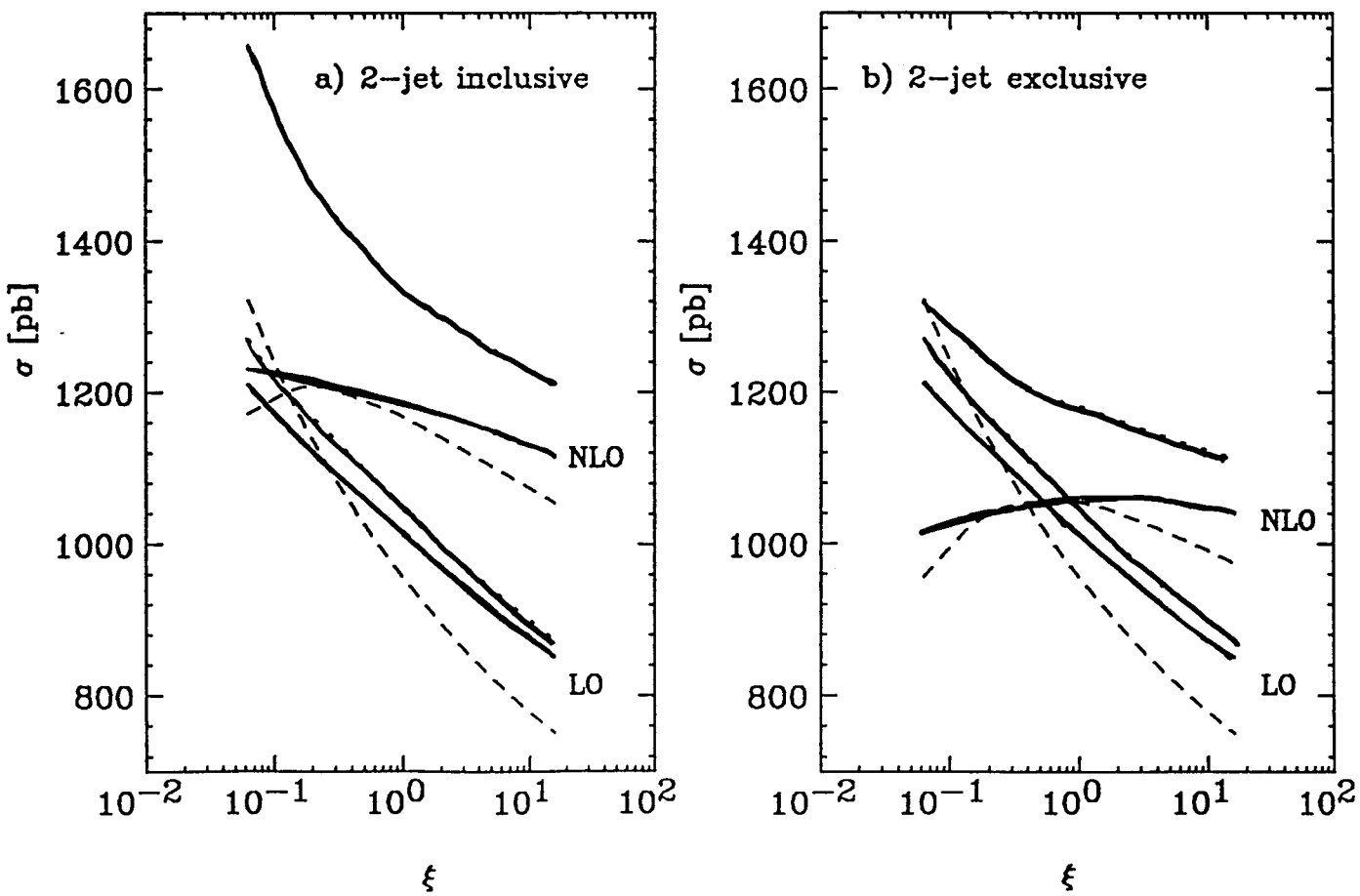
- factorization scale ($q(x, \mu_F^2)$)
- renormalization scale ($\alpha_s(\mu_R^2)$)

Two choices:

$$\mu_R^2 = \mu_F^2 = \xi Q^2$$

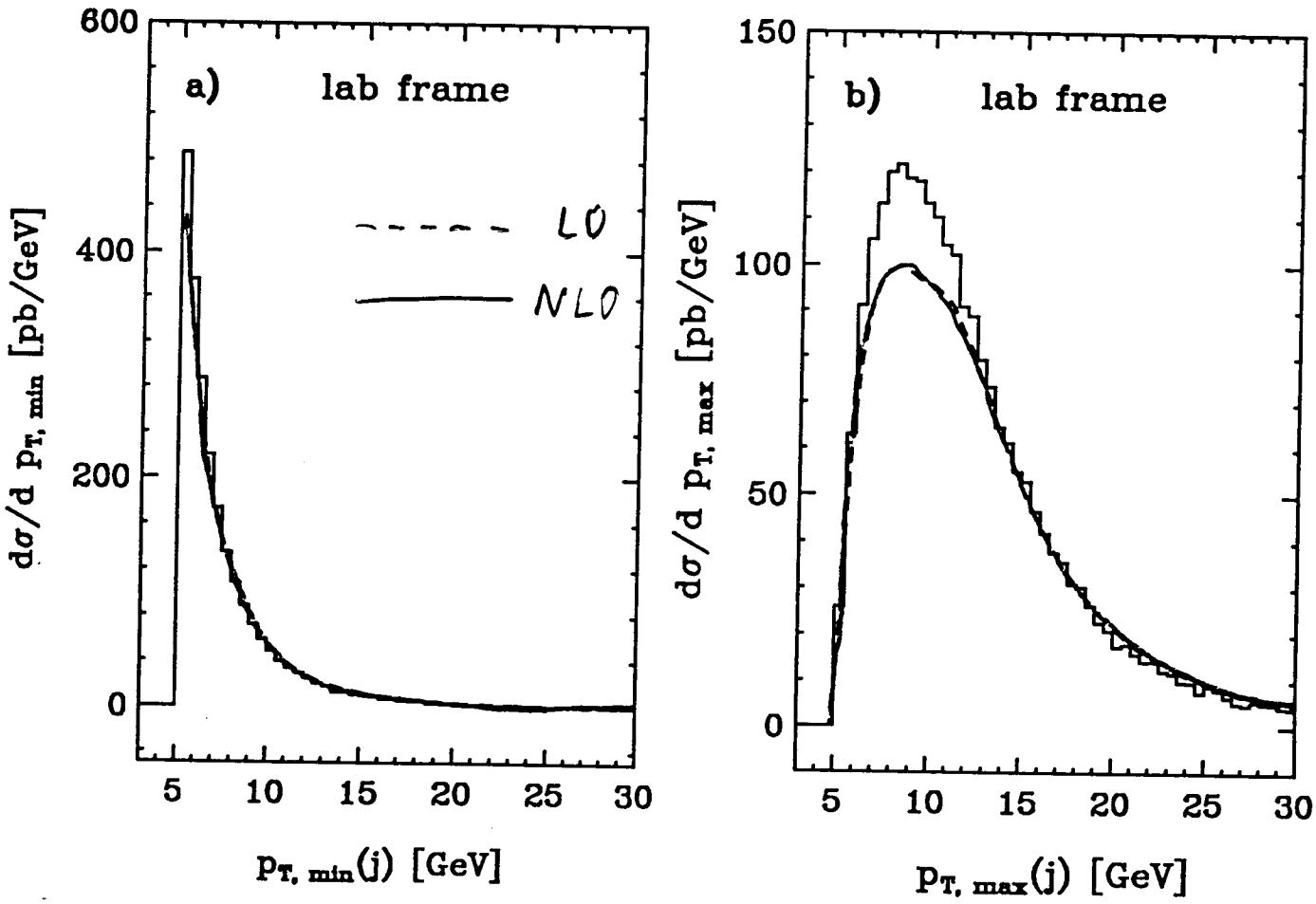
$$\mu_R^2 = \mu_F^2 = \xi \left[\sum_{\text{partons}} p_T^{\text{Breit}} \right]^2$$

cone scheme



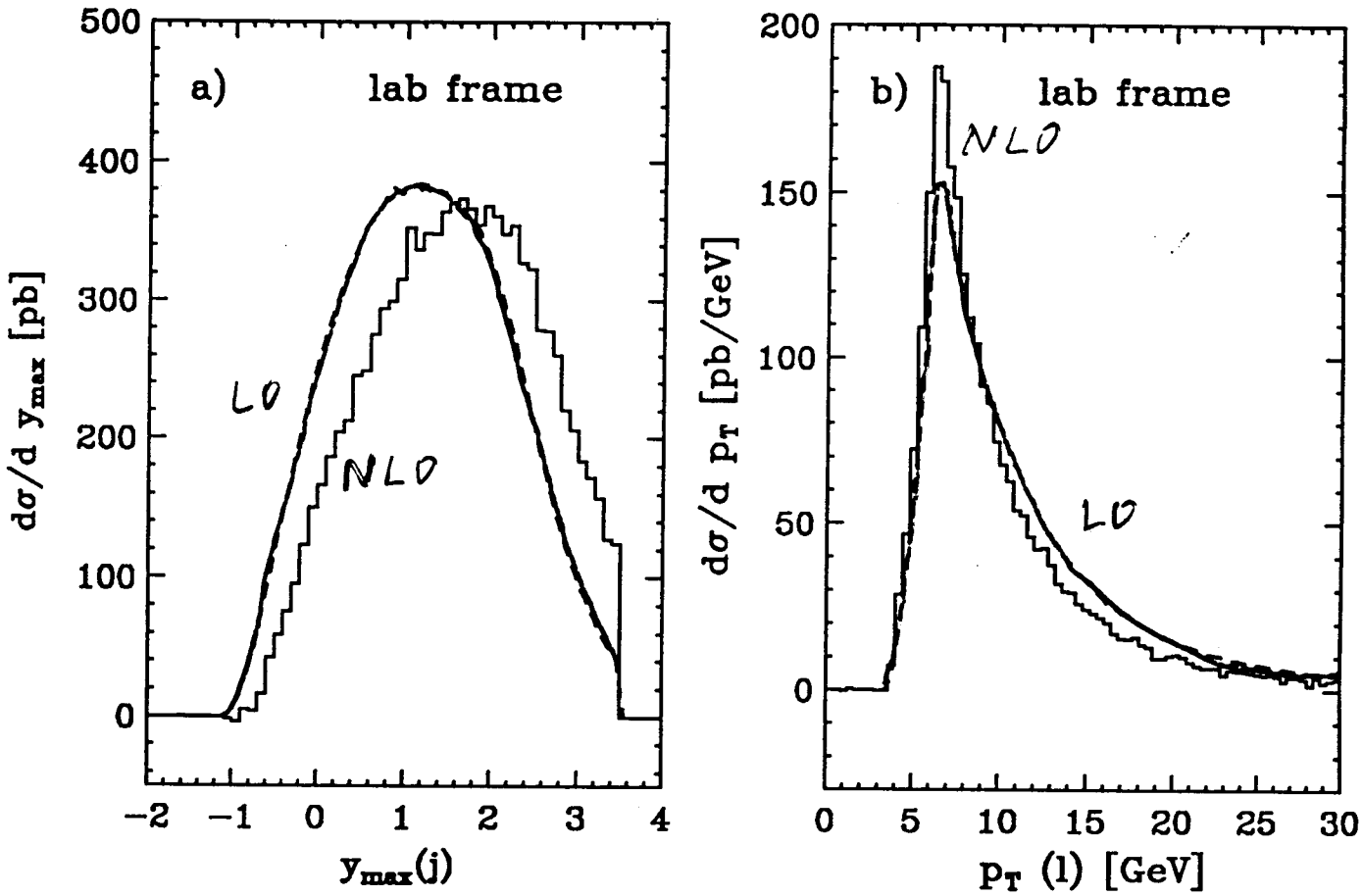
Comparison LO vs. NLO

cone scheme



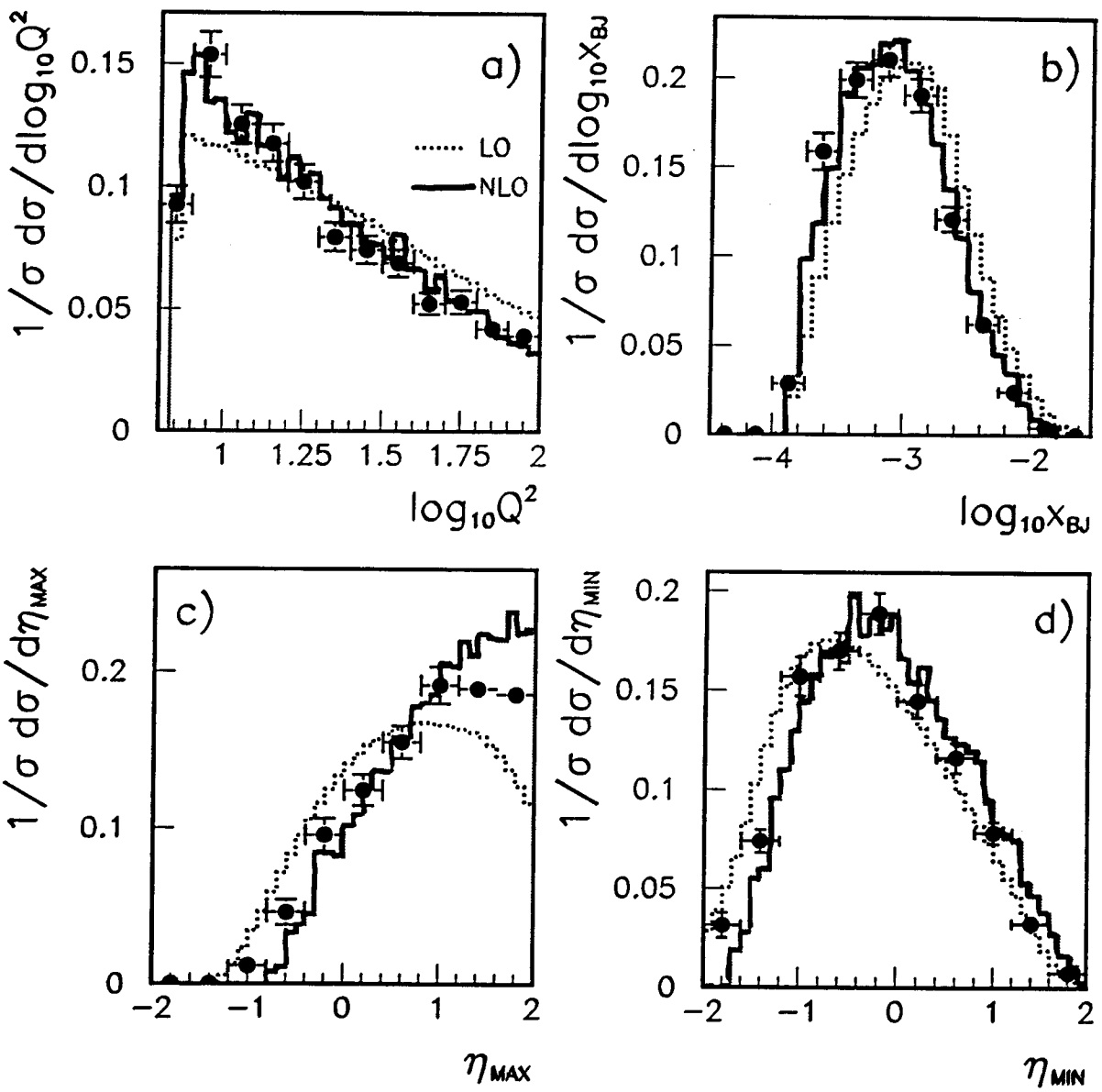
loop effects are sizable in some regions of phase space

K_T scheme



NLO shapes agree well with data.

Comparison ZEUS data – MEPJET



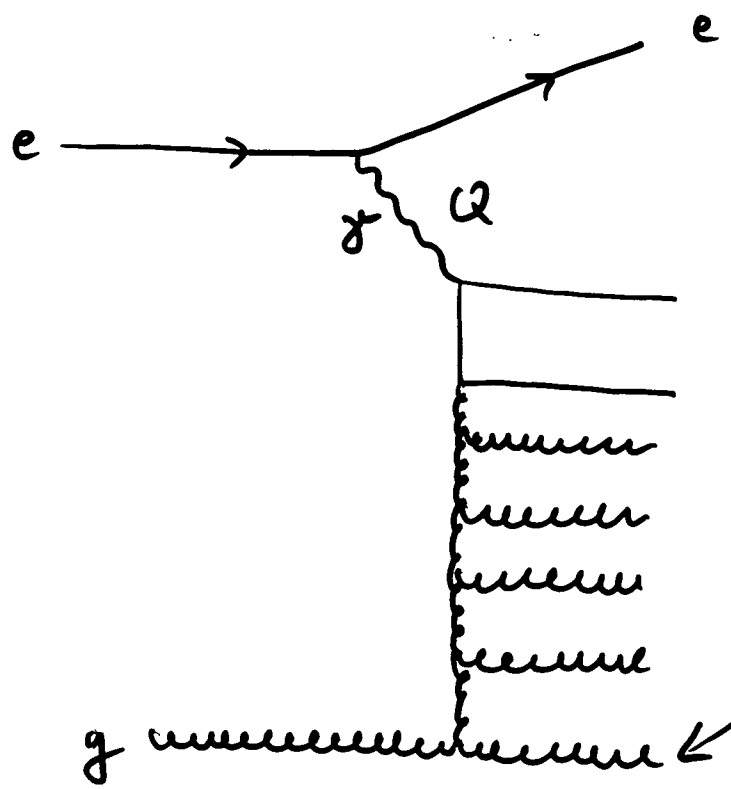
cone scheme : $\Delta R > 1$

Lab frame: $|\eta_j| < 2$, $E_{T_j} > 2.5$ GeV

$\gamma^* p$ frame: $E_{T_j} > 4$ GeV

Forward jets and BFKL dynamics

Isolate BFKL dynamics (gluon ladders) by tagging forward (Mueller-Navelet) jet



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

$$p_T \approx Q$$

$$x_{jet} = \frac{p_z(jet)}{E_p} \gg x$$

BFKL prediction

$$\frac{\sigma_{BFKL}\,(x \ll x_{jet})}{\sigma_{\text{fixed order QCD}}} \sim \left(\frac{x_{jet}}{x}\right)^{\alpha_P - 1} \gg 1$$

Fixed order QCD is "background"

Fixed order QCD contribution: at $O(\alpha_s^2)$

- 1 (massless) parton in final state at 2 loops

  forbidden by $x_{jet} \gg x$

- 2 partons at 1 loop
- 3 partons at tree level

} same as $ep \to e j j X$ at NLO

$\Rightarrow$ MEPJET can determine 1-jet inclusive forward jet cross section at full $O(\alpha_s^2)$

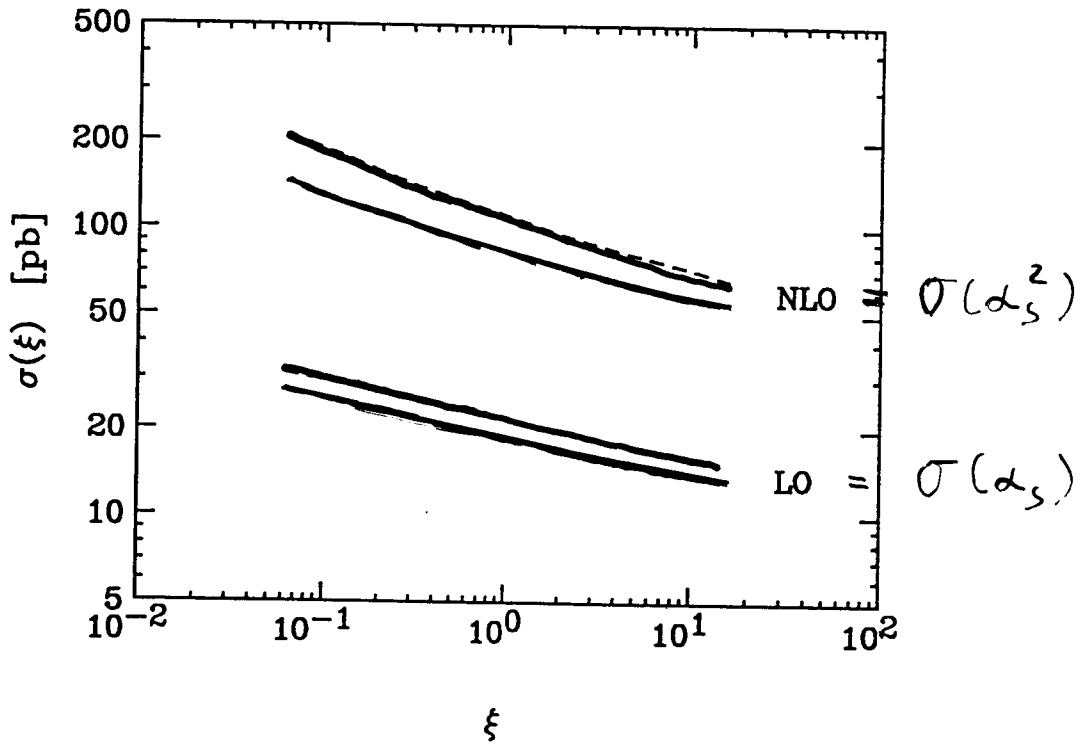
Uncertainties of fixed order results

- strong scale dependence

$$\mu_R^2 = \mu_F^2 = \begin{cases} \xi \left(\frac{1}{2}\sum K_T^B\right)^2 \\ \xi\, Q^2 \end{cases}$$

- Large effective K factor

$$K \approx 4-5$$

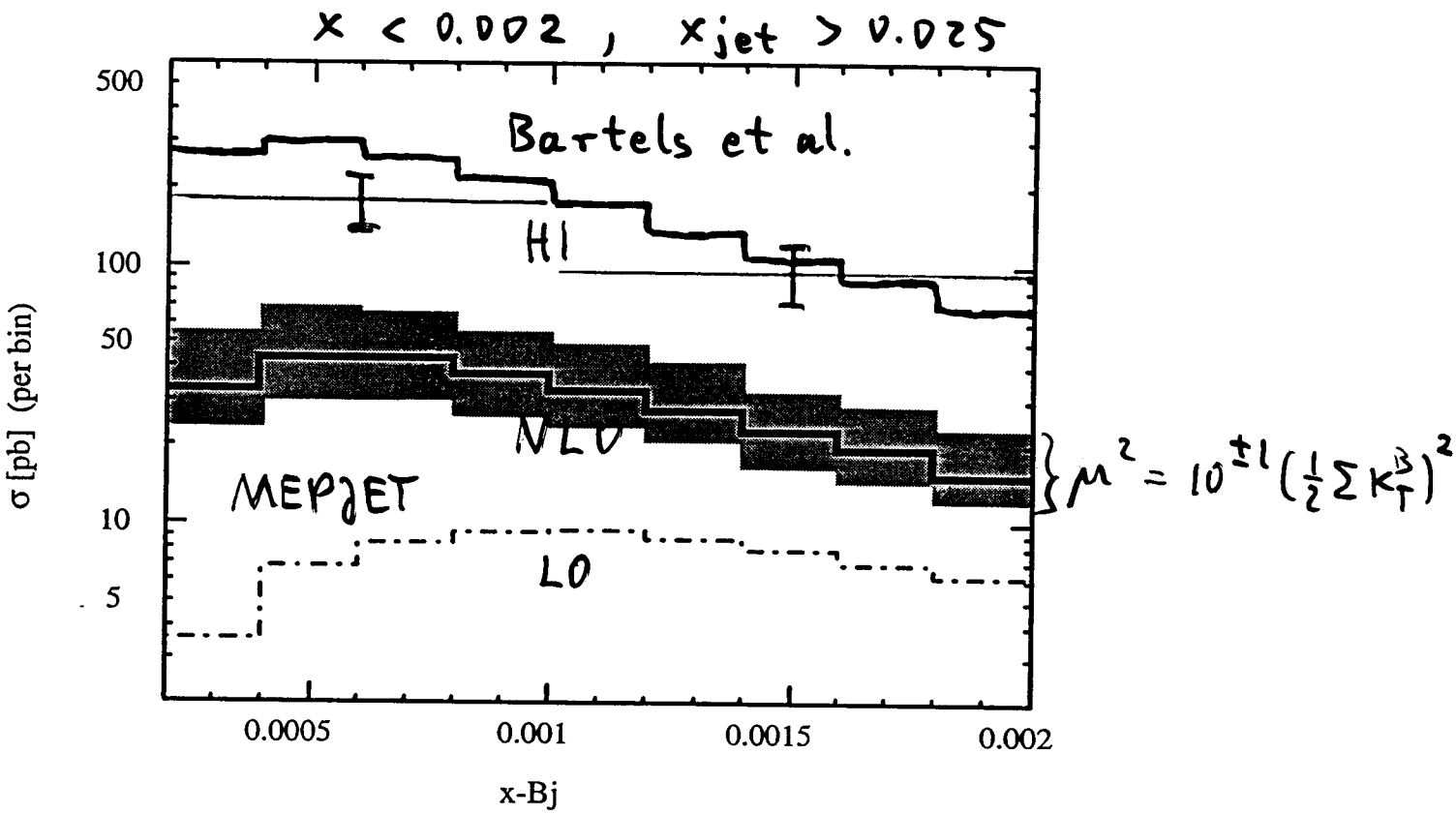


3-parton final states dominate

$\Rightarrow \sigma(\alpha_s^2)$ cross section is effectively LO

Comparison with

- BFKL calculation (Bartels et al, hep-ph/9604272)
- H1 data (P.L. B356 (1995) 118)



Data show evidence for BFKL dynamics: enhancement above NLO QCD

Summary

NLO corrections to dijet production in DIS now exist in the form of NLO Monte Carlo programs.

Large recombination scheme effects and NLO corrections make the W and JADE schemes unsuitable for NLO QCD studies.

NLO QCD cannot explain rate of forward jet events observed at HERA
→ evidence for BFKL effects.