Forward jets and particle production
(Experimental results and phenomenology)

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Outline of the talk:
- Introduction
- Fixed order QCD calculations
- Phenomenological models
- Inclusive jet production
- Forward jet production
- Forward pion production
- Summary

Introduction

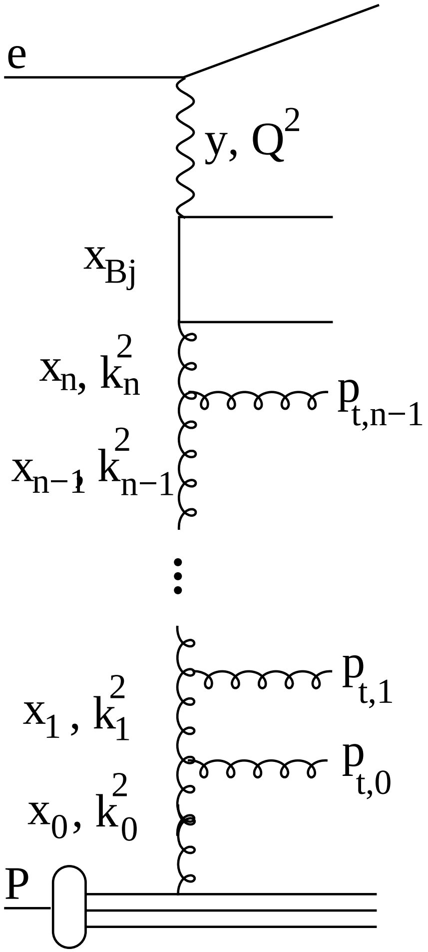
- QCD is one of the corner stones of the Standard Model
- The qualitative aspects of asymptotic freedom and confinement are under control
- Quantitative predictions not yet satisfactory
- Remaining problems to be understood:
  - parton dynamics at small x
  - long range interactions
  - saturation
  - diffractive scattering
  - multi-parton exchange

  etc.

Introduction

• At large x_{Bj} the parton evolution is expected to be govered by ordering in the virtuality of the propagators: $k_n^2 \gg k_{n-1}^2 \gg \ldots \gg k_1^2 \gg k_0^2$
$\Rightarrow$ strict ordering in the transverse momenta of the emitted partons: $p_{tn-1} \gg p_{tn} \gg \ldots \gg p_{t1} \gg p_{t0}$

• At small x_{Bj} the parton evolution is believed to be characterized by ordering in the longitudinal momentum fractions of the propagators:
$x_{Bj} \ll x_n \ll x_{n-1} \ll \ldots \ll x_1 \ll x_0$
$\Rightarrow$ No ordering in the transverse momenta of the emitted partons



Fixed order QCD calculations

- Non-ordering in the transverse momenta of the emitted partons may appear at $O(\alpha_s^3)$ i.e. processes with at least four final state partons.
- A conventional fixed order QCD calculation up to $O(\alpha_s^2)$ contains no trace of non-ordering.
- Evidence for non-ordered parton dynamics therefore appears as enhanced cross sections compared to expectations for two- and three parton final states
- It is important to remember that LO and NLO refer to a specific observable

	LO	NLO
1-jet	$O(\alpha_s^0)$	$O(\alpha_s^1)$
2-jets	$O(\alpha_s^1)$	$O(\alpha_s^2)$
3-jets	$O(\alpha_s^2)$	$O(\alpha_s^3)$

Fixed order QCD calculations

DISENT: Offers a completely general algorithm for calculating single- and di-jet cross sections in NLO QCD. It applies to any jet observable in a given scattering process and to any hard scattering process.

DISASTER++: Provides calculations of single- and di-jet-like quantities in DIS at NLO accuracy. Generate events of final state partons, weighted with the respective hard scattering cross section. The rest is left to the user.

Both these programs uses the subtraction method in the numerical integration to handle singularities due to soft and collinear radiation i.e. a point-by-point subtraction is applied.

Fixed order QCD calculations cont.

MEPJET and JetViP:

These programs provide a complete package to handle the convolution of the hard, perturbative calculable cross sections with the parton density functions in the initial state, and recombination of final state partons from the subprocess to jets.

They use the phase space slicing method to handle divergencies in the cross section calculation due to soft and collinear final state partons, i.e. an invariant mass cut-off is introduced.

JetViP:

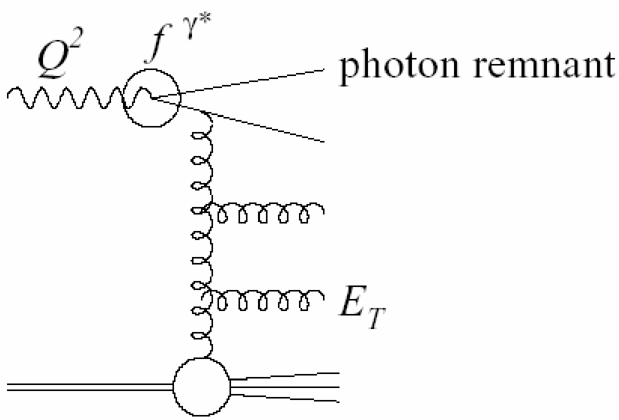
- Includes contributions from resolved photon processes
- Uses the cone-algorithm according to the Snowmass convention

JetVip

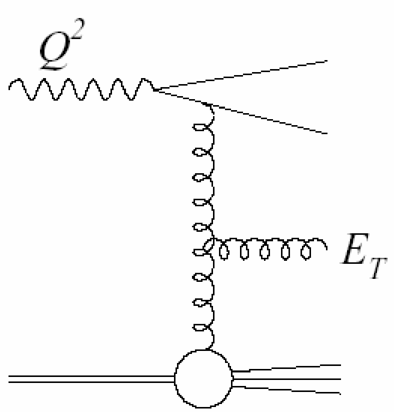
The NLO resolved contribution supplies higher order in two ways:

- Through the NLO correction in the hard scattering cross section
- In the leading log approximation by evolving the PDF's of the virtual photon to the chosen factorization scale.

Convolution of the of the pointlike term in the the photon PDF with the NLO resolved matrix elements provides two gluons in the final state and gives an approximation to the NNLO direct cross section without resolved contributions



NLO resolved photon process



NLO direct photon interaction

JetViP selection criteria: $|\eta| < 3.5$ $x_{Bj} > 0.004$ $Q^2 > 8$ GeV

$E_T^B > 4$ GeV $y > 0.1$ $E_e' > 11$ GeV

$160° < \theta_e < 173.5°$

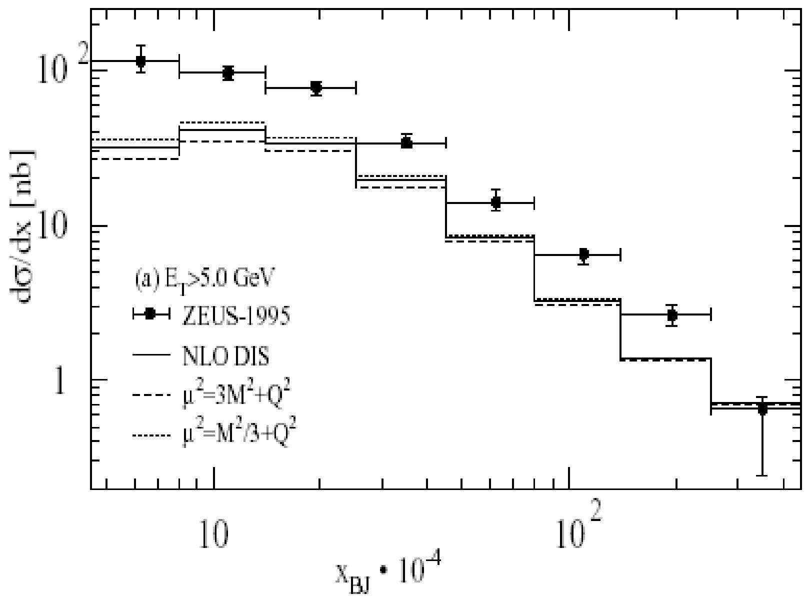
Forward jet criteria: $E > 5$ GeV $1.735 < \eta_{fwd\text{-}jet} < 2.90$

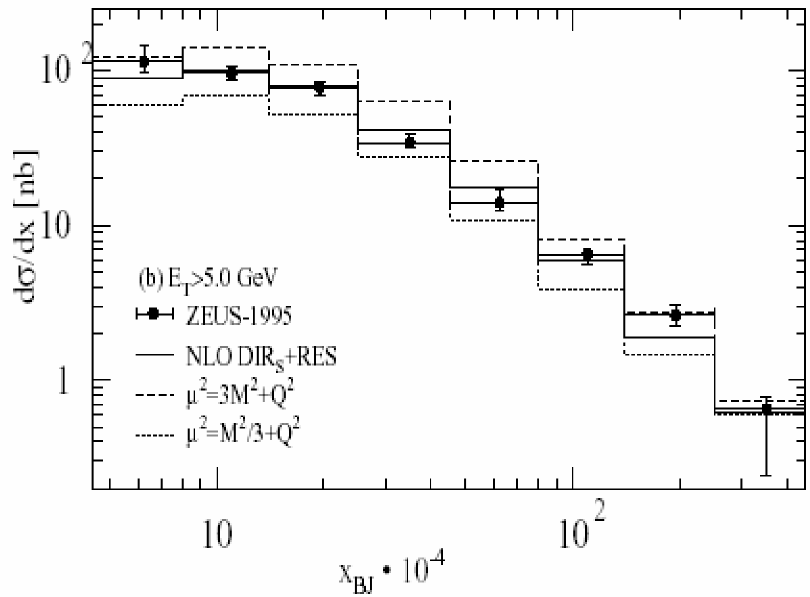
$p_z/E_p > 0.05$ $0.5 < E_T^2/Q^2 < 4$ GeV^2

Proton PDF: CTEQ4M

Photon PDF: SaS1D

Scales: $\mu_r^2 = \mu_f^2 = Q^2+(E_T^B)^2$





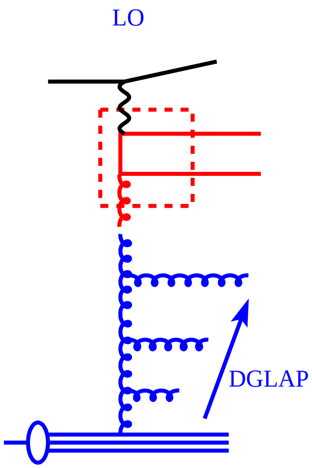
NLOJET++

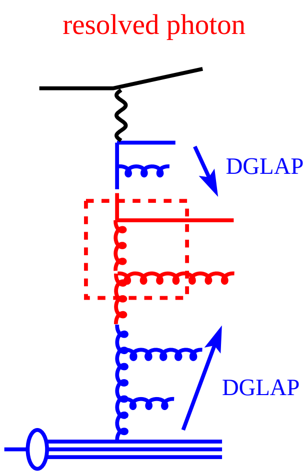
NLOJET++: Provides perturbative calculations of cross sections for one jet inclusive production as well as 2- and 3-jet exclusive final states in DIS at NLO accuracy.

It uses the subtraction method in the numerical integration to handle singularities due to soft and collinear radiation

It uses the k_T-algorithm to reconstruct jets

Penomenological QCD models





DGLAP (collinear approximation)

- QCD expansion by resumming terms of the type $(\alpha_S \ln Q^2)^n$
- Strict ordering in virtuality of the propagators

$\mu^2 = Q^2 >> k_n^2 >> \ldots >> k_1^2 >> k_0^2$

which means strict ordering in transverse momenta of the propagators

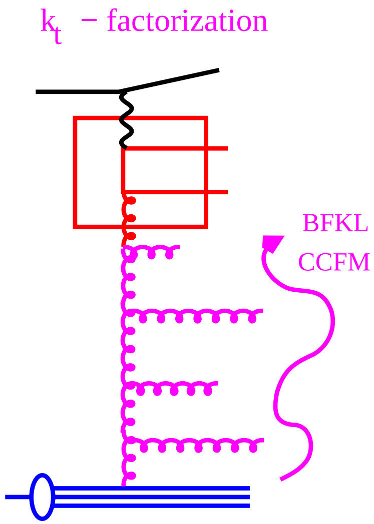
$\mu^2 = Q^2 >> k_{tn}^2 >> \ldots >> k_{t1}^2 >> k_{t0}^2$

- The hard scale (Q^2) is dominating $\Rightarrow$ the propagators can be treated massless and collinear with the proton
- Good approximation at high Q^2 values
- DGLAP direct: the photon interacts like a point-particle

Resolved photons

- The photon can interact via its partonic content $\Rightarrow$ two DGLAP chains (DGLAP resolved)

QCD models contd.



BFKL (k_t-factorization)

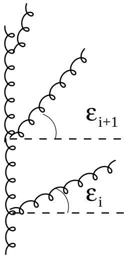
- Evolution equation includes terms of the type $(\alpha_s \ln 1/x)^n$
- These terms become important at small x-values
- Strict ordering in the longitudinal momentum, ln(1/x), of the propagators, ln(1/x) $\Rightarrow x_0^2 >> x_1^2 >> \ldots >> x_n^2 >> x_{Bj}^2$
- no ordering in transverse momenta

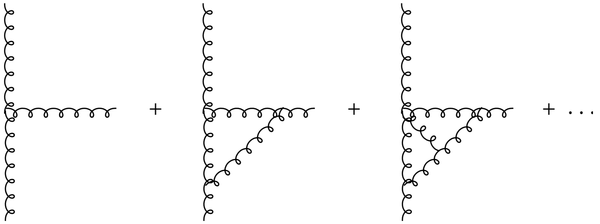
CCFM

- CCFM combines in a consistent manner the properties of DGLAP and BFKL since it resums terms of both the form $(\alpha_s \ln(Q^2))^n$ and $(\alpha_s \ln(1/x))^n$
- CCFM evolution is valid both at large and small x
- The CCFM evolution is based on angular ordering of the emitted partons:

$\Xi >> \xi_n >> \xi_{n-1} \ldots >> \xi_o$

- Virtual corrections in the gluon vertex are automatically taken into account (resummed to all orders)

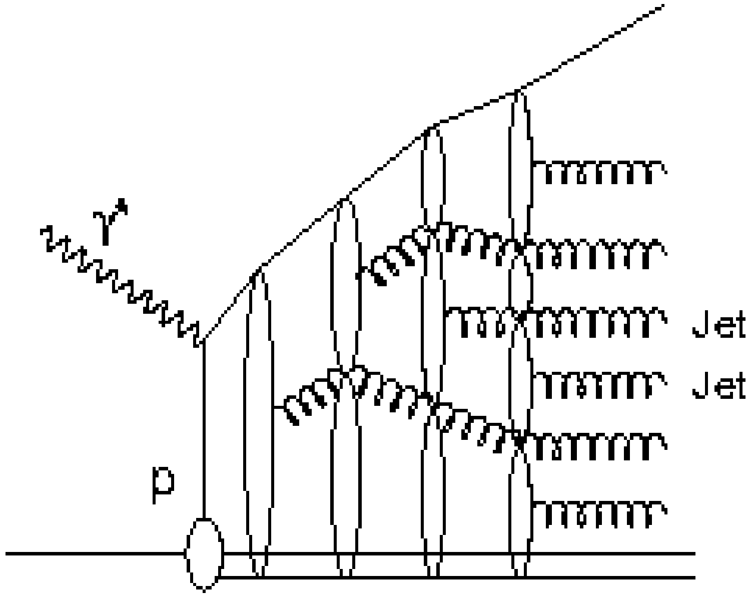




QCD models contd.

The Colour Dipole Model (CDM)

- Gluon emission originates from colour dipoles which radiate independently.



Single inclusive jet measurements (ZEUS)

1) The 'global' phase space region:
- $Q^2 > 25$ GeV^2
- $0.04 < y < 0.95$
- $E_e' > 10$ GeV

Jet search is performed with the longitudinally invariant k_T-algorithm requiring:
- $E_{t,jet} > 6$ GeV
- $-1 < \eta_{jet} < 3$ in the laboratory frame

This phase space region is expected to be dominated by QPM-type events

2) The 'BFKL' phase space region

Additional requirements:
- $\cos\gamma_h < 0$, ($\gamma_h > 90°$)

  where $\cos\gamma_h = ((1-y)xE_p - yE_e)/((1-y)xE_p + yE_e)$

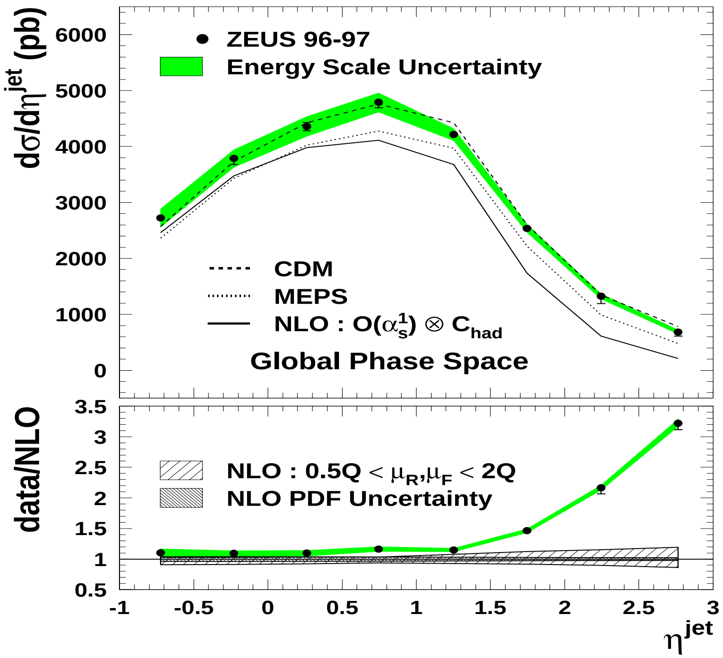
At least one jet with:
- $0 < \eta_{jet} < 3$, ($\theta_{jet} < 90°$)
- $0.5 < E^2_{T,jet}/Q^2 < 2$

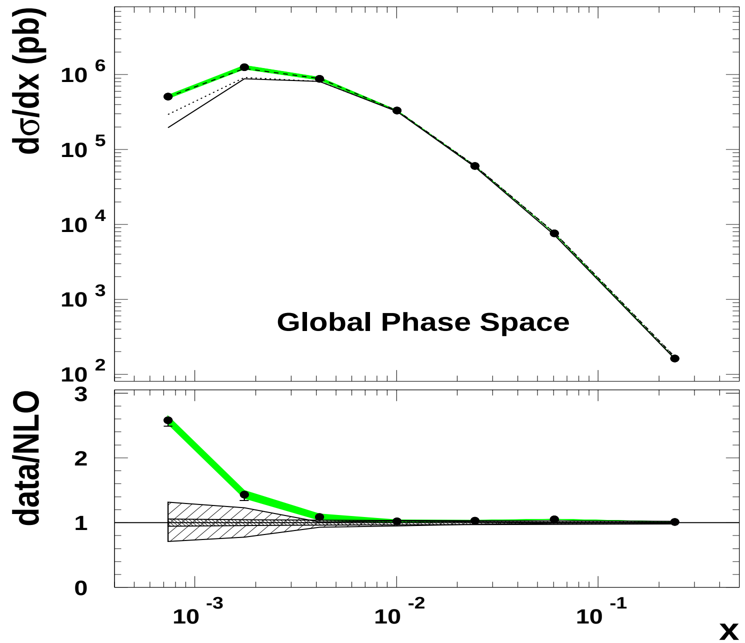
This phase space region is expected to be dominated by multijet events

3) The 'forward BFKL' phase space region

At least one jet with:
- $2 < \eta_{jet} < 3$

Single inclusive jet cross sections, 'global' phase space

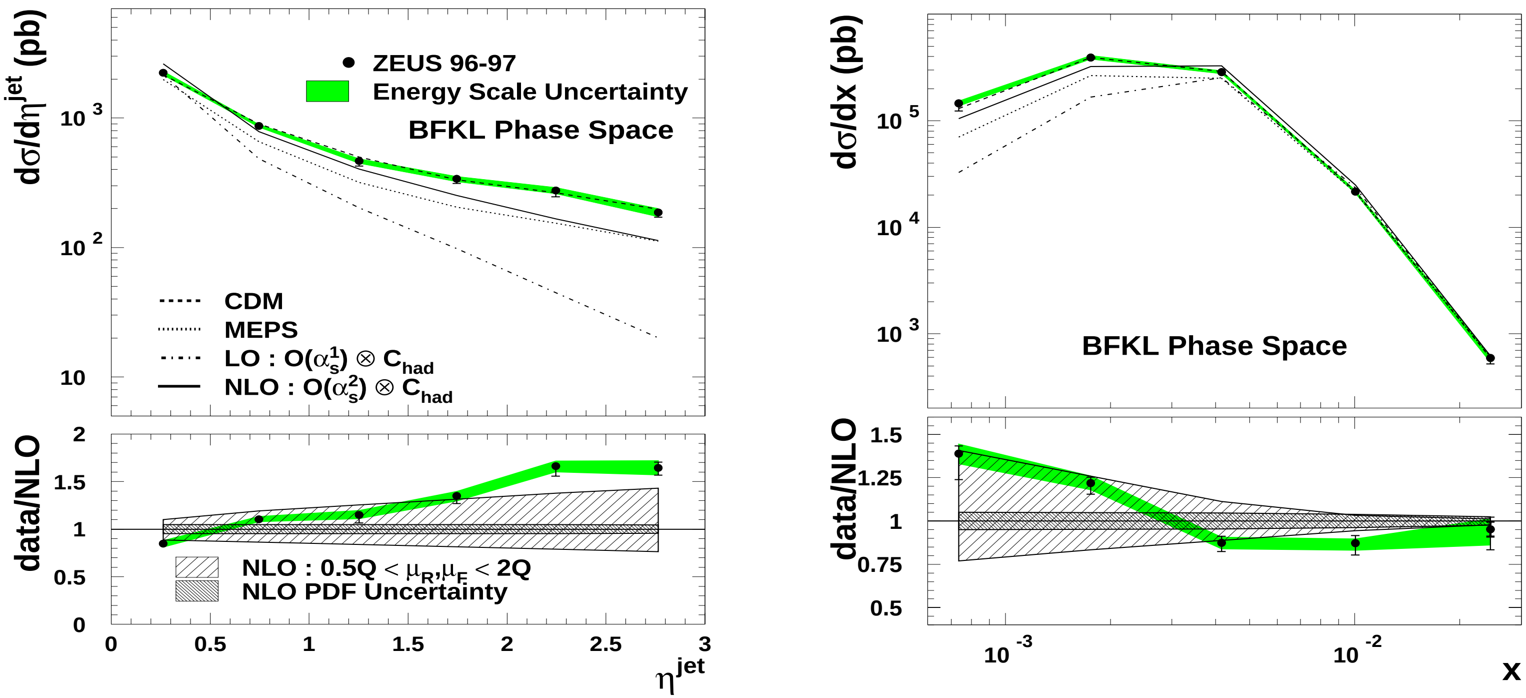




- The CDM model (ARIADNE) gives a very good description of the data, both as a function of η_{jet} and x_{Bj}.
- The LO MEPS model (LEPTO) undershoots the data over the full rapidity range and in the small x region
- The NLO calculation (DISENT O(α_s) can not describe the rapidity distribution and can also not reproduce the small x behaviour

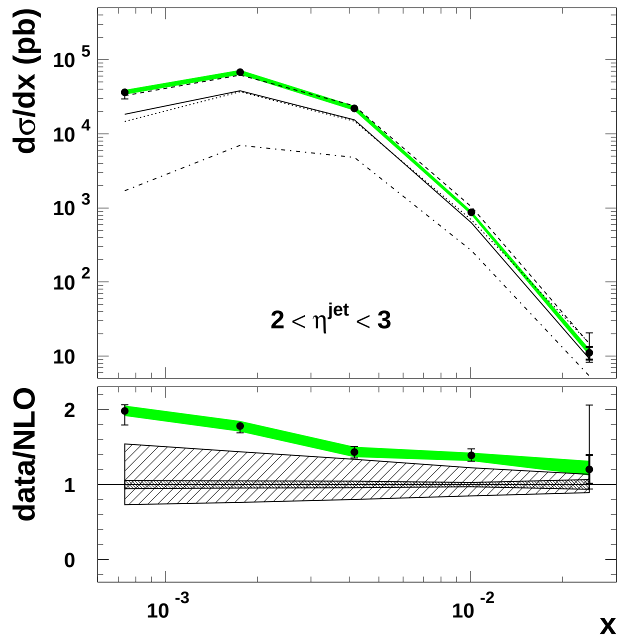
⇒ NLO is not enough; higher order corrections are necessary

Single inclusive jet cross sections, 'BFKL' phase space



- The CDM model (ARIADNE) again gives the best description of the data
- The LO MEPS model (LEPTO) clearly undershoots data over the full rapidity range and in the small x region
- The NLO calculation (DISENT) does not reproduce the shape of the rapidity distribution but is in reasonable agreement with the x_{Bj} distr.
- NLO/LO ~ 5 at η_{jet} ~ 3
- Notice: the scale uncertainties are very big which excludes firm conclusions

Single inclusive jet cross section, 'forward BFKL' phase space



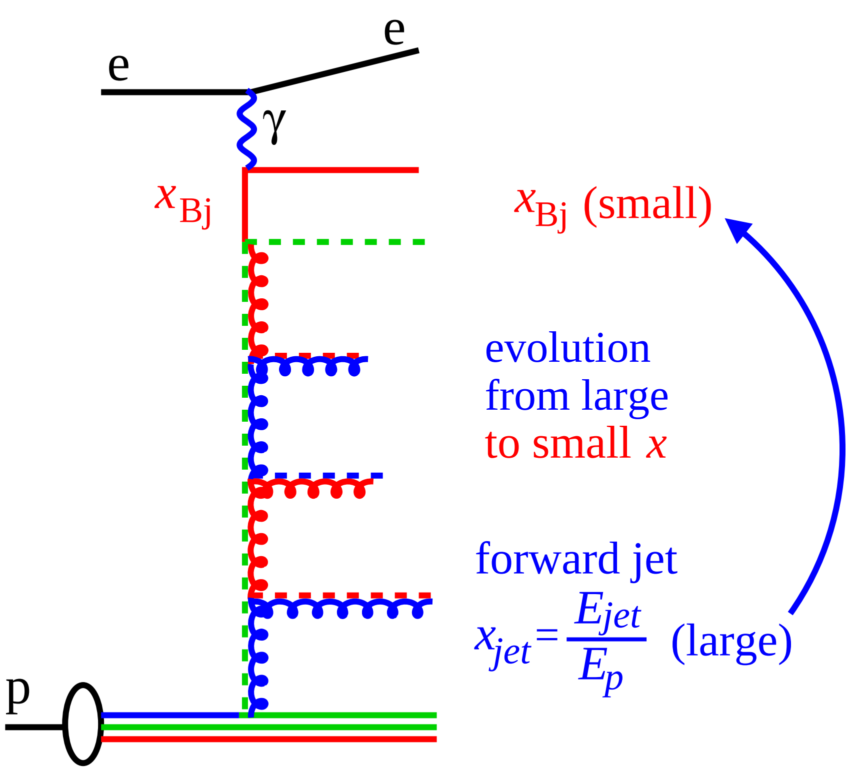
- The CDM model (ARIADNE) describes the data well
- The LO MEPS model (LEPTO) clearly undershoots data especially in the small x region
- The NLO calculation (DISENT) gives similar behaviour as MEPS and underestimates the data at low x_{Bj} by a almost factor two
- NLO/LO reaches values of 10 at low x_{Bj}
- The increased scale variation at NLO compared to the 'BFKL' region

$\Rightarrow$ higher order calculations needed

Forward jet selection (H1)

DIS: $E_e > 10$ GeV
$156^\circ < \theta_e < 175^\circ$
$0.1 < y < 0.7$
$0.0001 < x_{Bj} < 0.004$
$5 < Q^2 < 85$ GeV^2

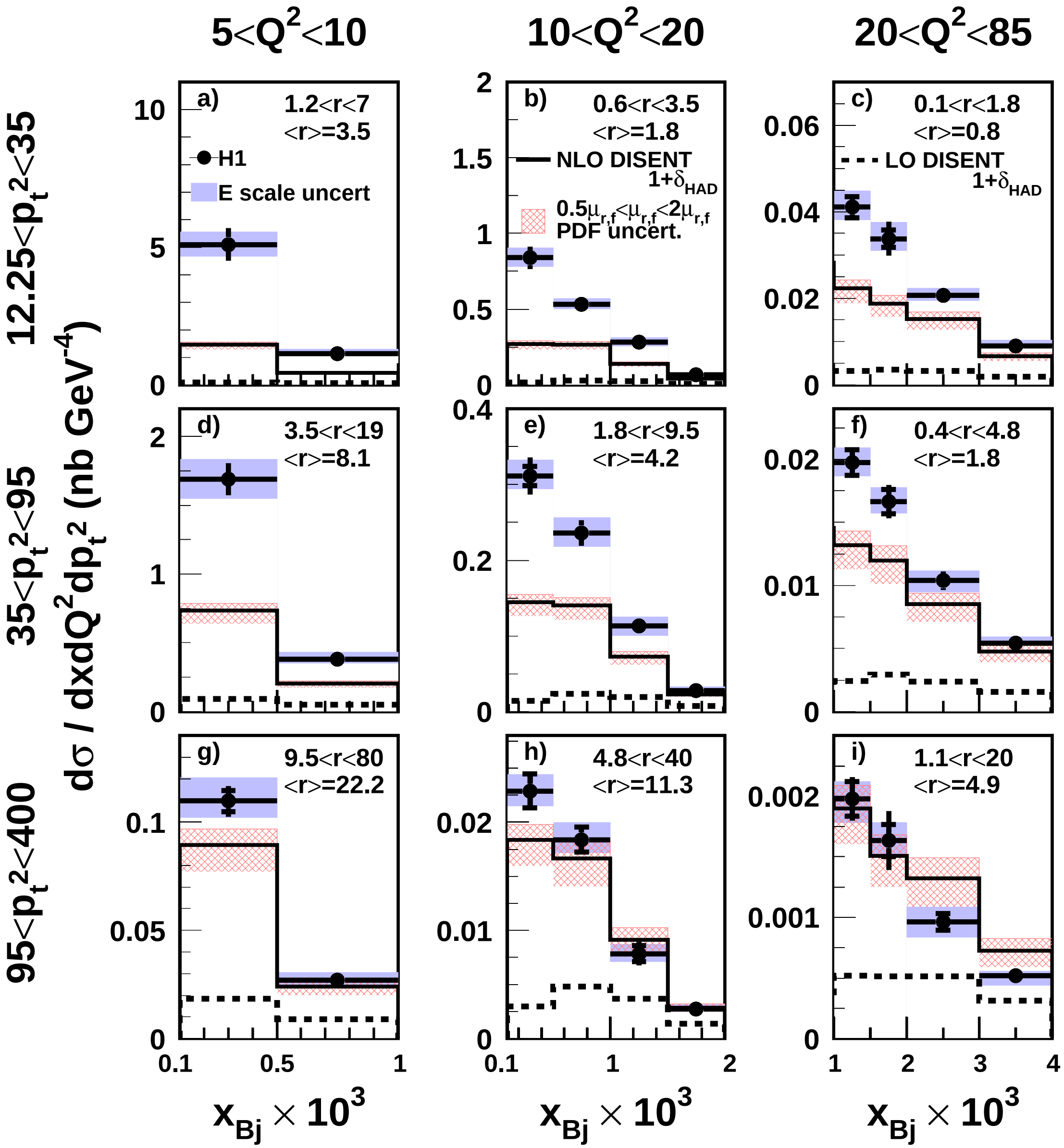
Fwd jet: the k_t-algoritm in Breit frame
$P_{t\ jet} > 3.5$ GeV
$7.0^\circ < \Theta_{jet} < 20.0^\circ$



• Suppress the DGLAP evolution by choosing the momentum transferred by the virtual photon equal to the transverse momentum of the first propagator in the ladder (forward jet; $0.5 < p_t^2/Q^2 < 5$)

• Enhance BFKL by choosing Bjorken-x much smaller than the momentum fraction of the first propagator in the ladder ($x_{jet} > 0.035$ where $x_{jet} = E_{jet}/E_p$)

Triple differential cross sections (H1)

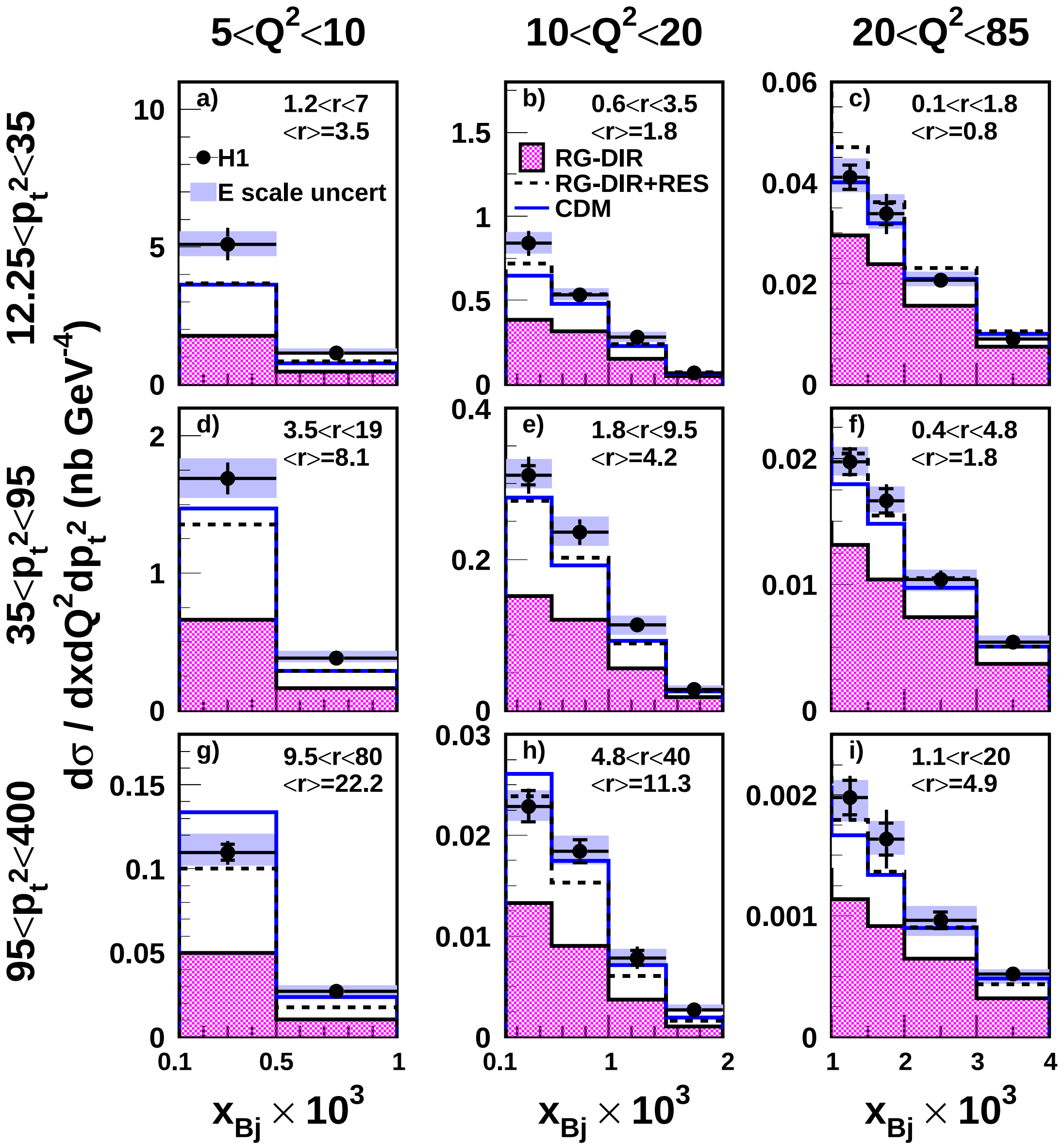


$r = p^2_{t,jet}/Q^2$

- $r \sim 1$ BFKL-enhanced
- $r < 1$ DGLAP-enhanced
- $r > 1$ Resolved photon like

- NLO calculations generally undershoot the data at lower x_{Bj}
- For high $P_{t,jet}$ and/or high Q^2 the NLO description improves
- NLO/LO large since forward jets in LO is suppressed by kinematics

Triple differential cross sections (H1)



$r = p^2_{t,jet}/Q^2$

r ~ 1 (BFKL-enhanced):
- Data are best described by the res. γ model and CDM

r < 1 (DGLAP-enhanced):
- CDM and the res. γ model reproduce data
- DGLAP dir. comes closer to data than in other regions

r > 1 (Resolved photon like):
- The res. γ model and CDM give good overall description of data

The CCFM model fails to reproduce the shape of the data in all bins (not shown)

'2+forward jet' selection

- Same cuts to select DIS events as before

- Require at least two reconstructed jets in addition to the forward jet

- All jets should have momenta > 6 GeV

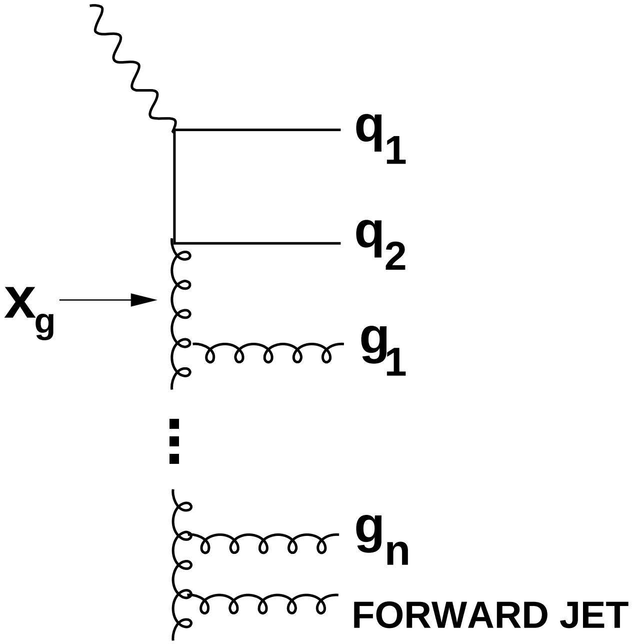
- Ordering of the jets:

$\eta_{fwdjet} > \eta_{jet2} > \eta_{jet1} > \eta_e$

- Two rapidity intervals:

$\Delta\eta_1 = \eta_{jet2} - \eta_{jet1}$

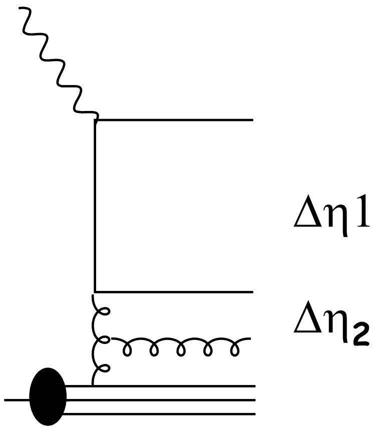
$\Delta\eta_2 = \eta_{fwdjet} - \eta_{jet2}$

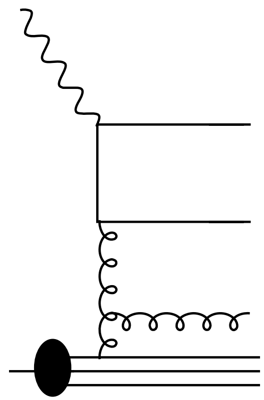


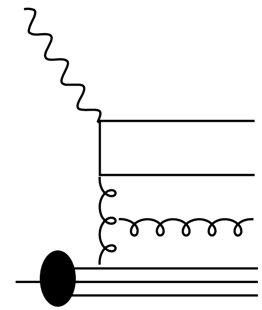
'2+forward jet' analyses

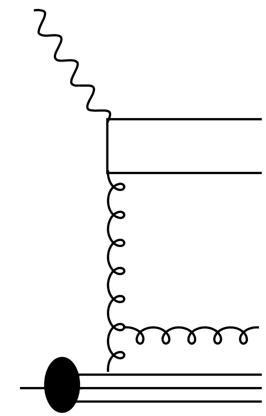
General idea:

$\Delta\eta_1>1$; $\Delta\eta_2$ small	$\Delta\eta_1>1$; $\Delta\eta_2$ large	$\Delta\eta_1<1$; $\Delta\eta_2$ small	$\Delta\eta_1<1$; $\Delta\eta_2$ large
DGLAP enhanced			BFKL enhanced

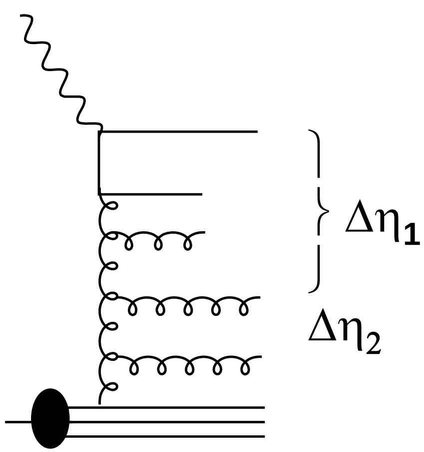


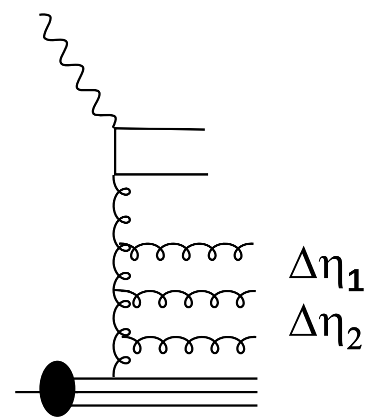




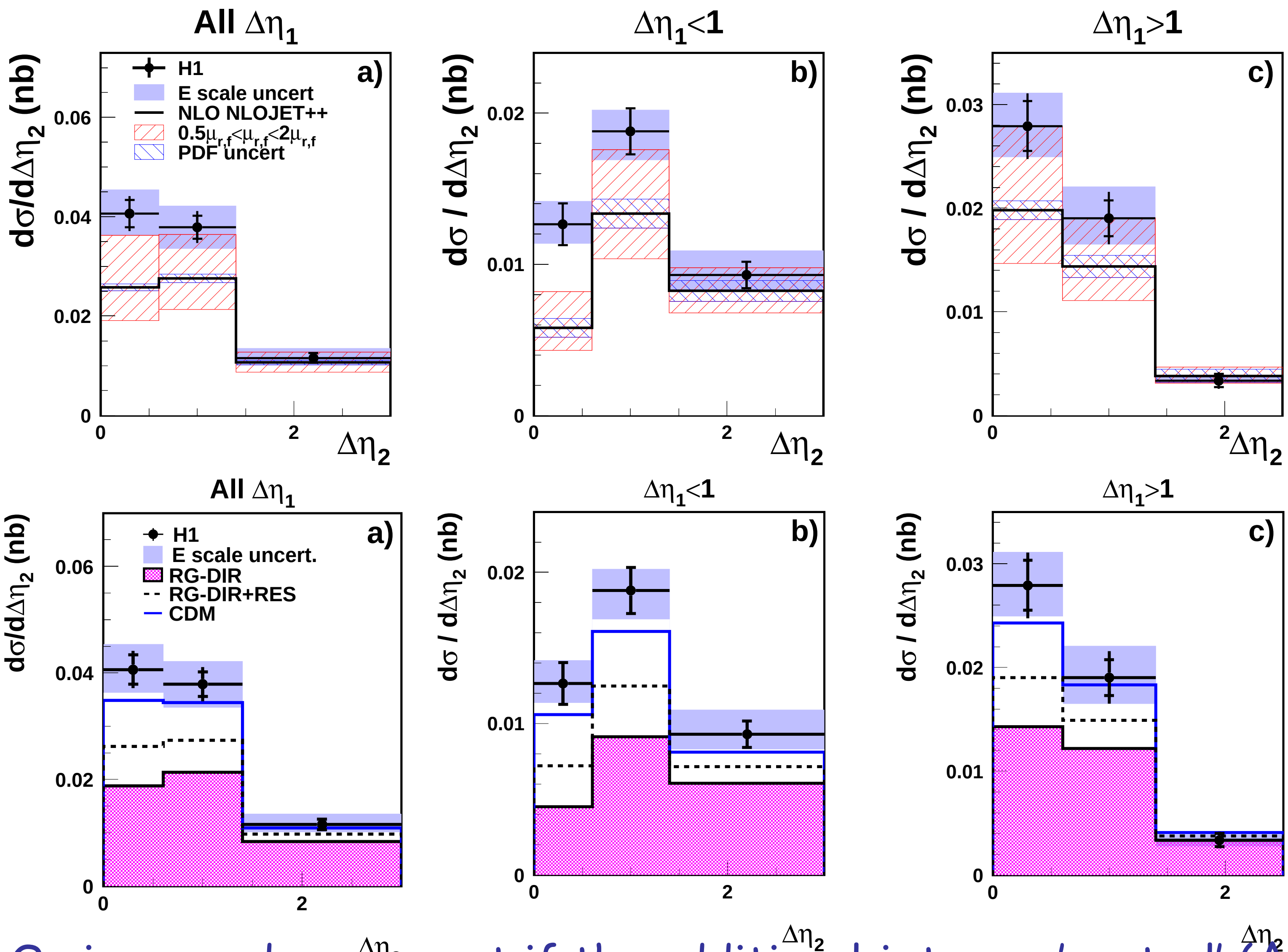


Reality: only the forward jet fixed in rapidity space
the other jets are related to the forward jet





2+forward jet final states



- NLO gives good agreement if the additional jets are 'central' ($\Delta\eta_2$large)
- CDM gives significantly better agreement than the res. γ model

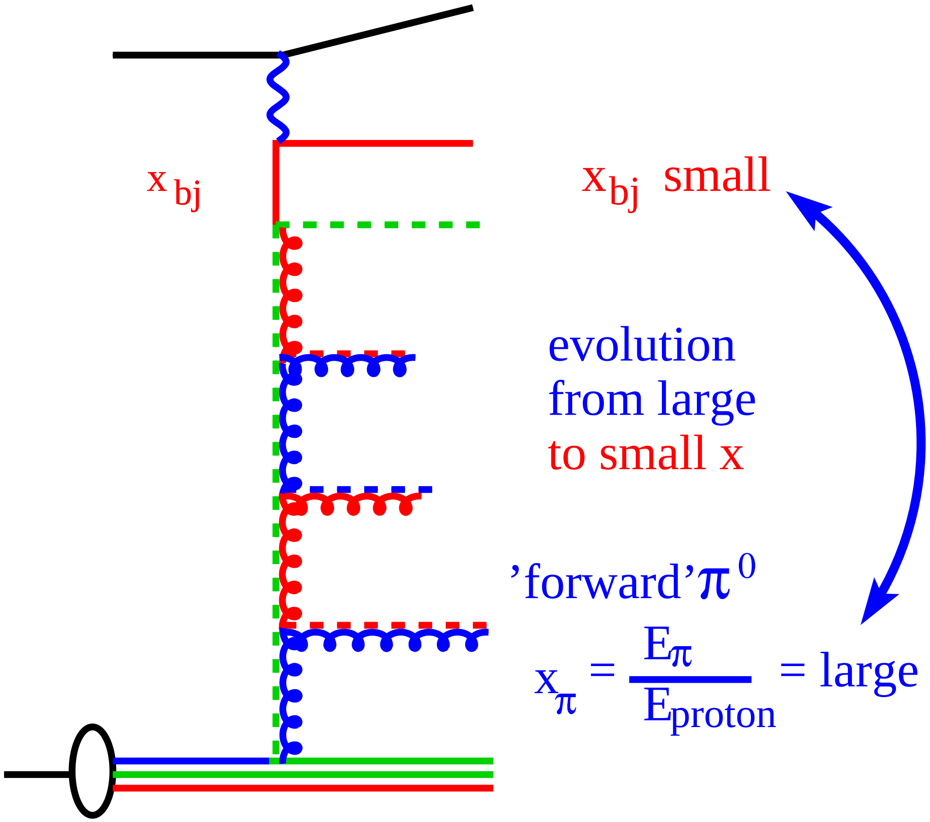
Forward pion production

Select π^0 mesons via their two-photon decay using the calorimeter

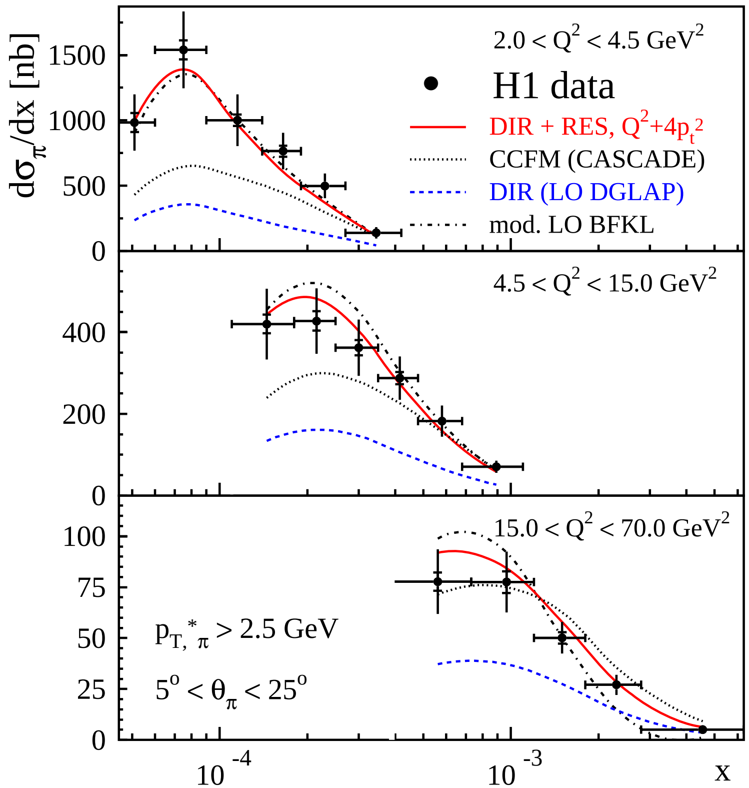
Require:
- $5^o < \Theta_\pi < 25^o$
- $x_\pi = E_\pi/E_p > 0.01$
- $p^*_{T,\pi} > 2.5$ GeV

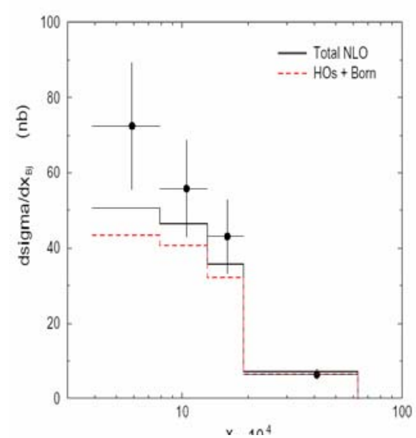
Advantage:
- Extends the forward region to smaller angles and to smaller x

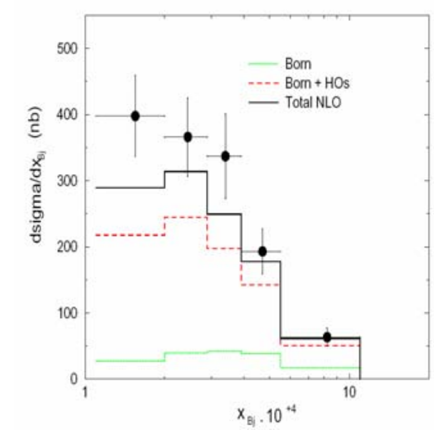
Disadvantage:
- Smaller rates compared to jets
- Fragmentation effects more significant

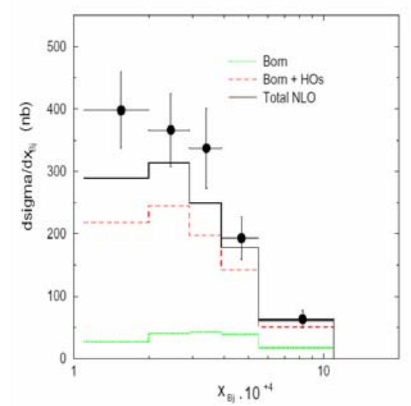


x dependence of the forward π^o cross section







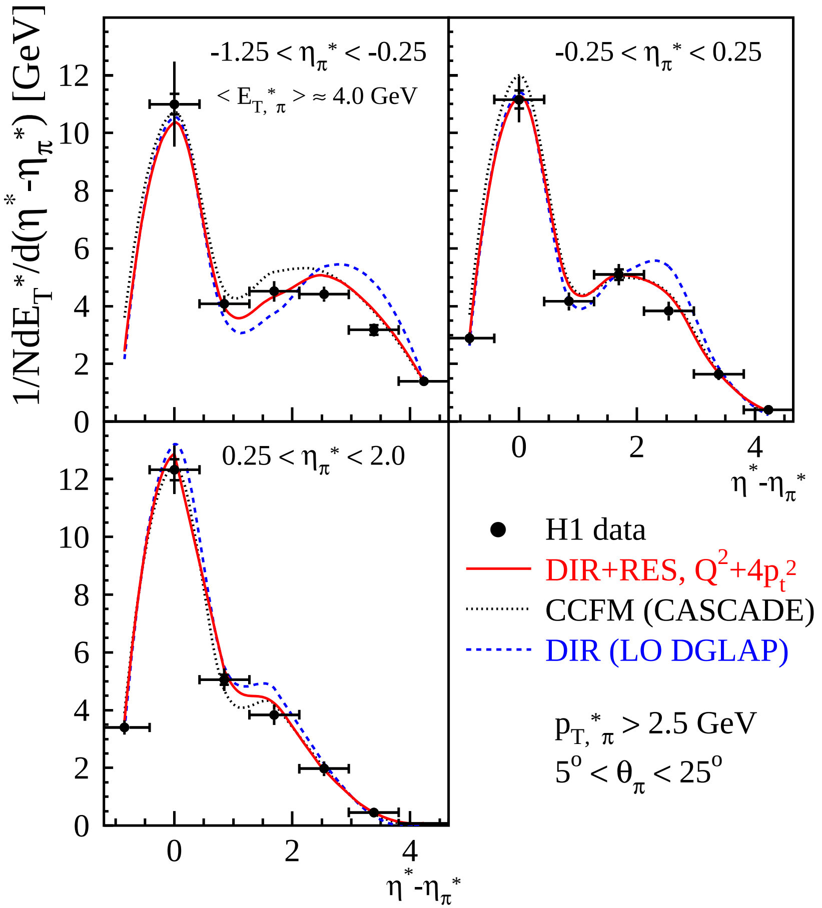


NLO calculations by Aurenche et al.

- DGLAP direct undershoots the data
- DGLAP direct + resolved gives the best description using $\mu^2 = Q^2+4p_t^2$
- LO BFKL modified by Kwiecinski, Martin Outhwait also reproduces the data
- CCFM too low at small x
- Agreement with forward jet data in the overlapping region

Transverse energy flow around forward π^o

- DGLAP direct + resolved gives the best description of the data compared to DGLAP direct and CASCADE
- The flat distribution of the data points outside the pion peak indicates that energy compensation occurs over the full phase space



Summary

- LO calculations are insufficient to describe cross sections on forward jet production
- NLO improves the agreement with data considerably but gives still too low cross sections
- The MEPS model (DGLAP direct) gives results similar to NLO
- The resolved photon model reproduces data much better in the inclusive forward jet measurement but gives some deviations especially at the smallest x values
- The CDM has a behaviour similar to that of the resolved photon model
- The CCFM model (CASCADE) gives too hard x_{Bj}-spectra (due to the parametrization of the uPDF:s or missing quark emissions?)
- More exclusive final states provide better separation of models
- The '2+forward jet' sample is much better described by the CDM than the resolved photon model
- First evidence for breaking of k_t beyond the resolved photon model