Forward Jets and Particles at HERA

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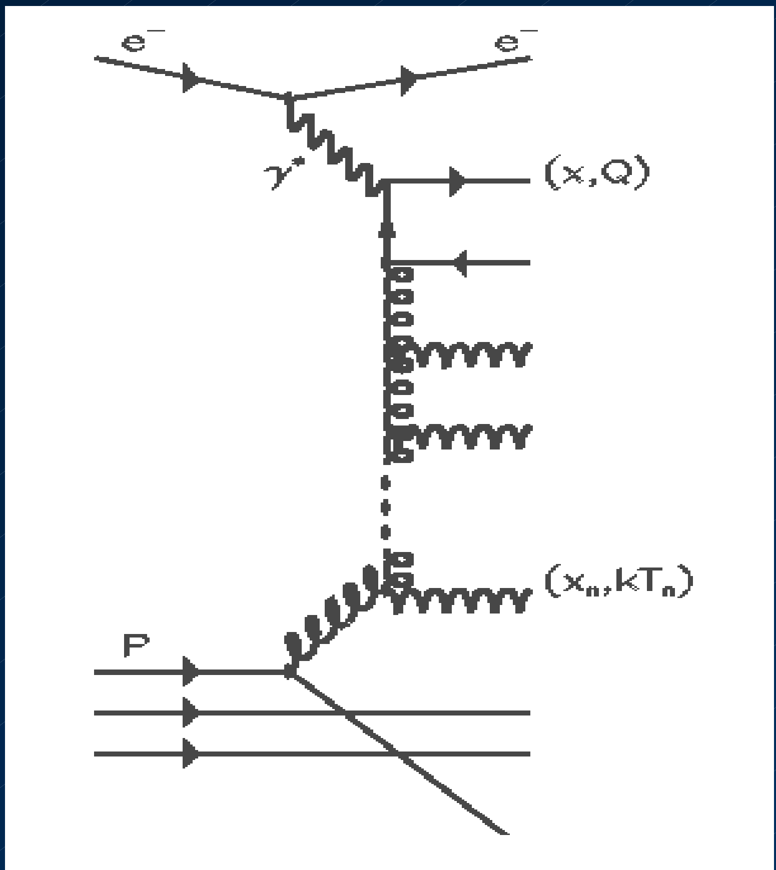
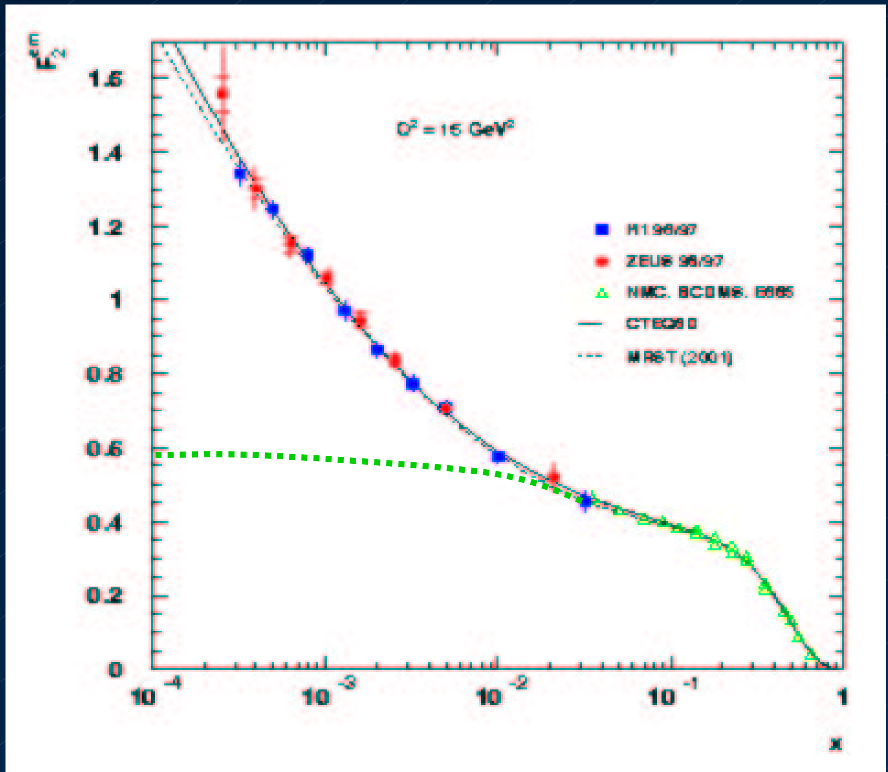


- Introduction – Low x Parton Density Evolution
- Inclusive Jets
- Forward Jets
- Forward π^0s
- Azimuthal Decorrelation of Dijets
- Summary

Proton Structure – post HERA

Steep rise of the proton structure function $F_2(x,Q^2)$ at small x



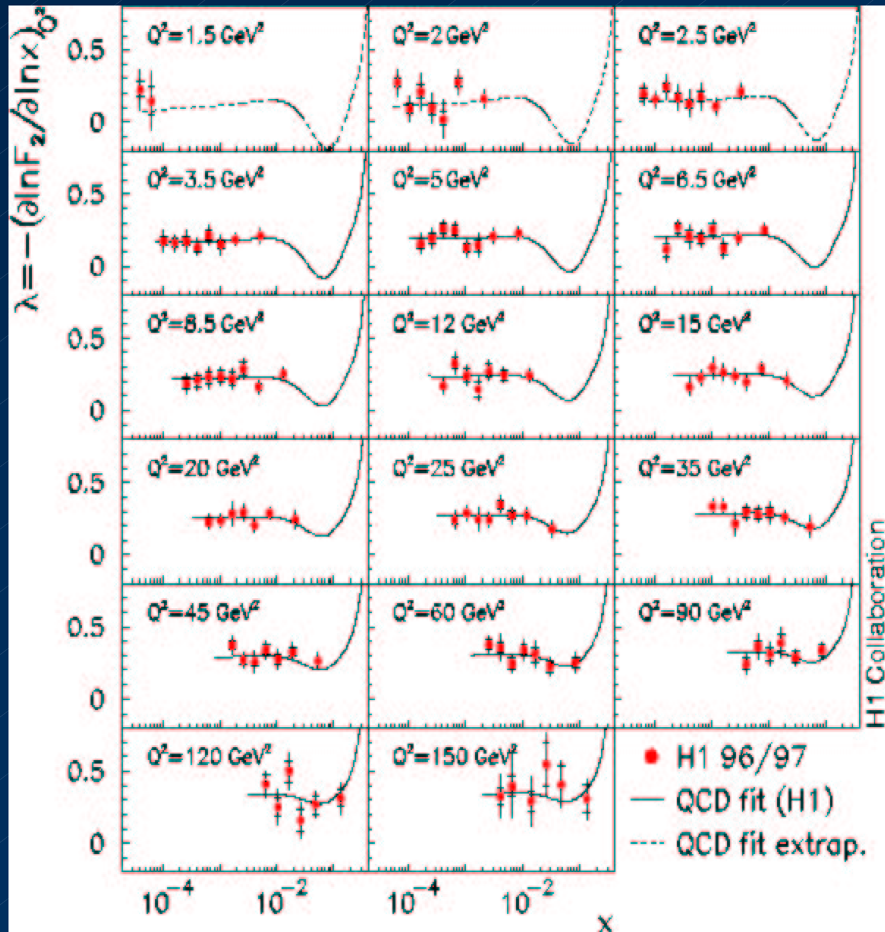
Parton evolution mechanisms

BFKL (partons evolve with 1/x) dominating at small x?

DGLAP (partons evolve with Q2) – adequately describes ALL F_2 data!

Approaching unitarity – partons fill up the proton?

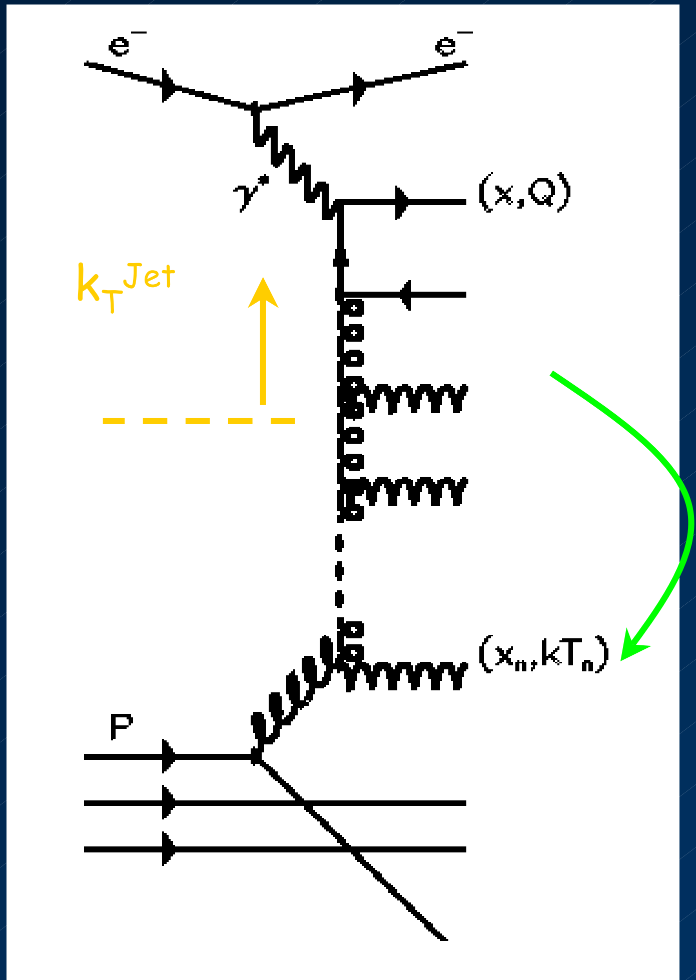
Saturation effects seen? – Not yet



Small x Evolution of Parton Densities

DGLAP

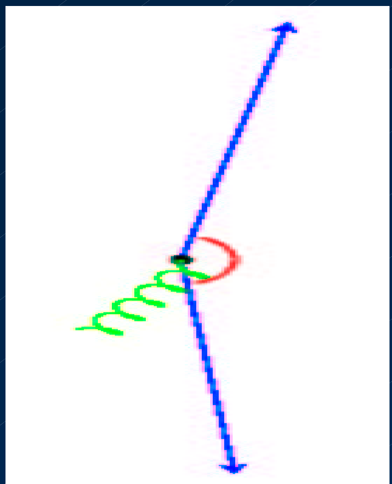
evolves with Q^2
large Q^2
$(\alpha_s \ln Q^2)^n$
angular, x, k_T ordering



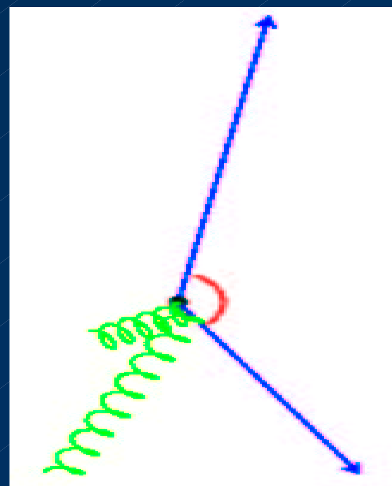
BFKL

evolves with x
small x
$(\alpha_s \ln 1/x)^n$
angular, x ordering
<u>No k_T ordering</u>

$k_{Tn} \sim Q \rightarrow$ no Q^2
evolution on the ladder
$\therefore \sigma_{DGLAP} \sim 0$ for
$x_n \gg x \rightarrow$ large $\ln x_n/x$

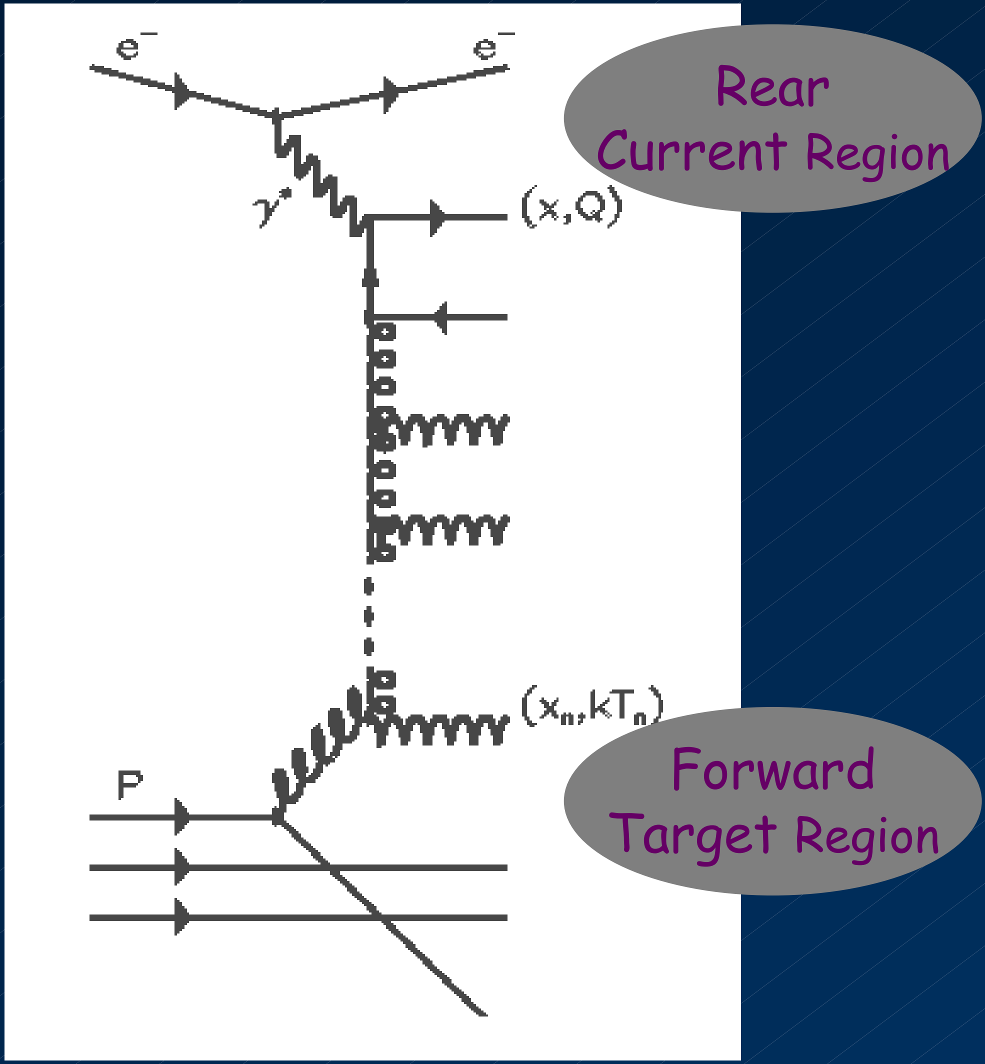


~180 degrees
since k_T^{gluon} small



< 180 degrees -
Azimuthal decorrelation

Why Study Forward Jets and Particles?



With forward jets and particles :

- Study physics of the target region in the proton
- Investigate parton densities and evolution mechanisms at small x
- Search for local density fluctuations where saturation effects begin :

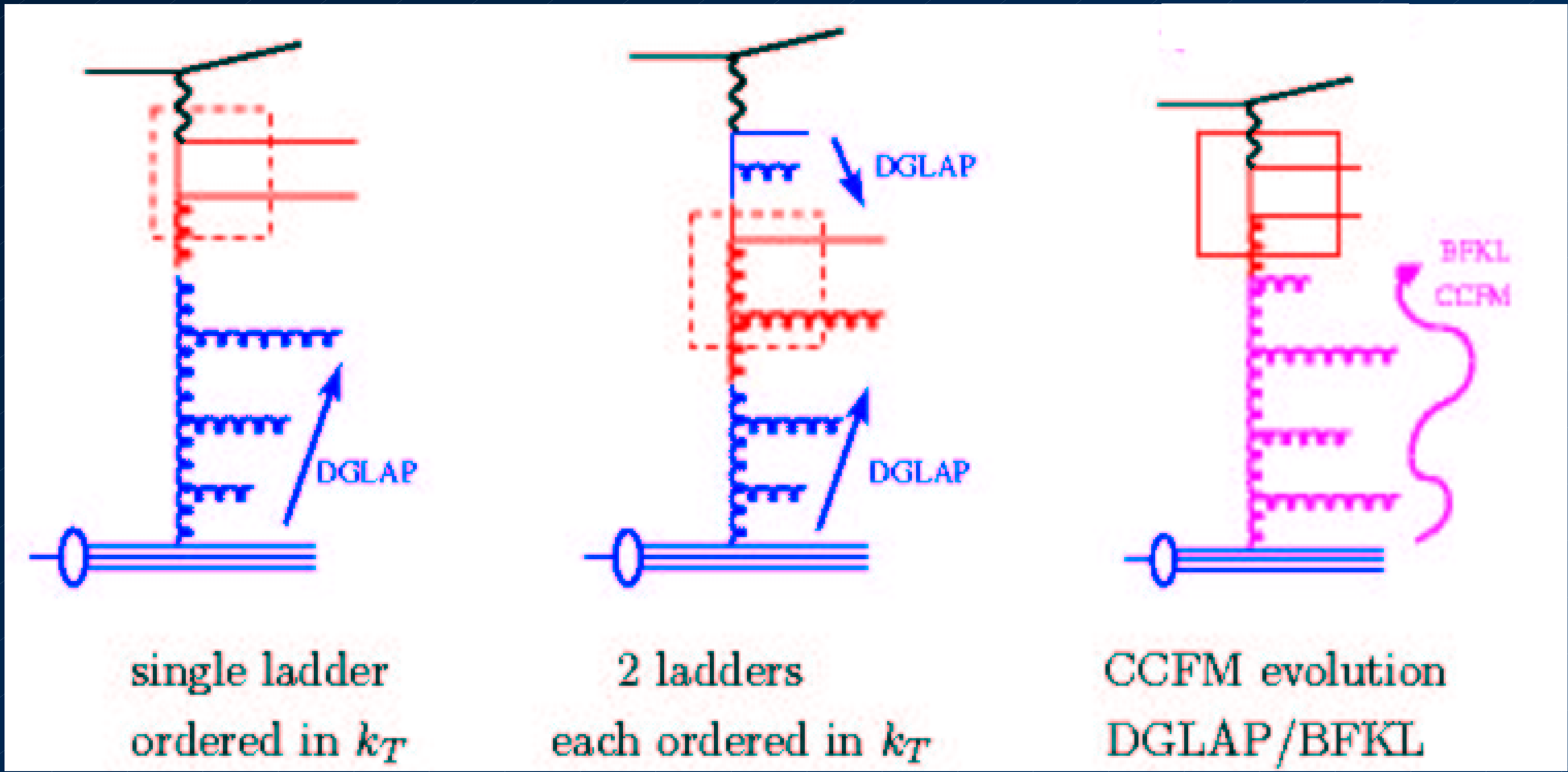
  Approach to saturation might start in small, local regions of the proton – "hot spots" (A. Mueller)
  -> Future analyses

Implementation of Evolution Schemes

DGLAP PS Models
- MEPS (LEPTO)
- HERWIG
- RAPGAP (DIR)

RAPGAP (RES)

BFKL-like Models
- CDM (ARIADNE)
- CCFM (CASCADE)



$E_T < Q$ $E_T > Q$ $E_T \sim Q$

Fixed-Order QCD Calculations

DGLAP NLO QCD
- MEPJET
- DISENT
- NLOJET

Order α_s^2 calculations including DGLAP evolution of parton density functions

Includes ability to apply jet algorithms

BFKL
- LO BFKL
- Mod. LO BFKL

LO tree-level diagrams only with no higher order corrections

No jet algorithm

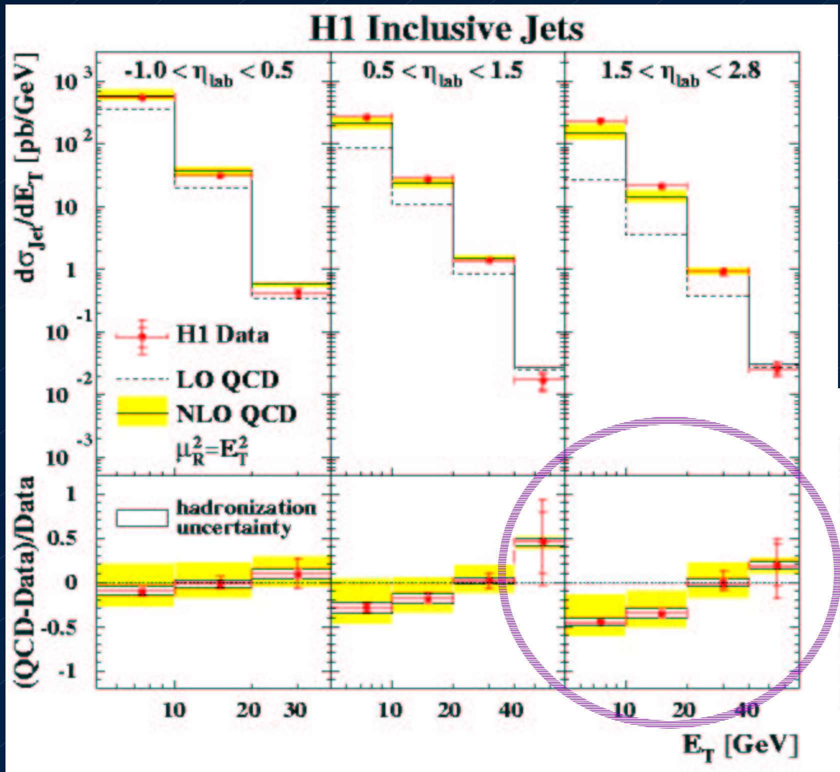
Kwiecinski, Martin, Outhwaite – hep-ph/9903439

Gluon emissions are modified by "consistency constraint" – requires k_T of emitted parton to be limited by the transverse momentum of its corresponding ladder gluon

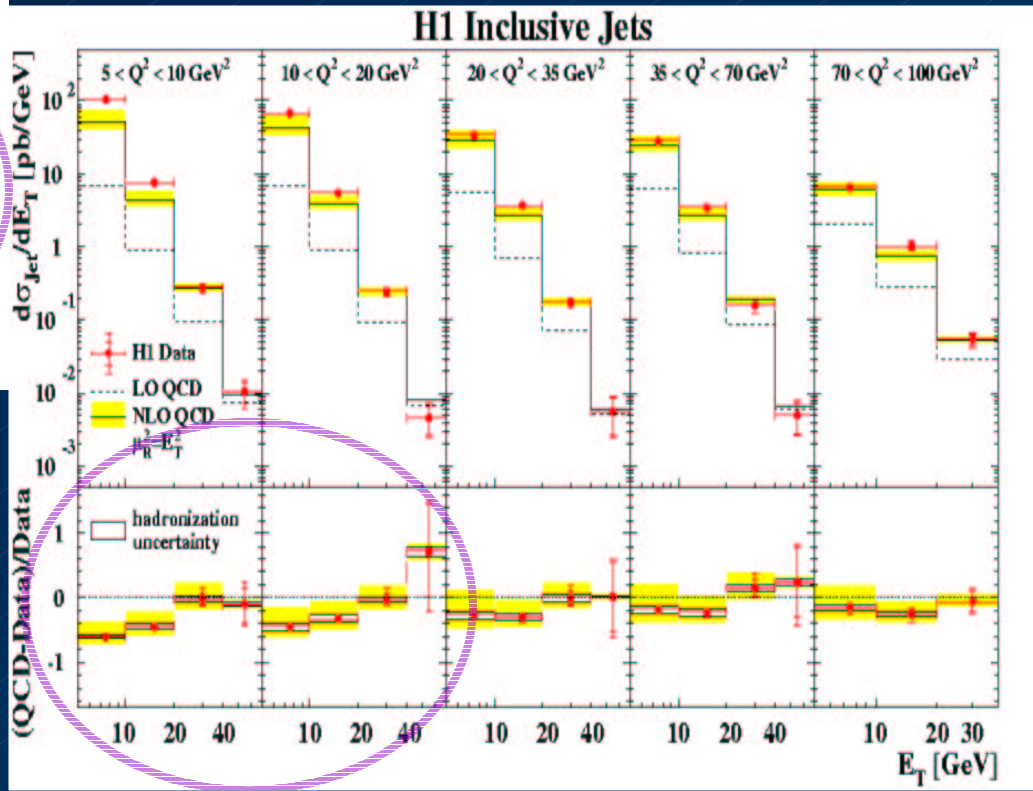
Major parts of the non-leading BFKL equation are included

Normalization is sensitive to infrared cut-off and scale of αs

HERA Data - Inclusive Jets in DIS vs NLO QCD

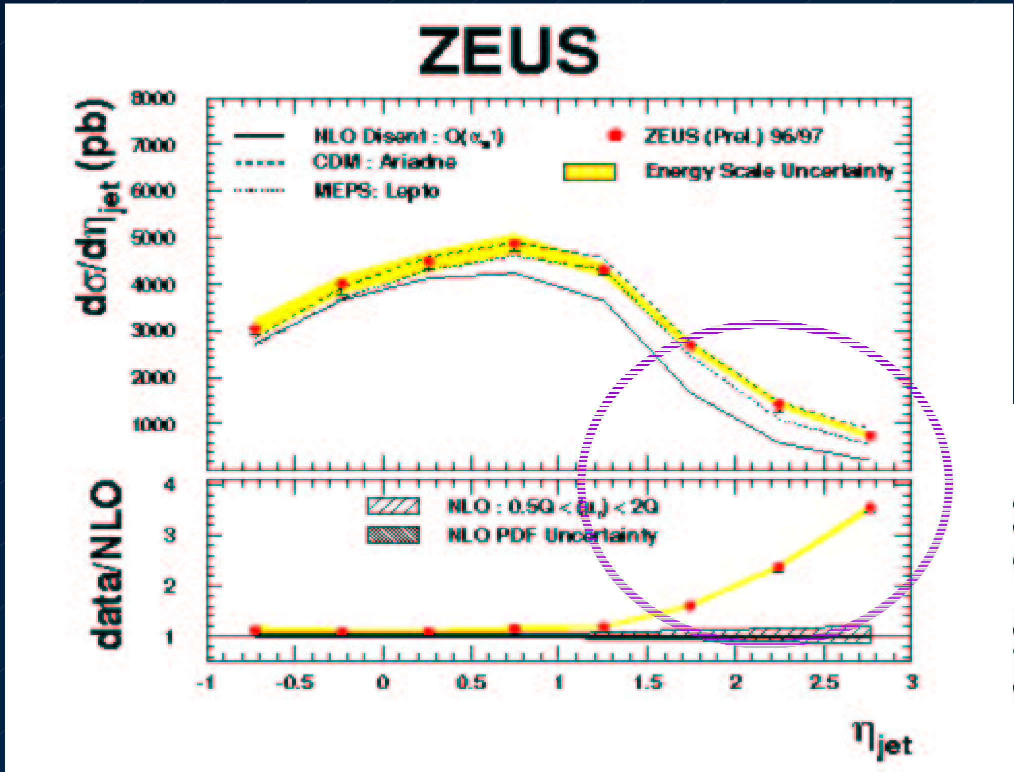


Jet data compared to fixed-order (NLO QCD) calculation with DGLAP evolution

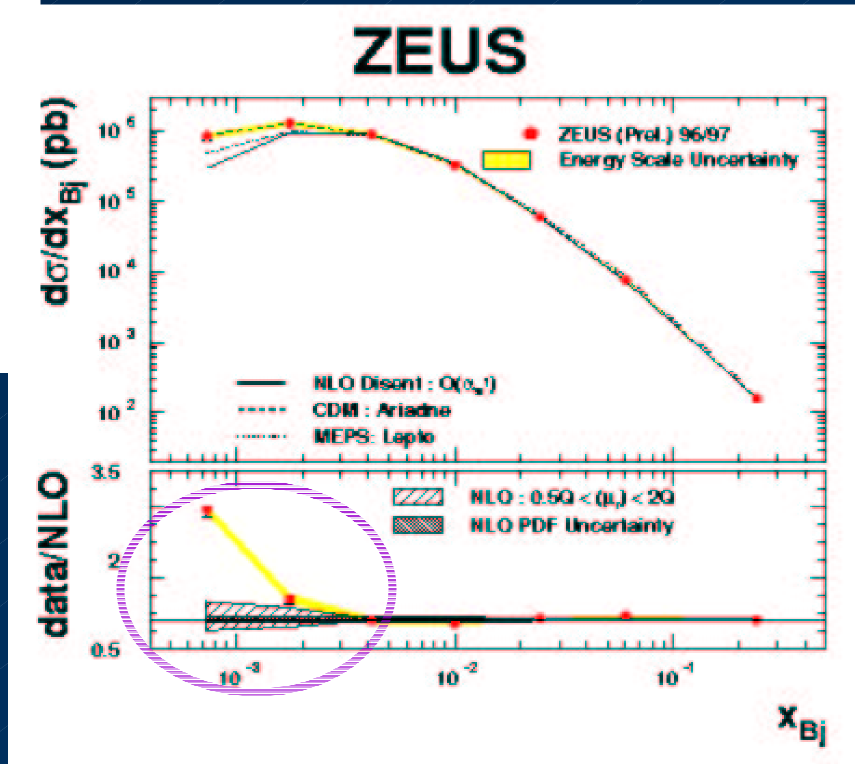


NLO QCD with DGLAP unable to describe data in forward region, at low Q2 and low ET

Inclusive Jets in DIS - MC Models

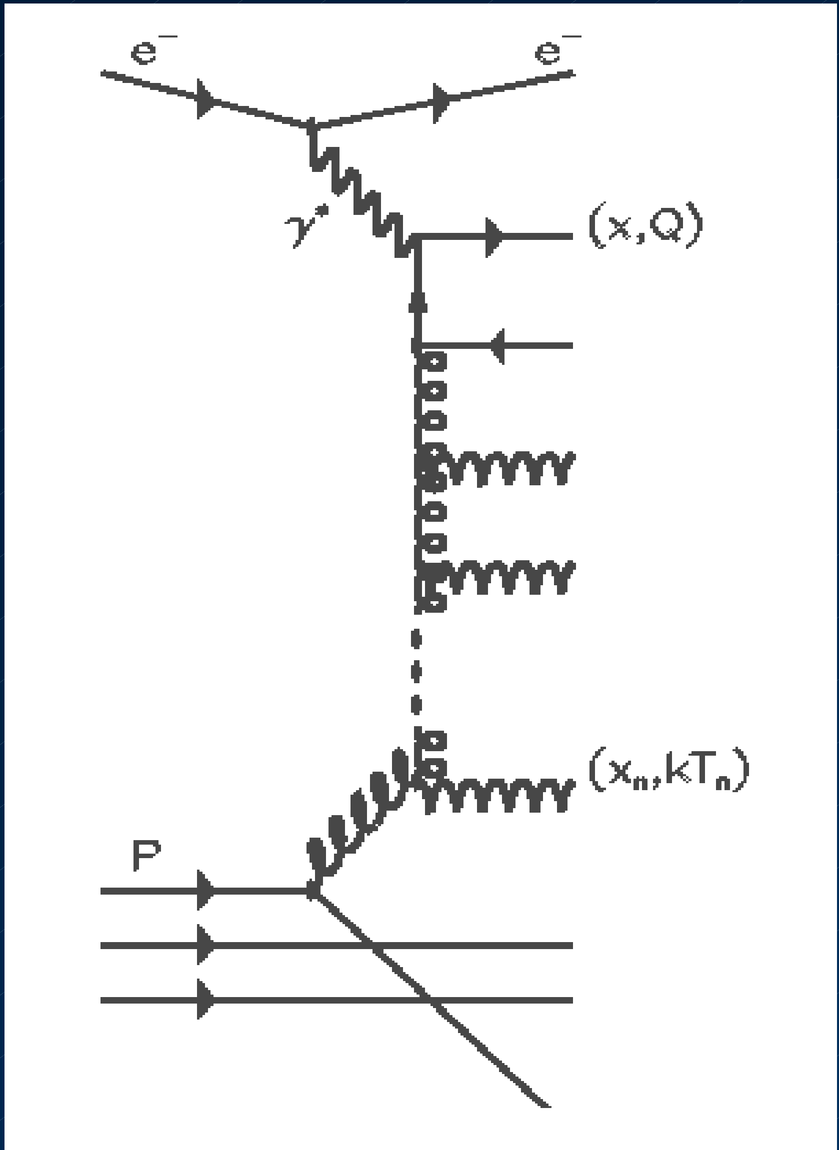


Low x behavior not described well by DGLAP approach - fixed-order (NLO QCD) or parton shower model



-> Clear excess of data over fixed-order calculation (NLO QCD) in the forward region (high η)
-> Good agreement with CDM
-> Not good agreement with DGLAP

Forward Jets at HERA



Select events with jets in forward region :

-> All target region jets in Breit Frame analysis

-> Jets with minimum η cut in Lab Frame

DIS kinematics :

x - as small as possible, 10^{-3} -> 10^{-4}

Q^2 - ~ 10 GeV^2 and higher

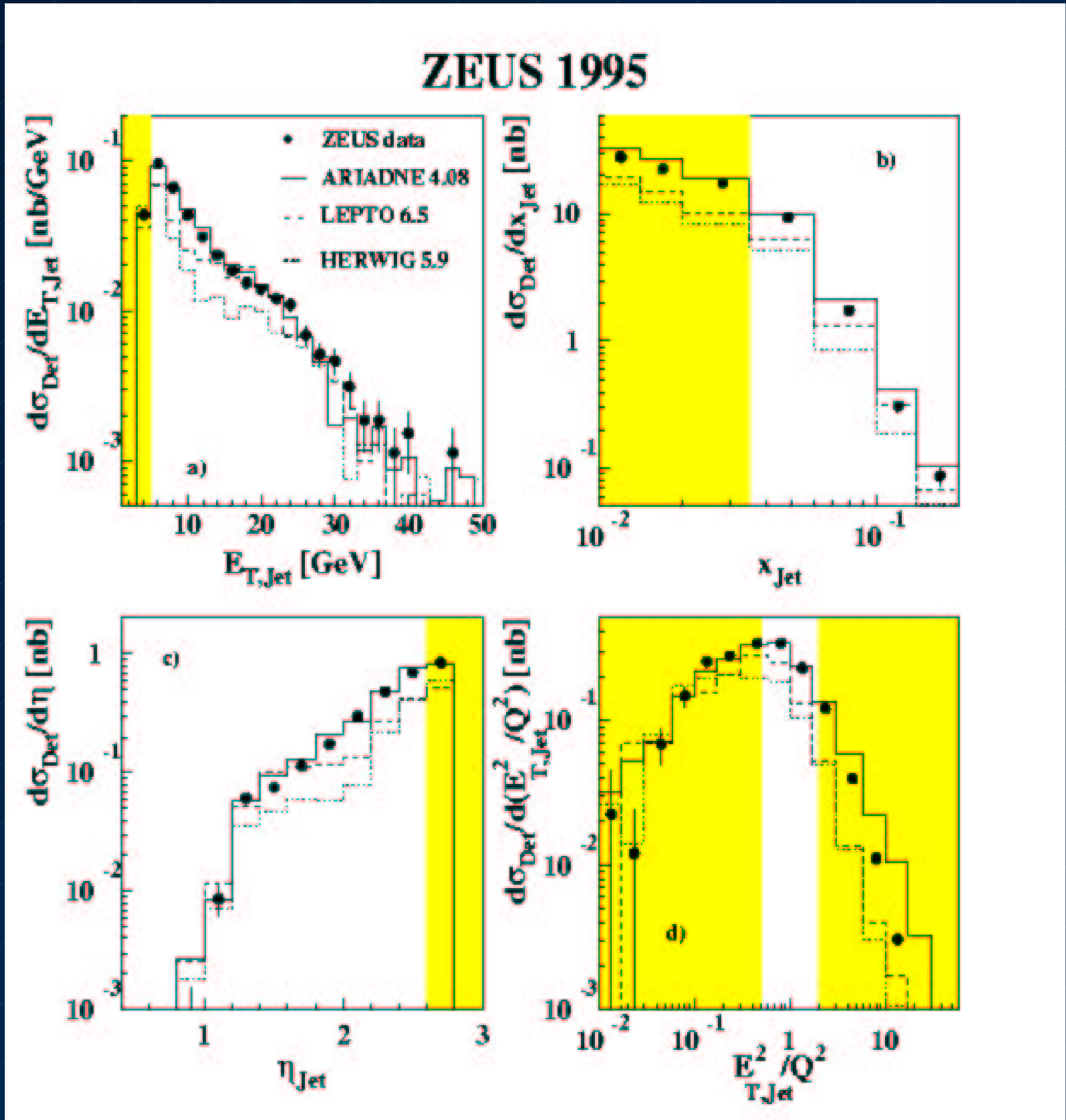
Jets - k_T or cone algorithm :

x_{jet} – as large as possible (~.025 -> .1)

x_{jet}/x is therefore large, ~100

k_T^{jet} ~ Q – suppresses DGLAP contribution

Forward Jet Properties

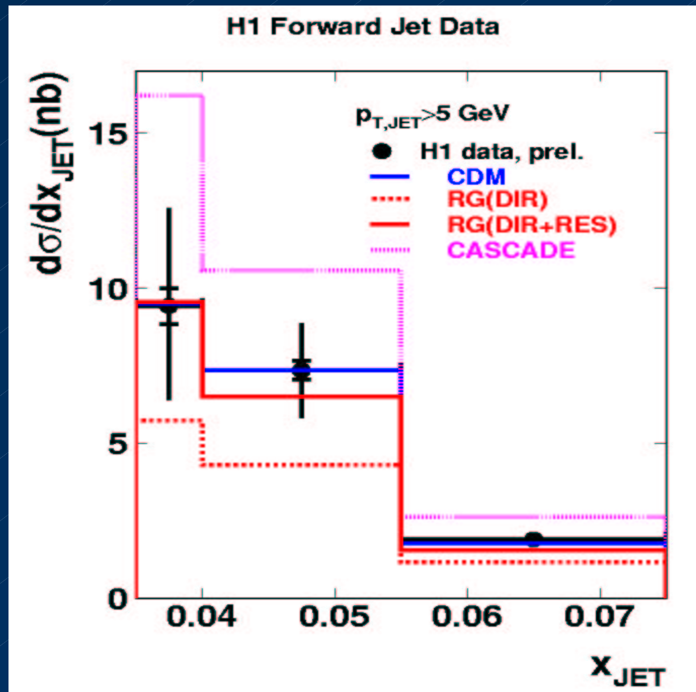


BFKL-like Models

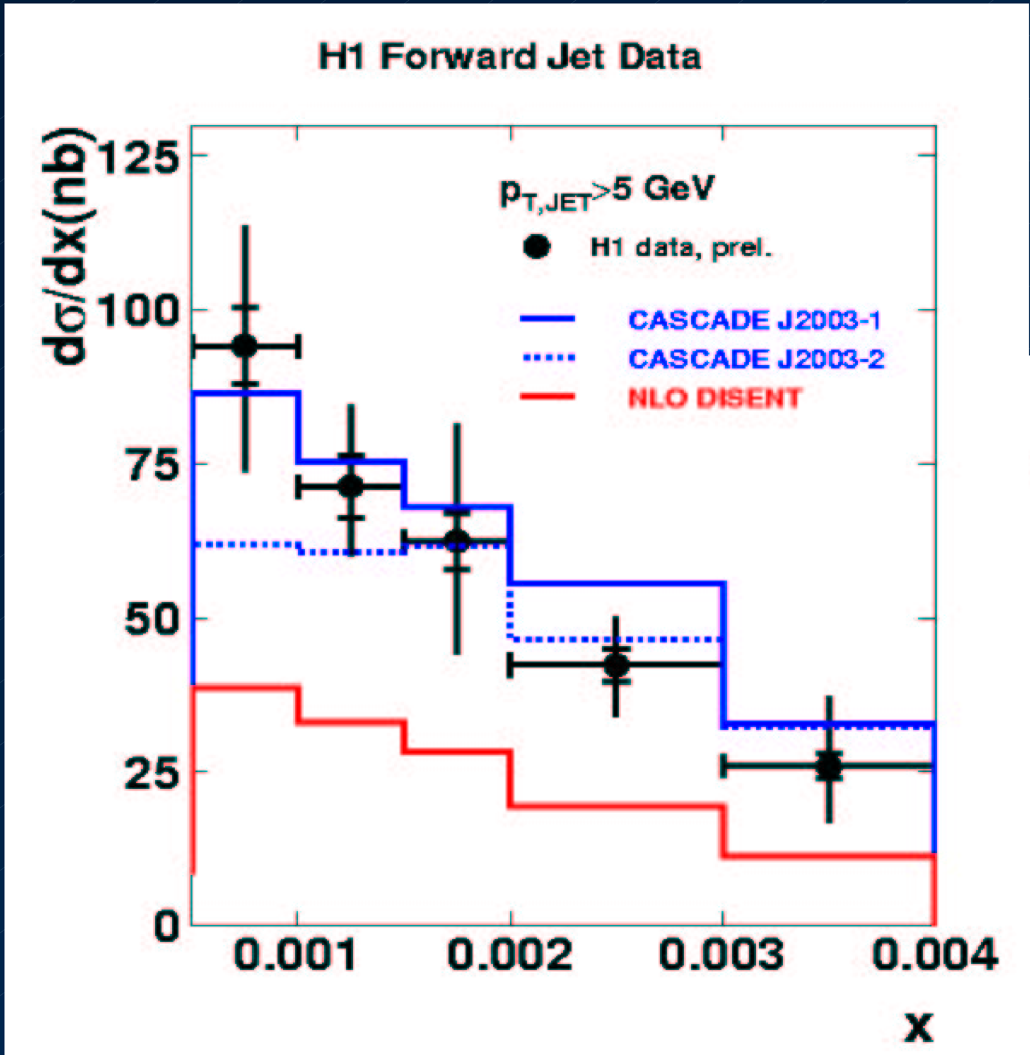
- CDM (ARIADNE) ✓
- CCFM (CASCADE) ✗

DGLAP PS Models

- LEPTO ✗
- HERWIG ✗
- RAPGAP (DIR) ✗
- RAPGAP (DIR+RES) ✓



Forward Jet Cross Sections I

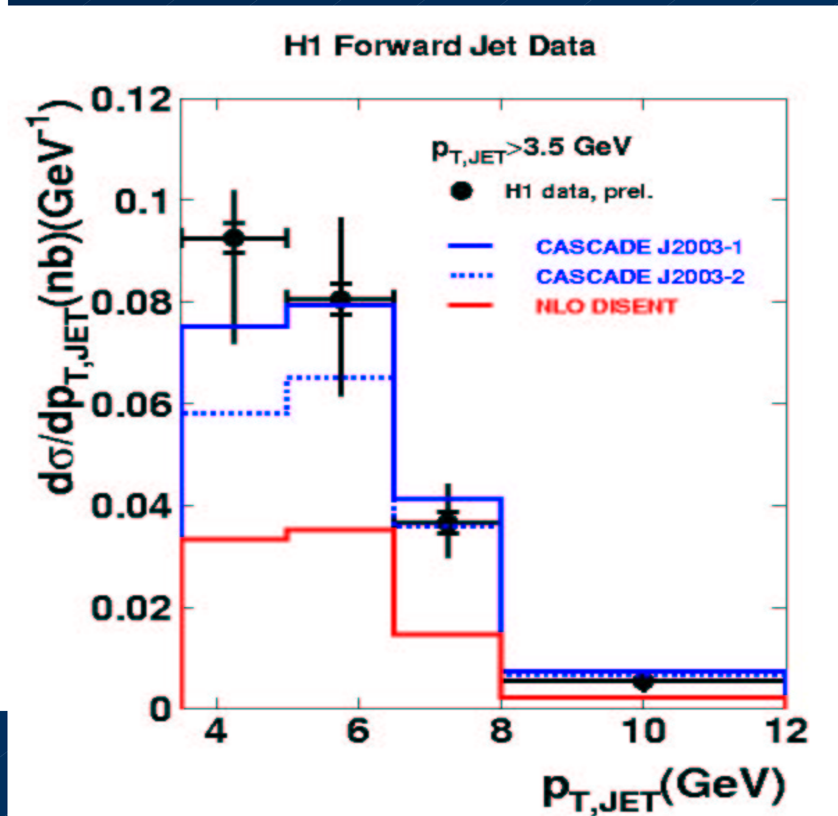


BFKL-like Models

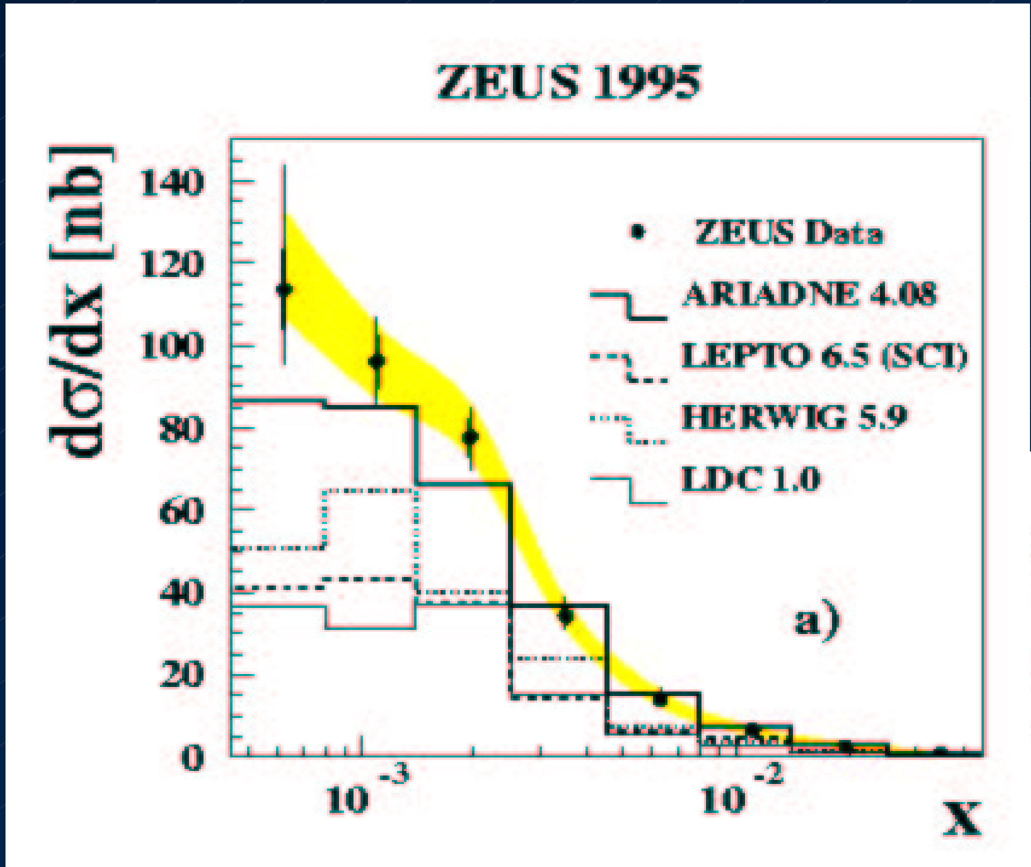
- CCFM (CASCADE-1) ✓
- CCFM (CASCADE-2) ✓-

DGLAP NLO QCD

- DISENT ✗



Forward Jet Cross Sections II

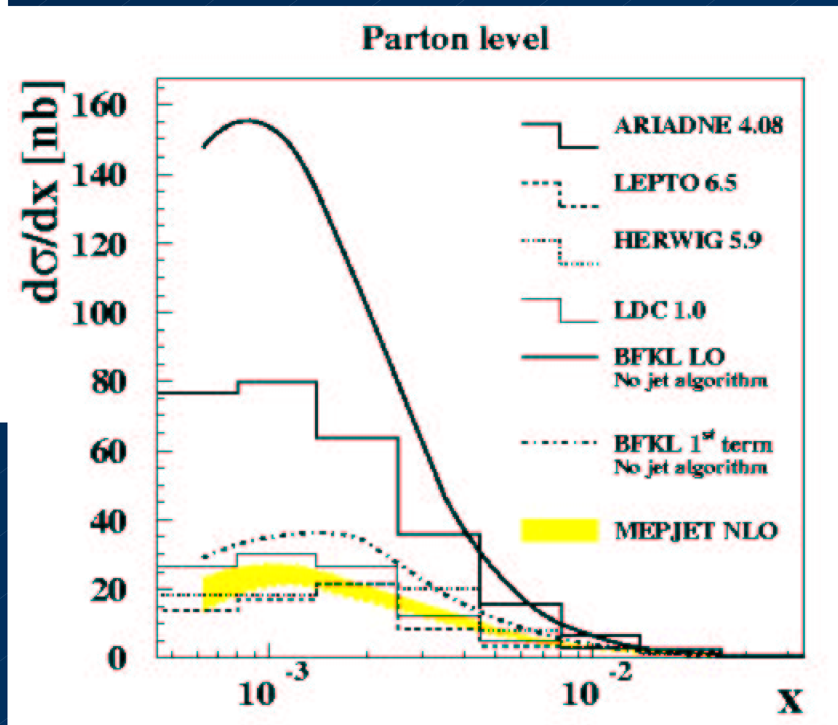


BFKL-like Models

- CDM (ARIADNE) ✓-

DGLAP PS Models

- LEPTO ×
- HERWIG ×
- LDC ×



DGLAP NLO QCD

- MEPJET ×

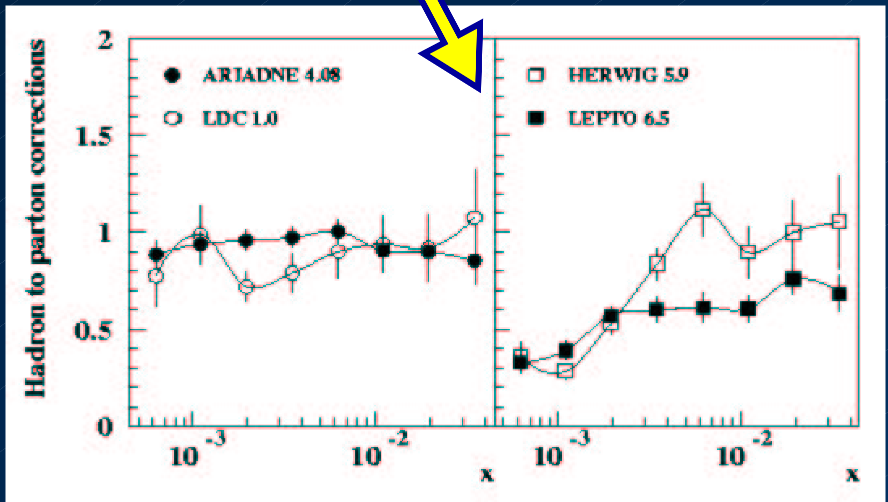
BFKL

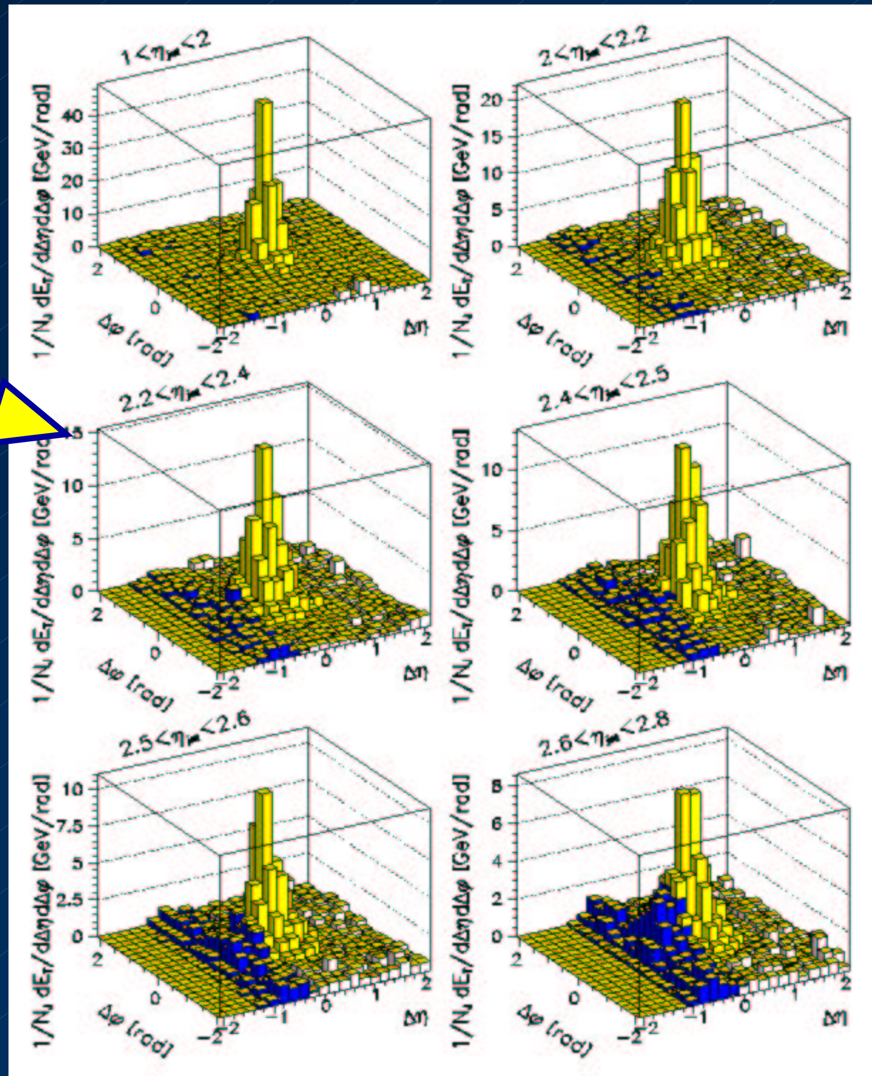
- BFKL LO ×

Forward Jets -> Forward Particles?

Experimental challenges :

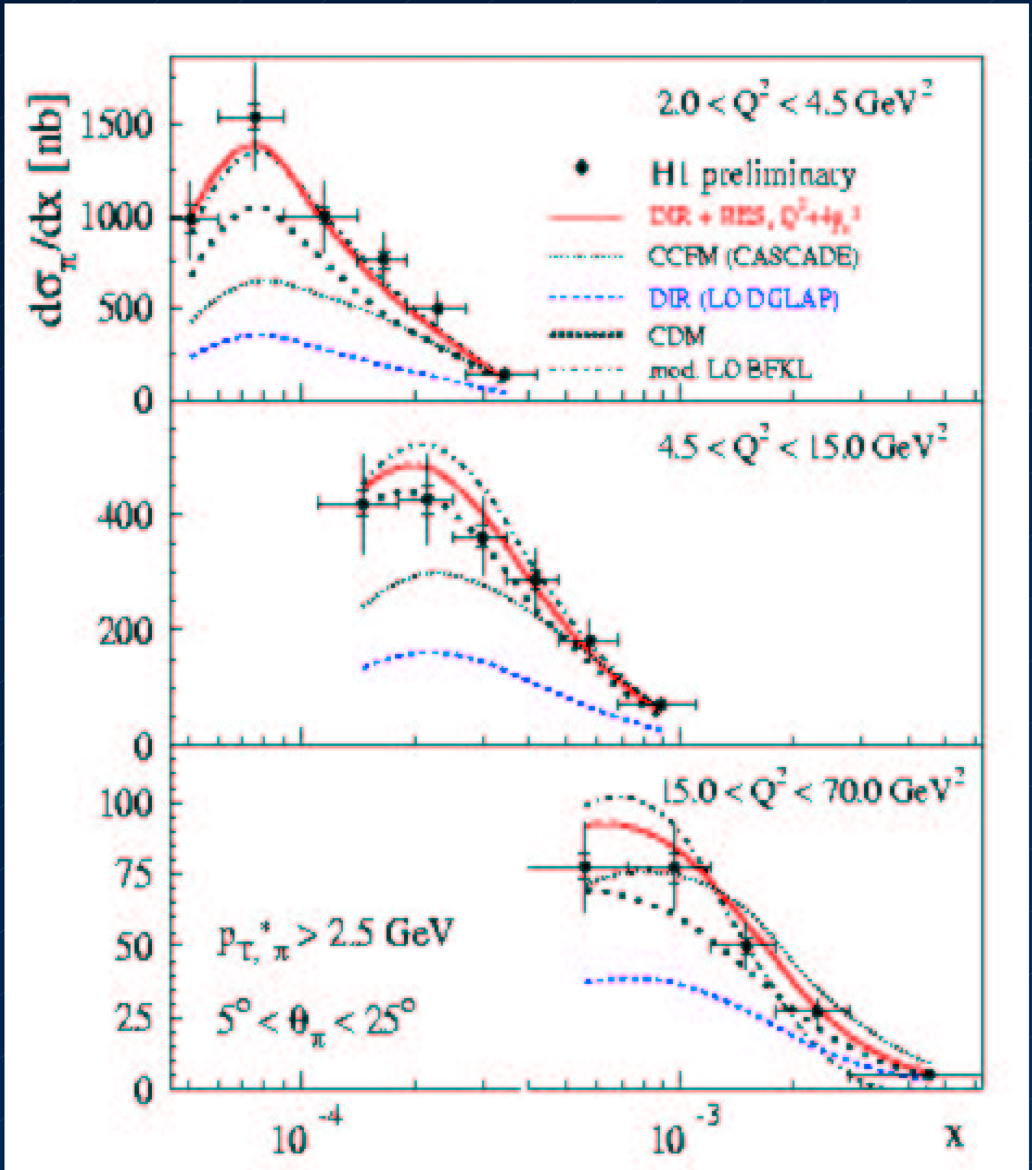
- Clean separation of jet from rest of proton remnant
- Model-dependent hadronization at small x





Try high p_T forward particles ->

Forward π^0 Cross Sections



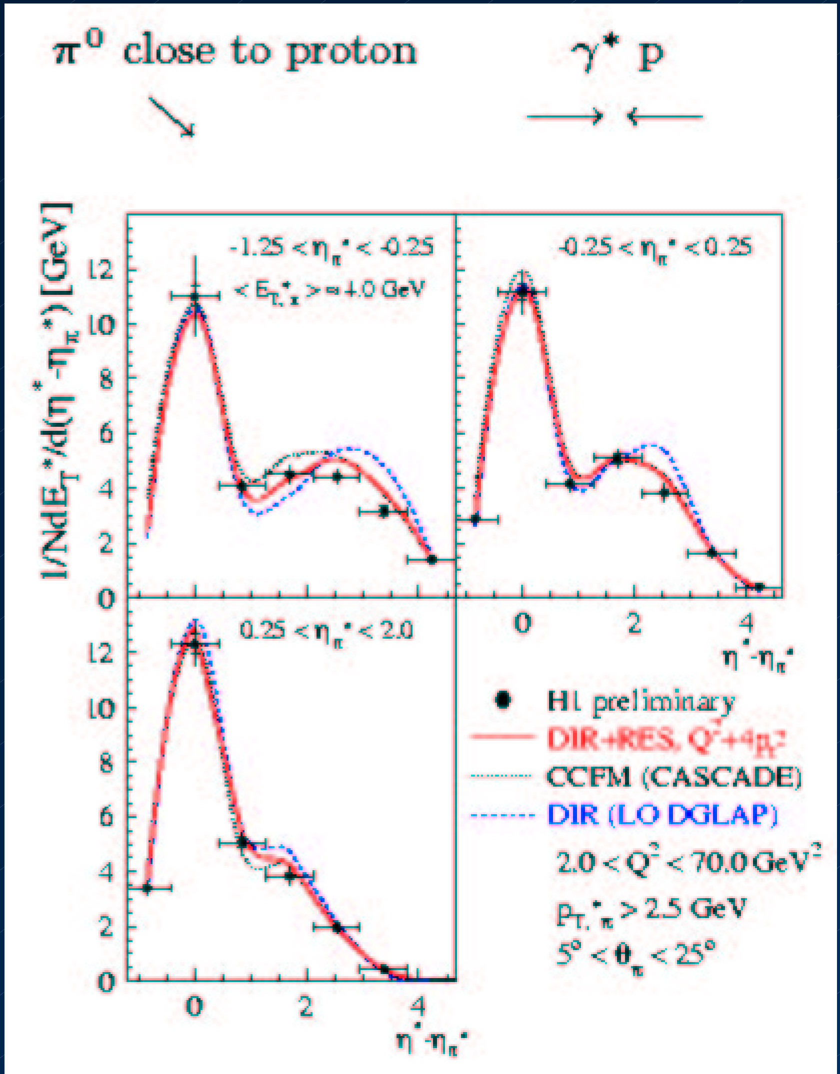
BFKL-like Models
- CDM (ARIADNE) ✓
- CCFM (CASCADE) ×+

DGLAP PS Models
- RAPGAP (DIR) ×
- RAPGAP (DIR+RES) ✓

BFKL
- Mod. LO BFKL ✓

CCFM OK where tuned to jet data

Transverse Energy Flow around Forward π^0s



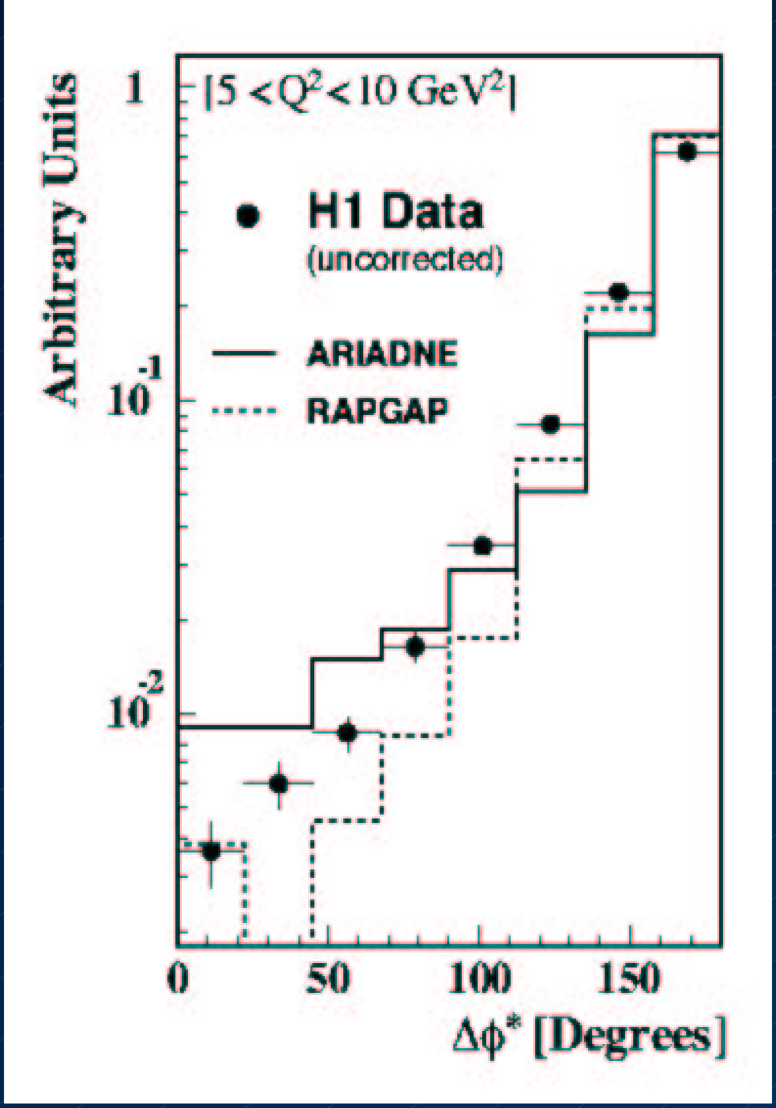
Transverse energy flow is highly collimated around the π^0

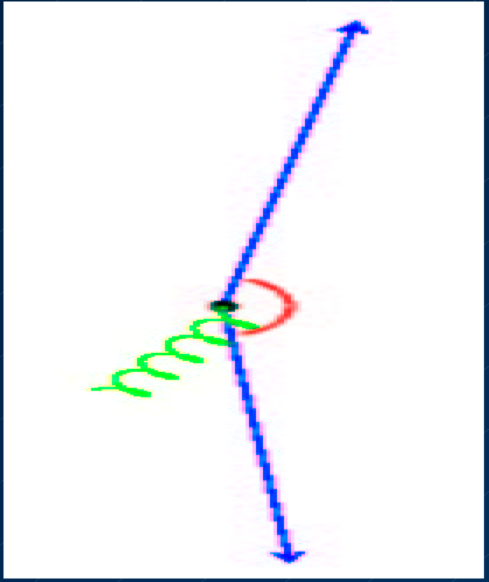
Most forward π^0s – top left plot (HCM)

Data around the π^0 is described best by CCFM or RAPGAP with resolved virtual photon

The transverse momentum of the forward π^0s is compensated near the particle, not far away as predicted by (and expected for) the DGLAP model RAPGAP with direct virtual photon only

Azimuthal Decorrelation of Dijets



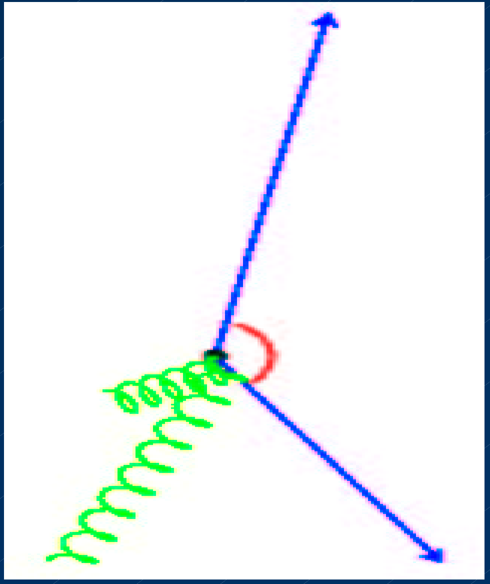


DGLAP Picture

Small k_T forward gluon barely perturbs dijets -> almost back-to-back

BFKL Picture

Large k_T forward gluon(s) force dijets to recoil -> $\Delta\Phi < 180^o$



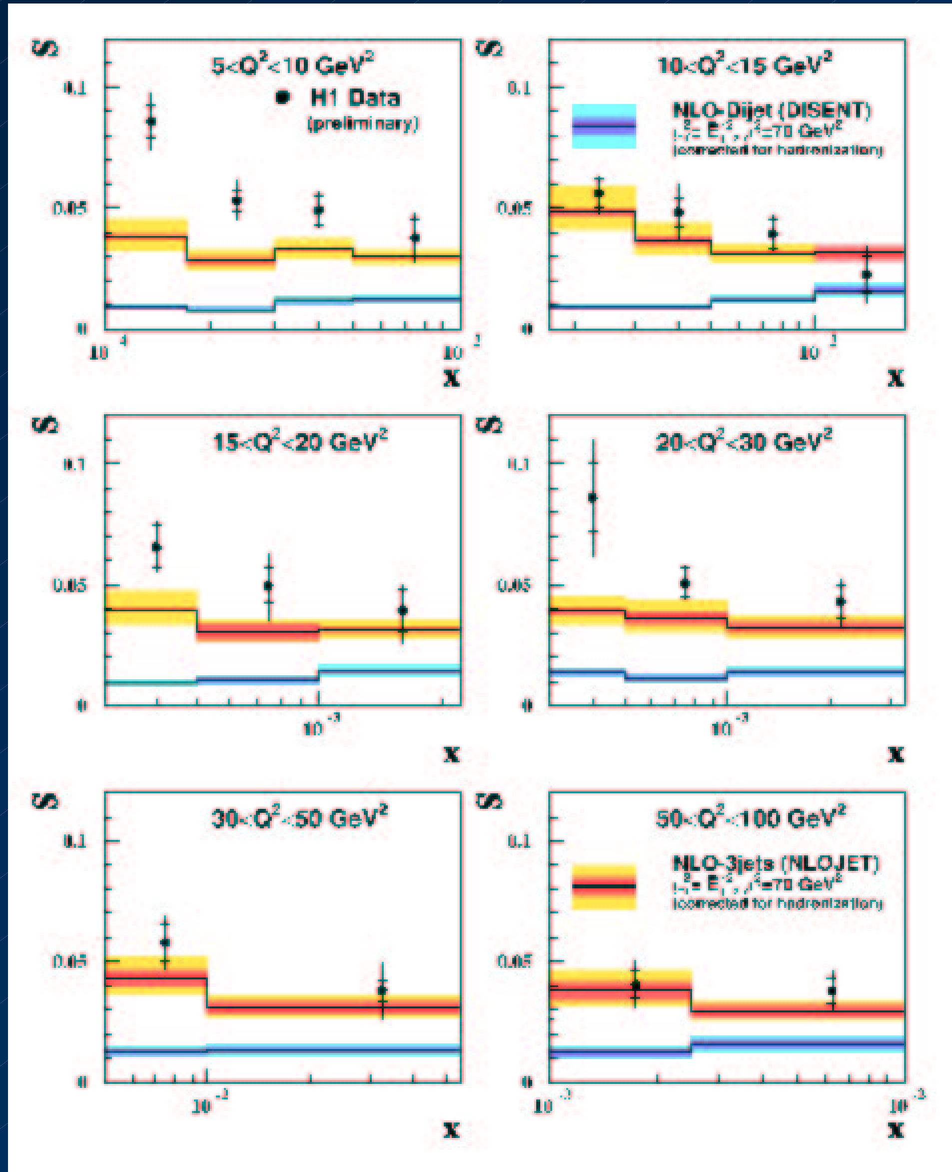
Study of $\Delta\Phi$ tails - S Ratio

Compare tails to peak using the ratio :

$$S = \frac{\int_0^\alpha N_{2-\mathrm{jet}}(\Delta\phi^*, x, Q^2)\mathrm{d}\Delta\phi^*}{\int_0^\pi N_{2-\mathrm{jet}}(\Delta\phi^*, x, Q^2)\mathrm{d}\Delta\phi^*}, \quad 0 < \alpha < \pi$$

$\Delta\phi^*$ = azimuthal angle between two hardest E_T jets

$\alpha = 2/3\ \pi$



DGLAP NLO QCD

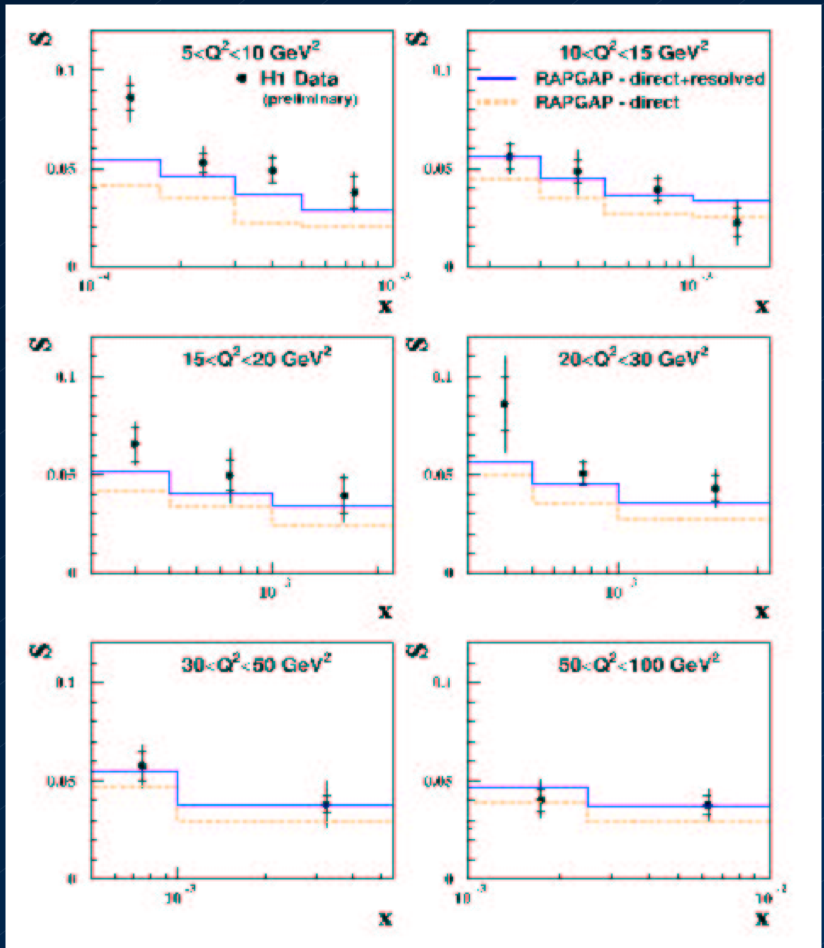
DISENT (2-jet) ×

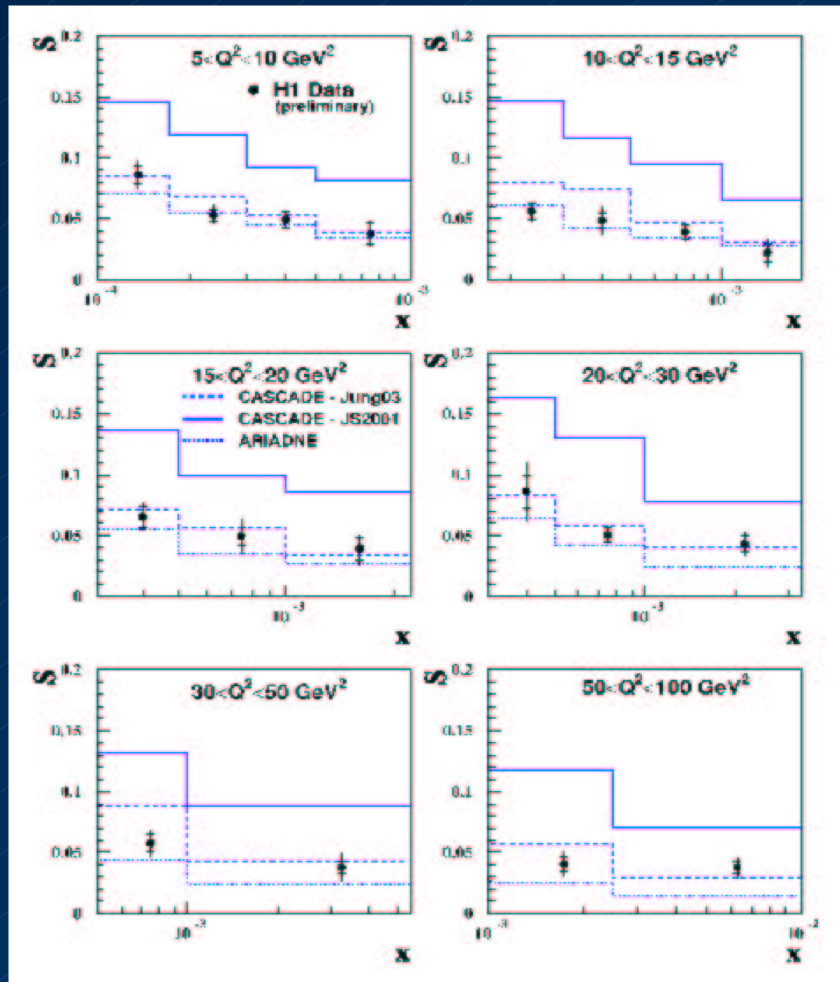
NLOJET (3-jet) ×

S Ratio vs x – MC Models

BFKL-like Models

- CDM (ARIADNE) ✓
- CCFM (CASCADE*) ✓
- CCFM (CASCADE) ✗

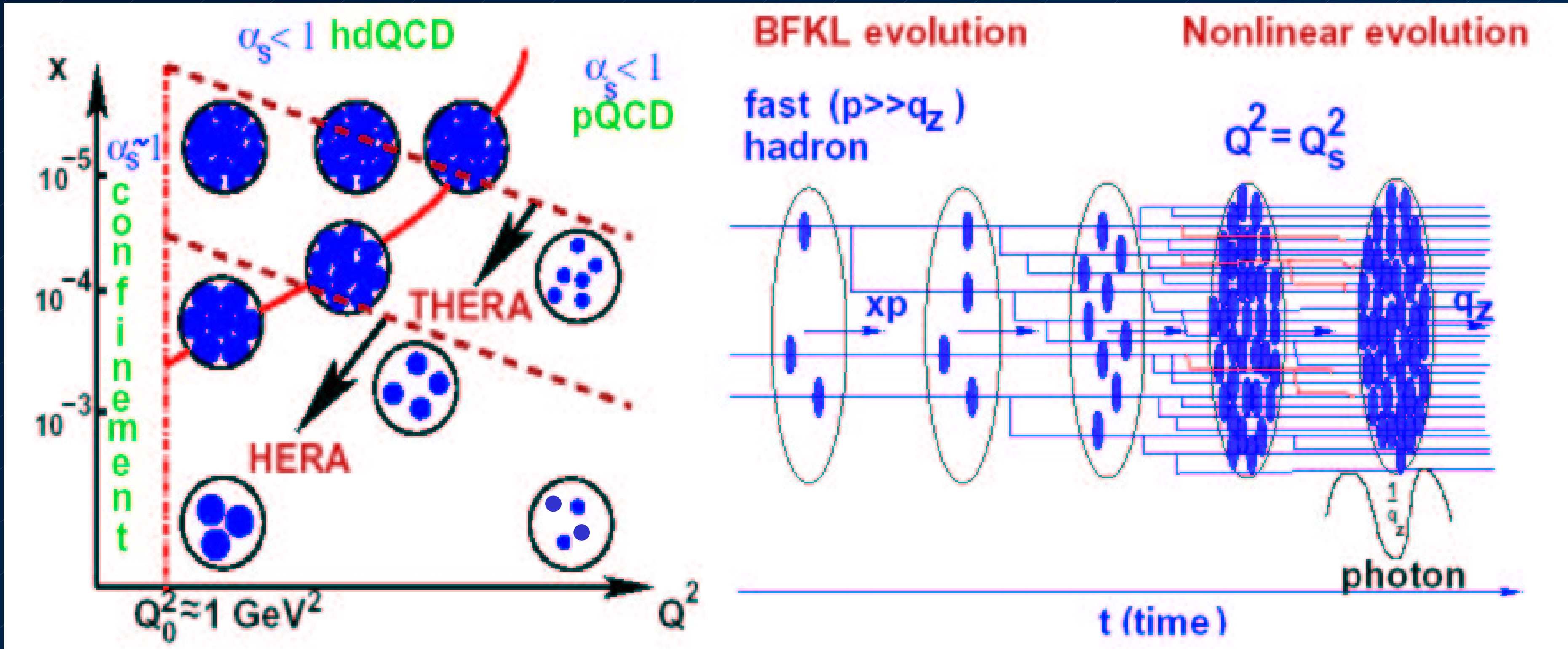




DGLAP PS Models

- RAPGAP (DIR) ✗
- RAPGAP (DIR+RES) ✓ –

Saturation of partons – Nonlinear evolution



1. The number of partons increases with time (emission ∝ density).
   Note that transverse size (∝ 1/Q) of the partons is constant (BFKL case).
2. The number increases until partons cover the surface of the (flat) proton.
3. Overlapping (low x) partons can recombine into a high x parton (∝ density^2).
4. The tradeoff between emission and recombination produces saturation in the parton evolution.

Hot Spots – Approach to Saturation

Very difficult to reach saturation region at HERA

But, suppose saturation begins in small local regions in the proton first, at higher x and Q^2 than is necessary for the entire proton.

These "Hot Spots" as proposed by Al Mueller would be regions of intense parton-parton interactions that might exhibit saturation effects in forward jets.

1. Select DIS events with a forward jet – use Breit frame to eliminate current jets
2. Characterize each event by its most forward jet – x_{jet} large, $k_T^{jet} \sim Q$
3. Measure the cross section; which is a function of x, k_T^{jet}, and x_{jet}; vs x at fixed x_{jet}, k_T^{jet}
4. Compare to steep rise of inclusive F_2 at small x to see evidence of saturation effects

Summary

- ZEUS and H1 have studied forward jets and particles in DIS, comparing several types of measurements to alternative parton evolution mechanisms in MC models and fixed-order QCD calculations.

- DGLAP-based parton shower MC models as well as fixed-order NLO QCD calculations are unable to adequately describe all of the data, with the exception of a model in which the exchanged virtual photon has a significant resolved component.

- MC models utilizing BFKL-like evolution are able to describe most of the data adequately as is the modified LO BFKL calculation.

- Studies of QCD dynamics are continuing, including extensions to more forward regions using calorimeter upgrades, higher statistics data with multiple forward jets, and other scattering processes.

- Also, with the large data sets available now, measurements sensitive to possible saturation effects are underway.