Parton Dynamics Studies at HERA

low $x \lesssim 5 * 10^{-3}$

- **QCD dynamics at high parton densities**
- **determines high energy behaviour of hadronic cross sections**
- **LHC physics to a large extent is low x physics!**

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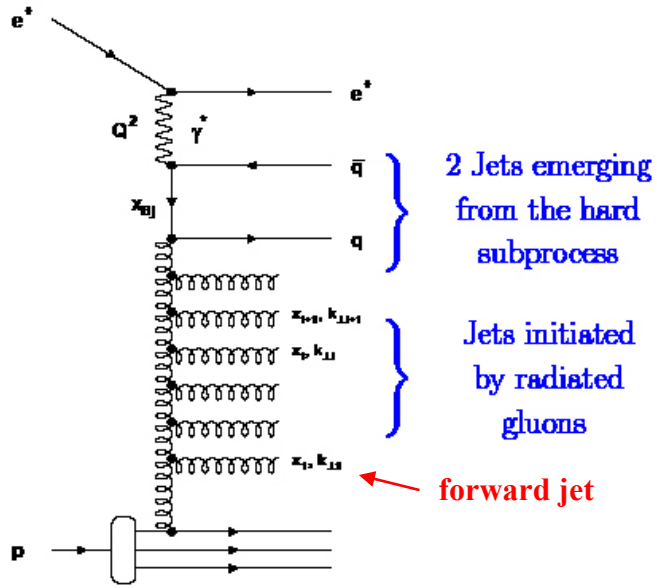
Session5: QCD hard interactions

Low x Physics: new kinematic domain at HERA

new parton dynamics at low x is longstanding question

- Evolution terms ~ $[\ \alpha_s \ln(Q^2)\ ]^n$ and $[\ \alpha_s \ln(1/x)\ ]^n$ are both large for small $x \leq 10^{-3}$



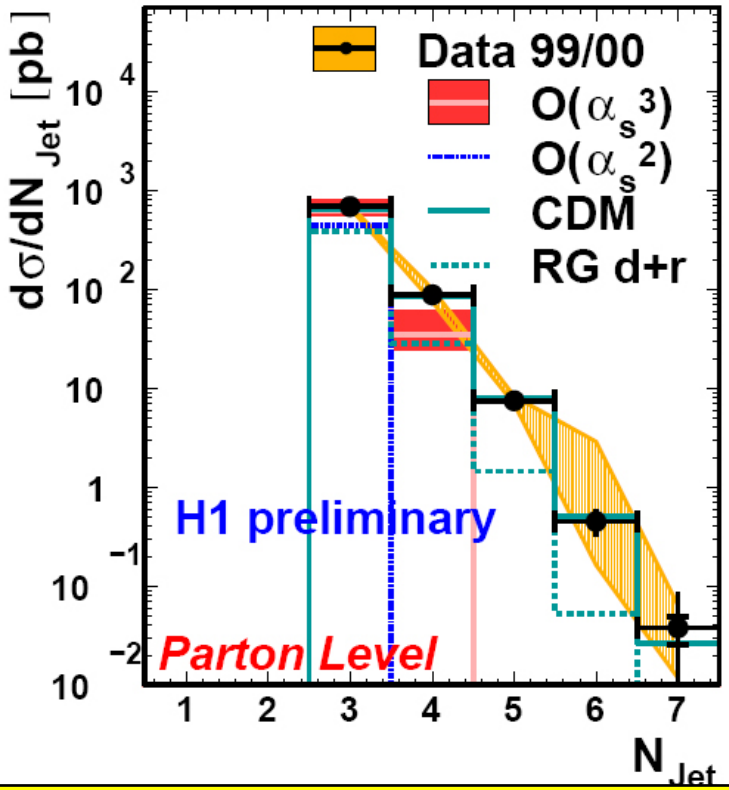
- not resummed in DGLAP evolution equation
  (first terms appear in higher order)
- do these terms ~ln(1/x) play a major role in the parton dynamics
  as suggested by the BFKL evolution equation (sums ln(1/x terms) ?
- ln (1/x) terms lead to unordered gluon radiation in k_T.

→ more hard gluons radiated away from the hard interaction vertex

- **Look at multijet final states at low x: 3- and 4 jet events** → at least 1 rsp. 2 gluons radiated
  (also 2-jet and single forward jets studied)
- **Concentrate on hard forward jets (near proton direction, where relative effect of unordered gluon radiation should be largest *(A. Mueller)***

Jet multiplicity (H1 prelim.)

$5 < Q^2 < 80\ GeV^2$
$10^{-4} < x < 10^{-2}$
Jets:
PT* > 4 GeV
$-1 < \eta < 2.5$



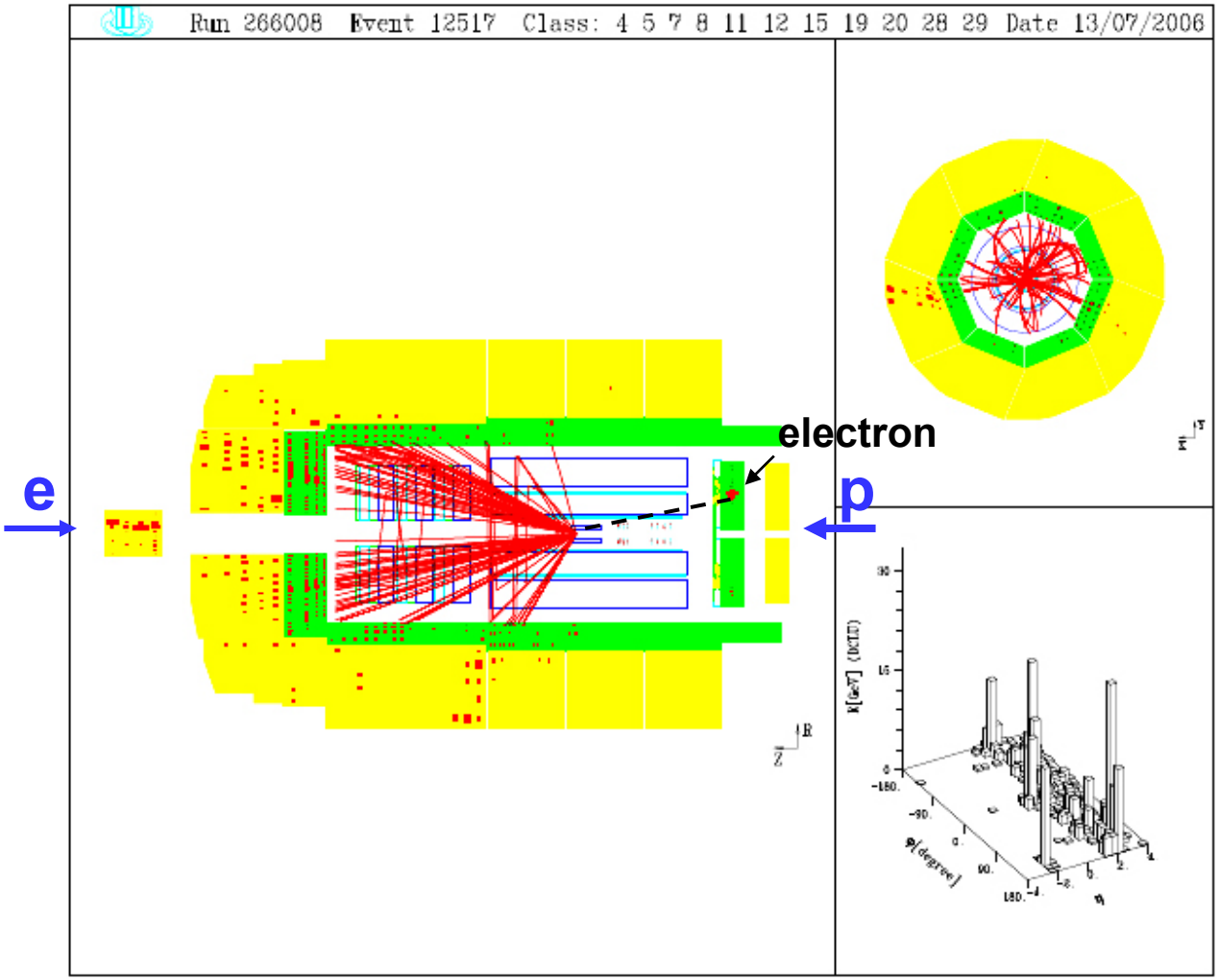
- **gluon radiations are frequent!**
- **by far too few jets for LO + initial state MC**
- **Color Dipole Model is perfect! Why?**
- **3-jet coss-section well predicted by NNLO prediction (allows for 2 gluon radiations) but higher orders needed – where are the events with ≥ 4 jets missing?**

1. Fixed order QCD $\sim \alpha_s^2$ NLO (1 gluon)

   $\sim \alpha_s^2$ NNLO (2 gluons)

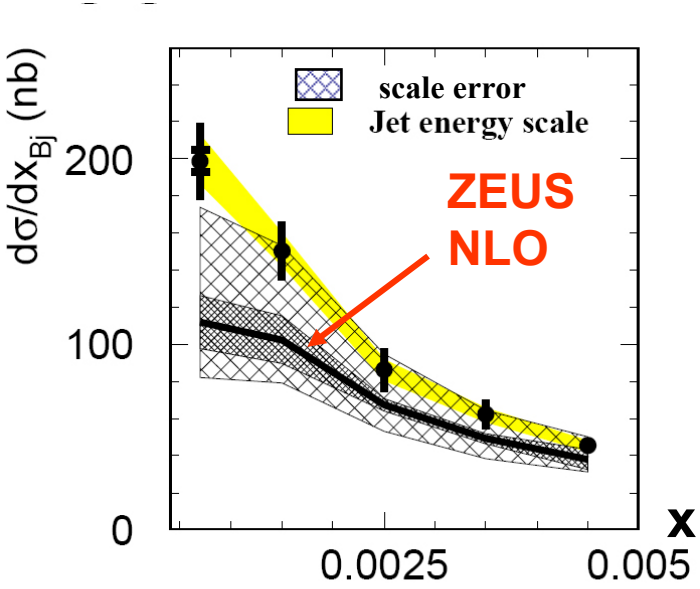
2. LO - MC generators + higher order effects via
   - initial state radiation (RAPGAP + res. γ)
   - color dipole model (CDM, gluon radiation unordered in k_T)

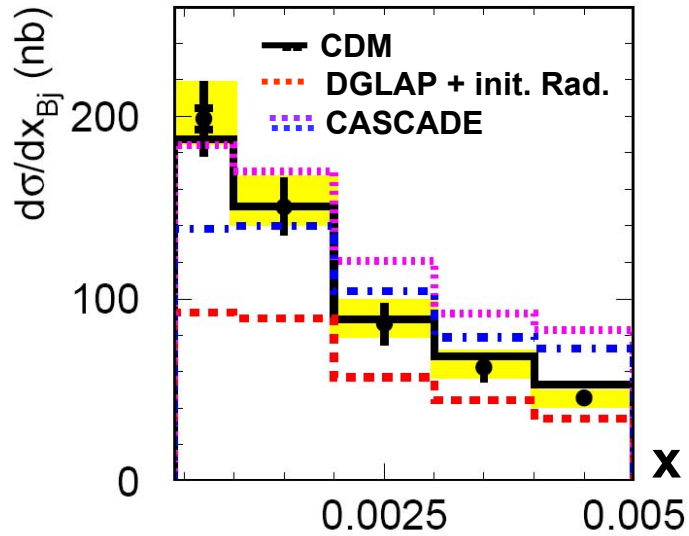
Multijet event



5-jet event at Low x

very Forward jets (inclusive)





1. *High P_T forward jets (inclusive)*

typically:

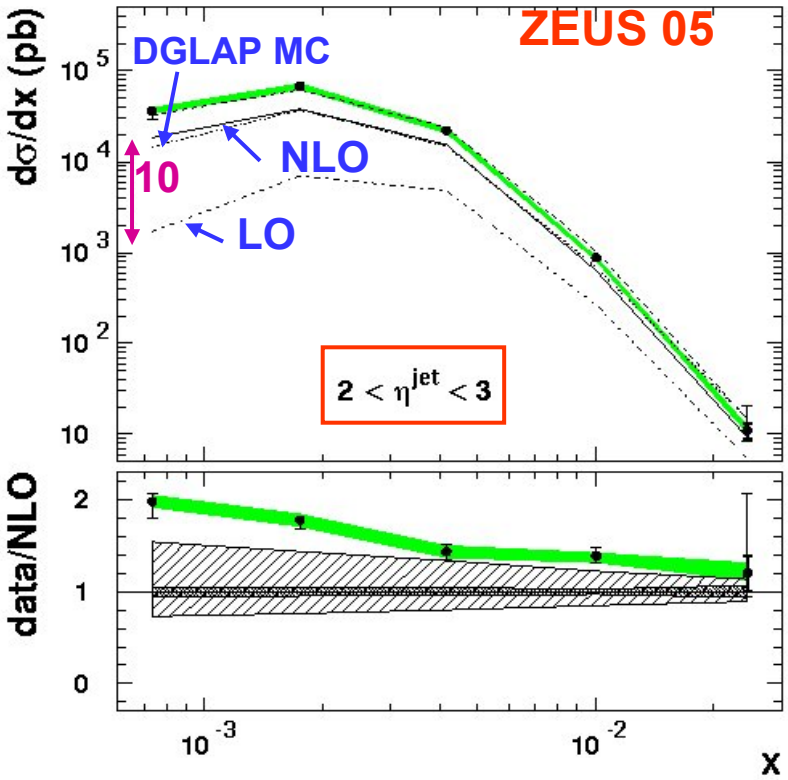
- one jet in $2 < \eta^{jet} < 3.5$ (ZEUS)
- $0.5 < E_T^2/Q^2 < 2$ *(suppressed in DGLAP)*

- Large excess w.r.t. LO and NLO DGLAP masked by large scale uncertainties
  (even including initial state radiation)
- LO MC + CDM good description
- LO MC + initial state radiation not adequate
- But : + resolved photon contribution (H1) gives adequate description

- *Inclusive forward jets are not too selective large contribution from quark jets*

Forward jets: twojet selection

Two-jet selection with one forward jet (BFKL-phase-space)

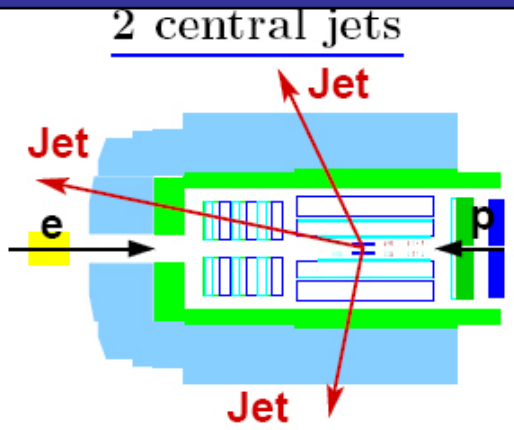


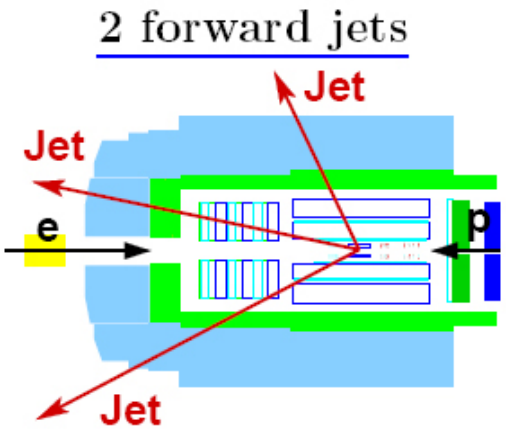
2. ***Twojet- Events (ZEUS05):***

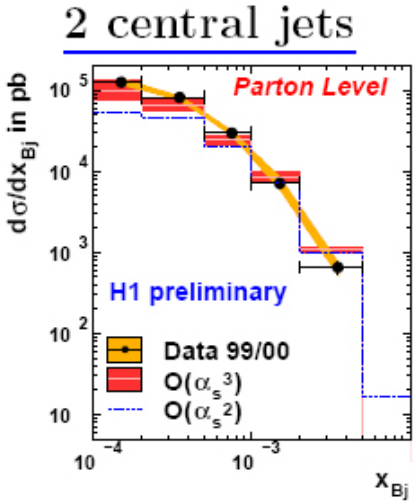
- **excess of jets at low x in 'BFKL phase space region'- *gluon radiation expected***
- **huge corrections from LO→ NLO (α_s^2) at low x (factor 10)**
  NLO includes gluon radiation for the first time
- **LO MC + init. State rad. works equally well**

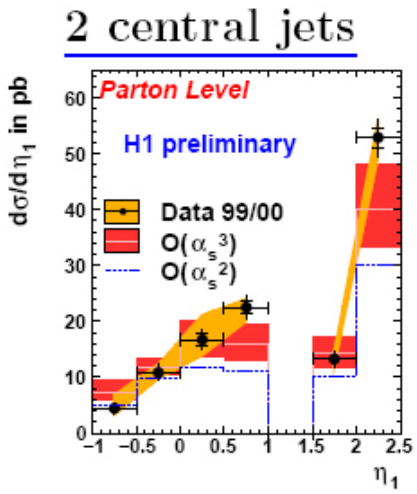
What happens with 3-jet events (next order) where at least 1 gluon radiation is required ?

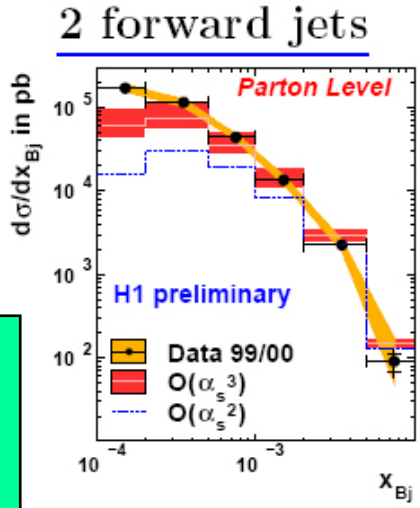
Forward jets: ≥ Threejet selection (H1 2006)

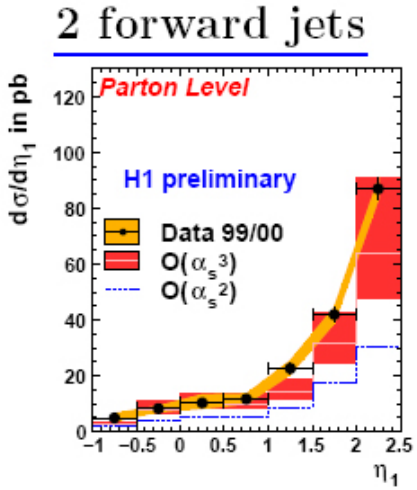








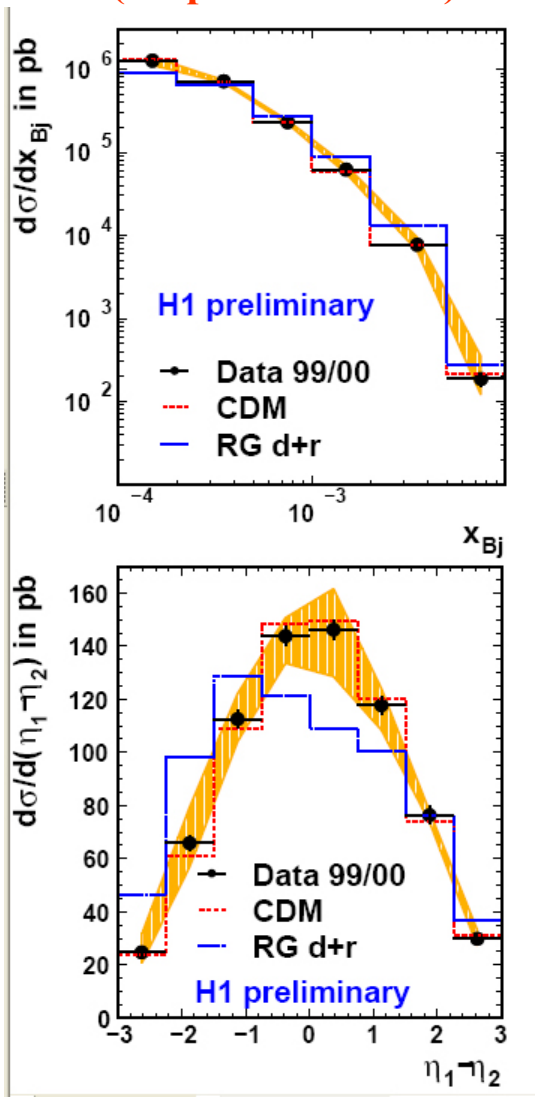




- **huge improvement going from α_s^2 (1 gluon) to α_s^3 (2 gluons rad.)**
- **good agreement for 2 central jets**
- **large deficit for 2 forward jet topology**
  → MC: two gluon radiations mostly!

Comparison to LO MC Generators

Threejet events
(shape normalised)

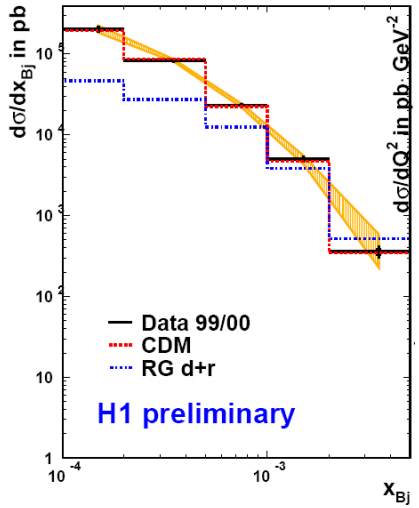


- **CDM gives perfect description (for PT<15 GeV)**
- **LO+initial state radiation + resolved photon (RG d+r)**

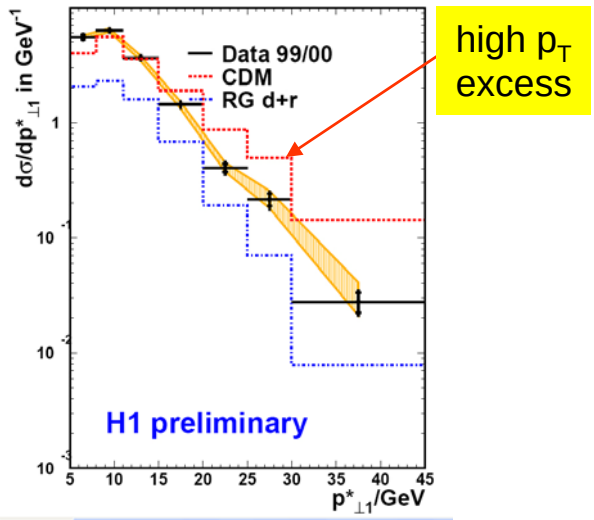
→Complete failure!

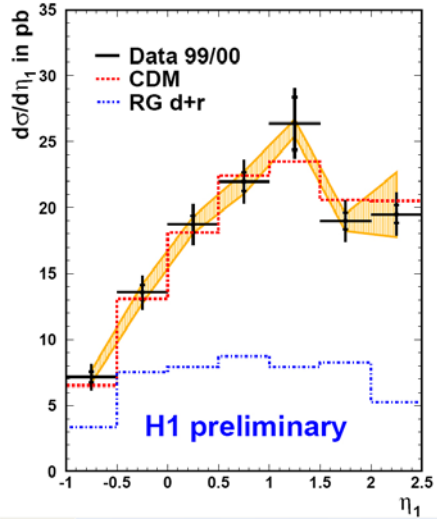
Multijet events discriminate In favour of CDM

four-jet events



fourjet events





- **not everything is perfect, CDM fails at high p_T**

Intermediate Summary

- There is lot of gluon radiation at small x
- many hard gluons are radiated forward (large kinematic separation from hard interaction vertex)

Fixed Order QCD DGLAP Predicitons

- give huge improvement for every oder in α_S - allowing a further gluon to be radiated BUT
- there always remains a substantial deficit at large rapidities and small x

(higher oders include first ln(1/x) terms, but convergence slow)

MC models for gluon radiation:

- the color dipole model gives an (embarrasingly) good description of multijet events (except at $P_T > 20$ GeV)
- Gluon radiation via (ordered) initial state radiation fails completely

There is substantial evidence for stong unordered gluon radiation at low x as expected from ln(1/x) contributions in the evolution equations

Is there a better approximation for the QCD dynamics at low x?

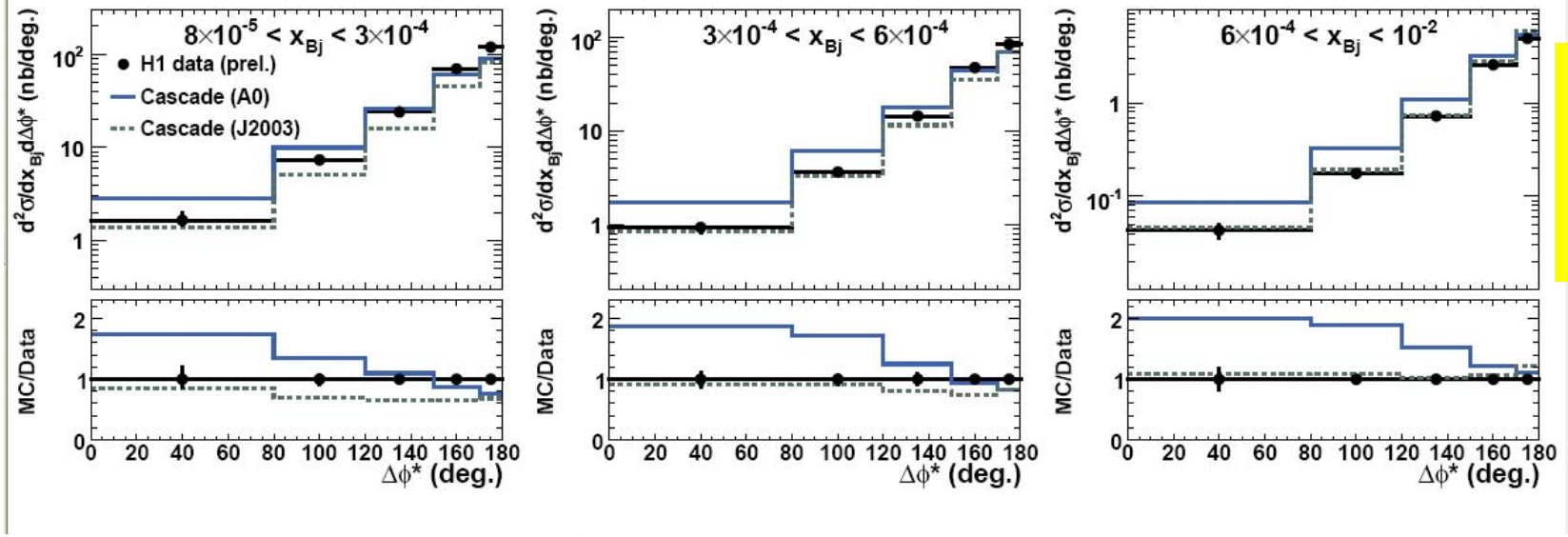
BFKL does not seem to converge..

DGLAP slow convergence

CCFM evolution equation: a better approximation?

- Considers both $[\alpha_s \ln(Q^2)]^n$ and $[\alpha_s \ln(1/x)]^n$ terms
- Approximates DGLAP for larger x and BFKL for low x and high Q^2

- Approximately implemented in CASCADE MC generator (H. Jung)
  → needs unintegrated gluon density to be determined from data
- Two sets used which both describe $F_2(x, Q^2)$ to predict data below:



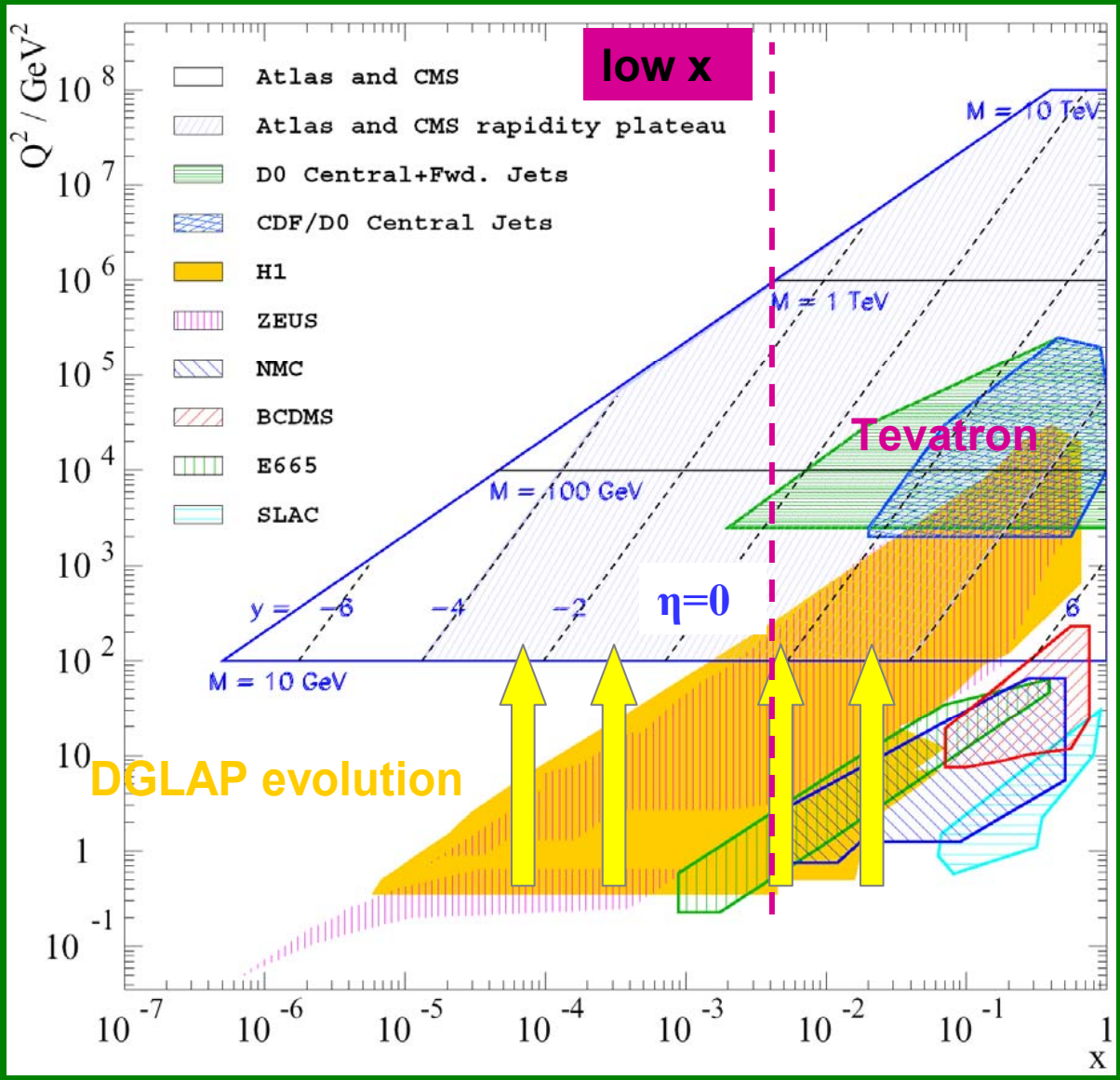
H1 prelim. 2-jet events

- H1 preliminary data on $\Delta\Phi^*$ (angle between the 2 jets in γp system)
  →This distribution of 2-jet events is sensitive on gluon transverse momentum

→Unintegrated gluon density could be be determined... not yet done
- CASCADE predictions (based on CCFM evolution) could then be compared to many other data sets e.g. multijet cross sections at low x. ...we have to wait

Implications for LHC predictions?

(personal comments)



- **large part of LHC phase space is at small x!**

(one of the parton has small x for M<100 GeV)

- **Tevatron is at large x**
- **Standard Model predictions based on fixed order ME's and initial state radiation will not work! Even if tuned to Tevatron data**
- **low x dynamics has to be implemented**
- ***use of CDM for additional radiation?***