Low x dynamics with final states

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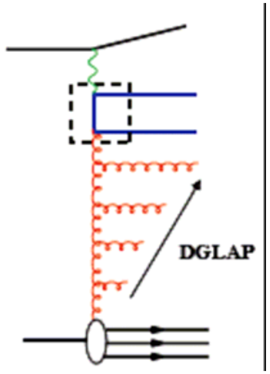
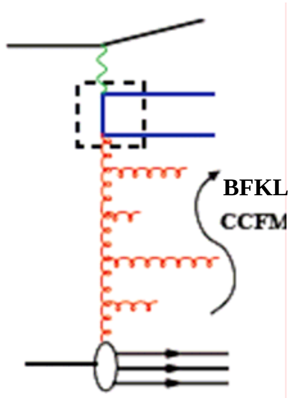
On behalf of the H1

- QCD dynamics at low x at HERA
- Azimuthal jet decorrelation H1-prelim-06-032
- Forward jets : inclusive approach H1: EPJ C46 (2006) 27
- Forward jets in multijet configurations H1:EPJ C54 (389)2008
- What have we learned about low x dynamics at HERA

QCD dynamics at low x

Low x → long gluon cascades, need for approximations





DGLAP : $\sum \left(\alpha_s \ln Q^2\right)^n$

- **Strong ordering in k_t** transverse momenta of emissions
- Expected to fail at very small Bjorken x

BFKL : $\sum \left(\alpha_s \ln 1/x\right)^n$, designed to describe small x region

- Random walk in transverse plane, **no k_t ordering**
- Strong ordering in longnitutdinal momenta

CCFM: $\sum \left(\alpha_s \ln Q^2\right)^n$ & $\sum \left(\alpha_s \ln 1/x\right)^n$

- Anglular ordering, **no k_t ordering at low x**
- Expected to work both at large and small x

Questions we ask when studying low *x* dynamics at HERA

- Do we really need BFKL (CCFM) evolution to describe all HERA data at low *x*? (would higher orders in fixed order DGLAP, which already include log 1/x terms, be enough ?)
- Which QCD calculation method (model) provides best description of the small-x data ?
- Are HERA small-x data sensitive to unintegrated Parton Density Functions uPDF (can we determine uPDF required by BFKL&CCFM schemes from HERA data ?)

Strategies to answer „small-x" questions

Study of hadronic final states which reflect the kinematic structure of gluon emissions

- Azimuthal dijet separation – variable particularly sensitive to amount of gluon radiation and its k_{tg} distribution
- Inclusive forward jets: restrict phase space to suppress DGLAP and enhance BFKL evolution
- 3-jets: tag multiple emissions at small x
- 3-jets subsamples with forward jets designed to control kinematics of emissions

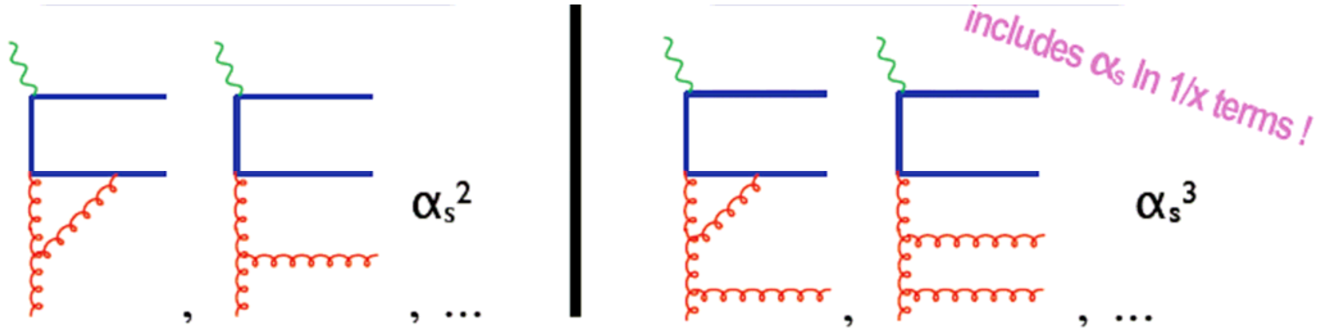
Decreasing phase space for radiation

Increasing parton kinematics control

HERA covers about 4 rapidity units→we expect about 3 – 4 hard emissions.

NLO parton level MC

DISENT, NLOJET++	NLOJET++



•NLO calculation for inclusive jets in Breit Frame, inclusive dijets

•LO calculation for trijets

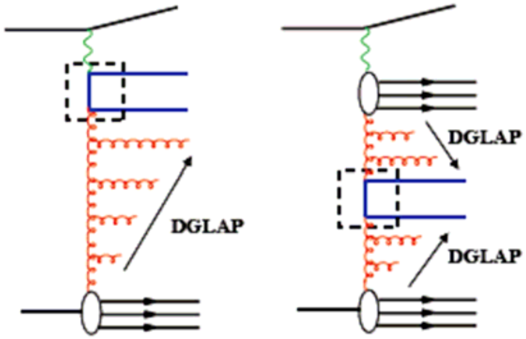
•NNLO calculation for dijets

•NLO calculation for trijets

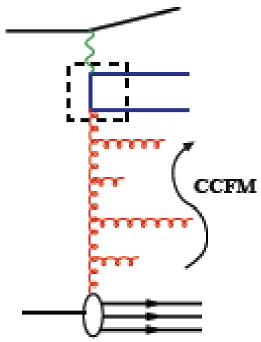
•LO calculation for fourjets

•Trijet calculation contains $\alpha_s \ln 1/x$ terms !

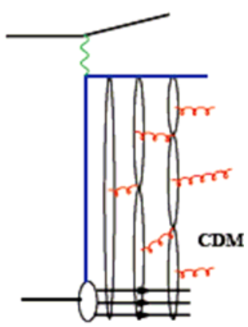
QCD models based on DGLAP, CCFM and CDM



- RAPGAP : implements DGLAP evolution with k_t ordering
- RAPGAP RESOLVED: also evolution from „hadronic photon" side, in a sense breaks ordering, but within DGLAP scheme



- CASCADE: implements CCFM evolution
- No k_t ordering in small-x region
- Requires uPDF (onlu gluon implemented so far)

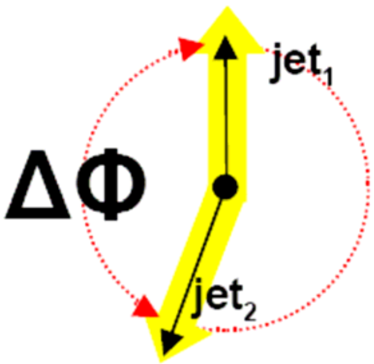


- ARIADNE: implements Color Dipoles Model:
- Quasi-classical color dipoles radiate independently
- No k_t ordering

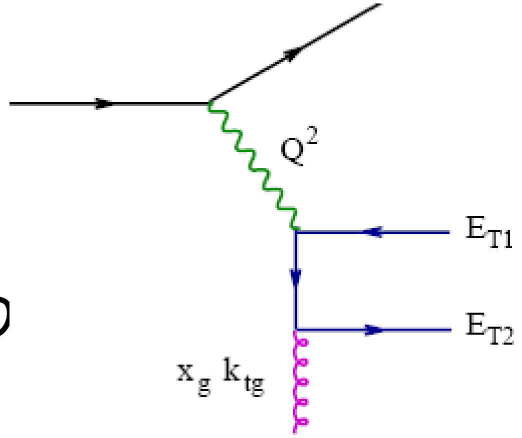
Azimuthal correlations in dijets

Azimuthal jet separation $\Delta\Phi^*$ sensitive to:

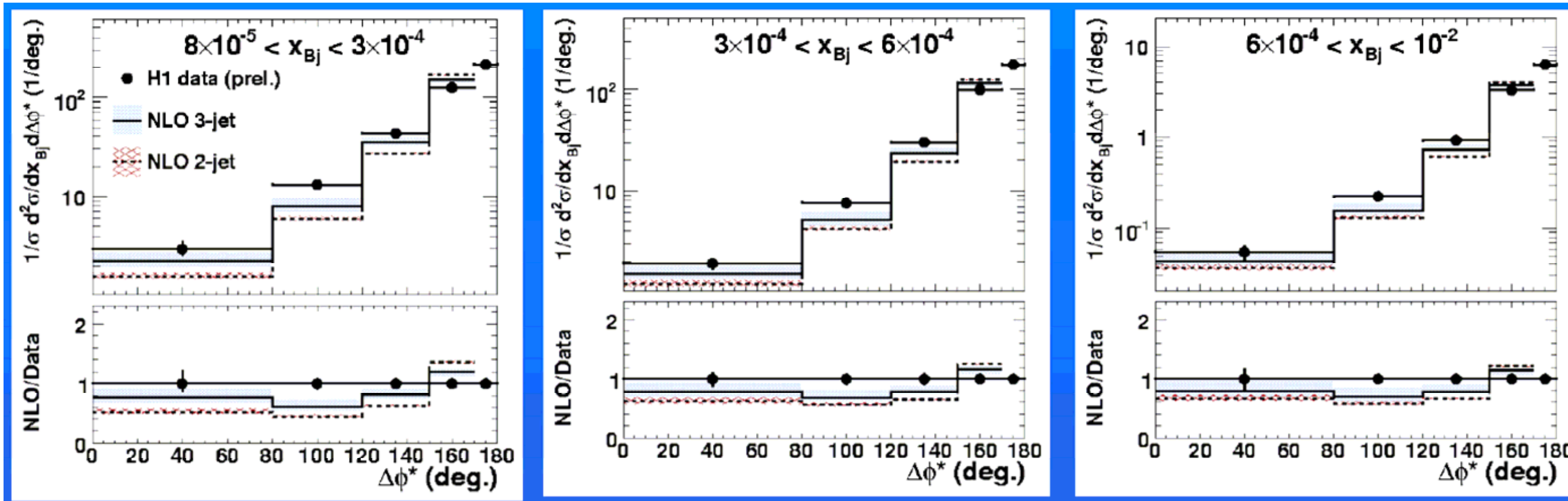
- HO terms of perturbative expansion
- evolution scheme:



- DGLAP LO : jets back-to-back in HCMS
- DGLAP HO : $k_{tg} \neq 0$ but limited (ordering)→ $\Delta\phi^*$ spectrum of limited width
- BFKL, CCFM: „random walk" in k_{tg} →wider $\Delta\phi^*$ distribution in comparison to DGLAP
- BFKL, CCFM employ uPDF→ $\Delta\phi^*$ spectrum in LO
- We expect that azimuthal jet separation is sensitive not only to parton dynamics but also to uPDF



Azimutal correlations in dijets



H1-prelim-06-032

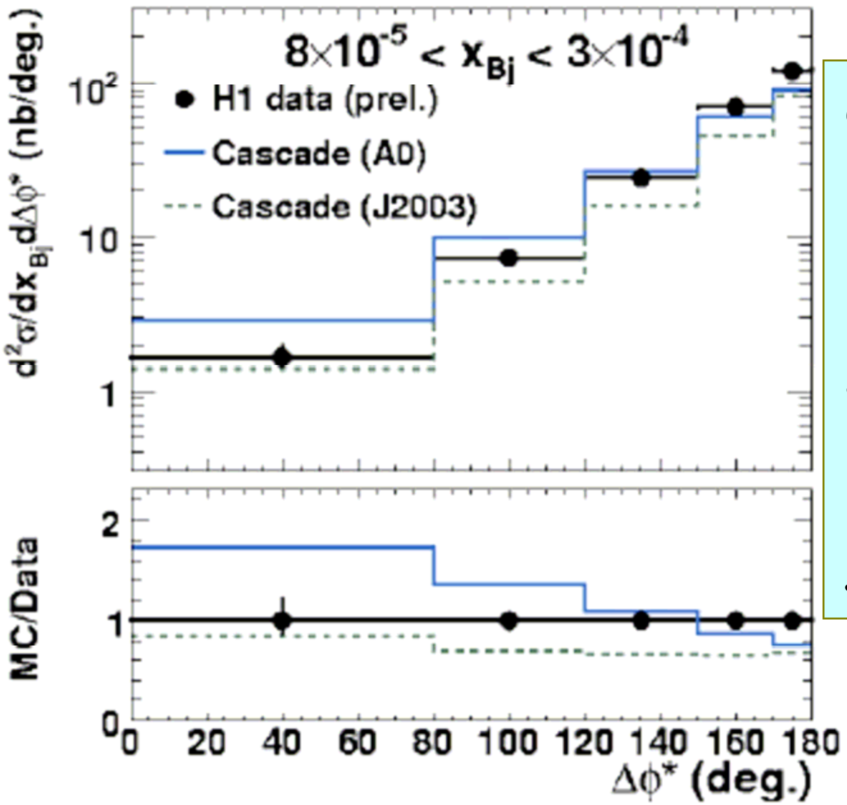
$\Delta \Phi^* = | \Phi_{jet1} - \Phi_{jet2}|$
in HCM

H1 99-00 data (64 pb^{-1}):
DIS: $5 < Q^2 < 100$ GeV^2

2 jets with:
$-1 < \eta_{jet} < 2.5$ (LAB)
$E^*_{Tj} > 5$ GeV (HCM)

- one parton radiation (NLO 2-jet) not enough to describe the data
- two parton radiation (NLO 3-jet) still systematically low at low x_{Bj}, low $\Delta \Phi^*$

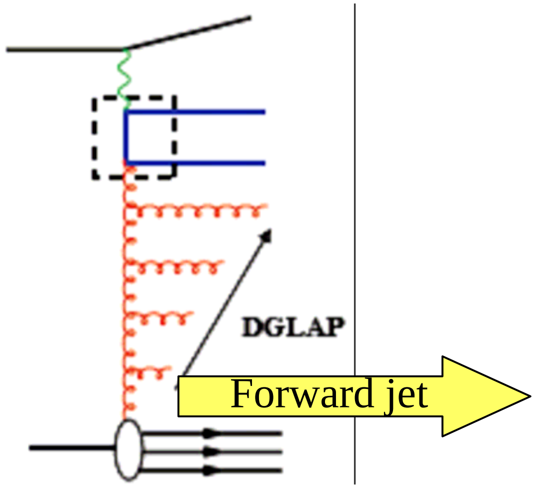
Azimutal correlations in dijets



Comparison with CASCADE (CCFM):

- two sets of gluon uPDF: A0, J2003
- $\Delta\phi^*$ distribution very sensitive to choice of uPDF

Forward jet strategy

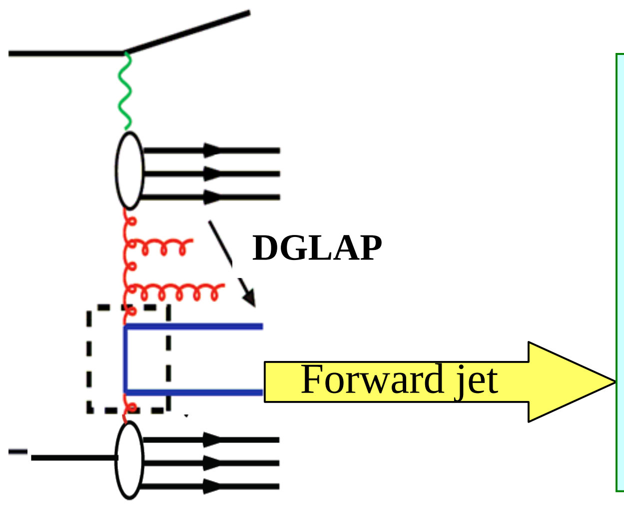


Suppress DGLAP evolution in Q^2 :

$$p_{T,jet}^2 \approx Q^2$$

Enhance BFKL evolution in x :

$$x_{jet} >> x_B \qquad x_{jet} = \frac{E_{jet}}{E_p}$$



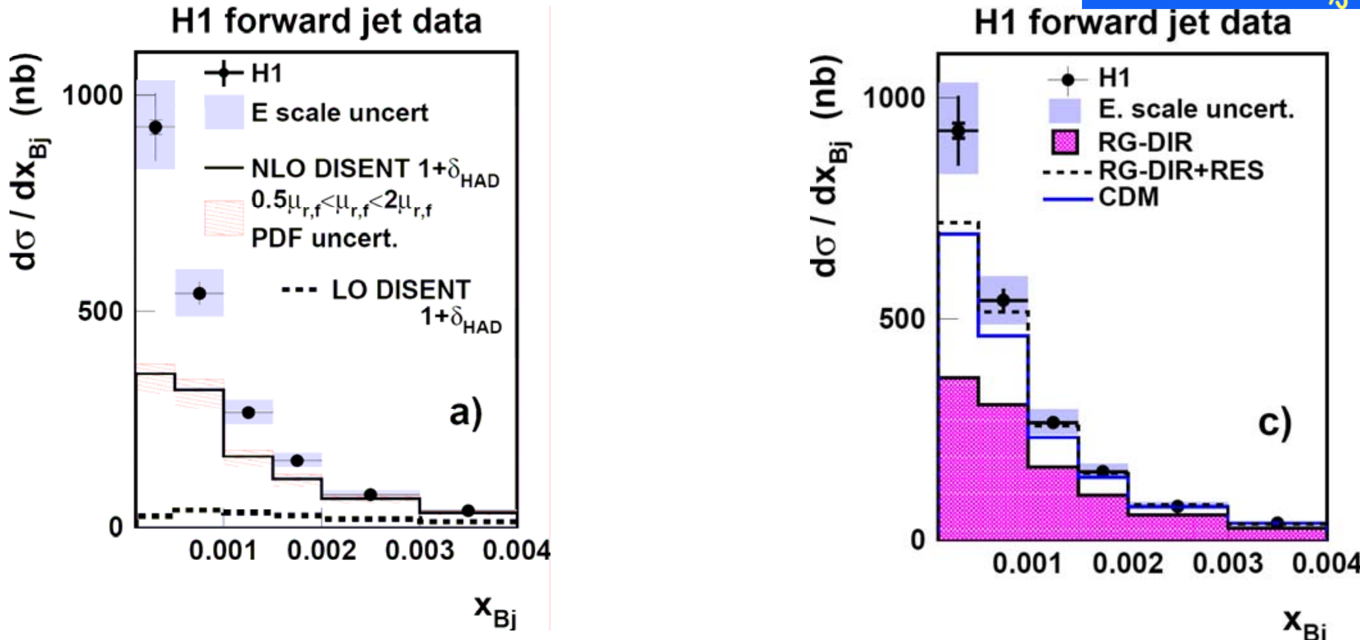
- In resolved photon processes quark from matrix element can become „forward jet"
- Forward jet is not „100%clean" signature for non-ordered, non-DGLAP evolution

Forward jets

H1 data in the kinematic region: $10^{-4} < x < 4 \times 10^{-3}$, $p_{T,jet} > 3{,}5$ GeV, $5 < Q^2 < 85$ GeV^2, $7^o < \Theta_{jet} < 20^o$

$x_{jet} = E_{jet}/E_p > 0.035$

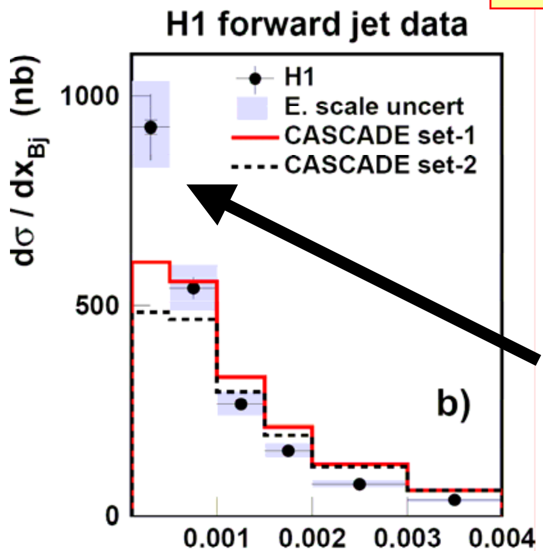
$0.5 < (p_{T,jet})^2/Q^2 < 2$



- NLO-DGLAP (DISENT) too low
- scale: $\mu_R^2 = \mu_F^2 = \langle p_{T,dijet}^2 \rangle$

- RAPGAP direct ≈ NLO-DGLAP, too low
- Resolved component helps a lot, only lowest x-bin too low
- CDM very close to RAPGAP(DIR+RES)

Forward jets



- CASCADE with unintegrated gluon density set1&set2 fails, shape is not described, lowest x-bin too low
- Forward jet x-section ad $x \approx 10^{-4}$ remains to be a challenge for QCD theory

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The NLO Jet Vertex for Mueller-Navelet and Forward Jets: the Gluon Part

J. Bartels[1a], D. Colferai[1b], and G.P. Vacca[2]

What remains is the numerical evaluation of the cross section formulae, using the results derived in this paper. ....

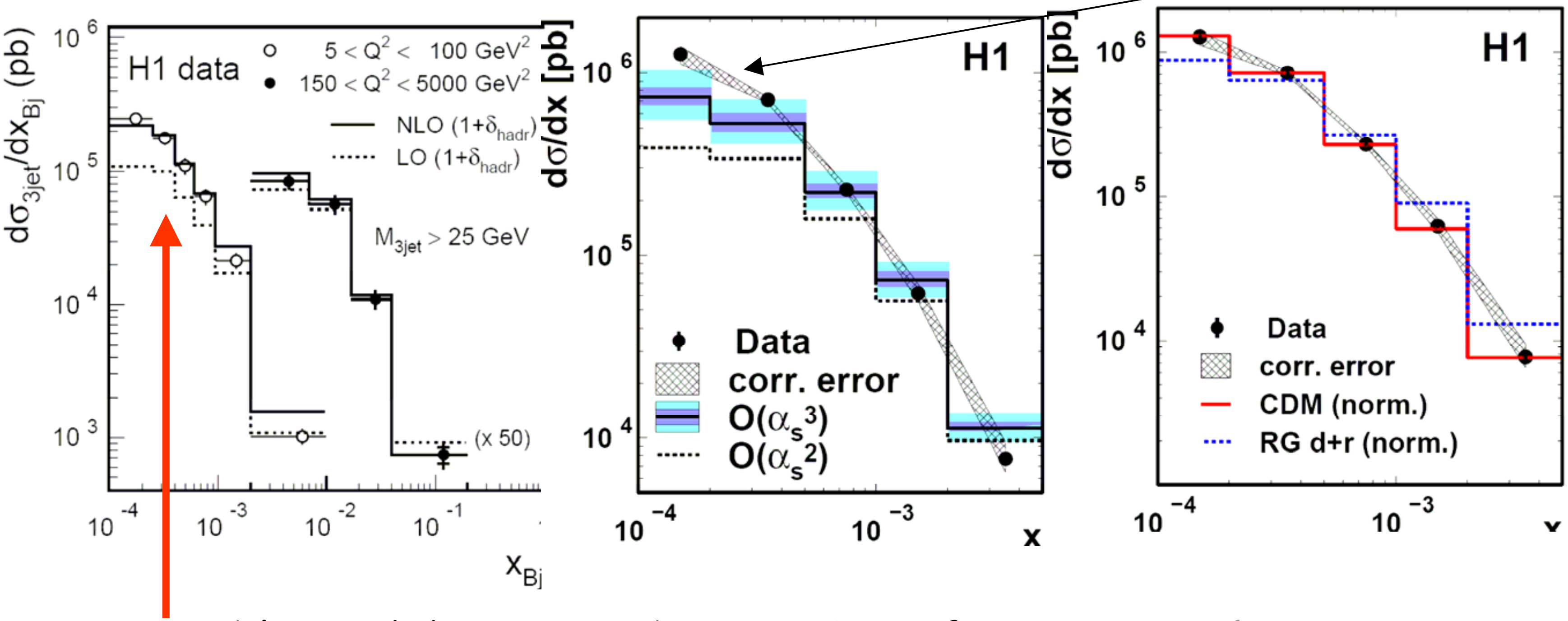
perimental cuts have to be formulated. We hope to be able to report first numerical results in the near future.

3-jet inclusive sample

Selection: at least 3 jets with $p_{t,jet} > 4$ GeV

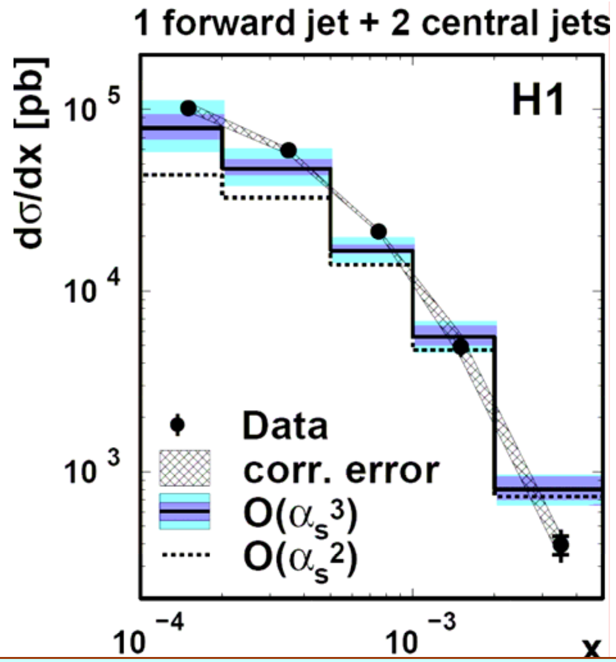
Evolution with strong k_t ordering not favoured

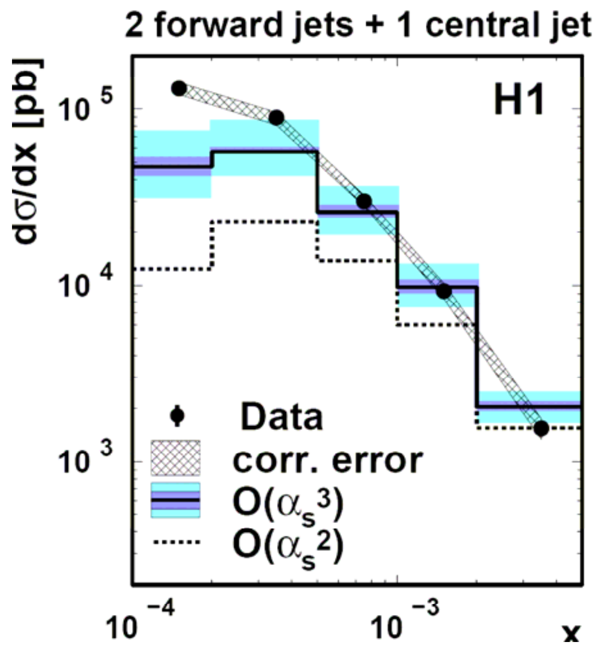
$$\frac{data}{NLO} \approx 0.6$$



- Reasonably good description by 3-jet NLO for $M_{3\text{-jet}} > 25$ GeV
- Opening of the phase space results in poor description at low *x*
- CDM unlike DGLAP(dir+res) provides excellent description

3-jet subsamples





- 1f+2c described fairly well by 3-jet NLO which includes log 1/x term – not much of free phase space left for additional radiations
- 2f+1c discrepancy at lowest x_{Bj} and forward rapidities where unordered emissions are expected to be important
- 2f+1c mainly 4-jet, 3-jet NLO is LO calculation for this sample → we really need 4-jet NLO to look for non-DGLAP effects

Summary and Conclusions

DGLAP (both parton level NLO and ME+PS) fail to describe many aspects of small *x* data :

- Azimutal decorrelation in inclusive dijets
- Forward jets inclusive
- 3-jets inclusive at very small *x*
- Subset of 3-jet sample with enhanced gluon radiation in proton direction

❖Need for full resummation of log 1/*x* terms in perturbative expansion has not been proven, nevertheless BFKL (CCFM) evolution may be usefull tool for description of small-*x* HERA data with potential to determine uPDF

❖Color Dipol Model based on quasi-classical radiation of uncorrelated color dipols, describes most of the small-*x* data and seems to contain most salient features of QCD evolution in many-parton processes.

❖HERA data still wait for interpretation in terms of NLO BFKL calculation (e.g. inclusive jets at $x_{Bj} \approx\sim 10^{-4}$)

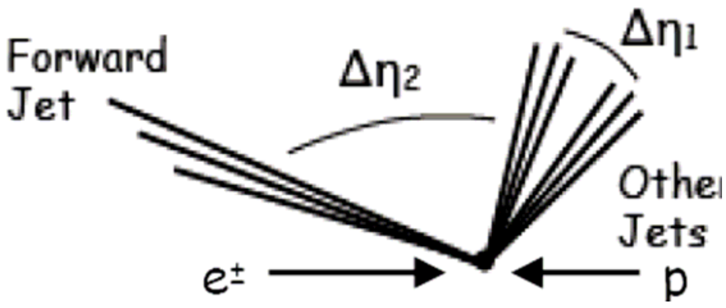
Backup slides

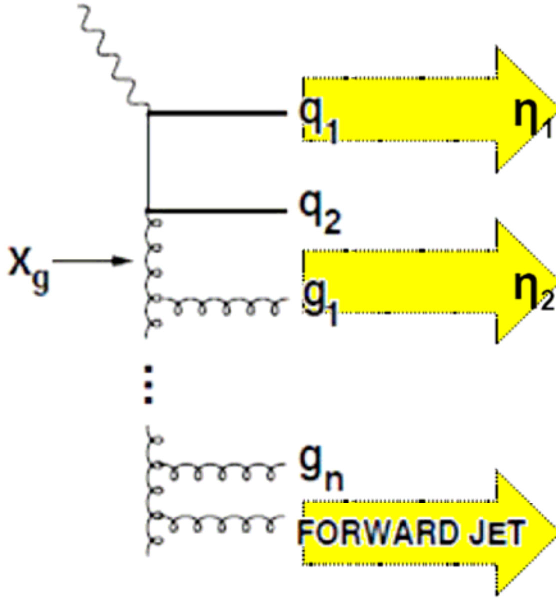
3-jet subsamples

Forward $\eta_{jet} > 1.74$; $x_{jet} > 0.035$

forward (not central) $\eta_{jet} > 1$

Central jet: $-1 < \eta_{jet} < 1$





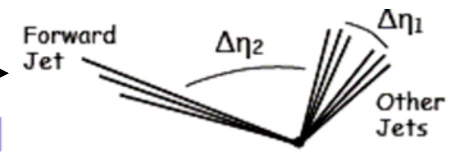
Two samples studied:

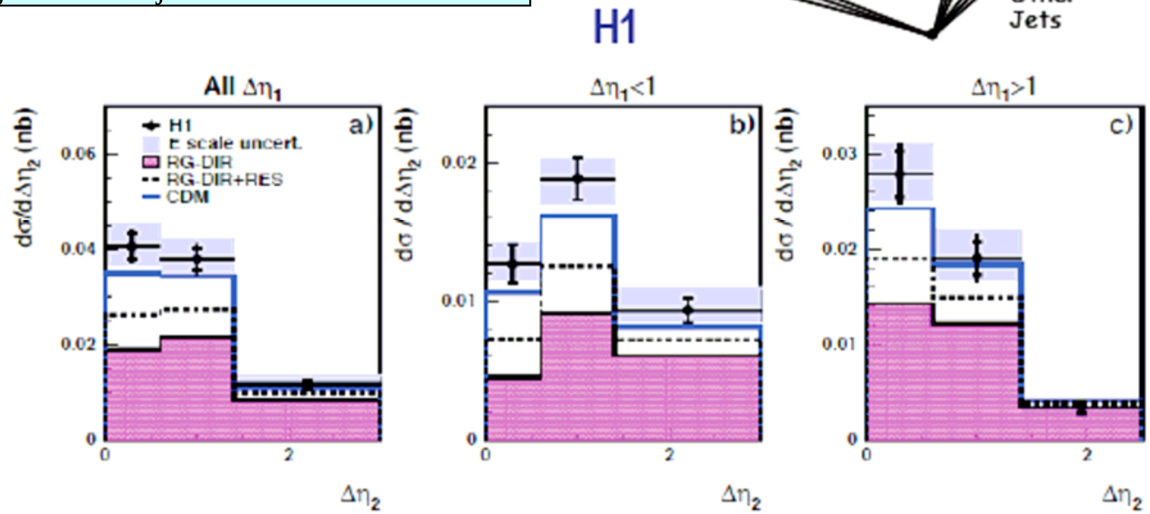
- 1 Forward + 2 central (1f+2c)
- 1 Forward + 1 non-central + 1 central (2f+1c) dominated by 2-gluon radiation i.e. 4-jet sample q+qbar+g+g

3-jet sample: forward + 2 hardest

Forward jet : $p_{t,jet}$ > 6 GeV, $7^0 < \Theta_{jet} < 20^0, x_{jet} > 0.035$

Other jets : $p_{t,jet}$ >6 GeV





- $\Delta\eta_1 > 1 \quad \Delta\eta_2 > 1$ CDM≈DGLAP(RAPGAP&3-jet NLO)≈data, phase space exhausted, no freedom for dynamical variations
- $\Delta\eta_2 < 1$ DGLAP(RAPGAP&3-jet NLO) fail to describe the data, while CDM describes the data fairly well. Contrast with more inclusive sample

Incl. forward jet requirements

	H1	ZEUS
Q^2 [GeV^2]	5 - 85	20 - 100
y	0.1 - 0.7	0.04 - 0.7
x_{Bj}	10^{-4} - 4 10^{-3}	4 10^{-4} - 5 10^{-3}
$p_{T,jet}$ [GeV]	3.5	5
η_{jet} (θ_{jet})	1.74 - 2.79 (20° - 7°)	2 - 4.3 (15.4° - 1.6°)
x_{jet}	> 0.035	> 0.036
$r = p_{T,jet}^2/Q^2$	0.5 - 5.0	0.5 - 2.0

- ZEUS: DESY-07-100 (July 2007) submitted to EPJ C
- H1: EPJ C46 (2006) 27

significantly increased coverage with FPC !

	DISENT		NLOJET++	
	H1	ZEUS	H1	ZEUS
μ_R^2	$< p_{T,dijet}^2 >$	Q^2	$(p_{T,jet1}^2 + p_{T,jet2}^2 + p_{T,fwdjet}^2)/3$	Q^2
μ_F^2	$< p_{T,fwdjet}^2 >$	Q^2	$(p_{T,jet1}^2 + p_{T,jet2}^2 + p_{T,fwdjet}^2)/3$	Q^2
proton PDF	CTEQ6M	CTEQ6M	CTEQ6M	CTEQ6M