HERA results on small x and forward jets

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on behalf of the H1 and ZEUS collaborations

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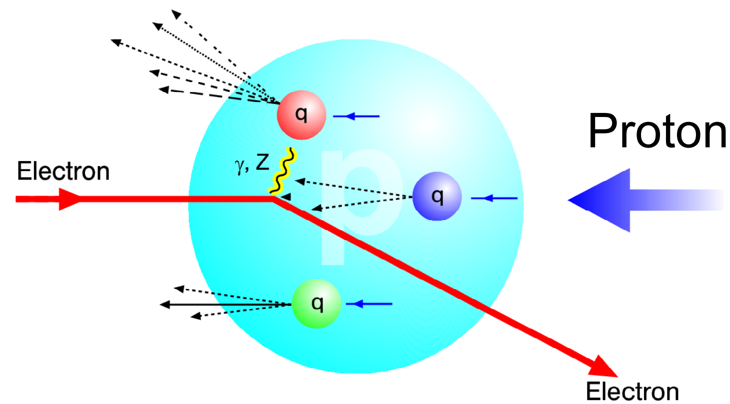
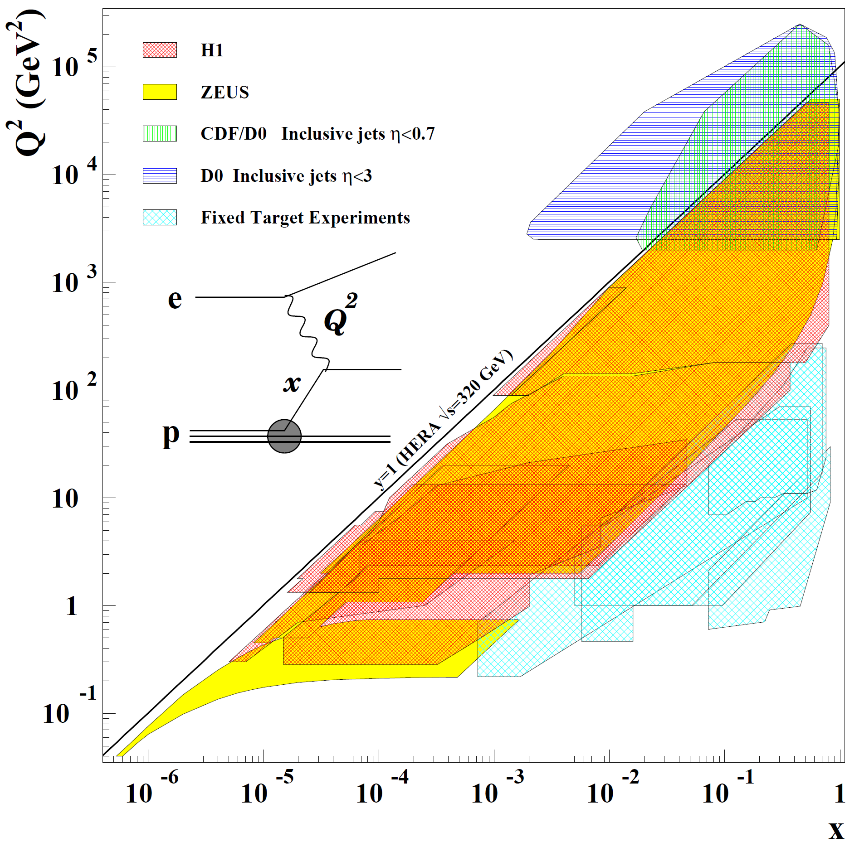
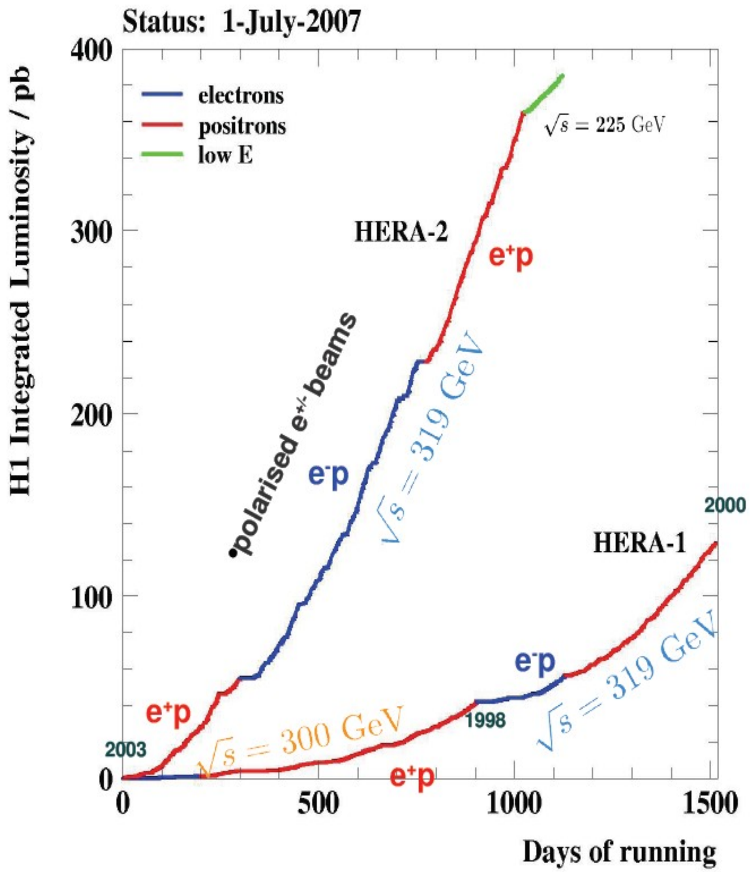
eP collider HERA



Parton kinematics at HERA & luminosity





	E_p (GeV)	HERA (pb^{-1})	ZEUS (pb^{-1})
HERA-I	820 / 920	193	143
HERA-II	920	562	407
LER/MER	460 / 575	16 / 9	13 / 8

Parton dynamics in pQCD

Perturbative expansion of parton evolution equations $\sim \Sigma_{mn} A_{mn} \ln(Q^2)^m \ln(1/x)^n$

Cannot be explicitly calculated to all orders

1. Fixed order calculations

2. Approximations ⇨ resumming certain infinite subsets of terms according to the phase space region

- **DGLAP, collinear factorisation:** $\sum (\alpha_s \ln Q^2)^n$

  Ordering in x, ***strong ordering in k_T***

- **BFKL, k_T factorisation** : $\sum (\alpha_s \ln (1/x))^n$

  Strong ordering in x, ***no k_T ordering***

- **CCFM, k_T factorisation**: resum $\ln Q^2$ and $\ln (1/x)$

  Angular ordering ⇨ ***k_T non-ordering at small x_{Bj}***

Parton dynamics in pQCD

- DGLAP - approximation for high enough Q^2 and not very small x_{BJ}
- BFKL – approximation for small x_{BJ}
- DGLAP is successful in describing practically all existing data
- DGLAP should experience problems at small x_{BJ}
- If HERA x_{BJ} are small enough to reveal these problems?
- BFKL should replace DGLAP at small x_{BJ}
- If BFKL accomplishes this for HERA?
- At small x saturation is inevitable to preserve unitarity
- How HERA can help us in understanding saturation?

The main of characteristics of parton evolution for distinguishing between approaches experimentally is the way of k_T ordering

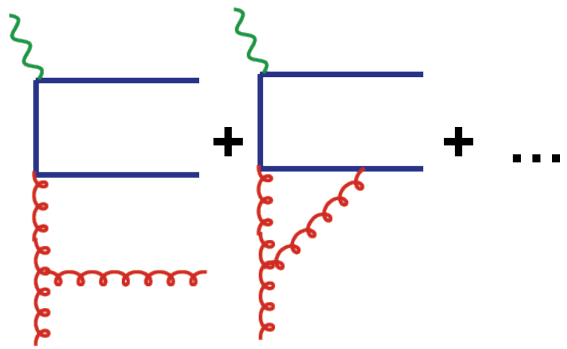
Three several realisations of breaking strict DGLAP k_T ordering are compared with DGLAP:

- Resolved photon, i.e. addition of DGLAP evolution from the photon side.
- CCFM
- Color Dipole Model where emitted gluons are in random walk in k_T

DGLAP is represented by LO, NLO, NNLO fixed order calculations and LO matrix element+parton showers Monte Carlo

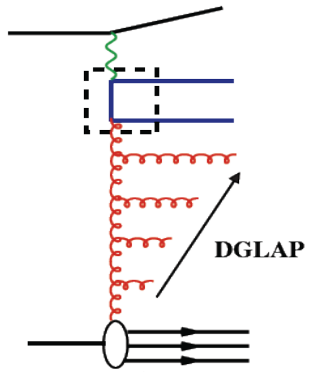
QCD calculations & Monte Carlo

Disent, NLOjet++



NLO Di-jet (α_s^2)

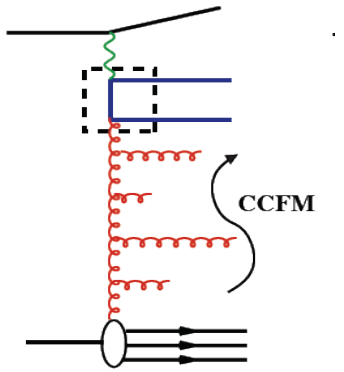
Lepto/Rapgap DIR



DGLAP

direct photon

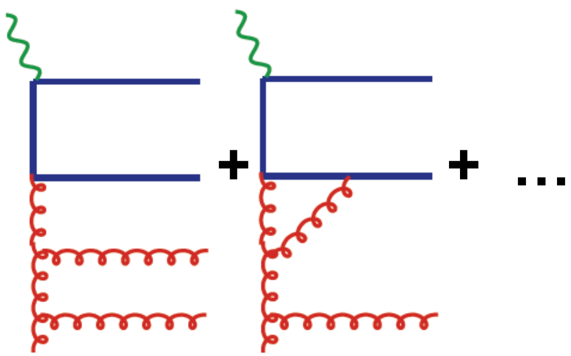
Cascade



CCFM, angular ordering,

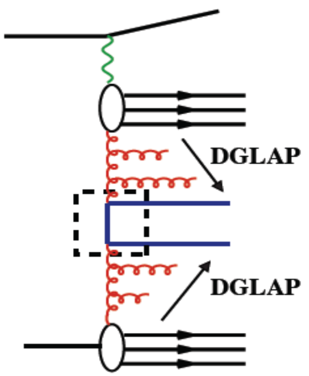
Unintegrated g(x,kt,μ)

NLOjet++



NLO Tri-jet (α_s^3)

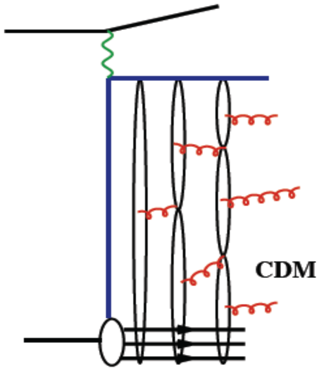
Rapgap DIR+RES



DGLAP, direct +

resolved photon

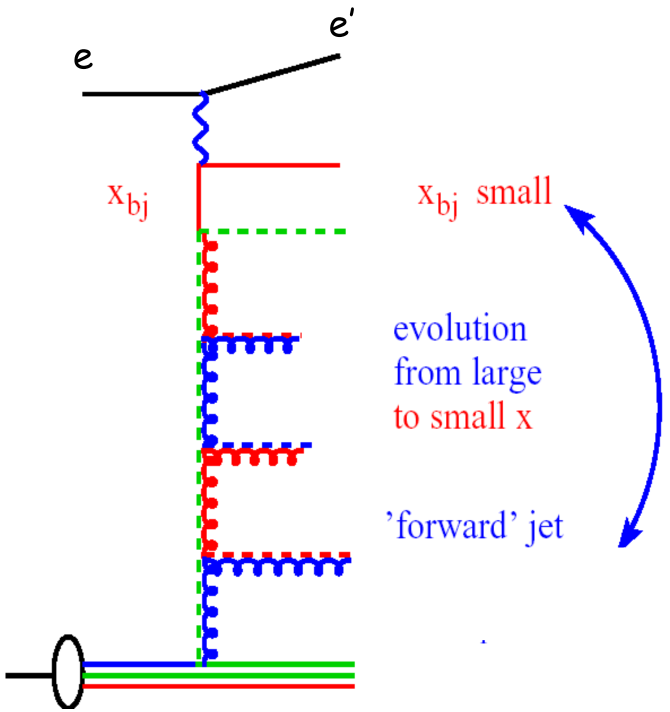
Ariadne



Color Dipole Model (CDM)

Non- k_t ordered partons

Inclusive forward jets



Jet selection

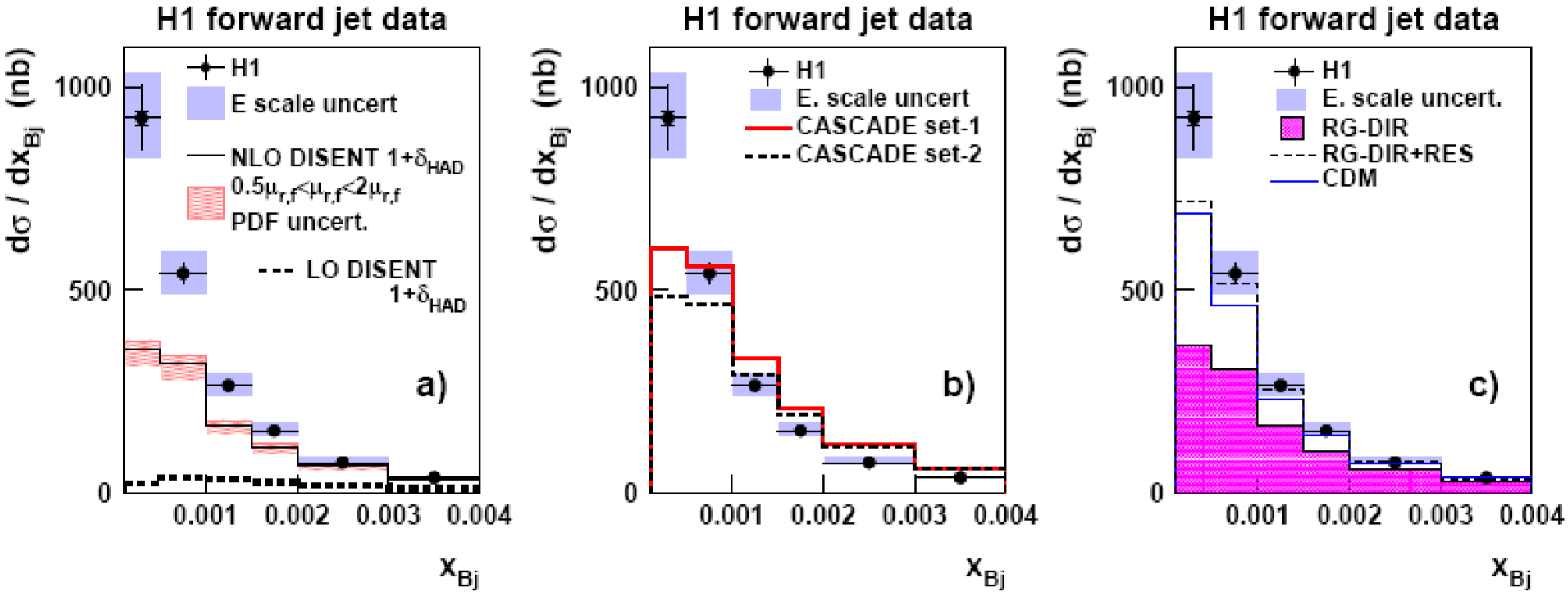
	H1	ZEUS
Q^2 [GeV^2]	5 - 85	20 - 100
y	0.1 - 0.7	0.04 - 0.7
x_{Bj}	10^{-4} - 4 10^{-3}	4 10^{-4} - 5 10^{-3}
$p_{T,jet}$ [GeV]	3.5	5
η_{jet} (θ_{jet})	1.74 - 2.79 (20° - 7°)	2 - 4.3 (15.4° - 1.6°)
x_{jet}	> 0.035	> 0.036
$r = p_{T,jet}^2/Q^2$	0.5 - 5.0	0.5 - 2.0

$(p_t^{jet})^2 \sim Q^2$ suppresses DGLAP evolution

$x_{jet} = E_{jet}/E_{proton} >> x_{Bj}$ enhances BFKL evolution

Inclusive forward jets

H1



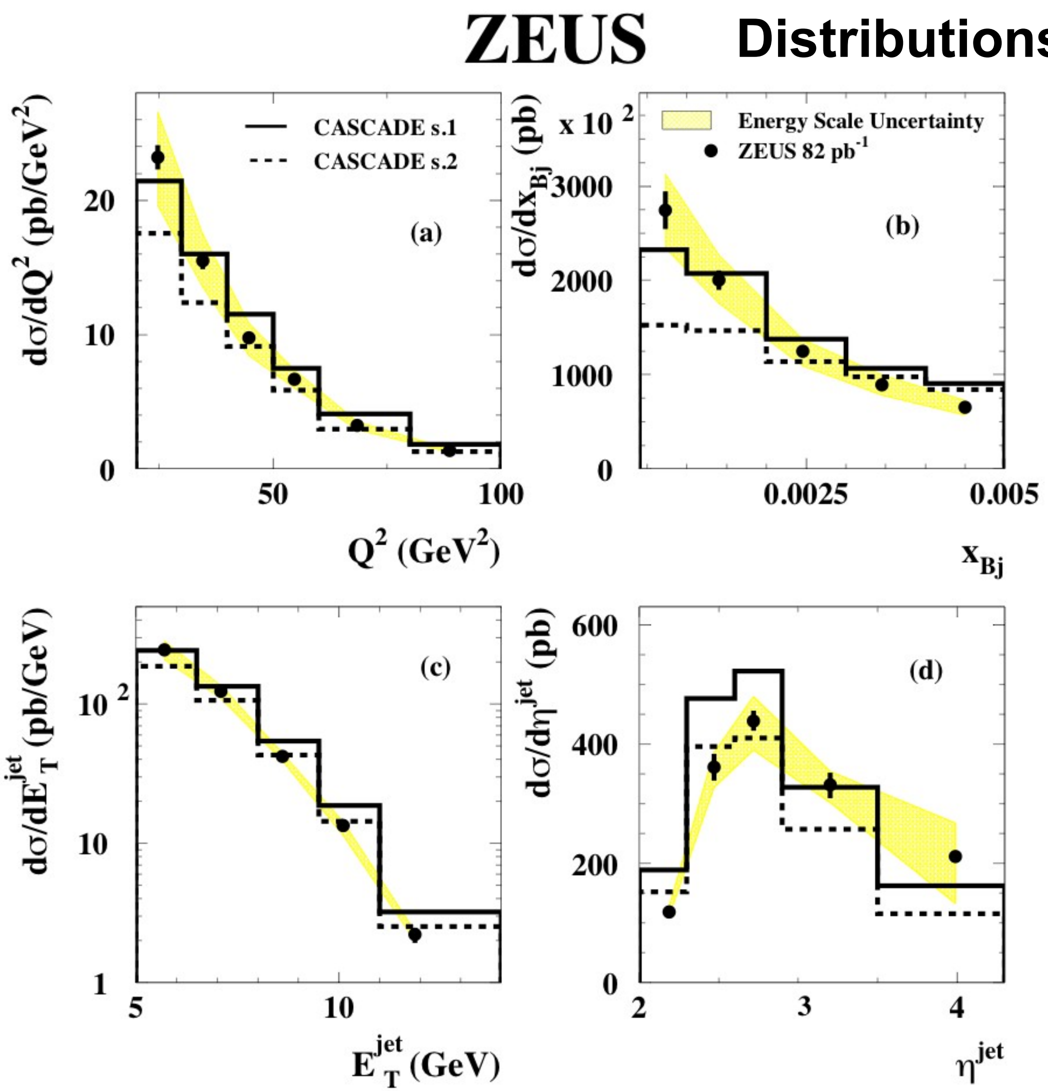
LO DGLAP can hardly produce forward jets NLO DGLAP produces too few forward jets at low x_{BJ}

CASCADE with set-1 produces more forward jets than with set-2, nevertheless too few at the smallest x_{BJ} Both sets differ from data in shape of distribution

RAPGAP-DIR is below data by ~2 times RAPGAP-DIR+RES and CDM are similar They are close to data except at smallest x_{BJ}

Inclusive forward jets & CASCADE

Distributions over different variables



Same as in H1 comparison: shapes of distributions are in disagreement with data

Trijet with a forward jet

Kinematic range the same as for inclusive forward jets

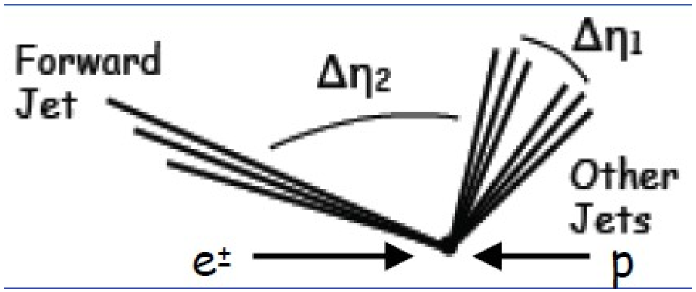
Forward jet the same,

$(E_t^{jet})^2/Q^2$ **constraint excluded**

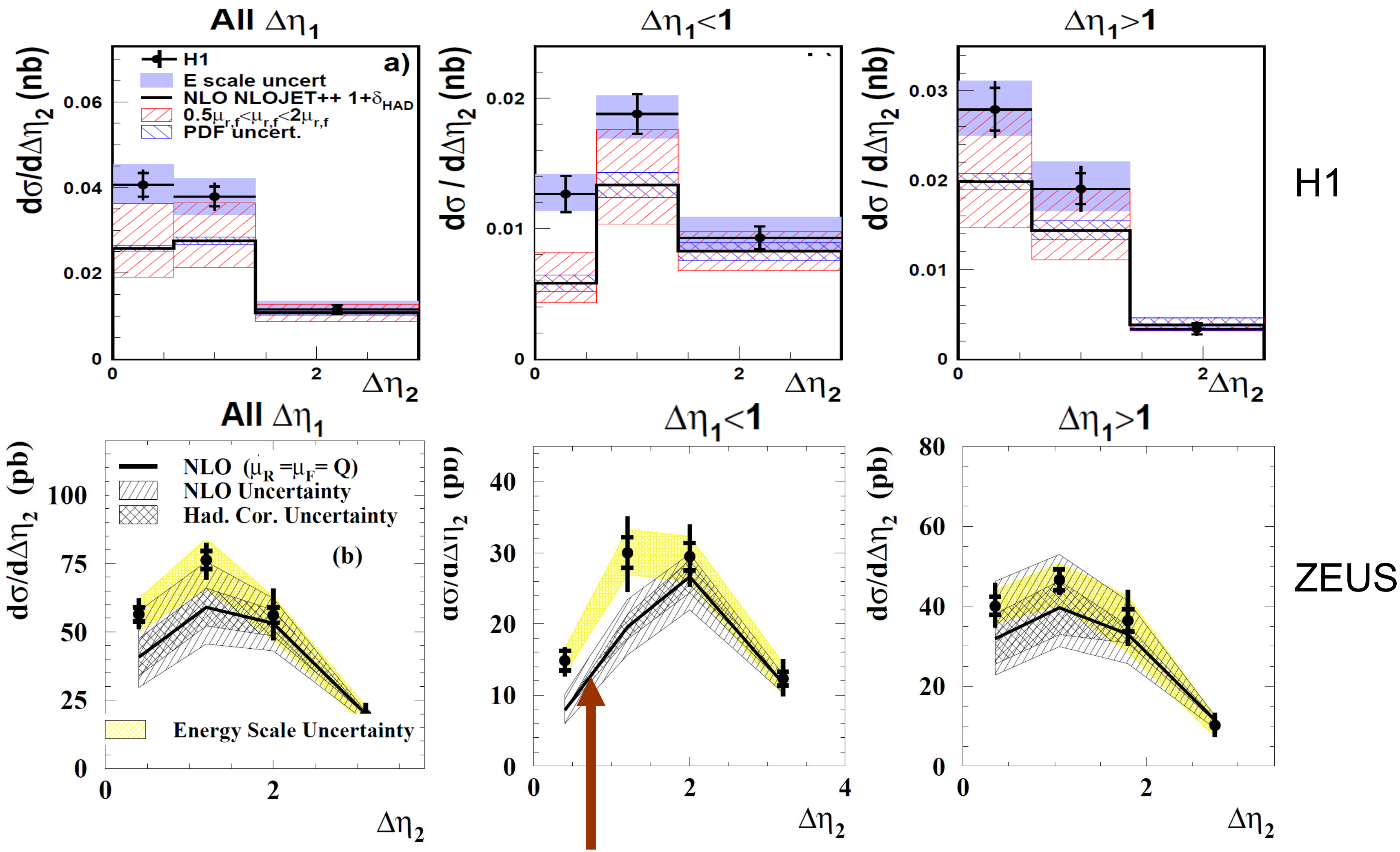
Two additional jets with

$E_t^{jet} > 5$ GeV (ZEUS), 6 GeV (H1)

$\eta_{el} < \eta_{jet\ 1} < \eta_{jet\text{-}2} < \eta_{forward\text{-}jet}$

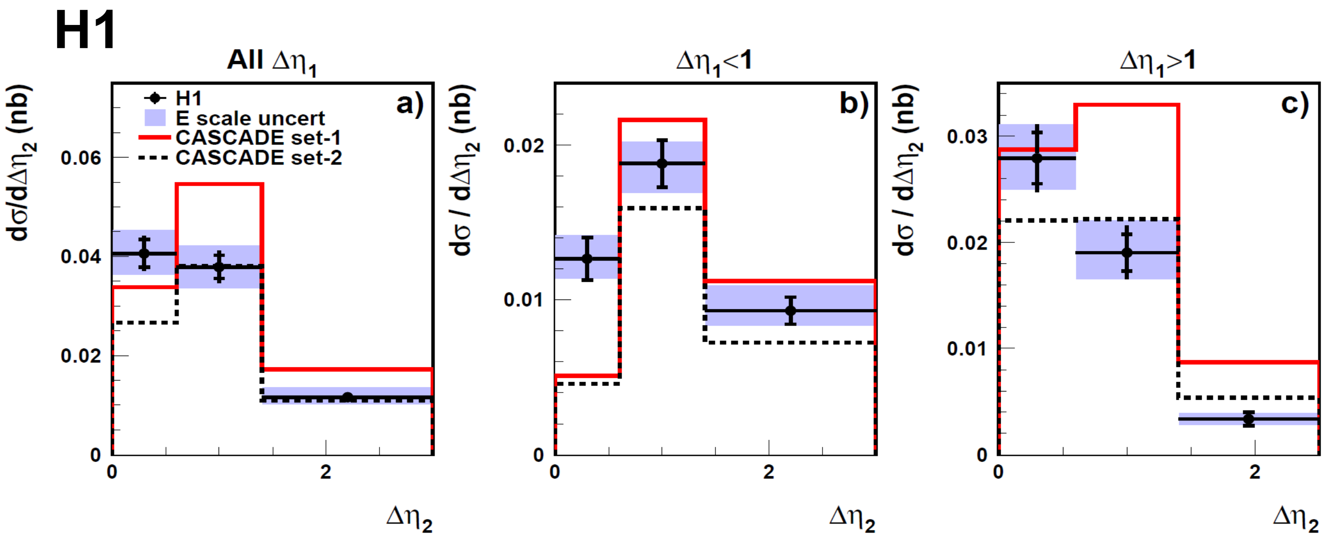


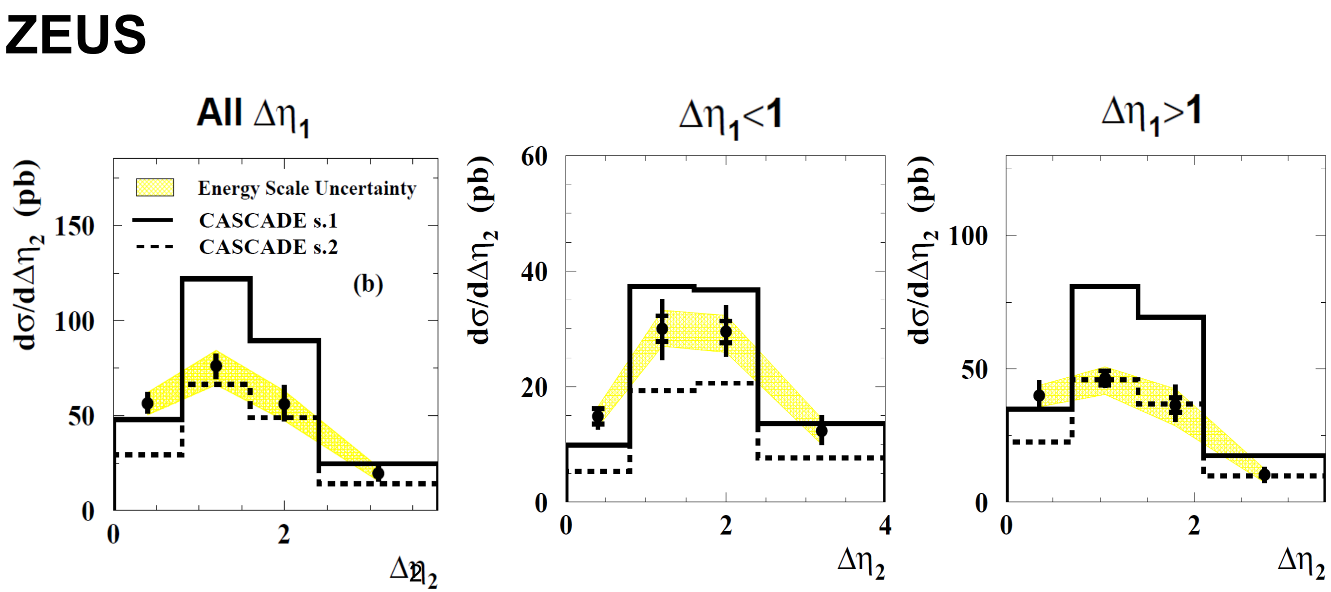
Trijet with a forward jet & fixed order QCD



At small $\Delta\eta_1$ and $\Delta\eta_2$ jets are most forward. At small x_{Bj} space is left for additional partons closer to the photon. NLOJET++ underpredicts >=4 partons → *below data*

Trijet with a forward jet & CASCADE

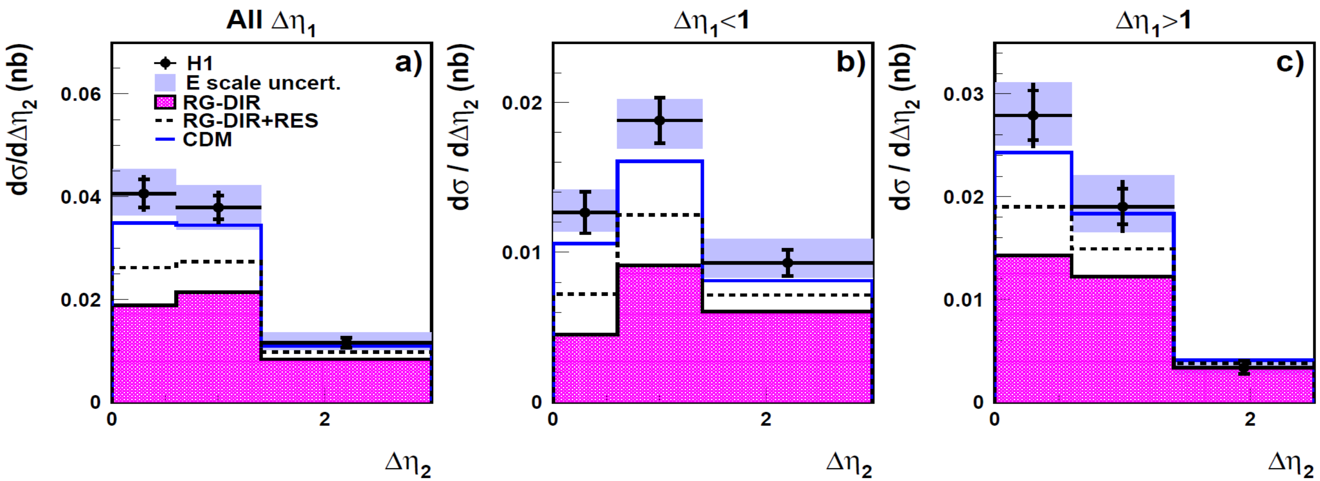




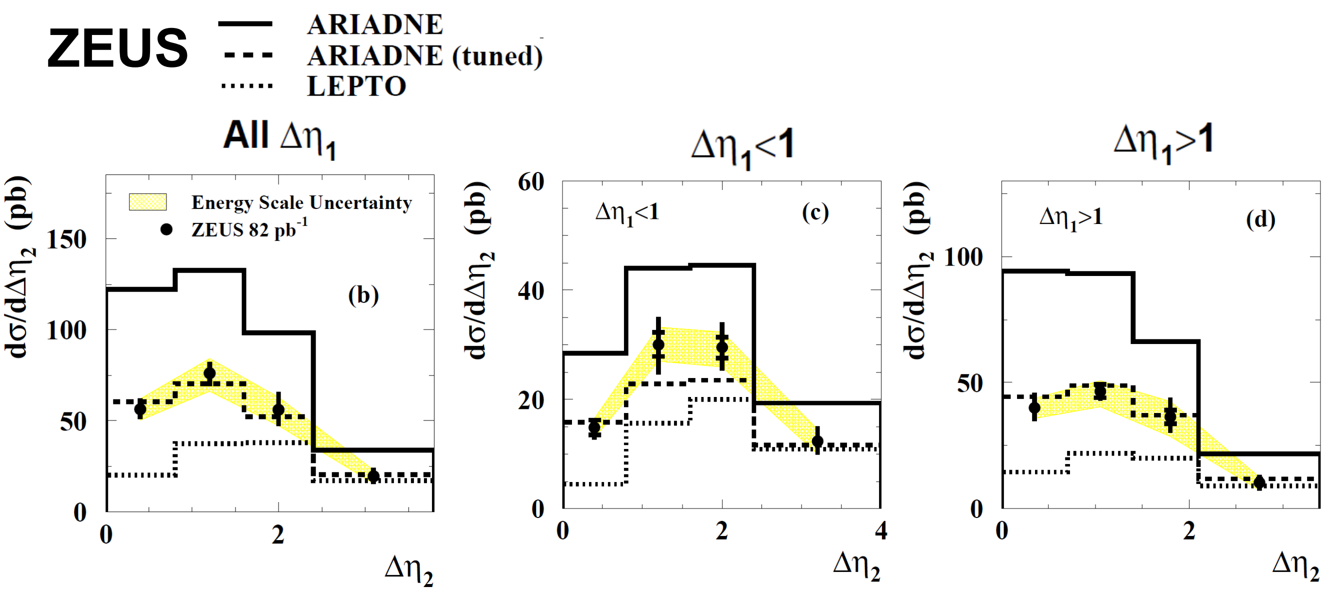
Neither set of uPDF describes the whole set of data

Trijet with a forward Jet

H1

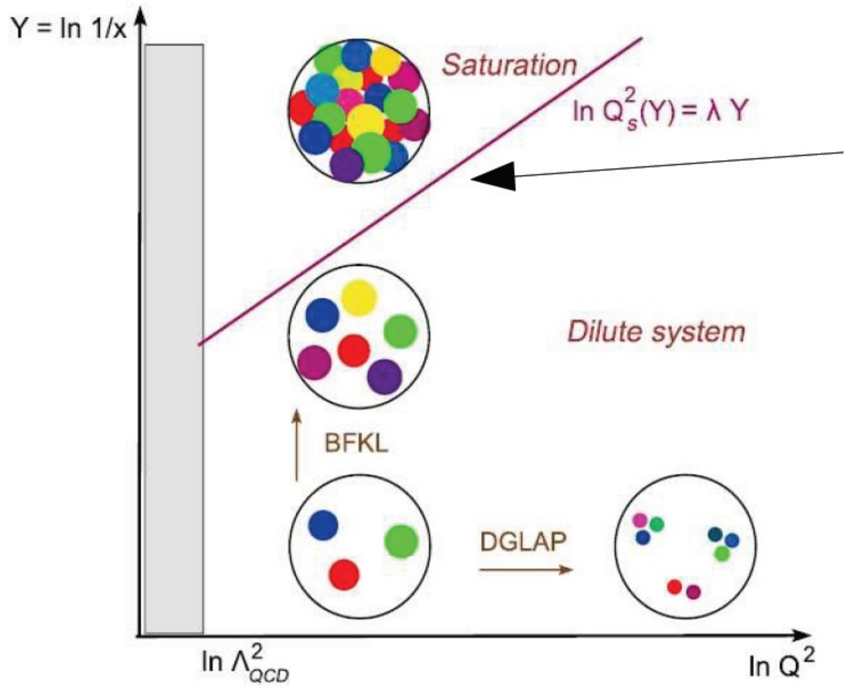


ZEUS



- LEPTO (RG-DIR) much below data
- RG-DIR+RES below data at small $\Delta\eta_2$
- CDM (ARIADNE-tuned) describes data well

Saturation

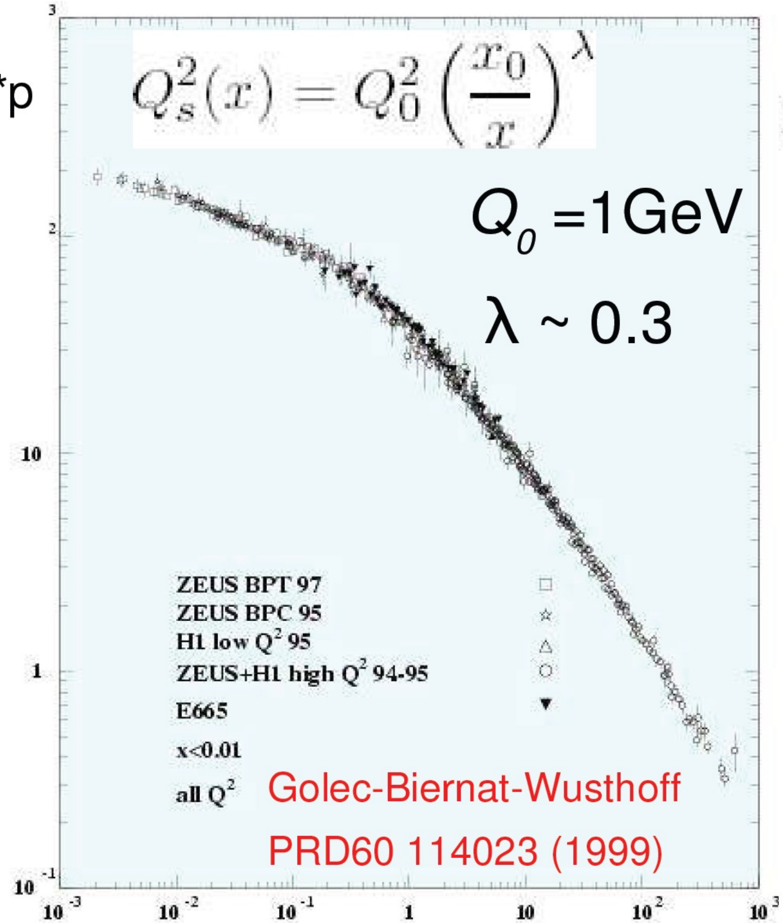


What is considered as HERA's main implications of saturation?

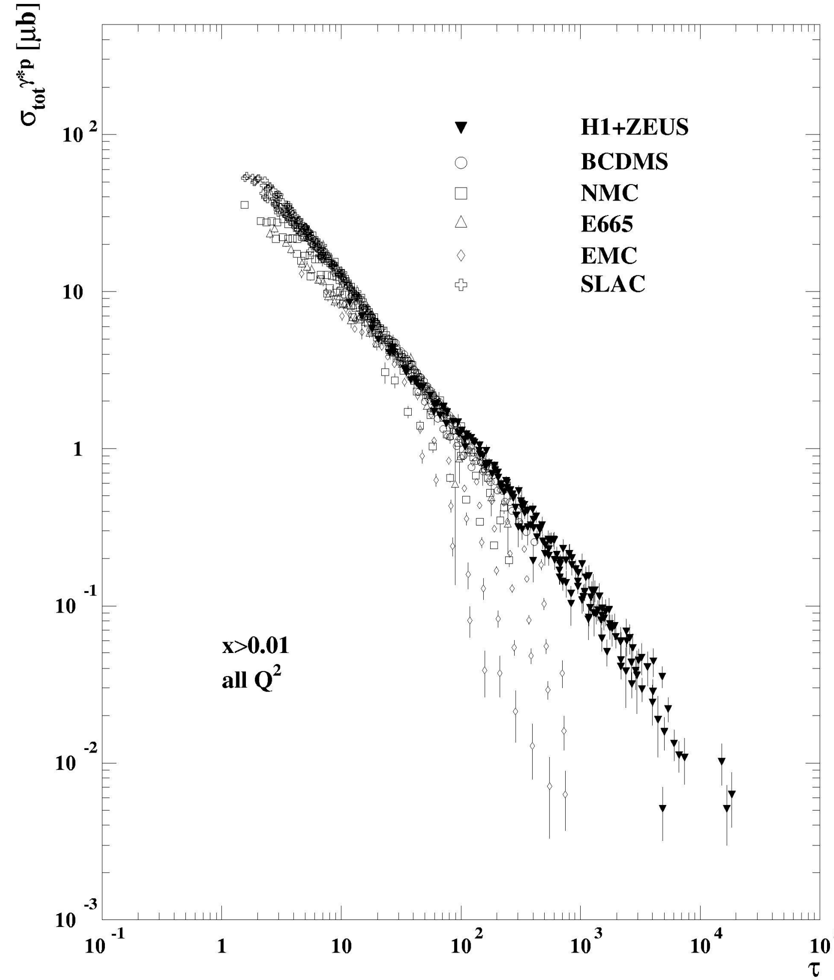
- ❖ **Geometrical scaling**
- ❖ **Flatness of the ratio $\sigma_{dif}/\sigma_{tot}$ in W (or 1/x)**

Geometrical scaling

$\sigma_{\gamma^* p}$



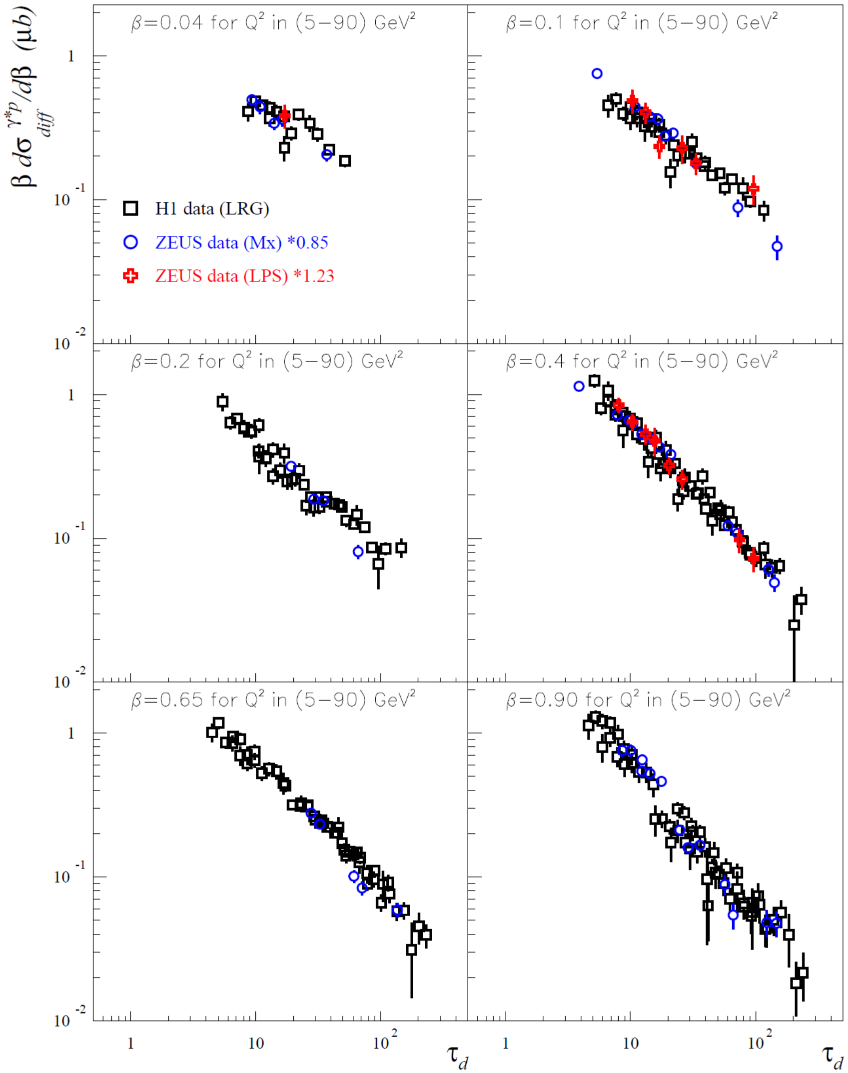
$\tau = Q^2/Q^2_s$

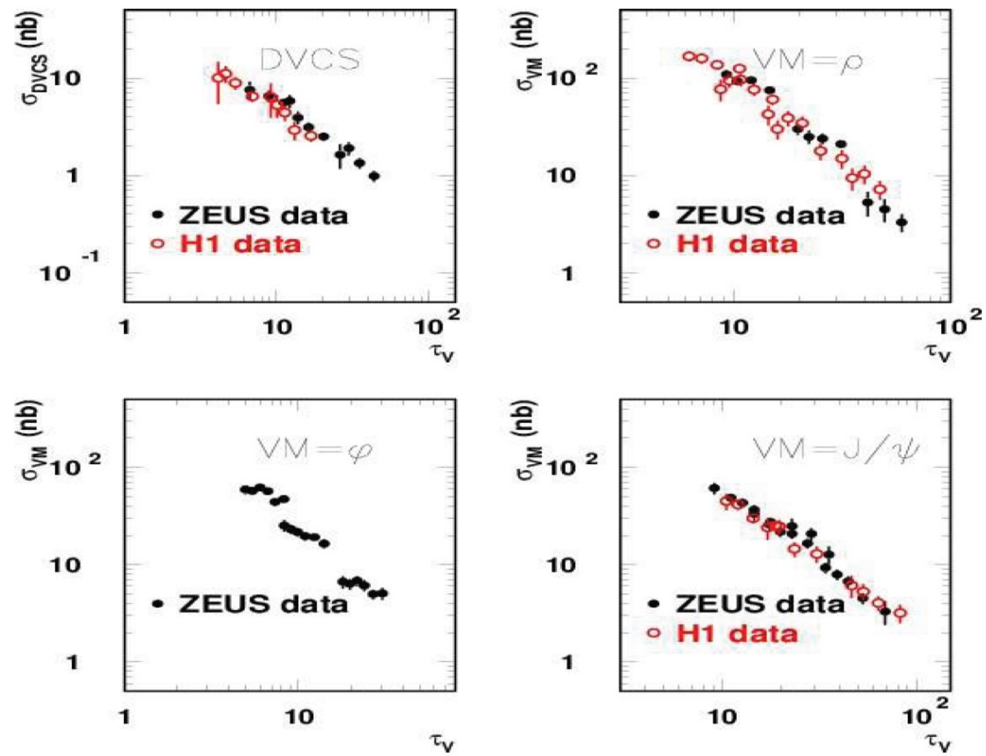


There is scaling at small x

Geometrical scaling

Exclusive data also exhibit geometrical scaling





Geometrical scaling -> saturation

Pro:

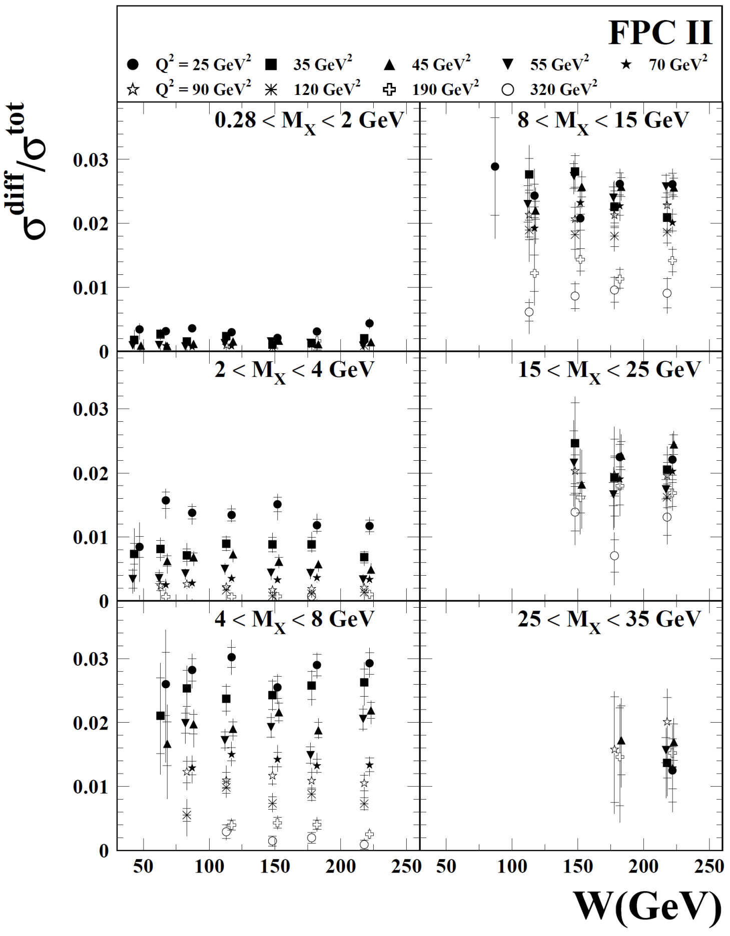
Geometrical scaling very naturally derives from dipole with saturation

Contras:

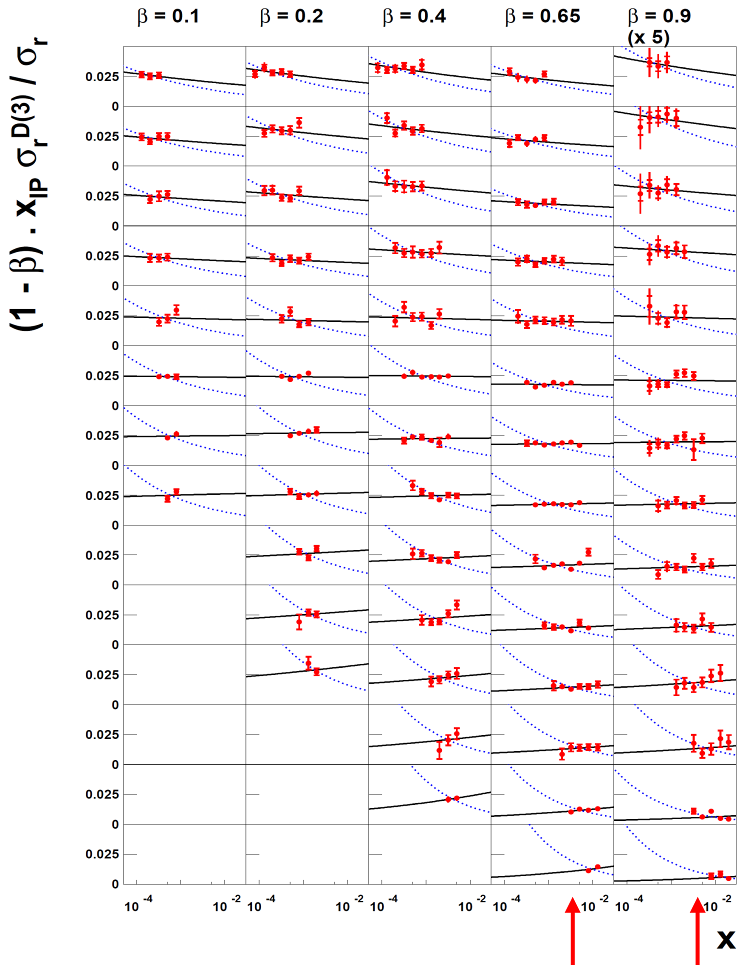
- Seen in the phase space region where there should be no saturation
- Could be obtained from linear BFKL and even DGLAP (at Q^2>5-10 GeV^2)

σ diff/tot puzzle

ZEUS



H1



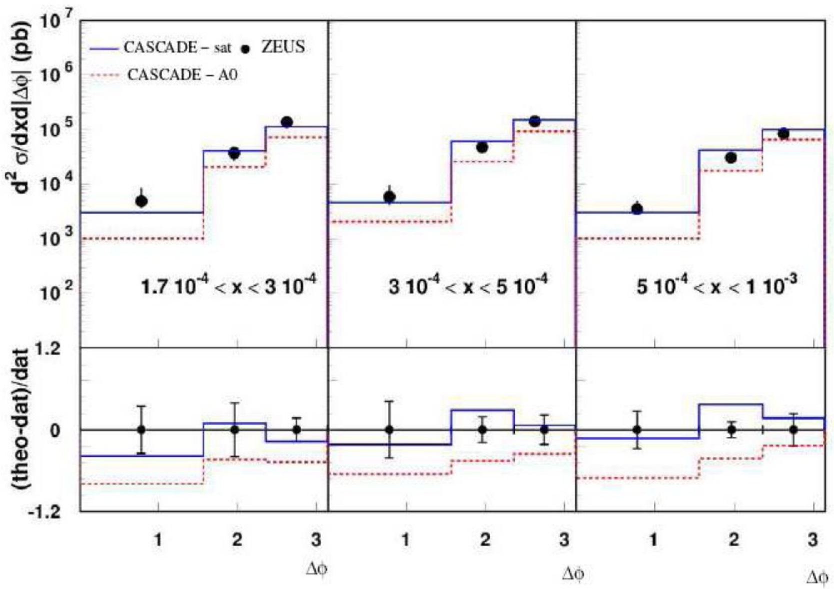
These plots could be measleading since
provoke too plain treatment of saturation

This is not a low-x effect (seen at $x=10^{-3}$-10^{-2})

Saturation & CCFM

Saturation helps CCFM to solve problems in describing experiment at low-x.

CASCADE does not describe ZEUS data on angular correlations in three jets at small x.
After including saturation through absorptive boundary and refitting gluon distribution to data on F_2 agreement is obtained



Conclusions

☎Forward jets at HERA could reveal failure of DGLAP at small x_{BJ}, i.e. large deficiency of leading log resummed DGLAP, and smaller defiecency of NLO DGLAP seen at the smallest x_{BJ}.

☎Breaking of k_T ordering by inclusion of resolved photon improves description but fails at the smallest x_{BJ} in forward jet+dijet case.

☎ LO CCFM based MC, CASCADE, cannot fully describe data on forward jets, other sets of uPDF are to be tried (and/or more serious problems show up, i.e. lack of quarks).

☎ Only CDM (ARIADNE MC), featured by BFKL-like non-ordered in k_T parton cascade, is capable of successful description of the whole volume of data on

forward jets. A problem could to be, nevertheless, that largely being based on phenomenology ARIADNE is too free in tuning.

☎ HERA cannot provide clear indications of saturation. Effects which are considered as indications of saturation, geometrical scaling and constant ratio of diffractive to total cross-sections vs x_{BJ}, unlikely should be considered as such.

However, friendliness of dipole with saturation to HERA, that provides easy and natural solution of almost every problem of HERA data description,

which otherwise requires sofisticated study with unclear results, could be considered as argument in favour of saturation