Forward jet production @ HERA: a challenge for QCD

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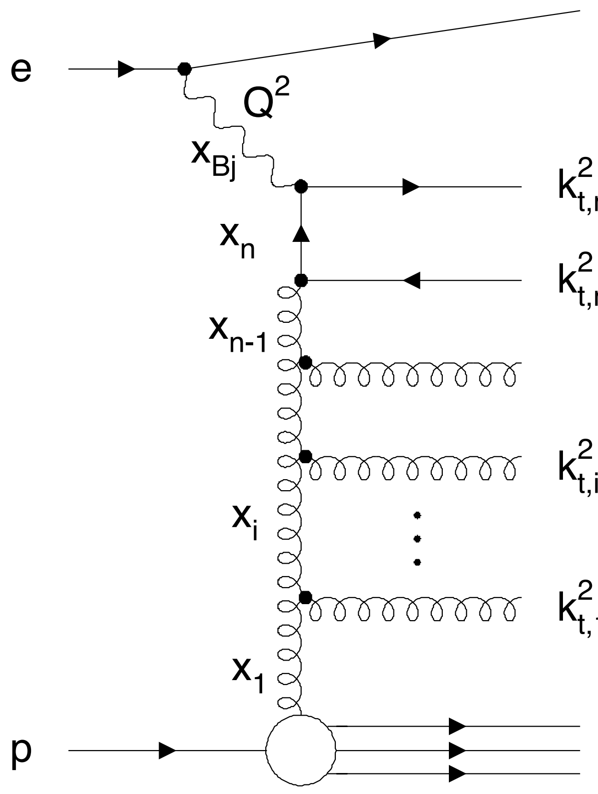
on behalf of H1 and ZEUS

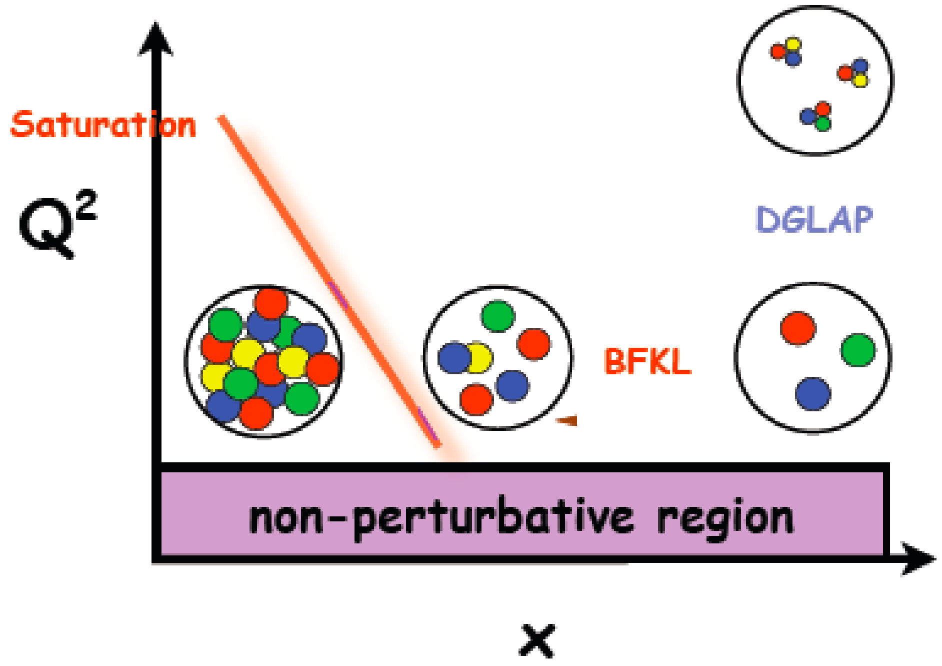
July 19-25, Manchester

- parton dynamics at low x
- incl. forward jets
- forward jet + dijets

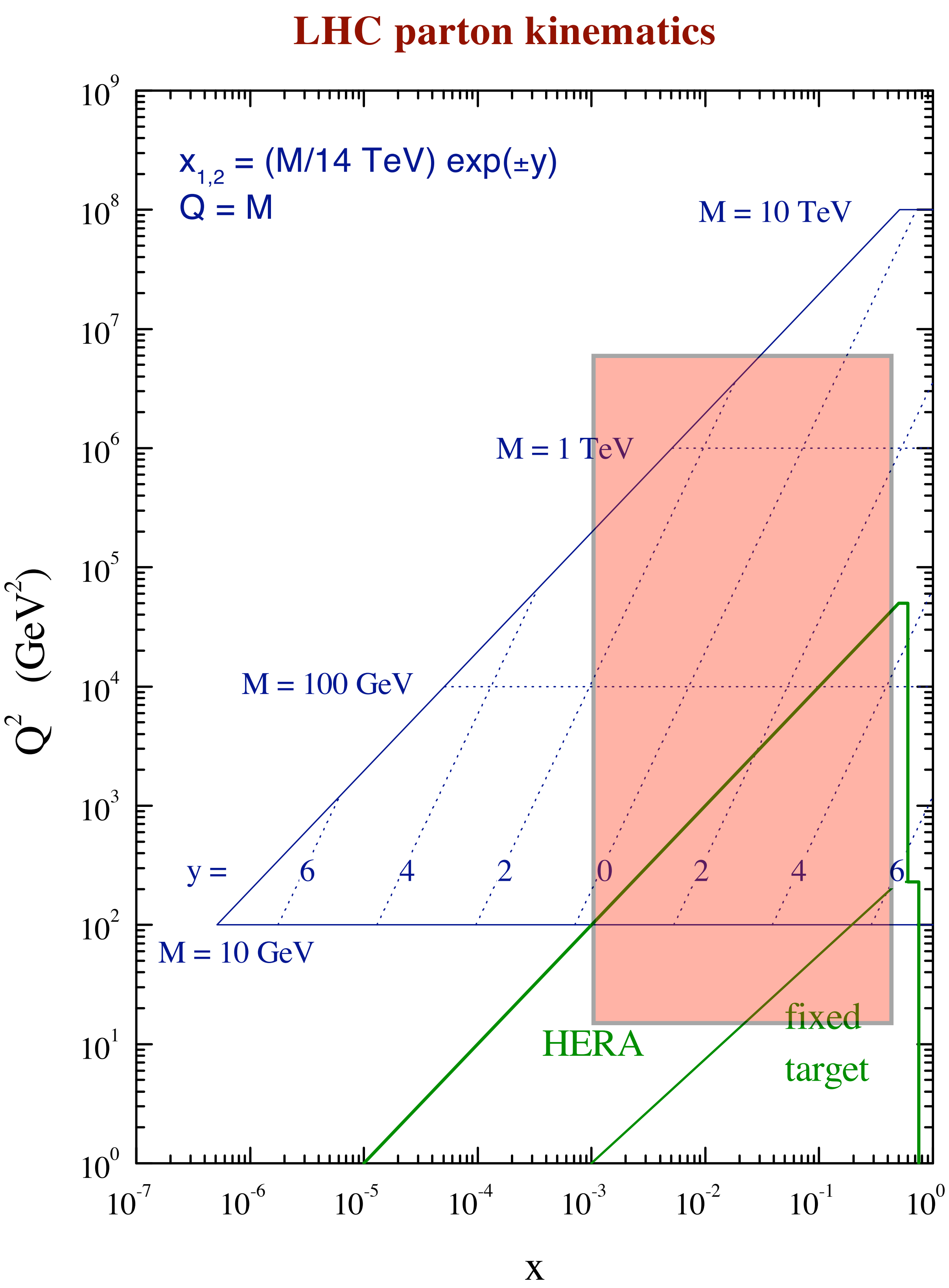
Parton dynamics at low x in ep collisions

- different approximations to the summation of the perturbative expansion of parton evolution
  - DGLAP $\sum(\alpha_s \ln Q^2)^n$
    - strong ordering in virtuality, i.e. $k_{t,1}^2 \ll k_{t,2}^2 \ll \ldots \ll Q^2$
    - weak ordering in x, i.e. $x_1 > x_2 > \ldots > x_{Bj}$
    - works very well at large Q^2; expected to fail at low Q^2 and x
  - BFKL $\sum(\alpha_s \ln 1/x)^n$
    - random walk in k_t
    - strong ordering in x, i.e. $x_1 \gg x_2 \gg \ldots \gg x_{Bj}$
    - expected to work well at low x
  - CCFM $\alpha_s \ln Q^2$ & $\alpha_s \ln 1/x$
    - angular ordering, i.e. $\theta_1 \ll \theta_2 \ll \ldots \ll \theta_n$
    - expected to work at high Q^2 and low Q^2 and x
- novel QCD effects at lowest x when gluon density becomes very large (saturation, cgc, ...)





Parton kinematics at HERA and LHC



- At the LHC at large Q^2 (M^2) and x → take PDFs from HERA and evolve them with Q^2 using DGLAP.
- What about low x ? Are HERA data described by DGLAP down to low x ? If not, what are the implications for the LHC ?
- Are novel QCD effects like saturation, etc. observed ? What are the consequences for LHC ?
- F_2 measurements by H1 & ZEUS are described down to low x by DGLAP evln. alone, but also when adding BFKL terms (e.g. see C.White, R.Thorne, DIS07 talk)
- Look at more exclusive measurements with better sensitivity to BFKL effects

Forward jet measurements in DIS at HERA

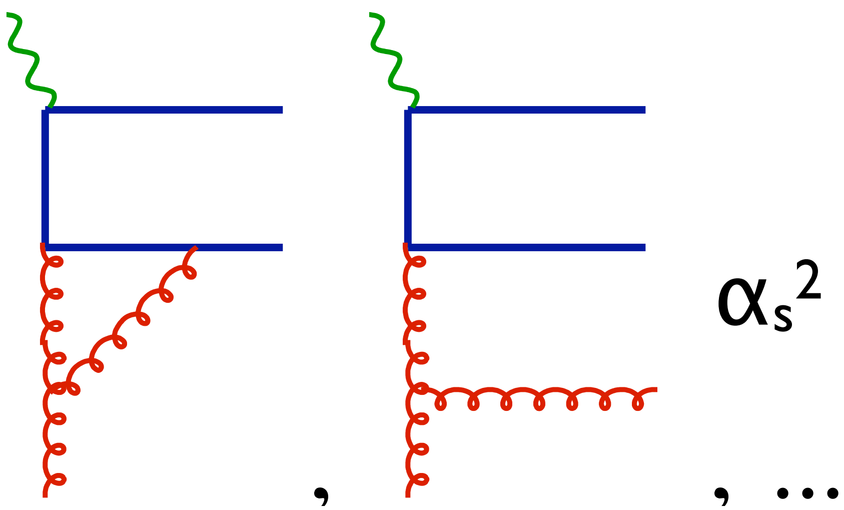
- the following HERA I measurements by H1 and ZEUS will be discussed:
  - inclusive forward jets: dependence on x_{Bj}, Q^2, $E_{T,jet}$, η_{jet}
  - forward jet + dijet: dependence on $\Delta\eta_1$, $\Delta\eta_2$ and on x_{Bj}, ...
- they are compared to
  - NLO QCD calculations (implementing collinear factorisation and DGLAP)
  - models implementing different QCD based assumptions

NLO QCD calculations

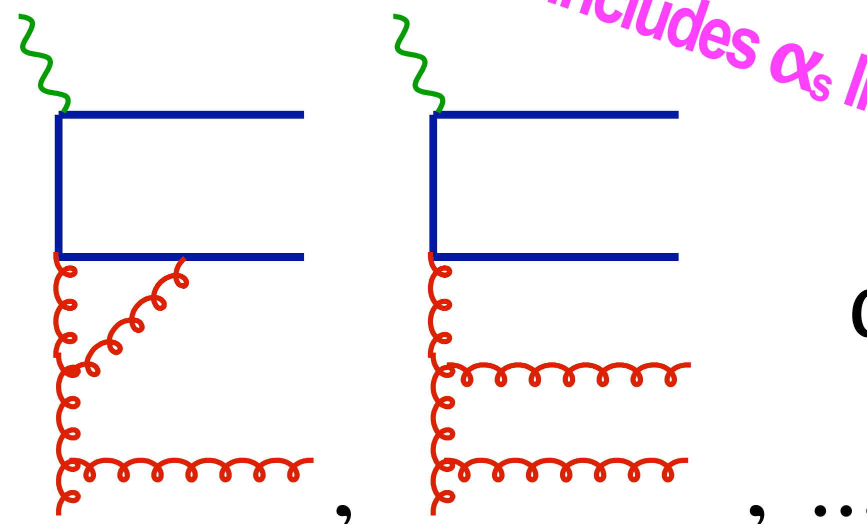
NLO Dijet
DISENT + NLOJET++

NLO Trijet
NLOJET++

includes $\alpha_s \ln 1/x$ terms !



α_s^2

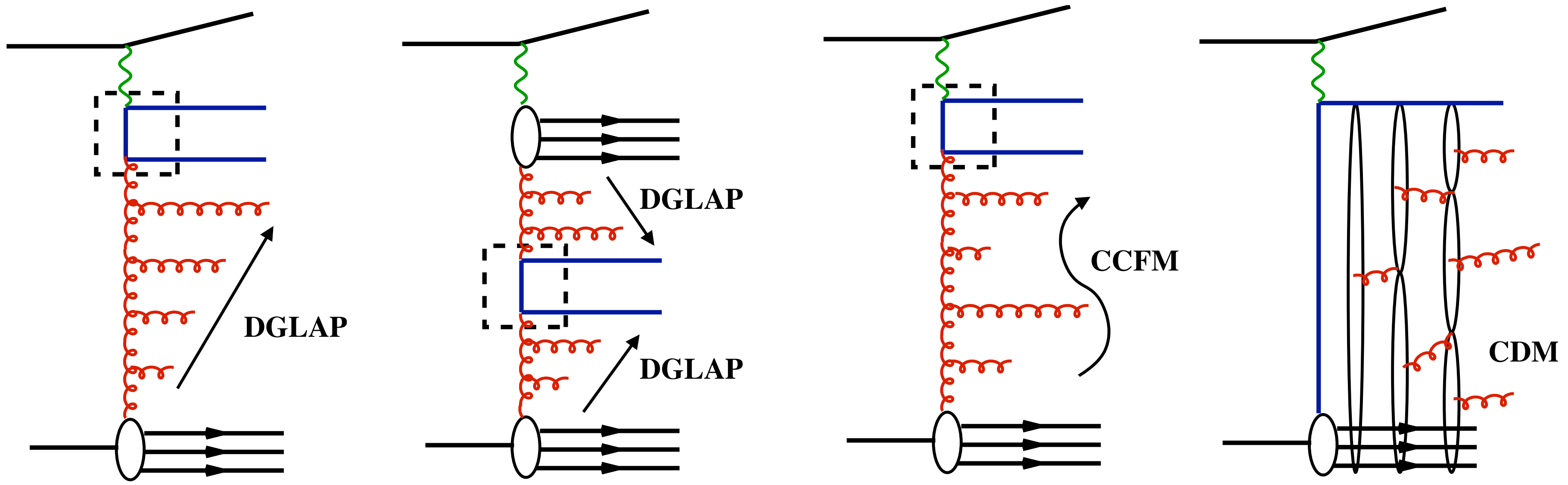


α_s^3

	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

- hadronization corrections are applied to these calculations

QCD Models based on DGLAP, CCFM & CDM



Lepto/Rapgap DIR

Rapgap DIR+RES

Cascade DIR

ARIADNE

DGLAP resums lnQ^2
at low x, strong ordering of k_T
of emitted partons
$g(x,\mu^2)$

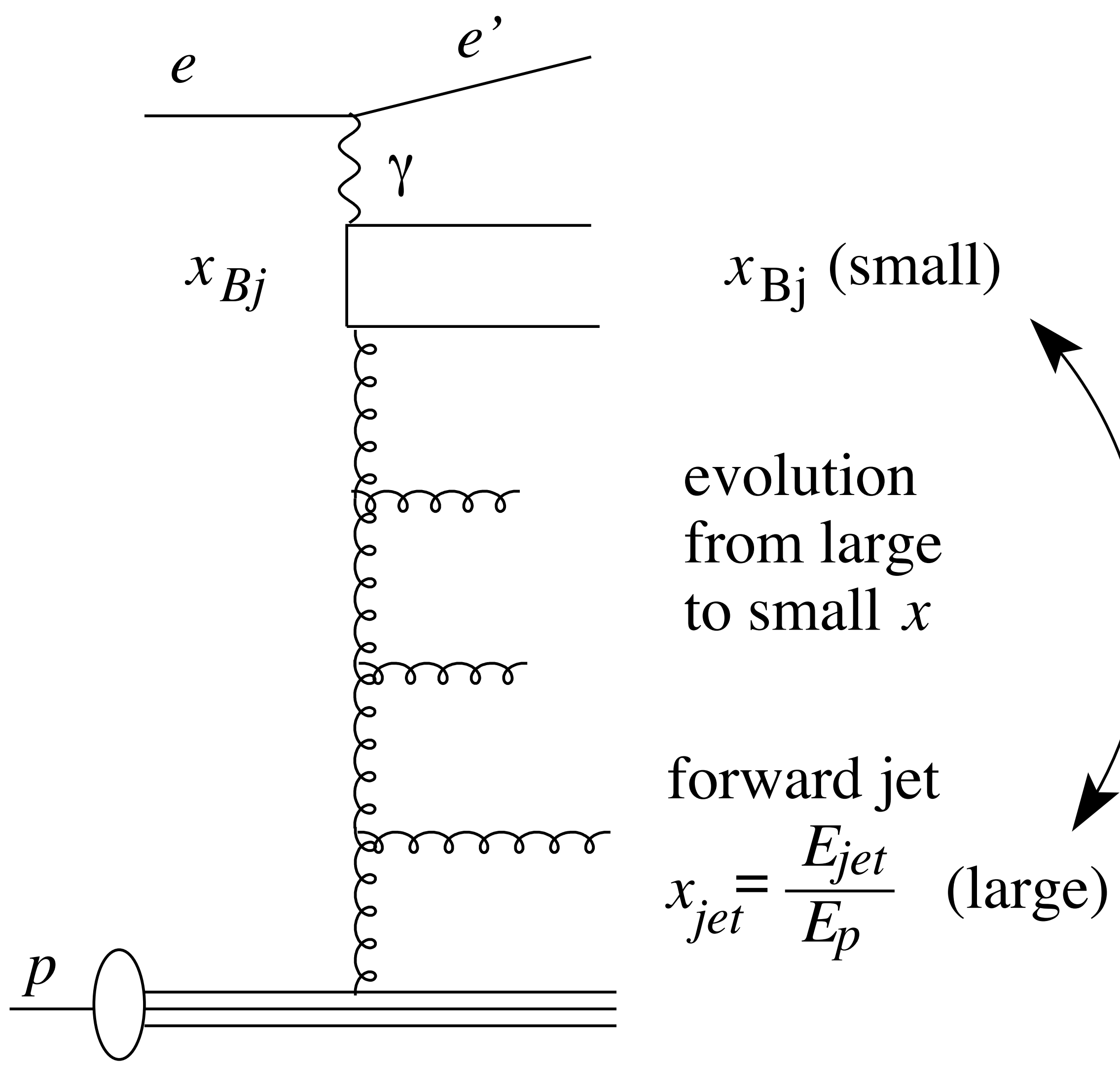
CCFM resums lnQ^2 & ln1/x
angular ordering of partons
off-shell ME
$g(x,k_T,\mu^2)$

Color Dipoles radiate
independently
k_T non-ordered partons

$\mu_R^2 = \mu_F^2$	$Q^2 + < p_{T,dijet}^2 >$
proton PDF	CTEQ6L
photon PDF	SaS1D

μ_R^2	$< p_{T,dijet}^2 > + \hat{s}^2$
μ_F^2	shat + Q^2_T
proton PDF	J2003 set-1 & set-2

Forward jets in DIS



- in DGLAP the strong ordering in virtuality gives softest p_t gluon closest to proton
- suppress DGLAP: $p_{T,jet}^2 \approx Q^2$
- in BFKL the gluon p_T close to the proton can be hard; strong ordering occurs in x
- enhance BFKL: $x_{jet} >> x_{Bj}$

☛ measure forward jet as close to the proton as possible

☛ x_{Bj} as small as possible

☛ $p_{T,jet}$ as small as possible, since $p_{T,jet}^2 \approx Q^2$ forces Q^2 to increase, which in turn increases min. x_{Bj}

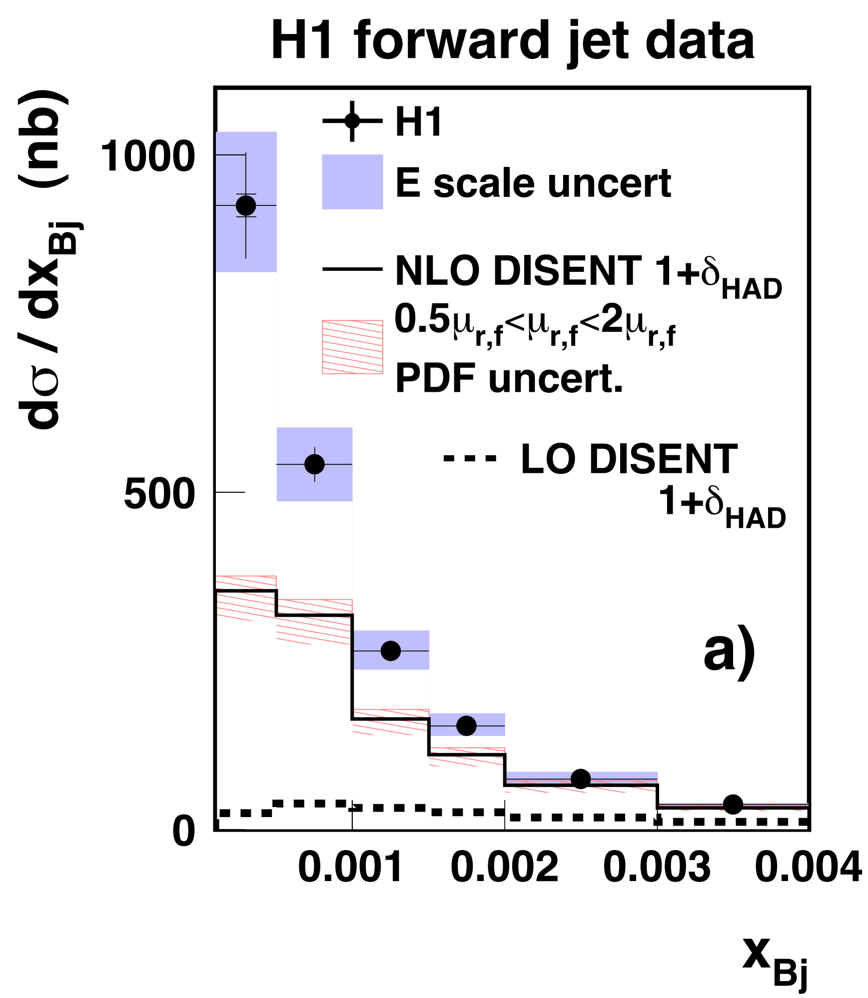
Incl. forward jet requirements

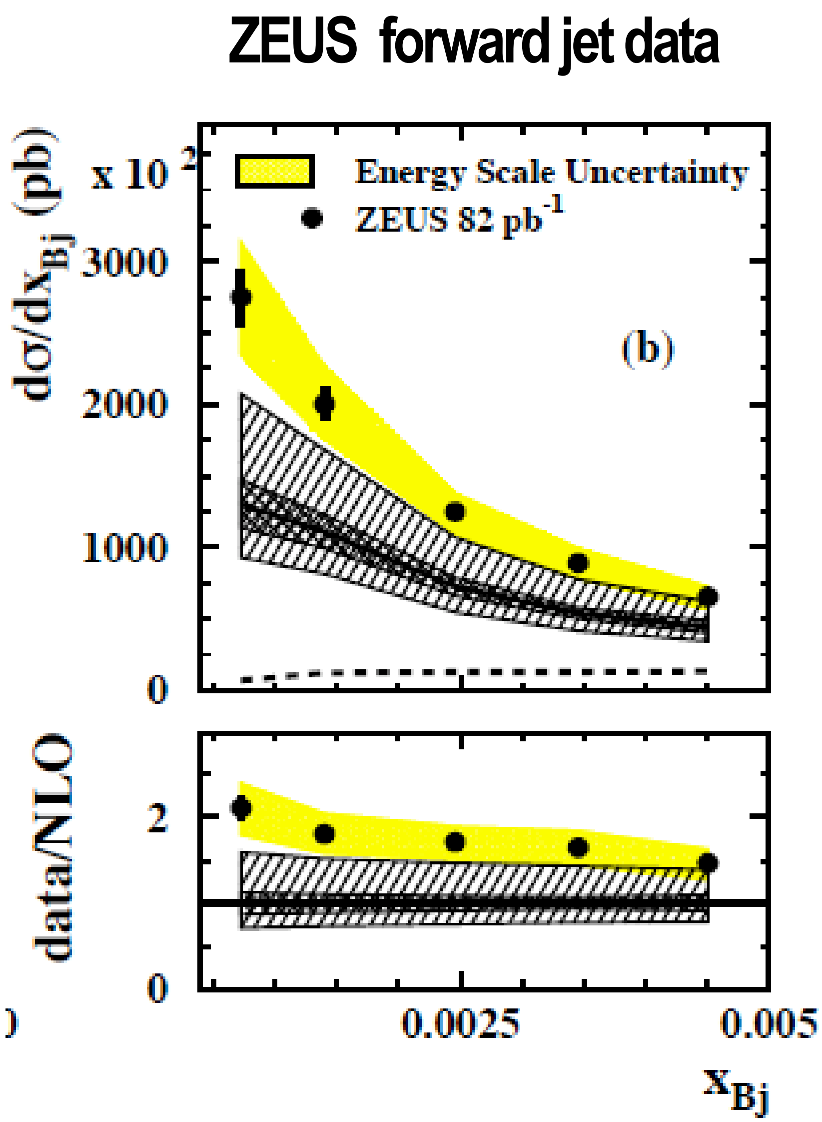
	H1	ZEUS
Q^2 [GeV^2]	5 - 85	20 - 100
y	0.1 - 0.7	0.04 - 0.7
x_{Bj}	10^{-4} - 4 10^{-3}	4 10^{-4} - 5 10^{-3}
$p_{T,jet}$ [GeV]	3.5	5
η_{jet} (θ_{jet})	1.74 - 2.79 (20° - 7°)	2 - 4.3 (15.4° - 1.6°)
x_{jet}	> 0.035	> 0.036
$r = p_{T,jet}^2/Q^2$	0.5 - 5.0	0.5 - 2.0

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

significantly increased coverage with FPC !

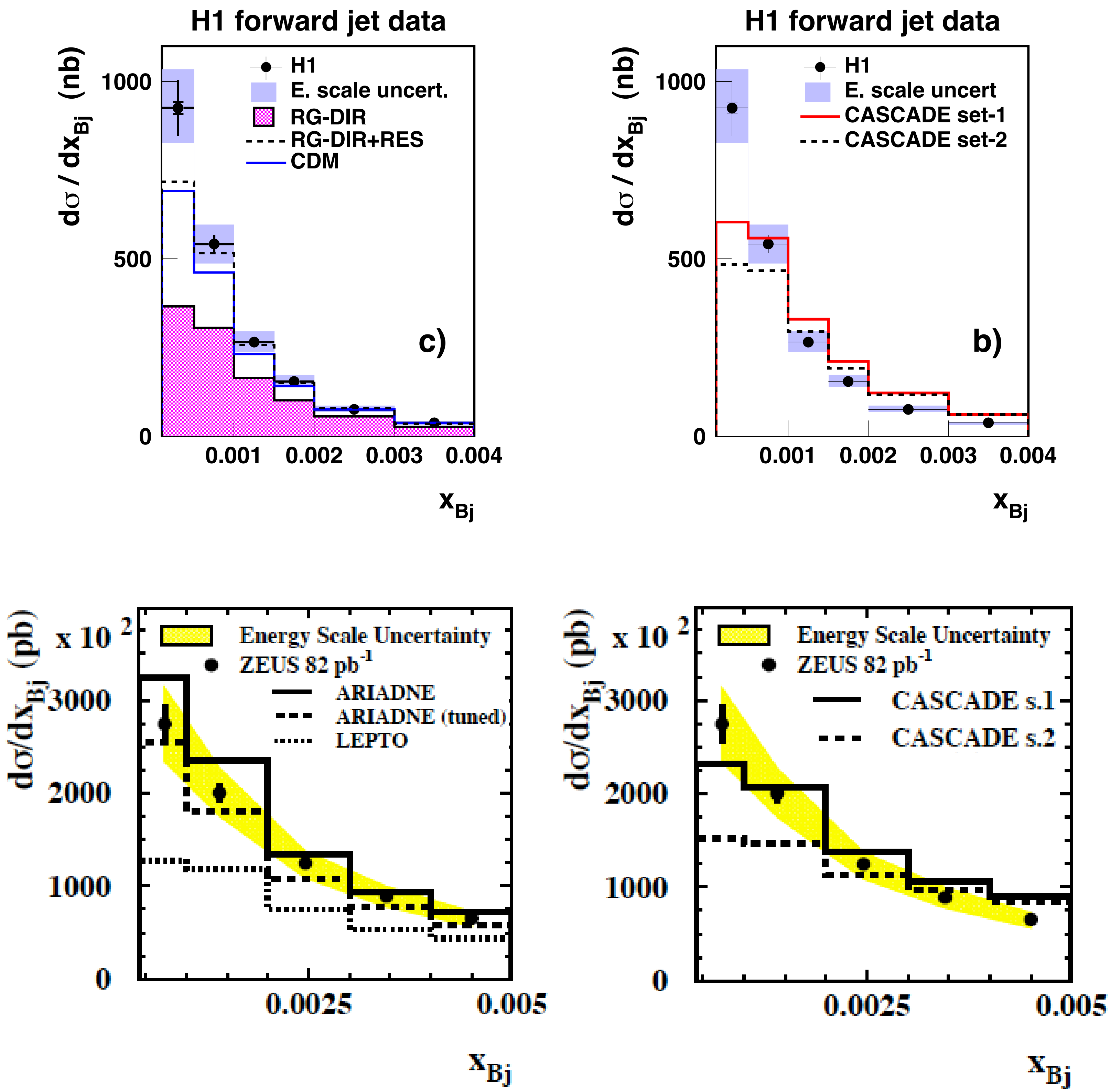
Forward jets & NLO: $d\sigma/dx_{Bj}$





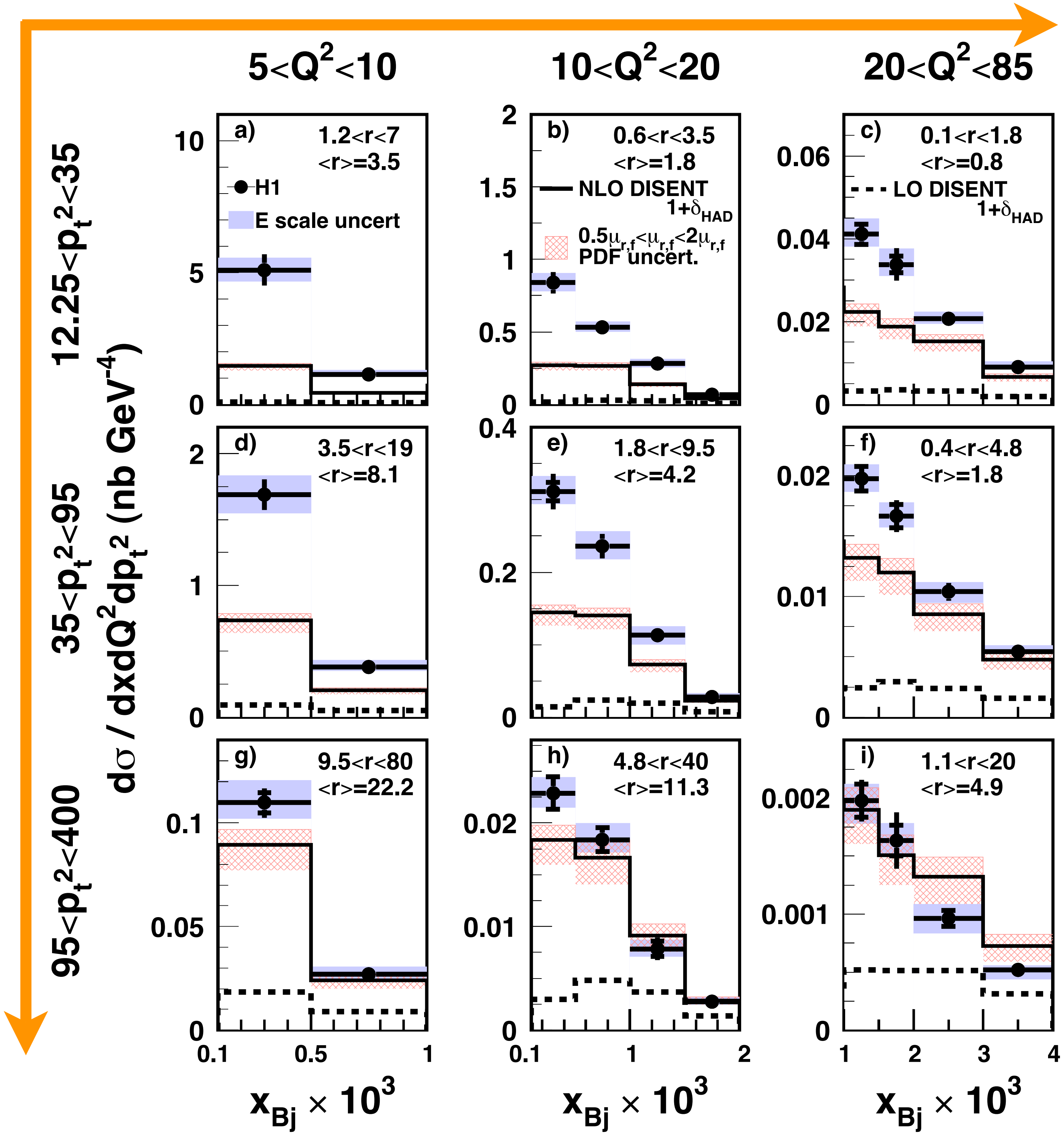
- H1 data exhibits steeper slope than ZEUS data due to lower Q^2 and x_{Bj}
- Large k-factor from LO to NLO; mainly due to kinematics ☛ NLO more like LO
- ☛ at small x_{Bj} data clearly above NLO calc.
- ☛ higher order contributions are important in his phase space
- H1 indicates smaller theory scale error

Forward jets & QCD models: dσ/dx$_{Bj}$



- ☞ Rapgap (RG-DIR) & LEPTO fail to describe data
- ☞ RG-DIR+RES & CDM provide a reasonable description; CDM = ARIADNE (tuned)
- ☞ CASCADE with the unintegrated gluon densities set1 & set 2 also fails; shape is not described

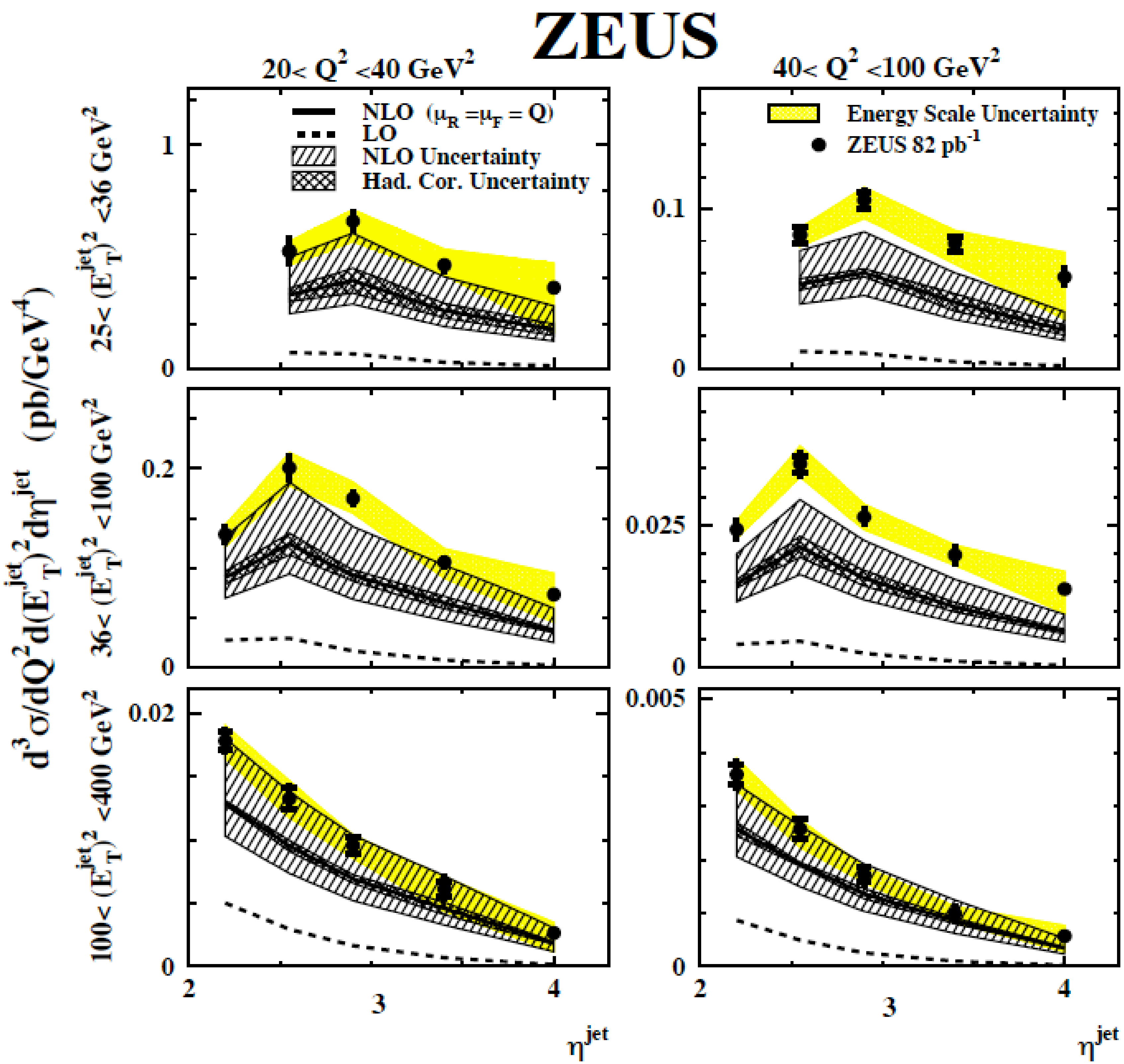
Forward jets: $d^3\sigma/dx_{Bj}dQ^2dp_{T,jet}^2$ H1



- here we only compare data to NLO (for QCD models see paper)
- σ as a function of x_{Bj} in bins of $p_{T,jet}^2$ - Q^2 (no cut on $r = p_{T,jet}^2/Q^2$)
- range and average r shown for each bin

- ☛ NLO in general below data
- ☛ NLO better at high x_{Bj}, Q^2 and $p_{T,jet}^2$ (for jet with high $p_{T,jet}^2$ less energy left for gluon radiation)

Forward jets: $d^3\sigma/dx_{Bj}dQ^2d\eta_{jet}$ ZEUS



- here we only compare data to NLO (for models see paper)
- σ as a function of η_{jet} in bins of $E_{T,jet}^2$ - Q^2 (no cut on $r = E_{T,jet}^2/Q^2$)

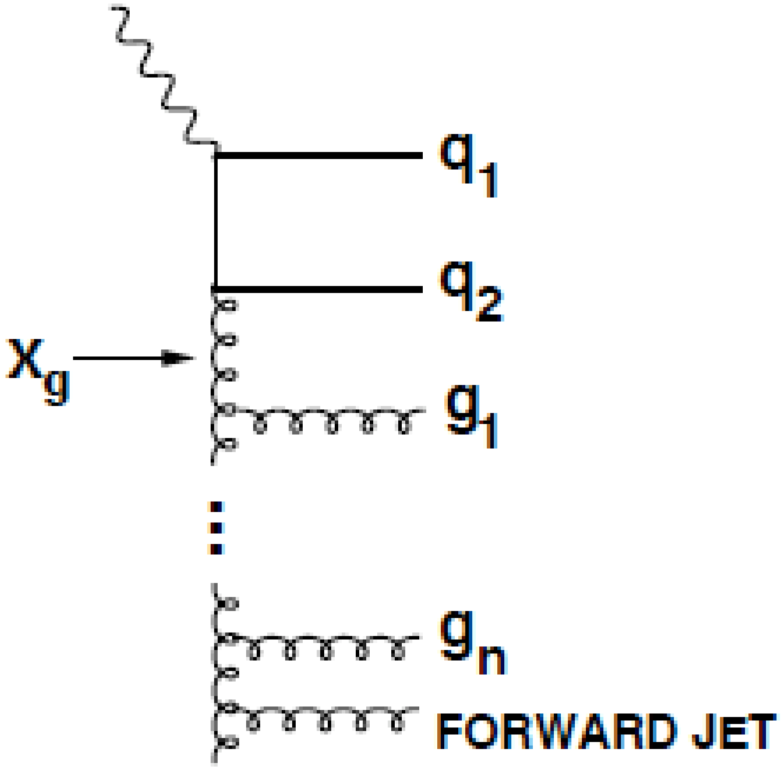
- ☛ NLO in general below the data as for H1
- ☛ better at large $E_{T,jet}^2$
- ☛ largest discrepancy seen in high Q^2 bin for $E_{T,jet}^2 < 100$ GeV^2 (region of multi-gluon emissions not included in NLO)

Forward jet & dijet requirements

- for the forward jet the same cuts are applied as already mentioned (except for $p_{T,fwdjet}$ in case of H1) and no cut on $p_{T,jet}^2 / Q^2$
- all other cuts are given here
- of the dijets the two jets with the highest E_T are taken
- the three jets are ordered in η_{jet} : $\eta_e < \eta_1 < \eta_2 < \eta_{fwd}$

	H1	ZEUS
$p_{T,fwdjet}$ [GeV]	6	5
$p_{T,jet1,2}$ [GeV]	6	5
$\eta_{jet1,2}$	$\eta_e < \eta_1 < \eta_2 < \eta_{fwd}$	-1.5 - 4.3

Forward jet & dijet

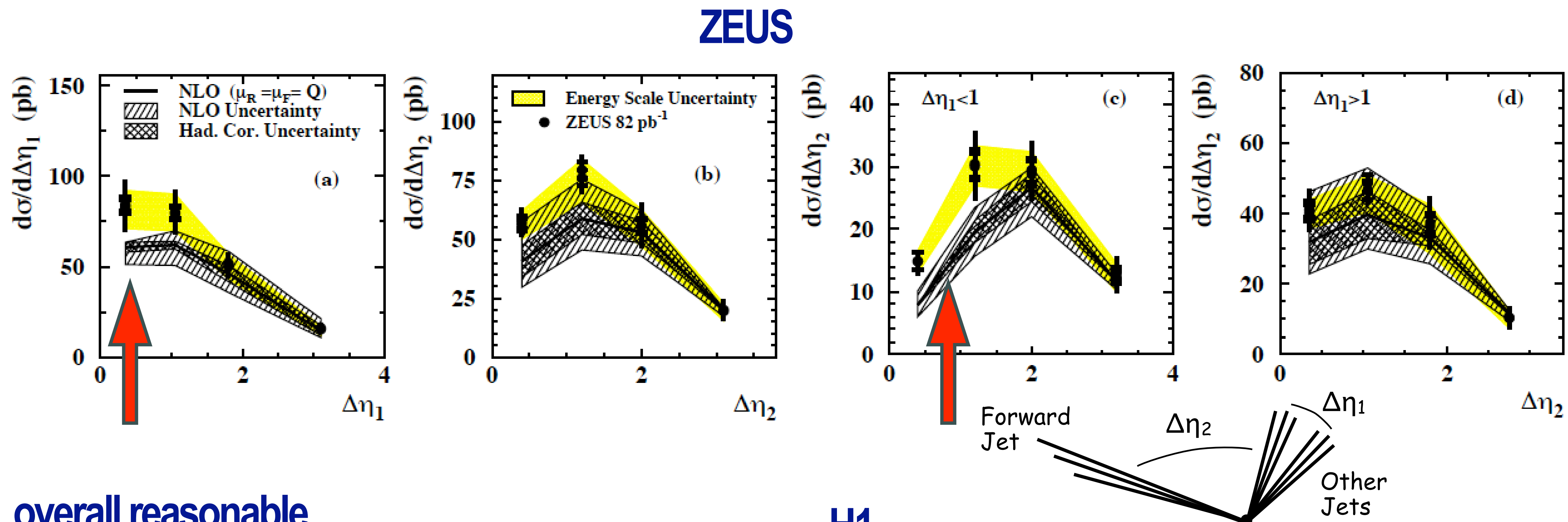


$\Delta\eta_1 = \eta_2 - \eta_1$

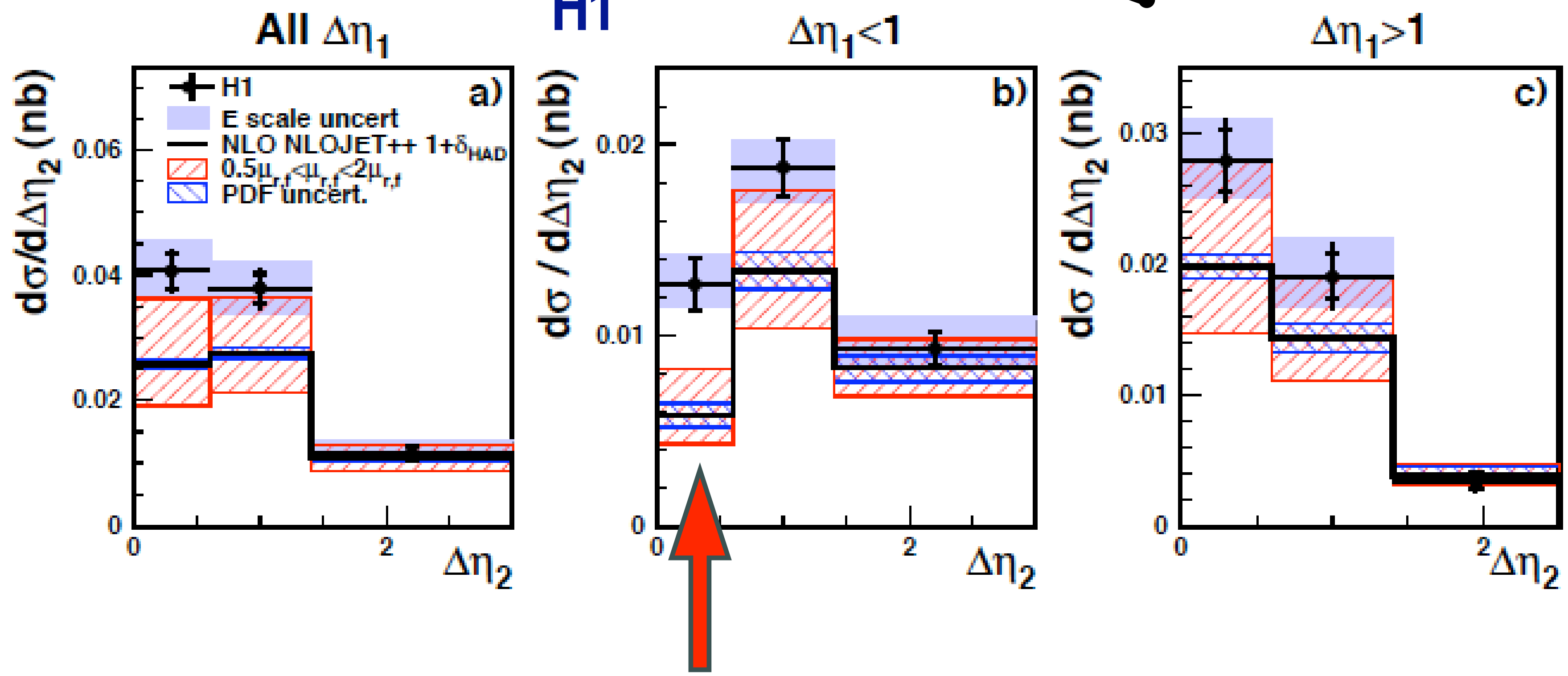
$\Delta\eta_2 = \eta_{fwd} - \eta_2$

- by applying the same $p_{T,jet}$ cut to all three jets strongly k_T ordered emissions are disfavoured
- jets are ordered in rapidity: $\eta_e < \eta_1 < \eta_2 < \eta_{fwd}$
- x-sections are measured as a func. of $\Delta\eta_1$ and $\Delta\eta_2$ and as a func. of $\Delta\eta_2$ for two regions, i.e. $\Delta\eta_1 < 1$ and $\Delta\eta_1 > 1$
- if $\Delta\eta_1 = \eta_{q2} - \eta_{q1}$ and small ☛ x_g small)
- if $\Delta\eta_1$ large ☛ one may be sensitive to BFKL gluons between the dijets
- if $\Delta\eta_2$ small ☛ jet 1 and jet 2 may be due to gluon radiation close in η to the fwd jet

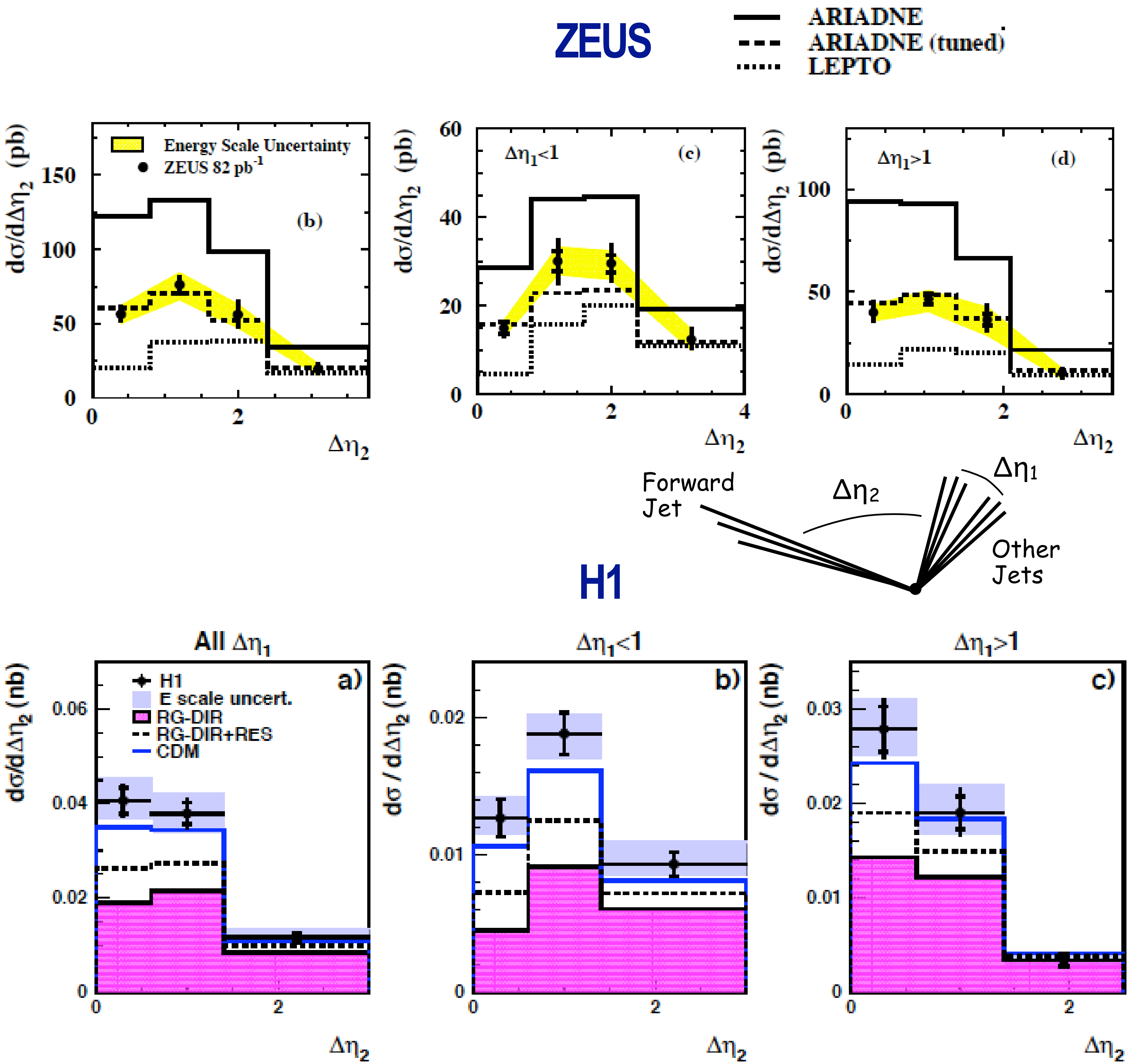
Forward jet & dijet and NLO



- overall reasonable description of data by NLOJET++ with partly large scale uncertainty
- discrepancy at low $\Delta\eta_1$ and $\Delta\eta_2$, i.e. where all 3 jets tend to go fwd.
- ☛ additional higher orders or BFKL resummation needed



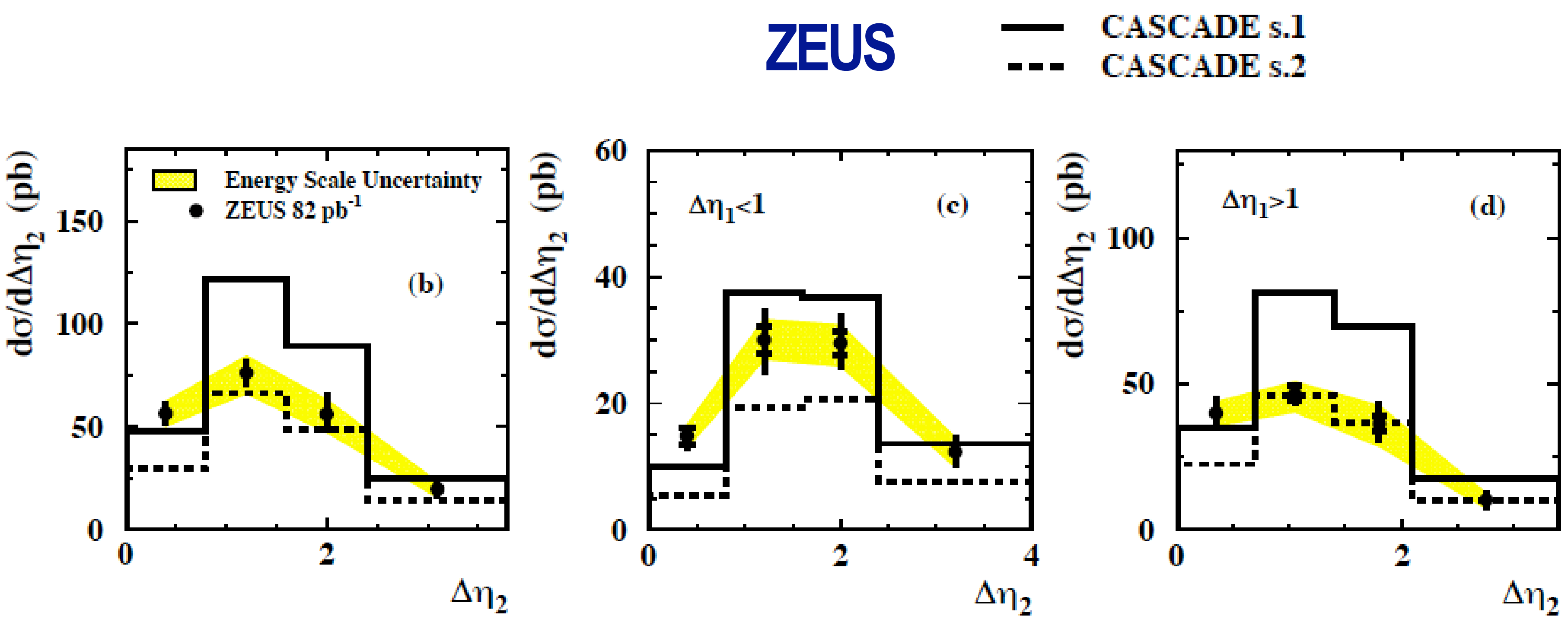
Forward jet & dijet and QCD models

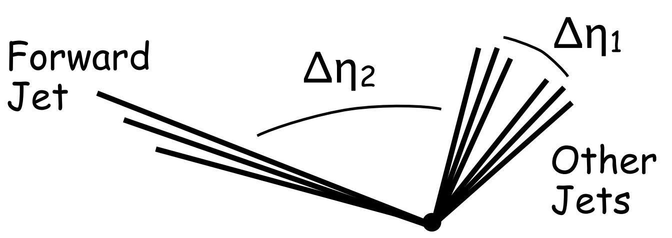


- ARIADNE (tuned) = CDM
- LEPTO ≈ RG-DIR
- RG-DIR+RES

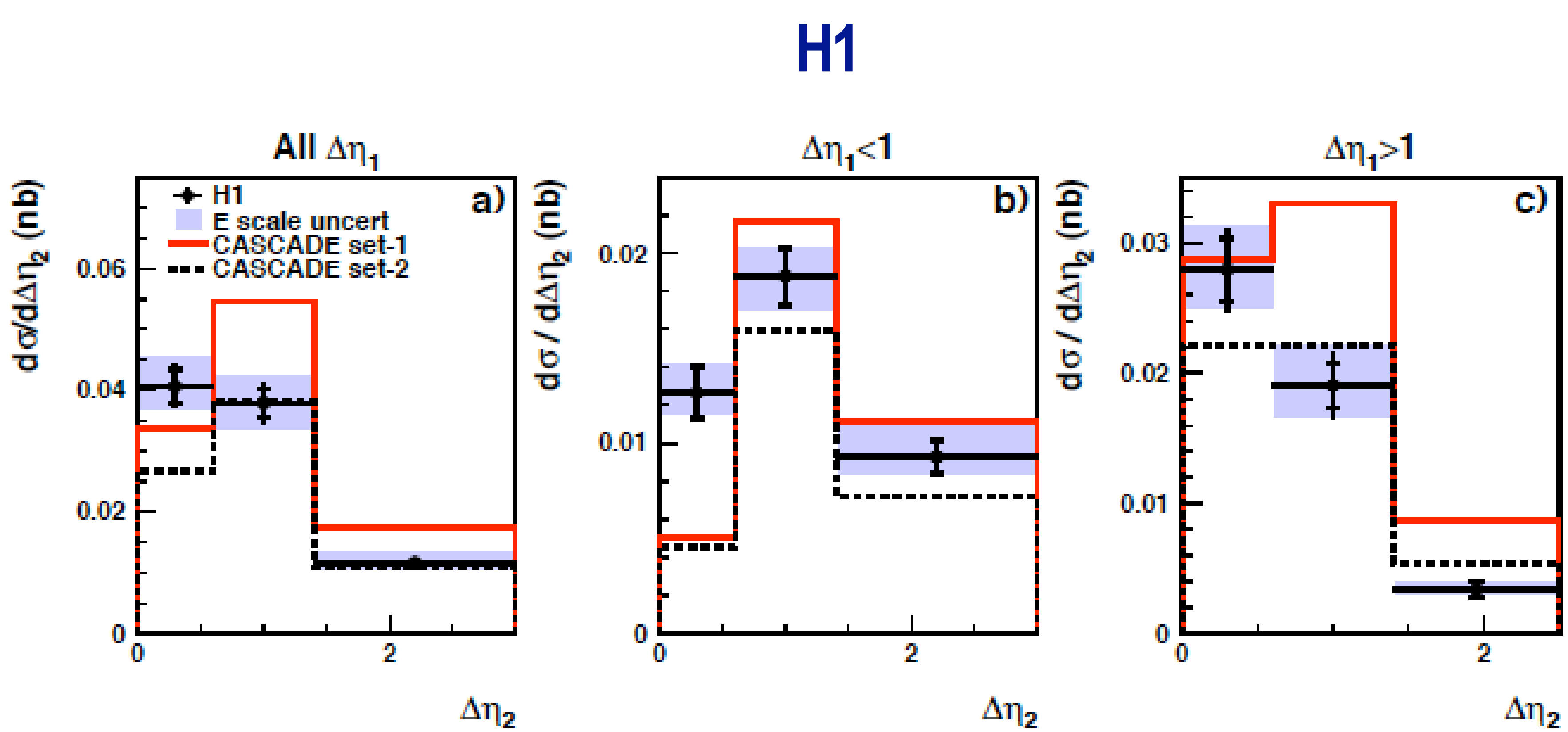
- ☛ CDM describes data reasonably well
- ☛ RG-DIR & LEPTO fail completely, RG-DIR+RES fails at small $\Delta\eta_2$
- ☛ the breaking of k_T ordering is best modelled by CDM, but not by RG-DIR+RES contrib. a la DGLAP;
- ☛ fwd-jet + dijet sample allows to distinguish between RG-DIR+RES and CDM

Forward jet & dijet and QCD model CASCADE





- ☛ **CASCADE** with current unintegrated gluon densities is not able to describe data



“Exclusive” trijets in DIS

- H1 preliminary result on trijets at low x and Q^2 (see also previous talk by Mara Soares)
- here we will look only at topologies of
  - 1 fwd-jet & 2 central jets and
  - 2 fwd-jets & 1 central jet
- DIS phase space
  - $5 < Q^2 < 80$ GeV^2
  - $0.1 < y < 0.7$
  - $0.0001 < x_{Bj} < 0.01$
- jet phase space (incl. k_T algo in γ^*p-frame)
  - $E_{T,jet1,2,3} > 4$ GeV
  - $E_{T,jet1} + E_{T,jet2} > 9$ GeV
  - $-1 < \eta_{lab} < 2.5$
  - 1 jet has to be a fwd-jet
    - $\theta_{jet} < 20°$ ($\eta_{jet} > 1.74$)
    - $x_{jet} > 0.035$

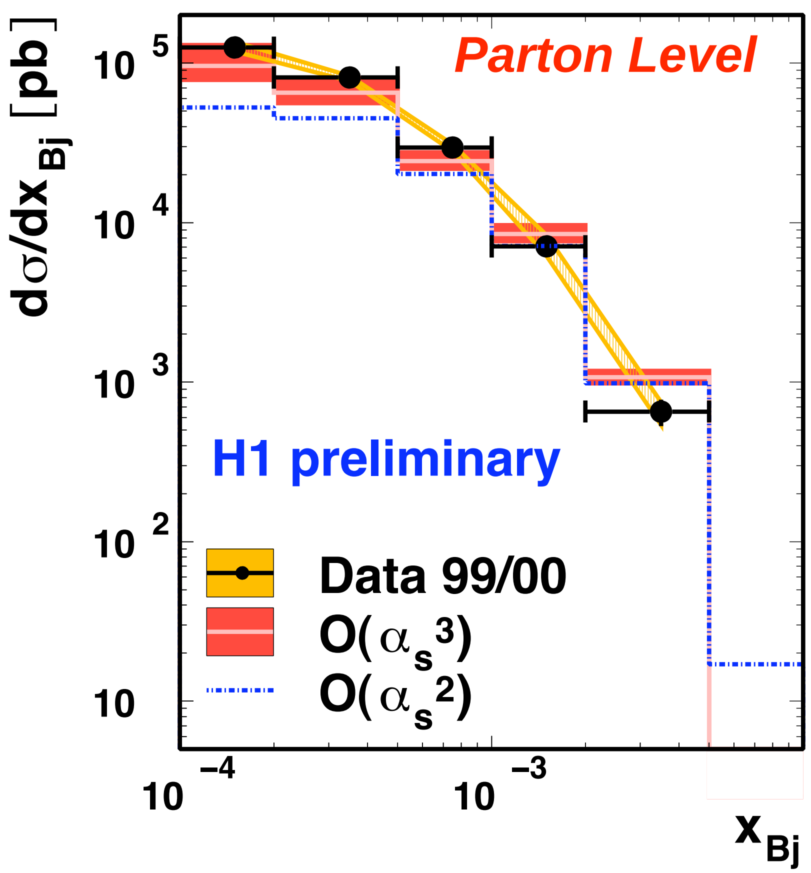
2 event samples are studied

- 1 fwd-jet & 2 central jets
  - central jets $-1 < \eta_{jet} < 1$

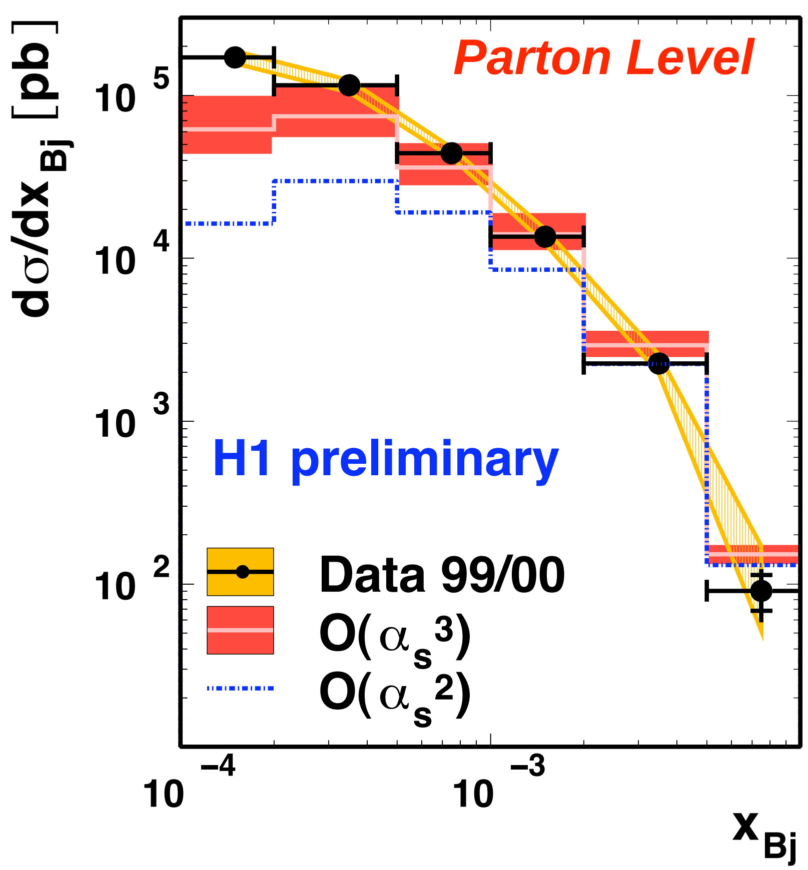
- 2 fwd-jets & 1 central jet
  - 1 fwd-jet and one more with $\eta_{jet} > 1$

“Exclusive” trijets in DIS: $d\sigma/dx_{Bj}$

1 fwd-jet & 2 central jets



2 fwd-jets & 1 central jet



from LO to NLO a factor of 2 @ low x_{Bj}; NLO in agreement with data

from LO to NLO a factor of 3.5 @ low x_{Bj}, and NLO still factor of 3 below the data

- 2 fwd-jets are mainly due to gluons according to MC studies (CDM)
- discrepancy at lowest x_{Bj} and forward rapidities is in a region where unordered gluon emissions are expected to be important !

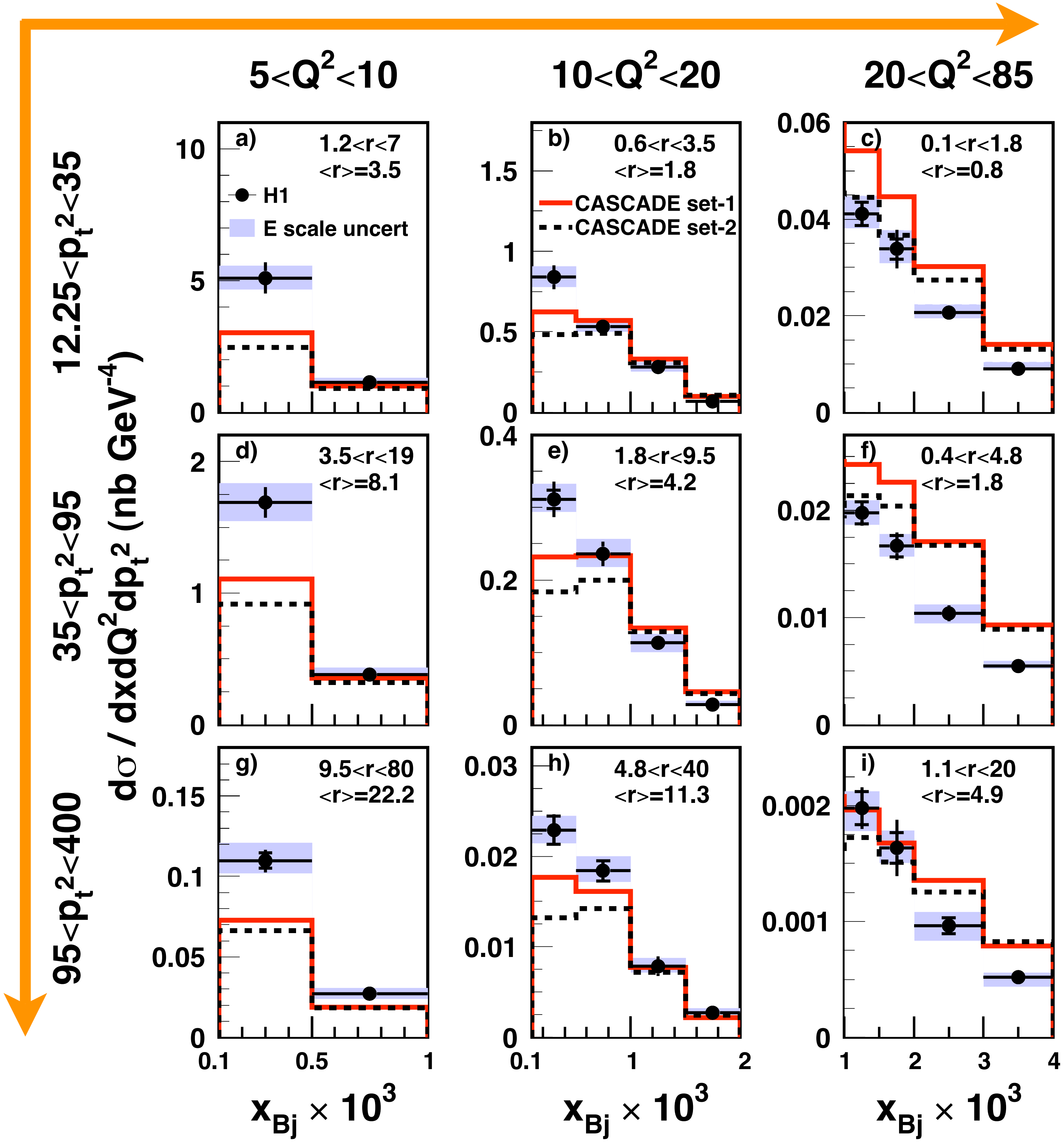
Summary/Conclusion

- H1 and ZEUS provide new data on inclusive forward jets and forward jets + dijets
- ZEUS significantly extends pseudorapidity coverage, up to $\eta = 4.3$, by using their FPC
- CDM as implemented in ARIADNE (tuned) provides best description of all data (its gluon emissions are not ordered in k_T)
- NLO does not describe the data at low x_{Bj}, Q^2, E_{Tjet} and small $\Delta\eta_1$ and $\Delta\eta_2$, where multiple gluon emissions are important
- LO DGLAP models with parton showers, like LEPTO or RAPGAP-DIR, fail to describe the data
- Models which include additional resolved photon contributions do a lot better, but fail to describe the forward jet + dijet data
- CASCADE with currently used sets of unintegrated gluon densities fails to describe shape of most distributions; these data could be used to determine the ugd
- Finally, it would be very interesting to compare these data (and HERA II data) to a full NLO BFKL calculation, for which all ingredients have recently become available

Which low-x analyses should still be done?
There are much more HERA II data on low-x on tape.

Extra Plots

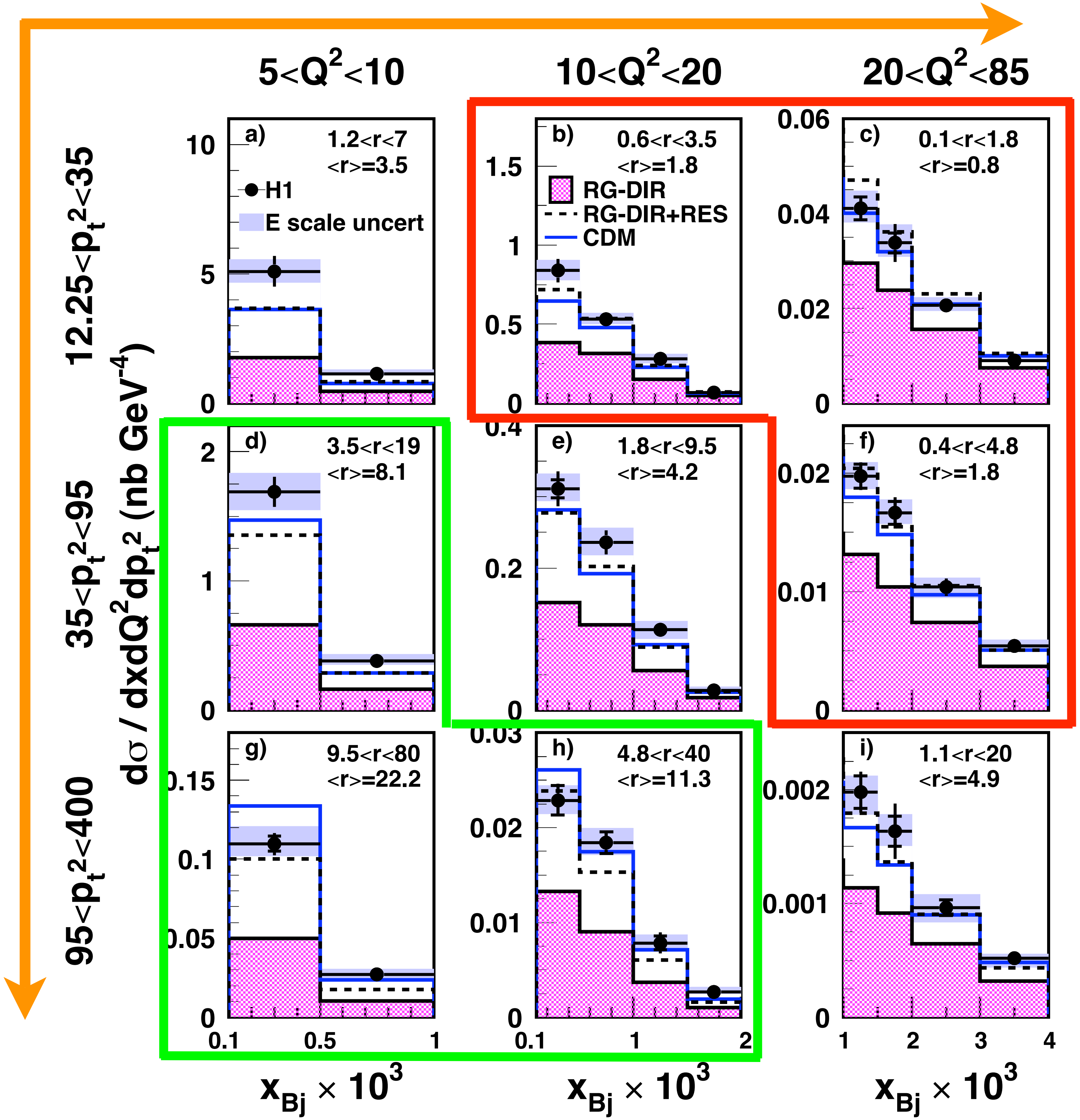
Forward jets: $d^3\sigma/dx_{Bj}dQ^2dp^2_{T,jet}$ H1



Data and CASCADE

- cross section as funct. of x_{Bj} in bins of p_T^2 - Q^2 (no cut on p_T^2/Q^2)
- range and average $r = p_T^2/Q^2$ shown for each bin
- ☛ CASCADE under and overshoots the data
- ☛ can the unintegrated gluon density be "improved" such that CASCADE can describe the data ?

Forward jets: $d^3\sigma/dx_{Bj}dQ^2dp^2_{T,jet}$ H1



Data

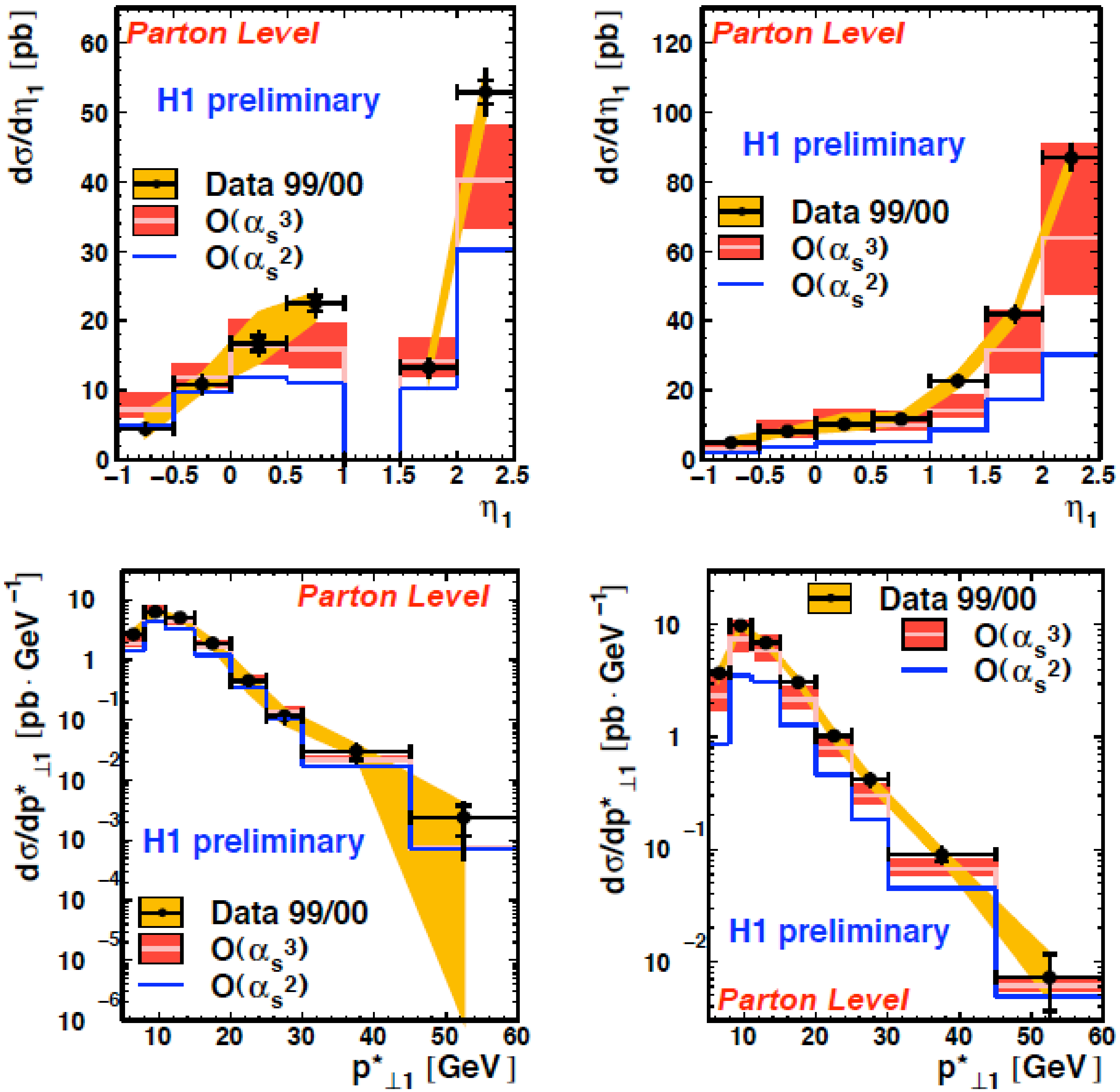
RAPGAP direct & resolved

CDM

- check 2 kinematic regions
  - $p^2_t \approx Q^2$ ($r \approx 1$), ordered emissions suppressed
  - ☛ best described by DIR+RES (CDM not too bad)
  - $p^2_t \gg Q^2$ ($r \gg 1$), expect resolved contributions
  - ☛ best described by DIR+RES (CDM not too bad)

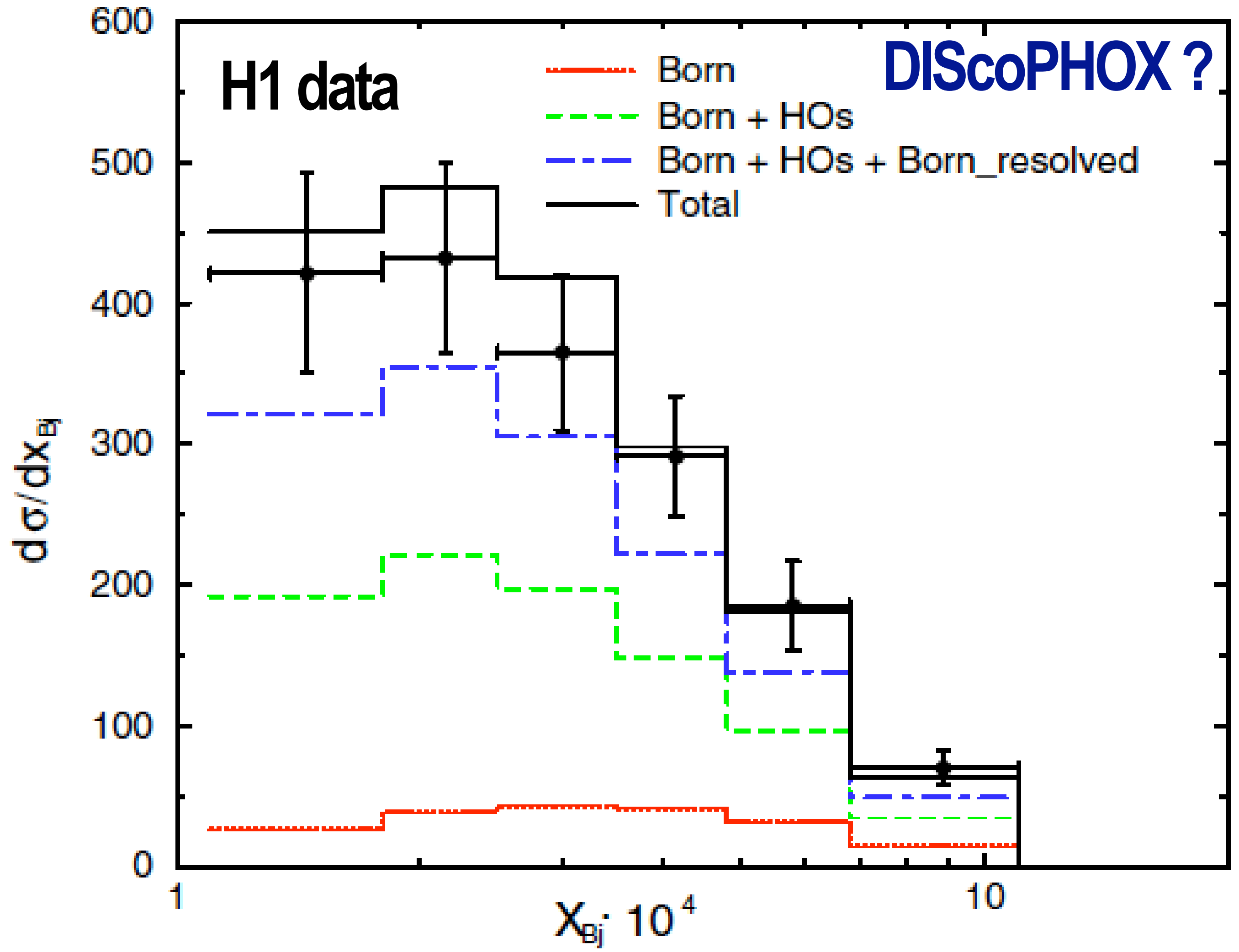
“Exclusive” trijets in DIS

1 fwd-jet & 2 central jets | **2 fwd-jets & 1 central jet**



$d\sigma/dx_{Bj}$ for events with a forward π^0

- H1: EPJ C 36, 441 (2004); 21pb-1
  - $4.5\ (2) < Q^2 < 15\ (70)\ GeV^2$
  - $0.1 < y < 0.6$
  - $5° < \theta_\pi < 25°$
  - $x_\pi > 0.1$
  - $E^*_{T,\pi} > 2.5$ GeV
- NLO calc. by Fontannaz
  - includes virtual photon struct. in NLO
  - CTEQ6M, γ^* PDF also by Fontannaz
  - all scales = $\mu^2 = E^{*2}_{T,\pi} + Q^2$
  - Kniehl, Kramer, Pötter frag. function

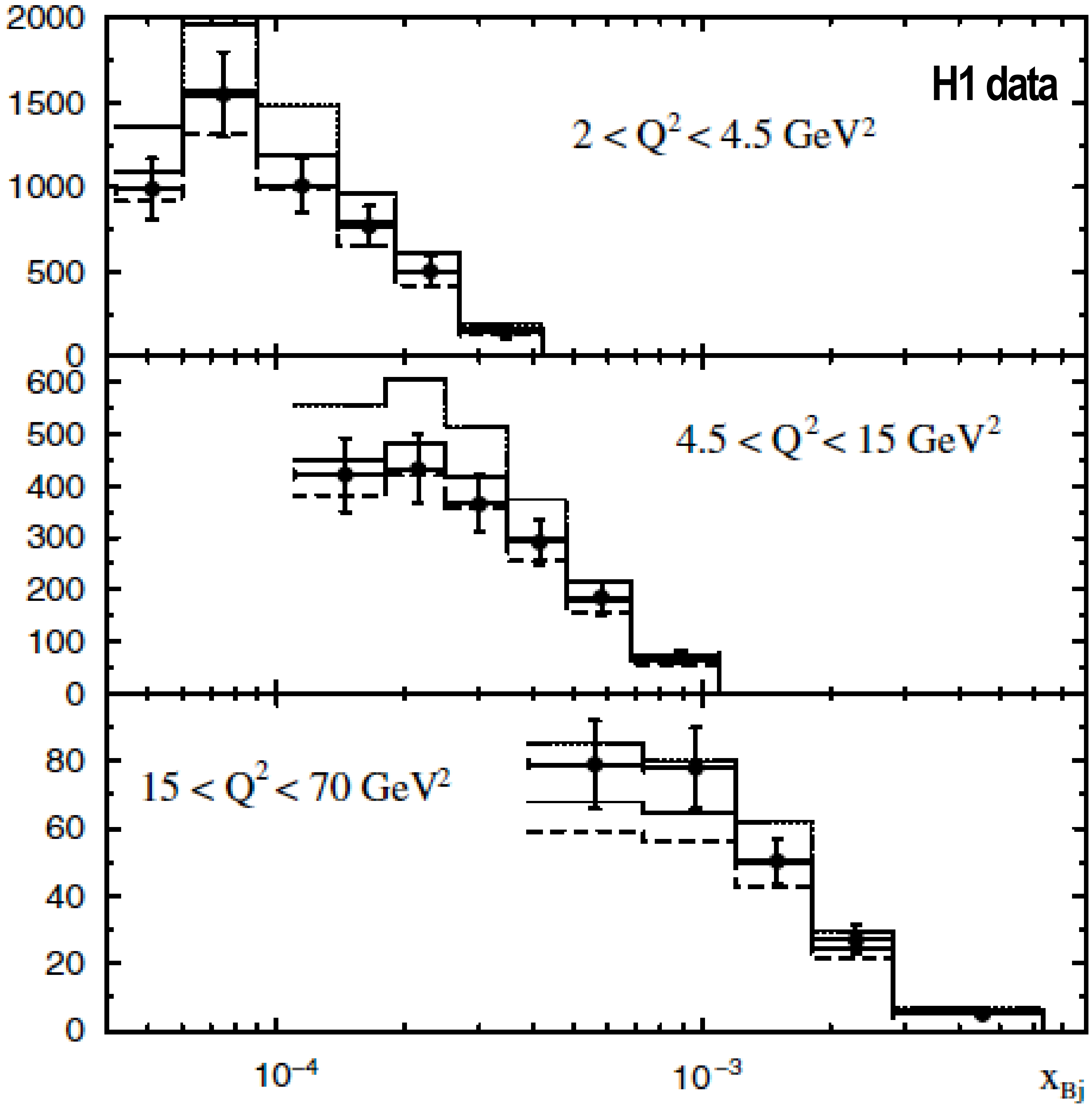


NLO from Aurenche et al., EPJ C 42, 43 (2005)

☛ good description of the data

☛ all corrections LO dir to NLO dir , LO resolved to NLO resolved are large (at least for the chosen scale)

$d\sigma/dx_{Bj}$ for events with a fwd π^0 : scale dep.



NLO from Aurenche et al., EPJ C 42, 43 (2005)

- $\mu^2 = 0.5\,(E^{*}_{T,\pi}{}^2 + Q2)$
- $\mu^2 = E^{*}_{T,\pi}{}^2 + Q2$
- $\mu^2 = 2(\,E^{*}_{T,\pi}{}^2 + Q2)$

- ☛ large scale dependence; see detailed study in theory paper