Forward Jet Production
in Deep Inelastic Scattering at HERA

H1 Collaboration, A.Aktas et al., DESY-05-135, Accepted by Eur. Phys. J. C, hep-ex/0508055

Outline:

- Introduction and Motivation
- Forward Jet Selection
- Theory and QCD Models
- Results:
  - Differential Forward Jet Cross Sections
  - Dijet + Forward Jet Cross Section
- Summary & Conclusions

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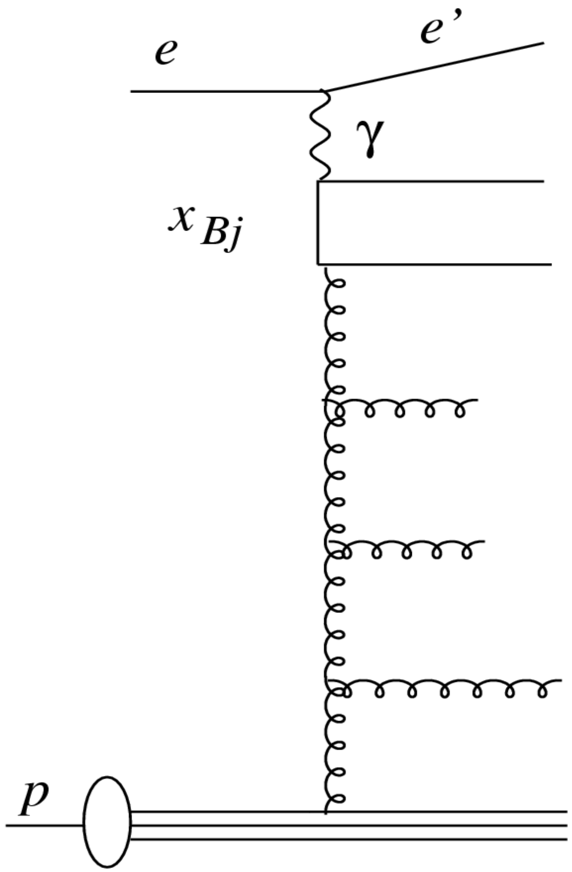
on behalf of the H1 collaboration

April 22nd 2006, DIS 2006, Tsukuba, Japan

Introduction



- Inclusive measurement F_2
  well described by DGLAP

- Dijet cross section, jet rates
  hard subsytem

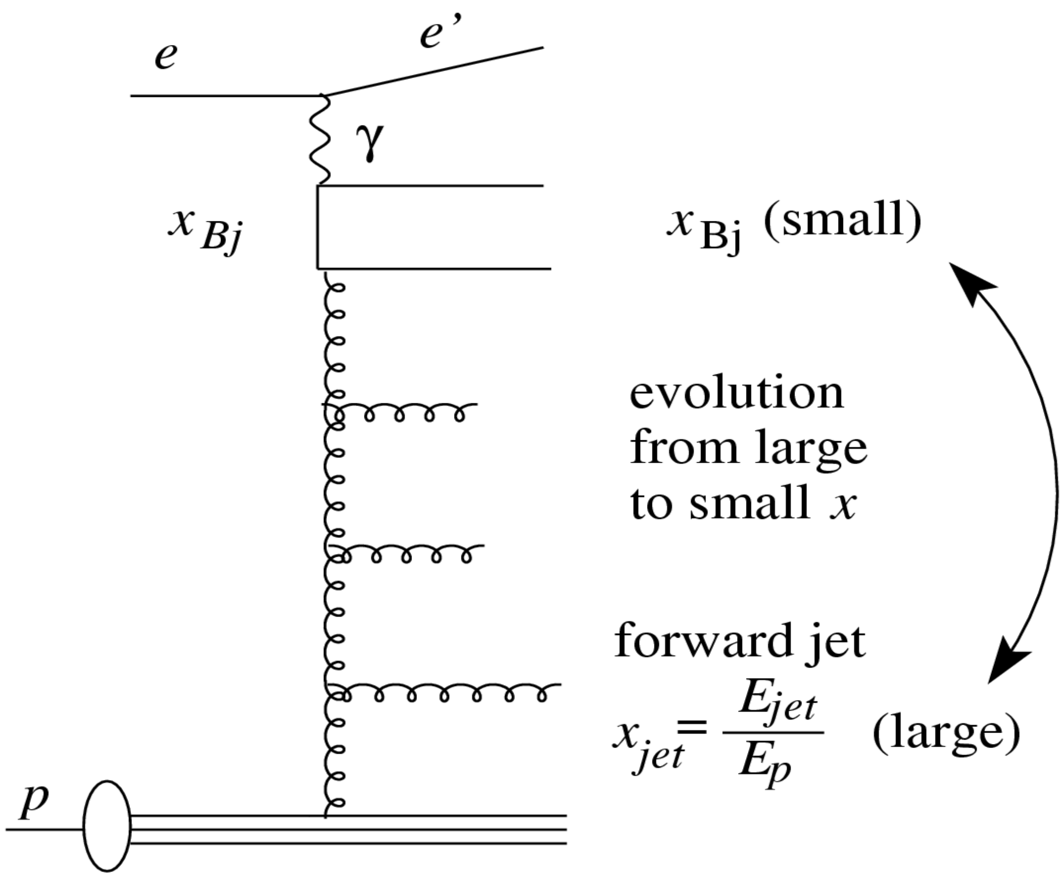
- Jets in forward region
  gluon emissions close to proton direction
  well away from photon end of ladder
  study parton dynamics
  most sensitive to different evolution schemes

in fwd region:

DGLAP ordered in k_t – soft emissions only

BFKL non-ordered in k_t – arbitrary k_t

Introduction



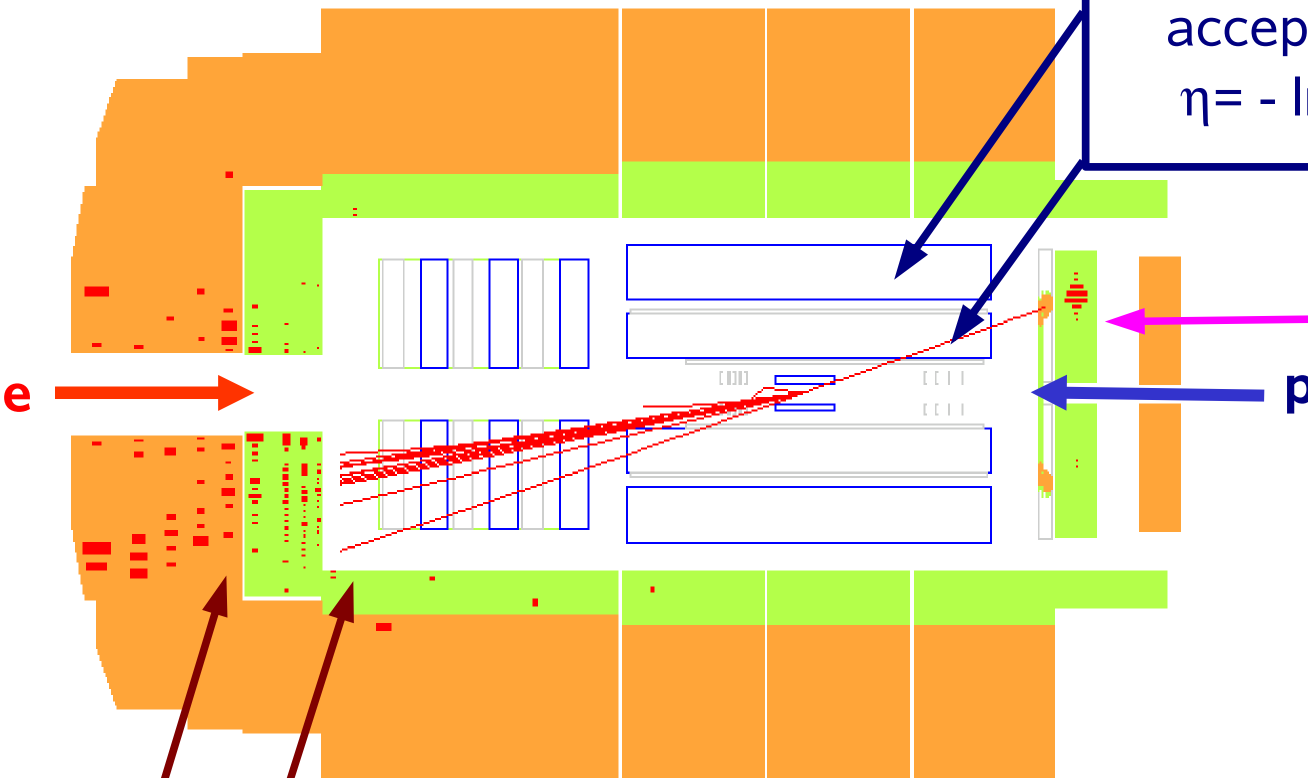
test QCD at small x
parton dynamics beyond DGLAP?

Select phase space for evolution in x
BFKL
xbj << xjet

suppress phase space for
evolution in Q2 DGLAP
$p_{t,\mathrm{fwd\ jet}}^{2} \sim Q^2$

H1 detector at HERA

HERA: E_e=27.6 GeV
E_p=820 GeV
$\sqrt{s} \approx 300$ GeV



Central jet chamber CJC
acceptance $-1.75 < \eta < 1.75$
$\eta = -\ln \tan \theta/2$

backward electromagnetic calorimeter SpaCal
$152° < \theta < 177°$
rec. of scattered e

Lar Calorimeter
$4° < \theta < 154°$

Hadronic final state:
LAr calorimeter
SpaCal
central tracker

Fwd jet analysis:
1997 data L=13.7 pb^{-1}
Kinematic Range:
$5 < Q^2 < 85$ GeV^2
$0.1 < y < 0.7$
$0.0001 < x_{bj} < 0.004$

Event and Jet Selection

Forward jet selection

inclusive kt-algorithm in Breit frame

$1.74 < \eta_{jet} < 2.79$ forward jet

$p_{T,jet} > 3.5$ GeV

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

if $N_{jet} > 1$: choose jet with highest η

- single differential cross sections $d\sigma/dx_{bj}$
  $0.5 < r = p_{T,jet}^2/Q^2 < 5$
  suppress DGLAP
- triple differential cross sections $d^3\sigma/dx_{bj}dQ^2dp_t^2$

Dijet + forward jet selection

in addition 2 more jets = 2 highest pt jets

$p_T > 6$ GeV for all 3 jets

$\eta_e < \eta_{jet1} < \eta_{jet2} < \eta_{jetfwd}$ $(-3.1 < \eta < 2.79)$

no cut on $p_{T,jet}^2/Q^2$

other cuts on fwd jet as above

- study η separation of three jets

QCD Predictions

Monte Carlo Event Generator (LO calc + PS + hadronisation)

- **RAPGAP:** LO ME + PS, DGLAP evolution, parton shower k_t ordered

  direct γ interactions
- **RAPGAP RES:** includes resolved γ interactions,

  additional DGLAP ladder from photon to hardsubproces
- **CDM (ARIADNE):** parton shower in CDM – BFKL like
- **CASCADE:** LO ME, CCFM evolution (initial state PS)

  unintegrated gluon densities

all modesl use Lund String Model Hadronisation

QCD Predictions

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direct γ interactions

proton PDF: CTEQ6L
photon PDF: SaS1D

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PDF: CTEQ6M

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unintegrated gluon densities

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NLO parton level Calulations

•**DISENT:**

dijet production at LO(α_s) and NLO(α_s^2) forward jet cross section

PDF: CTEQ6M

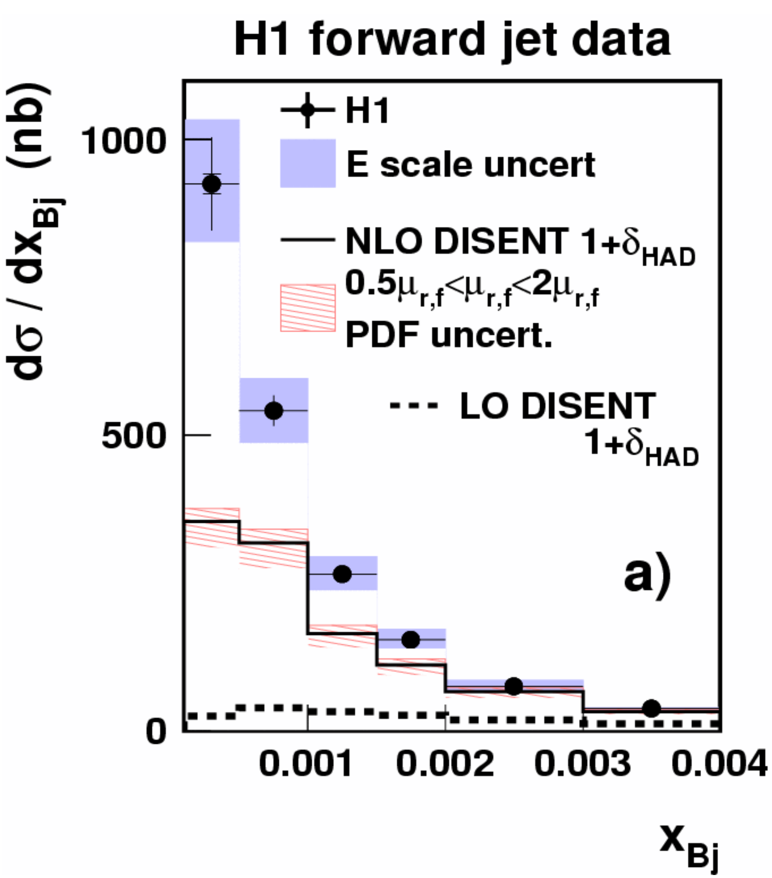
•**NLOJET++:**

three jet production at NLO(α_s^3) dijet+forward jet cross section

hadr. corrections applied to caluclations: $(1+\delta_{HAD})$

Forward jets cross section: x_{bj}

Comparison with NLO predictions



LO contributions suppressed
in selected phase space

DISENT LO(α_s) and NLO(α_s^2)

$\mu_r^2=p_T^2$

$\mu_f^2=<p_{T,fwdjet}^2> = 45\ \mathrm{GeV}^2$

$0.25\ \mu_{r,f}^2 < \mu_{r,f}^2 < 4\ \mu_{r,f}^2$

$(1+\delta_{HAD})$

at low x_{bj}:

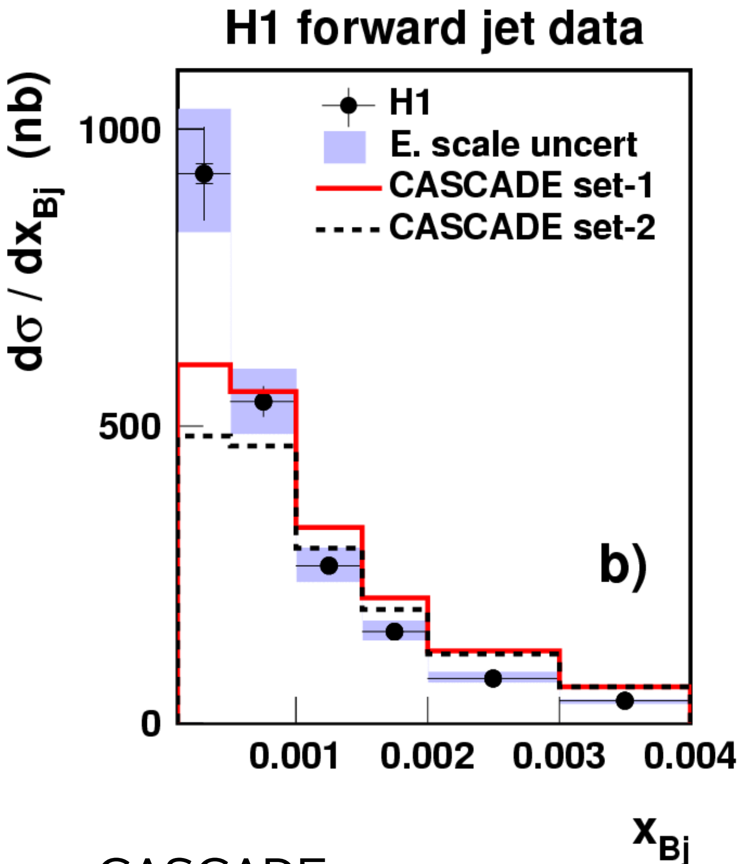
- LO << NLO
- NLO below data

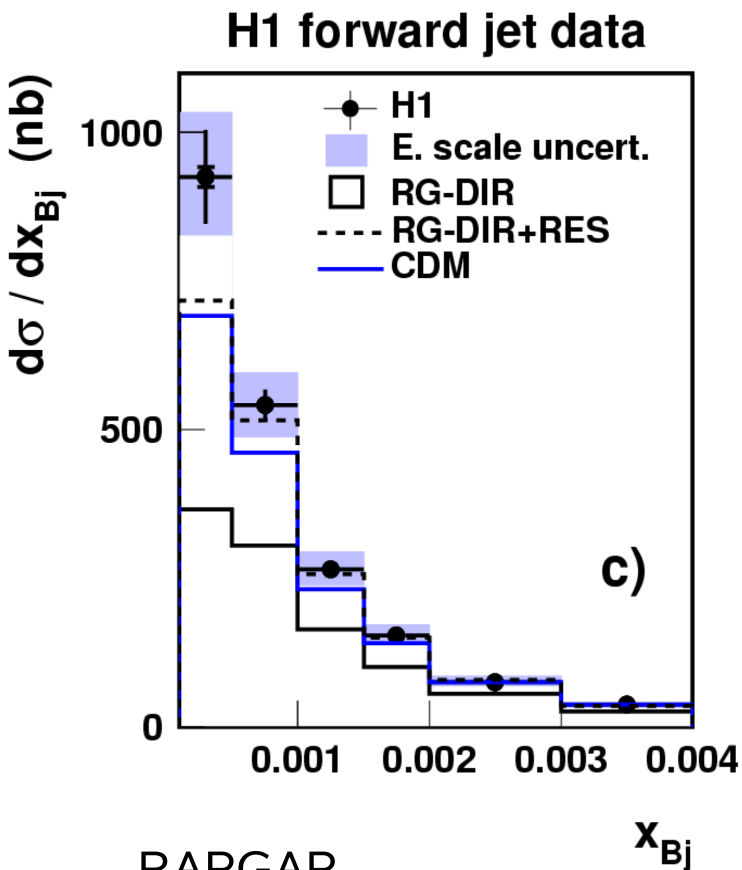
at high x_{bj}:

- NLO better agreement

Forward jets cross section: x_{bj}

Comparison with QCD models : CASCADE, RAPGAP and CDM





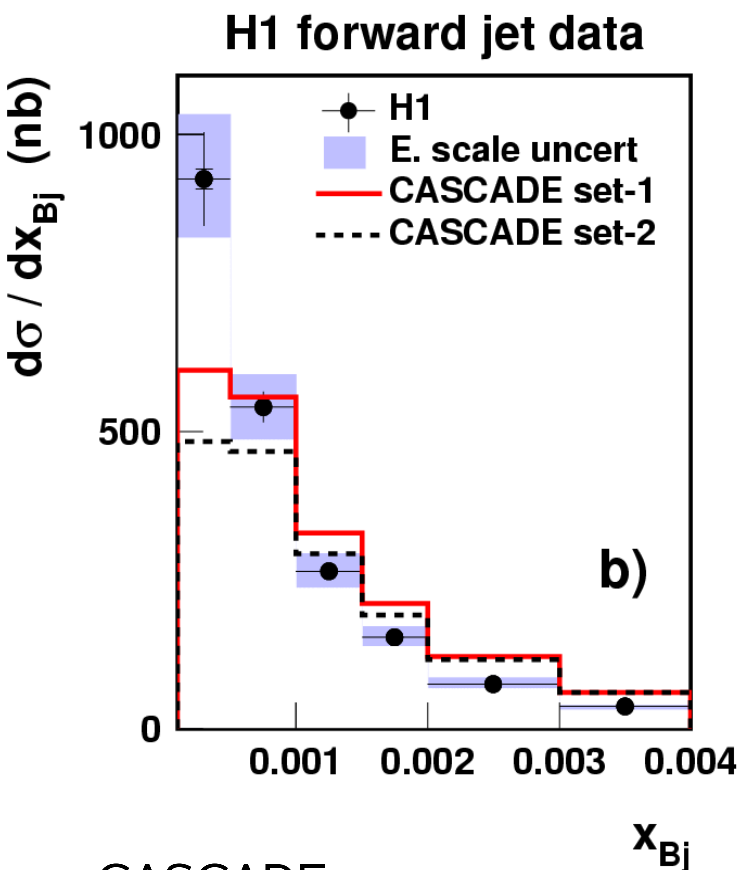
CASCADE
- harder x_{bj} spectrum
- poor description of data

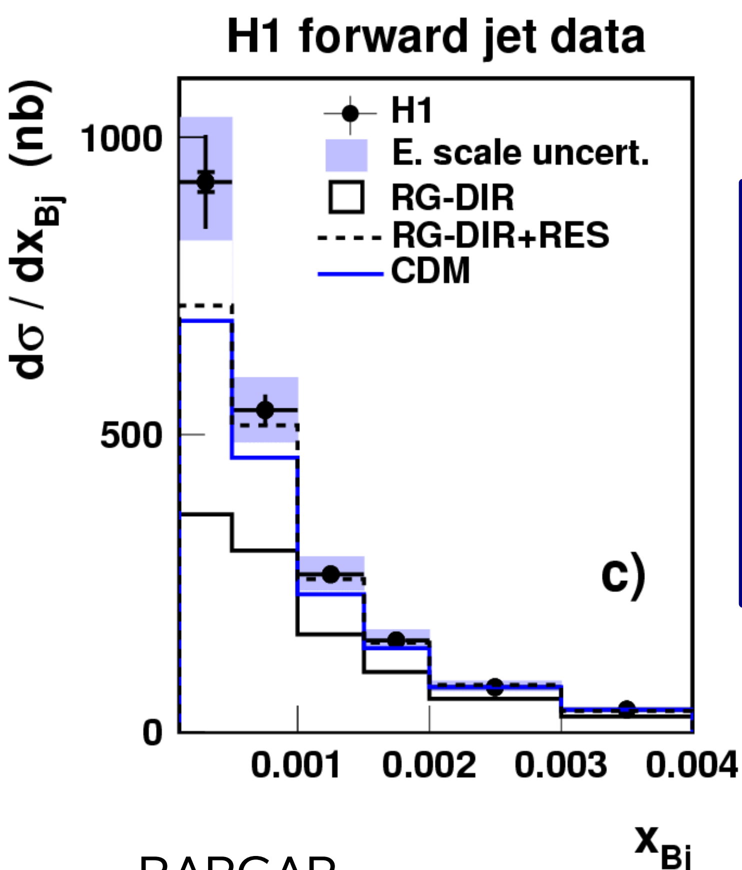
RAPGAP
- DIR – similar to NLO
- DIR+RES improved description of data

CDM
- Similar to RAPGAP-DIR+RES

Forward jets cross section: x_{bj}

Comparison with QCD models : CASCADE, RAPGAP and CDM





$d\sigma/dx_{bj}$:
best description:
RG-DIR+RES or CDM

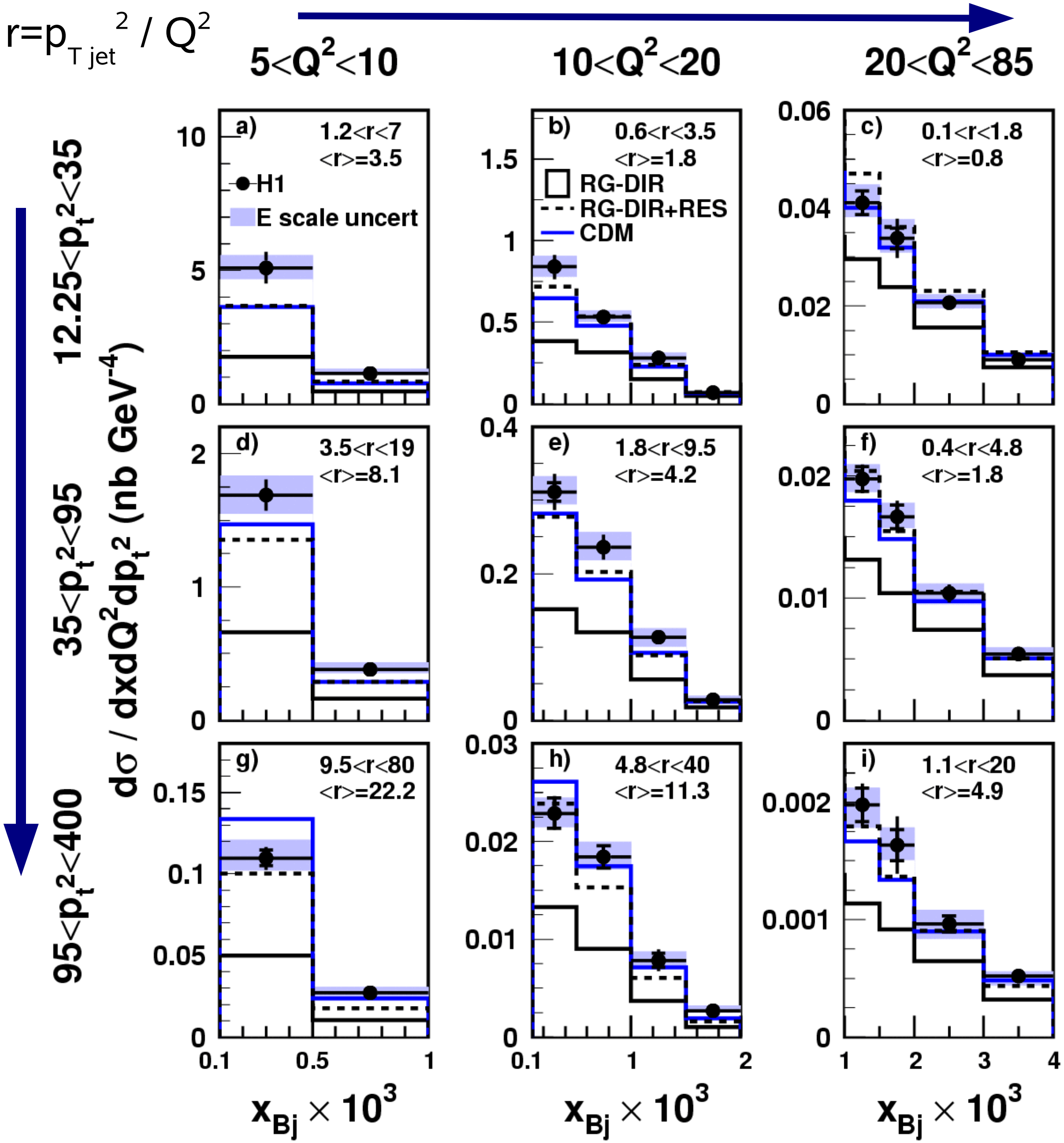
CASCADE, RG-DIR,
DISENT fail

CASCADE
- harder x_{bj} spectrum
- poor description of data

RAPGAP
- DIR – similar to NLO
- DIR+RES improved description of data

CDM
- Similar to RAPGAP-DIR+RES

Triple Differential Forward Jet Cross Section: x_{bj}, Q^2, p_T^2

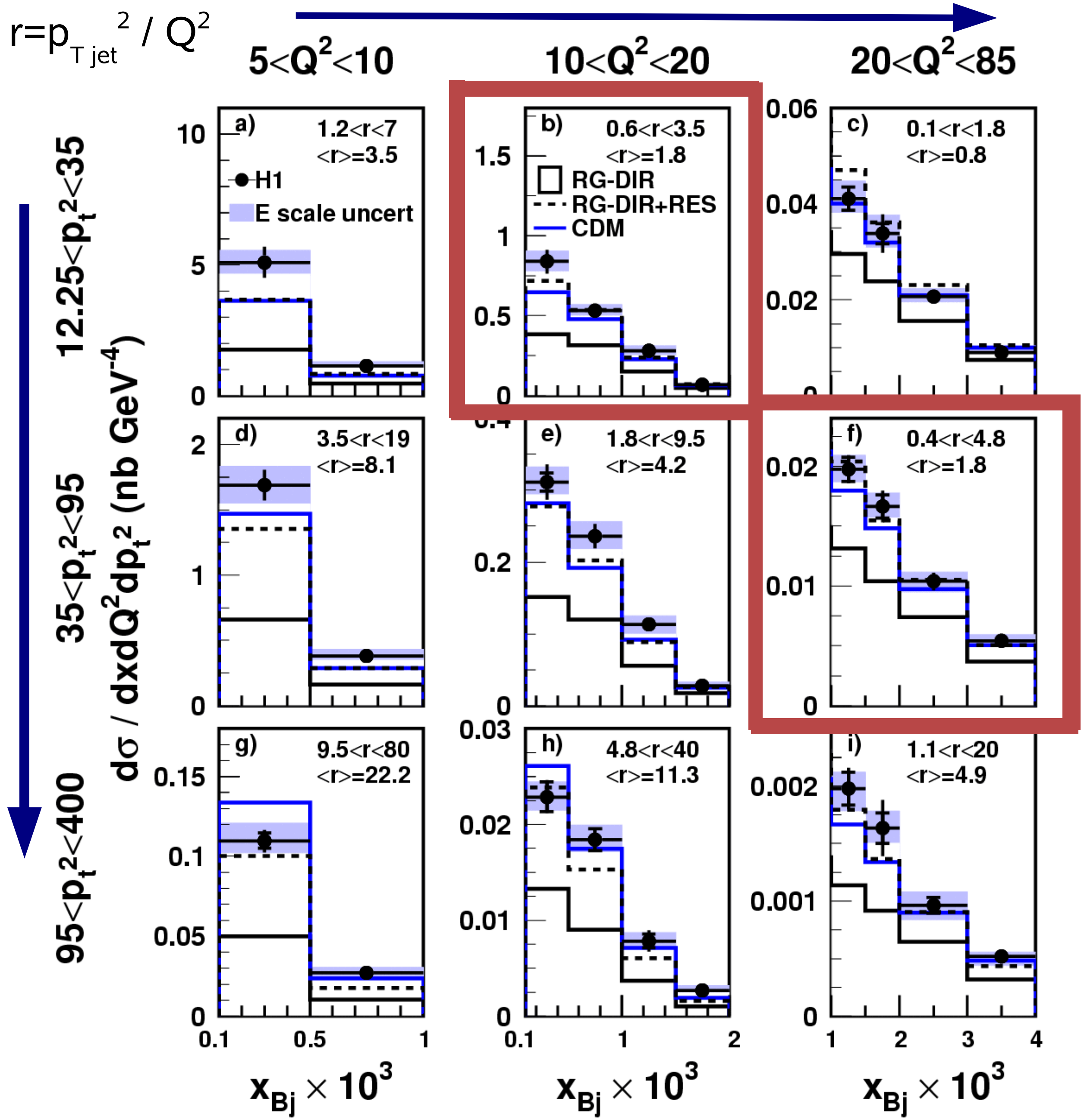


Cross Section as fct. of x_{bj} in 3x3 p_T^2-Q^2 bins (no $p_{T\,jet}^2 / Q^2$ cut)

Comparison with RAPGAP and CDM

3 kinematic regions:

Triple Differential Forward Jet Cross Section: x_{bj}, Q^2, $p_T^{\,2}$



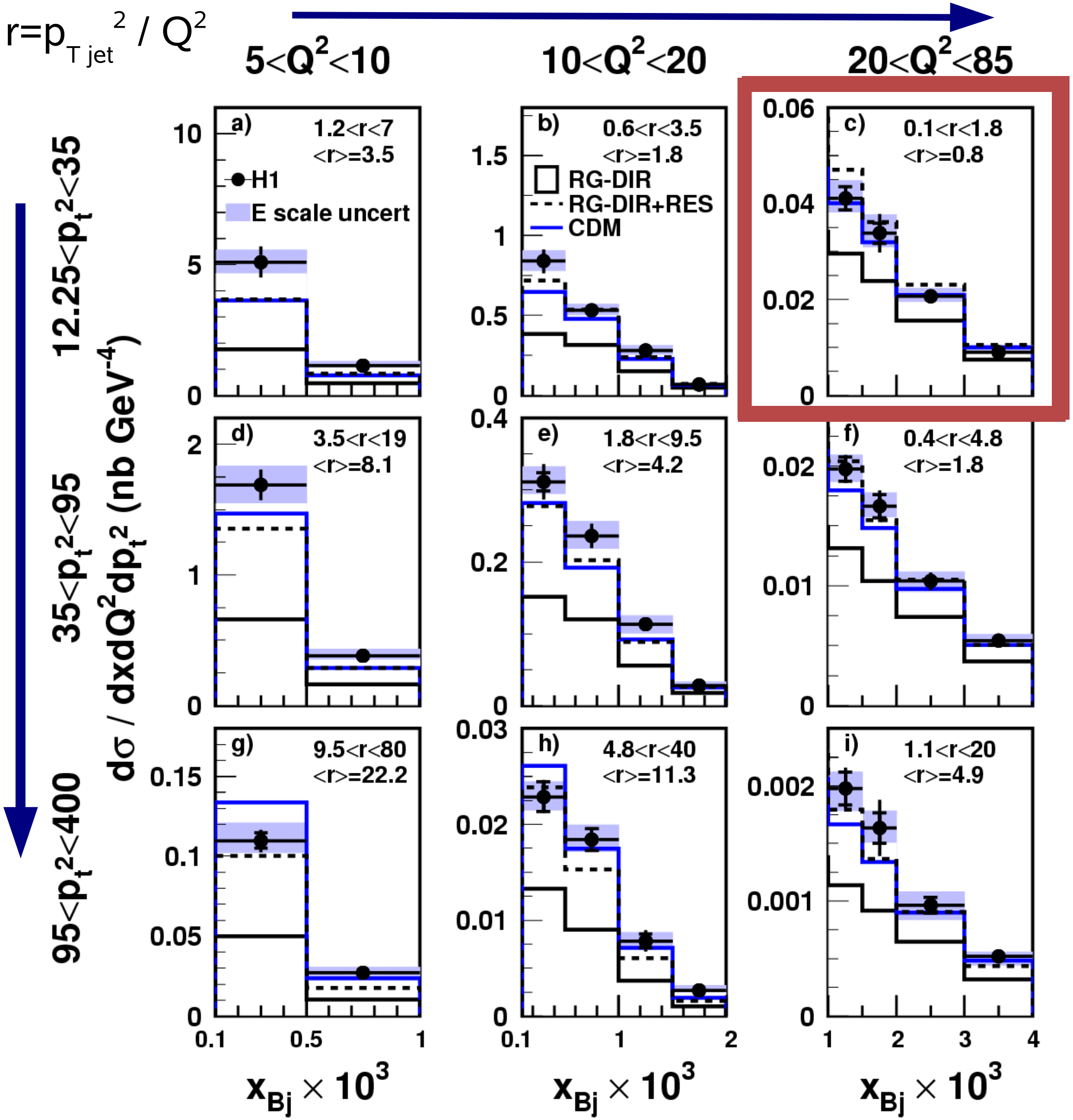
Cross Section as fct. of x_{bj} in 3x3 $p_T^{\,2}$-Q^2 bins (no $p_{T\,jet}^{\,2} / Q^2$ cut)

Comparison with RAPGAP and CDM

3 kinematic regions:

- **$p_{T\,jet}^{\,2} \sim Q^2$ (r~1) e.g. (b),(f)**
  p_T ordered emission suppressed
  BFKL-like dynamics
  RAPGAP DIR+RES gives best description

Triple Differential Forward Jet Cross Section: x_{bj}, Q^2, $p_T^{\,2}$



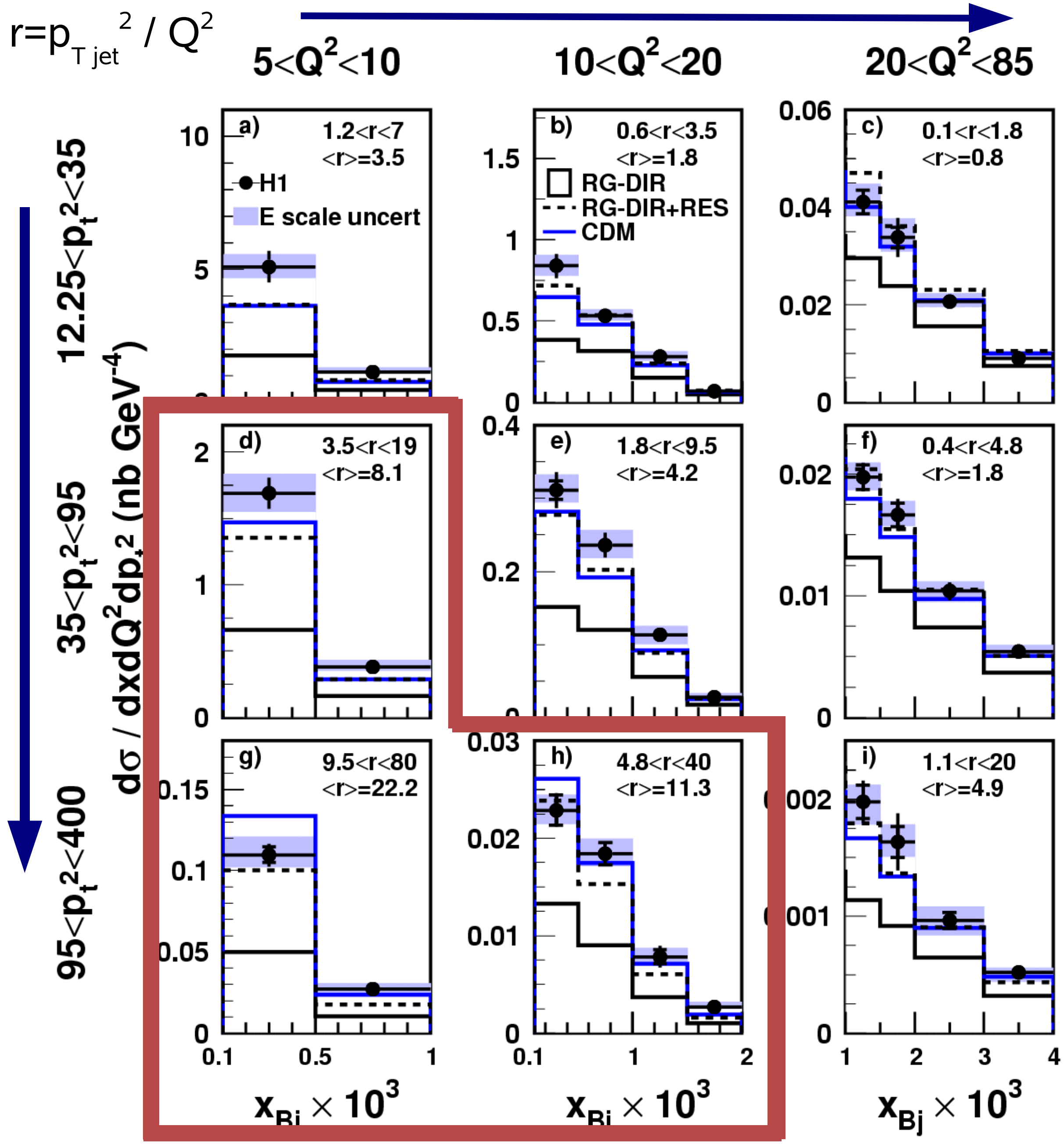
Cross Section as fct. of x_{bj} in 3x3 $p_T^{\,2}$-Q^2 bins (no $p_{T\,jet}^{\,2}$ / Q^2 cut)

Comparison with RAPGAP and CDM

3 kinematic regions:

- **$p_{T\,jet}^{\,2} < Q^2$ (r<1) e.g. (c)**
  direct photon IA
  DGLAP-like dynamics
  RAPGAP-DIR: no good descr.
  RAPGAP DIR+RES, CDM: better

Triple Differential Forward Jet Cross Section: x_{bj}, Q^2, $p_T^{\ 2}$



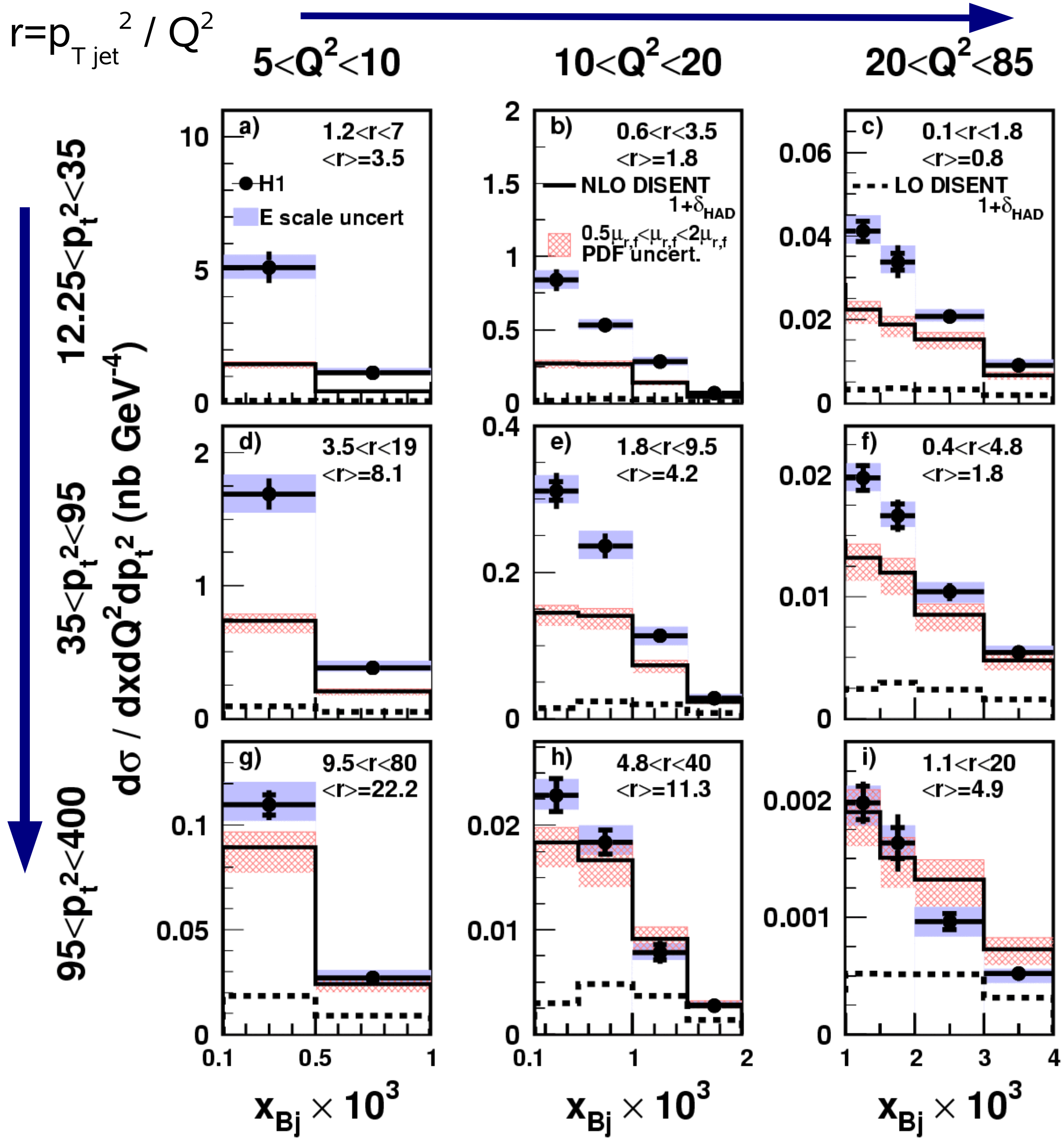
Cross Section as fct. of x_{bj} in 3x3 $p_T^{\ 2}$-Q^2 bins (no $p_{T\,jet}^{\ 2}$ / Q^2 cut)

Comparison with RAPGAP and CDM

3 kinematic regions:

- **$p_{T\,jet}^{\ 2}$ > Q^2 (r>1) e.g. (d),(g),(h)**
  resolved virtual photons dynamics
  RAPGAP DIR+RES: good descr.
  CDM: similar, RAPGAP DIR: too low

Triple Differential Forward Jet Cross Section: x_{bj}, Q^2, $p_T^{\ 2}$



Cross Section as fct. of x_{bj} in 3x3 $p_T^{\ 2}$-Q^2 bins (no $p_{T\ jet}^{\ 2}$ / Q^2 cut)

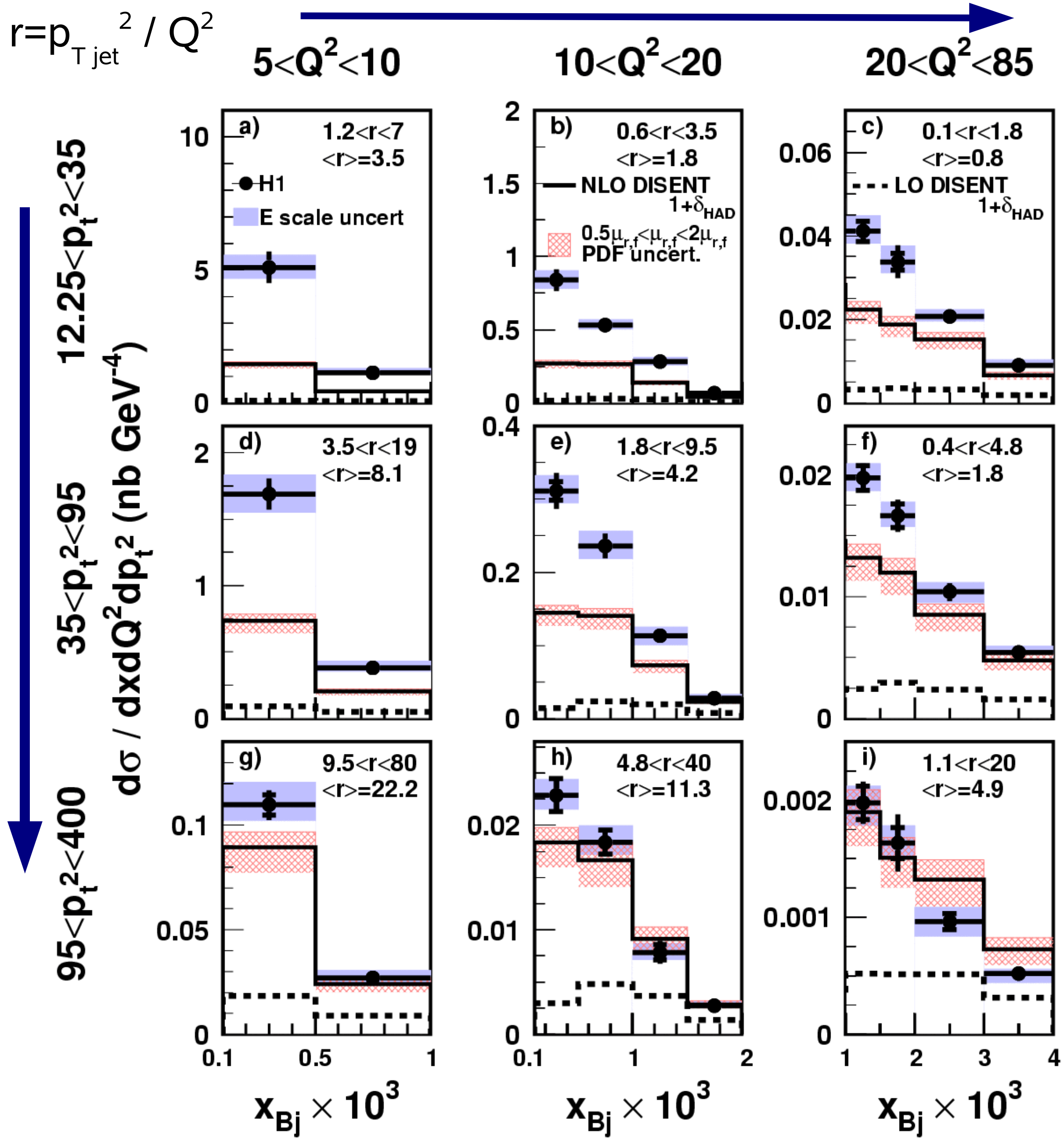
Comparison with LO(α_s) and NLO($\alpha_s^{\ 2}$) predictions by DISENT

NLO undershoots the data

- large x_{bj}, Q^2, $p_T^{\ 2}$

  NLO describes data better

Triple Differential Forward Jet Cross Section: x_{bj}, Q^2, $p_T^{\,2}$



Cross Section as fct. of x_{bj} in 3x3 $p_T^{\,2}$-Q^2 bins (no $p_{T\,jet}^{\,2} / Q^2$ cut)

$d^3\sigma/dx_{bj}dQ^2dp_t^{\,2}$:

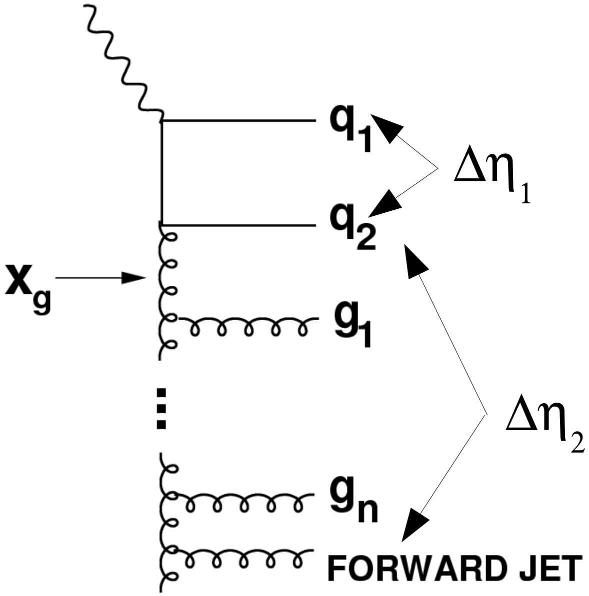
best description: RG-DIR+RES or CDM

RG-DIR below data, best at r~1

DISENT better at larger x_{bj}, Q^2, $p_T^{\,2}$

CASCADE as single diff σ too hard x_{bj} spectra

High p_T dijets + forward jet



2 hardest jets (p_T>6GeV): jet1, jet2

+ forward jet (p_T>6GeV) selected

(no $p_{T\,jet}^{\;2} / Q^2$ cut)

$\eta_e < \eta_{jet1} < \eta_{jet2} < \eta_{fwdjet}$

$\Delta\eta_1 = \eta_{jet1} - \eta_{jet2}$

$\Delta\eta_2 = \eta_{jet2} - \eta_{fwdjet}$

further handle to control parton dynamics

rapidity separation

$\Delta\eta_1 < 1$: jet1 and jet2 close in η, small x_g

many emissions in x

$\Delta\eta_1 > 1$: large η separation between

2 hardest jets

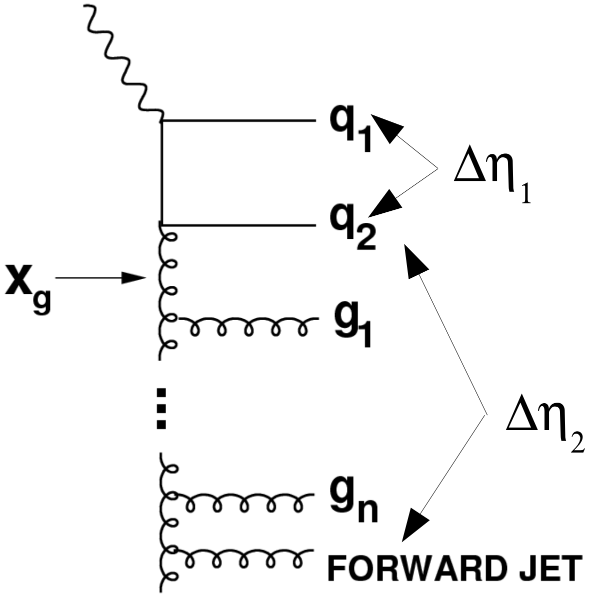
shorter parton ladder

$\Delta\eta_1$ small and $\Delta\eta_2$ small: all jets “fwd”,

2 or 3 jets from gluons?

non-ordering in kt!

High p_T dijets + forward jet



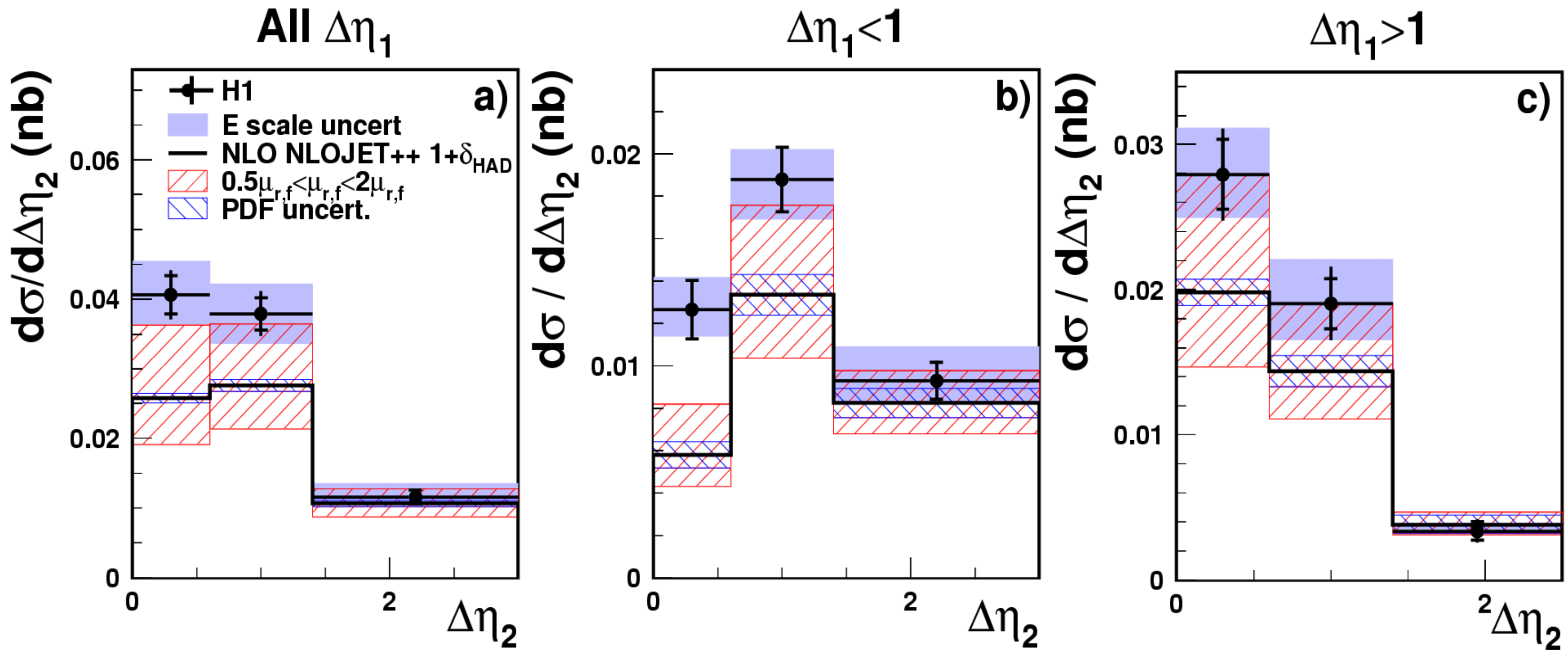
Comparison with NLOJET++

NLO(α_s^3) three jet production

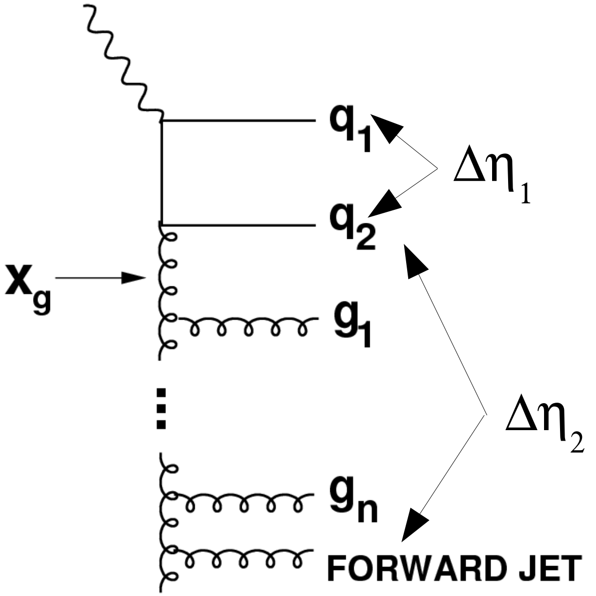
- good agreement with data at large $\Delta\eta_2$
- data less well described at low $\Delta\eta_2$, especially if $\Delta\eta_1$ small

  2 gluon + 1 quark jet: only LO in O(α_s^3) three jet calc.

  3 gluon jets: missing



High p_T dijets + forward jet



Comparison with RAPGAP and CDM

CDM
- good description everywhere

RAPGAP
- too low cross section, best when $\Delta\eta_1$ and $\Delta\eta_2$ large

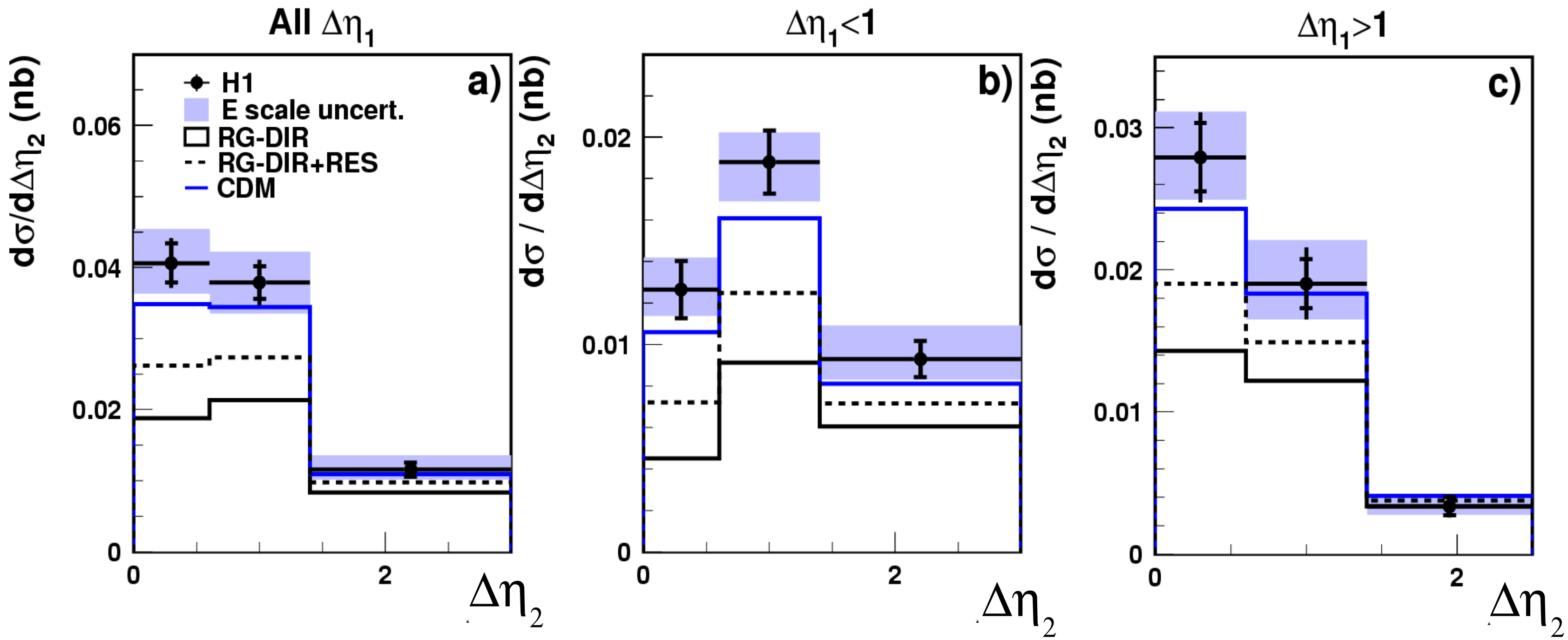
dijets-produced by gluon radiation – k_t ordering broken

likely if both forward i.e. if $\Delta\eta_1$ and $\Delta\eta_2$ small:

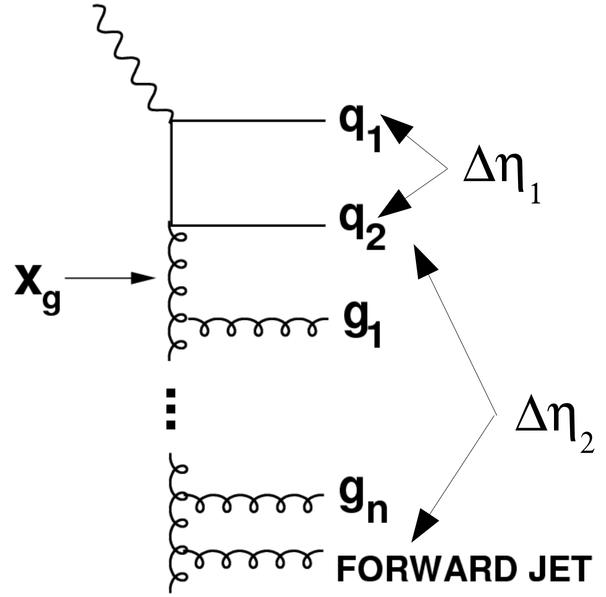
CDM best description, RAPGAP DIR, DIR+RES fail

dijet+fwd jet sample can differentiate RG DIR+RES and CDM

additional breaking of kt ordering needed !

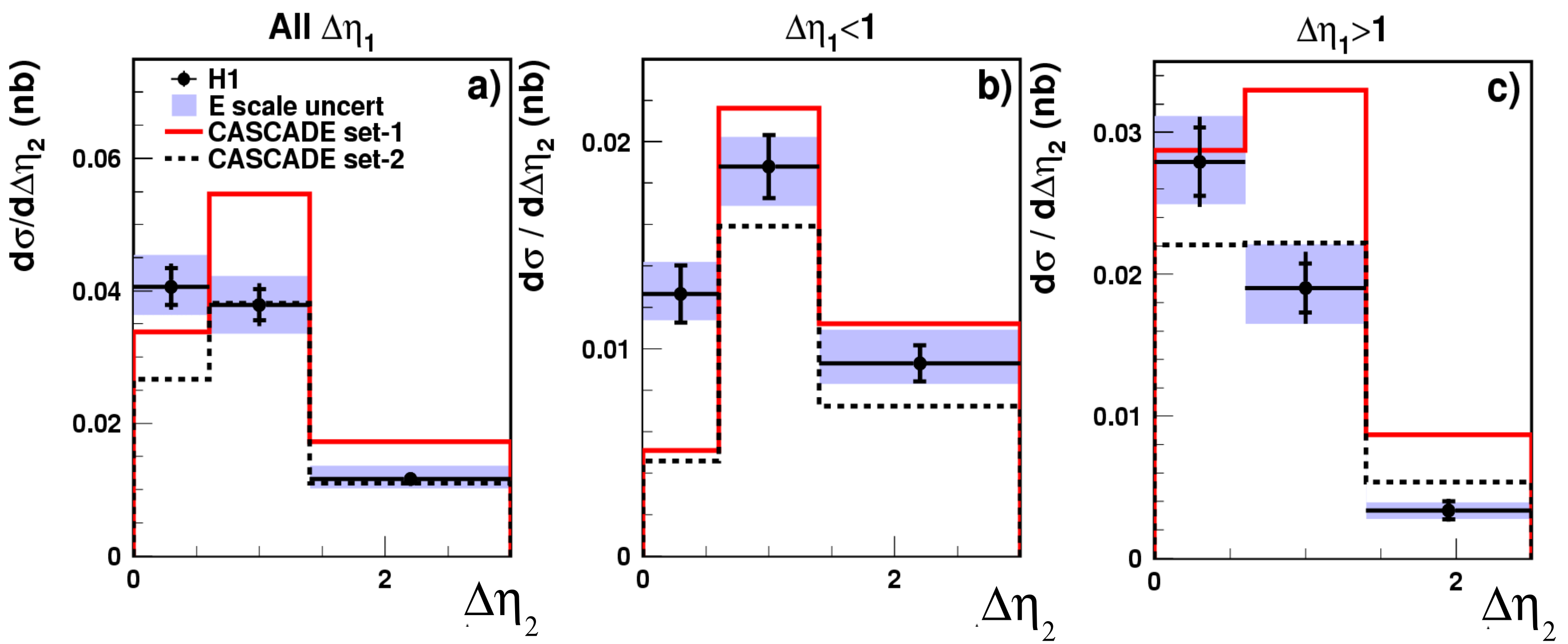


High p_T dijets + forward jet



Comparison with CASCADE

- does not describe data



Summary & Conclusions

- Jets in forward direction in DIS
  with constraints in order to suppress DGLAP evolution and
  enhance phase space for non-ordered parton evolutions

- Single and triple differential forward jet cross section as fct of x_{bj} and Q_2, p_t^2
  best desription of data by RAPGAP-DIR+RES and CDM
  while CASCADE, RG-DIR fail
  NLO(α_S^2) dijet only good description at large x_{bj} or large Q_2, large p_t^2

- η separation in dijet+forward jet sample
  further handle on parton dynamics,
  best description: CDM and RG-DIR+RES

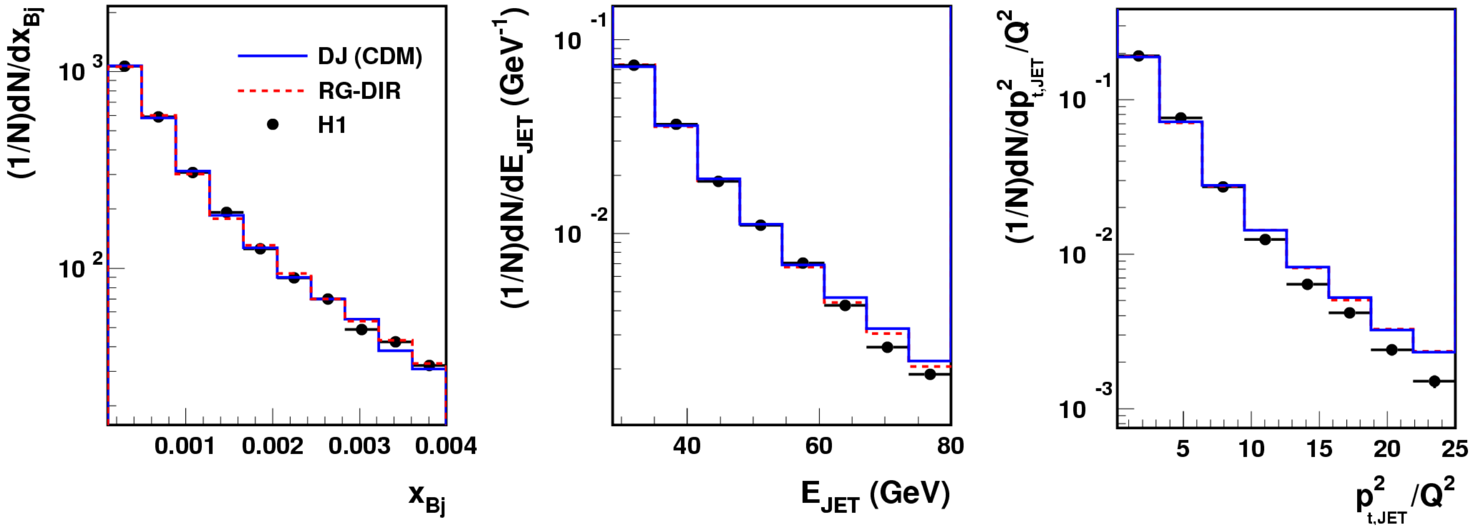
- higher order parton emissions which break k_t ordering needed,
  while simple DGLAP evolution restricts phase space too much

- dijet + fwd jet sample can differentiate between CDM and RG-DIR+RES:
  CDM gives better description
  additional breaking of k_t ordering compared to resolved γ model needed

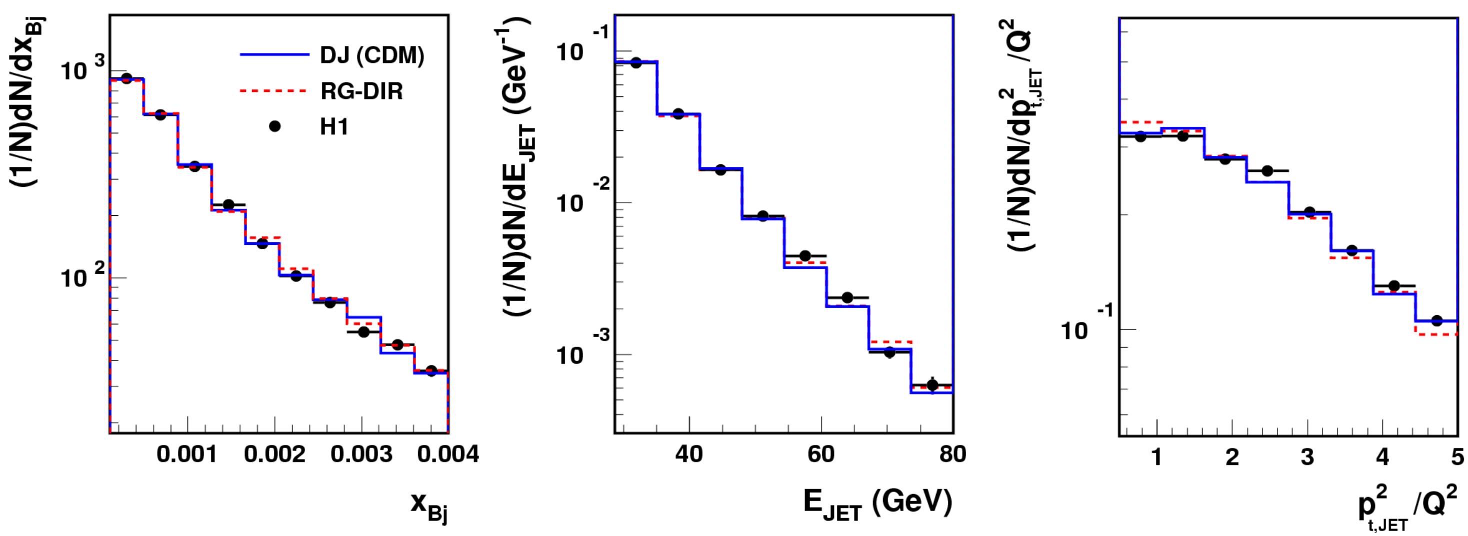
Additional material

Control Plots

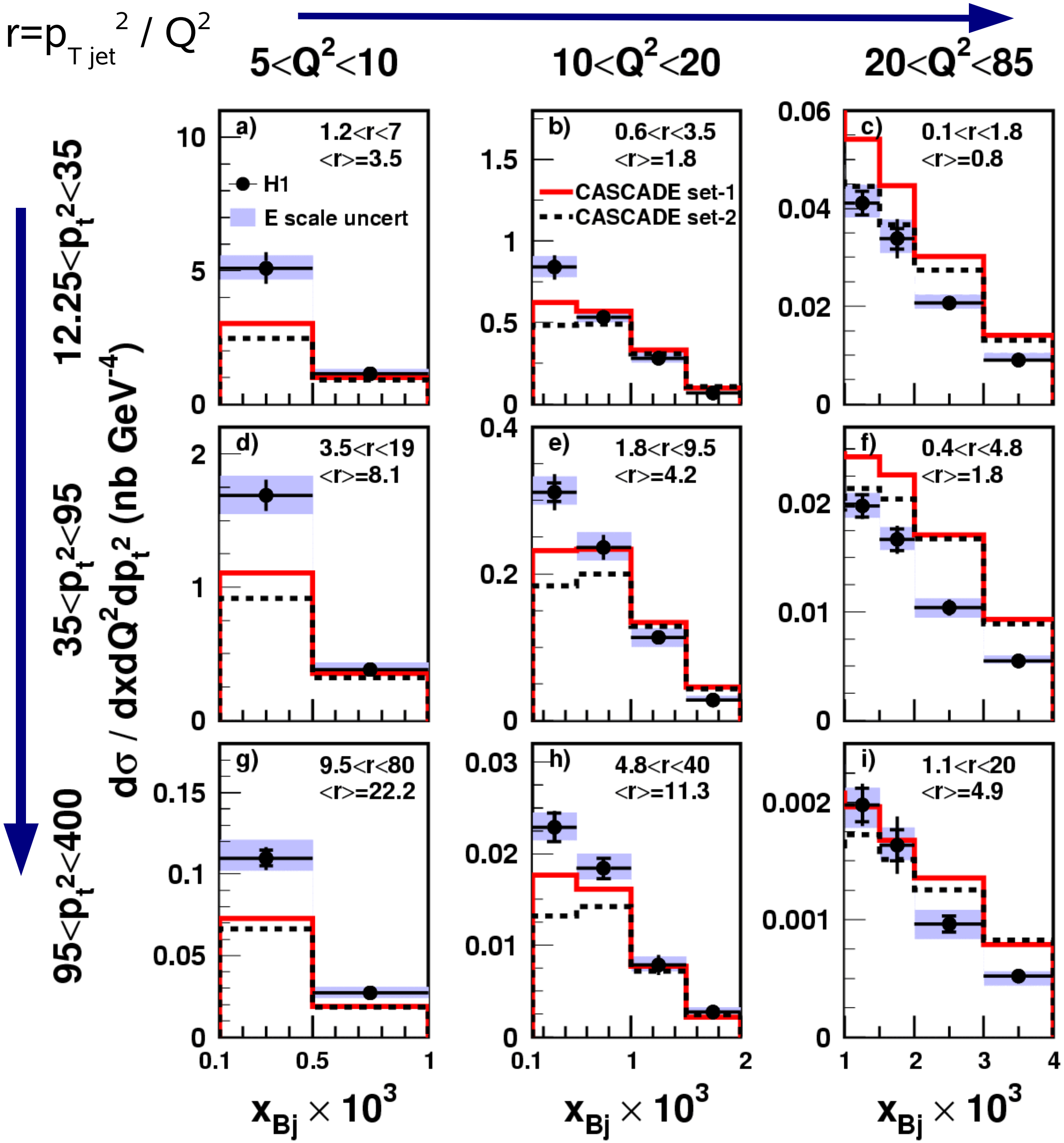
forward jets:



forward jets with $0.5 < p_{T,jet}^2/Q^2 < 5$:



Triple Differential Forward Jet Cross Section: x_{bj}, Q^2, $p_T^{\ 2}$



Cross Section as fct. of x_{bj} in 3x3 $p_T^{\ 2}$-Q^2 bins (no $p_{T\ jet}^{\ 2}$ / Q^2 cut)

Comparison with CASCADE

harder x_{bj} spectrum than in data over full kinematic range