Forward Jets and Multi-Jets at HERA

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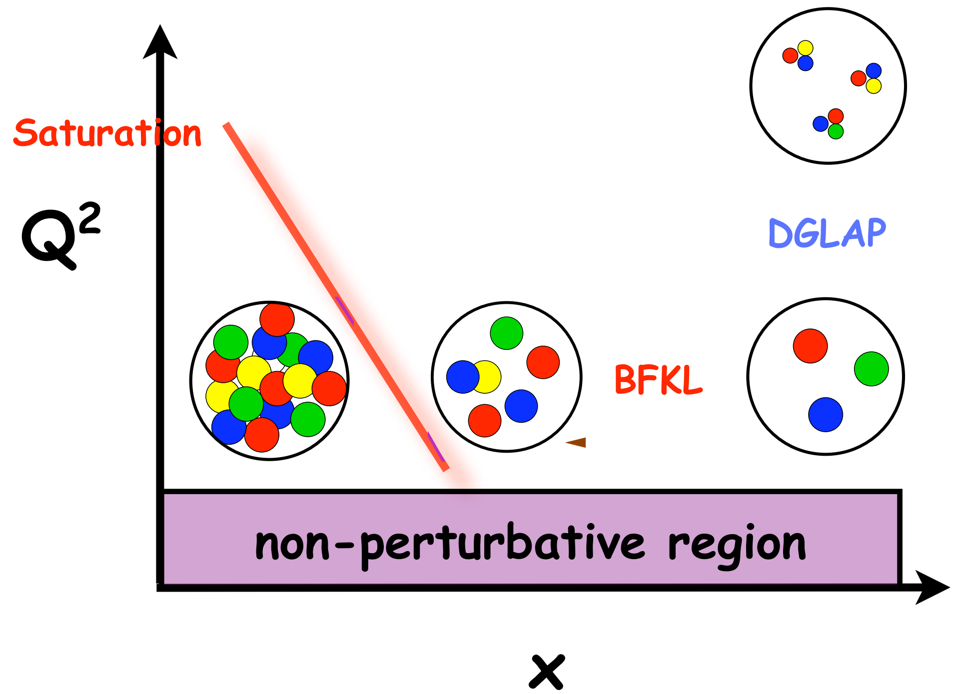
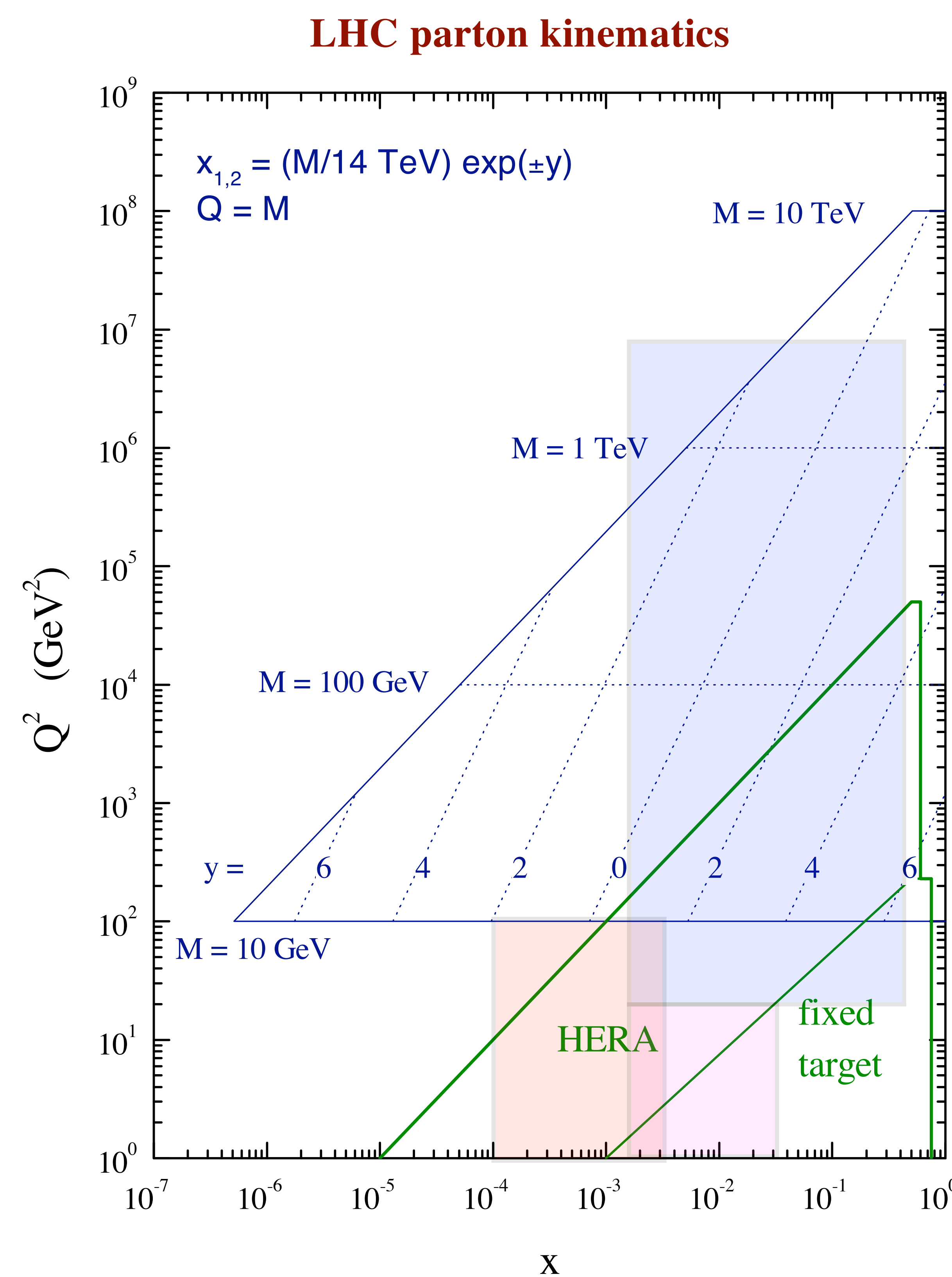
Low-x Workshop, Lisbon, June 28 - July 1, 2006

- introduction
- forward jets and more from H1
- three jets from H1
- three and four jets from ZEUS

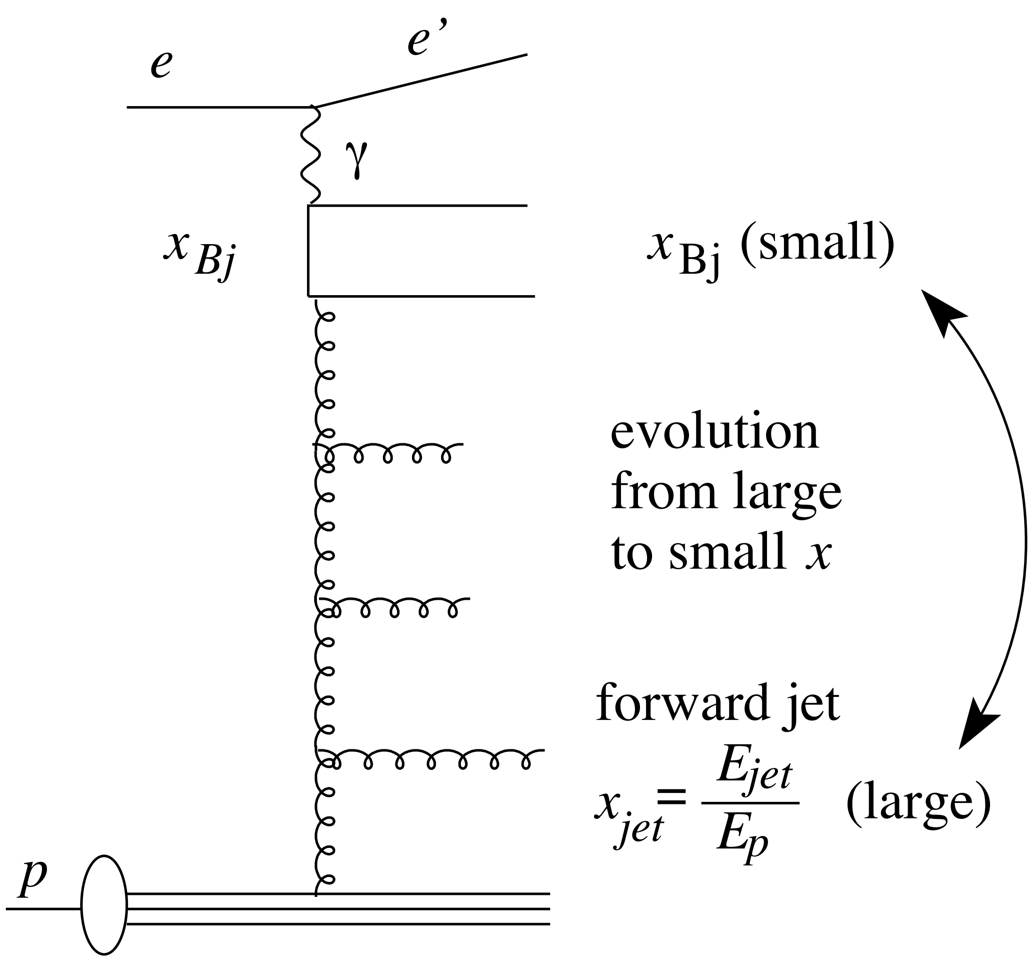
Parton Evolution & Kinematic Plane





- at the LHC: for moderate/large Q2 and x take pdfs from HERA & evolve them with DGLAP
- at the LHC: for which x and Q2 is the coll. approx. no longer sufficiently precise?
- what are the numerical values for the onset of low-x effects on the x and Q2 scale?
- what low-x effects are observed at HERA?
- at the LHC: what are the implications?

Forward Jets in DIS



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

Event & Forward Jet Selection

H1 Collab., Eur. Phys. J. C **46** (2006) 27
[arXiv:hep-ex/0508055]

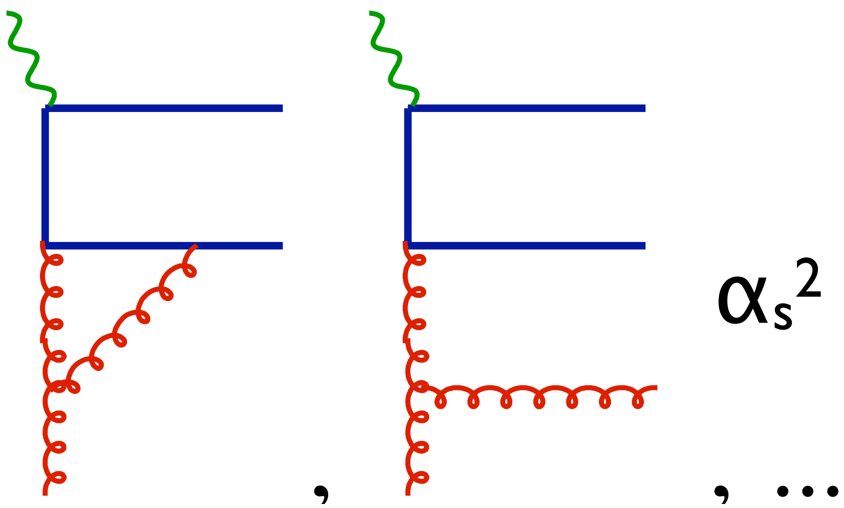
- event phase space
  - $5 < Q^2 < 85\ GeV^2$
  - $0.1 < y < 0.7$
  - $0.0001 < x_{Bj} < 0.004$
- fwd jet (incl. $k_\perp$ in Breit frame) & cuts in HERA frame
  - $7° (2.79) < \theta_{jet} (\eta_{jet}) < 20° (1.74)$
  - $p_{t,jet} > 3.5$ GeV
  - $x_{jet} = E_{jet}/E_p > 0.035$
  - if $N_{jet}>1$, take most forward jet

- $d\sigma/dx_{Bj}$ with
  $0.5 < r = p^2_{t,jet}/Q^2 < 5$
  to suppress evln. in Q^2

- $d^3\sigma/dx_{Bj}dQ^2dp^2_{t,jet}$

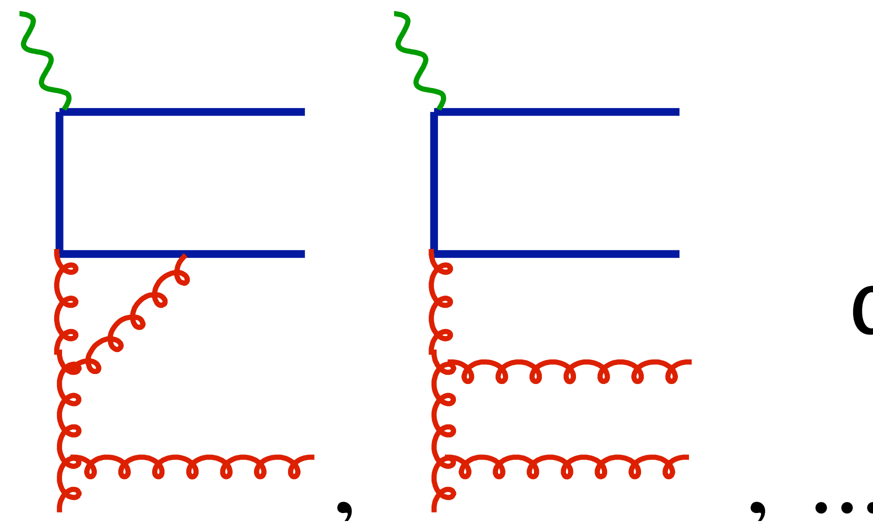
NLO Dijet & NLO Trijet Calc. in DIS

NLO Dijet
DISENT + NLOJET++



α_s^2

NLO Trijet
NLOJET++

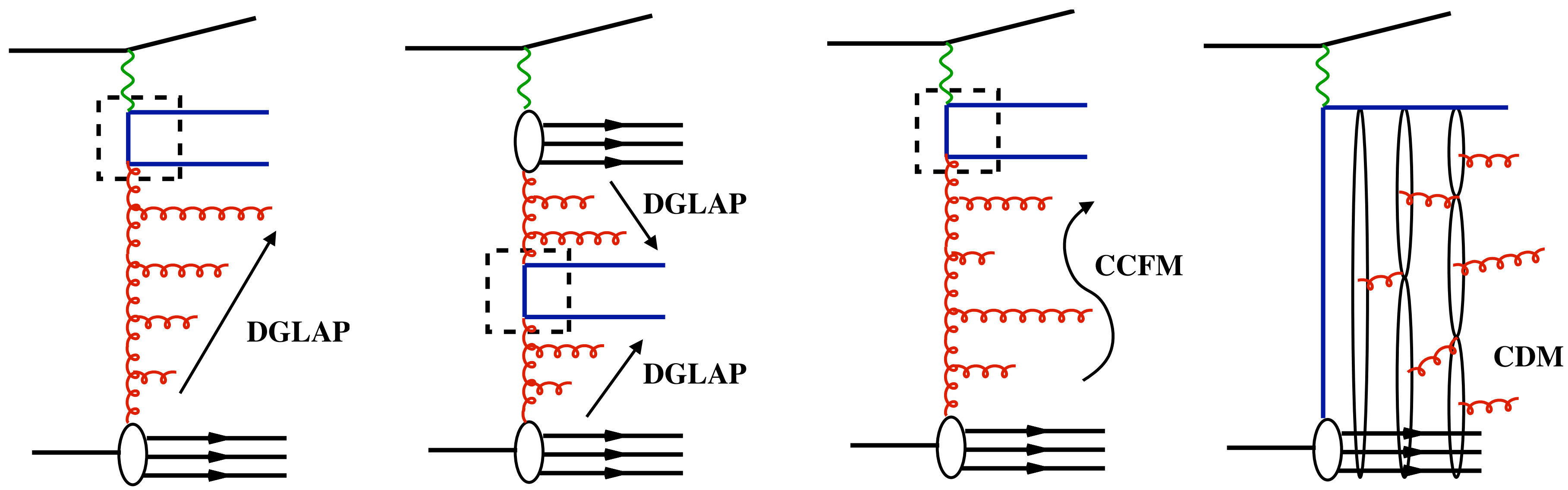


α_s^3

	DISENT	NLOJET++
μ^2(ren.)	$p^2_{t,dijet}$	$(p^2_{t,jet1}+p^2_{t,jet2}+p^2_{t,fwdjet})/3$
μ^2(fact.)	$\langle p^2_{t,jet} \rangle$	$(p^2_{t,jet1}+p^2_{t,jet2}+p^2_{t,fwdjet})/3$
proton PDF	CTEQ6M	CTEQ6M

hadronization corrections are applied to these calculations

QCD models in DIS



Rapgap DIR	Rapgap DIR+RES	Cascade DIR	ARIADNE

DGLAP resums $\ln Q^2$
at low x, strong ordering
of k_t of emitted partons
$g(x,\mu^2)$

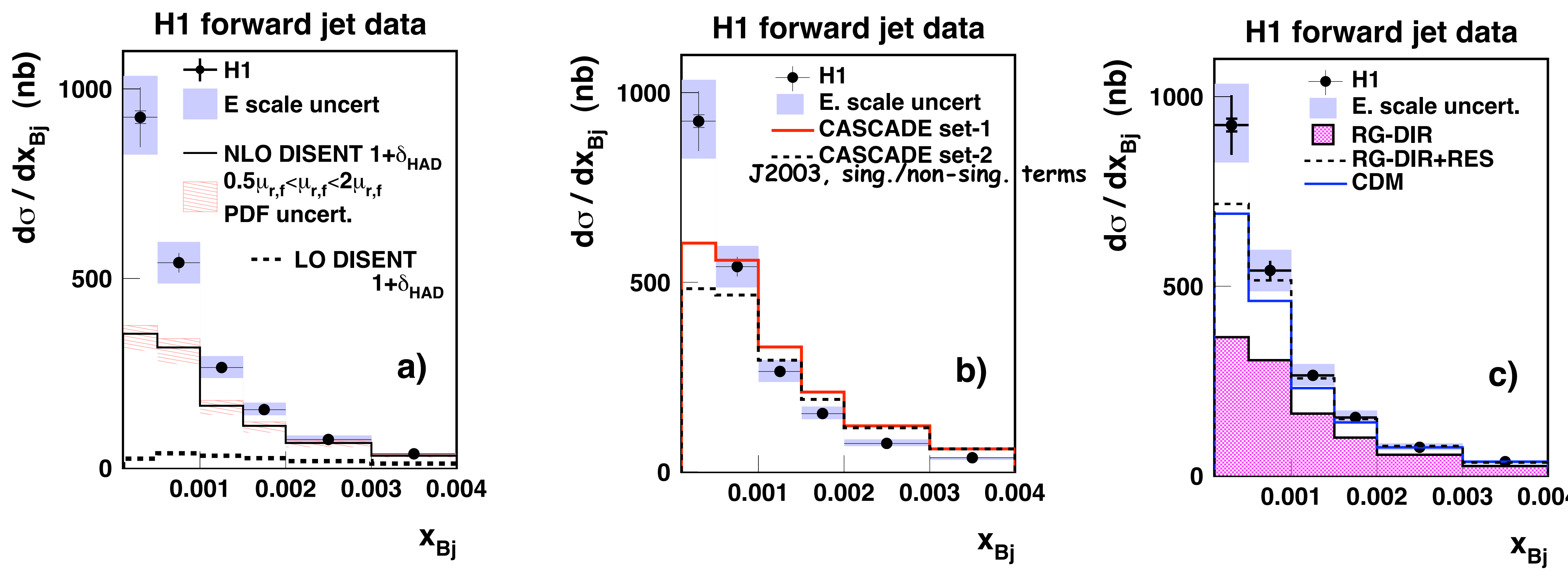
CCFM resums $\ln Q^2$ & $\ln 1/x$
angular ordering of partons
off-shell ME
$g(x,k_t,\mu^2)$

Color Dipoles radiate
independently
kt non-ordered
partons

μ^2(ren) = μ^2(fact)	Q2 + $\hat{p}^2_t$
proton PDF	CTEQ6L
photon PDF	SaS1D

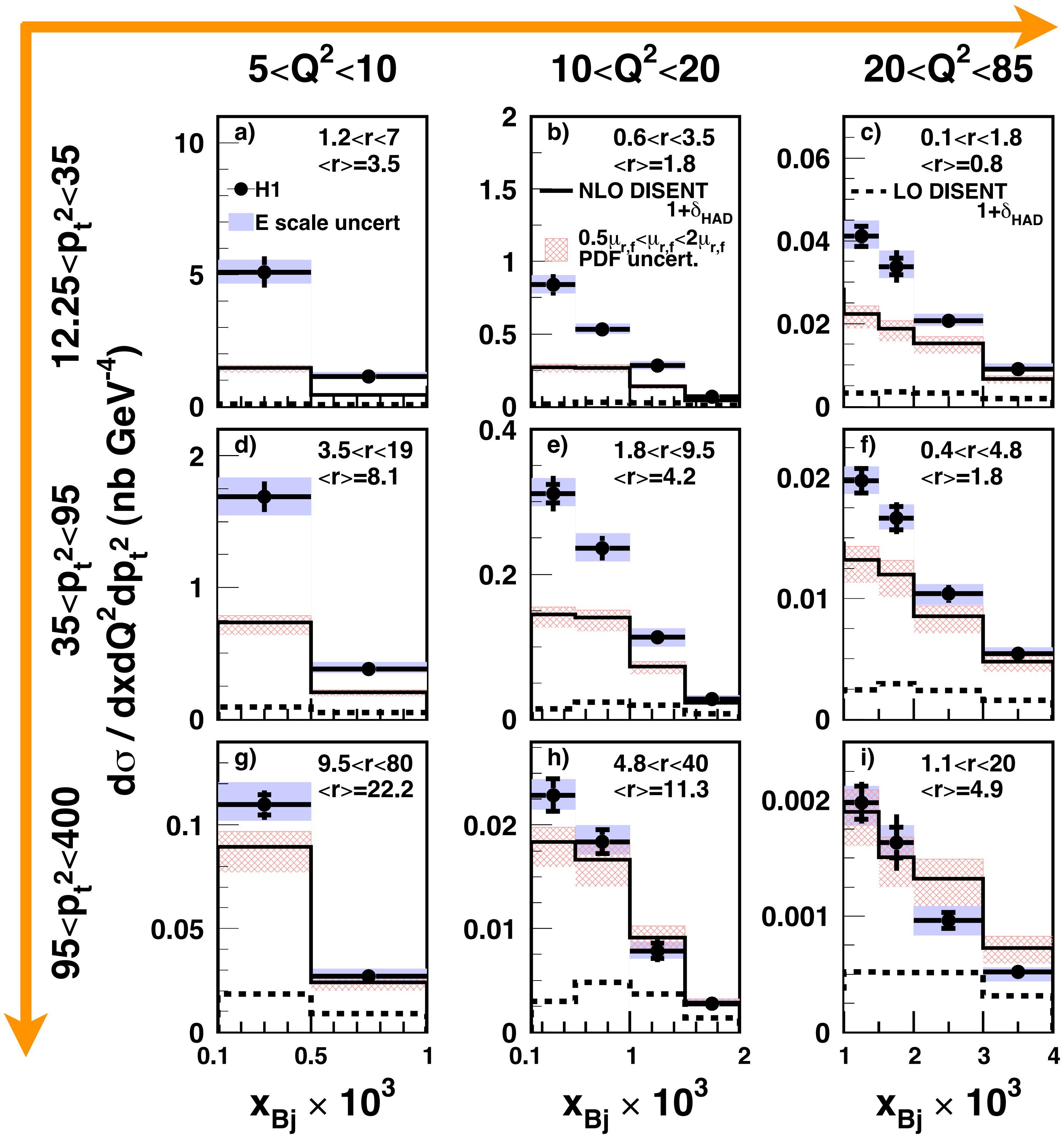
μ^2(ren)	$p^2_{t,q} + 4m^2$
μ^2(fact)	$\hat{s} + Q^2_t$
photon PDF	SaS1D

Forward Jets: $d\sigma/dx_{Bj}$



- NLO significantly below data for low x_{Bj}, LO << NLO, fwd-jets in LO suppressed by kinematics
- CASCADE (CCFM) doesn't describe shape of data, low at lowest x_{Bj}
- RAPGAP direct fails like NLO, direct+resolved and CDM give good description of data except at lowest x_{Bj}

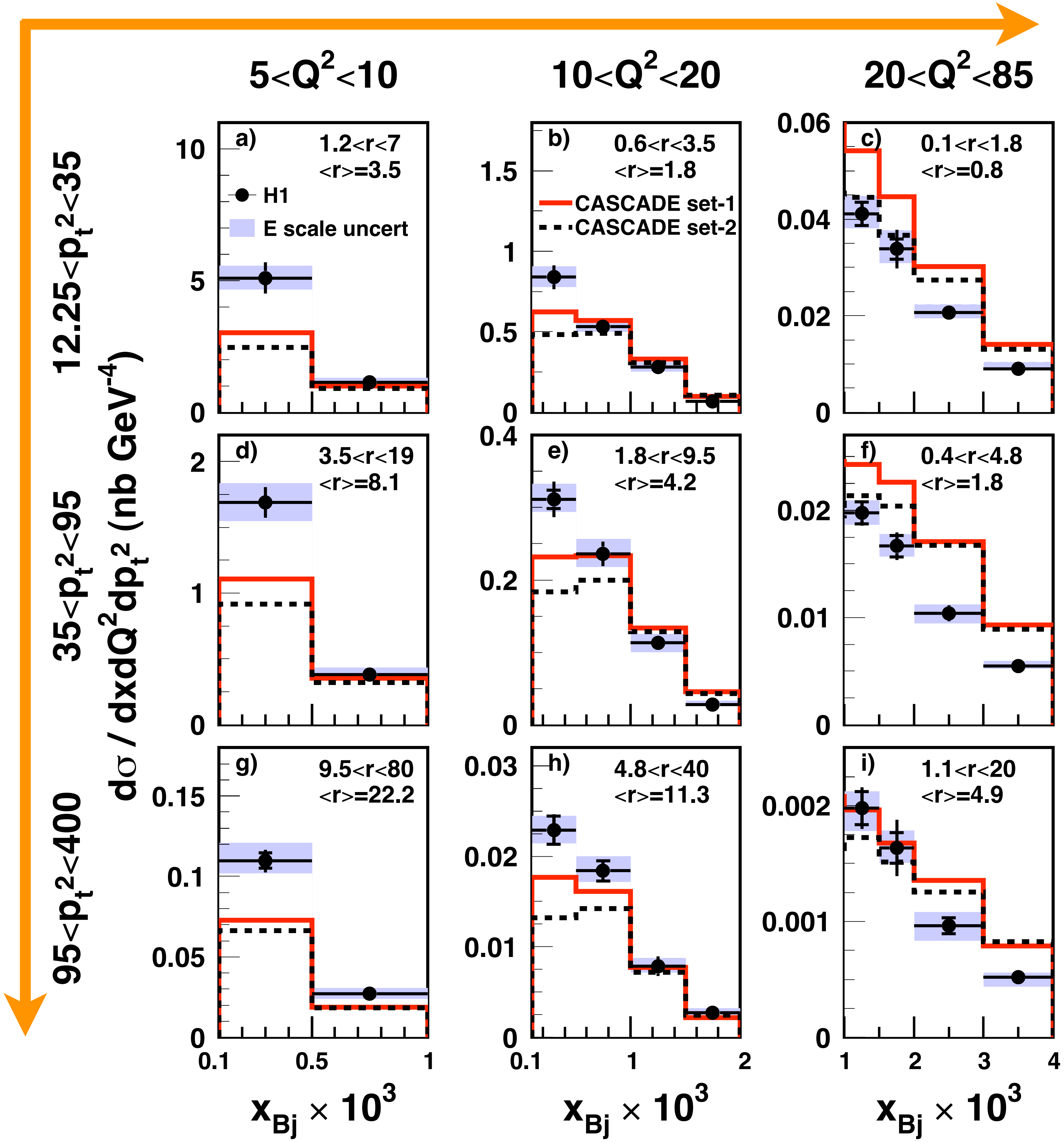
Forward Jets: $d^3\sigma/dx_{Bj}dQ^2dp^2_{t,jet}$



Data, LO and NLO

- cross section as funct. of x_{Bj} in bins of p^2_t-Q^2 **(no cut on p^2_t/Q^2)**
- range and average **$r=p^2_t/Q^2$** shown for each bin
- **NLO**
  - ***in general below data***
  - **better at high x_{Bj}, Q^2 and p^2_t**

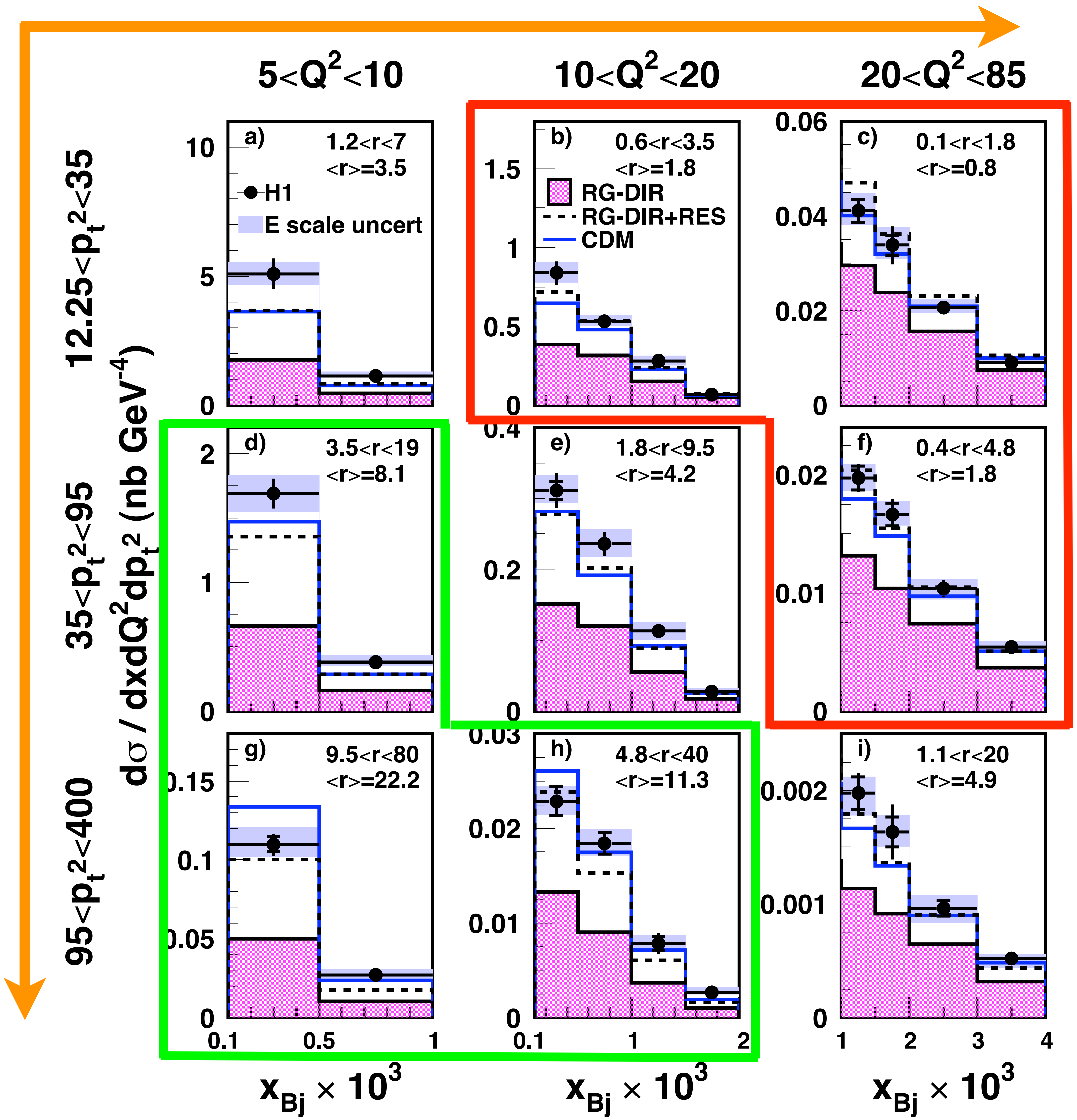
Forward Jets: $d^3\sigma/dx_{Bj}dQ^2dp^2_{t,jet}$



Data and CASCADE

- cross section as funct. of x_{Bj} in bins of p^2_t-Q^2 **(no cut on p^2_t/Q^2)**
- range and average **$r=p^2_t/Q^2$** shown for each bin
- **the CCFM model under and overshoots the data**
- does CASCADE need resolved contributions and/ or splitting into quark-pairs ?

Forward Jets: $d^3\sigma/dx_{Bj}dQ^2dp^2_{t,jet}$

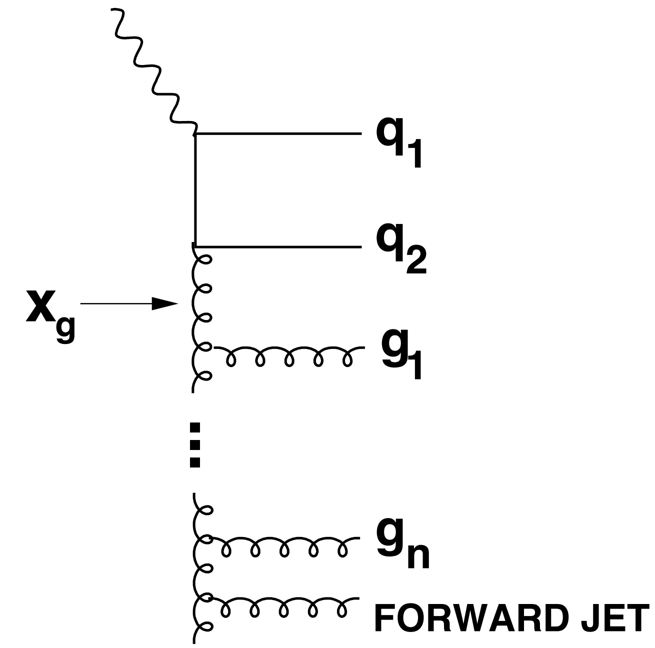


Data
RAPGAP direct & resolved
CDM

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

Forward Jet & Dijet Selection

- event phase space as before
- fwd jet (incl. k_t in Breit frame) & cuts in HERA frame
  - $7° (2.79) < \theta_{jet} (\eta_{jet}) < 20° (1.74)$
  - ~~$p_{T,jet} > 3.5$ GeV~~
  - $x_{jet} = E_{jet}/E_p > 0.035$
  - if $N_{jet}>1$, take most forward jet

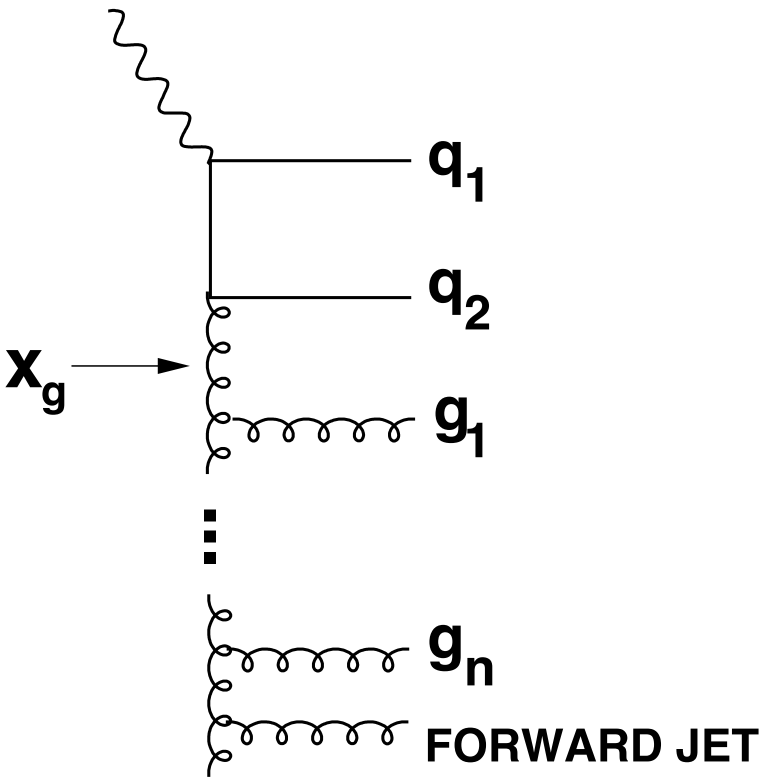


- fwd-jet & dijet (incl. k_t in Breit frame) & cuts in HERA frame
  - **$p_{t,jet} > 6$ GeV for all 3 jets (take as dijets the jets with highest p_t)**
  - $\eta_e < \eta_{jet1} < \eta_{jet2} < \eta_{fwdjet}$
  - other cuts on fwd-jet as before
  - no cut on $p^2_{t,jet}/Q^2$

same $p_{t,jet}$ cut for all 3 jets disfavors evln. with strong p_t ordering as in DGLAP

- $d^3\sigma/d\Delta\eta_1 d\Delta\eta_2$
  $\Delta\eta_1 = \eta_{jet2} - \eta_{jet1}$
  $\Delta\eta_2 = \eta_{fwdjet} - \eta_{jet2}$

Forward Jet & Dijet



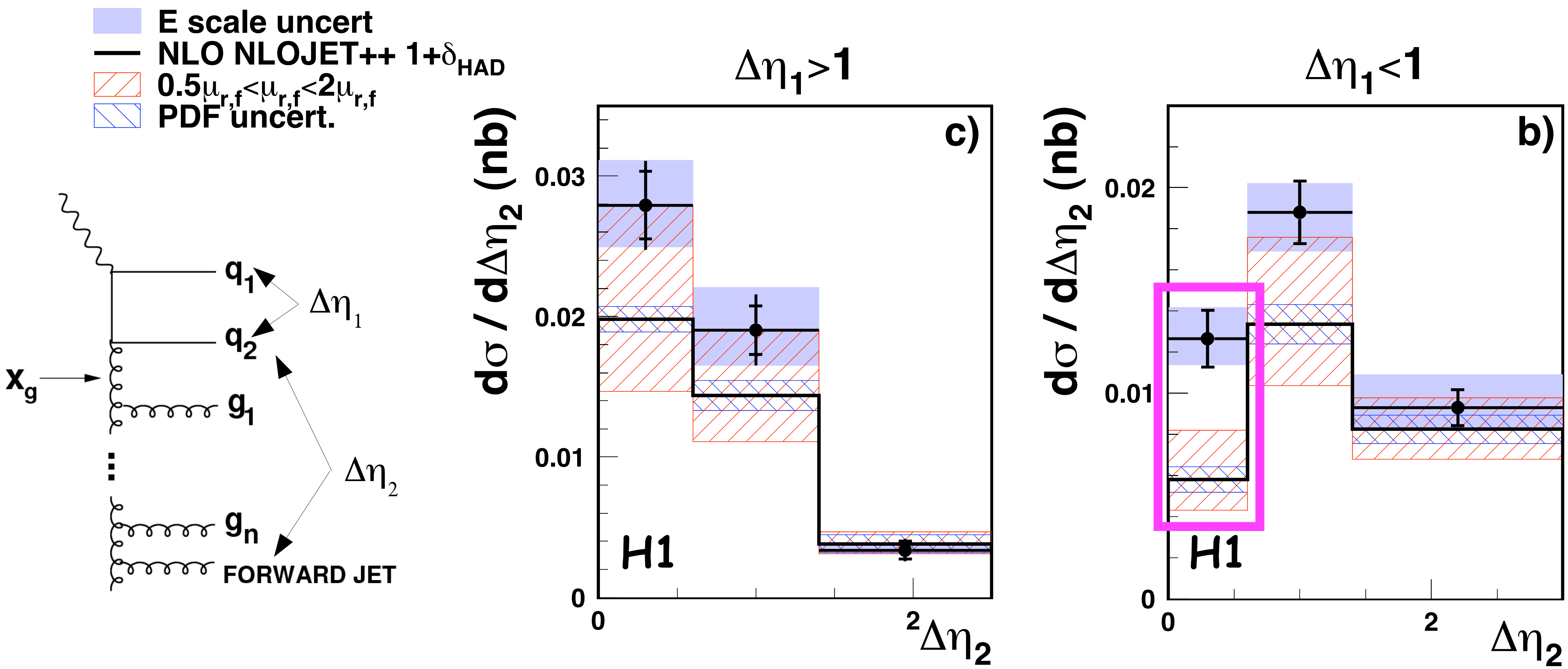
$\eta_e < \eta_{jet1} < \eta_{jet2} < \eta_{fwdjet}$

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

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

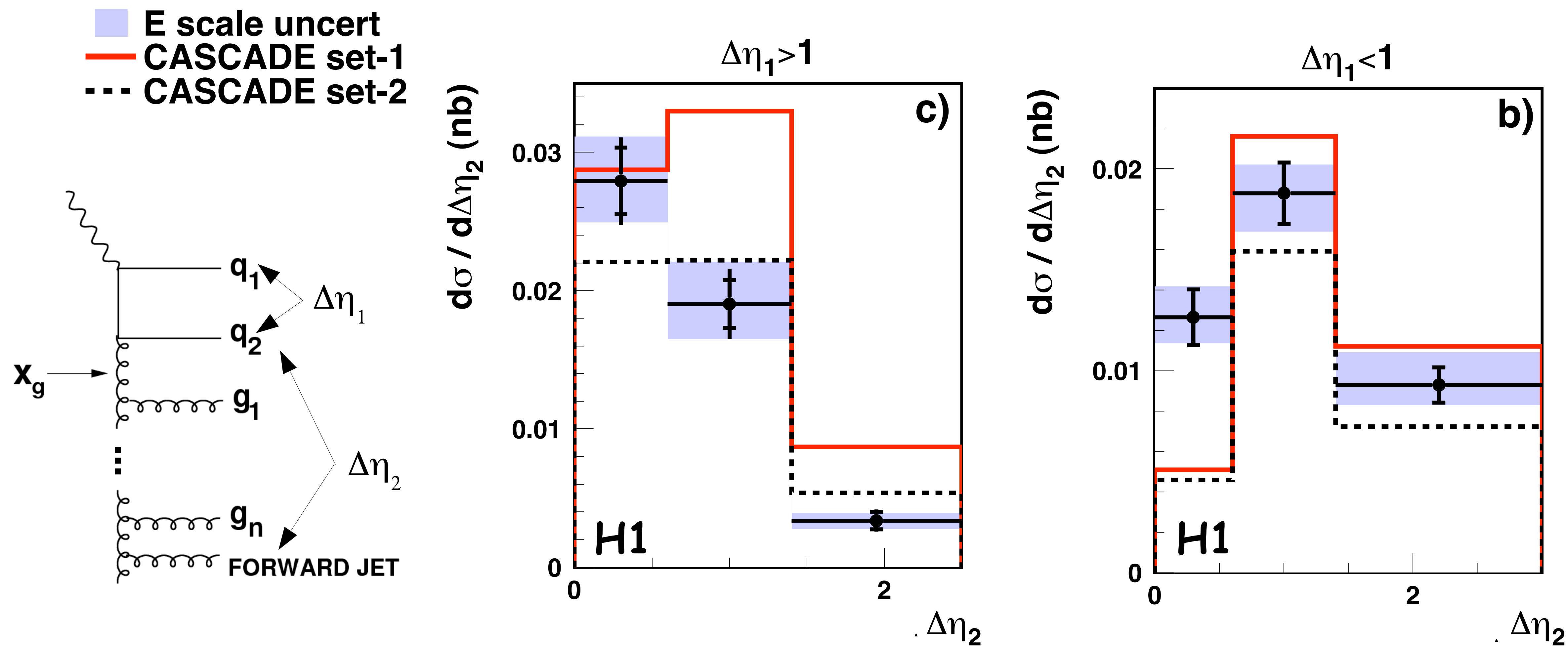
- Before $p^2_{t,jet}/Q^2$ was used to study different regions of parton dynamics; here instead jet momenta & rapidity separations are used to study different regions of parton dymanics.
- $\Delta\eta_1$ small
  - and if jet1/2 = $q_{1/2}$ then x_g small
  - $\Delta\eta_2$ large → room for evln. in x between dijet system and fwd-jet
  - $\Delta\eta_2$ small → all 3 jets may be more forward and jet1/2 may be gluon jets (not present in $O(\alpha^3_s)$ calc. → data above NLO
- $\Delta\eta_1$ large, evln. in x may occur between jets of dijet system

Forward Jet & Dijet



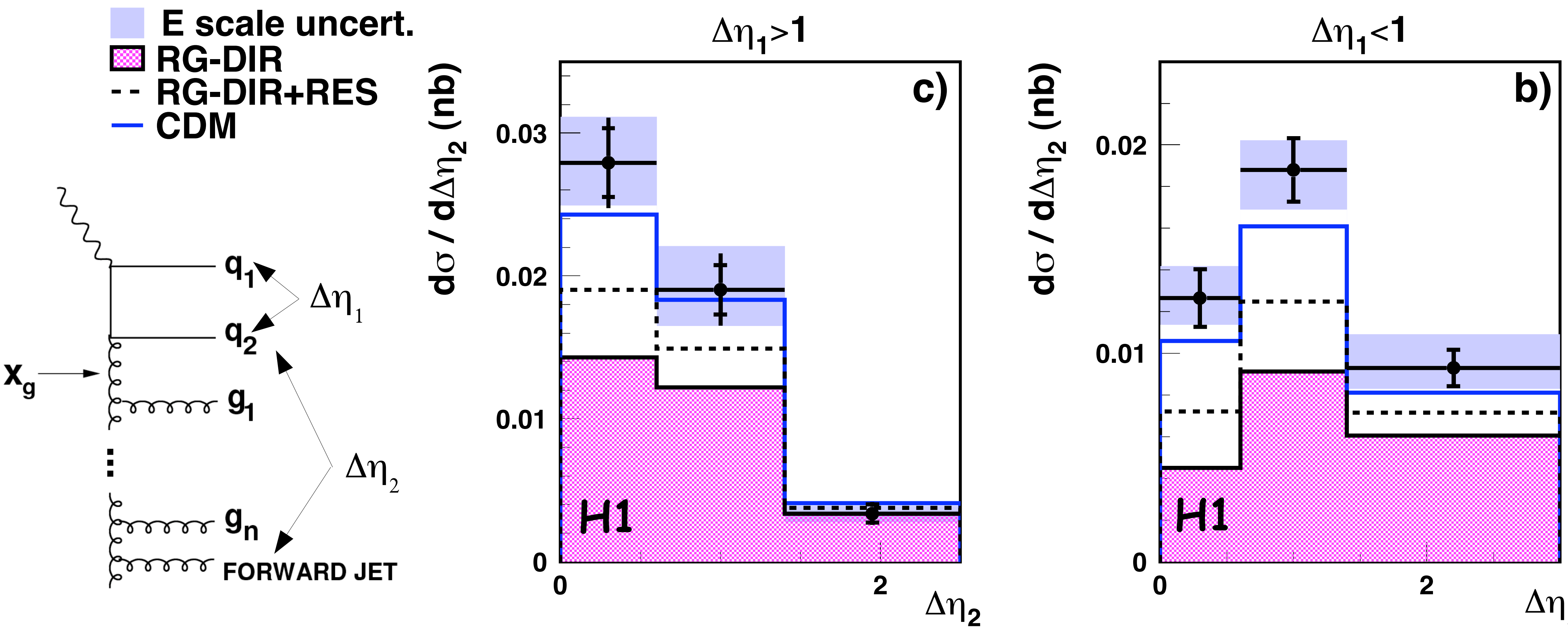
- NLOJET++ (NLO $O(\alpha^3_s)$ trijet production, includes ln1/x in $O(\alpha_s)$)
  - overall reasonable description of data within large uncertainties, except for $\Delta\eta_1 < 1$ and for decreasing $\Delta\eta_2$, i.e. when all 3 jets go forward (q+g+g is LO in $O(\alpha^3_s)$ calc. and g+g+g is higher order)
  - describes data well for $\Delta\eta_2$ large, i.e. for dijets at central rapidities

Forward Jet & Dijet



- CASCADE (CCFM)
  - does not describe data, “best” for $\Delta\eta_1 < 1$ and large $\Delta\eta_2$

Forward Jet & Dijet



- CDM: surprisingly good description of data everywhere
- RAPGAP (direct + resolved): fails to describe data

☛ the breaking of k_t ordering seems best modeled by CDM and not by direct and resolved contributions a la DGLAP as in RAPGAP
fwd-jet+dijet sample can distinguish between RG-DIR+RES and CDM

Event & Trijet Selection

H1 Prel., DIS 2006

- event phase space
  - $5 < Q^2 < 80$ GeV^2
  - $0.1 < y < 0.7$
  - $0.0001 < x_{Bj} < 0.01$
- jets (incl. k_t in γ^*p frame)
  - $E^*_{t,jet} > 4$ GeV (all 3 jets)
  - $E^*_{t,jet1} + E^*_{t,jet2} > 9$ GeV
  - $-1 < \eta_{jet} < 2.5$ in HERA frame
  - ≥ 1 central jet with $-1 < \eta_{jet} < 1.3$
  - $N_{jet} \geq 3$

fwd-jet: $\theta_{jet} < 20°$
$x_{jet} > 0.035$

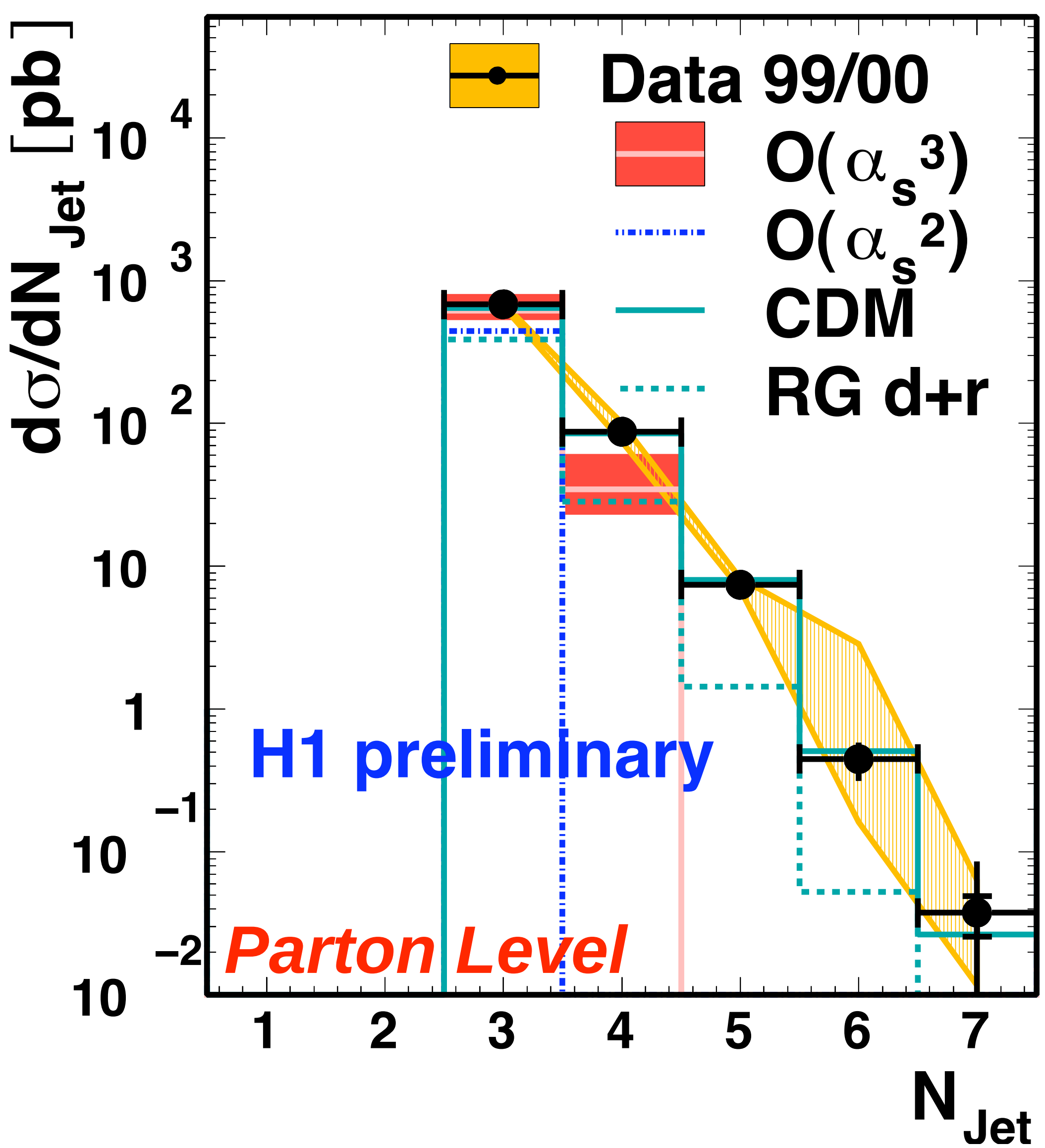
Motivation:
study **trijet parton dynamics** from **inclusive** to **very exclusive** (at least one jet is a gluon jet; expect sensitivity to gluon dynamics)

- inclusive trijet topologies
  - o N_{jet}, x_{Bj}, η_1, η_2, η_3,
  - o X_1, X_2, $\cos\theta$ and $\cos\psi$ in trijet rest frame

only a few distributions will be shown here

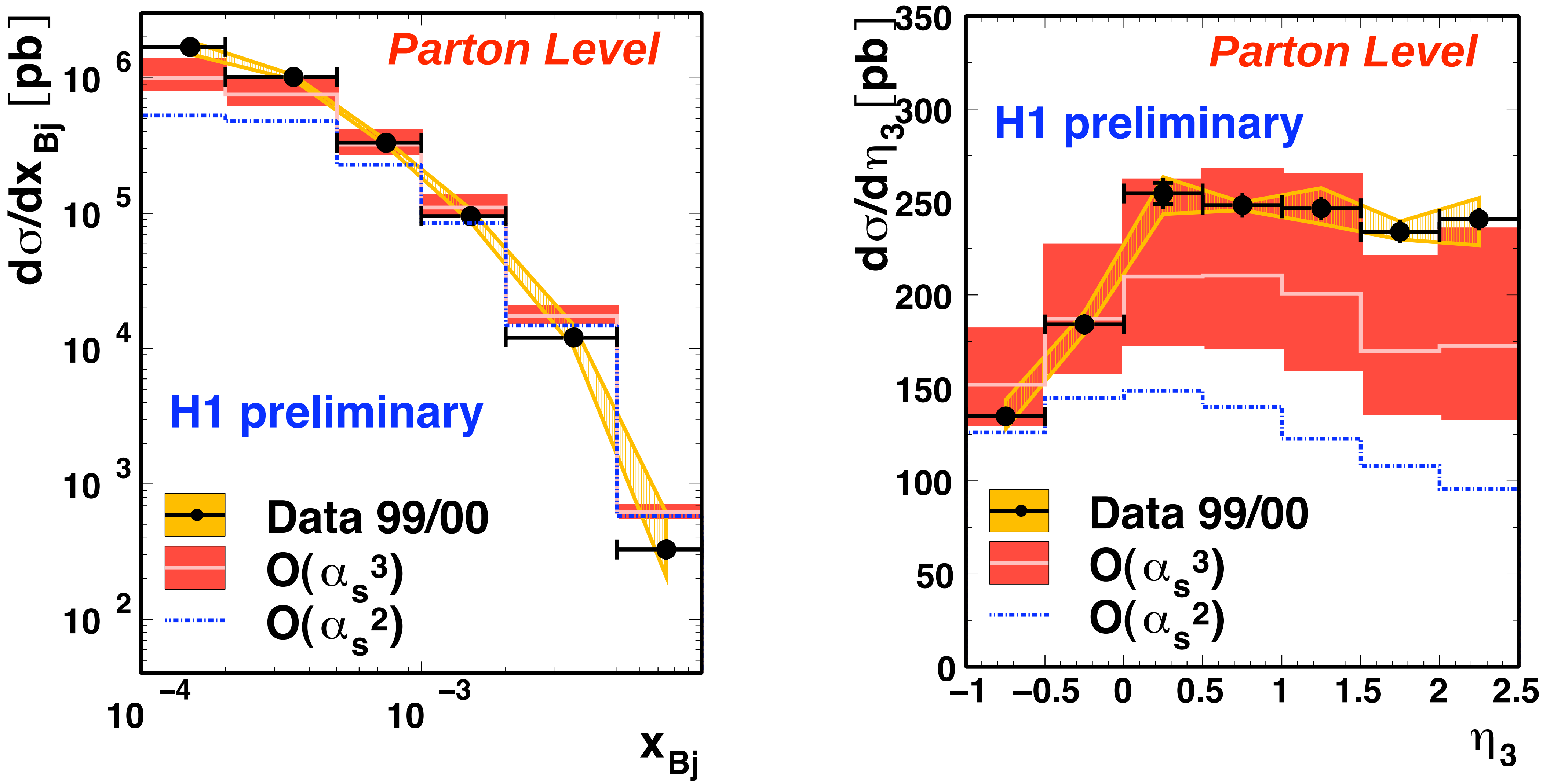
- 1 fwd-jet & 2 central jets
- 2 fwd-jets & 1 central jet
  - o x_{Bj}, η_1, $p^*_{t,jet1}$,
  - o X_1, X_2, $\cos\theta$, $\cos\psi$ in trijet rest frame

Inclusive Trijets: $d\sigma/dN_{jet}$



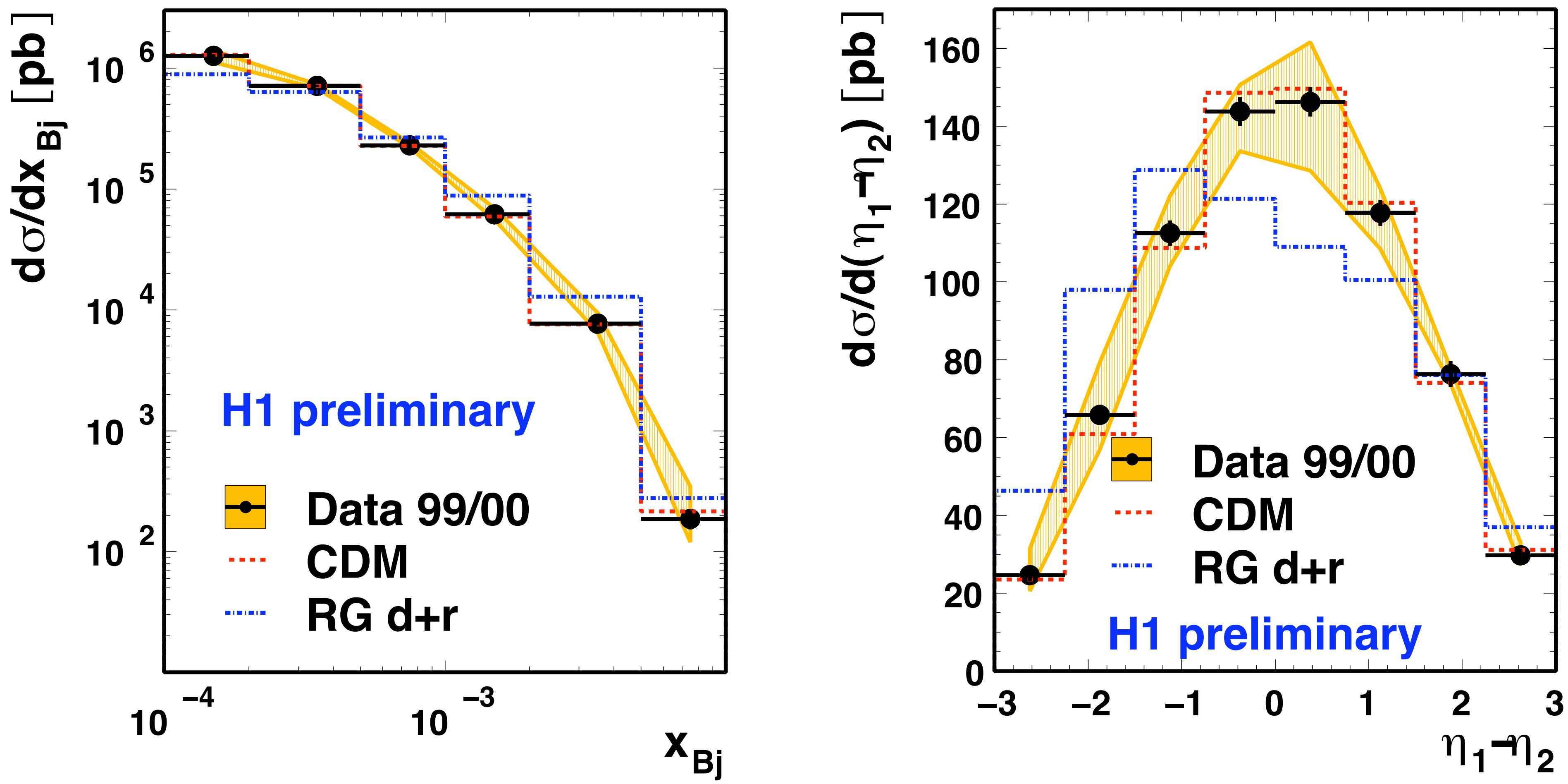
- NLOJET++
  - NLO $O(\alpha^3_s)$ misses ≈ 50% of events with $N_{jet} \geq 4$
- CDM
  - provides excellent description
- RAPGAP (direct + resolved)
  - undershoots data for all N_{jet}

Inclusive Trijets: $d\sigma/dx_{Bj}$



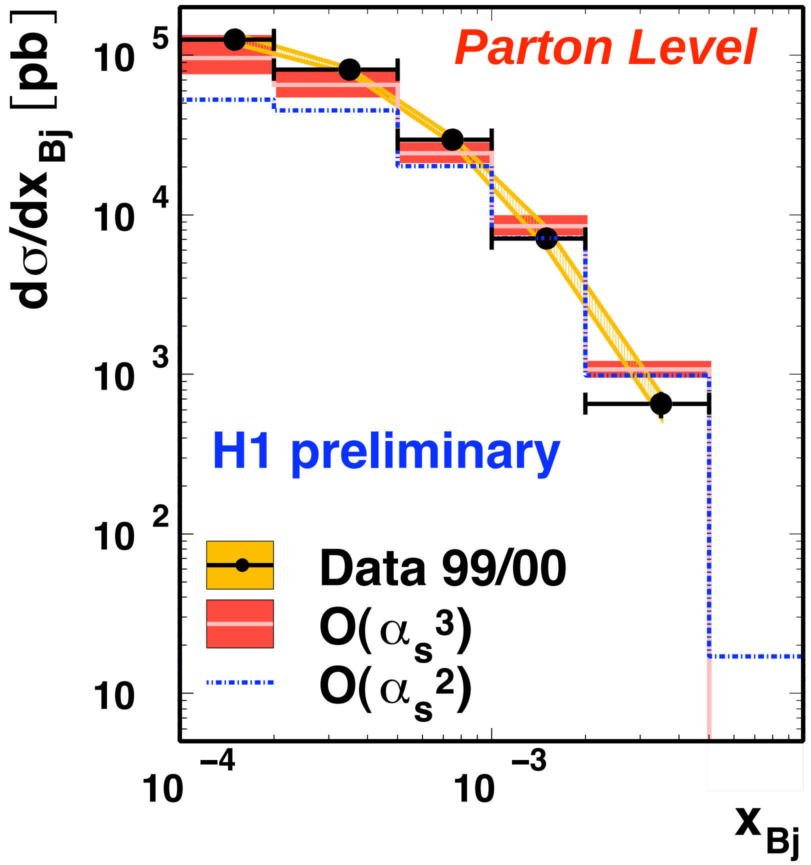
- NLOJET++
  - observe significant improvement from LO to NLO $O(\alpha^3_s)$, particularly at low x_{Bj} and large η_{jet}

Inclusive Trijets: $d\sigma/dx_{Bj}$



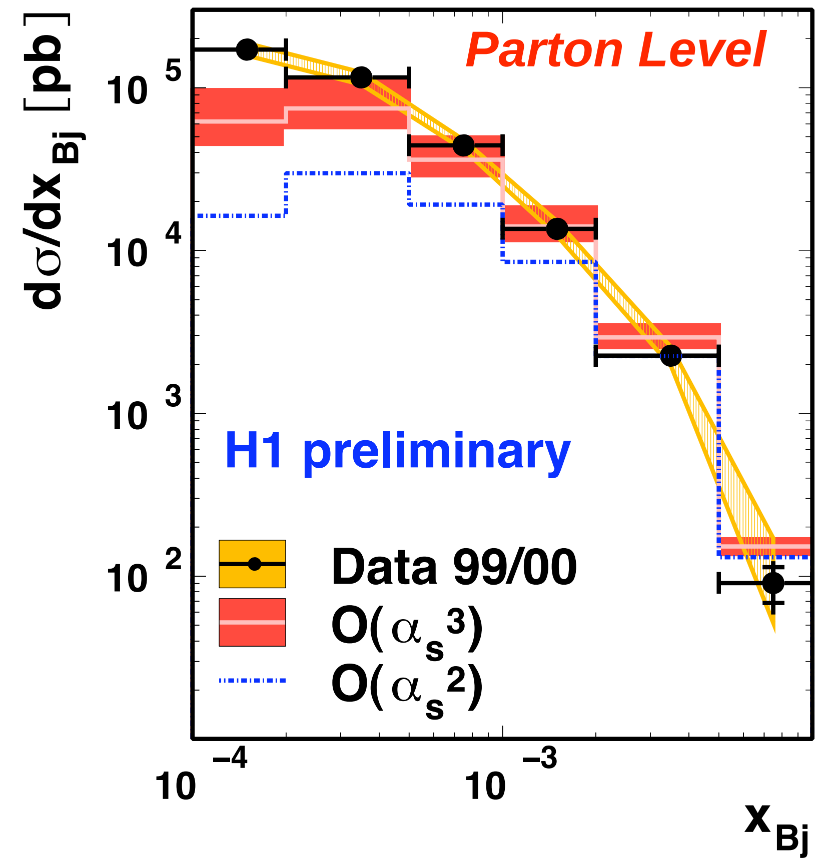
- CDM provides a good description of both distributions
  - CDM normalized to data by factor 1.08
- RAPGAP (direct+resolved) fails to describe the data
  - RAPGAP normalized to data by factor 1.7

"Exclusive" Trijets: $d\sigma/dx_{Bj}$



1 fwd-jet & 2 central jets

NLOJET++
- o NLO describes data well



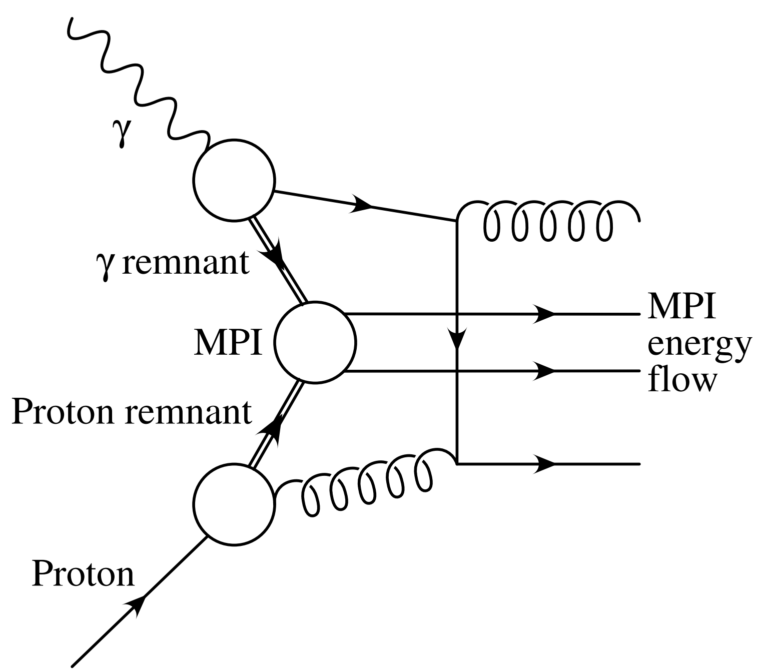
2 fwd-jets & 1 central jet

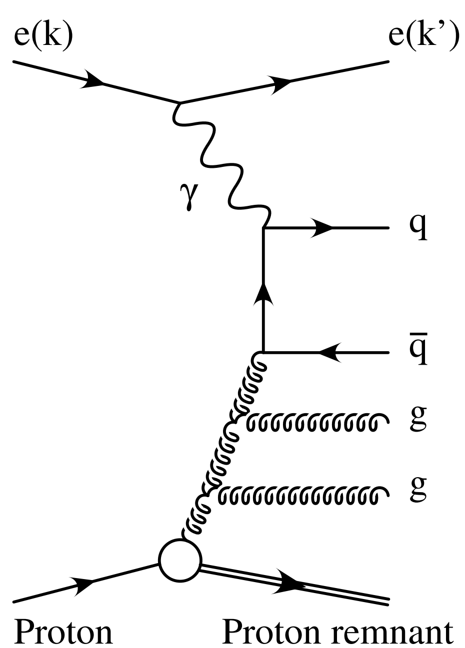
NLOJET++
- o NLO describes data well for $x_{Bj} > 5\ 10^{-4}$
- o NLO fails at lowest x_{Bj}

2 fwd-jets, mainly gluon jets ☛ at lowest x_{Bj} un-ordered gluon emissions play an important role !

Three and Four-Jets in γp

MPI ... multi-parton interactions



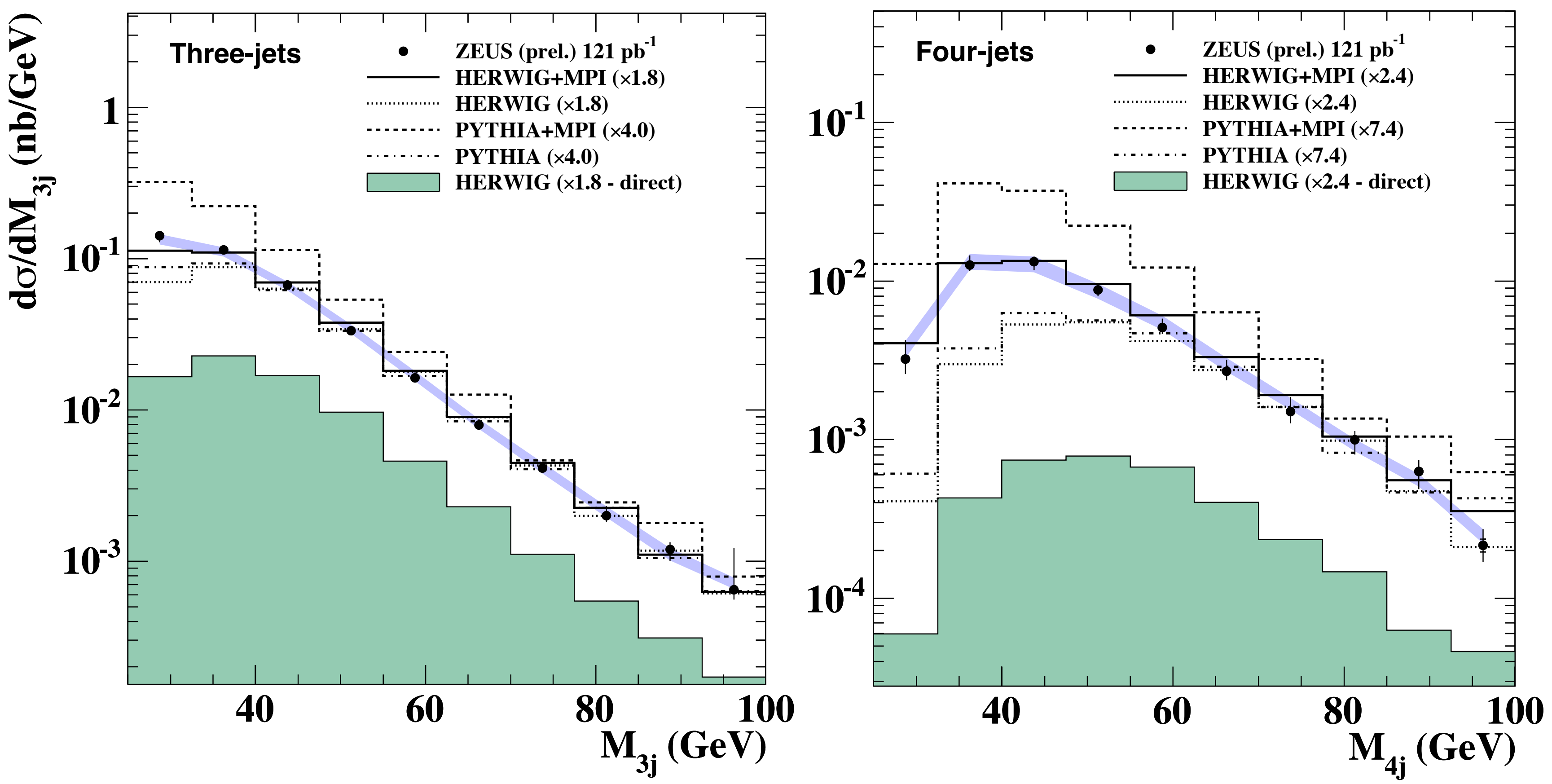


- Motivation:
  - expect multi-jets and underlying event/ MPIs to be significant at LHC
  - test LO ME + matched parton shower QCD models in generating multi-jets
  - look for sensitivity to MPIs and test MPI models
  - is the physics of MPI's between the photon remnant and the proton the same as between proton and antiproton?
  - test fixed higher order pQCD calcs. in γp when available, currently only LO for 3-jets (O(α2s) at hand.

Three and Four-Jets in γp

ZEUS prel., DIS 2006

- event and jet phase space (incl. $k_\perp$, massless)
  - $Q^2 < 1.0$ GeV^2, $0.2 < y < 0.85$
  - $E_{T,jet1,2} > 7$ GeV, $E_{T,jet3,4} > 5$ GeV
  - $|\eta_{jet}| < 2.4$, $\cos\theta_{3'} < 0.95$, $X_{3'} < 0.95$
- observables
  - $x_\gamma^{obs} = \Sigma^{njet} E_{T,i}\, e^{(-\eta i)}/(2yE_e)$
  - $M^2_{nj} = (\Sigma^{njet}\, p_i)^2$
  - $E_{T,i}$, $\cos\theta_{3'}$, $\cos\psi_{3'}$, y
- study two regions in mass: $M_{nj} \geq 25$ GeV & $M_{nj} \geq 50$ GeV

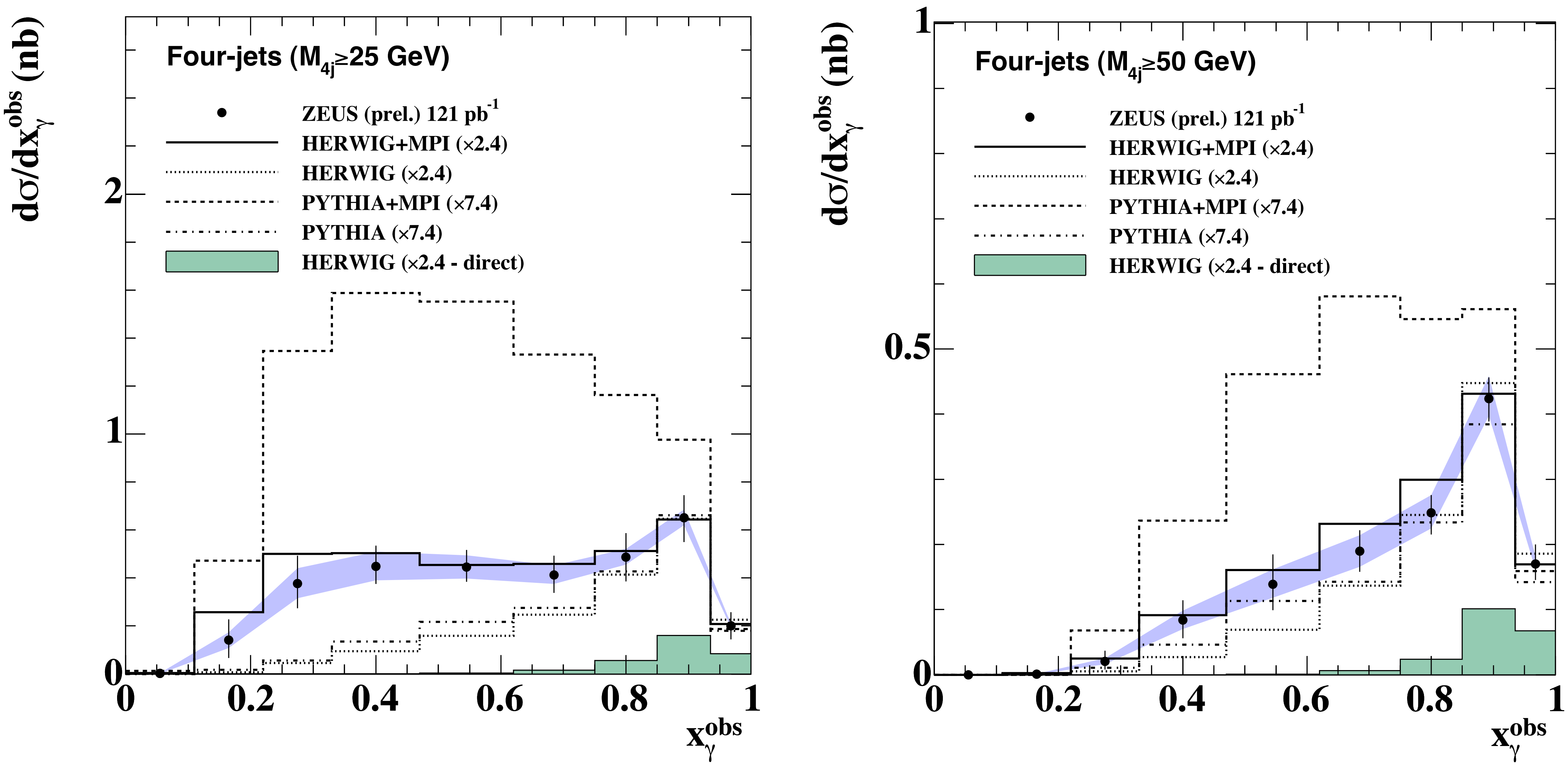


Monte Carlo Models

- PYTHIA 6.2 & HERWIG 6.5 with/without MPIs
  - PYTHIA MPIs tuned to collider data (JETWEB)
  - HERWIG MPIs tuned to ZEUS multi-jets
    - MCs without MPIs normalized to data for $M_{nj} > 70$ GeV

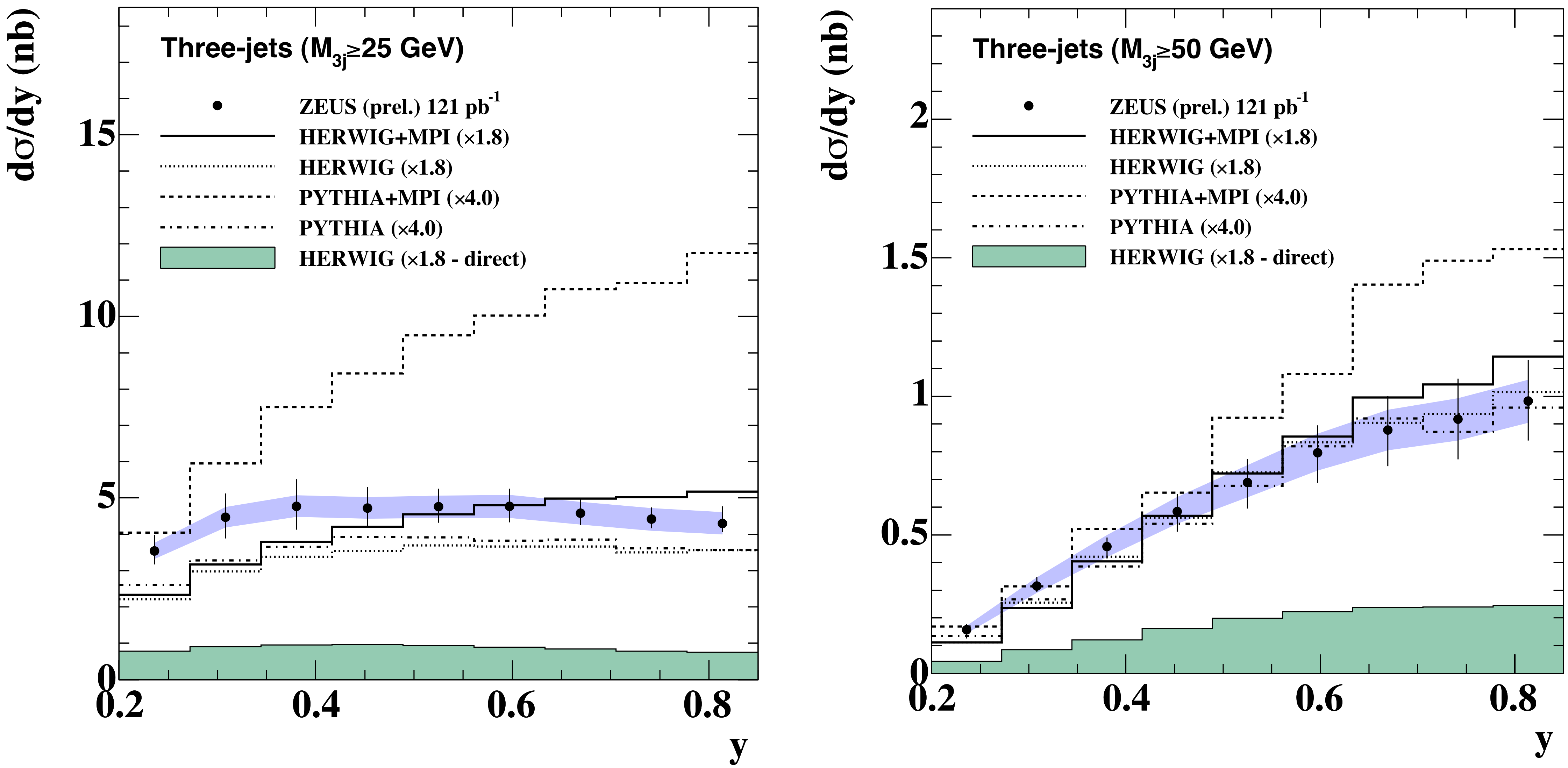
→ Effect of MPIs larger for 4-jets and small M_{nj}

Four-Jets in γp: $d\sigma/dx_\gamma^{obs}$



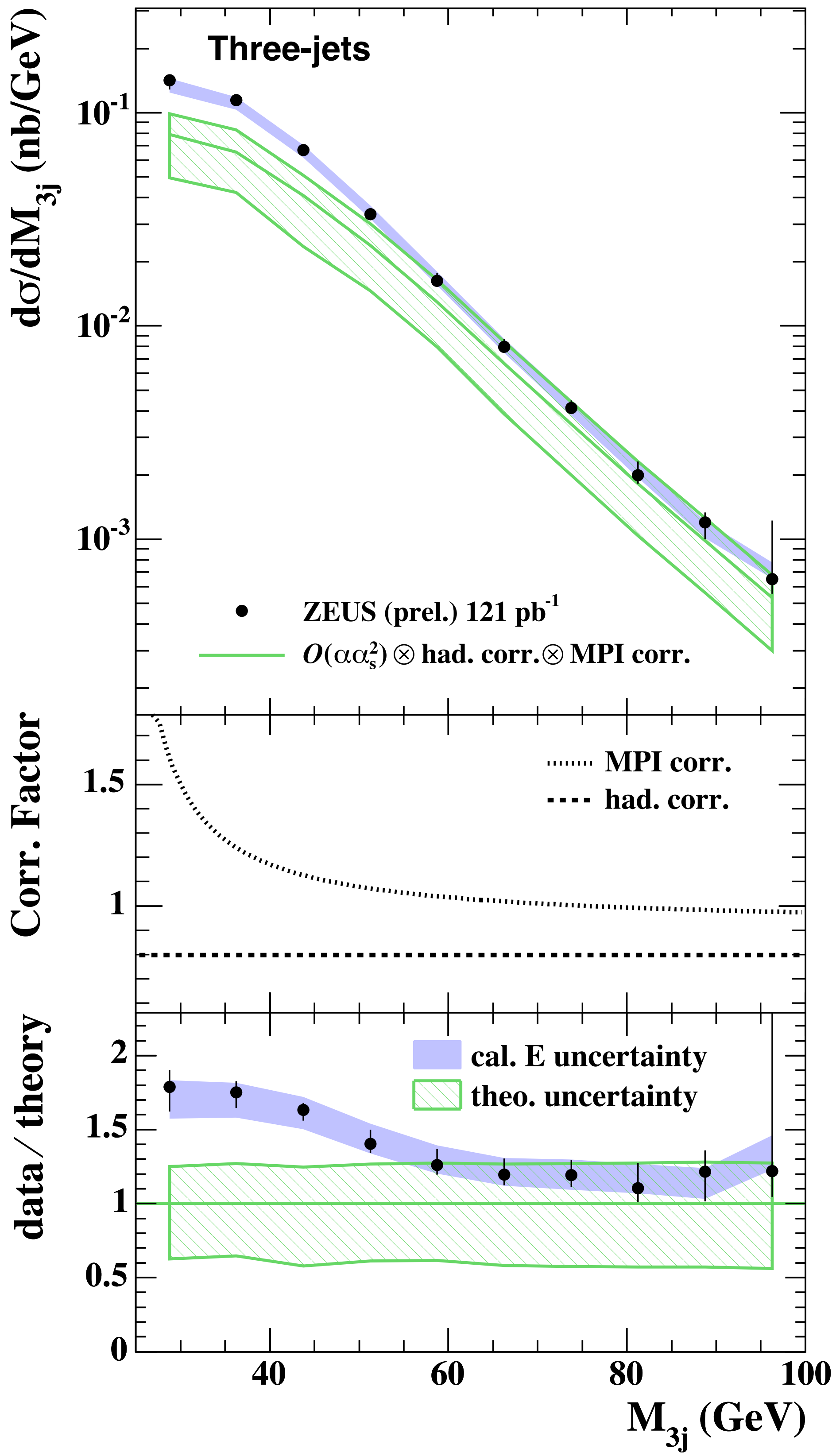
- MCs without MPIs describe x_γ^{obs} even for high M_{4j} only for large x_γ^{obs}
- PYTHIA & HERWIG without MPIs are roughly in agreement
- HERWIG with MPIs (JIMMY 4.0) provides a good description of data
- PYTHIA with MPIs fails completely

Three-Jets in γp: dσ/dy



- HERWIG with MPIs fails to describe data (for low M_{3j})
- PYTHIA with MPIs fails completely
- Both MCs without MPIs describe shape of dσ/dy

Three-Jets in γp & LO pQCD



- for 3-jets in γp only LO ($O(\alpha^2_s)$) calc. available (e.g. Klasen et al.)
- $\mu_r = \mu_f = E_{T,jet1}$
- evaluate scale uncertainties using $2^{\pm 1}\, E_{T,jet1}$ for scales
- proton & photon pdfs: CTEQ4L & GRV-G LO
- LO results corrected for hadronization and MPI corrections
- LO describes high M_{3j}, but fails for $M_{3j} < 50$ GeV
- NLO 3-jet calc. needed to learn more about MPIs

Summary/Conclusion

- CDM provides best description of all data, appears to have the necessary non-ordering in k_t.
- NLO
  - fails for low(est) x_{Bj}, Q^2 and $p^2_{t,jet}$
  - improves a lot w.r.t. to LO, when compared to inclusive trijets; $O(\alpha^3_s)$ contains ln1/x term in LO.
  - fails when fwd-jet and dijet go forward, i.e. when two or even three jets are gluon jets
- DGLAP (DIR+RES)
  - describes many data reasonably
  - fails specific fwd-jet and dijet topologies; the k_t-breaking via resolved appears not sufficient.
- CCFM surprisingly fails

Summary/Conclusion

- MPI in 3 and 4-jets in γp
  - PYTHIA & HERWIG without MIPs agree, but fail to describe data for low x_γ
  - HERWIG with MPIs describes data, except shape of $d\sigma/dy$
  - PYTHIA with MPIs fails completely
  - LO calc. fails for low M_{nj} ☛ need NLO 3-jet ($O(\alpha^3_s)$) calc. for γp

**We have one more year of data taking at HERA.
Which low-x measurements should still be done?**