Resolved γ^* & NLO QCD @ HERA

Günter Grindhammer, MPI Munich

on behalf of H1 and ZEUS

PHOTON 2007, July 9-13, Paris

physics at low/medium Q2:

- what is this talk about?
- jets, dijets, forward jets
- forward π^0
- charm jets
- charm meson production

Introduction

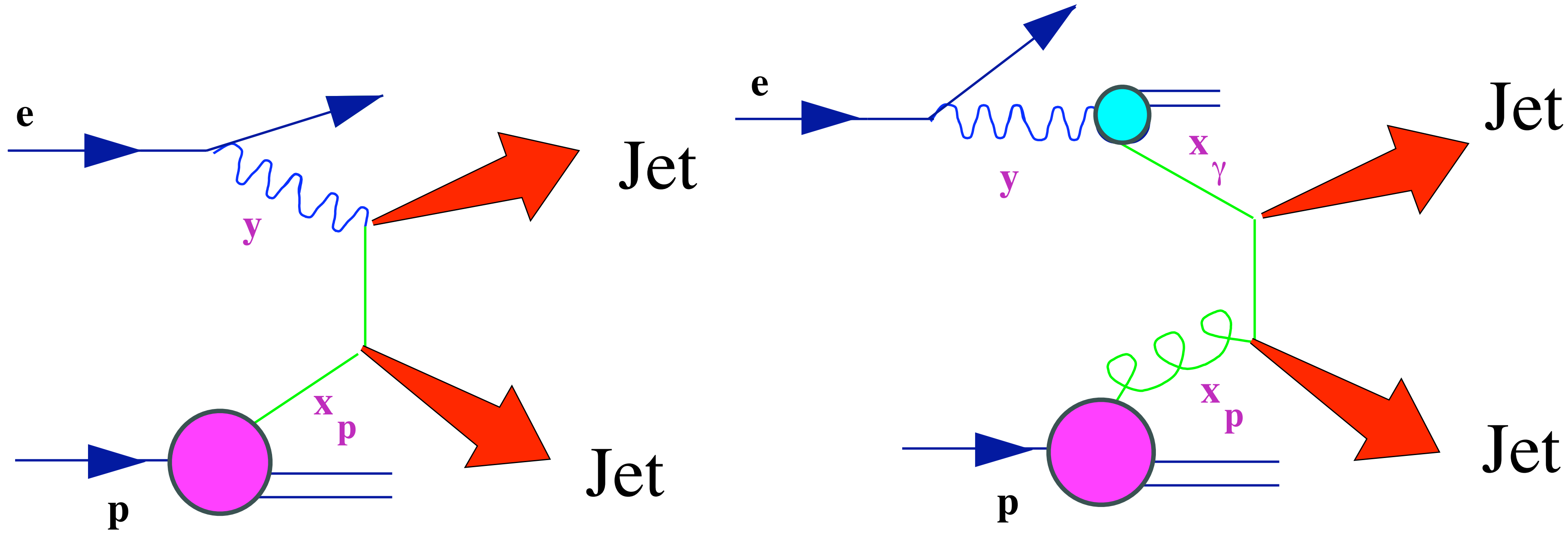
- What this talk is not about:
  - Measurements of hard processes in photoproduction or at high Q2 at HERA and their comparison with NLO QCD calculations were already covered, for example in talks on jets by Bussey, Jimenez, Brownson, and on heavy flavours by Loizides and Boenig, ...
    - Conclusions have been:
      - NLO calculations provide reasonable description of the data
      - improvements may come from:
        - fitting PDFs of the photon using the high jet E_T data
        - also better understanding of multi-parton interactions at low jet E_T

Introduction

- What this talk is (should be) about:
  - do NLO calculations of DIS require resolved γ^* contributions in NLO, i.e. beyond what is already included in LO via perturbative photon splitting to describe DIS data?
    - look at the transition region from DIS to photoproduction, i.e. few $\mathrm{GeV}^2 < Q^2 < 100\ \mathrm{GeV}^2$, where Q^2 is still a hard scale
    - to probe the photon structure we require another hard scale, e.g. jet or particle $E_T^2 >> Q^2$
    - at HERA we have data with $E_T^2 \approx Q^2$, but also with $E_T^2 >> Q^2$
  - unfortunately, low Q^2 at HERA implies more or less also low x (or large ln 1/x) and therefore sensitivity to other possible effects:
    - BFKL/CCFM, colour dipole model, cgc, modifying in one way or another the gluon evolution at low x and leading to effects not described by NLO calcs. in standard collinear factorisation with DGLAP evolution

☞ If data are not described by NLO QCD (without photon PDFs), there are many options of what might be missing besides the virtual photon structure

Introduction



- $\sigma_{jj} \propto f_{\gamma^*/e}(y,Q^2) \otimes f_{i/\gamma^*}(x_\gamma,\mu_R,\mu_{F\gamma^*}) \otimes f_{j/p}(x_p,\mu_{Fp}) \otimes \sigma_{ij}(x_\gamma,x_p,\mu_R)$
  - $f_{i/\gamma^*}(x_\gamma,\mu_R,\mu_{F\gamma^*}) = f_{i/\gamma^*}^{pert} + f_{i/\gamma^*}^{non\text{-}pert}$
  - simplicity lets us typically set all scales equal to $\mu^2 = E_T^2$ or $E_T^2+Q^2$
  - $x_\gamma = (E_{T,1}\, e^{-\eta 1} + E_{T,2}\, e^{-\eta 2}) / 2yE_e$ or $x_\gamma = \sum_{1,2} (E - P_z) / \sum_{had} (E-P_z)$; $\Delta\Phi = \Phi_1 - \Phi_2$

MC tools for "DIS"

- MEPJET[1], DISENT[2], DISASTER++[3], NLOJET++[4] for dijet production at NLO
- NLOJET++ for trijet production at NLO

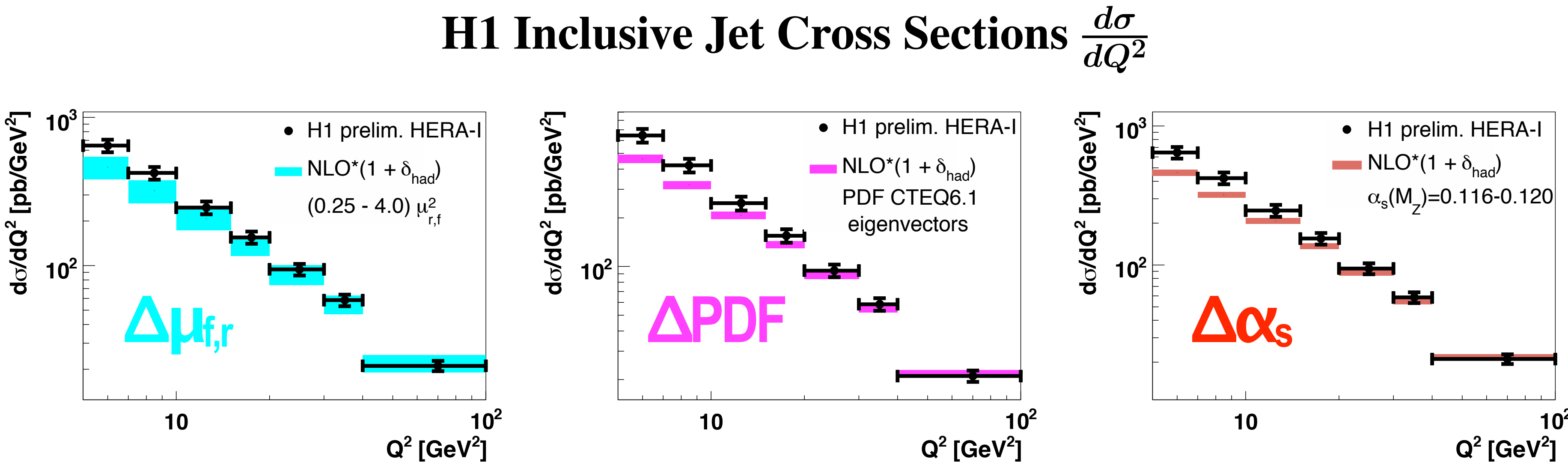
1 Mirkes, Zeppenfeld; 2 Seymour, Catani; 3 Graudenz;
4 Nagy , Trocsany; 5 Pötter, Klasen, Kramer

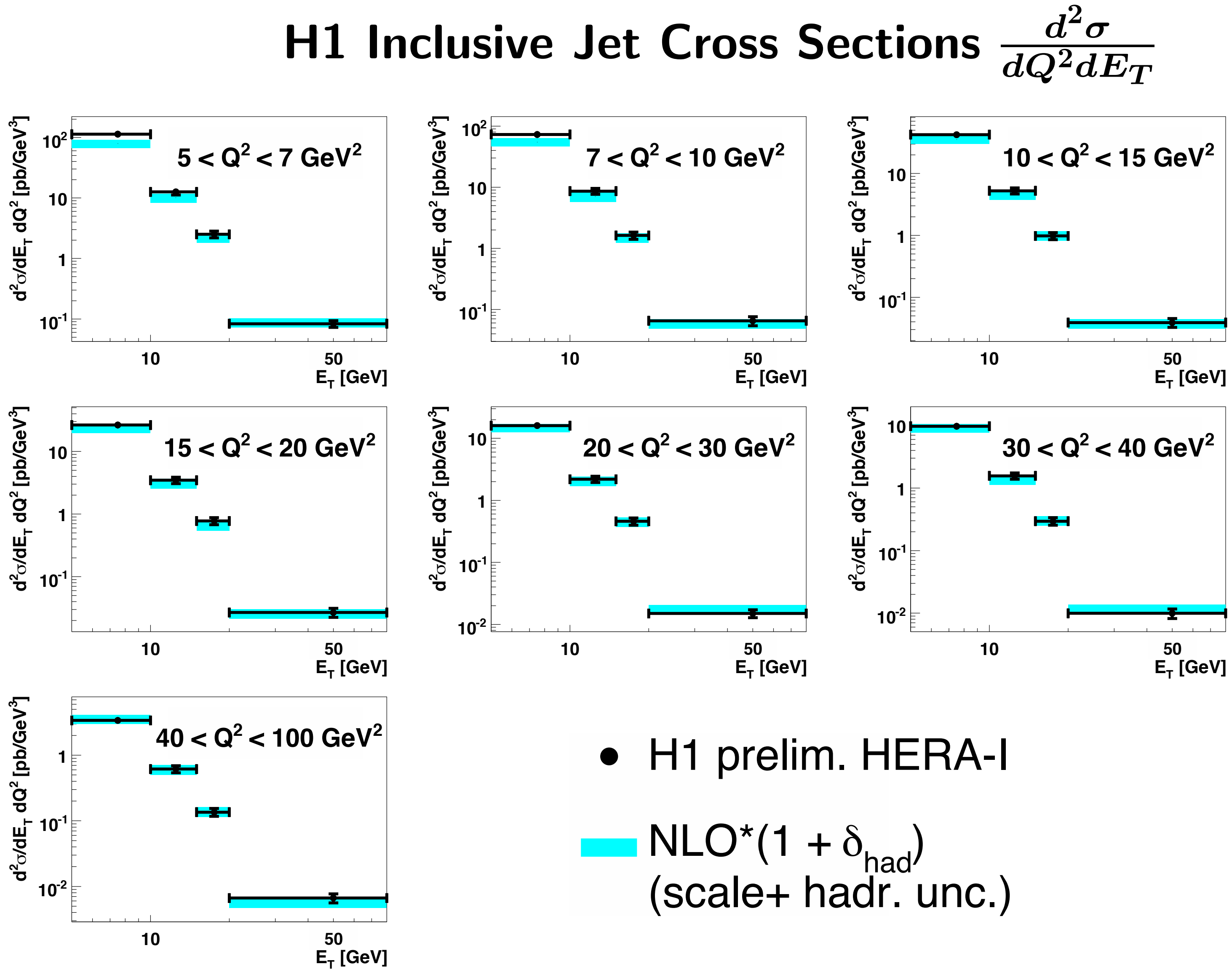
- JETVIP[5] for dijet production at NLO; it is based on the phase space slicing method. This MC simulates direct processes for dijets in NLO (like e.g. DISENT) and it allows to include resolved processes at NLO, using PDFs of the virtual photon, BUT
  - the main author Björn Pötter has left HEP some years ago
  - for directs processes: disagreement with other programs (in some regions of phase space for distributions differential in jet variables)
  - for resolved processes: problem with the stability of NLO resolved (slicing parameter y_c)
  - ☛ difficult to draw quantitative conclusion
- Program by Fontannaz et al. for forward hadron (π^0) production, including direct and resolved processes at NLO
- all other NLO calculations contain a perturbative resolved contrib. in LO only

Inclusive jets: $5 < Q^2 < 100$ GeV^2, $0.2 < y < 0.7$

- H1 preliminary result
  - 43.5 pb^{-1}
  - jets: incl. kt algo in Breit frame
  - $E_T > 5$ GeV
  - $-1 < \eta_{lab} < 2.5$
- NLOJET++
  - CTEQ6.1M
  - $\mu_R^2 = E_T^2$, $\mu_F^2 = Q^2$
  - corr. for had. effects

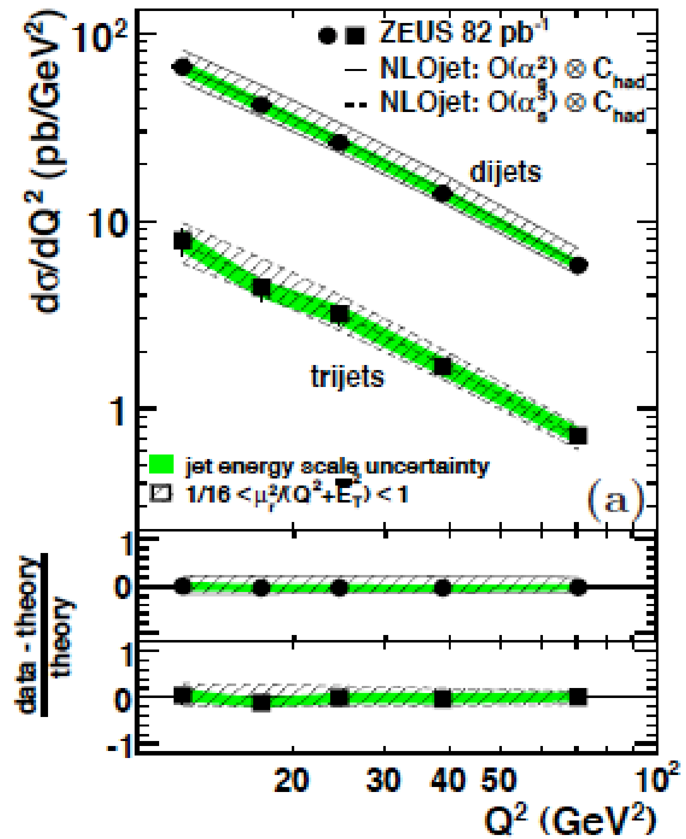
- NLO QCD describes data for $Q^2 > 10$ to 20 GeV^2 & jet $E_T > 10$ GeV
- large scale uncertainties, perhaps underestimated ?
- room for higher orders or resolved contrib. at low Q^2

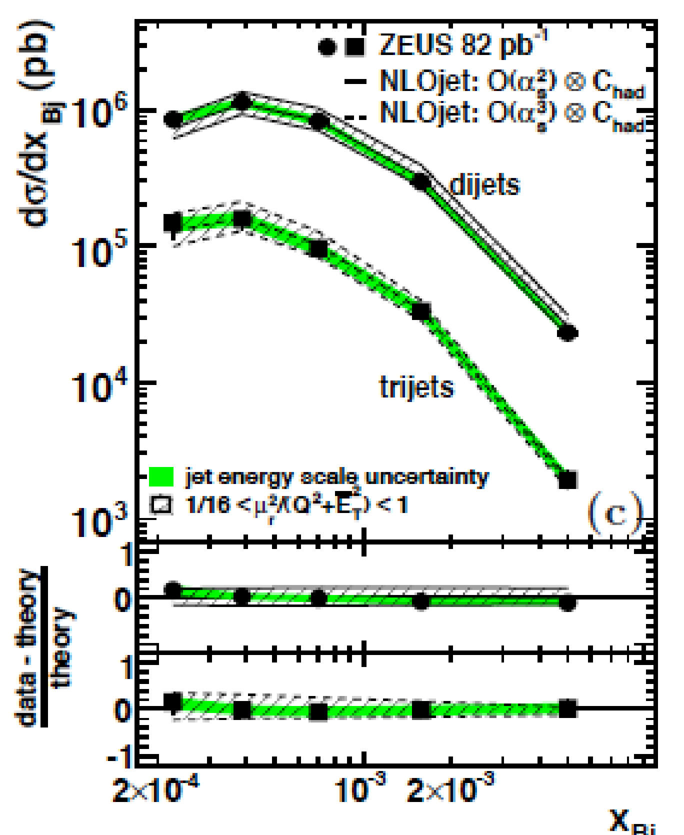




Dijets & trijets: $10 < Q^2 < 100$ GeV^2, $0.1 < y < 0.6$

- ZEUS, DESY-07-062, arXiv:0705.1931
  - 82 pb^{-1}
  - jets: incl. kt algo in HCM frame
  - E_{T1} ($E_{T2,3}$) > 7 (5) GeV
  - $-1 < \eta_{lab} < 2.5$
- NLOJET++: $O(\alpha_s^2)$ & $O(\alpha_s^3)$
  - CTEQ6M
  - $\mu_f^2 = \mu_r^2 = (Q^2 + \langle E_T \rangle^2) / 4$
  - correct for had. effects



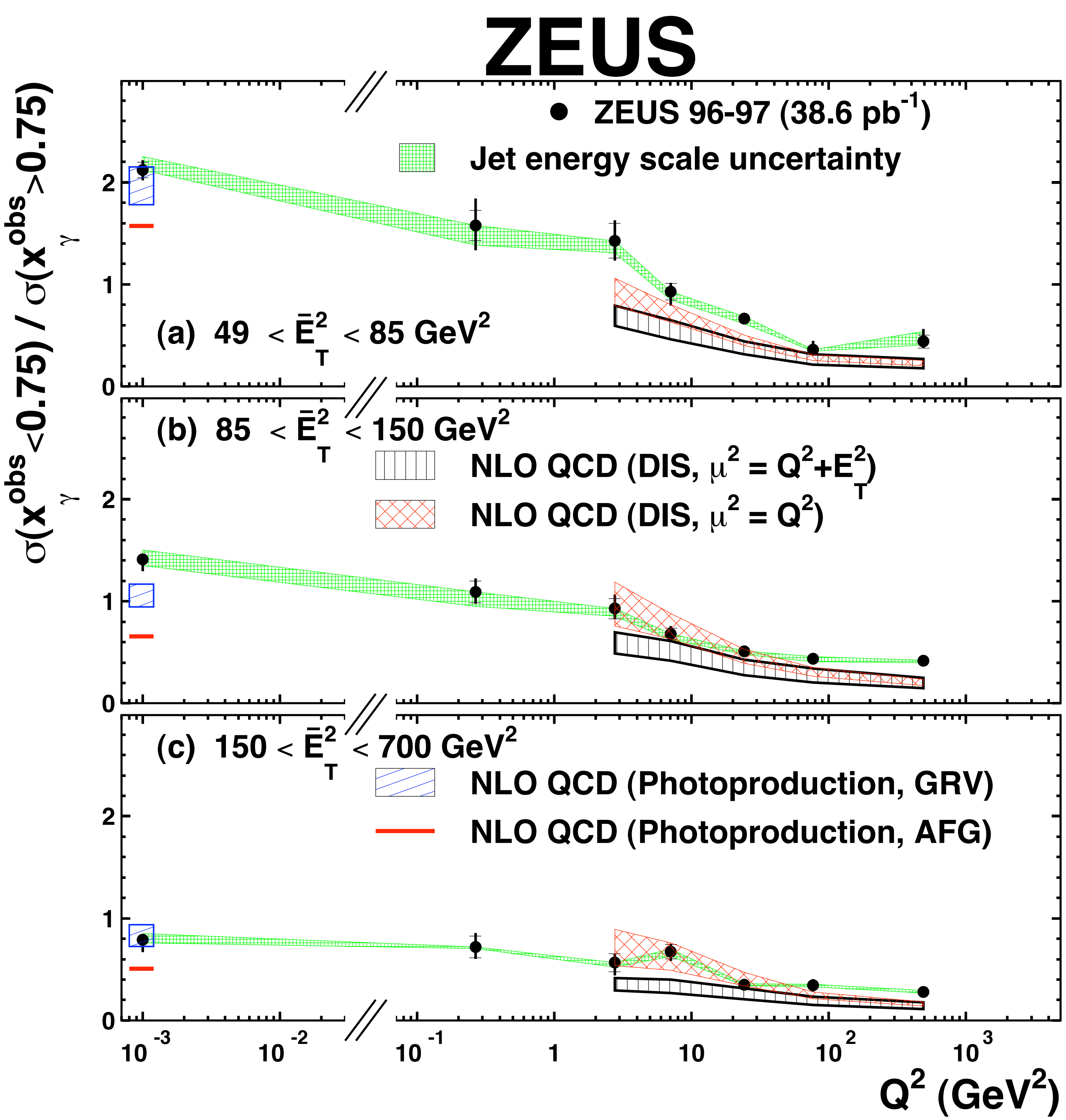


☞ $d\sigma/dQ^2$ & $d\sigma/dx_{Bj}$ for dijets and trijets well described by NLO QCD for $Q^2 \geq 10$ GeV^2, $x_{BJ} \geq 1.7\ 10^{-4}$

☞ no need for resolved contributions beyond pert. LO

Dijets: $0 \le Q^2 < 2000$ GeV^2, $0.2 < y < 0.55$

σ("resolved") / σ("direct")



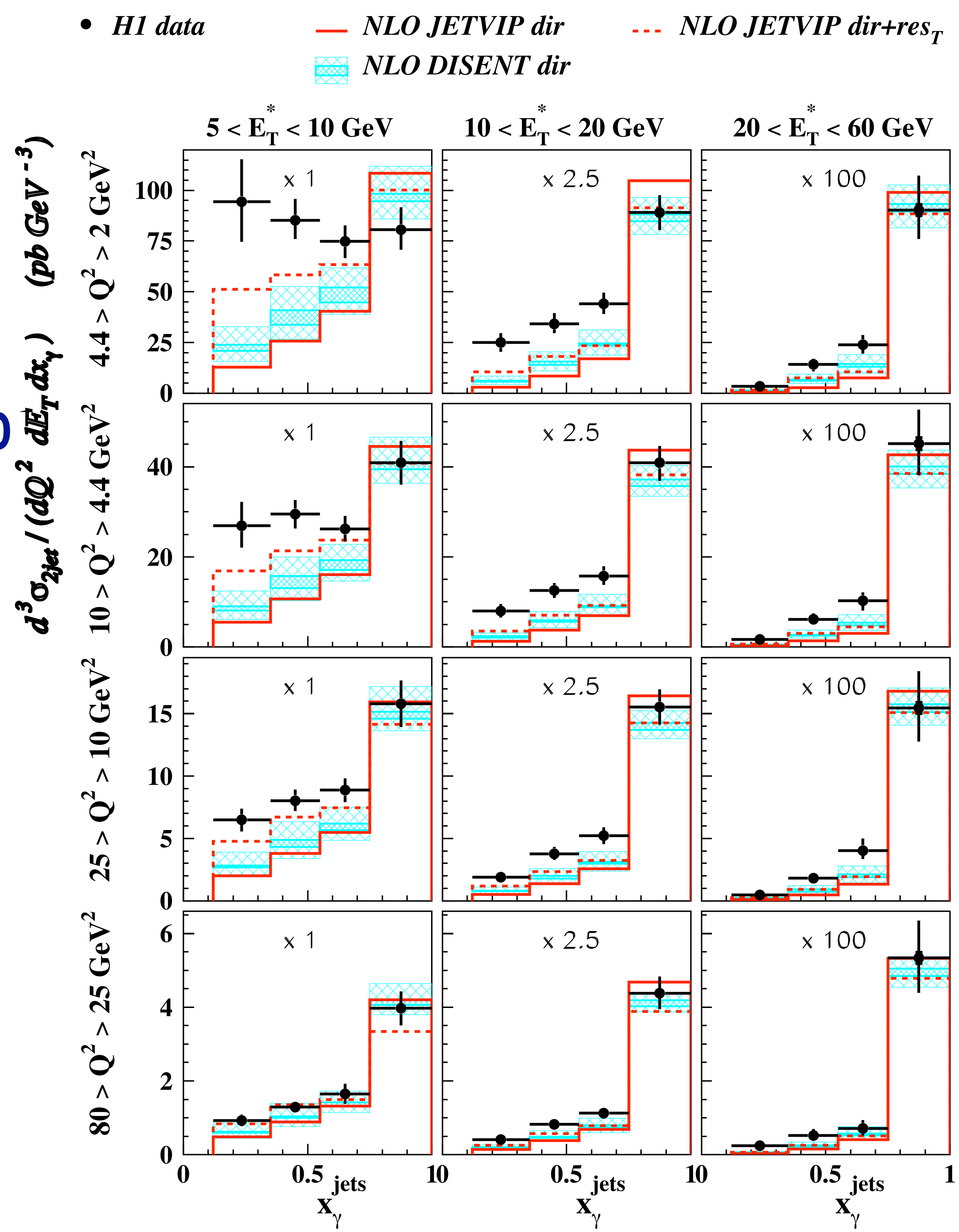
- ZEUS EPJC 35, 487, 2004 (38.6 pb^{-1})
- jets: incl. k_t algo in the γ^*p-frame
  - E_{T1} (E_{T2}) > 7.5 (6.5) GeV
  - $-3 < \eta^*_{1,2} < 0$
  - $\sigma(x_\gamma < 0.75) / \sigma(x_\gamma > 0.75)$ vs. Q^2 and for three regions in mean jet E_T^2
- NLO calculations:
  - FMNR, $\mu^2 = E_T^2$, CTEQ5M1 & GRV or AFG
  - DISASTER++, $\mu^2 = Q^2 + E_T^2$, CTEQ5M1
- photoprod. reasonably well described
- DIS: NLO QCD below the data
- with $\mu^2 = Q^2$ as scale in DIS, the theory uncertainty increases significantly
- previous new result, with smaller scale μ^2, agrees with data !?!

Dijets: $2 \le Q^2 < 80$ GeV^2, $0.1 < y < 0.85$

- H1 EPJ C37, 141, 2004 (57pb^{-1})
- jets: incl. k_t algo in the γ^*p-frame
  - E_{T1} (E_{T2}) > 7 (5) GeV
  - $-2.5 < \eta_{1,2} < 0$

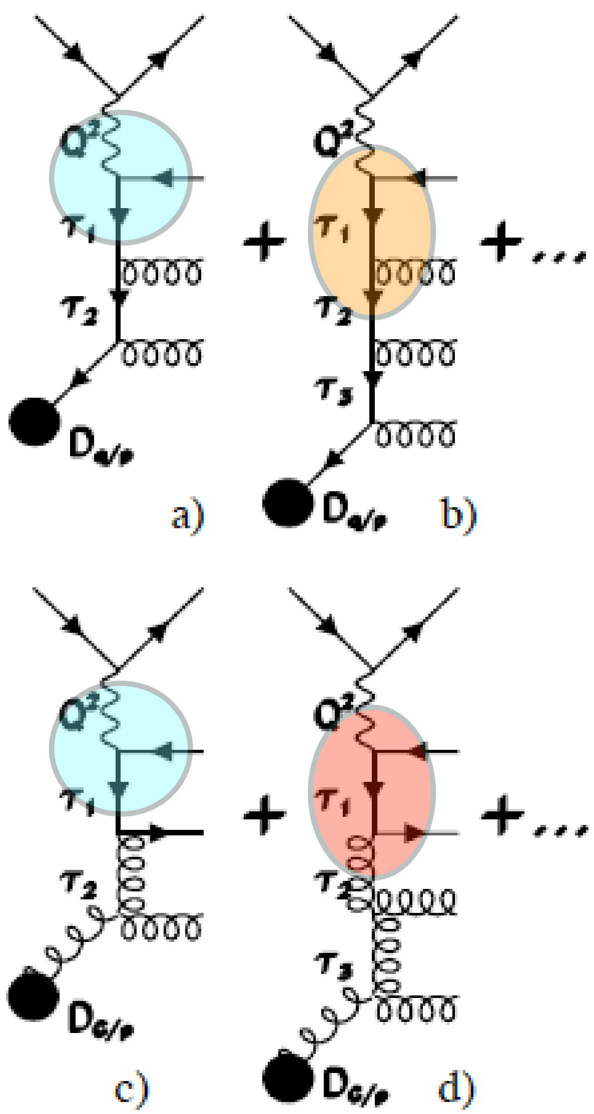
mean jet E_T

- DISENT: $\mu_r^2 = E_{T1}^2$, $\mu_f = 9$ GeV, CTEQ6M
- JETVIP: $\mu_r^2 = \mu_f^2 = E_{T1}^2$, CTEQ6M, SAS1D
- for DISENT hadronisation and scale uncertainty are shown
- $x_\gamma > 0.75$ reasonably well described by direct NLO calculations
- $x_\gamma < 0.75$ data not well described, particularly at small x_γ, low Q^2 and jet E_T
- JETVIP dir ≠ DISENT; both are LO calc. for $x_\gamma < 1$
- JETVIP dir+res still below the data for small x_γ

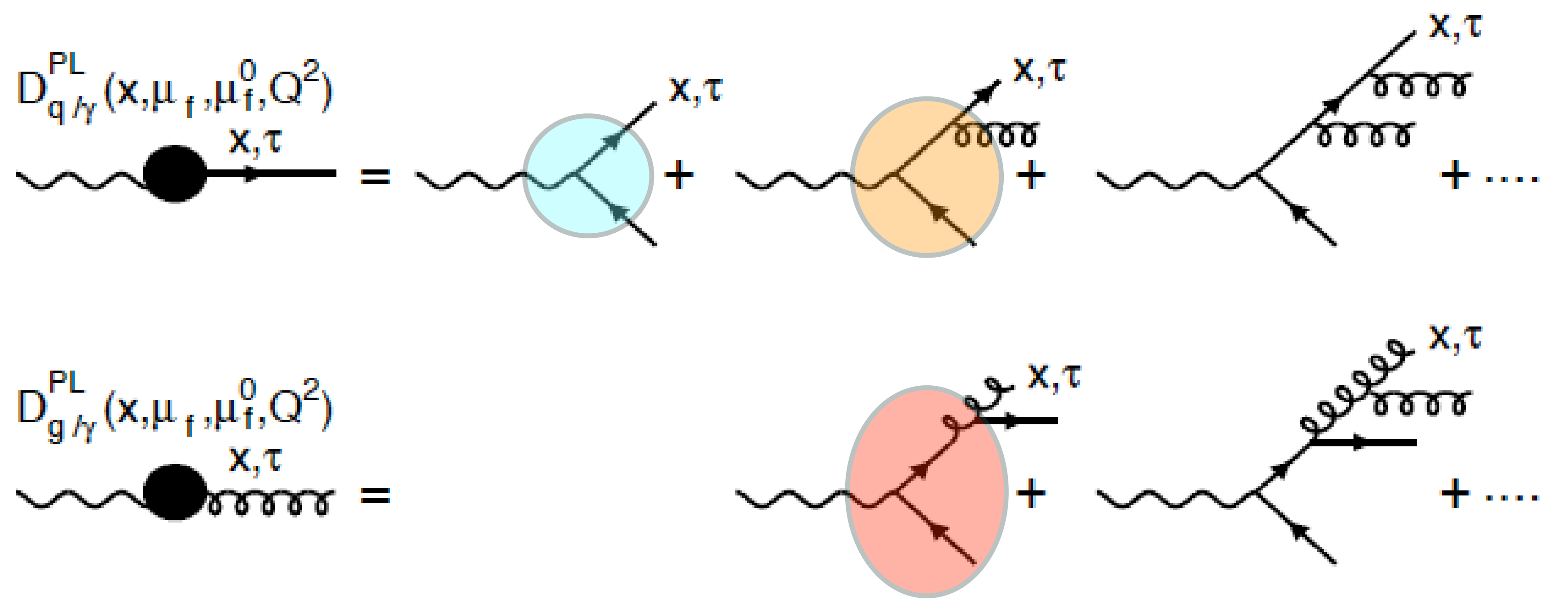


NLOJET++: dijets at NLO & trijets at NLO

3-jets at LO 3-jets at NLO



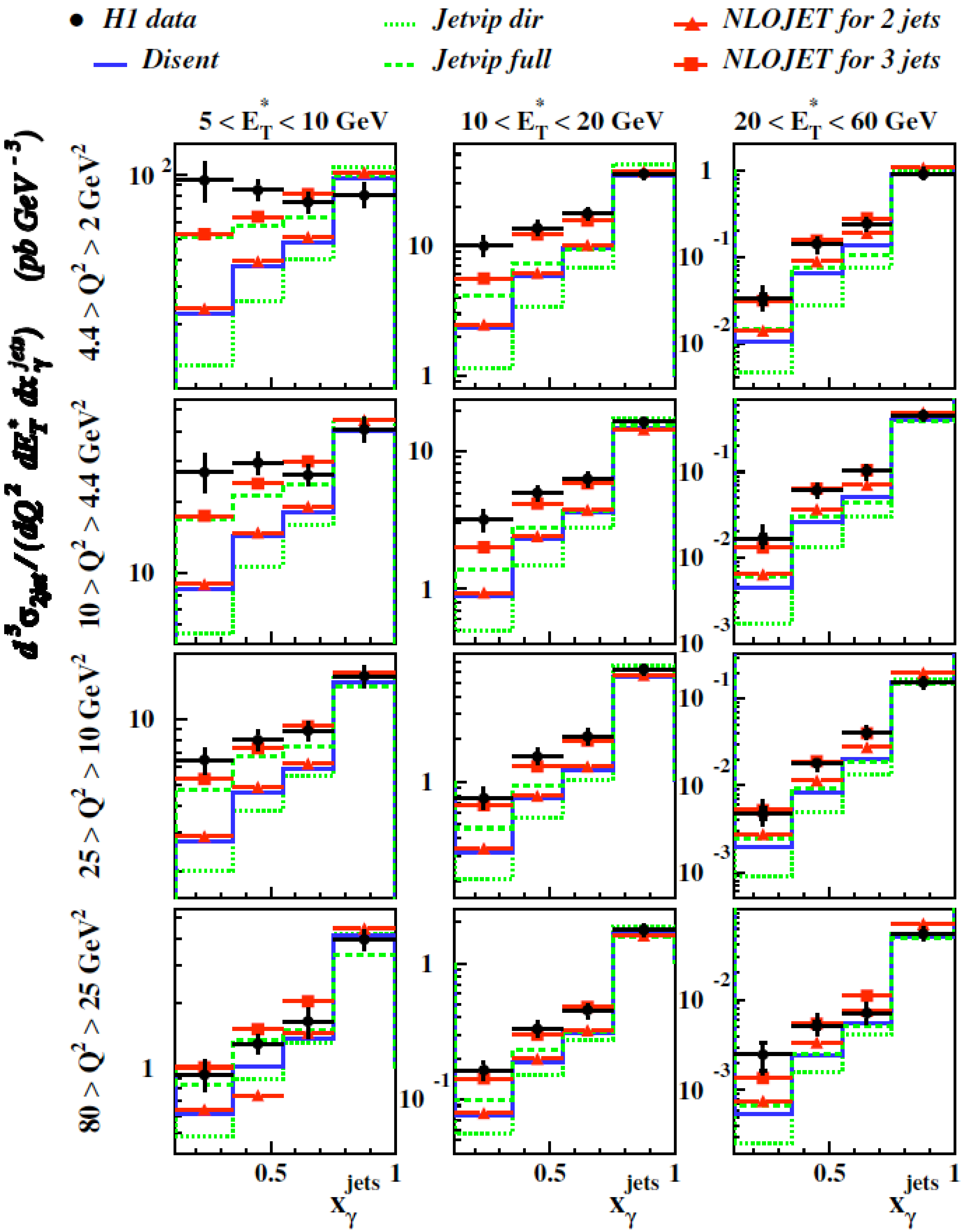
point-like part of the photon structure



- point-like part of the photon structure provides an approximate method for including higher order direct contributions
- $x_\gamma < 1$ is populated by events with at least three jets (at parton level), for programs like DISENT, JETVIP dir this is LO only; with NLOJET++ can calculate at NLO

Dijets: $2 \le Q^2 < 80$ GeV^2, $0.1 < y < 0.85$

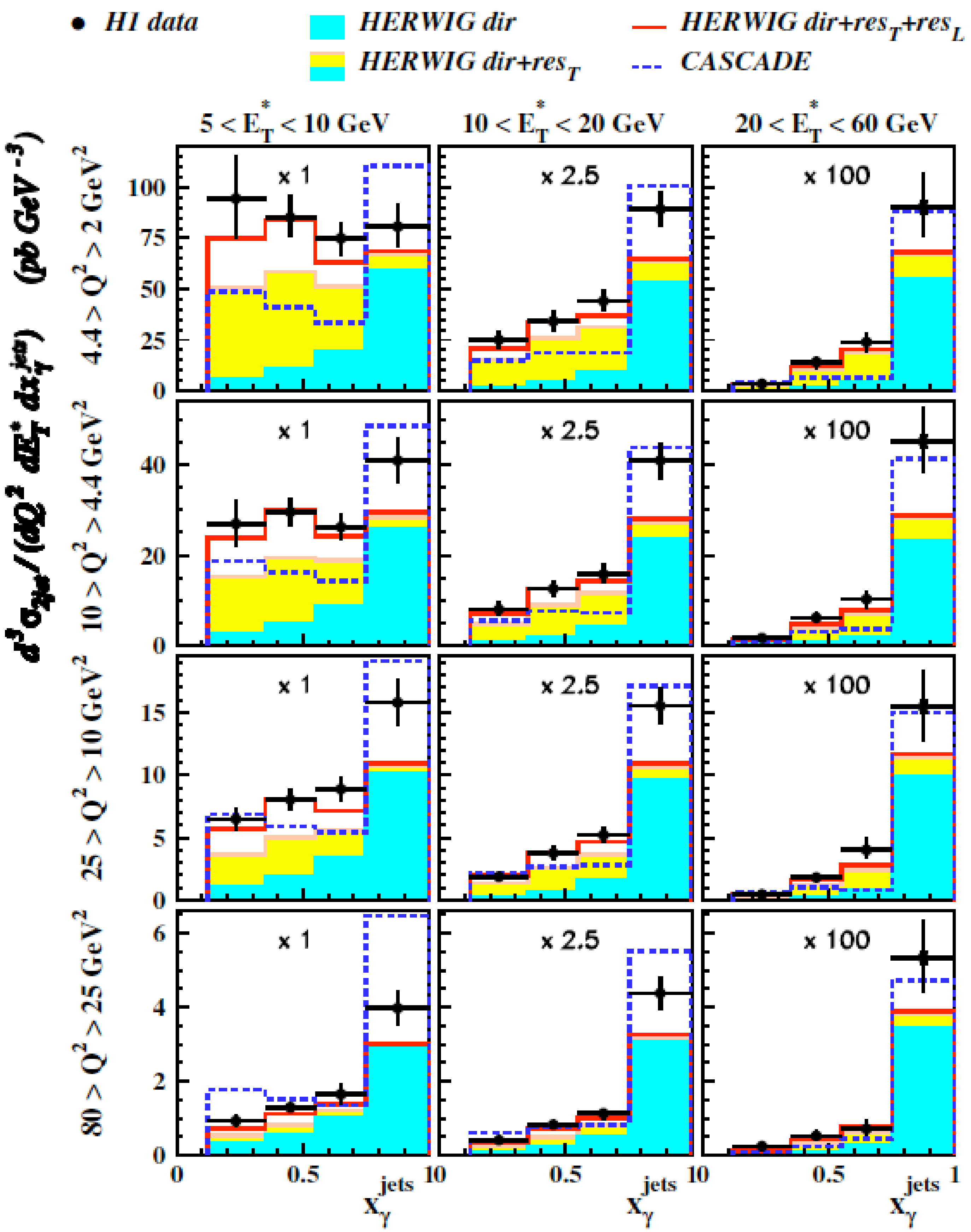
- H1 data as on previous page & J.Chyla et al., EPJ C40, 469, 2005 (NLOJET++ predictions)
- good agreement for 2-jets at NLO, i.e. DISENT = NLOJET++
- best description of data for 3-jets at NLO using NLOJET++ (k-factor≈2 at lowest x_γ and Q^2 bin !)
- remaining difference, mainly at low x_γ and Q^2, indicate need for still higher orders or resummation as in case of photon structure
- what are the scale uncertainties for NLOJET++ (3-jets) ?
- need reliable full NLO calculation of resolved contribution



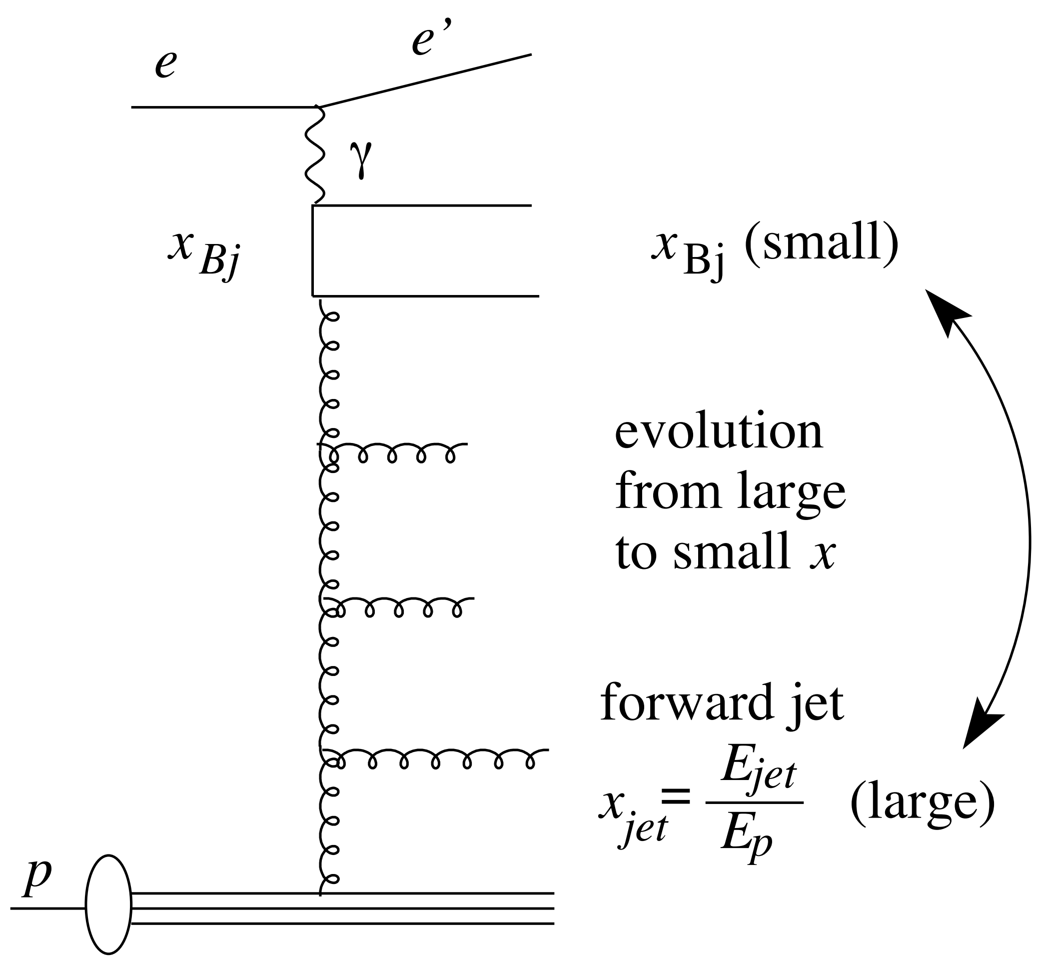
Dijets: $2 \leq Q^2 < 80$ GeV^2, $0.1 < y < 0.85$

a small aside on LO+PS MC:
a comparison with HERWIG

- same dijet data as on previous page
- best description of these data by HERWIG, LO+PS and with a virtual photon structure for transverse and longitudinal photons (calc. by J.Chyla)



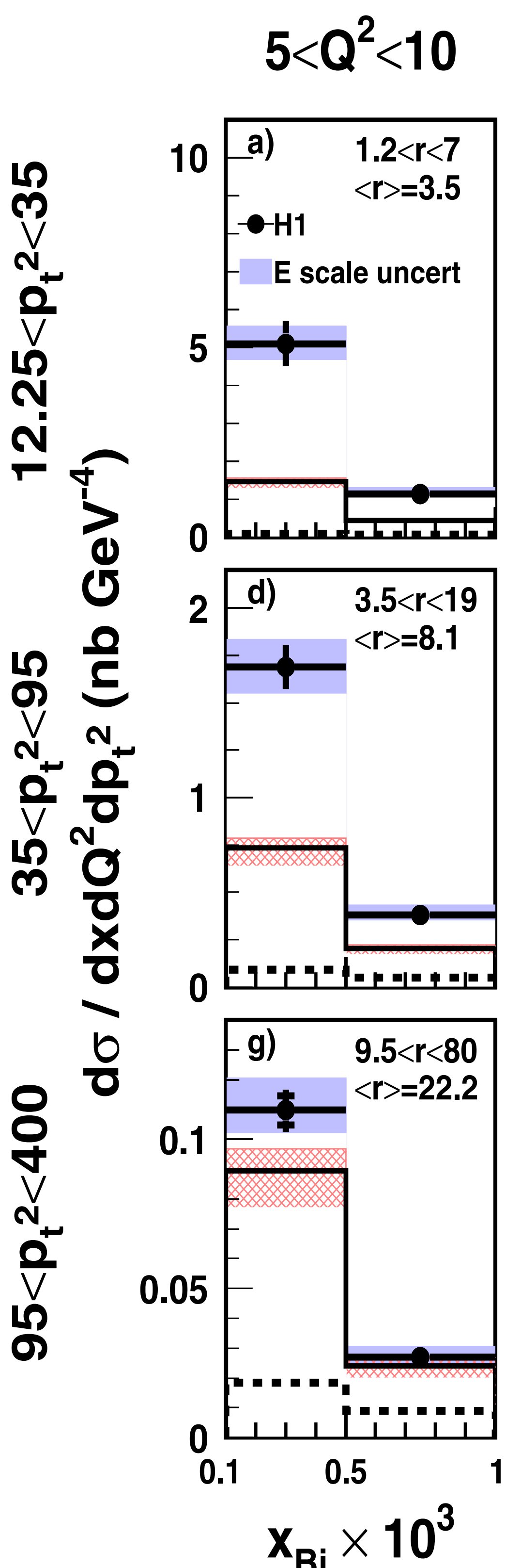
Forward jets in DIS: $5 < Q^2 < 85$ GeV^2, $0.1 < y < 0.7$

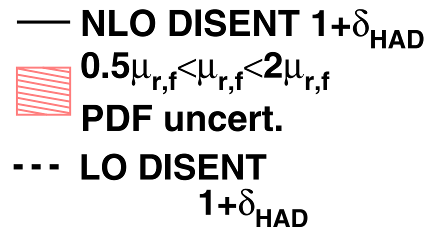


H1 Collab., Eur. Phys. J. C **46** (2006) 27
[arXiv:hep-ex/0508055]

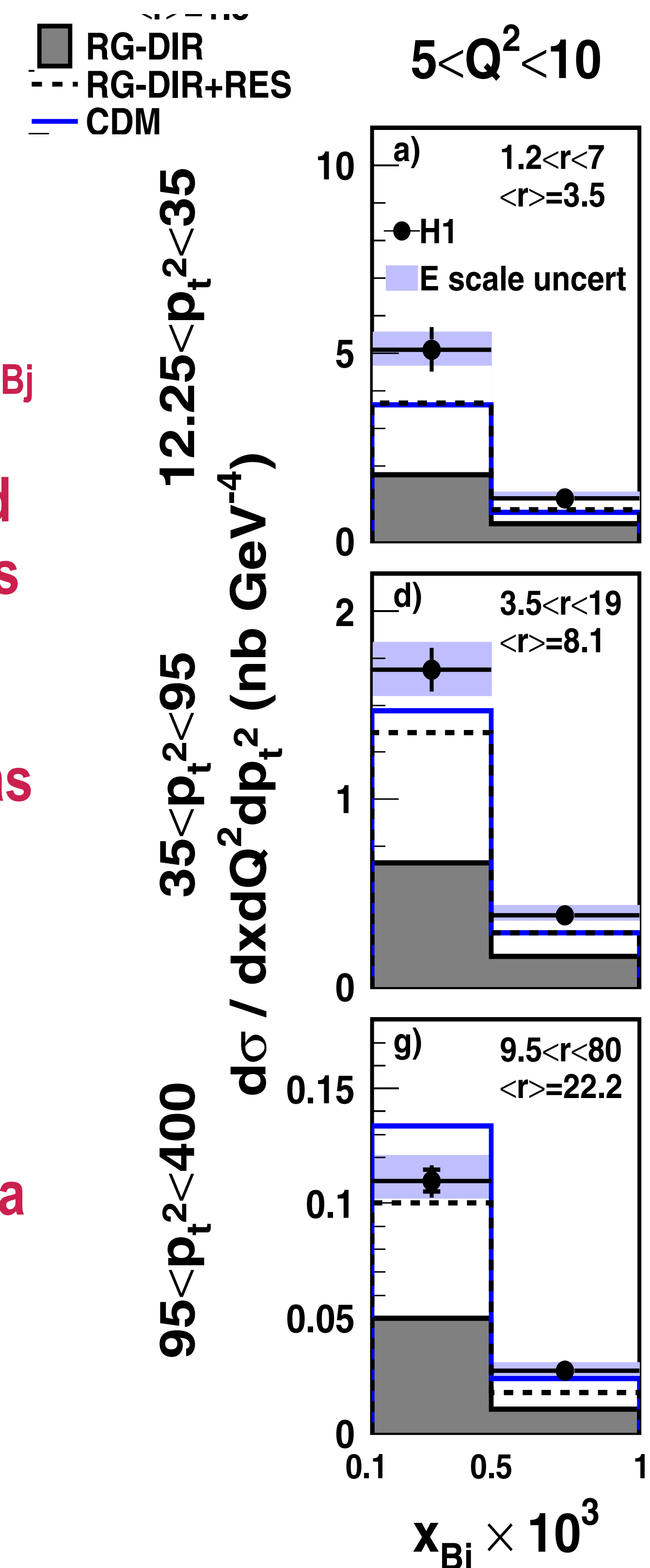
- in DGLAP the strong ordering in virtuality gives softest p_t gluon closest to proton
- suppress DGLAP: $p^2_{T,jet} \sim Q^2$
- in BFKL the gluon p_T close to the proton can be hard; strong ordering occurs in x
- enhance BFKL: $x_{jet} >> x_{Bj}$
- fwd jet (incl. k_T in Breit frame) & cuts in HERA frame
  - 7° (2.79) < θ_{jet} (η_{jet}) < 20° (1.74)
  - $p_{T,jet} > 3.5$ GeV
  - $x_{jet} = E_{jet}/E_p > 0.035$
- enhance resolved contributions → large $r = p_{T,jet}^2/Q^2$

dσ/dx$_{Bj}$ for events with large r = $p_{T,jet}^2/Q^2$





- NLO significantly below data for low x$_{Bj}$
- LO << NLO, fwd-jets in LO suppressed by kinematics → NLO ≈ LO for fwdjets
- bands includes scale (1/4 & 4 $\mu^2 = p_{T,jet}^2$) and PDF uncertainty; using Q^2 as scale the prediction increases by 35% at low x$_{Bj}$ and Q^2 and the uncertainty increases
- RAPGAP direct fails, direct+resolved and CDM give good description of data except at lowest x$_{Bj}$



see paper for more

- triple diff. x-sections (x$_{Bj}$, Q^2, $p_{T,jet}$)
- x-sections for events with additional dijets

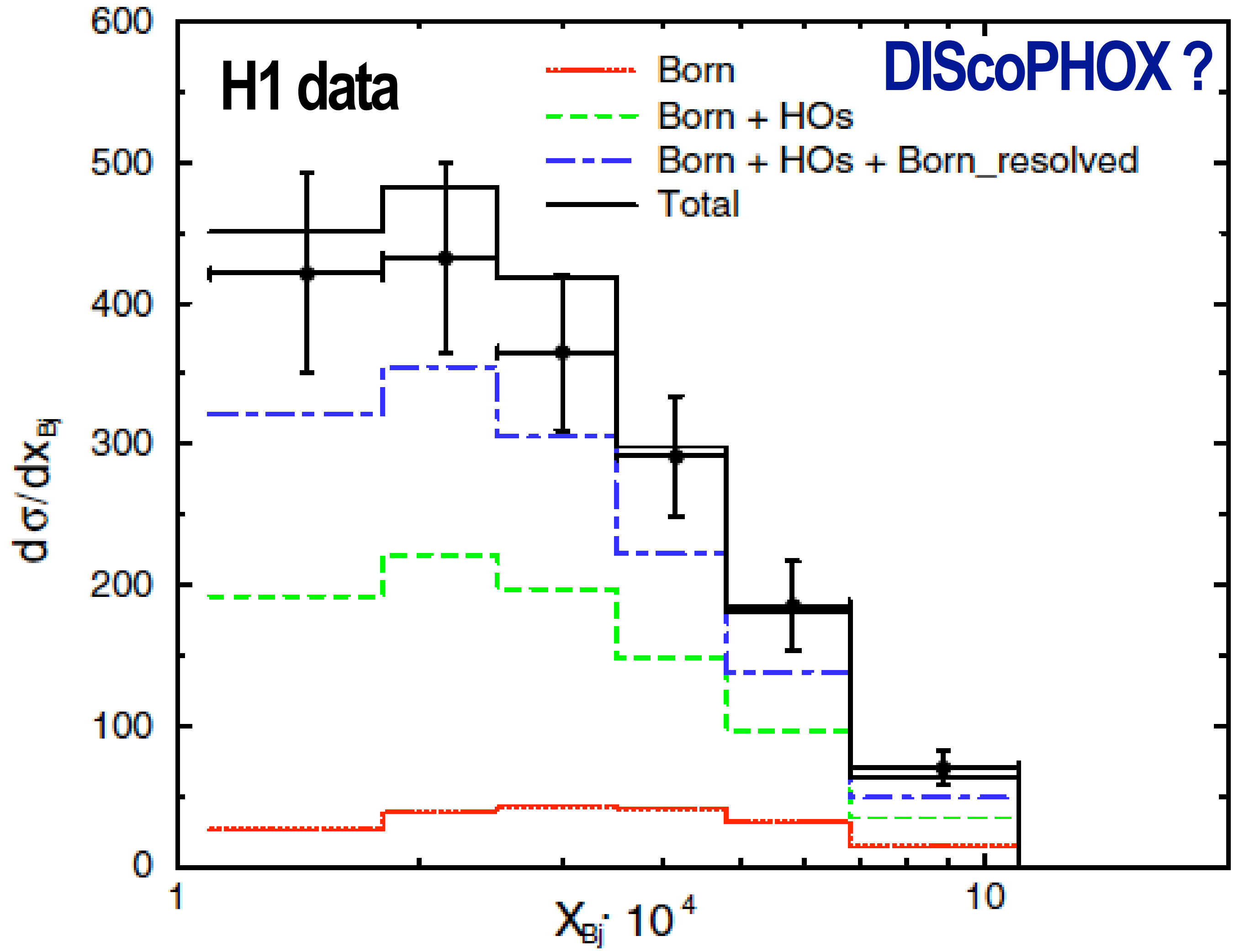
$d\sigma/dx_{Bj}$ for events with a forward π^0

- H1: EPJ C 36, 441 (2004); 21pb-1
  - $4.5\ (2) < Q^2 < 15\ (70)\ \mathrm{GeV}^2$
  - $0.1 < y < 0.6$
  - $5° < \theta_\pi < 25°$
  - $x_\pi > 0.1$
  - $E^*_{T,\pi} > 2.5\ \mathrm{GeV}$

- 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

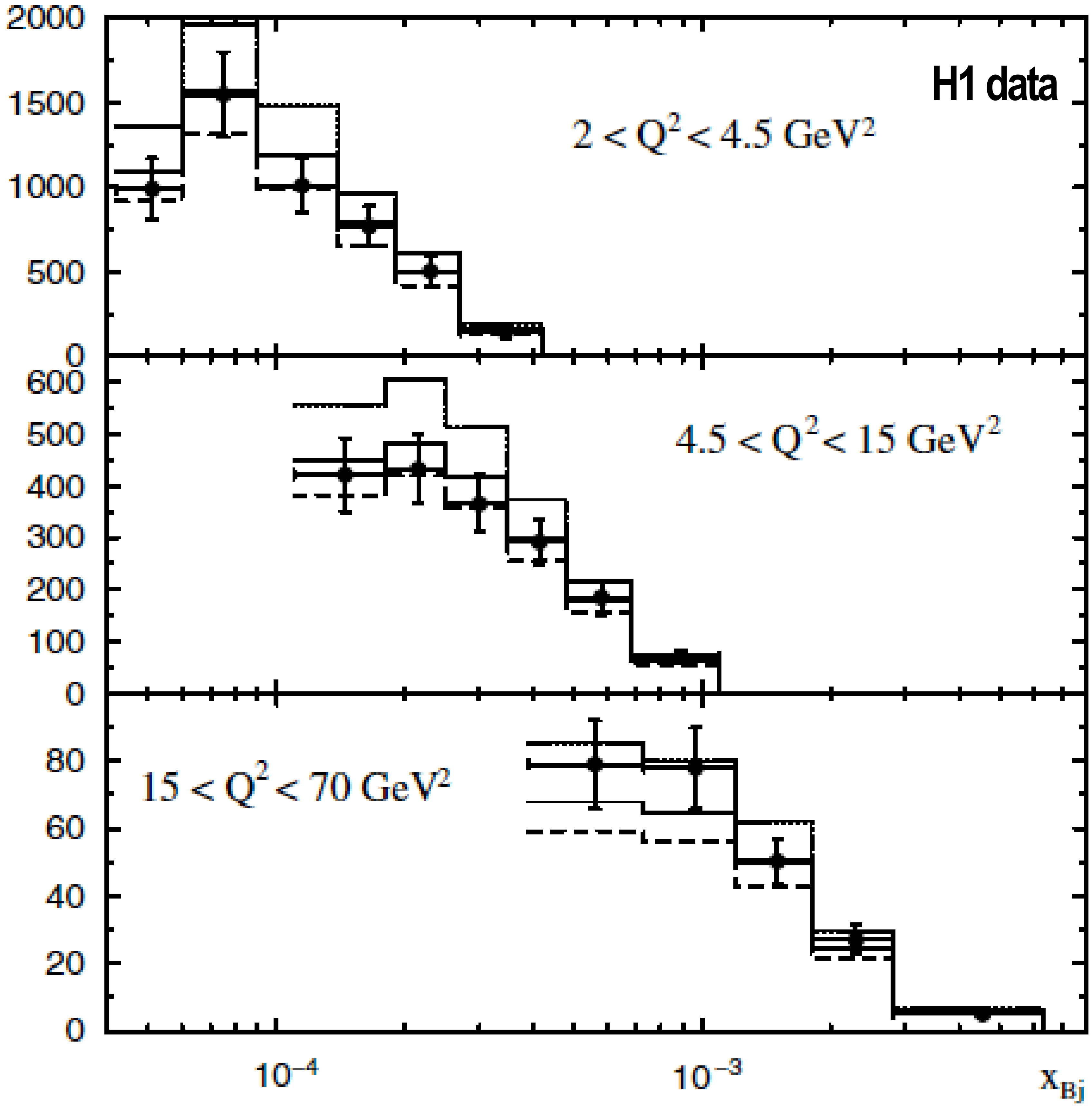
☛ good description of the data

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



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

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

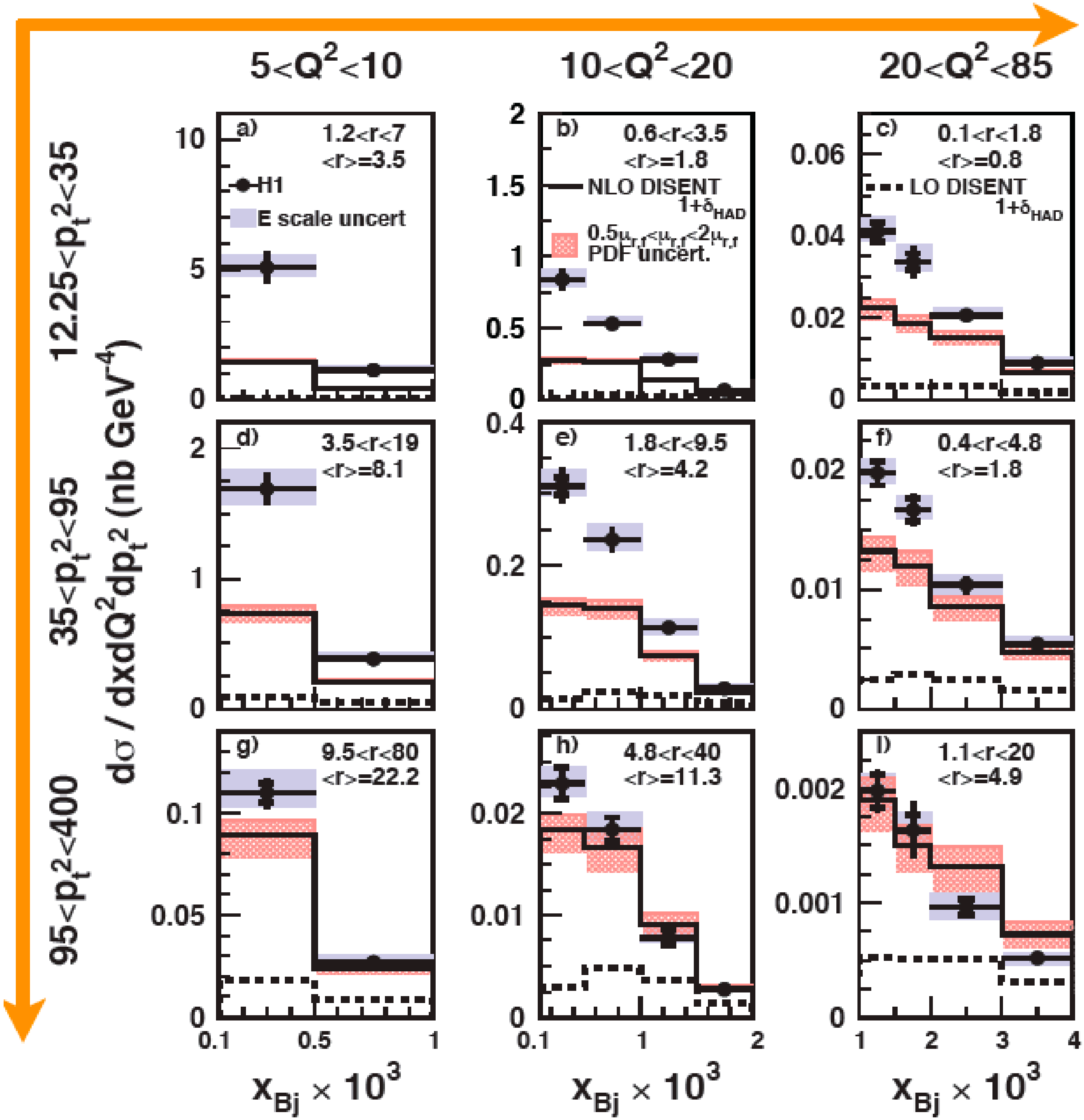


NLO from Aurenche et al., EPJ C 42, 43 (2005)

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

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

Fwd-jet: more differential distributions

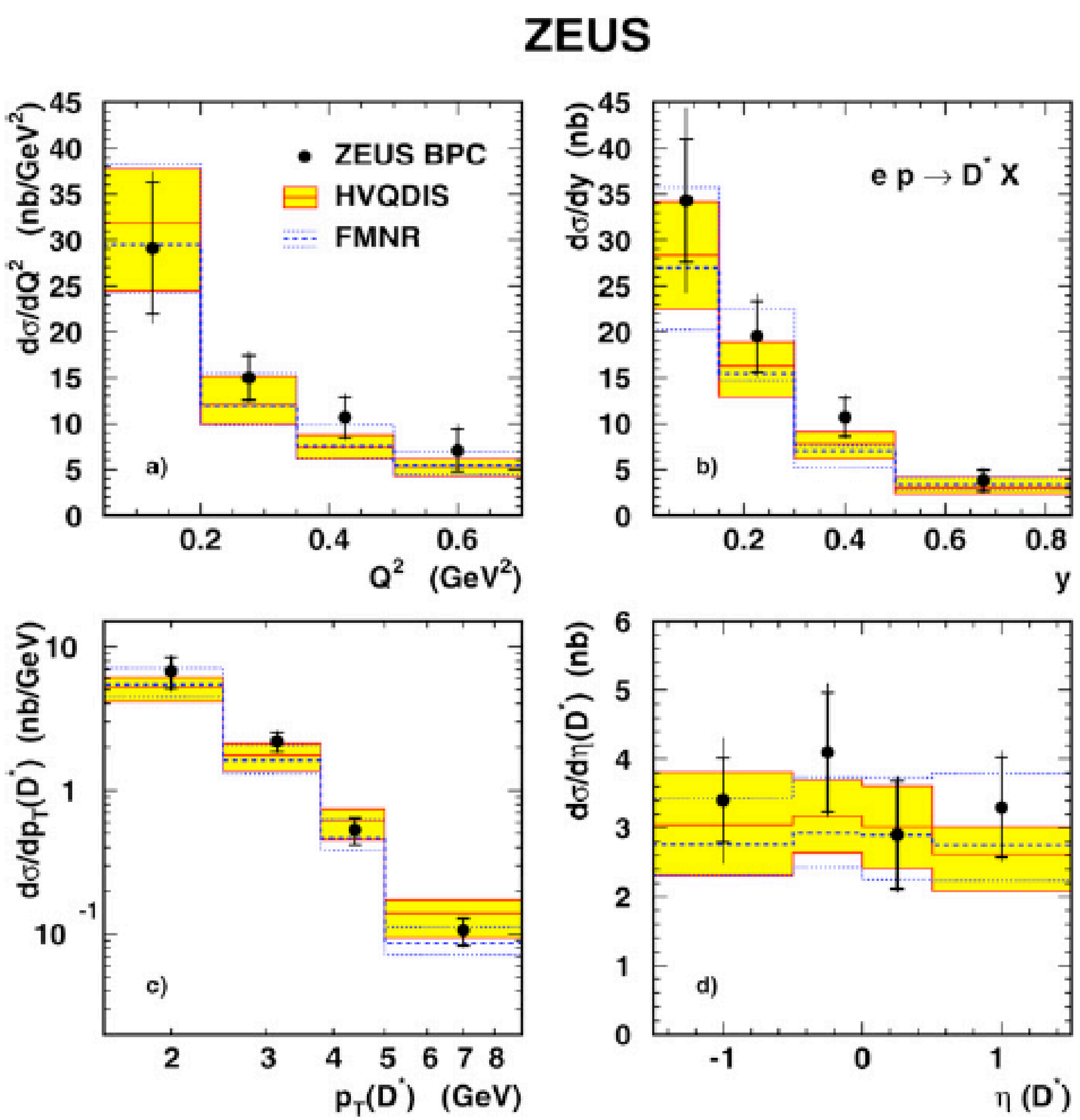


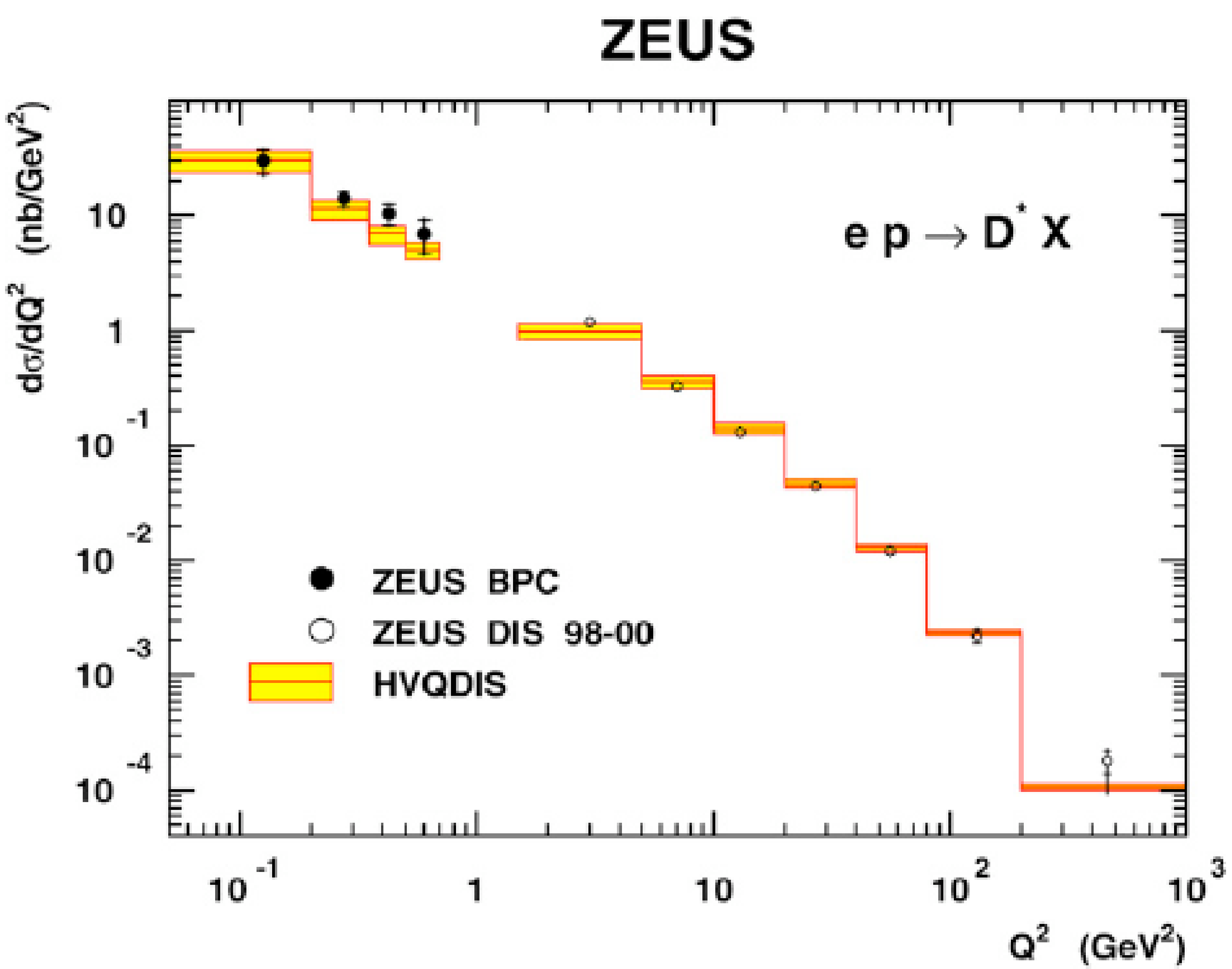
- would be interesting to have these data & data on fwd-jet + dijets compared to the NLO calc. by Fontannaz !
- remember $r = p_{T,jet}^2/Q^2$
  - large r → resolved region

$D^{*\pm}$, D meson & $D^{*\pm}$ + jet production

- ZEUS:
  - "Measurement of $D^{*\pm}$ meson production in $e^{\pm}p$ scattering at low Q^2", PLB 649 (2007) 111
    - $0.05 < Q^2 < 0.7$ GeV^2, $0.02 < y < 0.85$; $1.5 < p_T(D^*) < 9$ GeV, $|\eta(D^*)| < 1.5$; 82 pb^{-1}
    - compare data to FMNR (+WW) & HVQDIS using ZEUS PDF-fit in FFNS, $m_c = 1.35$ GeV, $\mu_r^2 = \mu_f^2 = p_T^2 + m_c^2$ (FMNR), $\mu_r^2 = \mu_f^2 = Q^2 + 4m_c^2$ (HVQDIS)
    - also compare to data from PRD 69 012004 (2004) with $1.5 < Q^2 < 1000$ GeV^2
  - " Measurement of D mesons prod. in DIS at HERA", DESY-07-052, arXiv:0704.3562, JHEP
- H1:
  - "Incl. $D^{*\pm}$ meson cross sects. and $D^{*\pm}$ - jet correlations in photoprod. ...", EPJ C50 (2007) 251
    - Q2 < 0.01 GeV2, $0.29 < y < 0.65$; a) $p_T(D^*) > 2$ GeV, $|\eta(D^*)| < 1.5$; 51 pb^{-1}
    - b) $D^{*\pm}$ + other jet: $p_{T,jet} > 3$ GeV; c) $D^{*\pm}$ tagged dijet: $p_{T,jet1}$ ($p_{T,jet2}$) > 4 (3) GeV
    - compare data to FMNR using CTEQ6M, GRV-G HO, $m_c = 1.5$ GeV, $\mu_r^2 = m_c^2 + (p_{T,c}^2 + p_{T,c}^2)/2$, $\mu_f^2 = 2\mu_r^2$
  - "Production of $D^{*\pm}$ mesons with dijets in DIS at HERA", EPJ C51 (2007) 271
    - $2 < Q^2 < 100$ GeV^2, $0.05 < y < 0.7$; $1.5 < p_T(D^*) < 15$ GeV, $|\eta(D^*)| < 1.5$; 47 pb^{-1}
    - compare data to HVQDIS using CTEQ5F3, $m_c = 1.5$ GeV, $\mu_r^2 = \mu_f^2 = Q^2 + 4m_c^2$

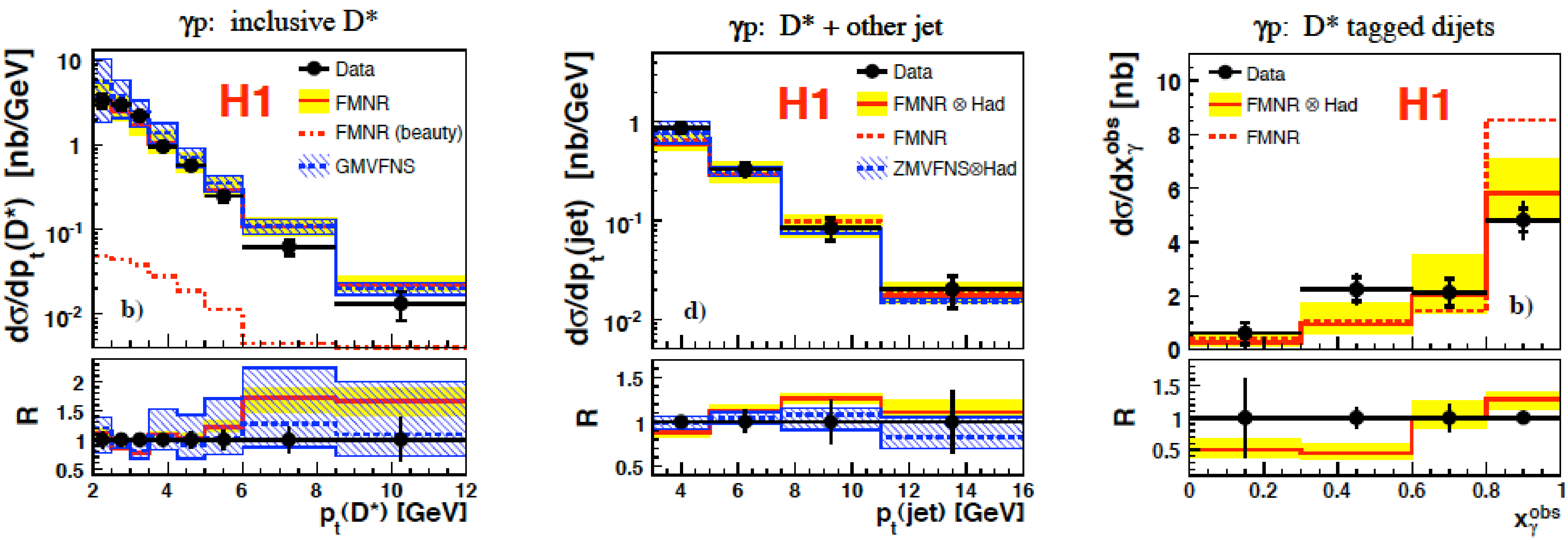
D*± meson production in "DIS"

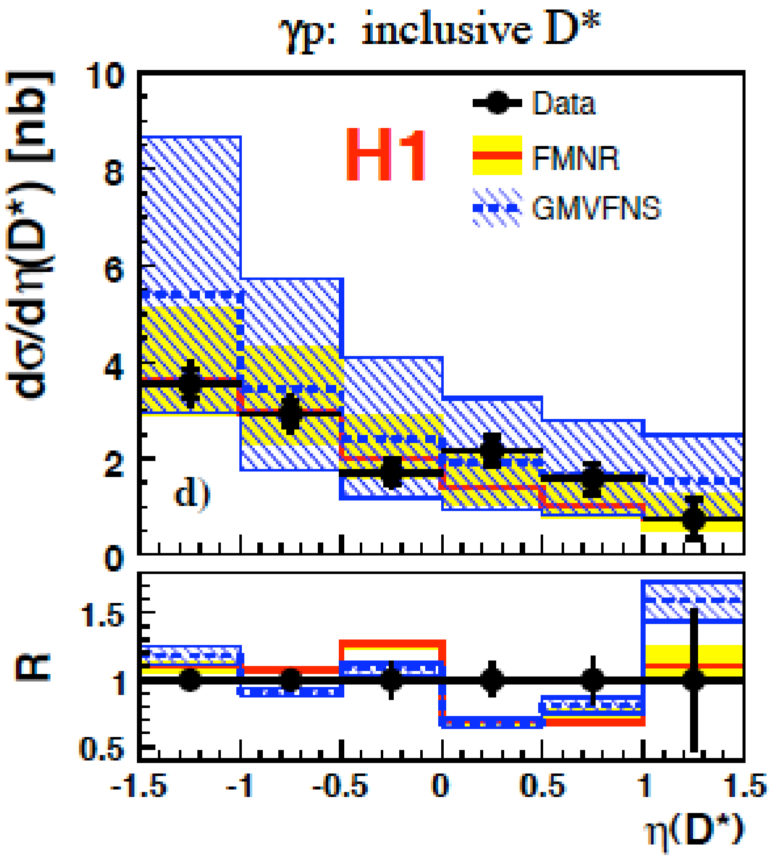


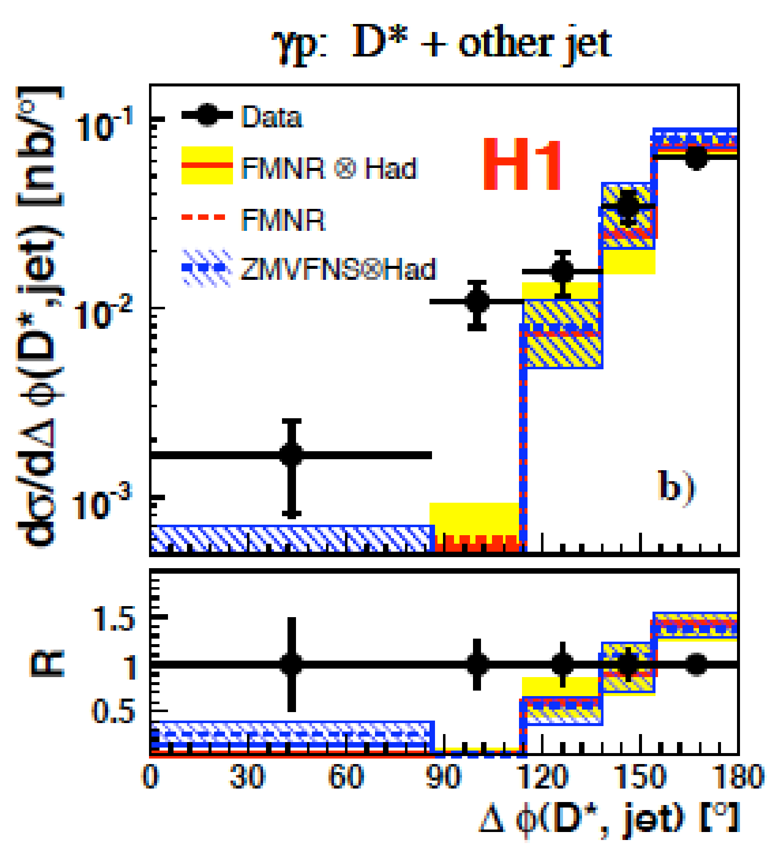


- $d\sigma/dQ^2$ at very low Q^2 described by HVQDIS and FMNR (within large exp. and theory uncertainties)
- HVQDIS describes the whole range in Q^2
- no resolved contr. needed beyond LO in HVQDIS

D*± & D*± + jets production in γp

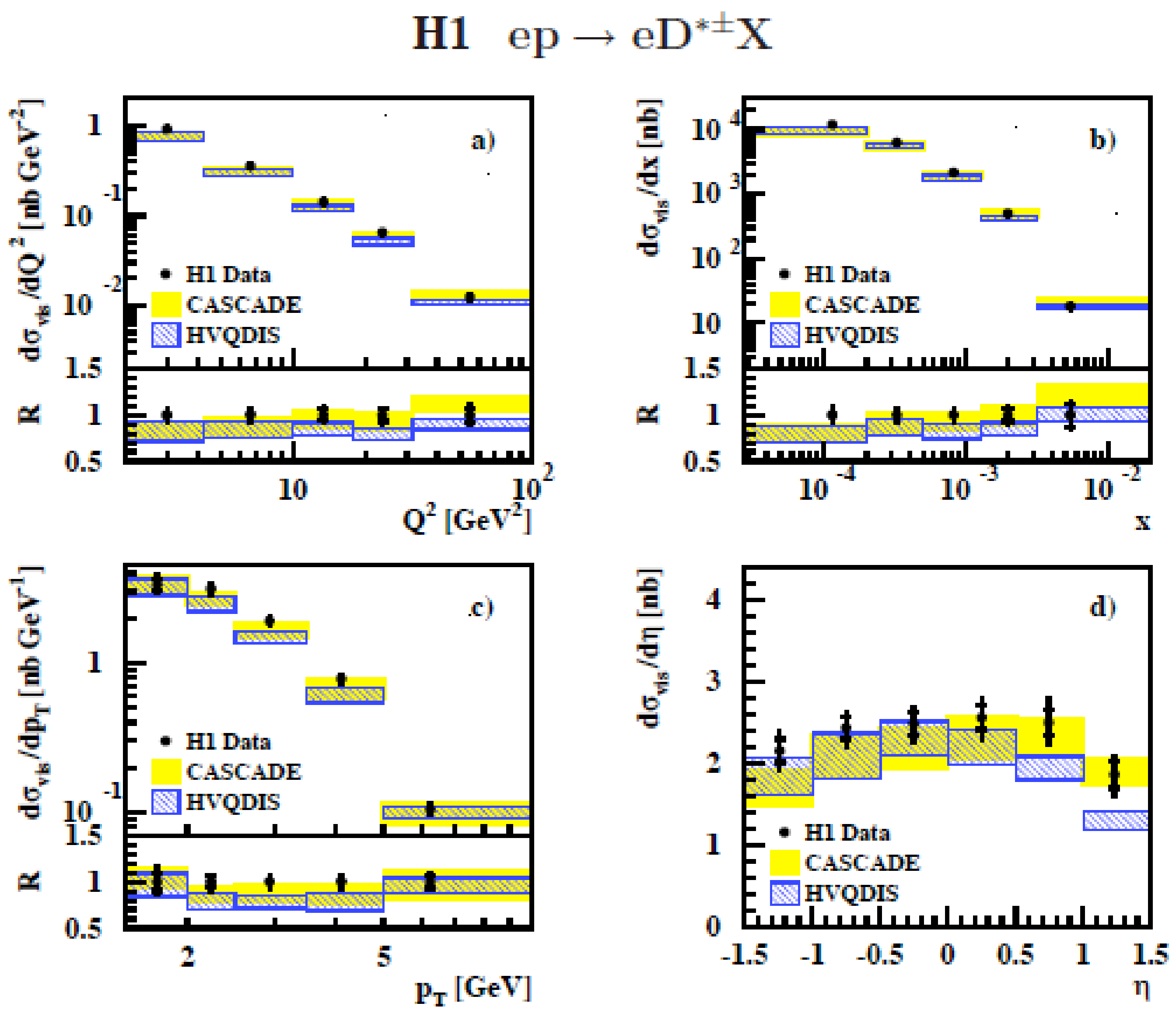


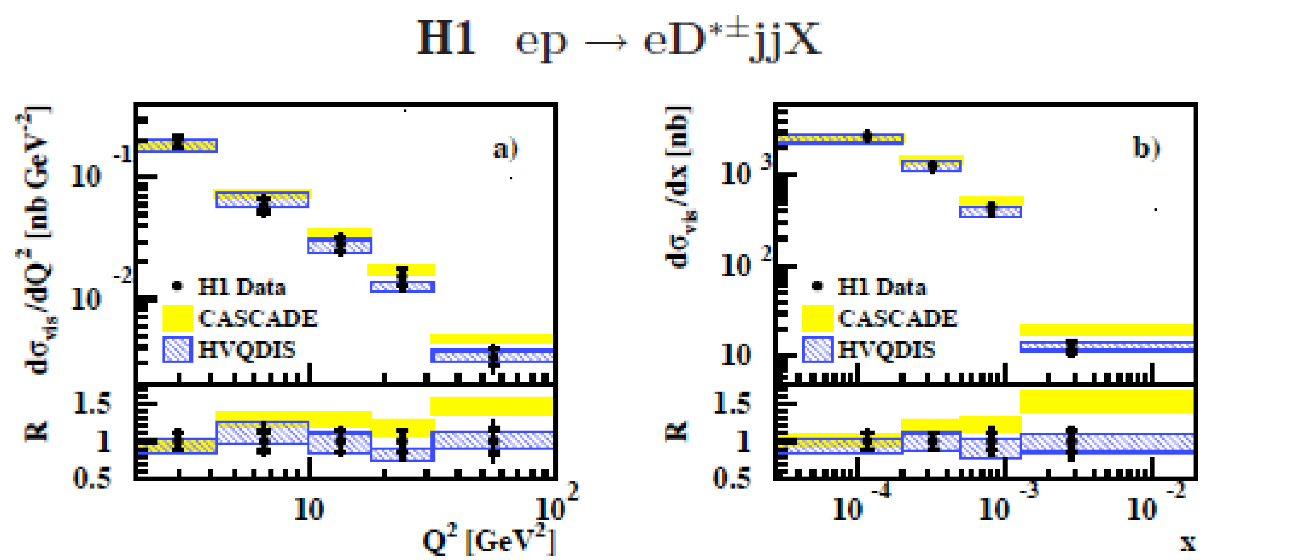


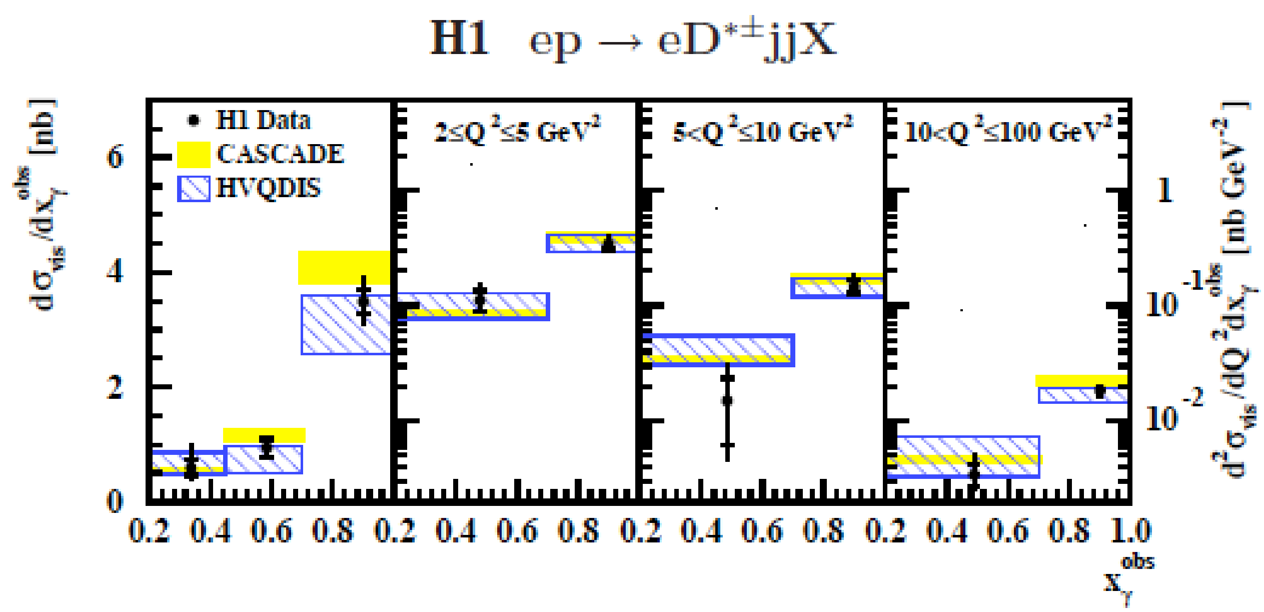


- R=(1/σ dσ/dv)$_{data}$/(1/σ dσ/dv)$_{theo}$ reduces exp. & theo uncertainties
- overall reasonable description of data by NLO
- except for ΔΦ; data are more de-correlated than NLO (also seen by ZEUS)
- uncertainty in theory often larger than in data

D*± & D*± + jets production in DIS







- R is the ratio of the normalized x-sections of data to NLO

☛ overall reasonable description of data (better for jets) by NLO (HVQDIS)

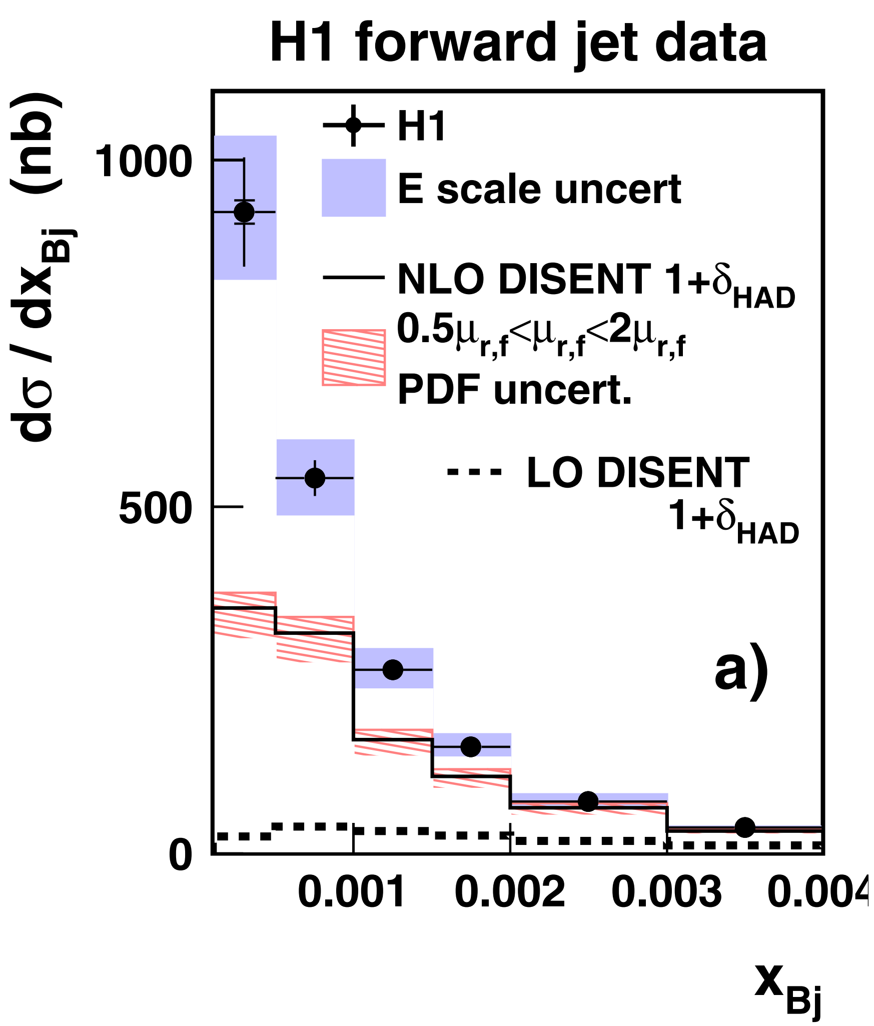
☛ x_γ described by NLO without need for additional resolved contribution

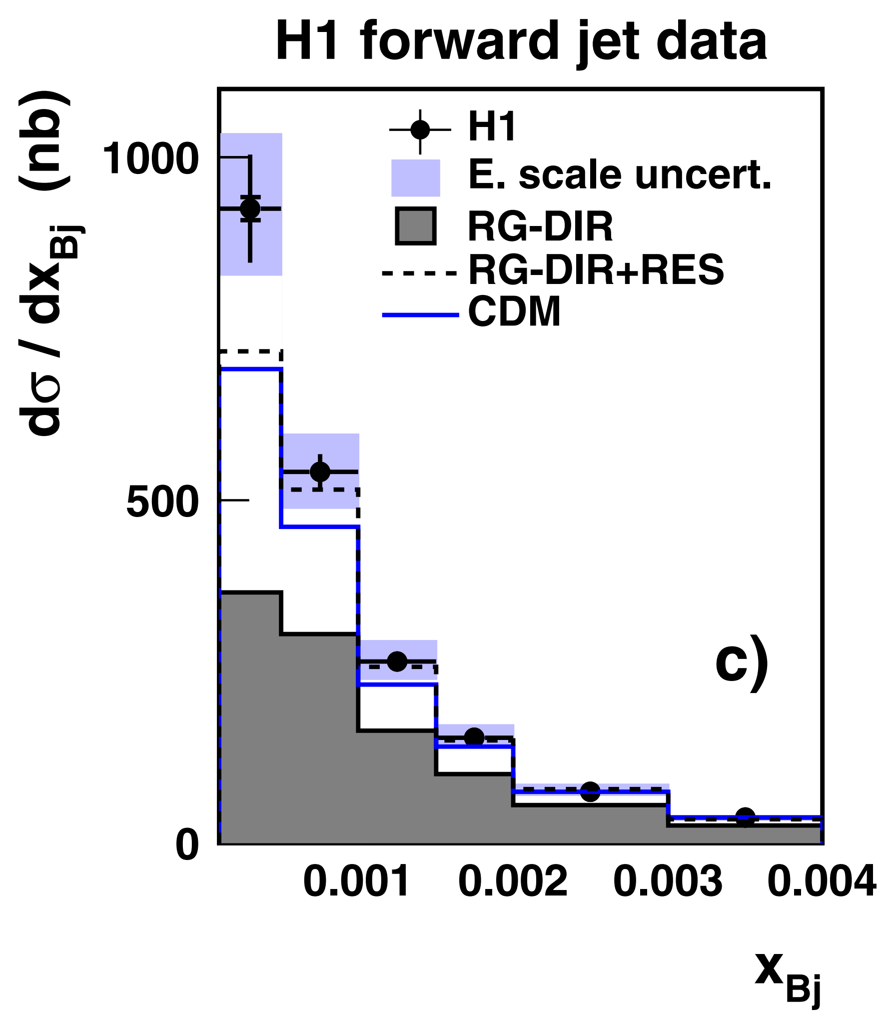
☛ scale uncertainty ≥ data uncertainty

Summary/Conclusions

- NLO calc. for DIS appear to work remarkably well even down to very low Q^2 (e.g. D meson prod.)
- NLO at low Q^2 is however not very predictive, the scale uncertainties are very large, "clever" scale choices have to be made, e.g. $\mu^2 = (E_T^2 + Q^2) / 4$ or E_T^2 or Q^2
- NLO has problems - not surprisingly -
  - the more differential the distributions, e.g.
    - for $d\sigma_{dijet} / dQ^2 dE_T^2 d x_\gamma$, particularly at low Q^2, low x_γ and low jet E_T
    - for observables like $\Delta\Phi < \pi$ and $x_\gamma < 1$
  - when only processes at tree level contribute
- Charm data are overall described by NLO, within the large scale uncertainties no need for resolved contributions, beyond what is included at LO direct
  - in charm prod. there is always a hard scale, i.e. the charm mass, could this be the reason?
- Deficiencies & typically large scale uncertainties indicate the need for higher orders, direct and/or resolved, or for other approaches like k_T-factorization and unintegrated parton densities, etc.
- To make progress two NLO programs with resolved contrib. at NLO, like JETVIP and "DIScoPHOX, would be needed

extra plots

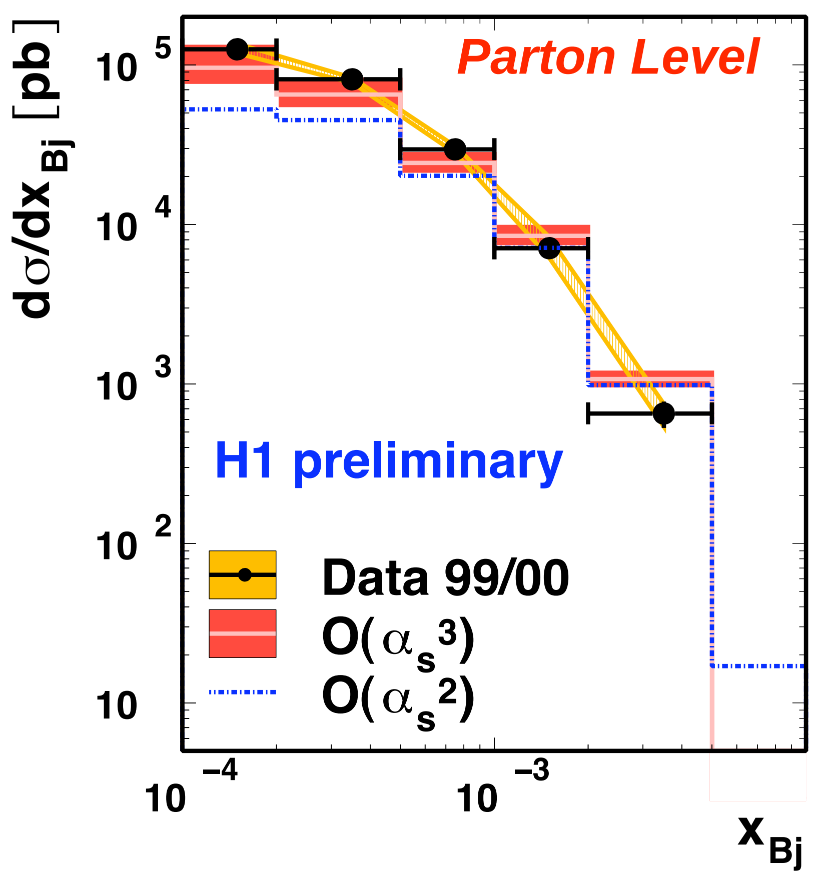

H1 forward jet data
H1
E scale uncert
NLO DISENT 1+δ_{HAD}
0.5$\mu_{r,f}$<$\mu_{r,f}$<2$\mu_{r,f}$
PDF uncert.
LO DISENT
1+δ_{HAD}
a)
$d\sigma / dx_{Bj}$ (nb)
1000
500
0
0.001
0.002
0.003
0.004
x_{Bj}


H1 forward jet data
H1
E. scale uncert.
RG-DIR
RG-DIR+RES
CDM
c)
$d\sigma / dx_{Bj}$ (nb)
1000
500
0
0.001
0.002
0.003
0.004
x_{Bj}

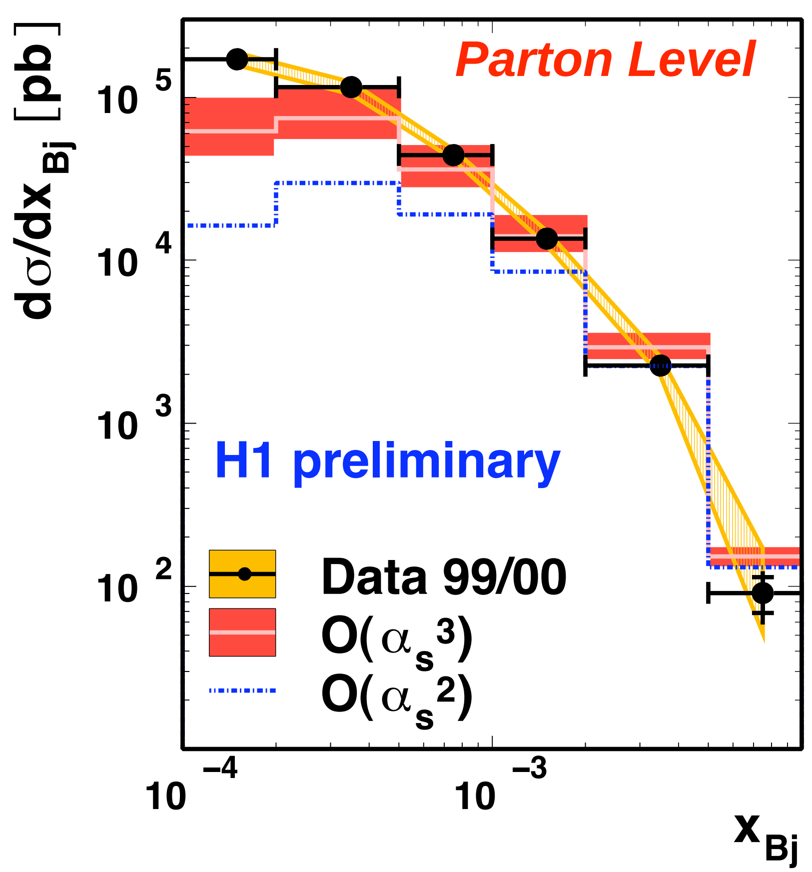
extra plots

- $E_{T,jet1,2,3} > 4$ GeV & $E_{T,jet1} + E_{T,jet2} > 9$ GeV
- fwd-jet: $\theta_{lab} < 20°$, $x_{jet} > 0.035$
- central jets: $-1 < \eta_{lab} < 1.3$
- fwd-jets are mainly gluon jets; al lowest xBj gluon emissions unordered in pT

1 fwd-jet & 2 central jets



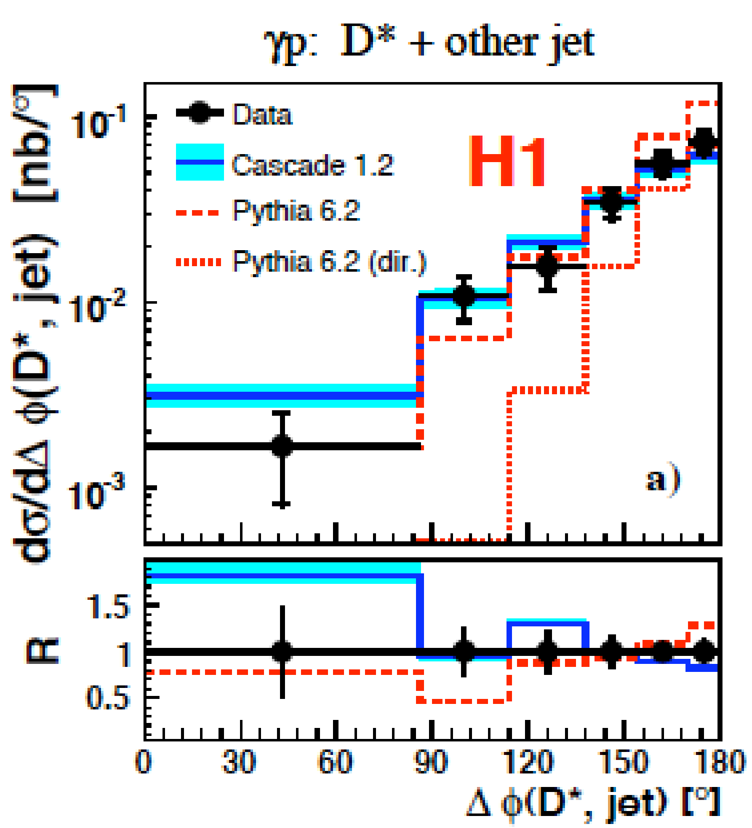
2 fwd-jets & 1 central jet

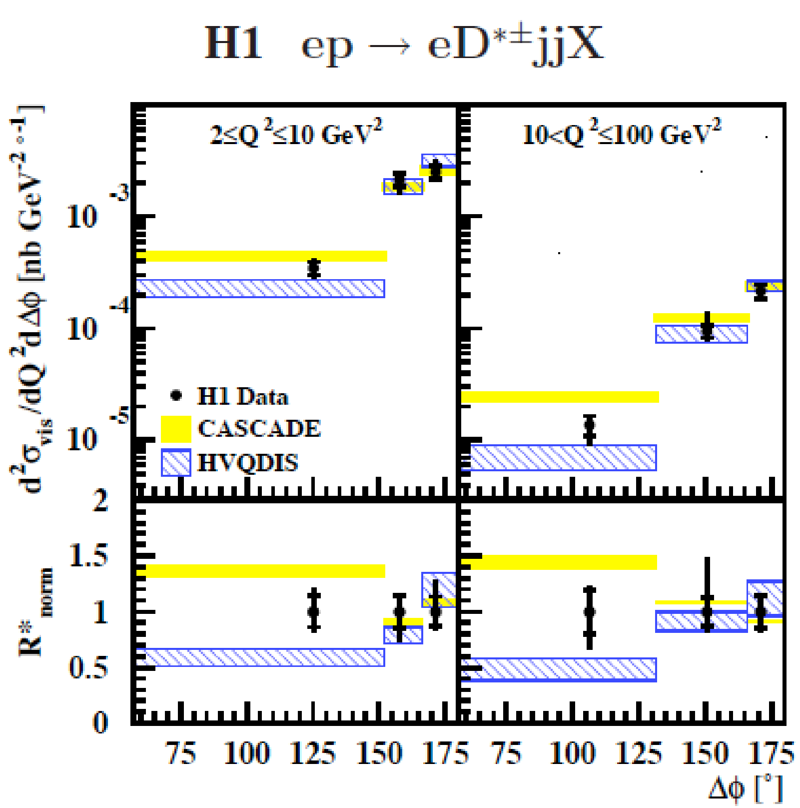


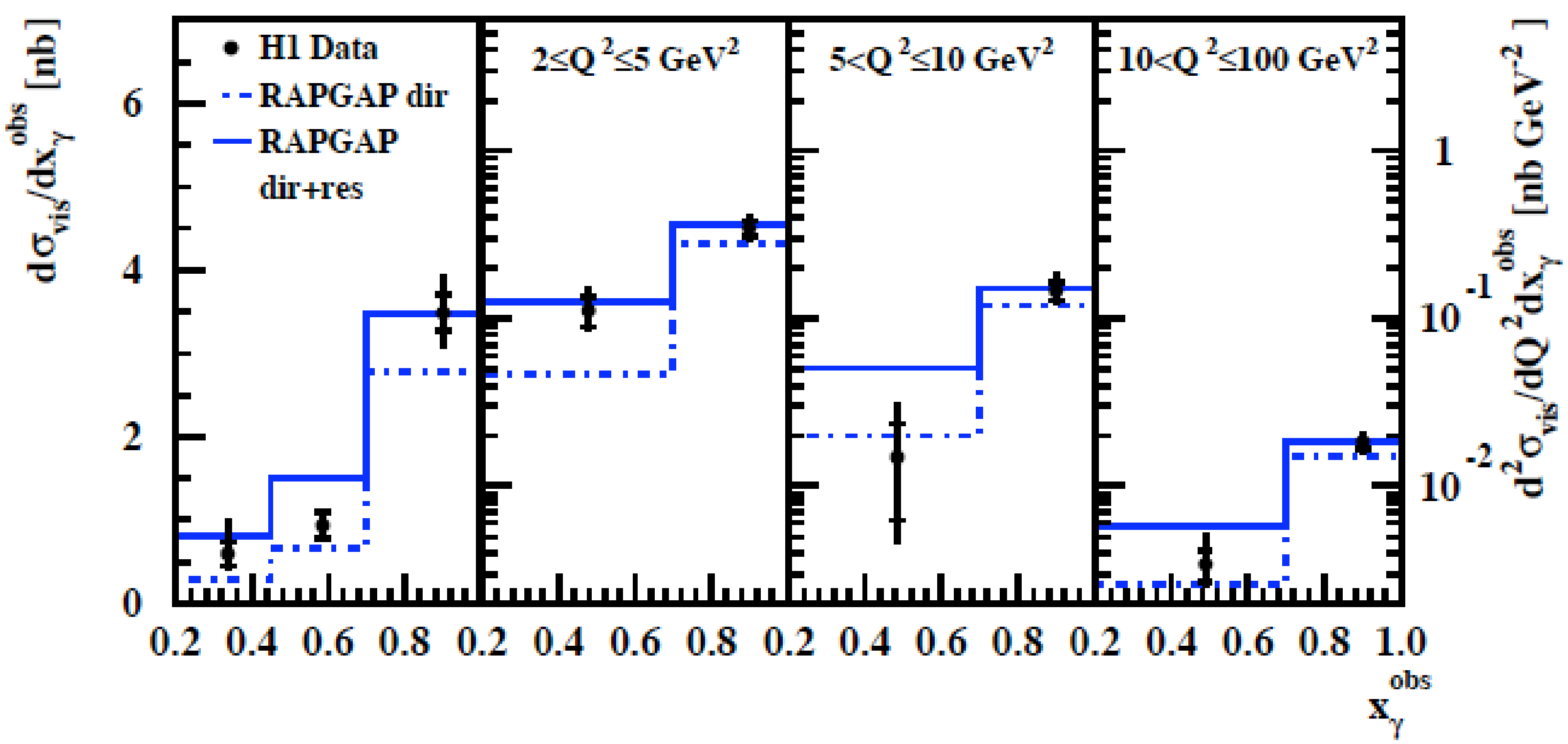
NLOJET++
- o NLO describes data well

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

extra plots


γp: D* + other jet
Data
Cascade 1.2
Pythia 6.2
Pythia 6.2 (dir.)
H1
a)
dσ/dΔ φ(D*, jet) [nb/°]
R
Δ φ(D*, jet) [°]


H1 ep → eD*±jjX
2≤Q²≤10 GeV²
10<Q²≤100 GeV²
H1 Data
CASCADE
HVQDIS
d²σvis/dQ²dΔφ [nb GeV⁻² °⁻¹]
R*norm
Δφ [°]


H1 Data
RAPGAP dir
RAPGAP dir+res
2≤Q²≤5 GeV²
5<Q²≤10 GeV²
10<Q²≤100 GeV²
dσvis/dxγobs [nb]
d²σvis/dQ²dxγobs [nb GeV⁻²]
xγobs