Low x Hadronic Final State Studies at H1

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Overview

- Quick Introduction to the low x issue.
- New results from H1.
- Implications for the LHC.

Parton Evolution

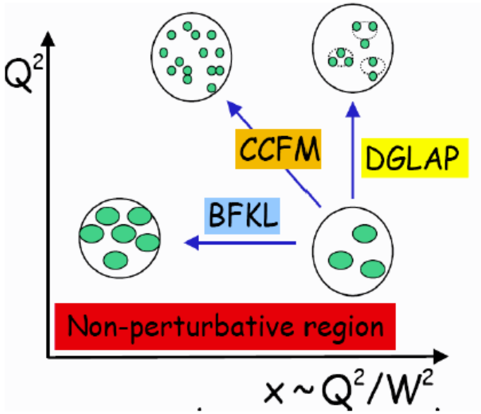
Standard DGLAP approximation, large Q^2:
sums terms $\sim\alpha_s \log Q^2$, strong ordering in k_T of parton emmision (collinear factorisation).

non DGLAP effects expected to produce a significat enhancement of gluon radiation

BFKL evolution equation, low x:
sums terms $\sim\alpha_s \log(1/x)$, strong ordering in x_i, no ordering in k_T, (k_T factorisation).

Inclusive F2 measurment not able to discriminate between different QCD approaches.
Study Hadronic final state.

CCFM equation applicable at all x and Q^2:
includes both $\alpha_s \log Q^2$ and $\alpha_s \log(1/x)$ terms.
implements angular ordering resulting from QCD interference effects

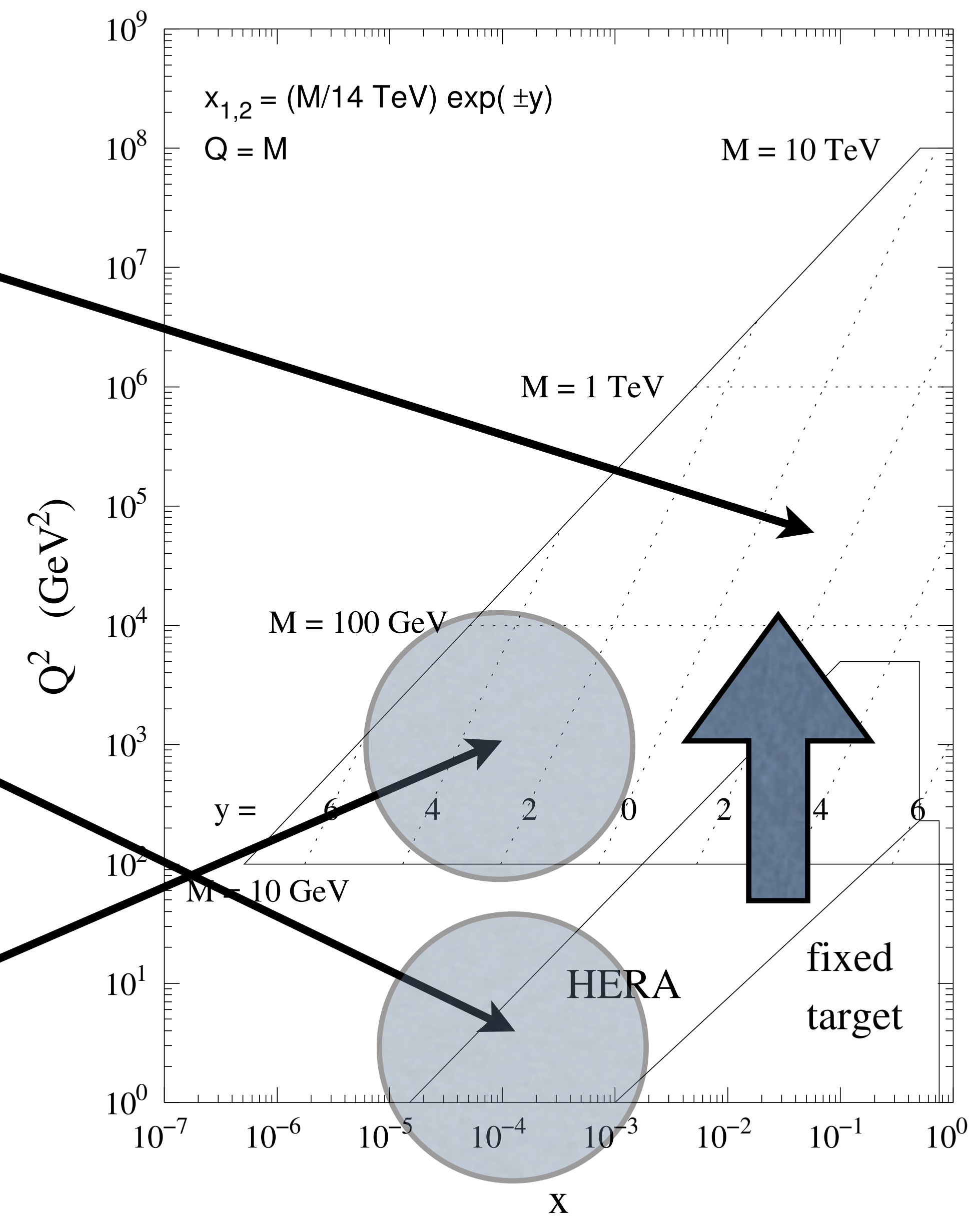


Low x Domain

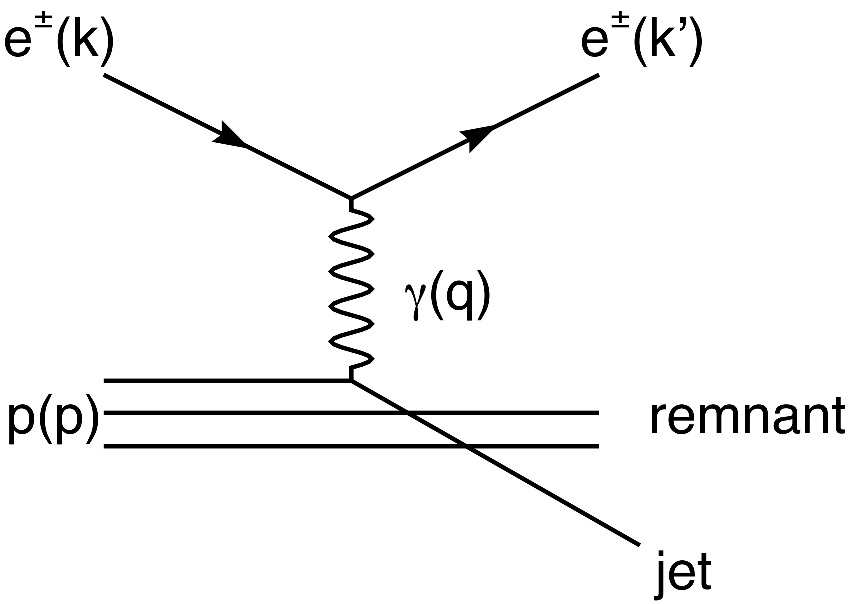
Conventional DGLAP QCD approach evolves with Q

Possibility of non DGLAP behaviour of the parton evolution at HERA

What does this mean for the LHC?



DIS and HERA



Kinematic Variables:

$$Q^2 = -q^2 = -(k-k')^2$$

Momentum transfer

$$x = \frac{Q^2}{2p \cdot q}$$

Fraction of the proton's momentum that participates in the hard scatter

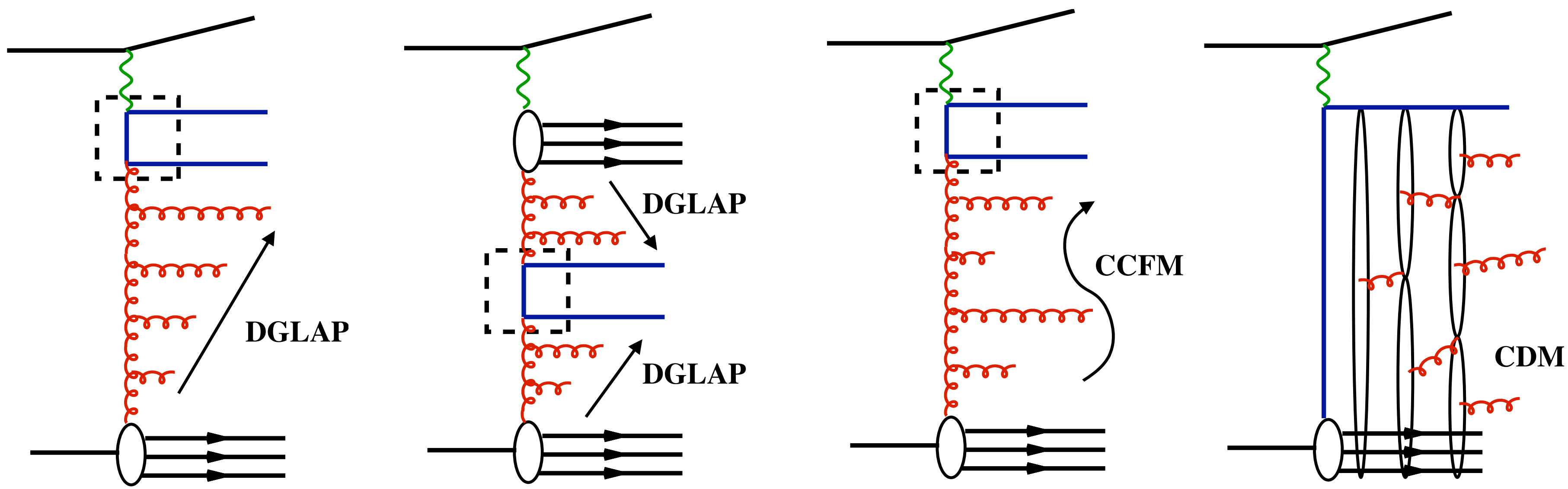
$$y = \frac{p \cdot q}{p \cdot k}$$

Fraction of the electron's energy available in the proton's rest frame

$$Q^2 = sxy$$

s=center of mass energy squared

Monte Carlos for DIS



Rapgap (dir)	Rapgap (dir+res)	Cascade	Ariadne

Strong ordering in k_t of emitted partons

CCFM resumes both $\log(Q^2)$ and $\log(1/x)$ angular ordering

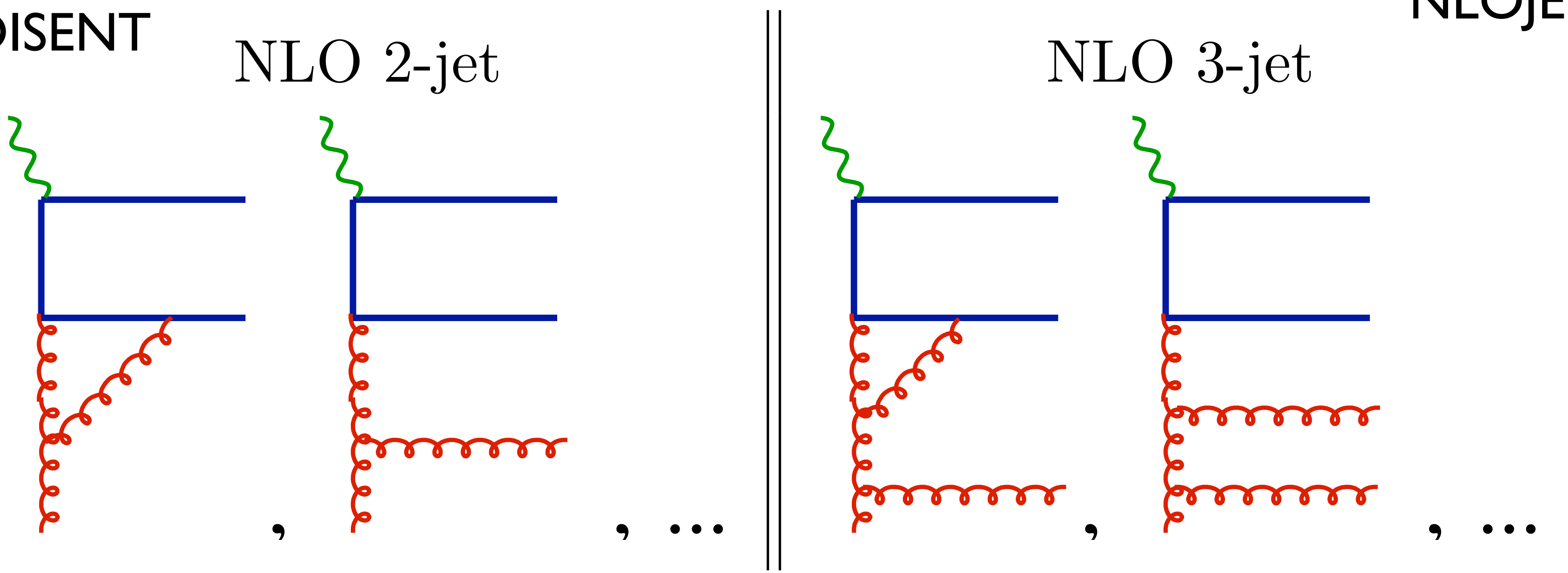
Dipoles radiate independently

as is PYTHIA and HERWIG

NLO QCD Calculations

NLOJET++, DISENT

NLOJET++



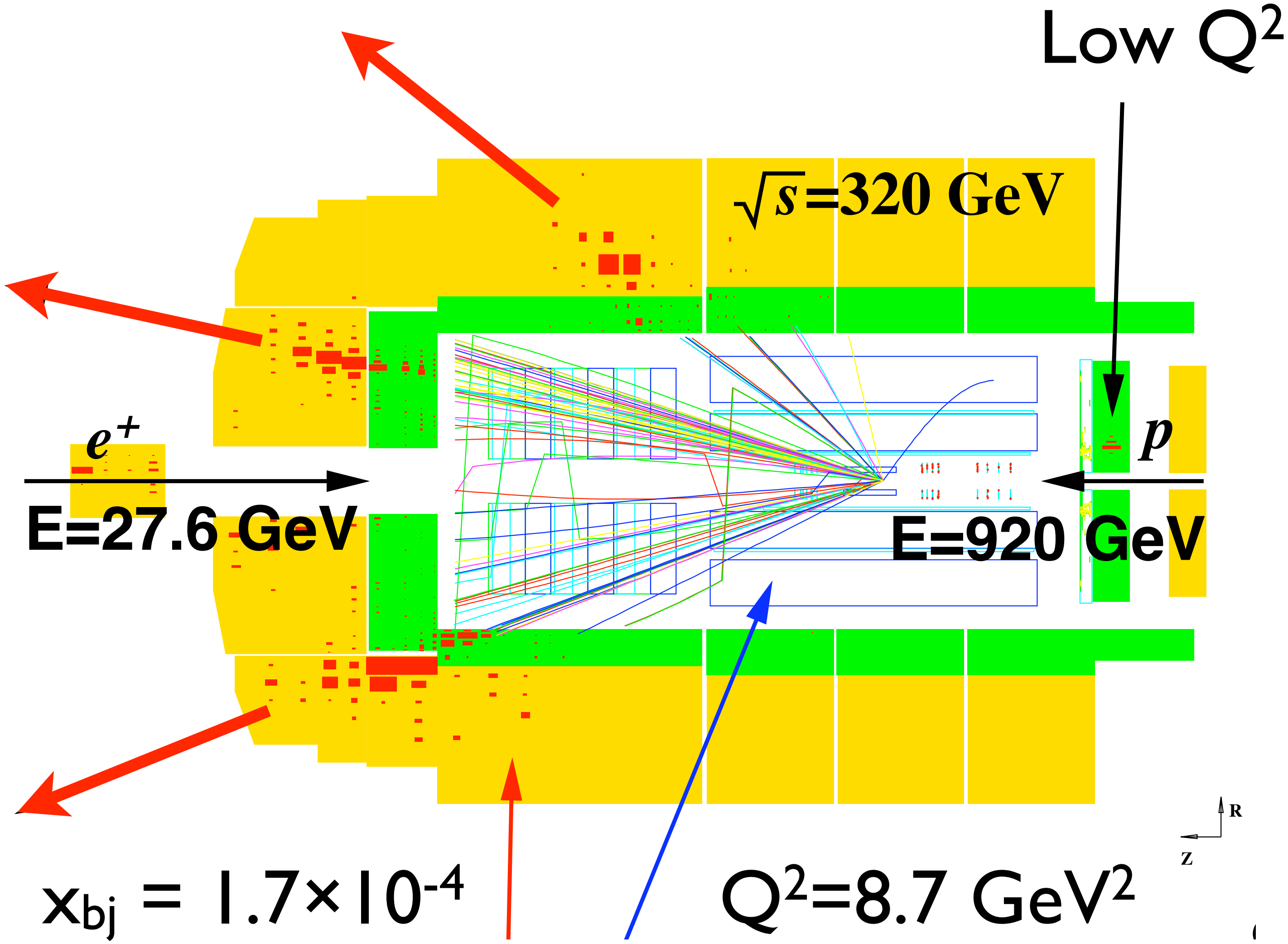
Scale $\mu_r = \mu_f = Q$ or E_t or some similar combination

Scale Uncertainty $1/2\ \mu_{r,f} < \mu_{r,f} < 2\mu_{r,f}$,changing both scales simultaneously

PDF : CTEQ, MRST, H1, ZEUS

Hadronisation correction from Monte Carlo

H1

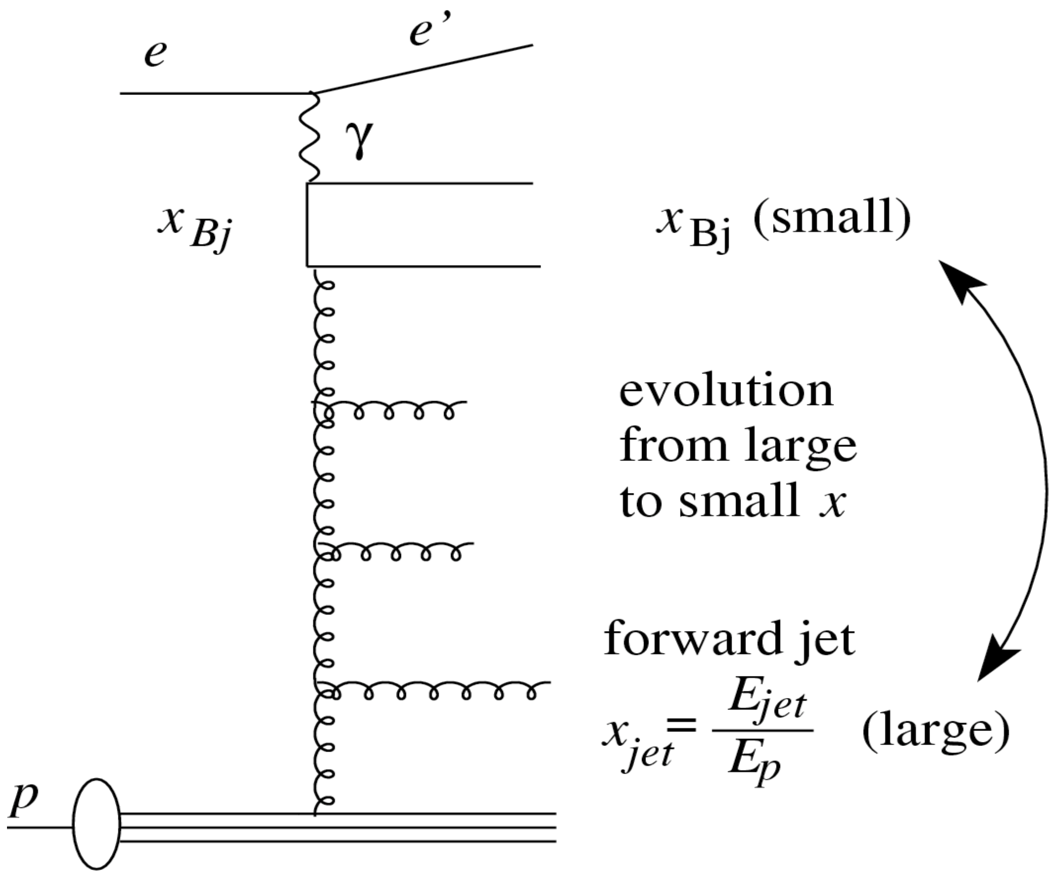


Jets measured by tracking and calorimeters

$-1 < \eta_{jet} < 2.8$

Forward Jets in DIS

Forward Jet Production



Test QCD at small x and look for parton dynamics beyond DGLAP

Suppress DGLAP ($p_{t,\, fwd\, jet}^2 \sim Q^2$)
Enhance BFKL ($x_{bj} << x_{jet}$)

Forward jets = jets away from hard interaction.

DGLAP (ordered kt) - soft parton emissions

BFKL (non-ordered kt) - more (harder) jets

Forward Jet Production

Kinematic selection:
$5 < Q^2 < 85$ GeV^2
$0.1 < y < 0.7$
$0.0001 < x_{bj} < 0.004$

1997 data L=13.7 pb^{-1}
E_p=820, E_e=27.6
$\sqrt{s} \approx 300$ GeV

Forward jet selection:
Inclusive kt-algorithm in Breit frame
$1.75 < \eta_{jet} < 2.8$
$P_{t,jet,lab} > 3.5$ GeV
$x_{jet} = E_{jet}/E_p > 0.035$
$0.5 < p_{t,jet}^2/Q^2 < 5$
if Njet>1, choose highest η jet

Forward Jet Production

DISENT LO (α_s) and NLO (α_s^2):

$\mu_r^2 = p_t^2$

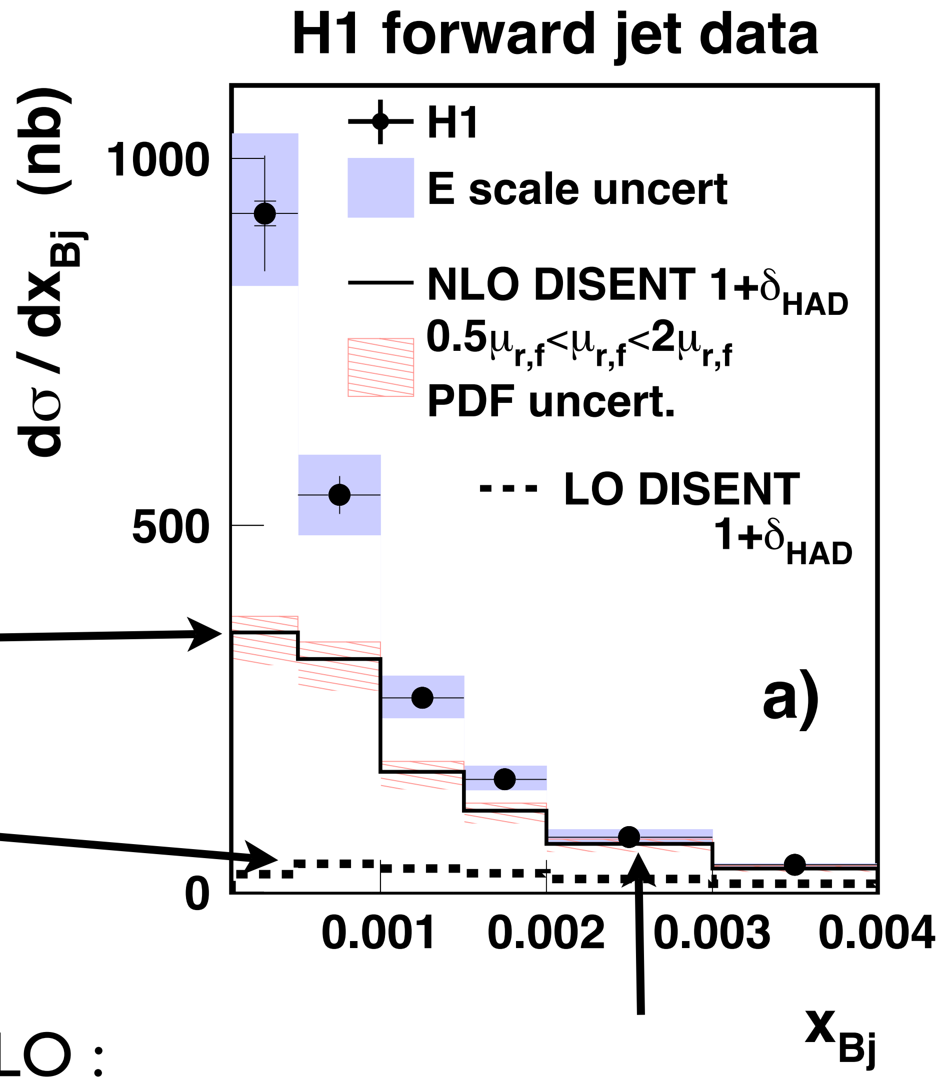
$\mu_f^2 = \langle p_{t,fwdjet}^2 \rangle = 45\ \text{GeV}^2$

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

$(1+\delta_{HAD})$

NLO below data

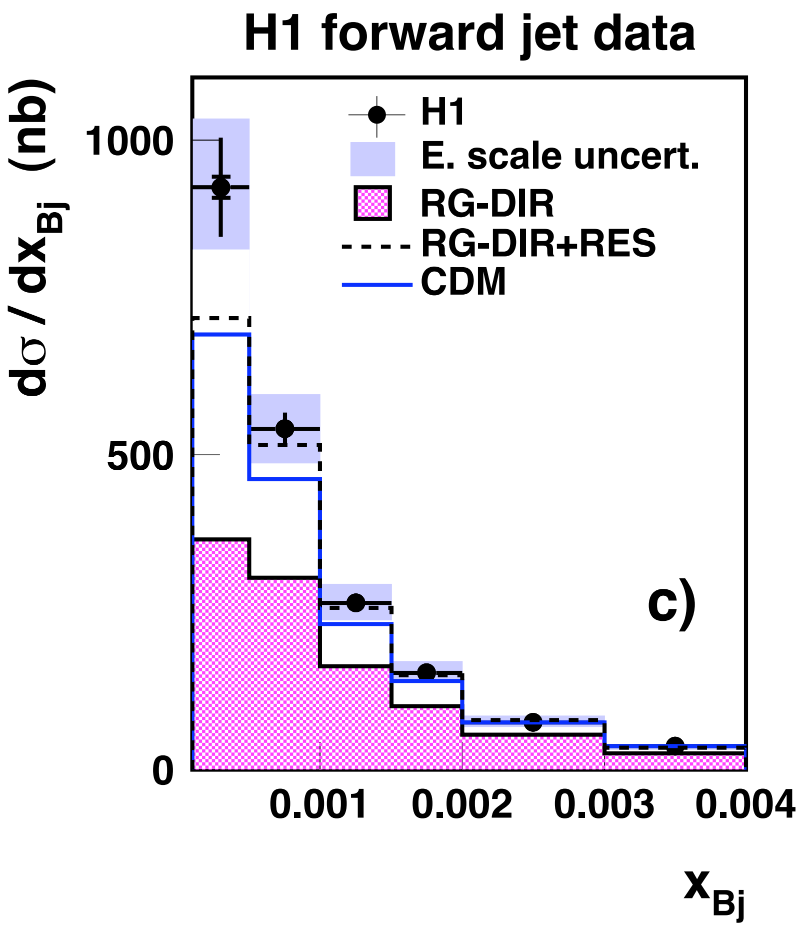
LO << NLO

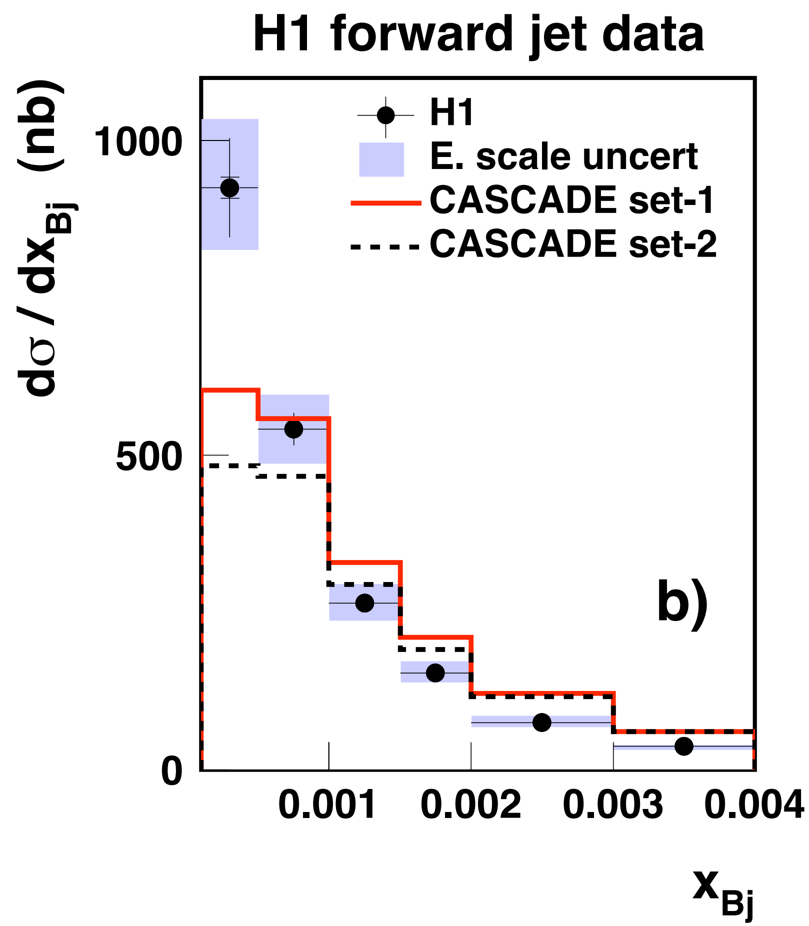


large difference between LO and NLO :
scale error underestimated?
Is this really an inclusive cross section?

NLO better here

Forward Jet Production





RAPGAP direct fails,
addition of resolved photon processes improves description.

CDM prediction also better.

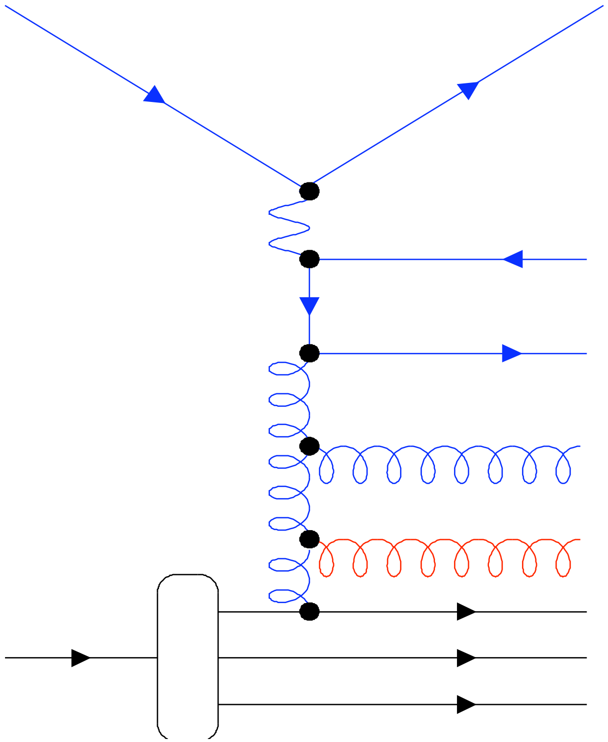
CASCADE fails to describe spectrum.

Differences between different updfs.

Harder spectrum
(only gluon initiated processes?)

Three Jets in DIS

Three Jet Production



For events with three or more jets, at least one jet should come from gluon radiation

Should be sensitive to the dynamics of gluon radiation

Provides a more testing environment to compare with theory

Three Jet Production

Kinematic selection:
$10^{-4} \leq x_{bj} \leq 10^{-2}$
$5 \leq Q^2 \leq 80\ GeV^2$
$0.1 < y < 0.7$

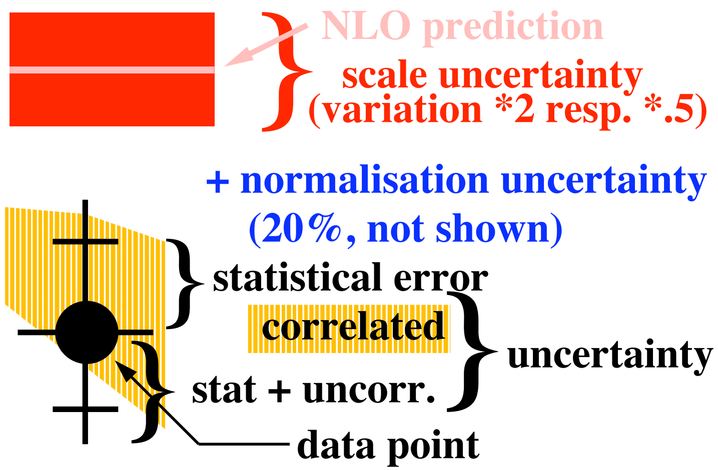
99/2000 data $L = 44.2\ pb^{-1}$
$E_p=920$, $E_e=27.6$
$\sqrt{s} \approx 318$ GeV

Three Jet Selection:
Inclusive kt-algorithm in $\gamma^* p$ rest frame
$E_{\perp,jet} > 4$ GeV

$-1 < \eta_{jet,lab} < 2.5$
$N_{jet} \geq 3$
$E_{\perp 1} + E_{\perp 2} > 9$ GeV

one jet in range $-1 < \eta_{jet,lab} < 1.3$

Three Jet Production

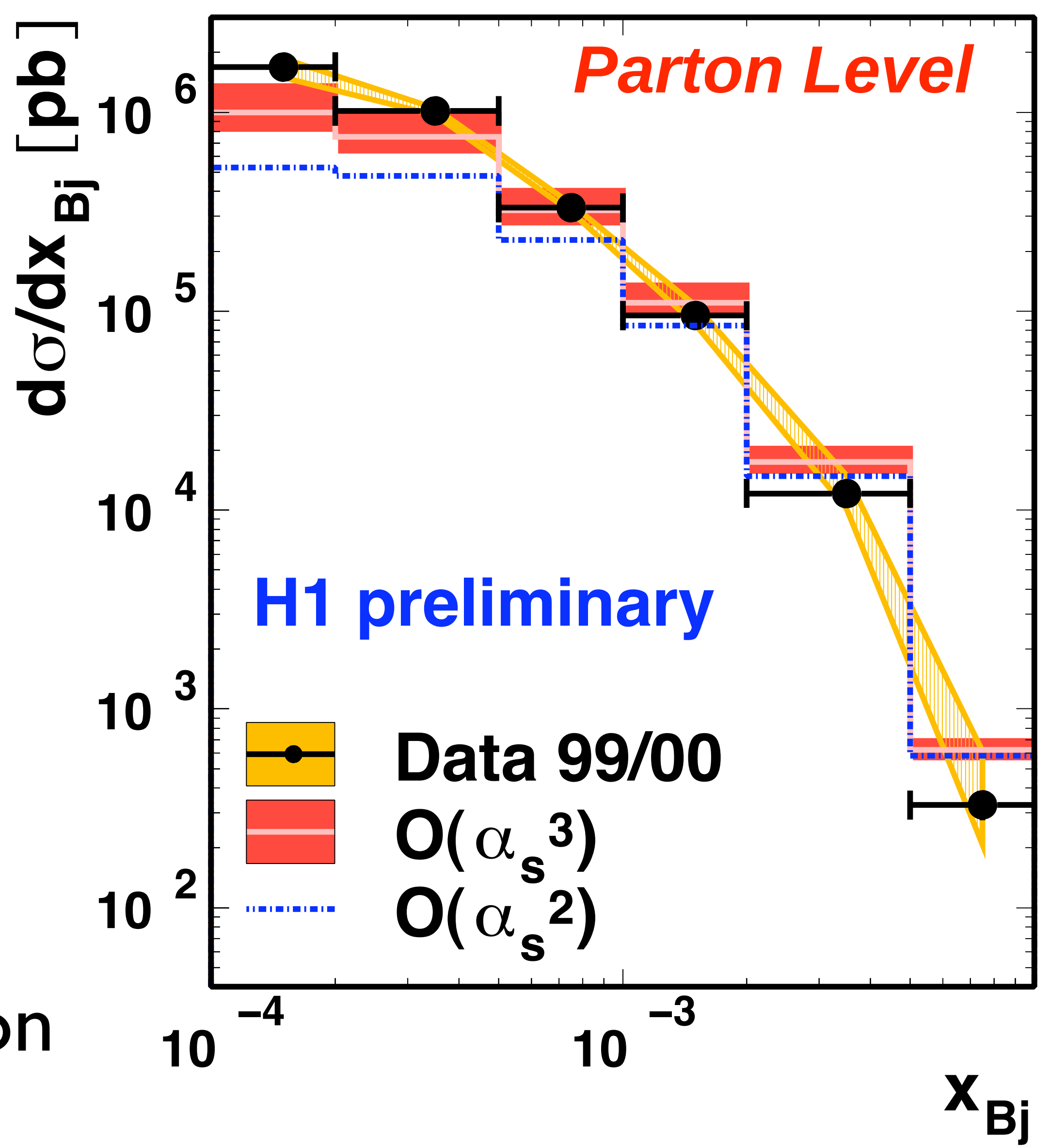


$O(\alpha^2) \rightarrow O(\alpha^3)$

up to 3 jets — up to 4 jets

×3.3 — ×1.7

at low x



Improvement in description especially at low x_{bj}

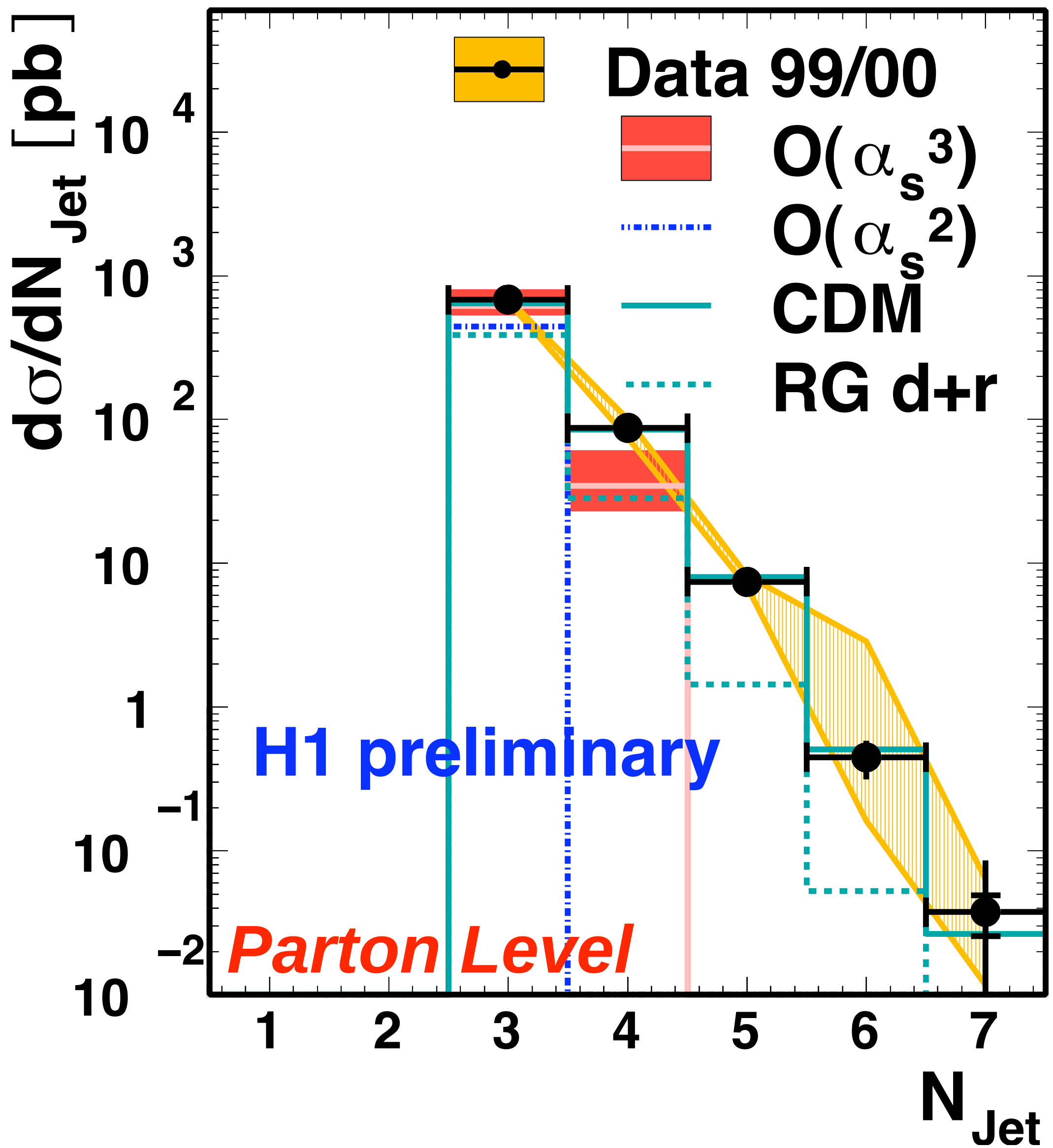
Three Jet Production

For 3 jets $O(\alpha^3)$ = data

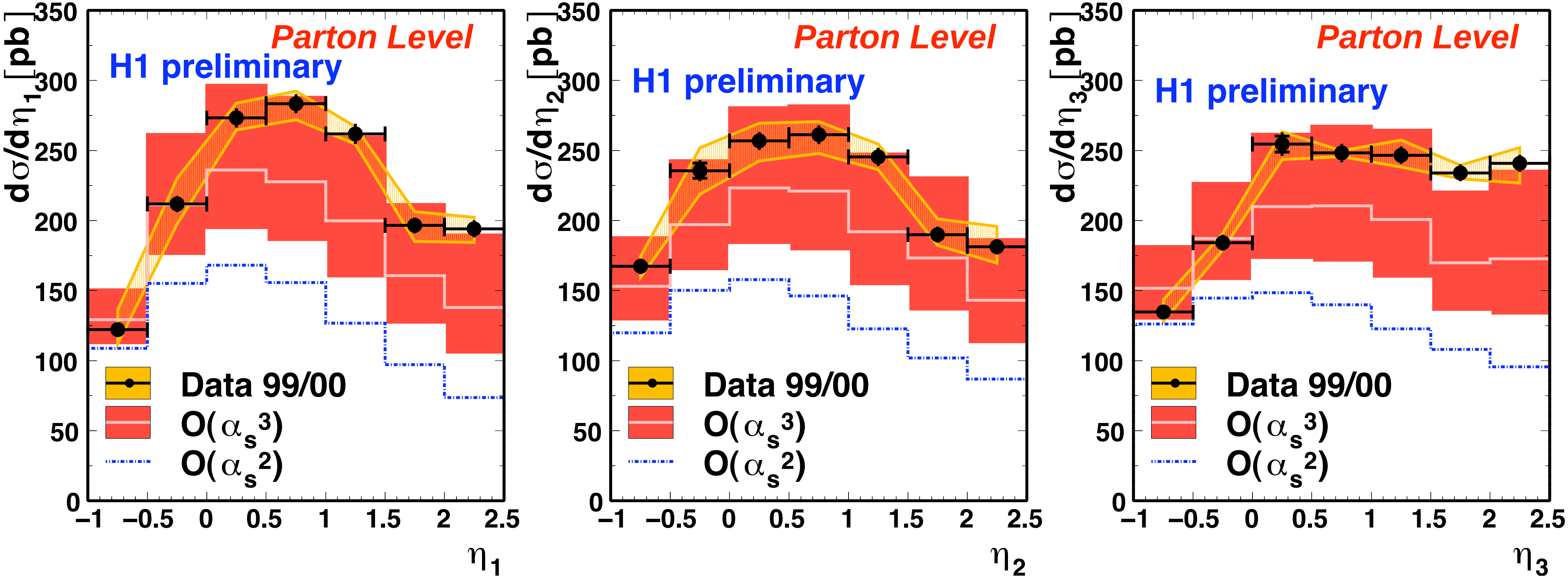
$O(\alpha^3)$ misses ~20% of events with 4 or more jets

CDM gives excellent description

RAPGAP fails even for 3 jets



Three Jet Production

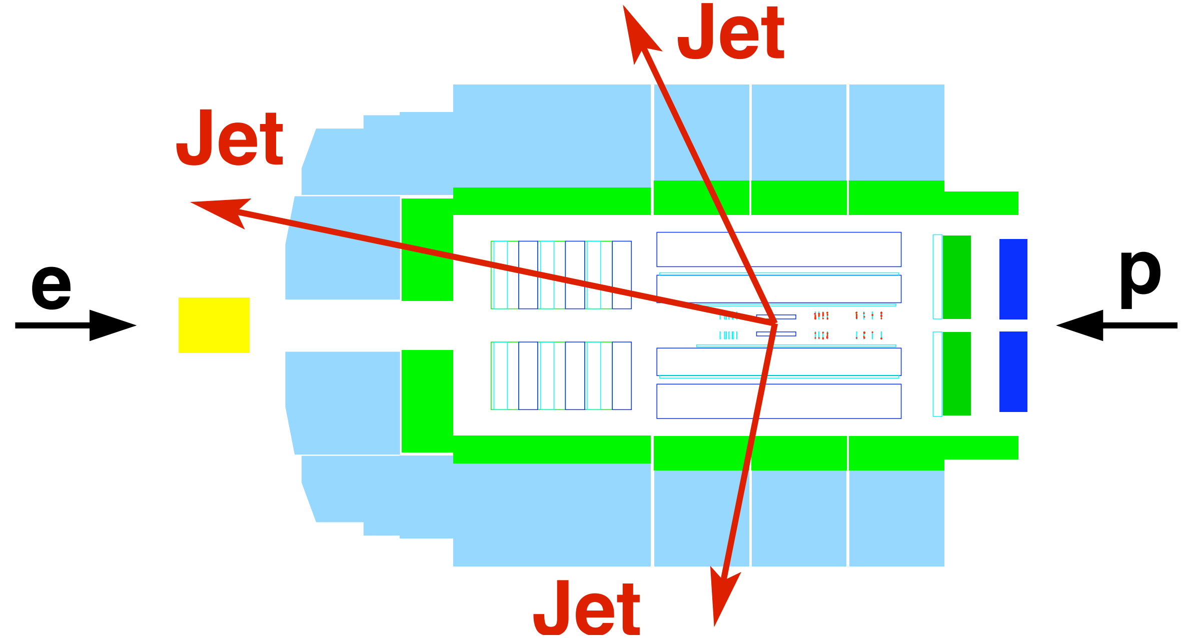


Main discrepancies at low x and large η (forward region)

Other distributions are well described apart from ~20% normalisation difference

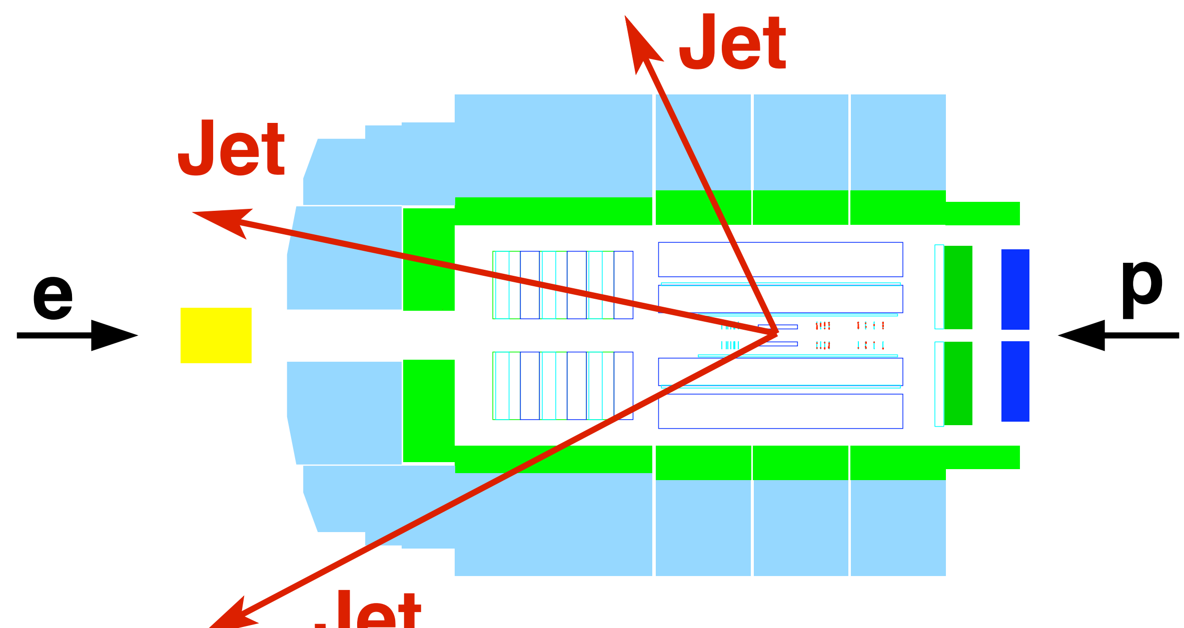
Three Jet Production

Two central jets

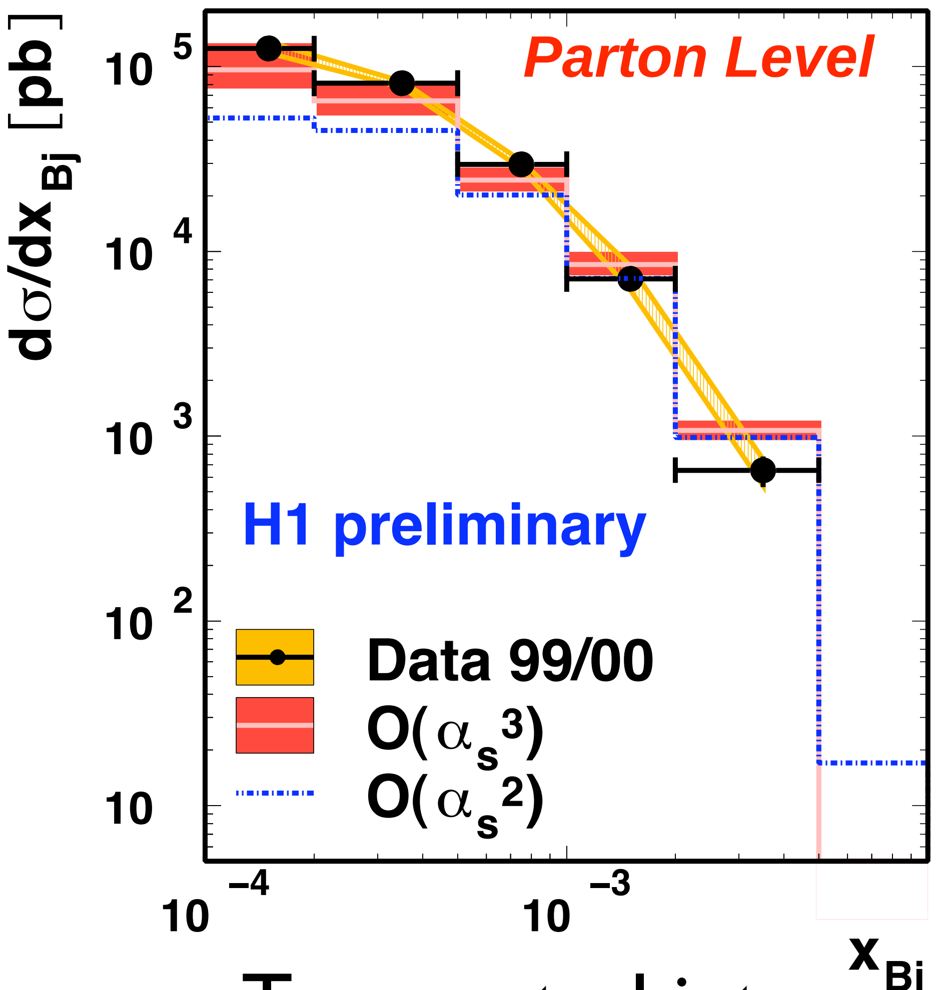


Forward jet selection:
$\eta_{jet} > 1.75$, $x_{jet} > 0.035$

Two forward jets

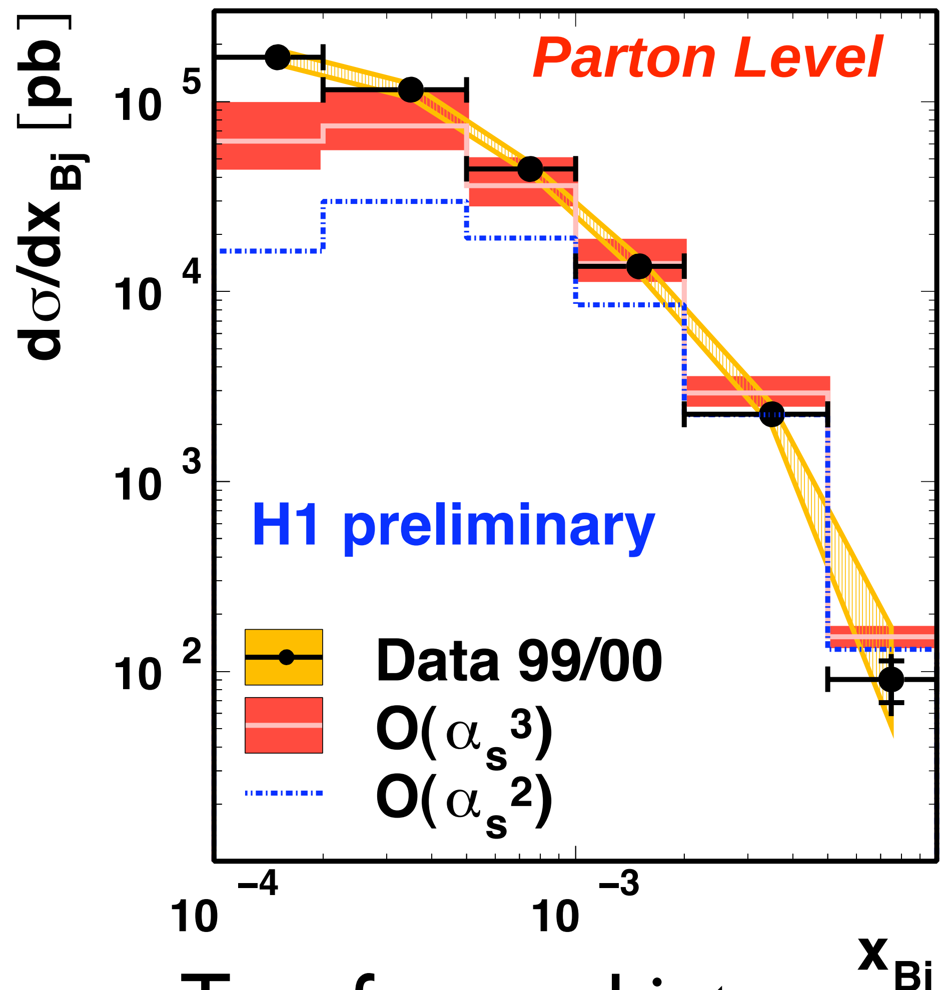


Three Jet Production



Two central jets

reasonably well described



Two forward jets

Data = $O(\alpha^2) \times 10$

Data = $O(\alpha^3) \times 3.5$

at low x

Three Jet Production

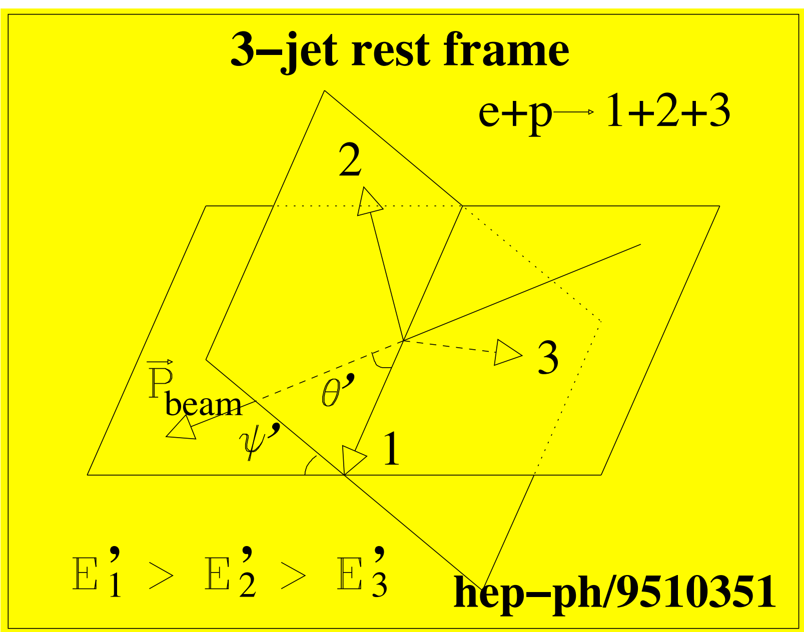
Two forward jets

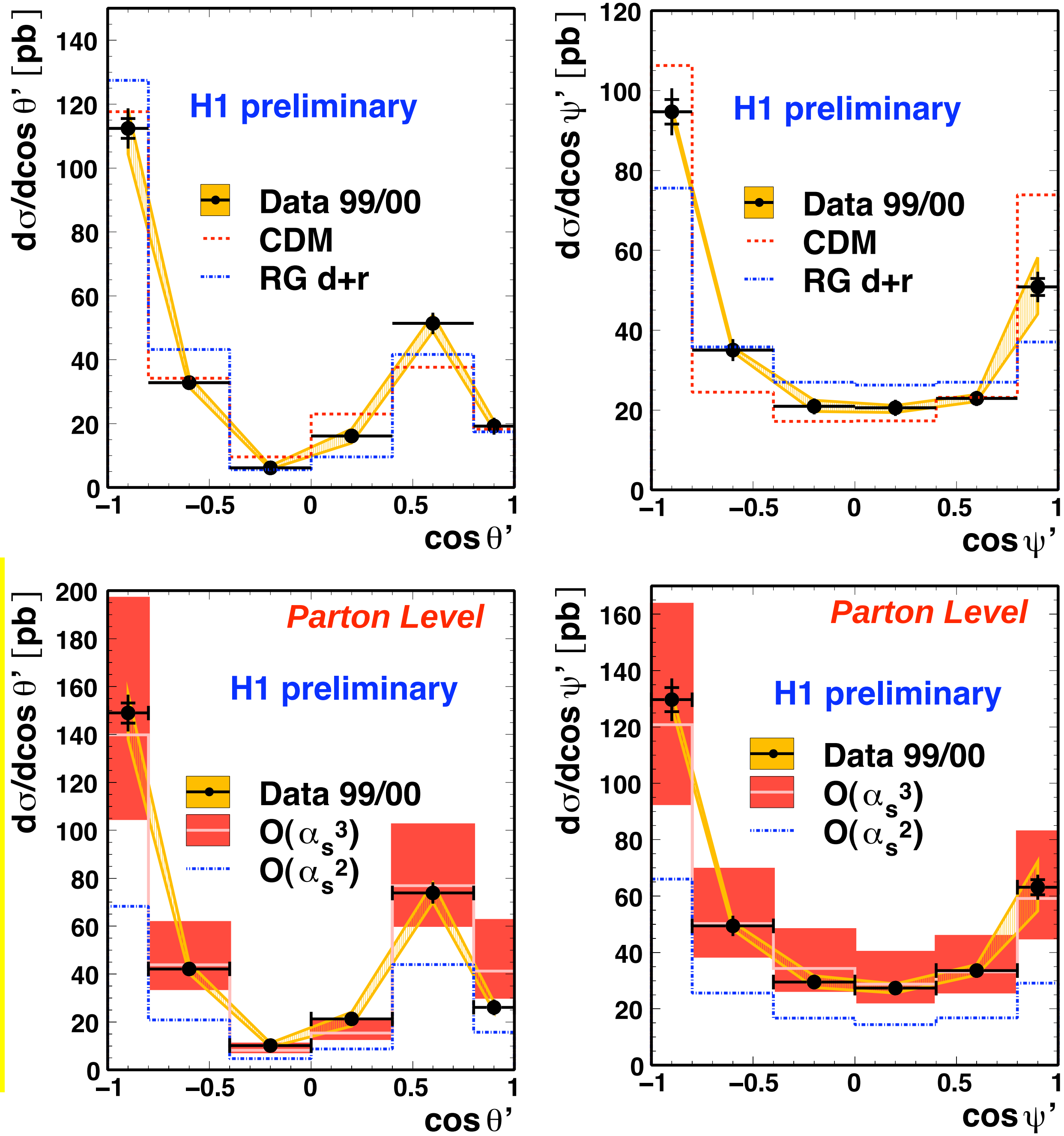
compare shapes:

$O(\alpha^2)$, $O(\alpha^3)$ x 1.34

Rapgap x 1.74

CDM x 1.08

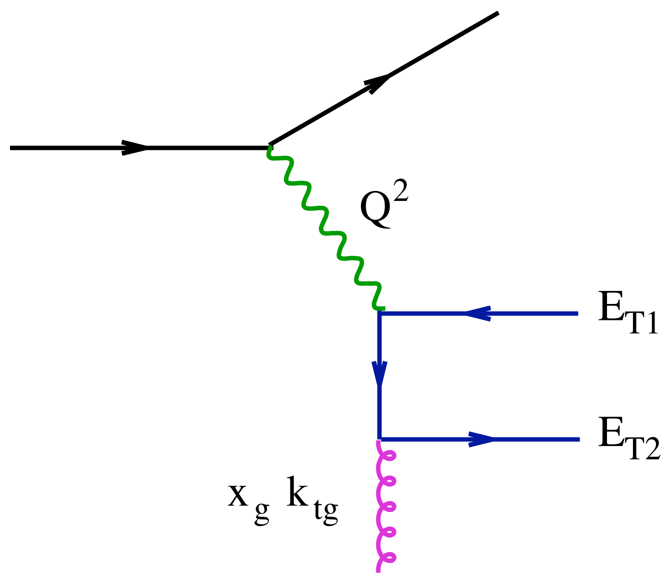




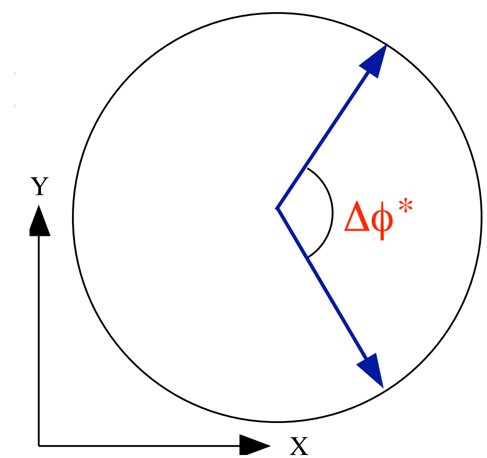
Dijet Azimuthal Correlations in DIS

Dijet Azimuthal Correlations

DGLAP:
In LO gluon collinear with proton
$k_{t,g}$=0, Jets back-to-back in HCM, $\Delta\phi^*$=180°
Higher order QCD radiation
$k_{tg}\neq 0$, $\Delta\phi^*$<180°
Gluon emissions ordered in virtuality
k_{tg} ordered



BFKL, CCFM:
unordered k_{tg}
Broader $\Delta\phi^*$ compared to DGLAP
sensitive to unintegrated (u)PDF
$\Delta\phi^*$ <180° at LO!



Sensitive to different parton dynamics
Sensitive to unitegrated gluon density

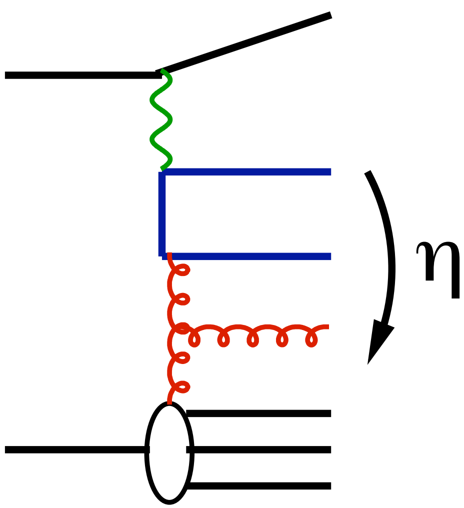
Dijet Azimuthal Correlations

Kinematic Selection:
$5 < Q^2 < 100$ GeV^2
$0.1 < y < 0.7$

99/2000 data L = 64.3 pb^{-1}
E_p=920, E_e=27.6
$\sqrt{s} \approx 318$ GeV

Dijet Selection:
Inclusive Kt-algorithm
$E^*_{\perp jet} > 5$ GeV

$-1 < \eta_{lab} < 2.5$



Two jets closest in η to the scattered electron chosen as the dijet system

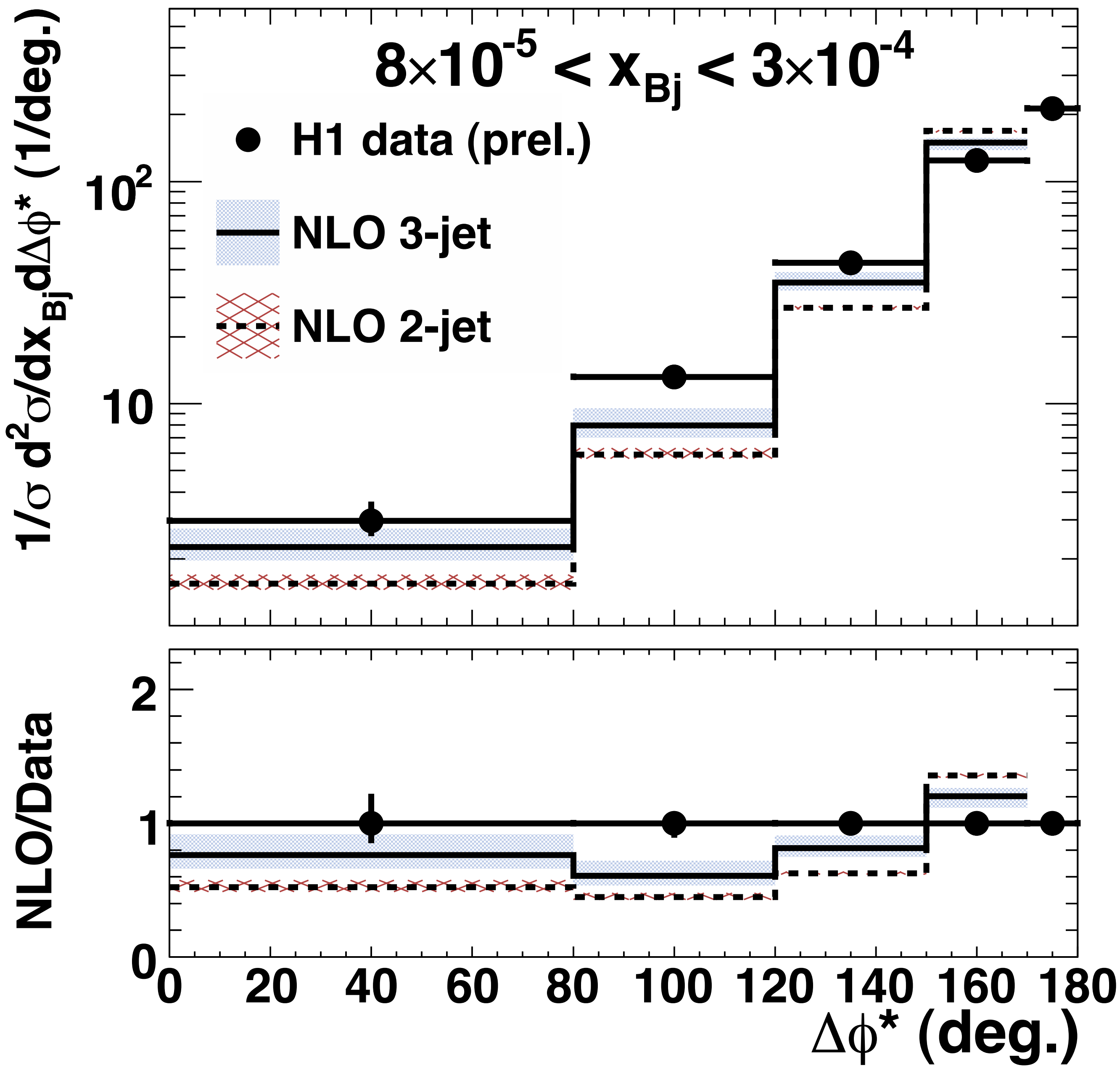
Dijet Azimuthal Correlations

Infrared sensitivity, no NLO for $\Delta\phi^* \sim 180°$

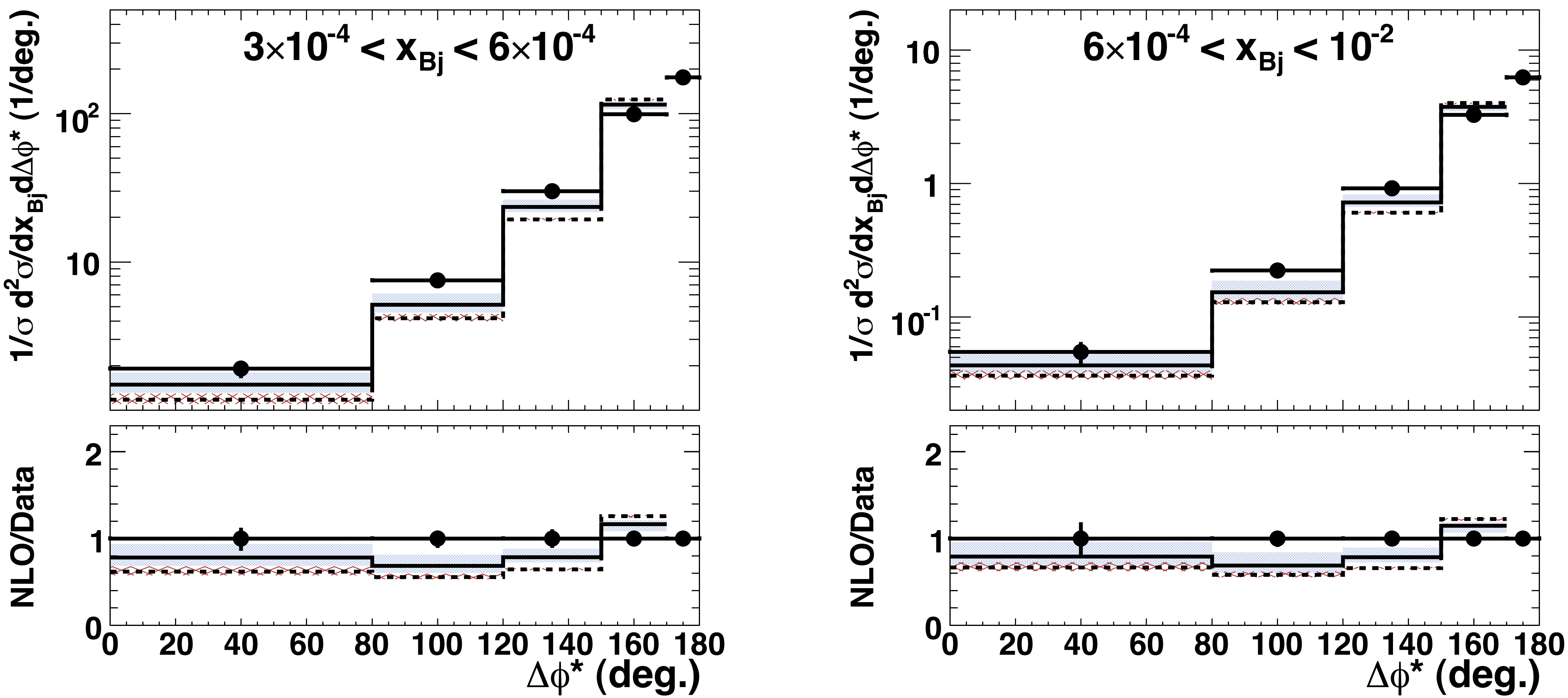
Normalise to visible cross section to reduce scale uncertainties (<20%)

NLO 2 jet (α_s^2) fails ~ effectively LO

NLO 3 jet () better but still systematically below data for $\Delta\phi^* < 160°$

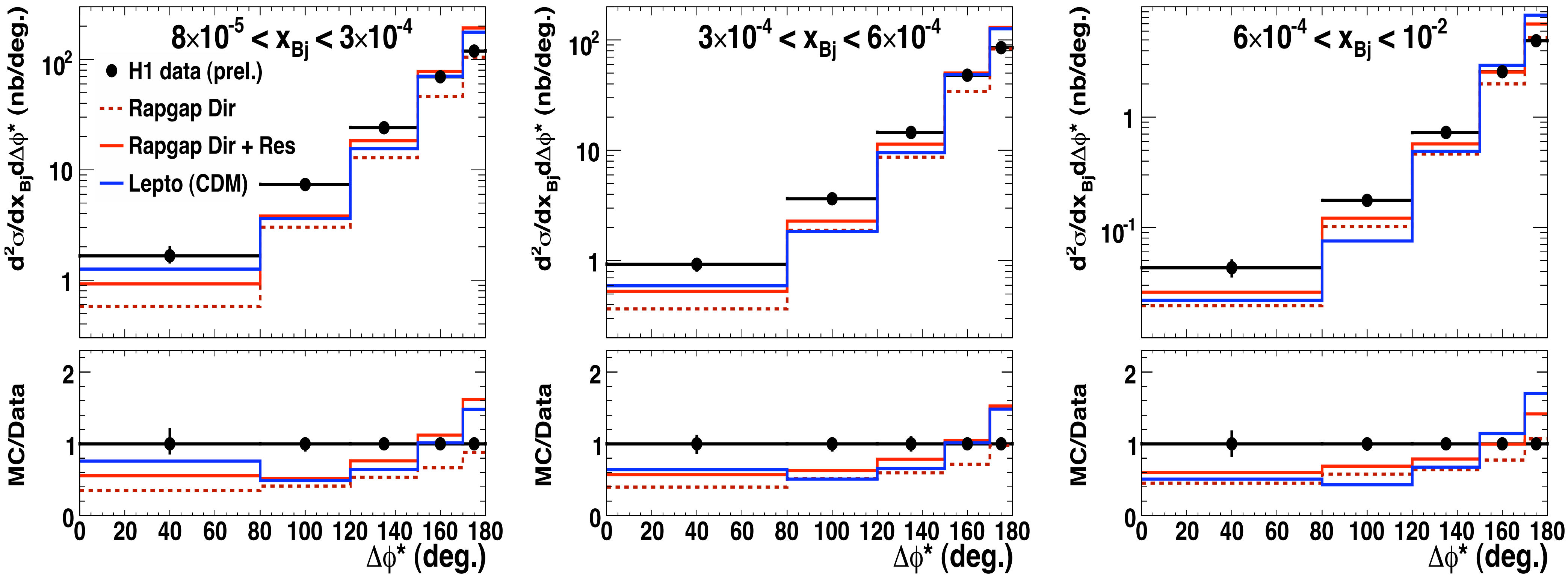


Dijet Azimuthal Correlations



Similar story at higher x_{bj}!

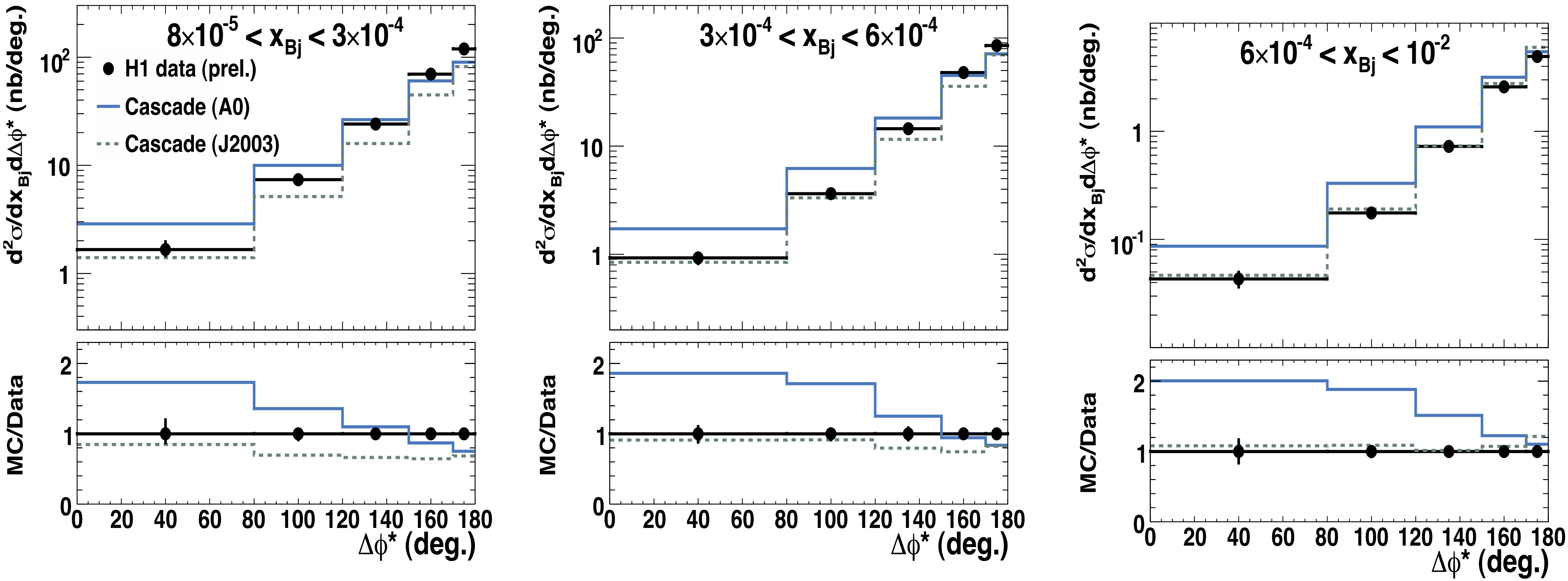
Dijet Azimuthal Correlations



Rapgap (direct) describes back-to-back ($\Delta\phi^* = 180°$) jets

Rapgap (dir+res) and CDM give too many back-to-back jets and too few small $\Delta\phi$ dijets

Dijet Azimuthal Correlations



Sensitivity to unintegrated gluon density

Cascade J2003 much better than A0 (too hard)

Cascade + J2003 gives best description of any model

Summary

- $O(\alpha^3)$ huge improvement compared to $O(\alpha^2)$ predictions.
- Rapgap (direct fails) → ordered gluon radiation.
- Rapgap (direct + resolved) is better but it still fails → ordered gluon radiation.
- In general CDM gives best description of the data (even in normalisation) → unordered gluon radiation.
- Cascade expect improvements with new updf fits including new data.
- Non DGLAP dynamics clearly favoured by hadronic final state measurements at low x.

Results in full

- Measurement of Dijet Production at Low Q^2 at HERA (H1 Collab., A. Aktas et al., Eur. Phys. J. C37 (2004) 141-159). hep-ex/0401010
- Inclusive Dijet Production at Low Bjorken-x in Deep Inelastic Scattering (H1 Collab., A. Aktas et al., Eur. Phys. J. C33 (2004) 477). hep-ex/0310019
    - See also: QCD Analysis of Dijet Production at Low Q^2 at HERA (J.Chýla et al., hep-ph/0501065).
- Forward π^0 Production and Associated Transverse Energy Flow in Deep-Inelastic Scattering at HERA (H1 Collab., A. Aktas et al., Eur. Phys. J. C36 (2004) 441-452). hep-ex/0404009
    - See also: B. A. Kniehl, G. Kramer and M. Maniatis, Nucl. Phys. B711, 345 (2005); B720, 231(E) (2005). 8. A. and Daleo, D. de Florian and R. Sassot, Phys. Rev. D71, 034013 (2005).
- Forward Jet Production in Deep Inelastic Scattering at HERA (H1 Collab., A. Aktas et al., Eur. Phys. J. C46 (2006) 27-42). hep-ex/0508055
    - See also: Forward jet production in deep inelastic ep scattering and low-x parton dynamics at HERA (ZEUS Collaboration; S. Chekanov et al. Letters B 632 (2006) 13-26).
- 3-jet cross sections at low x and Q^2 (H1prelim-06-034). DIS06
- Azimuthal correlations in dijet events at low Q^2 DIS (H1prelim-06-032). DIS06

Implications for LHC?

- Use best models at HERA for LHC. But....

- Cascade only includes gluon processes. This limits present use for LHC. Can compare with like processes in Pythia (*fg*→*fg*, *gg*→*ff*, *gg*→*gg*).

- Unintergrated pdfs need to be better constrained (useful results presented here).

- Ariadne missing splitting kernal g→qq (see contribution by Leif Lönnblad "ARIADNE at HERA and at the LHC" from HERA/LHC workshop proceedings for more details).

- Improvements expected, part of HERA/LHC program

Multi-Jet Production and Multi-Scale QCD

PYTHIA

ARIADNE

HERWIG

HERA/LHC workshop proceeding CERN-2005-014

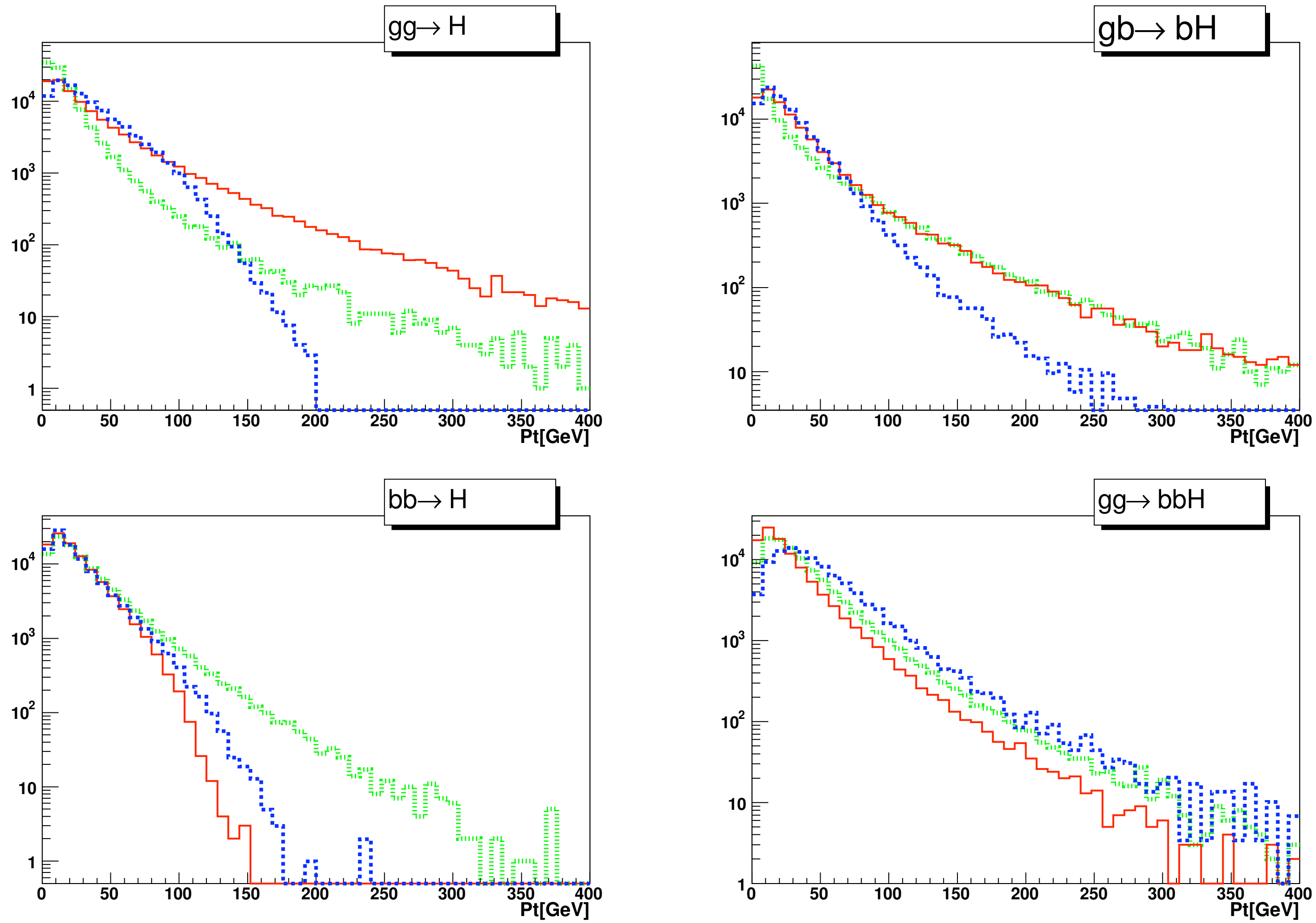


Fig. 1: The transverse momenta of the Higgs boson, p_T^{Higgs} for 3 different shower models for each production mechanism. The red solid line represents PYTHIA, the dashed green line ARIADNE and the dotted blue line HERWIG events. The vertical scale gives the number of events per bin, and a total of 10^5 events have been generated with each program.

Multi-Jet Production and Multi-Scale QCD

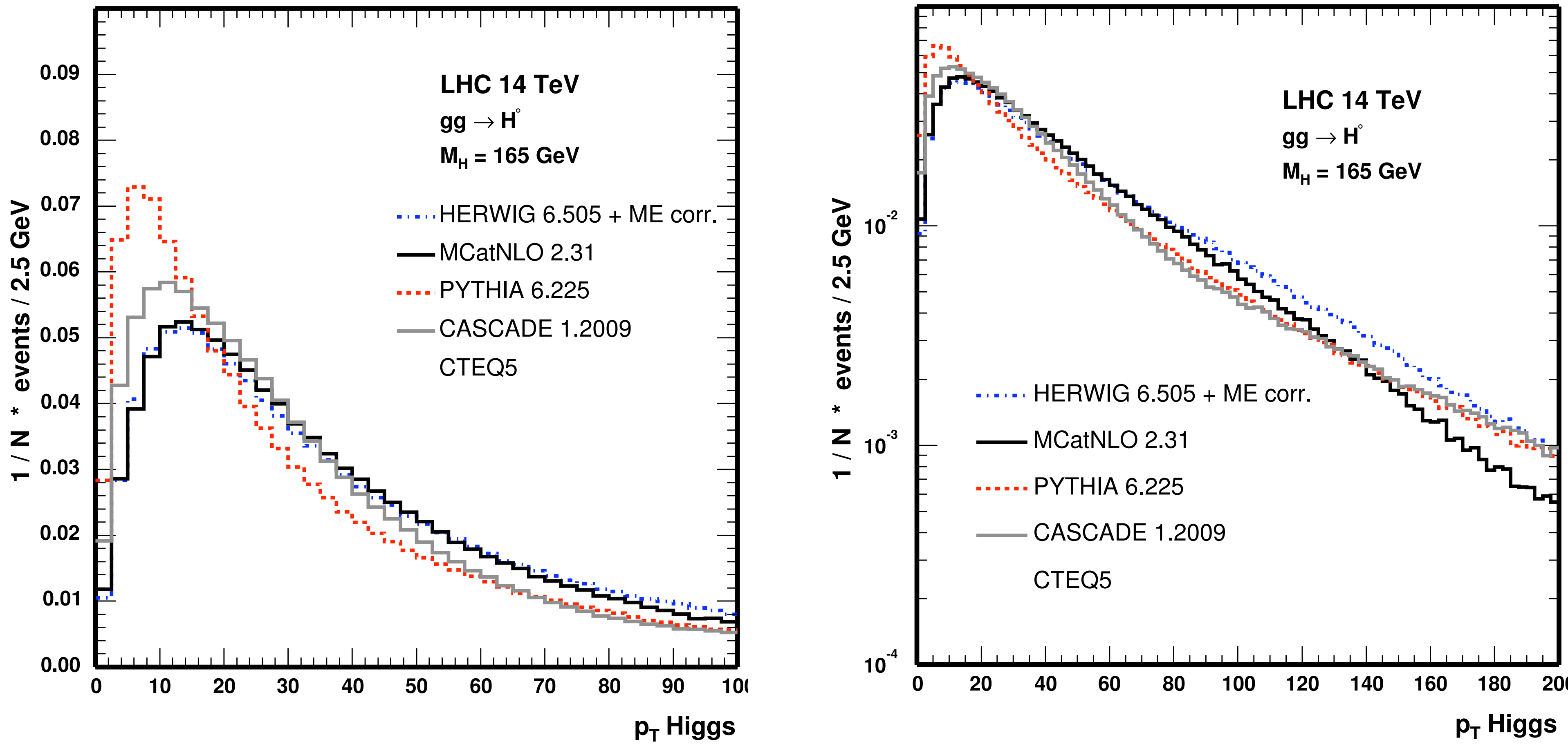
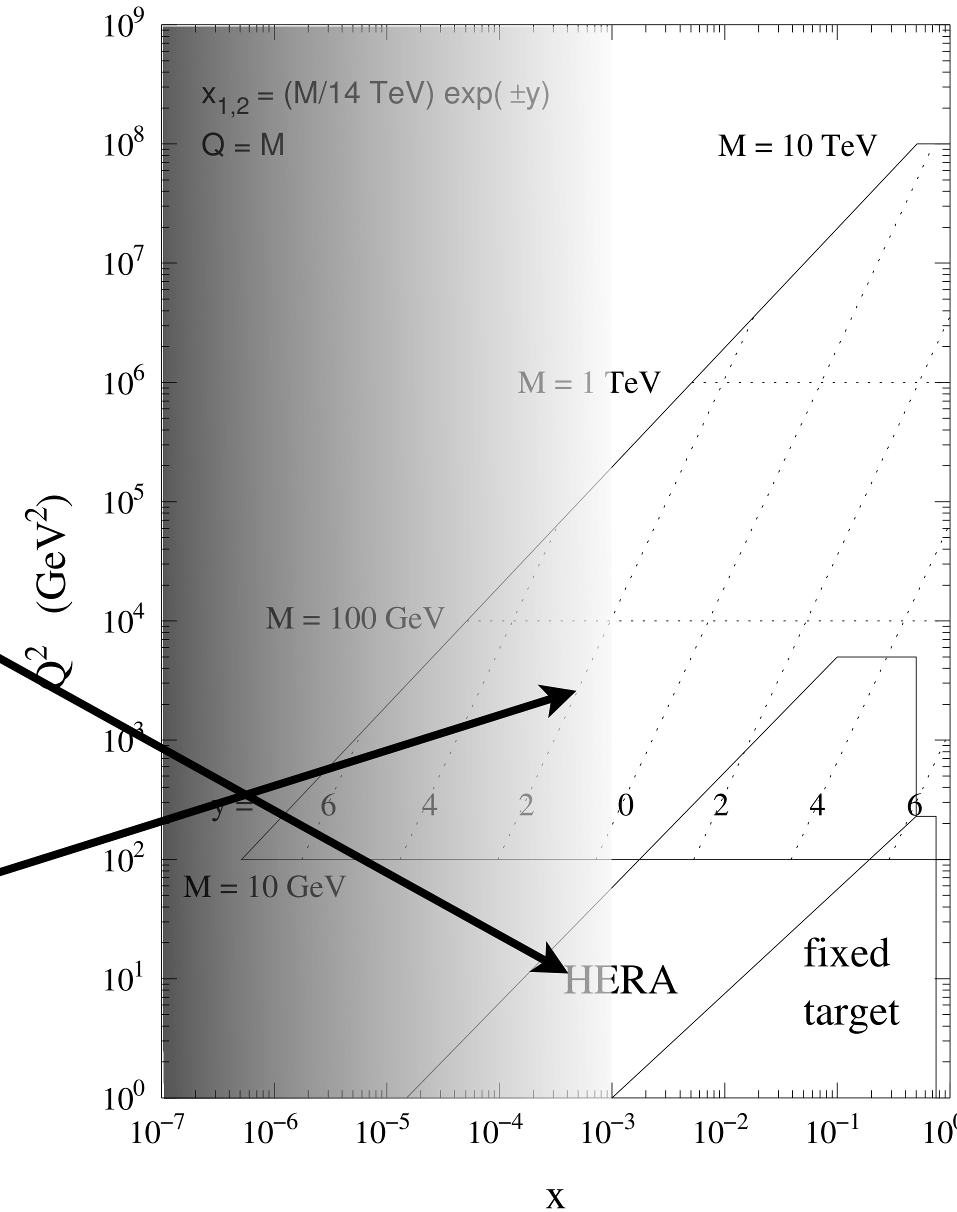


Fig. 7: p_T^{Higgs} Higgs of PYTHIA, HERWIG + ME Corrections, MC@NLO and CASCADE, linear and logarithmic scale.

Low x Summary

Strong evidence of non DGLAP behaviour of the parton evolution at HERA (x < 0.001)

What does this mean for the LHC?



Backup

$$S = \frac{\int_0^{2\pi/3} N_{Dijet}(\Delta\phi^*, x, Q^2)\, d\Delta\phi^*}{\int_0^{\pi} N_{Dijet}(\Delta\phi^*, x, Q^2)\, d\Delta\phi^*}$$

- Data show significant increase towards low x
- Study effect of higher orders:
  - LO predictions [$O(\alpha_s)$]
    - at most 3 jets in final state
    - completely fails to describe data
  - NLO calculations [up to $O(\alpha_s^3)$]
    - 3 or 4 jets in final state
    - reasonable description at large x, Q^2
    - but still too low at small x, Q^2

Luminosity: 21pb^{-1}

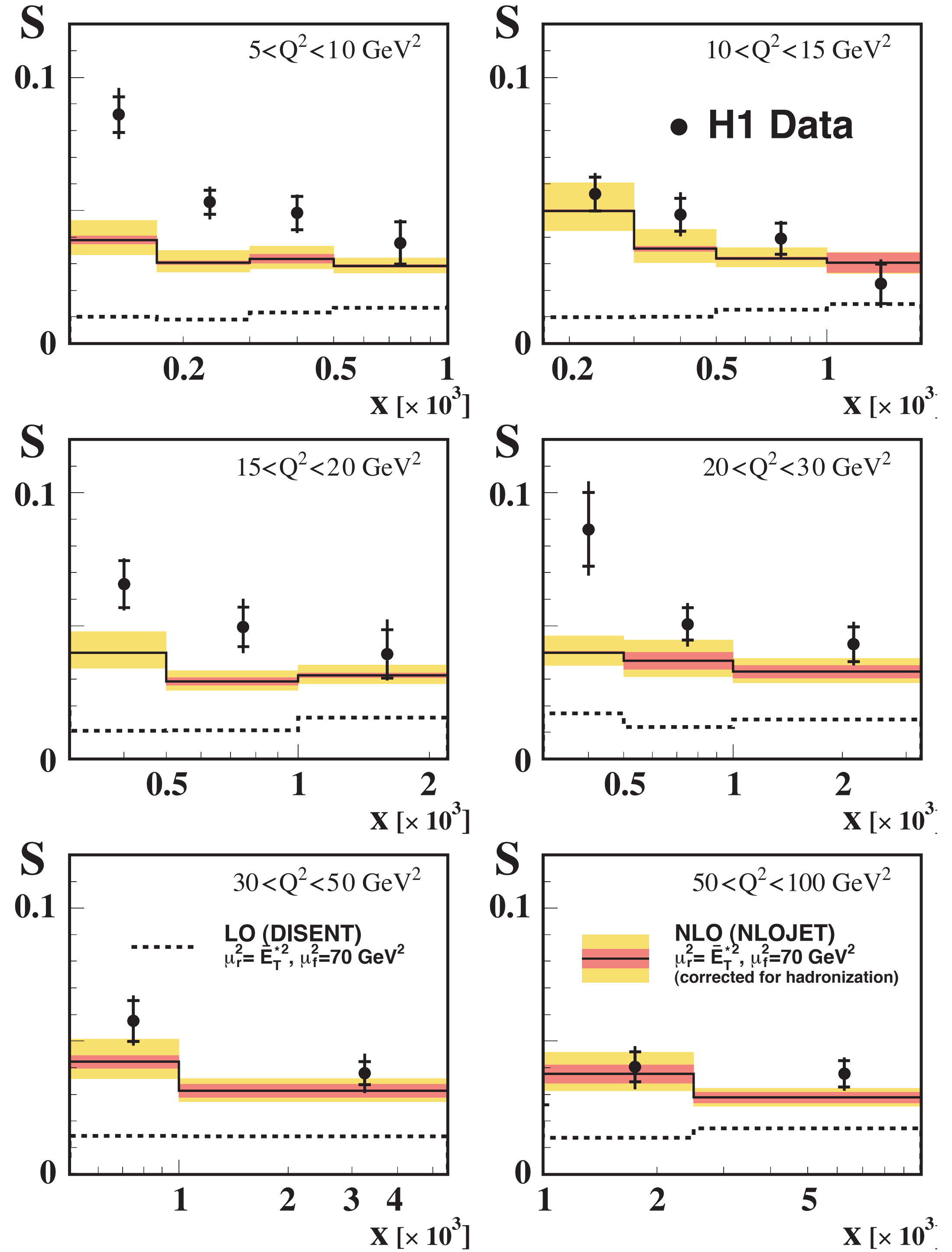
$5 < Q^2 < 100$ GeV^2

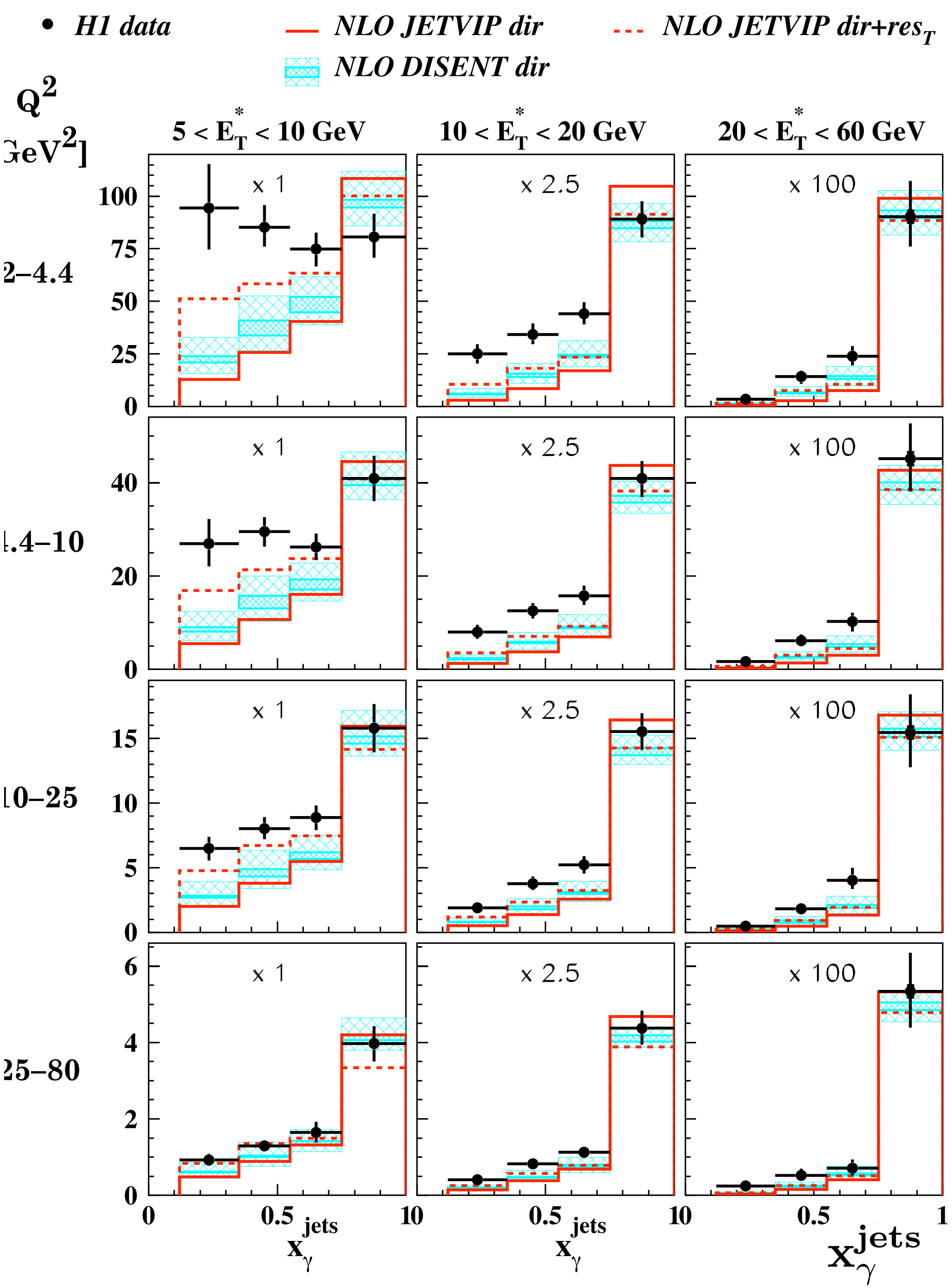
$0.1 < y < 0.7$

$E^*_{T,1} > 7$ GeV

$E^*_{T,2} > 5$ GeV

$-1 < \eta < 2.5$



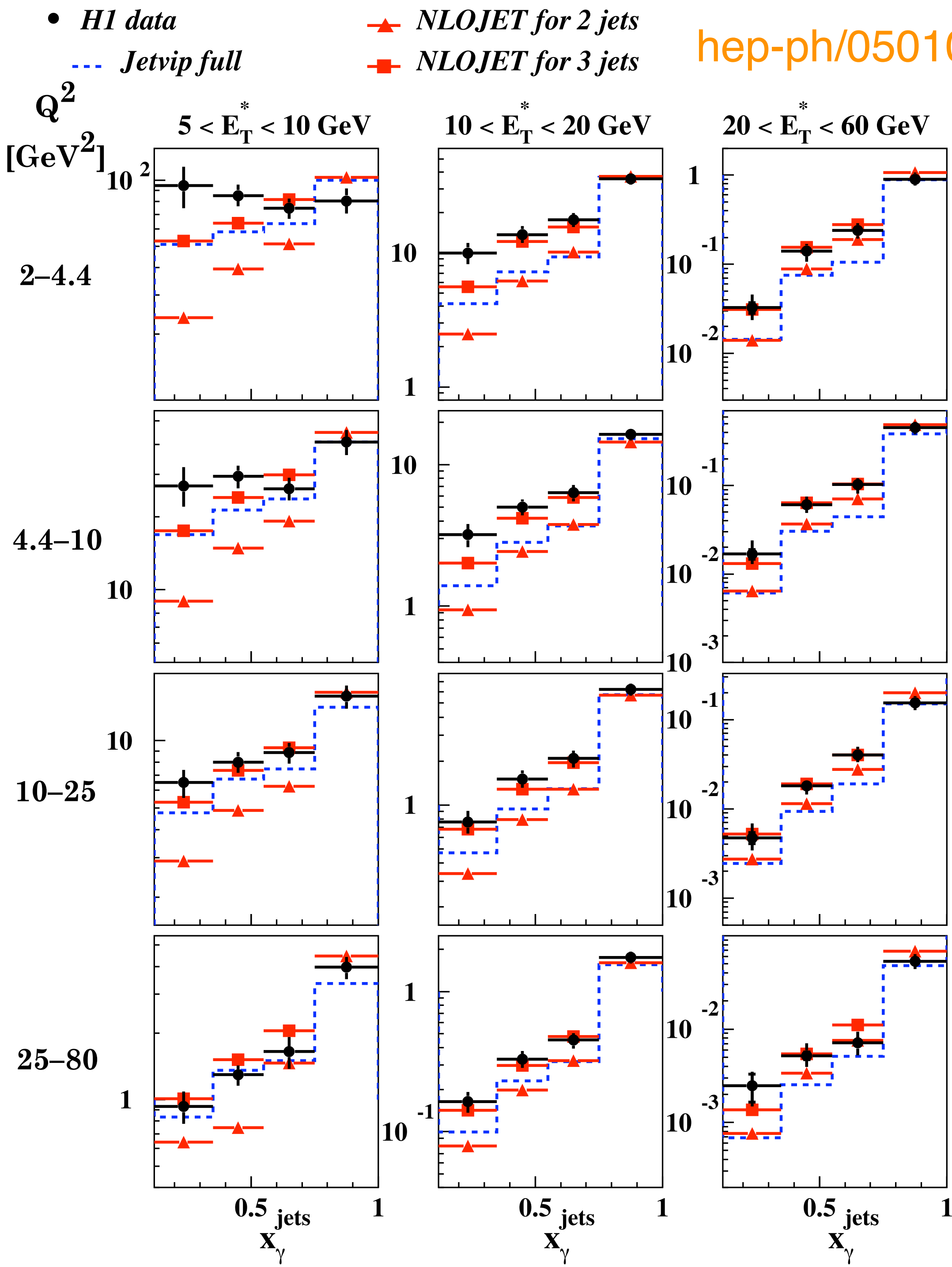


H1 (57 pb^{-1}, 1999-2000)
$\sqrt{s}$ = 318 GeV
2 < Q^2 < 80 GeV^2
0.1 < y < 0.85
E^*_{T1} > 7 GeV E^*_{T2} > 5 GeV
$-2.5 < \eta^*_{1,2} < 0$
longitudinally invariant k_t jet algorithm, $\gamma^* p$ CMS
Eur. Phys. J. C37 (2004) 141-159

- Estimate fraction of photon four momentum carried by parton in hard interaction:

$$x_\gamma^{jets} = \sum_{j=1,2} (E_j^* - p_{z,j}^*) / \sum_{hadrons} (E^* - p_z^*)$$

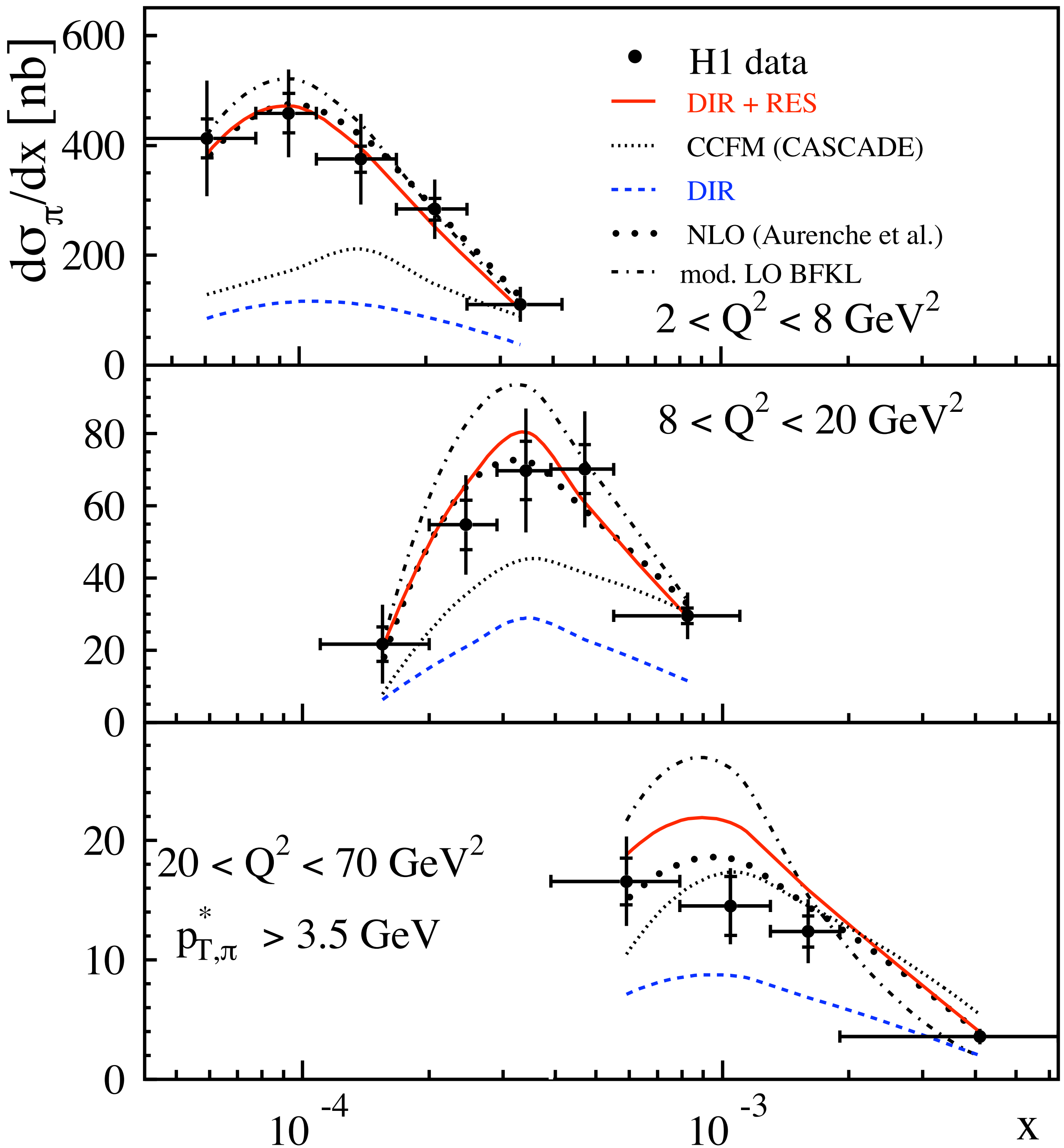
  - direct part ($x^{jets}_\gamma > 0.75$) well described
  - resolved fraction ($x^{jets}_\gamma < 0.75$) increases at smaller Q^2
    - data significantly above NLO calculations when using direct photon only
    - excess decreases with increasing Q^2
- JETVIP including γ^*_T improves description but excess for $x^{jets}_\gamma < 0.75$ remains



hep-ph/0501065

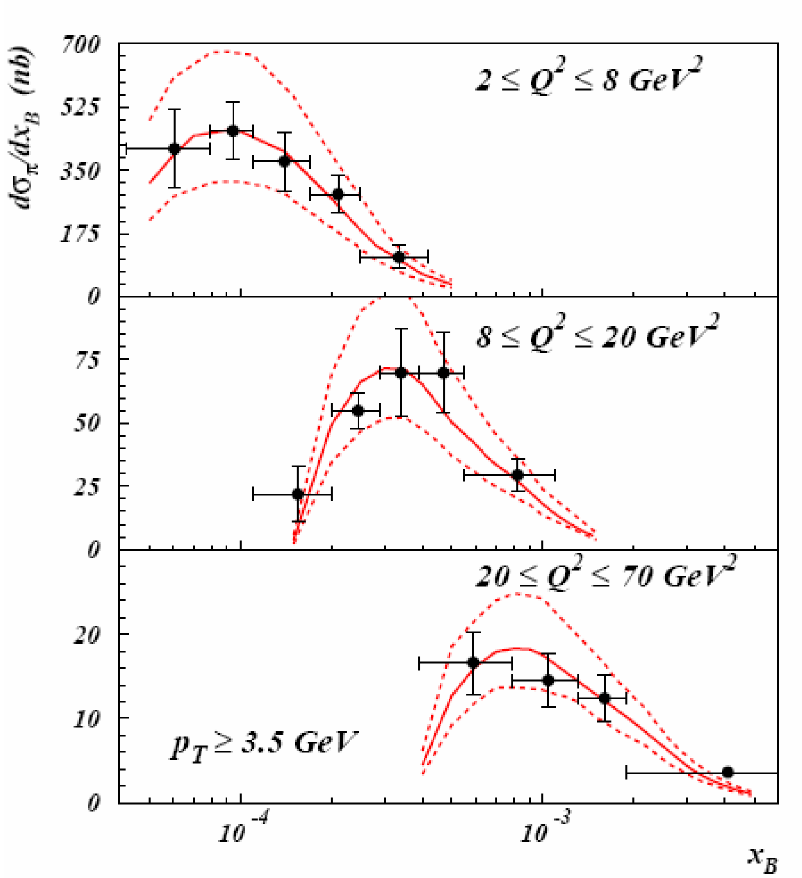
- NLOJET++ results in 3-jet mode significantly closer to data than those of 2-jet mode
  - have to cut out region $x_\gamma \sim 1$
  - no resolved photon
- largest corrections at small x_γ and Q^2
- remaining gap between data and NLOJET++ 3-jet also most pronounced for small x_γ and low Q^2
  - there is need for further higher order QCD corrections

Forward π^0-meson production

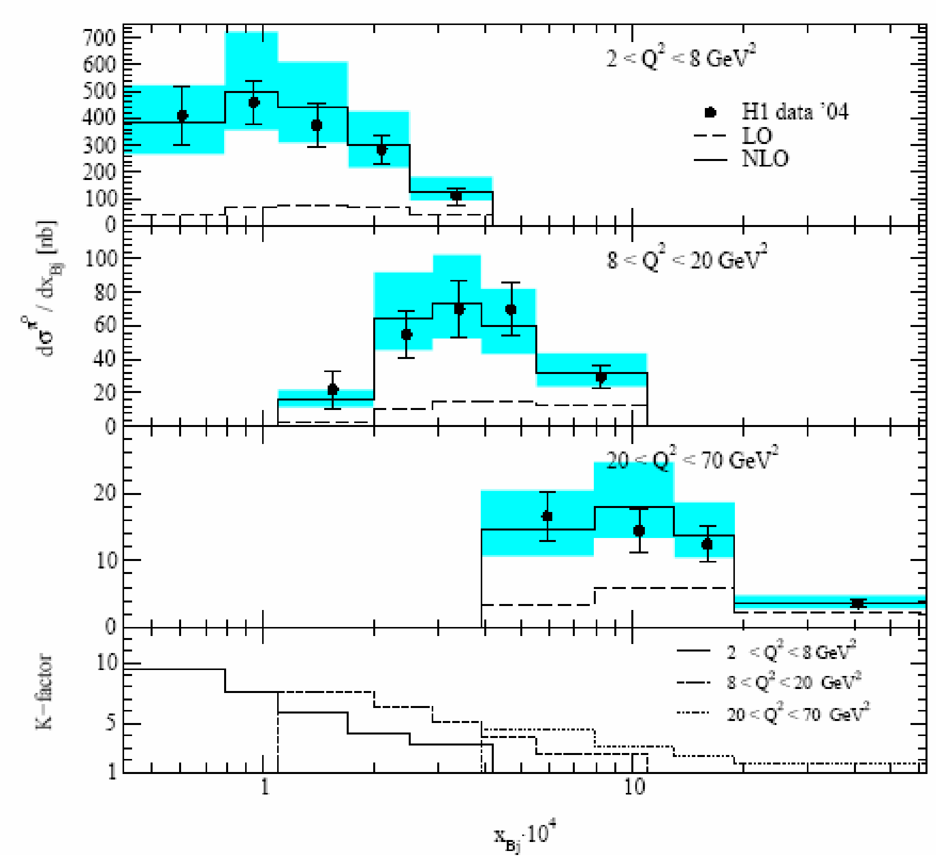


Forward π^0-meson production

Daleo et al.



Kniehl et al.

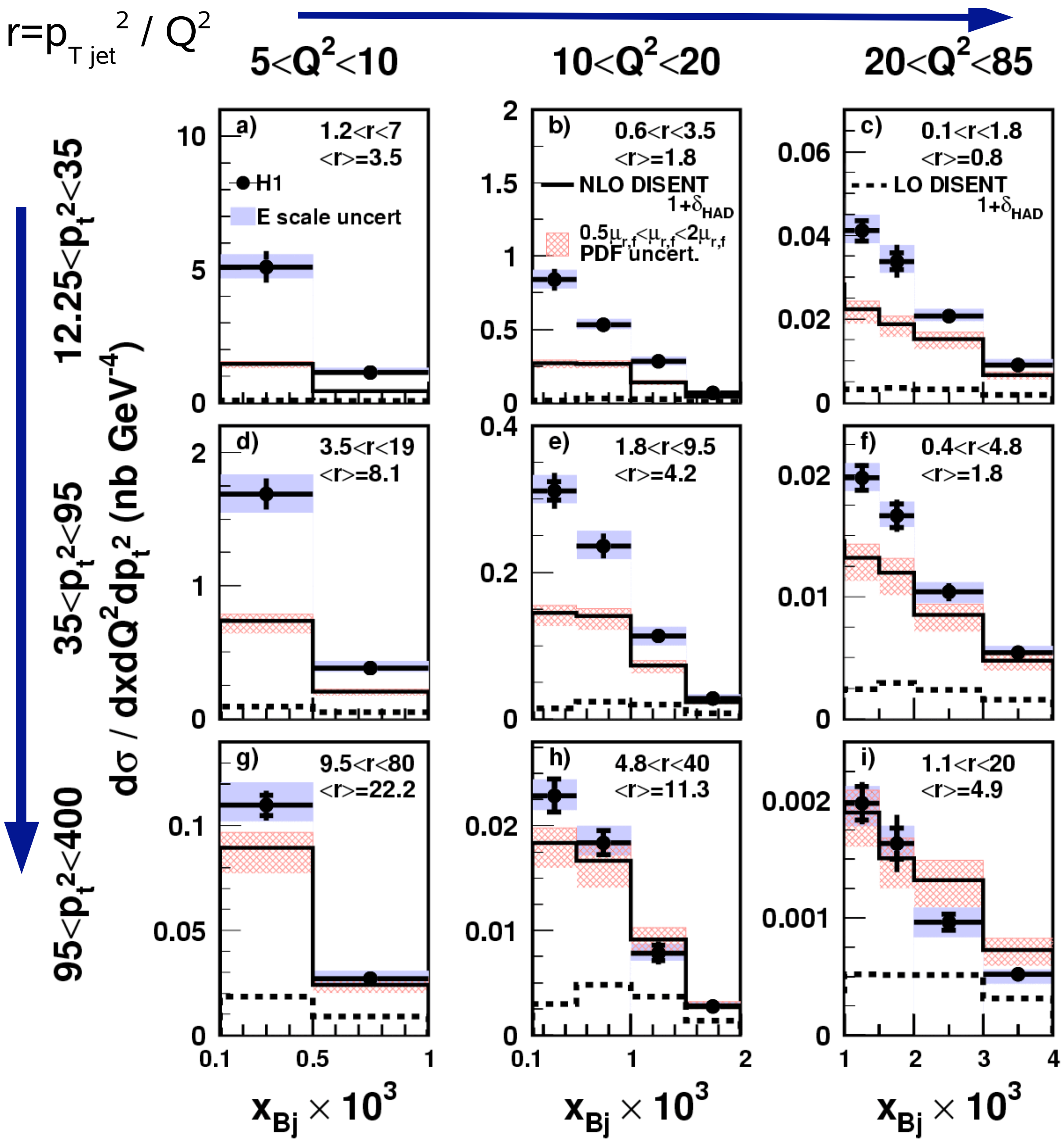


NLO predictions in good agreement with the H1 data

Large K factors and theoretical uncertainties

Need for NNLO analysis

H1 forward jets: triple differential cross section



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

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

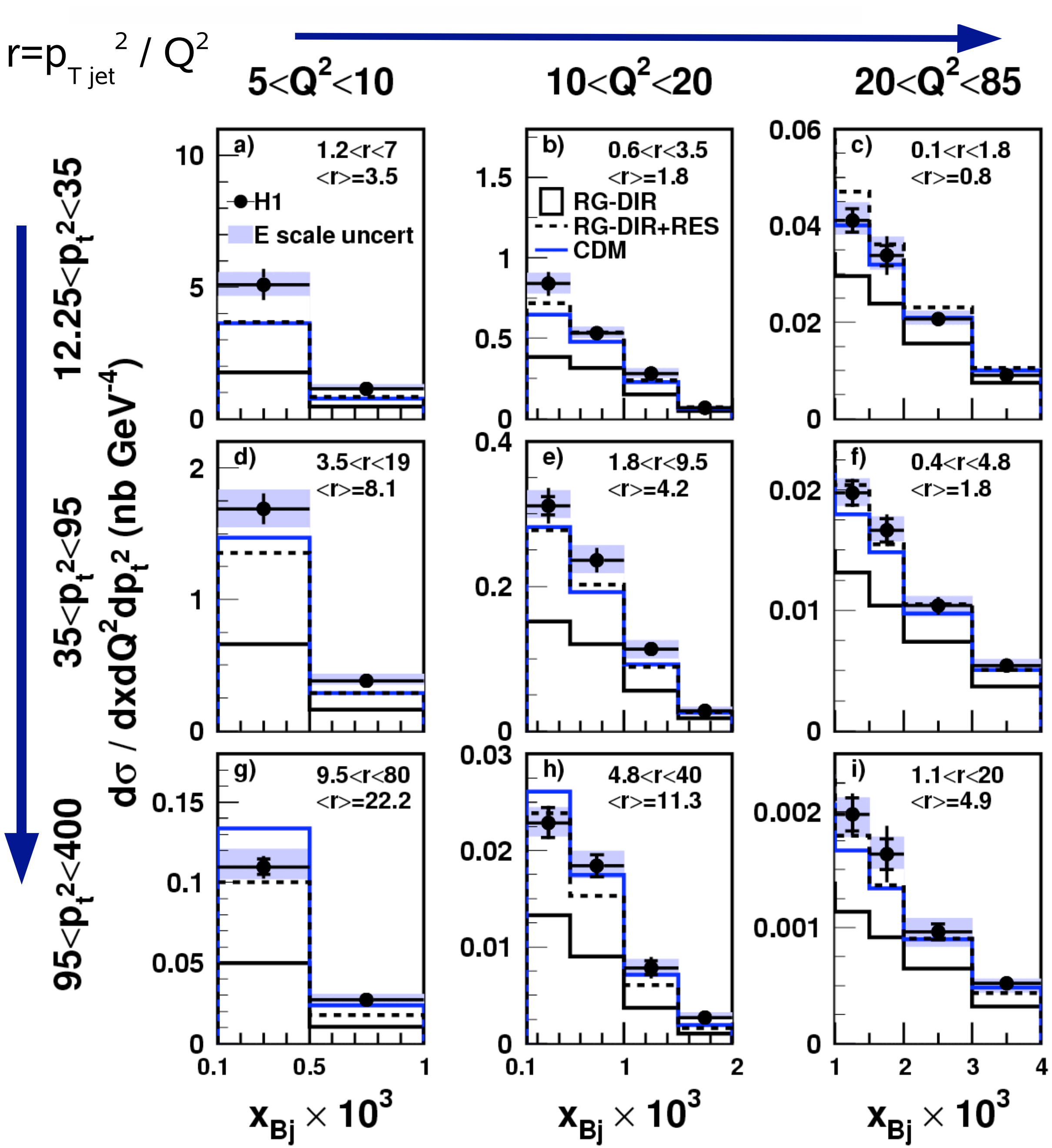
best description: RG-DIR+RES or CDM

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

H1 forward jets: triple differential cross section



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: