Dijets at low x and low Q^2

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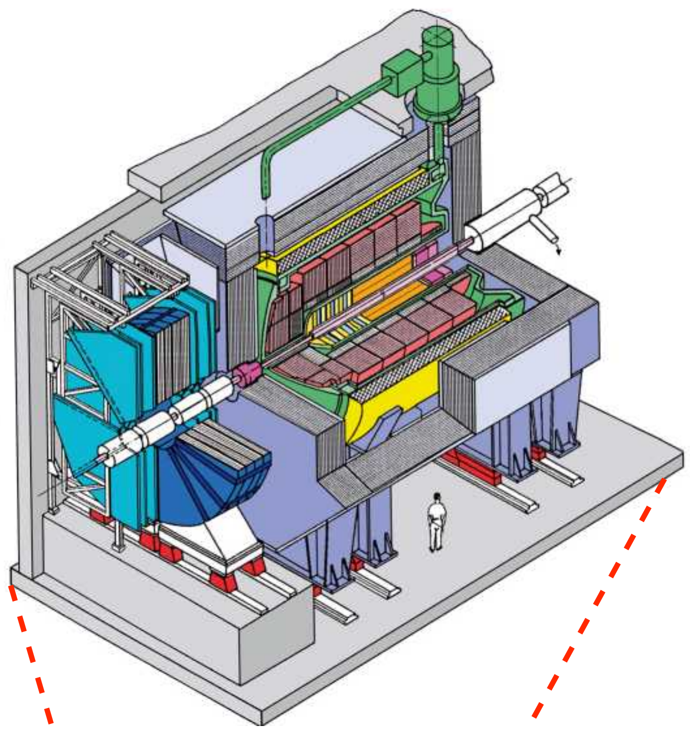
for the H1 Collaboration

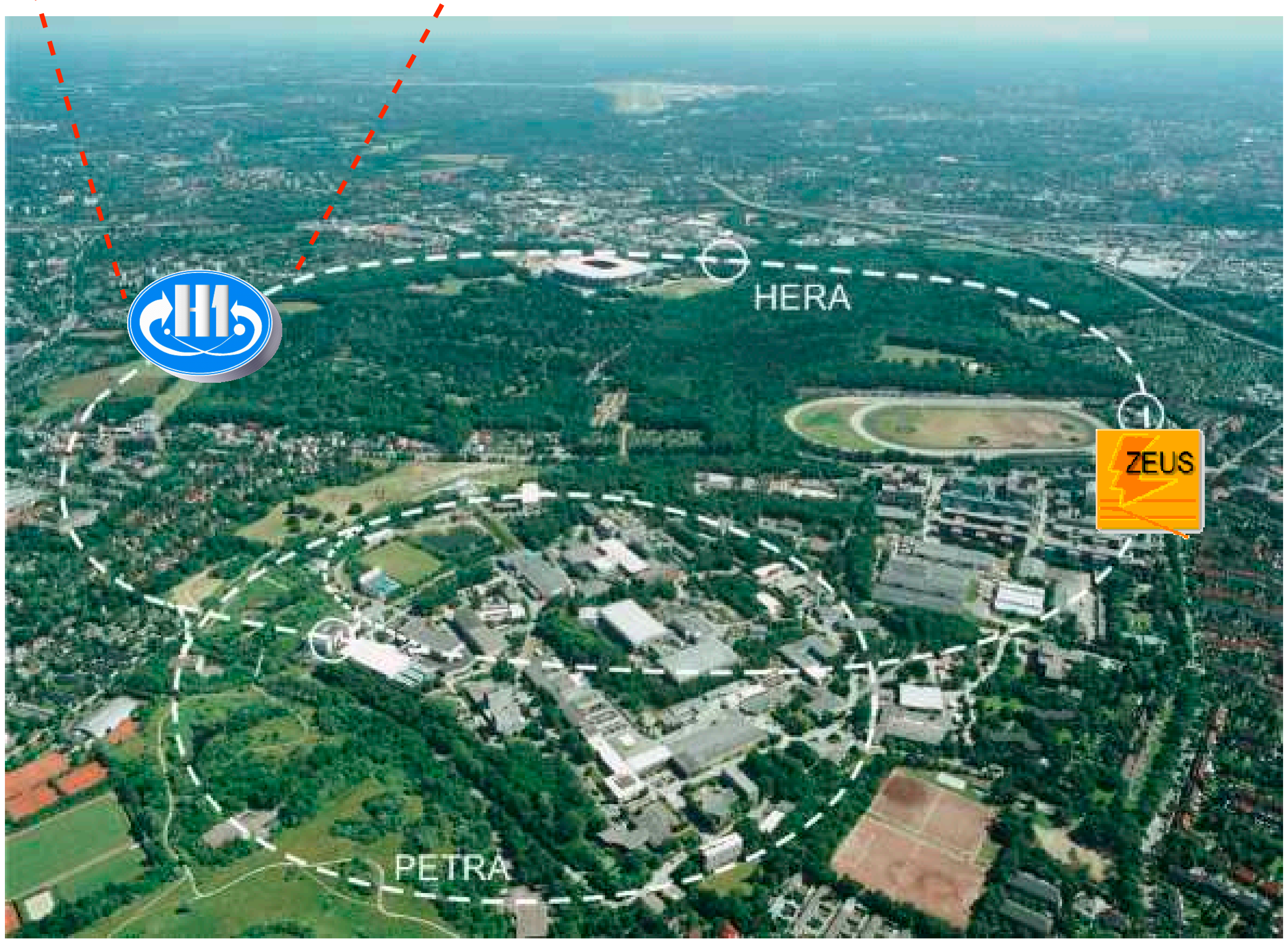
EPS2005, Lisbon Portugal

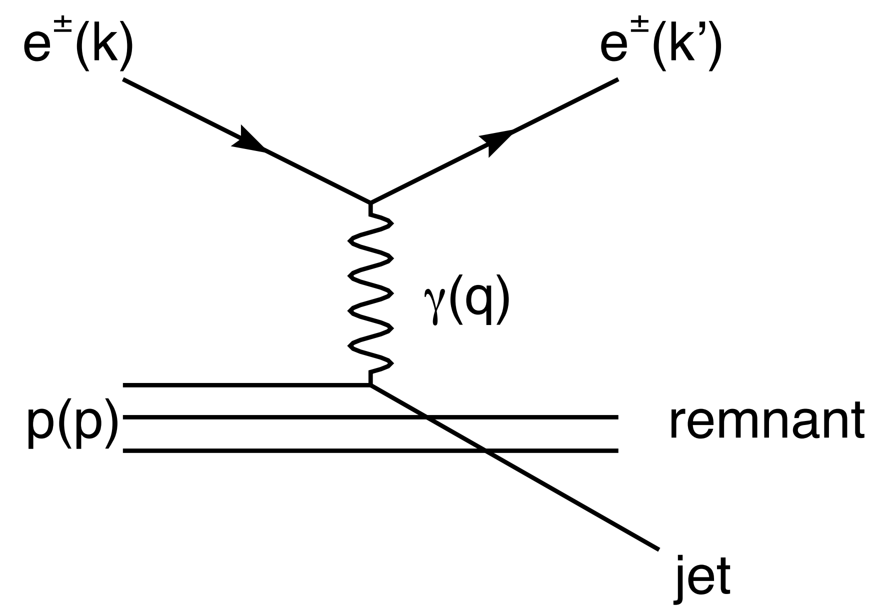
Deep Inelastic Scattering at HERA



27.6 GeV $e^{\pm}$

920 GeV p





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

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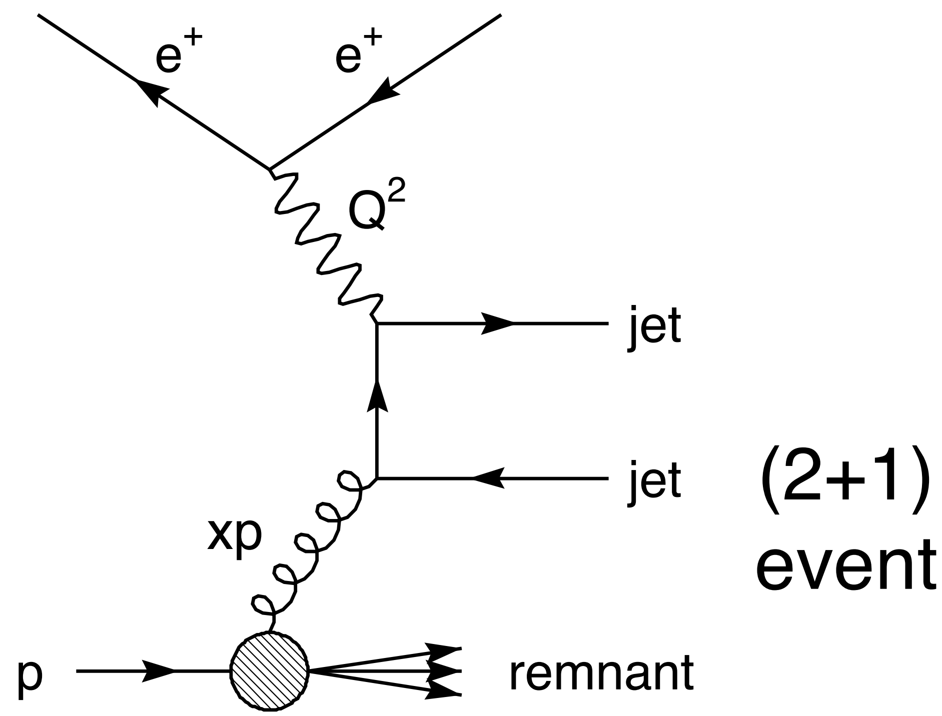
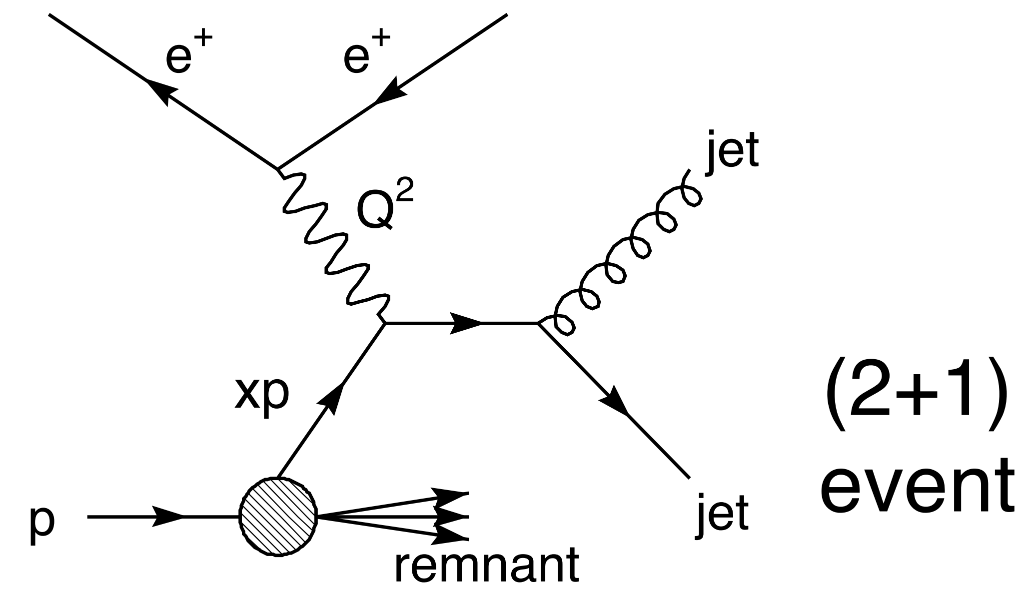
Dijet Production at HERA

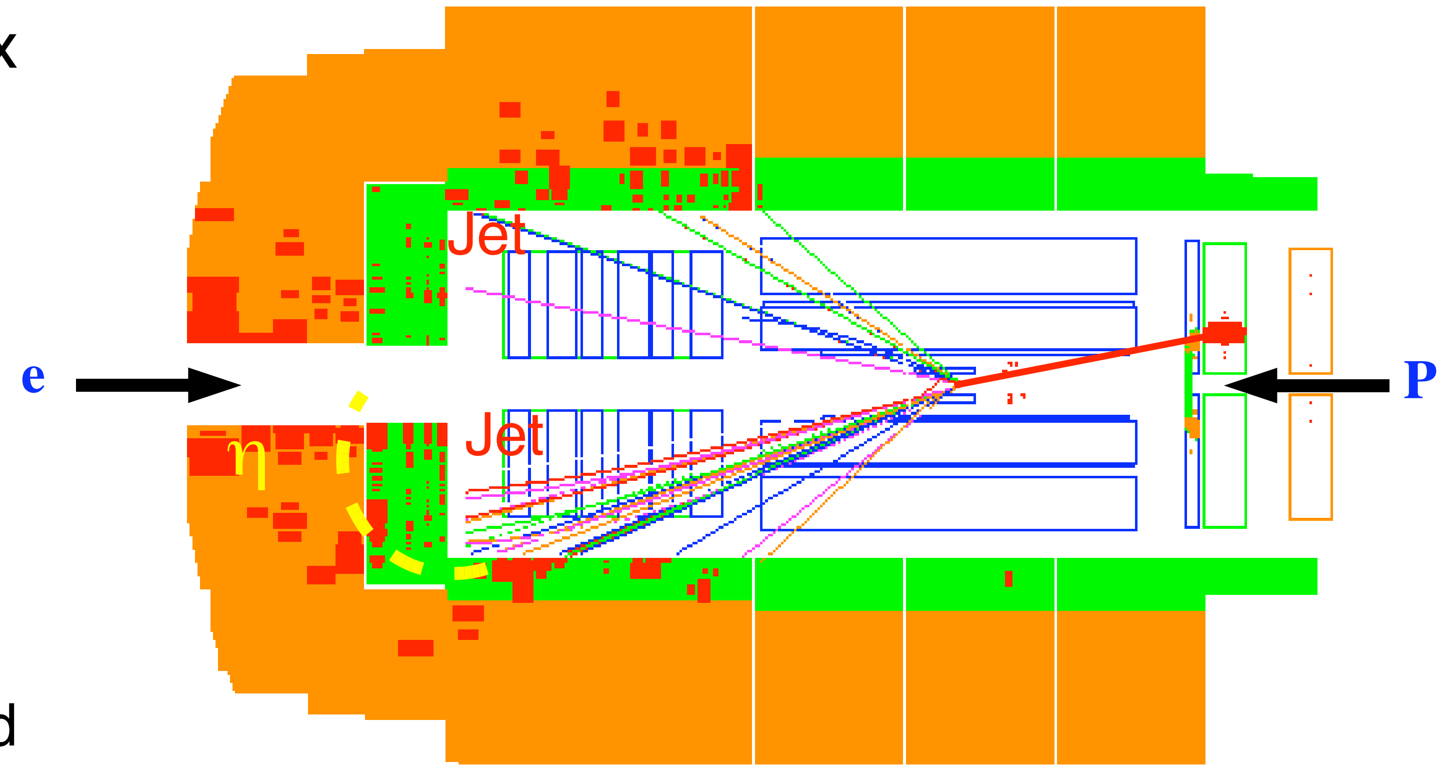
Boson Gluon Fusion



QCD Compton



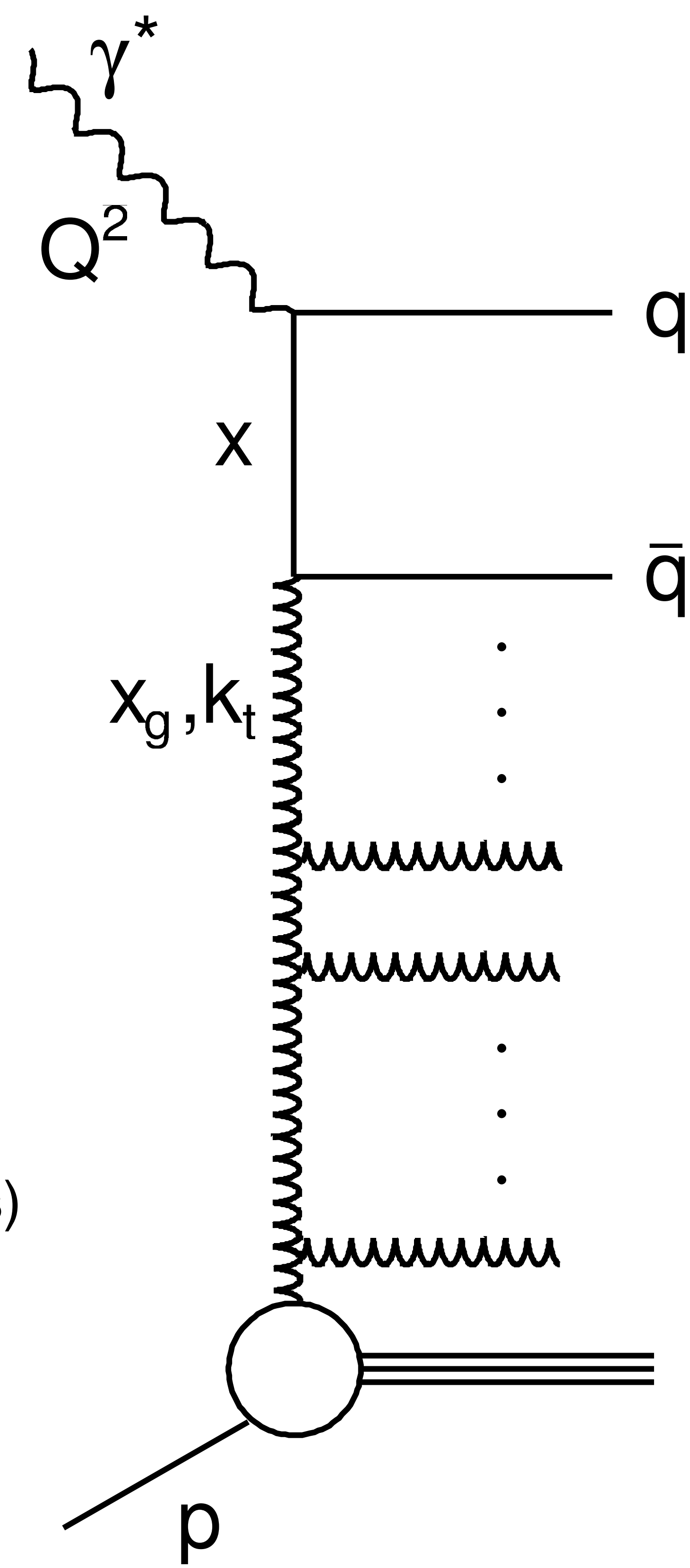
- Boson Gluon Fusion dominates at low x
- Dijet production provides sensitivity to parton distribution & evolution
- Data presented here are at medium Q^2
  - $2 < Q^2 < 100$ GeV^2
  - scattered electron detected in backward calorimeter (SPACAL)



Parton Dynamics in DIS

Different parton evolution schemes exist:

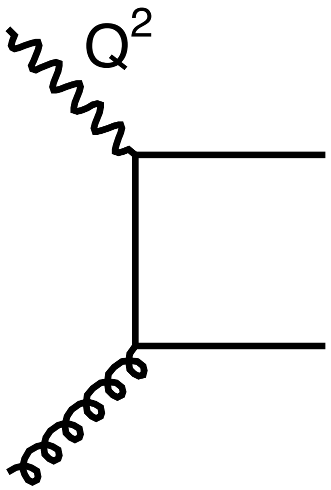
- DGLAP
  - evolution in Q^2 or $k_T{}^2$
  - at small x strong k_T ordering: $\mathbf{k^2_{T,1} \ll \ldots \ll k^2_{T,i} \ll \ldots \ll Q^2}$
  - neglects log(1/x) terms, expected to break down at very low x
- BFKL
  - evolution in x => appropriate at small x
  - no k_T ordering, instead: $\mathbf{x_1 \ll \ldots \ll x_i \ll \ldots \ll x}$
  - successful for forward jets and forward particle production
- CCFM
  - no k_T ordering, instead angular ordering (gluon coherence effects)
    - for small x: CCFM ➔ BFKL
    - for large x: CCFM ➔ DGLAP
  - MC implementation: CASCADE
  - use of unintegrated PDFs



LO and NLO Monte Carlo Programs based on DGLAP

HERWIG

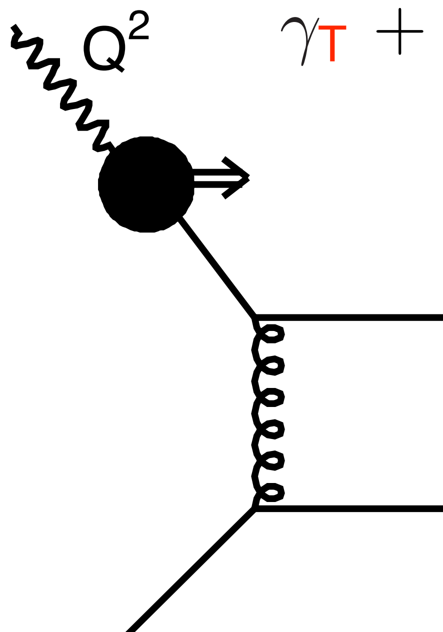
LO direct



+

LO resolved

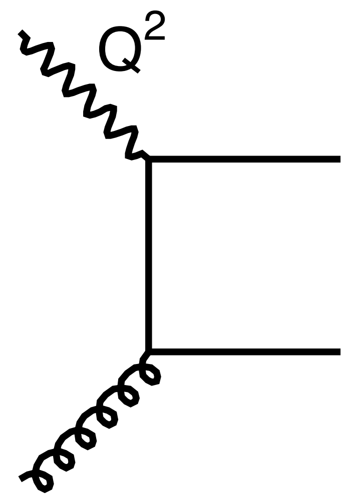
$\gamma_T + \gamma_L$



+ parton showers

RAPGAP

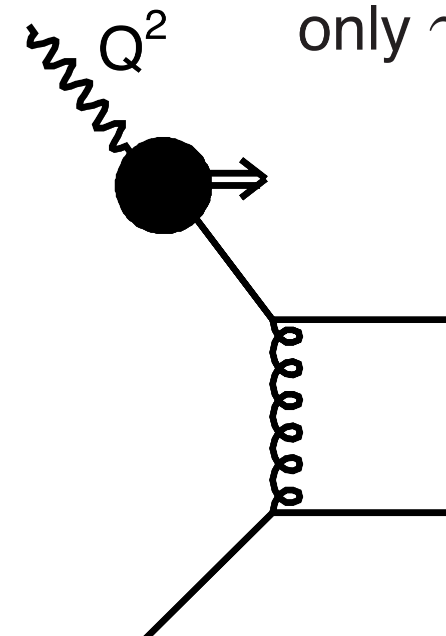
LO direct



+

LO resolved

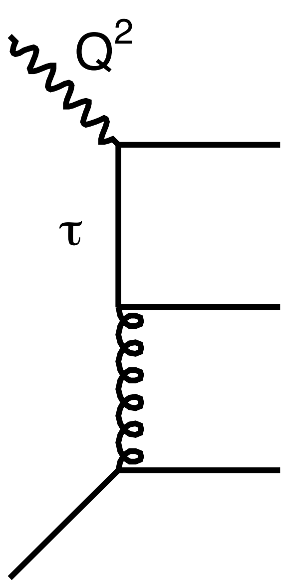
only γ_T



+ parton showers

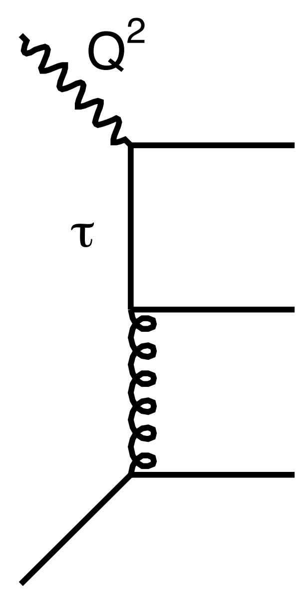
DISENT

NLO direct



JETVIP

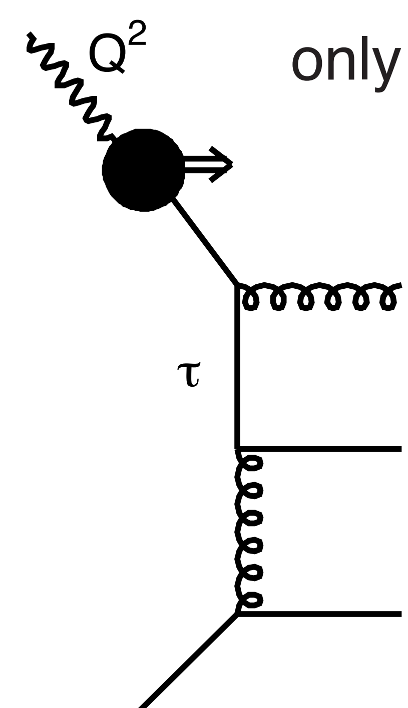
NLO direct



+

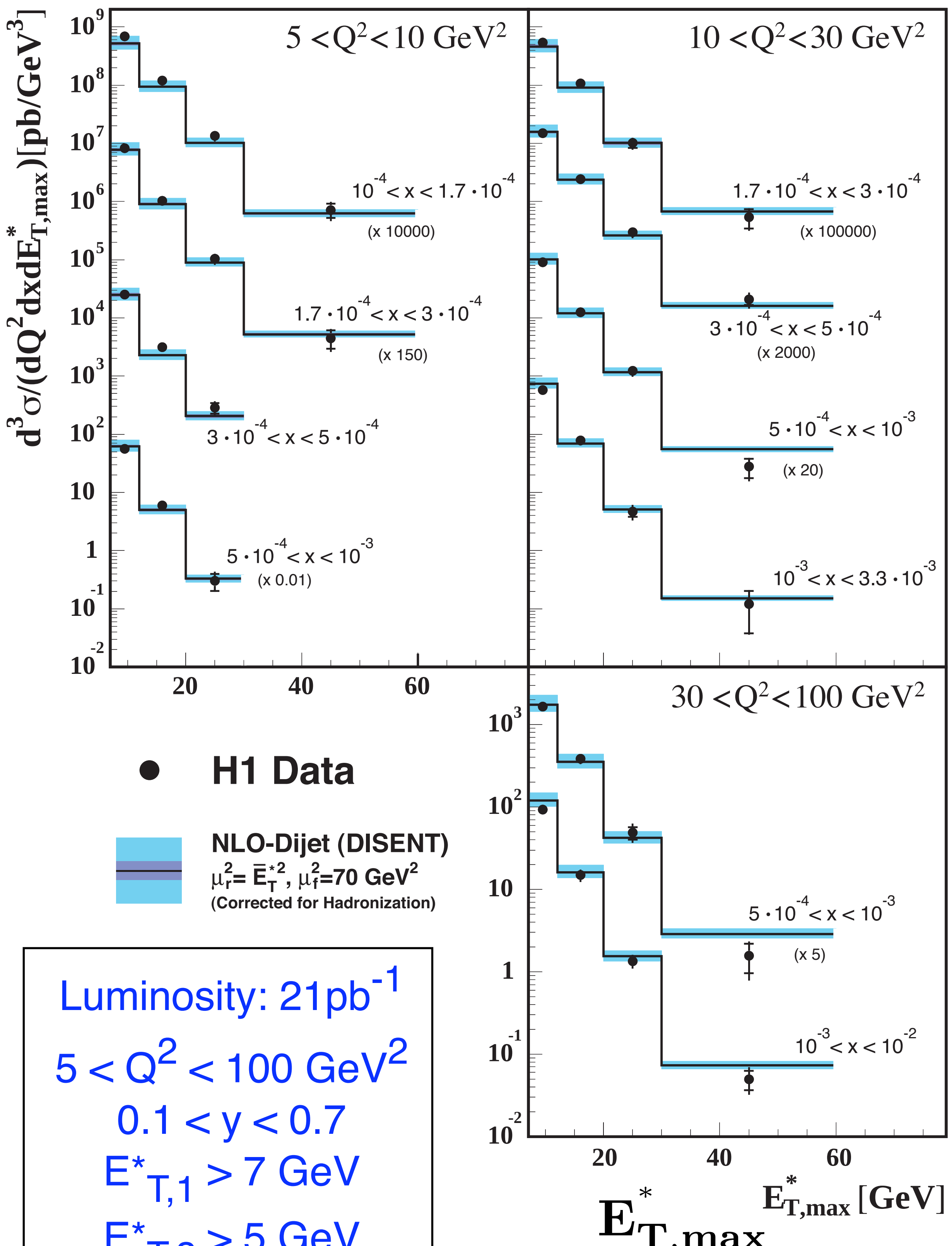
NLO resolved

only γ_T



≈ NNLO direct

Triple Differential Dijet Cross Section



Luminosity: 21pb^{-1}

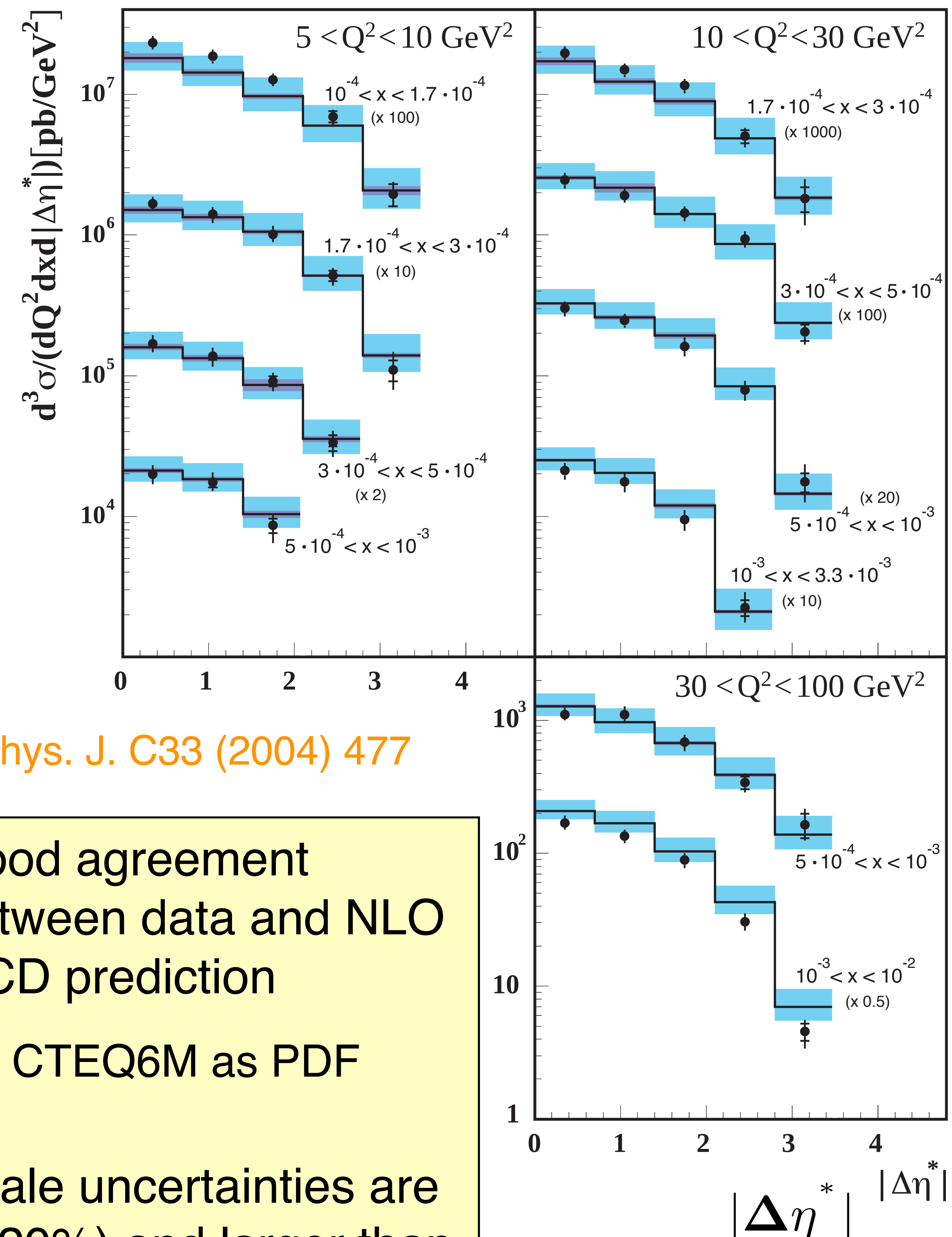
$5 < Q^2 < 100$ GeV^2

$0.1 < y < 0.7$

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

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

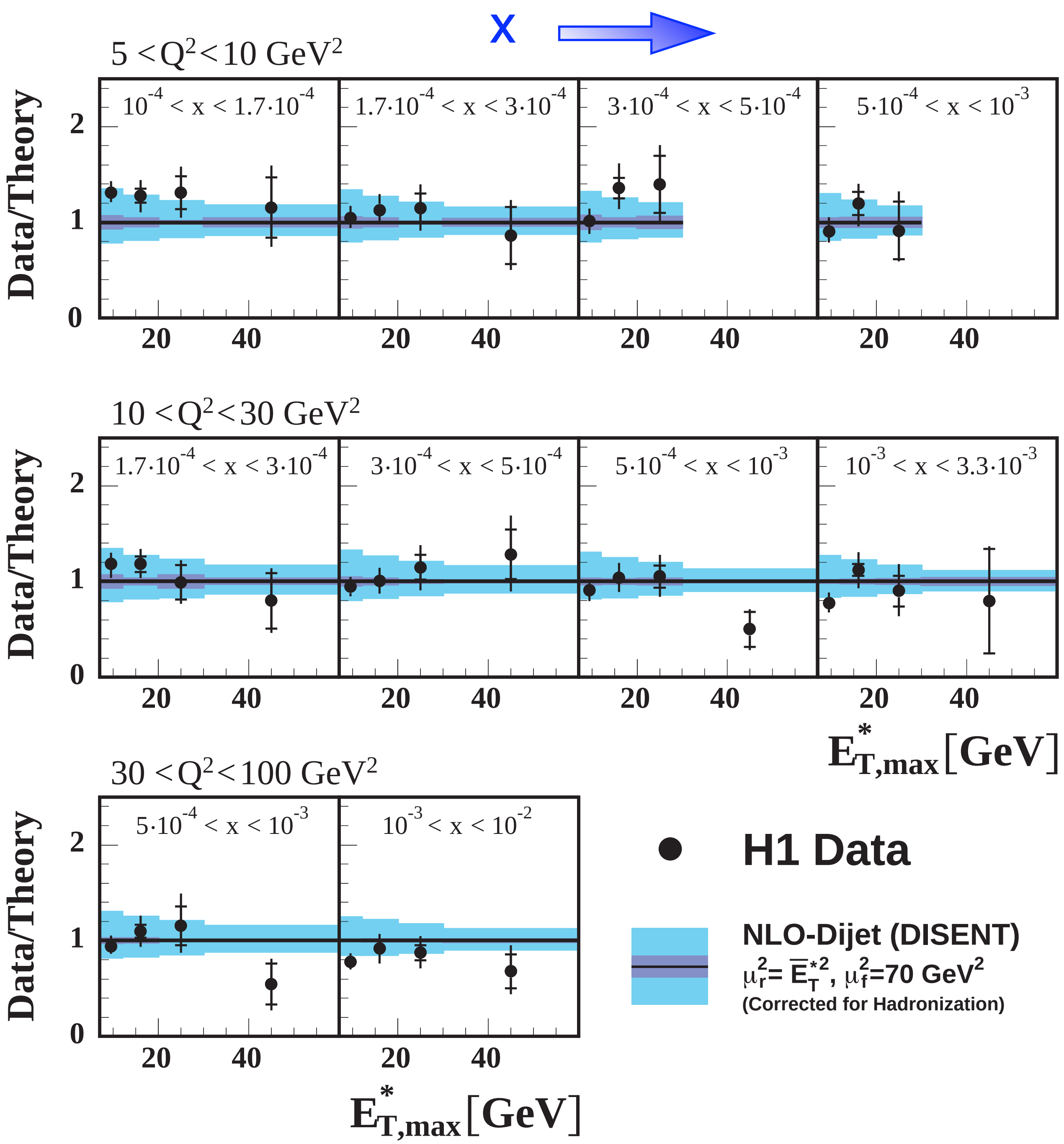
$-1 < \eta < 2.5$

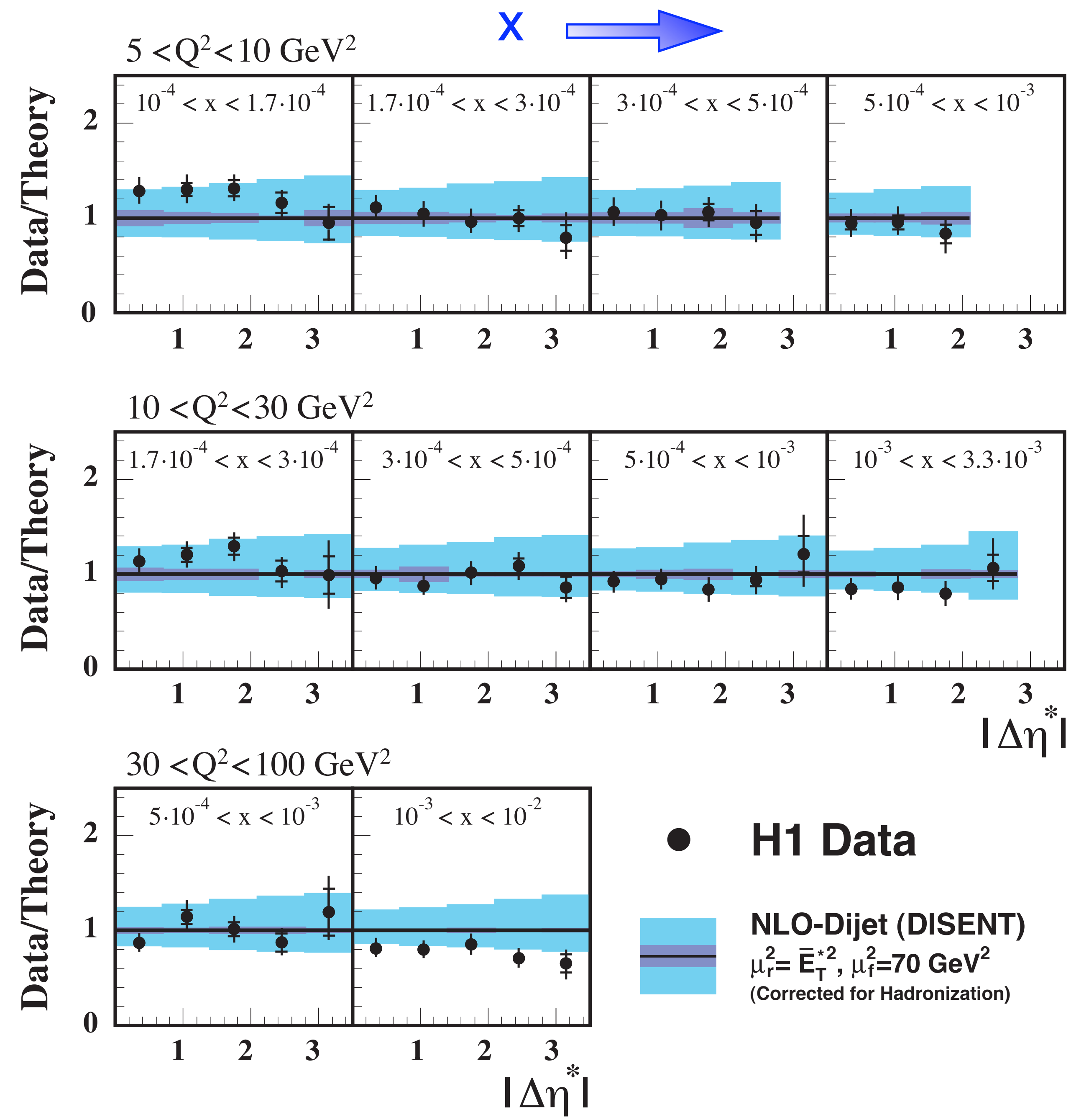


Eur. Phys. J. C33 (2004) 477

- Good agreement between data and NLO QCD prediction
  - CTEQ6M as PDF
- Scale uncertainties are *O*(20%) and larger than experimental error

Data / NLO for Triple Differential Dijet Cross Section





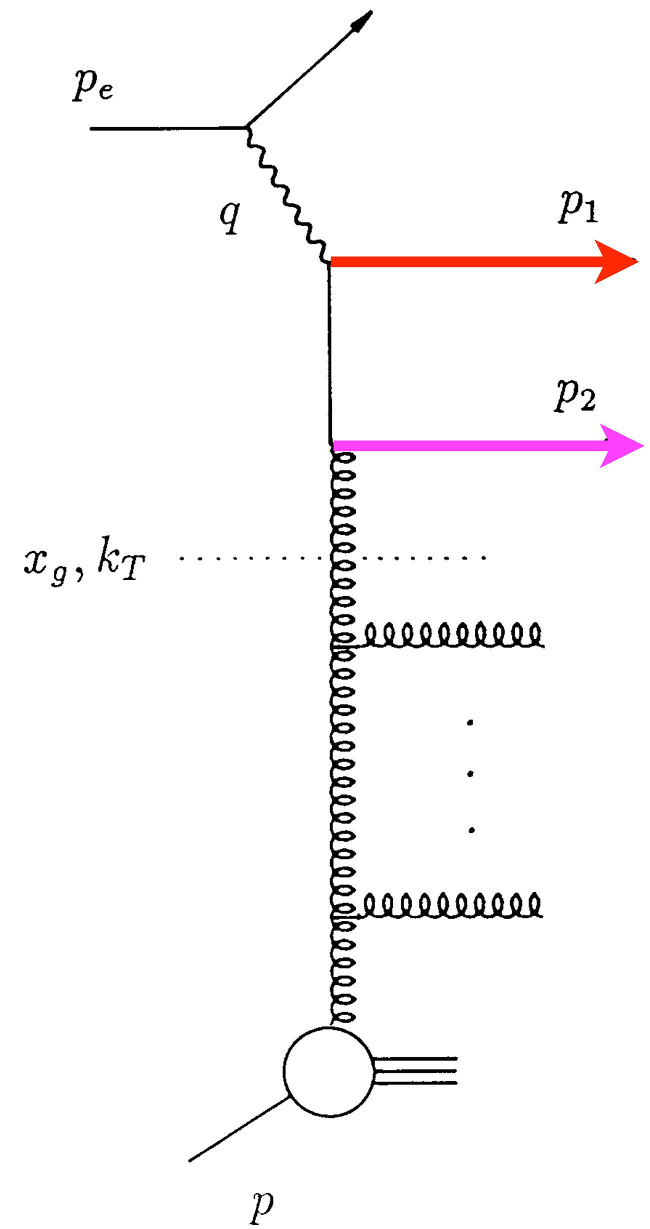
- Effects from low-x dynamics expected to be largest at small $E^*_{T,max}$ and $|\Delta\eta^*|$
- Even in these regions observe good agreement between data and NLO calculations
- To find deviations from DGLAP have to look into more details of final state properties

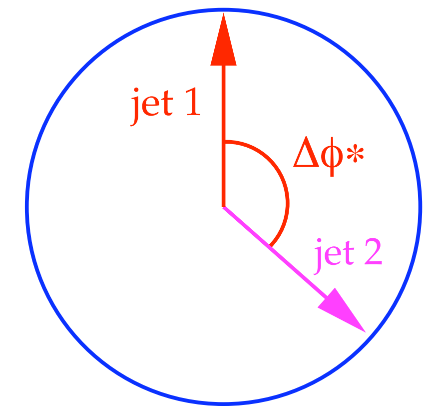
Dijet Azimuthal Separation

- In LO DGLAP jets are in a back-to-back azimuthal configuration ($k_T \approx 0$)
- Deviations can be due to:
  - higher orders in conventional QCD (NLO, NNLO, ...) and/or
  - alternative parton evolution leading to non-zero k_T
- Study fraction of dijet events for which $\Delta\phi^*$ is significantly smaller than π :

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

  - choose $\alpha = 2\pi/3$





$$\vec{k}_T = \vec{p}_{T,1} + \vec{p}_{T,2}$$

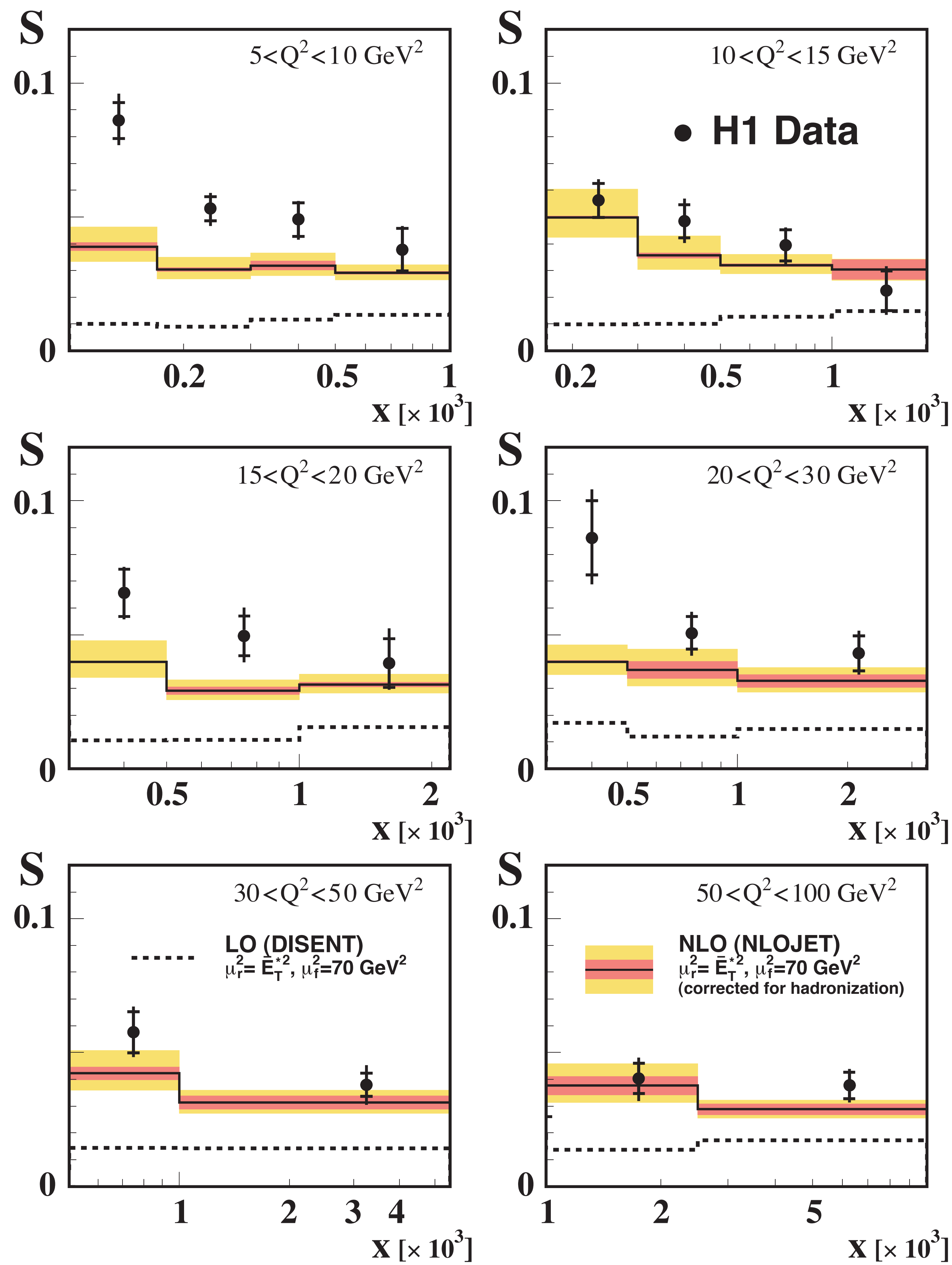
$$k_T^2 = p_{T,1}^2 + p_{T,2}^2 + 2 p_{T,1} p_{T,2} \cos \Delta\phi^*$$

=> for $k_T \approx 0$ jets are ~back-to-back

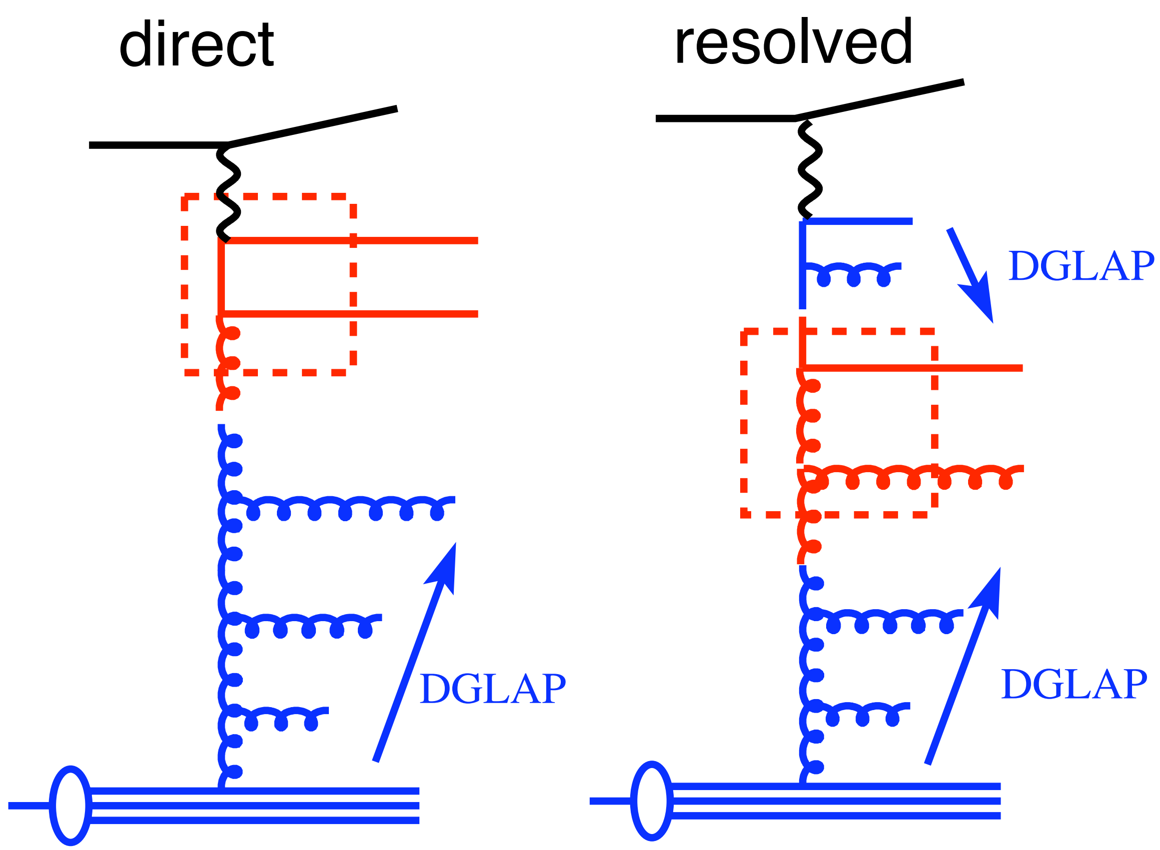
Compare with LO and NLO Calculations

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

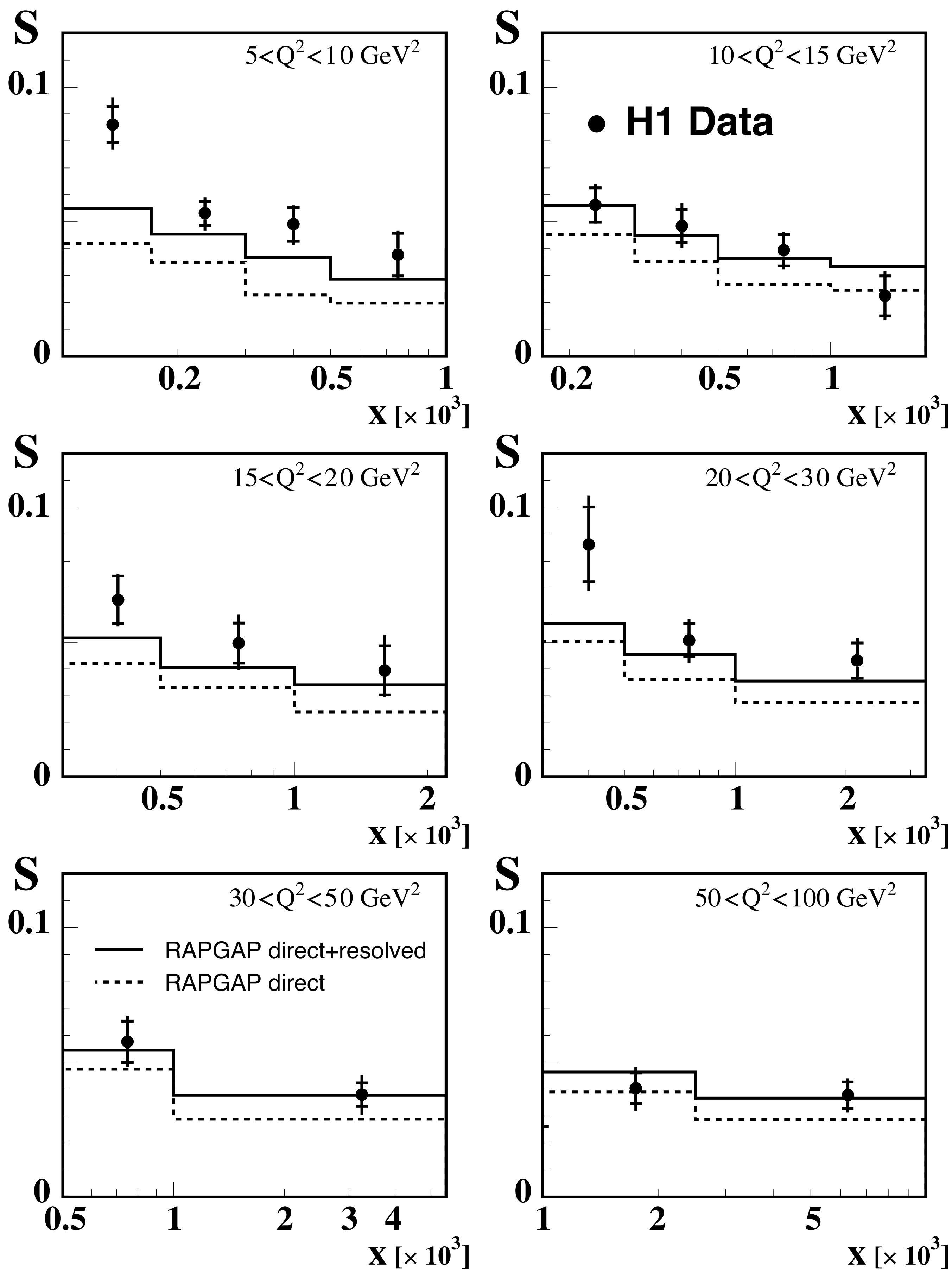
- Data show significant increase towards low x
- Study effect of higher orders:
  - LO predictions [$O(\alpha_s)$]
    - at most 3 jets in final state
    - completely fails to describe data
  - NLO calculations [up to $O(\alpha_s^3)$]
    - 3 or 4 jets in final state
    - reasonable description at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



Influence of Resolved Photon Contribution



- Resolved photon contribution emulates non-k_T-ordered parton emissions
- Description improves but still falls below the data at small x and Q^2



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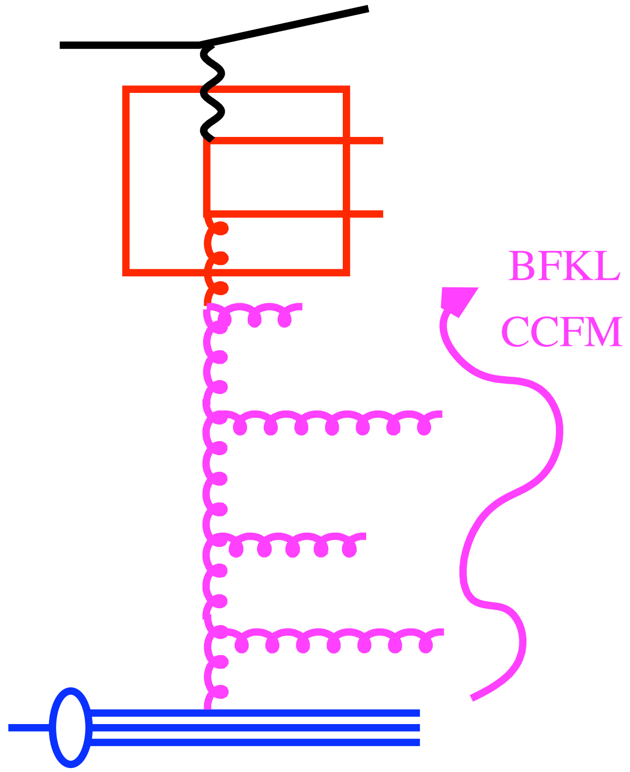
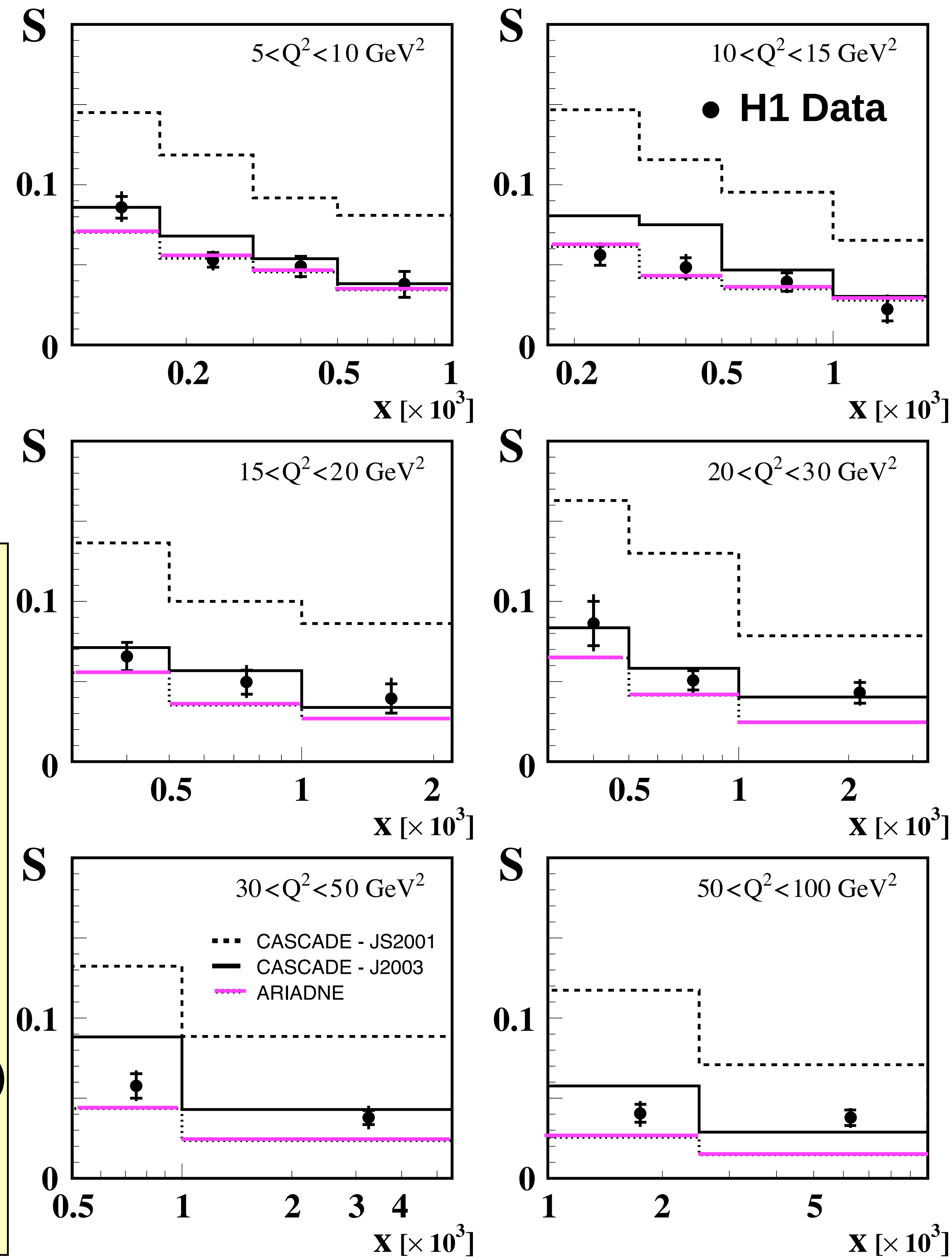
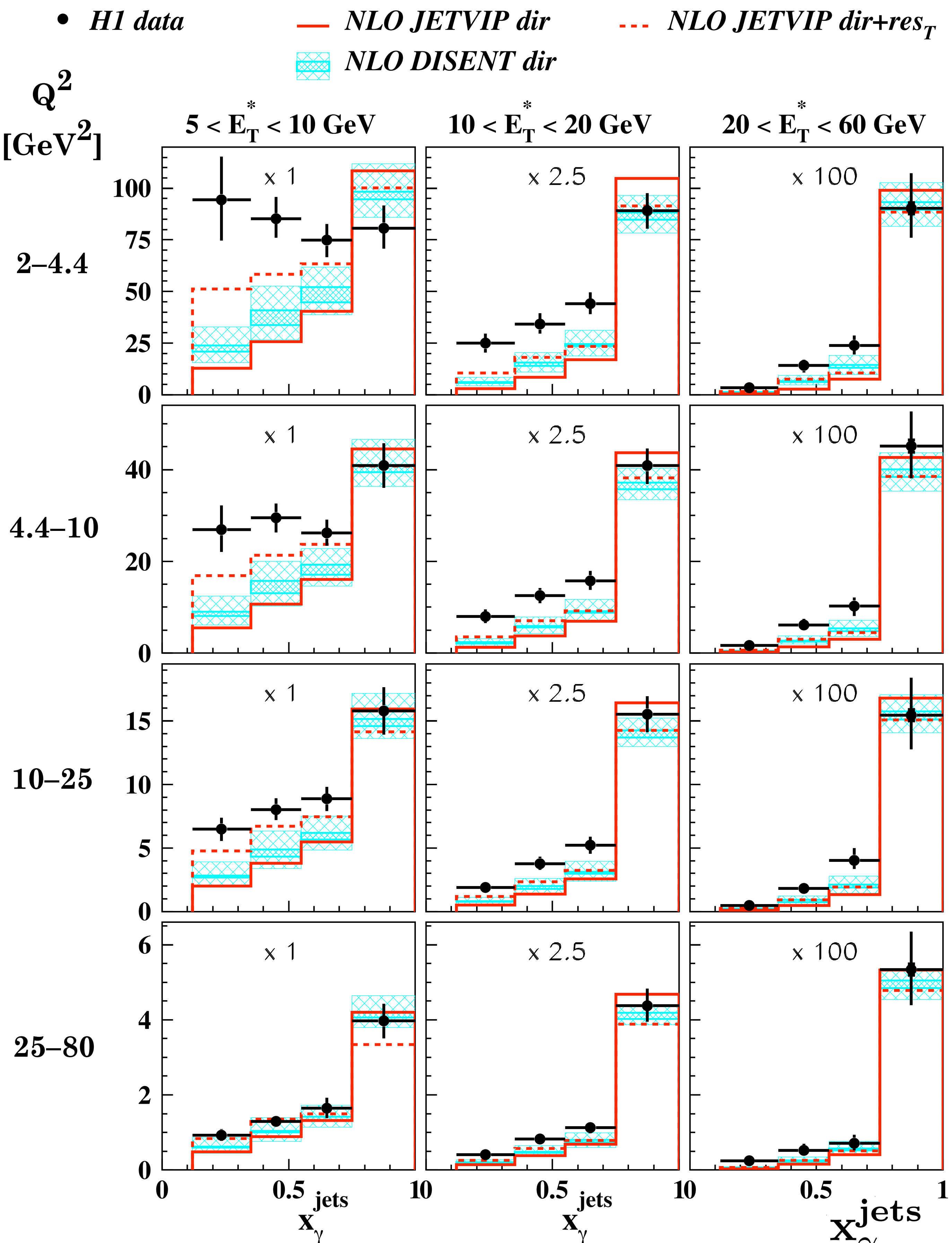
Alternative Parton Evolutions





- CASCADE (CCFM evolution) using unintegrated PDFs decribes data well
- Data provide sensitivity to choice of unintegrated PDF
  - J2003 much better than JS2001
    - JS2001 only singular terms
    - J2003 full splitting function [set 2 shown]
- ARIADNE (Color Dipole Model: ‘BFKL like’) also describes the data at low x, Q^2
  - but systematically too low at larger Q^2

Comparison with NLO Calculations $\mathbf{d^3\sigma_{2jet}/(dQ^2\,dE_T^*\,dx_\gamma^{jets})}$



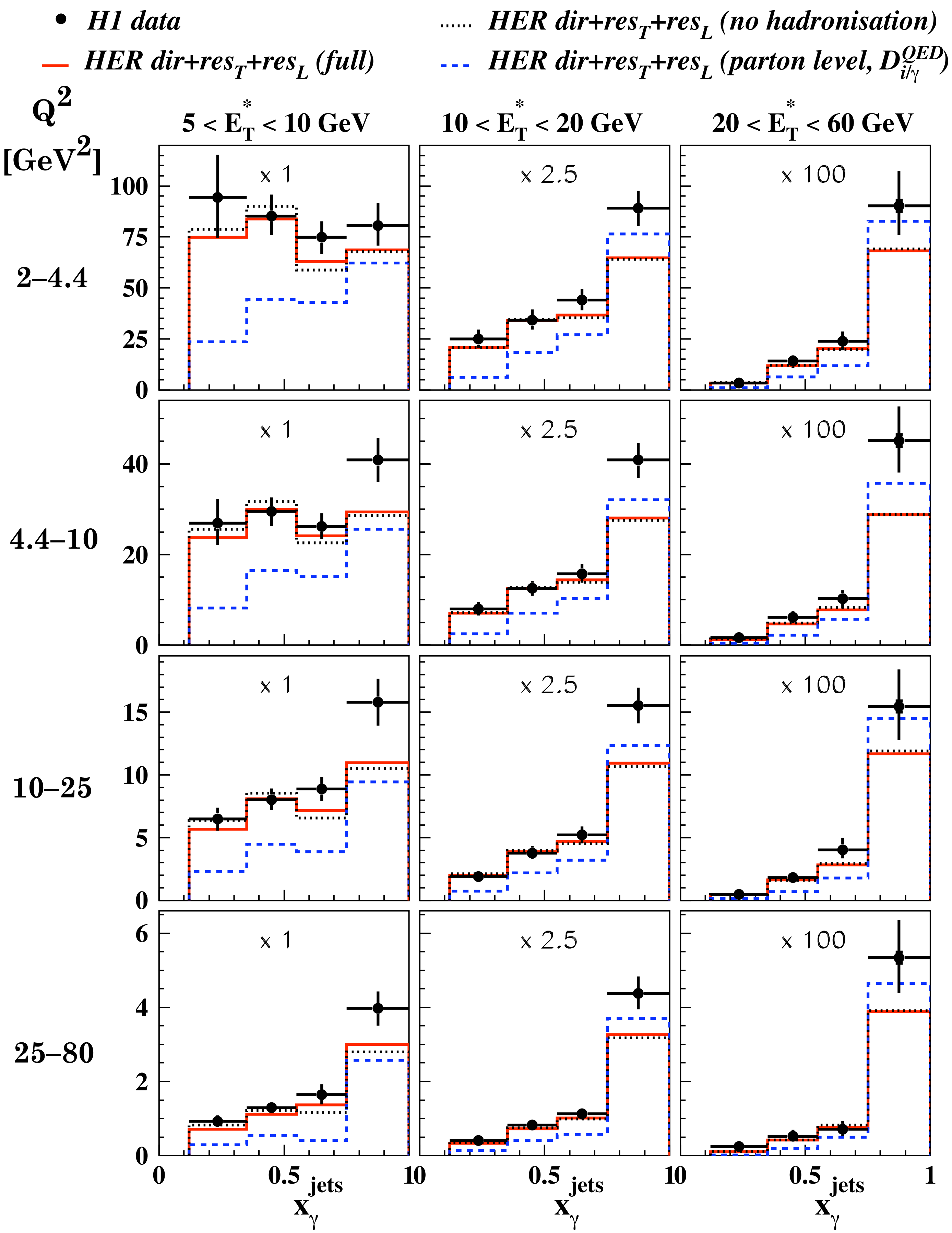
H1 (57 pb^{-1}, 1999-2000)
$\sqrt{s}$ = 318 GeV
2 < Q^2 < 80 GeV^2
0.1 < y < 0.85
E^*_{T1} > 7 GeV E^*_{T2} > 5 GeV
$-2.5 < \eta^*_{1,2} < 0$
longitudinally invariant k_t jet algorithm, γ^*p CMS
Eur. Phys. J. C37 (2004) 141-159

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

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

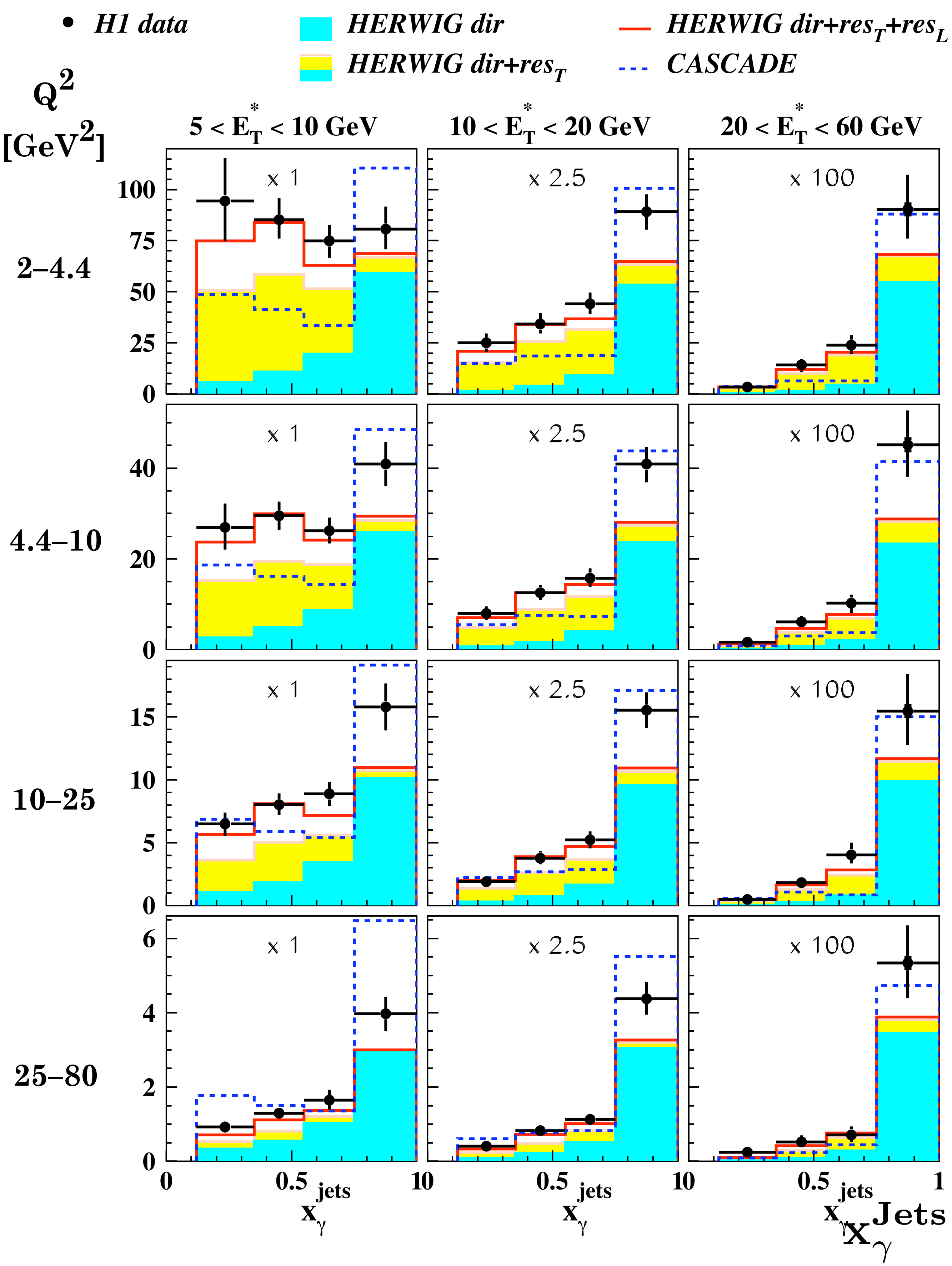
  - direct part ($x^{jets}_\gamma > 0.75$) well described
  - resolved fraction ($x^{jets}_\gamma < 0.75$) increases at smaller Q^2
    - data significantly above NLO calculations when using direct photon only
    - excess decreases with increasing Q^2
- JETVIP including γ^*_T improves description but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

Comparison with LO Monte Carlo including Parton Showers



- Inclusion of QCD parton showers in HERWIG LO Monte Carlo significantly improves description
  - Hadronisation corrections small
- Some deficit remains in region of high x^{jets}_γ
- Best agreement reached when transversly AND longitudinally polarised resolved virtual photons are included (see next slide)

Comparison with Alternative Parton Evolution Schemes



- HERWIG reasonably describes data if transversly and longitudinally polarised resolved photons are included
  - Contribution from resolved photon ladder can be viewed as deviation from k_T - ordering
- CASCADE based on CCFM
  - non-k_T -ordered parton emissions
  - although no explicit virtual photon structure is included can generate sizable contribution at $x^{jets}_\gamma < 0.75$
  - main trends of data described
  - large sensitivity to choice of unintegrated PDF [J2003 set 1 shown]

Summary

- Dijet production very sensitive tool to study properties of parton distributions and evolution at small x
- HERA data at medium Q^2 [$2<Q^2<100$ GeV^2] used to measure triple differential cross sections
  - Eur. Phys. J. C33 (2004) 477
  - Eur. Phys. J. C37 (2004) 14
- Established clear evidence for effects that go beyond the fixed-order NLO QCD calculations
  - NLO calculations do not provide satisfactory agreement at small Q^2, E_T, x_γ
- LO Monte Carlo predictions give reasonable description if
  - supplemented with parton showers
  - transversly and longitudinally polarised resolved photon contribution are included
- CASCADE (based on CCFM) qualitatively describes main features of data

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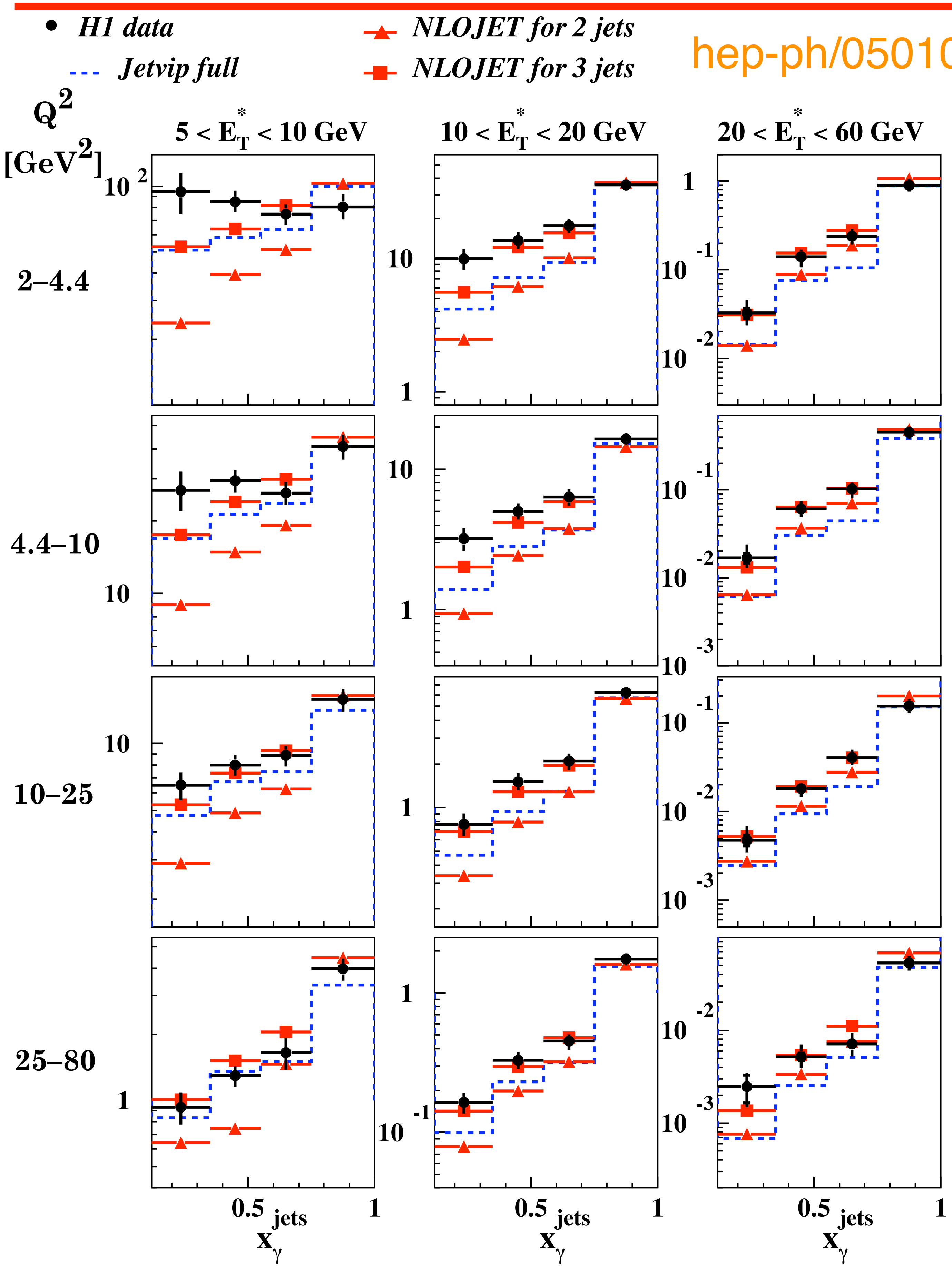
Backup Slides

Comparison with NLOJET++

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

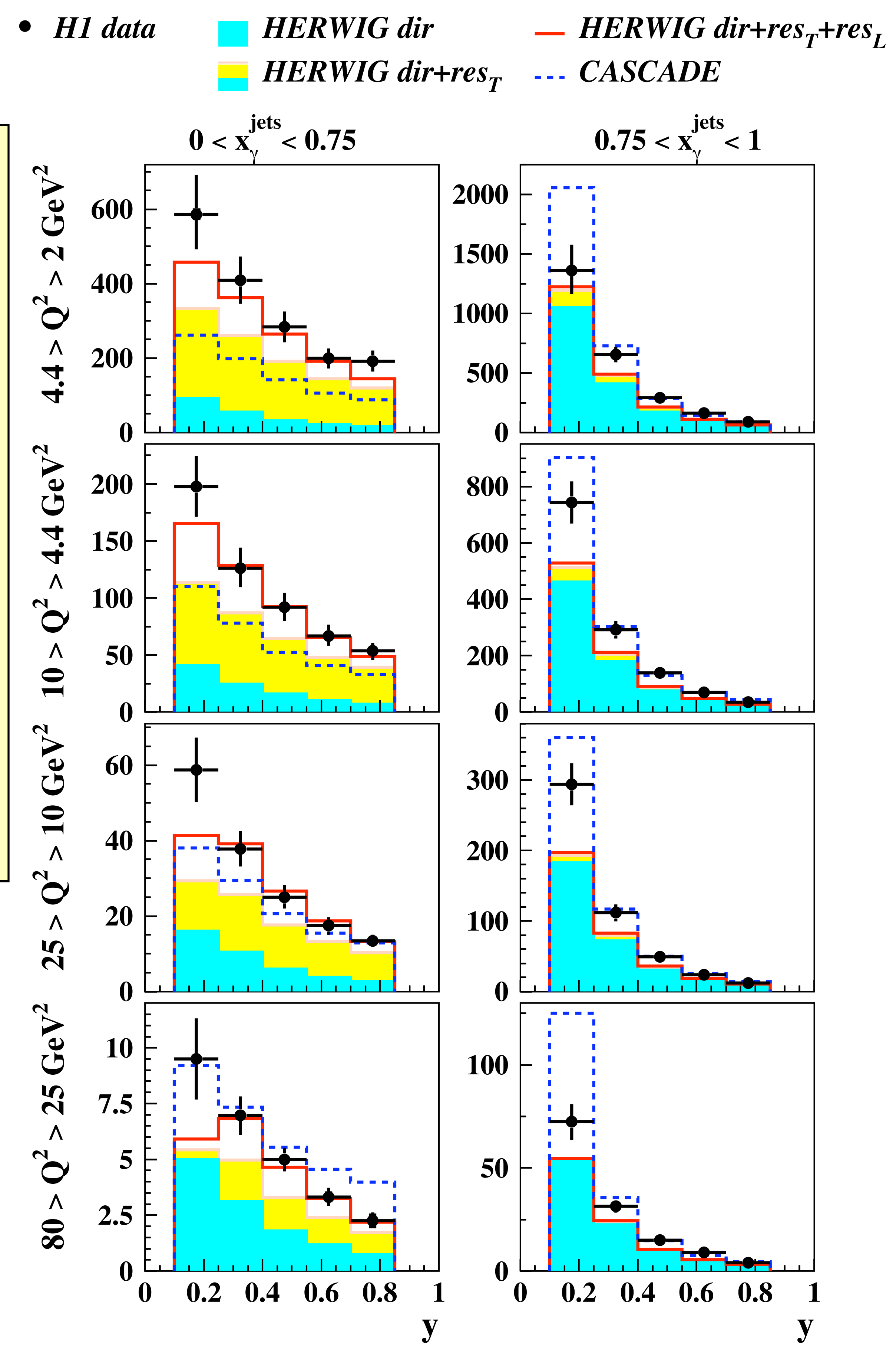
Triple differential cross section: $d^3\sigma_{2jet}/(dQ^2\, dx_\gamma^{jets}\, dy)$

- photon flux is different for transverse and longitudinal photons:

$$f_T(y,Q^2) = \frac{\alpha}{2\pi}\left(\frac{2(1-y)+y^2}{y}\frac{1}{Q^2} - \frac{2m_e^2 y}{Q^4}\right)$$

$$f_L(y,Q^2) = \frac{\alpha}{2\pi}\left(\frac{2(1-y)}{y}\frac{1}{Q^2}\right)$$

- ratio of longitudinally to transversly polarised photons decreases with increasing y



Triple differential cross section: $d^3\sigma_{2jet}/(dQ^2\,dy\,d\eta^*)$

- Excess observed at low Q^2 and high y
- Most pronounced at $\eta^* \sim 0$ in the forward region of lab frame