Recent Results in DIS and PHP from HERA (with MPI on my mind)

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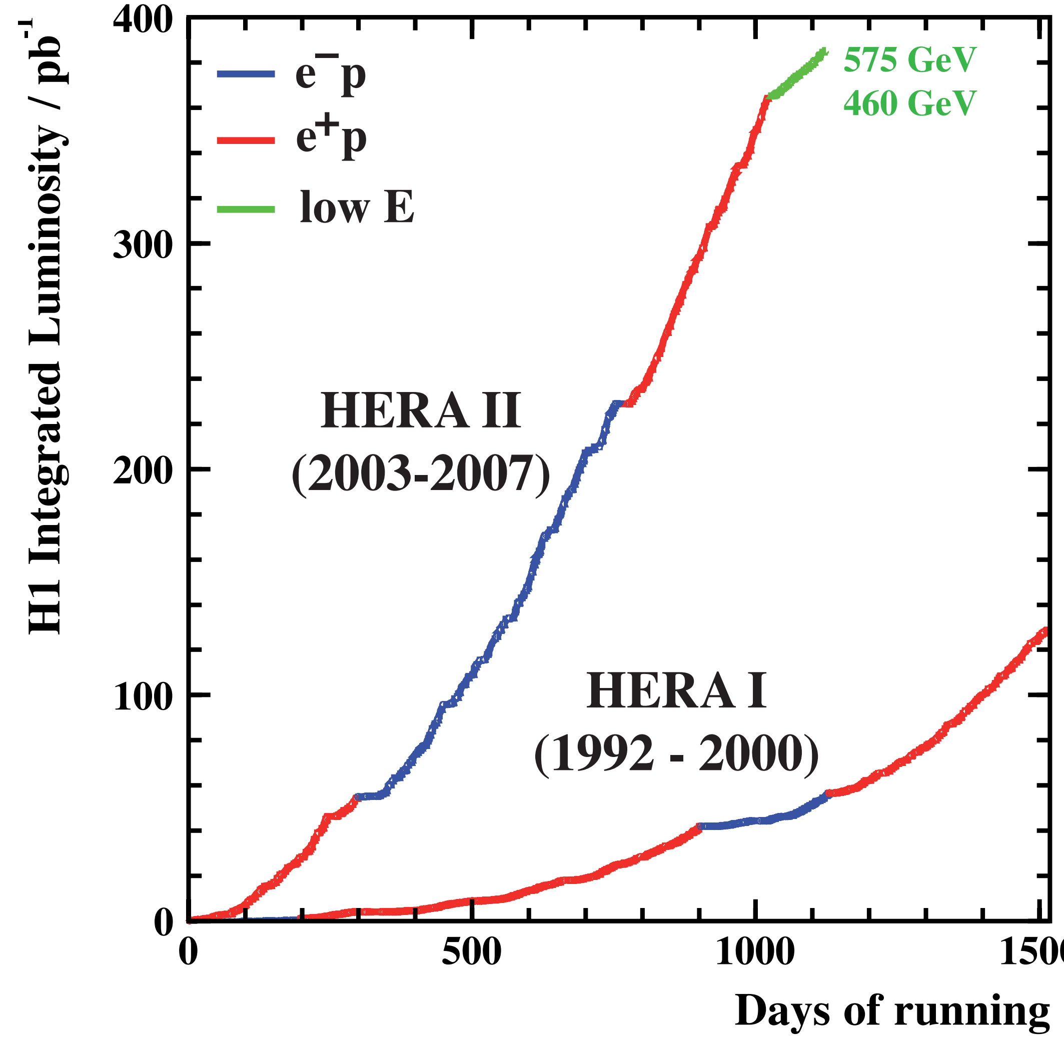
on behalf of the H1 and ZEUS collaborations

- deep-inelastic scattering (DIS), photoproduction (PHP) and multi-parton interactions (MPI)
- multi-jet production in DIS
- azimuthal asymmetry in forward (+central) jet production in DIS
- very forward photon production in DIS
- inclusive jet production in PHP

The HERA ep collider



World's only ep collider

$E_e = 27.6\,GeV$ $E_p = 920\,GeV$

$\sqrt{s} = 319$ GeV

- **HERA I: 1992 - 2000**
  $L \sim 130\ pb^{-1}$ / experiment
- **luminosity (detector) upgrade**
- **HERA II: 2003 - 2007**
  $L \sim 400\ pb^{-1}$ / experiment

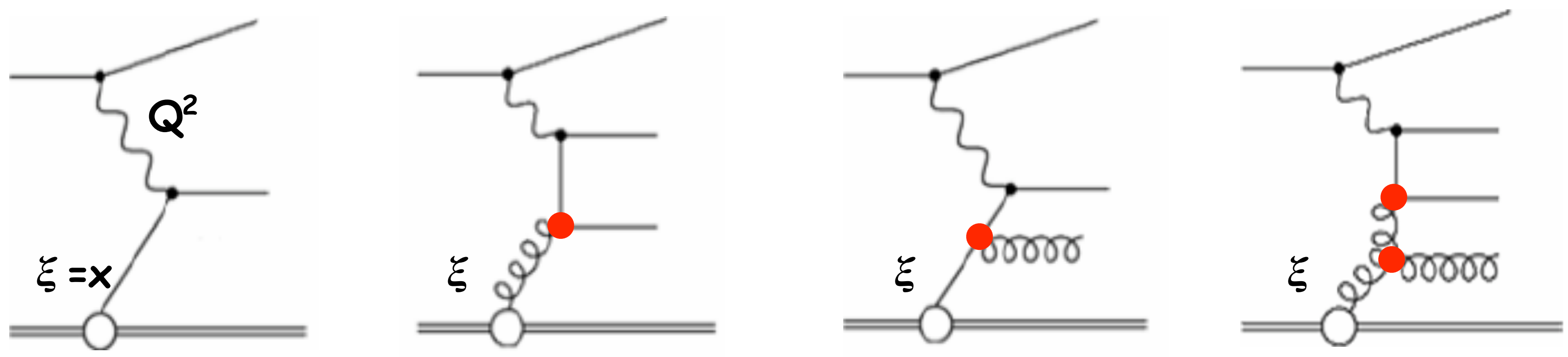
DIS, PHP and MPI

- An interesting and very comprehensive talk on MPI measurements at HERA has been given at MPI@LHC 2011 by Albert Knutsson.
- I am not showing any of these results here again, even though there is no new specific MPI measurement from HERA, except one which may perhaps indicate effects of MPI.
- My focus today is firstly on how well do we understand hard and soft processes in DIS. If one wants to understand/model MPI one has to be able to rely on our understanding of QCD processes, where MPI are not expected to play any role, as in DIS. Do NLO calculations and/or MC models provide an adequate description of the data?
- Secondly, what happens when we look at hard processes in PHP? Do we see MPI effects there? At low scales they are needed to describe the data (see talk by Knutsson).

Within this context I want to show a few recent results from the H1 and ZEUS experiments.

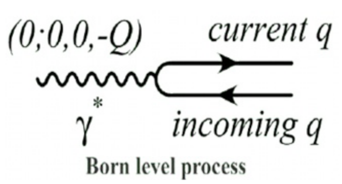
Deep-inelastic scattering

direct processes in DIS



$\propto \alpha_s^1$ $\propto \alpha_s^1$ $\propto \alpha_s^2$

+ h.o.



in DIS: two relevant scales in pQCD: Q^2 & $(P_T)^2$ → $(Q^2 + (P_T)^2)/2$ or $(P_T)^2$ ...

- processes where a point-like photon interacts with a parton in the proton provide an ideal opportunity to see whether we understand them in terms of NLO QCD and MC models involving ME matched with parton showers.

- in DIS with Q^2 large enough, resolved photon processes are suppressed and thus MPI are expected to play no role.

- if we observe discrepancies they could be due to:
  - missing higher orders or deficiencies in ME+parton shower models
  - deficiencies in the PDFs of the proton

Multi-jet production at hard scales (H1)

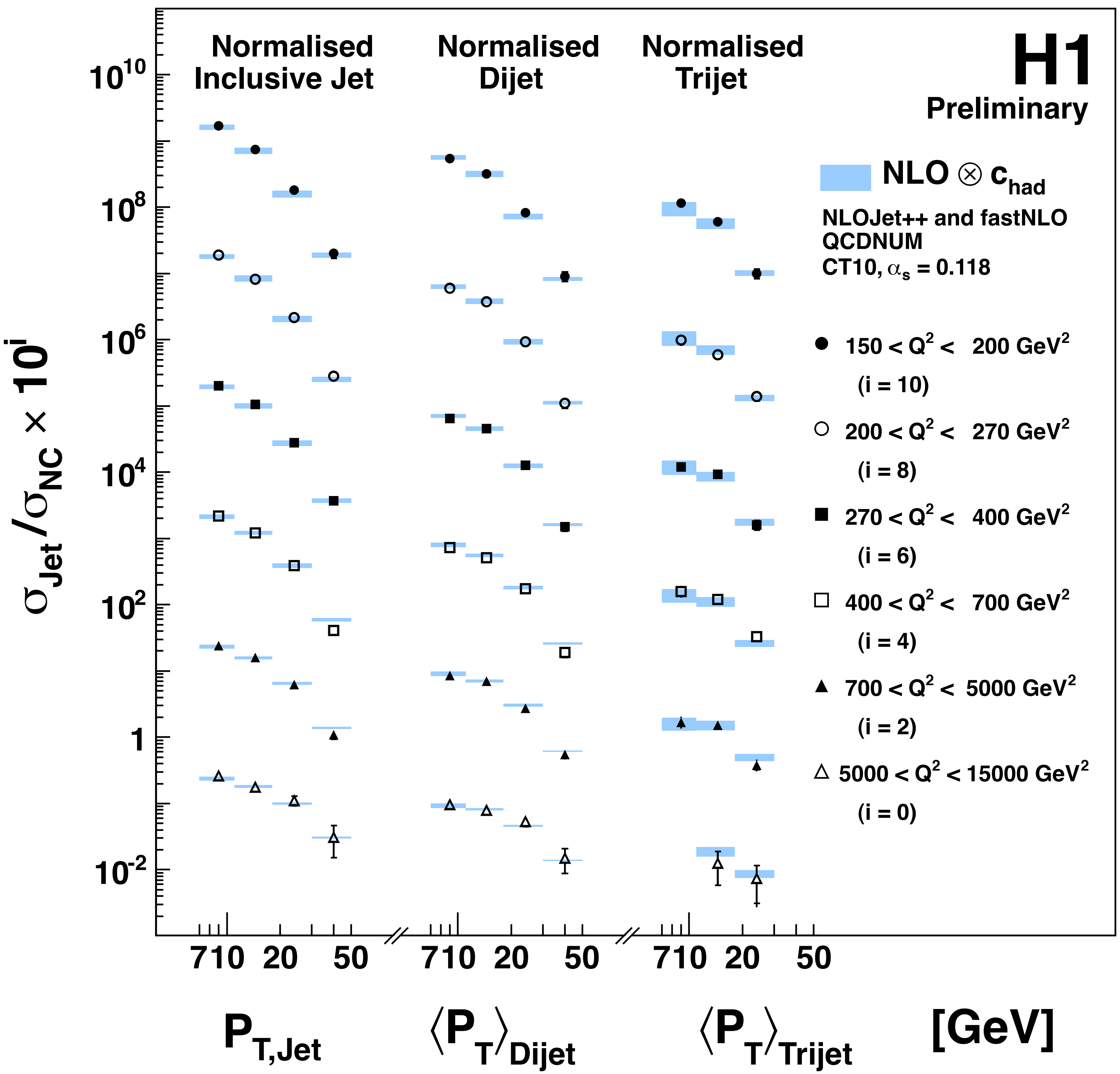
H1prelim-12-031 Normalised Multi-Jet Cross Sections at High Q^2 using Regularised Unfolding and Extraction of $\alpha_s(M_Z)$ in DIS at HERA

- L = 351 pb^{-1}, small stat. uncertainties
- systematic uncertainties:
  - electron energy scale: 0.5 to 1%
  - jet energy scale: 1%, effect on jet cross sections 3-10%
  - acceptance correction: 4-5%
- normalised double differential inclusive jet, dijet, and trijet cross sections in Q^2 and P_T (<P_T>)

NC DIS Selection	$150 < Q^2 < 15000\,\mathrm{GeV}^2 \quad 0.2 < y < 0.7$		
Inclusive jet	$7 < P_\mathrm{T} < 50\,\mathrm{GeV}$		$-1.0 < \eta_\mathrm{lab} < 2.5$
Dijet	$5 < P_\mathrm{T}^\mathrm{jet1},\ P_\mathrm{T}^\mathrm{jet2} < 50\,\mathrm{GeV}$	$M_{12} > 16\,\mathrm{GeV}$	
Trijet	$5 < P_\mathrm{T}^\mathrm{jet1},\ P_\mathrm{T}^\mathrm{jet2},\ P_\mathrm{T}^\mathrm{jet3} < 50\,\mathrm{GeV}$		

Normalised multi-jet cross cections

NLOJet++ (Nagy, Trocsanyi)
fastNLO (Britzger, Kluge, et. al)
QCDNUM (Botje)



NLO calculation:

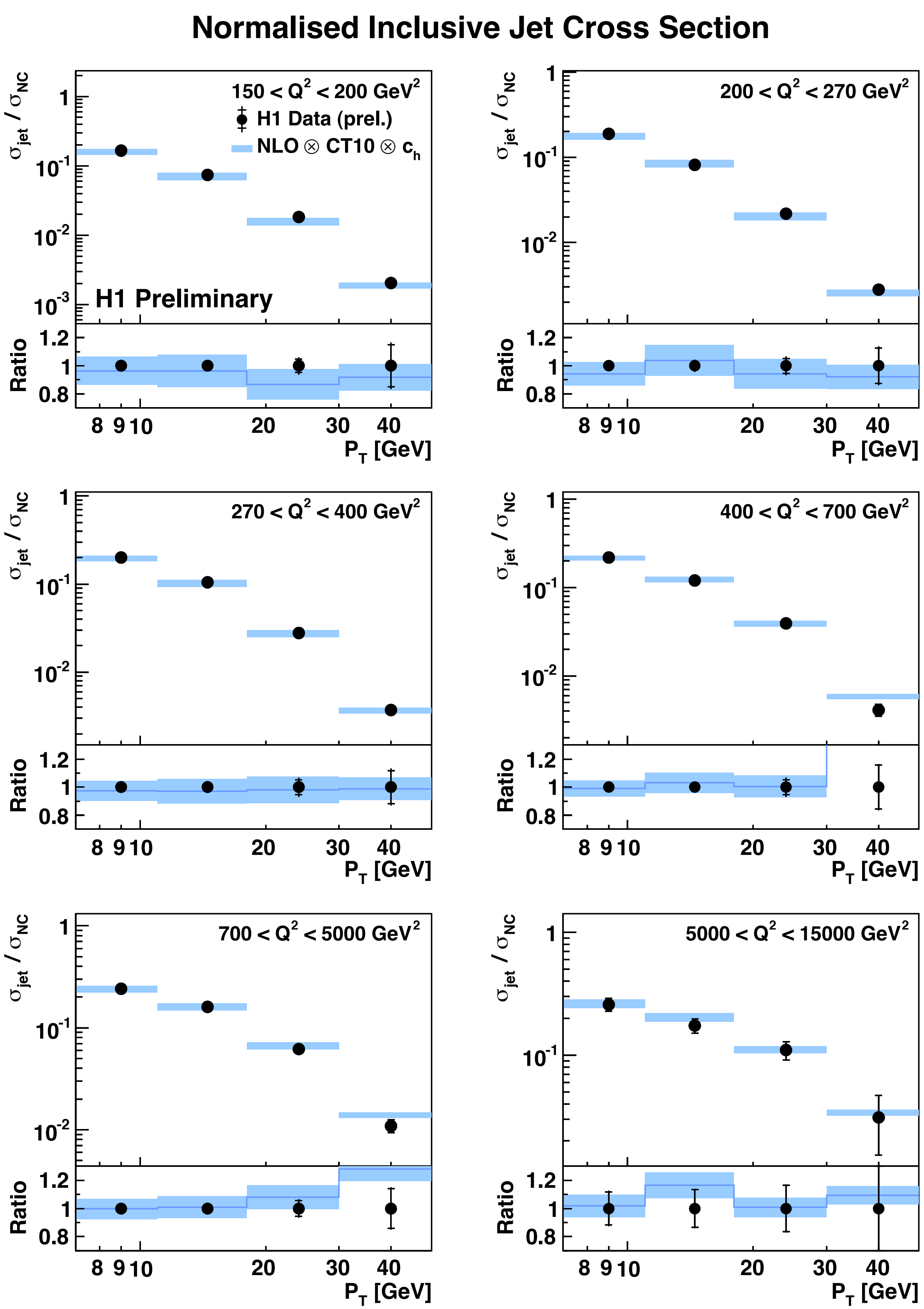
NLOJet++ and fastNLO, corrected for hadronization effects, and QCDNUM

Scale choice:

$$\mu_r = \sqrt{(Q^2 + P_T^2)/2}$$
$$\mu_f = Q$$

let's look more precisely at the norm. incl. jet cross section

Normalised inclusive jet cross sections



normalised multi-jet cross sections:
experimental uncertainties: 6 - 10%
theory uncertainties: 10 (30) % at high (low) Q^2, P_T
they are dominated by missing higher orders

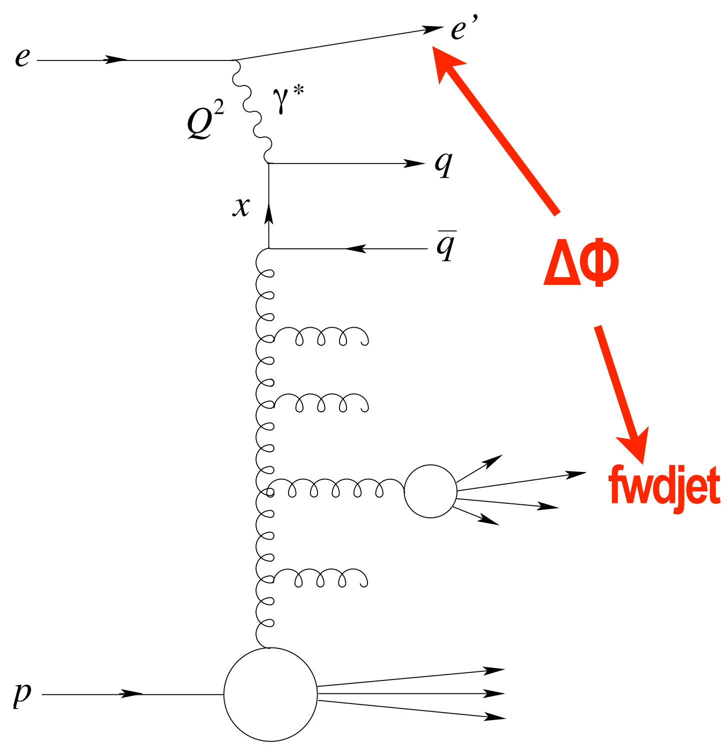
these and other measurements of jet cross sections in DIS at are usually quite well described by NLO within the theory uncertainties, which typically are significantly larger than the experimental ones

observed differences may be due to missing higher orders and non-optimal proton PDFs and $\alpha_s(M_Z)$

DIS MC models (ME+PS and CDM, as implemented in LEPTO, RAPGAP, ARIADNE) usually provide a slightly worse description than NLO, for example a slightly differing slope in the jet P_T and discrepancies at low Q^2 (which for inclusive DIS is very well described)

Azimuthal correlation in DIS (H1)

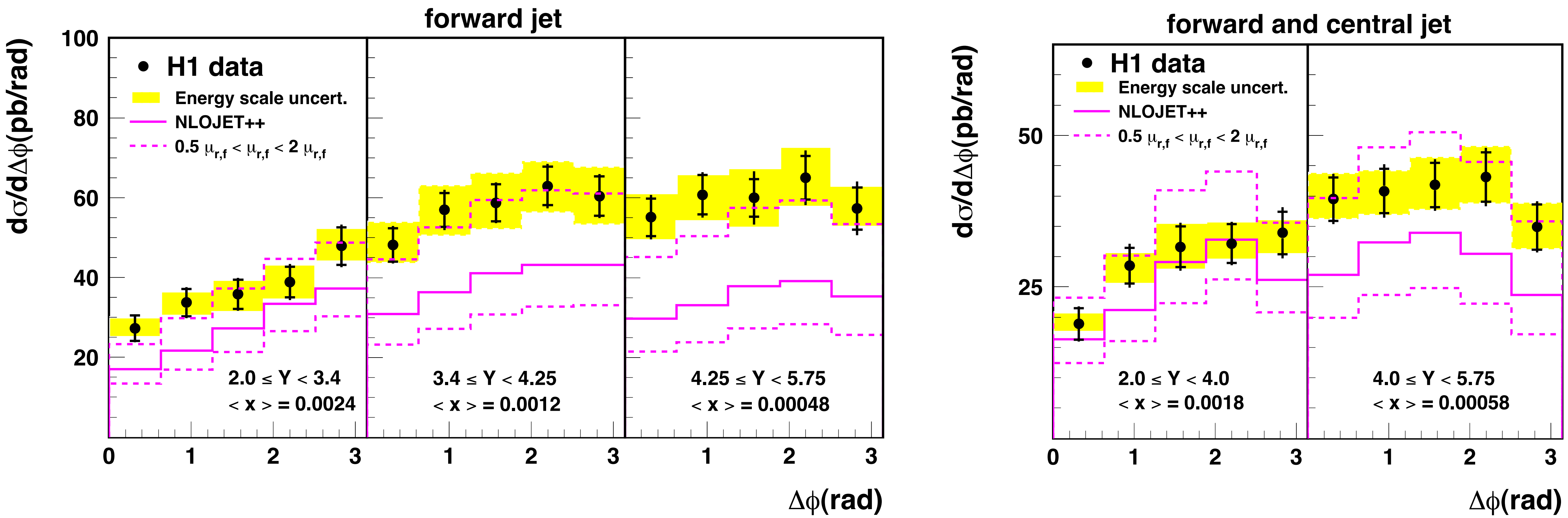
Measurement of the Azimuthal Correlation between the most Forward Jet and the Scattered Positron in DIS at HERA, EPJC72 (2012) 1910



- idea by Mueller and Navelet was to test QCD dynamics at low x (large $W_{\gamma p}$).
  - requiring $P^2_{T,fwdjet} \sim Q^2$ suppresses the DGLAP evolution in Q^2
  - requiring $x_{fwdjet} >> x_{Bj}$ enhances the BFKL evolution in x
- measure $\Delta\Phi = \Phi_e - \Phi_{fwdjet}$ in bins of the rapidity distance between the scattered positron and the forward jet ($Y \sim \ln(x_{fwdjet}/x_{Bj})$)
- additional analysis: require also a central jet

DIS selection	Forward jets	Central jets
$0.1 < y < 0.7$	$1.73 < \eta_{\mathrm{fwdjet}} < 2.79$	$-1 < \eta_{\mathrm{cenjet}} < 1$
$5 < Q^2 < 85\ \mathrm{GeV}^2$	$P_{\mathrm{T,fwdjet}} > 6\ \mathrm{GeV}$	$P_{\mathrm{T,cenjet}} > 4\ \mathrm{GeV}$
$0.0001 < x < 0.004$	$x_{\mathrm{fwdjet}} > 0.035$	$\Delta\eta = \eta_{\mathrm{fwdjet}} - \eta_{\mathrm{cenjet}} > 2$
	$0.5 < P^2_{\mathrm{T,fwdjet}}/Q^2 < 6$	

Azimuthal correlation in DIS (H1)



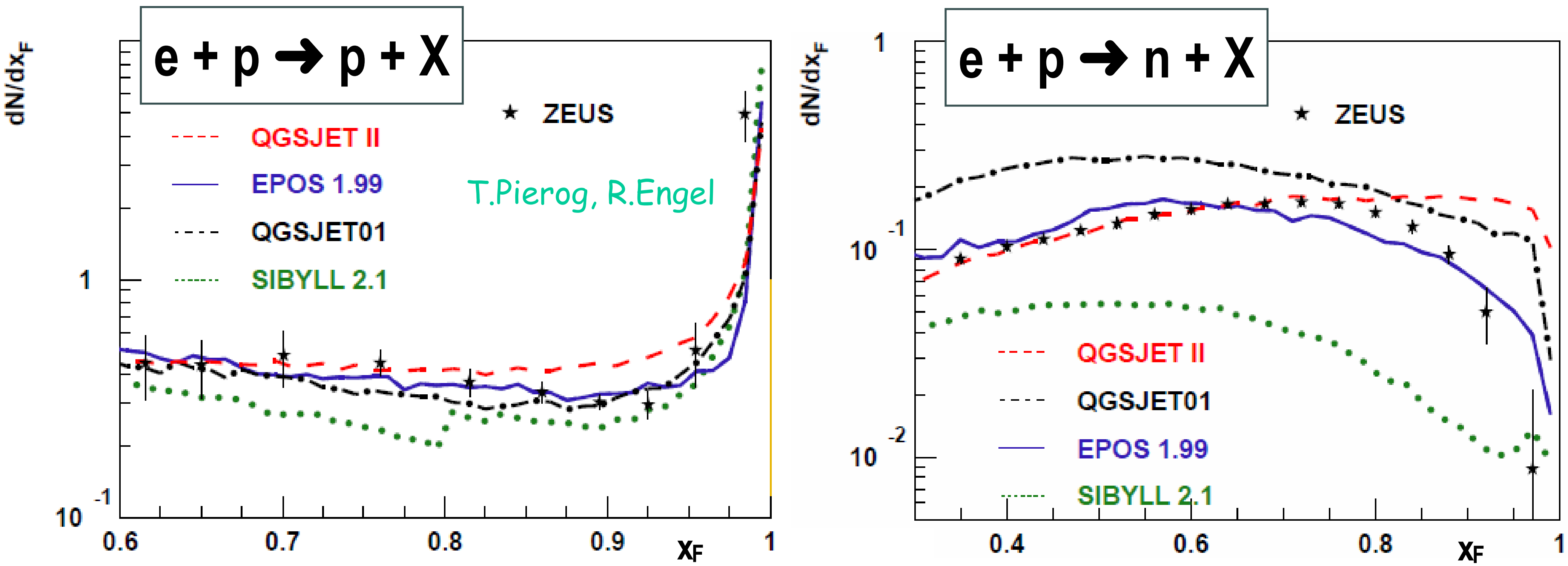
"fwd jet": the data are at the upper edge of the NLO prediction. The conventionally estimated theory uncertainty is up to 50%, i.e. higher orders are probably important. The largest difference to NLO is seen in the largest Y bin, i.e. at smallest x.

"fwd + central jet": the data are described by NLO at low Y, at high Y it is again above NLO but within the theory uncertainty.

The BFKL-like CDM model provides in general a reasonable description of the data, while the DGLAP-based model RAPGAP is substantially below the data (see back-up).

Very forward p & n prod. in DIS

- understanding the production of very forward ($\theta < 0.75$ mrad) particles (p, n, π^0, photons) are of great importance in understanding cosmic ray showers and forward and other measurements at the LHC, particularly when the production mechanism is mainly due to hadronization/fragmentation/np effects.



QGSJET
(Kalmykov, Ostapchenko)

EPOS
(Pierog, Werner)

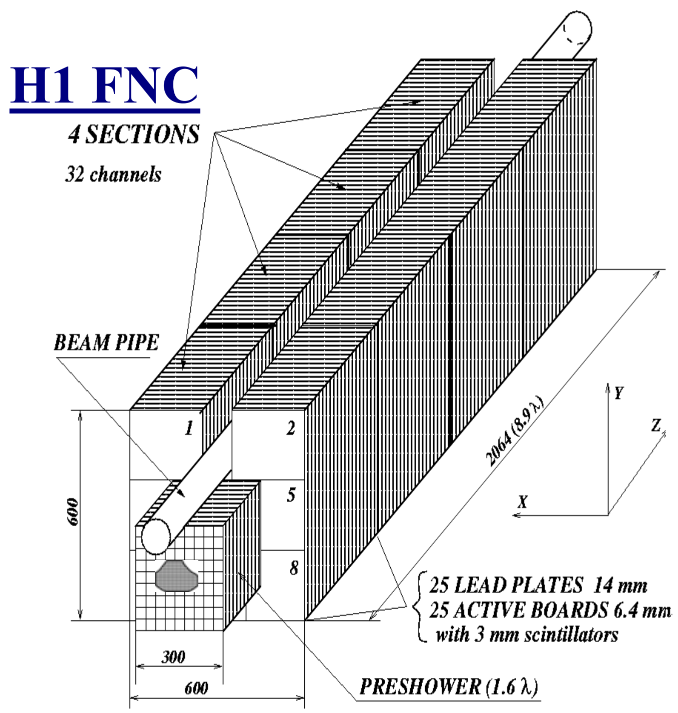
SIBYLL
(Engel, Fletcher, Gaisser, Lipari, Stanev)

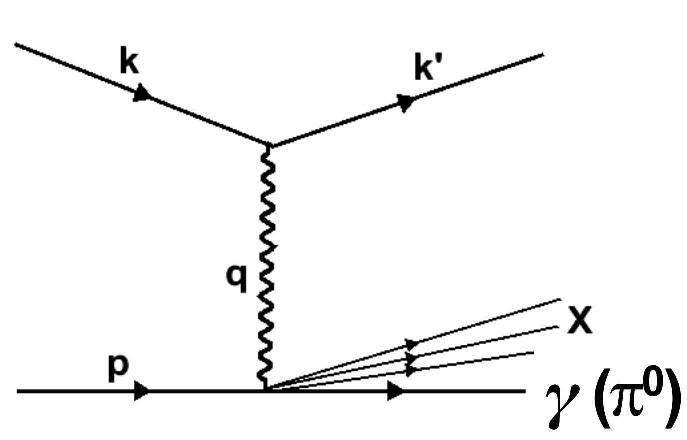
- reasonable predictions of the forward proton data
- none of the models describe forward neutron data well

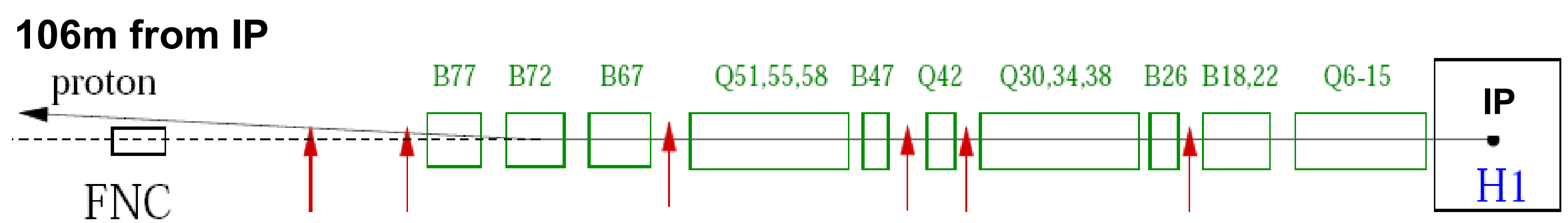
➡ let's look at forward photon production

Very forward photon prod. in DIS (H1)

Measurement of Photon Production in the Very Forward Direction in Deep-Inelastic Scattering at HERA, EPJC71 (2011) 1771

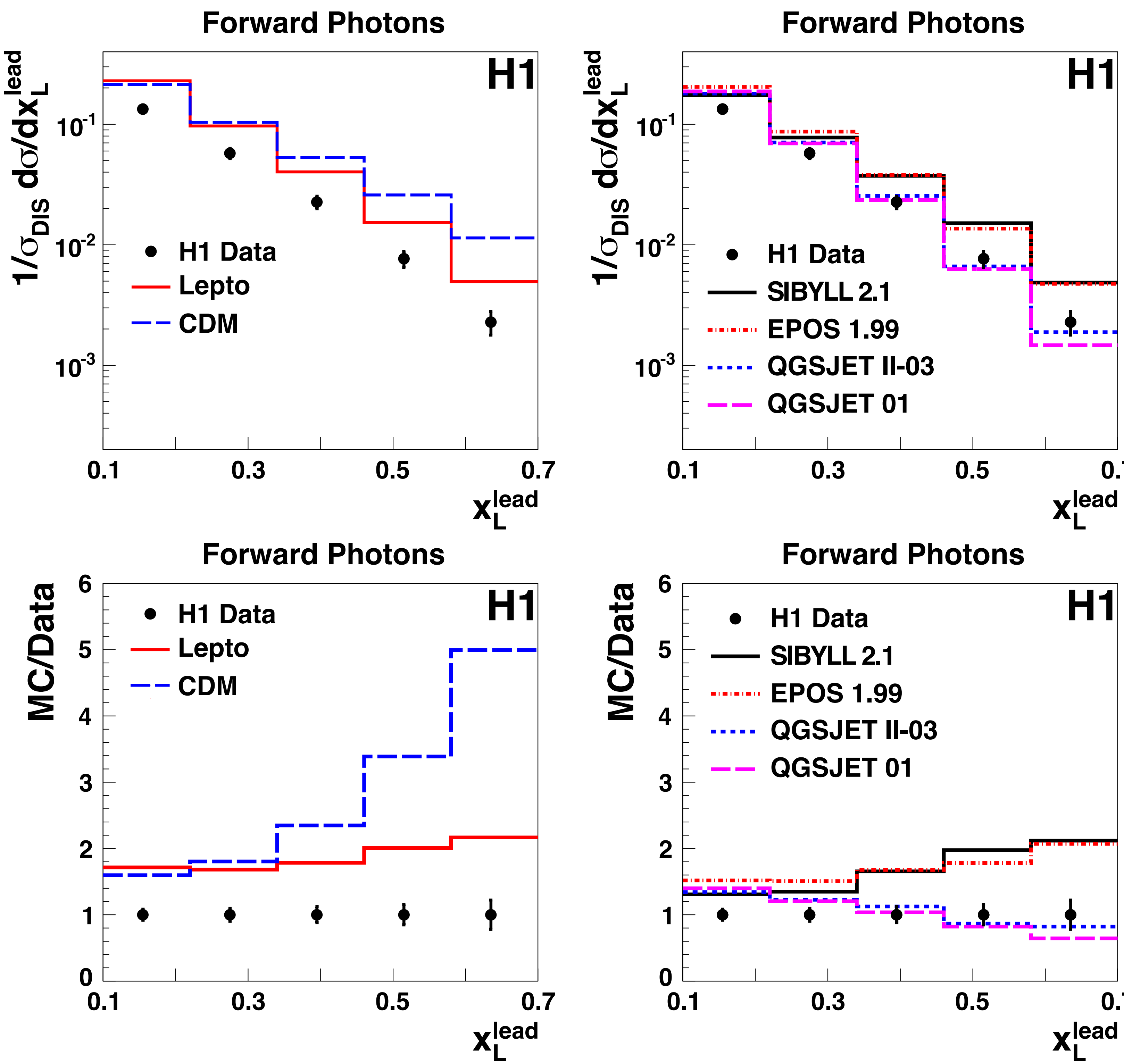






- measure photons in the FNC calorimeter; its longitudinal segmentation allows excellent discrimination between em and hadronic showers, i.e. between photons and neutrons
- the acceptance (~ 30%) is limited by the beam apertures and the detector
- for x_L > 0.7 many of the em clusters are from 2 photons, i.e. the measurement represents the sum of photons in the FNC with $\eta < 7.9$.
- for $x_L < 0.7$ single photons dominate within the FNC acceptance
- according to all models most of the photons are from π^0 decays

Very forward photon prod. in DIS

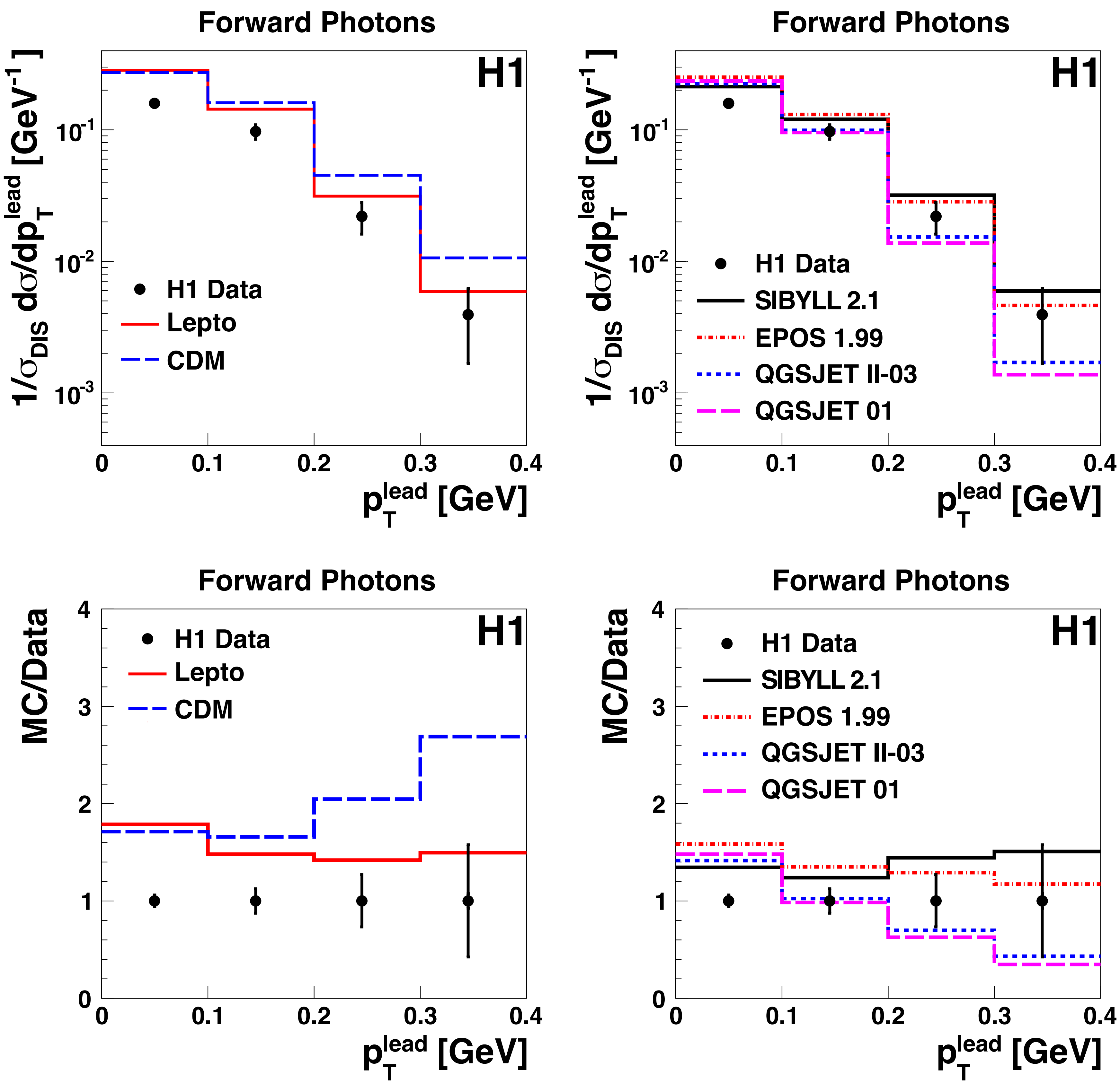


- $6 < Q^2 < 100$ GeV^2
- $70 < W_{\gamma p} < 250$ GeV
- $\eta_\gamma > 7.9$
- cross sections are normalized to σ_{DIS}

- the total photon rate is significantly below all predictions
- LEPTO describes the shape, CDM predictions differs greatly from LEPTO prediction
- QGSJET ok at higher x_L

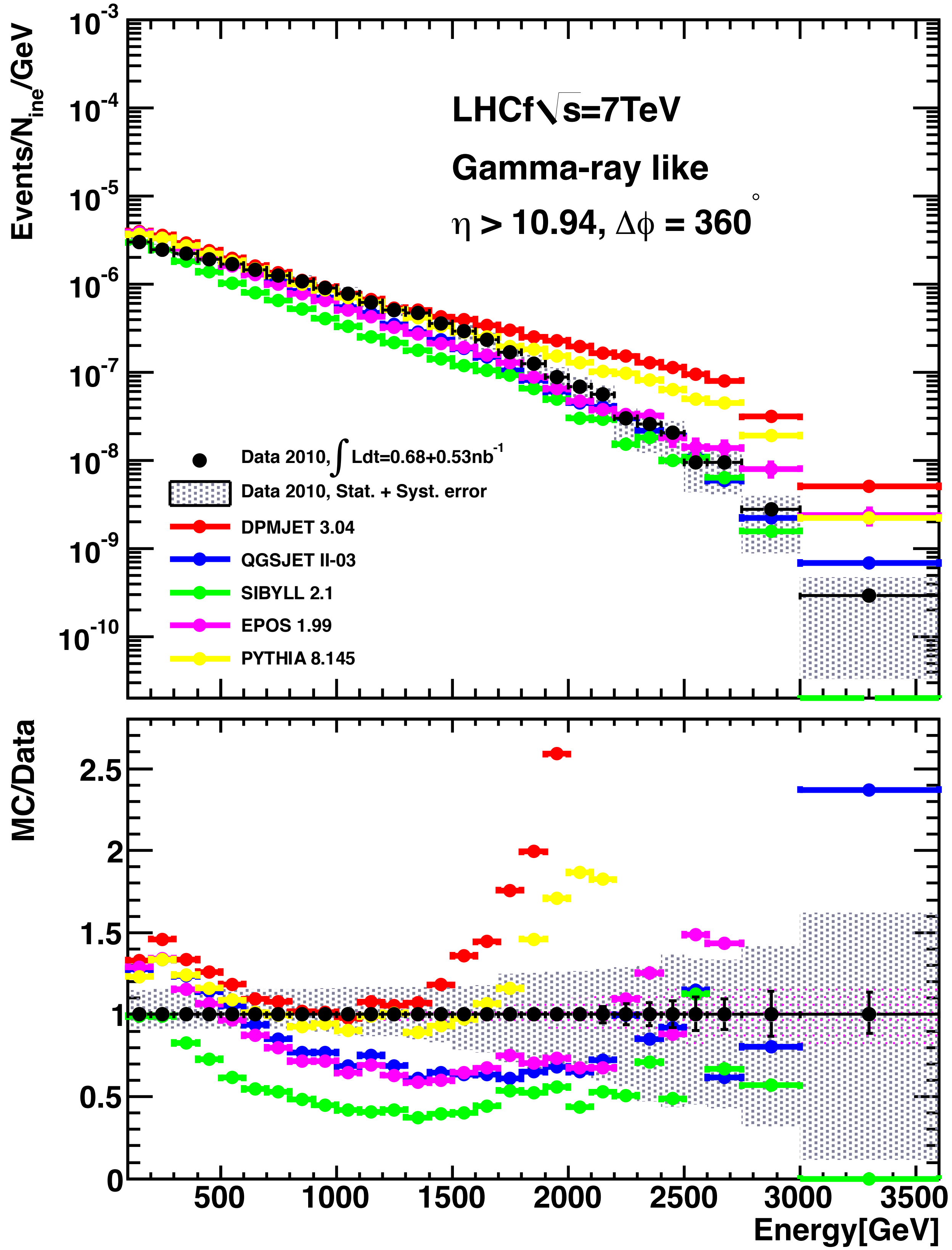
LEPTO (Ingelman, Edin, Rathsman)
CDM ~ ARIADNE (Lönnblad)

Very forward photon prod. in DIS



- P_T^{lead} shape reasonably well described by LEPTO, SIBYLL and EPOS

Very forward photons from LHCf



- the LHCf data (PLB703 (2011)) and the H1 data cannot be compared due to the different kinematics
- none of the models shown provide a good description of the data
- as in case of H1, the P_T of π^0 from LHCf (PRD86 (2012)) are better described by EPOS

Very forward photon prod. in DIS

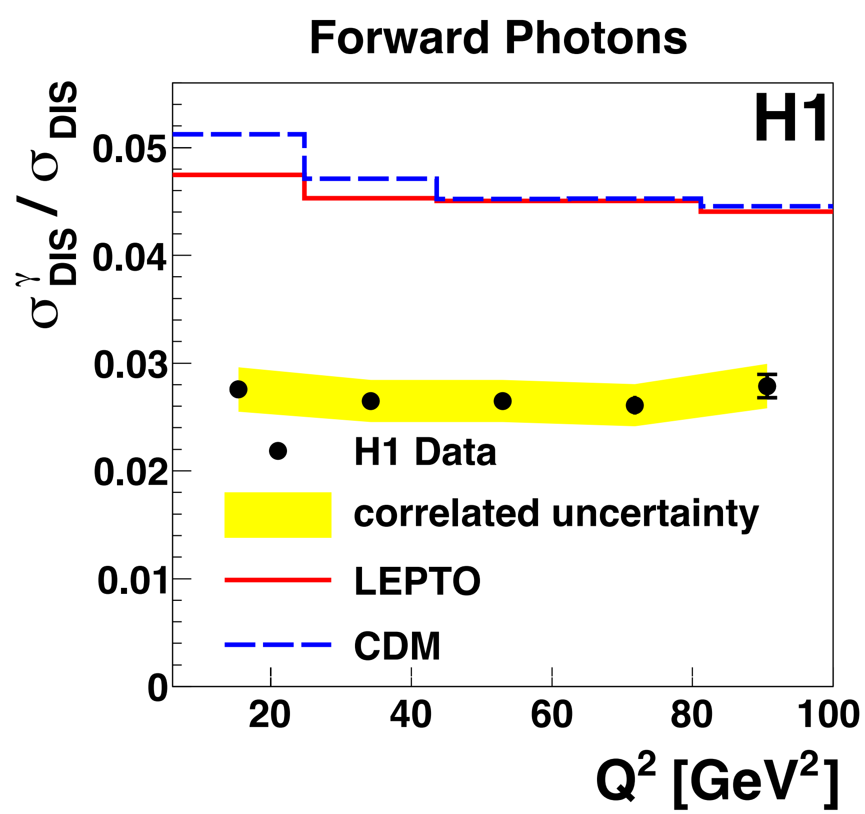
- all models fail to describe the data and most predict far too many photons (30-70% above data)
- particularly CDM predicts much harder x_L and P_T spectra (as compared to LEPTO)
- it is interesting to note that both, LEPTO and CDM, describe the hadronic final state in DIS in the main detector reasonably well
- since they both use the Lund string model for fragmentation one suspects differences in parton showers to be responsible

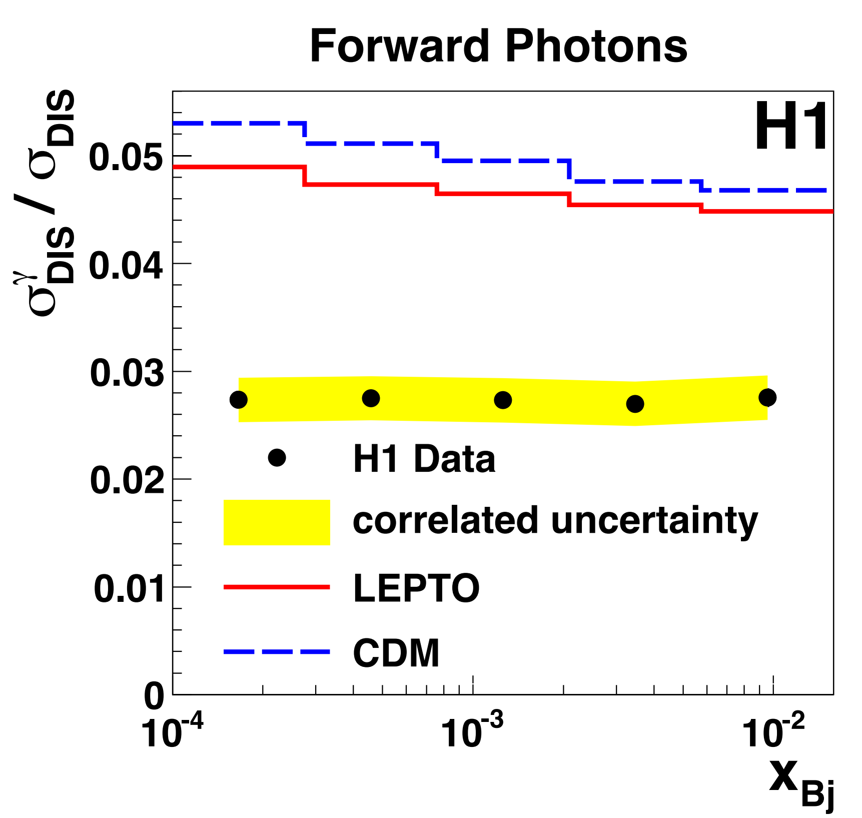
Very forward photon prod. in DIS

hypothesis of limiting fragmentation (Benecke, Chou, Yang, Yen '69, '74)

- in the high energy limit, the production of particles in the target fragmentation region becomes independent of the incident particle energy ➦ in DIS it should be independent of Q^2 and x_{Bj}

- the observed fraction of DIS events with very forward photons support the hypothesis of limiting fragmentation



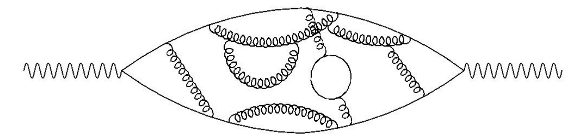


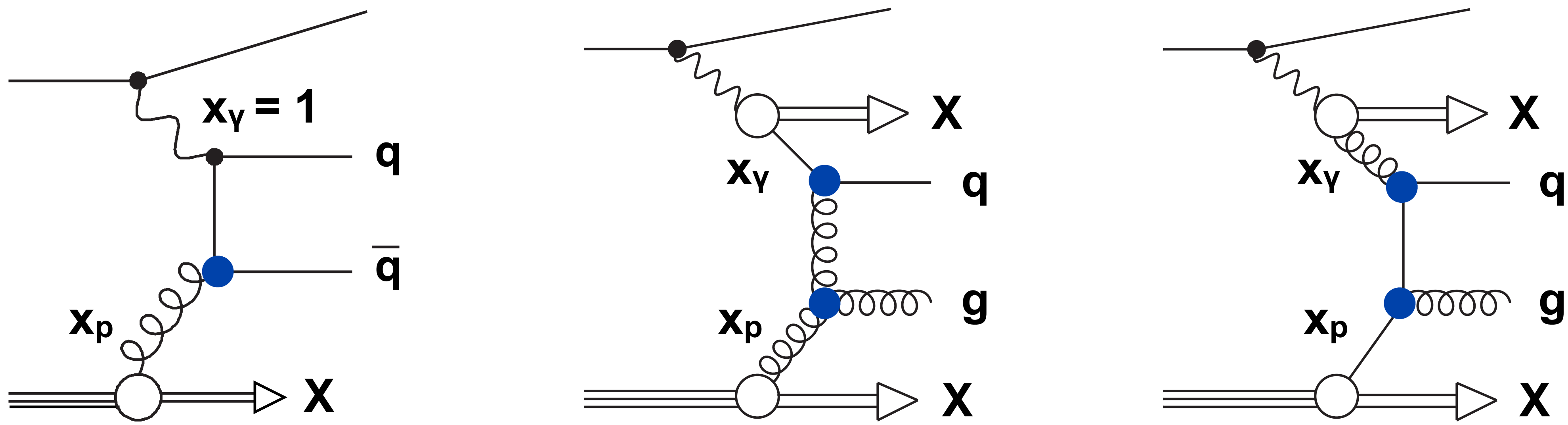
here: $0.1 < x_L^{sum} < 0.95$

Jet production in PHP ($Q^2 \sim 0$ GeV^2)

direct php

resolved php

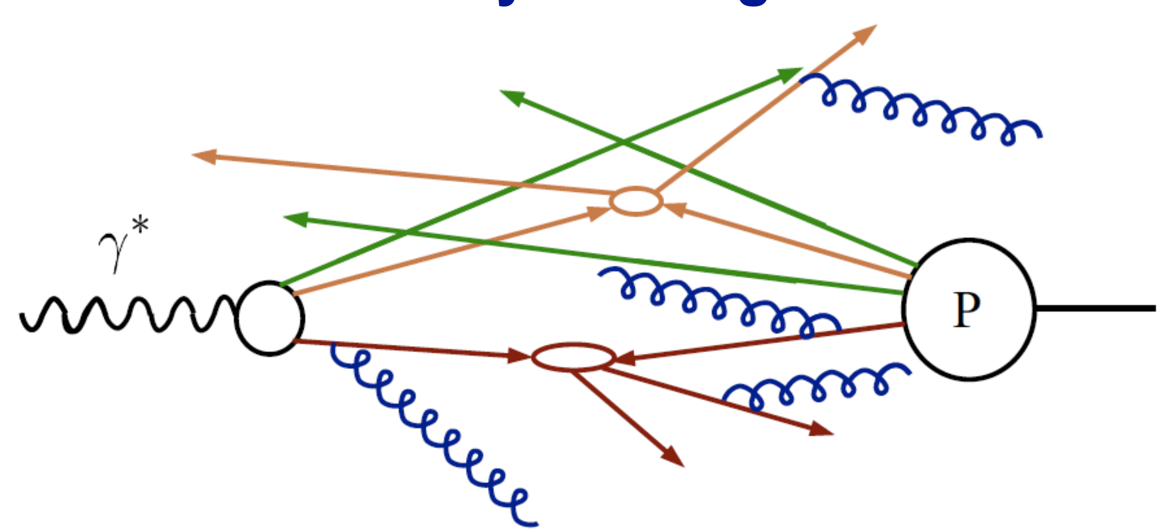




in PHP: one relevant scale in pQCD: $(P_{T,jet})^2$

note: the distinction between direct and resolved contributions is only unambiguous in LO

- the resolved photon allows secondary interactions of one of its partons with a parton from the proton

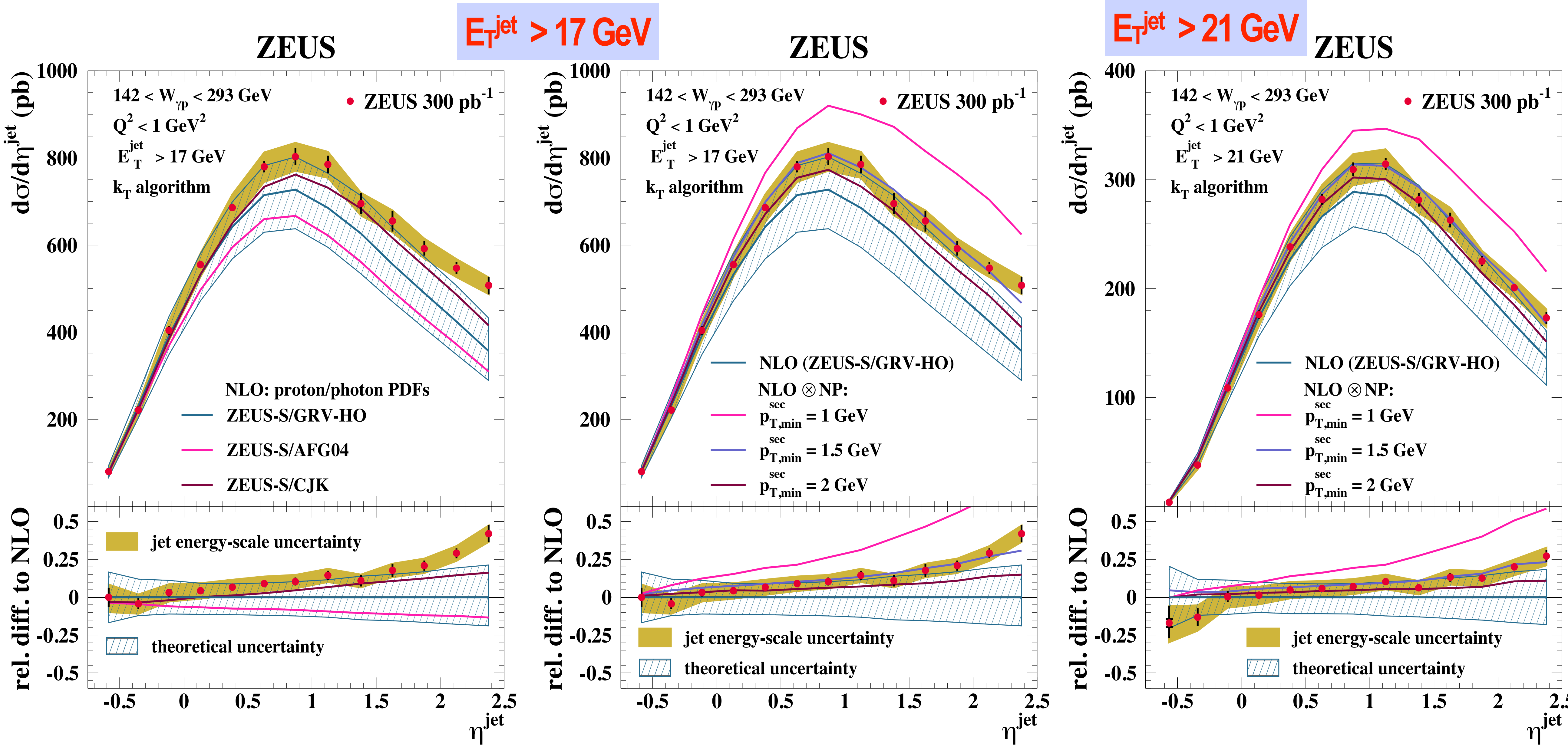


Inclusive jet production in PHP (ZEUS)

Inclusive-jet photo-production at HERA and determination of $\alpha_s(M_Z)$, NPB864 (2012) 1

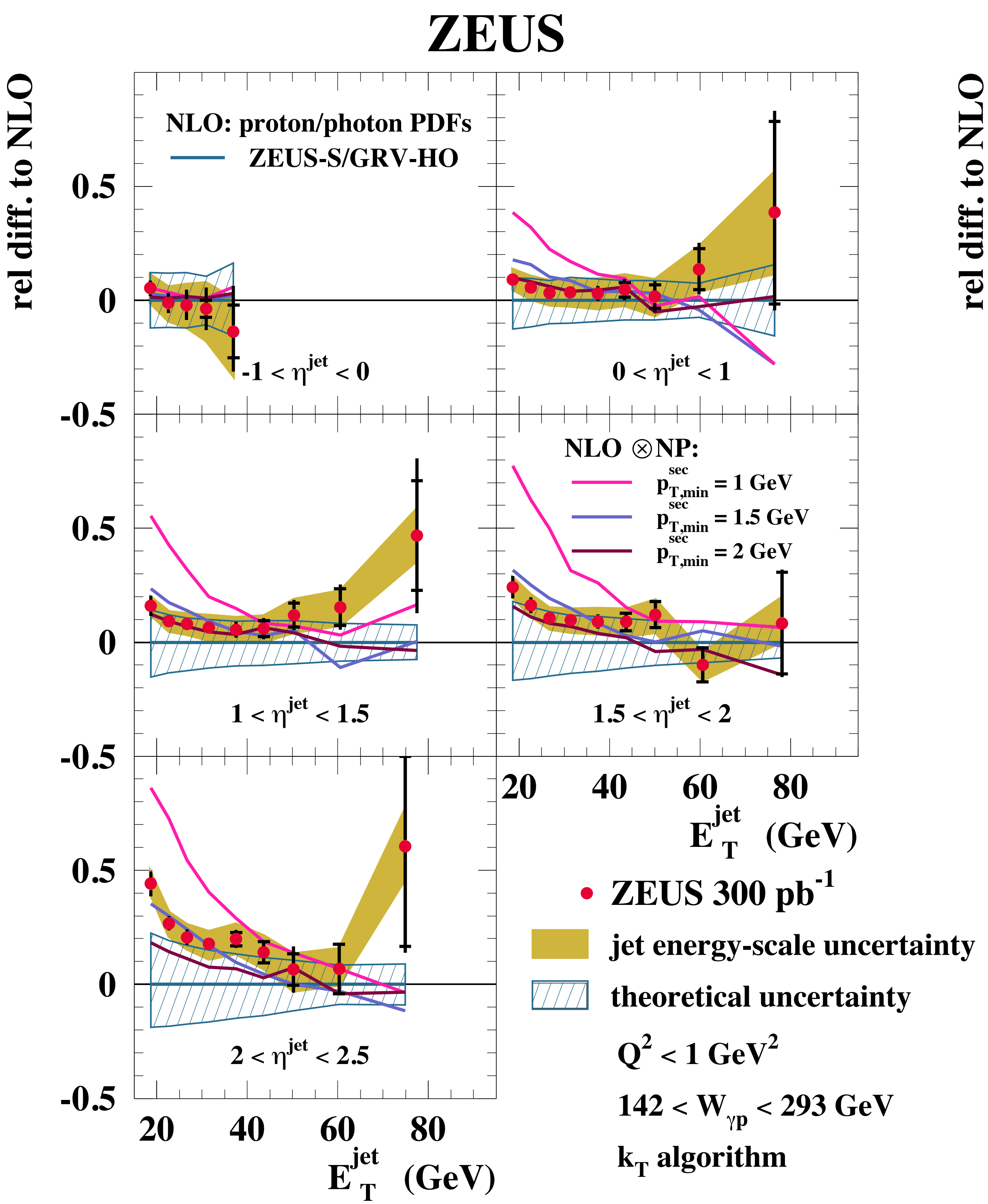
- $Q^2 < 1$ GeV^2
- $142 < W_{\gamma p} < 293$ GeV
- $L = 300$ pb^{-1}
- $E_T^{jet} > 17$ (21) GeV
- $-1 < \eta^{jet} < 2.5$
- systematic uncertainies
  - typically below 5%
  - jet energy scale (1%) ➜ 5 (10)% at low (high) E_T^{jet}
- theory uncertainties
  - higher orders: 10 (4)% at low (high) E_T^{jet}
  - proton-PDFs: 1 (5)% at low (high) E_T^{jet}
  - photon-PDFs: 1-3 (9)% at high (low) E_T^{jet}
  - hadronization : < 3%
  - $\alpha_s(M_Z)$: < 2%

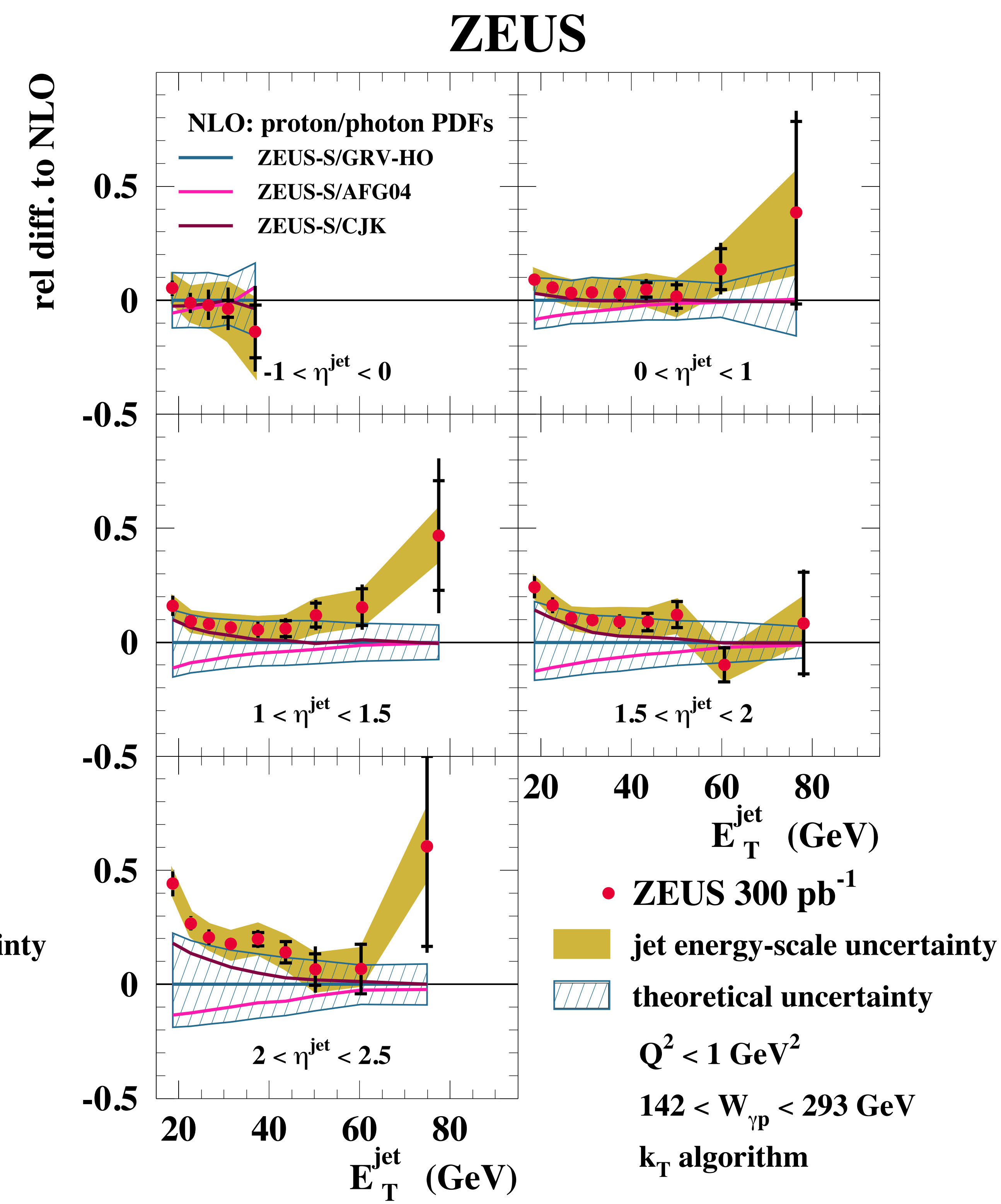
Inclusive jet production in PHP



- disagreement between data and NLO at high η^{jet} can be reduced by
  - γ-PDFs (AFG04 ➜ CJK) or
  - NP effects, i.e. corrections for MPI in PYTHIA 6.1
- the disagreement is also reduced, when increasing E_T^{jet} from > 17 to > 21 GeV

Inclusive jet production in PHP





- the discrepancy w.r.t. NLO is at large η_{jet} and low E_T^{jet}

Summary/Conclusions

- DIS
  - jet measurements involving hard scales are well described by NLO, however, currently the theory uncertainty > exp. uncertainty.
  - jet and other measurements at lower scales or in specific regions of phase space (forward jet, very forward photon production, ...) often fail to be well described by ME+PS models or hadronic interaction models.

➡ in DIS we can test higher order corrections (DGLAP, BFKL, …) to the hard scattering and hadronization, the exp. precision is there. Models which aim to include MPI should get DIS correct first.

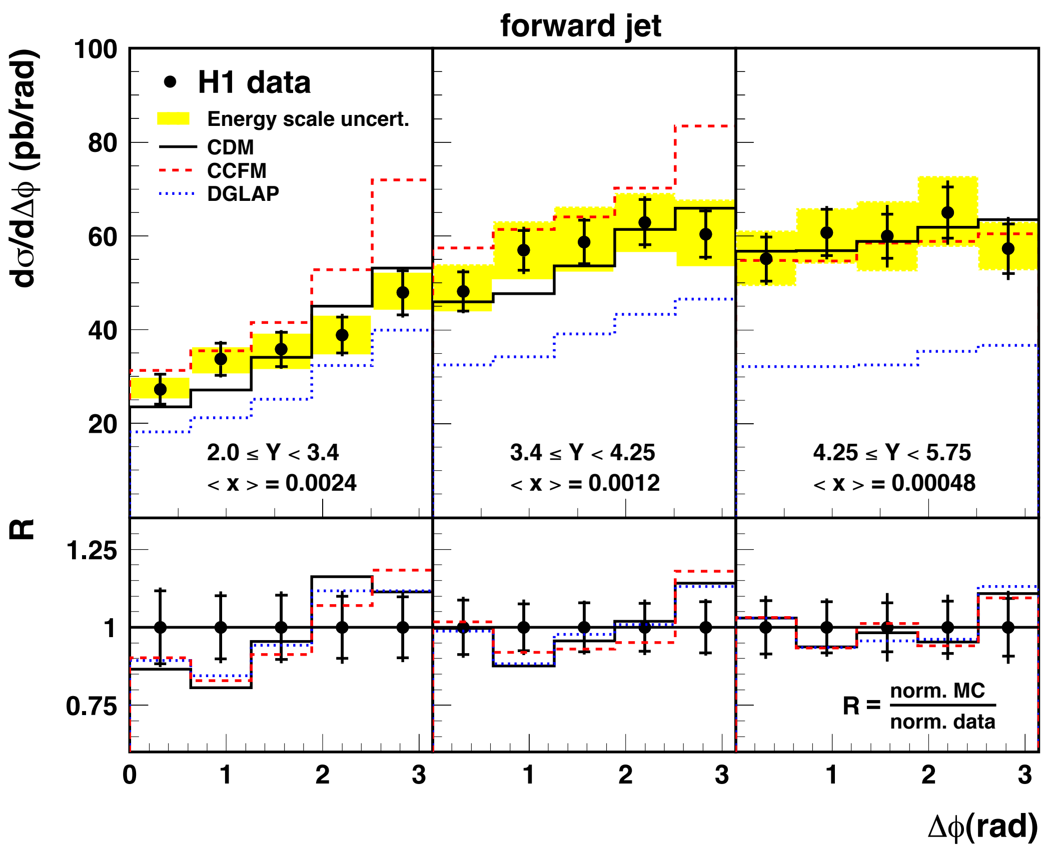
- PHP
  - jet measurements are sensitive to photon-PDFs and to MPI.
  - with increasing jet P_T the sensitivity to MPI can be made negligible.
  - lower energy PHP measurement (low P_T jets, particle flow) require the inclusion of MPI for them to be described.

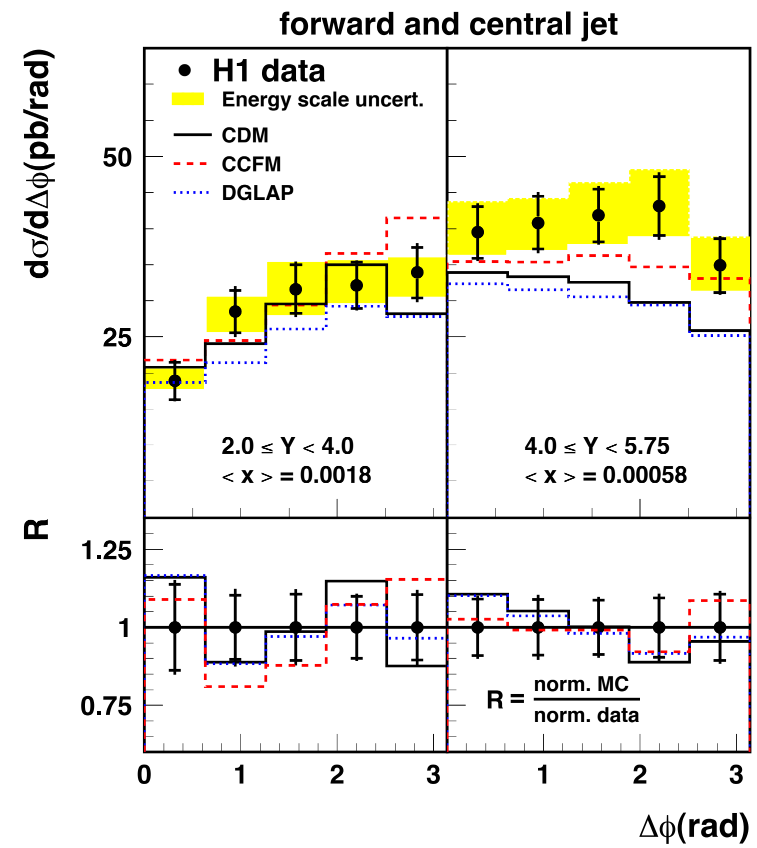
➡ to my knowledge, MPI provides just additional hadronic energy to the hard jets, i.e. an underlying event, and not additional hard scatterings.

➡ HERA PHP data are also a testing ground for MPI models, but it would help to have the photon-PDFs and their uncertainty better determined

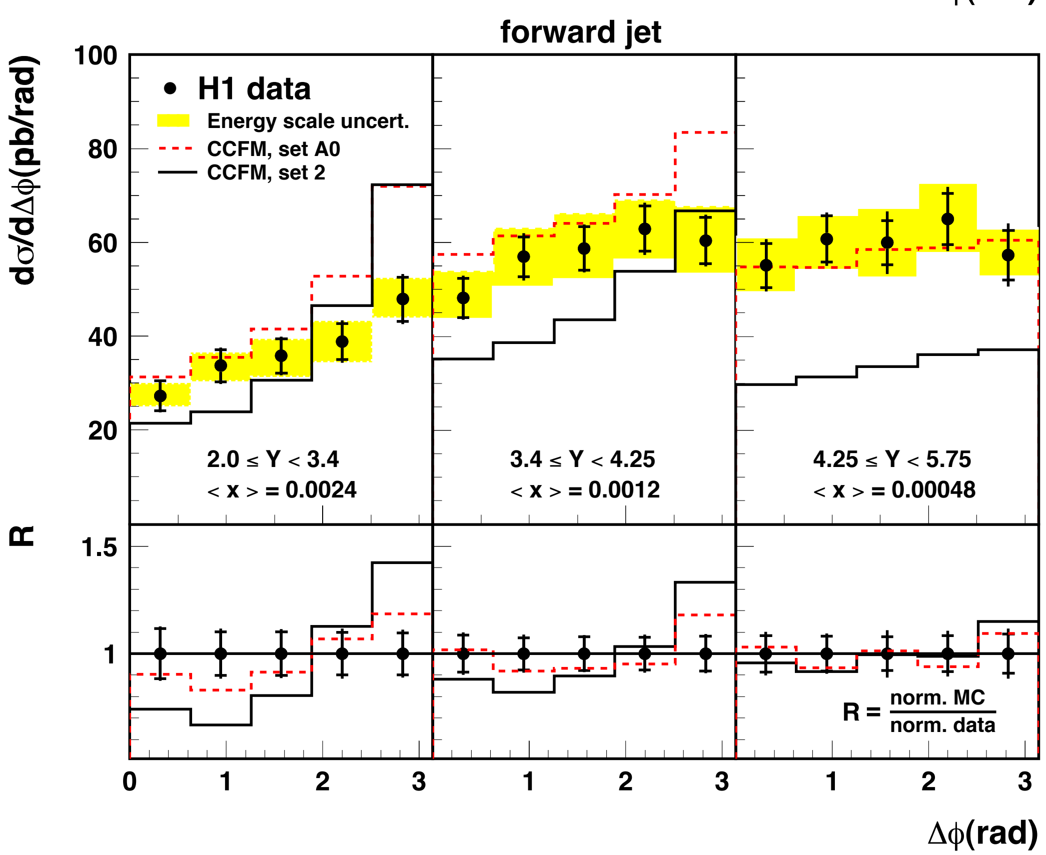
Additional slides

Azimuthal correlation and models now

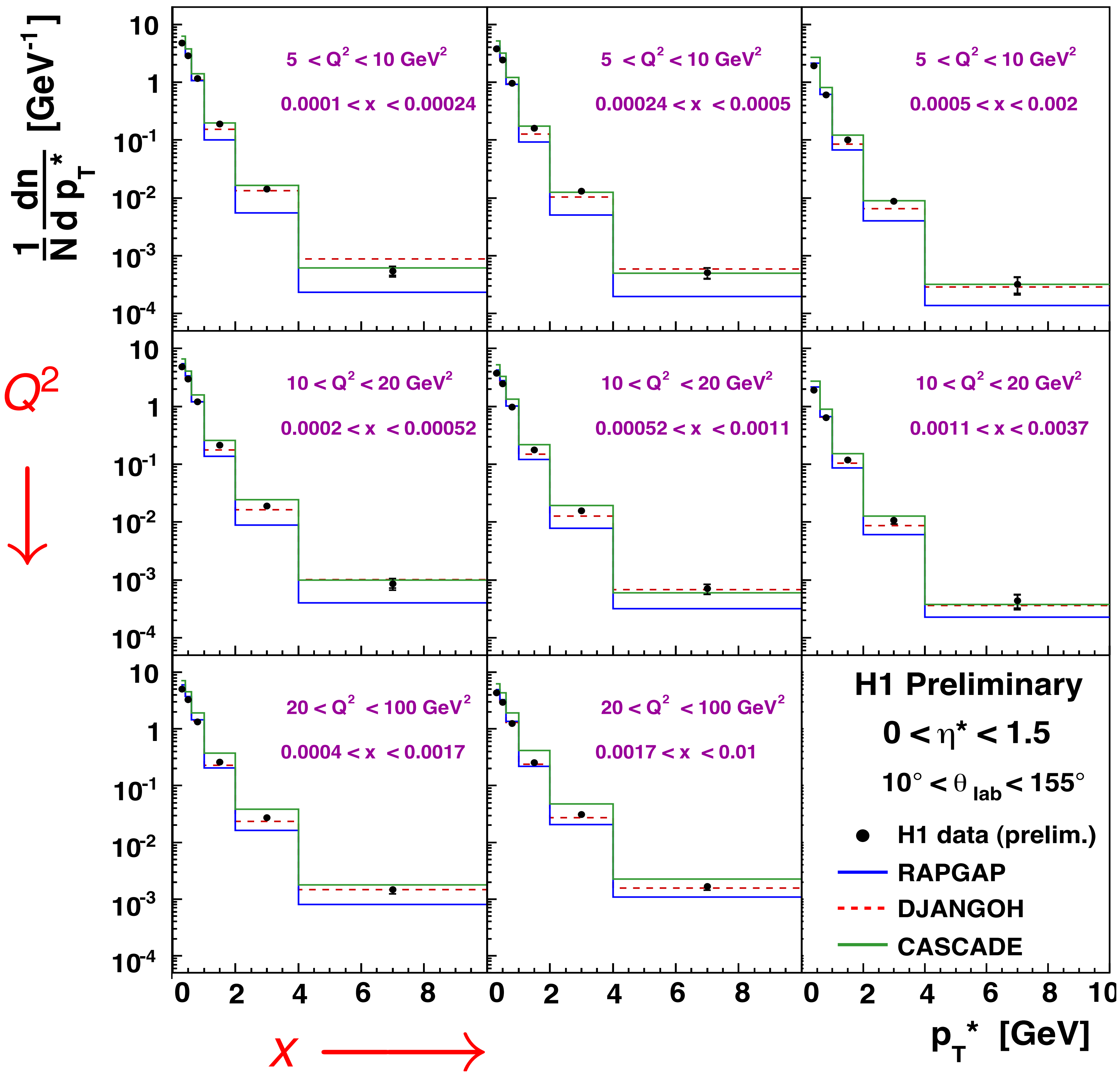




$$Y = \ln(x_{\mathrm{fwdjet}}/x)$$

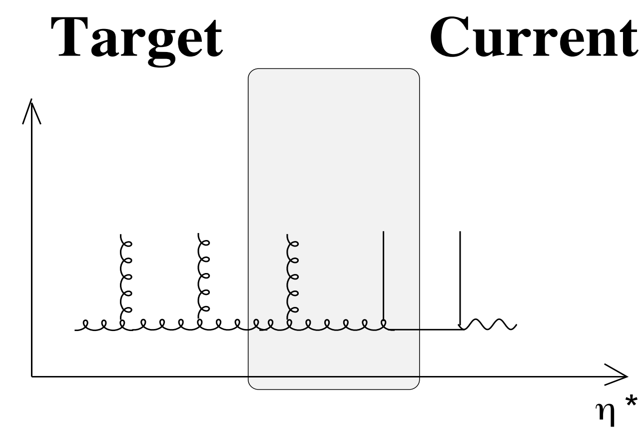


Particle P_T^* spectra



$5 < Q^2 < 100\ \mathrm{GeV}^2,\ 10^{-4} < x < 10^{-2}$

γp - frame



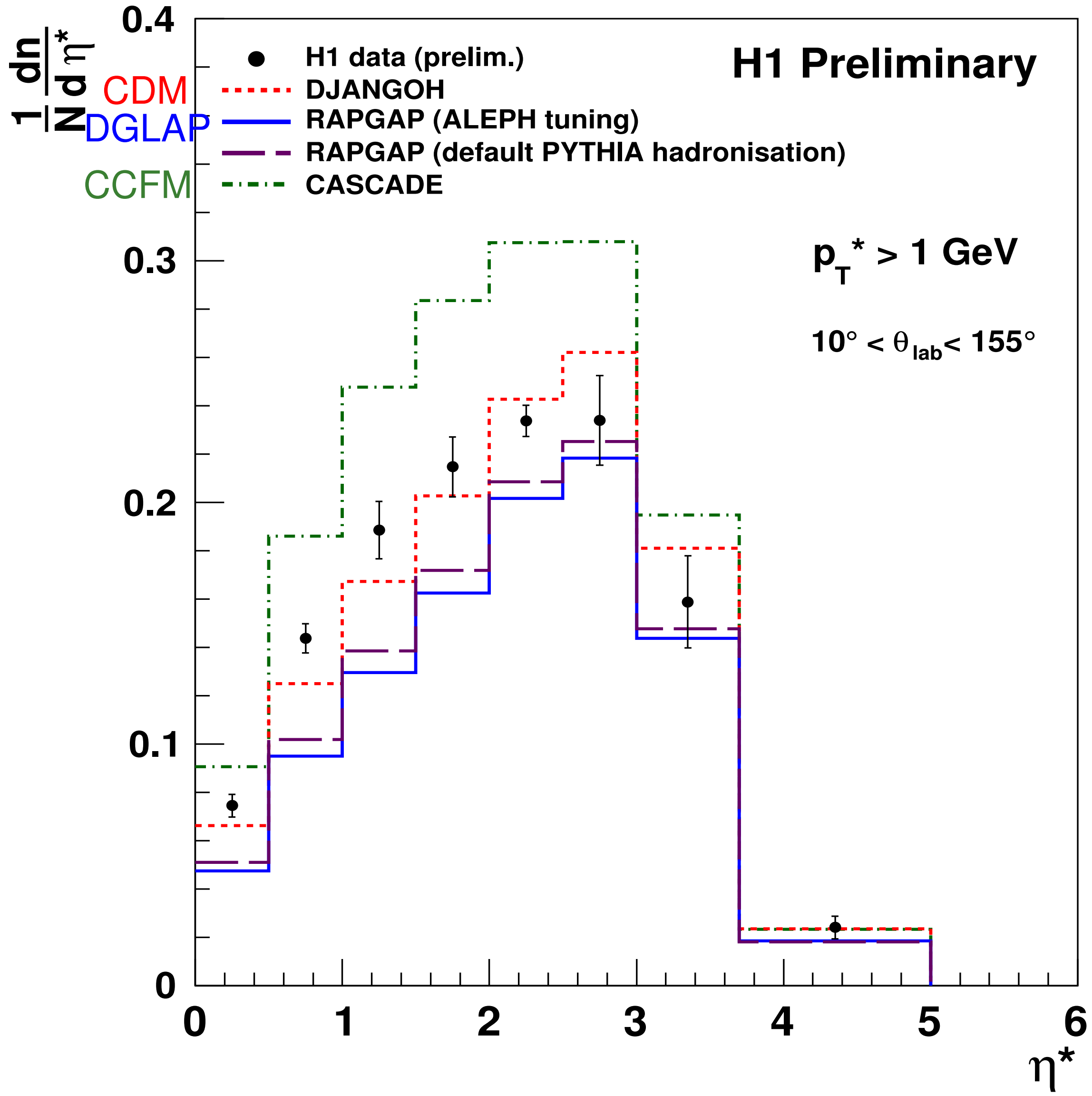
DJANGOH(CDM) describes the data for whole p_T^* spectra

strong deviation from RAPGAP(DGLAP) at low x and Q^2

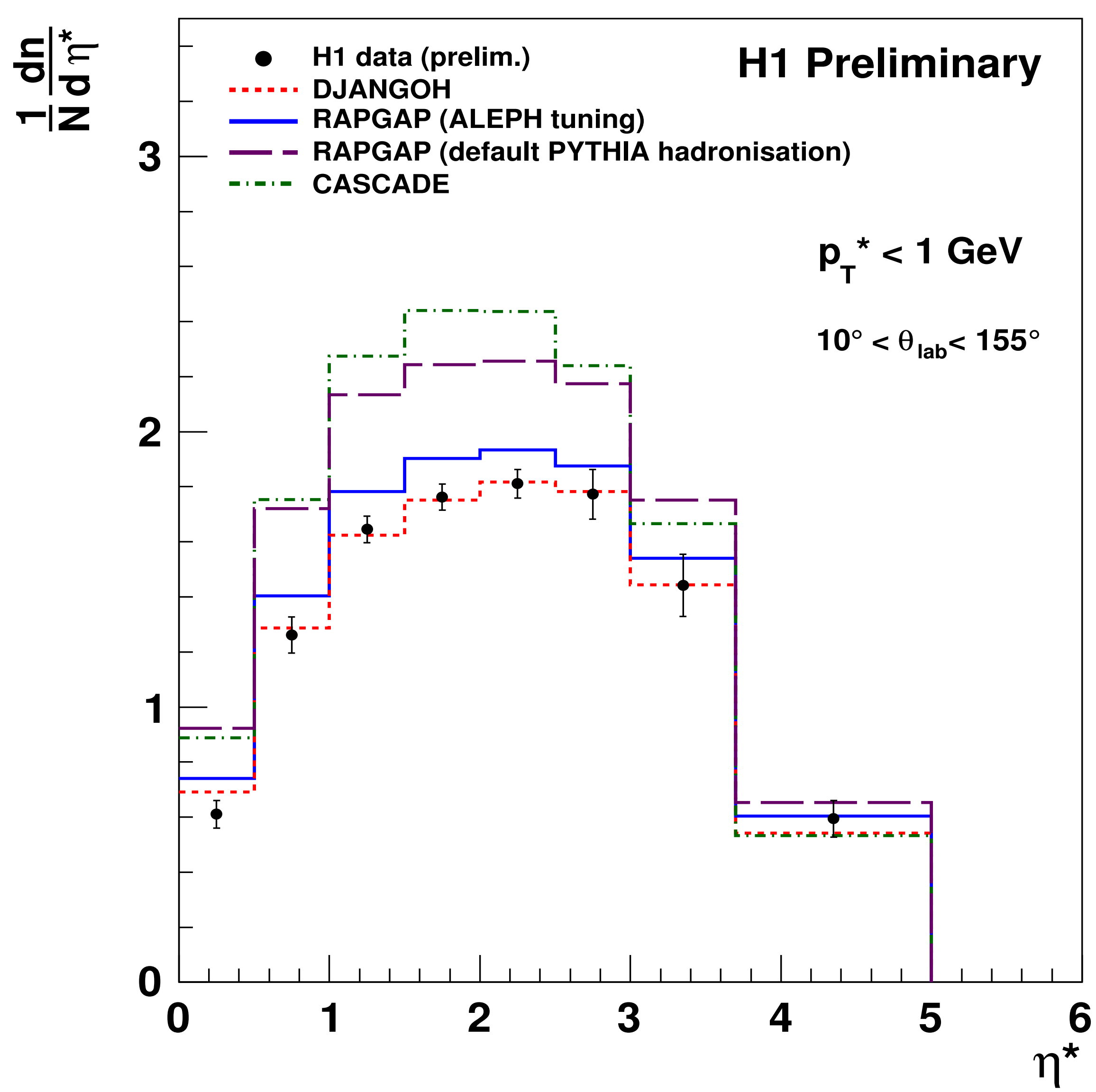
CASCADE(CCFM) describes the data at high p_T^*

Particle pseudorapidity spectra

Charged particles with $p_T^* > 1$ GeV:



Charged particles with $p_T^* < 1$ GeV:

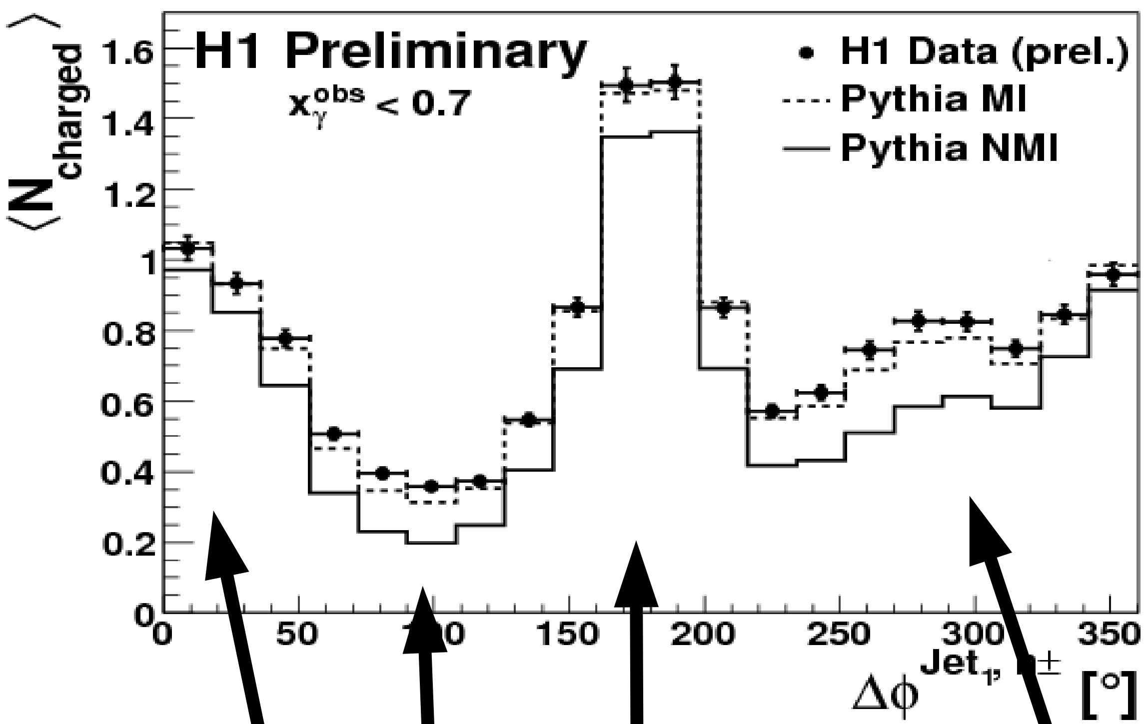


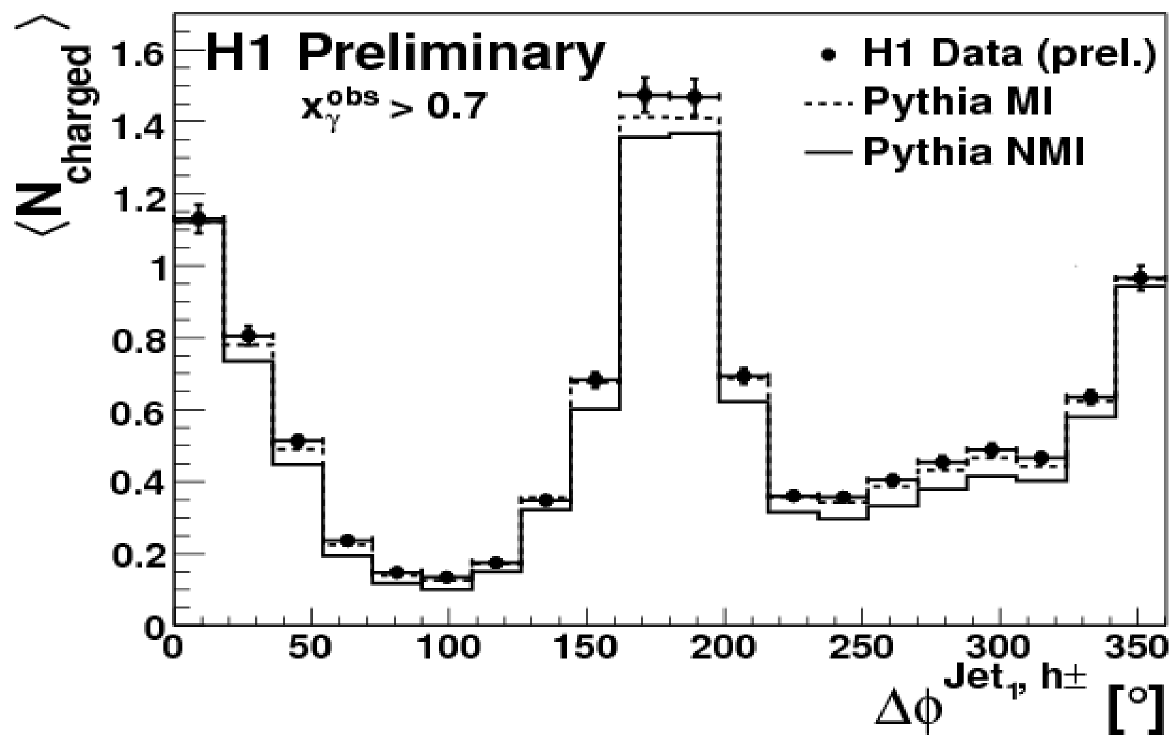
significant sensitivity to parton dynamics
less sensitivity to hadronization

significant sensitivity to hadronization

Charged particle flow in PHP

Measure** charge particle multiplicity **as a function of the** azimuthal difference between the leading jet and the particles, **ΔΦ



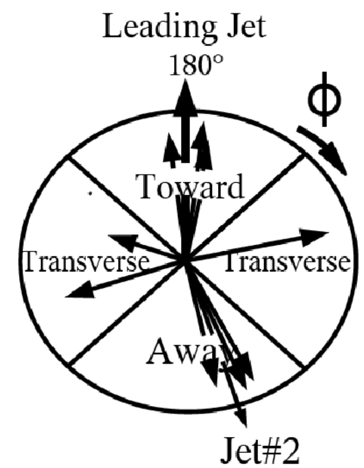


Sub-Leading Jet

High active region

Low active region

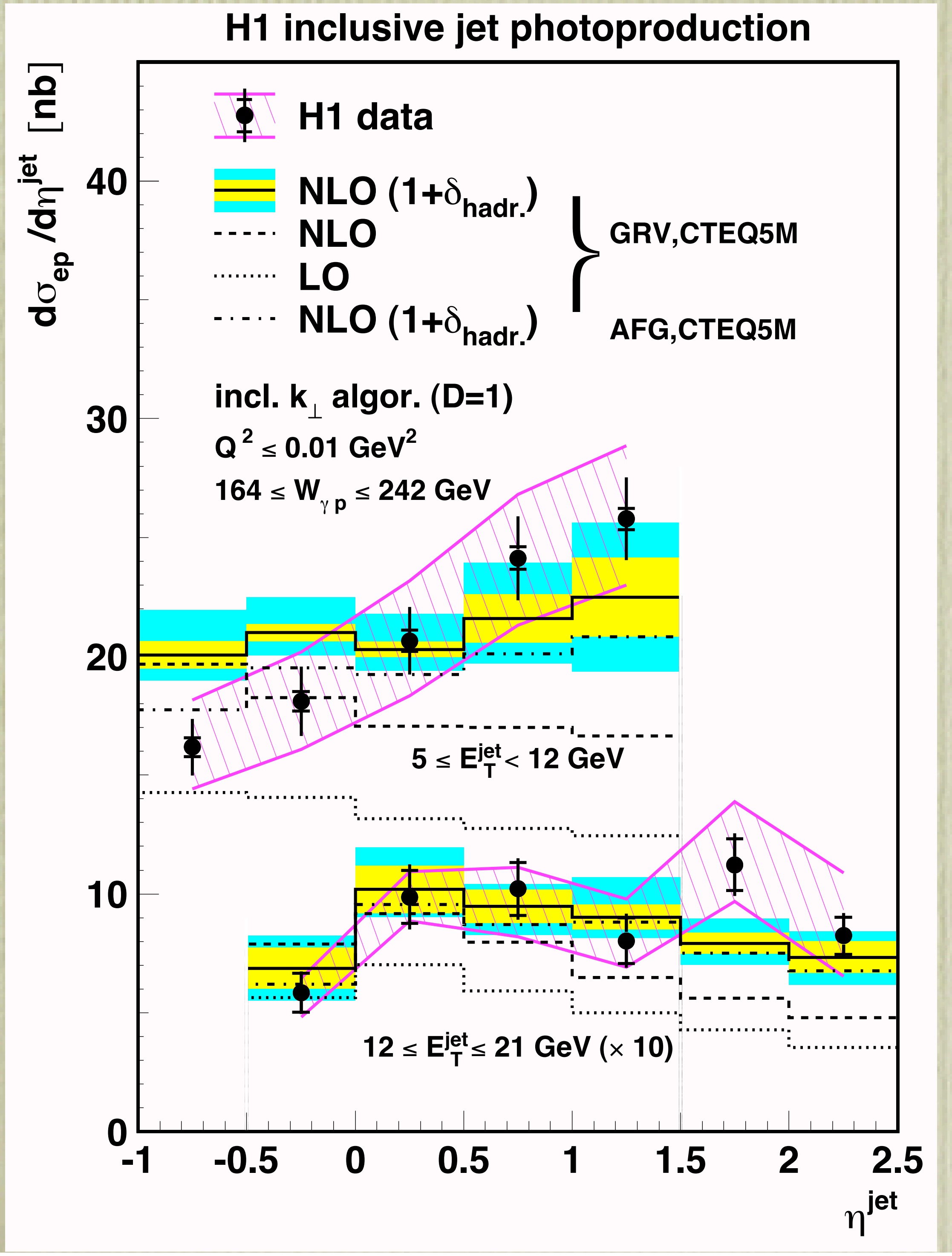
Leading Jet
(Here ΔΦ = 180^0)



~ 0.1 particle at low x gamma

Incl. jets in PHP down to low E_T^{jet}

Inclusive Jets: Data vs. NLO



- *$5 \leq E_T < 12$ GeV*
- *falling LO/NLO prediction for increasing η*
- *with hadronisation, incl. MI, the predictions rise*
- $1 + \delta_{had} = (1 + \delta_{MI})(1 + \delta_{frag})$
- $\delta_{MI} \approx 0.3$ at $\eta \approx -0.75$

  $\delta_{MI} \approx 1.0$ at $\eta \approx 1.25$(p – dir.)

  $\delta_{frag} \approx -0.3$
- *H1, Eur. Phys. J C29 (2003) 497*