ISVHECRI 2014 Symposium on Very High Energy Cosmic Ray Interactions
18-22 August 2014, CERN

Measurement of Feynman-x spectra of Forward Photons and Neutrons in DIS at HERA

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H1 Collaboration *arXiv:1404.9201*
Eur.Phys.J. C74 (2014) 2915

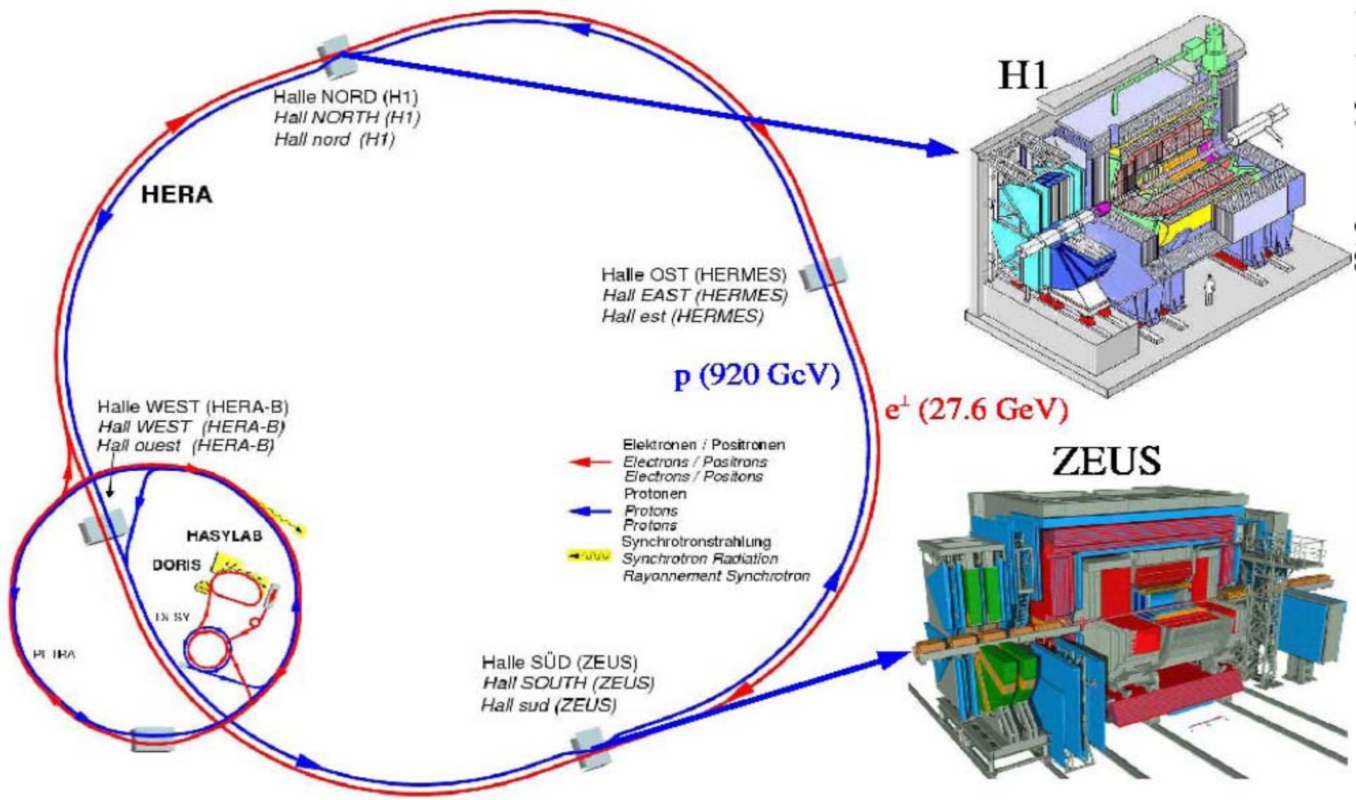
The first electron-proton collider at DESY Hamburg (1992-2007)

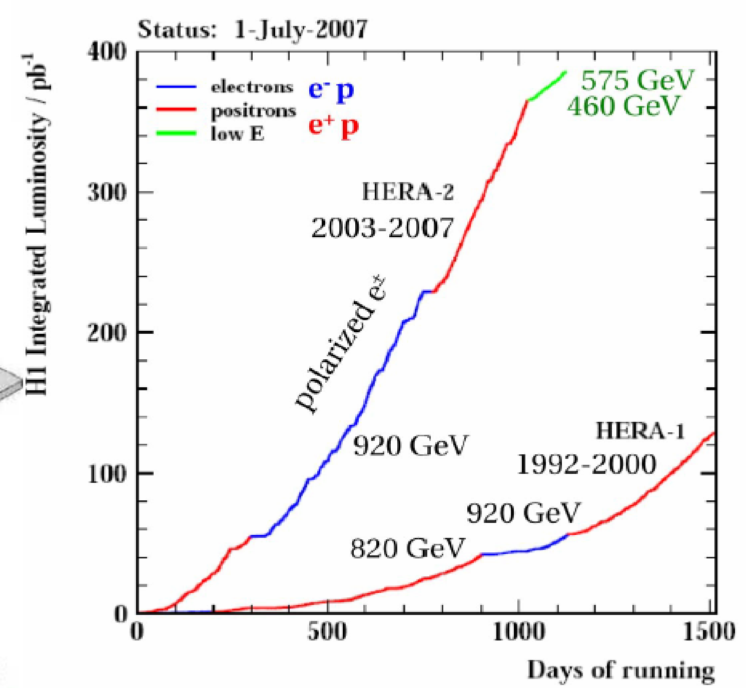
$E_{e\pm}$ = 27.6 GeV E_p = 920 GeV

Total centre-of-mass energy of collision up to $\sqrt{s} \approx 320$ GeV

(equivalent to $5 \cdot 10^{13}$eV photon on a stationary proton target)

Two collider experiments: H1 and ZEUS

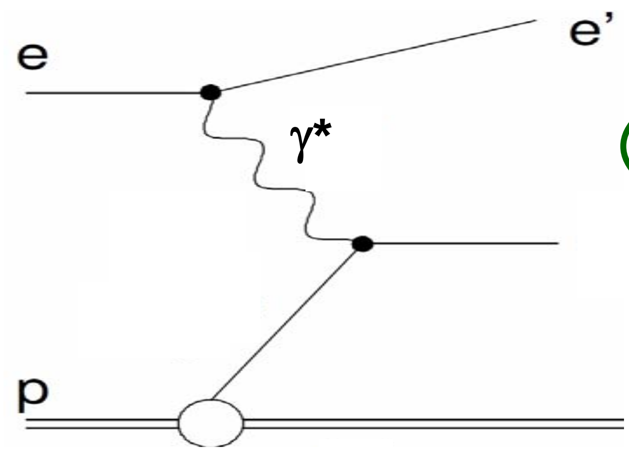


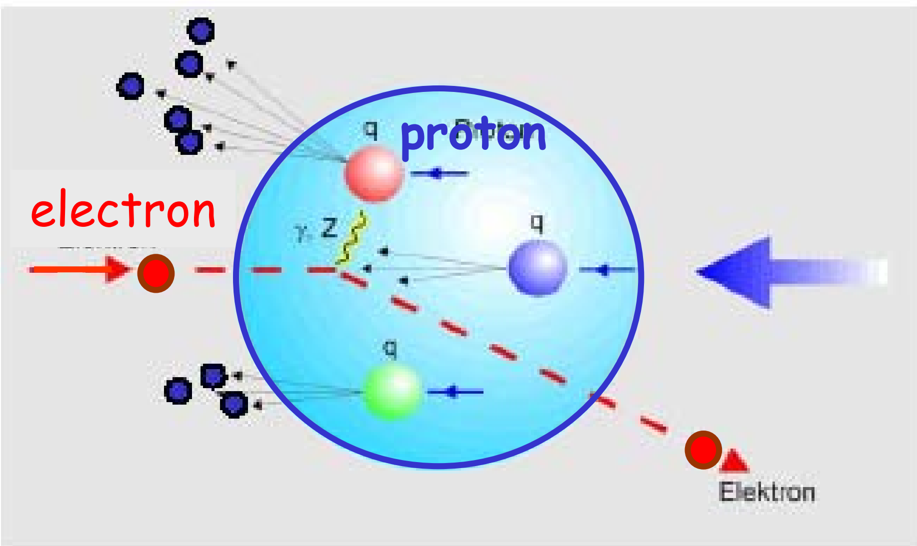


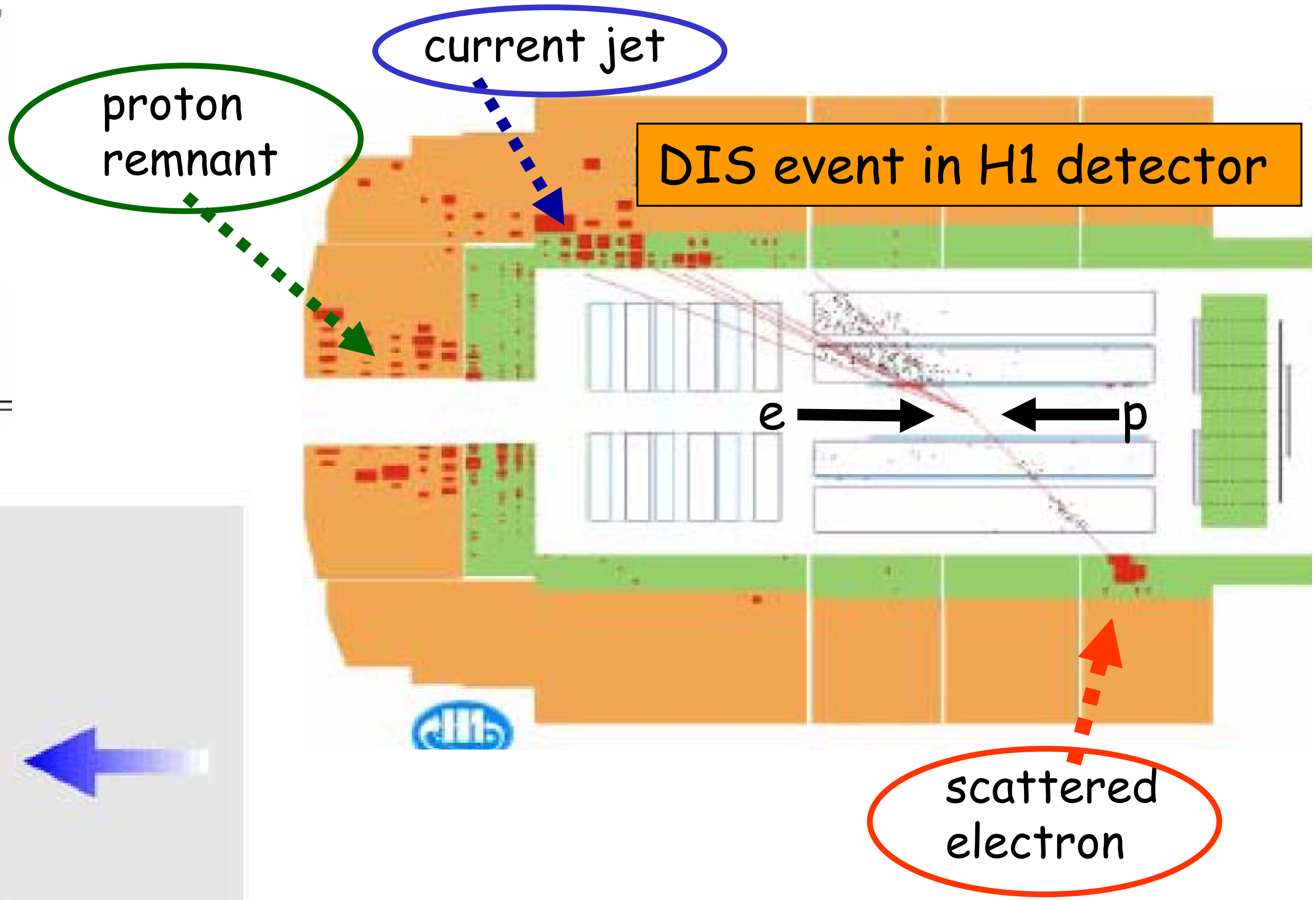
total lumi:
0.5 fb^{-1} per experiment

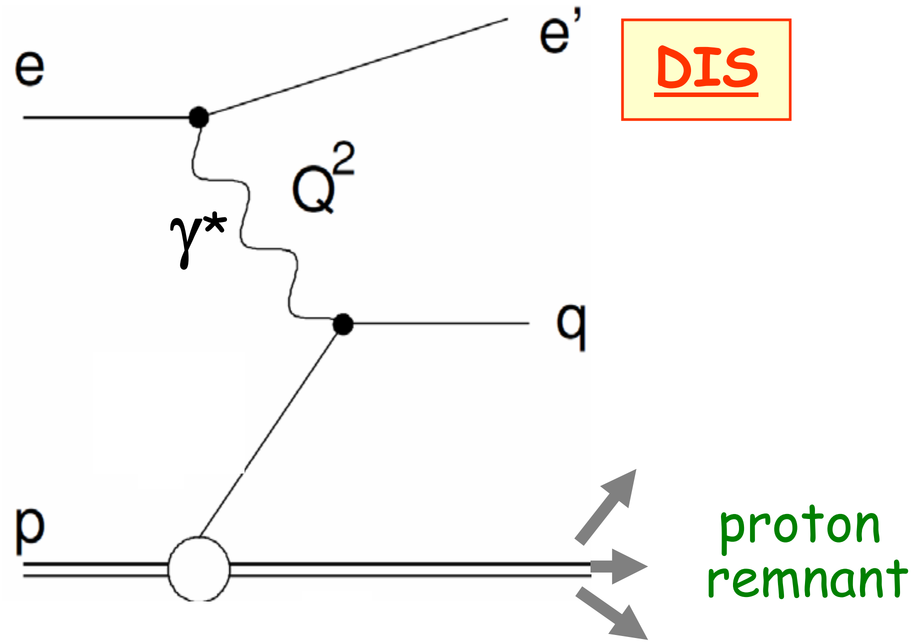
Deep Inelastic electron-proton Scattering (DIS) at HERA

DIS - a probe of proton structure









Significant fraction of *ep* scattering events contains in the final state an energetic very forward particle, which carries a substantial fraction of the energy of the incoming proton

('forward'≡proton fragmentation region)

In central (current) region the hard QCD scale is given by Q^2 (and/or high p_T, m_q) ; the proton fragmentation region is non-pQCD regime - essential differences between theory predictions

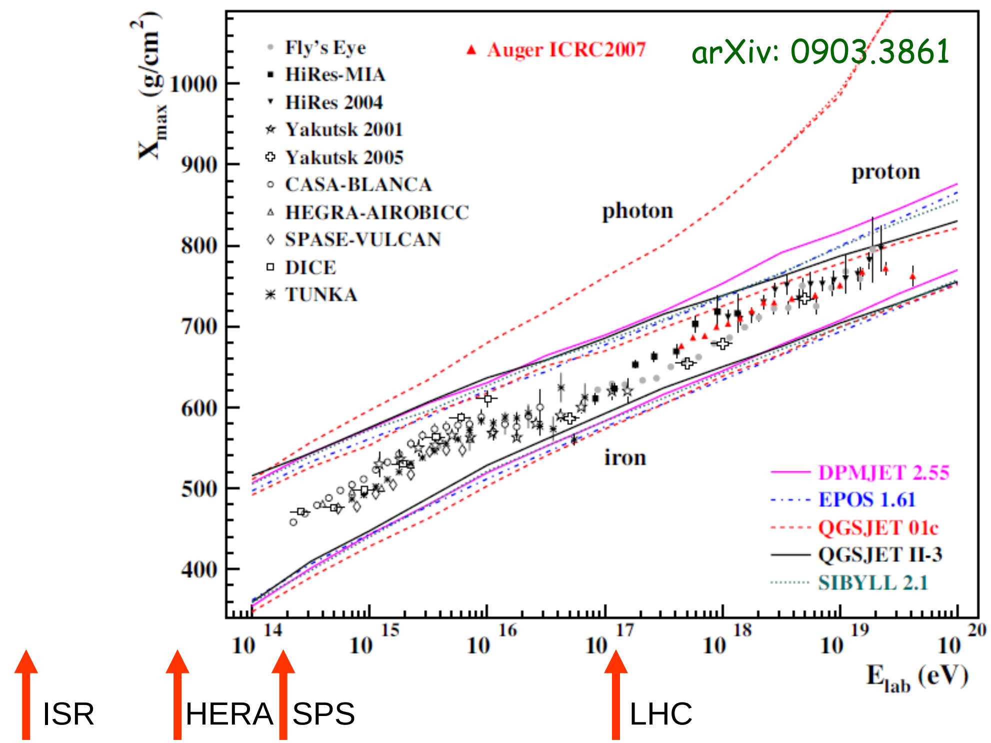
A better understanding of forward particle production is needed

***ep* collisions – a clean environment to study the proton fragmentation**

Measurements very useful for MC model tuning

Motivation: High Energy Cosmic Ray Physics

Shower max vs. CR (lab) Energy



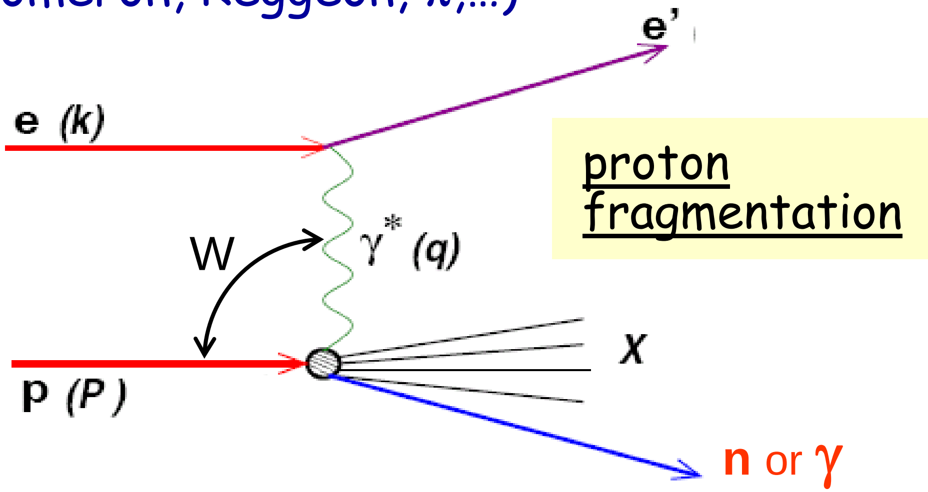
The tuning of cosmic ray interaction models crucially depends on the input from the measurements at accelerators

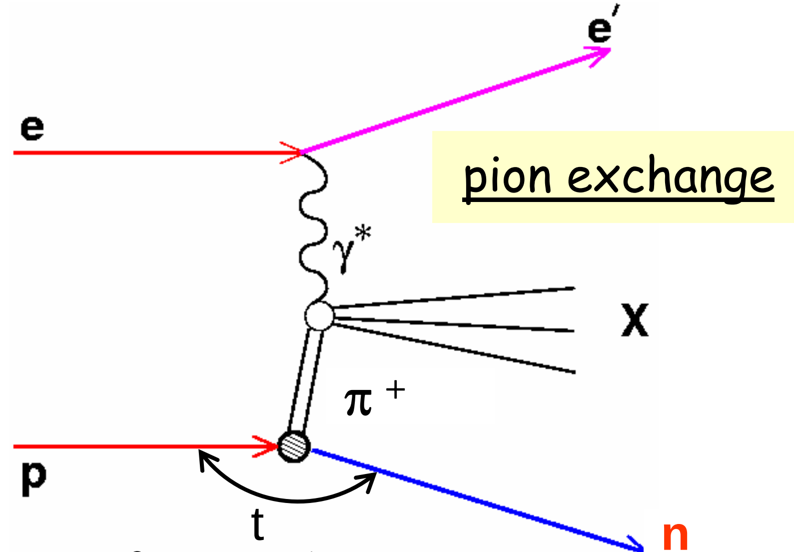
In particular, the forward measurements ($baryons$, π^0, γ) are of the greatest importance, since the shower development is dominated by the forward, soft interactions.

So far, only scarce data on Forward Production at High Energies, e.g. UA5, UA7 (SPS), LHCf at 900 GeV, 7 TeV

Forward neutron and photon production in ep interaction

Energetic forward particles are produced at a very small angles from the fragmentation of proton remnant (e.g. Lund string) or from the exchange mechanism (Pomeron, Reggeon, π,...)





Photons - from proton fragmentation (mainly from π^0 decay)

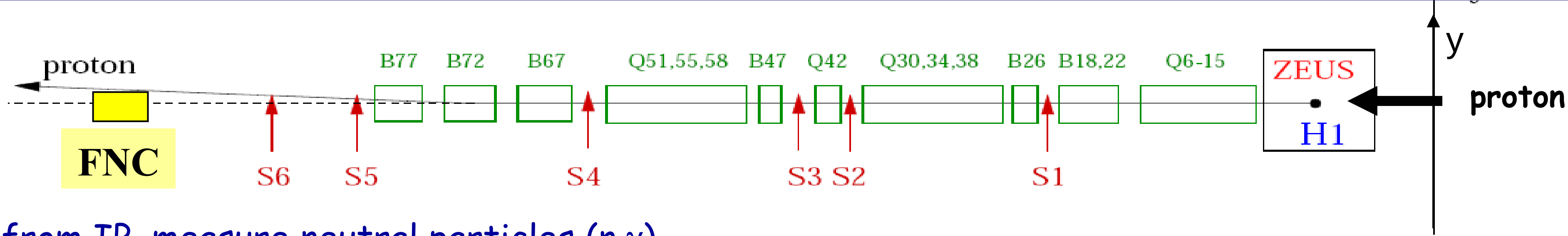
Neutrons - from proton fragmentation **and** from pion exchange

$Q^2 = -q^2 = -(k-k')^2$	photon virtuality
$y = (q\cdot p)/(k\cdot p)$	inelasticity
$W^2 = (q+p)^2$	γ^*p CM energy

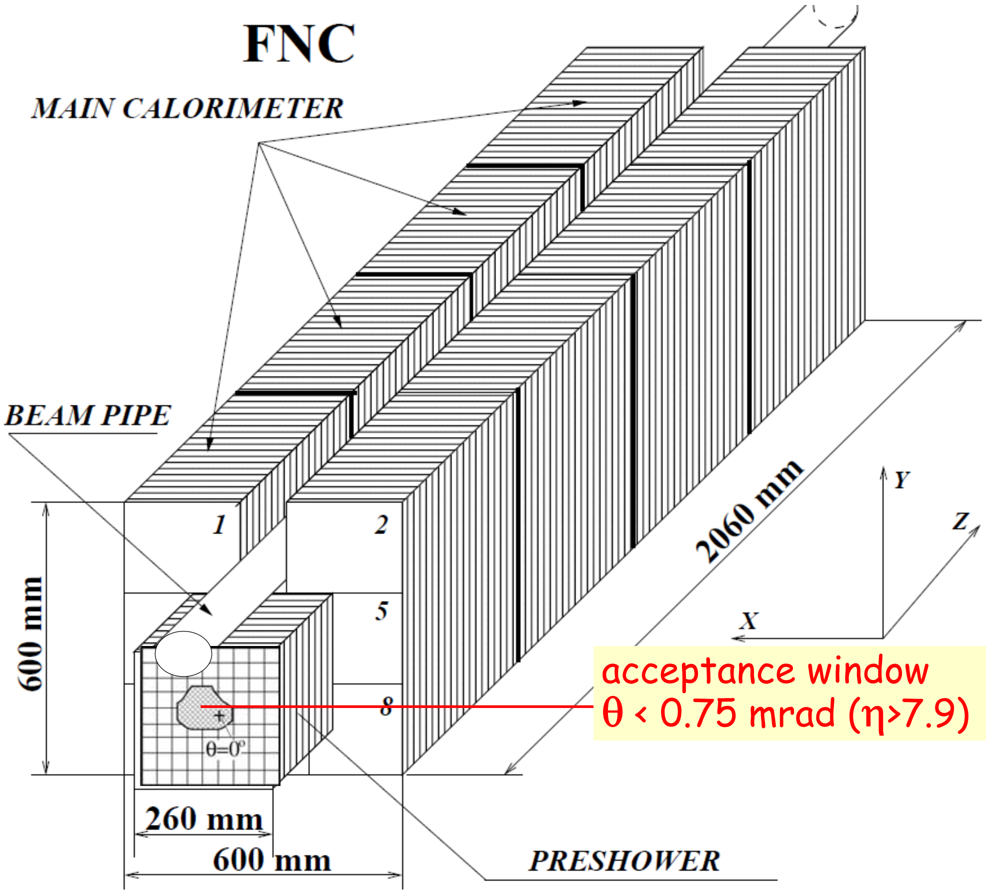
$x_L = E_{n,\gamma}/E_p$	long. momentum fraction
$x_F = \frac{p^*_{\parallel}}{p^*_{\parallel max}} = \frac{2p^*_{\parallel}}{W}$	Feynman x

(for very forward particles $x_F \approx x_L$)

H1 Forward Neutron Calorimeter FNC



106m from IP, measure neutral particles (n,γ)
Acceptance limited by beam apertures and detector size



Main Calorimeter: 8.9λ

$\sigma(E)/E \approx 63\%/\sqrt{E\,[\text{GeV}]} \oplus 3\%$

$\sigma(x,y) \approx 10\text{cm}/\sqrt{\text{E}\,[\text{GeV}]} \oplus 0.6\,\text{cm}$

Preshower: $1.6\lambda\ (60X_0)$

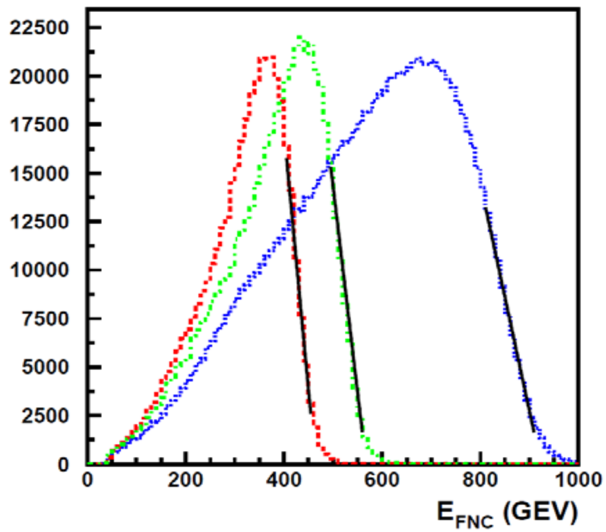
$\sigma(E)/E \approx 20\%/\sqrt{E\,[\text{GeV}]} \oplus 2\%$

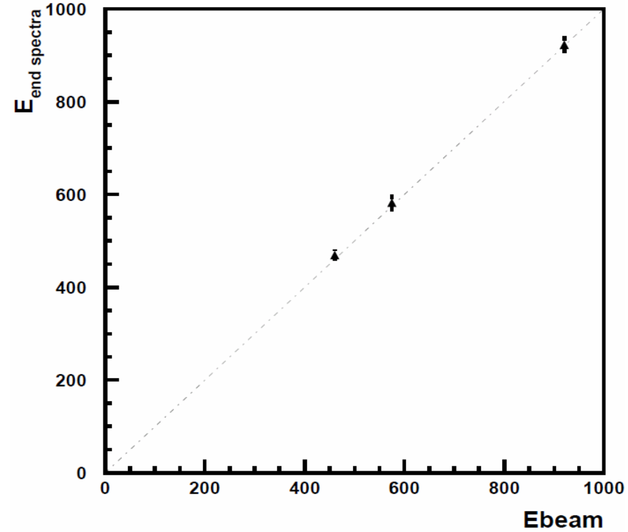
$\sigma(x,y) \approx 2\text{mm}$

Control of energy calibration and linearity check

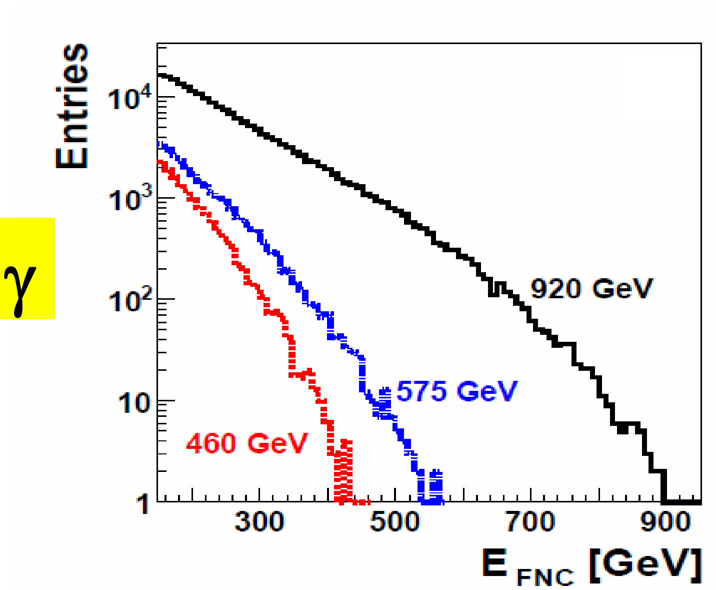
HERA ep data: LER (460 GeV), MER (575 GeV), HER (920 GeV)

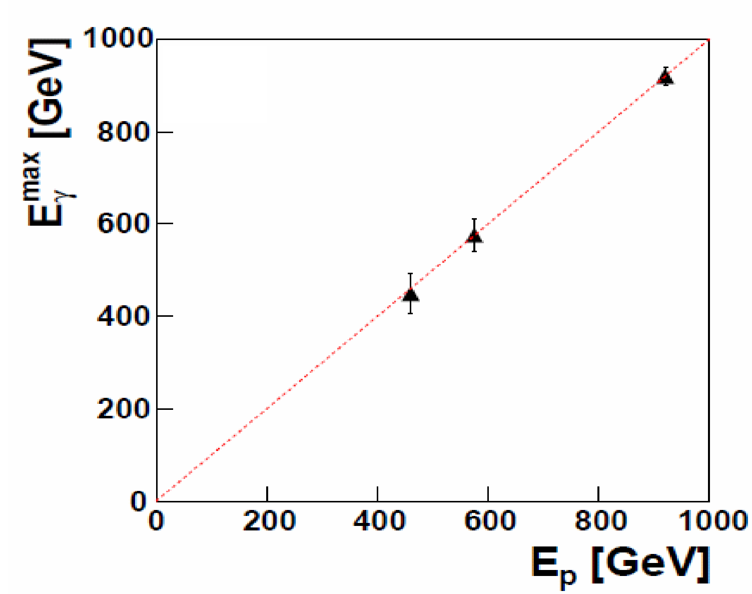
n





γ

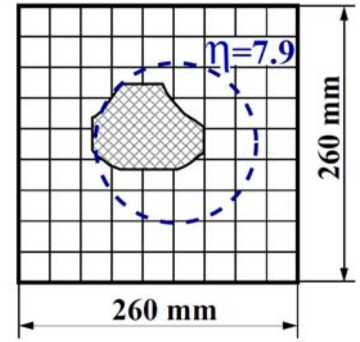




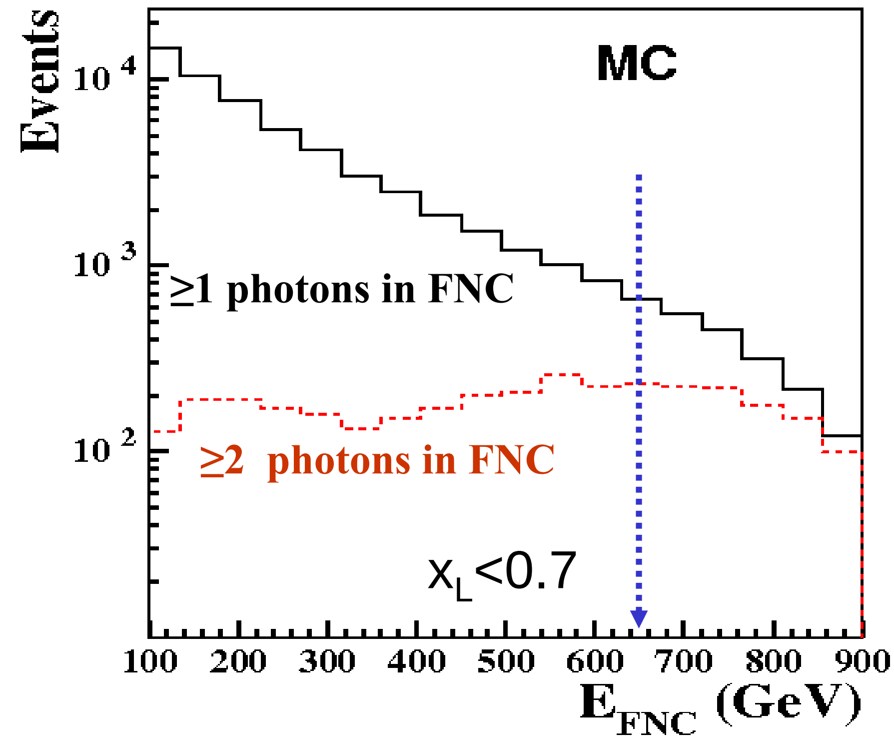
The phase space of the measurements

HERA II period 2006-2007
Luminosity= 131 pb^{-1}
230000 neutron events; 83000 photon events

NC DIS Selection	
$6 < Q^2 < 100$ GeV^2	
$0.05 < y < 0.6$	
$70 < W < 245$ GeV	
Forward photons	**Forward neutrons**
$\eta > 7.9$	$\eta > 7.9$
$0.1 < x_F < 0.7$	$0.1 < x_F < 0.94$
$0 < p_T^* < 0.4$ GeV	$0 < p_T^* < 0.6$ GeV
W ranges for cross sections $\frac{1}{\sigma_{DIS}} \frac{d\sigma}{dx_F}$	
$70 < W < 130$ GeV	
$130 < W < 190$ GeV	
$190 < W < 245$ GeV	



at high x_L, many photon candidates FNC clusters originate from more than one photons;
→ suppress multi-photon events with cut x_L<0.7



Results

- Study the energy dependence of forward photon and neutron production
- Measure cross sections $\sigma_{n,\gamma}/\sigma_{DIS}$ vs $W_{\gamma p}$
- Measure cross sections $1/\sigma_{DIS}\ d\sigma/dx_F$

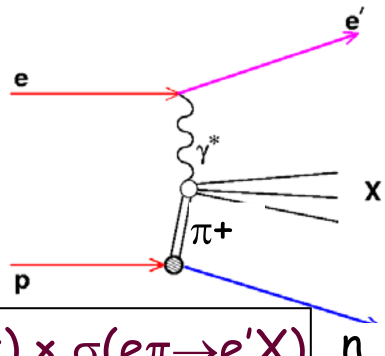
  (cross sections are normalised to the total DIS cross section σ_{DIS})
- Confront MC predictions with the measurements

I. Confront commonly used ep scattering MC models with data

LEPTO: DJANGOH & Leading Log PS for higher orders; SCI option for forward photons

CDM: DJANGOH & ARIADNE with Colour Dipole Model for higher orders

RAPGAP-π: RAPGAP, virtual photon scattering off the exchanged pion



Two production mechanisms for neutrons:
data is well described by linear combination of proton fragmentation and π-exchange simulations

$$\sigma(ep \rightarrow e'nX) = f_{\pi/p}(x_L,t) \times \sigma(e\pi \rightarrow e'X)$$

pion flux | eπ scattering

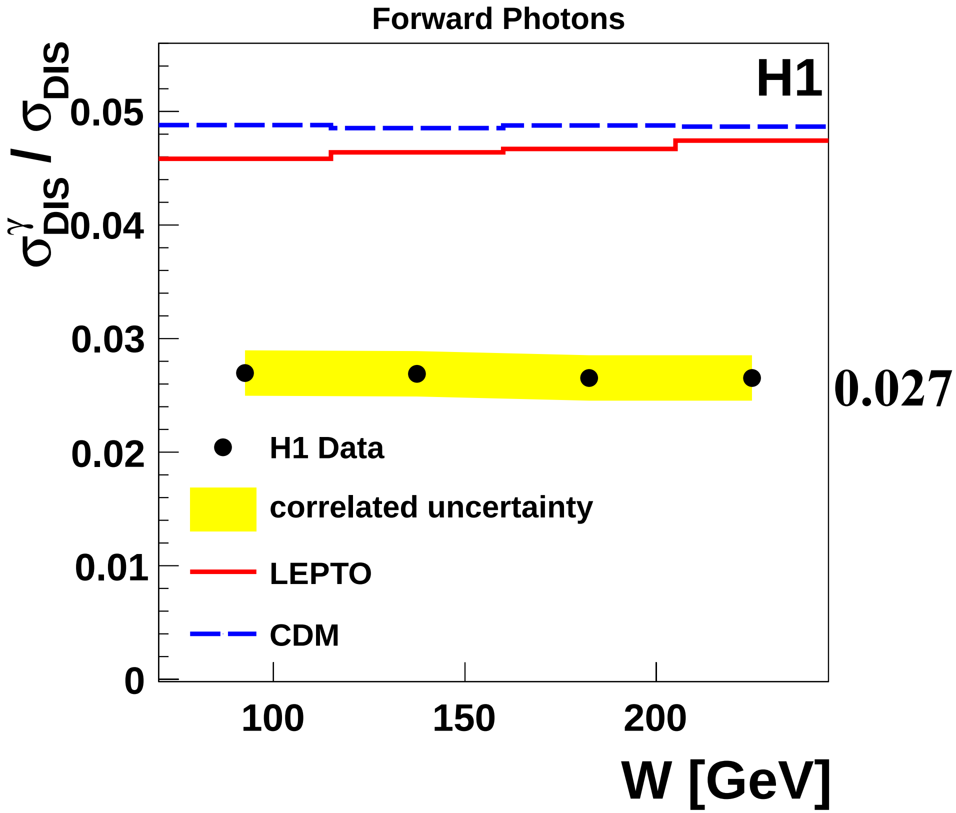
II. Confront Cosmic Ray hadronic interaction models with data

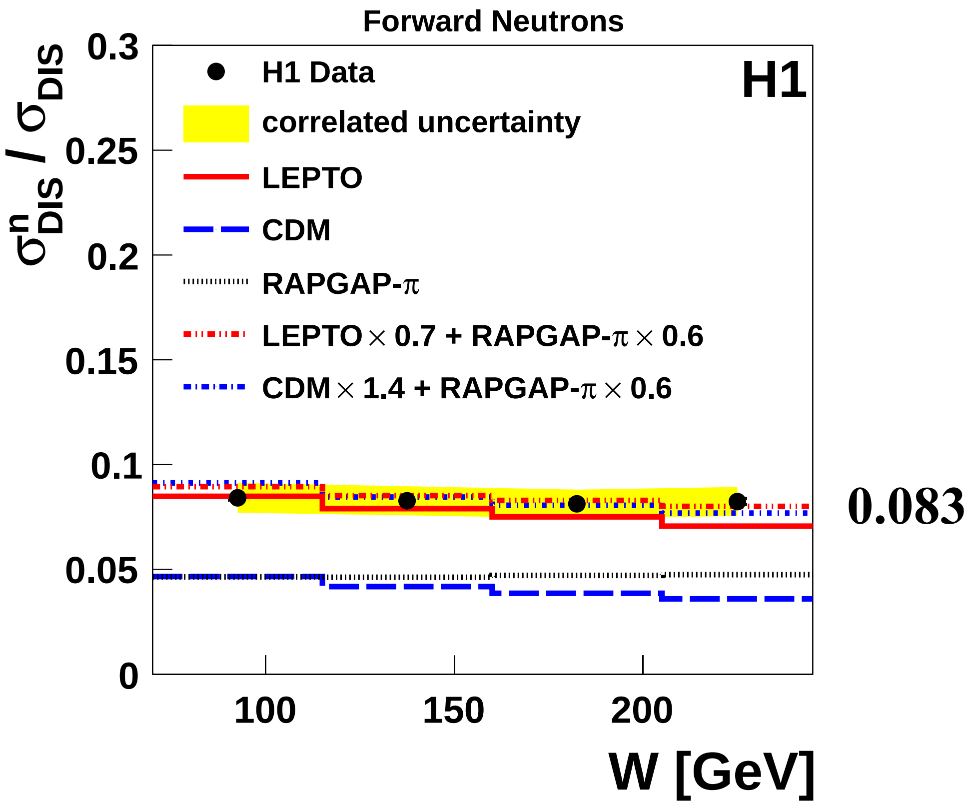
EPOS LHC, SIBYLL 2.1, QGSJET 01, QGSJET II-04

(thanks to Tanguy Pierog, Ralph Engel and Sergey Ostapchenko for providing the model predictions)

- Programs adapted to ep scattering kinematics via interface to PHOJET
- Based on Regge theory, Regge-Gribov approximation, pQCD, Unitarisation
- Internal differences in treatment of minijet production, colour string formation, fragmentation, saturation, multiparton interactions, hadron remnant treatment

Normalised Cross Sections as a function of W

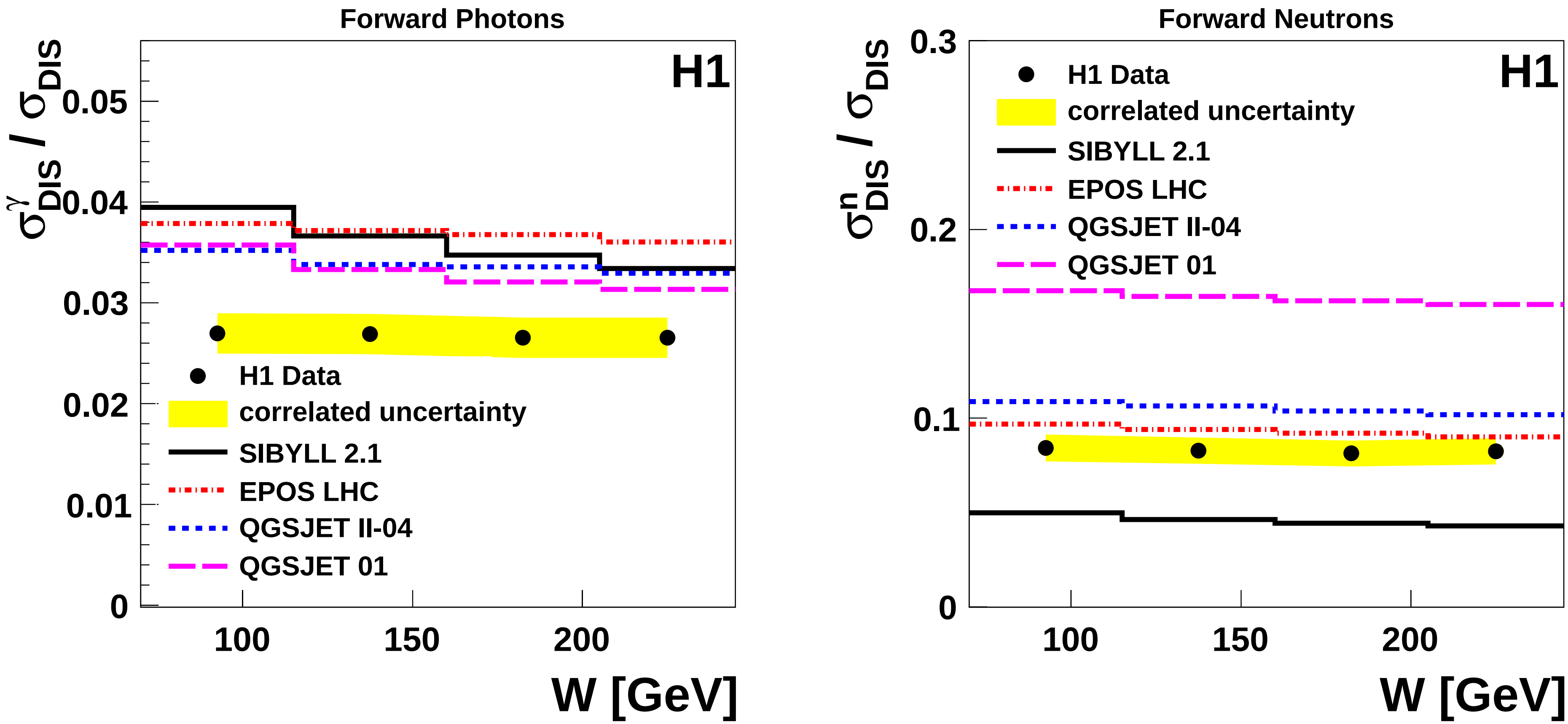




Fraction of forward photons and neutrons in DIS events independent of W
➔ limiting fragmentation

- LEPTO and CDM predict too high rate of photons, by ~70%
- LEPTO predicts the neutron rate rather well, CDM has too low rate
- slight W dependence for LEPTO (opposite for photons and neutrons)
  ~constant W dependence for CDM

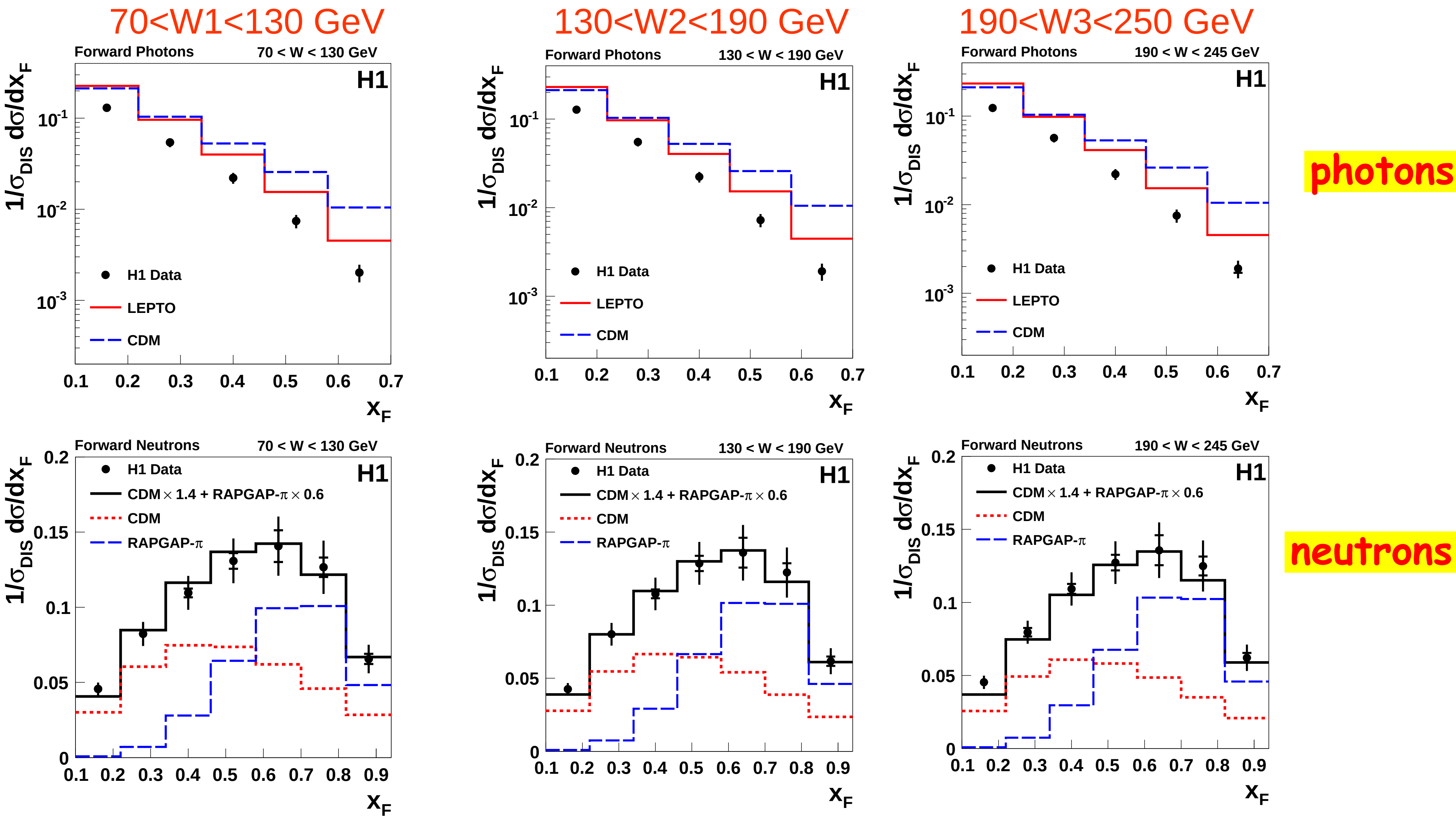
Normalised Cross Sections as a function of W



- All CR models predict too high rate of forward photons, by 30÷40%
- Large spread in the forward neutron predictions
- EPOS LHC closest, but still different

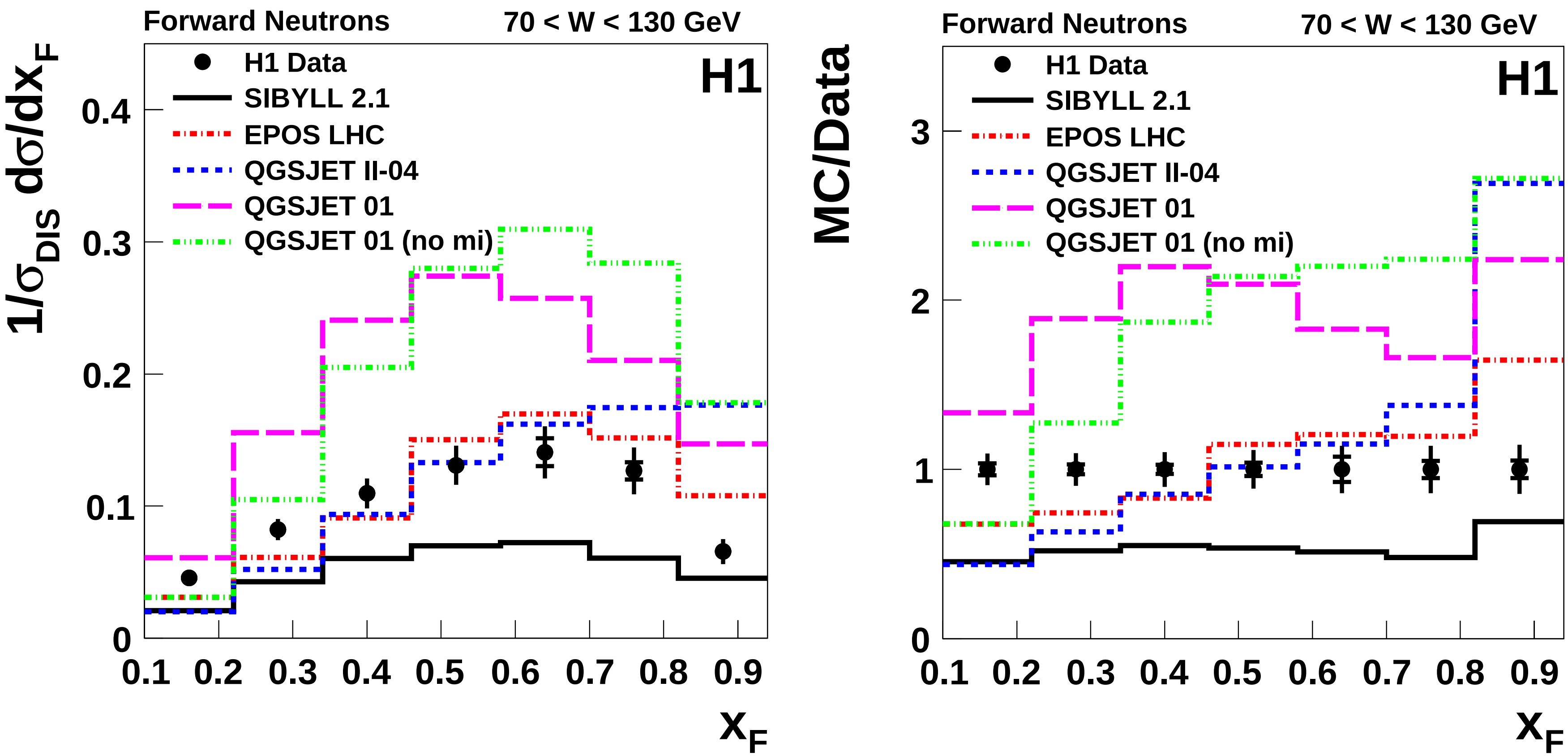
- CR models indicate a slight W dependence for photons, but less for neutrons

Normalised Cross Sections as a function of x_F in 3 W-intervals



- Both LEPTO and CDM overestimate the photon rate significantly
- LEPTO describes the shape of photon x_F spectra well, CDM is too hard
- Neutron x_F spectra well described by Combination of MC models

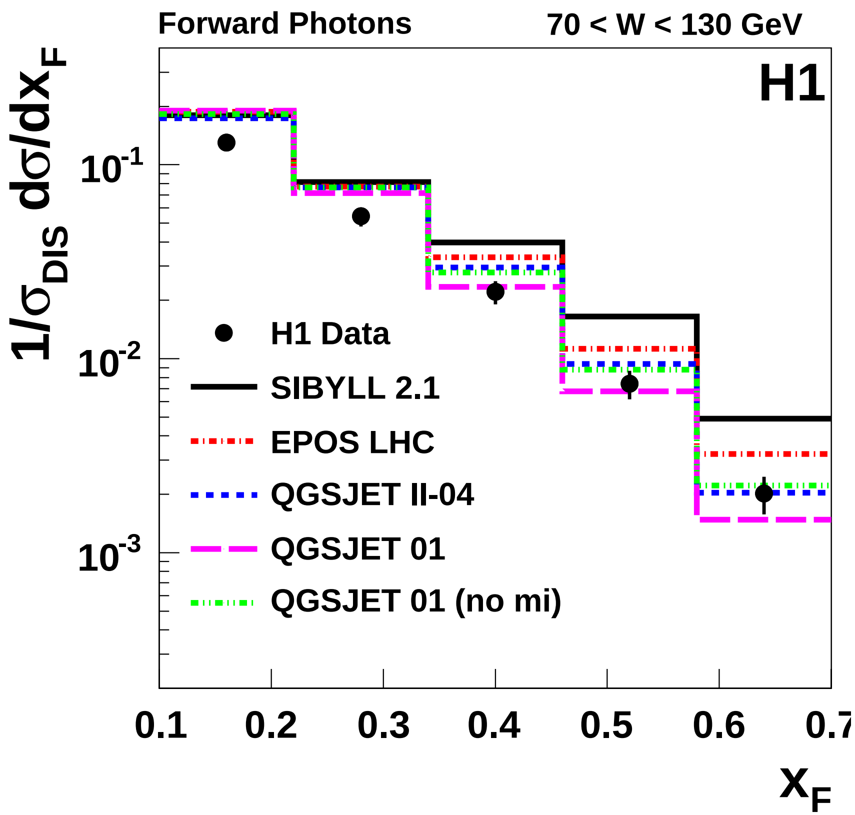
Normalised Cross Sections as a function of x_F: Neutrons

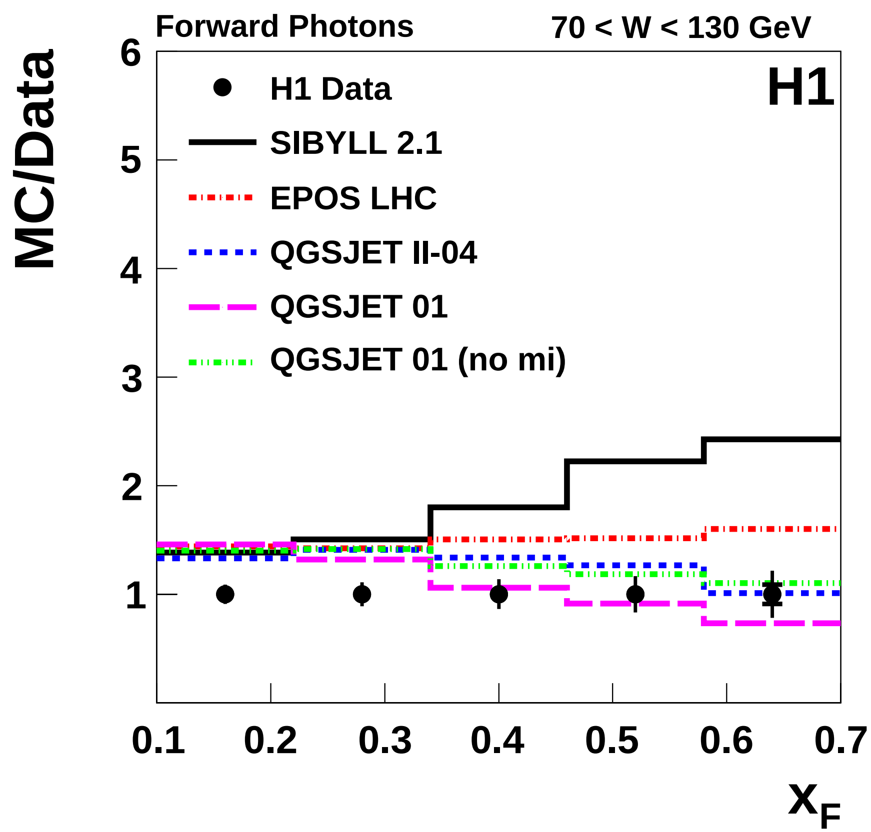


(other W-ranges look similar)

- CR models predict very different neutron rates
- SIBYLL 2.1 describes the x_F dependence (shape) but too low rate
  EPOS LHC gives reasonable description, except at highest x_F
  QGSJET II-04 model is too hard and predict too high rates
  QGSJET 01 – too high rates
  Multi-parton interactions in QGSJET 01: harder x_F dependence with "no mi"

Normalised Cross Sections as a function of x_F: Photons



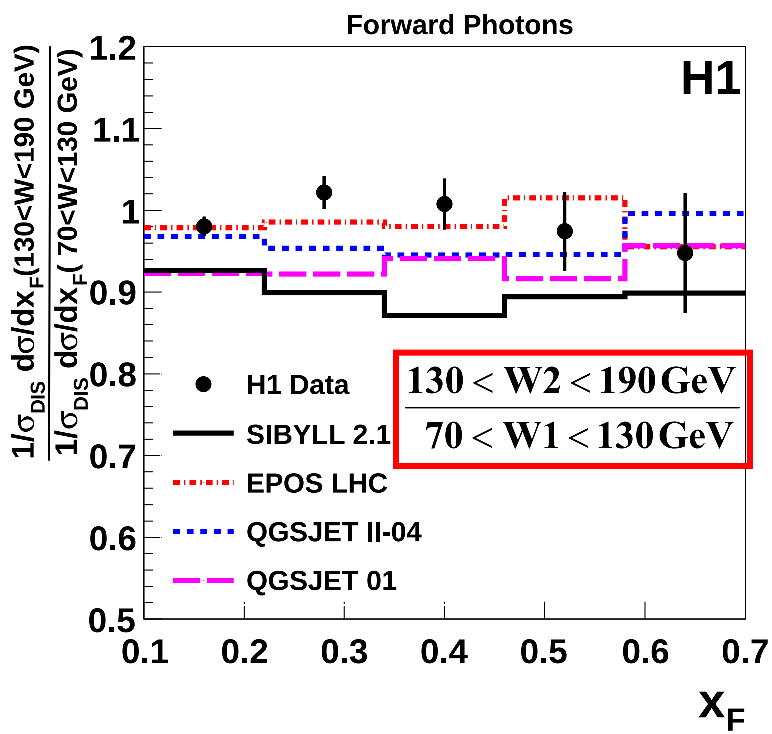


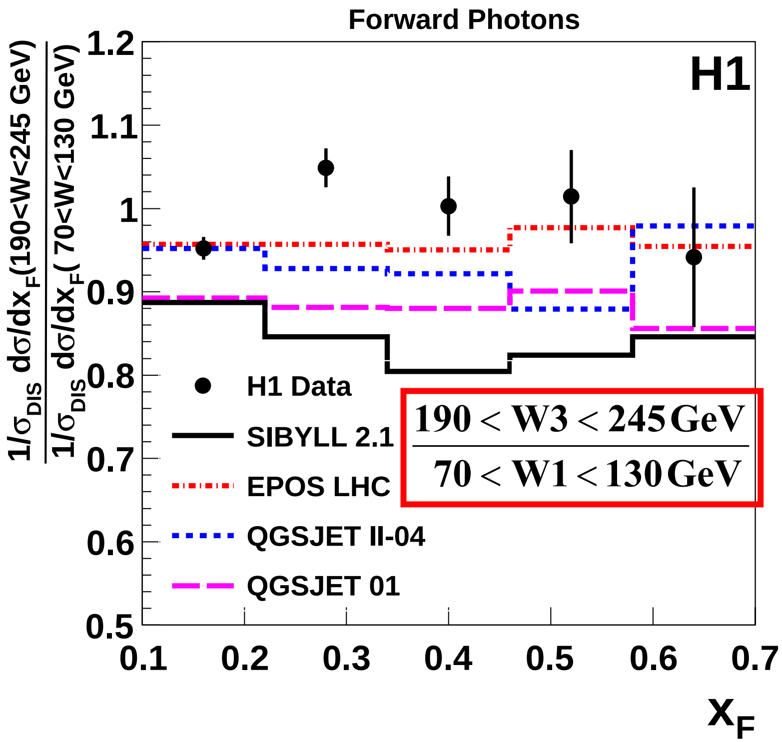
(other W-ranges look similar)

- CR models predict higher photon rates (30÷40%), but better than standard DIS models
- x_F dependence:
  QGSJET models are too soft
  SIBYLL 2.1 is too hard
  EPOS LHC gives the best description os a shape (somewhat too hard)
- Multi-parton interactions: only small effect in QGSJET 01 (no mi)

Feynman scaling:

- expect Feynman-x distribution to stay unchanged in the high energy limit;
- compare x_F distributions in three energy intervals by making ratios

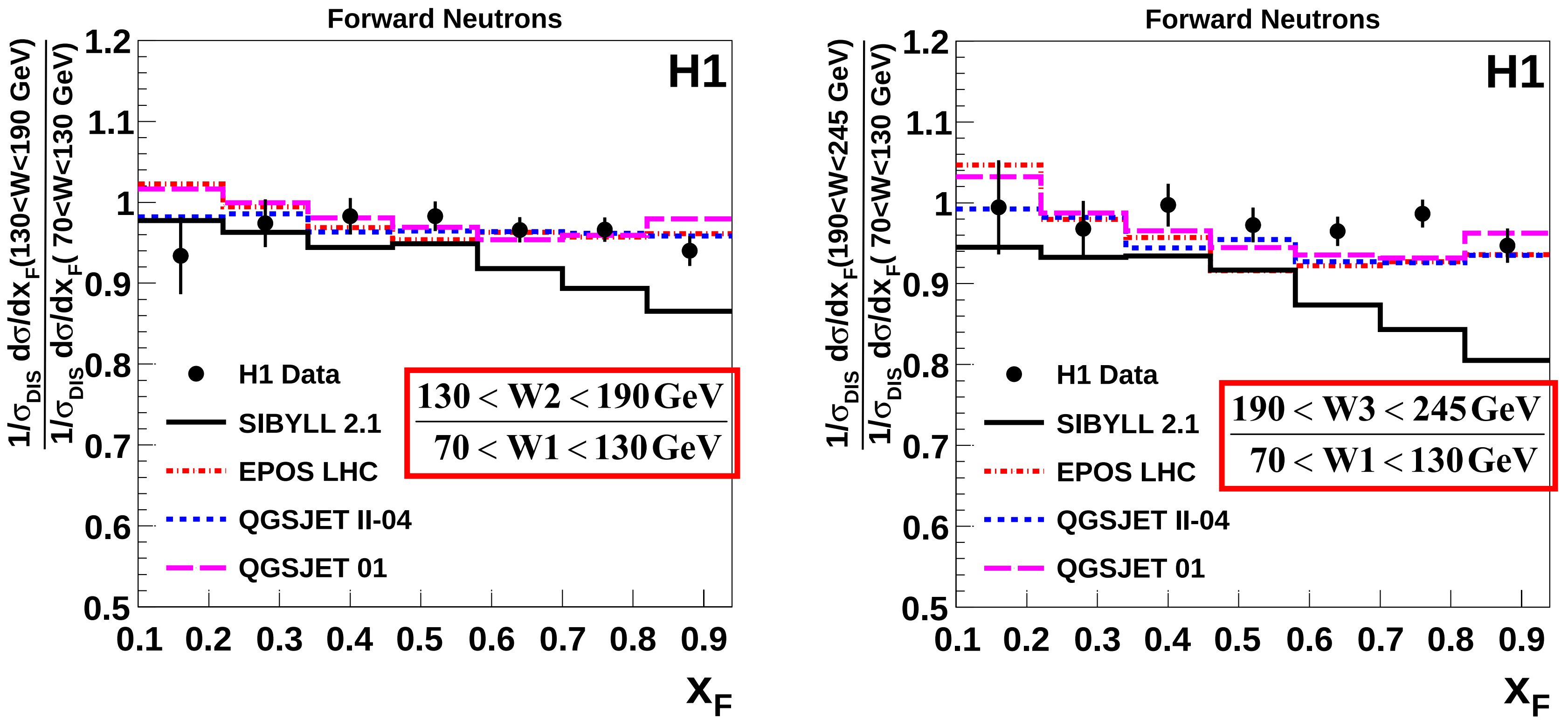




Data compatible with Feynman scaling for forward photons

CR models: Feynman scaling violated (lower rates with increasing W)
Effect strongest for SIBYLL and QGSJET
EPOS LHC closer to data

Test of Feynman Scaling: Neutrons vs CR models



Data compatible with Feynman scaling for forward neutrons

<u>**CR models**</u>: compatile with Feynman scaling except SYBILL

Summary

- precision measurements of forward protons and neutrons in ep collisions,

  $6<Q^2<100$ GeV^2, $0.05<y<0.6$, $\eta>7.9$

- forward γ and n measurements are **consistent with the hypotheses of limiting fragmentation and Feynman scaling** in W range 70 GeV -245 GeV

- large sensitivity to the proton fragmentation models
- ep DIS models (LEPTO, CDM) overestimate photon rate by 70%
  Shapes of photon spectra described by LEPTO; CDM fails at large x_F
- fragmentation models underestimate the leading neutron yield at high x_L

neutron energy spectra well described by the combination of 'standard' fragmentation and exchange models;

- all CR models predict higher yield of photons by 30÷40%
- none of CR models is able to describe photon and neutron rate simultaneously well
- EPOS LHC is closest to give a good description, but still different

- Outlook: new information to improve understanding of proton fragmentation
  new input to MC model simulation of collider and cosmic ray data

Future Physics with HERA Data for Current and Planned Experiments

11-13 November 2014 *DESY Hamburg*
Europe/Berlin timezone

Search

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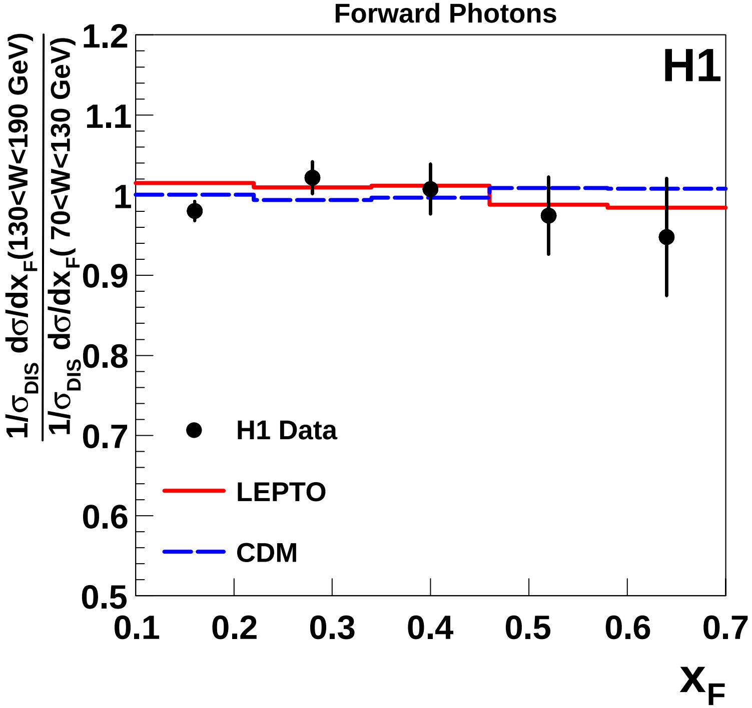
The workshop addresses the question:
Which measurements could/should be still carried out with the unique HERA data collected by the H1, ZEUS and HERMES experiments and what is their relevance/impact on current or future experiments at the LHC, ILC, LHeC, EIC or other facilities?

Topics:
o Proton structure and PDFs
o Nucleon spin
o 3D nucleon structure
o Diffraction and low x
o Hadronic final states
o Jets and heavy flavours
o Monte Carlo development and tuning

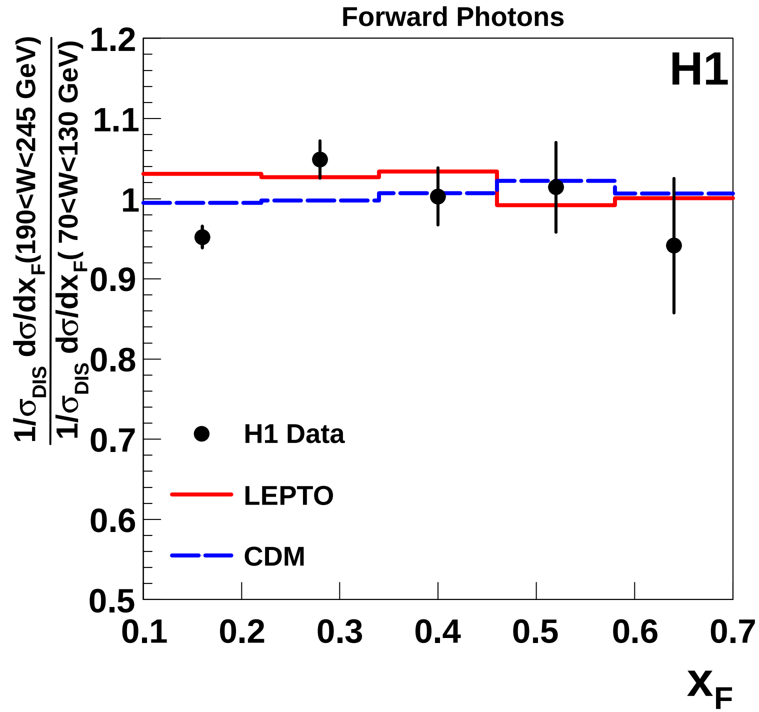
The workshop starts with a symposium on the latest HERA results and continues with topical sessions.

Feynman scaling:

- expect Feynman-x distribution to stay unchanged in the high energy limit;
- compare Feynman-x distributions in three energy intervals



$$\frac{130 < W2 < 190\,GeV}{70 < W1 < 130\,GeV}$$



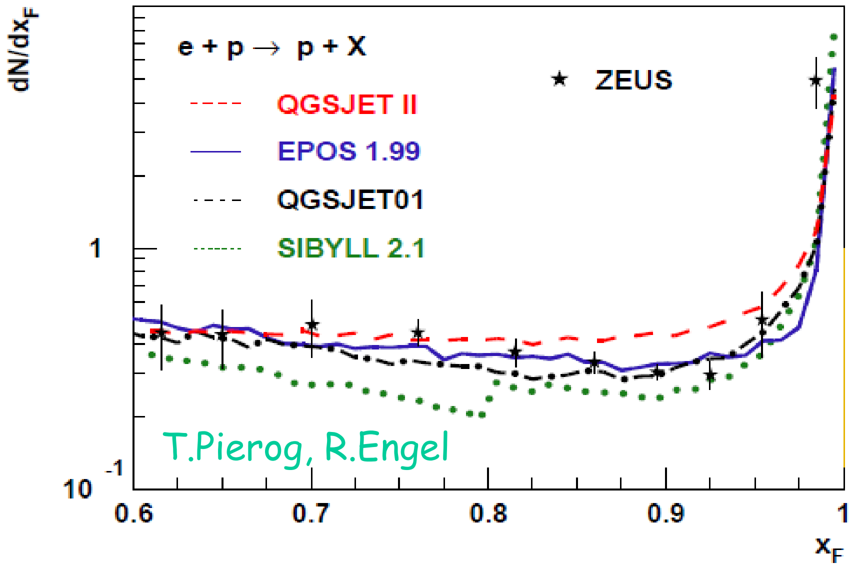
$$\frac{190 < W3 < 245\,GeV}{70 < W1 < 130\,GeV}$$

Data and fragmentation models are compatible with Feynman scaling

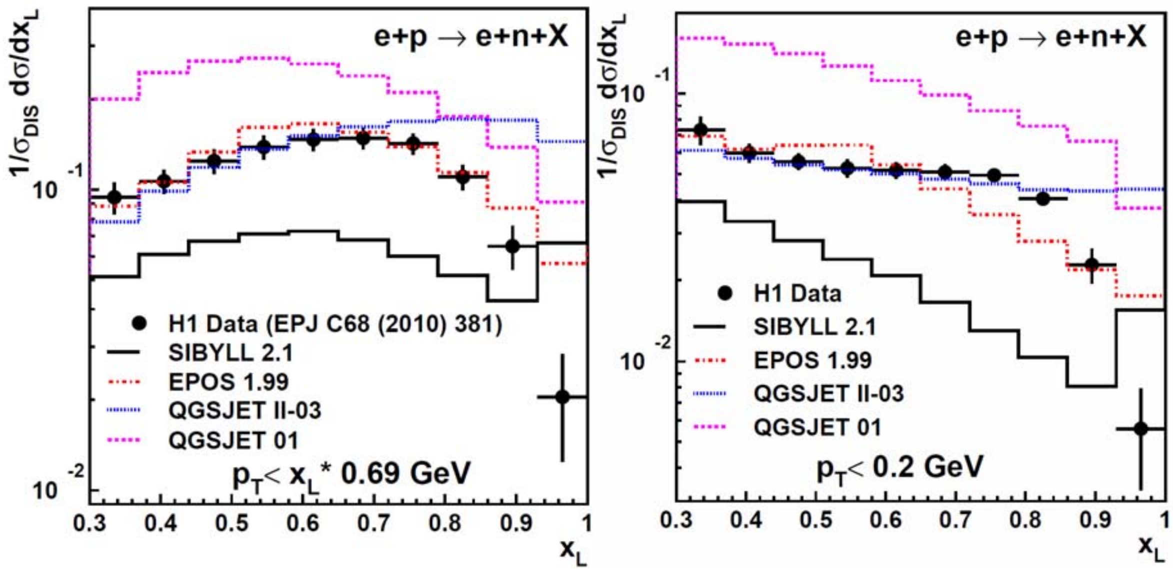
The tuning of cosmic ray interaction models crucially depends on the input from the measurements at accelerators

In particular, the forward measurements (baryons, π^0 , γ) are of the greatest importance, since the shower development is dominated by the forward, soft interactions.

Leading protons



Leading neutrons



Comparison HERA leading baryons vs CR models:

EPOS 1.9: *(Pierog, Werner)*
QGSJET 01 and II: *(Kalmykov, Ostapchenko)*,
SIBYLL 2.1: *(Engel, Fletcher, Gaisser, Lipari, Stanev)*

- reasonable predictions for leading **proton** data
- large difference between models for leading **neutrons**;

The Year is 1969 ... Quark Model proposed, but no Gluons, no pQCD

Limiting Fragmentation

J.Benecke et al. Subm. 8/1969
Publ. 12/1969

PR 188 (1969) 2159

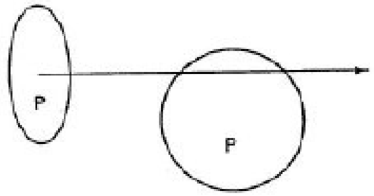


Fig. 4. Passage of Lorentz-contracted projectile through an extended target in the lab system.

Feynman Scaling

R.P.Feynman Subm. 10/1969
Publ. 12/1969

PRL 23 (1969) 1415

Both concepts based on the same fact: the Lorentz Contraction of the Projectile

Both concepts aim at Finding Regularities in Multi-Particle Production

Both Hypotheses predict that cross sections at high enough energy for given particles approach limits, with different limits for different particles.

Thus, both hypotheses predict a Scaling Behaviour:

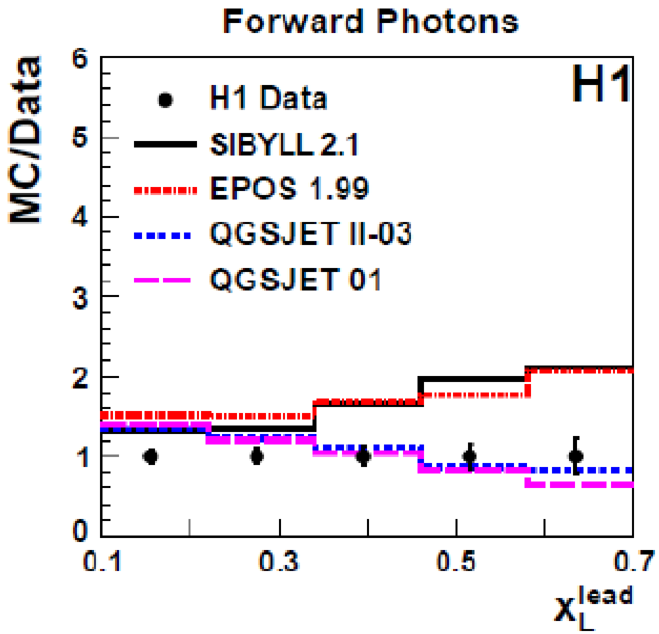
Cross sections measured at high enough energies allow predictions about cross sections at still higher energies --> CR MC Models

Are Limiting Fragmentation and Feynman Scaling the same thing ?

Yes, in the Fragmentation Region they are identical.

But, Feynman Scaling was proposed to be valid also in the Central Region, at small values of Longitudinal Momenta.

Forward photon production: compare H1 vs LHCF



Different behaviour of MC models for H1 and LHCF data