Hadronic Final States at HERA

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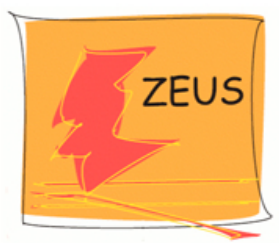
On behalf of H1 and ZEUS Collaborations
ISMD 2012, Kielce

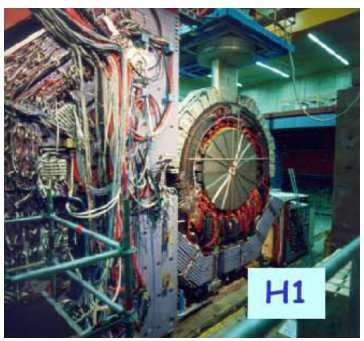


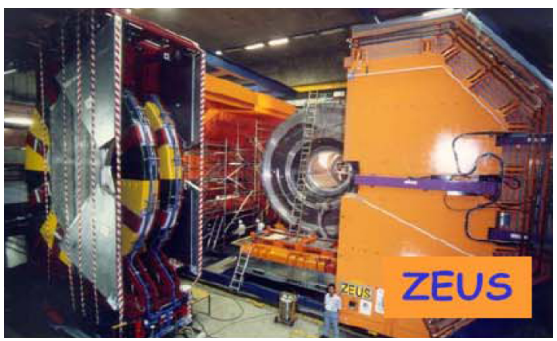
Outline

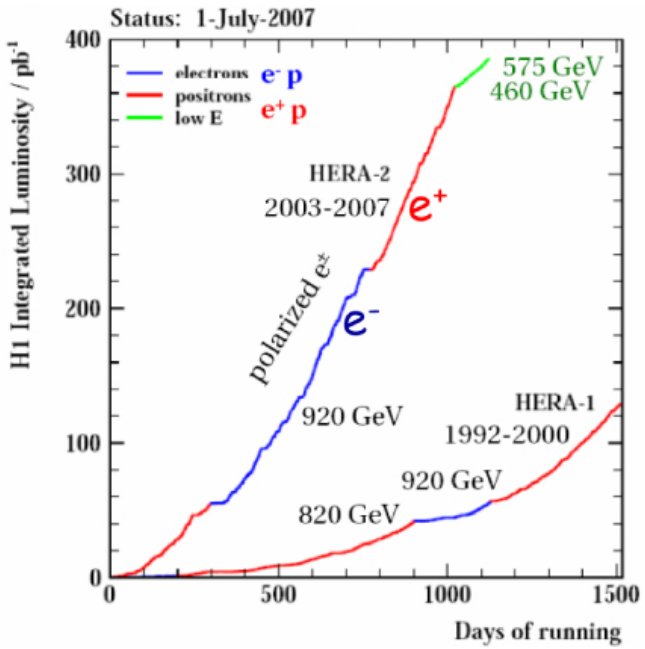
★ **Hard QCD:**
- Prompt photons + jets in DIS

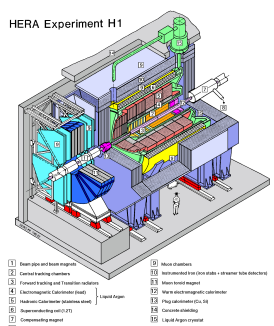
★ **Parton dynamics:**
- Transverse momentum spectra

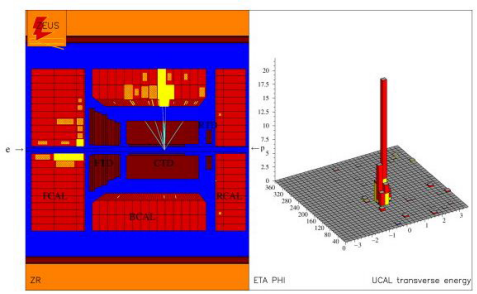
★ **Hadronisation:**
- Production of forward photons
- Fragmentation function

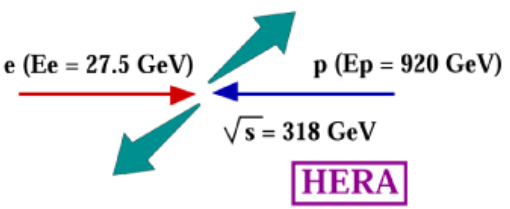




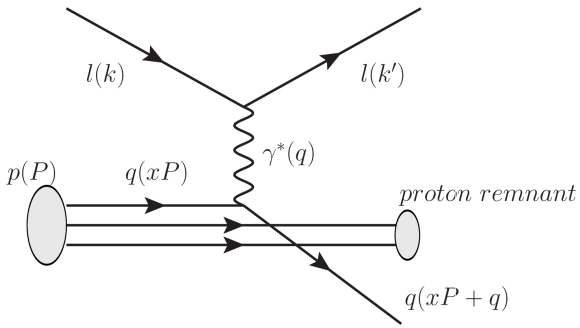


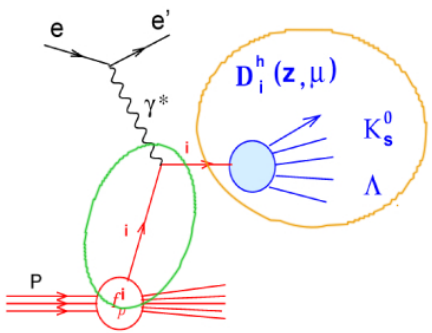






Kinematic variables





hard QCD parton dynamics hadronisation

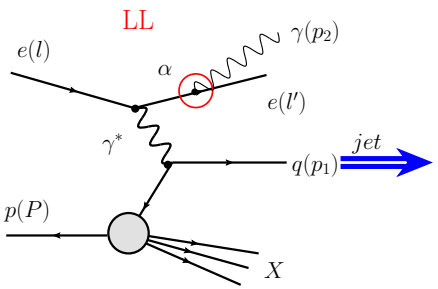
$$\frac{d\sigma}{dx_p} = f(x,Q^2) \otimes \sigma^{\wedge}(Q^2) \otimes D(z,Q^2)$$

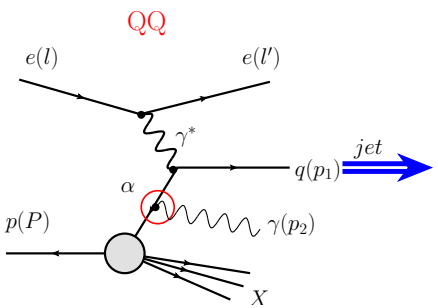
- Q^2 exchanged boson virtuality:
  $Q^2 = -q^2 = -(k-k')^2$
  k - 4-momentum of incoming electron
  k' - 4-momentum of outgoing electron

- x Bjorken scaling variable:
  $x = \frac{q^2}{2P(k-k')}$
  P - momentum fraction of the proton carried by the struck quark

Photoproduction: $Q^2 < 1\text{GeV}^2$
DIS: $Q^2 > 1\text{GeV}^2$

Prompt photons + jets in DIS





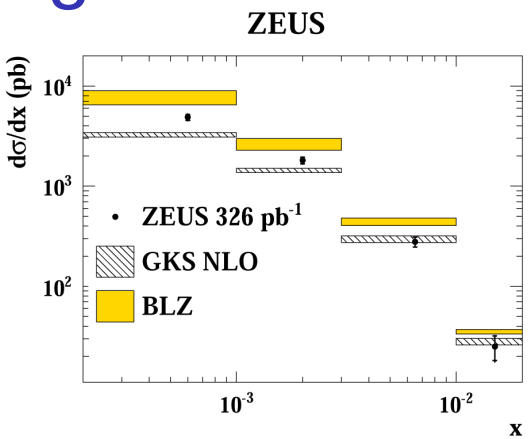
Motivation:

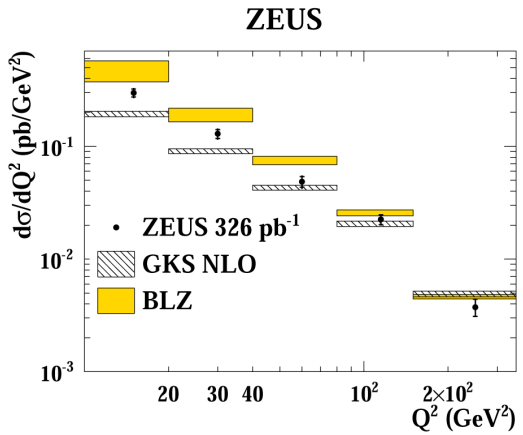
- Events with isolated photons provide a clean test of QCD
- Do not undergo the hadronisation process
- Arrive in the detector unchanged after their production
- The requirement for an accompanying jet provides a test of pQCD with two hard scales

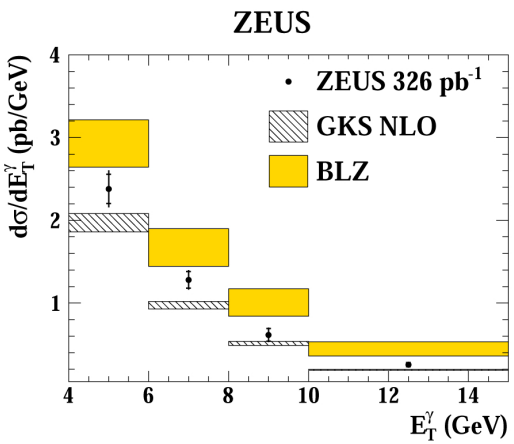
ZEUS Physics Letters B 715 (2012) 88-97

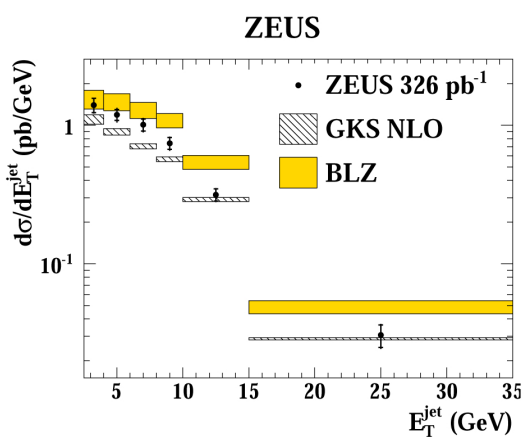
- ZEUS 2004-2007, $\int Ldt = 326\ \mathrm{pb}^{-1}$
- $10 < Q^2 < 350\mathrm{GeV}^2$
- $E_T^{jet} > 2.5\mathrm{GeV}$, $-1.5 < \eta^{jet} < 1.8$
- jet reconstruction done with inclusive $k_T$clus algorithm
- photon identification using shower shapes

Production of isolated photons with jets in DIS ep scattering



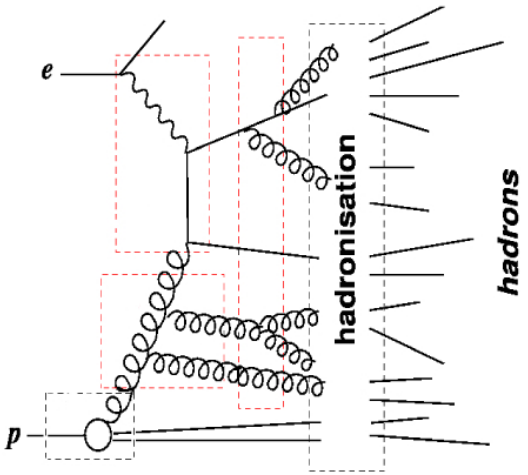






GKS (A.Gehrmann-De Ridder, G.Kramer and H.Spiesberger): fixed order NLO ($\alpha^3\alpha_s$) = LL, QQ contributions, LQ interference term;
agrees better with the cross sections as function of jet variables, below the data.
BLZ (S.P.Baranov, A.V.Lipatov and N.P.Zotov): QCD k_T factorisation approach;
overestimate the data by $\sim 20\%$.

Transverse momentum of charged particles



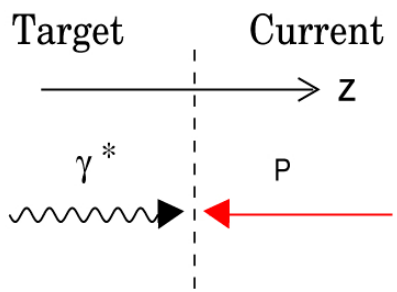
Motivation:

- Low-x dynamics is challenging
- Semi-inclusive measurements $ep \to e^{'} hX$ may potentially discriminate between DGLAP and beyond-DGLAP

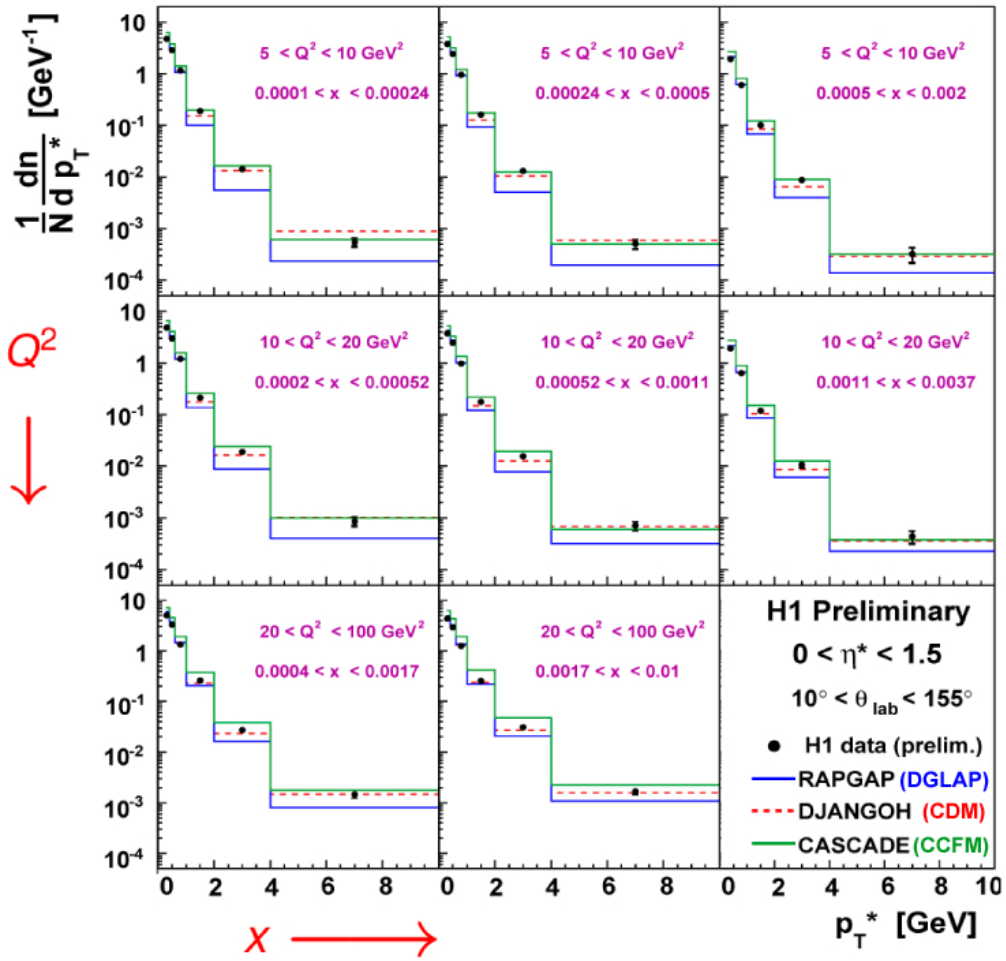
H1 Preliminary results (H1prelim-11-035)

- H1 2006, $\int Ldt = 88.64\ \mathrm{pb}^{-1}$
- $5 < Q^2 < 100\mathrm{GeV}^2$
- $10^{-4} < x < 10^{-2}$
- Measurements are performed in hadronic centre-of-mass system (p_T^*, η^*)

- Distributions are normalised to $\frac{1}{\mathrm{N_{event}}} \frac{\mathrm{dn}}{\mathrm{dp_T^*}}$



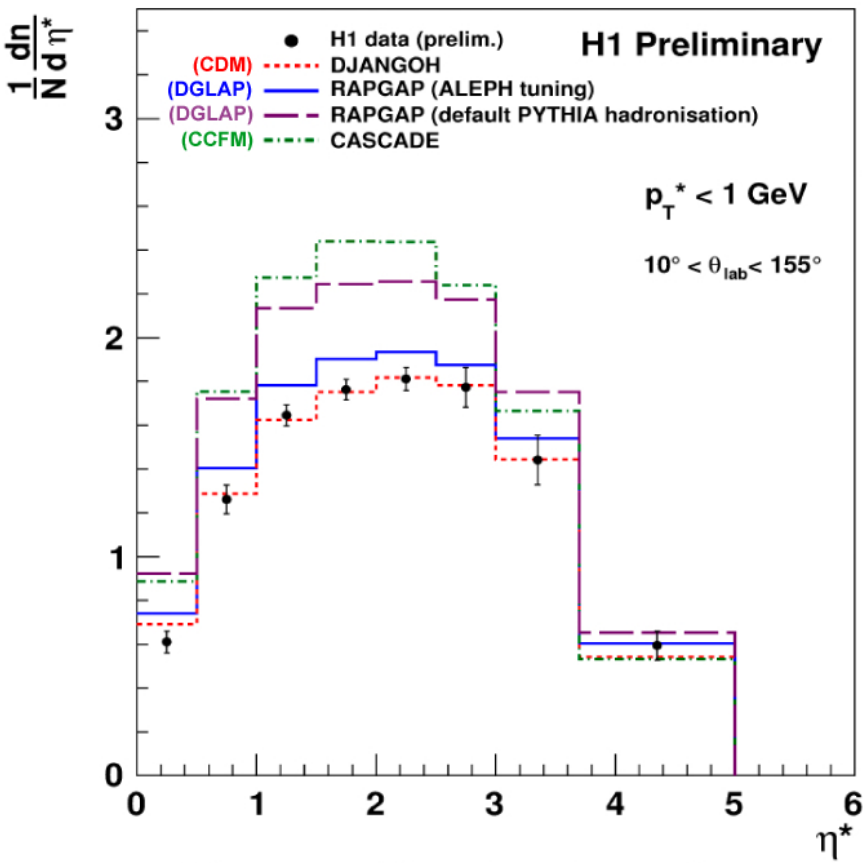
p_T^* distribution



- DJANGOH works better in current p_T^* region
- RAPGAP shows strong deviation at low x and Q^2
- CASCADE describes the data at high p_T^*

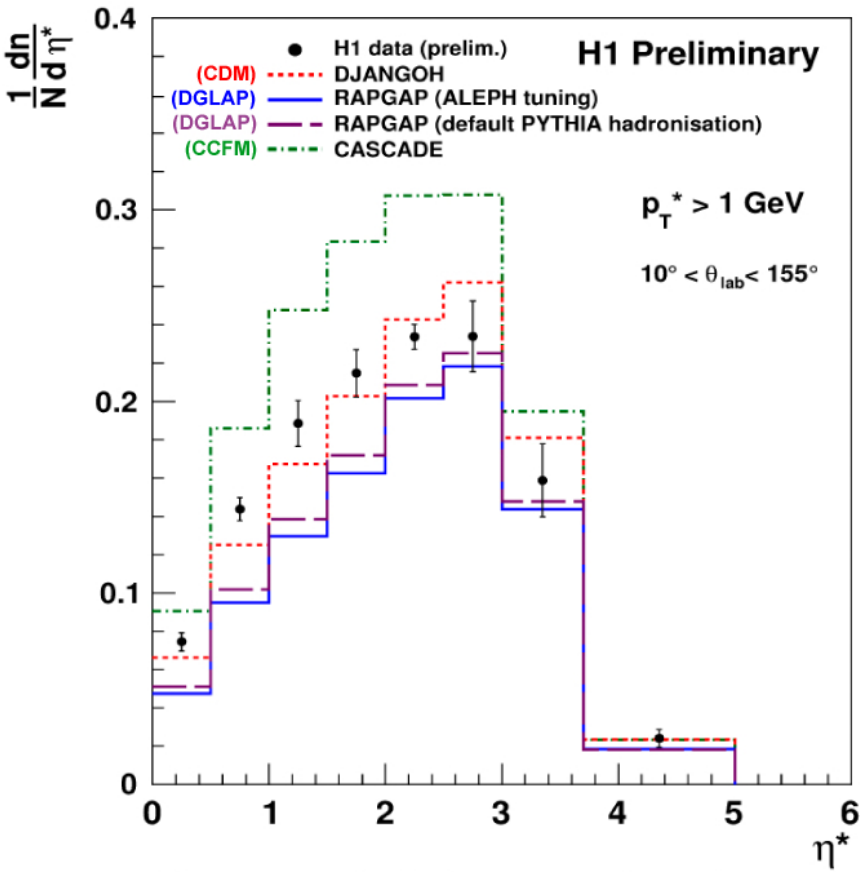
η^* distributions

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



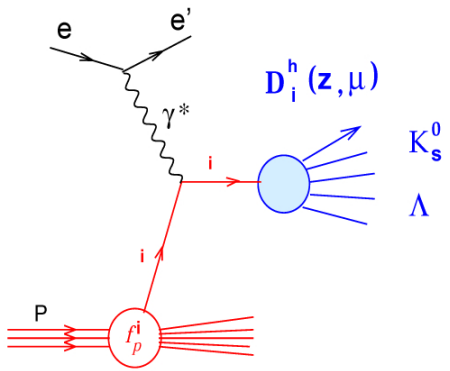
Strong sensitivity to hadronisation

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



Strong sensitivity to parton dynamics

Fragmentation function (FF) for K^0_s and Λ



$$\frac{d\sigma}{dx_p} = f(x,Q^2) \otimes \sigma^{\wedge}(Q^2) \otimes D(z,Q^2)$$

Observable:

- $x_p \equiv \frac{|\vec{p_h}|}{p_{max}} \equiv \frac{2p_h}{Q}$ (Breit frame)
- $\frac{1}{N_{event}} \frac{dn}{dx_p}$

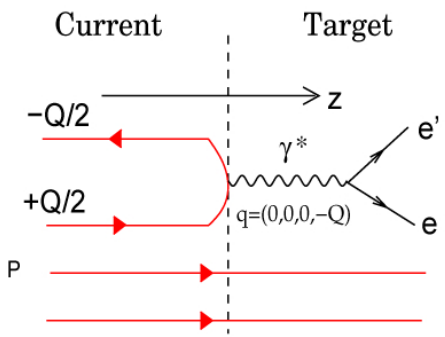
NLO QCD calculations $\otimes$ FF:
AKK+CYCLOPS: FFs from fits to e^+e^- data
DSS: FFs from fits to e^+e^-, ep and pp data

Motivation:

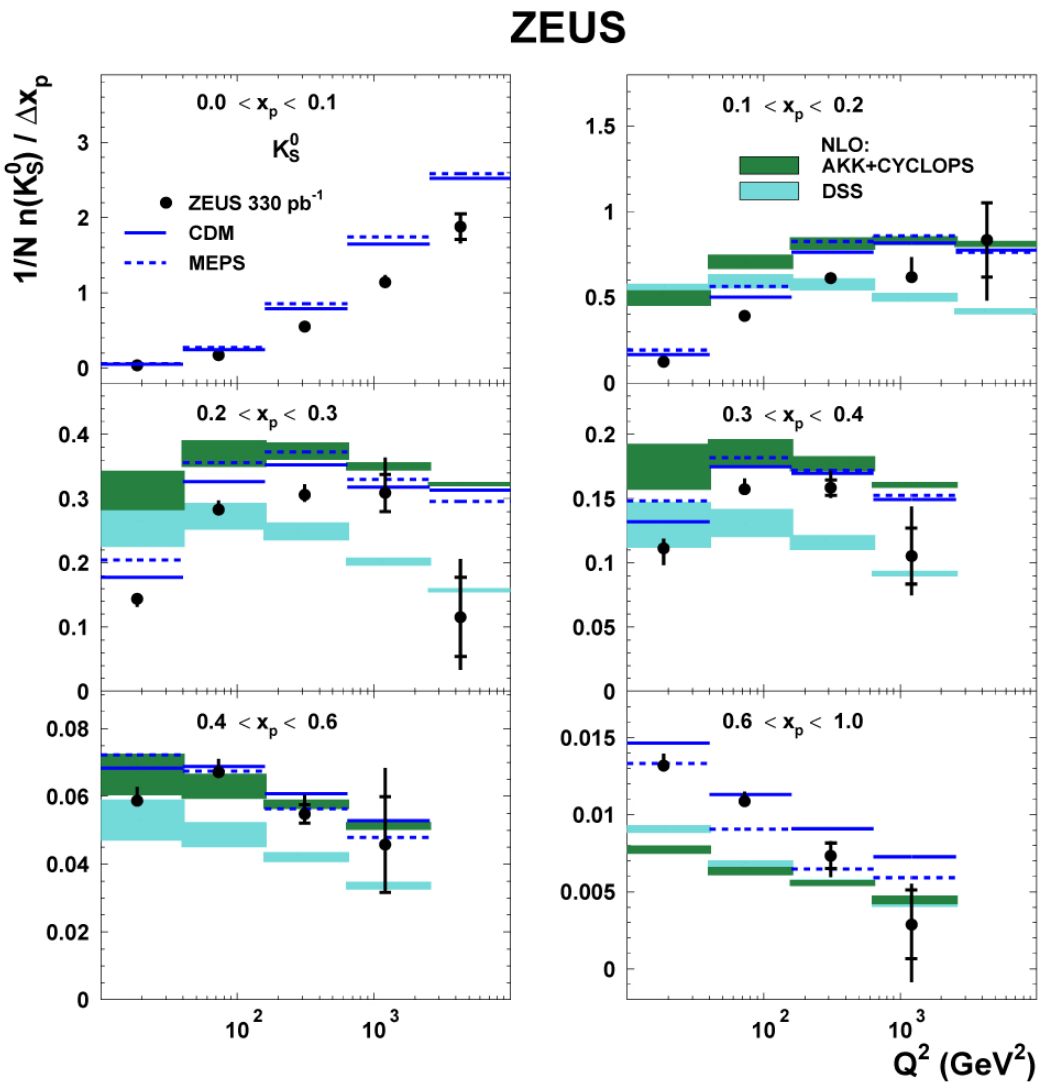
- Scaling violations in fragmentation functions
- Universality of fragmentation function
- Test NLO QCD calculations and universality of factorisation theorem

ZEUS JHEP 03 (2012) 020

- ZEUS 2005-2007, $\int Ldt = 330\ \mathrm{pb}^{-1}$
- $10 < Q^2 < 40000\mathrm{GeV}^2$
- $0.001 < x < 0.75$
- Measurements are performed in current region of Breit frame (similarity with e^+e^-)

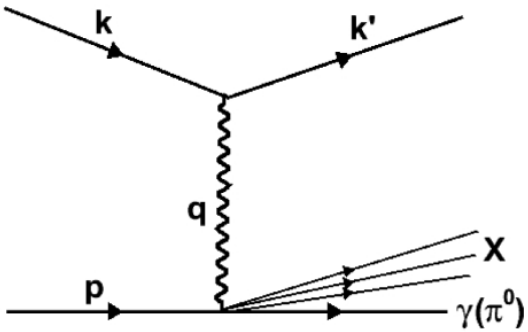


Scaled momentum distributions: K_s^0



- Scaling violations: Q increases $\Longrightarrow$ more soft gluon radiation $\Longrightarrow$ more particles with low x_p
- ARIADNE and LEPTO describe the data in most parts of phase space
- QCD NLO predictions fail to describe the data
- Data may constrain further FF
- Similar behaviour for Λ

Production of very forward photon in DIS



Main source: $\pi^0 \rightarrow \gamma\gamma$

Observable:

- Normalised differential cross sections for leading forward photon:

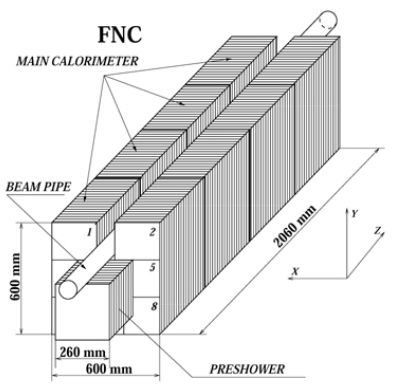
$$\frac{1}{\sigma_{\mathrm{DIS}}} \frac{\mathrm{d}\sigma}{\mathrm{dx}_{\mathrm{L}}^{\mathrm{lead}}}$$

Motivation:

- Understanding the photon fragmentation
  - Testing the hypothesis of limiting fragmentation
  - Models tuning, in particular for hadron interaction Cosmic Ray models
  - Fragmentation of the proton does not feel the hard process

H1 Eur. Phys. J.C71 (2011) 1771

- H1 2006-2007, $\int Ldt = 126\ \mathrm{pb}^{-1}$
  - $6 < Q^2 < 100\mathrm{GeV}^2$
  - $0.05 < y < 0.6$
  - $\eta_\gamma > 7.9$, $X_L = E_\gamma / E_p > 0.1$
  - γ is detected in e/m part of Forward Neutron Calorimeter



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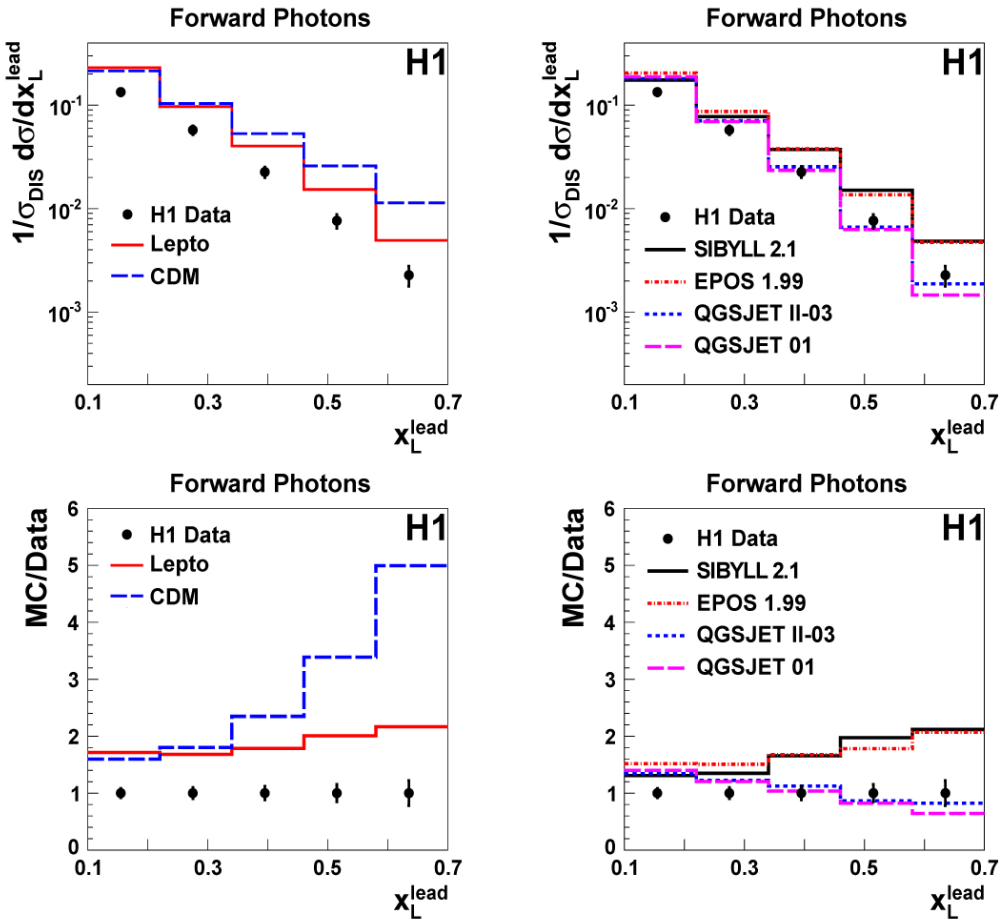
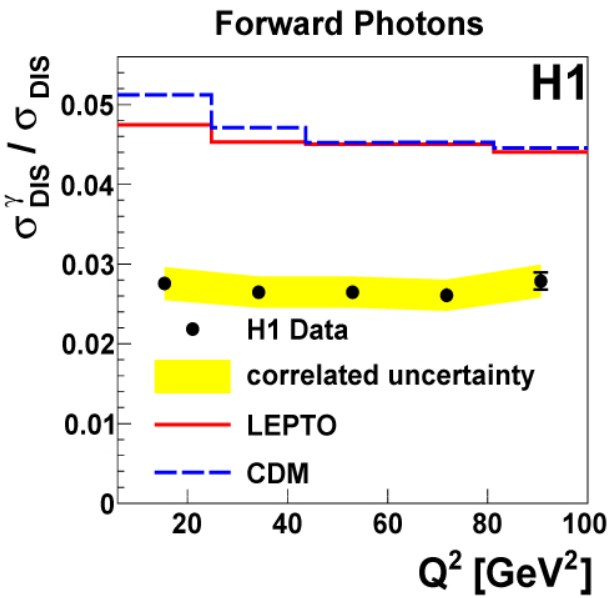
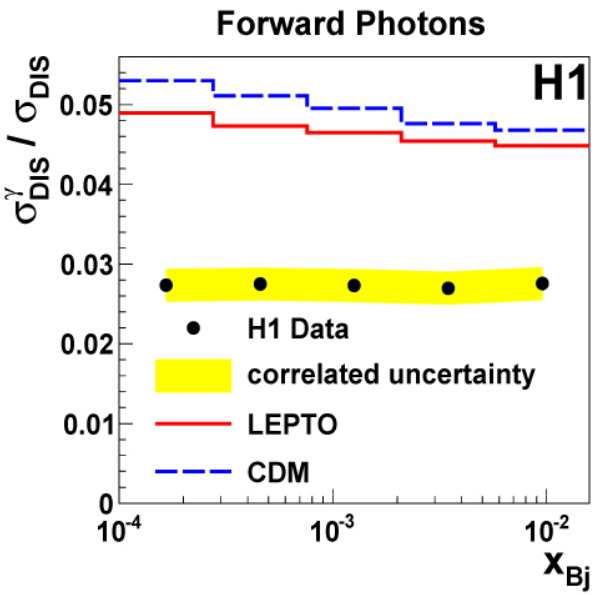


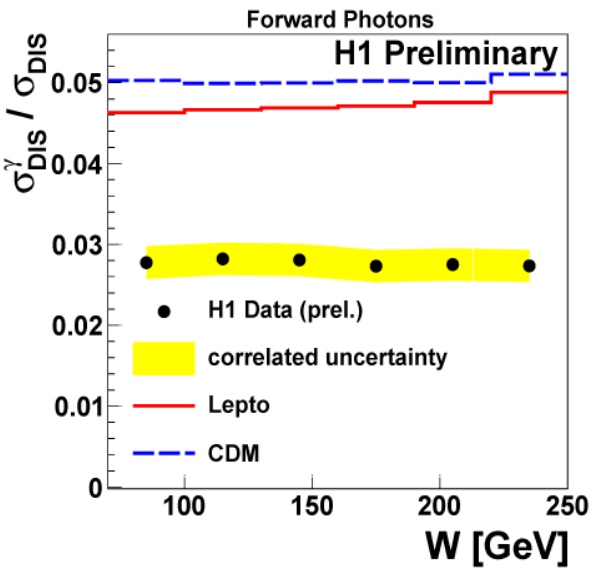
- Both CDM and LEPTO (standart high energy MC) models are significantly higher than data
- Monte Carlo models SIBYLL, EPOS and QGSJET are Cosmic Ray models
- QGSJET models have steeper behavior than the data, close to data in absolute values except at low X_L
- Cosmic ray doing better in normalisation
- Similar behavior observed for p_T^{lead}

Production of DIS events with very forward photons

H1prelim-12-111







- Test of limiting fragmentation hypothesis (forward particle production insensitive to Q^2, x_{bj} and W)
- Proton remnant does not ”feel” the hard interaction
- Data support the hypothesis of limiting fragmentation

Summary

⋆ Hard QCD:

- **Prompt photons + jets in DIS**
  - Both theoretical predictions reproduse the shapes of all the measured experimental distributions reasonably well
  - However neither calculation gives a correct normalisation
  - The results can be used to make further improvements in the QCD calculations

⋆ Parton dynamics:

- **Transverse momentum spectra**
  - CDM is the best in description of charged particle spectra
  - DGLAP is below the data for low x and and large p_T of charged particles

⋆ Hadronisation:

- **Fragmentation function for K_s^0 and Λ**
  - Scaled momentum distributions show the scaling violation
  - NLO QCD calculations fail to describe the data
  - Measurements can be used for further FF fit
- **Production of forward photons**
  - Models predict higher yield of photons than data
  - Data supports the hypothesis of limiting fragmentation