Particle Production at HERA

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on behalf of the H1 and ZEUS collaborations

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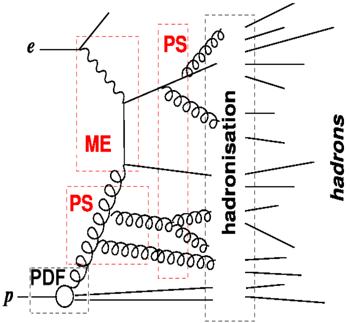
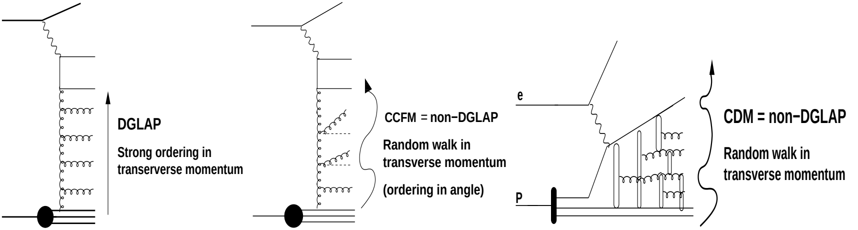
Outline

- Introduction
- Sensitivity to parton dynamics
- Sensitivity to hadronisation
- Summary



Models for *ep* scattering

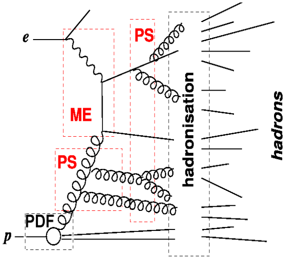
RAPGAP	CASCADE	DJANGOH
DGLAP	CCFM	CDM (Colour Dipole Model)



LO ME +		
PS(DGLAP)	PS(CCFM)	Dipole(BFKL-like)
+ String fragmentation		

Fragmentation parameters tuned to e^+e^- data (ALEPH tune)

Charged particle spectra



Low p_T region:
hadronisation is expected to play a role.
Small sensitivity to different parton dynamic models.

Hadrons at large p_T:
disfavoured by the strong p_T ordering $\longrightarrow$ difference between different parton dynamics

Observable:

Event normalised charged particle distribution: $\frac{1}{N_{event}} \frac{dn}{dp_T^*}$

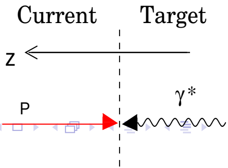
Charged particle momentum spectra

Motivation:

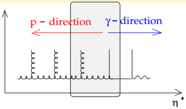
- Low-x dynamic is challenging
- Semi-inclusive measurements $ep \longrightarrow e'hX$ can potentially discriminate between DGLAP and beyond-DGLAP

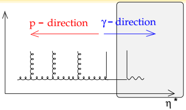
H1 preliminary results (H1prelim-11-035):

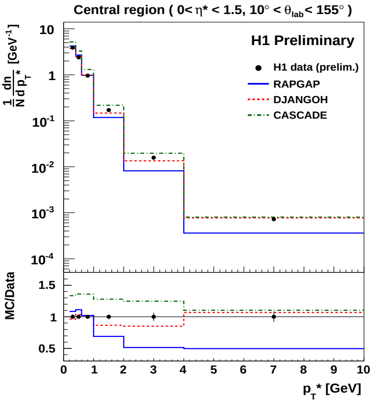
- $5 < Q^2 < 100$ GeV^2, $10^{-4} < x < 10^{-2}$
- Measurements are performed in hadronic centre-of-mass system (p_T^*, η^*)

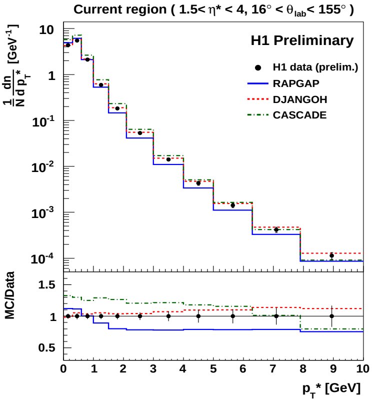


p_T^* distribution





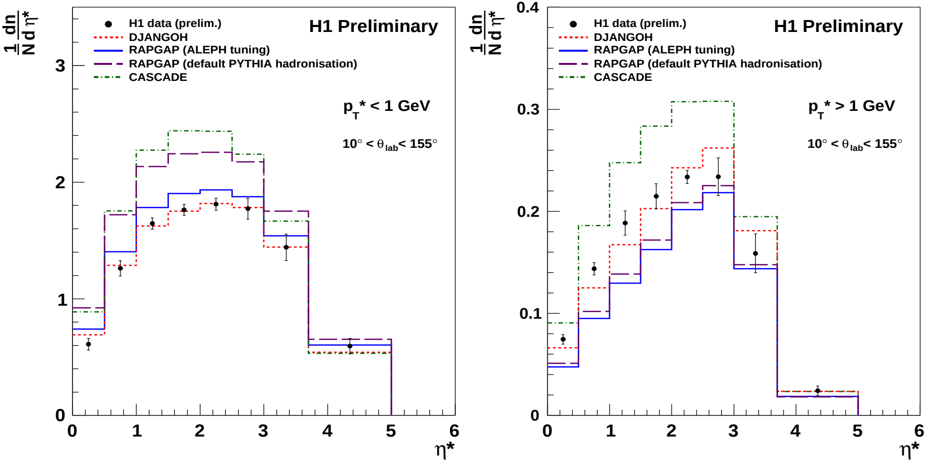




- DJANGOH(CDM) describes the data for whole p_T^* spectra
- RAPGAP(DGLAP) is below the data for $p_T^* > 1$ GeV (especially in the central region)
- In contrast, CASCADE(CCFM) is systematically above the data (except high p_T^*)

η^* - distributions

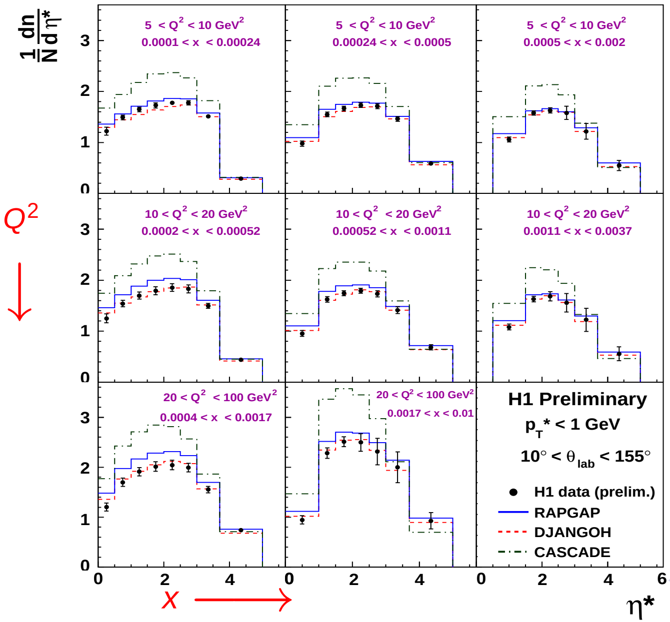
Charged particles with $p_T^* < 1$ GeV: Charged particles with $p_T^* > 1$ GeV:



Strong sensitivity to hadronisation parameters.
Little sensitivity to different parton dynamics.

Strong sensitivity to different parton dynamics.
Little sensitivity to hadronisation parameters.

η^* distribution in bins of (x, Q^2) for $p_T^* < 1$ GeV

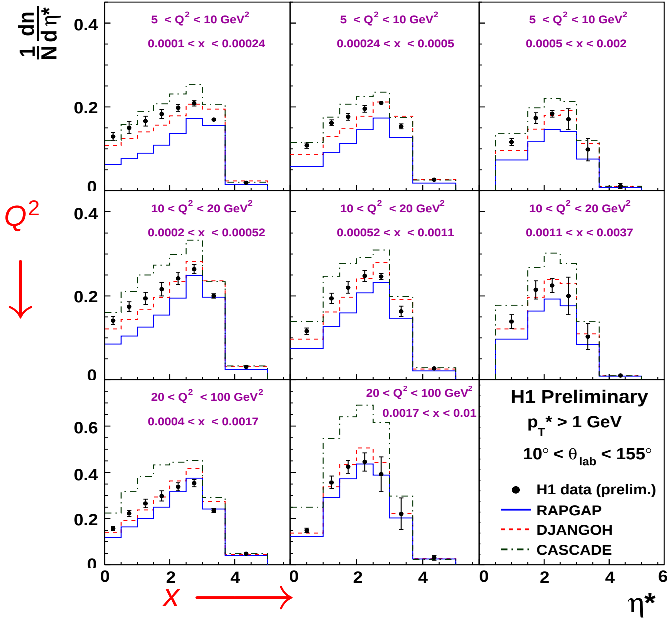


DJANGOH(CDM) provides reasonable description of the data for all (x, Q^2)-bins.

RAPGAP(DGLAP) is slightly above the data for lowest x.

CASCADE is above the data independently of (x, Q^2)-bins.

η^* distribution in bins of (x, Q^2) for $p_T^* > 1$ GeV;



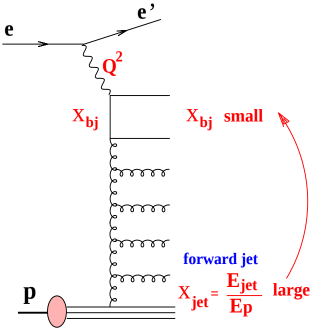
RAPGAP(DGLAP) is below the data for almost all (x, Q^2)-bins. The difference is more pronounced in proton direction ($\eta^* < 2$)

CASCADE is better in the data description at low (x, Q^2)-bins

? quark contributions are missing

Forward jets measurements

Forward jets



Azimuthal correlations between scattered electron and the forward jet:

$\Delta\phi = \phi_{el} - \phi_{fj}$
(QPM: $\Delta\phi = \pi$)

Motivation:

- Studies of forward jets are an experimental challenging
- Signature for BFKL evolution in the hadronic final state

Enhance BFKL phase space:
$x_{jet} \gg x_{bj}$

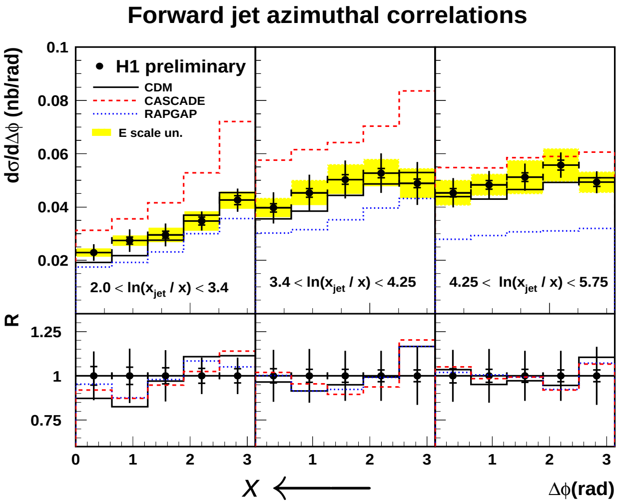
Suppress DGLAP phase space:
$p^2_{Tjet} \sim Q^2$

H1 preliminary results (H1prelim-10-131):

- 5< Q^2< 85 GeV^2, $10^{-4} < x < 4 \cdot 10^{-3}$
- $P_{T,fj} > 6$ GeV, 1.7 < η_{fj} < 2.8
  $x_{jet} > 0.035$
  $0.5 < p^2_{T,jet}/Q^2 < 6.0$

Inclusive forward jet cross-section $d\sigma/d\phi$

In three intervals of rapidity distance between the scattered electron and the forward jet $Y = \ln(x_{jet}/x)$



- At lower x the forward jet is more decorrelated from the scattered electron
- Cross-section described best by BFKL-like model (CDM)

- Ratio R of MC to data for normalised cross-section

$$R = \left(\frac{1}{\sigma^{MC}}\frac{d\sigma^{MC}}{d\Delta\phi}\right)/\left(\frac{1}{\sigma^{data}}\frac{d\sigma^{data}}{d\Delta\phi}\right)$$

- The shape of $\Delta\phi$ distributions does not discriminate between different models

Summary: beyond DGLAP physics

- CDM is the best in description of charged particle spectra as well as forward jet measurements
- DGLAP is below the data for low x and large p_T of charged particles
- CCFM overall above the data except high p_T; description is better at low x compared to high x
- The shape of $\Delta\phi$ distributions does not discriminate between different models

Prompt photon

The term 'prompt photon' refers to isolated, high-p_T photon in the final state

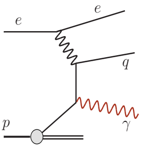
Motivation:

- Direct probe of hard process dynamics, test of QCD
- Direct information about involved quark, complementary to jet studies
- No hadronisation corrections, good energy measurements

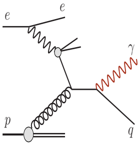
Prompt photon in photoproduction:

γ emitted by quark direct $\gamma q \to \gamma q$, resolved $gq \to \gamma q$

$\gamma q \to \gamma q$



$gq \to \gamma q$



+ direct/resolved fragmentation processes

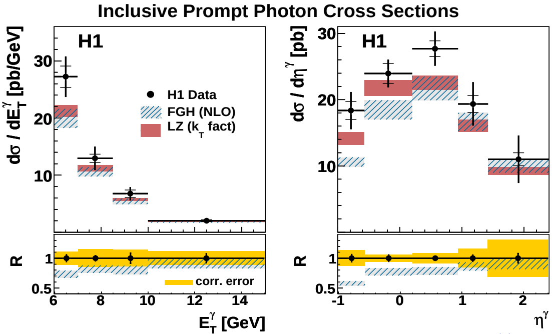
Prompt photon: Inclusive cross sections

H1: Eur.Phys.J. C66 (2010) 17

$6 < E_T^\gamma < 15$ GeV, $-1.0 < \eta^\gamma < 0.7$, $E_T^{jet} > 4.5$ GeV, $-1.3 < \eta^{jet} < 2.3$

Theory:

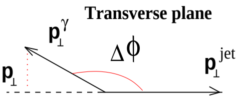
- Fontannaz, Guillet, Heinrich (FGH): collinear factorisation+DGLAP evolution; NLO corrections; CTEQ6L, AFG04
- Lipatov, Zotov (LZ): k_T factorisation, direct+resolved unintegrated parton densities – KMR, GRV



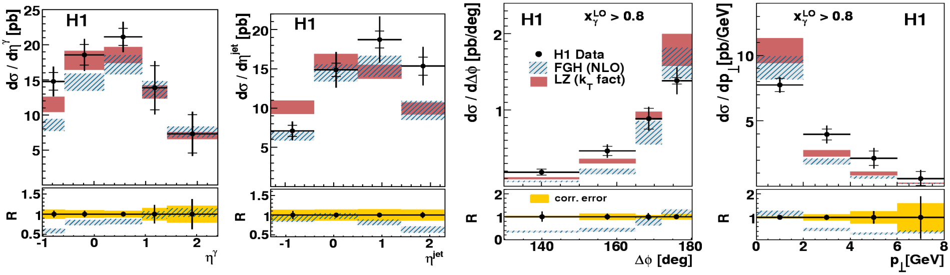
- Both calculations are below the data

Prompt photon plus jet cross section in photoproduction

H1: Eur.Phys.J. C66 (2010) 17



Transverse correlations, $x_\gamma > 0.8$ (direct process):

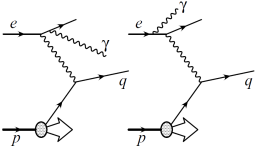


- LZ favoured by η_γ but problems with η_{jet}
- both calculations underestimate non back-to-back configuration

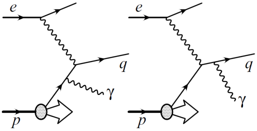
Prompt photon

Prompt photon in DIS:

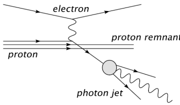
LL - hard radiation from leptons



QQ - hard radiation from quarks



$D_{q\to\gamma}(z)$ - quark to photon fragmentation



Prediction: Total = LL + QQ + $D_{q\to\gamma}(z)$

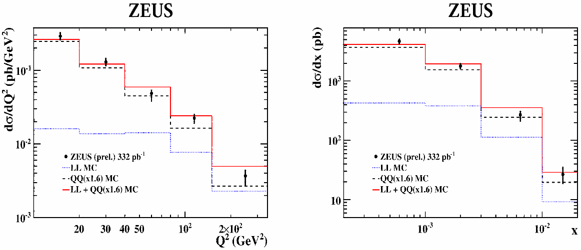
$D_{q\to\gamma}(z)$ is suppressed

Prompt photon plus jet cross section in DIS

ZEUS preliminary (ZEUS-prel-11-007):

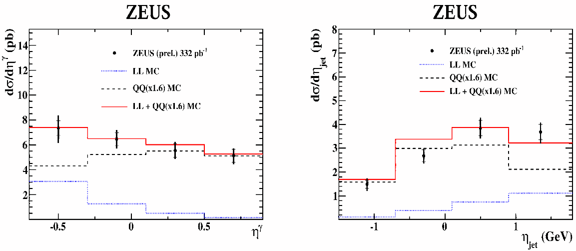
($10 < Q^2 < 350$ GeV^2, $4 < E_T^\gamma < 15$ GeV, $-0.7 < \eta^\gamma < 0.9$, $E_t^{jet} > 2.5$ GeV, $-1.5 < \eta^{jet} < 1.8$)

Prompt photons + jets differential cross sections vs Q^2 and x



- LL contribution
- QQ contribution is scaled by factor of 1.6 to give good agreement to the data
- LL+QQ($\times$1.6) MC describes data well

Prompt photons + jets differential cross sections vs η_γ and η_{jet}

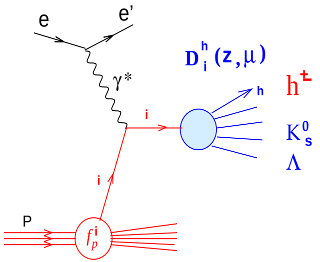


- LL+QQ($\times$1.6) MC describes data well

Summary: prompt photon

- Prompt photon in photoproduction
  - Calculations generally underestimate cross section
  - Calculations fail to describe shapes in several kinematical regions
- Prompt photon in DIS
  - MC model describes data well after scaling the QQ component

Fragmentation function (FF) for charged particles ($h^{\pm}$), K_s^0 and Λ



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

Scale dependence of FF is driven by an evolution equation

Observable:

$x_p \equiv \frac{|\vec{p}_h|}{p_{max}} = \frac{2p_h}{Q}$ (Breit frame)

Event normalised scaled momentum distribution: $\frac{1}{N_{event}} \frac{dn}{dx_p}$

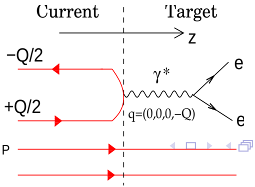
Motivation:

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

ZEUS results

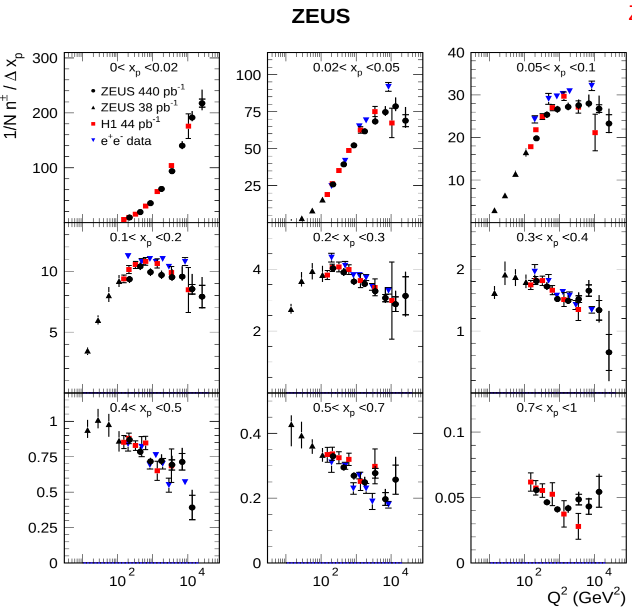
(JHEP06(2010)009 ($h^{\pm}$), ZEUS-prel-10-013 (K_s^0,Λ)):

- 160< Q^2< 40960 GeV^2, 0.002< x< 0.75 ($h^{\pm}$)
- 10< Q^2< 40000 GeV^2, 0.001< x< 0.75 (K_s^0 and Λ)
- Measurements are performed in current region of Breit frame (similarity with e^+e^-)



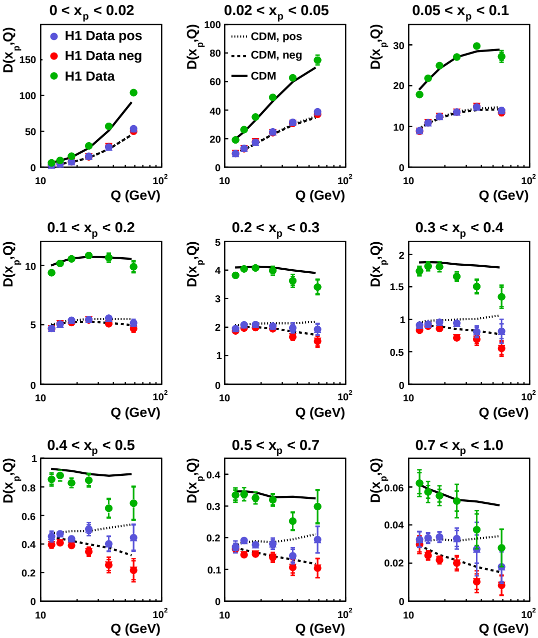
Scaled momentum distribution for charged particles

ZEUS: JHEP06(2010)009



- Scaling violation is observed
- ep-collision: $\mu = Q/2$
- e^+e^--annihilation: $\mu = \sqrt{s}/2$
- Overall agreement with e^+e^- data except at large Q and small x_p
- Overall agreement with H1 data

Scaled momentum distribution for charged particles: charge asymmetry



H1

Phys.Lett.B, 681(2009),pp.391-399

small x_p - fragmentation

large x_p - hard interaction

⟶ positively and negatively charged particles provide information about valence quarks and their fragmentation

- Charged asymmetry depends on x_p
- Charged asymmetry at large x_p increases with Q

Fragmentation function

Comparison with NLO QCD calculations + FF

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

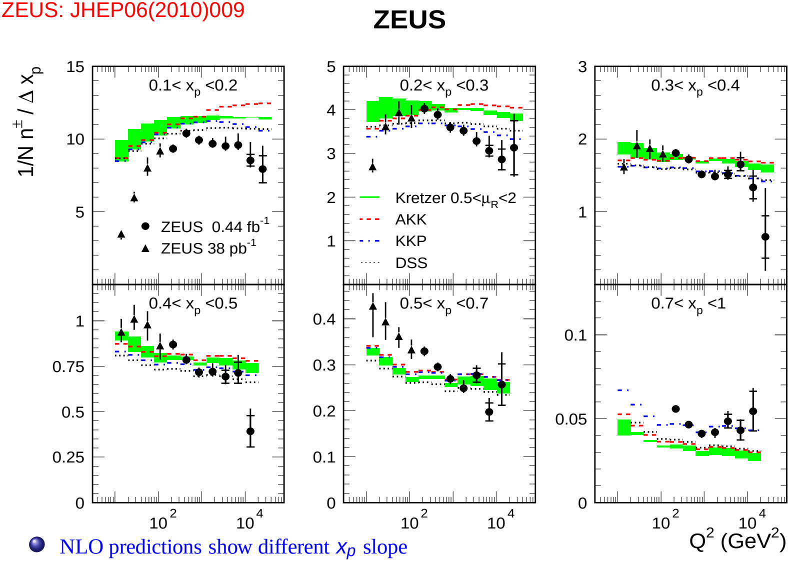
$\widehat{\sigma}(Q^2)$ - hard-scattering process with NLO matrix element

Two different approaches are compared with the data:

- AKK05+CYCLOPS (for charged particles, K_s^0 and Λ)
  - S. Albino, B.A. Kniehl, G. Kramer, Nucl. Phys. B 725 (2005) 181
    S. Albino, B.A. Kniehl, G. Kramer, Nucl. Phys. B 734 (2006) 50
  - FFs were obtained from fits to e^+e^- data
  - Hadrons mass effect is included
- DSS (for charged particles and K_s^0)
  - D. de Florian, R. Sassot, M. Stratmann, Phys. Rev. D75 (2007) 114010
  - FFs were obtained from fits to lp and pp data
  - Hadrons mass effect is not included

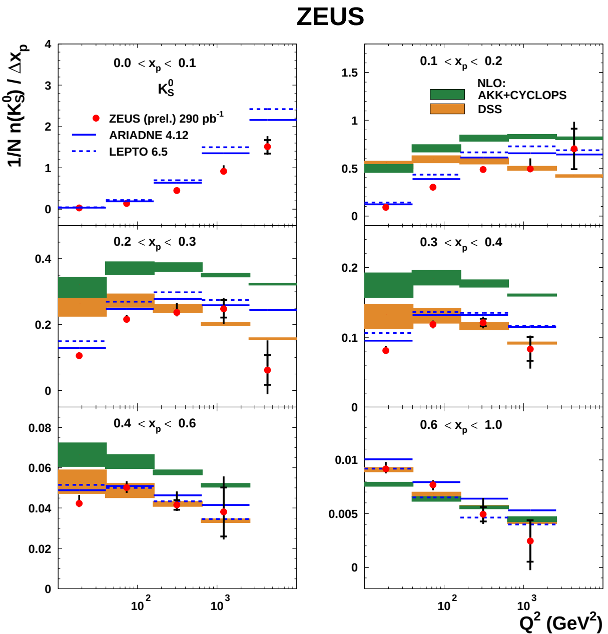
Scaled momentum distribution for charged particles

ZEUS: JHEP06(2010)009



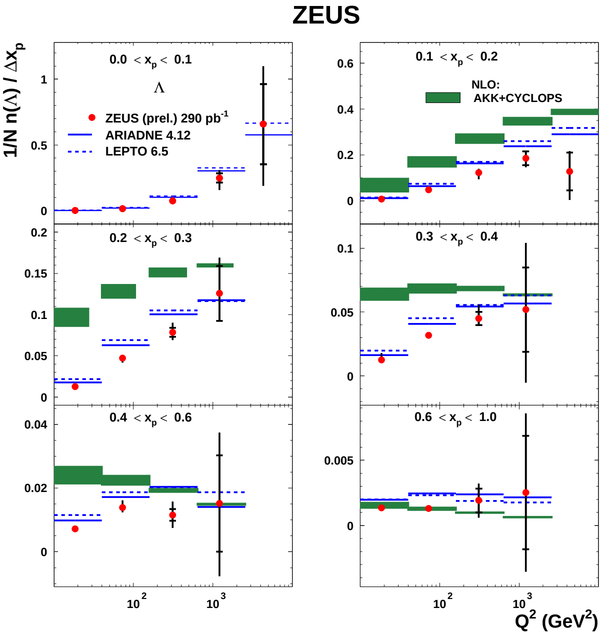
- NLO predictions show different x_p slope
- Scaling violation in NLO predictions is less pronounced

Scaled momentum distributions: K_S^0



- Scaling violations are observed
- ARIADNE (CDM) and LEPTO (MEPS) describe the data in full phase space
- QCD NLO predictions describe the data only in certain regions of the phase space

Scaled momentum distributions: Λ

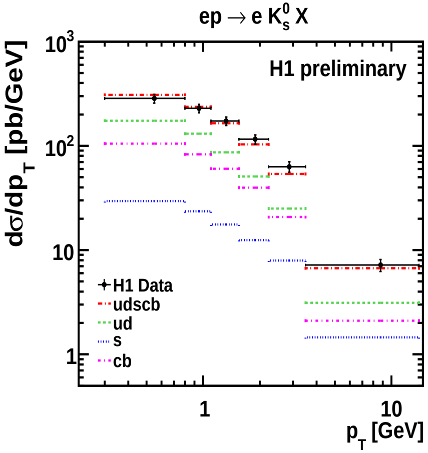


- Scaling violations are observed
- ARIADNE (CDM) and LEPTO (MEPS) describe the data in most parts of phase space.
- QCD NLO predictions does not describe the data

Strangeness production

Motivation:

- What is the production mechanism of strange particles?



H1 preliminary results (H1prelim-10-031):

- $145 < Q^2 < 20000\ \mathrm{GeV}^2$, $0.2 < y < 0.6$
- $p_T(K_s^0) > 0.3\ \mathrm{GeV}$, $-1.5 < \eta(K_s^0) < 1.5$

Flavour decomposition:

udscb

ud

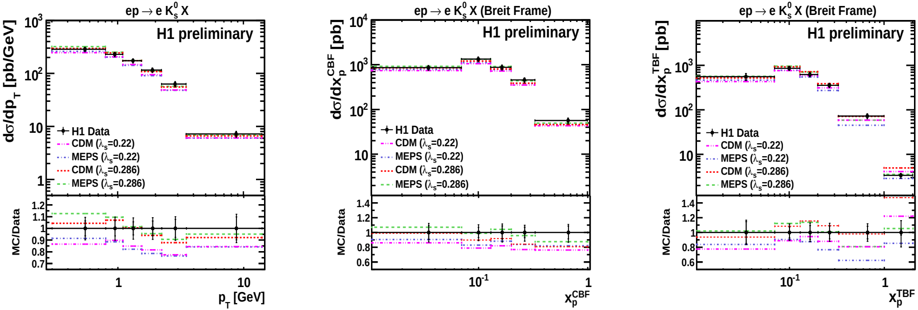
cb

s

- The contribution of ud light quarks dominates
- The s quark contribution increases at large p_T

Strangeness production: cross section

Laboratory frame



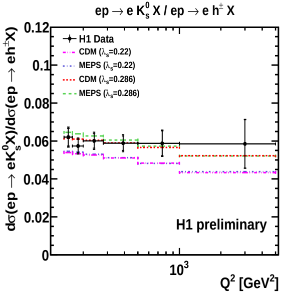
Strangeness suppression factor:

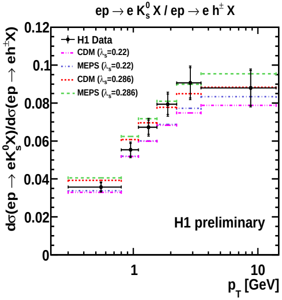
$\lambda_s = \frac{2<n_{s\bar{s}}>}{<n_{u\bar{u}}>+<n_{d\bar{d}}>}$; ALEPH tune: $\lambda_s = 0.286$

- Better agreement with $\lambda_s = 0.286$
- MEPS and CDM give similar description of the data

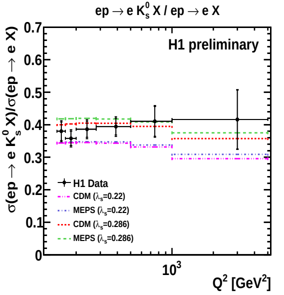
The ration of K_S^0 over charged particle production

$\sigma(ep \to eK_S^0X)/\sigma(ep \to eh^{+-}X)$





$\sigma(ep \to eK_S^0X)/\sigma(ep \to eX)$



- Ratio almost flat as function of Q^2
- Ratio rises in p_T
- $\lambda_s = 0.286$ describes the data

Summary

- Hadronisation
- Fragmentation function:
  - Scaled momentum distributions show the scaling violation
  - NLO QCD calculations describe the data only in certain region of the phase space
- Strangeness production:
  - The production is dominated by hadronisation