

Particle Production and Fragmentation at HERA

- HERA kinematics
- Charged particle production
- Strangeness production at high Q^2
- Charm fragmentation into D^*
- Summary

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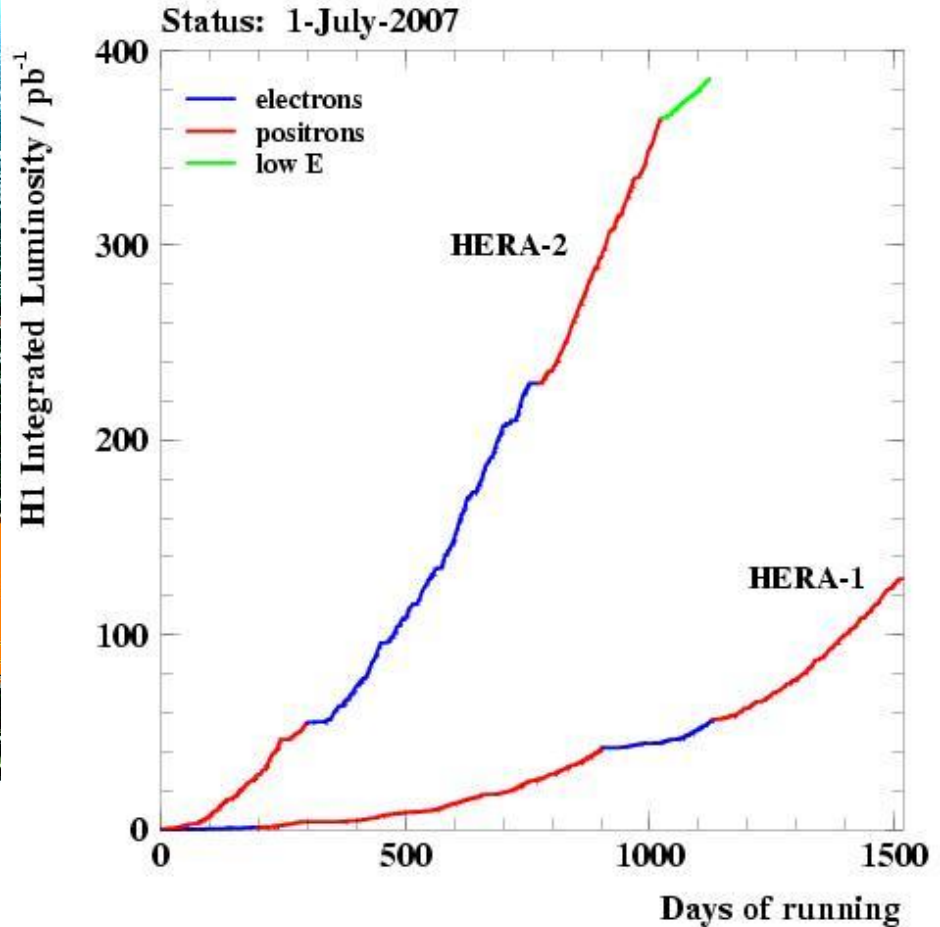
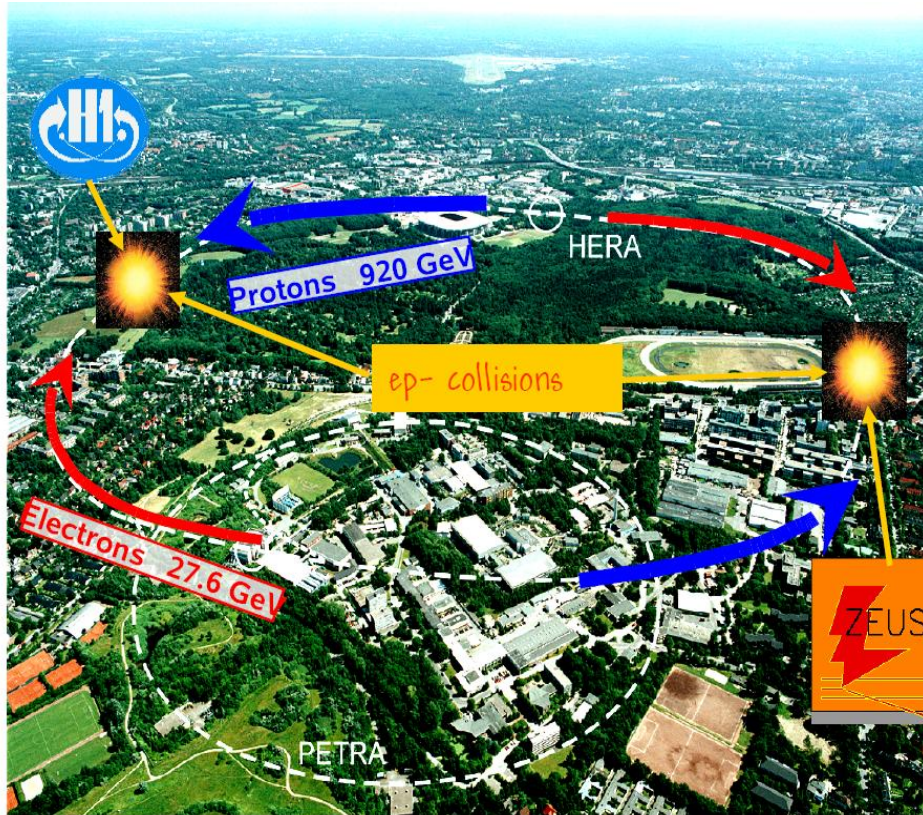


representing the H1 and ZEUS
Collaborations



$e^{\pm}p$ Collider HERA

HERA I unpolarised e^{\pm} beams 1992-2000
 HERA II polarised e^{\pm} beams 2002-2007



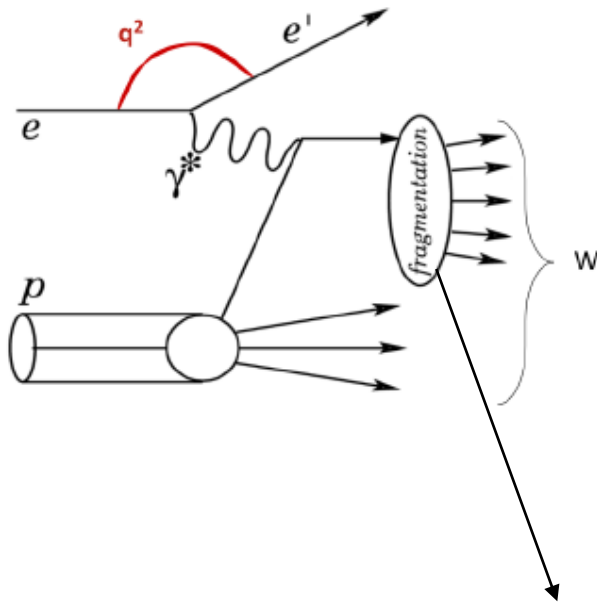
$E_e = 27.6 \text{ GeV}$ $E_p = 920 (820) \text{ GeV}$



ep collisions at $\sqrt{s} \approx 300\text{-}320 \text{ GeV}$

0.5 fb^{-1} per experiment (H1 and ZEUS)

HERA kinematics



$$Q^2 = -q^2 \quad \text{exchanged 4-momentum squared}$$

$$s = (P + e)^2 \quad \text{ep center of mass energy squared}$$

$$W^2 = (P + q)^2 \quad \text{hadronic final state mass squared}$$

$$x_{Bj} = Q^2/2qP \quad \text{Bjorken scaling variable}$$

non-perturbative process leading to hadrons:
light, strange, heavy
in the hadronic final state

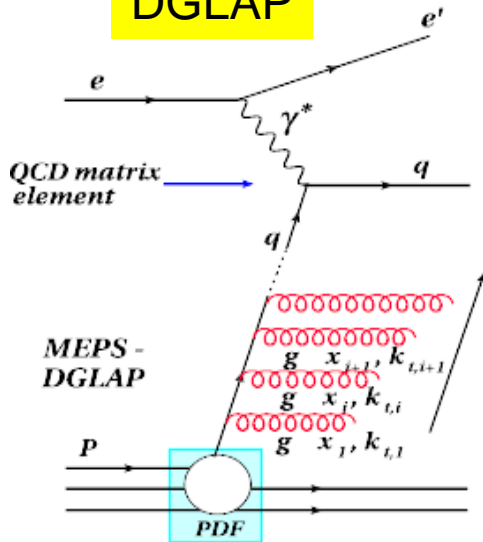
Two regimes:

$Q^2 < 1 \text{ GeV}^2$ photoproduction (γp)

$Q^2 > 1 \text{ GeV}^2$ Deep Inelastic Scattering (DIS)

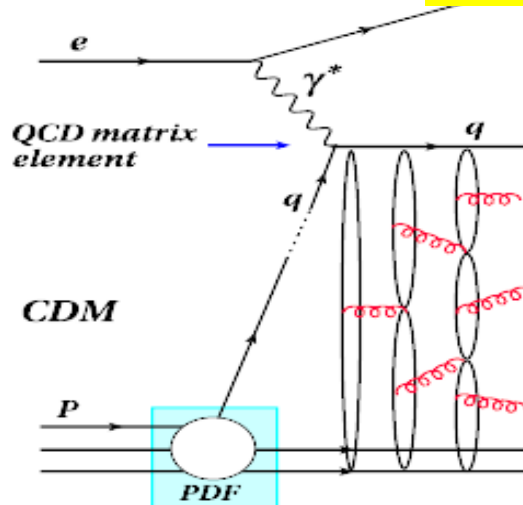
LO QCD Models for DIS ep Interactions

DGLAP

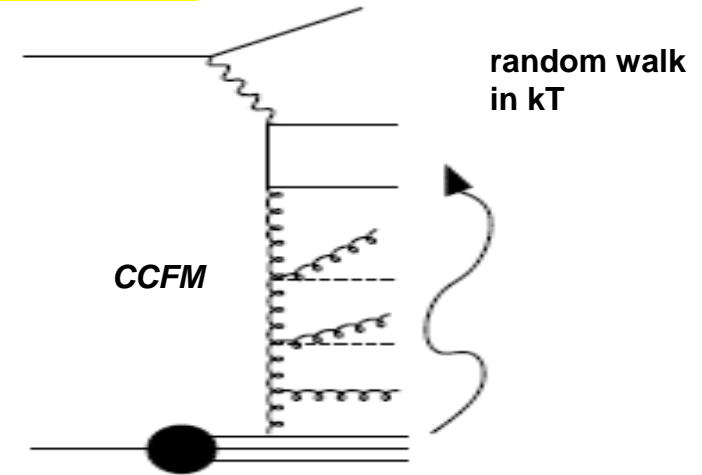


DGLAP- RAPGAP,LEPTO(MEPS)

NON-DGLAP



CDM -DJANGO



CCFM-CASCADE

MEPS Matrix Element + Parton Shower:
DGLAP evolution:
strong ordering in k_T
of emitted partons

CDM Colour Dipole Model
 Parton Shower:
 Dipoles radiate independently
no ordering in k_T of emitted partons

CCFM evolution
 Parton Shower with angular ordering,
 k_T -unintegrated gluon density function,
no ordering in k_T of emitted partons

Hadronisation of partons with Lund string model...

Transverse momenta of charged particles in DIS

$$5 < Q^2 < 100 \text{ GeV}^2$$



charged tracks in LAB; $p_T > 0.15 \text{ GeV}$, $20^\circ < \theta < 155^\circ$

Expect discrimination between models:

low p_T region :

sensitive to hadronization effects,

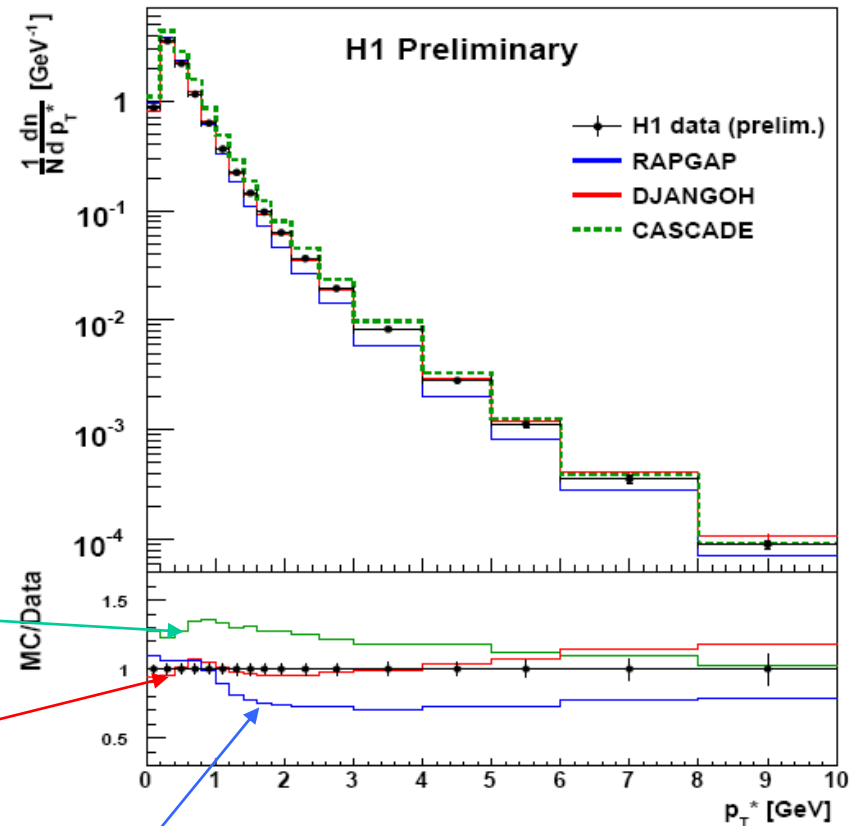
high p_T region:

sensitive to parton dynamic

CCFM (CASCADE) is above the data

data well describe by **CDM** (DJANGO) over the whole p_T^* spectrum

DGLAP (RAPGAP) for $p_T^* > 1 \text{ GeV}$ below the data

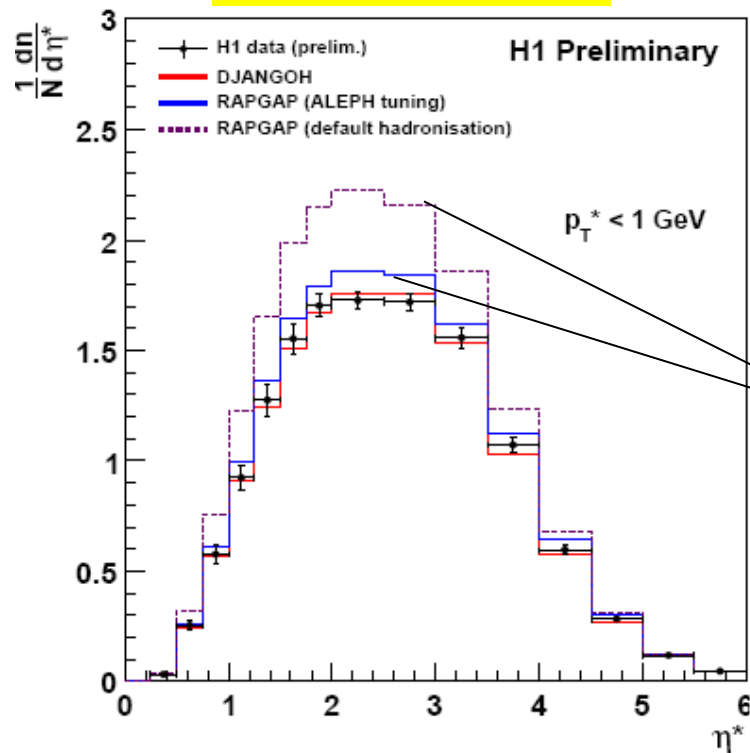


p_T^* distribution in $1.5 < \eta^* < 2.5$ region

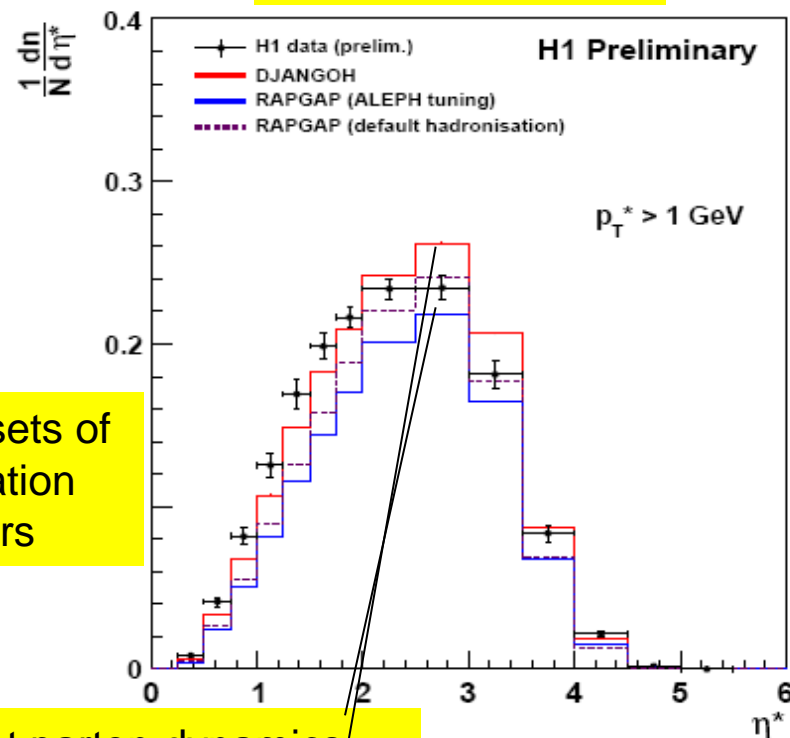
η^* distributions of charged particles



low $p_T^* < 1$ GeV



high $p_T^* > 1$ GeV



different sets of hadronization parameters

different parton dynamics

low p_T^*

strong dependence on hadronization parameters
weak dependence on parton dynamics

high p_T^*

strong dependence on parton dynamics
weak dependence on hadronization param.

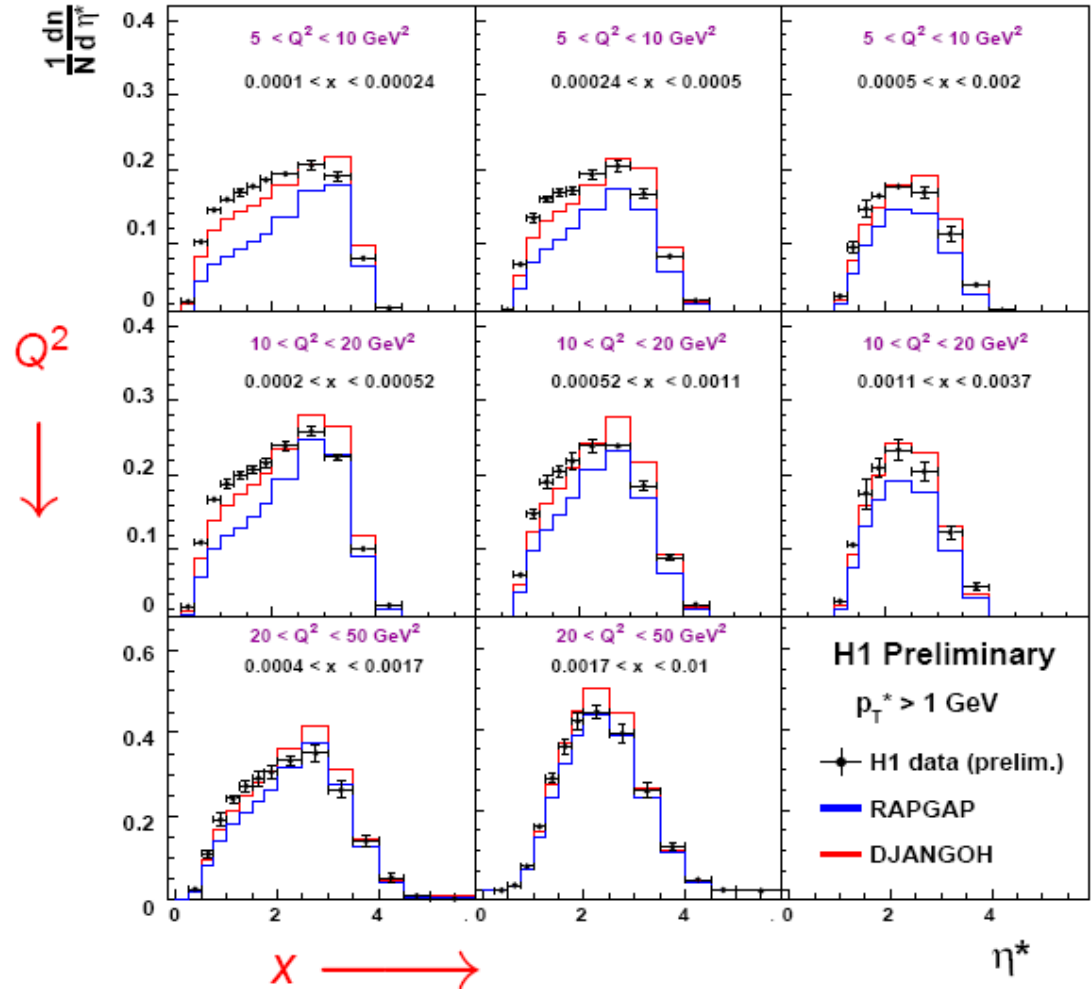
η^* distributions of charged particles in (x, Q^2) bins



$p_T^* > 1 \text{ GeV}$

CDM (DJANGO) in better agreement with data

Differences between models larger at low Q^2 and low x





Scaled momentum spectra of charged particles in dijet- γp and in DIS

jet formation = parton showering & hadronization

pQCD

npQCD

fixed order in α_s calculations

or **resummation approach e.g. MLLA**
(Modified Leading-Logarithmic Approximation)

from partons to hadrons:

Local Parton Hadron Duality (**LPHD**) hypothesis:
charged-hadron and parton distributions are related
by a constant normalization scaling factor κ^{ch}

Predictions:

- momentum spectra of partons in the cone around the initial parton, at scales above some minimum cutoff, Λ_{eff}
- shape of spectrum \sim Gaussian

Prediction: κ^{ch} is process independent

Λ_{eff} process independent

$\Lambda_{eff}, \kappa^{ch}$ measured in other processes

Test MLLA+LPHD approach; $\Lambda_{eff}, \kappa^{ch}$ universality

Scaled momentum distributions

$$\xi = \ln(1/x_p)$$



$$x_p = \frac{2p^{\text{Breit}}}{Q}$$

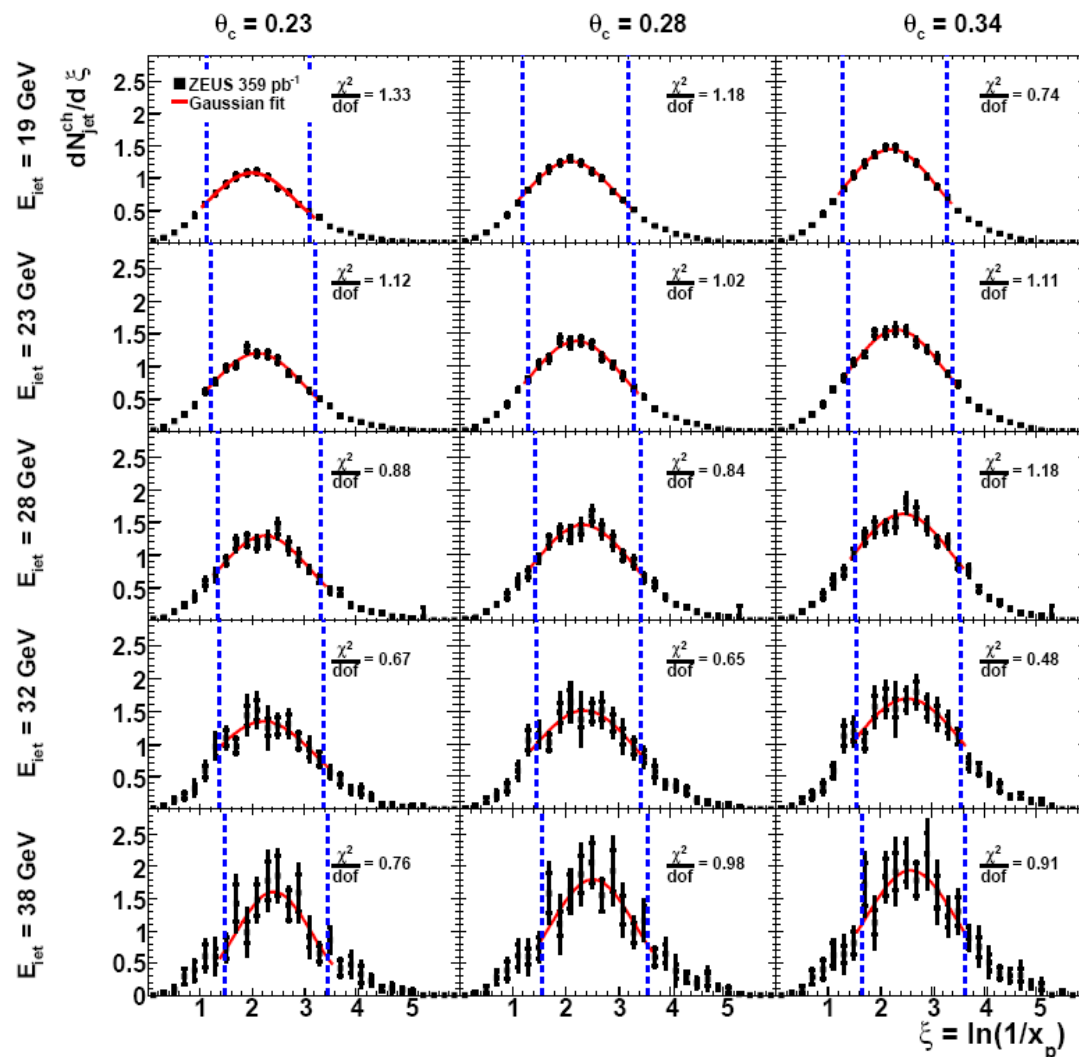
2-jets events in photoproduction

cone opening angle \rightarrow

Extraction of Λ_{eff}

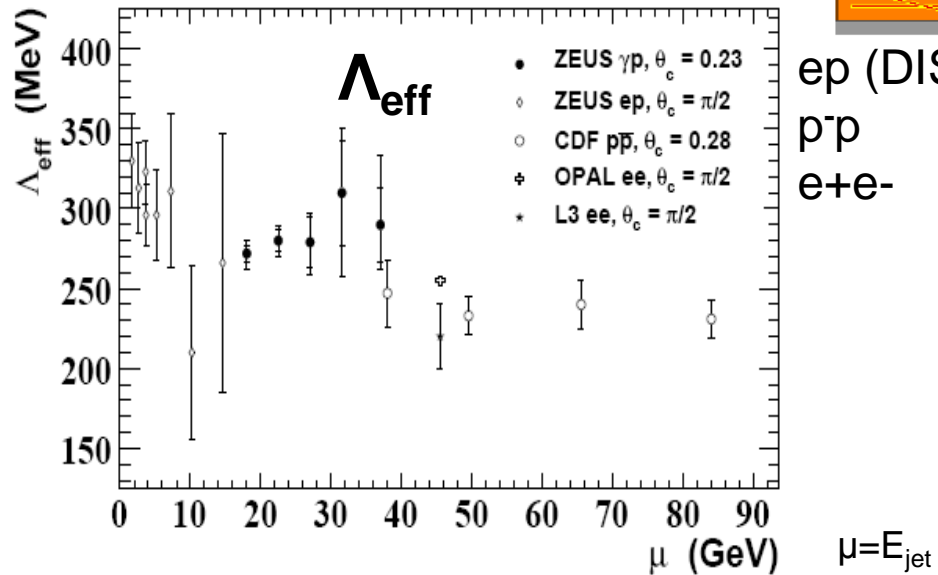
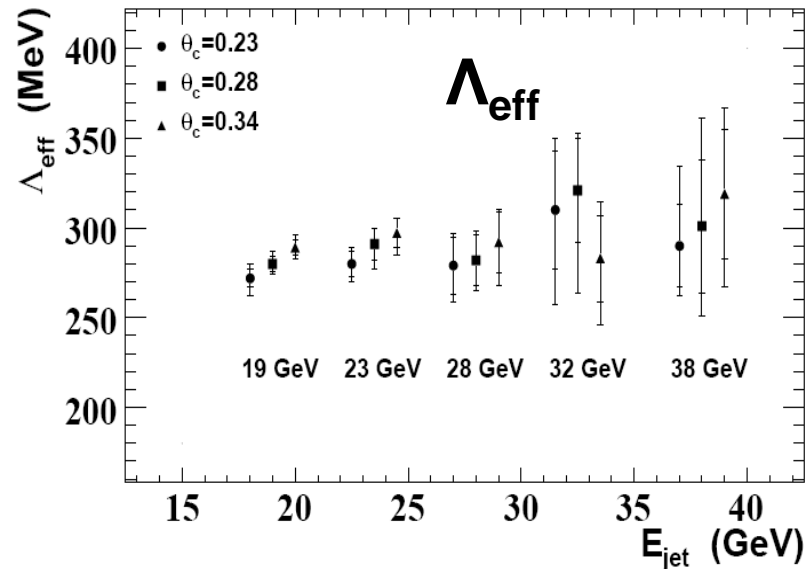
- fit gaussian 1 around the arithmetic mean of the ξ distribution
- fit dependence of the peak position on energy scale

E_{jet}



$$\Lambda_{\text{eff}} = 275 \pm 4(\text{stat.}) +4_{-8}(\text{syst.}) \text{MeV}$$

Scaled momentum distributions $\Lambda_{\text{eff}}, \kappa^{\text{ch}}$



ep (DIS, γp)
 $p\bar{p}$
 e^+e^-

no dependence on energy scale
 weak dependence on cone
 opening angle θ_c

data for different processes support
 the **universality of Λ_{eff}** parameter

Extraction of κ^{ch} from the fit to the shape of ξ distribution

$$\kappa^{\text{ch}} = 0.55 \pm 0.01(\text{stat.})^{+0.03}_{-0.02}(\text{syst.})^{+0.11}_{-0.09}(\text{theo.})$$

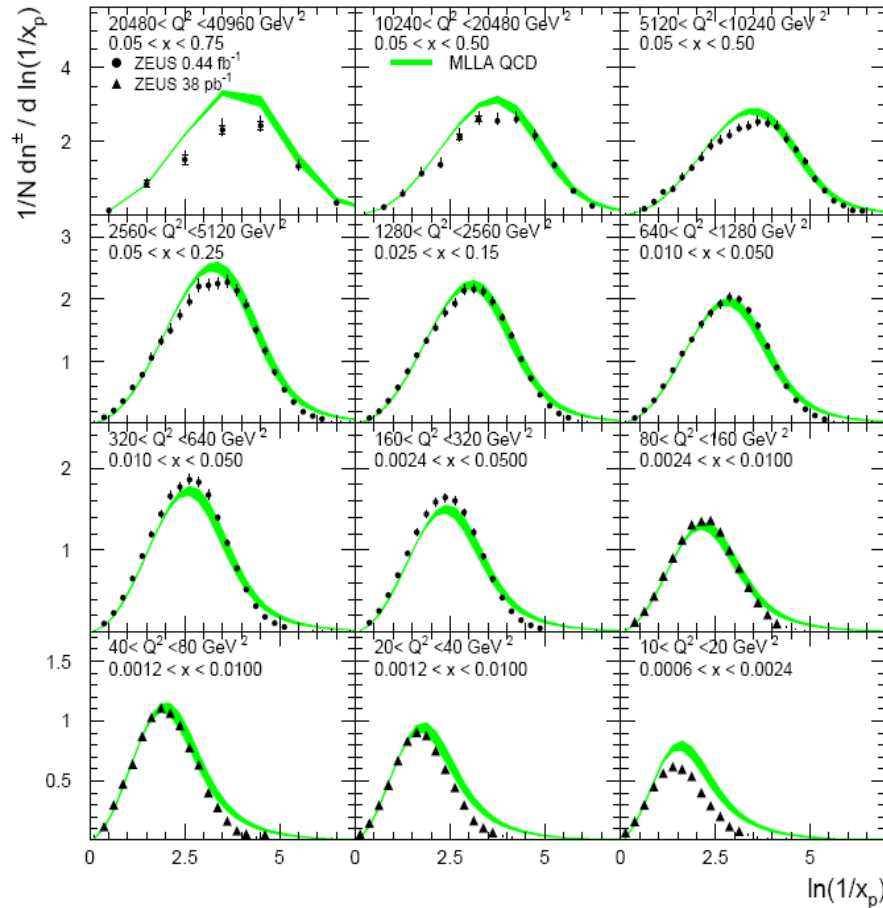
from pp^-
 $\kappa^{\text{ch}} = 0.56 \pm 0.05(\text{stat.}) \pm 0.09(\text{syst.})$

data support the **universality of κ^{c}** parameter



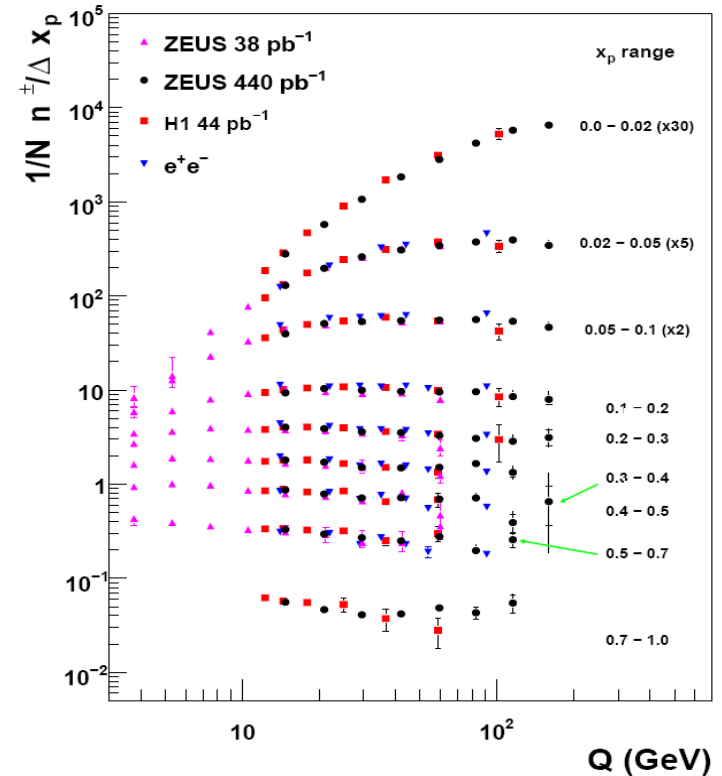
MLLA+LPHD predictions

observation of scaling violation



parameters from e^+e^- (LEP)
 low and high Q^2 – too many particles
 agreement at medium Q^2

n increases with Q^2 at low x_p
 n decreases with Q^2 at high x_p



comparison of ep data (ZEUS and H1)
 to e^+e^- results supports the concept of
quark fragmentation universality

Hadronic final state charge asymmetry in high Q^2 DIS



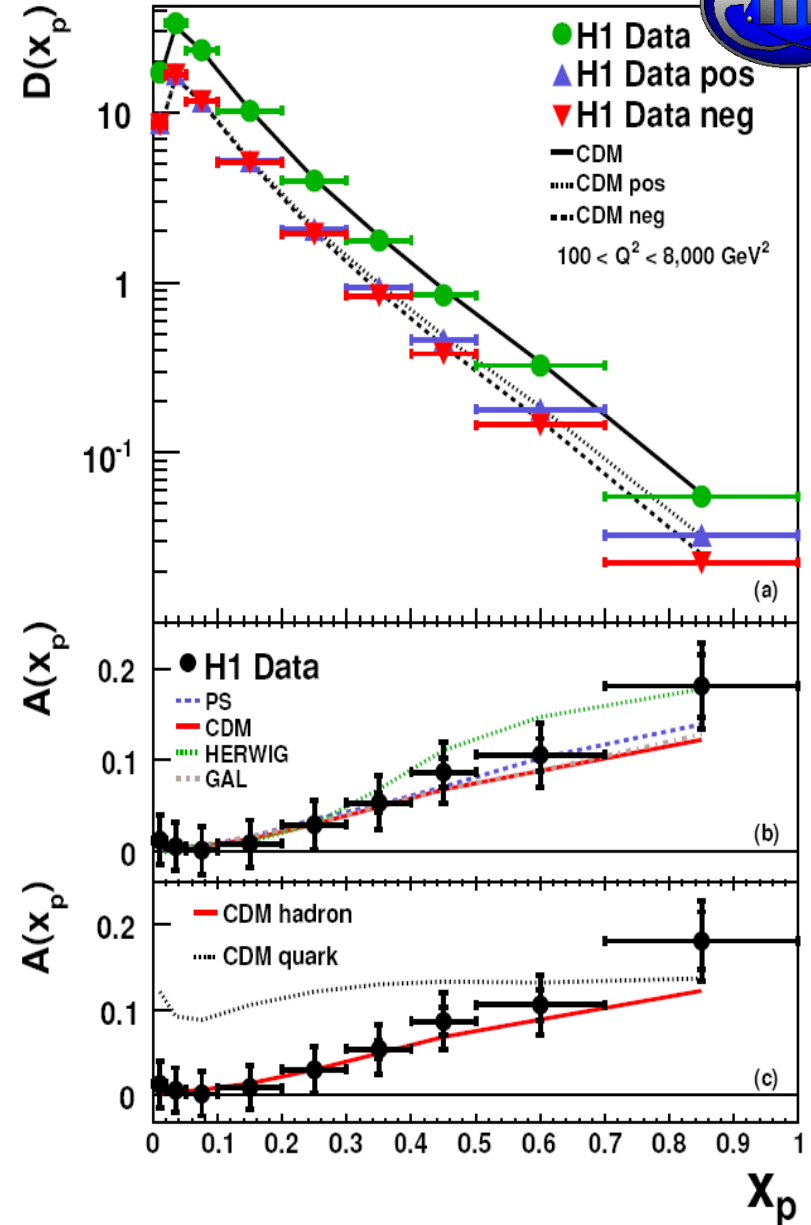
$D(x_p) = 1/N \frac{dn}{dx_p}$ now defined separately for **positively** and **negatively** charged particles

low x_p dominated by fragmentation
similar distributions
 independent of the charge

high x_p sensitive to the hard subprocess
difference between pos and neg
excess of positive charge
 due to the quark content of the proton

$$\text{Asymmetry } A(x_p) = \frac{\text{pos} - \text{neg}}{\text{pos} + \text{neg}}$$

Monte Carlo models well describe the magnitude and evolution of the asymmetry

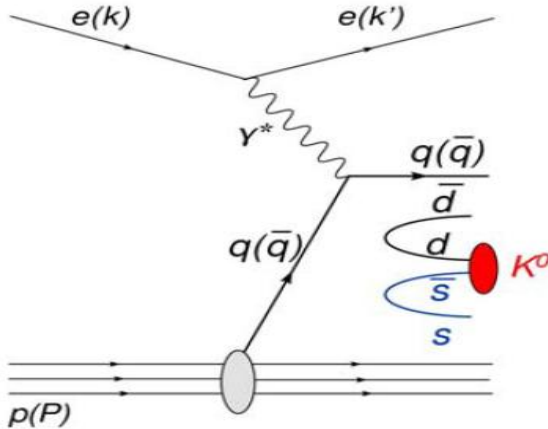


Strangeness Production in DIS ep Scattering

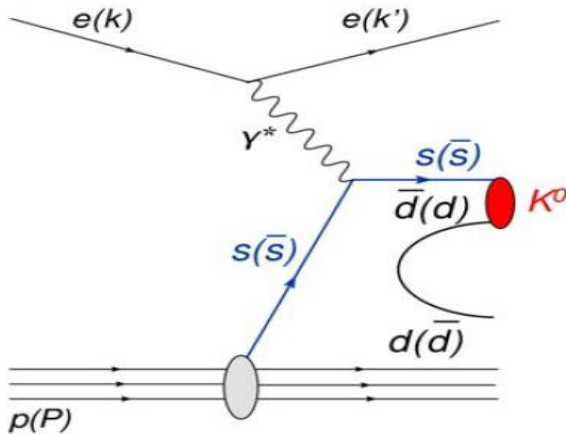
non-perturbative process: hadronisation

LUND string fragmentation model
strangeness suppression factor

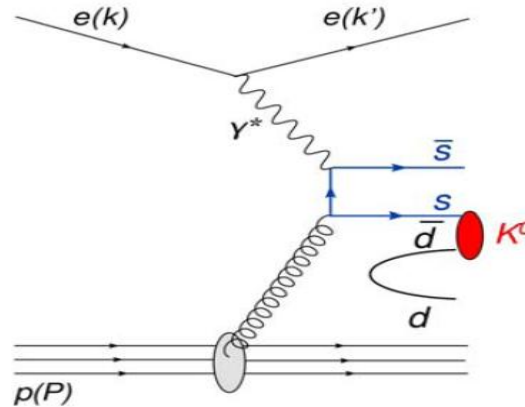
$$\lambda_s = P(s)/P(q)$$



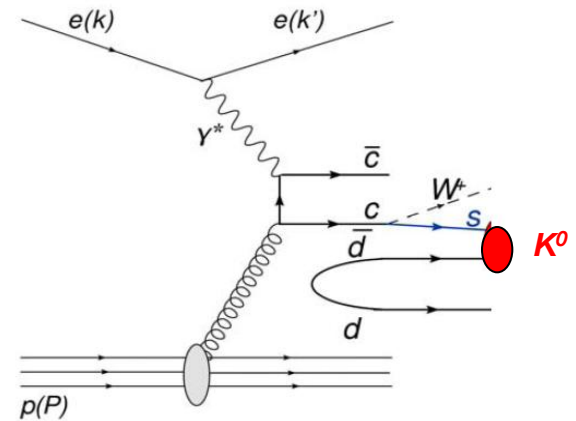
hard processes: QPM



boson-gluon fusion



decays of heavy quarks



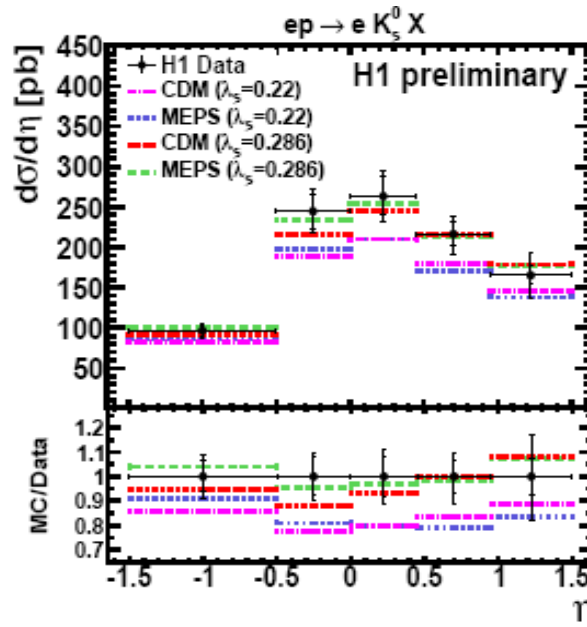
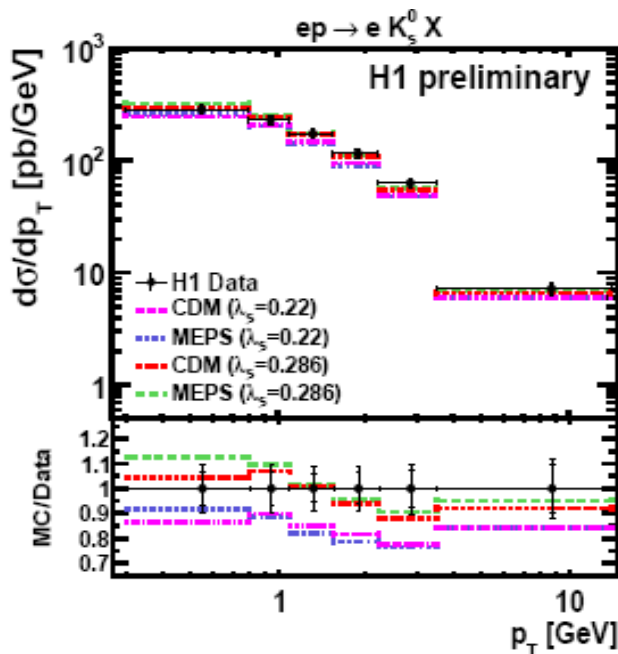
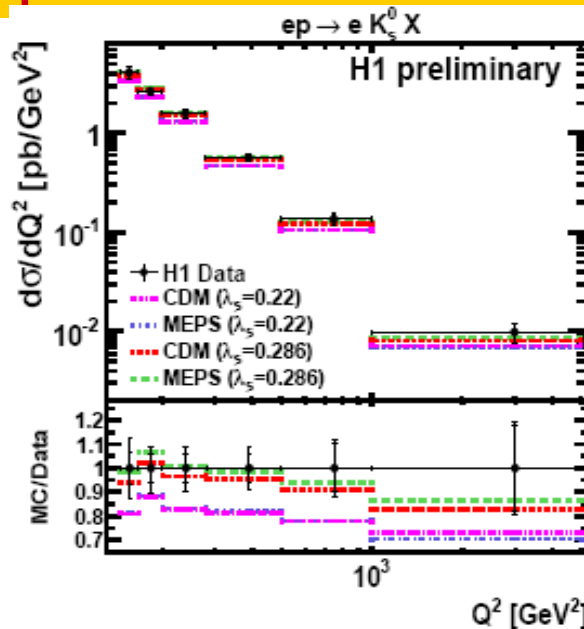
K^0_s differential prod. x-secs in LAB in Q^2, η, p_T



Kinematic phase-space
 $145 < Q^2 < 20000 \text{ GeV}^2$
 $P_T(K^0_s) > 0.3 \text{ GeV}$
 $|\eta(K^0_s)| < 1.5$

$K^0_s \rightarrow \pi^+\pi^-$

LO Monte Carlo predictions with
 $\lambda_s = 0.22$ and $\lambda_s = 0.286$



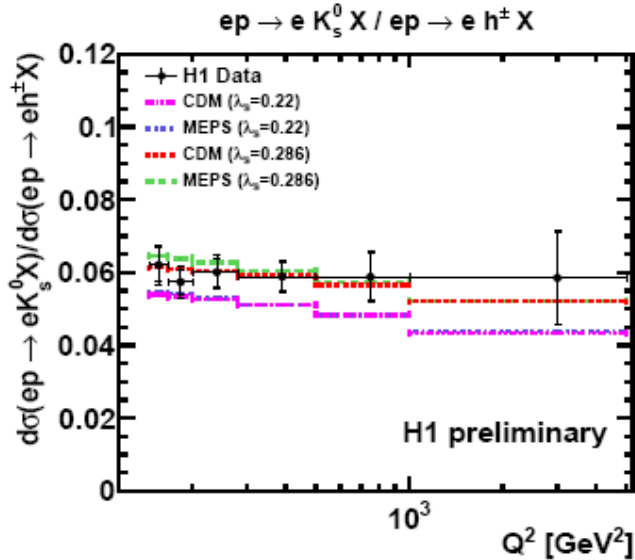
MEPS and CDM
 with $\lambda_s = 0.286$
 describe the
 differential cross-
 sections

Ratio of x- sections: K_s^0 /charged hadrons



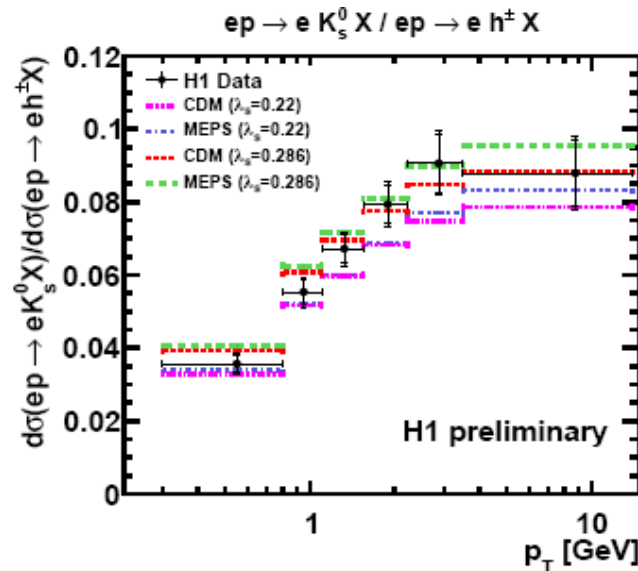
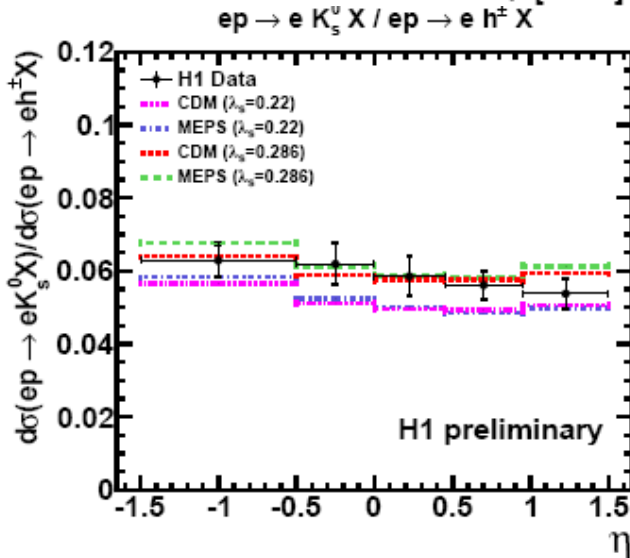
$$ep \rightarrow e K_s^0 X / ep \rightarrow e h^\pm X$$

h in the same kinematic region as K_s^0



- ratio rises strongly with p_T
- \sim constant as a function of Q^2 and η

LO Monte Carlos with $\lambda_s = 0.286$ describe the data



Charm fragmentation into D^*

Prod. of a charmed hadron = **perturbative production** of c -quark & **non-perturbative transition** of c -quark into a charmed had.

Transition process characterized by the transfer of the quark energy to a given hadron parametrized by **fragmentation functions**.

Parameters determined in e^+e^- experiments

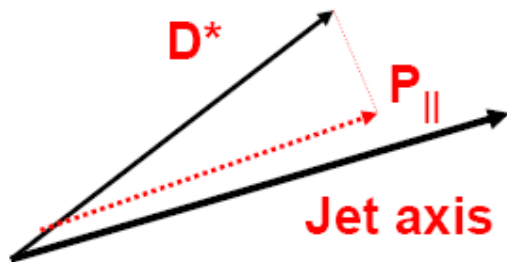
check in ep experiments **universal?**

observables e^+e^- $z \sim E_{D^*}/E_{\text{beam}}$ (E_{beam} = energy of the c -quark)
 ep z_{hem} and z_{jet}

Jet method (ZEUS,H1)

E of the c -quark is approximated by E of the reconstructed D^* jet

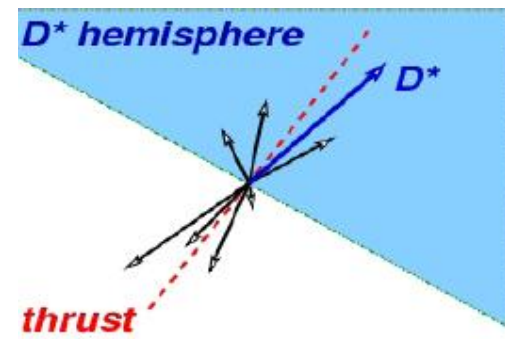
$$z_{\text{jet}} = (E + p_{\parallel})_{D^*} / (E + p)_{\text{jet}}$$



Hemisphere method (H1)

E of the c quark is approx. by E of the reconstructed D^* hemisphere

$$z_{\text{hem}} = (E + p_{\parallel})_{D^*} / \sum_{\text{hem}} (E + p)$$



Charm fragmentation in Photoproduction



$Q^2 < 1 \text{ GeV}^2$, $130 < W_{\text{yp}} < 280 \text{ GeV}$
at least one jet (reconstructed with
 k_T clustering algorithm)
 $E_T(\text{jet}) > 9 \text{ GeV}$, $|\eta^{\text{jet}}| < 2.4$

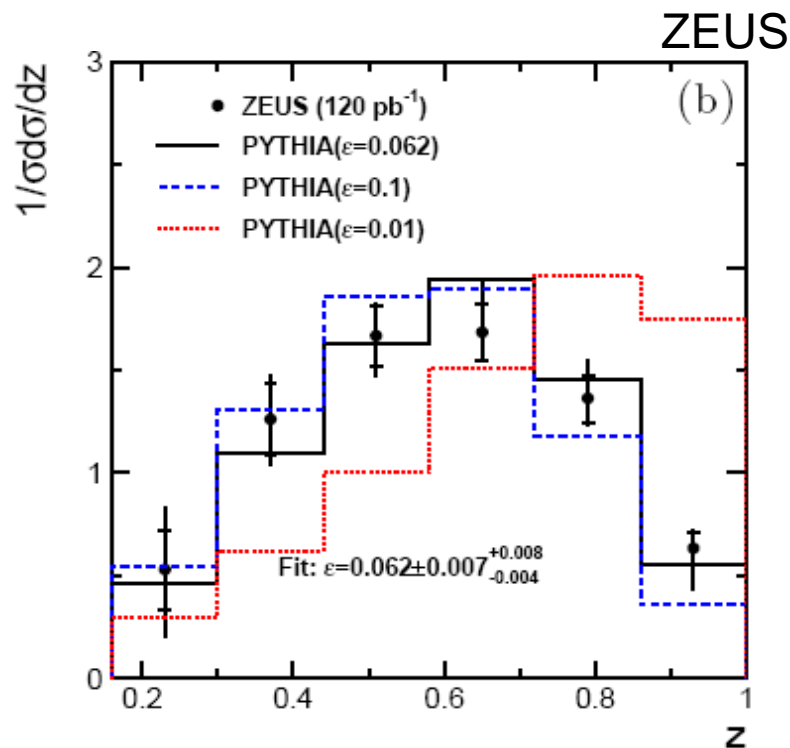
$D^* \rightarrow D^0 \pi_S \rightarrow K \pi \pi_S$
 $p_T(D^*) > 2 \text{ GeV}$,
 $|\eta(D^*)| < 1.5$
associated with a jet

value of ϵ parameter extracted from fitting
MC predictions to the data

$$\epsilon = 0.062 \pm 0.007(\text{stat.})^{+0.008}_{-0.004}(\text{syst.})$$

Consistent with the value 0.05 obtained
from $e+e-$ experiments

Comparison with
Peterson fragmentation function
(one free parameter ϵ)
in PYTHIA



Comparison with NLO QCD calculations from Frixione-Mangano-Nason-Rudolfi (FMNR)

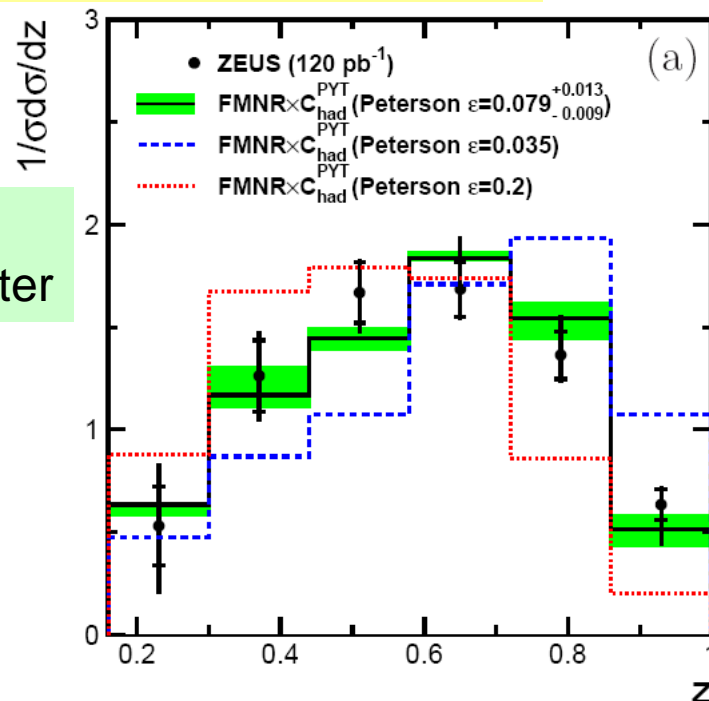
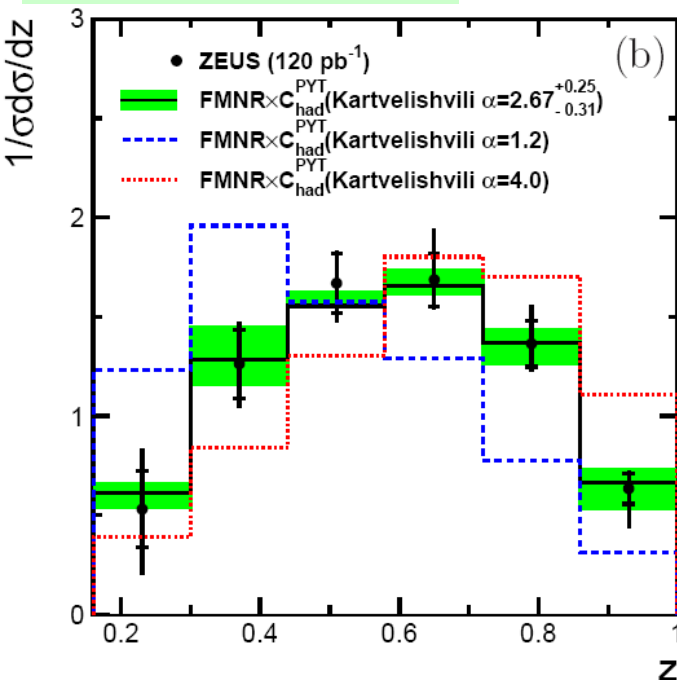
calculations corrected for effects of hadronization

fits to the data with

Kartvelishvili FF
free α parameter

ZEUS

Peterson FF
free ϵ parameter



fit results:

$$\epsilon = 0.079 \quad 0.008(\text{stat.})^{+0.010}_{-0.005} \text{ (syst.)}$$

$$\alpha = 2.67 \quad 0.18(\text{stat.})^{+0.17}_{-0.25} \text{ (syst.)}$$



Charm fragmentation in DIS

$2 < Q^2 < 100 \text{ GeV}^2$

$D^* \rightarrow D^0 \pi_S \rightarrow K \pi \pi_S$

$1.5 < p_T(D^*) < 15 \text{ GeV}$,

$|\eta(D^*)| < 1.5$

jets found by k_T cluster algorithm

D* jet sample

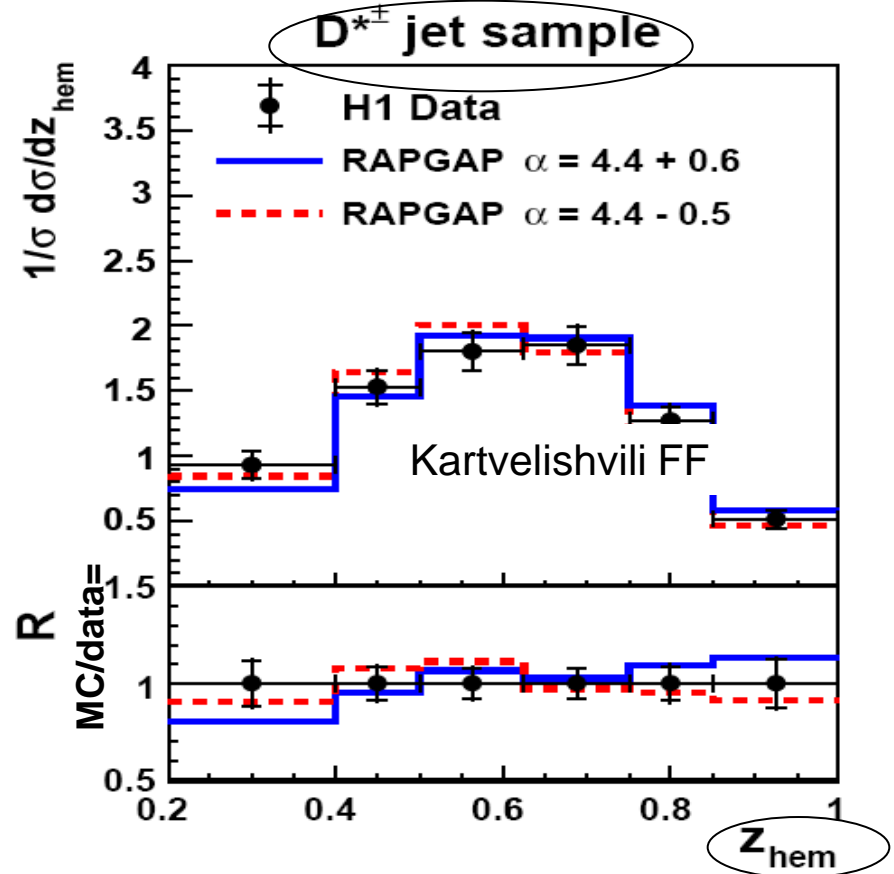
jet containing the D^* meson

$E_T(\text{jet}) > 3 \text{ GeV}$

no D* jet sample

no such jet is allowed

Comparison with RAPGAP
(LO ME+DGLAP) simulations



Kartvelishvili (α)

Peterson (ϵ)

jet method $4.3^{+0.5}_{-0.4}$

$0.035^{+0.007}_{-0.006}$

(higher excited charm states included)

hemisp. meth. $4.4^{+0.6}_{-0.5}$

$0.030^{+0.007}_{-0.006}$

(from e^+e^- $\epsilon=0.04$ with the same setting)

Both methods give consistent results

**fragmentation universality
in e^+e^- and ep processes**

Charm fragmentation in DIS

Comparison with RAPGAP (LO ME+DGLAP) simulations



Events without a D*jet with $E_T > 3$ GeV \rightarrow investigation of charm fragmentation close to the kinematic threshold possible due to hemisphere method.

values of fitted parameters:

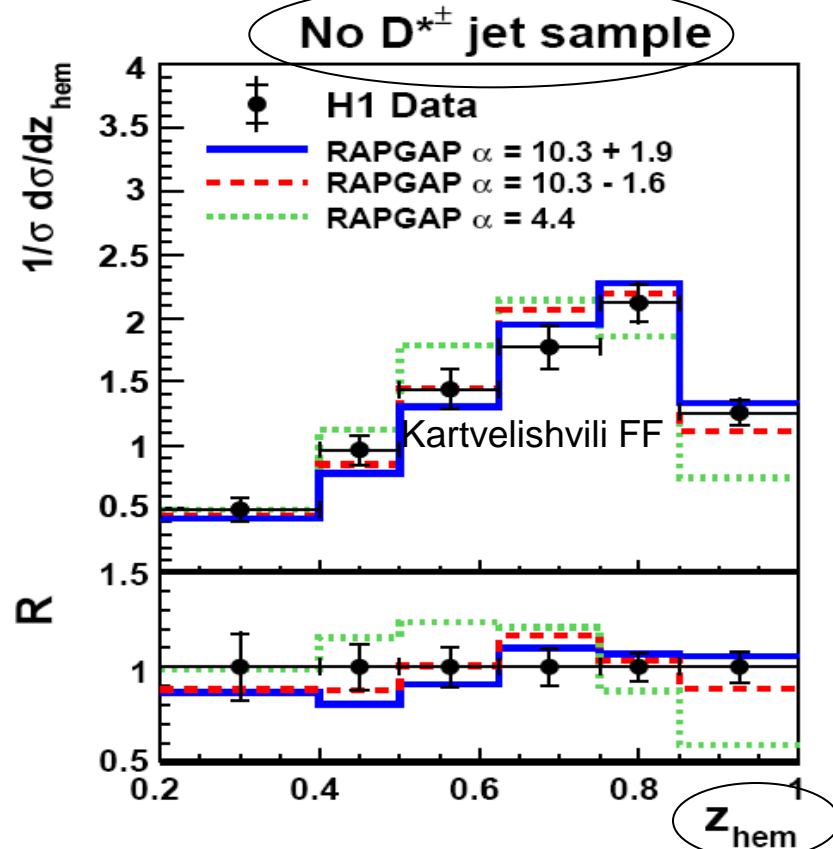
Kartvelishvili (α)

$$10.3^{+1.9}_{-1.6}$$

Peterson (ϵ)

$$0.006^{+0.003}_{-0.002}$$

significantly **different** from values obtained for the D*jet sample



The QCD model with the same value for the fragmentation function parameter is not able to describe charm fragmentation consistently in the full phase space down to the kinematic threshold

Studies also performed with CASCADE and NLO QCD – same conclusions

Summary

Charged particles production has been studied in photoproduction and DIS processes at HERA.

The production is sensitive to the fragmentation parameters.

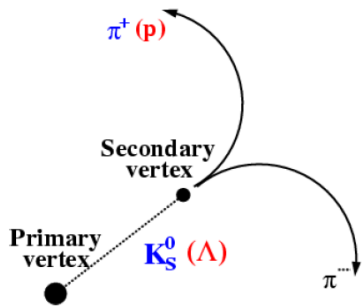
The extracted parameters support the hypothesis of fragmentation universality between ep and e+e- processes.

Production of neutral strange mesons is well describe by LO Monte Carlos.

LO MC models and NLO calculations fail to provide a consistent description of charm fragmentation over the full space down to the kinematic threshold.

Back-up slides

Observation of K_s^0



Kinematic phase-space

$$145 < Q^2 < 20000 \text{ GeV}^2$$

$$0.2 < y < 0.6$$

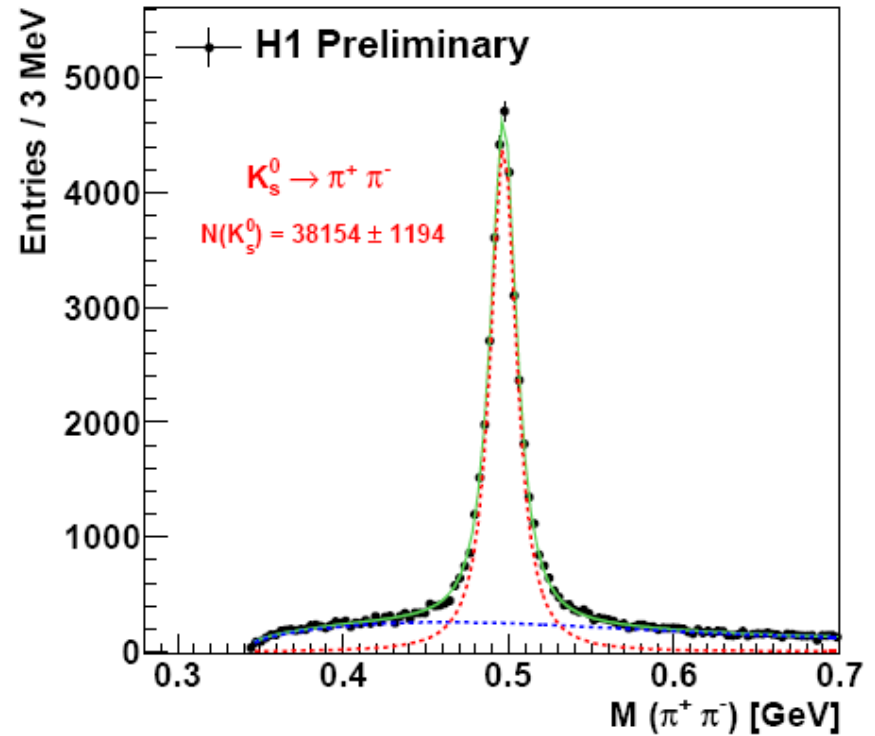
$$P_T(K_s^0) > 0.3 \text{ GeV}$$

$$|\eta(K_s^0)| < 1.5$$

int. luminosity of $\sim 340 \text{ pb}^{-1}$

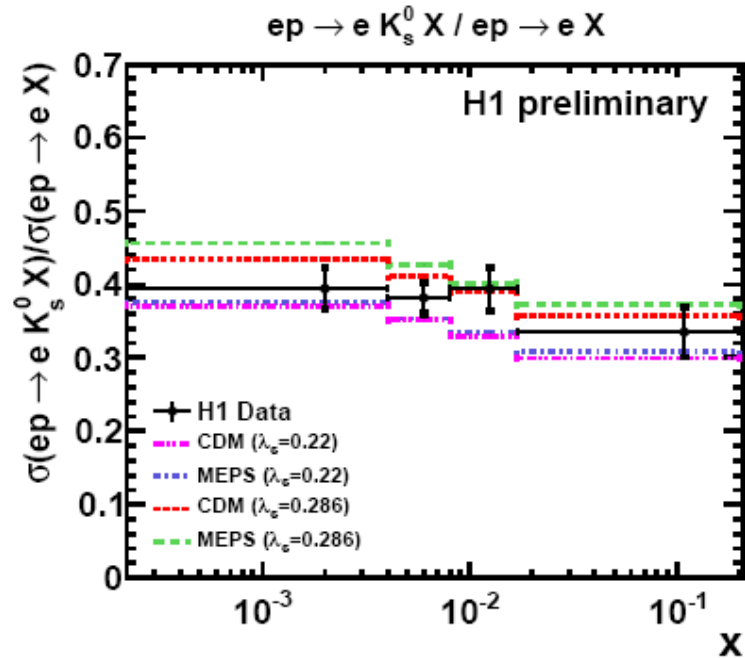
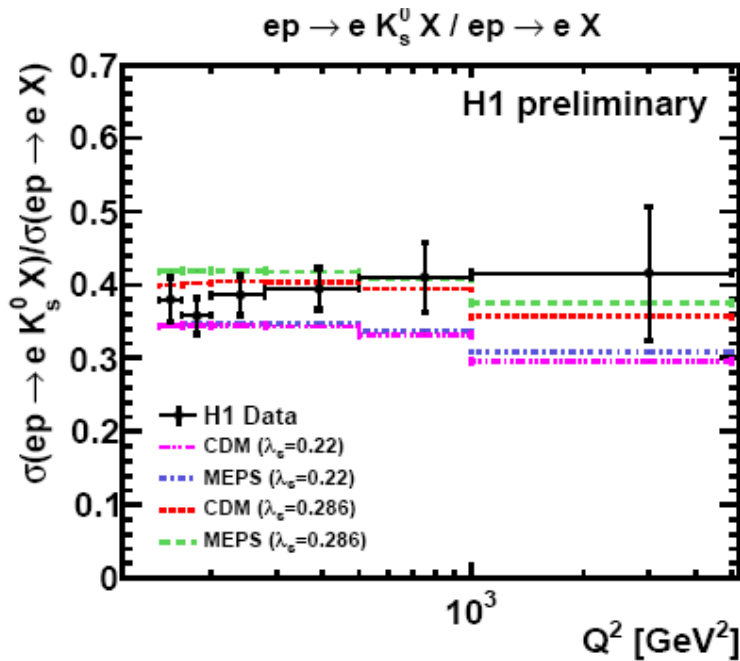
Inclusive x-section

$$\sigma_{\text{vis}} = 531 \pm 17(\text{stat.})^{+37}_{-39}(\text{syst.}) \text{ pb}$$



K_s^0 density

$$\sigma(ep \rightarrow eK_s^0 X) / \sigma(ep \rightarrow eX)$$



- density ~ 0.4

- no dependence on Q^2

- models predictions consistent with a small falling at higher x

Frames of reference

LAB frame

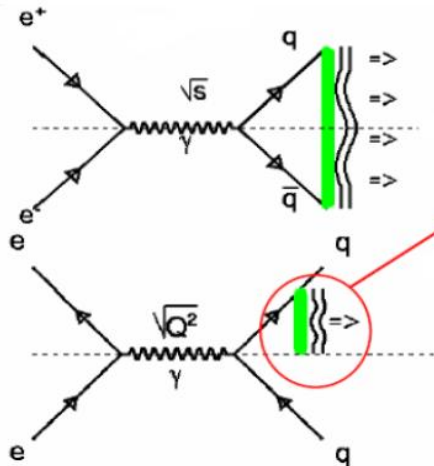
$$\eta = -\ln \tan(\theta/2)$$

θ with respect to proton direction

$\eta > 0$ proton direction

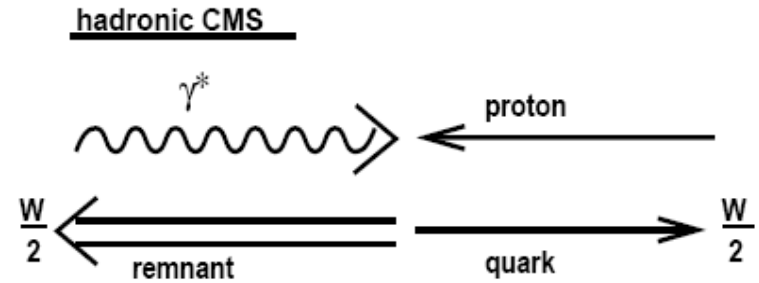
Breit frame:

photon and proton are moving collinearly
 photon has momentum Q but no energy,
 photon direction defines the negative z -axis



Current region similar to one hemisphere in e^+e^-

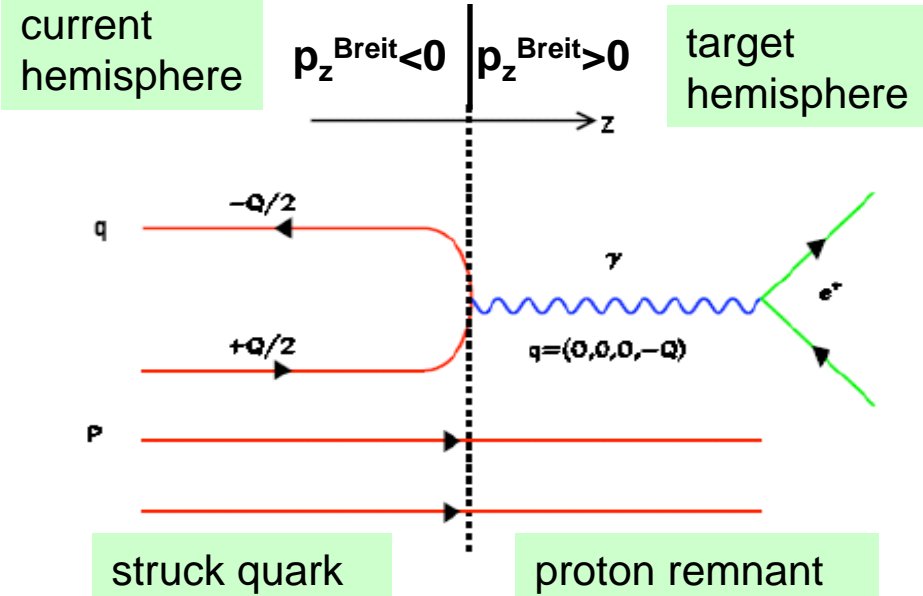
Hadronic Center of Mass



$$\eta^* = -\ln \tan(\theta^*/2)$$

θ^* with respect to γ^*

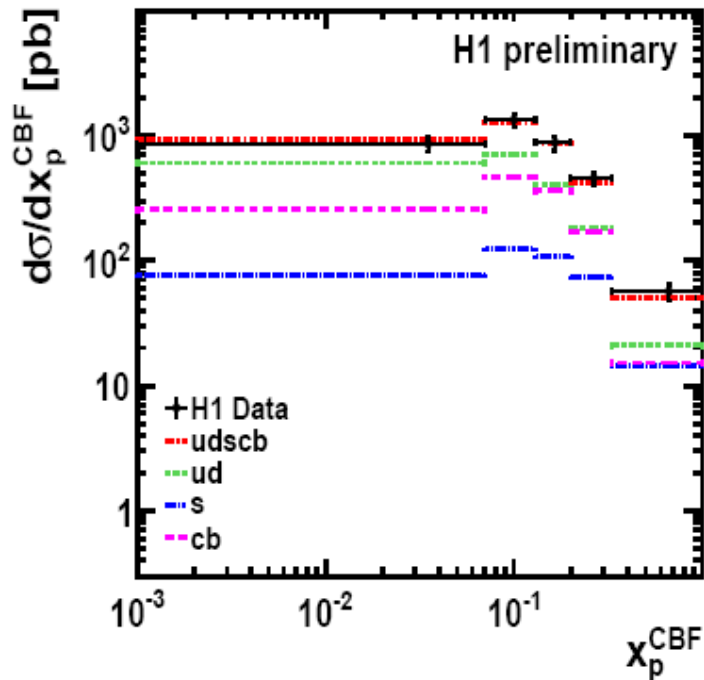
$\eta^* < 0$ proton direction



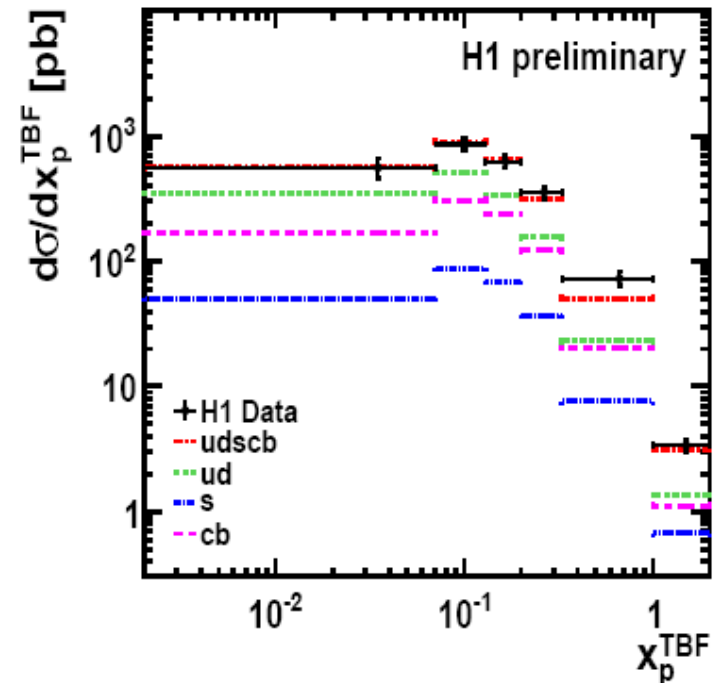
Flavour contributions to x-sec in Breit frame



$ep \rightarrow e K_s^0 X$ (Breit Frame)



$ep \rightarrow e K_s^0 X$ (Breit Frame)

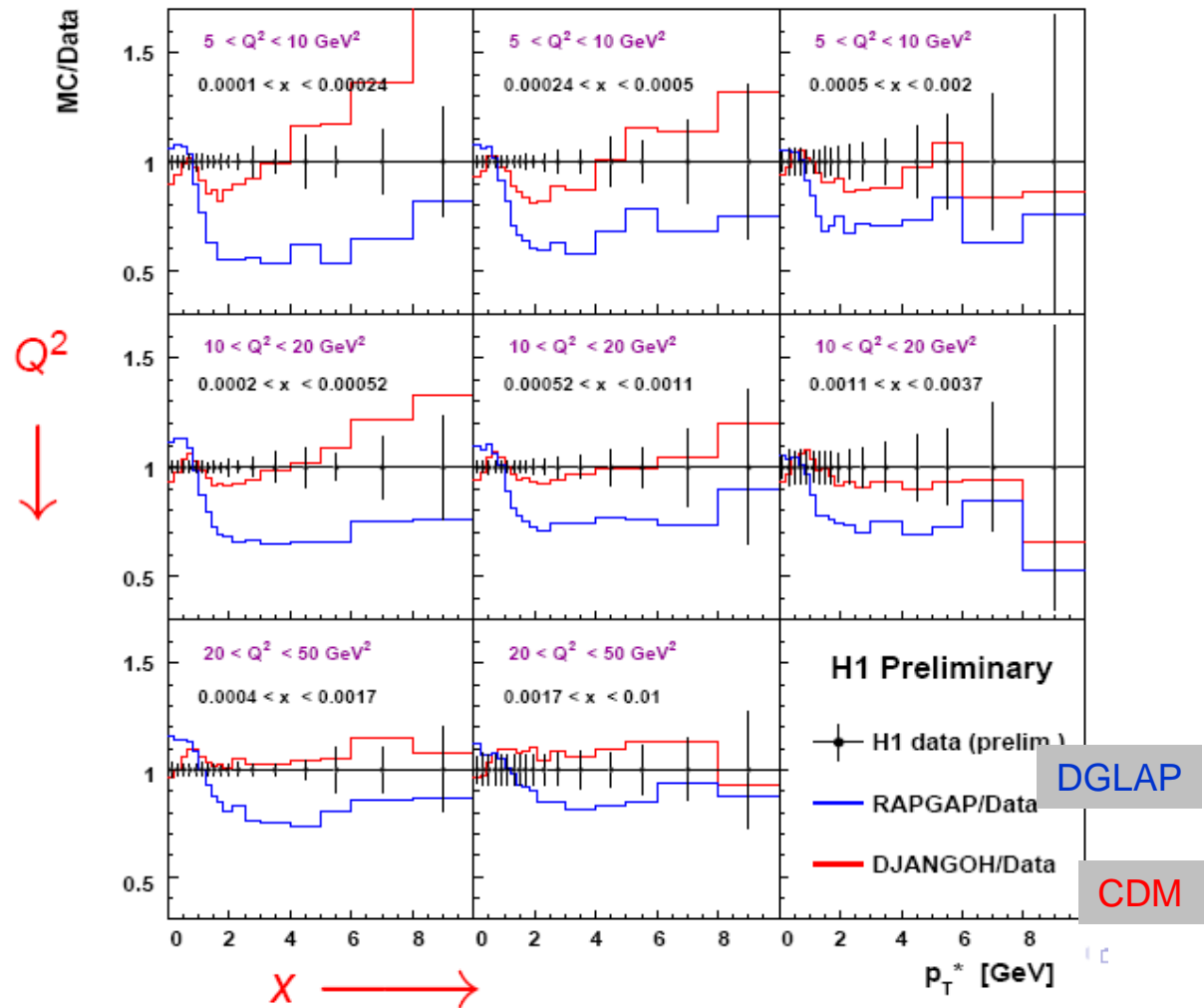


In the current region the contribution of s quark is enhanced and equals the heavy cb quarks contribution in the region of high x_p^{CBF}

ratios: MC/data of p_T^* distributions in (x, Q^2) bins



strongest disagreement
between both models
(DGLAP, CDM)
and the data
at high p_T^* ($p_T^* > 1$ GeV)
at low Q^2 and low x

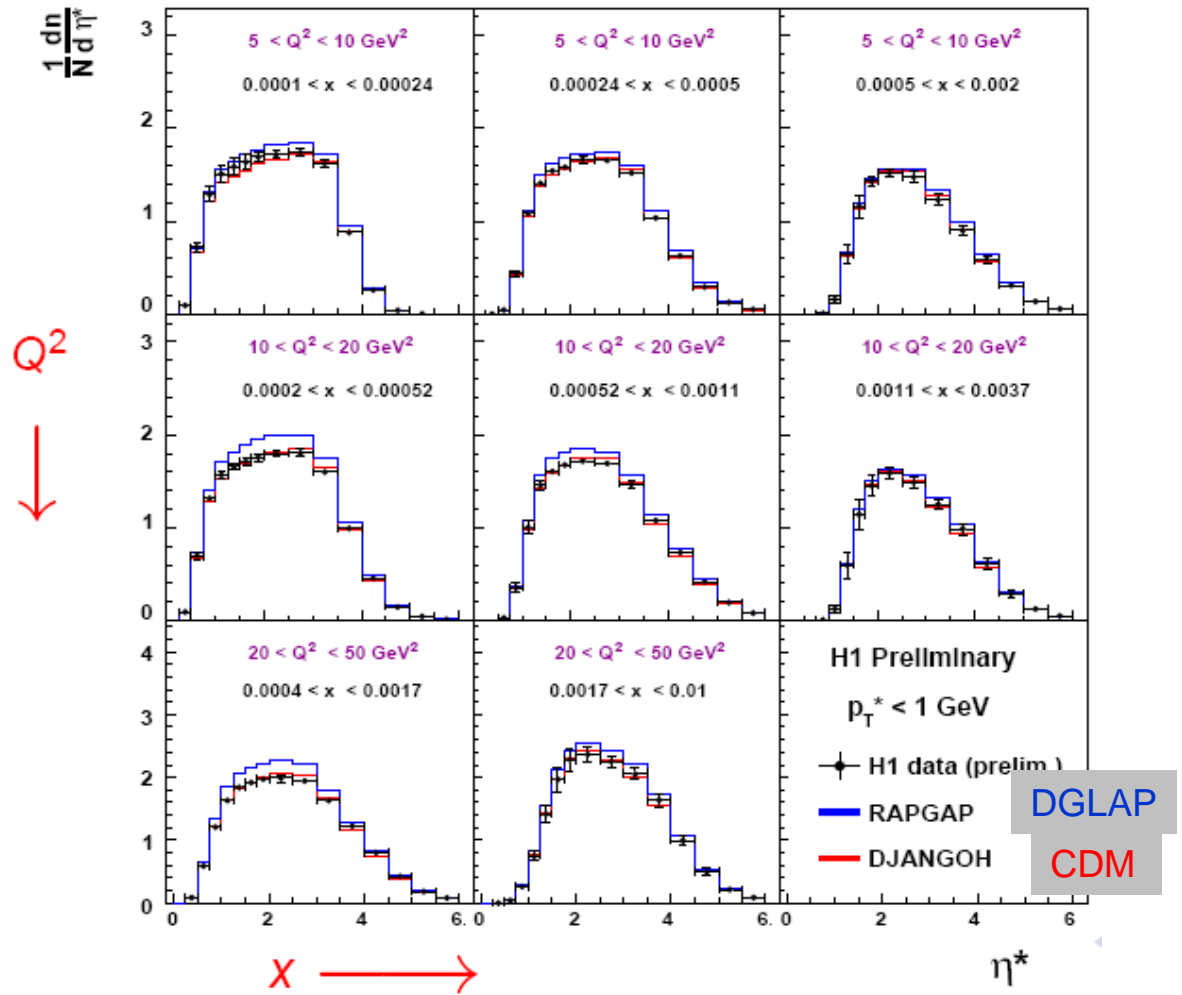


η^* distributions of charged particles in (x, Q^2) bins

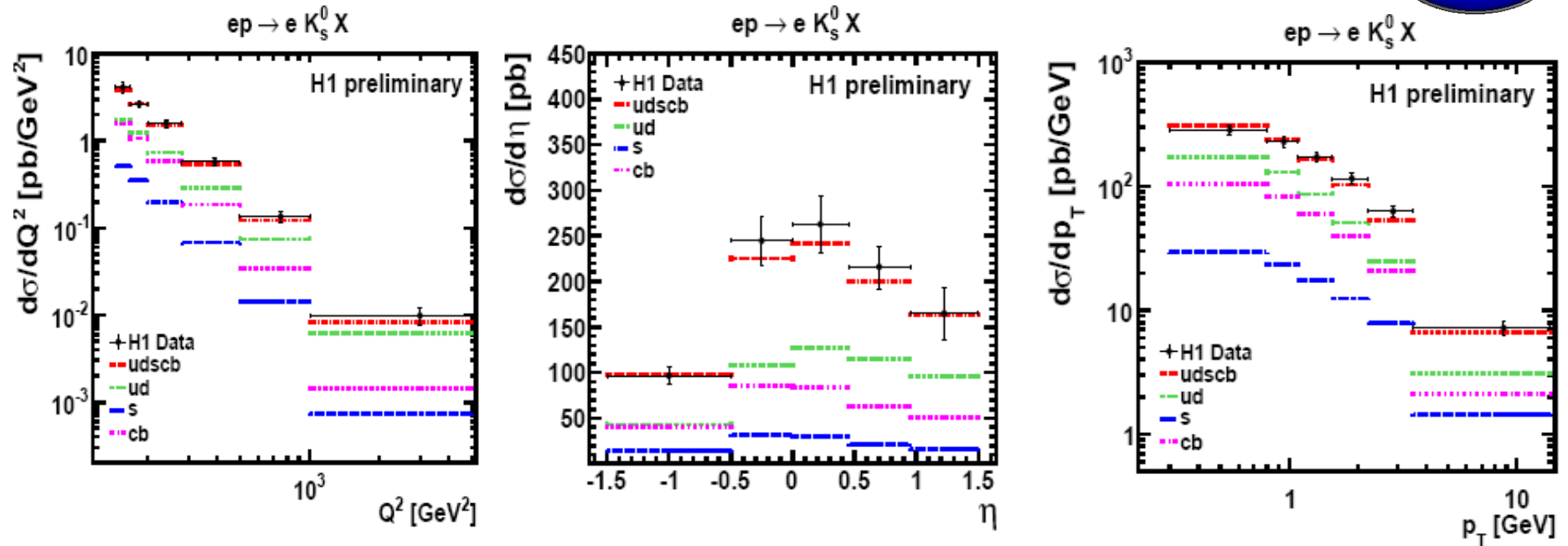


$p_T^* < 1 \text{ GeV}$

Reasonable description of the data for all (Q^2, x) bins by models with different parton dynamics: DGLAP (RAPGAP) and CDM (DJANGOH)



Flavour contributions to x-section in LAB

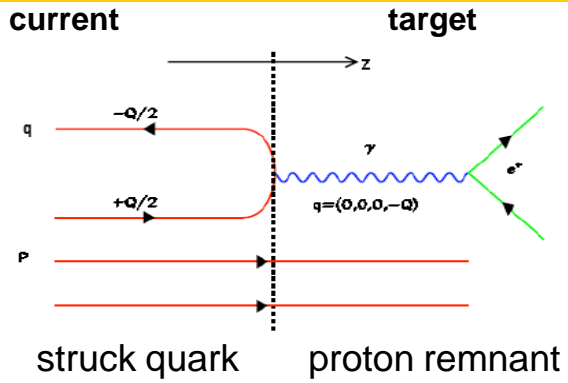
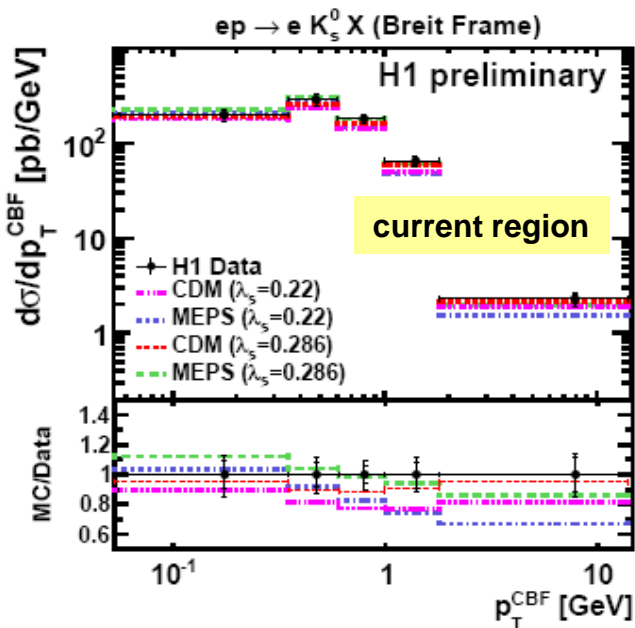


- dominant contributions from light quarks (u, d)
- heavy quarks (c, b) as the second dominant contribution
- the fraction of s quarks increases at high p_T

K^0_s diff. x-sec in Breit frame in p_T^{Breit}, x_p^{Breit}



$$X_p^{Breit} = \frac{(2P_h^{Breit})}{Q}$$



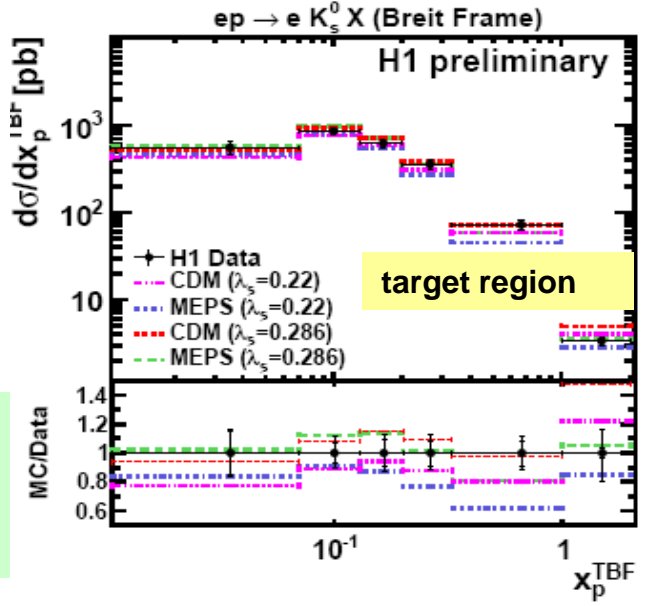
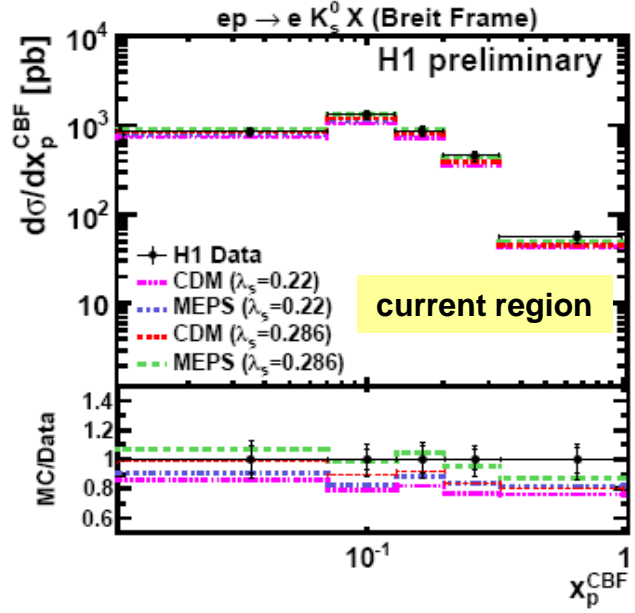
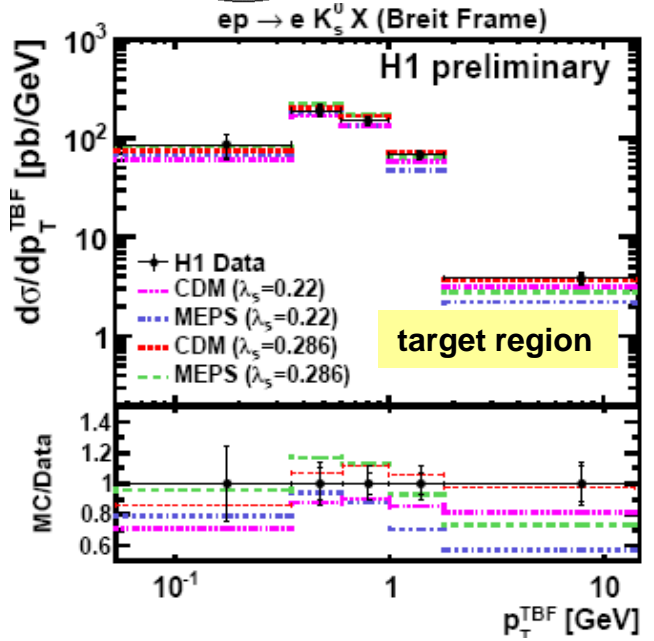
current region

- s-quark from hard processes preferentially
- less sensitivity to λ_s with respect to the target hem. or laboratory frame

target region

- hadronization process predominantly
- more sensitivity to λ_s

CDM and MEPS with $\Lambda_s = 0.286$ better describe the differential x-sections



Charm fragmentation in Photoproduction



photoproduction

$Q^2 < 1 \text{ GeV}^2$, $130 < W_{\text{yp}} < 280 \text{ GeV}$

at least one jet (reconstructed with
 k_T clustering algorithm)

$E_T(\text{jet}) > 9 \text{ GeV}$

$|\eta^{\text{jet}}| < 2.4$

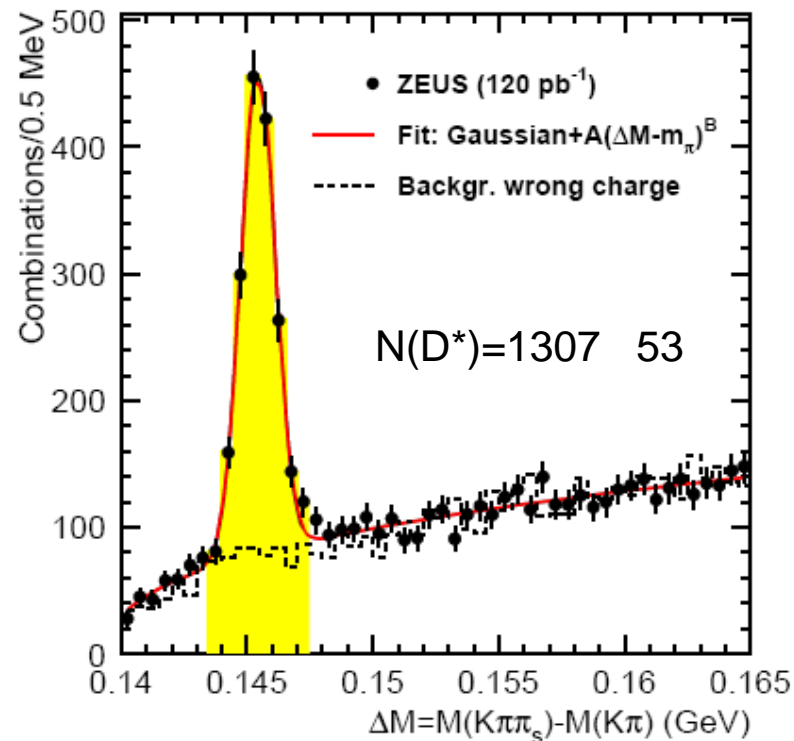
$D^* \rightarrow D^0 \pi_S \rightarrow K \pi \pi_S$

$p_T(D^*) > 2 \text{ GeV}$,

$|\eta(D^*)| < 1.5$

associated with a jet

ZEUS



Charm fragmentation in DIS



$$2 < Q^2 < 100 \text{ GeV}^2$$

$$D^* \rightarrow D^0 \pi_S \rightarrow K \pi \pi_S$$

$$1,5 < p_T(D^*) < 15 \text{ GeV},$$
$$|\eta(D^*)| < 1.5$$

jets found by k_T cluster algorithm

D* jet sample

jet containing the D* meson

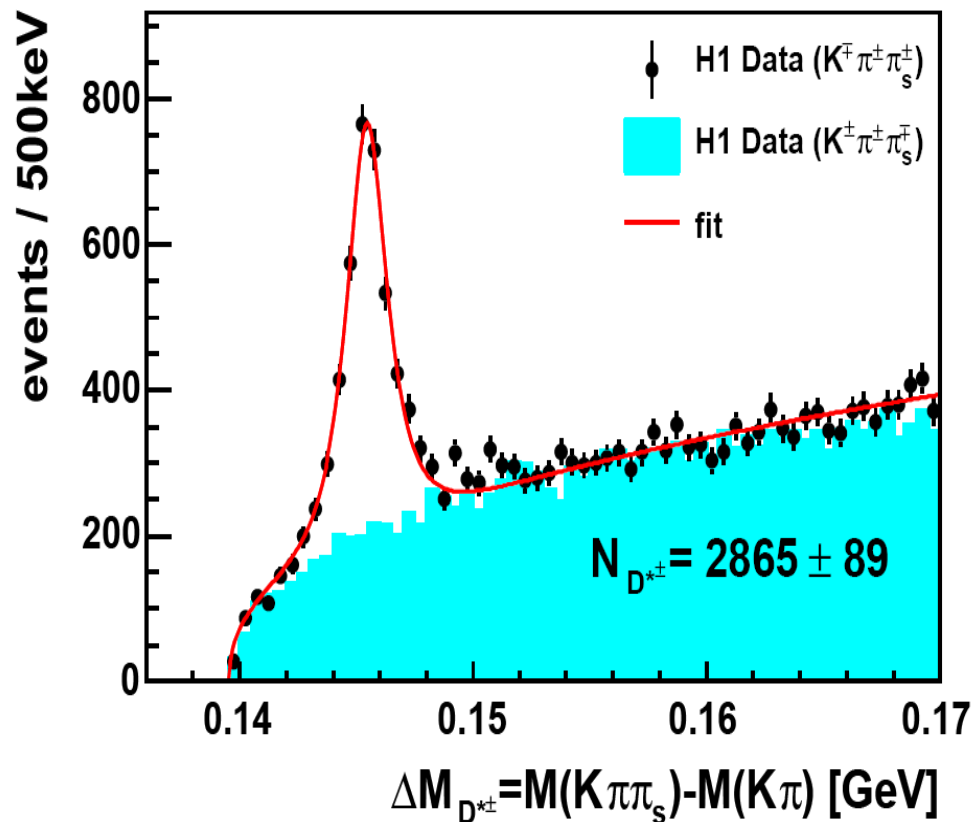
$$E_T(\text{jet}) > 3 \text{ GeV}$$

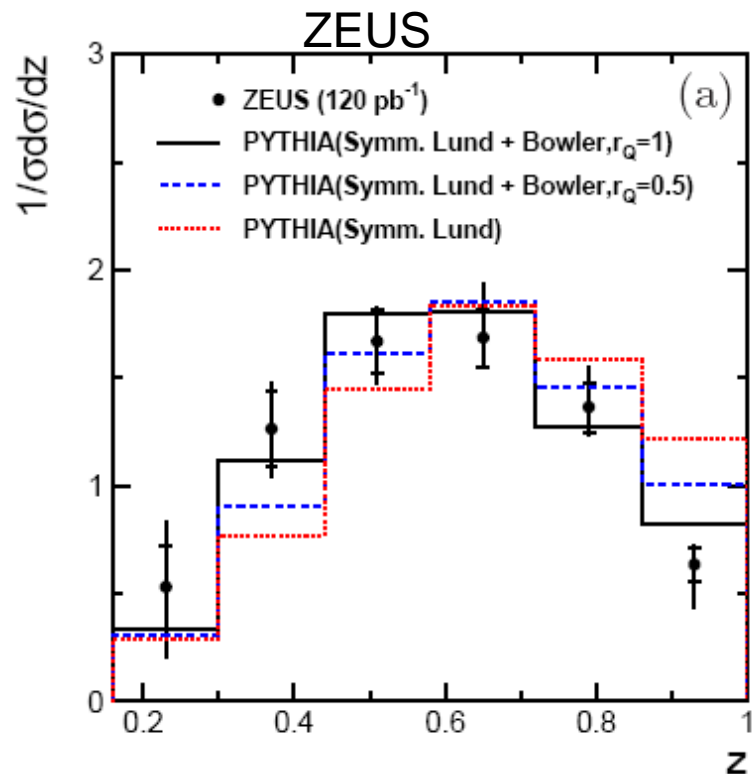
$$N(D^*) = 1508 \quad 68(\text{stat.})$$

no D* jet sample

$$N(D^*) = 1363 \quad 54(\text{stat.})$$

wrong charge combinations ■





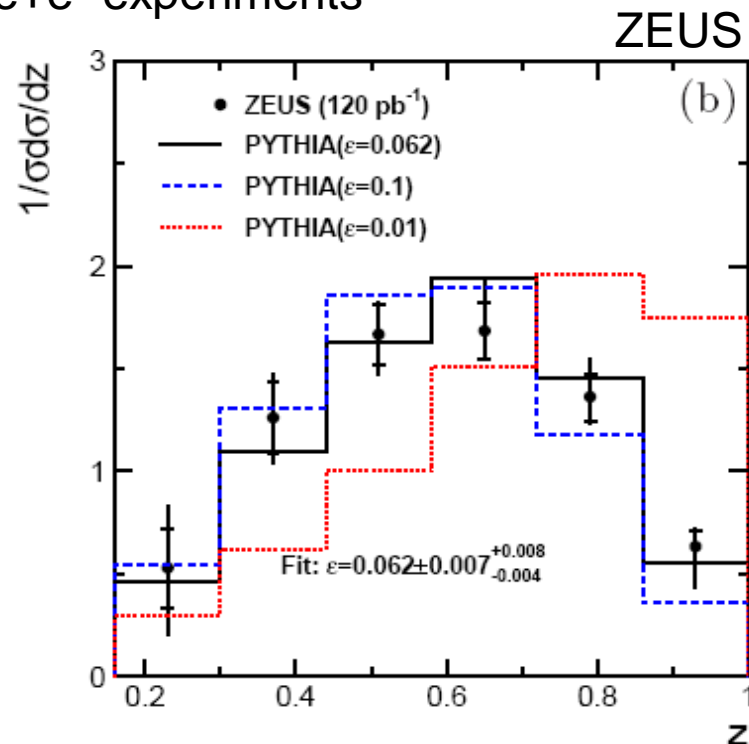
PYTHIA with symmetric Lund string fragmentation f.+ modif. for heavy quarks (Bowler f.)
 $r_Q = 1$ (default setting) gives a reasonable description
 deviation increases with decreasing value of r_Q

PYTHIA with Peterson fragm. function

value of ϵ parameter extracted from fitting MC to the data

$$\epsilon = 0.062 \pm 0.007(\text{stat.})^{+0.008}_{-0.004}(\text{syst.})$$

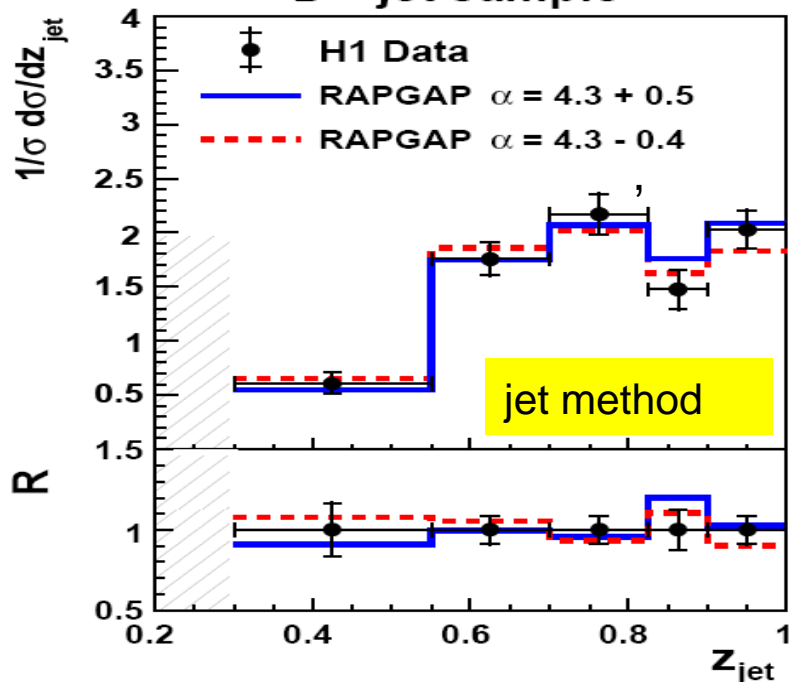
Consistent with the value 0.05 obtained from e+e- experiments





RAPGAP (LO ME + DGLAP evolutions)

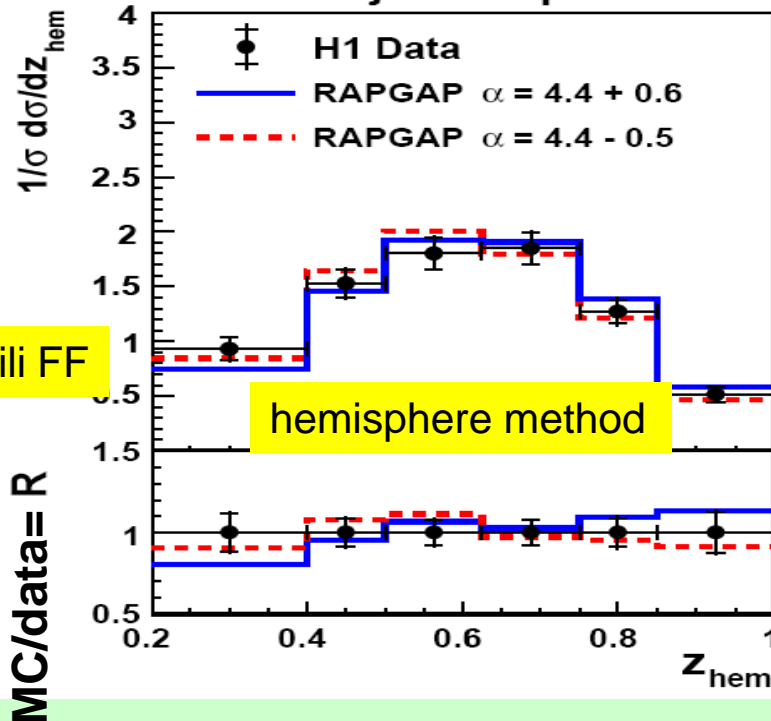
$D^{*\pm}$ jet sample



jet method

Kartvelishvili FF

$D^{*\pm}$ jet sample



hemisphere method

MC/data = R

Kartvelishvili (α) Peterson (ϵ)

jet method	$4.3^{+0.5}_{-0.4}$	$0.035^{+0.007}_{-0.006}$	ALEPH setting (higher res. included)
hemisp. meth.	$4.4^{+0.6}_{-0.5}$	$0.030^{+0.007}_{-0.006}$	(from e^+e^- $\epsilon=0.04$ fragm.universality)
jet method	$3.1^{+0.3}_{-0.3}$	$0.061^{+0.011}_{-0.009}$	default PYTHIA setting (w/o higher res.)
hemisp. meth	$3.3^{+0.4}_{-0.4}$	$0.049^{+0.012}_{-0.010}$	

Both methods give consistent results

all settings reasonably describe the data

Similar results obtained with CASCADE simulation (k_T factorization+CCFR evolution)



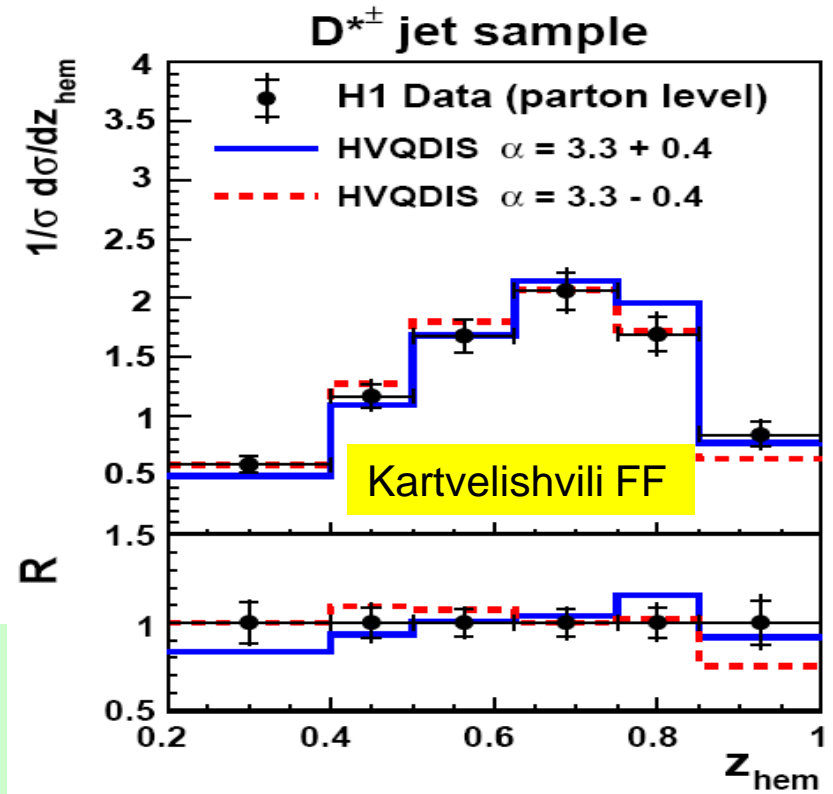
Predictions from:
 NLO QCD program HVQDIS
 with fixed flavour number scheme
 using the independent c -quark
 fragmentation into D^* mesons

Data corrected to the parton level

Poor description if Peterson FF used

Good description of the data with
 Kartvelishvili parametrization

	α
jet method	$3.8^{+0.3}_{-0.3}$
hemisphere method	$3.3^{+0.4}_{-0.4}$





Data corrected to the parton level
 Predictions from NLO QCD program HVQDIS

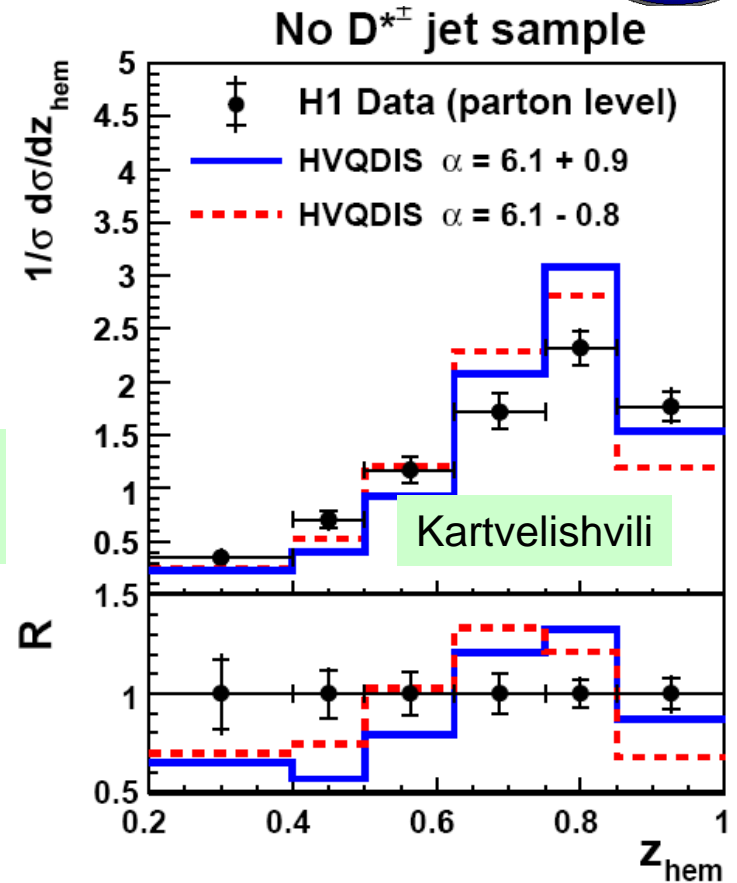
Events without a D^* jet with $E_T > 3$ GeV \rightarrow investigation of charm fragmentation close to the kinematic threshold possible due to hemisphere method.

The values for the best fits:

Kartvelishvili (param α)	Peterson (param. ϵ)
$6.1^{+0.9}_{-0.8}$	$0.007^{+0.001}_{-0.001}$

Predictions with fragmentation parameters obtained from D^* jet sample are not able to describe the no D^* jet data.

The same observation is true for the QCD models (RAPGAP, CASCADE): fragmentation parameters fitted to the D^* jet sample differ significantly from those for the no D^* jet sample



Hadronic final state charge asymmetry in high Q^2 DIS



$$\text{Asymmetry} = \frac{\text{pos} - \text{neg}}{\text{pos} + \text{neg}}$$

$100 < Q^2 < 8000 \text{ GeV}^2$

at low Q^2 (low x_{Bj}) asymmetry ~ 0

as Q^2 increases asymmetry develops at high x_p
at low x_p it remains ~ 0

behaviour consistent with expectations from charged asymmetry of valence quark in the proton

Monte Carlo models describe the magnitude and evolution of the asymmetry

