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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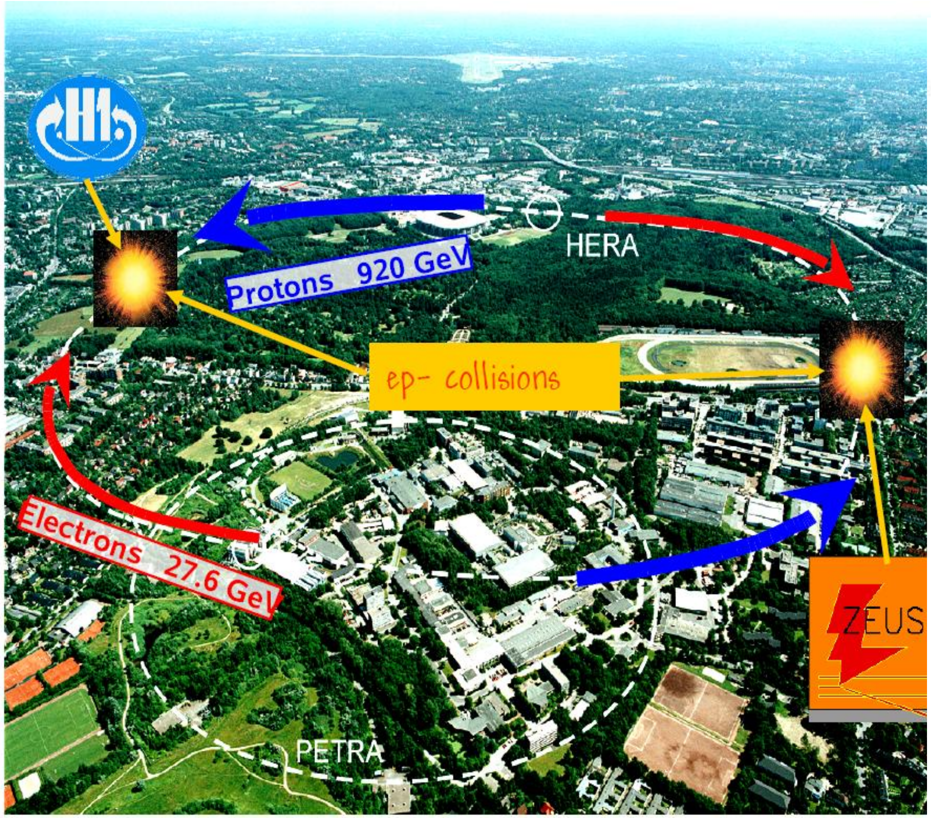
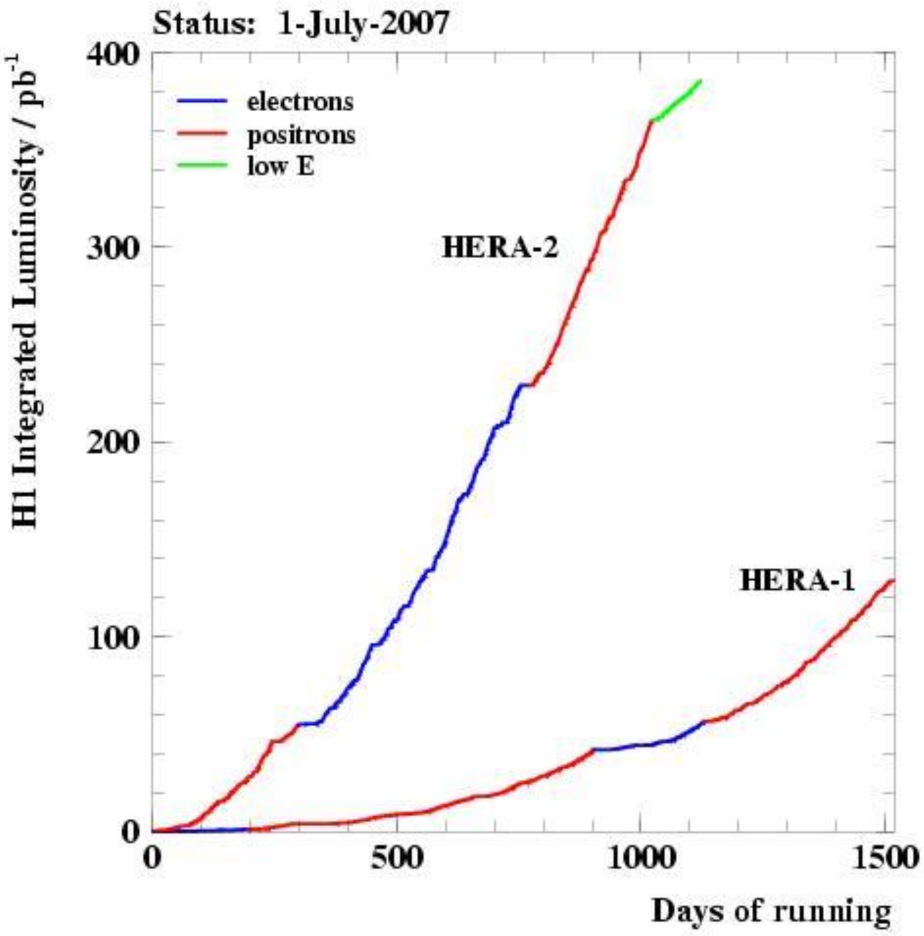
representing the H1 and ZEUS Collaborations

$e^{\pm}p$ Collider HERA

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





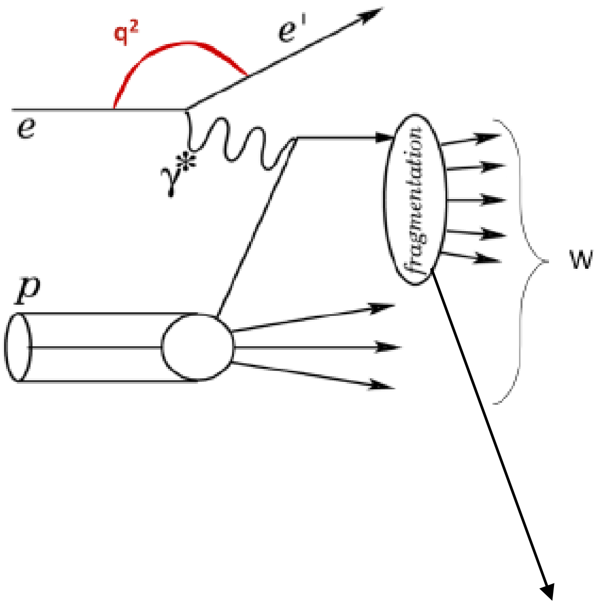
E_e = 27.6 GeV

E_p = 920 (820) GeV

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

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

HERA kinematics



$Q^2 = -q^2$ exchanged 4-momentum squared

$s = (P + e)^2$ *ep* center of mass energy squared

$W^2 = (P + q)^2$ hadronic final state mass squared

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

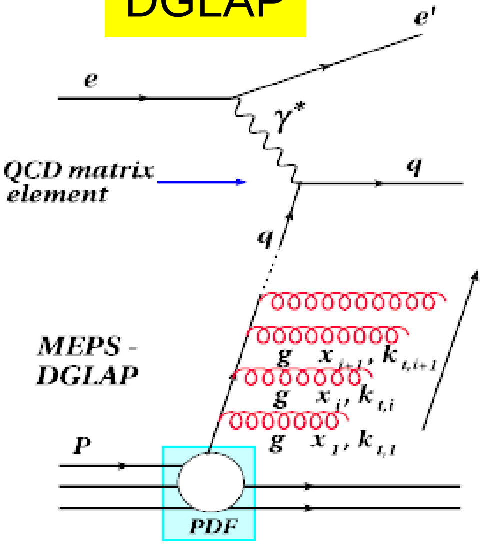
non-perturbative process leading to hadrons:
light, strange, heavy
in the hadronic final state

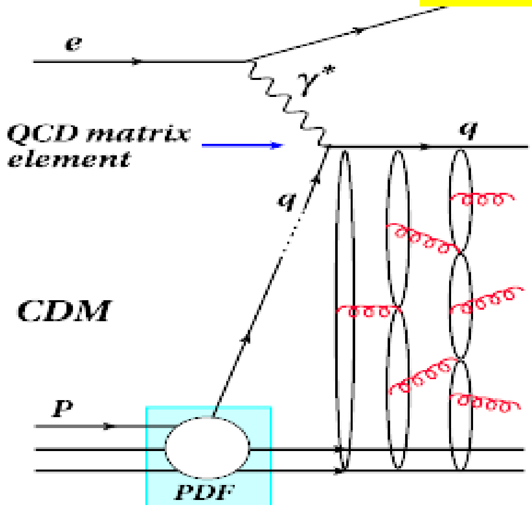
Two regimes:
$Q^2 < 1$ GeV^2 photoproduction (*γp*)
$Q^2 > 1$ GeV^2 Deep Inelastic Scattering (*DIS*)

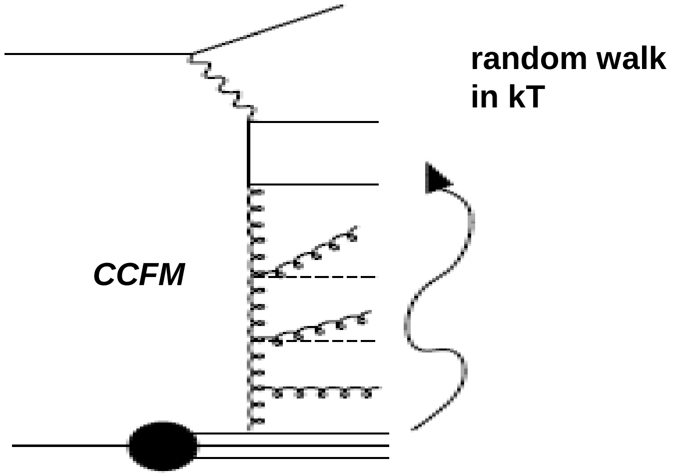
LO QCD Models for DIS *ep* Interactions

DGLAP

NON-DGLAP







DGLAP- RAPGAP,LEPTO(MEPS)

CDM -DJANGOH

CCFM-CASCADE

MEPS Matrix **E**lement + **P**arton **S**hower:
DGLAP evolution:
strong **ordering in k_T**
of emitted partons

CDM Colour **D**ipole **M**odel
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

$5<Q^2<100$ GeV^2

charged tracks in LAB; $p_T>0.15$ GeV, $20^0<\theta<155^0$

Expect discrimination between models:

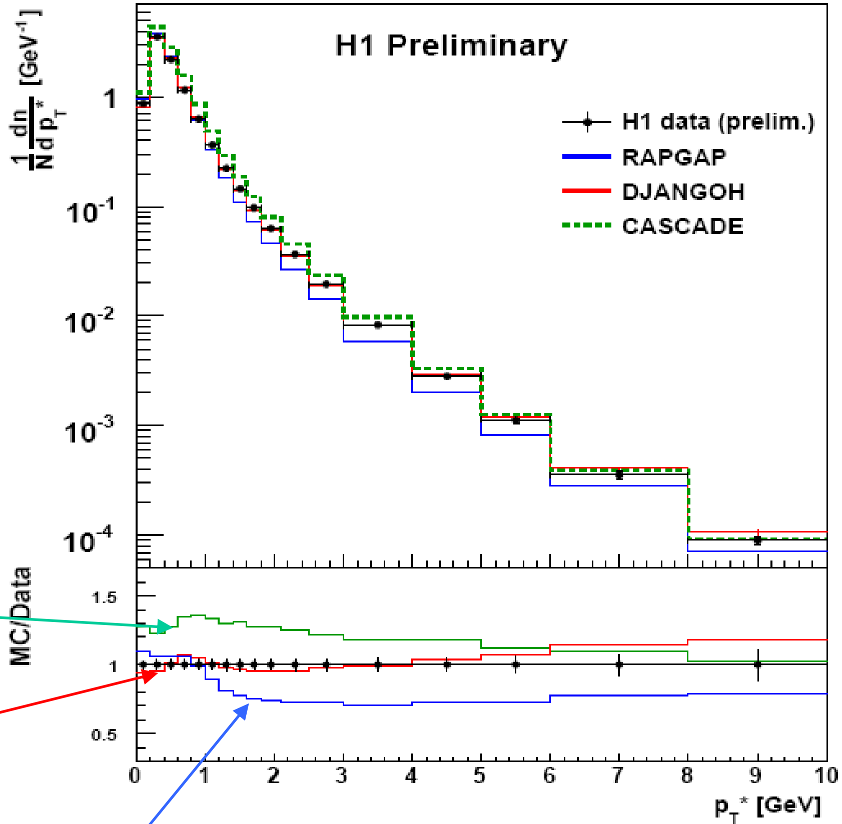
low p_T region :
sensitive to hadronization effects,

high p_T region:
sensitive to parton dynamic

CCFM (CASCADE) is above the data

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

DGLAP (RAPGAP) for p_T* >1 GeV below the data

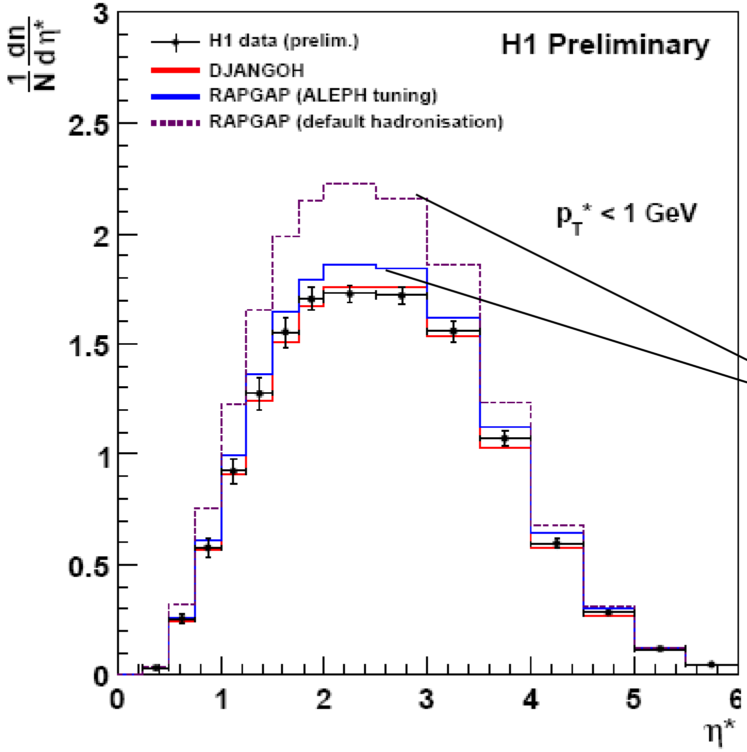


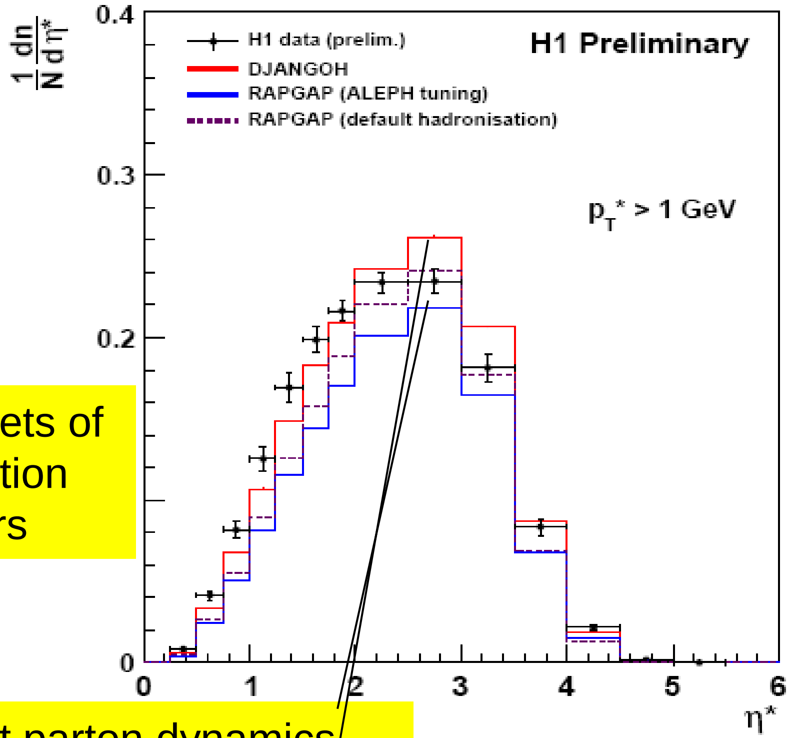
p_T^* distribution in $1.5<\eta^*<2.5$ region

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

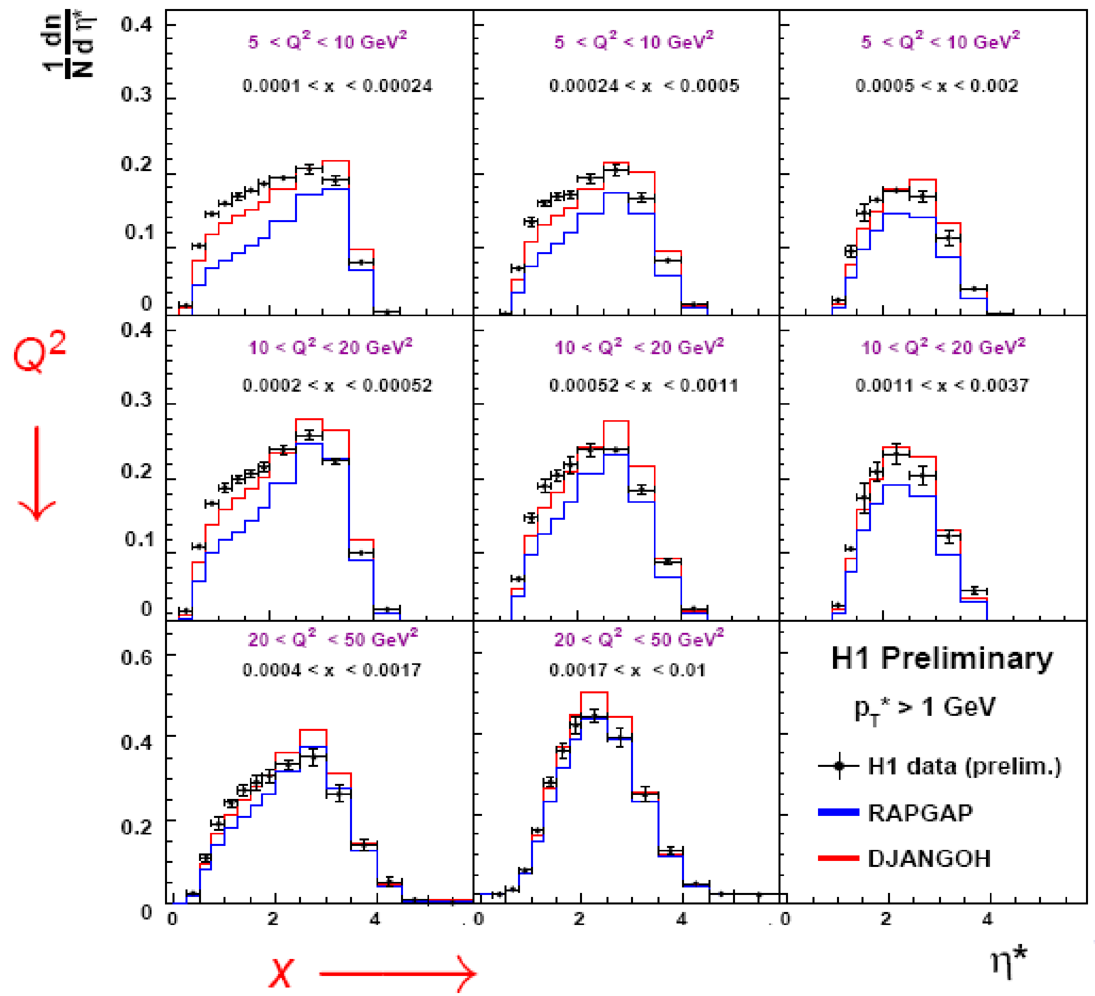
high p_T^*

strong dependence on parton dynamics

weak dependence on hadronization param.

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

$p_T^* > 1$ GeV



CDM (DJANGOH) 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) →

Predictions:

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

↓

- Λ_{eff} process independent

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}

↓

Prediction:

- κ^{ch} is process independent

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

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

Scaled momentum distributions

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

$$x_p = \frac{2P^{Breit}}{Q}$$

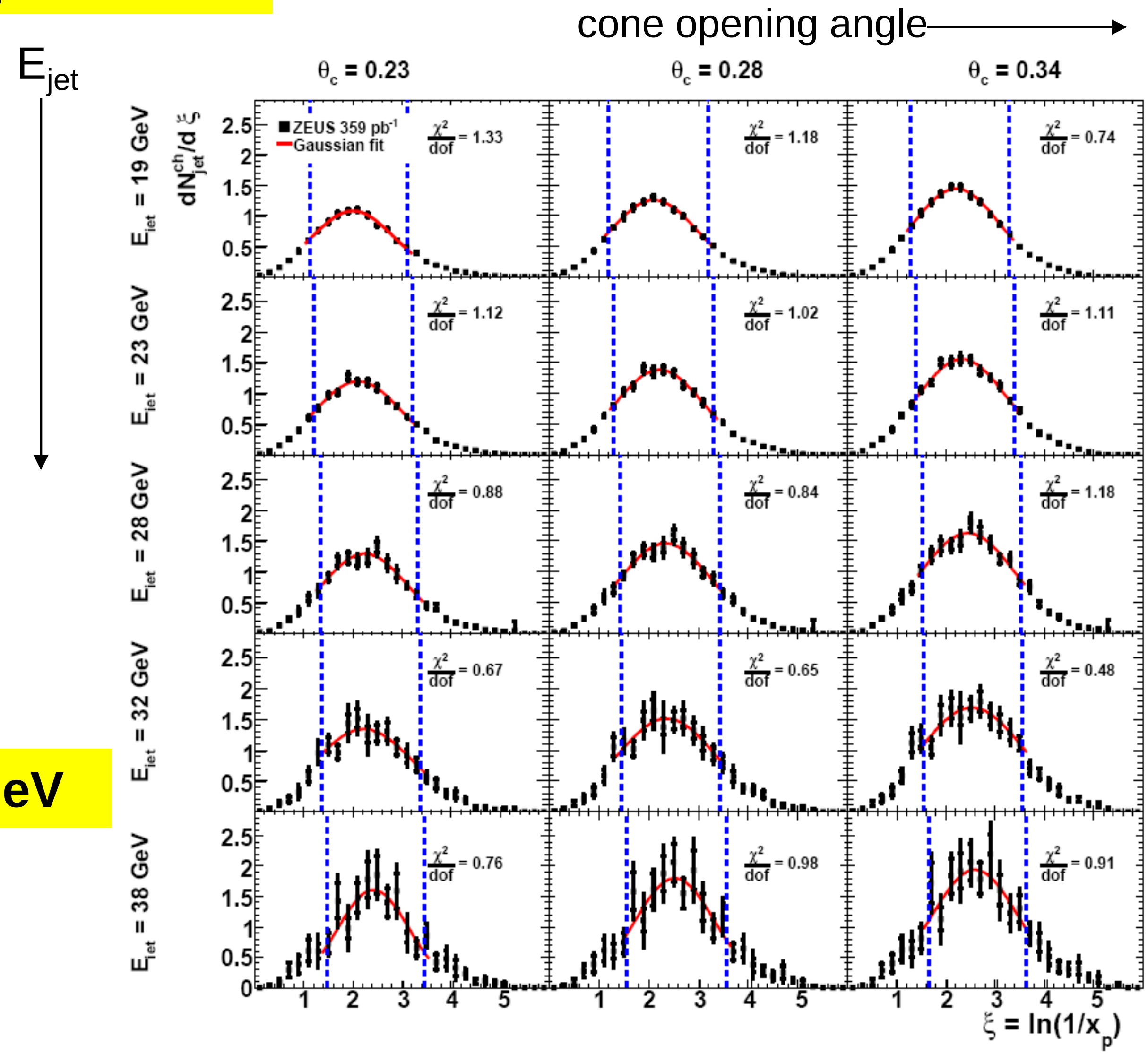
2-jets events in photoproduction

Extraction of Λ_{eff}

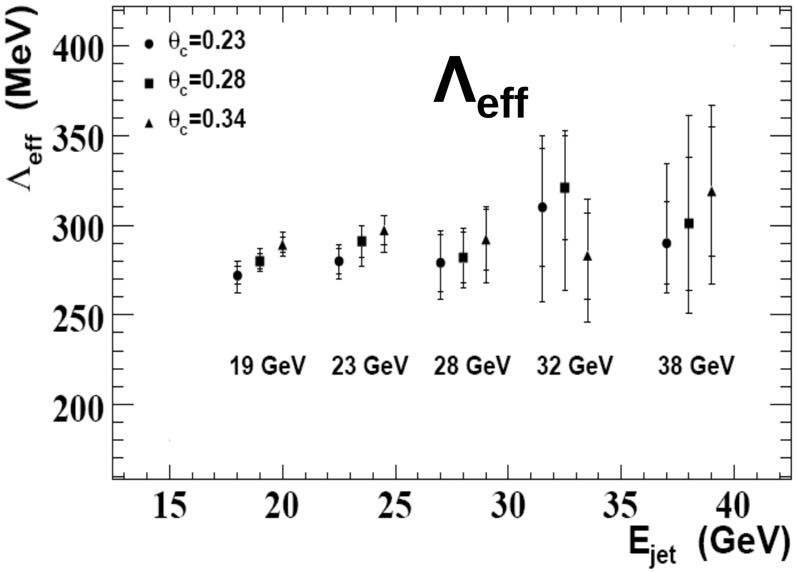
- fit gaussian 1 around the arithmetic mean of the ξ distribution

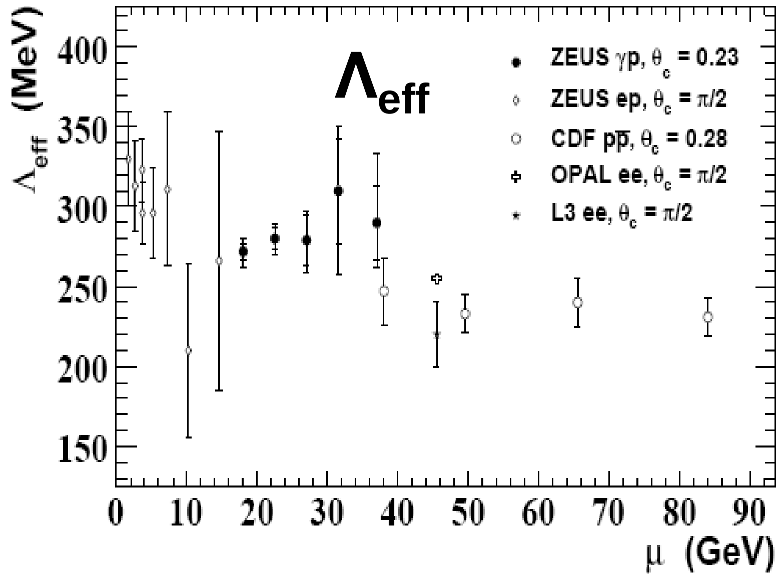
- fit dependence of the peak position on energy scale

Λ_{eff} = 275±4(stat.)$^{+4}_{-8}$(syst.)MeV



Scaled momentum distributions Λ_{eff}, κ^{ch}





ep (DIS,γp)
p⁻p
e+e-

$\mu = E_{jet}$

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

data for different processes support the **universality of** $\boldsymbol{\Lambda_{eff}}$ parameter

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

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

from $p\bar{p}$
$\kappa^{ch} = 0.56 \quad 0.05(stat.) \quad 0.09(syst,)$

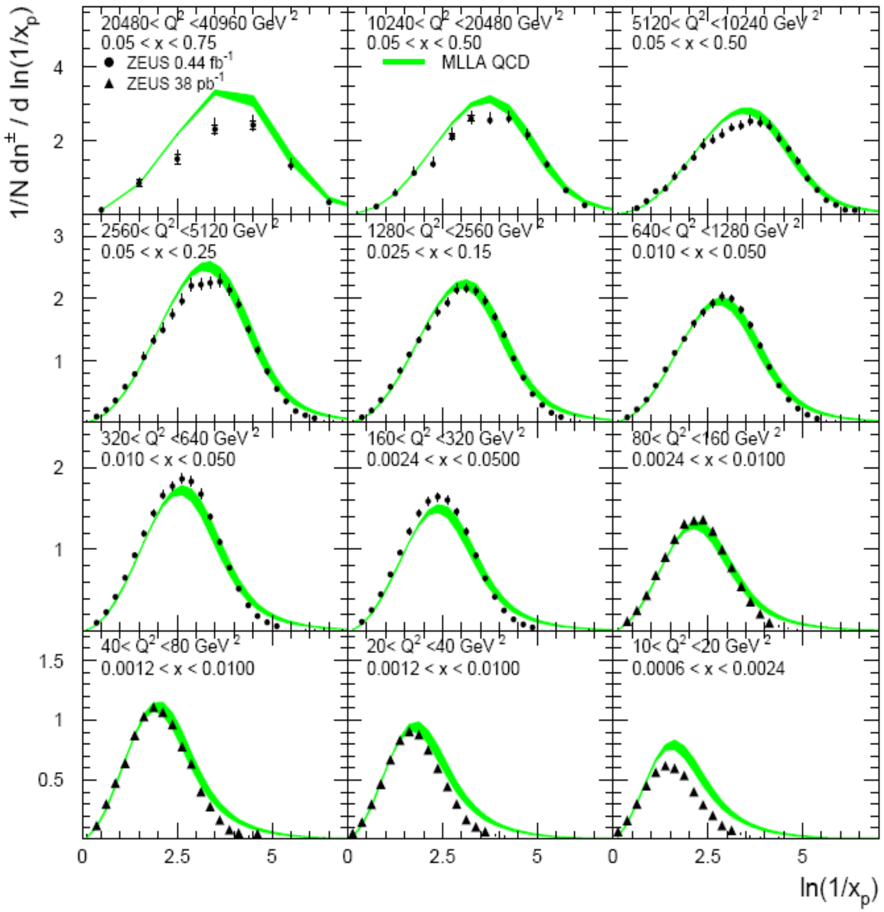
data support the **universality of** $\boldsymbol{\kappa^{c}}$ parameter

x_p distributions in DIS

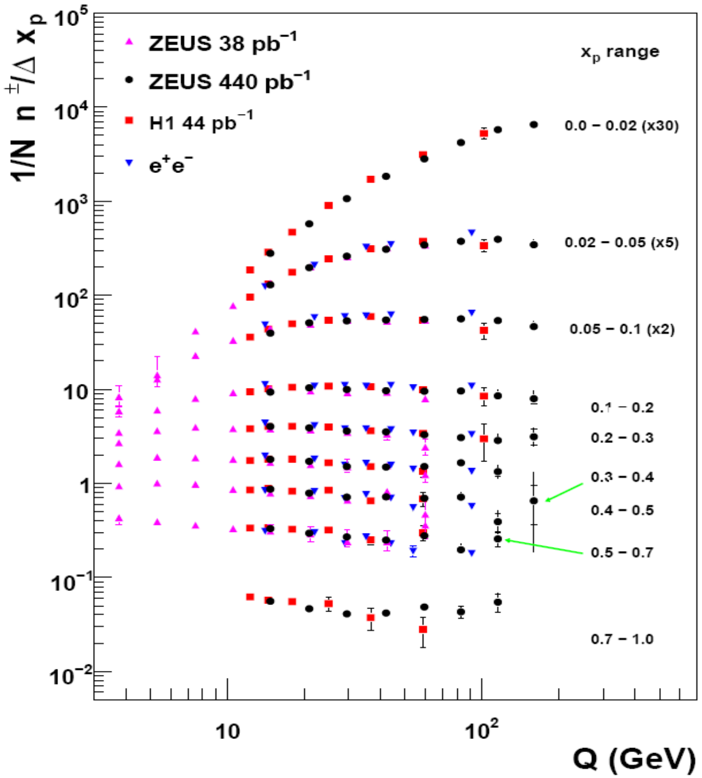
$10 < Q^2 < 40960$ GeV^2

MLLA+LPHD predictions

observation of scaling violation



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



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

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

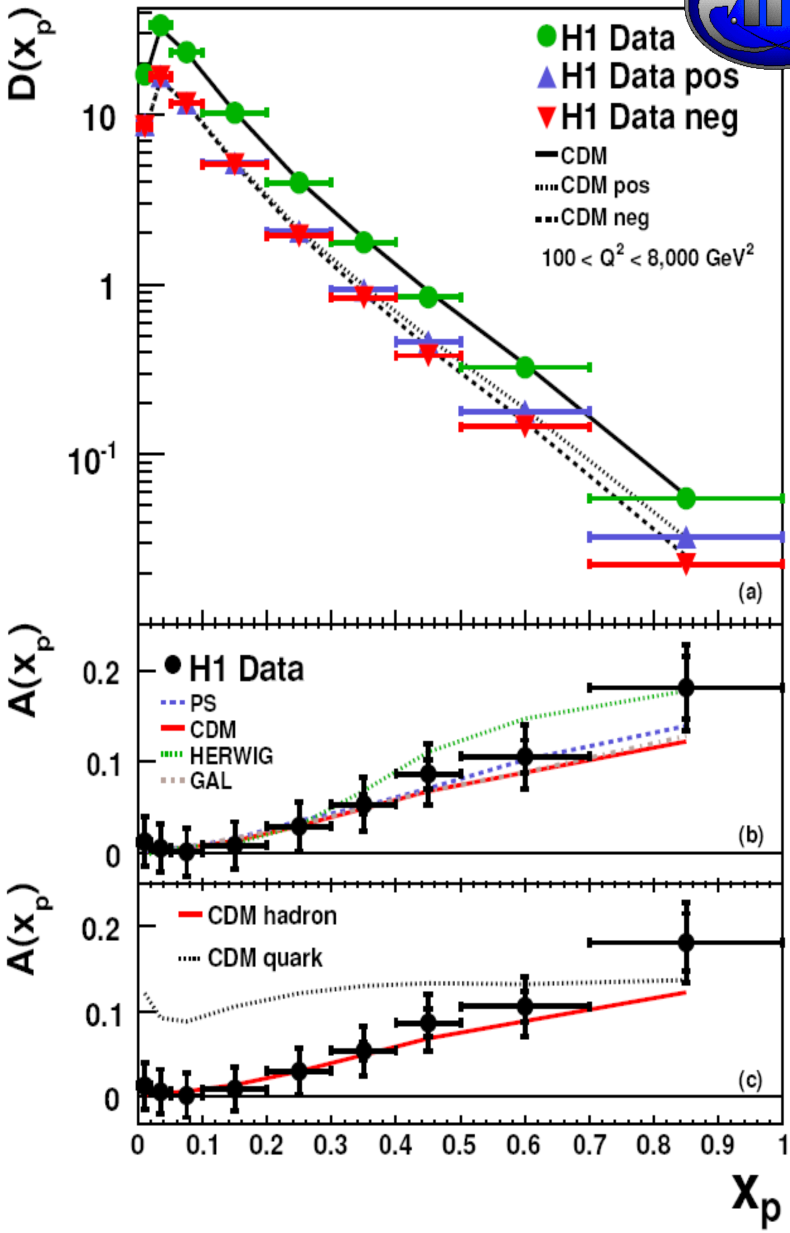
$D(x_p)=1/N\ dn/dx_p$ now defined separately for **positively** and **negatively** charged particles

low x_p dominated by fragmentation
similar distributions
indepedent of the charge

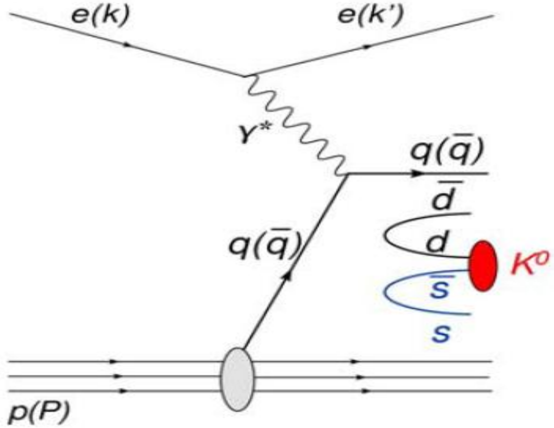
high x_p sensitive to the hard subprocess
difference between pos and neg
excess of **positive** charge
due to the quark content of the proton

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

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



Strangeness Production in DIS *ep* Scattering

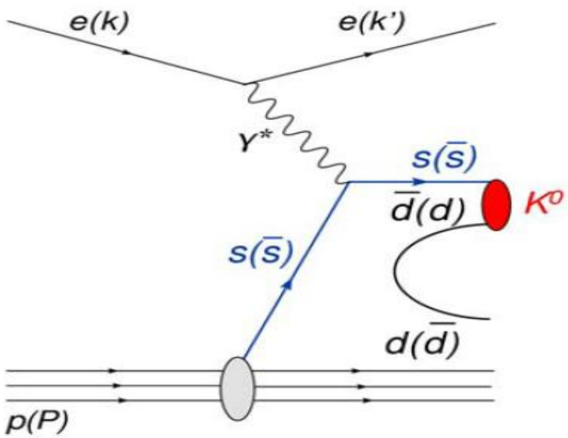


non-perturbative process: **hadronisation**

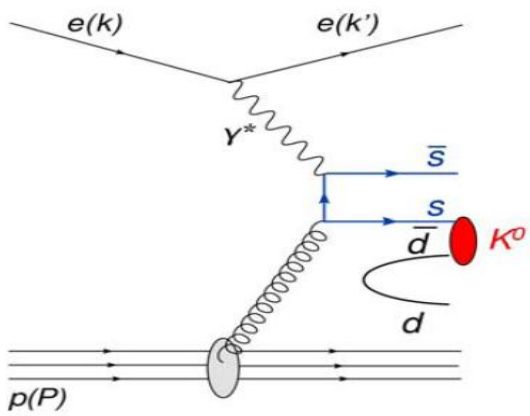
LUND string fragmentation model
strangeness suppression factor

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

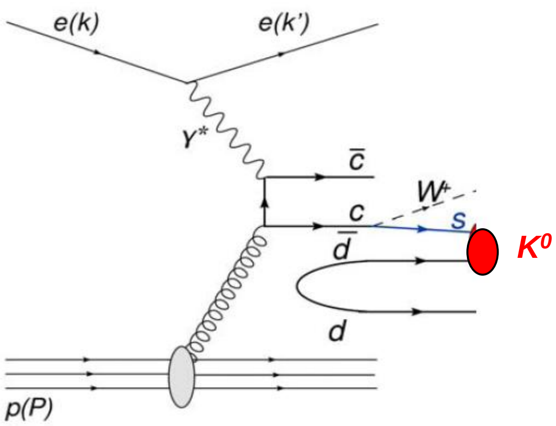
hard processes: **QPM**



boson-gluon fusion



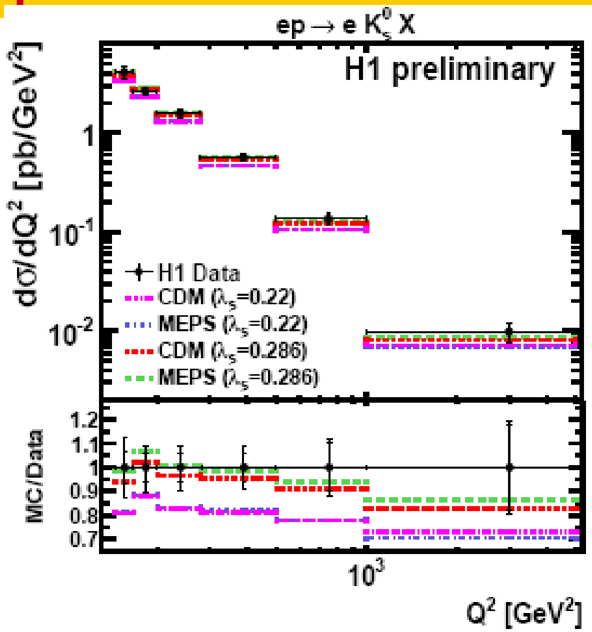
decays of heavy quarks



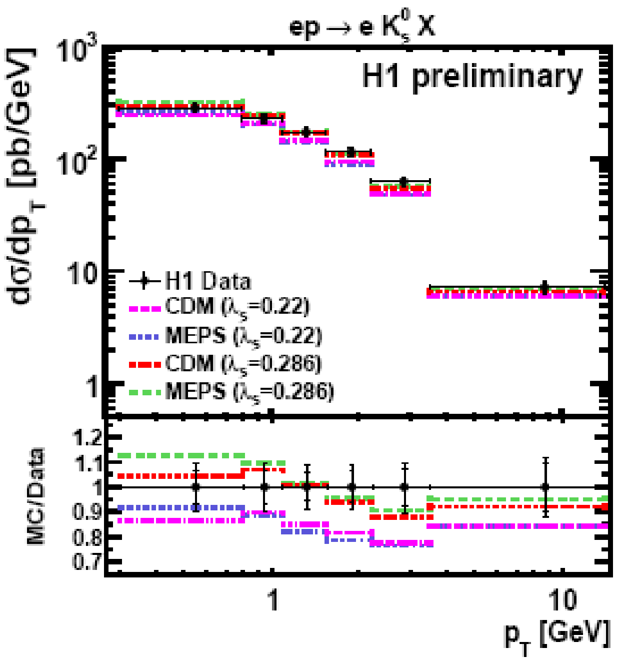
K^0_s differential prod. x-secs in LAB in Q^2,η,p_T

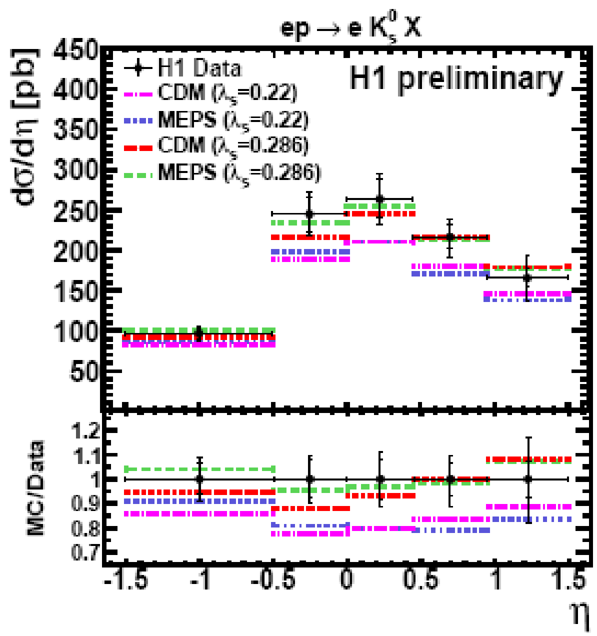
Kinematic phase-space
$145 < Q^2 < 20000$ GeV^2
$P_T(K^0_s) > 0.3$ GeV
$|\eta\ (K^0_s)| < 1.5$

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



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



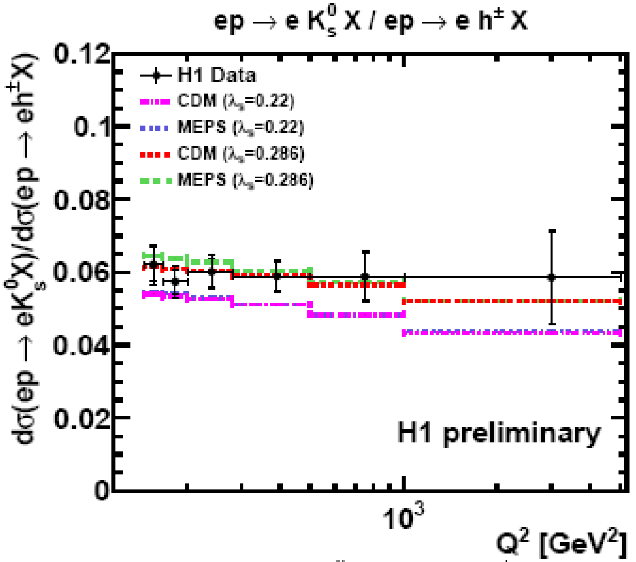


MEPS and CDM wih $\lambda_s = 0.286$ describe the differential cross-sections

Ratio of x- sections: K^0_s/charged hadrons

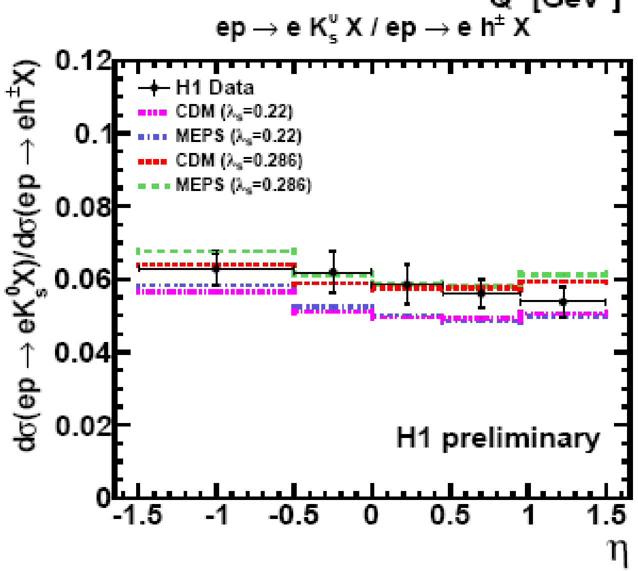
$$e\,p \rightarrow e\,K^0_s\,X \,/\, e\,p \rightarrow e\,h^{\pm}\,X$$

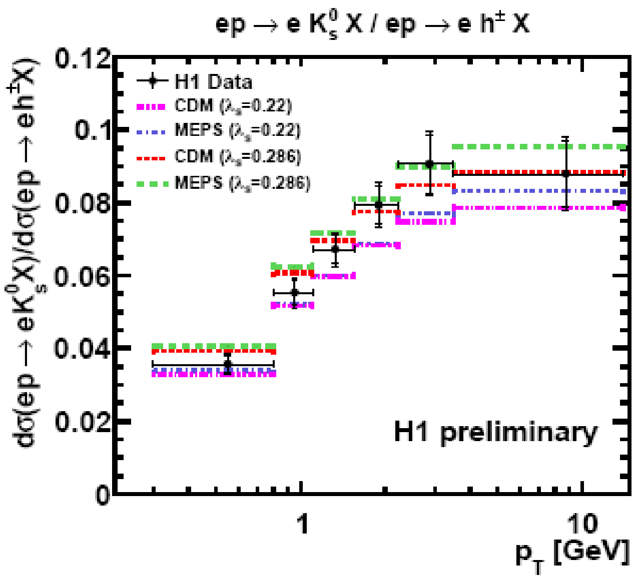
h in the same kinematic region as K^0_s



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

LO Monte Carlos with λ_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**?

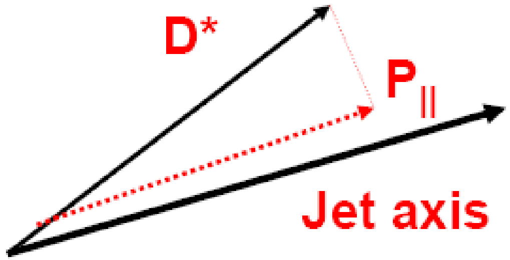
observables *e+e-* $\mathbf{z \sim E_{D*}/E_{beam}}$ (E_{beam} = energy of the *c*-quark)
ep z_{hem} and z_{jet}

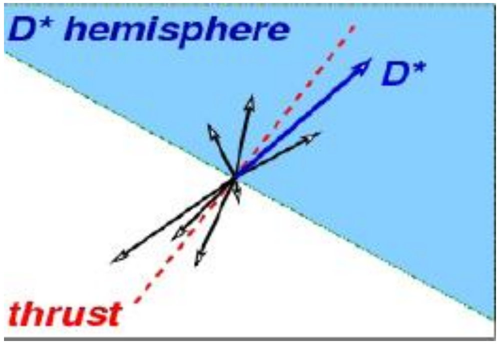
Jet method (ZEUS,H1)

E of the *c*-quark is approximated by *E* of the reconstructed D*jet
$$\mathbf{z_{jet}=(E+p_{||})_{D*}/(E+p)_{jet}}$$

Hemisphere method (H1)

E of the *c* quark is approx. by *E* of the reconstructed D* hemisphere
$$\mathbf{z_{hem}=(E+p_{||})_{D*}/\sum_{hem}(E+p)}$$



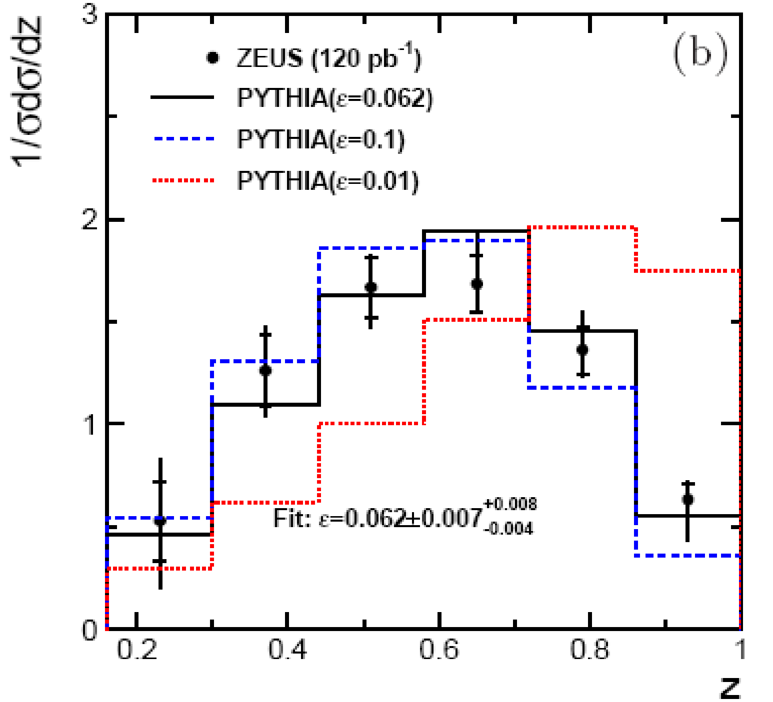


Charm fragmentation in Photoproduction

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

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

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



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

$\varepsilon = 0.062 \;\; 0.007\text{(stat.)} \, ^{+0.008}_{-0.004}\text{(syst.)}$

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

Charm fragmentation in Photoproduction

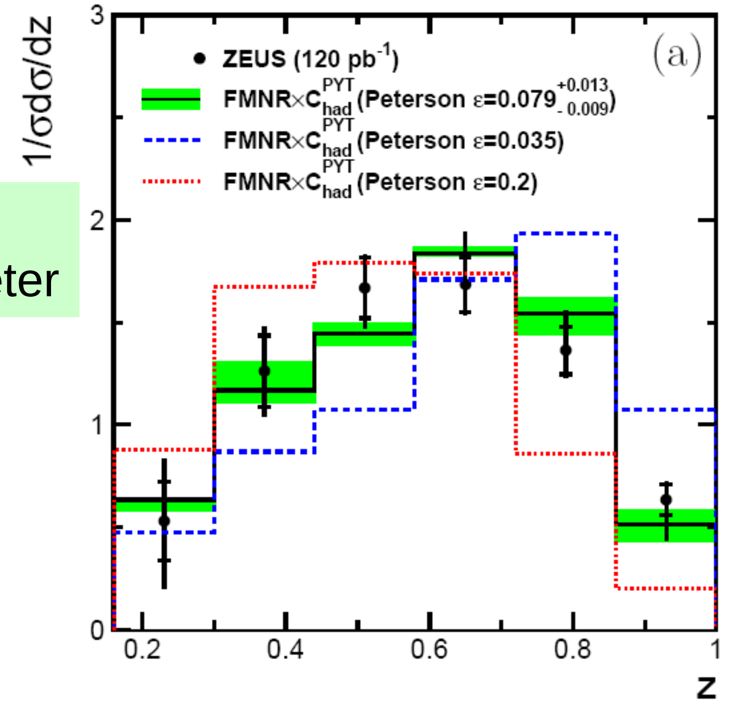
Comparison with NLO QCD calculations from Frixione-Mangano-Nason-Rudolfi (FMNR)

calculations corrected for effects of hadronization

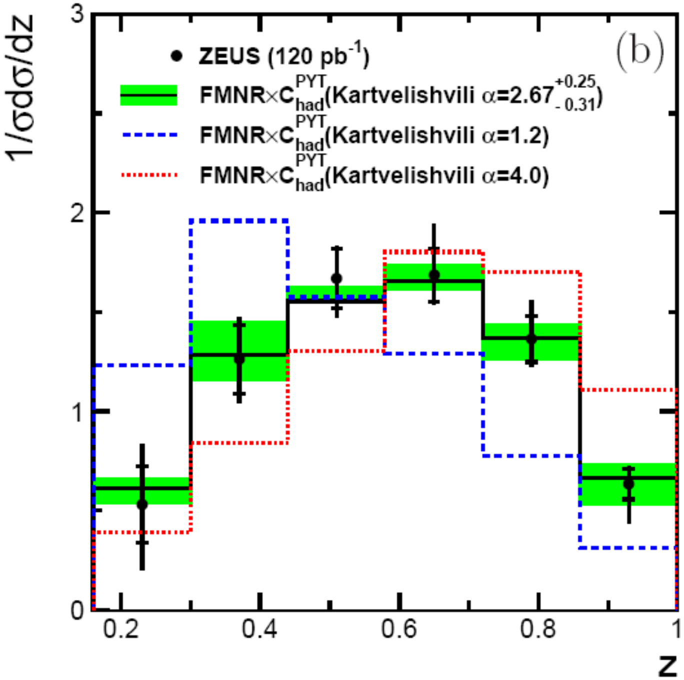
fits to the data with

Peterson FF
free ε parameter

Kartvelishvili FF
free α parameter



ZEUS



fit results:

ε = 0.079   0.008(stat.) $^{+0.010}_{-0.005}$ (syst.)

α = 2.67   0.18(stat.) $^{+0.17}_{-0.25}$ (syst.)

Charm fragmentation in DIS

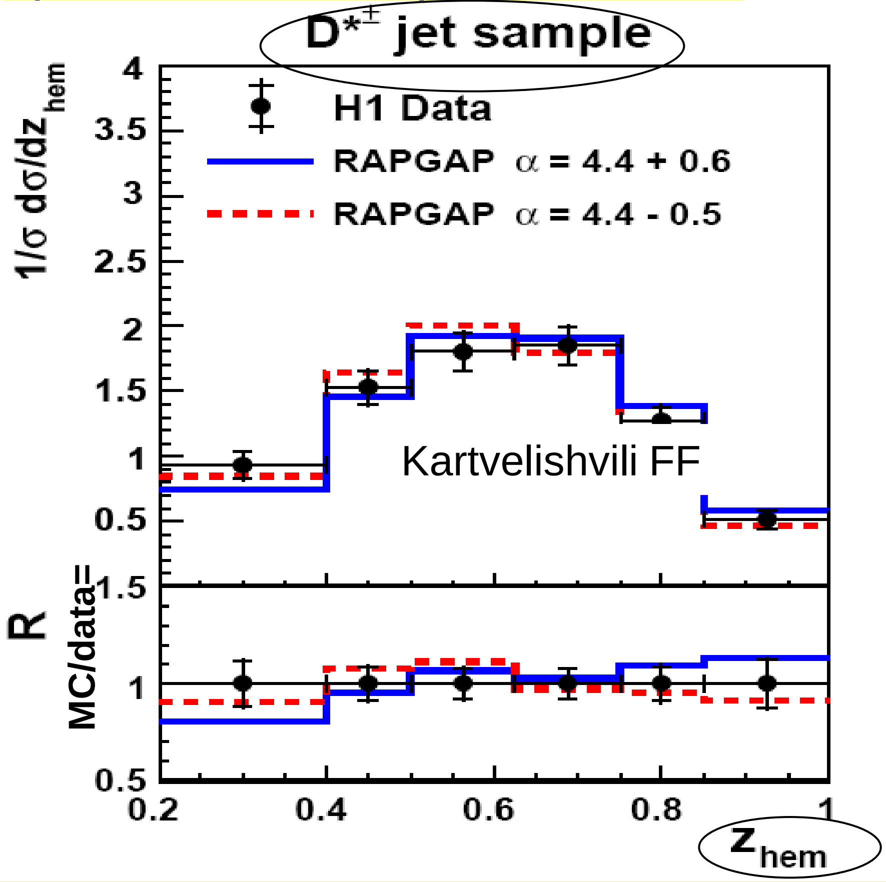
Comparison with RAPGAP (LO ME+DGLAP) simulations

$2 < Q^2 < 100$ GeV^2

$D^* \rightarrow D^0 \pi_S \rightarrow K\pi\pi_S$
$1{,}5 < p_T(D^*) < 15$ GeV,
$|\eta(D^*)| < 1.5$
jets found by k_T cluster algorithm

D* jet sample
jet containing the D* meson
E_T(jet)>3 GeV

no D* jet sample
no such jet is allowed



	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- ε=0.04 with the same setting)**

Both methods give consistent results

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

Charm fragmentation in DIS

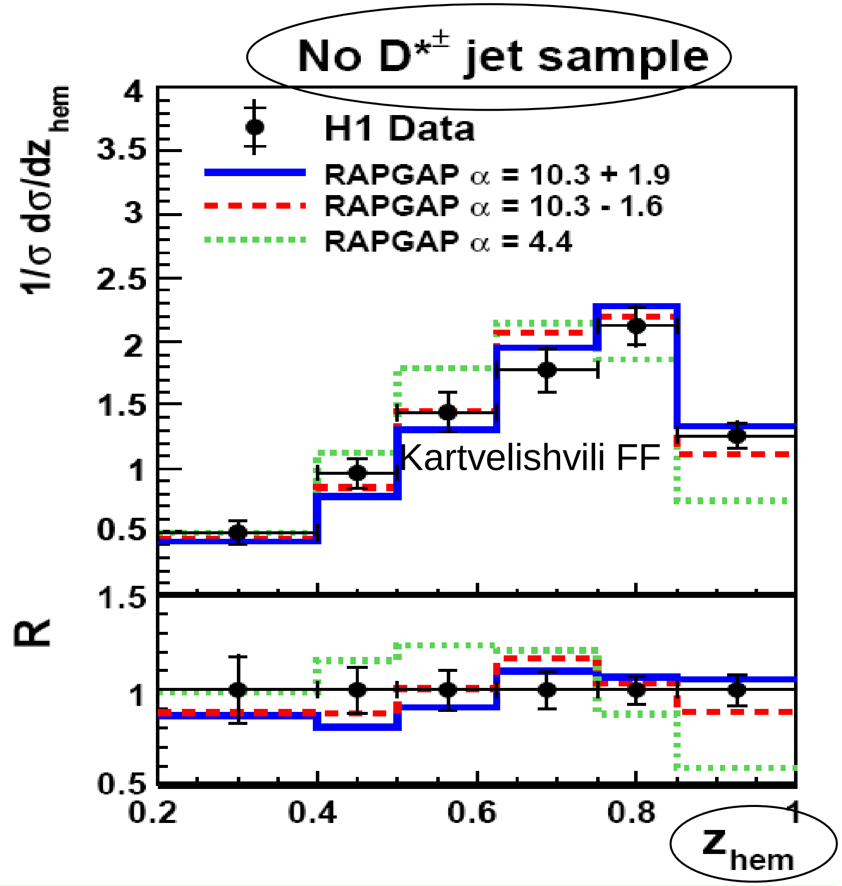
Comparison with RAPGAP (LO ME+DGLAP) simulations

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

values of fitted parameters:

Kartvelishvili (α)	Peterson (ε)
$10.3^{+1.9}_{-1.6}$	$0.006^{+0.003}_{-0.002}$

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.

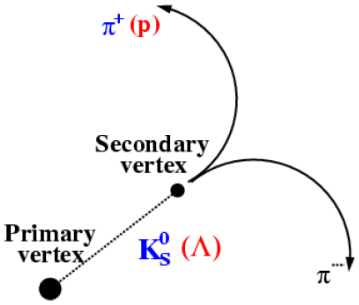
The extracted parameters support the hypothesis of fragmentation universality between ep and e+e- porcesses.

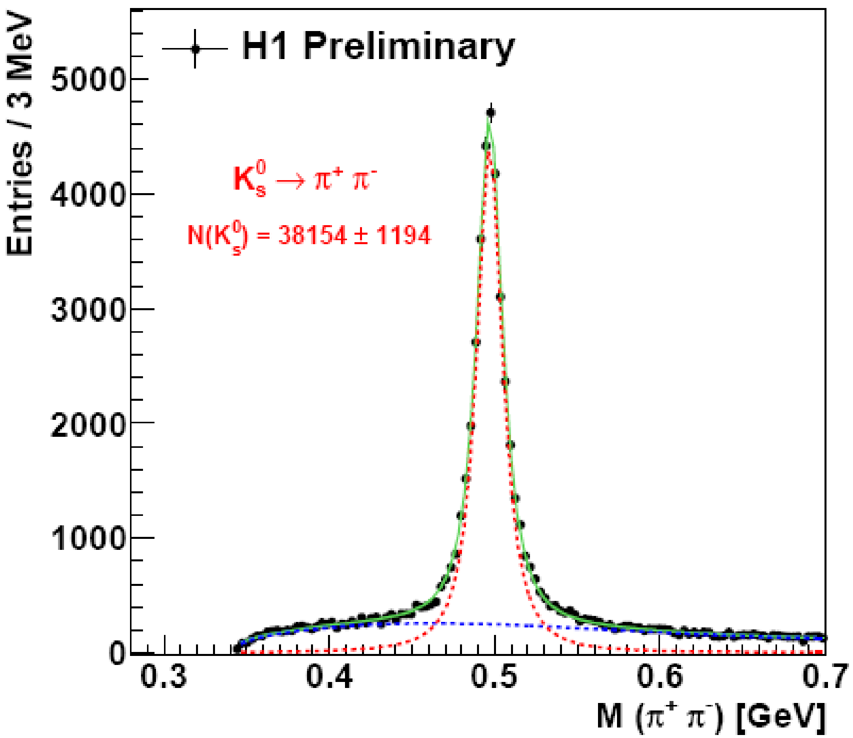
Production of neutral strange mesons is well describe by LO Monte Carlos.

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^0_s





Kinematic phase-space
$145 < Q^2 < 20000$ GeV^2
$0.2 < y < 0.6$
$P_T(K^0_s) > 0.3$ GeV
$|\eta (K^0_s)| < 1.5$

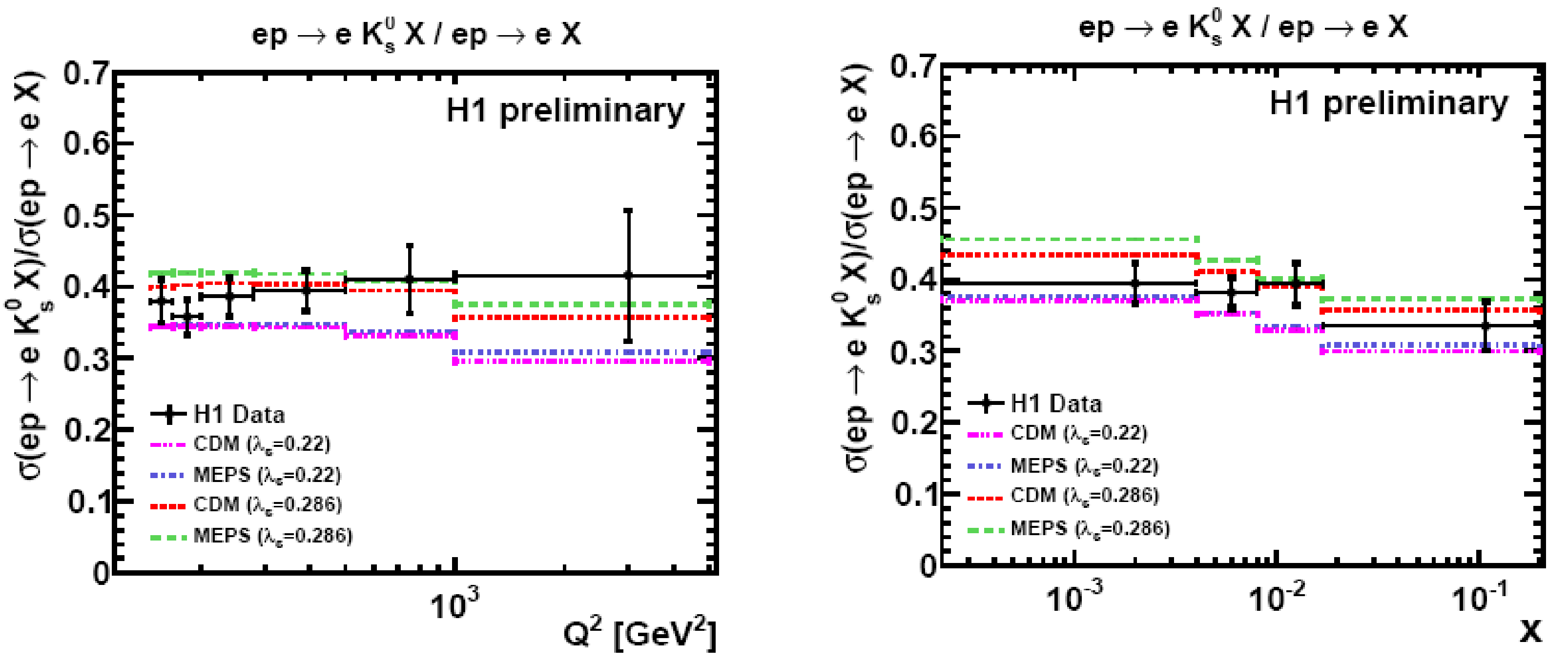
int. luminosity of ~ 340 pb^{-1}

Inclusive x-section

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

K^0_s density

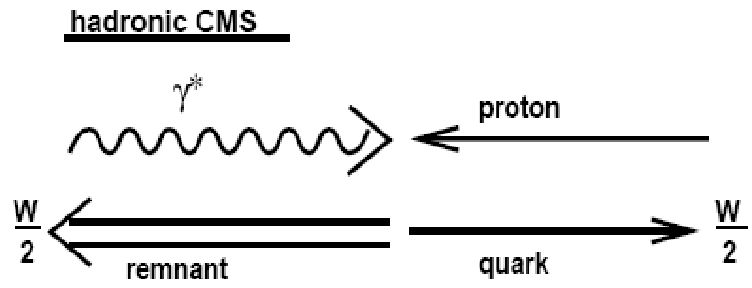
$\sigma(ep \to eK^0_sX)/\sigma(ep \to eX)$



- **density** ~ 0.4
  no dependence on Q^2
  models predictions consistent with a small falling at higher *x*

Frames of reference

Hadronic Center of Mass



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

θ^* with respect to γ^*

$\eta^* < 0$ proton direction

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

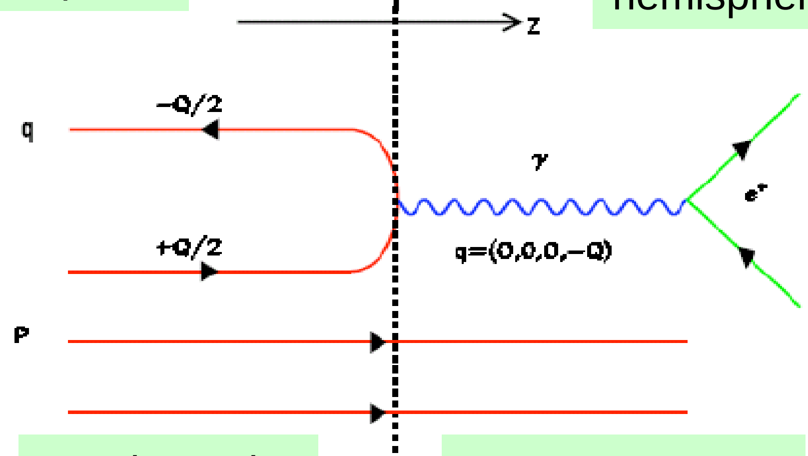
photon has momentum *Q* but no energy,

photon direction defines the negative z-axis

current hemisphere

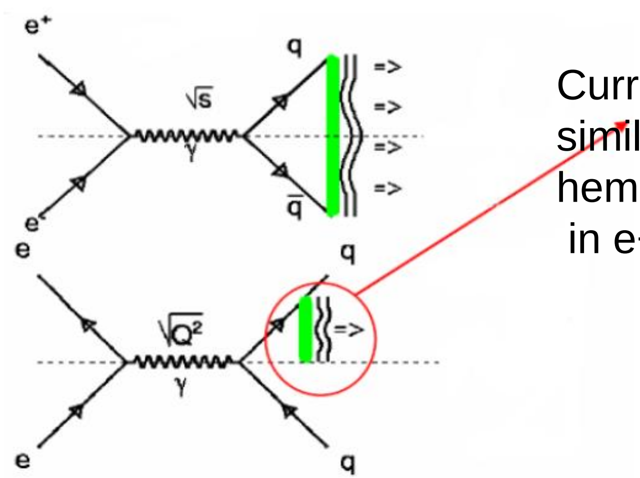
$p_z^{Breit} < 0$ | $p_z^{Breit} > 0$

target hemisphere



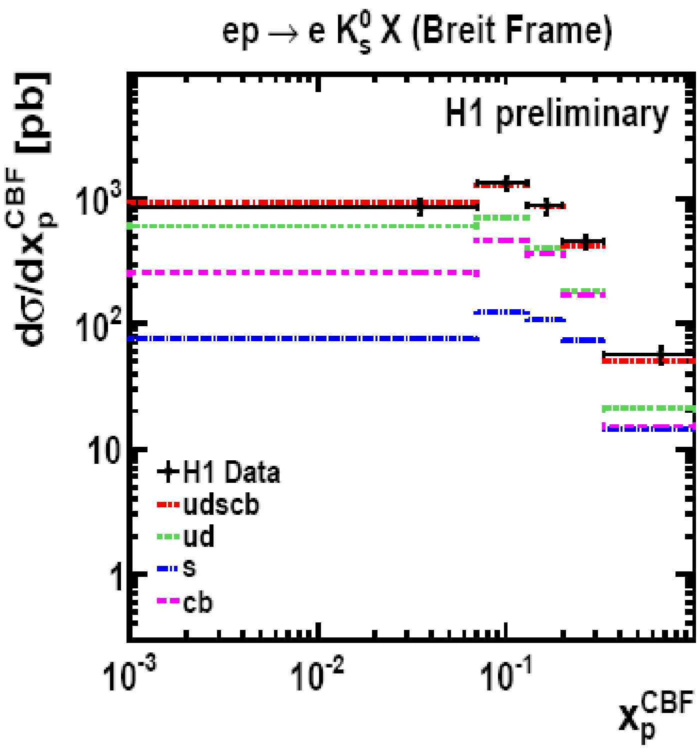
struck quark

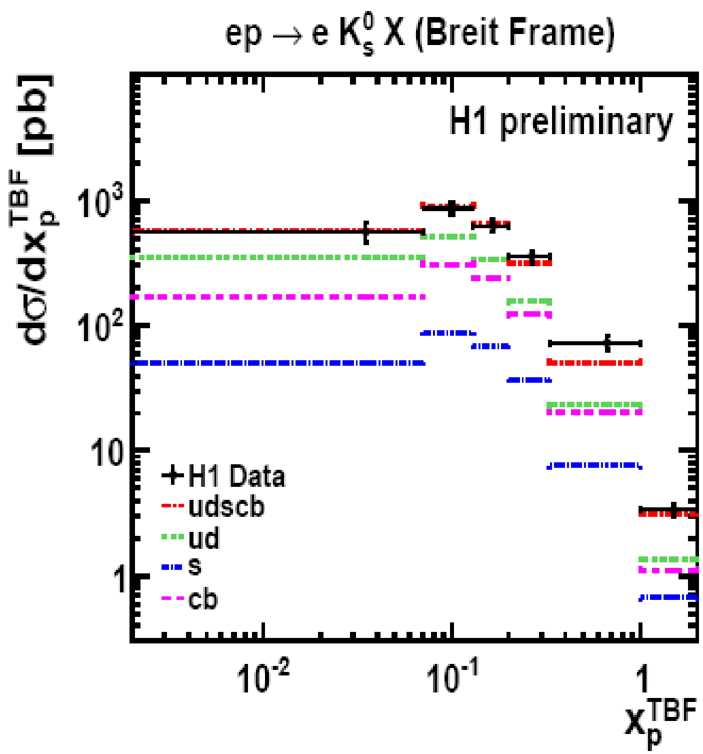
proton remnant



Current region similar to one hemisphere in e+e-

Flavour contributions to x-sec in Breit frame

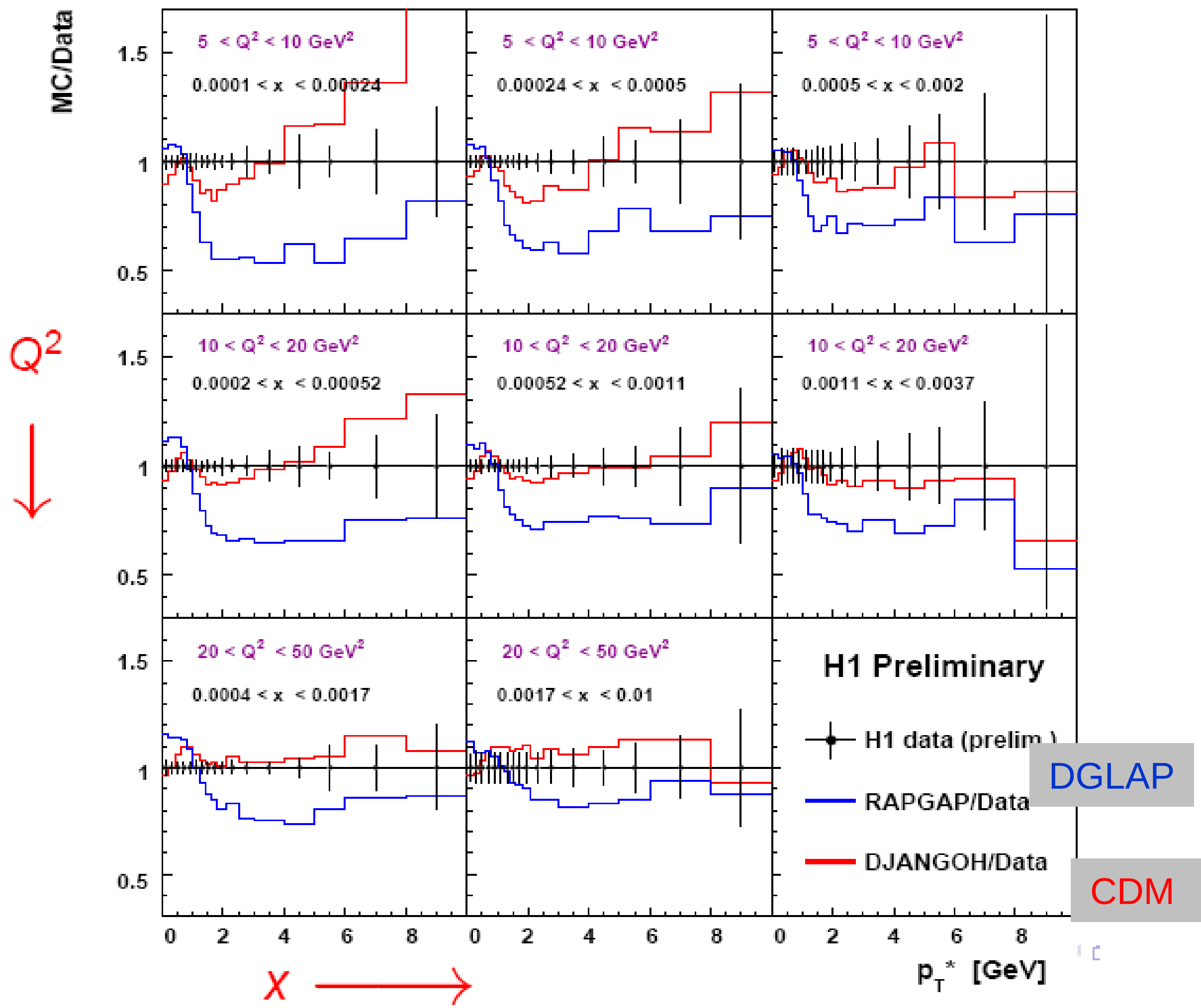




In the current region the contribution of *s* quark in enhanced and equals the heavy *cb* quarks contribution in the region of high x_p^{CBF}

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

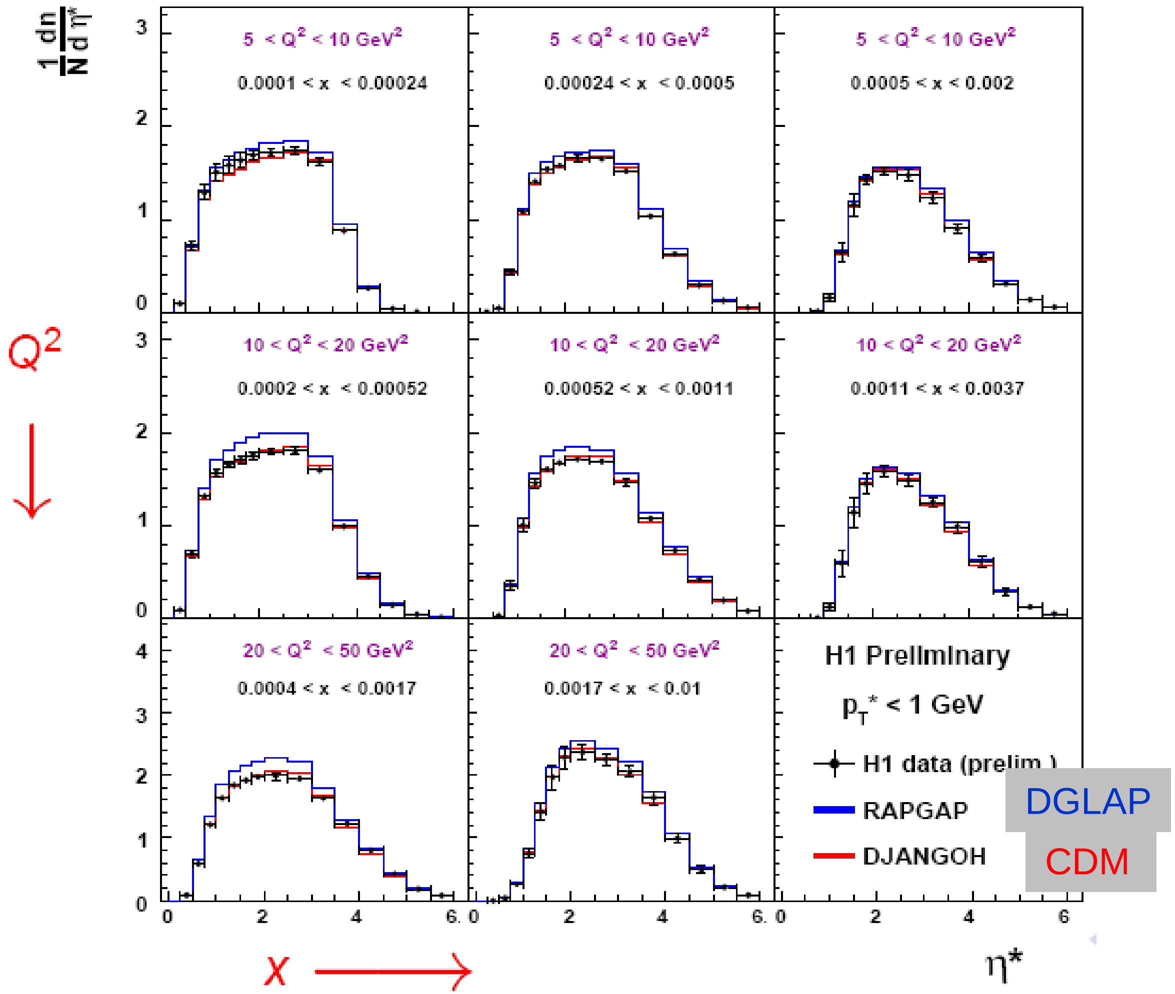
strongest disagreement
between both models
(DGLAP , CDM)
and the data
at high p_T^* (p_T^*>1 GeV)
at low Q^2 and low x



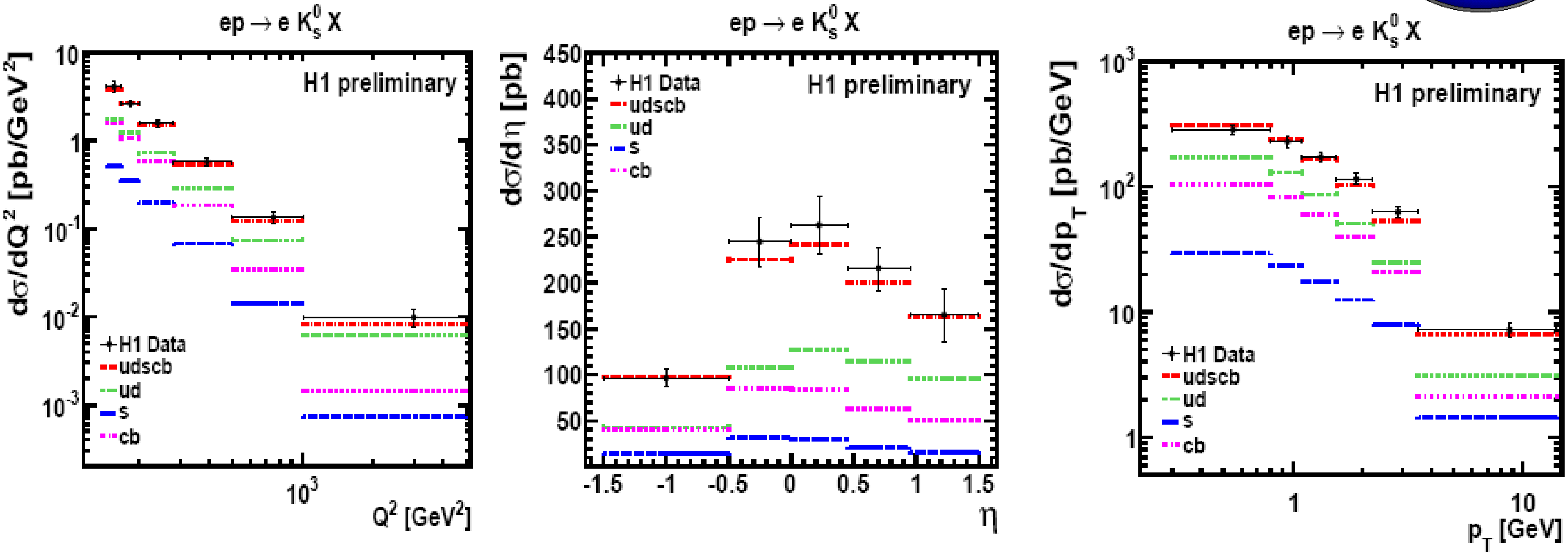
η^* distributions of charged particles in (x,Q^2) bins

$p_T^* < 1$ GeV

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



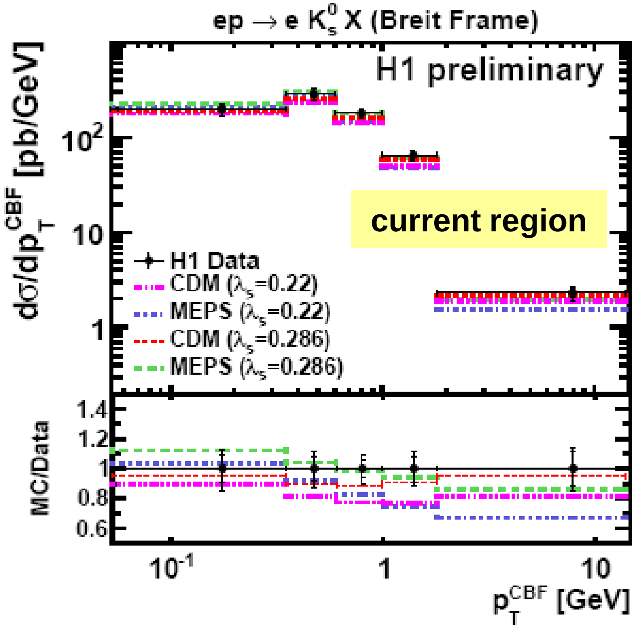
Flavour contributions to x-section in LAB



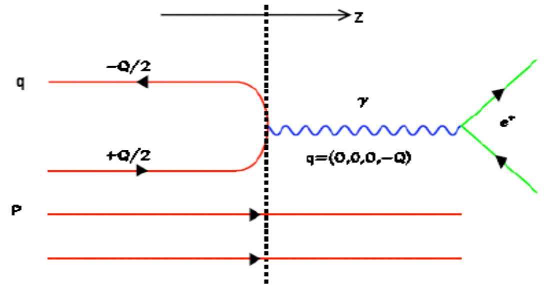
- dominant contributions from light quarks (*u*,*d*)
- heavy quarks (*c*,*b*) as the second dominant contribution
- the fraction of *s* quarks increases at high p_T

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

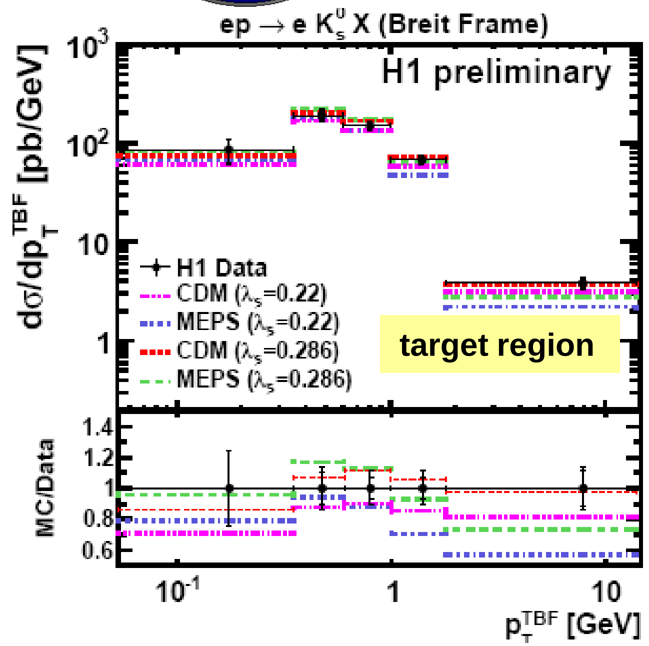
$x_p^{Breit} = \frac{(2P_h^{Breit})}{Q}$



current target



struck quark proton remnant

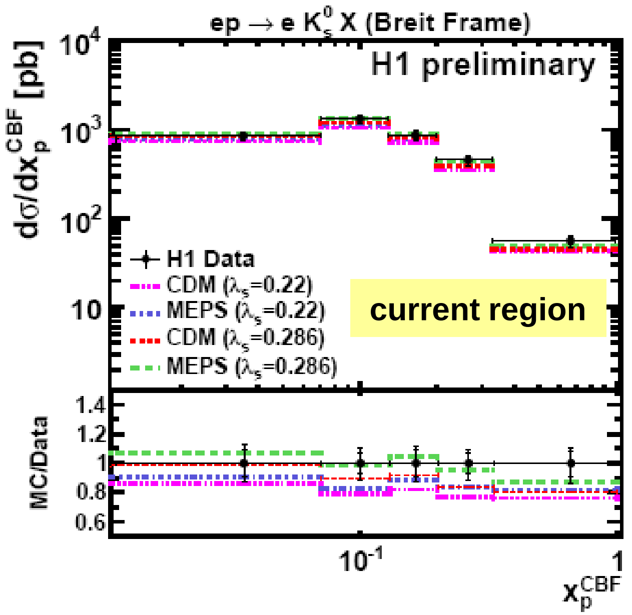


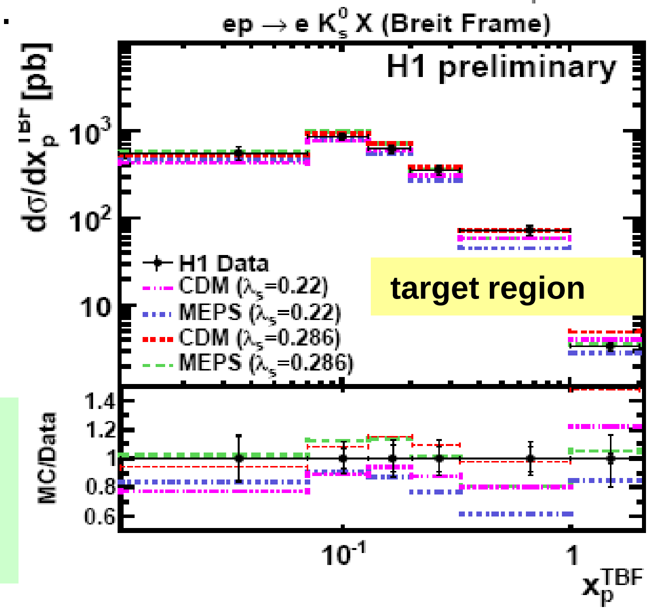
current region

- *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

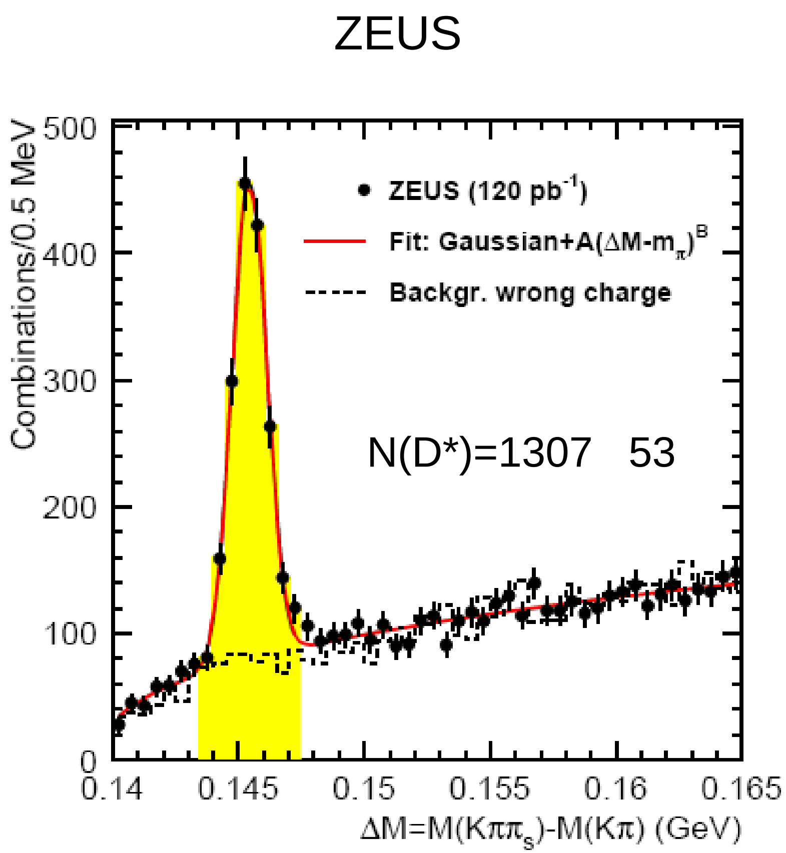




CDM and MEPS with Λ_s =0.286 better describe the differential x-sections

Charm fragmentation in Photoproduction

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



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

$p_T(D^*)>2$ GeV,
$|\eta(D^*)|<1.5$
associated with a jet

Charm fragmentation in DIS

$2 < Q^2 < 100$ GeV^2

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

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

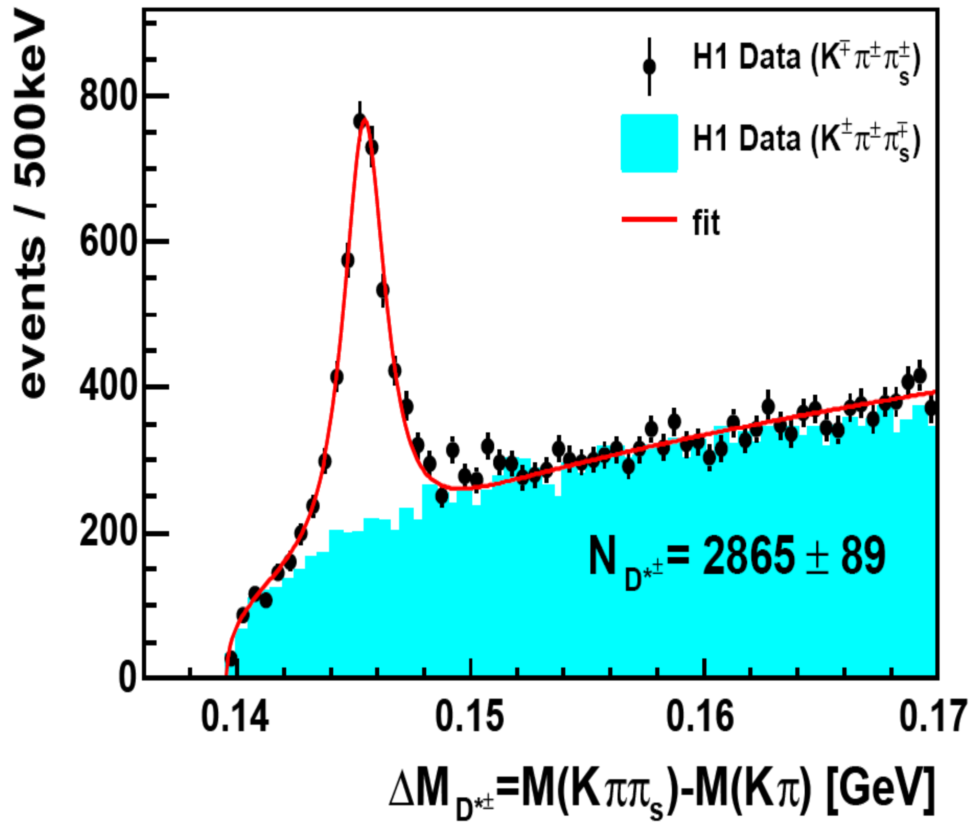
jets found by k_T cluster algorithm

<u>D* jet sample</u>
jet containing the D* meson
E_T(jet)>3 GeV
N(D*)=1508 68(stat.)

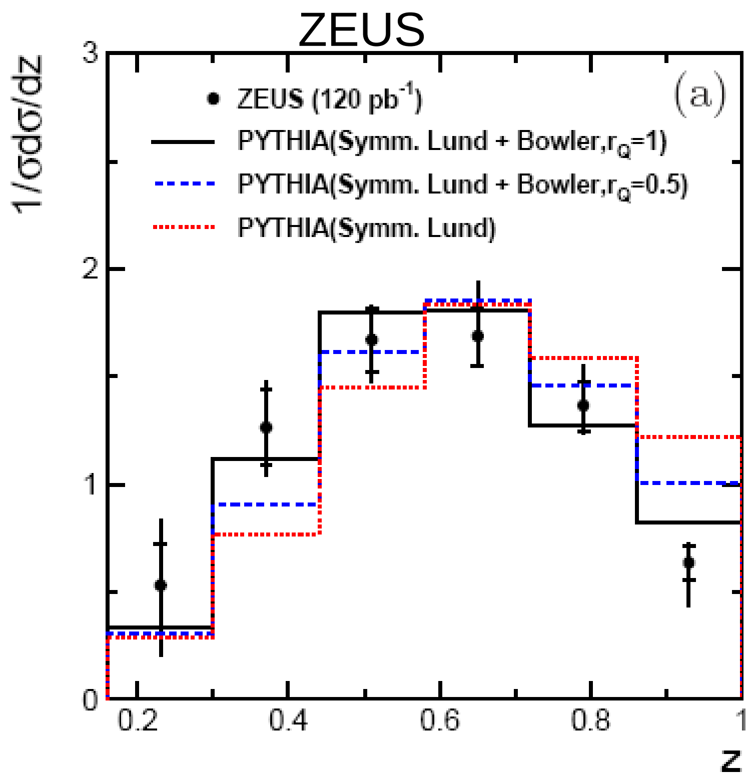
<u>no D* jet sample</u>

N(D*)=1363 54(stat.)

wrong charge combinations



Comparison with fragmentation models in PYTHIA

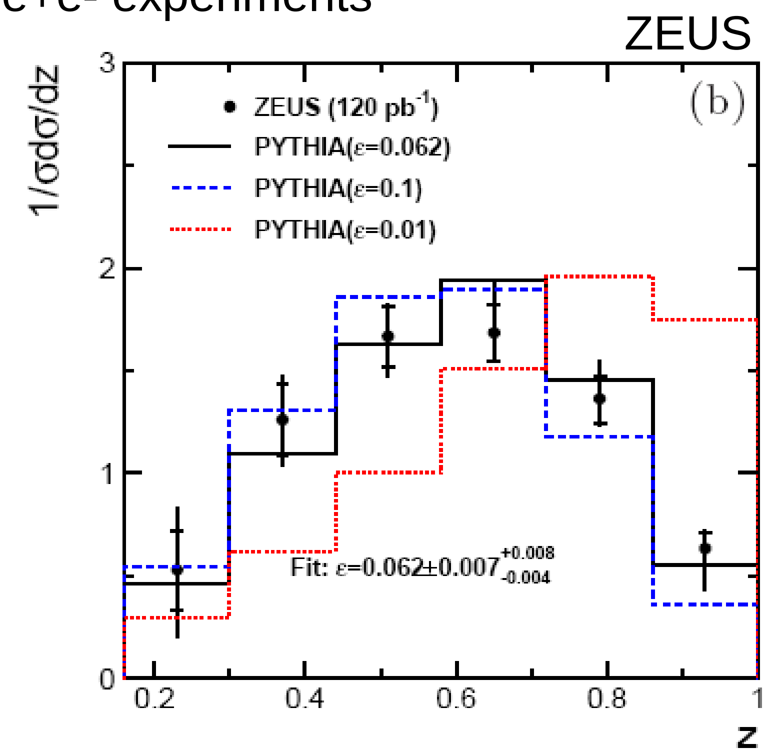


PYTHIA with Peterson fragm. function

value of ε parameter extracted from fitting MC to the data

$\varepsilon = 0.062 \;\; 0.007(\text{stat.})\; ^{+0.008}_{-0.004}\,(\text{syst.})$

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



PYTHIA with symmetric Lund string fragmentation f.+ modif. for heavy quarks (Bowler f.)

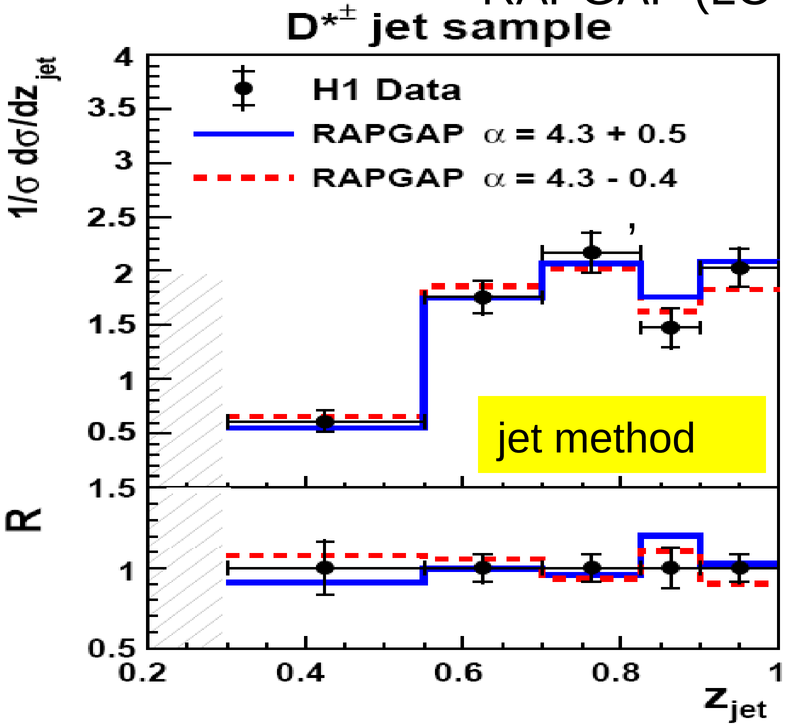
r_Q =1 (default setting) gives a reasonable description

deviation increases with decreasing value of r_Q

Comparison with RAPGAP simulation

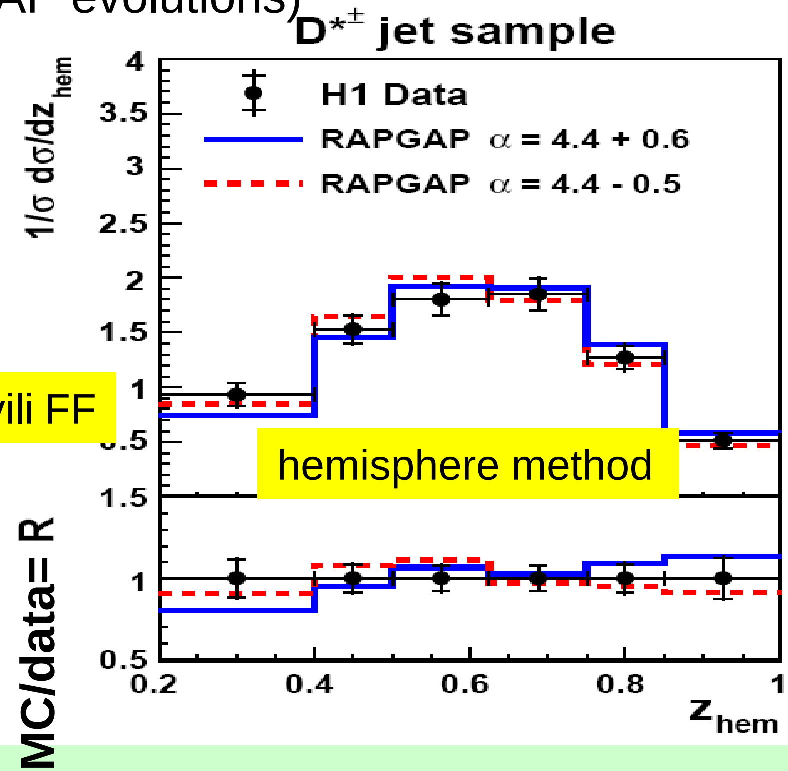
Jet sample

RAPGAP (LO ME + DGLAP evolutions)



jet method

Kartvelishvili FF



hemisphere method

	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- ε=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

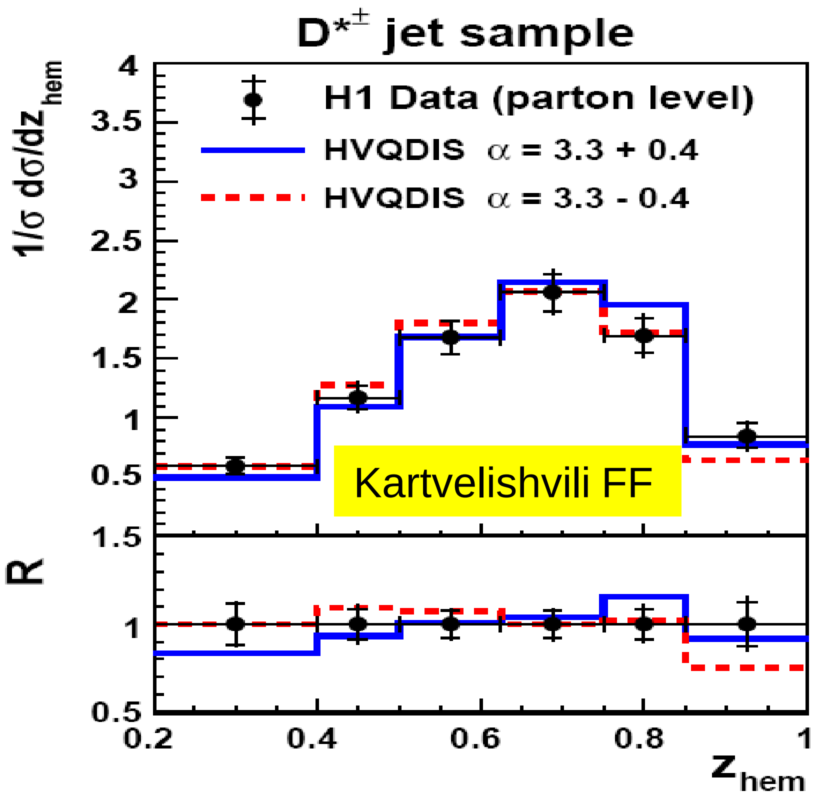
Similar results obtained with CASCADE simulation (k_T factorization+CCFR evolution)

Comparison with NLO QCD calculations

Jet sample

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	$3.3^{+0.4}_{-0.4}$

Comparison with NLO QCD calculations

no jet sample

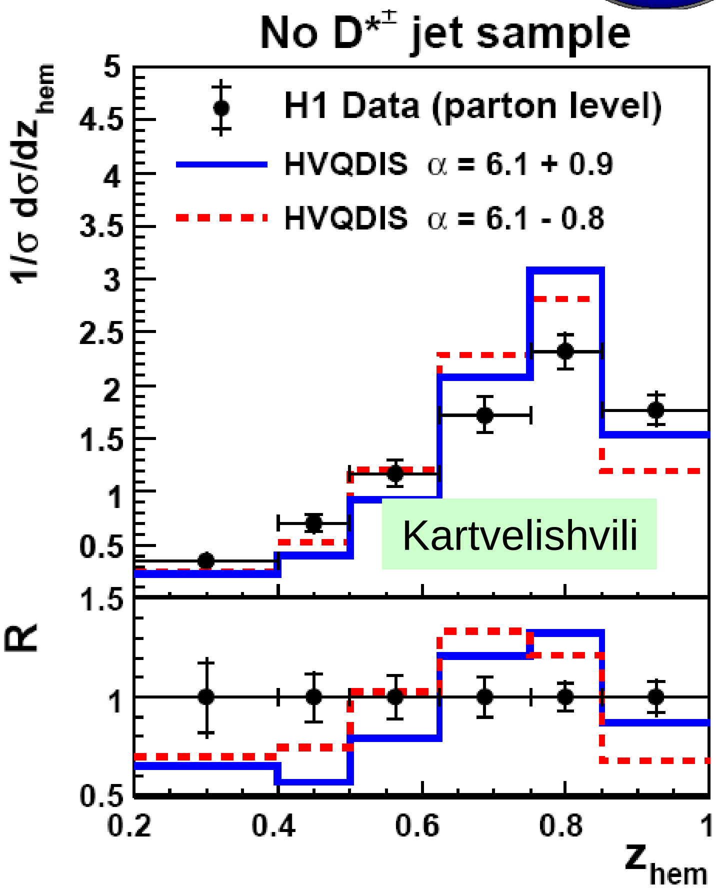
Data corrected to the parton level
Predictions from NLO QCD program HVQDIS

Events without a D*jet with E_T>3 GeV → 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

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

$100<Q^2<8000$ 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