Particle production at HERA

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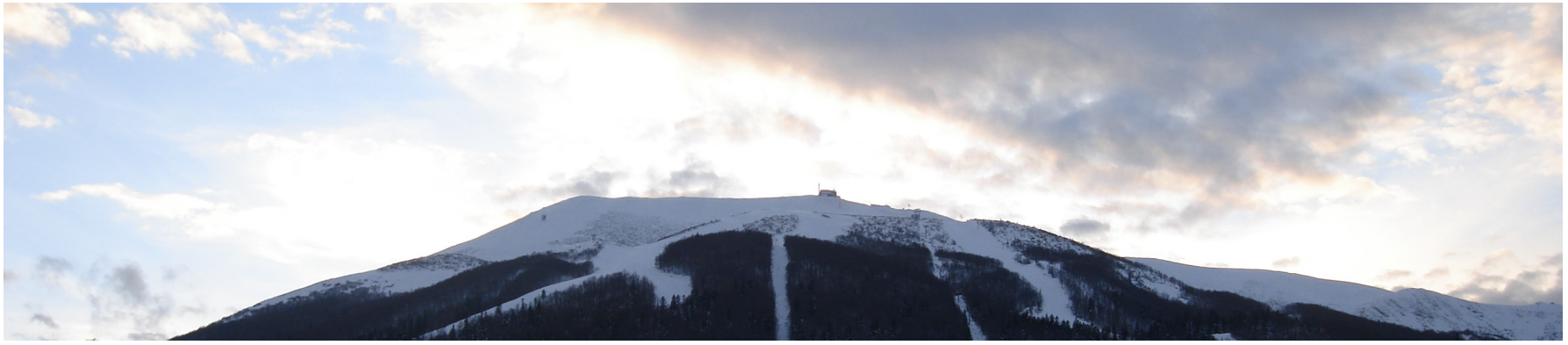
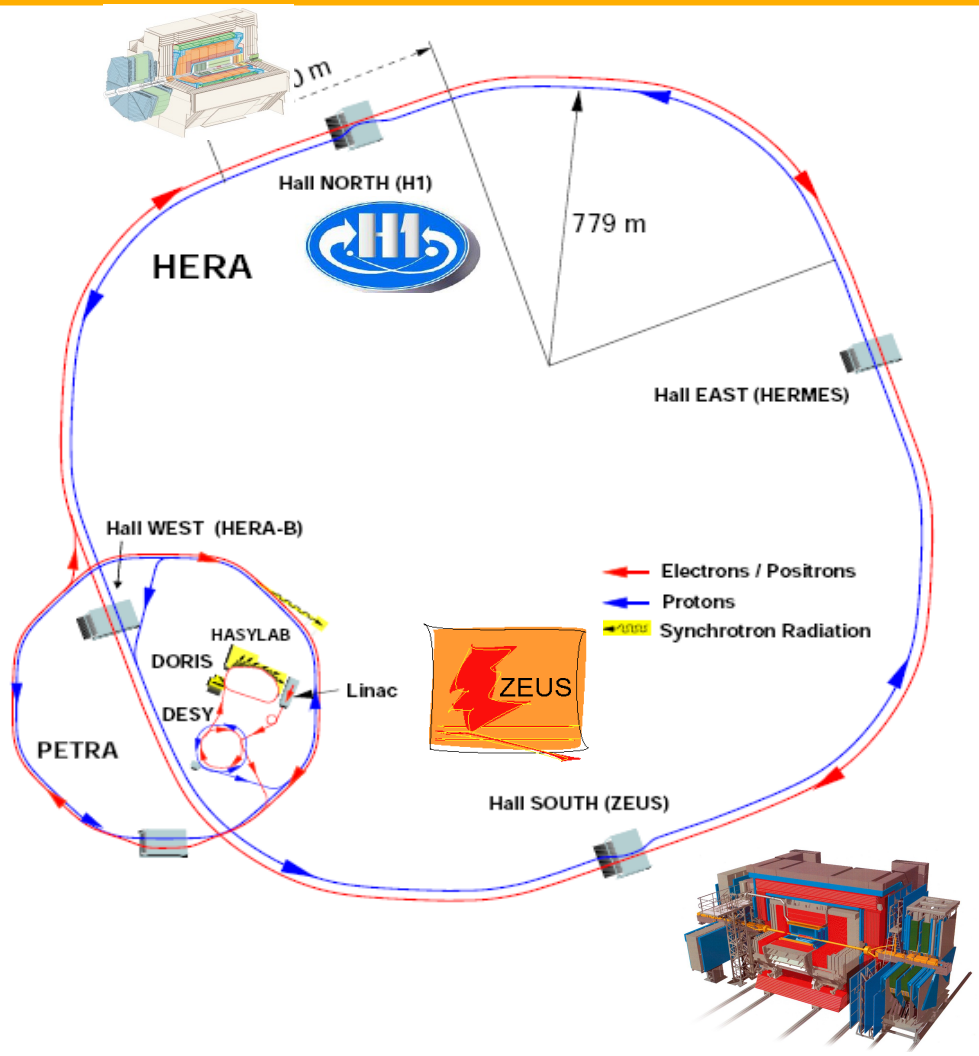
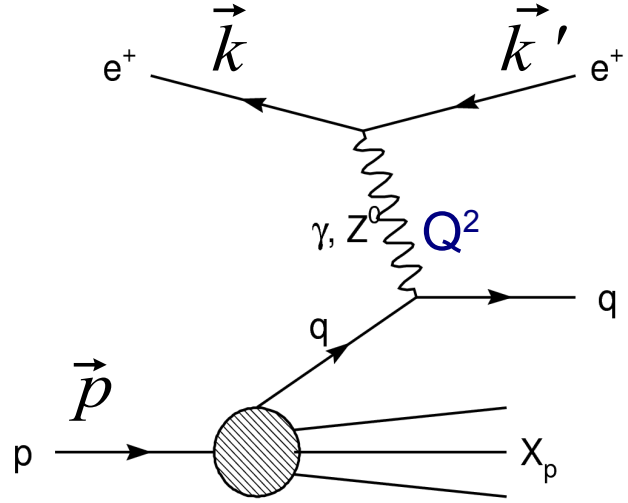
DESY

on behalf of the H1 and ZEUS Collaborations



DIS at HERA





Photon virtuality:

$$Q^2 = -q^2 = -(k - k')^2$$

Bjorken x: $x = \frac{Q^2}{2\, q \cdot p}$

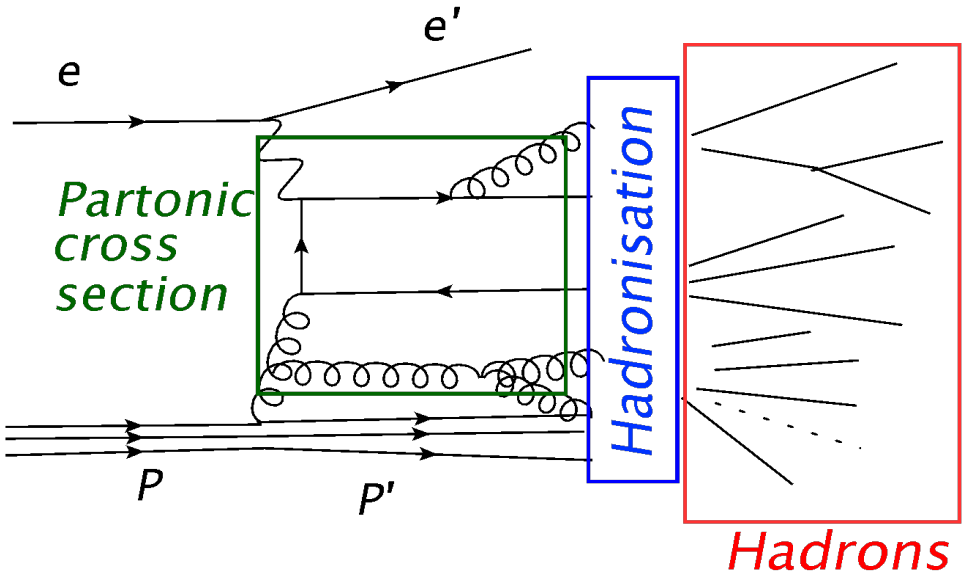
Inelasticity: $y = \frac{q \cdot p}{k \cdot p}$

$E_p = 920\,GeV \qquad E_e = 27.5\,GeV$

$\sqrt{s} = 318\,GeV$

Deep Inelastic Scattering (DIS): $Q^2 > 1\ GeV^2$

Particle production



$$\sigma(ep \to e\,H\,X) = \sum_{j,j'=q,\bar{q},g} f_j(x,Q^2) \otimes \hat{\sigma}_{j,j'}(x,Q^2) \otimes F_{j' \to H}(z,Q^2)$$

Proton PDF

non-perturbative

Partonic cross section

pQCD: LO or NLO

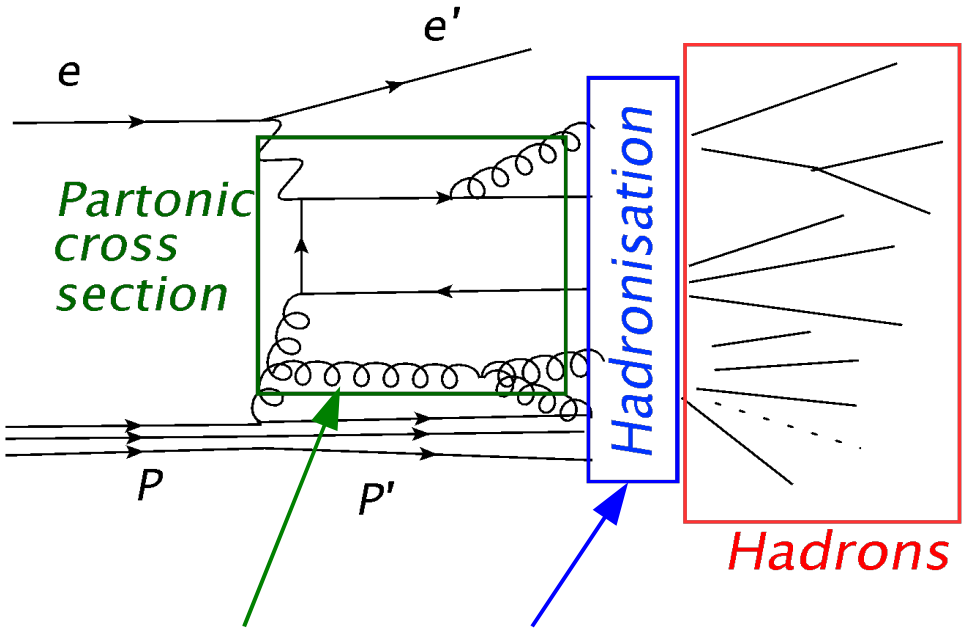
Monte Carlo:
LO+parton showers (PS)

Hadronisation,

Fragmentation function (FF)

non-perturbative

Fixed-order QCD calculations



NLO QCD ⊗ FF

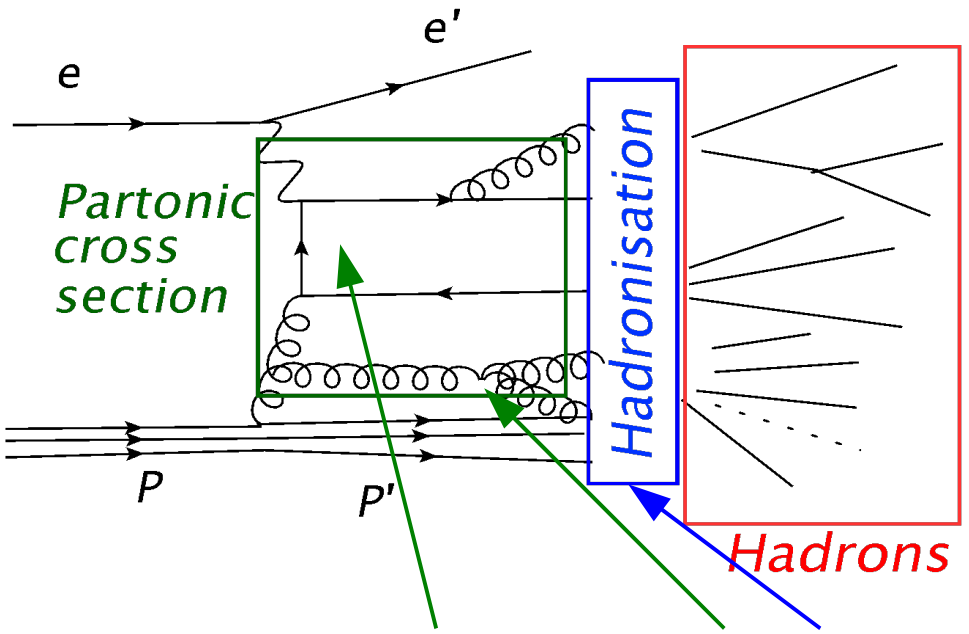
AKK+CYCLOPS: e^+e^-

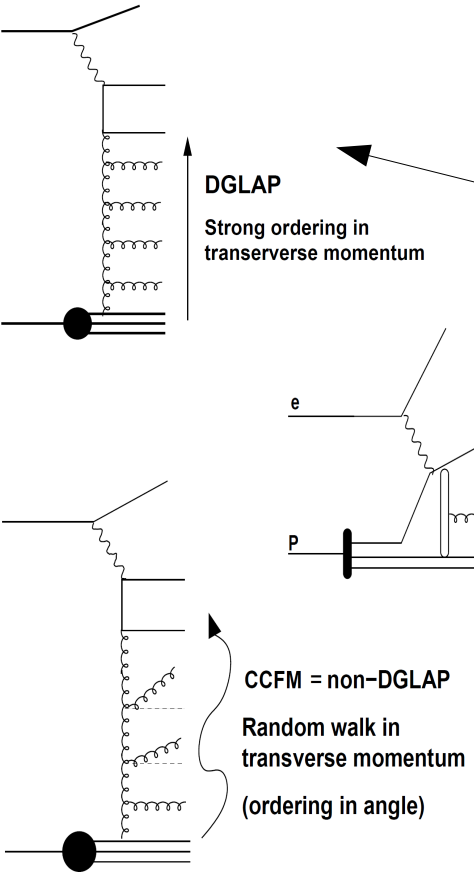
Albino, Kniehl, Kramer

DSS: e^+e^-, pp, ep

De Florian, Sassot, Stratmann

Particle production





MC: LO QCD+PS+Lund string model

DGLAP (strong ordering in k_T):
RAPGAP, LEPTO/MEPS.

BFKL-like/CDM (strong ordering in x):
DJANGOH.

CCFM (ordering in angle): CASCADE

Overview

Parton dynamics

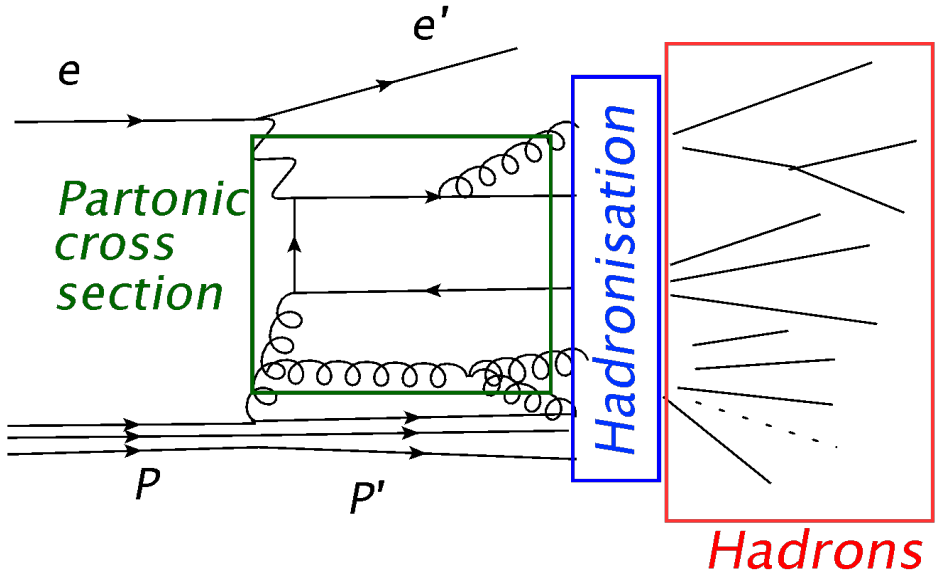
- Charged particle spectra in DIS

Hadronisation

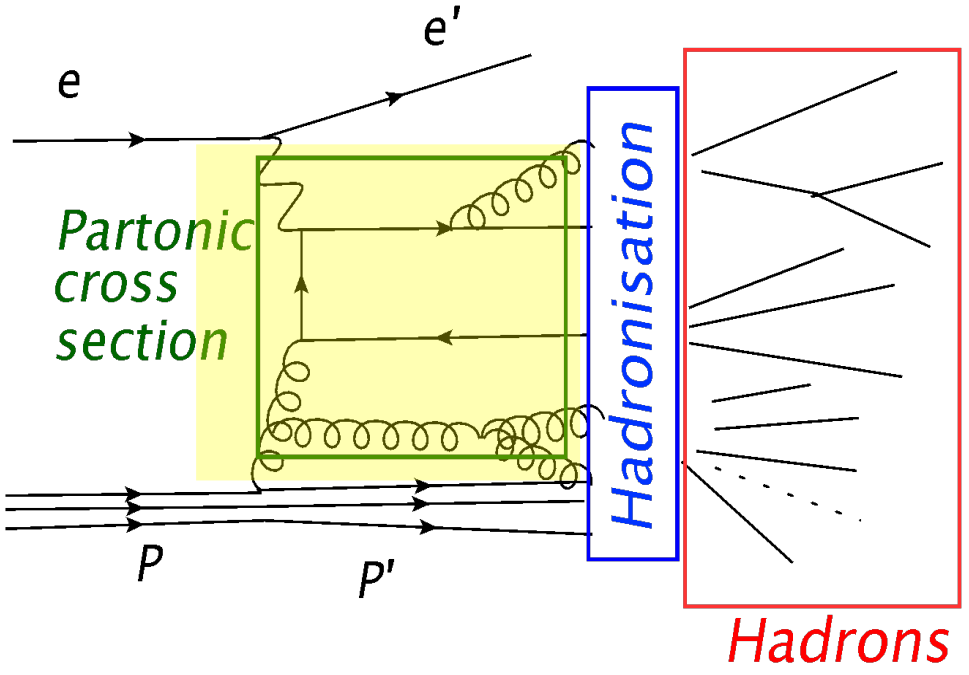
- K^0_s / Λ^0 scaled momentum spectra in DIS
- K^0_s production at high Q^2

Hadrons

- Excited charm mesons



Parton dynamics



Transverse momentum spectra of charged particles

Motivation:

- Test of low-x dynamics (various PS approaches are based on different approximations in the low-x region).
- Test of different models of parton emissions in PS (DGLAP, BFKL, CCFM)

Low p_T^*:

Sensitivity to hadronisation process.

High p_T^*:

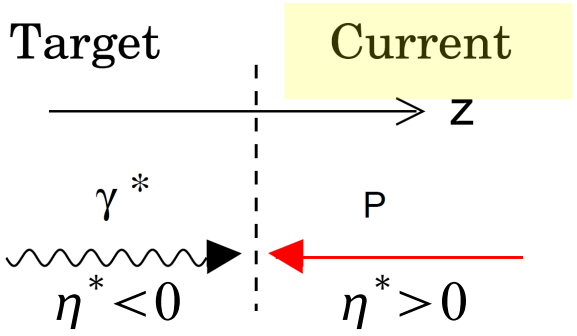
Sensitivity to modelling of parton dynamics

Observables:

Particle densities (event-normalised charged particle distributions): $\frac{1}{N}\frac{dn}{dp_T^*}$ $\frac{1}{N}\frac{dn}{d\eta^*}$

$5 < Q^2 < 100\ GeV^2$, $10^{-4} < x < 10^{-2}$,
$p_T^* < 10\ GeV$, $0 < \eta^* < 4$,
$p_T^{lab} > 150\ MeV$, $-2 < \eta^{lab} < 2.5$

Hadronic centre-of-mass (HCM) frame (p_T^*,η^*)



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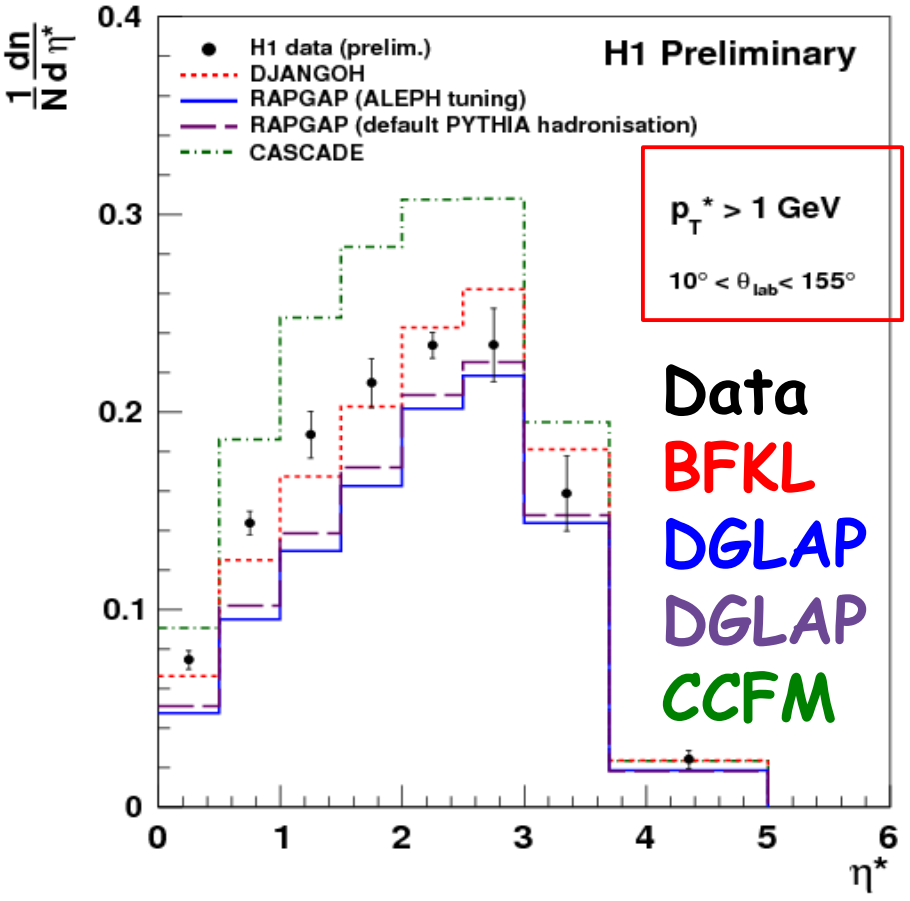
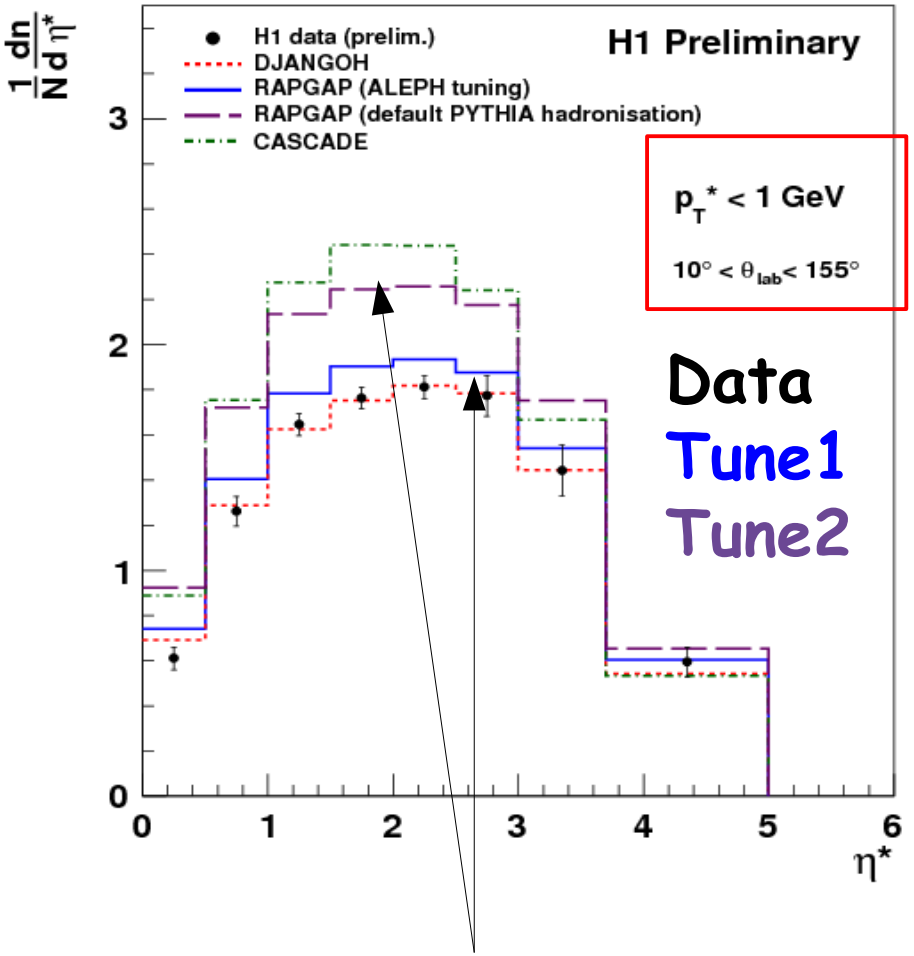
η^* distributions





Sensitivity to parton dynamics

Sensitivity to hadronisation

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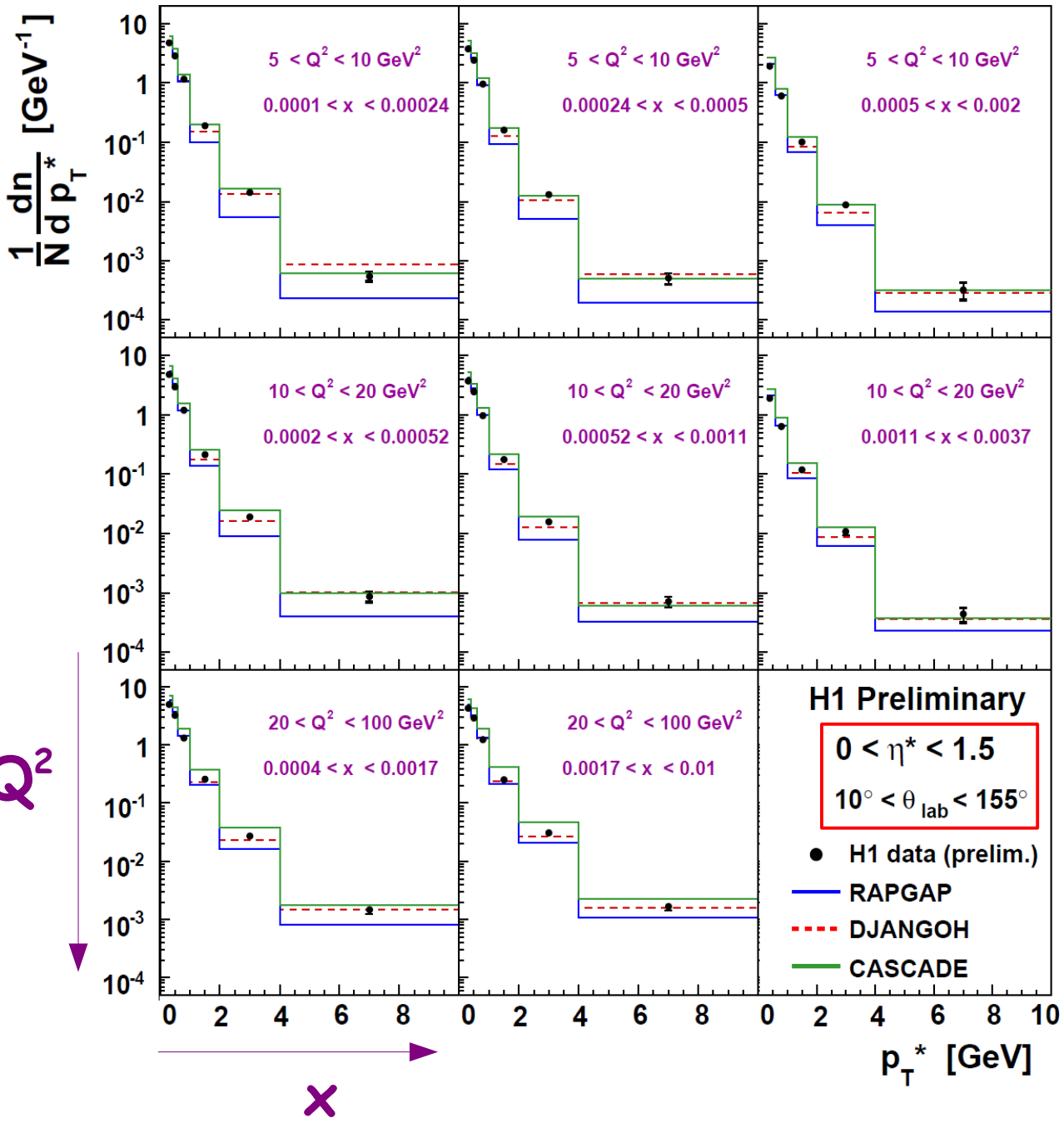
p_T^* distributions for $0<\eta^*<1.5$



BFKL-like model describes the data for in the whole measured region.

DGLAP approach fails at low Q^2 and low x.

CCFM model describes only the high-p_T^* data.

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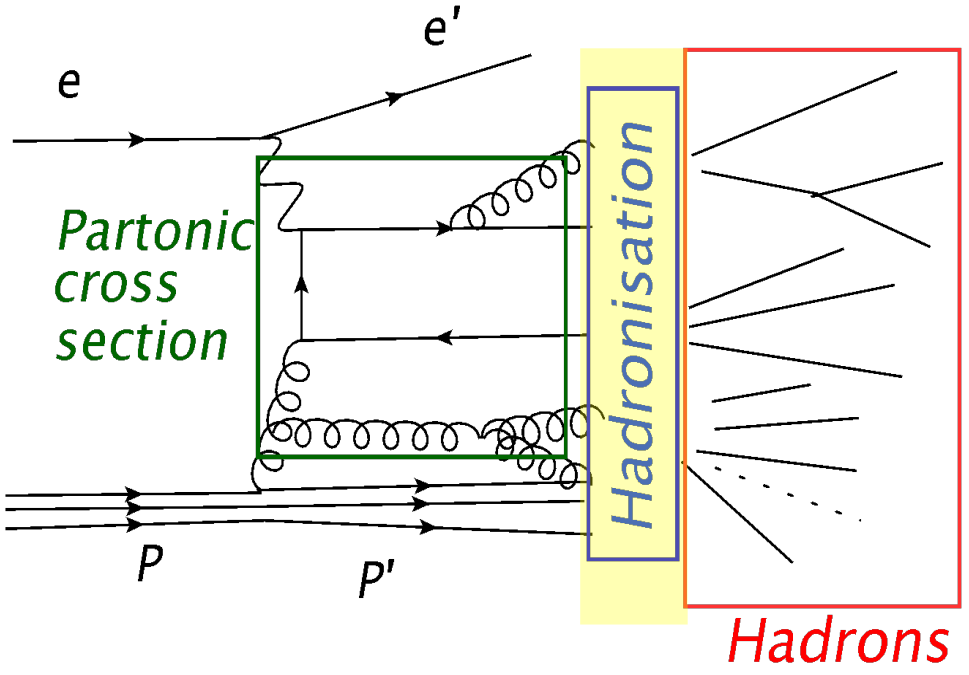
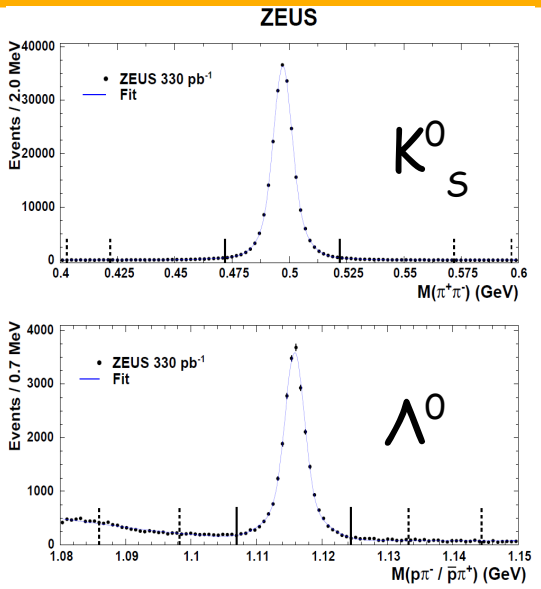
Hadronisation
Fragmentation function



Strange scaled momentum spectra in DIS

Motivation:

- FFs for strange hadrons are poorly constrained => potential constraints from new data.
- Strange-hadron production in ep allows to constrain quark, antiquark and gluon contributions to the FFs.



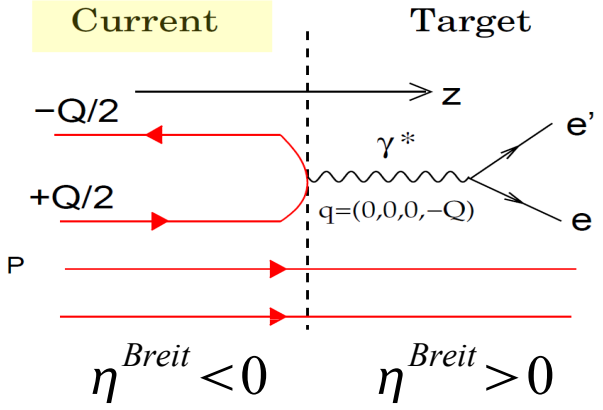
Observables:

Scaled momentum (estimator for z, the parton momentum fraction carried by the hadron:

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

$10 < Q^2 < 40000\ GeV^2,\ 10^{-3} < x < 0.75$

Breit frame (p^{Breit},η^{Breit}): the current region



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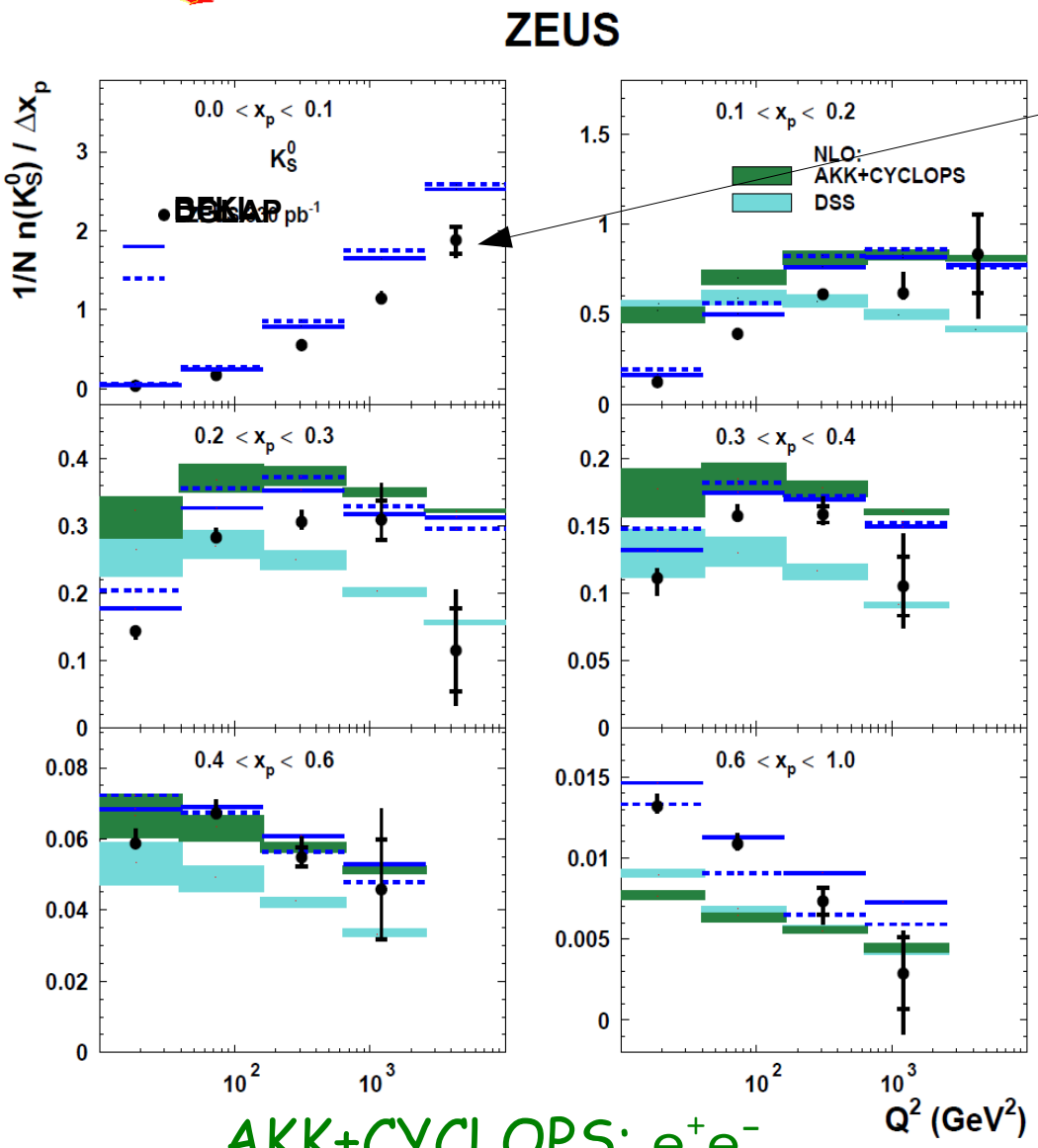
x_p distribution: K^0_S



- Clear indication of scaling violations in FF: larger Q^2 → more soft gluons emitted → more particles at low x_p.
  Analogy: scaling violations in inclusive DIS.
- Both NLO QCD+FF predictions fail to describe the data. DSS calculations do a bit better at medium x_p and low Q^2, while AKK at high Q^2.
- MCs provide reasonable description.
- Similar conclusions for Λ.

AKK+CYCLOPS: e^+e^-

DSS: e^+e^-, pp, ep

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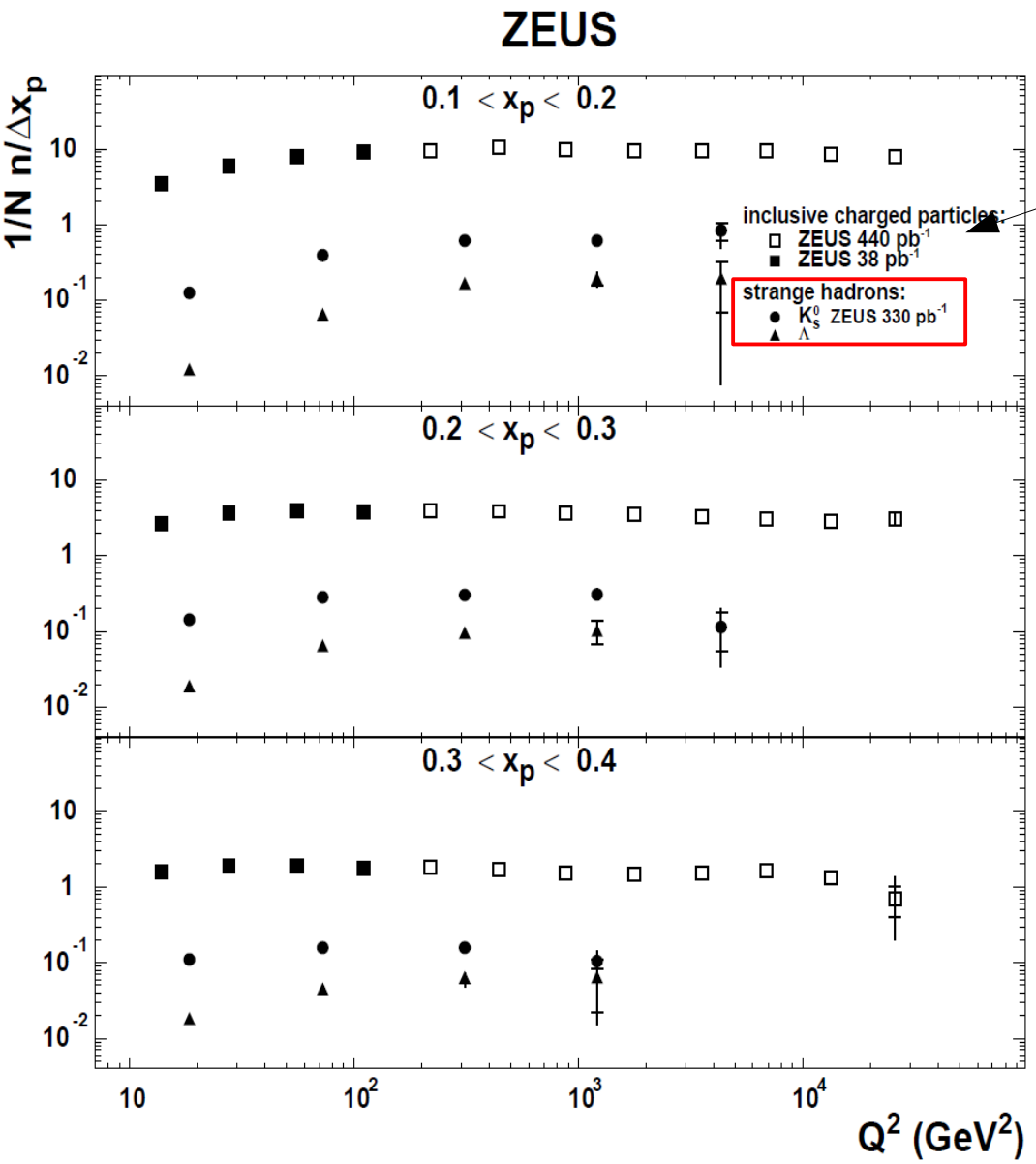
Strange x_p distribution: comparison to inclusive data



- Inclusive scaled momentum spectra for charged particles in DIS (JHEP 6 (2010) 1). Most charged particles are pions.
- Inclusive charged-particle and neutral-strange-hadron data show a plateau for $Q^2 > 100$ GeV^2.
- At low Q^2 mass effects are expected (most pronounced at low x_p)

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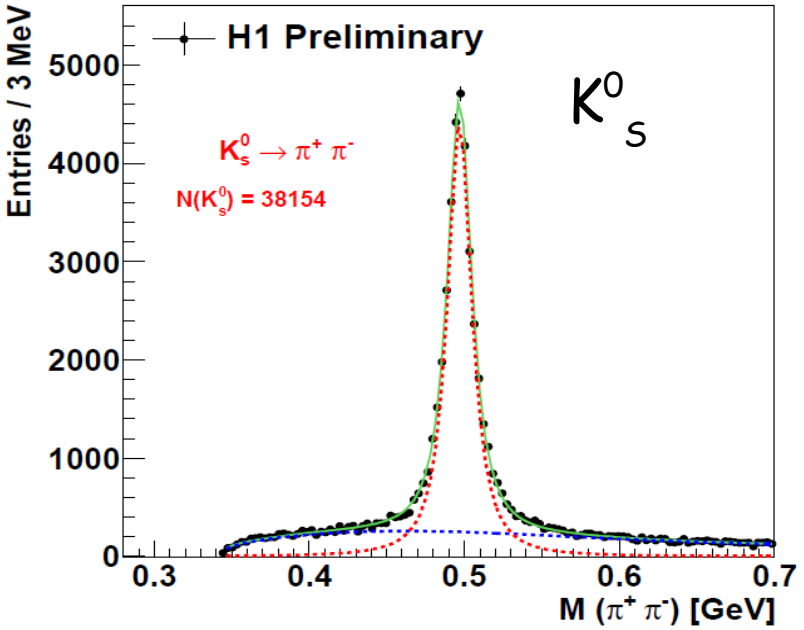
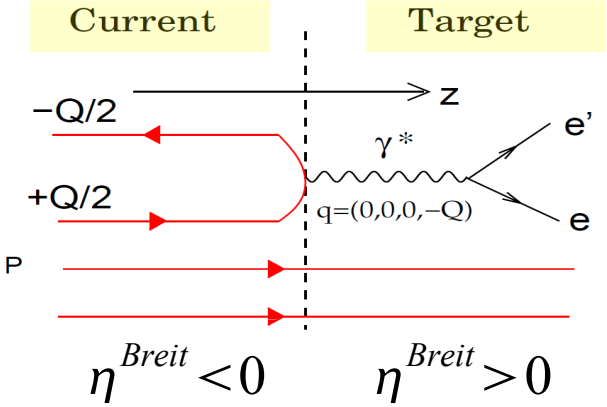
K^0_s production at high Q^2

Motivation:

- Test various fragmentation models.
- Test universality of the strangeness-suppression factor (λ_s = P(s)/P(q)) in the Lund string fragmentation model



Breit frame (p^{Breit},η^{Breit}): the current and the target regions



Observables:

Scaled momentum: $x_p = \frac{p^{Breit}}{\sqrt{Q^2}/2}$,

Q^2 , p_T

145 < Q^2 < 20000 GeV², 0.2 < y < 0.6
$p^T(K^0_s)$ > 0.3 GeV, $|\eta(K^0_s)|$<1.5

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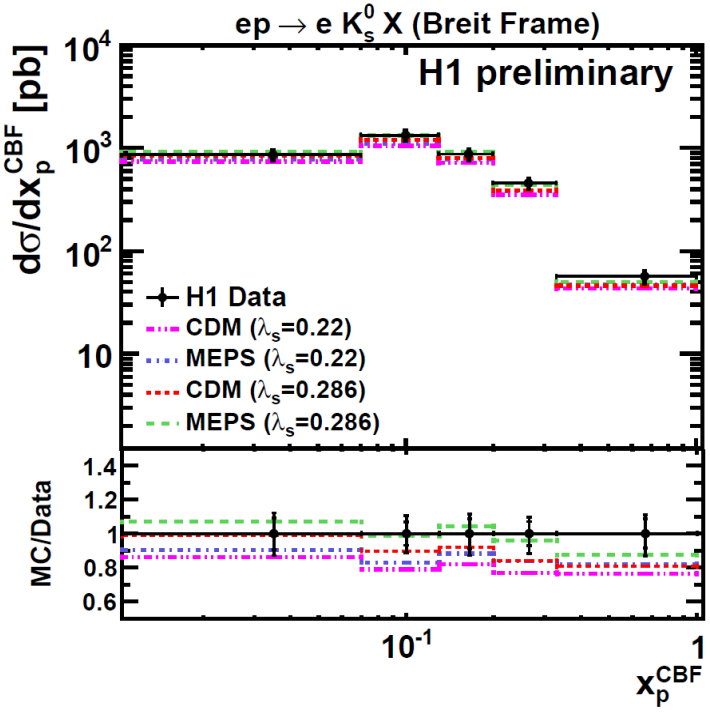
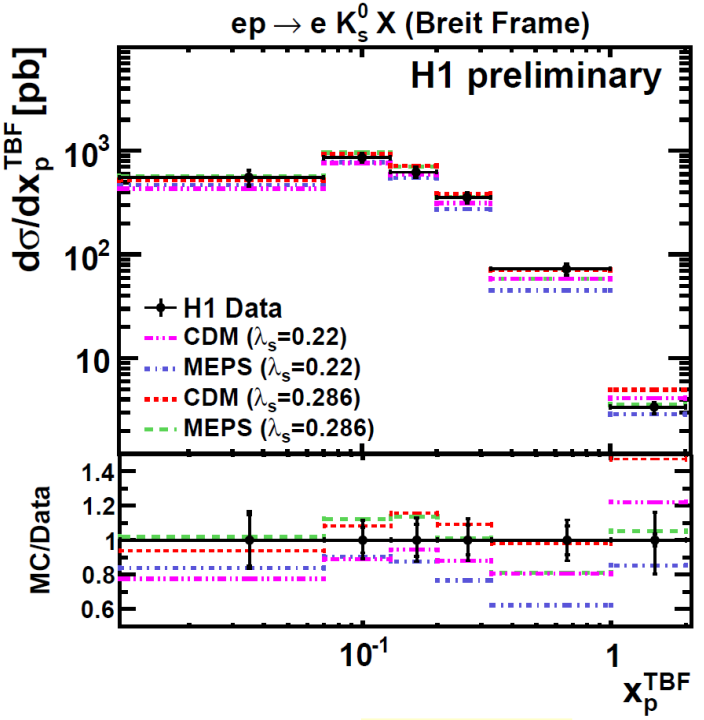
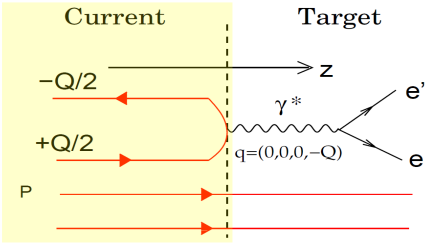
K^0_s cross sections at high Q^2



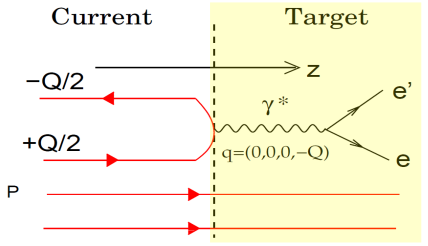
Data
BFKL
DGLAP
BFKL
DGLAP





Similar to the e^+e^- topology

- λ_s = 0.286 is preferred over λ_s = 0.220
- Both MCs describe the data



Hadronisation effects are more pronounced

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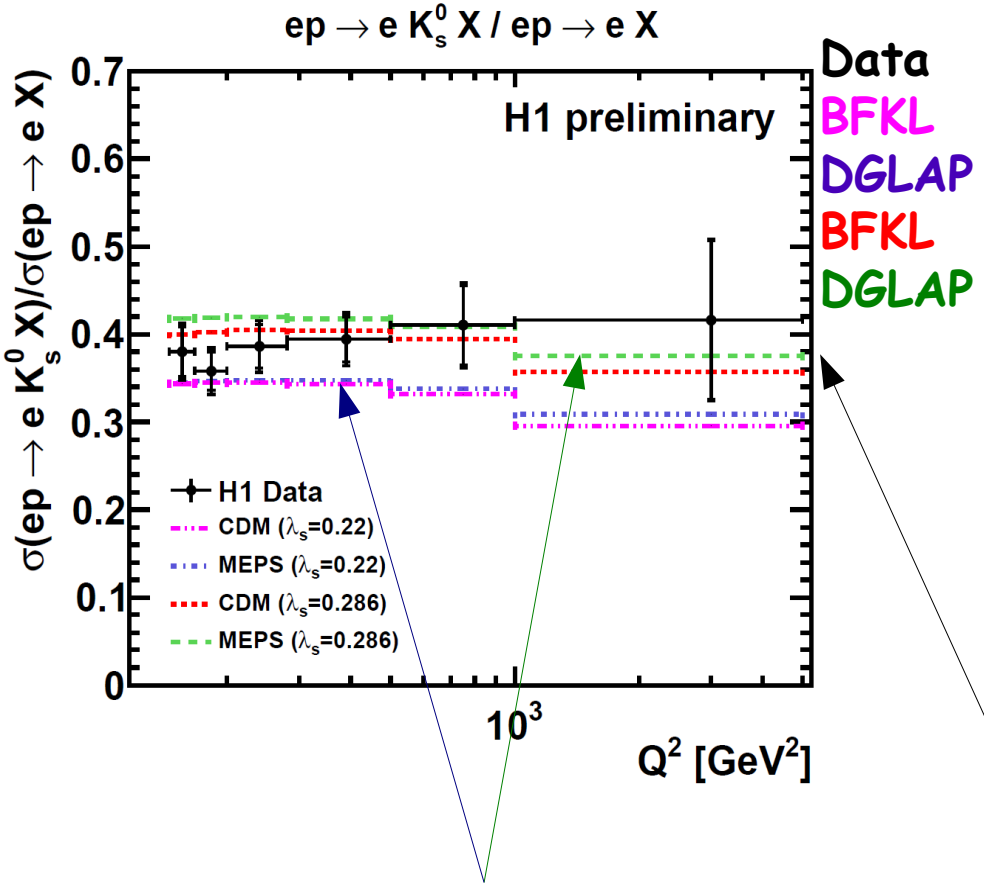
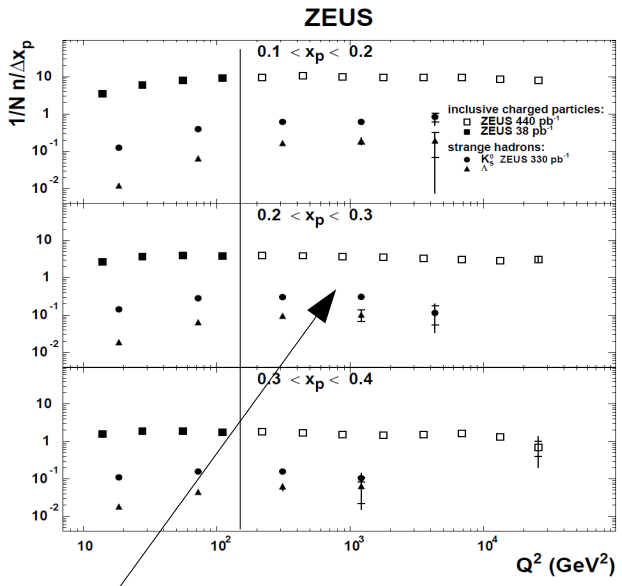
Ratio of K^0_s cross section to DIS





- Improved sensitivity to λ_s
- K^0_s density features a plateau as a function of Q^2.

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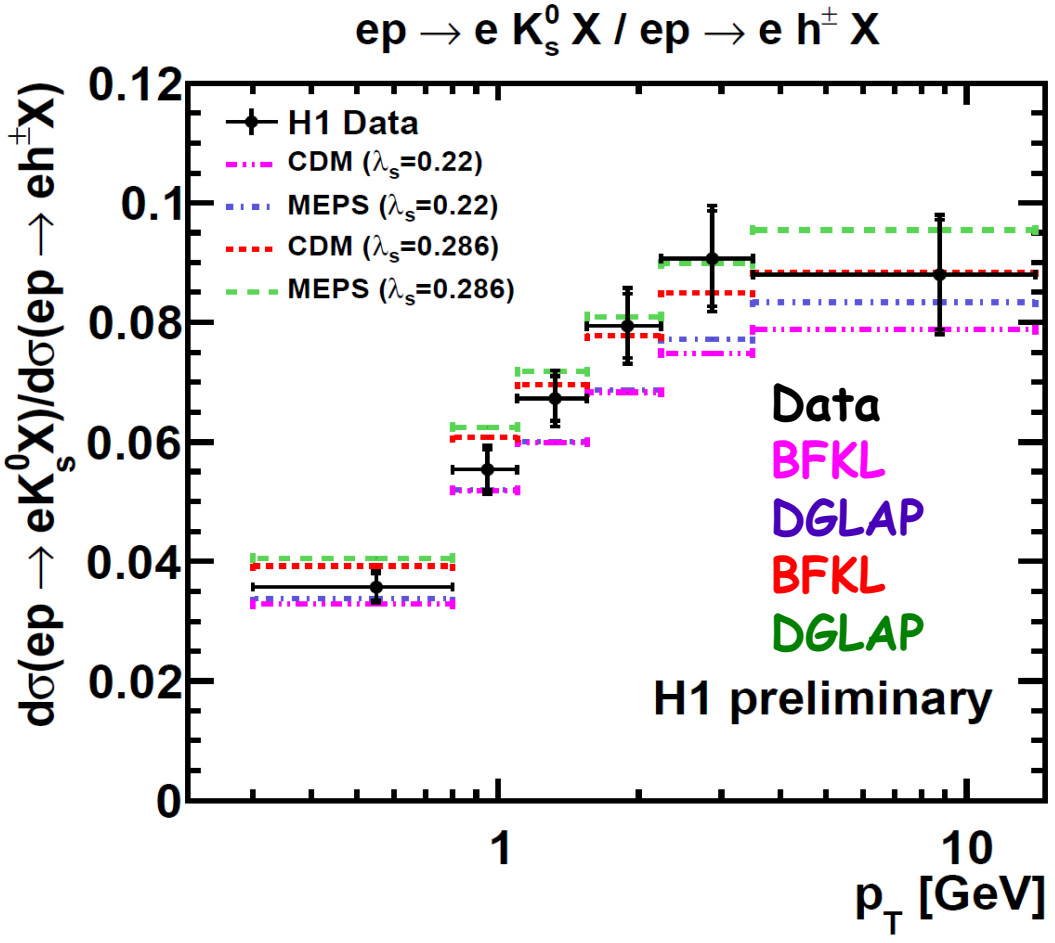
Ratio of K^0_s cross section to charged hadrons



- Strong dependence of the ratio in p_T is expected due to mass effects

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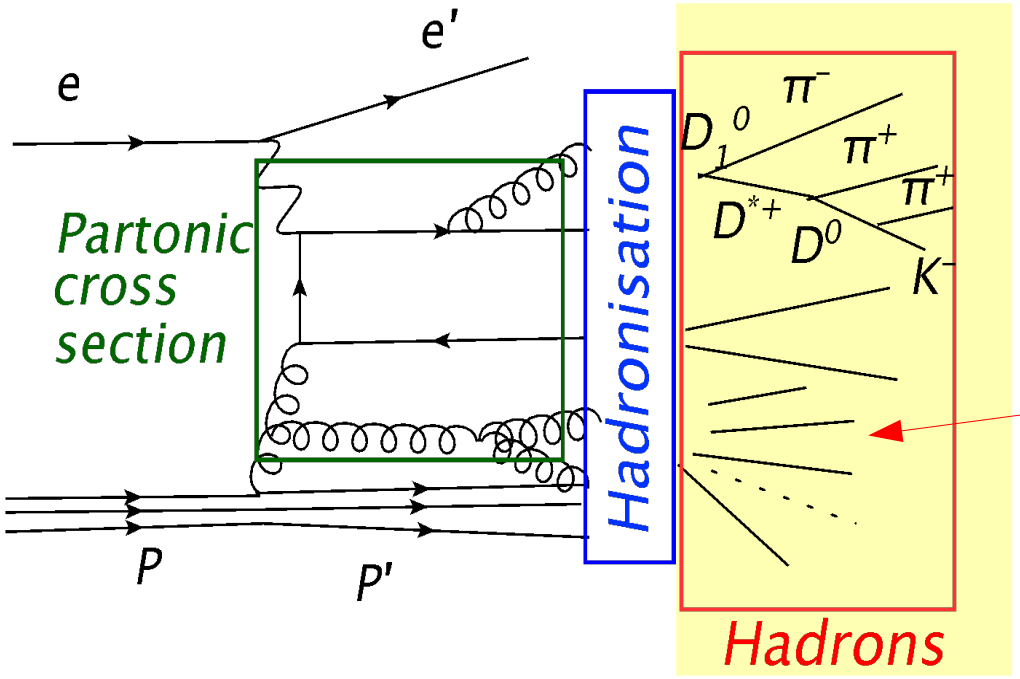
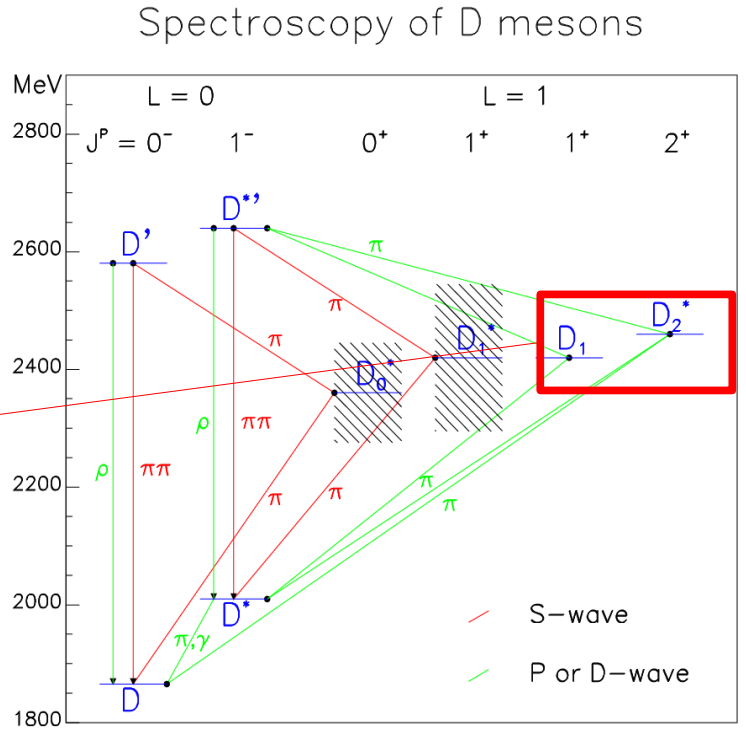
Spectroscopy of excited charm mesons

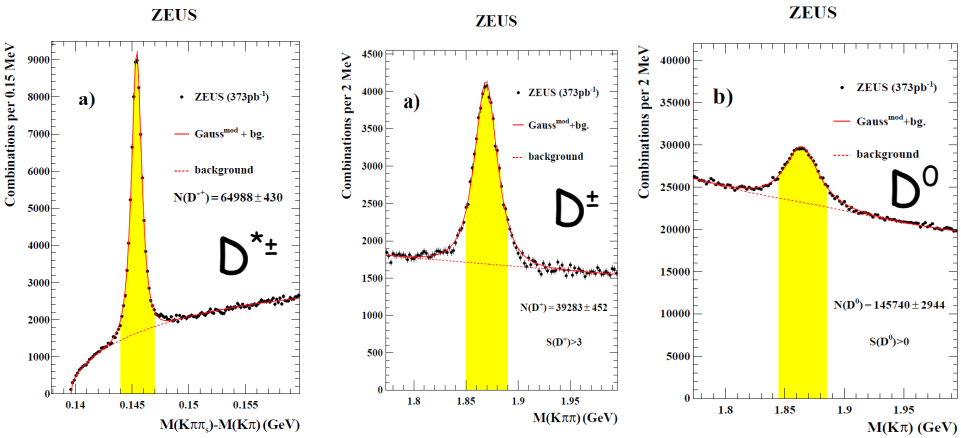


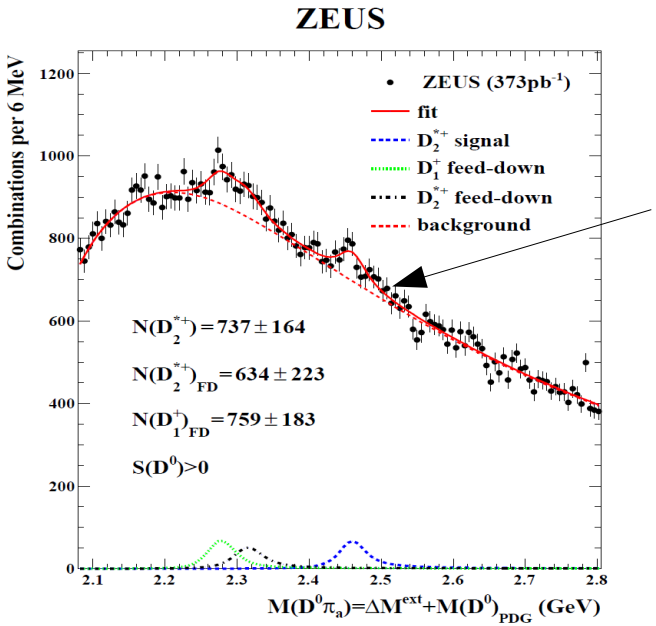


$D_1^{\pm,0}(2420)$ and $D_2^{*\pm,0}(2460)$

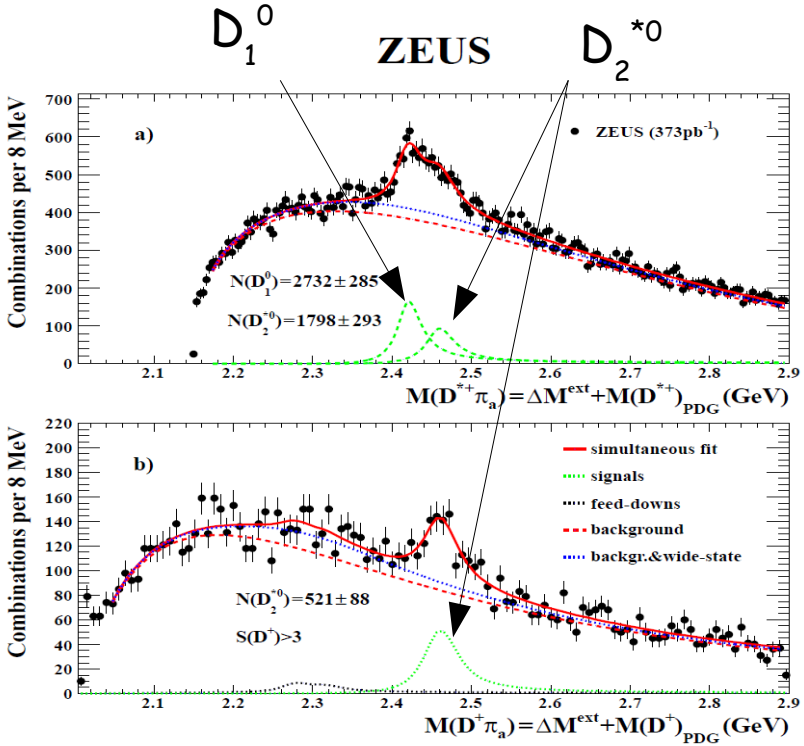
Motivation:

- Measurement of parameters of charged and neutral excited D mesons with L=1.
- Measurement of fragmentation fractions into these states.
- Very limited experimental data so far.





Charged states were studies for the first time at HERA



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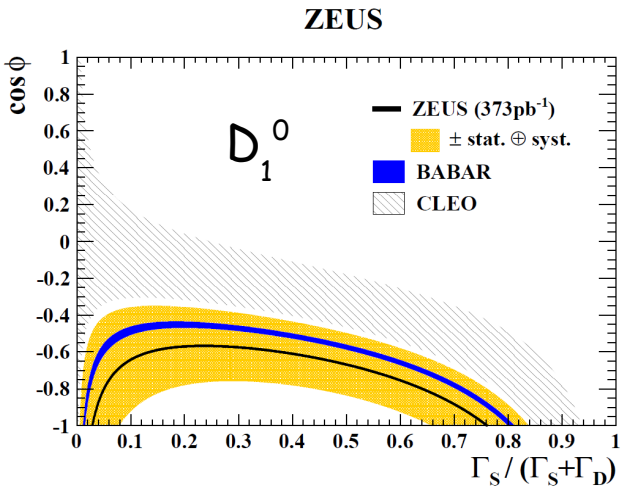
$D_1^0(2420)$ and $D_2^{*0}(2460)$

	HERAII	HERAI	PDG
$M(D_1^0)$, MeV	$2423.1 \pm 1.5^{+0.4}_{-1.0}$	$2420.5 \pm 2.1 \pm 0.9$	2421.3 ± 0.6
$\Gamma(D_1^0)$, MeV	$38.8 \pm 5.0^{+1.9}_{-5.4}$	$53.2 \pm 7.2^{+3.3}_{-4.9}$	27.1 ± 2.7
$h(D_1^0)$	$7.8^{+6.7+4.6}_{-2.7-1.8}$	$5.9^{+3.0+2.4}_{-1.7-1.0}$	
$M(D_2^{*0})$, MeV	$2462.5 \pm 2.4^{+1.3}_{-1.1}$	$2469.1 \pm 3.7^{+1.2}_{-1.3}$	2462.6 ± 0.7
$\Gamma(D_2^{*0})$, MeV	$46.6 \pm 8.1^{+5.9}_{-3.8}$	43 fixed	49.0 ± 1.4



- Spectroscopy: measured masses and widths are in good agreement with PDG. Improved precision compared to previous ZEUS measurement.
- D_1^0 helicity: good agreement with previous BABAR and CLEO measurements. Agrees with an S- and D-wave mixture as well as a pure D-wave hypothesis.
- Fragmentation fractions, BR ratios and fractions of ground states originating from the excited states were measured.

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$D_1^{\pm}(2420)$ and $D_2^{*\pm}(2460)$

	HERAII	PDG
$M(D_1^+)$, MeV	$2421.9 \pm 4.7^{+3.4}_{-1.2}$	2423.4 ± 3.1
$M(D_2^{*+})$, MeV	$2460.6 \pm 4.4^{+3.6}_{-0.8}$	2464.4 ± 1.9

Measured for the first time:

$$f(c \to D_2^{*+}) = 3.2 \pm 0.8(\text{stat.})^{+0.5}_{-0.2}(\text{syst.})\,\%$$
$$f(c \to D_1^{+}) = 4.6 \pm 1.8(\text{stat.})^{+2.0}_{-0.3}(\text{syst.})\,\%$$

- So far, very limited data on $D_1^{\pm}(2420)$.
- Spectroscopy: masses are in good agreement with PDG. Improved precision compared to previous ZEUS measurement.
- Fragmentation fractions, BR ratios and fractions of ground states originating from the excited states were measured. Good agreement with the neutral states

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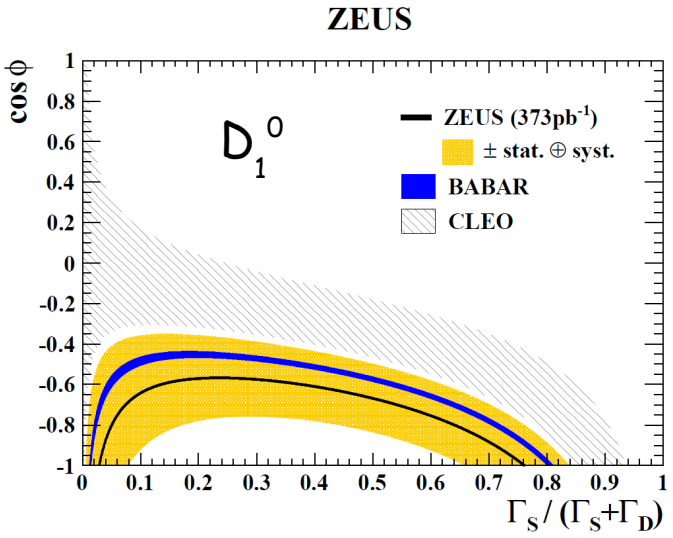
Conclusions

Various aspects of particle production were studied in ep collisions at HERA:

- Particle dynamics was studied with transverse momentum spectra of charged hadrons. The BFKL-like model (DJANGOH) performs the best at low x.
- Hadronisation was studied with scaled momentum spectra for charged hadrons and neutral strange hadrons.
  - Scaling violations were observed.
  - NLO QCD calculations with recent fits of FFs are not able to describe the HERA data. Therefore, the data have potential to further constrain fragmentation functions.
  - The strange-hadron data can constrain λ_s.
- $D_1^{\pm,0}(2420)$ and $D_2^{*\pm,0}(2460)$ were studied. All parameters agree with previous measurements. Fragmentation fractions for charged states were measured for the first time.

$D_1^{\pm,0}(2420)$ and $D_2^{*\pm,0}(2460)$ (backup)



$$\cos\phi = \frac{(3-h)/(3+h) - r}{2\sqrt{2r(1-r)}}$$

$$r = \Gamma_S/(\Gamma_S + \Gamma_D)$$

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Scaled momentum spectra in DIS

Motivation:

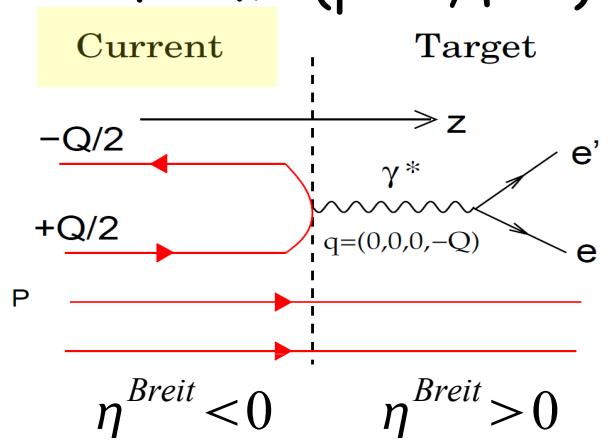
- Scaling violations in FF.
- Test hypothesis of limiting fragmentation (density of charged particles per η unit depends only on the energy of the γp system, W).
- Test fragmentation universality.

Observables:

Scaled momentum (estimator for z, the parton momentum fraction carried by the hadron):

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

Breit frame (p^{Breit},η^{Breit})



$10 < Q^2 < 41000\ GeV^2$, $2*10^{-3} < x < 0.75$

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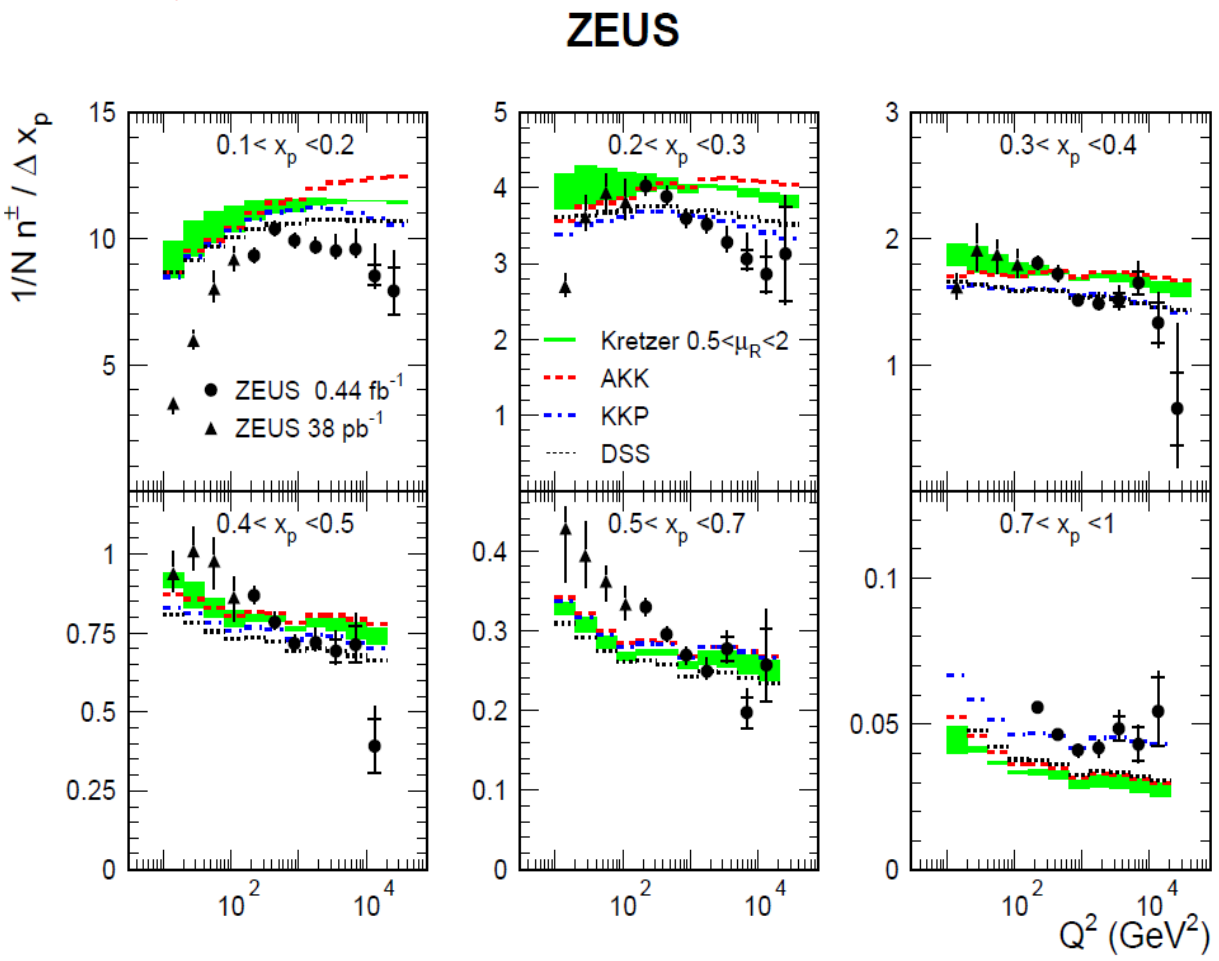
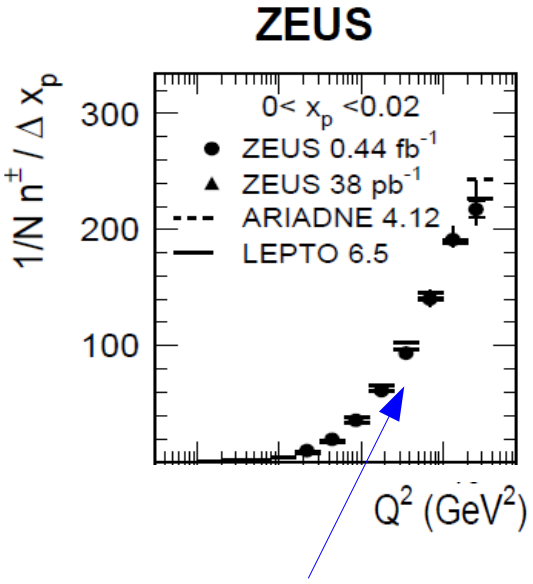
Scaling violations in FF





Clear indication of scaling violations: larger Q^2 → more soft gluons emitted → more particles at low x_p. Analogy: scaling violations in inclusive DIS.

None of NLO QCD calculations + FF extracted from e^+e^- describes the data

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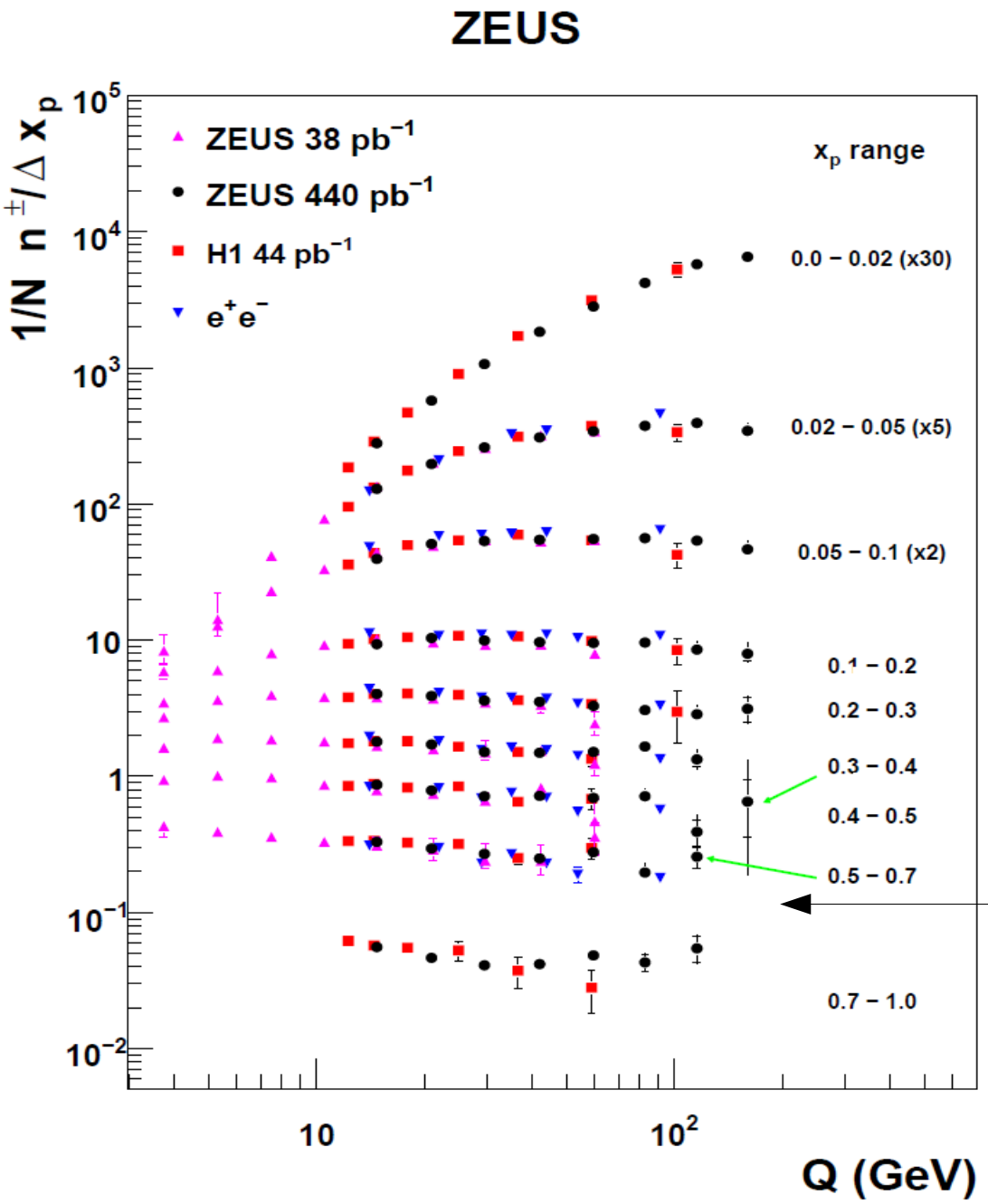
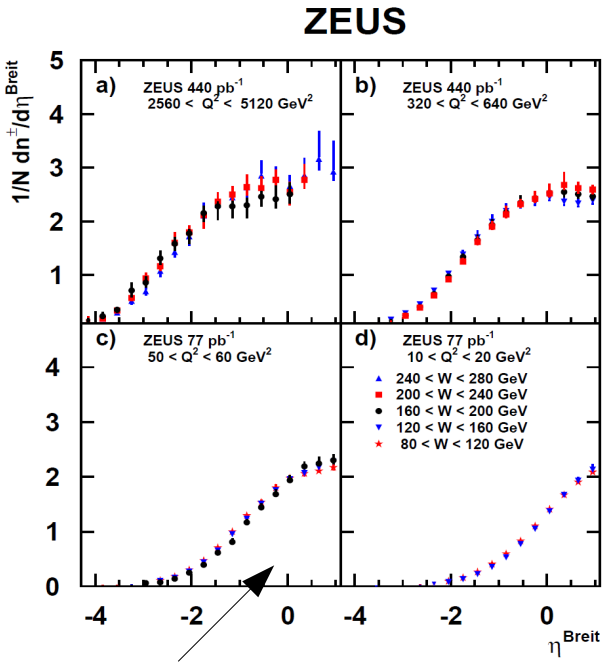
Quark-fragmentation universality





- Limiting fragmentation checked (no Q2 and W depenedence)
- Good agreement between ep data (from ZEUS and H1) and e+e- data. => fragmentation universality supported by the new data.

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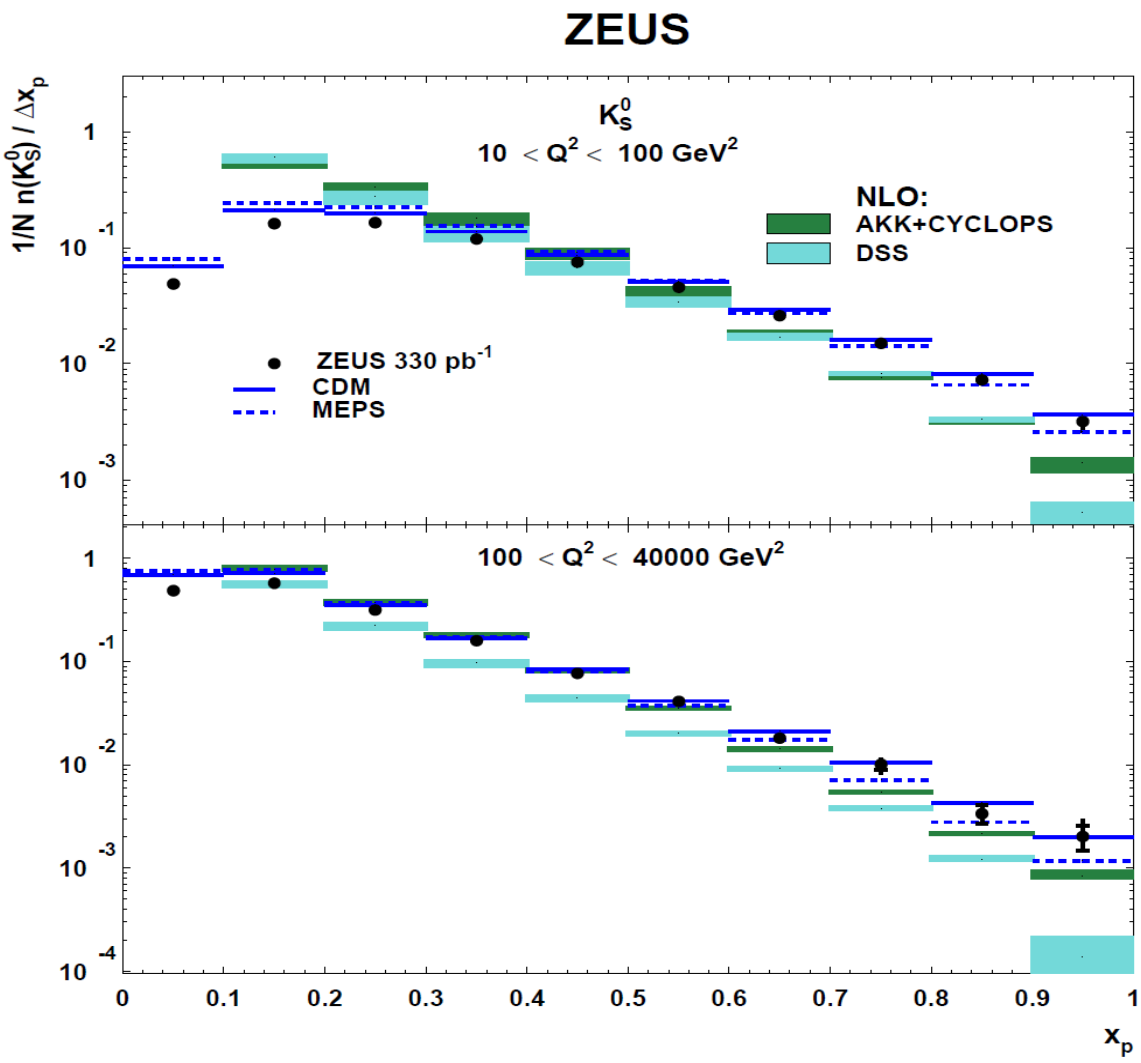
x_p distribution: K^0_S



AKK+CYCLOPS: e^+e^-

DSS: e^+e^-, pp, ep

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$D_1^{\pm,0}(2420)$ and $D_2^{*\pm,0}(2460)$

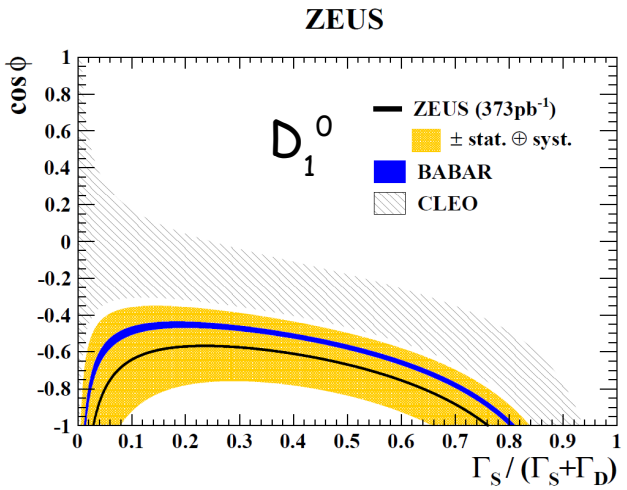
Neutral states

	HERA II	HERA I	PDG
$N(D_1^0 \to D^{*+}\pi)$	2732 ± 285	3110 ± 340	
$N(D_2^{*0} \to D^{*+}\pi)$	1798 ± 293	870 ± 170	
$N(D_2^{*0} \to D^{+}\pi)$	521 ± 88 $(S(D^+) > 3)$	690 ± 160	
$M(D_1^0)$, MeV	$2423.1 \pm 1.5^{+0.4}_{-1.0}$	$2420.5 \pm 2.1 \pm 0.9$	2421.3 ± 0.6
$\Gamma(D_1^0)$, MeV	$38.8 \pm 5.0^{+1.9}_{-5.4}$	$53.2 \pm 7.2^{+3.3}_{-4.9}$	27.1 ± 2.7
$h(D_1^0)$	$7.8^{+6.7+4.6}_{-2.7-1.8}$	$5.9^{+3.0+2.4}_{-1.7-1.0}$	
$M(D_2^{*0})$, MeV	$2462.5 \pm 2.4^{+1.3}_{-1.1}$	$2469.1 \pm 3.7^{+1.2}_{-1.3}$	2462.6 ± 0.7
$\Gamma(D_2^{*0})$, MeV	$46.6 \pm 8.1^{+5.9}_{-3.8}$	43 fixed	49.0 ± 1.4
$h(D_2^{*0})$	-1 fixed	-1 fixed	
$D_1(2430)^0/D_1^0$	1.0 fixed	1.0 fixed	
$D_0^*(2400)^0/D_2^{*0}$	1.1 ± 1.1	1.7 fixed	
Feed-downs/D_2^{*0}	0.3 ± 0.4		

- Spectroscopy: good agreement with PDG. Improved precision compared to previous ZEUS measurement.
- D_1^0 helicity: good agreement with previous BABAR and CLEO measurements. Agrees with an S- and D-wave mixture as well as a pure D-wave hypothesis.
- Fragmentation fractions, BR ratios and fractions of ground states originating from the excited states were measured.

Charged states

	HERA II	PDG
$N(D_1^+ \to D^{*0}\pi^+)$	759 ± 183	
$N(D_2^{*+} \to D^{*0}\pi^+)$	634 ± 223	
$N(D_2^{*+} \to D^{0}\pi^+)$	737 ± 164	
$M(D_1^+)$, MeV	$2421.9 \pm 4.7^{+3.4}_{-1.2}$	2423.4 ± 3.1
$\Gamma(D_1^+)$, MeV	25 fixed	25 ± 6
$h(D_1^+)$	3.0 fixed	
$M(D_2^{*+})$, MeV	$2460.6 \pm 4.4^{+3.6}_{-0.8}$	2464.4 ± 1.9
$\Gamma(D_2^{*+})$, MeV	37 fixed	37 ± 6
$h(D_2^{*+})$	-1.0 fixed	



Measured for the first time:

$$f(c \to D_2^{*+}) = 3.2 \pm 0.8(\text{stat.})^{+0.5}_{-0.2}(\text{syst.})\,\%$$

$$f(c \to D_1^{+}) = 4.6 \pm 1.8(\text{stat.})^{+2.0}_{-0.3}(\text{syst.})\,\%$$

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