Charm production at HERA

ZEUS results

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Outlook

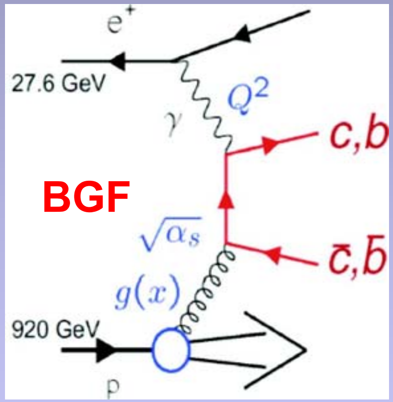
- Charm Physics: general motivations and themes
- D mesons in DIS, in photoproduction and in the transition region
  - Cross sections
  - Charm Fragmentation fractions and ratios

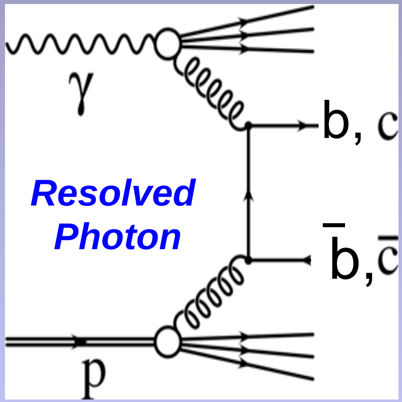
    - Neutral / Charged
    - Strangeness-suppression factor
    - Vector / Total
- D mesons at HERA II with tracking methods
- Excited charm and charm-strange mesons (PHP + DIS)
- Conclusions

HQ production in *ep* collisions:
the charm physics potentiality

- Powerful test of QCD.
- Clean measurement of the charm contribution to the structure function F_2^c
- Information on *c* quark production and fragmentation (independent, if QCD factorisation theorem holds)
- Testing different hadronisation models and fragmentation parameterisations
- Rich D mesons spectroscopy

Main processes contributing to HFL production at HERA are the boson-gluon fusion (BGF), directly sensitive to the ***p*** gluon content, and the resolved photon





Charm tagged via the reconstruction of different charmed mesons: D^*, D^+, D^0, D_s^+…

D mesons ($D^{\pm}$, D^0, $D_s^{\pm}$) in DIS

1998-2000 data, ~82 pb^{-1} $1.5 < Q^2 < 1000$ GeV²

Data compared to

Theoretical predtion from HVQDIS:
NLO $c\bar{c}$ BGF + FFNS (lq, g evolving DGLAP, Zeus-NLO fit to F_2 for p PDF)

Peterson fragm. (ε =0.035, def. value)
Fragm fractions: the measured ones
m_c = 1.35 GeV, $\Lambda^{(3)}_{QCD}$ =363 MeV; $\mu_R = \mu_F = \sqrt{Q^2 + 4m_c^2}$

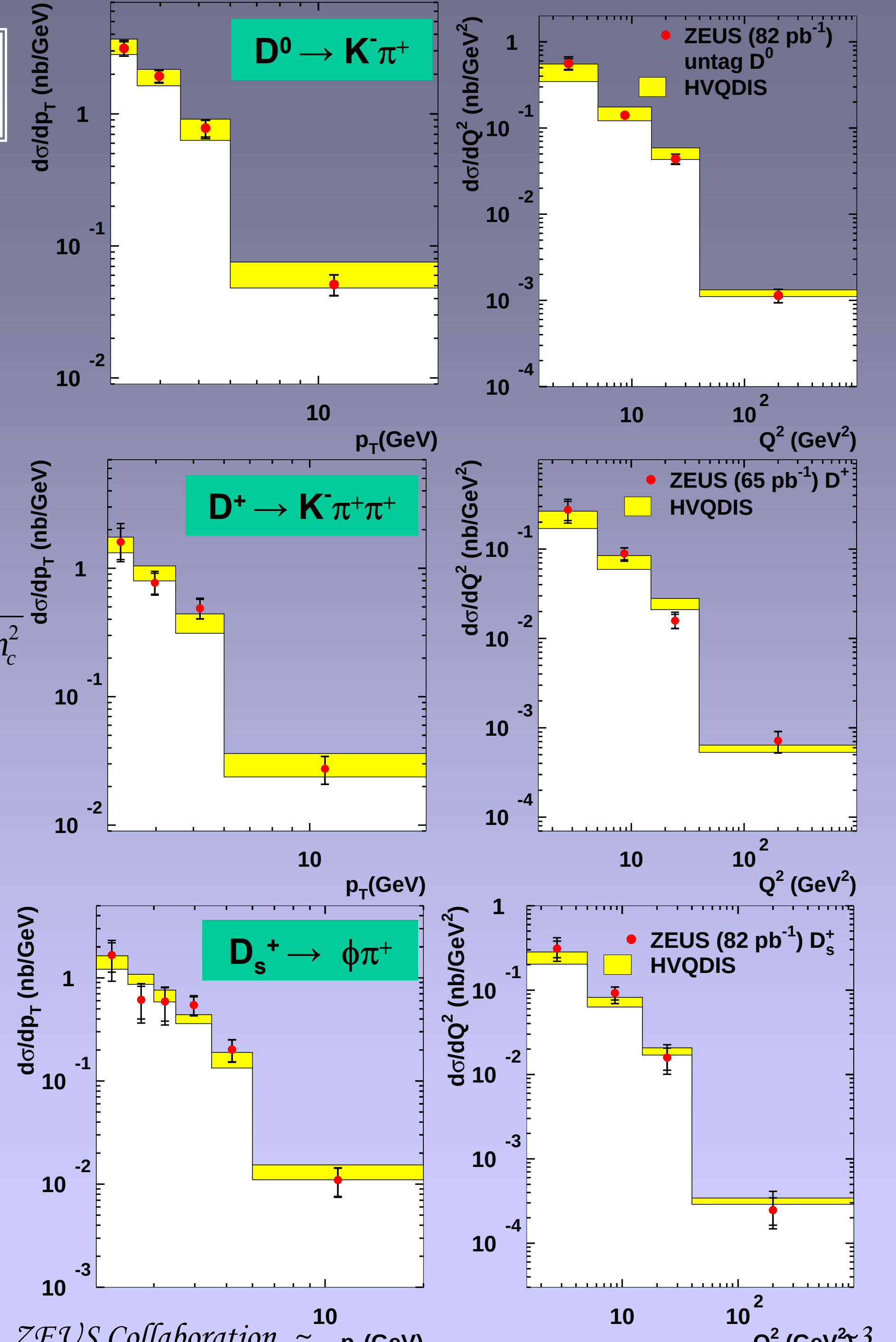
Measured: differential cross sections in Q^2, $P_T(D)$, $\eta(D)$ and x; used to extract charm fragmentation ratios and fractions

Main theoretical systematics:

- PDF uncertainty
- Fragmentation models
- m_c

The overall agreement data-NLO calculations is good

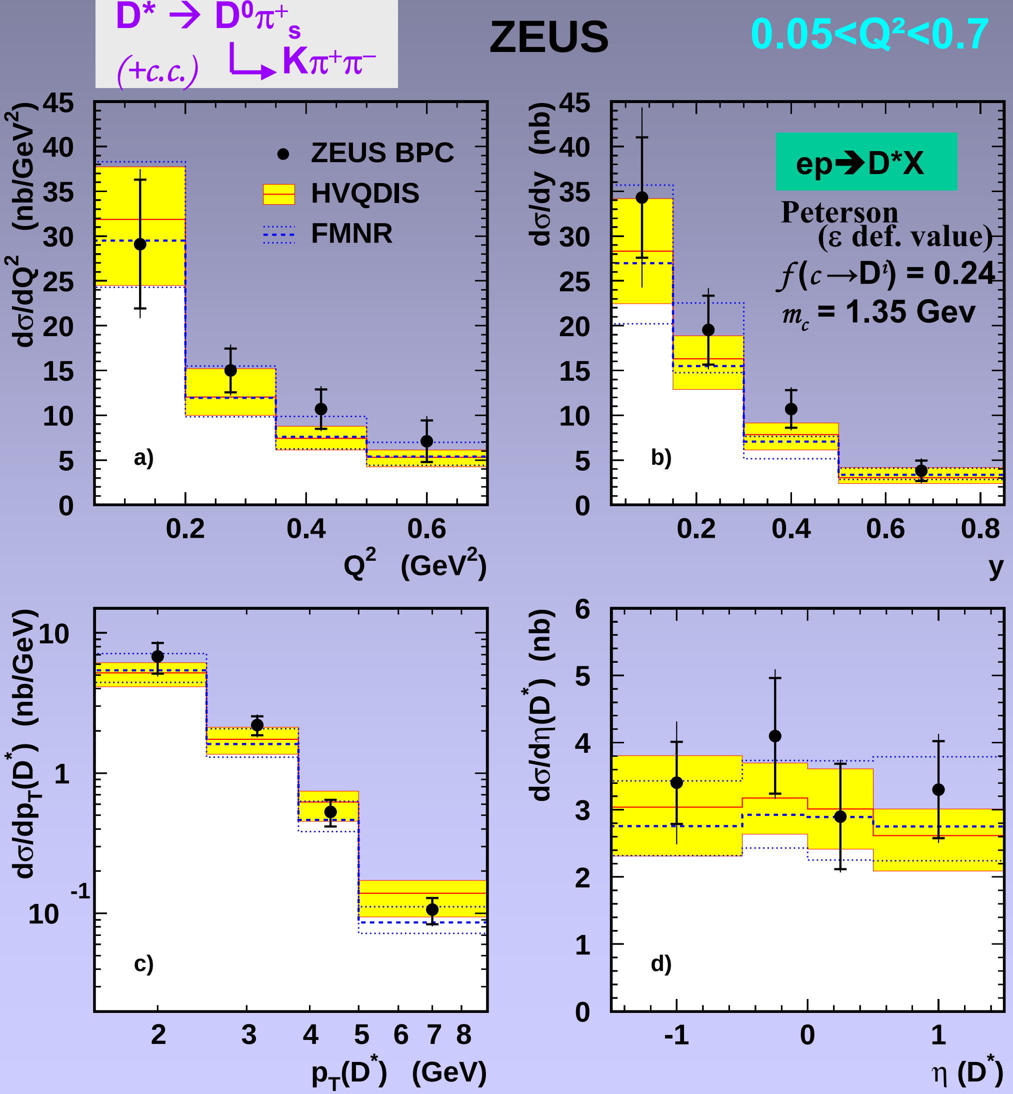
Cross sections can be used to extract F^{cc}_2
(see M. Turcato's talk)



$D^{*\pm}$ Mesons at low Q2

Using low-angle calorimeter, extend measurements to low Q^2

$D^* \to D^0 \pi^+_s$ (+c.c.) $\hookrightarrow K\pi^+\pi^-$



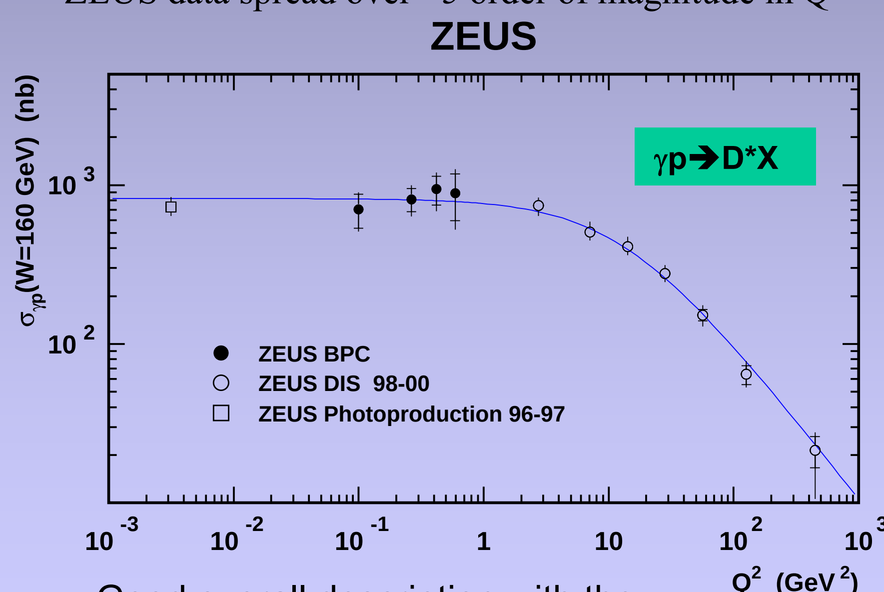
$\sigma(ep \to e\, D^* X)$ measurements compared with two different NLO QCD calculation:

- **FMNR** designed for PHP i.e. valid $Q^2 \sim 0$ $\quad \mu_R = \mu_F = \sqrt{\langle p_T \rangle^2 + 4m_c^2}$
- **HVQDIS** for DIS (no hadron-like structure for the γ) $\quad \mu_R = \mu_F = \sqrt{Q^2 + 4m_c^2}$

Agreement with both the predictions

Results combined with the previous DIS and photoproduction measurements

ZEUS data spread over ~5 order of magnitude in Q^2



Good overall description with the parameterisation: $\sigma(Q^2) = \sigma_{PHP} * M^2/(Q^2+M^2)$

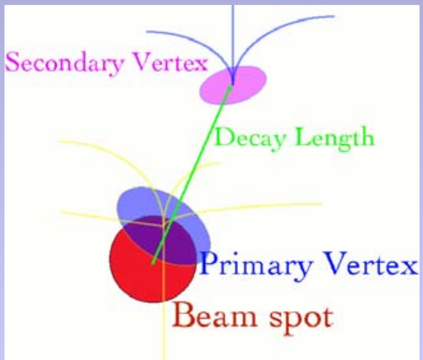
$\sigma^0_{PHP} = 823 \pm 63$ nb; $\quad M^2 = 13 \pm 2$ GeV^2 ($\cong 4m_c^2$)

Not only ‘old’ data: D^0, D^+ at HERA II

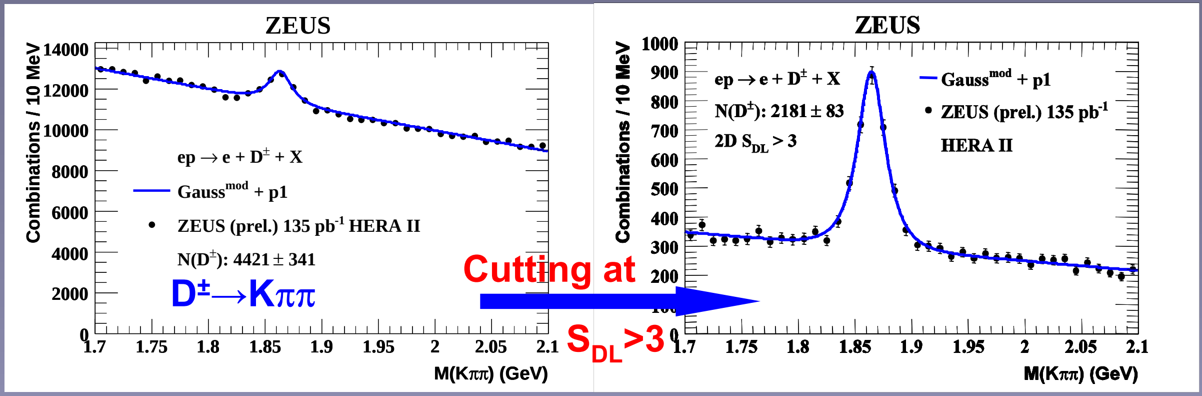
~135 pb^{-1}, 2005 data

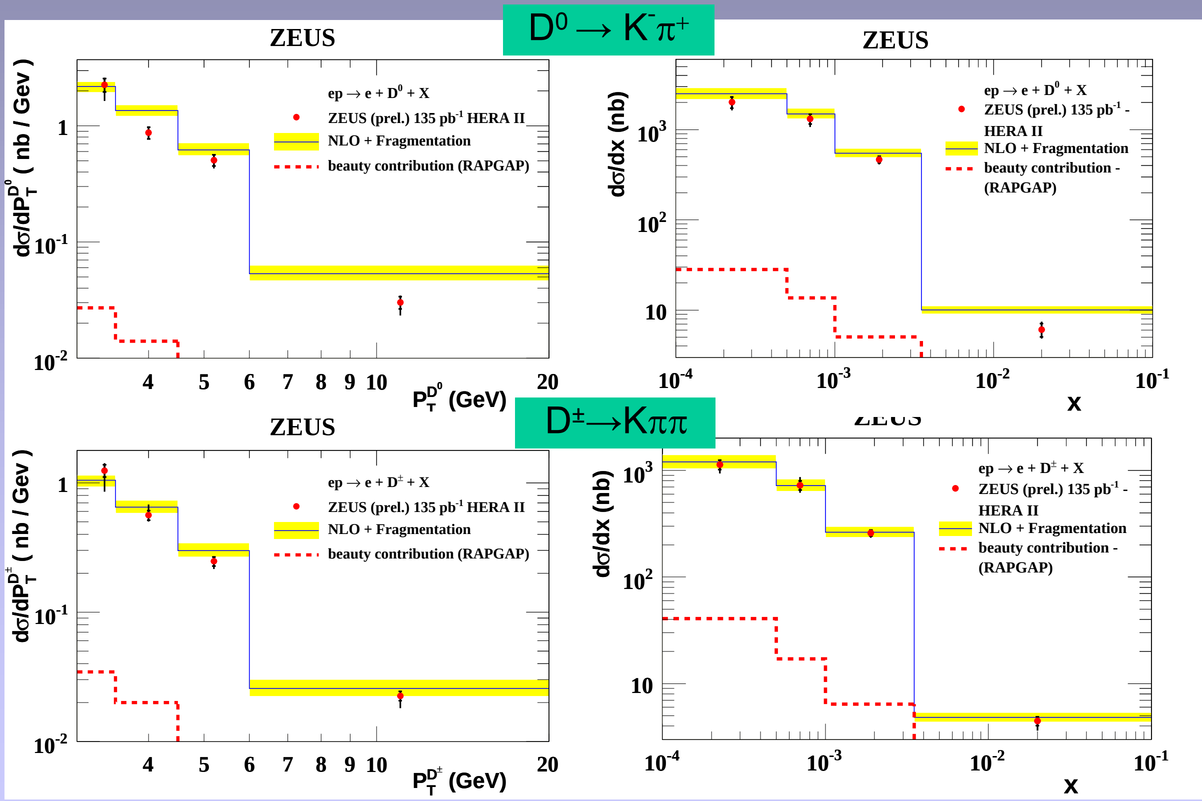
Major upgrade: inner Si tracking system → great improvement of the tracking performances, allowing:

- Analysis based mainly on the tacking techniques (Impact Parameter, Decay Length.)
- Signals with high purity (~90%)



Long lived D mesons have a displaced SV which can be reconstructed by the MVD.





Fair agreement with NLO; F_2^{cc} extraction

Charm fragmentation ratios and fractions

- The fragmentation functions parameterize the energy transfer from a quark to a given meson: $f(c \rightarrow D^i)$
- Some of them not yet measured in *ep* or *pp* collisions (e.g. for D* in PHP); usually fitted from e^+e^- data
- Source of large uncertainty in the σ_{prod} calculation
- Test different fragmentation and hadronisation models
- Ratios of the production rates for different D mesons → information on the quarks production
- Test for the universality of charm fragm. when compared to e^+e^- results

Analysed channels and contest:

•DIS (1.5 < Q^2 < 1000 GeV^2):

PS:
- $D^0 \rightarrow K^-\pi^+$
- $D^+ \rightarrow K^-\pi^+\pi^+$
- $D_s^+ \rightarrow \phi\pi^+ \rightarrow K^+K^-\pi^+$

+ c.c.

V: $D^{*+} \rightarrow D^0\pi^+ \rightarrow K^-\pi^+\pi_s^+$

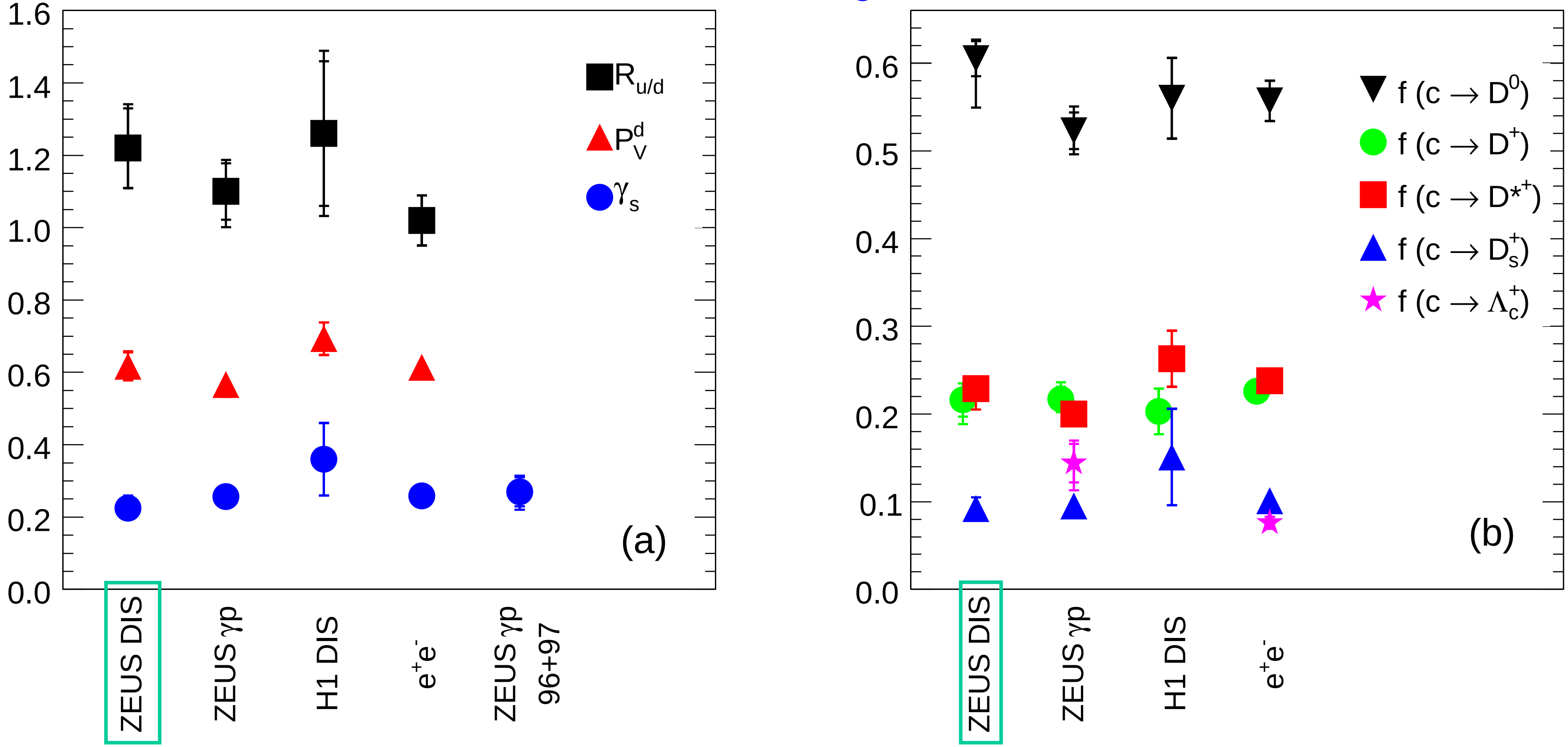
($\Lambda_c^+ \rightarrow K^- p\pi^+$ ~3σ, not used)

•Photoproduction:

$D^* \rightarrow D^0\pi$ + c.c.

$\hookrightarrow K\pi\pi$

From D^0, D^+ and D_s decays in DIS:



$R_{u/d}$: ratio for the neutral to charged D meson production rates

P_V^d: fraction of charged D meson produced in a vector state / total

γ_s: strangeness suppress. factor

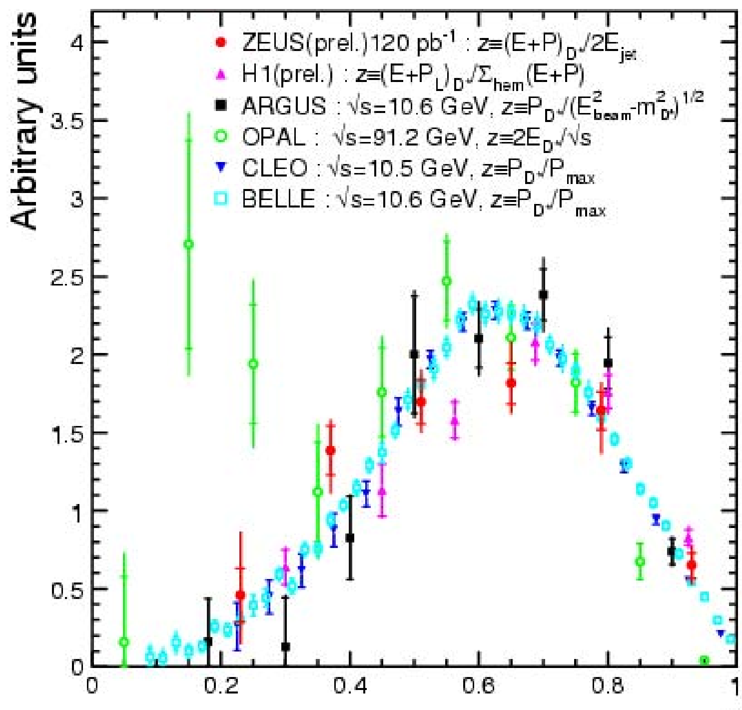
$$\gamma_s = \frac{2\sigma(D_s^+)}{\sigma^{eq}(D^+) + \sigma^{eq}(D^0)} \quad (\sim 20\%)$$

$$\sigma^{eq}(D^i) = direct + (D^{*+}, D^{*0})contr$$

$$f(c \to D^i) = \frac{\sigma^{eq}(D^i)}{\sigma^c_{gs}}$$

σ_{gs} = all charmed ground state decaying weakly (Ω,Ξ,Λ_c corrected)

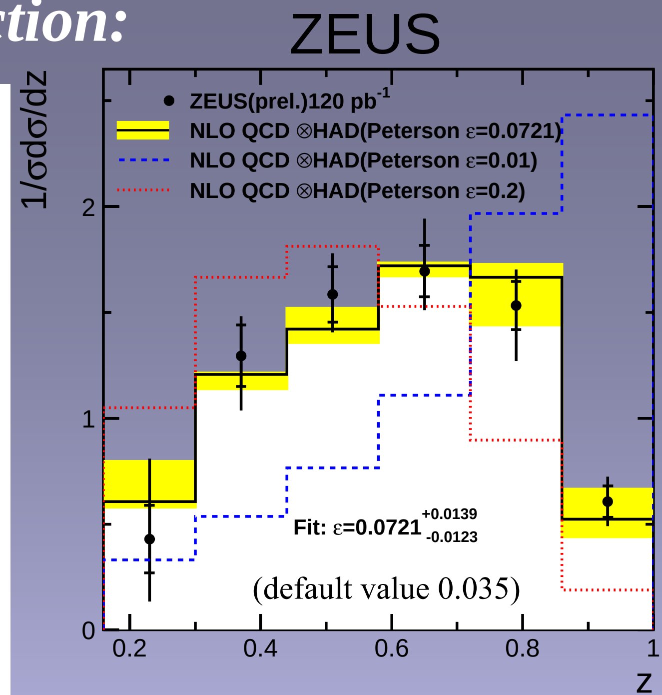
From D decays in photoproduction:*



OPAL's points z < 0.3 not taken into account for the normalisation (higher energy, more gluon splitting)

The fragmentation variable *z* computed as:

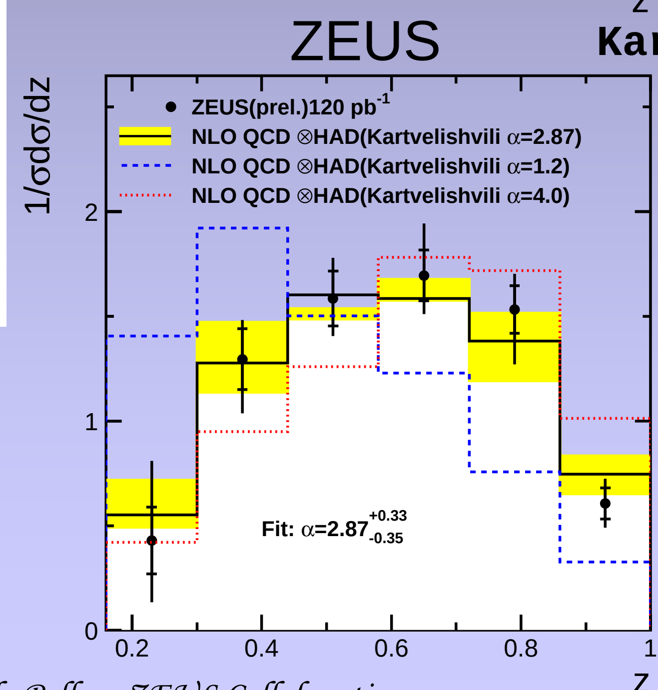
$$z = (E+p_{//})^{D^*} / (E+p_{//})^{jet}$$



PETERSON:

$$f(z) \propto \frac{1}{\left[z\left(1-\frac{1}{z}-\frac{\varepsilon}{(1-z)}\right)^2\right]}$$

Relative syst. uncertainties smaller for α, better description



Kartevelishvili:

$$f(z) \propto z^{\alpha}(1-z)$$

Hadronisation correction performed bin by bin with:

$$d\sigma_{|data} = d\sigma^{NLO} \cdot \frac{d\sigma_{MC}^{hadrons}}{d\sigma_{MC}^{partons}}$$

Excited charm and charm-strange mesons (PHP + DIS)

cq states:

S-waves(L=0) : D (spin 0), D*(spin 1) meson, well known

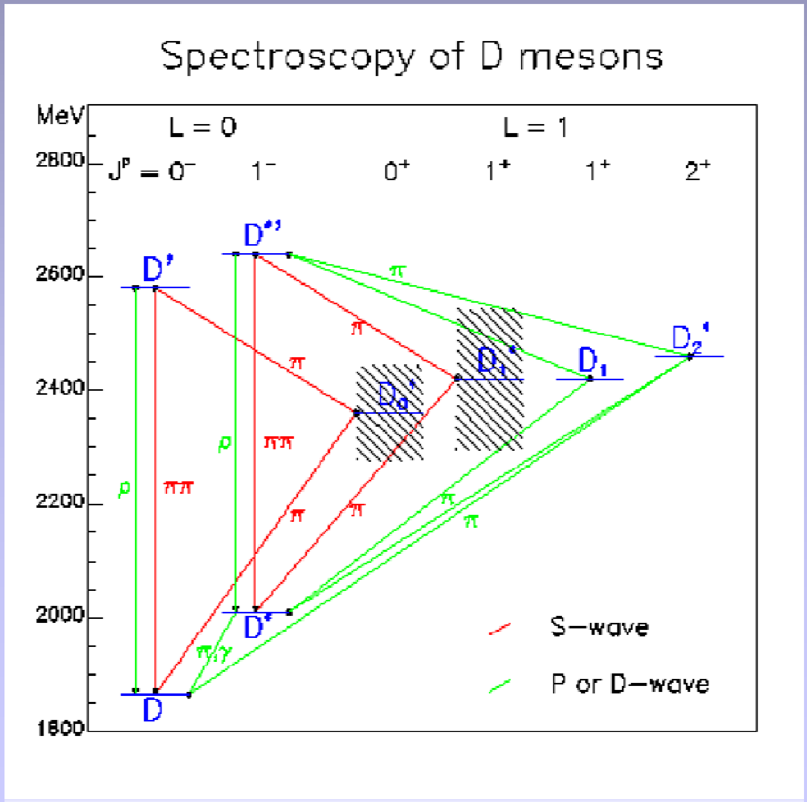
P-waves(L=1): 1 singl + 1 tripl. expected, decaying to S-waves + K or π

HQET ($m_Q \to \infty$) says:
P-waves properties
fixed by the lq spin *s*

j= L+*s* → the 4 states become 2+2 doublets:

j=3/2: only D-wave decays; narrow

j=1/2: S-wave decay; broad



Recently observed $D_1(2420)^0$, $D^*_2(2460)^0$

$D_{s1}^{\pm}(2536)$, $D_{s2}^{\pm}(2573)$ all narrow,

identified as the j=3/2 doublet members ($J^P = 1^+, 2^+$ respectively);

New *c*, *cs* broad mesons recently observed, as well as the radially excited $D^{*'\pm}$

Aim: to measure masses, widths, fragm. fractions, helicity dependence

(A) $D_1(2420)^0$, $D^*_2(2460)^0 \rightarrow D^{*+}\pi_a^-$

(B) $D^*_2(2460)^0 \rightarrow D^+\pi_a^-$ **+ c.c.**

(C) $D_{s1}^+(2536) \rightarrow D^{*+} K_s^0$ **(with SV)**

(C`) $D_{s1}^+(2536) \rightarrow D^{*0} K^+$

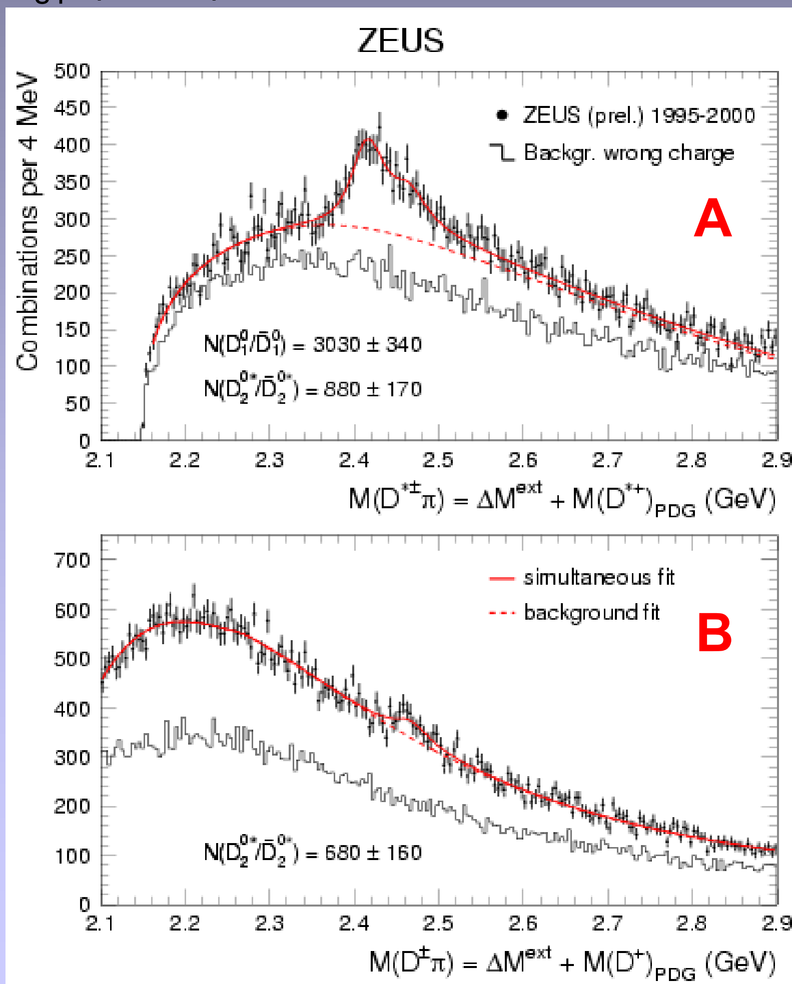
Orbital Excitation

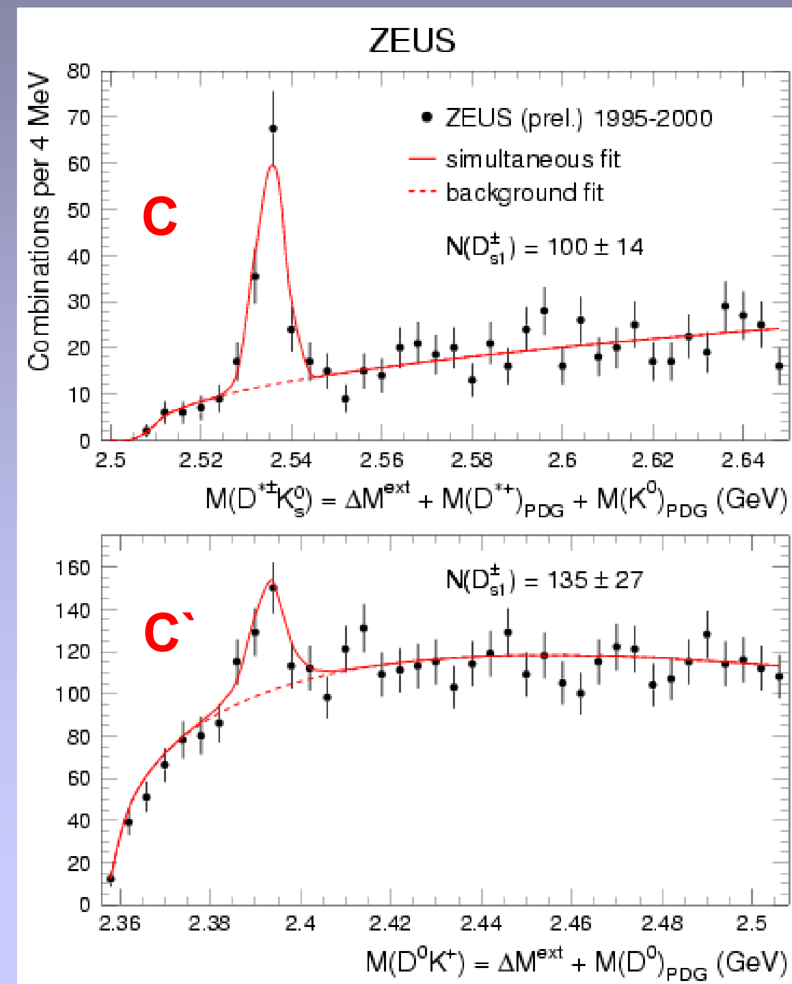
$D^{*+} \rightarrow D^0\pi_s^+ \rightarrow (K^-\pi^+)\pi_s^+$

$D^{*+} \rightarrow D^0\pi_s^+ \rightarrow (K^-\pi^+\pi^+\pi^-)\pi_s^+$

$D^0 \rightarrow K^-\pi^+$;

$D^+ \rightarrow K^-\pi^+\pi^+$ $K_s^0 \rightarrow \pi^+\pi^+$





$dN/d(\cos\alpha) \propto (1+R\cos^2\alpha)$; R=?

Our best fits:

$$R(D_1^0) = 6.1 \pm 2.3(\text{stat})^{+2.0}_{-0.8}(\text{syst})$$

$$R(D_{s1}^+) = -0.74^{+0.23}_{-0.17}(\text{stat})^{+0.06}_{-0.05}(\text{syst})$$

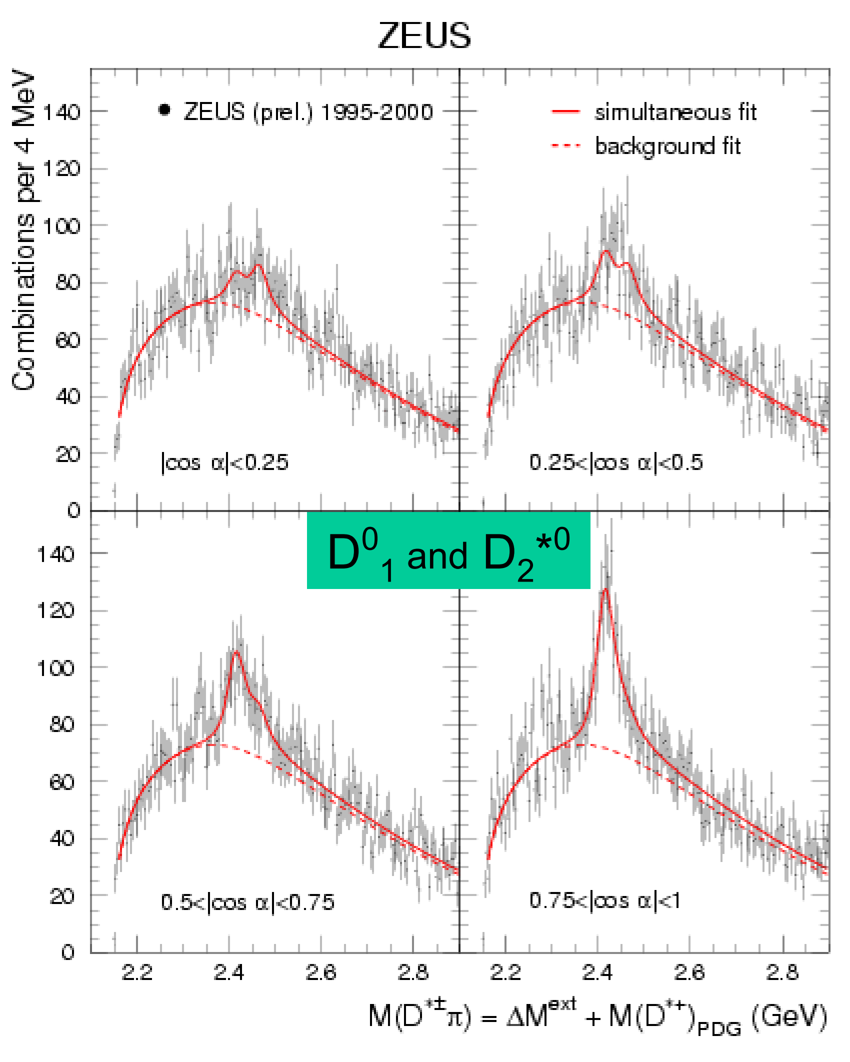
HQET: (valid for *cs* ?) $\alpha := \angle\{\pi_s, \pi_a\}|_{D^{*+}}$

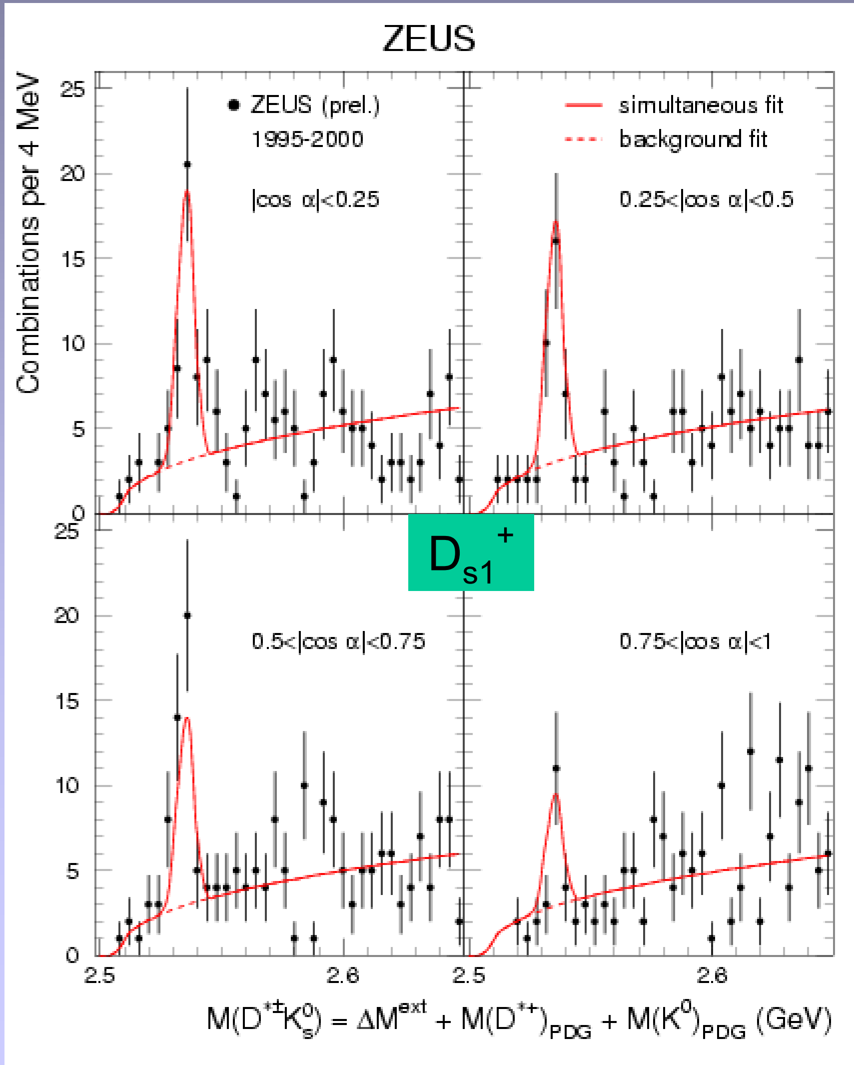
R=0 j=1/2, 1^+;

R=3 j=3/2, 1^+ (D_1^0);

R=-1 j=3/2, 2^+ (D_2^{*0}).

For D_{s1}^+ PDG06 says, 1^+ (R=0) to confirm;
CLEO: -0.23±35; BELLE prel.: -0.70±0.03





Fits results

D_1^0, $D^*{}_2^0$, D_{s1}^+ masses and yields, widths and D_1^0, D_{s1}^+ helicity as free parameters;

Masses values agree with the word average

$\Gamma(D_1^0)$ above

$R(D_{s1}^+)$ hardly consistent with R = 0, i.e. $J^P = 1^+$ does not contradict to R = -1, expected for 1^+, 2^+. Mixture of S and D waves for interference with D_{s1}^+2460 ?

Measured also the charm fragmentation fractions:

$f(c \to D_1^0)$, $f(c \to D^*{}_2^0)$, $f(c \to D_{s1}^+)$, and γ^{D1} (assuming isospin conservation)

Consistent with e^+e^- results

$$N(D_1^0 \to D^{*+}\pi^-) = 3030 \pm 340$$
$$N(D_2^{*0} \to D^{*+}\pi^-) = 880 \pm 170$$
$$N(D_2^{*0} \to D^{+}\pi^-) = 680 \pm 160$$

	PDG 06
$M(D_1^0) = 2419.8 \pm 2.0(\text{stat.})^{+0.8}_{-1.0}(\text{syst.})$	$2422.3 \pm 1.3\,\text{MeV}$
$M(D_2^{*0}) = 2468.4 \pm 3.6(\text{stat.})^{+1.1}_{-1.3}(\text{syst.})$	$2461.1 \pm 1.6\,\text{MeV}$
$\Gamma(D_1^0) = 51.6 \pm 7.0(\text{stat.})^{+1.9}_{-4.1}(\text{syst.})$	$20.4 \pm 1.7\,\text{MeV}$
$R(D_1^0) = 6.1 \pm 2.3(\text{stat.})^{+2.0}_{-0.8}(\text{syst.})$	HFTQ: +3
$M(D_{s1}^+) = 2535.30^{+0.44}_{-0.41}(\text{stat.})^{+0.09}_{-0.08}(\text{syst.})\,\text{MeV}$	$2535.35 \pm 0.34\,\text{MeV}$

Performed also a search for the radial excited $D^{*\prime+}(2640)$ meson (~5σ @DELPHI) decaying to $D^{*+}\pi^-\pi^+$;

<u>NO signal detected</u> → upper limit set on:

$f(c \to D^{*\prime+}) * Br(D^{*\prime+} \to D^{*+}\pi^-\pi^+) < 0.45\%$

(0.9% stronger than the OPAL one)

Conclusions

- Charm physics provides a lot of food for thought;
- ZEUS is extensively studying this sector: several results coming out
- Precision competitive with other experiments (and further enhancing with new tracking tools)
- Much more to come with the new data and full statistics analysis

BACKUP SLIDES

D mesons ($D^{\pm}$, D^0, $D^{*\pm}$, $D_s^{\pm}$) in DIS

1998-2000 data, ~82 pb^{-1}

PS

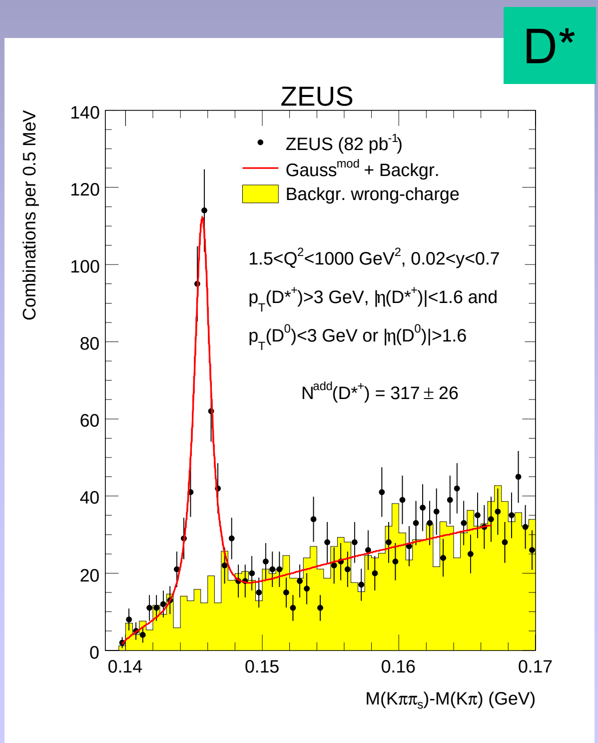
- $D^0 \to K^- \pi^+$
- $D^+ \to K^- \pi^+ \pi^+$ + c.c.
- $D_s^+ \to \phi \pi^+ \to K^+ K^- \pi^+$

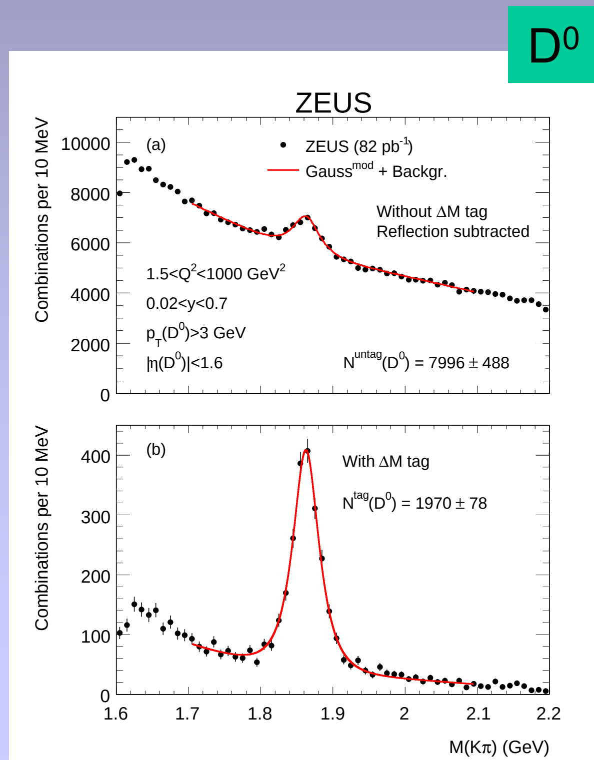
V

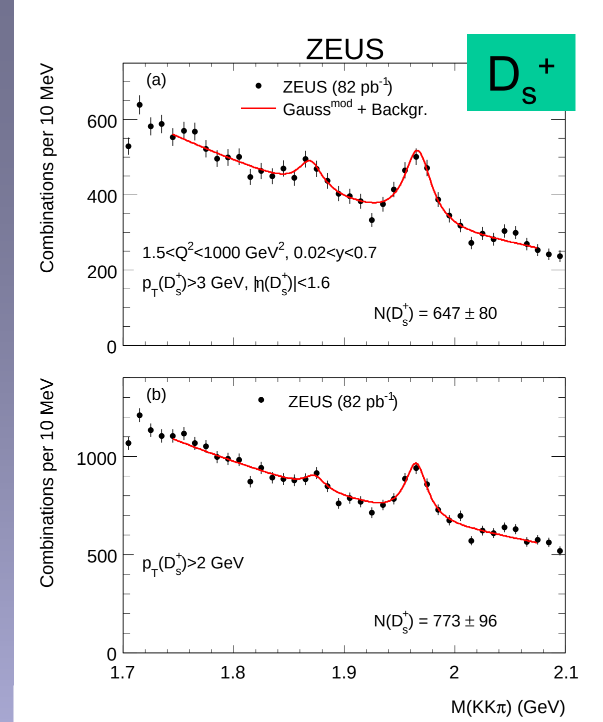
- $D^{*+} \to D^0 \pi^+ \to K^- \pi^+ \pi_s^+$

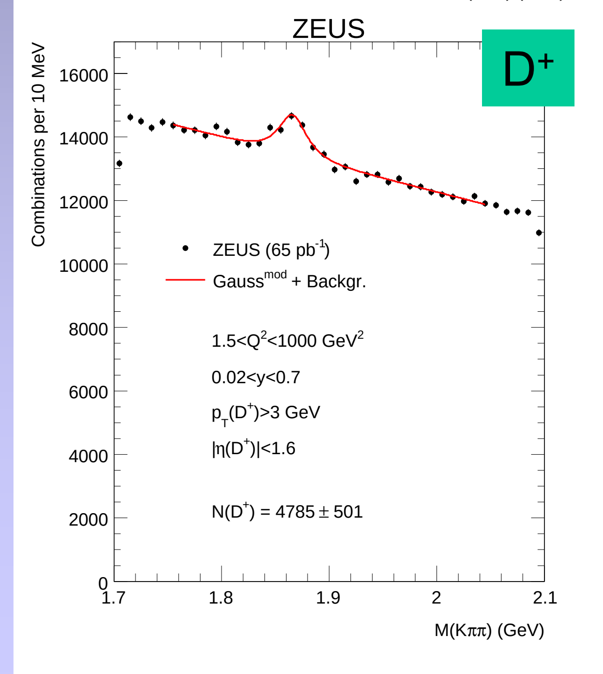
($\Lambda_c^+ \to K^- p \pi^+$ ~3σ, not used)

- $E(e^-) > 10$ GeV
- $1.5 < Q^2_{e\Sigma} < 1000$ GeV²
- $40 < \Sigma_{hadr}(E-p_z) < 65$ GeV
- $y_{JB} > 0.02$ & $y_{el} < 0.95$
- $|Z_{vertex}| < 50$ cm
- |boxcut_x| < 12 cm; |boxcut_y| < 7 cm

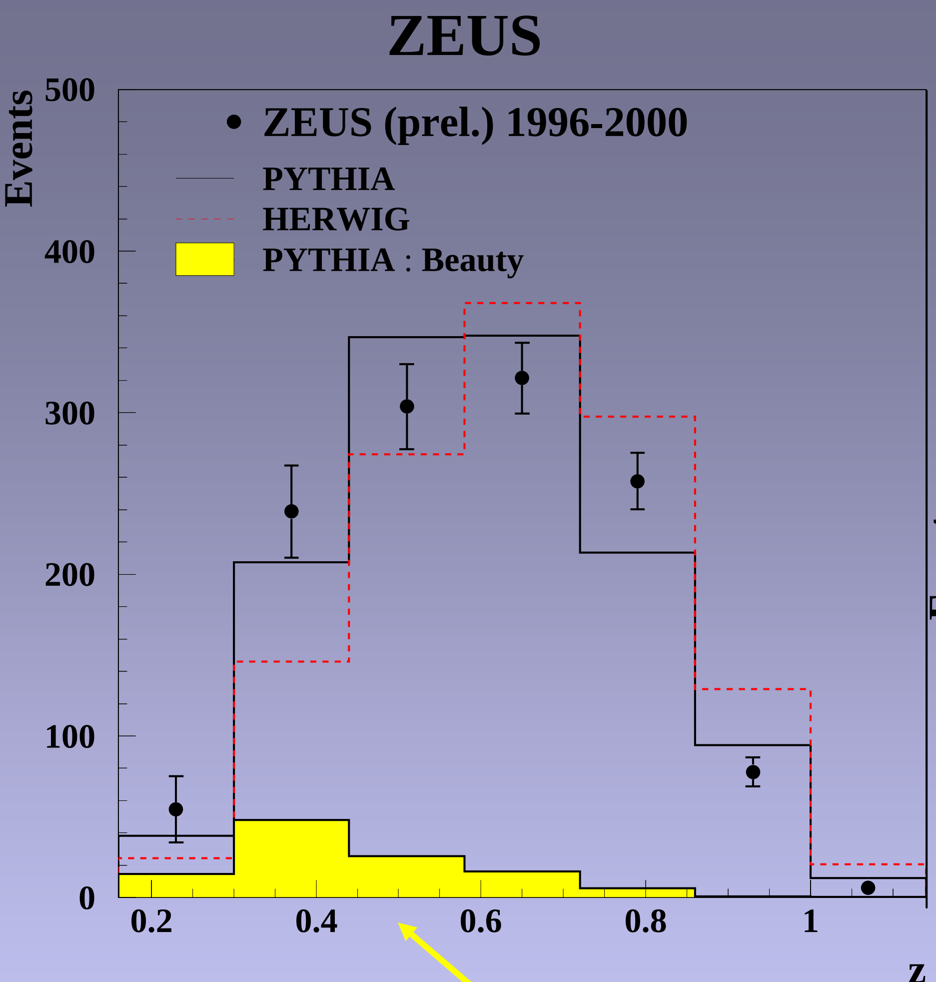


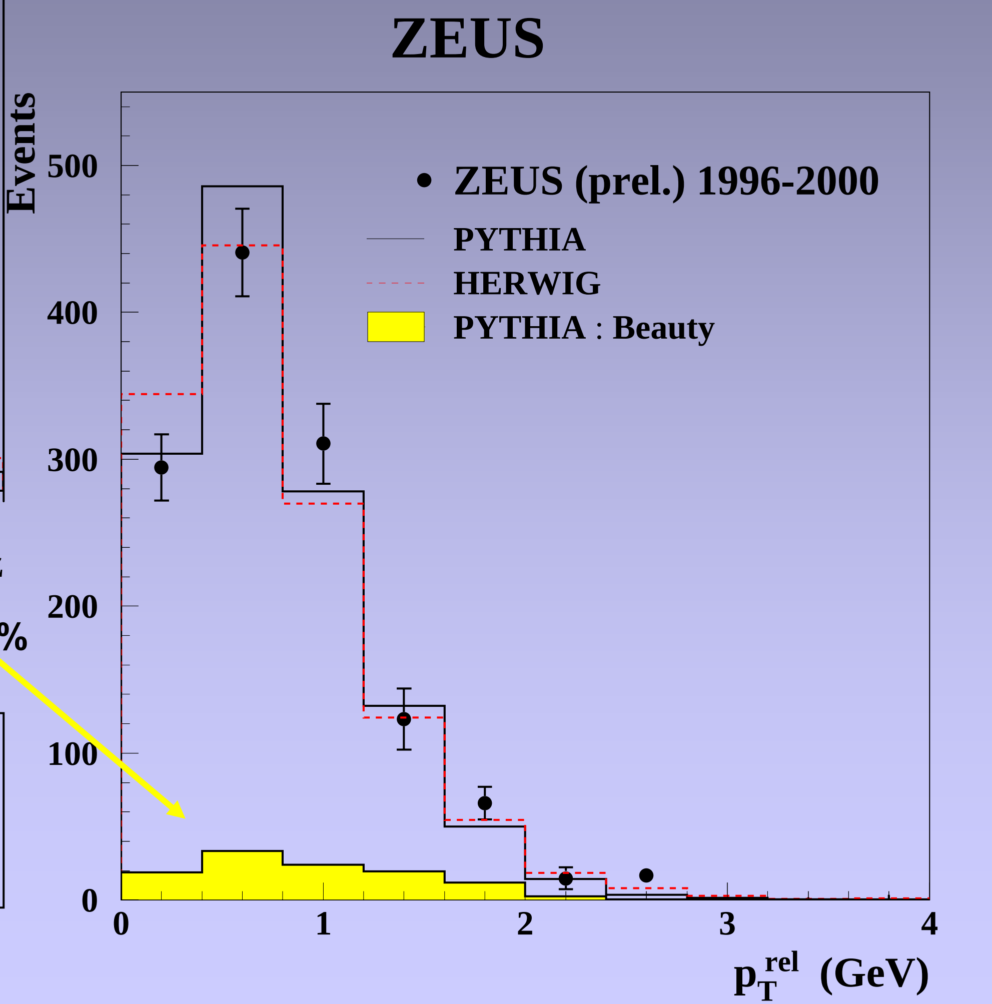






PYTHIA: Lund 'String' model
HERWIG: Cluster hadroniz.



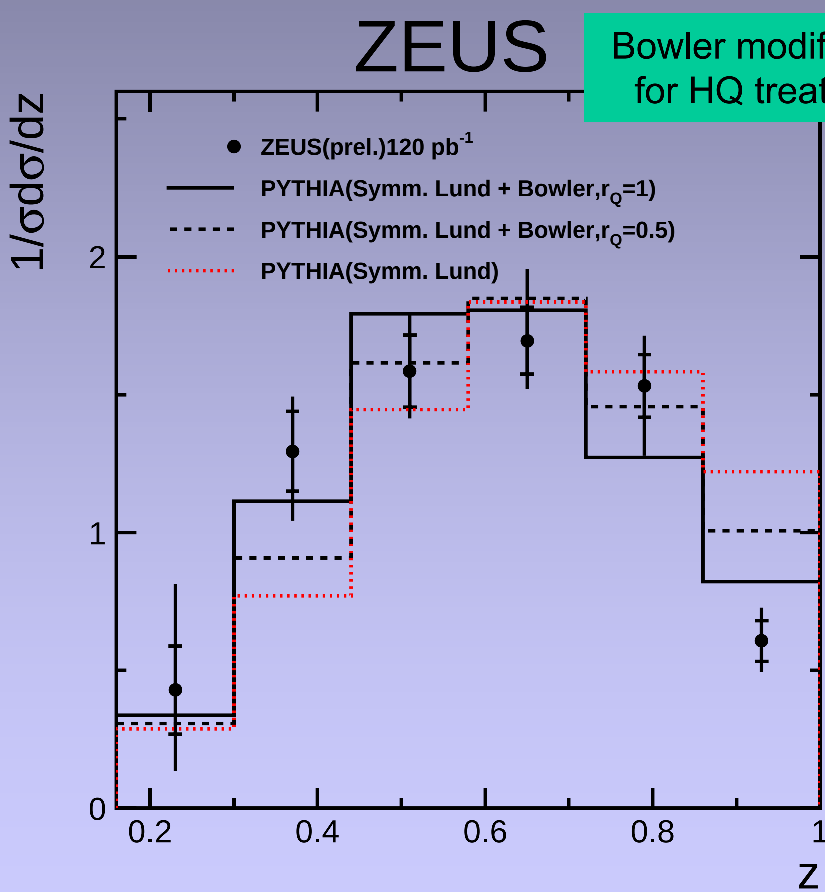


Beauty contamination ~9%

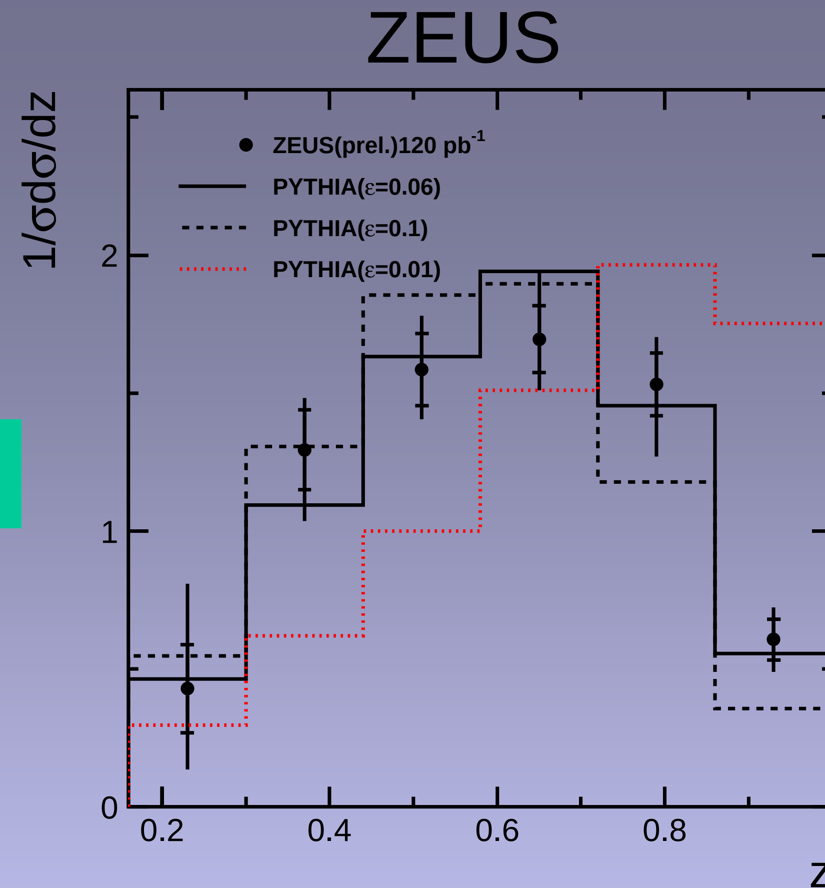
PYTHIA better agreement
→ taken for systematics and detector effic. corrections

(LUND)

$$f(z) \propto \frac{1}{z^{1+r_Q b m_Q^2}} (1-z)^a e^{(-\frac{b m_\perp^2}{z})}$$



Bowler modification for HQ treatment



$$f(z) \propto \frac{1}{[z(1-1/z-\varepsilon/(1-z))^2]}$$

(PETERSON)

Best value (χ^2min):
$\varepsilon = 0.0595 \pm 0.0078$
(default value 0.05)

Data corrected for reconstruction accept., efficiency, migrations

RAPGAP MC+ Heracles (1° ord. EW correction) LO ME +LL PS (Lund); CTEQ5L (p) and GRV-LO(γ) PDF

HVQDIS: NLO $c\bar{c}$ BGF + FFNS (lq, g evolving DGLAP, Zeus NLO fit to F_2 for p PDF)

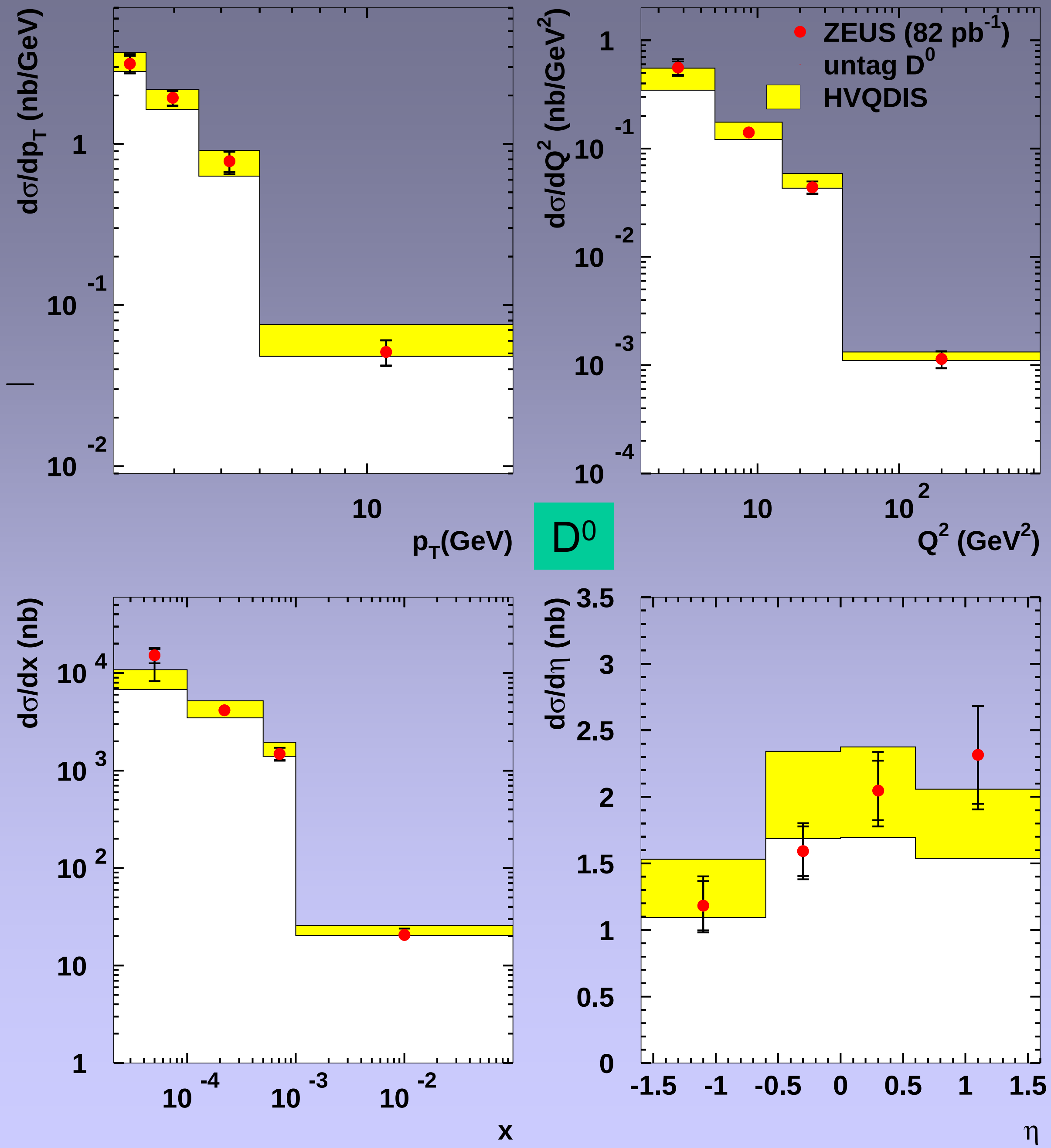
Lund string fragment.
(ε =0.035, def. value)

Fragm fractions: the measured ones

m_c = 1.35 GeV, Λ_{QCD} =363 MeV

$$\mu_R = \mu_F = \sqrt{Q^2 + 4m_c^2}$$

J/ψ negligible



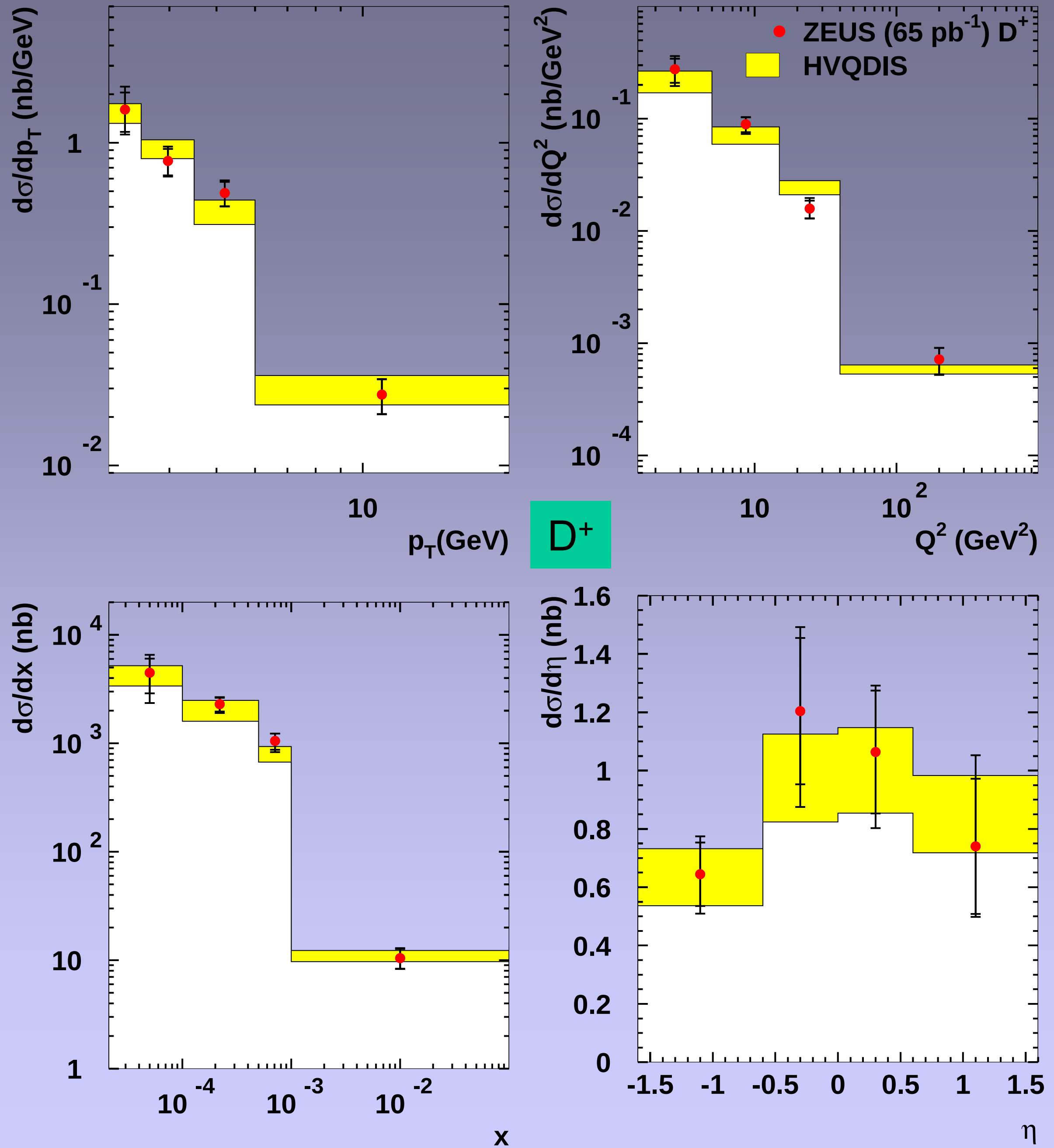
Main systematic uncertainties:

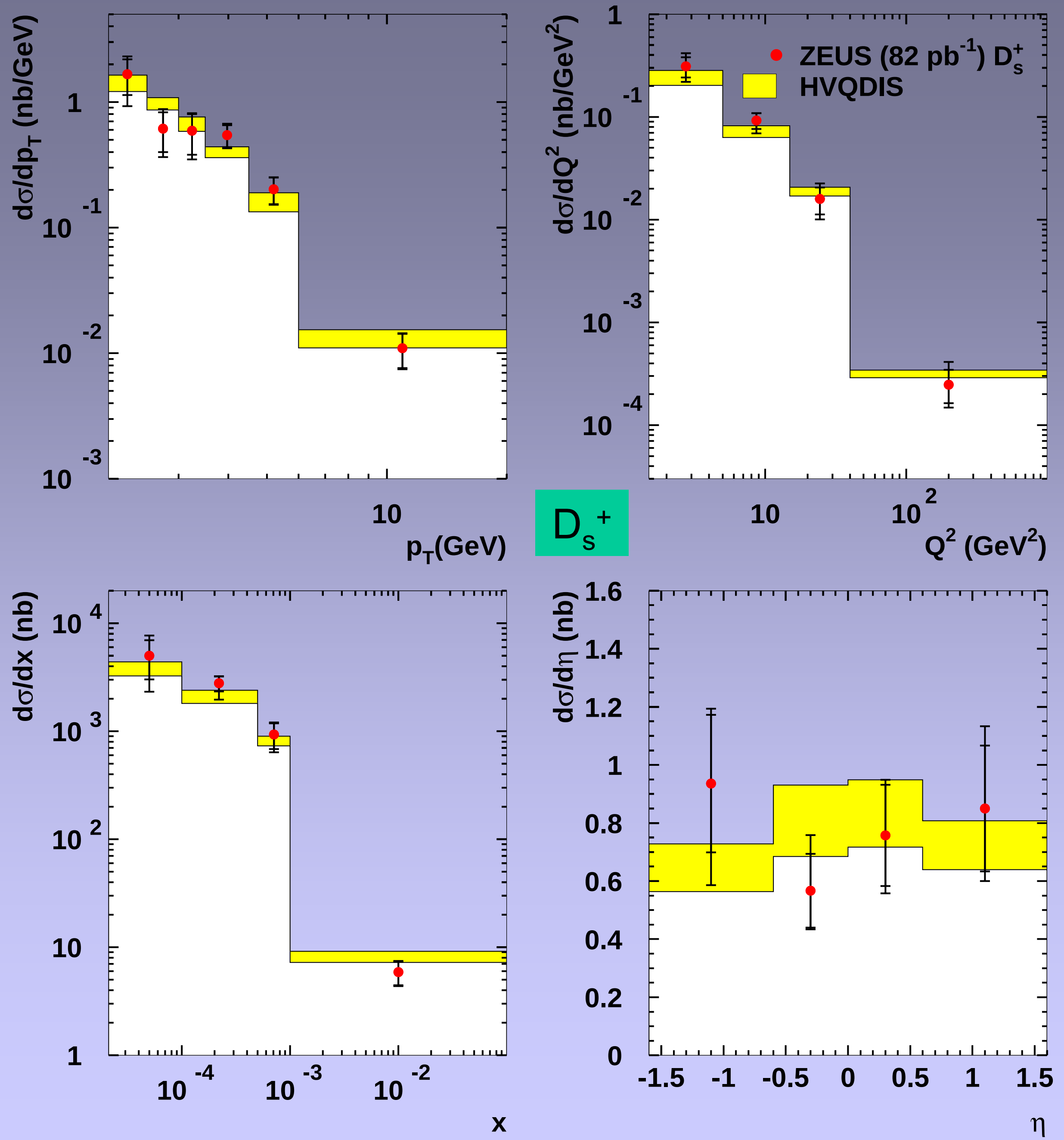
EXP.

- Beauty contribution subtraction
- signal extraction procedures
- $\sigma(\Lambda_c)$ estimation
- CAL energy scale
- Luminosity meas.

TH.

- Fragmentation models
- m_c
- PDF uncertainty





dσ/dp$_T$ (nb/GeV)
p$_T$(GeV)
dσ/dQ^2 (nb/GeV^2)
Q^2 (GeV^2)
ZEUS (82 pb^{-1}) D_s^+
HVQDIS
D_s^+
dσ/dx (nb)
x
dσ/dη (nb)
η

Signals extraction:

χ^2 fit in each helicity bin: D-wave BW ⊗ Gaussian resolution function (widh and acceptance corr. from MC) + Polynomial x exponential bkgr for D_1^0, $D^*_2{}^0$;

Added to the fit function: Feed-down from decays with undetected part (#ev from MC) and signals from $D_1(2430)^0$, $D^*_0(2400)^0$ states

for D_{s1}: unbinned Likelihood fit with gaussian funct. combining the two channels with K^0,K^+.

D_1^0, $D^*_2{}^0$,D_{s1}^+ masses and yields, widths and D_1^0, D_{s1}^+ helicity as free parameters;

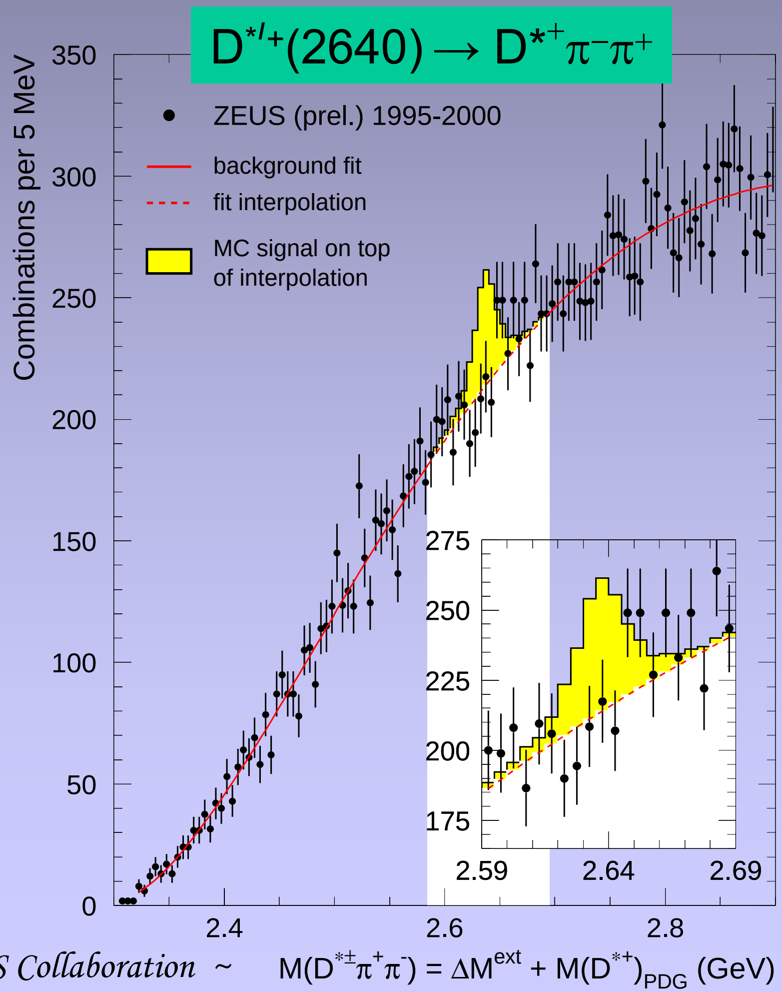
The mass values agree with the word average, Γ (D_1^0) above (51.6 ± 7.0 VS 20.4 ±1.7)…

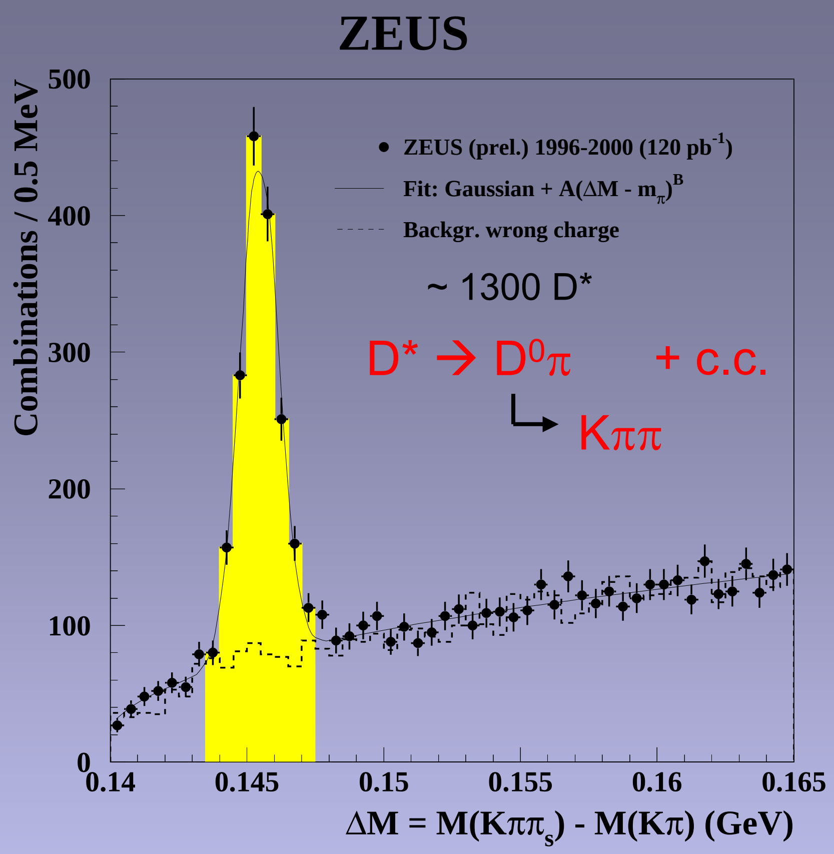
$f\,(c \rightarrow D_1^0)$,$f\,(c \rightarrow D^*_2{}^0)$, $f\,(c \rightarrow D_{s1}^+)$, γ^{D1} also measured (assuming isospin conservation); consistent with e^+e^- results

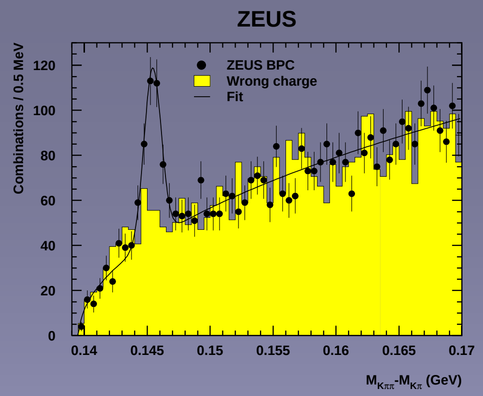
Performed also a search for the radial excited $D^{*\prime+}(2640)$ meson [DELPHI] decaying to $D^{*+}\pi^-\pi^+$;

<u>no signal detected</u> → upper limit set on:

$f\,(c \rightarrow D^{*\prime+})$ * Br ($D^{*\prime+} \rightarrow D^{*+}\pi^-\pi^+$) < 0.45%
(0.9% stronger than the OPAL one)







$$\sigma(ep) = \int_{\Delta y} \phi_\gamma(y)\, \sigma_{\gamma p}(sy)\, dy$$

EXP.

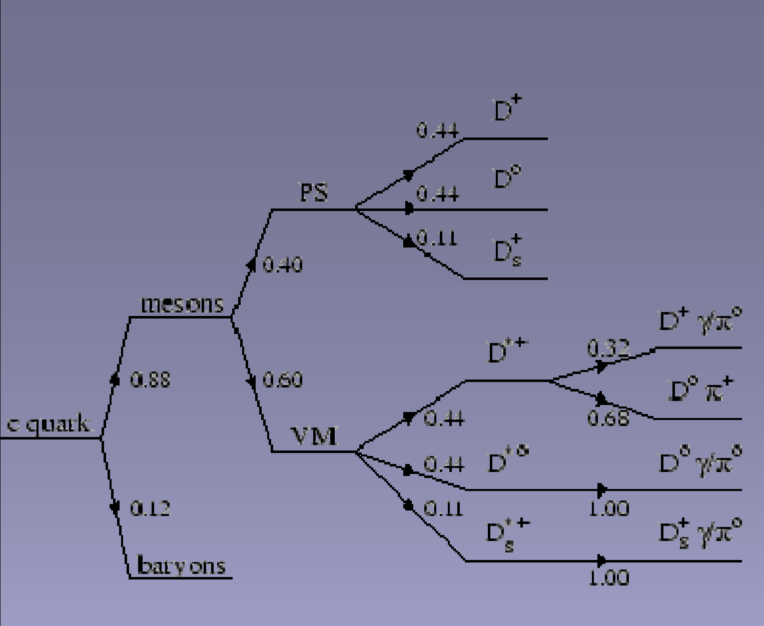
- Beauty contribution subtraction
- signal extraction procedures
- $\sigma(\Lambda_c)$ estimation
- CAL energy scale
- Luminosity meas.

RAPGAP MC+ Heracles (1° ord. EW correction) LO ME +LL PS (Lund); CTEQ5L (p) and GRV-LO(γ) PDF

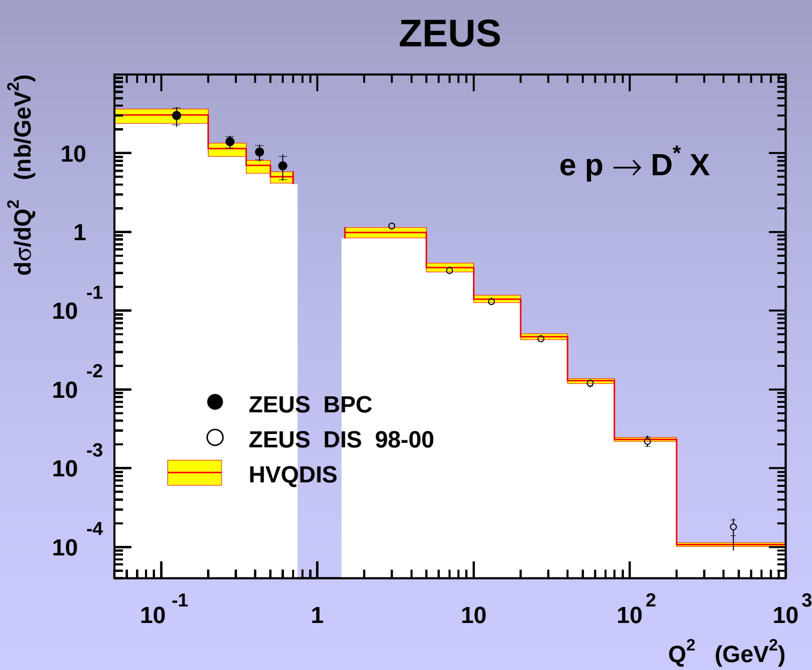
$P_V^d = 0.617 \pm 0.038\,(stat)^{+0.017}_{-0.009}\,(syst) \pm 0.017\,(Br)$

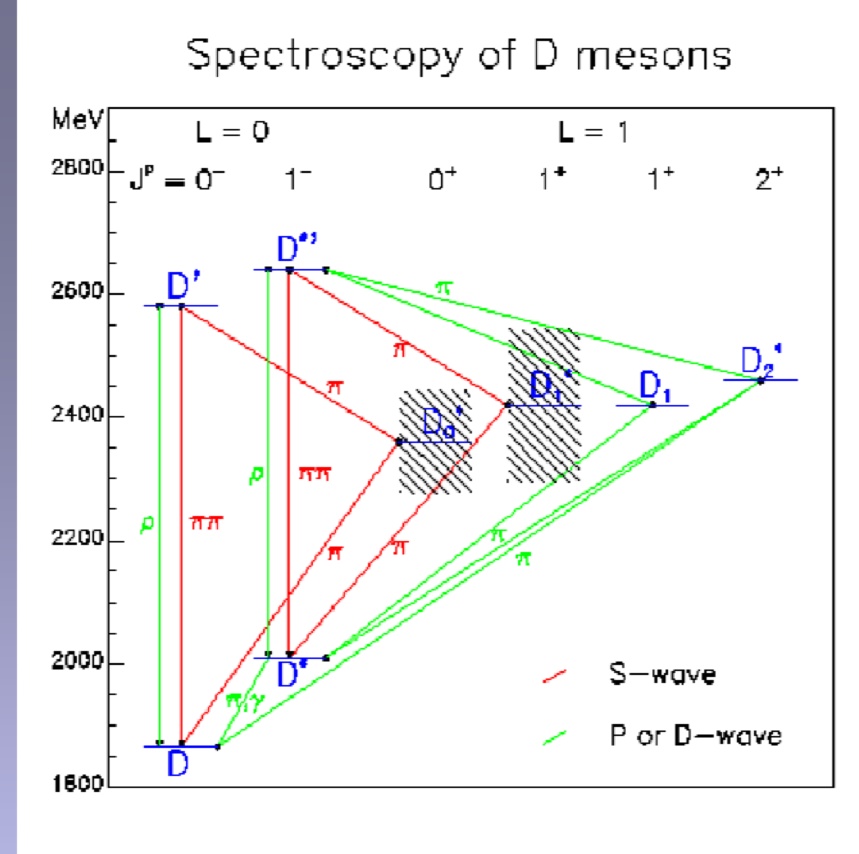
(Naïve spin-counting: 0.75)

$R_{u/d} = 1.22 \pm 0.11\,(stat)^{+0.05}_{-0.03}\,(syst) \pm 0.03\,(Br)$



D+	D0	Ds+
0.156		
	0.156	
		0.040
0.076		
	0.159	
	0.234	
		0.061
0.232	0.549	0.101





ep→D*X

$$Br(D^{*0}_{2} \rightarrow D^{+}\pi^{-})\ Br(D^{*0}_{2} \rightarrow D^{*+}\pi^{-})$$

To distinguish $D^*_1(2420)^0$ and $D^*_2(2460)^0$ from each other and from the wide state $D_1(2430)^0$ and to extract the D_{s1}^+ properties→ helicity angular distributions

$$R_{u/d} = \frac{\sigma^{untag}(D^0)}{\sigma(D^+) + \sigma^{tag}(D^0)}$$