Heavy quark production and spectroscopy at HERA

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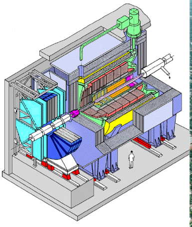
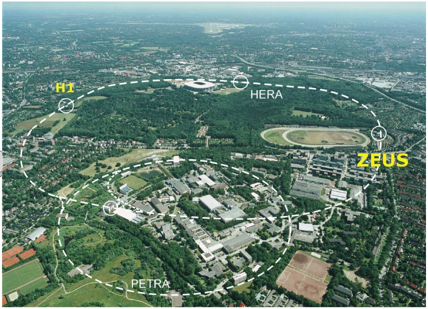
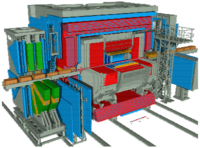
- Introduction
- Heavy quark production
- Spectroscopy

H1 and ZEUS

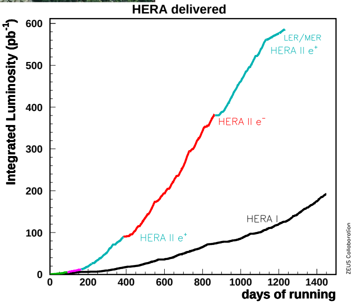






- 27.5 GeV $e^{\pm}$
  920 GeV $p \rightarrow \sqrt{s} = 318$ GeV
- HERAI: 1992-2000
- HERAII: 2003-2007

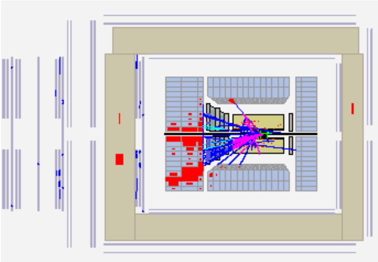
$\rightarrow \sim$ 0.5 fb^{-1} per experiment



Motivation

Heavy flavour production as a good probe of different production and decay mechanisms:

- Open production (pQCD)
- Resonance production (NRQCD)
- Searches for exotic bound states



$\sigma_{uds} : \sigma_c : \sigma_b \sim 2000 : 200 : 1$

Kinematical regions:

Photoproduction (γp) $\rightarrow Q^2 \lesssim 1 GeV^2$

Electroproduction (DIS) $\rightarrow Q^2 \gtrsim 1 GeV^2$

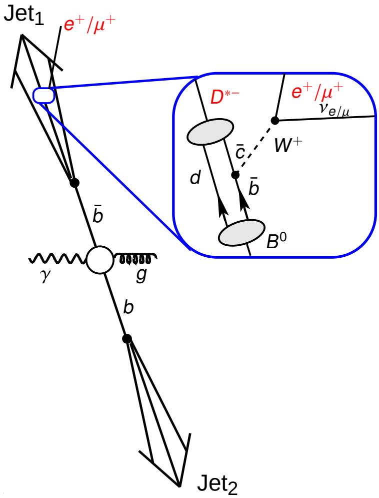
Part I

Heavy quark production

Heavy flavour tagging

Different experimental techniques used (combined) for heavy flavour tagging:

- Meson identification
  $D^{*\pm}$ tagging ("Golden Decay")
- Decay spectra
  p_T^{rel} of lepton to jet axis
- Lifetime information
  Measure impact parameter with respect to primary vertex (beamspot)



HERAI data:

1996-2000 ($\mathcal{L} \approx 120\,\mathrm{pb}^{-1}$)

Kinematic region:

$Q^2 < 1\,\mathrm{GeV}^2$, $0.2 < y < 0.8$,

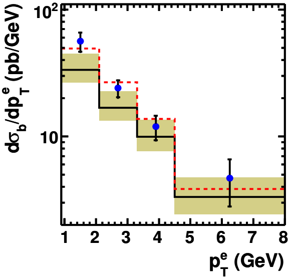
$E_T^{jets} > 7(6)\,GeV$, $|\eta^{jets}| < 2.5$

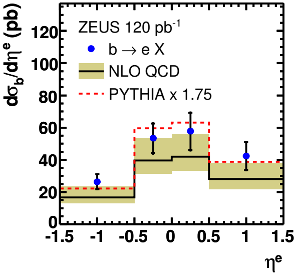
$p_T^e > 0.9\,\mathrm{GeV}$, $-1.5 < \eta^e < 1.5$

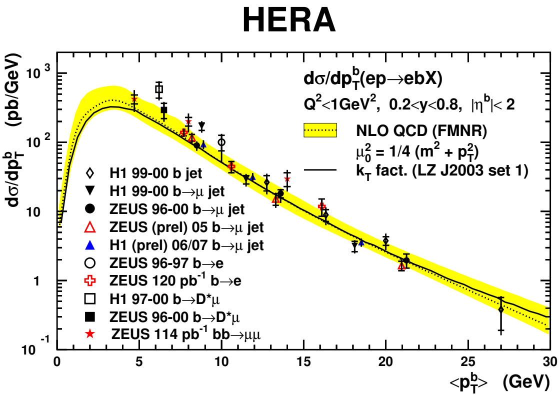
Method:

p_T^{rel} and $\Delta\phi(\not{p},e)$ combined with particle ID

- PYTHIA prediction scaled by a factor of **1.75**
- NLO QCD prediction (FMNR) describes data
- Measured points at upper edge of NLO prediction





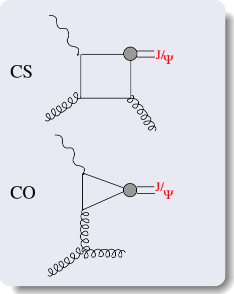


Several measurements with different methods and systematics confirming each other and covering different p_T^b-ranges:
General good agreement observed!

Charmonium production:

1. heavy quark pair ($c\bar{c}$) produced at short distances
2. formation of Ψ bound state in
   - colour singlet (CS)
   - colour octet (CO)

   in non-relativistic QCD model (NRQCD)
   both CS and CO exists
   →transition to real J/Ψ by non-perturbative long distance matrix elements (LDME)



Sensitivity to production mechanism:

different regions of inelasticity $z \sim \frac{E_{J/\Psi}}{E_\gamma}$

- CS in medium $z-$ region
- CO (and diffraction) populate high $z-$values
- "resolved" processes lead to lower $z-$values

HERAII data:

electroproduction (DIS)

2004-2006 ($\mathcal{L} \approx 258\,\text{pb}^{-1}$)

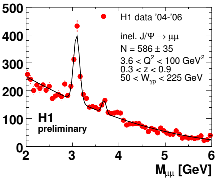
Kinematic region:

$3.6 < Q^2 < 100\,\text{GeV}^2$,

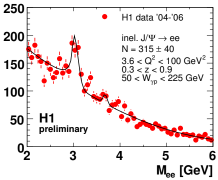
$50 < W_{\gamma p} < 225\,\text{GeV}$,

$0.3 < z < 0.9$, $p^*_{t,\Psi} > 1\,\text{GeV}$

$J/\Psi \to \mu^+\mu^-$



$J/\Psi \to e^+e^-$



photoproduction (γp)

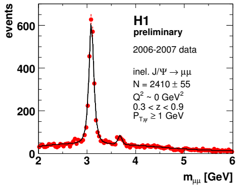
2006-2007 ($\mathcal{L} \approx 166\,\text{pb}^{-1}$)

$Q^2 \sim 0\,\text{GeV}^2$,

$60 < W_{\gamma p} < 240\,\text{GeV}$,

$0.3 < z < 0.9$, $p^*_{t,\Psi} > 1\,\text{GeV}$

$J/\Psi \to \mu^+\mu^-$



Cross-sections measured as a function of Q^2, z, $W_{\gamma p}$, p_T^2

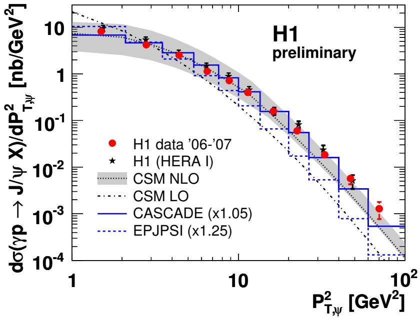
Double differential cross-sections in z, p_T and p_T^2, z

CASCADE:
data well reproduced

EPJPSI MC:
too steep

CS LO:
too steep

CS NLO:
data well described
(large normalisation uncertainties)



→ No direct indication for contribution of colour octet

J/ψ helicity in photoproduction

HERAI+II data:

1996-2007 ($\mathcal{L} \approx 470\,\mathrm{pb}^{-1}$)

Helicity measurement:

$$\frac{1}{\sigma}\frac{d^2\sigma}{d\cos\Theta dz} \propto 1 + \lambda(z)\cos^2\Theta$$

$$\frac{1}{\sigma}\frac{d^2\sigma}{d\phi dz} \propto 1 + \frac{\lambda(z)}{3} + \frac{\nu(z)}{3}\cos^2\phi$$

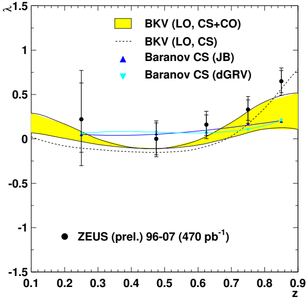
Theory predictions:

CS at LO, CS+CO at LO, (BKV)

CS in the k_t framework (Baranov)

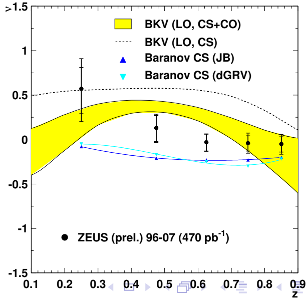
- λ: good agreement with predictions; not possible to distinguish between different models
- ν: wide variation between different model predictions; still large uncertainties (→ NLO)

λ



z

ν



z

Part II

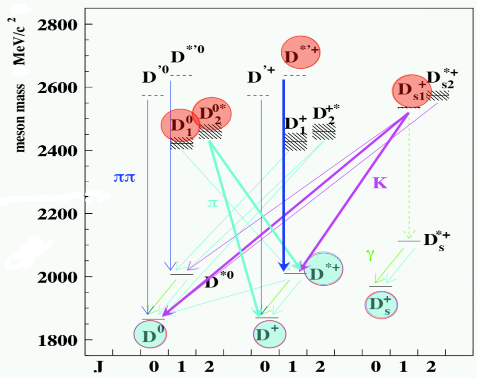
Spectroscopy

HERAI data:

1995-2000 ($\mathcal{L} \approx 127\,\mathrm{pb}^{-1}$)

Decay channels:

$$
\begin{aligned}
D_1(2420)^0 &\rightarrow D^{*\pm}\pi^{\mp} \\
D_2^*(2460)^0 &\rightarrow D^{*\pm}\pi^{\mp} \\
&\rightarrow D^{\pm}\pi^{\mp} \\
D_{S1}(2536)^0 &\rightarrow D^{*+}K_s^0 \\
&\rightarrow D^{*0}K_s^{+}
\end{aligned}
$$



$(D^{*'}(2640)^{\pm} D^{*\pm}\pi^{\pm}\pi^{\mp})$?:

No production observed!

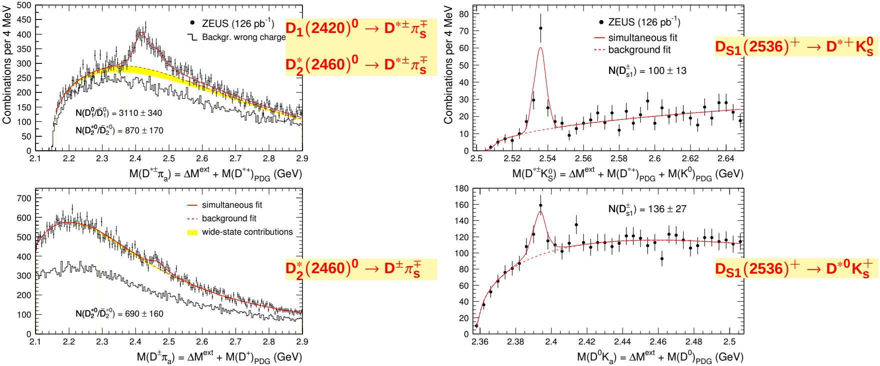
$f(c \rightarrow D^{*'+}) \cdot \mathcal{B}_{D^{*'+} \rightarrow D^{*+}\pi^{+}\pi^{-}} < 0.4\%$

(at 95% C.L.)

OPAL result: $< \mathbf{0.9}\%$

Excited charm and charm-strange mesons

ZEUS



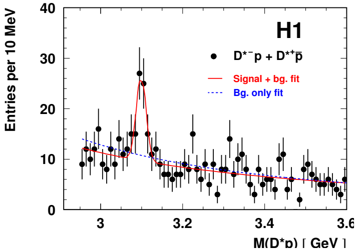
Selected results:

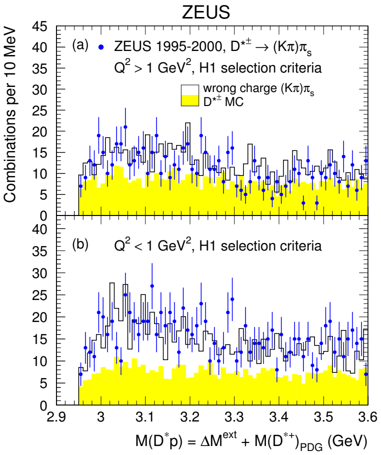
$$\Gamma(D_1^0) = 53.2 \pm 7.2(stat.)^{+3.3}_{-4.9}(syst.)\ \text{MeV}$$ World av.: 20.4 ± 1.7 MeV

$$h(D_1^0) = 5.9^{+3.0}_{-1.7}(stat.)^{+2.4}_{-1.0}(syst.)$$ HQET: $h = 3$ (D-wave)

$$h(D_{s1}^+) = -0.74^{+0.23}_{-0.17}(stat.)^{+0.06}_{-0.05}(syst.)$$ $h = 0$ (S-wave)

HERAI data: $(\mathcal{L} \approx 75\,\text{pb}^{-1})$:





Narrow resonance observed at:

$M(D^*p) = 3099 \pm 3(stat.) \pm 5(syst.)$ MeV

→ anti-charm baryon with

minimum quark content $uudd\bar{c}$

$\frac{N(D^*p)}{N(D^*)} \sim 1\%$

No evidence in other experiments:

BaBar, CDF, ZEUS, ALEPH, FOCUS

D^*p resonance

H1

HERAII data:

2004-2007 ($\mathcal{L} \approx 348\,\mathrm{pb}^{-1}$)

Kinematic region:

$2 < Q^2 < 100\,\mathrm{GeV}^2$

$0.05 < y < 0.7$

Visible range:

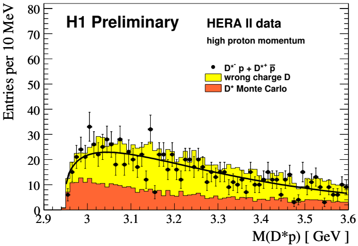
$p_T(D^*) > 1.5\,\mathrm{GeV}$

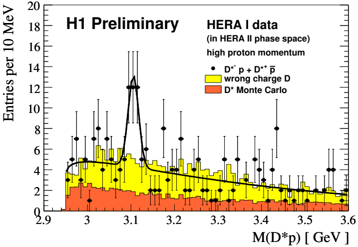
$-1.5 < \eta(D^*) < 1$

$\mathbf{p}(\mathbf{p}) > \mathbf{2}\,\mathrm{GeV}$

Result:

- **no excess in HERAII data;** upper limit of $\frac{N(D^*p)}{N(D^*)} \sim 0.1\%$ (95 % C.L.)
- signal still there in HERAI data (with reduced phase space)





Summary

- Beauty production in photoproduction from different channels consistent with NLO prediction
- New measurement of inelastic $\mathbf{J/\Psi}$ production in γp
  Colour-Singlet model provides good description of data
- J/Ψ helicity measurement compared with different theoretical predictions

- Significant production of excited charm and charm-strange mesons observed
  -Detailed studies of $\mathbf{m}(\mathbf{D})$, $\mathbf{\Gamma}(\mathbf{D})$, $\mathbf{h}(\mathbf{D})$ and $\mathcal{B}(\mathbf{D})$
- No signal observed in the most recent $\mathbf{D}^{*}\mathbf{p}$ resonance search

References

Beauty photoproduction using decays into electrons at HERA
DESY-08-056 (May 2008)

Inelastic Electro-Production of J/Psi Mesons at HERA
H1prelim-07-071

Inelastic Photo-Production of J/Psi Mesons at HERA
H1prelim-07-172

Measurement of J/psi helicity distributions in inelastic photoproduction at HERA
ZEUS-prel-07-036

Measurement of excited charm and charm-strange mesons production at HERA
DESY-08-093 (July 2008)

Evidence for a Narrow Anti-Charmed Baryon State
DESY-04-038

Search for a narrow charmed baryonic state decaying to $D^{*\pm}p^{\pm}$ in ep collisions at HERA
DESY-04-164 (September 2004)

Search for a D*p resonance at HERA II
H1prelim-08-075

HERAI data:

1996-2000 ($\mathcal{L} \approx 120\,\text{pb}^{-1}$)

Kinematic region:

$Q^2 < 1\,\text{GeV}^2$, $0.2 < y < 0.8$,

$E_T^{jets} > 7(6) GeV$, $|\eta^{jets}| < 2.5$

$p_T^e > 0.9\,\text{GeV}$, $-1.5 < \eta^e < 1.5$

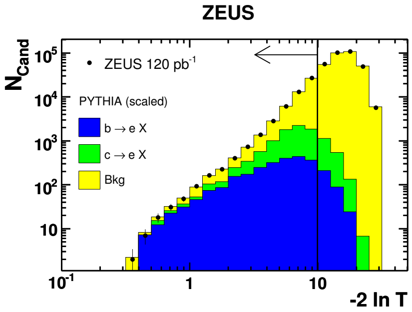
Method:

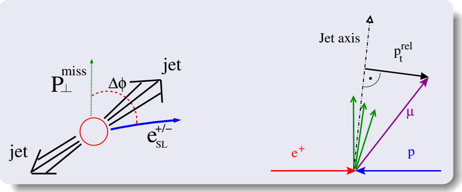
Combine discriminating input variables in a likelihood function to a hypothesis test

$$T_{B\to eX} = \frac{\mathcal{L}_{B\to eX}}{\sum_j \mathcal{L}_j}$$

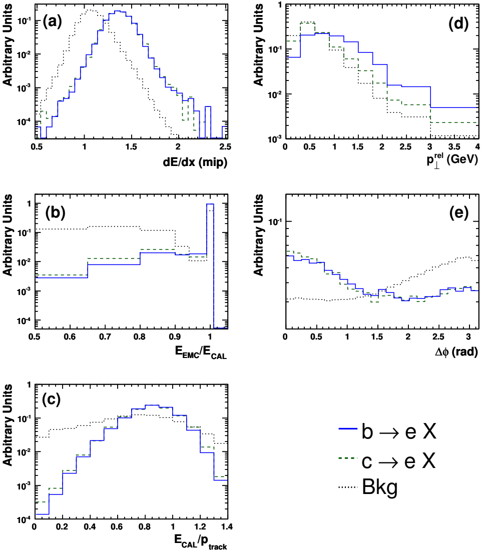
$\Delta\phi$: $b,c \leftrightarrow LF$ separation

p_T^{rel}: $b \leftrightarrow c$ separation





Backup - Beauty in Dijet γp



Backup - Inelastic J/Ψ production

Monte Carlo:

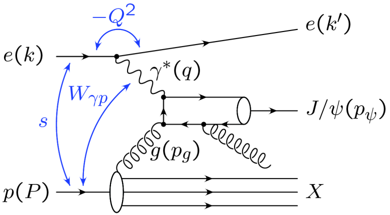
CSM LO (DGLAP): EPJPSI

CSM LO (kt-factorization): CASCADE v2.0/v1.2 (γp/DIS)

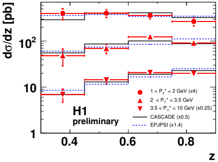
CSM NLO Krämer et al.

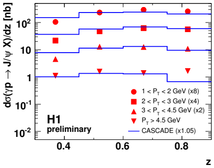
Kinematic variables:

$$Q^2 = -q^2$$
$$s = (P + k)^2$$
$$W^2_{\gamma p} = (P + q)^2$$
$$z = \frac{p_\Psi \cdot P}{q \cdot P} = \frac{E^*_\Psi}{E^*_\gamma} \text{ (in p rest frame)}$$



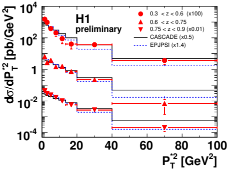
Backup Inelastic J/Ψ production

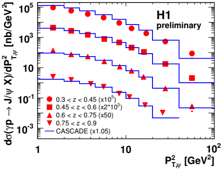




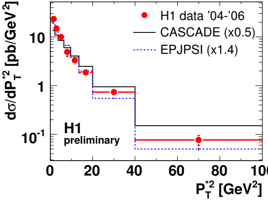
DIS

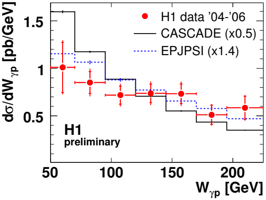
γp



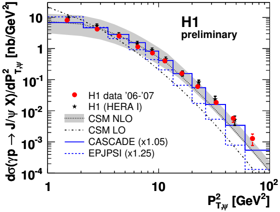


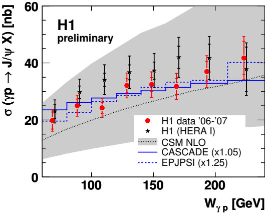
DIS


H1 data '04-'06
CASCADE (x0.5)
EPJPSI (x1.4)
H1
preliminary
dσ/dP*2T [pb/GeV²]
P*2T [GeV²]


H1 data '04-'06
CASCADE (x0.5)
EPJPSI (x1.4)
H1
preliminary
dσ/dWγp [pb/GeV]
Wγp [GeV]

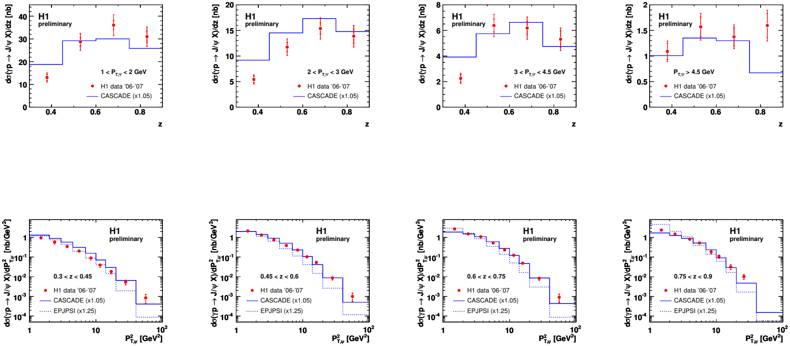
γp


H1
preliminary
H1 data '06-'07
H1 (HERA I)
CSM NLO
CSM LO
CASCADE (x1.05)
EPJPSI (x1.25)
dσ(γp → J/ψ X)/dP²T,ψ [nb/GeV²]
P²T,ψ [GeV²]


H1
preliminary
H1 data '06-'07
H1 (HERA I)
CSM NLO
CASCADE (x1.05)
EPJPSI (x1.25)
σ (γp → J/ψ X) [nb]
Wγp [GeV]

Backup - Inelastic J/Ψ production

γp



Backup J/ψ helicity in photoproduction

Helicity Parametrisation:

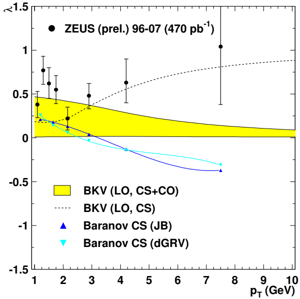
$$\frac{d^2\sigma}{d\Omega dy} \propto 1 + \lambda(y)\cos^2\Theta + \mu(y)\sin 2\Theta\cos\phi + \frac{1}{2}\nu(z)\sin^2\Theta\cos^2\phi$$

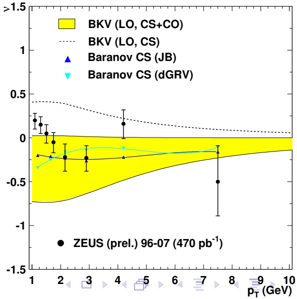
(M. Beneke, M.Krämer and v. Vänttinen, Phys. Rev. D57, 4258 (1998))

k_t factorization:

Two different parametrisations of unintegrated gluon distributions:

- JB: solution to the leading-order BFKL equation obtained in the double-logarithm approach
- dGRV: derived from the collinear gluon density by differentiating it with respect to μ^2 and setting $\mu^2 = k_t^2$





Search for radially excited charm mesons:

$D^{*'}(2640)^{\pm} \rightarrow D^{*\pm}\pi^{\pm}\pi^{\mp}$

Results:

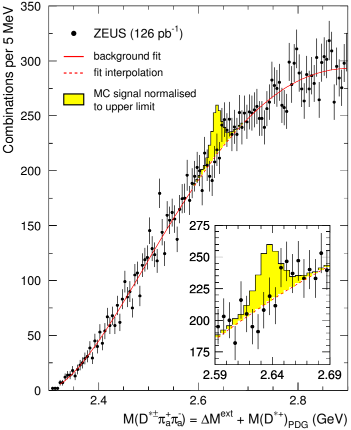
No significant production observed!

upper limit:

$f(c \rightarrow D^{*'+}) \cdot \mathcal{B}_{D^{*'+} \rightarrow D^{*+}\pi^{+}\pi^{-}} < 0.4\%$

(at 95% C.L.)

OPAL result: < 0.9%



Monte Carlo:

PYTHIA 6.156

RAPGAP 2.0818 with HERACLES 4.61

Struct. functions:: CTEQ5L, GRV LO

Masses: $m_c = 1.5 GeV, m_b = 4.75 GeV$

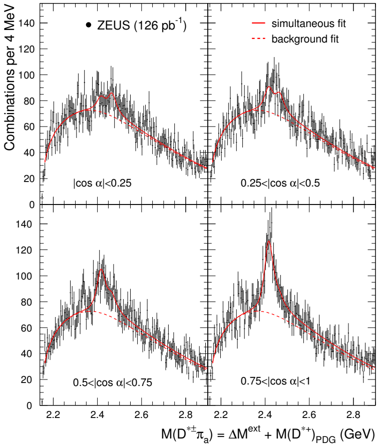
Helicity:

$$\frac{dN}{dcos\alpha} \propto 1 + h\cos^2\alpha$$

Ratio measurements:

$$\frac{\mathcal{B}_{D_2^{*0} \to D^+ \pi^-}}{\mathcal{B}_{D_2^{*0} \to D^{*+} \pi^-}} = 2.8 \pm 0.8(stat.)^{+0.5}_{-0.6}(syst.)$$

$$\frac{\mathcal{B}_{D_{s1}^+ \to D^{*0} K^+}}{\mathcal{B}_{D_{s1}^+ \to D^{*+} K0}} = 2.3 \pm 0.6(stat.) \pm 0.3(syst.)$$



Kinematic Cuts:

- $E_{e'} > 10GeV$
- $\Theta_e < 3.09$
- $2 < Q^2 < 100GeV^2$
- $(x_{Sp} + 2.025cm)^2 + y_{Sp}^2 > (12.cm)^2$
- $0.05 < y < 0.7$

No particle identification by

dE/dx requirements