Charm final states at HERA

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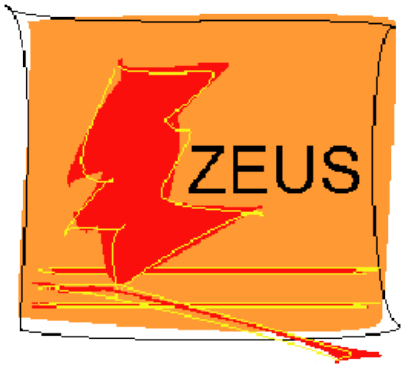
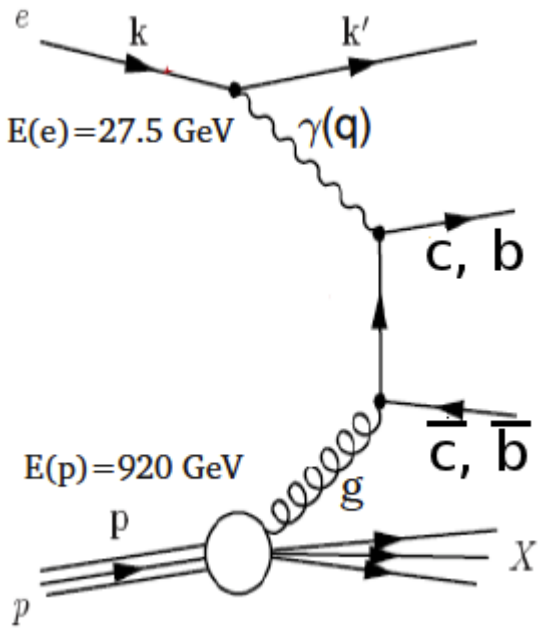


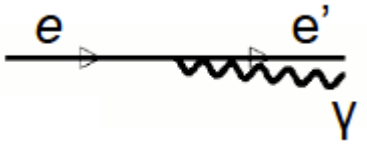
Motivation to measure heavy flavour production

- Charm and Beauty quarks at HERA are mainly produced in Boson-Gluon-Fusion.



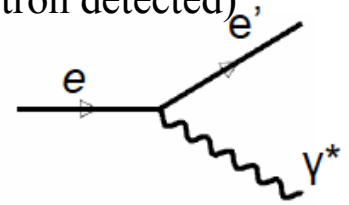
- Event kinematics:
  - Photon virtuality: $Q^2 = -q^2 = -(k-k')^2$
  - Inelasticity: $y = (q \cdot p) / (k \cdot p)$
  - Bjorken x: $x = Q^2 / (2\, p \cdot q)$

- Two kinematic regimes:
  - Photoproduction: $Q^2 \approx 0$ GeV^2



  - Deep Inelastic Scattering: $Q^2 > 1$ GeV^2

(scattered electron detected)



Motivation to measure heavy flavour production

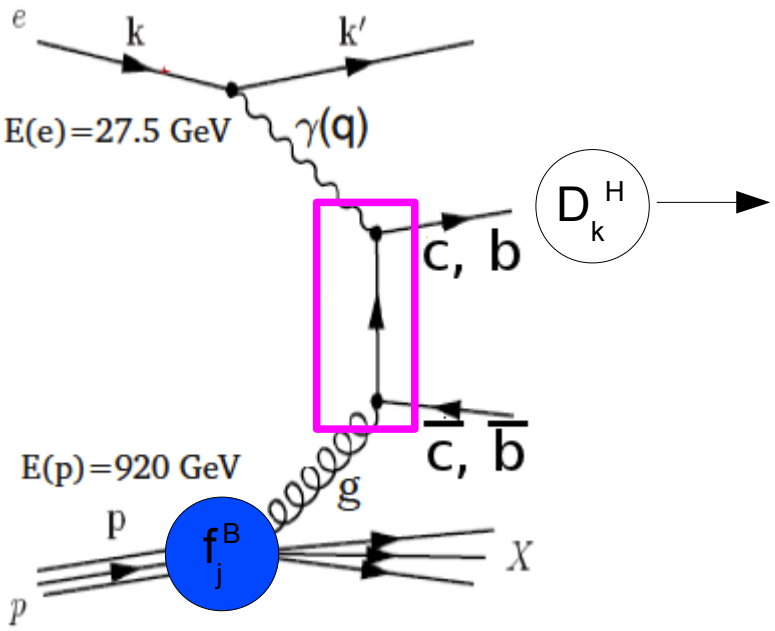
- Heavy Flavour cross sections can be calculated via the factorisation ansatz:

$$d\sigma = \sum_{ijk} f_j^B(x, \mu_f) \otimes d\sigma_{ij \to kX} \otimes D_k^H(\mu_f)$$

Parton density function (from global fits)

pQCD matrix element

Fragmentation function (from ee data)



- Interpretation of heavy flavour measurements:
  - Use the pQCD calculations and constrain the gluon density of the proton.
  - Take the gluon density from elsewhere and test the consistency of the pQCD calculation.

QCD models

QCD scheme:

- Massive scheme – Fixed Flavour Number Scheme (FFNS):
  - c and b quarks generated dynamically via boson-gluon-fusion.
  - c and b quarks treated massive.
  - Expected to be valid for **small scales $\mu^2 \approx m_{b,c}^2$**

QCD predictions:

- QCD LO + Parton shower Monte Carlo generators:
  - Collinear factorisation, DGLAP evolution (PYTHIA).
  - k_T factorisation, CCFM evolution (CASCADE).
  - Used for data corrections and model comparisons.

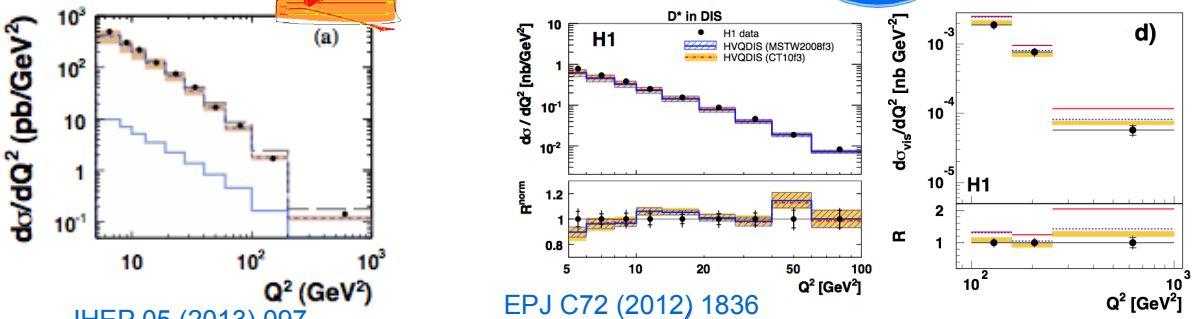
- QCD NLO calculations:
  - Massive scheme, NLO(α_s^2):
    - HVQDIS

Used for comparisons and small phase space corrections.

D* combination in visible phase space in DIS

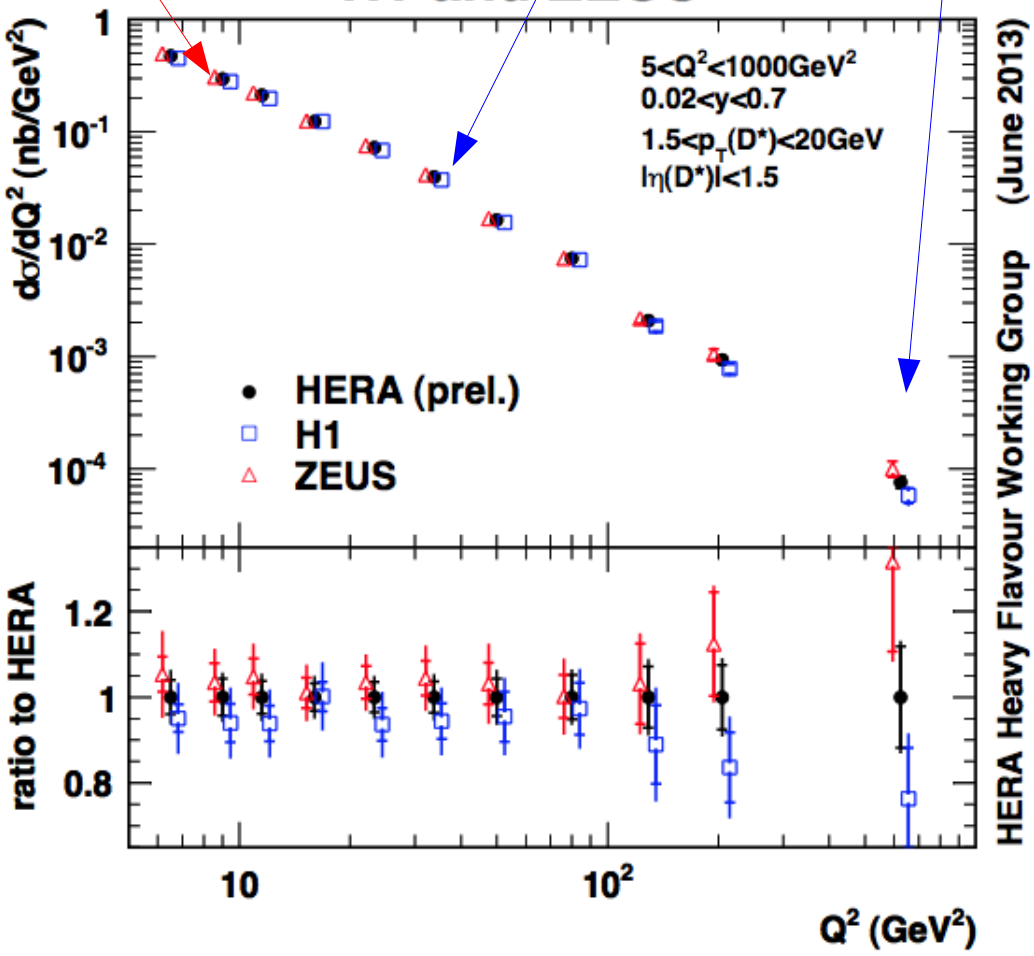
- Combination of most precise D* measurements from H1 and ZEUS within visible phase space.
- Minimal extrapolation factors to common phase space → minimal theory related uncertainties.
- Good agreement between measurements: χ^2 probability between 0.15 and 0.86.
- Uncorrelated systematics and larger statistics → improved experimental precision of typically 5%.

Full Q^2 | Medium Q^2 | High Q^2



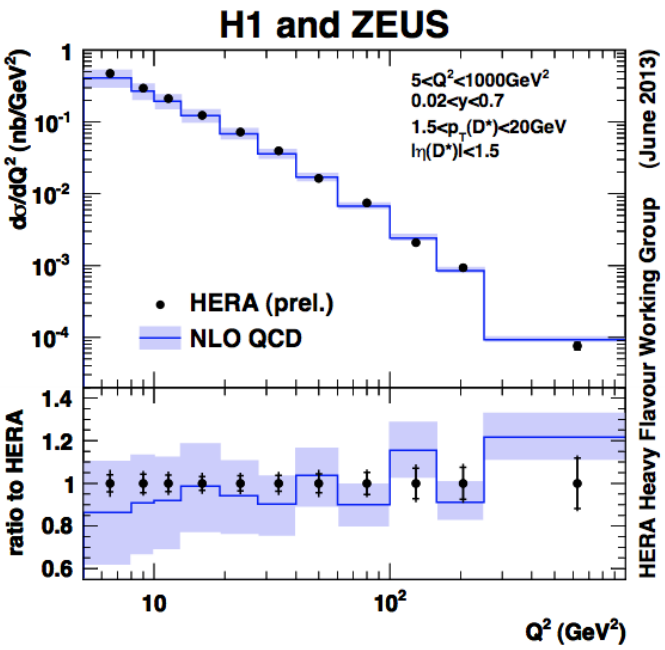
JHEP 05 (2013) 097 | EPJ C72 (2012) 1836 | PL B686 (2010) 3989

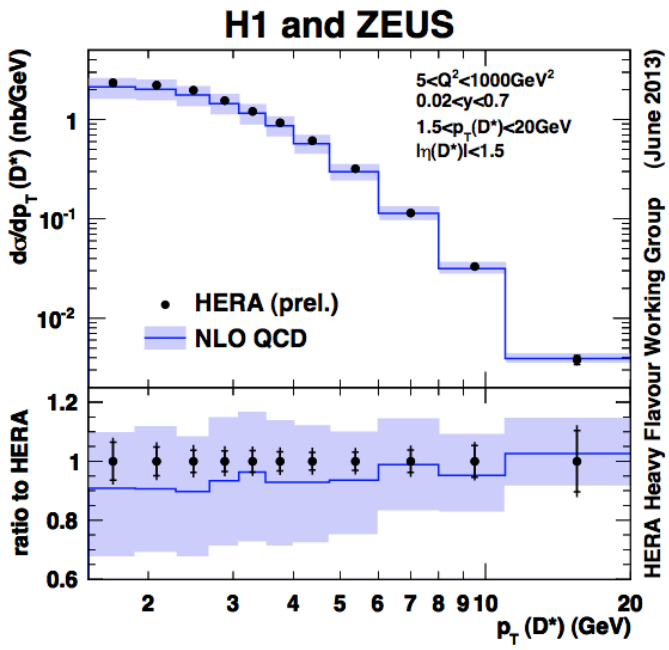
H1 and ZEUS

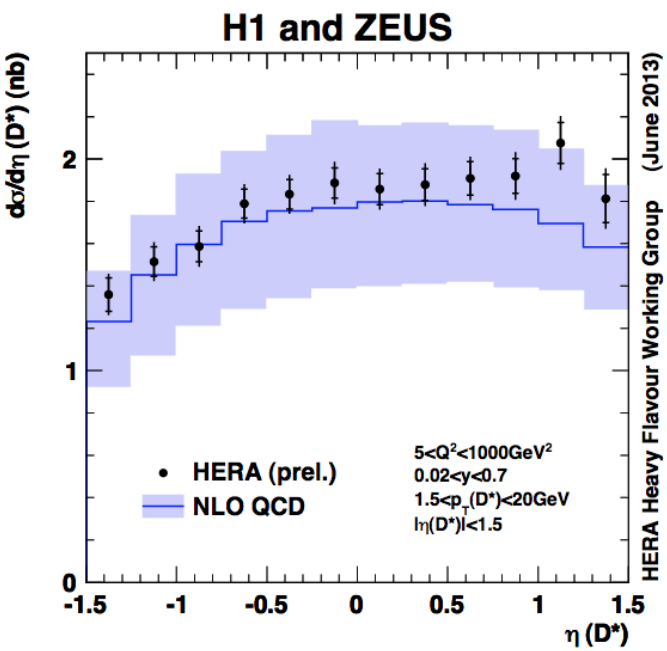


H1-prelim-13-171, ZEUS-prel-13-002

Combined D* data compared to NLO QCD

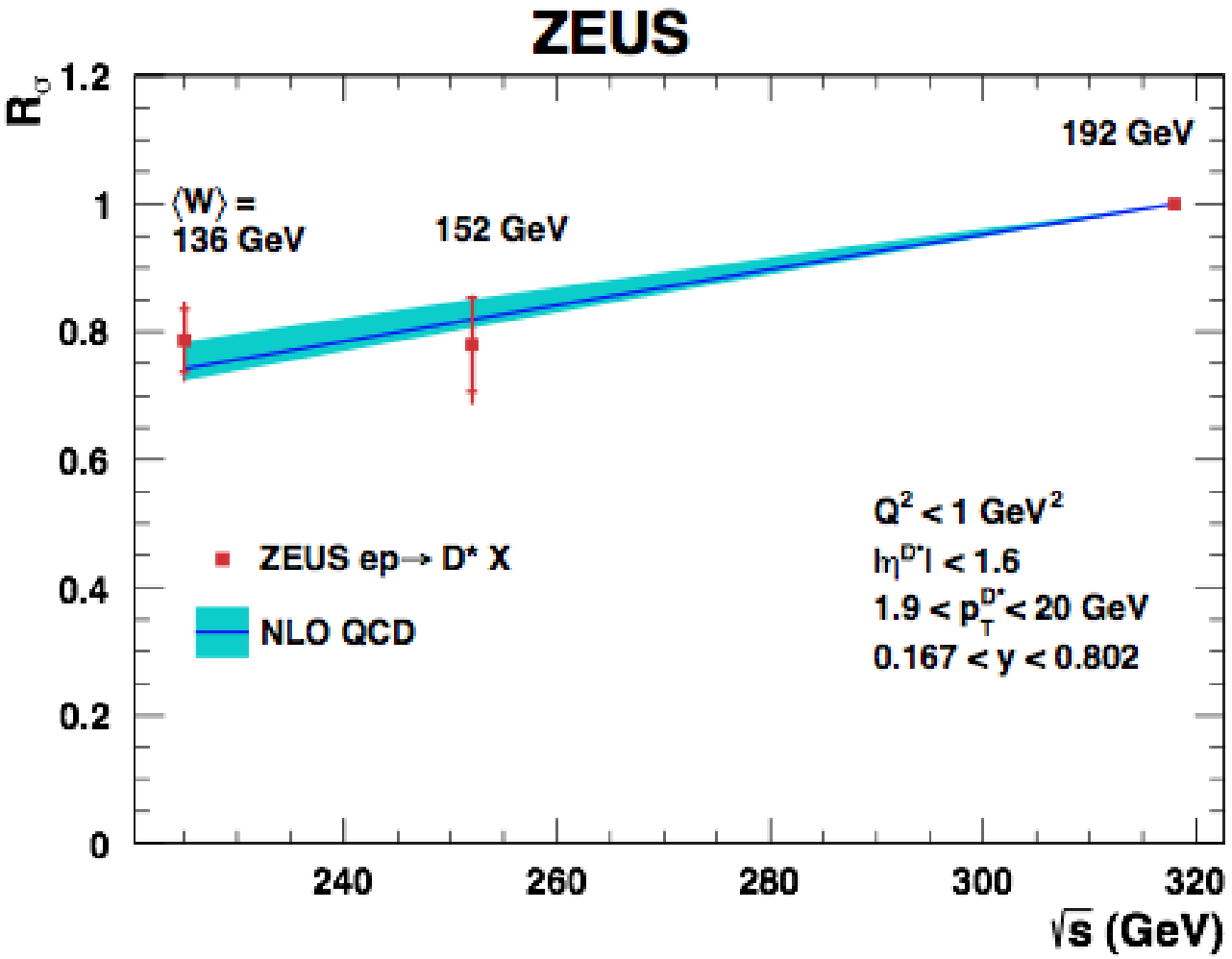






- Most precise D* measurement in DIS within visible phase-space.
- NLO QCD predictions describe data well; theory uncertainties are typically larger than data precision.

D* in photoproduction at different CMS energies



- Exploit low energy runs of HERA, with reduced proton energy.
- Look at ratio of visible D* cross section R_σ from reduced CMS energy to D* cross sections from nominal CMS energy.

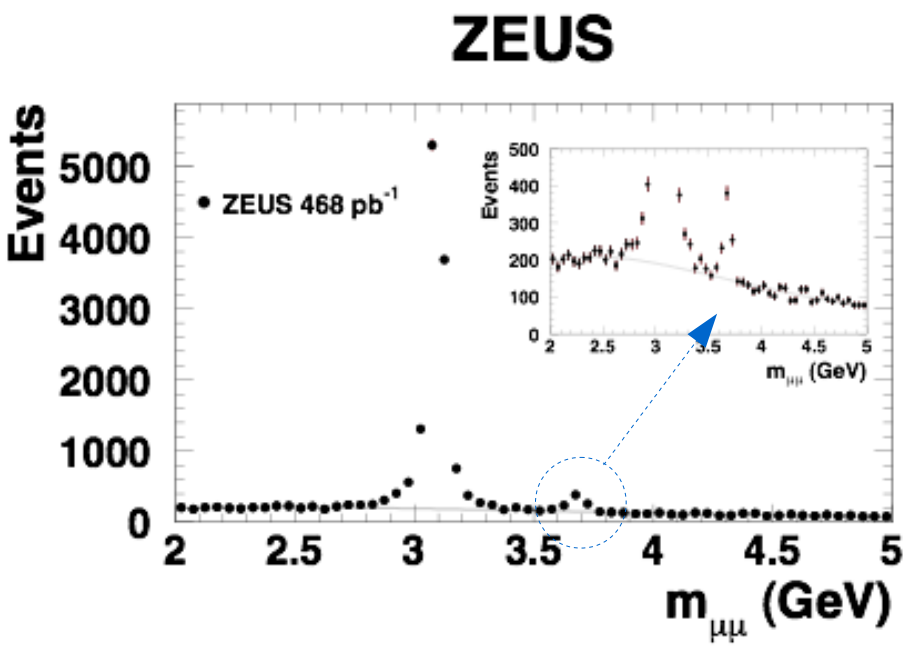
- Measured D* cross section increases with higher CMS energy.
- Behavior predicted by NLO QCD.

DESY-14-082, ZEUS Collaboration; to be published in JHEP

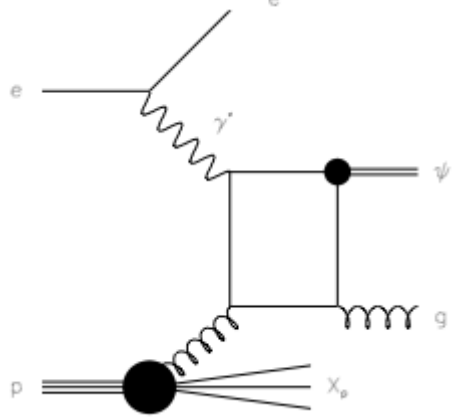
Inelastic J/ψ and ψ' in photoproduction

- Differential measurement of ψ' to J/ψ ratio.
- Differential J/ψ cross sections as a function of:
  - p_T^2
  - Inelasticity z, $z = \frac{P \cdot p_\psi}{P \cdot q}$

- Theory comparisons to
  - non-relativistic QCD, based on CS and CO model.
  - k_T-factorisation + CS.

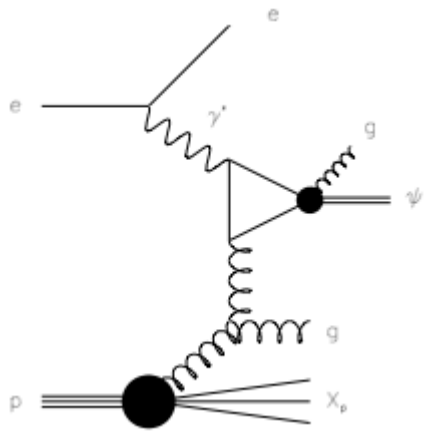


Color Singlet (CS)

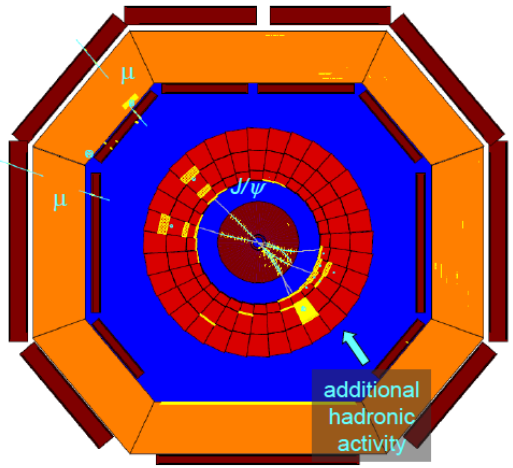


→ radiation of hard gluon

Color Octet (CO)



→ radiation of soft gluons

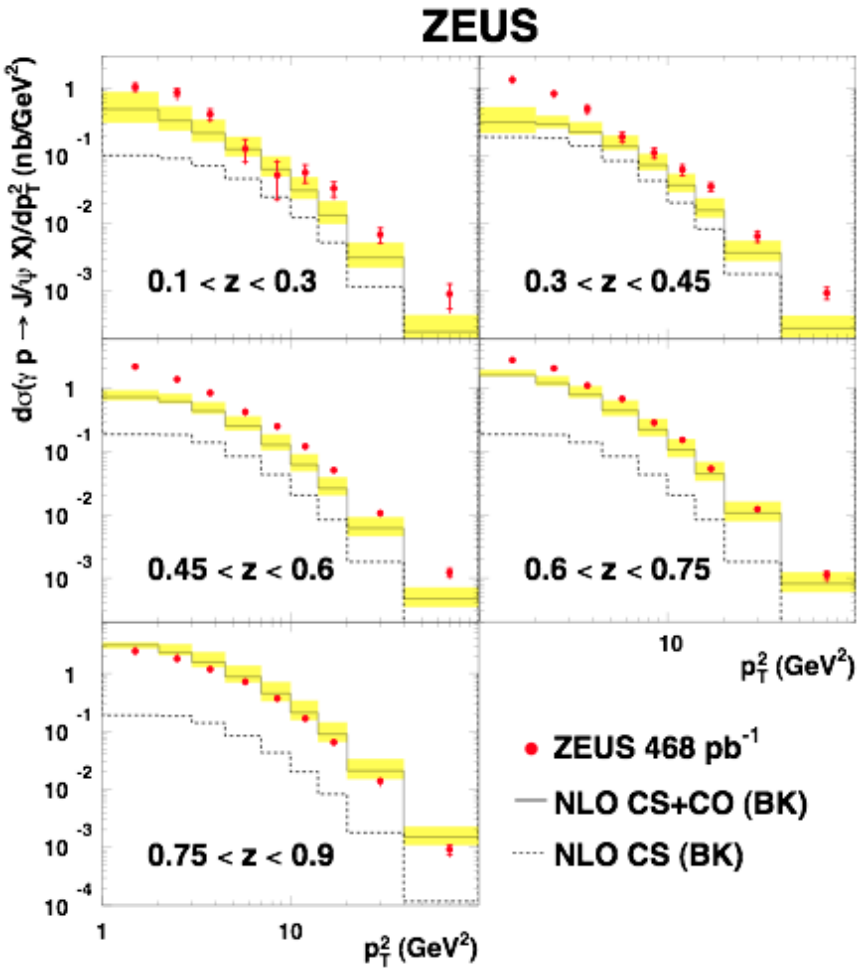


z<0.9 → no diffraction, high track multiplicity.

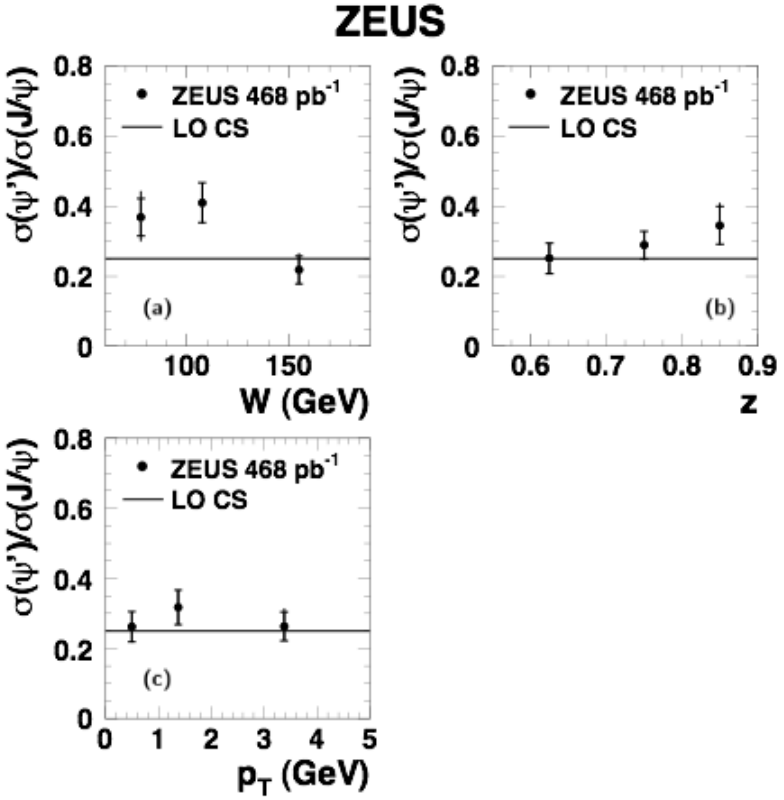
DESY-12-226, ZEUS Collaboration; JHEP 02 (2013) 071

Inelastic J/ψ and ψ' in photoproduction

- Differential J/ψ cross section compared to NRQCD:
  - rough description by CS+CO predictions.



- ψ' to J/ψ ratio agrees to LO CS prediction:

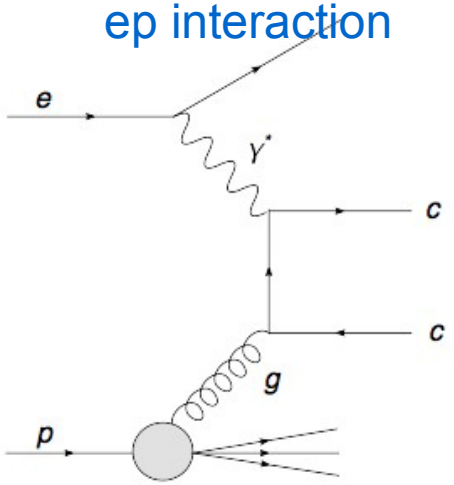


- Very high precision of the data, compared to the uncertainties of the NLO predictions.
- Prediction in general show a reasonable agreement.

Charm fragmentation fraction

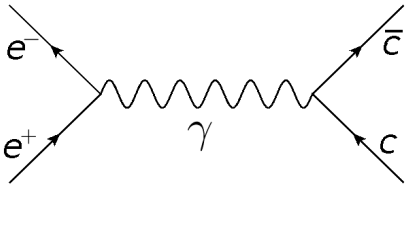
- Is the charm fragmentation fraction f universal?

ep interaction



$\rightarrow$ D^{*+}, D^{+}, D^{+}_{s}, D^{0}, Λ^{+}_{c}

ee interaction



$\rightarrow$ D^{*+}, D^{+}, D^{+}_{s}, D^{0}, Λ^{+}_{c}

$f\rightarrow$ Probability of c-quark to hadronise into particular charm meson:

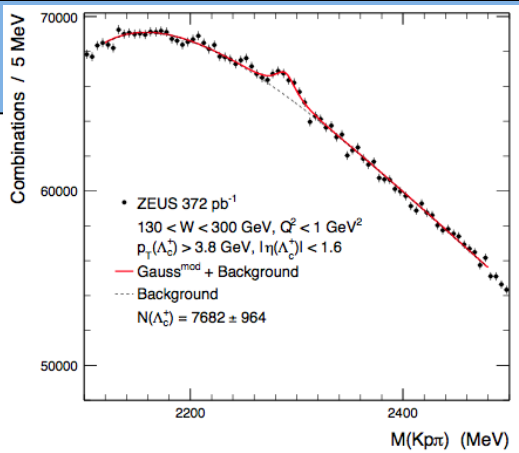
$$f(c\rightarrow D,\ldots,\Lambda_c)=\frac{\sigma_{D,\Lambda_c}}{\sigma_{gs}}$$

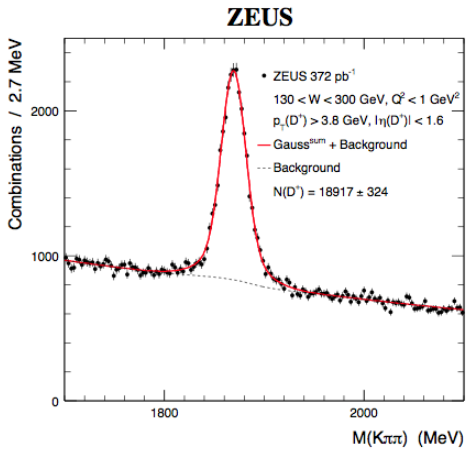
$$\sigma_{gs}=\sigma^{eq}(D^{+})+\sigma^{eq}(D^{0})+\sigma(D_s^{+})+\sigma(\Lambda_c^{+})\cdot 1.14$$

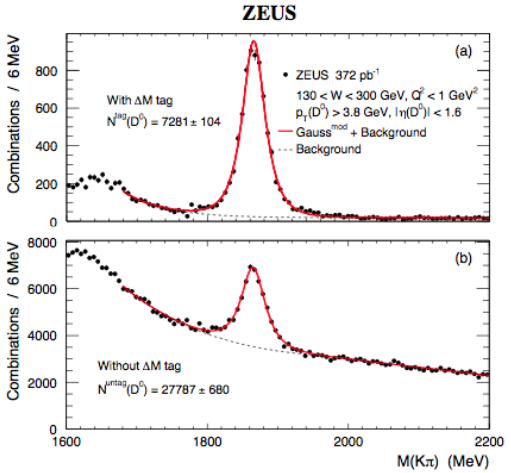
DESY-13-106, ZEUS Collaboration; JHEP 09 (2013) 058

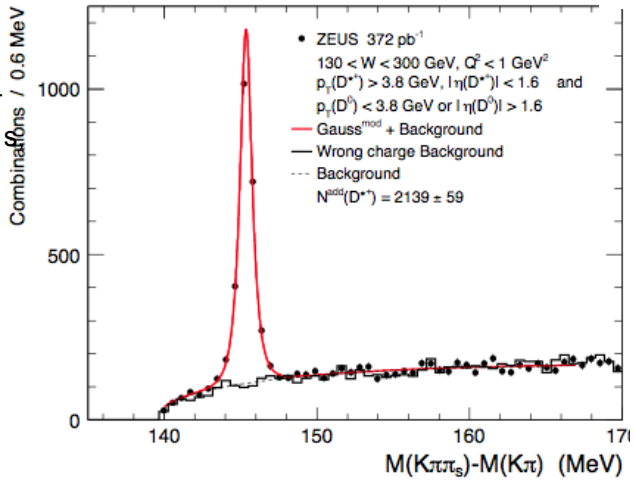
Analysed channels:

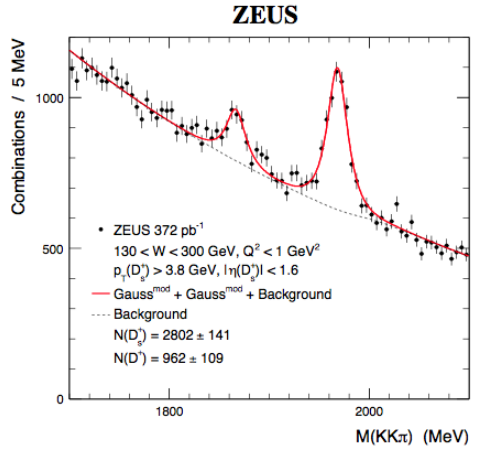
- $D^{+} \rightarrow K^{-}\pi^{+}\pi^{+}$
- $D^{*+} \rightarrow K^{-}\pi^{+}\pi^{+}$
- $D^{0} \rightarrow K\pi$
- $D^{+}_{s} \rightarrow K^{+}K^{-}\pi^{+}$
- $\Lambda^{+}_{c} \rightarrow pK^{-}\pi^{+}$



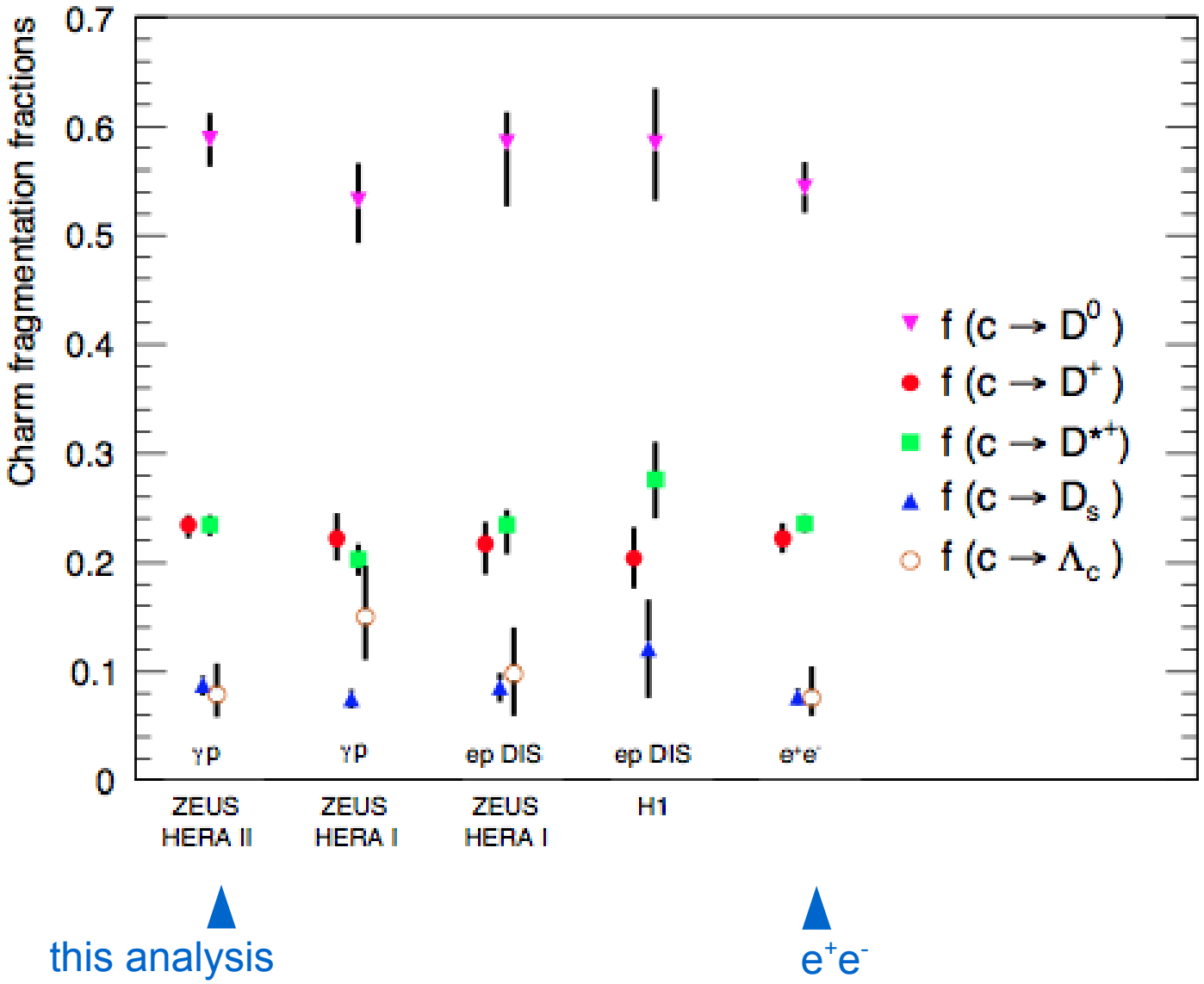








Charm fragmentation fraction



- Universality of charm fragmentation confirmed.

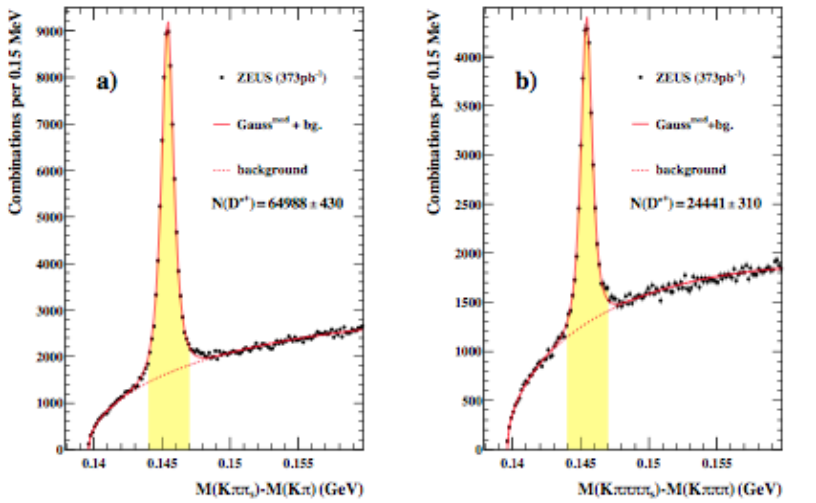
Excited charm mesons D_1 and D^*_2

- Exploit large samples of "D-ground states" to reconstruct excited charm states $D_1(2420)^0$, $D^*_2(2460)^0$, $D_1(2420)^+$, $D^*_2(2460)^+$.

- Look at invariant mass distributions of
  - $M(D^{*+}\pi) \Rightarrow D_1^0, D^*_2{}^0$
  - $M(D^+\pi) \Rightarrow D^*_2{}^0$
  - $M(D^0\pi) \Rightarrow D_1^+, D^*_2{}^+$

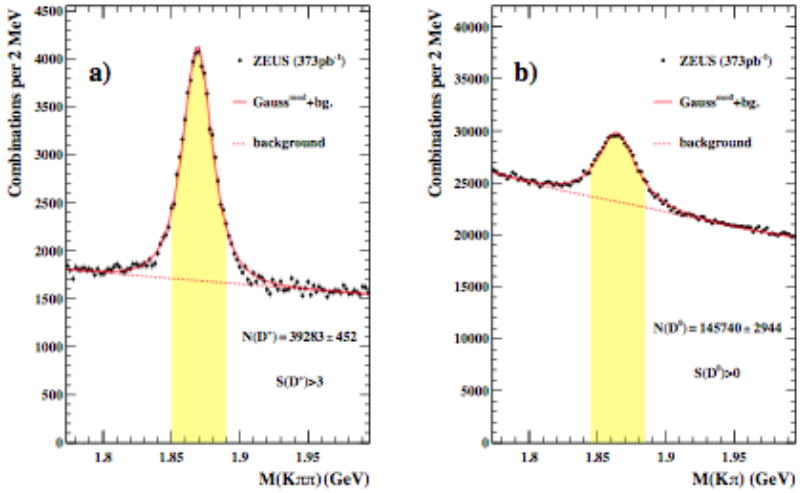
- Measurement of masses, widths, angular distributions and fragmentation fractions of excited charm states.

$D^{*+} \to K\pi\pi_s$ $D^{*+} \to K3\pi\pi_s$



~90000 D^{*+}

$D^+ \to K^-\pi^+\pi^+$ $D^0 \to K^-\pi^+$



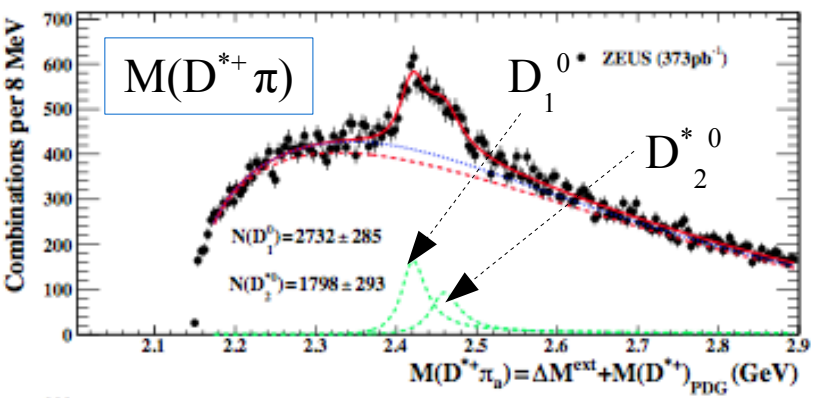
~40000 D^+ ~150000 D^0

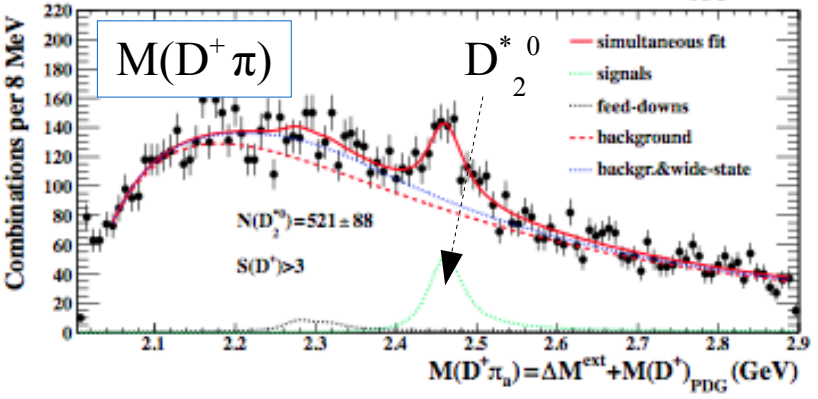
DESY-12-144, ZEUS Collaboration; Nuclear Phys. B 866 (2013) 229-254

Excited charm mesons D_1 and D^*_2

- Neutral excited states:

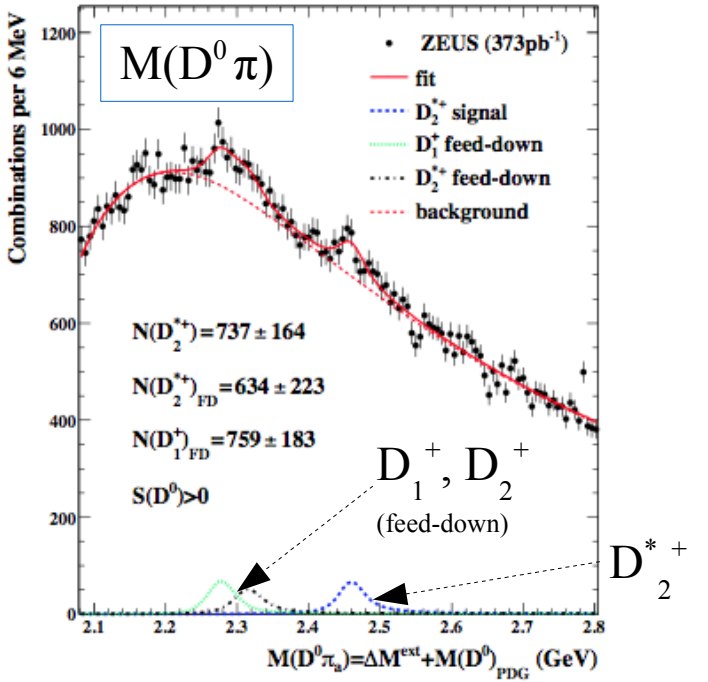
	HERA-II (this)	HERA-I	PDG
$M(D_1^0)$, MeV	$2423.1 \pm 1.5^{+0.4}_{-1.0}$	$2420.5 \pm 2.1 \pm 0.9$	2421.3 ± 0.6
$\Gamma(D_1^0)$, MeV	$38.8 \pm 5.0^{+1.9}_{-5.4}$	$53.2 \pm 7.2^{+3.3}_{-4.9}$	27.1 ± 2.7
$h(D_1^0)$	$7.8^{+6.7+4.6}_{-2.7-1.8}$	$5.9^{+3.0+2.4}_{-1.7-1.0}$	
$M(D_2^{*0})$, MeV	$2462.5 \pm 2.4^{+1.3}_{-1.1}$	$2469.1 \pm 3.7^{+1.2}_{-1.3}$	2462.6 ± 0.7
$\Gamma(D_2^{*0})$, MeV	$46.6 \pm 8.1^{+5.9}_{-3.8}$	43 fixed	49.0 ± 1.4
$h(D_2^{*0})$	-1 fixed	-1 fixed	





- Charged excited states:

	HERA-II (this)	PDG
$M(D_1^+)$, 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 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 fixed	



- Accurate measurement of D_1 and D_2^* spectroscopy and fragmentation (not shown) parameters.
- All values consistent with PDG values.

Summary

- H1 and ZEUS combined D* cross sections in DIS:
  - High data precision in visible phase space (→ negligible theory uncertainty).
  - Test pQCD at various variables.
- D* cross sections rises with CMS energy, as predicted by pQCD.
- New precise measurement of inelastic J/ψ production.
- Confirmation of charm fragmentation universality.
- Spectroscopy and fragmentation parameters of excited charm states.

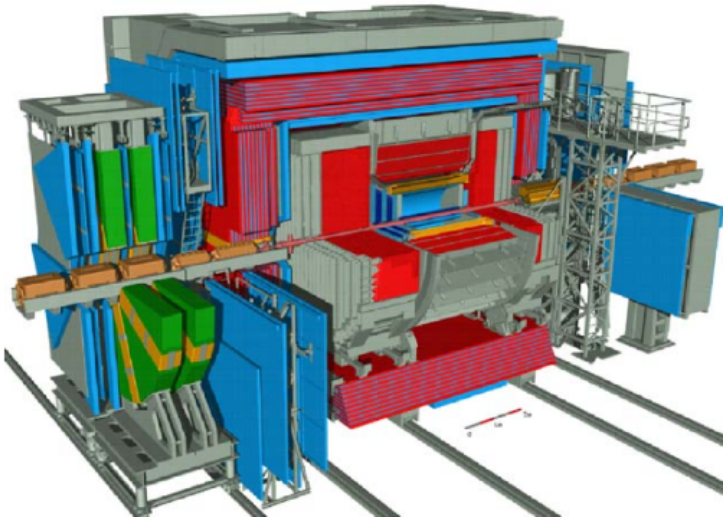
Measurements discussed in this talk:

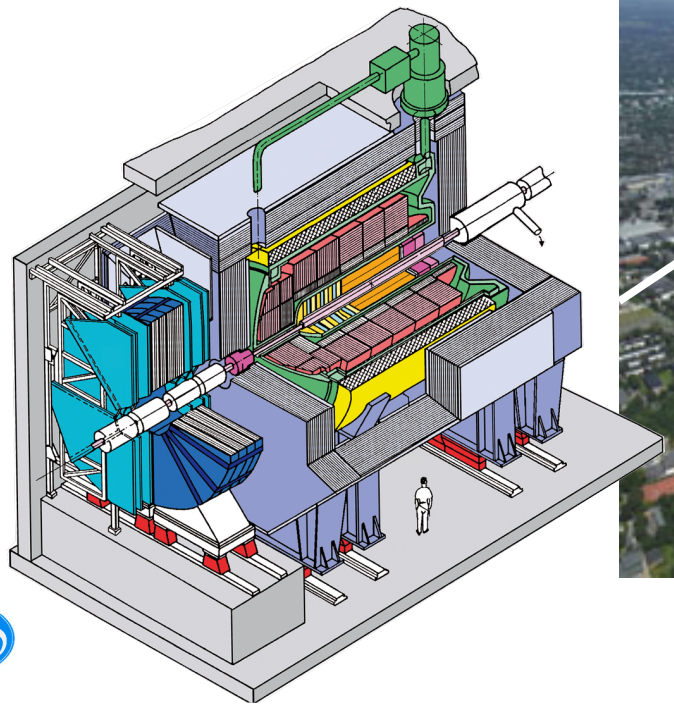
- "Combination of D* Differential Cross Section Measurements in Deep-Inelastic ep Scattering at HERA"
  H1-prelim-13-171, ZEUS-prel-13-002
- "Measurement of D* photoproduction at three different centre-of-mass energies at HERA"
  DESY-14-082, ZEUS Collaboration; to be published in JHEP
- "Measurement of Inelastic J/ψ and ψ' photoproduction at HERA"
  DESY-12-226, ZEUS Collaboration; H. Abramowicz et al., JHEP 02 (2013) 071
- "Measurement of Charm Fragmentation Fractions in Photoproduction at HERA"
  DESY-13-106, ZEUS Collaboration; H. Abramowicz et al., JHEP 09 (2013) 058
- "Production of the excited charm mesons D_1 and D^*_2 at HERA"
  DESY-12-144, ZEUS Collaboration; H. Abramowicz et al., Nuclear Phys. B 866 (2013) 229-254

Backup

The HERA ep collider (1992 – 2007) at DESY in Hamburg

- ep collider:
- $e^{\pm}$ energy: 27.6 GeV
- p energy: 920 GeV
- Centre of mass energy: 319 GeV
- 2 collider experiments: H1 and ZEUS
- Integrated luminosity: ~0.5 fb^{-1} (per experiment)





Tagging methods for heavy flavours at HERA

- Rates at HERA behaved like $\sigma(b) : \sigma(c) : \sigma(uds) \approx 1 : 50 : 2000$
- Charm and beauty enrichment is possible with:

1) Full reconstruction
   - Only possible for charm at HERA, eg. $D^* \rightarrow K\pi\pi$.
2) Lepton tagging: Use semileptonic b/c decay channels
   - look for μ or e , high BR(c,b→ lepton + anything)
3) p_T^{rel} tagging : b/c quark have large masses
   - look for decay leptons with a high transverse momentum w.r.t the b quark flight direction.
4) Lifetime tagging: b/c quark have long lifetimes:
   - look for displaced vertices.
   - look for tracks with large impact parameters δ.
5) Secondary vertex mass tagging: long lifetime and large masses
   - look for high secondary vertex masses.