Charm and beauty at HERA

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for the HERA collaborations
H1 and ZEUS

Outline

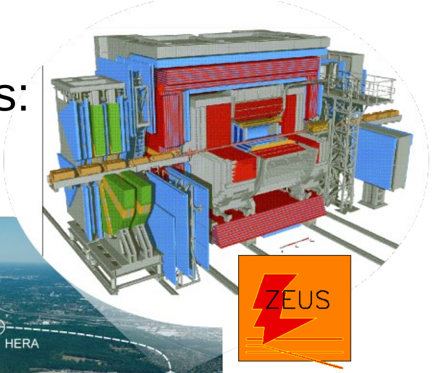
- The HERA collider
- Charm and beauty production in deep-inelastic scattering
- Data combination
- The new combined HERA charm and beauty data
- Comparisons to NLO QCD
- Charm production in diffractive DIS

The HERA collider

- World's only ep collider 1992-2007
- 920 x 27.6 GeV ($\sqrt{s}$=320 GeV)
- Two collider experiments, H1 and ZEUS
- Integrated Luminosity:

  ~$2\times0.5\ \mathrm{fb}^{-1}$
- $e^{+}p$ and $e^{-}p$ data

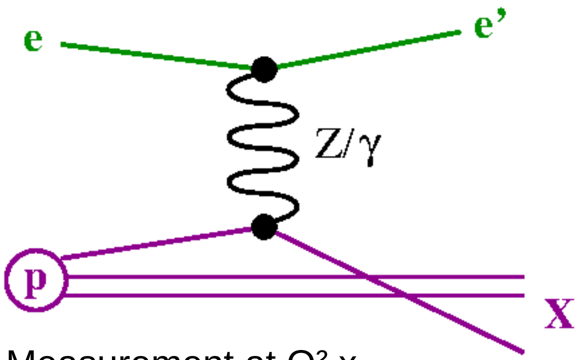
Two collider experiments:
H1 and ZEUS



Angular coverage with EM+had calorimeters to low angles
Tracking in the central region

Deep-inelastic scattering

- Inclusive processes
  - Neutral current (NC)
  - Charged current (CC)
- Momentum transfer Q^2
- Inelasticity y
- Bjorken-x
- This talk: NC scattering with charm or beauty detected in the hadronic final state X



Measurement at Q^2,x
probes sum of (anti-) quark PDFs
$\sigma \sim \Sigma |M|^2 e_i^2 f_i(Q^2,x)$
(gluon enters at higher orders)

exchanged 4-momentum:

$$q = e - e' = X - p$$

Kinematic variables

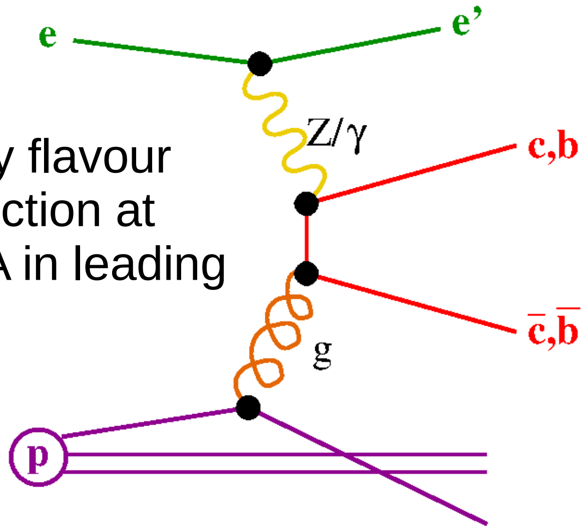
$$Q^2 = -q^2$$

$$y = \frac{p\,q}{p\,e}$$

$$x = \frac{Q^2}{sy}$$

Charm and beauty production at HERA

Heavy flavour production at HERA in leading order



Measured quantity: reduced cross section σ_{red} with charm or beauty in final state

Reduced cross section: double-differential cross section divided by kinematic factors

NLO calculations: fixed-flavour number scheme (FFNS) where PDF only contains light flavours u,d,s and the gluon. Massive heavy quarks are in the matrix elements

Experimental methods:
- High pt lepton
- Reconstructed D,D* mesons
- Impact parameter, secondary vertex

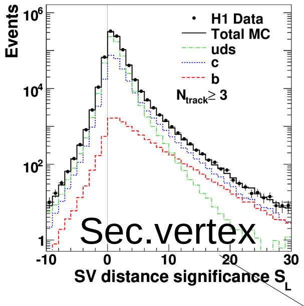
Alternative (not used in this talk): variable-flavour number scheme and massless c,b quarks in the PDF above threshold. PDFs can be converted between schemes.

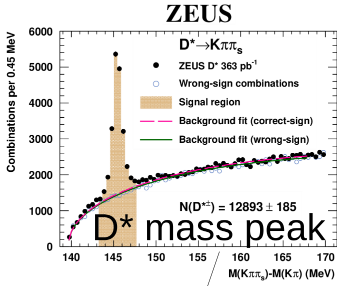
HERA combination of charm and beauty

- Two experiments H1 and ZEUS
- First combination of HERA charm data published in 2012
- Eur.Phys.J.C73 (2013) 2311
- This talk: new combination of charm and beauty data
- **H1prelim-17-071, ZEUS-prel-17-01**
- 13 datasets, using different experimental methods

(Data combination details: see backup slides)

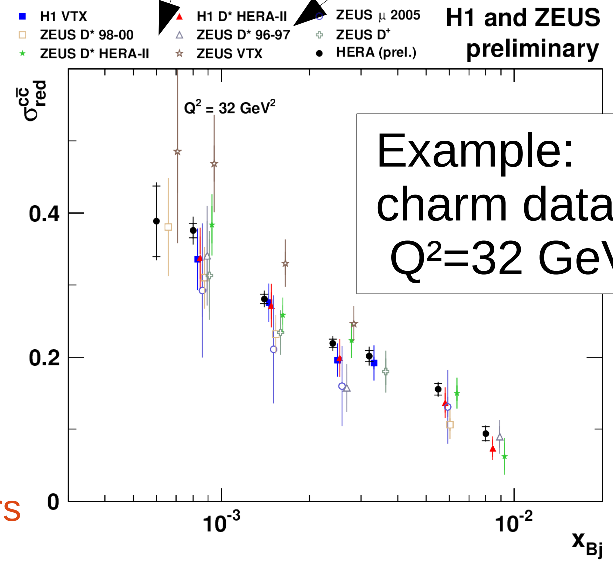
https://www.desy.de/h1zeus/combined_results/index.php?do=heavy_flavours





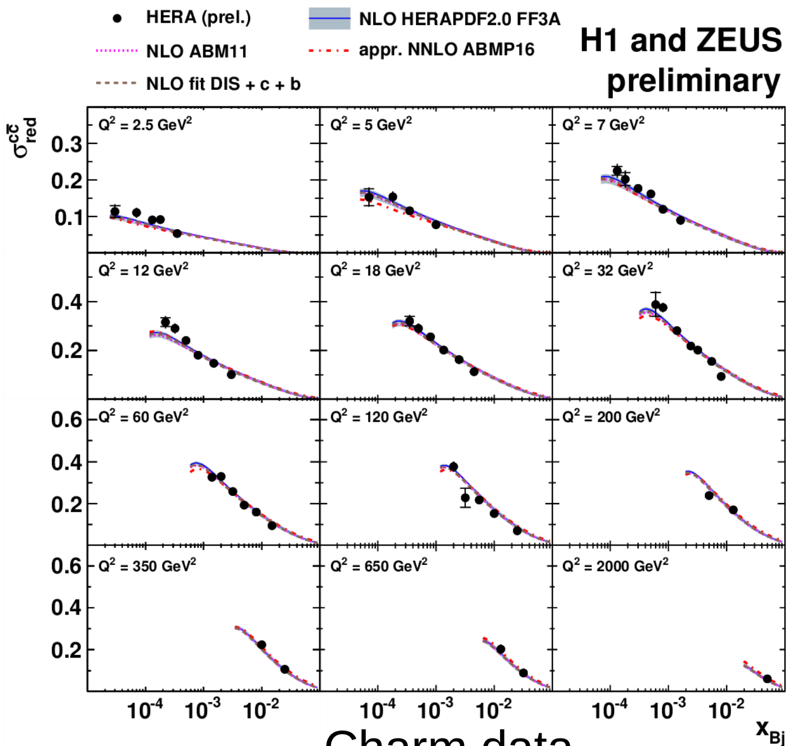
+11 more HERA (H1 or ZEUS) analyses

Combined data: 12 bins in Q², 52 charm data points and 27 beauty data points, all point-to-point correlations taken into account



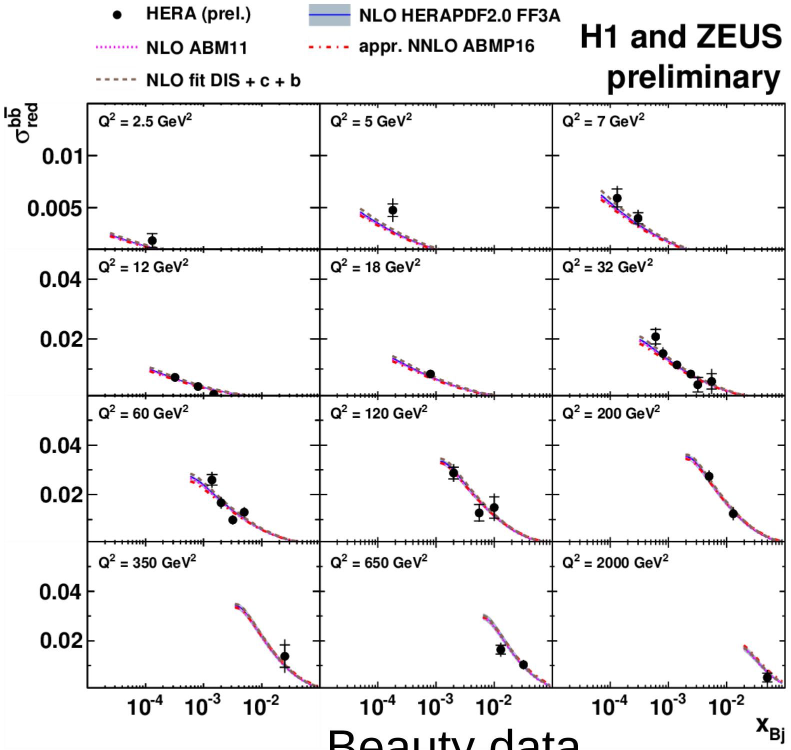
Example: charm data at Q²=32 GeV²

Results and comparison to NLO QCD



Charm data

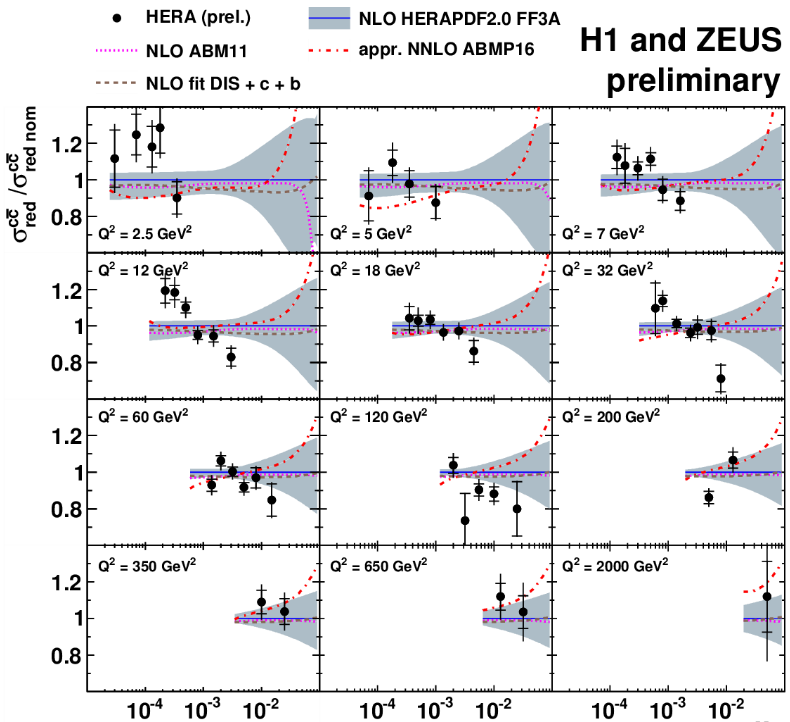
- Rise to low x: typical for sea and gluon
- Cross section evolves with Q^2
- NLO predictions describe data reasonably well
- Improved precision compared to the 2012 measurement (see backup slides)
- First combination of HERA beauty data



Beauty data

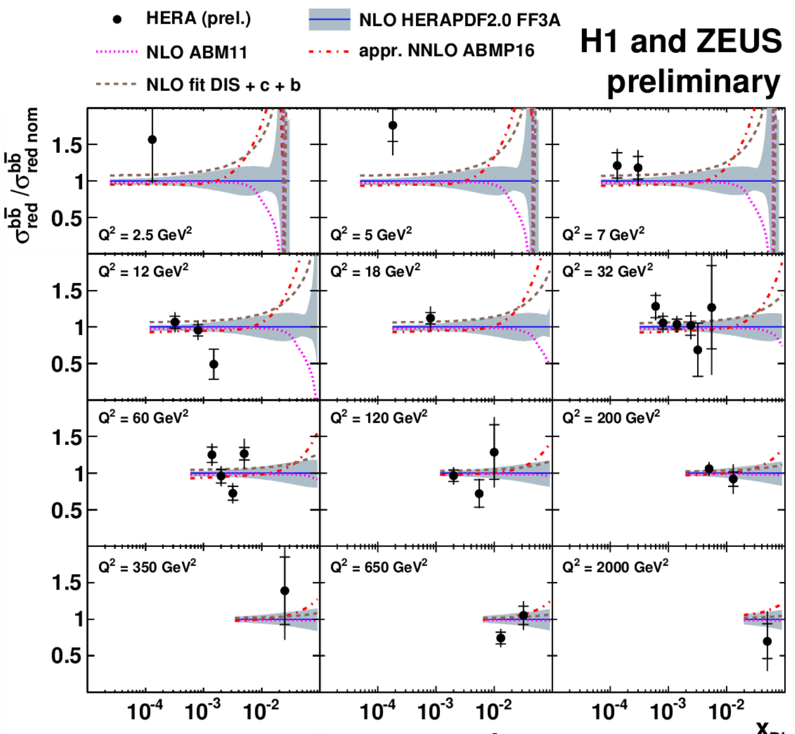
https://www.desy.de/h1zeus/combined_results/index.php?do=heavy_flavours

Ratios to NLO QCD



Charm data

- Overall satisfactory description of the HERA c and b data by NLO QCD, not much dependent on PDF choice
- No improvement by approximate NNLO
- Slope difference between data and theory as a function of x is visible for charm data at $Q^2 \sim 12$ GeV^2



Beauty data

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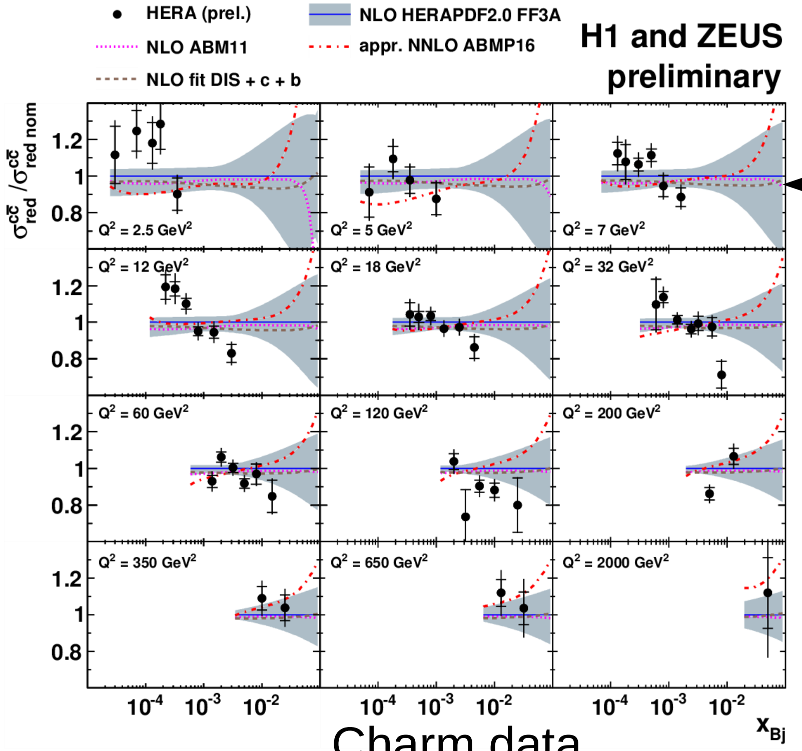
NLO QCD fit and c,b masses



Charm data

- Charm and beauty data together with HERA inclusive DIS data are taken as input to a NLO QCD fit (dashed line)
- Simultaneously extract PDFs and c,b masses

$$m_c(m_c)=1209^{+46}_{-41}(\text{fit})^{+62}_{-14}(\text{model})^{+7}_{-31}(\text{param})\ \text{MeV}$$
$$m_b(m_b)=4049^{+104}_{-109}(\text{fit})^{+90}_{-32}(\text{model})^{+1}_{-31}(\text{param})\ \text{MeV}$$

- Compatible with previous HERA analyses and with world data

PDG: $m_c(m_c)=1270\pm30\ \text{MeV}$ and $m_b(m_b)=4180\pm30\ \text{MeV}$

Also see talk by A. Gizhko on runing charm mass (Friday)

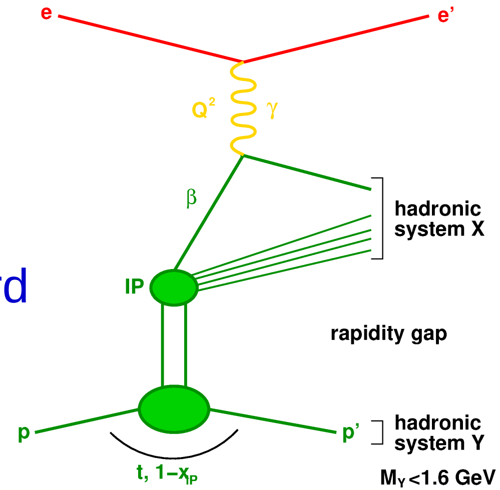
https://www.desy.de/h1zeus/combined_results/index.php?do=heavy_flavours

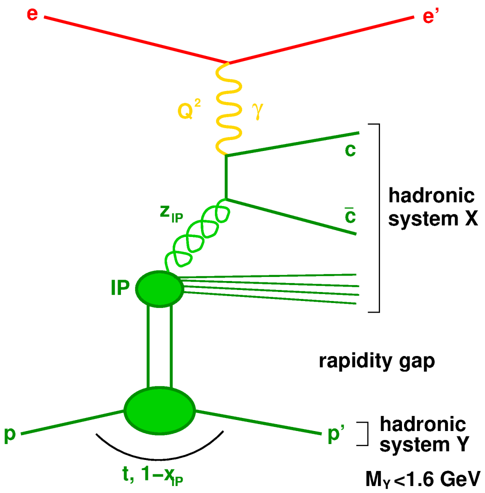
Charm production in diffractive DIS

- About 10% of the inclusive DIS cross section an HERA are diffractive at low x
- Experimental signature: proton stays intact, no activity in forward detectors, large rapidity gap

  t : p vertex 4-mom. transfer squared
  x_{IP} : IP long. mom. fraction
  β or z_{IP} : parton long. mom. fraction

- Theory (Collins): QCD factorisation holds in diffractive DIS → concept of diffractive PDFs (DPDFs)





predict →

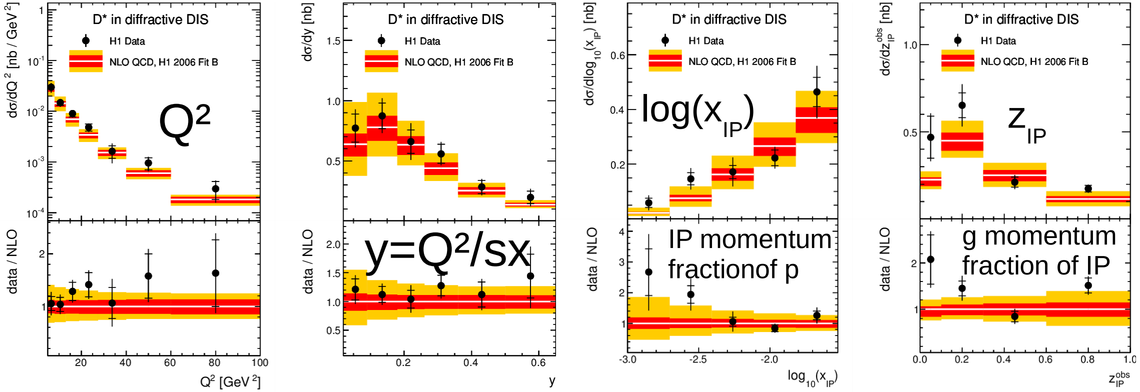
Inclusive diffraction: extract DPDFs

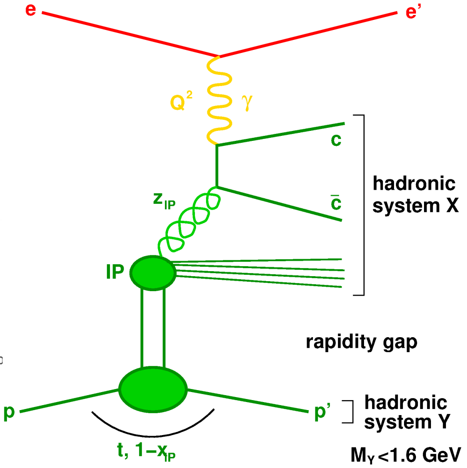
$$f_i(Q^2, \beta, t, x_{IP})$$

Diffractive charm production: test factorisation theorem in diffraction

Diffractive D* cross sections

DIS phase space
$5 < Q^2 < 100\ \mathrm{GeV}^2$ $0.02 < y < 0.65$
D^* kinematics
$p_{t,D^*} > 1.5\ \mathrm{GeV}$ $-1.5 < \eta_{D^*} < 1.5$
Diffractive phase space
$x_{I\!P} < 0.03$ $M_Y < 1.6\ \mathrm{GeV}$ $\lvert t\rvert < 1\ \mathrm{GeV}^2$





- Electron variables: Q^2 and y
- Diffractive variables: $\log(x_{IP})$, z_{IP}

- Well described by NLO QCD, large theory scale uncertainties (yellow band)
- DPDF uncertainties (red) similar to data precision
- D* kinematic distributions also described (→ backup)

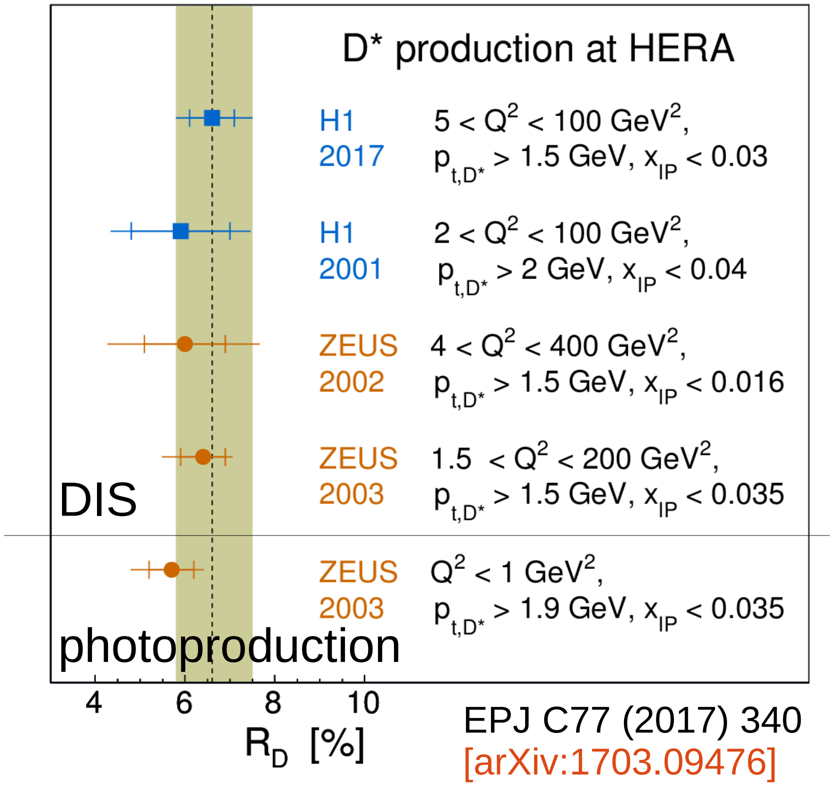
EPJ C77 (2017) 340
[arXiv:1703.09476]

Diffractive to inclusive D* ratio

- Investigate diffractively produced fraction of D* mesons
- Results of many analyses largely agree with each other
- Similar ratios are observed in deep-inelastic scattering and in photoproduction, where one possibly expects to see differences

Note: diffractive QCD factorisation theorem is proven only for DIS [Q^2»0] not for photoproduction [Q^2=0]

Diffractive fraction



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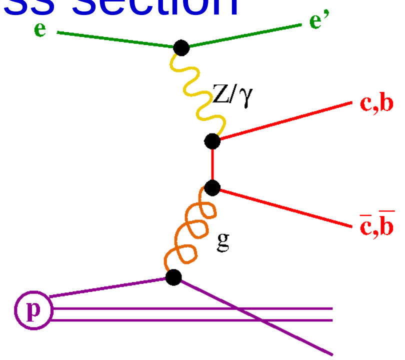
Summary

- New combination of charm and beauty double-differential cross section measurements in deep-inelastic scattering at HERA



- Test of QCD with massive quarks (multiple scale problem)
- Fixed flavour-number calculations provide good description
- PDF fit: charm and beauty data constrain quark masses

  → measure running quark masses from HERA data alone

$$m_c(m_c) = 1209^{+46}_{-41}(\text{fit})^{+62}_{-14}(\text{model})^{+7}_{-31}(\text{param})\ \text{MeV}$$
$$m_b(m_b) = 4049^{+104}_{-109}(\text{fit})^{+90}_{-32}(\text{model})^{+1}_{-31}(\text{param})\ \text{MeV}$$

- New measurement of charm in diffractive DIS at HERA: test of diffractive QCD factorisation and diffractive PDFs

  → Data are described by theory within large scale+DPDF uncertainties

Backup

HERA datasets on charm and beauty

- Two experiments H1 and ZEUS
- First combination of HERA charm data published in 2012

  Eur.Phys.J.C73 (2013) 2311

- This talk: new combination of charm and beauty data

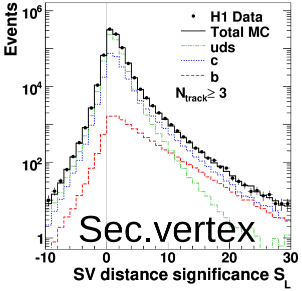
  H1prelim-17-071, ZEUS-prel-17-01

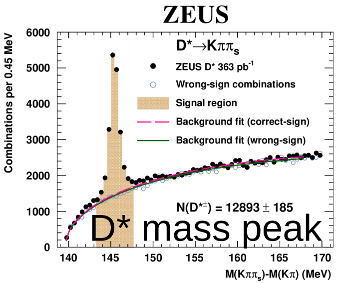
- 13 datasets, using different experimental methods

(Data combination details: see backup slides)

	Data set	Tagging	Q^2 range [GeV^2]	N_c	$\mathcal{L}$ [pb^{-1}]	$\sqrt{s}$ [GeV]	N_b
1	H1 VTX [8]	VTX	5 – 2000	29	245	318	12
2	H1 D^{*+} HERA-I [9]	D^{*+}	2 – 100	17	47	318	
3	H1 D^{*+} HERA-II (medium Q^2) [10]	D^{*+}	5 – 100	25	348	318	
4	H1 D^{*+} HERA-II (high Q^2) [11]	D^{*+}	100 – 1000	6	351	318	
5	ZEUS D^{*+} 96-97 [12]	D^{*+}	1 – 200	21	37	300	
6	ZEUS D^{*+} 98-00 [13]	D^{*+}	1.5 – 1000	31	82	318	
7	ZEUS D^0 2005 [14]	D^0	5 – 1000	9	134	318	
8	ZEUS μ 2005 [7]	μ	20 – 10000	8	126	318	8
9	ZEUS D^+ HERA-II [2]	D^+	5 – 1000	14	354	318	
10	ZEUS D^{*+} HERA-II [3]	D^{*+}	5 – 1000	31	363	318	
11	ZEUS VTX HERA-II [4]	VTX	5 – 1000	18	354	318	17
12	ZEUS e HERA-II [5]	e	10 – 1000		363	318	9
13	ZEUS μ + jet HERA-I [6]	μ	2 – 3000		114	318	11

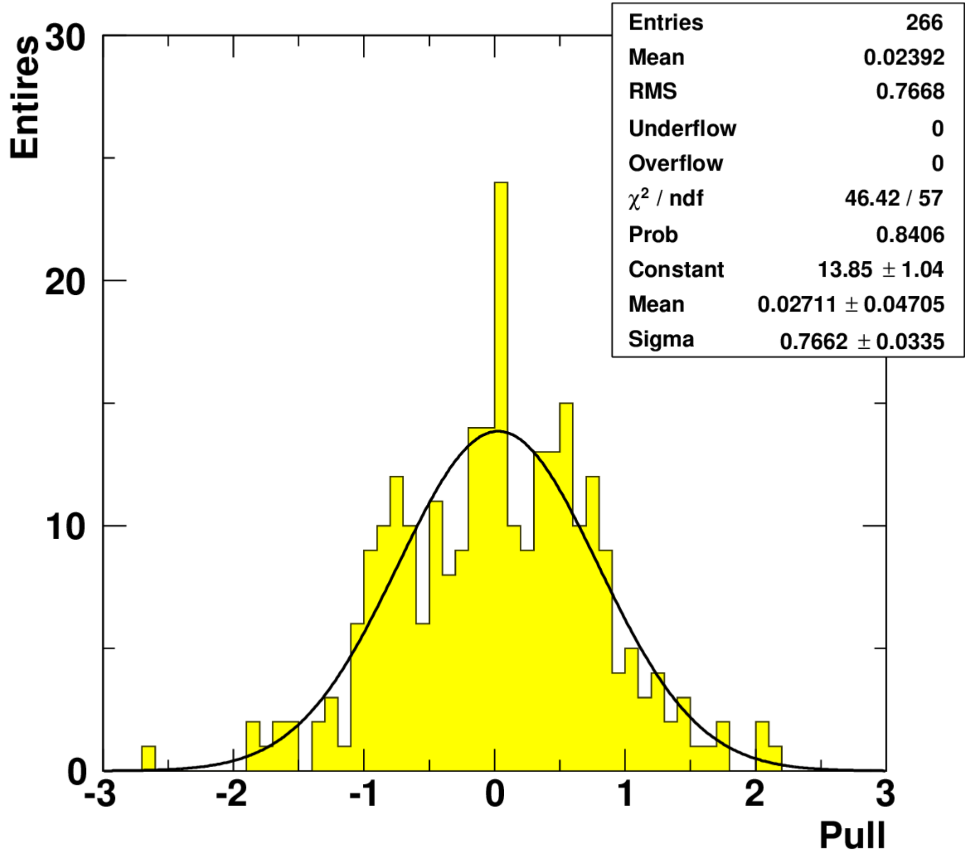
Most precise: secondary vertex, D* meson





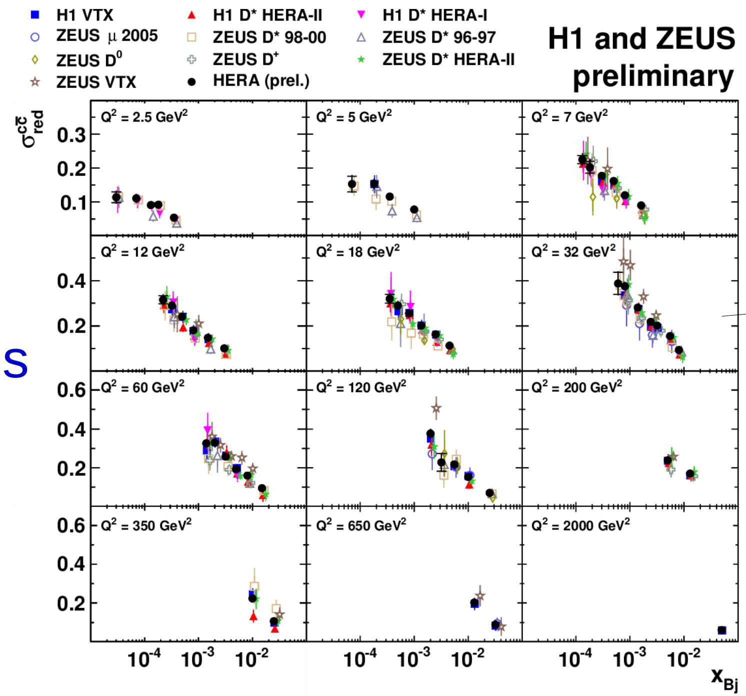
Data combination technical details

- Measurements are extrapolated to a common grid in (Q^2,x) using NLO theory. Correction factors near unity, theory variation considered as systematic uncertainty
- Combination χ^2/Ndf=149/187
- Pull distribution approximately Gaussian

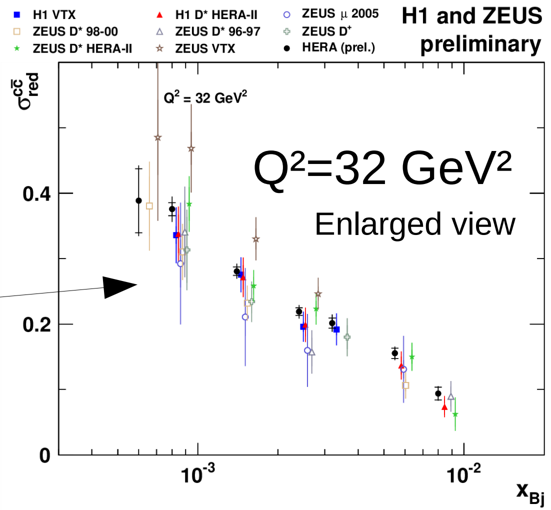


Data combination

- Many measurements are combined to a single point, large gain in precision
- Correlations of systematic uncertainties between input data points accounted for
- Shown here: charm data before/after combination



Kinematic range: $2.5 \leq Q^2 \leq 2000$ GeV²
$3\times10^{-4} \leq x \leq 5\times10^{-2}$

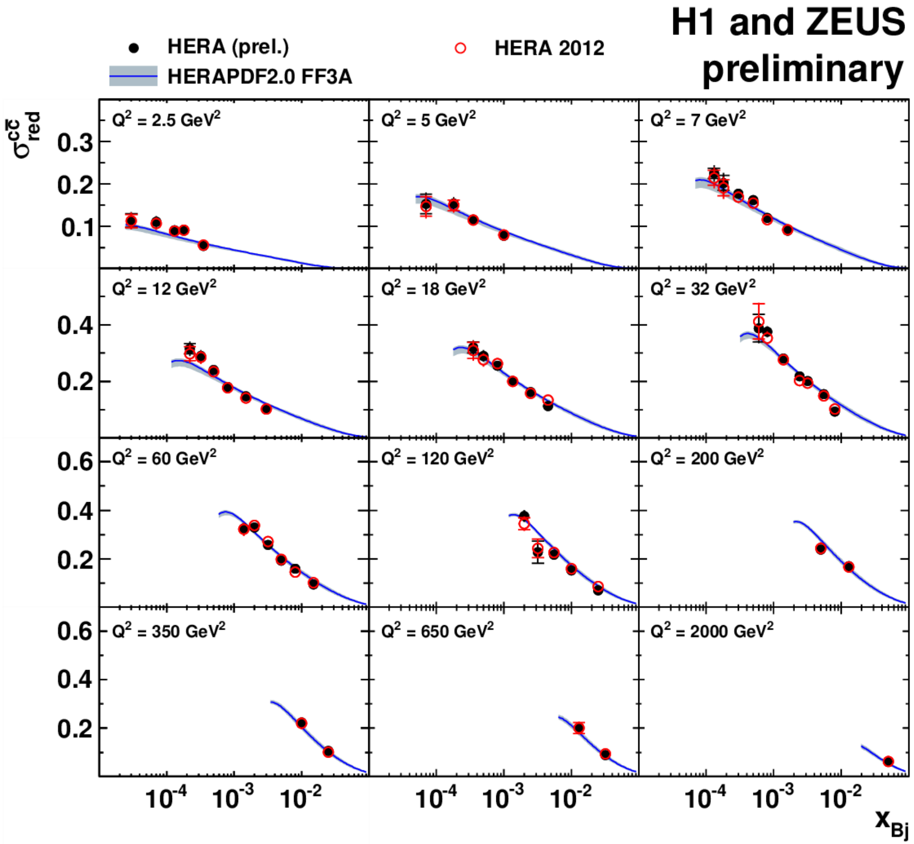


Charm: 12 bins in Q^2, a total of 52 combined data points

Beauty: 12 bins in Q^2, a total of 27 combined data points

Charm combination: 2017 and 2012

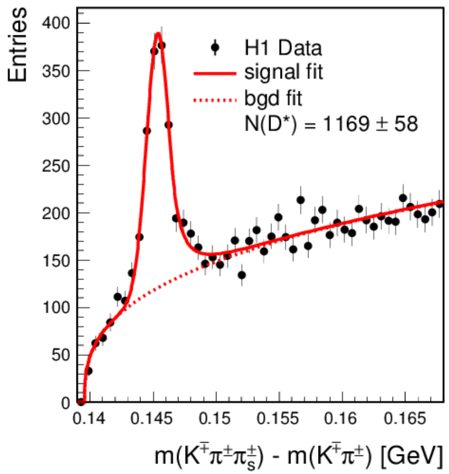
- Compare 2017 combination to 2012 combination of charm data
- Central points are similar
- Improved uncertainties by ~20% at intermediate Q²

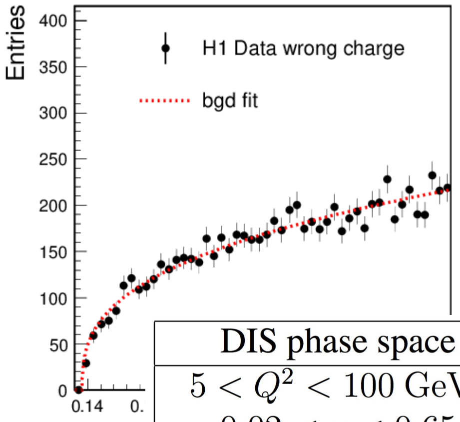


Diffractive D* analysis

- New analysis by H1
- Large-rapidity gap to select diffractive events
- Electron in backward calorimeter
- D* reconstructed in Kππ channel
- Cross sections from fit of mass distribution in each analysis bin
- NLO QCD (FFNS) with DPDF from 2006 H1 analysis of inclusive diffraction

D* in diffractive DIS



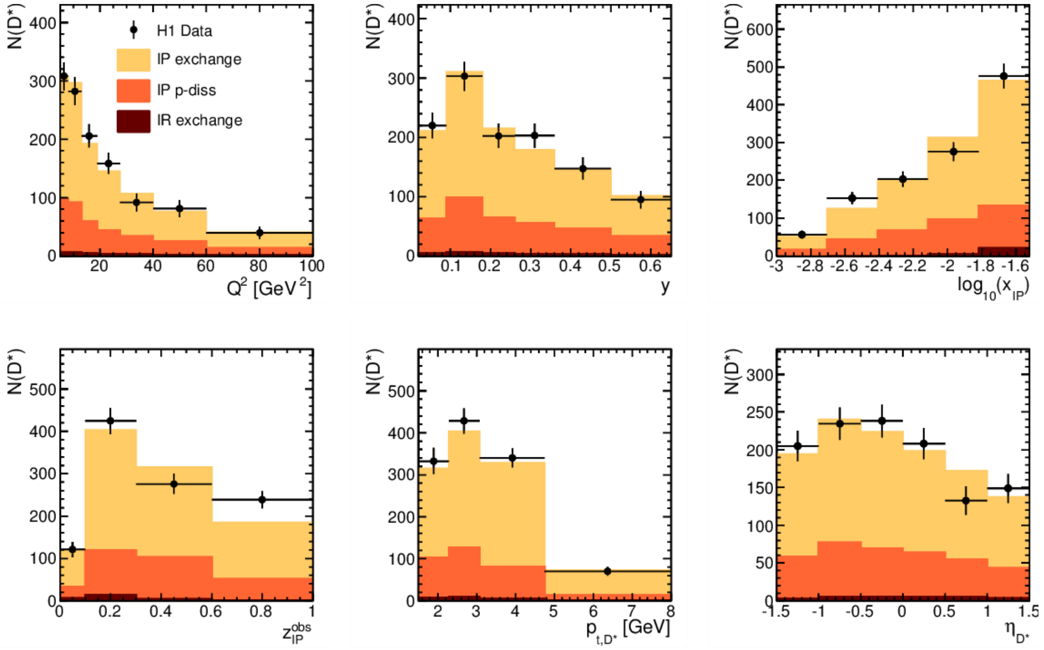


About 1100 D* mesons reconstructed.
Background shape from wrong-charge combinations

DIS phase space
$5 < Q^2 < 100\ \mathrm{GeV}^2$ $0.02 < y < 0.65$
D^* kinematics
$p_{t,D^*} > 1.5\ \mathrm{GeV}$ $-1.5 < \eta_{D^*} < 1.5$
Diffractive phase space
$x_{I\!P} < 0.03$ $M_Y < 1.6\ \mathrm{GeV}$ $\lvert t\rvert < 1\ \mathrm{GeV}^2$

Diffractive D* control distributions

- Analysis of difrractive D*
- Number of D* mesons is determined from a fit of the mass in each analysis bin
- The results are well described by the MC model which is used for acceptance corrections



Diffractive D* kinematic variables

- The cross section is also studied wrt D* kinematic variables
- The results are described by the NLO calculation

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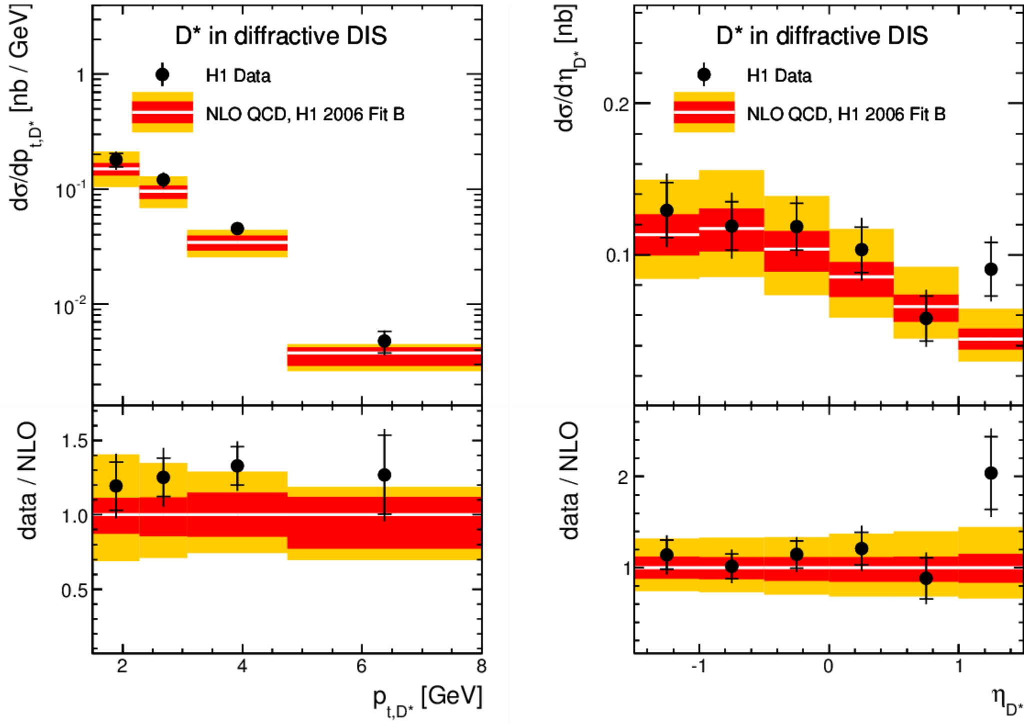

Ratio to inclusive D* production

- D* production in inclusive DIS has been measured earlier at HERA
- Shown here: ratios of diffractive to inclusive D* production
- Ratio variations are expected from diffractive phase-space limitations
- Theory: NLO (diffractive) divided by NLO (inclusive) describes data well

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