Heavy flavour production at HERA

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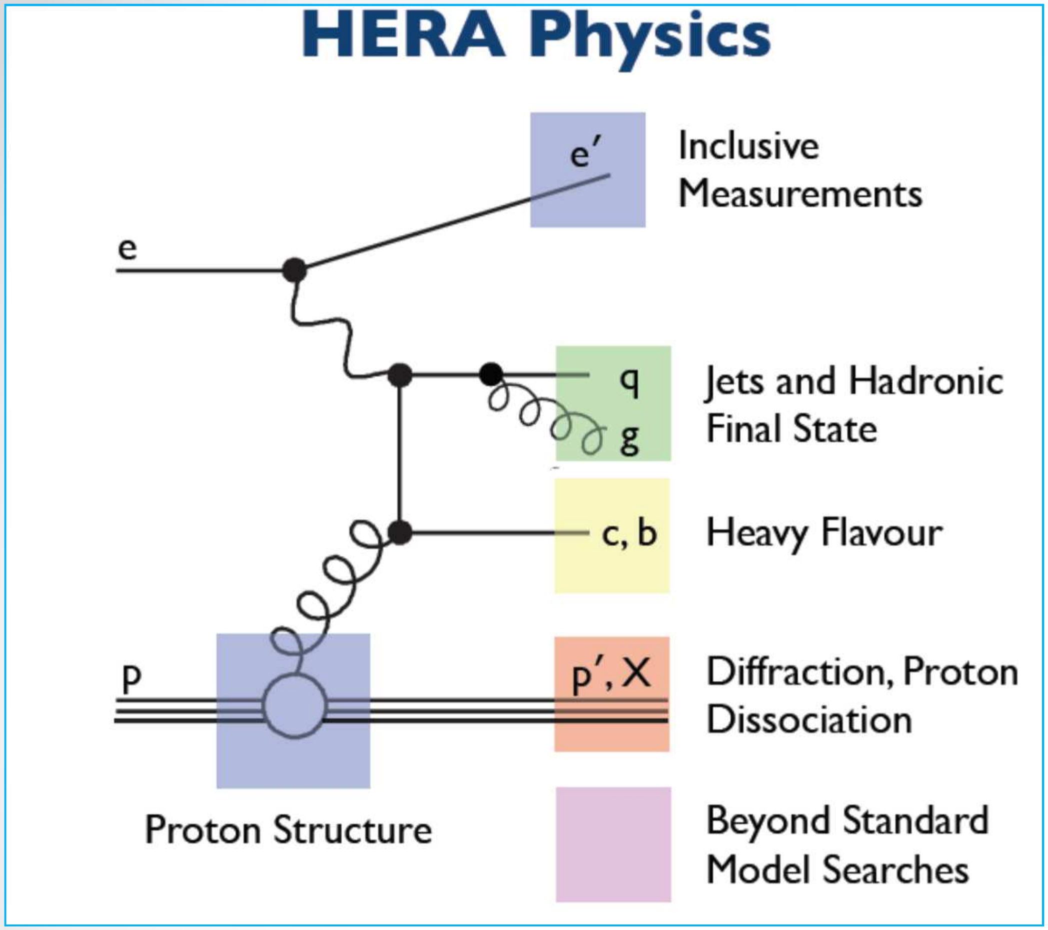
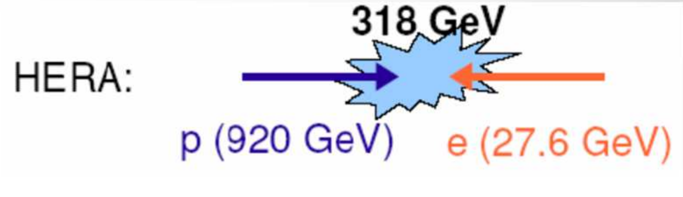
(on behalf of the H1 and ZEUS Collaborations)

Gatchina, Russia, June 30 – July 4, 2014

1992: Hadron-Electron Ring Accelerator (HERA) @ DESY





- *located* at Hamburg, Germany;
- *operated during* 1992-2007;
- *Two data-taking periods*:
  - ➡ HERA I (92-00)
  - ➡ HERA II (03-07)

HERA operated with 4 different proton beam energies (Ep):

HERA II:

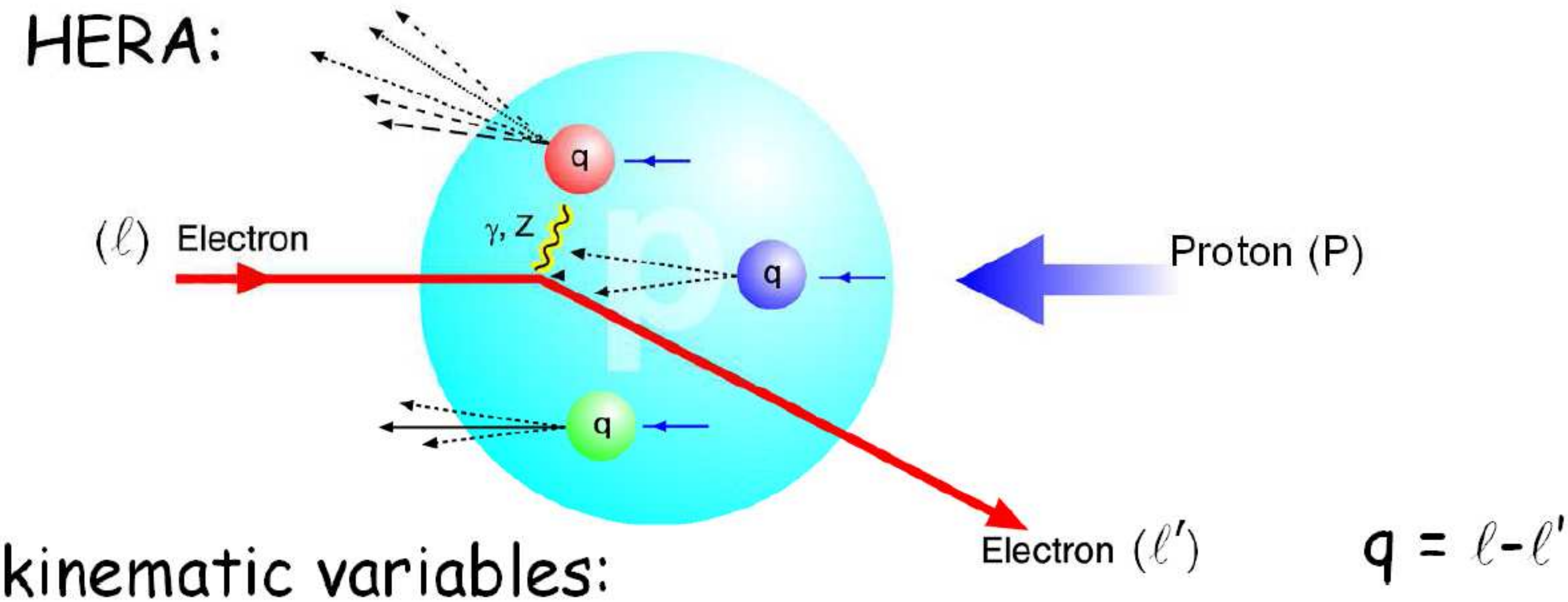
- **920 GeV** - High Energy Run (HER);
- **575 GeV** - Middle Energy Run (MER);
- **460 GeV** - Low Energy Run (LER);

HERA I:

93/98 years - energy **820 GeV**;

and electron beam energy (Ee):27.5 GeV

Deep inelastic scattering at HERA



kinematic variables:

$Q^2 = -q^2$ photon (or Z) virtuality, squared momentum transfer

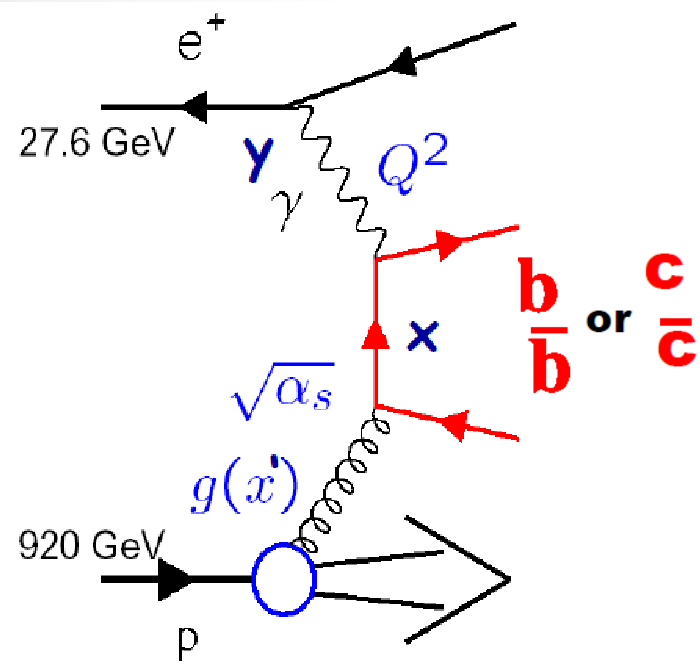
$x = \frac{Q^2}{2Pq}$ Bjorken scaling variable,
for $Q^2 \gg (2m_q)^2$: momentum fraction of p constituent

$y = \frac{qP}{\ell P}$ inelasticity,
γ momentum fraction (of e)

$Q^2 \lesssim 1\ GeV^2$: photoproduction

$Q^2 \gtrsim 1\ GeV^2$: DIS

Charm and beauty at HERA



- boson-gluon fusion is a dominant process for the charm creation in DIS;
- charm contribution to the inclusive DIS cross section is up to 30% at HERA;
- beauty cross sections much smaller than charm: $\sigma_{cc} \sim 1\ \mu b$ $\sigma_{bb} \sim 10$ nb;
- heavy flavour production sensitive to the gluon density of the proton;
- possibility to test pQCD;
- better understanding of the charm and beauty is one of the key issues for LHC experiments;

Measurement of beauty and charm production in deep inelastic scattering at HERA and measurement of the beauty-quark mass

Beauty and charm content in events with at least one jet have been extracted using the invariant mass of charged tracks associated with secondary vertices and the decay-length significance of these vertices.

ZEUS Collaboration

DESY–14–083,

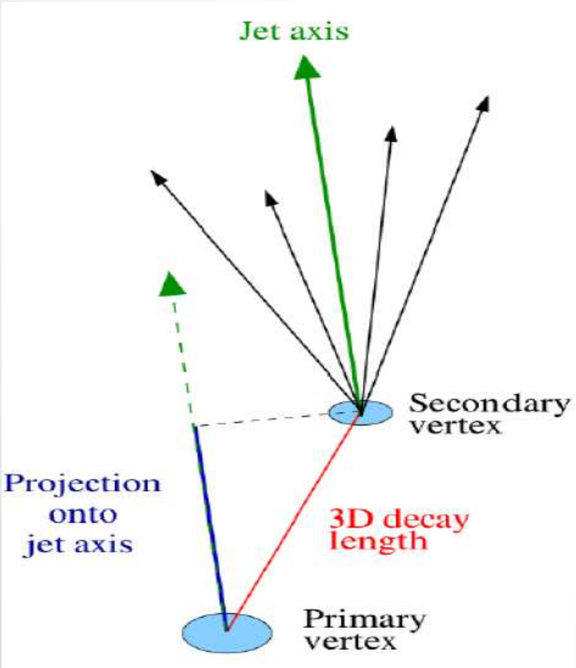
arXiv:1405.6915

May 2014

Kinematic range

- $5 < Q^2_{da} < 1000$ GeV^2
- $y_{el} < 0.7$
- $y_{jb} > 0.02$

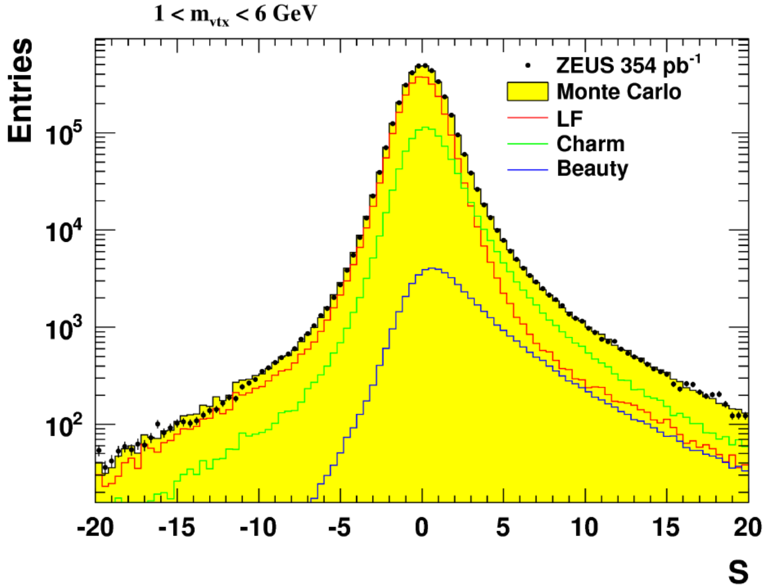
HERA II 04–07, 354 pb^{-1}



Project decay length on XY plane (L_{SV}) and then on jet axis

Calculate it's significance ***S*** defined as *d/δd*, where *δd* - uncertainty on decay-length d.

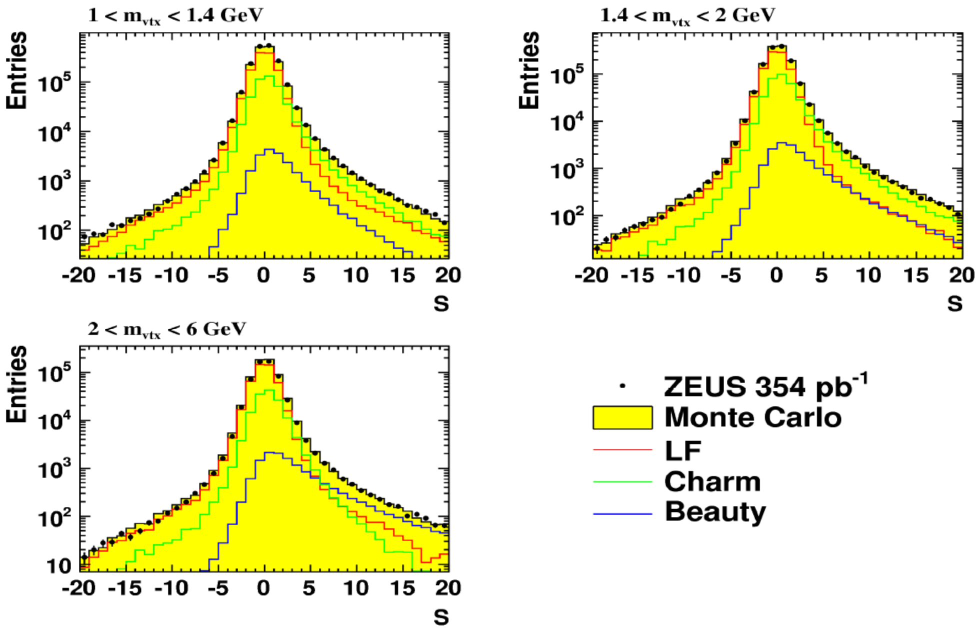
Significance



- Good description
- Beauty and charm are asymmetric due to long lifetime

Beauty and charm content in the selected sample was determined using the shape of the decay-length significance distribution together with the secondary-vertex mass distribution, m_{vtx}.

Significance in bins of vertex mass



MC simulation provides a good description of the data

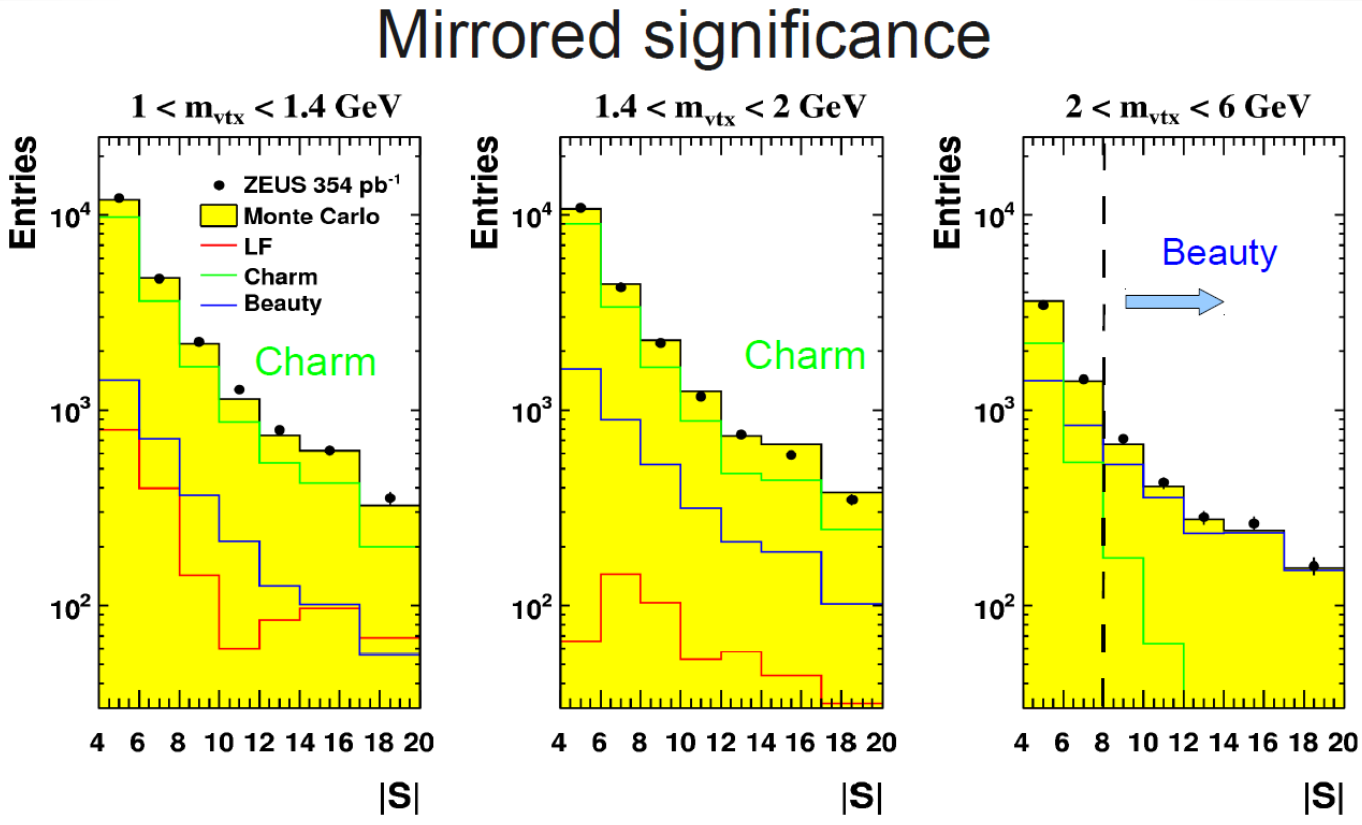
Highest mass bin is more sensitive to beauty
Subtract the negative part from the positive (mirror) to suppress LF

Charm enrichment: mirroring, S^+-S^->4, 1<M_{vtx}<2 GeV

Beauty enrichment: mirroring, S^+-S^->8, 2<M_{vtx}<6 GeV

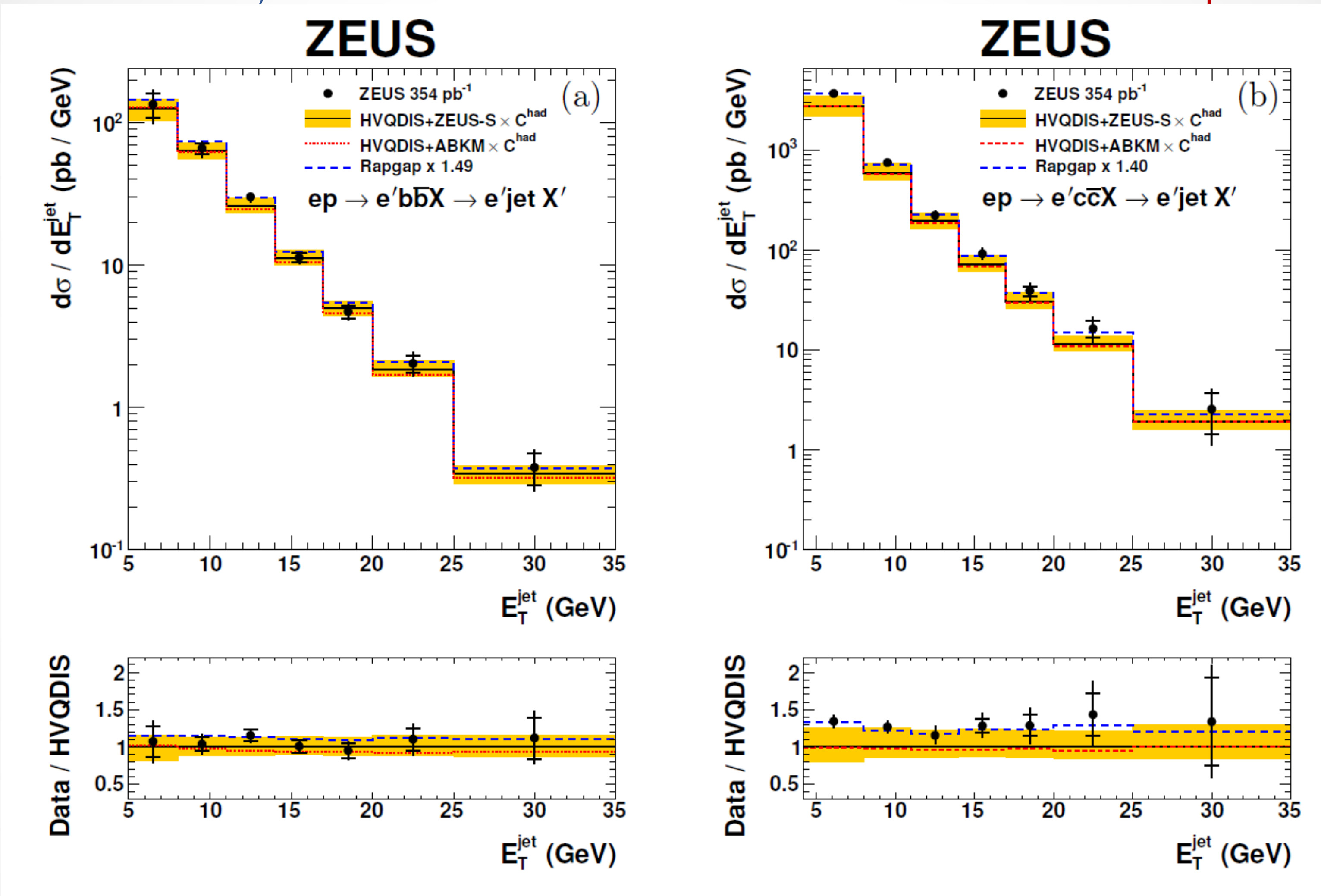
Charm and Beauty in DIS with inclusive secondary vertices

Contents of the negative bins of the significance distribution, N(S-), were subtracted from the contents of the corresponding positive bins, N(S+), yielding a subtracted decay length significance distribution: contribution from light-flavour quarks is minimized. To reduce the contamination of tracks originating from the primary vertex: |S| > 4 .



– Simultaneous fit of three massbins, and inclusive one (unmirrored)

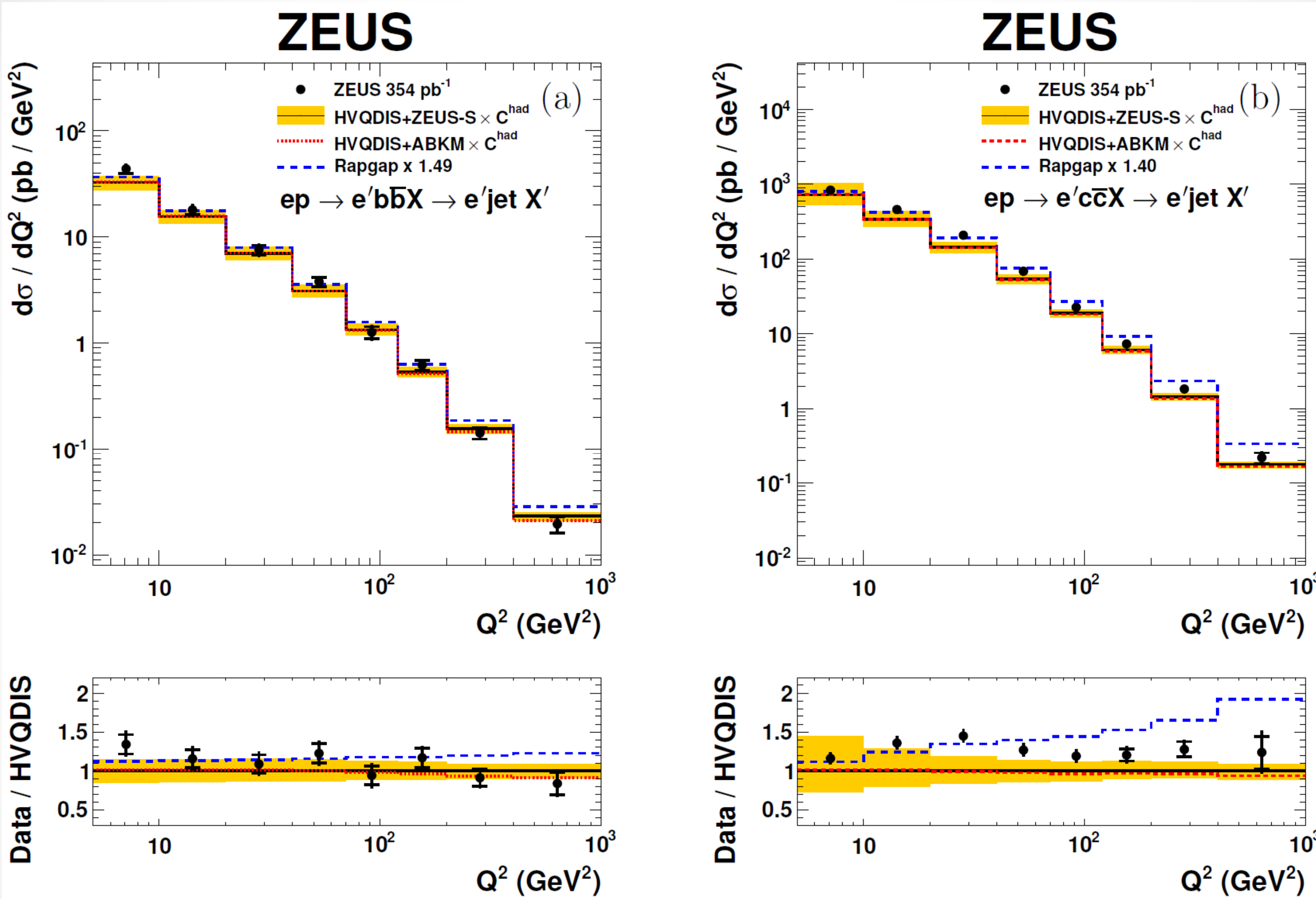
Differential cross sections for inclusive jet production in beauty and charm events as a function of E^{jet}_T



Beauty cross sections are reasonably well described

Charm cross sections: Rapgap provides a worse description than Hvqdis

Differential cross sections for inclusive jet production in beauty and charm events as a function of Q^2

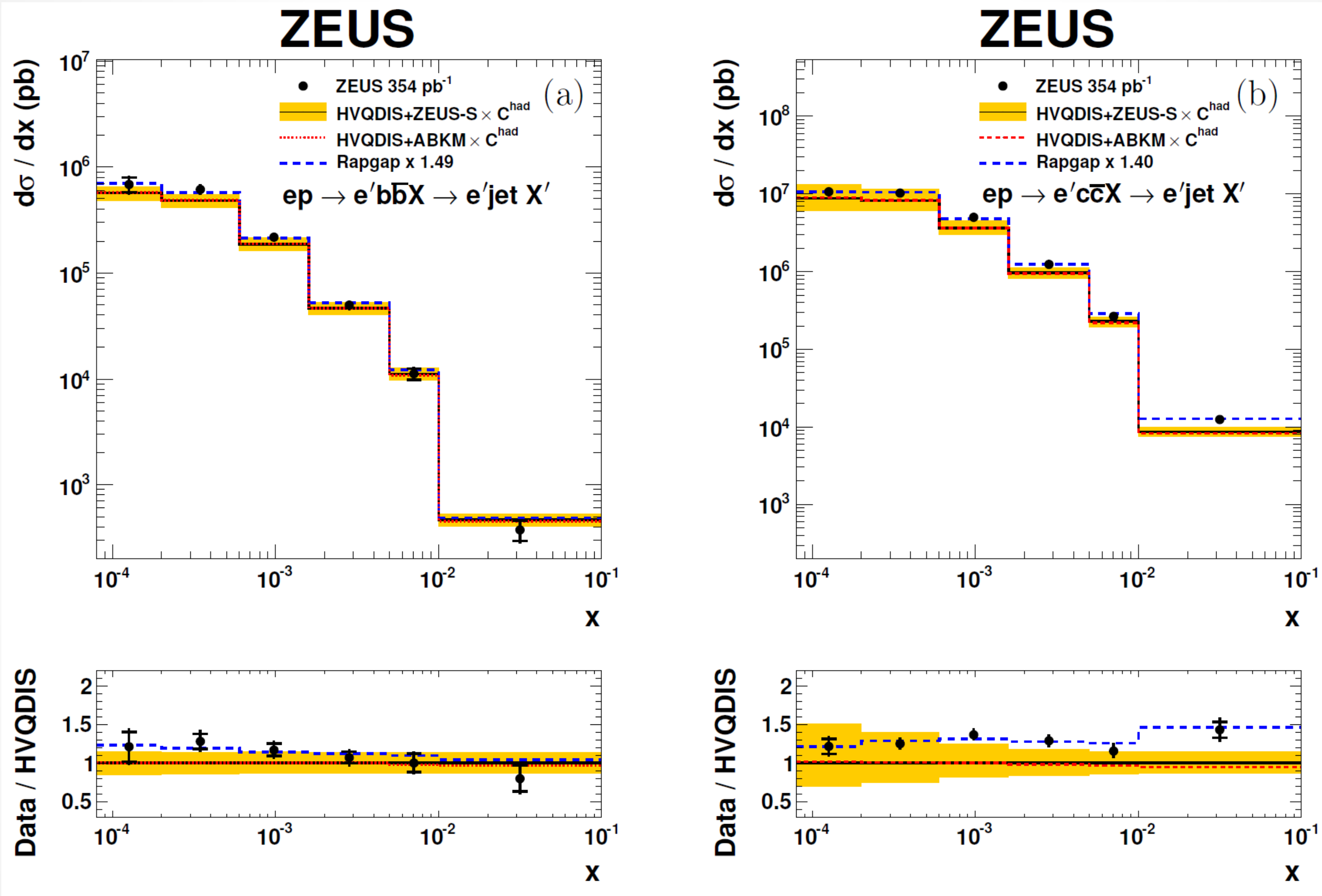


Data more precise than theory in most bins !

Beauty cross sections are reasonably well described

Charm cross sections: Rapgap provides a worse description than Hvqdis

Differential cross sections for inclusive jet production in beauty and charm events as a function of x

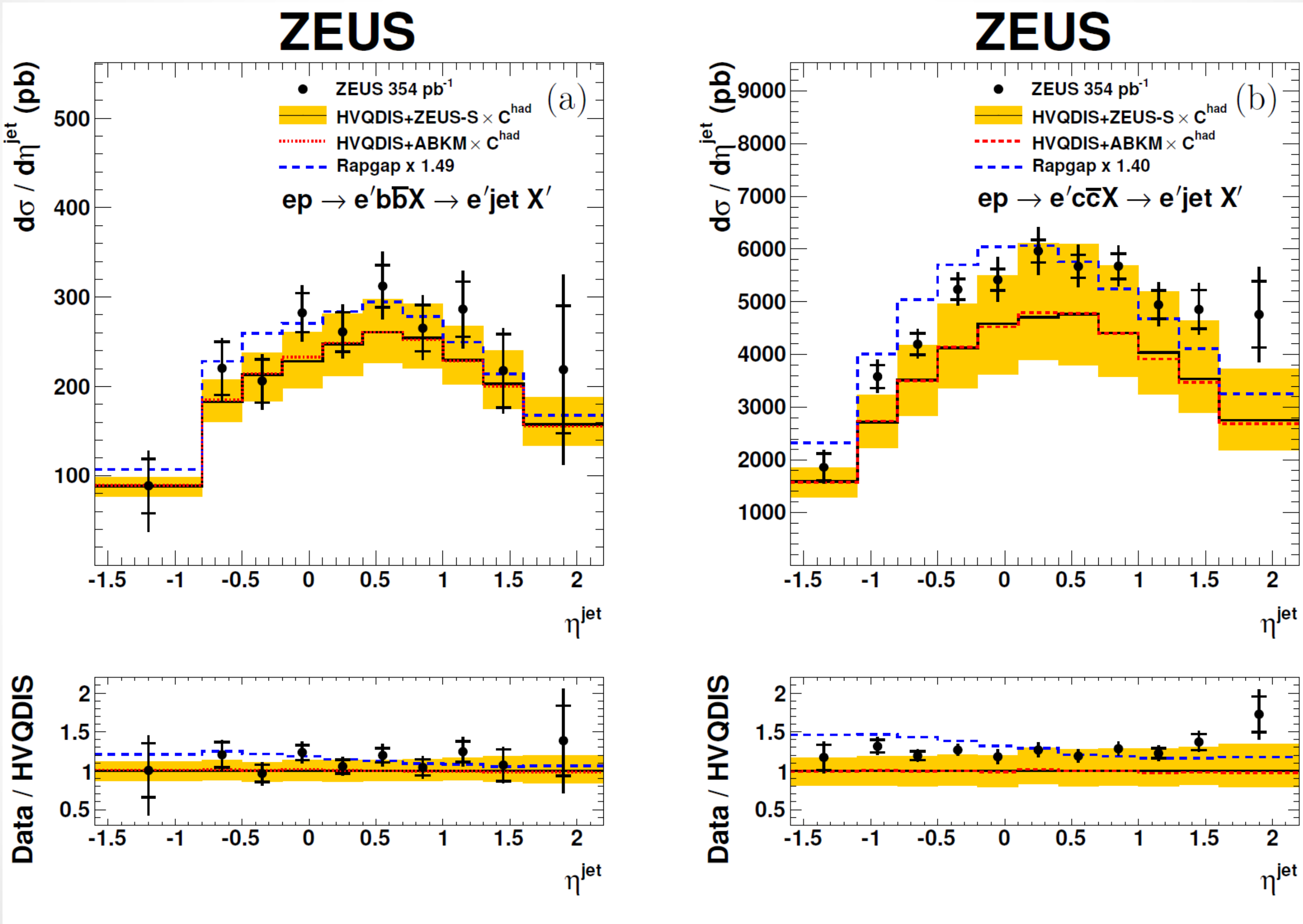


Data more precise than theory in most bins !

Beauty cross sections are reasonably well described

Charm cross sections: Rapgap provides a worse description than Hvqdis

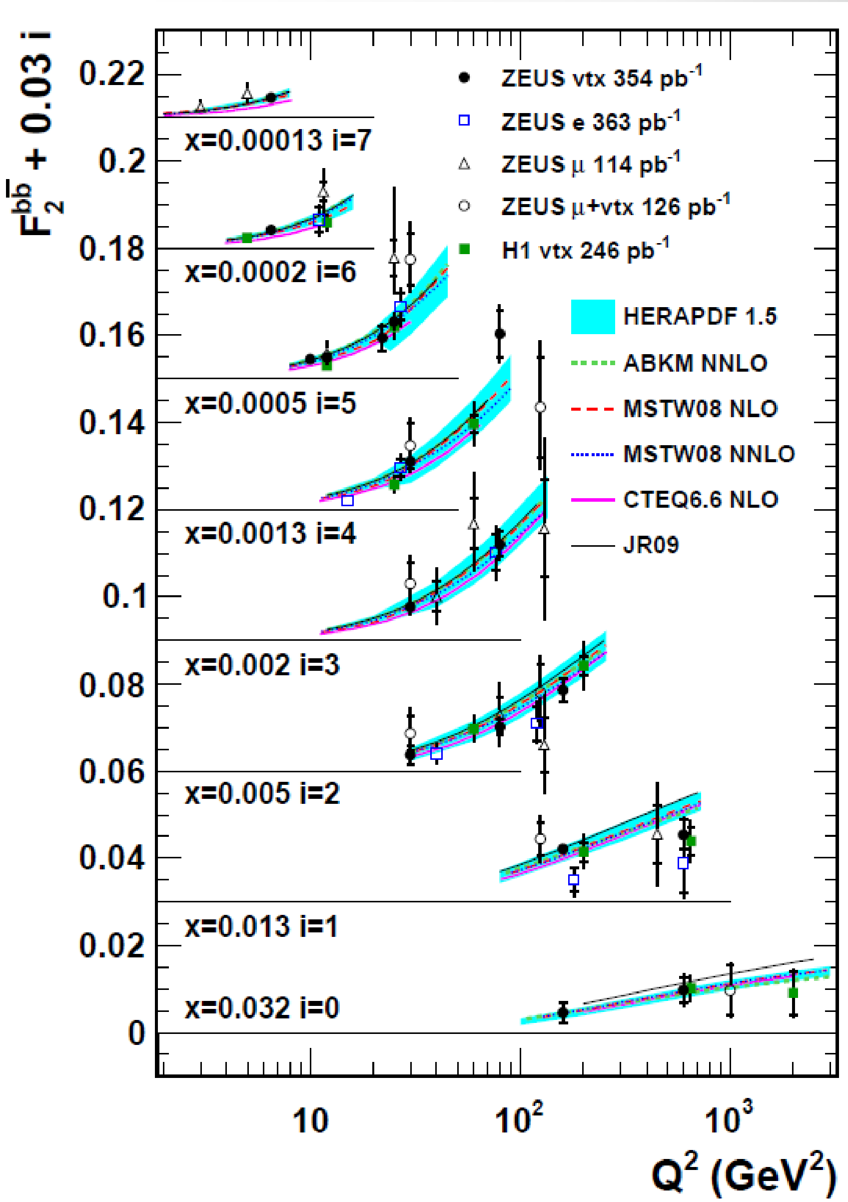
Differential cross sections for inclusive jet production in beauty and charm events as a function of η^{jet}



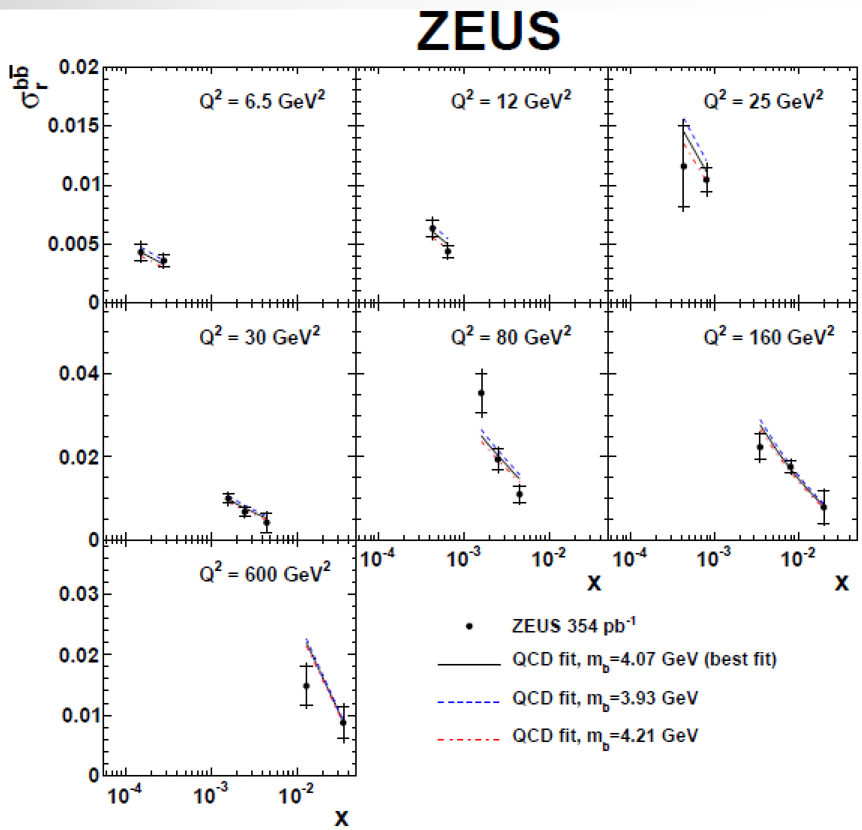
Data more precise than theory in most bins !

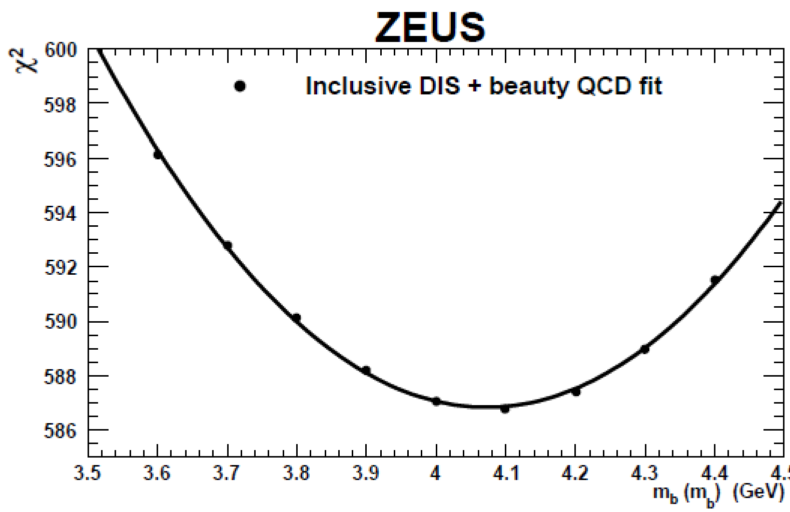
F_2^{bb} measurement as a function of Q^2 for fixed x

- **Beauty and charm contributions to the proton structure functions were extracted from the double-differential cross section as a function of x and Q^2.**
- **Very competitive precision: in a wide range of Q2, this measurement represents the most precise determination of F_2^{bb} at HERA.**
- **Good agreement with the previous ZEUS analyses and H1 measurements.**



Measurement of the running beauty-quark mass





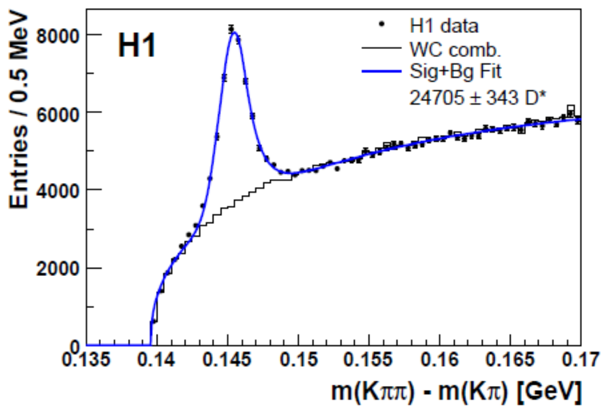
- Beauty data are well described by FFNS
- Measured running mass $m_b(m_b) = 4.07 \pm 0.14(exp)^{+0.01}_{-0.07}(mod)^{+0.05}_{-0.00}(param)^{+0.08}_{-0.05}(theo)\ GeV$ agrees with world average $m_b(m_b) = 4.18 \pm 0.03\ GeV$

Charm combination

[EPJ C73 (2013) 2311]

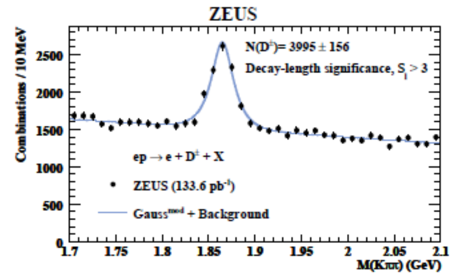
- Combination done in terms of $\sigma^{c\bar{c}}_{red} = \frac{d^2\sigma^{c\bar{c}}}{dxdQ^2} \cdot \frac{xQ^4}{2\pi\alpha^2(Q^2)(1+(1-y)^2)}$
- $\sigma^{c\bar{c}}_{red}$ are measured in a fiducial phase space $\Rightarrow$ extrapolated to the full phase space with FFNS NLO predictions $\Rightarrow$ extrapolation uncertainties
- Two experiments $\Rightarrow$ independent systematic uncertainties
- Different tagging techniqes $\Rightarrow$ independent systematic uncertainties
- **Significant reduction of both statistical and systematic uncertainties in the combination**

Charm combination

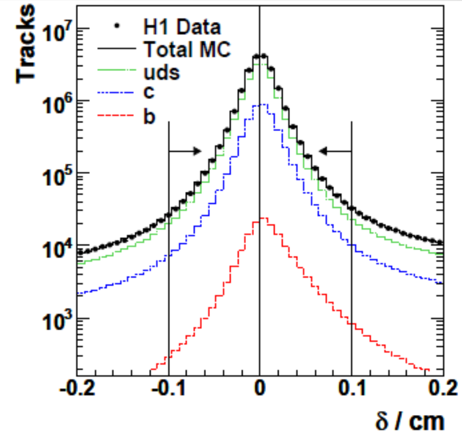


"Golden channel"

$D^{*\pm} \to D^0(\to K^\mp\pi^\pm)\pi_s^\pm$



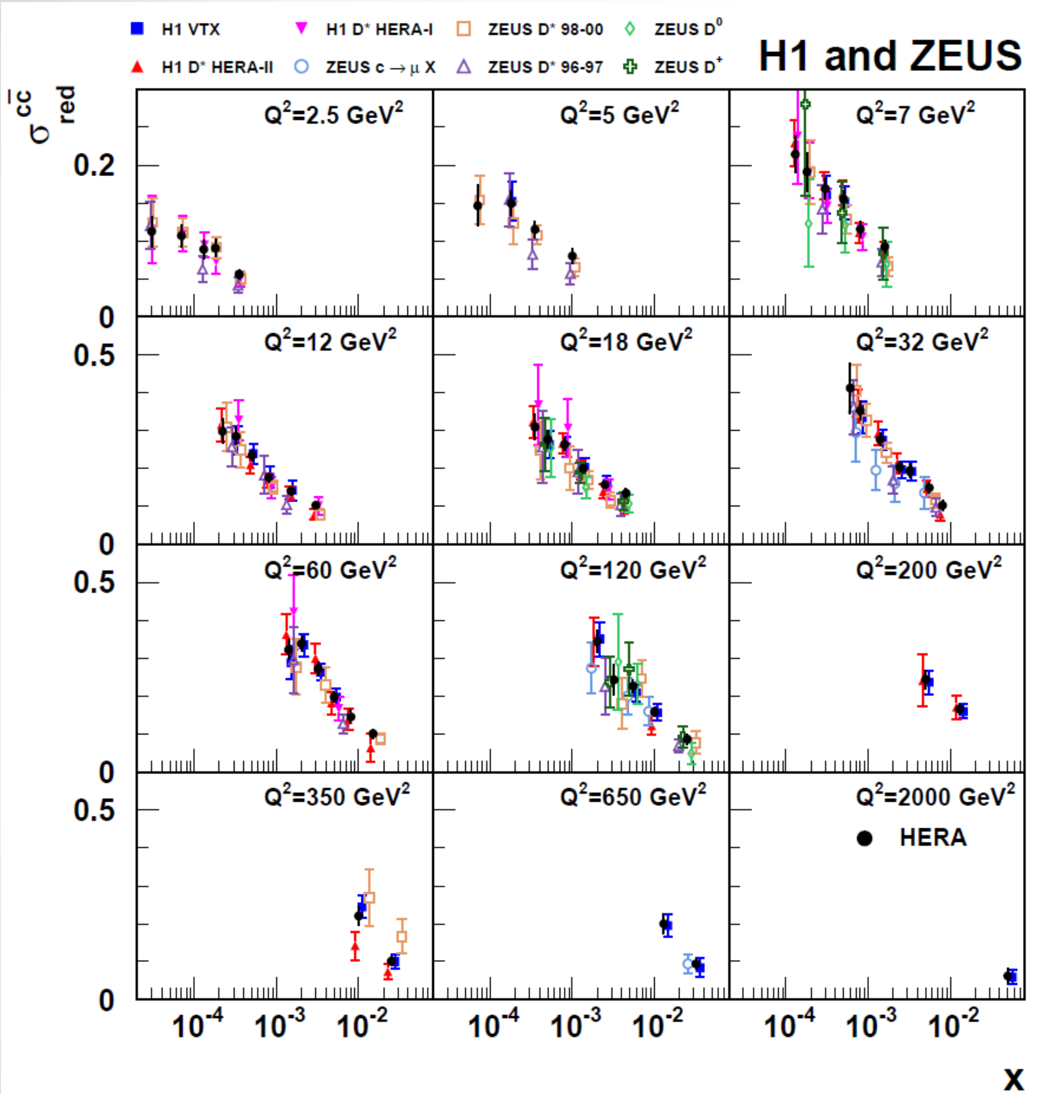
Lifetime tagging of weak decays



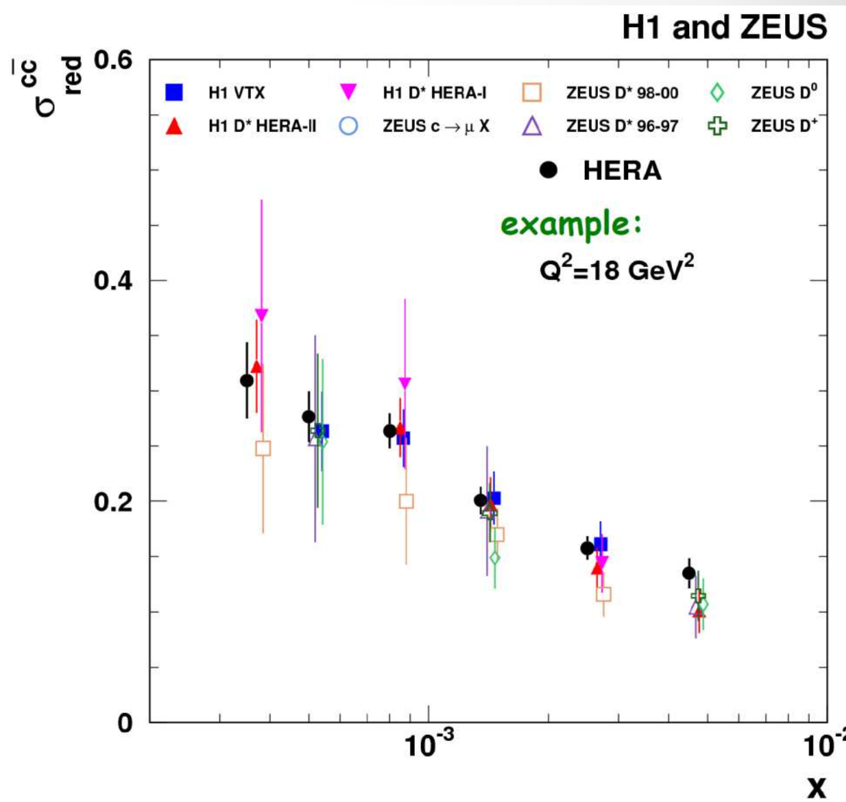
Inclusive lifetime tagging

	Data set	Tagging method	Q^2 range [GeV^2]	N	$\mathcal{L}$ [pb^{-1}]
1	H1 VTX [14]	Inclusive track lifetime	5 – 2000	29	245
2	H1 D^* HERA-I [10]	D^{*+}	2 – 100	17	47
3	H1 D^* HERA-II [18]	D^{*+}	5 – 100	25	348
4	H1 D^* HERA-II [15]	D^{*+}	100 – 1000	6	351
5	ZEUS D^* (96-97) [4]	D^{*+}	1 – 200	21	37
6	ZEUS D^* (98-00) [6]	D^{*+}	1.5 – 1000	31	82
7	ZEUS D^0 [12]	$D^{0,\mathrm{no}D^{*+}}$	5 – 1000	9	134
8	ZEUS D^+ [12]	D^+	5 – 1000	9	134
9	ZEUS μ [13]	μ	20 – 10000	8	126

Combination results

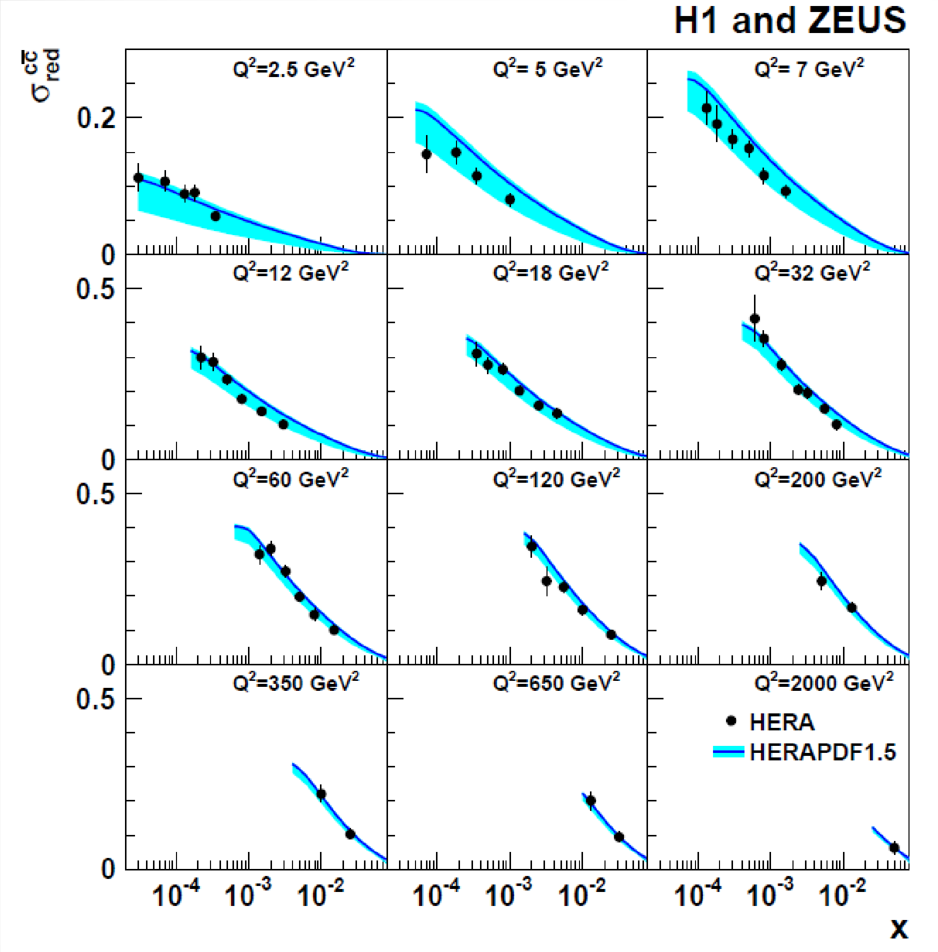


EPJ C73 (2013) 2311



Very good self consistency of data!

Running charm quark mass



Strong charm mass dependence:
blue band: 1.35÷1.6 GeV

Well described using HERAPDF1.5

Measured running mass $m_c(m_c) = 1.26 \pm 0.05(exp) \pm 0.03(mod) \pm 0.02(param) \pm 0.02(\alpha_s)\ GeV$ agrees with world average $m_c(m_c) = 1.275 \pm 0.025\ GeV$ (based mainly on lattice calculations)

H1-ZEUS combination: D* visible cross sections in DIS

The most precise measurements of D* visible differential cross sections done by ZEUS and H1 experiments in deep-inelastic scattering were combined to get ultimate precision.

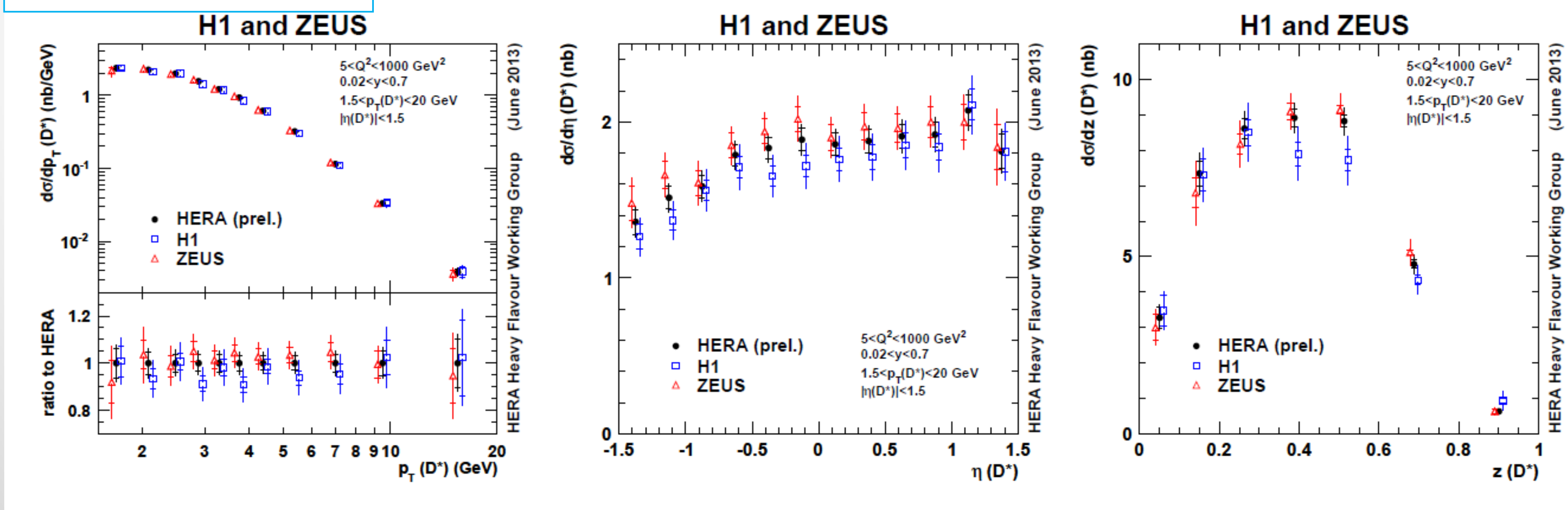
$5 < Q^2 < 1000\ \mathrm{GeV}^2,$

$0.02 < y < 0.7,$

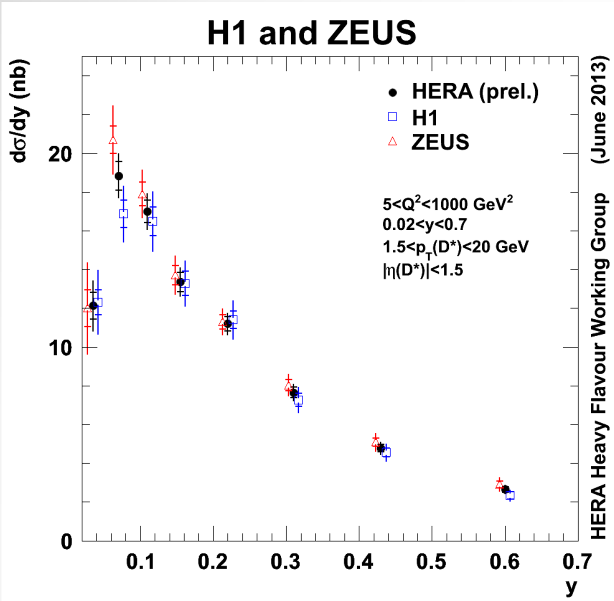
$1.5 < P_T^{D^*} < 20\ \mathrm{GeV},$

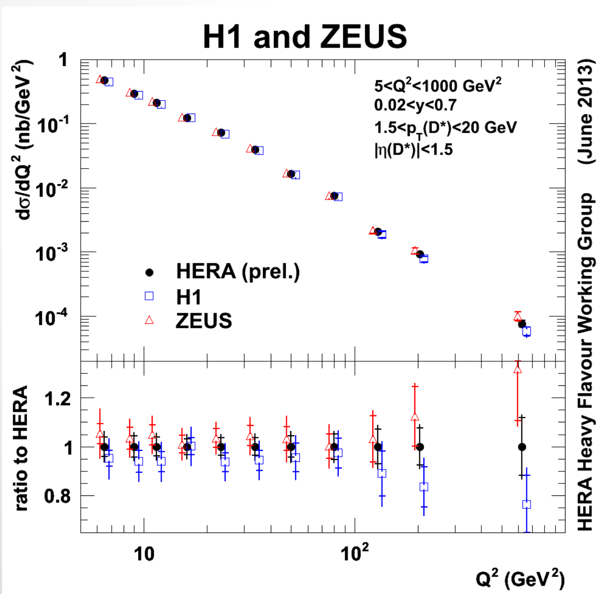
$|\eta^{D^*}| < 1.5.$

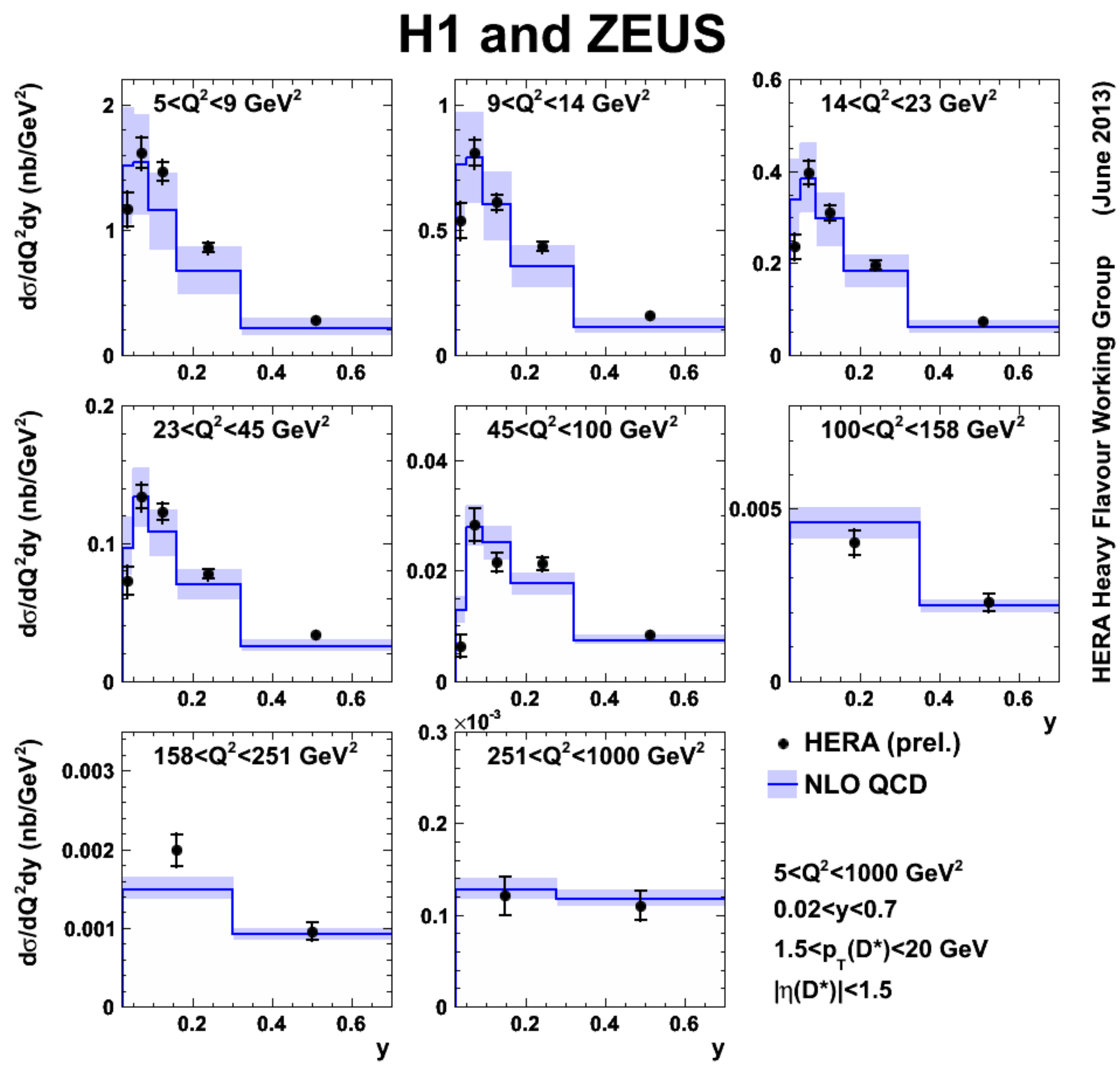
$$z^{D^*} = (E^{D^*} - p_Z^{D^*})/(2E_e y)$$



Single and double differential cross sections

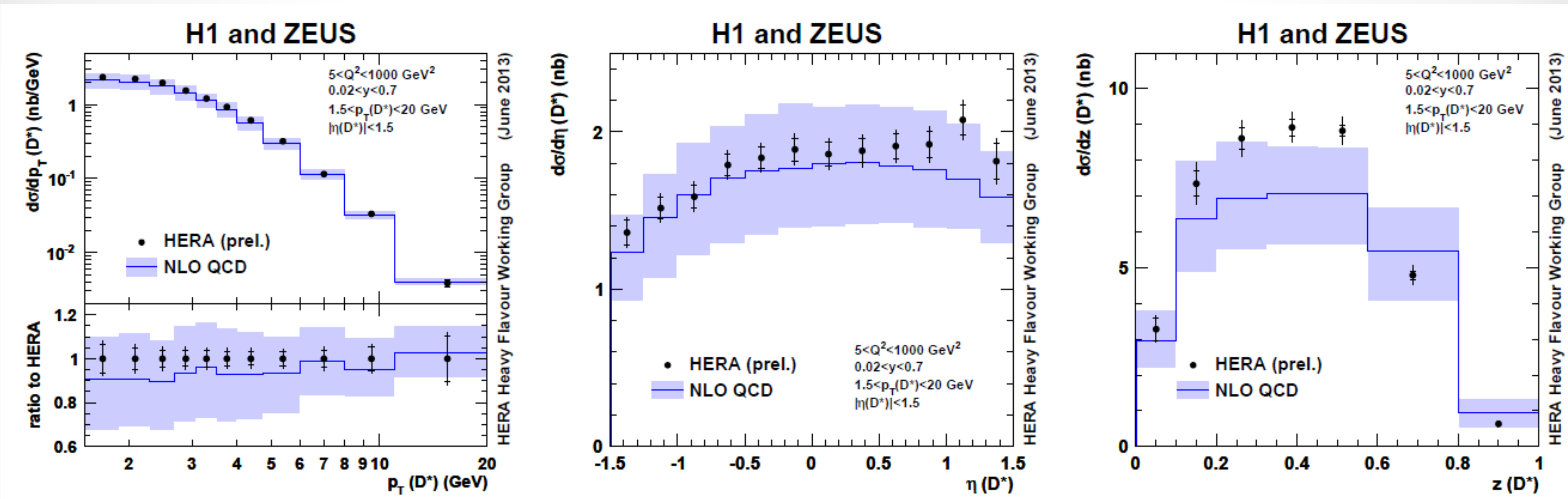






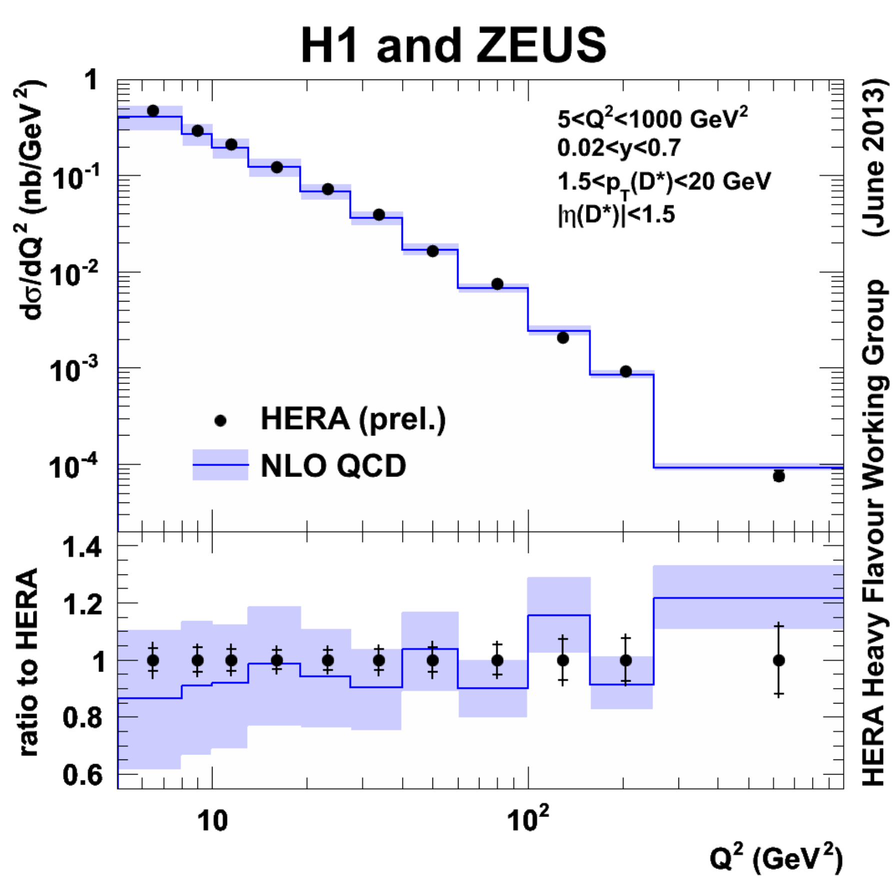
D* visible cross sections compared to NLO predictions

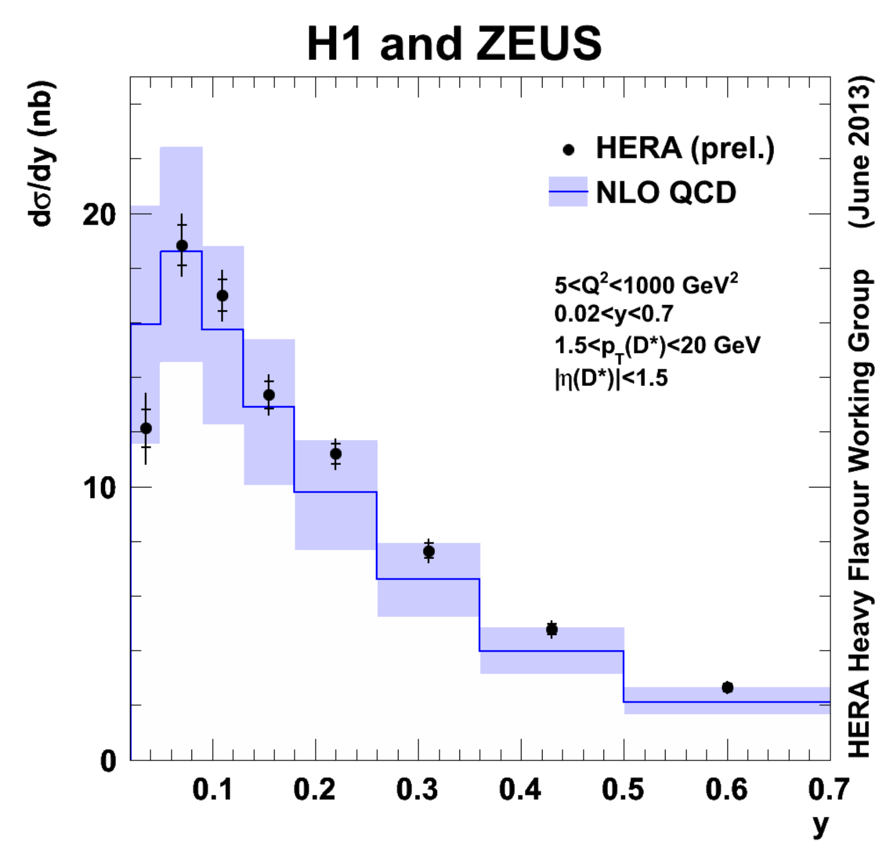
Visible level: data can be compared directly to differential NLO cross section predictions without the need for extrapolation.



- ❑ **well described by FFNS NLO;**
- ❑ **data are more precise than theory;**
- ❑ **more advanced theory is really needed !**

D* visible cross sections: comparison with NLO calculations





- well described by FFNS NLO;
- data are more precise than theory;
- more advanced theory is really needed !

Measurement of D* photoproduction at three different centre-of-mass energies at HERA

$D^{*+} \rightarrow D^0 \pi^+_{ss} \rightarrow (K^-, \pi^+)\, \pi^+_{ss}$

920 GeV - High Energy Run (HER);
575 GeV - Middle Energy Run (MER);
460 GeV - Low Energy Run (LER);

Phase Space:

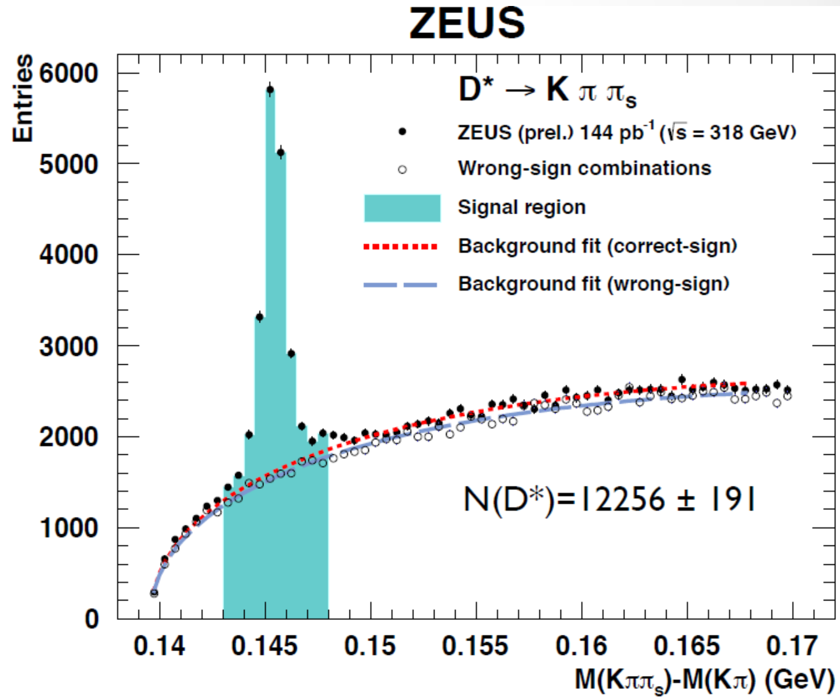
$130 < W_{HER} < 285$ GeV
$103 < W_{MER} < 225$ GeV
$92 < W_{LER} < 201$ GeV

$0.167 < y < 0.802$

$1.9 < p_T(D^*) < 20$ GeV

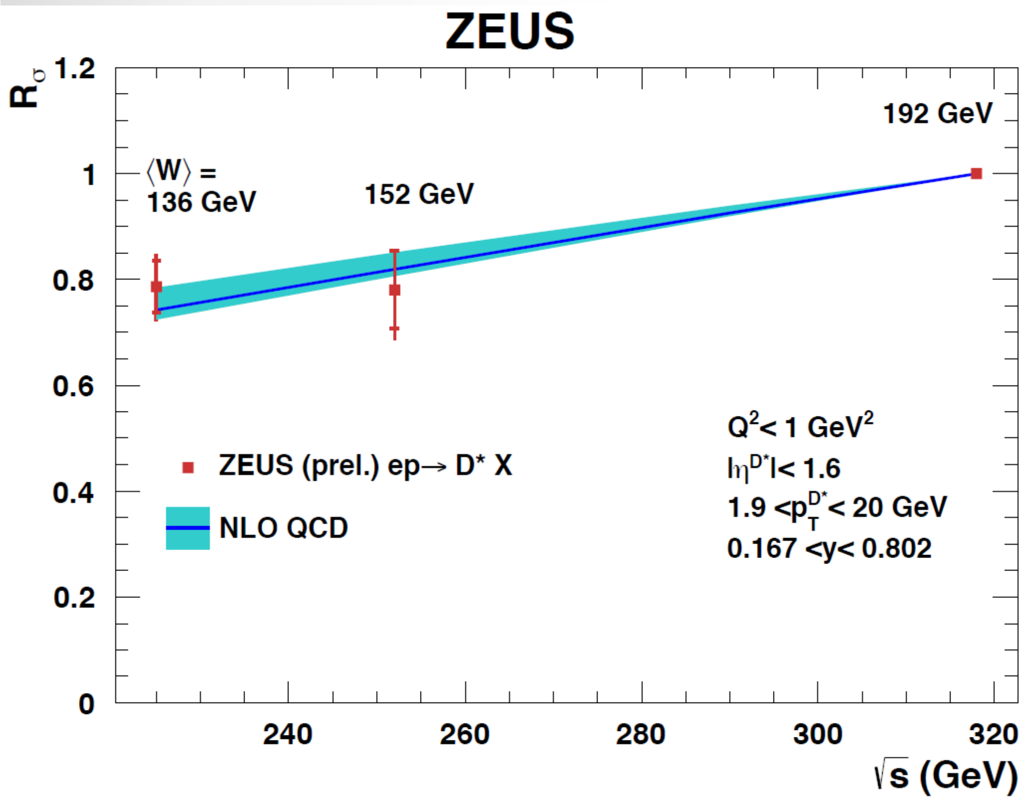
$|\eta(D^*)| < 1.6$

DESY–14–082
May 2014
to be published in JHEP



The dependence on √s was studied by normalizing to the high-statistics measurement at √s = 318 GeV. This led to the cancellation of a number of systematic effects both in data and theory.

Cross section ratios as a function of the centre-of-mass energies and comparison with the theoretical predictions



Parameters for NLO QCD calculation:

Fixed-flavor-number scheme (FFNS):

Strong coupling constant : $\alpha_s(M_Z) = 0.118$,

mass of c quarks: m =1.50 GeV

Fragmentation fraction f(c->D*)=0.237

PDFs : proton - ZEUS-S FFNS

photon - GRV-G HO

Peterson fragmentation function: = 0.079

Scales were set to $\mu = \sqrt{m_c^2 + \hat{p}_T^2}$

The cross section, normalized to that for the highest √s,

This dependence on the ep centre-of-mass energy is measured for the first time at HERA !

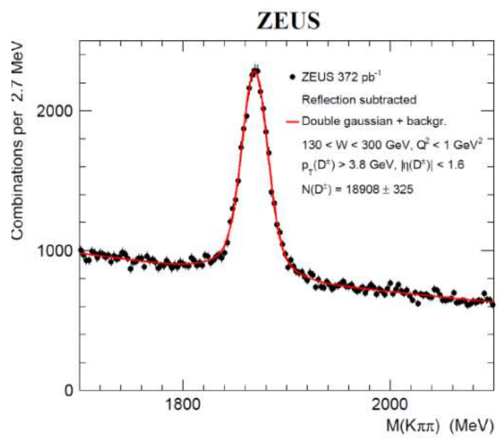
Increasing with √s is predicted well by perturbative QCD, demonstrating consistency of the gluon distribution probed here with that extracted in fits to the proton PDFs and enhancing confidence in predictions for future higher energy ep colliders!

Measurement of charm fragmentation fractions

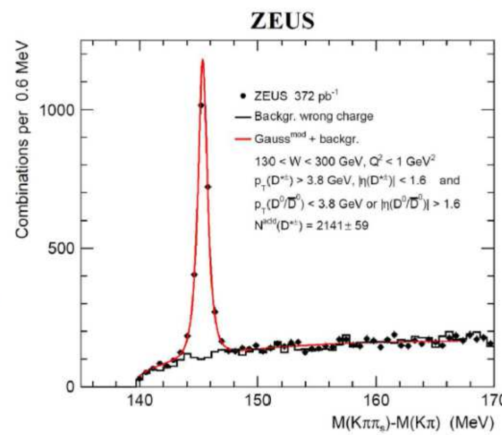
JHEP 09 (2013) 058

- **Determined fragmentation fractions of charm hadrons with HERA II data(372pb^{-1}), i.e. the probability of c-quark to hadronising into particular charm meson *$f(c \rightarrow D^0, D^+, D_s^+, D^{*+}, \Lambda_c)$***
- **Kinematic range: transverse momentum *$p_T(D^0, D^+, D_s^+, D^{*+}, \Lambda_c)$>3.8 GeV* and their pseudorapidity *|η|<1.6*;**
- ***Significantly suppressed* background using microvertex detector (MVD);**

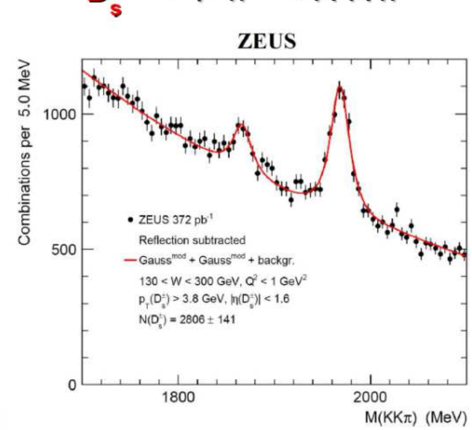
$D^+ \rightarrow K^-\pi^+\pi^+$



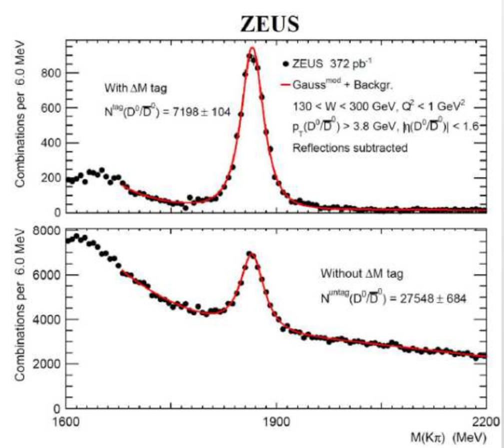
$D^{*+} \rightarrow D^0\pi_s^+ \rightarrow K^-\pi^+\pi_s^+$



$D_s^+ \rightarrow \Phi^0\pi^+ \rightarrow K^+K^-\pi^+$



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

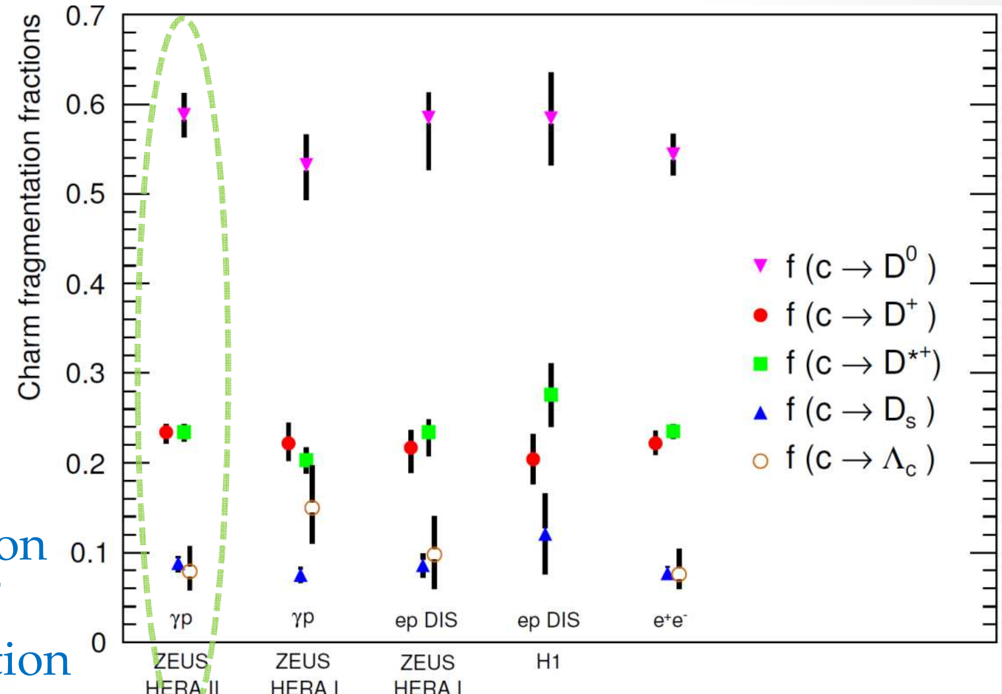


The obtained precision is competitive with results in e+e- collisions!

New results

	ZEUS (γp) HERA II			ZEUS (γp) [1] HERA I			ZEUS (DIS) [3,4] HERA I		
	stat.	syst.	br.	stat.	syst.	br.	stat.	syst.	br.
$f(c \to D^+)$	0.234 ± 0.006	${}^{+0.004}_{-0.006}$	${}^{+0.006}_{-0.008}$	0.222 ± 0.015	${}^{+0.014}_{-0.005}$	${}^{+0.011}_{-0.013}$	0.217 ± 0.018	${}^{+0.002}_{-0.019}$	${}^{+0.009}_{-0.010}$
$f(c \to D^0)$	0.588 ± 0.017	${}^{+0.011}_{-0.006}$	${}^{+0.012}_{-0.018}$	0.532 ± 0.022	${}^{+0.018}_{-0.017}$	${}^{+0.019}_{-0.028}$	0.585 ± 0.019	${}^{+0.009}_{-0.052}$	${}^{+0.018}_{-0.019}$
$f(c \to D_s^+)$	0.088 ± 0.006	${}^{+0.002}_{-0.007}$	${}^{+0.005}_{-0.005}$	0.075 ± 0.007	${}^{+0.004}_{-0.004}$	${}^{+0.005}_{-0.005}$	0.086 ± 0.010	${}^{+0.007}_{-0.008}$	${}^{+0.005}_{-0.005}$
$f(c \to \Lambda_c^+)$	0.079 ± 0.013	${}^{+0.005}_{-0.009}$	${}^{+0.024}_{-0.014}$	0.150 ± 0.023	${}^{+0.014}_{-0.022}$	${}^{+0.038}_{-0.025}$	0.098 ± 0.027	${}^{+0.020}_{-0.017}$	${}^{+0.025}_{-0.023}$
$f(c \to D^{*+})$	0.234 ± 0.006	${}^{+0.004}_{-0.004}$	${}^{+0.005}_{-0.007}$	0.203 ± 0.009	${}^{+0.008}_{-0.006}$	${}^{+0.007}_{-0.010}$	0.234 ± 0.011	${}^{+0.006}_{-0.021}$	${}^{+0.007}_{-0.010}$

	H1 (DIS) [2]		Combined e^+e^- data [5–16]	
	stat.⊕syst.	br.	stat.⊕syst.	br.
$f(c \to D^+)$	0.204 ± 0.026	${}^{+0.009}_{-0.010}$	0.222 ± 0.010	${}^{+0.010}_{-0.009}$
$f(c \to D^0)$	0.584 ± 0.048	${}^{+0.018}_{-0.019}$	0.544 ± 0.022	${}^{+0.007}_{-0.007}$
$f(c \to D_s^+)$	0.121 ± 0.044	${}^{+0.008}_{-0.008}$	0.077 ± 0.006	${}^{+0.005}_{-0.004}$
$f(c \to \Lambda_c^+)$			0.076 ± 0.007	${}^{+0.027}_{-0.016}$
$f(c \to D^{*+})$	0.276 ± 0.034	${}^{+0.009}_{-0.012}$	0.235 ± 0.007	${}^{+0.003}_{-0.003}$



New results

The fragmentation fractions of charm quarks are independent of the production process and supports the hypothesis of universality of heavy quark fragmentation

Summary and conclusions

- **H1 and ZEUS still providing new charm and beauty results, exploiting the full HERA statistics. Both charm and beauty provide very precise data for testing pQCD.**
- **HERA DIS charm data have been combined with very good consistency and reduced uncertainties -> measure charm mass $m_c(m_c)$;**
- **ZEUS DIS beauty data well described by NLO QCD -> measure beauty mass $m_b(m_b)$;**
- **Combination of D* visible cross sections: most precise charm measurements -> shows that more advanced theory is really needed;**
- **Energy dependence of $D^{*\pm}$ photoproduction has been measured for the first time at HERA: increasing cross section with increasing energy is predicted well by NLO QCD -> enhance confidence in the NLO QCD predictions of charm production rates, specifically, and QCD processes, in general, for a future TeV-scale ep collider (LHeC) .**
- **Measured production of D^0, D^+, D_s^+, D^{*+}, Λ_c : fragmentation fractions of charm quarks are independent of the production process;**