Heavy Flavours in High Energy *ep* Collisions

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on behalf of the H1 and ZEUS collaborations

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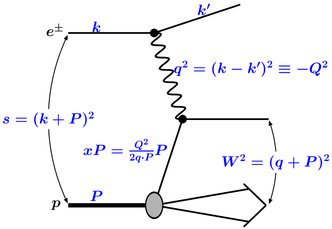
1. Introduction
2. Charm production
3. Beauty production
4. Summary

Colliding experiments at HERA

$e^{\pm}$ → ← p

	E_e	E_p	$\sqrt{s}$
94-98	27.5 GeV	820 GeV	300 GeV
99-	27.5 GeV	920 GeV	318 GeV



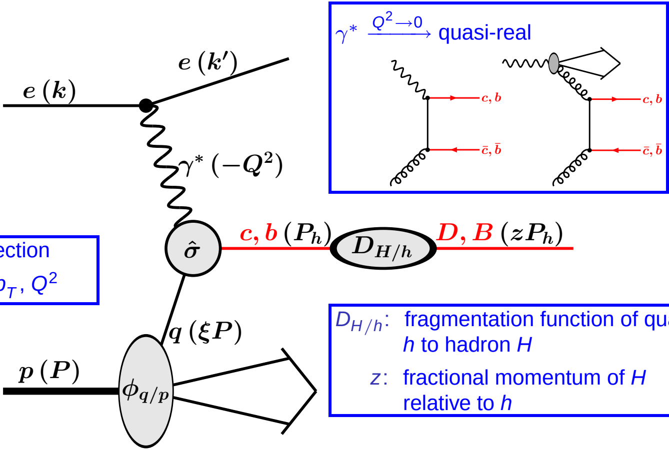
Q^2 exchanged boson virtuality

x proton's fractional momentum carried by struck parton

$$0 \xleftarrow{\text{photoproduction}(\gamma p)} Q^2(\sim 1\,\text{GeV}^2) \xrightarrow{\text{deep inelastic scattering}(DIS)} \infty$$

Heavy flavours in QCD

Factorisation: Parton densities ⊗ pQCD ⊗ Fragmentation



$\hat{\sigma}$: Partonic cross section

Hard scales: $m_{c,b}$, p_T, Q^2

$D_{H/h}$: fragmentation function of quark h to hadron H

z: fractional momentum of H relative to h

$\phi_{q/p}$: probability density of finding parton q in proton, carrying momentum ξP

Charm production

Previous measurements of inclusive charm production have shown general agreement with NLO QCD predictions.

Recent measurements:

- Exclusive *charm* $+$ *jet* photoproduction to understand photon's hadronic behaviour
- Charm production in DIS to constrain gluon density in the proton
- Charmed hadrons production to confirm charm fragmentation universality

$D^* + jet$ photoproduction

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

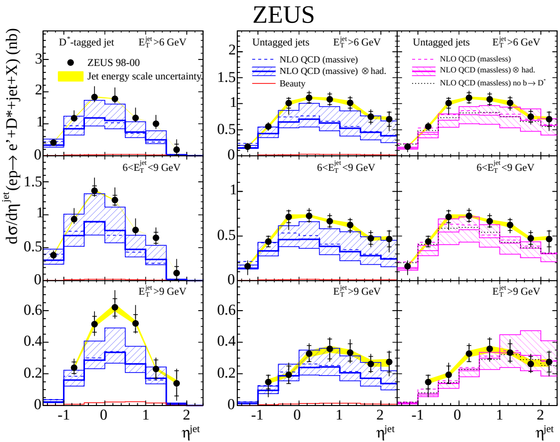
$130 < W < 280\,\text{GeV}$

$p_T^{D^*} > 3\,\text{GeV}$

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

$E_T^{jet} > 6\,\text{GeV}$

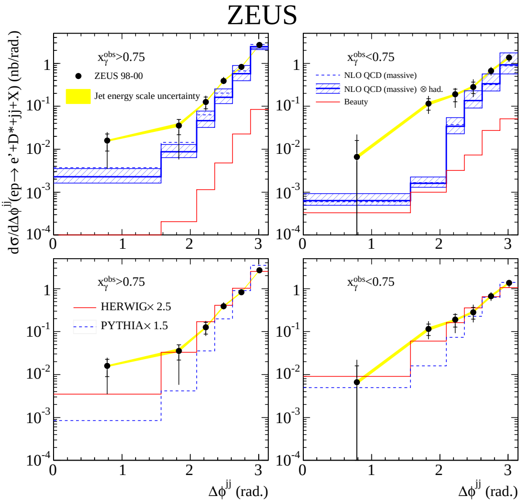
$-1.5 < \eta^{jet} < 2.4$



- Consistent with NLO massive and massless calculations
- No excess in the forward direction

Dijet correlation

$\Delta\phi^{jj} \rightarrow$ sensitive to higher-order topologies



$E_T^{jet_1} > 7\,\text{GeV} \quad E_T^{jet_2} > 6\,\text{GeV}$

$$x_\gamma^{obs} = \frac{\sum_{i=1,2} E_T^{jet_i} e^{\eta^{jet_i}}}{2yE_e}$$

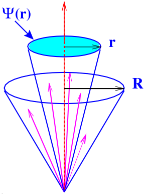
NEEDS:
higher-order calculations or additonal parton showers in current NLO calculations!

Jet shape in *charm* + *dijet* photoproduction

Tag charm jet by muon and look at the other jet

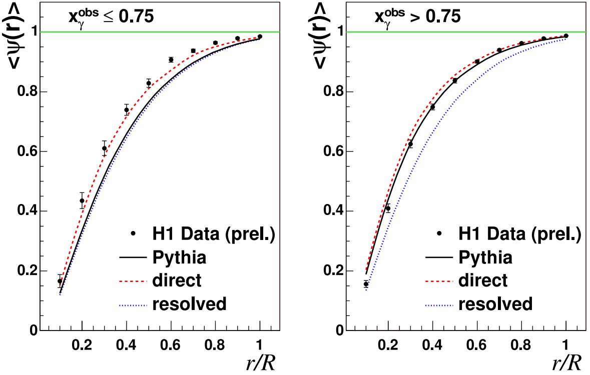
$$\Psi(r) \equiv \frac{p_T^{jet}(r' < r)}{p_T^{jet}(r' < R)}$$

$$\langle \Psi(r) \rangle = \frac{\sum_{jets} \Psi(r)}{N_{jets}}$$



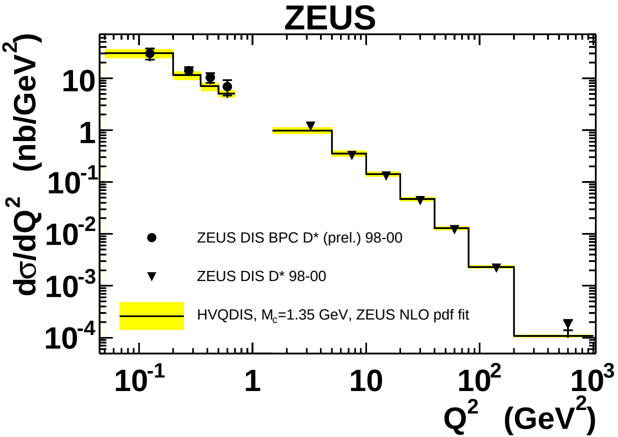
PYTHIA:

- excitation $\sim 35\%$
- proton: CTEQ5L
- photon: GRV-LO



DATA: fewer gluon jets at low x_γ

Exploiting low Q^2 region



$0.05 < Q^2 < 0.7\,\text{GeV}^2$

$0.02 < y < 0.085$

$p_T^{D^*} > 1.5\,\text{GeV}$

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

NLO QCD: well over 4 orders of magnitude in Q^2

First charm result from HERA II

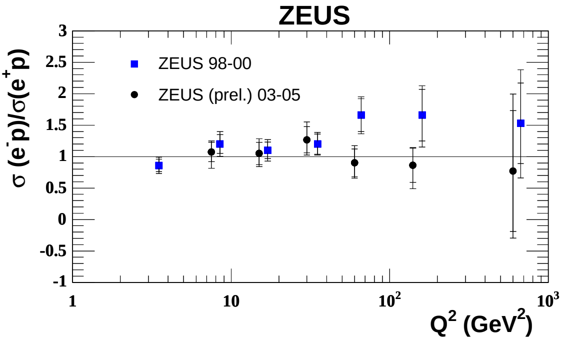
Year	$\mathscr{L}$ (pb^{-1})	
	e^-p	e^+p
98-00	17	65
03-05	33	40

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

$0.02 < y < 0.7$

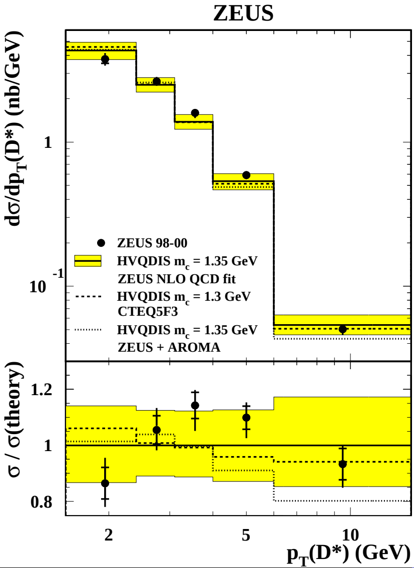
$1.5 < p_T^{D^*} < 15\,\mathrm{GeV}$

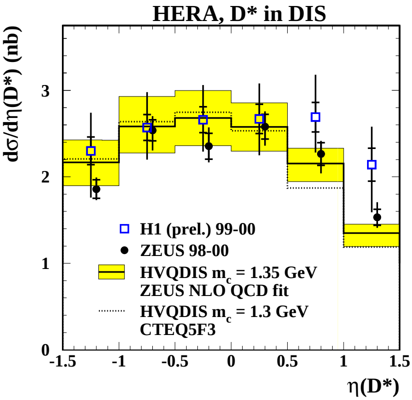
$|\eta^{D^*}| < 1.5$



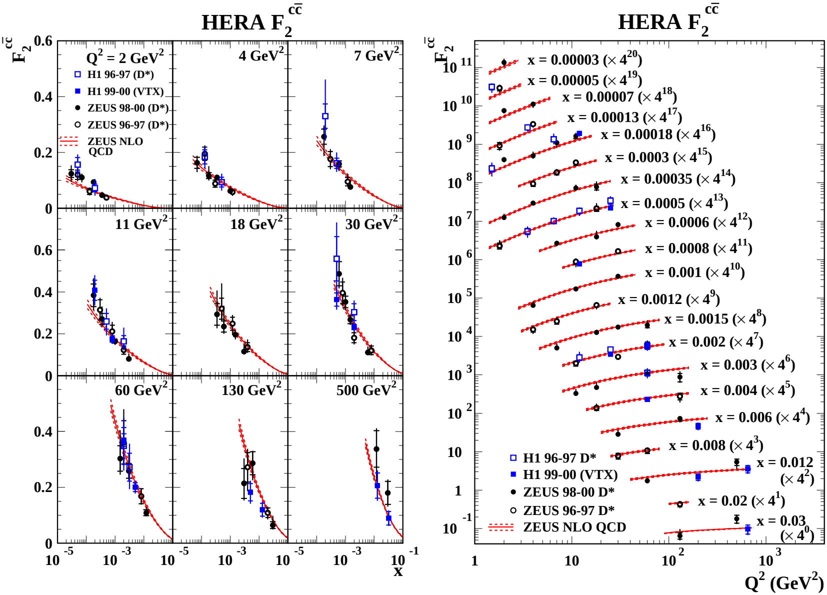
$\frac{\sigma_{e^-p\to e^-D^*X}}{\sigma_{e^+p\to e^+D^*X}}$ excess in the previous measurement NOT confirmed

Probing gluon density in the proton

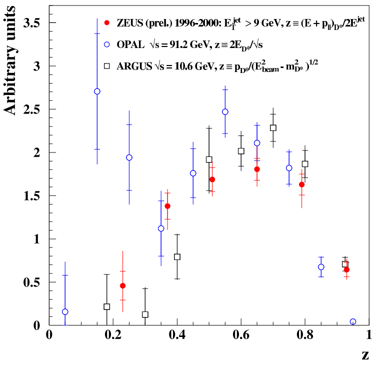


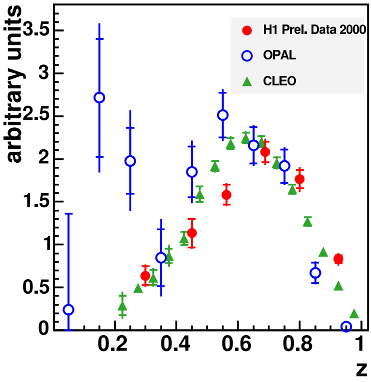


Precise measurements of $F_2^{c\bar{c}}$ at HERA



Charm fragmentation function

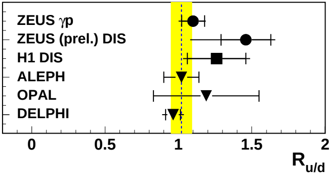




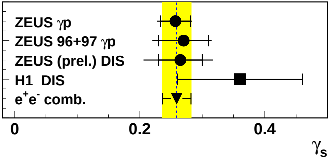
Spectra similar in shape despite different definitions

Charm fragmentation ratios and fractions

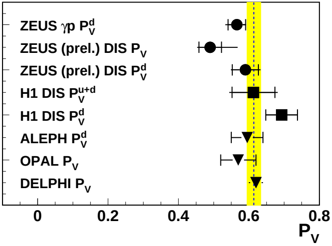
$R_{u/d} = \frac{c\bar{u}}{c\bar{d}} \approx 1 \Rightarrow$ isospin invariance

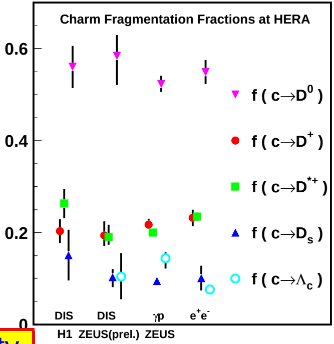


$\gamma_s = \frac{2c\bar{s}}{c\bar{d}+c\bar{u}} \approx 1/4 \Rightarrow s$ suppression



$P_V = \frac{V}{V+PS} \neq 3/4 \Rightarrow$ NOT naïve spin counting

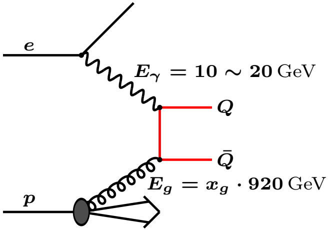




Consistent with fragmentation universality

Beauty production

- $m_b > m_c$: pQCD calculations more reliable
- But, suppresion $\Rightarrow \sigma_{uds} : \sigma_c : \sigma_b \sim 2000 : 200 : 1$



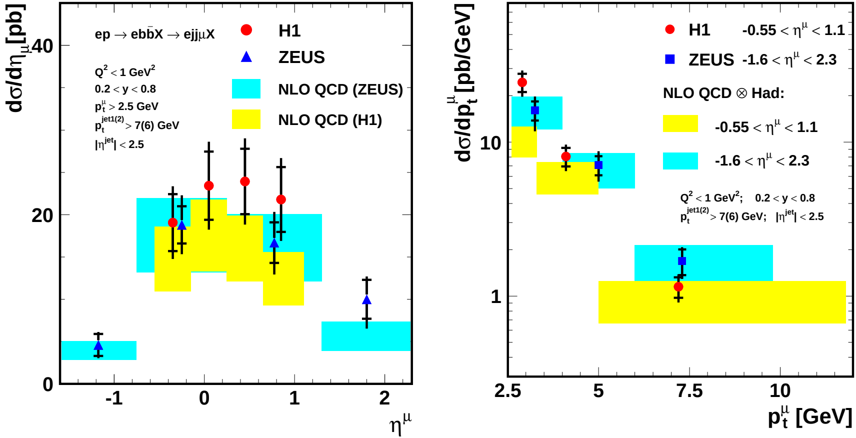
$$x_g \geq \frac{m_Q^2}{E_\gamma \cdot 920\,\text{GeV}}$$

$$c : x_g \geq 10^{-4}$$

$$b : x_g \geq 10^{-3}$$

- Anyway, beauty “puzzle” seems to be over…

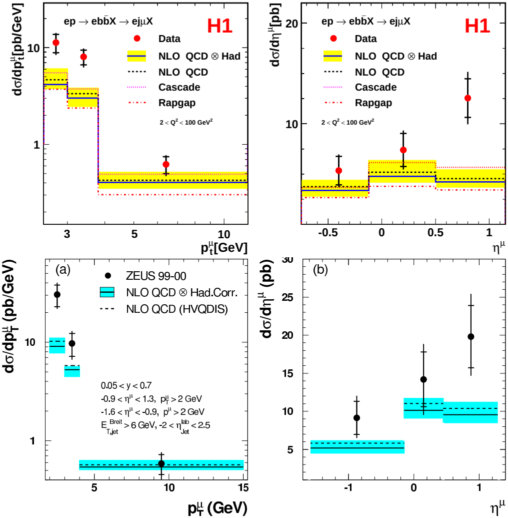
Beauty photoproduction: $\mu + dijet$



NLO: describing data well

H1: excess at low p_T^{μ}

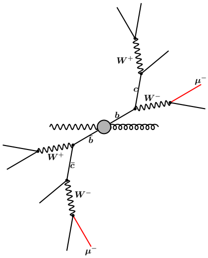
Beauty production in DIS: $\mu + jet$

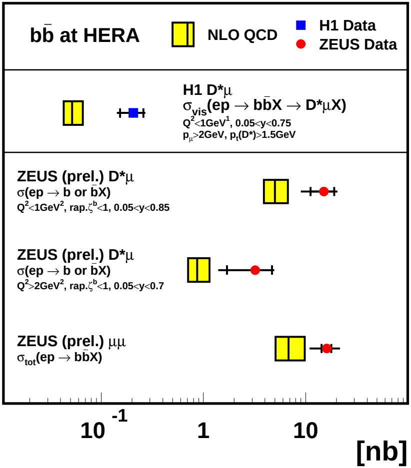


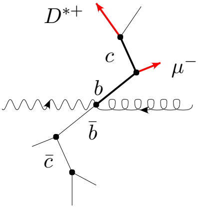
- H1 and ZEUS: good agreement
- NLO: describing DATA well except at low p_T^μ and high η^μ

Total beauty production

Excess confirmed by integrated cross section measurements



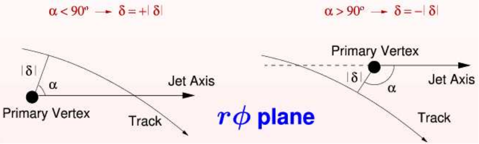


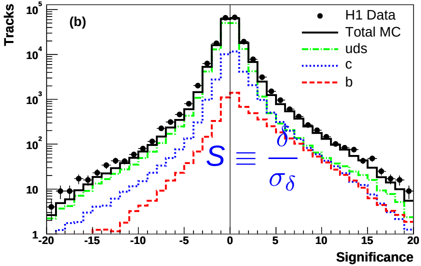


NLO (FNMR+HVQDIS): too small?

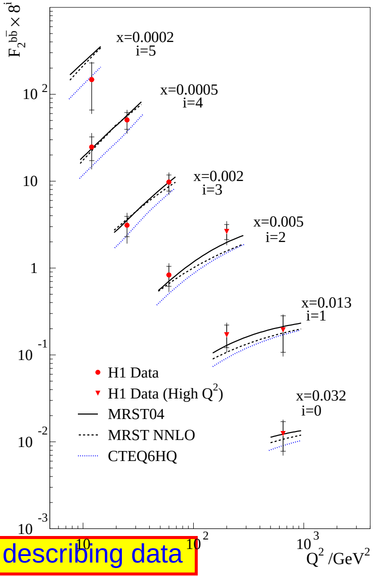
First measurement of $F_2^{b\bar{b}}$

Inclusive impact parameters(δ) of tracks



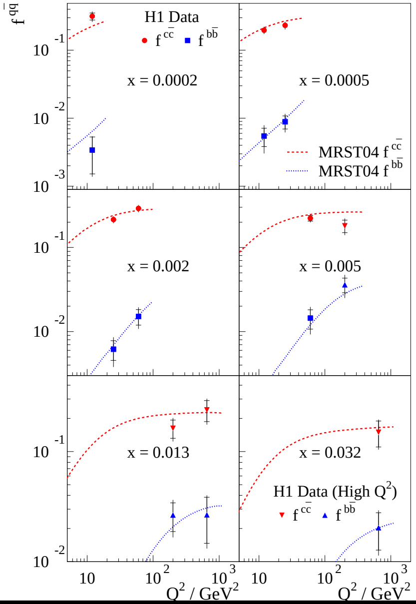


$$S \equiv \frac{\delta}{\sigma_\delta}$$



Two VFNS NLOs and one NNLO reasonably describing data

Heavy flavour contributions to *ep* cross section



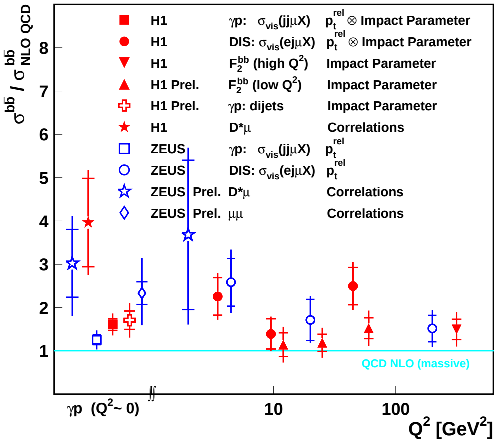
$$f^{q\bar{q}} = \frac{d^2\sigma^{q\bar{q}}}{dx\,dQ^2} \Big/ \frac{d^2\sigma}{dx\,dQ^2}$$

Charm: increasing slightly with Q^2, roughly 24% on average

Beauty: increasing rapidly with Q^2, 0.4% at $Q^2 = 12\,\text{GeV}^2$ 3% at $Q^2 > 150\,\text{GeV}^2$

NLO QCD predictions of MRST describing data reasonably well

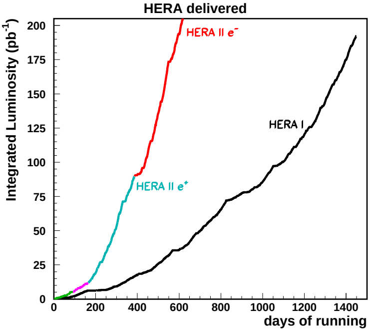
Latest version of beauty production summary



- . . . many new points — large excess of early measurments NOT confirmed,
- although NLO calculation still consistently below data.

Summary & Outlook

- Some recent heavy flavour measurements at HERA were reviewed
- NLO calculations are in general agreement with the data
- There are still problematic regions at small Q^2 and p_T, and in the forward direction
  $\Rightarrow$ Improved models needed!



- Outlook — HERA II results!
  - Higher luminosity
  - Improved detector