

F_2^c measurements at HERA

Katerina Lipka



New trends in HERA Physics, Ringberg 2008

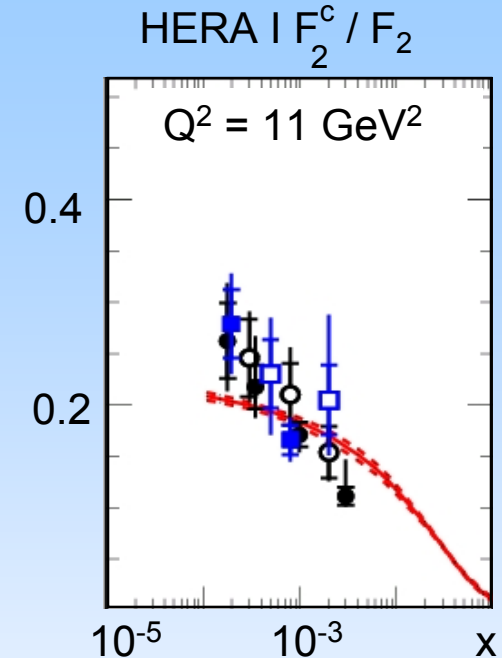
Charm production at HERA: why now?

HERA I : PDF – central measurement of HERA

- PDF obtained from the fits to inclusive F_2
- Inclusive F_2 experimentally very precise
- Contribution of events with charm to F_2 high
- Measurement of F_2^c has large uncertainties

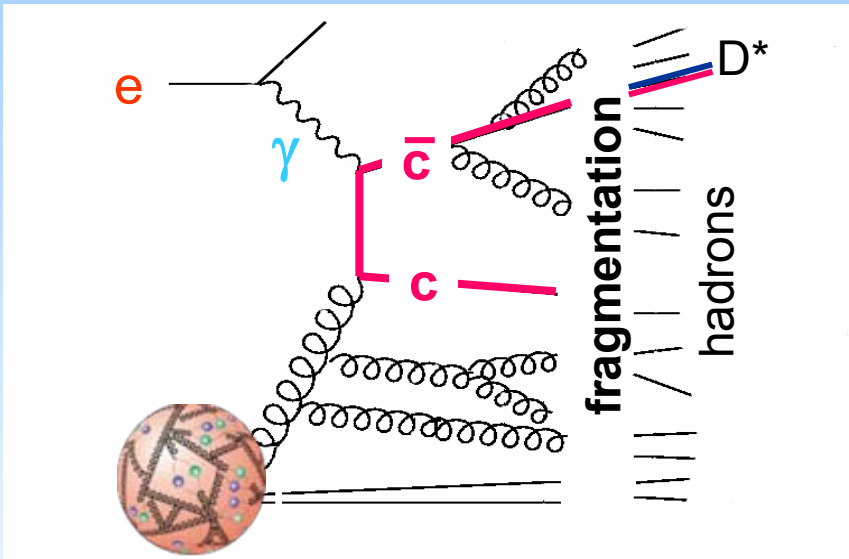
now: precise PDF – crucial importance for the LHC

- Combined HERA PDF are of unprecedented precision
- BUT dependent on parameterization of the QCD fit
- Need a cross check / direct access to the gluon
- Final state measurements (jets, heavy quarks) extremely important
- F_2^c @ HERA II on the way to precision measurement



Charm production at HERA

Dominated by Boson – Gluon Fusion (BGF)



- gluon directly involved:
include in a global PDF fit
important cross-check of the $g(x_g)$
- charm mass – additional hard scale:
pQCD calculations possible;
multiple scales: calculations complicated

Factorization:

$$\sigma(ep \rightarrow D^*X) = \text{Proton Structure} \otimes \text{Photon Structure} \otimes \text{Matrix Element} \otimes \text{Fragmentation}$$

to learn something about PDFs:

calculate hard ME, measure cross section, understand fragmentation

Presented in this talk

➤ **Hard ME:**

- NLO calculations and Monte-Carlo simulations

➤ **Charm tag methods and extraction of F_2^c :**

- Charm tag via reconstruction of charmed mesons
- Extrapolation to the full phase space
- Fragmentation measurement
- Charm tag via track displacement measurement

➤ **Results and discussion**

Models of charm production

Massive calculation, fixed order QCD calculation, FFNS

- correct threshold suppression, no collinear divergences, terms $\sim \log(\mu/m)$
- no factorization, no conceptual necessity for FFs, no resummation
- valid for $0 \leq p_t^2 \leq m_c^2$, fixed order logarithms $\ln(p_t^2/m_c^2)$ large for $p_t^2 \gg m_c^2$

Models for charm at HERA: FMNR (Photoproduction), HVQDIS (DIS),

Massless calculation (ZM-VFNS)

- large collinear $\ln(\mu^2/m_c^2)$ -terms resummed in evolved PDFs and FFs (LL, NLL), good for large $\mu^2 \sim p_t^2 \gg m_c^2$
- universality of PDFs and FFs via factorization theorem, global analysis
- terms $(m_c/p_t)^n$ neglected in the hard part – breaks down @ threshold

Not appropriate for charm production at HERA (close to threshold)

Generalized mass calculation (GM-VFNS) → Hubert's talk

Available for charm production in γp at HERA, DIS is on the way

Monte-Carlo models for data corrections

RAPGAP

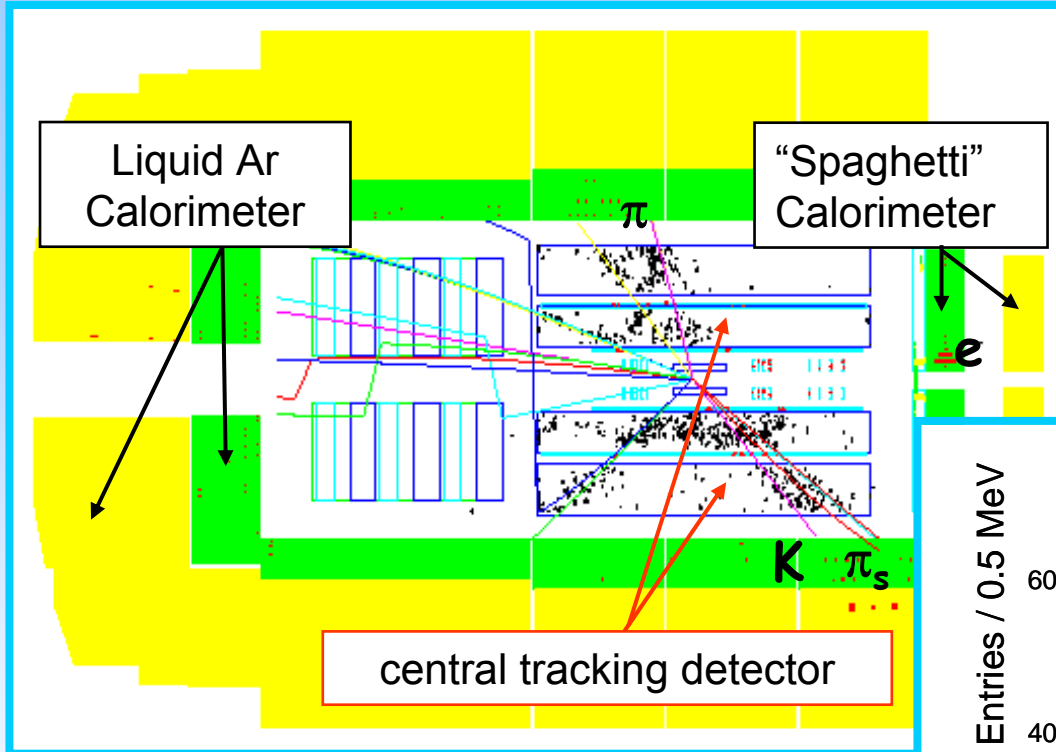
- matrix element calculated in LO QCD
- higher order contributions via parton showers
- parton evolution in collinear approximation (DGLAP equations)
- charm is massive in BGF

CASCADE

- gluon density unintegrated in gluon transverse momentum k_T
- only gluons in proton
- higher order contributions via initial state parton showers
- based on CCFM equations
- charm is massive in BGF

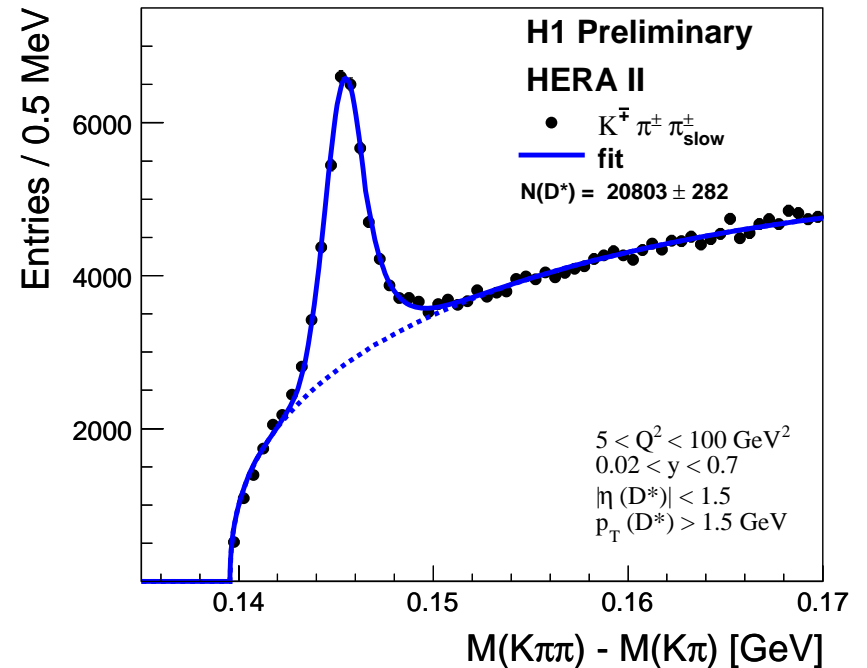
Hadronization via Lund String model (Jetset)

Charm tag via $D^{*\pm}$ production



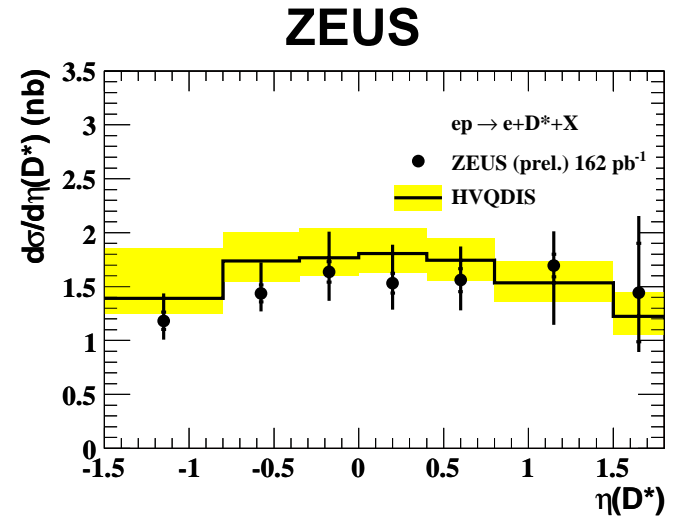
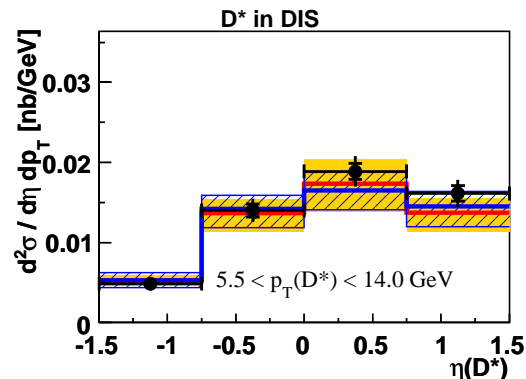
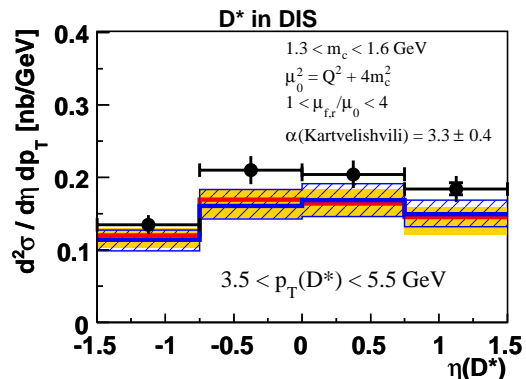
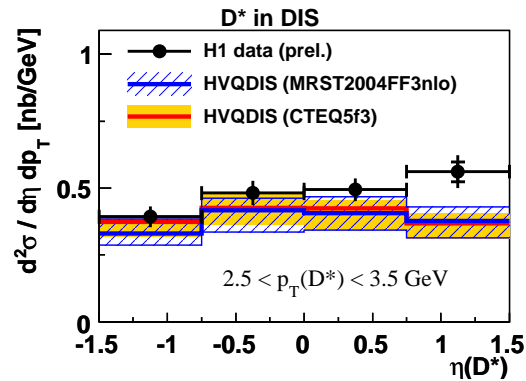
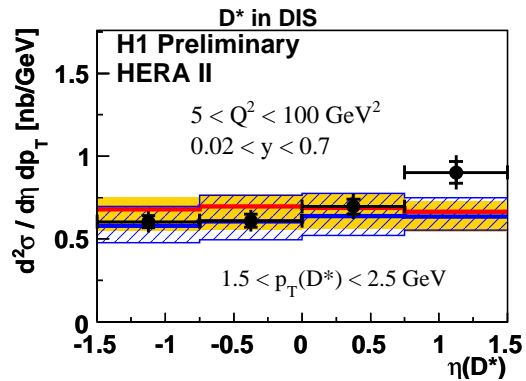
Kinematics regimes:
 DIS: $5 < Q^2 < 1000 \text{ GeV}^2$
 Photoproduction $Q^2 < 2 \text{ GeV}^2$

$D^{*+} \rightarrow D^0 \pi_s^+ \rightarrow K^- \pi^+ \pi_s^+ (+ \text{c.c.})$



Electron reconstructed in
 SpaCal: $Q^2 < 100 \text{ GeV}^2$
 LAr: $Q^2 > 100 \text{ GeV}^2$

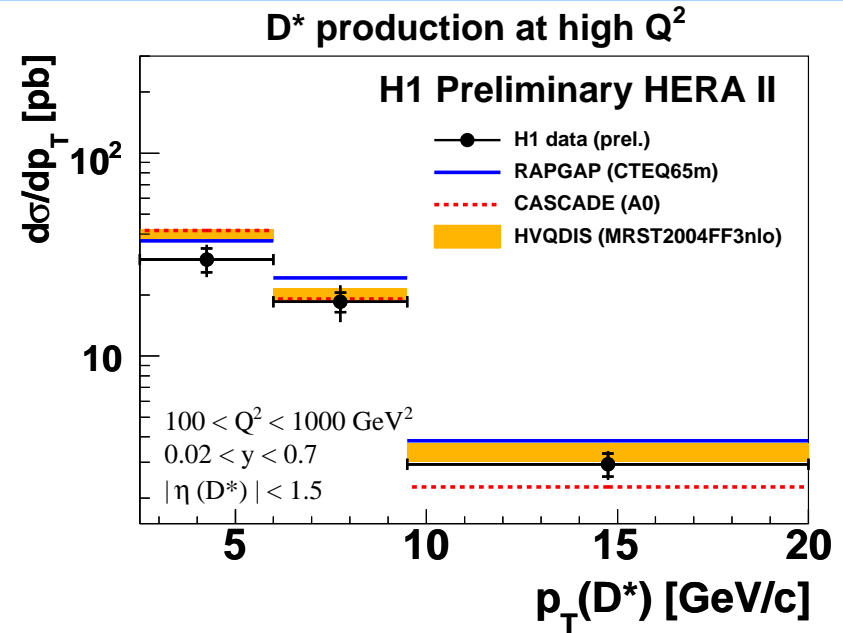
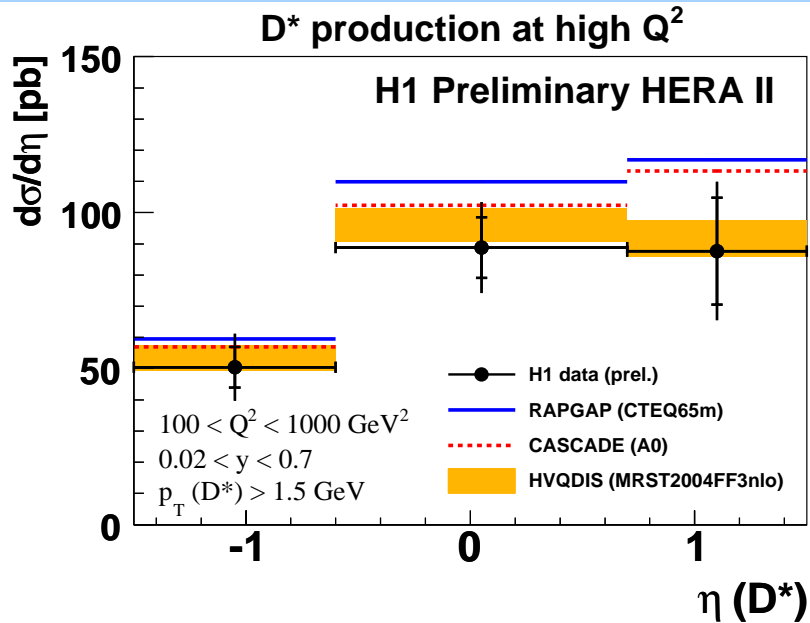
D* production in DIS ($5 < Q^2 < 100 \text{ GeV}^2$)



H1: FFNs NLO does good job describing the D* kinematics,
 but underestimates forward region at low $p_T(D^*)$

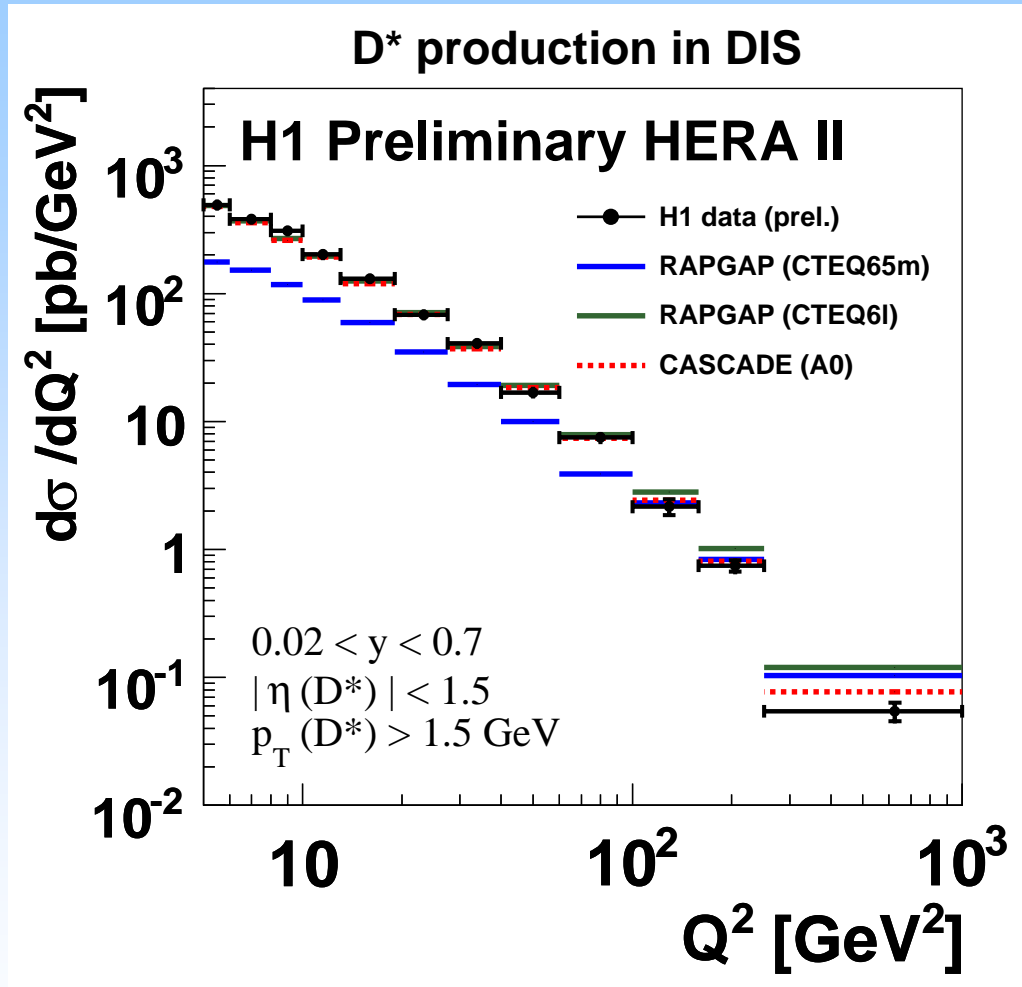
ZEUS: no forward access in the data seen. Data precision will improve

D* production in DIS ($Q^2 > 100 \text{ GeV}^2$)



- D* production at high Q^2 : description by the LO Monte-Carlo gets worse
- NLO FFNs describes data very well

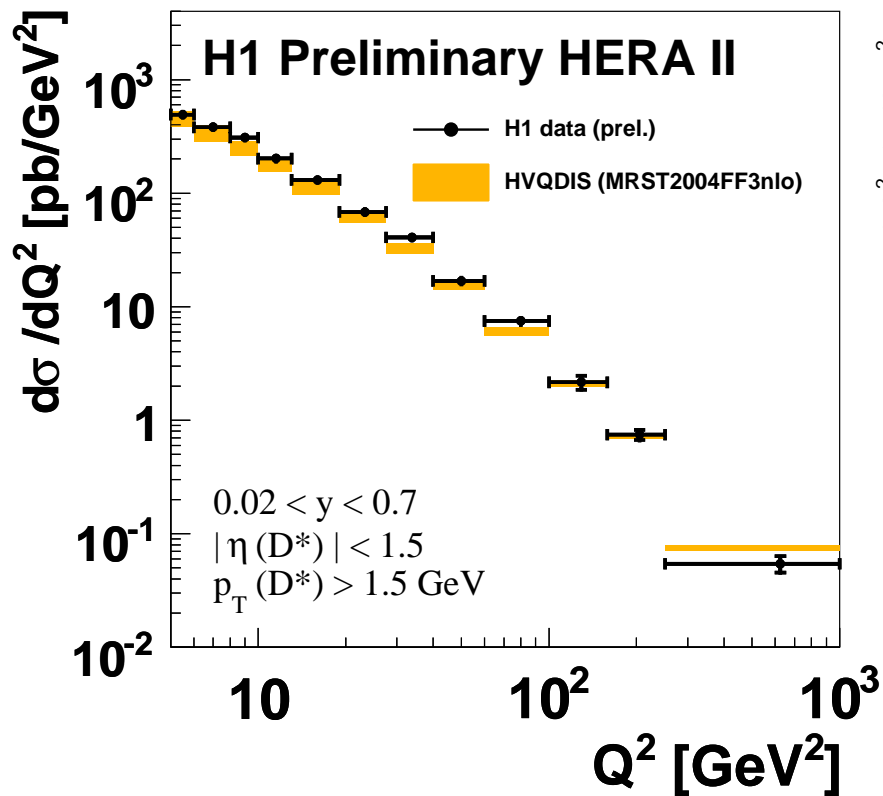
D* production in DIS: Q² slope



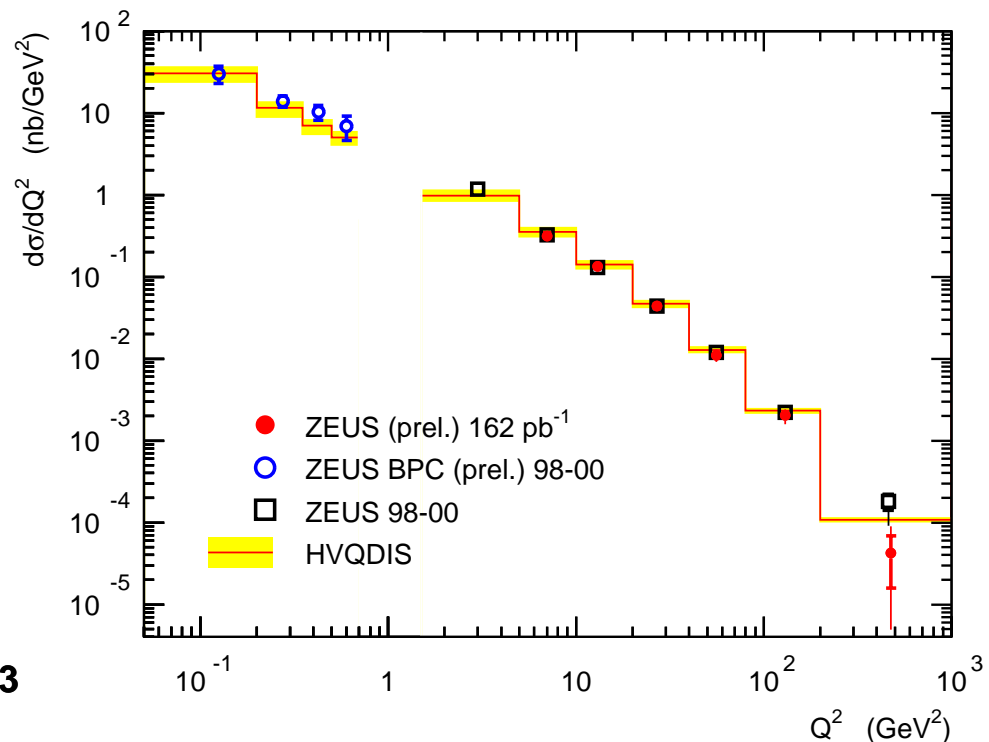
Monte-Carlo models don't describe the Q² slope of the D* cross section

D* production in DIS

D* production in DIS



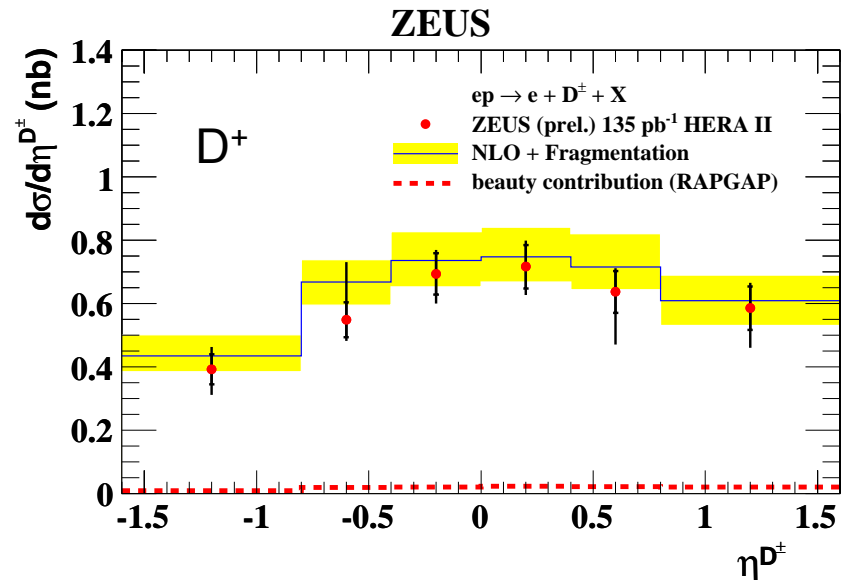
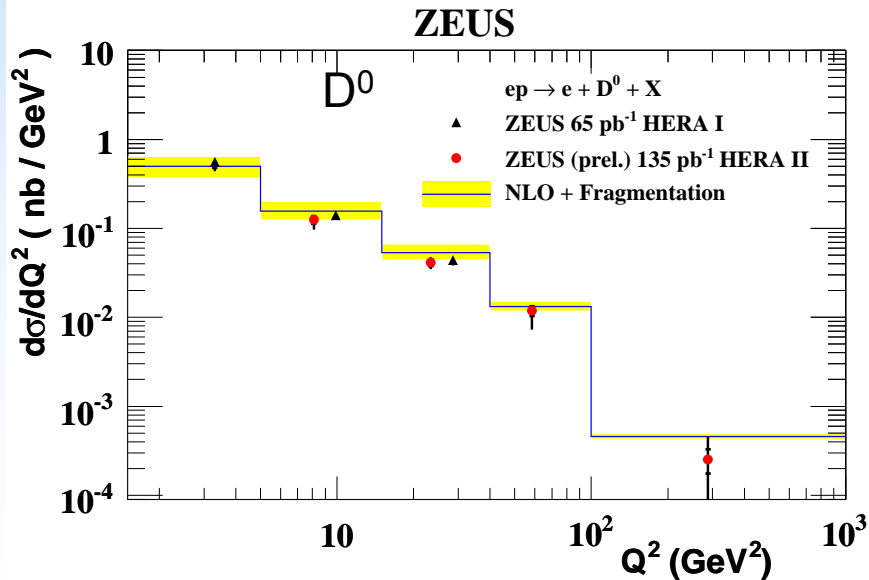
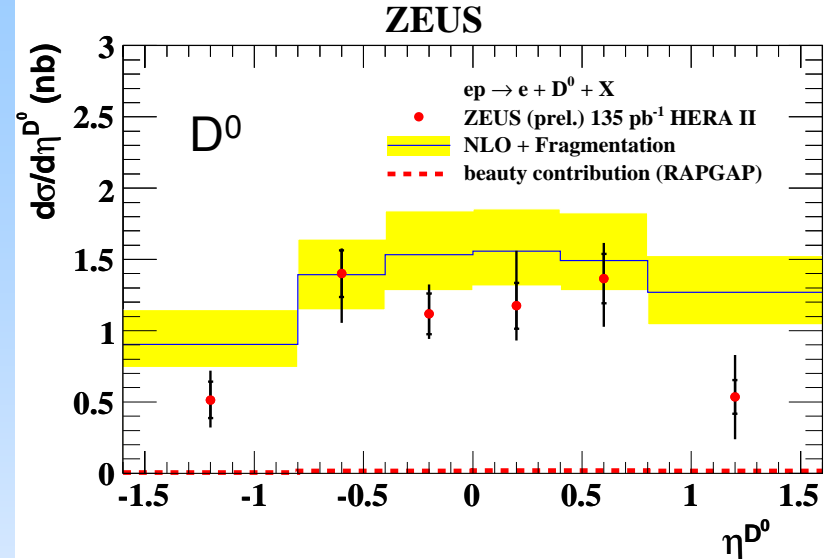
ZEUS



NLO FFNs calculation does good job (surprising, should break down for high Q^2)

More to charmed meson production

- HERA-II, $L=135\text{pb}^{-1}$
 $5 < Q^2 < 1000 \text{ GeV}^2$,
 $p_T(D) > 3 \text{ GeV}$, $|\eta(D)| < 1.6$
- Lifetime information from the ZEUS Micro Vertex Detector used
- NLO FFNS describes data well



Extraction of F_2^c from meson cross section

$$F_2^{c\bar{c}}(\text{exp}) = \frac{\sigma_{\text{vis}}(\text{exp})}{\sigma_{\text{vis}}(\text{theory})} F_2^{c\bar{c}}(\text{theory})$$

Visible cross section: $p_T(D^*) > 1.5 \text{ GeV}$, $|\eta(D^*)| < 1.5$
 $0.02 < y < 0.7$, $5 < Q^2 < 1000 \text{ GeV}^2$

Problem: detector sees only 30% of the phase space for $c \rightarrow D^*$

→ strong model dependence due to large extrapolation factors

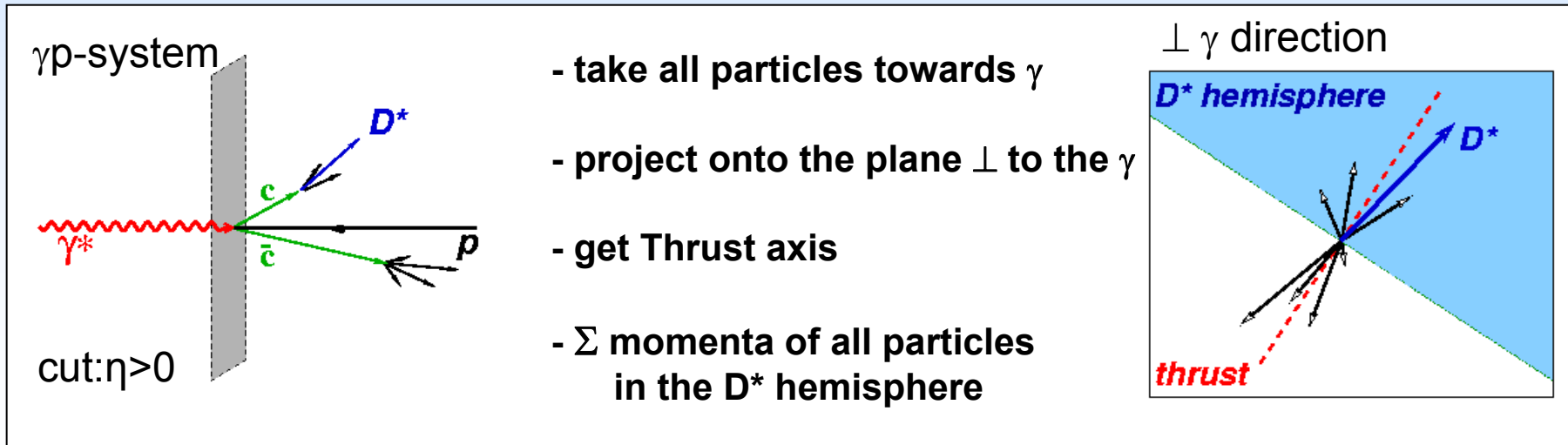
Extrapolation problems:

- 1) Different extrapolation models
- 2) Unknown parameters within a single model:
mass of charm quark, scales,
fragmentation model → experimentally measurable: see next slides

Measurement of charm fragmentation in ep

Methods to reconstruct the energy of the parent quark:

- Jet containing D^* ; problem: only small region of phase space accessible
 - DIS: inclusive k_{\perp} algorithm applied in the γp frame, $E_{\text{T}}(D^*\text{-jet}) > 3 \text{ GeV}$
 - significant contribution only from $\hat{s} > 100 \text{ GeV}^2$ (much above threshold)
- Hemisphere containing D^* :
 - experimental setup similar to e^+e^- , works at threshold, $\hat{s} \approx 4m_c^2$



Charm fragmentation in photoproduction

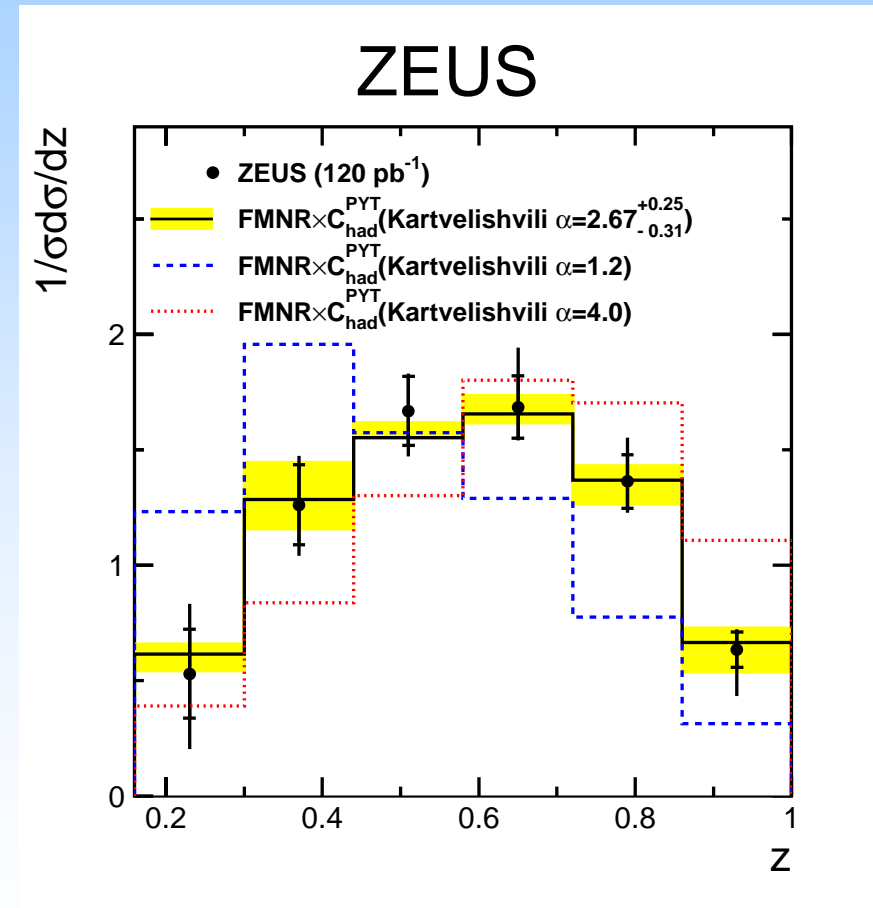
Parent quark approximated by a jet containing D^*

$$z = \frac{(E + P_{II})_{D^*}}{2E_{jet}}$$

- data: HERA1, $\mathcal{L} = 120 \text{ pb}^{-1}$, $Q^2 < 1 \text{ GeV}^2$;
- $p_T(D^*) > 2 \text{ GeV}$, $|\ln(D^*)| < 1.5$
- inclusive k_{\perp} algorithm, $E_T(D^* \text{-jet}) > 9 \text{ GeV}$
- compared to the NLO FFNS (FMNR) fragmentation model: Kartvelishvili

$$D_c^{D^*}(z) \propto z^{\alpha} (1-z)$$

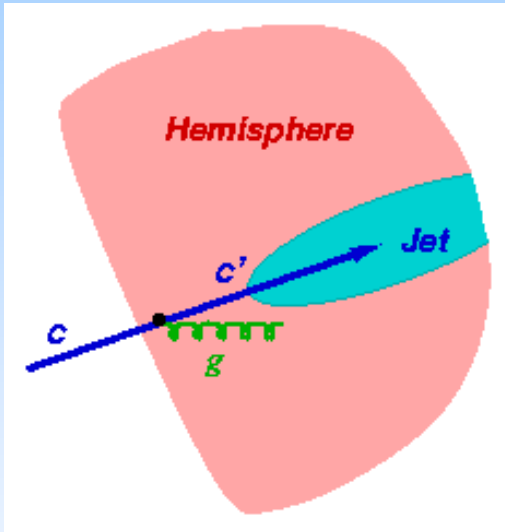
best fit $\alpha = 2.67$



Measurement of charm fragmentation in DIS

Data: H1 HERA I, $\mathcal{L}=75 \text{ pb}^{-1}$ both methods used: $z_{jet} = \frac{(E + p_L)_{D^*}}{(E + p)_{jet}}$, $z_{hem} = \frac{(E + p_L)_{D^*}}{(E + p)_{hem}}$

Differences between the methods:



Hemisphere method should include more final state gluon radiation than jet method

⇒ Measured distributions of the fragmentation variable should be different

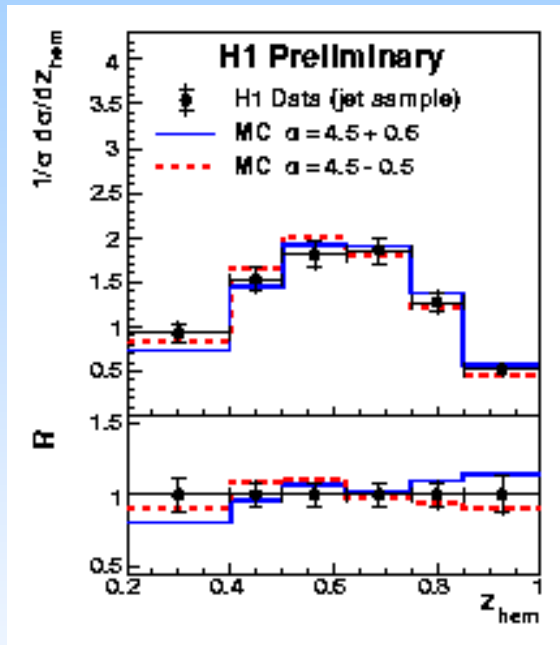
⇒ Extracted parameters of the non-perturbative fragmentation function should agree

- Measure in the common phase space: require presence of a D^* jet
- Extract parameters for n.-p. FF using MC/ HVQDIS.
- Expect : parameters agree for different methods, different for MCs and HVQDIS
- Any differences at the threshold (absence of a D^* -jet)?

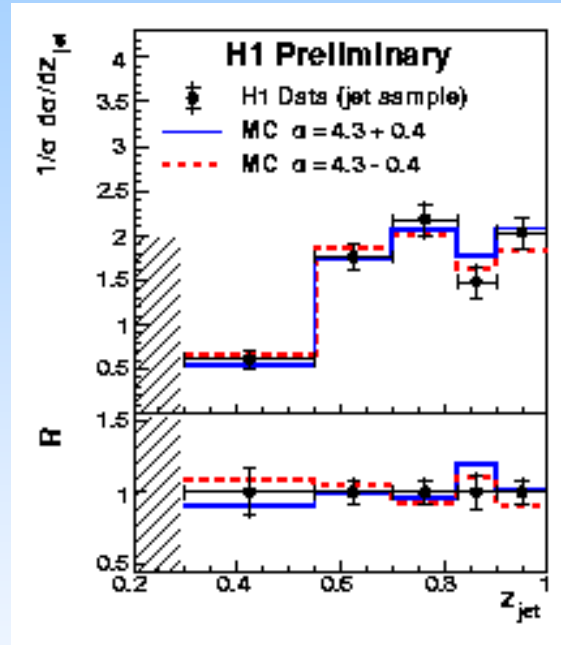
Fragmentation measurement: D* - Jet sample

RAPGAP MC:

Hemisphere method

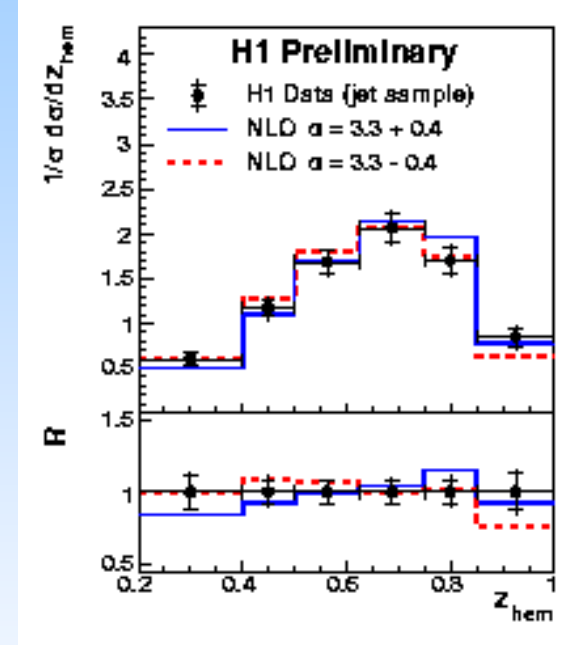


Jet method



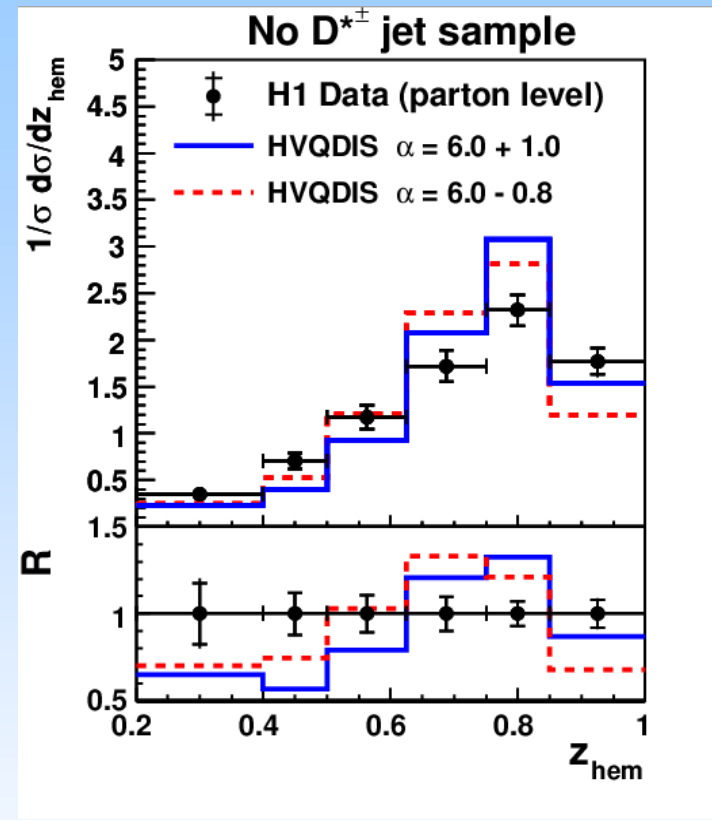
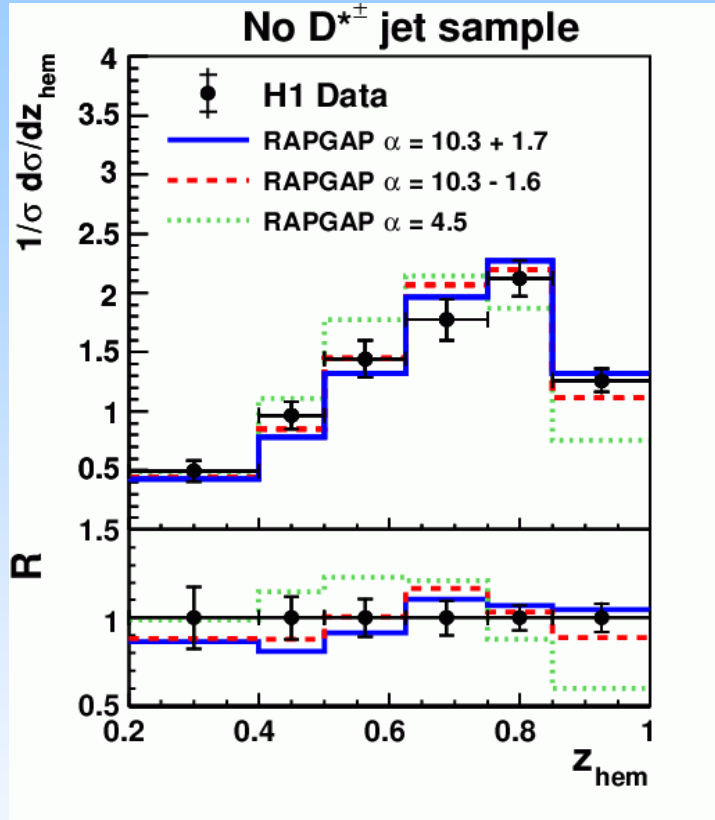
NLO (HVQDIS):

Hemisphere method



- Distributions on hadron level look different (as expected)
- MC (Rapgap) with standard n.p. FF yield reasonable description of data
- Extracted n.p. FF parameters from z_{hem} ($\alpha=4.5\pm0.6$) and z_{jet} ($\alpha=4.3\pm0.4$) agree
- HVQDIS \otimes Kartvelishvili fragmentation: extracted parameters z_{hemi} and z_{jet} agree

Fragmentation $c \rightarrow D^*$. No D^* -jet sample



MC: Extracted parameters ($\alpha=10.3_{-1.6}^{+1.7}$) inconsistent with jet-sample ($\alpha=4.5\pm 0.6$)

HVQDIS: “no jet” ($\alpha=6.0_{-0.8}^{+1.0}$) inconsistent with jet-sample ($\alpha=3.3\pm 0.4$)

Fragmentation at threshold significantly harder than expected from the jet-sample

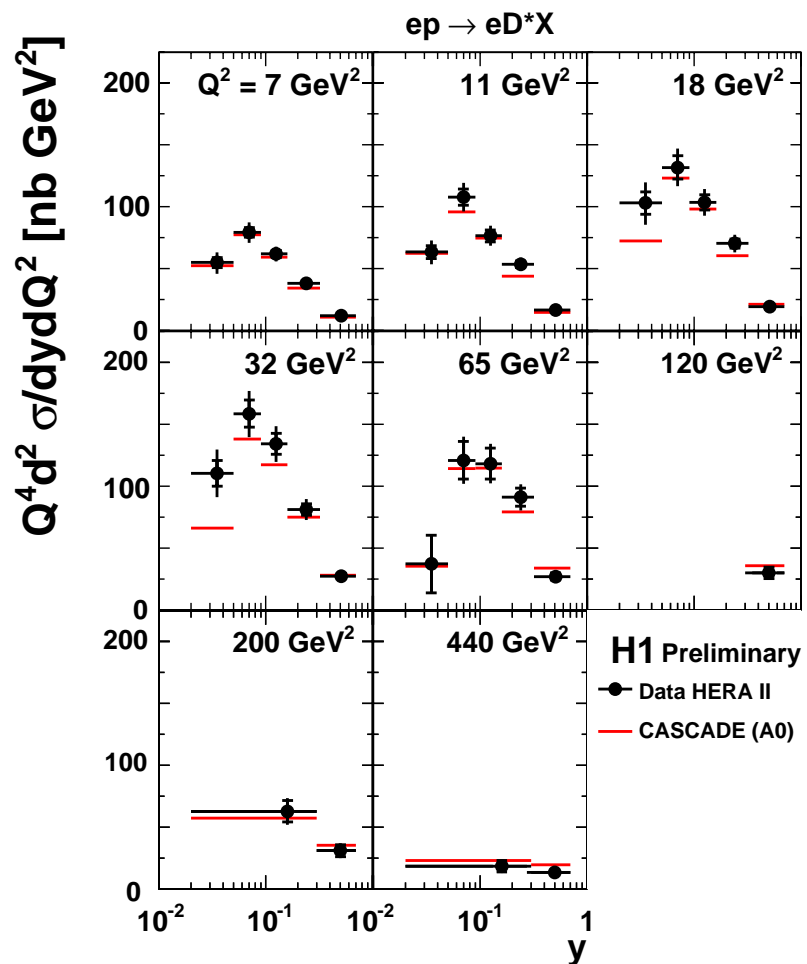
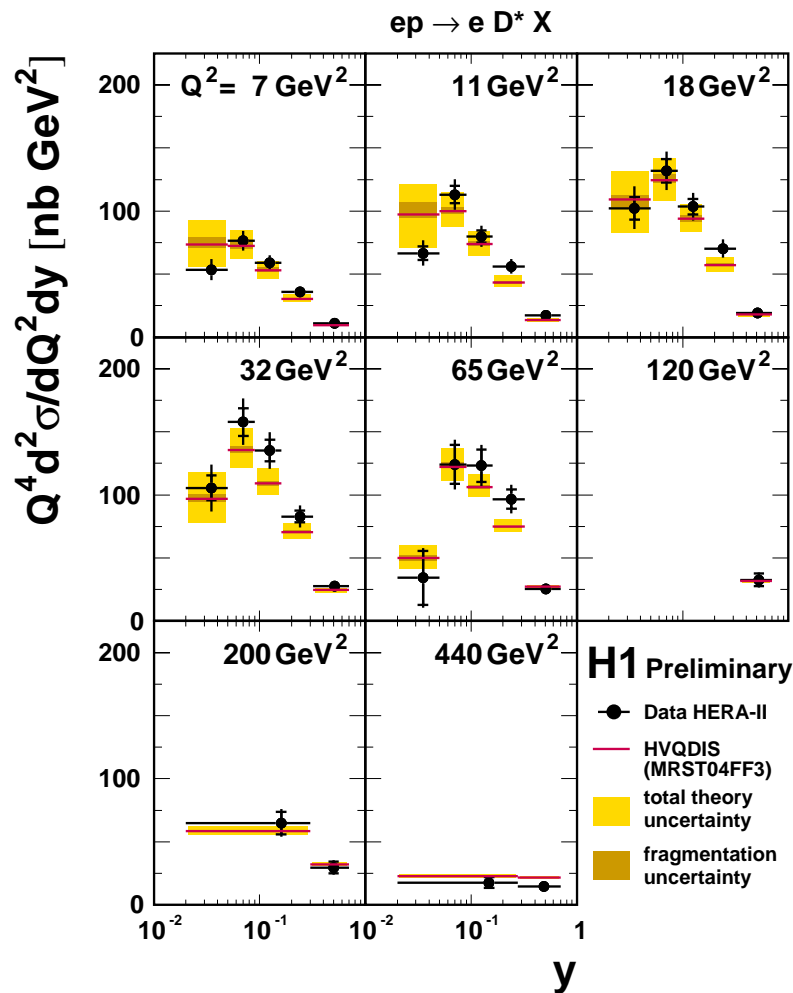
Treatment in extrapolation models: \hat{s} -dependent fragmentation

Back to extrapolation of $\sigma(D^*)$ to the F_2^c

Extrapolation Models in use:

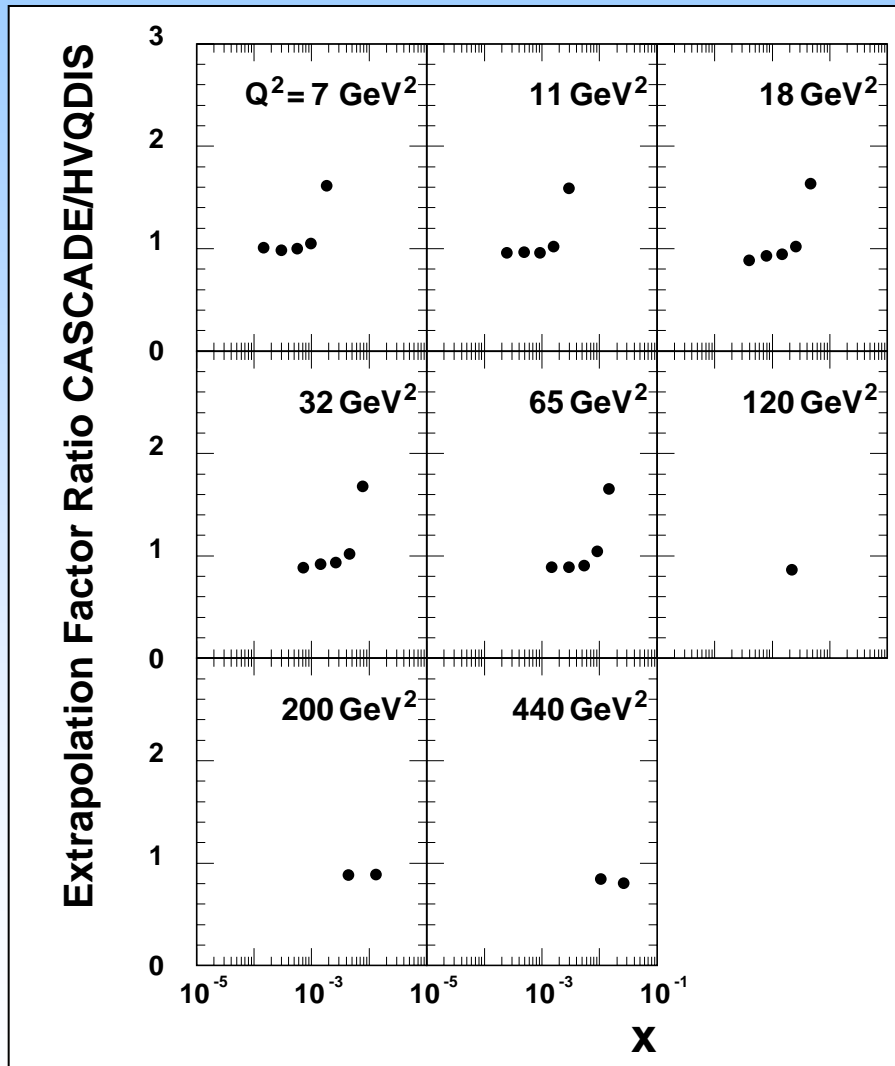
- NLO: Riemersma et al: integrated form; HVQDIS: differential form, fixed order massive calculation, $N_f=3$, FFNS, evolution: DGLAP
Parameters: PDFs: MRST04F3, $m_c = 1.43 \text{ GeV}$, $\mu_r = \mu_f = \mu = \sqrt{Q^2 + 4m_c^2}$
Fragmentation: $\hat{s} < 70 \text{ GeV}^2$: $\alpha = 6.0$, otherwise $\alpha = 3.3$
- CASCADE: massive LO ME + Parton showers,
proton structure: gluons only, evolution: CCFM
Parameters: PDFs: A0, $m_c = 1.43 \text{ GeV}$, $\mu_r = \mu_f = \mu = \sqrt{Q^2 + 4m_c^2}$
Fragmentation: $\hat{s} < 70 \text{ GeV}^2$; $\alpha = 8.2$, otherwise $\alpha = 4.3$

D* cross sections vs NLO/CASCADE



Lowest y (highest x) overestimated by NLO, underestimated by CASCADE

Extrapolation factors NLO/CASCADE



Extrapolation factors ($\sigma_{\text{tot}}/\sigma_{\text{vis}}$)
differ in NLO vs CASCADE:
3%-10% (low x) -100% (high x)

Differences in the models:

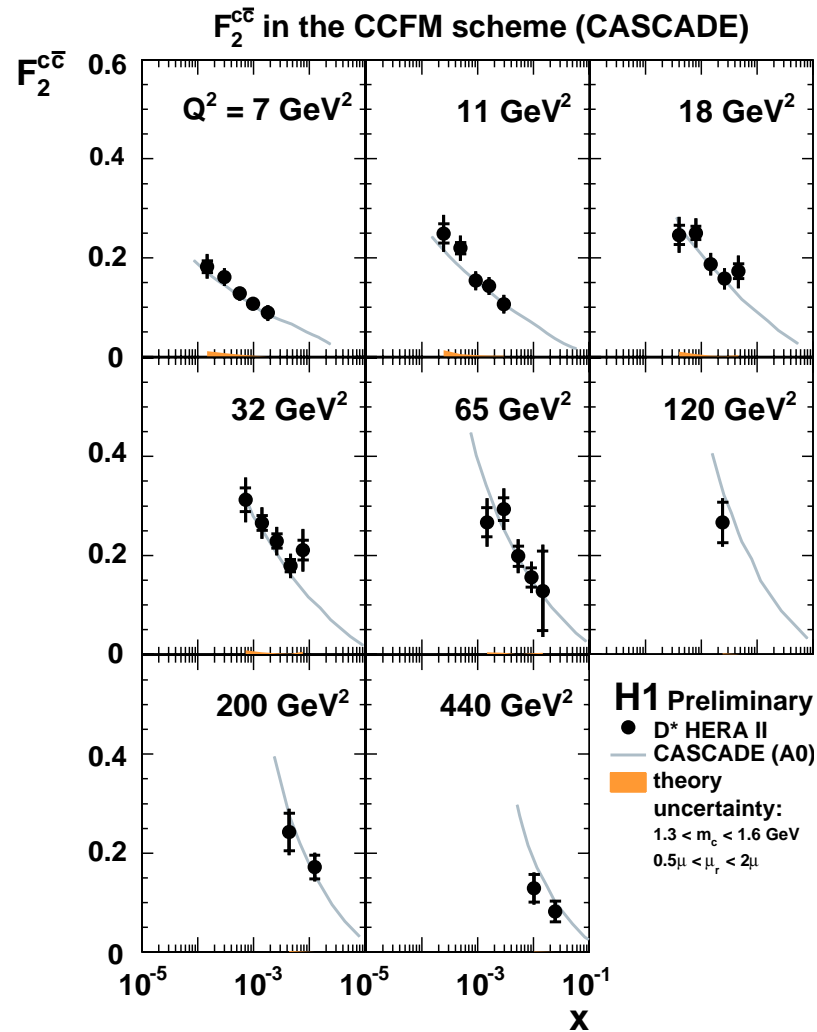
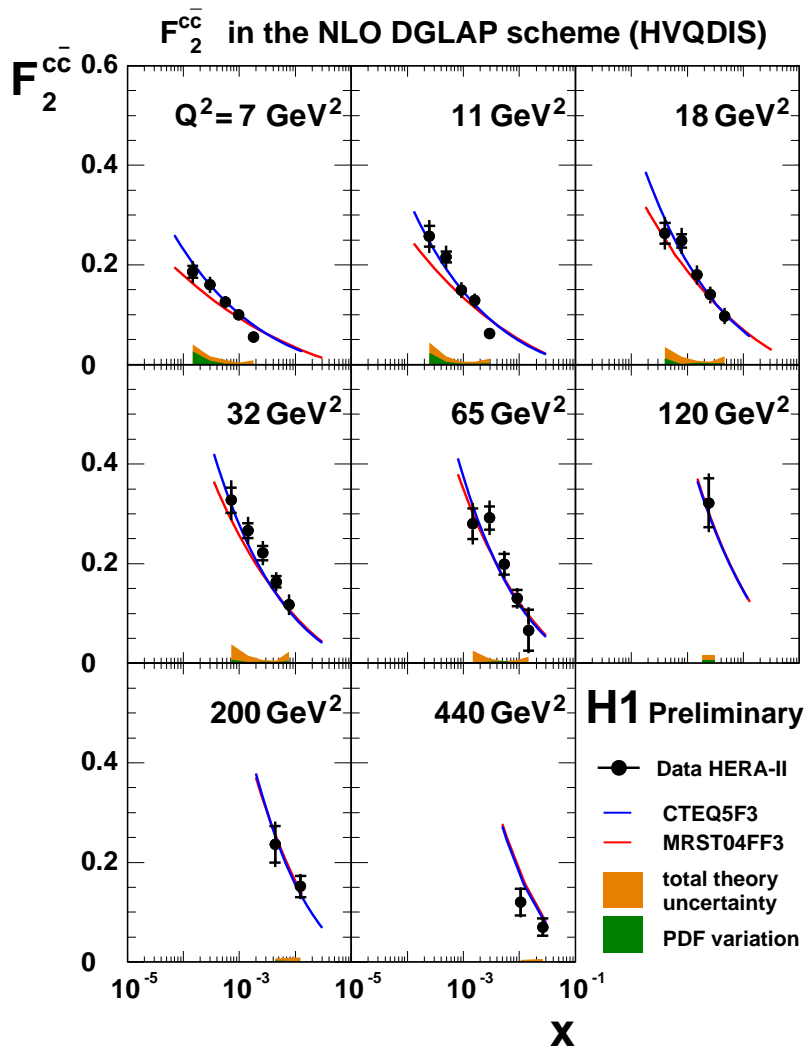
- LO+PS vs NLO
- Evolution
- Hadronization

Possible reason:

Hadronization

More studies have to be done

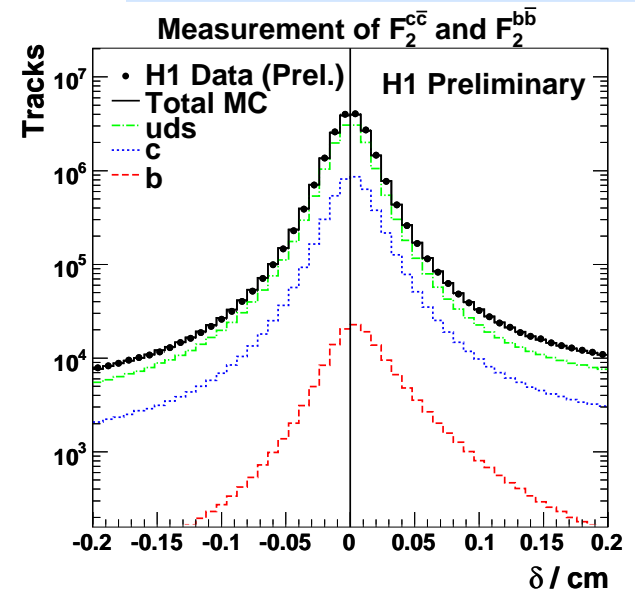
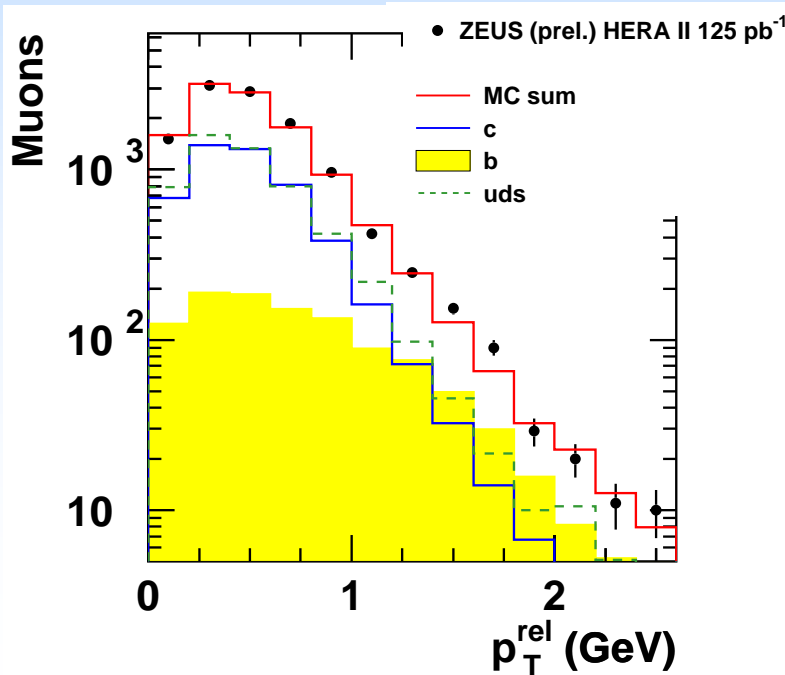
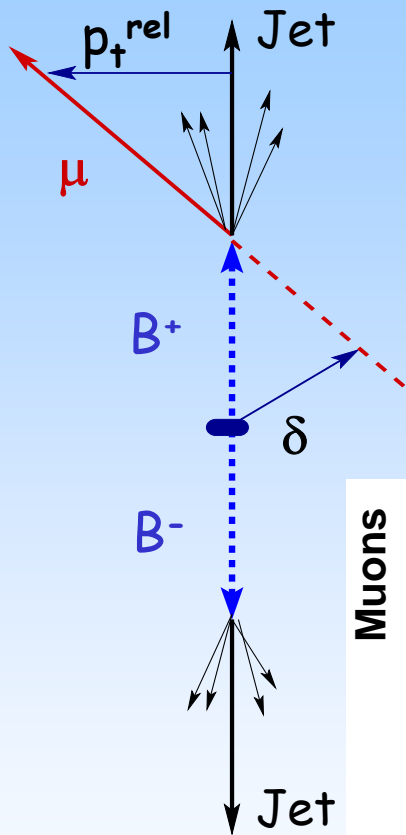
Results: $F_2^{c\bar{c}}$ from D^* measurement



Experimental errors will further decrease – we are on the way to the final precision

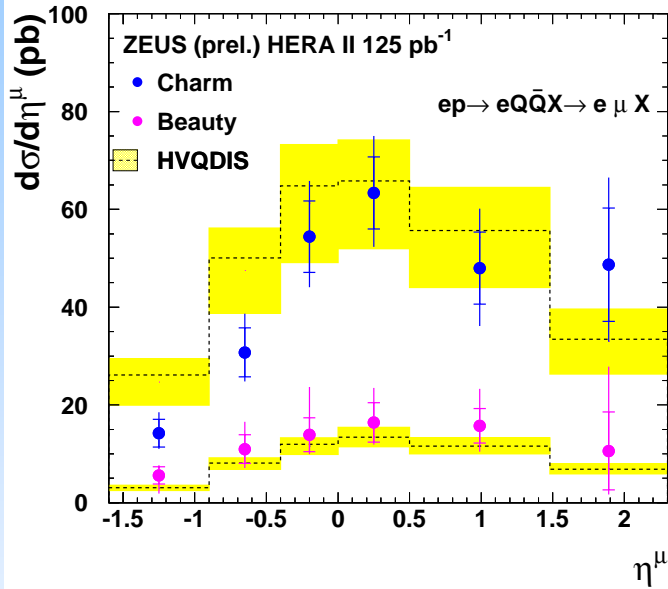
Charm/beauty via other tag methods

- Charm comes along with beauty:
 - More experimental details in Massimo's talk
- Large mass : transverse momentum to Jet axis: muon p_t^{rel}
- Large lifetime: impact parameter δ , Significance $S=\delta/\sigma(\delta)$
- Semileptonic decays (e, μ)
- Different systematic uncertainties wrt. D-meson measurements

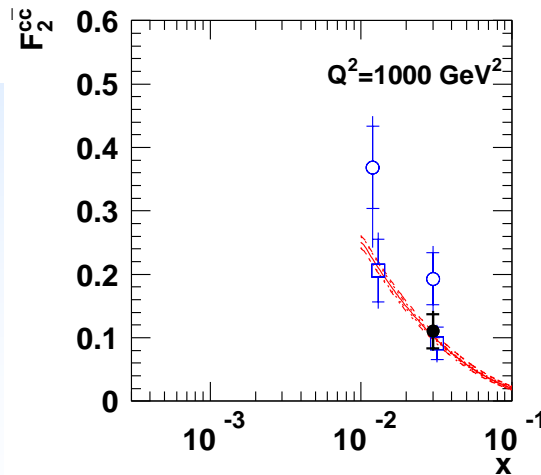
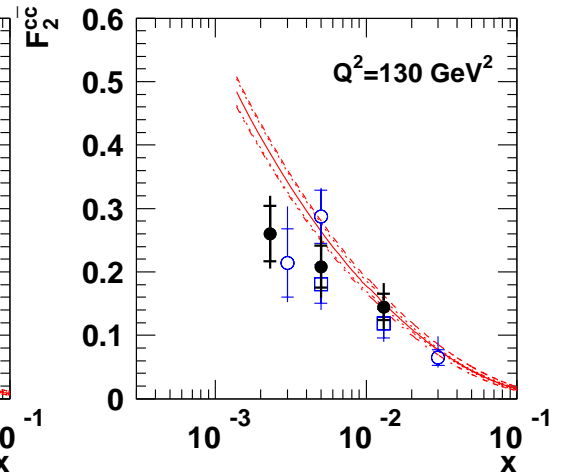
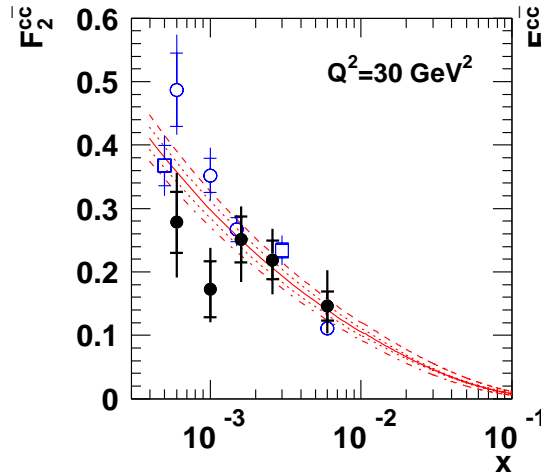


Charm in semileptonic events

ZEUS



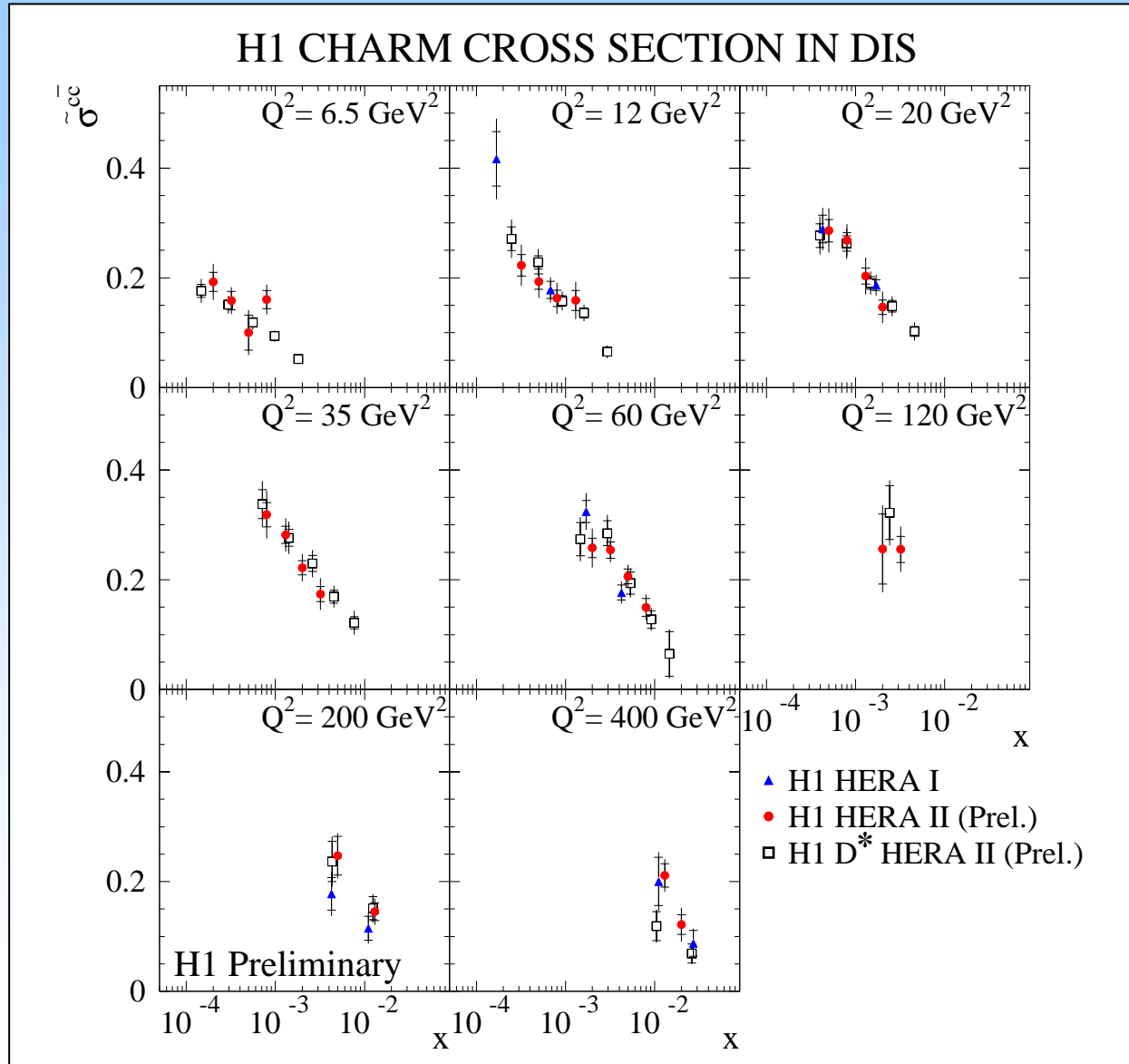
ZEUS



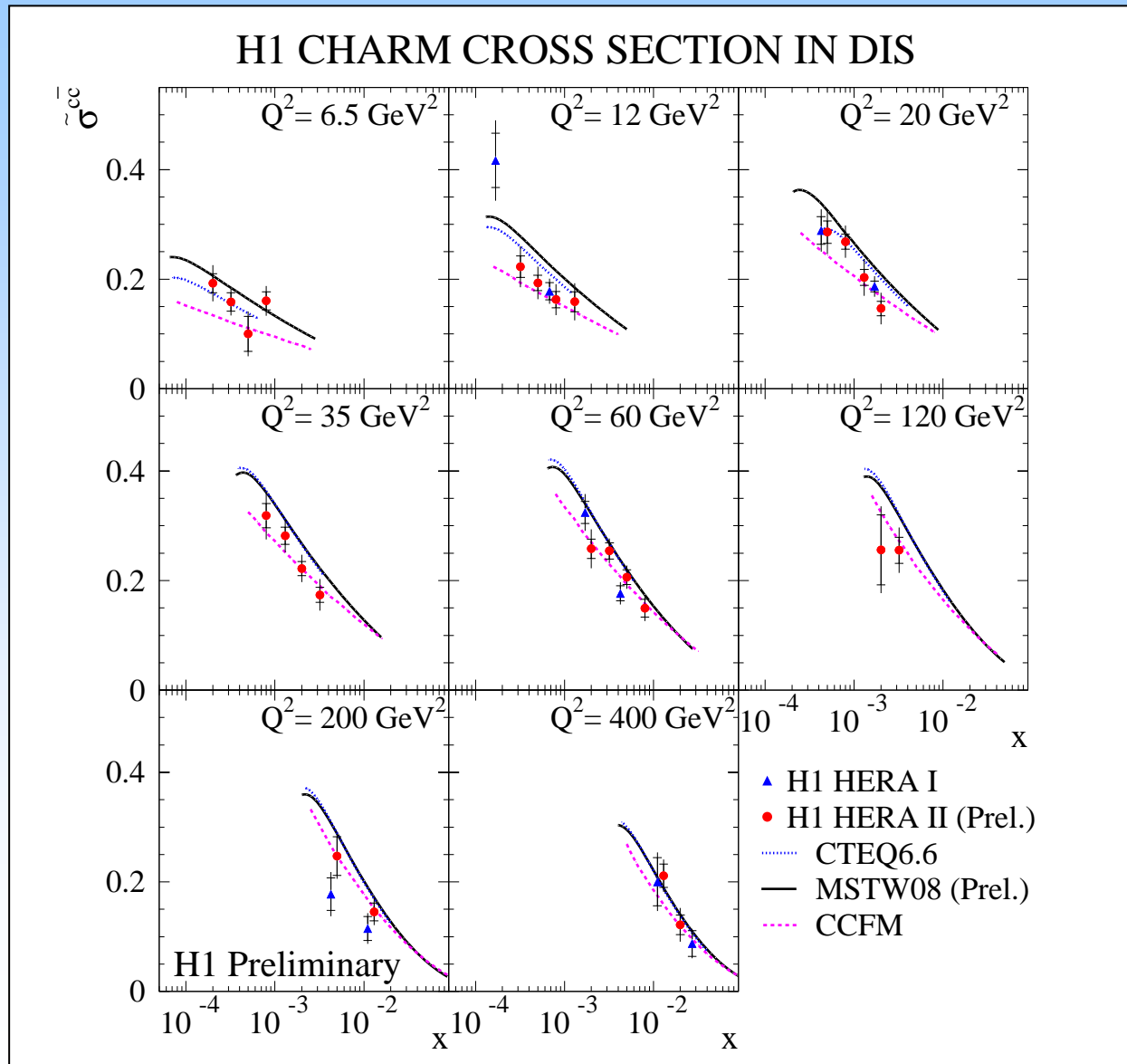
- Charm
- ZEUS (prel.) HERA II, 125 pb⁻¹ (μ)
 - ZEUS HERA I, 82 pb⁻¹ (D*)
 - H1 HERA I, 57 pb⁻¹ (VTX)
-
- ZEUS-S-FF $m_c=1.5, m_b=4.75 \text{ GeV}$
 - ⋯ PDF uncertainty
 - - - $m_c=1.3, m_b=4.5 \text{ GeV}$
 - · - $m_c=1.7, m_b=5.0 \text{ GeV}$

Reasonable description
by the NLO FFNS

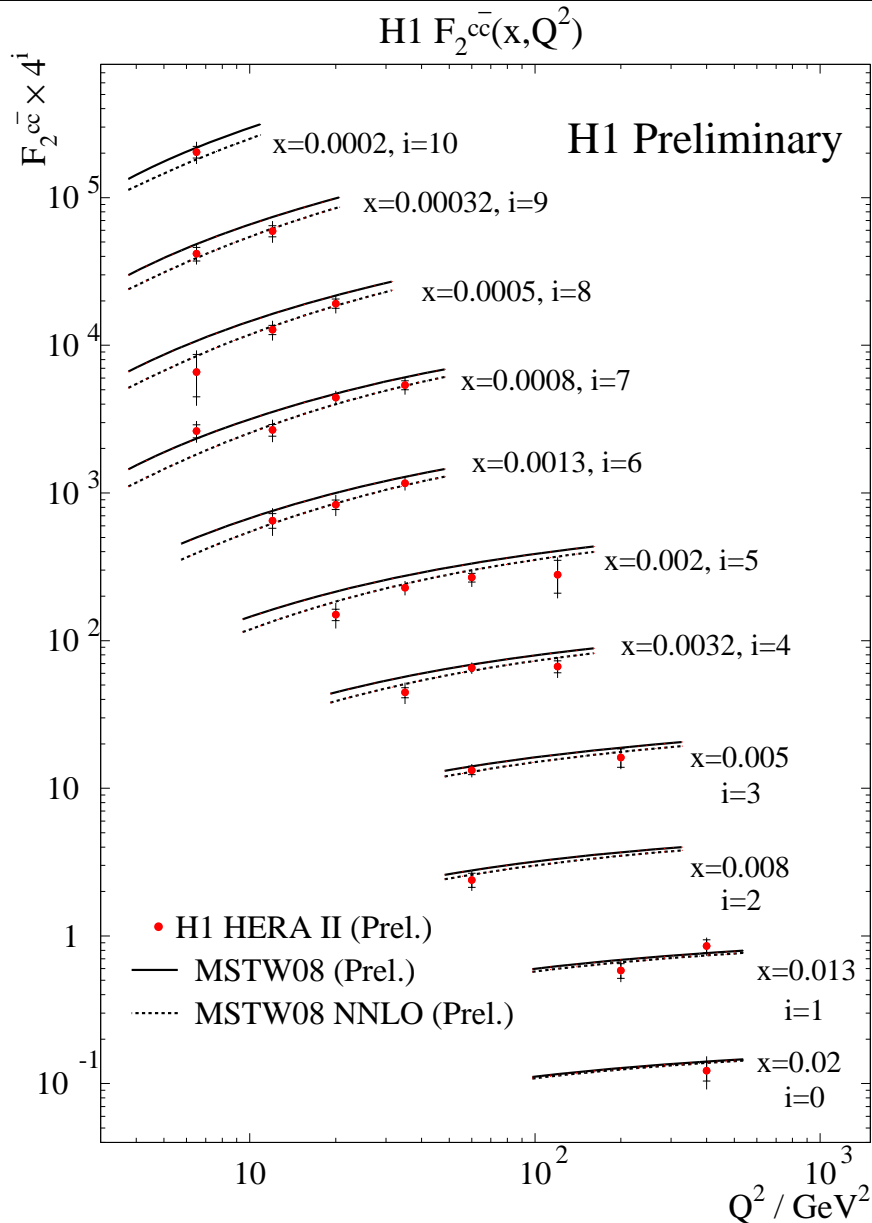
Charm cross sections via lifetime tag vs D^*



Charm cross sections vs VFNS (TR)



F_2^c from lifetime tag vs MSTW NNLO



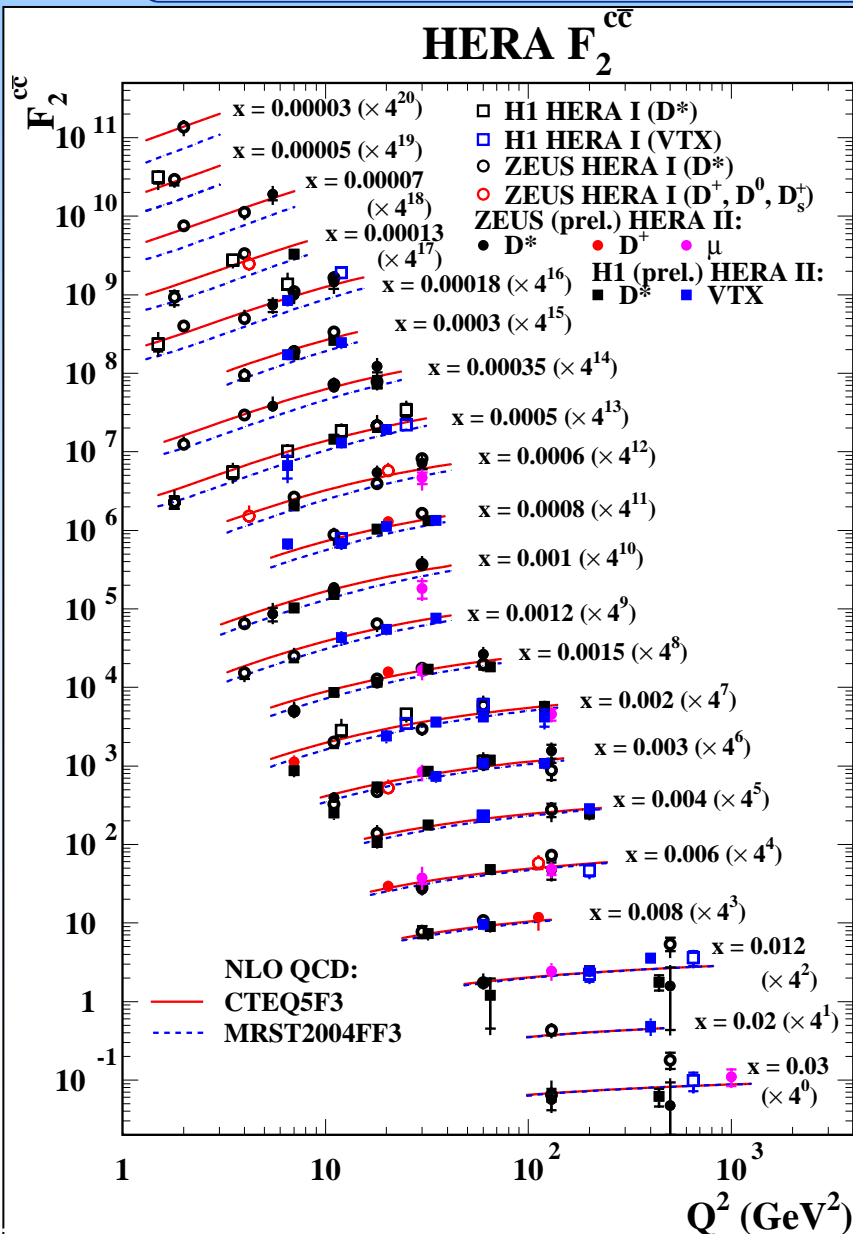
Recall Robert's talk on Monday:

NNLO better fits the measured F_2^c

Only Lifetime data of H1 are shown

Data will get better !

HERA measurement of F_2^{cc}



- Plenty of measurements
- Nice agreement between methods
- Experimental precision of several measurements will further improve
- Different methods will be combined: orthogonal errors!
- H1 and ZEUS results will be combined
- Sensitivity to the models (PDFs)
- Need proper (precise) theory

Conclusions

Experimentally charm measurements at HERA get very precise:

We will get soon

- D* measurement at H1 on the way to 5% precision measurement
- D* measurements at ZEUS full HERA-II on the way
- Combination of different measurement methods
- Combination of H1 and ZEUS: cross calibration
- Enlarge the visible phase space (H1)

Extrapolation to the full phase space model dependent

Theory: massive NLO pQCD describes the data quite well

Model uncertainties larger than experimental errors

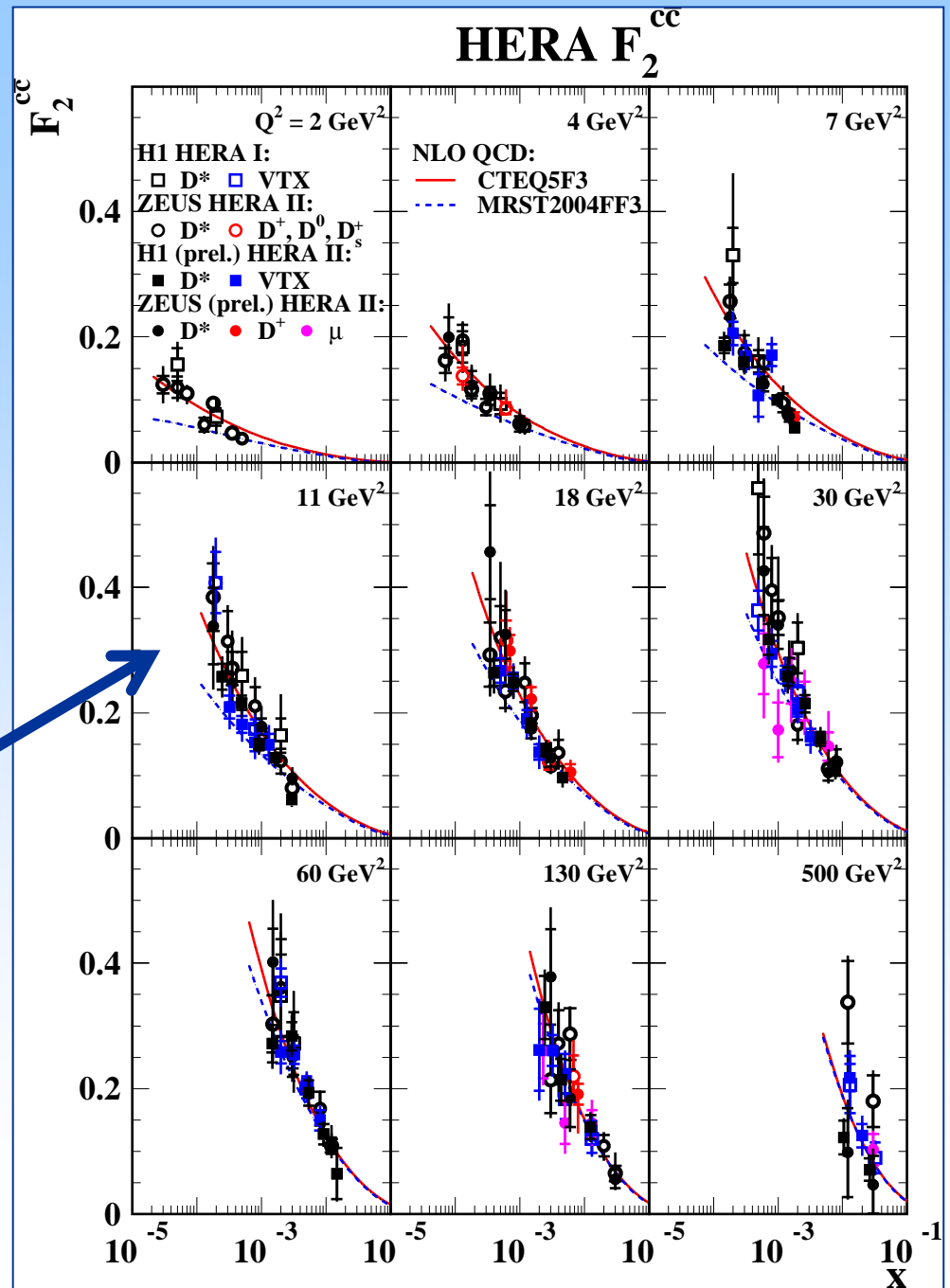
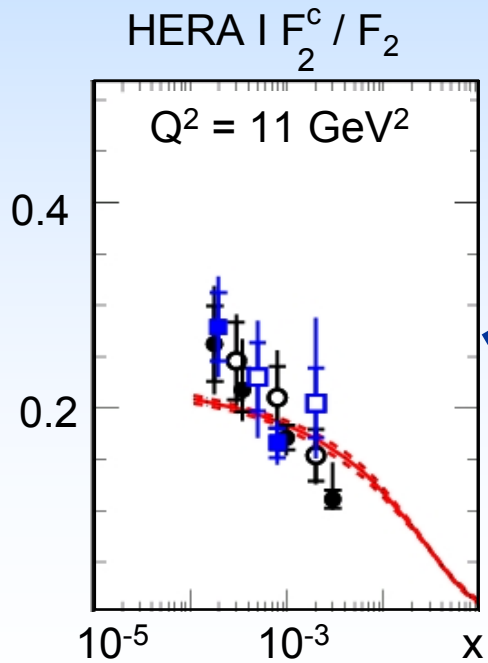
We still need:

- GMVFNS for DIS : proper charm treatment in the global fit
- NNLO

Outlook:

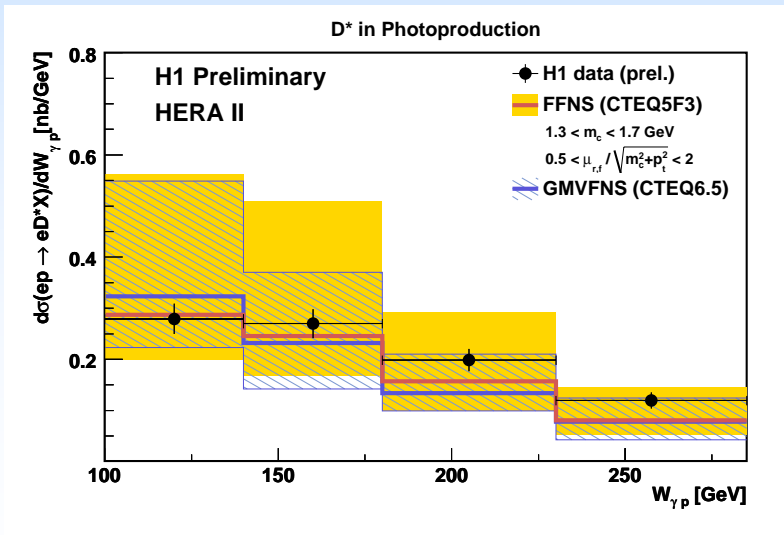
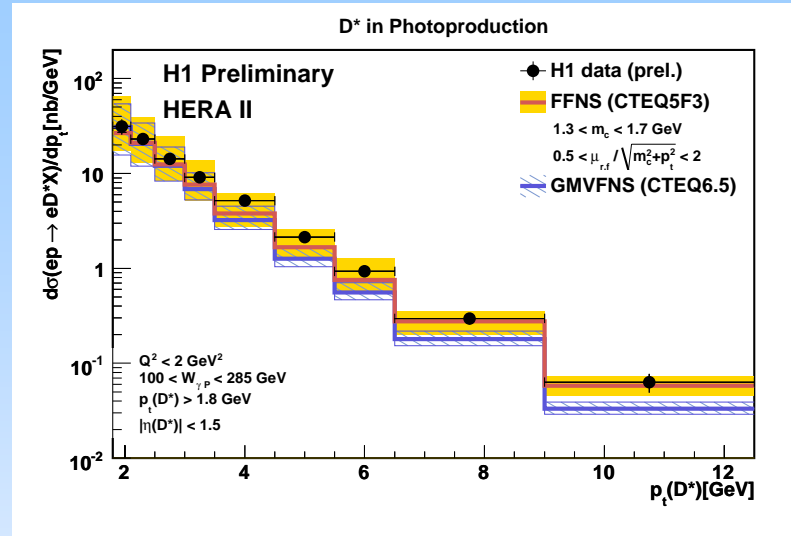
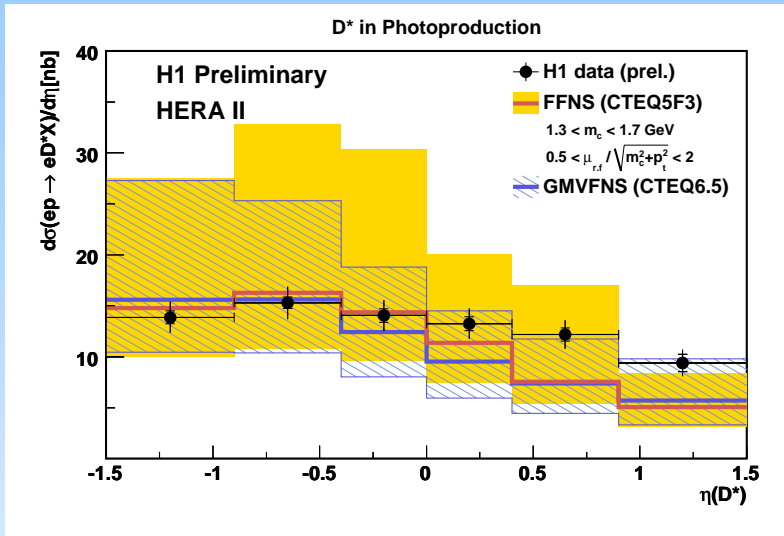
Precision will improve

Results will be combined



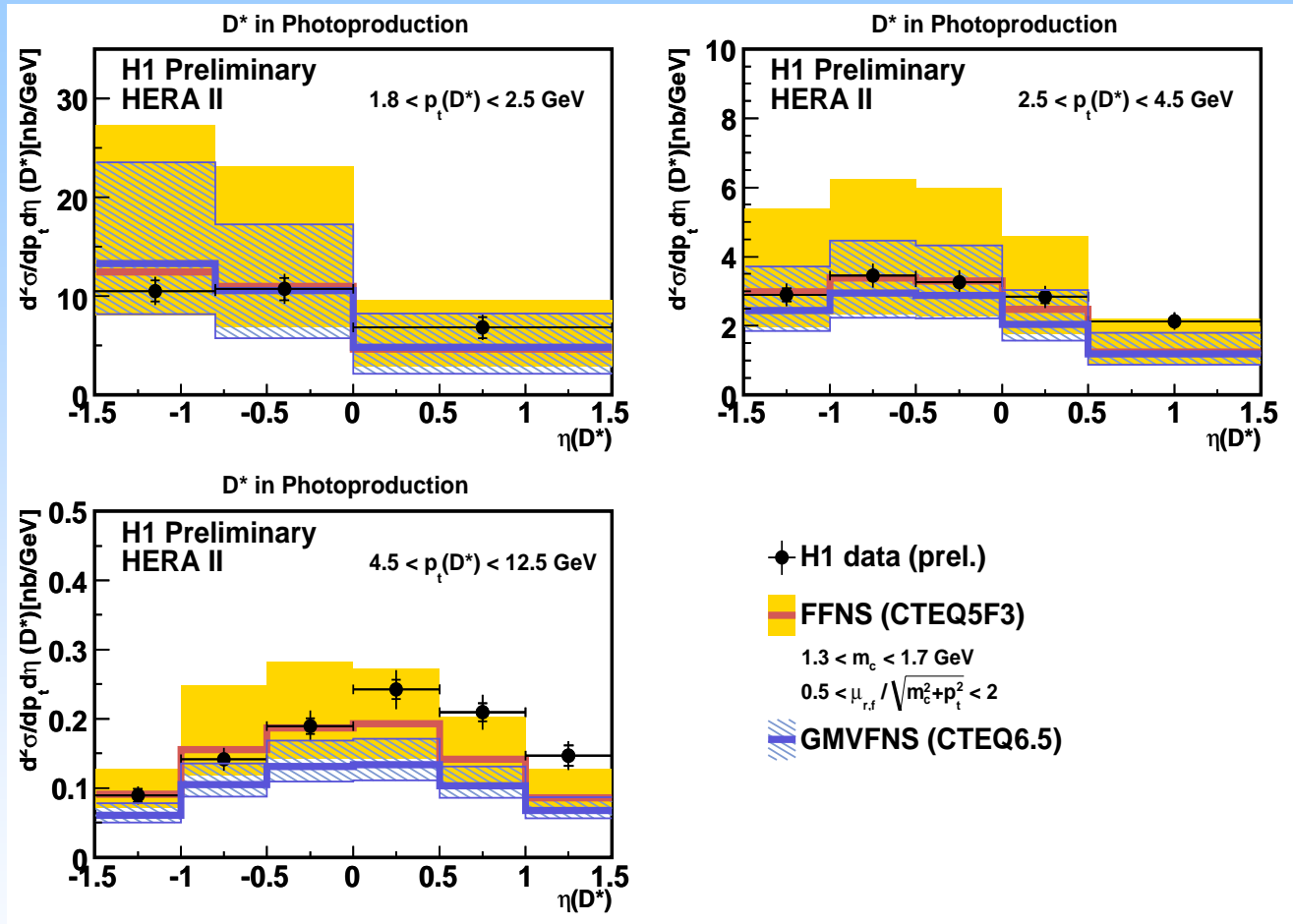
Backup

D* in photoproduction ($Q^2 < 2 \text{ GeV}^2$)



- Measurement in the visible range:
 $P_T(D^*) > 1.8 \text{ GeV}$, $|\eta(D^*)| < 1.5$
 $Q^2 < 2 \text{ GeV}^2$, $0.1 < y < 0.8$
- Good agreement with both NLO
- Large model uncertainties due to variation of the scales

D* in photoproduction



GM VFNS underestimates the forward region at high p_T