F^c_2 measurements at HERA

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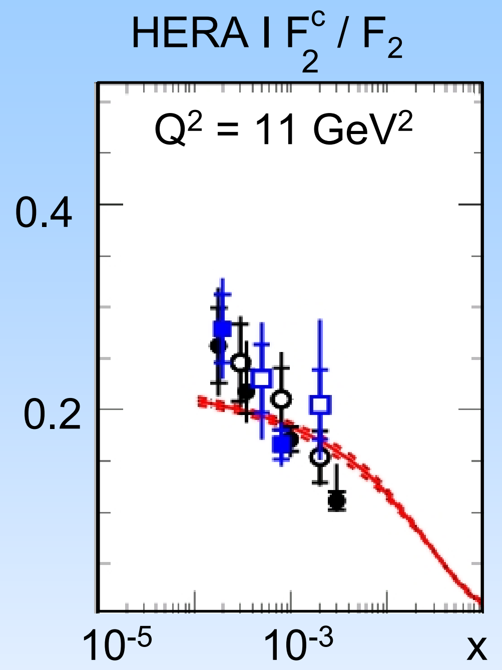
H1 ZEUS

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^c_2 has large uncertainties

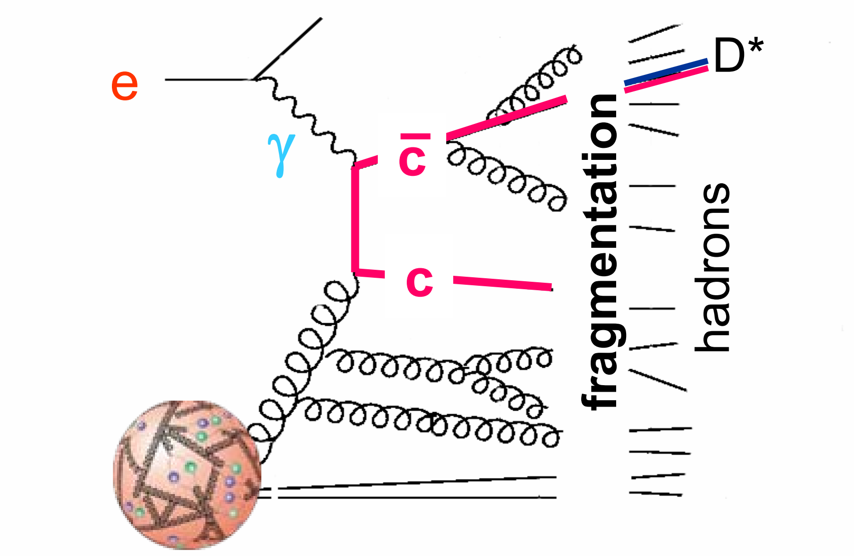


now: precise PDF – crucial importance for the LHC

- 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^c_2 @ 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:

$\sigma(ep\rightarrow D^*X)$=Proton Structure ⊗ Photon Structure ⊗ Matrix Element ⊗ 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^c_2 :**
  - 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 ~log(μ/m)
- no factorization, no conceptual necessity fo 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 $p_t^2 >> m_c^2$

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

Massless calculation (ZM-VFNS)

- large collinear ln (μ^2/m^2_c)-terms resummed in evolved PDFs and FFs (LL, NLL), good for large $\mu^2 \sim p_t^2 >> m_c^2$
- 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

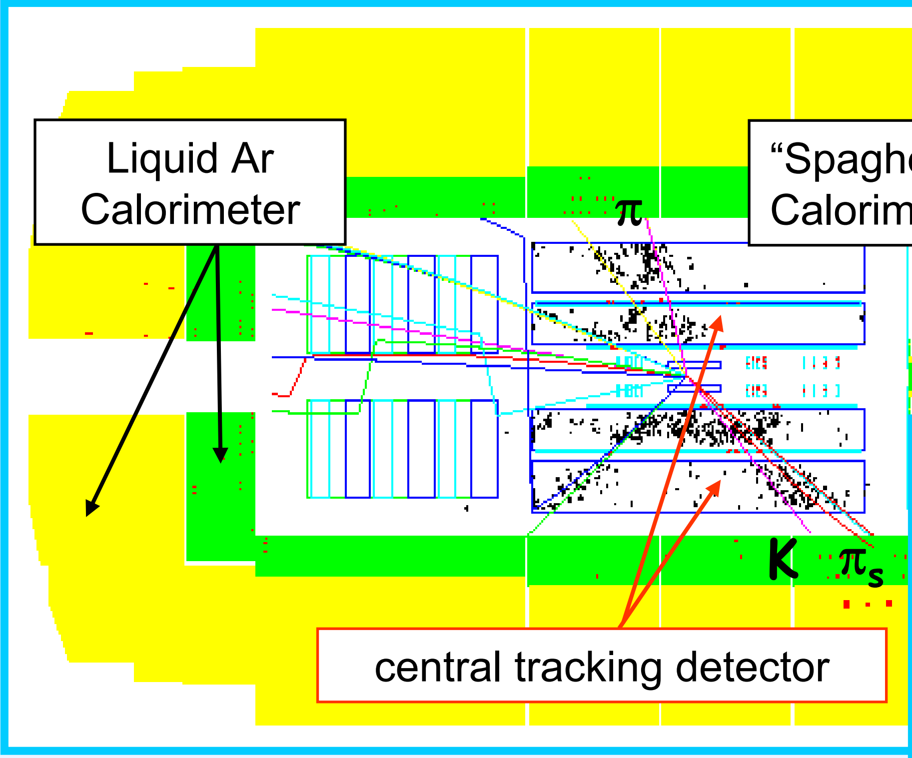
- matrix element calculated in LO QCD
- higher order contributions via parton showers
- parton evolution in collinear approximation (DGLAP equations)
- charm is massive in BGF

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*± production

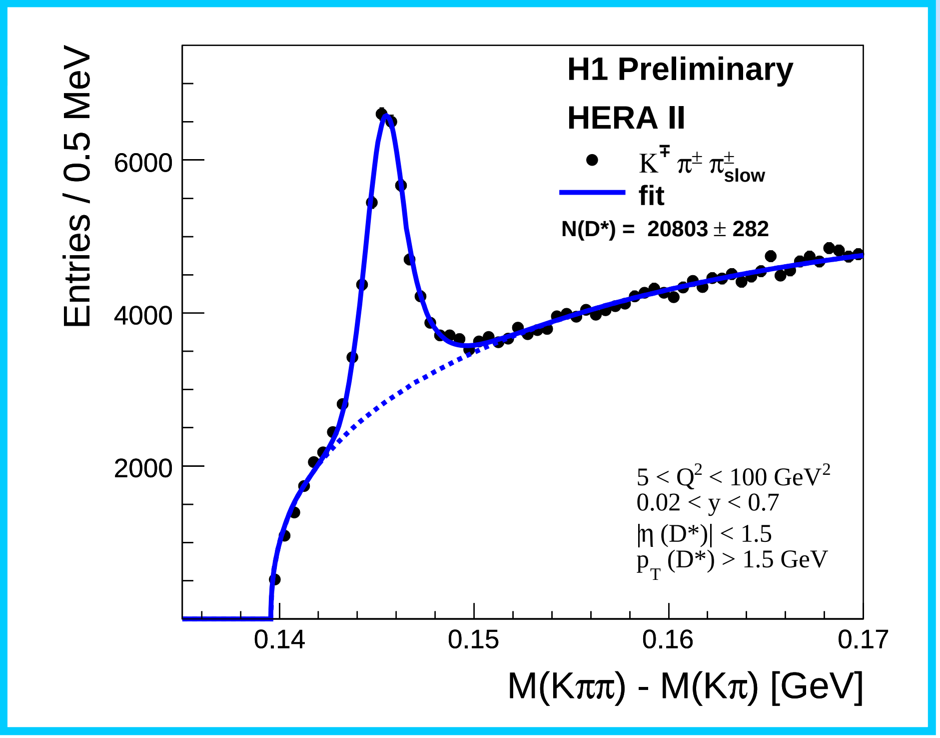


Kinematics regimes:

DIS: 5 <Q^2< 1000 GeV^2

Photoproduction Q^2< 2 GeV^2

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

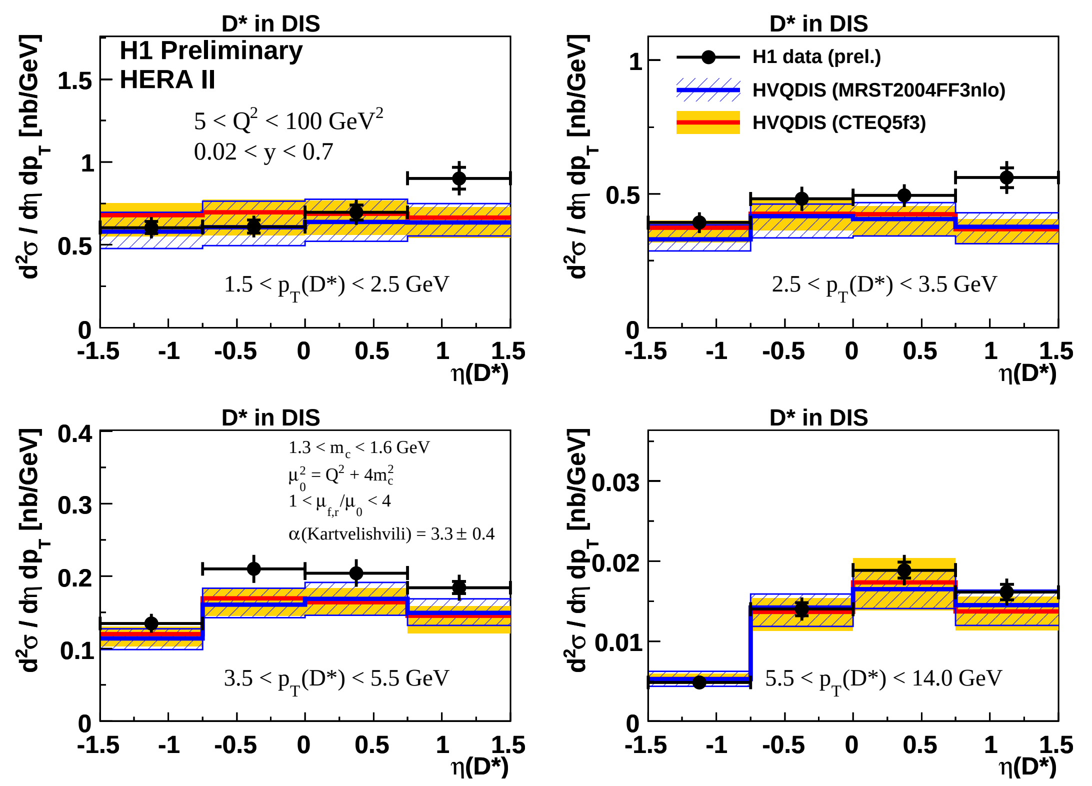


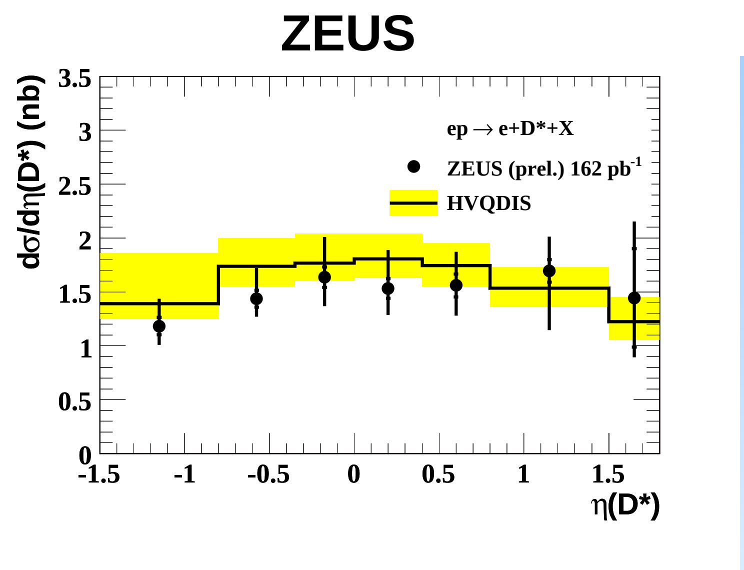
Electron reconstructed in

SpaCal: Q^2<100 GeV^2

LAr: Q^2>100 GeV^2

D* production in DIS ($5<Q^2<100$ GeV^2)



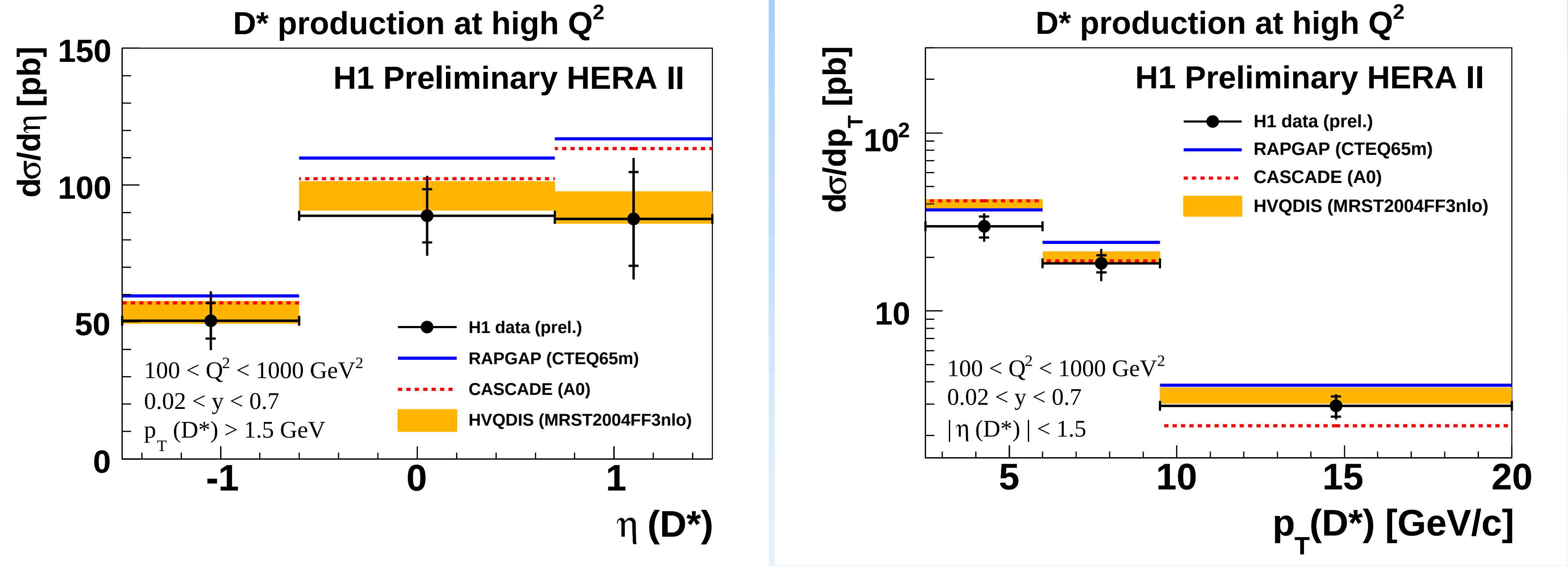


H1: FFNs NLO does good job describing the D* kinematics,

but underestimates forward region ay low p_T(D*)

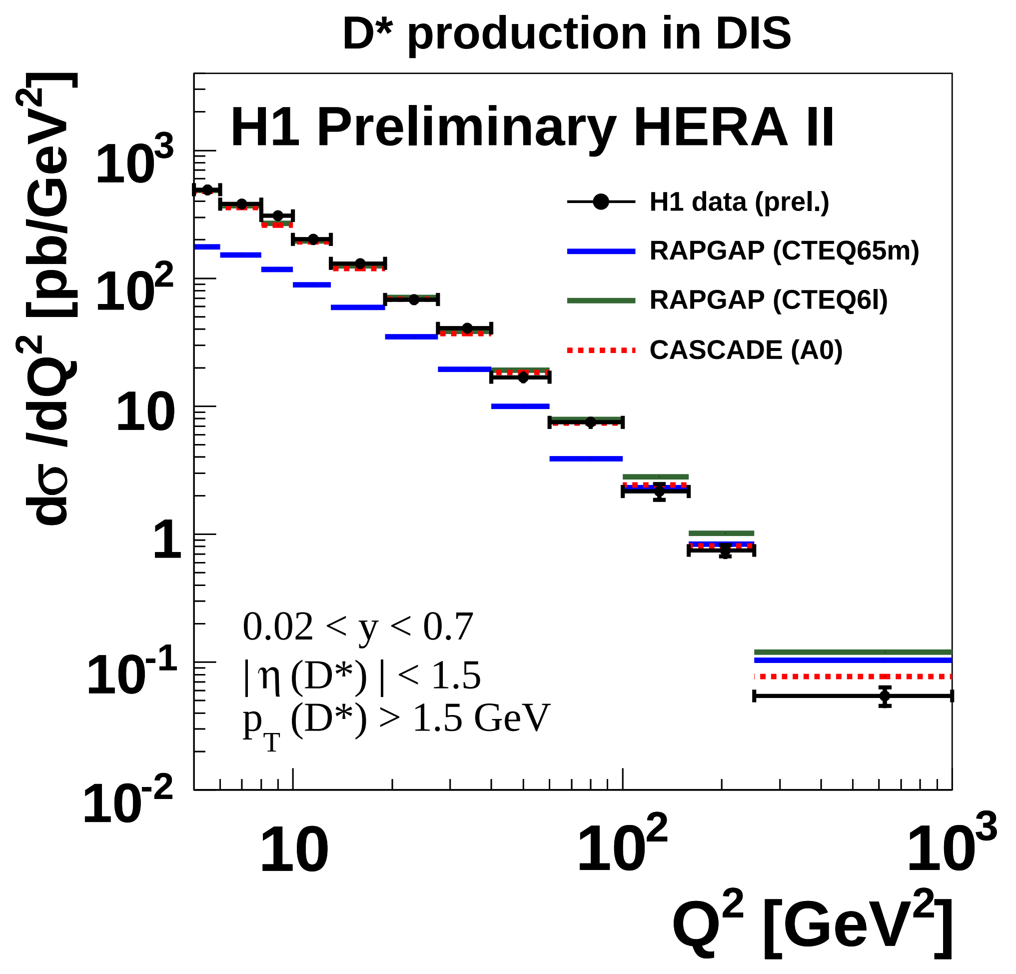
ZEUS: no forward access in the data seen. Data precision will improve

D* production in DIS (Q^2>100 GeV^2)



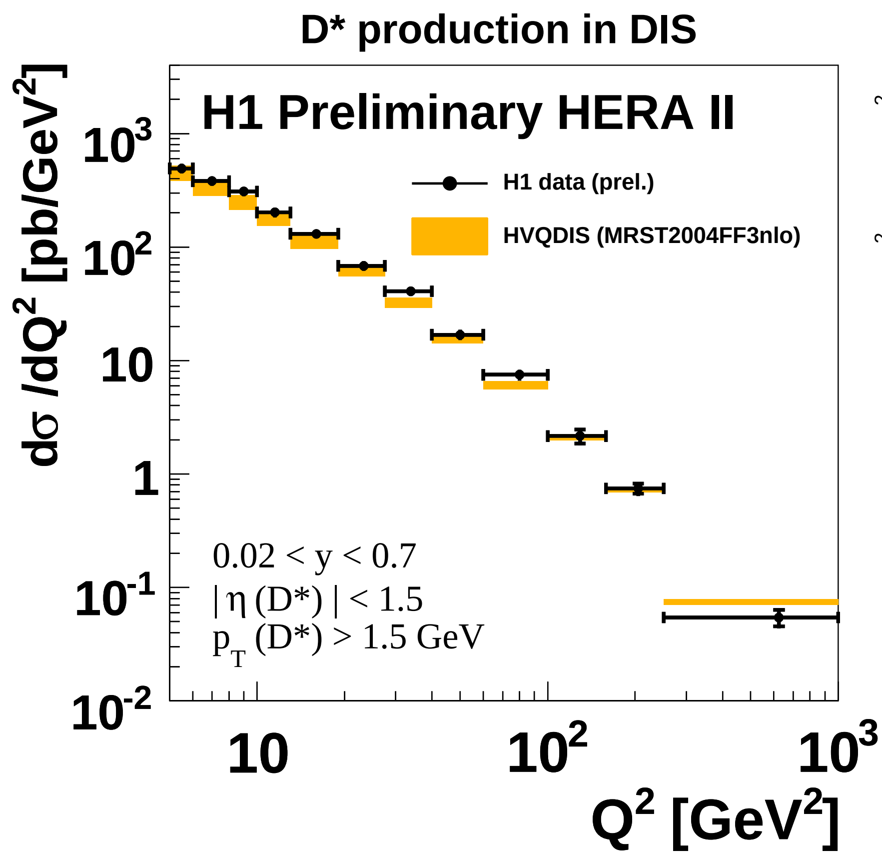
- D* production at high Q^2: description by the LO Monte-Carlo gets worse
- NLO FFNs describes data very well

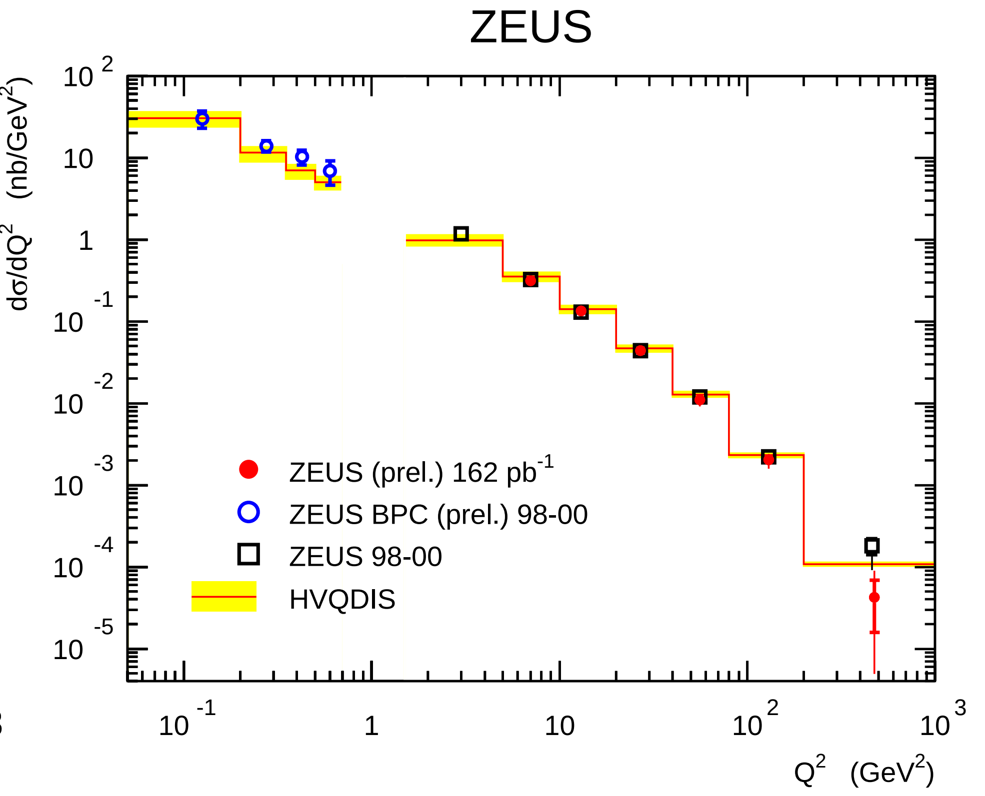
D* production in DIS: Q^2 slope



Monte-Carlo models don't describe the Q^2 slope of the D* cross section

D* production in DIS





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

More to charmed meson production

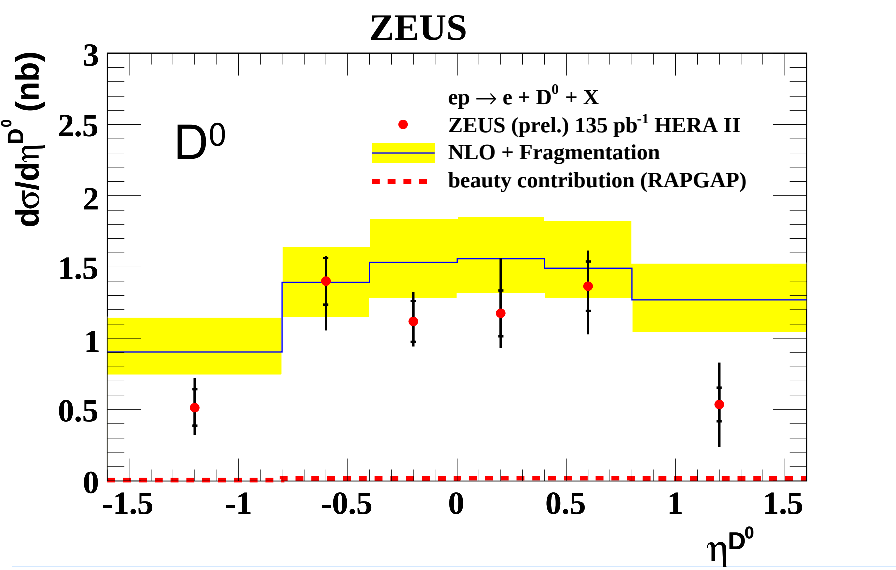
- HERA-II, L=135pb^{-1}

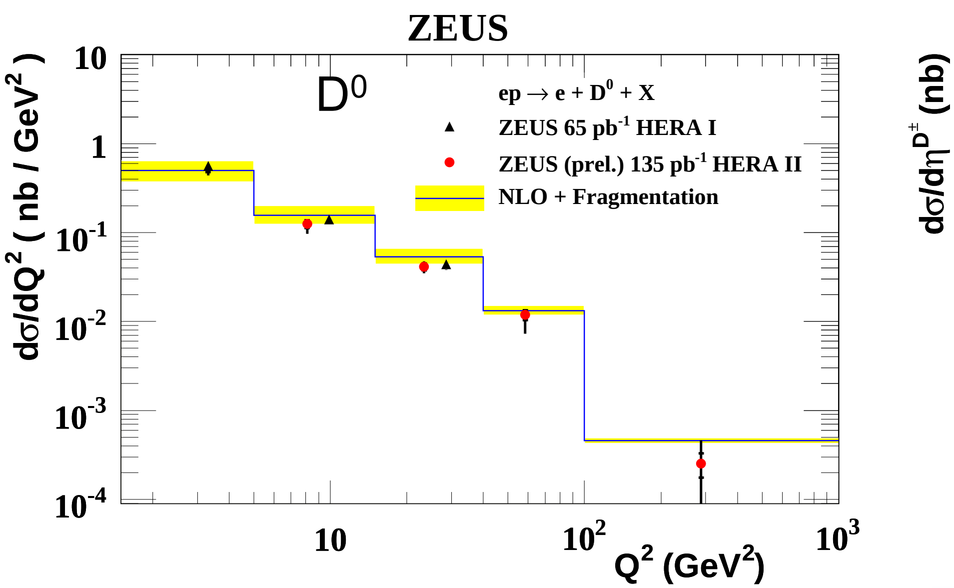
  5<Q^2<1000 GeV^2 ,

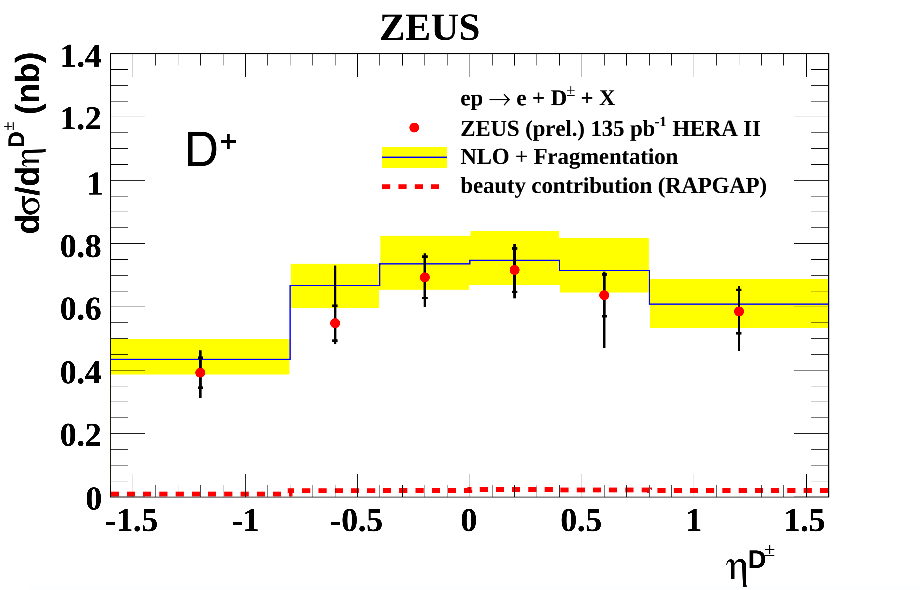
  $p_T(D)$>3 GeV, $|\eta(D)|$<1.6

- Lifetime information from the ZEUS Micro Vertex Detector used

- NLO FFNS describes data well







Extraction of F^c_2 from meson cross section

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

Visible cross section: $p_T(D^*) > 1.5$ GeV, $|\eta(D^*)| < 1.5$

$0.02 < y < 0.7$, $5 < Q^2 < 1000$ GeV^2

Problem: detector sees only 30% of the phase space for c→D*

→ strong model dependence due to large extrapolation factors

Extrapolation problems:

1) Different extrapolation models
2) Unknown parameters within a single model:

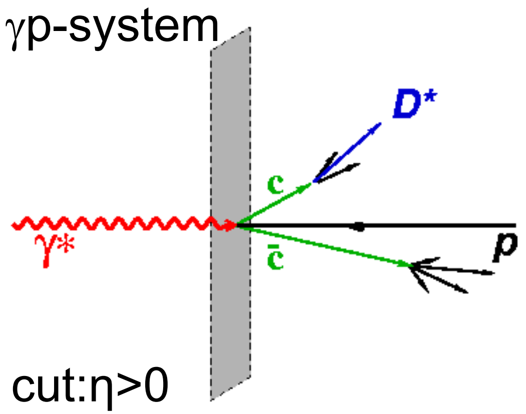
mass of charm quark, scales,

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_T(D*-jet)>3 GeV
  - significant contribution only from $\hat{s} > 100$ GeV² (much above threshold)
- Hemisphere containing D*:
  - experimental setup similar to e^+e^- , works at threshold, $\hat{s} \approx 4m^2_c$

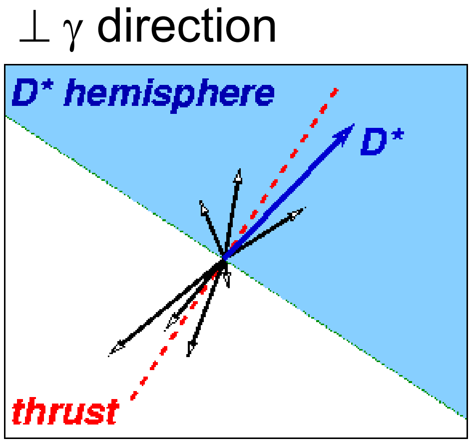


- take all particles towards γ

- project onto the plane $\perp$ to the γ

- get Thrust axis

- Σ momenta of all particles in the D* hemisphere

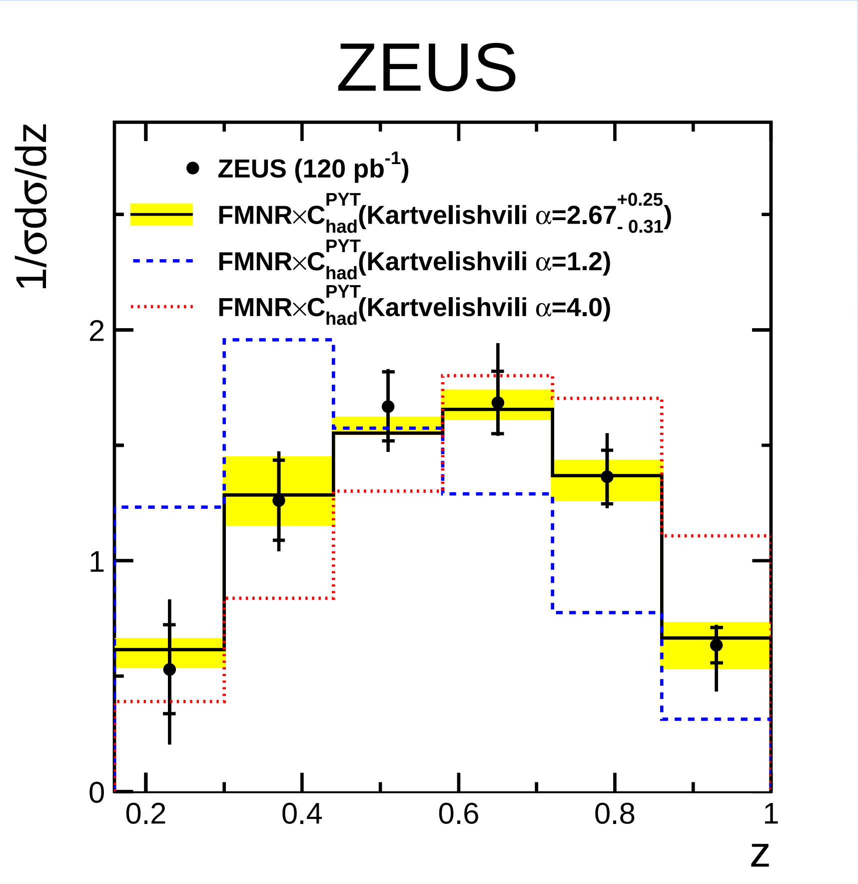


Charm fragmentation in photoproduction

Parent quark approximated by a jet containing D*

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

- data: HERAI, $\mathcal{L}$ =120 pb^{-1}, Q^2<1GeV^2;
- p_T (D*) >2 GeV, Iη(D$*$)I<1.5
- inclusive $k_\perp$ algorithm, E_T(D*-jet)>9 GeV



- compared to the NLO FFNS (FMNR)

  fragmentation model: Kartvelishvili

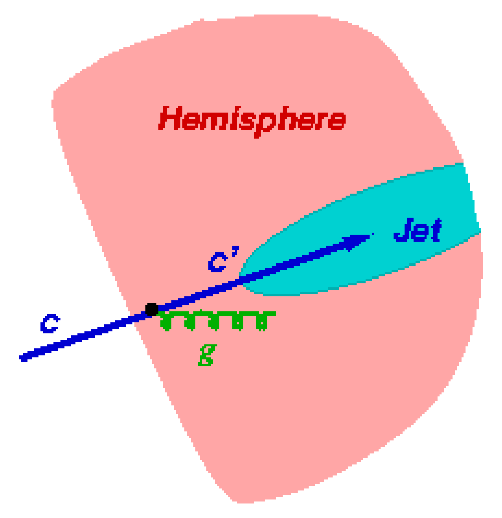
$$D_c^{D^*}(z) \propto z^{\alpha}(1-z)$$

best fit α=2.67

Measurement of charm fragmentation in DIS

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

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

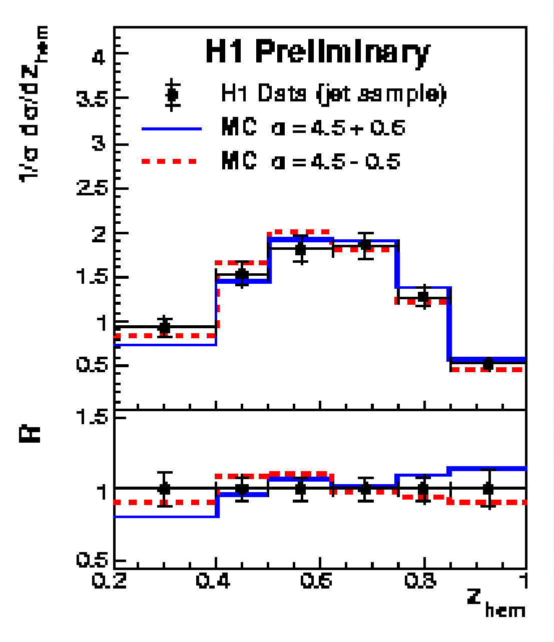
⇒ Extracted parameters of the non-perturbative fragmentation function should agree

- 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)?

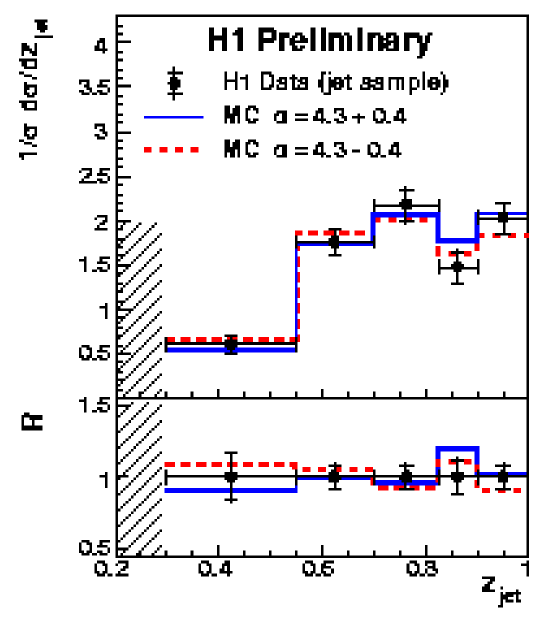
Fragmentation measurement: D*- Jet sample

RAPGAP MC:

Hemisphere method

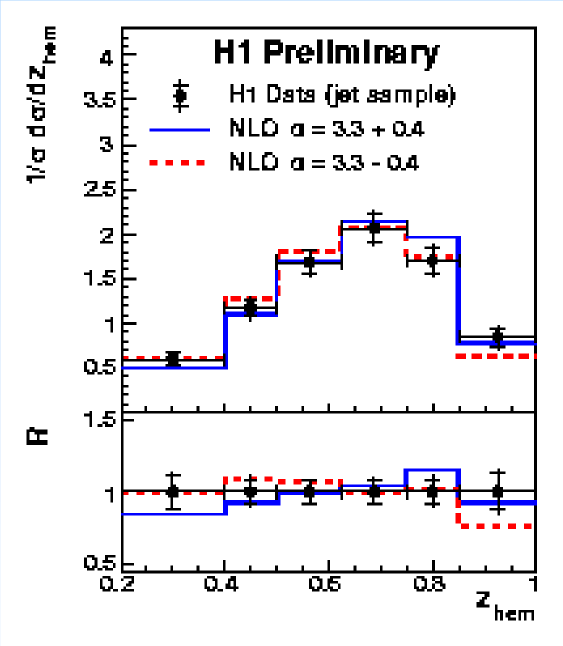


Jet method



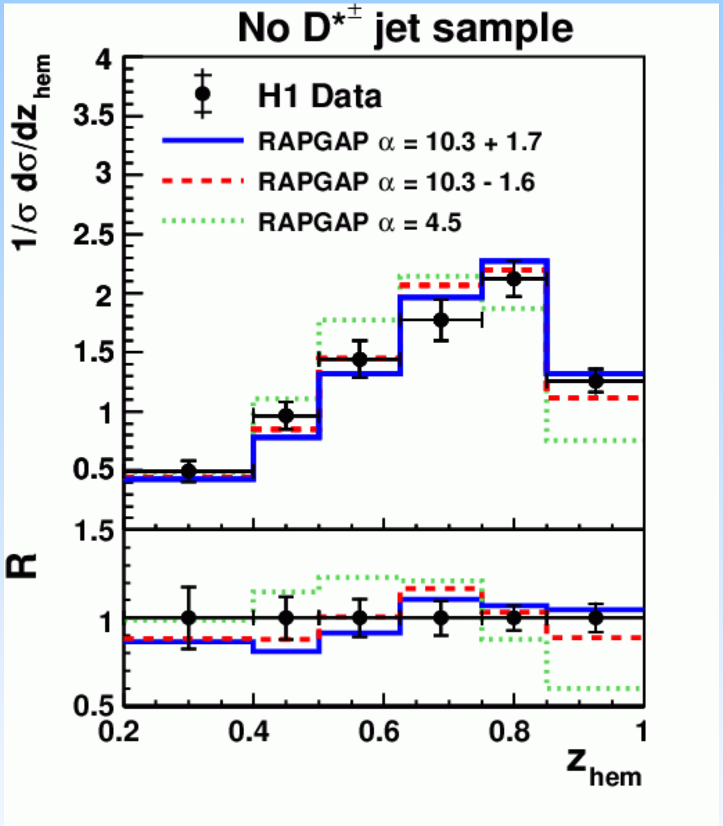
NLO (HVQDIS):

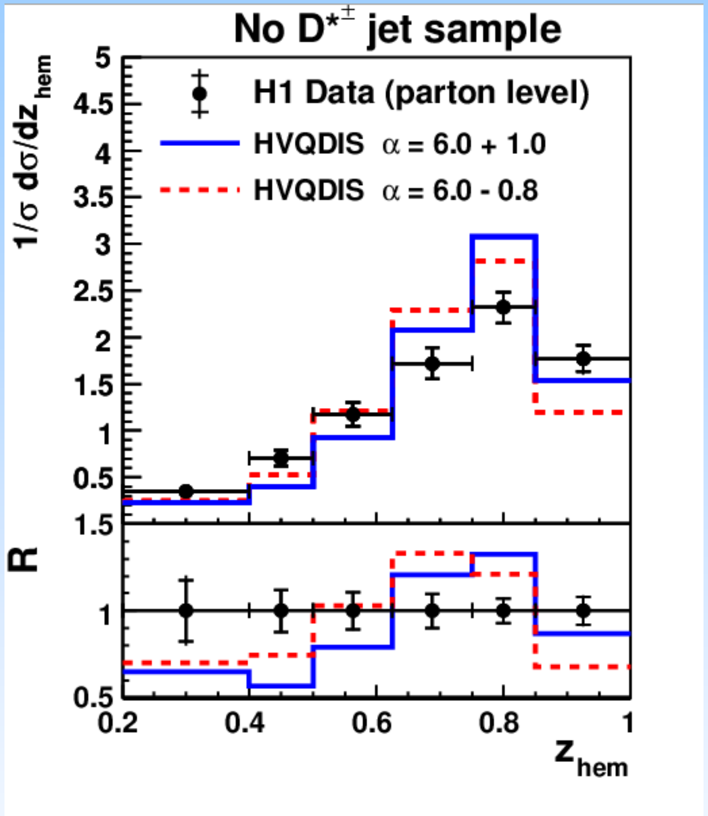
Hemisphere method



- 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} (α=4.5±0.6) and z_{jet} (α=4.3±0.4) agree
- HVQDIS ⊗ Kartvelishvili fragmentation: extracted parameters z_{hemi} and z_{jet} agree

Fragmentation c → D*. No D*- jet sample





MC: Extracted parameters ($\alpha=10.3^{+1.7}_{-1.6}$) inconsistent with jet-sample ($\alpha=4.5\pm0.6$)

HVQDIS: “no jet” ($\alpha=6.0^{+1.0}_{-0.8}$) inconsistent with jet-sample ($\alpha=3.3\pm0.4$)

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

Treatment in extrapolation models: ŝ-dependent fragmentation

Back to extrapolation of $\sigma(D^*)$ to the F^c_2

Extrapolation Models in use:

- NLO: Riemersma et al: integrated form; HVQDIS: differential form,

  fixed order massive calculation, Nf=3, FFNS, evolution: DGLAP

  Parameters: PDFs: MRST04F3, m_c = 1.43 GeV , $\mu_r=\mu_f=\mu=\sqrt{Q^2+4m_c^2}$

  Fragmentation: $\hat{s}<70$ GeV^2: α =6.0, otherwise α=3.3

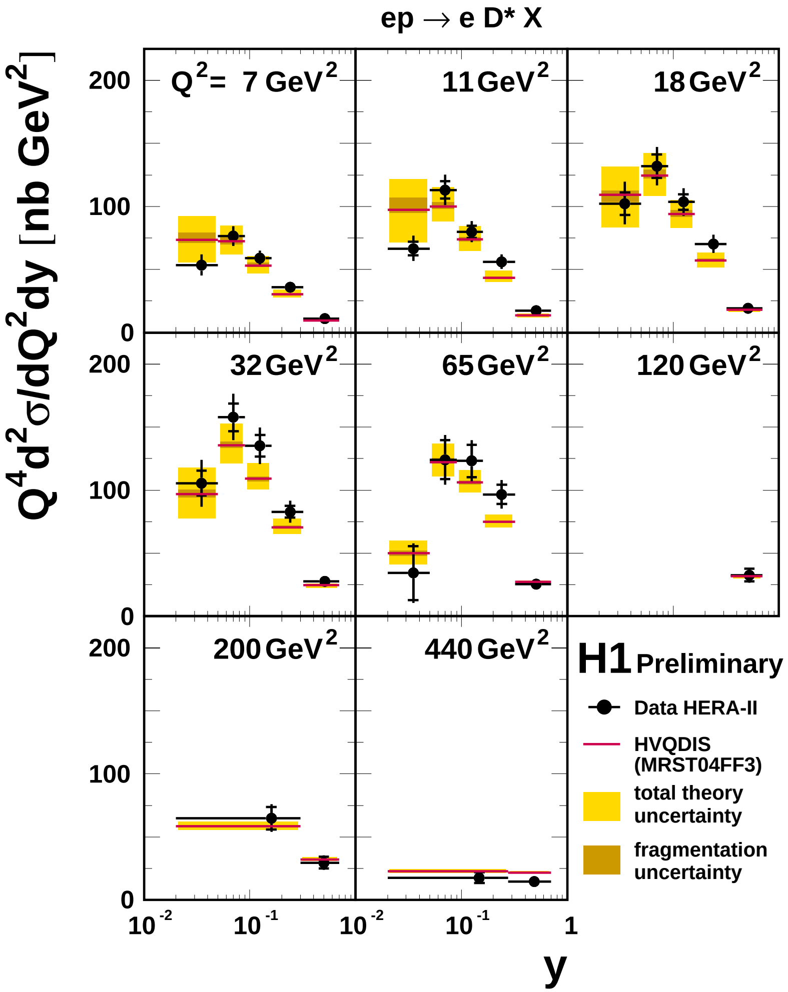
- CASCADE: massive LO ME + Parton showers,

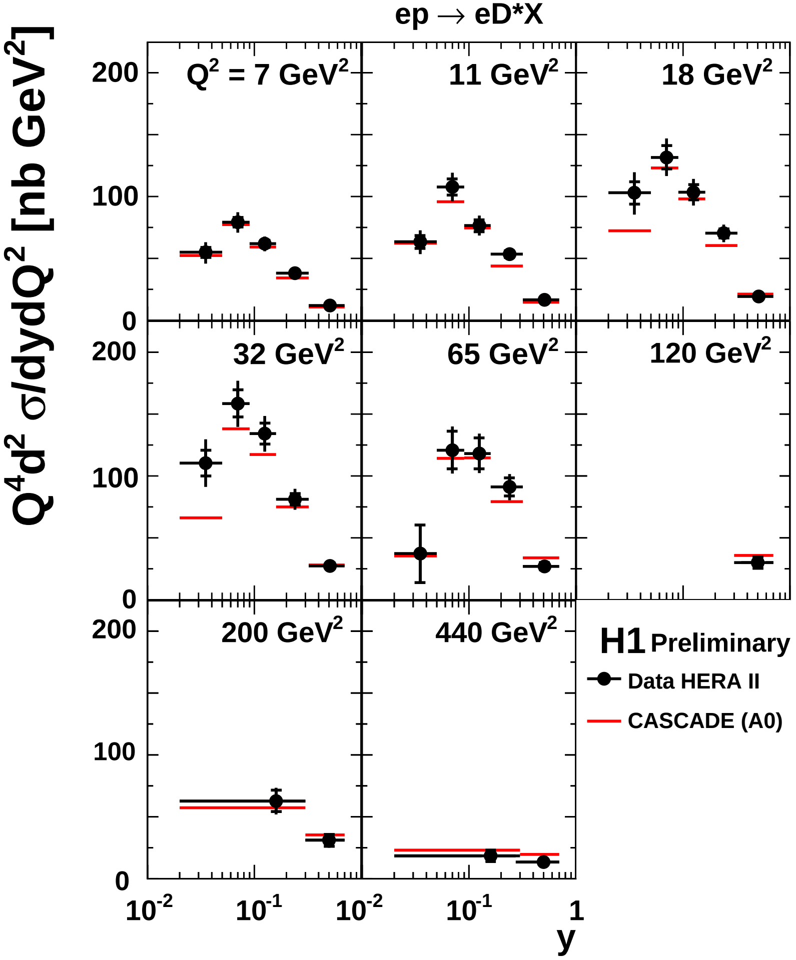
  proton structure: gluons only, evolution: CCFM

  Parameters: PDFs: A0, m_c = 1.43 GeV, $\mu_r=\mu_f=\mu=\sqrt{Q^2+4m_c^2}$

  Fragmentation: $\hat{s}$ <70 GeV^2; α = 8.2, otherwise α = 4.3

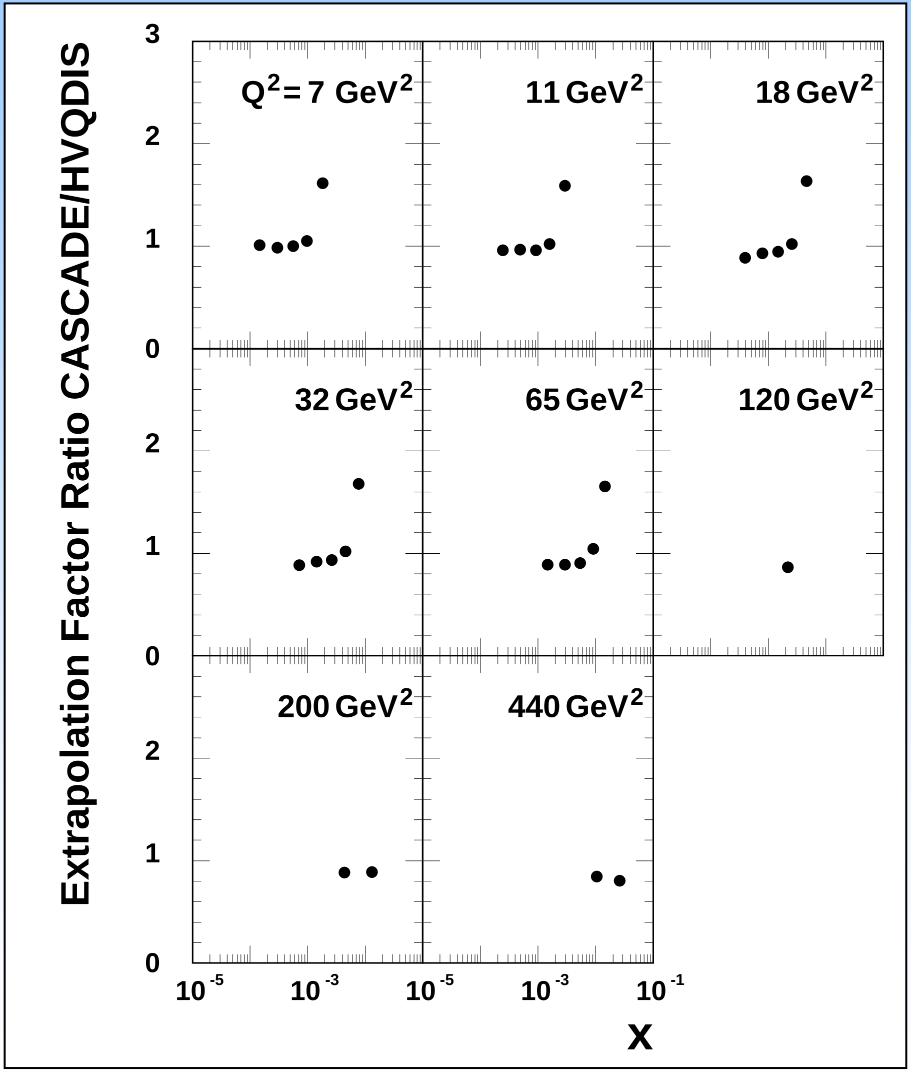
D* cross sections vs NLO/CASCADE





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

Extrapolation factors NLO/CASCADE



Extrapolation factors ($\sigma_{tot}/\sigma_{vis}$)

differ in NLO vs CASCADE:

3%-10% (low x) -100% (high x)

Differences in the models:

- LO+PS vs NLO
- Evolution
- Hadronization

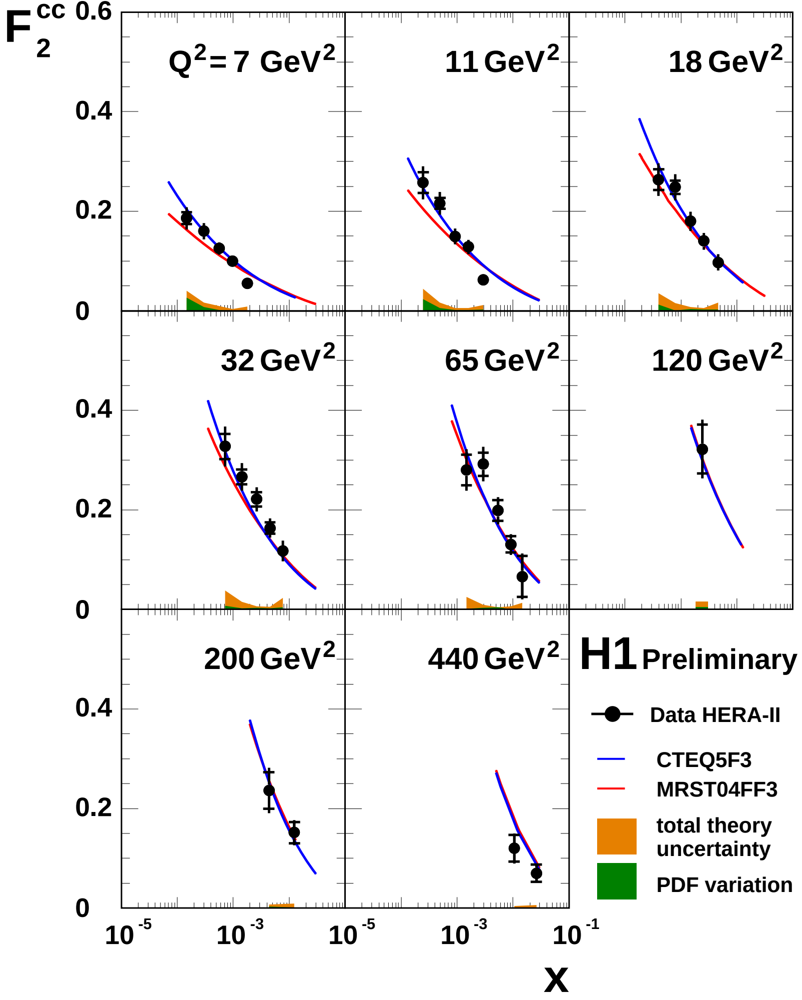
Possible reason:

Hadronization

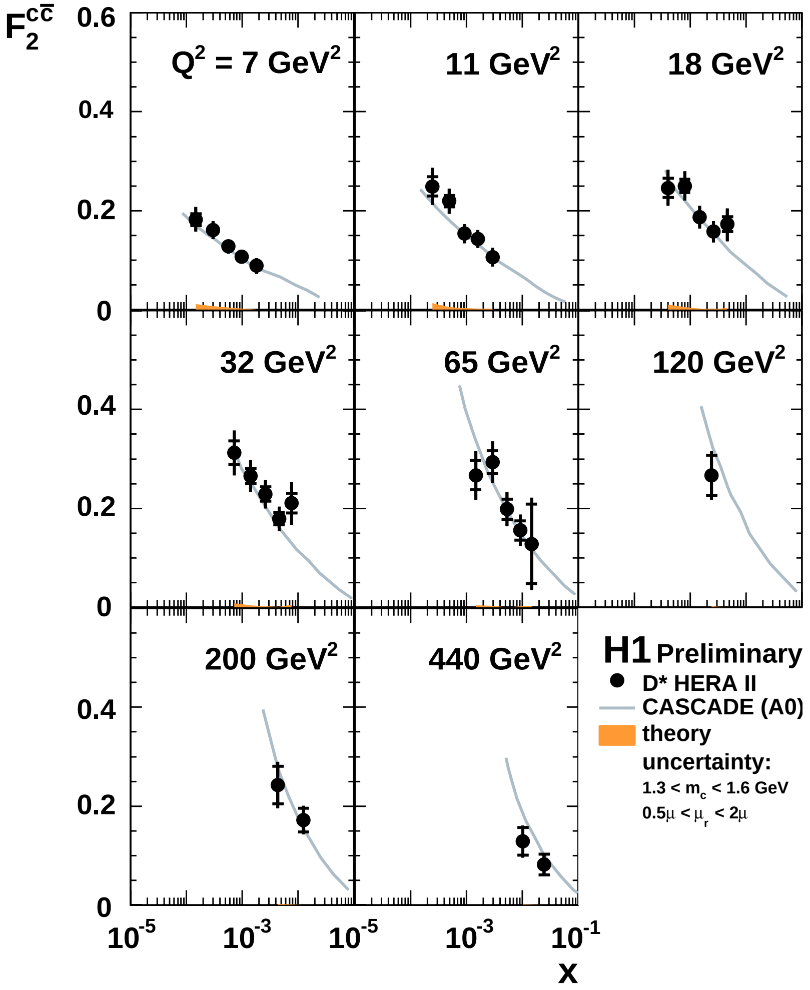
More studies have to be done

Results: F^c_2 from D* measurement

$F_2^{c\bar{c}}$ in the NLO DGLAP scheme (HVQDIS)

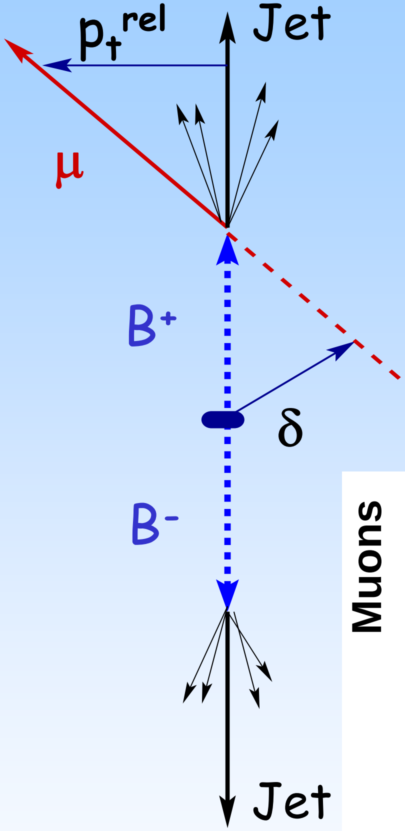


$F_2^{c\bar{c}}$ in the CCFM scheme (CASCADE)



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

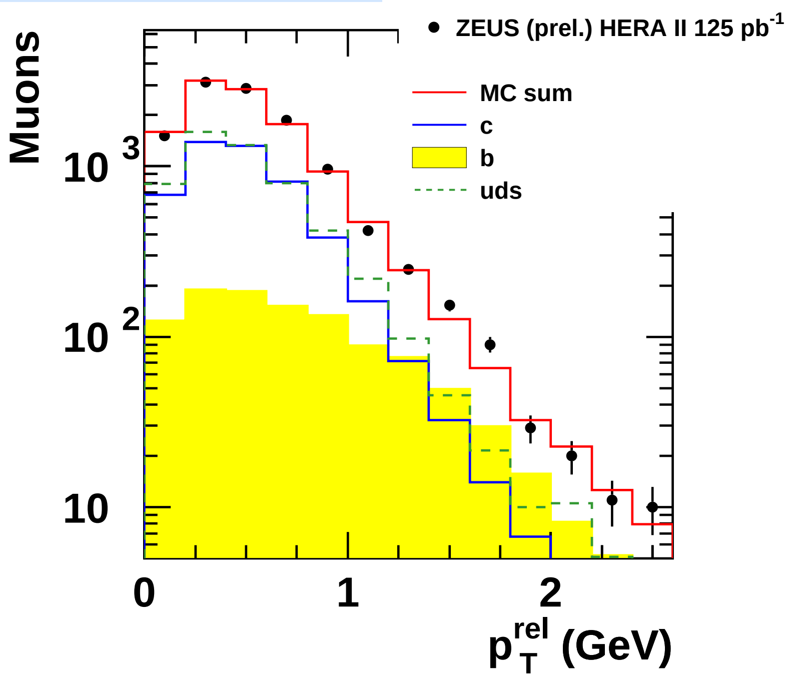
Charm/beauty via other tag methods

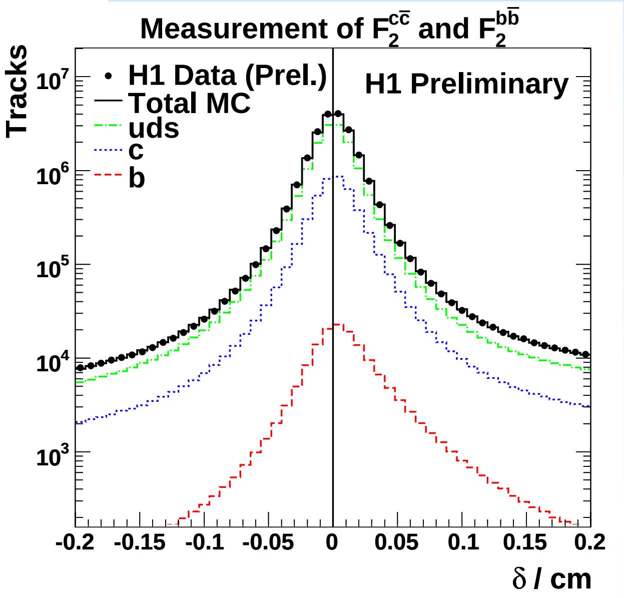


- Charm comes alone with beauty:

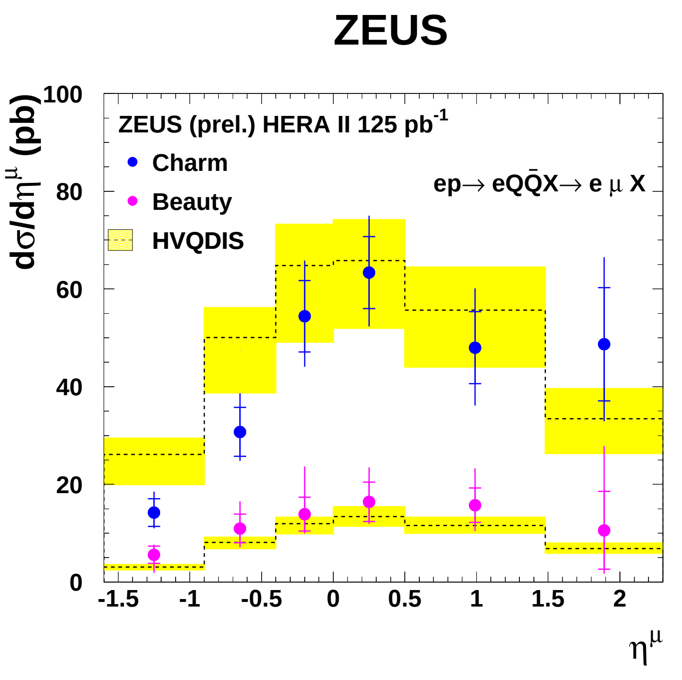
  - More experimental details in Massimo’s talk

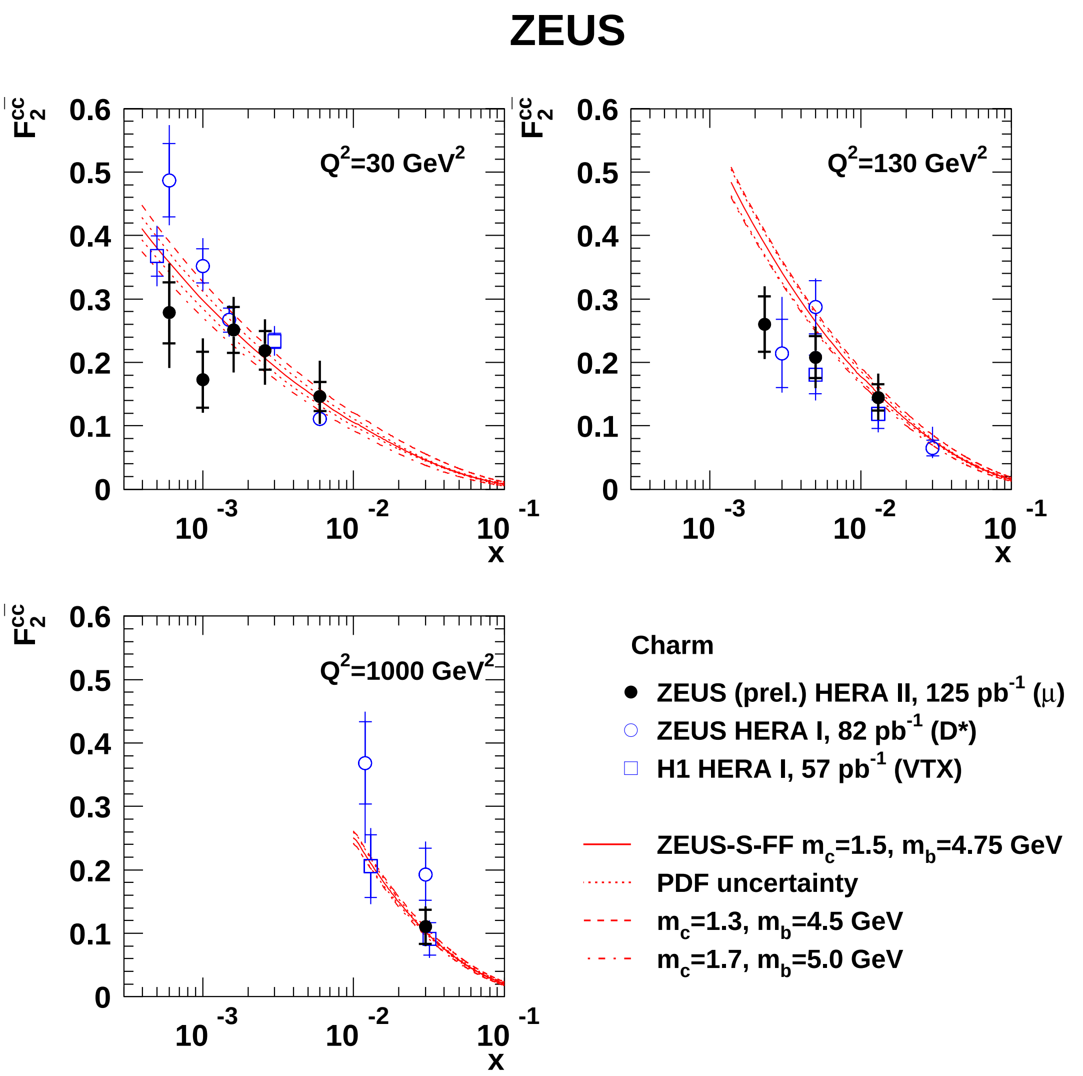
- Large mass : transverse momentum to Jet axis: muon p_t^{rel}
- Large lifetime: impact parameter δ, Significance $S=\delta/\sigma(\delta)$
- Semileptonic decays (e,μ)
- Different systematic uncertainties wrt. D-meson measurements





Charm in semileptonic events

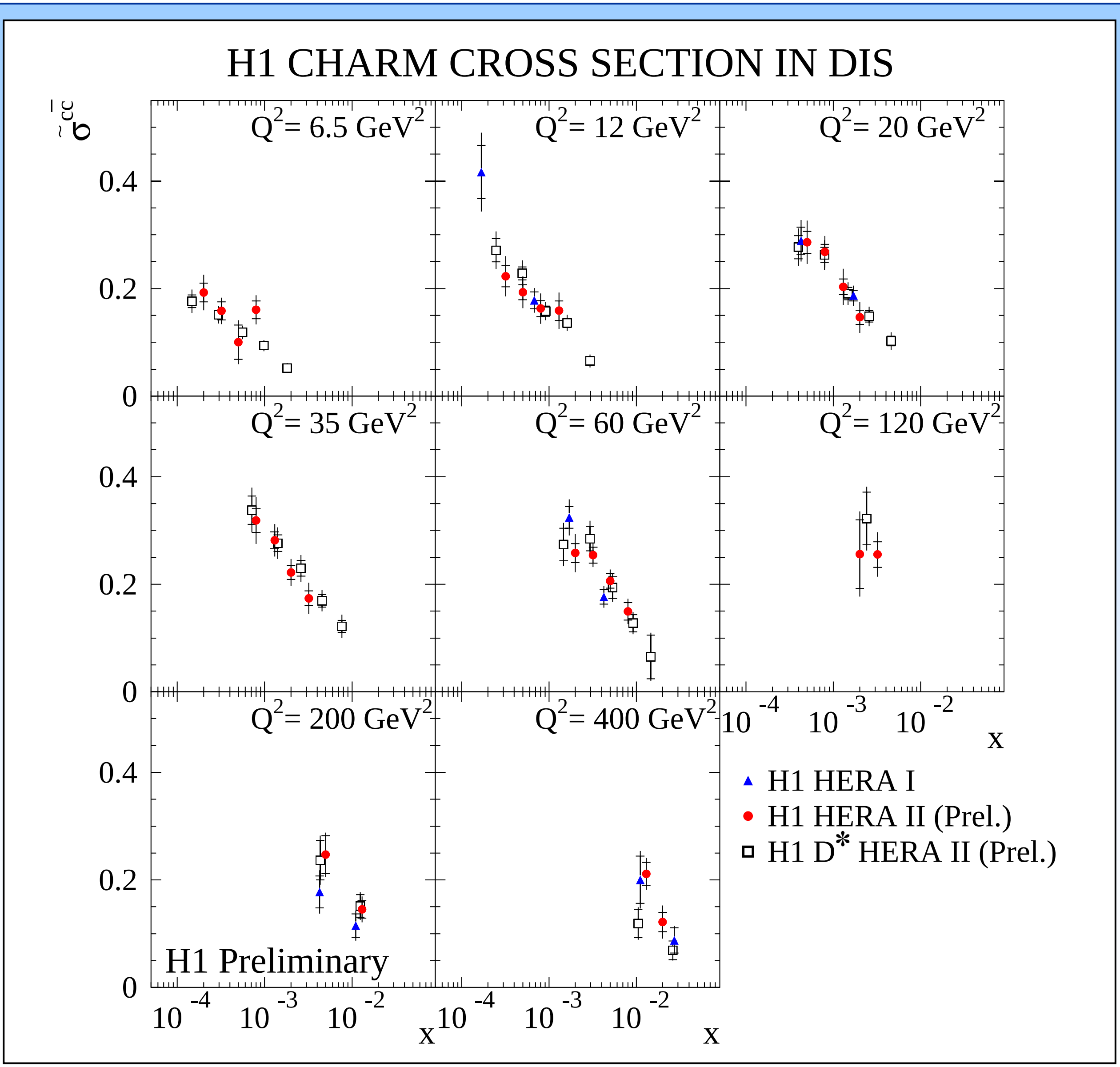




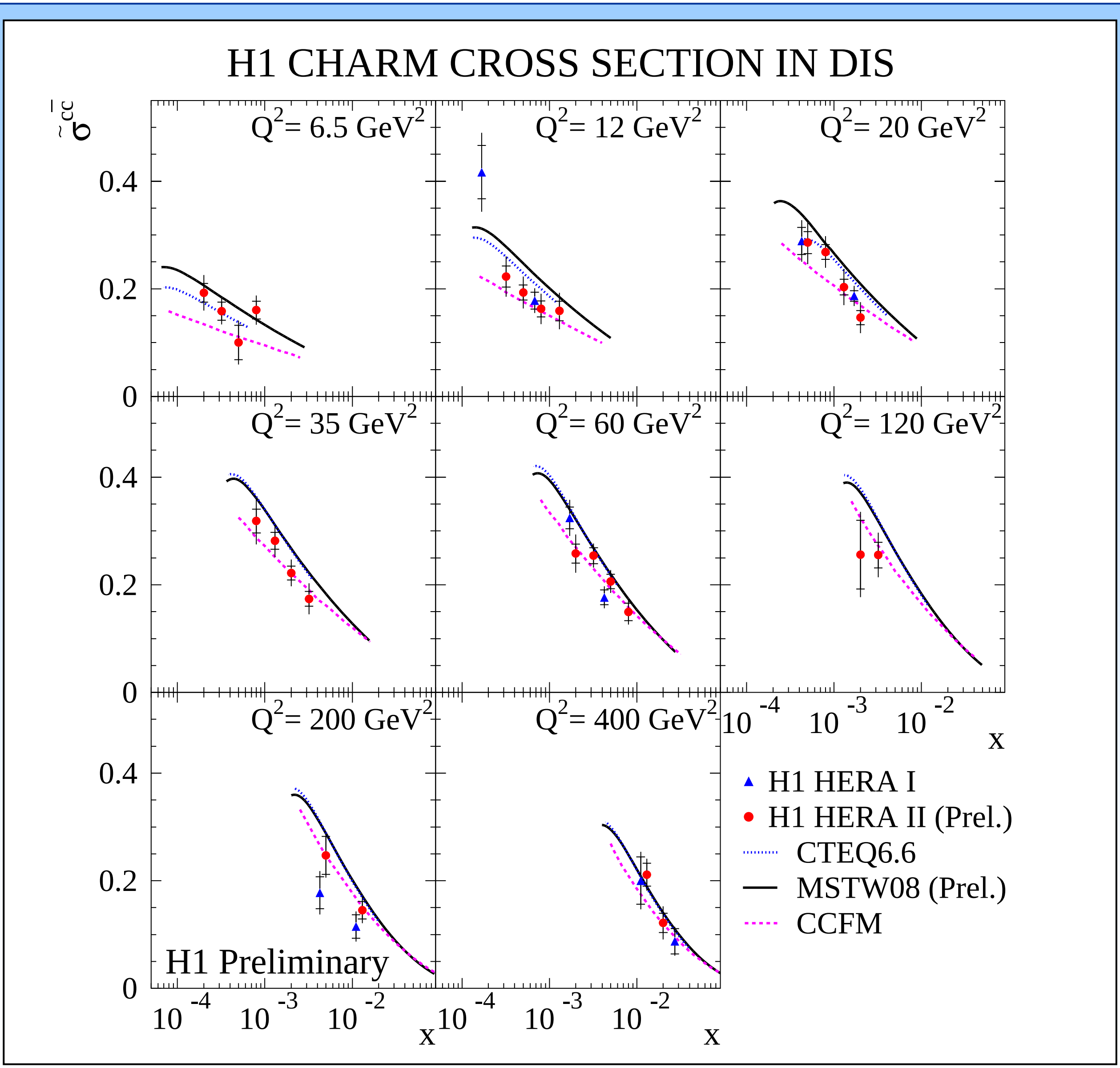
Reasonable description

by the NLO FFNS

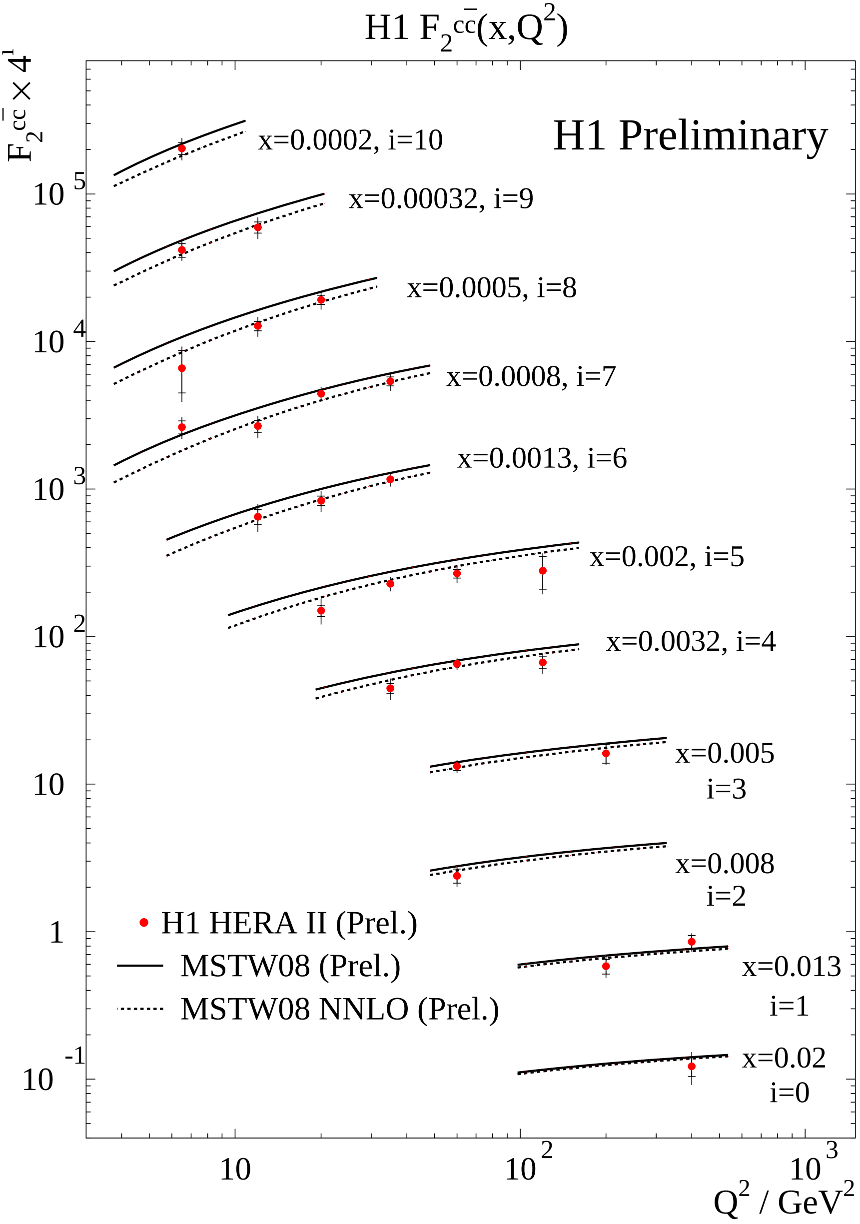
Charm cross sections via lifetime tag vs D*



Charm cross sections vs VFNS (TR)



F^c_2 from lifetime tag vs MSTW NNLO



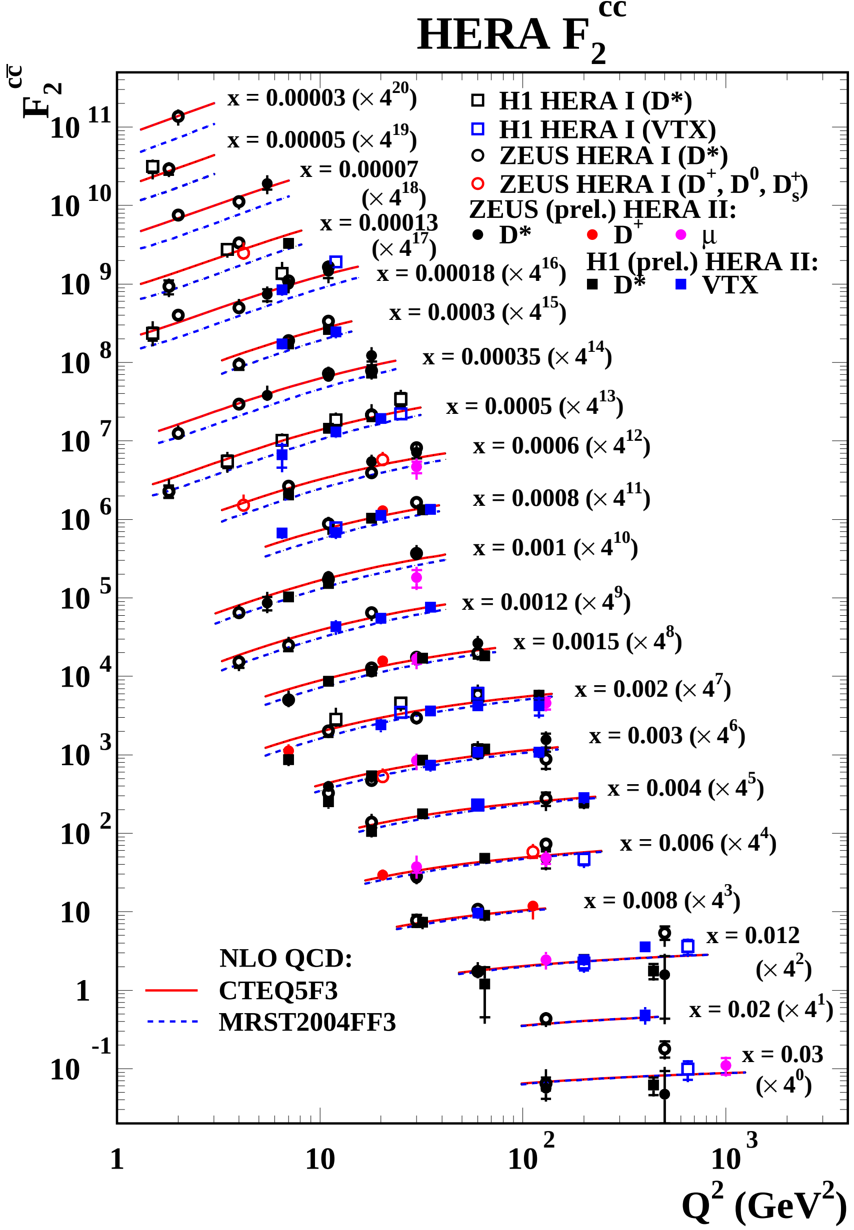
Recall Robert's talk on Monday:

NNLO better fits the measured F^c_2

Only Lifetime data of H1 are shown

Data will get better !

HERA measurement of F^c_2



- 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

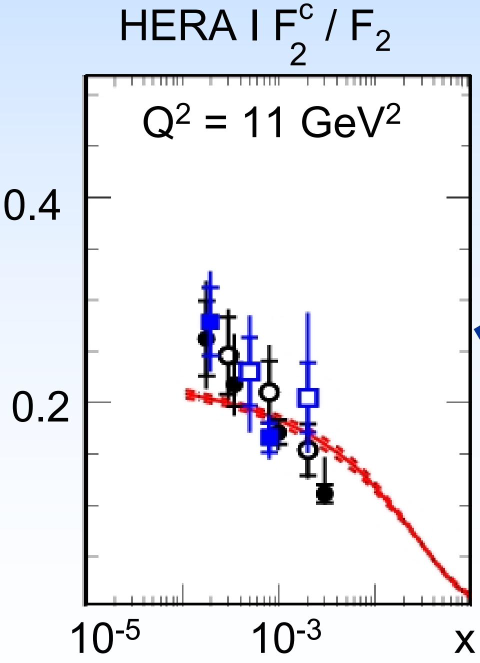
We still need:

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

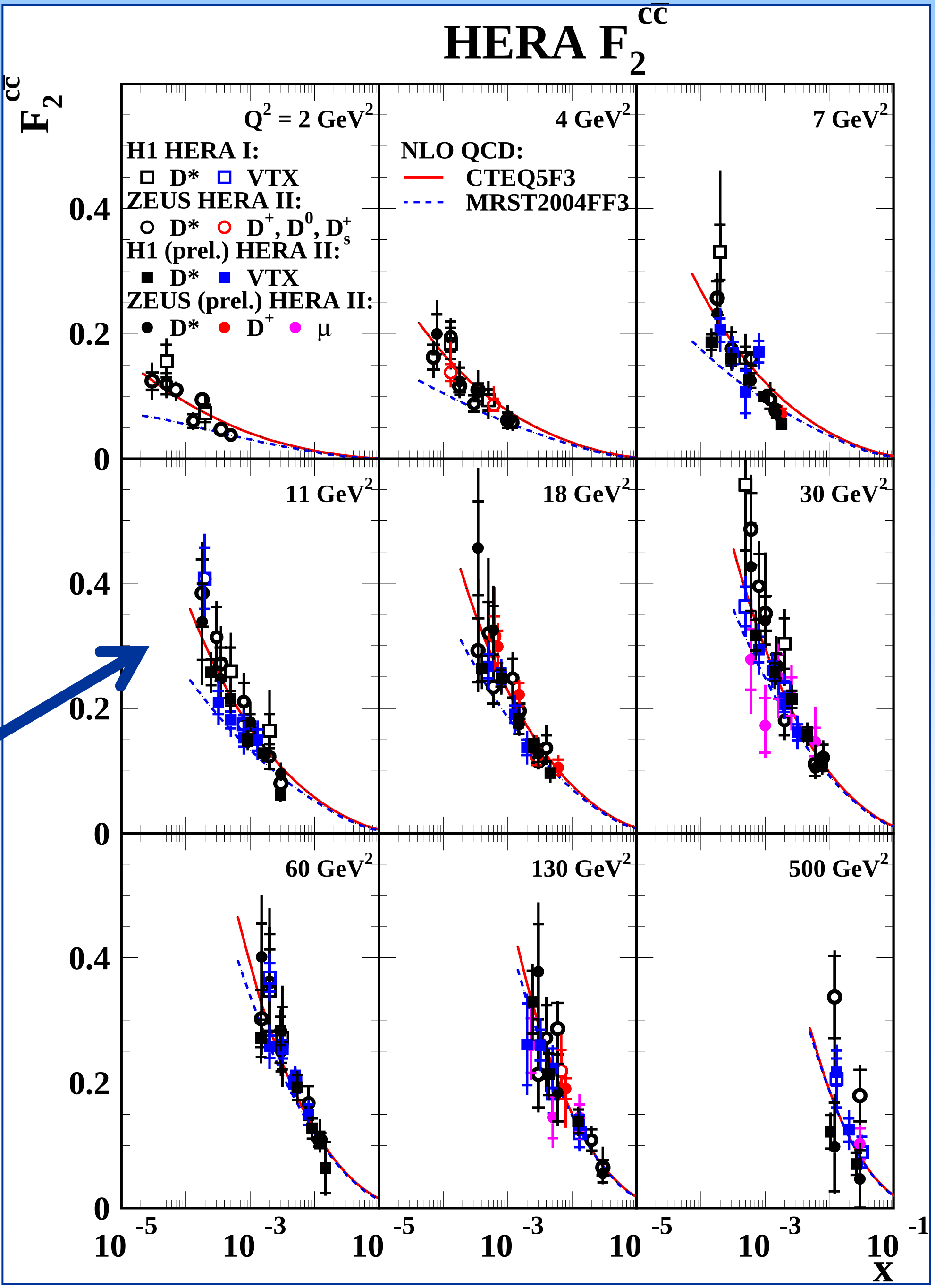
Outlook:

Precision will improve

Results will be combined



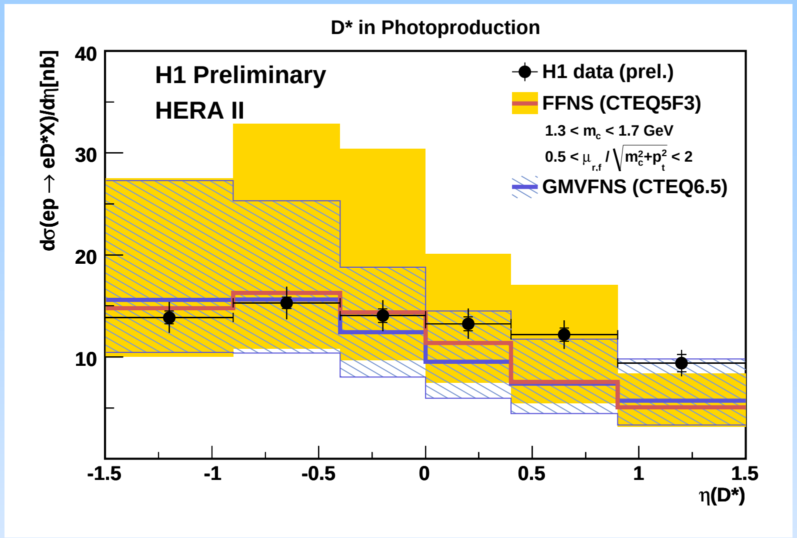
HERA I F_2^c / F_2

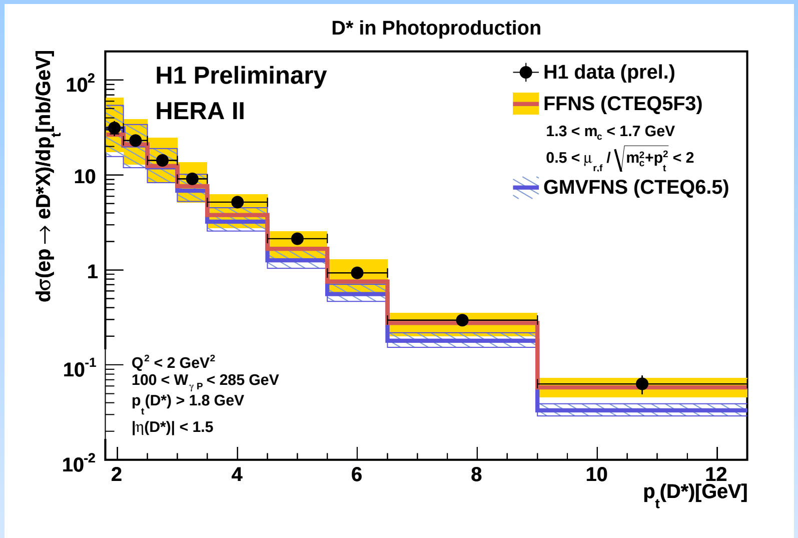


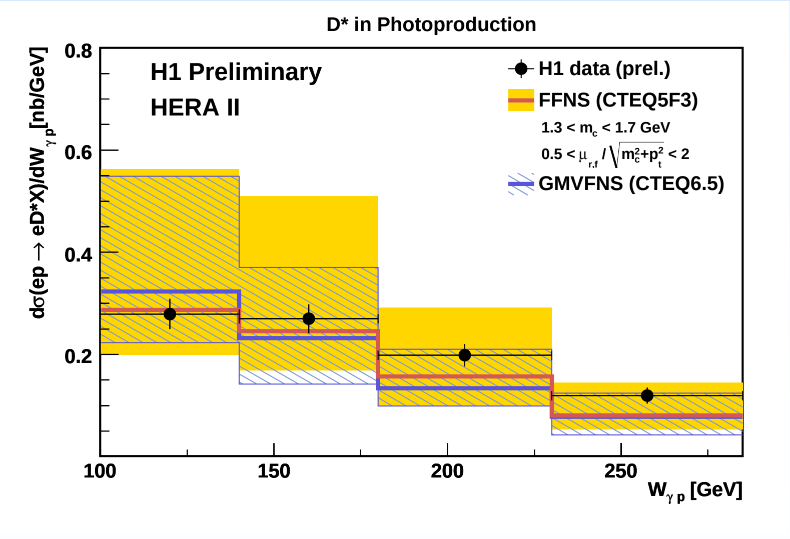
HERA $F_2^{c\bar{c}}$

Backup

D* in photoproduction ($Q^2 < 2$ GeV^2)







- Measurement in the visible range:

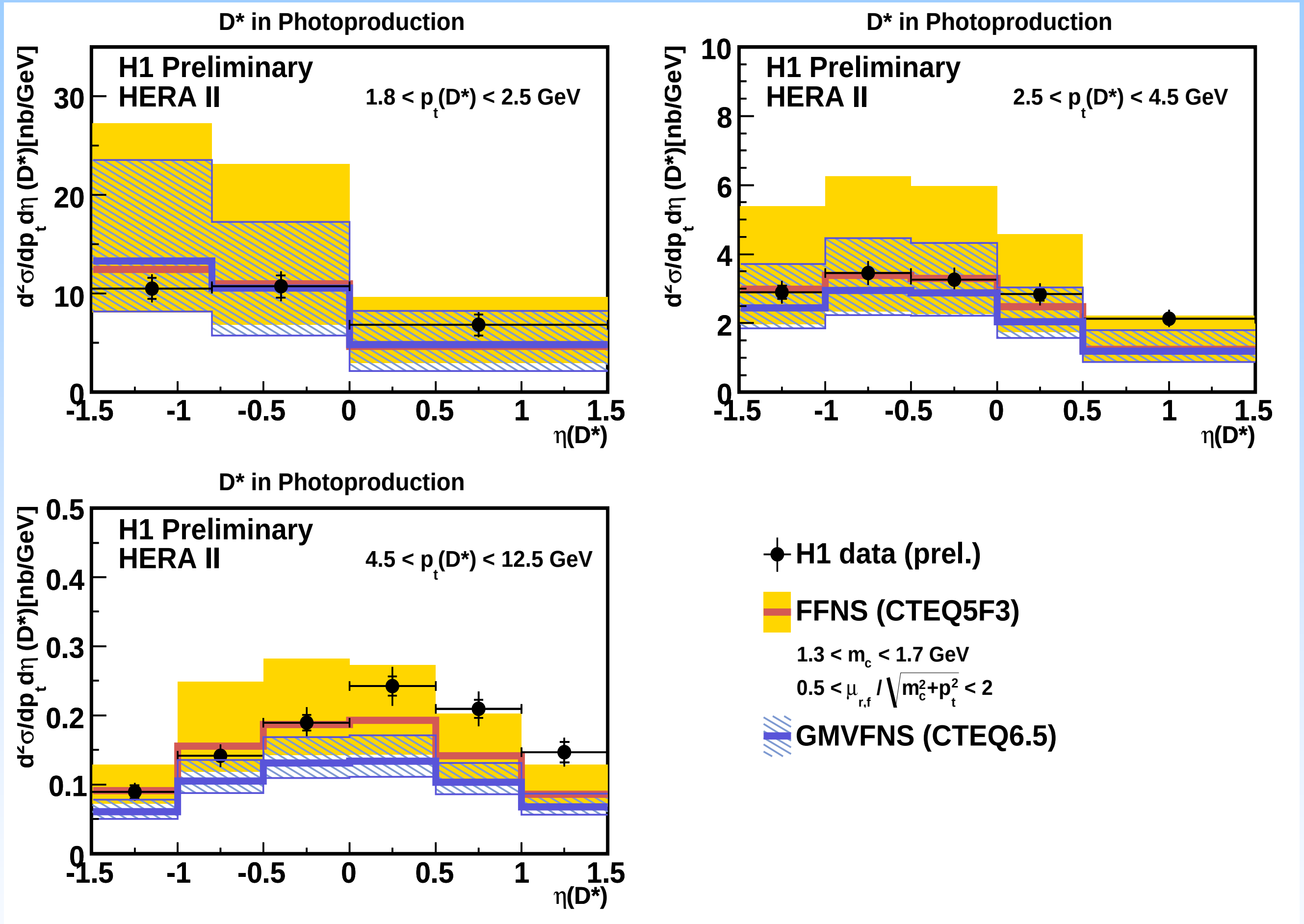
  $P_T(D^*)>1.8$ GeV, $|\eta(D^*)|<1.5$

  $Q^2 < 2$ 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