Open charm production in DIS at HERA

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On behalf of the H1 and ZEUS Collaborations

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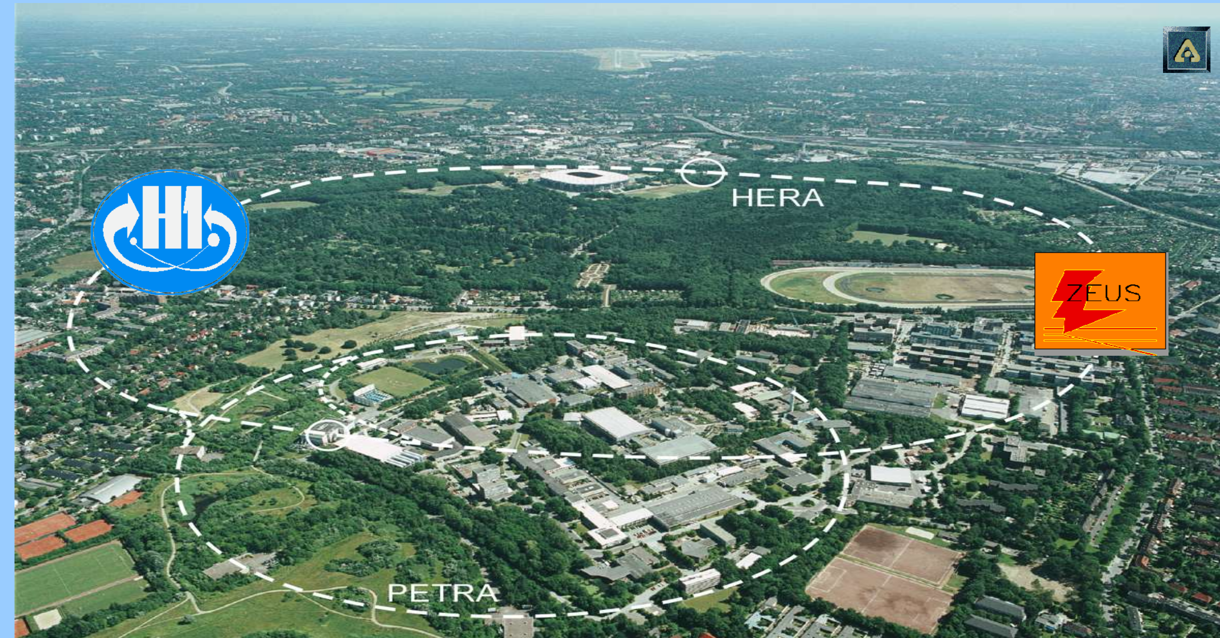
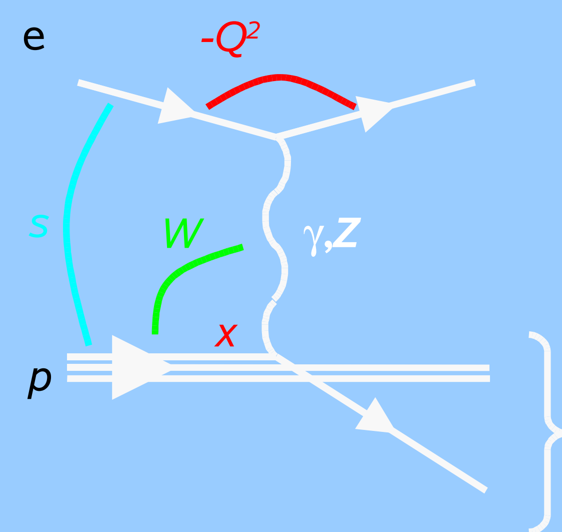


Proton 820/920 GeV **Electron/positron 27.6 GeV**

Plan of the talk:

- **Introduction and theoretical framework**
- **Charm reconstruction methods**
- **Cross sections vs QCD predictions**
- **Extrapolation results**
- **Conclusions**

- ***s***: *e-p* c.m. energy
- $Q^2 = -q^2$: 4-momentum transfer squared
- ***x***: fraction of proton momentum carried by quark
- ***y***: inelasticity parameter



QCD studies using heavy quarks

- **Heavy-quark mass provides a hard scale for reliable pQCD calculations ($m_c >> \Lambda_{QCD}$)**
- **2 (extreme) charm treatments:**
  - **FFNS:**

    1) charm quark is a heavy quark with mass m_c produced by the boson-gluon fusion (BGF) $Q^2 \sim m_c^2$

    2) can be described by fixed-order perturbative QCD (so far up to NLO)

    HVQDIS NLO calculations (B.Harris / J.Smith) based on DGLAP evolution for GRV, CTEQF3 PDF

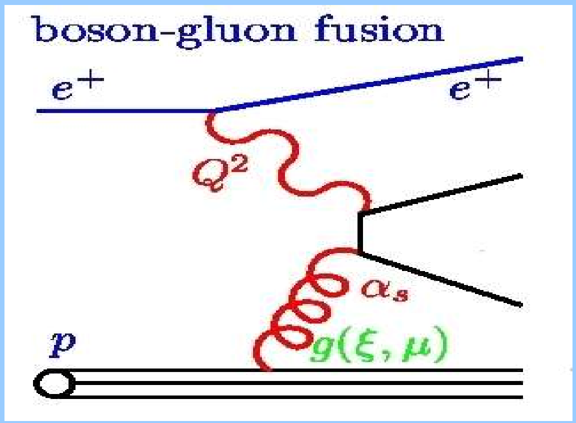
  - **ZM-VFNS:** Assumes $Q^2 \gg m_c^2$ - resums the terms $\ln^i(Q^2/m_c^2)$

    charm quark is massless and can be represented by a parton density $f_c(x, \mu^2)$

- **Extrapolation schemes (VFNS) – a unified framework for all scales**

There is a strong experimental evidence that the BGF based on FFNS dominates the charm cross sections in DIS at HERA

☞ Production rates directly depend on the gluon density
large cross section at low x



Testing ground for the CCFM evolution → DGLAP Q^2 evolution (large x) / → BFKL 1/x evolution

CASCADE Monte Carlo model (H.Jung) based on
- unintegrated gluon density
- off-shell matrix elements

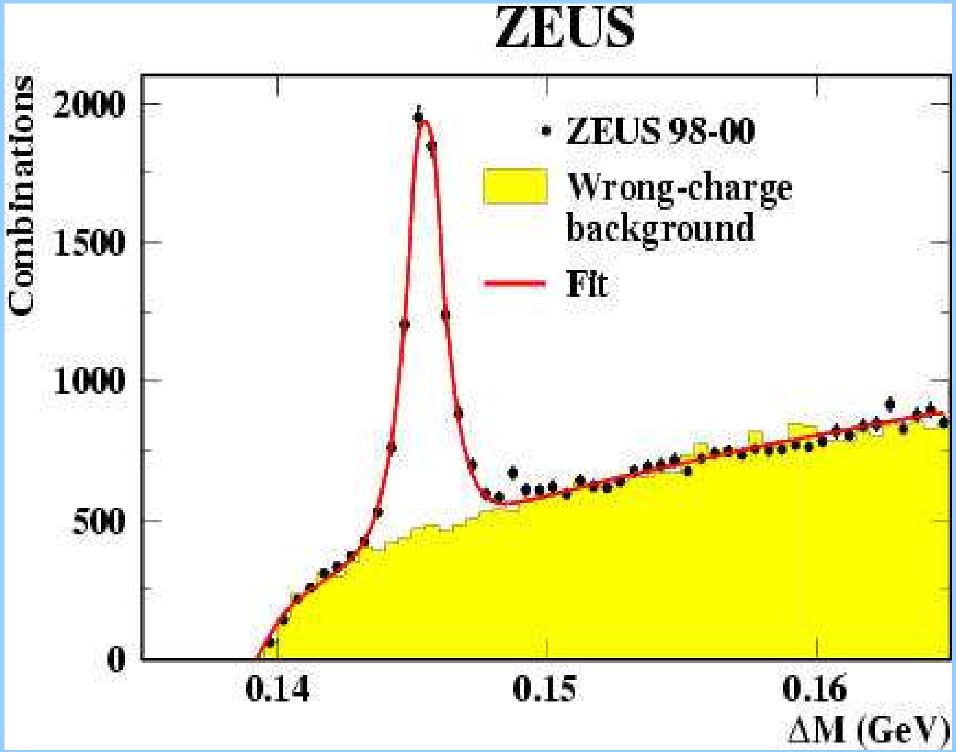
D-meson reconstruction procedures

Best decay channel for reconstruction:

$D^{*+} \to D^0 \pi_s^+ \to (K^- \pi^+) \pi_s^+$ $\quad BR = 2.6\,\%$

$f(c \to D^{*+}) \simeq 24\,\%$

$\Delta M = M(D^{*+}) - M(D^0) \sim m_\pi$



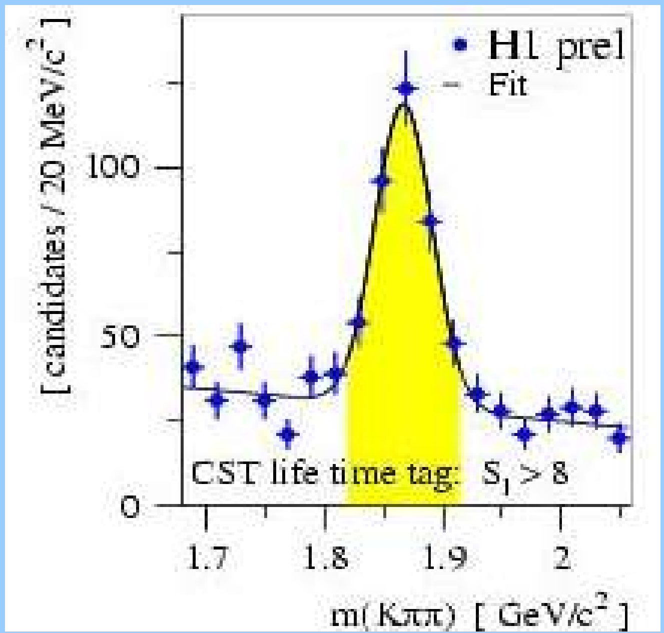
Large background for:

$D^+ \to K^- \pi^+ \pi^+$ $\quad D^0 \to K^- \pi^+$

The lifetime of 0.4-1.0 ps leads to a separation of their production and decay vertices; use decay length significance: S=L/σ

Good agreement between all measured D-meson cross sections and AROMA model (LO BGF)

(Abs. 096, H1 Collaboration)



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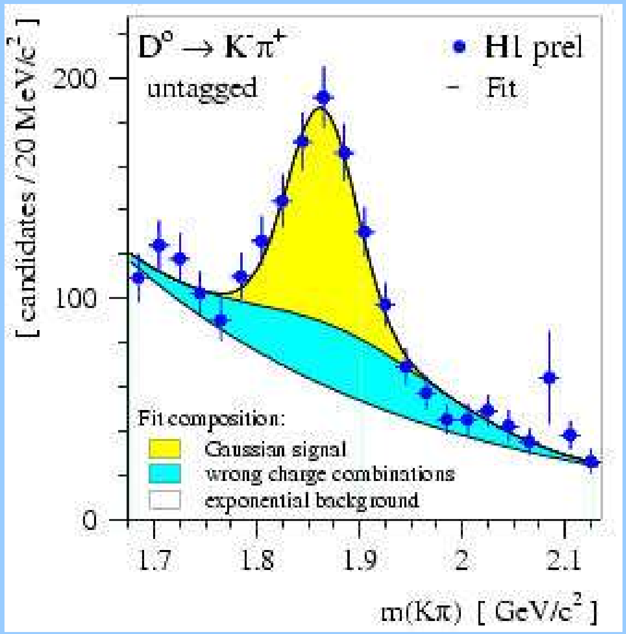

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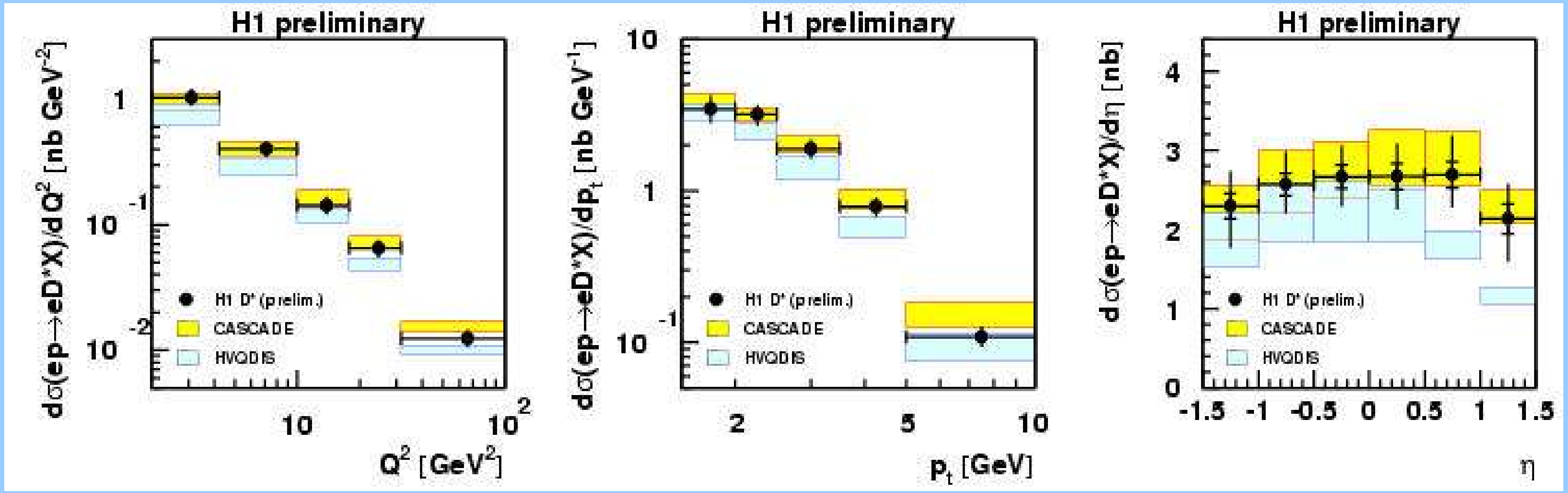
Inclusive D^*-meson production

Kinematic range: $2 < Q^2 < 100\, GeV^2$

$-1.5 < \eta(D^*) < 1.5$

$p_t(D^*) > 2.5\, GeV$

$$\sigma(ep \rightarrow eD^* X)$$



- NLO QCD (HVQDIS program) based on the CTEQ5F3 PDF + DGLAP
- CASCADE model based on the CCFM evolution
- Both models use the Peterson fragmentation
- NLO QCD fails, while CASCADE describes the data

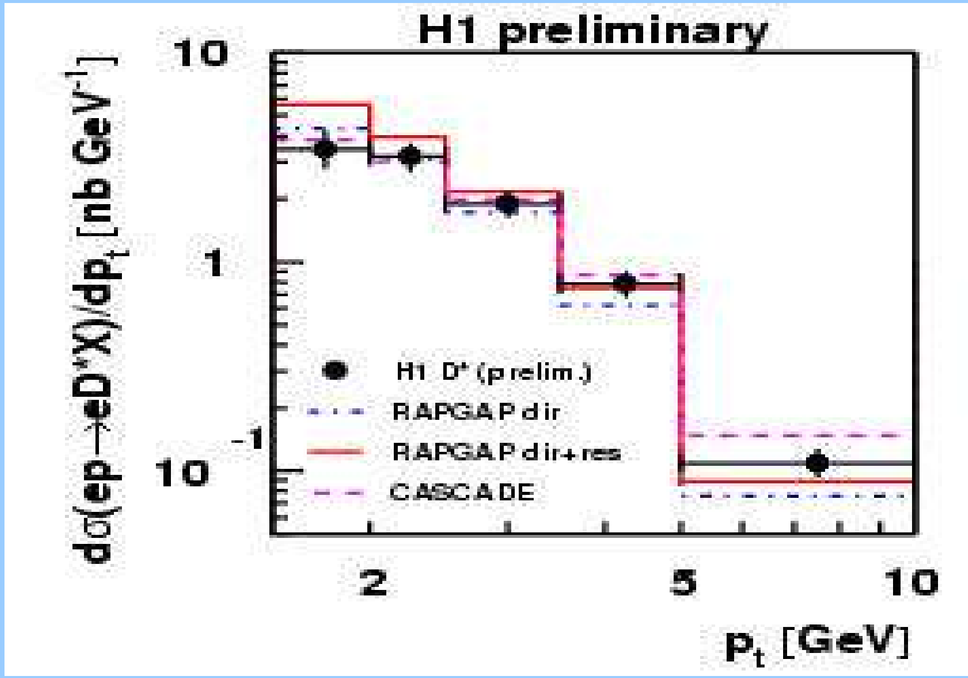
Theoretical uncertainties:

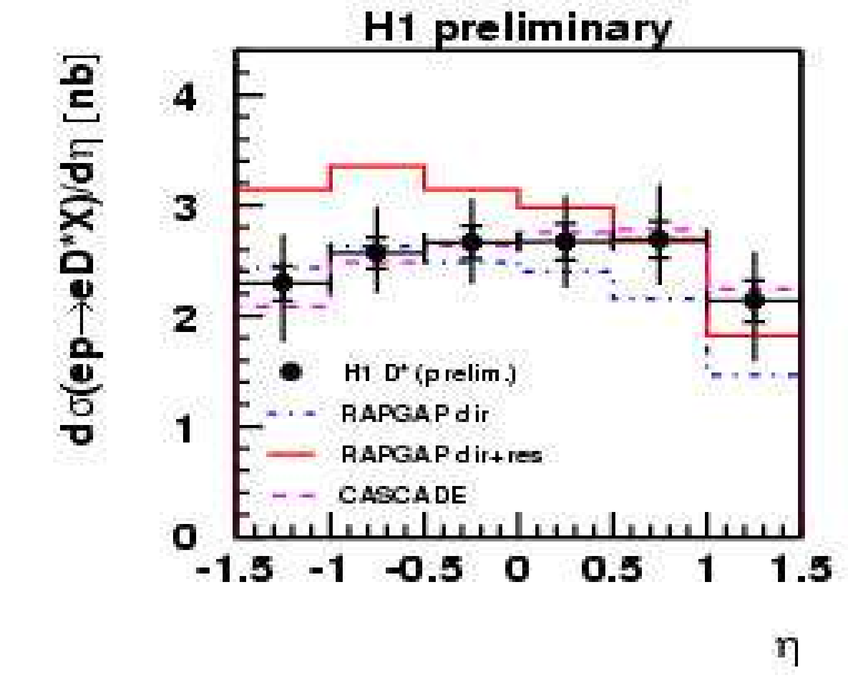
$m_c = 1.35\, GeV \wedge \epsilon_c = 0.035$

$m_c = 1.5\, GeV \wedge \epsilon_c = 0.10$

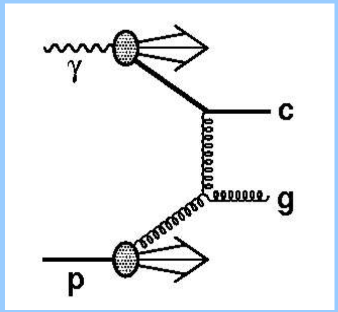
Can this be attributed to the CCFM evolution ?

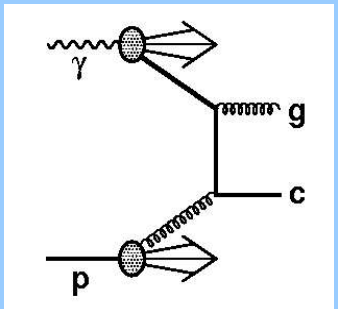
Resolved contribution to open charm production





RAPGAP (dir) ☞ **LO BGF**
RAPGAP (dir+res) ☞ **LO BGF +**
contribution from resolved events:





It is unlikely that problems in the forward region can be attributed to "resolved" photon contribution

Charm production with associated dijets

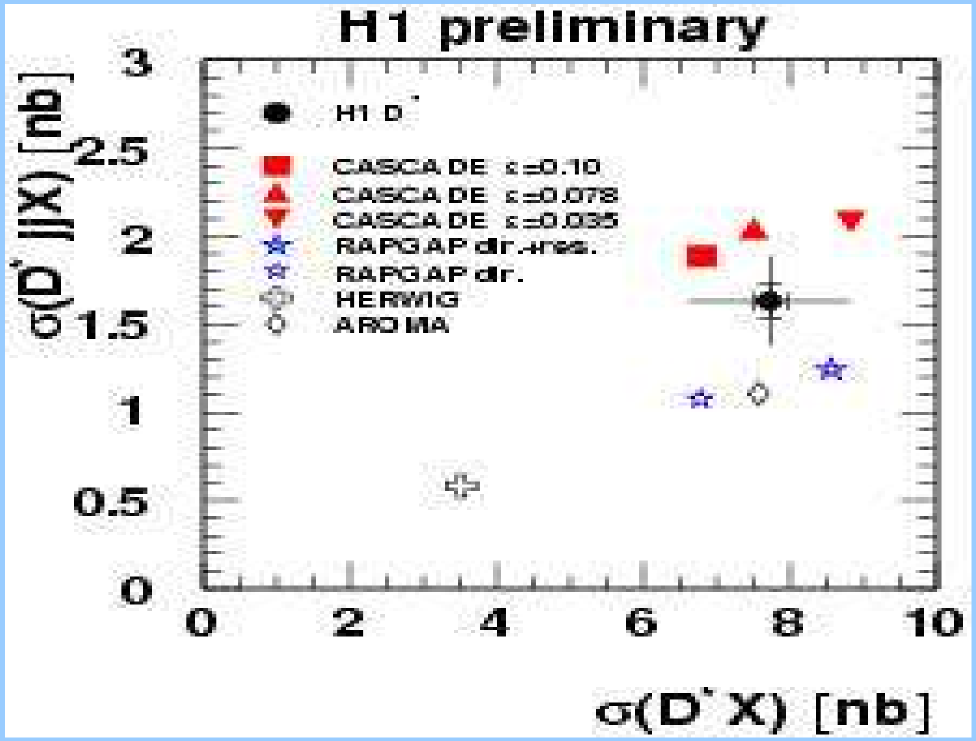
D* kinematics as before

Dijet kinematic range

$E_t > 4\,GeV,\ E_t > 3\,GeV$

$-1.5 < \eta < 1.5$

For better understanding of the production mechanism – look at dijets

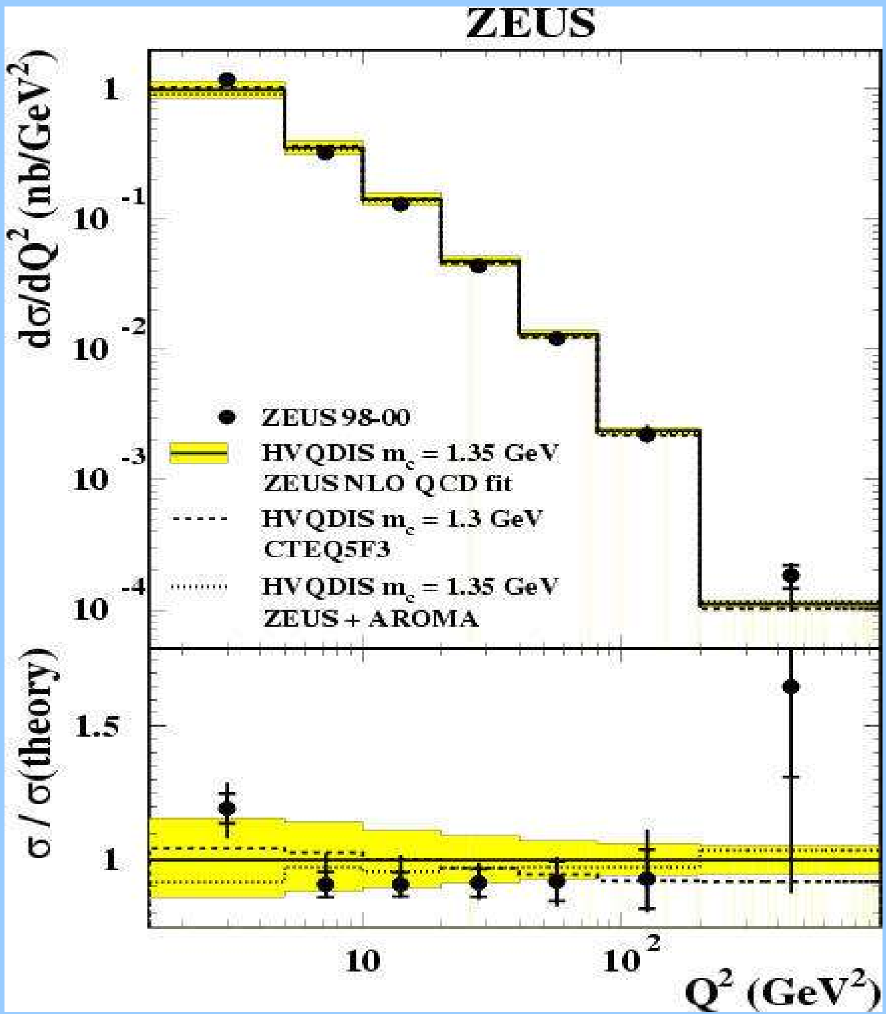


- **Large sensitivity to fragmentation**
- **All models show discrepancies with the data**
- **Large difference between CASCADE and LO BGF predictions (AROMA/RAPGAP)**

Inclusive D* production in DIS

ZEUS used highest statistics from HERA-I ~ 82 pb^{-1} for inclusive D* measurements:

- Kinematic range extended to Q^2 =1000 GeV^2
- Calculations for e-p and e+p collisions separately
- Comparisons with NLO QCD, MC models, tests of different PDFs



- ZEUS NLO fit is performed in FFNS (to describe ZEUS F_2)
- Renorm./factor. scale is $\sqrt{Q^2+4m_c^2}$
- $f(c \to D^*)=0.235 \qquad \epsilon_c=0.035$

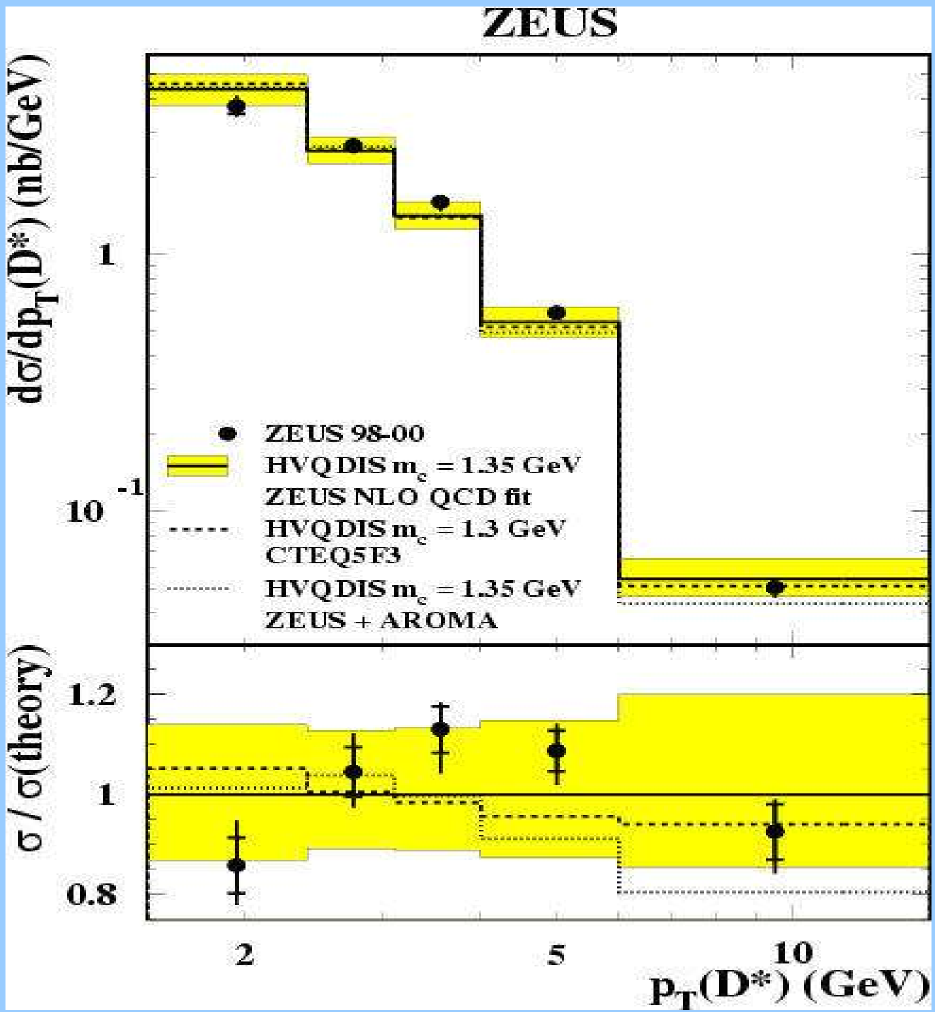
HVQDIS+AROMA: NLO corrected using the Lund string fragmentation from AROMA:

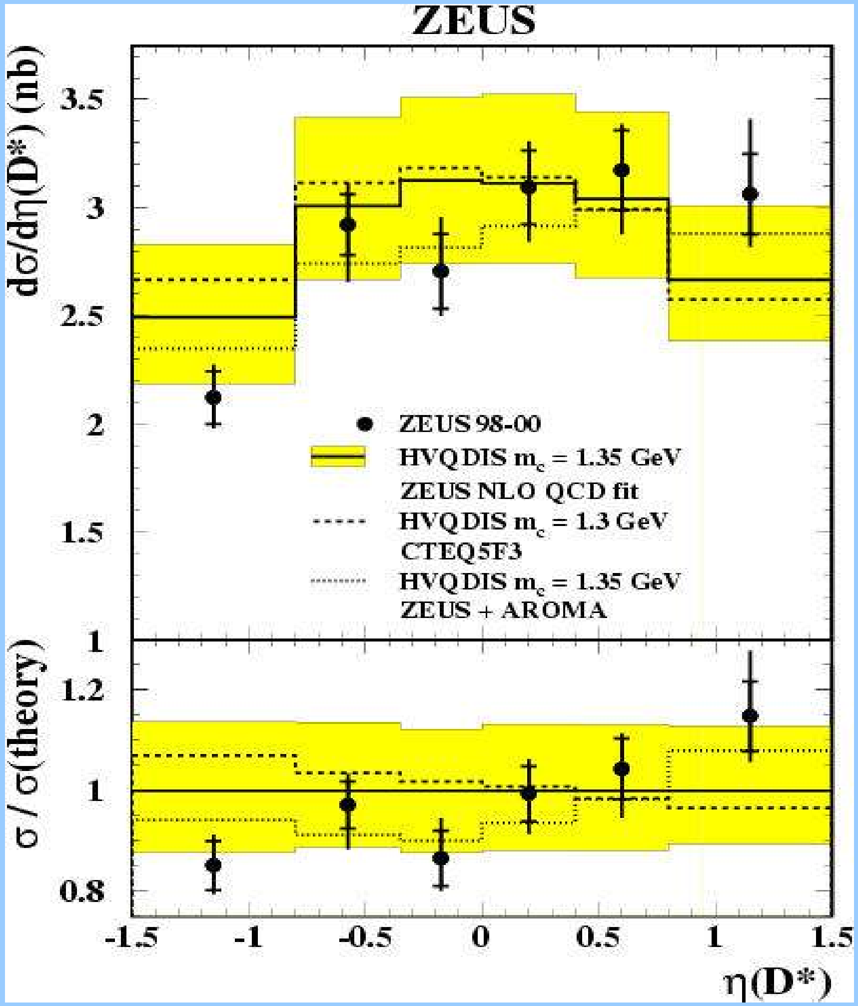
$$C_{hadr}=\frac{d\sigma_{AROMA}(c\to D^*)}{d\sigma_{AROMA}(c\bar{c})}$$

Theoretical uncertainties:

- Scale variations: 0.5-2 factor
- Charm mass variations +/- 0.15 GeV
- PDF fit uncertainties (for ZEUS NLO fit)

Data vs NLO QCD

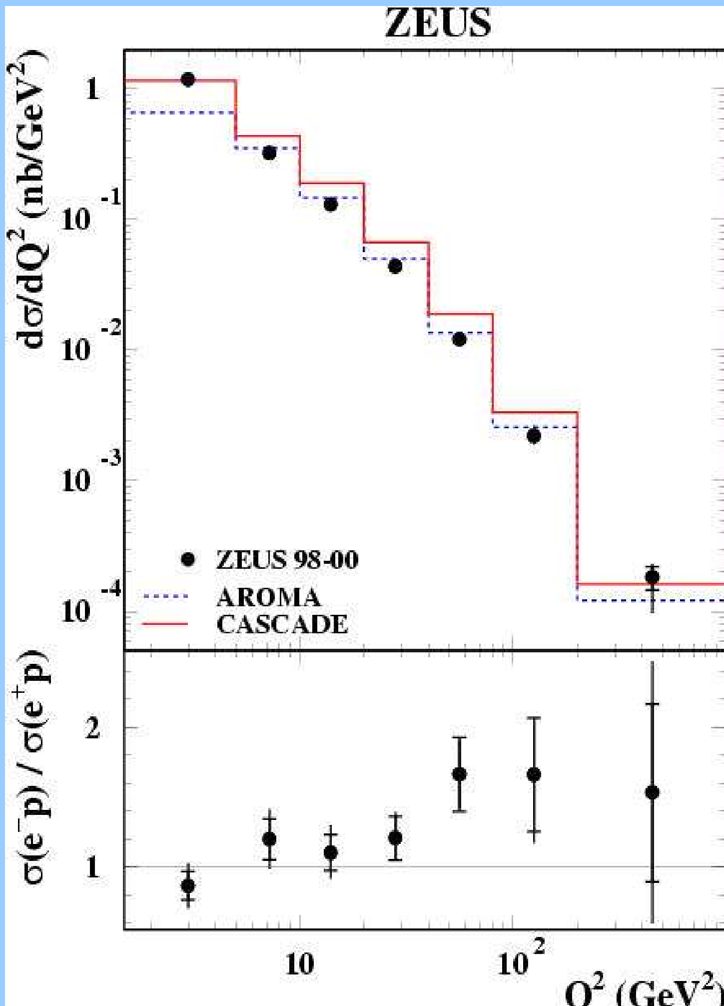


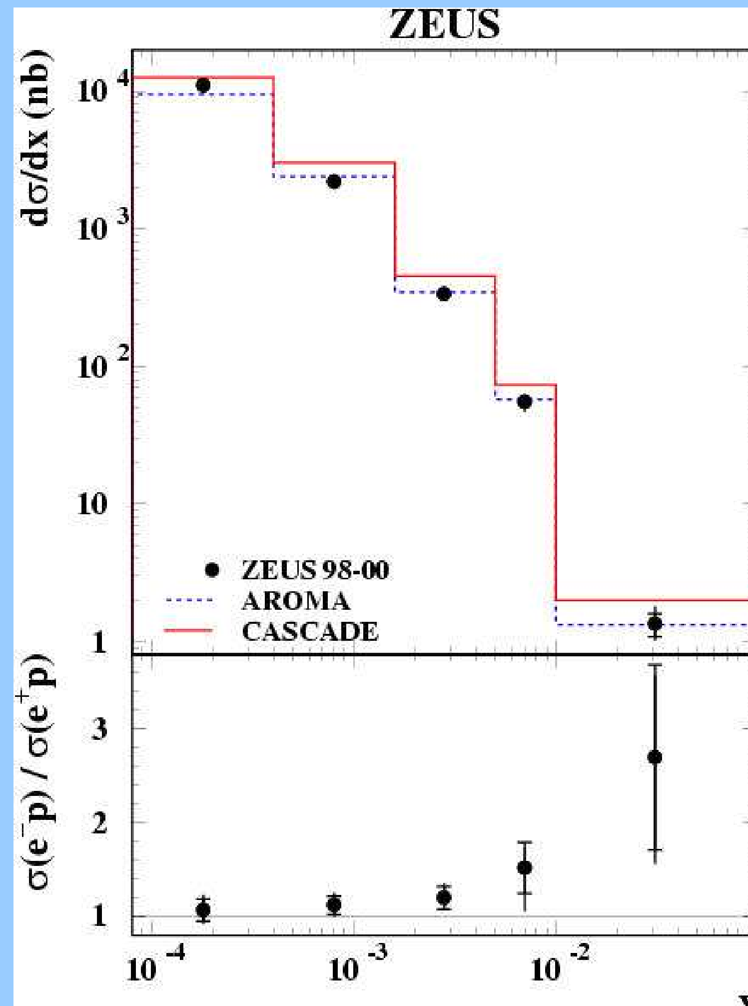


- $\eta(D^*)$ is sensitive to fragmentation and the proton PDF (i.e. the gluon density)
- ZEUS NLO fit gives a better agreement with the data than CTEQ5F3
- LUND string fragmentation from AROMA also improves the description

No need for the CCFM evolution ?

Comparisons with Monte Carlo models; e-p vs e+p D^* cross sections





CASCADE overestimates the cross sections

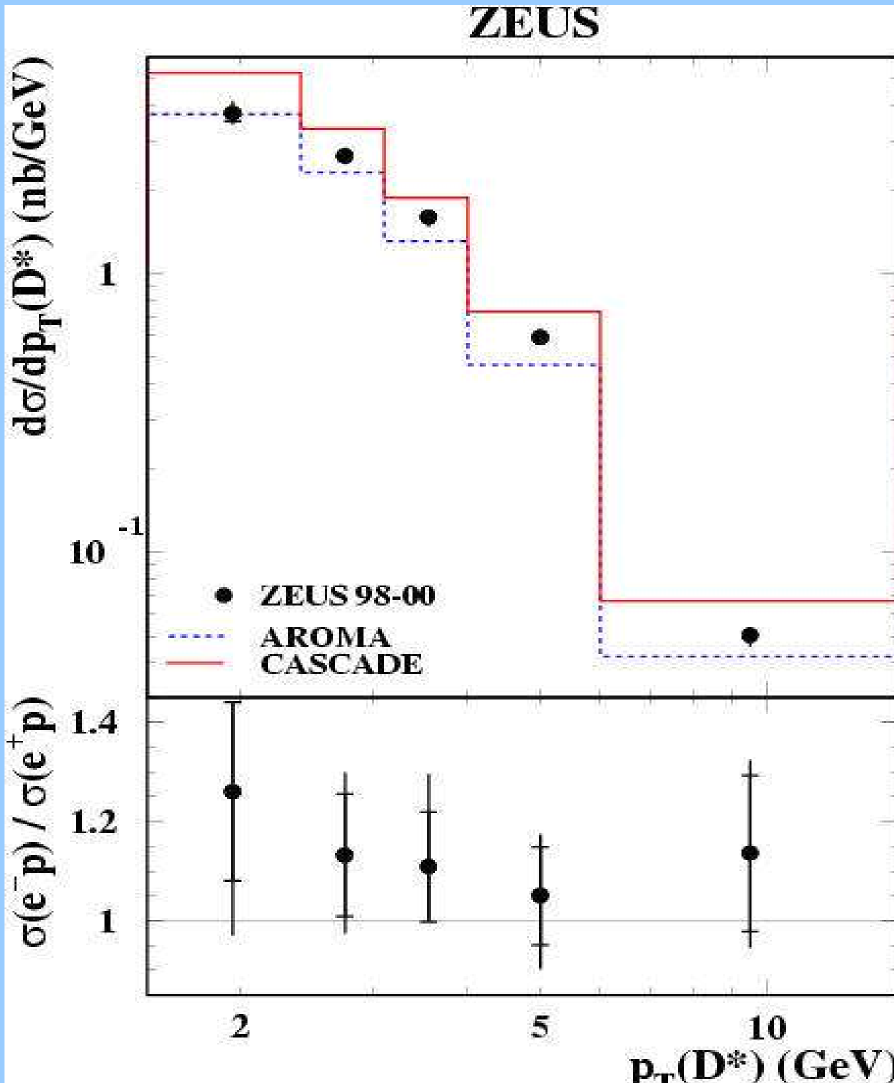
AROMA has correct normalization, but fails at low Q^2

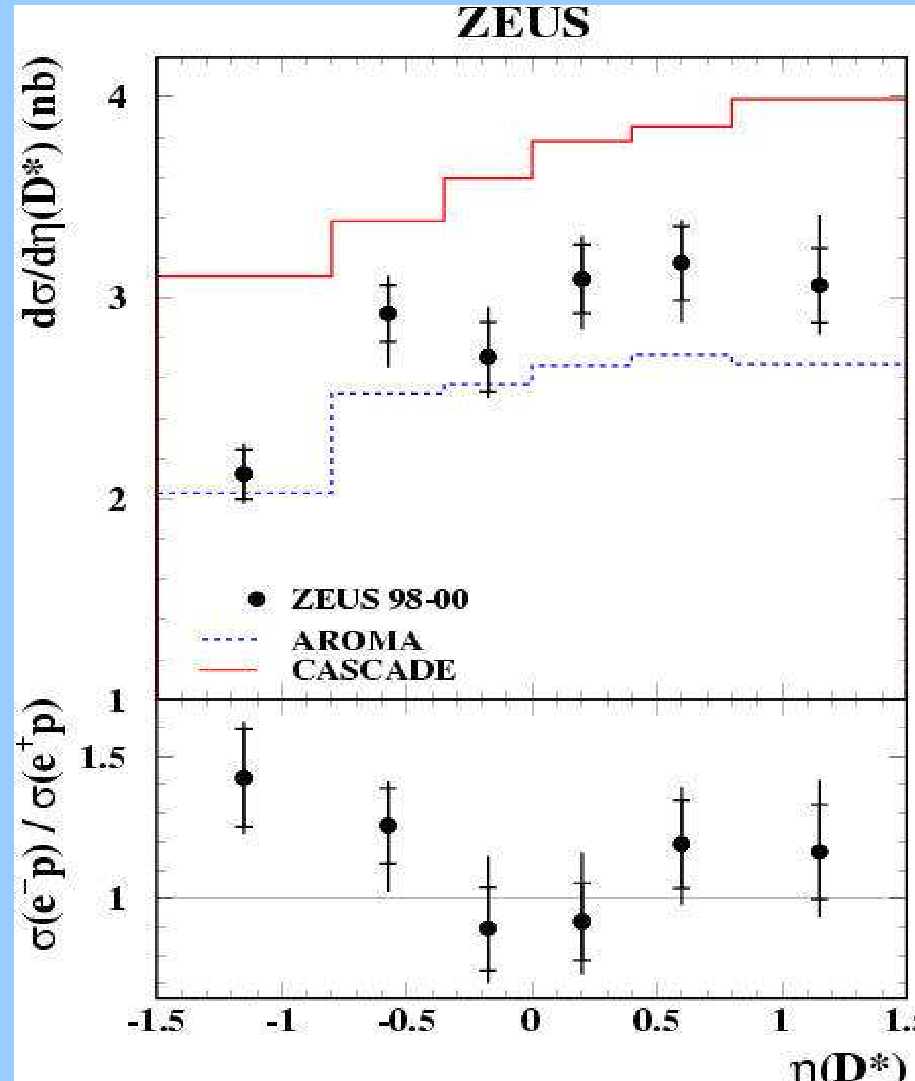
Note: Theoretical uncertainties were not estimated

- ~3 σ difference between e+p and e-p data (increasing with Q^2)
- For $Q^2 > 40$ GeV^2- e-p and e+p difference mainly in the forward region
- First reported by ZEUS at ICHEP00 (Osaka) – now the results are final
- Assume a statistical fluctuation ☞ e-p and e+p data were combined

According to the Standard Model, cross sections for e-p and e+p should be equal– need more statistics from HERA II to check

Inclusive D* production in DIS: AROMA vs CASCADE





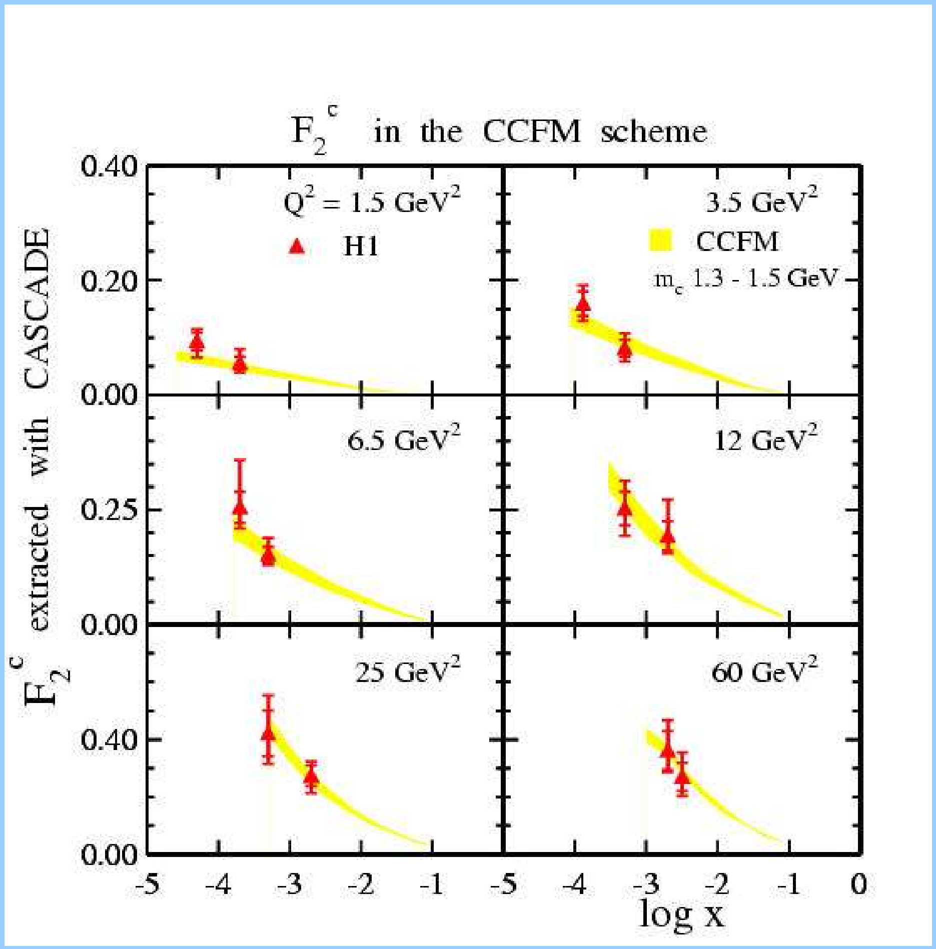
- CASCADE has a steeper rise in the forward direction than AROMA – CCFM effect?
- Absolute normalization for CASCADE is too high
- Data agrees in shape with both AROMA and CASCADE
- Both models use the Lund string fragmentation (PF - for H1 results shown before)

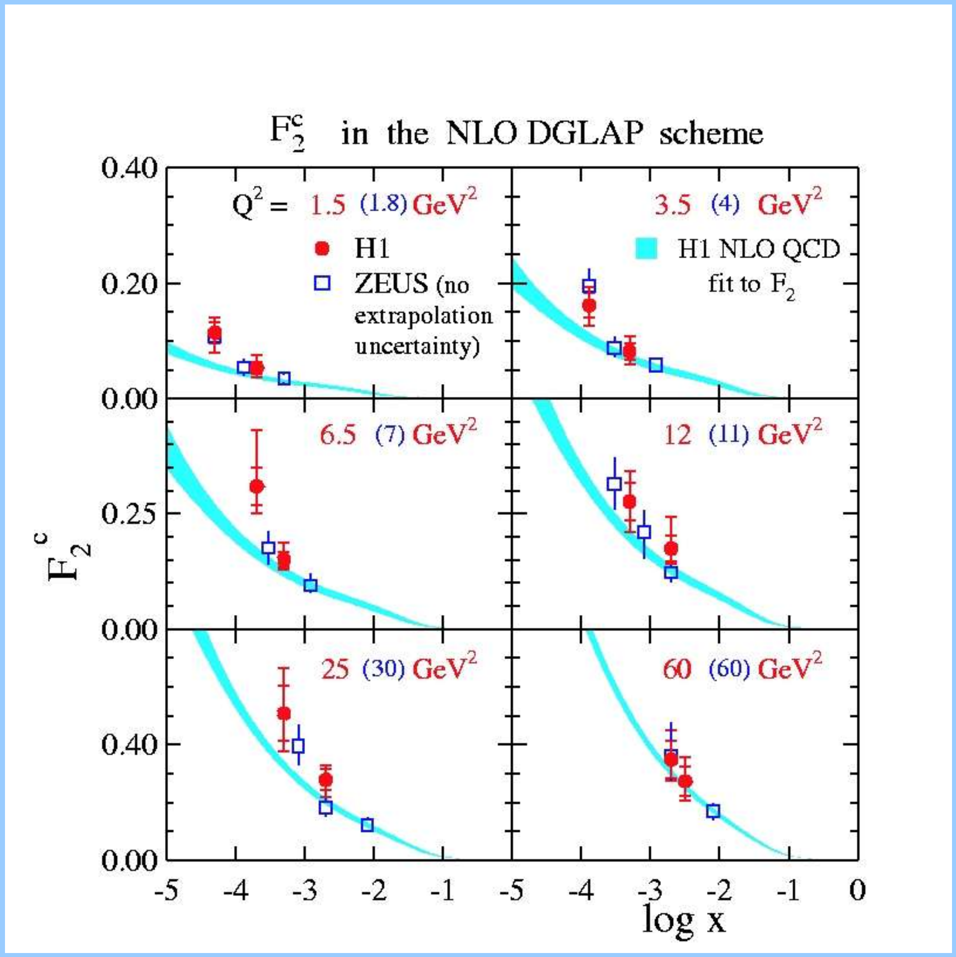
Extrapolated results

$$F_2^{c\bar{c}}(x,Q^2)=\frac{\sigma_{meas}}{\sigma_{theor}}F_{2,theor}^{c\bar{c}}(x,Q^2)$$

- **Extrapolation factors ~ 2-5 to the full kinematic regions**
- **Fully rely on theory in regions where cross sections cannot be measured**
- **Model dependent !**
  The VFNS is not used - should be able to calculate charm kinematics

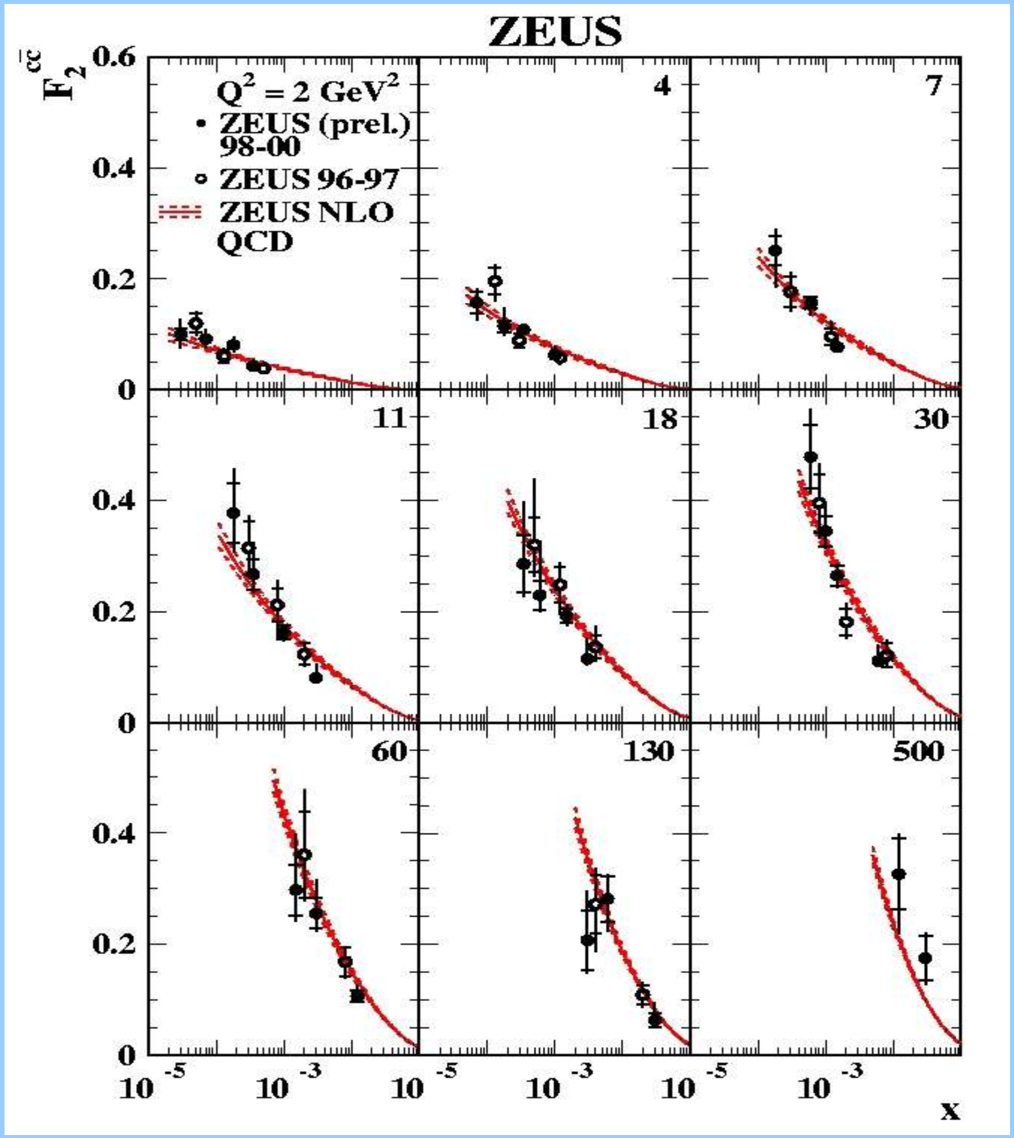
σ - D* cross section in restricted kinematic range

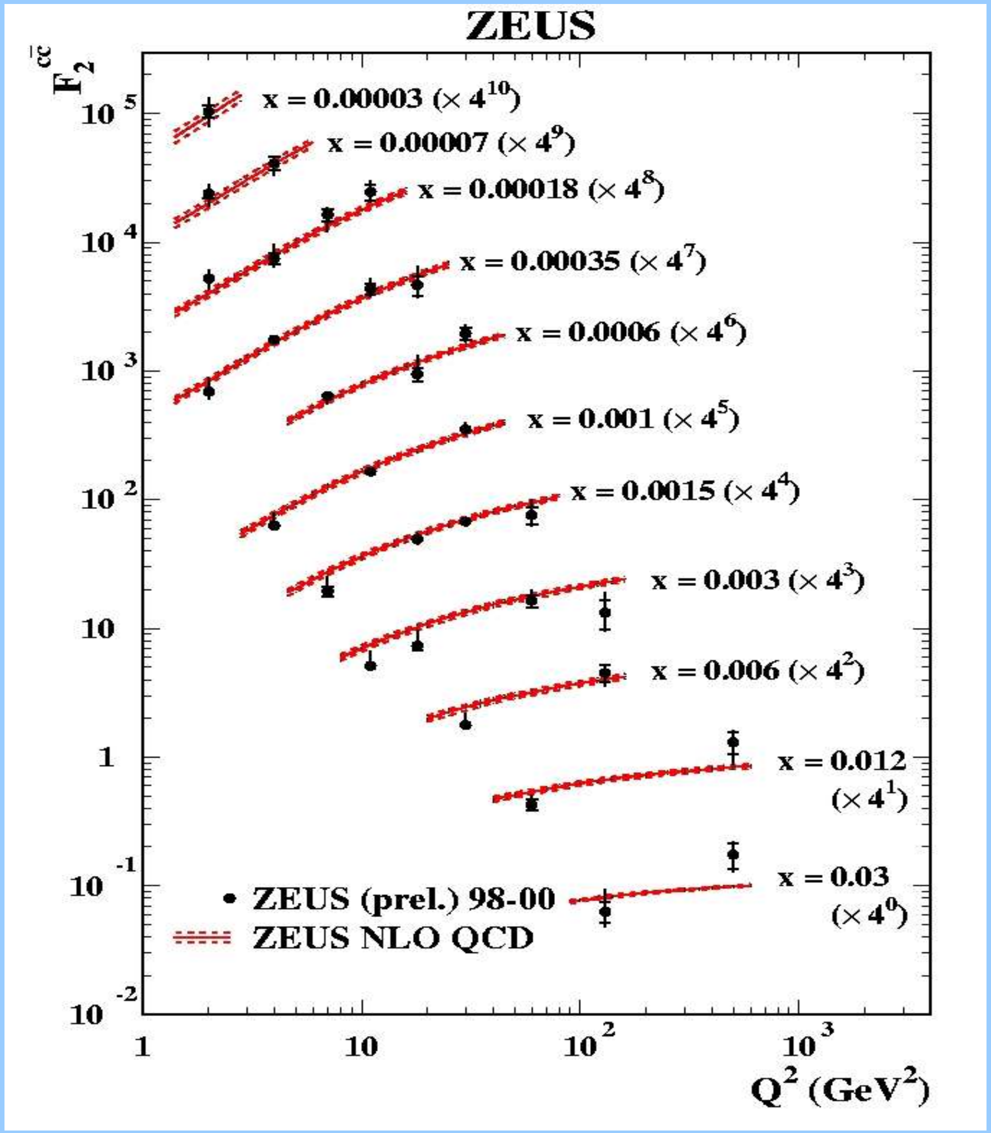




- Better agreement between data and the CCFM scheme when CASCADE is used for extrapolations
- H1 and ZEUS data are consistent

Extrapolated results





- Agreement between data and FFNS (HVQDIS with ZEUS NLO+PF) over a wide range in Q^2 and x
- Extrapolation uncertainties: Lund string fragm., c-mass and b-component variations
- Demonstrates the scaling violation in charm production

Summary

- Good agreement between data and QCD predictions for impressive range in Q^2 (1 - 1000 GeV^2);
- Precise (and consistent) measurements from H1 and ZEUS over a wide kinematic region;
- Several effects can improve the agreement with the data, especially for the η cross sections:
  - QCD evolution - CCFM vs DGLAP;
  - Gluon in the proton (ZEUS NLO fit gives a better agreement);
  - Fragmentation (LUND strings vs Peterson fragmentation), "beam-drag" effect?
  - QCD scheme for charm description? So far only the FFNS was tested...
- At present, no conclusive statement on the CCFM can be made;
- FFNS shows good agreement with the data up to highest Q^2 range measured (~1000 GeV^2)

Does ZEUS observe a deviation from the Standard Model (e-p/e+p difference)?
Can we look at charm kinematics at high Q^2 to verify the FFNS ?

☞ **More data is needed**

Charm results will benefit from HERA II upgrade (microvertex/forward tracking)
Looking forward to lots more data soon (~1 fb^{-1} per experiment)