Physics with charm quarks at HERA

On behalf of the ZEUS and H1 Collaborations

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RINGBERG WORKSHOP: New Trends in HERA Physics

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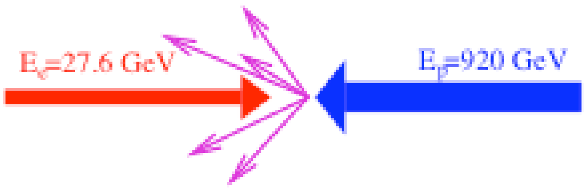
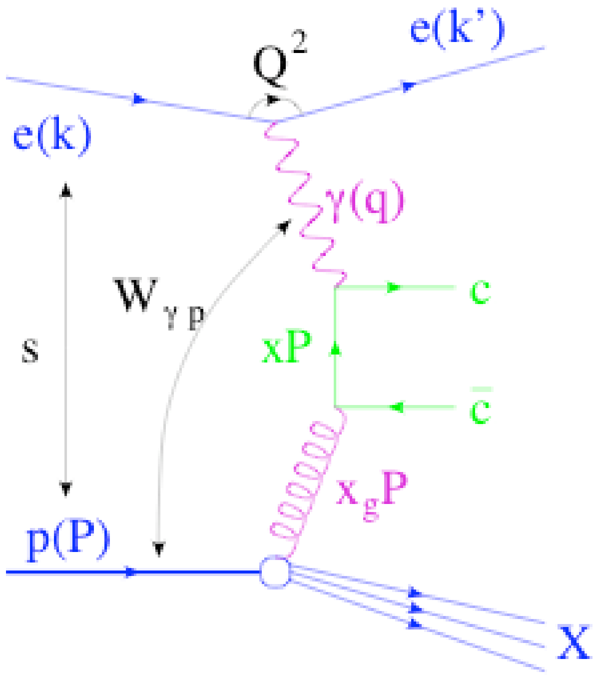
Outline of charm at HERA

- HERA and its charm
- Perturbative QCD calculations.
- D* cross sections
- D* and Jet production.
- Charm fragmentation aspects.
- F_2^{cc}.

HERA's charm production





Boson Gluon fusion

Charm directly sensitive to the proton gluon density.

Study of charm over huge kinematical ranges: $1.5 < p_T^c < 30$ GeV, $0 < Q^2 < 1000$ GeV^2.

Photoproduction: $Q^2 \leq 1$ GeV^2

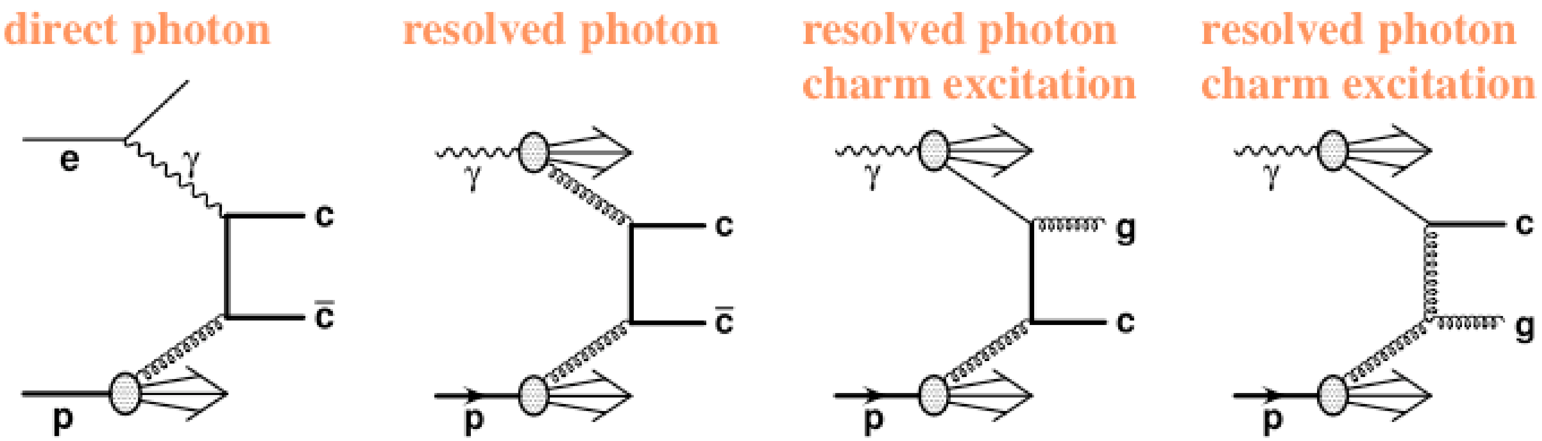
DIS: $Q^2 > 1$ GeV^2

HERA's charm production

At LO Boson Gluon Fusion (BGF) dominates -> $\gamma g \rightarrow c\bar{c}$

Direct and Resolved contributions

σ = proton PDF $\otimes$ $\sigma_{\gamma g \rightarrow QQ}$ $\otimes$ photon PDF $\otimes$ fragmentation function



Charm pQCD calculations

pQCD calculations are performed in different ways: Massive (PHP S.Fixione et al) (DIS Harris and Smith), Massless(B. Kniehl et al) and a combined method (M. Cacciari et al).

The "Massive" approach, to fixed order in α_s:

$\rightarrow m_Q \neq 0$ and the heavy quarks (c and b) are not parts of the structure functions. Heavy quarks produced dynamically in the hard interaction. $\rightarrow$ reliable at $p_T \approx m_Q$

DGLAP evolution is used to obtain the quark and gluon densities.

Programs for Photoproduction: FMNR (Frixione et al.) and

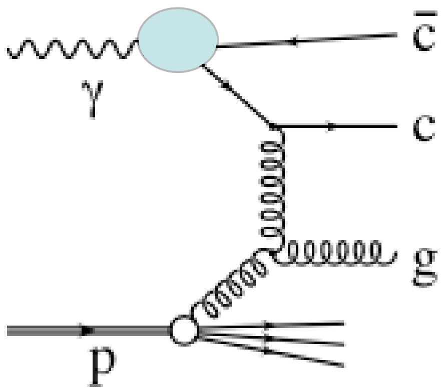
DIS: HVQDIS (Harris+Smith)

Charm pQCD calculations

"Massless" Approach: re-summation of $\alpha_s \ln(p_T^2 / m_c^2)$ at orders in α_s:

$\rightarrow M_Q = 0 \rightarrow$ the heavy quarks are an active flavour in the PDF

Heavy quarks can also be produced in flavour excitation



Relaible $p_T >> m_Q$, (B. Kniehl et al)

Charm Tagging

Charm tagging via D* meson

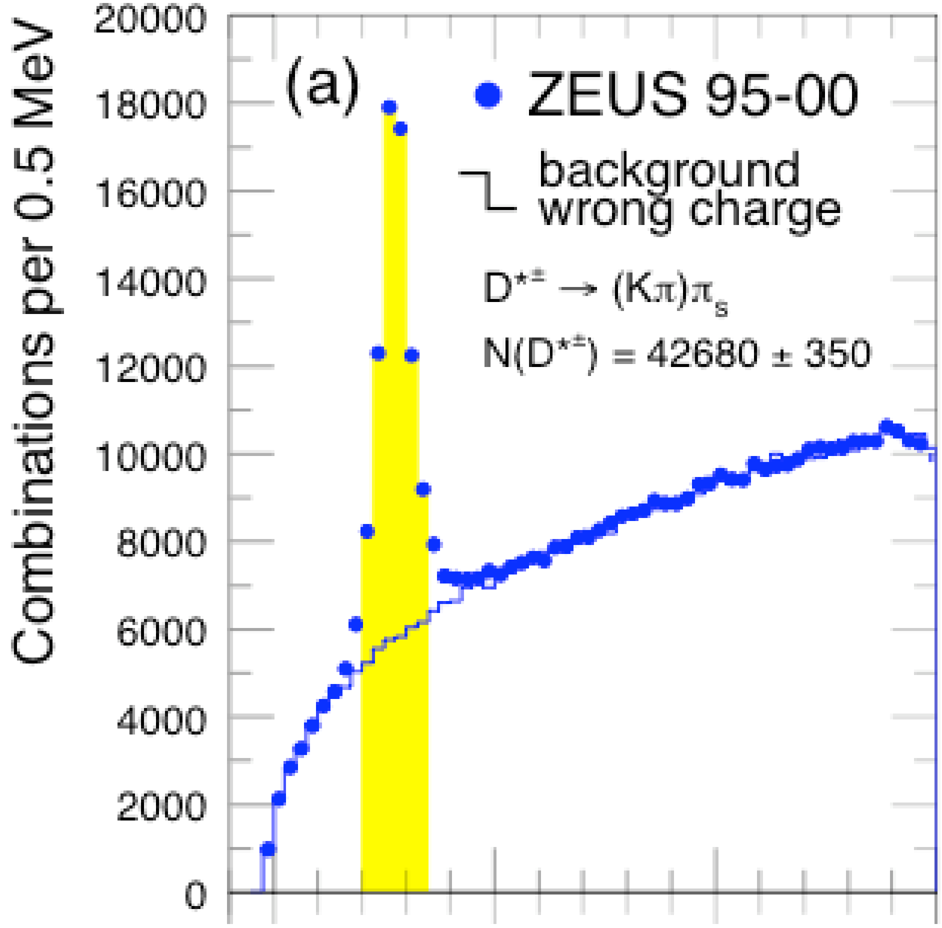
$D^* \rightarrow D^0, \pi$ Where $D^0 \rightarrow K, \pi$

HERA is a charm factory

42680 ± 350 D* mesons.

H1 & ZEUS for HERA I

50<luminosity <100 pb^{-1}.



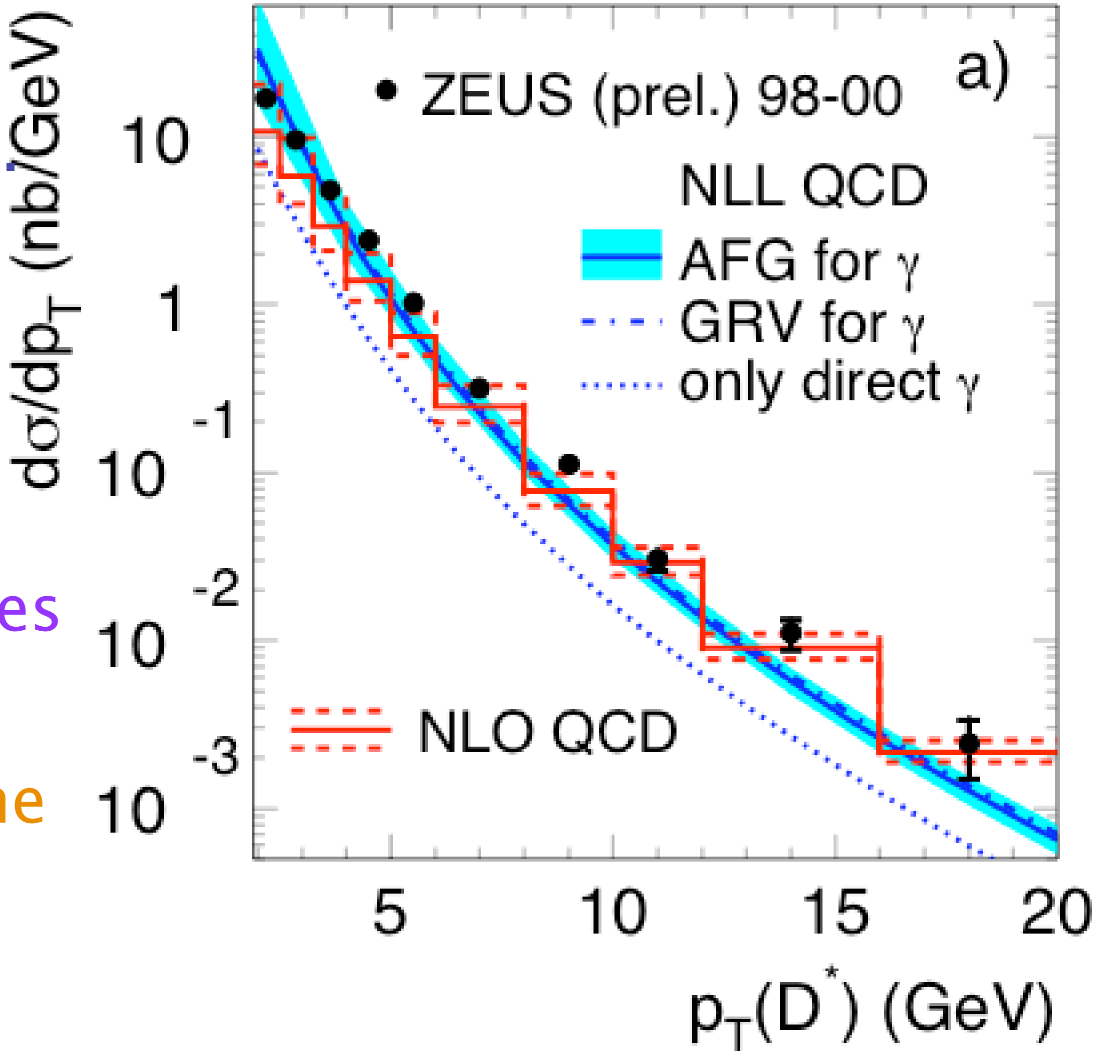
D* Photoproduction inclusive cross sections

Inclusive D* production over a large lage of p_T^{D*}.

At large p_T^{D*} massive calculation does better then massless.

At lower values of p_T^{D*} massless calculation does better then massive.

Expect scenario to be the other way round.



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D* Photoproduction inclusive cross sections

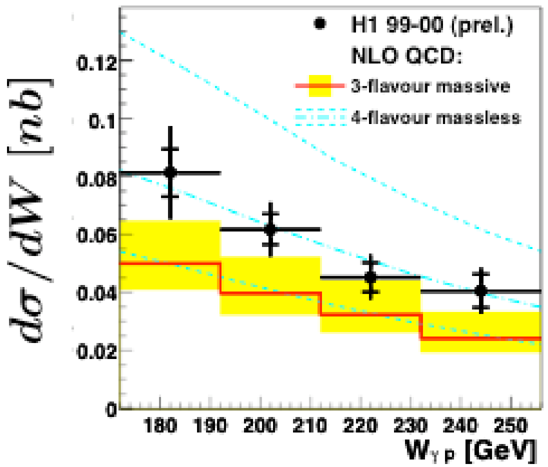
•D* selection in photoproduction

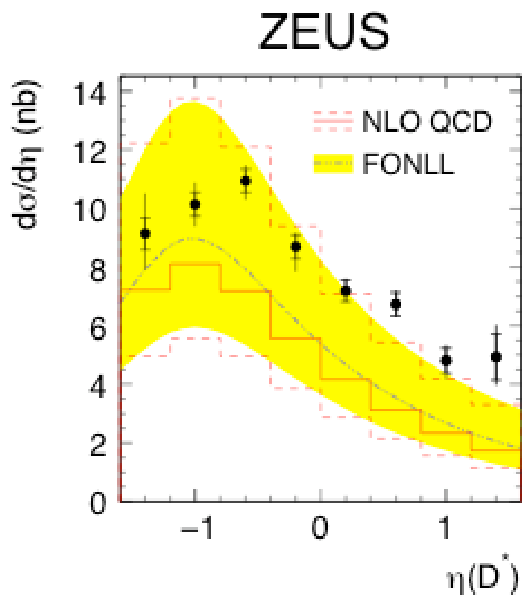
•NLO “massive” and “massless” predictions are compared to the data.

•dσ / dW is described well, but the shape of d σ / dη(D*) is not well described in shape.

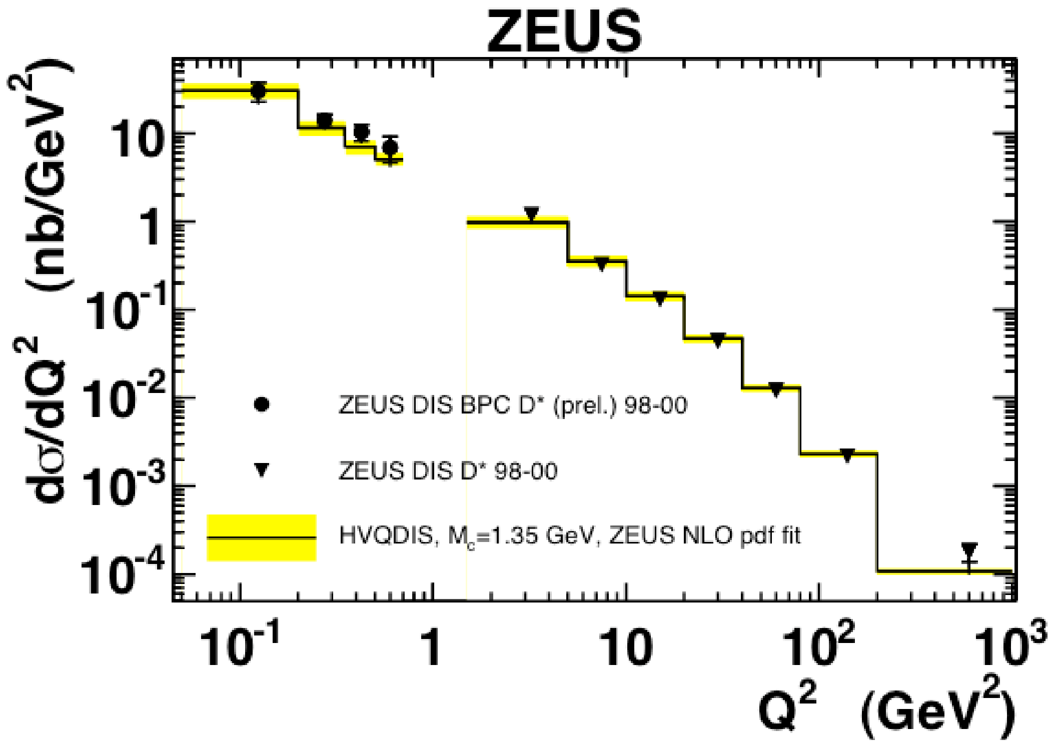
•Theoretical uncertainties from charm mass and renormalisation scale are large!

•Precise data → Need for NNLO.





Charm over all Q^2



Comparison of low Q^2 data, using the beam pipe calorimeter (BPC) to tag the scattered electron.

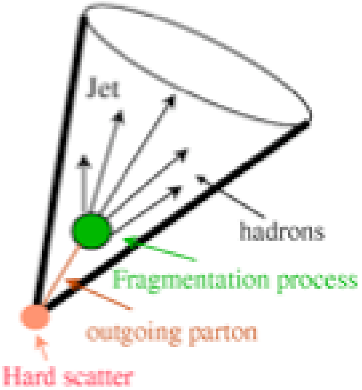
NLO charm production tested across the transition region from DIS to Photoproduction.

Low Q^2 is much smaller than charm mass.

High Q^2 is much larger than charm mass

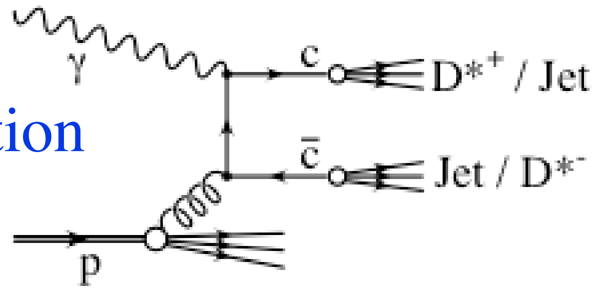
Good agreement with massive theory.

Charm Jet Production



•D* production and Jet production

•Tag second hard parton by a using a Jet (k_T Algorithm definition)



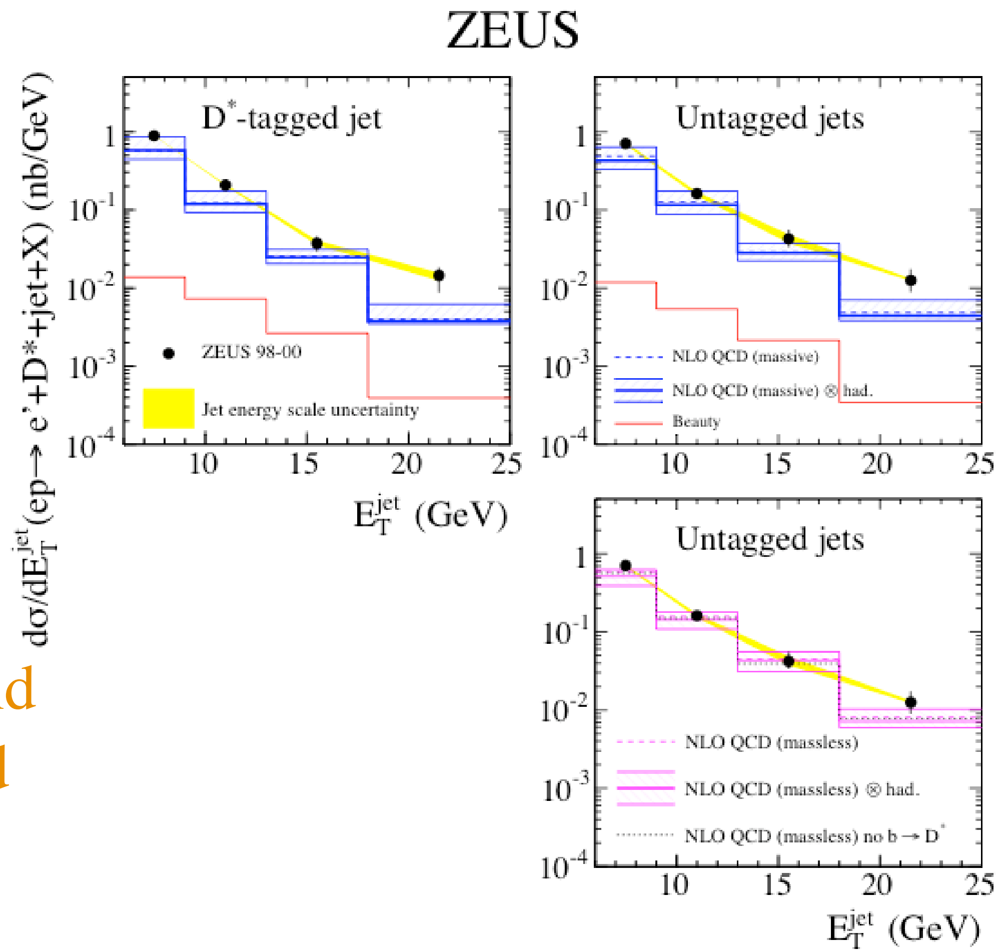
• Jet and D* correlations can be studied when the D* is NOT associated to with a Jet → angular correlations arising from higher orders.

• Jet E_T provides an extra hard scale: test QCD!

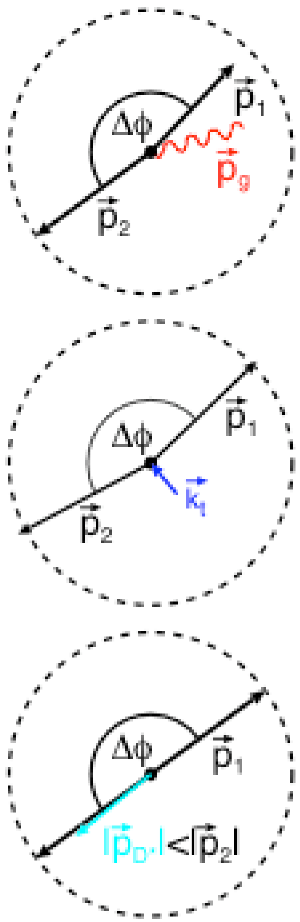
Charm Jet Production

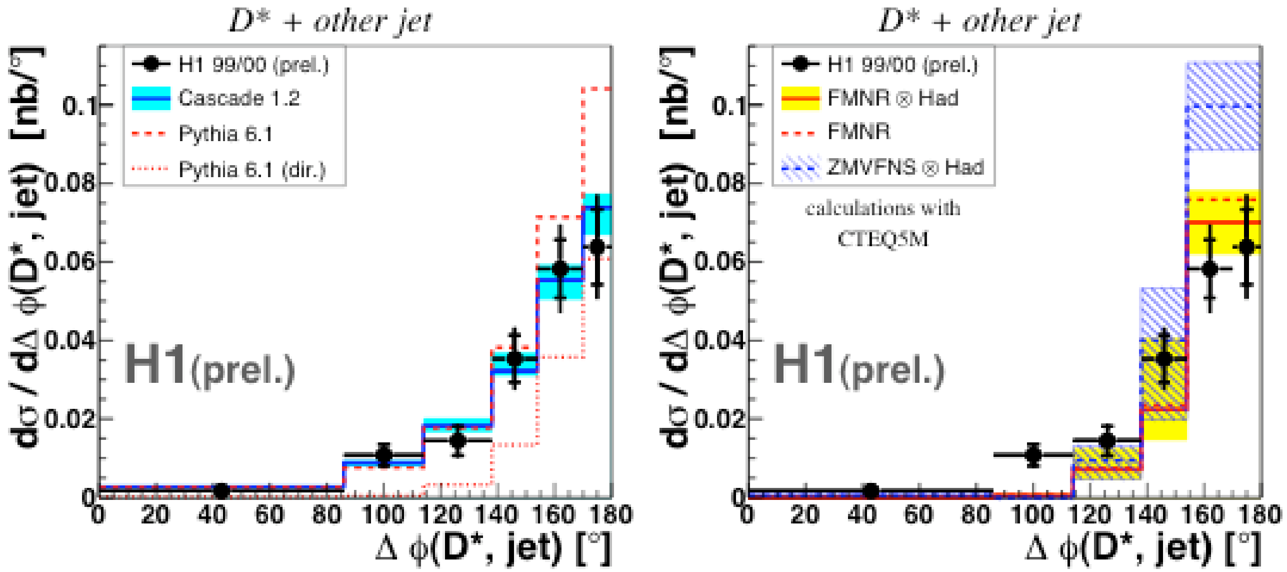
- D* photoproduction and Jet selection.
- “massive” and “massless” pQCD predictions give reasonable descriptions of the data.
- Data lie on upper bound of NLO → lower charm mass and renormalisation scale changed simultaneously.

→ Large theoretical uncertainties.



Charm Jet Production



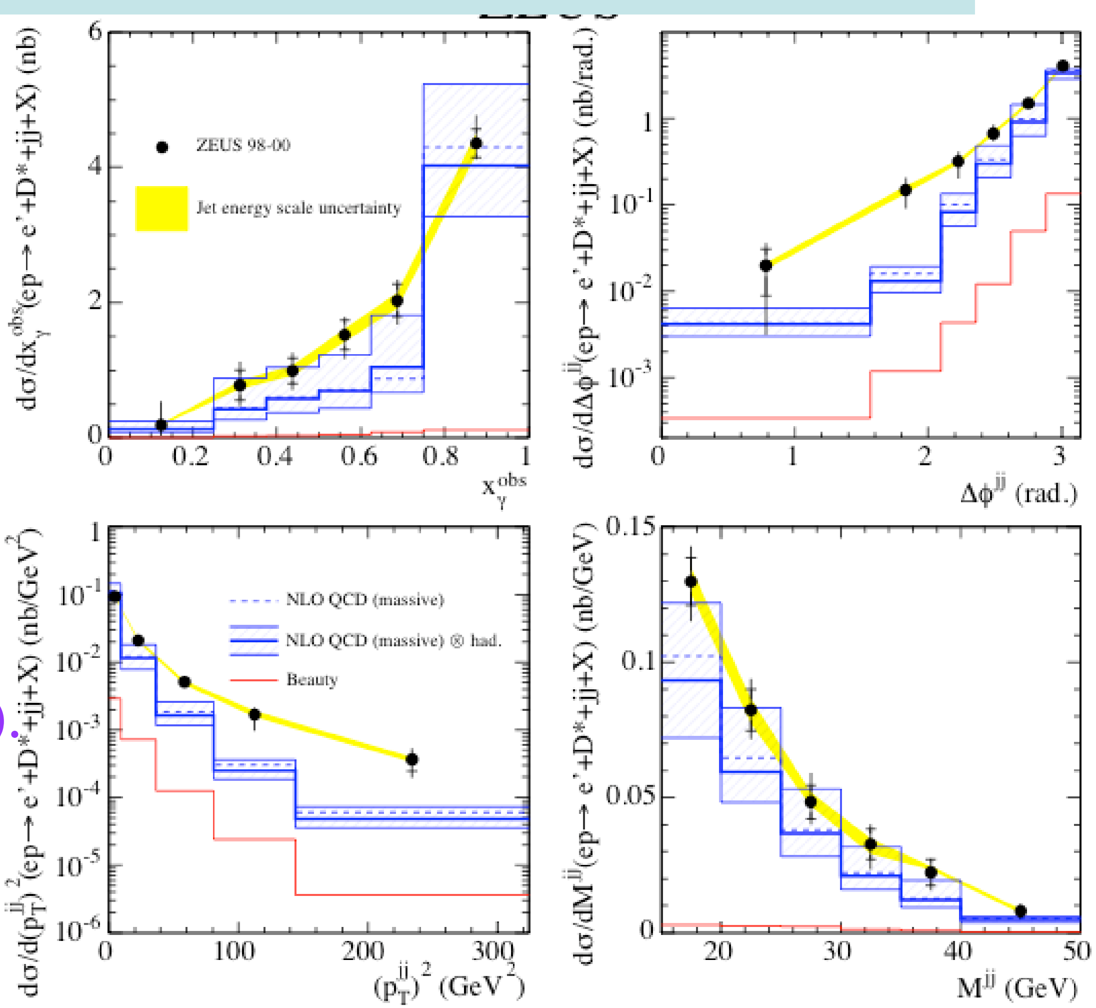


- D* + Jet selection in photoproduction. Different Kinematic region from ZEUS, lower E_T^{Jet}.
- Comparison to pQCD and LO+PS models. → CASCADE and PYTHIA describe data. pQCD does not.
- Only one parton radiation from NLO not sufficient to describe the data.

Charm Dijet Production

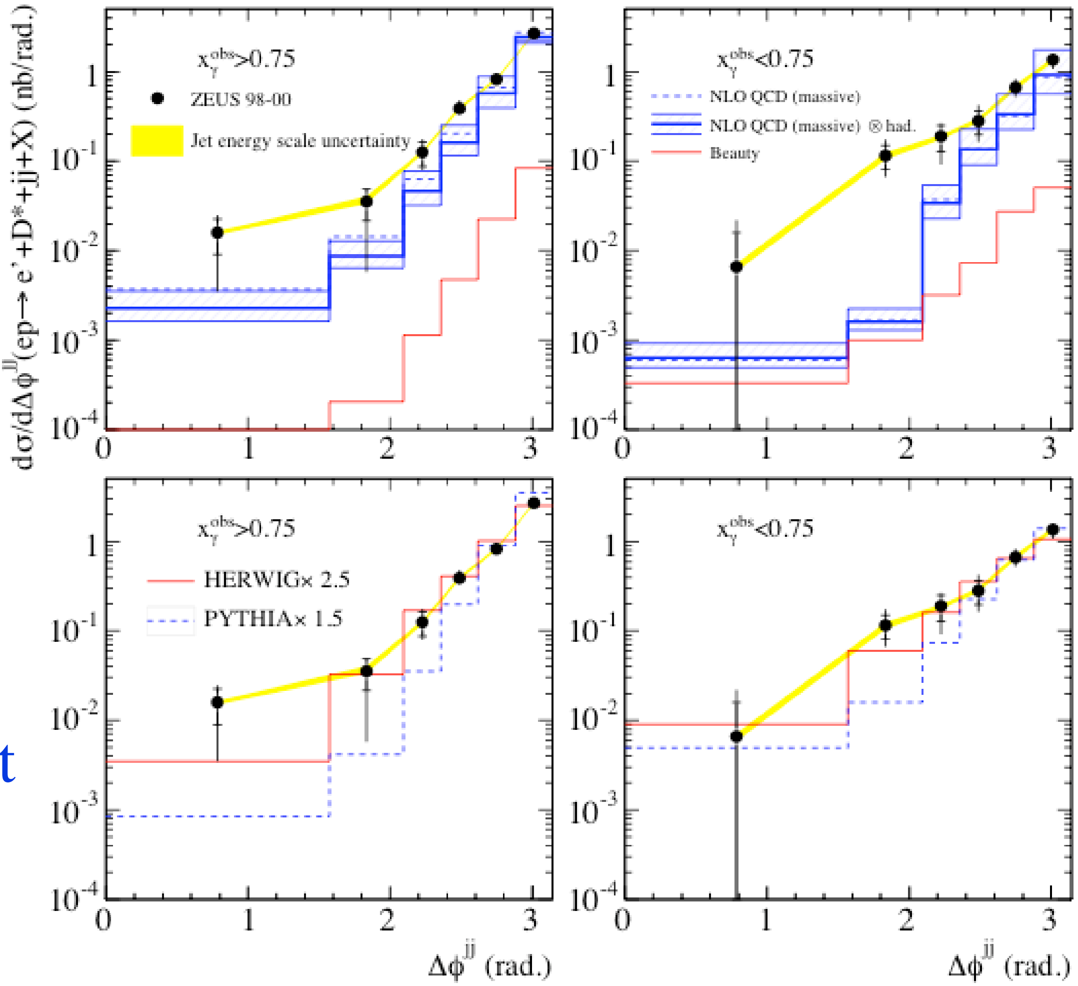
- D^* Dijet photoproduction.
- M^{JJ} and x_γ^{obs} well described.
- Angular correlations $(p_T^{JJ})^2$ and $\Delta\phi^{JJ}$ are not described.
- Split sample:
direct-enriched ($x_\gamma^{obs} > 0.75$),
resolved-enriched($x_\gamma^{obs} < 0.75$).

Does one sample contribute more then other to the discrepancy?



Charm Dijet Production

- D* Dijet photoproduction.
- Split sample direct-enriched ($x_\gamma^{obs} > 0.75$) resolved-enriched($x_\gamma^{obs} < 0.75$).
- Discrepancies between pQCD and resolved-enriched ($x_\gamma^{obs} < 0.75$).
- LO+PS can describe shape but not normalisation.
- → need for higher order calculations e.g. NLO +PS



Charm Fragmantation

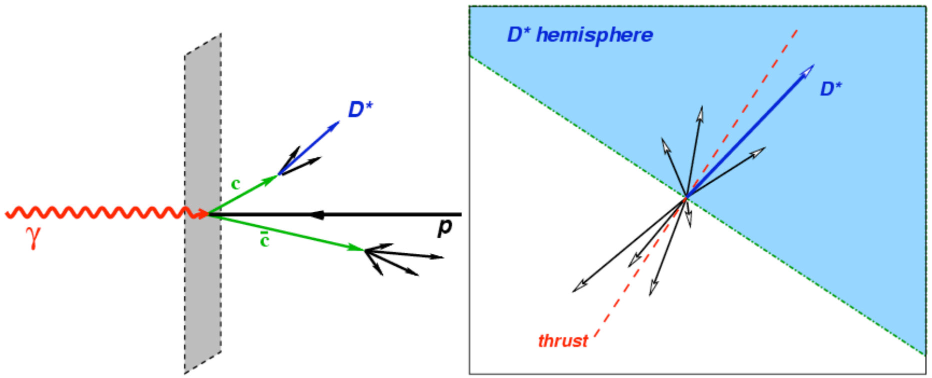
•What is the proper parameterisation for the fractional transfer of c-quark energy/momentum to a given D-meson (z)? Fragmentation function, f(z).

Find a jet containing a D* and relate the D* energy to the energy of the jet:

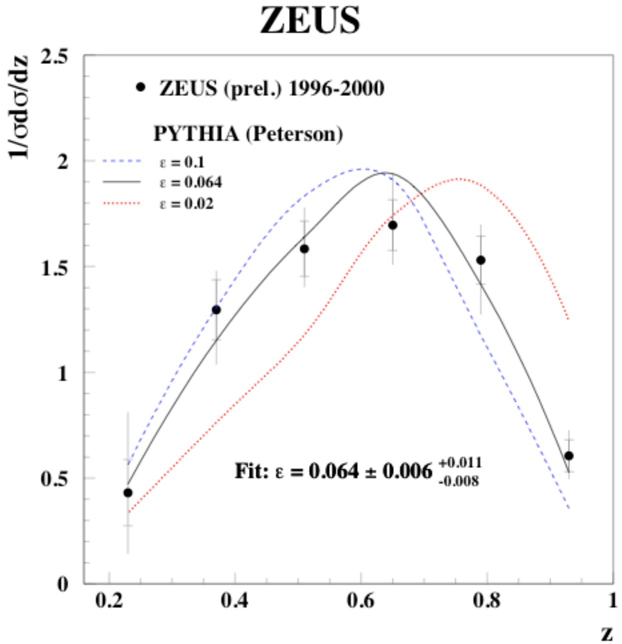
ZEUS:
$Q^2 < 1\text{GeV}^2, P_T^{D*} > 2\text{GeV}, E_T^{Jet} > 9\text{GeV}$
$z = (E + P_{||})^{D*} / (E + P_{||})^{Jet} \equiv (E + P_{||})^{D*} / 2\, E^{jet}$

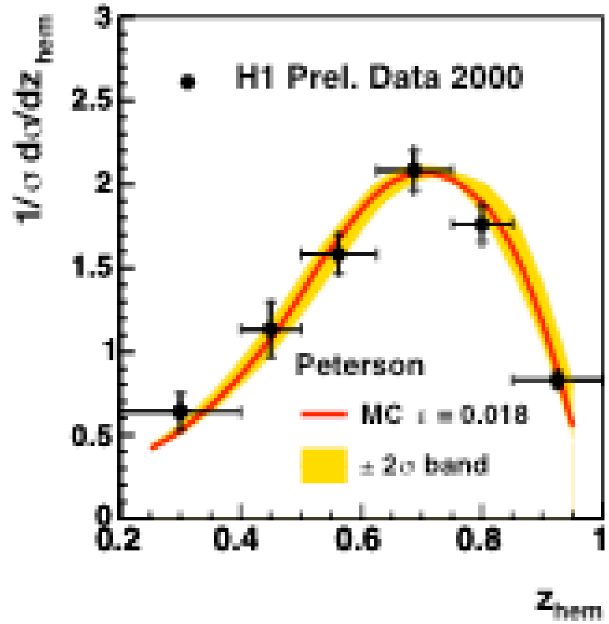
H1 jet method:
$Q^2 > 2\text{GeV}^2, P_T^{D*} > 1.5\text{GeV}, E_T^{Jet} > 3\text{GeV}$
$z_{jet} = (E + P_{||})^{D*} / (E + P)^{Jet}$ in $\gamma^* p$

H1 hemisphere method:
$Z_{hem} = (E + P_{||})^{D*} / \Sigma_{hem} (E + P)$ in $\gamma^* p$



Charm Fragmantation





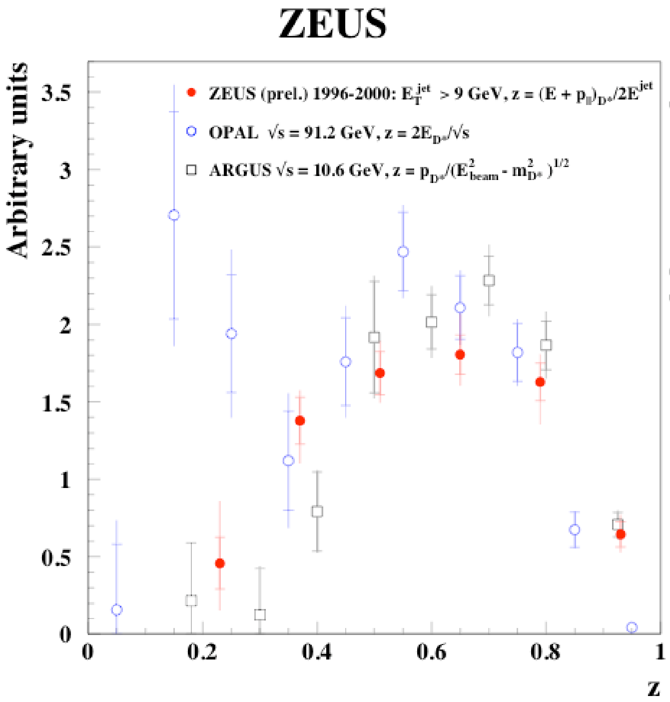
Peterson parameterisation → $$f(z) \propto \frac{1}{z(1-1/z-\epsilon/(1-z))^2}$$

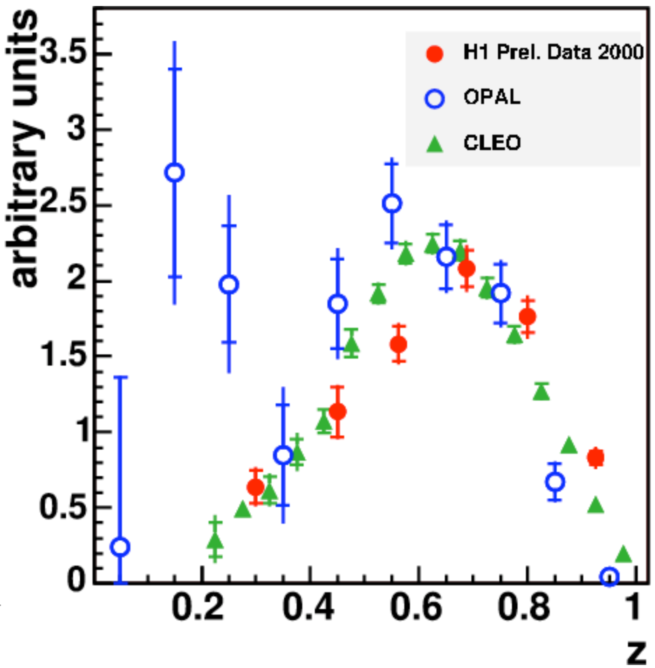
ZEUS: ε = 0.064 ± 0.006, H1(HEM): ε = 0.018 ± 0.004

H1(Jet) : ε = 0.030 (+ 0.006 - 0.005)

Differences in kinematical region selected as well as different parameters tuned from H1 to ZEUS in the Monte Carlos.

Charm Fragmantation





H1 hemisphere method

$<\sqrt{s}> \approx 10$ GeV,

$z = \frac{(E+p_L)_{D*}}{\sum_{hem}(E+p)}$

OPAL $\sqrt{s} = 91.2$ GeV,

$z = 2E_{D*}/\sqrt{s}$

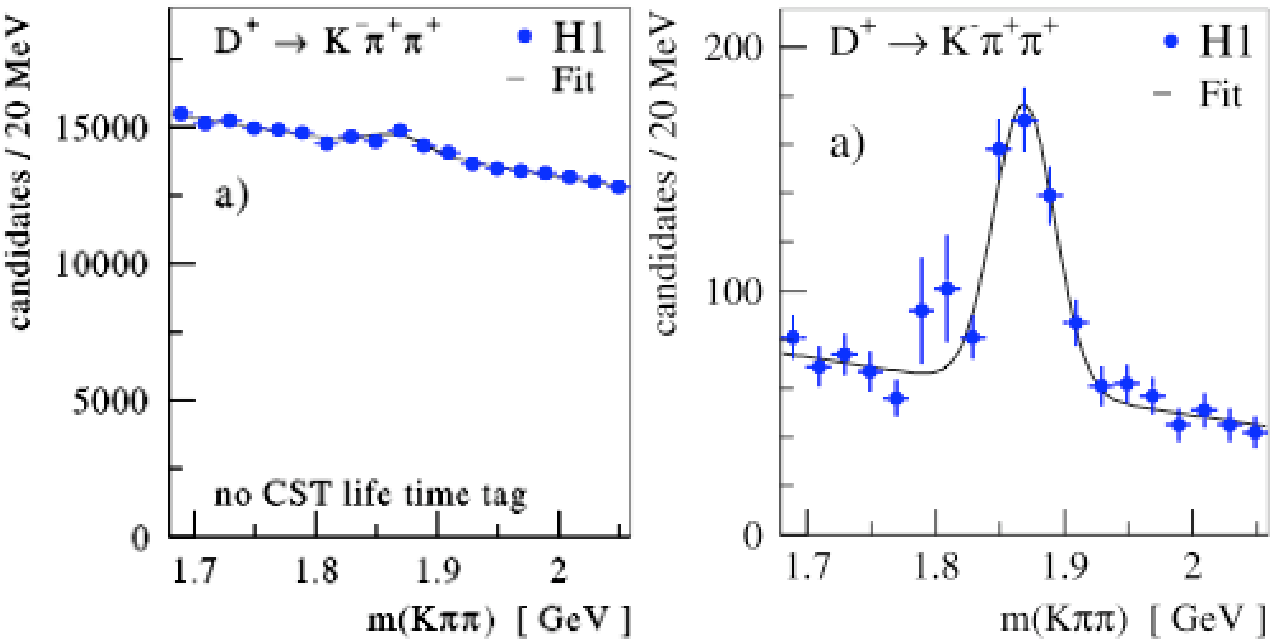
CLEO $\sqrt{s} \approx 10$ GeV,

$z = p_{D*}/p_{max}$

No gluon splitting in low-energy data, seen at low z in e^+e^-.

A global fit of the z values would result in a more rigorous test of the compatibility of these results.

Charm fragmentation fractions

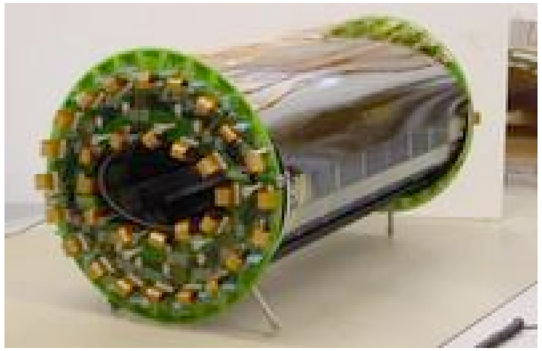


- Secondary vertex tagging, $D^+ \rightarrow K^- \pi^+ \pi^+$. Use of silicon tracker.

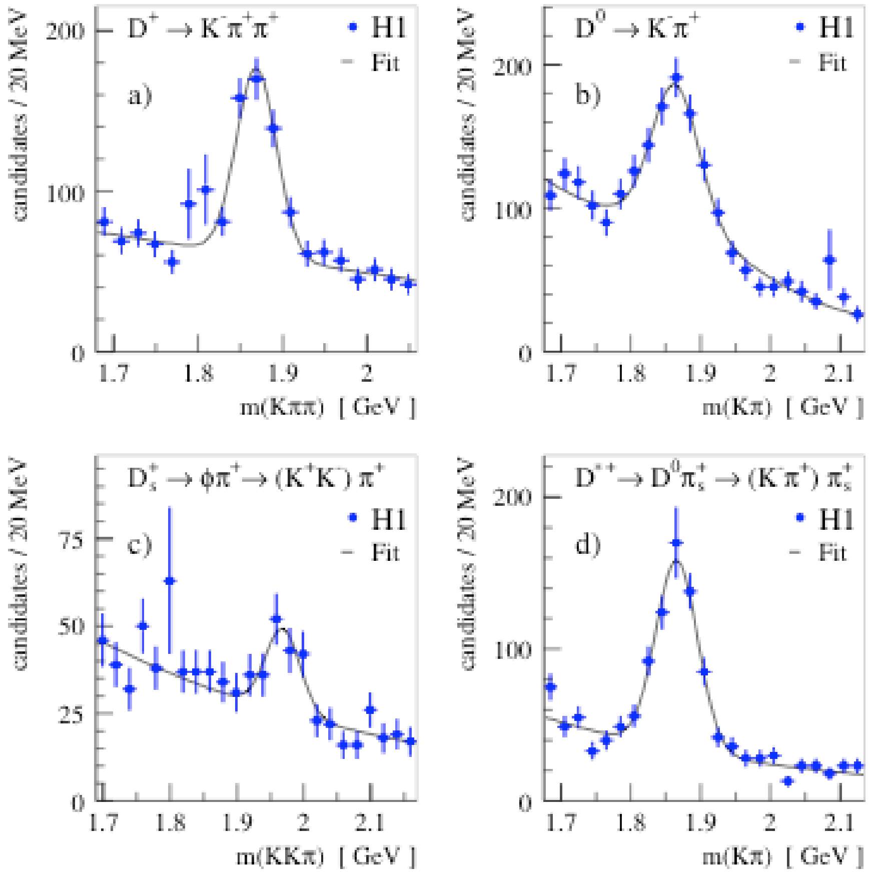
- Significance ($S_L = L / \sigma_L$) provided better signal to background ratio for many of the D mesons.

Charm fragmentation fractions

- D meson signals for D^+, D^0, D_s^+ and D^{*+} in DIS using secondary vertex tagging.
- Clean signals to study fragmentation processes.

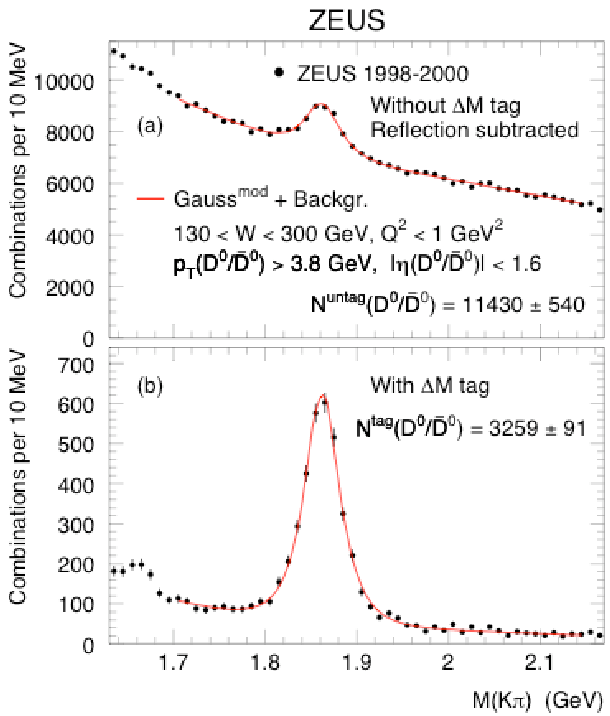


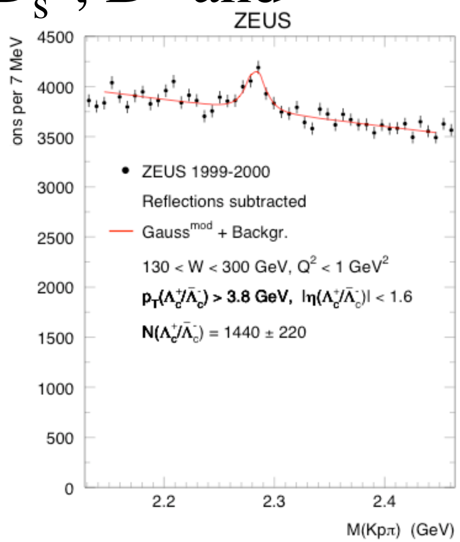
[Eur.Phys.J.C38:447-459,2005]

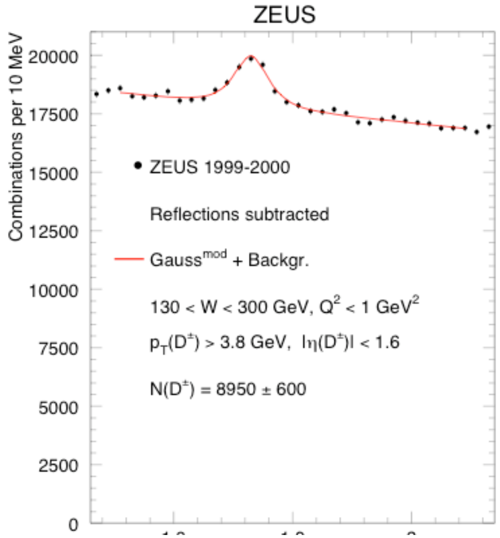


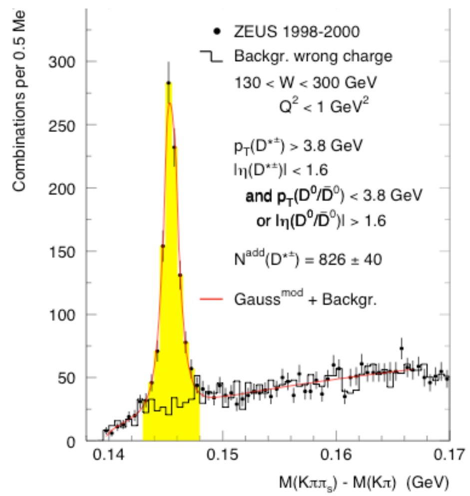
Charm fragmentation fractions

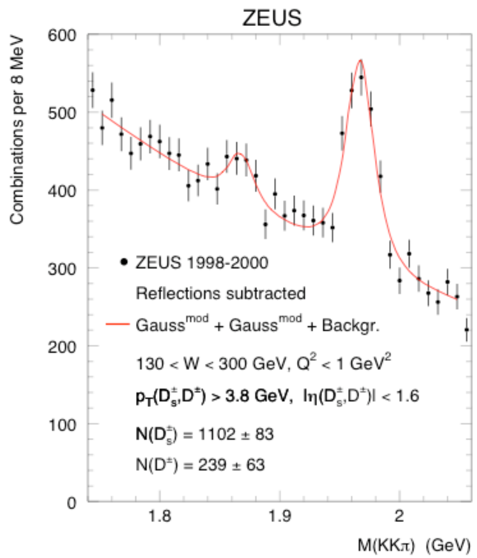
- Photoproduction of D^{*+} and D meson ground states D^0, D_s^+, D^+ and Λ_c.







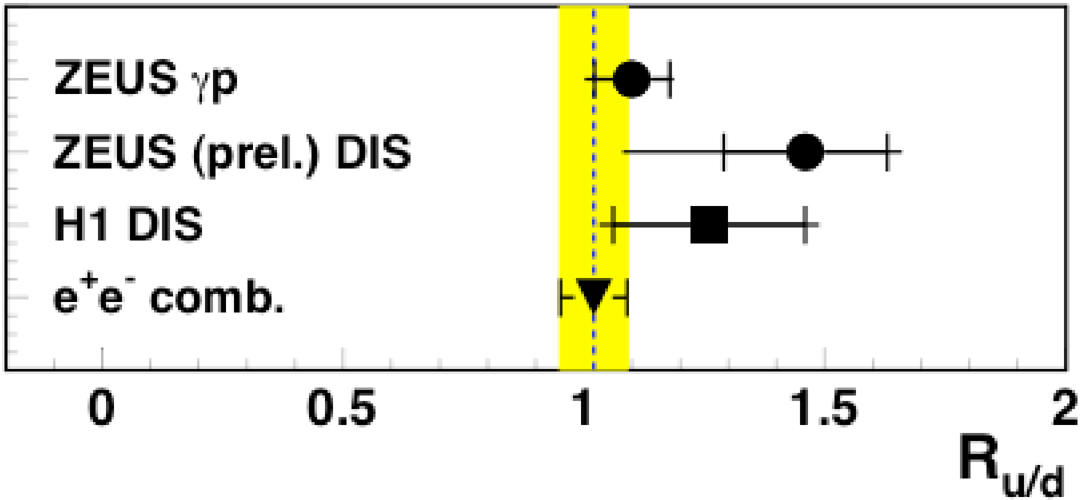




Charm fragmentation fractions

$R_{u/d}$ measurement

- Are u and d quarks produced equally? $R_{u/d}$ = cu / cd .
- N.B// different production mechanism to LEP and at lower momentum.

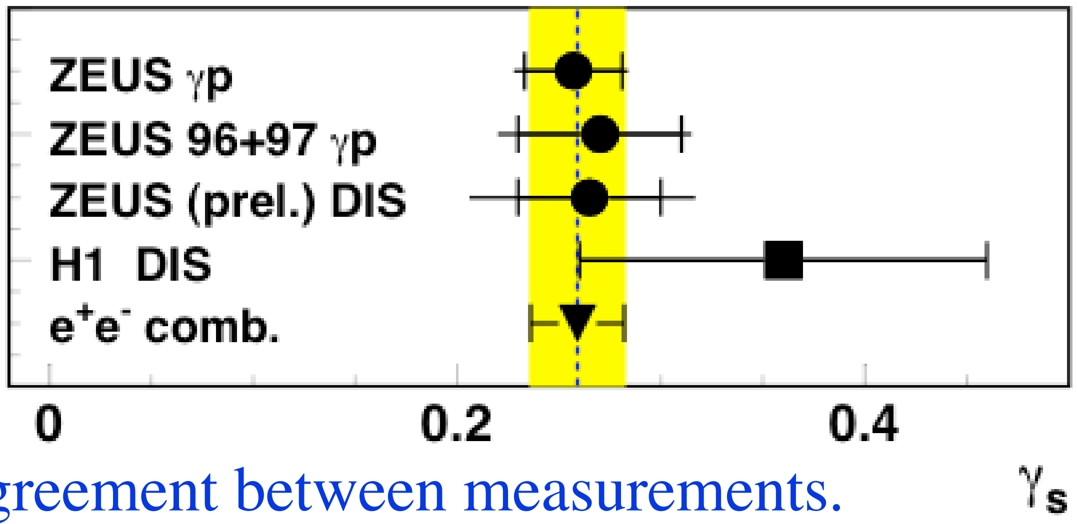


→ u and d quarks are produced equally in charm fragmentation

Charm fragmentation fractions

γ_s measurement

What is the s-quark production suppression? $\gamma_s = 2cs / (cd + cu)$



Very good agreement between measurements.

Charm strange meson production is suppressed by a factor of ≈ 3.9 in charm fragmentation.

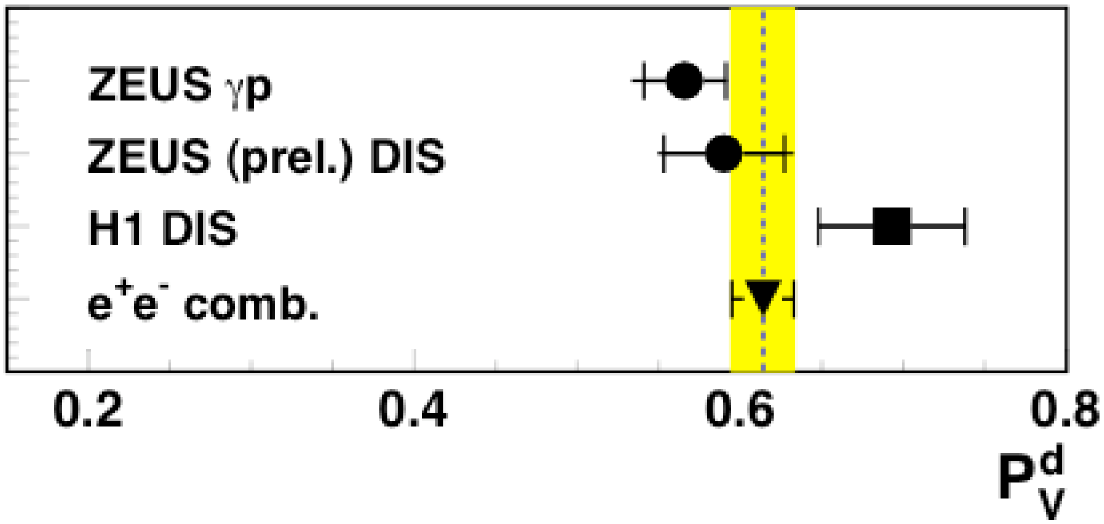
Excited charm-strange mesons like to decay to non-strange D mesons.

Charm fragmentation fractions

P_V^d measurement

Are vector D* and pseudo scalar (D) mesons produced by spin counting?

$P_v = V / (V + PS)$ (= 0.75?)



$P_V \neq 0.75 \rightarrow$ naïve spin counting does not work for charm.

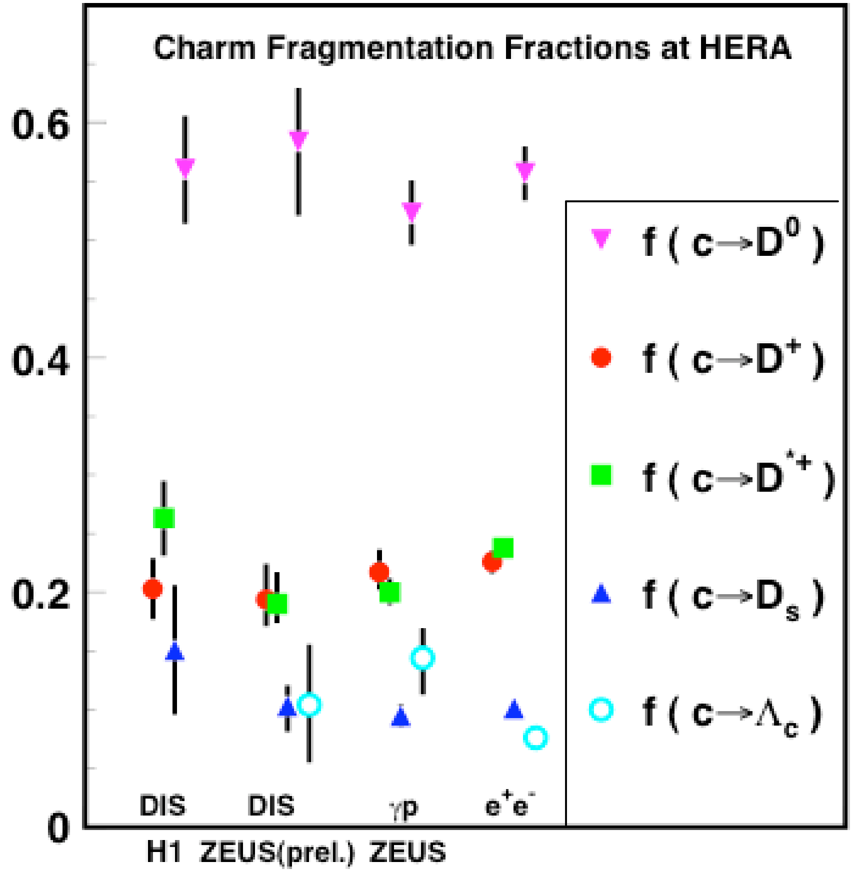
Charm fragmentation fractions

$F(c \rightarrow D) = N(D) / N(c) = \sigma(D) / \Sigma_{all}\, \sigma(D)$

Are these functions, ratios and fractions universal? Compare HERA results to those from e^+e^- annihilations.

Consistent with the universality of charm fragmentation fractions.

Half of $f(c \rightarrow D^*)$ is due to different in $f(c \rightarrow \Lambda_c)$, could this be due to a proton in the initial state? → More data from HERA II may provide the answer.



Extraction of F_2^{cc}

$$F_{2\ \text{meas}}^{c\bar{c}}(x,Q^2) = \frac{\sigma_{\text{meas}}(ep \to D^*X)}{\sigma_{\text{theory}}(ep \to D^*X)} F_{2\ \text{theory}}^{c\bar{c}}(x,Q^2)$$

- Extraction of F_2^{cc} from measured D* meson cross sections to full phase space using consistent 'massive' NLO QCD scheme (HVQDIS program)

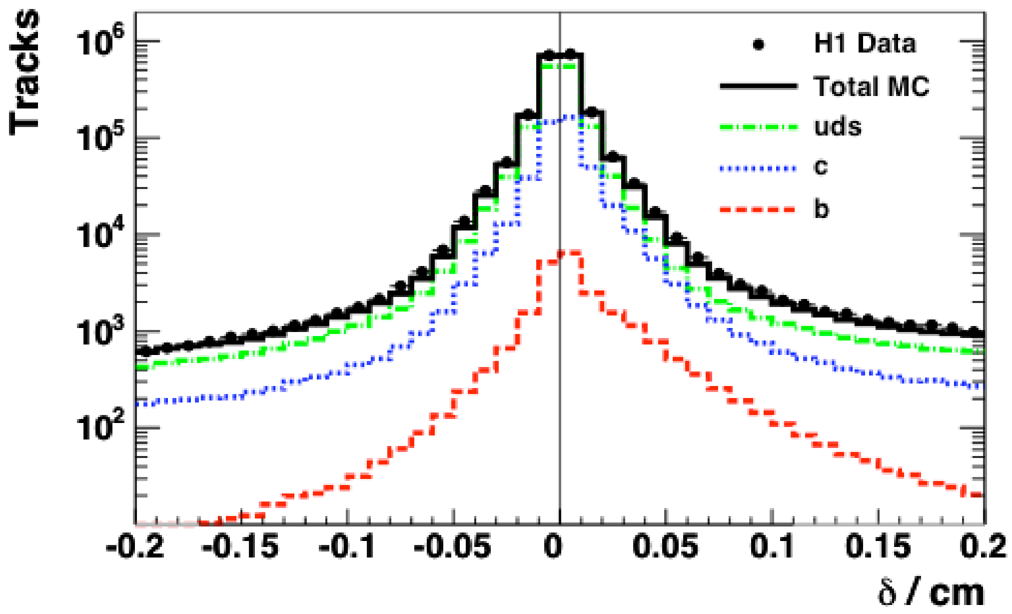
- Extrapolation factors (4.7 - 1.5) in p_T and η decreasing with Q^2. Sensitivity $p_T(D^*) > 1.5$ GeV and $|\eta(D^*)| < 1.5$.

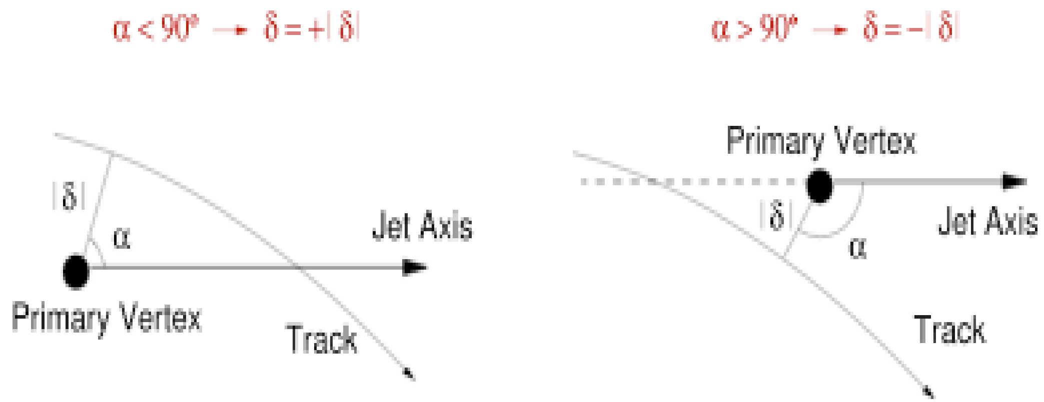
- Uncertainties in extrapolation due to fragmentation, charm mass, PDF typically around 10% and less than 20%.

Extraction of F_2^{cc}

- Impact Parameter method. All tracks have $p_T > 0.5$ GeV
- Much larger acceptance than for D* mesons.
- Smaller extrapolation factors.
- For each track within a jet, plot the distance of closest approach (DCA) to the primary vertex in the r-ϕ plane.
- Heavy flavours have a large positive impact parameter.
- Light flavours have a small symmetric negative and positive impact parameter.

→ 2 times smaller statistical errors Compared to D* measurements.





Extraction of F_2^{cc}

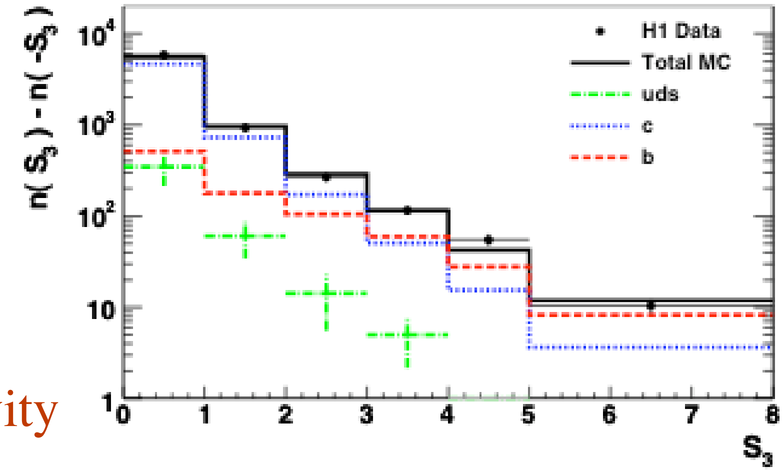
- Impact Parameter significance $S_i = \delta/\sigma(\delta)$

3 significance distributions:

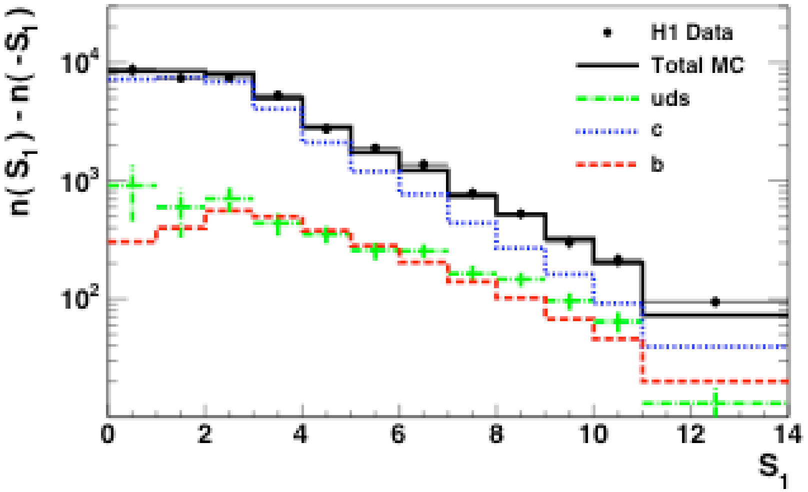
S_1 - highest significnce track

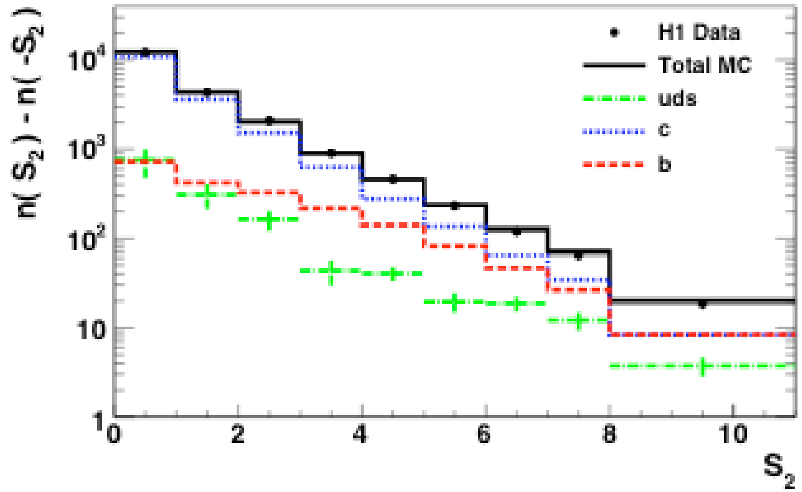
S_2 - 2^{nd} highest significnce track

S_3 - 3^{rd} highest significnce track

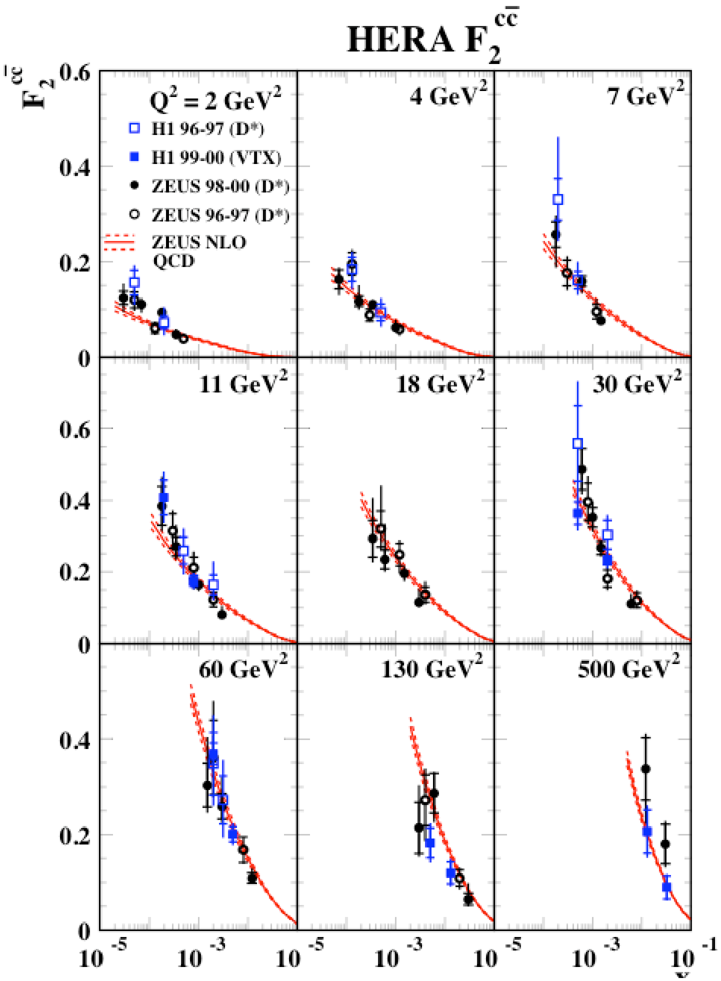


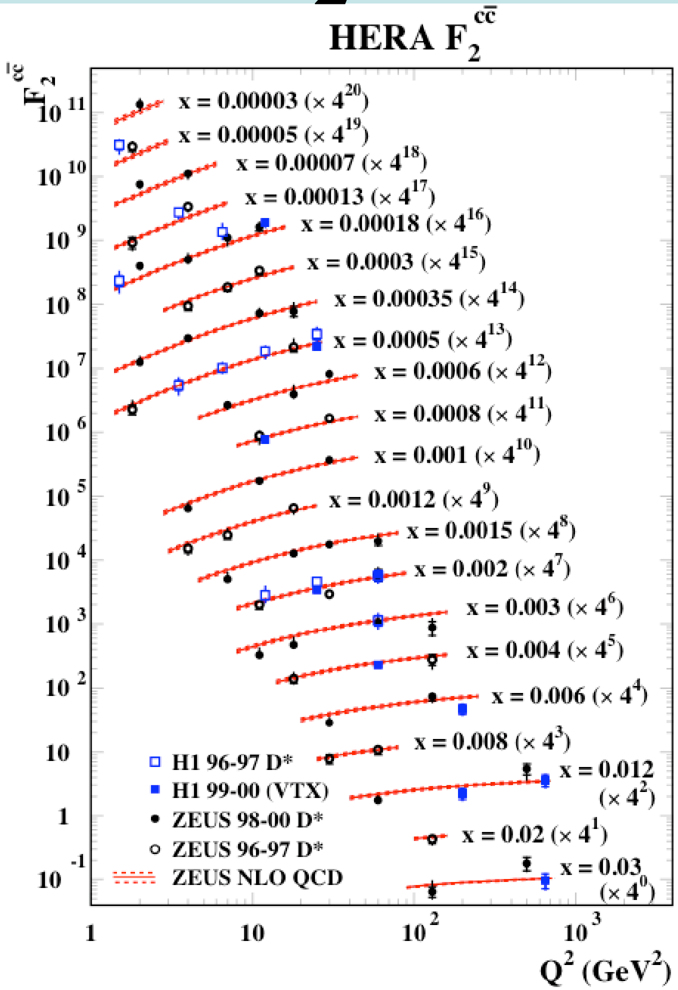
Subtraction from positive side reduces sensitivity to the resolution of light quarks





Extraction of F_2^{cc}

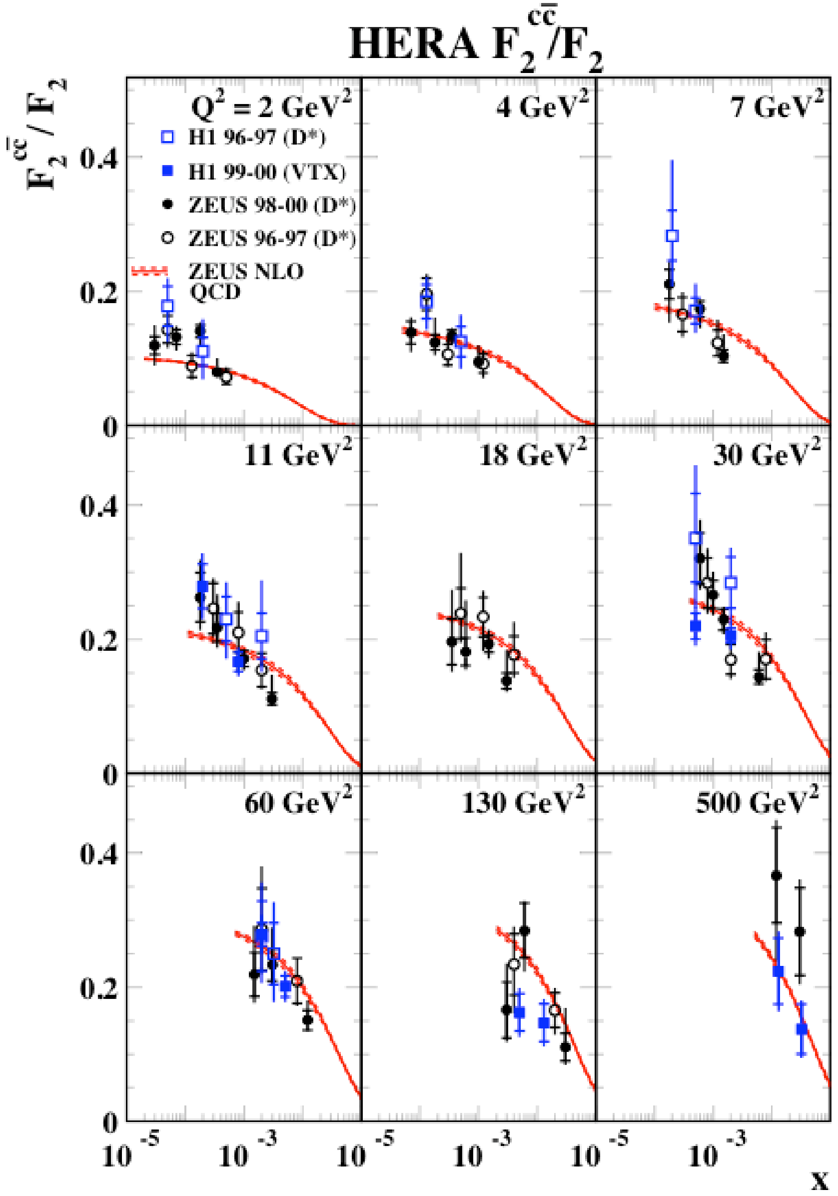




Lots of data, comparable methods.

→ Gluon density visible. Good agreement with NLO QCD.

Extraction of F_2^{cc}



Contribution of F_2^{cc} can be as large as 30%.

Different methods of extraction agree.

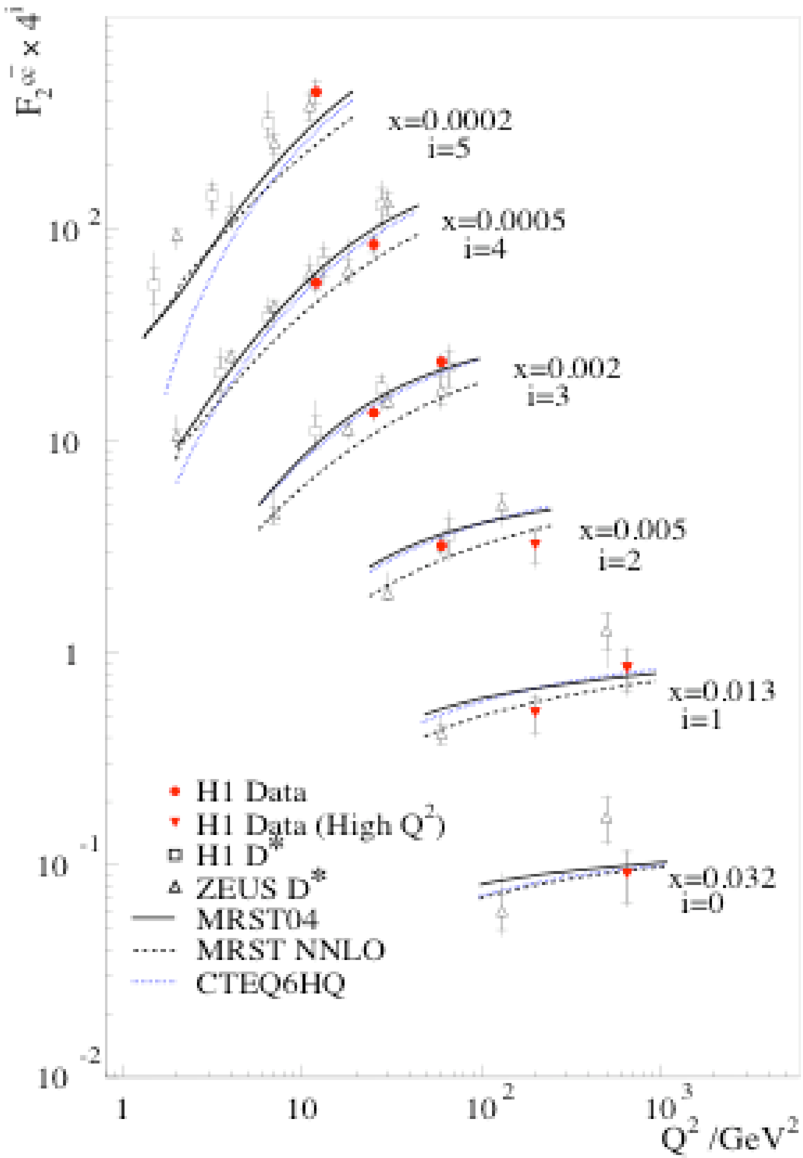
Good description by NLO QCD calculation.

Extraction of F_2^{cc}

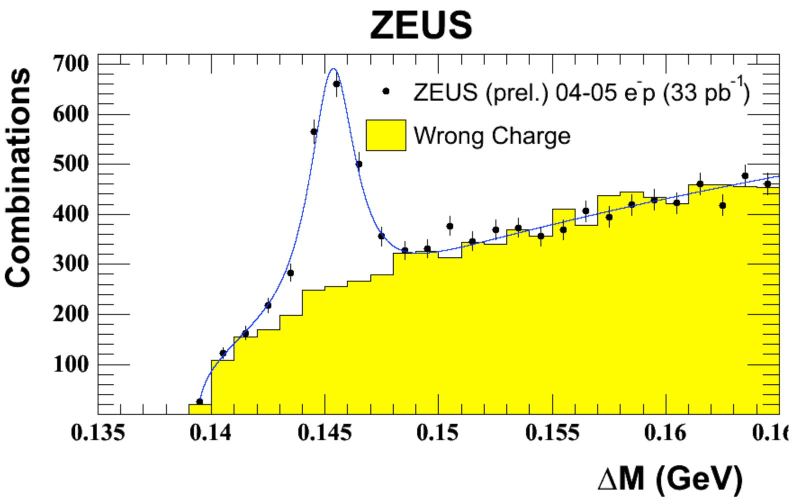
QCD calculations fit the data reasonably well.

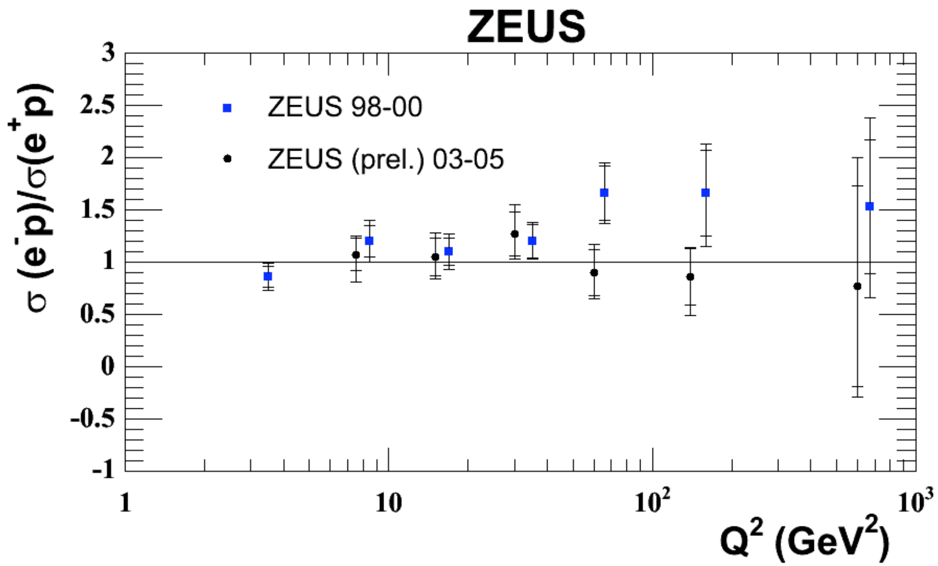
NNLO calculations → different from NLO in some regions.

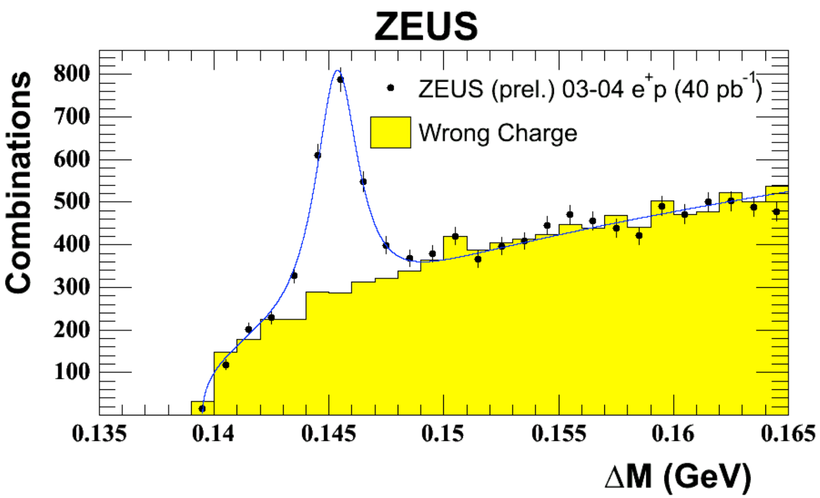
At smallest x and low Q^2 MRST NLO and NNLO differ from CTEQ6HQ.



Charm in DIS at HERA II







- HERA I data → higher D* cross sections for e^-p than for e^+p running.
- Revisited at HERA I I → ratio is 1.

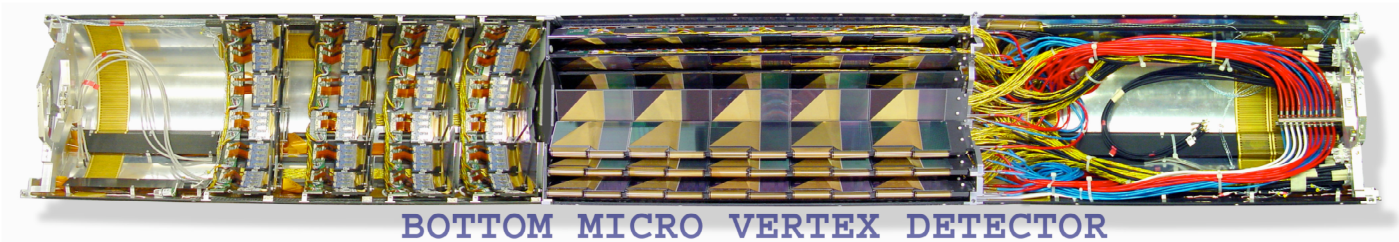
Summary

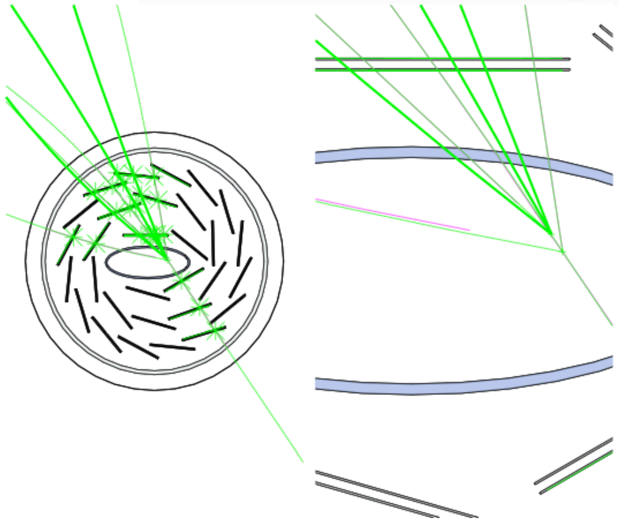
• Charm results in reasonable agreement with pQCD.

•Areas of disagreement can be selected(e.g. D* + dijets) indicating the need for higher order corrections e.g. MC@NLO.

•There is evidence that charm fragmentation is universal in e^+e^- and ep.

•HERA errors small compared to theoretical uncertainties.





Future charm prospects:

• Higher Q^2, and highest x, F_2^{cc} to a precision of better than 10%.

• Extend phase space to the forward region.

•Impact of charm data on PDF fits.