Charm Physics at HERA

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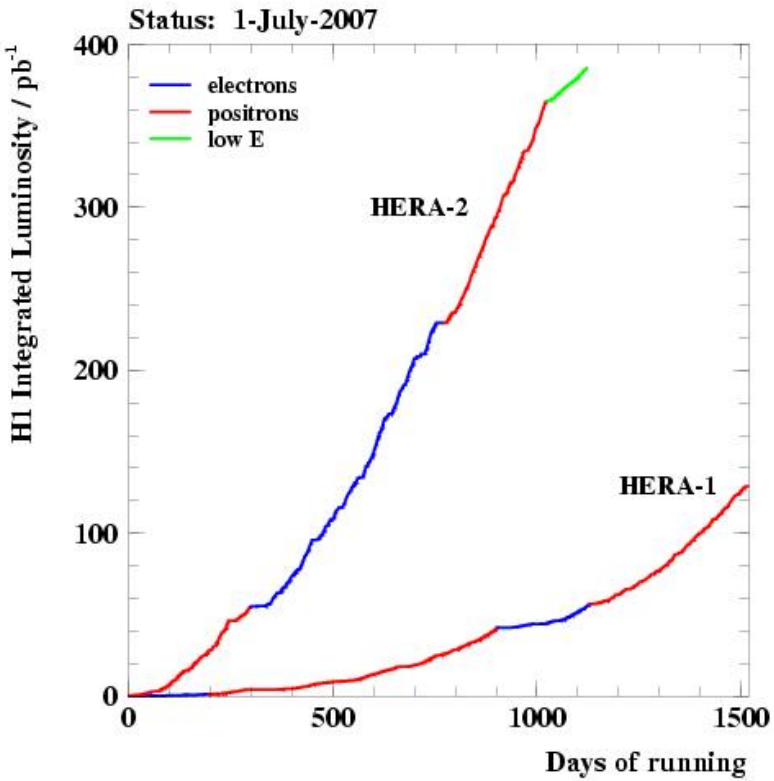
for the H1 & ZEUS Collaborations

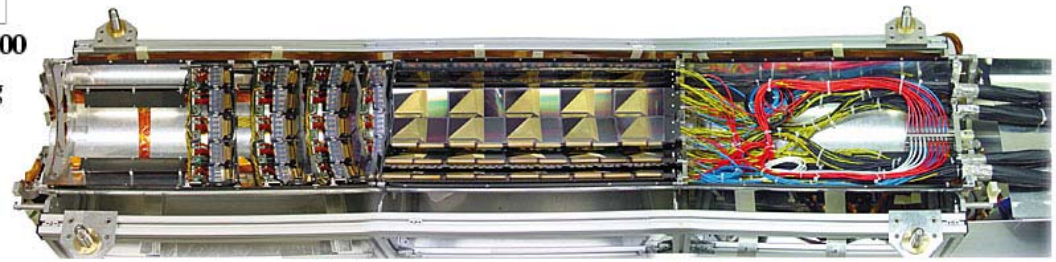
- HERA
- Charm production and theory
- D meson measurements
- Measurements of F_2^{cc}
- Comparison and combination of results

Low x, Ischia Island, Italy 8^{th}-12^{th} September, 2009

Available Data



- In total ~500pb^{-1} of high energy data collected per experiment
- Luminosity upgrade in 2001
- Detectors upgraded
- ZEUS: micro vertex detector installed



Many analyses on full HERA II data

Working on final publication and combination of results

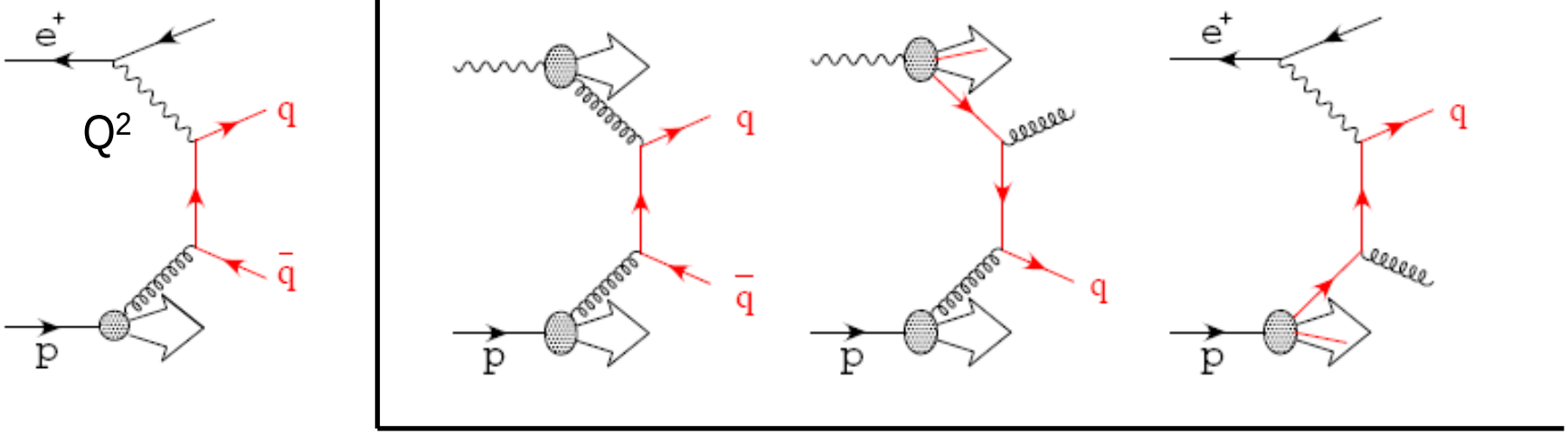
Production of Charm

Contribution of quasi-real photons at low Q^2

Direct γ

Resolved γ

(flavour excitation)



Predominantly via boson gluon fusion

Test of perturbative QCD:

multi-scale problem (Q^2, m_c^2, p_t^2)

Directly sensitive to gluon density in the proton (PDFs)

Predictions for Heavy Quark Production

Number of theoretical approaches:

Massless (Zero Mass), massive (Fixed Flavour) and general mass (GM) flavour number schemes (combination of massless/massive should provide best theoretical model).

QCD Calculations:
Fixed order - massive FFNS NLO(α_s^2) (FMNR, HVQDIS)
GM-VFNS PDFs
MSTW08 to NLO (α_s^2) and NNLO (α_s^3)
CTEQ 6.6 to NLO (α_s)

Monte-Carlo: LO (α_s) + Parton shower:

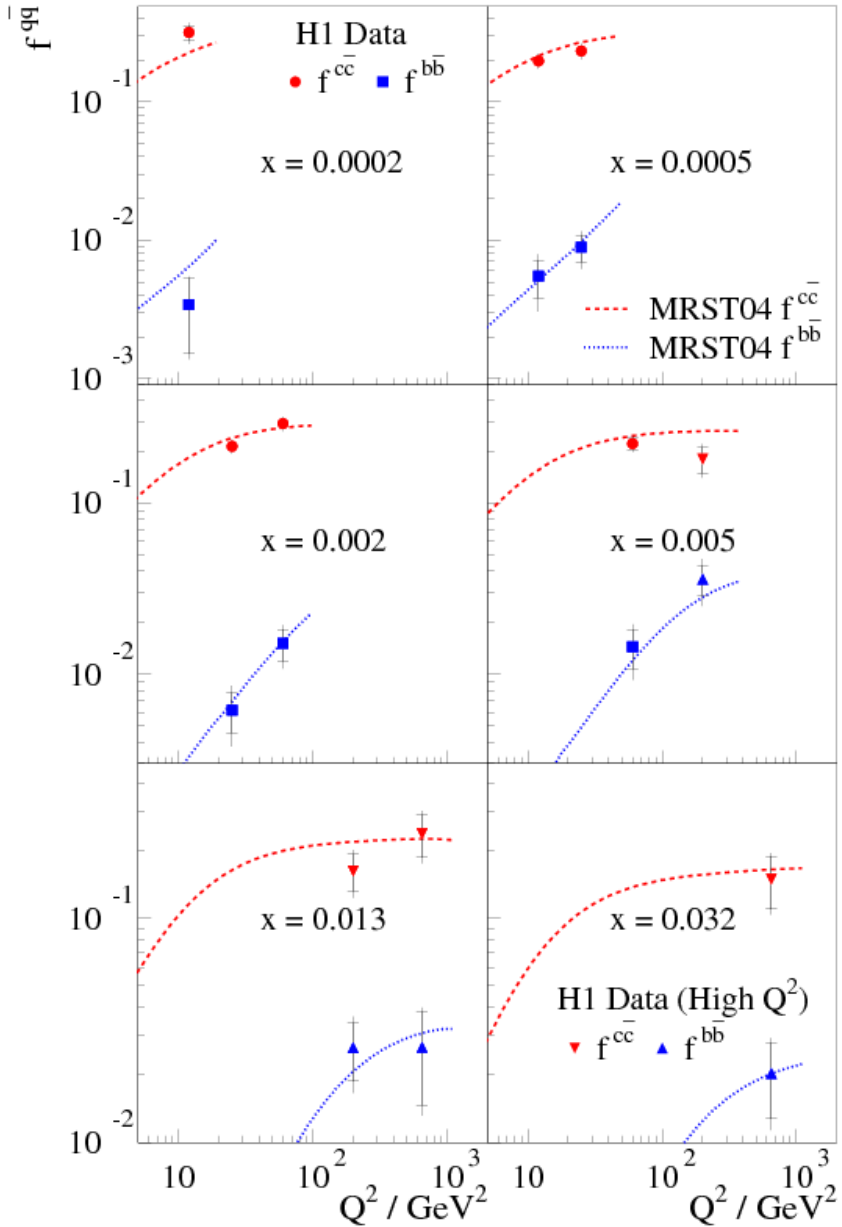
Collinear factorisation, DGLAP (RAPGAP, PYTHIA)

K_T factorisation, CCFM (CASCADE)

Contribution to Cross Section

HERA I result:

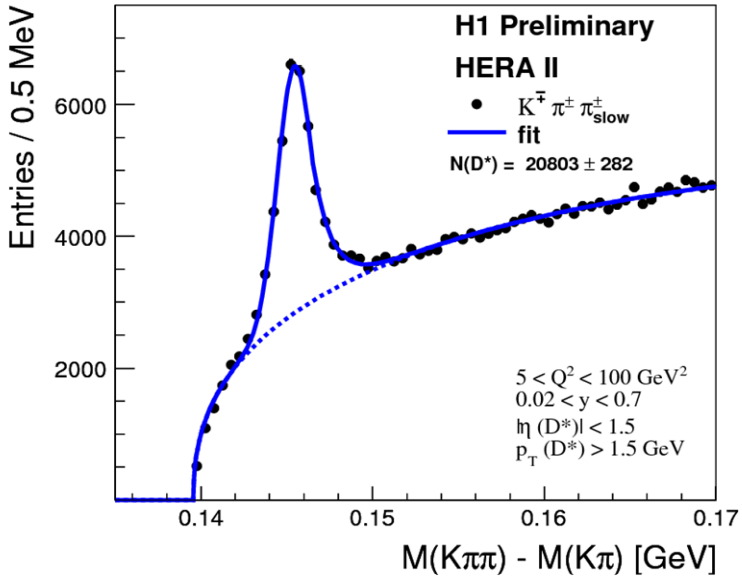
- fraction of total DIS cross section from charm and beauty
- large charm fraction (~30%)
- mass thresholds visible
- reasonable description by QCD

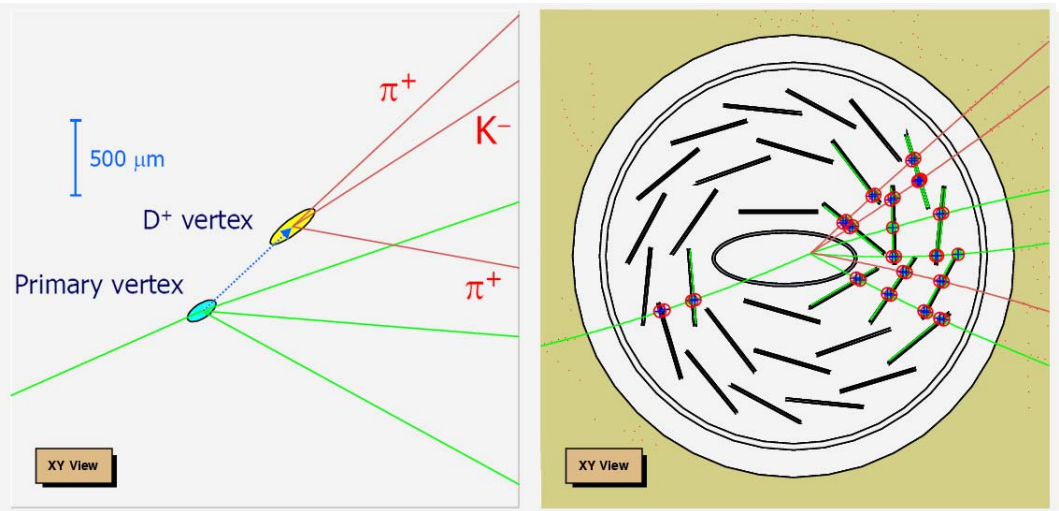


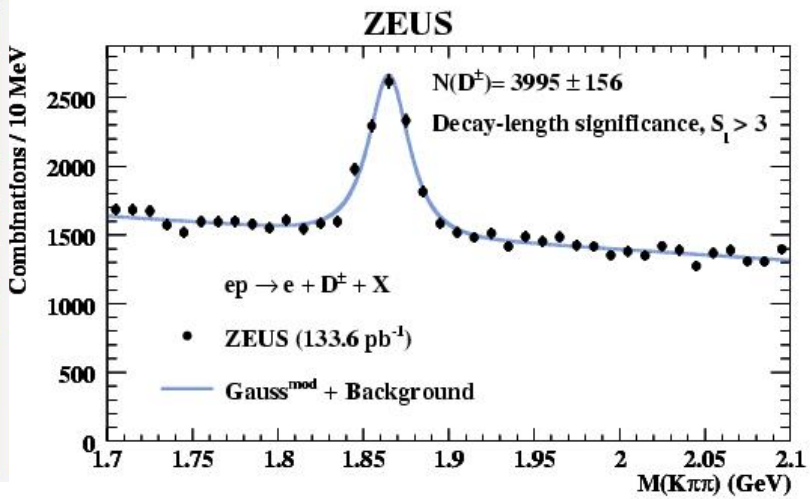
Charm Tagging using D mesons

Fully reconstruct D meson resonances D^*, D^+, D^0,...

Reject background by asking for a non-zero decay length, reconstructed from vertex detectors

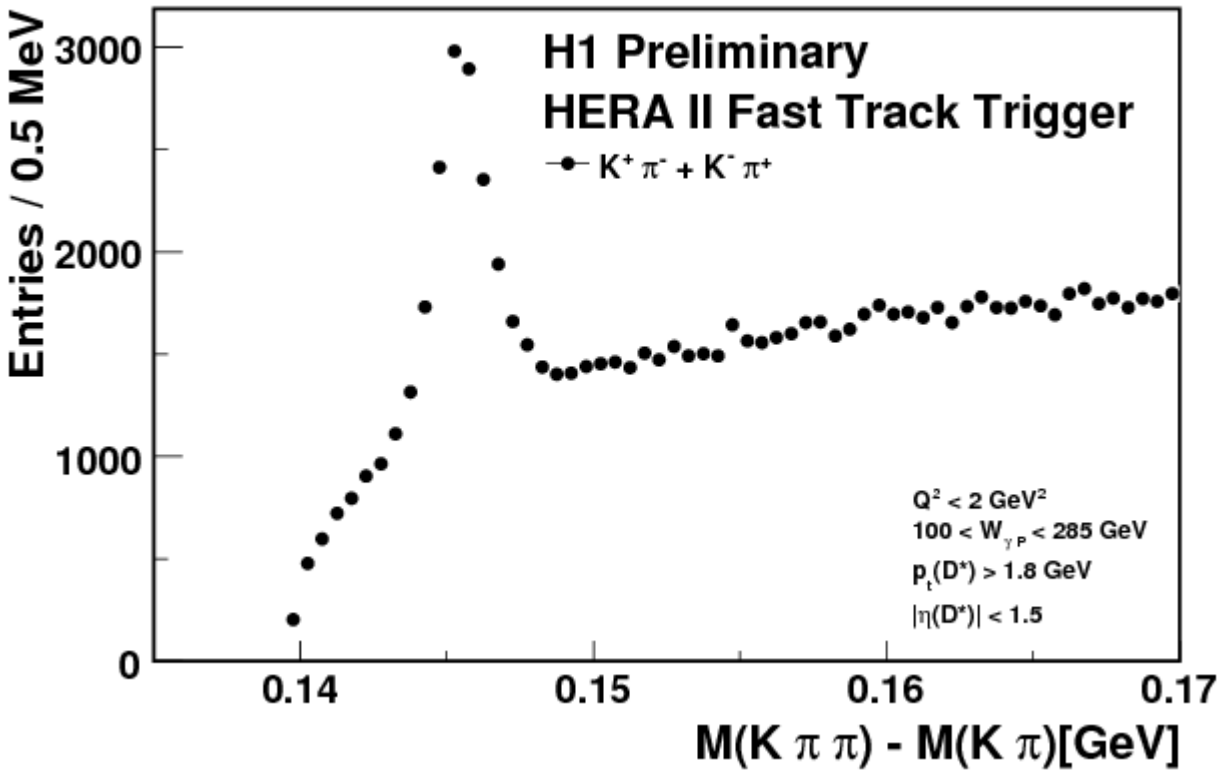






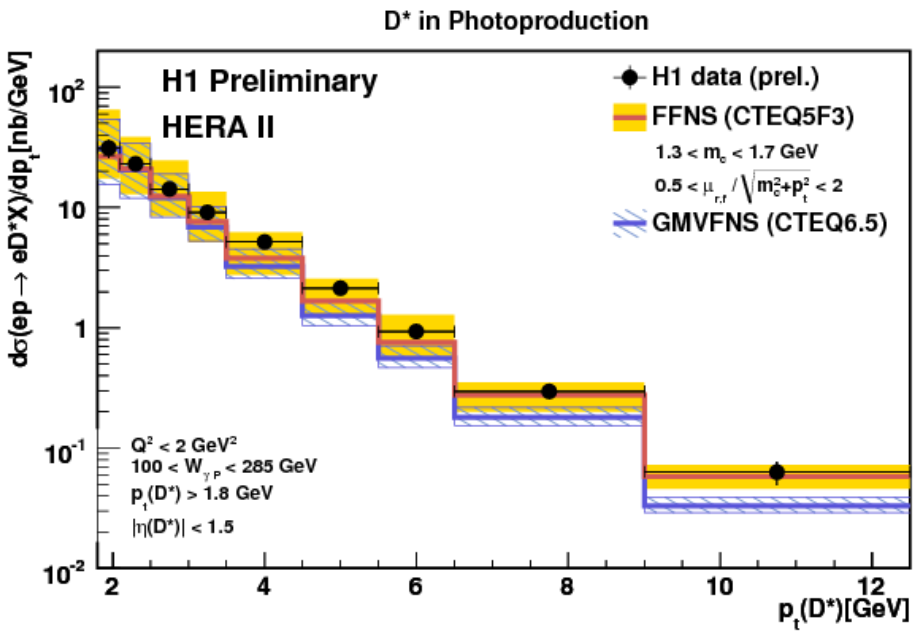
Charm in Photoproduction

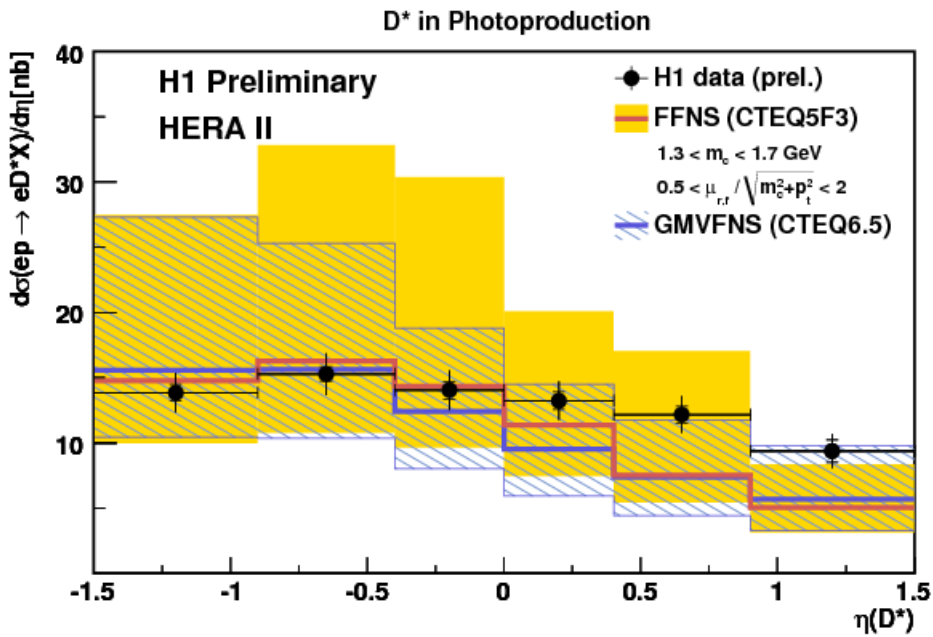
Use golden decay channel $D^* \to D^0 \pi_s \to K\pi\pi_s$ H1prelim-08-073



- Use Fast Track Trigger to collect HERA II data at low P_T
- L = 93pb^{-1}

D* in Photoproduction



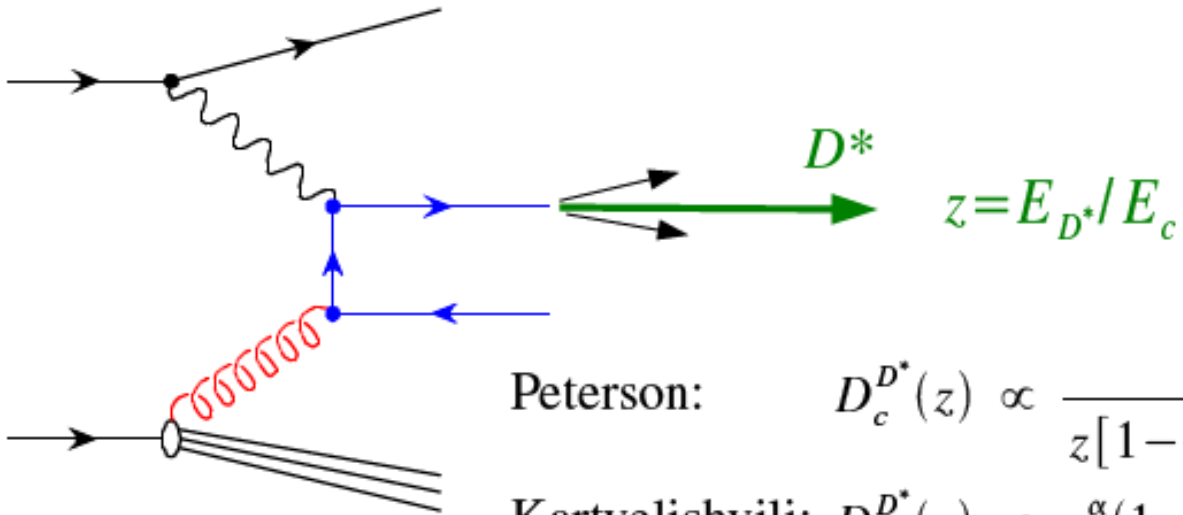


- Compare with FFNS and GM VFNS
- Theoretical errors are large at low $P_T(D^*)$
- Fixed Flavour gives a reasonable description
- General mass flavour scheme is below data at large P_T
- Still some theoretical understanding needed

D* Fragmentation

$$\sigma_{D^*} \propto f_{g/p} \otimes \hat{\sigma} \otimes D_c^{D^*}(z)$$

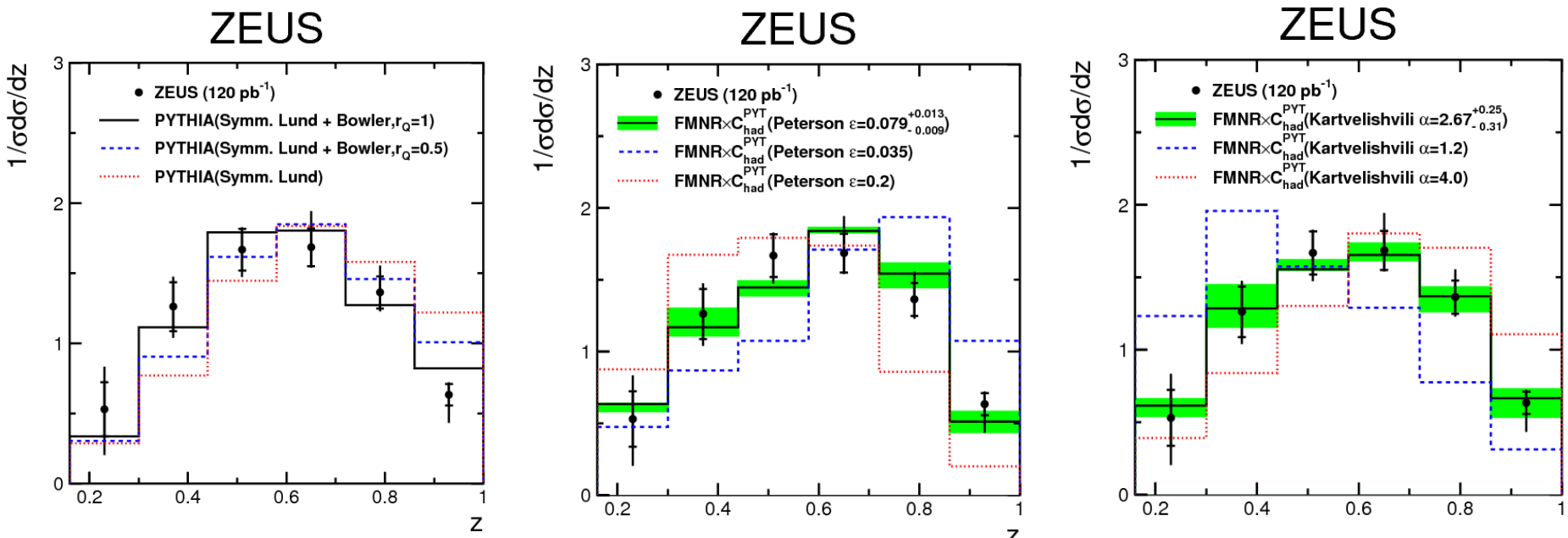
parton density function (non-perturbative)	parton scattering cross section (perturbative)	fragmentation function (non-perturbative)



Peterson: $D_c^{D^*}(z) \propto \dfrac{1}{z[1-(1/z)-\epsilon/(1-z)]^2}$

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

D* Fragmentation in γp



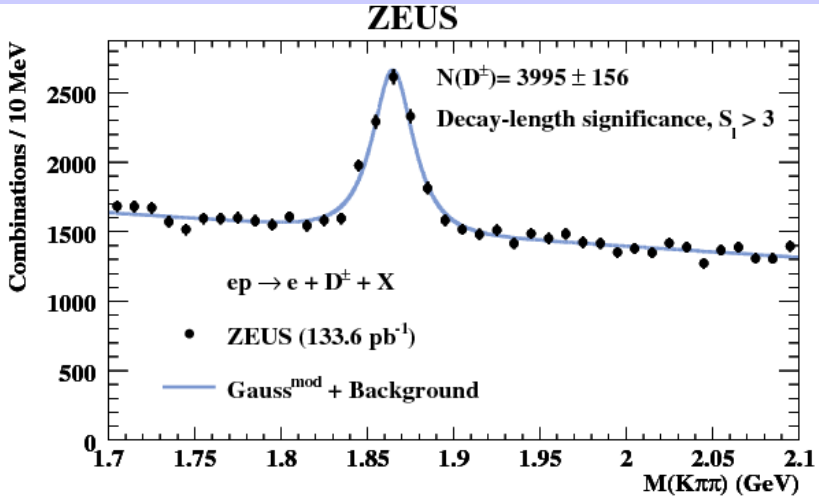
$z = (E + p_{\parallel})^{D^*}/2E^{\mathrm{jet}}$ $E_T^{\mathrm{jet}} > 9\,\mathrm{GeV}$

arXiv:0901.1210

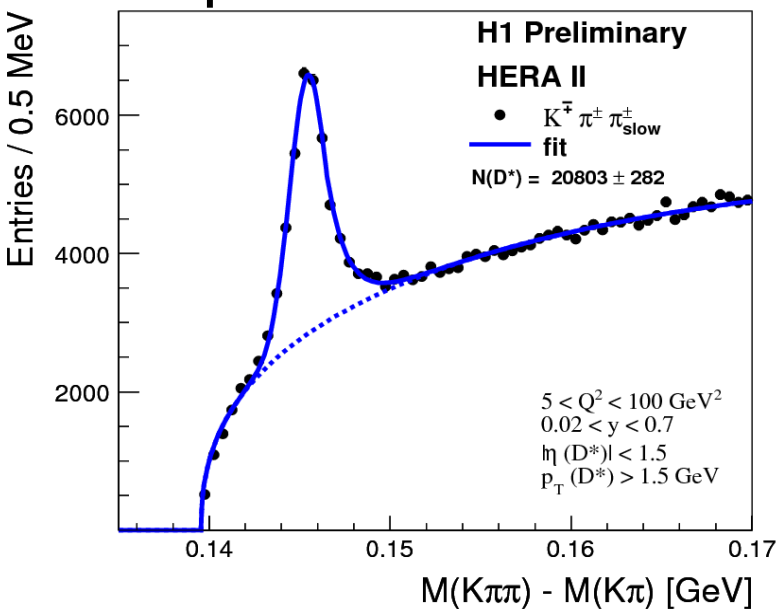
- *ep* data consistent with a symmetric Lund-Bowler (R_Q=1).
- NLO plus Peterson or Kartvelishvili fragmentation functions also describe data. Extracted parameters within NLO/PYTHIA framework agree with those from e^+e^-
- Similar study in DIS by H1 arXiv:0808.1003

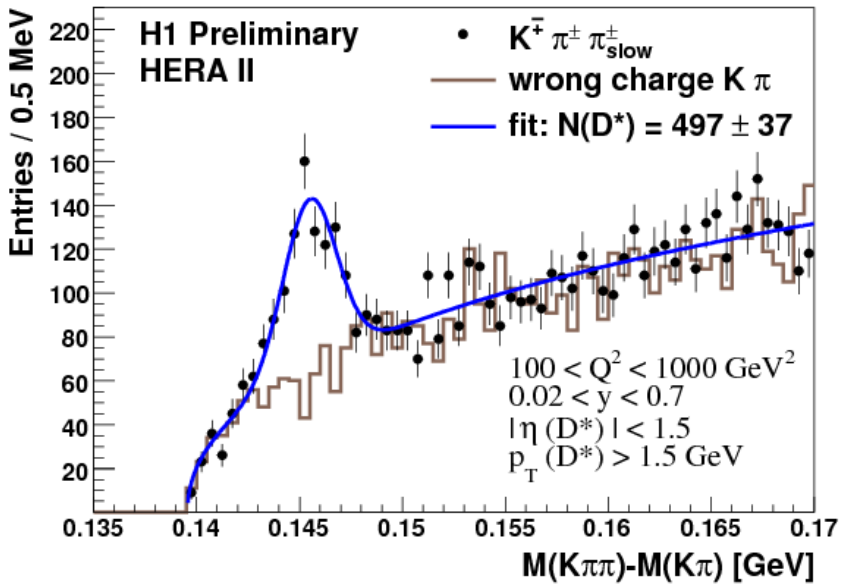
Charm in DIS

ZEUS $5 < Q^2 < 1000$ GeV^2
D^+ and D^0 mesons using vertex detector
arXiv:0812.3775

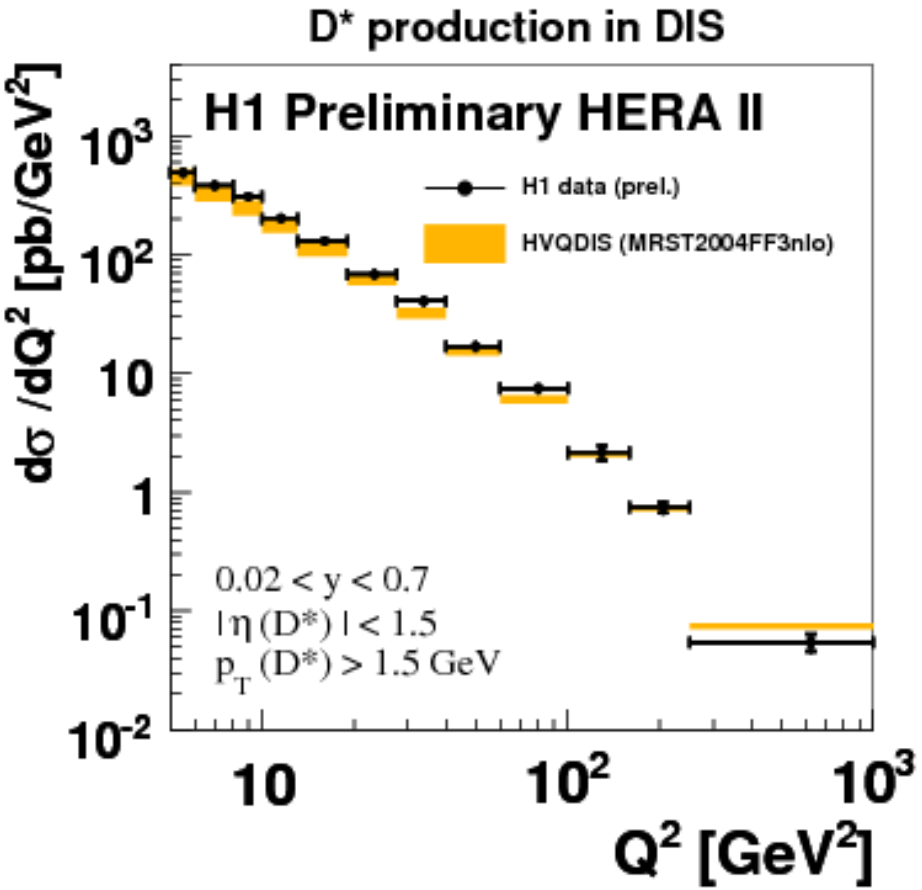


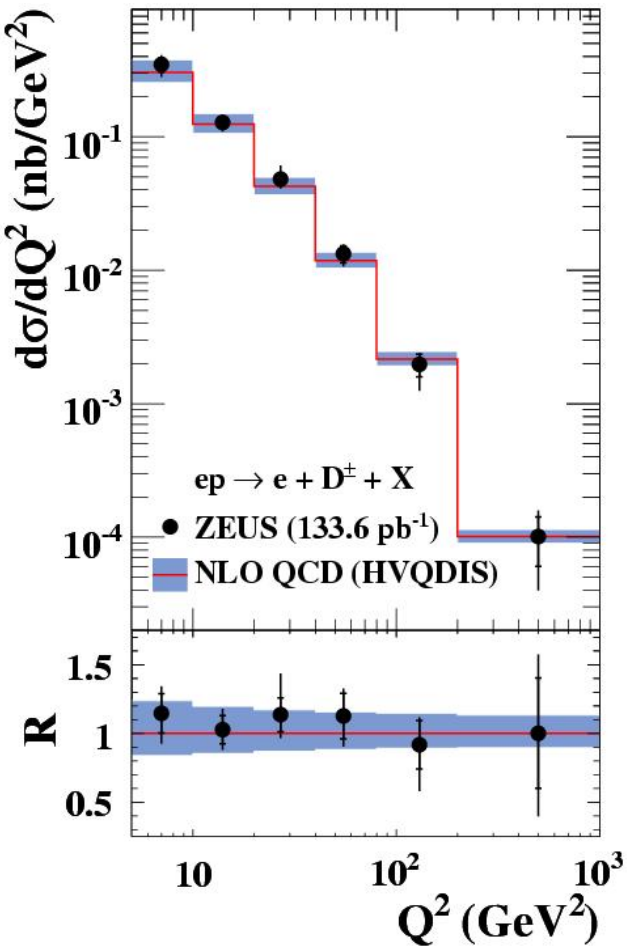
$5 < Q^2 < 100$ GeV^2 H1 full HERA II $100 < Q^2 < 1000$ GeV^2
H1prelim-08-072 stats (~350pb^{-1}) H1prelim-08-074





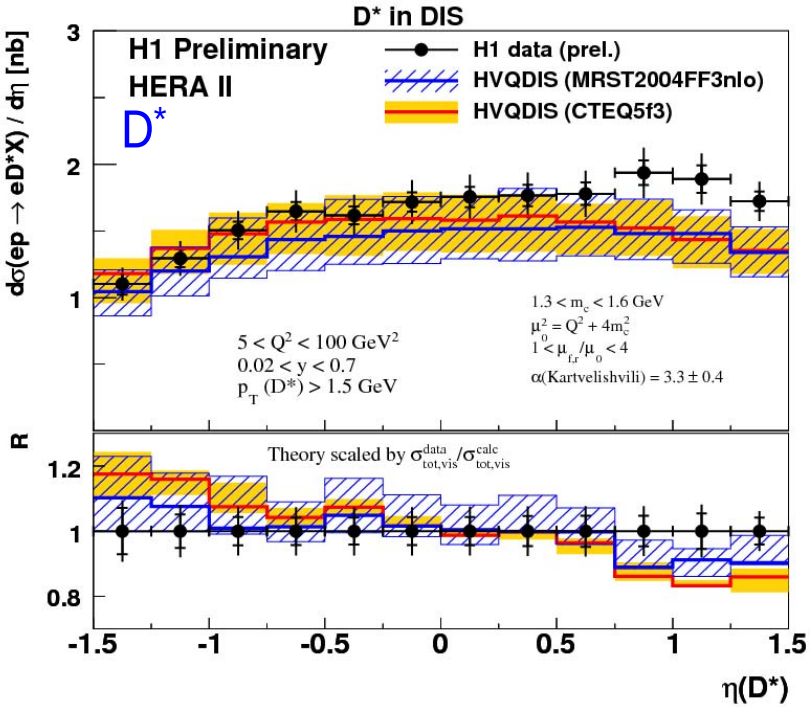
D Meson DIS Cross Sections

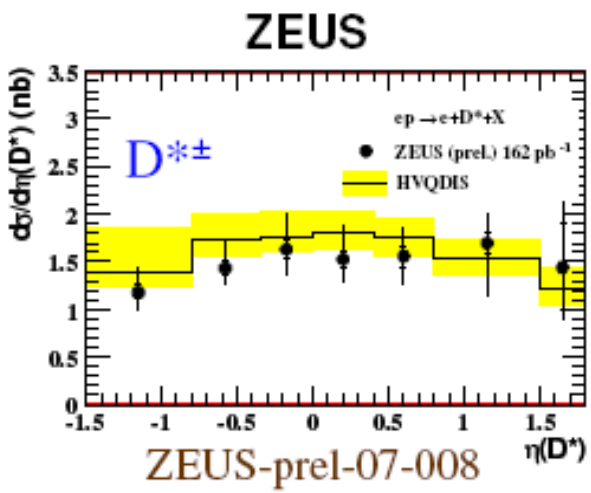




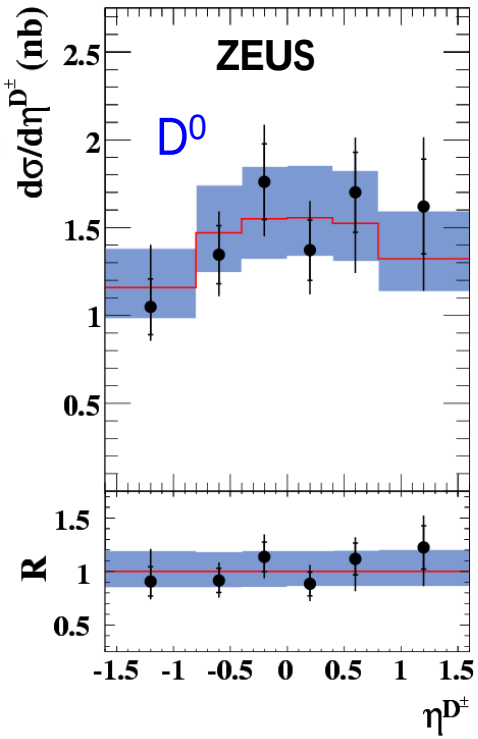
- Good description by NLO calculation (HVQDIS) in wide Q^2 range
- Also at large Q^2, where massive approach not expected to be appropriate

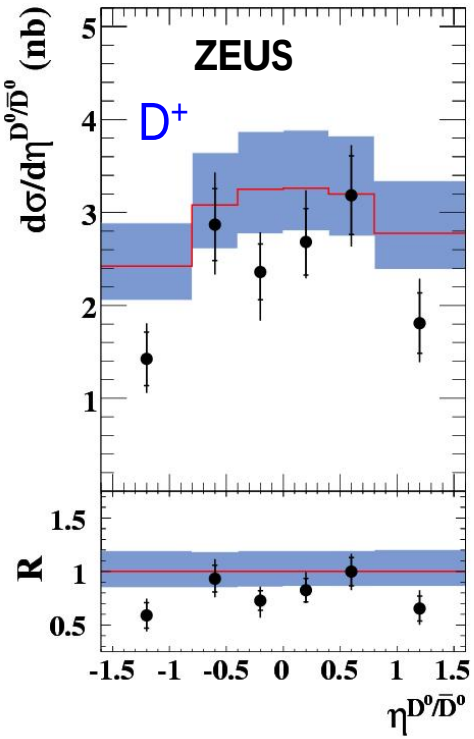
D Meson DIS Cross Sections





- differential cross sections of several D mesons measured
- reasonably described by NLO QCD
- double differential in x and Q^2 allows extraction of F_2^{cc} (see later)





Other charm tagging techniques

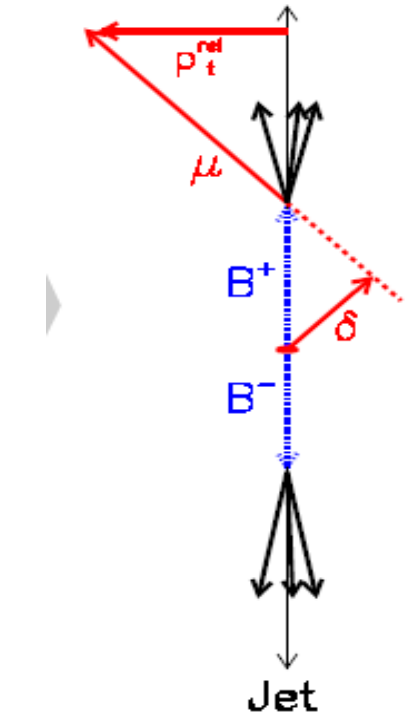
Look for semileptonic decays of charm

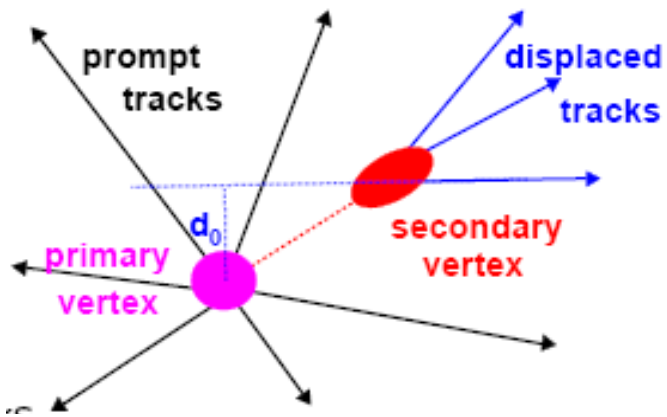
- transverse momentum p_t^{rel} relative to jet axis
- impact parameter of muon δ
- P_t^{miss} relative to muon from neutrino

Lifetime of all tracks

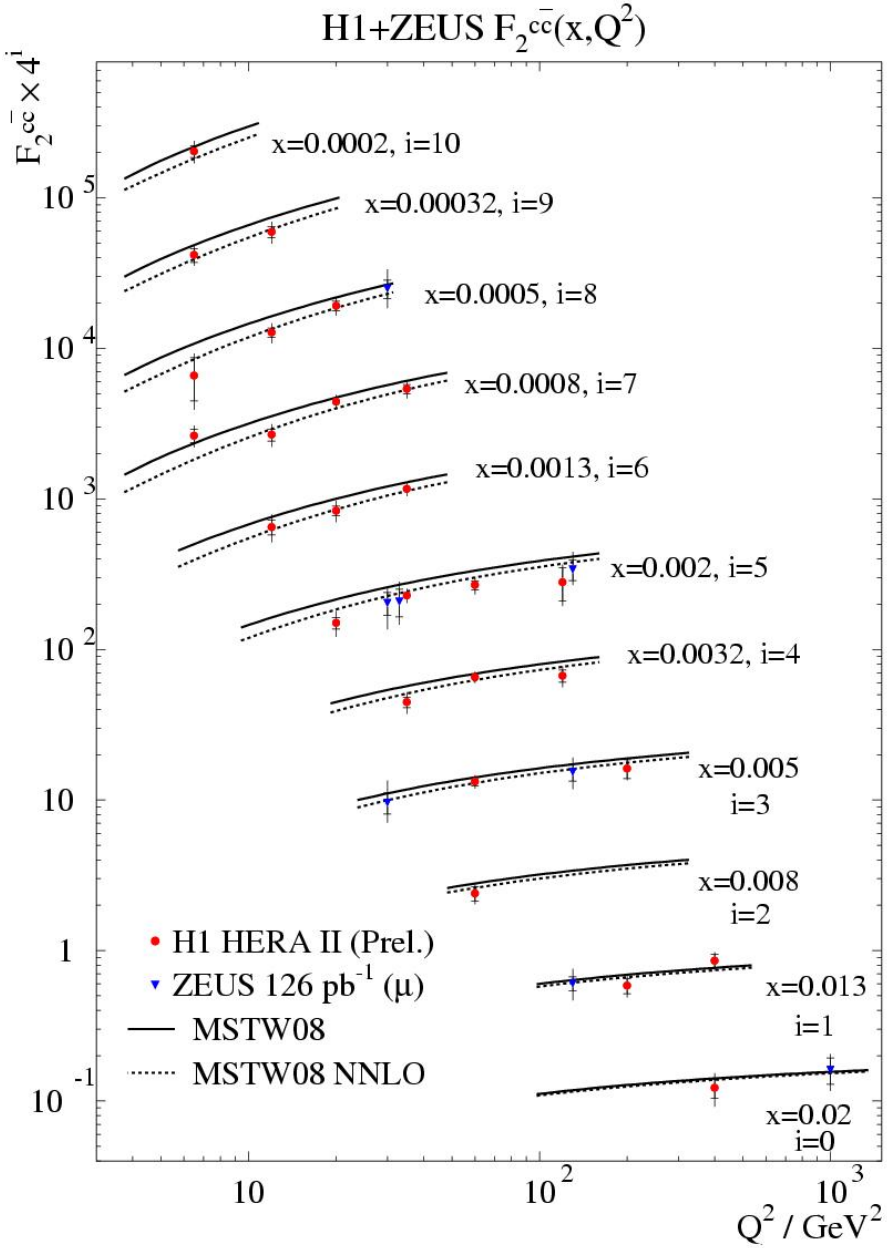
- reconstruction of a secondary vertex
- impact parameter of tracks δ

Methods are used to simultaneously tag bottom (see talk by Markus Juengst)



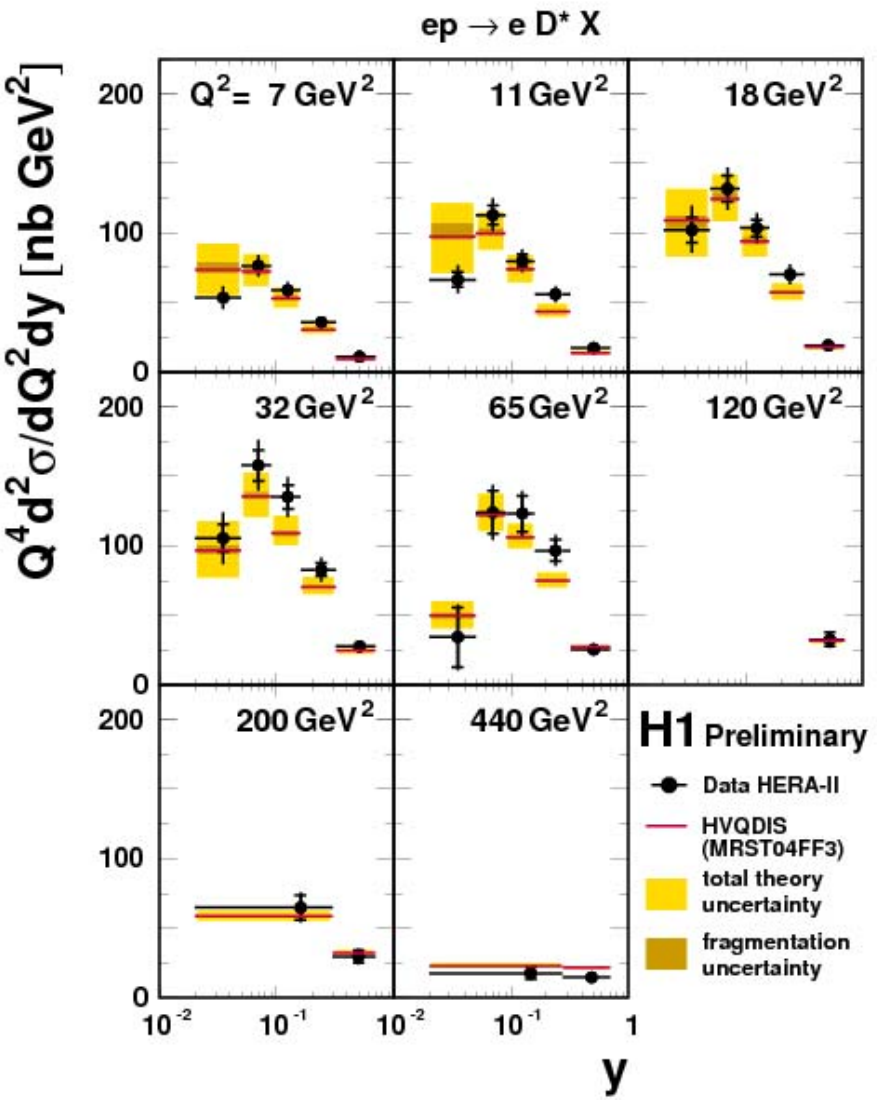


F_2^{cc} using Lifetime and μ's



- F_2^{cc} directly from lifetime tag
- Convert double differential μ cross sections to F_2^{cc}
- Different measurements using different techniques agree
- Charm measurements span large range in Q^2 and x
- Scaling violations clearly visible
- Measurements sensitive to difference between theory models

From D cross sections to F_2^{cc}



Extrapolation factors calculated from ratio of $\sigma_{vis}(Q^2,y)$ to σ_{tot}

Use either NLO FFNS (HVQDIS) or CCFM (CASCADE)

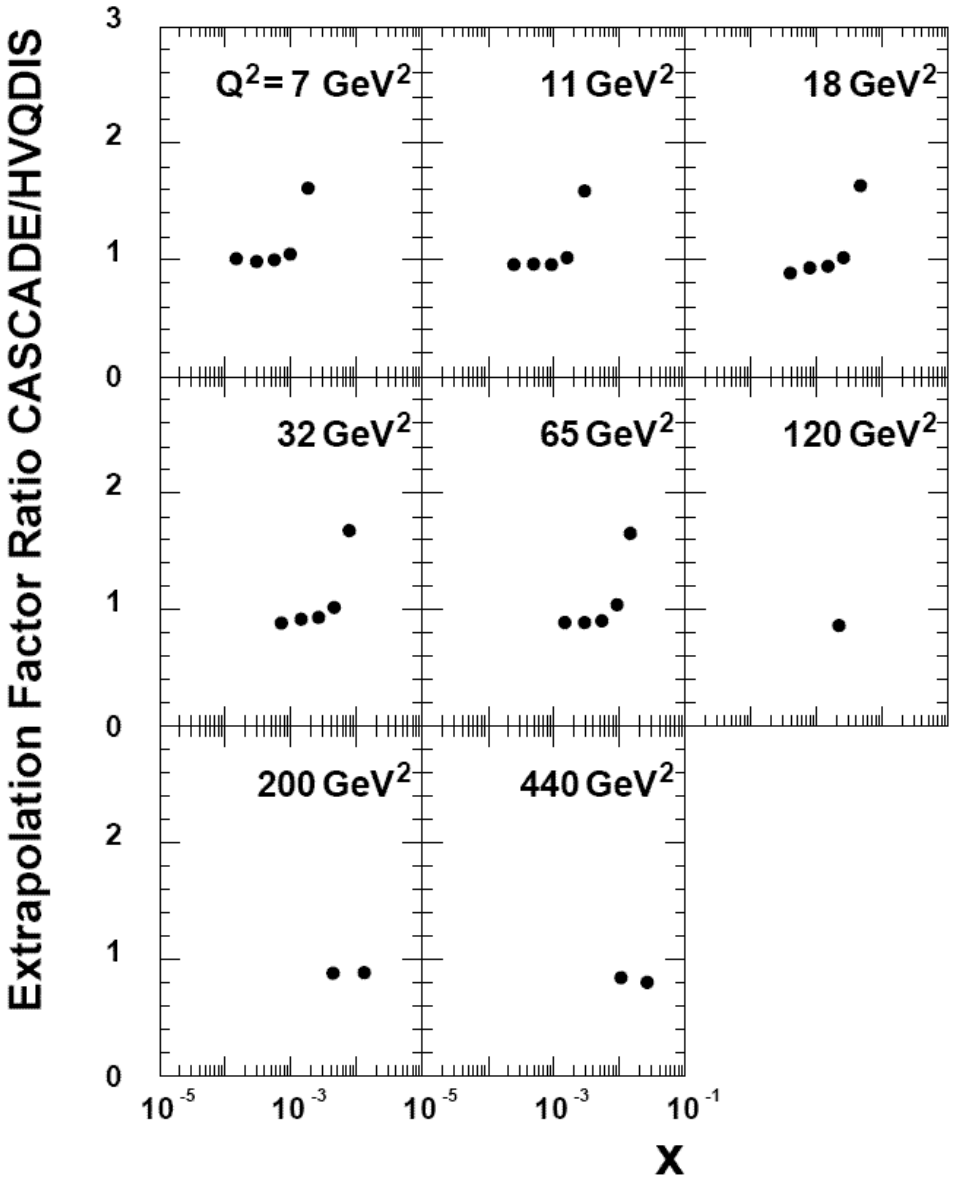
Extrapolation values in the range:

1.5 – 5

high Q^2 - low Q^2(low y/high x)

Average ~3

D* extrapolation



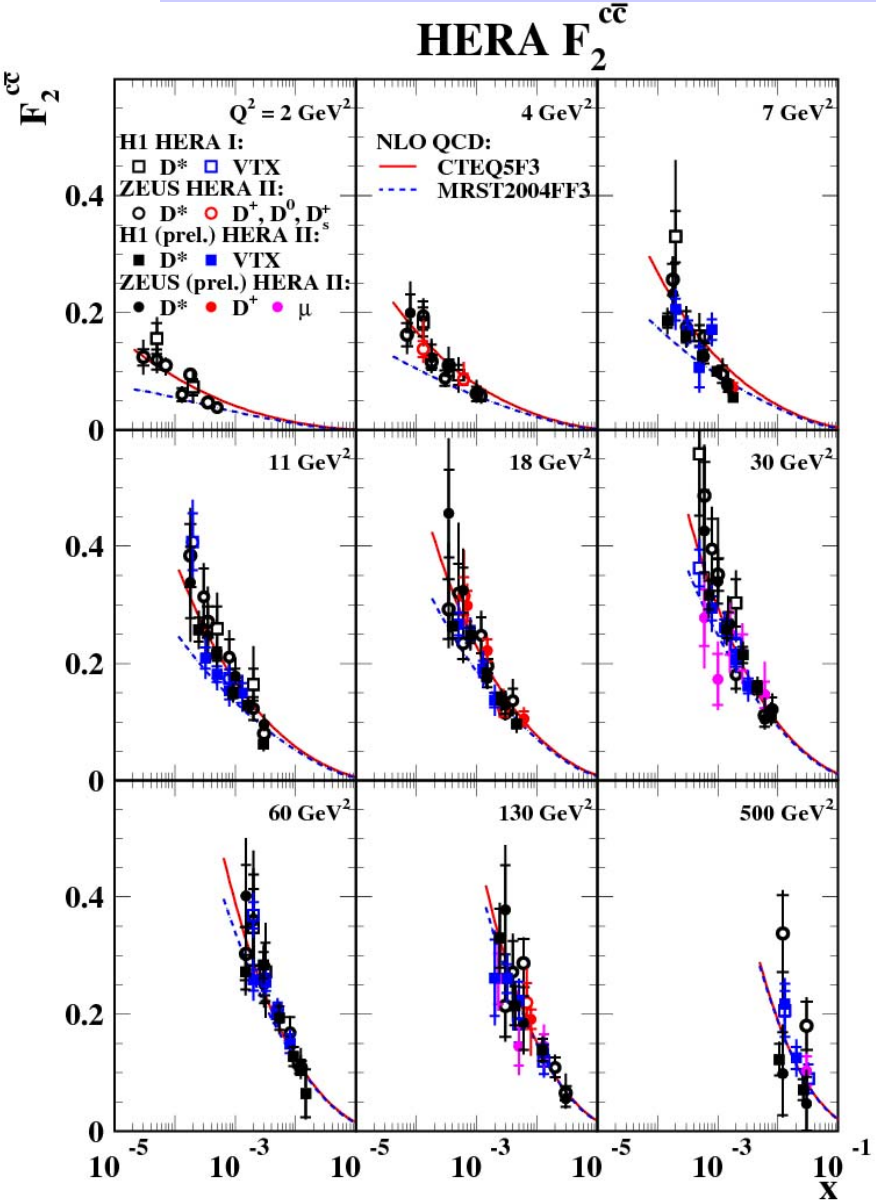
Differences in extrapolation factors HVQDIS vs CASCADE:

Generally <10% (low x) but up to 80%(high x). Due to:

- LO+PS vs NLO
- Different evolution
- Different hadronization

Highest *x* points not included in the combination procedure (see later). The difference between MC/NLO accounted for in model uncertainty

F_2^{cc} vs x



- Many measurements with different techniques
- Comparison of different methods [acceptance]

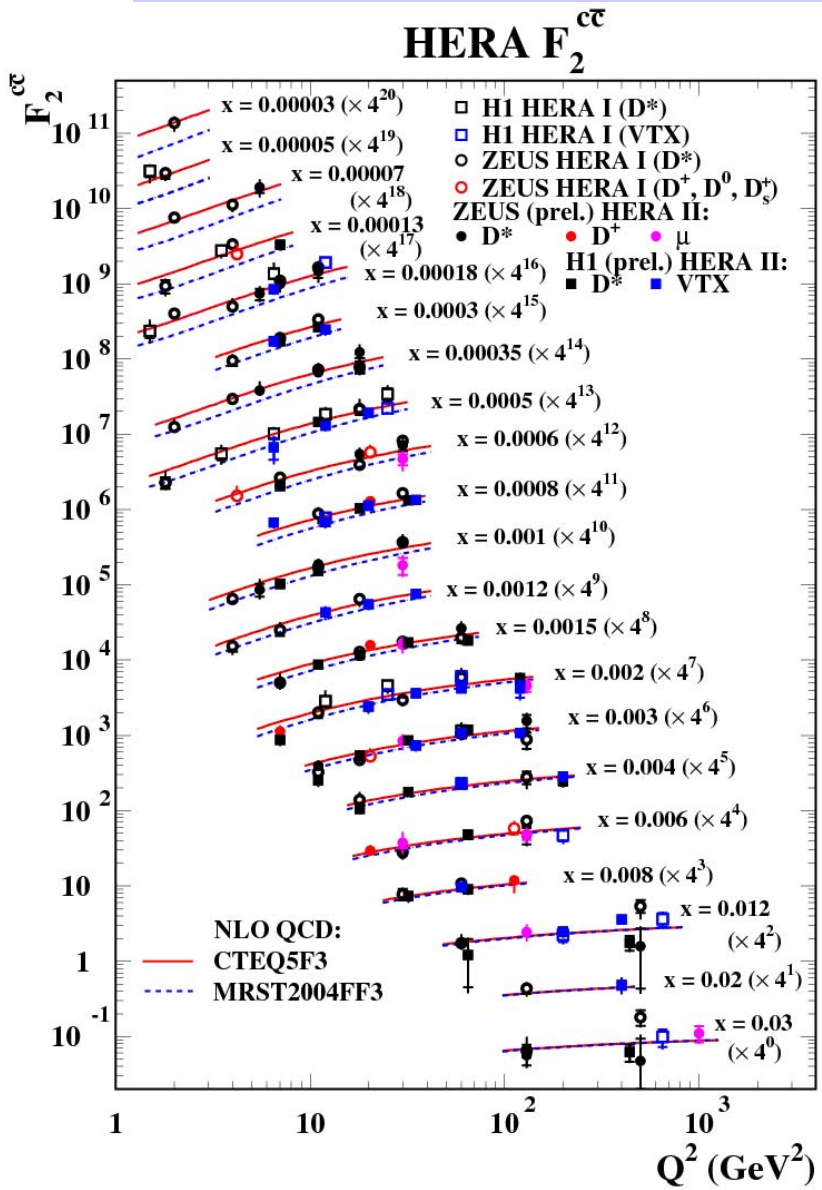
- Inclusive lifetime tagging [>70%]

- Mu $p_t^{rel}+\delta$ [25-50%]

- D* cross sections [20-70%]

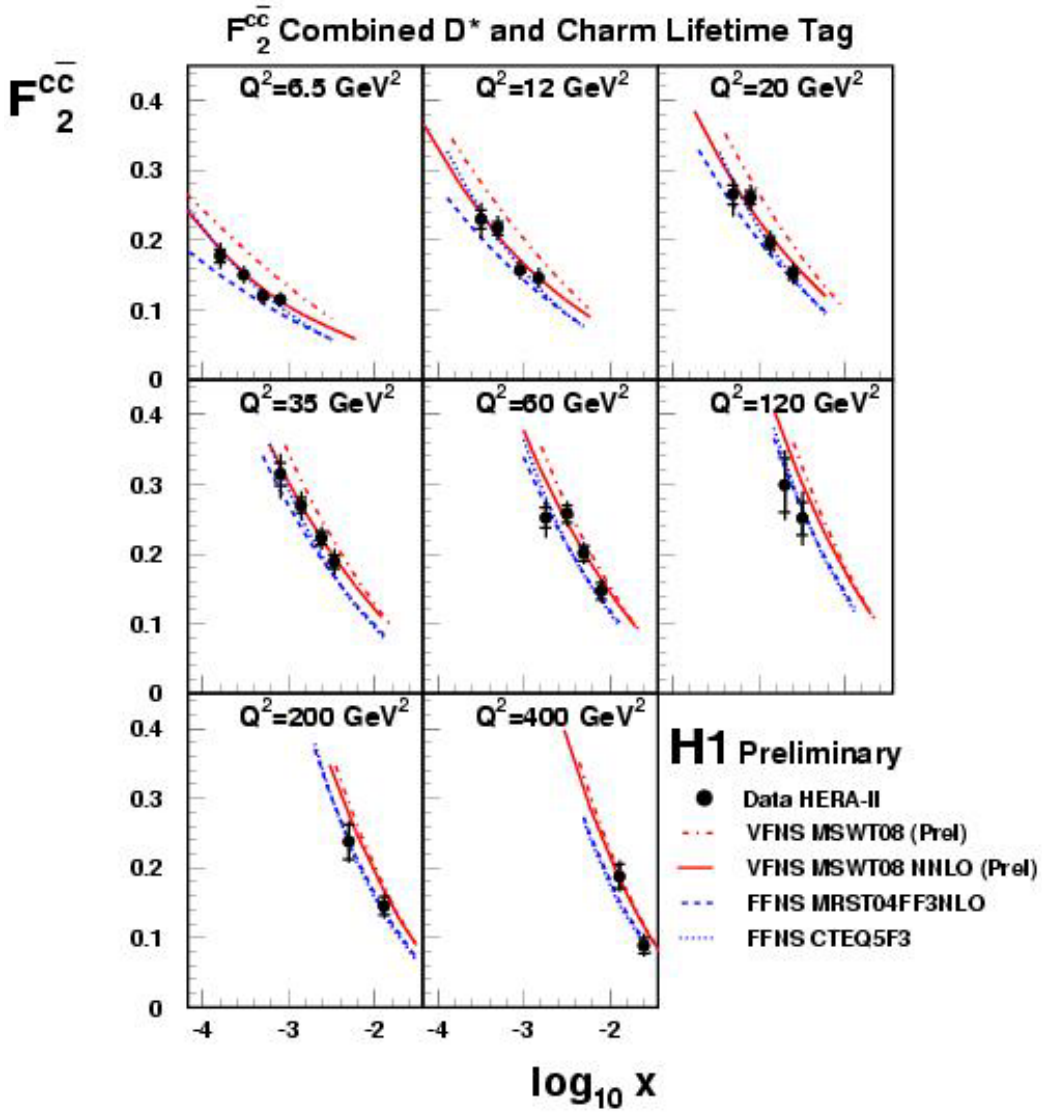
- Different methods agree well
- Reasonable description by NLO QCD in FFNS
- Combine data to improve precision…

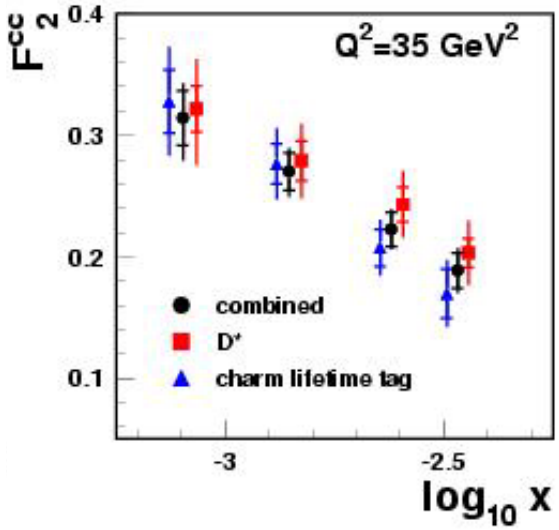
F_2^{cc} vs Q^2



- Again reasonable description by NLO QCD in FFNS
- Combine measurements with different precision, systematics, phase space
- As a *start* combine H1 preliminary results
- Combination takes into account statistical and correlated systematic errors

Combined D* and lifetime tag





- Improvements in precision of 10-50%. Best where methods have similar precision
- Measurements sensitive to the different QCD predictions.

Conclusions

- Wealth of measurements of the charm content of the proton from HERA I and HERA II data
- Final results coming with full HERA statistics
- Combination improves precision. H1+ZEUS combination being worked on
- Data are generally described by (N)NLO pQCD calculations. Improving precision suggests need for further improvement
- HERA data help to constrain PDFs and treatment of HQ mass in QCD (in time for LHC!)

Back Up

Averaging procedure

- Data in combination:

  - H1 Preliminary "lifetime" HERA-II

  - H1 Preliminary D* HERA-II. Inclusive cross section obtained from differential cross section(Q^2,y) using NLO FFNS (see next slide)

- Measurements at different x and Q^2:

  - point swimming to the common grid using FFNS NLO DGLAP (Riemersma), PDF MRST04FF, m_c=1.43 GeV

- Correlation of experimental uncertainties taken into account

  - 20 sources of point-to-point systematic correlations

  - 3 correlated sources between the methods

Averaging procedure: definition

$$\chi^2(M^{i,true}, \Delta\alpha_j) = \sum \frac{\left[M^{i,true} - \left(M^i + \sum_j \frac{\partial M^i}{\partial \alpha_j} \frac{M^{i,true}}{M_i} \Delta\alpha_j \right) \right]^2}{\left(\sigma_i \frac{M^{i,true}}{M_i} \right)^2} + \sum_j \frac{(\Delta\alpha_j)^2}{\sigma^2_{\alpha_j}}$$

Detailed in H1 paper arXiv:0904.0929

M^i measured central values

σ_i statistical + uncorrelated systematic error

$\sigma_{\alpha j}$ – correlated systematic error

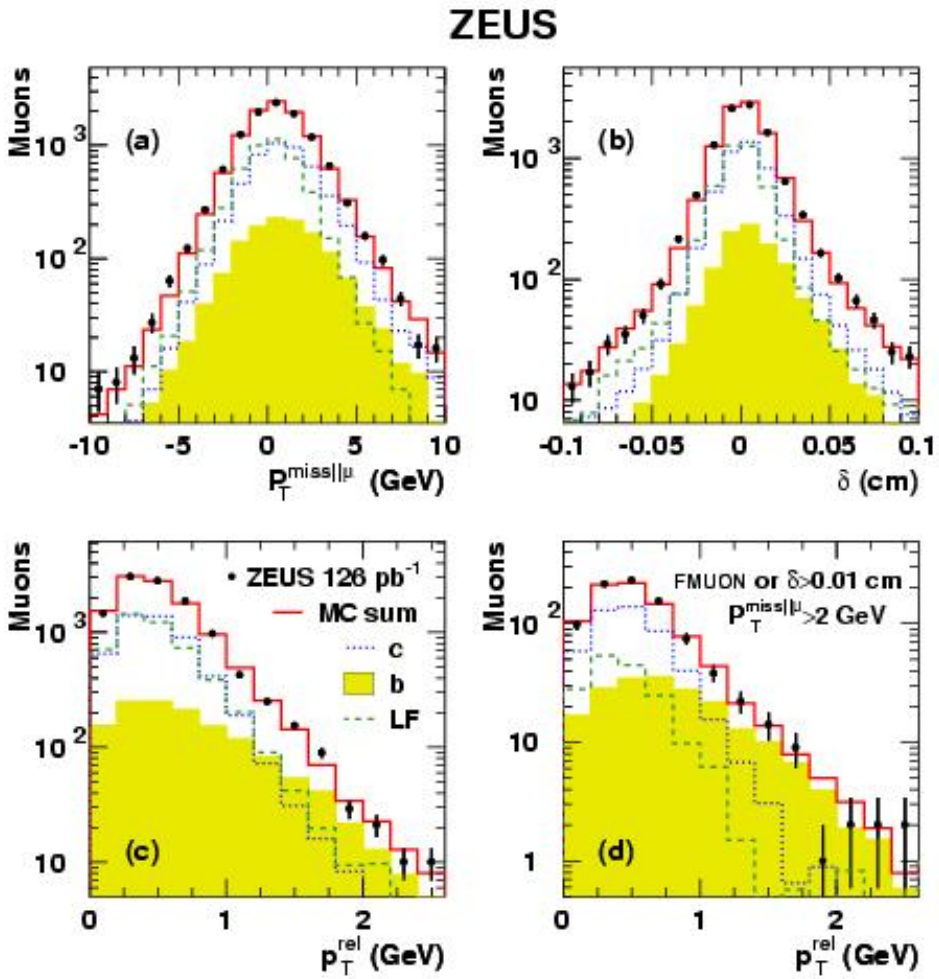
$dM^i/d\alpha_j$ – sensitivity of data *i* to systematic uncertainty *j*

$M^{i,true}$ - fitted combined data D* + lifetime

$\Delta\alpha_j$ – fitted shifts of correlated uncertainties

Charm and Beauty Cross Section

- combine $p_T^{miss||\mu}$, p_T^{rel} and impact parameter distributions
- use 3D fit to decompose into beauty, charm and light flavour



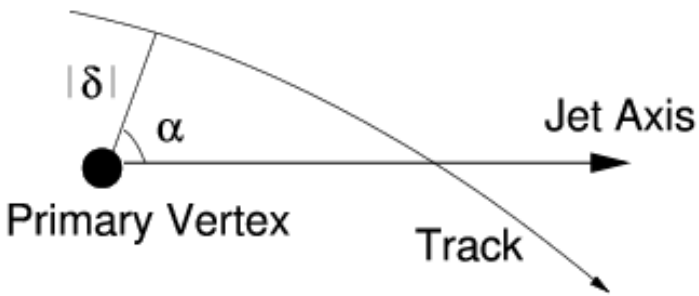
For beauty results see talk by Markus Juengst

Inclusive Analysis (lifetime)

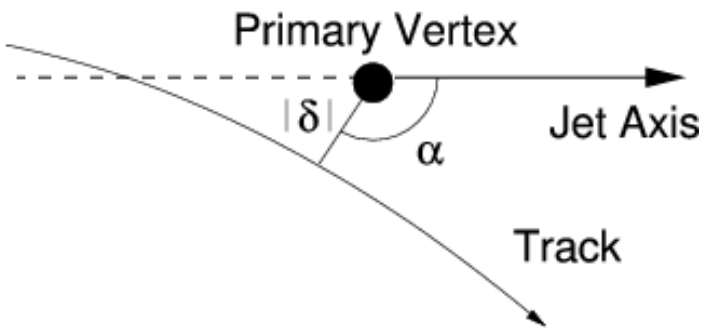
- Inclusive analysis: use all tracks with hits in silicon detector ($p_t > 0.3$ GeV)
- H1 CST rebuilt to account for HERA II beamline
- Precise determination of impact parameter in transverse plane

Signed impact parameter δ

$\alpha < 90^o \rightarrow \delta = +|\delta|$



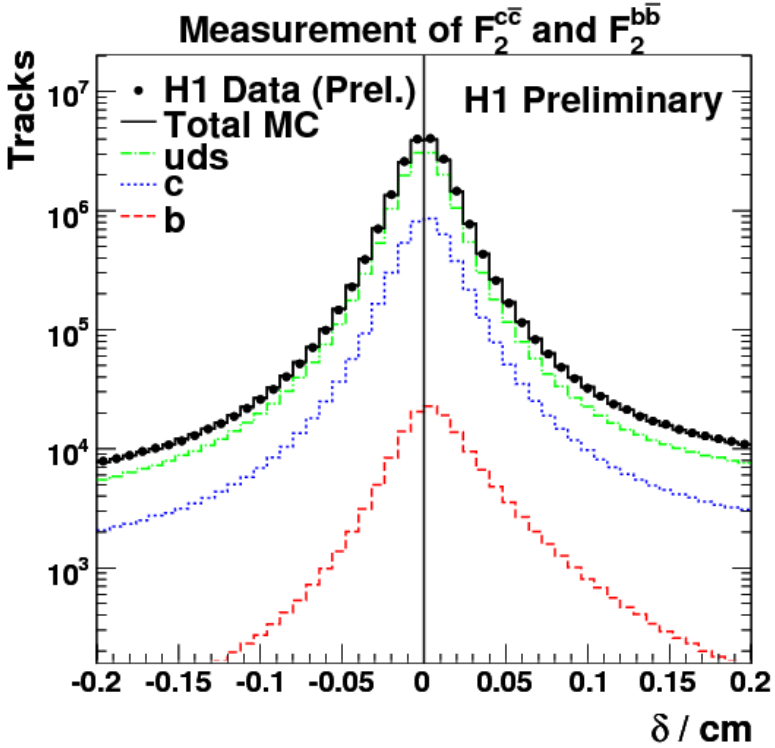
$\alpha > 90^o \rightarrow \delta = -|\delta|$



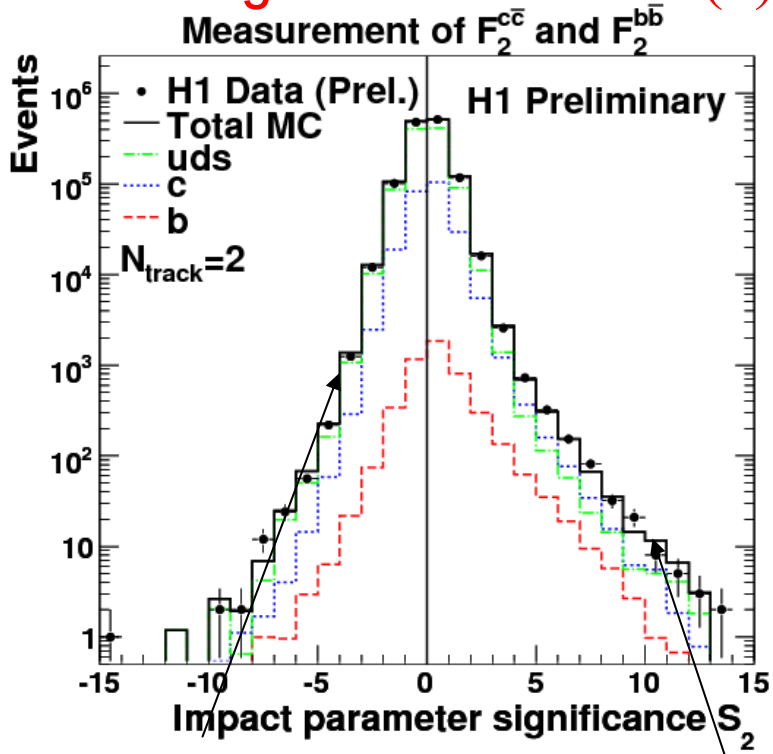
Inclusive lifetime tagging

Use all tracks with vertex hits

Signed Impact parameter δ



Significance = $\delta/\sigma(\delta)$



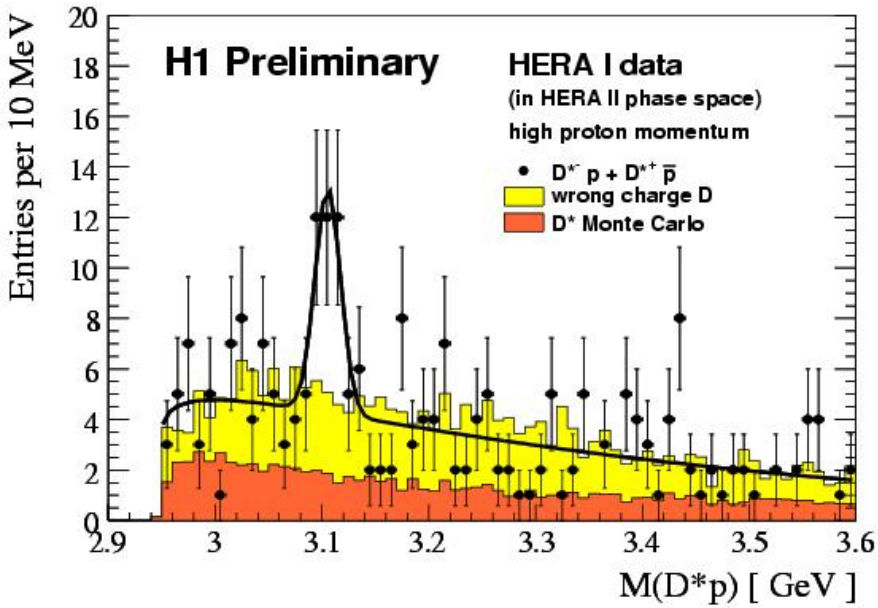
Charm and beauty asymmetric due to lifetime

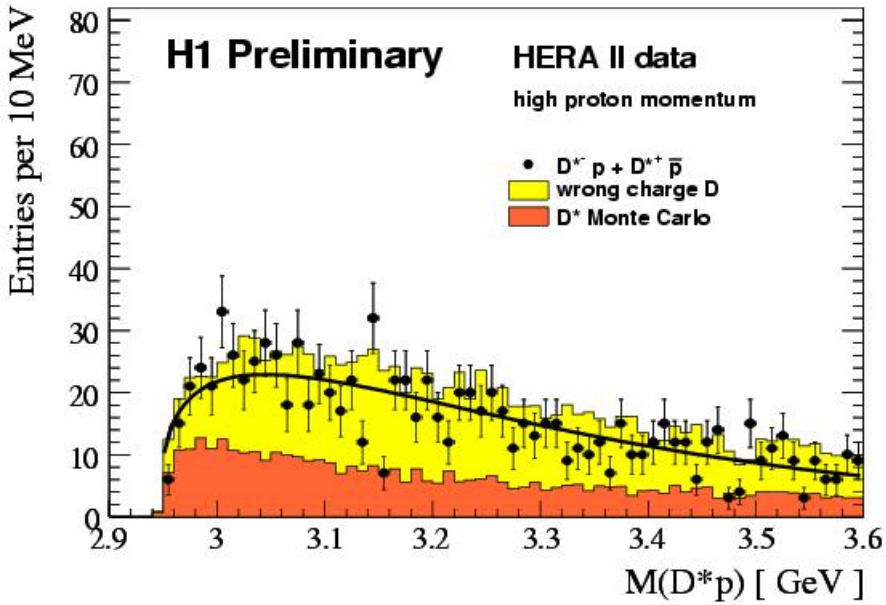
Light flavours mostly symmetric

resolution

lifetime

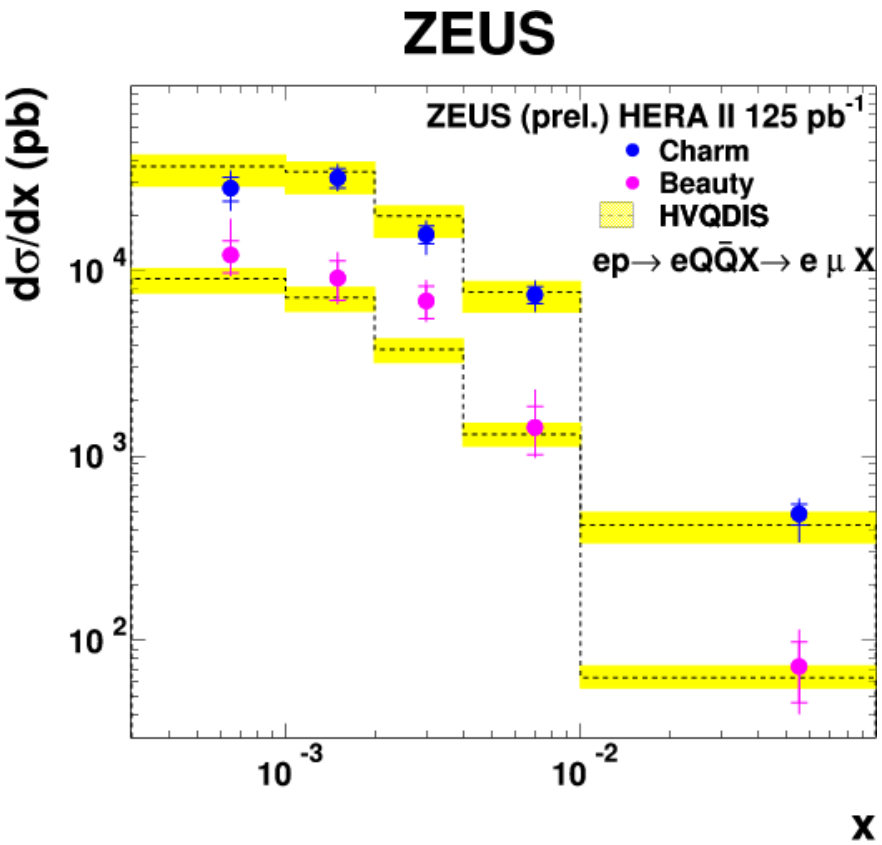
Search for a D*p resonance

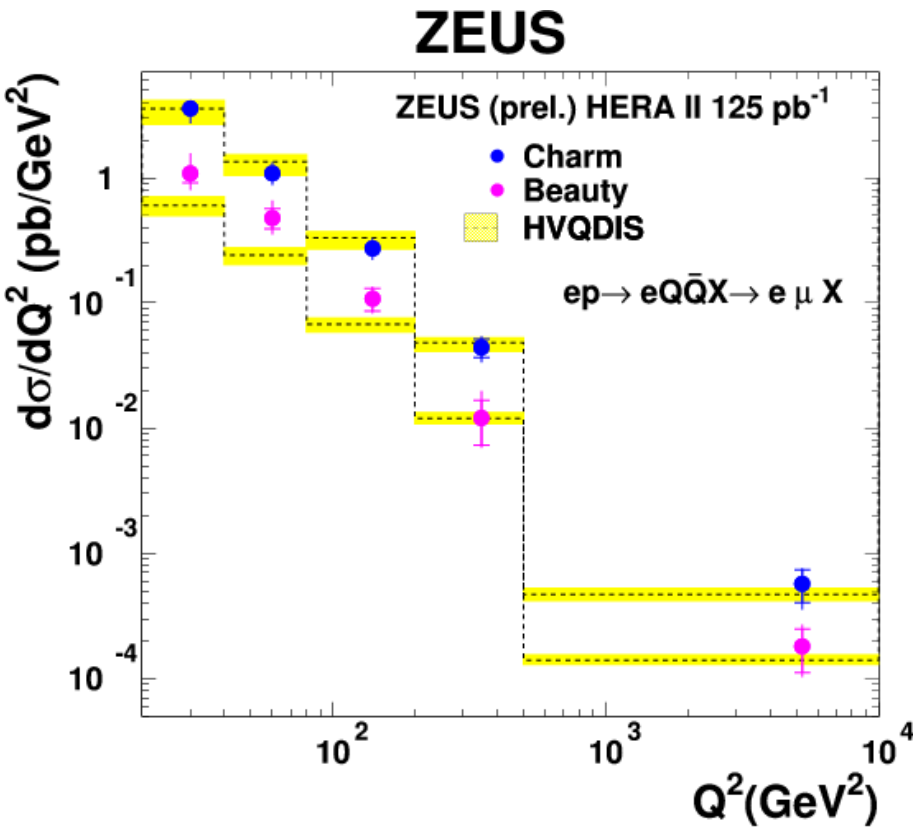




- Hint of excess of events seen in HERA I data around 3.1 GeV
- No evidence of peak seen in HERA II data (4 statistics)

Charm and Beauty Cross Section





- beauty tends to be above NLO QCD at low Q^2
- may be measured double differentially in x, Q^2 and extrapolated to full phase space to compare F_2^{cc}, F_2^{bb}

Scale Uncertainty (c)