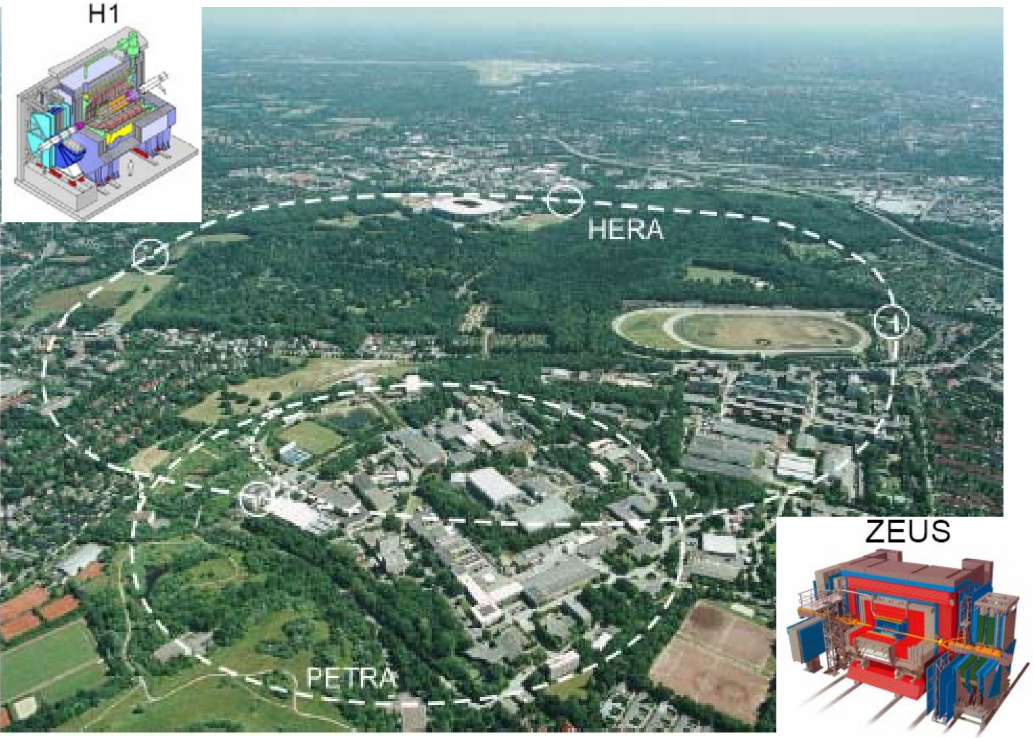
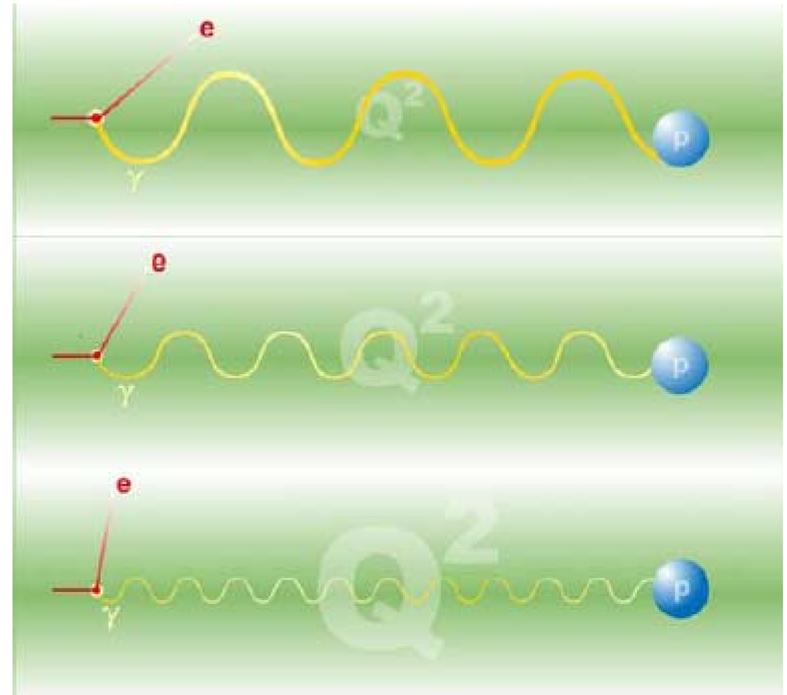
Heavy Flavour Content of the Proton

Paul Thompson, Birmingham Seminar, 8th October 2008

- Reminder of HERA and kinematics
- Why measure proton structure (PDFs)?
- Why measure heavy flavours?
- Experimental Techniques
- charm and beauty cross sections at HERA
- Outlook

HERA ep collider



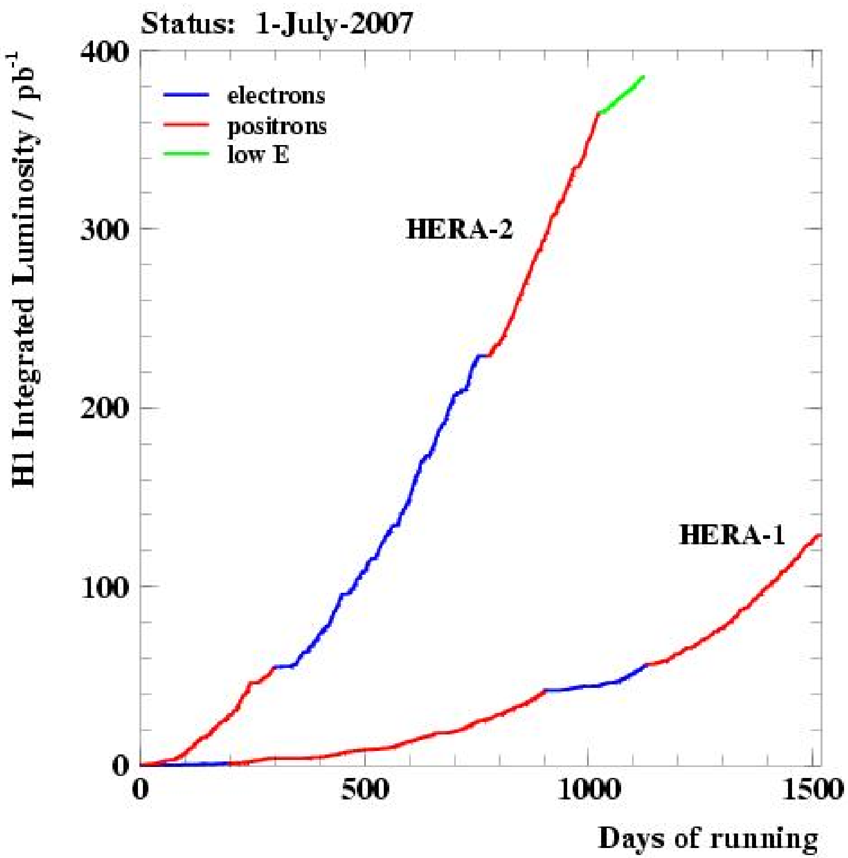


- Collided protons with $e^{\pm}$ 92-07
- E_e : 27.5 GeV
- E_p : 920 GeV
- Centre of mass energy : $\sqrt{s} = 320\ GeV$

- Q^2 corresponds to the spatial resolution of probe
- $\lambda \sim 1/\sqrt{Q^2} \qquad Q^2_{\max} \sim 10^5\ GeV^2$
- $\lambda_{\min} \sim 10^{-18} m \sim R_{proton}/1000$

Deep Inelastic Scattering - DIS

Available Data



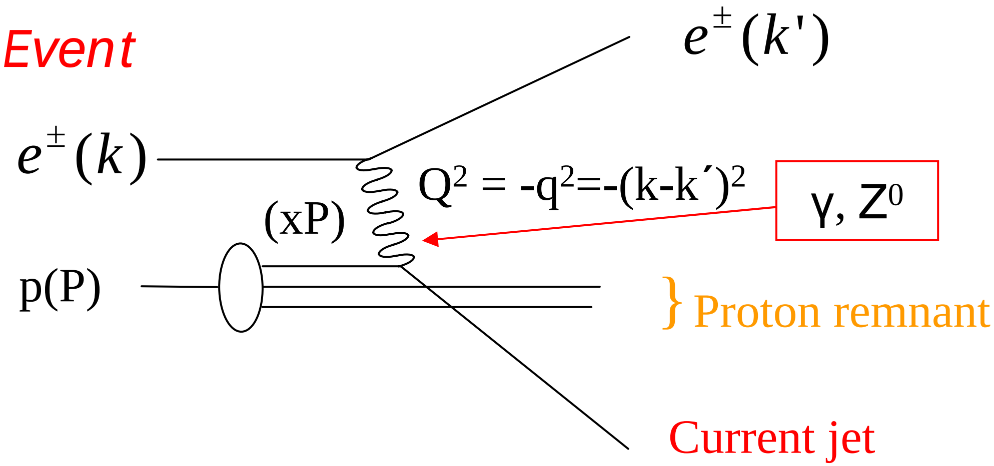
- In total ~500pb^{-1} of high energy data collected per experiment
- luminosity upgrade in 2001
- detectors adjusted to accommodate focussing magnets
- Low energy running to measure F_L

Many preliminary analyses on full HERA II data

Working on final publication and combination of results

Deep Inelastic Scattering (DIS)

Neutral Current Event



- DIS cross section can be described in terms of:
  - Q^2 : Virtuality of the intermediate boson

$$Q^2 = s\,x\,y$$

  - x : Bjorken scaling factor

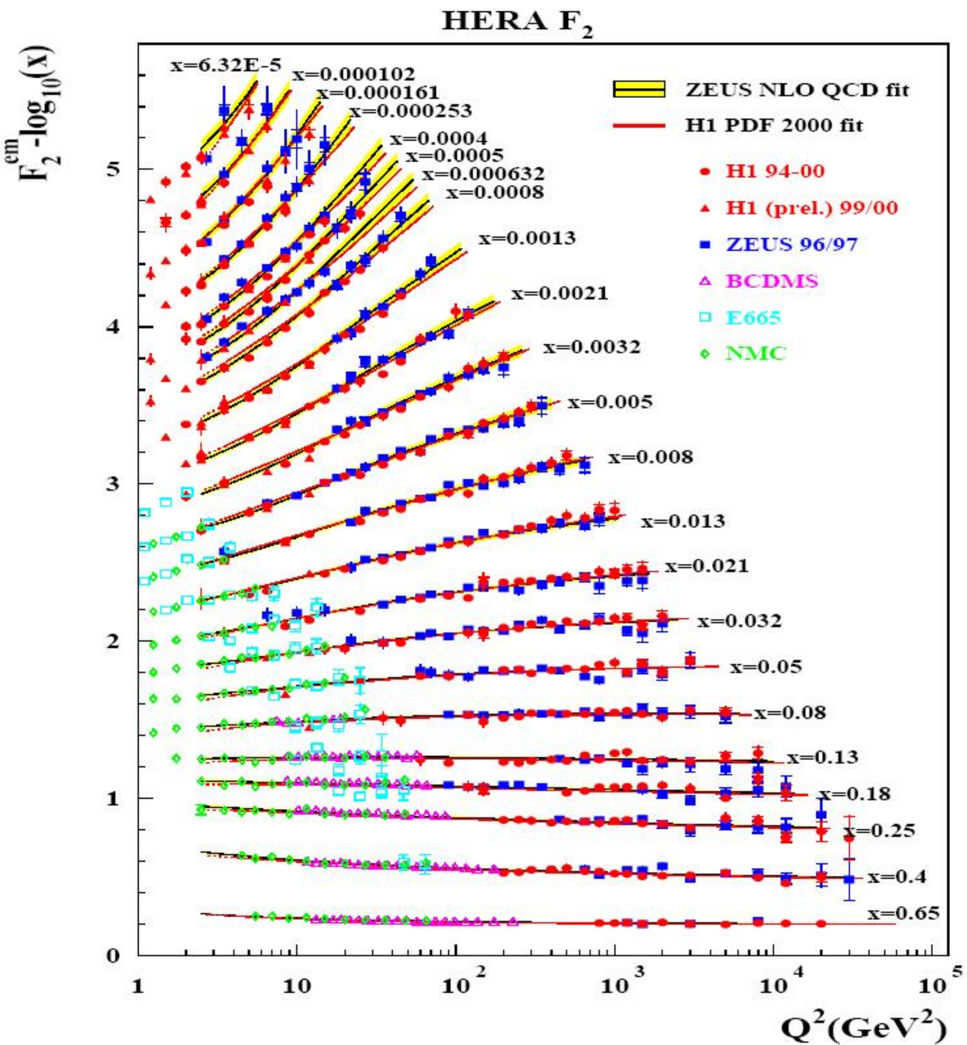
  -fraction of proton's momentum carried by struck quark

  - y : Inelasticity

  -energy fraction transferred from lepton in proton rest frame

Neutral Current Cross Section F_2

$$\frac{d^2\sigma(e^{\pm}p)}{dxdQ^2} = \frac{2\pi a^2}{xQ^4} Y_+[F_2(x,Q^2) - \frac{y^2}{Y_+} F_L(x,Q^2) \pm xF_3(x,Q^2)]$$



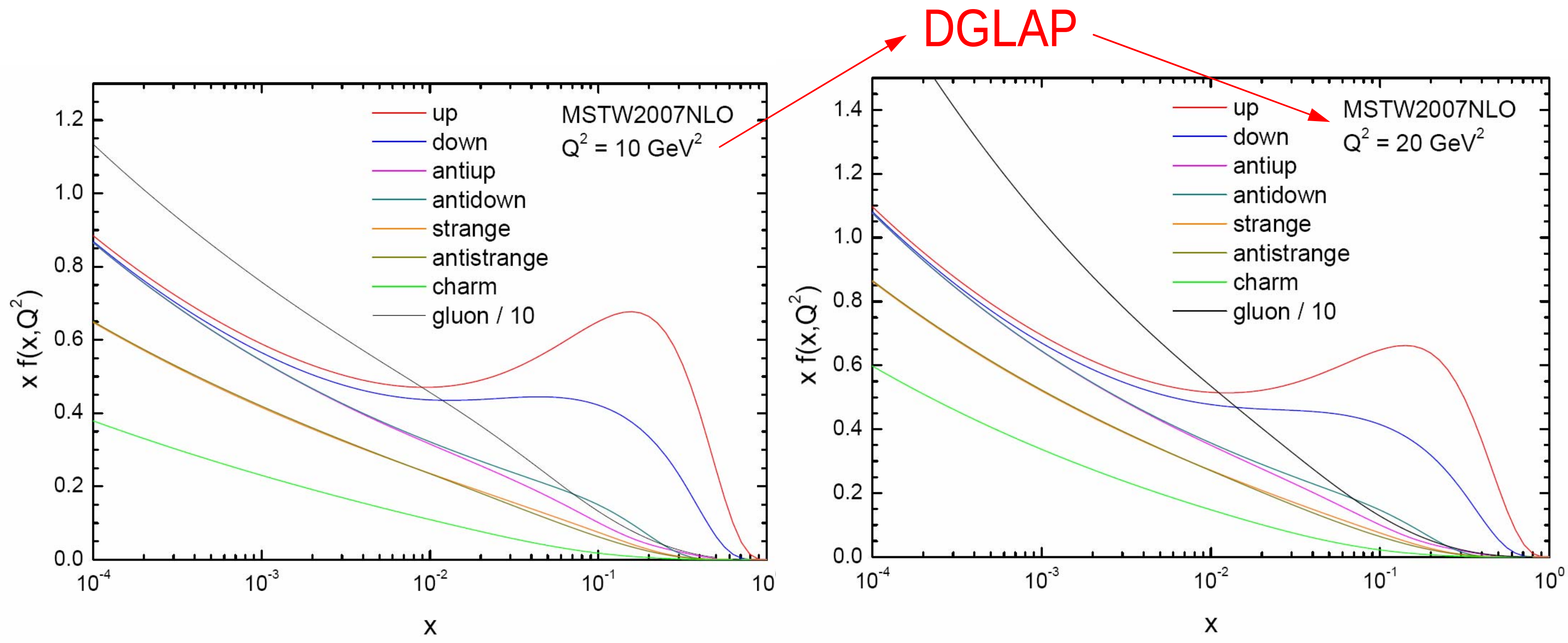
F_2 – dominant contribution to the cross section

$$F_2 = \sum_q e_q^2 x\,(\mathrm{q} + \overline{\mathrm{q}})$$

Scaling violations indicate presence of gluons

Data evolution with Q^2 (at fixed *x*) described by perturbative QCD

QCD Factorisation and Proton PDF

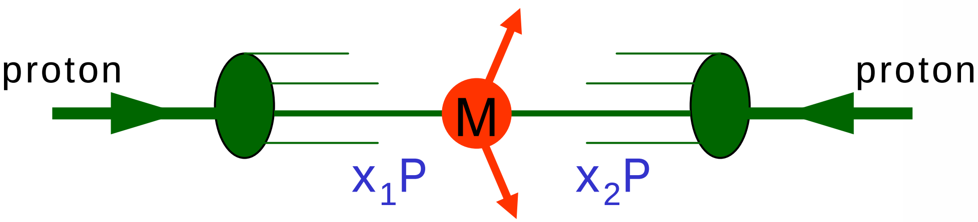


$$F_2(x,Q^2) \;=\; \sum_k f_k(\mu) \otimes C_k^j(Q,m,\alpha_s(\mu))$$

f_k are parton density functions – parameterised at Q_0^2 and evolved to high Q^2 using DGLAP equations

C_k^j perturbative coefficient functions

PDFs for the LHC

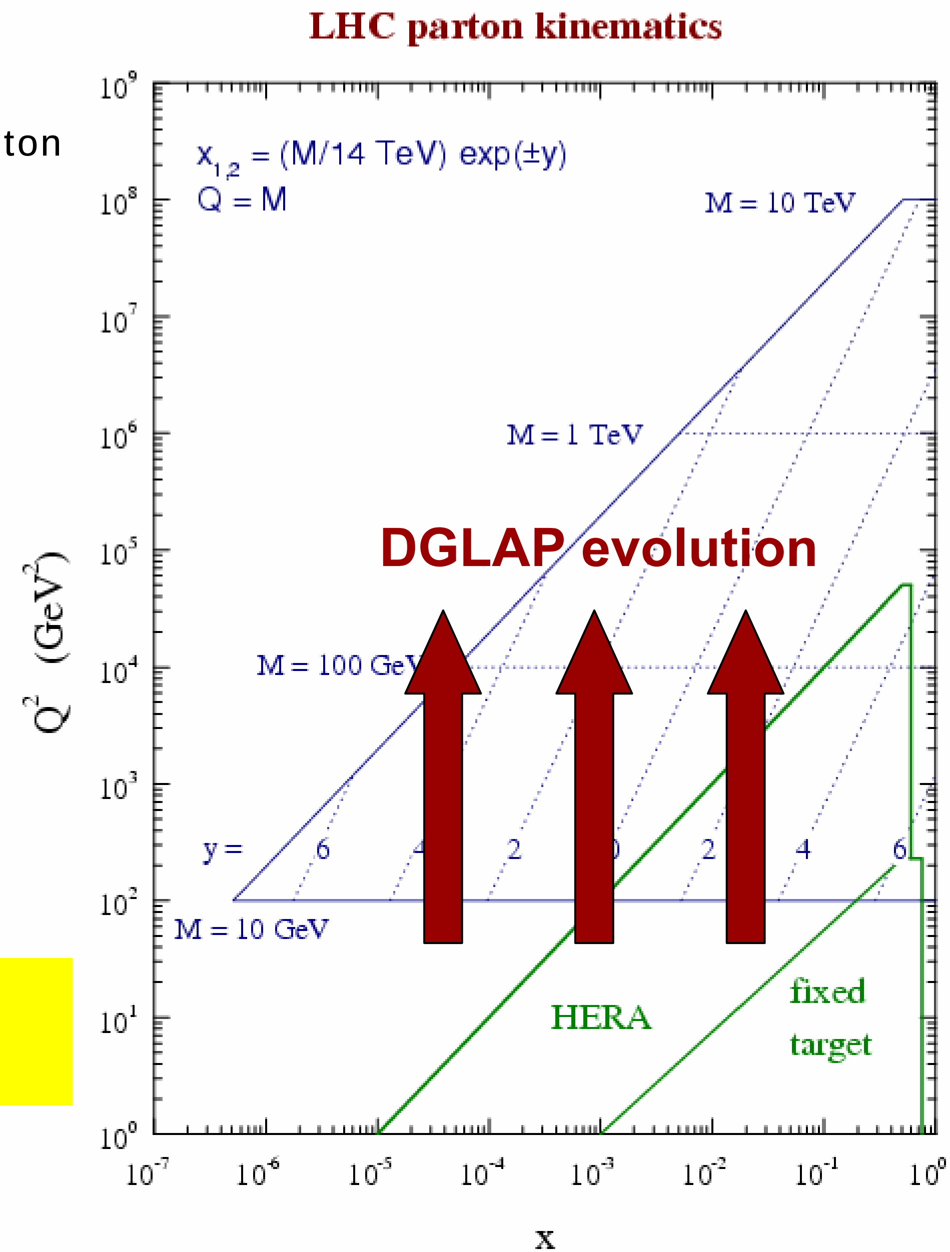


momentum fractions x_1 and x_2 determined by mass and rapidity of **X**

x dependence of $f(x,Q^2)$ determined by fit to data, Q^2 dependence determined by **DGLAP** equations

full NNLO DGLAP now known*, also with small x, QED etc improvements

*Moch, Vermaseren, Vogt (2004)



Why do we need PDFs?

- high precision (SM and BSM) cross section predictions require precision pdfs: $\delta\sigma_{th} = \delta\sigma_{pdf} + \ldots$
- improved signal and background predictions → easier to spot new physics deviations
- 'standard candle' processes (e.g. $\sigma(Z)$) to
  - check formalism (factorisation, DGLAP, …)
  - measure machine luminosity?
- learning more about pdfs from LHC measurements. e.g.
  - high-E_T jets → gluon?
  - W^+, W^-, Z^0 → quarks?
  - forward DY → small x?
  - …

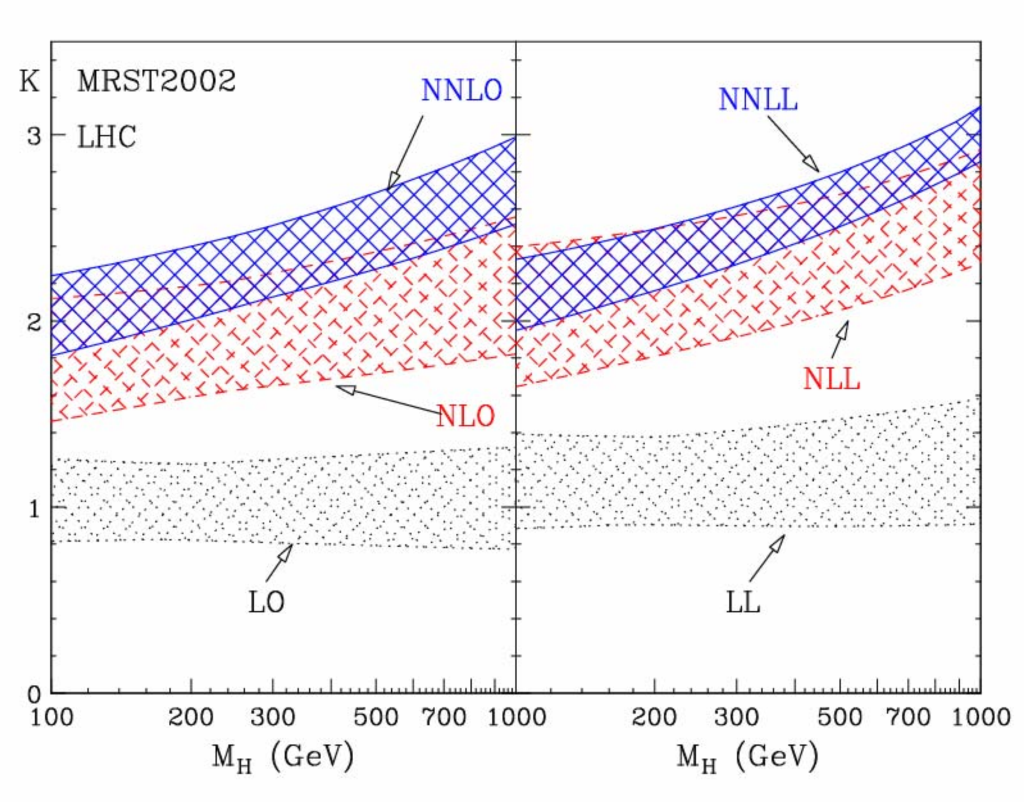
How Important Is PDF Precision?

- Example 1: $\sigma(M_H$=120 GeV) @ LHC

  $\delta\sigma_{pdf} \approx \pm 3\%$, $\delta\sigma_{ptNNL0} \approx \pm 10\%$

  $\delta\sigma_{ptNNLL} \approx \pm 8\%$

$\rightarrow \delta\sigma_{theory} \approx \pm 9\%$



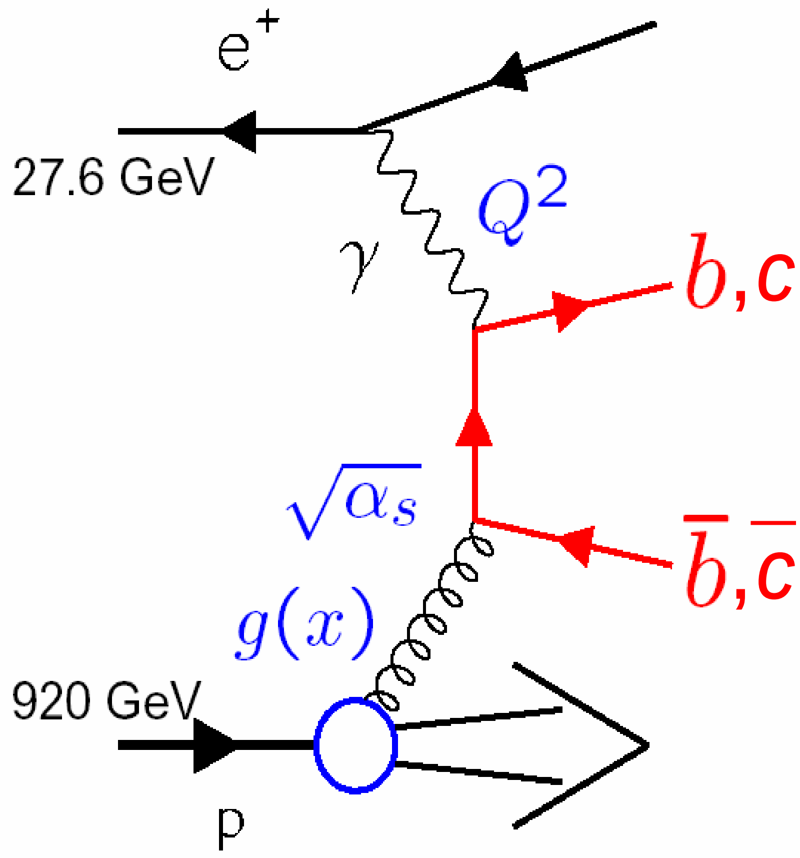
- Example 2: $\sigma(Z^0)$ @ LHC

  $\delta\sigma_{pdf} \approx \pm 3\%$, $\delta\sigma_{ptNNL0} \approx \pm 2\%$

$\rightarrow \delta\sigma_{theory} \approx \pm 4\%$

Catani et al,
hep-ph/0306211

Production of Heavy Quarks at HERA



Predominantly via boson gluon fusion

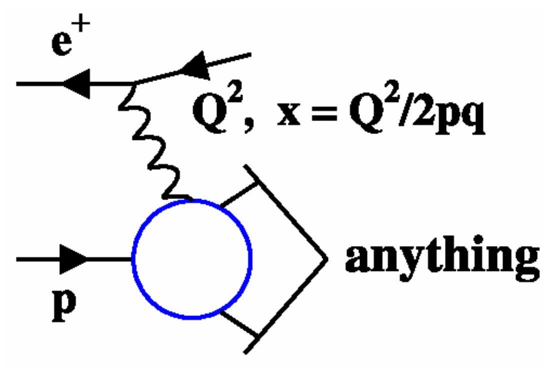
Test of perturbative QCD:

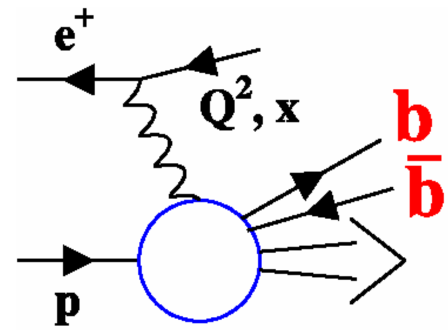
multi-scale problem (Q^2, m_b^2, p_t^2)

Directly sensitive to gluon density in the proton (PDFs)

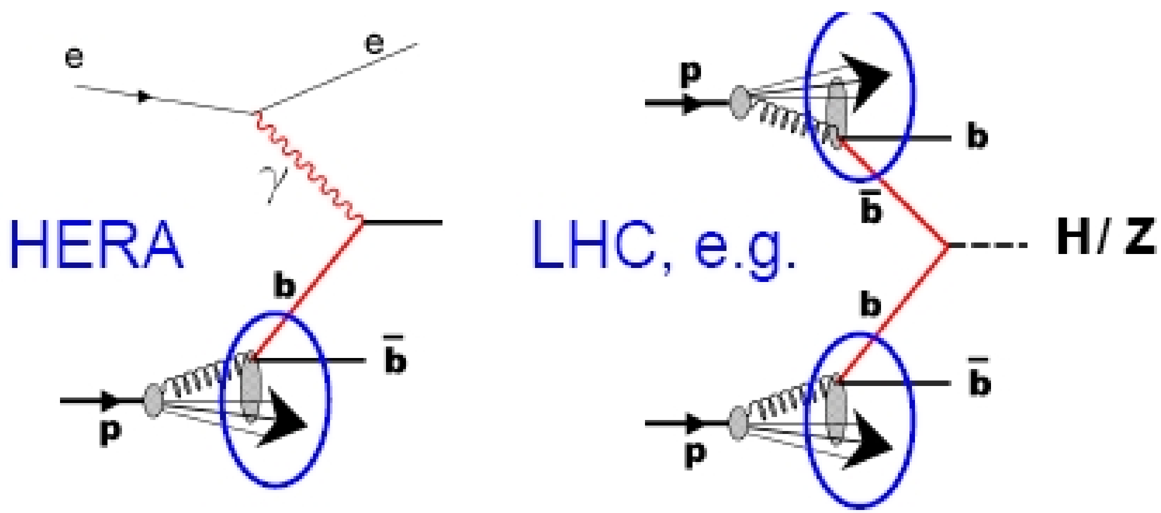
F_2^{cc} and F_2^{bb}

At HERA we can measure the contribution of c and b to the total DIS cross section F_2^{bb} and F_2^{cc}





F_2^{bb} measurements at high Q^2 important for LHC e.g. bb->H



Predictions for Heavy Quark Production

Massive scheme: $\rightarrow m_b$

- **b massive**
- **neglects** $[\alpha_s \ln(Q^2/m_b^2)]^n$

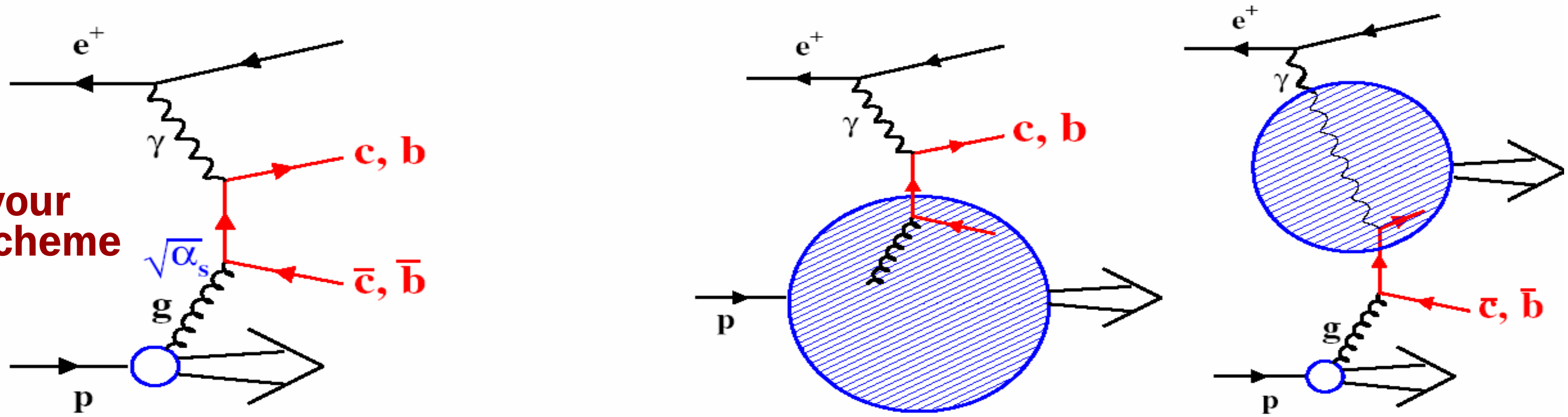
$\rightarrow$ **Perturbative production:**

Massless scheme: $\rightarrow p_T, Q^2$

- **b massless!!!**
- **Resums** $[\alpha_s \ln(Q^2/m_b^2)]^n$

$\rightarrow$ **b also in Proton and Photon!**

Fixed Flavour Number Scheme (FFNS)



Variable schemes (VFNS):

$\rightarrow$ **at small Q^2 massive, at large Q^2 massless**

General Mass VFNS (GM VFNS)

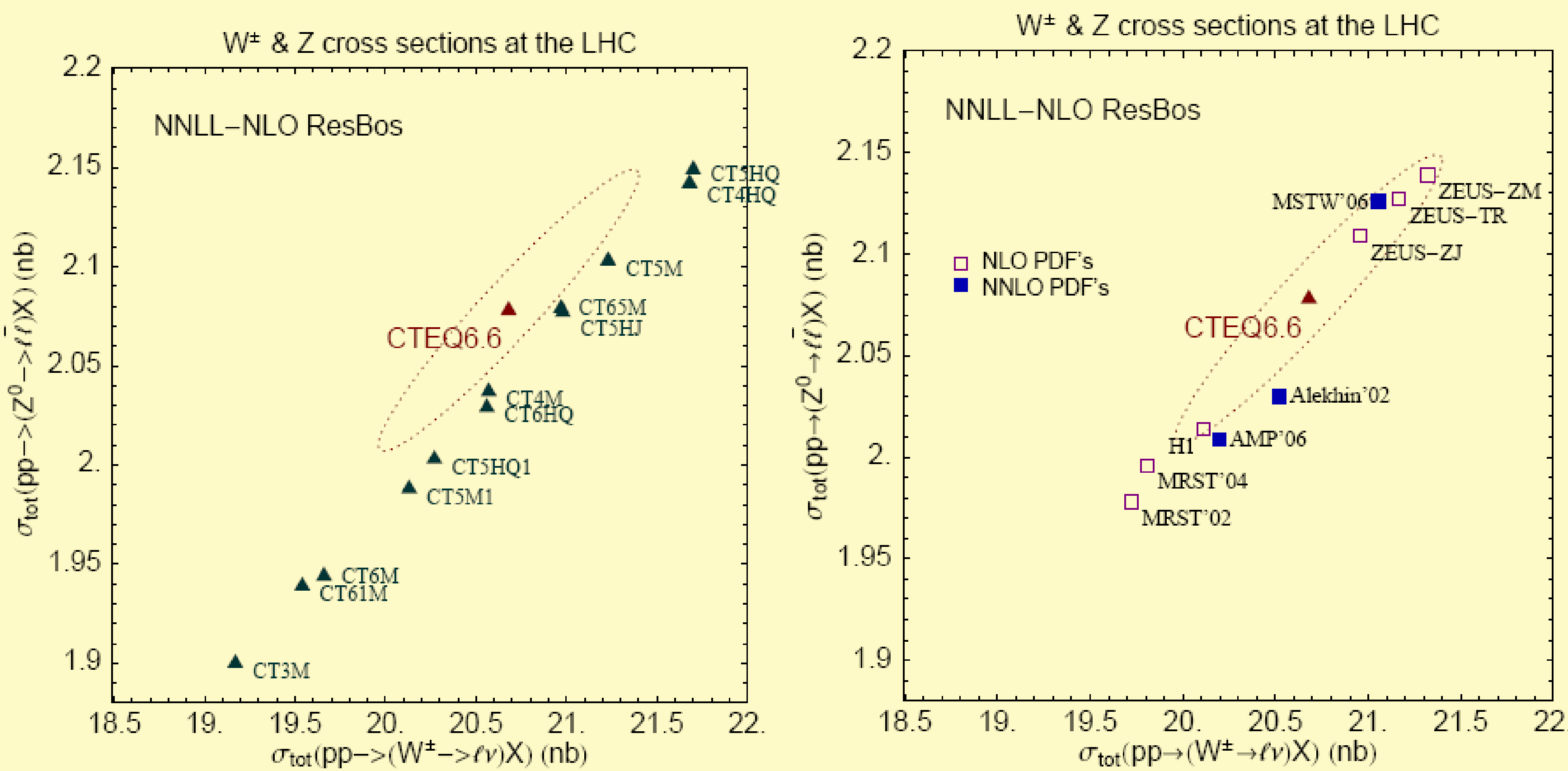
Zero Mass Variable Number Scheme (ZM VFNS)

CTEQ6.5 uses a *General Mass* scheme changed from a *massless* in CTEQ6.1

MRSTW improved their *General Mass* scheme from MRST2004 to MSTW2006

Thorne, Tung arXiv:0809.0714, P.T. hep-ph/0703103

Impact on W, Z @ LHC

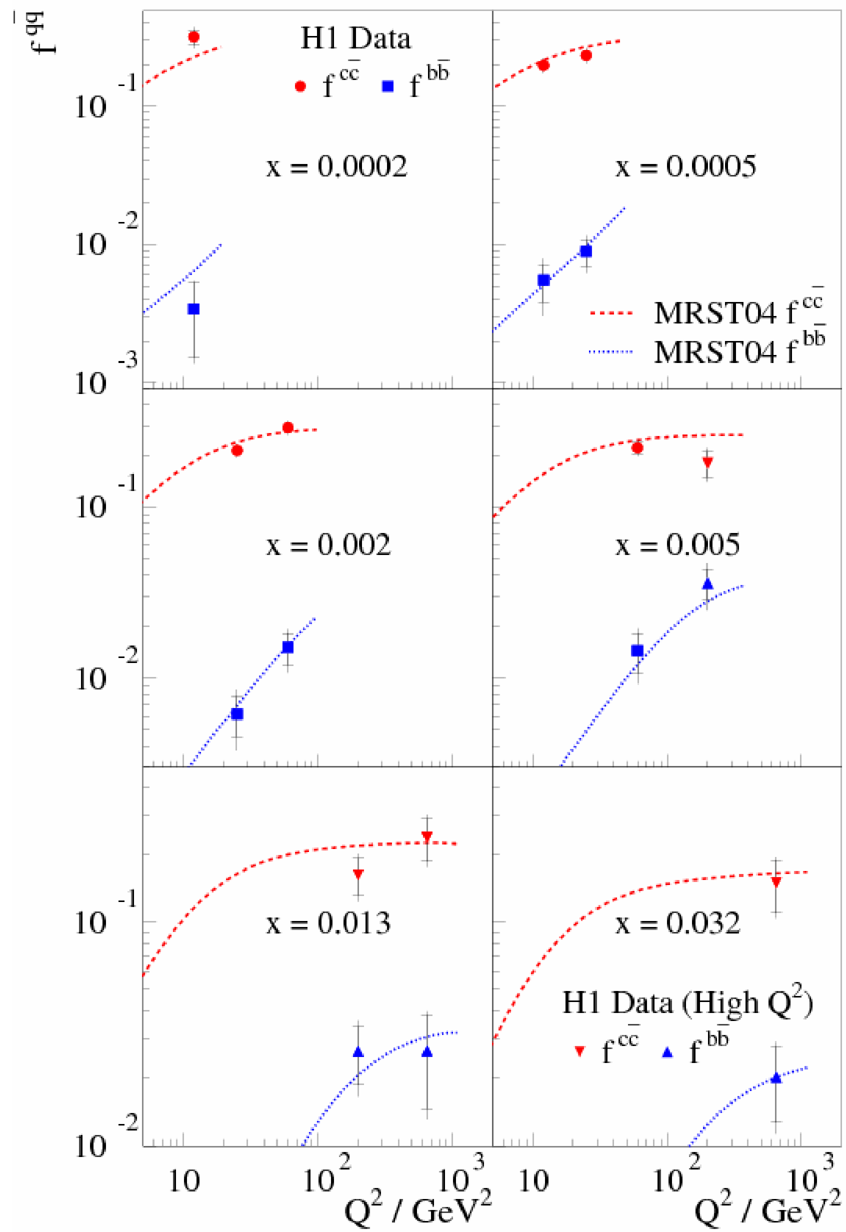


- Correct heavy flavour treatment affects light partons!
- changes in CTEQ 6.1 -> CTEQ 6.6 due to *c,b,s* treatment
- Improved agreement between latest PDFs

Heavy Quark contribution to DIS cross section

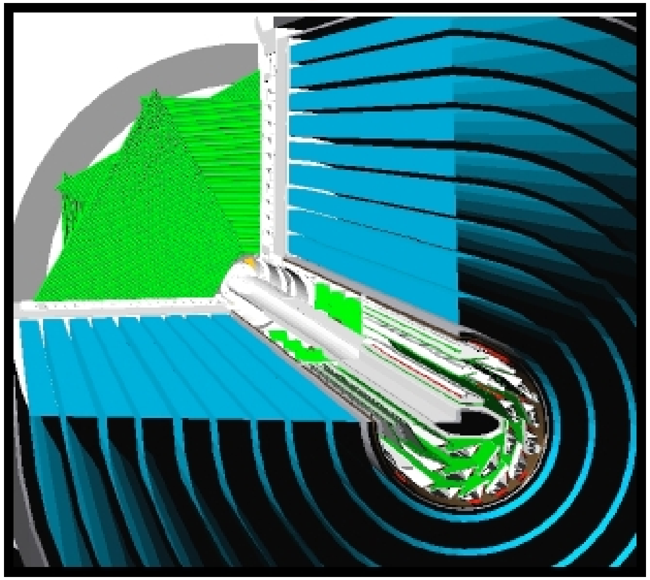
HERA I result:

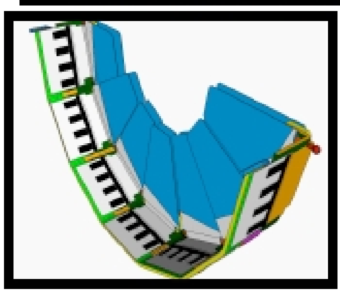
- fraction of total DIS cross section from charm and beauty
- large charm fraction(~30%)
- small beauty fraction ~% (lower at low Q^2)
- mass thresholds visible
- reasonable description by pQCD



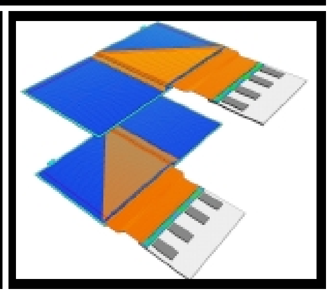
Flavour Tagging - Vertex Detectors

ZEUS tracking (MVD)





Half Wheel



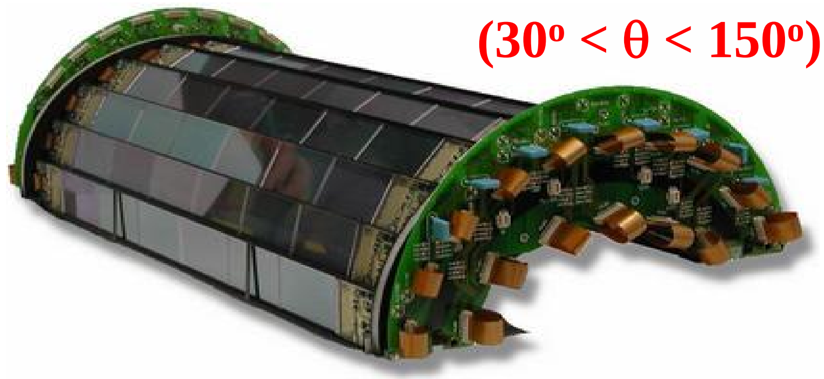
Barrel module

Installed for HERA II

H1

CentralSiliconTracker

($30^o < \theta < 150^o$)

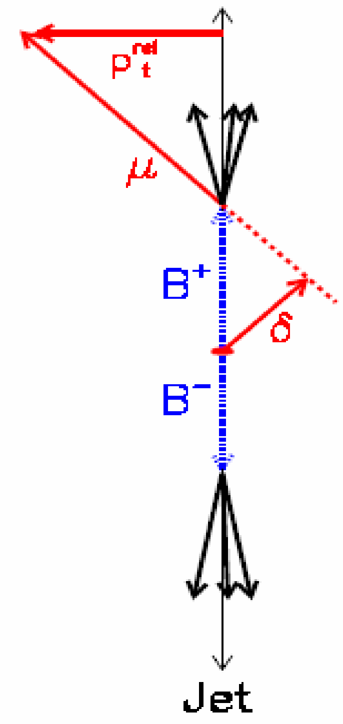


- Double layer double sided strips
- Precise determination of impact parameter in transverse plane
- Resolution of $|\delta|$ for hits in both layers;

$$33\mu m \oplus \frac{90\mu m}{P_T}[GeV]$$

Installed 1997 (first pub 2004)!

Tagging Heavy Quarks (*b*)



Beauty quarks rarely produced, use properties of beauty hadrons:

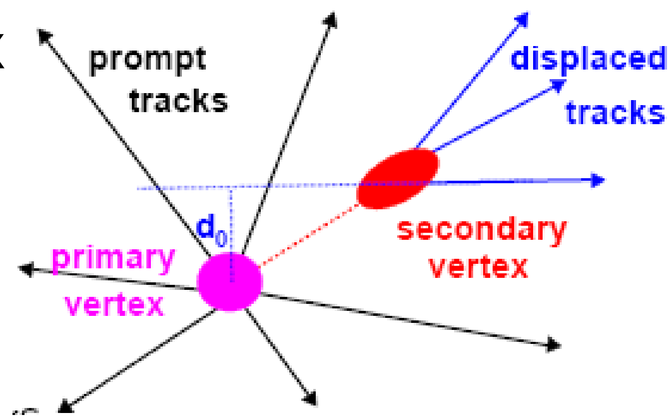
- semileptonic decays(μ,*e*)
- mass

  - transverse momentum p_t^{rel} relative to jet axis

- lifetime (vertex detectors)

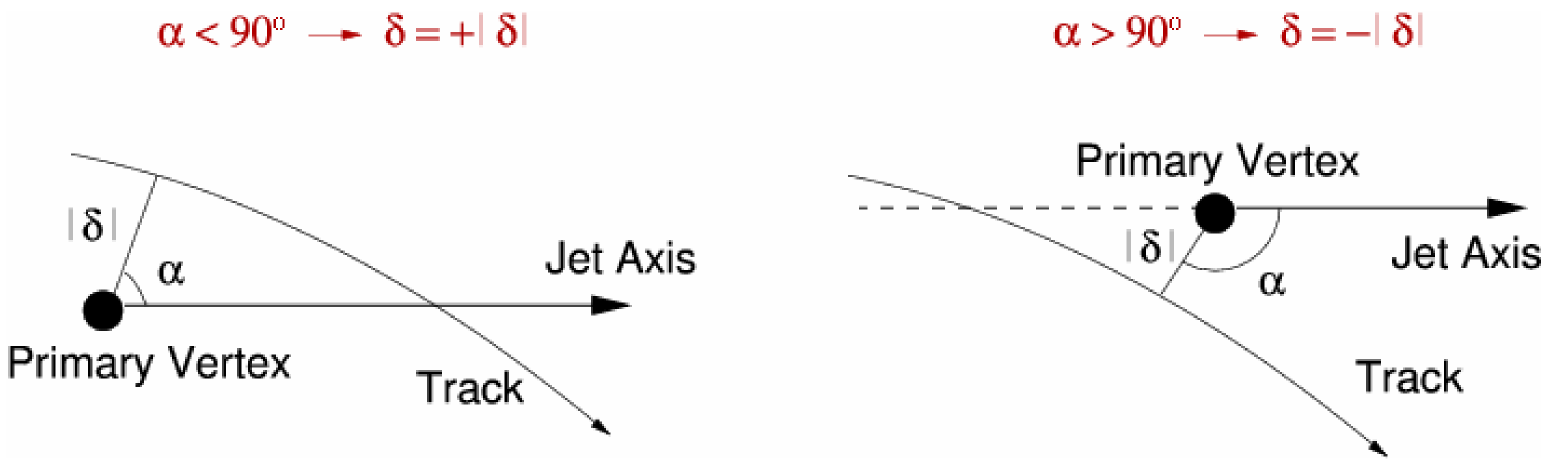
  - reconstrucion of a secondary vertex

  - impact parameter δ



Signed Impact Parameter δ

Signed impact parameter δ , Significance = $\delta/\sigma(\delta)$



Charm and beauty asymmetric (positive) due to lifetime

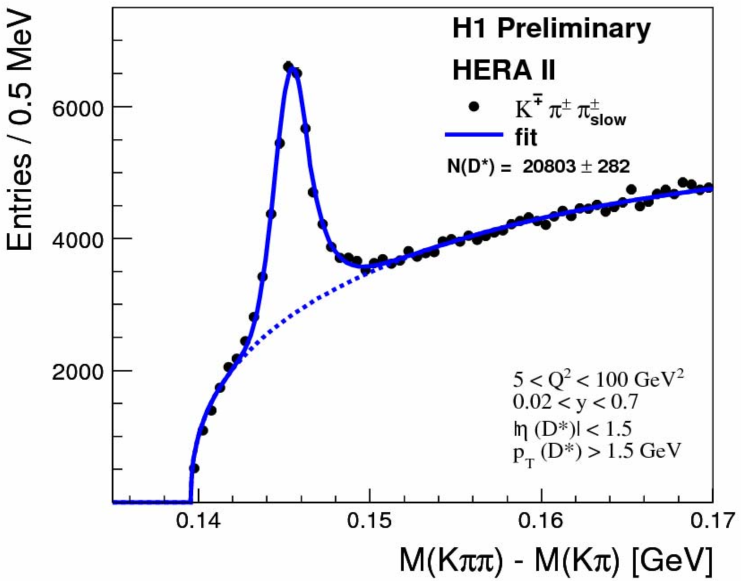
Light flavours mostly symmetric (resolution dominates)

Similarly for secondary vertices (>=2 tracks), decay length L and decay length significance =$L/\sigma(L)$

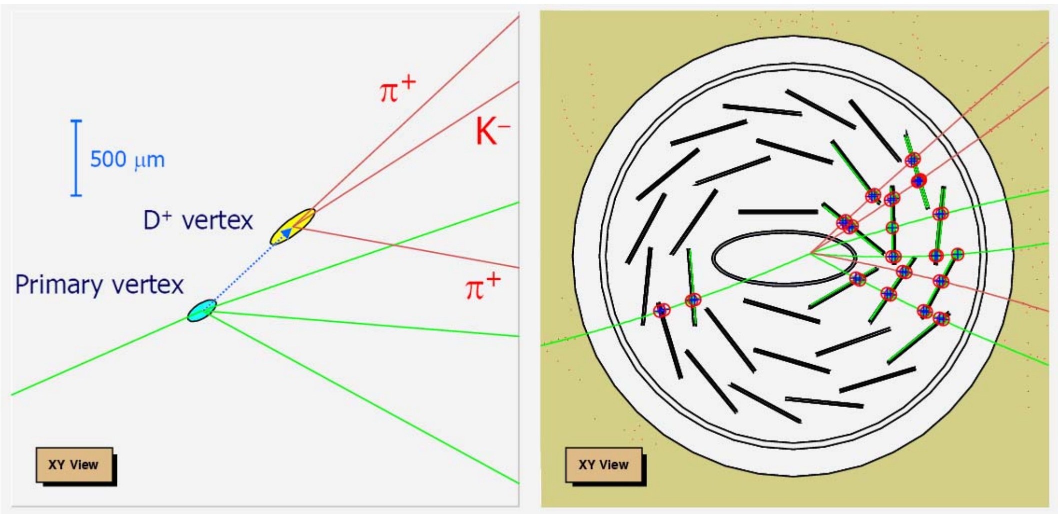
Tagging Heavy Quarks (c)

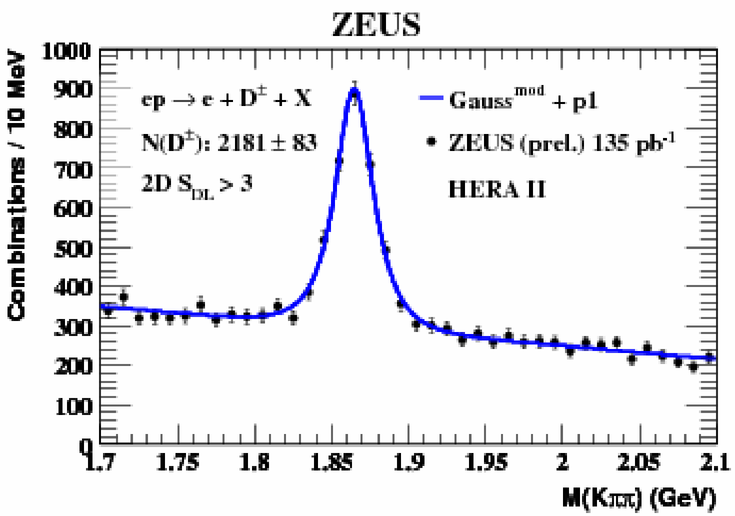
resonances D*, D^+, D^0,...

Full HERA II statistics (~$350 pb^{-1}$)

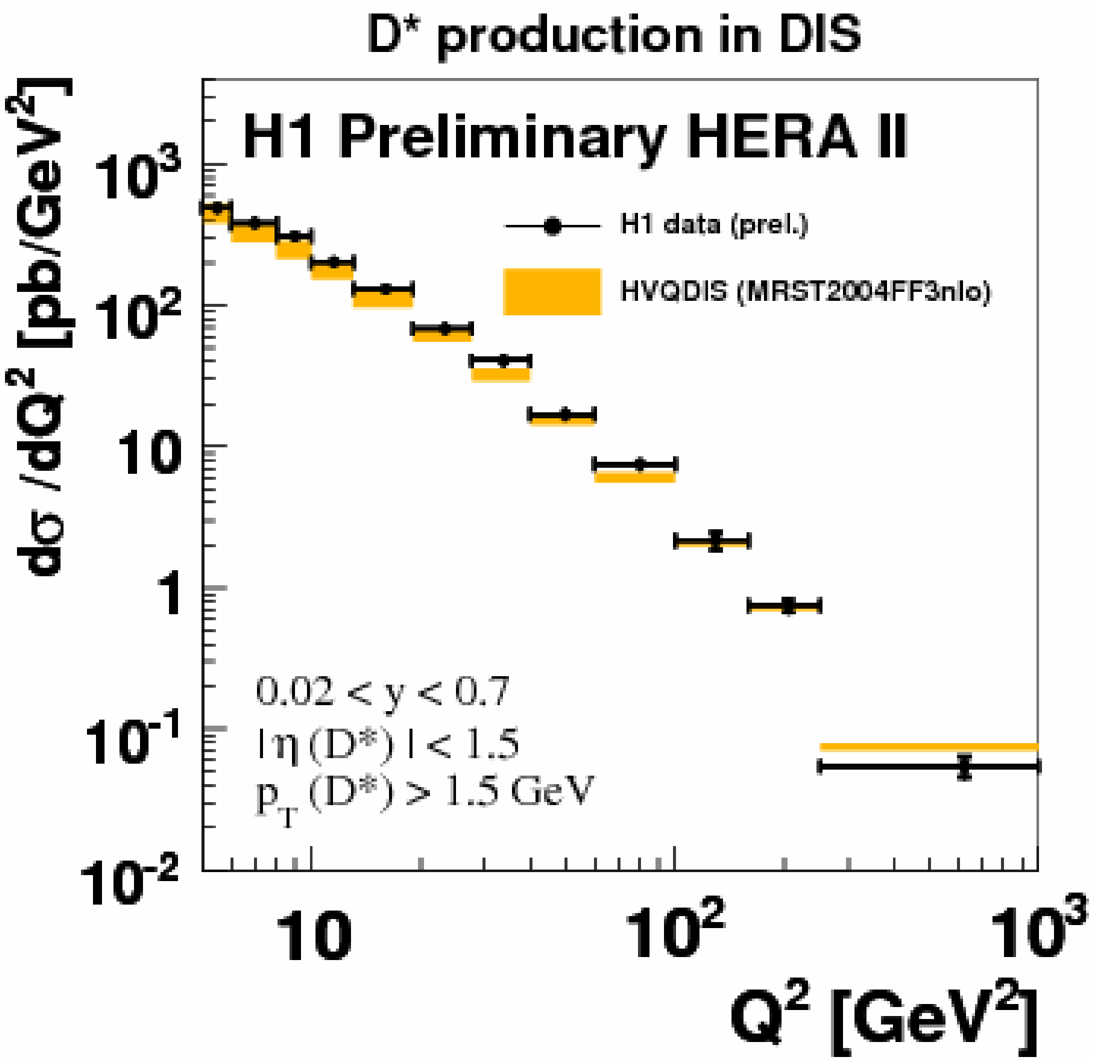


resonances and decay length tagging using vertex detectors





D* Cross Section

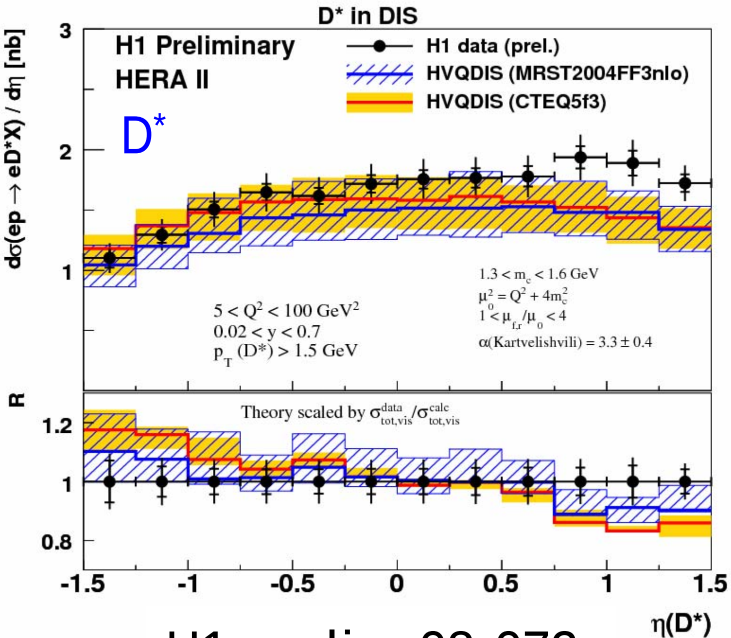


H1 prelim-08-072

H1 prelim-08-074

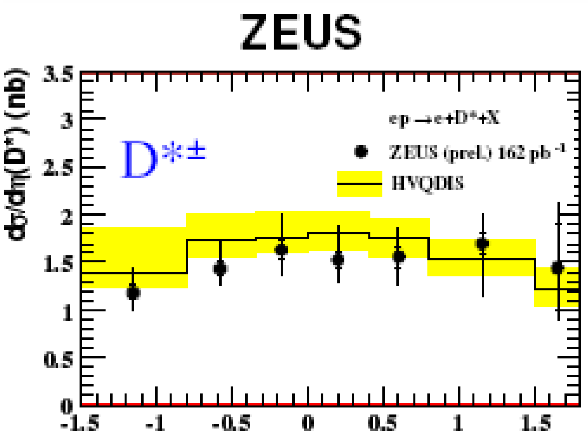
- good description by NLO calculation (HVQDIS) in wide Q^2 range
- Also at large Q^2, where massive approach not expected to be appropriate

D* Cross Section

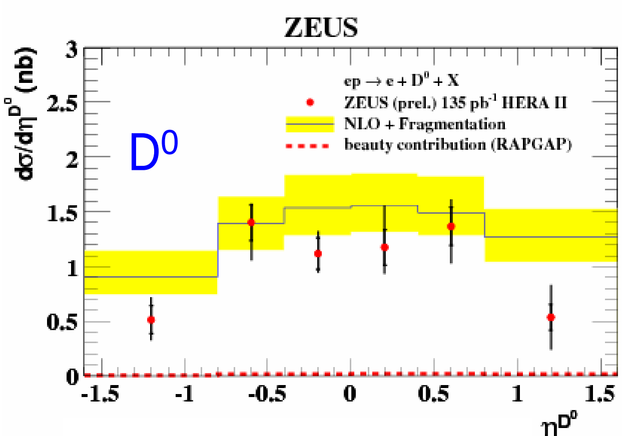


H1 prelim-08-072

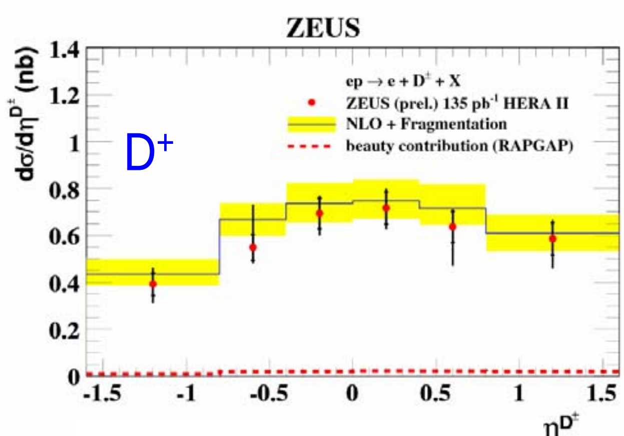
- differential cross sections of several D mesons measured
- reasonably described by NLO QCD (HVQDIS)
- double differential in x and Q^2 allows extraction of F_2^{cc}



ZEUS-prel-07-008



ZEUS-prel-07-034

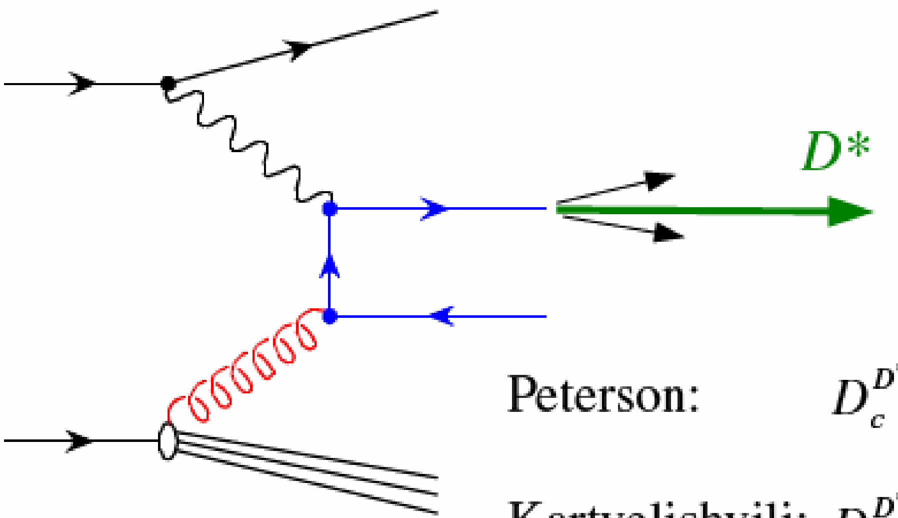


ZEUS-prel-07-009

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)

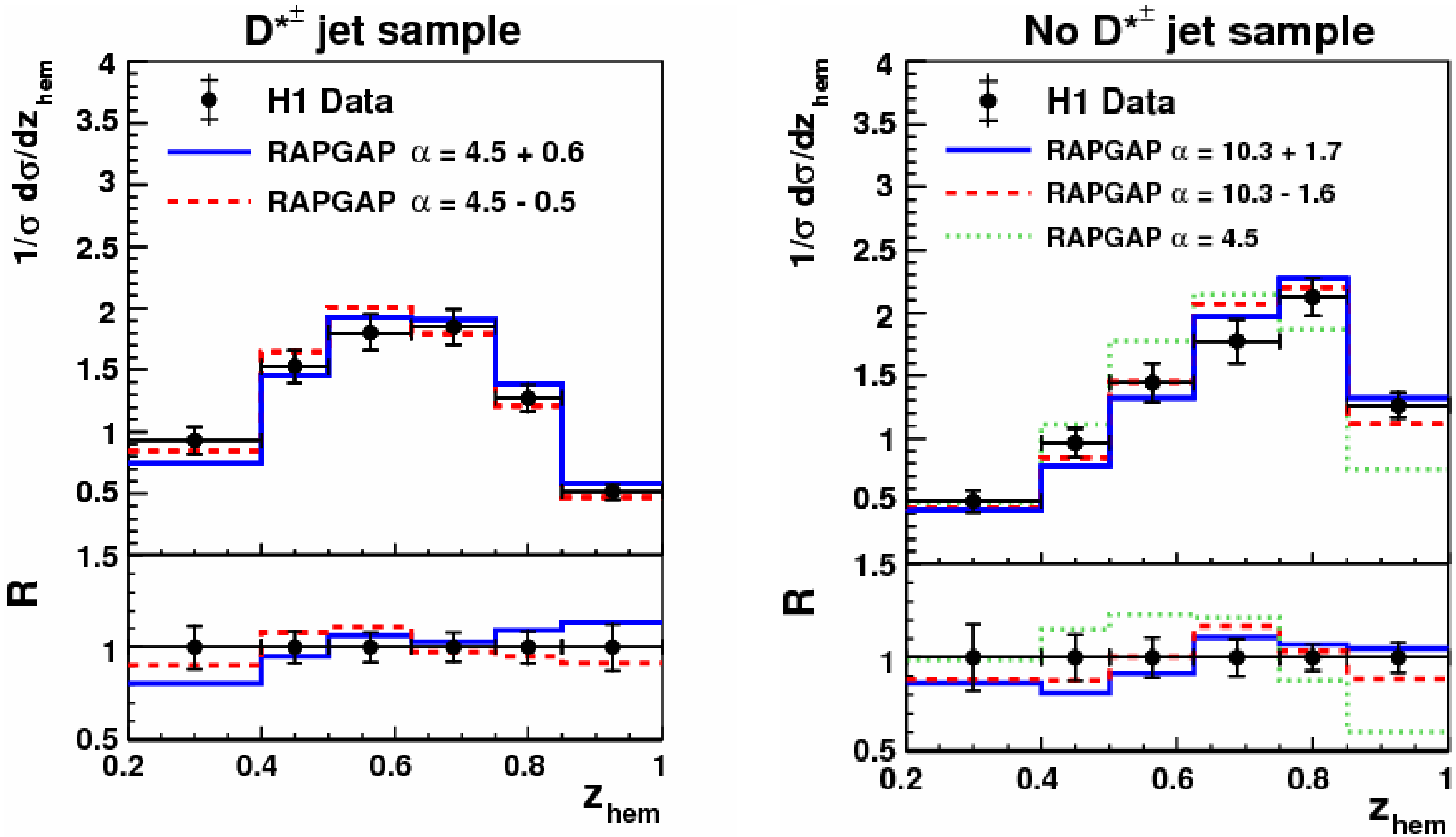


$$z = E_{D^*} / E_c$$

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

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

D* Fragmentation



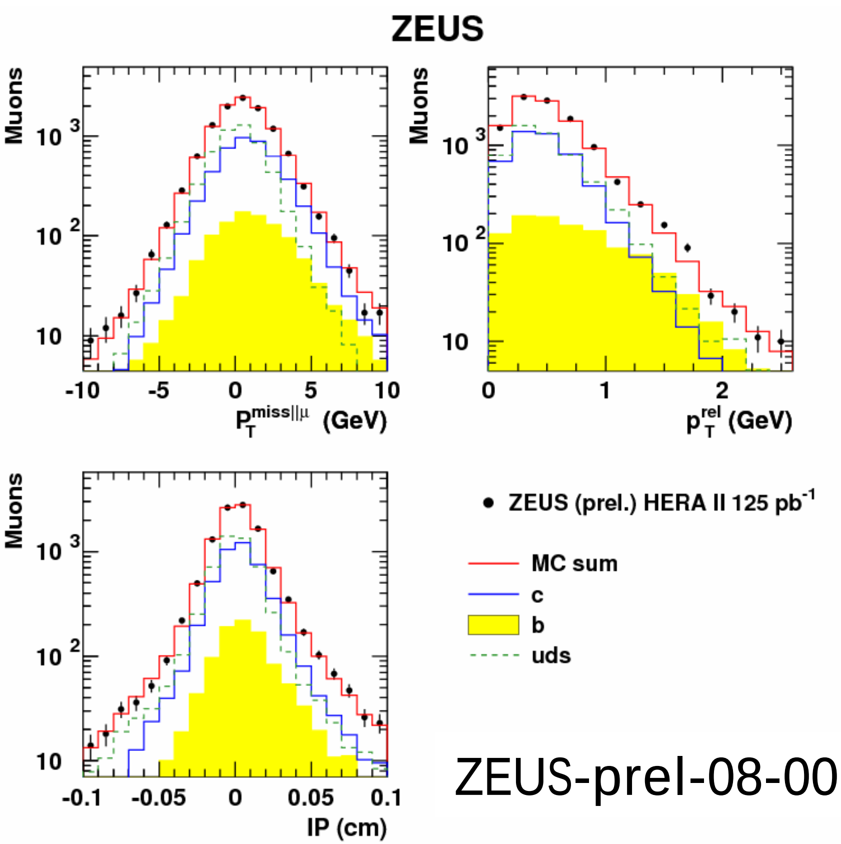
- RAPGAP MC: $p_{T,jet}$> 3 GeV, parameters consistent with e^+e^-
- no jet sample (low photon gluon COM) needs harder frag.
- Similar story for NLO QCD

DESY-08-080

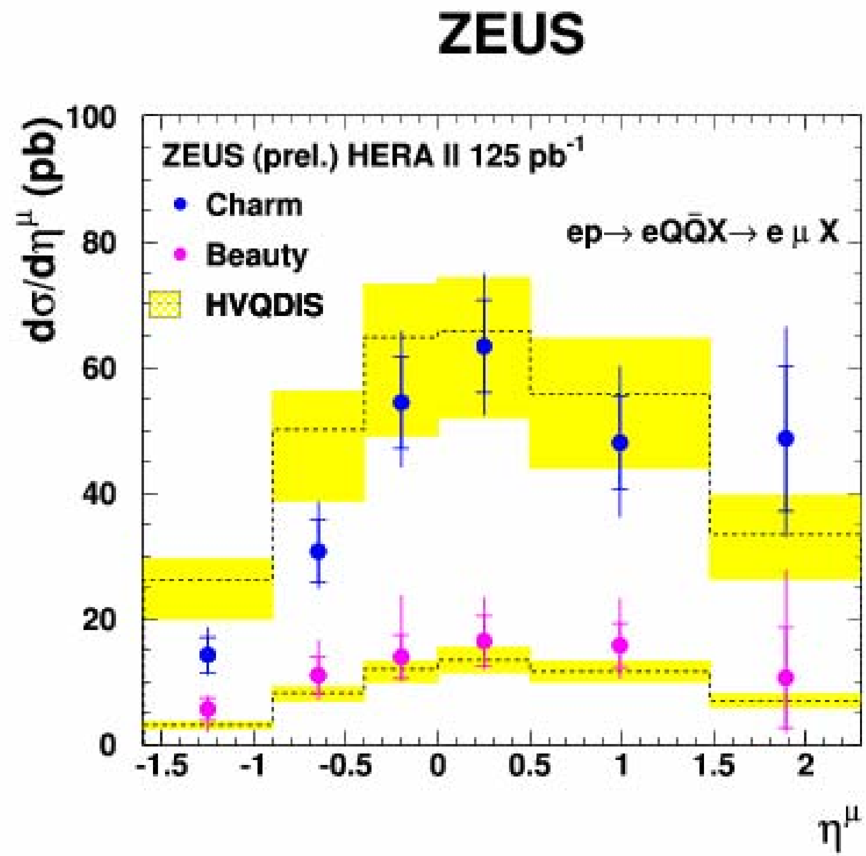
(Juraj Bracinik)

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

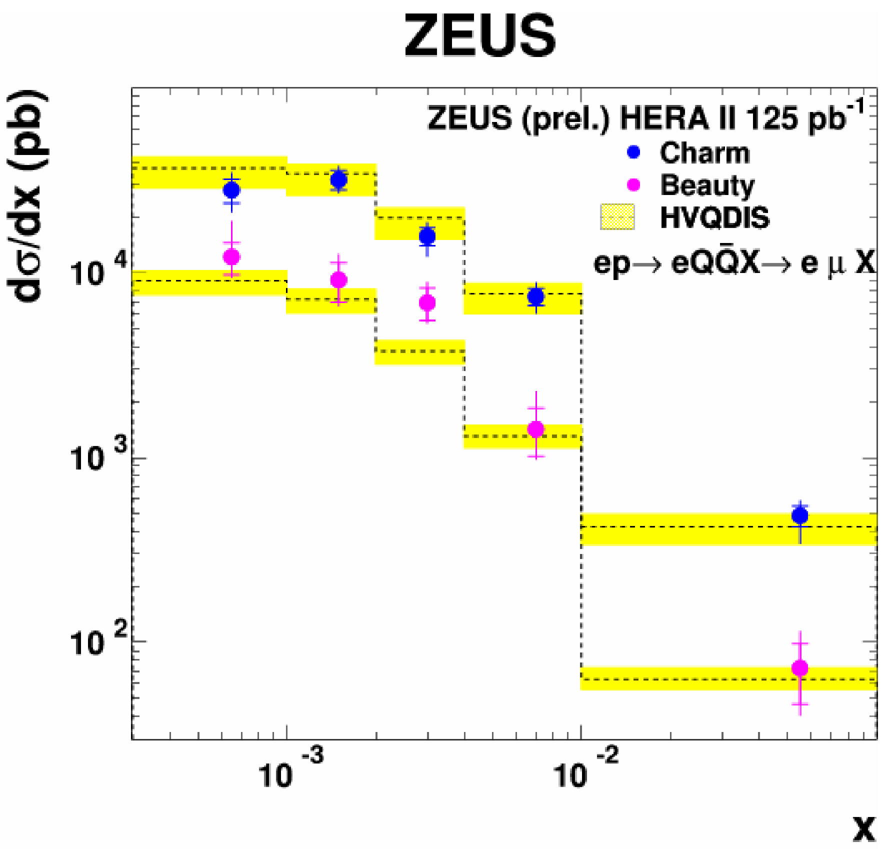


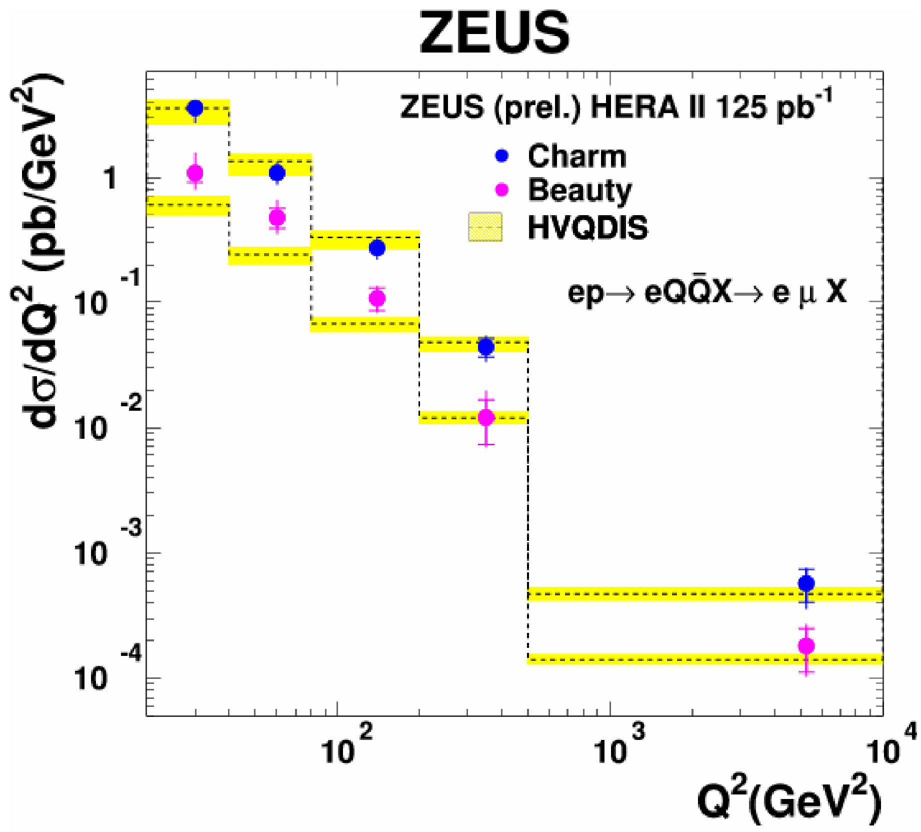
ZEUS-prel-08-007



- $Q^2 > 20$ GeV^2, $0.01 < y < 0.7$, $P_T\mu > 1.5$ GeV, $-1.6 < \eta_\mu < 2.3$
- *c* and *b* cross sections described by NLO QCD(HVQDIS)

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}

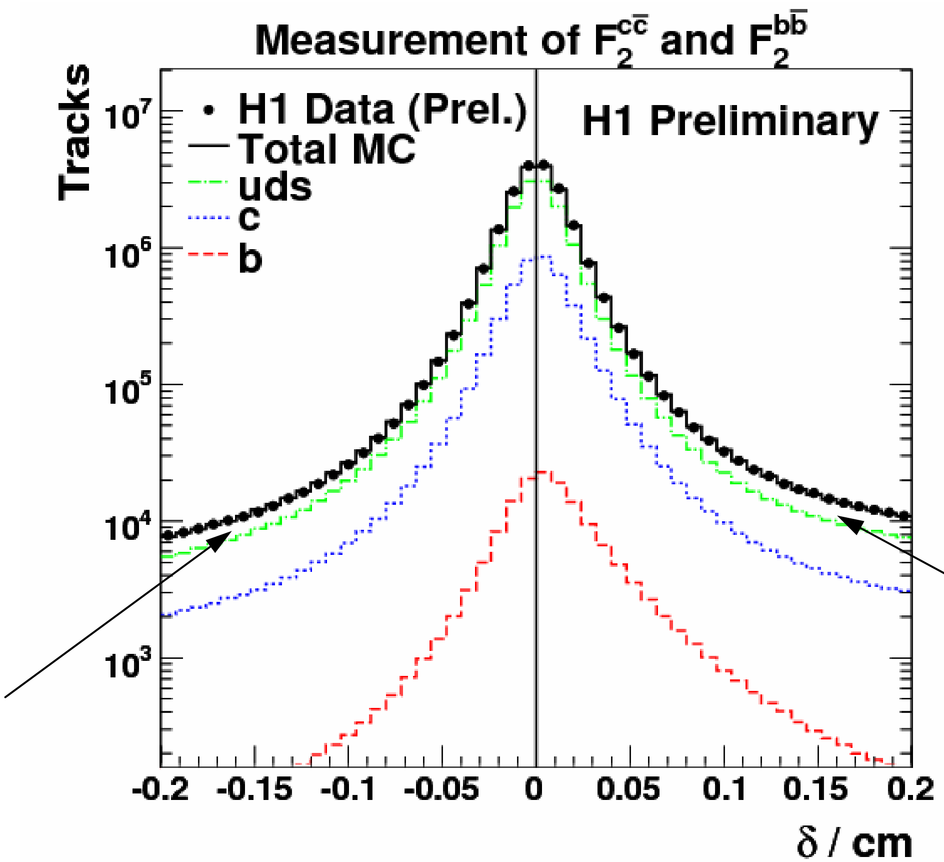
H1 Inclusive Analysis

H1 prelim-08-173

- Publication on HERA I data (54 pb^{-1}) in 2004 & 2005
- H1 CST rebuilt to account for HERA II beamline
- Preliminary analysis on full HERA II data (190pb^{-1}) this summer (H1prelim-08-173)
- Inclusive analysis: use all tracks with hits in silicon detector ($p_t > 0.3$ *GeV*)
- Precise determination of impact parameter in transverse plane
- Divide events into 1 track, 2 track and >= 3 track samples

Signed Impact Parameter (H1)

H1 prelim-08-173



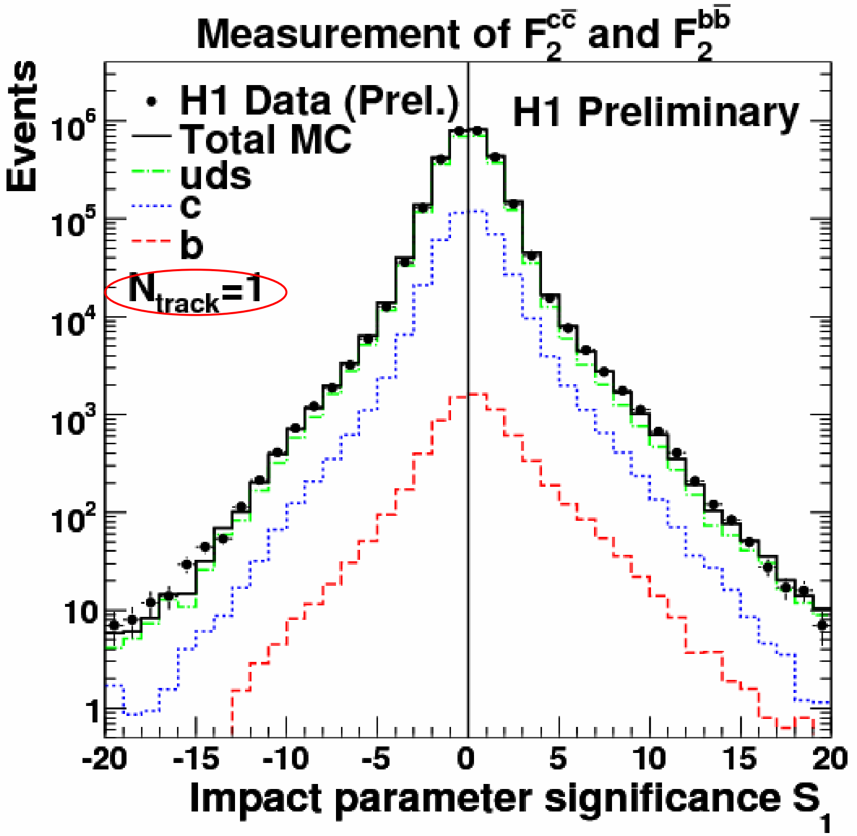
resolution

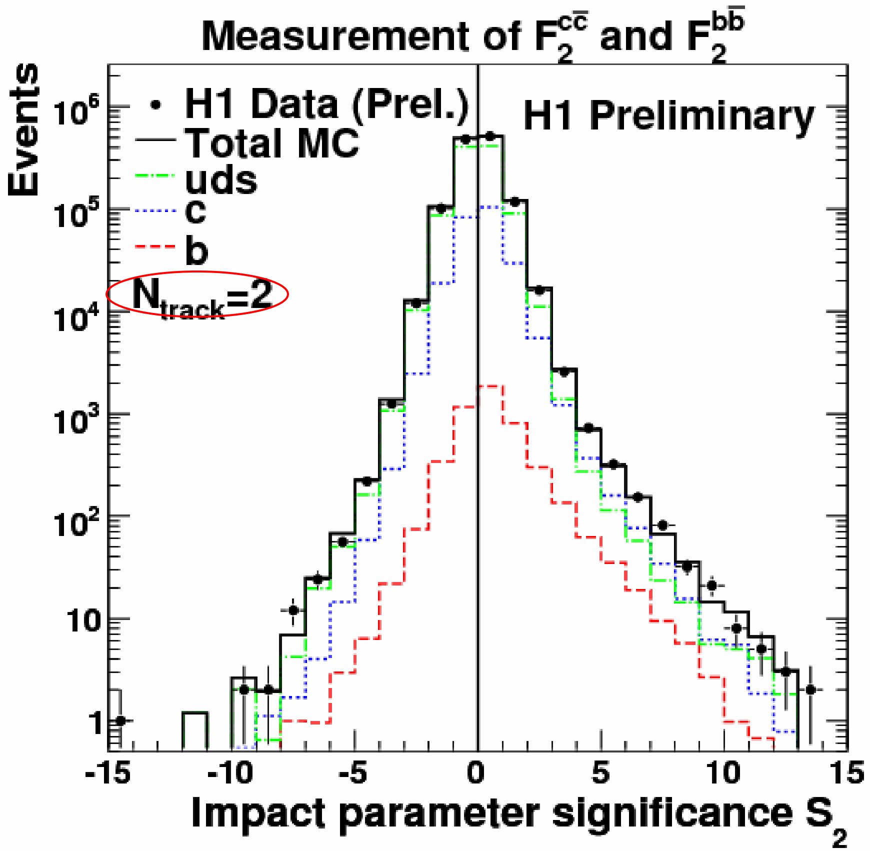
lifetime

Charm and beauty asymmetric due to lifetime, Light flavours mostly symmetric

MC describes resolution!

Signifcance





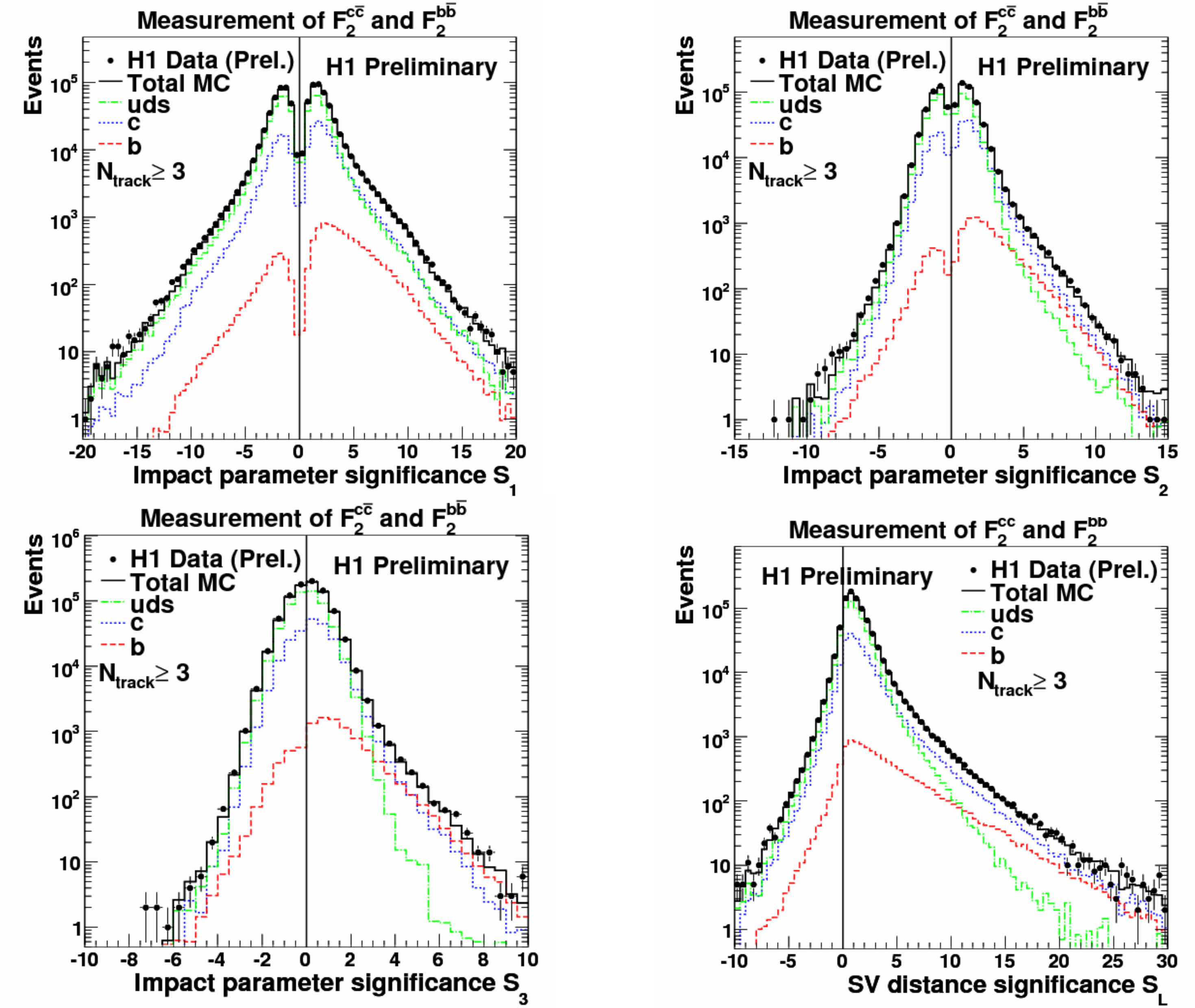
Significance for N_{track}=1

2^{nd} highest significance for N_{track}=2

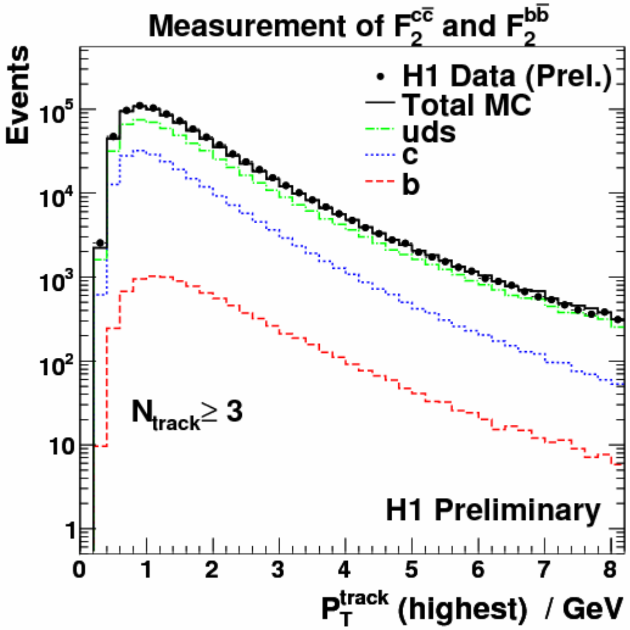
Neural Network

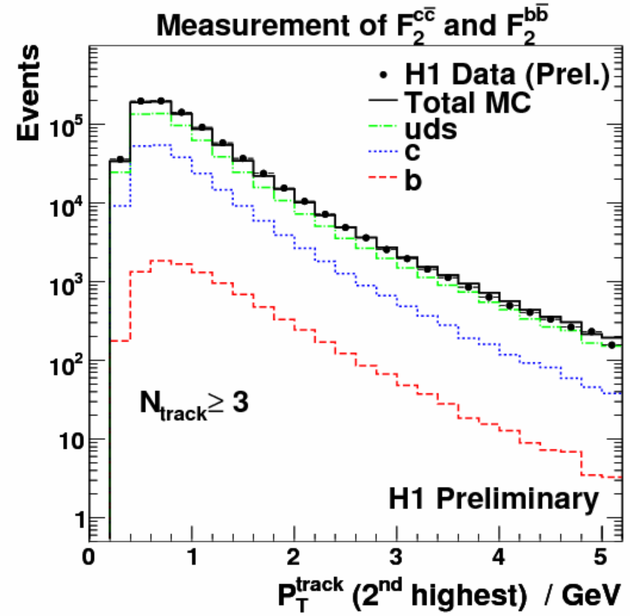
- Improve *c,b* separation power (especially at low Q^2): use neural network for >= 3 track events
- Choose inputs which are different for c and b, and largely physics model independent
- Inputs: S_1, S_2, S_3, S_L, track p_t, 2nd highest track p_t, number of CST tracks, number of tracks associated to secondary vertex
- Network trained with b as “signal” c as “background”. Light flavours will be subtracted out due to their symmetry (see later)

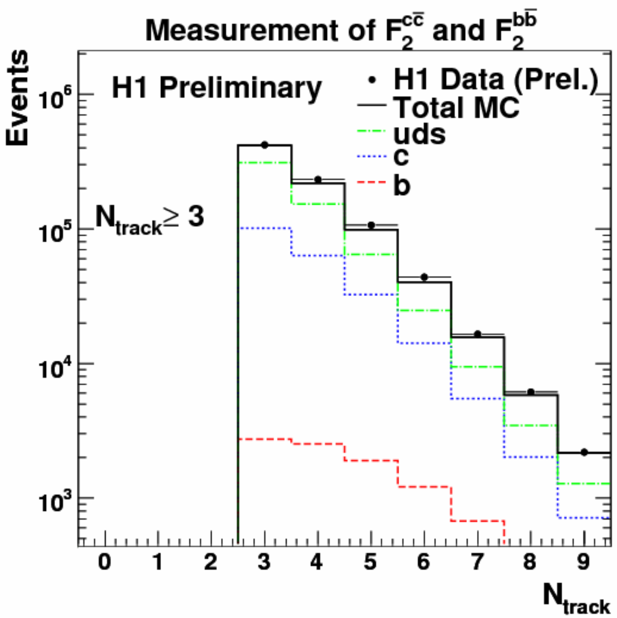
Neural Network Inputs

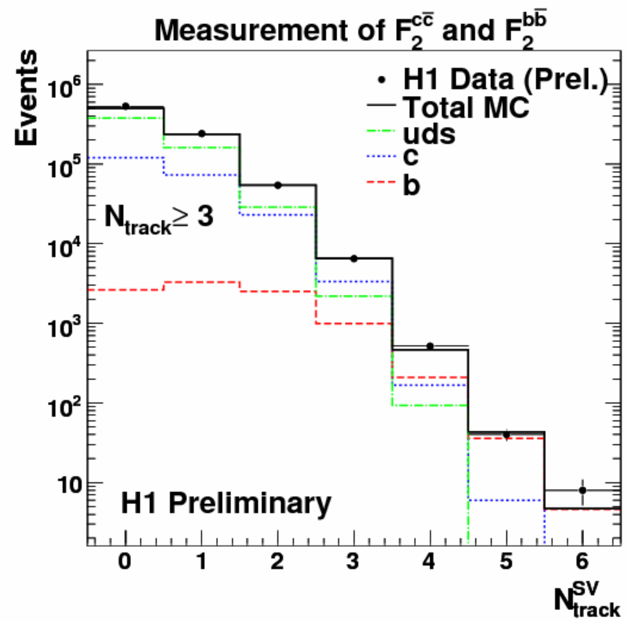


Neural Network Input

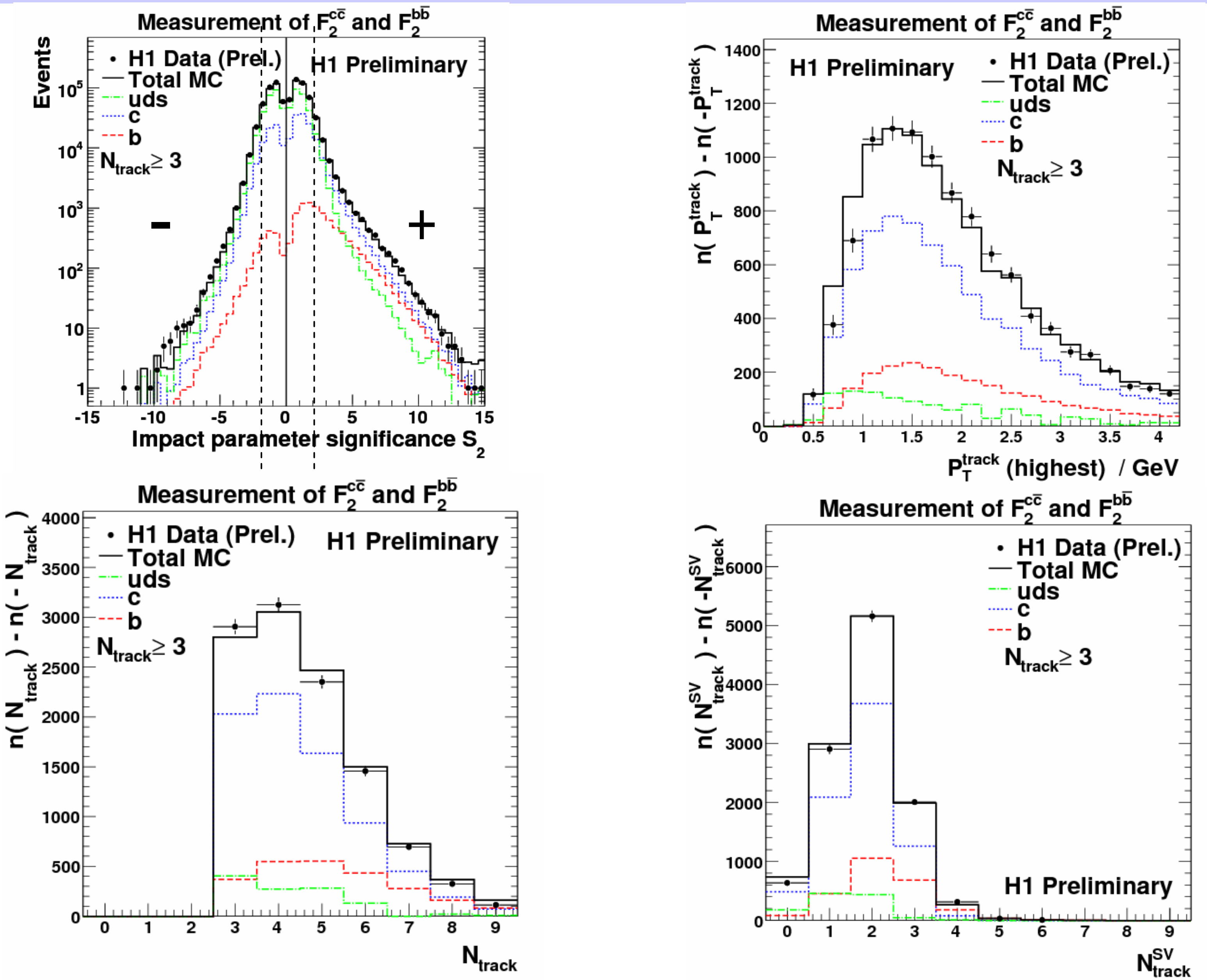






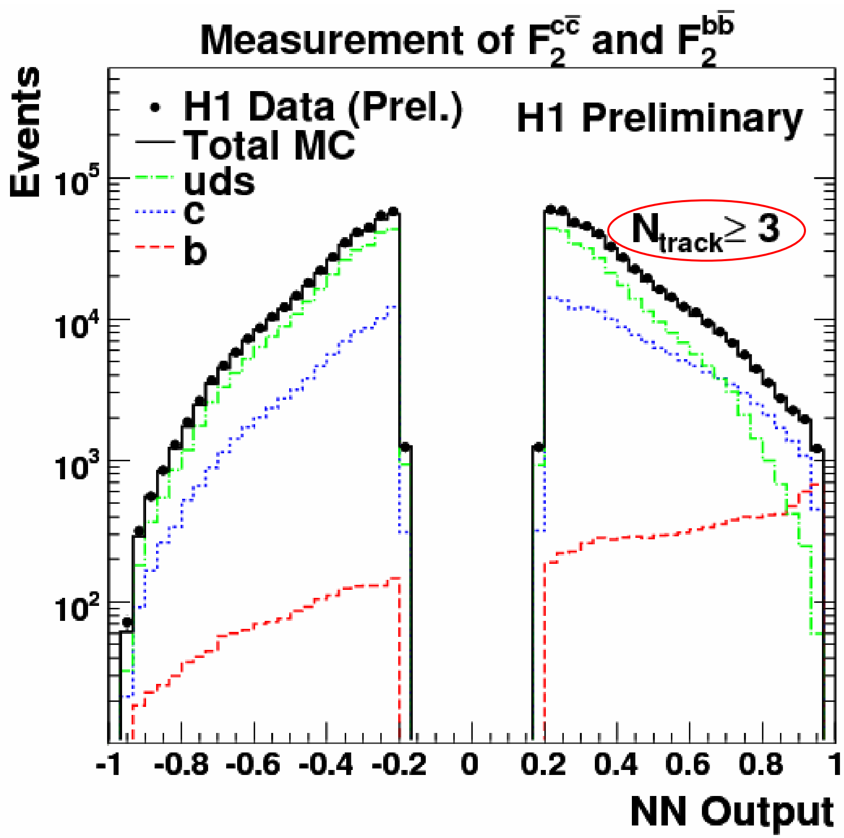


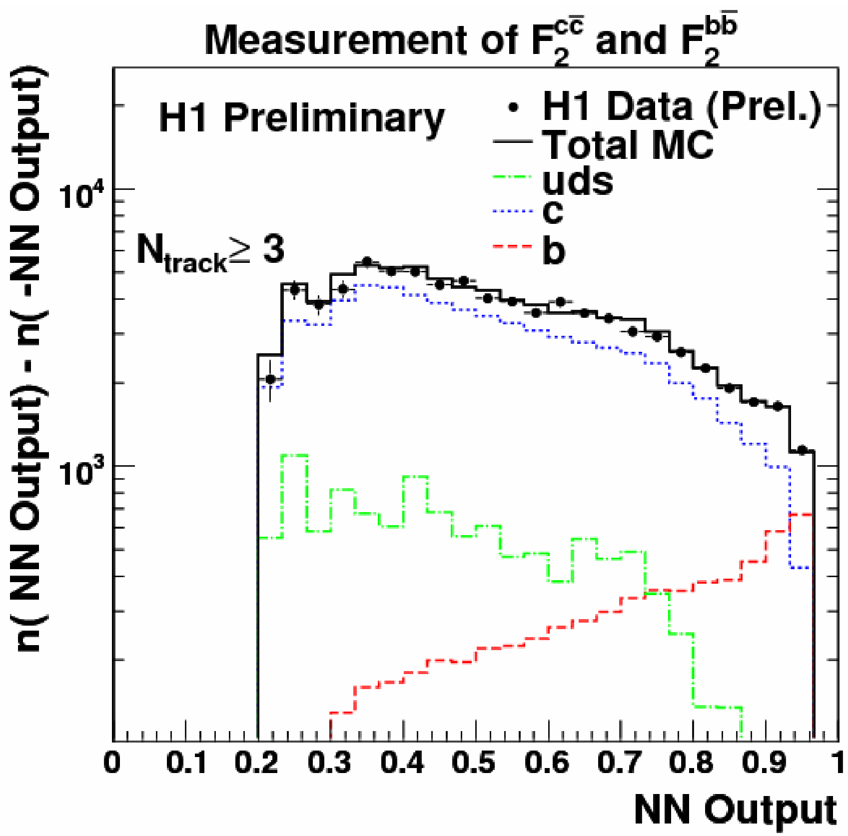
Neural Network Input (Neg. subtracted)



Neural Network Output

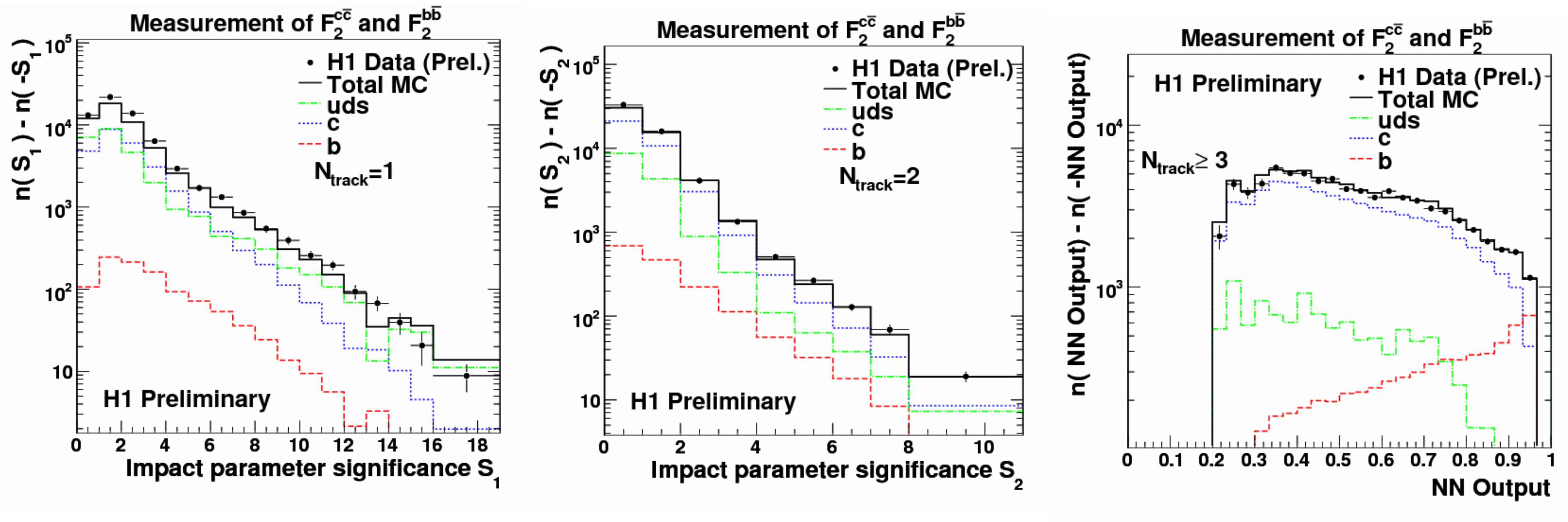
- Sign given by S_1. Subtract –'ve from +'ve to reduce systematic error due to resolution and light contribution





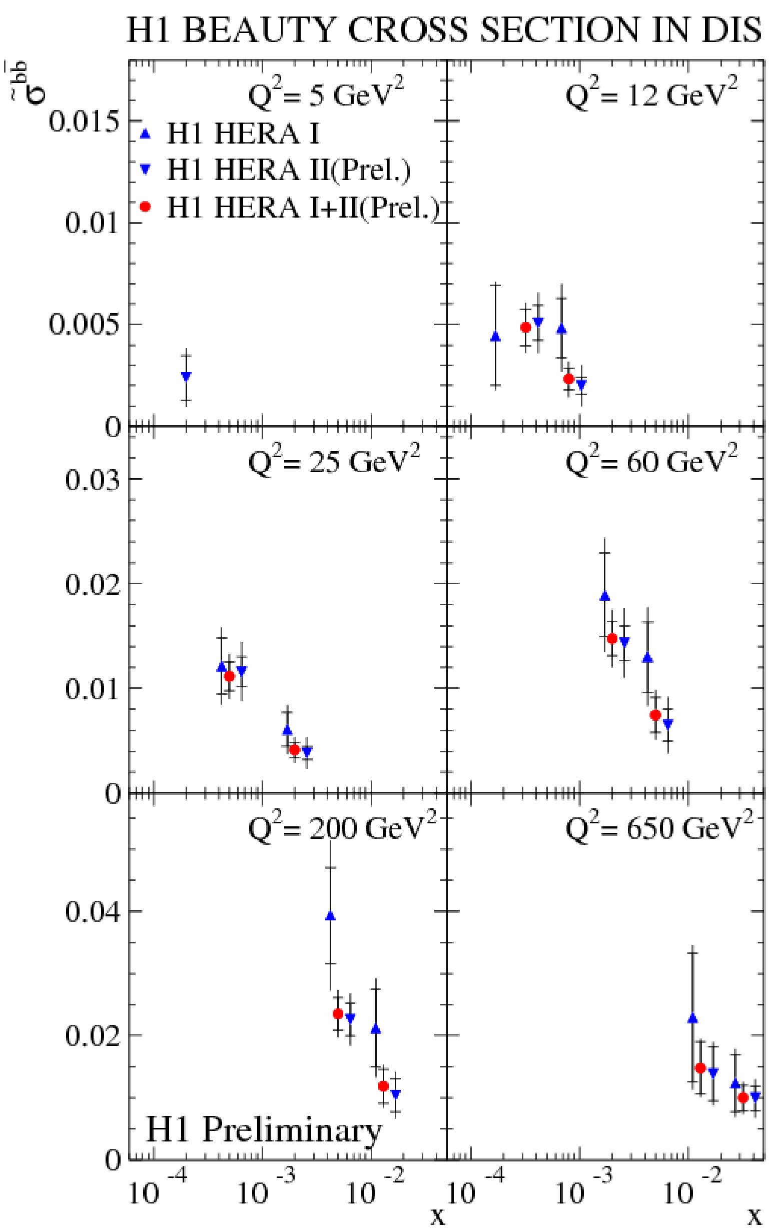
Extracting Flavour Fractions

These distributions are fitted for ρ_c, ρ_b in each x,Q^2 bin with ρ_{uds} constrained by total number of DIS events



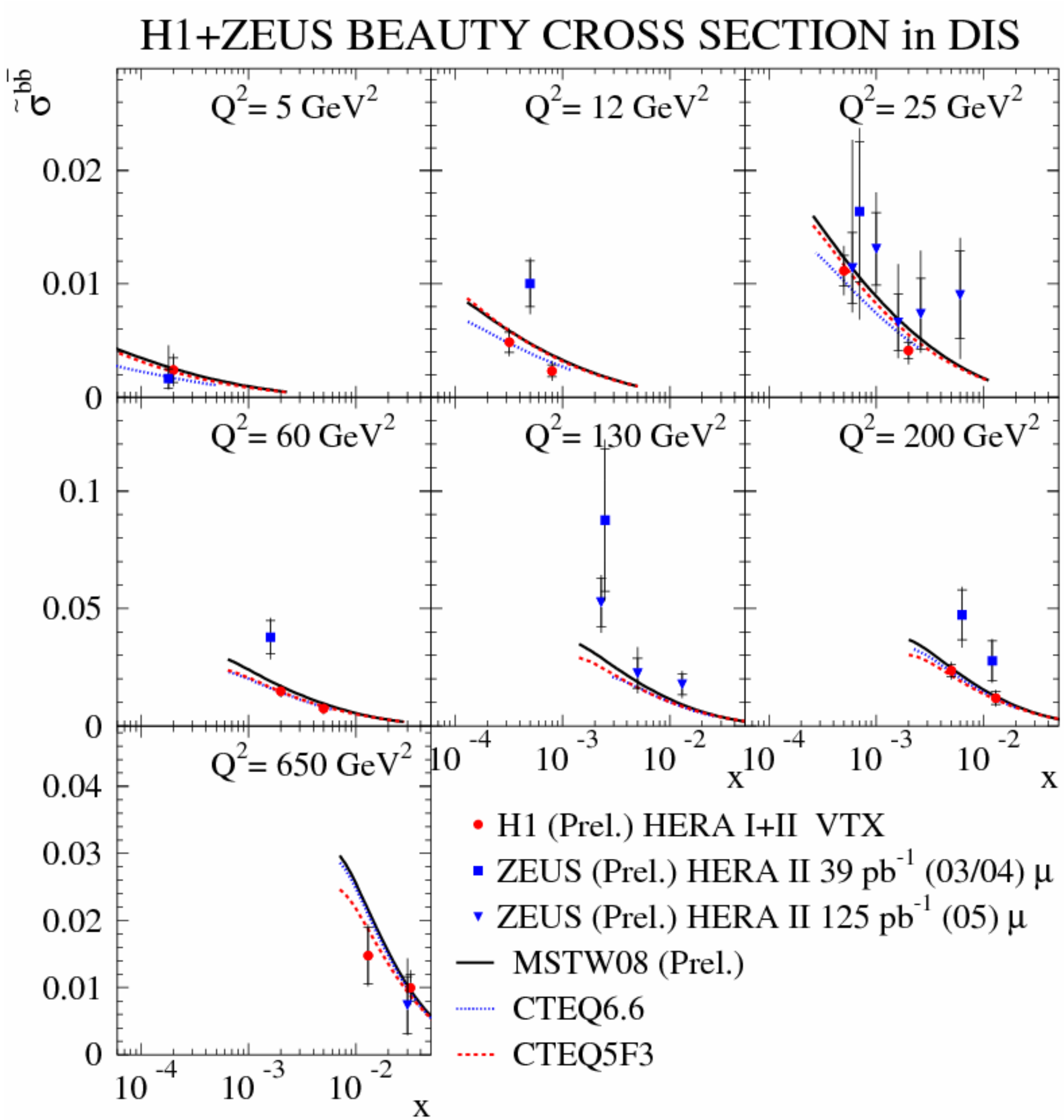
$$f_c = \frac{\rho_c . N_c^{gen}}{\rho_c . N_c^{gen} + \rho_b N_b^{gen} + \rho_{uds} . N_{uds}^{gen}}$$

Inclusive b cross section (H1)



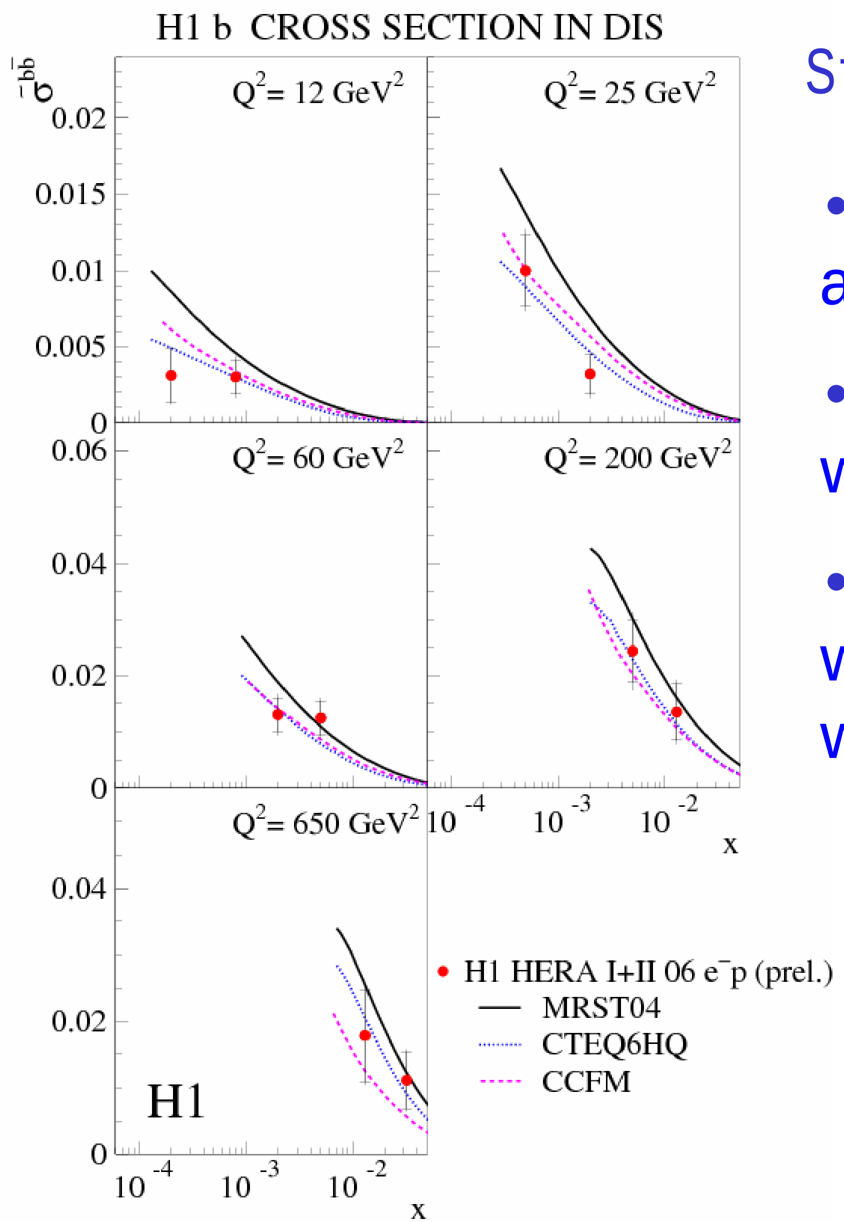
- HERA I agrees with HERA I
- HERA II reaches lower Q^2 (NN)
- HERA I and HERA II data combined for improved precision

Inclusive b Cross Section (HERA)



- comparison of different methods [acceptance]
  - Inclusive (H1VTX) [>90%]
  - μ p_t^{rel} (ZEUS 03/04 μ) [20-35%]
  - μ p_t^{rel} + δ (ZEUS 05 μ) [25-50%]
- ZEUS tend to be higher than H1
- generally described by NLO QCD (FFNS, GM-VFNS)

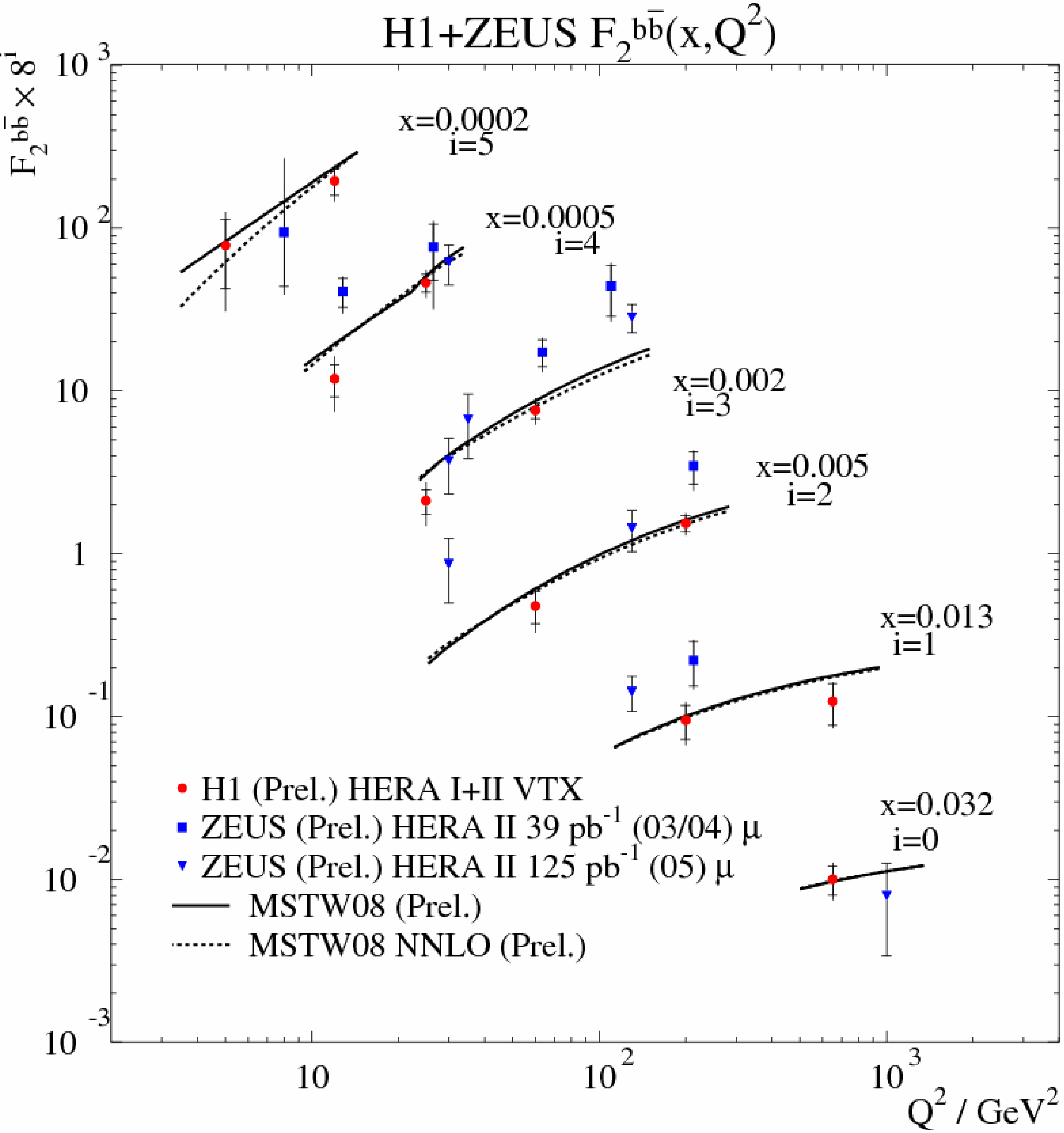
Improvements in Theory



Status summer 2007 (e^- data)

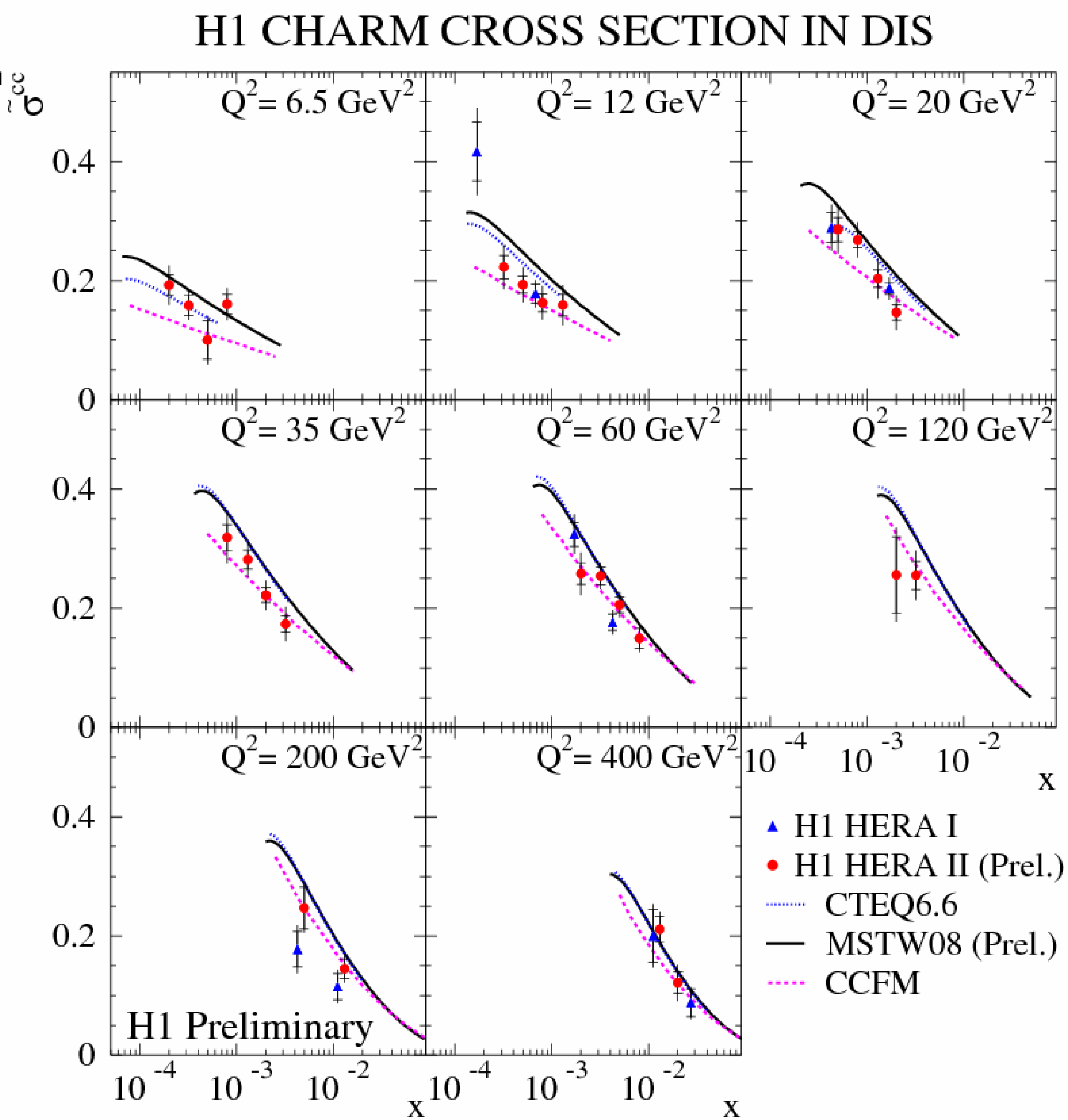
- MRST04 factor 2 larger than CTEQ at Q^2=12 GeV^2
- Chance to distinguish models with full HERA II data
- Since then MSTW08 was released which is in much better agreement with CTEQ (and data)!

Measurements of F_2^{bb} (HERA)



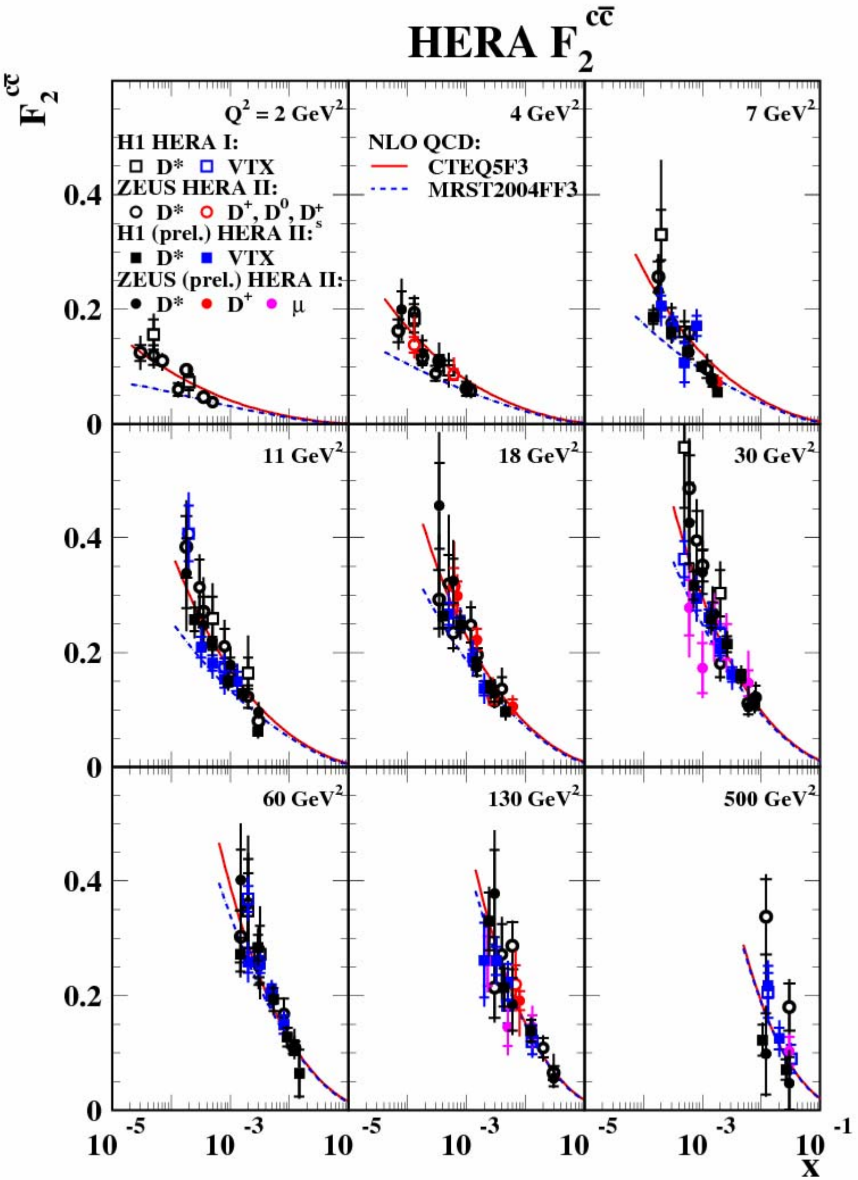
- Beauty structure function versus Q^2
- NNLO predictions available
- Differences between NLO and NNLO small except for $Q^2 < (m_b)^2$

Inclusive Charm Cross Section (H1)



- HERA I agrees with HERA II
- HERA II has finer binning for charm and reaches lower Q^2
- Reasonable description by GM VFNS PDFs from CTEQ and MSTW
- Also by PDF based on CCFM evolution.

Inclusive Charm Cross Section (HERA)



- comparison of different methods [acceptance]

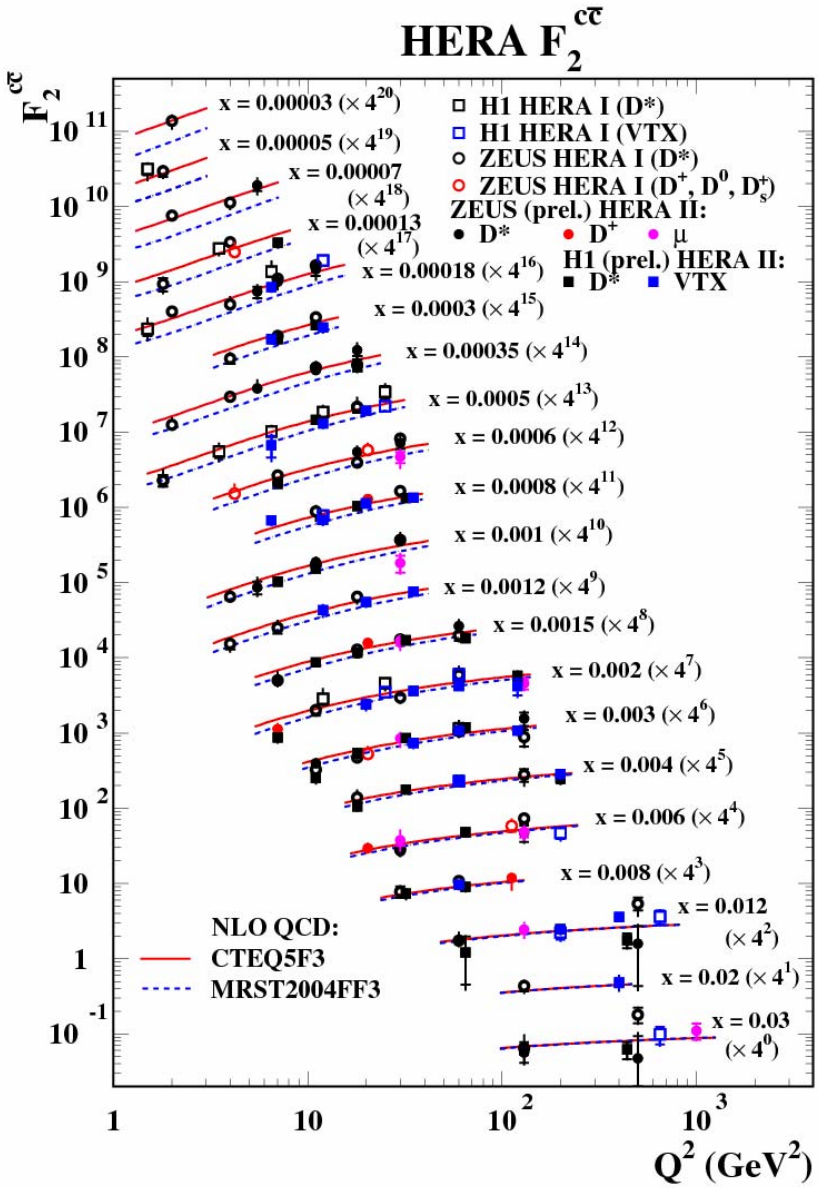
-Inclusive (H1 HERA I II VTX) [>70%]

-Mu ptrel+δ (ZEUS HERA II μ) [25-50%]

-D* cross sections [20-70%]

- different methods agree well
- wealth of precise measurements
- combine to improve precision

Measurements of F_2^{cc}(HERA)



- Charm measurements span large range in Q^2 and x
- Theory differences for $Q^2<(2m_c)^2$
- These are the "massive" FFNS PDFs (because the D* measurements involve model dependent extrapolations) and are not the latest GM VFNS technology

Conclusions

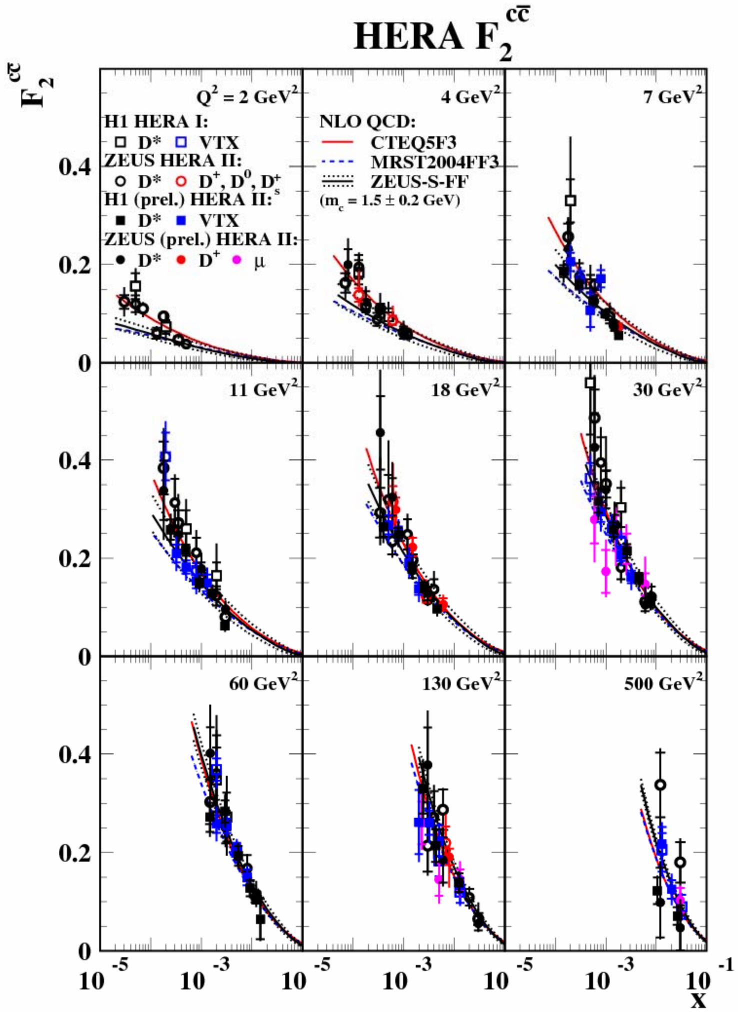
- Wealth of new measurements of the heavy flavour content of the proton from HERA data.
- Extraction of structure functions F_2^{cc} and F_2^{bb} allow comparison of many different measurement techniques.
- Data are described by latest (N)NLO pQCD calculations.
- Final results with full HERA statistics expected soon
- Data help to constrain theory mass treatments and PDFs in time for LHC!

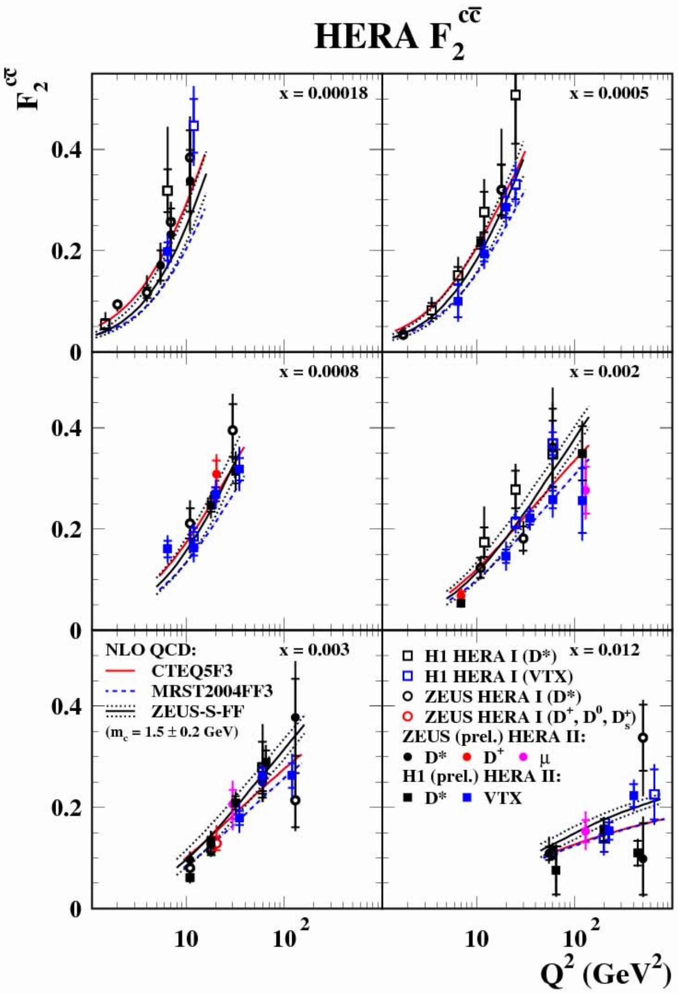
Hope there are more prizes to discover at the LHC…!

Annual CERN Road Race Sept. 2008

Back Up

Scale Uncertainty (c)





Scale Uncertainty (b)