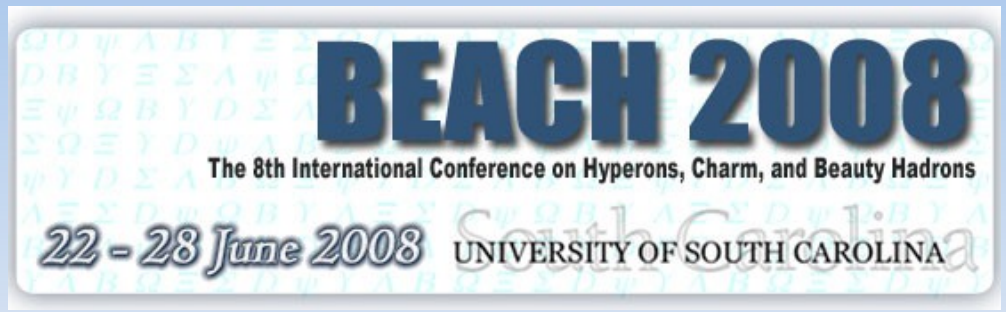
Heavy Quark Production at HERA



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On behalf of the H1 and ZEUS Collaborations

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universitätbonn

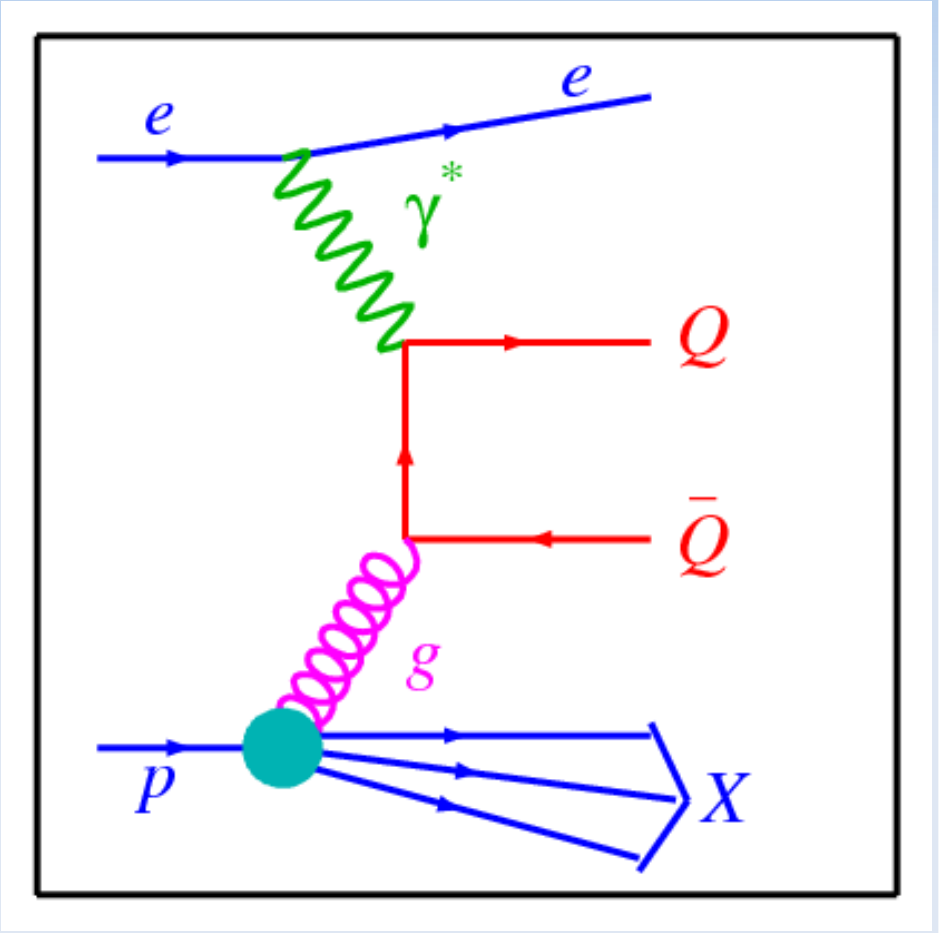
GEFÖRDERT VOM
Bundesministerium
für Bildung
und Forschung

Outline

- Introduction
- Charm via D*
- Beauty via semileptonic decays to μ
- Charm and Beauty via semileptonic decays to e
- Beauty correlations
- F_2^{bb}, F_2^{cc}
- Conclusions & Outlook

Heavy Flavour Production at HERA

- Boson-gluon fusion (BGF) is main production mechanism
- Concentrate on studies of production mechanism:
  - Test QCD (different hard scales, m_Q, p_T, Q^2)
  - Gluon Parton Density Function?



Heavy Flavour Production at HERA

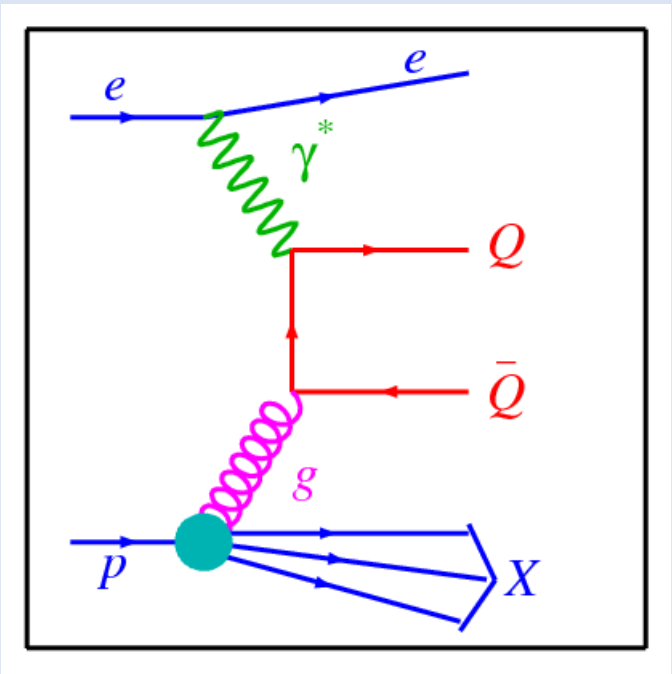
- Life (QCD) is not quite so simple ☹

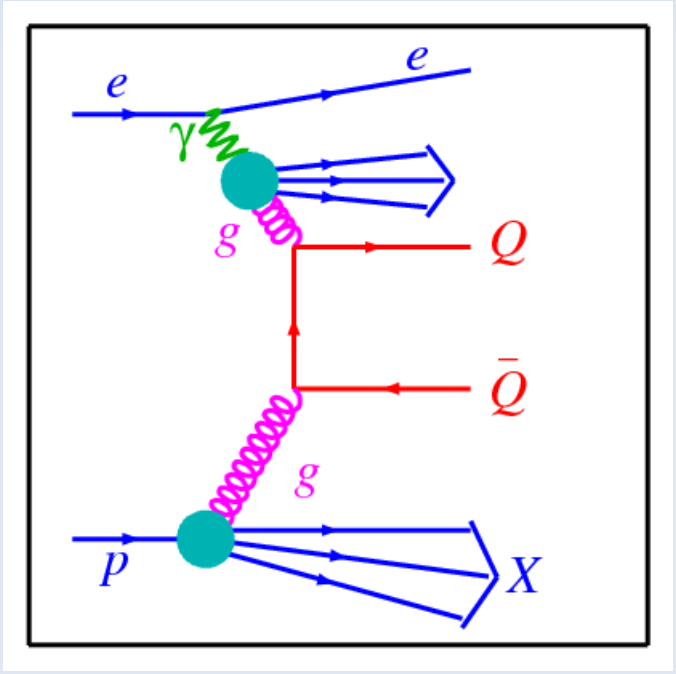
Non-Direct

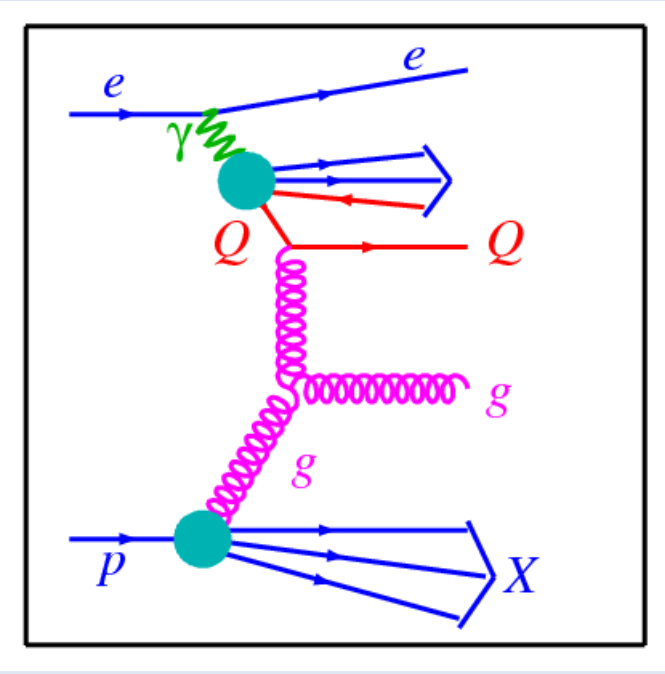
Direct

Resolved

Excitation

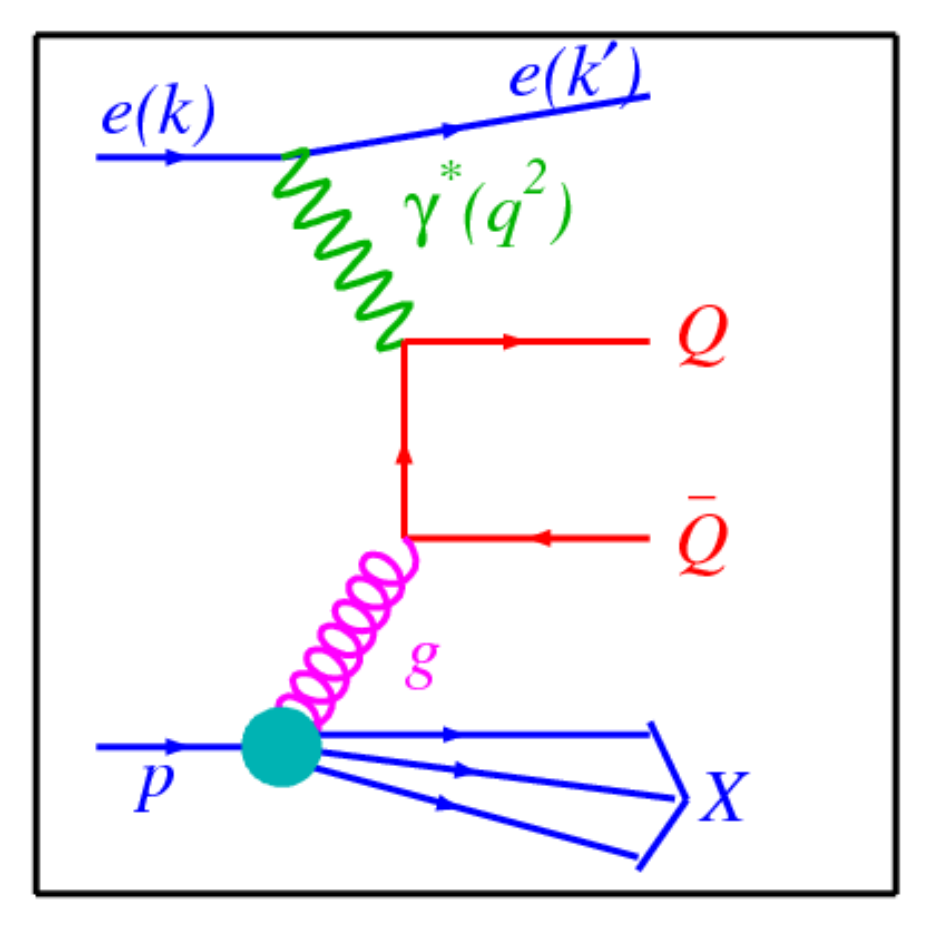






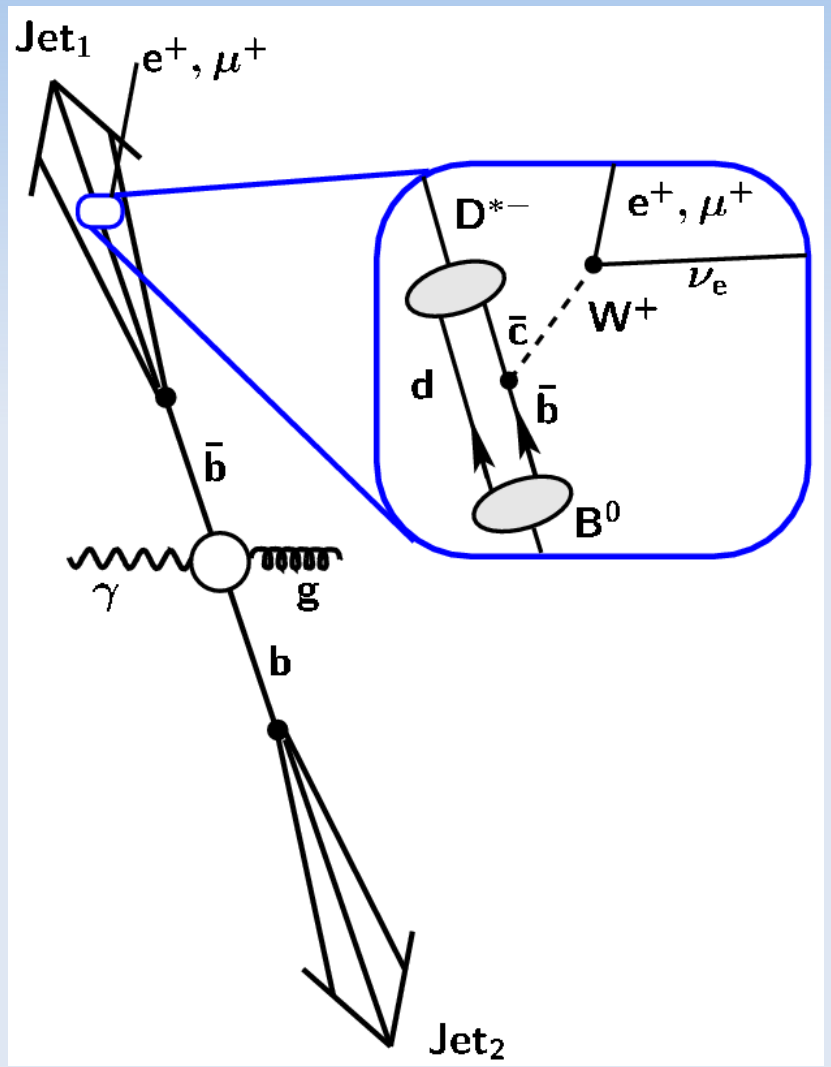
Heavy Flavour Production at HERA

- HERA (ep):
  - p: 920 (820) GeV
  - e: 27.5 GeV
- $Q^2 = -q^2 = (k-k')^2$
- $Q^2 < 1\ GeV^2$
  - Photoproduction
- $Q^2 > 1\ GeV^2$
  - DIS



Heavy Flavour Decay

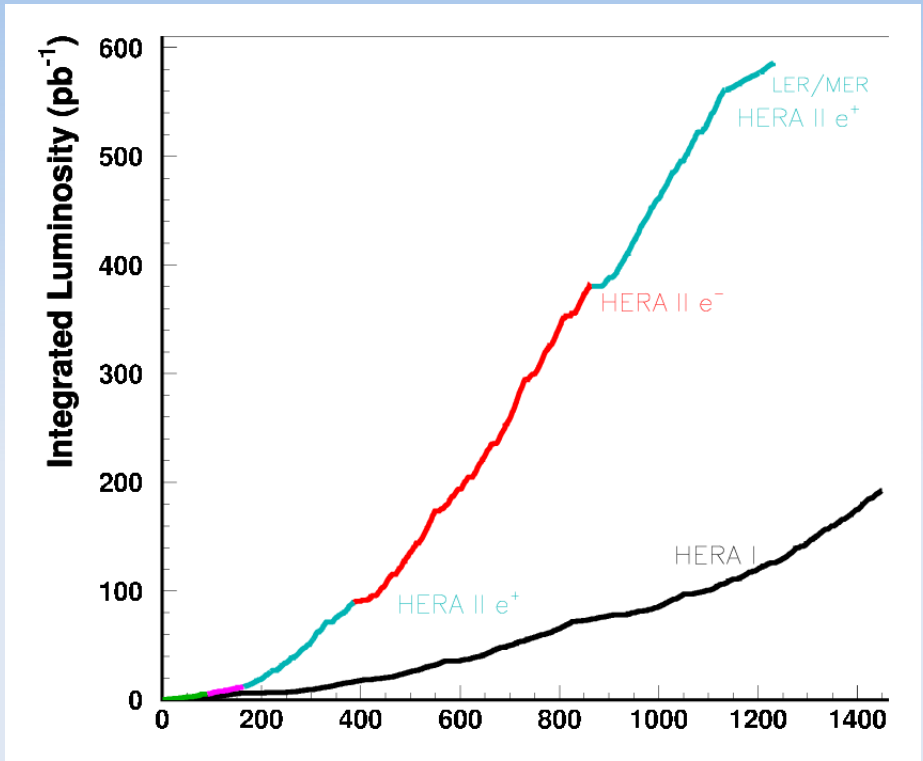
- Methods to tag HF:
  - Reconstruct D* (or other D mesons)
  - Tag semileptonic decay to e, μ
  - Use long B,D hadron lifetime
  - Jet properites
- Different tags probe different kinematic regions

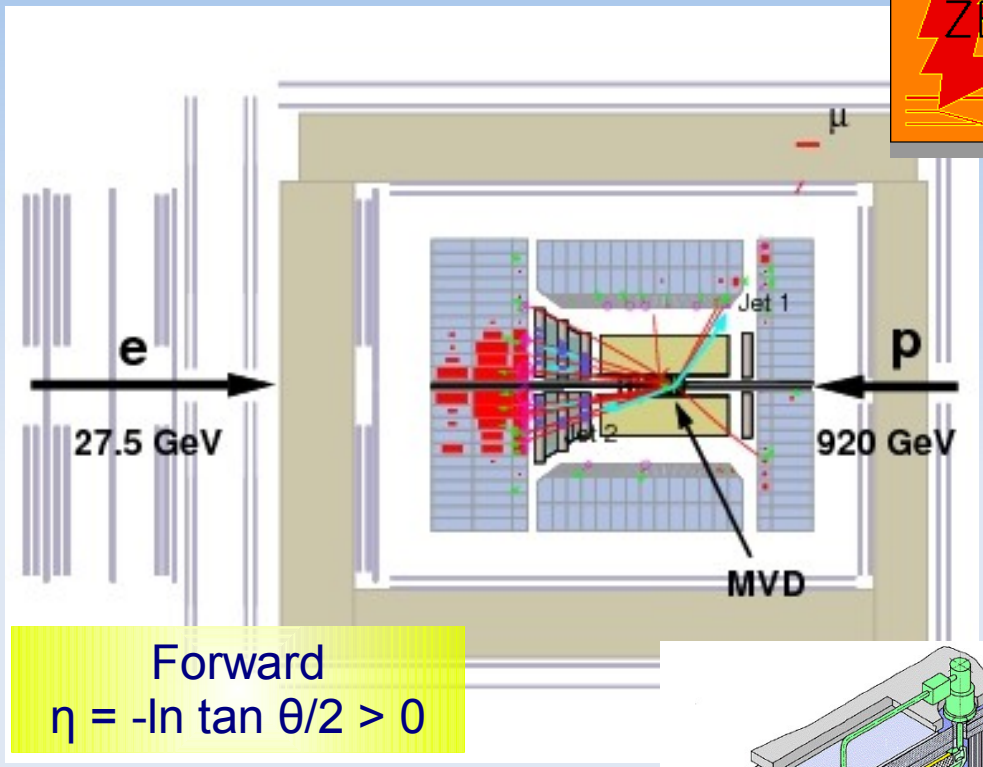


The Theory

- QCD Leading Order + Parton Shower Monte Carlos
- PYTHIA, RAPGAP, HERWIG, CASCADE
  - Massless & massive matrix elements for charm
  - Massive for beauty
  - Used for acceptance corrections
- QCD NLO programs
  - Weighted events
  - Do not include parton shower
  - FMNR for Photoproduction
  - HVQDIS for DIS
- Usually compare with experiment by applying hadronic corrections from LO Monte Carlo

Luminosity & Detectors

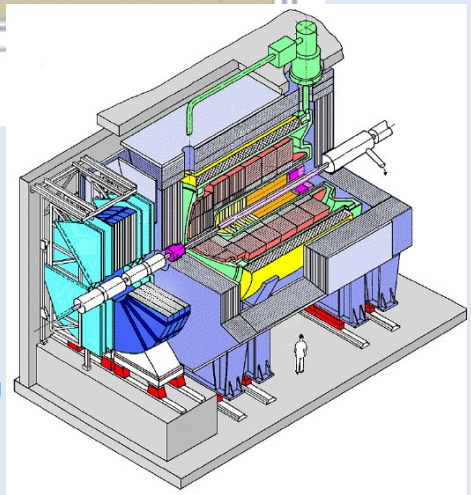




Forward
$\eta = -\ln \tan \theta/2 > 0$

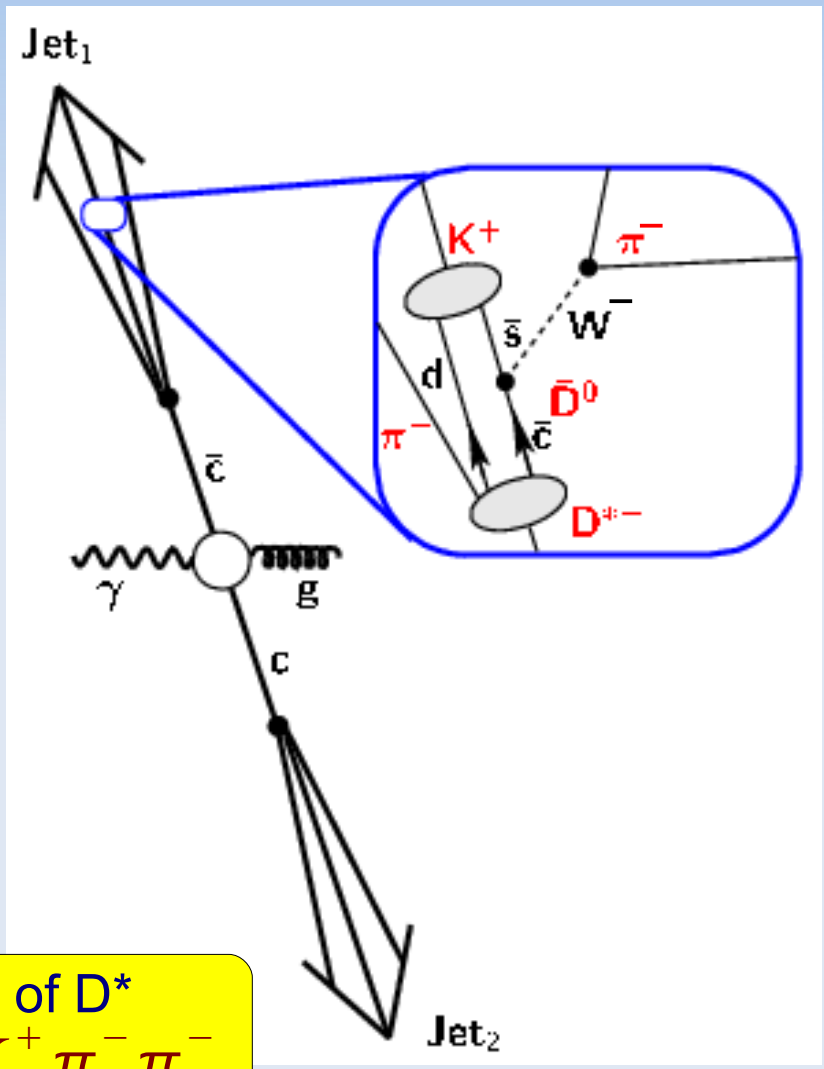
HERA I 1996-2000
HERA II 2004-2007

Integrated luminosity on tape
~0.5 fb^{-1} per experiment



Charm Production

- HERA II data
- Two recent H1 analyses using new Fast Track Trigger
  - Photoproduction
    - 93 pb^{-1} (2006/7)
  - DIS at low Q^2
    - 247 pb^{-1} (2004-7)

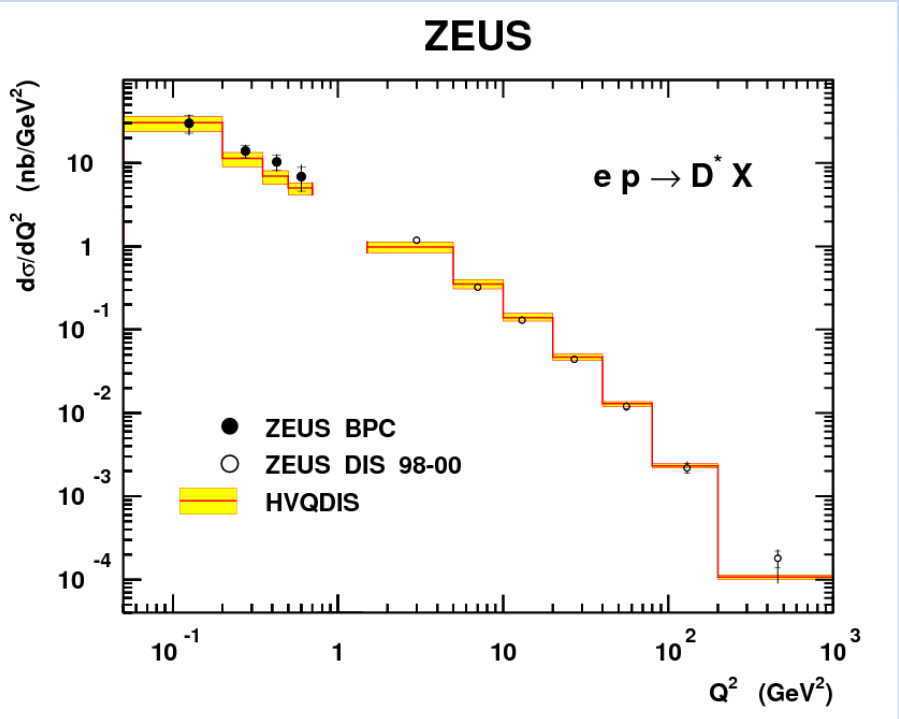


"Golden" Decay of D*

$$D^{*-} \rightarrow \bar{D}^0 \pi^- \rightarrow K^+ \pi^- \pi^-$$

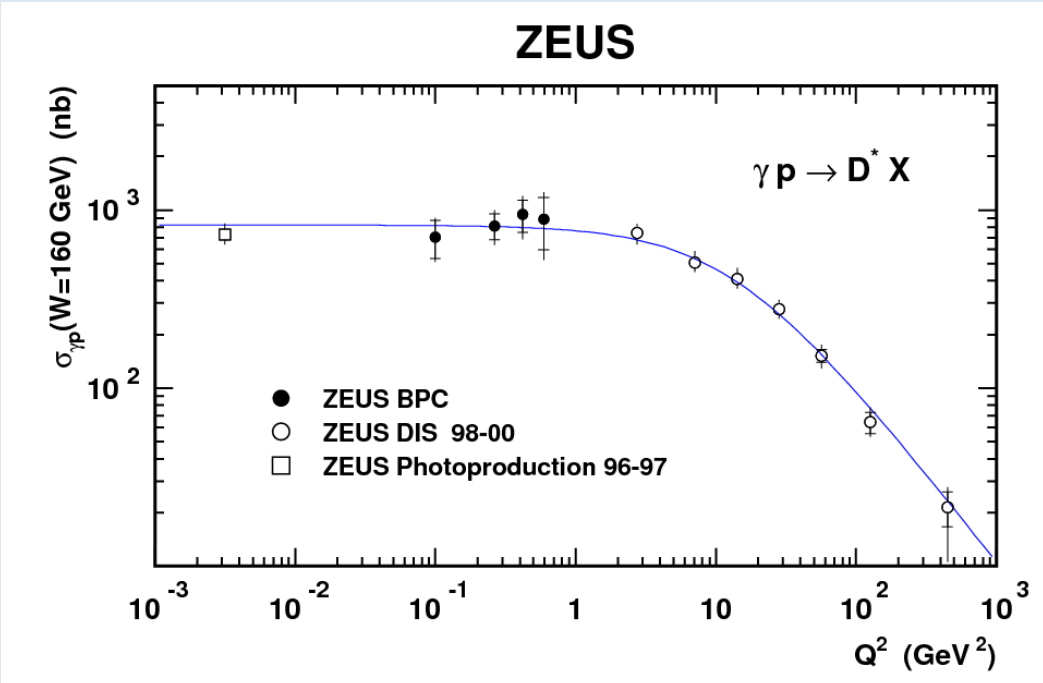
Charm Production

- Earlier ZEUS measurements include very low Q^2



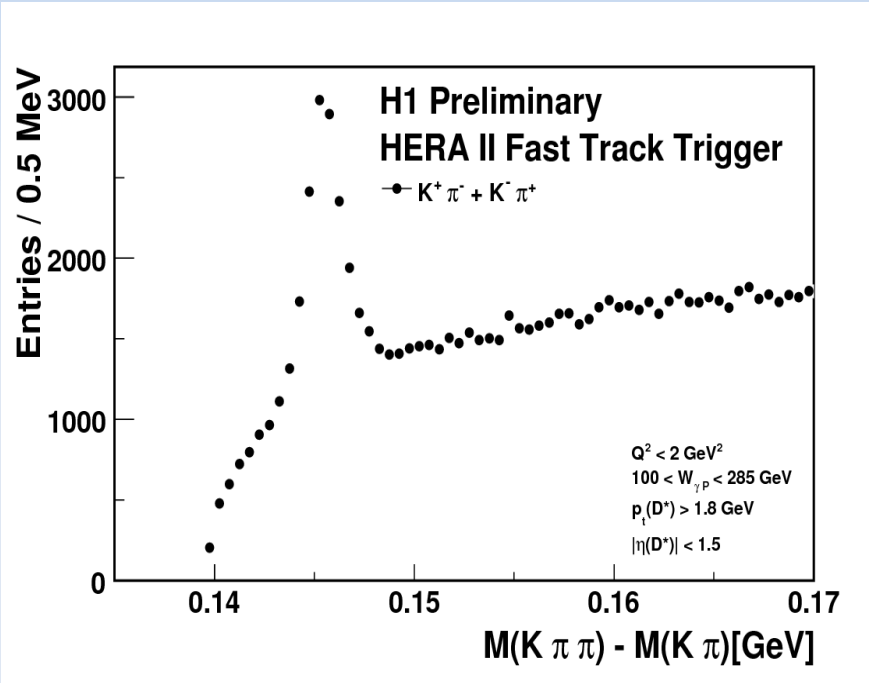
HVQDIS describes data over 5 orders of magnitude cross-section variation

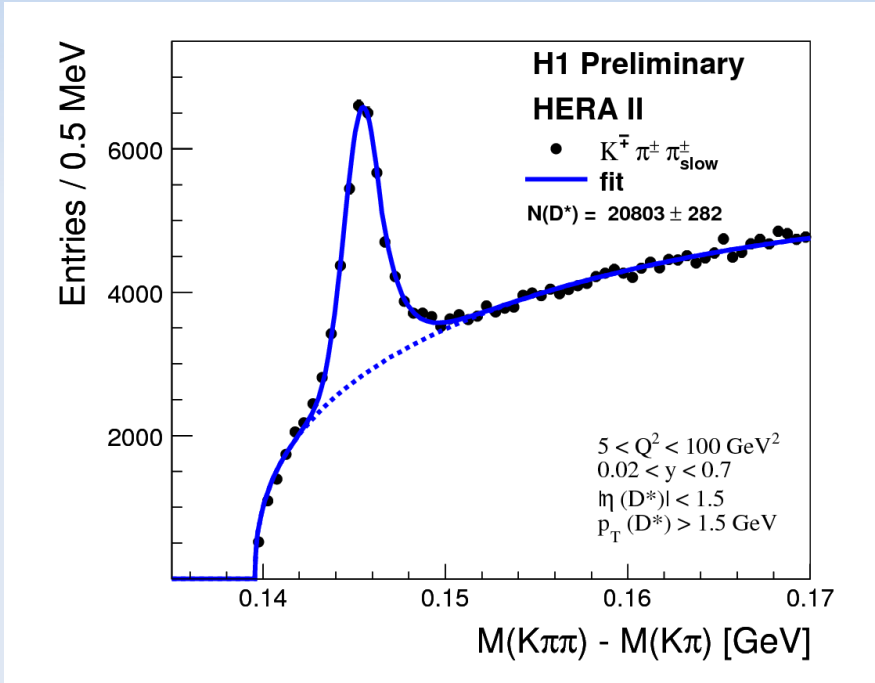
- Single function to describe γp cross-section over full Q^2 range



Charm Production

- Photoproduction:
  $Q^2 < 2$ GeV^2
- DIS:
  $Q^2 > 5$ GeV^2

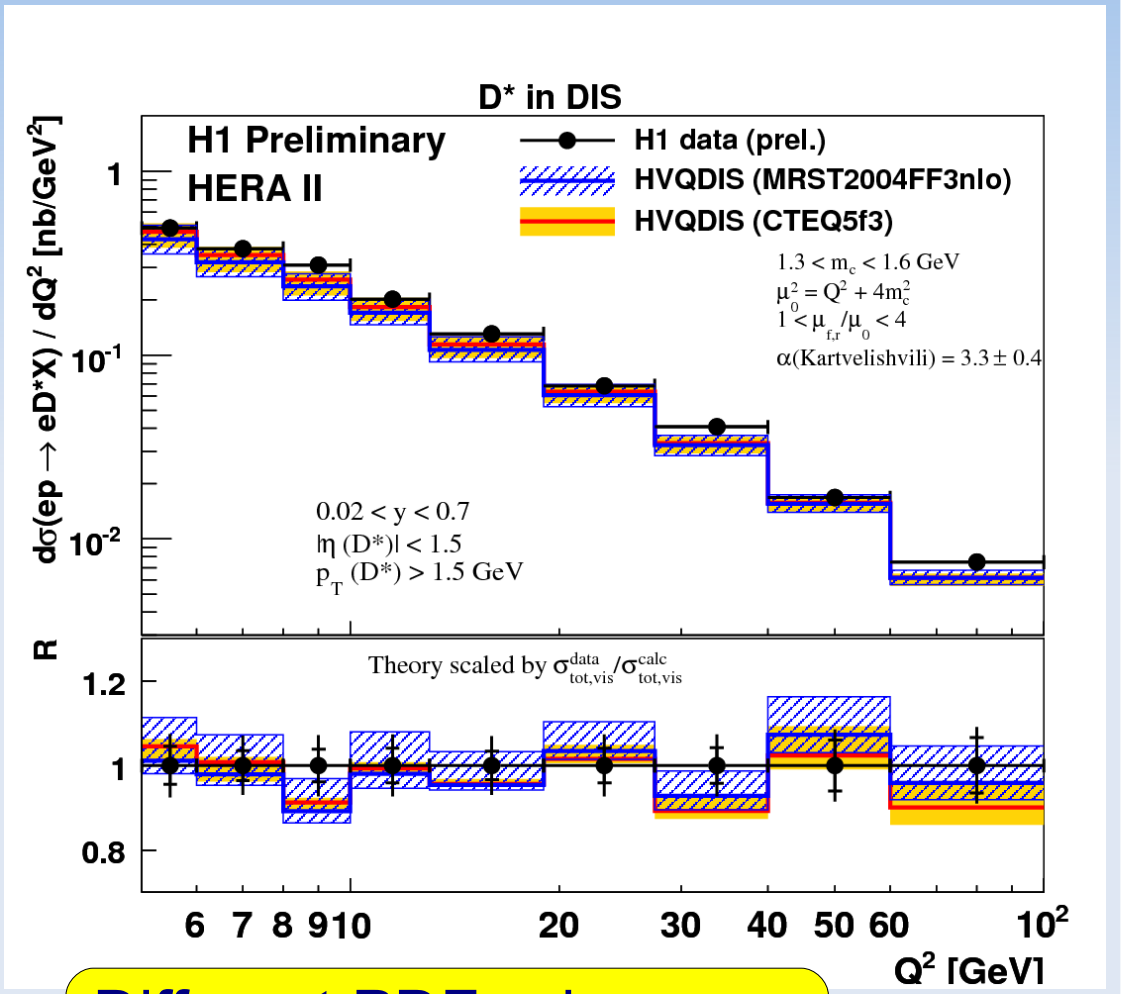




$$D^{*-} \to \bar{D}^0 \pi^- \to K^+ \pi^- \pi^-$$

Charm Production

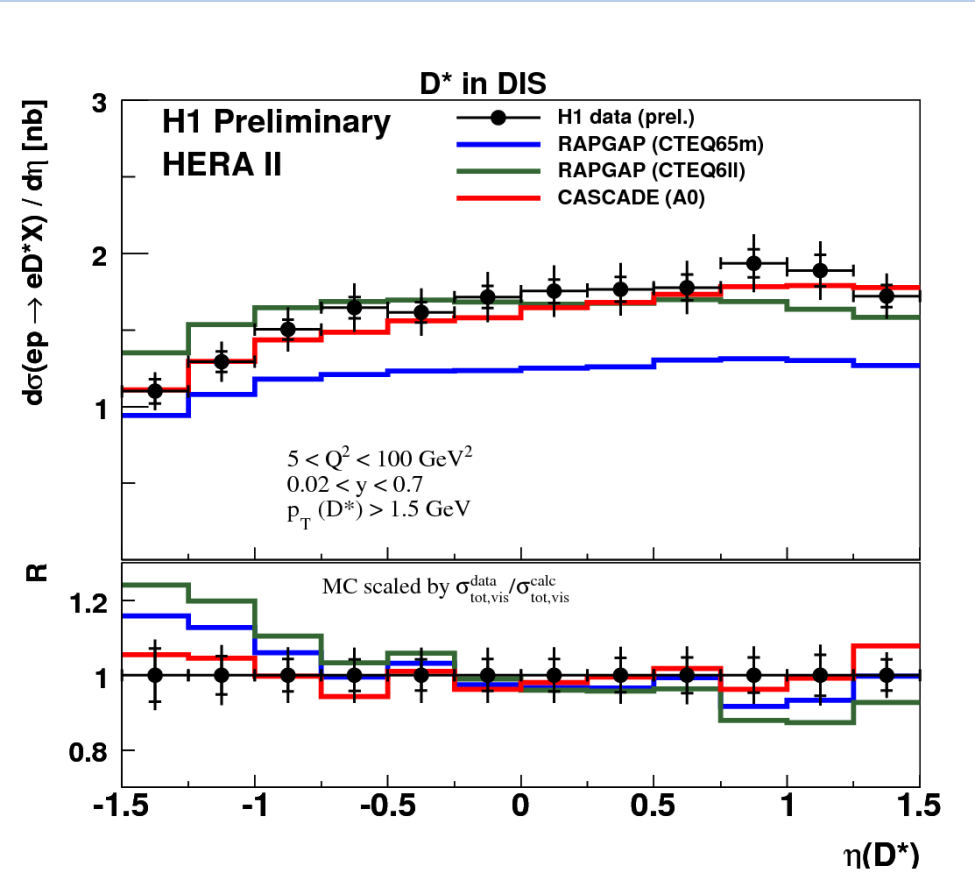
- Cross-section as a function of
  - Q^2
  - P_T, η of D*
  - Photoproduction:
    - W (γp CM energy)
  - DIS
    - y (inelasticity)
- Compared to MC and NLO predictions



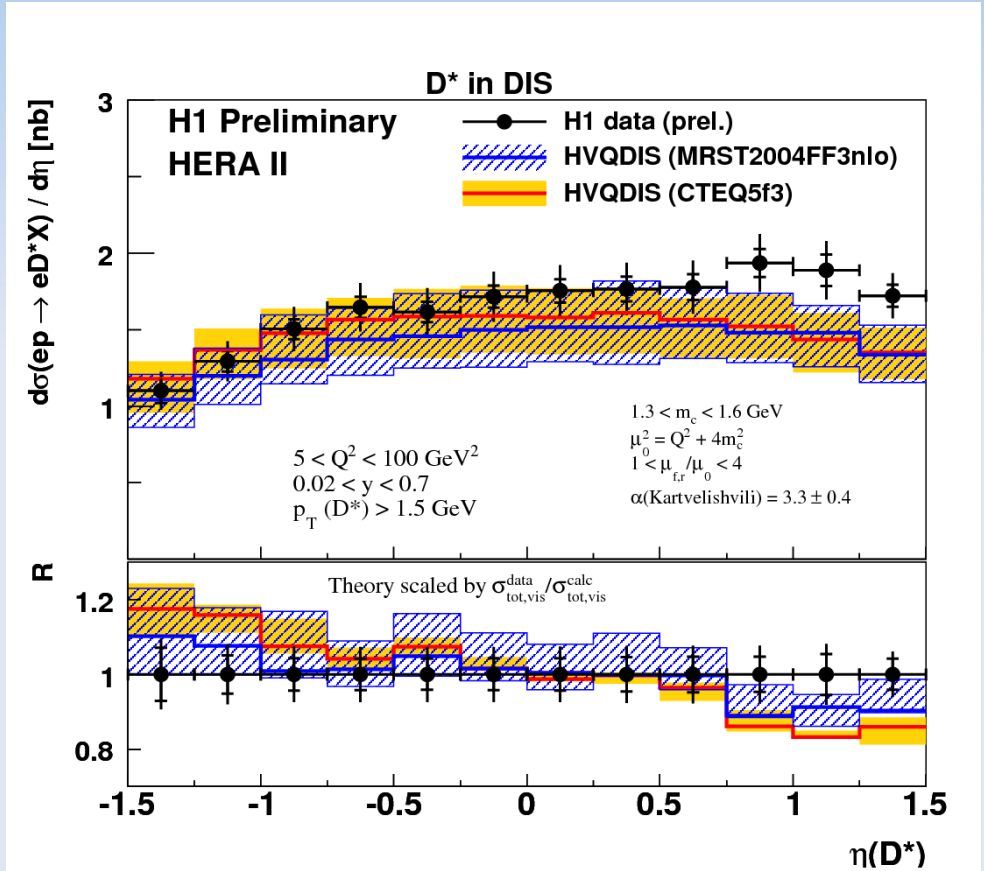
Different PDFs show very similar Q^2 behaviour

Charm in DIS

- Compare with MC



- Compare with NLO

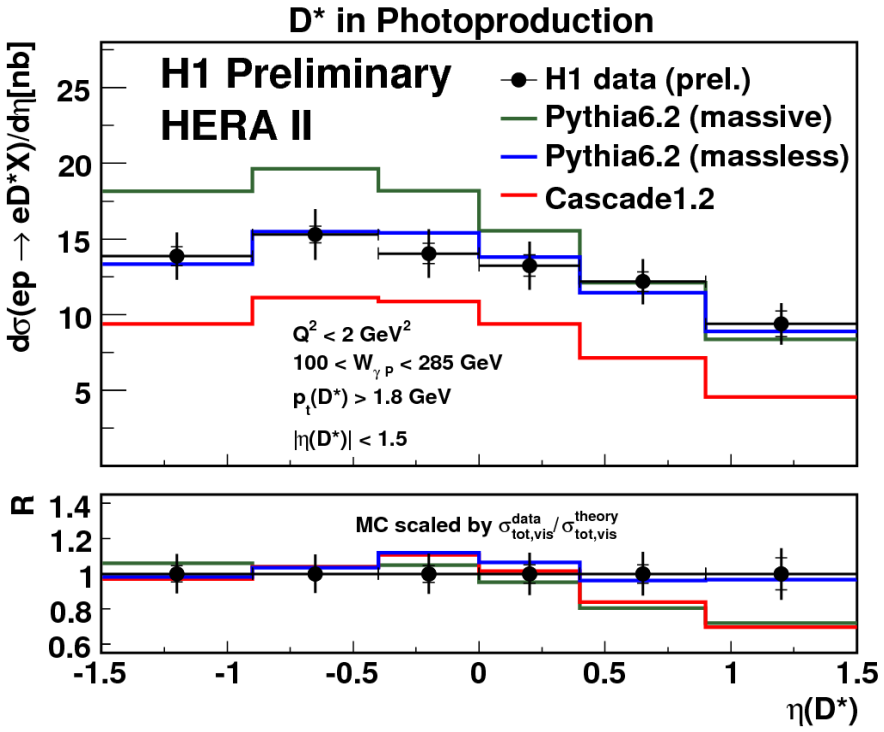


Significant changes for different PDFs
Cascade agrees very well with data

Data overshoot prediction at large η
Some sensitivity to gluon: MRST vs CTEQ

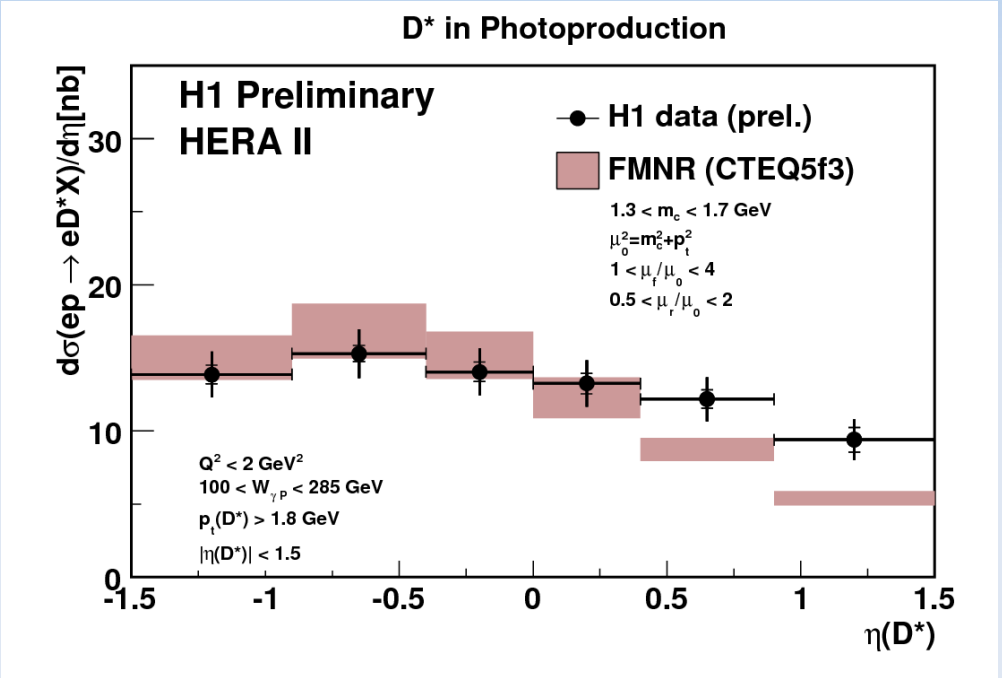
Charm in Photoproduction

- Compare with MC



Significant changes for different MCs
Pythia with massless charm
agrees very well with data

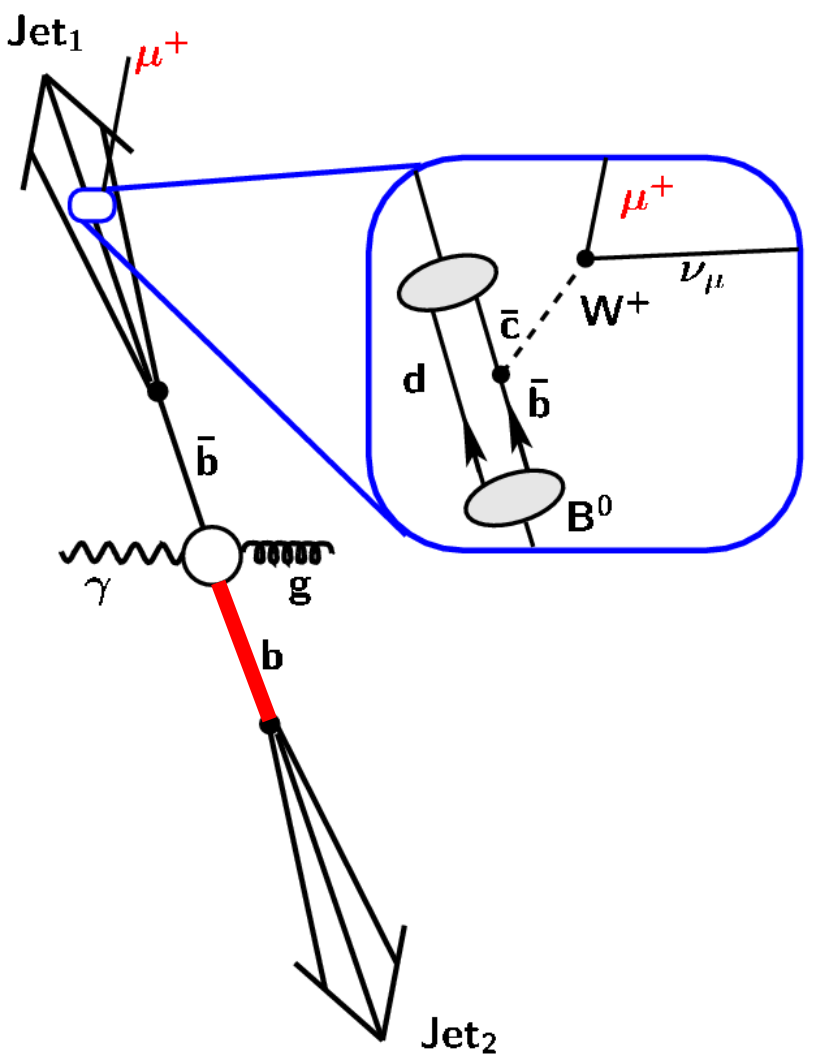
- Compare with NLO



Data overshoot prediction at large η

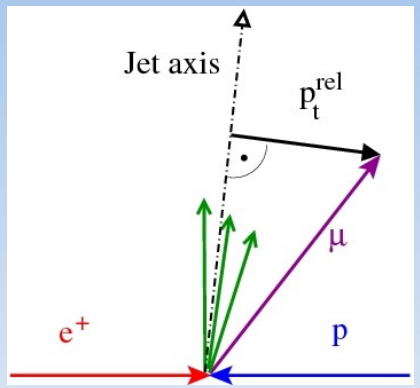
Beauty in Photoproduction

- HERA II data
  - 124 pb^{-1} (2005)
- Photoproduction
- Dijet events
  - $P_T^{jet} > 7(6)$ GeV
- Semileptonic decays to muons ($p_T^{\mu} > 2.5$ GeV)
- Include lifetime information

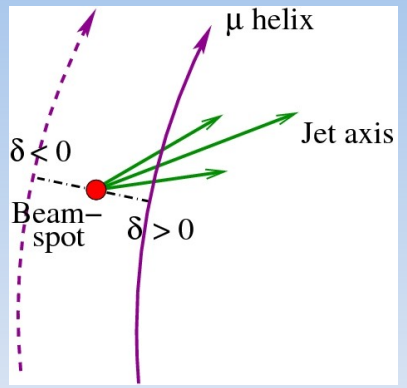


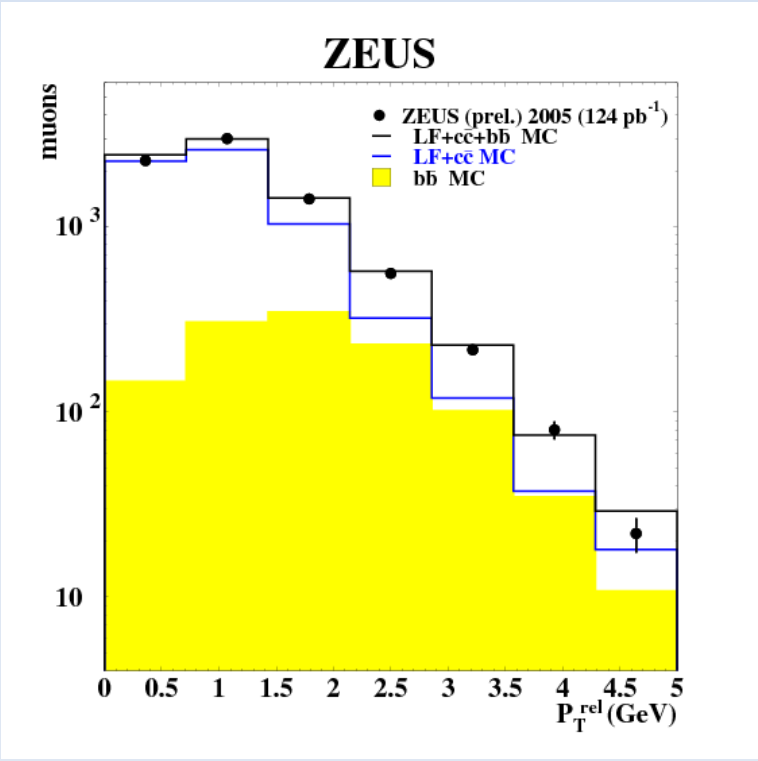
Beauty in Photoproduction

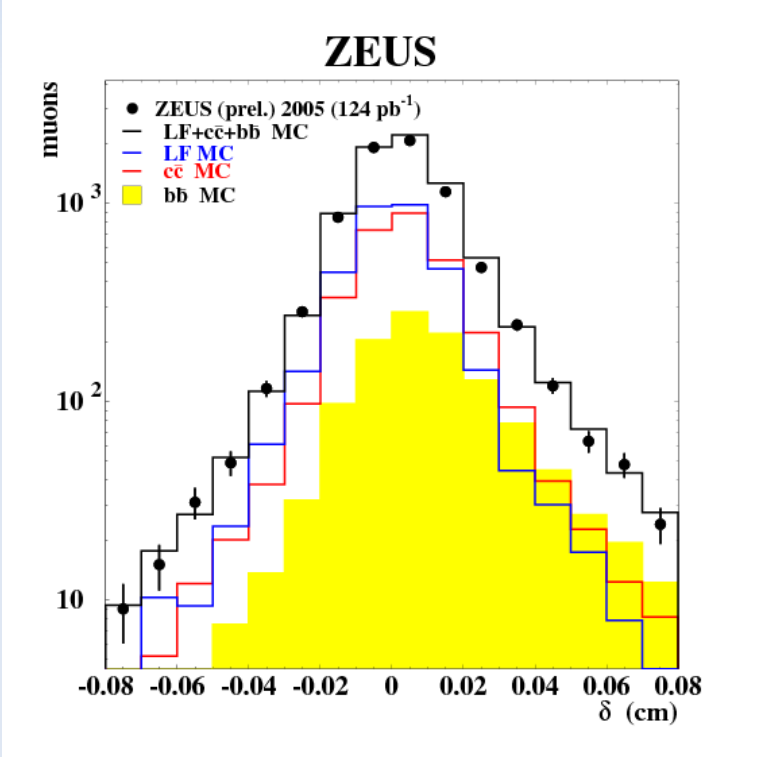
- p_T^{rel}



- Impact parameter





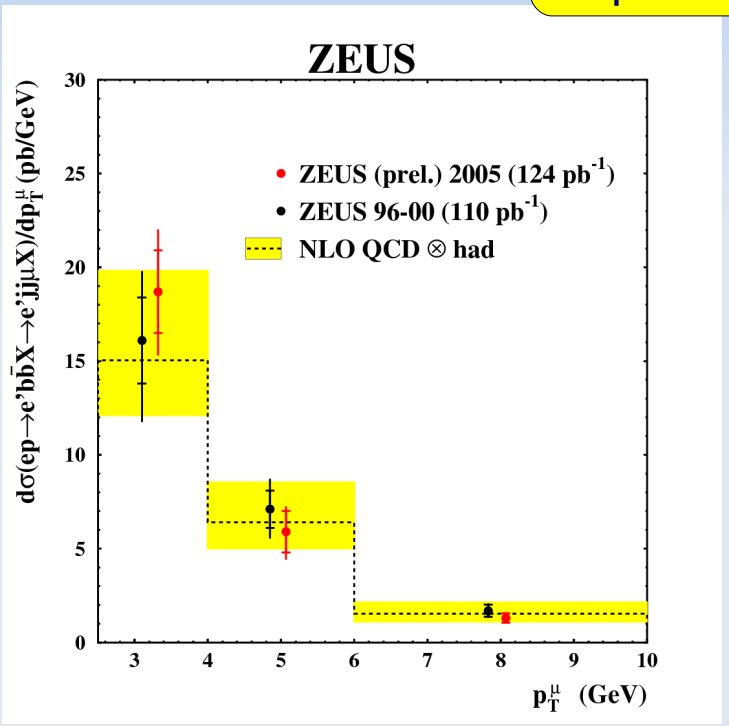


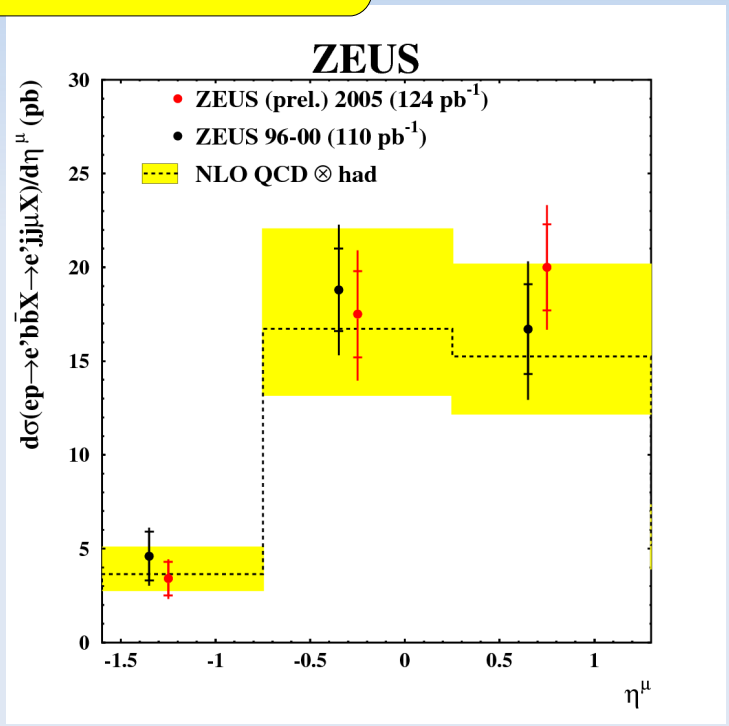
Beauty in Photoproduction

$$\sigma^{vis} = 46.8 \pm 4.0(stat.)^{+6.1}_{-7.2}(syst.)\,\text{pb}$$

$$\sigma^{NLO} = 41.5^{+13.9}_{-8.9}\,\text{pb}$$

Renormalisation/factorisation scales
b quark mass



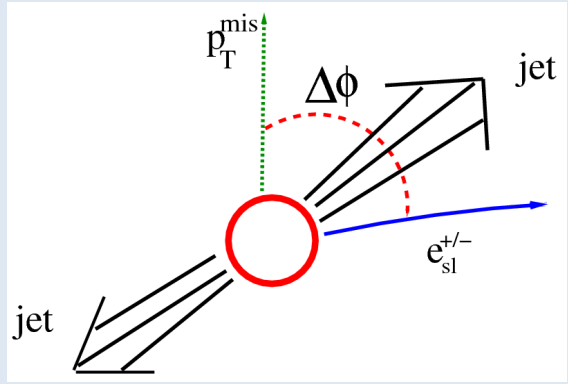


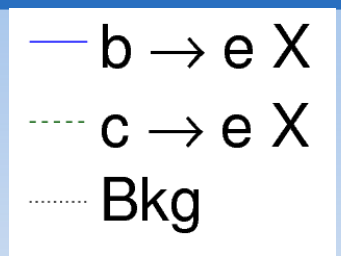
$P_T^\mu > 2.5$ GeV

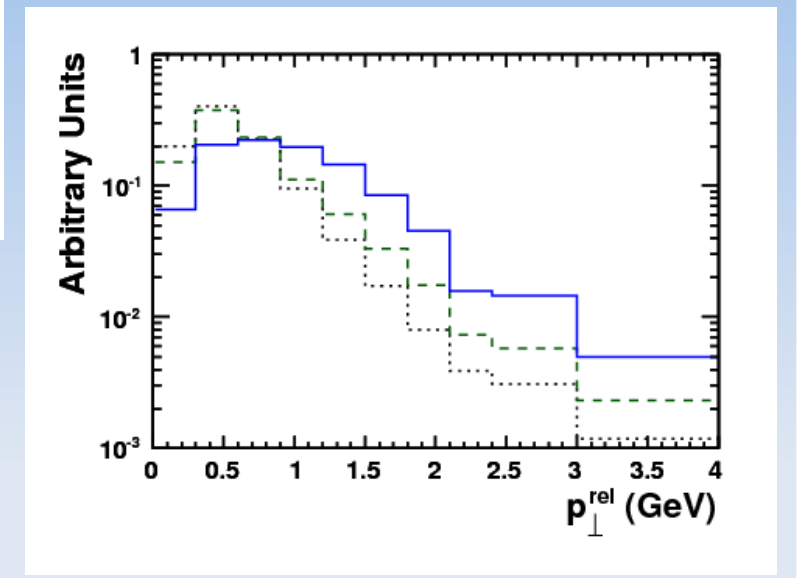
Good agreement between
HERA I and HERA II cross-sections

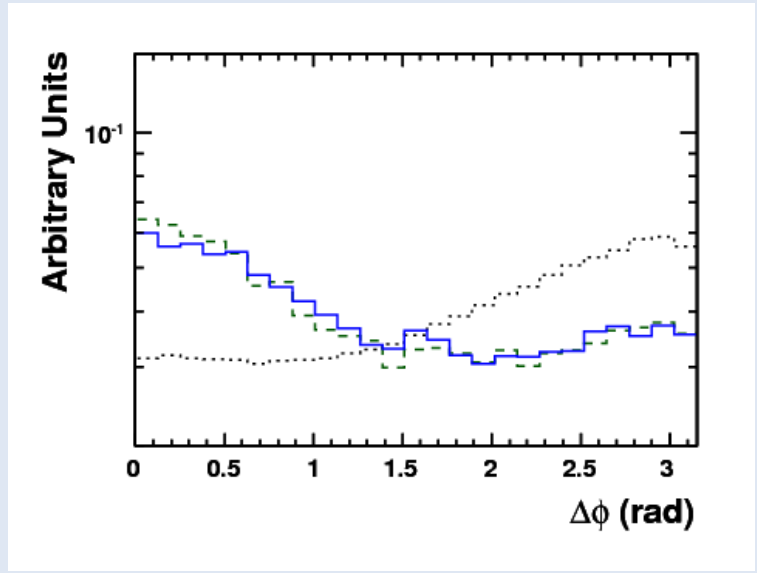
b & c in Photoproduction

- HERA I data
  - 120 pb^{-1} (1996-2000)
- Dijet photoproduction events
  - $E_T^{jet} > 7(6)$ GeV
- Semileptonic decays to electrons ($p_T^e > 0.9$ GeV)
- Look for more variables to determine b and c quark fractions separately



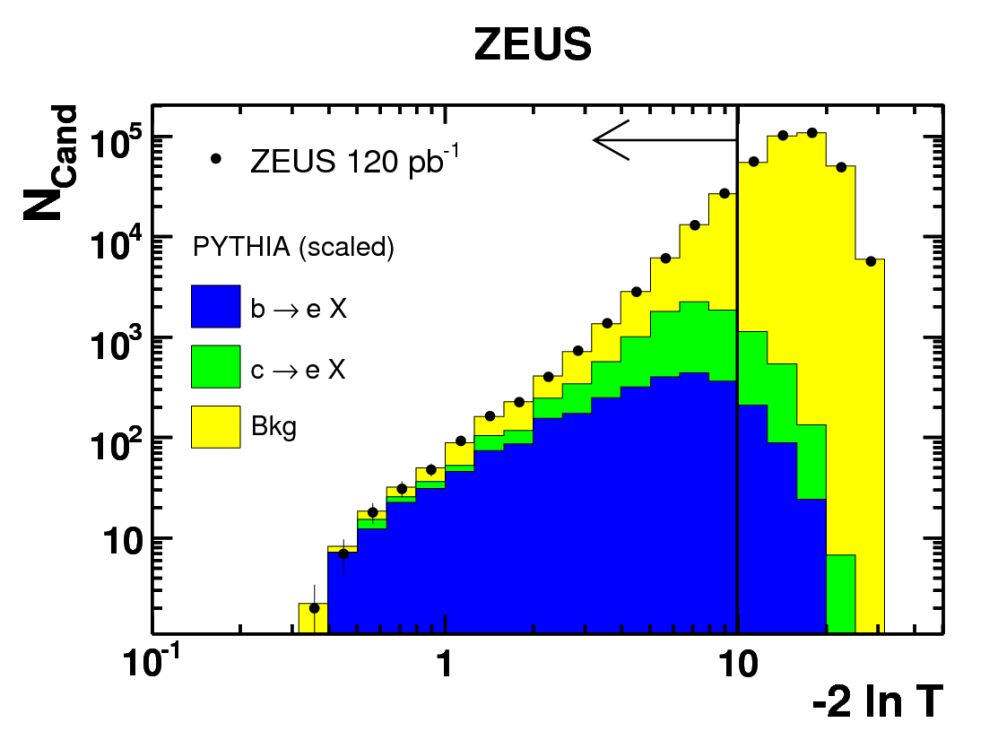




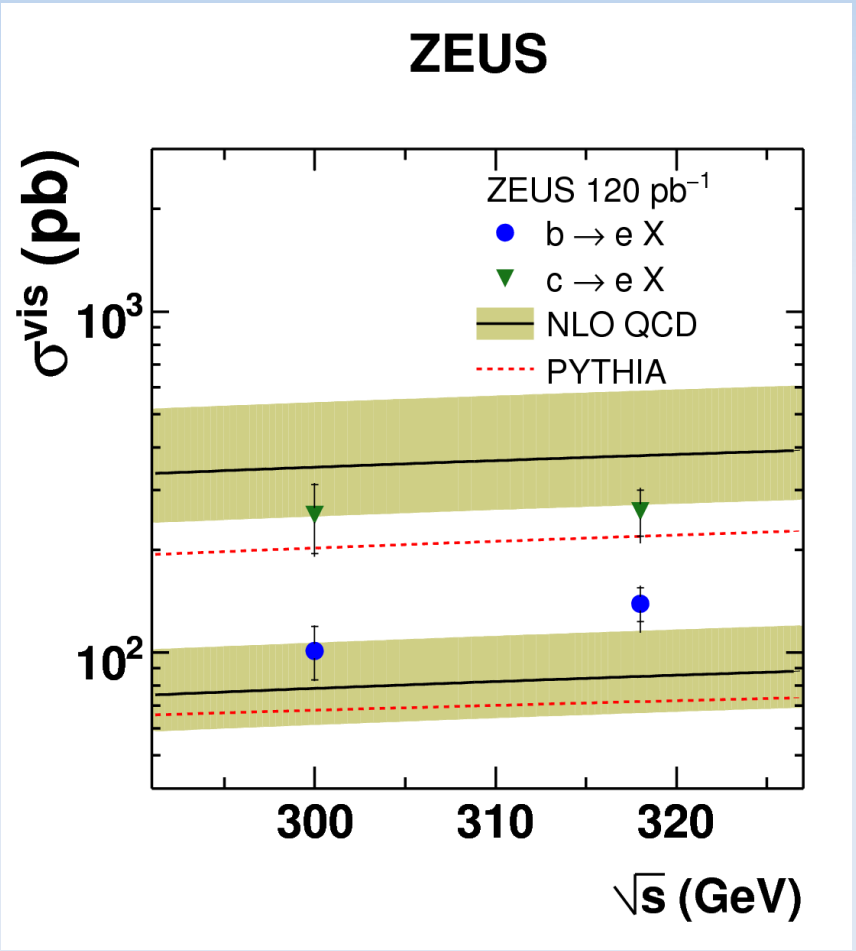


b & c in Photoproduction

- Use a likelihood ratio method to separate b,c and light flavour



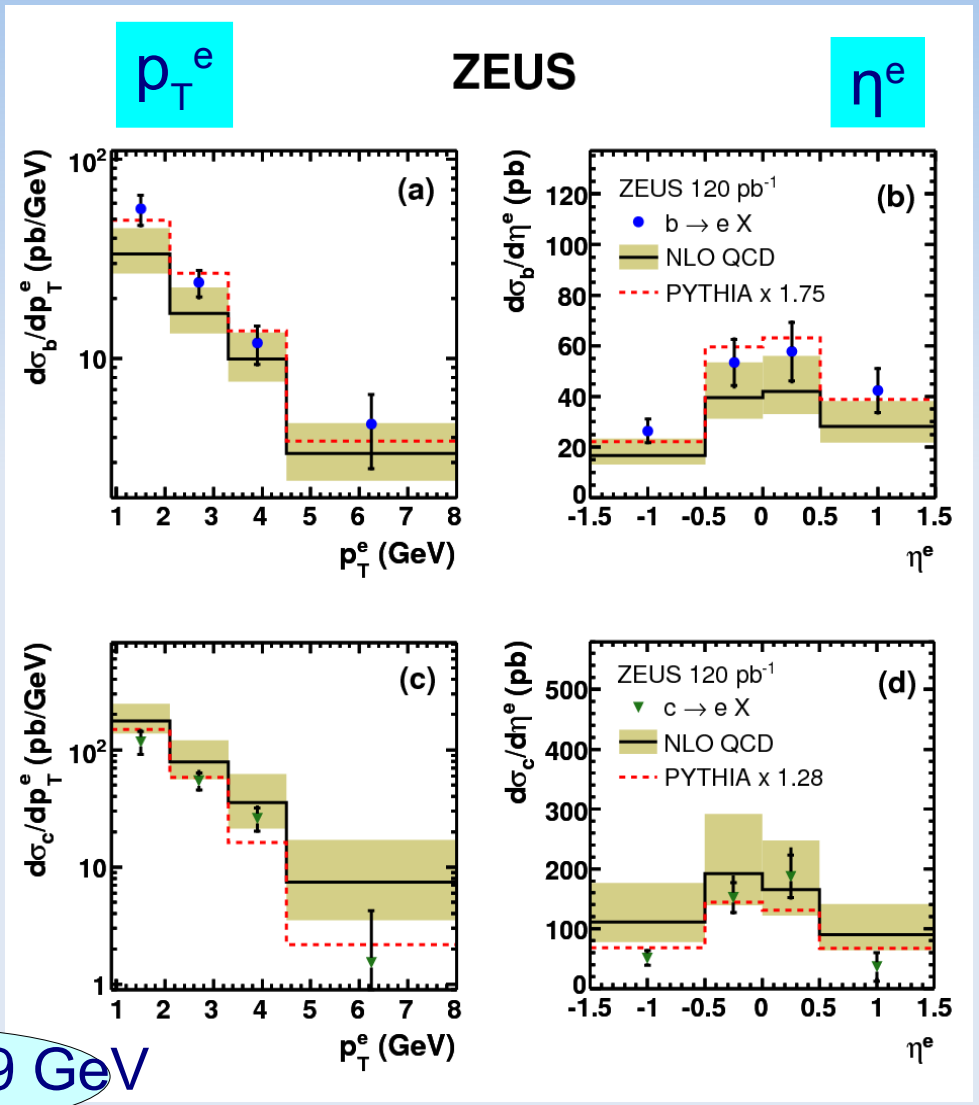
- Visible cross-section



b & c in Photoproduction

Beauty

Charm

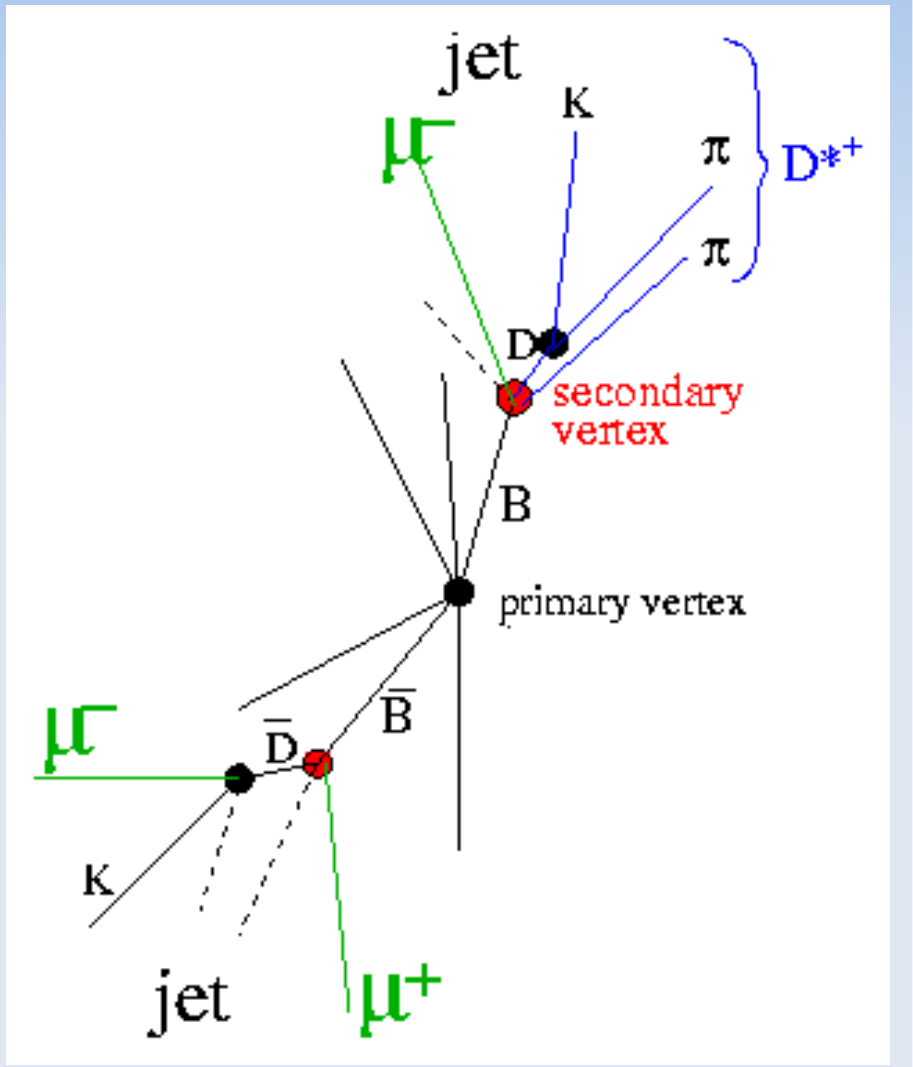


$P_T^e > 0.9$ GeV

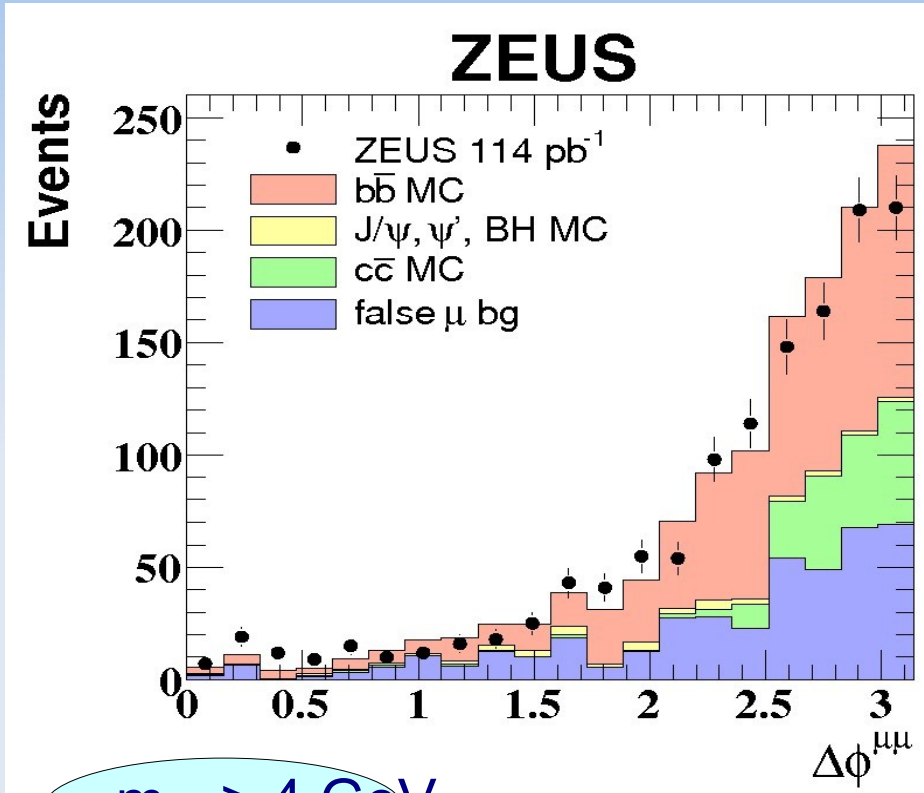
- LO Monte Carlo scale factors:
  - b x 1.75
  - c x 1.28
- NLO absolute predictions

$b\bar{b}$ Production

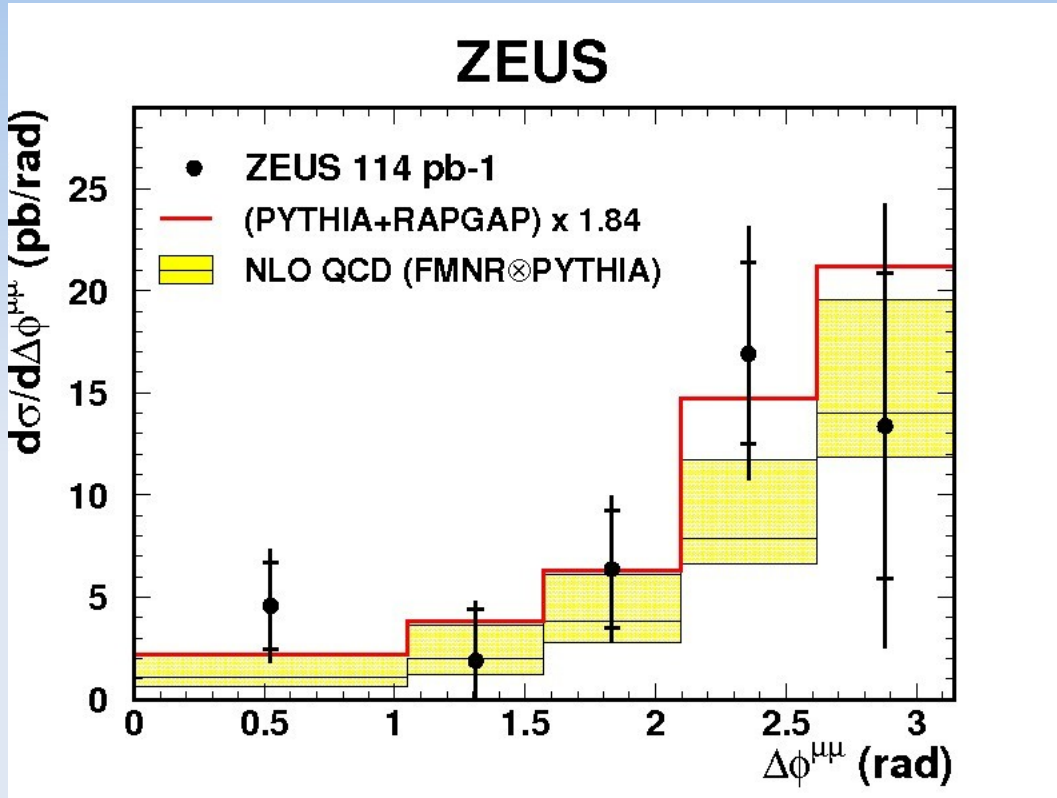
- Double tag events
  - Low background ☺
  - Larger kinematic range ☺
  - Low statistics ☹
- $E_T > 8$ GeV
- Two identified muons
- PhP + DIS
- Measure $b\bar{b}$ correlations
  - Probe NLO effects



$b\bar{b}$ Production

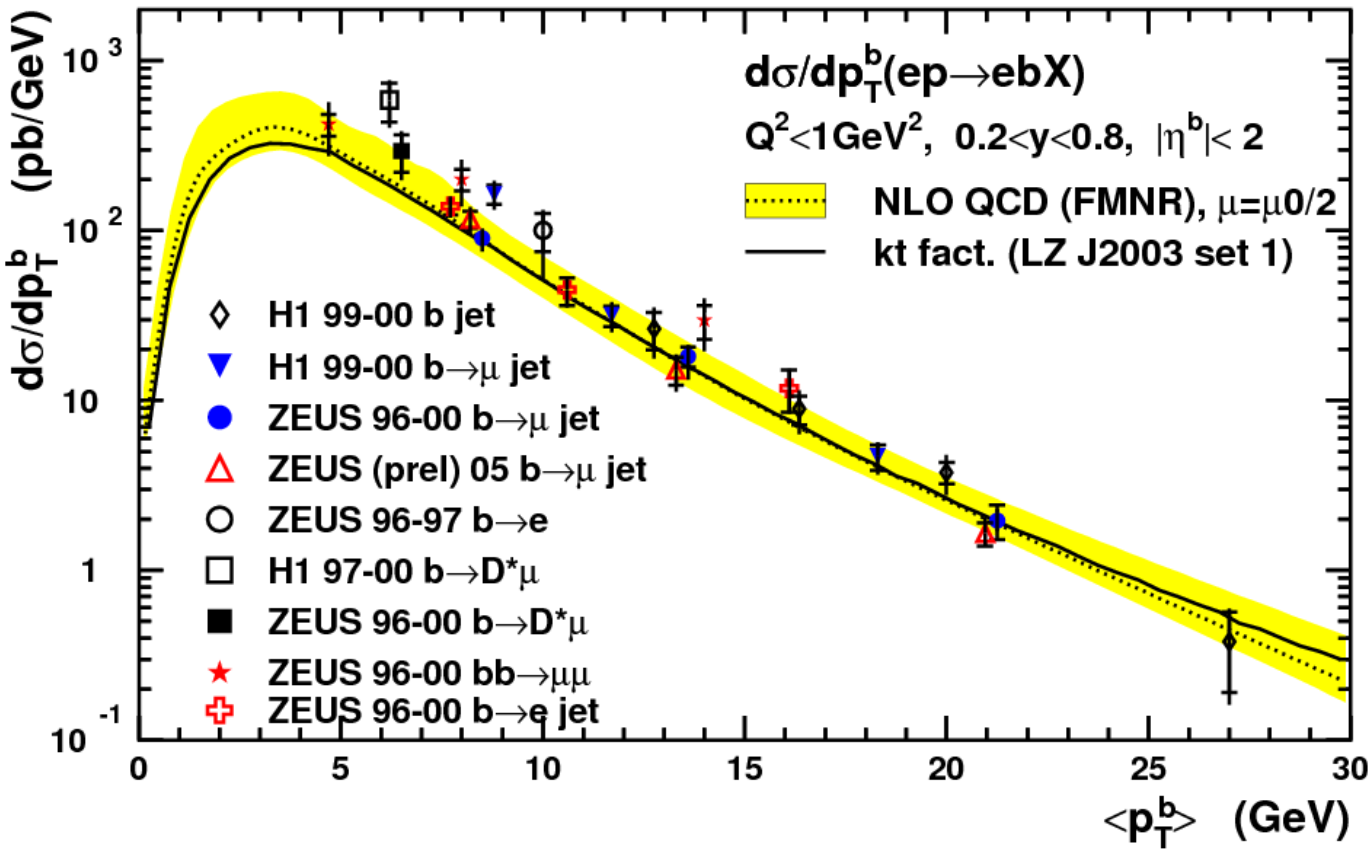


$m_{\mu\mu} > 4$ GeV



- Δφ between muons from different quarks
- Correlations reasonably well described

Summary of b Photoproduction

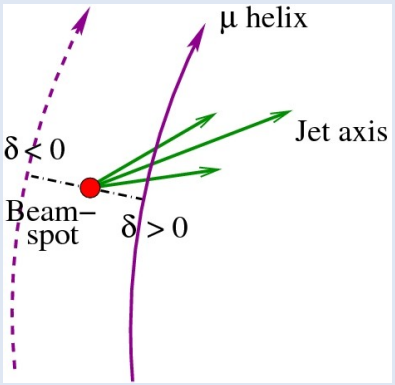


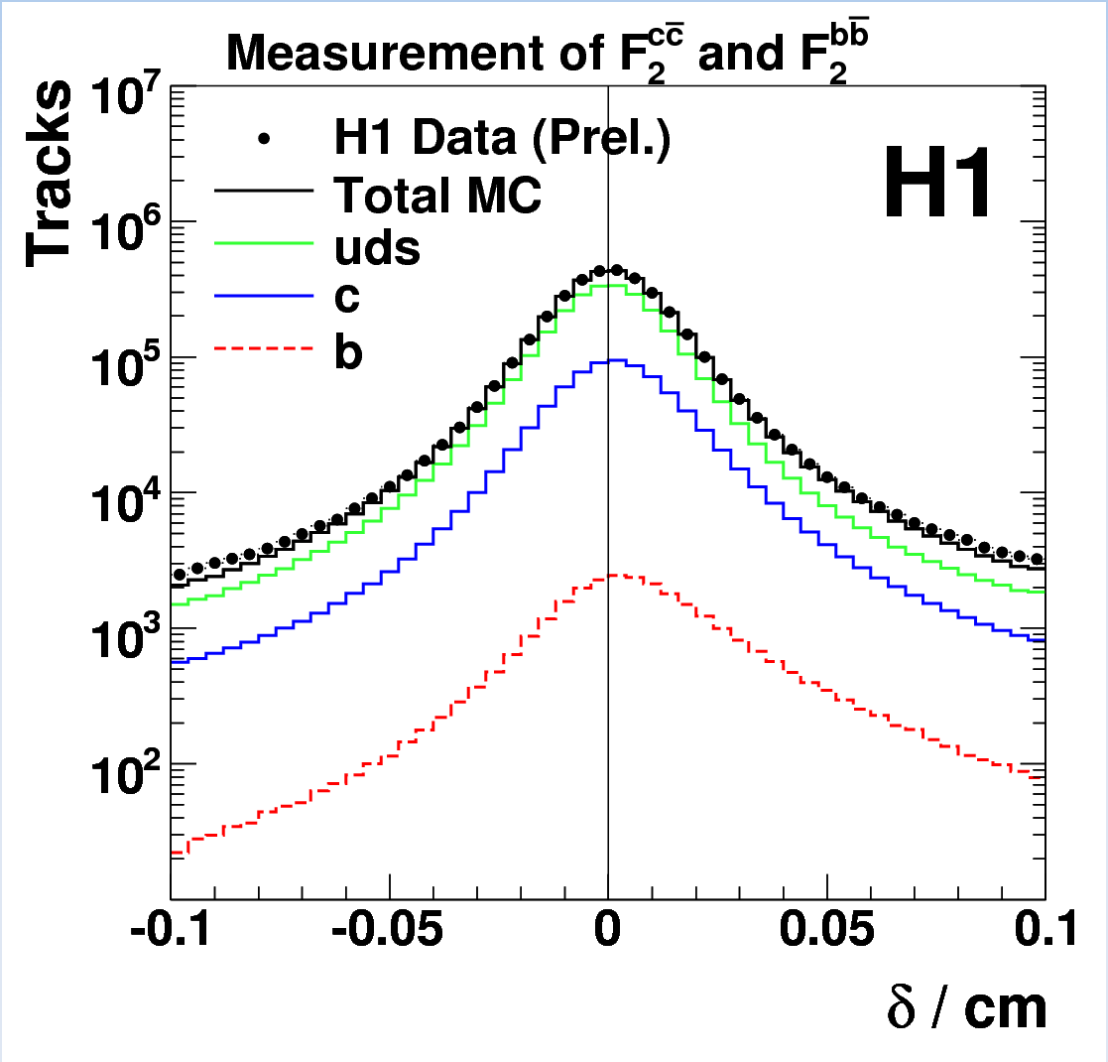
Plot actually shows ratio of measurement to FMNR prediction

No sign of large excess seen in first b production measurements

b & c in DIS

- HERA II data
- 54 pb^{-1} (2006)
- DIS
  - $Q^2 > 12\ GeV^2$
- Use lifetime information

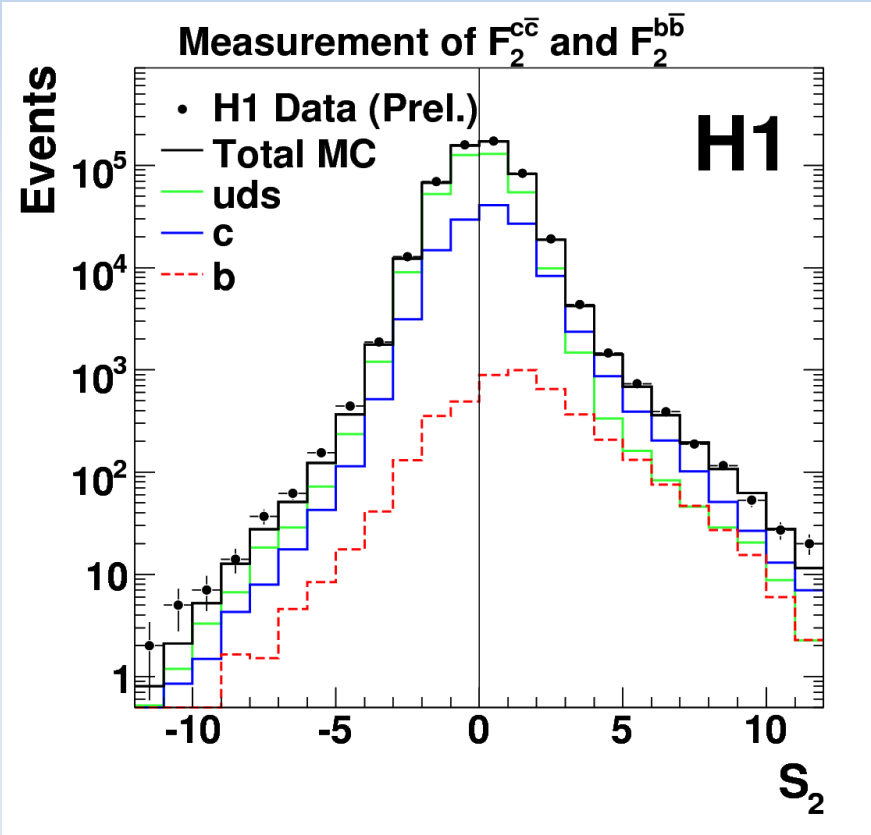




b & c in DIS

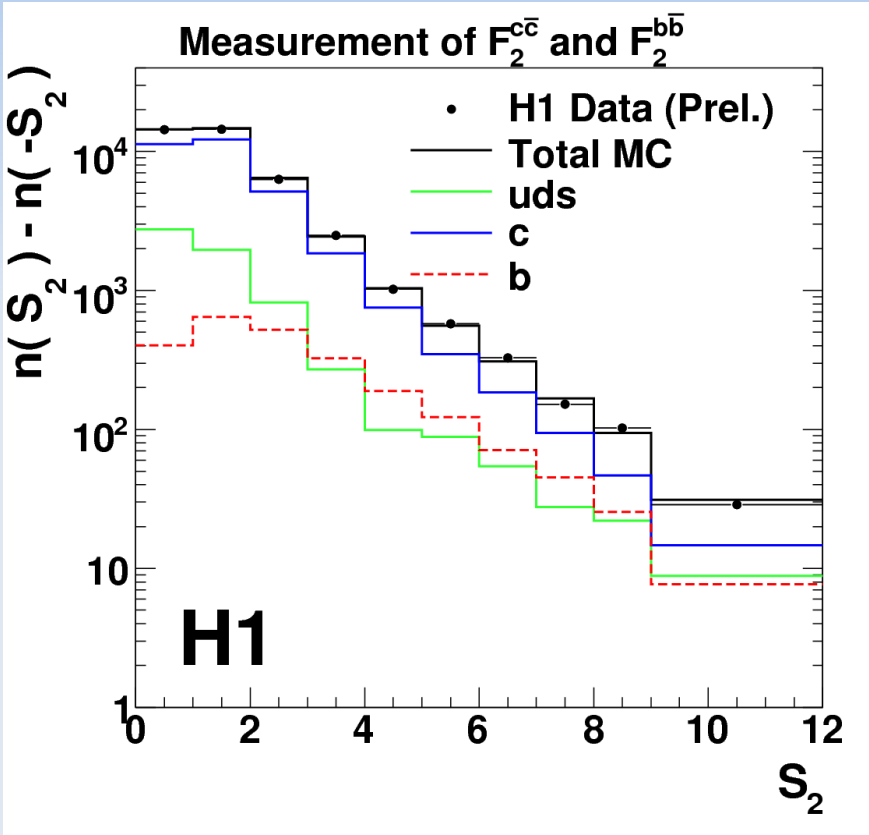
- Significance: δ / σ_δ

S_1 highest
S_2 2nd highest



Reject events when S_1 and S_2 have opposite sign

- Subtracted significance



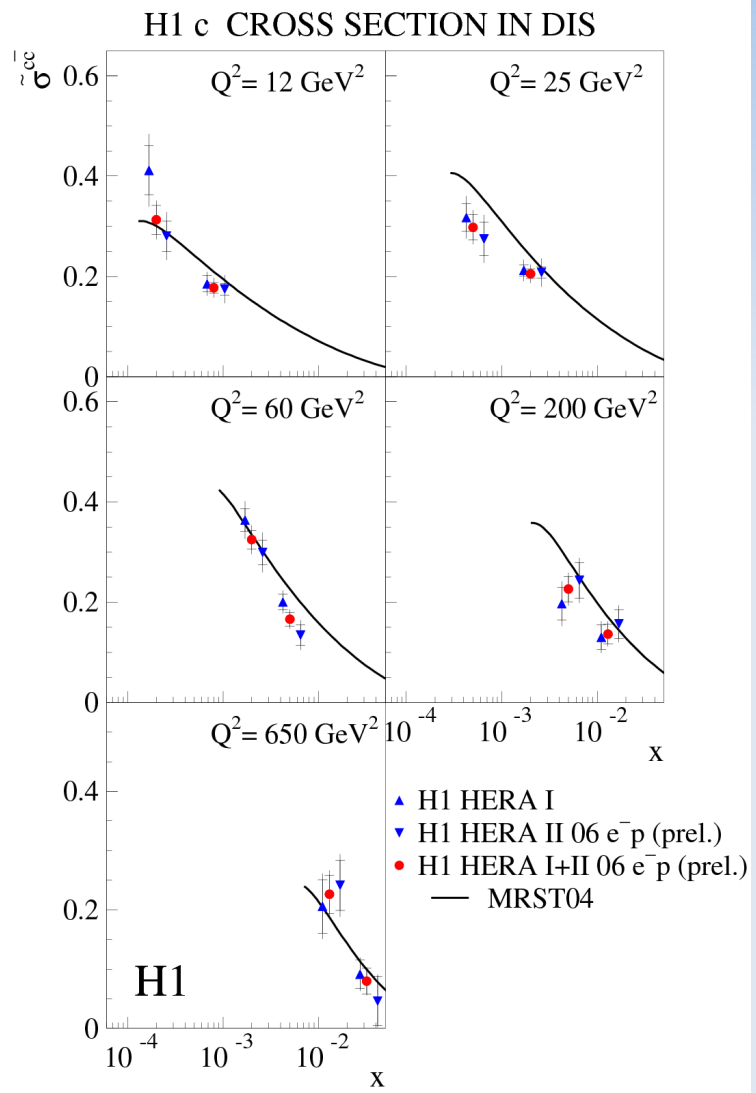
Dominated by charm
More beauty at high significance

b & c in DIS

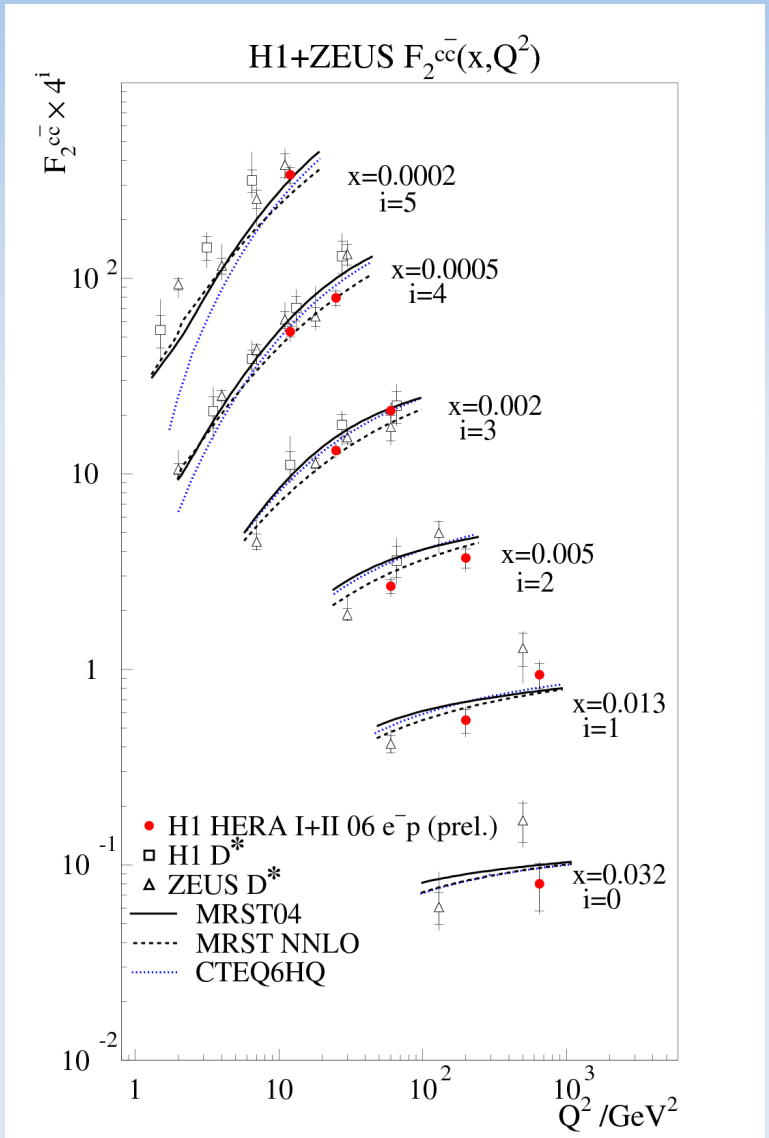
- Split data into Q^2 - x (Bjorken) bins
- Extract F_2 from reduced cross-sections:

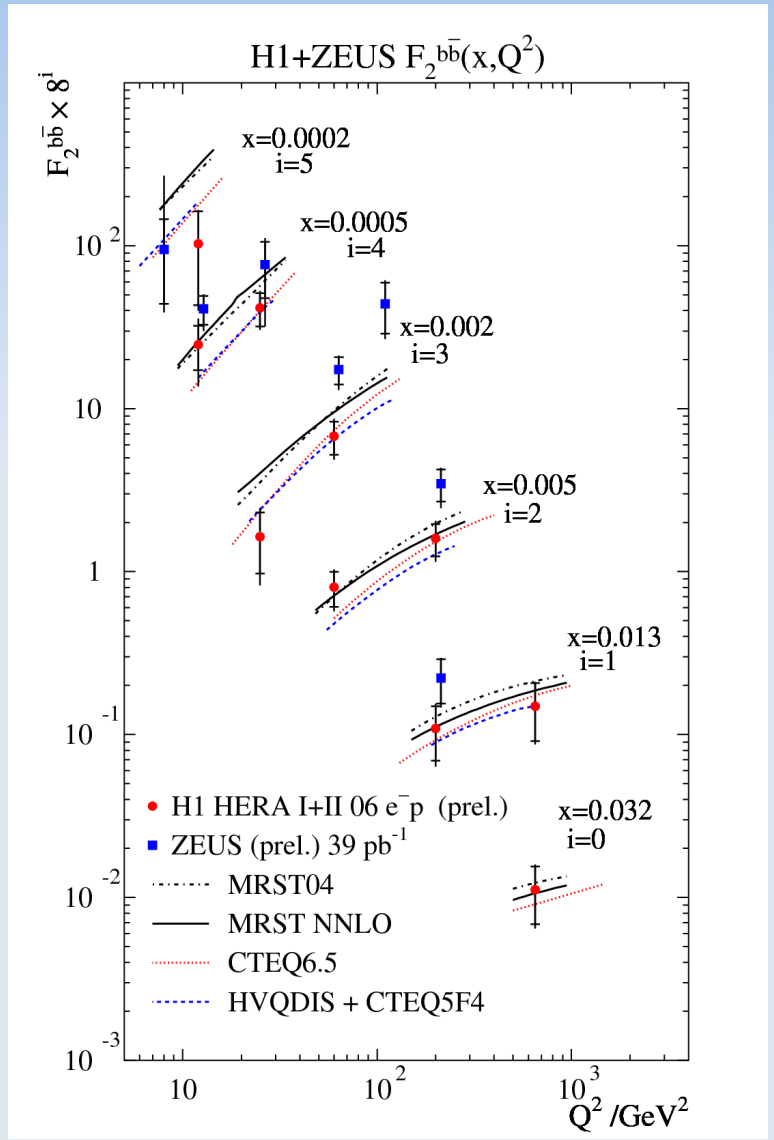
$$\tilde{\sigma}^{c\bar{c}}(x,Q^2) = F_2^{c\bar{c}} - \frac{y^2}{(1+(1-y)^2)} F_L^{c\bar{c}}$$

- Combine HERA I & HERA II measurements



b & c in DIS


H1+ZEUS $F_2^{c\bar{c}}(x,Q^2)$
$F_2^{c\bar{c}} \times 4^i$
x=0.0002 i=5
x=0.0005 i=4
x=0.002 i=3
x=0.005 i=2
x=0.013 i=1
x=0.032 i=0
H1 HERA I+II 06 e⁻p (prel.)
H1 D*
ZEUS D*
MRST04
MRST NNLO
CTEQ6HQ
Q^2 /GeV^2


H1+ZEUS $F_2^{b\bar{b}}(x,Q^2)$
$F_2^{b\bar{b}} \times 8^i$
x=0.0002 i=5
x=0.0005 i=4
x=0.002 i=3
x=0.005 i=2
x=0.013 i=1
x=0.032 i=0
H1 HERA I+II 06 e⁻p (prel.)
ZEUS (prel.) 39 pb^{-1}
MRST04
MRST NNLO
CTEQ6.5
HVQDIS + CTEQ5F4
Q^2 /GeV^2

Conclusions

- Small selection of HERA heavy flavour measurements presented:
  - D* production
  - Beauty production via semileptonic dcays to e,μ
  - Double μ tags
  - F_2^{cc}, F_2^{bb}
- General agreement with NLO QCD predictions
- LO Monte Carlos usually describe shape well
- Data often overshoot predictions in forward direction

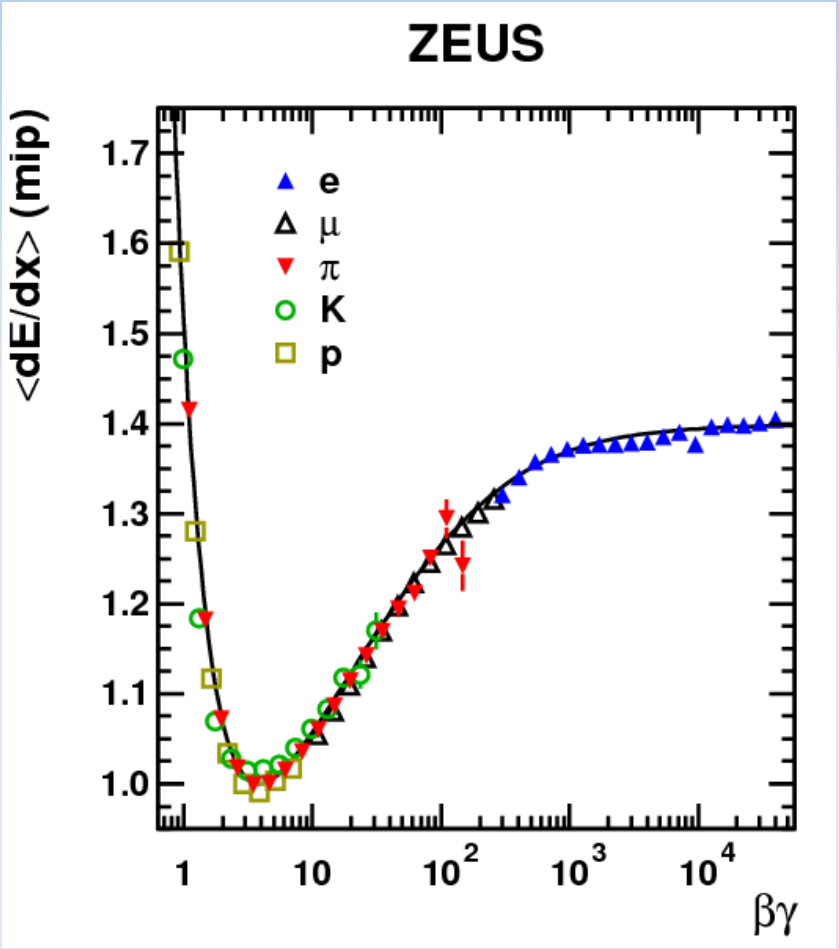
MC@NLO for HERA?

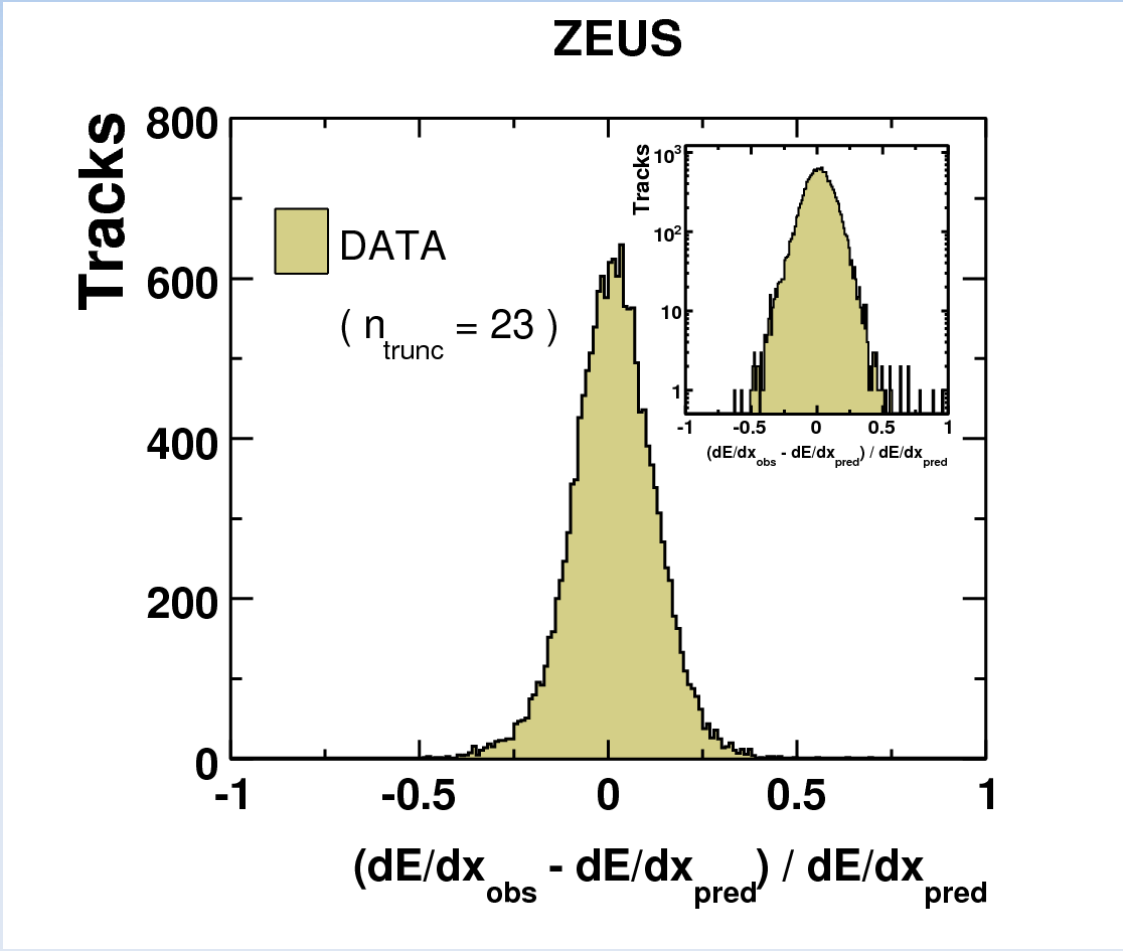
Outlook

- Several HERA I measurements still to be published
- Expand kinematic region:
  - Double tags
  - Semileptonic decays to electrons
  - Lifetime tags
  - Combine tags
- Go forward! (sensitivity to gluon PDF)
  - Use improved HERA II forward tracking
- Many results with complete HERA II dataset still to come

Backup

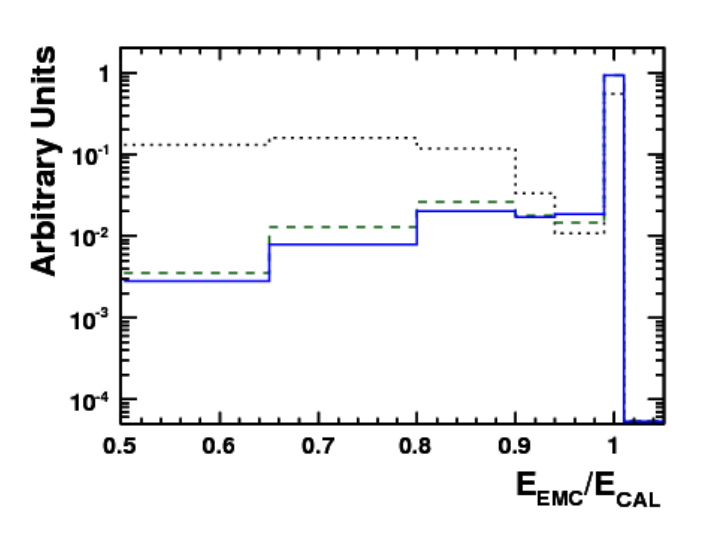
dE/dx in ZEUS

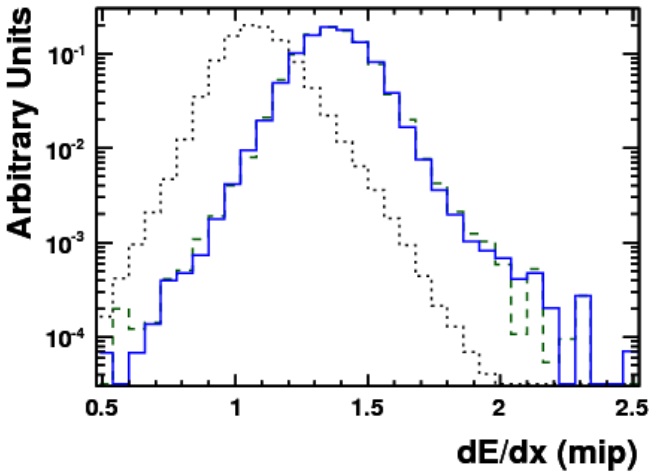

ZEUS
<dE/dx> (mip)
1.7
1.6
1.5
1.4
1.3
1.2
1.1
1.0
e
μ
π
K
p
1
10
10^2
10^3
10^4
βγ

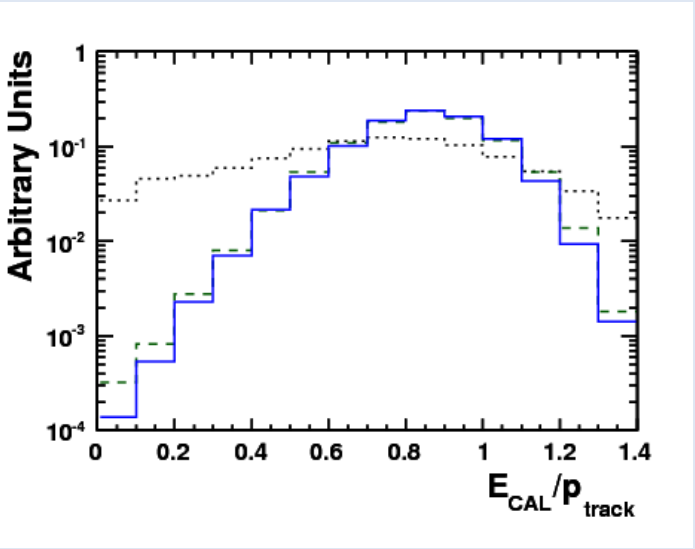

ZEUS
Tracks
800
600
400
200
0
DATA
(n_trunc = 23)
-1
-0.5
0
0.5
1
(dE/dx_obs - dE/dx_pred) / dE/dx_pred
Tracks
10^3
10^2
10
1
-1
-0.5
0
0.5
1
(dE/dx_obs - dE/dx_pred) / dE/dx_pred

b & c in Photoproduction

- Electron identification variables







$b \rightarrow e\ X$

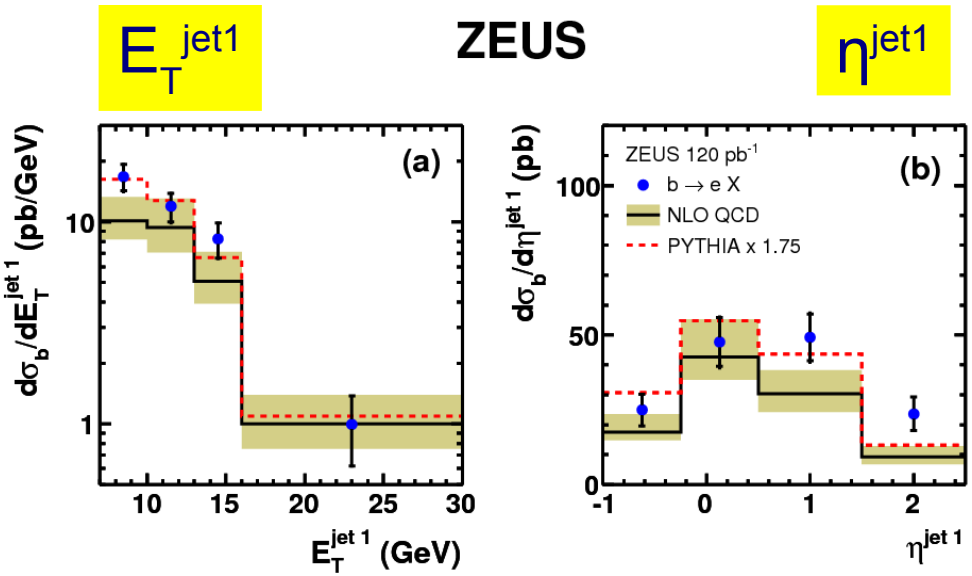
$c \rightarrow e\ X$

Bkg

b & c in Photoproduction

Beauty

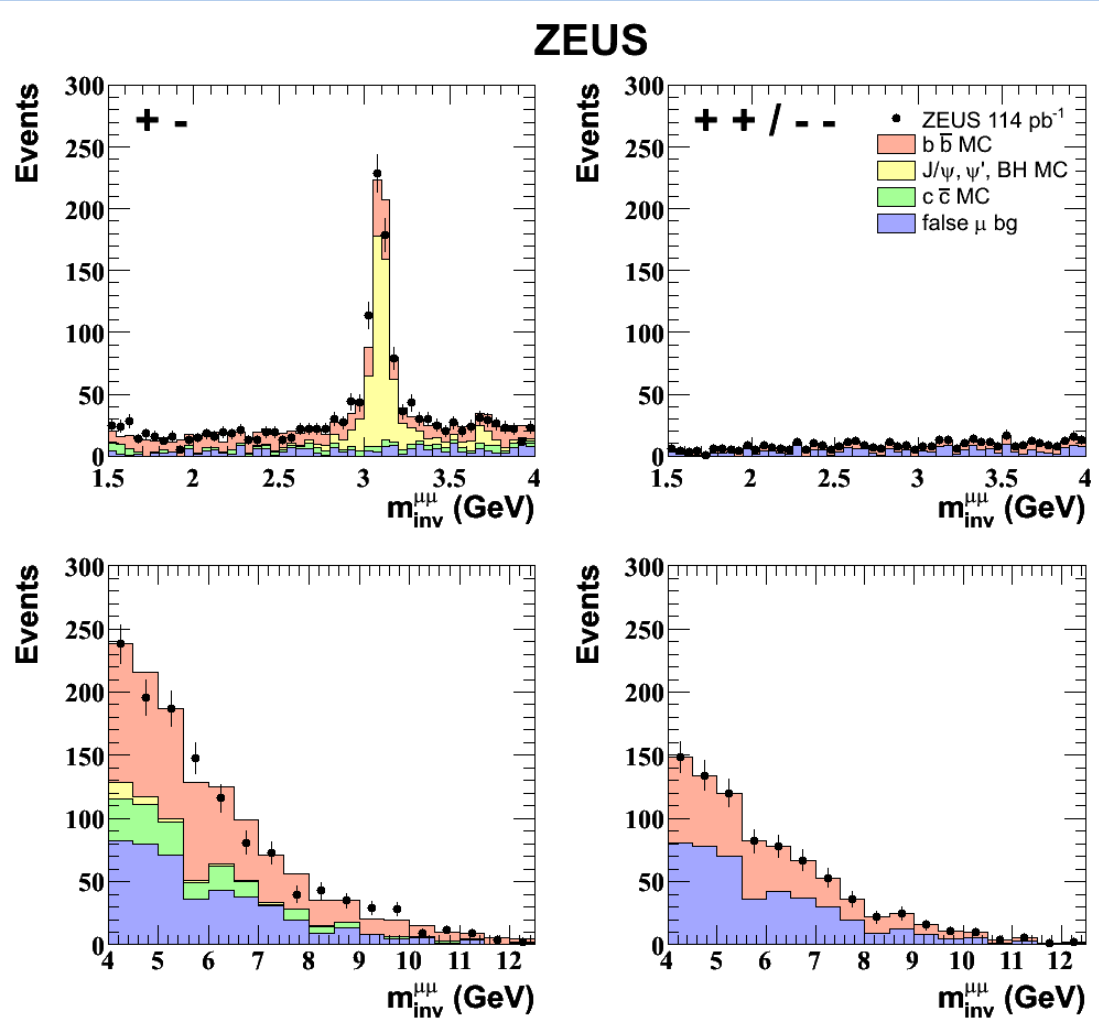
Charm



- LO Monte Carlo scale factors:
  - b x 1.75
  - c x 1.28
- NLO absolute predictions

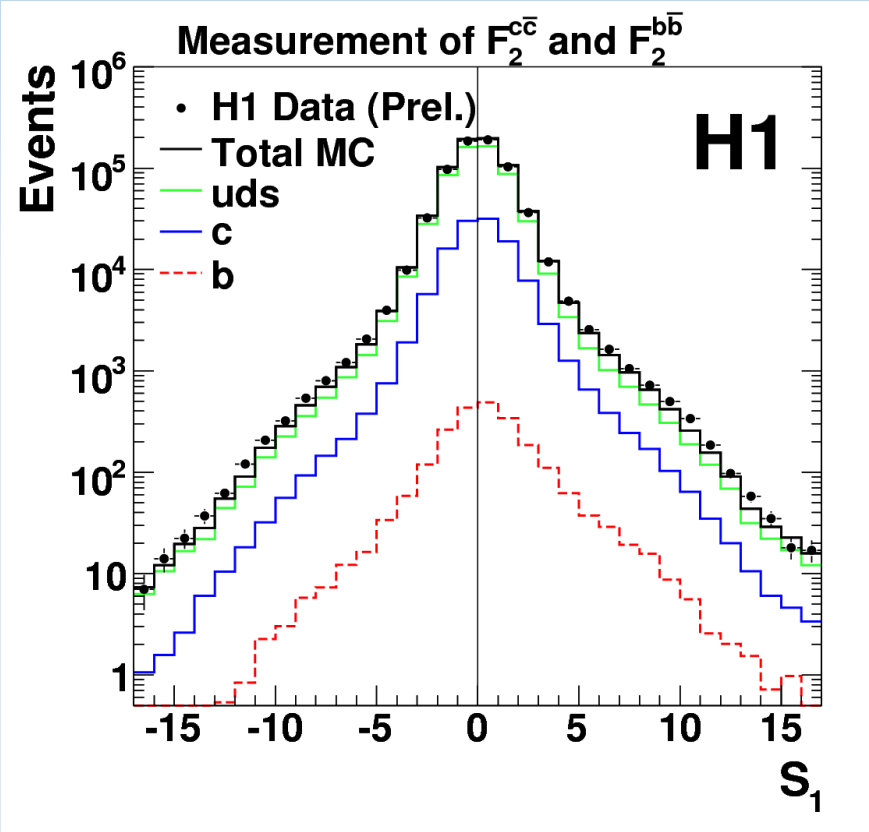
$b\bar{b}$ Production

- Split into different charge combinations
- Also use μμ invariant mass to separate signal and background
- Most of background can be estimated from the data

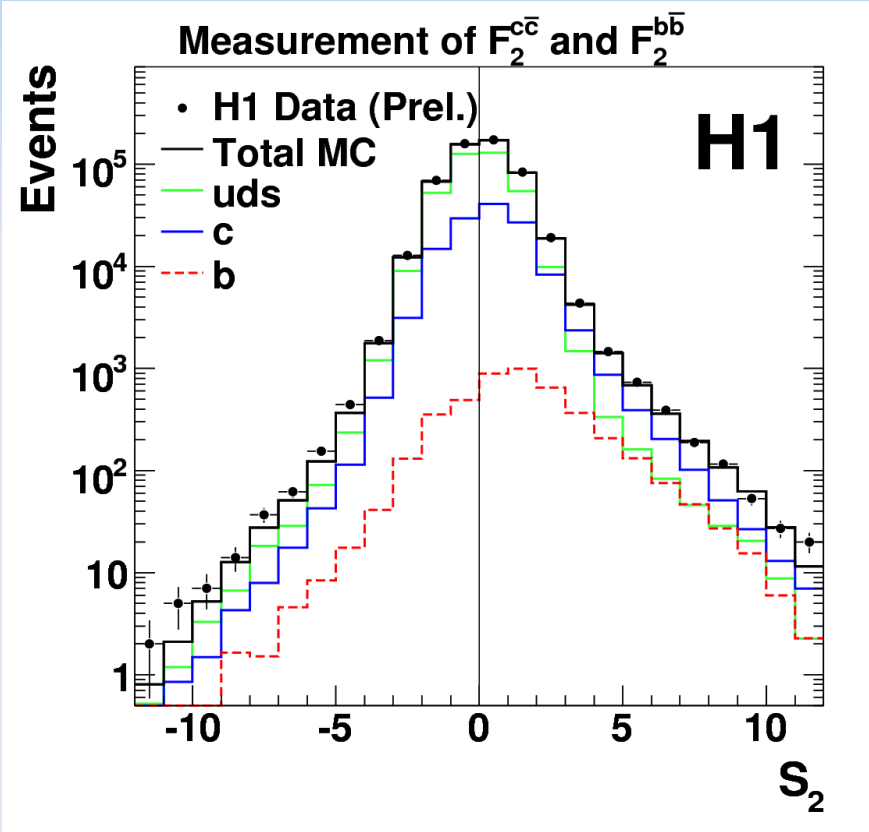


b & c in DIS

- Significance (1 track events)



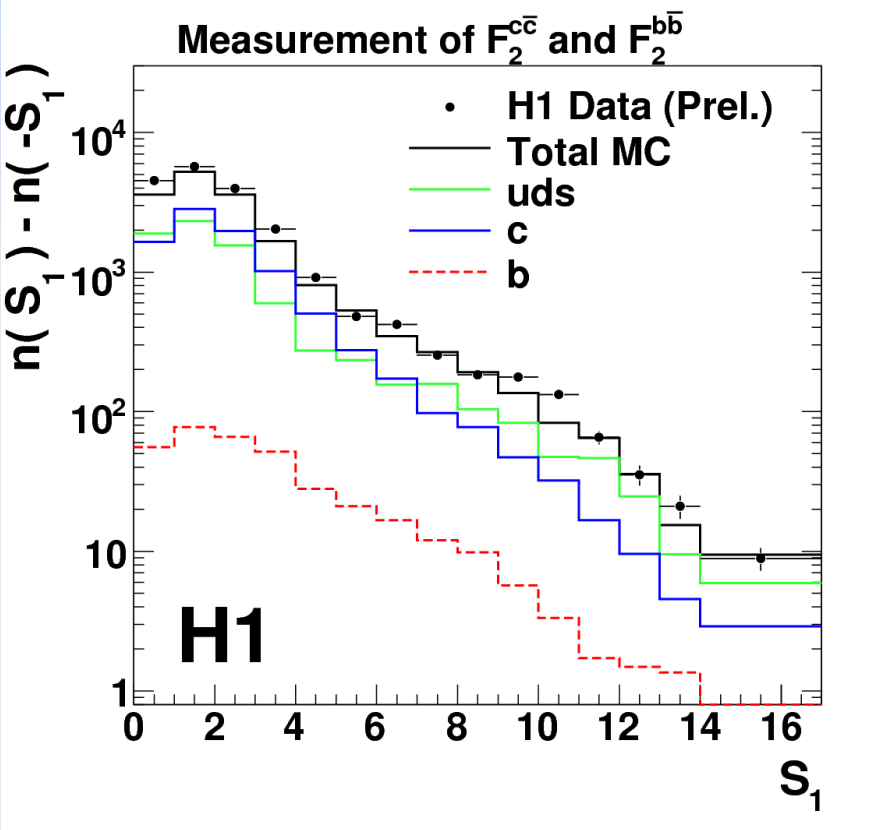
- Significance (2^{nd} highest significance track)

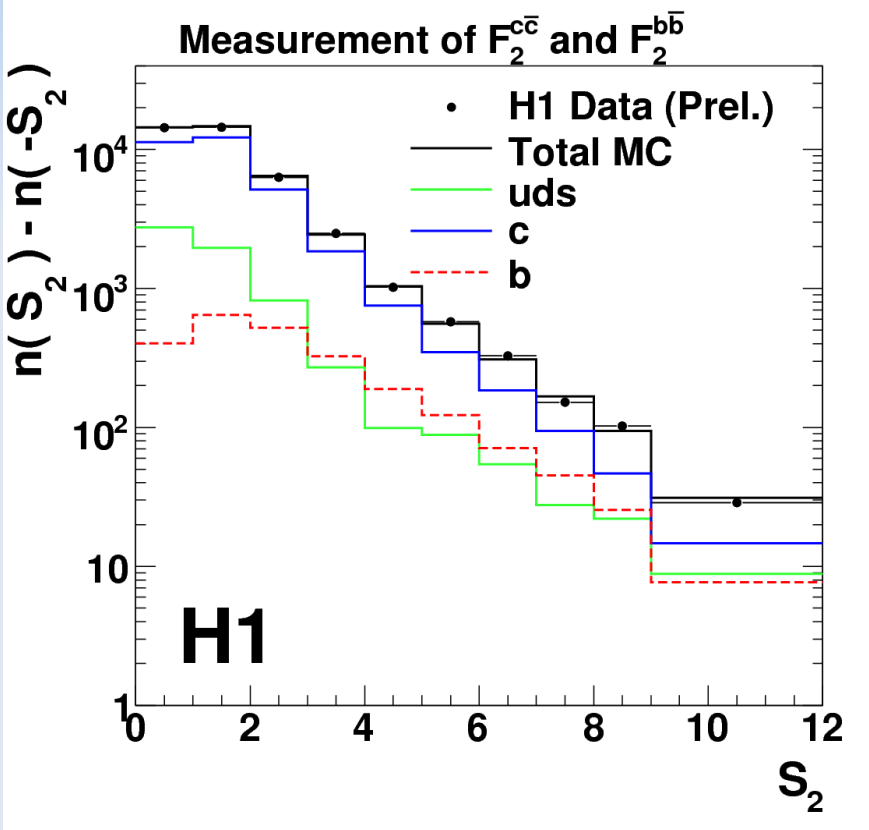


Reject events when S_1 and S_2 have opposite sign

b & c in DIS

Subtracted significance distributions





Reduced Cross-Section

$$\tilde{\sigma}^{c\bar{c}}(x,Q^2) = \frac{d^2\sigma^{c\bar{c}}}{dx\,dQ^2}\frac{xQ^4}{2\pi\alpha^2(1+(1-y)^2)}$$

$$\tilde{\sigma}^{c\bar{c}}(x,Q^2) = \tilde{\sigma}(x,Q^2)\frac{P_c N_c^{\mathrm{MCgen}}}{P_c N_c^{\mathrm{MCgen}} + P_b N_b^{\mathrm{MCgen}} + P_{LF} N_{LF}^{\mathrm{MCgen}}}$$

$$\tilde{\sigma}^{c\bar{c}}(x,Q^2) = F_2^{c\bar{c}} - \frac{y^2}{(1+(1-y)^2)}F_L^{c\bar{c}}$$