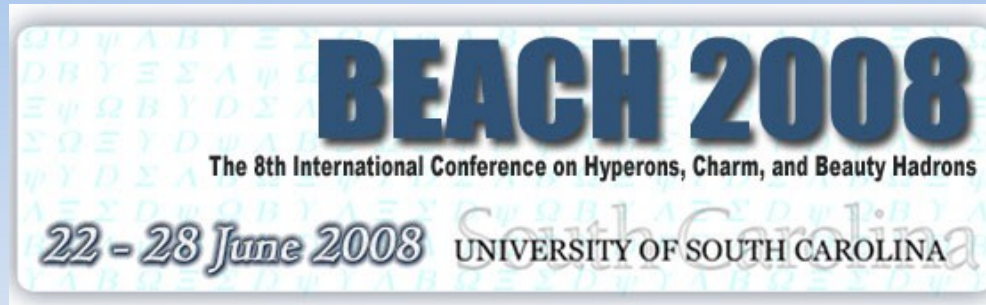


# Heavy Quark Production at HERA



Ian C. Brock  
University of Bonn

On behalf of the H1 and ZEUS Collaborations

24<sup>th</sup> June 2008

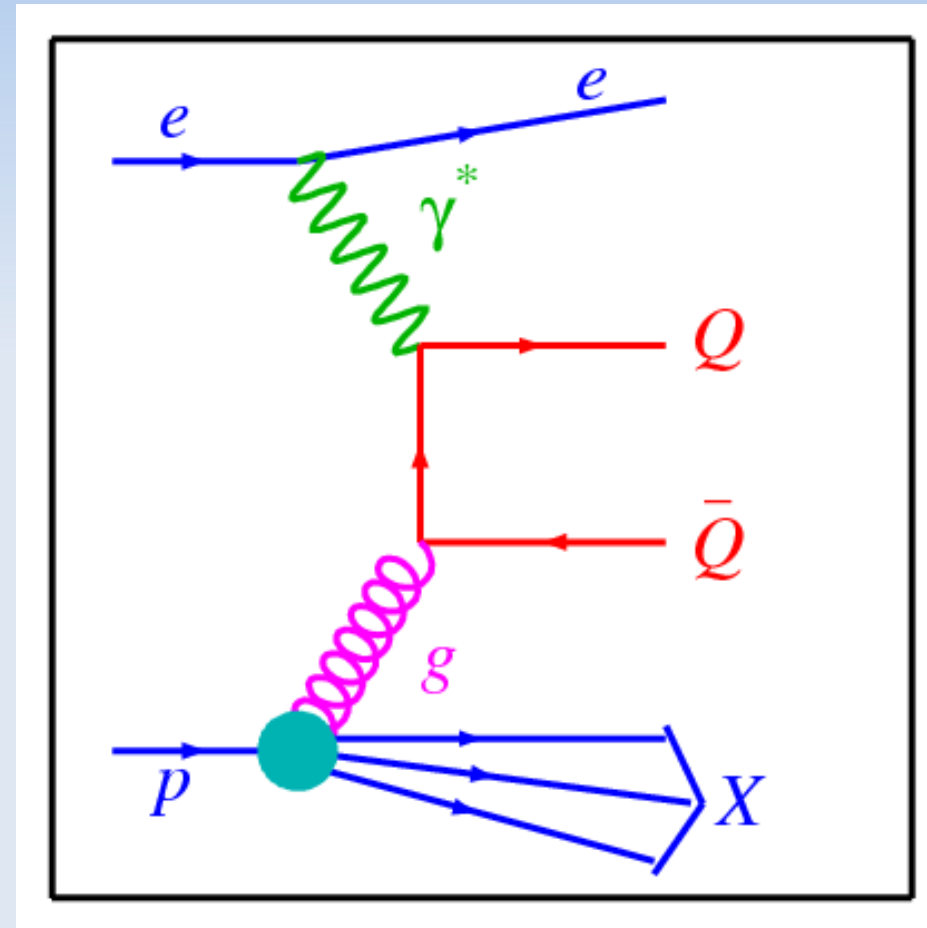


# Outline

- Introduction
- Charm via  $D^*$
- Beauty via semileptonic decays to  $\mu$
- 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

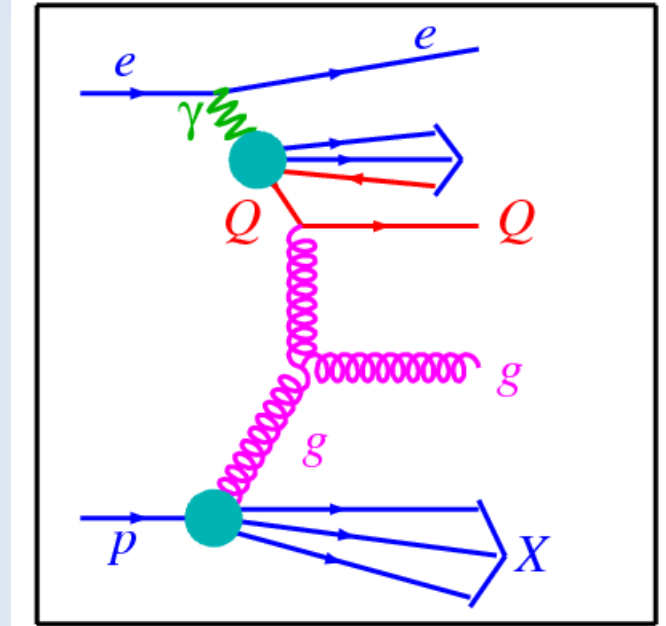
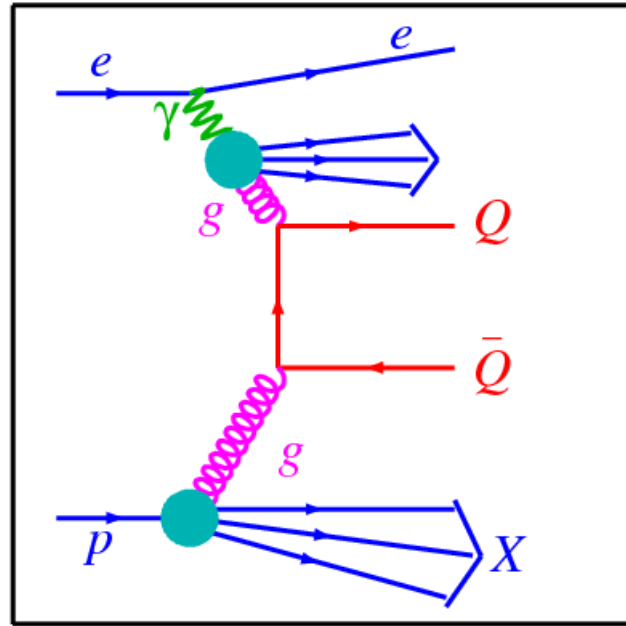
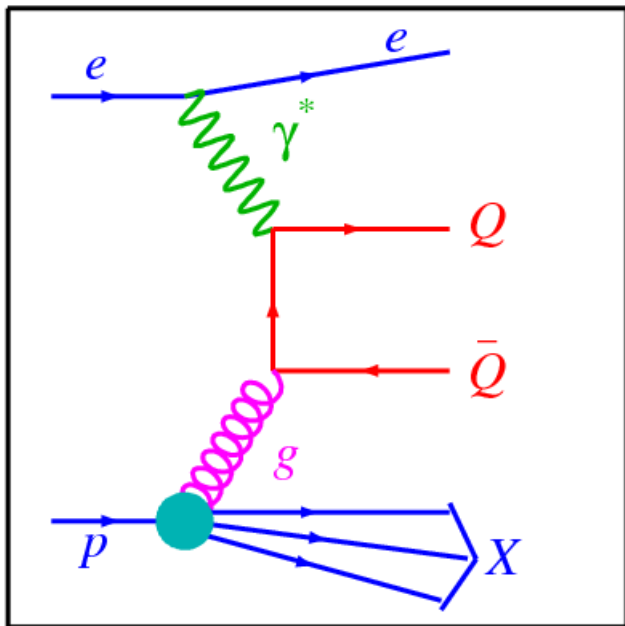
- Life (QCD) is not quite so simple ☹️

Non-Direct

Direct

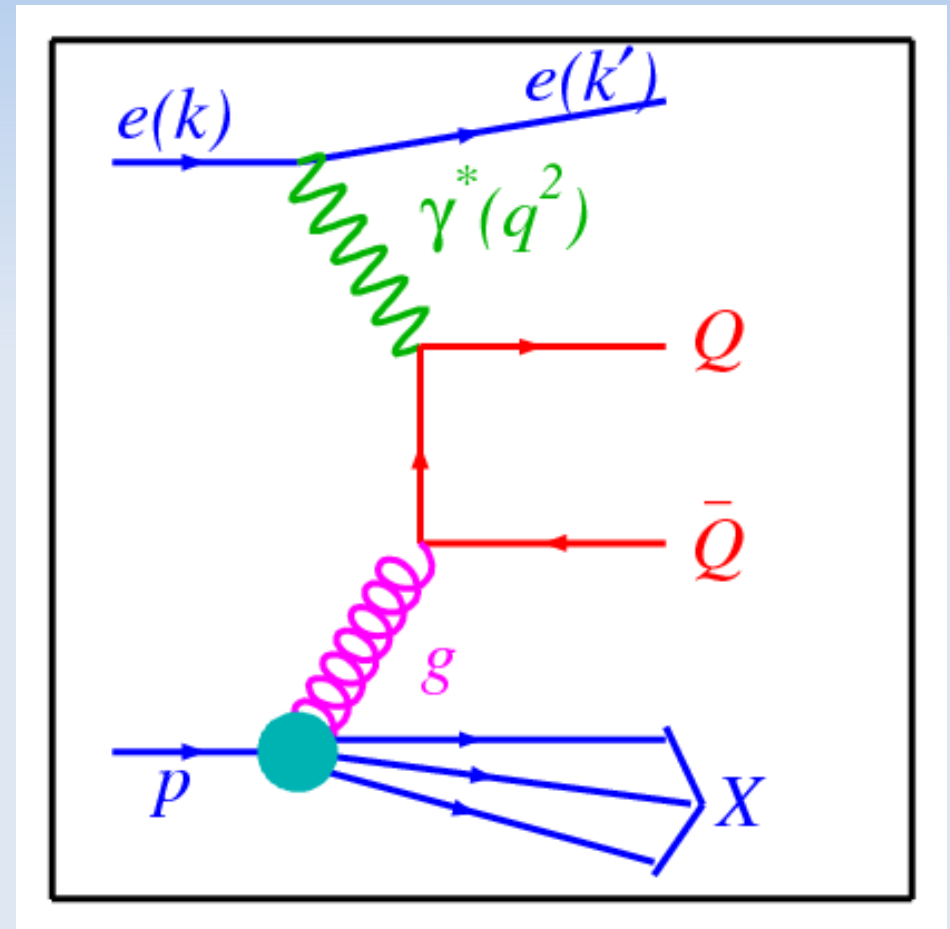
Resolved

Excitation



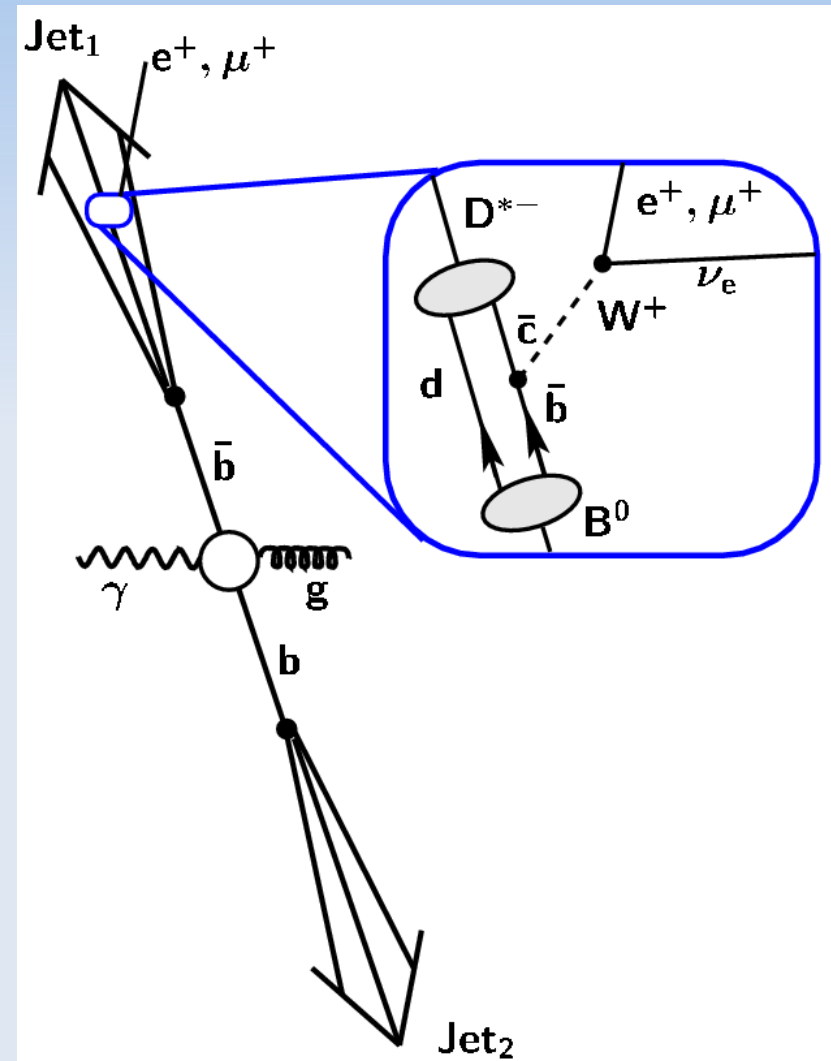
# Heavy Flavour Production at HERA

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



# Heavy Flavour Decay

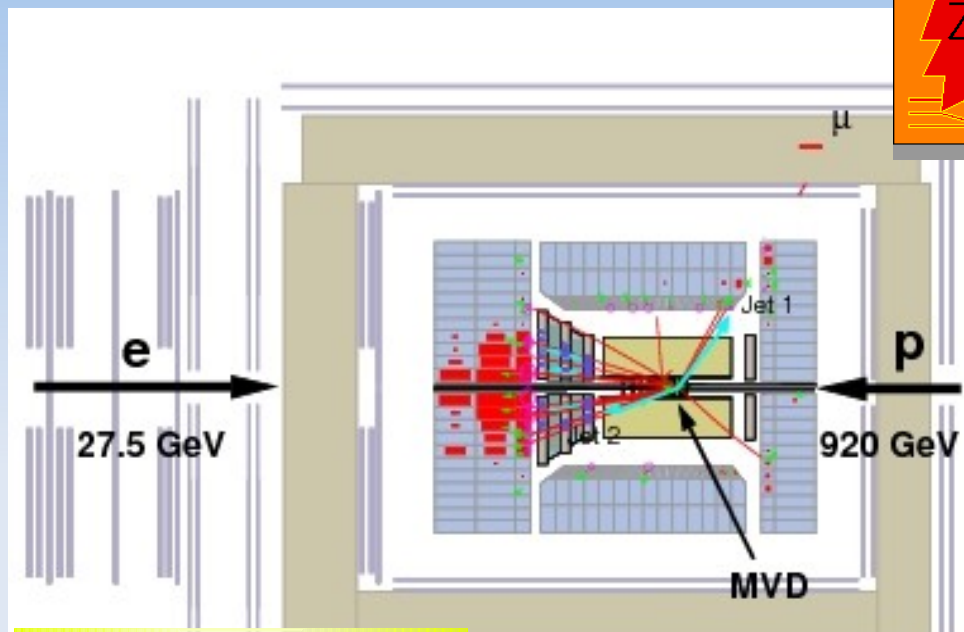
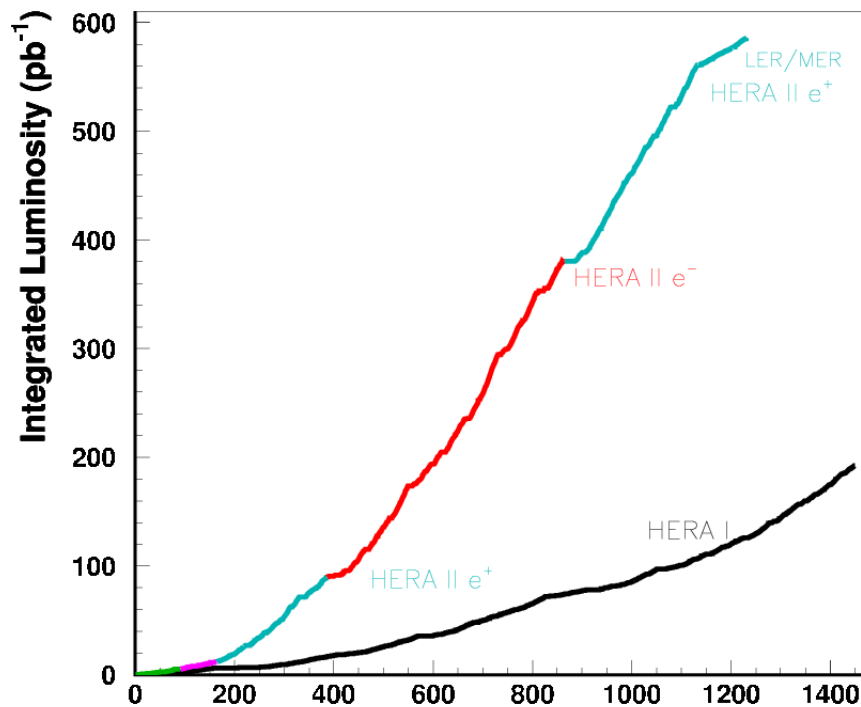
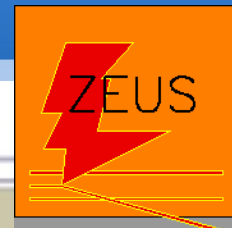
- Methods to tag HF:
  - Reconstruct  $D^*$  (or other D mesons)
  - Tag semileptonic decay to  $e, \mu$
  - Use long B,D hadron lifetime
  - Jet properties
- Different tags probe different kinematic regions



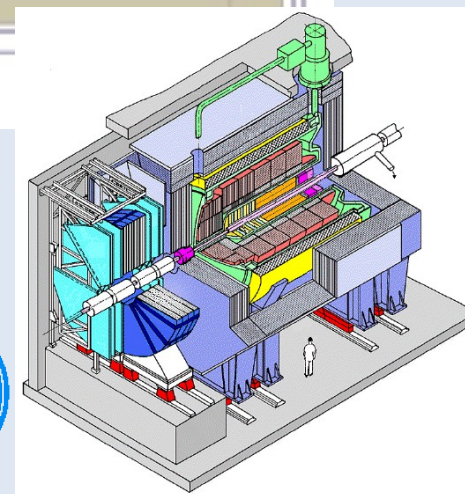
# The Theory

- QCD Leading Order + Parton Shower Monte Carlo
- 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  
 $\sim 0.5 \text{ fb}^{-1}$  per experiment

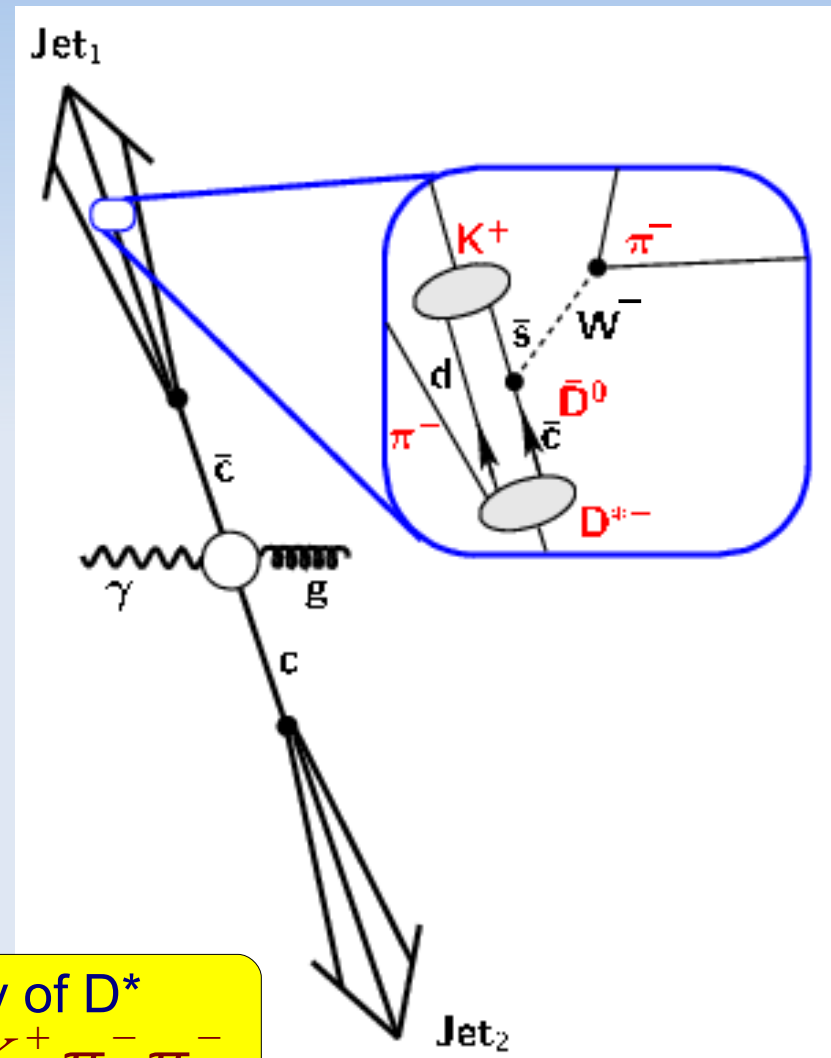




# Charm Production



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

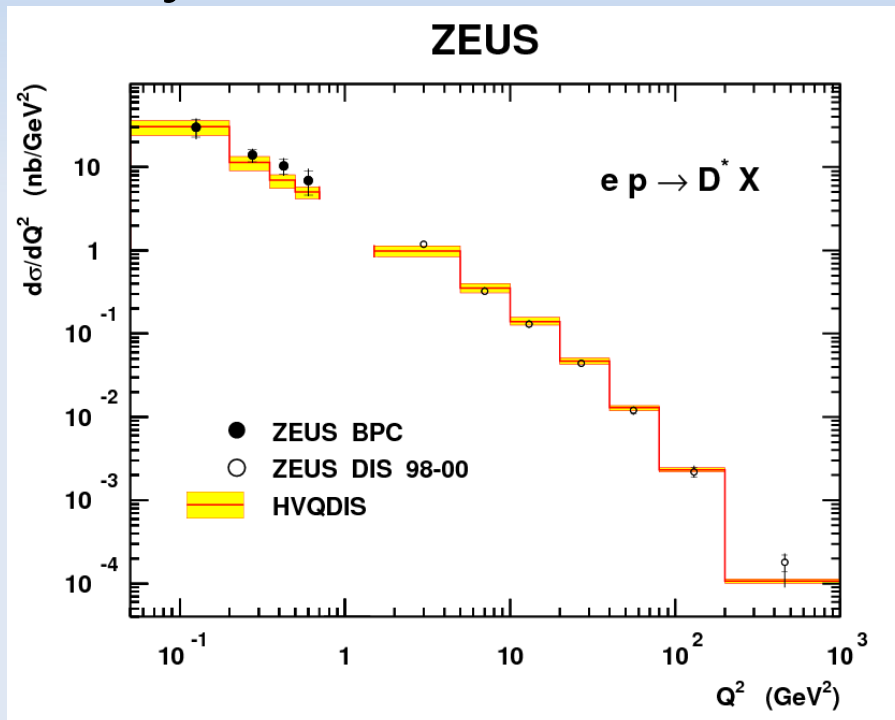


“Golden” Decay of  $D^*$   
 $D^{*-} \rightarrow \bar{D}^0 \pi^- \rightarrow K^+ \pi^- \pi^-$

# Charm Production

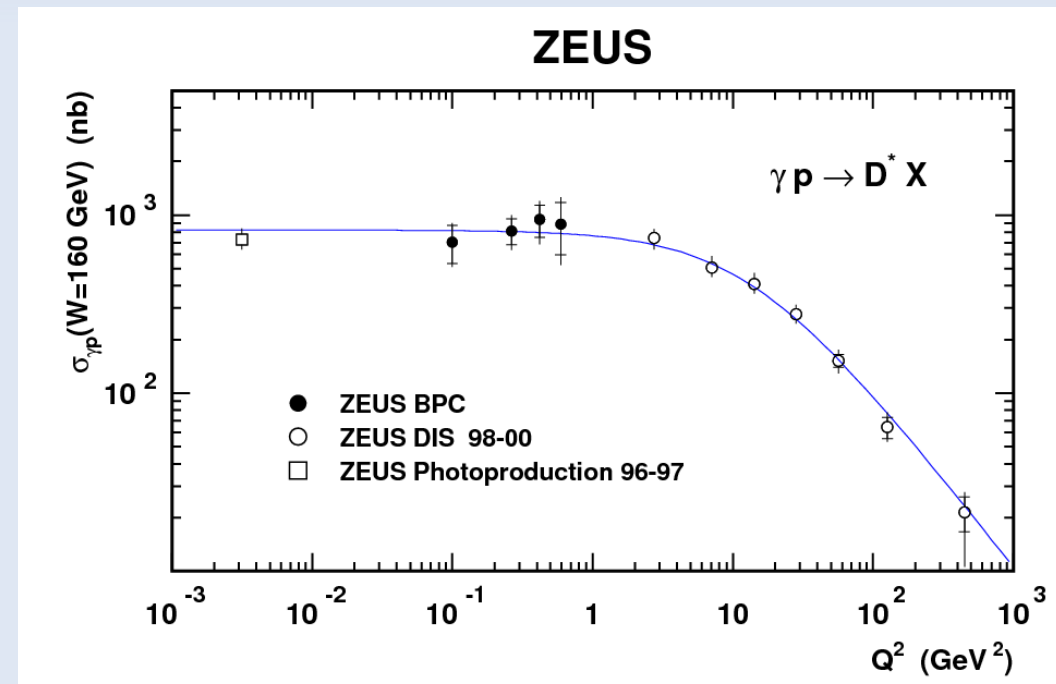


- Earlier ZEUS measurements include very low  $Q^2$



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

- Single function to describe  $\gamma p$  cross-section over full  $Q^2$  range

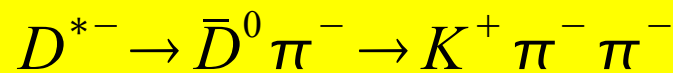
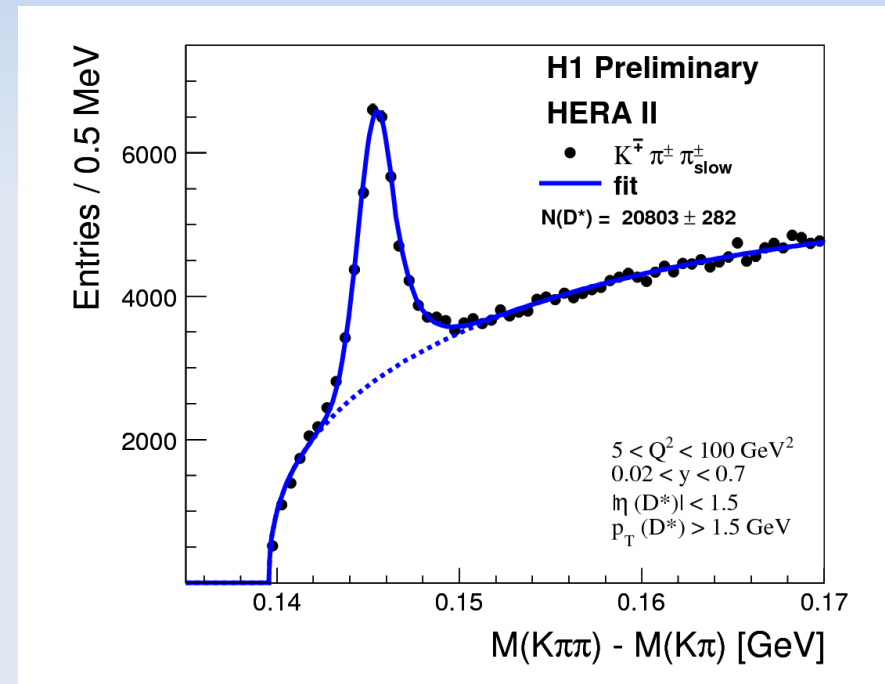
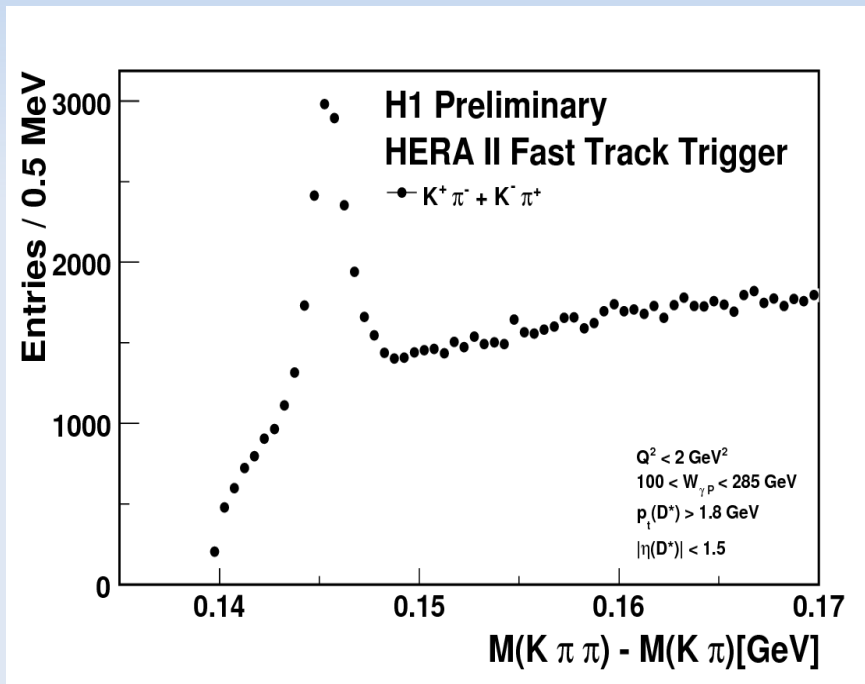


# Charm Production



- Photoproduction:  
 $Q^2 < 2 \text{ GeV}^2$

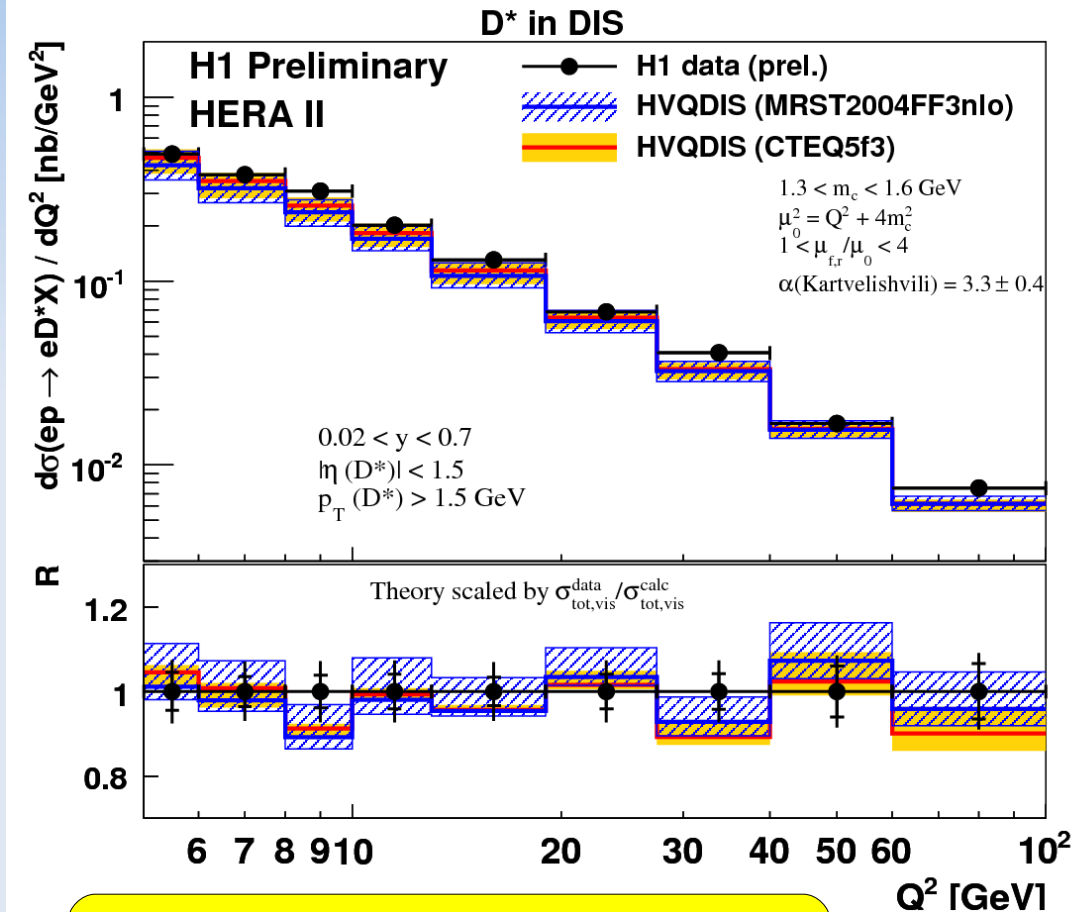
- DIS:  
 $Q^2 > 5 \text{ GeV}^2$



# Charm Production



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

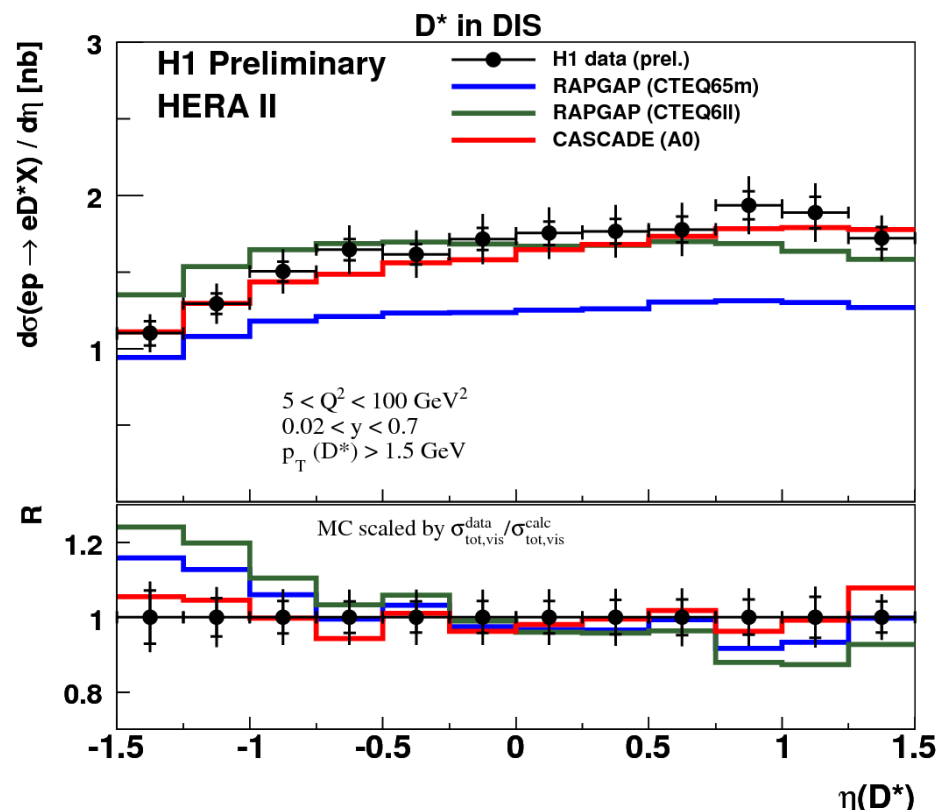


Different PDFs show very similar  $Q^2$  behaviour

# Charm in DIS

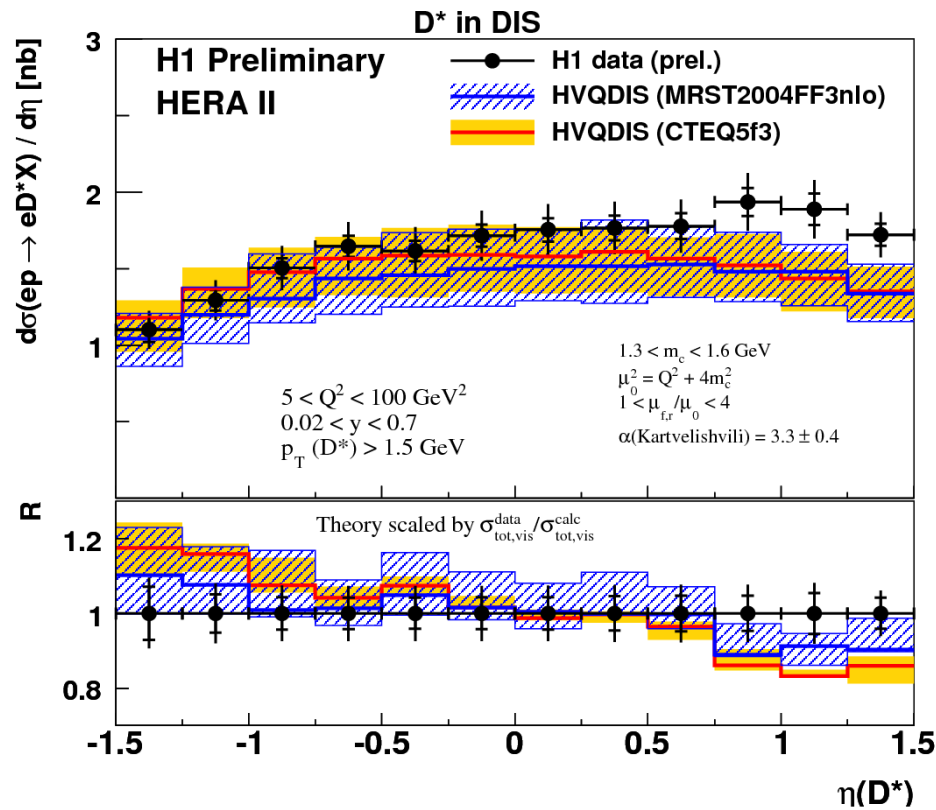


## Compare with MC



Significant changes for different PDFs  
Cascade agrees very well with data

## Compare with NLO

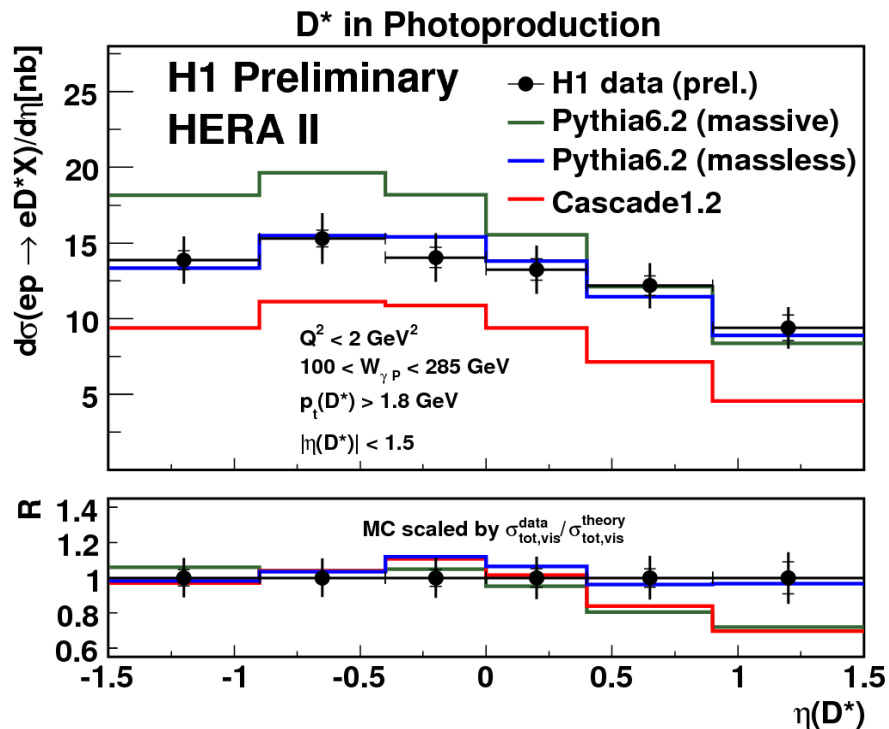


Data overshoot prediction at large  $\eta$   
Some sensitivity to gluon: MRST vs CTEQ

# Charm in Photoproduction

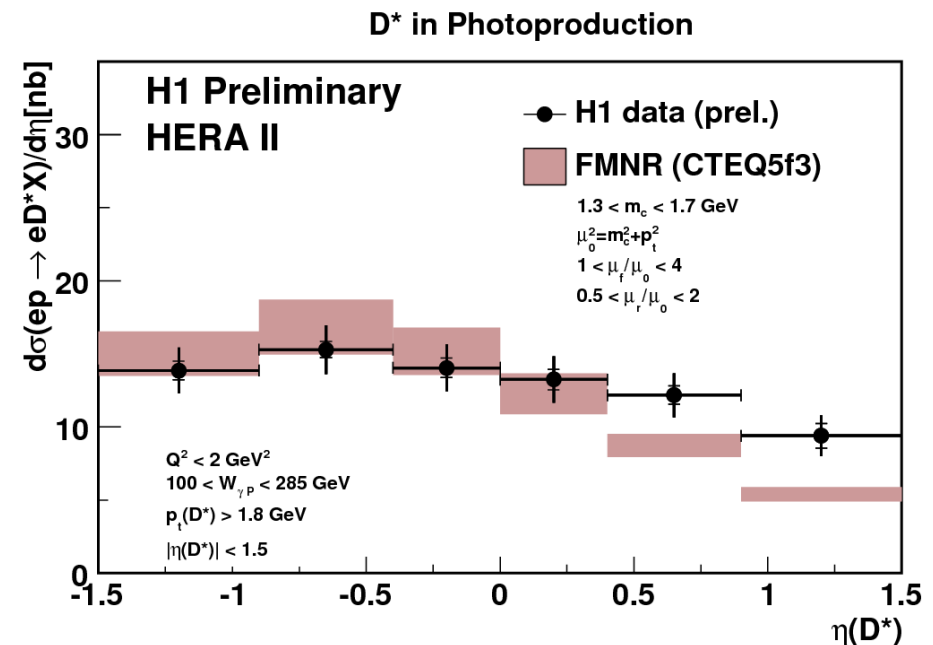


- Compare with MC



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

- Compare with NLO

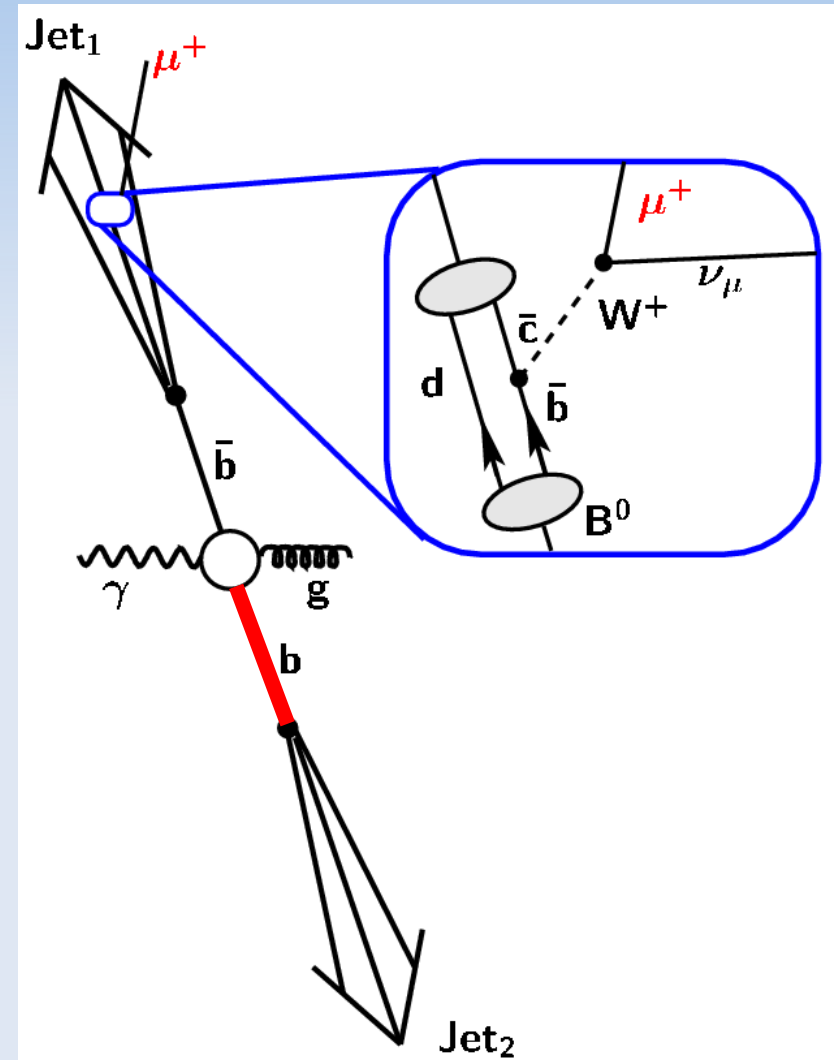


Data overshoot prediction at large  $\eta$

# Beauty in Photoproduction



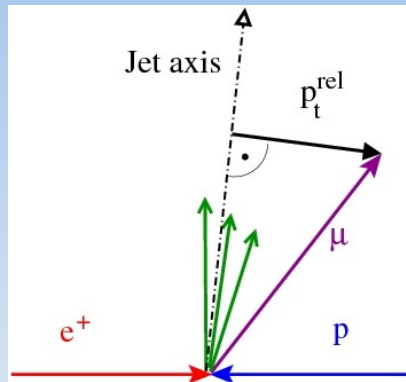
- HERA II data
  - 124 pb<sup>-1</sup> (2005)
- Photoproduction
- Dijet events
  - $P_T^{\text{jet}} > 7(6)$  GeV
- Semileptonic decays to muons ( $p_T^\mu > 2.5$  GeV)
- Include lifetime information



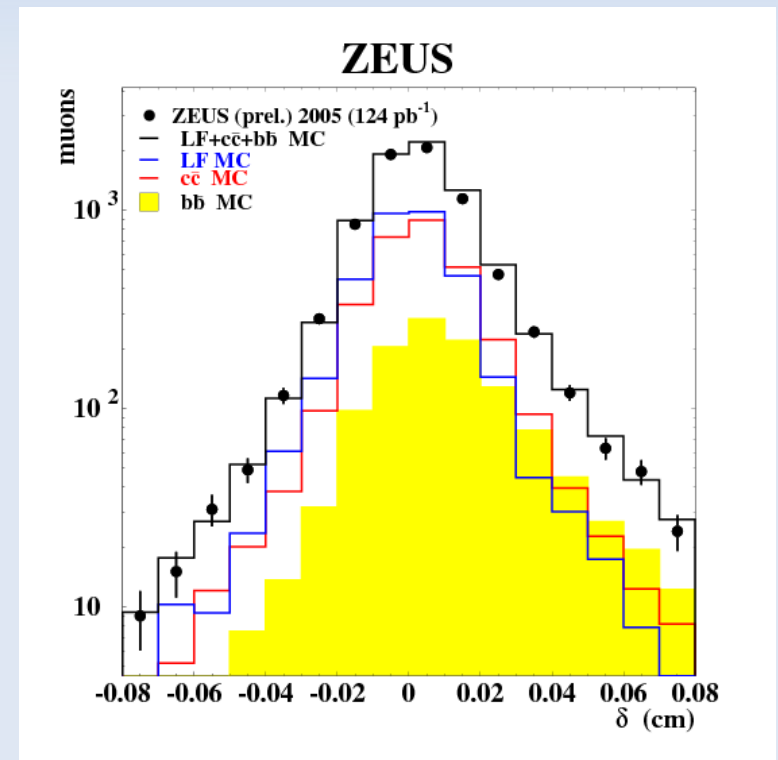
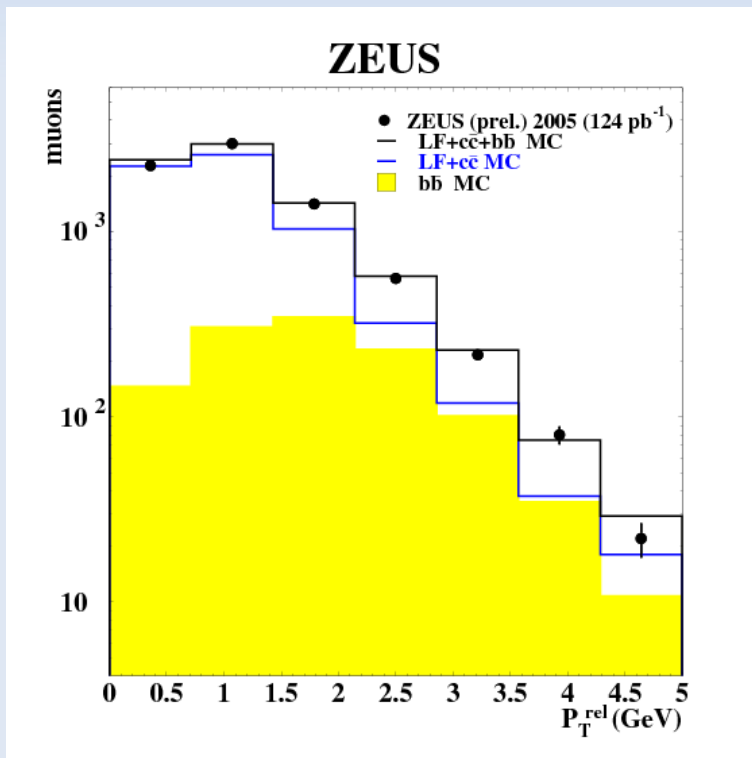
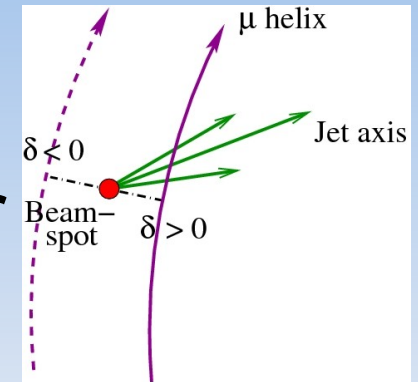
# Beauty in Photoproduction



■  $p_T^{\text{rel}}$



■ Impact parameter





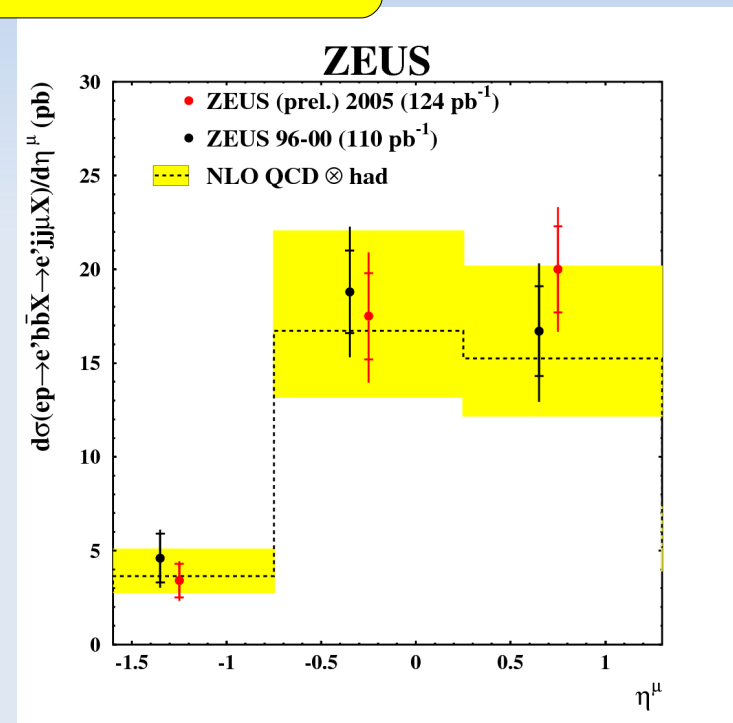
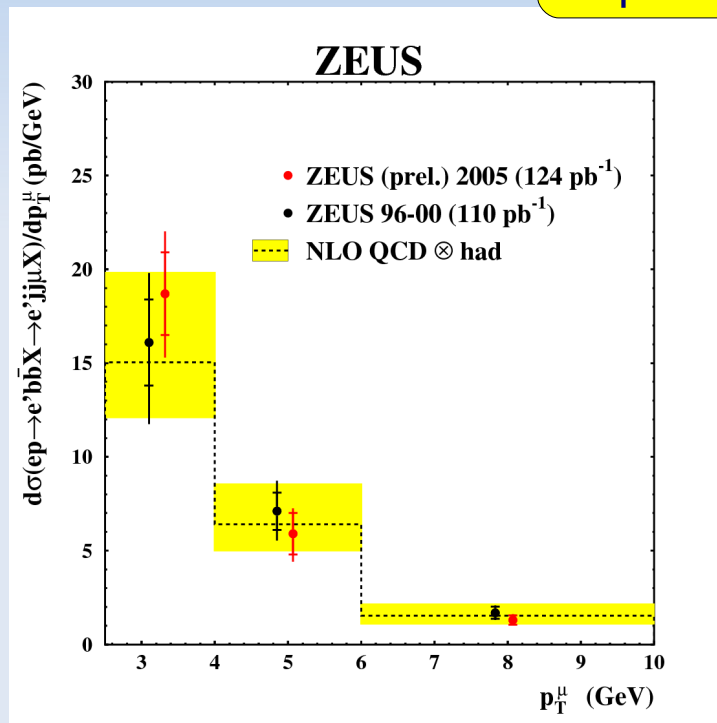
# Beauty in Photoproduction



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

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

Renormalisation/factorisation scales  
b quark mass



$P_T^\mu > 2.5 \text{ GeV}$

Good agreement between  
HERA I and HERA II cross-sections

# b & c in Photoproduction

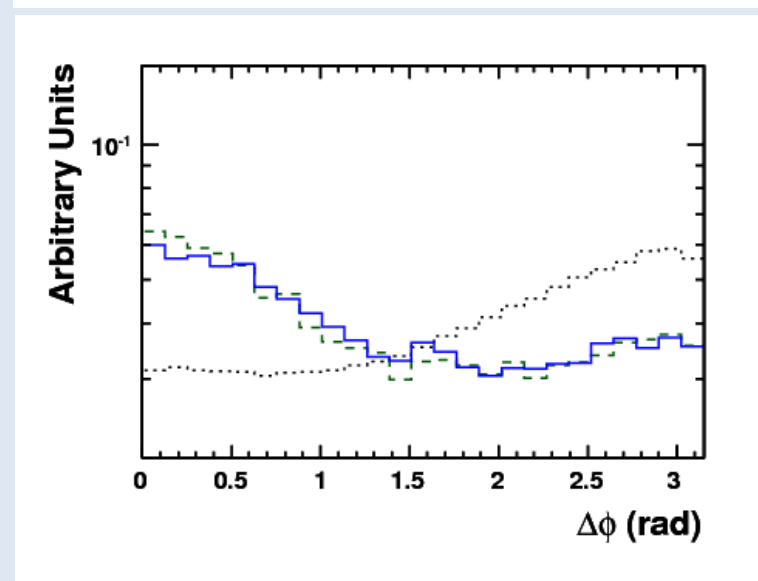
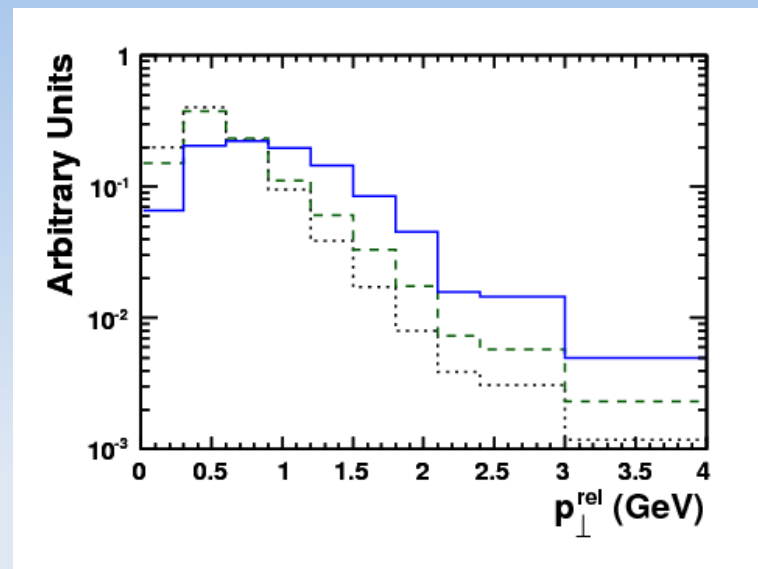
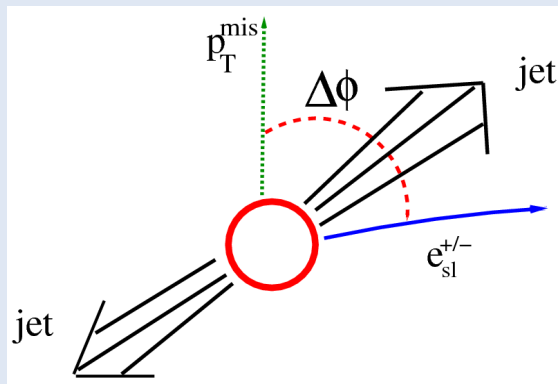


- HERA I data
  - 120 pb<sup>-1</sup> (1996-2000)
- Dijet photoproduction events
  - $E_T^{\text{jet}} > 7(6)$  GeV

— b → e X  
- - - c → e X  
⋯ Bkg

- Semileptonic decays to electrons ( $p_T^e > 0.9$  GeV)

- Look for more variables to determine b and c quark fractions separately

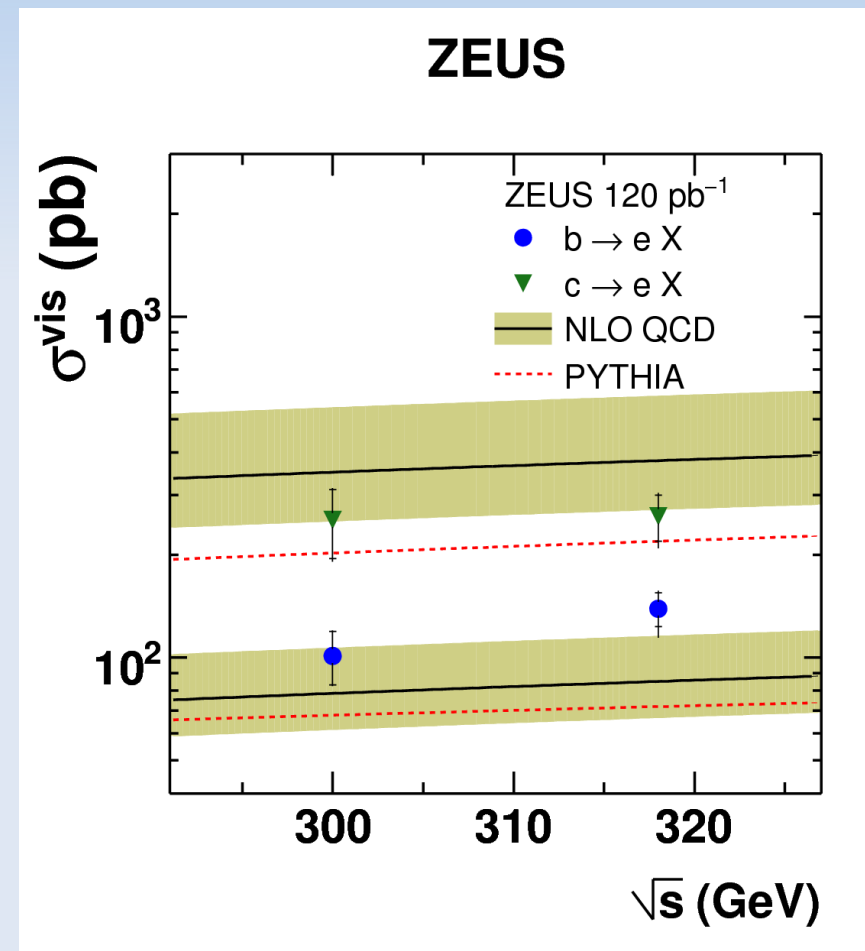
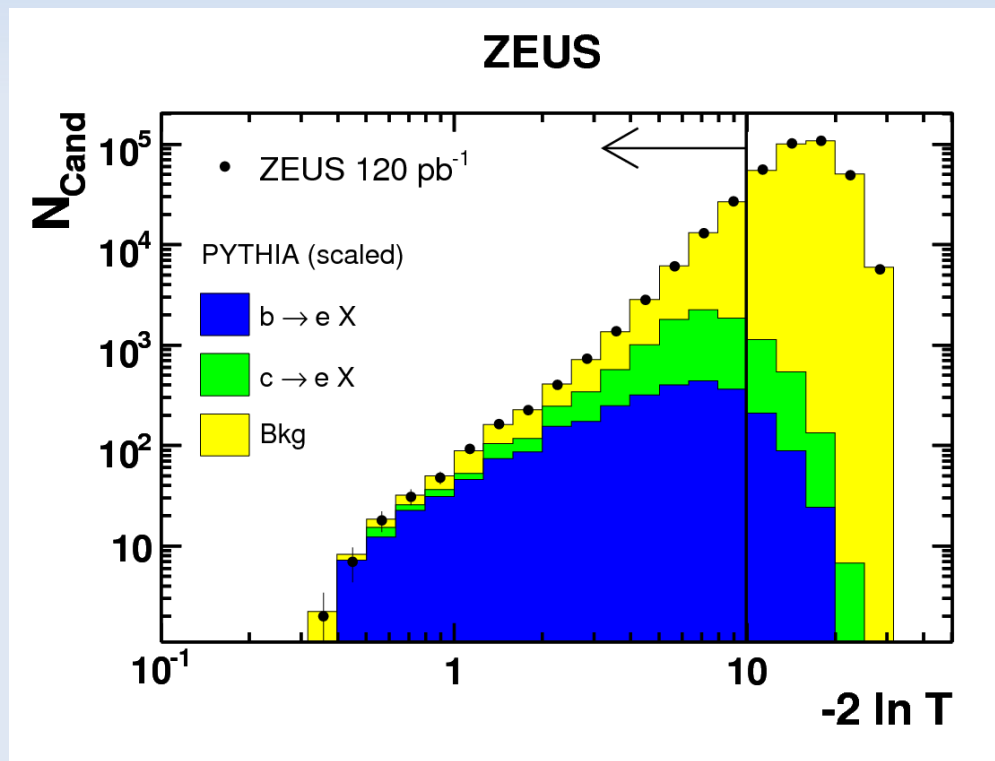


# b & c in Photoproduction



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

- Visible cross-section



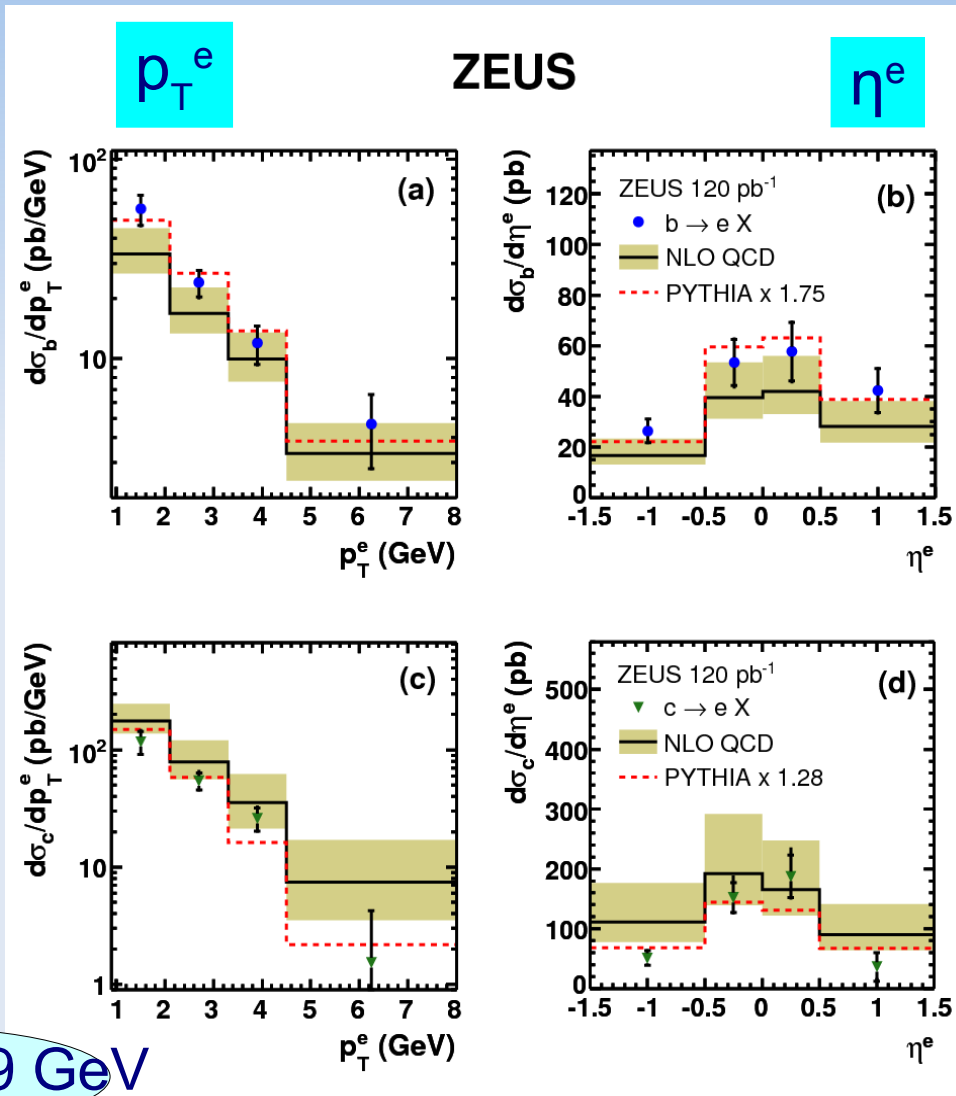
# b & c in Photoproduction



Beauty

Charm

$P_T^e > 0.9 \text{ GeV}$

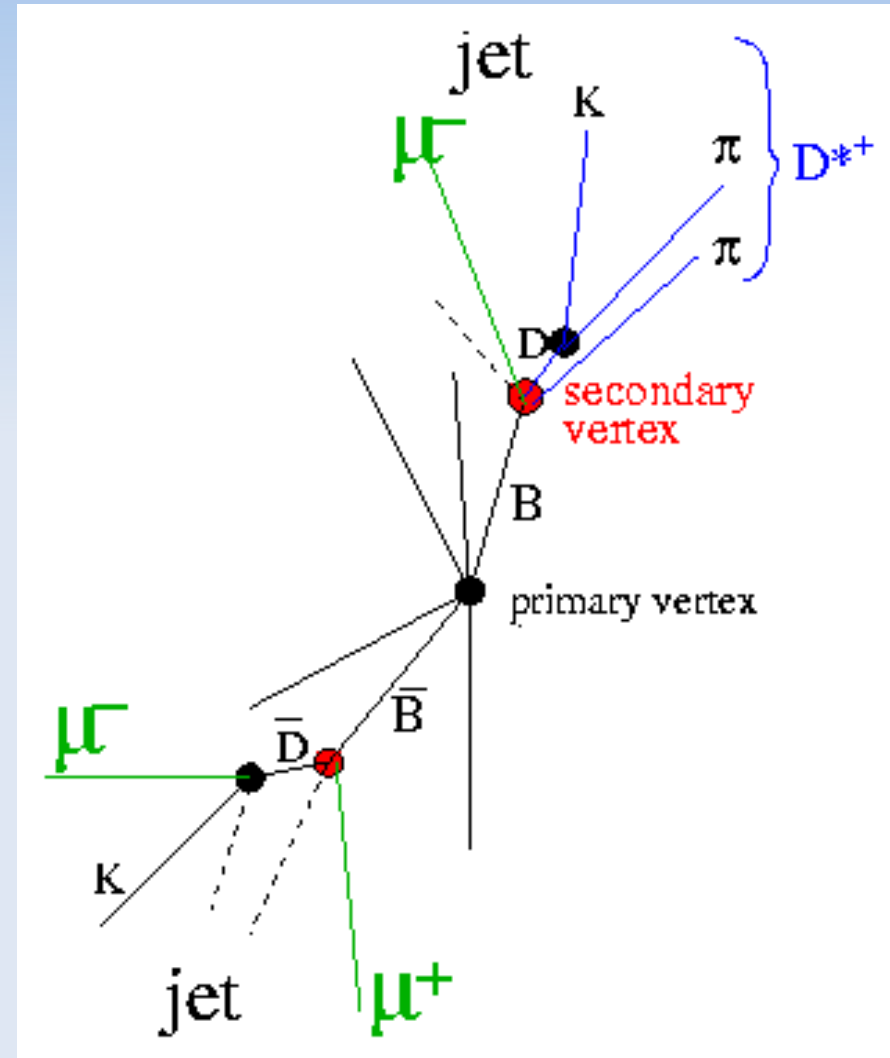


- LO Monte Carlo scale factors:
  - b x 1.75
  - c x 1.28
- NLO absolute predictions

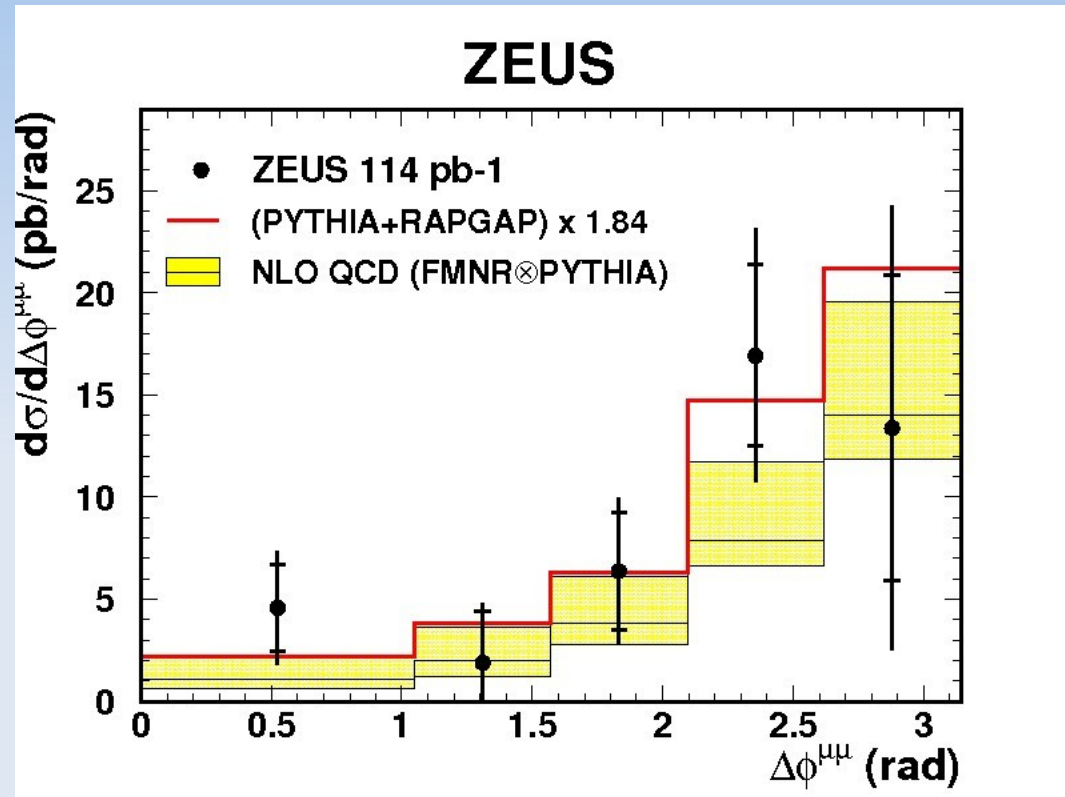
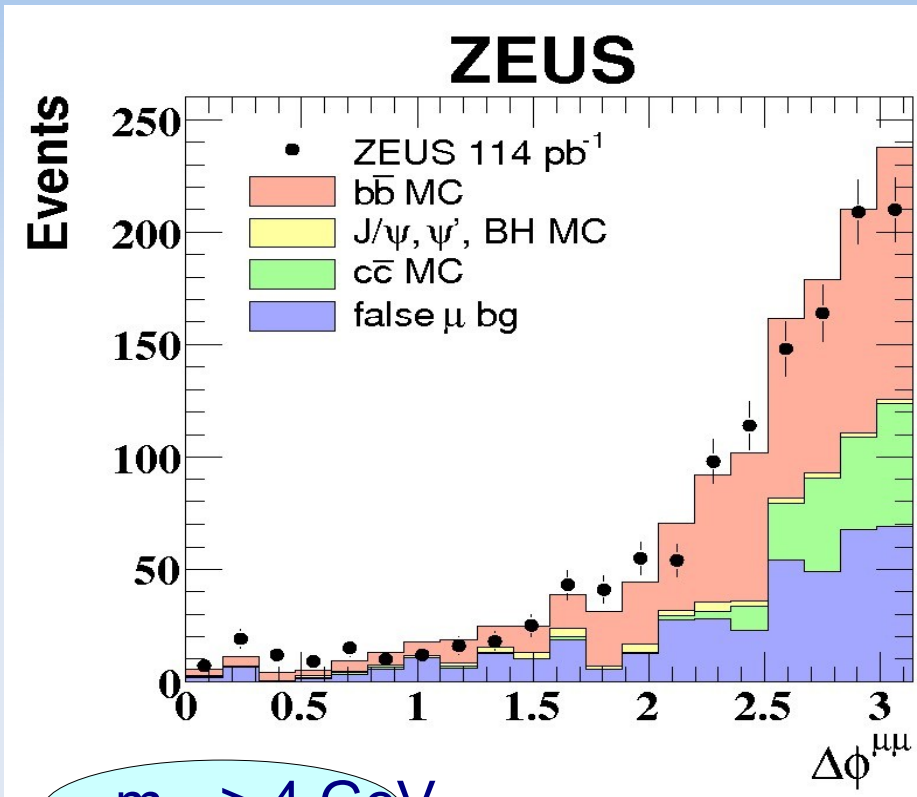
# $b\bar{b}$ Production



- 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

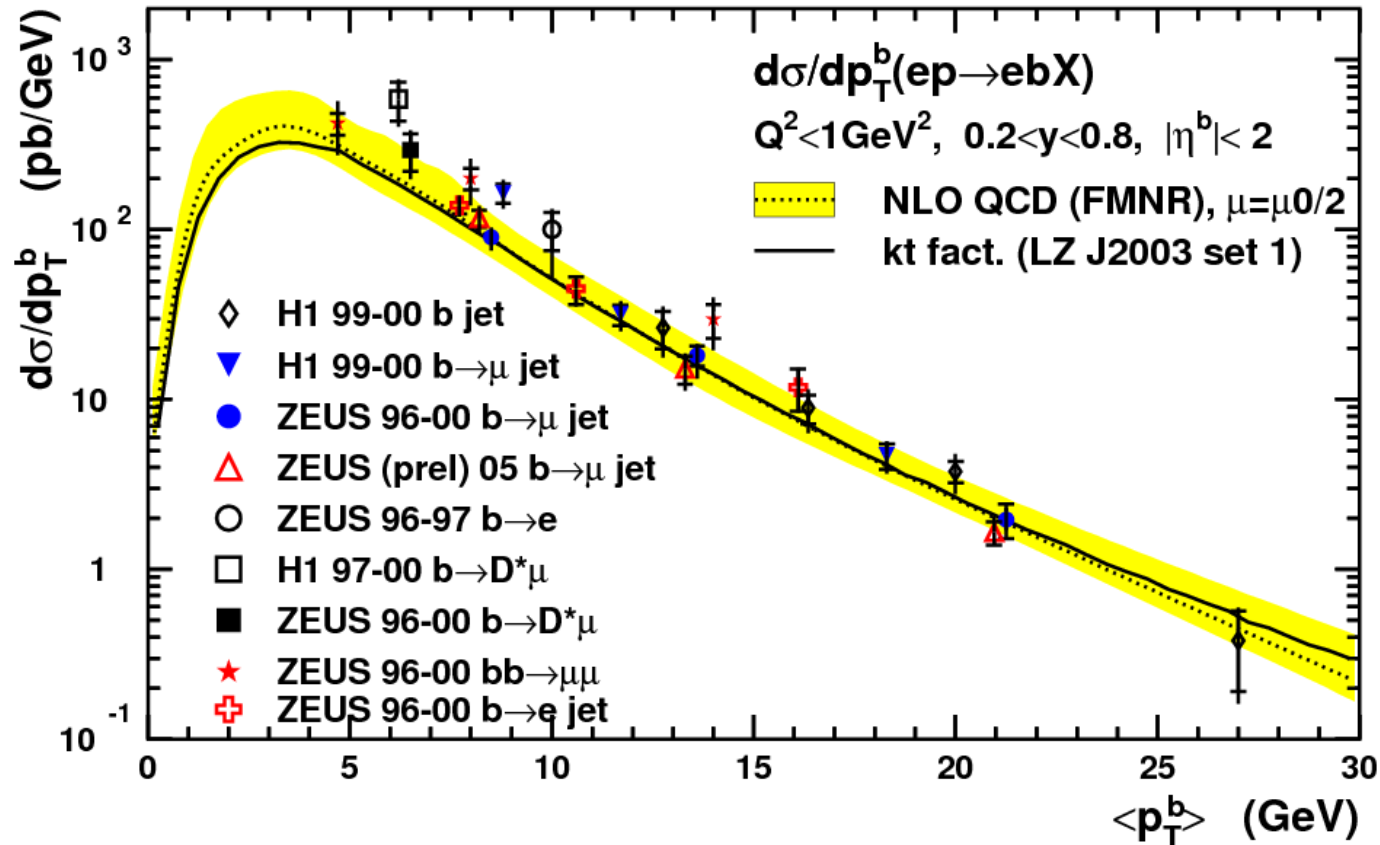


$m_{\mu\mu} > 4$  GeV

- $\Delta\phi$  between muons from different quarks
- Correlations reasonably well described

# Summary of b Photoproduction

## HERA

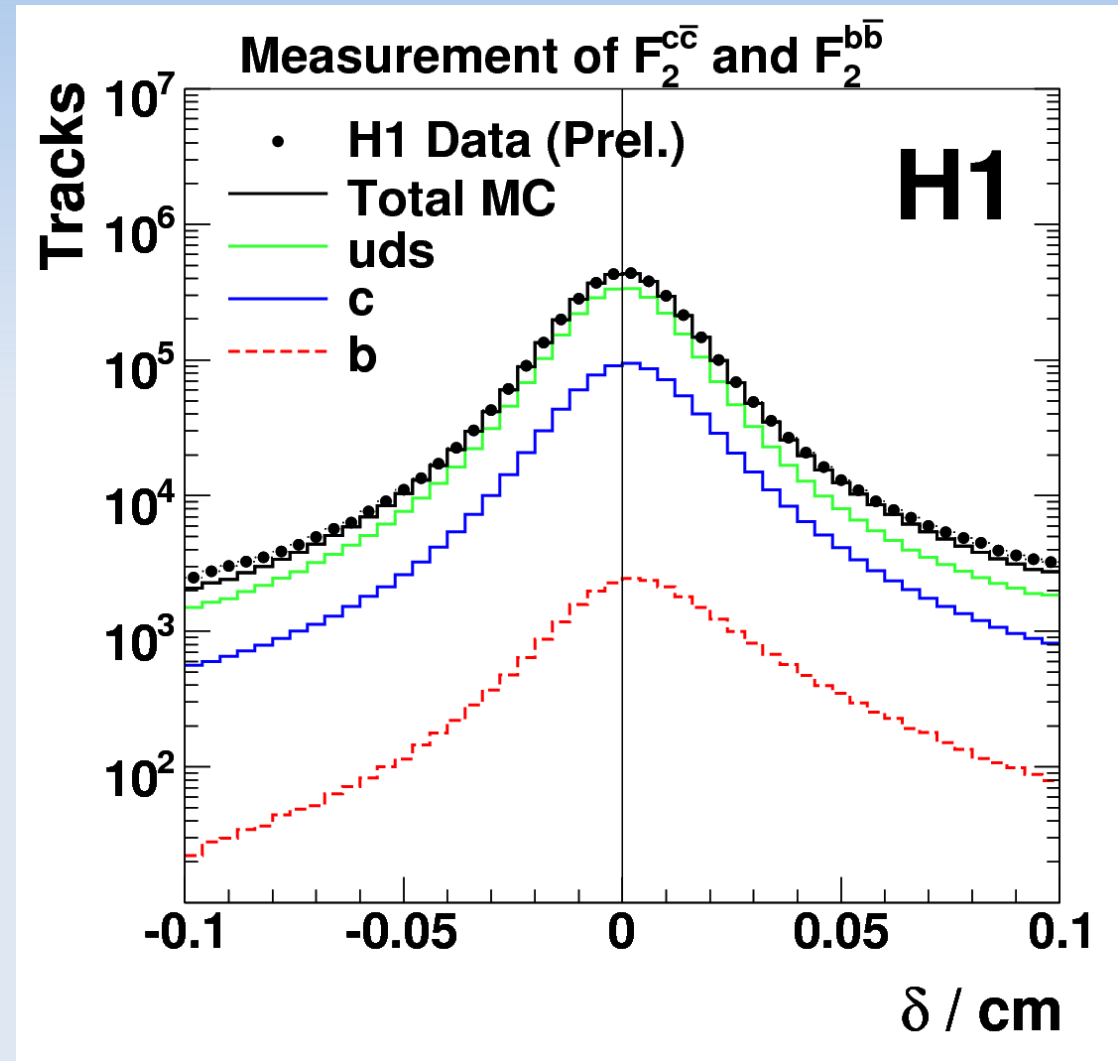
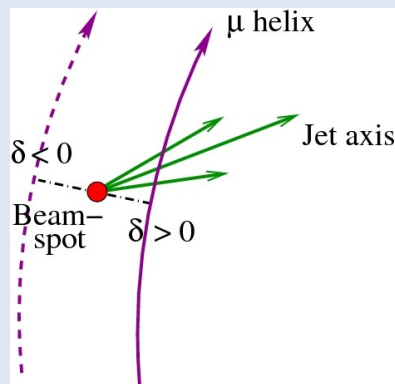


Plot actually shows ratio of measurement to FMNR prediction

No sign of large excess seen in first b production measurements

# b & c in DIS

- HERA II data
- 54 pb<sup>-1</sup> (2006)
- DIS
  - Q<sup>2</sup> > 12 GeV<sup>2</sup>
- Use lifetime information

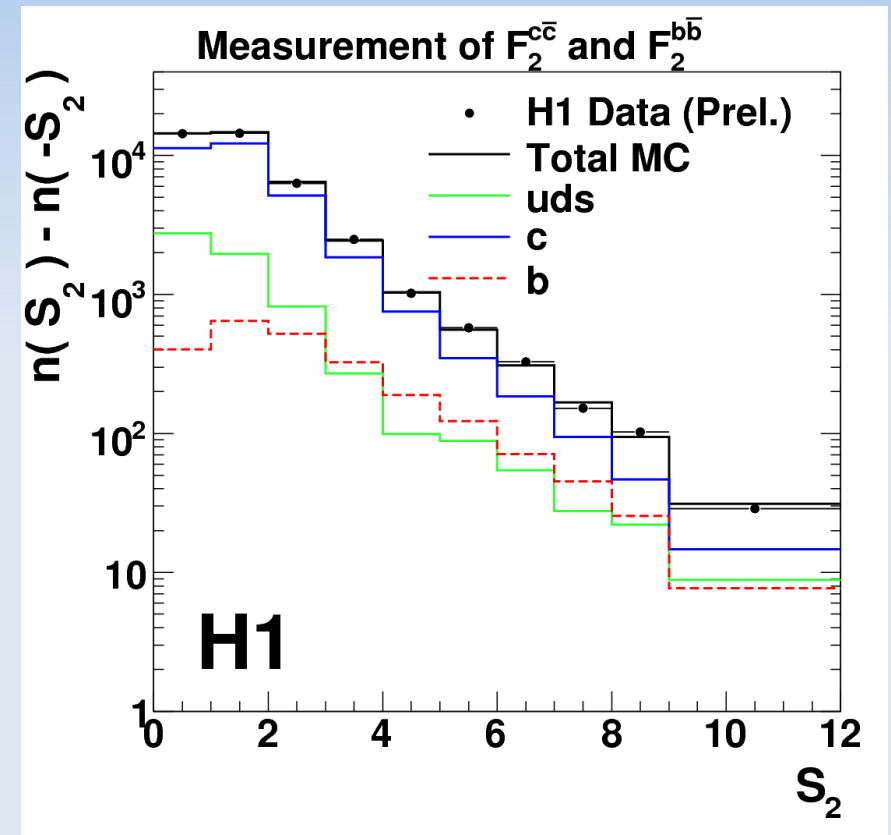
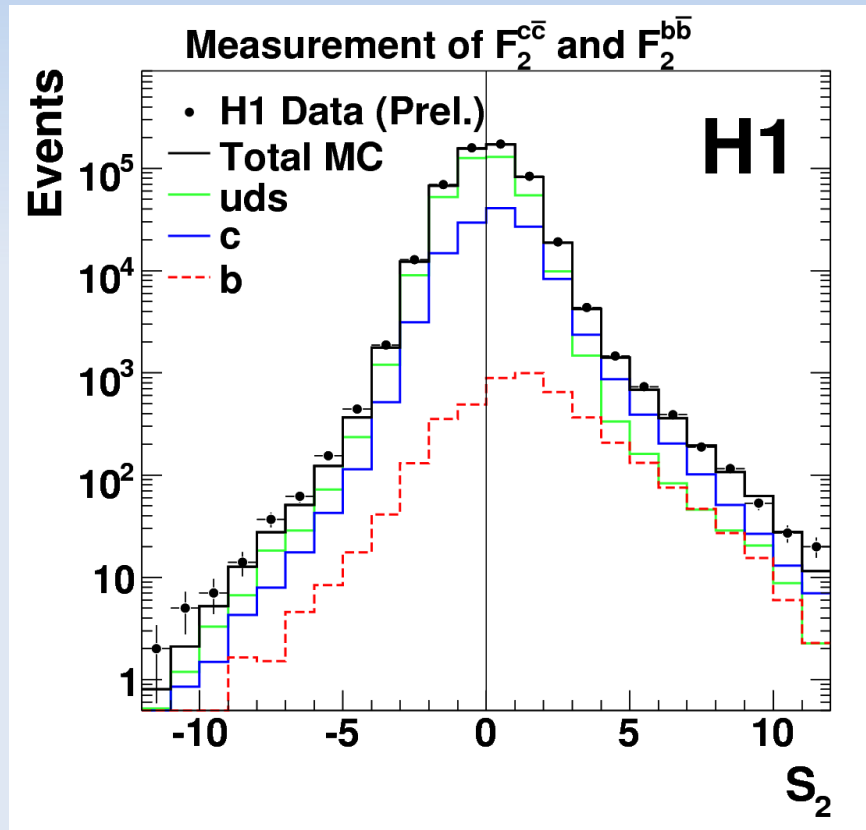




# b & c in DIS

- Significance:  $\delta / \sigma_\delta$
- $S_1$  highest  
 $S_2$  2<sup>nd</sup> highest

- Subtracted significance



Dominated by charm  
 More beauty at high significance

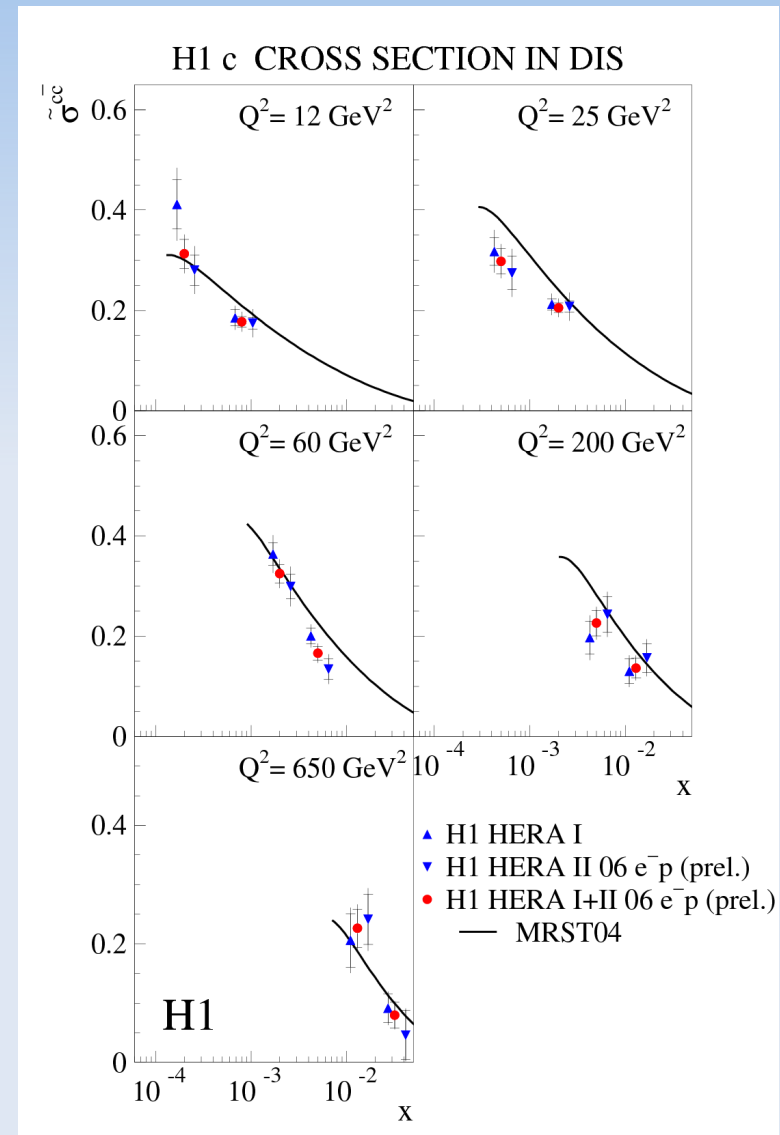
Reject events when  $S_1$  and  $S_2$  have opposite sign

# b & c in DIS

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

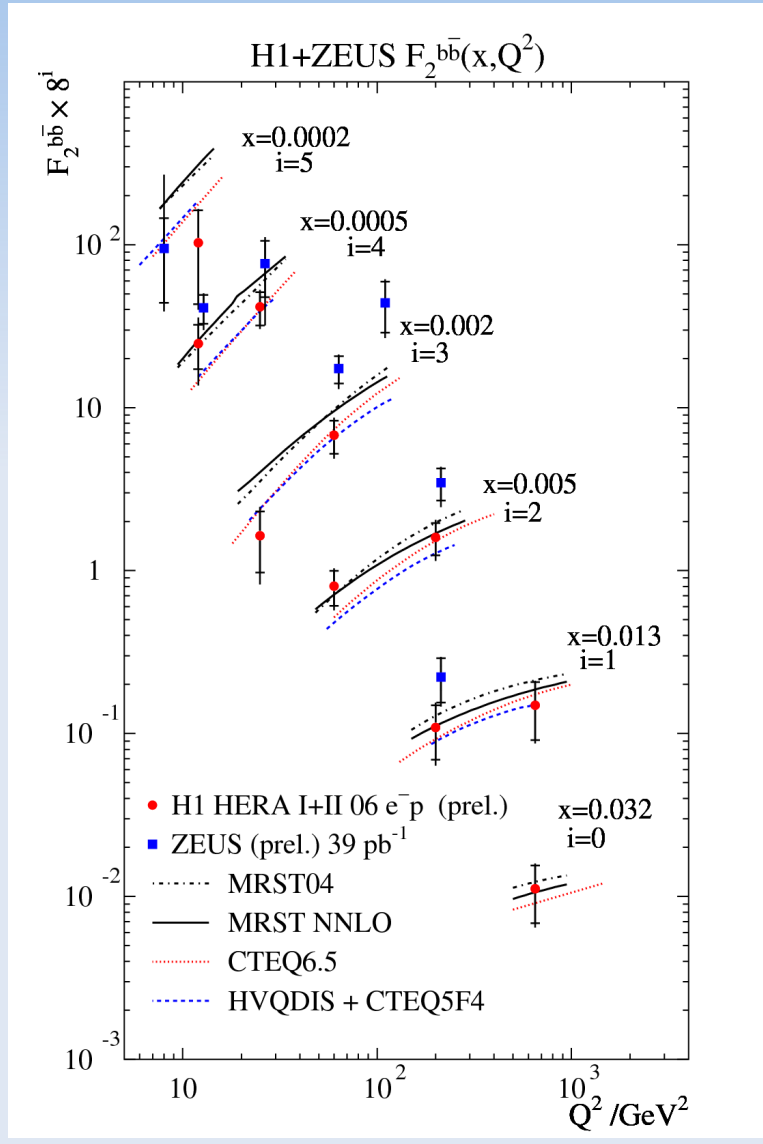
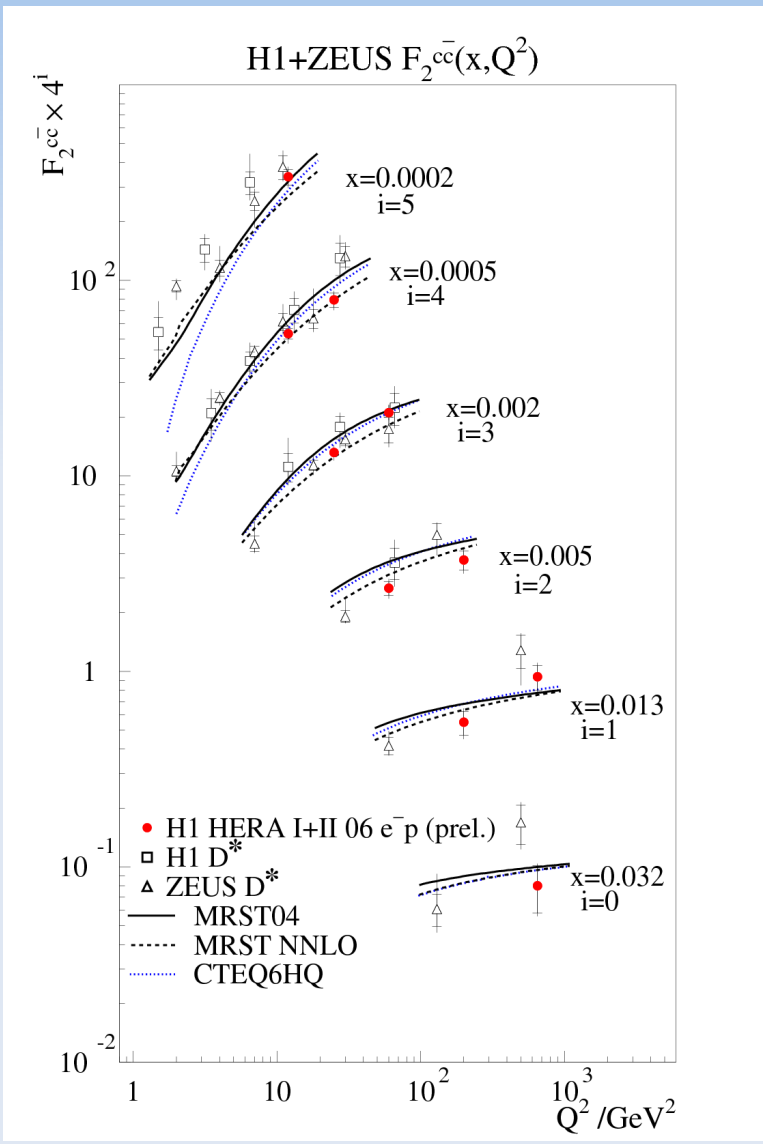
$$\tilde{\sigma}^{c\bar{c}}(x, Q^2) = F_2^{c\bar{c}} - \frac{y^2}{(1+(1-y)^2)} F_L^{c\bar{c}}$$

- Combine HERA I & HERA II measurements





# b & c in DIS



# Conclusions

- Small selection of HERA heavy flavour measurements presented:
  - $D^*$  production
  - Beauty production via semileptonic decays to  $e, \mu$
  - Double  $\mu$  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?

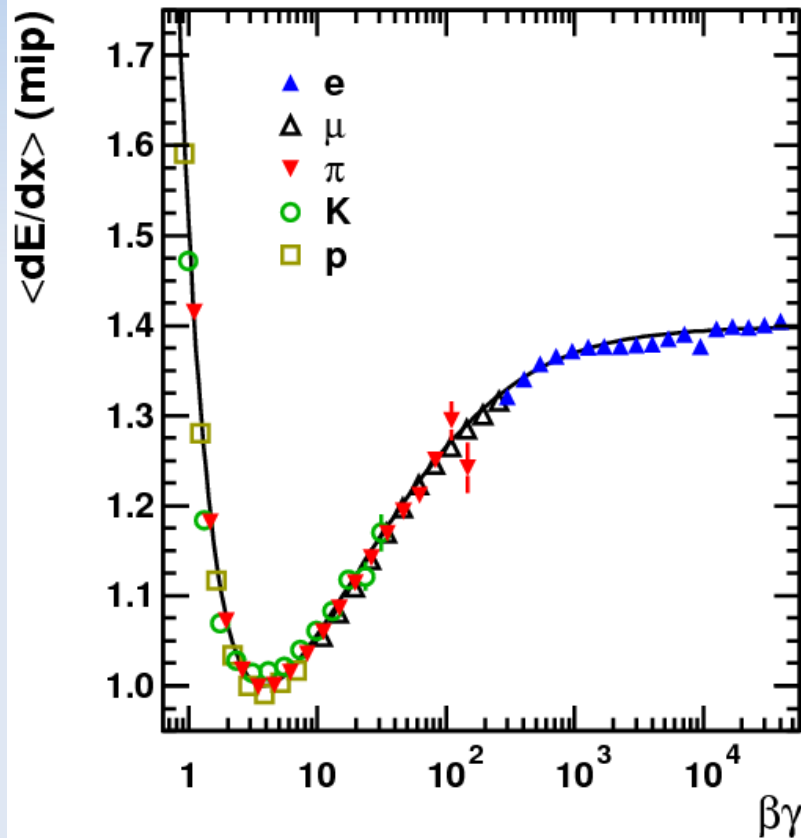
# Outlook

- 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

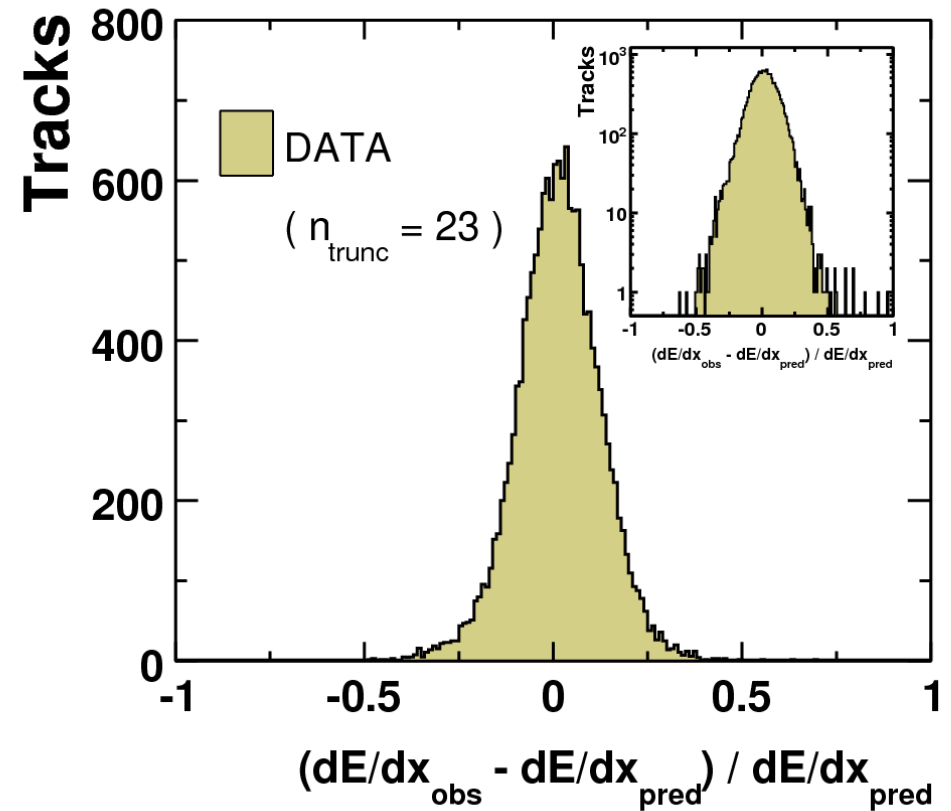
# Backup

# dE/dx in ZEUS

ZEUS



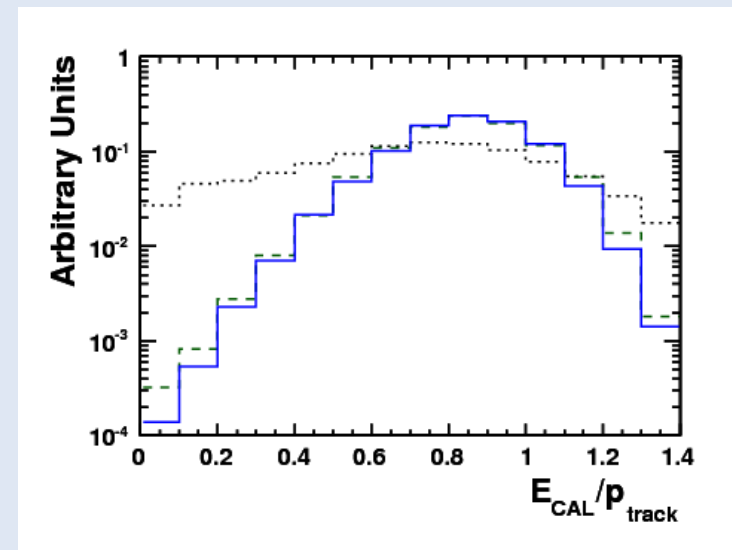
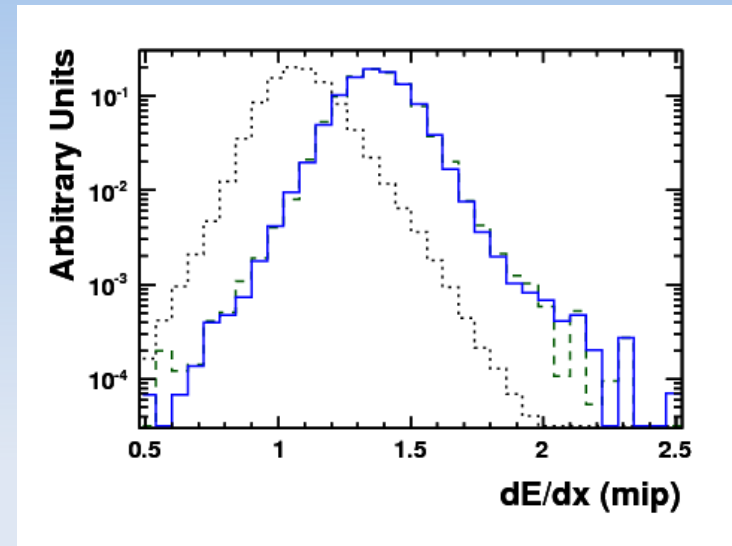
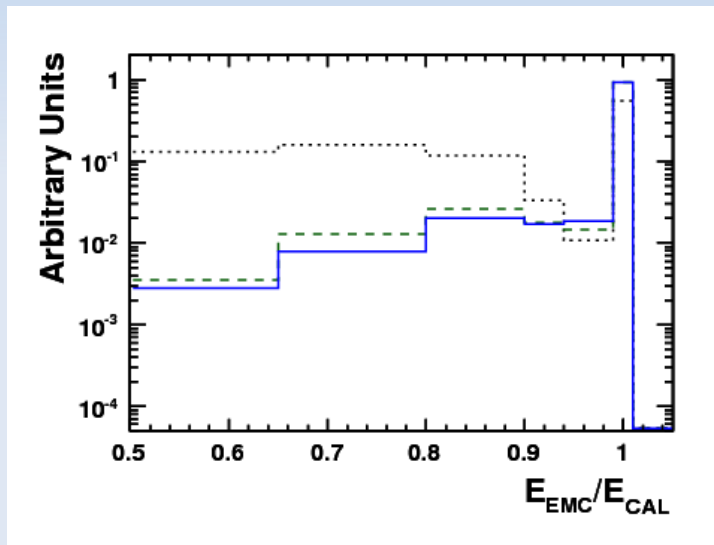
ZEUS



# b & c in Photoproduction



- Electron identification variables



—  $b \rightarrow e X$   
- - -  $c \rightarrow e X$   
..... Bkg

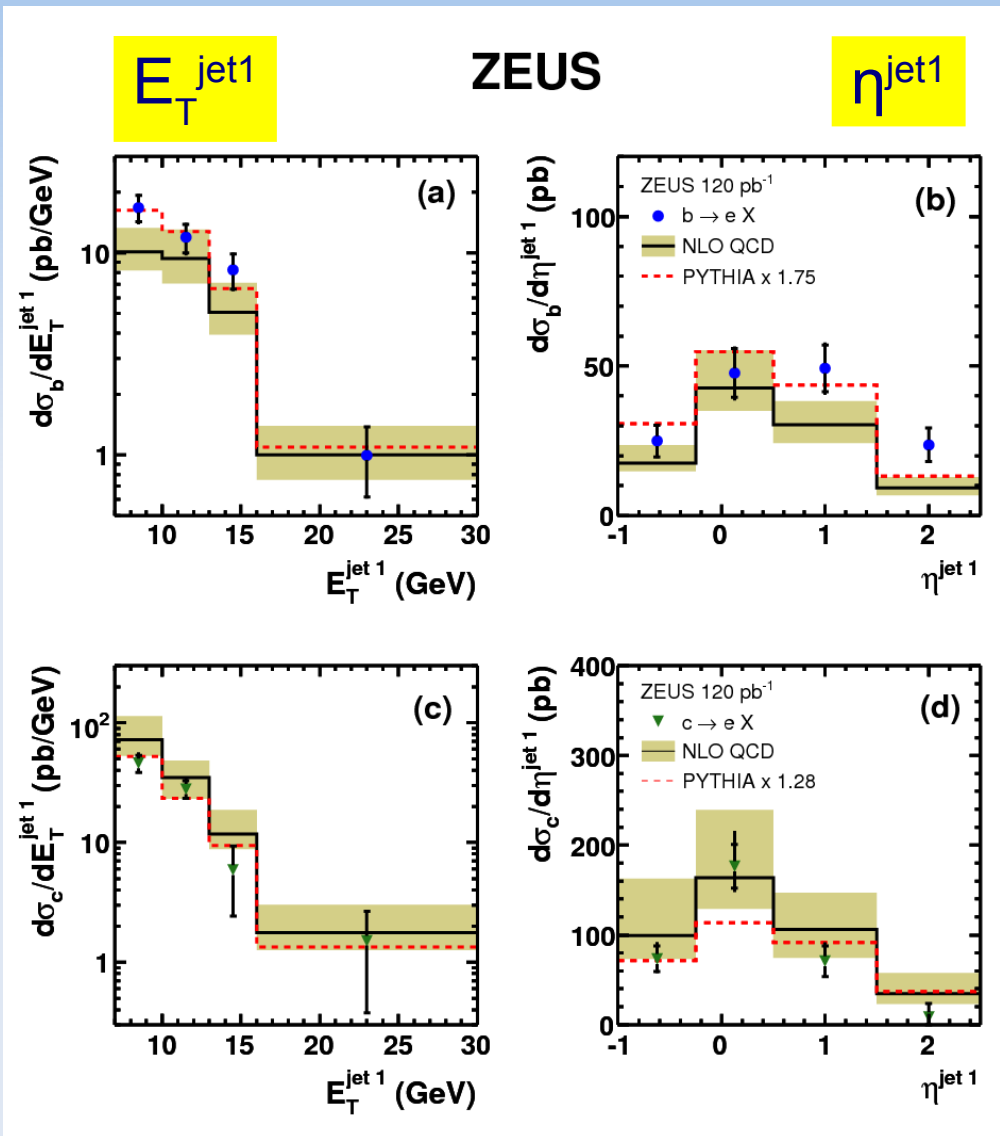


# b & c in Photoproduction



Beauty

Charm

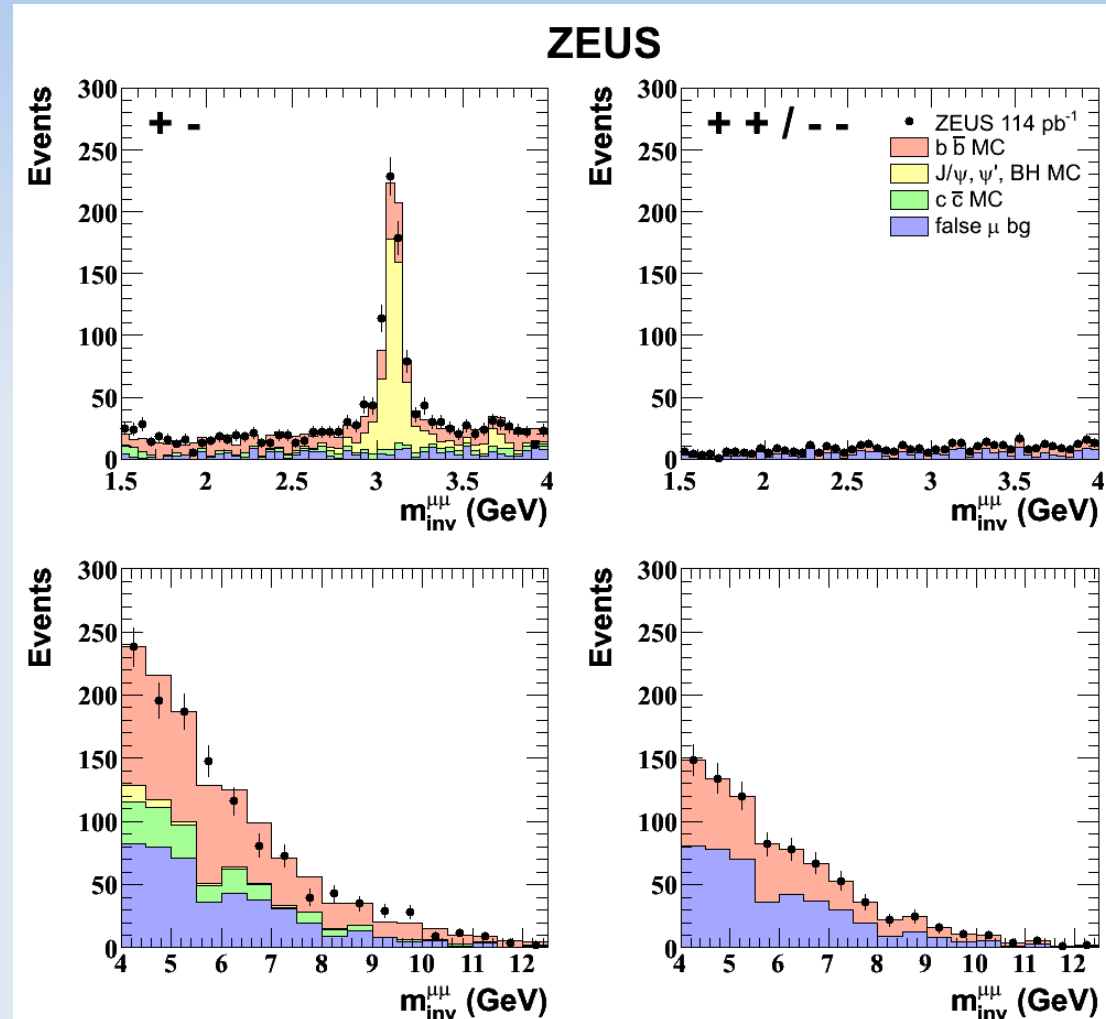


- LO Monte Carlo scale factors:
  - $b \times 1.75$
  - $c \times 1.28$
- NLO absolute predictions

# $b\bar{b}$ Production



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

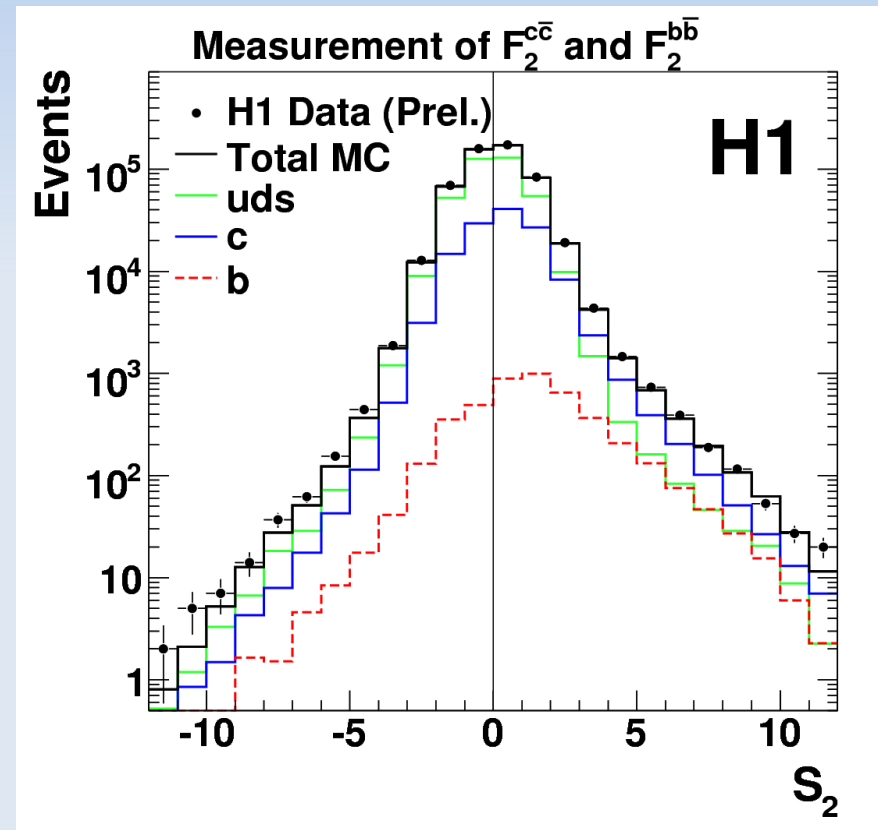
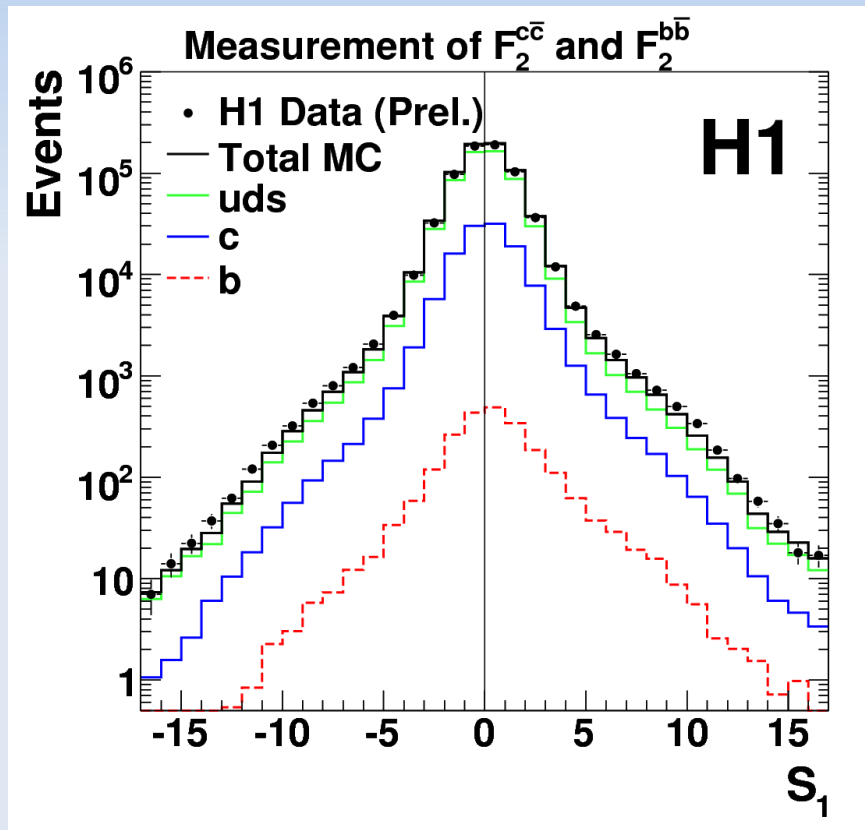


# b & c in DIS



- Significance (1 track events)

- Significance (2<sup>nd</sup> highest significance track)

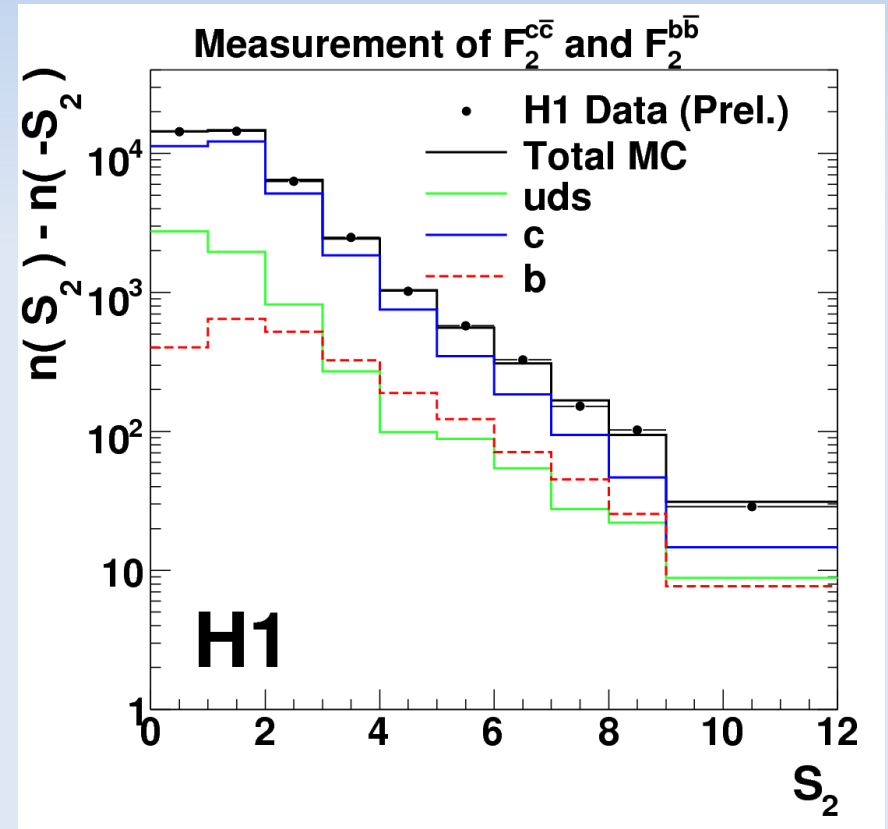
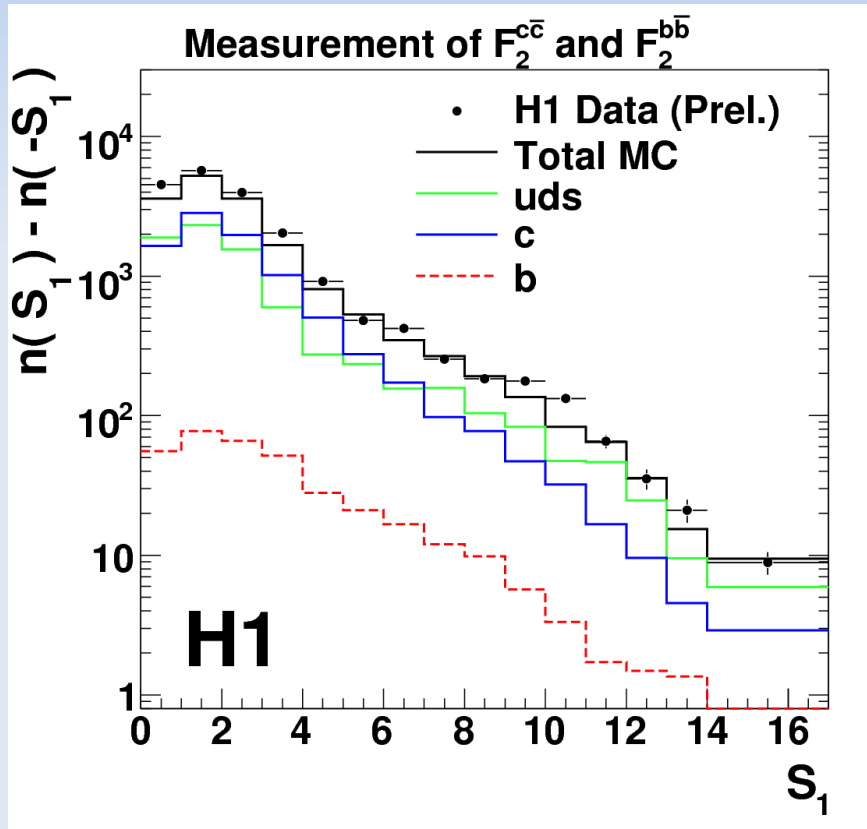


Reject events when  $S_1$  and  $S_2$  have opposite sign

# b & c in DIS



## Subtracted significance distributions



# Reduced Cross-Section

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

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

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