

Heavy Flavor Production at HERA as a Probe of Hard QCD

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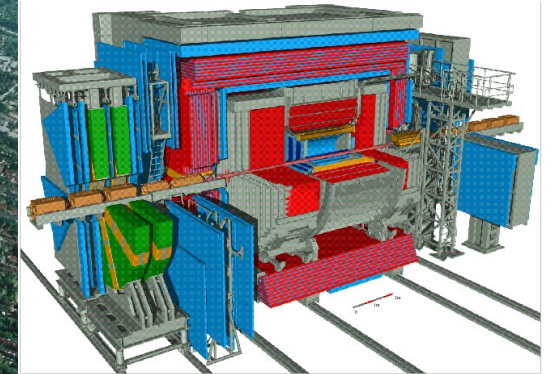
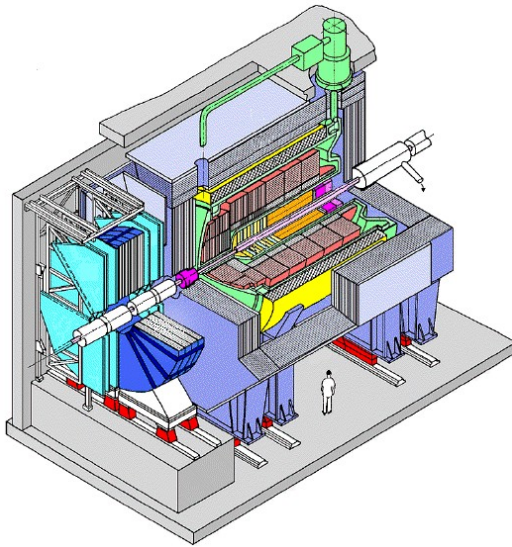
17 September 2008



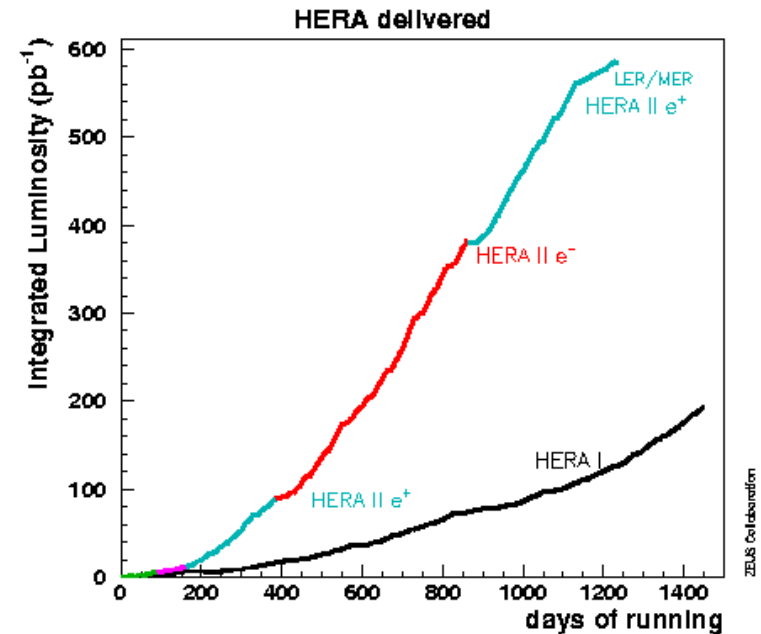
Outline

- H1 & ZEUS
- Motivation
- Theory
- Charm production
- Beauty production
- Summary & Conclusion

H1 and ZEUS



- 27.5 GeV e^\pm colliding with 920 GeV p
→ $\sqrt{s} = 318$ GeV
- HERAI: 1992-2000 ($\mathcal{L} \approx 150$ pb $^{-1}$)
- HERAII: 2003-2007 ($\mathcal{L} \approx 350$ pb $^{-1}$)
→ ~ 0.5 fb $^{-1}$ per experiment



Heavy Flavour Production Mechanism

- Dominant production process: **Boson-Gluon Fusion**
→ sensitive to gluon density in the proton

Kinematic variables:

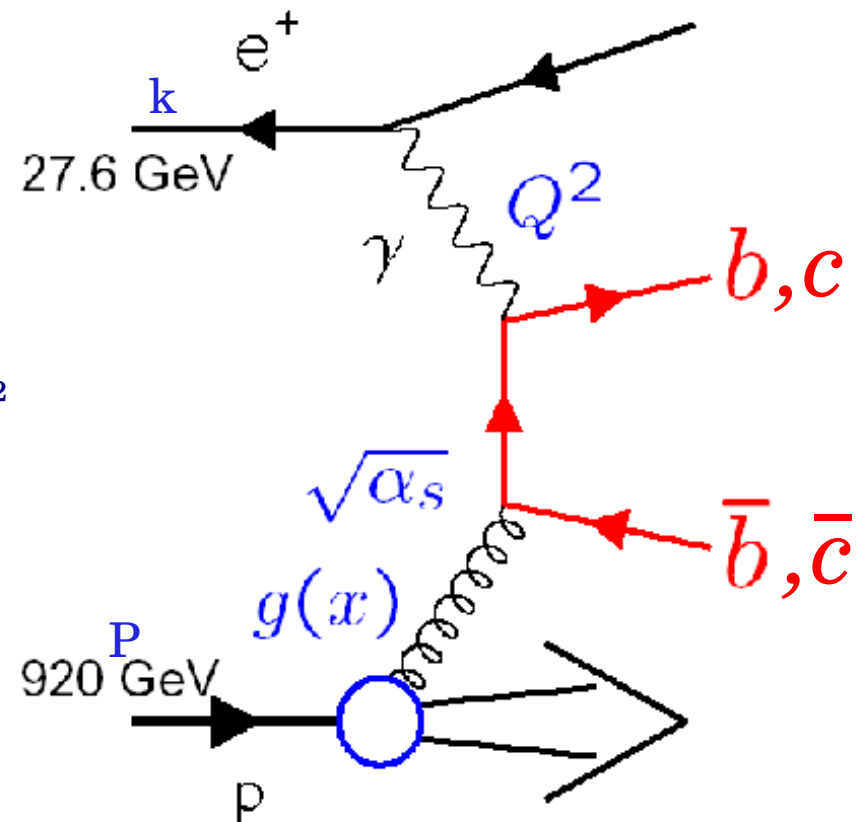
- $Q^2 = -q^2$ photon virtuality, squared momentum transfer
- $y = q \cdot P / k \cdot P$ inelasticity

Two kinematic regimes:

- Photoproduction (γp): γ quasi real, $Q^2 \lesssim 1\text{GeV}^2$
- Deep Inelastic Scattering (**DIS**): $Q^2 \gtrsim 1\text{GeV}^2$

Multiple hard scales:

- large mass $m_{c,b}$
 - large Q^2
 - high momenta p_T
- Different pQCD approaches



pQCD Approximations

Multiscale problem:

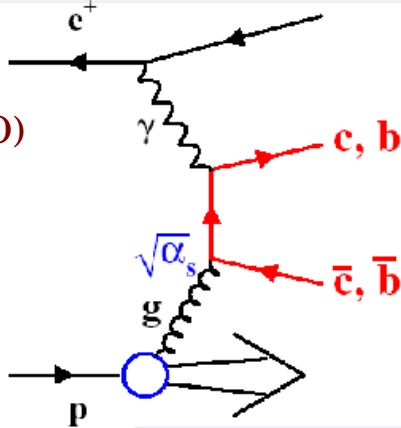
- terms $[\alpha_s \ln(Q^2/m_{c,b}^2)]^n$, $[\alpha_s \ln(p_T^2/m_{c,b}^2)]^n$, etc...
in perturbative expansions → potentially large theoretical errors

Assume one dominant hard scale:

Massive scheme: → $m_{c,b}$

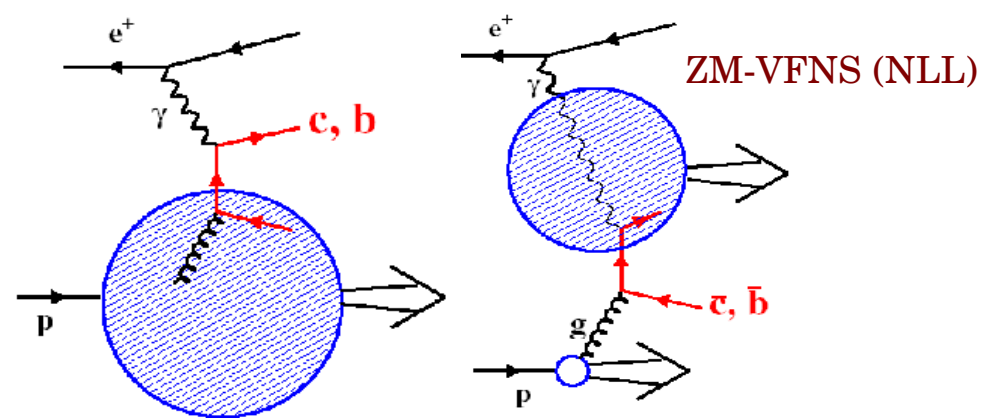
- c,b massive
- neglects $[\alpha_s \ln(Q^2, p_T^2/m_{c,b}^2)]^n$
- c,b produced perturbatively

FFNS (NLO)



Massless scheme: → Q^2, p_T^2

- c,b massless
- resums $[\alpha_s \ln(Q^2, p_T^2/m_{c,b}^2)]^n$
- c,b also in Proton and Photon!



Variable Flavour Number Schemes (VFNS):

- massive at small Q^2, p_T^2
- massless at large Q^2, p_T^2
- GM-VFNS (FONLL)

Monte Carlo Programs

(leading order + parton shower)

- DGLAP evolution
(collinear factorization)

RAPGAP (DIS)

PYTHIA, HERWIG (γp)

- CCFM evolution
(kt-factorization)

CASCADE (DIS+ γp)

NLO Calculations

- Massive scheme

FMNR (γp)
(Frixione, Mangano, Nason, Ridolfi)

- (Massive + Massless) scheme

GM-VFNS (γp)
(Kniehl, Kramer, Schienbein, Spiesberger)

- New development:

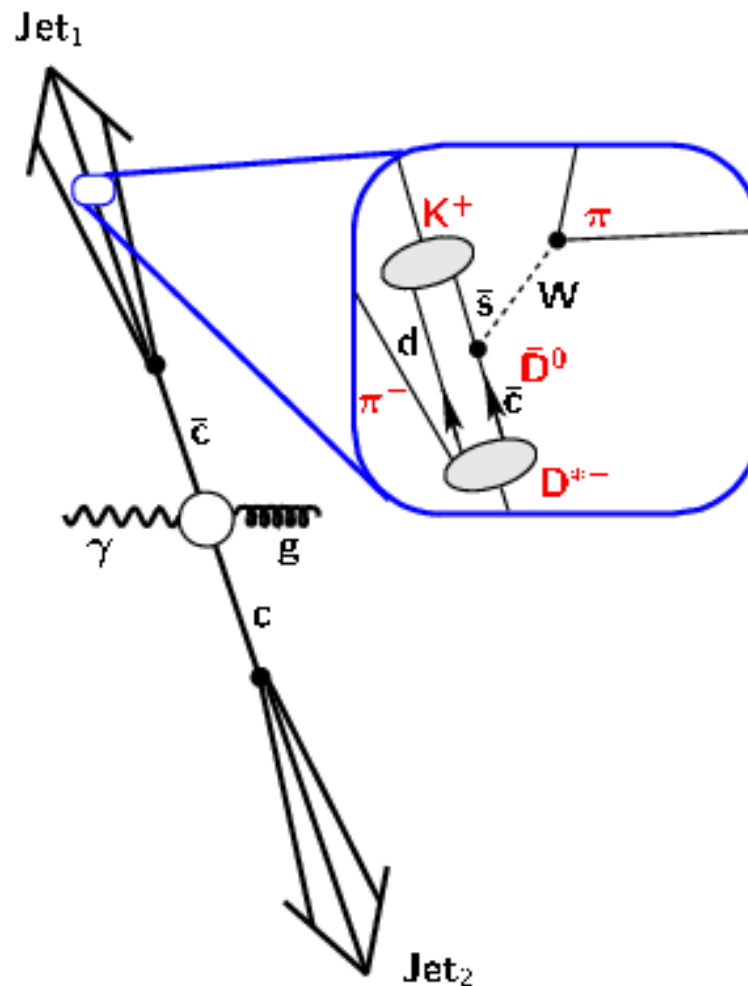
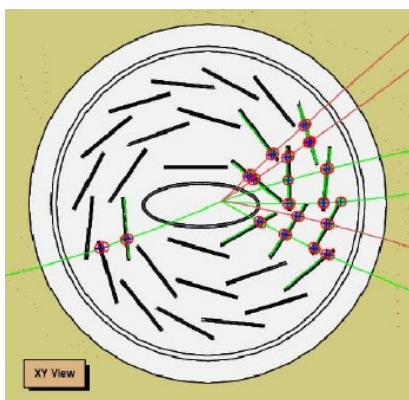
FMNR \otimes PYTHIA
(hadronization done with
PYTHIA)

- Comparison of data with different models yields important insights
- This talk focuses on γp results
- DIS results will be discussed on Thursday (cf. Talk by P. Thompson)

Heavy flavour tagging

Different experimental techniques to use (combine) for heavy flavor tagging

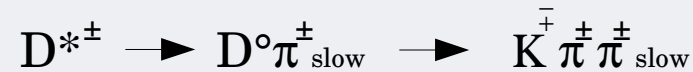
- Meson identification
 $D^{*\pm}$ tagging
- Decay spectra
 p_T^{rel} of lepton to jet axis
- Life time information
Measure impact parameter with respect to primary vertex (beam spot)



- Different tags probe different kinematic regions

Charm Production

Charm quark tagged by a D* meson decaying in the **golden channel**



Data/MC & NLO calculations:

Data: 2006-2007 ($\mathcal{L} \cong 93\text{pb}^{-1}$)

LO: PYTHIA & CASCADE

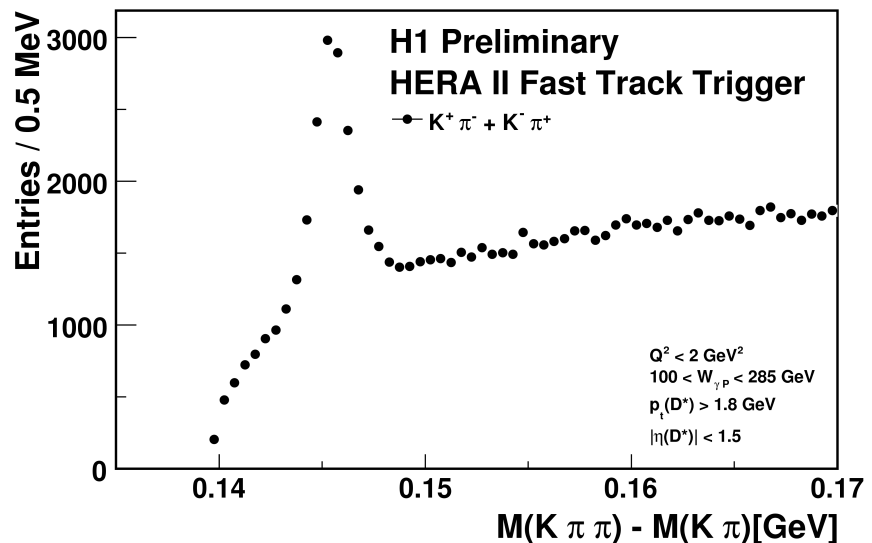
NLO: FFNS (CTEQ5F3)

GMVFNS (CTEQ6.5)

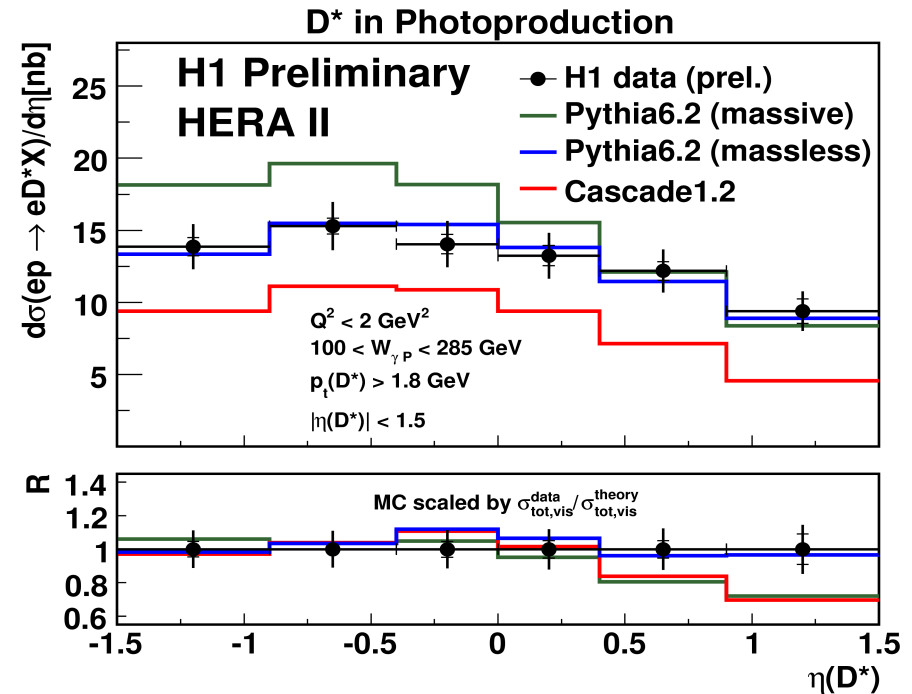
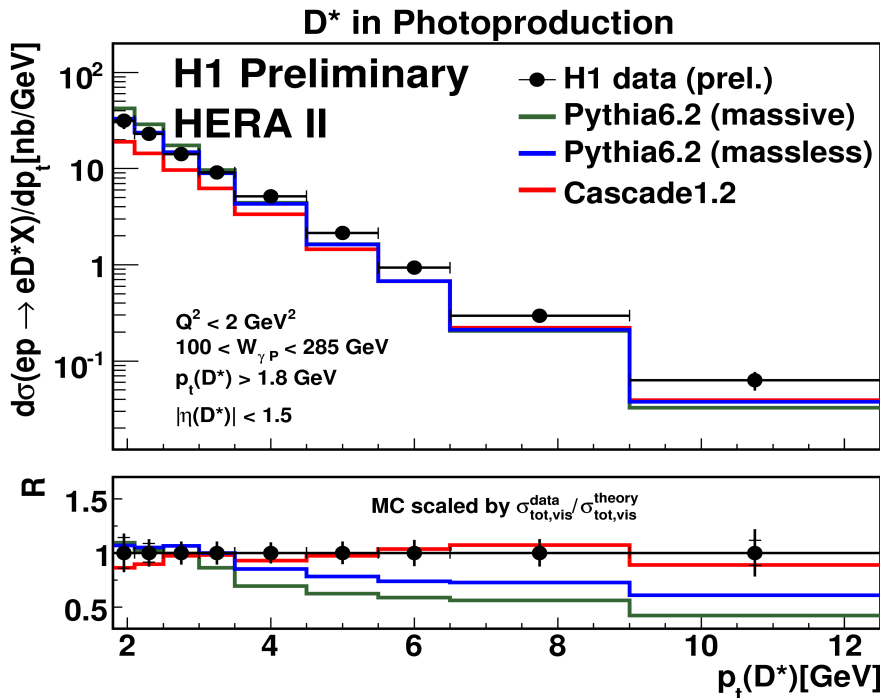
Kinematic range:

- $Q^2 < 2\text{GeV}^2$
- $0.1 < y < 0.8$
- $p_T(D^*) > 1.8\text{GeV}$
- $|\eta(D^*)| < 1.5$

- ΔM distribution to determine the number of D* mesons



Data compared to **Pythia(massive)**, **Pythia(massless)** & **Cascade** MCs



Significant changes for different MCs

- $p_T(D^*)$

Cascade describes the shape of $p_T(D^*)$, but is too low in normalisation

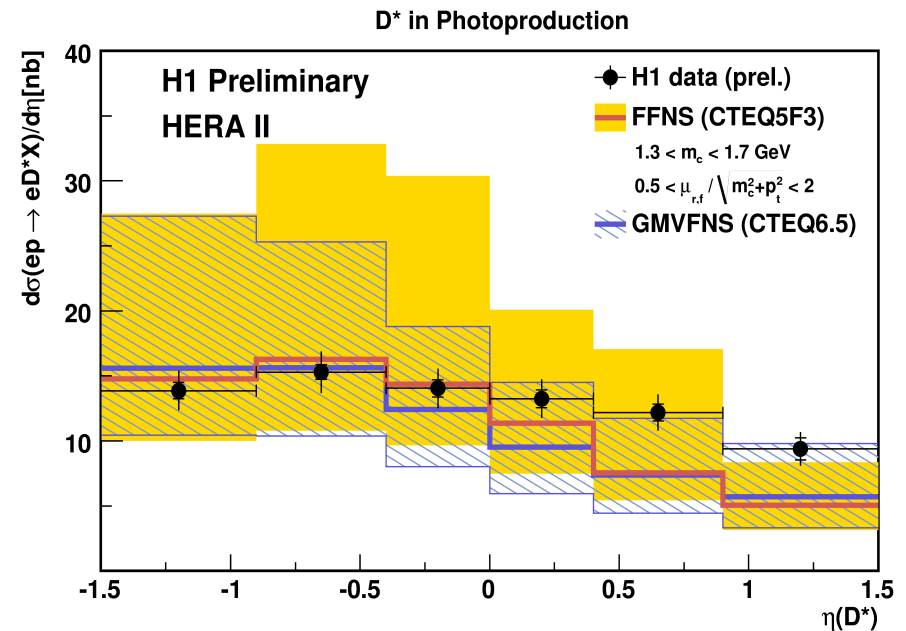
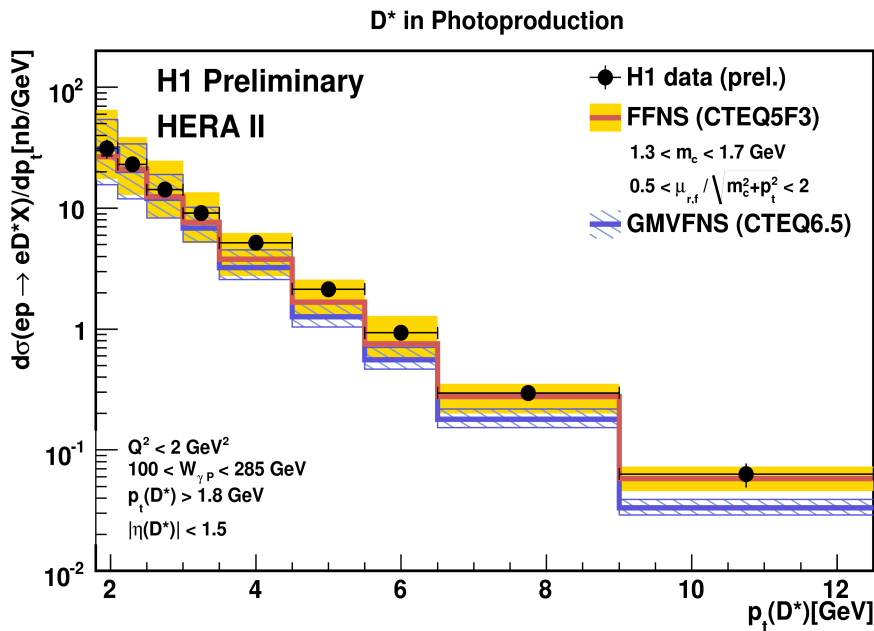
Both Pythia models are too steep

- $\eta(D^*)$

Massless Pythia describes shape and normalisation

Cascade and massive Pythia predict a stronger decrease in forward direction

Data compared to NLO predictions: (FFNS, GMVFNS)



- $p_t(D^*)$ spectrum well described by NLO QCD
- $\eta(D^*)$ shape not well reproduced:
 η depends on gluon density, but also on fragmentation model
- GM-VFNS does not give better predictions than FFNS
- Higher order calculations (NNLO) needed!

Beauty Production

Beauty in Dijet γp using muons



Data: (HERAII)

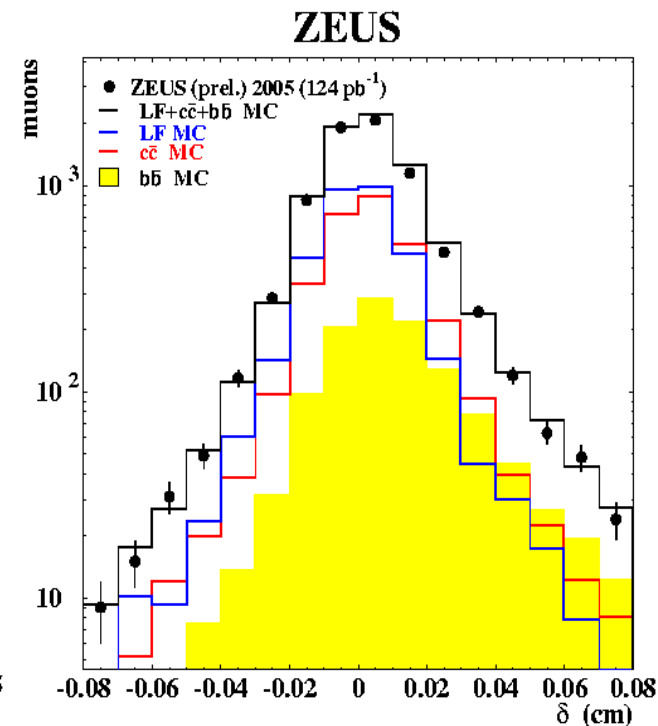
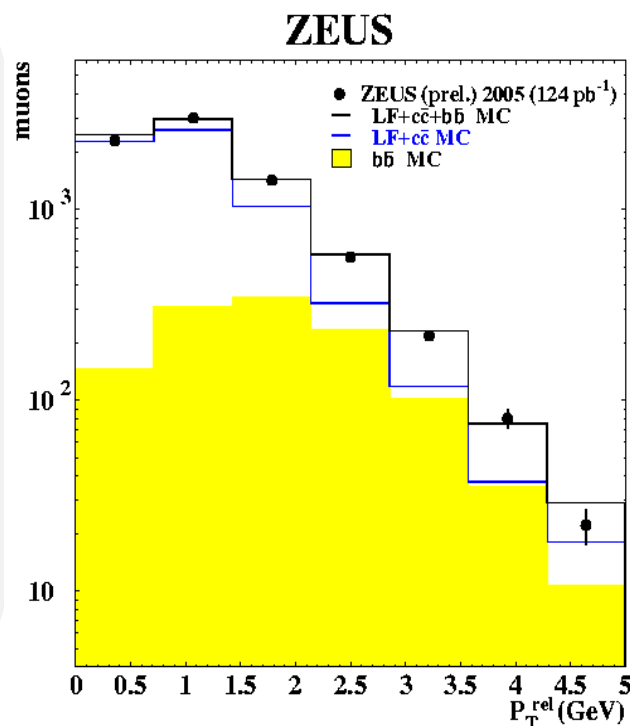
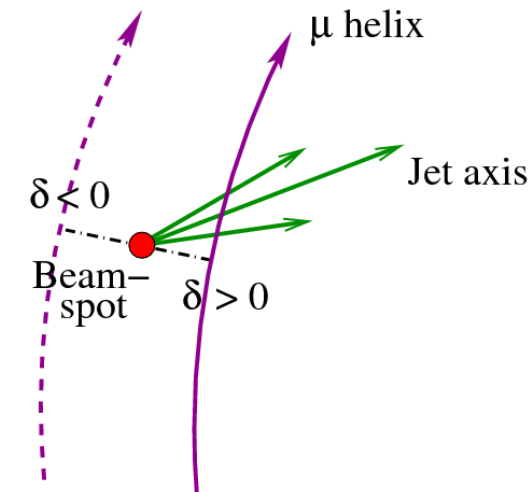
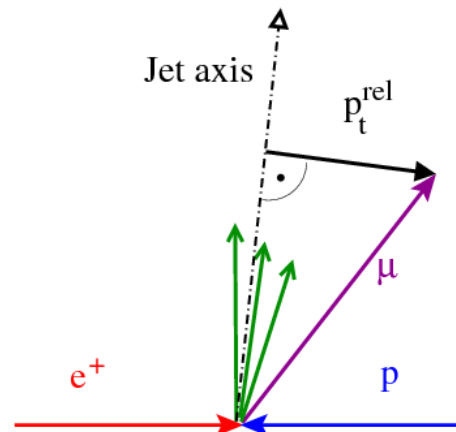
ZEUS: ($\mathcal{L} \cong 124\text{pb}^{-1}$)

H1: ($\mathcal{L} \cong 171\text{pb}^{-1}$)

LO: PYTHIA

NLO: FMNR

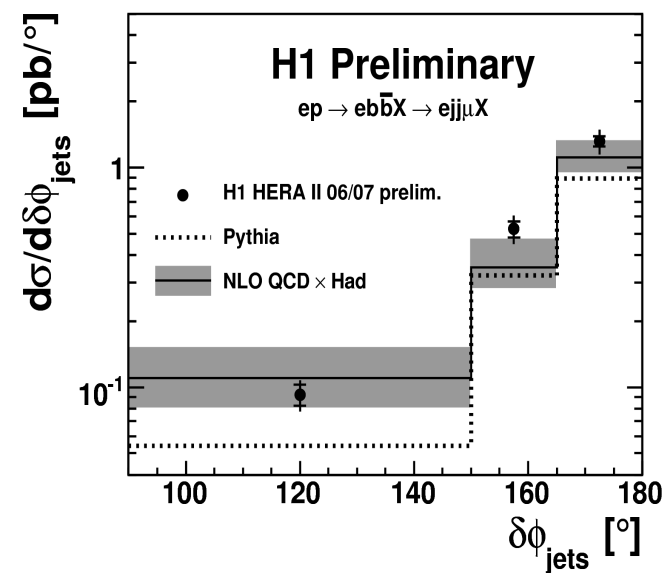
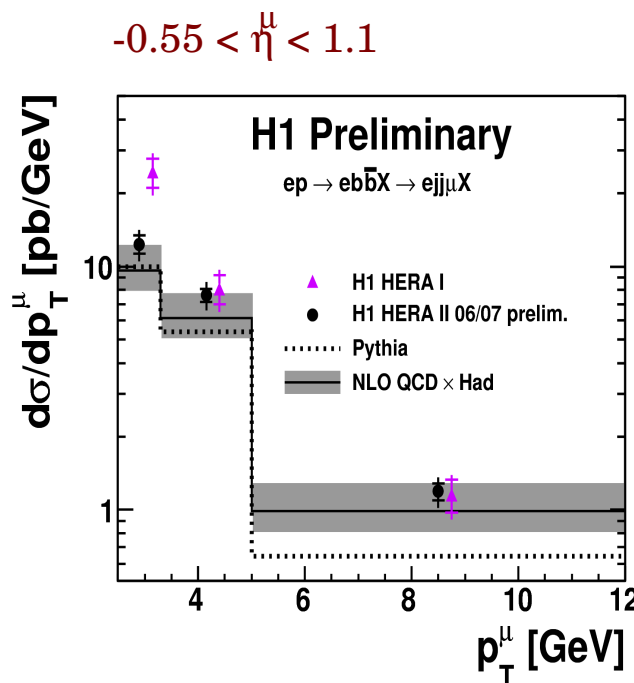
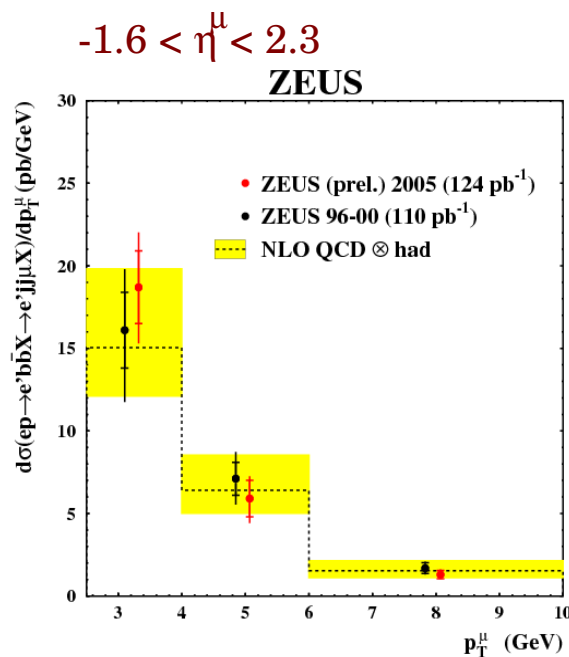
- Similar visible range
- Dijet γp events
 p_T of jets $> 7(6)$ GeV
- $0.2 < y < 0.8$
- $p_T(\mu) > 2.5\text{GeV}$
- Simultaneous fit of p_T^{rel} & impact parameter (δ)
- p_T^{rel} constrains b
- δ allows uds/c separation



Beauty in Dijet γp using muons



- Phase space: Similar, but not equal
 - Measurements consistent with NLO calculation
- ZEUS: Good agreement between HERAI & HERAII results
- H1: Excess (at low p_T) in HERAI analysis not confirmed
- Additional HERAII measurement at H1: ($d\sigma/d\delta\phi_{\text{jets}}$)
- $\delta\phi_{\text{jets}}$ = azimuthal angle difference of jets: 180° at LO
- direct sensitivity to higher orders. Well described



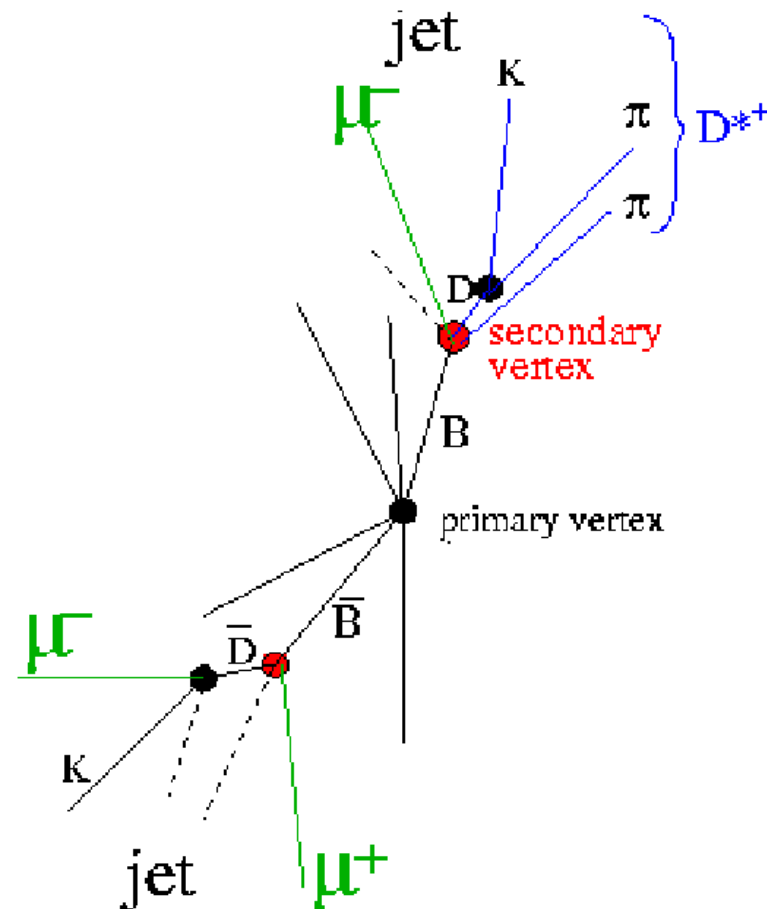
Data: (HERAI)

($\mathcal{L} \cong 114\text{pb}^{-1}$)

**LO: PYTHIA , RAPGAP,
HERWIG**

NLO: FMNR \otimes PYTHIA

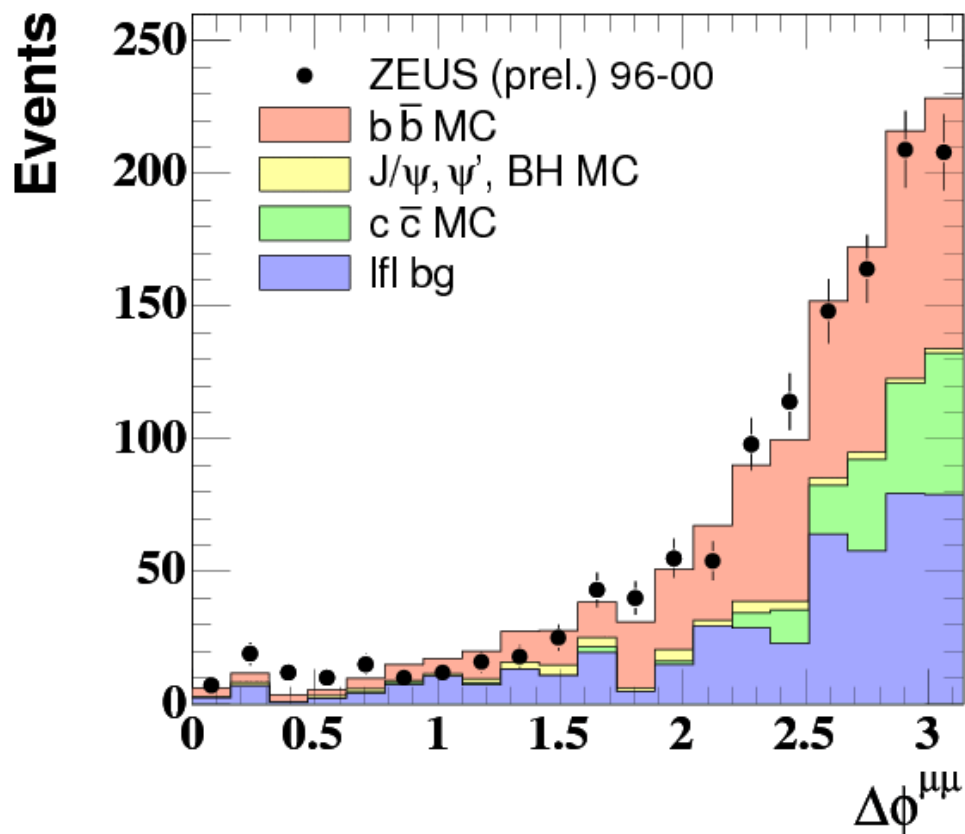
- Double tag events
- Sensitive to almost full phase space
- Low p_T^μ threshold
- Low background
- DIS + γp
- Two identified muons
- $E_T > 8\text{GeV}$
- Measure $b\bar{b}$ correlations
- Probe NLO effects



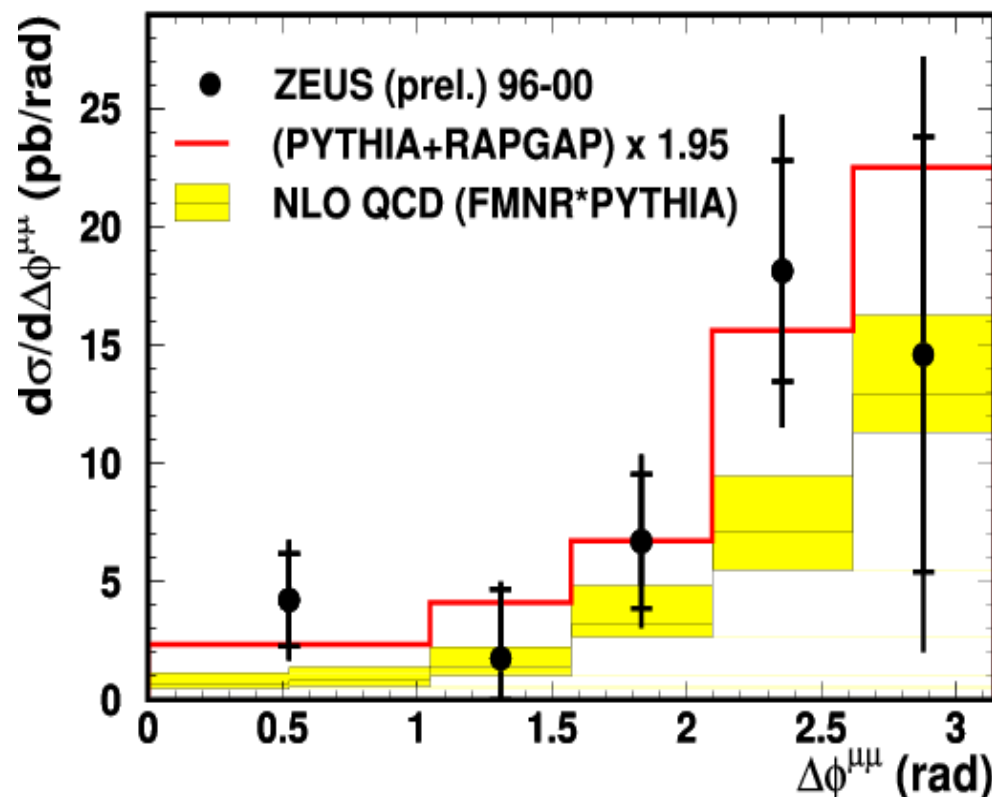
- **Extract b fraction from difference between unlike-sign and like-sign distributions**

$$\sigma_{\text{tot}}(ep \rightarrow b\bar{b}X) = 16.1 \pm 1.8 \text{ (stat.) } {}^{+5.3}_{-4.8} \text{ (syst.) nb}$$

ZEUS

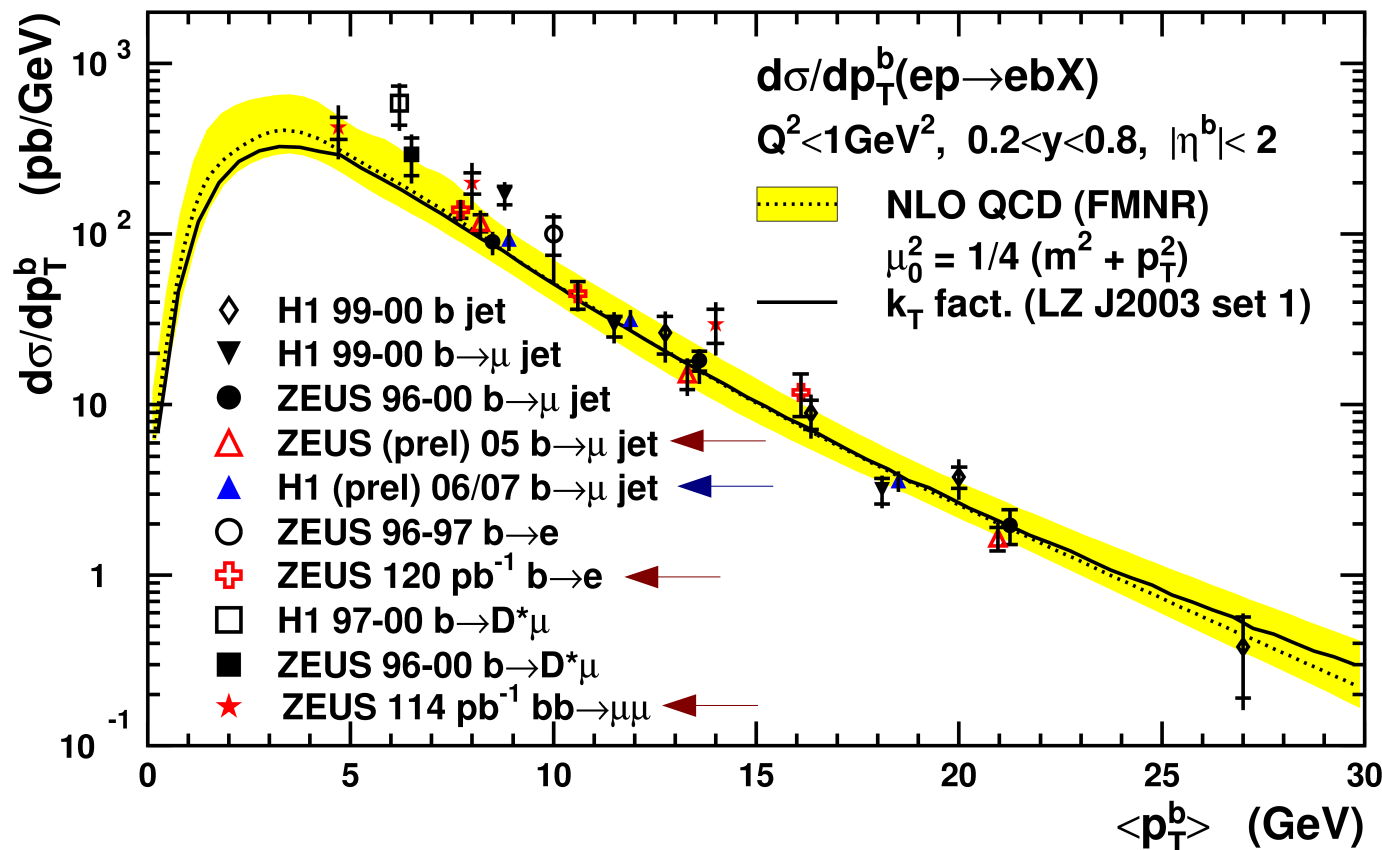


ZEUS



- $\Delta\phi^{\mu\mu}$ = angle between muons from different quarks
- Correlations expected to show higher order effects
- Good description, but large uncertainties

HERA



Recent results: colored (indicated by arrows)

- Improved precision of data (<20% total error)
- Data agree well with NLO QCD
- Data more precise than NLO QCD
- Better agreement with new scale factor!

Summary & Conclusions

Small selection of heavy flavor results from HERA presented:

- Charm production: via D^* decay channel (γp)
- Beauty production: via semileptonic decays to μ (γp)
: using dimuon tagging (γp)

- LO MCs usually describe shape well
- Overall good description of data by NLO QCD
- Most of the time mass and scale uncertainties are larger than experimental errors
 - ▶ limits the interpretation of data
- For beauty production NLO predictions on the low side
- Higher order calculations (NNLO) needed!
- Compare data to NLO MC with parton showers!

BACKUP SLIDES

Selection cuts:

- $p_T(K) > 0.5 \text{ GeV}$
- $p_T(\pi) > 0.3 \text{ GeV}$
- $p_T(\pi_{\text{slow}}) > 0.12 \text{ GeV}$
- $p_T(K) + p_T(\pi) > 2.2 \text{ GeV}$
- $|M(K\pi) - M(D^0)| < 0.08 \text{ GeV}$

Ratio (R):

$$R = \frac{\frac{1}{\sigma_{\text{vis}}^{\text{MC}}} \cdot \frac{d\sigma^{\text{MC}}}{dY}}{\frac{1}{\sigma_{\text{vis}}^{\text{data}}} \cdot \frac{d\sigma^{\text{data}}}{dY}}$$

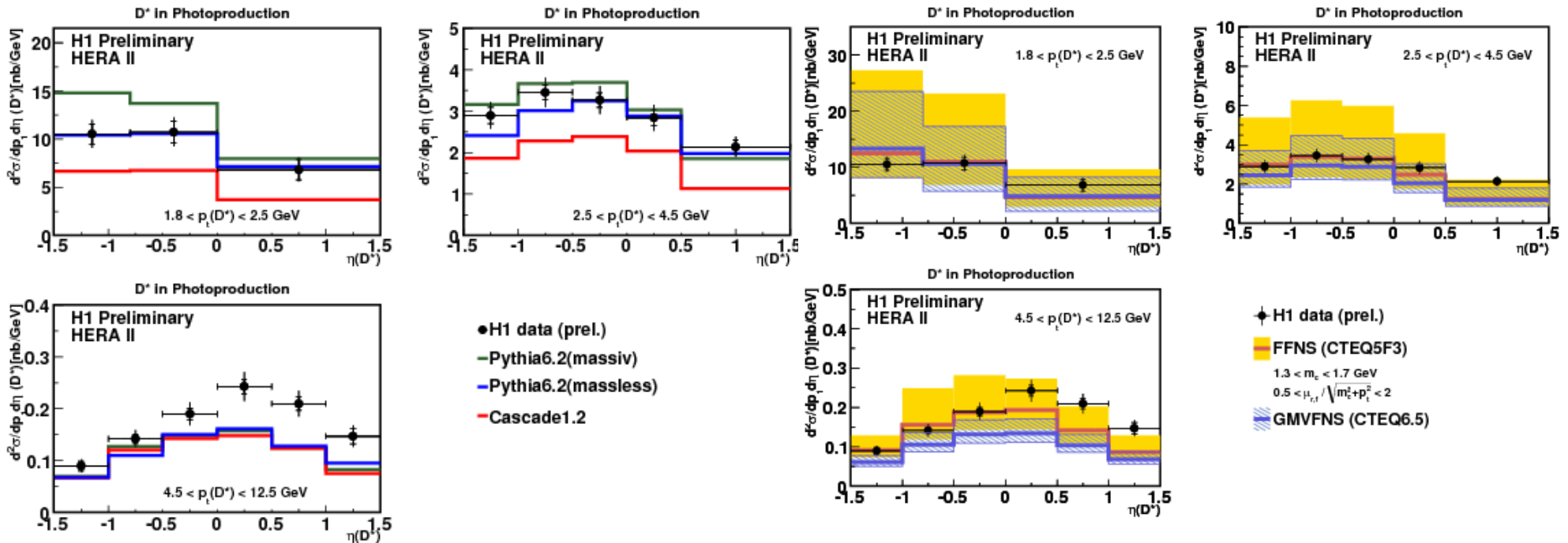
Differential Cross section determination:

$$\frac{d\sigma^{\text{vis}}}{dY} = \frac{N_{D^*} (1 - r)}{\Delta Y \mathcal{L} \cdot \mathcal{B}(D^* \rightarrow K\pi\pi_{\text{slow}}) \cdot A_{\text{Detector}} \cdot \epsilon_{\text{Detector}} \cdot \epsilon_{\text{Trigger}}}$$

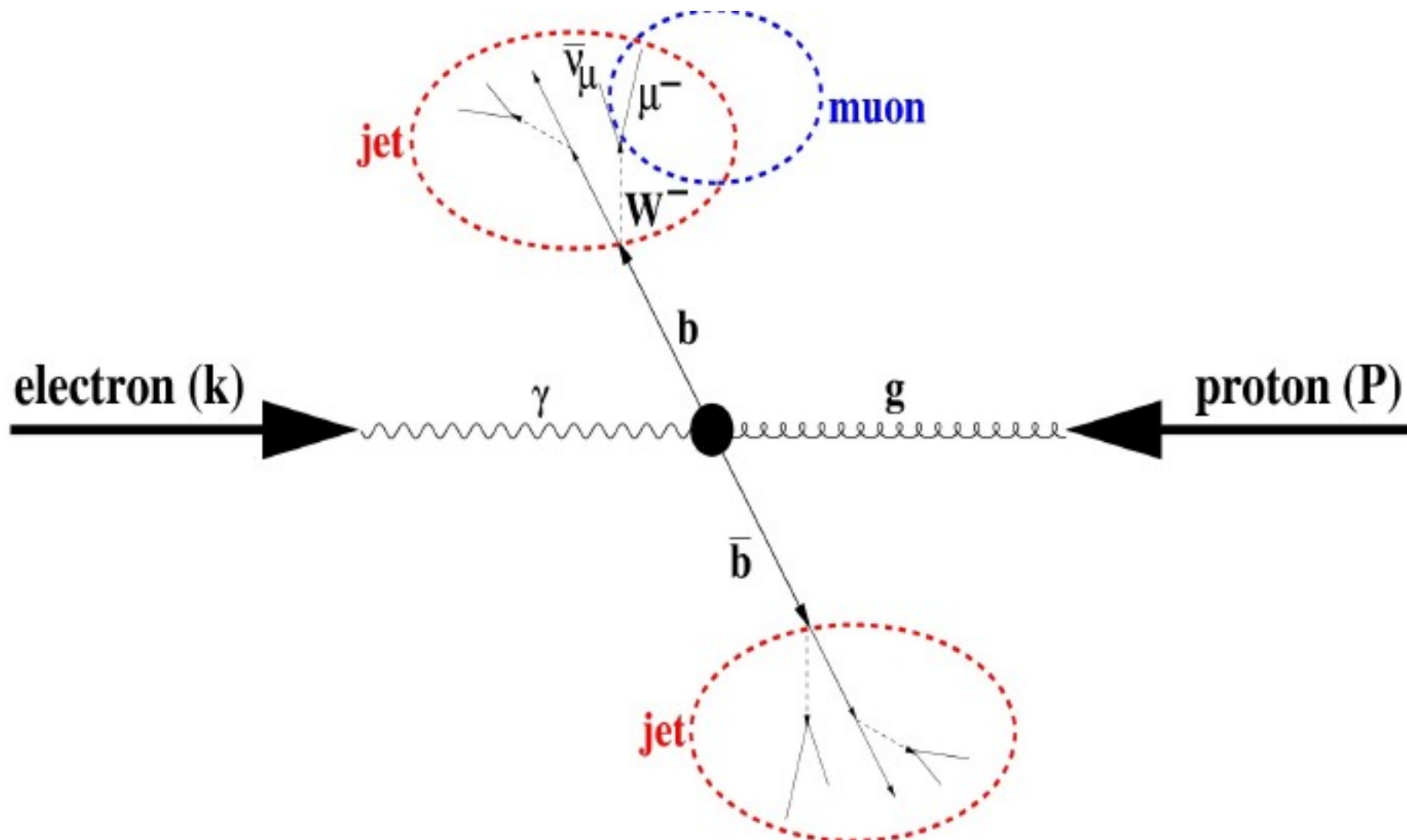
Total visible cross sections:

$$\sigma_{\text{vis}}^{\text{tot}}(e^\pm p \rightarrow e^\pm D^{*\pm} X) = 4.85 \pm 0.07(\text{stat.}) \pm 0.42(\text{sys.}) \text{nb}$$

Double differential cross sections:

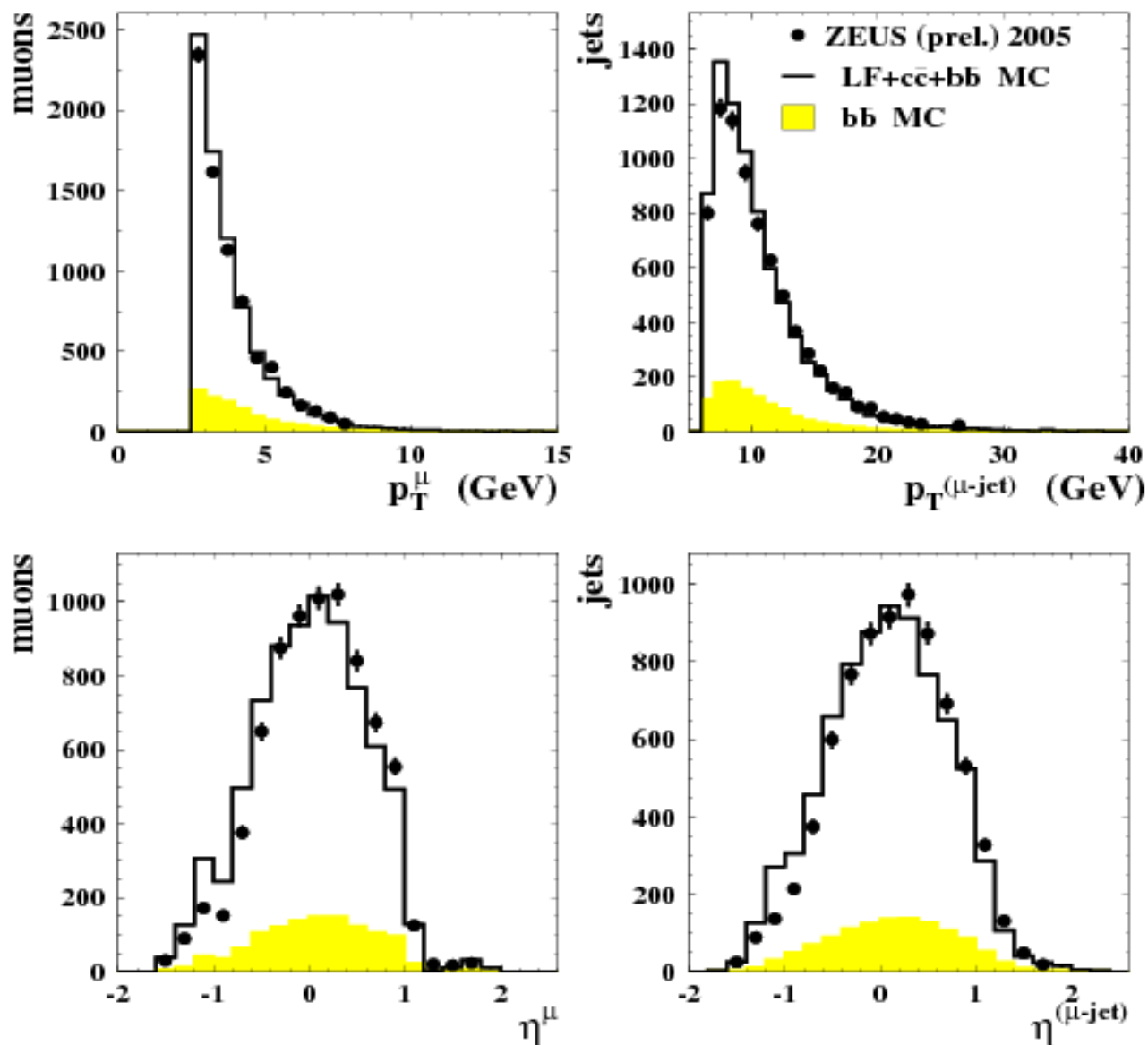


Beauty in Dijet γp using muons

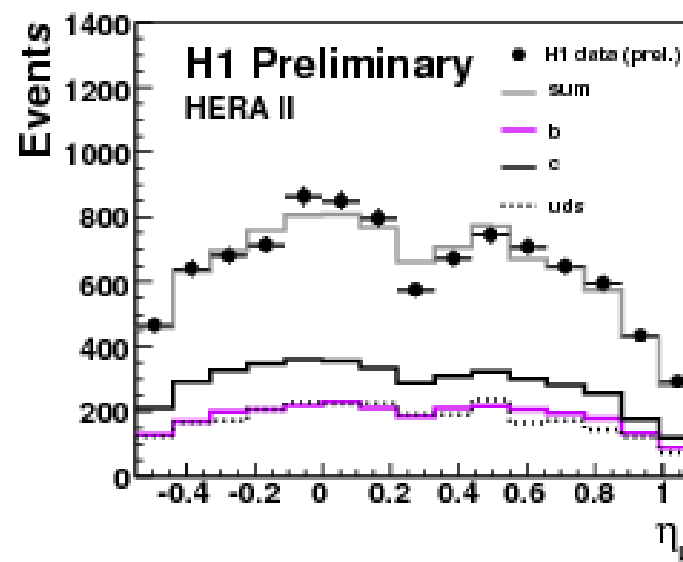
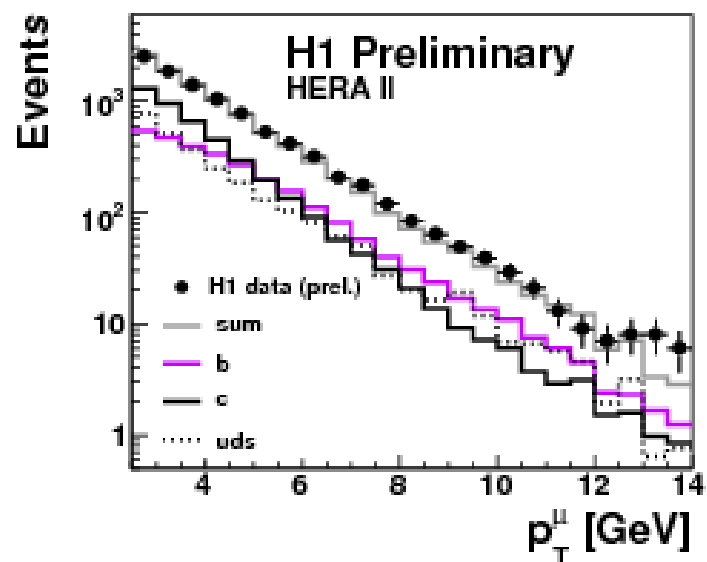


Control plots:

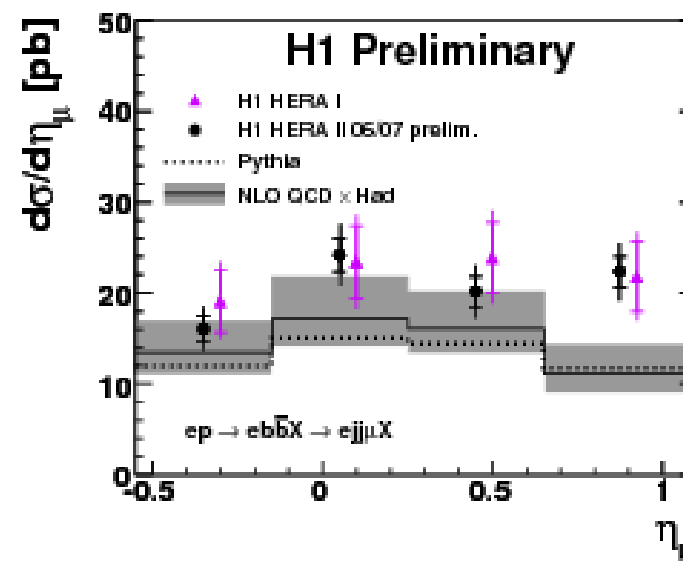
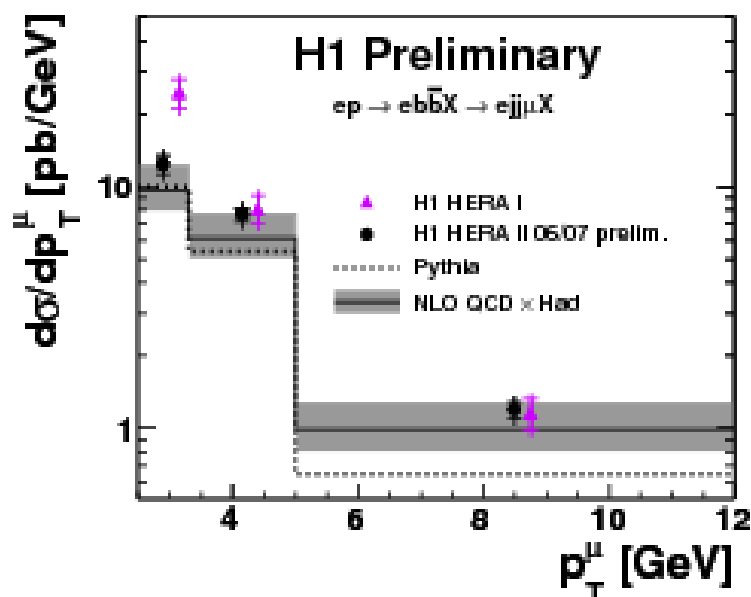
ZEUS



Control plots:



Differential cross sections:



Selection cuts:

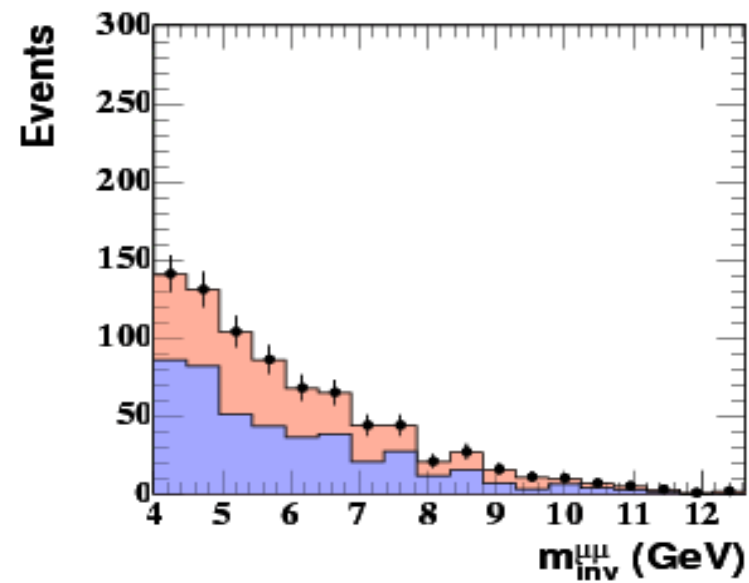
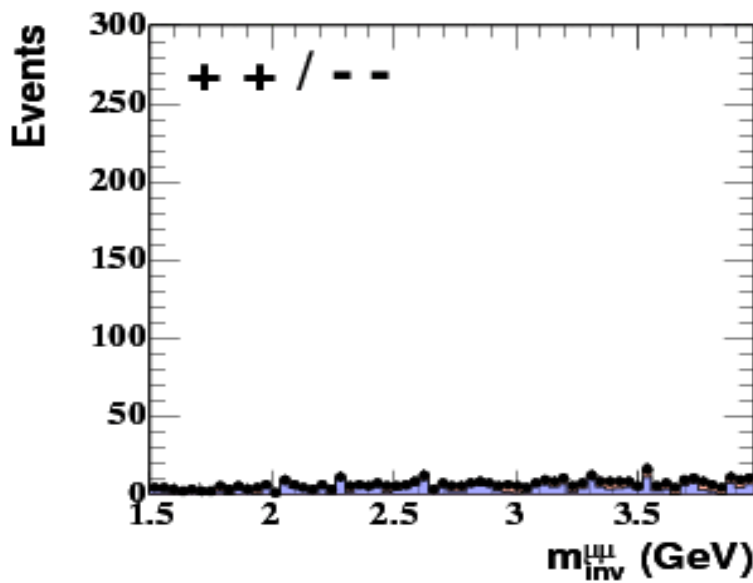
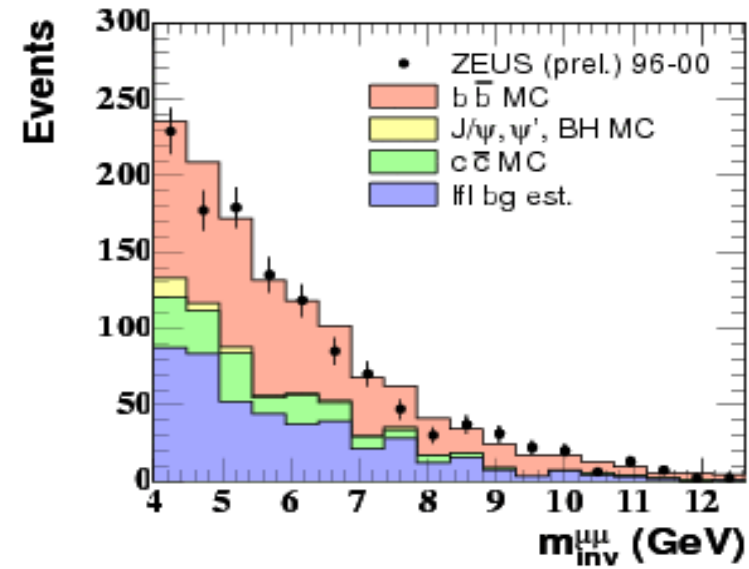
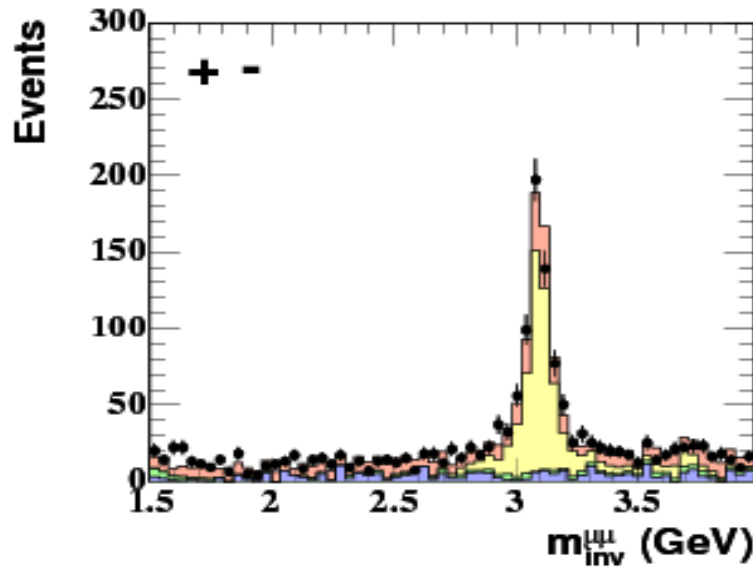
- $p_T^\mu > 1.5\text{GeV}$
- $p_T^\mu > 0.75\text{GeV}$
(high quality muons)
- Cal E_T - 10° cone $> 8\text{GeV}$
- Further cleaning cuts

Background sources:

- Open c \rightarrow high mass, unlike sign
Normalisation from $D^*\mu$ analysis
- Hidden c (J/ψ , ψ') \rightarrow low mass, unlike sign
Isolation cut
- Bethe-Heitler, hidden b \rightarrow high mass, unlike sign
Isolation cut
- Light flavour \rightarrow all regions
From data

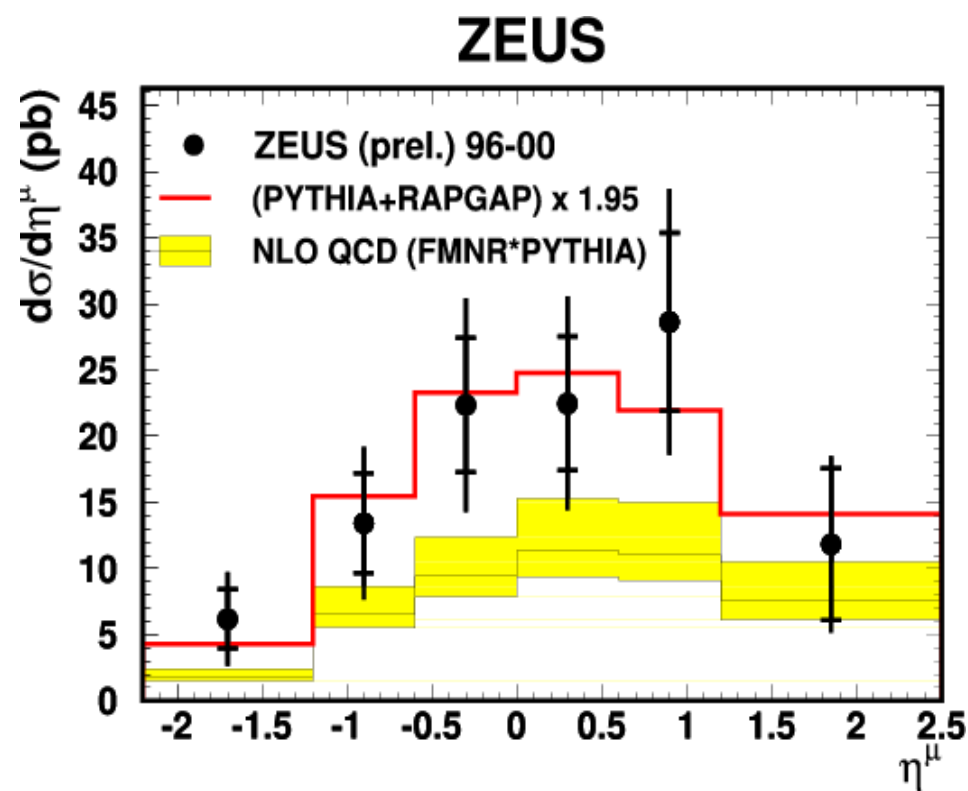
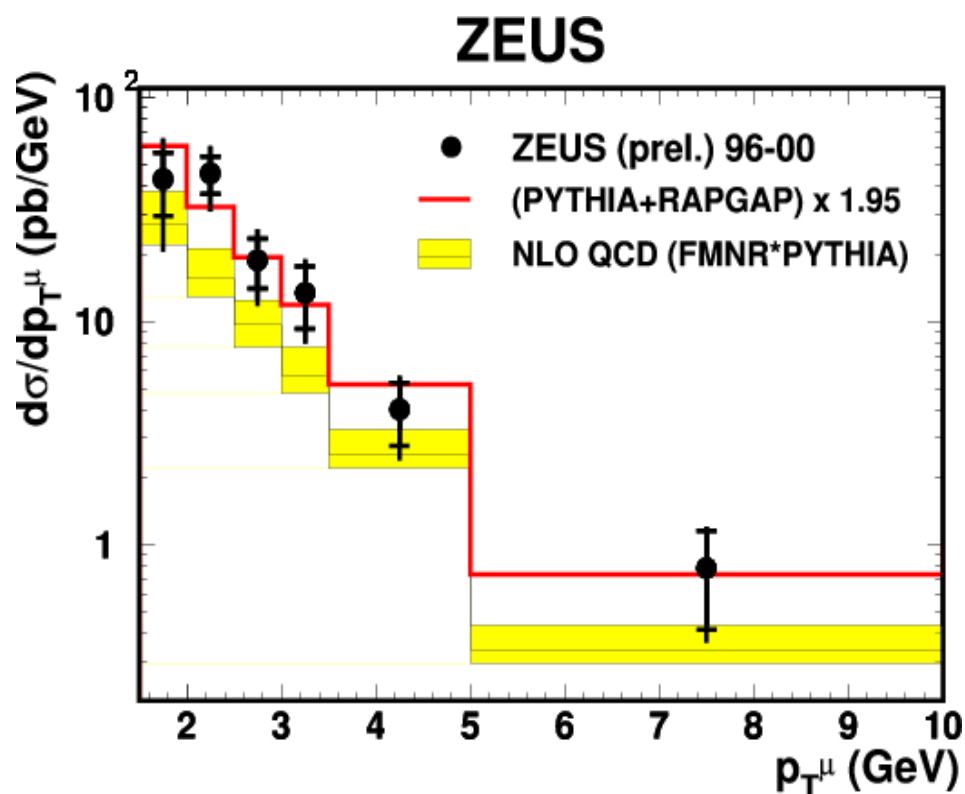
Dimuon Mass:

ZEUS



Differential muon cross sections:

Both muons $p_T > 1.5\text{GeV}$, $-2.2 < \eta < 2.5$



- Good agreement in shape
- Reasonable agreement in normalization
- No indication of excess at low p_T or high η