Heavy Flavor Production at HERA as a Probe of Hard QCD

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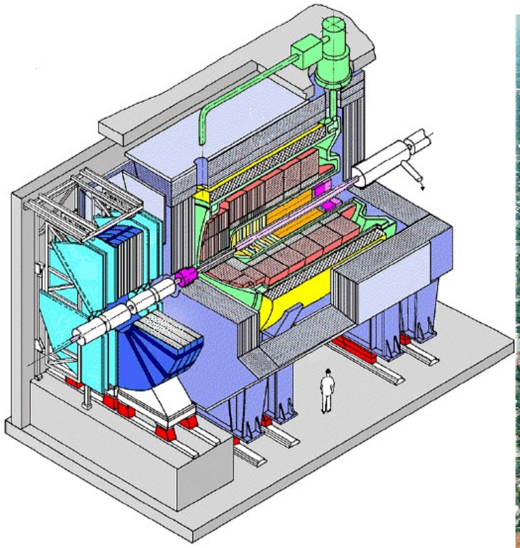
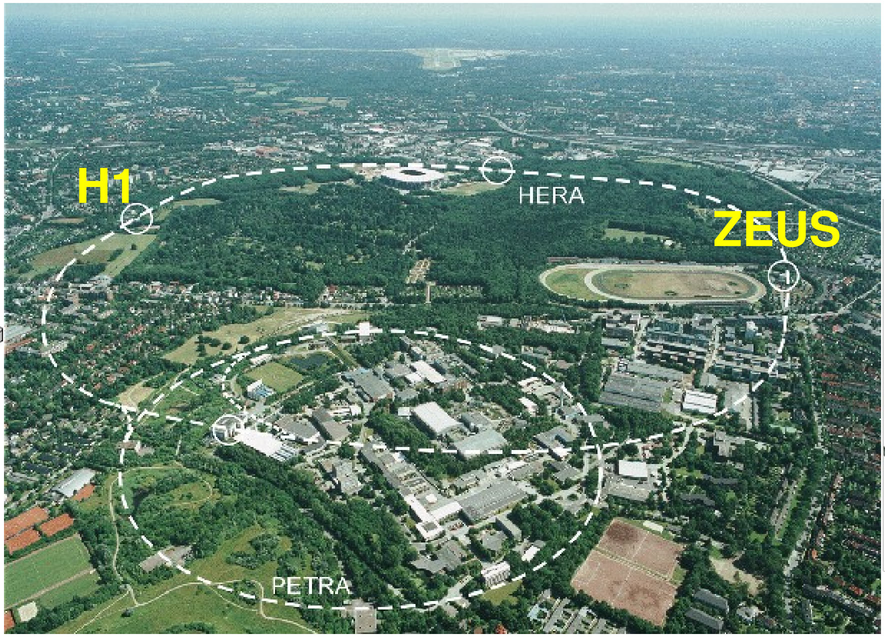
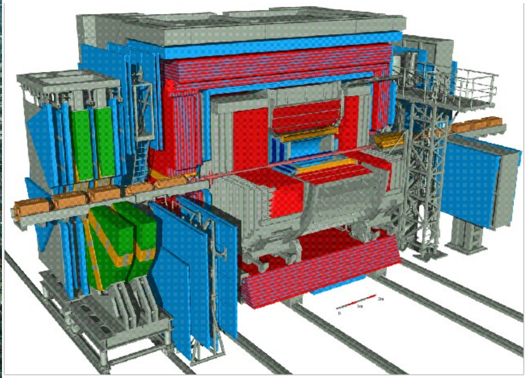
Outline

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

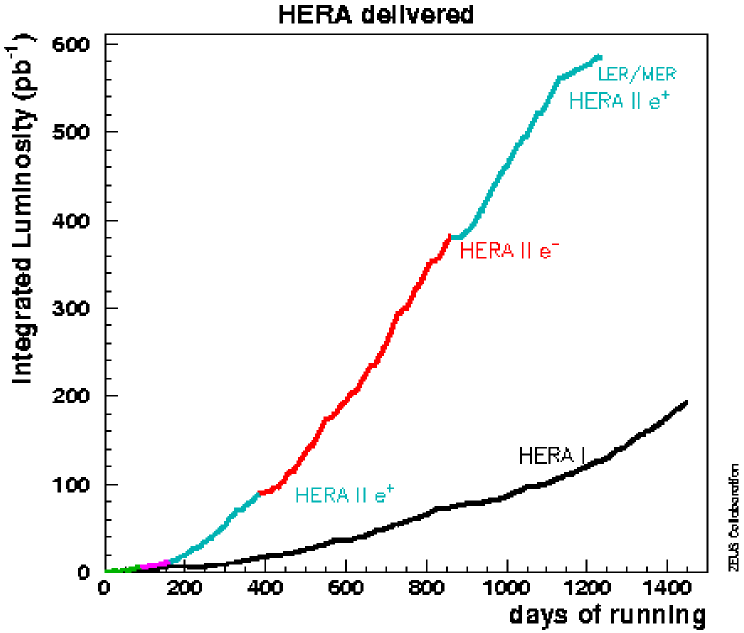
H1 and ZEUS







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



Heavy Flavour Production Mechanism

- Dominant production process: Boson-Gluon Fusion

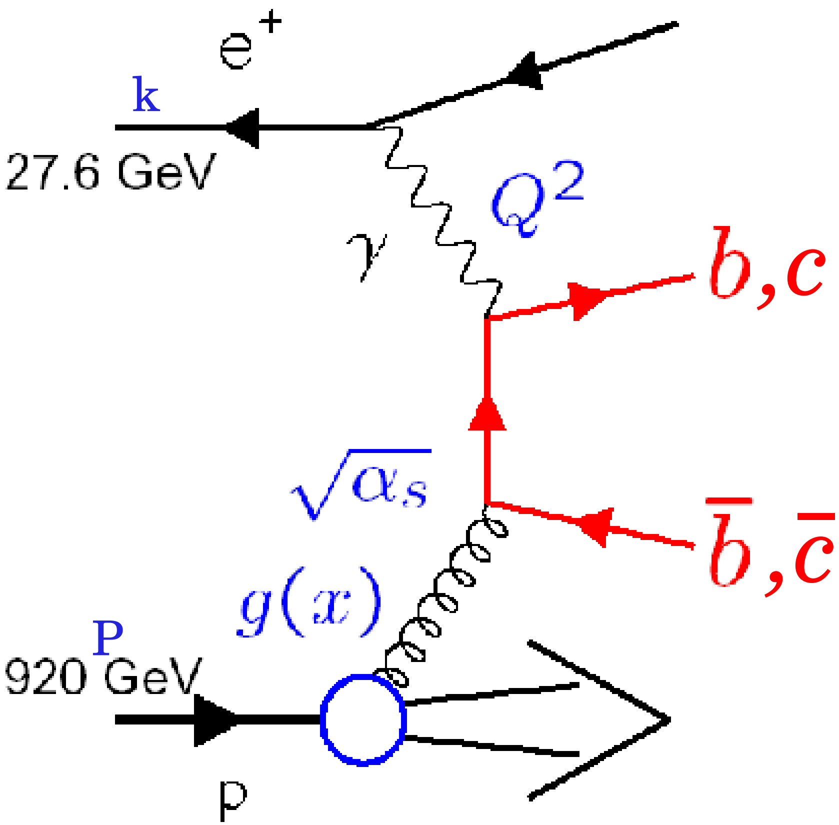
→ sensitive to gluon density in the proton

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, $Q^2 \lesssim 1 GeV^2$
- Deep Inelastic Scattering (DIS): $Q^2 \gtrsim 1 GeV^2$



Multiple hard scales:

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

→ Different pQCD approaches

pQCD Approximations

Multiscale problem:

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

Assume one dominant hard scale:

Massive scheme: → $m_{c,b}$

- c,b massive
- neglects $[\alpha_s \ln(Q^2,p^2_T/m^2_{c,b})]^n$

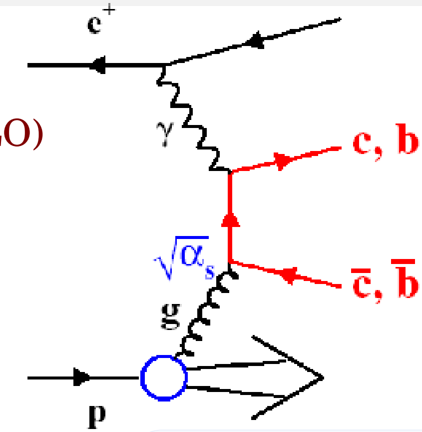
→ c,b produced perturbatively

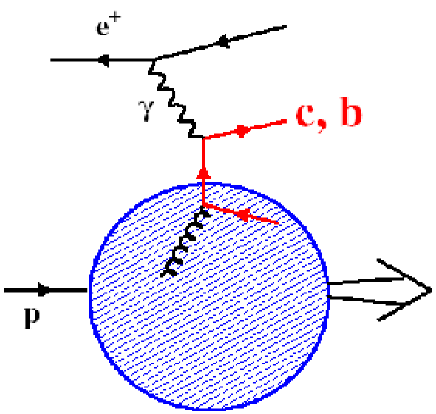
Massless scheme: → Q^2, p^2_T

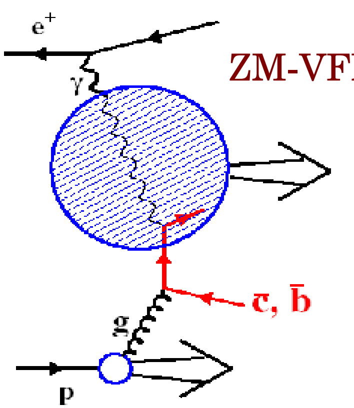
- c,b massless
- resums $[\alpha_s \ln(Q^2,p^2_T/m^2_{c,b})]^n$

→ c,b also in Proton and Photon!

FFNS (NLO)







ZM-VFNS (NLL)

Variable Flavour Number Schemes (VFNS):

- massive at small Q^2, p^2_T
- massless at large Q^2, p^2_T

→ GM-VFNS (FONLL)

QCD Models

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⊗PYTHIA
  (hadronization done with PYTHIA)

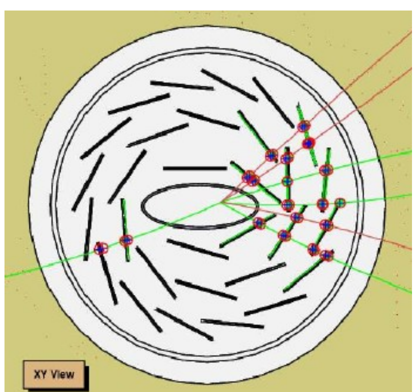
- Comparison of data with different models yields important insights

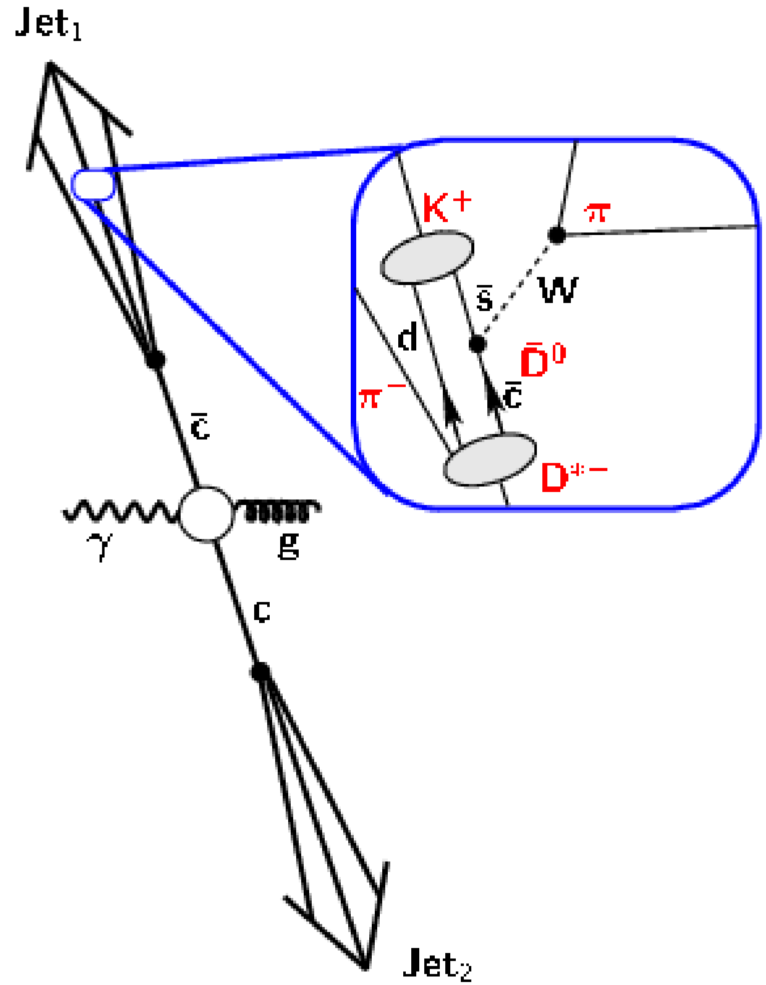
- This talk focuses on γp results
- DIS results will be discussed on Thursday (cf. Talk by P. Thompson)

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 iformation
  Measure impact parameter with respect to primary vertex (beam spot)





- Different tags probe different kinematic regions

Charm Production

D* Production in γp

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

$$D^{*\pm} \rightarrow D^{\circ}\pi^{\pm}_{slow} \rightarrow K^{\mp}\pi^{\pm}\pi^{\pm}_{slow}$$

Data/MC & NLO calculations:

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

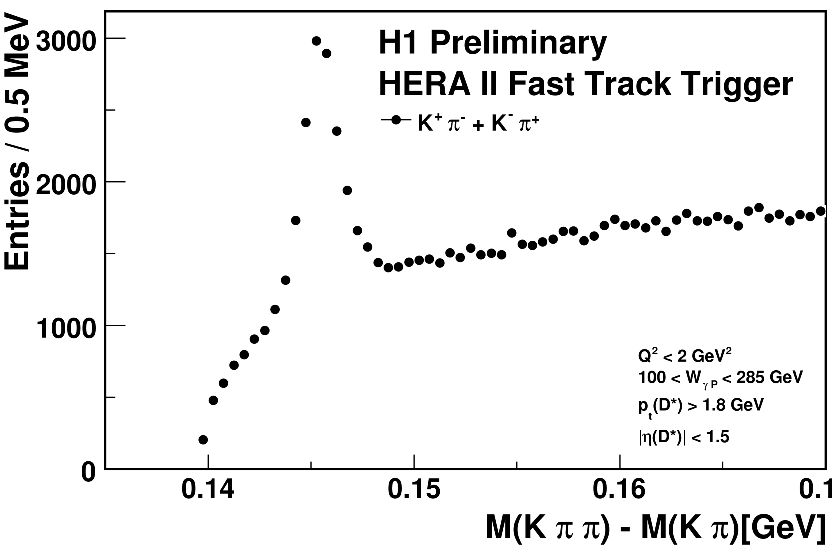
LO: PYTHIA & CASCADE

NLO: FFNS (CTEQ5F3)
GMVFNS (CTEQ6.5)

Kinematic range:

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

- ΔM distribution to determine the number of D* mesons



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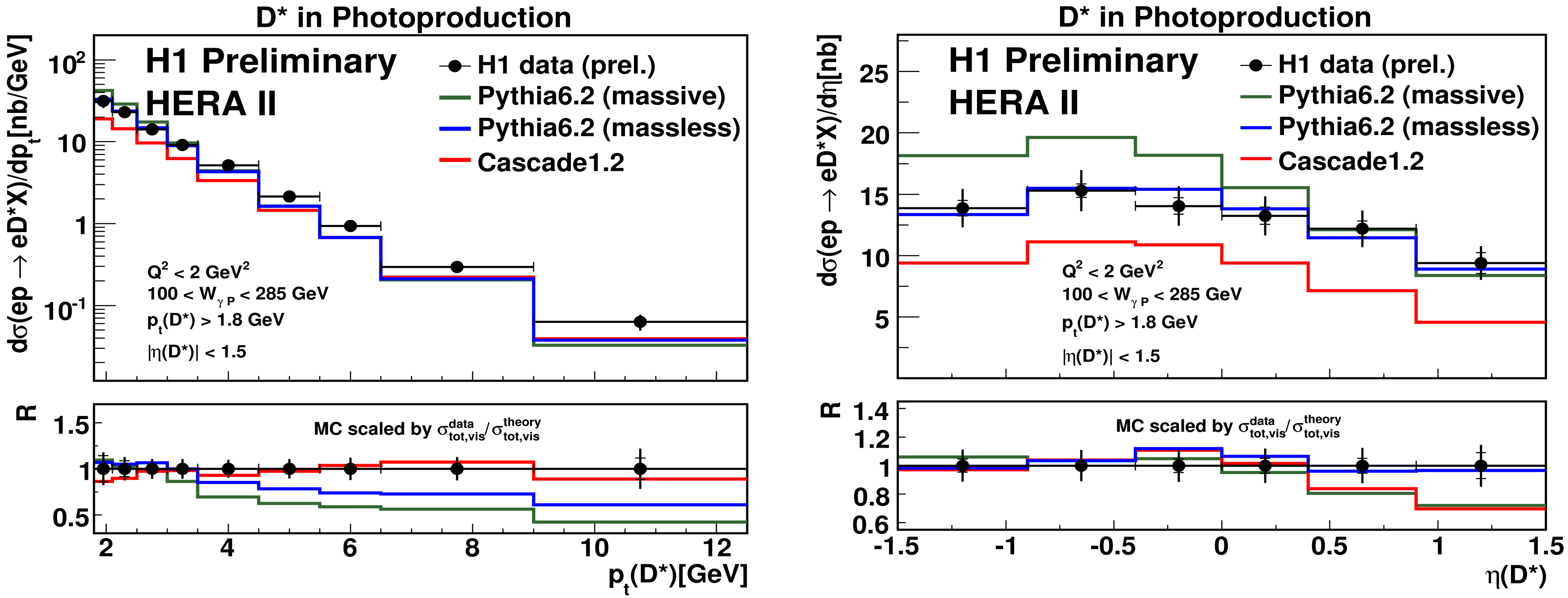
D* Production in γp

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

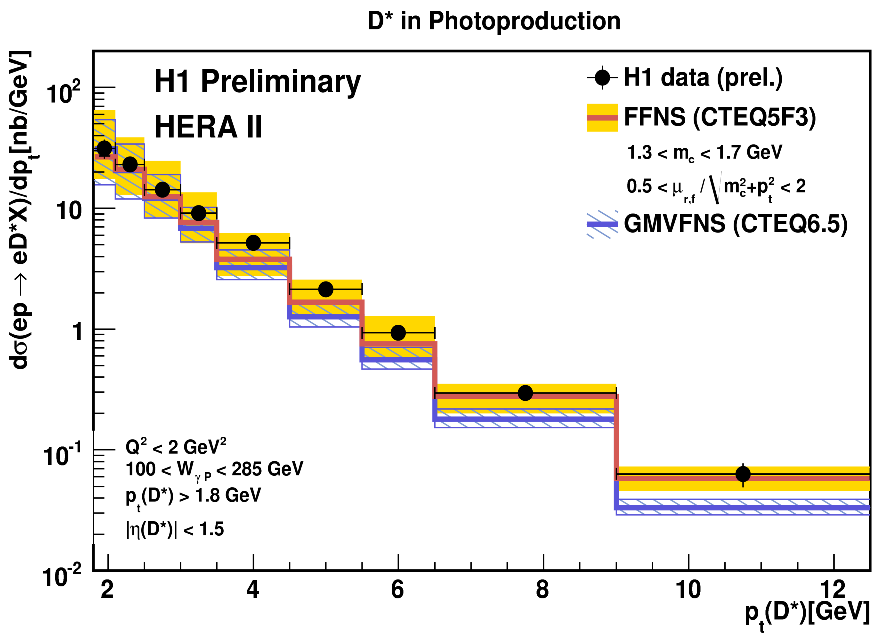
- **η (D*)**

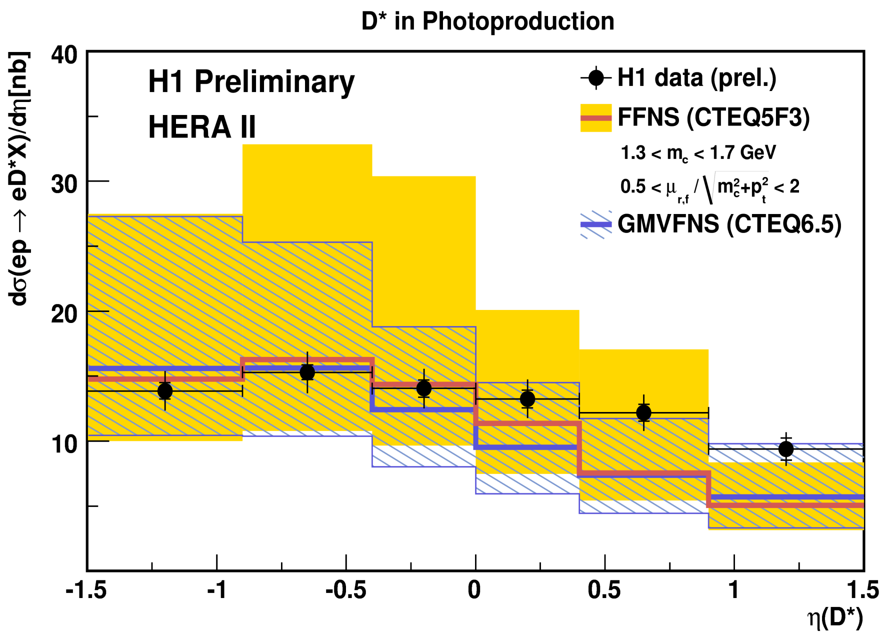
  Massless Pythia describes shape and normalisation

  Cascade and massive Pythia predict a stronger decrease in forward direction

D* Production in γp

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

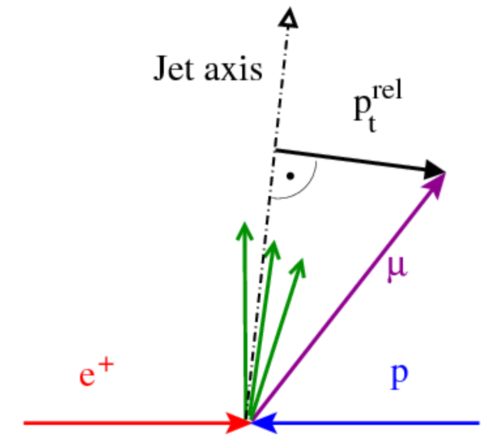
Beauty in Dijet γp using muons

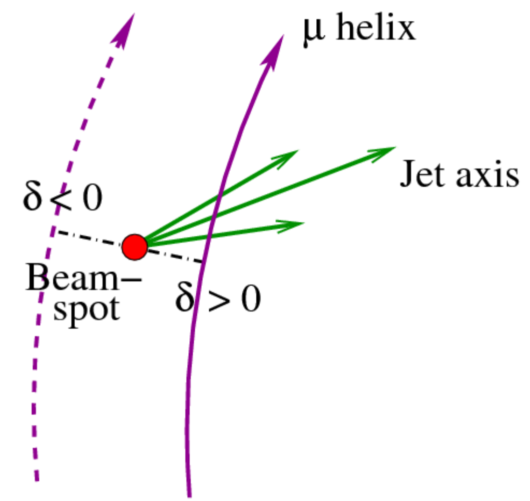
Data: (HERAII)
ZEUS: ($\mathcal{L} \cong 124 pb^{-1}$)
H1: ($\mathcal{L} \cong 171 pb^{-1}$)

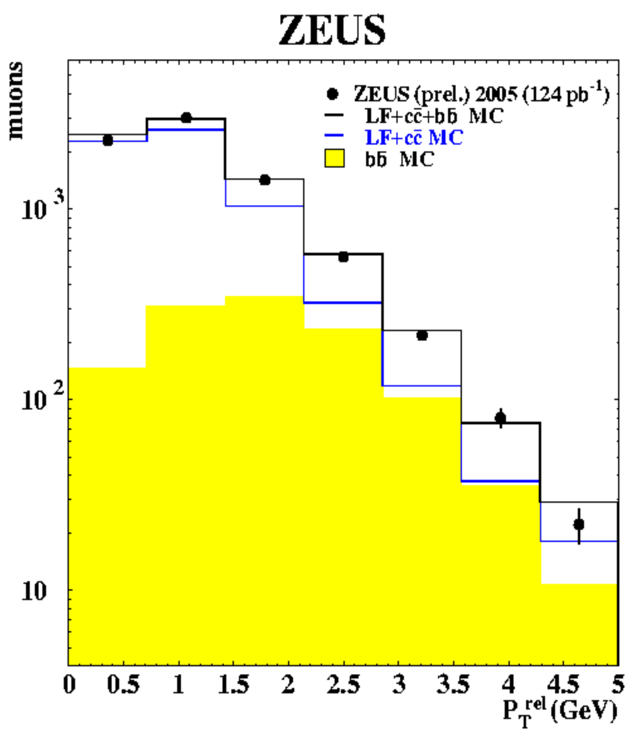
LO: PYTHIA

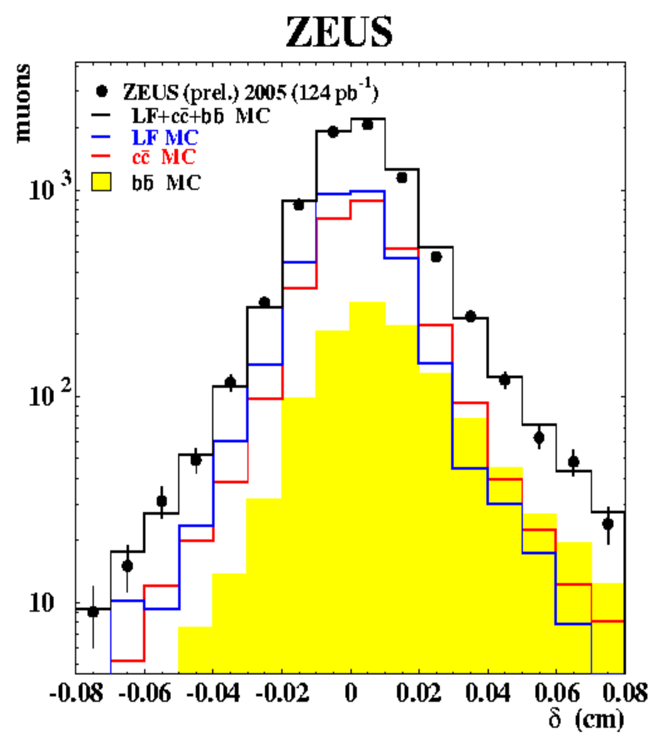
NLO: FMNR

- Similar visible range
- Dijet γp events
  p_T of jets > 7(6) GeV
- $0.2 < y < 0.8$
- $p_T(\mu) > 2.5$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

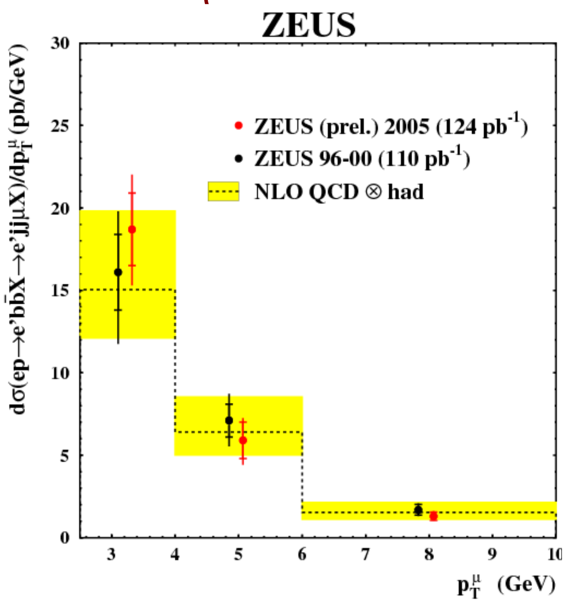
- Phase space: Similar, but not equal
- Measurements consistent with NLO calculation

  ZEUS: Good agreement between HERAI & HERAII results

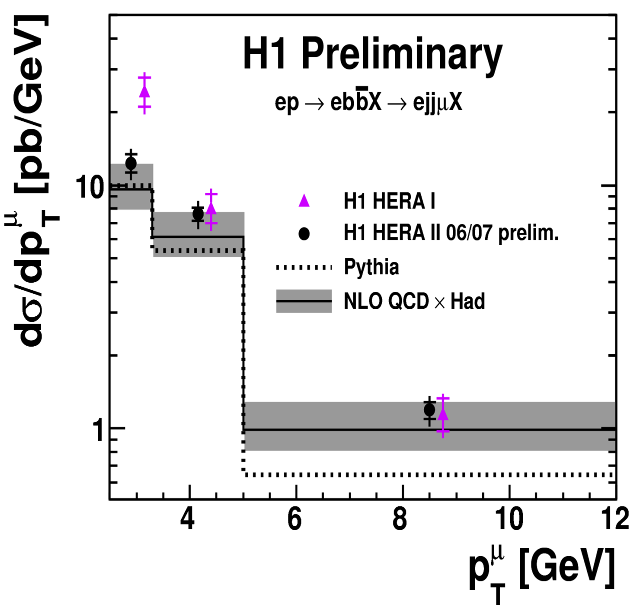
  H1: Excess (at low p_T) in HERAI analysis not confirmed
- Additional HERAII measurement at H1: **($d\sigma/d\delta\phi_{jets}$)**

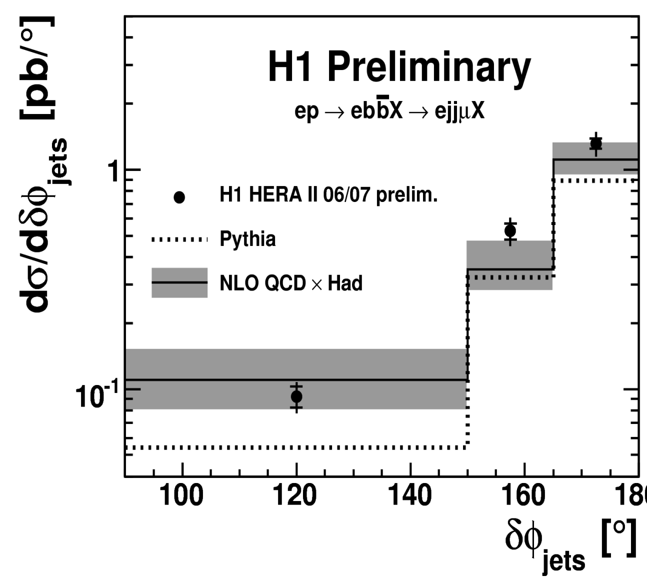
  $\delta\phi_{jets}$ = azimuthal angle difference of jets: 180° at LO
  → direct sensitivity to higher orders. Well described

$-1.6 < \eta^{\mu} < 2.3$



$-0.55 < \eta^{\mu} < 1.1$





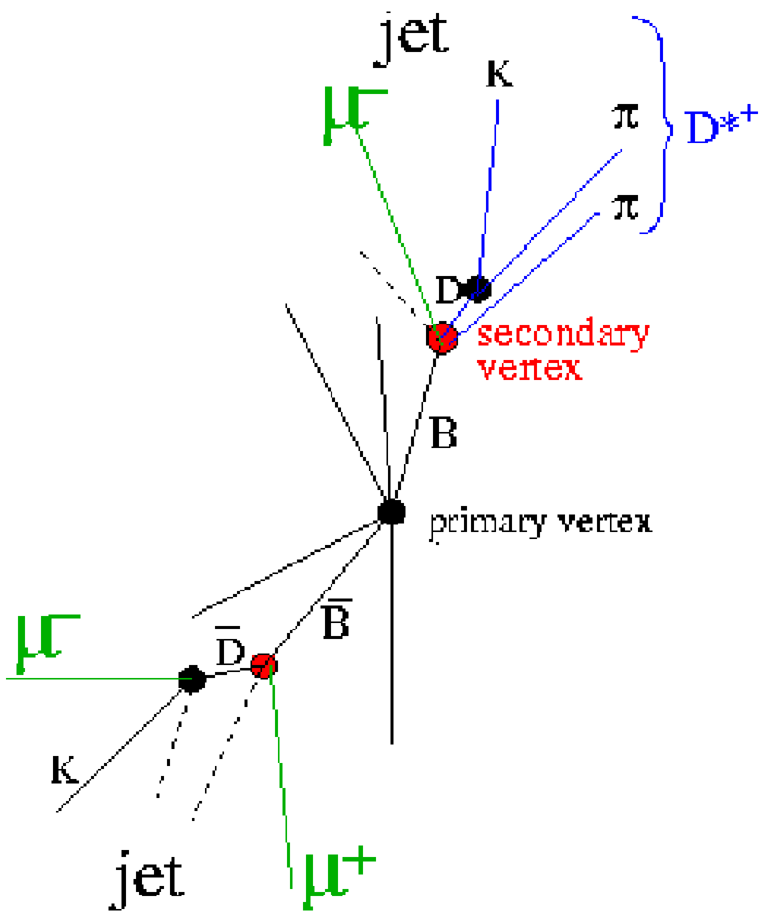
Beauty in γp - double tag

Data: (HERAI)
($\mathcal{L} \cong 114 pb^{-1}$)

LO: Pythia , Rapgap, Herwig

NLO: FMNR⊗Pythia

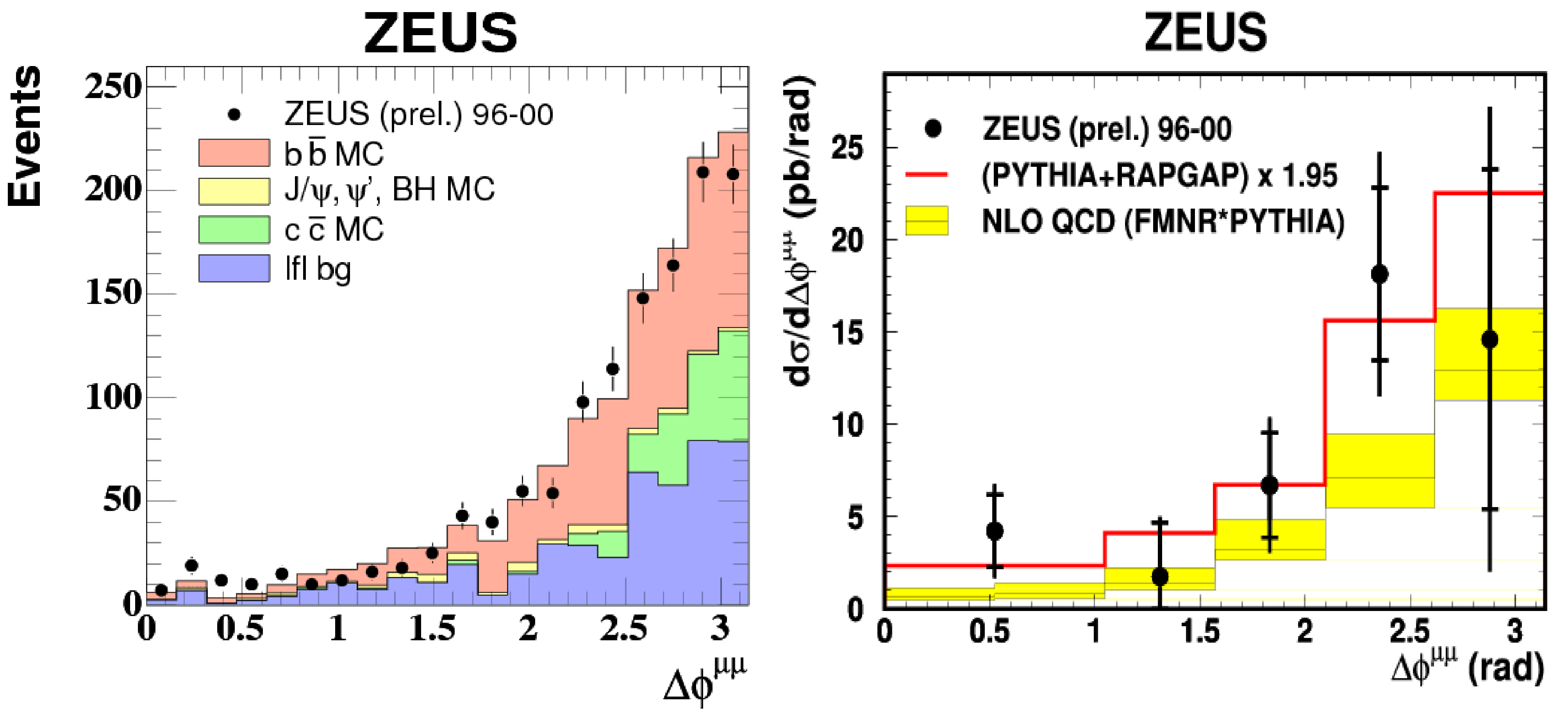
- Double tag events
  - ► Sensitive to almost full phase space
  - ► Low p_T^{μ} threshold
  - ► Low background
- DIS + γp
- Two identified muons
- E_T > 8GeV
- Measure $b\bar{b}$ correlations
  - ► Probe NLO effects



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

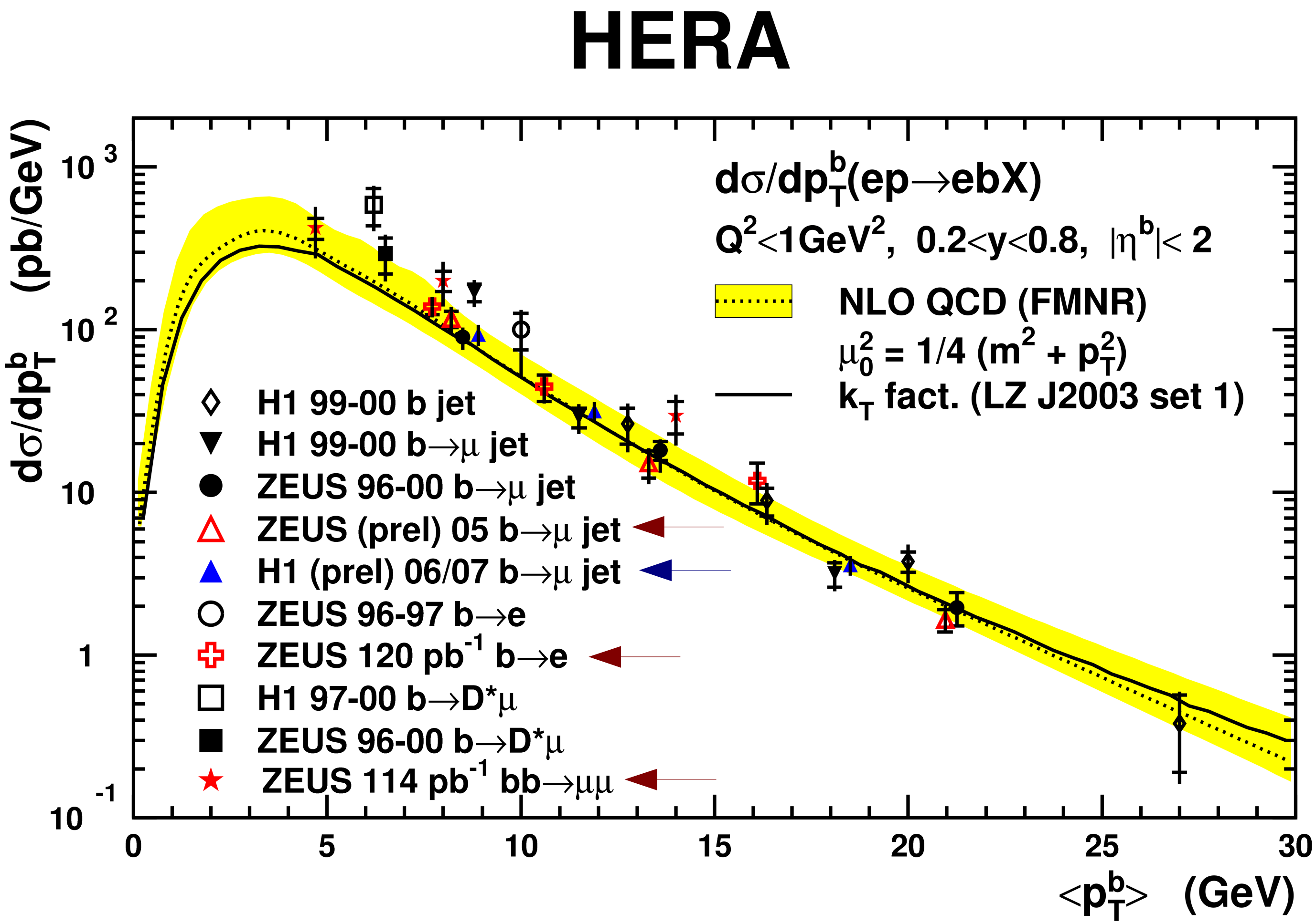
Beauty in γp - double tag

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



- $\Delta\phi^{\mu\mu}$ = angle between muons from different quarks
- Correlations expected to show higher order effects

→ Good description, but large uncertainties



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

D* Production in γp

Selection cuts:

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

Ratio (R):

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

Differential Cross section determination:

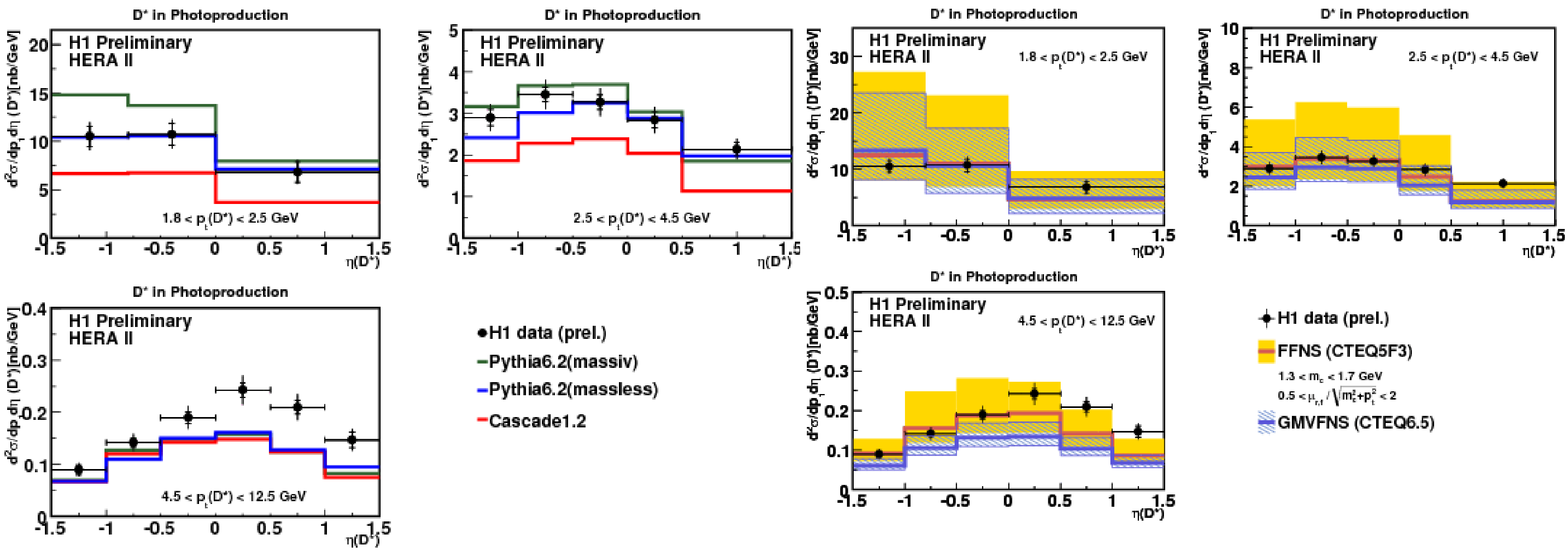
$$\frac{d\sigma^{vis}}{dY} = \frac{N_{D^*}(1 - r)}{\Delta Y \, \mathcal{L} \cdot \mathcal{B}(D^* \rightarrow K\pi\pi_{slow}) \cdot A_{Detector} \cdot \varepsilon_{Detector} \cdot \varepsilon_{Trigger}}$$

D* Production in γp

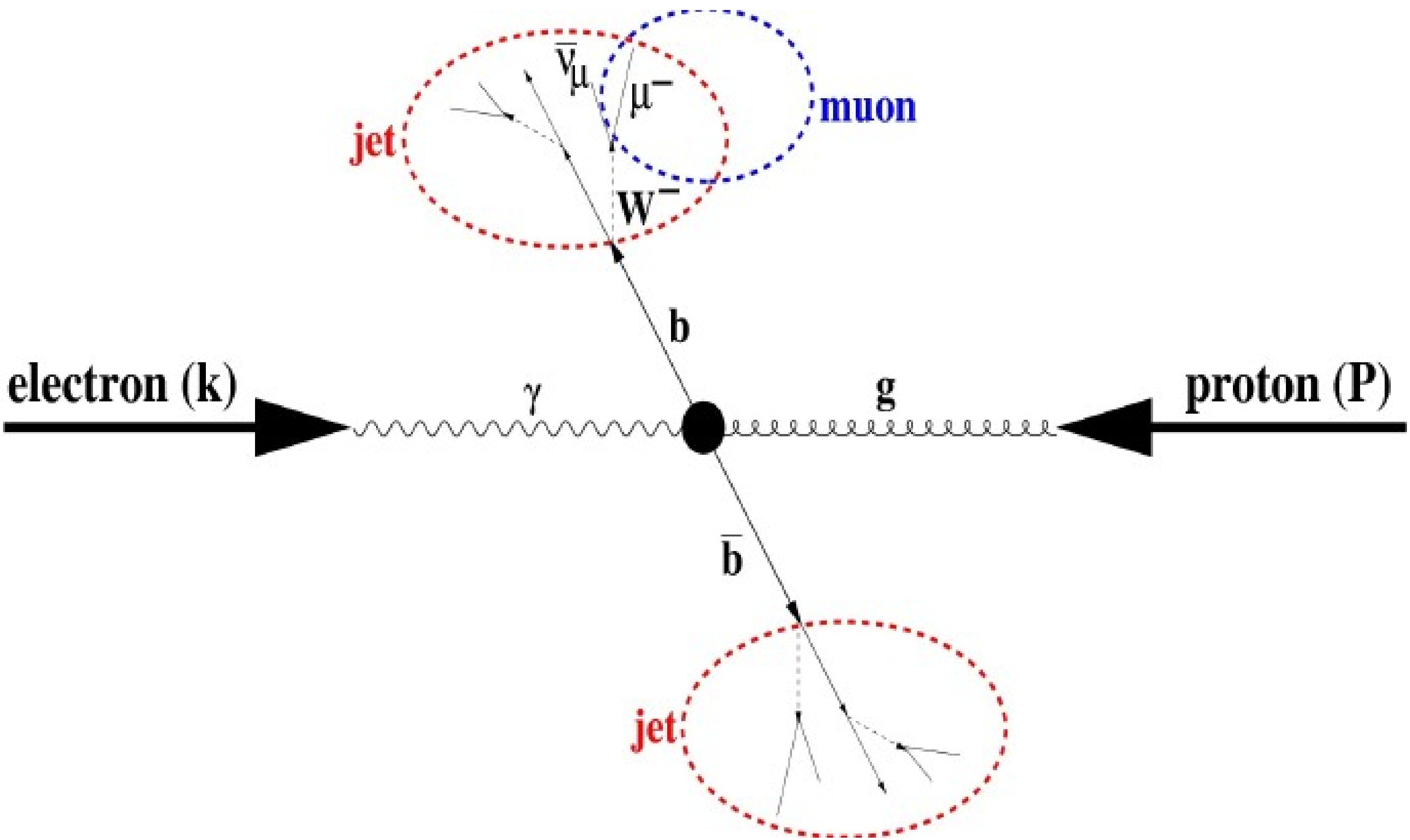
Total visible cross sections:

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

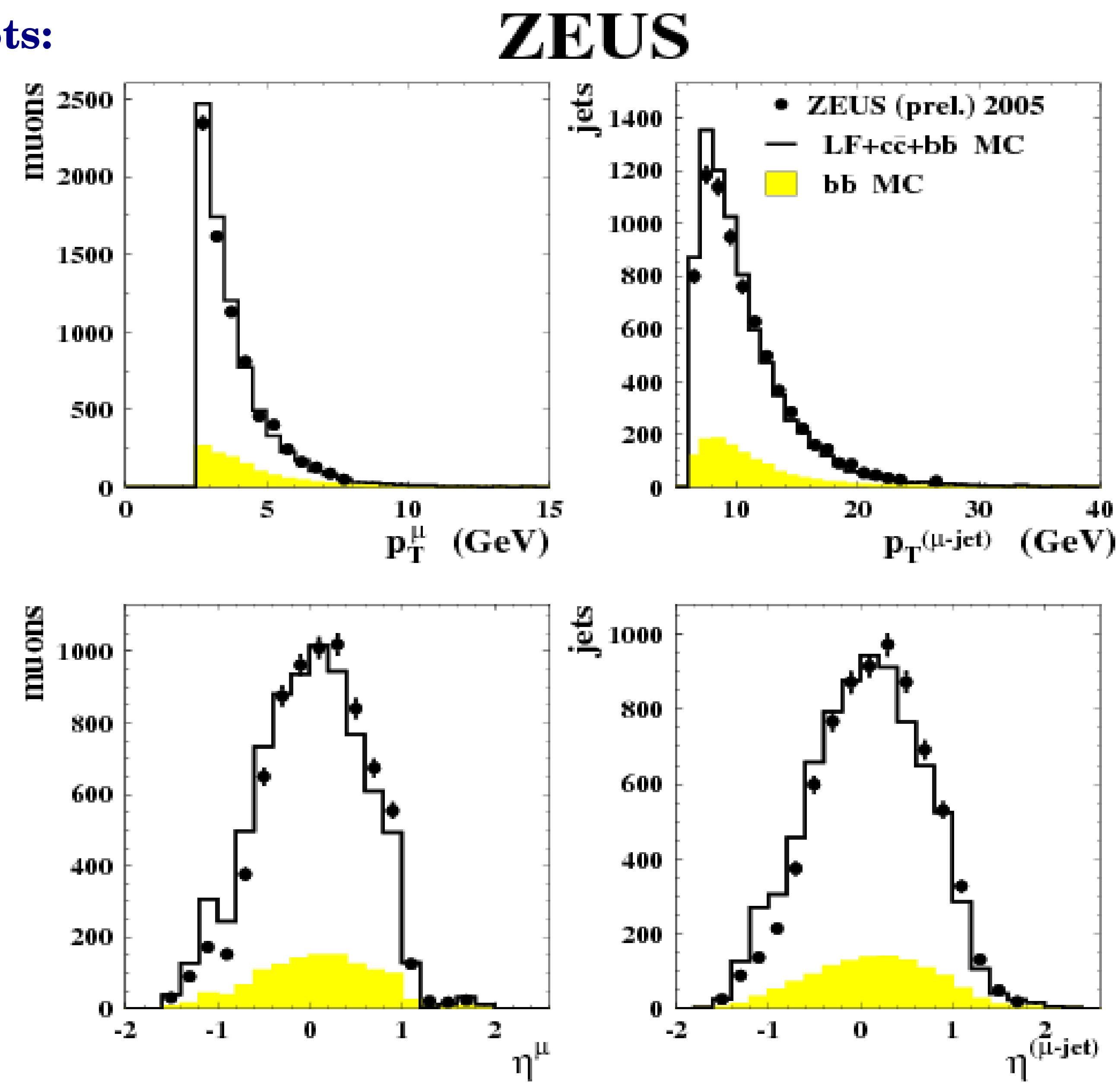
Double differential cross sections:



Beauty in Dijet γp using muons

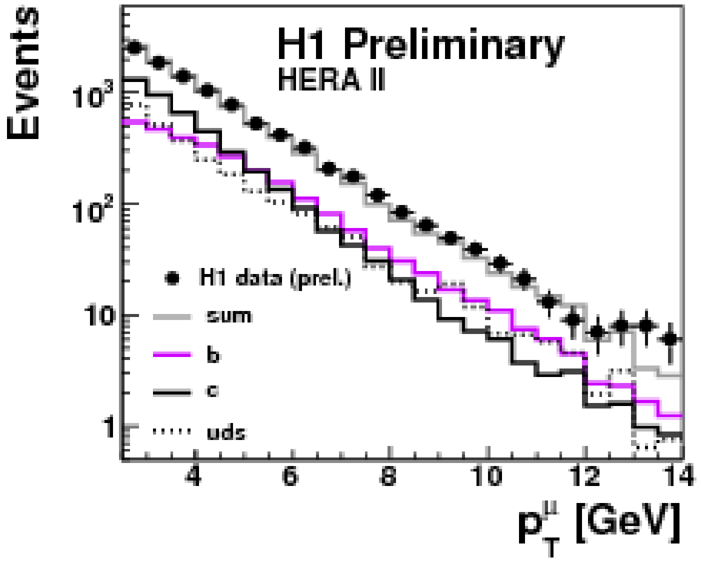


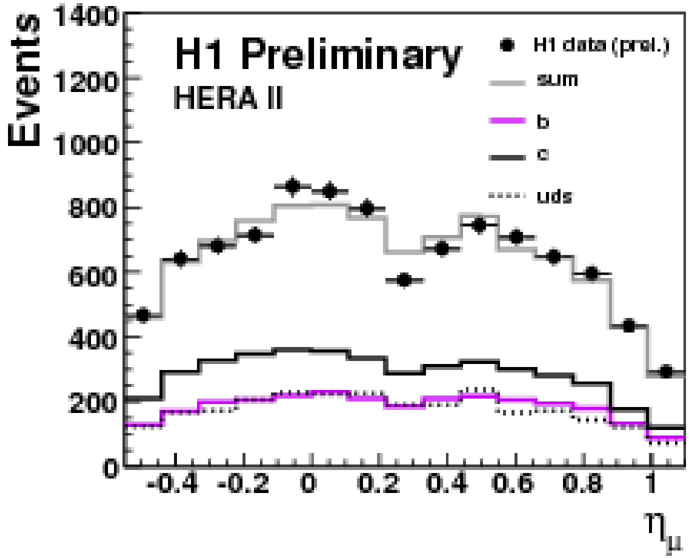
Control plots:



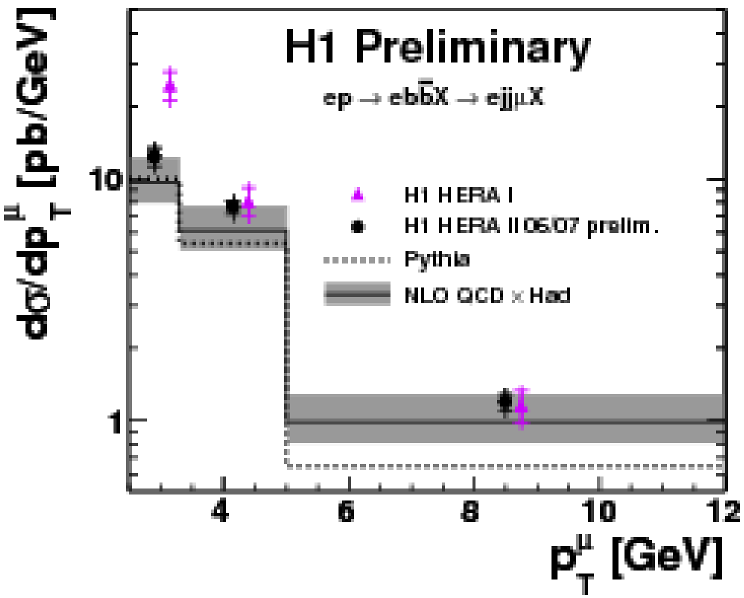
Beauty in Dijet γp using muons

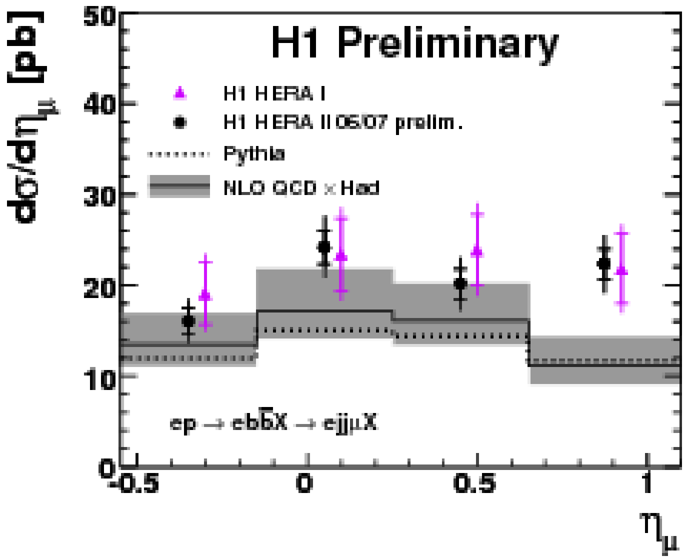
Control plots:





Differential cross sections:





Beauty in γp - double tag

Selection cuts:

- $p_T^\mu > 1.5$GeV
- $p_T^\mu > 0.75$GeV

  (high quality muons)
- Cal E_T -10° cone > 8GeV
- Further cleaning cuts

Background sources:

- Open c → high mass, unlike sign

  Normalisation from D*μ analysis
- Hidden c (J/ψ, ψ') → low mass, unlike sign

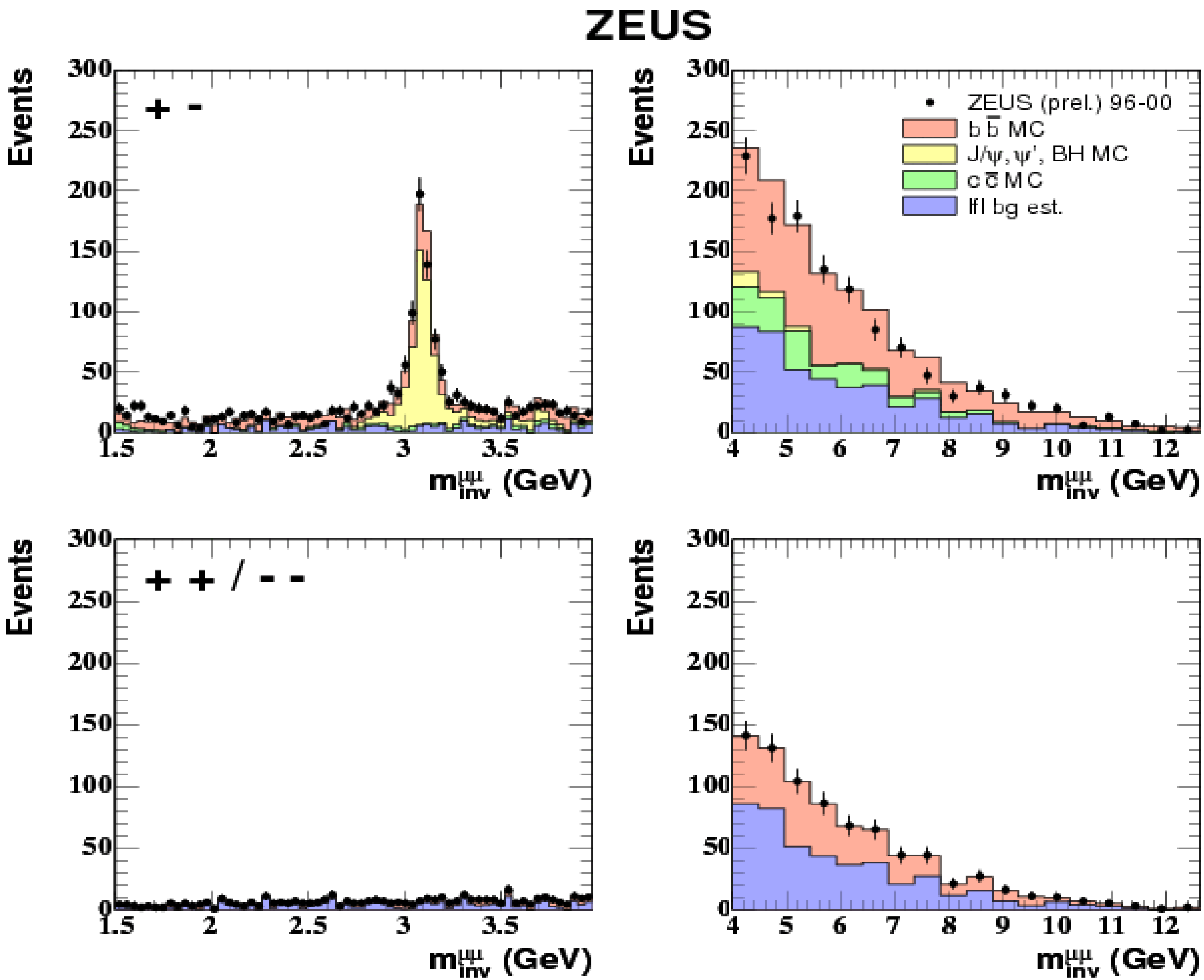
  Isolation cut
- Bethe-Heitler, hidden b → high mass, unlike sign

  Isolation cut
- Light flavour → all regions

  From data

Beauty in γp - double tag

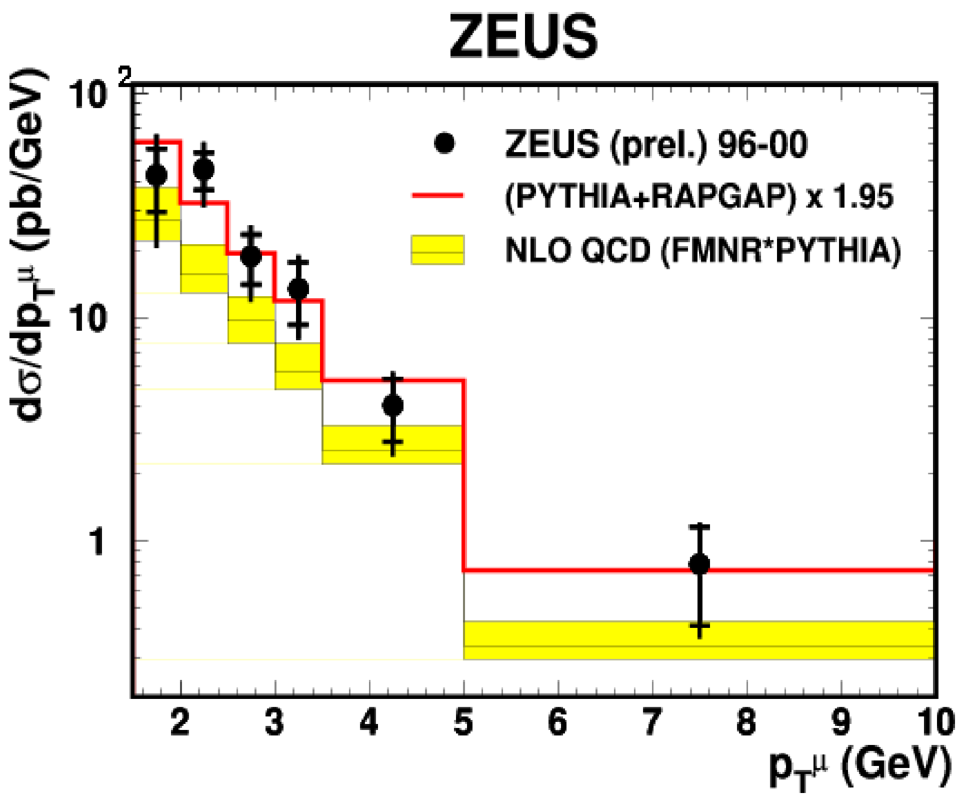
Dimuon Mass:

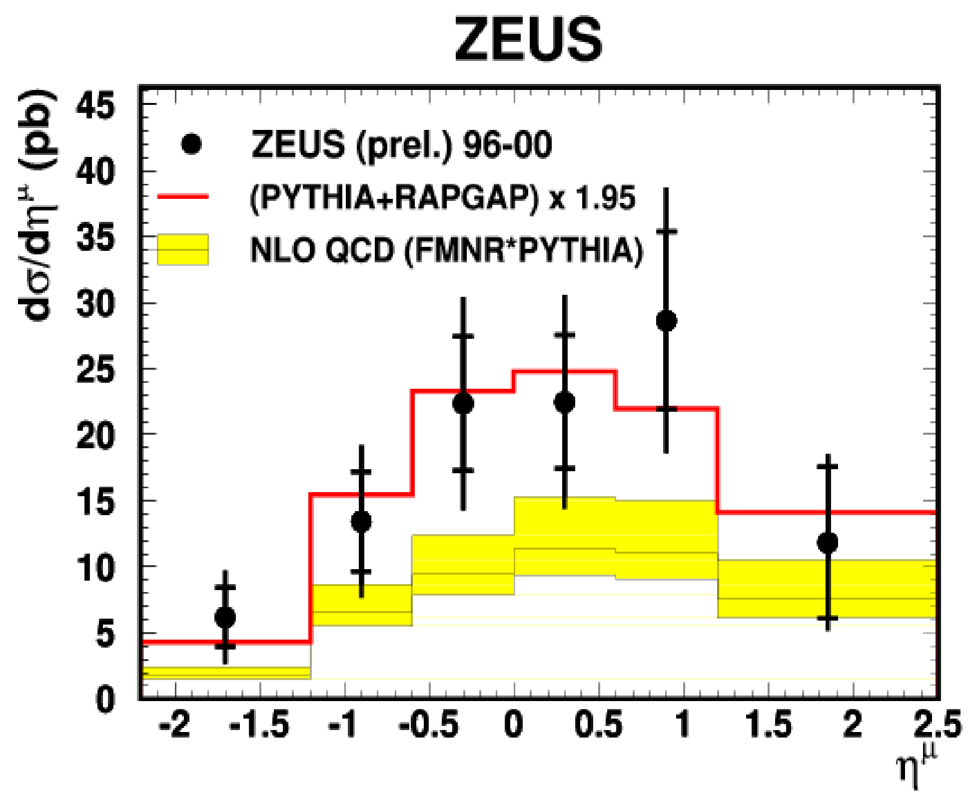


Beauty in γp - double tag

Differential muon cross sections:

Both muons $p_T > 1.5$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