# Production of Heavy Quarks at HERA

Beate Naroska
University of Hamburg

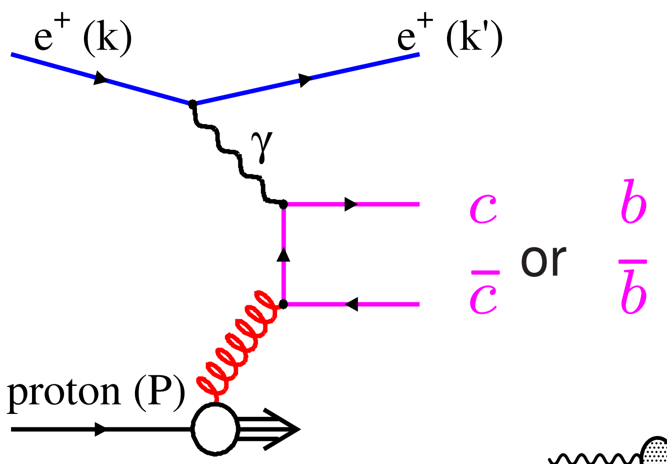
Introduction, Theoretical Framework

- Charm Tagging, Fragmentation
- Charm (+jets) in DIS
- Charm (+jets) in Photoproduction
- Charmonium→ Parallel
- Beauty Tagging
- Beauty (+jets) in DIS and $\gamma$ p
- $D^* - \mu$ Correlations
- Overview

# Introduction

This talk will concentrate on the collider experiments H1 and ZEUS at HERA (for time reasons)
Datataking of HERA I results in $\sim 120\,\mathrm{pb}^{-1}$/experiment –
not everything analysed yet for Heavy Flavour Production

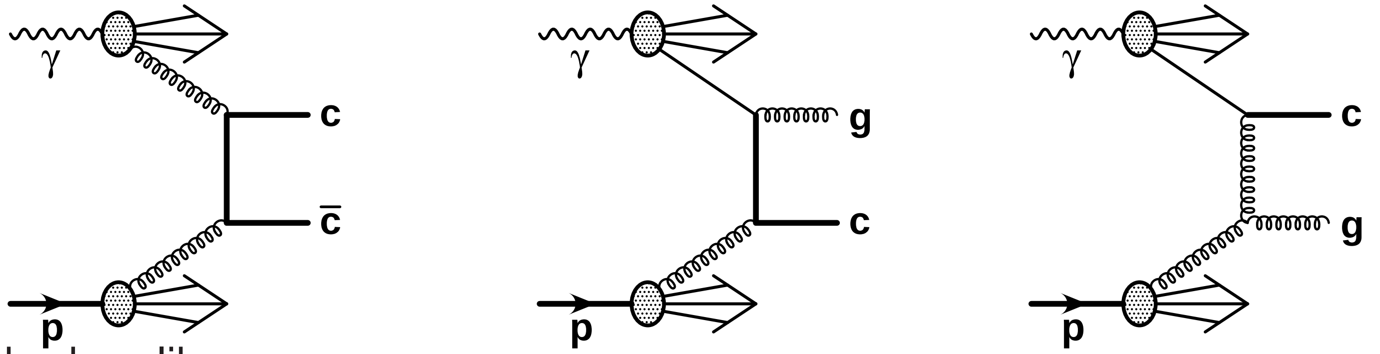
Main contributing processes to HF Production (LO): BGF (Boson Gluon Fusion)




'Direct Process' (pointlike photon)

Two kinematic regimes:
$Q^2 \rightarrow 0$ Photoproduction
$Q^2 \gtrsim 2\,\mathrm{GeV}^2$ Electroproduction "DIS"

'Resolved-$\gamma$': Hadron-like

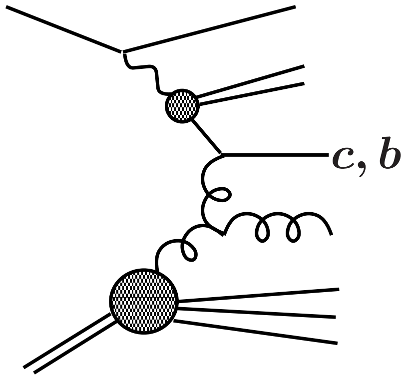



hadron-like — $c$-Excitation: $q$-Propagator — $g$-Propagator

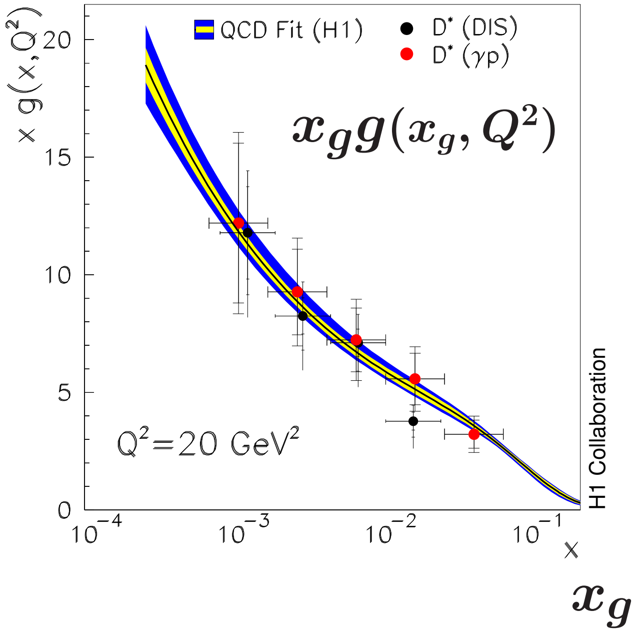
• HEAVY FLAVOUR PRODUCTION: PROBE OF HARD QCD

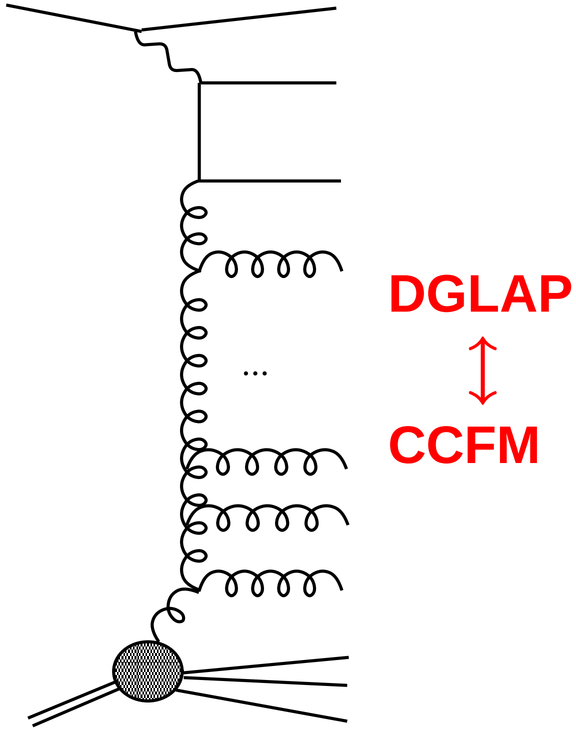
# Probing QCD with Charm and Beauty

**Resolved $\gamma$ contribution** **parton evolution model**




**gluon density**
in the proton




Many previous results for charm have shown that

- Charm is an important contribution to $F_2$; QCD NLO works well in DIS
- Photoproduction has an important resolved component, more problems with QCD

# Modelling Charm and Beauty Production

$$\sigma_{\gamma p} \sim f^{\gamma} \otimes \hat{\sigma} \otimes f^{p} \otimes \mathcal{D}(z)$$

**pQCD calculations in NLO**

fixed order, **massive scheme**:
HQ **produced dynamically**;
$p_t \lesssim m_q$

- $\gamma p$**:** FMNR (Frixione et al.)
- **DIS:** HVQDIS (Harris & Smith)

**Resummed calculations in NLL**

all orders, **massless scheme**:
HQ **in** $\gamma$ **or p;** $p_t \gg m_q$

- Cacciari et al., Kniehl et al.,...

**'Matched' scheme FONLL**

fixed order $+$ NLL scheme
incorporate mass effects up to NLO, avoid double counting

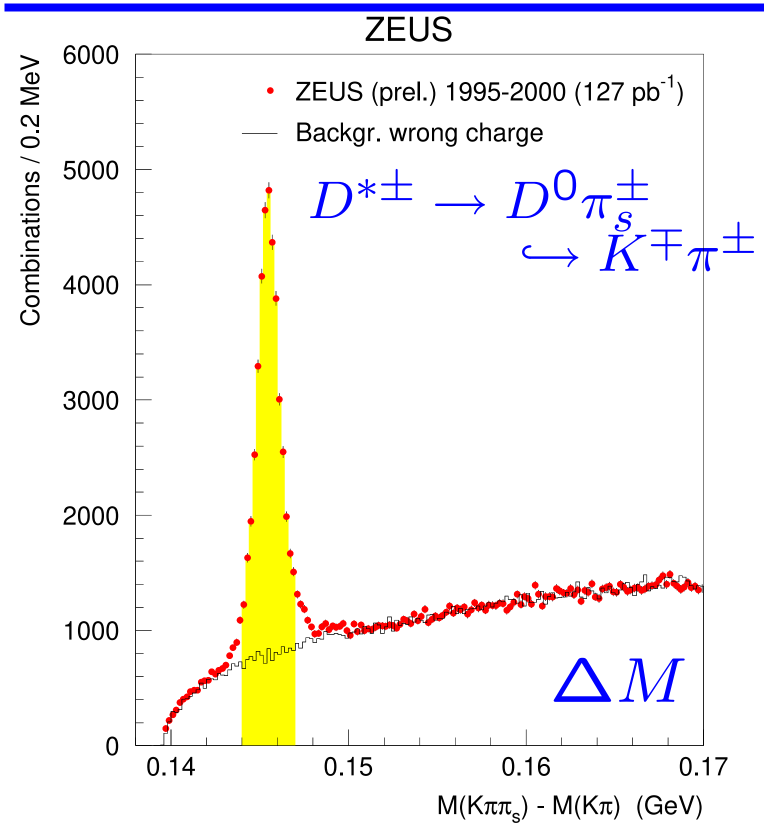
- Cacciari et al.
  **DGLAP** evolution

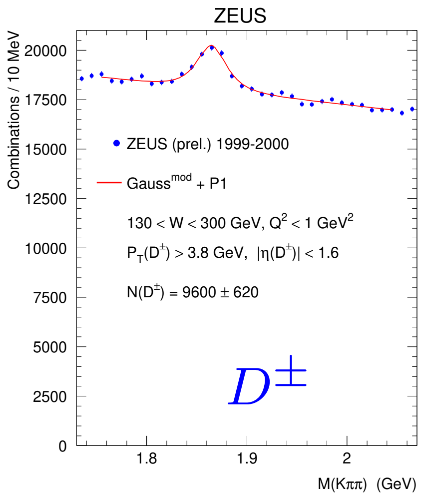
**MC generators (LO ME + PS)**

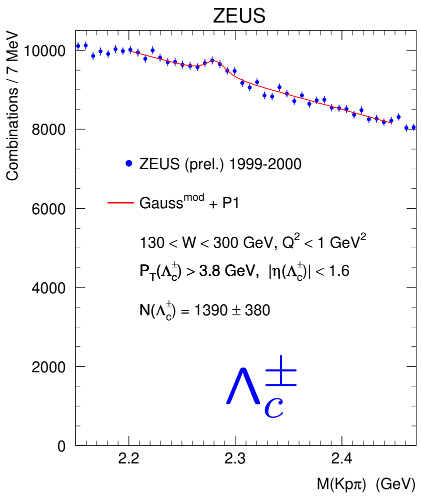
- **AROMA**:
  **direct** only, **DGLAP** evolution
- **PYTHIA, RAPGAP, HERWIG**:
  direct **+ resolved**, DGLAP
- **CASCADE**:
  direct only, **CCFM**–like evolution,
  $k_t$ dependent gluon density

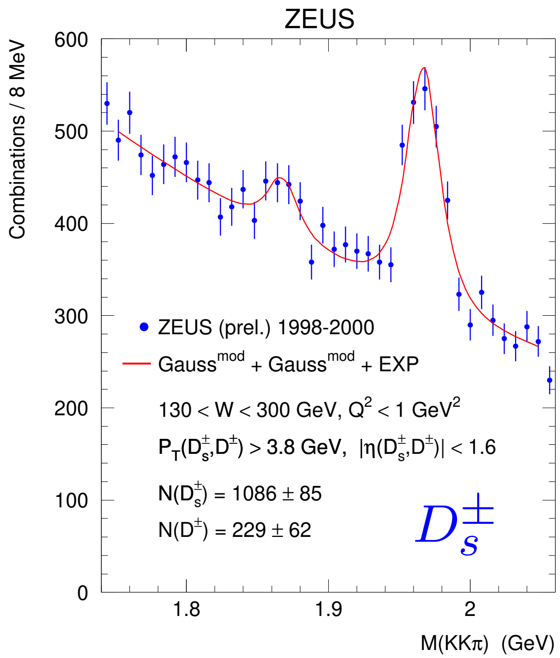
**Fragmentation:**
non perturbative models

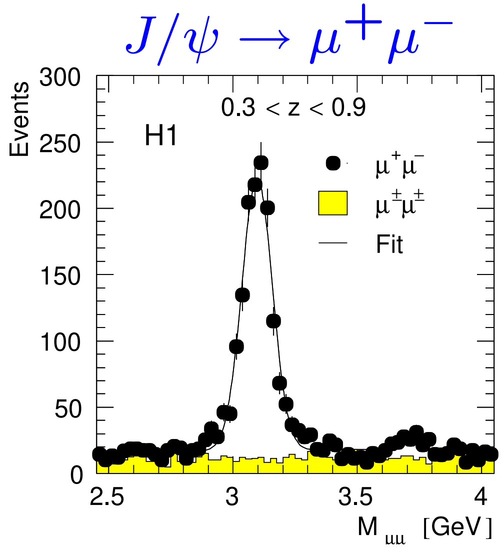
# CHARM Tagging Methods



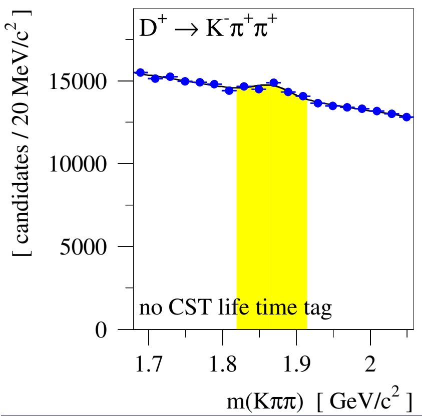



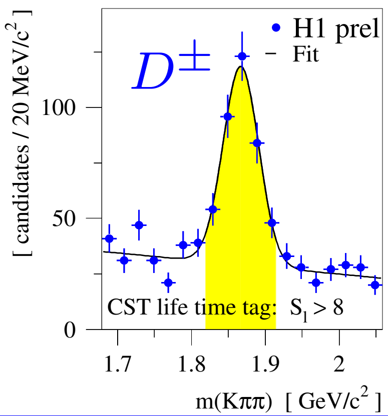




lifetime: no tag $\longrightarrow$ tag



# Charm Fragmentation Parameters

ZEUS: reconstruct all charm ground states, $D^{\pm}$, $D^0$, $D_s^{\pm}$, $\Lambda_c^{\pm}$ and $D^{*\pm}$ $\sim$ 66 or 79 $\mathrm{pb}^{-1}$

Determine from data:

| ZEUS prel. ($\gamma p$) $P_T(D,\Lambda_c) > 3.8\,\mathrm{GeV}$, $\lvert\eta(D,\Lambda_c)\rvert < 1.6$ | Combined $e^+e^-$ data | H1 prel. (DIS) |
|---|---|---|
| $f(c \to D^+) = 0.249 \pm 0.014^{+0.004}_{-0.008}$ | $0.232 \pm 0.010$ | $0.202 \pm 0.020^{+0.045}_{-0.033}{}^{+0.029}_{-0.021}$ |
| $f(c \to D^0) = 0.557 \pm 0.019^{+0.005}_{-0.013}$ | $0.549 \pm 0.023$ | $0.658 \pm 0.054^{+0.115}_{-0.148}{}^{+0.086}_{-0.048}$ |
| $f(c \to D_s^+) = 0.107 \pm 0.009 \pm 0.005$ | $0.101 \pm 0.009$ | $0.156 \pm 0.043^{+0.036}_{-0.035}{}^{+0.050}_{-0.046}$ |
| $f(c \to \Lambda_c^+) = 0.076 \pm 0.020^{+0.017}_{-0.001}$ | $0.076 \pm 0.007$ | |
| $f(c \to D^{*+}) = 0.223 \pm 0.009^{+0.003}_{-0.005}$ | $0.235 \pm 0.007$ | $0.263 \pm 0.019^{+0.056}_{-0.042}{}^{+0.031}_{-0.022}$ |

**charm fragmentation fractions are universal**

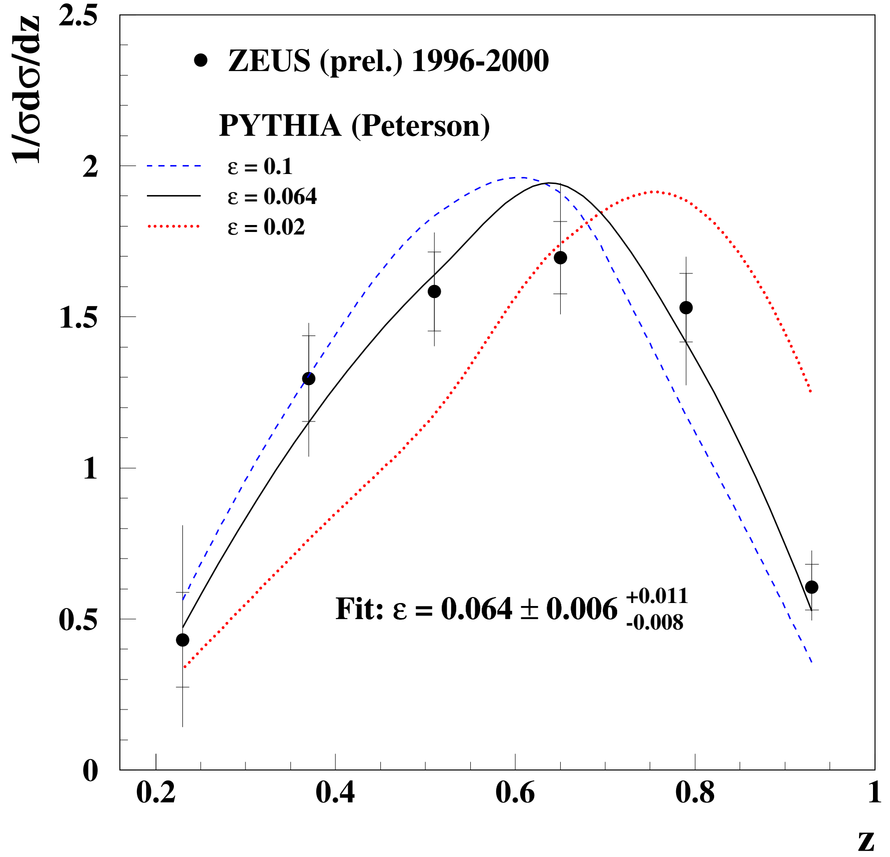
$\rightarrow$ HERA errors competitive!

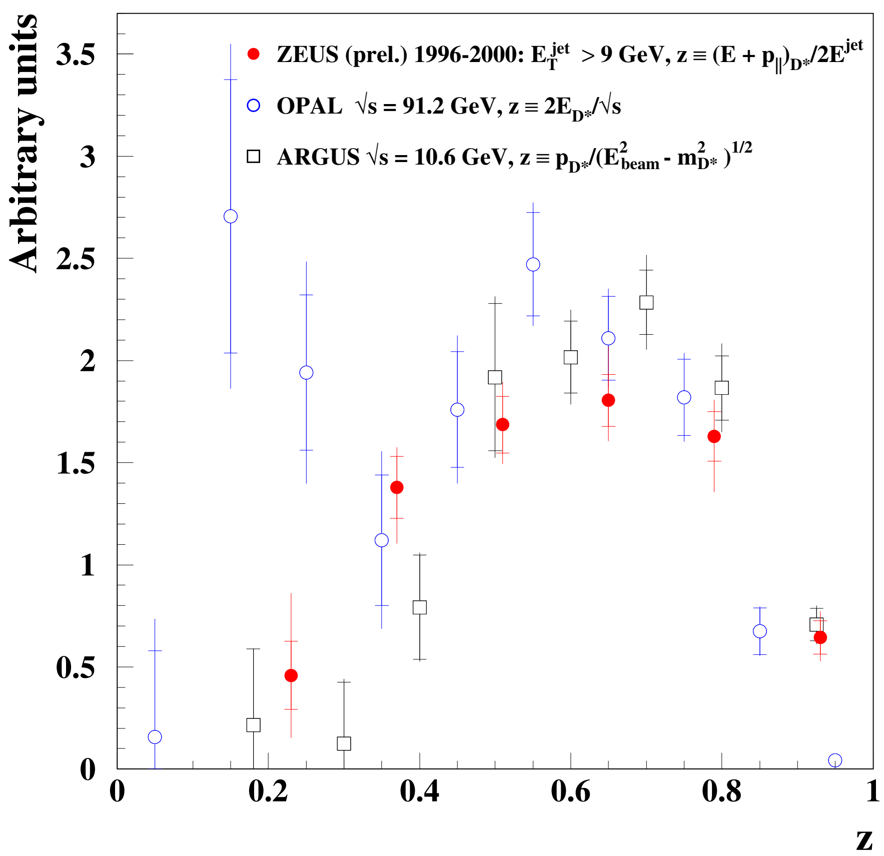
$R_{u/d}$, $\gamma_s$, $V/(P+V)$ also determined and in good agreement with w.a.

ZEUS: require a $D^{*\pm}$ and a jet $\quad Q^2 < 1\,\text{GeV}^2$; $130 < W_{\gamma p} < 280$ GeV

$p_T^{D^*} > 2$ GeV; $E_T^{jet} > 9$ GeV; $|\eta^{jet}| < 2.4$

$$z = \frac{(E+p_{||})^{D^*}}{2\,E_{jet}}$$



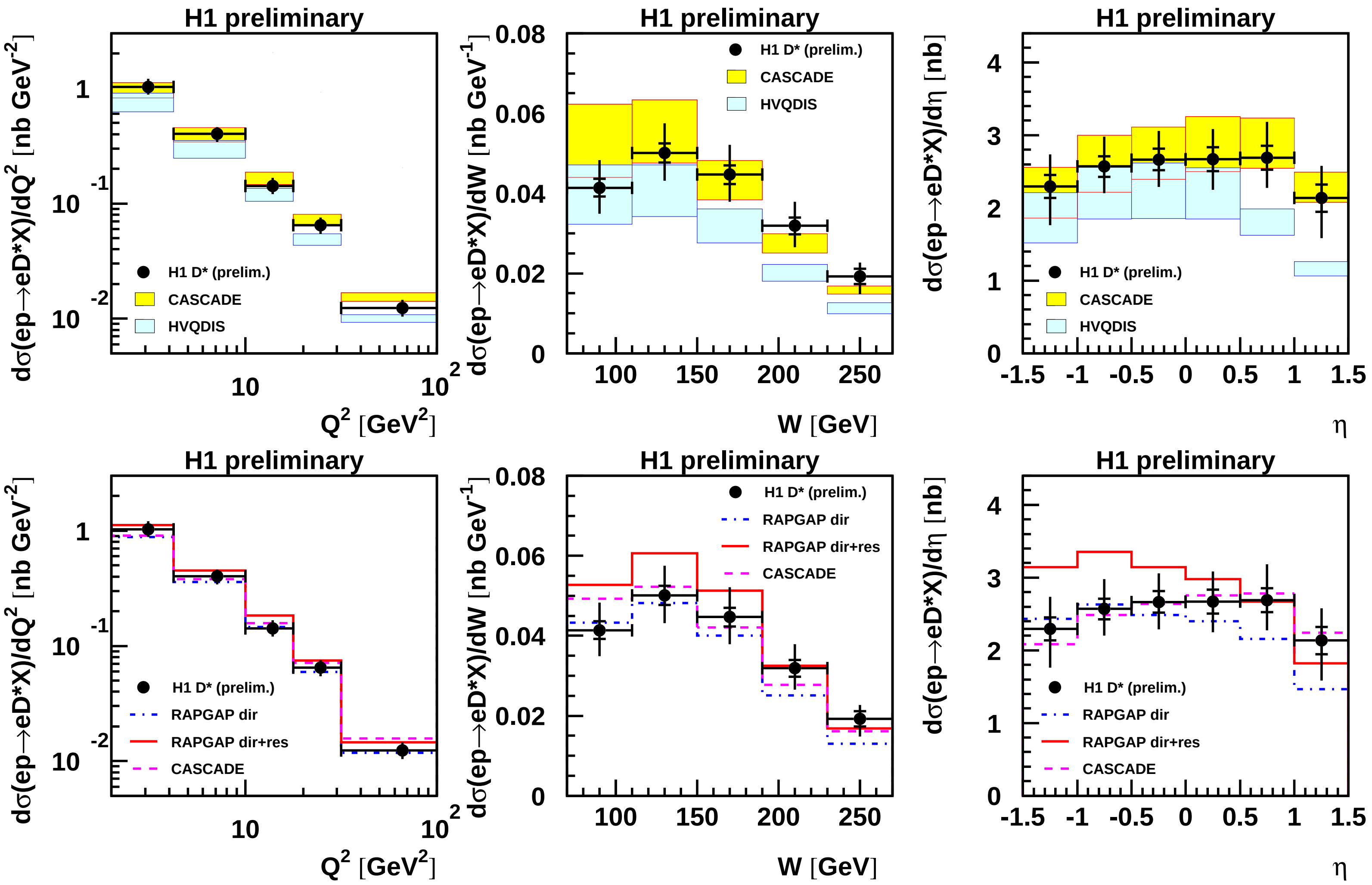

e.g. $\epsilon \sim 0.053$ for ARGUS data (Nason, Oleari)

FRAGMENTATION Function universal

H1: Inclusive $D^{*\pm}$ Cross Section

$Q^2 > 2$ GeV$^2$; $0.05 < y < 0.7$; 1999,2000 47 pb$^{-1}$

$p_T^{D^*} > 1.5$ GeV; $|\eta^{D^*}| < 1.5$

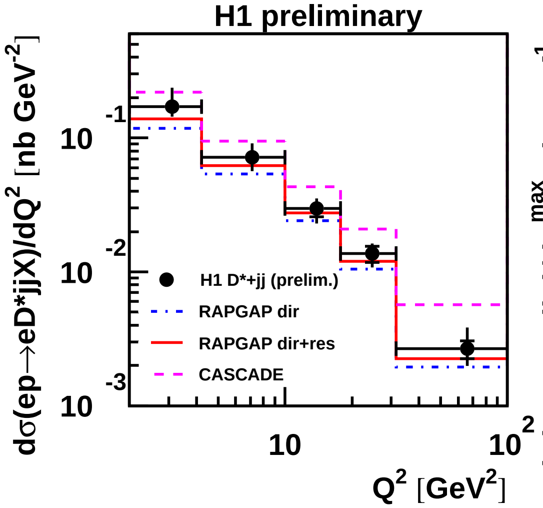


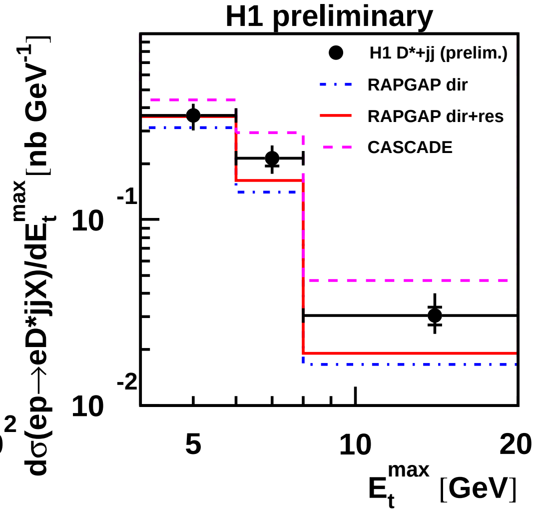

- NLO QCD low
- CASCADE (CCFM) better
- RAPGAP (LO+PS) high
- Shape of $\eta$ distribution well described by CASCADE only

# Jet Cross Section with $D^*$ in DIS (new)

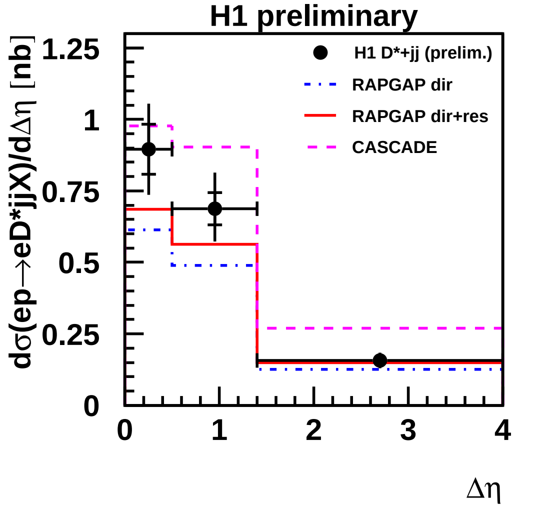
H1: $D^*$ and 2 jets (inclusive $k_t$ algorithm in Breit frame)

$$E_T^{jet} > 4, 3\,\text{GeV}; \; -1 < \eta_{lab}^{jet1,2} < 2$$

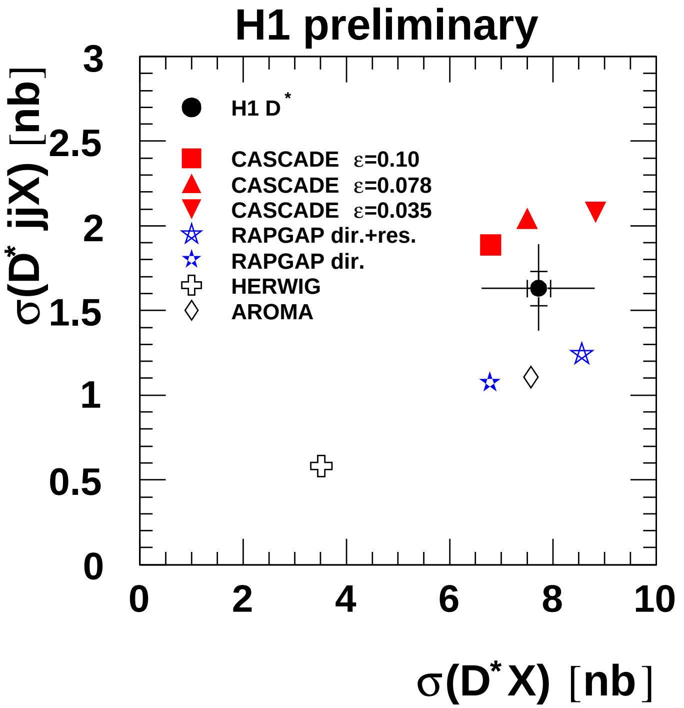



- CASCADE (CCFM) too high
- RAPGAP (LO+PS) too low

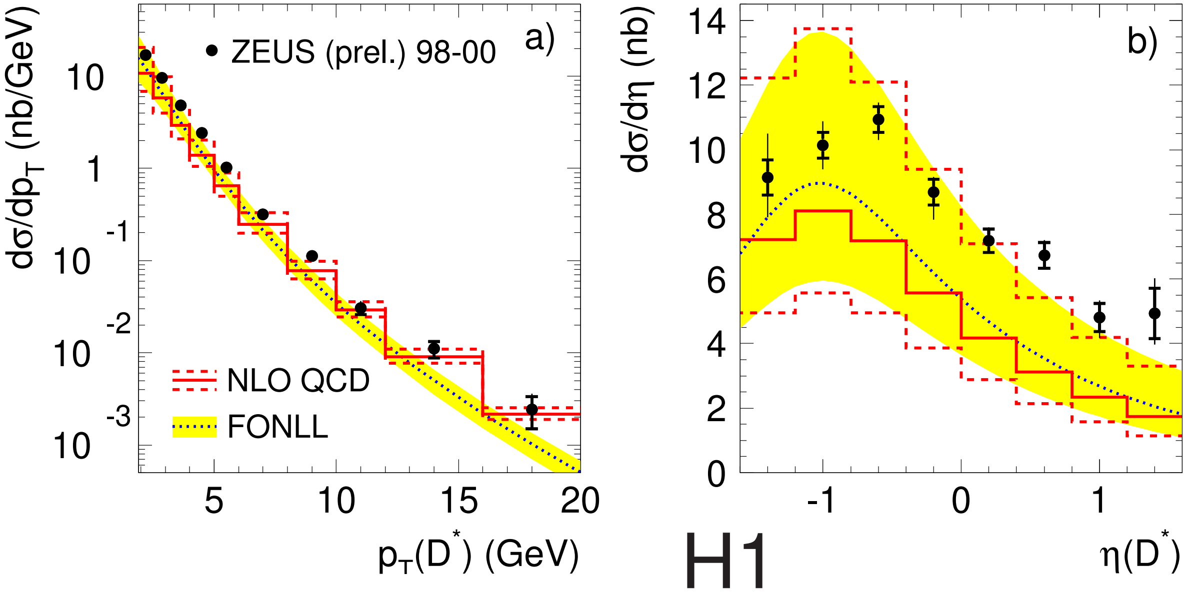



Summary plot: Jet cross section versus inclusive



# $D^*$ Photoproduction (new)

ZEUS

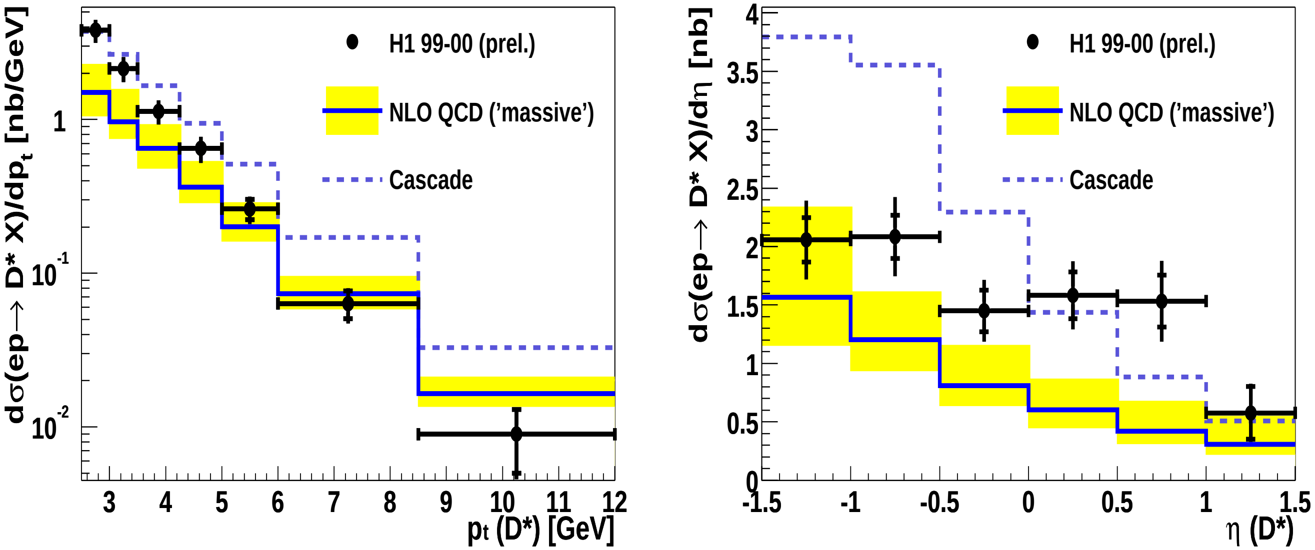



$Q^2 < 1$ GeV$^2$; 130 $< W_{\gamma p} <$ 280 GeV 79 pb$^{-1}$

$p_T^{D^*} > 1.9$ GeV; $|\eta^{D^*}| < 1.6$

No electron tag

H1



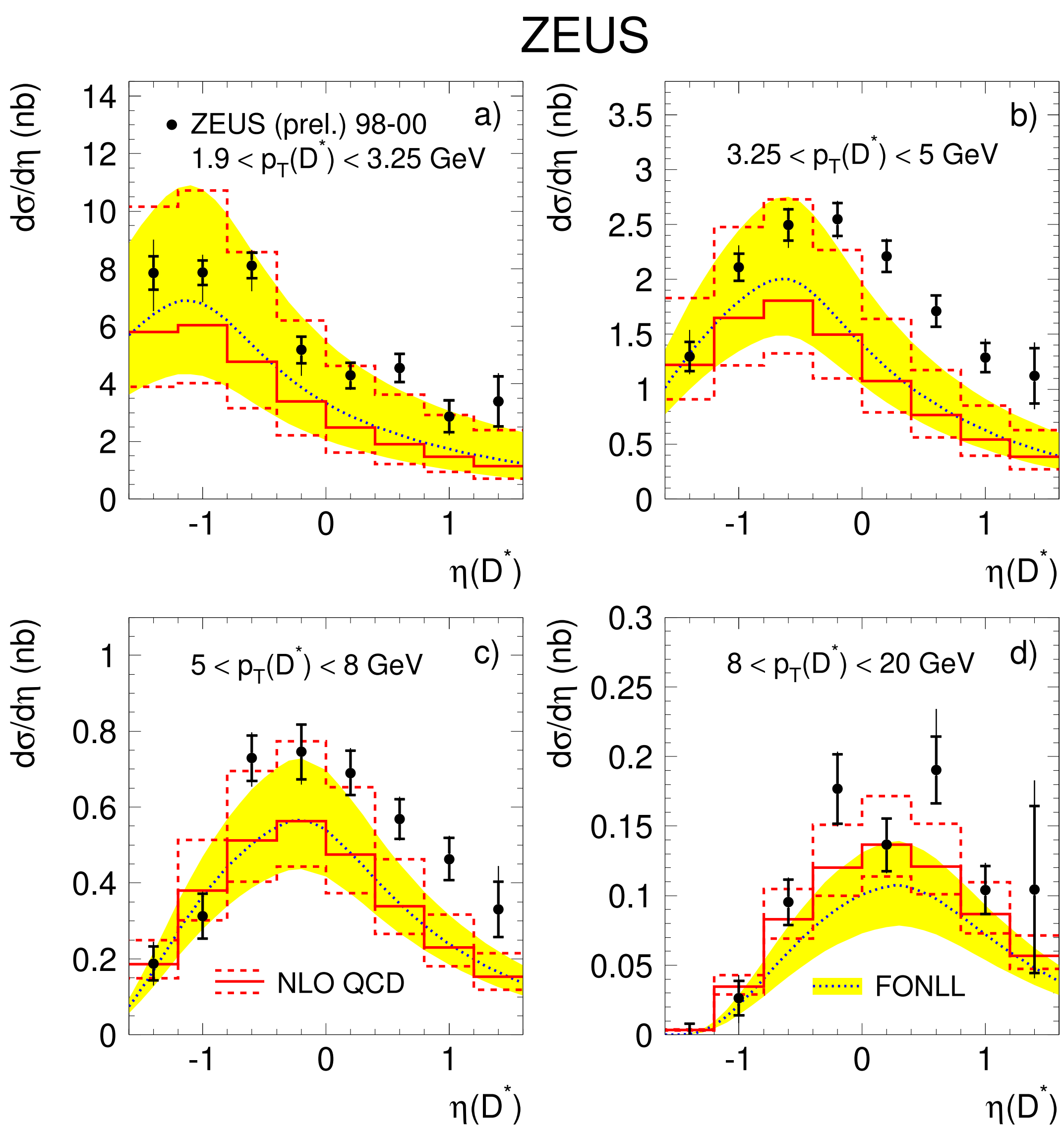

Electron tag: 49 pb$^{-1}$

$Q^2 < 0.01$ GeV$^2$; 171 $< W_{\gamma p} <$ 256 GeV

$p_T^{D^*} > 2.5$ GeV; $|\eta^{D^*}| < 1.5$

- NLO below data (low $p_T$, $\eta > 0$)
- FONLL not better even below NLO at high $p_T$
- CASCADE too hard

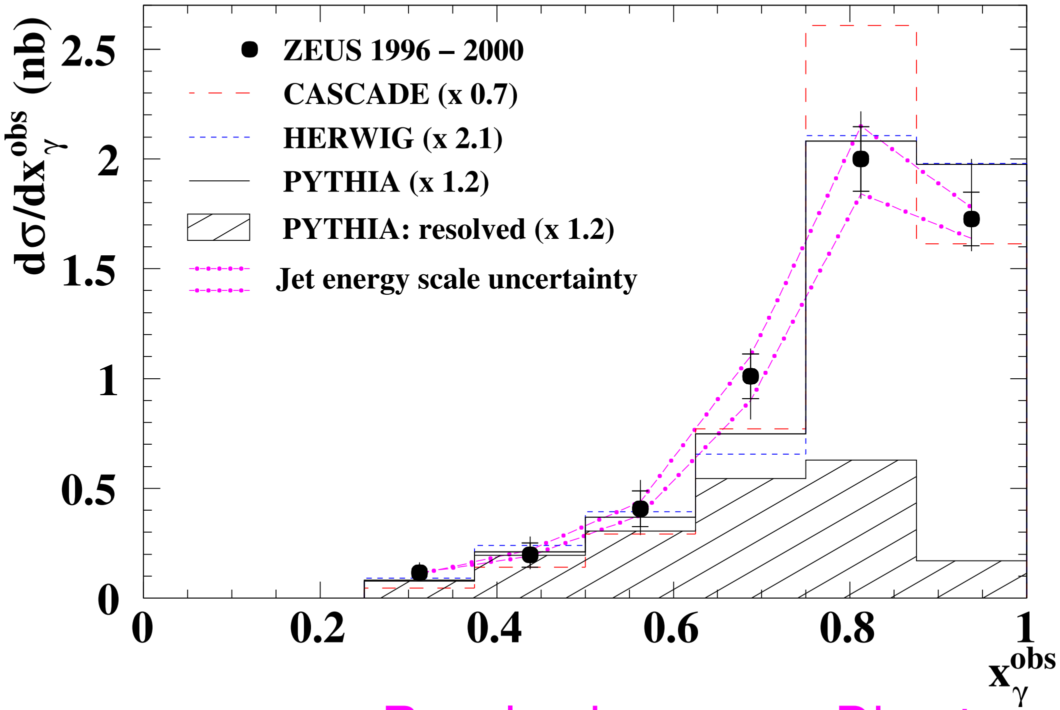
# $D^*$ Photoproduction double differential distributions




- $\eta$ distribution in $p_T^{D^*}$ bins
- NLO below data at medium $p_T^{D^*}$ and high $\eta$
- FONLL close to data only at low $p_T^{D^*}$

## ZEUS: $\gamma p \rightarrow D^{*\pm} + jj + X$

$\sim 120\,\mathrm{pb}^{-1}$

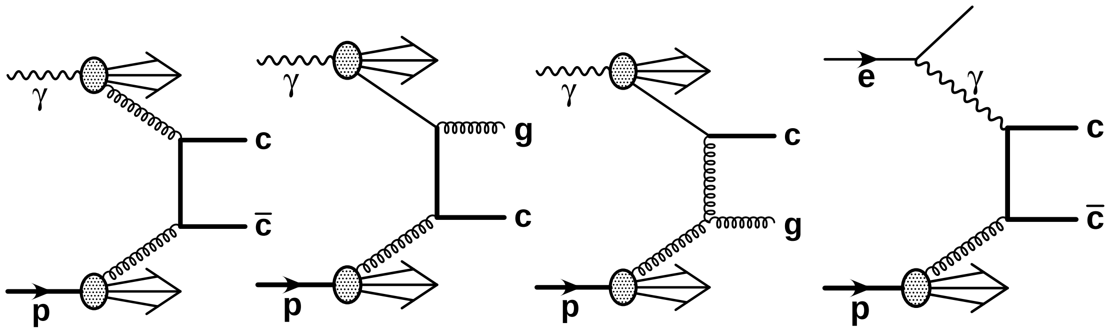



$p_T^{D^*} > 3$ GeV
2 jets: $E_T^{jet} > 5$ GeV, $|\eta^{jet}| < 2.4$;
$M_{jj} > 18$GeV

Momentum fraction of photon in jets:

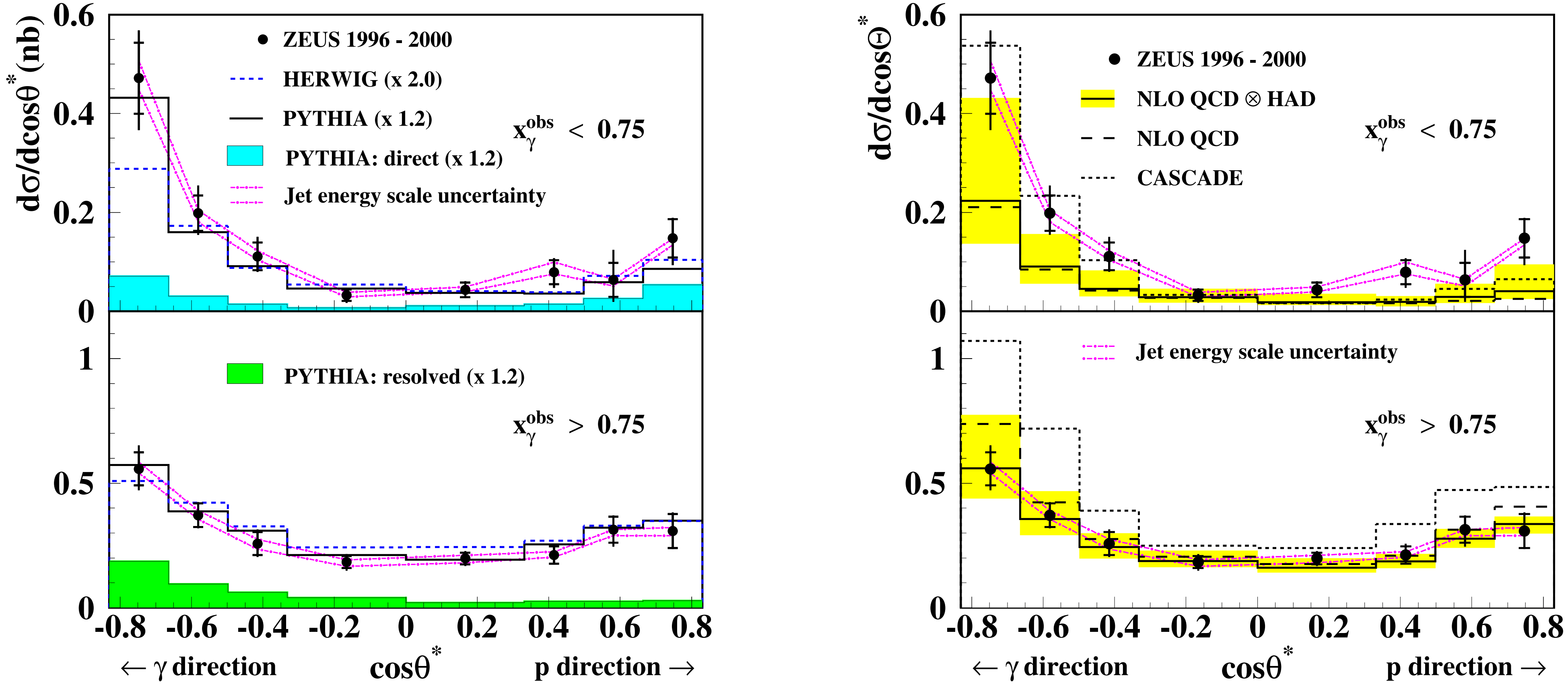
$$x_\gamma^{\mathrm{obs}} = \frac{\sum_{j_1,j_2}(E_T^j e^{-\eta^j})}{2yE_e}$$

Resolved-$\gamma$ Direct




- Significant contribution from resolved ($\sim$ 40%)
- MCs give good description of shape
- CASCADE too high at high $x_\gamma^{\mathrm{obs}}$
- NLO below data at low $x_\gamma^{\mathrm{obs}}$ (not shown)

# Charm: Dijet Angular Distributions (published:DESY-03-015)




- Contribution of LO resolved to $x_\gamma^{obs} > 0.75$ explains the asymmetric distribution in $\cos\theta^*$
- Strong rise in $d\sigma/d\cos\theta^*$ towards $\gamma$ direction for $x_\gamma^{obs} < 0.75$
- Clear evidence for charm from the photon
- NLO ok for $x_\gamma^{obs} > 0.75$
- NLO below data for $x_\gamma^{obs} < 0.75$ in $\gamma$ and $p$ direction
- CASCADE exceeds data, shape ok

# Summary Charm Production at H1 and ZEUS

Fragmentation Fractions and Fragm. Function measured

Good agreement with results from other experiments

DIS: $D^*$ with jets:

RAPGAP, CASCADE show some problems while they are ok for inclusive $D^*$

Photoproduction: New tagged inclusive analysis shows similar problems with QCD as untagged (mainly at low $p_T$ and large $\eta$); CASCADE too hard

Detailed analysis of angular distribution of jets with a $D^*$:

Resolved component has large contribution from charm in photon direction.

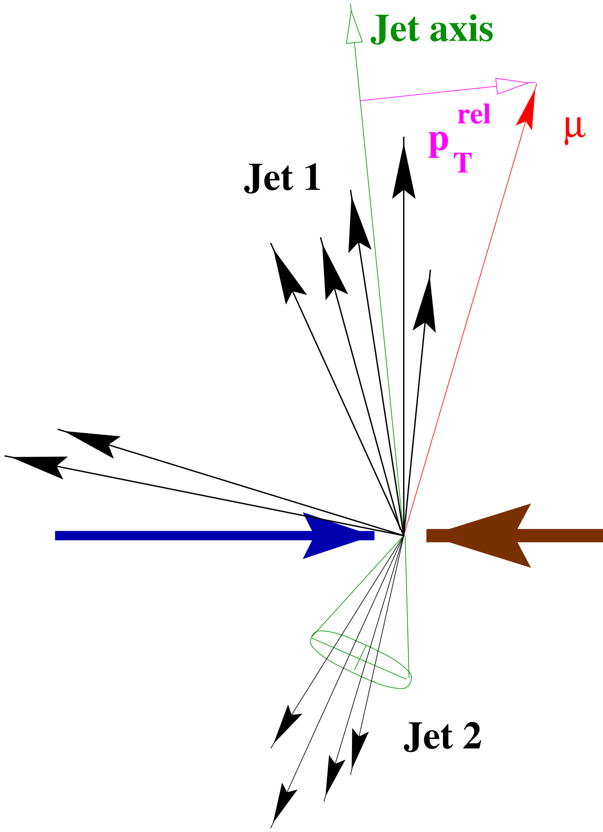
NLO QCD does not describe this component well; Shapes reproduced better by Monte Carlo Models

# Beauty Production

$\sigma(b\bar{b})$ : Factor $\sim$ 200 smaller than $\sigma(c\bar{c})$

Use semileptonic $b$ decays

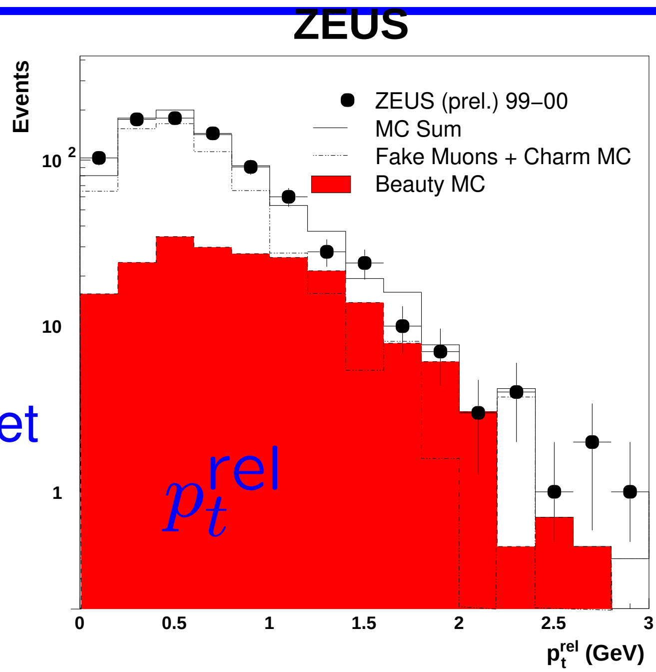
Two tagging methods




- High $B$-Mass:

  $p_t$ of $\mu$ relative to the jet

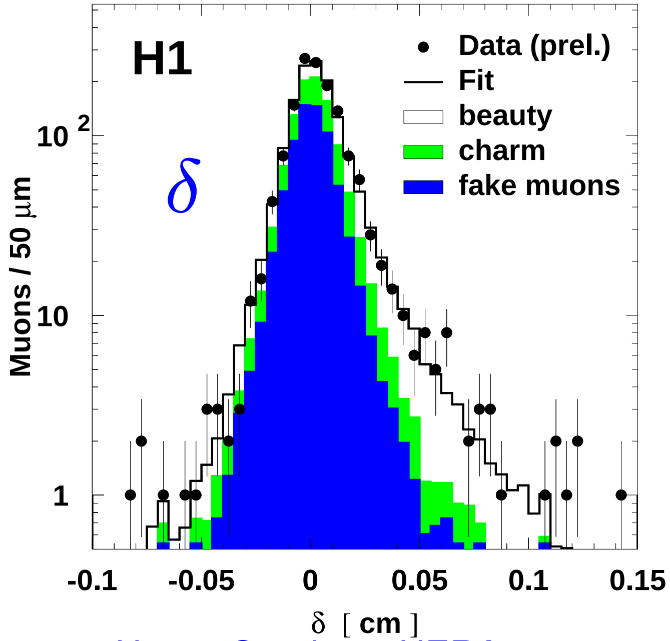
  $f_b \sim (25 \pm 5)\%$




- Long $B$-Lifetime:

  $\mu$ Impact Parameter

  $f_b \sim (26 \pm 5)\%$




Previous results:

$\sigma$(Data)/$\sigma$(NLO) $\sim 3$

# B in $\gamma p$ : 1996–2000 Results

ZEUS: $p_T^{rel}$ Method

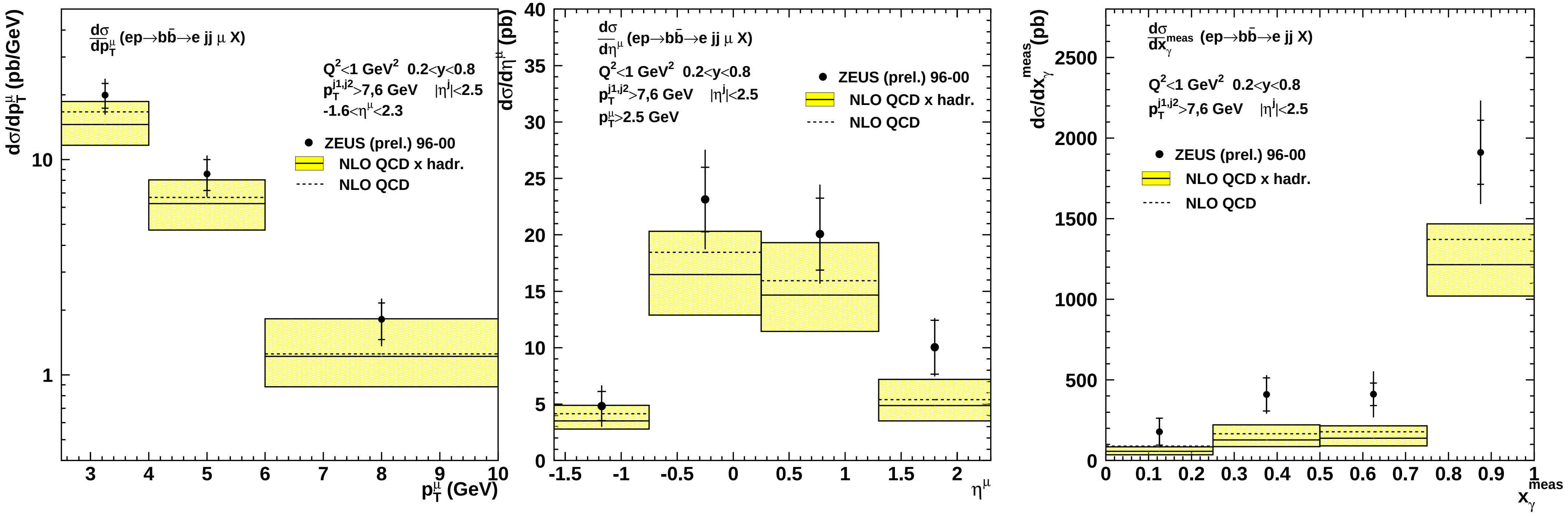
2 jets, $E_T^{jet1(2)} > 7$ (6) GeV; $|\eta^{jet}| < 2.5$

$p_T^\mu > 2.5$ GeV; $-1 < \eta^\mu < 2.3$

98 pb$^{-1}$

$Q^2 < 1$ GeV$^2$; $0.2 < y < 0.8$

$ep \to b\bar{b} \to e\, j\, j\, \mu\, X$ $\qquad$ $ep \to b\bar{b} \to e\, j\, j\, X$



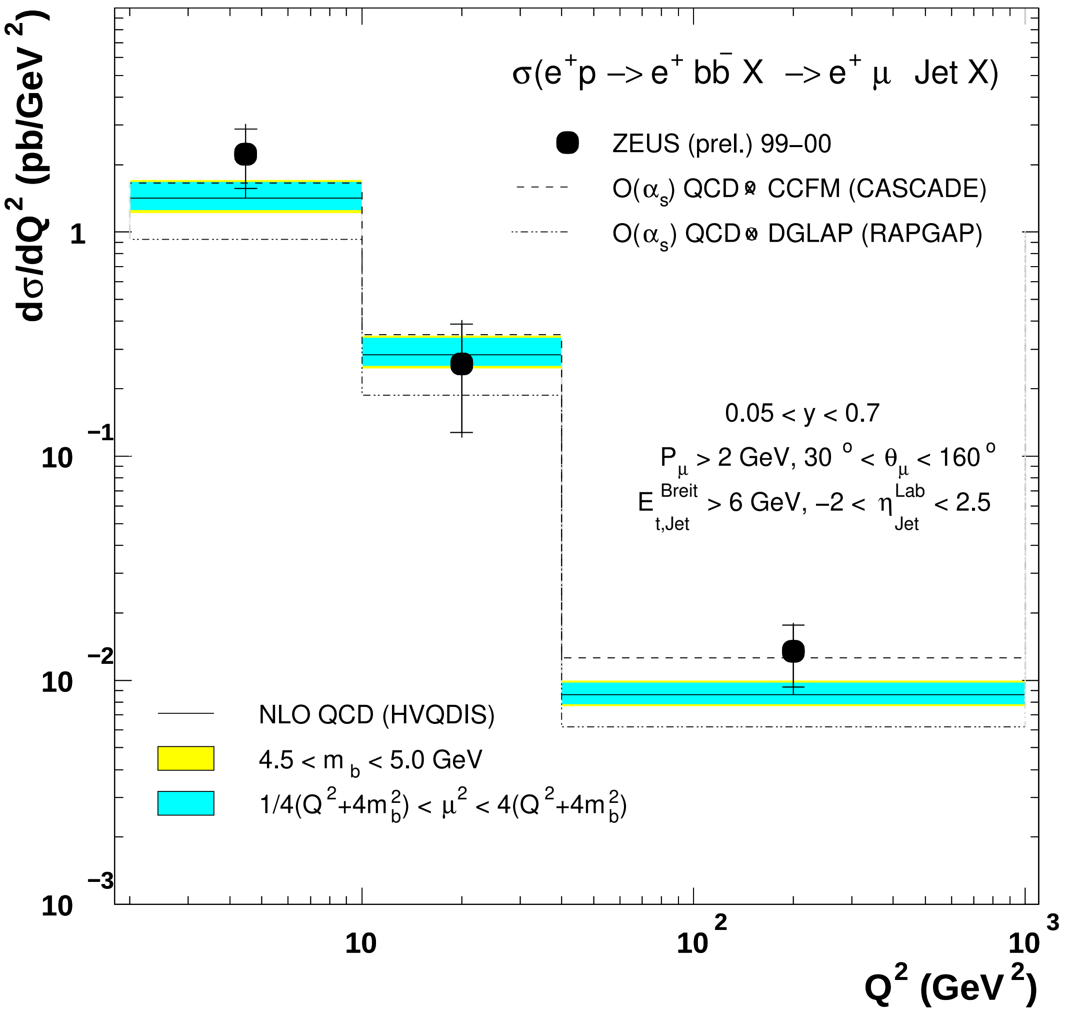

Comparison to NLO QCD: $p_T^\mu$ and $\eta^\mu$ in visible region, ok within errors

For $x_\gamma$ extrapolate muon phase space (PYTHIA),

Factor 2 disagreement

# Beauty in DIS

ZEUS: $ep \to b\bar{b} \to ej\mu X$




$Q^2 > 2$ GeV$^2$, $0.05 < y < 0.7$ $\sim 60\,\text{pb}^{-1}$

1 muon, $p_T^{\mu} > 2\,\text{GeV}$

1 jet: $E_T^{Breit} > 6\,\text{GeV}$

$\sigma^{\text{vis}} = (38.7 \pm 7.7^{+6.1}_{-5.0})$ pb

- QCD NLO (DGLAP) ok within errors

  NLO (Harris et al): $\sigma^{\text{vis}} = (28^{+5.3}_{-3.5})$pb

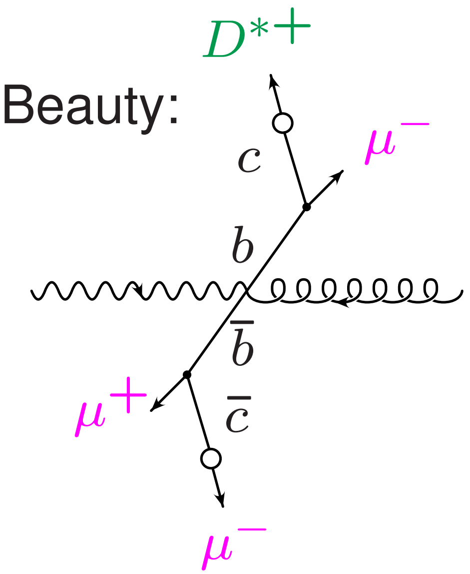
- CASCADE (CCFM) good agreement

  $\sigma^{\text{vis}} \approx 35$pb

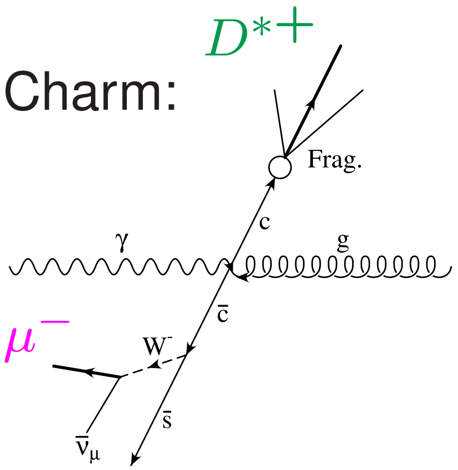
- RAPGAP (DGLAP, LO+PS) too low

# Heavy-Flavour Double-Tag: $D^*\mu$ – Correlations

Beauty:




Charm:

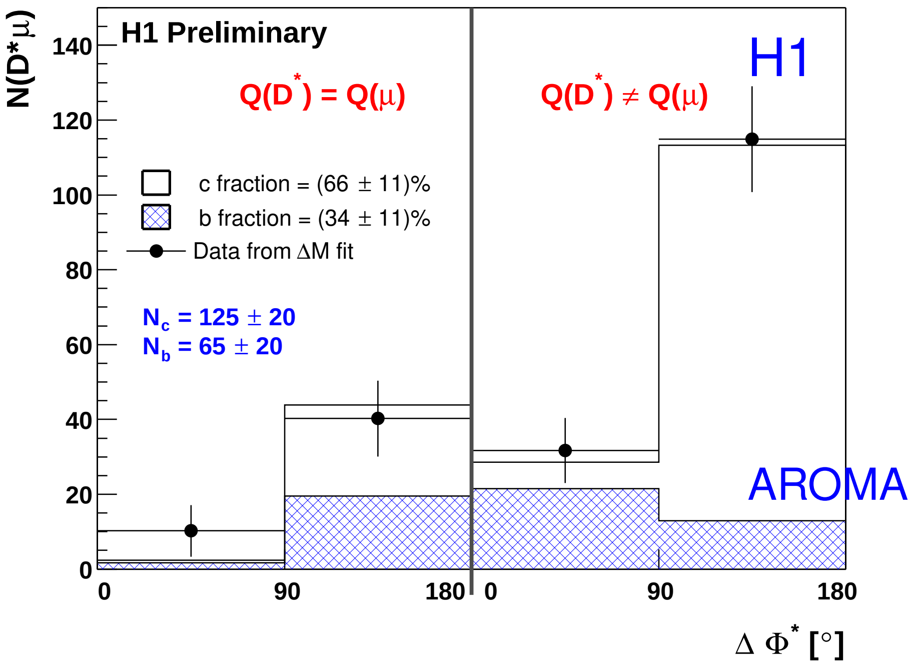



$c$-$b$ separation using charge and angular correlations

H1: $\gamma p \rightarrow D^{*\pm} + \mu + X$ $\sim 90\,\text{pb}^{-1}$

$p_T^\mu > 1.$ GeV, $|\eta^\mu| <$1.74, $0.05 < y < 0.75$

$p_T^{D^*} > 1.5$ GeV, $|\eta^\mu| <$1.5




combined $D^*$ **($\Delta M$)** + $D^*\mu$ **correlation** analysis

$\sigma(ep \rightarrow D^*\mu X)$

**charm :** $[720 \pm 115(stat.) \pm 245(syst.)]$pb

$\rightarrow$ **factor 1.8** above AROMA

**beauty:** $[380 \pm 120(stat.) \pm 130(syst.)]$pb

$\rightarrow$ **factor 3.6** above AROMA

ZEUS: $\gamma p \to D^{*\pm} + \mu + X$ $\sim 114\,\mathrm{pb}^{-1}$

$p_T^{D^*} > 1.9$ GeV, $-1.5 < \eta^{D^*} < 1.75$, $0.05 < y < 0.85$

$p_T^{\mu} > 1.4$ GeV, $-1.3 < \eta^{\mu} < 1.5$ $\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2}$

$\Delta R < 2$ $\Delta R > 2$

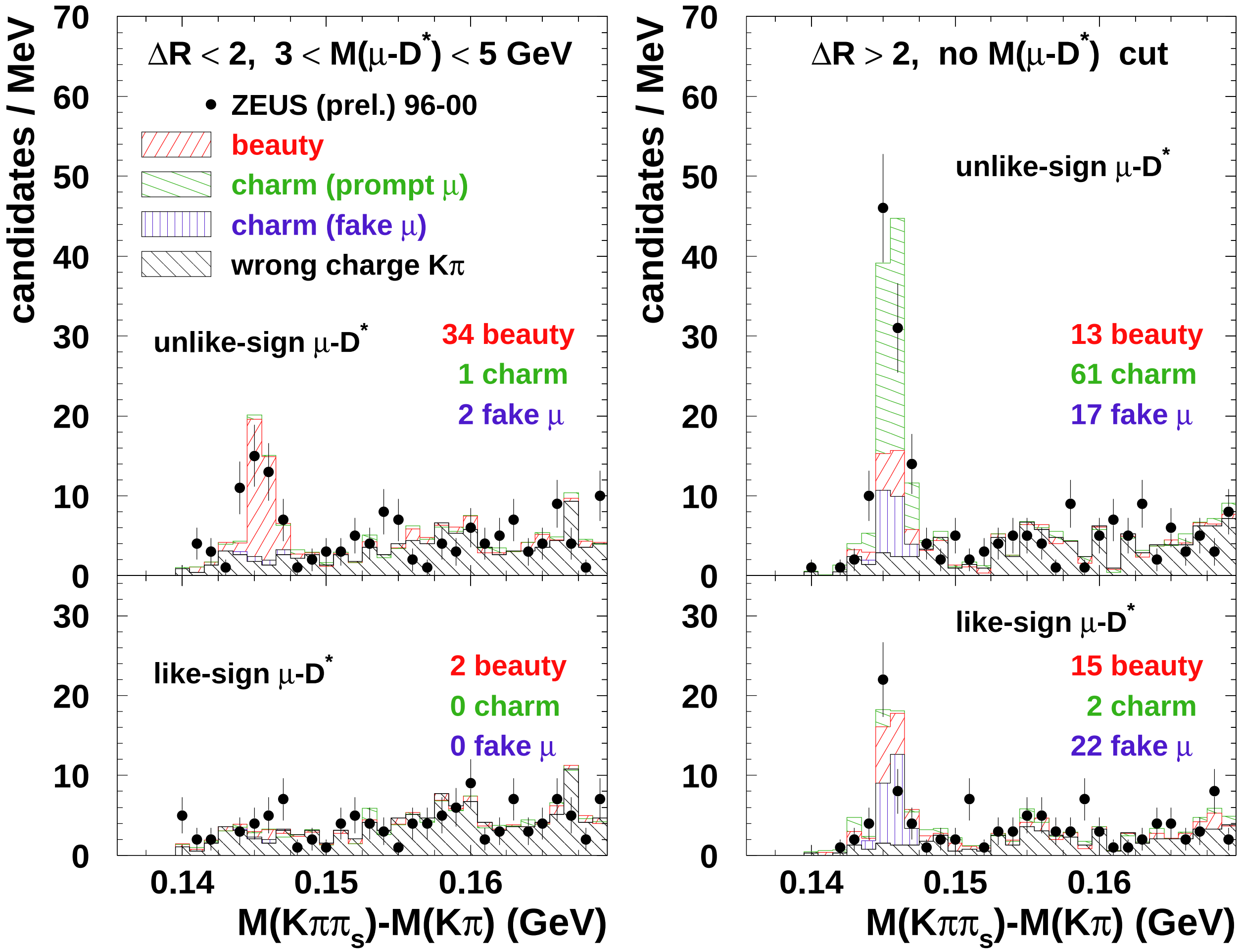
↓ PYTHIA MC ↓

**$\gamma p$ cross section**

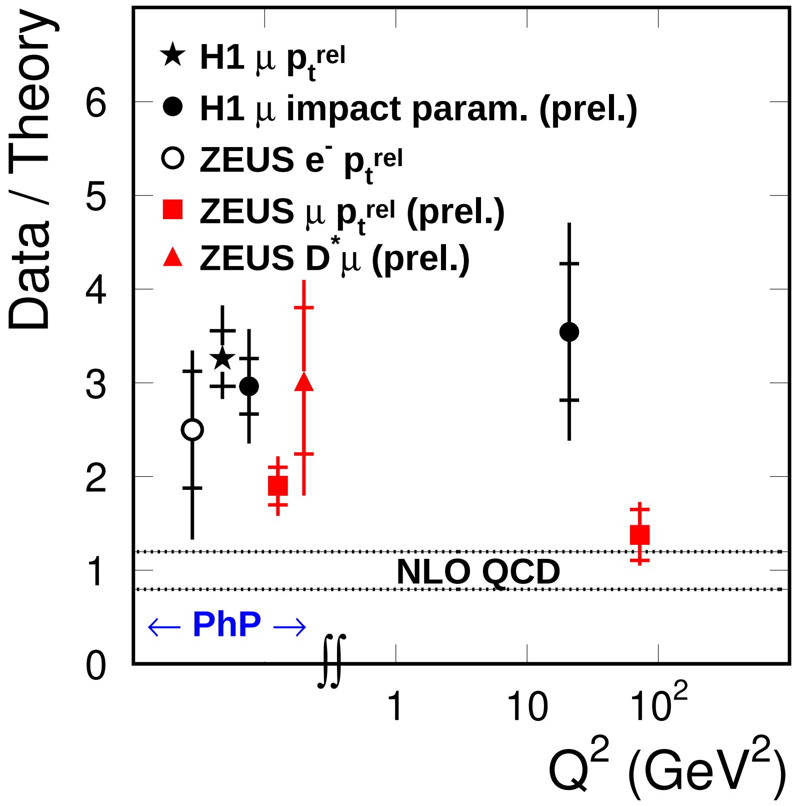
(for $\hat{y}^b < 1$, $Q^2 < 1\mathrm{GeV}^2$)

$$\sigma\,(ep \to b(\bar{b})X) = (15.1 \pm 3.9^{+3.8}_{-4.7})\,\mathrm{nb}$$

**NLO QCD:** $\left[5.0^{+1.7}_{-1.1}\right] nb$



# Summary Beauty Production at H1 and ZEUS




Present (mostly preliminary) results show:

Data/QCD$\sim$ 2 for $b\bar{b}$ production

Consistent using different methods ($p_T^{rel}$, $\delta$, $D^*\,\mu$)

and between H1 and ZEUS

Differential analyses have given new insights:

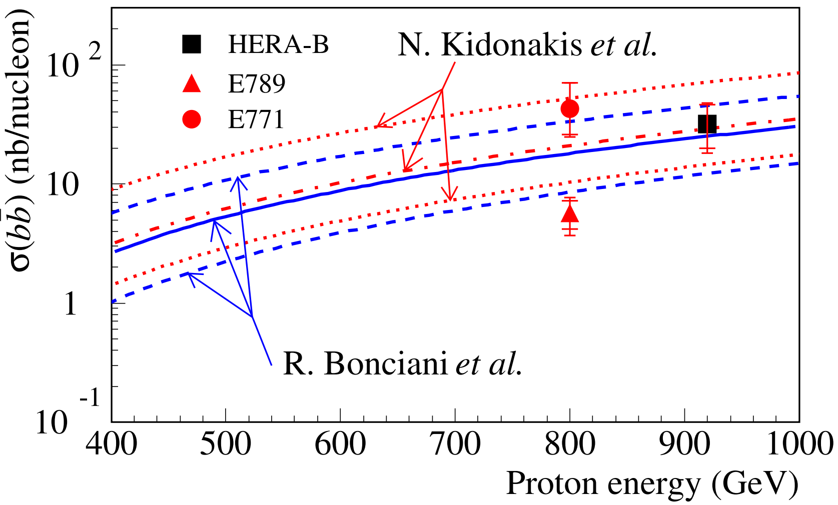
Excess is not localised in $p_T$, $\eta$ or $x_\gamma^{obs}$

Extrapolation procedure from measured 'visible' region is under discussion...

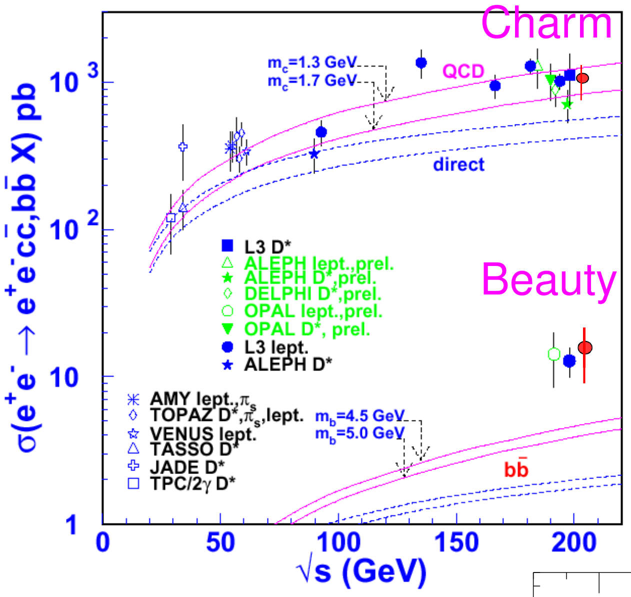
Waiting for final data from HERA I

# Overview: Beauty-Production: The World

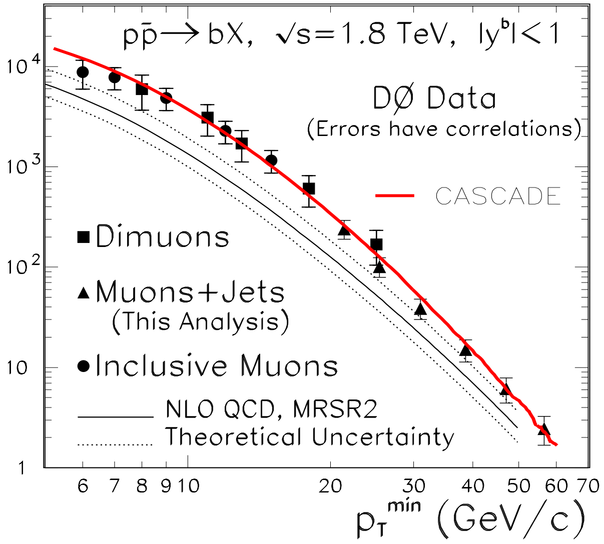
HERA-B




$\gamma\gamma$ LEP




$p\bar{p}$ Tevatron




- HERA-B at lower cms energy:
  Data agree with theory (spread large)
- LEP: NLO also too low for beauty
- $p\bar{p}$: FONLL closer to data than (older) NLO
- $p\bar{p}$: CASCADE just as good