DIS03 St. Petersburg

Production of Heavy Quarks at HERA

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Introduction, Theoretical Framework

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

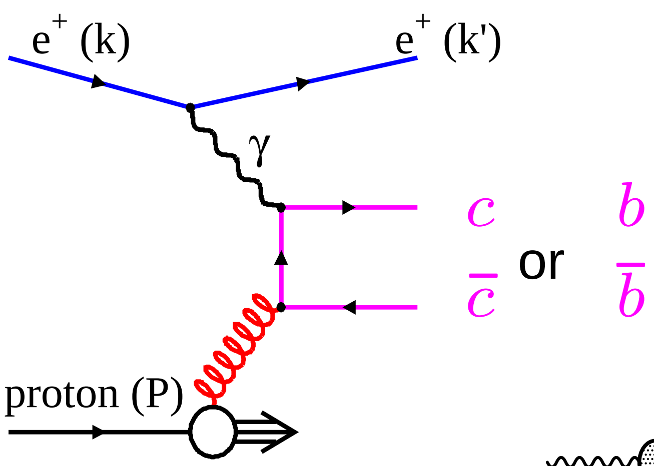
Introduction

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)



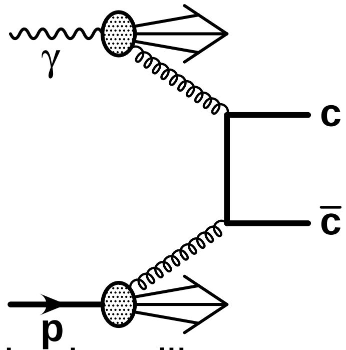
'Direct Process' (pointlike photon)

Two kinematic regimes:

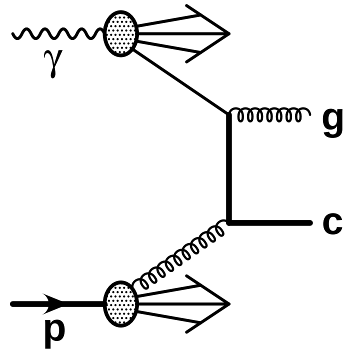
$Q^2 \to 0$ Photoproduction

$Q^2 \gtrsim 2\,\mathrm{GeV}^2$ Electroproduction "DIS"

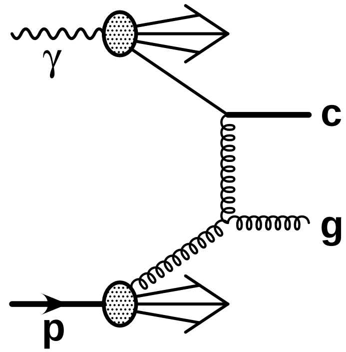
'Resolved-γ': Hadron-like



hadron-like



c-Excitation: q-Propagator

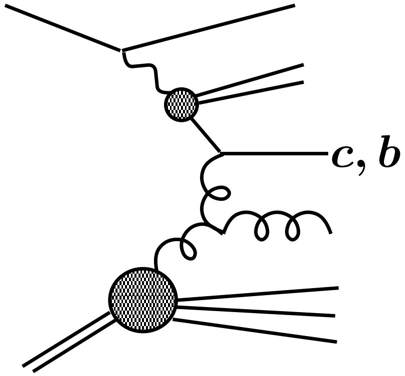


g-Propagator

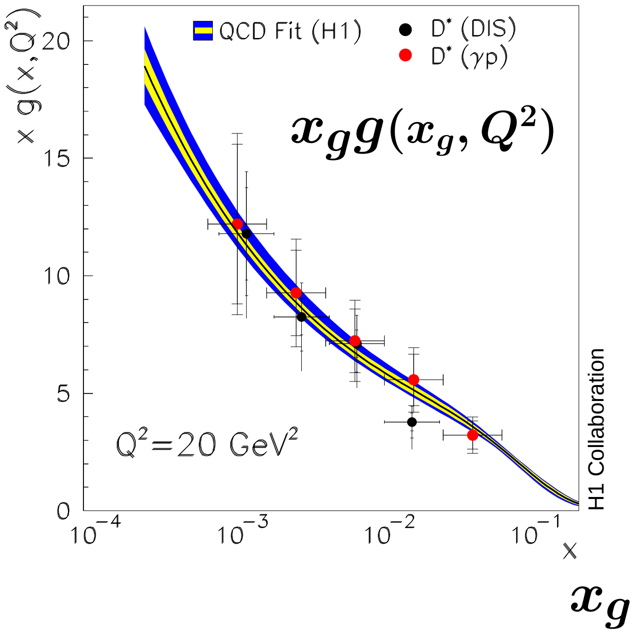
• HEAVY FLAVOUR PRODUCTION: PROBE OF HARD QCD

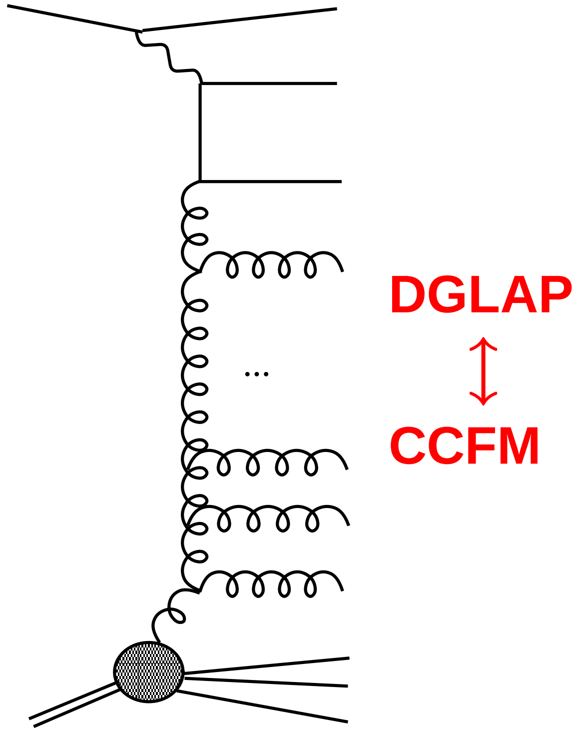
Resolved γ contribution

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**;

$p_t \lesssim m_q$

- γp**:** FMNR (Frixione et al.)
- **DIS:** HVQDIS (Harris & Smith)

Resummed calculations in NLL

all orders, **massless scheme**:

HQ **in** γ **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**:

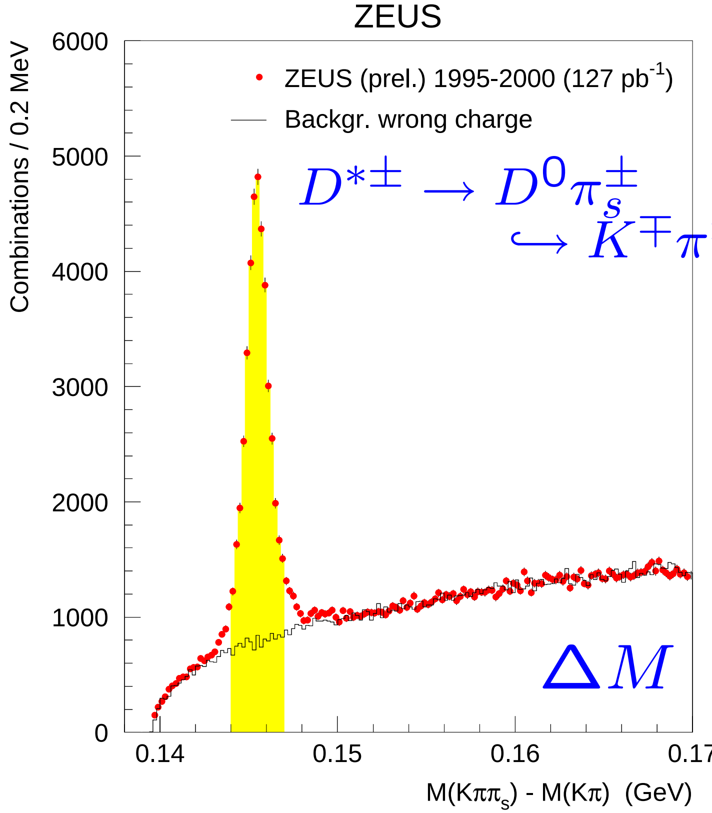
  direct only, **CCFM**–like evolution,

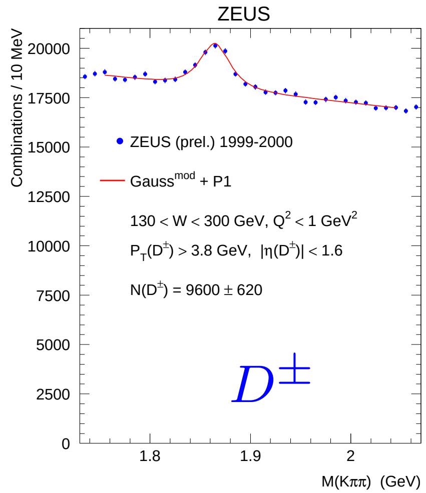
  k_t dependent gluon density

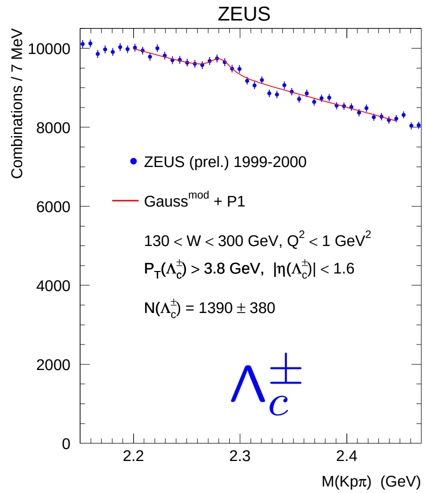
Fragmentation:

non perturbative models

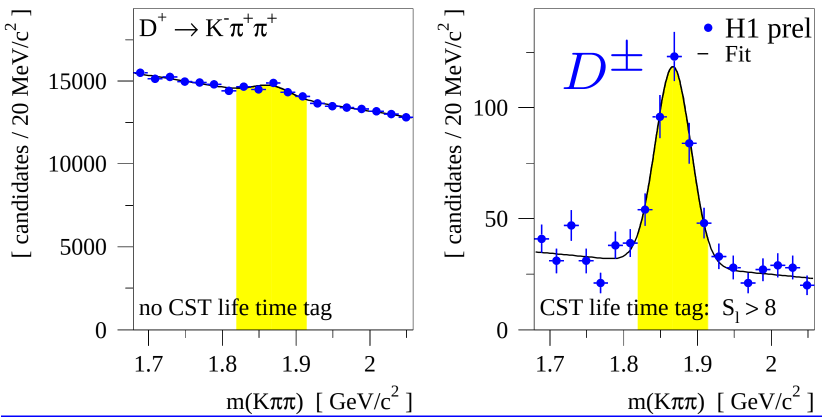
CHARM Tagging Methods

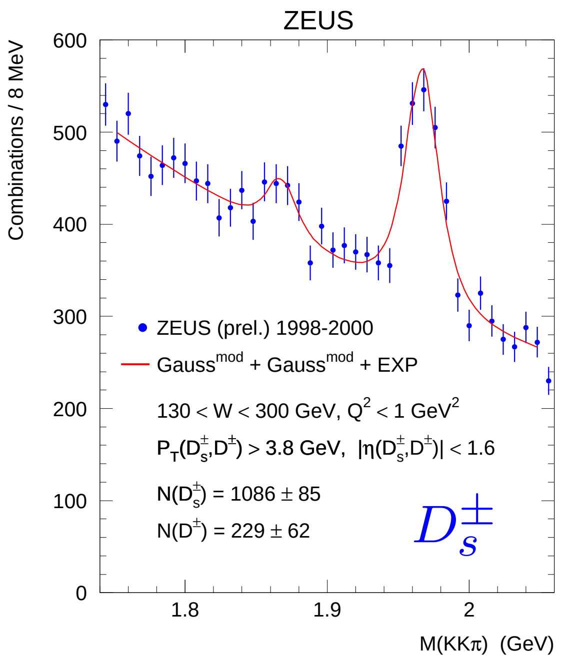


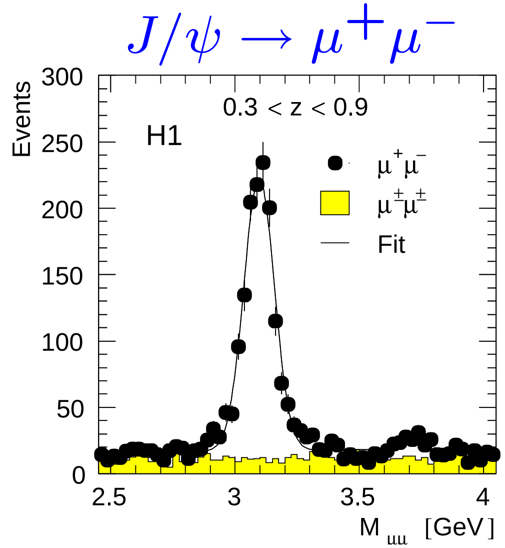




lifetime: no tag ⟶ tag







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 pb^{-1}

Determine from data:

ZEUS prel. (γp) $P_T(D,\Lambda_c) > 3.8\,\mathrm{GeV}$, $\lvert\eta(D,\Lambda_c)\rvert < 1.6$	Combined e^+e^- data	H1 prel. (DIS)
$f(c \to D^+) = 0.249 \pm 0.014^{+0.004}_{-0.008}$	0.232 ± 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 ± 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 ± 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 ± 0.007	
$f(c \to D^{*+}) = 0.223 \pm 0.009^{+0.003}_{-0.005}$	0.235 ± 0.007	$0.263 \pm 0.019^{+0.056}_{-0.042}{}^{+0.031}_{-0.022}$

charm fragmentation fractions are universal

$\longrightarrow$ HERA errors competitive!

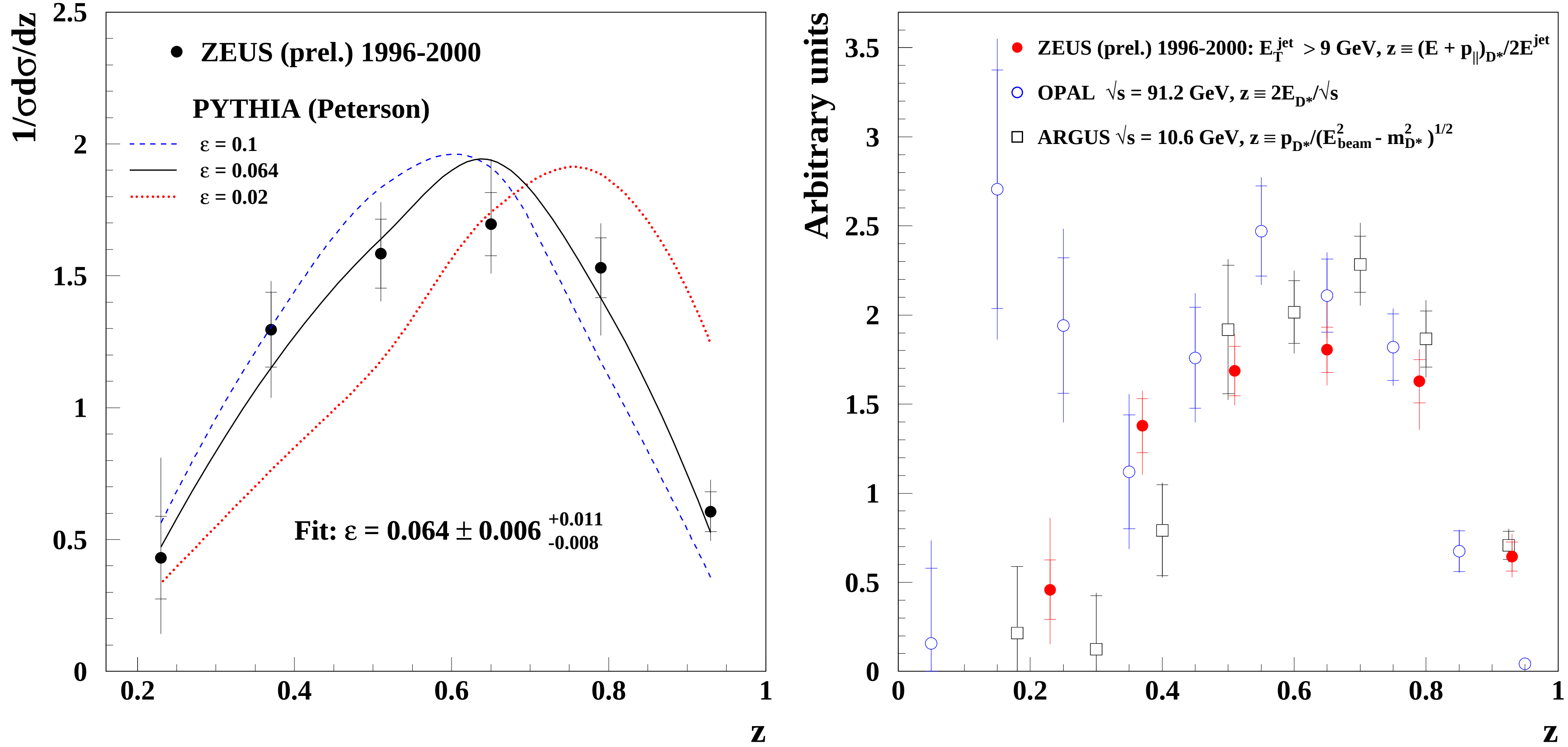
$R_{u/d}$, γ_s, $V/(P+V)$ also determined and in good agreement with w.a.

Fragmentation Function

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

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

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



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

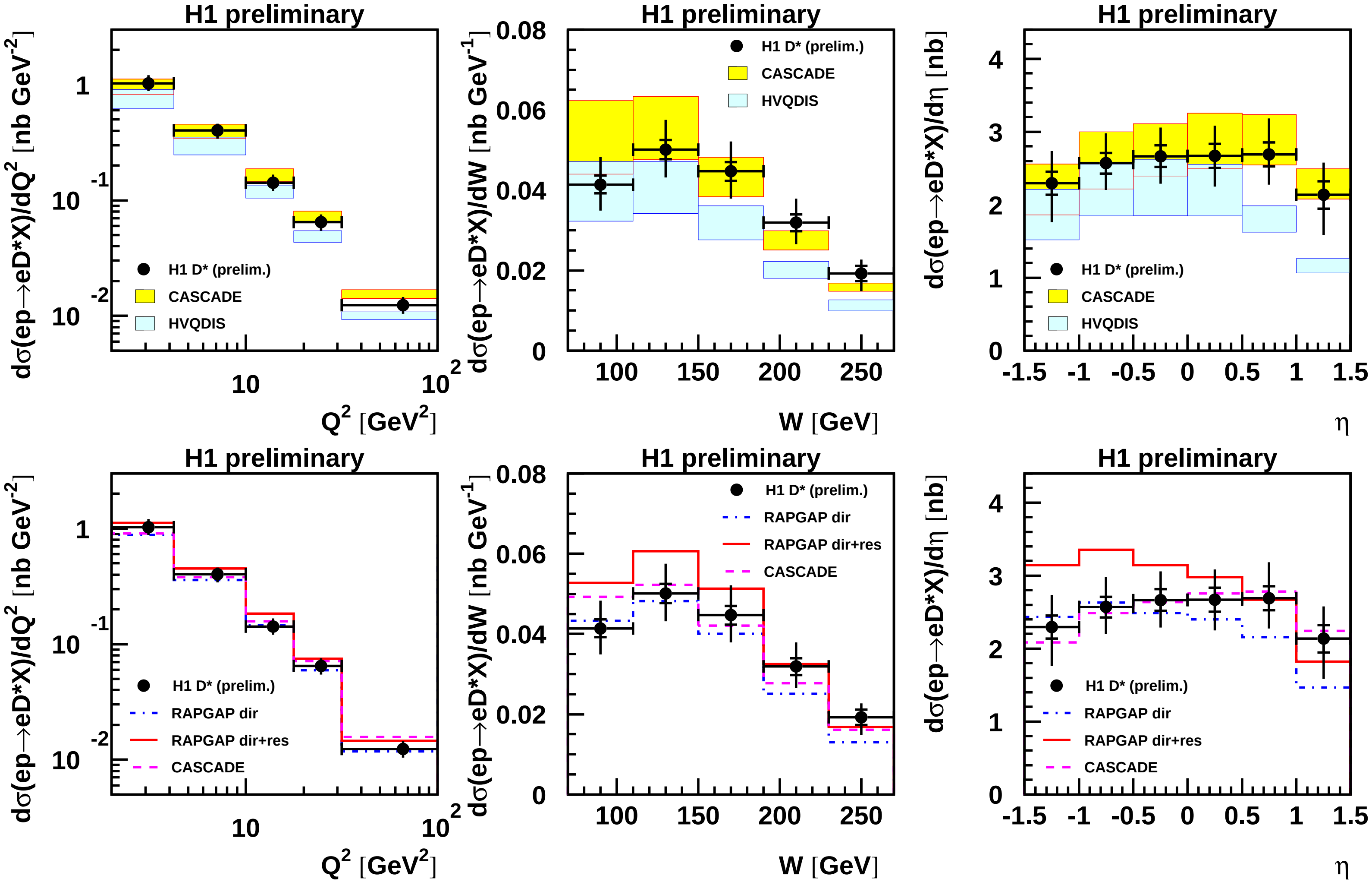
FRAGMENTATION Function universal

D^* in DIS (new)

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

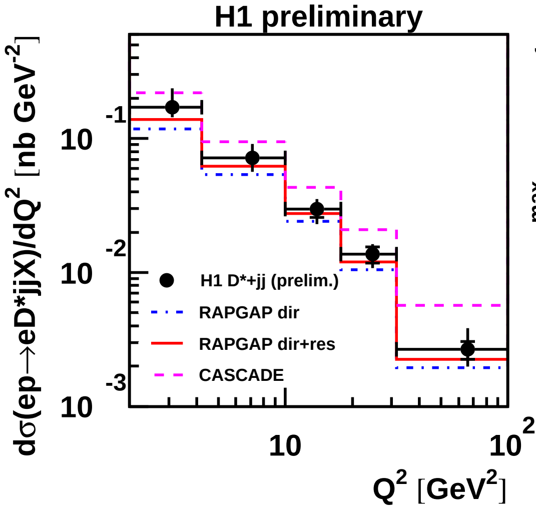


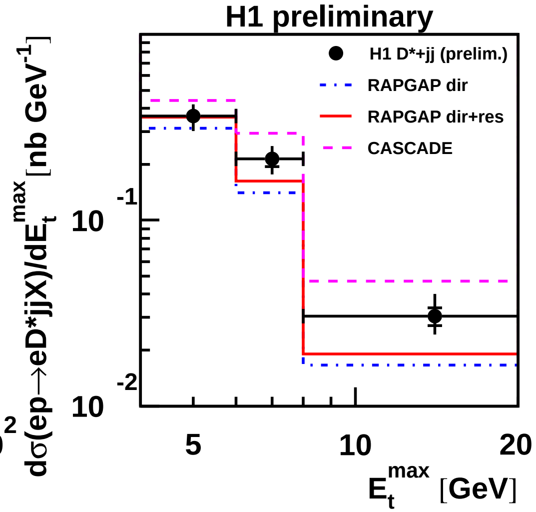
- NLO QCD low
- CASCADE (CCFM) better
- RAPGAP (LO+PS) high
- Shape of η distribution well described by CASCADE only

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

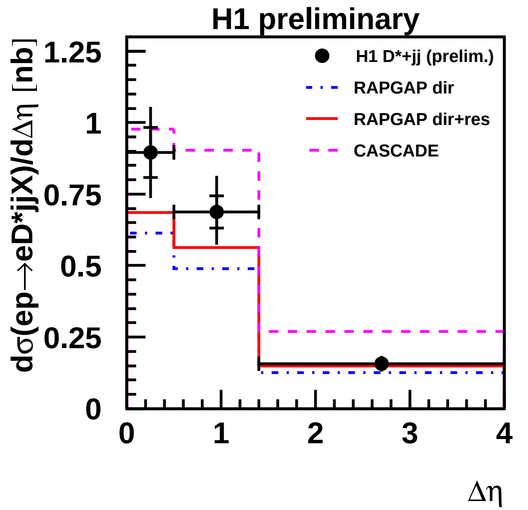
H1: D^* and 2 jets (inclusive k_t algorithm in Breit frame)

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

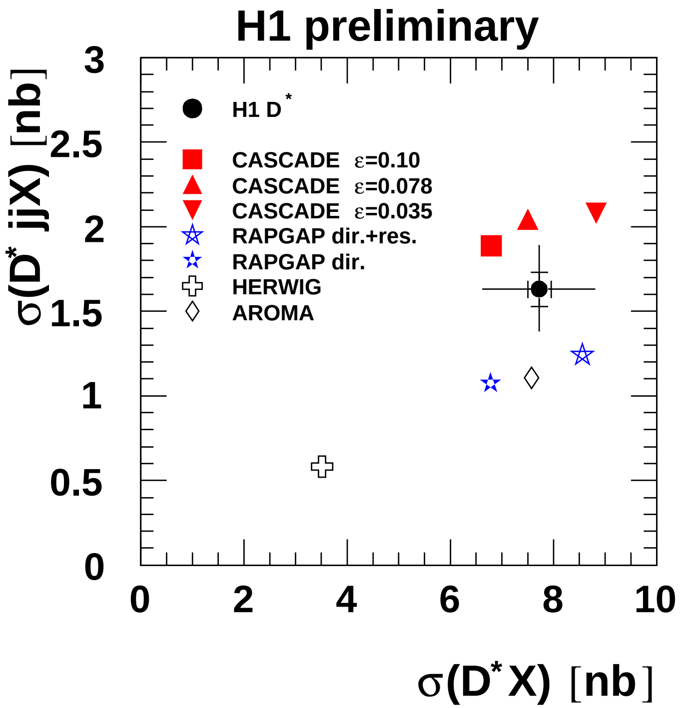




- CASCADE (CCFM) too high
- RAPGAP (LO+PS) too low

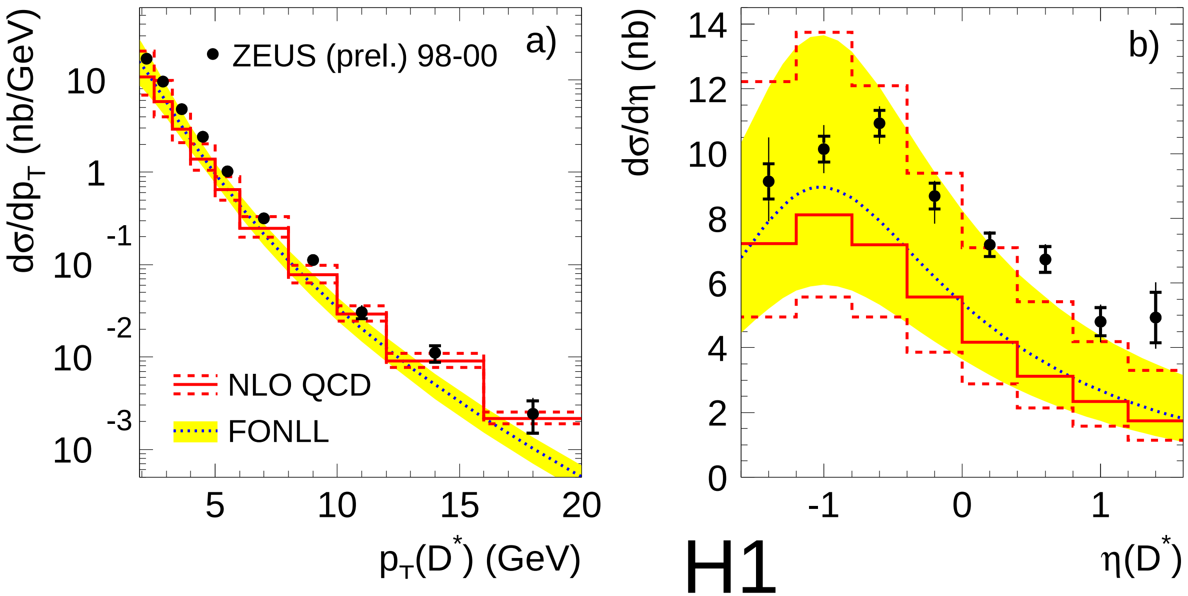


Summary plot: Jet cross section versus inclusive



D^* Photoproduction (new)

ZEUS

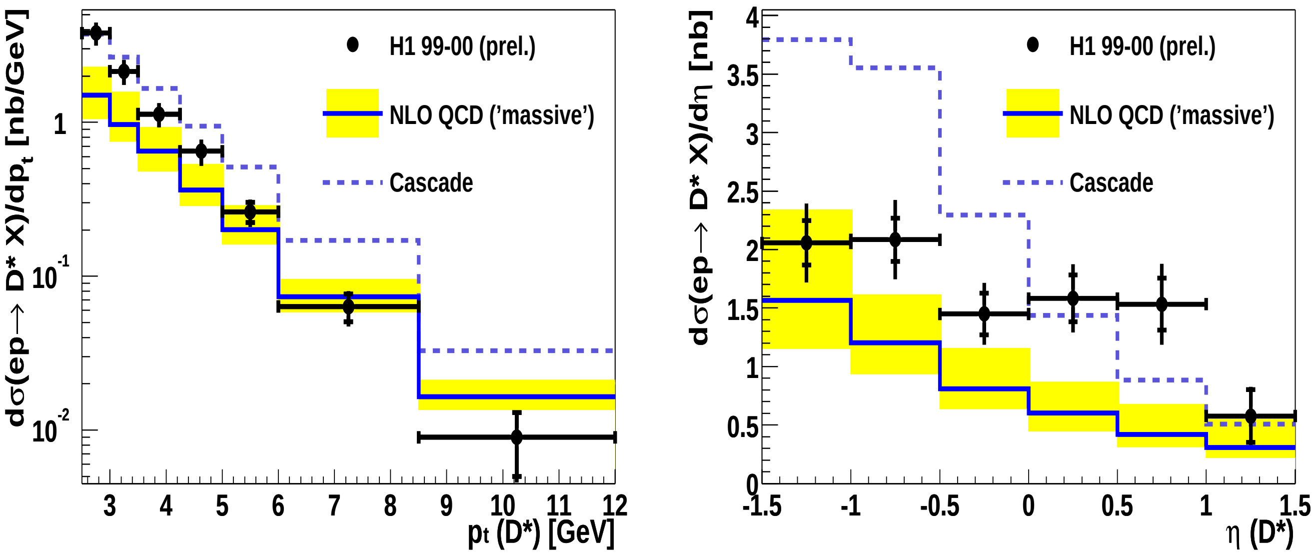


$Q^2 < 1$ GeV^2; $130 < W_{\gamma p} < 280$ GeV — 79 pb^{-1}

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

No electron tag

H1



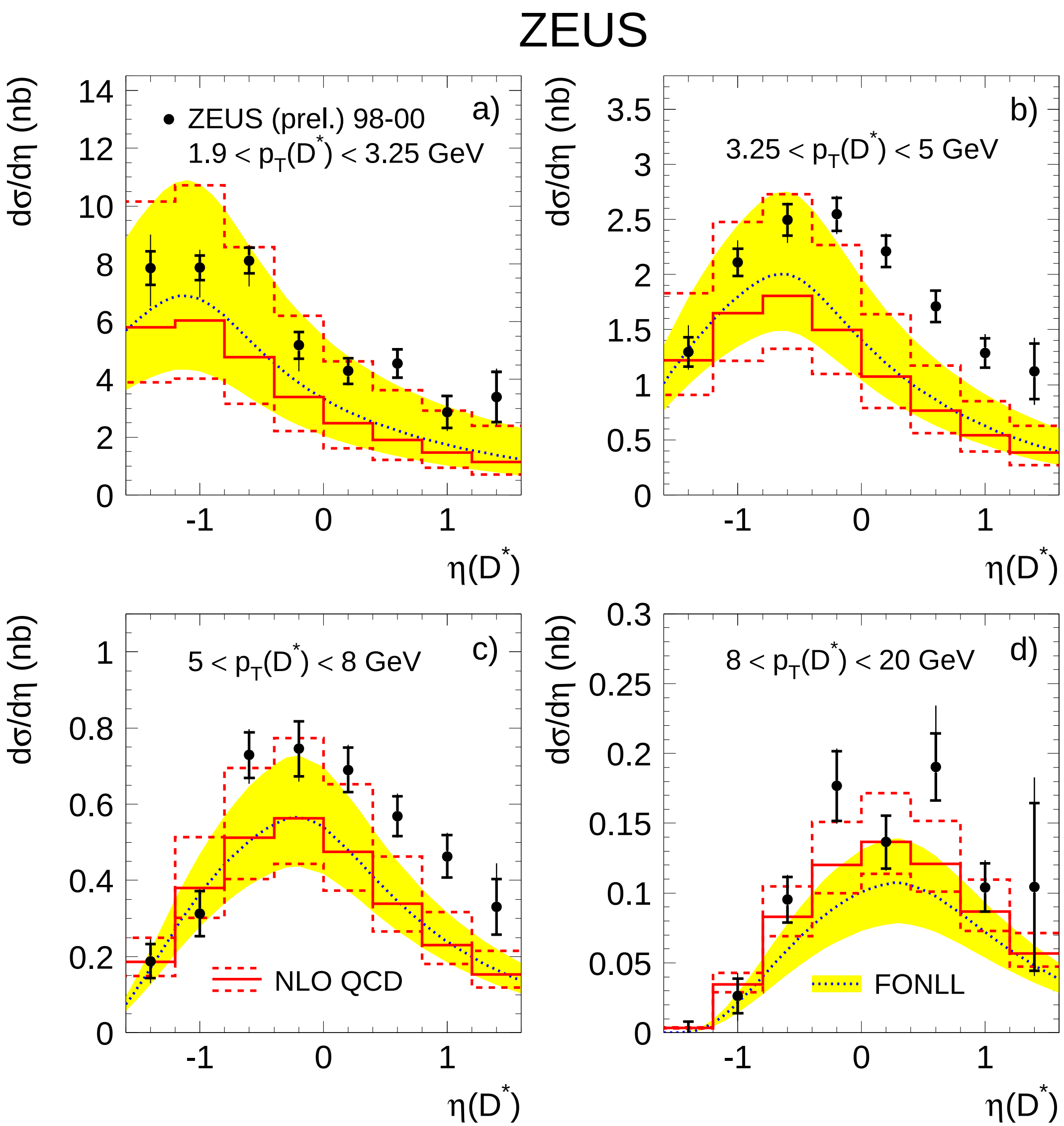
Electron tag: — 49 pb^{-1}

$Q^2 < 0.01$ 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

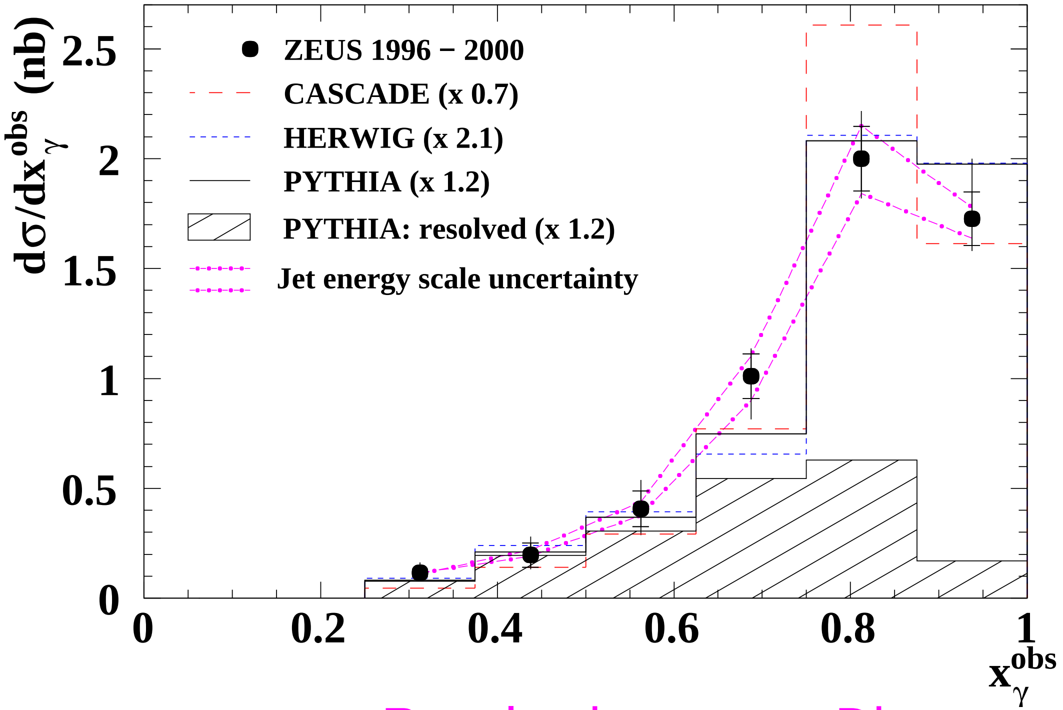
D^* Photoproduction double differential distributions



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

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

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



$p_T^{D^*} > 3$ GeV

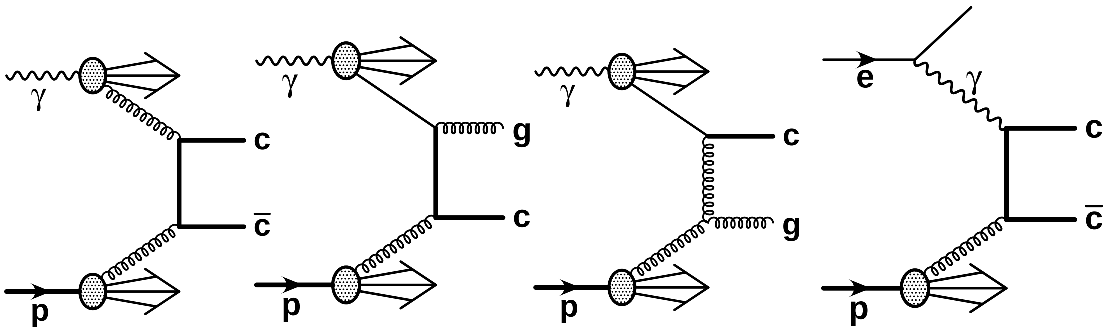
2 jets: $E_T^{jet} > 5$ GeV, $|\eta^{jet}| < 2.4$;

$M_{jj} > 18$GeV

Momentum fraction of photon in jets:

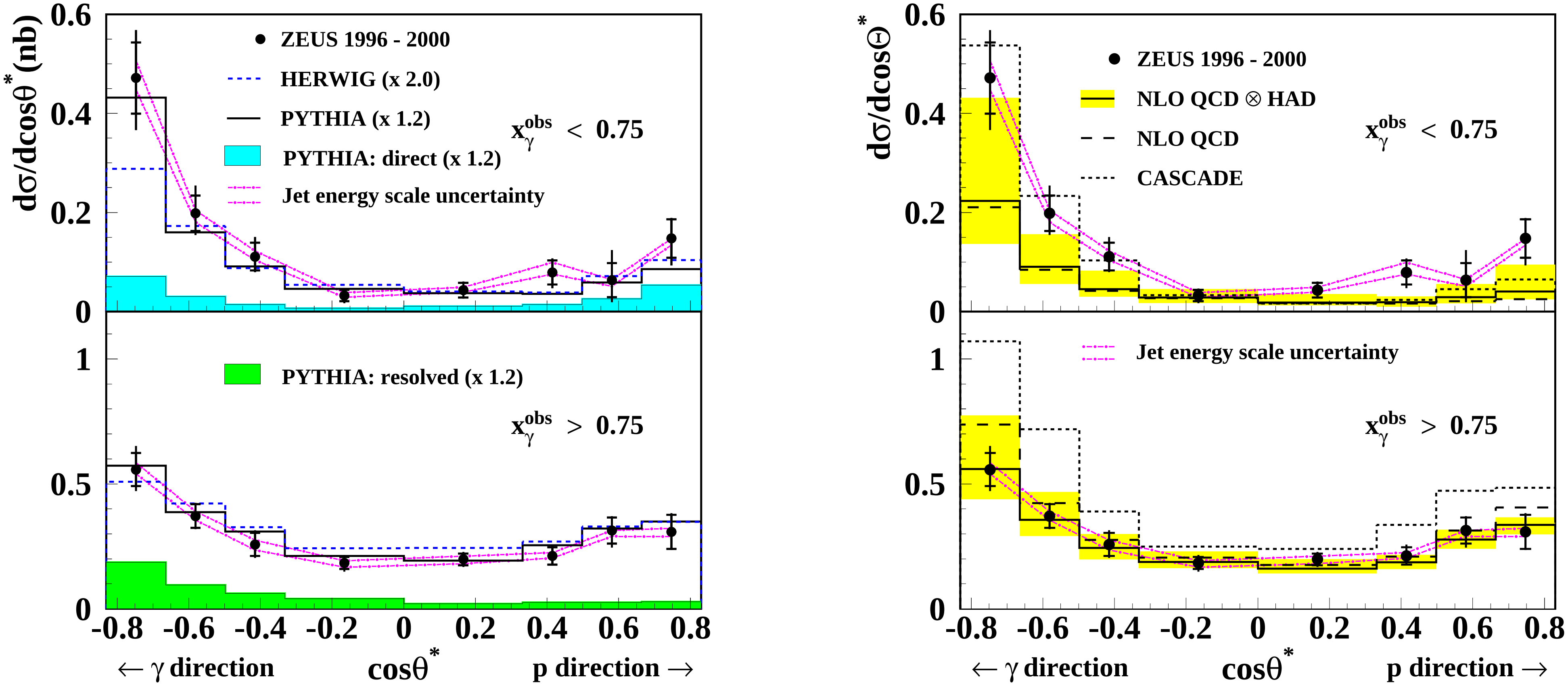
$$x_\gamma^{\text{obs}} = \frac{\sum_{j_1,j_2}(E_T^j e^{-\eta^j})}{2yE_e}$$

Resolved-γ Direct



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

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



- Contribution of LO resolved to $x_\gamma^{\rm obs} > 0.75$ explains the asymmetric distribution in $\cos\theta^*$
- Strong rise in $d\sigma/d\cos\theta^*$ towards γ direction for $x_\gamma^{\rm obs} < 0.75$
- Clear evidence for charm from the photon
- NLO ok for $x_\gamma^{\rm obs} > 0.75$
- NLO below data for $x_\gamma^{\rm obs} < 0.75$ in γ 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 η); CASCADE too hard

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

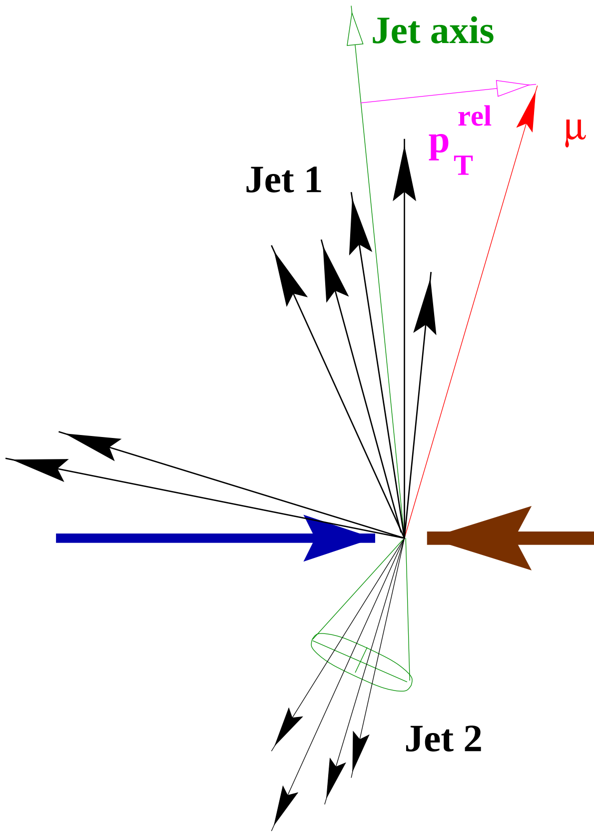
Resolved component has large contribution from charm in photon direction.

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

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

Use semileptonic b decays

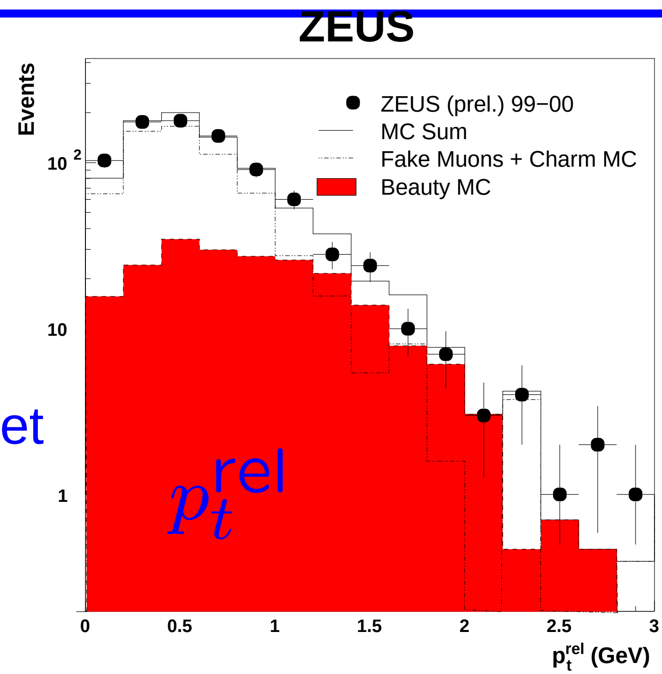
Two tagging methods



- High B-Mass:

  p_t of μ relative to the jet

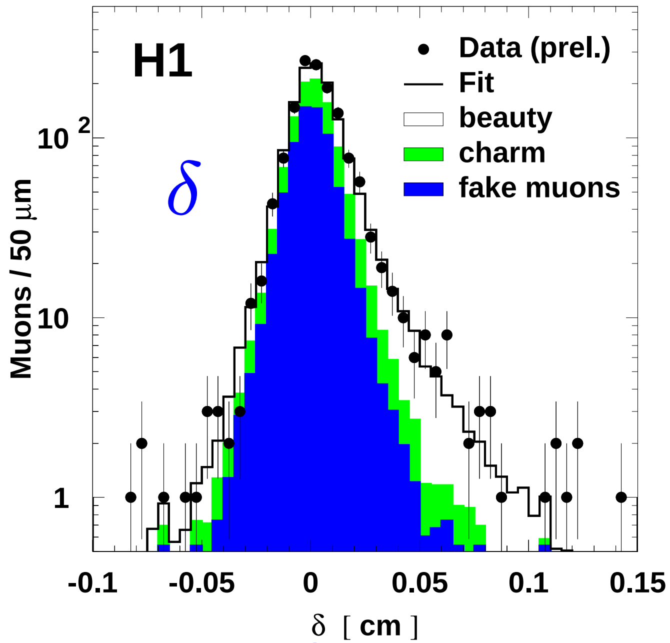
  $f_b \sim (25 \pm 5)\%$



- Long B-Lifetime:

  μ Impact Parameter

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



Previous results:

σ(Data)/σ(NLO) $\sim$ 3

B in γp : 1996–2000 Results

ZEUS: p_T^{rel} Method

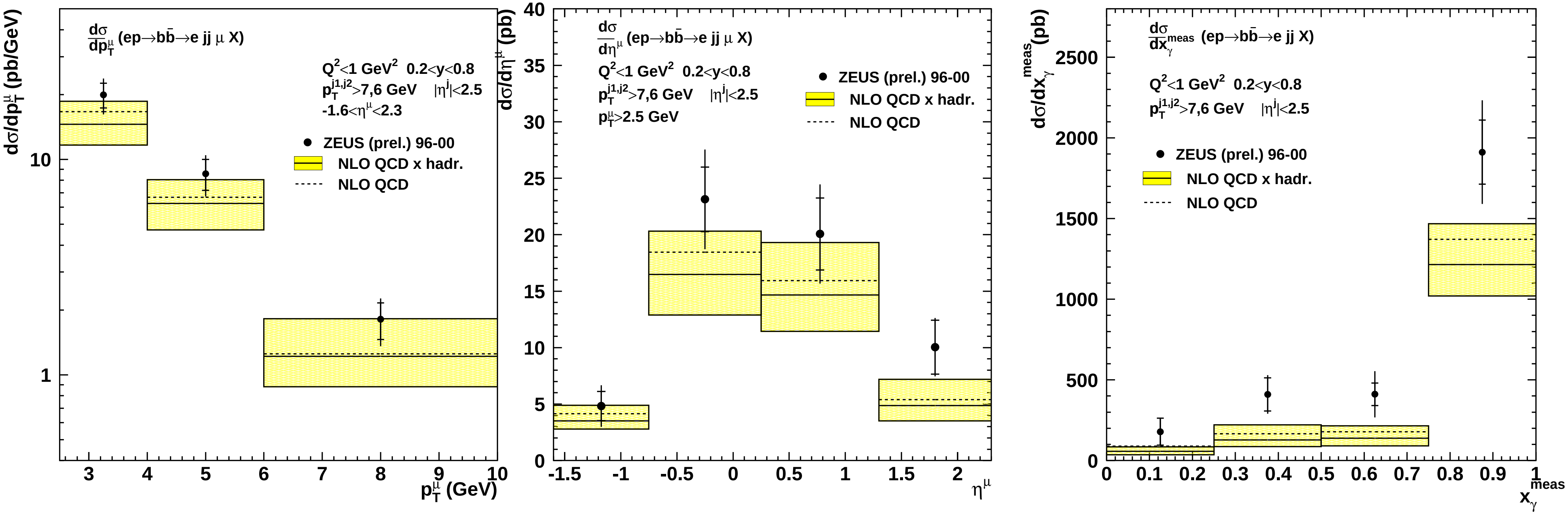
2 jets, $E_T^{jet1(2)} >$7 (6) GeV; $|\eta^{jet}| <$2.5

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

98 pb^{-1}

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

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



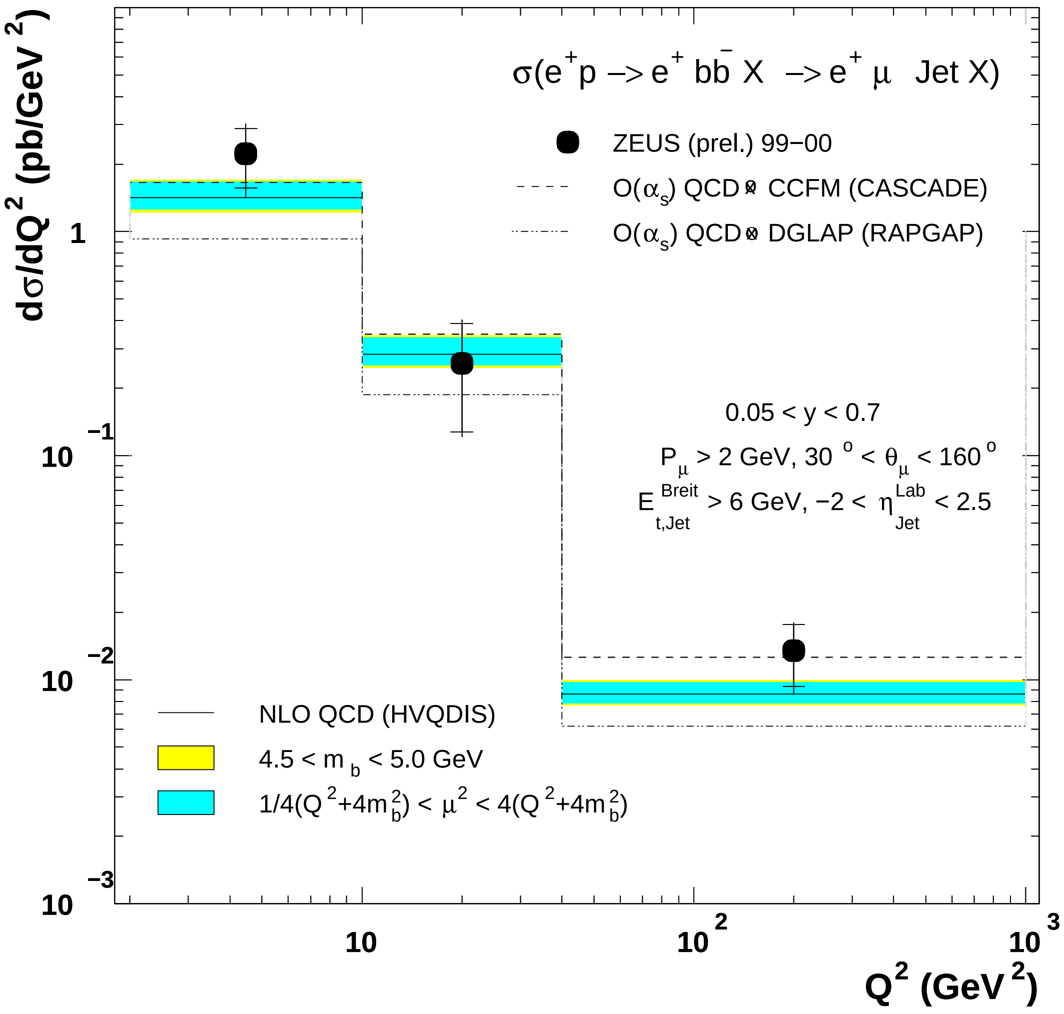
Comparison to NLO QCD: p_T^{μ} and η^{μ} in visible region, ok within errors

For x_γ 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, $0.05 < y < 0.7$ $\sim 60\,\mathrm{pb}^{-1}$

1 muon, $p_T^\mu > 2$ GeV

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

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

- QCD NLO (DGLAP) ok within errors

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

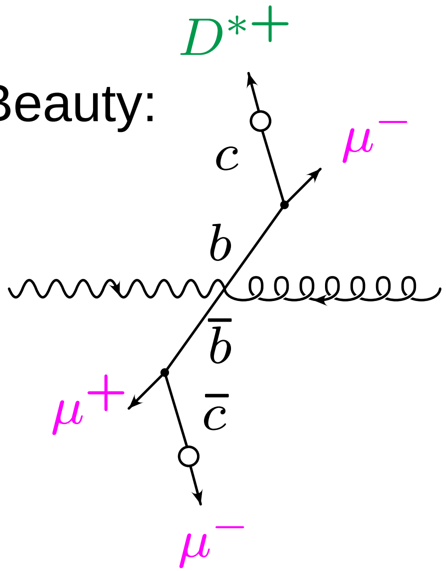
- CASCADE (CCFM) good agreement

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

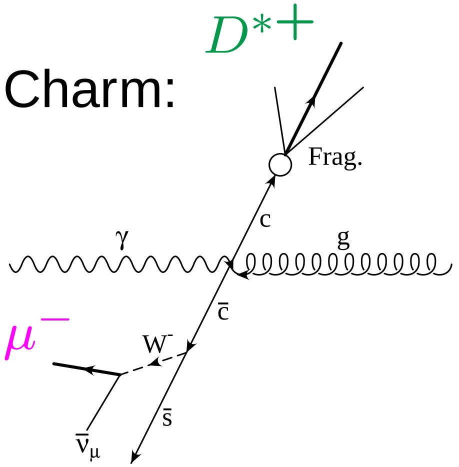
- RAPGAP (DGLAP, LO+PS) too low

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

Beauty:



Charm:

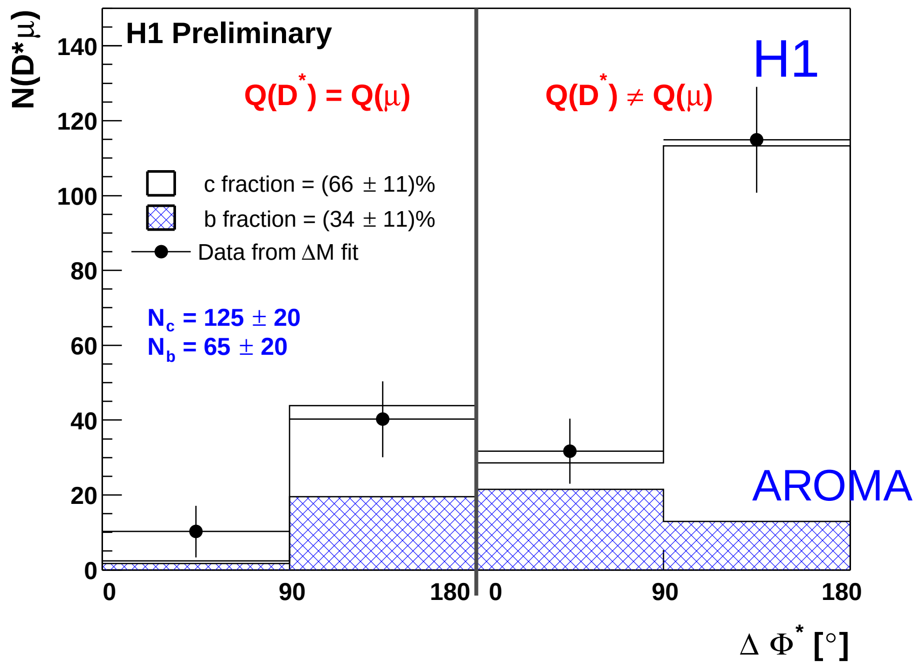


c-b separation using charge and angular correlations

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^* **(ΔM)** + **$D^*\mu$ correlation** analysis

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

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

$D^*\mu$ – Correlations

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

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

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

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

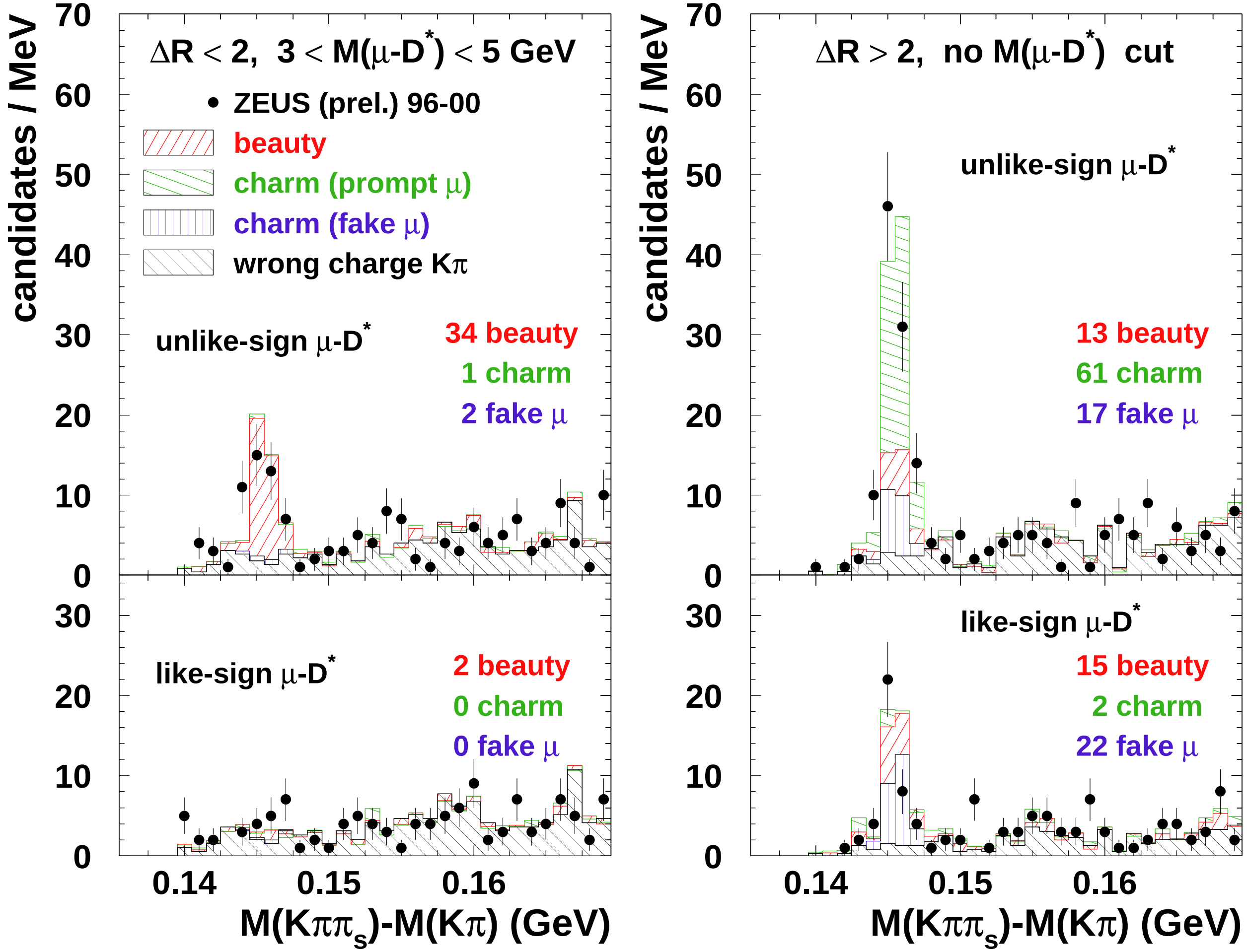
↓ PYTHIA MC ↓

γp cross section

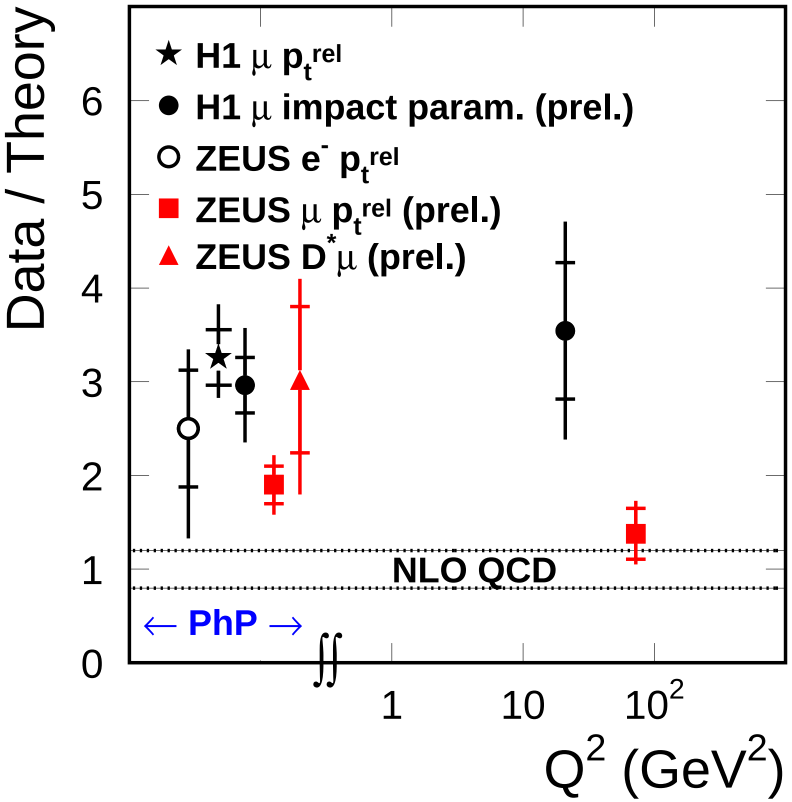
(for $\hat{y}^b < 1$, $Q^2 < 1\text{GeV}^2$)

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

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}, δ, $D^*\,\mu$) and between H1 and ZEUS

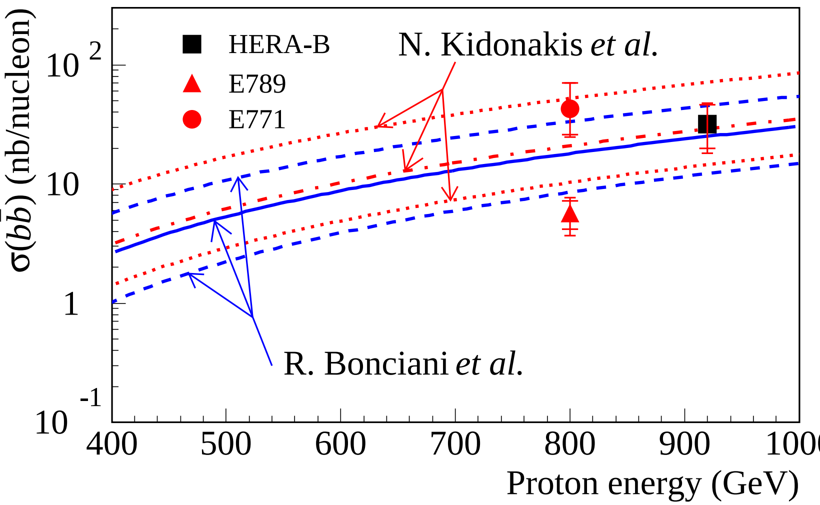
Differential analyses have given new insights:

- Excess is not localised in p_T, η or x_γ^{obs}
- Extrapolation procedure from measured ‘visible’ region is under discussion. . .

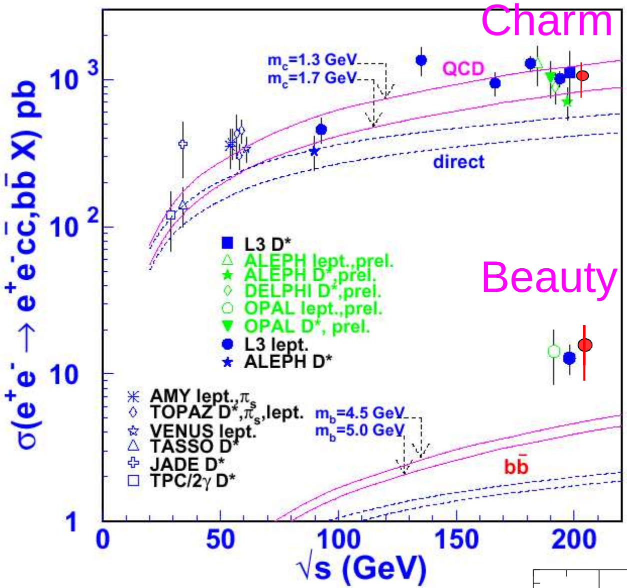
Waiting for final data from HERA I

Overview: Beauty-Production: The World

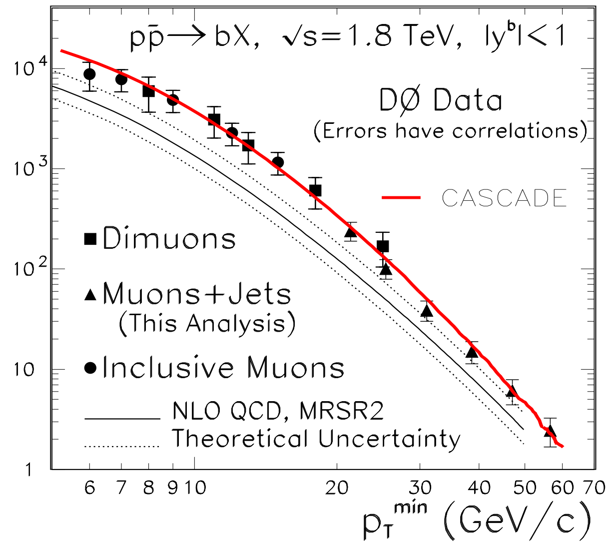
HERA-B

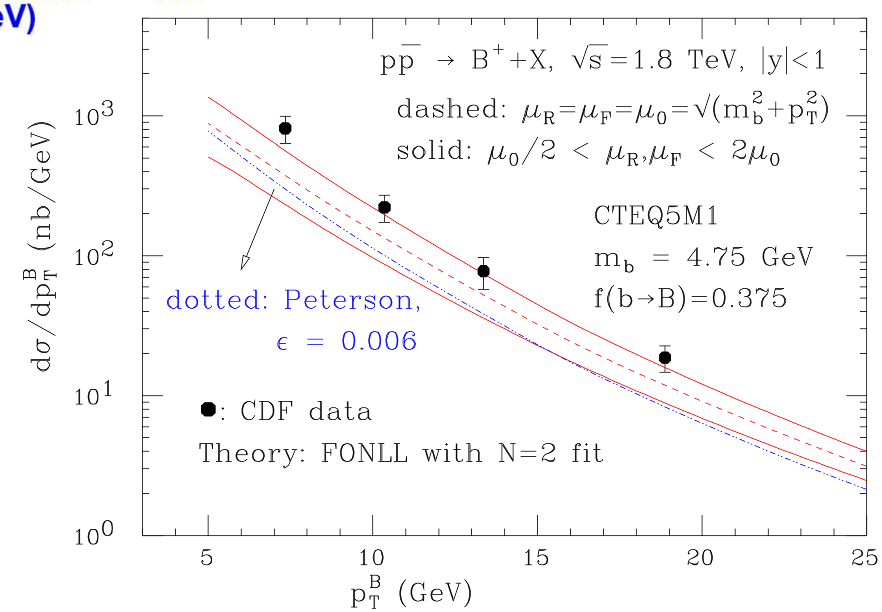


$\gamma\gamma$ LEP



$p\bar{p}$ 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