Heavy Flavour Production at HERA

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for the H1 & ZEUS Collaborations

introduction

charm

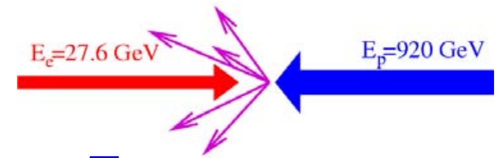
beauty

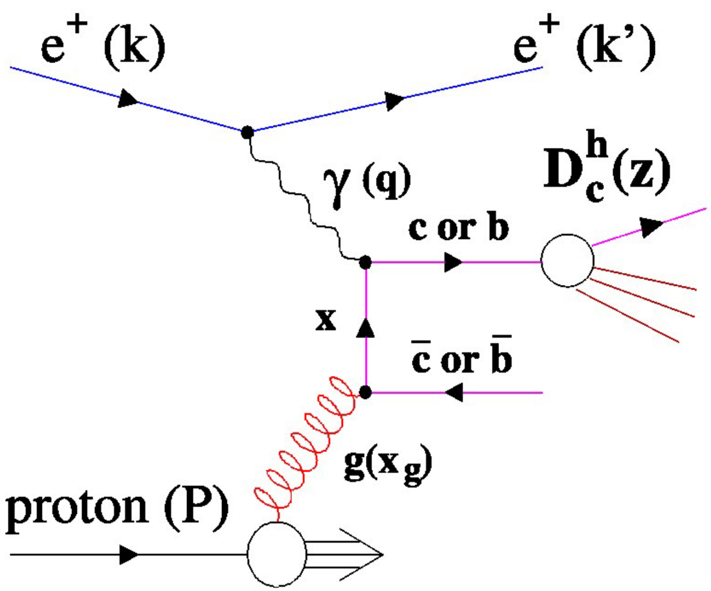
summary

Introduction

- Heavy flavour production dominated by Boson Gluon Fusion (BGF)

$$\gamma g \rightarrow c\bar{c} \text{ or } b\bar{b}$$





ep Kinematics: $\sqrt{s}$ = 300, 320 GeV

- Q^2 : 4-momentum transfer squared
- x : Bjorken x
- y : Inelasticity
- W : Mass of the hadronic system

Two kinematic regimes:

- $Q^2 \approx 0$ → Photoproduction
- $Q^2 \geq 1$ GeV^2 → DIS

- Factorization:

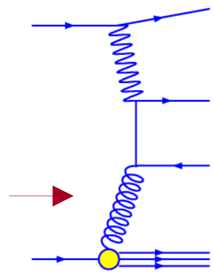
$$\text{Proton structure} \otimes \sigma_{\gamma g \rightarrow Q\bar{Q}} \otimes \text{Photon structure} \otimes \text{Fragmentation function}$$

Heavy Flavour Production at HERA

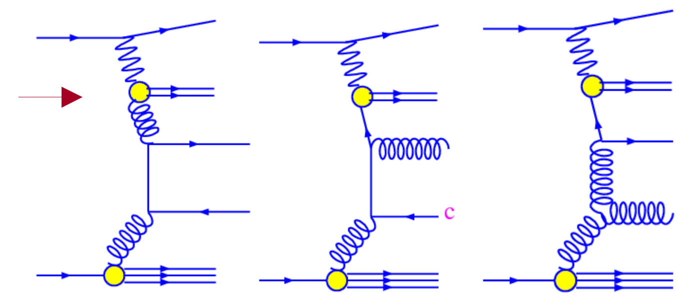
$Q^2 \to 0$ photoproduction

$Q^2 \geq 1\ \mathrm{GeV}^2$ DIS

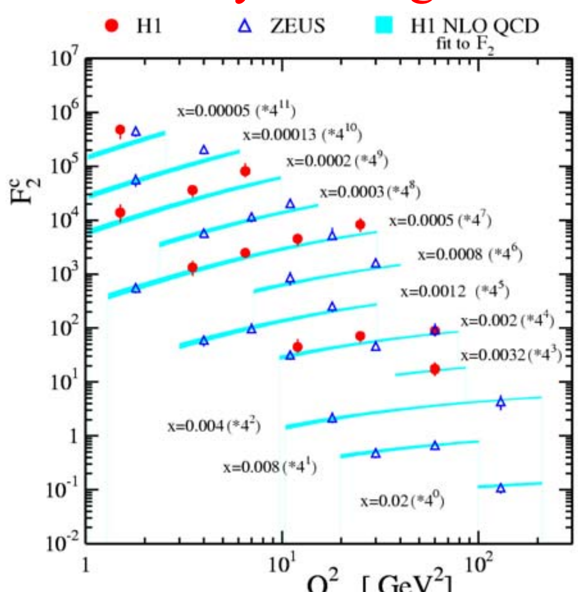
at LO
contribution
from direct



and resolved
processes

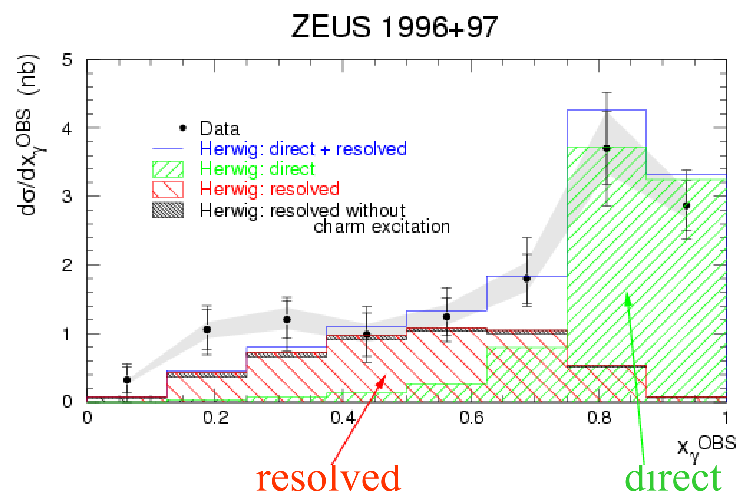


- large charm contribution to F_2
- universality of the gluon



previous results
on charm

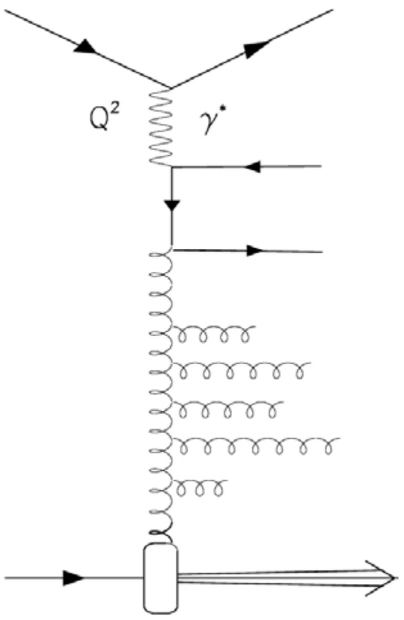
- Photoproduction has an important resolved component



Why heavy flavours?

study heavy flavour production mechanism

- m_c (m_b) provides a hard scale
  good testing ground for pQCD
- access parton densities in the proton and in the photon
- Q^2 and p_T (or E_T) also provide a hard scale
- sensitivity to the parton evolution model
- Fragmentation issues
  (fragmentation probabilities for different hadrons, strangeness suppression, ratio $V/(V+P)$, fragmentation function)



DGLAP
↕
CCFM

Theoretical Framework

Calculations in the DGLAP scheme

➢**Fixed order NLO calculations**
(massive scheme)
heavy quark produced dynamically

- γ p : FMNR • DIS : HVQDIS

➢**resummed NLL calculations**
(massless scheme)
heavy quark active flavour
of proton or photon
$p_t >> m_q$

- γ p : Cacciari et al., Kniel et al.

➢**Matched scheme FONLL**
(fixed order + NLL p_T resummation)

- Cacciari et al.

MC generators (ME + PS)

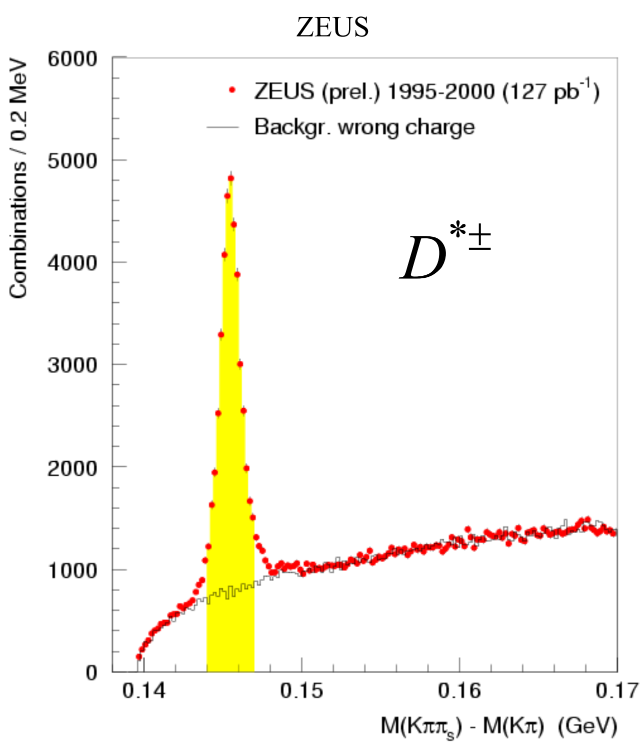
- AROMA:
  direct only, LO DGLAP evolution
- PYTHIA, RAPGAP, HERWIG:
  direct + resolved, LO DGLAP
- CASCADE:
  CCFM evolution
  k_t dependent gluon density

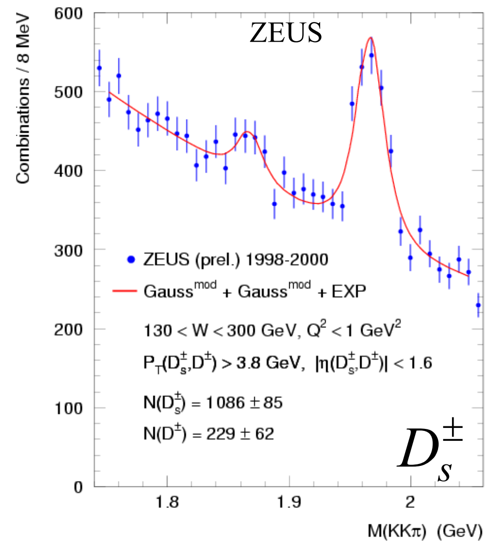
Fragmentation : non perturbative models

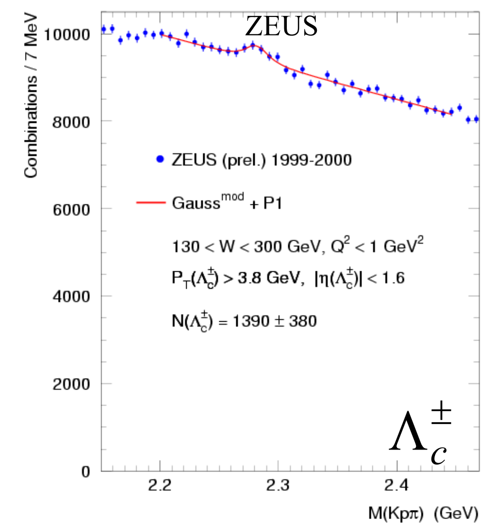
Charm tagging

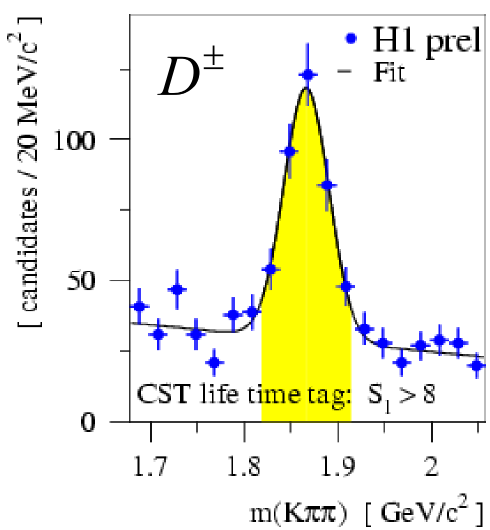
Luminosity collected at HERA I : $\approx$120 pb^{-1}

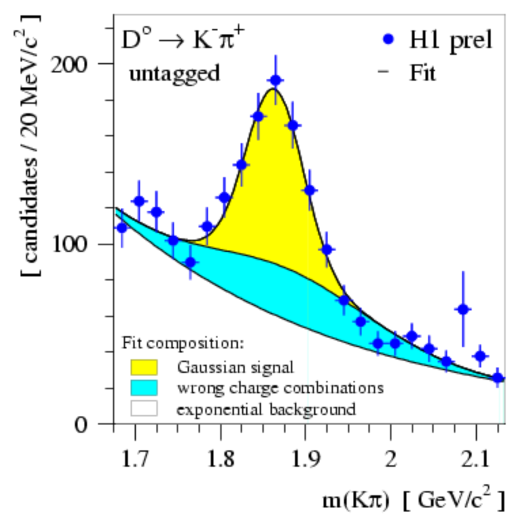
Heavy flavour analyses
still ongoing











Charm Fragmentation

ZEUS prel. (γp) $p_T(D,\Lambda_c) > 3.8$ GeV, $|\eta(D,\Lambda_c)| < 1.6$	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

→ HERA errors competitive!

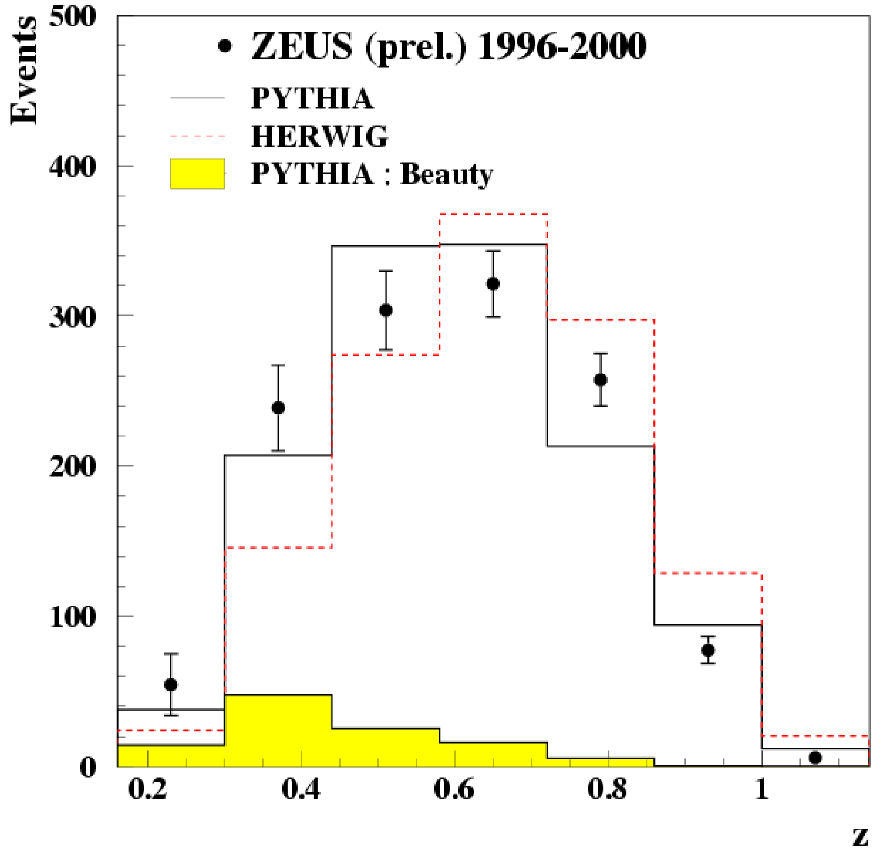
$R_{u/d}$, γ_s, $V/(P+V)$ also determined and in good agreement with w.a.

Measurement of the Fragmentation Function

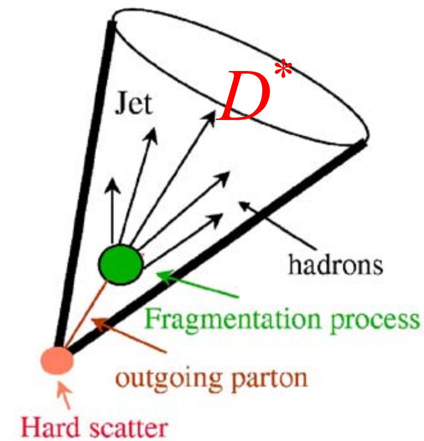
$p_T^{D^*} > 2$ GeV, $|\eta^{D^*}| < 1.5$ $\quad$ $Q^2 < 1$ GeV^2, $130 < W_{\gamma p} < 280$ GeV

Require that the D^* be associated with a jet of $E_T^{\text{jet}} > 9$ GeV and $|\eta^{\text{jet}}| < 2.4$

$\mathcal{L}_{\text{int}} = 120\ pb^{-1}$



k_t jet algorithm

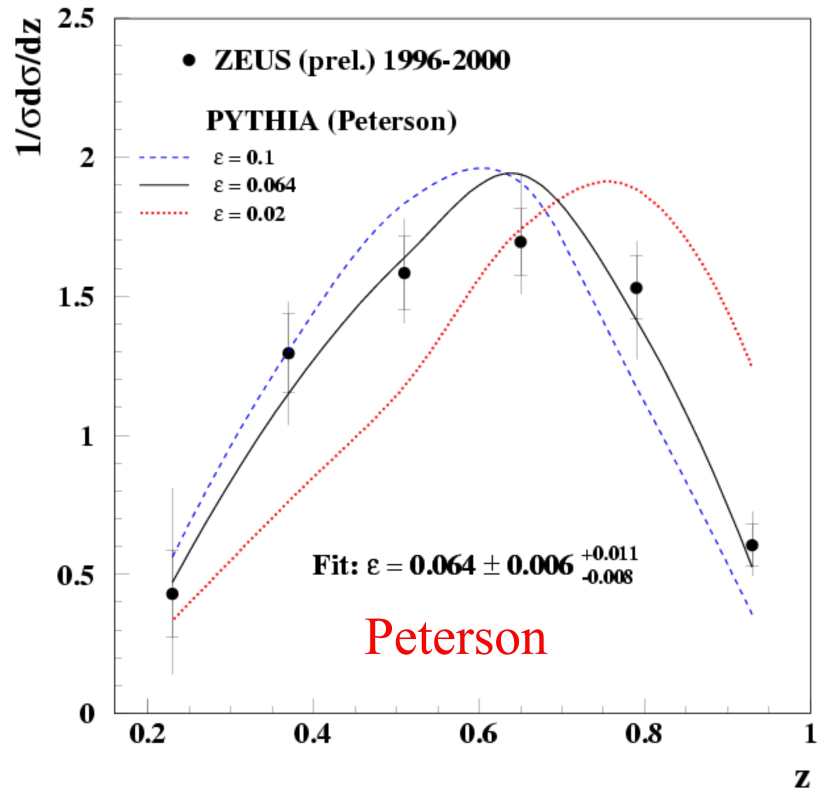


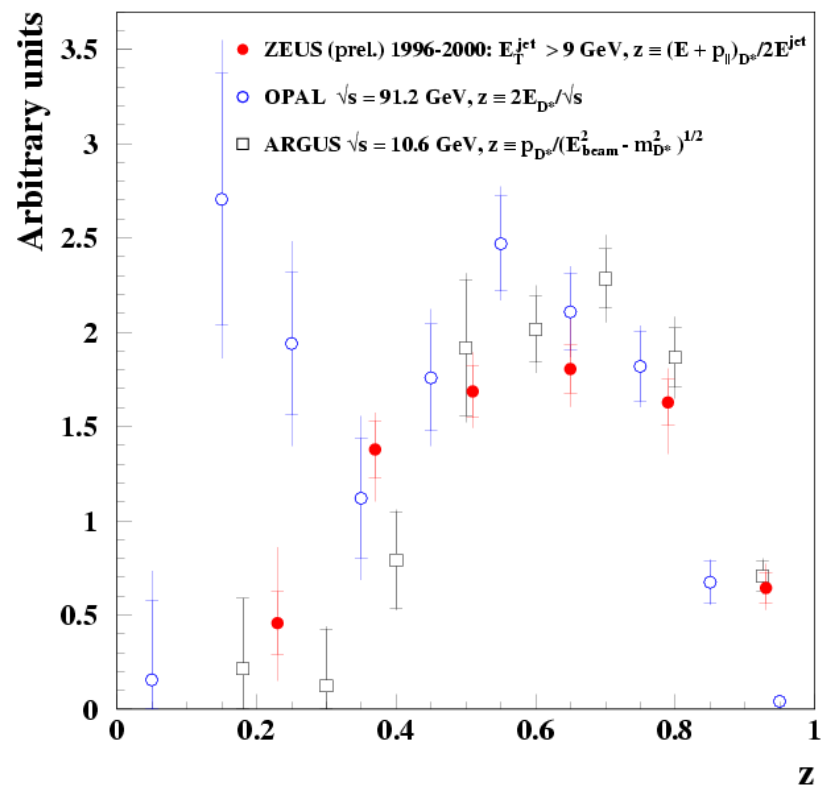
$$z = \frac{(E + p_{||})^{D^*}}{2\ E_{\text{jet}}}$$

PYTHIA (sym. Lund+Bowler) agreement with data

HERWIG (Cluster model) is too hard

Results on Fragmentation Function





$$f(z) \propto \frac{1}{z(1 - 1/z - \varepsilon/(1-z))^2}$$

$\varepsilon = 0.064 \pm 0.06^{+0.011}_{-0.008}$ (ZEUS prel)

$\varepsilon = 0.05$ (PYTHIA default)

$\varepsilon = 0.053$ (LL fit to ARGUS data Nason, Oleari)

Different definitions of z

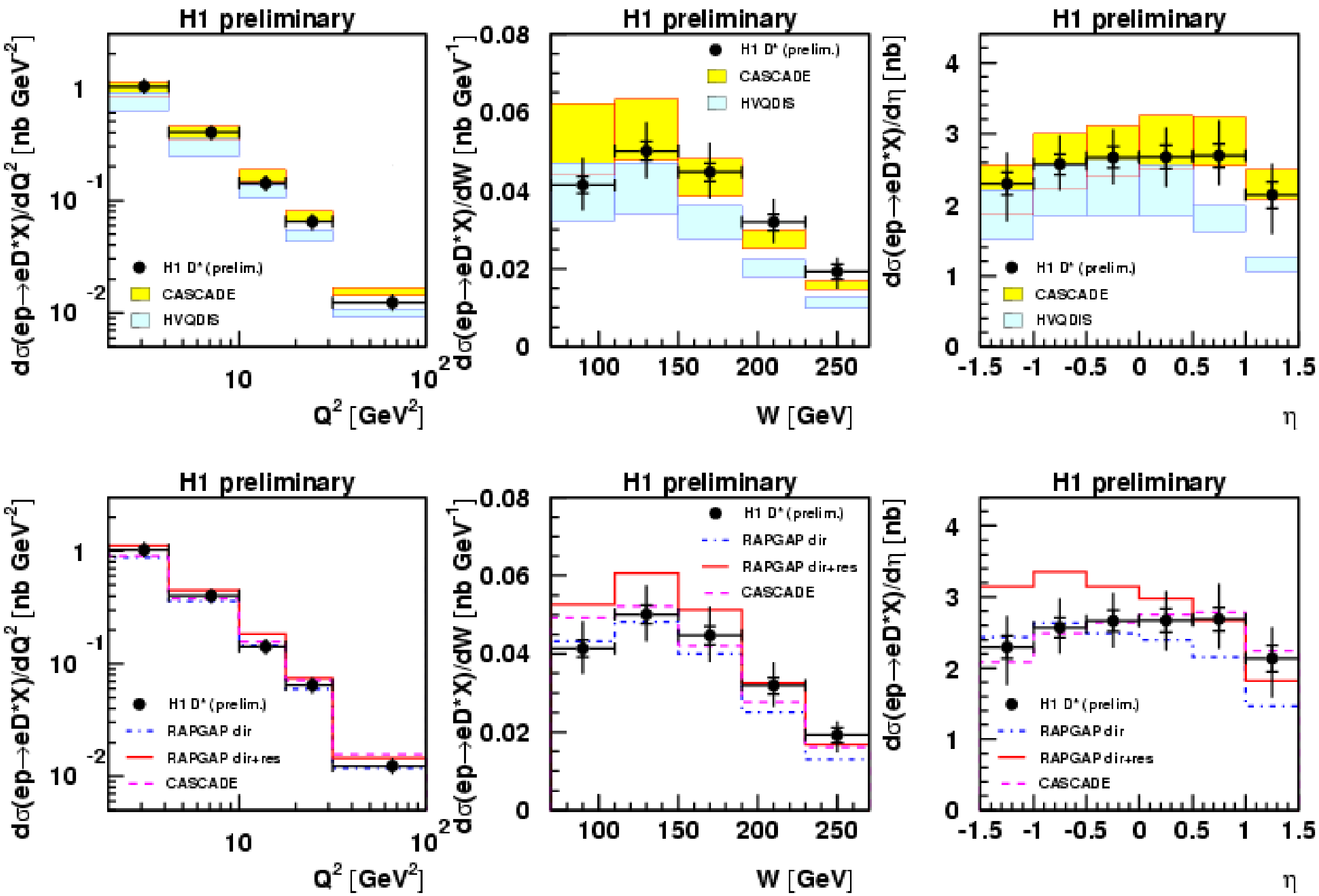
qualitative agreement

Fragmentation Function is universal

D^* in DIS

H1: Inclusive $D^{*\pm}$ Cross Section $Q^2 > 2\ \mathrm{GeV}^2,\ 0.05 < y < 0.7$

1999, 2000 47 pb^{-1} $p_T^{D^*} > 1.5\ \mathrm{GeV},\ |\eta^{D^*}| < 1.5$



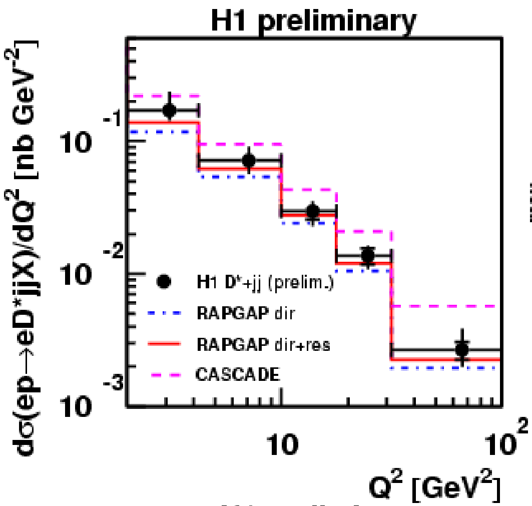
- NLO QCD low
- CASCADE (CCFM) better

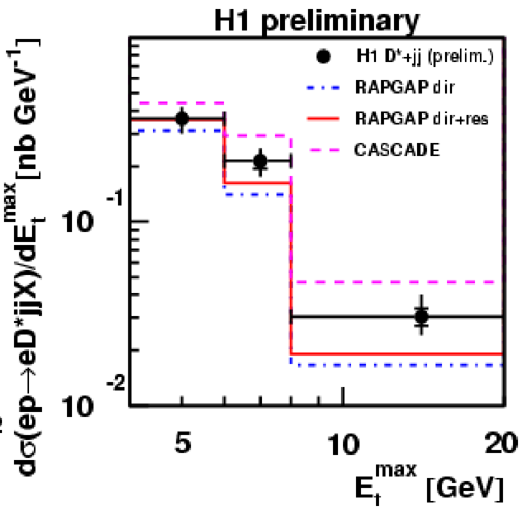
- RAPGAP (LO+PS) direct + resolved high
- shape of η distribution is well described only by CASCADE

Jet Cross Section with D^* in DIS

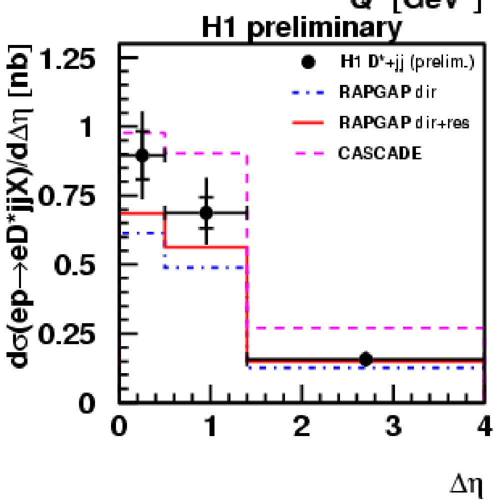
H1: D^* + 2 jets (inclusive k_t algorithm in the Breit frame) 1999, 2000 47 pb^{-1}

$E_T^{\text{jet}} > 4{,}3$ GeV, $-1 < \eta_{\text{lab}}^{\text{jet 1,2}} < 2.5$



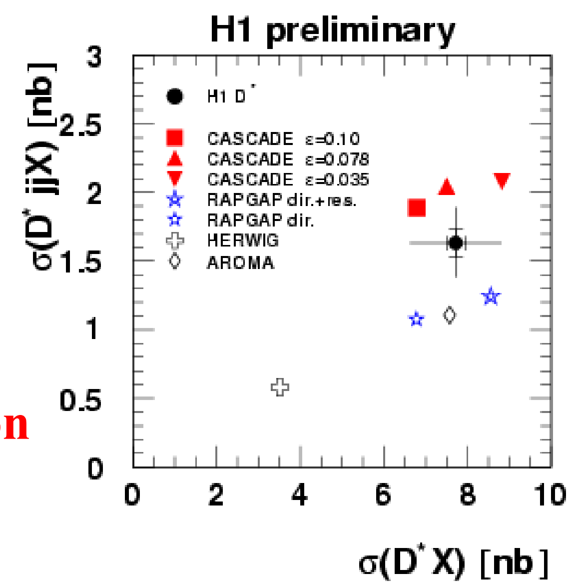


- CASCADE (CCFM) too high
- RAPGAP (LO+PS) too low



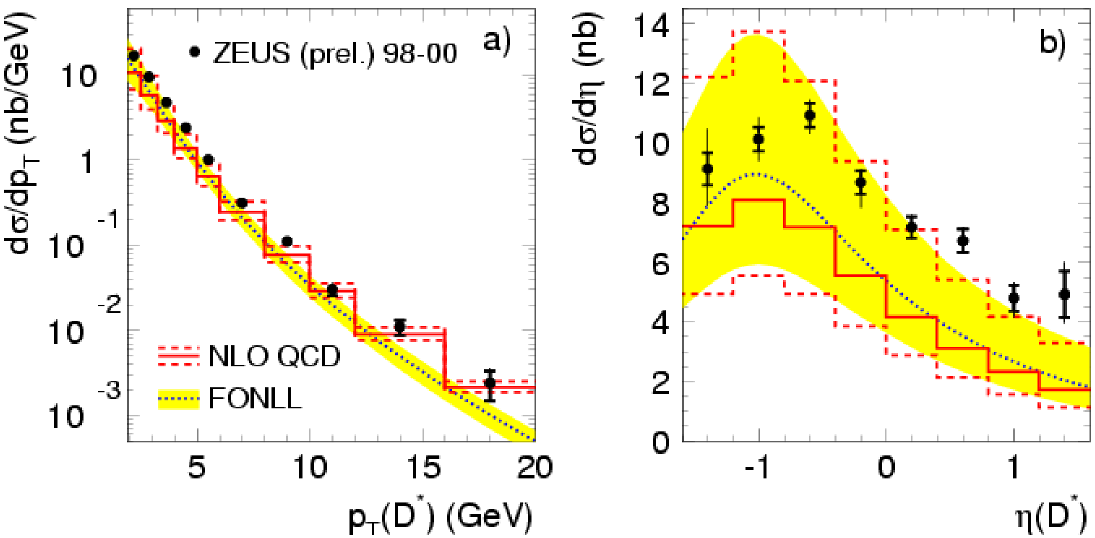
none of the models provides a perfect description when jets are required in addition to the D^*

Summary plot:
Jet versus inclusive cross section



D^* Photoproduction

ZEUS



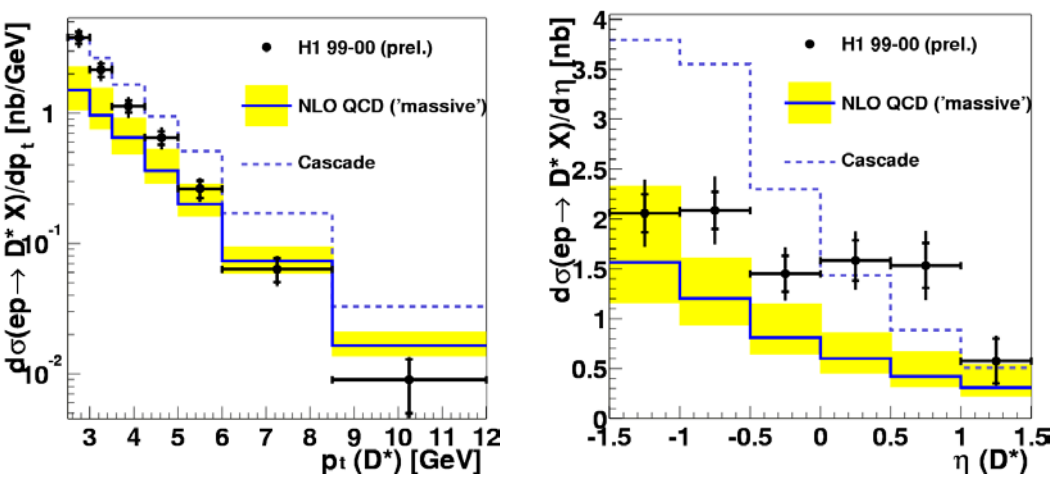
No electron tag $79 \; pb^{-1}$

$Q^2 < 1 \text{ GeV}^2, \; 130 < W_{\gamma p} < 280 \text{ GeV}$

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

Large theoretical uncertainties due to scale, mass and fragmentation

H1



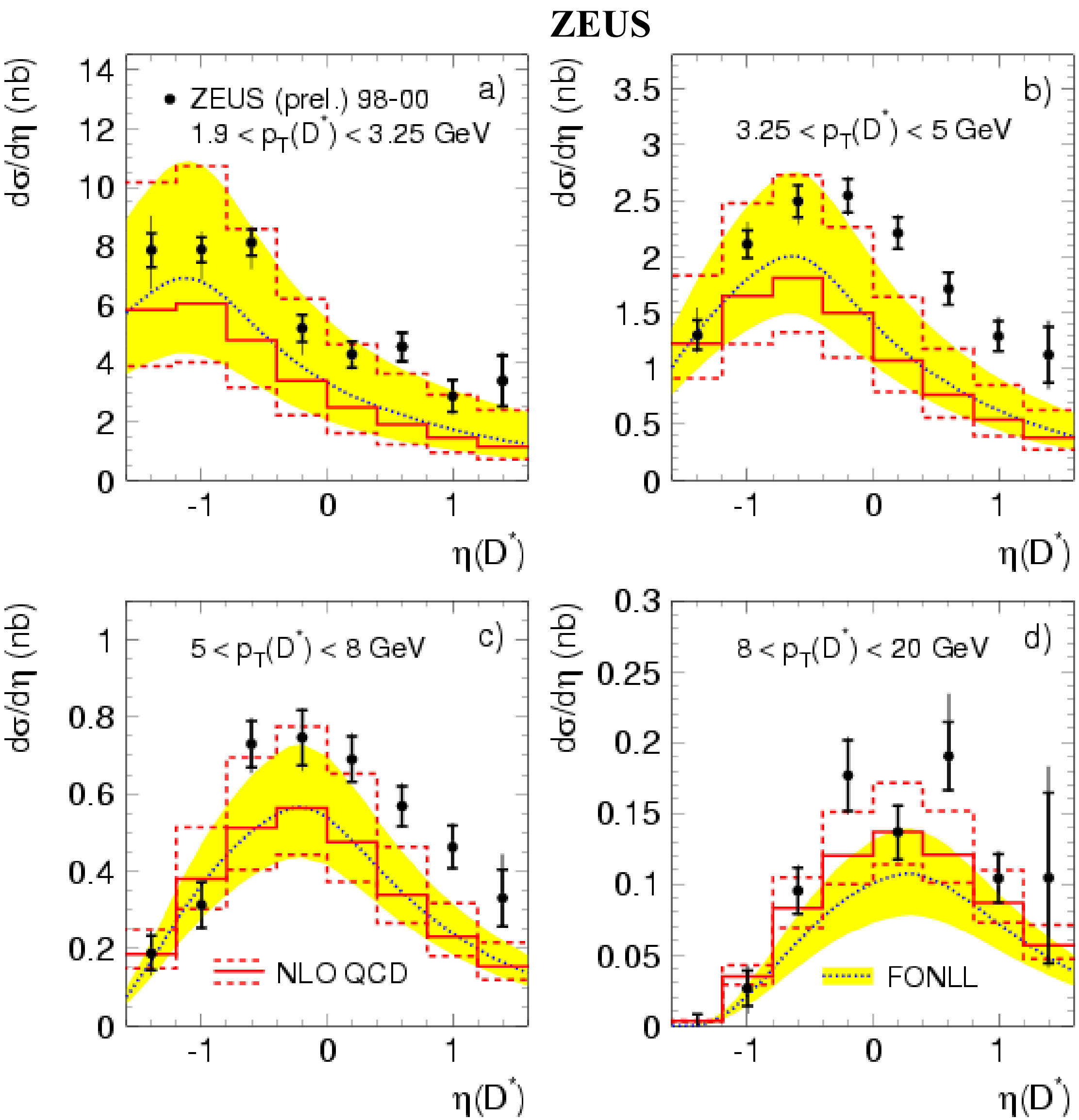
- NLO below data (low p_T, $\eta > 0$)
- FONLL also below the data even below NLO at high p_T
- CASCADE too hard

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

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

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

D^* Photoproduction double differential distributions



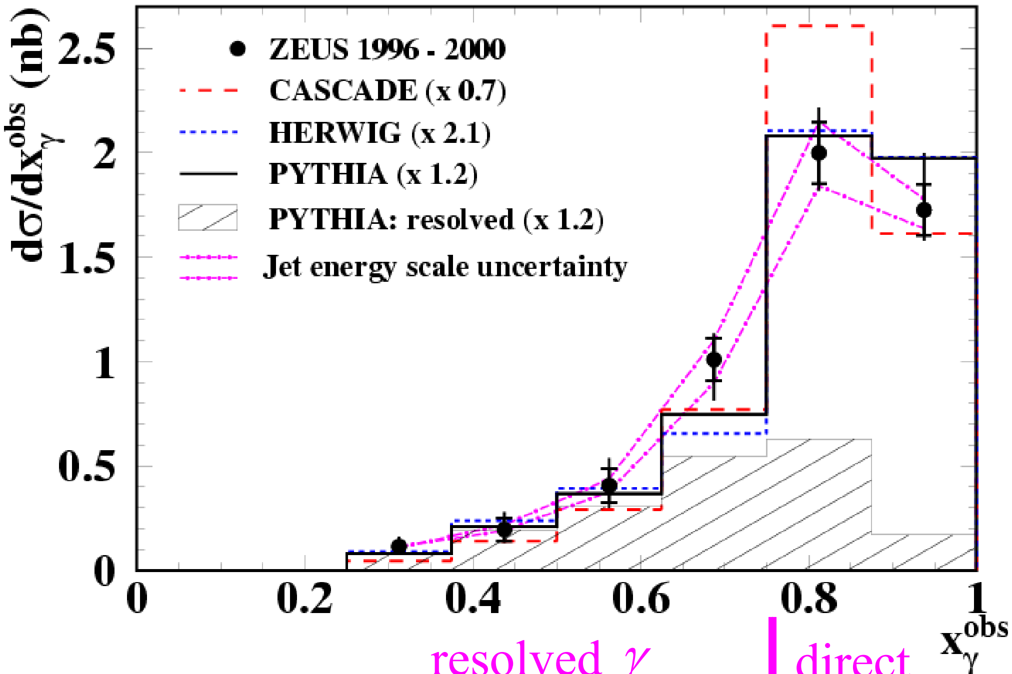
η distribution in $p_T^{D^*}$ bins

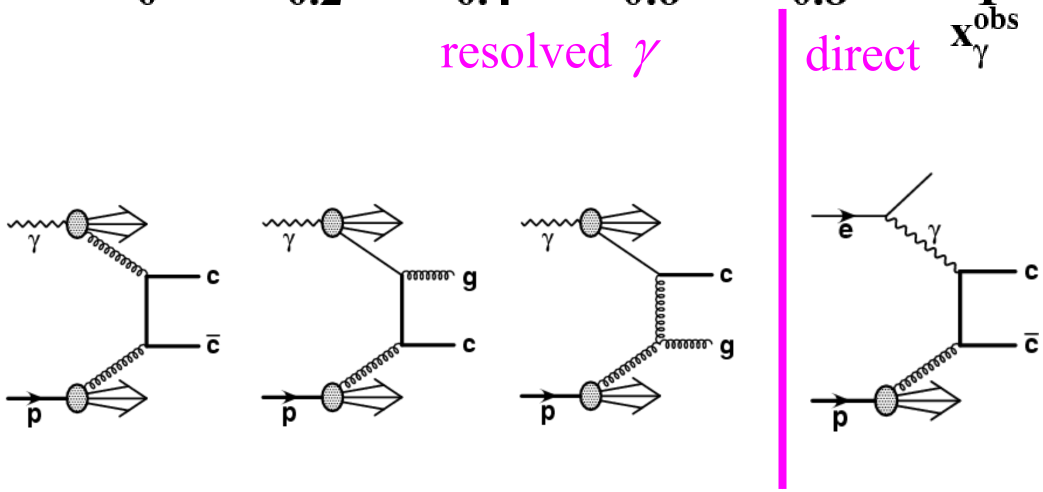
- NLO below data at medium $p_T^{D^*}$ and high η
- FONLL close to data only at low $p_T^{D^*}$

$D^* + 2$ Jet Events

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

$\approx 120\ pb^{-1}$





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

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

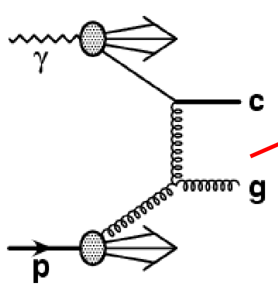
$M_{jj} > 18$ GeV

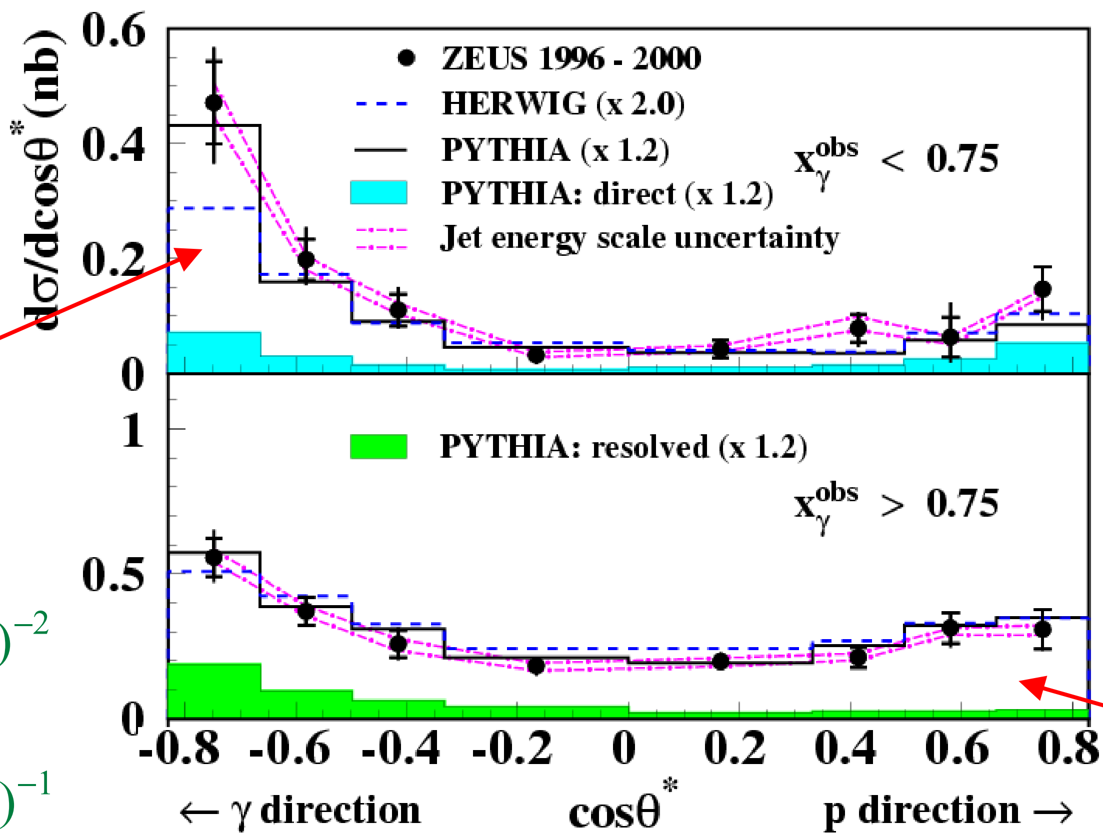
Momentum fraction of photon in jets:

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

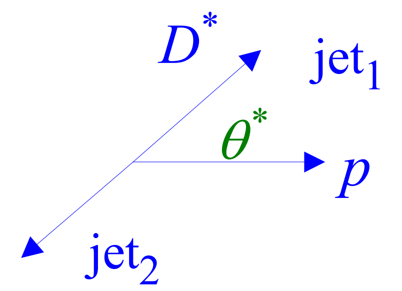
- Significant contribution from resolved ~40%
- MCs: good description of shape
- CASCADE different at high x_γ^{obs}
- NLO below data at low x_γ^{obs} (not shown)

Charm: Di-jet Angular Distributions



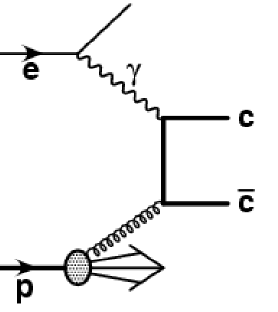


$\theta^* = \measuredangle(p, D^*\text{-Jet})$



g-exchange:
$\propto (1-|\cos\theta^*|)^{-2}$

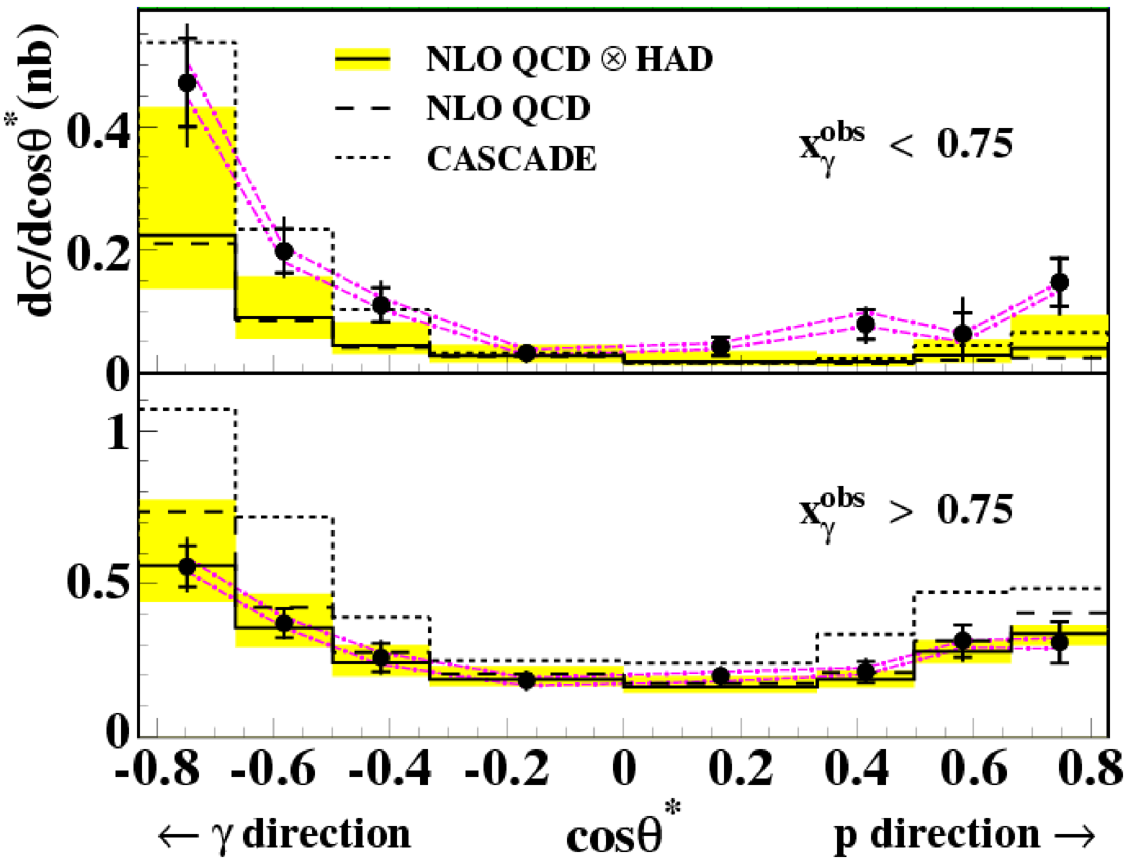
q-exchange:
$\propto (1-|\cos\theta^*|)^{-1}$



Clear evidence for charm from the photon

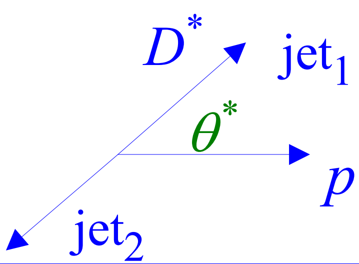
Strong rise in $d\sigma / d\cos\theta^*$ towards the γ direction for $x_\gamma^{obs} < 0.75$

Charm: Di-Jet Angular Distributions



- NLO DGLAP describes $x_\gamma^{obs} > 0.75$, but is too low for $x_\gamma^{obs} < 0.75$,
- CCFM (CASCADE) describes the shape, but the predicted cross section is too high

$$\theta^* = \measuredangle(p, D^*\text{-Jet})$$



Charm production – Summary

- Fragmentation Probabilities and Fragmentation Function measured
  good agreement with results from other experiments
  Charm fragmentation universal

- D^* production in DIS
  Inclusive: CASCADE: good description of the data
  other models: problems with the η distribution
  $D^* +$ jets: problems to describe the associated jet cross section

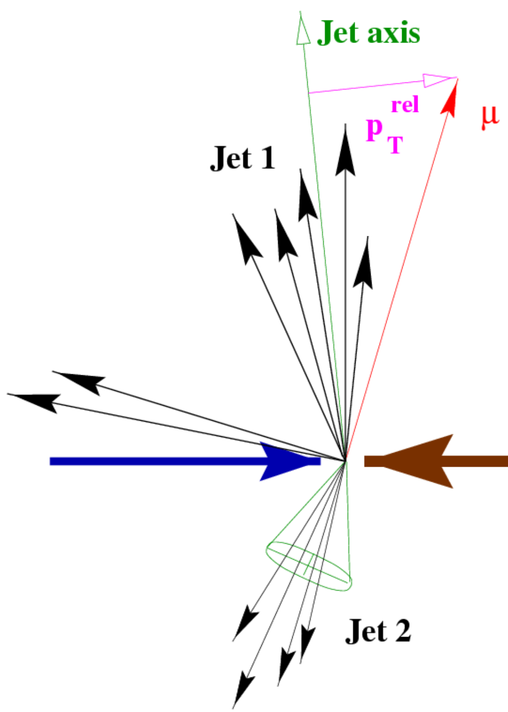
- D^* in photoproduction
  Inclusive: Problems of NLO QCD and CCFM to describe the data
  $D^* +$ jets: large charm component in the photon (LO+PS picture)
  NLO QCD does not describe this component well;
  shape is better described by MC models

Beauty: Tagging Methods

$m_b > m_c \Rightarrow$ theory should be more reliable

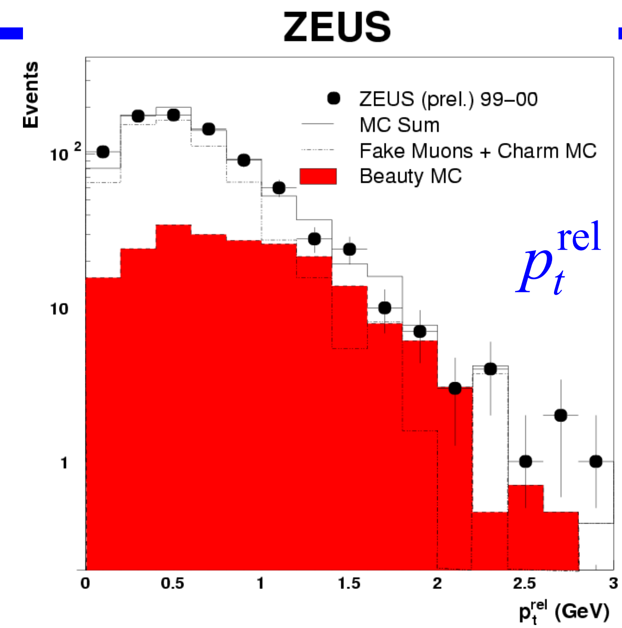
but $\sigma_{b\bar{b}} / \sigma_{c\bar{c}}$ very small <0.05

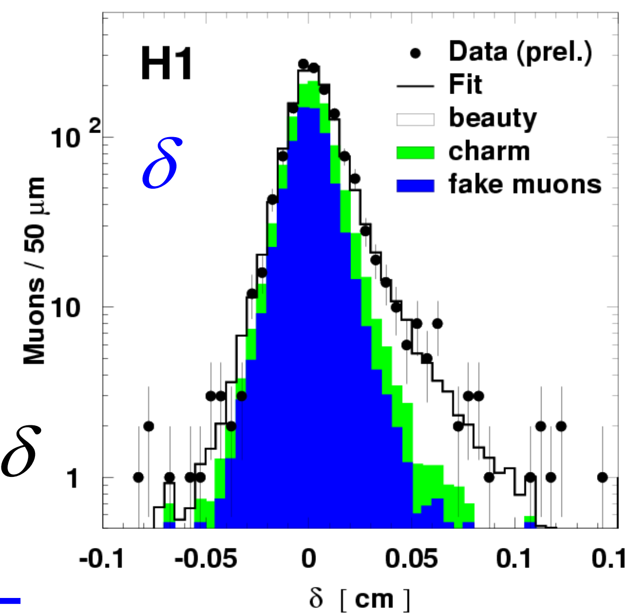
in 2-jet events $b \to \ell \bar{\nu} X$



- Large b mass: p_t of μ relative to the jet p_t^{rel}

- Long b lifetime μ impact parameter δ





Beauty in Photoproduction

ZEUS: p_t^{rel} method

2 jets, $E_T^{\text{jet }1(2)} > 7\ (6)$ GeV, $|\eta^{\text{jet}}| < 2.5$

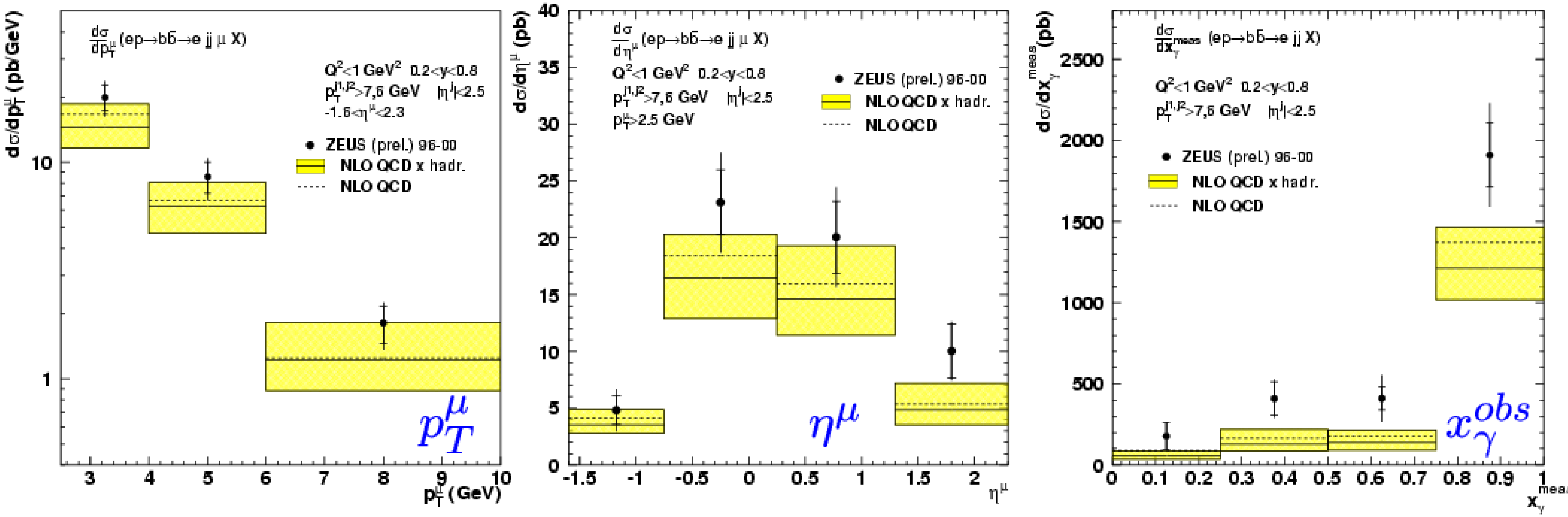
$p_t^{\mu} > 2.5$ GeV, $1 < \eta^{\mu} < 2.3$

$98\ pb^{-1}$

1996-2000

$Q^2 < 1\ \text{GeV}^2, 0.2 < y < 0.8$

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



Comparison to NLO QCD: p_t^{μ} and η^{μ} in visible range **ok within errors**

for x_{γ} extrapolate muon phase space

Factor of 2 disagreement

Beauty in DIS

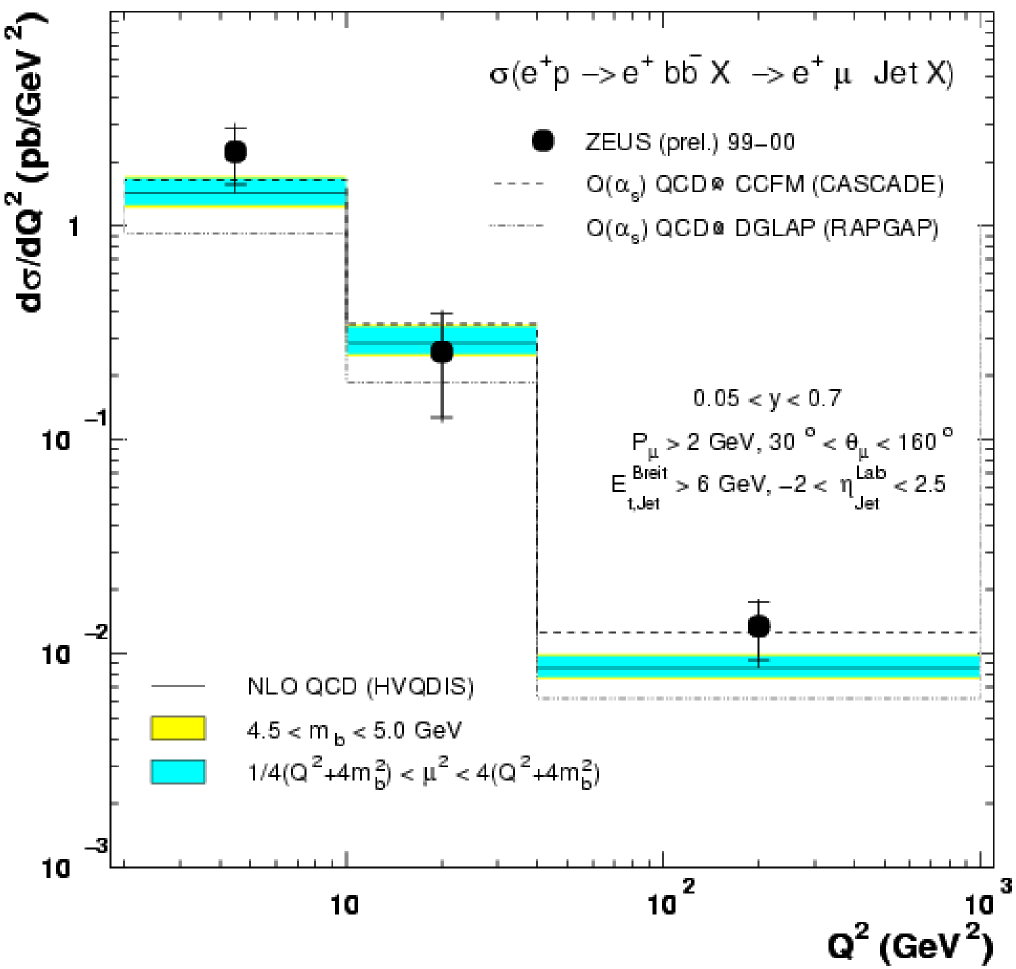
$\approx 60 \ pb^{-1}$

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

$Q^2 > 2 \text{ GeV}^2, 0.05 < y < 0.7$

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

$E_T^{\text{Breit}} > 6 \text{ GeV}$

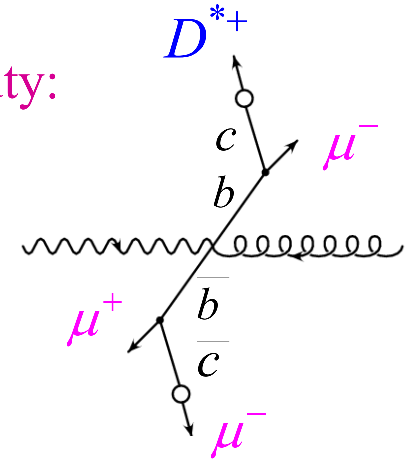


$\sigma^{\text{vis}} = (38.7 \pm 7.7^{+6.1}_{-5.0}) \ pb$

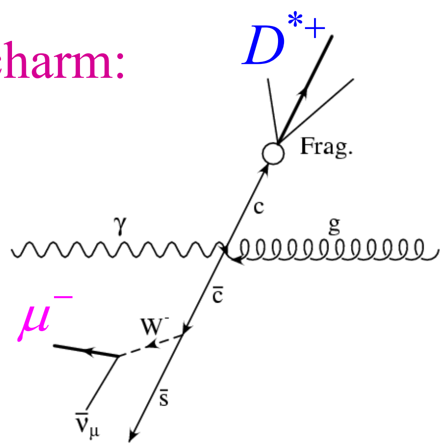
- **QCD NLO (DGLAP):**
  (Harris & Smith): $\sigma^{\text{vis}} = (28.0^{+5.3}_{-3.5}) \ pb$
- **CASCADE (CCFM):**
  good agreement $\sigma^{\text{vis}} \approx 35 \, pb$
- **RAPGAP (DGLAP, LO+PS)**
  too low

Heavy Flavour double tag: $D^{*}\mu$ – Correlations

beauty:



charm:



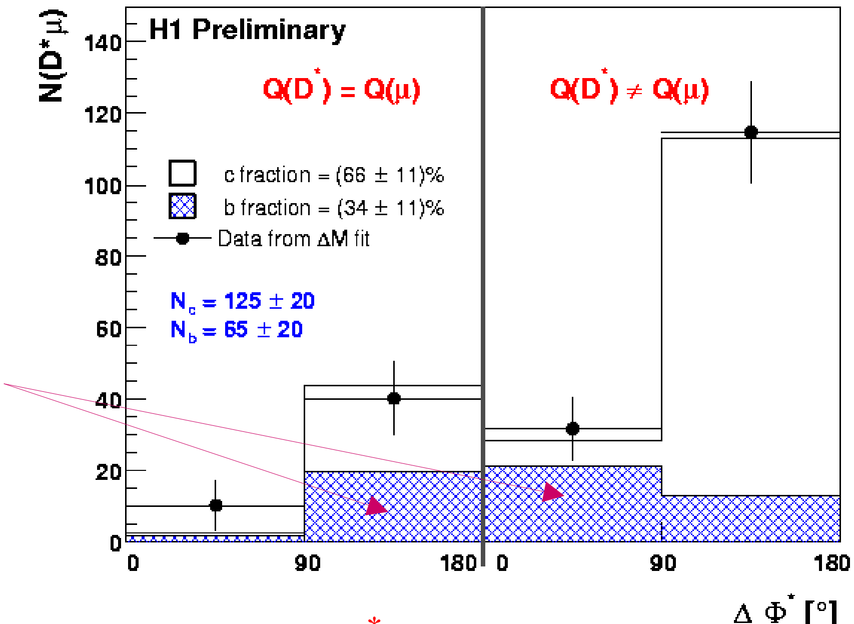
$c-b$ separation using charge and angular correlations

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

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

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

beauty:



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

charm: $720 \pm 115(\text{stat.}) \pm 245(\text{syst.})\ pb$

→ 1.8 * AROMA

beauty: $380 \pm 120(\text{stat.}) \pm 130(\text{syst.})\ pb$

→ 3.6 * AROMA

$D^* \mu$ – Correlations

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

$Q^2 < 1\ \text{GeV}^2,\ 0.05 < y < 0.85$

$\approx 114\ pb^{-1}$

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

$p_T^{\mu} > 1.4\ \text{GeV},\ -1.3 < \eta^{\mu} < 1.74$

$$\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2}$$

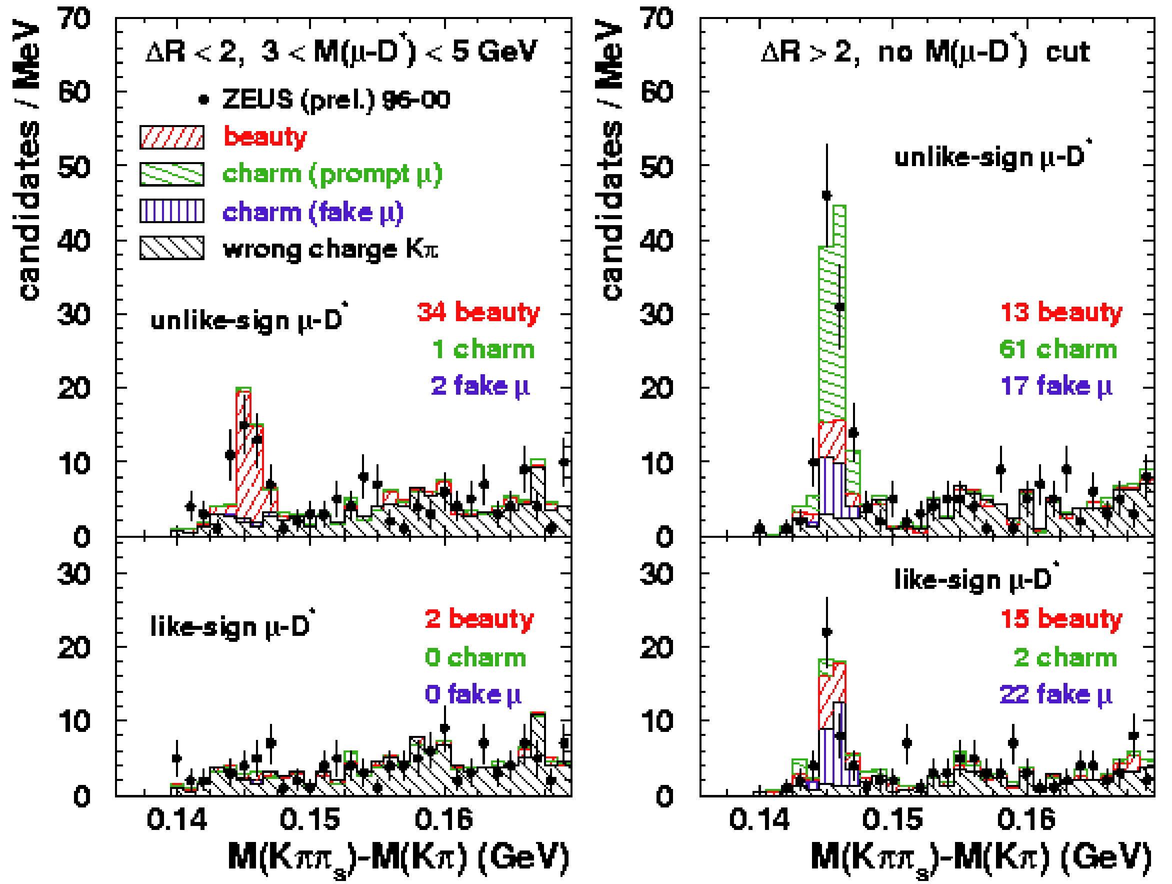
γp cross section

$\sigma(ep \to b(\bar{b})X) =$

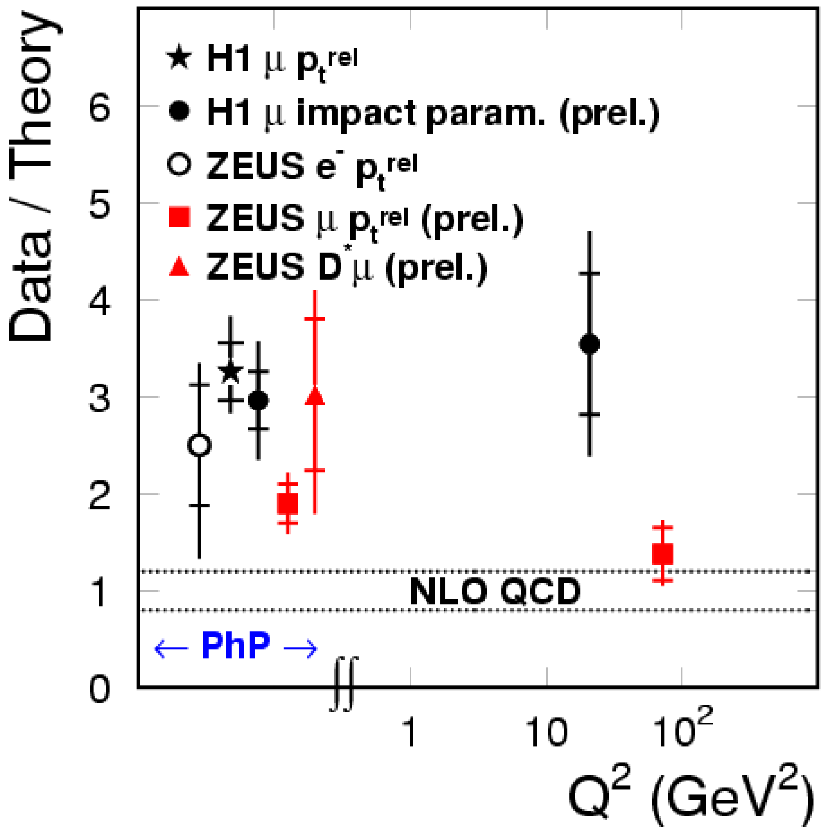
$(15.1 \pm 3.9^{+3.8}_{-4.7})\text{nb}$

NLO QCD: $(5.0^{+1.7}_{-1.1})$ nb

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



Beauty production – Summary



Current Status:

Data/QCD $\approx 2-3$ for $b\bar{b}$ production

Independent of method p_t^{rel}, δ, $D^*\mu$

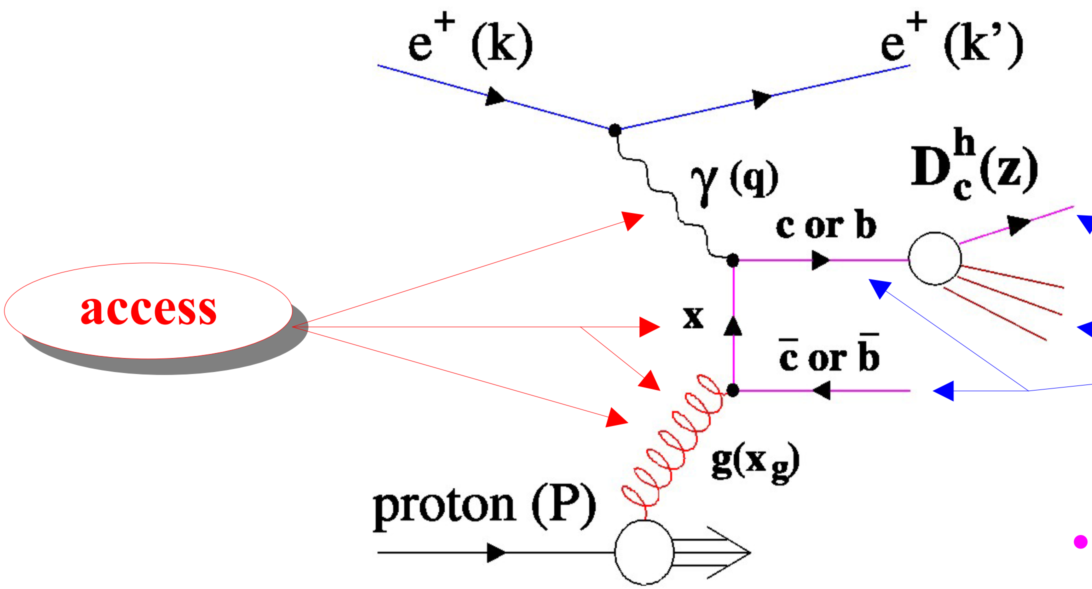
Differential analyses have shown that the excess is not localized in a specific corner of phase space

Beauty production is considered to be more safe in terms of theory

Summary

High statistics data on charm and beauty production lead to

high precision studies on the production mechanism



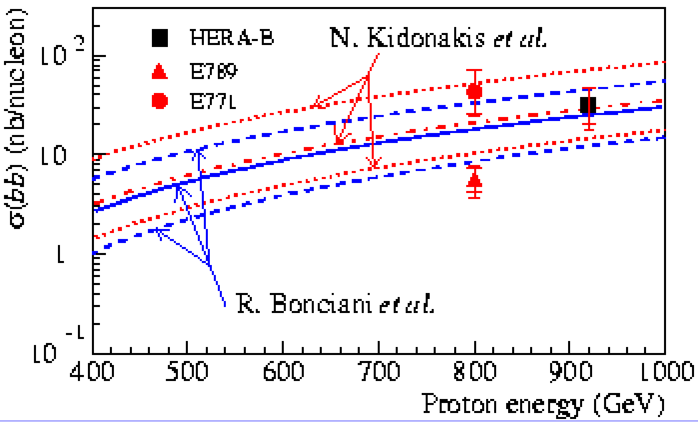
currently measure

- **all models have difficulties to describe all aspects of heavy flavour production**

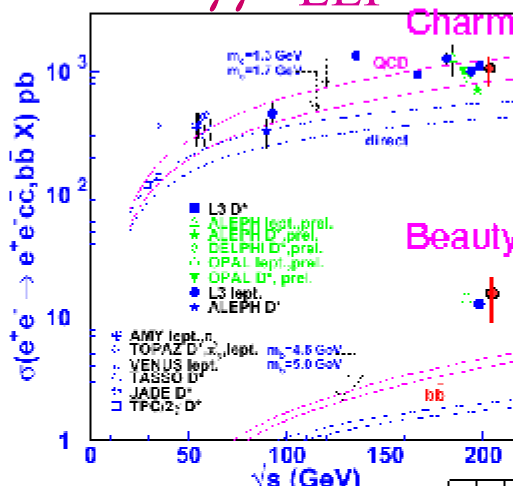
more to come from final HERA-I data and even more from HERA-II

Overview: Results on Beauty Production

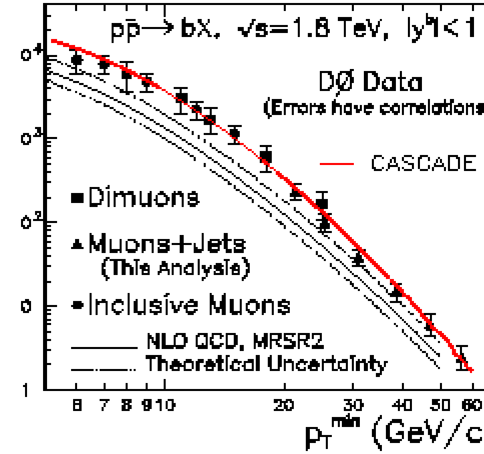
HERA-B

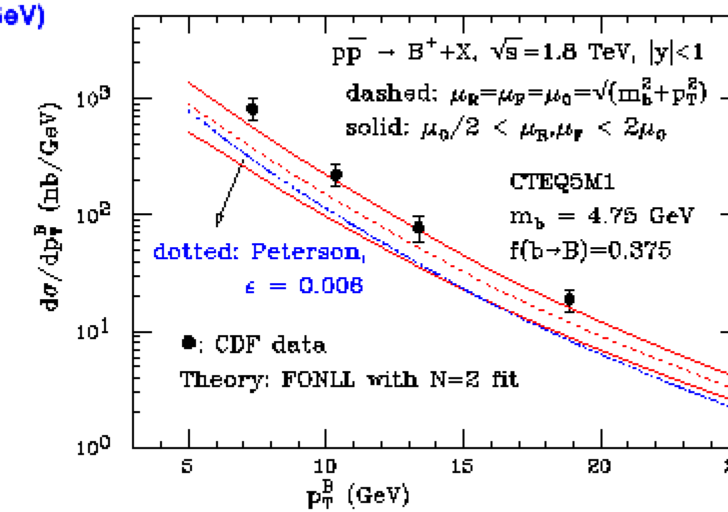


$\gamma\gamma$ LEP



$p\bar{p}$ Tevatron





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