New Trends in High-Energy Physics, Alushta 2003

Heavy Flavour Production at HERA

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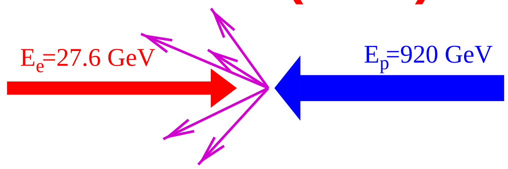
Introduction, Theoretical Framework

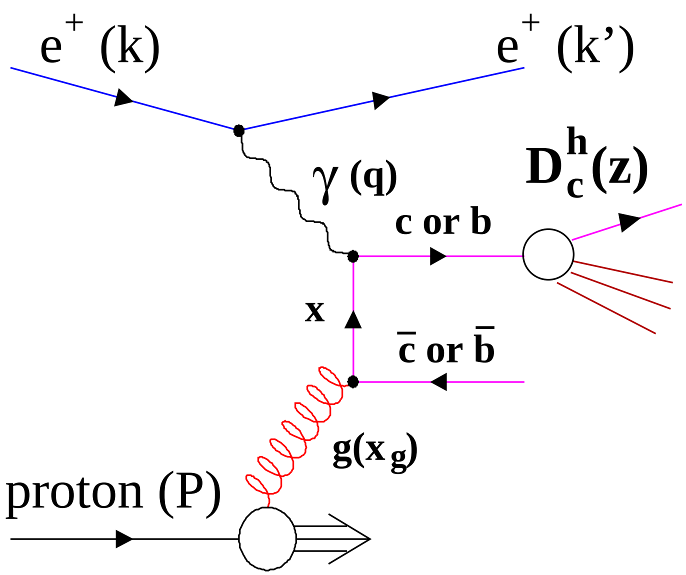
- Charm Tagging, Fragmentation
- Charm (+jets) in DIS
- Charm (+jets) in Photoproduction
- Beauty Tagging
- Beauty (+jets) in DIS and γ p
- $D^* - \mu$ Correlations

Introduction - Basics

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

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





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:

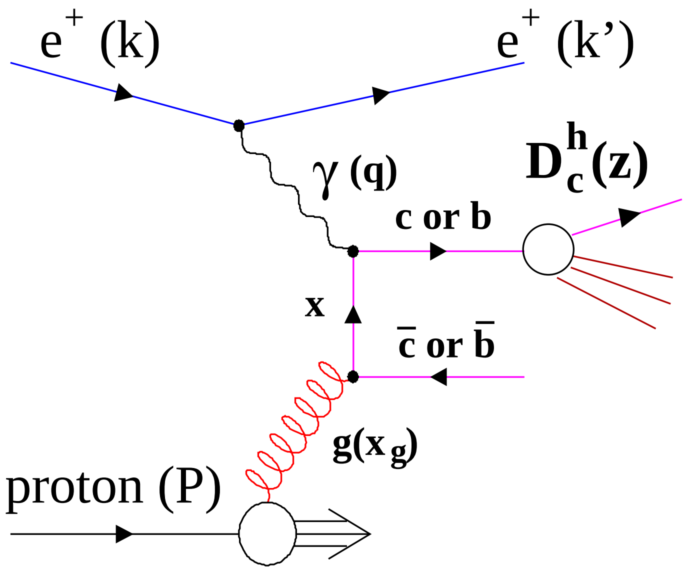
$Q^2 \approx 0$ $\longrightarrow$ Photoproduction

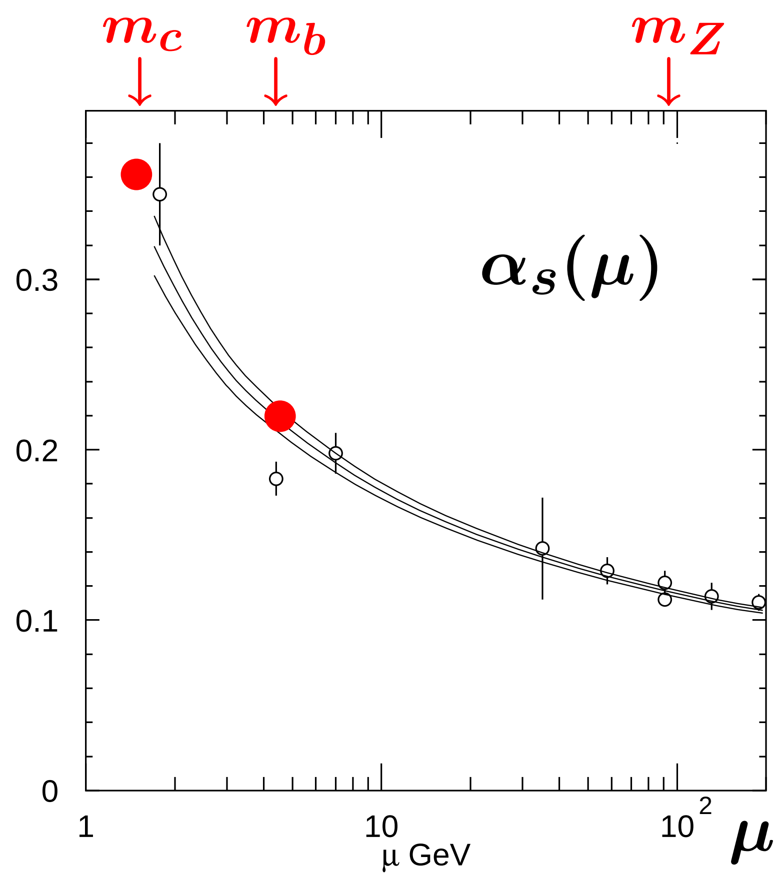
$Q^2 \gtrsim 2\,\text{GeV}^2$ $\longrightarrow$ Electroproduction “DIS”

- Factorization:

$$\text{Proton structure} \otimes \sigma_{\gamma g \rightarrow Q\bar{Q}} \otimes \text{photon structure} \otimes \text{fragmentation function}$$

Introduction - Strong Interaction



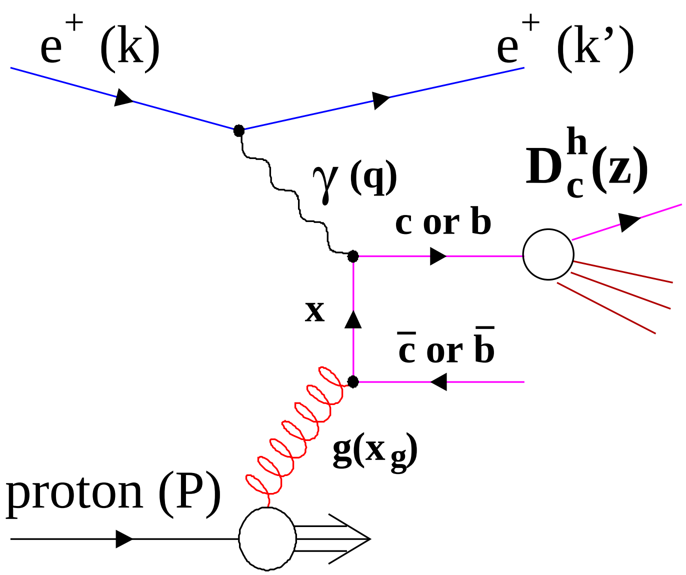


- **Perturbative QCD applicable**

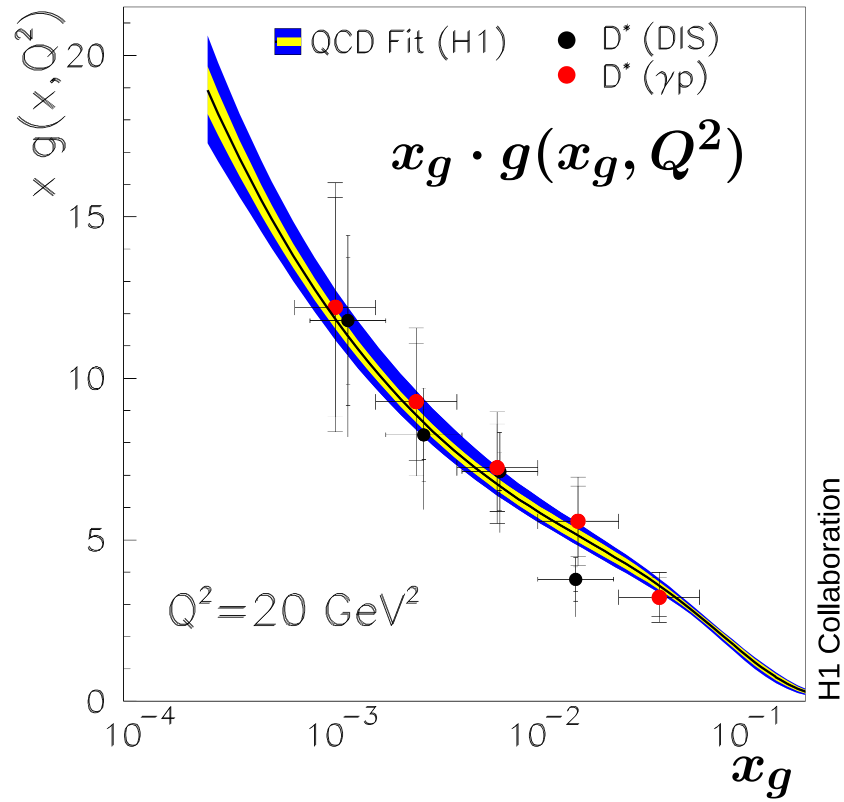
should work better for beauty than for charm

Proton structure $\otimes\ \sigma_{\gamma g \rightarrow Q\bar{Q}}\ \otimes$ photon structure $\otimes$ fragmentation function

- HEAVY FLAVOUR PRODUCTION AS A TEST OF HARD QCD

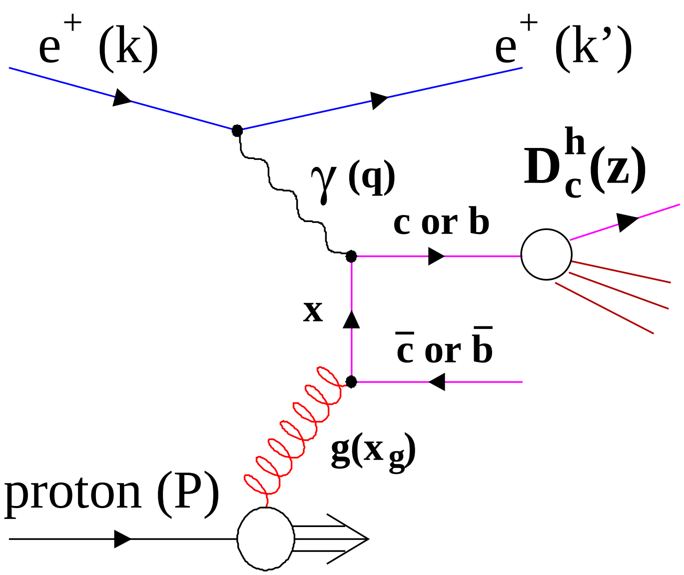


gluon density
in the proton

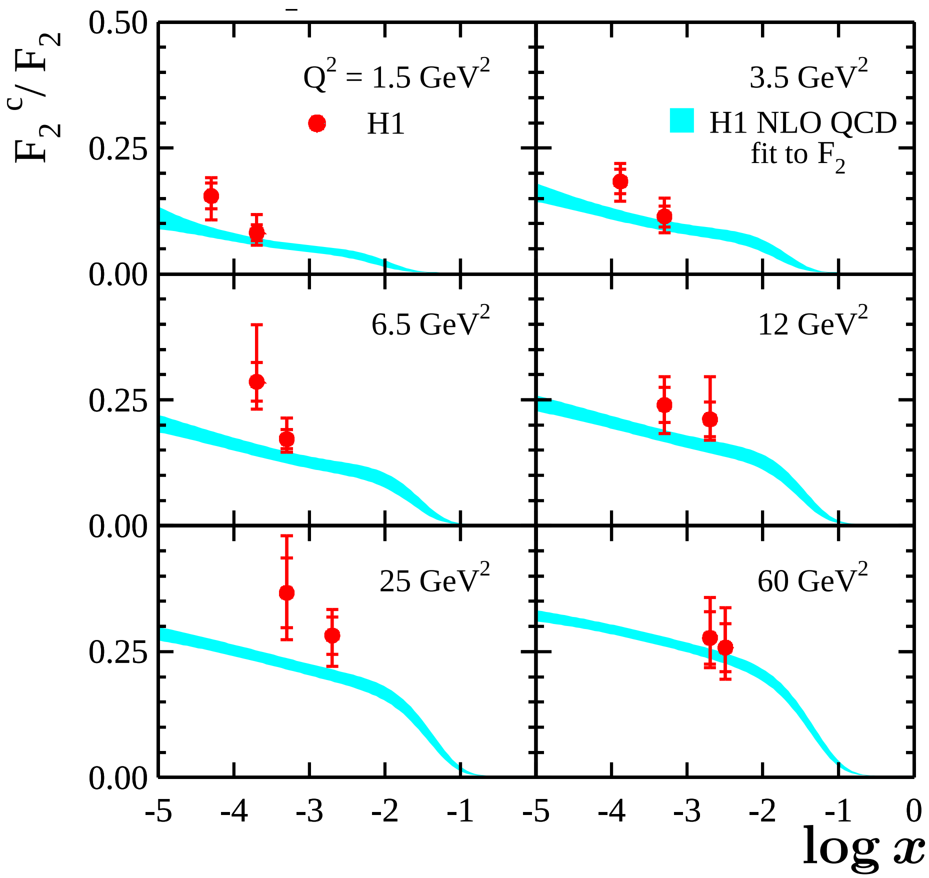


Proton structure $\otimes$ $\sigma_{\gamma g \rightarrow Q\bar{Q}}$ $\otimes$ photon structure $\otimes$ fragmentation function

☛ Universality of the gluon density

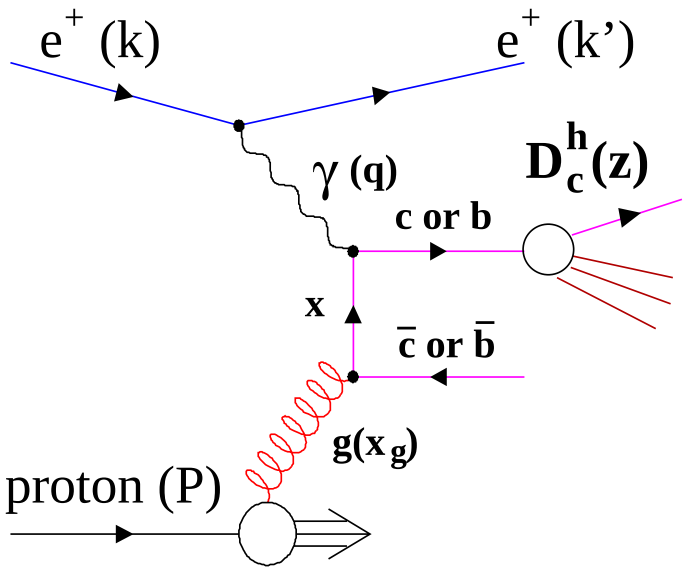


F_2^c/F_2



Proton structure $\otimes\ \sigma_{\gamma g \to Q\bar{Q}} \otimes$ photon structure $\otimes$ fragmentation function

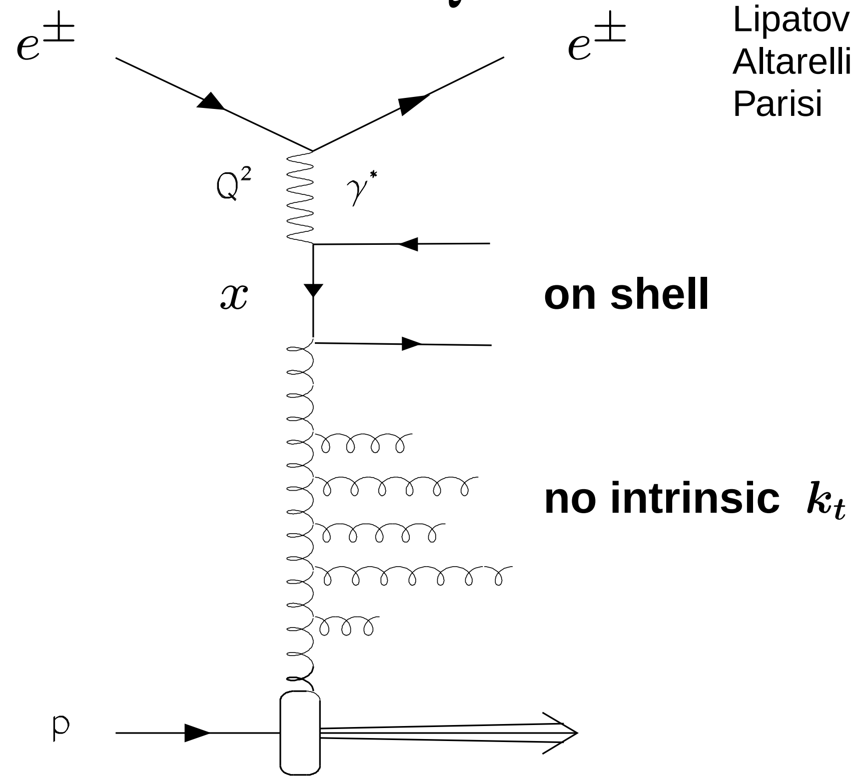
☛ Large charm contribution to F_2



Parton Evolution à la DGLAP

Dokshitzer
Gribov
Lipatov
Altarelli
Parisi

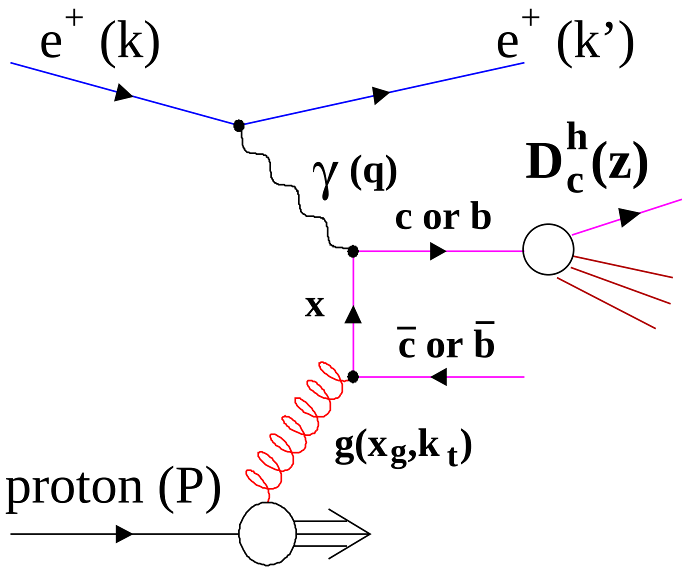
Evolution in Q^2



infinite momentum frame

Proton structure $\otimes$ $\sigma_{\gamma g \to Q\bar{Q}}$ $\otimes$ photon structure $\otimes$ fragmentation function

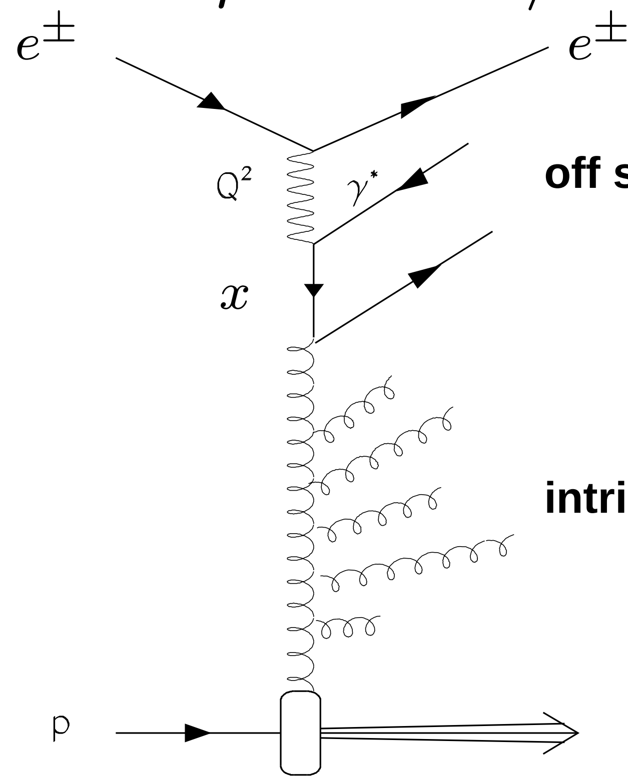
☛ Rigorously valid only at large x



Parton Evolution à la CCFM

Catani
Cafaloni
Fiorani
Marchesini

Evolution in $\eta = -\ln\tan\Theta/2$

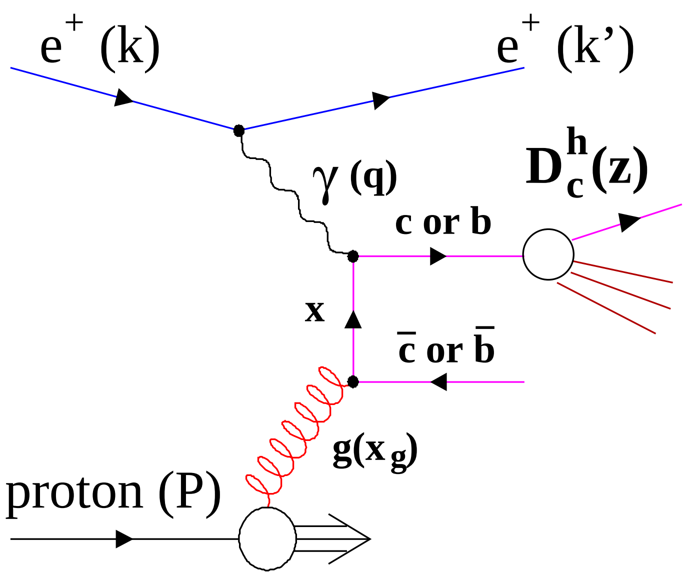


incorporates DGLAP at large x

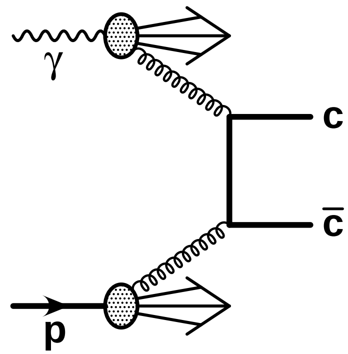
Proton structure $\otimes$ $\sigma_{\gamma g \to Q\bar{Q}}$ $\otimes$ photon structure $\otimes$ fragmentation function

☛ Valid for all x, but incomplete

Direct Process (pointlike photon)

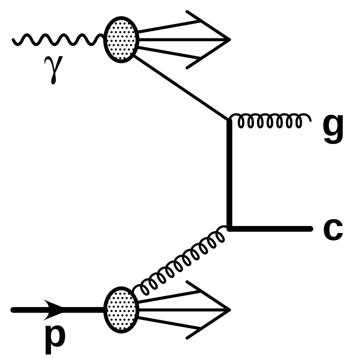


Resolved Photon

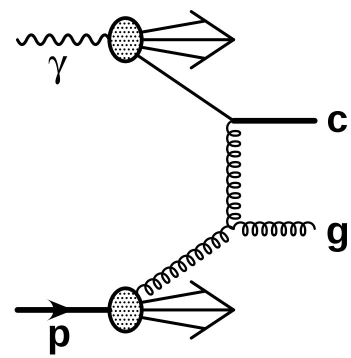


hadron-like

Gluon-Gluon-Fusion



q-Propagator



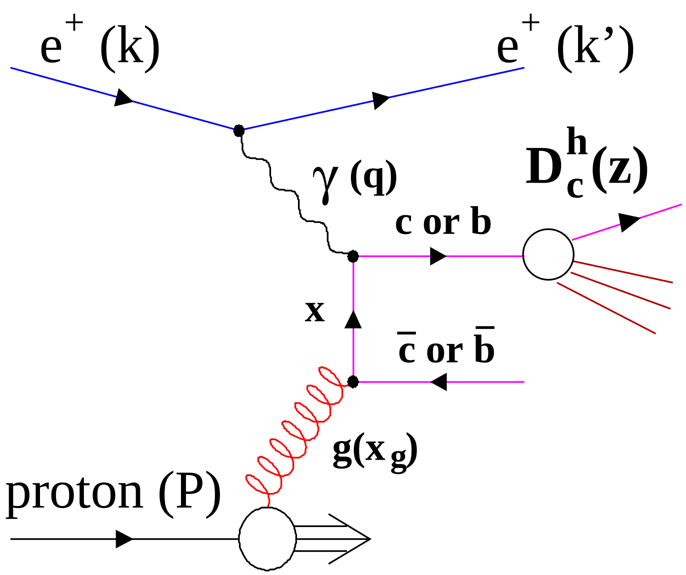
g-Propagator

Charm

-Excitation

Proton structure $\otimes$ $\sigma_{\gamma g \rightarrow Q\bar{Q}}$ $\otimes$ photon structure $\otimes$ fragmentation function

- Large resolved component in γp (details later)



- non-perturbative effect in strong interactions
- described phenomenologically

Questions to Charm Fragmentation

- Fragmentation probabilities for different Hadrons with charm?
- Isospin conserved ?
- Ratio of vector (D^*) to pseudo-scalar (D) mesons?
- Strangeness suppression?
- Fragmentation function?

Proton structure $\otimes$ $\sigma_{\gamma g \to Q\bar{Q}}$ $\otimes$ photon structure $\otimes$ fragmentation function

Is fragmentation universal ?

Introduction - Theory and Models

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

Calculations in the DGLAP scheme

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.

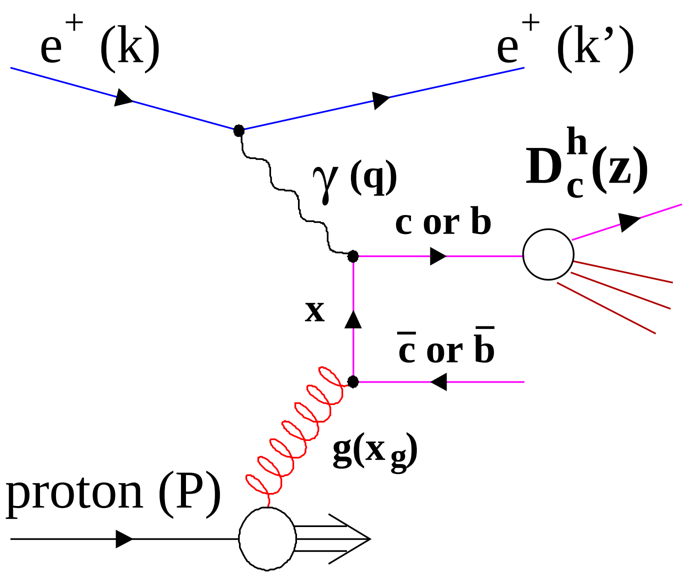
MC generators (ME + PS)

- **AROMA**:
  direct only, **LO DGLAP evolution**
- **PYTHIA, RAPGAP, HERWIG**:
  direct **+ resolved**,**LO DGLAP**
- **CASCADE**:
  direct only, **CCFM evolution**,
  initial state: **full calculation**
  final state: **LO**
  k_t dependent gluon density

Fragmentation:

non perturbative models

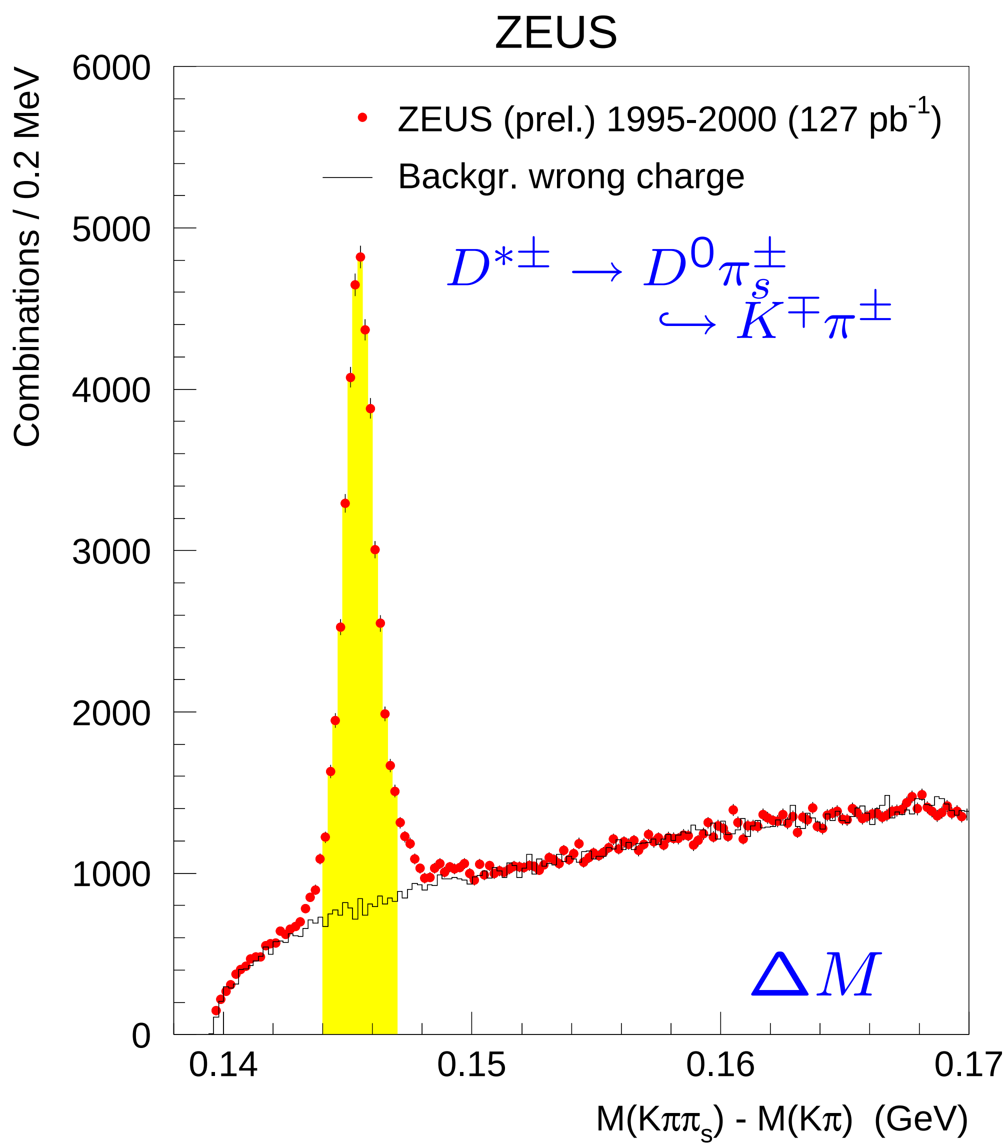
Introduction - A Challenge



- Heavy flavour production at HERA is a multi-parameter problem
- Additional uncertainties due to
  - heavy quark masses m_c and m_b
  - renormalization and factorization scale
- Charm production is a significant part of the ep cross section
- Understanding of charm production is partly limiting the accuracy in other physic topics (e.g. F_2)

Proton structure $\otimes$ $\sigma_{\gamma g \to Q\bar{Q}}$ $\otimes$ photon structure $\otimes$ fragmentation function

☛ Detailed study of heavy flavour production needed !



Tagging via reconstruction of hadrons with charm

Gold plated channel:

$$D^{*\pm} \rightarrow D^0 \pi_{sl}^\pm$$
$$\hookrightarrow K^\mp \pi^\pm$$

- 2-body decays
- $m_{D^{*\pm}} - m_{D^0} = 145.4$MeV

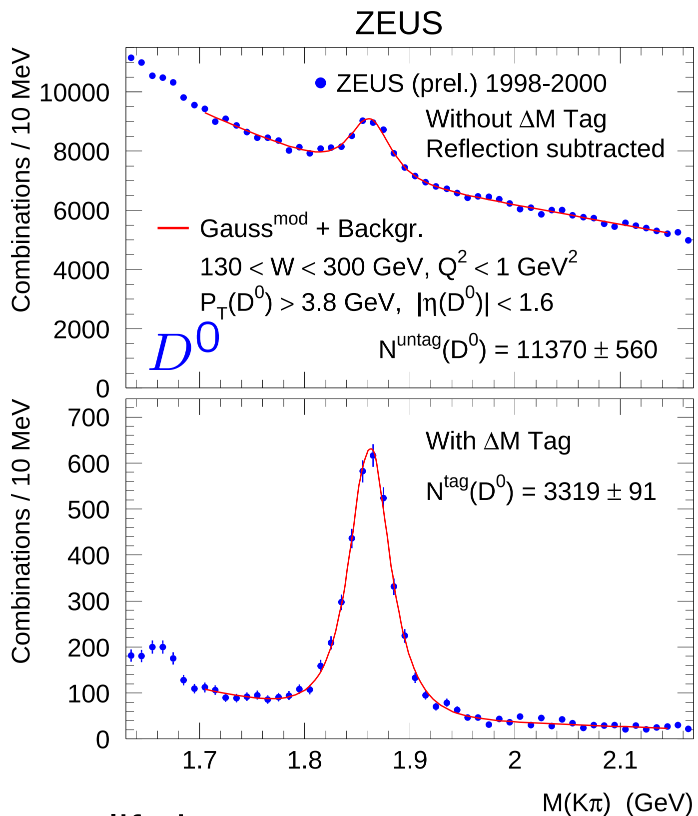
close to m_π

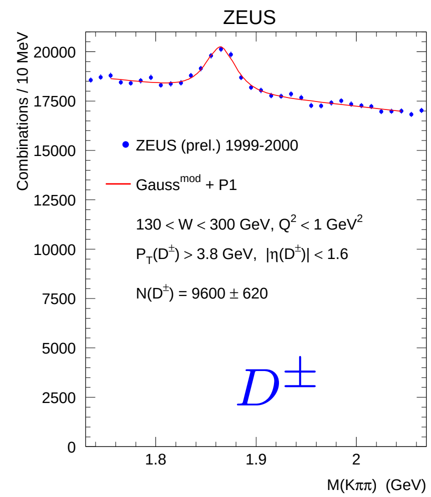
$\Rightarrow$ small background

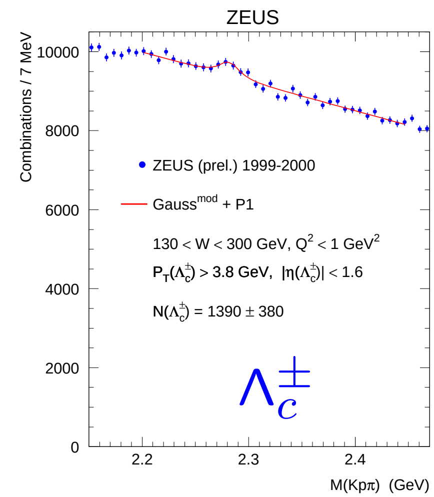
BUT: tagging rate:$\approx$ 0.006

$\rightarrow$ try to reconstruct other decay modes and other hadrons with charm

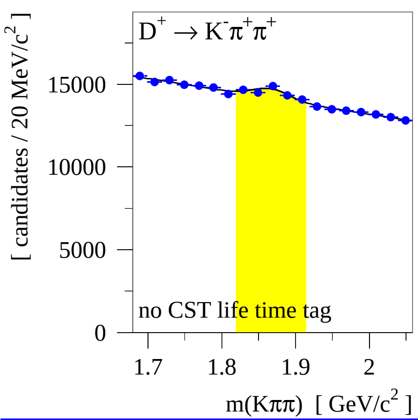
CHARM Tagging Methods

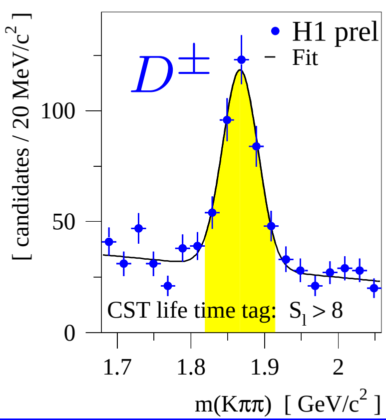


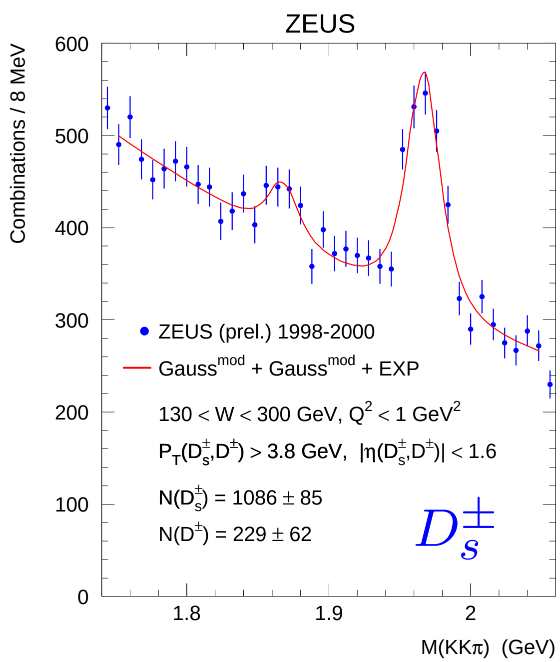




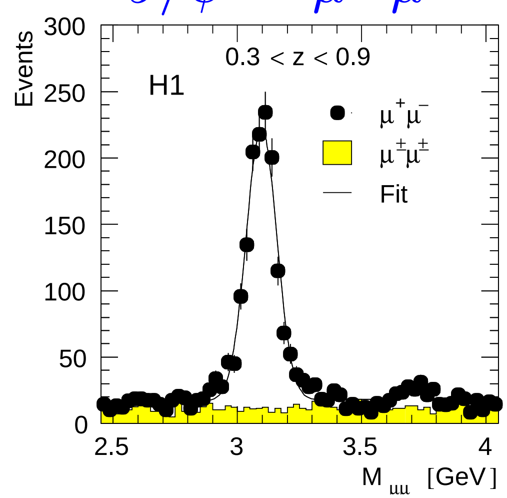
lifetime: no tag ⟶ tag







$J/\psi \rightarrow \mu^+\mu^-$



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) $P_T(D,\Lambda_c) > 3.8\,\text{GeV}$, $\lvert\eta(D,\Lambda_c)\rvert < 1.6$	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!

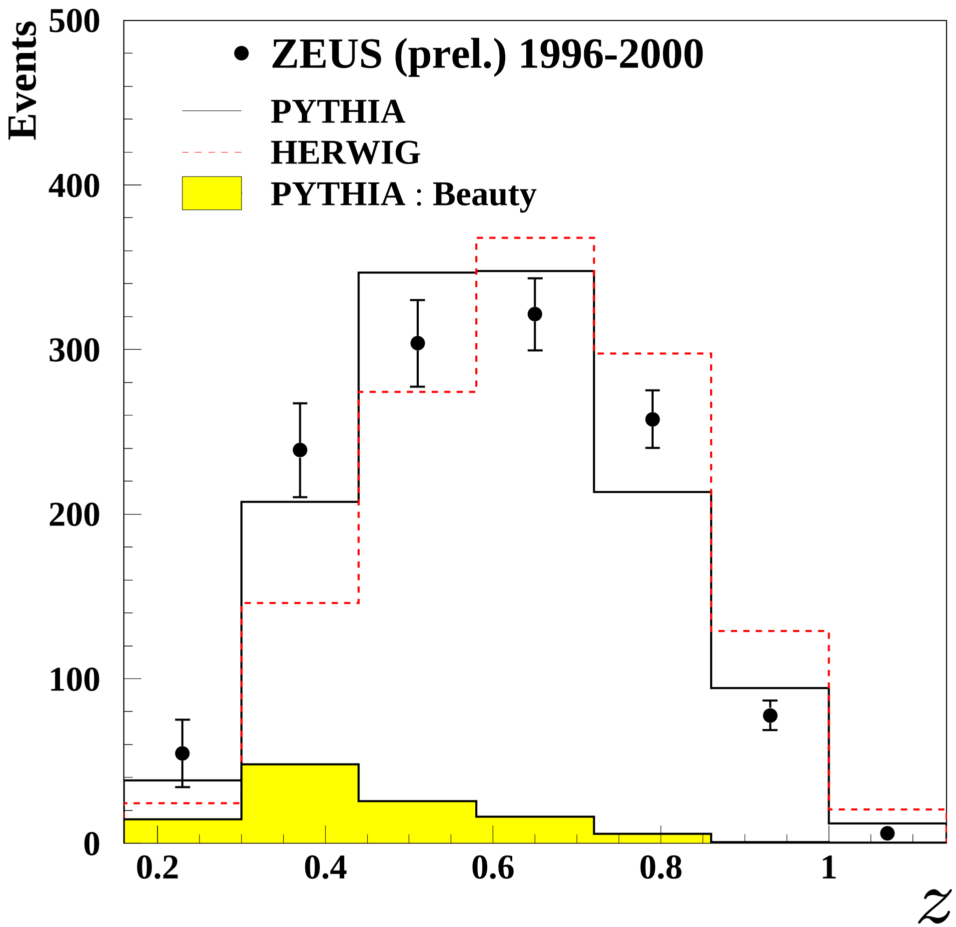
$R_{u/d}$, γ_s, $V/(P+V)$ also determined and in good agreement with w.a.

Measurement of the Fragmentation Function into $D^{*\pm}$

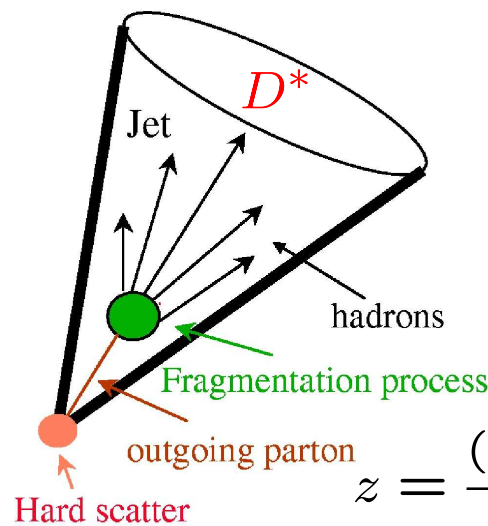
$Q^2 < 1\,\text{GeV}^2$; $130 < W_{\gamma p} < 280\,\text{GeV}$ $p_T^{D^*} > 2\,\text{GeV}$; $|\eta^{D^*}| < 1.5$

Requirements: $D^{*\pm}$ belongs to a jet with $E_T^{jet} > 9\,\text{GeV}$ and $|\eta^{jet}| < 2.4$

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



k_t jet algorithm

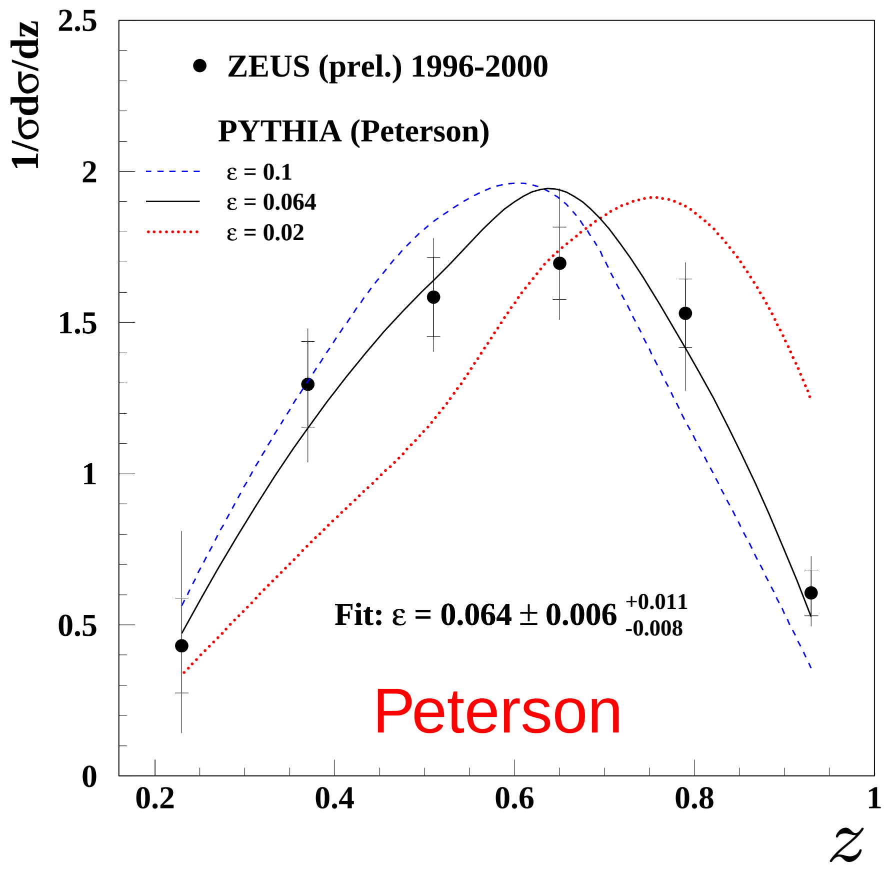


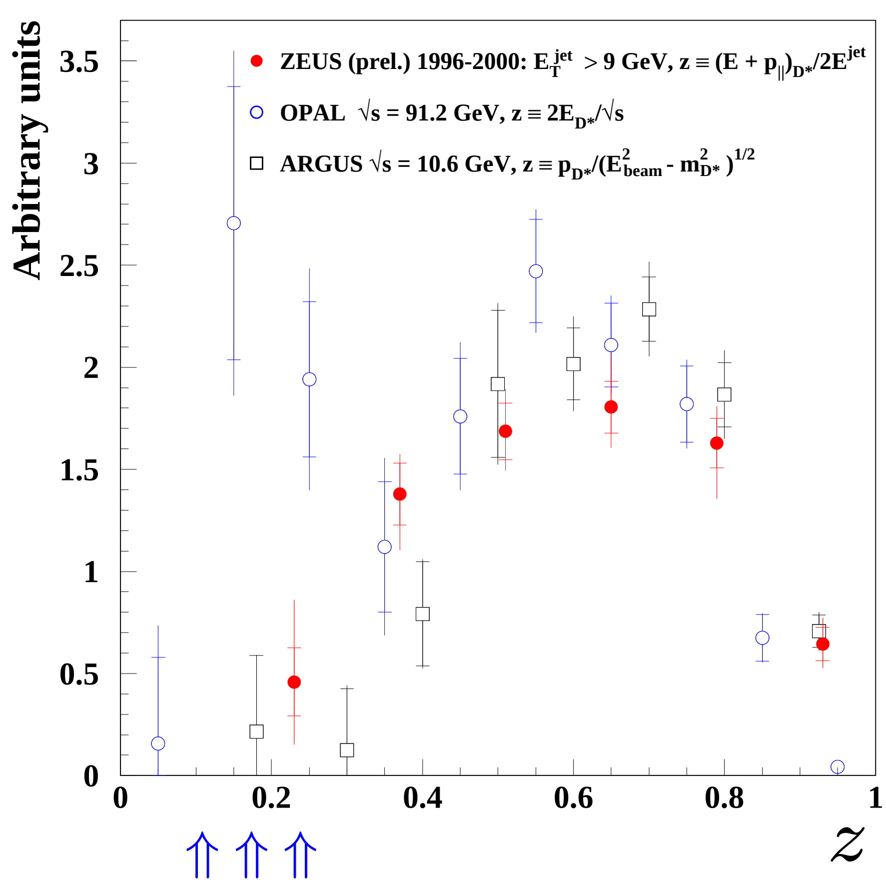
$$z = \frac{(E+p_{||})^{D^*}}{2\,E_{jet}}$$

PYTHIA (sym. Lund+Bowler) agrees with data

HERWIG (Cluster model) is too hard

Results on Fragmentation Function





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

⇑ ⇑ ⇑

no $g \to c\bar{c}$ visible in ARGUS and ZEUS data

$\epsilon = 0.064 \pm 0.006^{+0.011}_{-0.008}$ (ZEUS prel.)

$\epsilon = 0.05$ (PYTHIA default)

$\epsilon = 0.053$ (LL fi t to ARGUS data Nason, Oleari)

different definitions of z!
qualitative agreement

Fragmentation function universal?

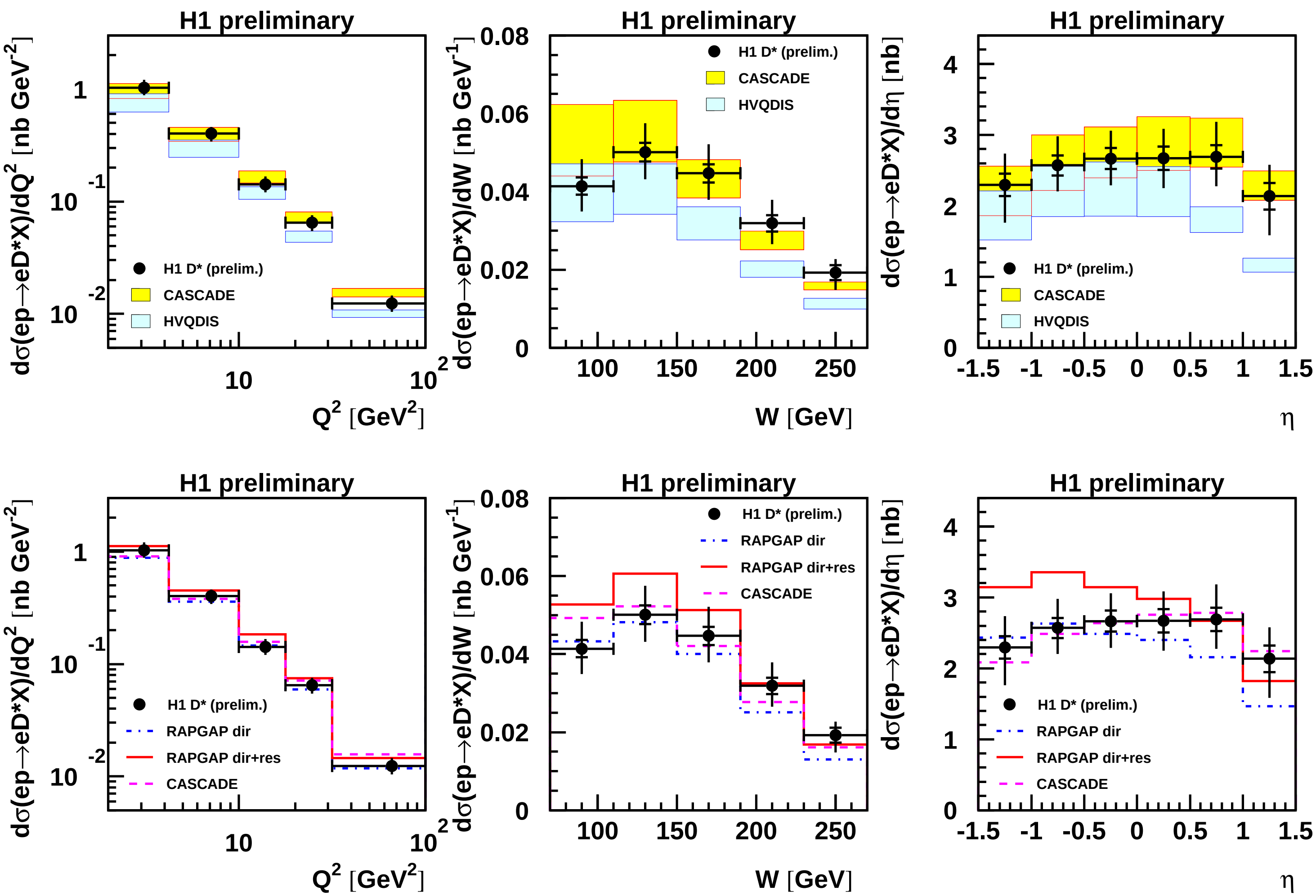
D^* in DIS

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

1999,2000 47 pb^{-1}

$Q^2 > 2$ GeV^2; $0.05 < y < 0.7$

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



- NLO QCD low
- CASCADE (CCFM) better

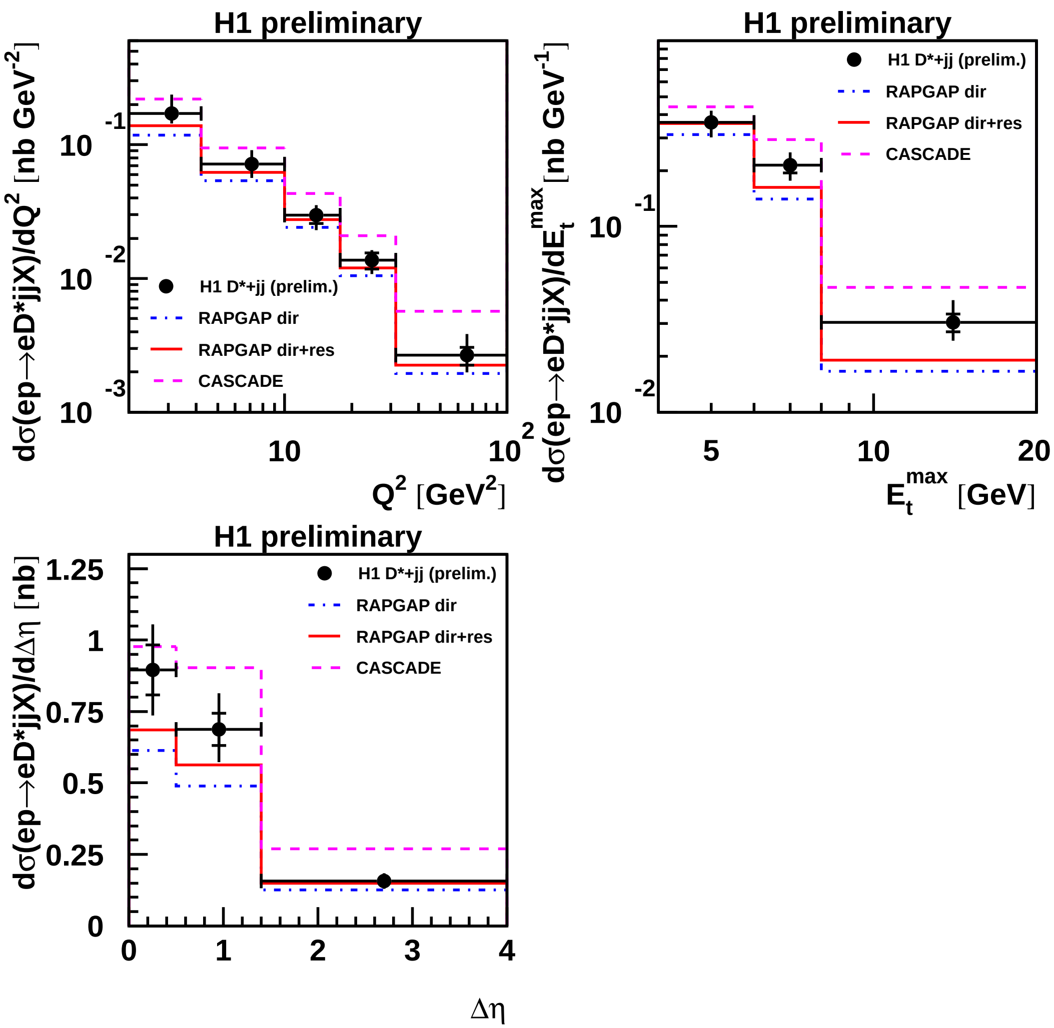
confi rms 96+97 results

- RAPGAP (LO+PS) high
- Shape of η distribution well described by CASCADE only

Jet Cross Section with D^* in DIS

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

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

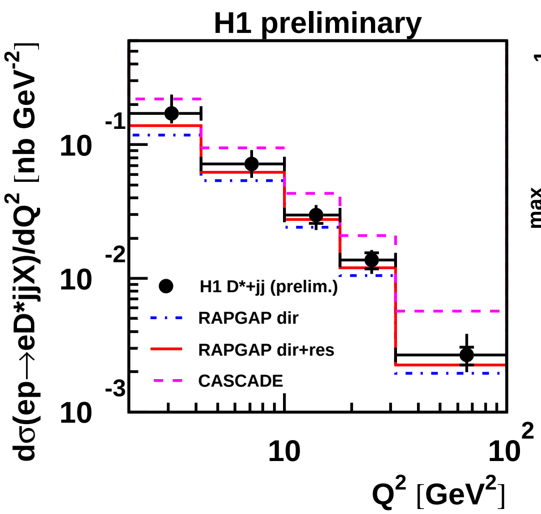


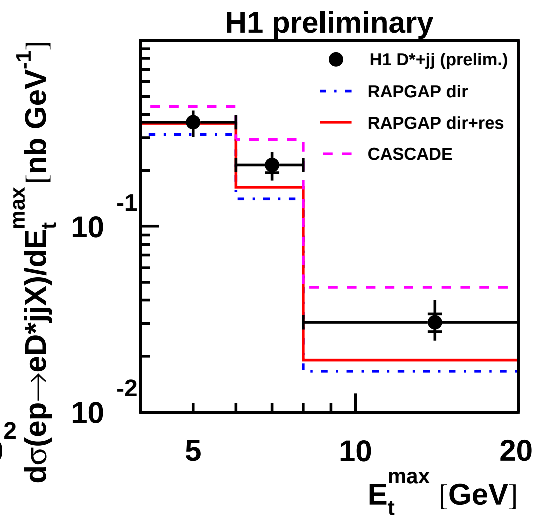
- CASCADE (CCFM) too high
- RAPGAP (LO+PS) too low

Jet Cross Section with D^* in DIS

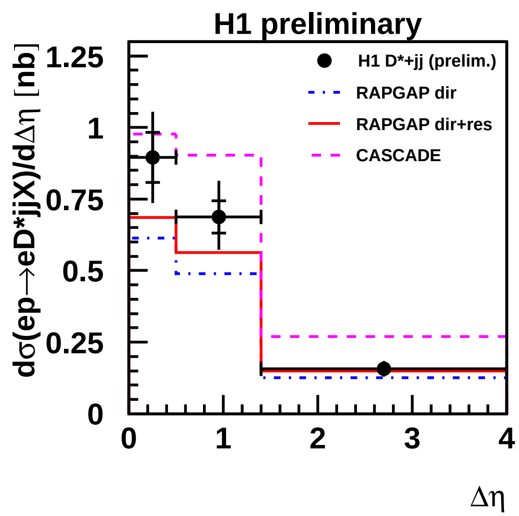
H1: D^* and 2 jets (inclusive k_t algorithm in Breit frame) 1999,2000 47 pb^{-1}

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



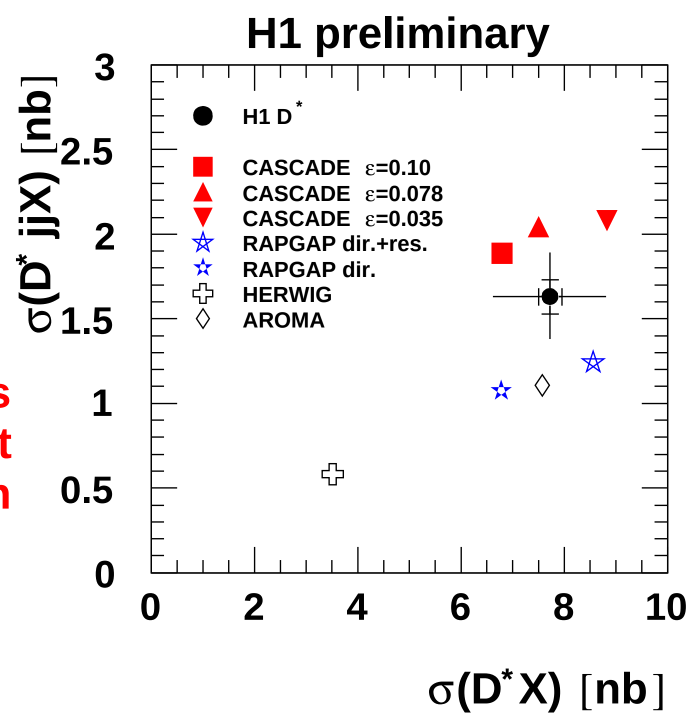


- CASCADE (CCFM) too high
- RAPGAP (LO+PS) too low

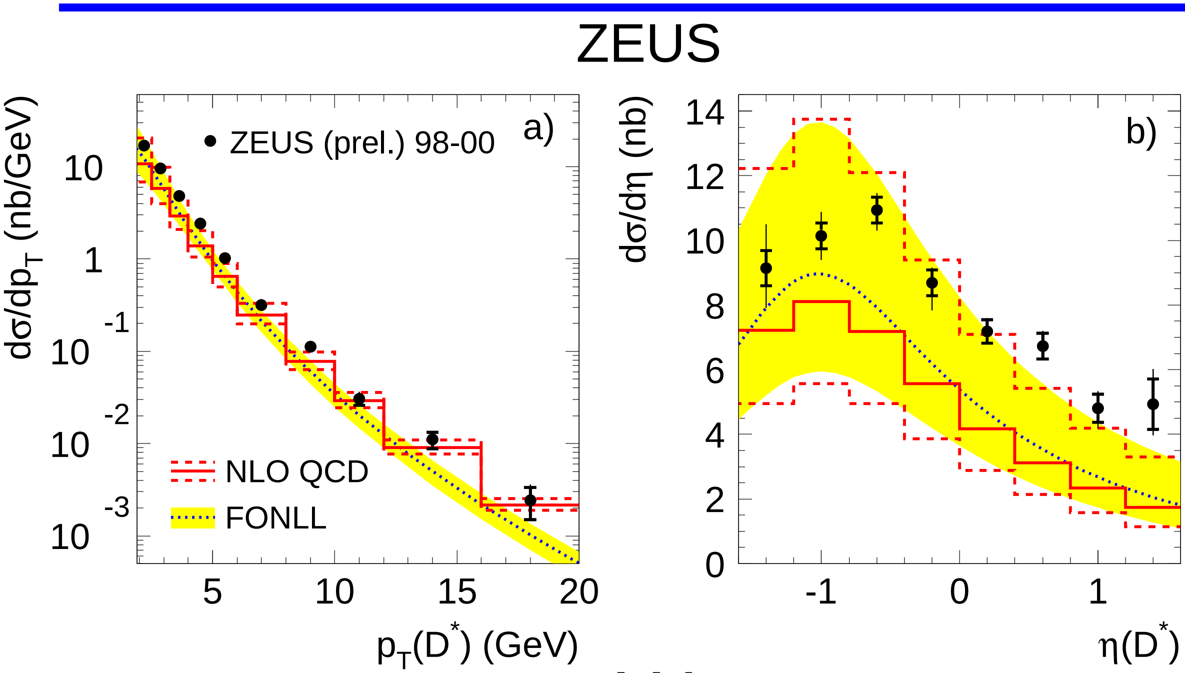


- **All theoretical models are found to be imperfect when jets are required in addition**

Summary plot: Jet cross section versus inclusive



D^* Photoproduction



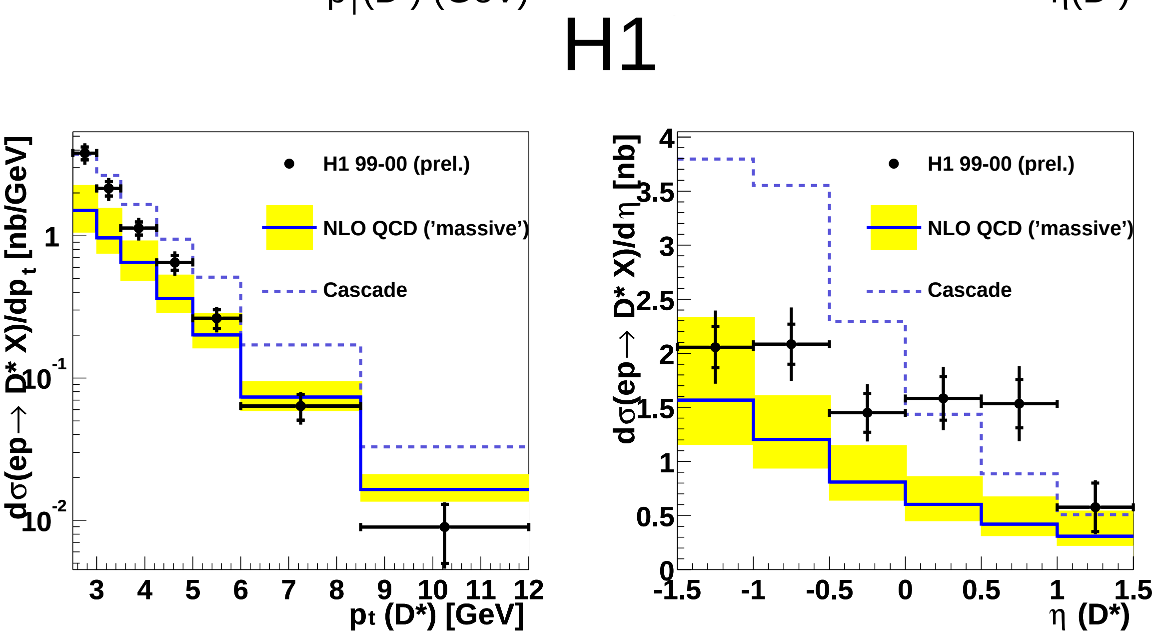
No electron tag — 79 pb^{-1}

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

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

Large theoretical uncertainties due to scale, mass and fragmentation uncertainties

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

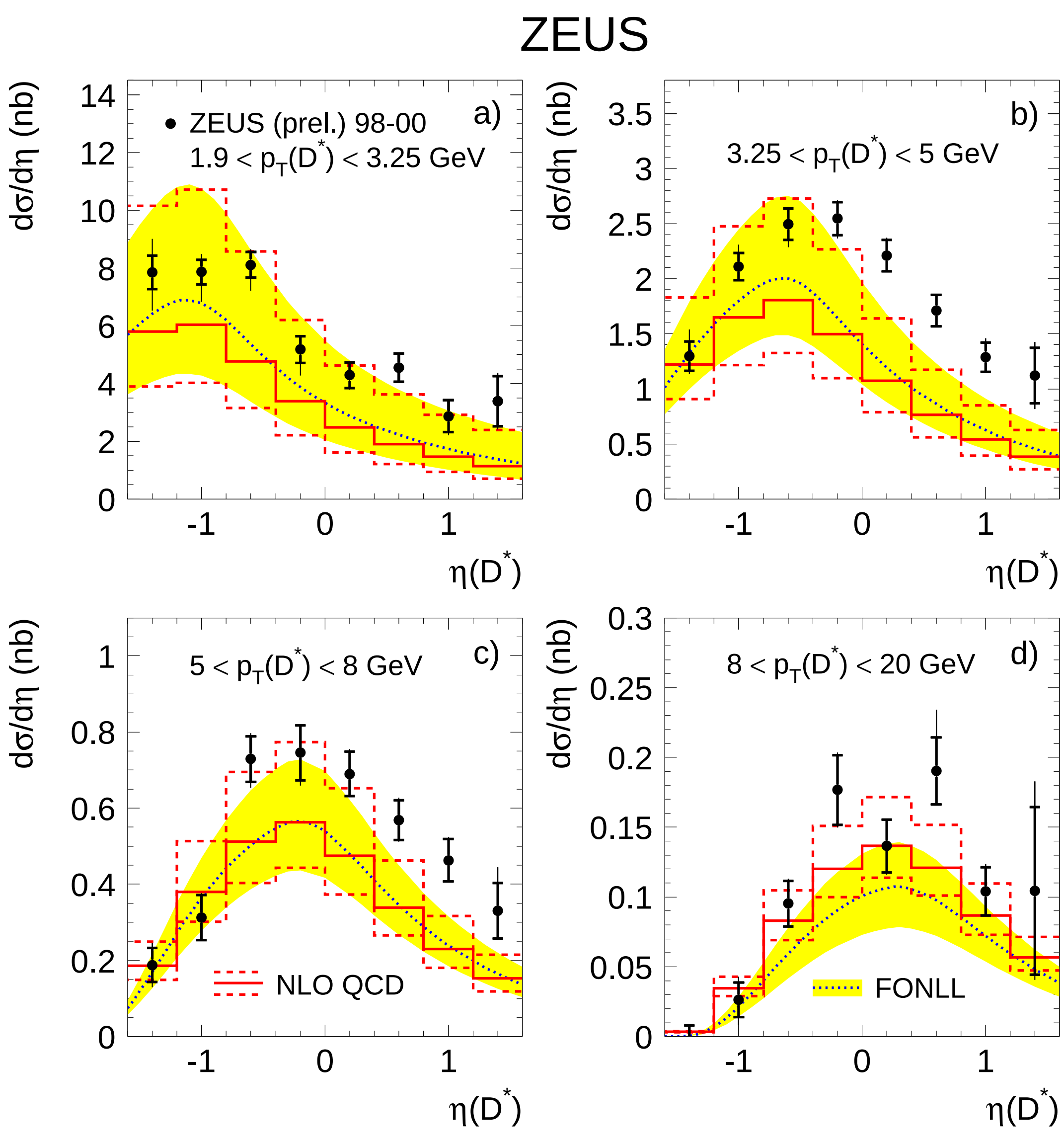


Electron tag: — 49 pb^{-1}

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

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

D^* Photoproduction double differential distributions

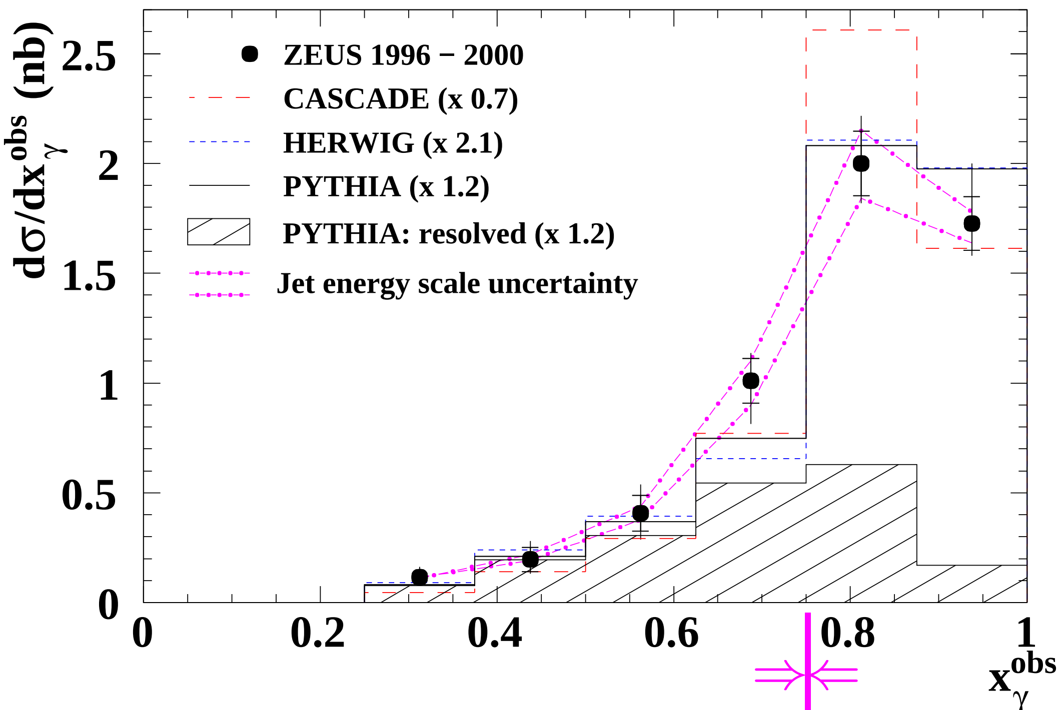


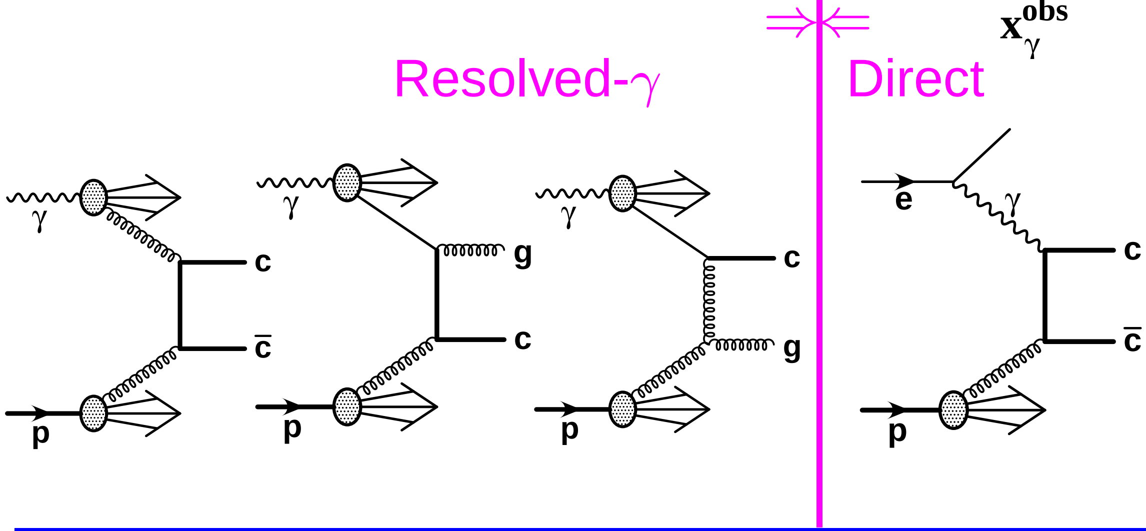
η distribution in $p_T^{D^*}$ bins

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

D^* + Two-Jet-Events

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:

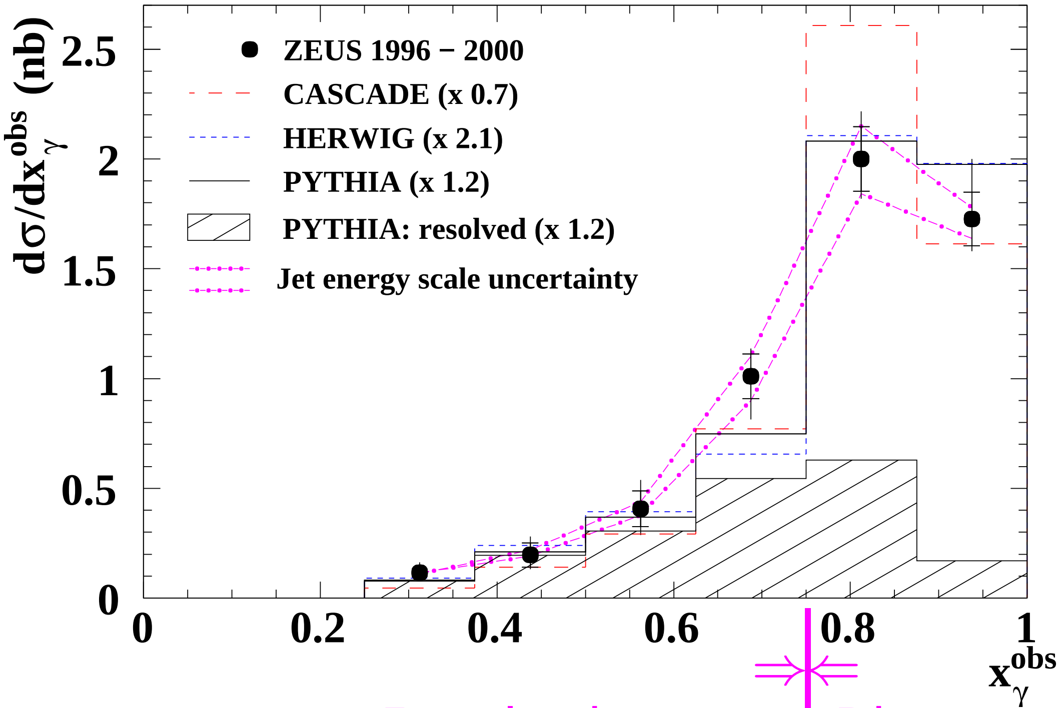
$$x_\gamma^{\text{obs}} = \frac{\sum_{j_1,j_2}(E_T^j e^{-\eta^j})}{2yE_e}$$

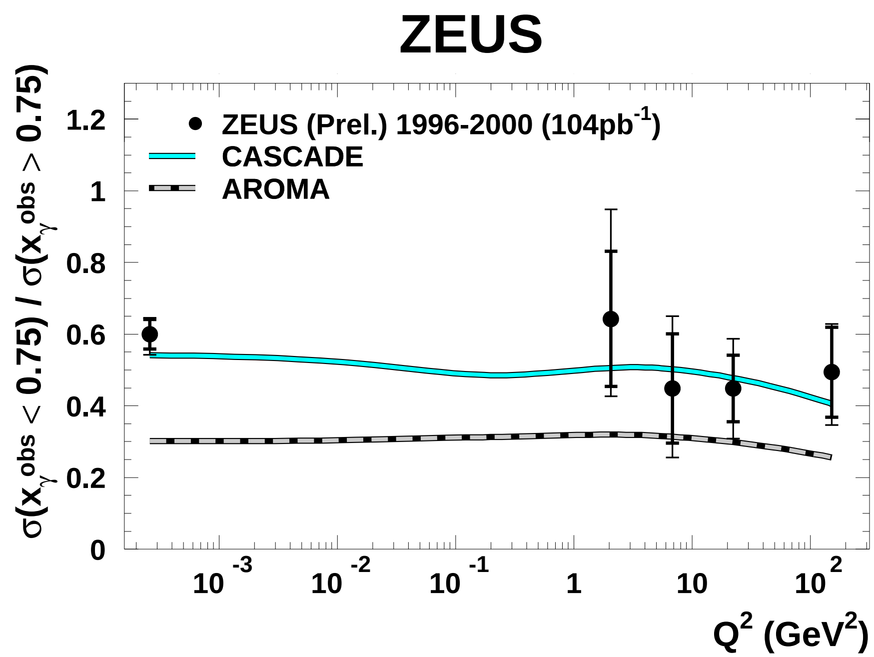
- Significant contribution from resolved ($\sim$ 40%)

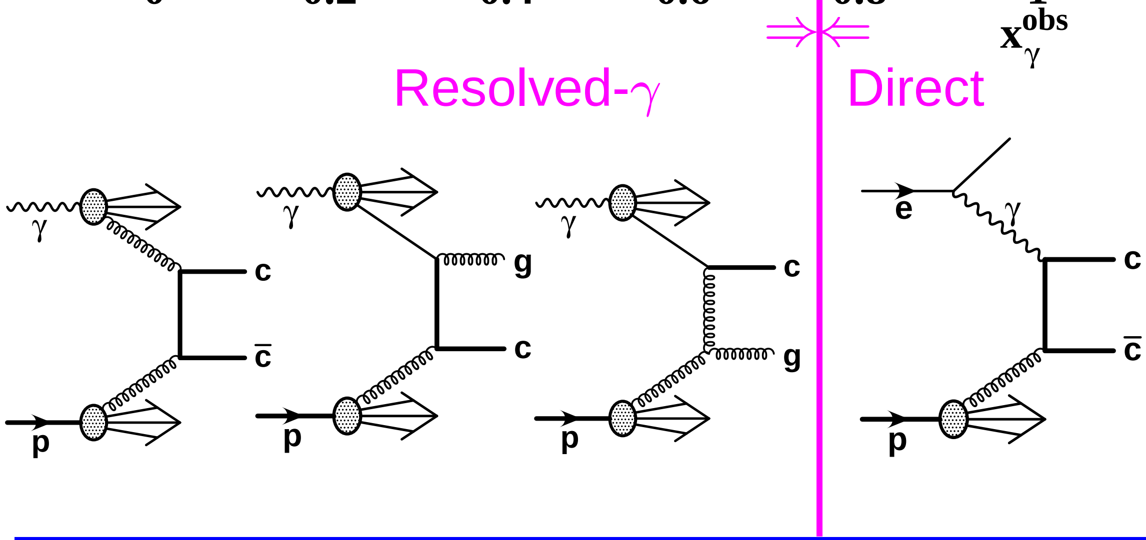
- MCs: good description of shape
- CASCADE different at high x_γ^{obs}
- NLO below data at low x_γ^{obs} (not shown)

D^* + Two-Jet-Events

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

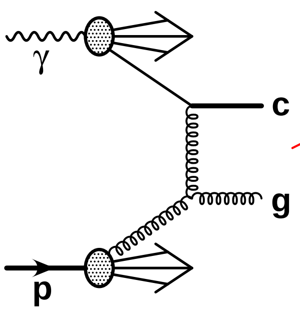


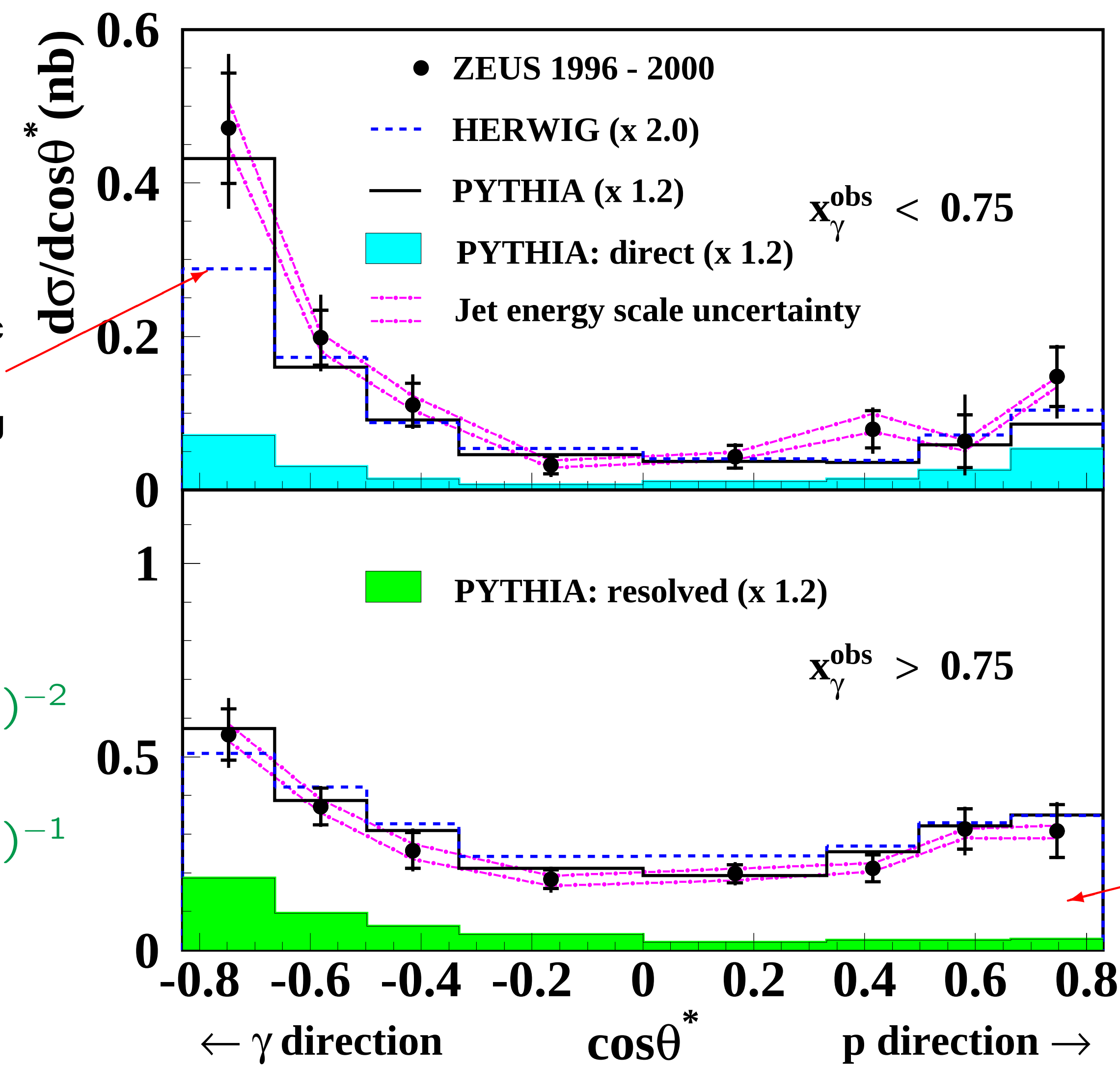




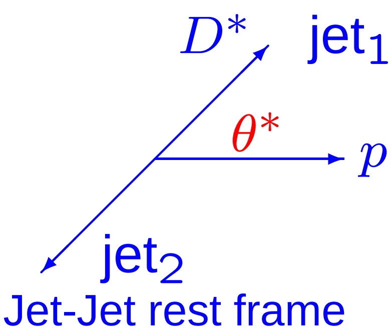
- Significant contribution from resolved ($\sim$ 40%) independent of Q^2
- MCs: good description of shape
- CASCADE different at high x_γ^{obs}
- NLO below data at low x_γ^{obs} (not shown)

Charm: Di-jet Angular Distributions (LO Picture)



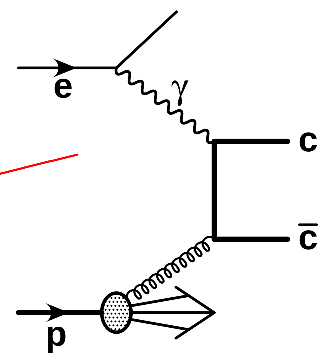


$\theta^* = \measuredangle(p, D^*\text{-Jet})$



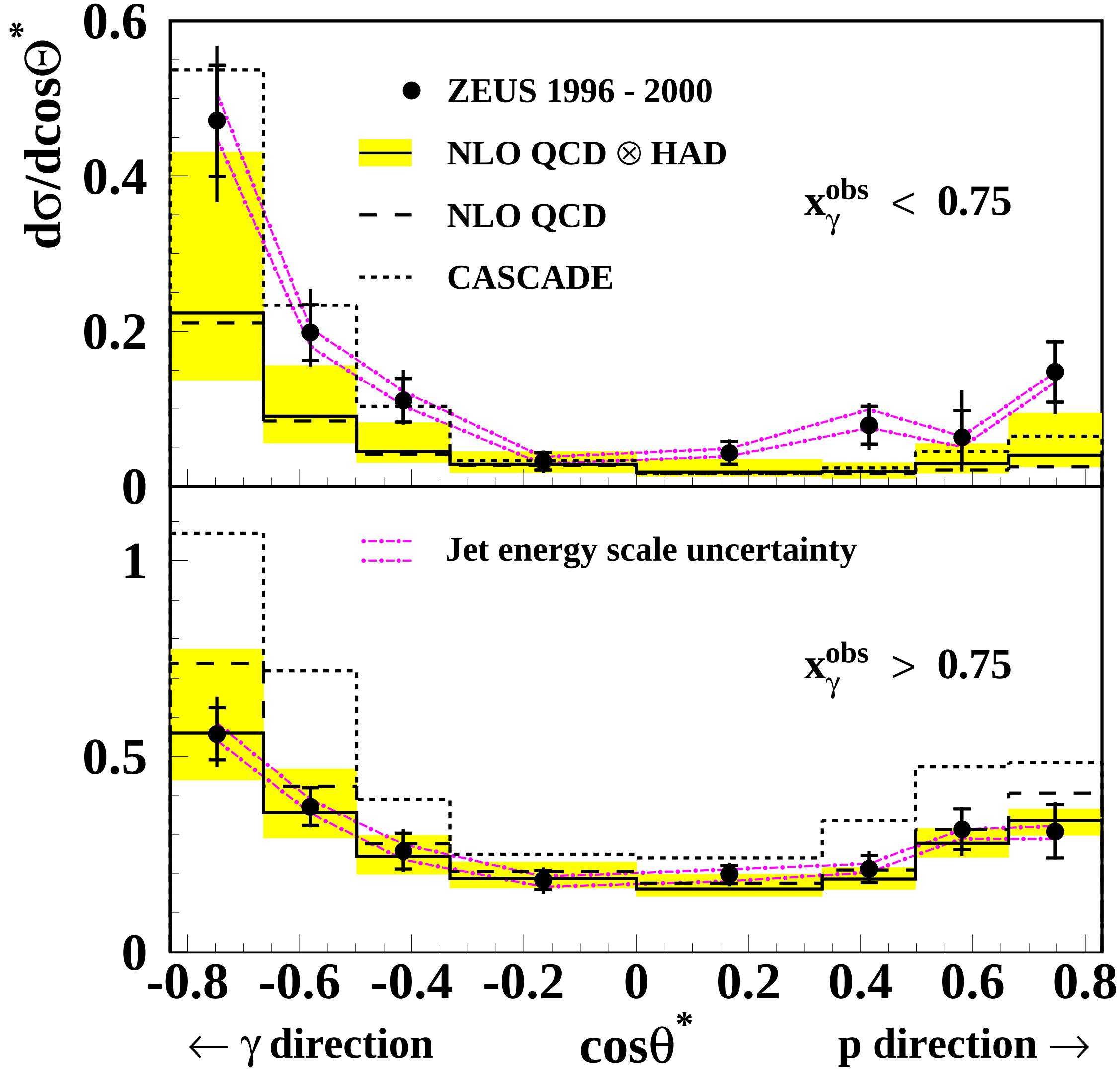
g-exchange:
$\propto (1 - |\cos\theta^*|)^{-2}$

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

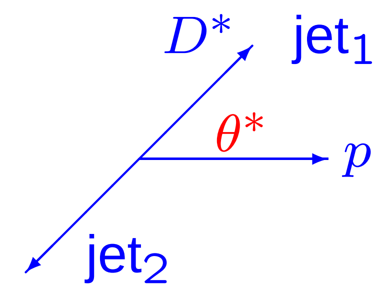


LO Picture:
- Strong rise in $d\sigma/d\cos\theta^*$ towards γ direction for $x_\gamma^{obs} < 0.75$
- Clear evidence for charm from the photon

Charm: Di-jet Angular Distributions (Evolution Scheme)

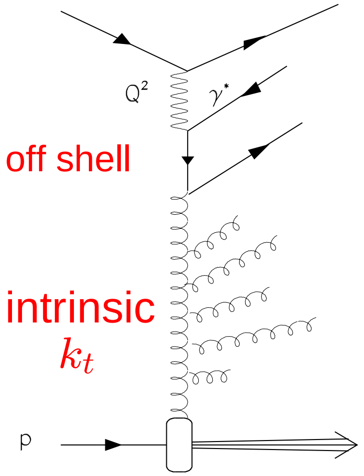


$\theta^* = \measuredangle(p, D^*\text{-Jet})$

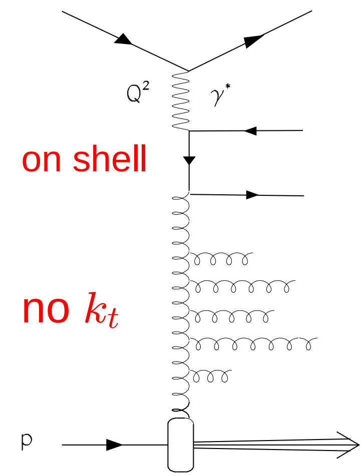


Jet-Jet rest frame

CCFM
(angular ordering)



DGLAP NLO



QCD Schemes:

- NLO DGLAP ok for $x_\gamma^{\text{obs}} > 0.75$, but too low for $x_\gamma^{\text{obs}} < 0.75$
- CCFM (Cascade) ok in shape, but too high in cross section

Charm Production - Summary

- Fragmentation Probabilities and Fragmentation Function measured
  agrees with results from other experiments (with some reservations)

☛ Charm fragmentation universal in high energy physics?

- Inclusive D^* production in DIS
  CASCADE: good agreement with data, other models fail

- D^* plus jets in DIS
  Problems of all models in describing $\sigma(D^{*\pm} + jj)$ vs. $\sigma(D^{*\pm})$

- Inclusive D^* in photoproduction
  Problems of NLO QCD and CCFM to describe the data

- D^* plus jets in photoproduction
  Sign of a large charm component in the photon in the LO+PS picture
  Sign of the off-shellness of partons in QCD calculations?

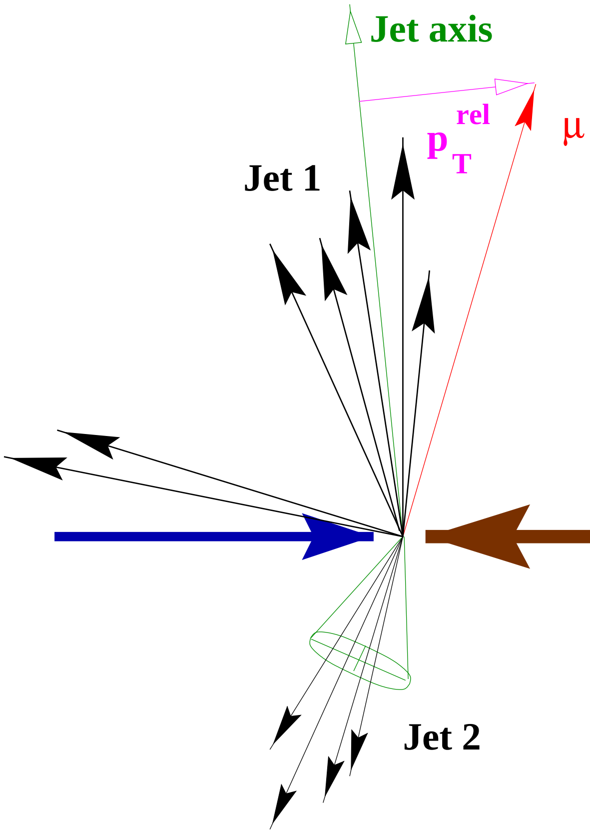
☛ **A good step forward, but still far from understanding charm production**

Beauty Tagging Methods

$\sigma_{b\bar{b}}/\sigma_{c\bar{c}} \approx 0.005$ in γp, $\approx 0.02 - 0.05$ in DIS

Rate small but theory should be more reliable

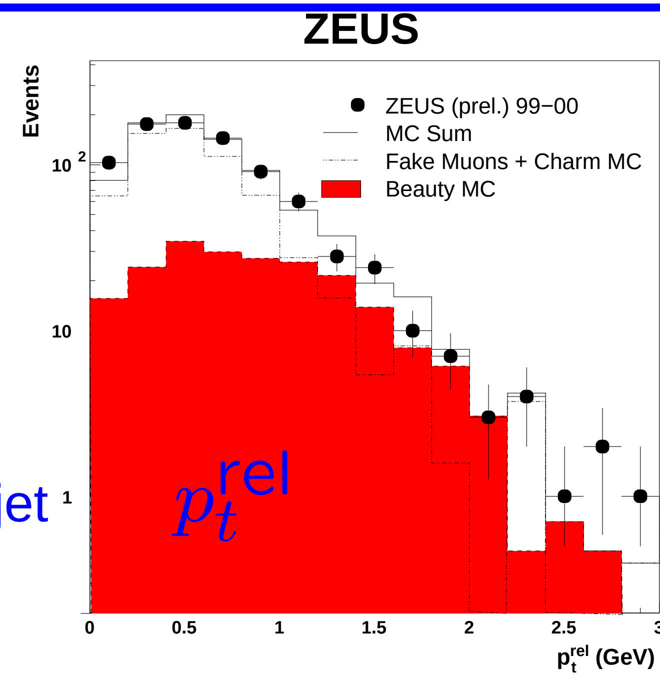
Semileptonic B decays in 2-jet events



- Large B-Mass:

p_t of μ relative to the jet

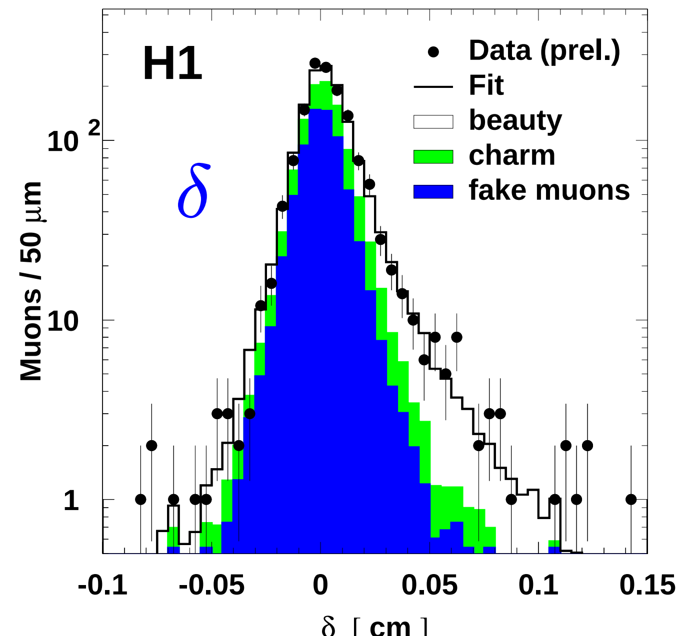
$f_b \sim (25 \pm 5)\%$



- Long B-Lifetime:

μ Impact Parameter

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



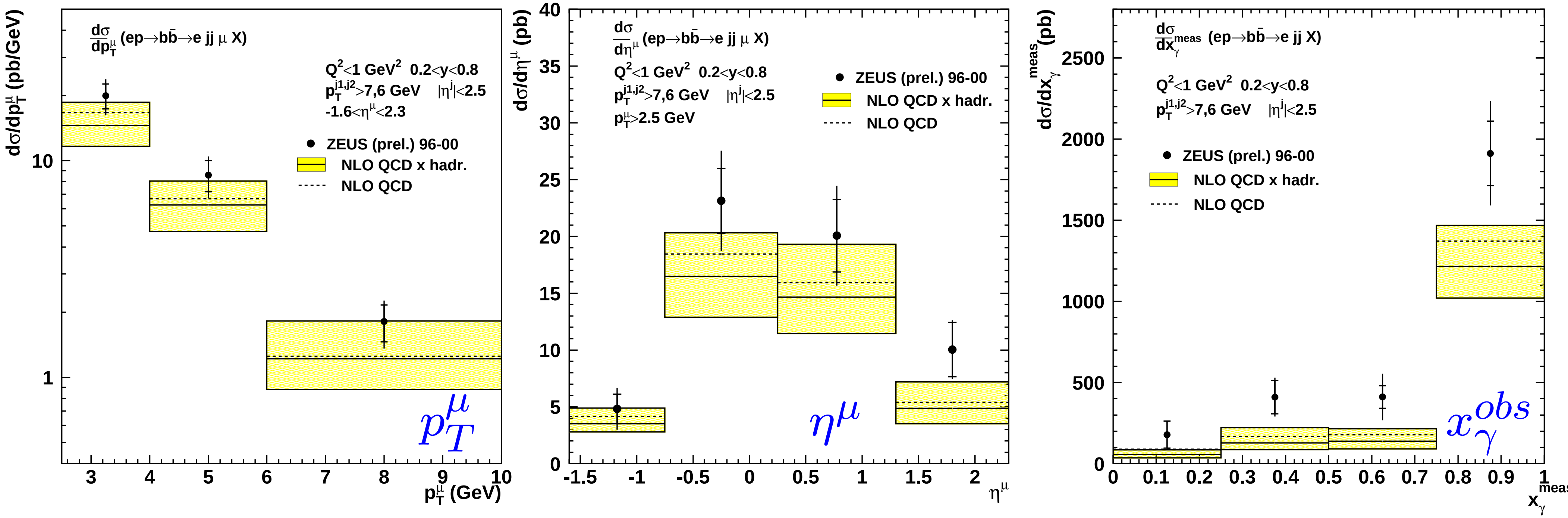
B in γp : 1996–2000 Results

ZEUS: p_T^{rel} Method — 2 jets, $E_T^{jet1(2)} >$7 (6) GeV; $|\eta^{jet}| <$2.5 — 98 pb^{-1}

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

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

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



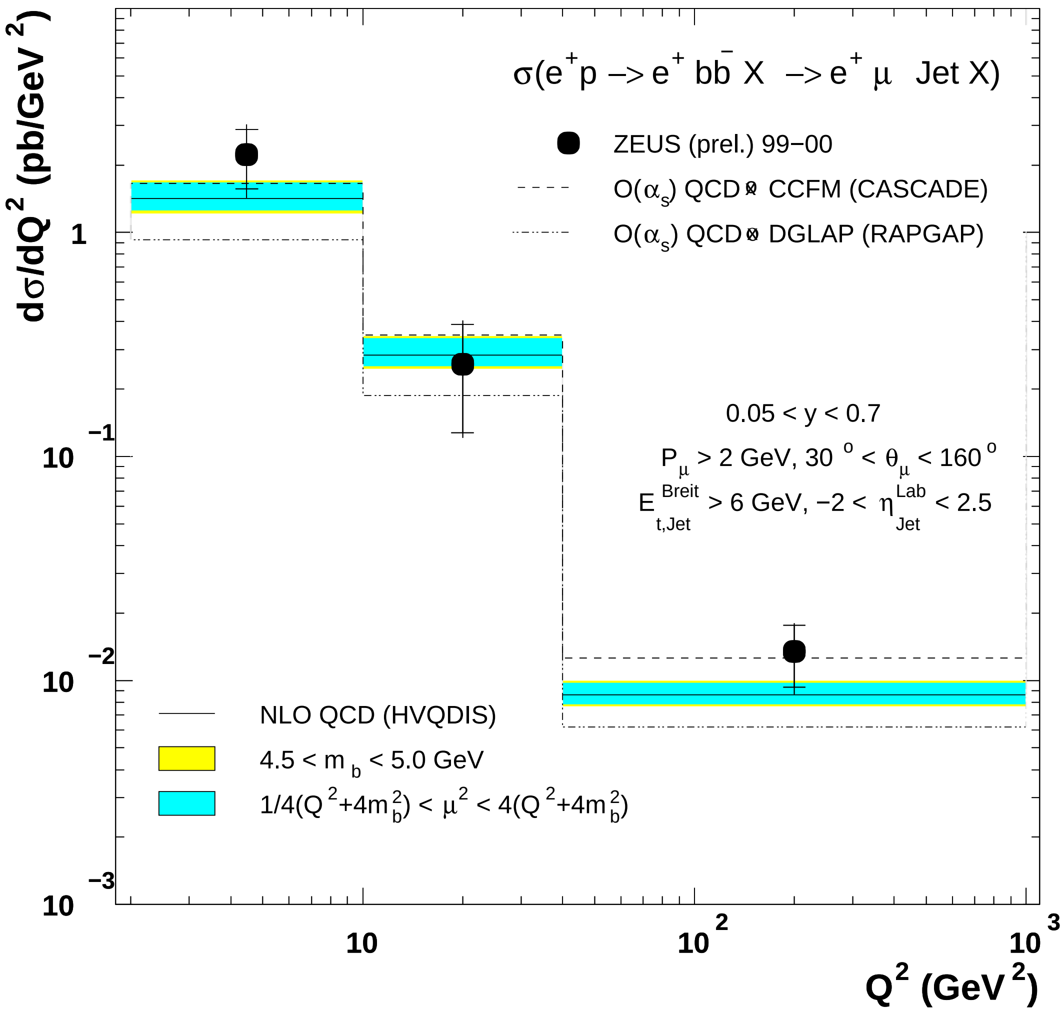
Comparison to NLO QCD: p_T^{μ} and η^{μ} in visible region, ok within errors

For x_γ extrapolate muon phase space (PYTHIA),

Factor 2 disagreement

Beauty in DIS

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



$Q^2 > 2$ GeV^2, $0.05 < y < 0.7$ ~ 60 p

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

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

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

- QCD NLO (DGLAP) ok within errors

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

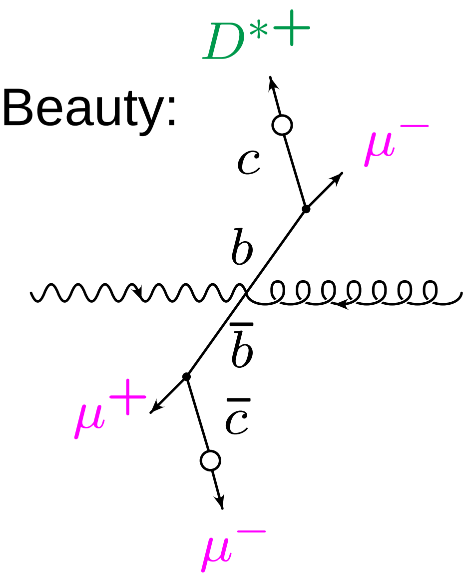
- CASCADE (CCFM) good agreemen

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

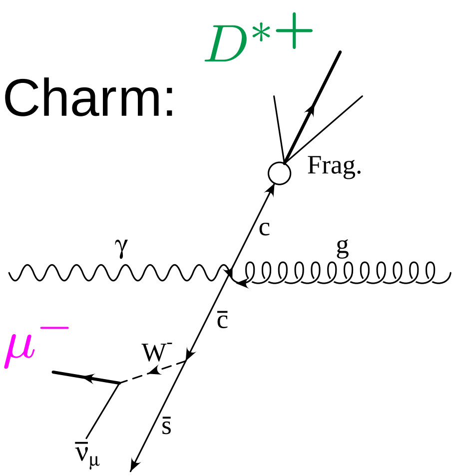
- RAPGAP (DGLAP, LO+PS) too low

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

Beauty:



Charm:

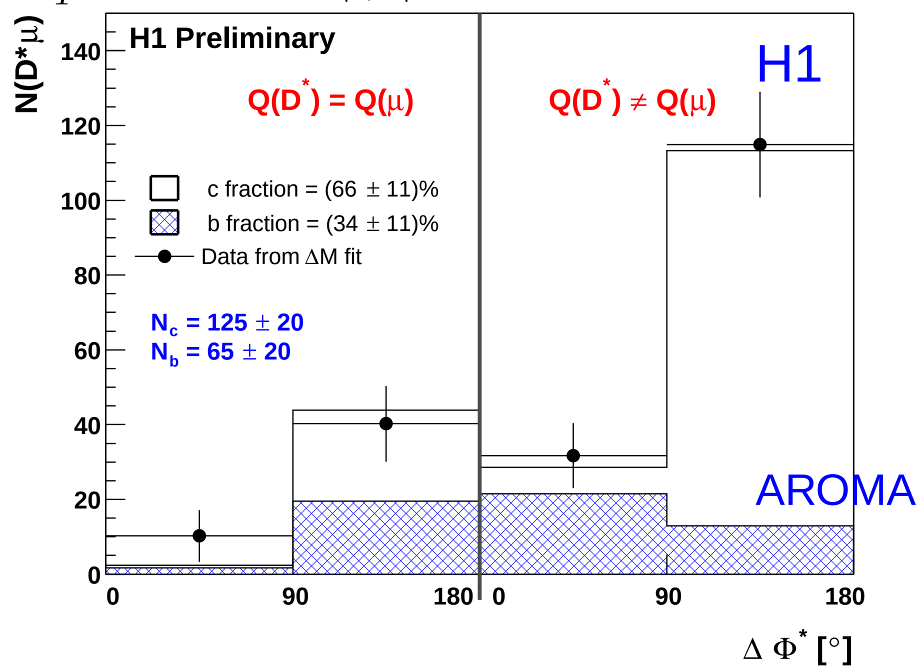


c-b separation using charge and angular correlations

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

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

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



combined D^* (ΔM) + $D^*\mu$ **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

$D^*\mu$ – 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, $-1.3 < \eta^{\mu} < 1.5$ $\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2}$

$\downarrow$ PYTHIA MC $\downarrow$

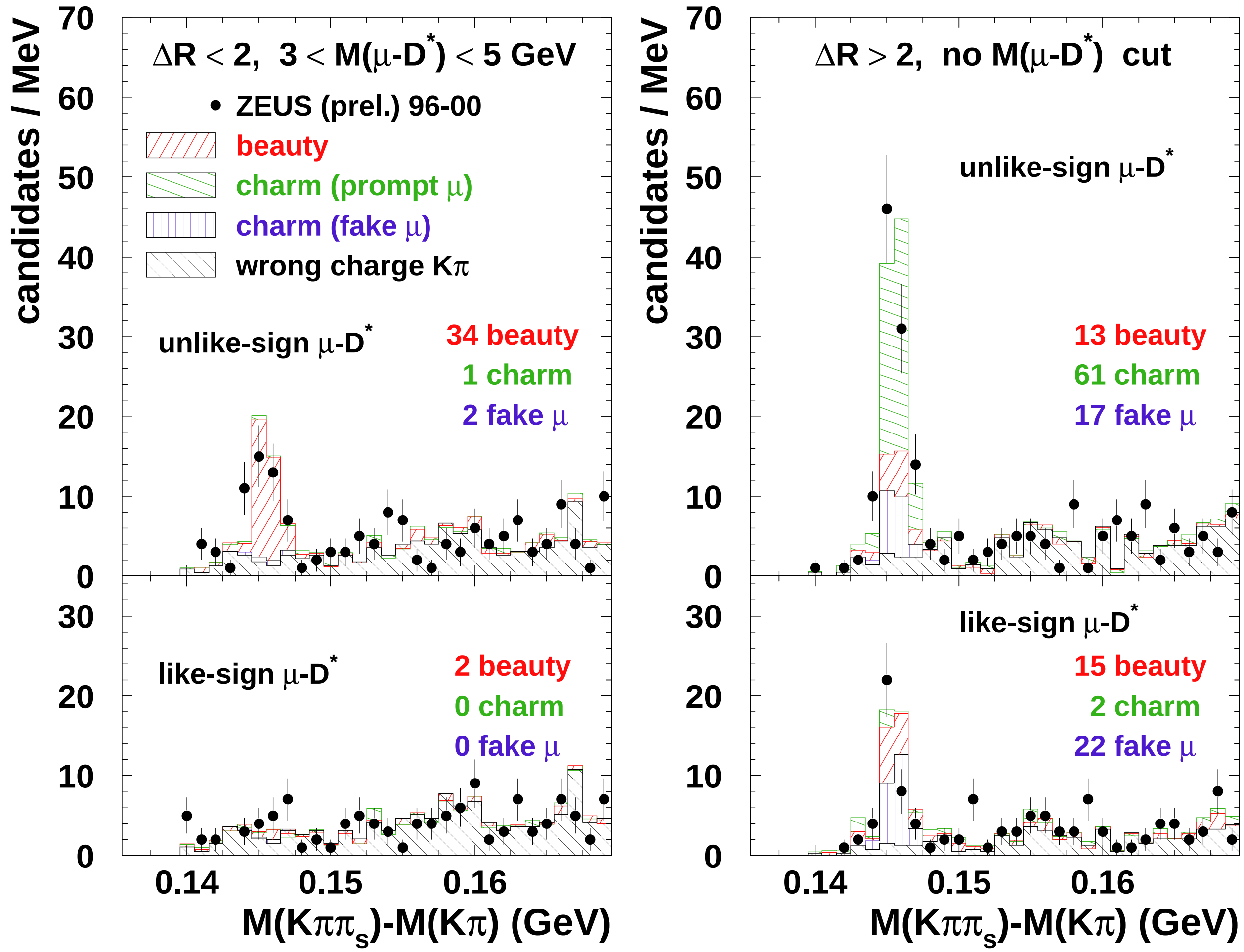
γp cross section

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

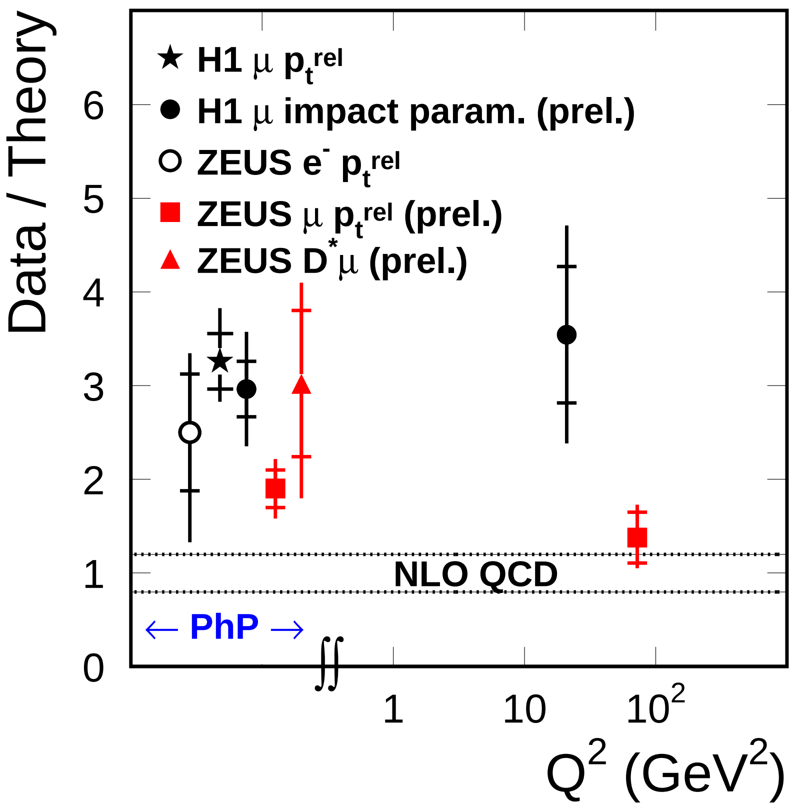
$$\sigma(ep \rightarrow b\bar{b}X) = (15.1 \pm 3.9^{+3.8}_{-4.7})\,\text{nb}$$

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

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



Beauty Production Summary



Present results show:

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

Independent of method (p_T^{rel}, δ, $D^*\ \mu$)

and independent of experiment (H1 or ZEUS)

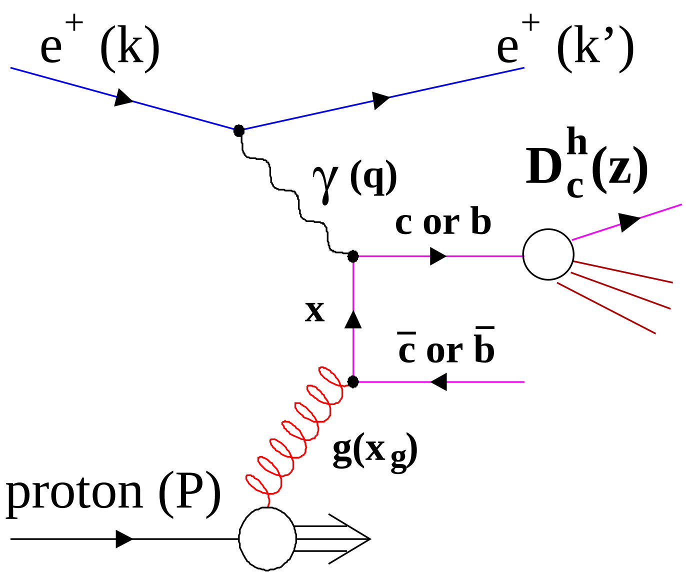
Differential analyses have given new insights:

Excess is not localised in a specific corner of phase space, e.g. in p_T, η or x_γ^{obs}

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

☞ **A good step forward, but still far from understanding beauty production**

Summary

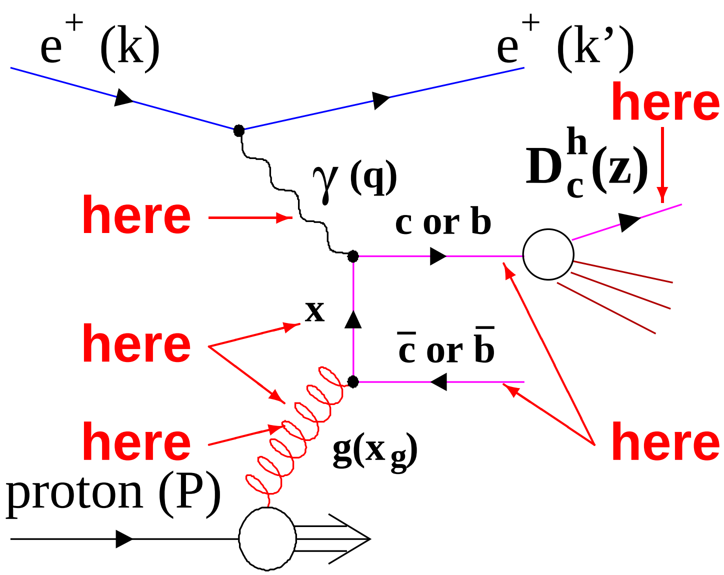


Proton structure $\otimes$ $\sigma_{\gamma g \to Q\bar{Q}}$ $\otimes$ photon structure $\otimes$ fragmentation function

Summary

- High statistics charm and beauty production data are used for detailed studies on the production mechanism

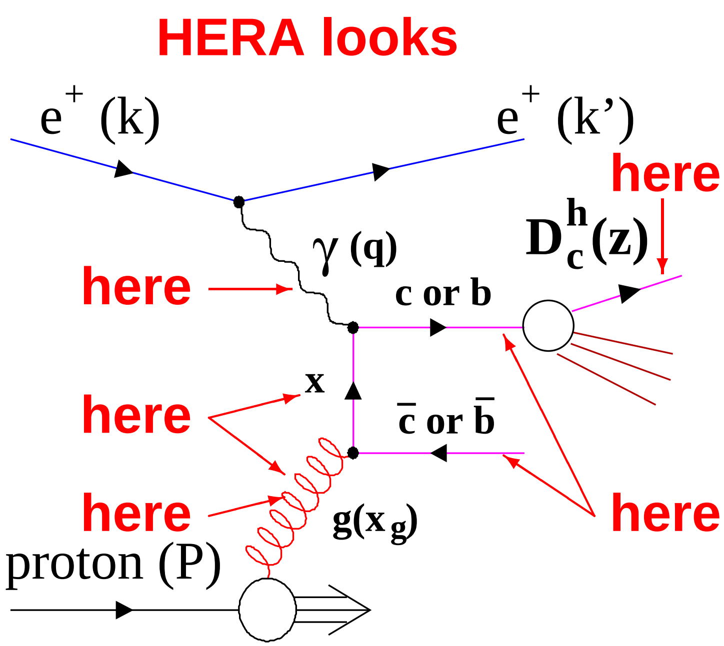
HERA looks



Proton structure $\otimes$ $\sigma_{\gamma g \to Q\bar{Q}}$ $\otimes$ photon structure $\otimes$ fragmentation function

Results: $\Uparrow$ here $\Uparrow$ here $\Uparrow$ here $\Uparrow$ here

Summary



- High statistics charm and beauty production data are used for detailed studies on the production mechanism
- The question of the heavy quark masses has not been addressed yet experimentally
- More to come from final HERA-I data and even more insight from HERA-II

- None of the models describes all aspects
- None of the QCD calculations describes all aspects
- Precision of data much better than theoretical uncertainties

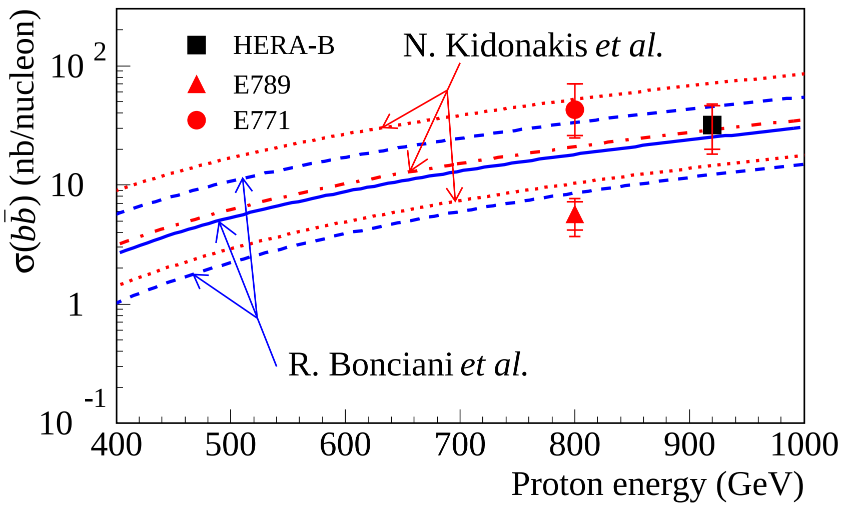
Proton structure $\otimes$ $\sigma_{\gamma g \to Q\bar{Q}}$ $\otimes$ photon structure $\otimes$ fragmentation function

Results: $\Uparrow$ here $\Uparrow$ here $\Uparrow$ here $\Uparrow$ here

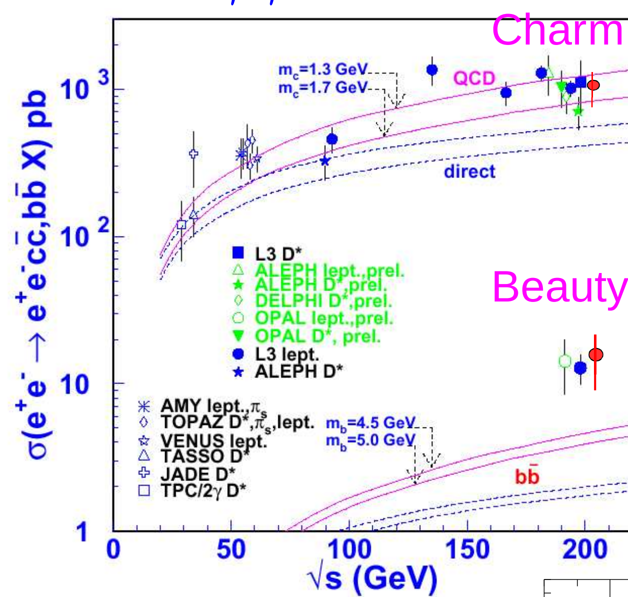
☛ More theoretical effort needed !

Overview: Beauty-Production: The World

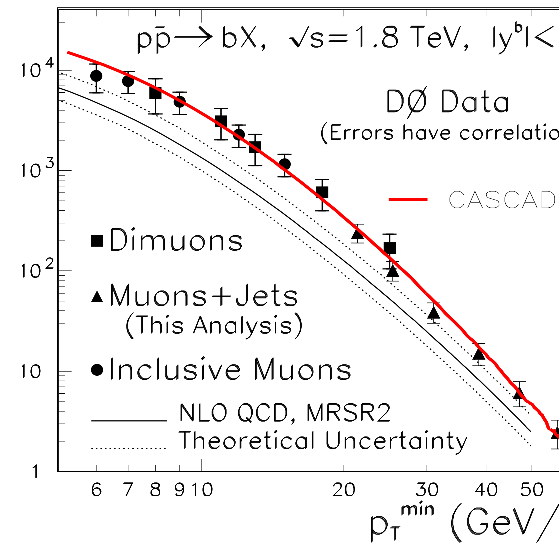
HERA-B

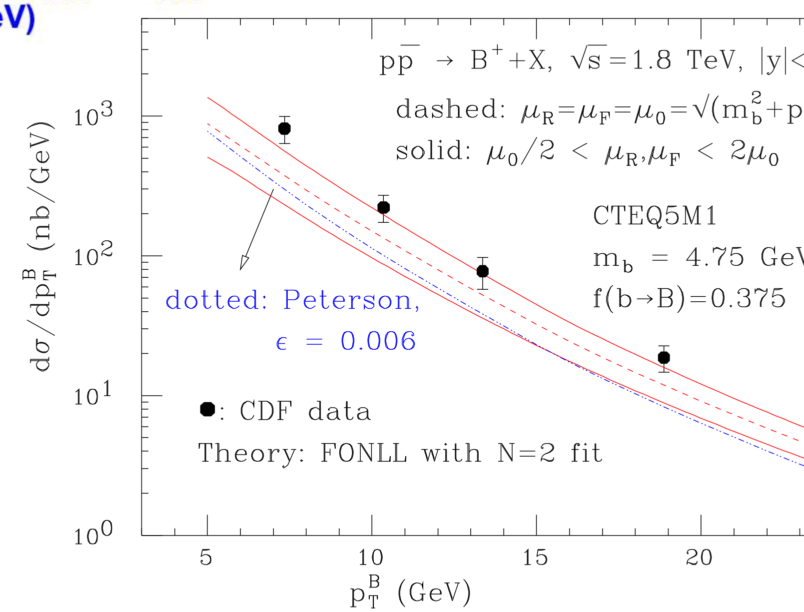


$\gamma\gamma$ LEP



$p\bar{p}$ 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