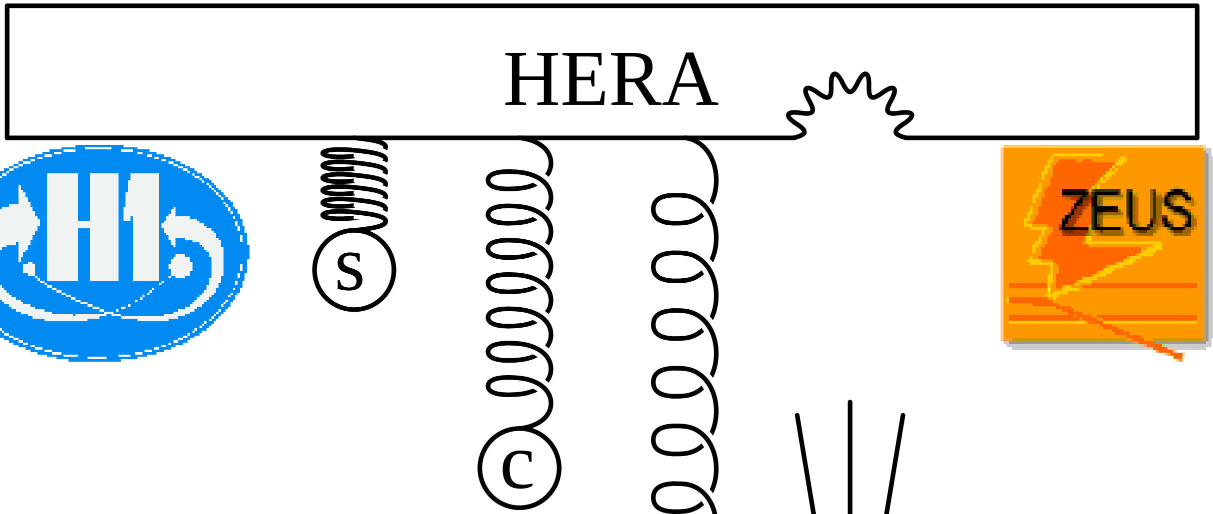
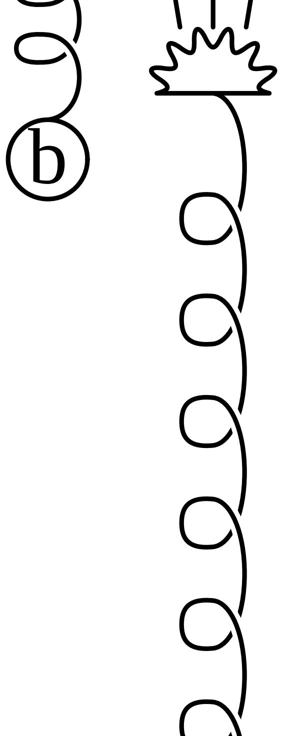
Open Charm and Beauty Production at HERA





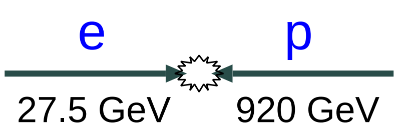
Gero Flucke

DESY Hamburg

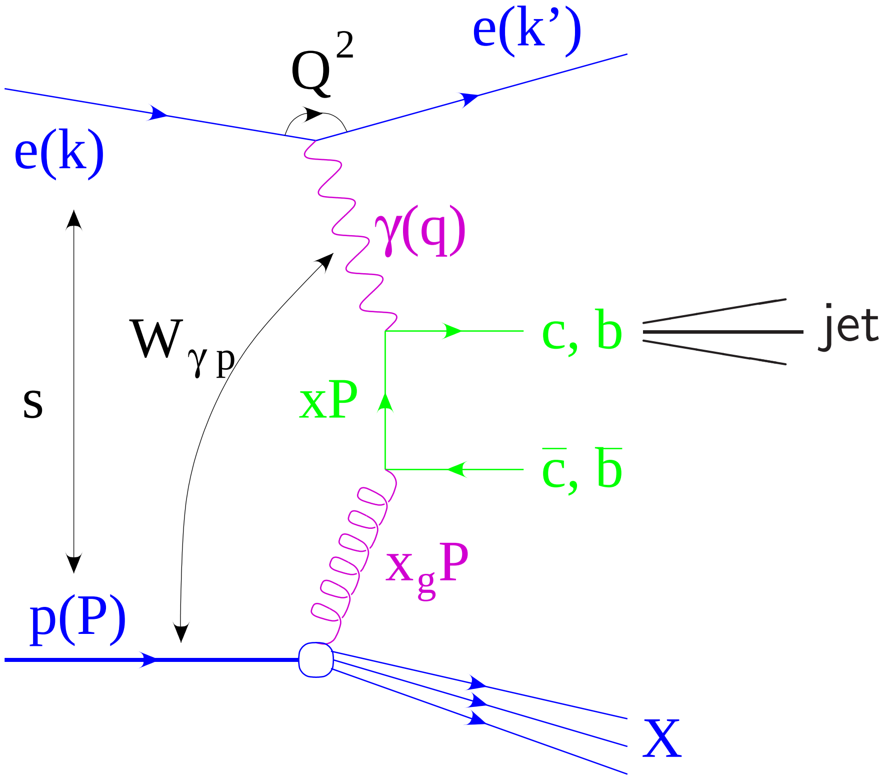
- D^* (and Jets) in DIS
  in Photoproduction

- $b \to \mu$ jet X in Photoproduction
  in DIS

Heavy Flavour Production at HERA: Kinematics



Boson-gluon fusion (LO)



$\sqrt{s} = 320$ GeV
$W_{\gamma p}$: γp center of mass energy

$Q^2 < 1$ GeV^2: Photoproduction
$Q^2 > 1$ GeV^2: DIS

y: Rel. energy loss of e in p rest frame

$x_g = 10^{-3} \ldots 10^{-1}$

$p_t^{jet} = 4 \ldots 25$ GeV

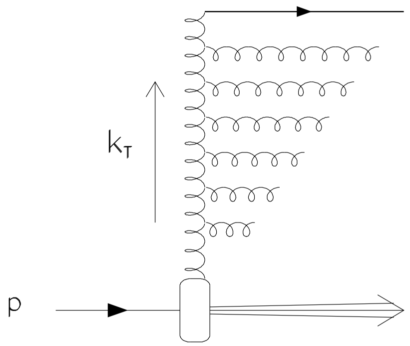
$\Longrightarrow$ Production close to threshold

QCD in Heavy Flavour Production: p-structure

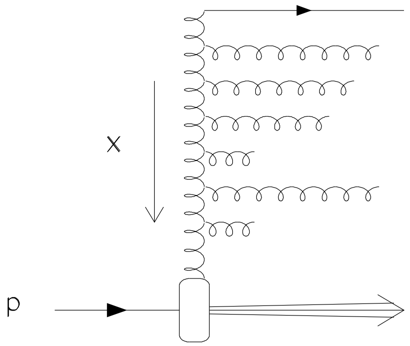
Factorisation: p structure $\otimes$ . . .

- Parton densities: $g(x_g, \mu^2, k_t, \ldots)$
- Structure functions: $F_2^{c\bar{c}}$
- Evolution models:

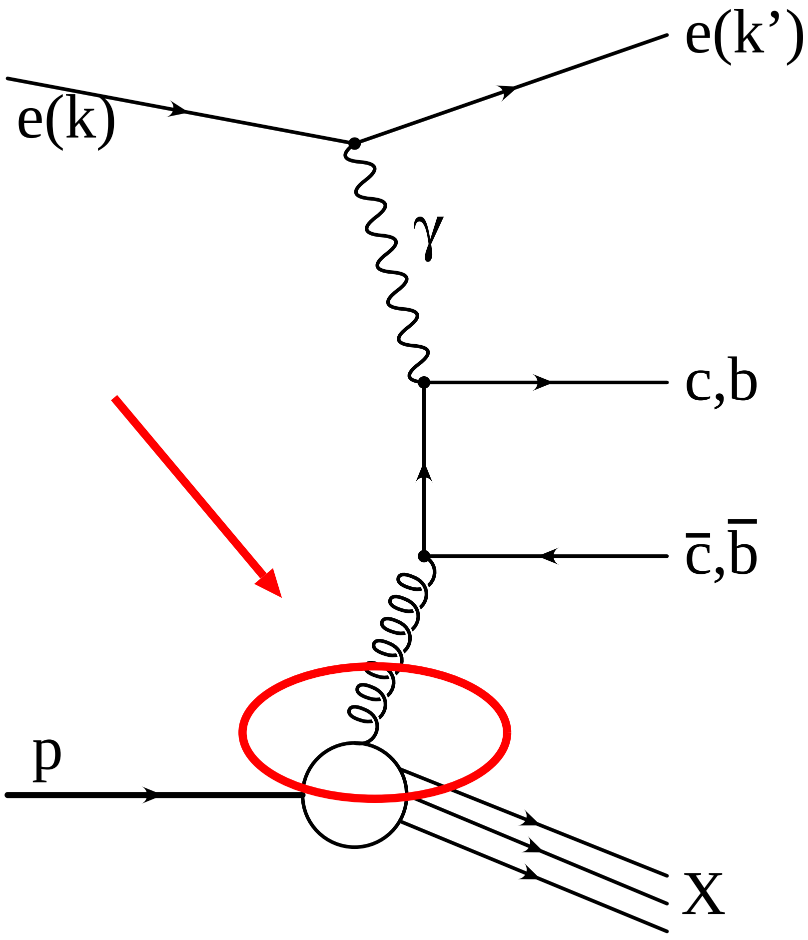
DGLAP



BFKL



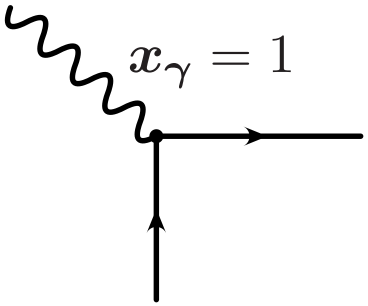
CCFM as interpolation



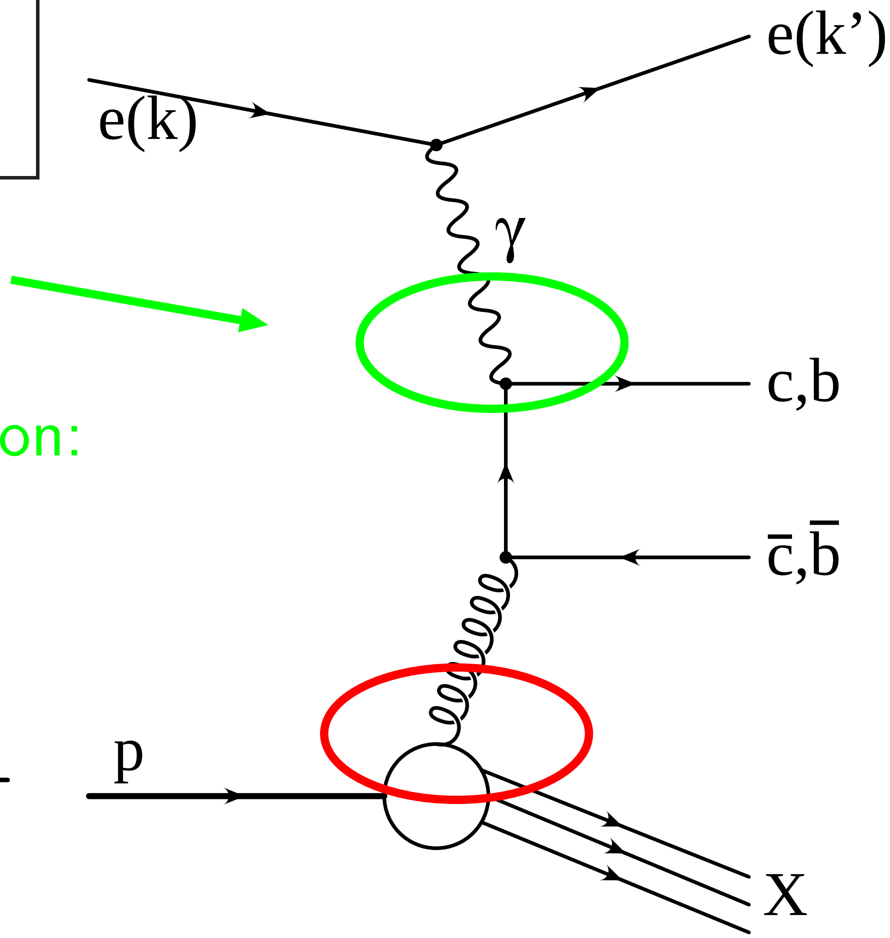
QCD in Heavy Flavour Production: γ-structure

Factorisation: p structure $\otimes$ γ structure $\otimes$ . . .

- pointlike photon

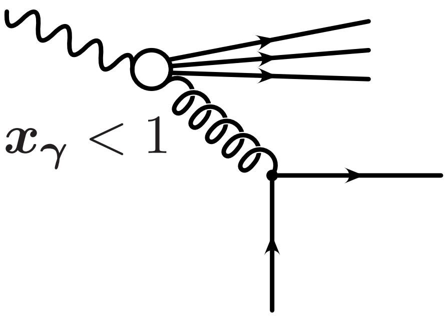


x_γ : Momentum fraction of photon

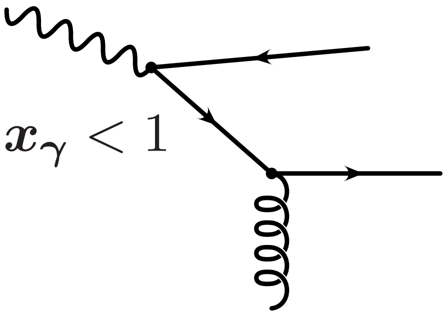


- soft fluctuation before hard interaction:

◇ hadronic component



◇ excitation

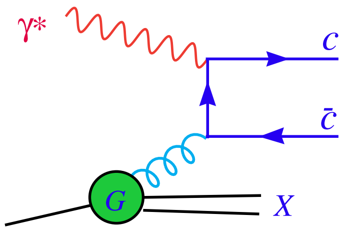


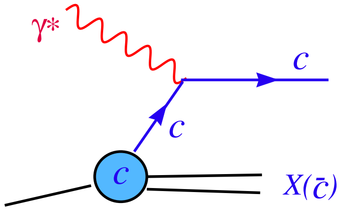
QCD and Heavy Flavour Production: pQCD

Factorisation: p structure $\otimes$ γ structure $\otimes$ pQCD $\otimes$ ...

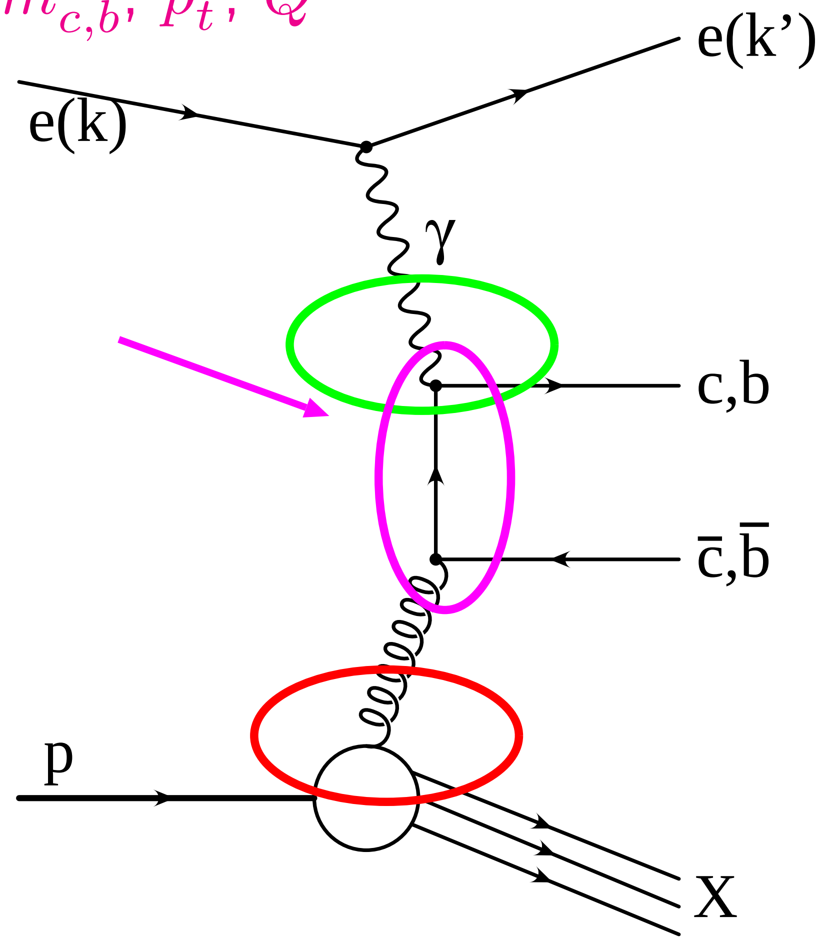
perturbative QCD: *multi scale* problem: $m^2_{c,b}$, p^2_t, Q^2

- NLO (collinear)
  - ◇ Fixed order *massive*
  - ◇ *Massless*





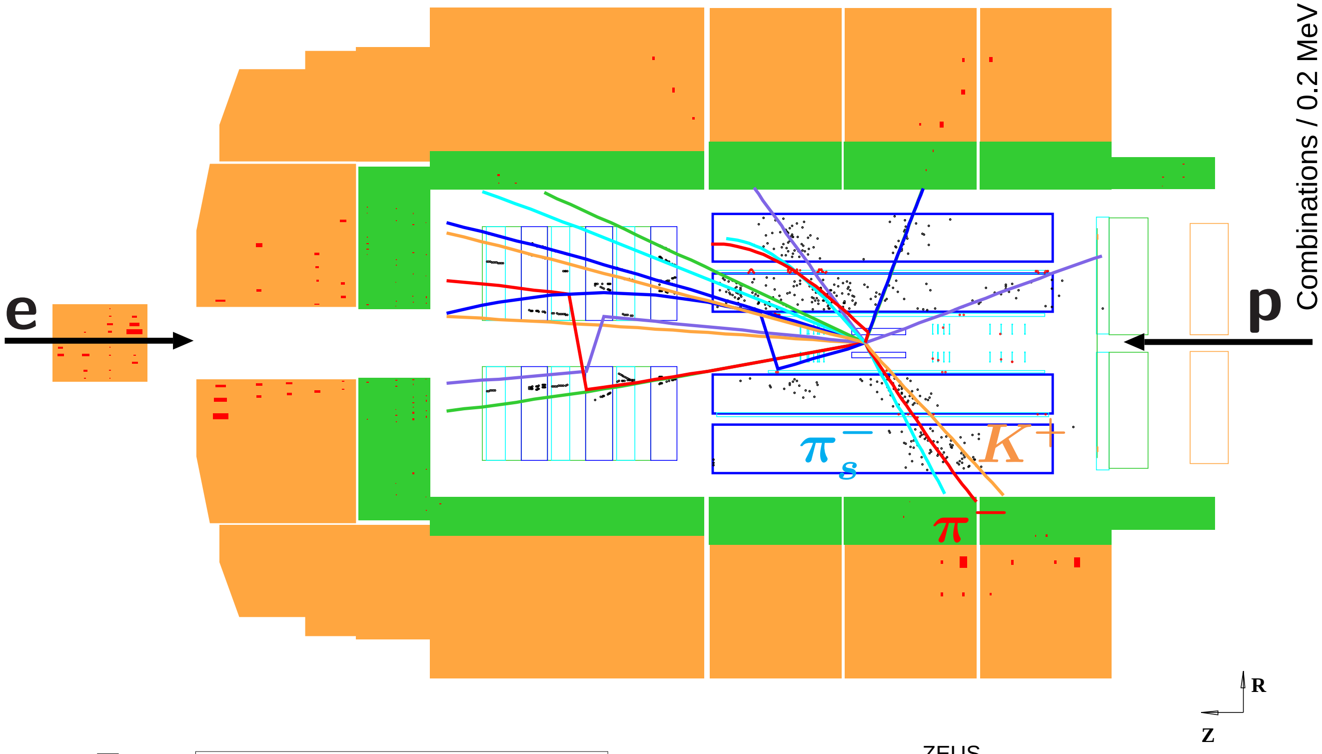
  - ◇ *Matched* scheme (FONLL)
- collinear LO + parton shower
  - ◇ Pythia, Herwig, Rapgap (DGLAP)
- k_t-factorised LO + parton shower
  - ◇ Cascade (CCFM)
- *No* NLO@MC (yet?)

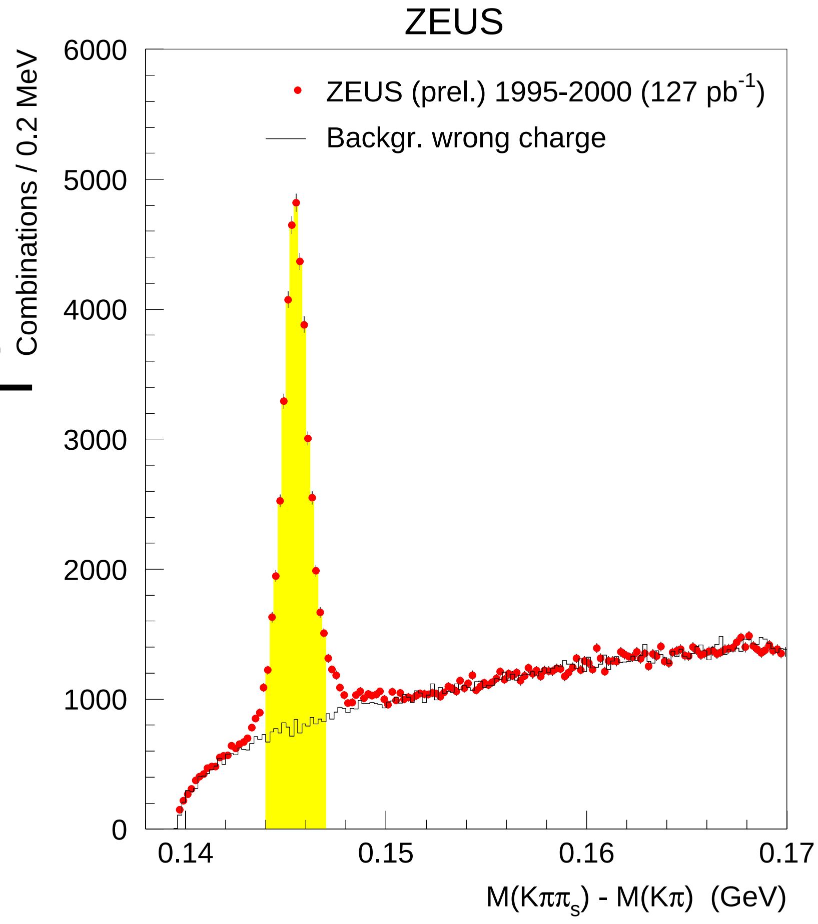


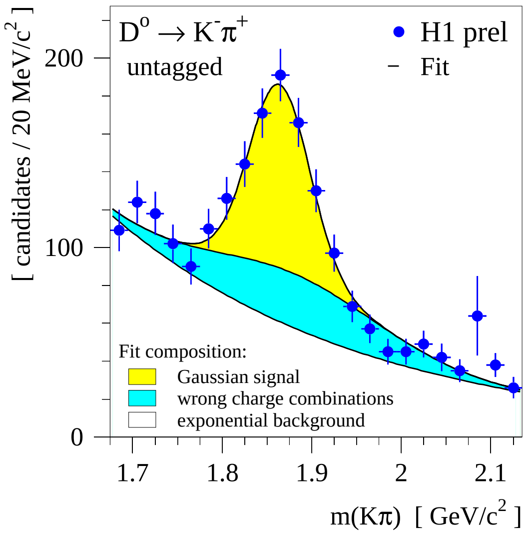
Through the Scales

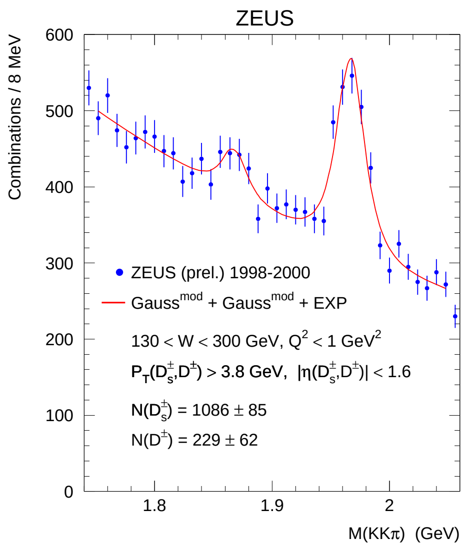
$Q^2 \longrightarrow$ $\downarrow m_Q$	Photoproduction $Q^2 \approx 0$	DIS $Q^2 > 1$ GeV
c 1.5 GeV	D^*, D^* + 2 jets Fragmentation: $c \rightarrow D^?$	D^*, D^* + 2 jets (F_2^c)
b 4.75 GeV	$b \rightarrow \mu jjX$	$b \rightarrow \mu jX$

Charm Tagging









Working horse:

$$D^* \to D^0\pi^\pm \to K^\mp\pi^\pm\pi^\pm$$

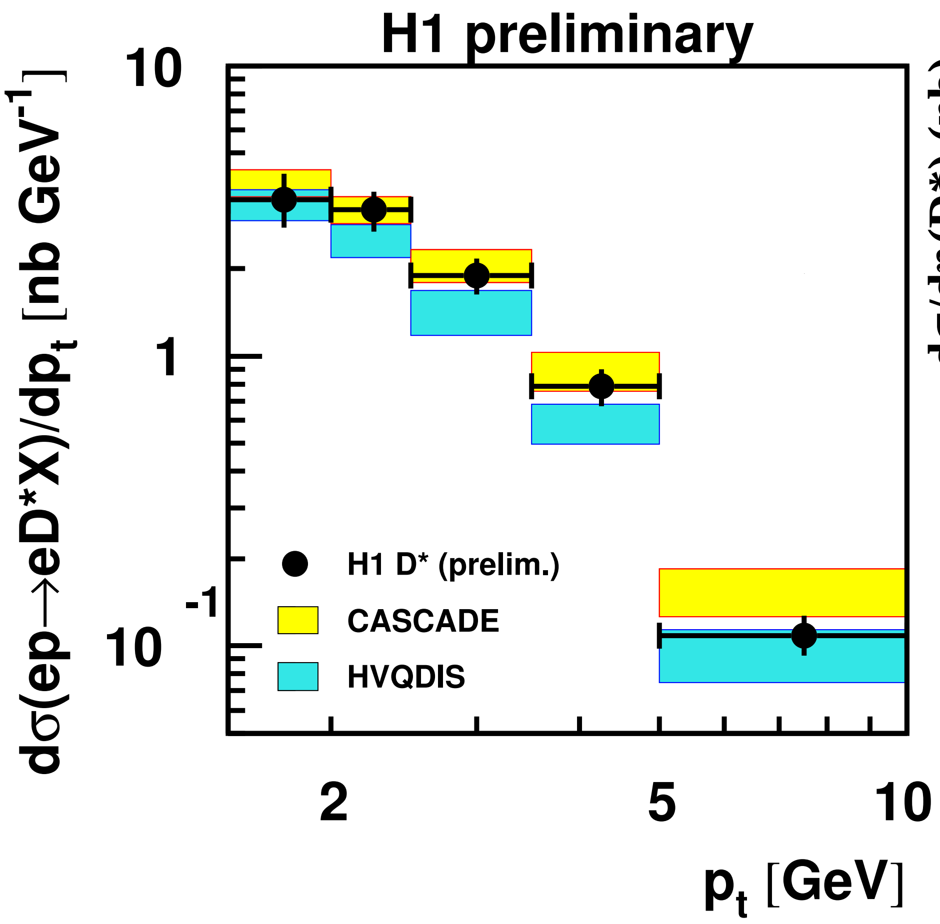
Charm Production in DIS

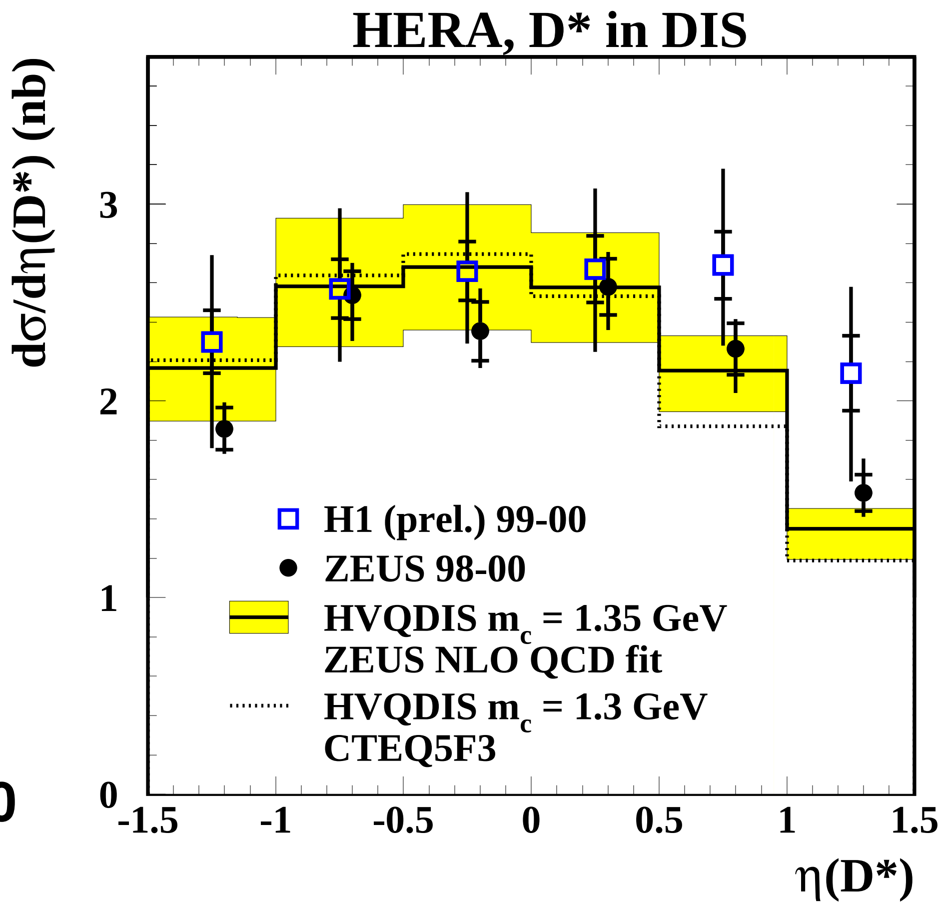
$1.5 \leq p_t(D^*) \leq 15$ GeV, $|\eta(D^*)| \leq 1.5$

$2 \leq Q^2 \leq 100$ GeV^2, $0.05 \leq y \leq 0.7$

ZEUS: 98-00, $\mathcal{L} = 82$ pb^{-1}

H1: 99e^+/00, $\mathcal{L} = 47$ pb^{-1}

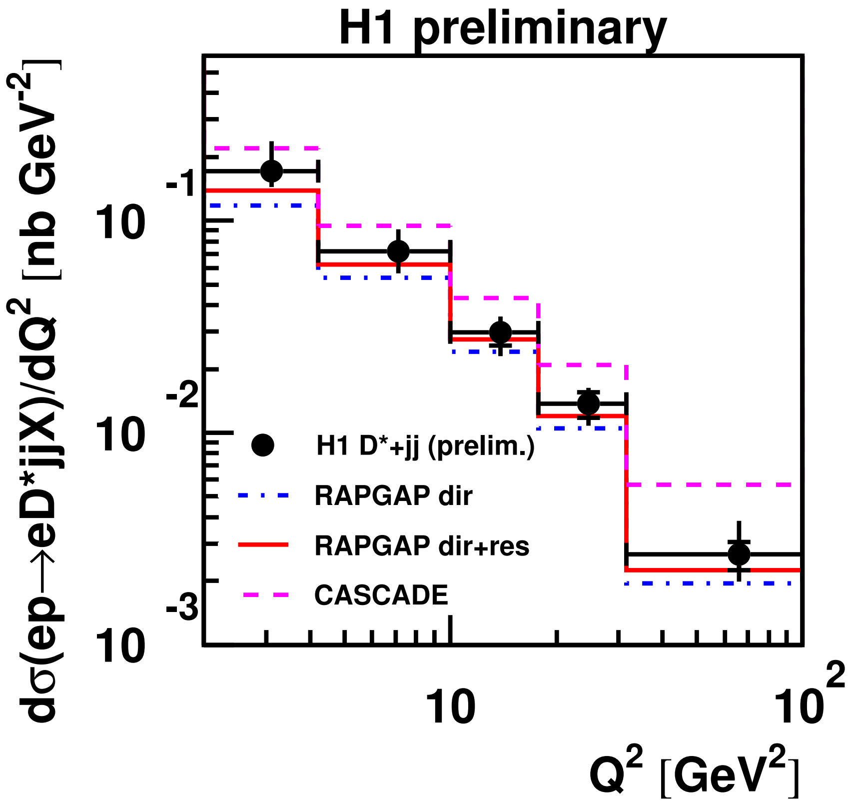


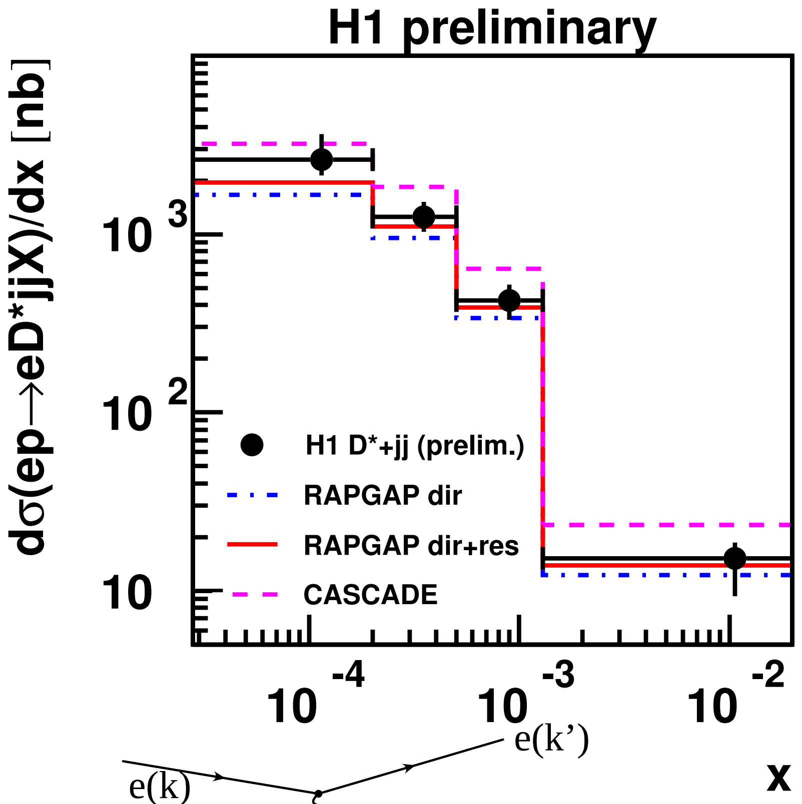


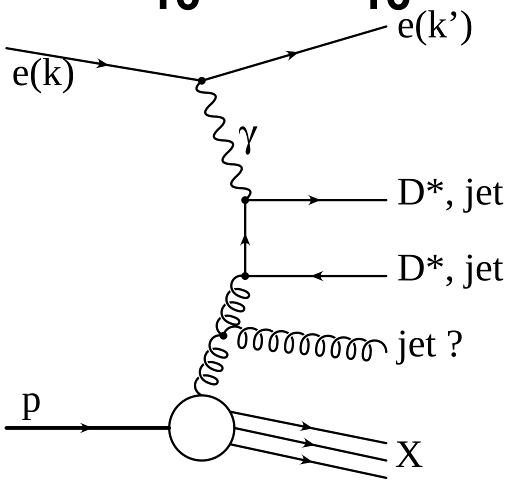
- Cascade tends to be *too hard* in p_t
- *Consistent* with massive NLO

◇ $E_t^{jet1(2)} \geq 3(4)$ GeV
◇ $-1 \leq \eta_{lab}^{jet1(2)} \leq 2.5$ GeV

D^* and 2 Jets in DIS



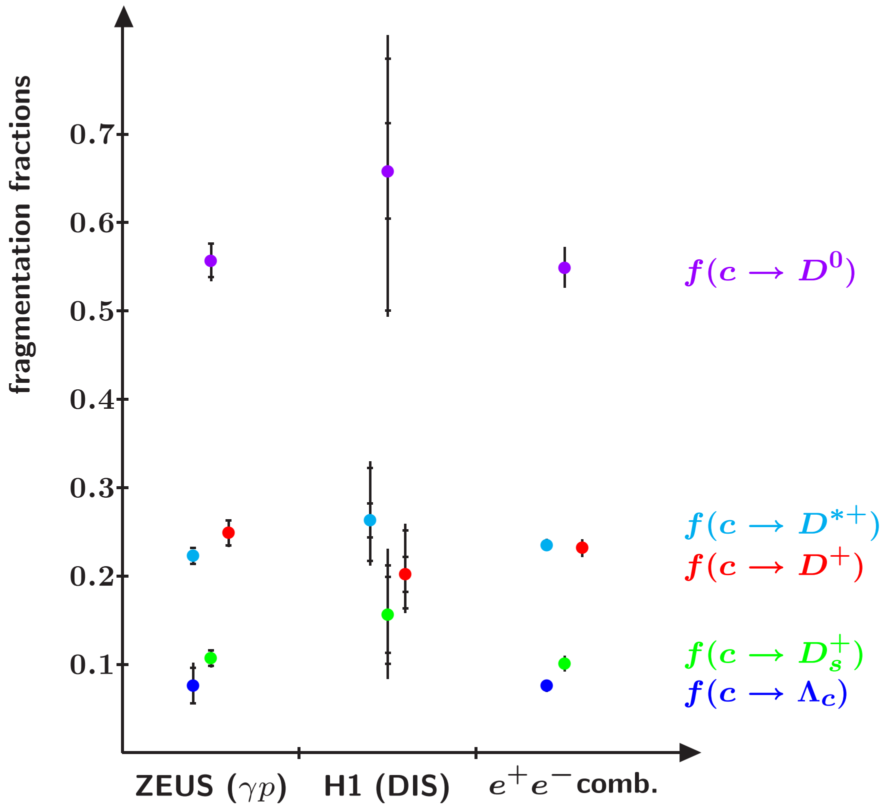


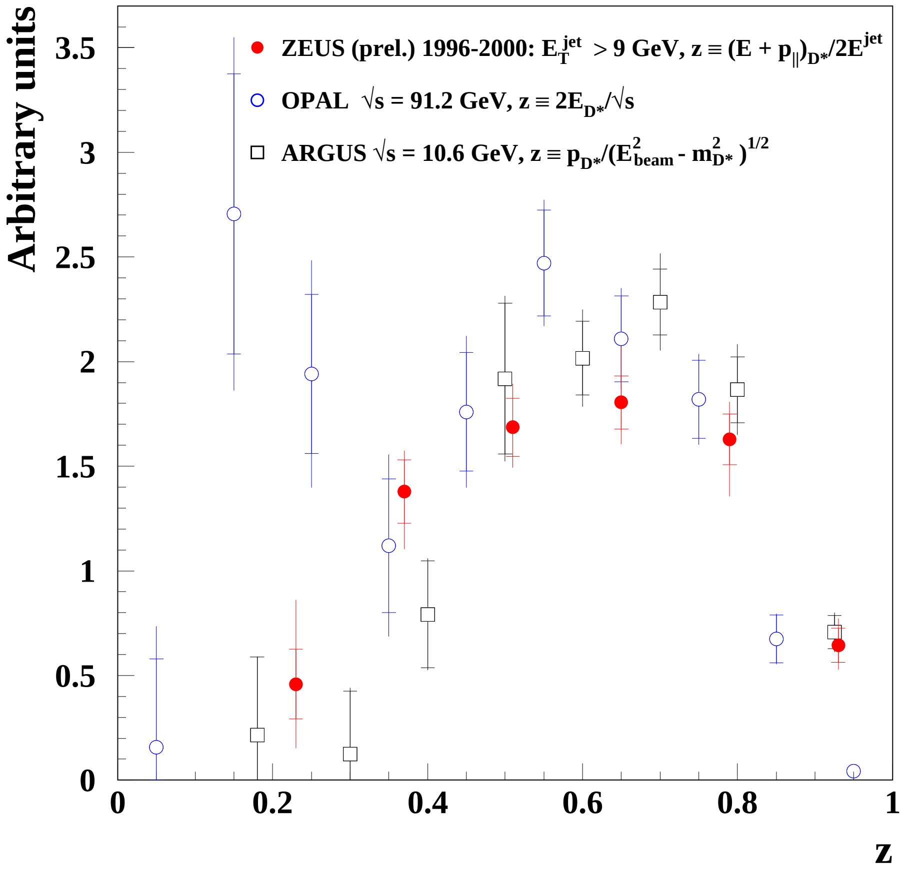


- Cascade now overshoots
- Rapgap now too low (fine without jets)

Fragmentation

Match pQCD calculations with real world: Universal?





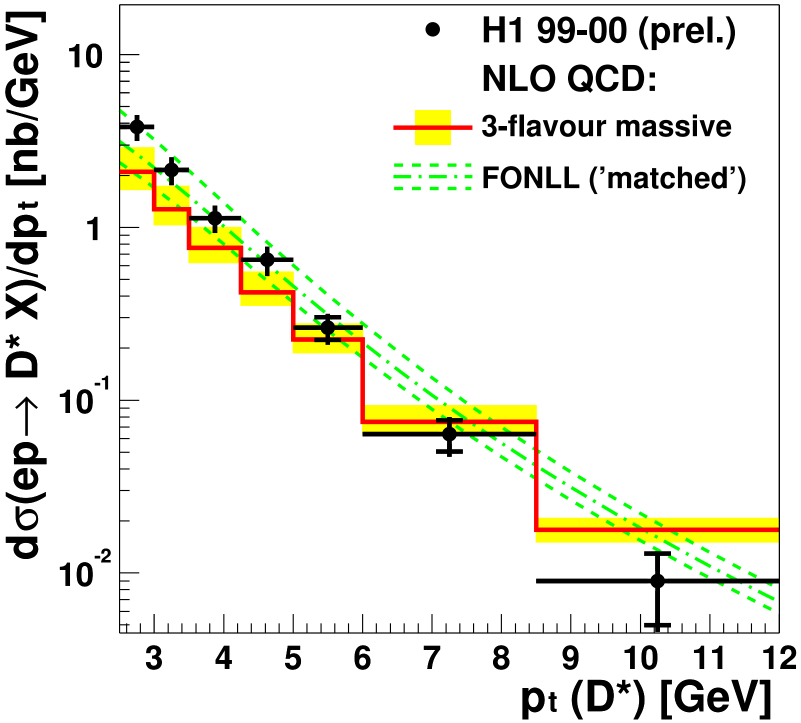
$\Longrightarrow$ Charm fragmentation and fractions the same in e^+e^-, ep, γp (and pp?)

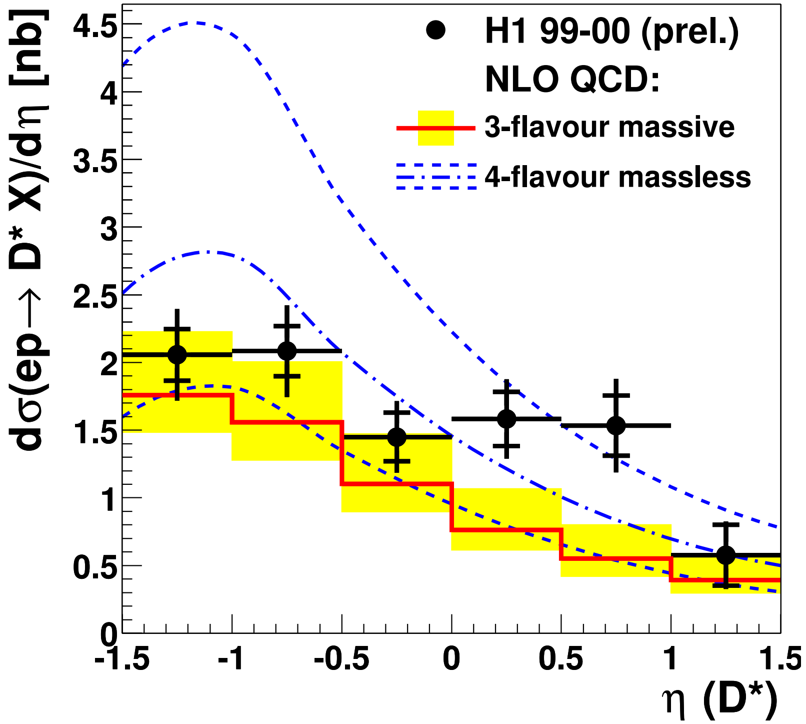
. . . and beauty?

D^* in Photoproduction

H1: D^* + tagged electron, $\mathcal{L} = 49$ pb^{-1}:

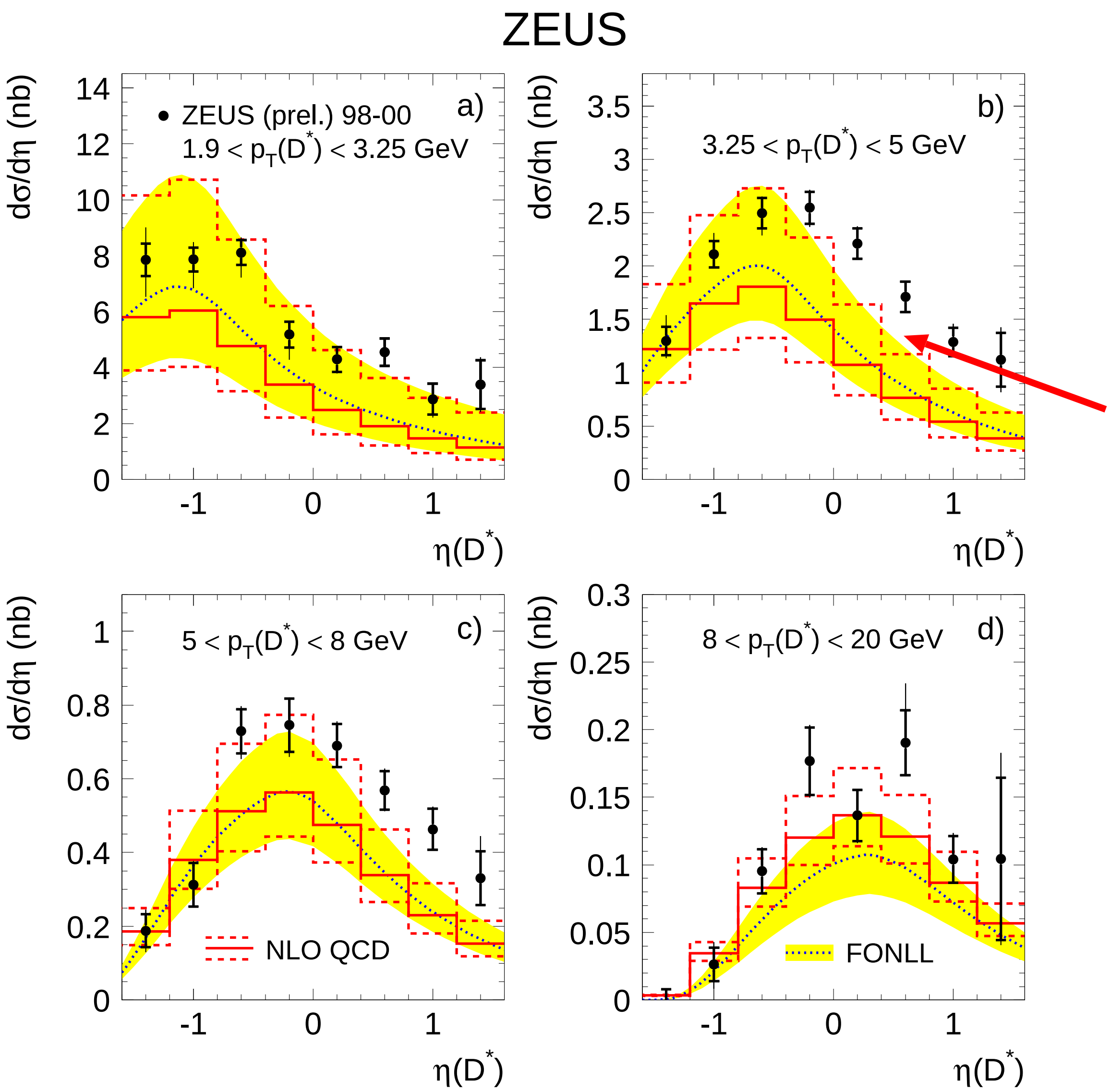
◇ $Q^2 < 0.01$ GeV^2, $171 < W_{\gamma p} < 256$, $p_t^{D^*} > 2.5$ GeV, $|\eta_{D^*}| < 1.5$





- Massive NLO below data, massless NLO reasonable, FONLL reasonable in p_t
- Large theoretical uncertainties ⇒ improvements needed

D^* Photoproduction: Double Differential



$\eta(D^*)$ in bins of $p_t(D^*)$

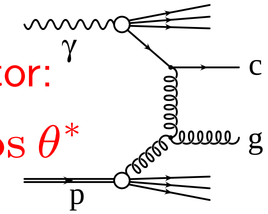
- ZEUS 98-00: $\mathcal{L} = 79$ pb^{-1}
- $Q^2 < 1$ GeV^2, $130 < W_{\gamma p} < 280$ GeV
- $p_t^{D^*} > 1.9$ GeV, $|\eta_{D^*}| < 1.6$

- massive NLO below data at medium $p_t^{D^*}$ and high η_{D^*}
- FONLL close to data only at low $p_t^{D^*}$

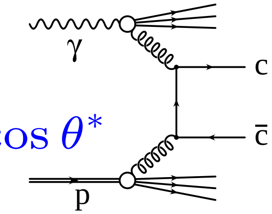
$\Rightarrow$ Theories not able to describe all aspects observed in data

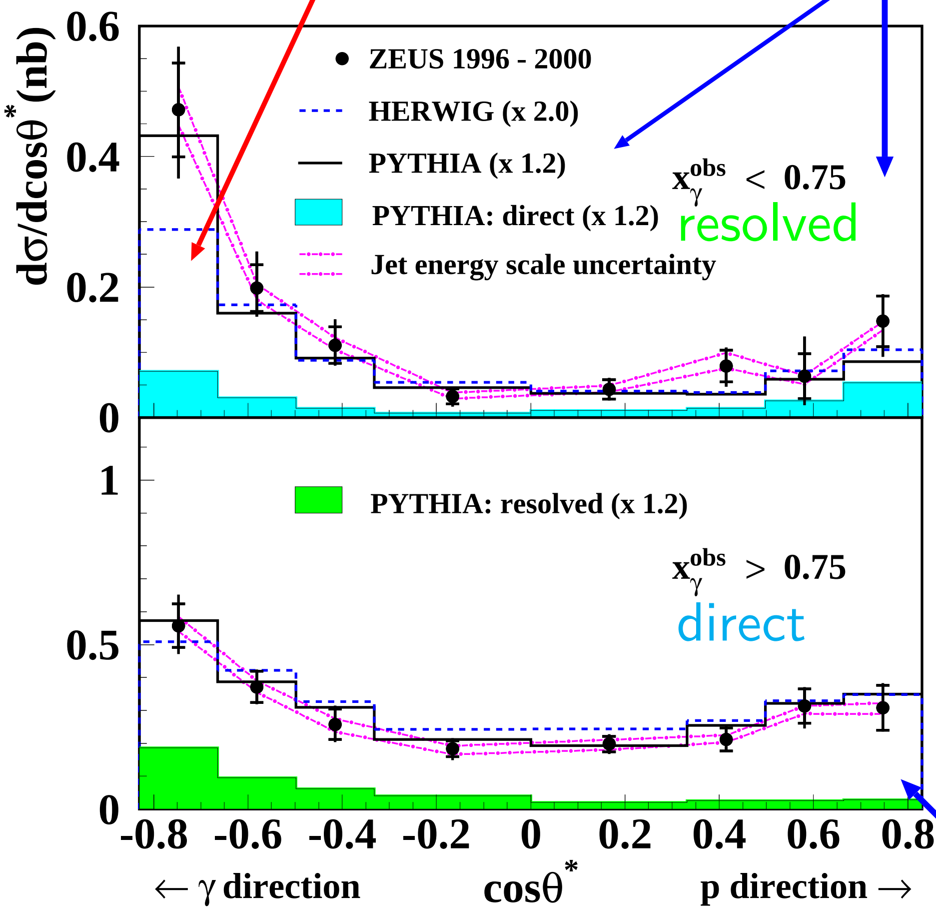
D^* Photoproduction: Dijet Angular Distributions

g-propagator:
steep in $\cos\theta^*$



q-prop.:
flat in $\cos\theta^*$





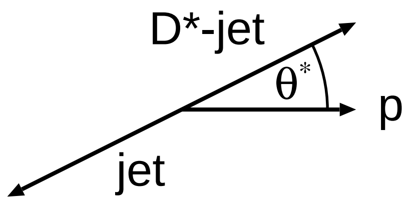
◇ ZEUS 96-00: $D^* + 2$ jets, $\mathcal{L} = 120$ pb^{-1}

◇ $p_t^{D^*} > 3$ GeV, $E_T^{jet} > 5$ GeV, $|\eta^{jet}| < 2.4$, $M_{jj} > 18$ GeV

- Momentum fraction of photon from jets:

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

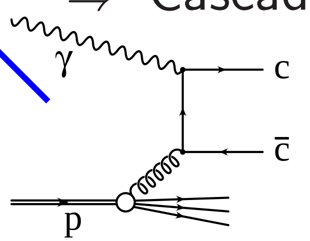
- θ^*: Angle between proton and D^*-jet



⇒ Charm as active flavour in photon

⇒ Massive NLO cannot desrcibe (not shown)

⇒ Cascade OK in shape (not shown)



Charm Summary

- **Fragmentation fractions and functions:**
  independent of hard physics: e^+e^-, ep. pp ?

- **Photoproduction:**
  ◇ NLO calculations with large uncertainties and some problems compared to data
  ◇ Model dependent charm content in the photon

- **Electroproduction (DIS):**
  Reasonable agreement data $\leftrightarrow$ theory,
  . . . but problems to describe full hadronic final state with jets

Need for NLO+PS = NLO@MC ?

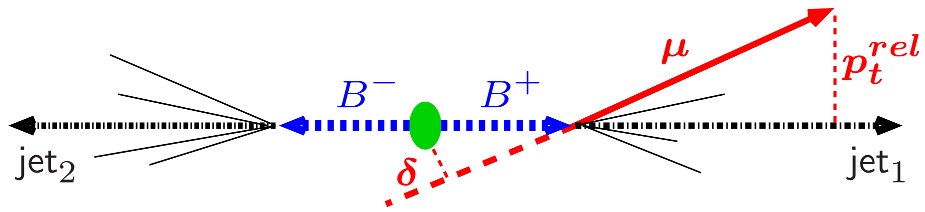
Need for initial k_t?

Beauty Tagging

- $\sigma(b\bar{b})$: Factor $\mathcal{O}(100)$ smaller than $\sigma(c\bar{c})$

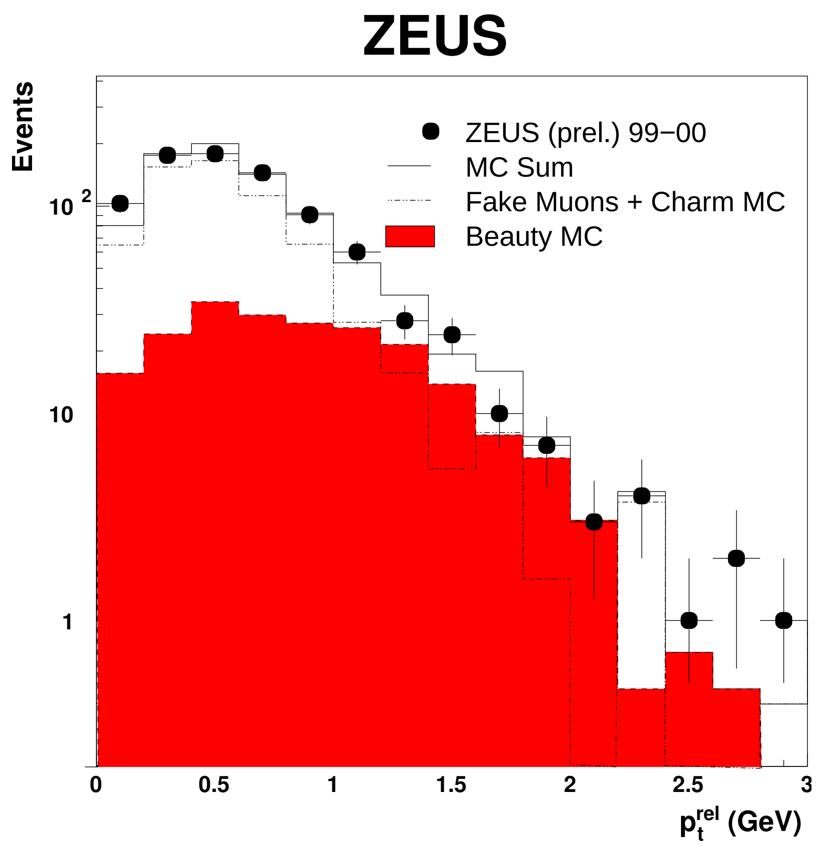
$\Rightarrow$ Use semileptonic $b \rightarrow \mu$ decays

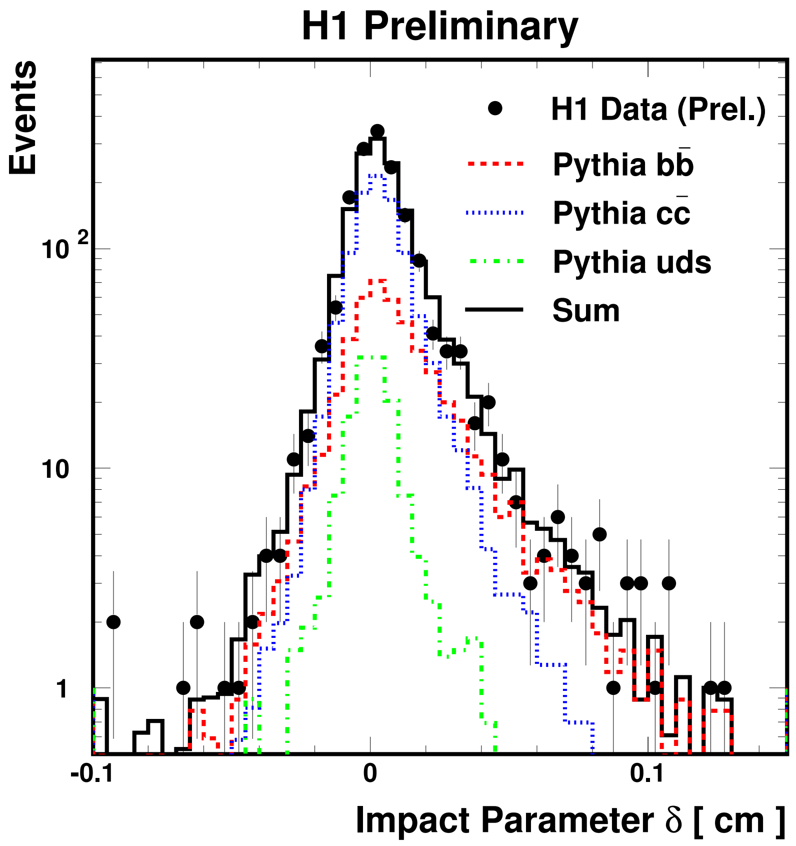
$\longrightarrow$ Two separation variables



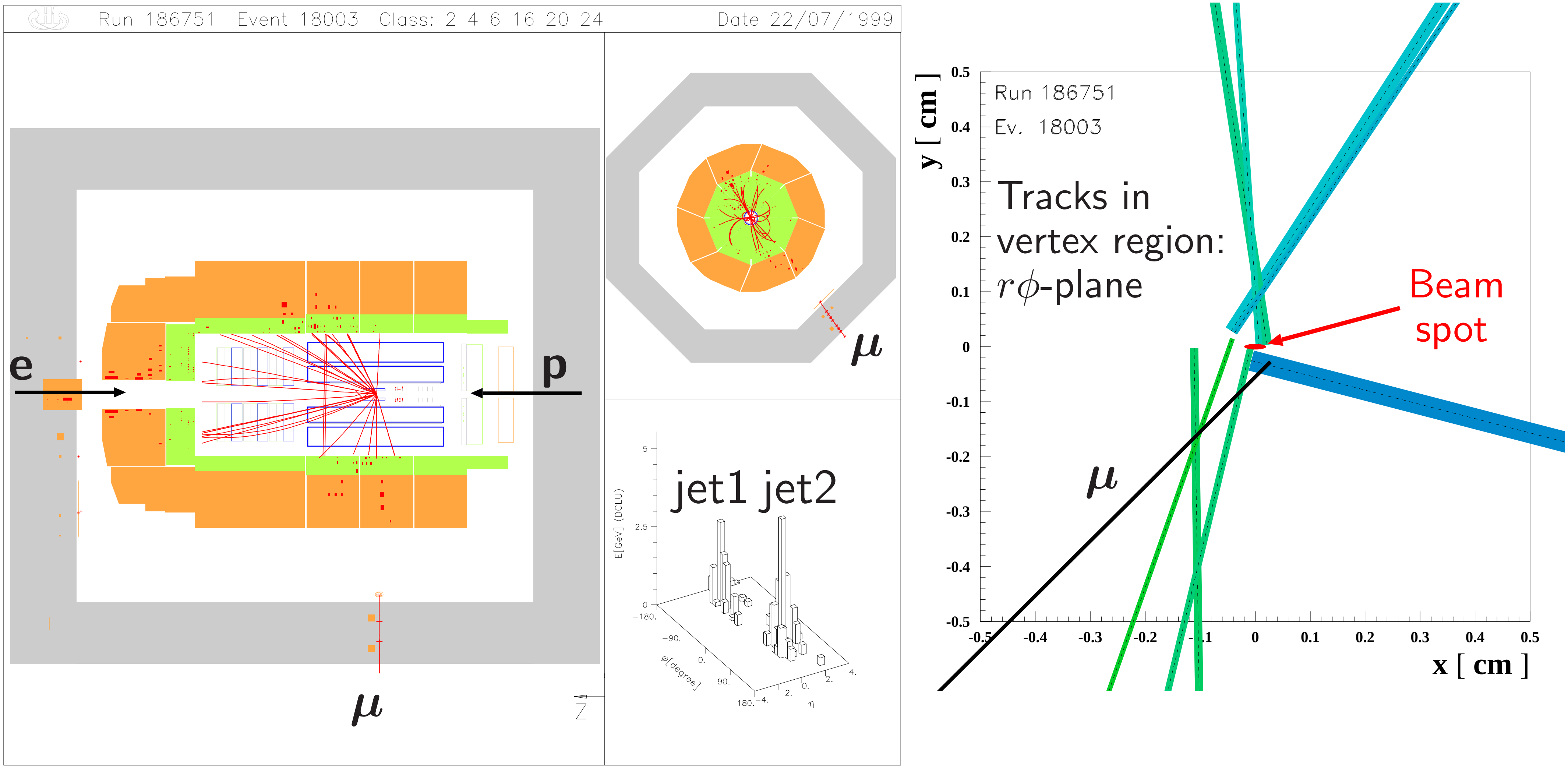
High B-mass $\Rightarrow p_t^{rel}$

Long B-Lifetime $\Rightarrow \delta$ impact parameter





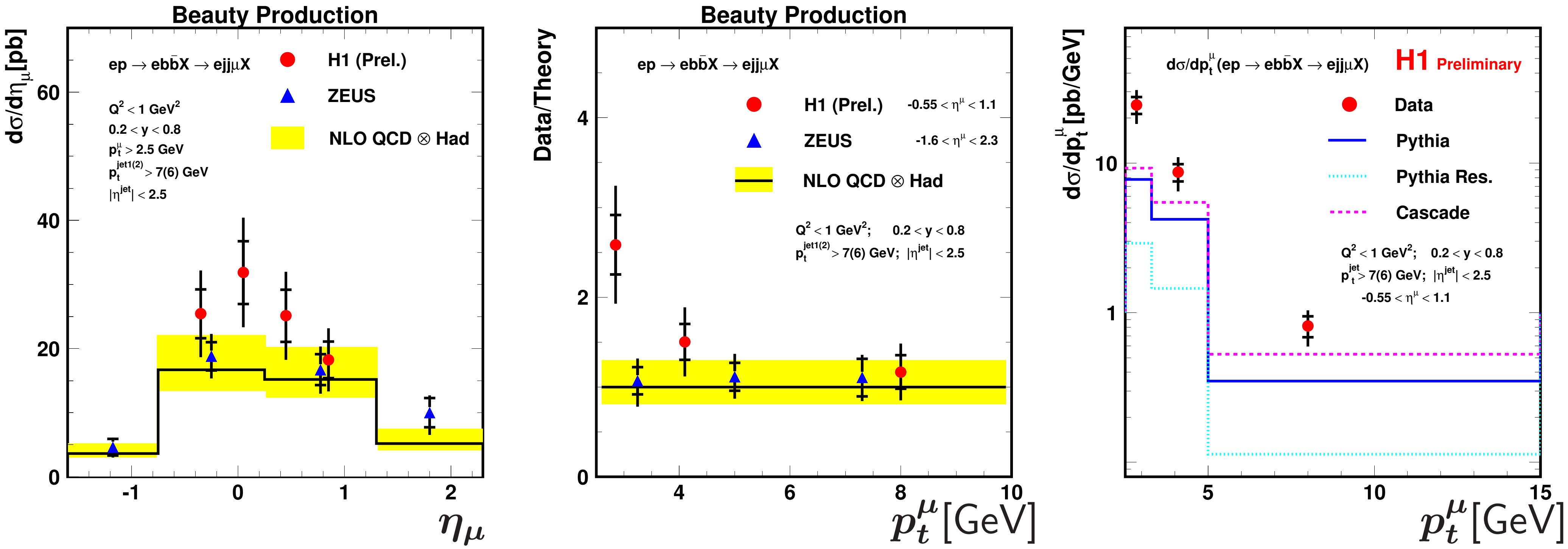
$B \rightarrow \mu X$ Event Candidate



Beauty: Photoproduction

$ep \to eb\bar{b}X \to ejj\mu X$

ZEUS: p_t^{rel} method ($\mathcal{L} = 98$ pb^{-1}) H1: p_t^{rel} and δ combined ($\mathcal{L} = 48$ pb^{-1})

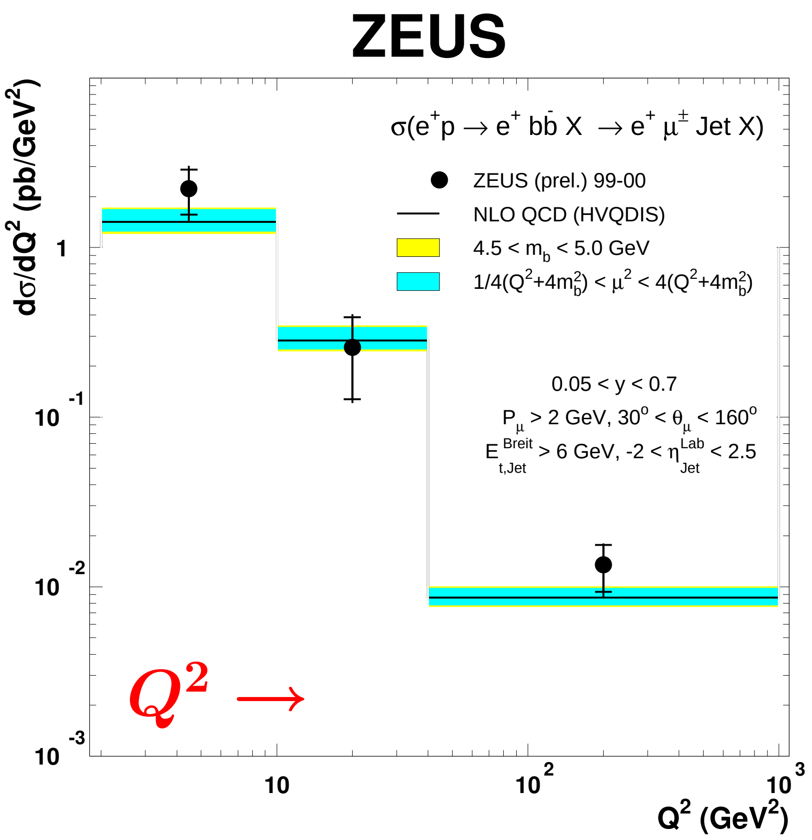


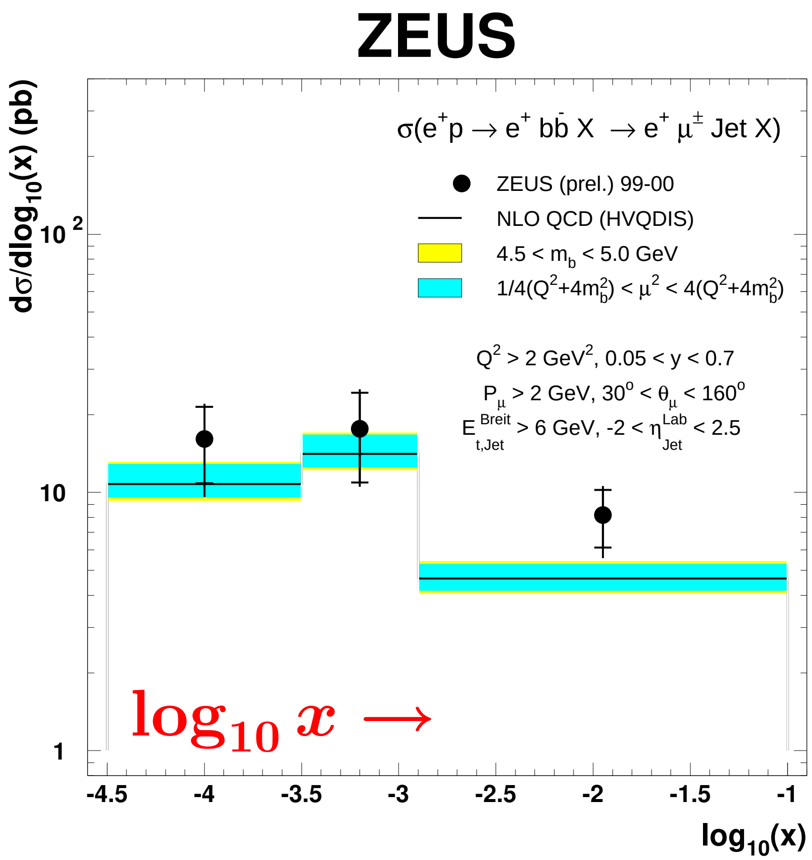
- Reasonable agreement data $\Leftrightarrow$ massive NLO
- But data slightly above prediction: low $p_t(\mu)$?
- LO+PS models: low in normalisation (parameter dependent)

Beauty Production DIS

$ep \longrightarrow eb\bar{b}X \longrightarrow ej\mu X$

◇ ZEUS ($\mathcal{L} = 120$ pb^{-1}): $Q^2 > 2$ GeV^2, $0.05 < y < 0.7$, $p_t^\mu > 2$ GeV, $E_{t,jet}^{Breit} > 6$ GeV

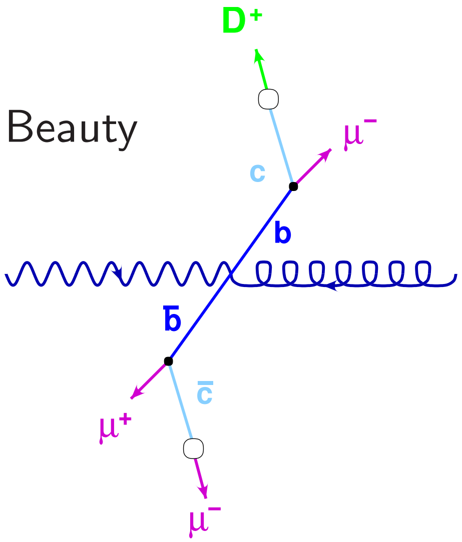




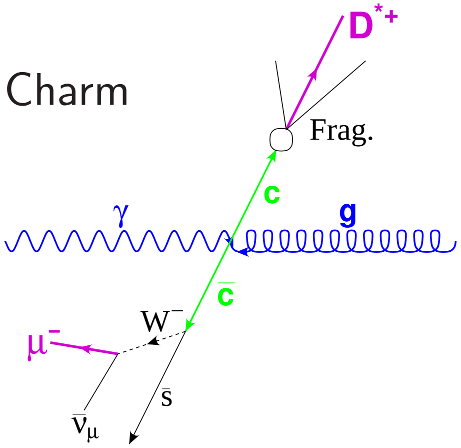
$\Longrightarrow$ Data and massive NLO agree

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

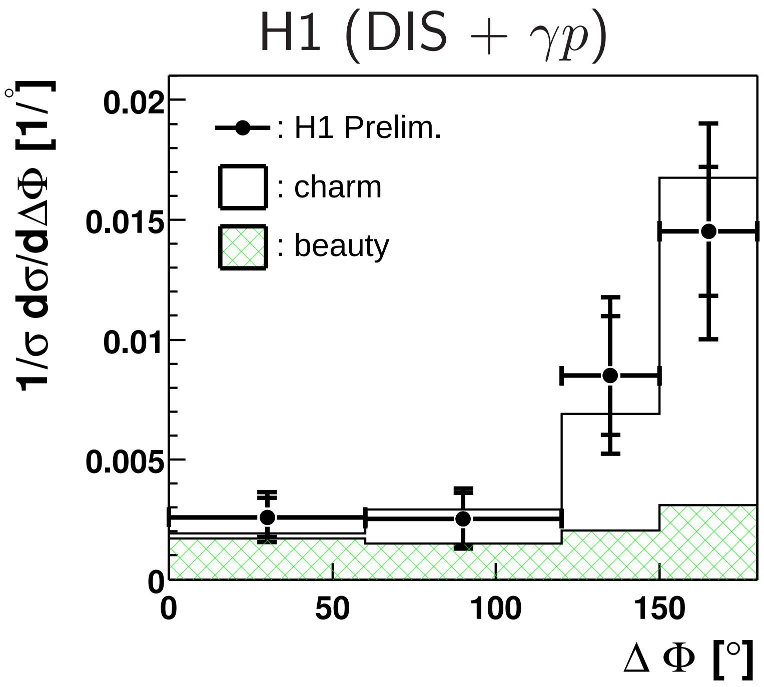
Beauty



Charm



c-b separation using charge and angular correlations

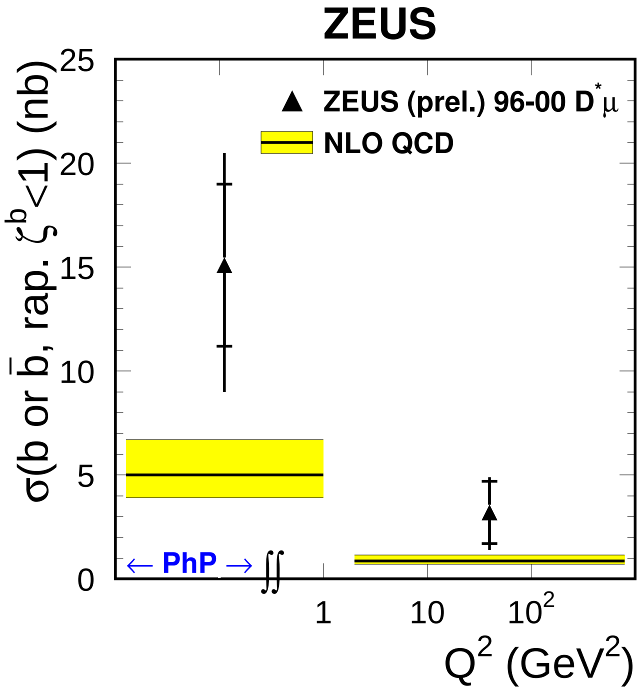


- ◇ LO $Q\bar{Q}$ picture:
  $\Delta\Phi = 0^\circ$ (c)
  $\Delta\Phi = 0^\circ$ or 180° (b)
- ◇ Smearing due to NLO and fragmentation

Data > NLO QCD, but large errors

Data versus NLO QCD:

b or $\bar{b}$ cross section



Beauty Summary

- Many new differential measurements

- Comparison with massive NLO calculation in visible range:
  - generally good agreement
  - slight tendency to understimate data
  - reconstruction of both heavy quarks ($D^*\mu$): not yet precise enough to judge

Fragmentation: Not at all measured for Beauty: Can it be an issue?

Perturbative QCD: Precise enough for more differential distribution as in Charm?

Finally

- Heavy quark production at HERA as a testing ground for QCD
- HERA is a driving force in develloping heavy quark production theory:
  Results are very promising
- More detailed measurements of final state are a new challenge for theory

---

$\Rightarrow$ Finalizing HERA I data

$\Rightarrow$ Start HERA II analyses with

- higher statistic (luminosity)
- better precision (silicon)
- more phase space (forward)

QCD and Heavy Flavour Production

Factorisation: p structure $\otimes$ γ structure $\otimes$ pQCD $\otimes$ fragmentation

- $c \longrightarrow D^*, D^{\pm}, D^0, \Lambda_c, \ldots$
- $b \longrightarrow B^0, \bar{B}^0, \ldots$

Hadron fractions?

Energy transfer quark $\rightarrow$ hadron?