Charm and beauty production at HERA

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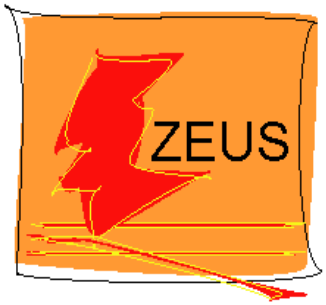
DESY

On behalf of the **H1** and **ZEUS** Collaborations

QCD@LHC, DESY, Hamburg, Germany



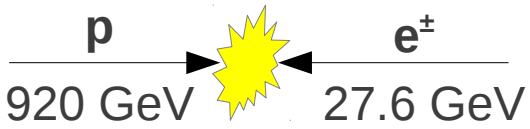
2nd September 2013

HERA ep collider

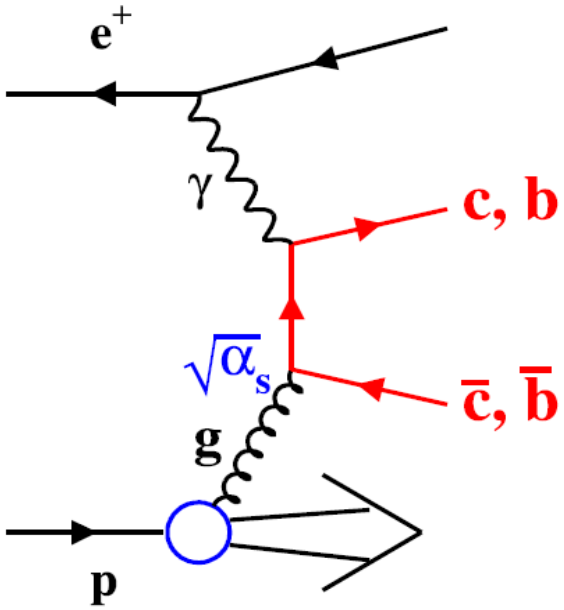
HERA – ep collider, *1992-2007*:

- Center-of-mass energy **318 GeV**
- Two collider experiments: **H1** and **ZEUS**

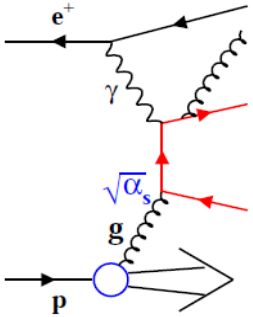
Totally accumulated **~500 pb^{-1}** of data per experiment



Charm and beauty production at HERA



LO process (BGF)

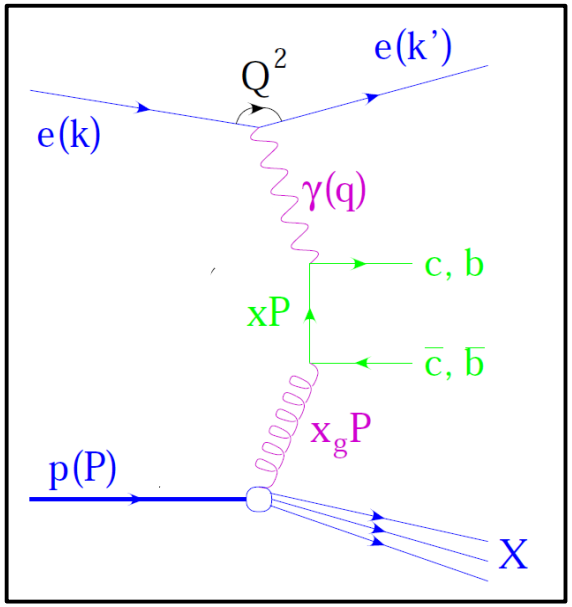


NLO process

- Main process of c&b production at HERA – **Boson-Gluon Fusion (BGF)** (photon exchange dominating)
- Directly sensitive to gluon density in proton
- Test of pQCD – hard scales (m_q, p_t, Q^2)

  Possible to test fragmentation universality with high precision

HERA kinematics and phase space



Set of kinematic variables:

$$Q^2 = -q^2 = -(k-k')^2 \rightarrow \text{Photon virtuality}$$

$$x = \frac{Q^2}{2P\cdot q} \rightarrow \text{Proton momentum fraction in parton}$$

$$y = \frac{P\cdot q}{P\cdot k} \rightarrow \text{Electron energy fraction in photon (}p\text{ rest frame)}$$

Two regimes:

$Q^2 \approx 0$ – Photoproduction

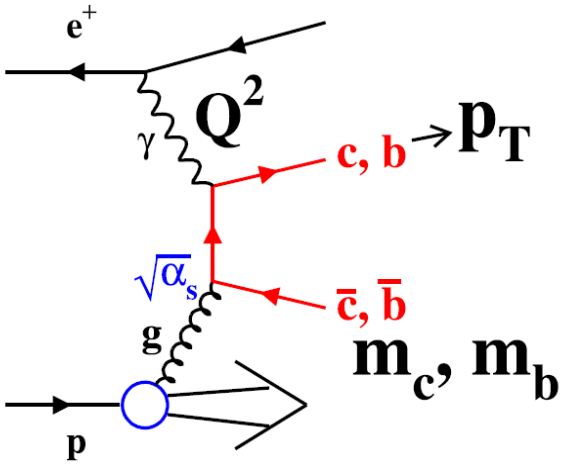
No scattered electron in the detector.

$Q^2 > 1$ – Deep Inelastic Scattering

High-energy electron is scattered to the detector area

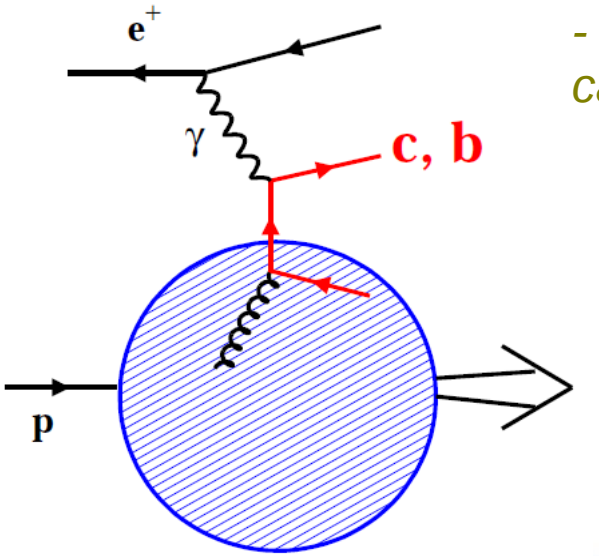
Heavy flavour schemes

Massive scheme: heavy quarks treated fully massive. $Q^2 \sim m_q$



FFNS calculations

Massless scheme: heavy quarks' mass is neglected. $Q^2 >> m_q$



- effects of collinear gluon radiation can be summed up to all orders

ZM-VFNS calculations

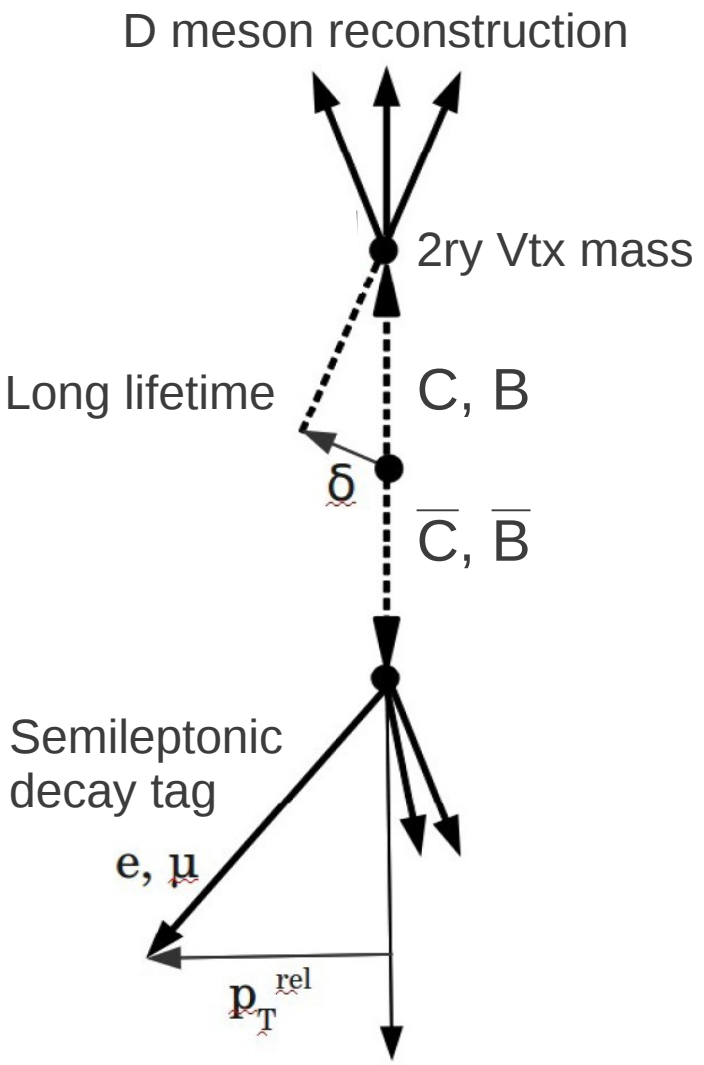
Mixed scheme:
massless at $Q^2 \sim m_q$
and massive at $Q^2 >> m_q$

GM-VFNS calculations

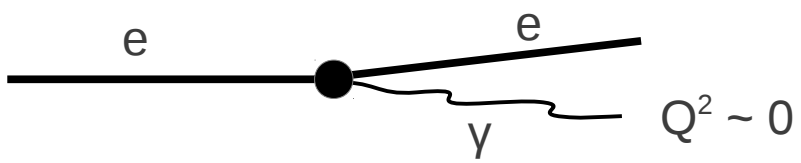
c&b tags

How can we select an event with charm or beauty?

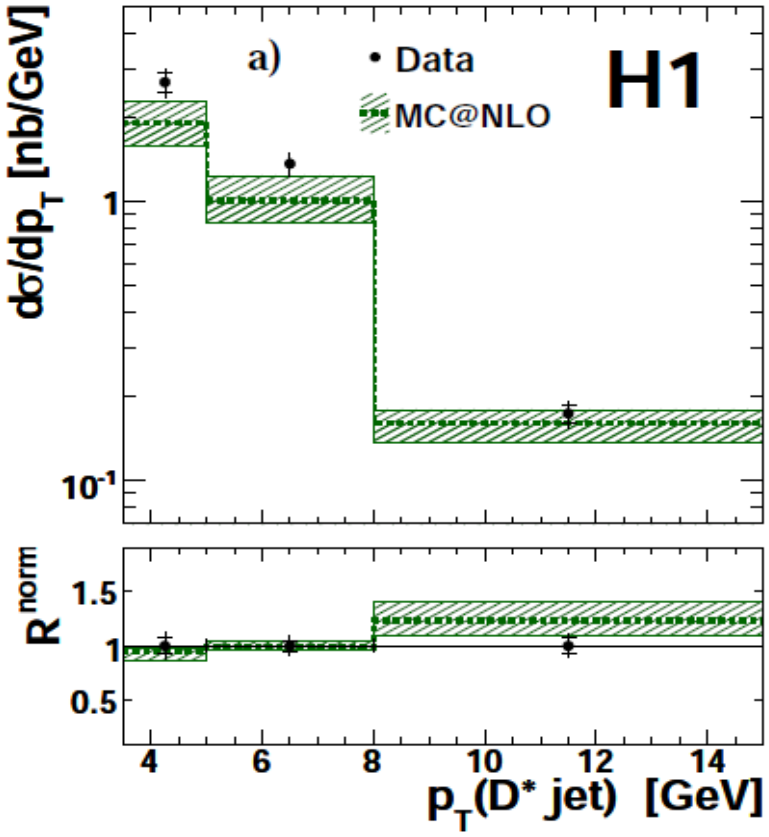
- Full D-meson reconstruction
- Semileptonic decay tag:
  - via lepton impact parameter
  - via the relative pt of the lepton with respect to jet axis
- Long lifetime and heavy flavour mass:
  - displaced secondary vertex
  - mass of the secondary vertex

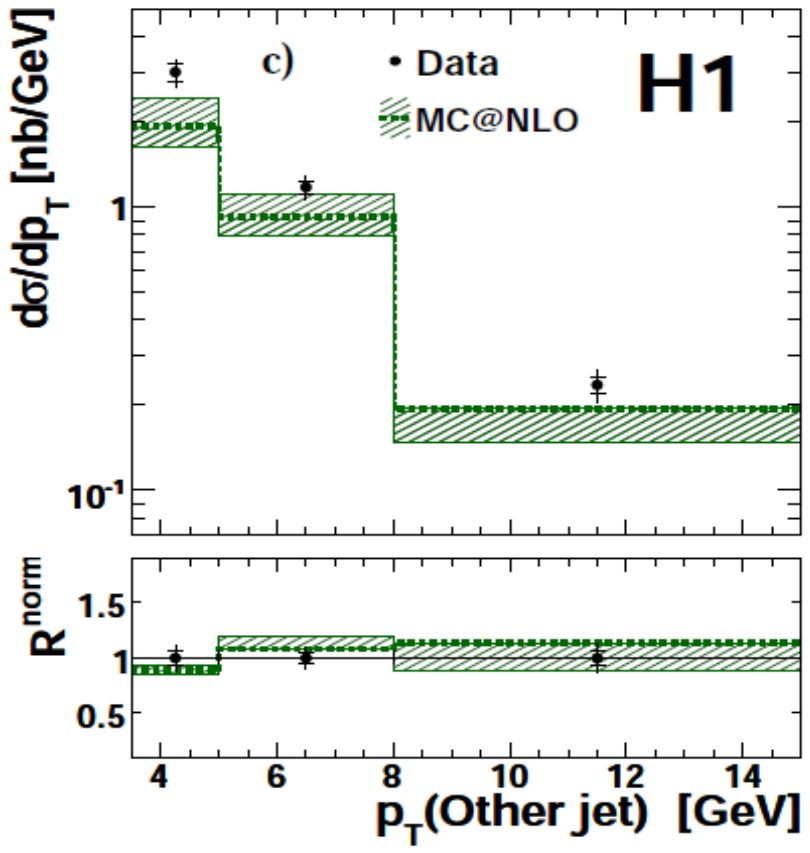


Charm in Photoproduction



Charm dijets with D*





- **2 jets** are selected with $p_t(jet)>3.5$ GeV
- One of the jets contains **D*** with $p_t(D^*) > 2.1$ GeV

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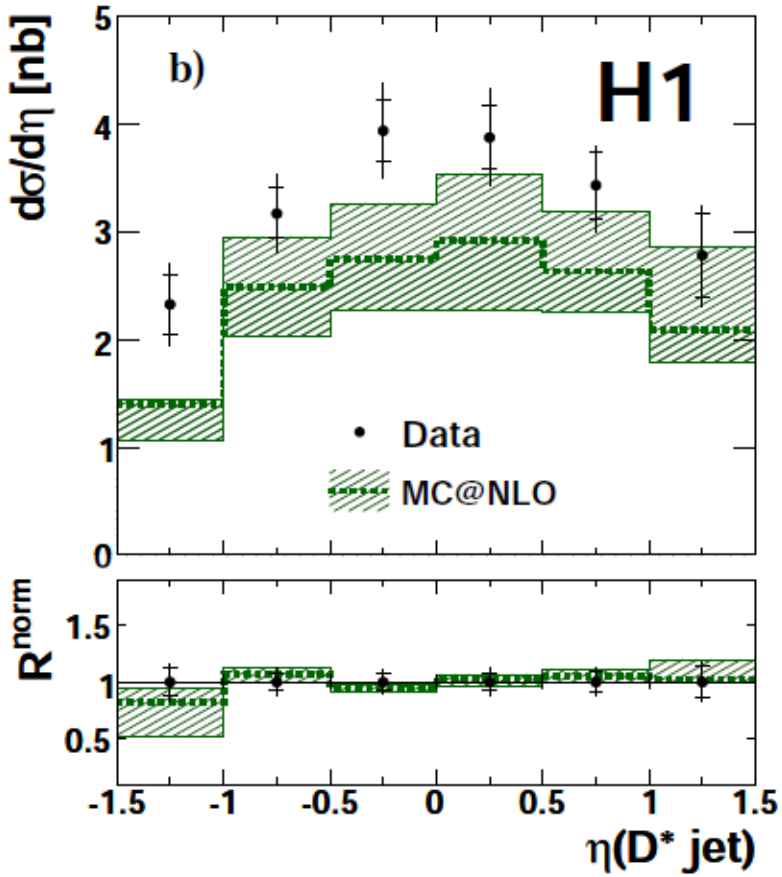
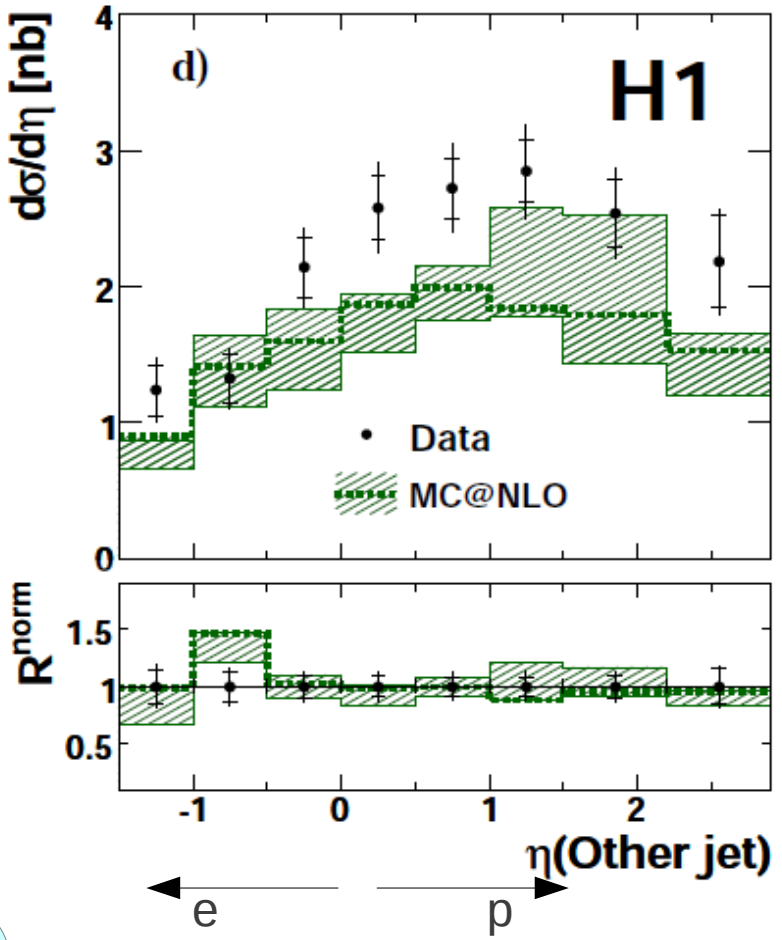
Charm dijets with D*





- Theoretical predictions (**MC@NLO** with massive scheme) *slightly below* data points
- In general, data and theory *agree within uncertainties*

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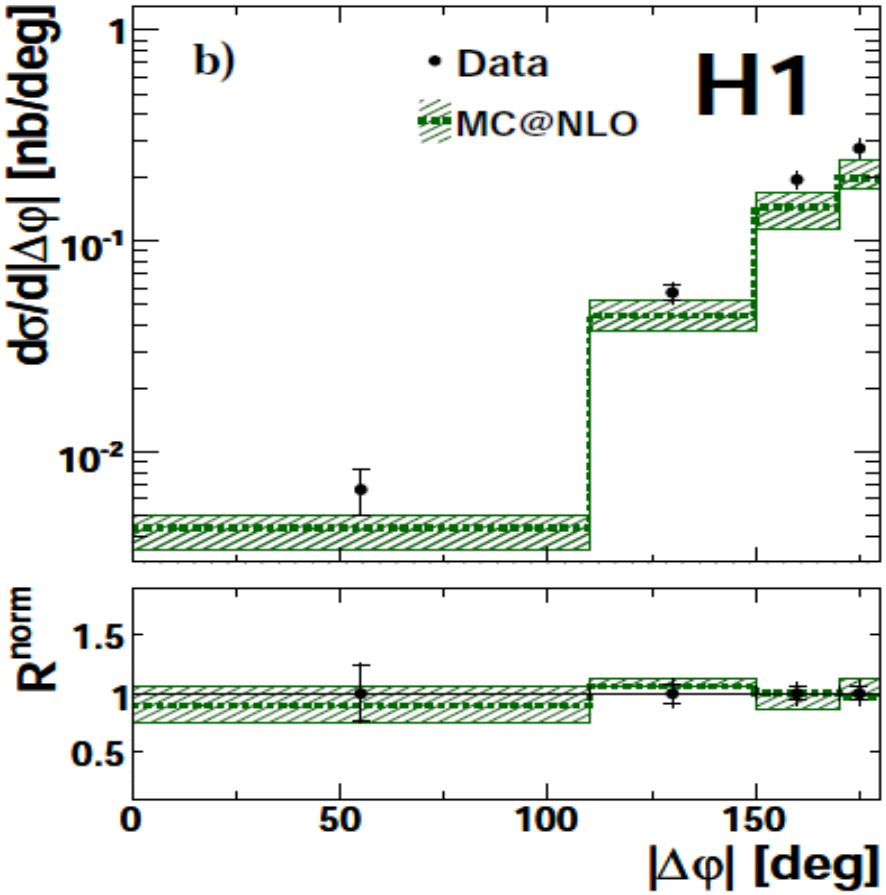
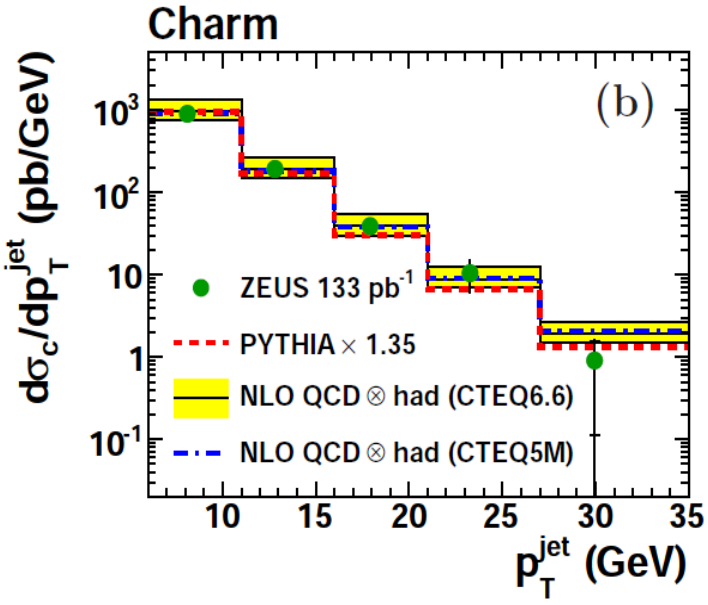
Charm dijets with D*
Jets correlation

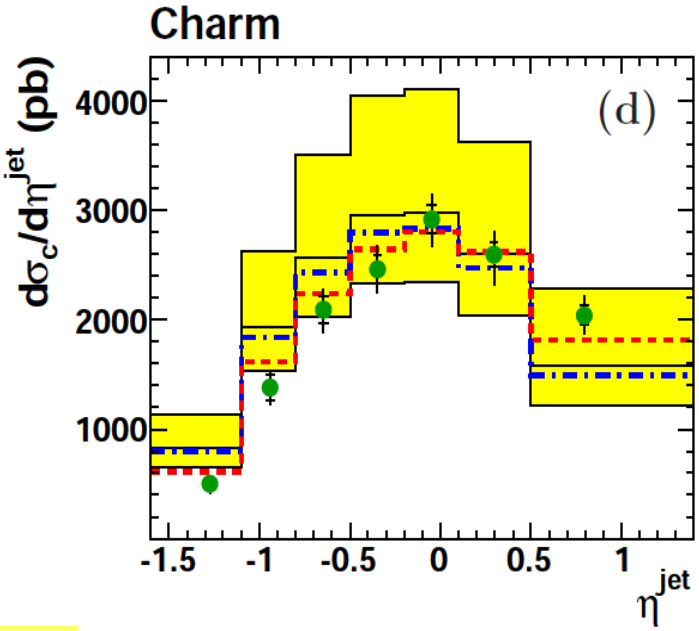


- **MC@NLO** underestimates the cross sections slightly, but provides *reasonable description*

*With **Δφ** not back-to-back jets we test higher order QCD radiation*

Charm inclusive jet cross sections





- Analysis was done for **jets** with p_t > 6(7) GeV → 35 GeV
- Tagged by **displaced secondary vertex** and its properties

- **Theoretical predictions** (*NLO QCD with massive scheme*) *describe* the measurements *well*
- Difference between two PDF definitions (**CTEQ6.6** and **CTEQ5M**) → *smaller than theory uncertainty*

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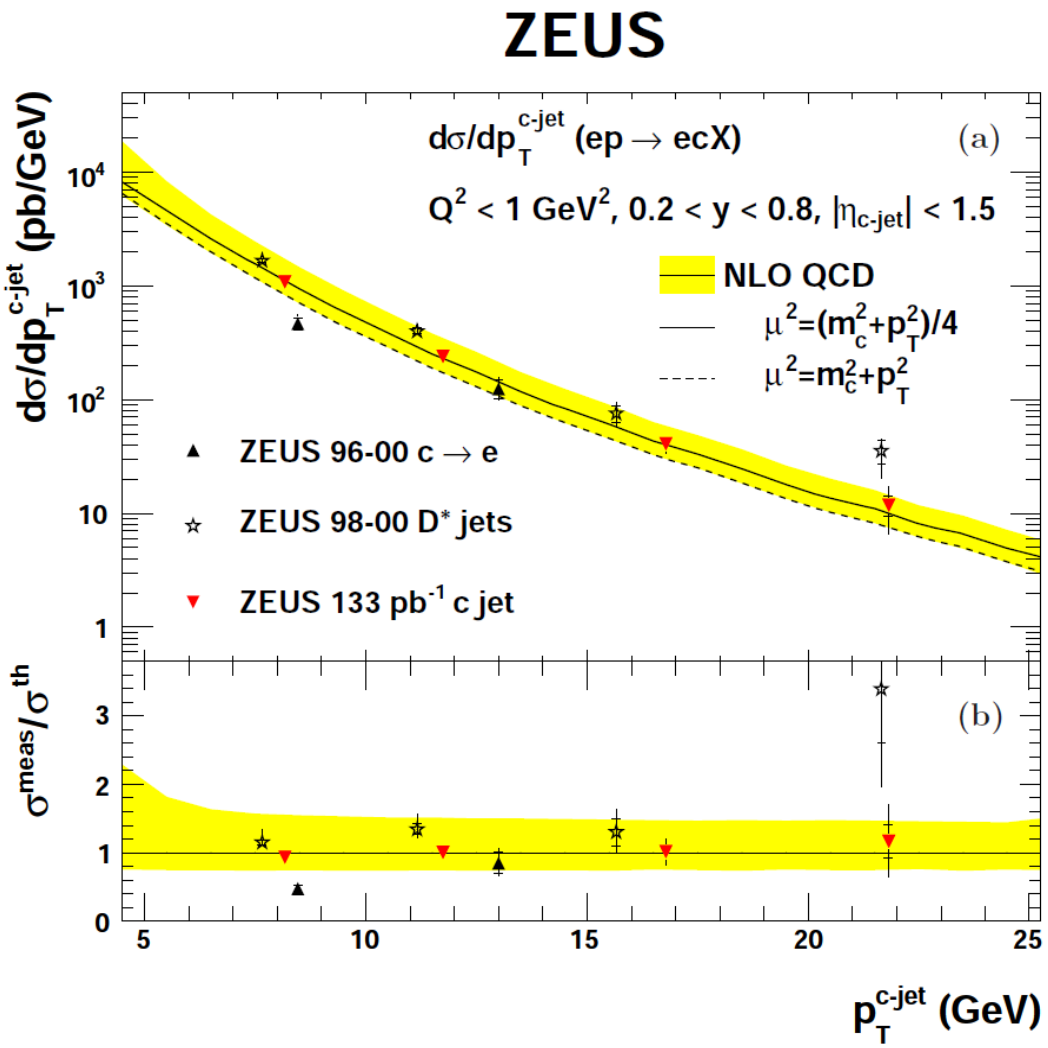
Charm inclusive jet cross sections

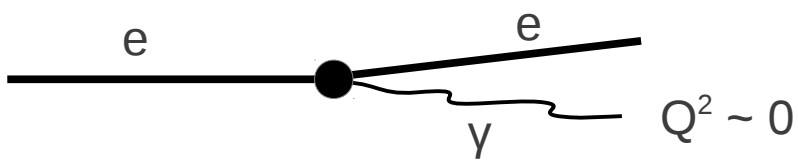
Cross section summary



- Comparison to previous ZEUS charm measurements and NLO QCD (massive scheme)
- Results show *good agreement* between each other and theory

DESY-11-067

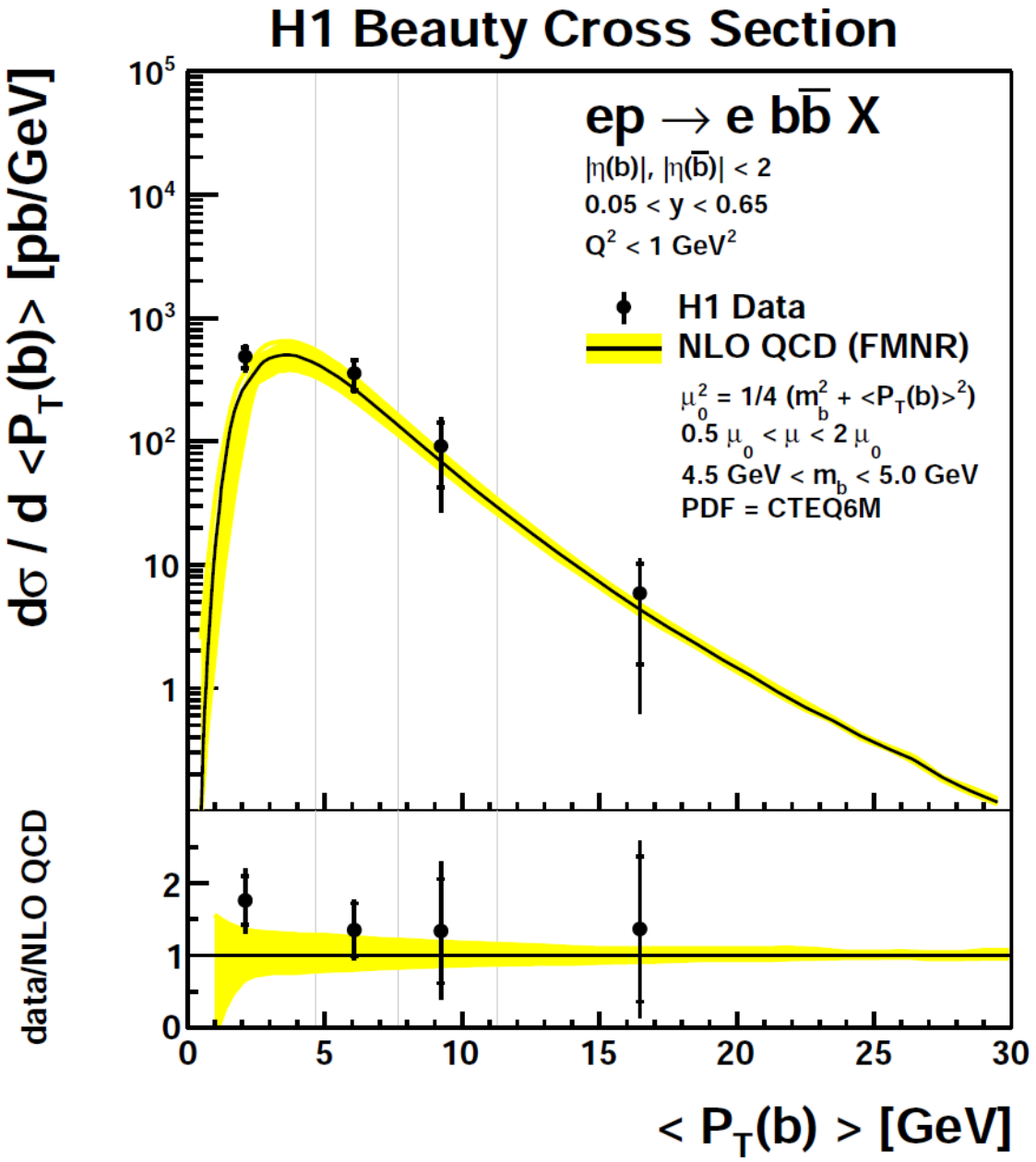
Beauty in Photoproduction



$b\bar{b}$ photoproduction with di-electrons

- **$b\bar{b}$ production on threshold**
- Tagged by *dielectron decays*
- **Selected electrons** with *$p_t(e) > 1$ GeV*

- **NLO QCD** (*with massive scheme*) *tends to underestimate* data
- Generally *in agreement* with data within large experimental and theoretical uncertainties



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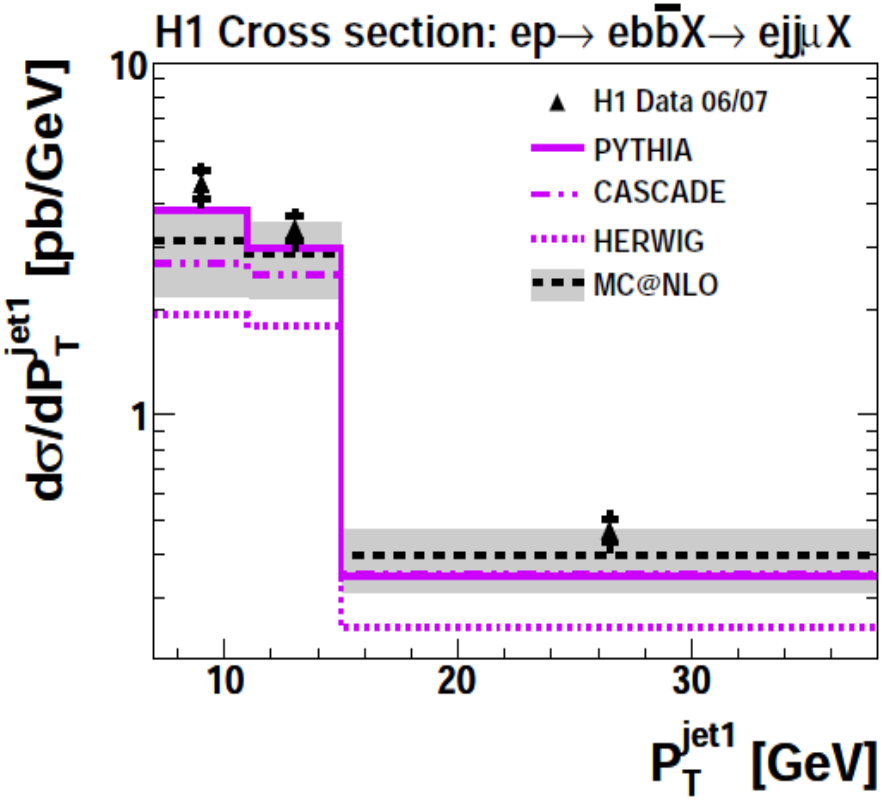
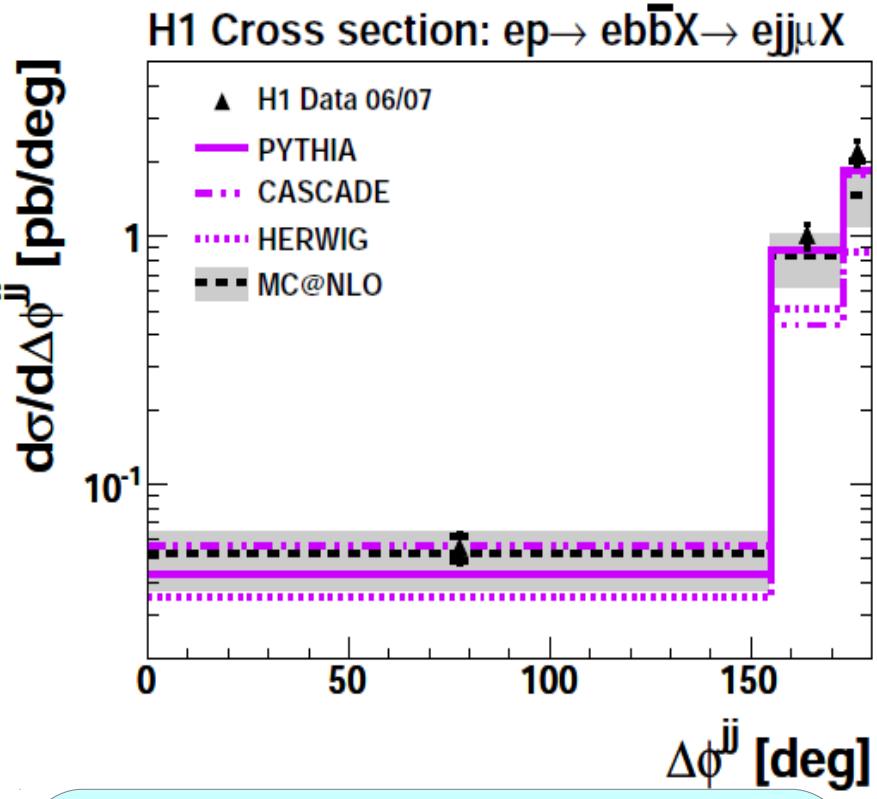
Beauty photoproduction with semimuonic decays in Dijet events



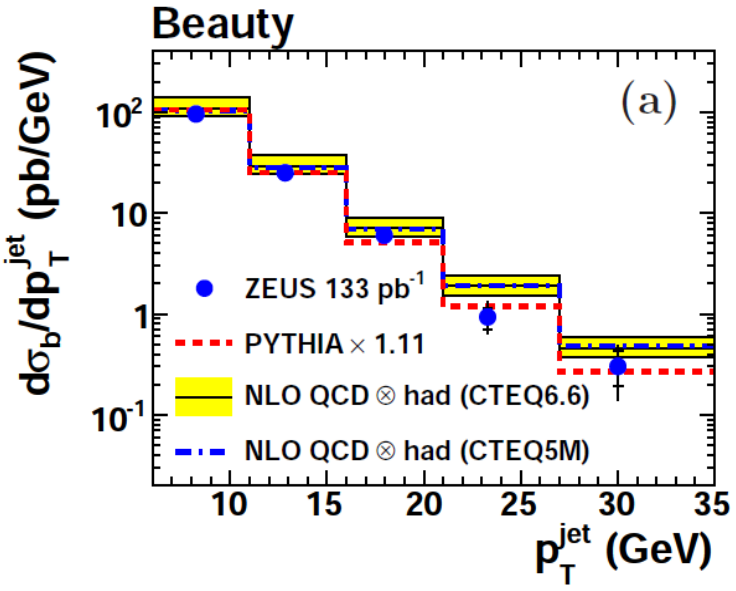


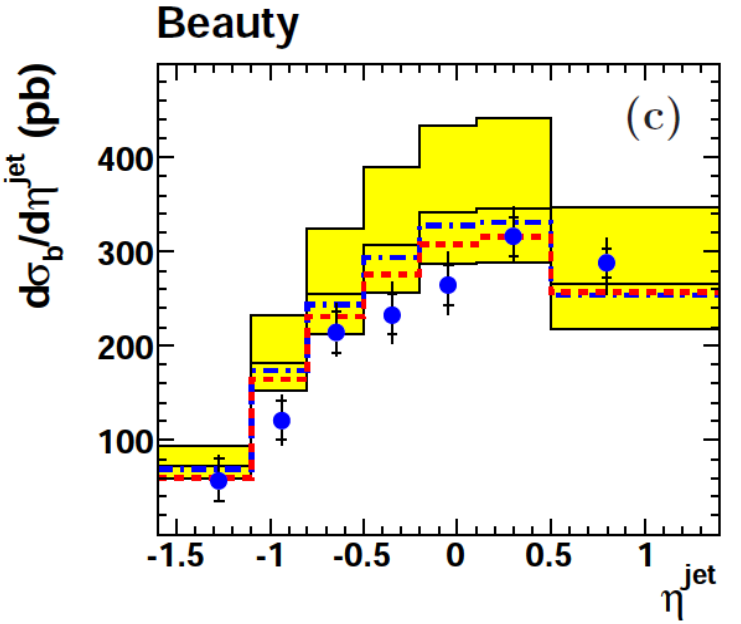
- Measurement **on medium to high p_t**
- Tagged with **semimuonic decays** (**muons** with $p_t > 2.5$ *GeV*)
- **2 jets** were selected with $p_t > 6(7)$ *GeV*

- **MC@NLO** (with massive scheme): *underestimates the data*, but generally agreement is nice
- **Δφ:** contributions from *not back-to-back jets,* but *smaller then for charm* (shown before for c with D*)

DESY-12-059

Beauty jet inclusive cross sections



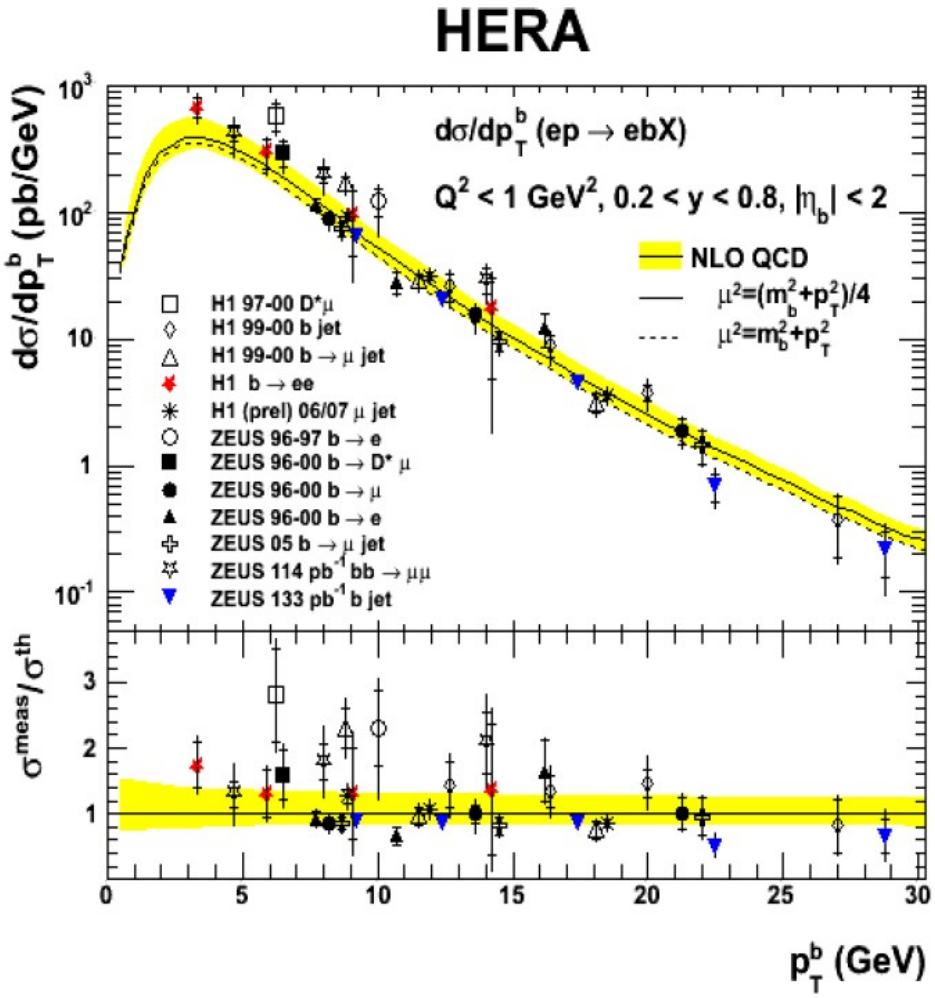


- **Two jets** with p_t > 6(7) GeV
- Inclusive measurement **on high p_t**
- Tagged by **displaced secondary vertex** and its properties

- **NLO QCD** (with massive scheme) tends to *overestimate* the data
- **Theory predictions** are generally *in agreement* with data points

DESY-11-067

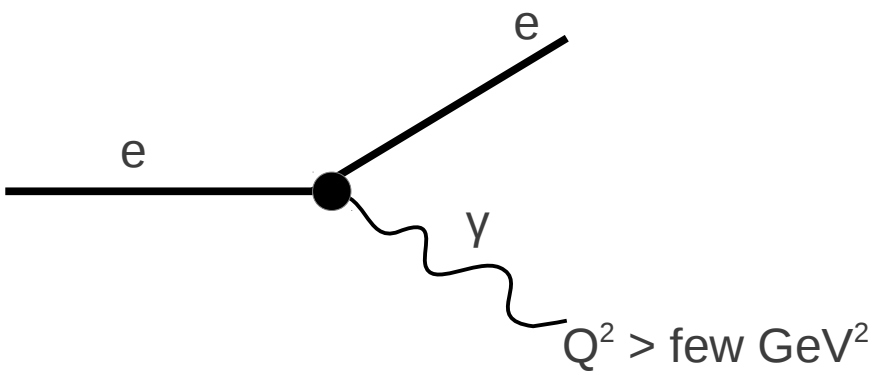
Beauty cross sections summary



- Cover large p_t range.

  Massive NLO describes data *over all the phase space*

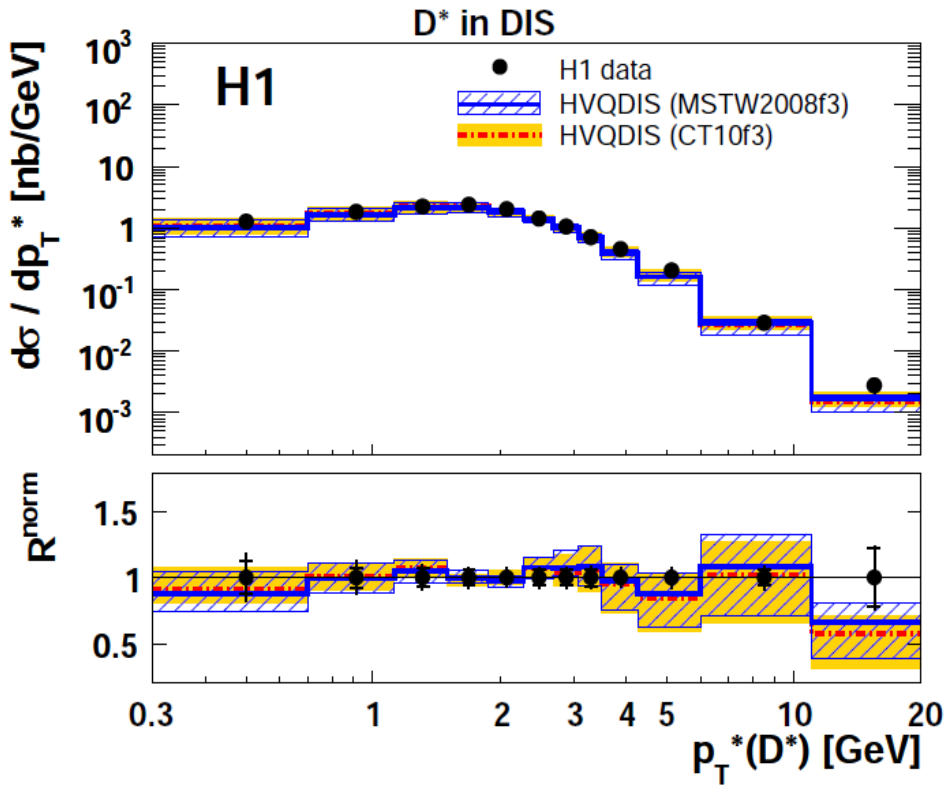
Charm in DIS

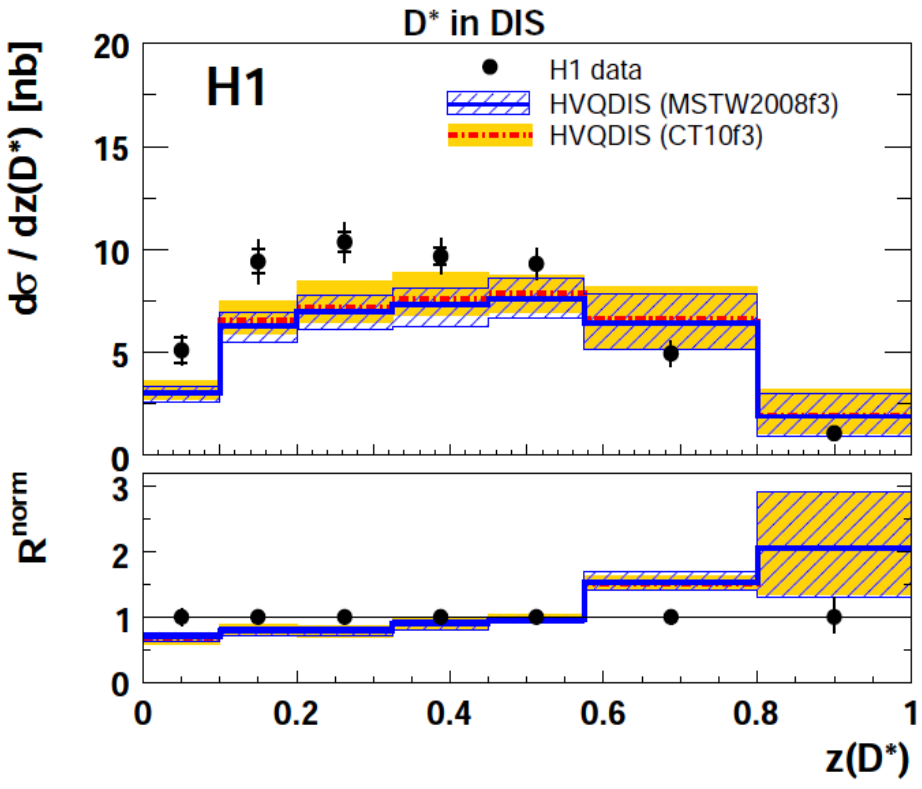


Charm with D*

- **D*** with $p_t > 1.25$ GeV

- $\mathbf{p_t^*}$ - transverse momentum in γp rest frame
- **z(D*)** - energy fraction of photon taken by D*

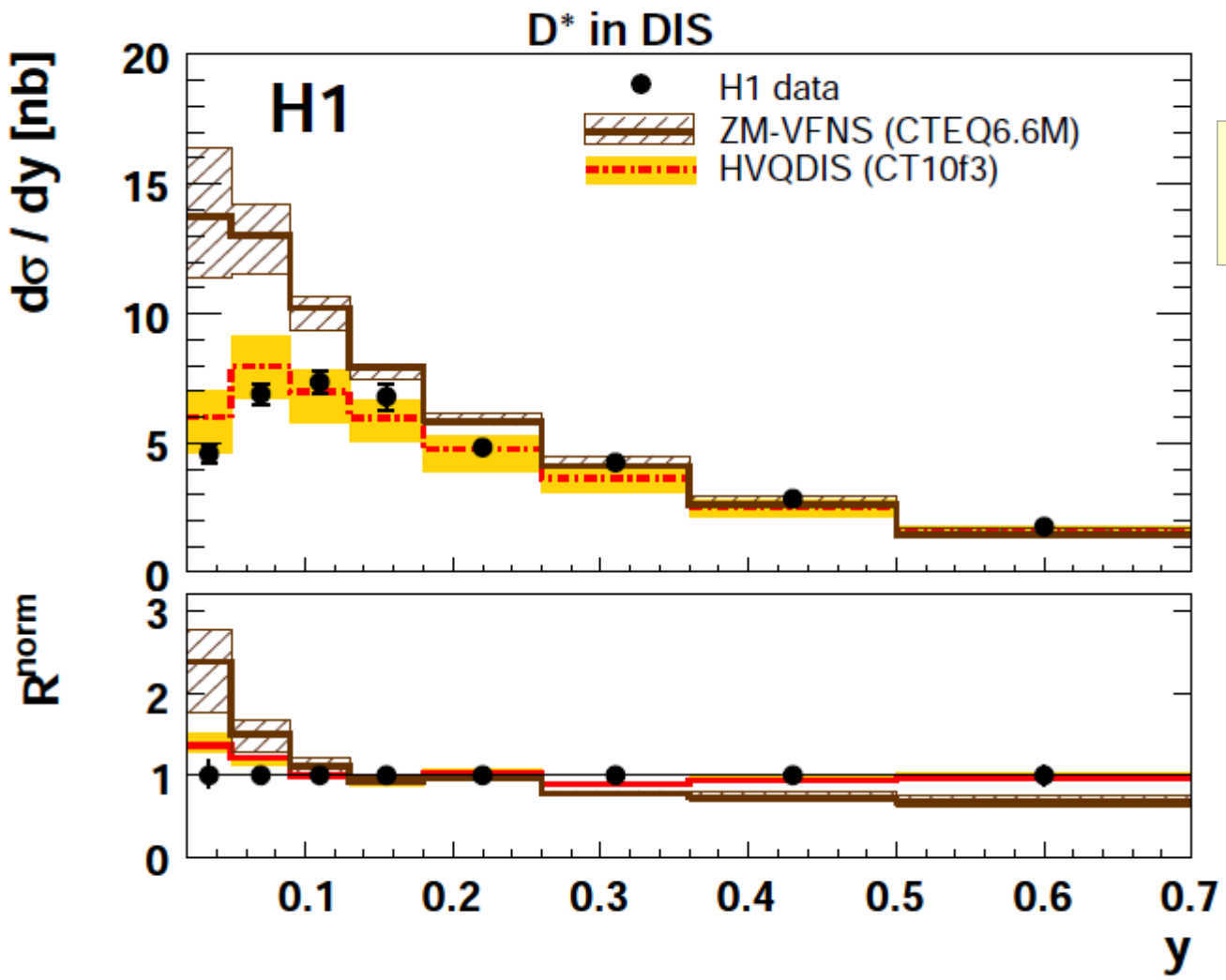




- **HVQDIS convoluted with fragmentation model** represents *NLO with massive scheme*
- **The theory** is generally in agreement with data, but fails to describe well z(D*)

DESY-11-066

Charm with D*



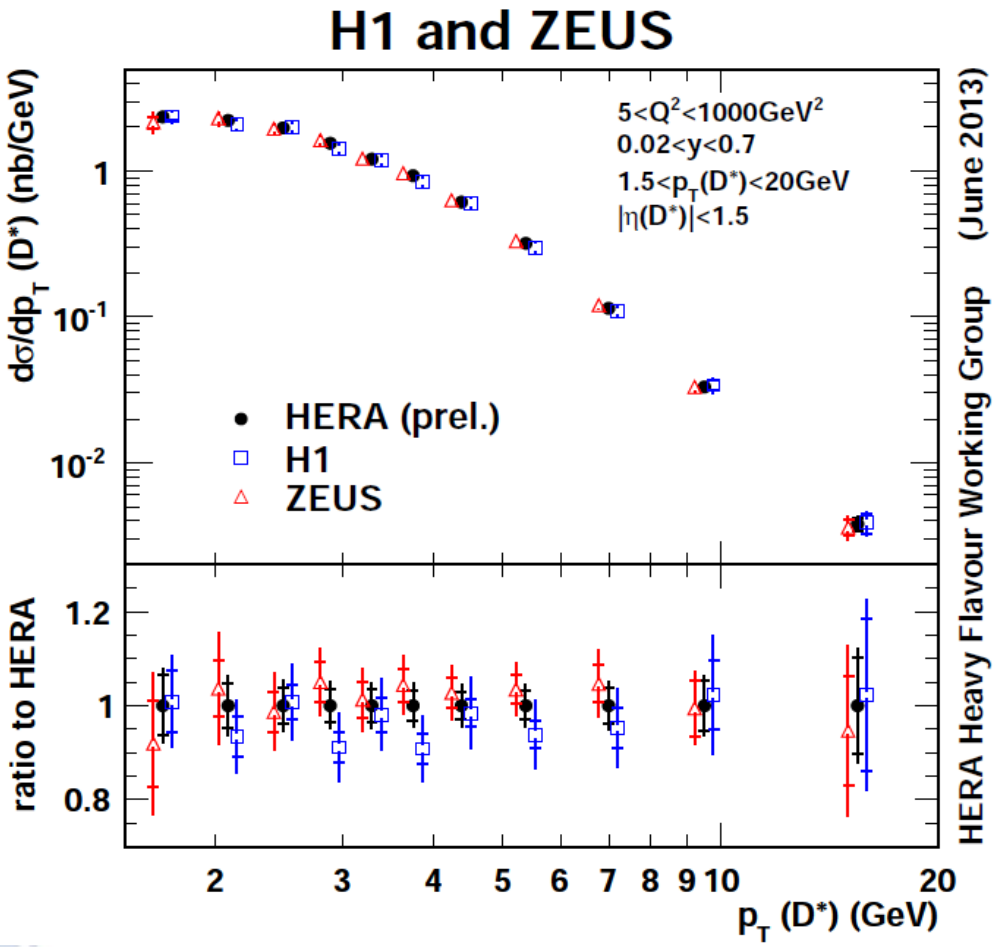
For **massless calculations**:

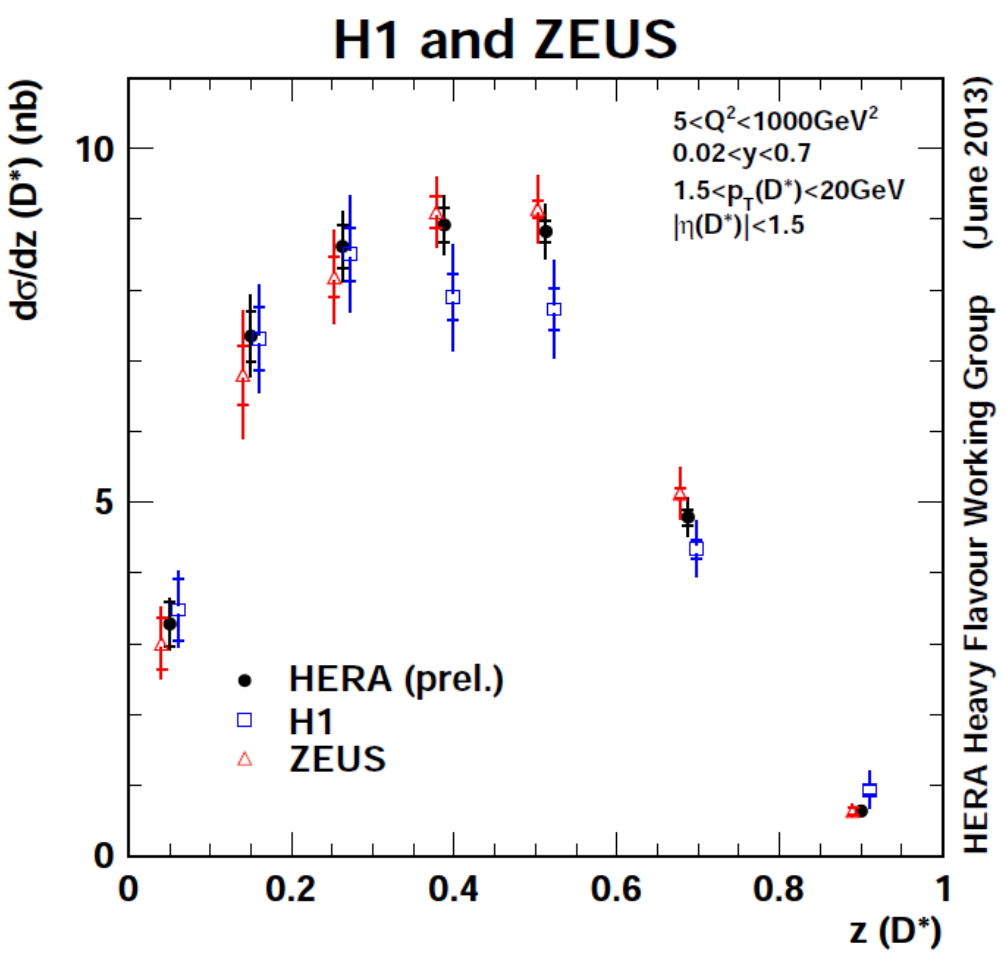
- added cut $p_t^*(D^*) > 2GeV$

Theory with **Massless approach** *fails* to describe data

DESY-11-066

H1&ZEUS combination for the D* production

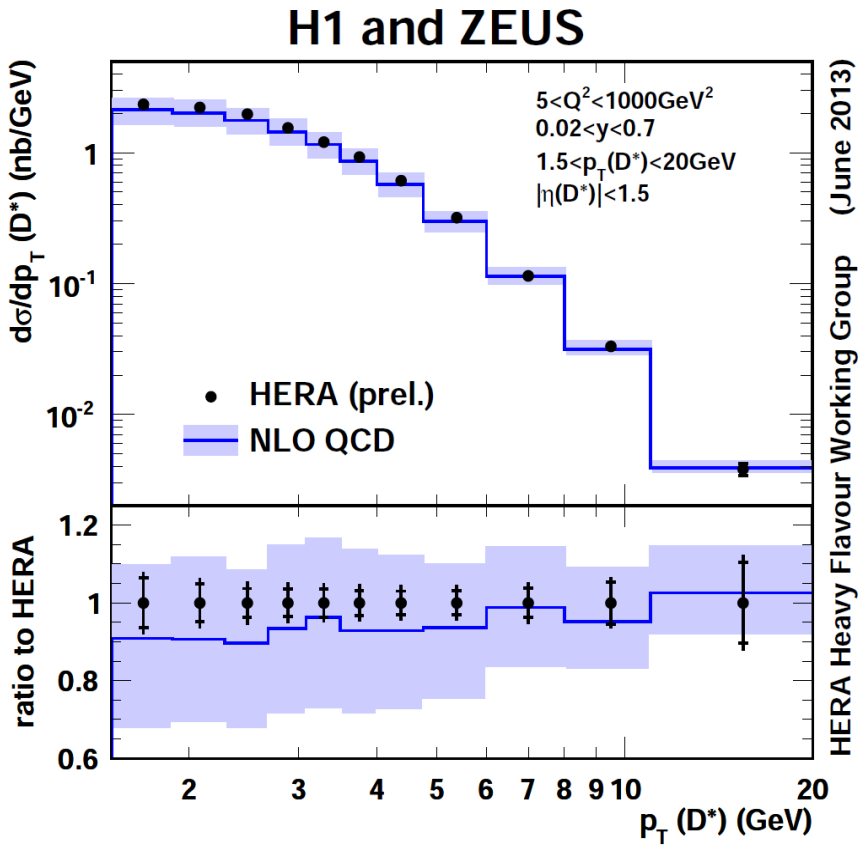


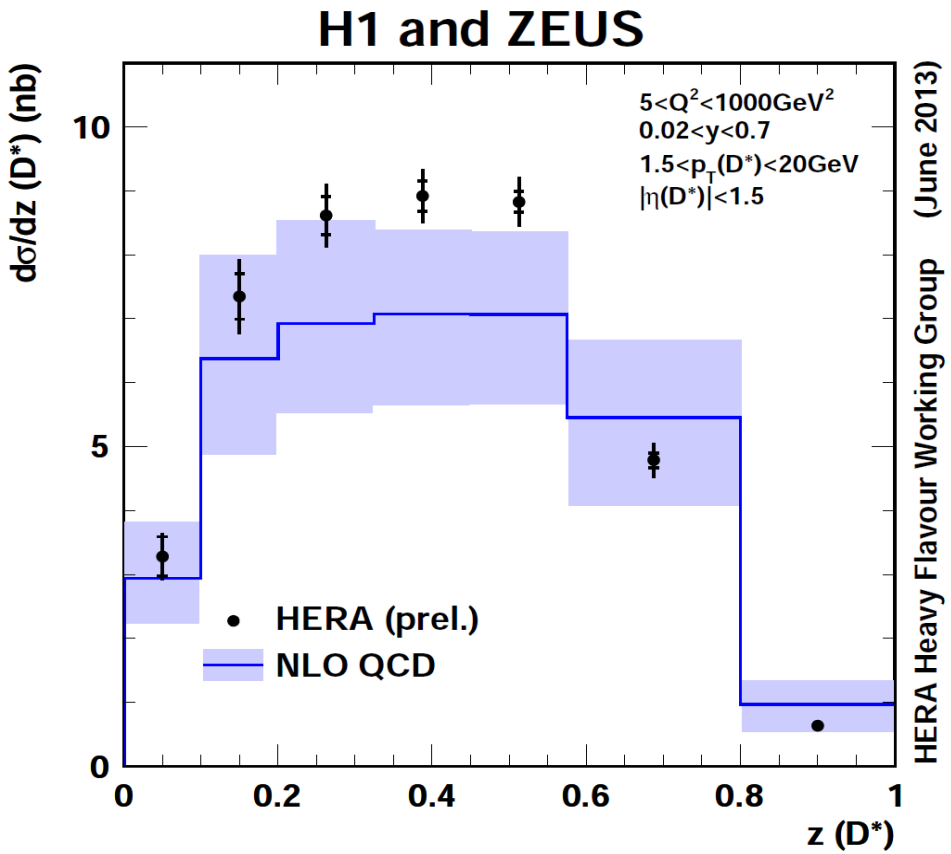


Measurements of D production are combined by H1 and ZEUS in visible phase space*

H1-prelim-13-141 ZEUS-prel-13-002

H1&ZEUS combination for the D* production

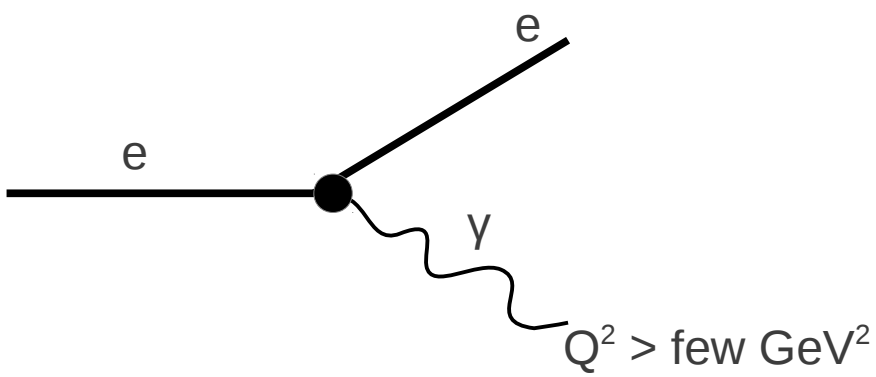




- **Data precision** reaches *~ 5%*
- **Theory uncertainty** – *from 30% to 10%*
- In general – *reasonable agreement* with **NLO QCD with FFNS**, but it again *does not describe well z(D*)*

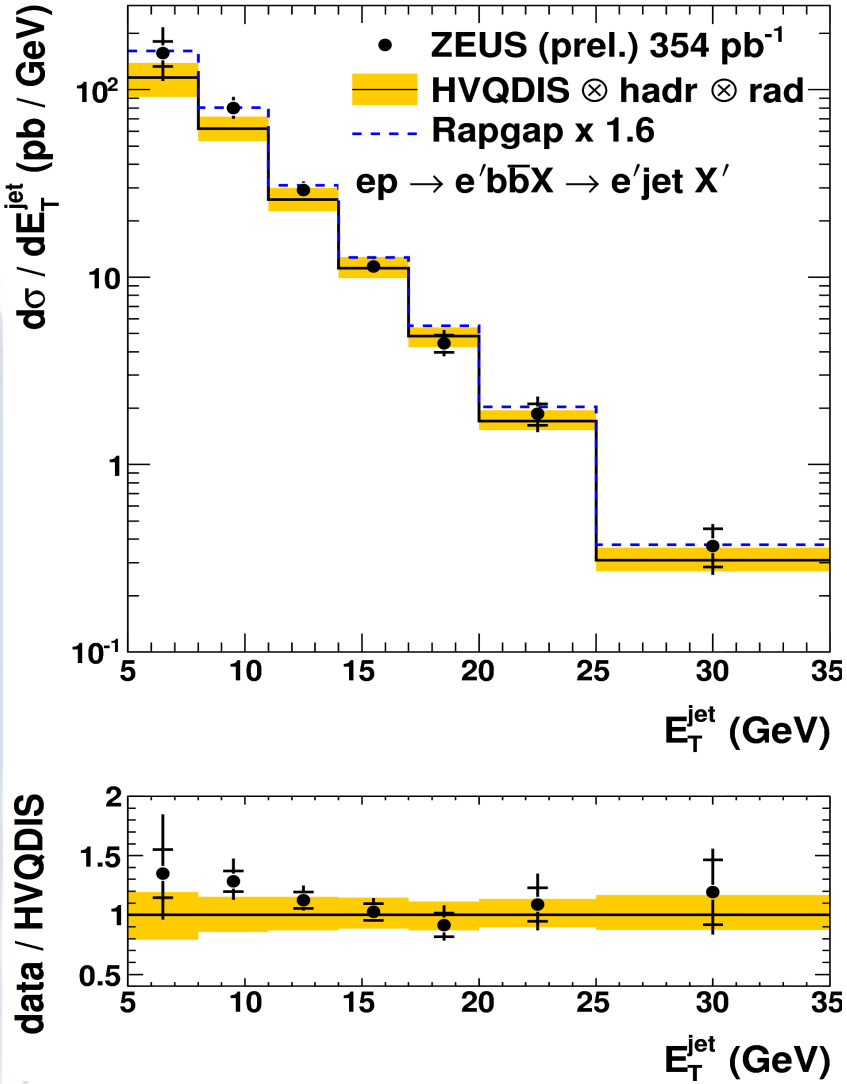
H1-prelim-13-141 ZEUS-prel-13-002

Beauty in DIS



Inclusive beauty cross section

ZEUS



- **Two jets** with $E_t > 5$ *GeV*
- **Inclusive measurement**
- Tagged by **displaced secondary vertex** and its properties

- **Most precise b measurement in DIS**
- Shows *good agreement* between data and **HVQDIS**

ZEUS-prel-10-004

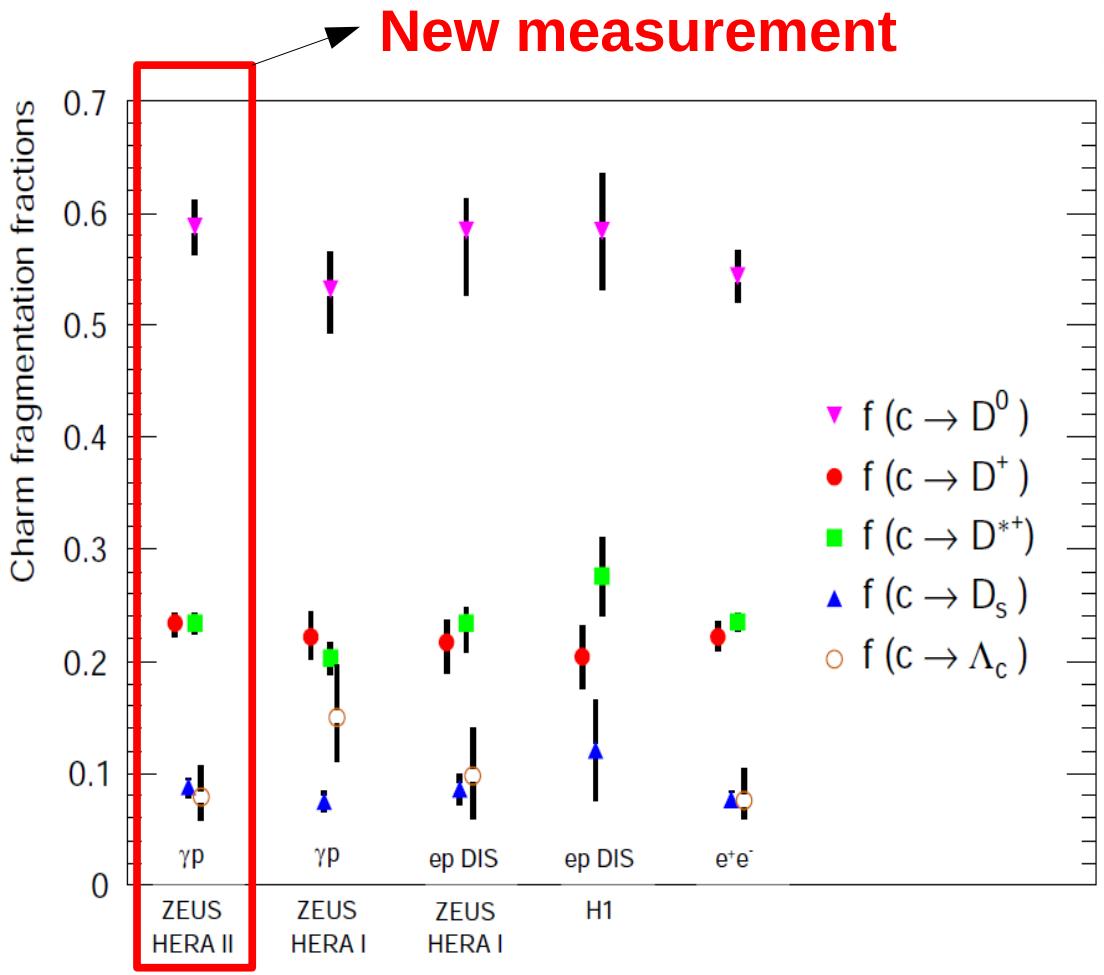
Charm fragmentation universality test

Charm fragmentation universality

Charm hadrons were reconstructed in different processes and experiments at HERA

Able to test fragmentation universality

- Fragmentation fractions measured at **H1** and **ZEUS** experiments, in *Photoproduction* and *DIS*
- Results were compared between each other and with e^+e^- data
  - Latest ZEUS results show **compatible precision to the one in e^+e^- measurement**
  - Overall the fragmentation fractions derived at HERA and e^+e^- **agree well.** That confirms fragmentation universality



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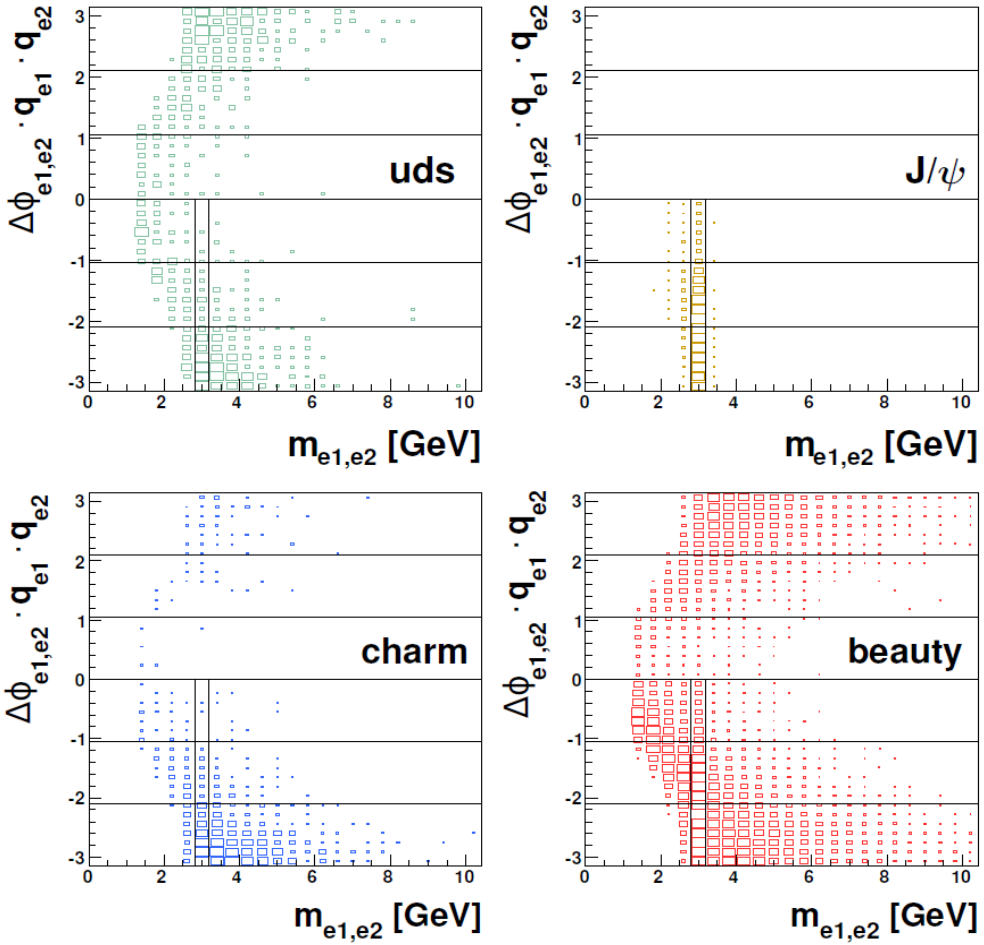
Summary

- Heavy quark production at HERA provides important testing ground for perturbative QCD
- The data with high precision were collected. And different tagging methods were applied
- Different experimental measurements are in agreement between each other
- The data are generally well described by massive scheme NLO QCD
- Theory uncertainties usually are larger than experimental ones:
  - ➔ Full NNLO calculations will be useful
  - ➔ For some phase space corners theoretical improvement can be better

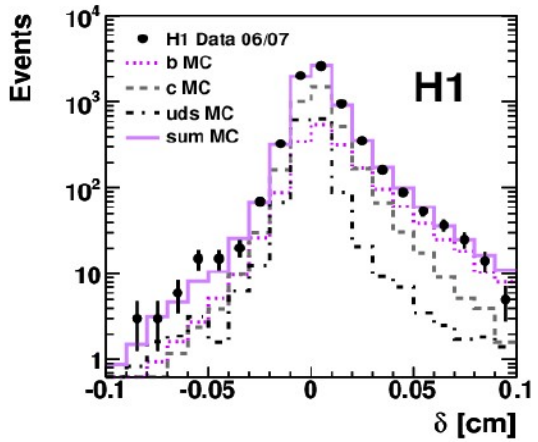
BACKUP

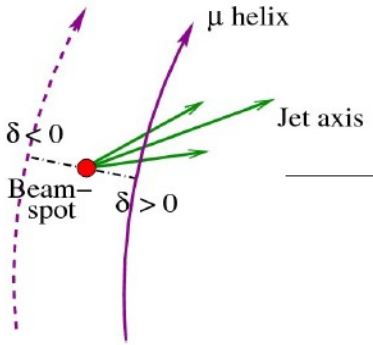
Tagging with di-electron properties



- J/ψ has a clear mass region
- Charm mostly produces back-to-back electrons with opposite charge
- Light flavours produce electrons with same and different charge, but having small mass
- Beauty covers large mass region

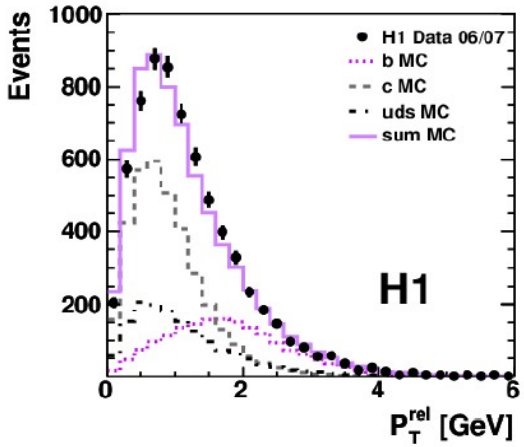
Tagging with muon impact parameter

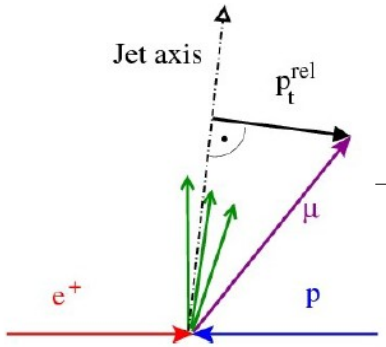




Muon impact parameter (δ) – distance of closest approach of muon track to the beam spot point

δ < 0.1 cm – cut the long living strange particles

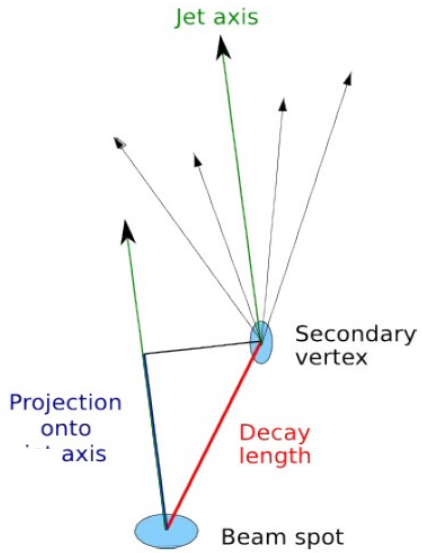




Transverse momentum of muon relative to the μ jet axis (p_t^{rel})

The **likelihood fit of the impact parameter and p_t^{rel}** is used to get the flavour fractions. The total number of events is multiplied by these fractions in cross section determination

Tagging with mirrored significance



$$Significance = \frac{l}{\sigma_l}$$

where *l* is a decay length

Mirrored significance (MS) – difference between S(+) and S(-)

↓

Sensitive to light flavour background

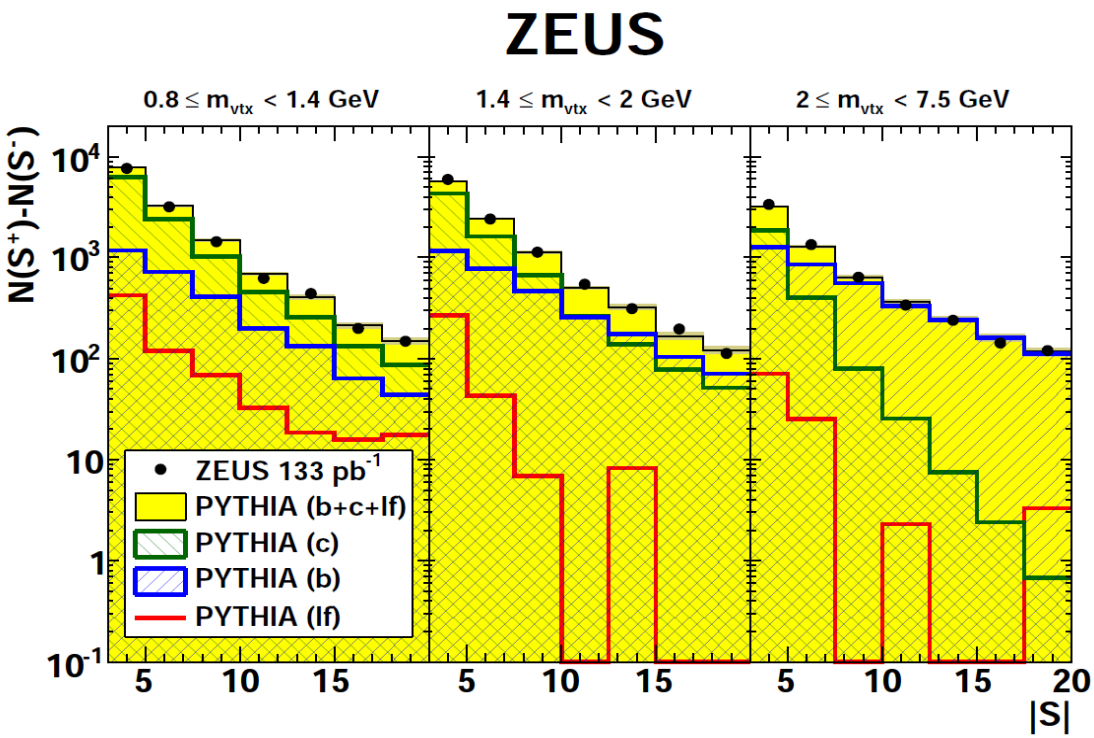
MS not 0 → assume to be signal

To distinguish between charm and beauty:

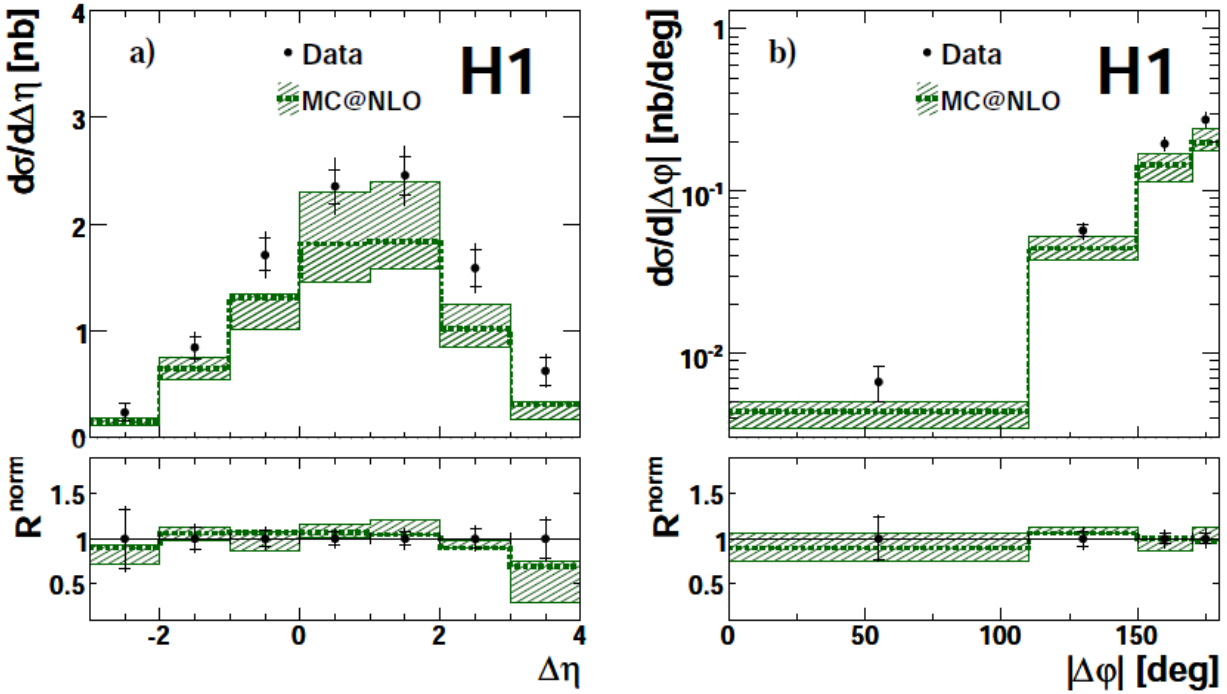
- Use N of MC events
- Multiply it by MC to Data scale factor obtained from χ2 fit

↓

Obtain N^c and N^b



Charm dijets with D*, Php
Jets correlation



- **Δη** is not symmetric → jet without D* is *not always originating from charm* (*Δη=η(other j)–η(D* j)*)
- In **Δφ:** events, where jets are *not back-to-back* – can be explained by *higher order QCD radiation*

***MC@NLO** provides reasonable description, though underestimated the cross sections*

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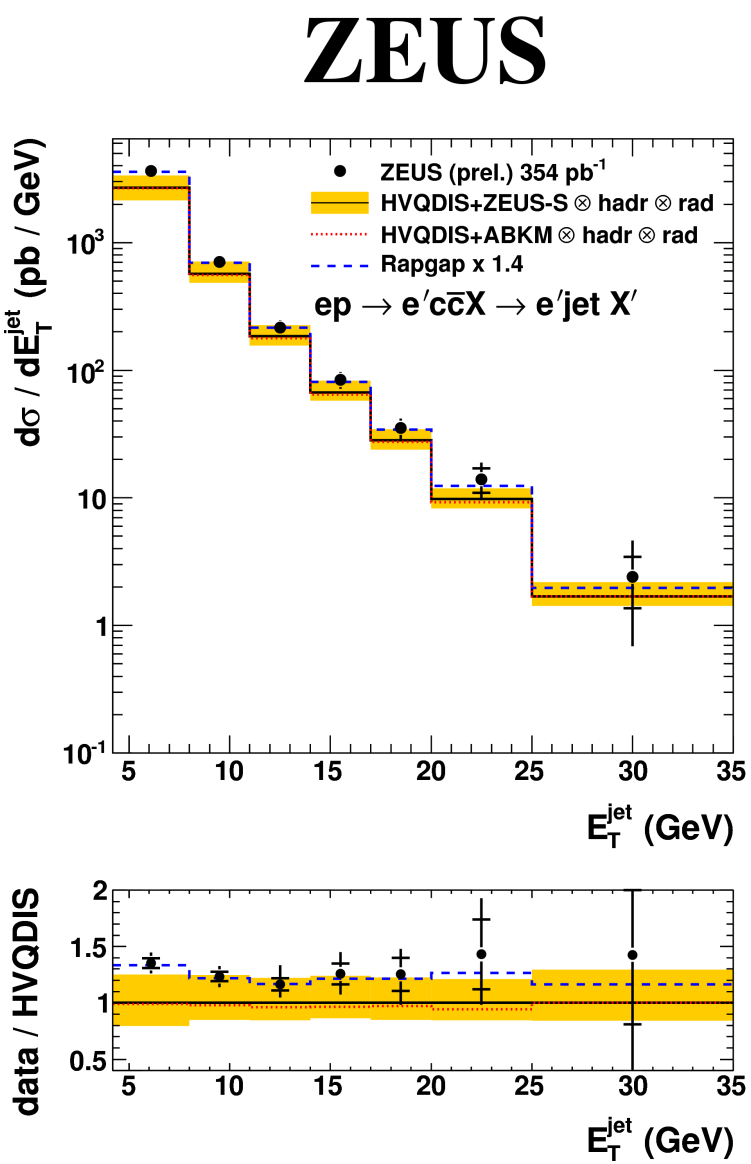
Charm inclusive jet production, DIS



- **Two jets** with E_t : *4.2 GeV → 35 GeV*
- **Inclusive measurement**
- Tagged by **displaced secondary vertex** and its properties

- **HVQDIS** (*NLO with massive scheme)* describes data cross sections pretty well within uncertainties, showing *slight underestimation*

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