# Heavy Flavour Production at HERA

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for the H1 and ZEUS Collaborations

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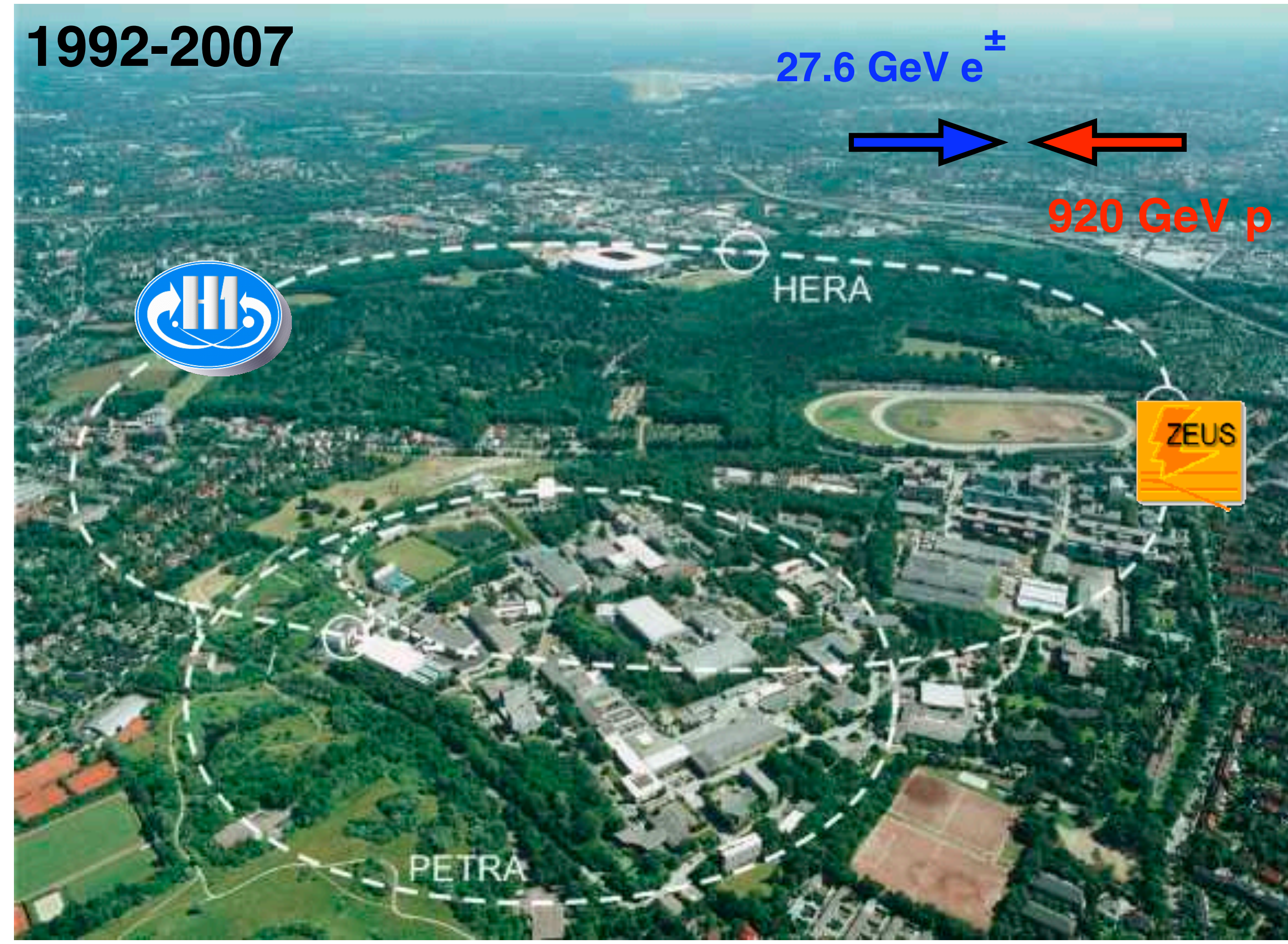
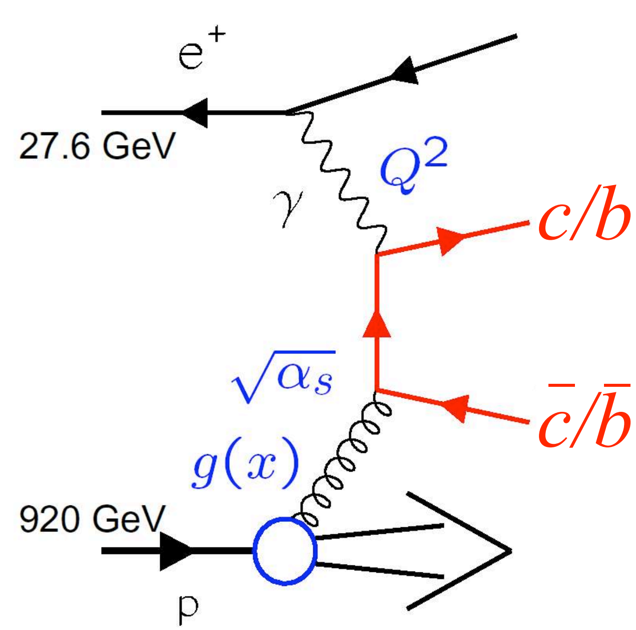
# Heavy Flavour Production at ep Collider HERA

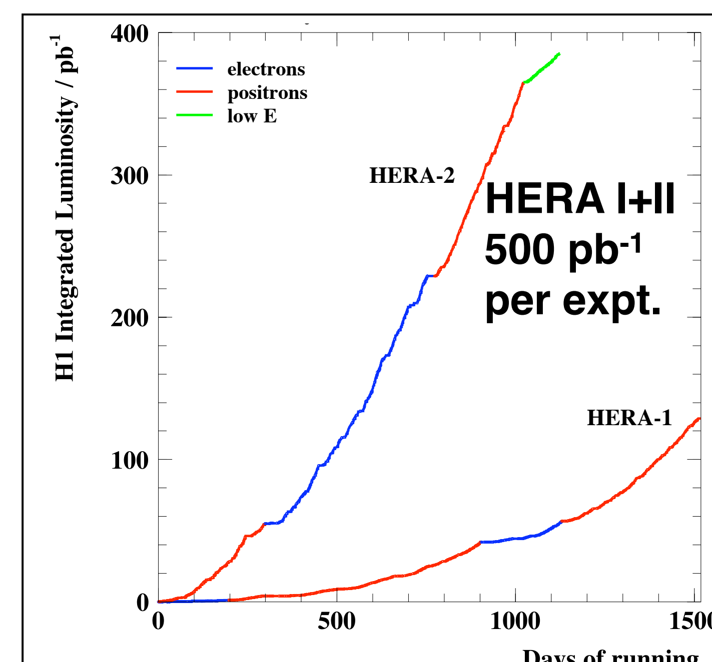
Interest in Heavy Flavour production:

- Perturbative QCD applicable due to large masses $m_c$, $m_b$
  - but often multi scale problem (i.e. additional scales $Q^2$, $p_t^2$, ...)
- Detailed understanding of the production mechanism sheds light on the underlying parton dynamics in QCD
- Dominant production process is boson gluon fusion
  - direct sensitivity to gluon density in proton
- Heavy-quark production provides core constraints in global fits on the parton distribution functions (PDFs)
  - reduced uncertainty
- Sizeable fraction of total cross section up to
  - 30% for charm and 2-3% for beauty
- Measurements relevant for interpretation of
  - LHC results (e.g. HQ treatment vs. $\sigma_{W/Z}$)
  - Cosmic Ray physics (UHE $\nu$ background)



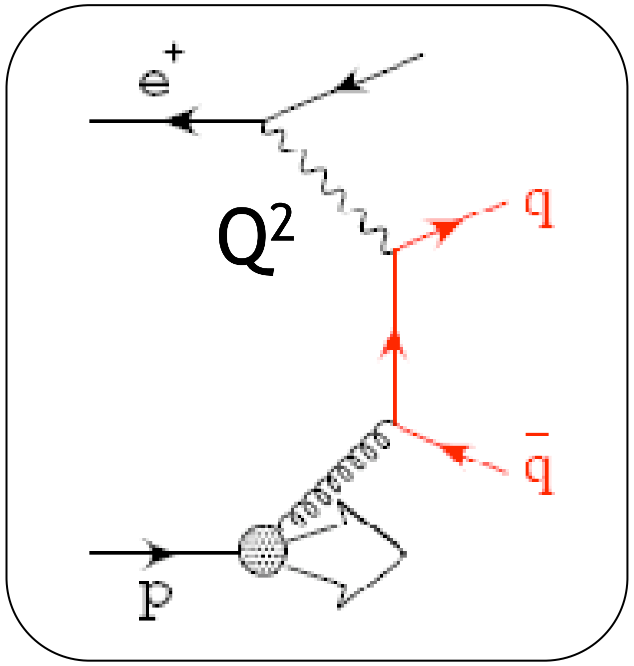

Boson Gluon Fusion



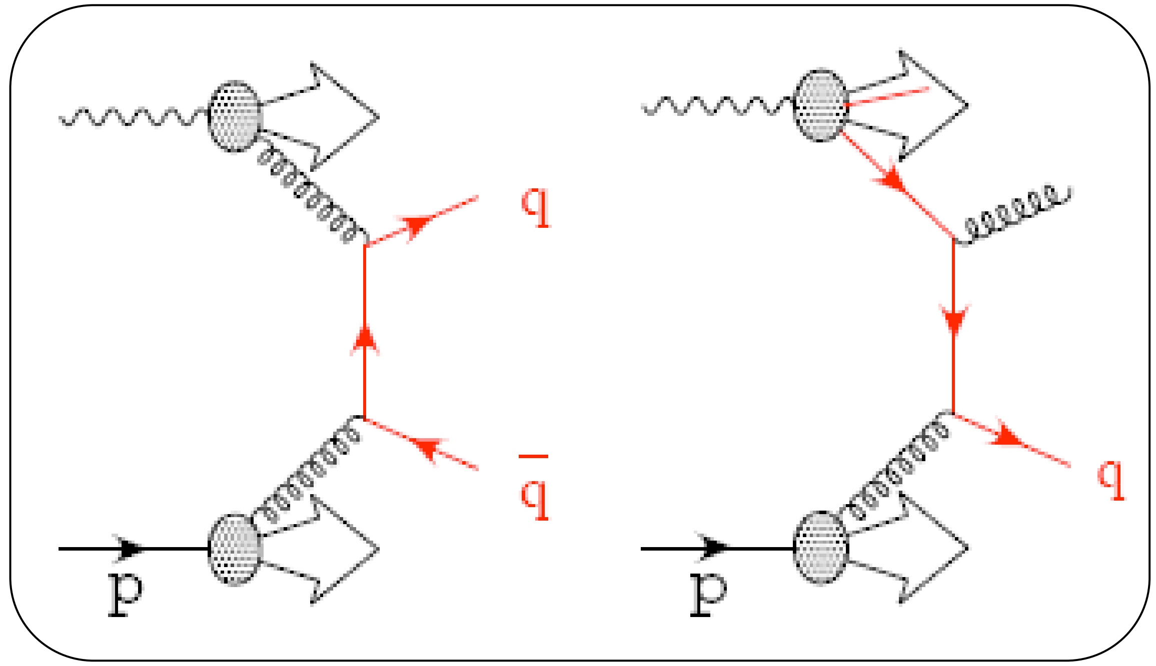



# Production of Heavy Flavour in ep Scattering

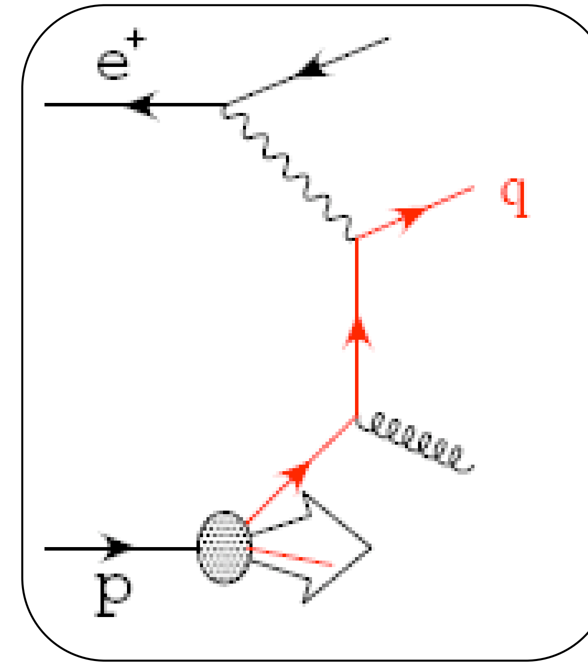
Direct $\gamma$




Resolved $\gamma$




Flavour excitation




Kinematics of ep scattering:

$$Q^2 = -q^2 = -(k - k')^2$$

$$x = \frac{Q^2}{2P \cdot q}$$ momentum fraction

$$y = \frac{P \cdot q}{P \cdot k}$$ inelasticity

Two regimes:

$Q^2 \simeq 0 \ \mathrm{GeV}^2$ Photoproduction ($\gamma$p)

$Q^2 > 1 \ \mathrm{GeV}^2$ Deep Inelastic Scattering (DIS)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# Theoretical Calculations and Monte Carlo Programs

Calculations and Monte Carlo programs used to describe Heavy Flavour production:

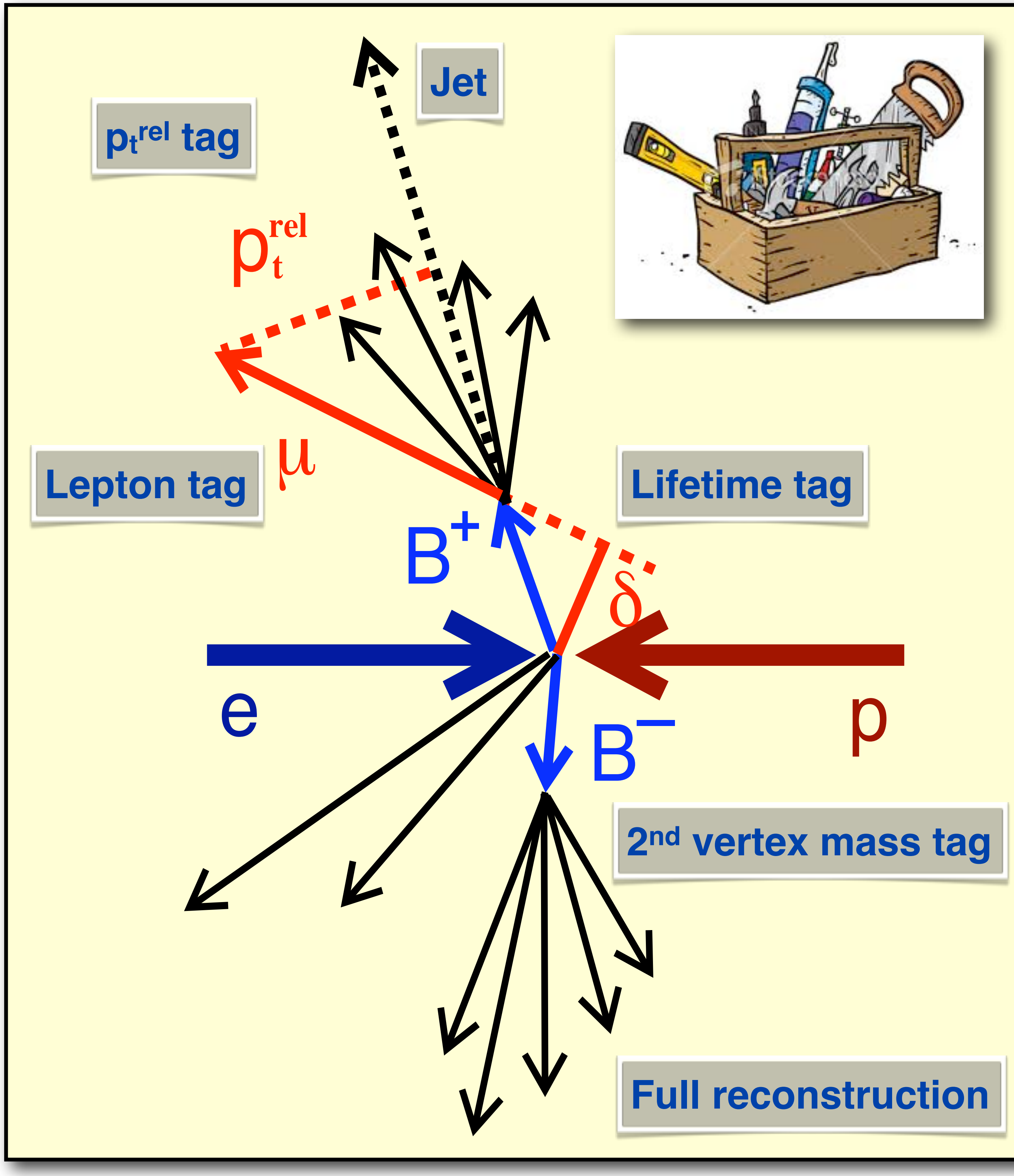
- Monte Carlo Programs
  - leading order (LO) + parton shower (PS) models available
    - DGLAP evolution (collinear factorization):
      - **$\gamma$p**: PYTHIA, HERWIG
      - **DIS**: RAPGAP
    - CCFM evolution ($k_t$ factorization) **$\gamma$p + DIS**: CASCADE

- Theoretical Calculations
  - full (massive) NLO calculations available
    - **$\gamma$p**: FMNR
    - **DIS**: HVQDIS

# Tagging Heavy Flavour at HERA

Exploit properties of charm/beauty hadrons:

- Full reconstruction
  - At HERA only possible for charm, *e.g.* $D^* \to K\pi\pi$, $J/\Psi \to \mu\mu$, ee
- Lepton tagging
  - Use semileptonic b/c decay channels:
    - μ or e, high BR(c,b → lepton + anything)
- Lifetime tagging
  - b/c hadrons have long lifetimes:
    - displaced vertices
    - tracks with large impact parameters δ
- $p_t^{rel}$ tagging
  - b hadrons have large mass:
    - decay leptons with high transverse momentum w.r.t. b quark flight direction
- Secondary vertex mass tagging
  - exploit high b quark mass
    - high secondary vertex masses
- Compare/combine different tagging methods



# Photoproduction of D* and Jets

Full reconstruction

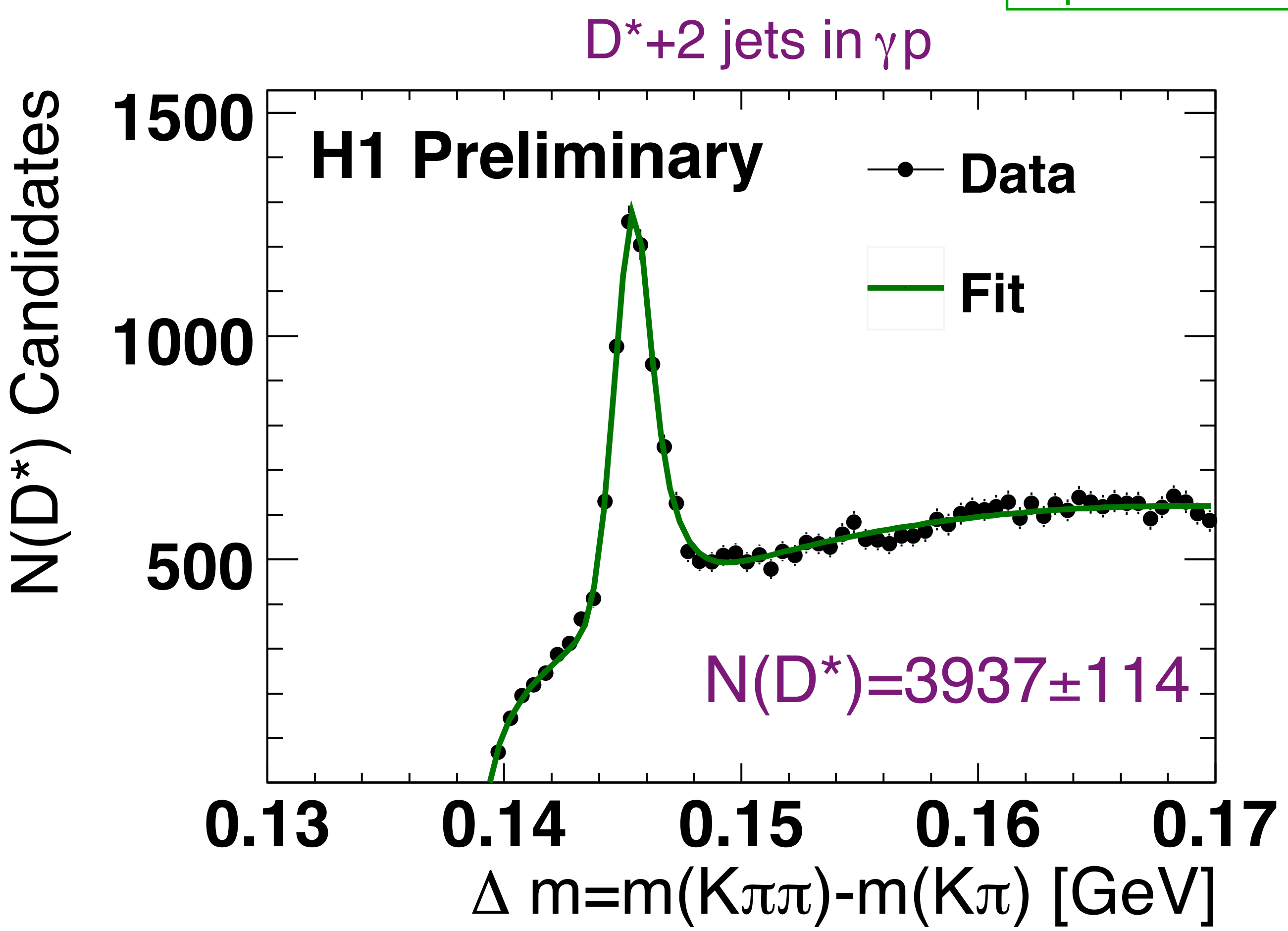
H1prelim-10-072

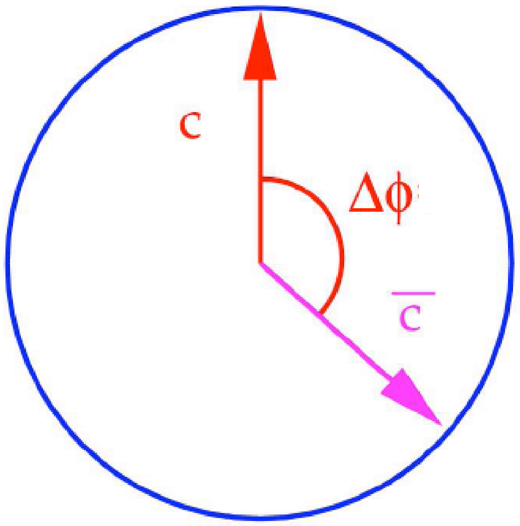
- Charm tagging by reconstructing D* decay in „golden channel“

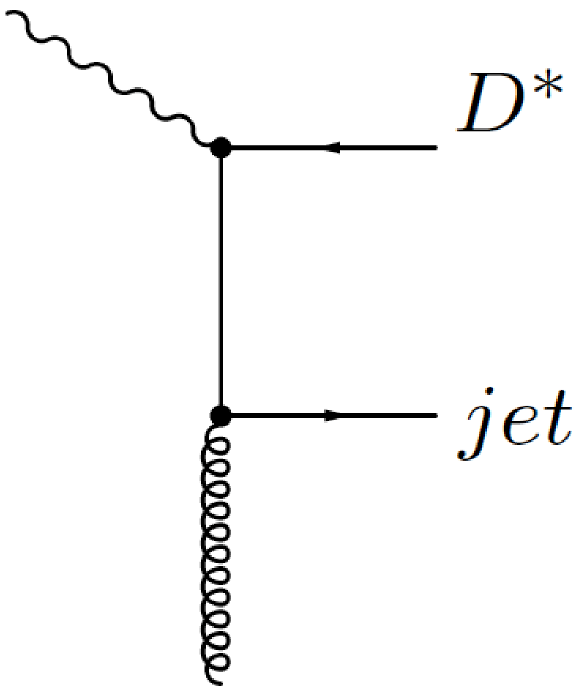
$$D^{*\pm} \rightarrow D^0 \pi^{\pm}_{slow} \rightarrow K^{\mp}\pi^{\pm}\pi^{\pm}_{slow}$$

- Measurements of jets gives access to both partons from hard process
  - D* jet quantities expected to be closer to charm quark quantities than D* alone
  - study angular correlation in transverse plane $\Delta\varphi$
  - sensitivity to resolved photons

- Models for comparison
  - Pythia (DGLAP)
  - Cascade (CCFM)
  - MC@NLO (FMNR + Herwig)



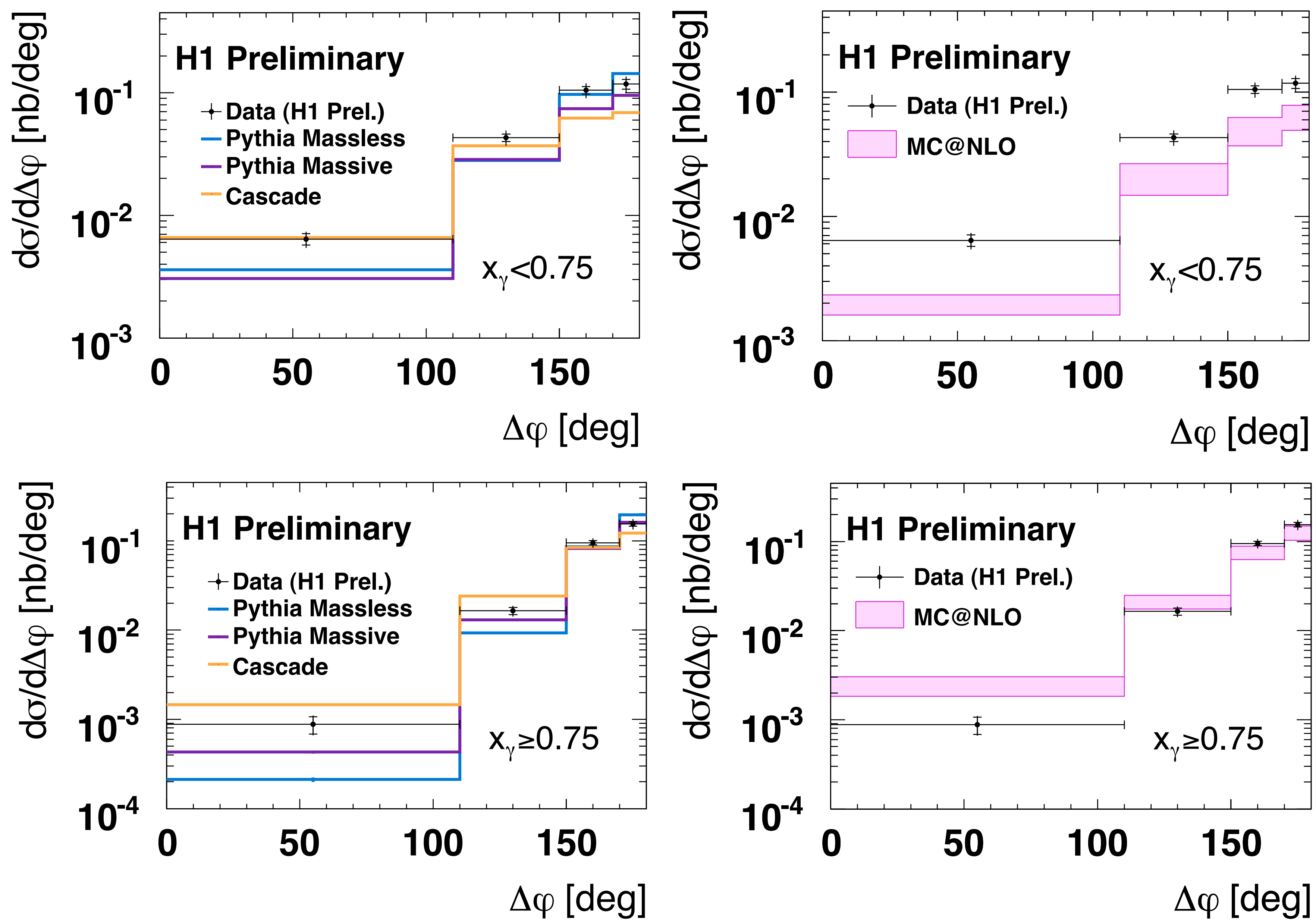
# D* + Dijets in Photoproduction

Jet | Full reconstruction

H1prelim-10-072

resolved $\gamma$

direct enriched $\gamma$



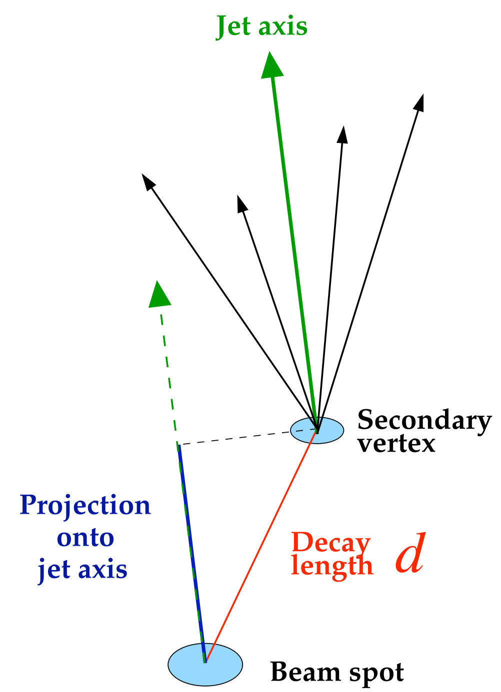

$x_\gamma$ : longitudinal momentum fraction of the photon carried by the jets

- LO Monte Carlo Pythia and Cascade
  - not able to reproduce $\Delta\varphi$ shape of the data
- MC@NLO
  - $\Delta\varphi$ shape reasonably well described
  - normalization too low at low $x_\gamma$

# Inclusive Heavy Flavour Jets in Photoproduction

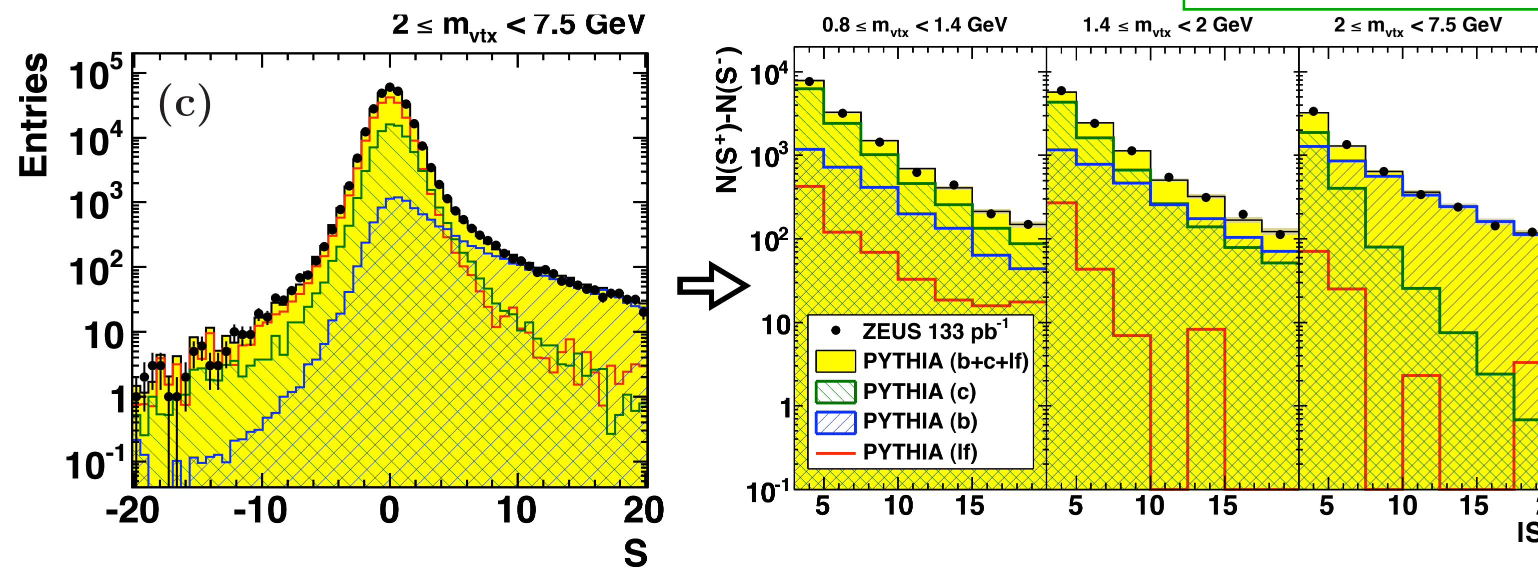
arXiv:1104.5444v1

Jet | Lifetime tag | 2nd vertex mass tag

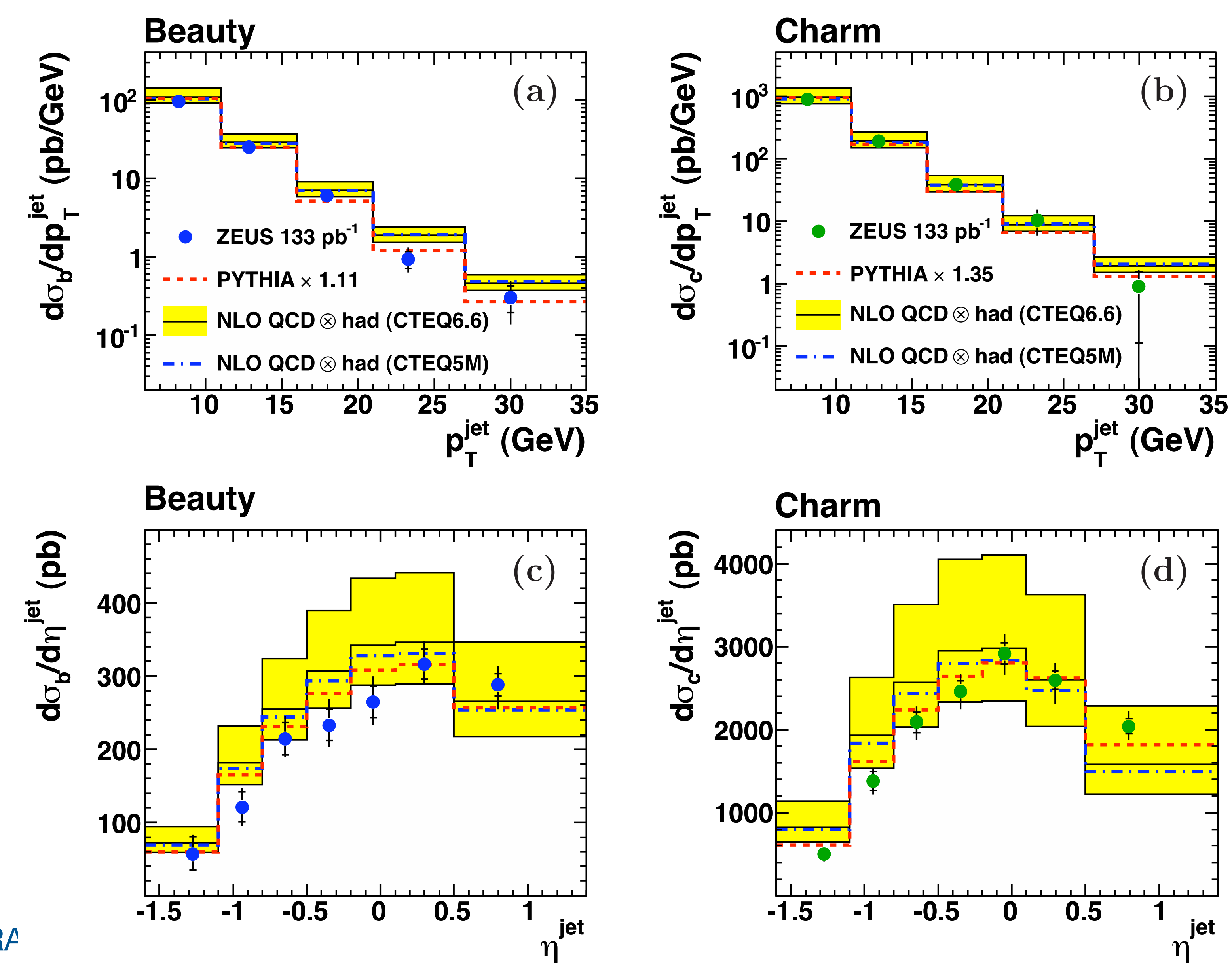



Significance:

$$S = \frac{d}{\delta d}$$




- Inclusive selection
  - 2 jets [$p_T^{jet} > 7(6)$ GeV]
  - secondary vertex
    - decay length significance
    - mass of tracks from 2nd vertex
- Compares well with scaled LO MC and NLO QCD predictions (FMNR)
  - large theory uncertainty
  - small dependence on proton PDF



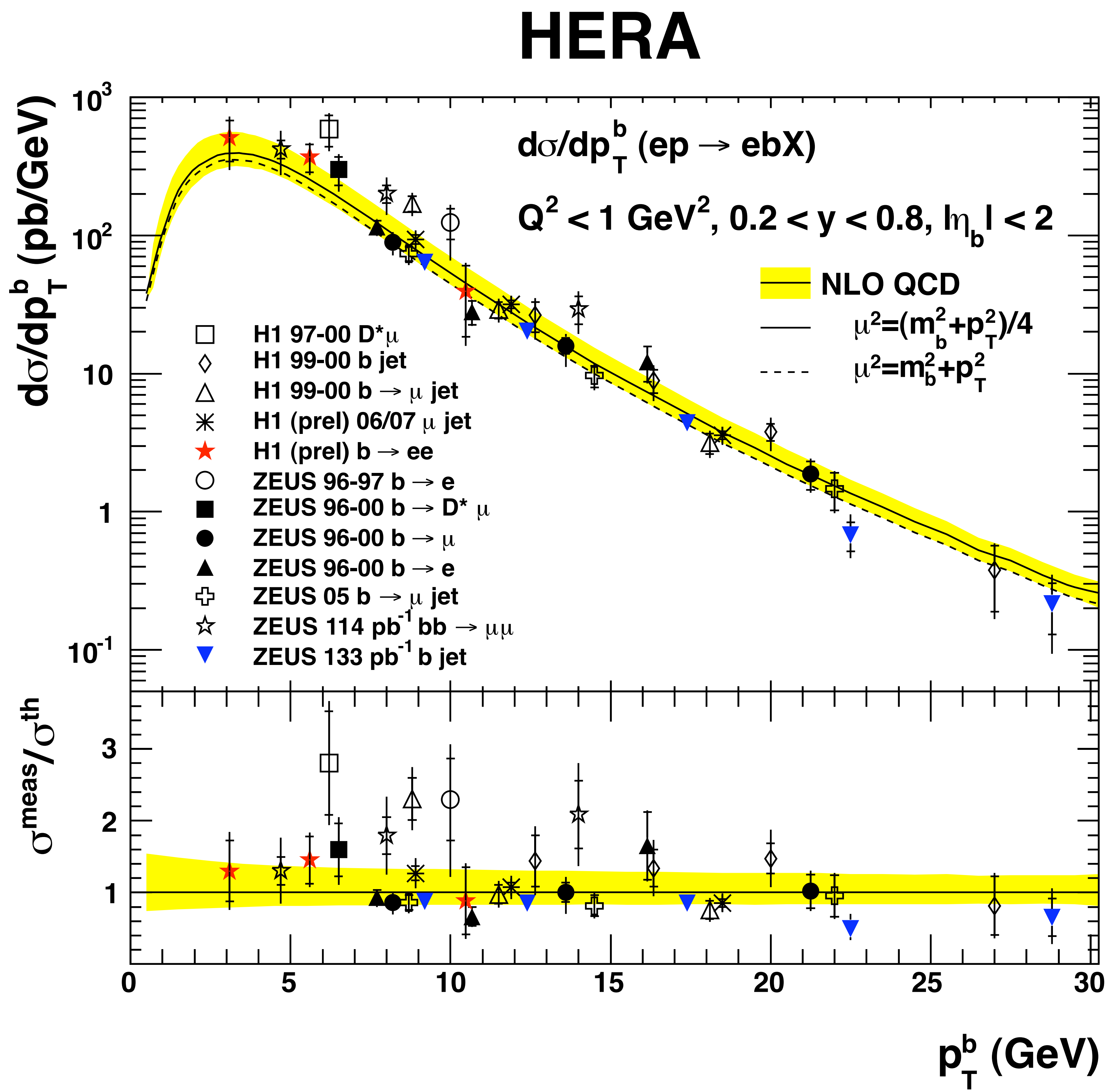
# Summary Plot Beauty in $\gamma p$ at HERA

- Large variety of measurement techniques yields consistent picture of b-quark photo-production at HERA over wide kinematic range
  - most recent measurements have improved precision and lead to extension of accessible $p_T$ range in both directions
    - Lepton tag b –> ee analysis [★]

      exploits product $m_{e1,e2} \cdot q_{e1} \cdot q_{e2}$ to extend phase space towards b-quark production threshold

      H1prelim-11-071

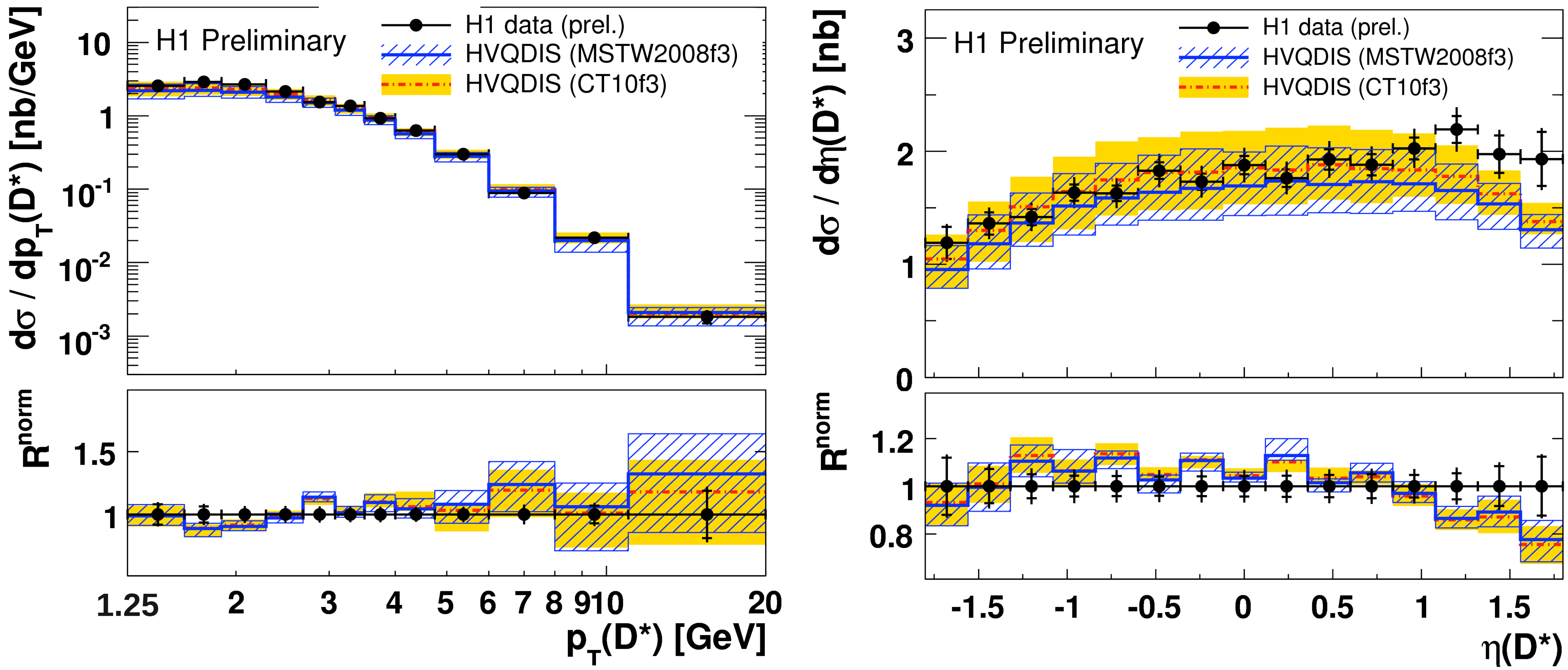
- Good description by massive NLO calculation (FMNR) over entire $p_T$ range



# D* Production in DIS at low Q²

**Full reconstruction**

H1prelim-10-172

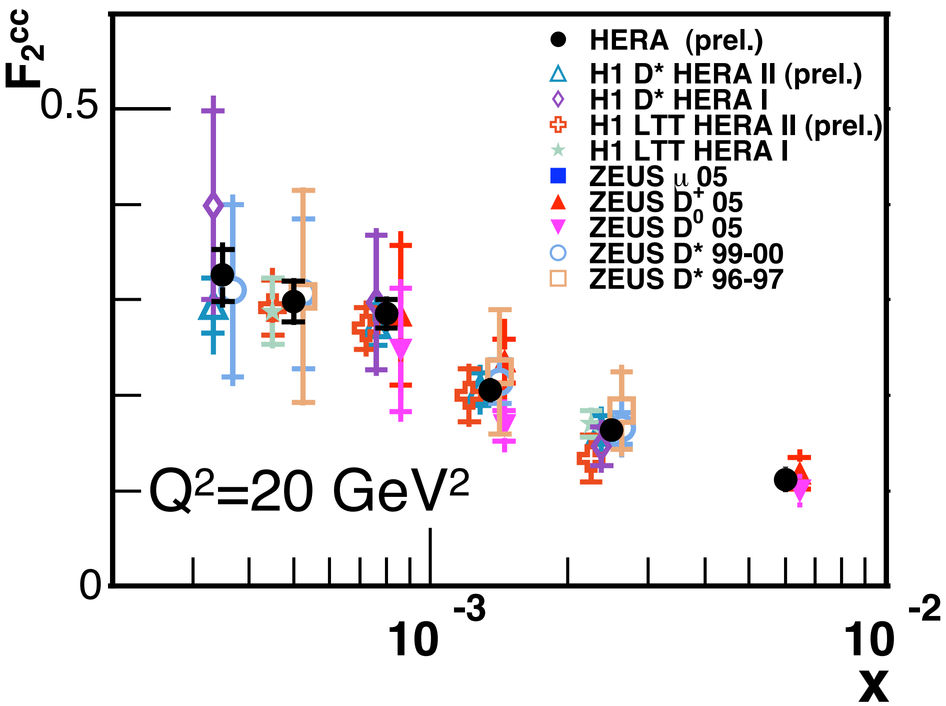


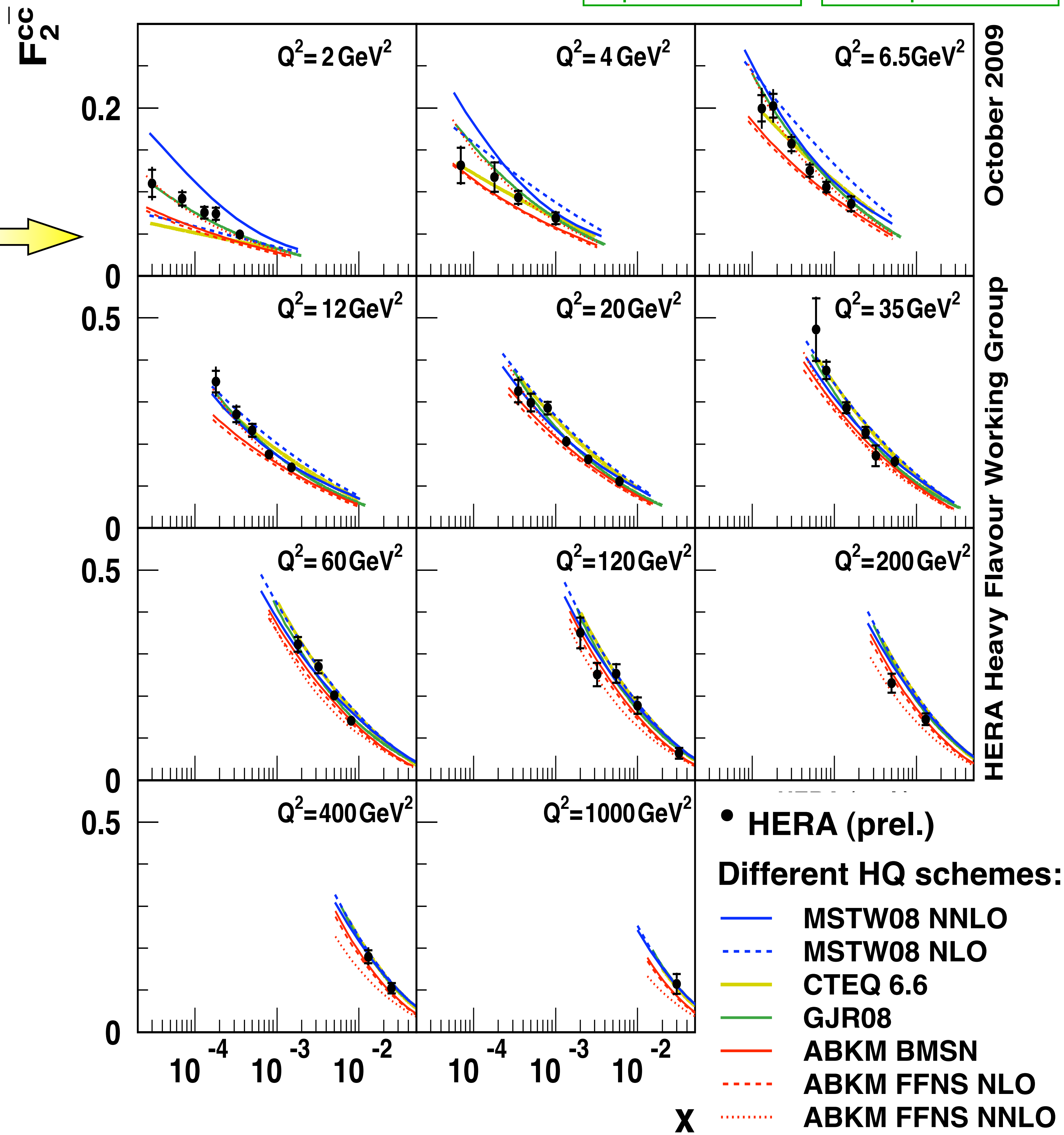

- D* reconstruction in golden decay channel $D^{*\pm} \rightarrow D^0 \pi^\pm_{\rm slow} \rightarrow K^\mp \pi^\pm \pi^\pm_{\rm slow}$
- Data reasonably well described by NLO calculation HVQDIS
- In forward direction predictions slightly undershoot data
  - from double differential distribution: excess mainly at low $p_T(D^*)$
- Double differential cross section $d^2\sigma/dydQ^2$ is used to extract charm contribution $F_2^{cc}(x,Q^2)$ to proton structure function $F_2$:

$$\frac{d^2\sigma^{c\bar{c}}}{dx\, dQ^2} = \frac{2\pi\alpha^2}{Q^4 x}[(1+(1-y)^2)\cdot F_2^{c\bar{c}}(x,Q^2) - y^2 F_L^{c\bar{c}}]$$

# HERA combined Charm Data for $F_2^{cc}$

H1prelim-09-171 ZEUS-prel-09-015



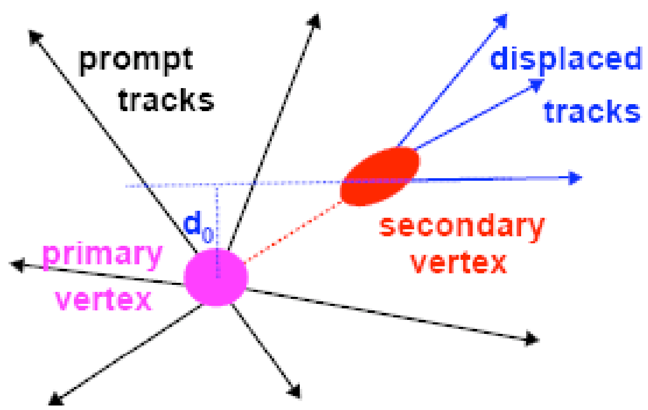




- Combination of 9 results based on different charm tagging methods
  - averaging procedure leads to significant reduction of cross-correlated systematic uncertainties
  - resulting precision of 5 - 10%
- Data can be used to study differences in available flavour number schemes
  - [massless (**Z**ero **M**ass)]
  - massive (**F**ixed **F**lavour)
  - general mass (**GM**)

# Charm and Beauty Jets in DIS

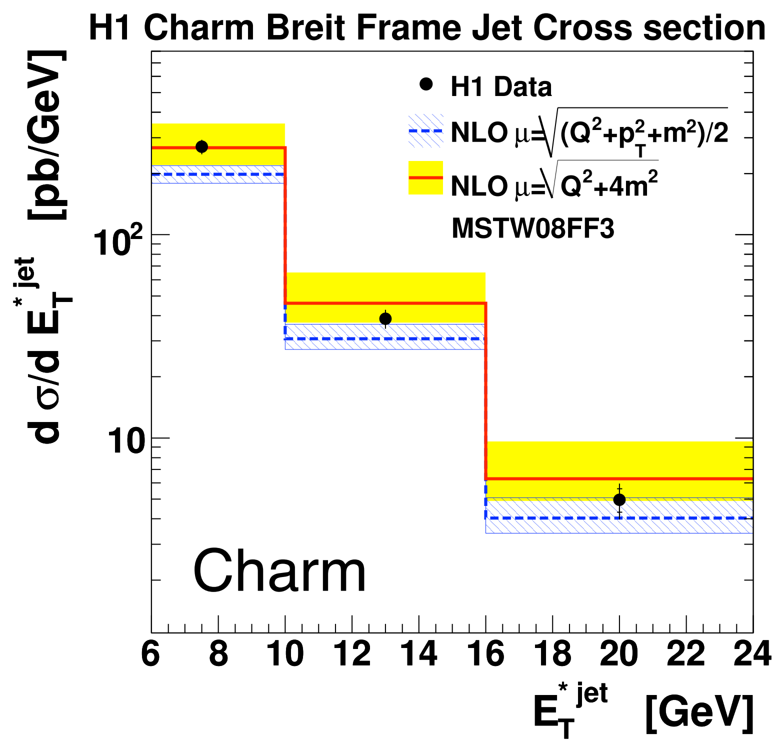
Jet | Lifetime tag

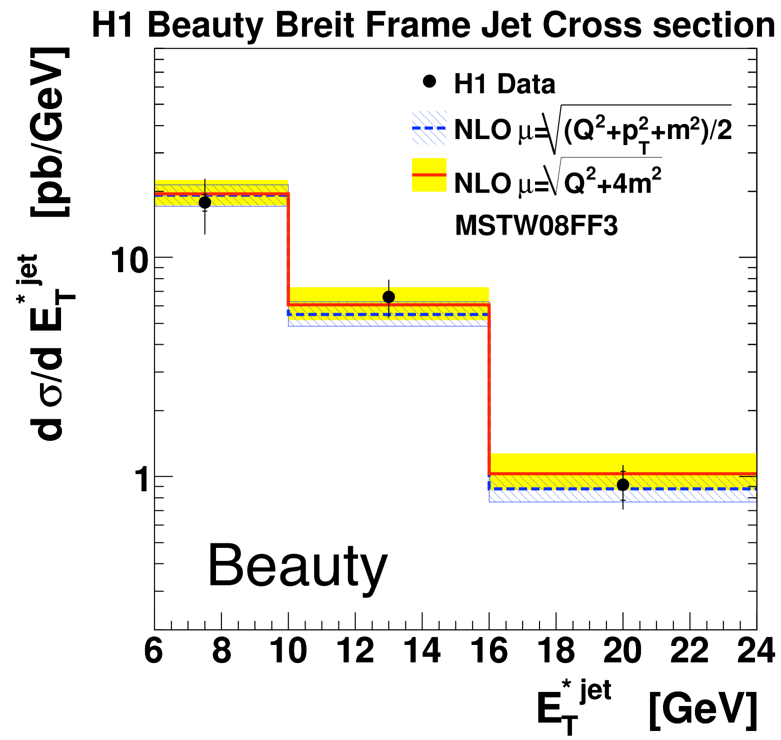
Eur.Phys.J.C71:1509,2011

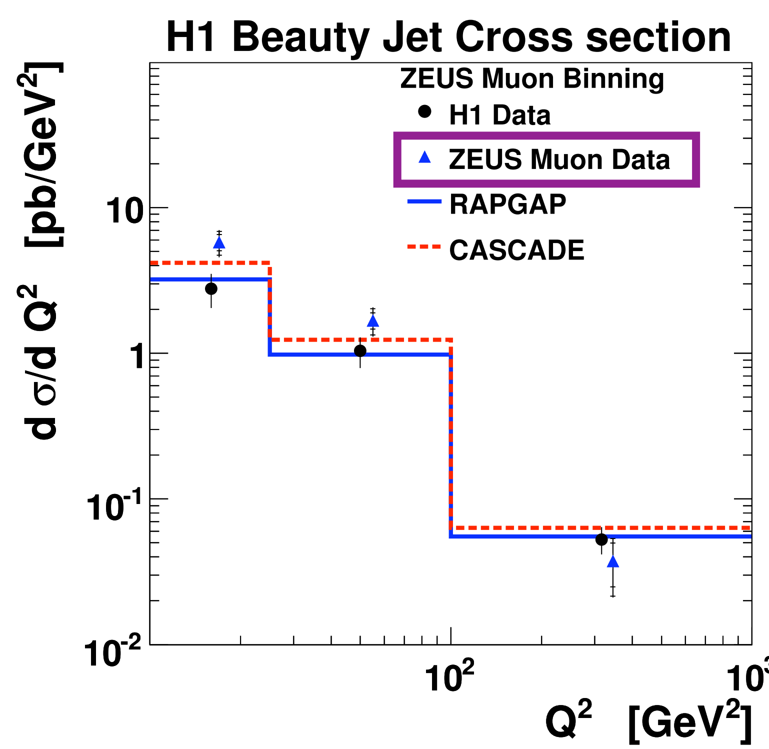


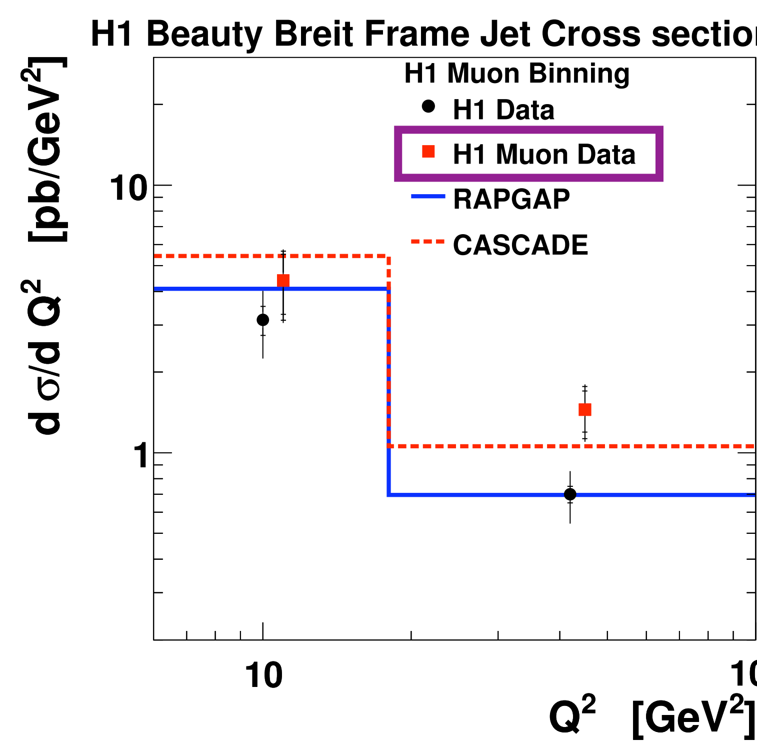

- Charm and beauty cross section as function of $E_T^{*jet}$ well described by NLO QCD calculation (HVQDIS)
  - only little dependence on scale choice

- Comparison with results from μ-tagging
  - relatively large extrapolation factors
  - ratio of the muon data to the lifetime tagged data ≈ 2, but in agreement within full error



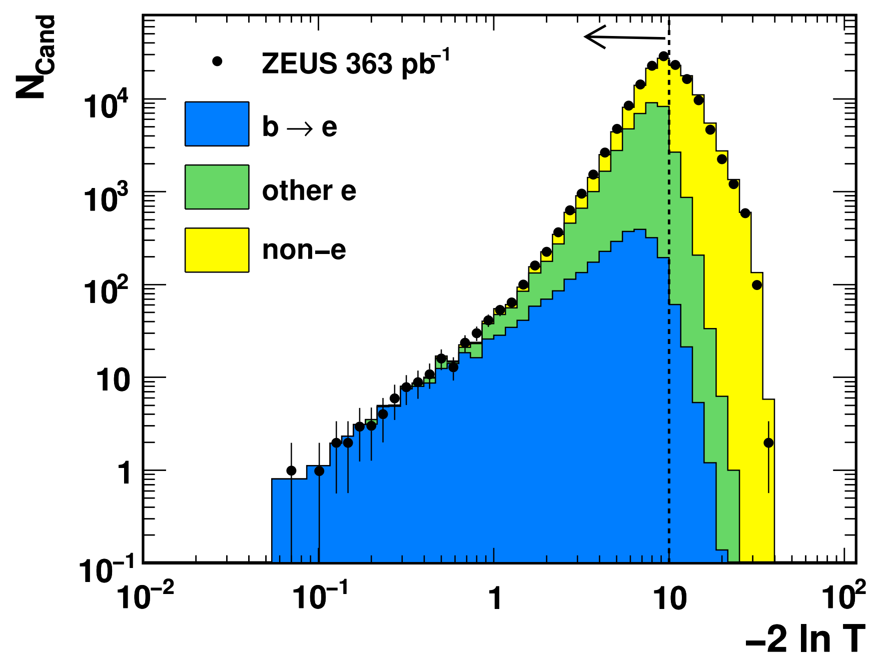



# Beauty from Exclusive Electrons in DIS

Lifetime tag | Lepton tag | $p_t^{rel}$ tag

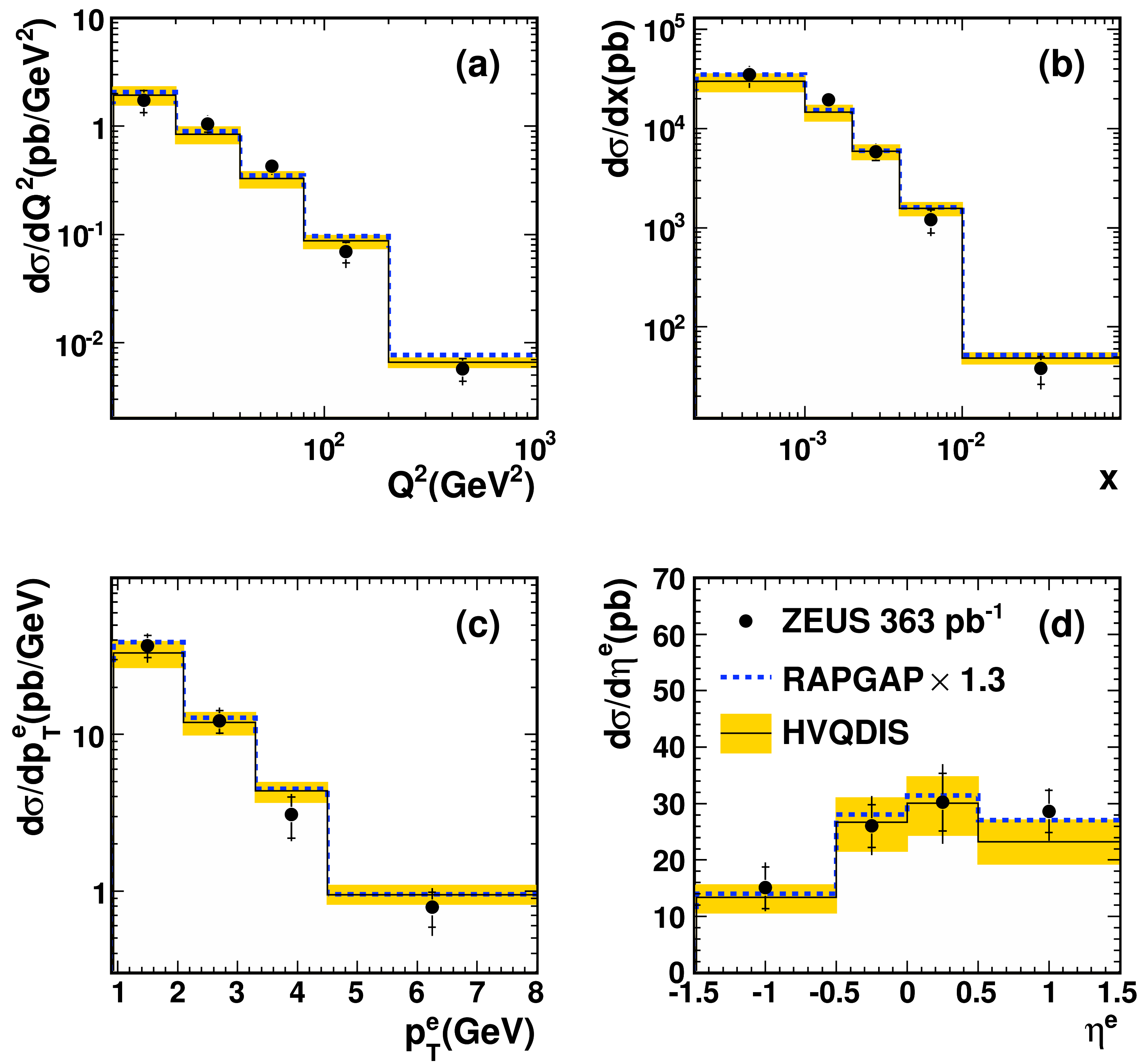



$$T = T\left(\frac{dE}{dx}, \frac{E^{CAL}}{p^{track}}, d_{cell}, p_T^{rel}, \Delta\phi, \frac{d}{\delta d}\right)$$

- Extraction of beauty content from semileptonic decays into electrons
  $ep \to e' b\bar{b} \to e' e X$
- Construct likelihood discriminator T and fit to MC templates
- Good description of data by
  - scaled LO prediction (RAPGAP)
  - NLO QCD calculation (HVQDIS)

ZEUS

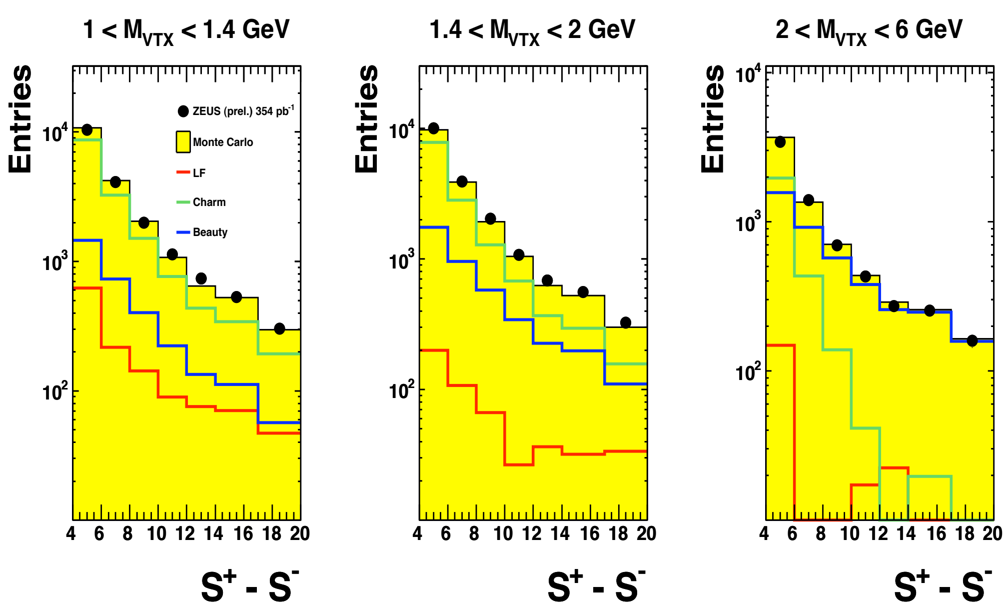
DESY-11-005

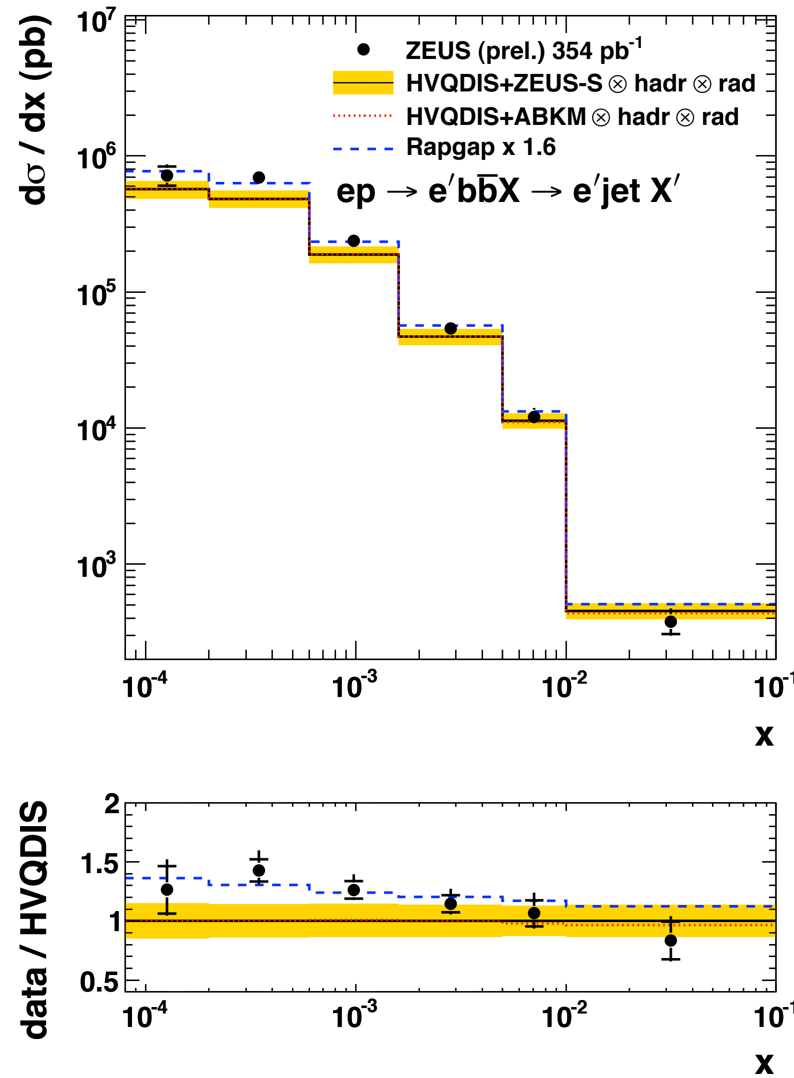


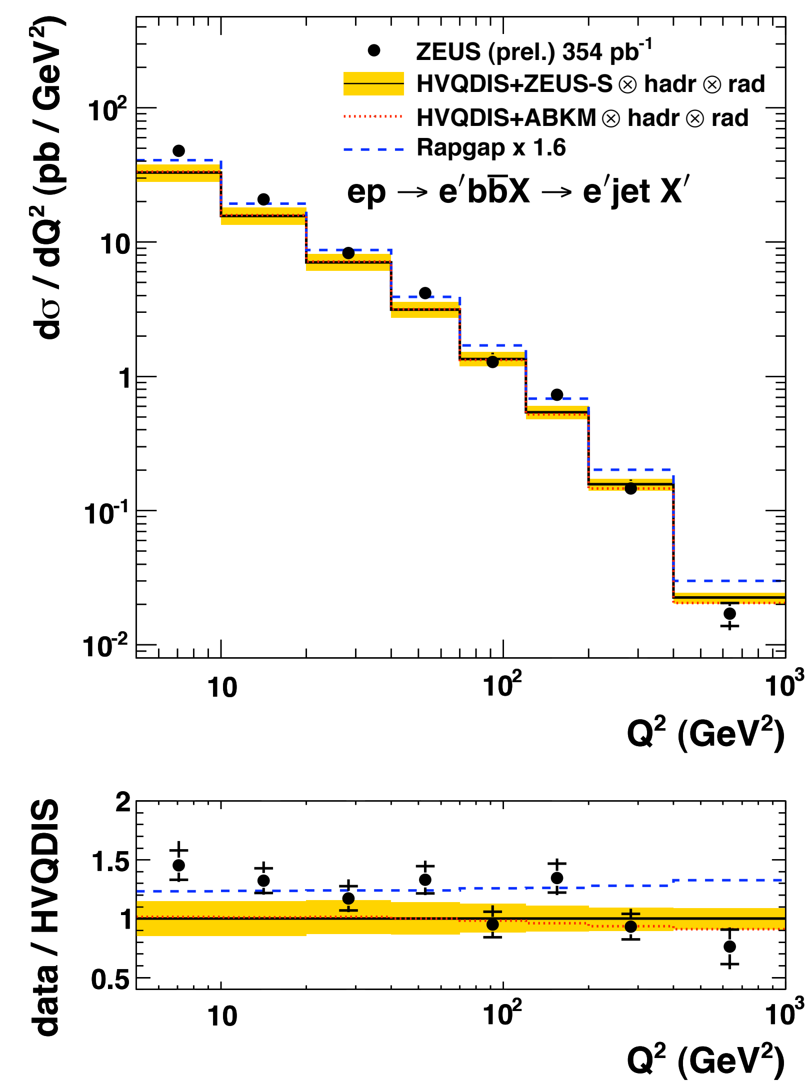
# Inclusive Beauty Production in DIS

Lifetime tag | $2^{nd}$ vertex mass tag

ZEUS-prel-10-004



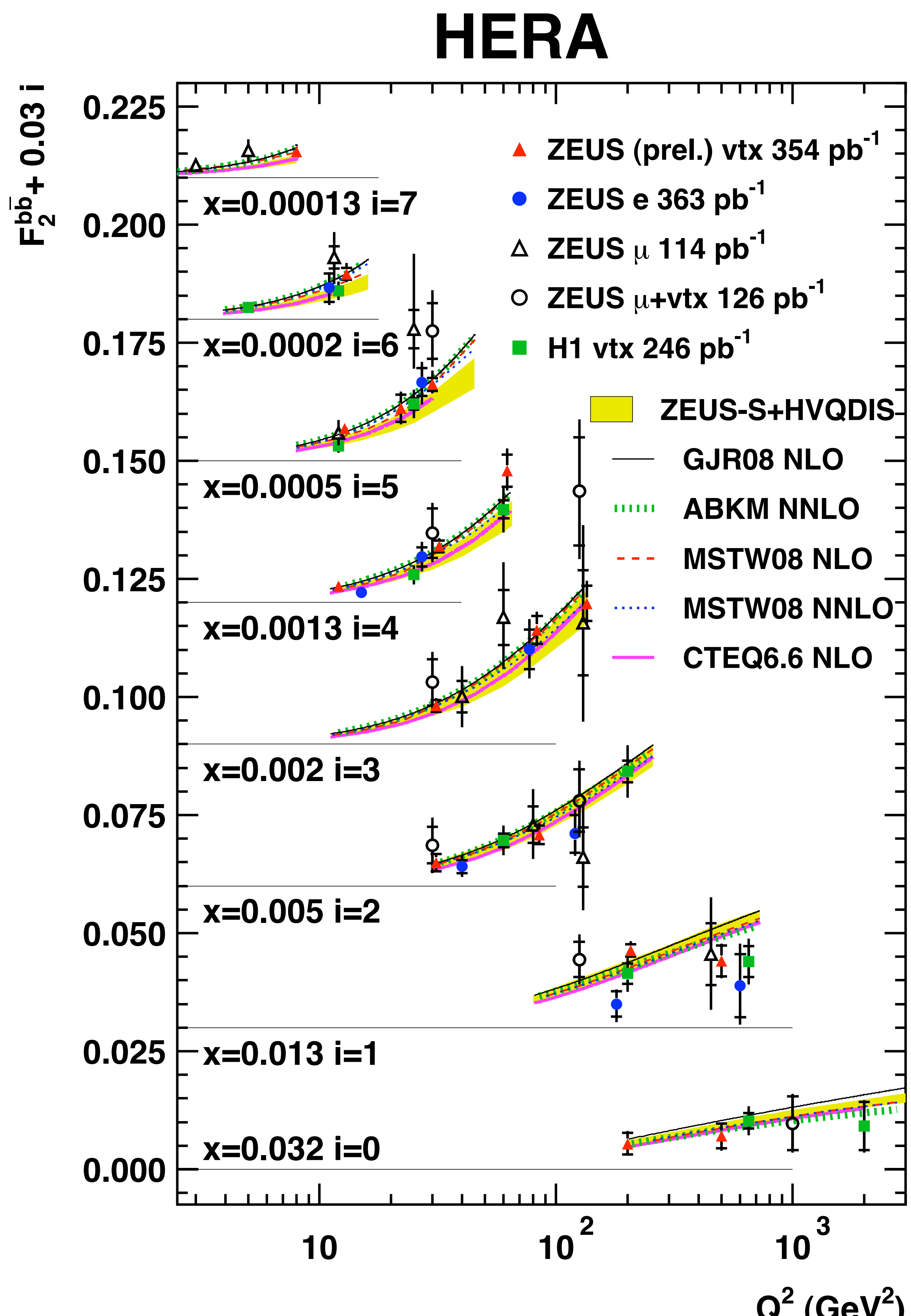

- Measurement of beauty production using inclusive secondary vertices
- Single differential cross sections in reasonable agreement with NLO QCD predictions (HVQDIS)
- $F_2^{bb}$ extracted from double-differential cross sections
  - extrapolation factors to full phase space typically quite small 1.0-1.3

$$\frac{d^2\sigma^{ep\to b\bar{b}x}}{dx\, dQ^2} = \frac{2\pi\alpha^2}{Q^4 x}[(1+(1-y)^2)\cdot F_2^{b\bar{b}}(x,Q^2) - y^2 F_L^{b\bar{b}}]$$

$$F_2^{b\bar{b}}(\mathrm{exp}) = \frac{\sigma_{vis}(\mathrm{exp})}{\sigma_{vis}(\mathrm{theo})} F_2^{b\bar{b}}(\mathrm{theo})$$

# Beauty Contribution to Proton Structure

- Large variety of different experimental methods to extract $F_2^{bb}$
- Measurements are compatible with each other within uncertainties
- NLO QCD predictions based on HVQDIS describe the data well



# Summary

- Wealth of heavy flavour results exploiting complete HERA statistics
  - increased precision
  - extended phase space
- Large variety of very different experimental techniques allow non-trivial cross checks to be made
  - measurements generally very well consistent with each other
- Reasonable description of data by up-to-date NLO QCD predictions