LANCASTER UNIVERSITY

ETH Institute for Particle Physics

Heavy Flavour Production at HERA

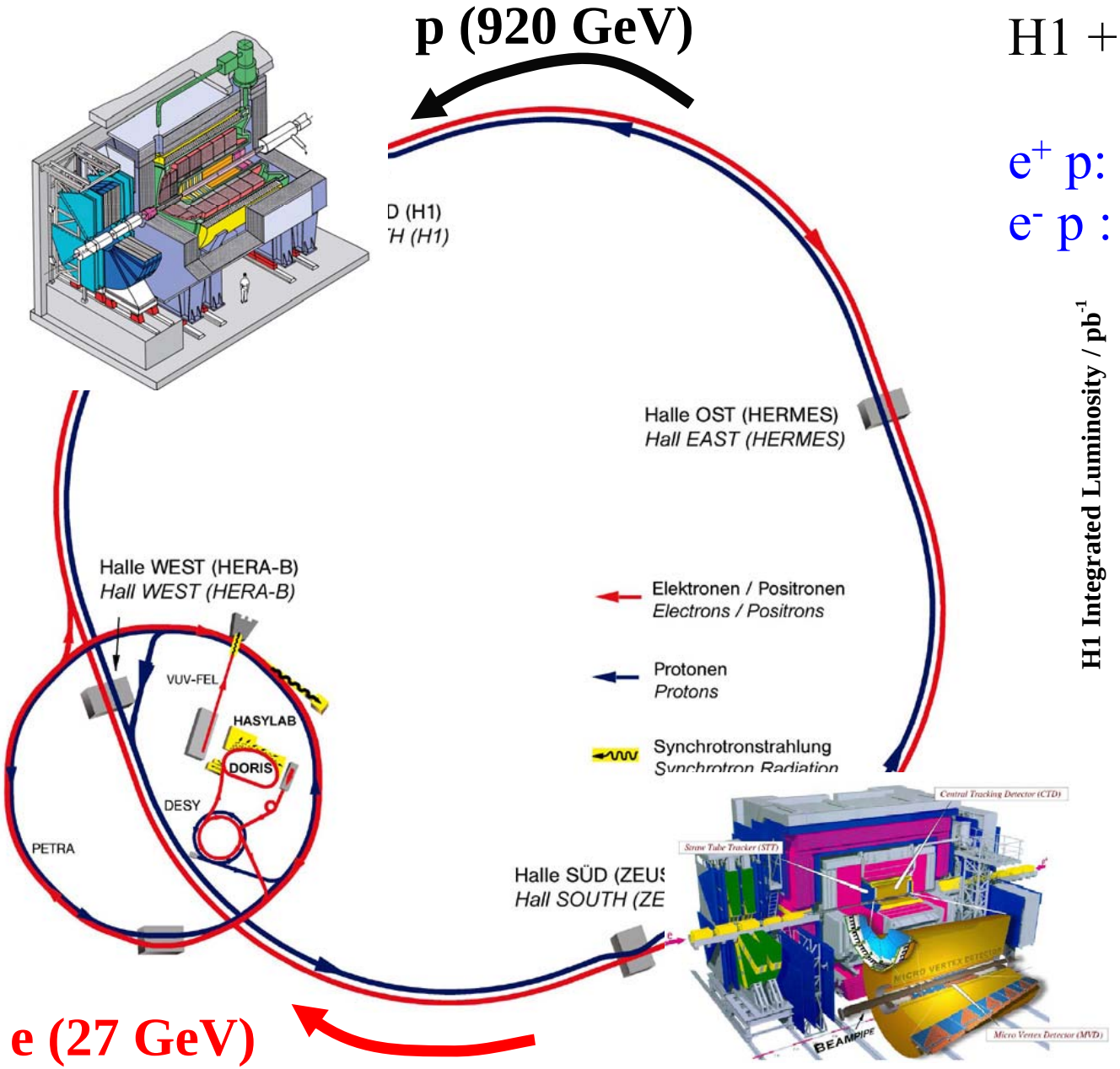
- Introduction
- Charm production
- Beauty production
- Heavy Flavour structure functions

Christoph Grab
ETH Zurich

representing

and

The HERA Collider

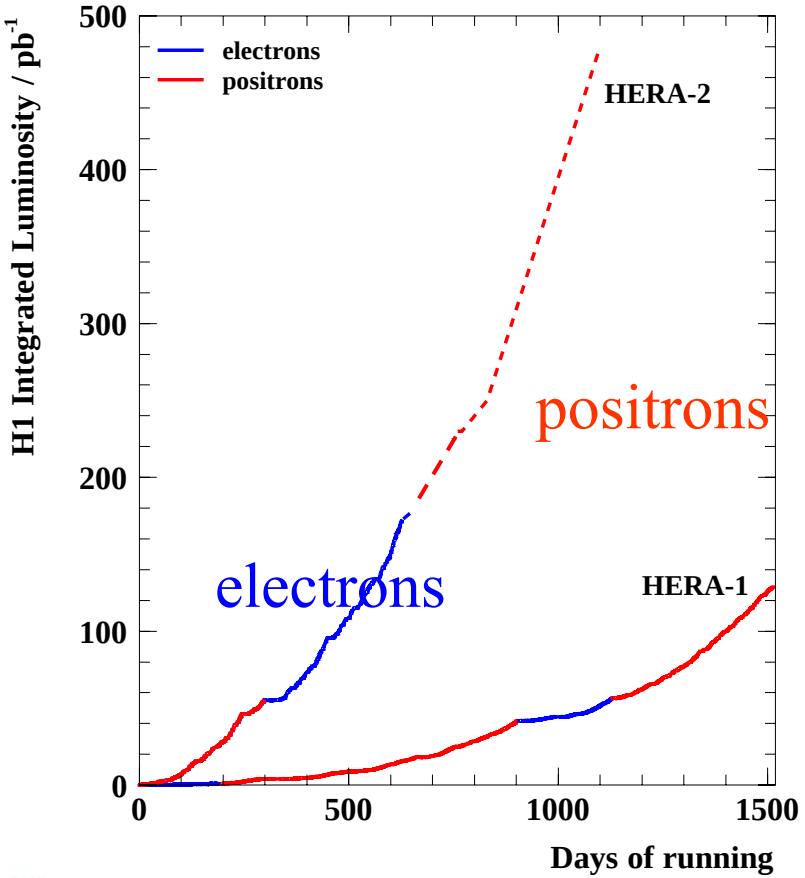


H1 + ZEUS integrated luminosity

96-00 / 03-06 (HERA-II)

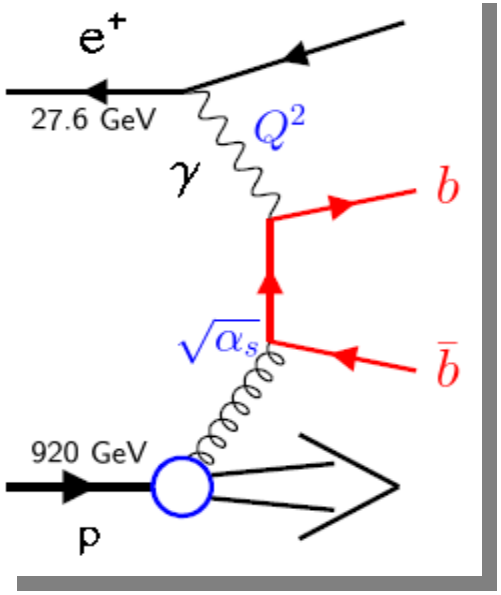
$e^+ p$: ~ 100 / 40 pb^{-1}

$e^- p$: ~ 15 / 180 pb^{-1}



2007 ~ 500 pb-1

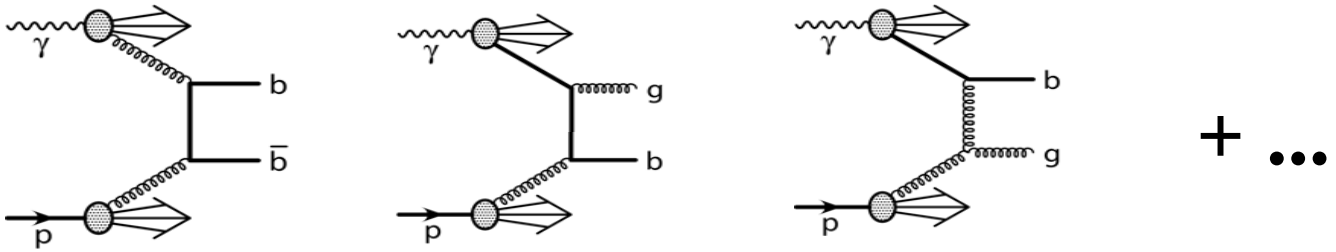
Heavy Flavour Production at HERA



- Dominant production is Boson-gluon fusion :

direct $\gamma g \rightarrow Q\bar{Q}$, driven by gluons in proton

+ resolved contributions ... "c/b-excitation"



Different scales involved, to make α_s small:

- $Q^2 > 1$ GeV^2: Deep Inelastic Scattering(DIS) ↔ $Q^2 < 1$ GeV^2 : Photoproduction (γP)
- M_b ,M_c~ 5, 1.5 GeV and E_T, p_T ~ few GeV

- **Powerful test of pQCD**:

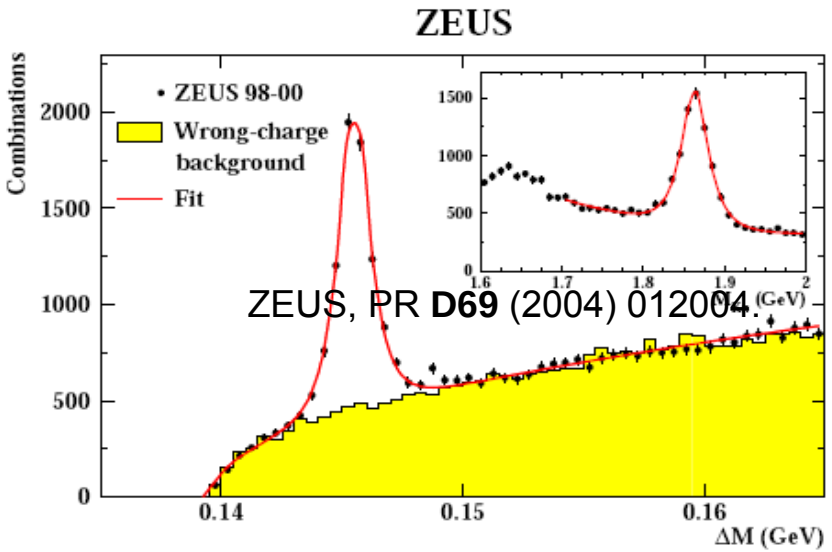
  massive vs massless schemes? is NLO enough? intrinsic k_t of gluon ? …
- Investigate g-density in proton and hadronic components of photon.

Charm Production

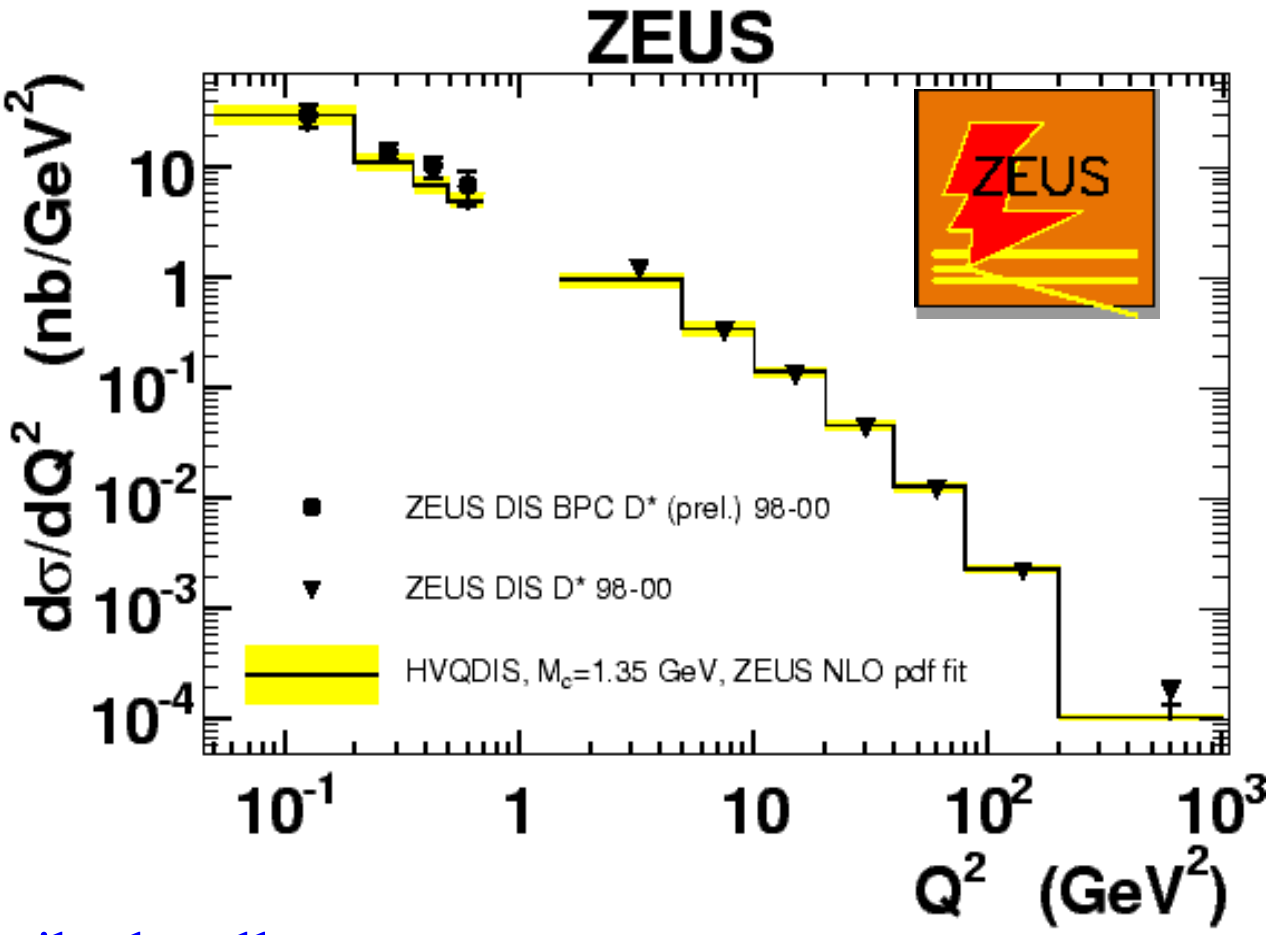
Charm Tagging via D^* Production

$\sigma_{uds} : \sigma_{charm} : \sigma_{beauty} \sim 2000 : 200 : 1$

tag $D^* \rightarrow (K\pi)\pi_s$ with Δm



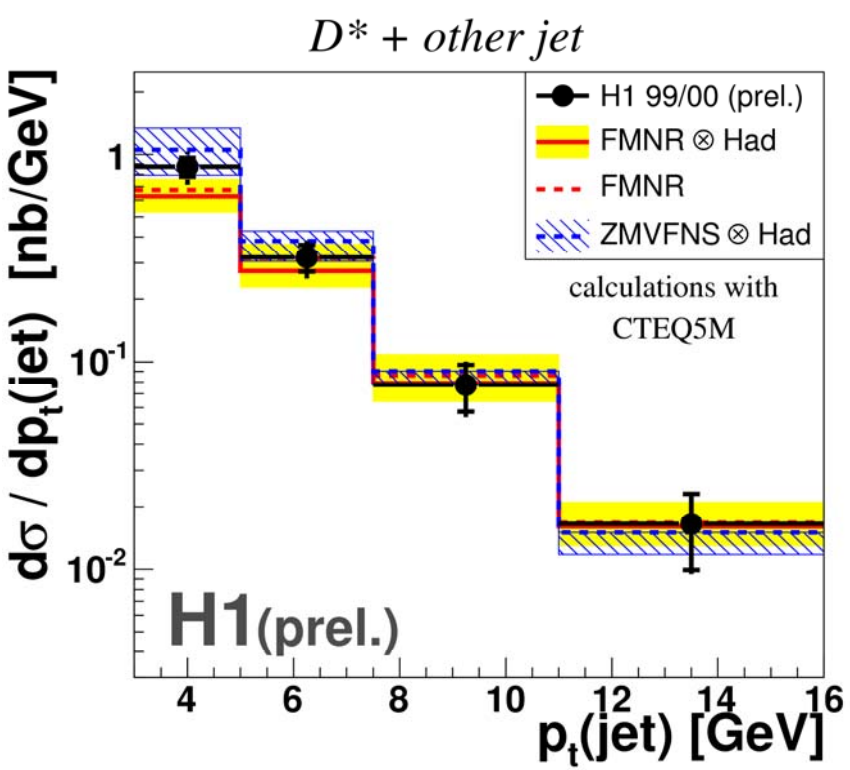
ZEUS, PR **D69** (2004) 012004.

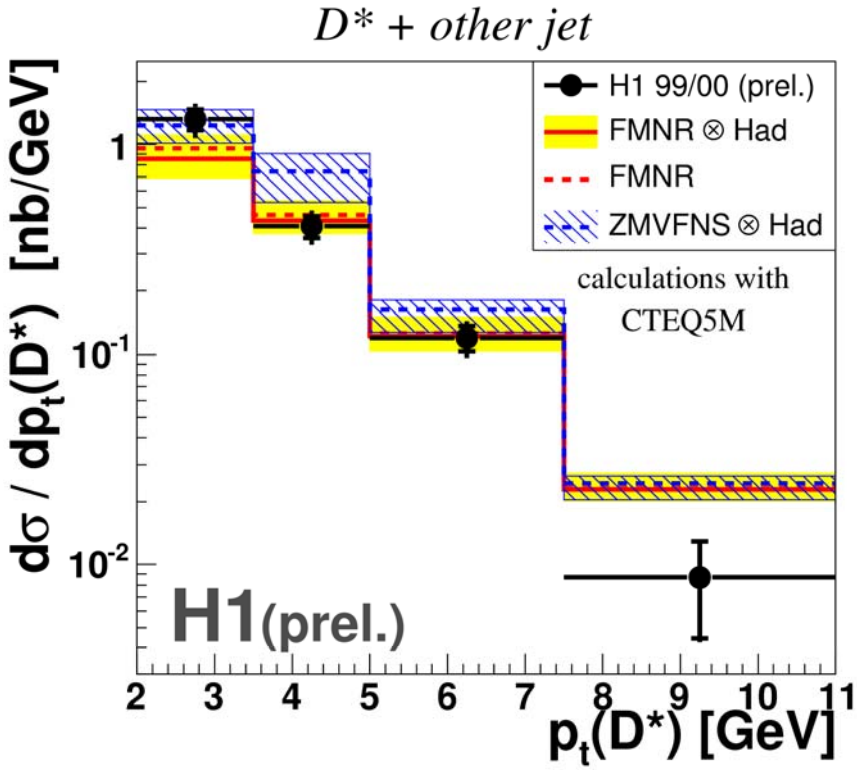


- Q^2 evolution measured and described well by NLO QCD over 4 orders of magnitude

ZEUS preliminary 04-024.
ZEUS, PR **D69** (2004) 012004.

Charm with Jets in Photoproduction



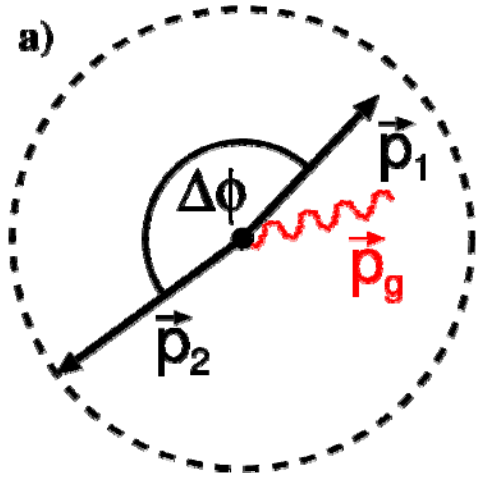


- H1: Events with a reconstructed D* + 2nd jet in photoproduction
- p_t spectra of both D* and jet well described by NLO QCD [PL B348(1995) 63]

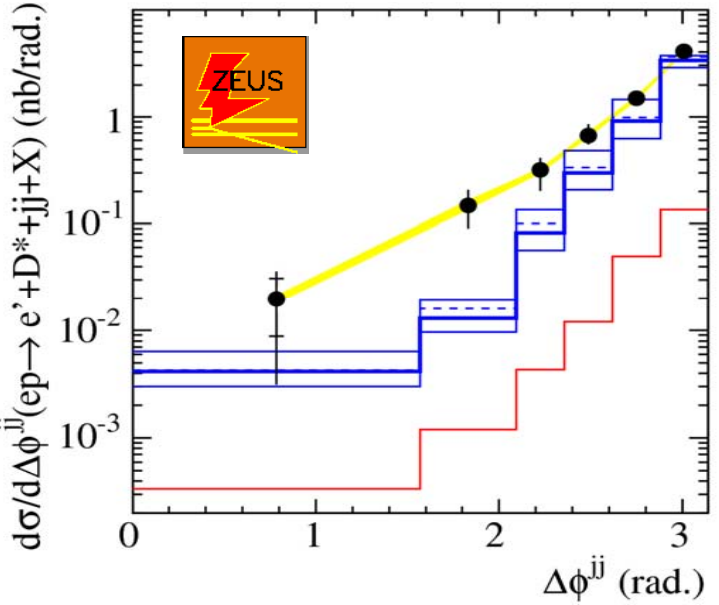
H1prelim-05-073

Dijets with Charm in γp: Testing NLO QCD

Test limitations of fixed order pQCD

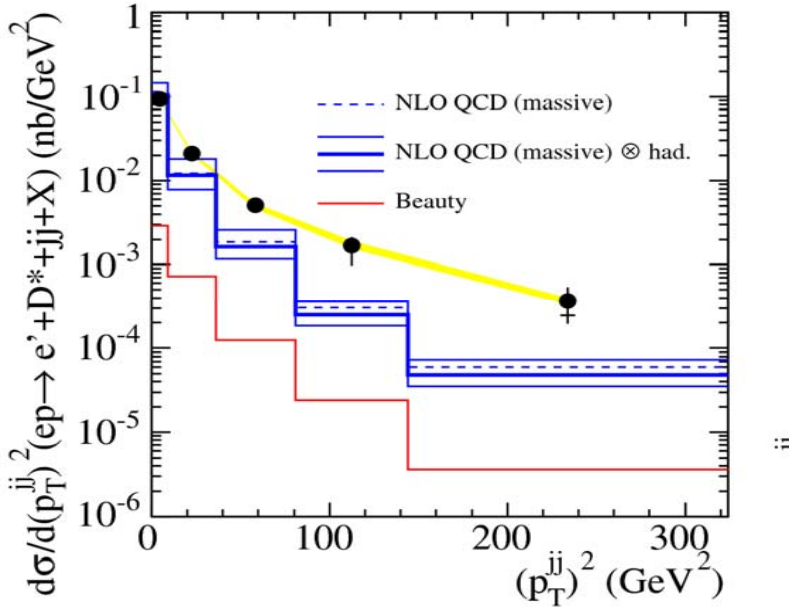


- LO: Quarks are back-to-back: $\Delta\phi=180^o$
- NLO: additional gluons show up at $\Delta\phi < \pi$



- $\Delta\phi(jj)$ and $p^2_T(jj)$ show large deviation from NLO at high $p^2_T(jj)$ and small $\Delta\phi(jj)$

  ➔ regions sensitiv to higher order effects.



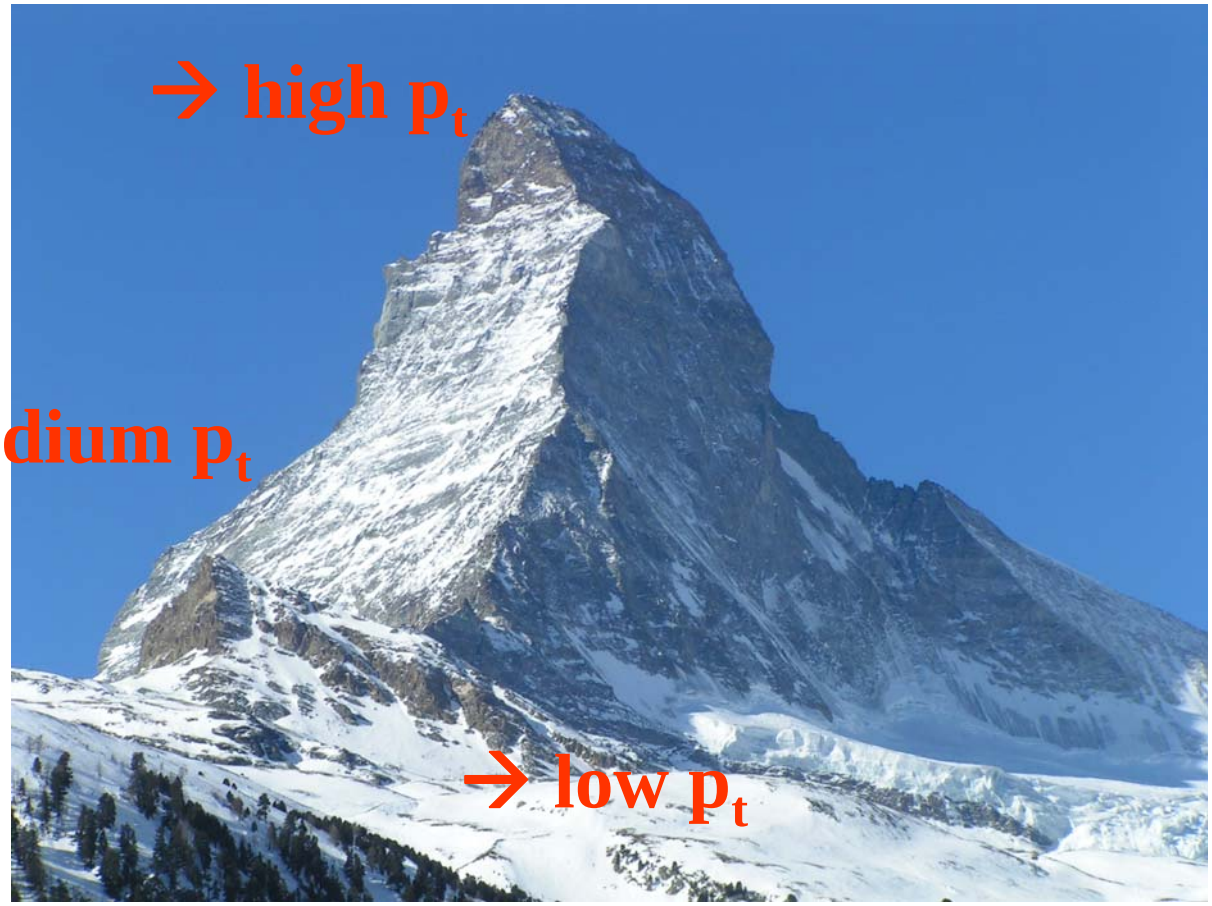
- Good agreement of NLO with data, except where HO are enhanced : NNLO, ... needed

ZEUS, Nucl. Phys. **B729** (2005) 492.

Beauty Production Results

Selection of results, ordered according to tagging methods, which correspond also to **different scales**

- **inclusive lifetime tagging** → **high p_t**
- **muons and jets** → **medium p_t**
- **double tags** → **low p_t**

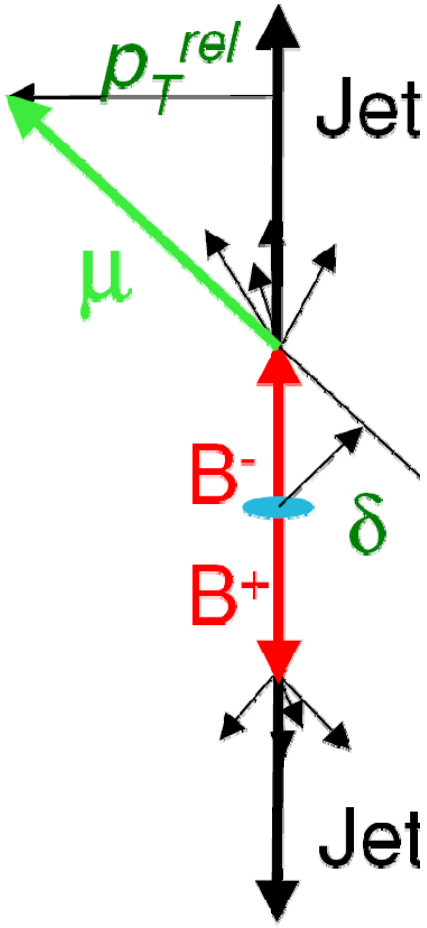


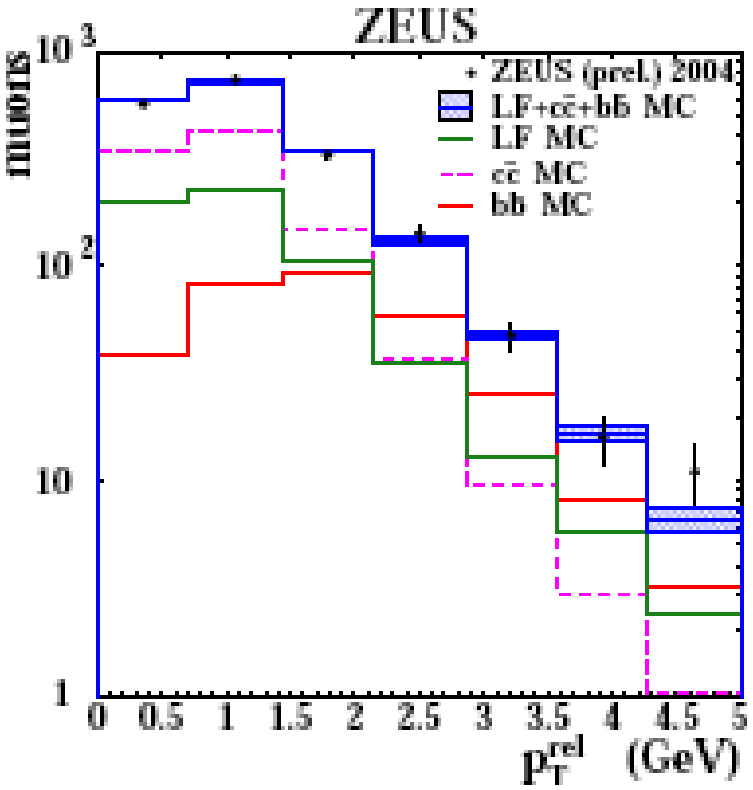
Beauty Tagging with muon and jets

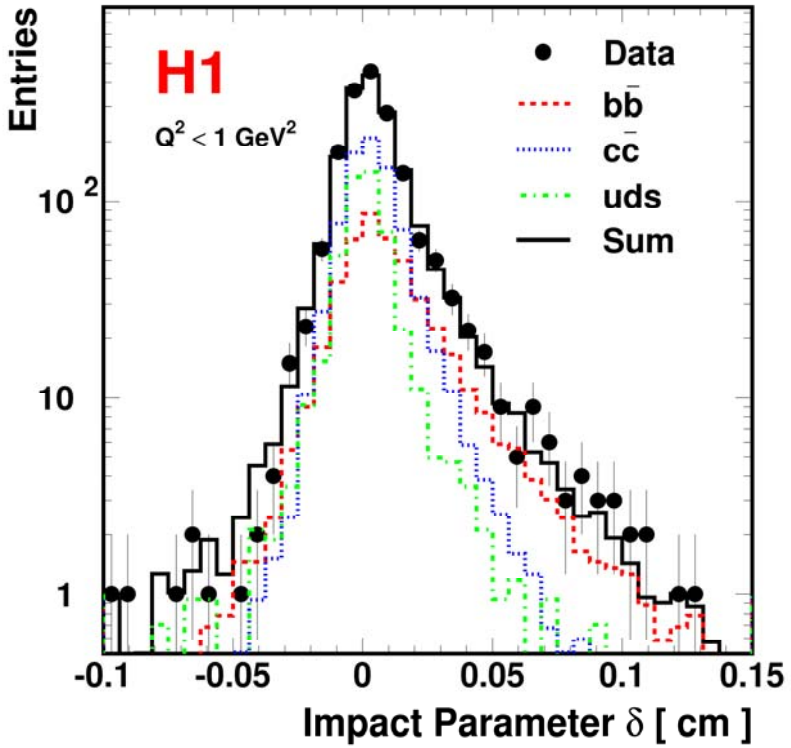
medium p_t → medium scale

Beauty Tagging

- Exploit the muons from semileptonic decays to separate charm and beauty.
- fit p_t^{rel} (large B mass) and/or impact parameter δ (large B-lifetime) distributions; extract c,b-fractions using MC-shapes ; b-fractions ~ 30%



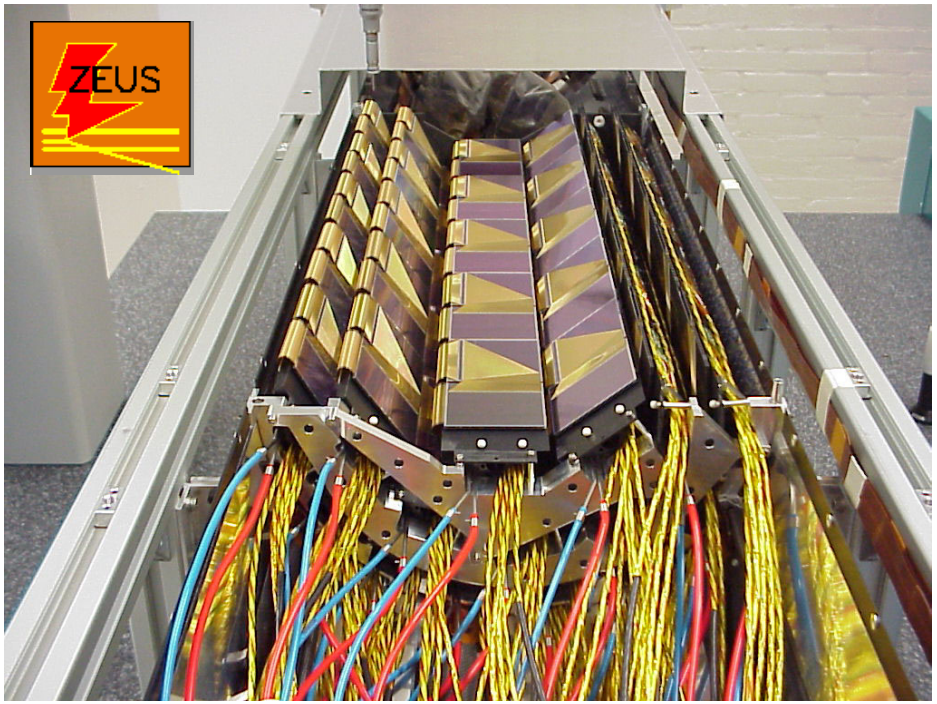




Tagging uses Silicon Trackers

H1 Central Silicon Tracker CST:

- Two layers, cylindrical (Hera-I)
- double sided strips
- DCA-resolution= 33 +90/pt [μm /GeV]



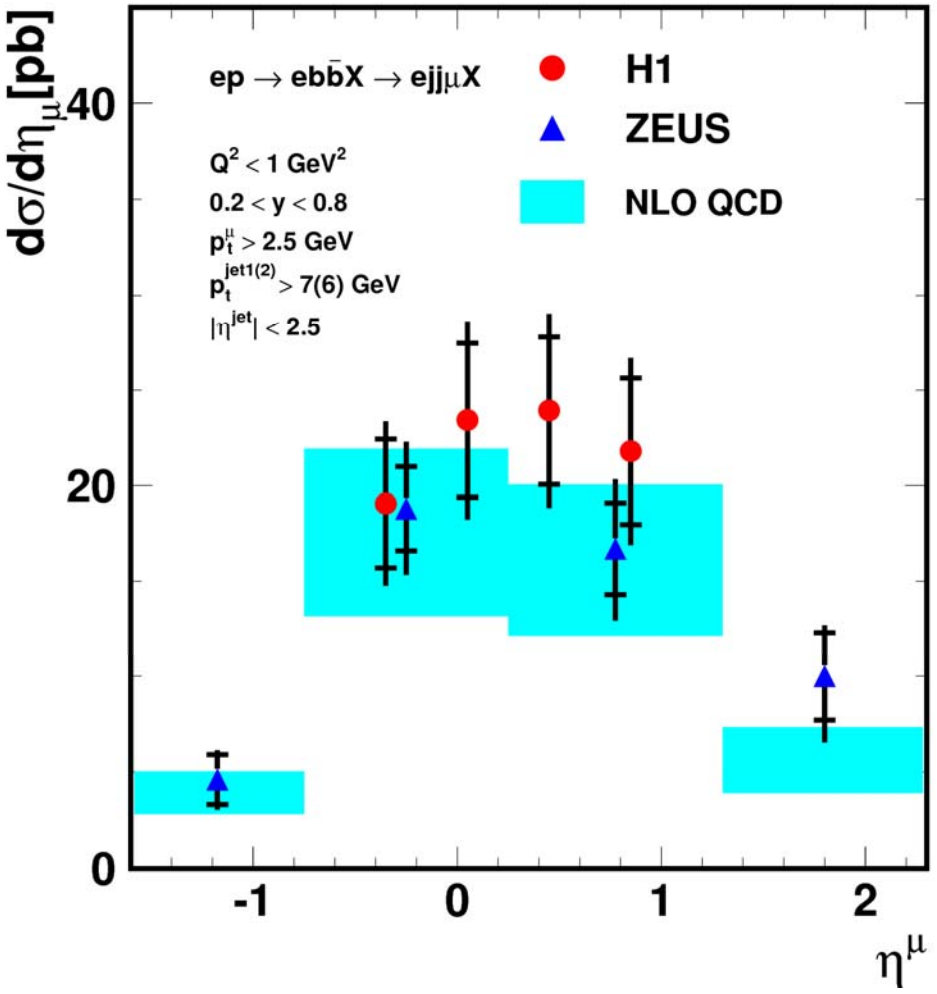
ZEUS Barrel Microvertex Detector MVD:

- 3 layers, double sided strips,
- 65 cm length, covering 30 - 150^{o}
- Beam spot size : 110 x 30 mm2 .

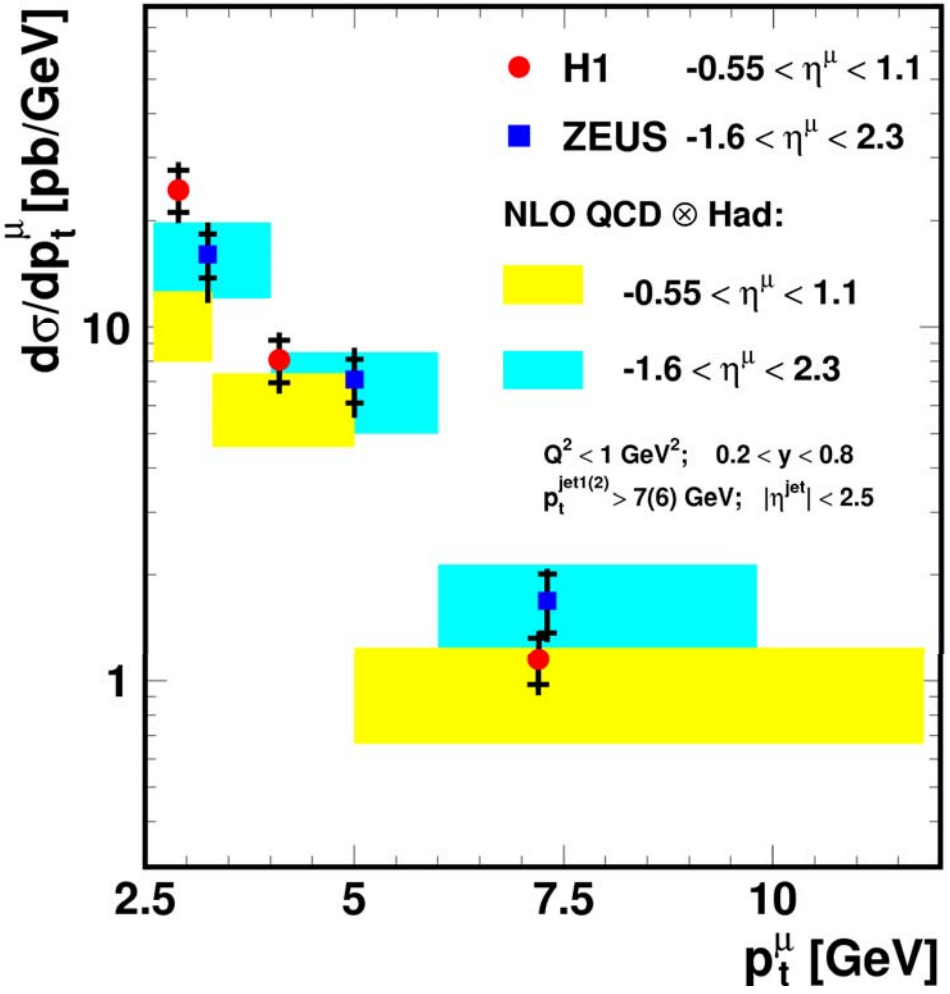
HERA-II

Beauty Tag μ+2j: (δ,p_t^{rel}) in γp

H1 : 2D-fit to p_t^{rel} and δ (~ 50 pb^{-1});



ZEUS : fit to p_t^{rel} (~ 110 pb^{-1})



H1, EPJ **C41** (2005) 453
ZEUS, PL **B599** (2004) 173.

- General agreement between H1 and ZEUS
- NLO (FMNR): shape close, agrees within errors
- H1: NLO tendency to be low at low p_t^{μ}

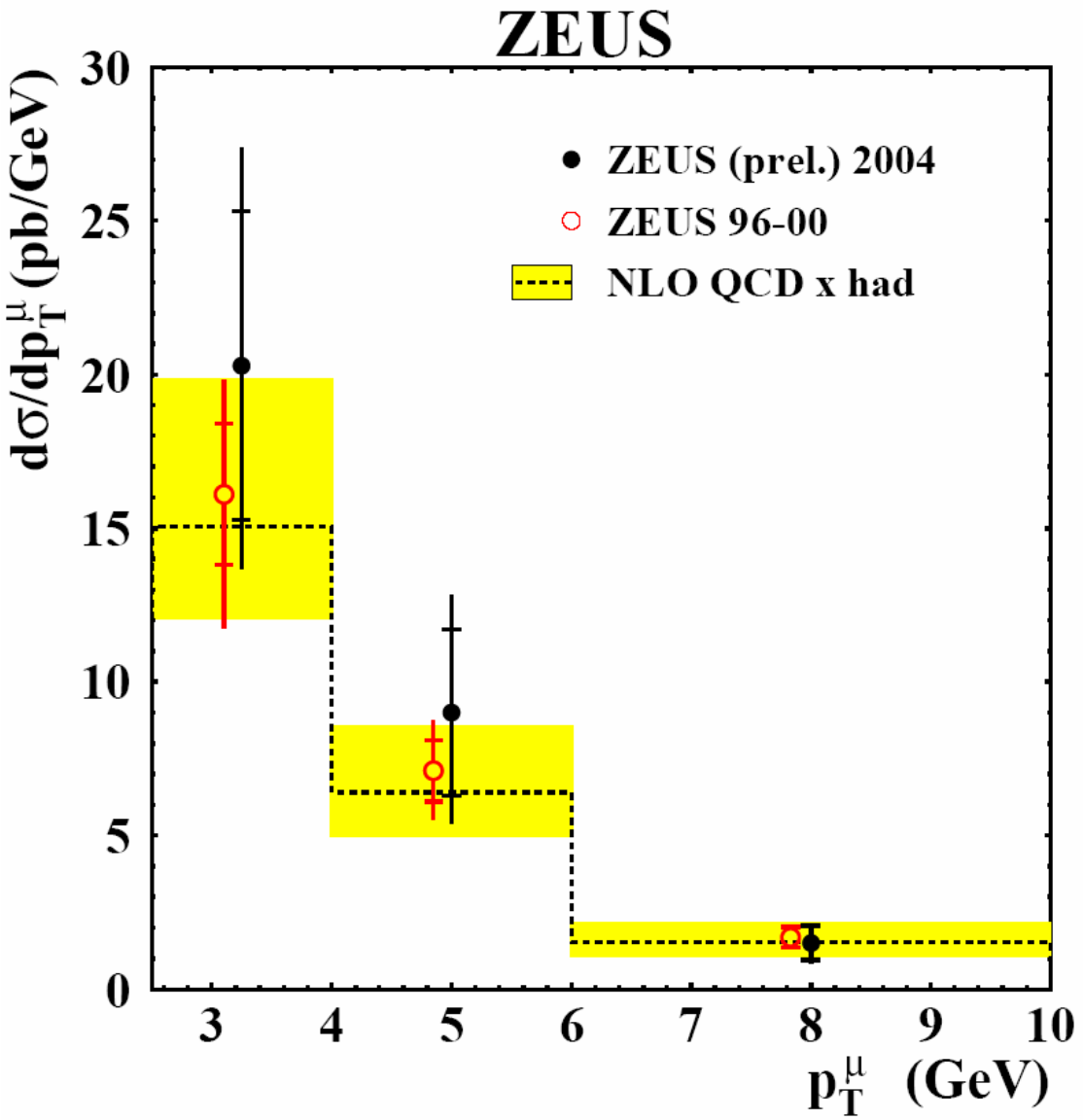
Beauty Tag (δ,p_t^{rel}): ZEUS @HERA-II with MVD

ZEUS: $Q^2<1$ GeV^2, $0.2<y<0.8$; $p_t^{jet}>7{,}6$ GeV, $|\eta_{jet}|<2.5$; $p_t^{\mu}>2.5$ GeV, $-1.6<\eta_{\mu}<2.3$

- First ZEUS HERA-II results with new MVD
- for 33 pb^{-1} from a 2-D fit (δ,p_t^{rel}) of events with muon + 2 jets yield:

  $f_b=(16.7\pm2.6)\%$ $f_c=(52\pm10)\%$

- pQCD NLO (FMNR) including had. corrections describes data well
- agrees with previous measurements (used p_t^{rel})



Beauty tagging using inclusive lifetime

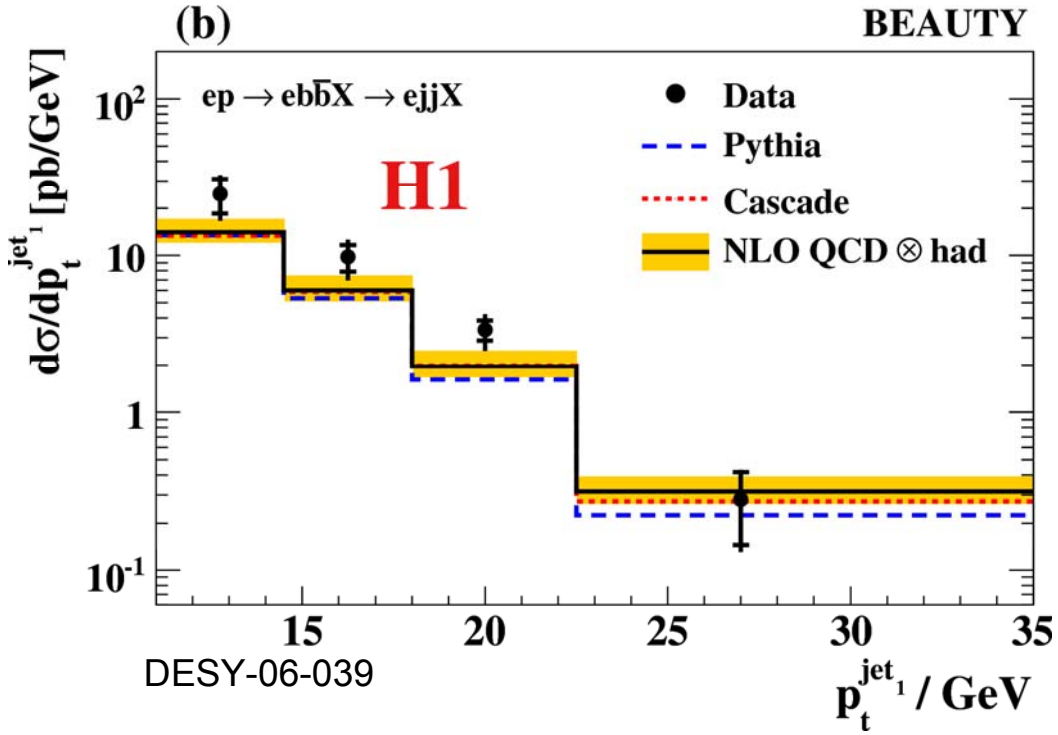
2 jets , NO muon

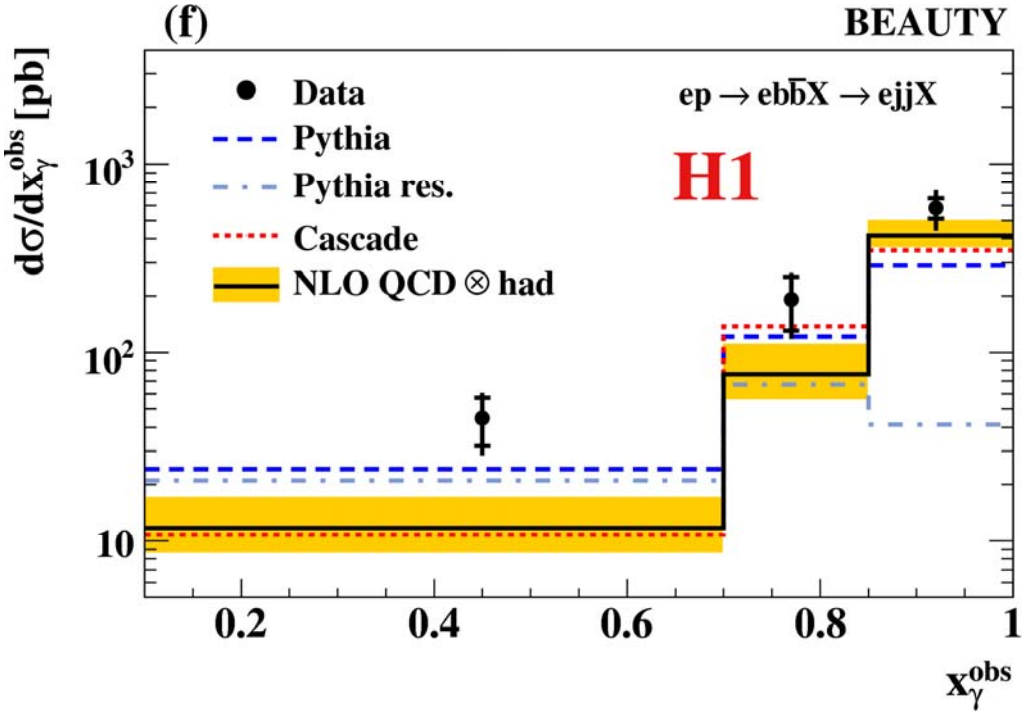
High p_t → large scale

H1: Inclusive b-lifetime Tag, 2 jets in γp

Fit subtracted impact parameter significances $S_i = \delta_i/\sigma(\delta_i)$, using MC shapes and measure c + b simultanously

$Q^2<1$ GeV^2; $0.15<y<0.8$; p_t(jet)> 11(8) GeV; $-0.88<\eta(\text{jet})<1.3$; from 57.7 pb^{-1}





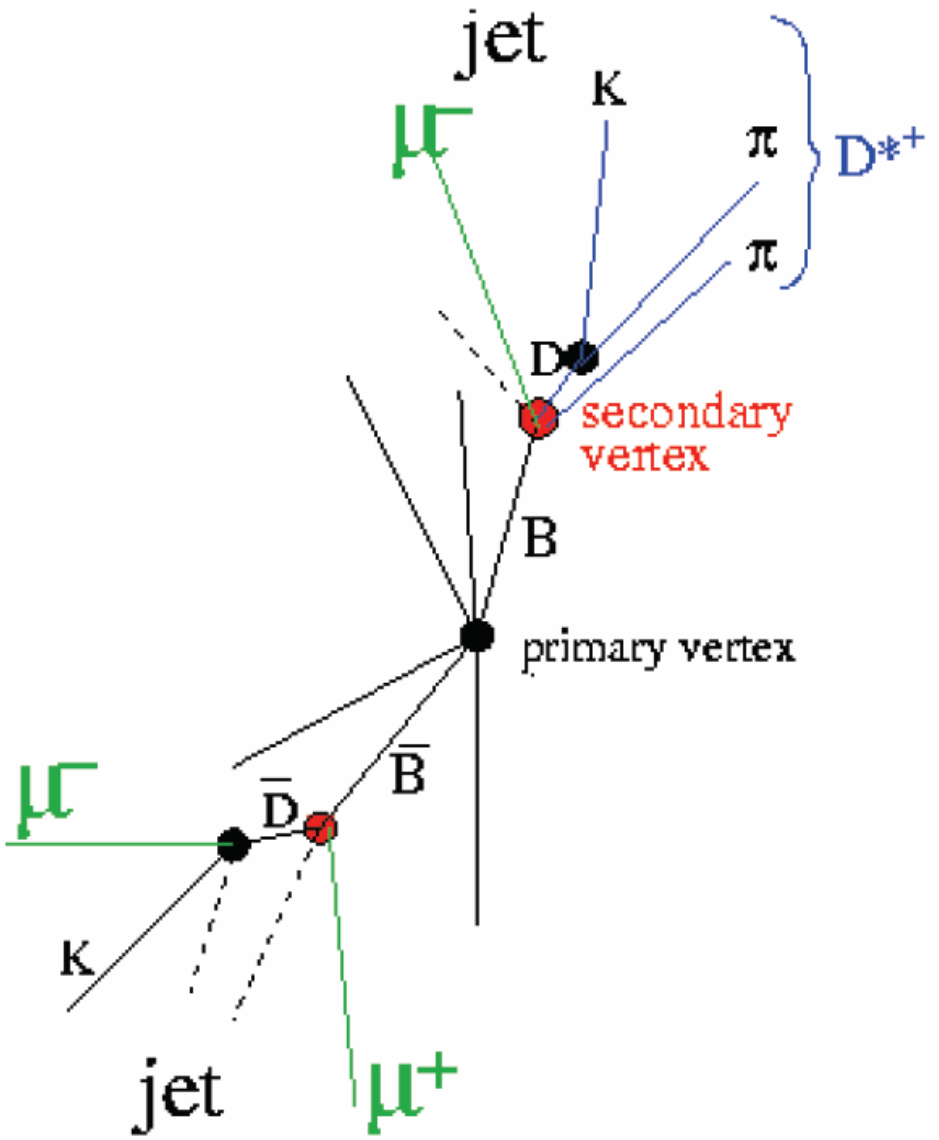
- General message : NLO/LO QCD somewhat below data, mainly at low p_t , low x_γ^{obs} (resolved region) and forward η (not shown).

$$x_\gamma = \frac{\sum_{jet1,\,jet2}(E - P_z)}{\sum_{hadrons}(E - P_z)}$$

Double tagging using D^*-muon or muon-muon correlations

Low p_t → small scale

Double Tagging



Tag BOTH b quarks by either a

- $D^* \rightarrow (K\pi)\,\pi$ and/or muon from semileptonic decay

A) $D^*\,\mu$: H1, ZEUS : Correlate charges and azimuthal angular separation $\Delta\phi(D^*\text{-}\mu)$

B) $\mu\mu$: ZEUS (prel) : Correlate charges and M_{inv} $(\mu\mu)$

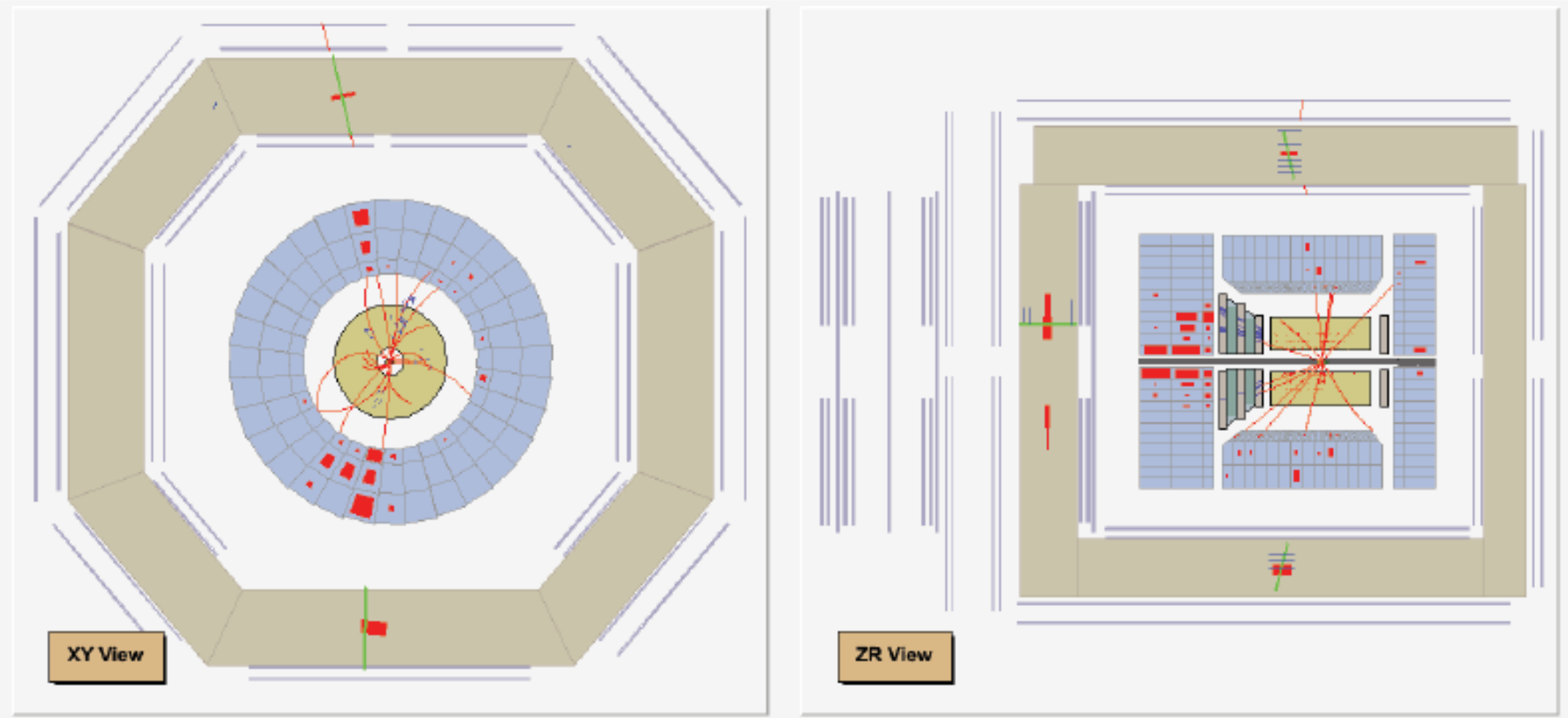
→ Obtain σ by fitting b,c,uds- fractions in 4 correlation regions

☺ Large phase-space for b:

- No jets required: reach lower $p_t(b)$
- large μ-acceptance in η of ZEUS

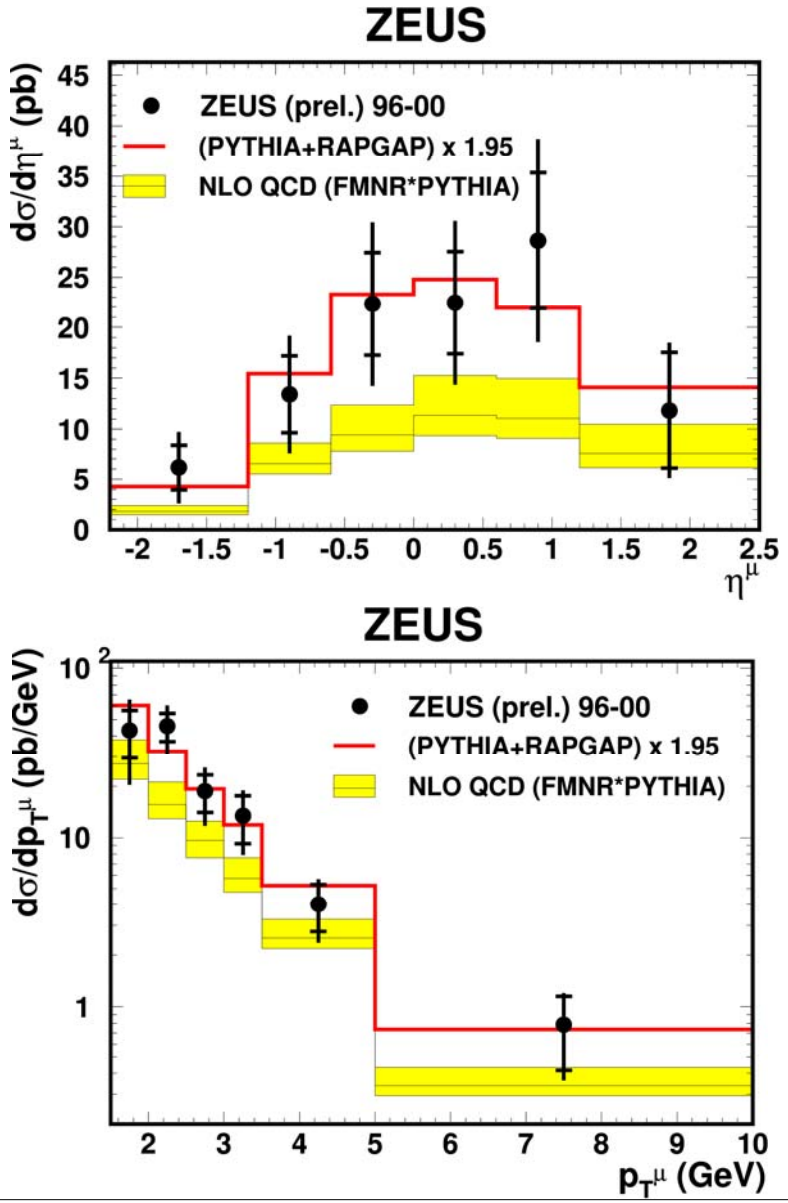
μμ Correlations – a ZEUS Event

Two muon event measured with ZEUS detector

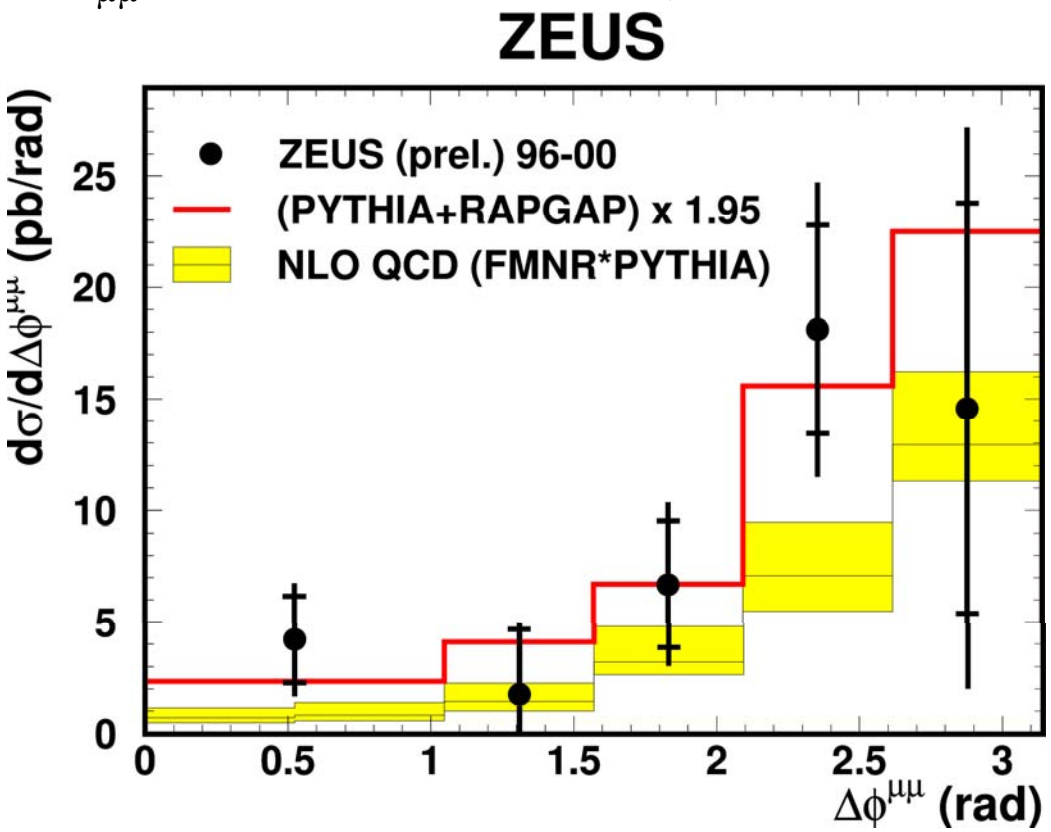


μμ correlations in γp : ZEUS Results

(For differential σ: harder cuts on μ: p_T>(μ)>1.5 GeV, -2.2<η(μ)<2.5)



$M_{\mu\mu}$ >3.25 GeV leaves two μ's from different b's

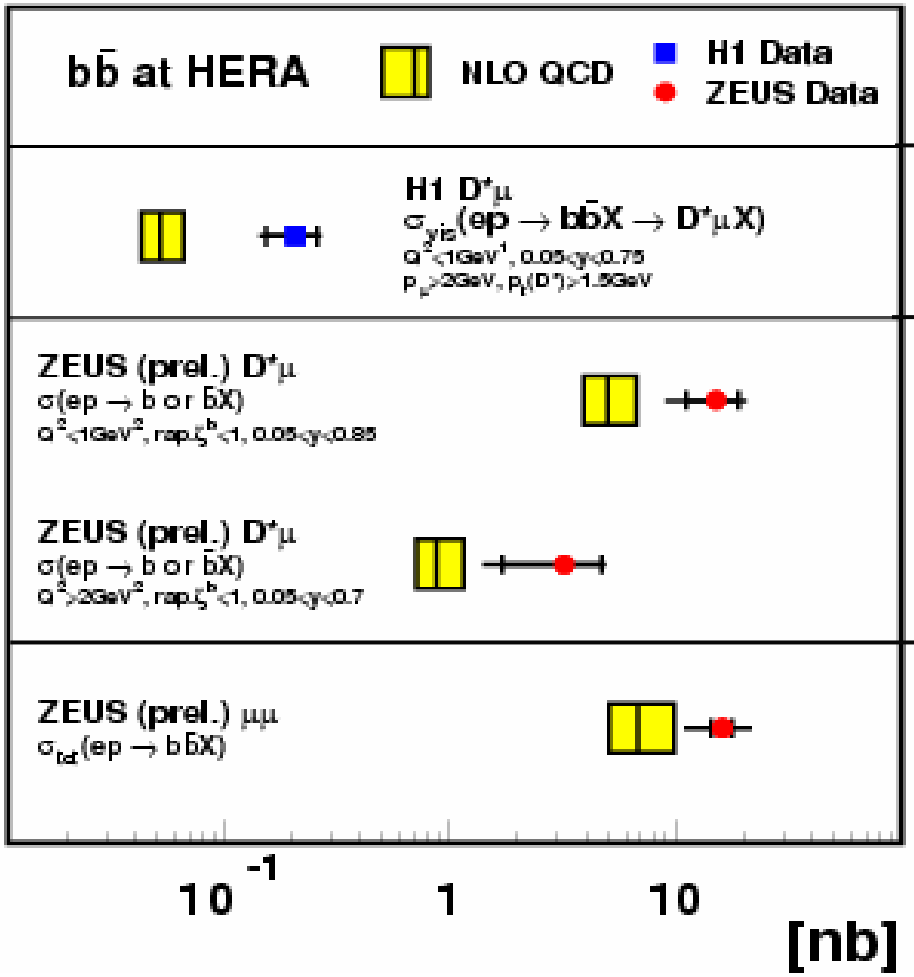


ZEUS prelim.05-008

LO: shapes agree, norm 2x too low

NLO: agrees within errors, tendency low

H1&ZEUS: D*μ and μμ vs NLO



H1, PL **B621** (2005) 56
ZEUS Prelim.05-008

D*μ H1 PHP (visible)

D*μ ZEUS PHP [η(b)<1, y]

D*μ ZEUS DIS [η(b)<1, y]

μμ ZEUS all Q^2 :
total inclusive [large b-phase space down to $p_t(b)\approx 0$]

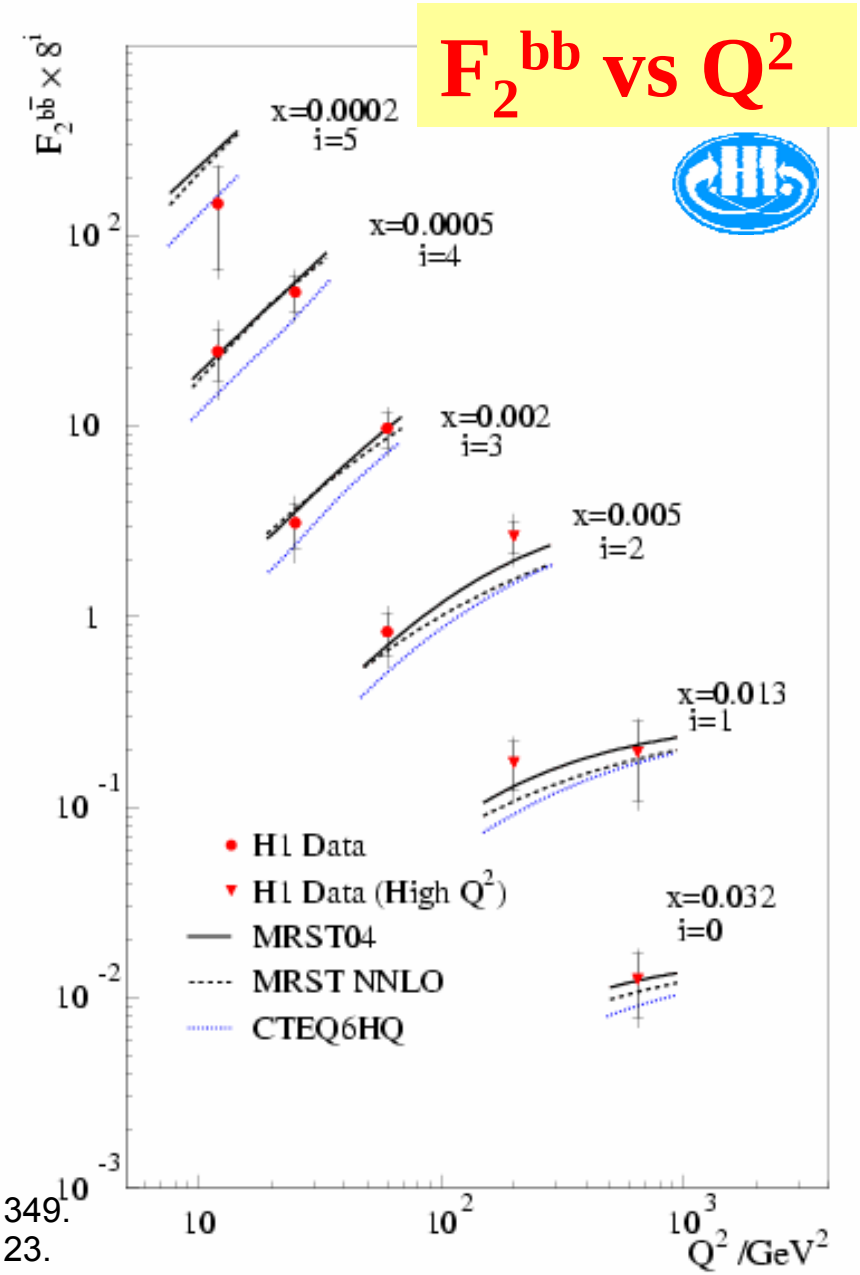
- Comparison cross sections: $D^*+\mu$: H1 and ZEUS are compatible
- Comparisons data/NLO : at visible level and b quark consistent.
- NLO: normalisation still tends to be below data in ALL cases !

Heavy Quark Structure Functions

Beauty Structure Function: $F_2^{bb}(x,Q^2)$

$$F_2^{b\bar{b}}(x,Q^2) \sim \frac{d^2\sigma^{ep\to b\bar{b}x}}{dx \cdot dQ^2} \cdot Q^4 x$$

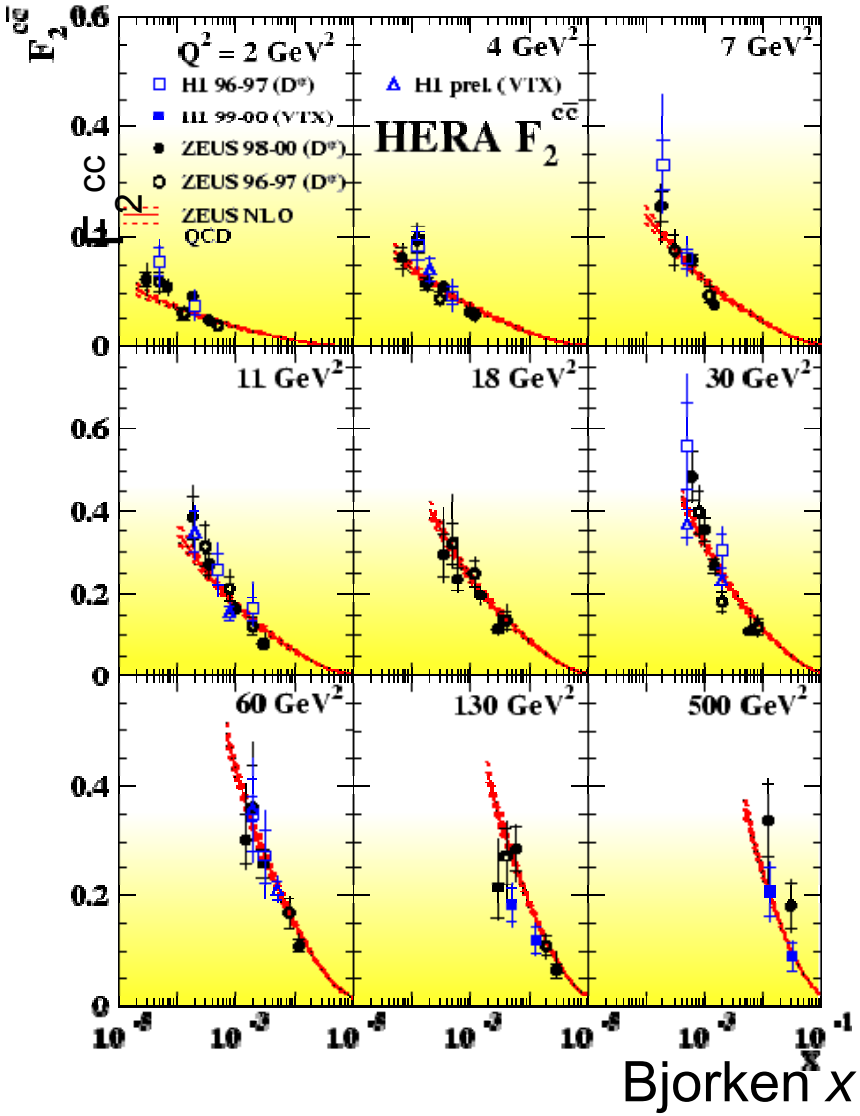
- First measurement of F_2^{bb} vs Q^2
- Large scaling violations observed, increasing with decreasing x (like F_2)
- pQCD describes data well in general
- BUT: data precision exceeds spread of QCD predictions
- First NNLO calculation available!
  (Thorne hep-ph/0506251)

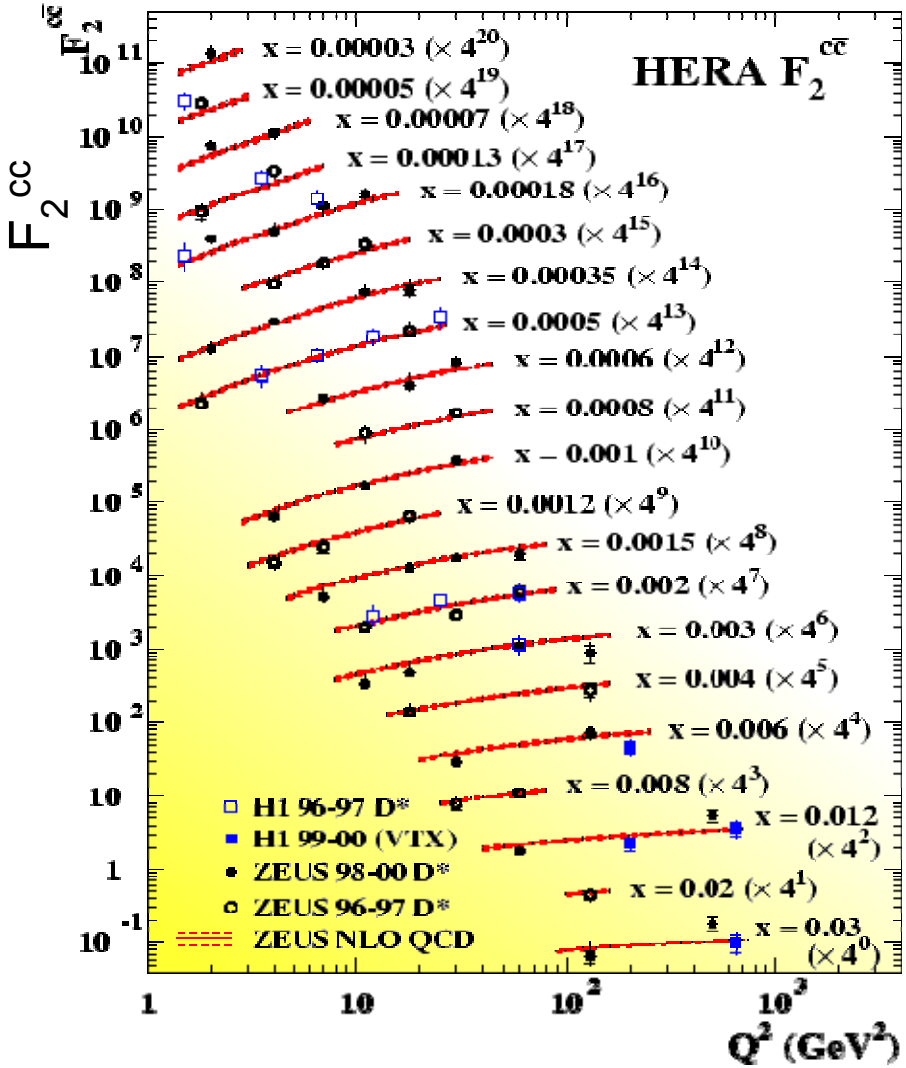


F_2^{bb} vs Q^2

H1, EPJ **C40** (2005) 349.
H1, EPJ **C45** (2006) 23.

Summary Charm $F_2^{c\bar{c}}$ from HERA-I





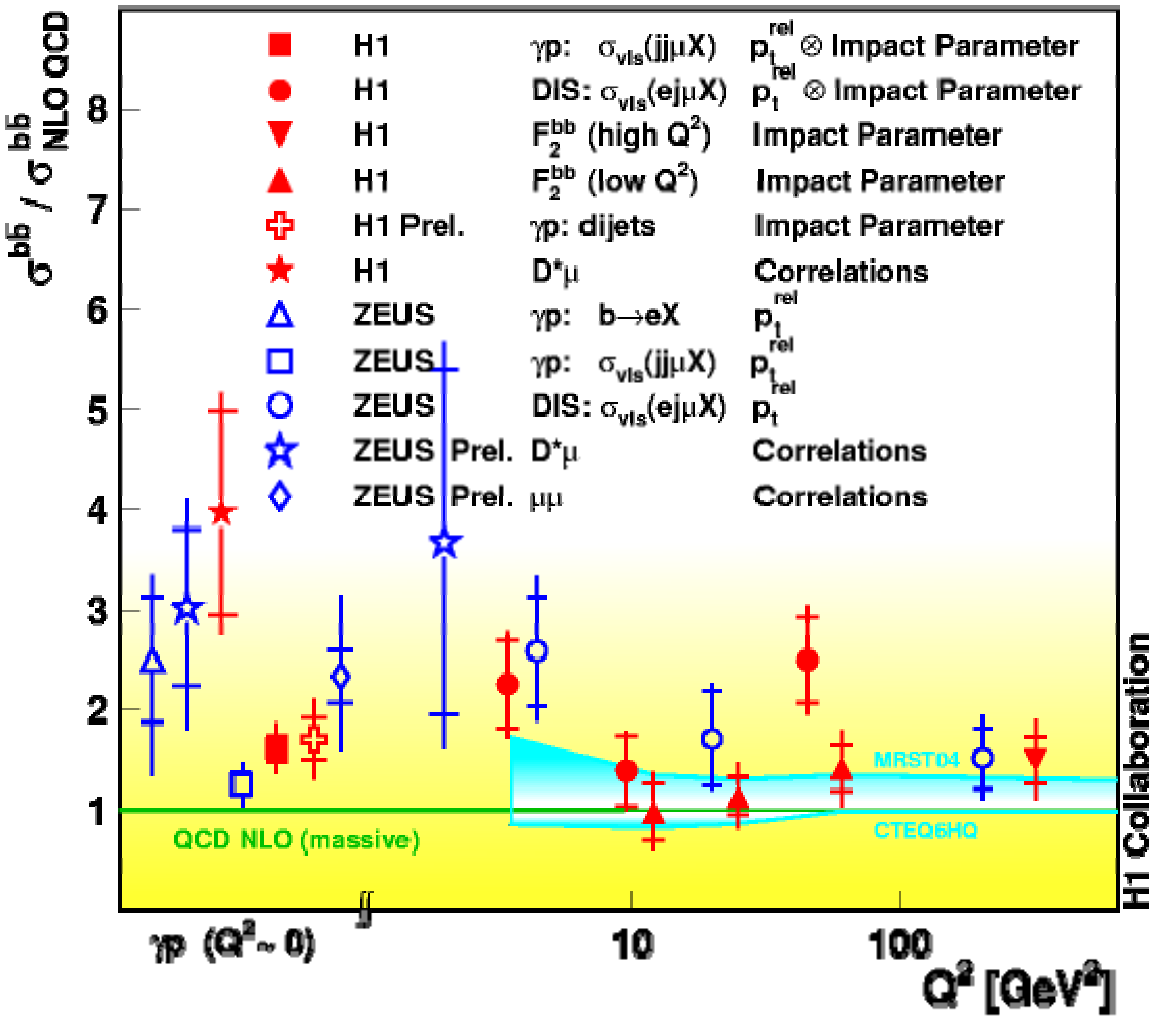
- NLO QCD fit with gluon from inclusive DIS fits well
- At low Q^2: Slight deviations visible

ZEUS, PR **D69**(2000)012004.
H1, EPJ **C40** (2005) 349.
H1, EPJ **C45** (2006) 23.

Overall Comparison with Theoretical Predictions

B-Production Cross Section Ratio : Data / NLO

- Comparison with pQCD NLO: **FMNR(γp) + HVQDIS (DIS)**



- All ratios consistent with 1.5; General trend: **NLO tends to be below data.**
- Theory errors not shown

Improvements in theory needed and start to appear on the horizon:

- MC@NLO is under way
- NNLO calculations coming
- Calculations including gluon k_t
- …

Summary

- Charm production: H1 and ZEUS data agree
  - High precision data reasonable well described by NLO predictions; :
    ➔ Need for NNLO / NLO+PS in certain regions of phase space
- Beauty production : H1 and ZEUS data agree
  - NLO predictions do reasonably well; tendency to be below data
  - Differential shapes deviate only in a few regions (low pt, forward η, low x_γ), seen in different measurements.
  - Double tags (D^*-μ, μ-μ) allow access to lower p_t and lower E_{cms}
- Structure Functions (F_2^{QQ})
  - both charm and beauty (first measurement) pretty well described by NLO QCD; c+b contribute a significant fraction to the overall !

With HERA-II performing well, we hope to obtain similar precision in b as we have in charm … ☺