Heavy quark photoproduction at HERA

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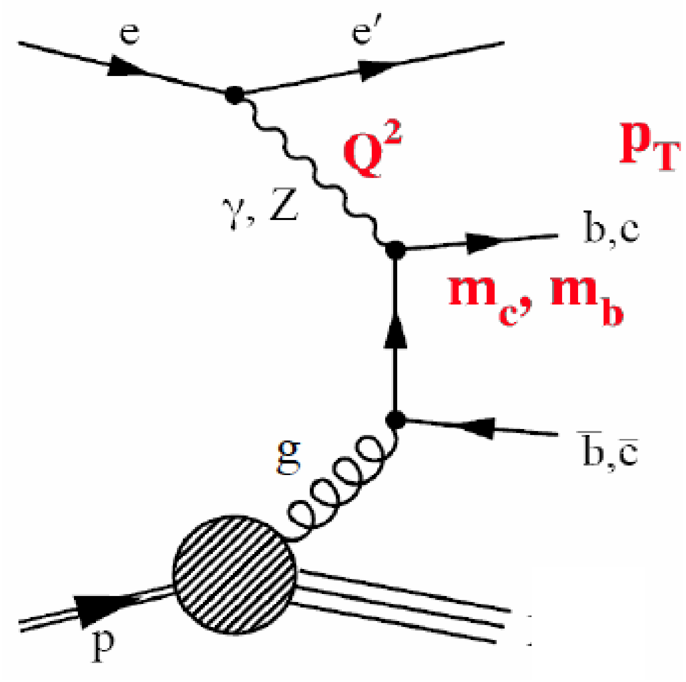
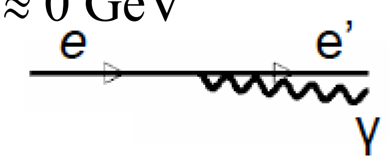
Motivation to measure heavy flavour production

- Charm and beauty quarks at HERA are mainly produced in Photon-Gluon-Fusion → sensitive to the gluon in the proton.
- Hard scales for perturbative QCD:
  - $m_{c,b}^2$, p_T^2, Q^2
    - multi-scale problem, for example combined to $\mu_0 = ½ \sqrt{(m_{b,c}^2 + p_T^2)}$
- Interpretation of heavy flavour measurements:
  - Use the pQCD calculations and constrain the gluon density of the proton.
  - Take the gluon density from elsewhere and test the consistency of the pQCD calculation.

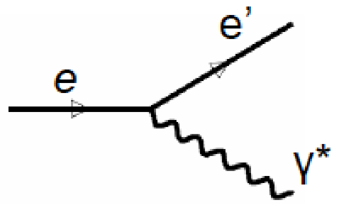


Two kinematic regimes:

- Photoproduction: $Q^2 \approx 0$ GeV^2



- Deep Inelastic Scattering: $Q^2 > 1$ GeV^2
  (scattered electron detected)



QCD models

QCD scheme:

- Massive scheme – Fixed Flavour Number Scheme (FFNS):
  - c and b quarks generated dynamically via boson-gluon-fusion.
  - c and b quarks treated massive.
  - Expected to be valid for **small scales $\mu^2 \approx m_{b,c}^2$**

QCD predictions:

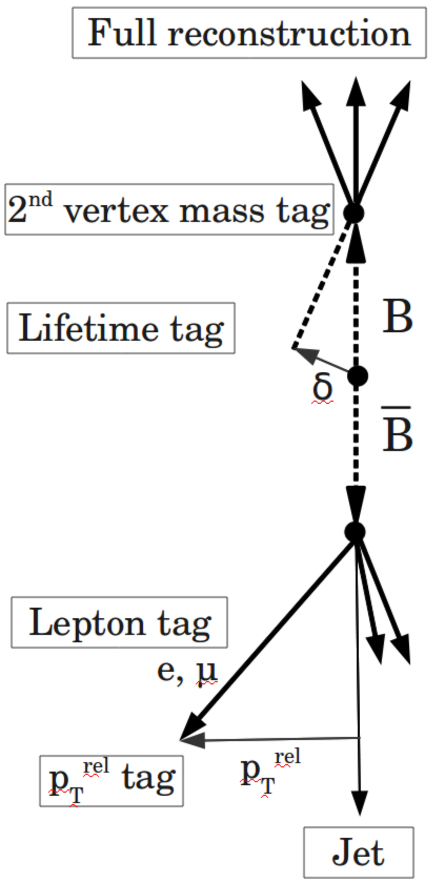
- QCD LO + Parton shower Monte Carlo generators:
  - Collinear factorization, DGLAP evolution (PYTHIA).
  - k_T factorization, CCFM evolution (CASCADE).
  - Used for data corrections and model comparisons.
- QCD NLO calculations:
  - Massive scheme, NLO(α_s^2):
    - FMNR
    - MC@NLO

Used for comparisons and extrapolations to full phase space of beauty production.

Tagging methods for heavy flavours at HERA

- Rates at HERA behaved like σ(b) : σ(c) : σ(uds) ≈ 1 : 50 : 2000
- Charm and beauty enrichment is possible with:

1) Full reconstruction
   - Only possible for charm at HERA, eg. D*→Kππ.
2) Lepton tagging: Use semileptonic b/c decay channels
   - look for μ or e , high BR(c,b→ lepton + anything)
3) p_T^{rel} tagging : b/c quark have large masses
   - look for decay leptons with a high transverse momentum w.r.t the b quark flight direction.
4) Lifetime tagging: b/c quark have long lifetimes:
   - look for displaced vertices.
   - look for tracks with large impact parameters δ.
5) Secondary vertex mass tagging: long lifetime and large masses
   - look for high secondary vertex masses.



<u>Methods used in the analyses discussed today:</u>
- D* analysis: D* reconstruction.
- Low p_T analysis: 2 electrons.
- Muon analysis: 1 μ for p_T^{rel} tag, lifetime with large impact parameters δ.
- Inclusive analysis: lifetime with displaced vertices, large secondary vertex masses.

Data sample: $\mathcal{L}$=93 pb^{-1}

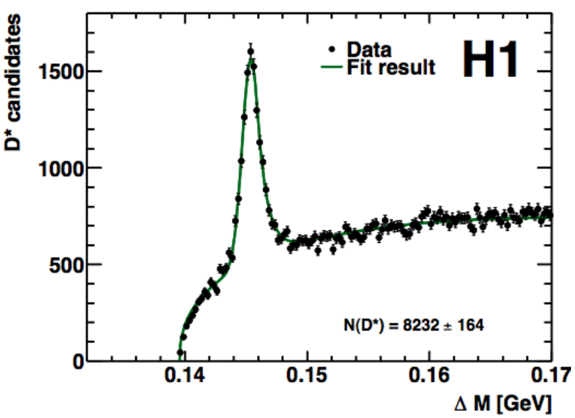
Phase Space

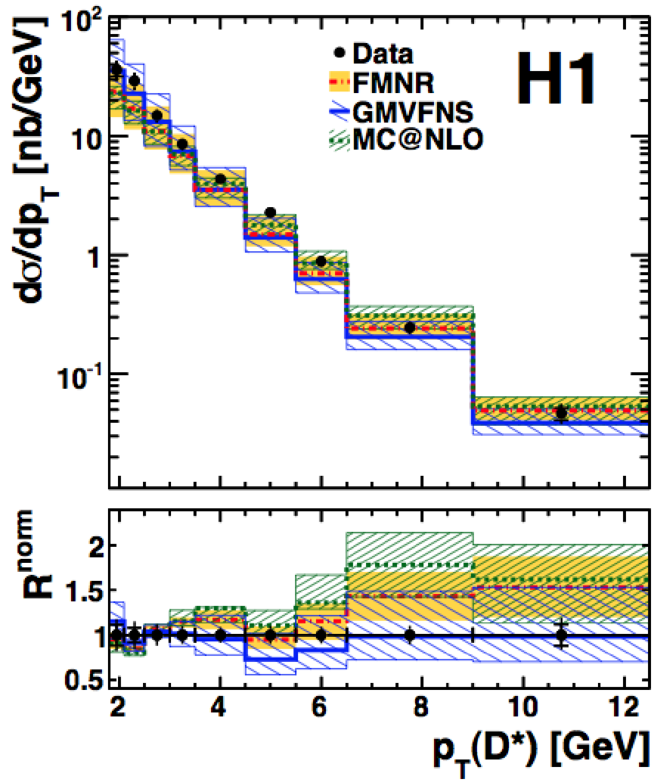
$Q^2 < 2\ GeV^2$, $p_T^{D*} > 1.8 GeV$

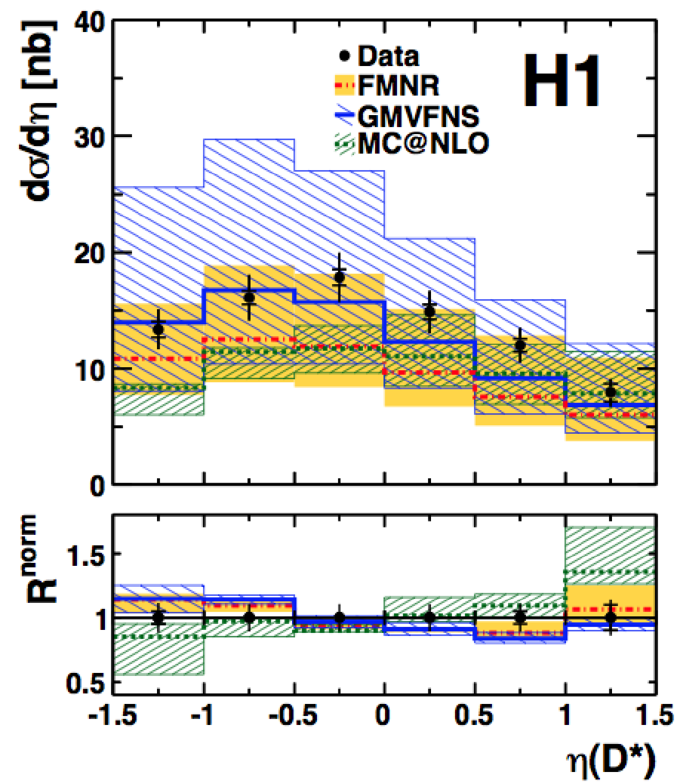
Charm tagging

D* meson reconstruction via:

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







- Very high precision of the data, compared to the uncertainties of the NLO predictions.
- NLO predicted shapes less sensitive to theoretical uncertainties, generally show a reasonable agreement with the data.

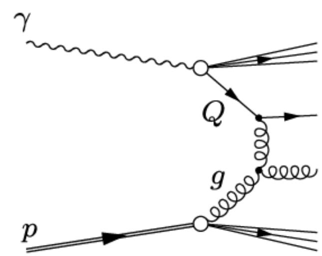
DESY-11-248, Eur. Phys. J. C72 (2012) 1995

Data sample: $\mathcal{L}$=93 pb^{-1}

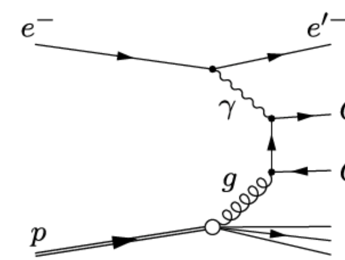
Phase Space

$Q^2 < 2GeV^2$, $p_T^{D*} > 2.1GeV$

2 jets with: $p_T^{jet\ 1} > 3.5$ GeV

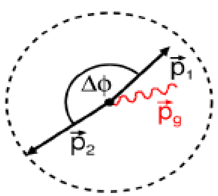


resolved enhanced



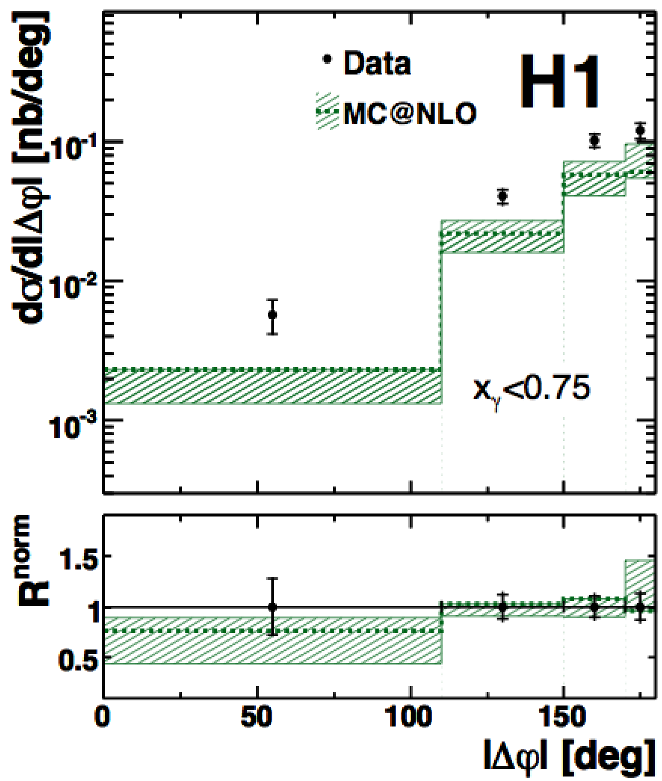
direct enhanced

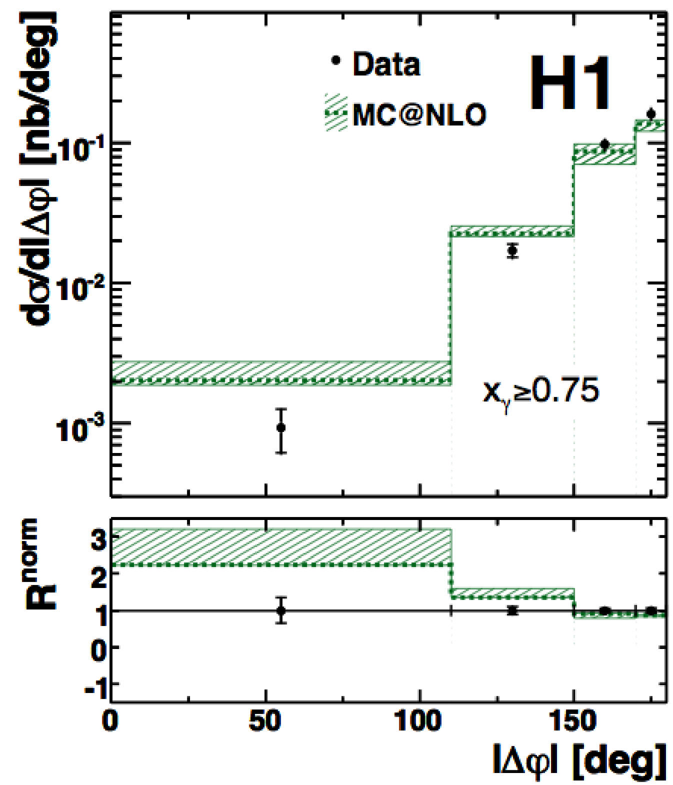
- Azimuthal correlation between the two jets, ΔΦ :



- Fraction of the photon energy entering the hard interaction (direct vs resolved), x_γ^{obs} :

$$x_\gamma^{obs} = \frac{\sum_{Jet1}(E-p_z) + \sum_{Jet2}(E-p_z)}{\sum_h (E-p_z)}$$





- MC@NLO predictions below the data for resolved photons, direct contribution reasonably well-described in normalization, shape not well described.

DESY-11-248, Eur. Phys. J. C72 (2012) 1995

Focus of the measurement:

- Low $p_T(b)$ momentum
  - Low experimental thresholds
  - Extraction of the b-cross section from two low p_T-electrons, $p_T(e) \gtrsim 1\,\text{GeV}$

Offline Electron Identification:

Combination of:

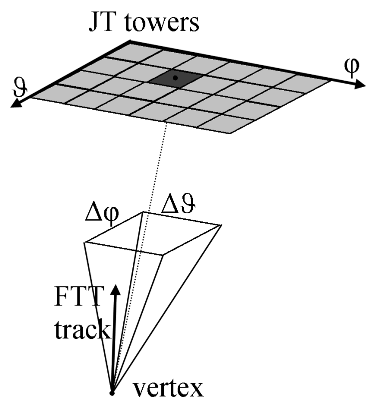
- calorimeter shower profiles
- dE/dx measured in the tracker
  - ~90% efficiency at a rejection of ~99%

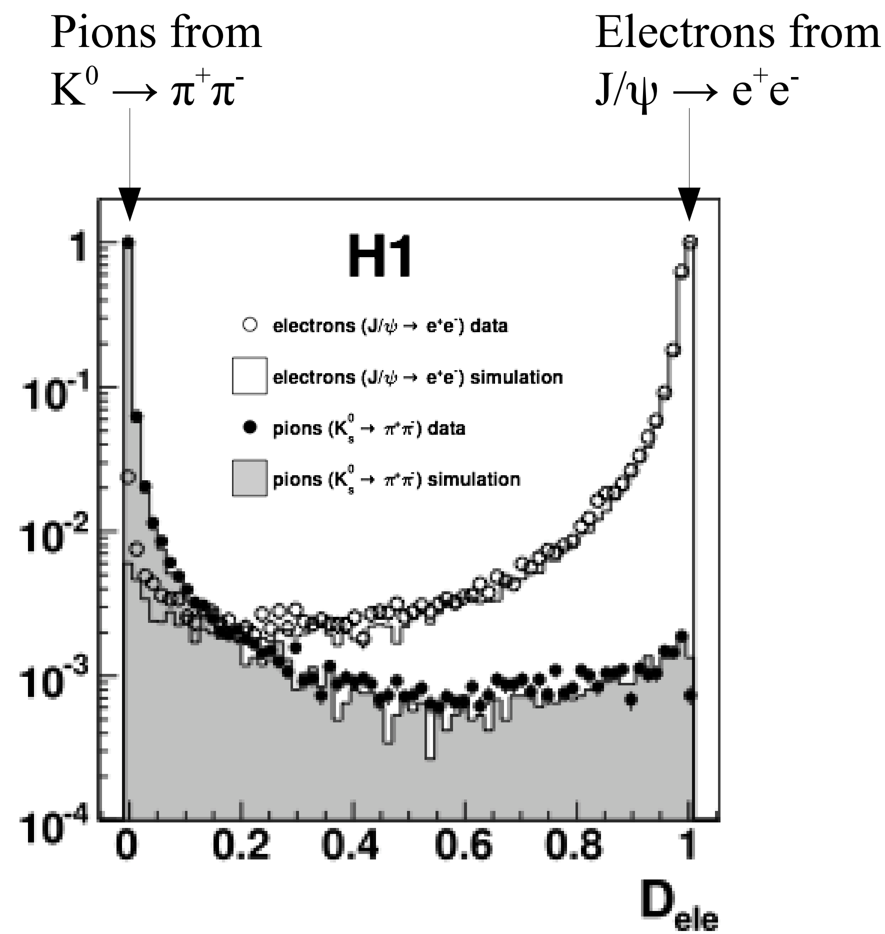
Trigger for low p_T-Electrons:

Combination of calorimeter (Jet Trigger) and tracker (Fast Track Trigger):

- Topological match
- Cut on $E_{T,JT}/p_{T,FTT}$

Data sample: $\mathcal{L}$=48 pb^{-1}

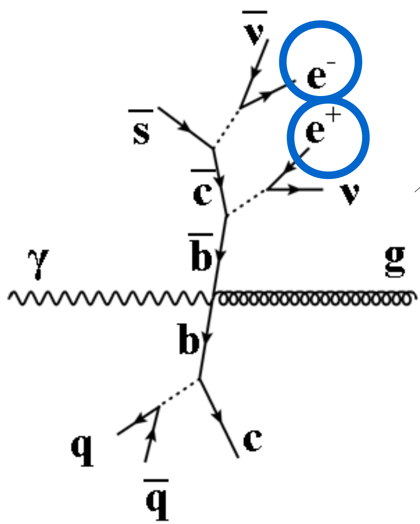


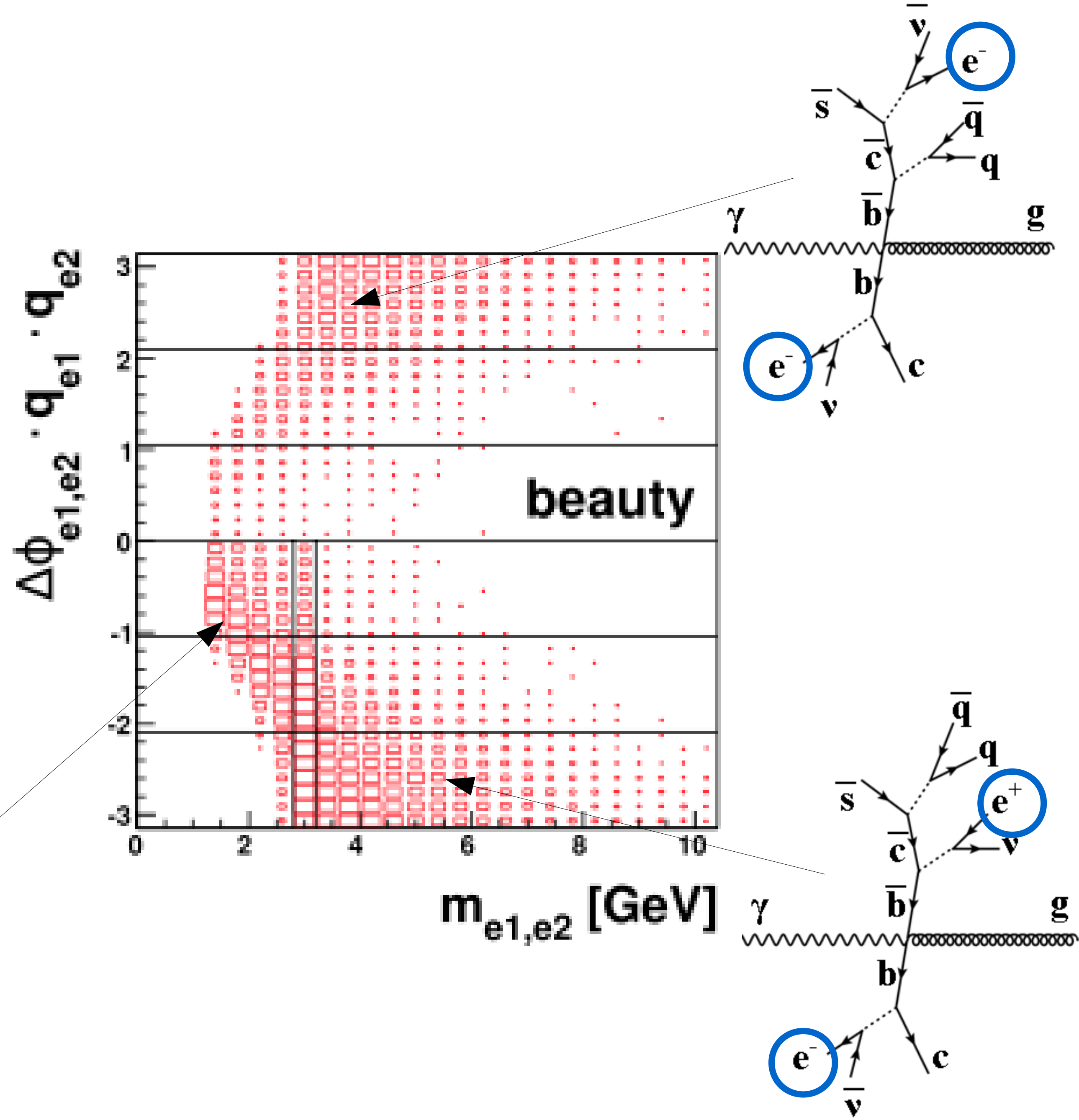


A. W. Jung et al., Proc. 15th IEEE-NPSS Real-Time Conference, (2007) 1.
B. Olivier et al. Nucl. Instrum. Meth. A 641 (2011) 58.

Heavy Flavour Tagging

- Exploit di-electron correlations:
  - Invariant mass m_{ee}
  - Azimuthal angle $\Delta\phi_{ee}$
  - Charge product q(e1)*q(e2)





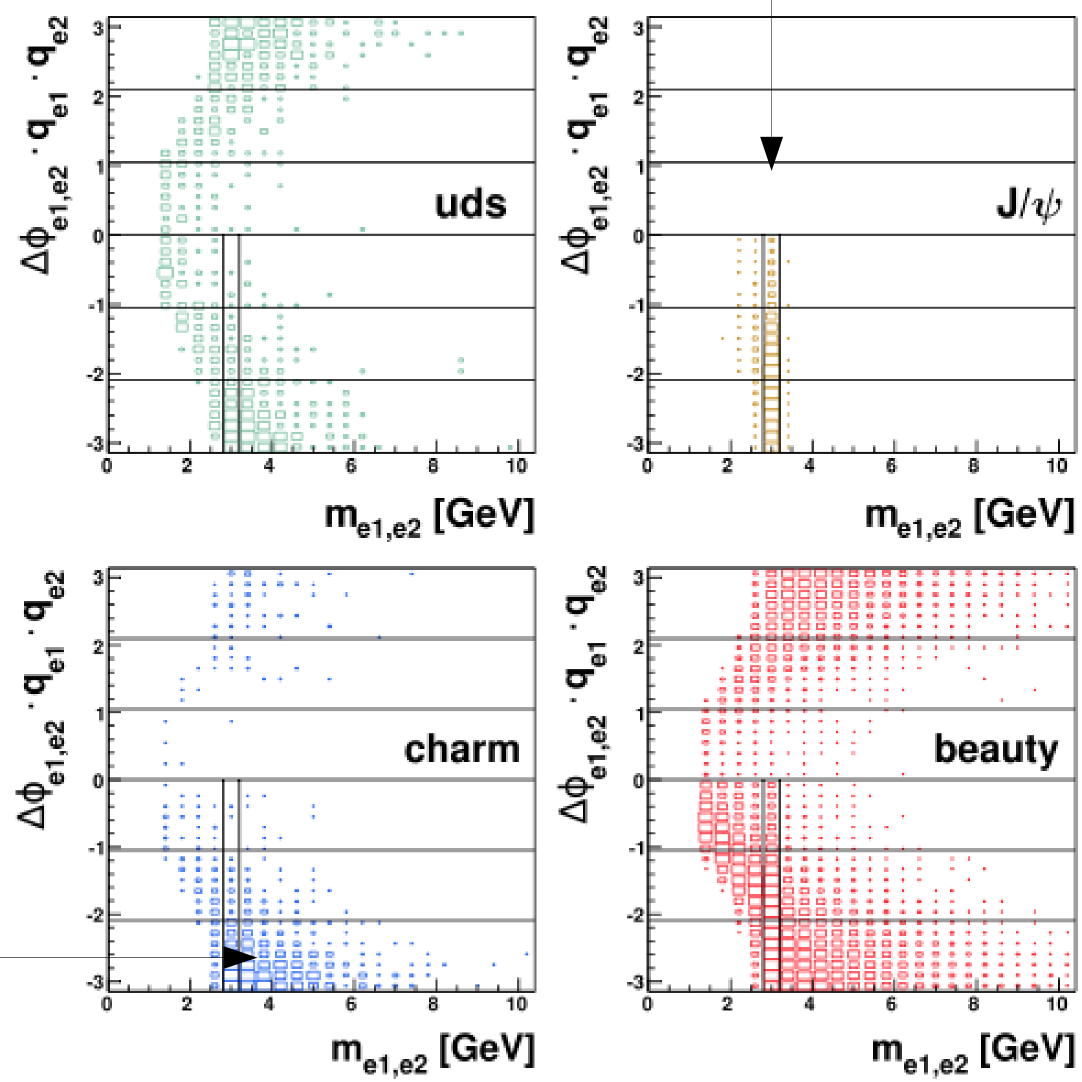
Beauty in photoproduction at low $p_T(b)$

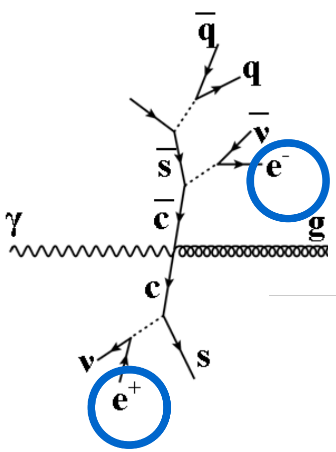
Low p_T analysis

Heavy Flavour Tagging

- Exploit di-electron correlations:
  - Invariant mass m_{ee}
  - Azimuthal angle $\Delta\phi_{ee}$
  - Charge product q(e1)*q(e2)
- An additional background region (open electron identification cuts) constrains uds.
- Matrix unfolding of the differential beauty cross section (similar to 2d template fit).

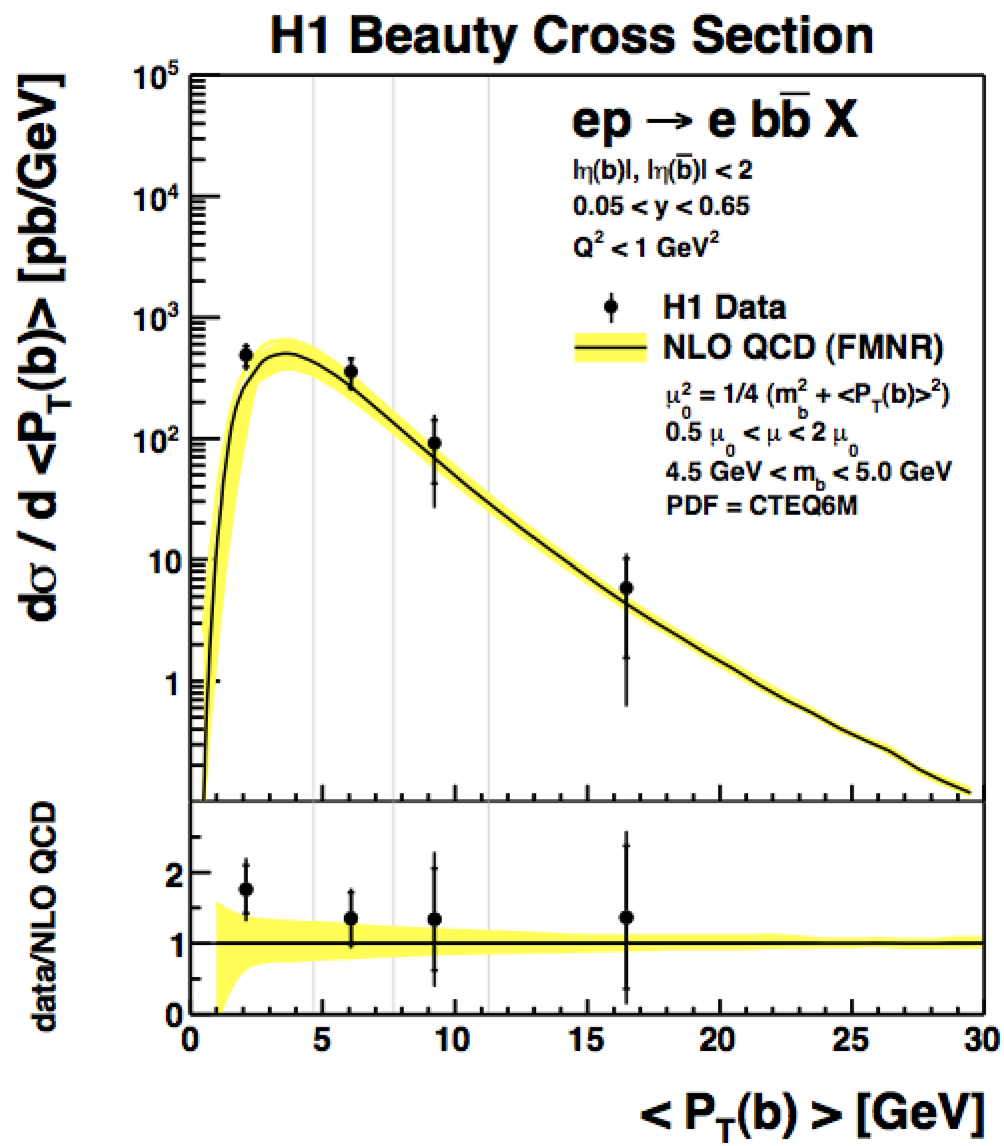
$J/\psi \rightarrow e^+e^-$ mass peak





Beauty in photoproduction at low $p_T(b)$

- Differential beauty cross section as function of the mean b quark momentum.



- Access to lowest $p_T(b)$ values ever measured in ep.
- Data in agreement with the NLO calculation, but slightly below.

DESY-12-072, Submitted to EPJC

Data sample: $\mathcal{L}$=179 pb^{-1}

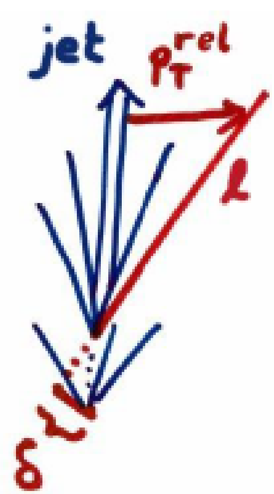
Phase Space

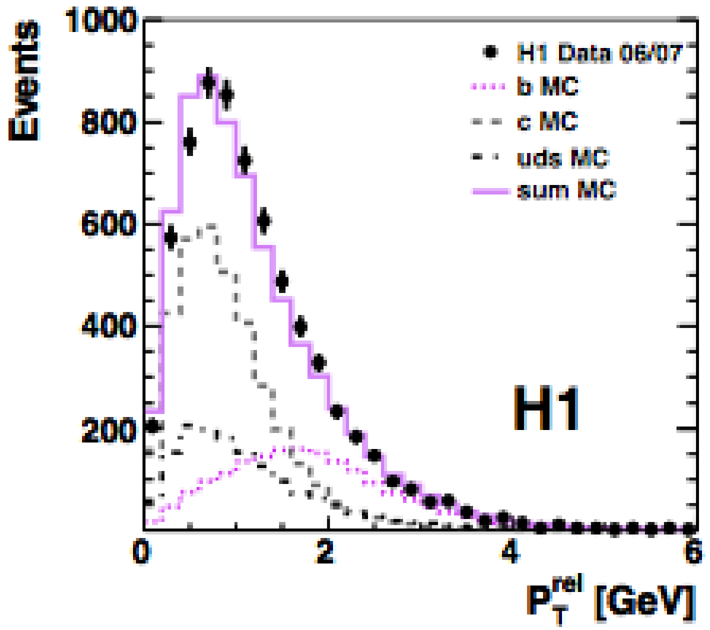
Events with:

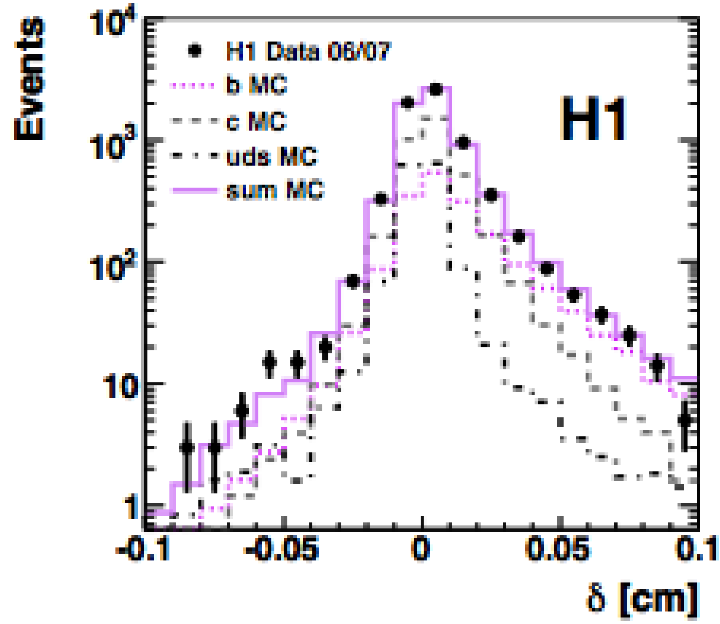
- 1 muon, $p_T^{\mu} > 2.5$ GeV
- 2 jets, $p_T^{jet\ 1(2)} > 7\ (6)$ GeV

Heavy Flavour Tagging

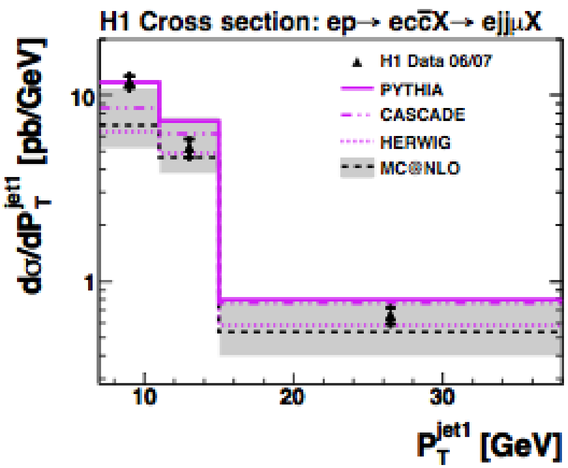
- Momentum relative to μ jet, p_T^{rel}.
- Impact parameter δ.
- 2d template fit.

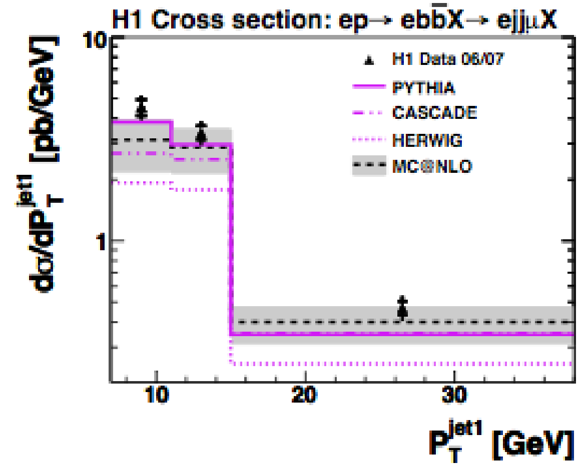


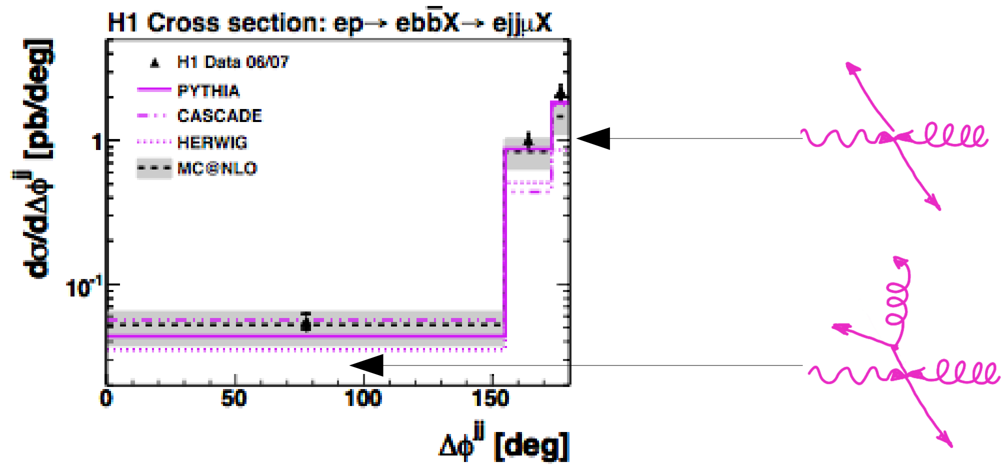




- Simultaneous measurement of differential charm and beauty jet cross sections.
- Azimuthal angle difference of jets $\Delta\phi^{jj}$ $\rightarrow$ sensitive to higher orders.







- The data are in agreement with NLO calculation (MC@NLO).
- $\Delta\phi^{jj}$ described by all models (LO, NLO).

DESY-12-059, accepted by EPJC

Data sample: $\mathcal{L}$=130 pb^{-1}

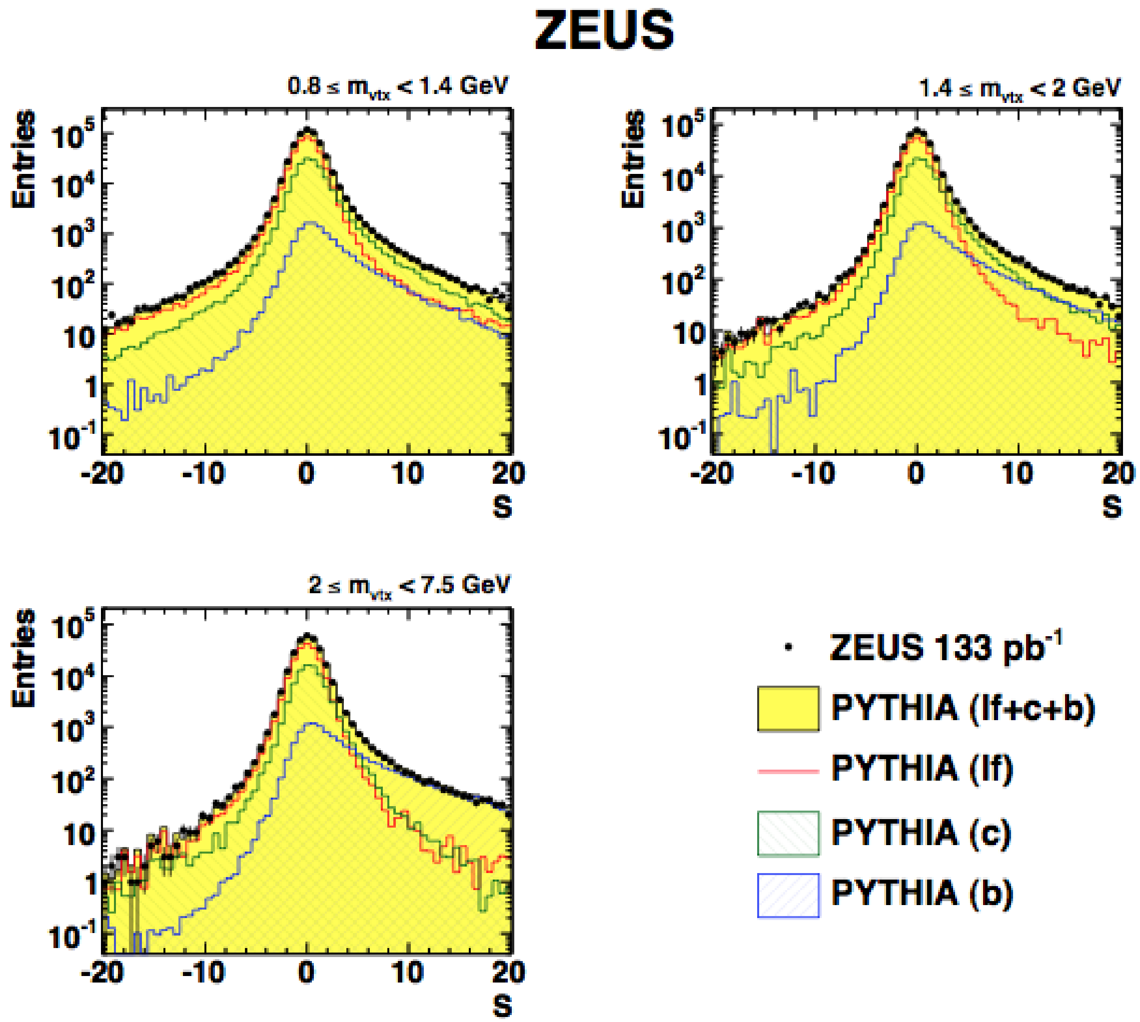
Phase Space
Events with at least 2 jets with:
$p_T^{jet\ 1(2)}$> 7 (6) GeV

Heavy Quark tagging

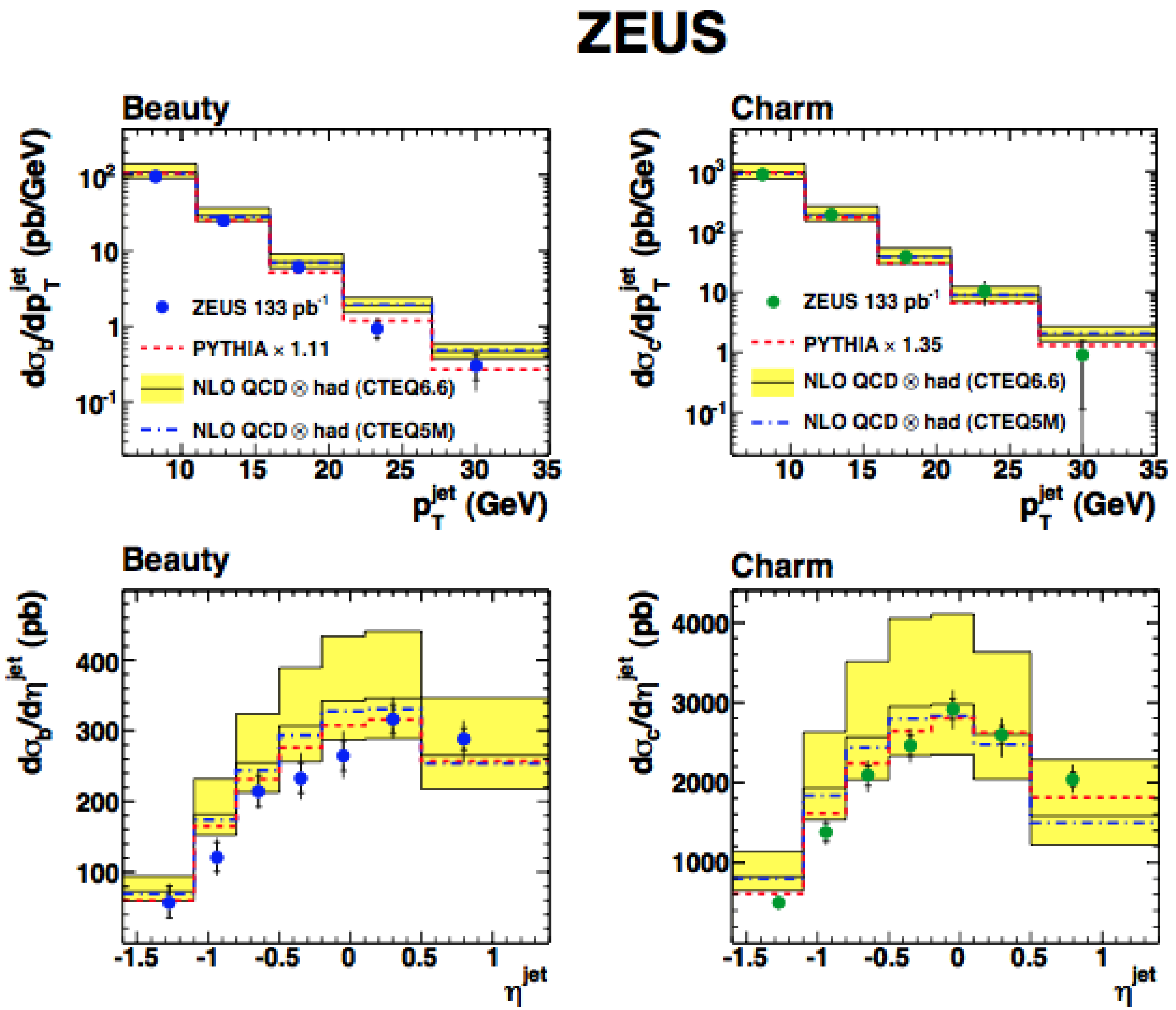
Reconstruction of secondary vertices:

- Decay length significance
  S = DL / σ(DL)
- Mass of tracks associated with the secondary vertex, m_{vtx}

Flavour separation: Fit MC templates for mirrored DL significance to data

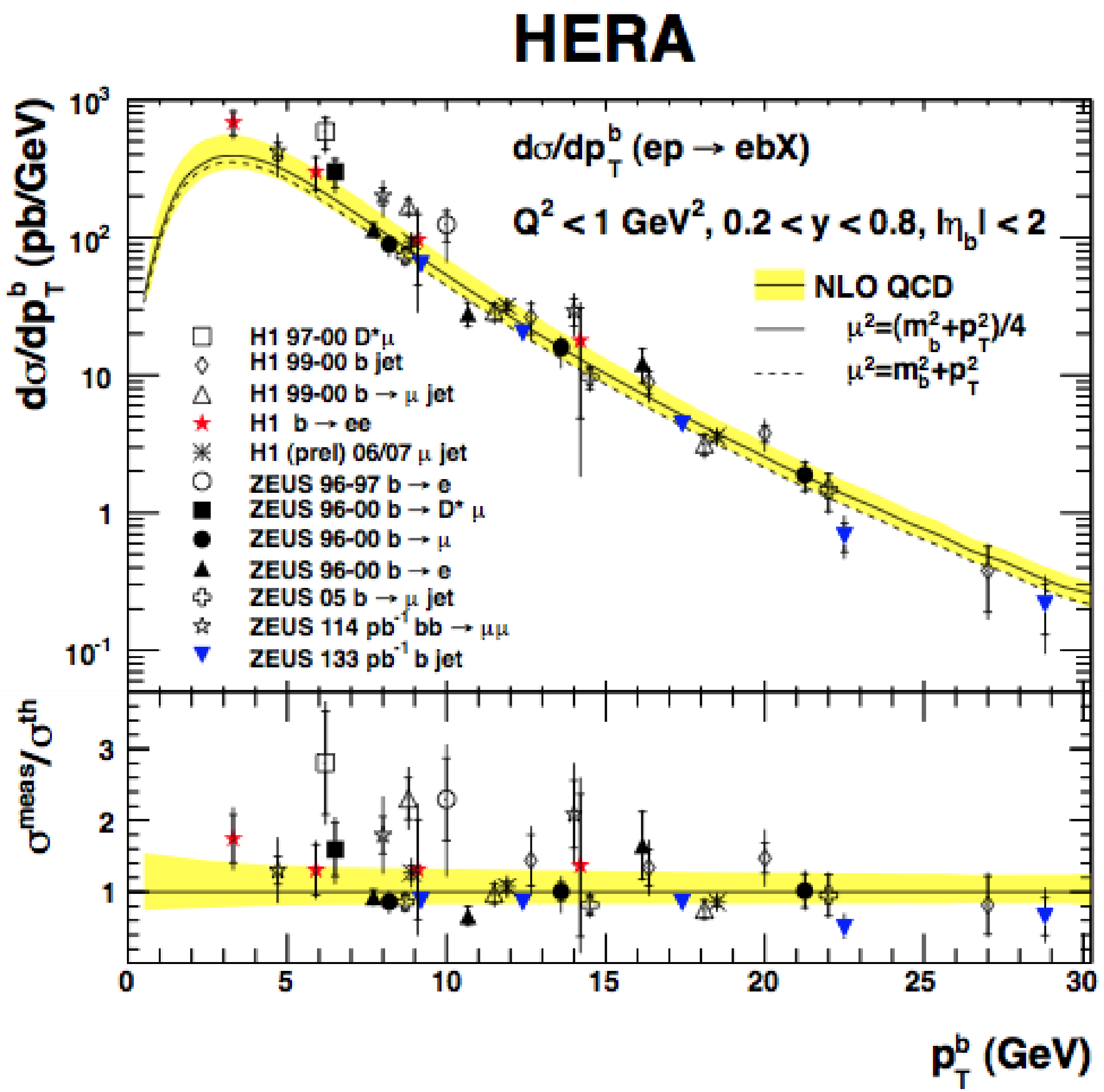


- Inclusive differential heavy flavour cross sections as function of p_T^{jet} and η^{jet}.



- Good agreement between the data the LO MC (Pythia) and the NLO prediction (FMNR).

DESY-11-067, Eur. Phys. J C72 (2011) 1659



- Many measurements agreeing with each other over a wide p_T(b) range.
- General NLO calculation (FMNR) consistent with data.

Summary

- Heavy flavour production at HERA allows to test QCD at different scales.
- Four new heavy flavour photoproduction measurements of ZEUS and H1 using different experimental techniques and having different systematics are in good agreement.
- The data is in general in agreement with NLO pQCD predictions.

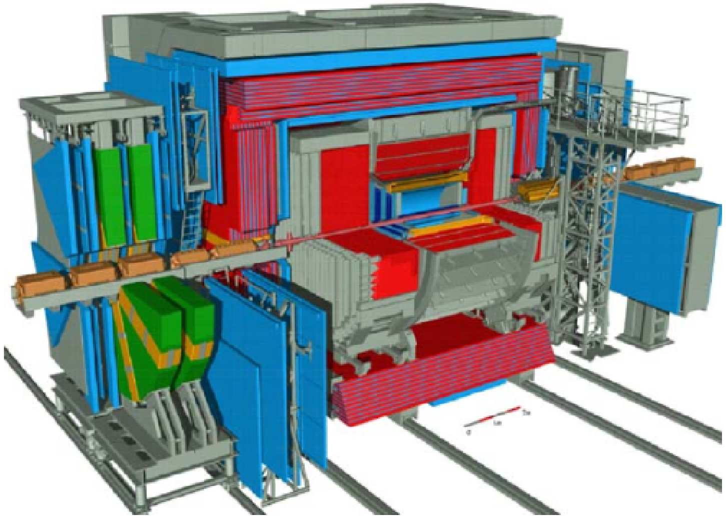
Backup

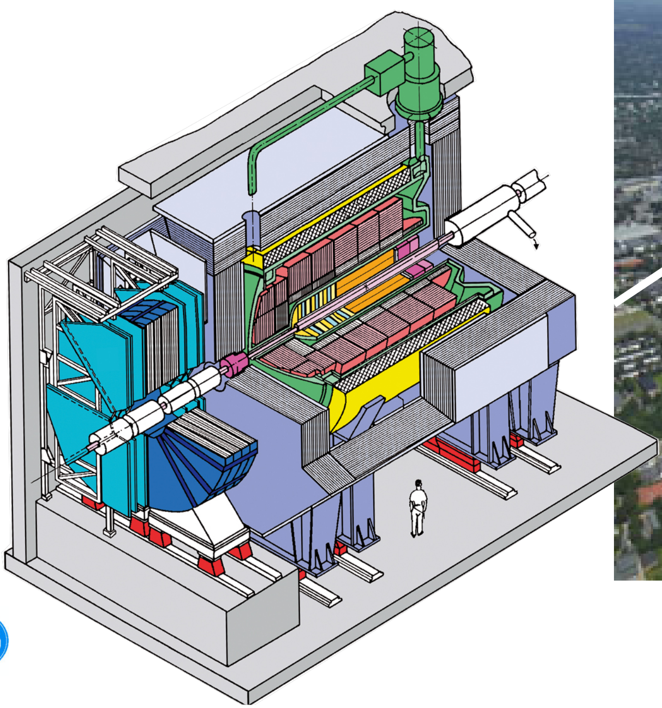
Heavy Flavor Measurements discussed in this talk:

- "Measurement of Inclusive and Dijet D* Meson Cross Sections in Photoproduction at HERA"
  DESY-11-248, H1 Collab., F.D. Aaron et al., Eur. Phys. J. C72 (2012) 1995
- "Measurement of heavy-quark jet photoproduction at HERA"
  DESY-11-067, ZEUS Collaboration; H. Abramowicz et al., Eur. Phys. J C72 (2011) 1659
- "Measurement of Beauty and Charm Photoproduction using Semi-muonic Decays in Dijet Events at HERA"
  DESY-12-059, H1 Collab., F.D. Aaron et al., Accepted by EPJC
- "Measurement of Beauty Photoproduction near Threshold using Di-electron Events with the H1 Detector at HERA"
  DESY-12-072, H1 Collab., F.D. Aaron et al., Submitted to EPJC

The HERA ep collider (1992 – 2007) at DESY in Hamburg

- ep collider:
- $e^{\pm}$ energy: 27.6 GeV
- p energy: 920 GeV
- Centre of mass energy: 319 GeV
- 2 collider experiments: H1 and ZEUS
- Integrated luminosity: ~0.5 fb^{-1} (per experiment)





Beauty in photoproduction at low $p_T(b)$

Low p_T analysis

Heavy Flavour Tagging

- An additional background region (open electron identification cuts) constrains uds.
- Electrons are identified by
  - Electron discriminator, D_{ele}
  - Isolation criterion, $R_{E,cone}$
- Definition of the background region:

$R_{\mathrm{E,cone}}^{\max(e1,e2)}$	$D_{\mathrm{ele}}^{\min(e1,e2)}$	
	$0.825 - 0.875$	$0.875 - 1.0$
$150 - 350\%$	$B1$	$B3$
$0 - 150\%$	$B2$	S

Open cut

Background templates