Photon 2013

Charm and Beauty Photoproduction at HERA

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On behalf of the H1 and ZEUS Collaborations

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GEFÖRDERT VOM

Bundesministerium
für Bildung
und Forschung

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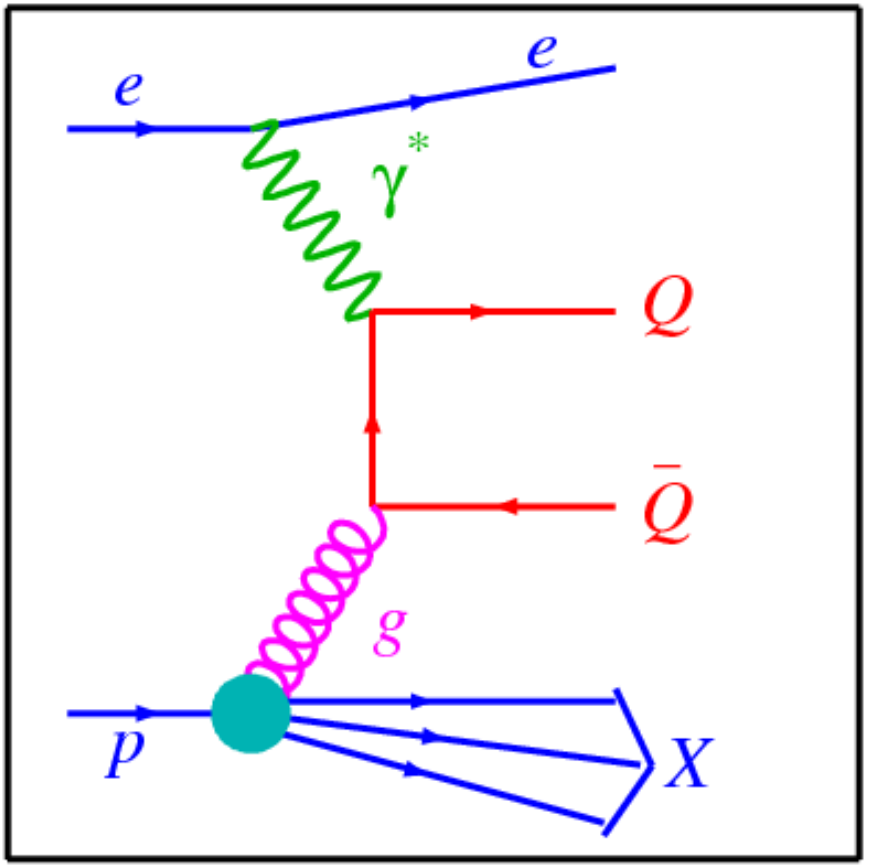
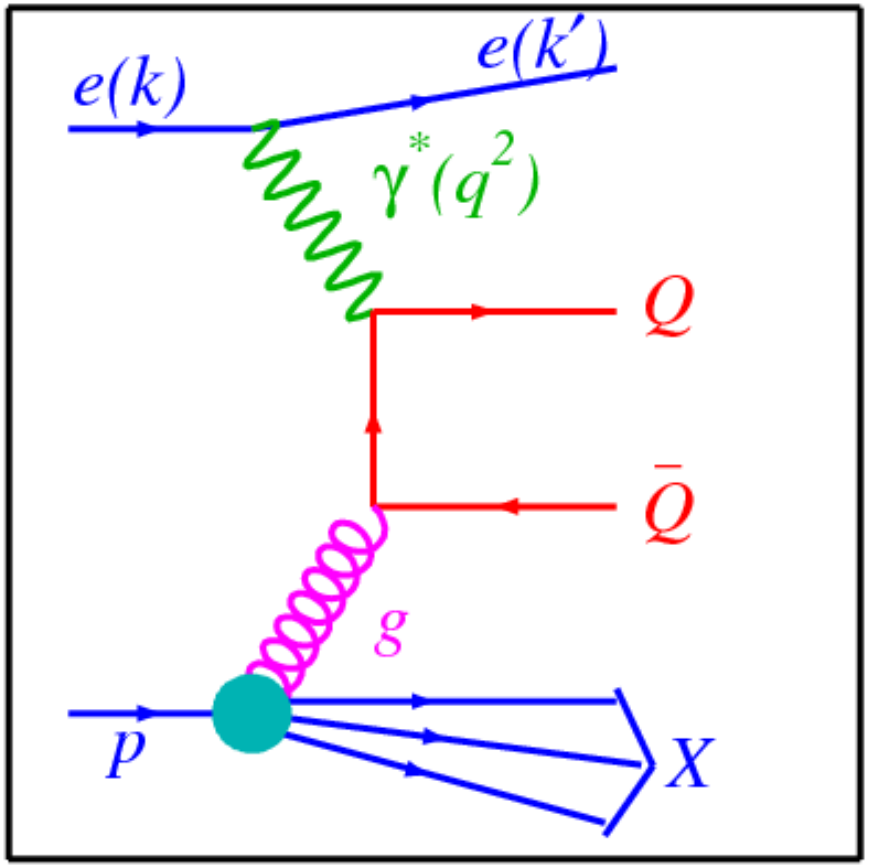
Heavy flavour production at HERA

- Boson-gluon fusion (BGF) is main production mechanism
- Studies of production mechanism:
  - Test QCD (different hard scales, m_Q, p_T)
- Charm fragmentation fractions
- Excited charm mesons



Heavy flavour production at HERA



- HERA (ep):
  - p: 920 (820) GeV
  - e: 27.5 GeV
- $Q^2 = -q^2 = -(k-k')^2$
- $Q^2 < 1$ GeV^2
  - Photoproduction
  - Quasi-real photon exchanged
  - No scattered electron in detector

Heavy flavour production at HERA

- Life (QCD) is not quite so simple ☹

Non-Direct

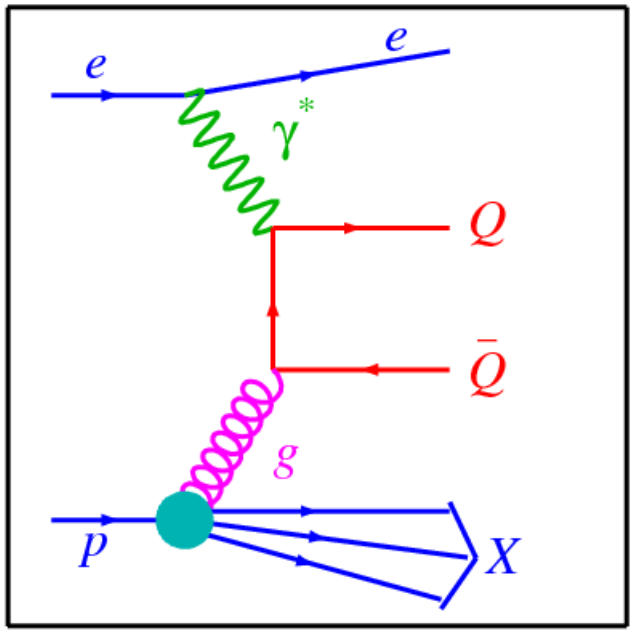
Direct

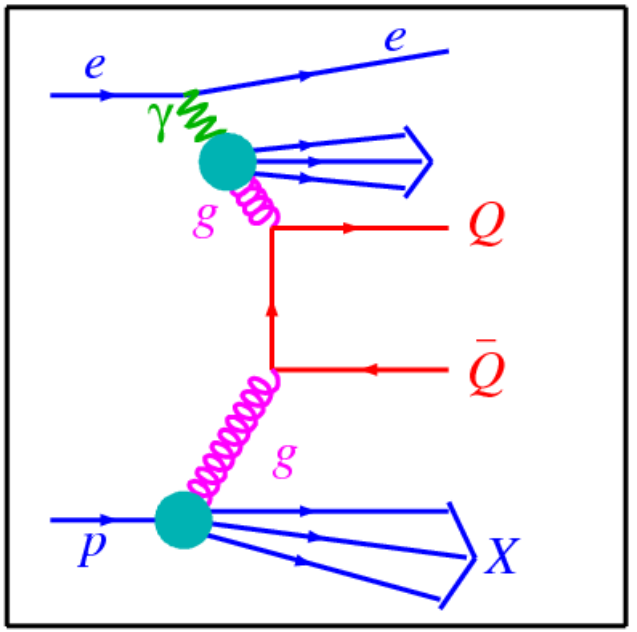
Resolved

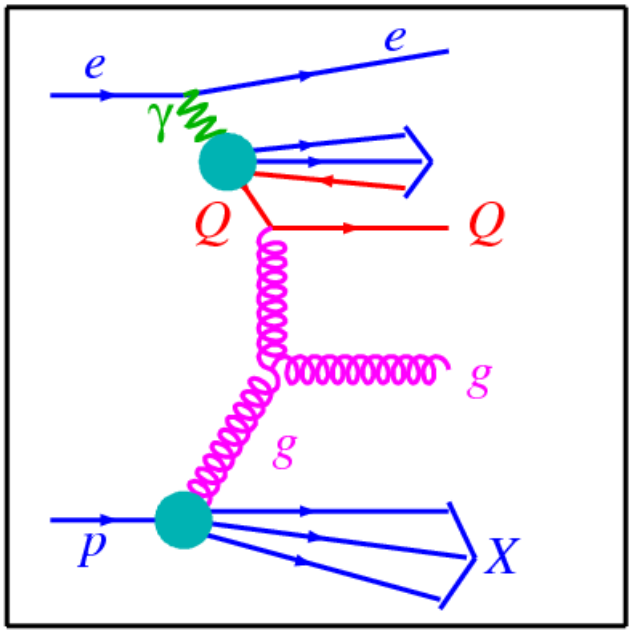
Excitation

$x_\gamma = 1$

$x_\gamma < 1$







x_γ : fraction of photon energy entering the hard interaction

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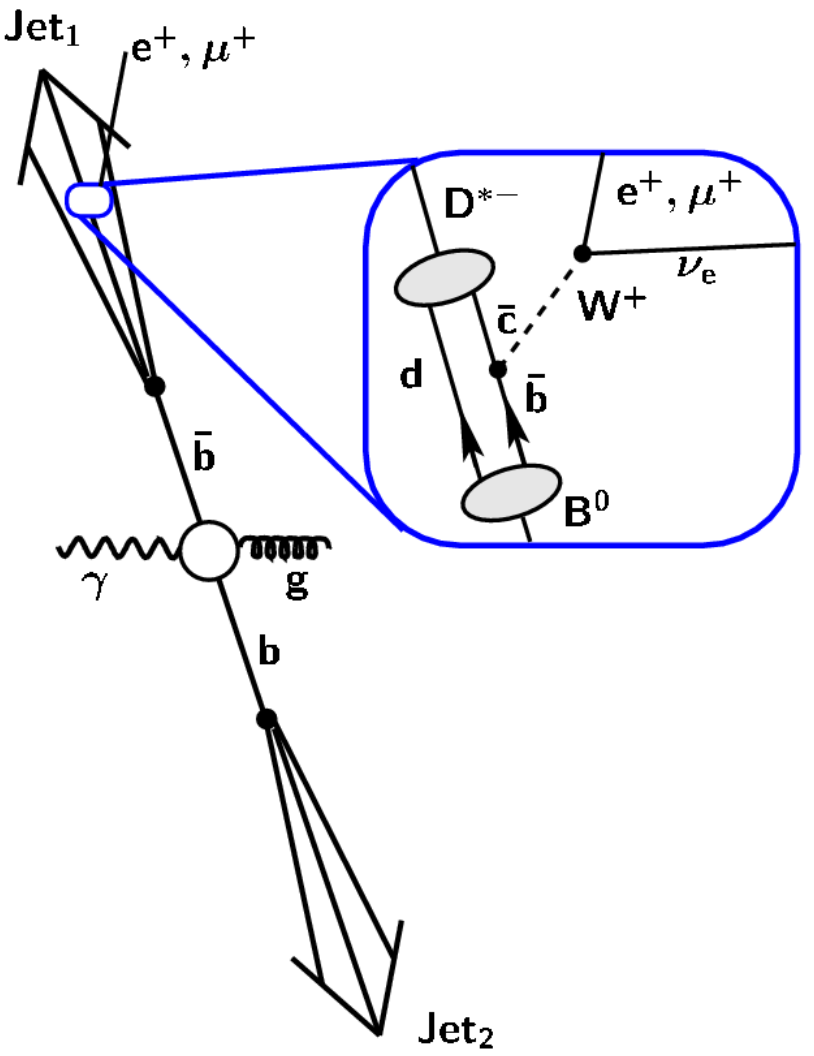
Heavy flavour decay

- Methods to tag HF:
  - Reconstruct *D** (or other *D* mesons)
  - Tag semileptonic decay to *e*, *μ*
  - Use long *B*,*D* hadron lifetime
  - Jet properties
    - e.g. secondary vertex mass
- Different tags probe different kinematic regions



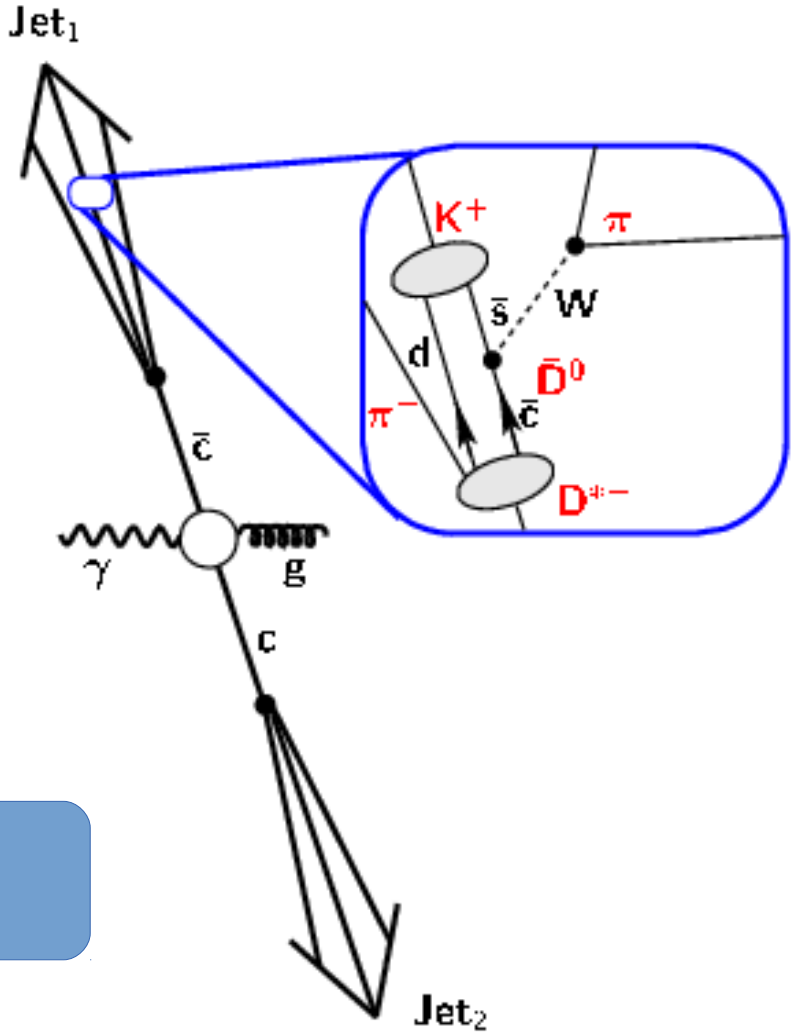
Theory

- QCD Leading Order + Parton Shower Monte Carlos
  - PYTHIA
  - HERWIG
  - CASCADE
  - RAPGAP (DIS)
- QCD NLO programs
  - Weighted events
  - Do not include parton shower
  - FMNR (GMVFNS)
- MC@NLO (finally) used for a few (H1) measurements

Usually compare NLO calculations with experiment by applying hadronic corrections from LO Monte Carlo

c production using *D**

- HERA II data
  - Up to 93 pb^{-1} (2006/7)
- Fast Track Trigger
- $p_T(D^*) > 1.8$ (2.1) GeV
- Inclusive and dijet analysis



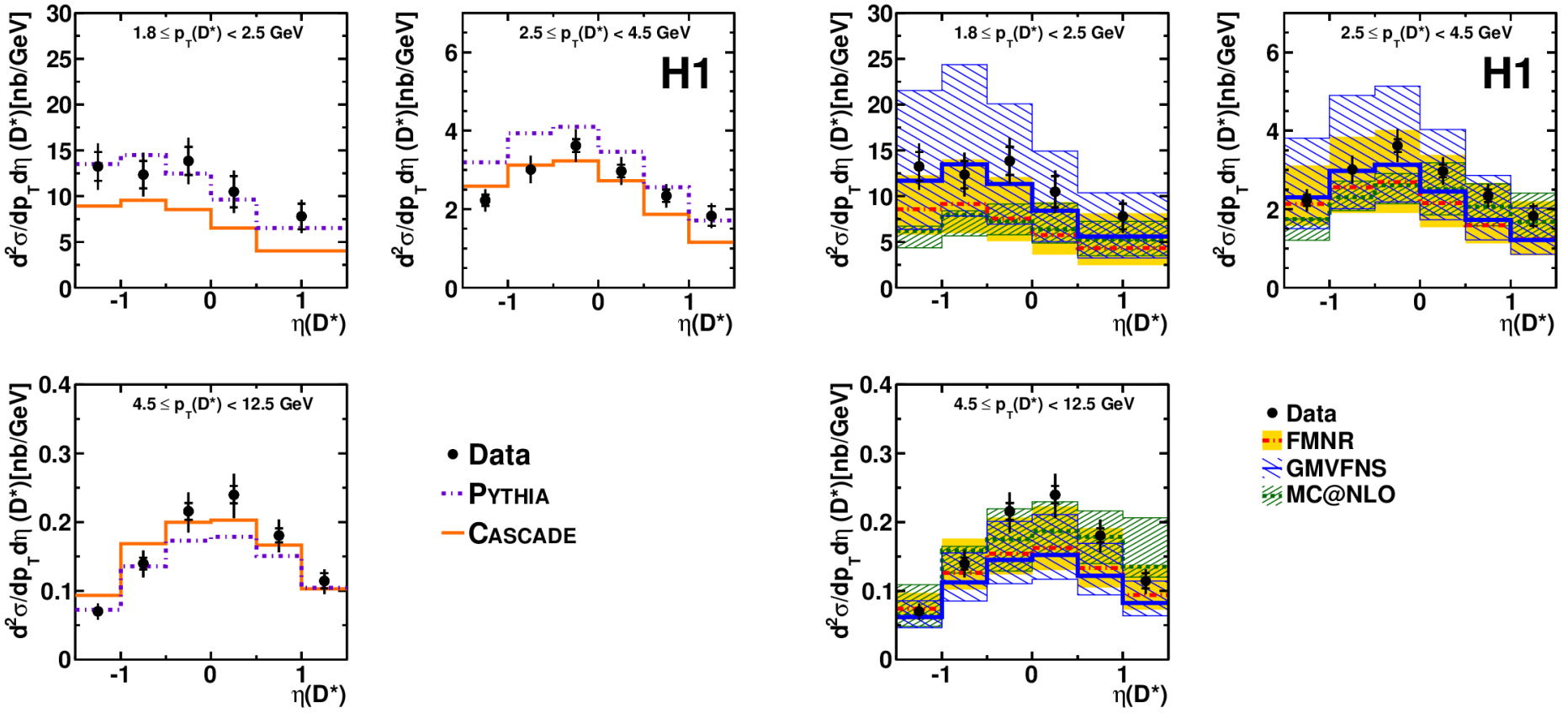
"Golden" Decay of D*

$$D^{*-} \rightarrow \bar{D}^0 \pi^- \rightarrow K^+ \pi^- \pi^-$$

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

c production using *D**

- Inclusive

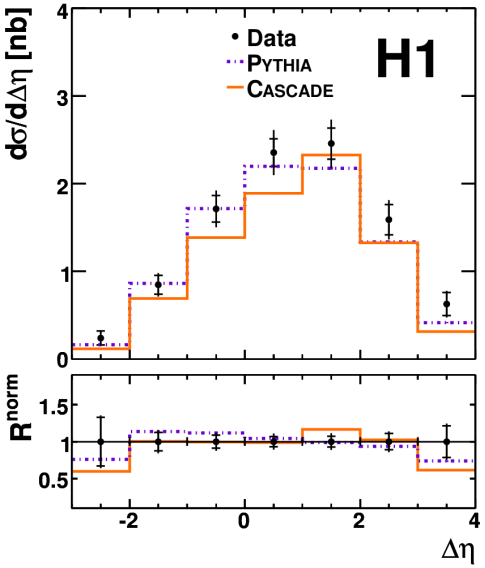


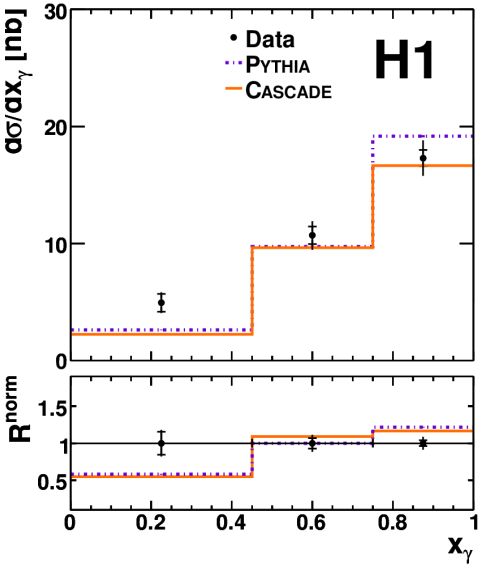
Different MCs each describe different aspects better
Measurement more precise than NLO predictions
(missing higher orders estimated by scale variations)

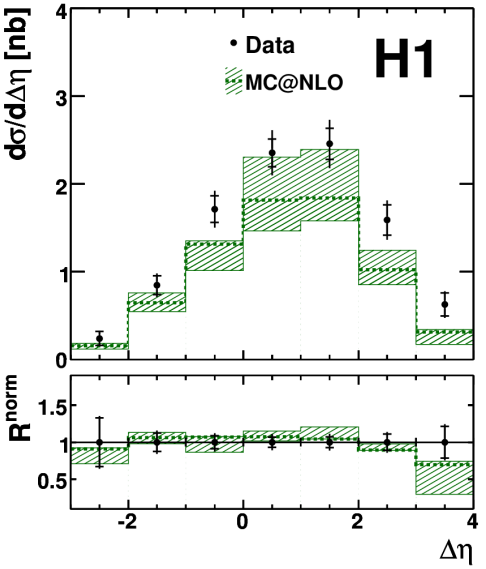
c production using *D**

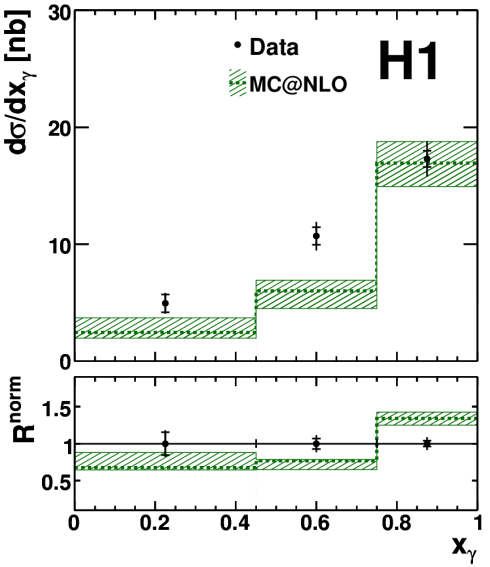
- Dijet correlations
- Compare with LO MC

- Compare with NLO
- MC@NLO a bit low







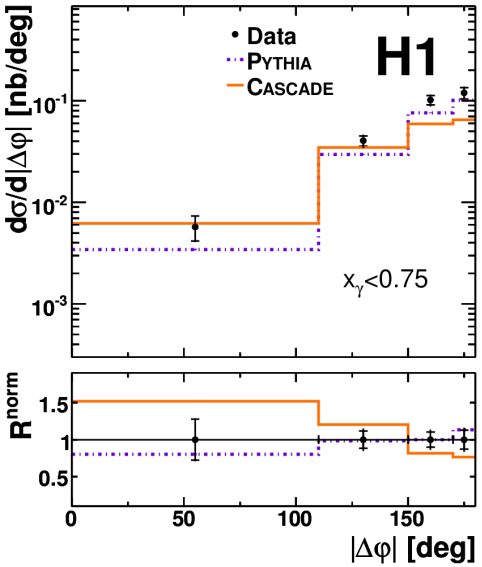


x_γ : fraction of photon energy entering the hard interaction

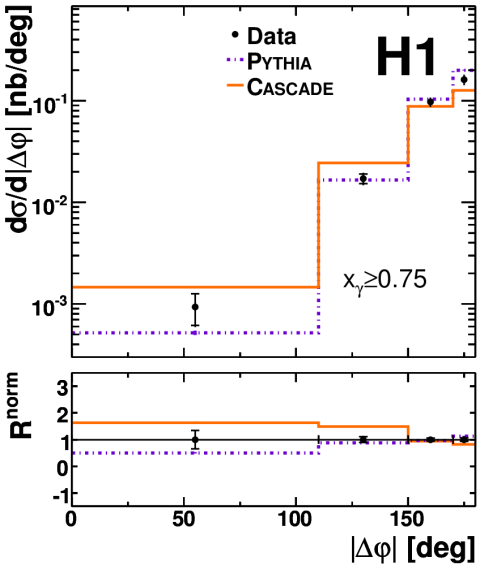
c production using *D**

- Split into 2 x_γ regions
  - Enhanced non-direct or direct production

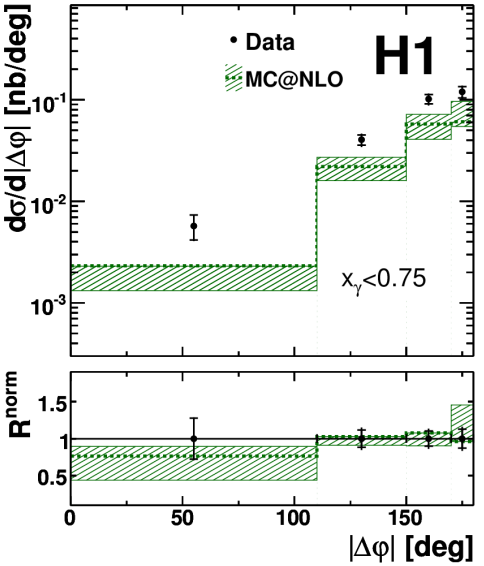
- Nobody's perfect ☺



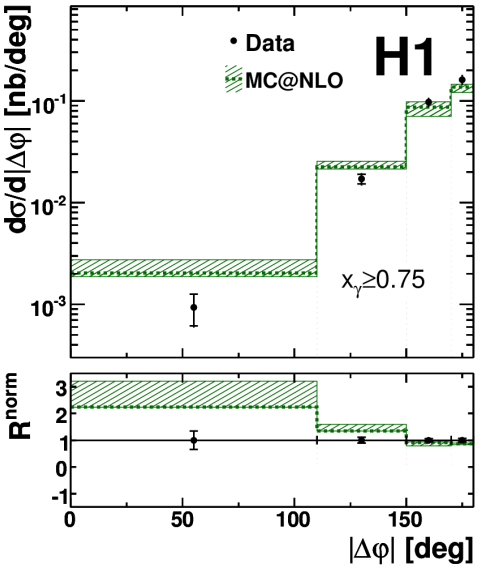
Non-direct



Direct



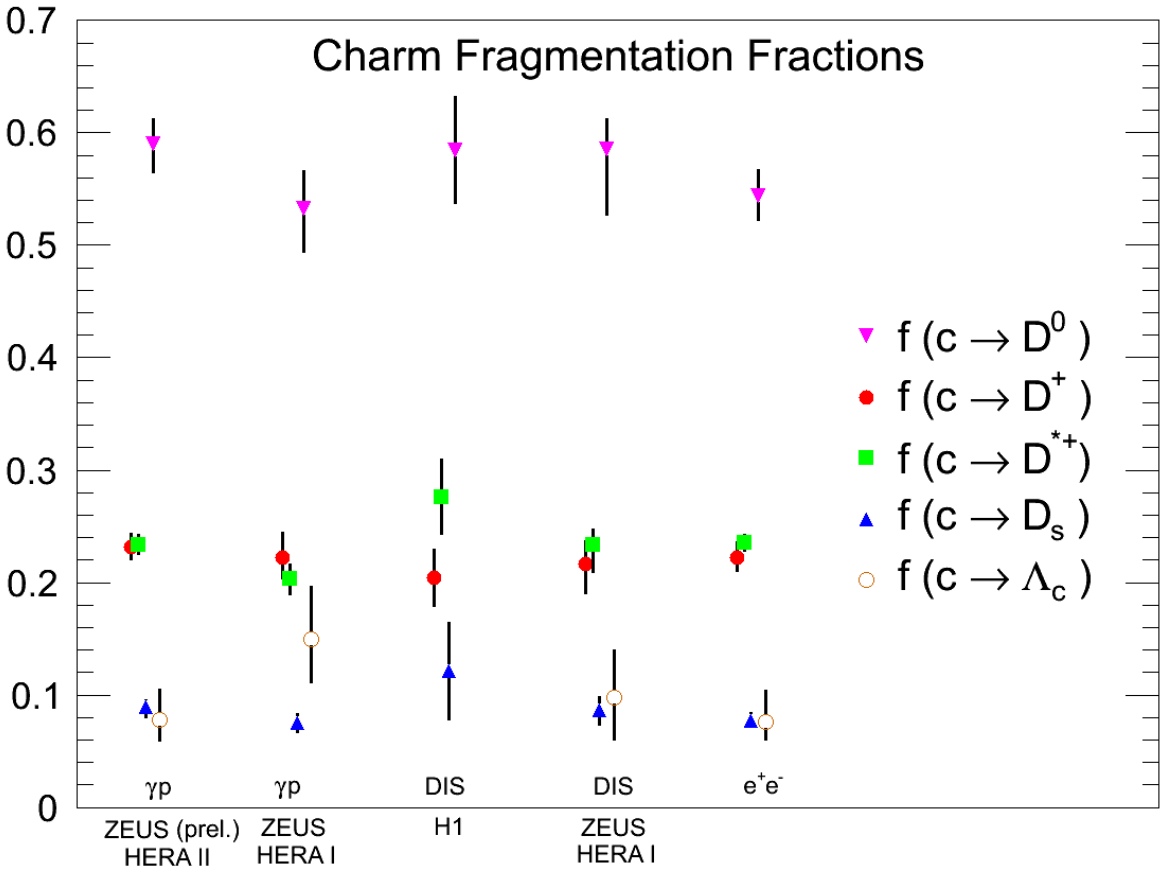
Non-direct



Direct

Charm fragmentation fractions

- HERA II data
  - 372 pb^{-1}



- Many charmed hadrons identified in ZEUS detector
- Fragmentation fractions consistent with those in DIS and as measured in e^+e^- with similar precision
- Supports idea of universal heavy quark fragmentation

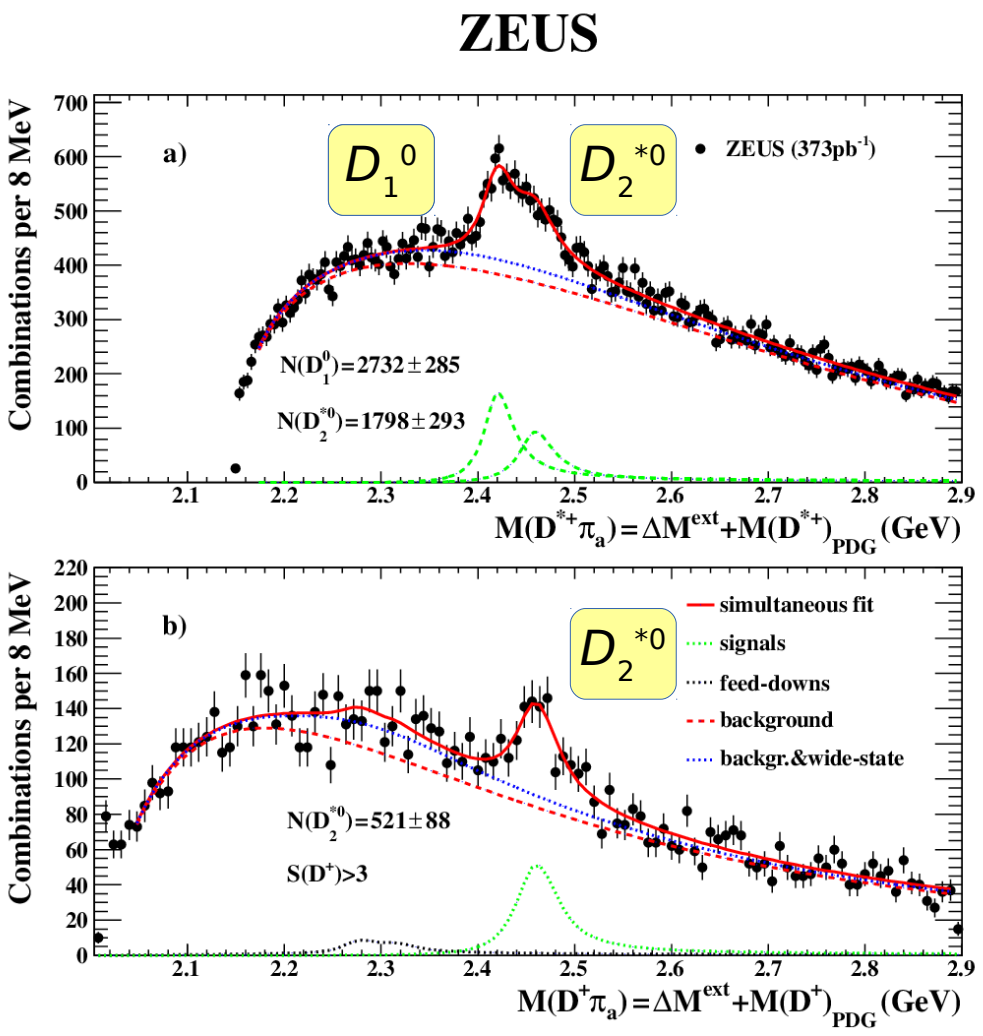
ZEUS-prel-12-003 (DIS 2012)

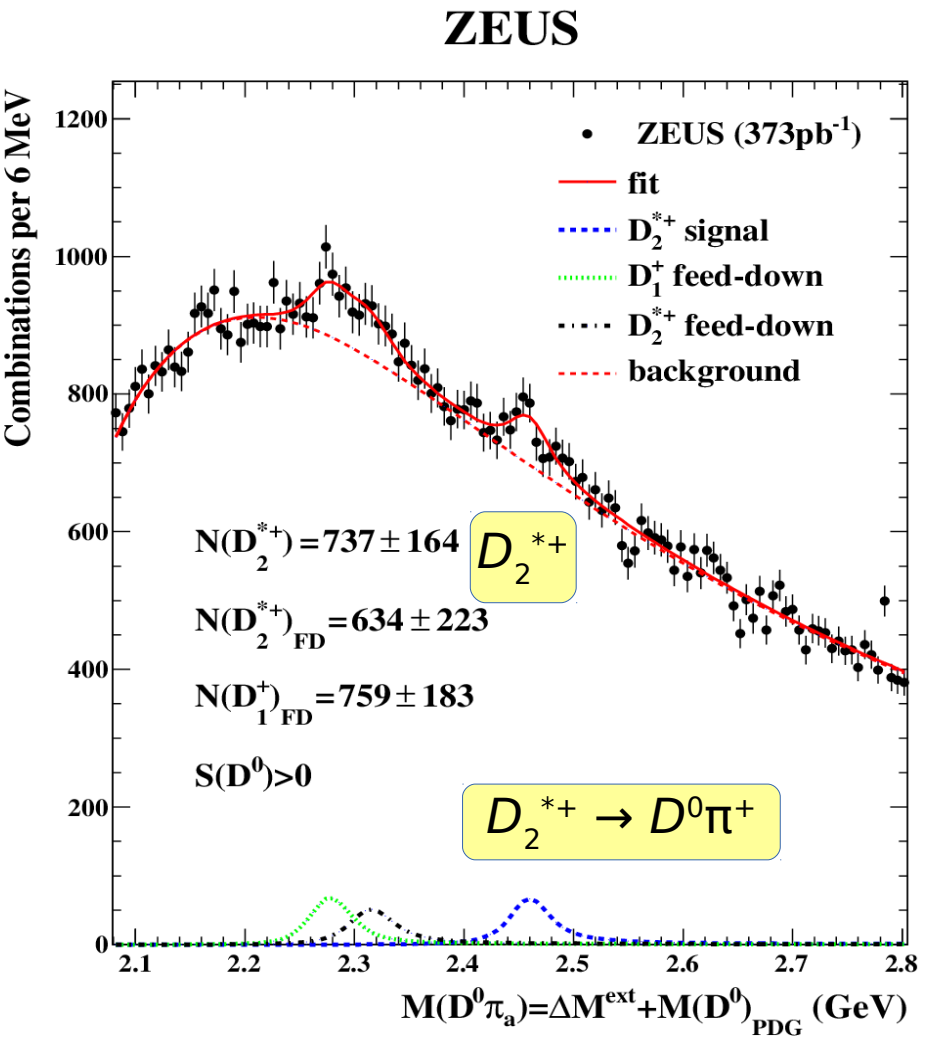
Excited charm mesons

- HERA II data (372 pb^{-1})
- Combine identified D^*, D^+ or D^0 with extra pion (π_a)
- Study
  - $D_1(2420)^0 \rightarrow D^{*+}\pi^-$
  - $D_2^*(2460)^0 \rightarrow D^{*+}\pi^-$
  - $D_2^*(2460)^0 \rightarrow D^{+}\pi^-$
  - $D_1(2420)^+ \rightarrow D^{*0}\pi^+$
  - $D_2^*(2460)^+ \rightarrow D^{*0}\pi^+$
  - $D_2^*(2460)^+ \rightarrow D^{0}\pi^+$
- Trigger on D mesons, but also allow other triggers
- PhP(80%) + DIS(20%)
- Use secondary vertices for D^0 and D^+
- Several cuts applied to reduce backgrounds
- Important to also model feed-down correctly

DESY 12-144, Nucl. Phys. B 866 (2013) 229

Excited charm mesons





Masses and widths consistent with BABAR, PDG
Fragmentation fractions consistent with each other and e^+e^- results

Excited charm mesons

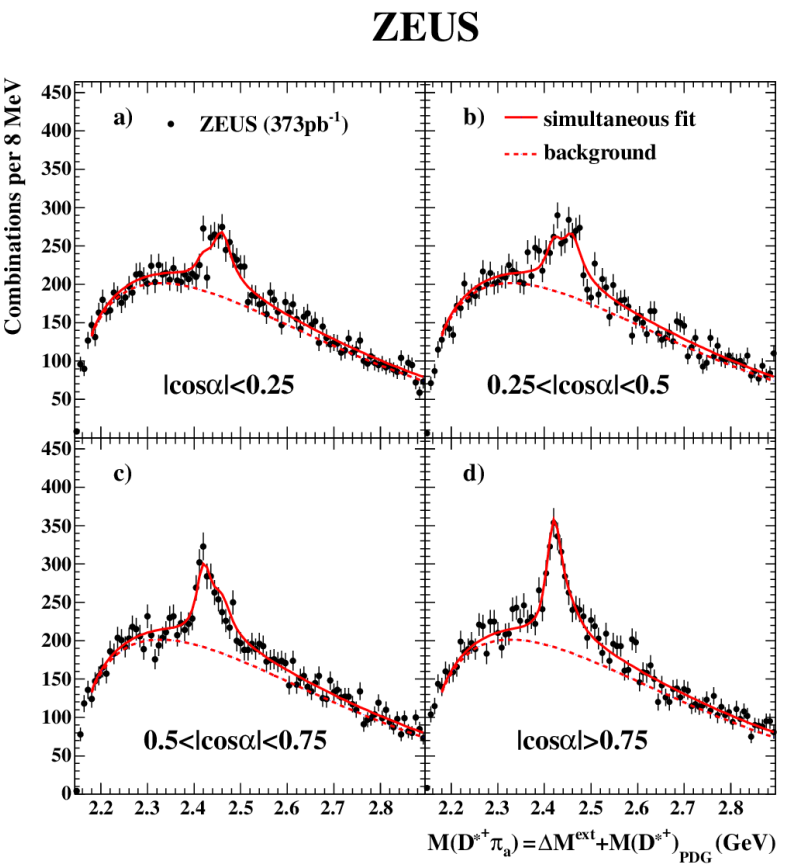
- Measure D_1^0 helicity parameter

$$\frac{dN}{d\cos\alpha} \propto 1 + h\cos^2\alpha$$

  - α is angle between π_a and π_s momenta in D^{*+} rest frame
- Split into 4 helicity intervals
- Measurement consistent with theoretical expectations

$D_1^0 \quad h = +3$

$D_2^{*0} \quad h = -1$

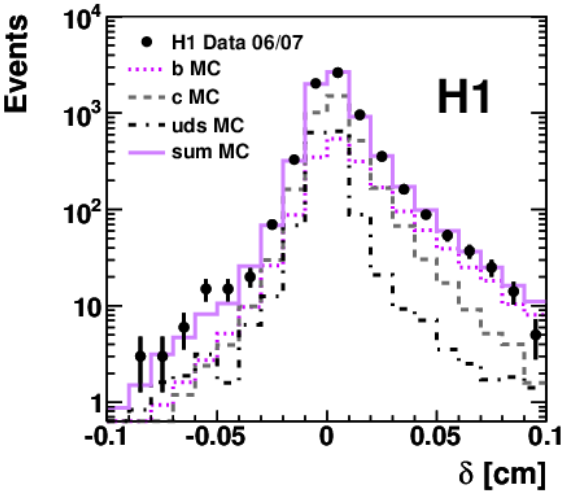


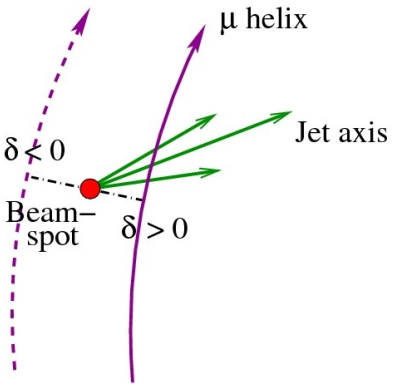
b & *c* in photoproduction using leptons

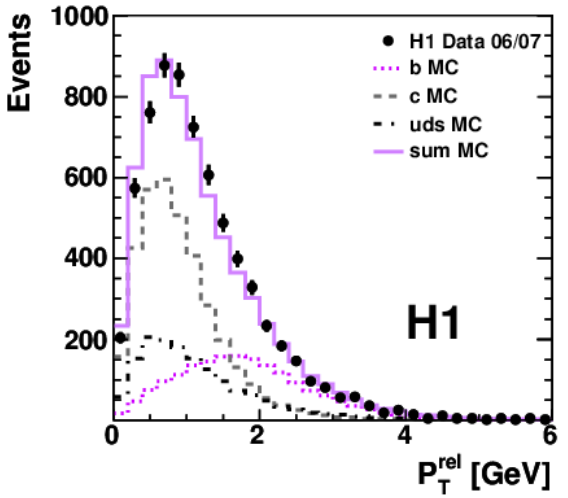
- ZEUS & H1: *b* production with muons
  - DESY 08-210, JHEP04 (2009) 133 (ZEUS)
  - DESY 05-004, Eur. Phys. J C41 (2005) 453 (H1)
- With improved resolution and/or more variables can measure both *b* and *c* cross-sections
- First measurement made by ZEUS using electrons
  - DESY 08-056, Phys. Rev. D 78 (2008) 072001
- Recent measurement from H1 using muons
  - DESY 12-059, Eur. Phys. J. C72 (2012) 2047

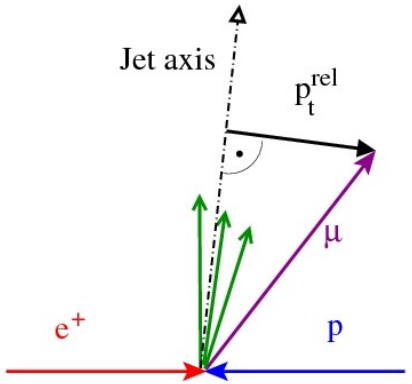
b & *c* in photoproduction using muons

- HERA II data
  - 179 pb^{-1} (2006/7)
- Dijet photoproduction events
  - p_T^{jet} > 7(6) GeV
- Semileptonic decays to muons
  - p_T^{μ} > 2.5 GeV
- Impact parameter + p_T^{rel} to separate *b* and *c*









DESY 12-059, Eur. Phys. J. C72 (2012) 2047

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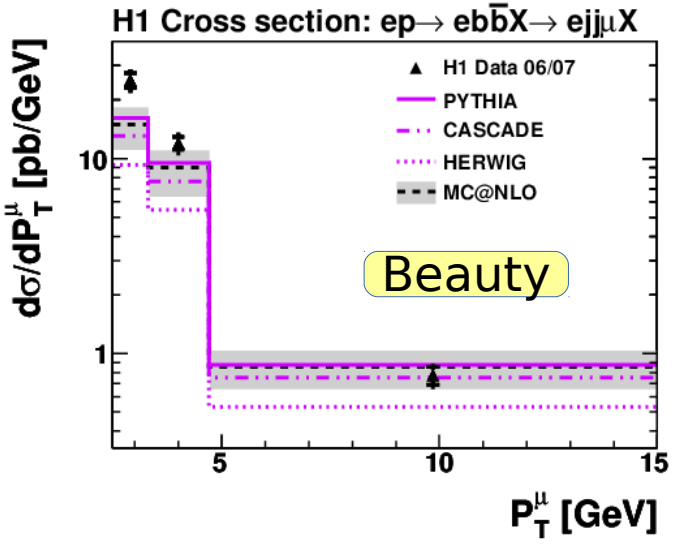
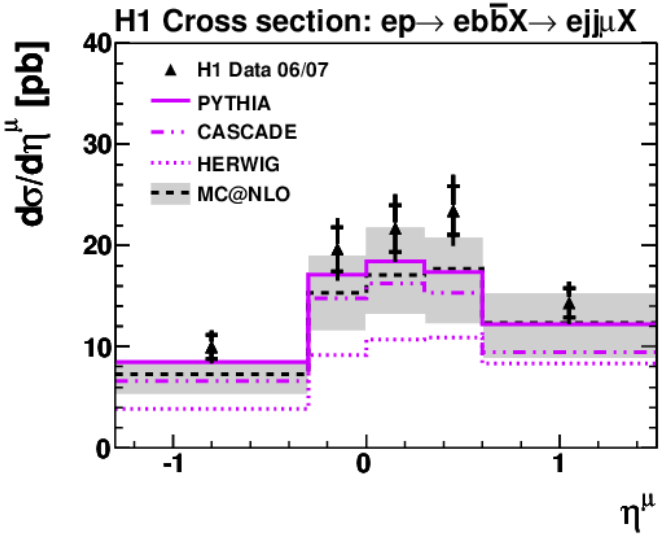
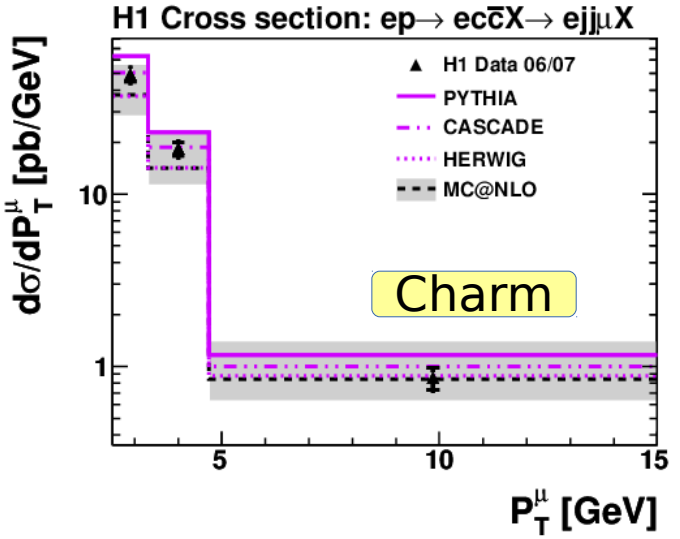
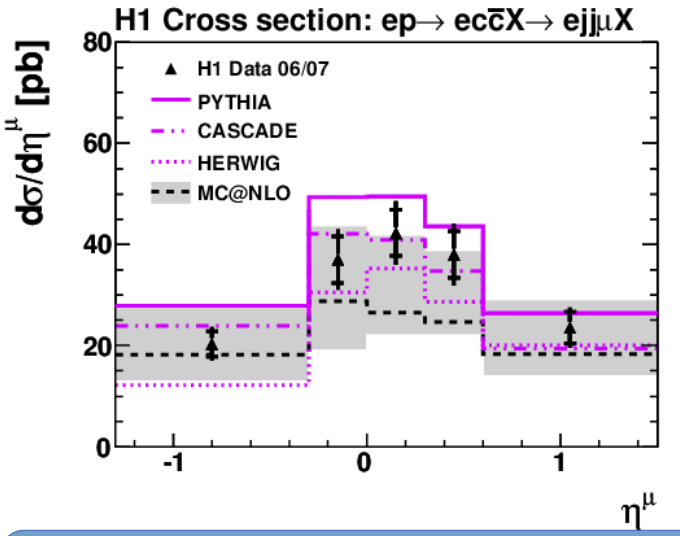
b & *c* in photoproduction using muons

- Muon cross-sections





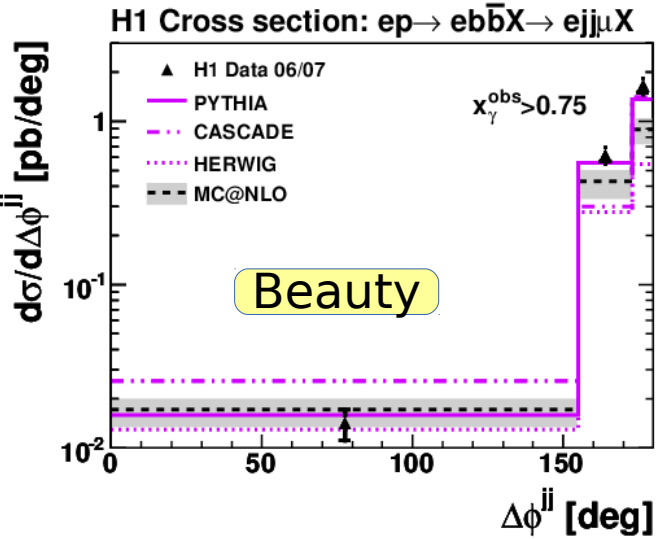


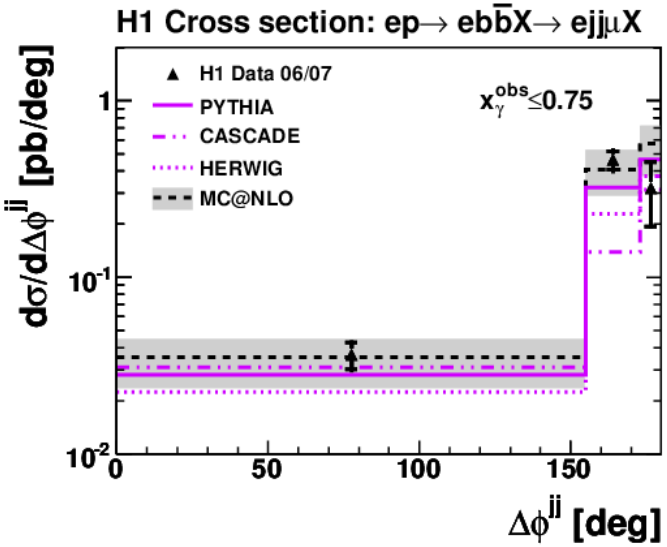


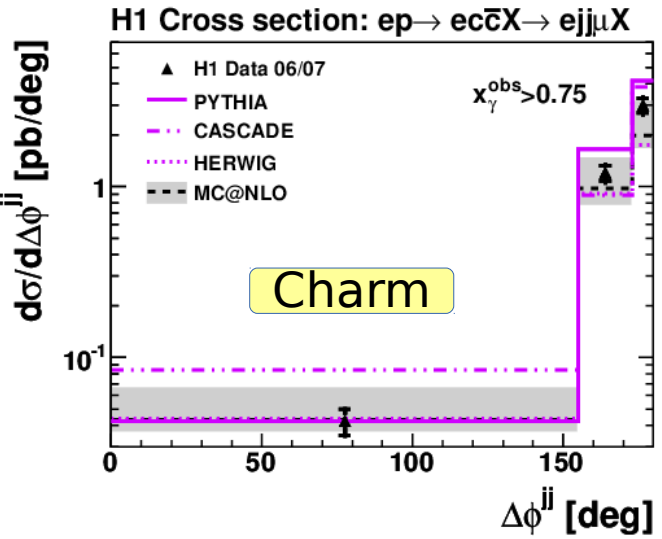
Reasonable agreement with LO and NLO predictions

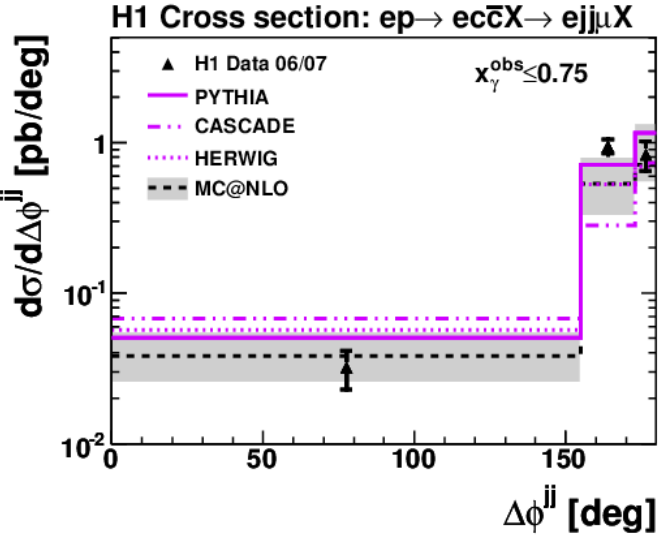
b & c in photoproduction using muons

- Dijet correlations





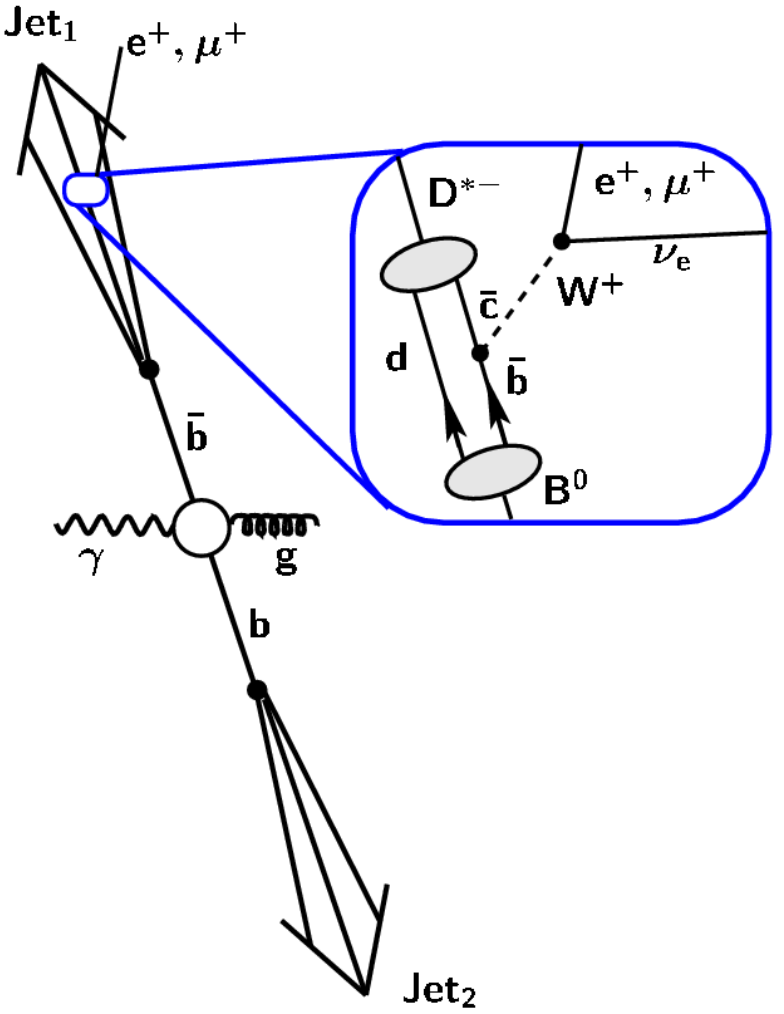




MC@NLO tends to be below data

b & *c* in photoproduction inclusive analysis

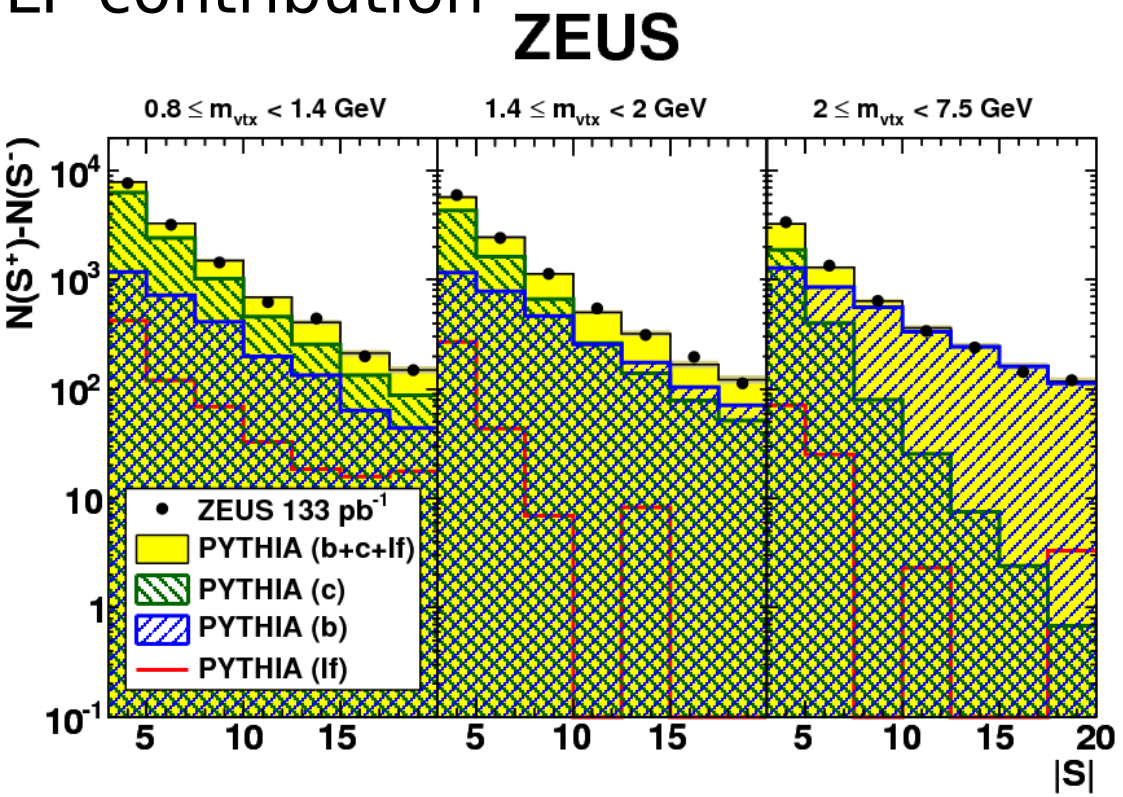
- HERA II data
  - 133 pb^{-1} (2005)
- Dijet photoproduction events
  - $p_T^{jet} > 7(6)$ GeV
- Secondary vertex and vertex mass to separate *b*,*c* jets from each other and from light-quark jets
- Keep analysis inclusive
  - High statistics
  - Less dependence on branching fractions

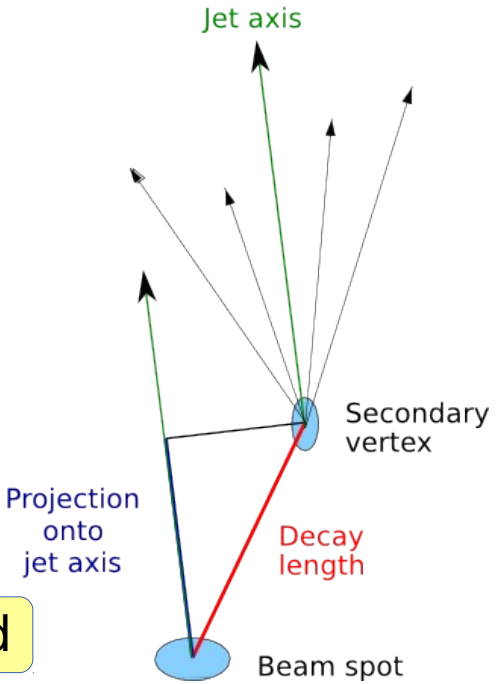


DESY 11-067, Eur. Phys. J. C71, 1659 (2011)

Mirrored significance

- Subtract -ve from +ve significance to (almost) remove LF contribution





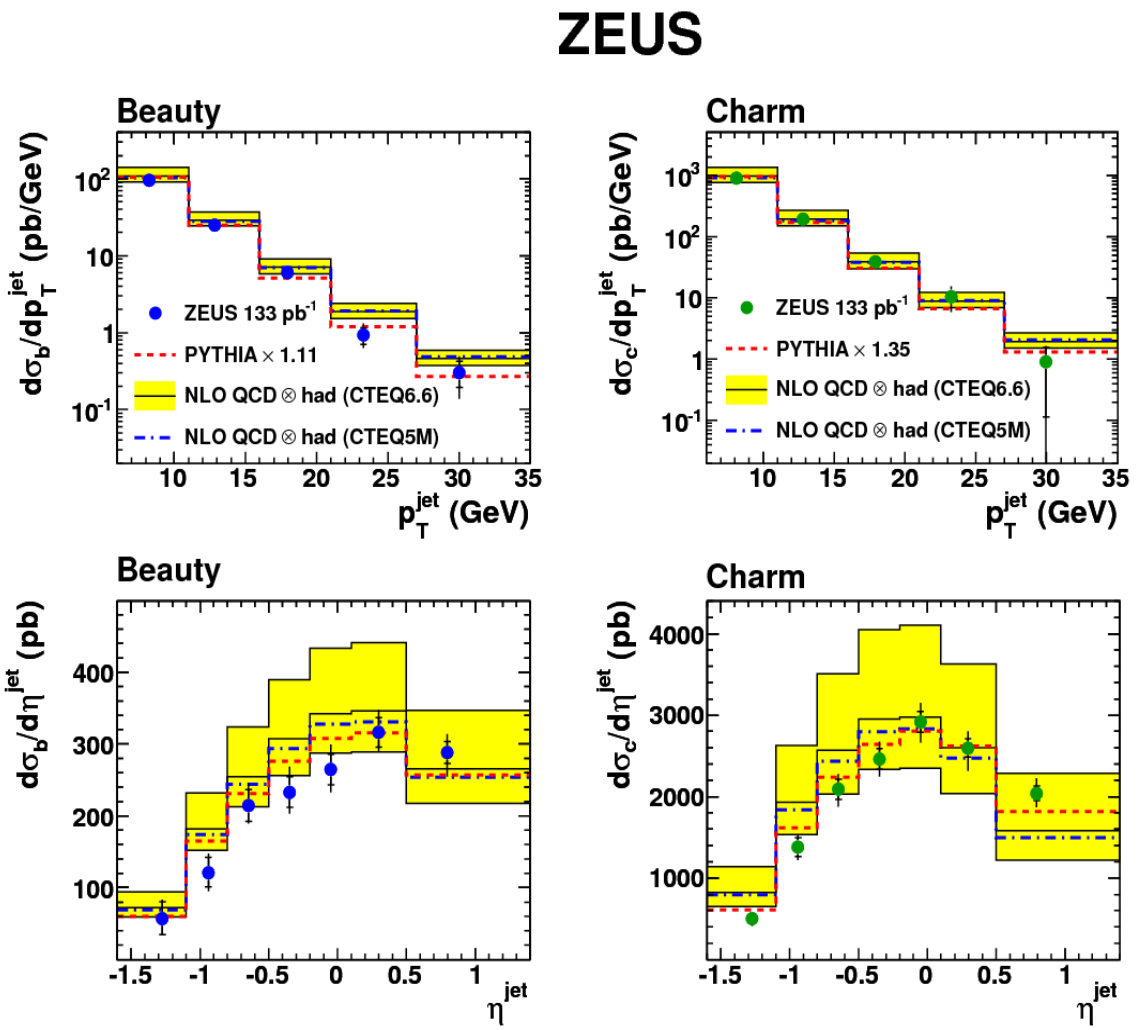
$S = d/\delta d$

LO Scale factors
$k_b = 1.11$
$k_c = 1.35$

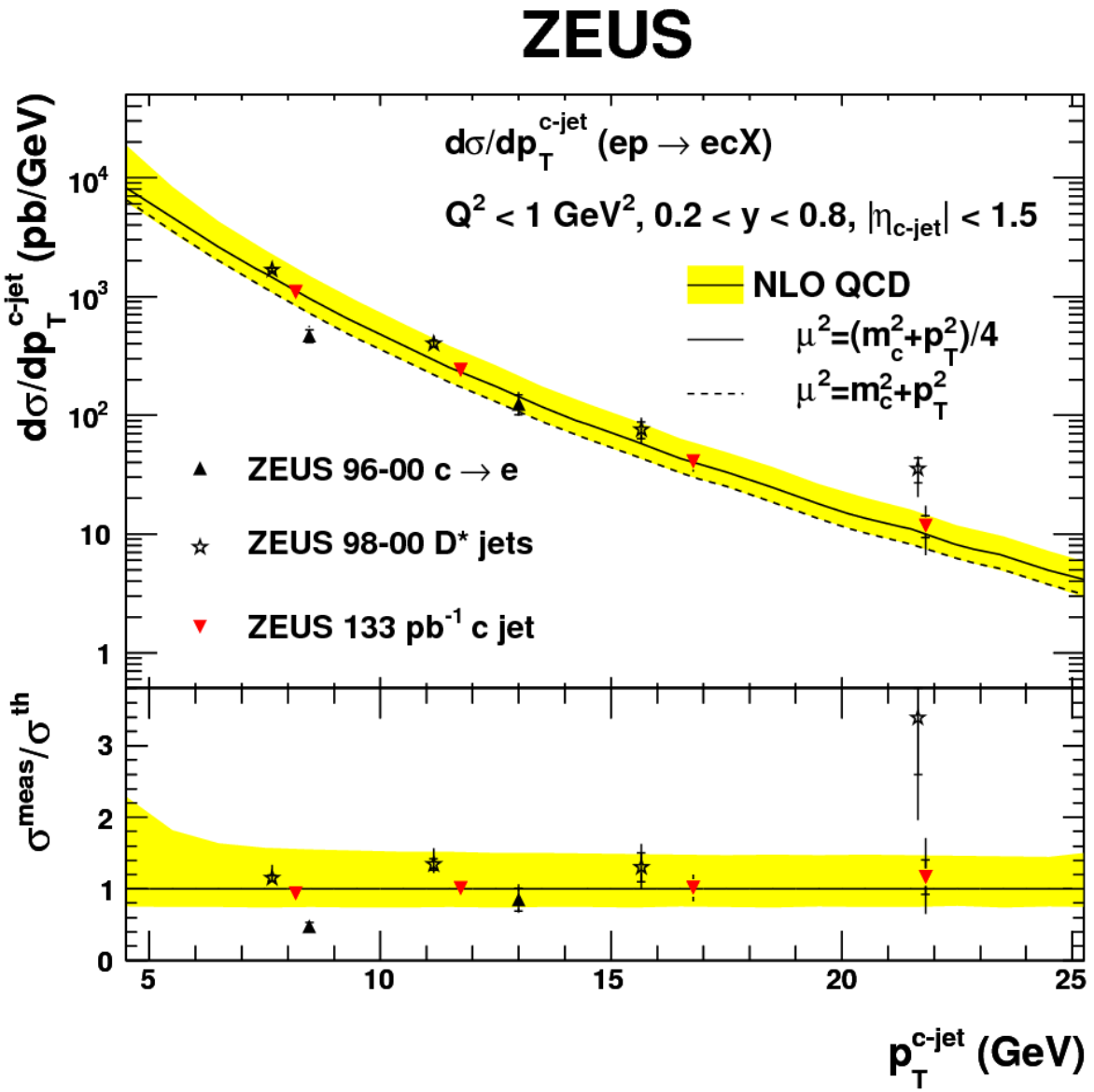
- Fit distribution to 3 contributions
- Use unsubtracted distribution to constrain overall normalisation

b & *c* cross-sections

- Compare measured cross-sections with scaled MC and NLO QCD predictions
- Good agreement
- Large theory uncertainty!
  - Small dependence on proton PDF



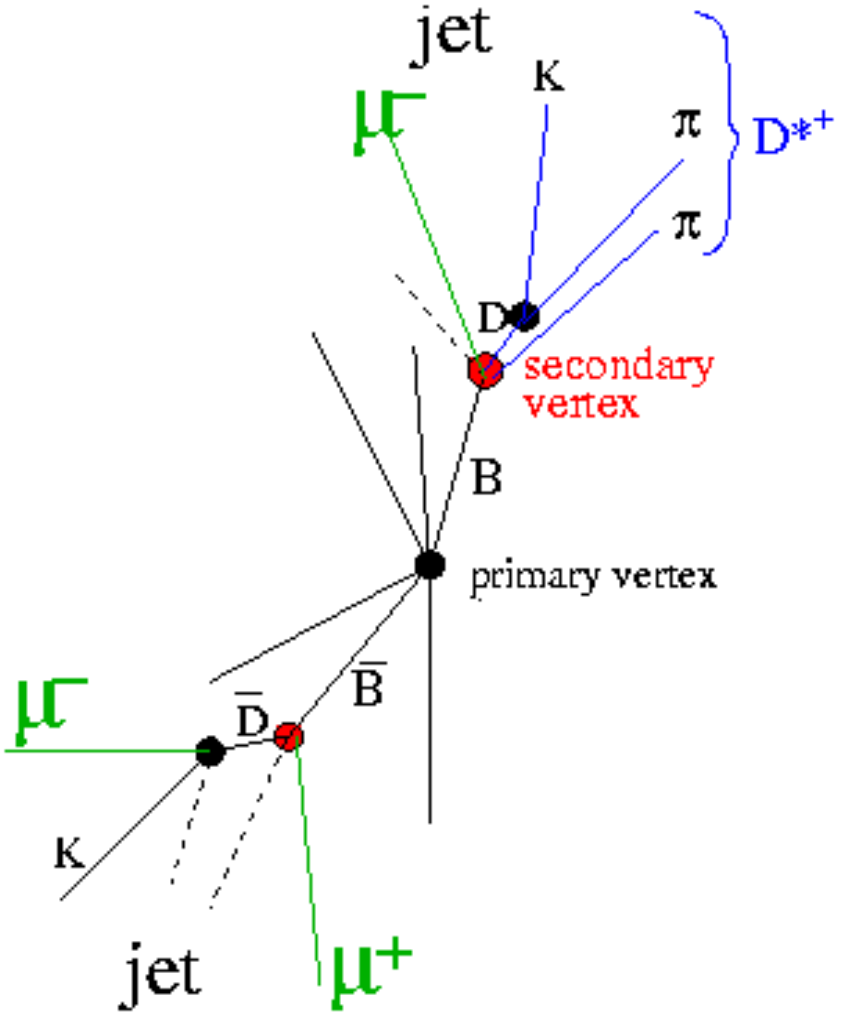
$p_T^{c\text{-}jet}$ comparison



- Reasonable agreement with previous ZEUS measurements
- Good agreement with NLO QCD predictions

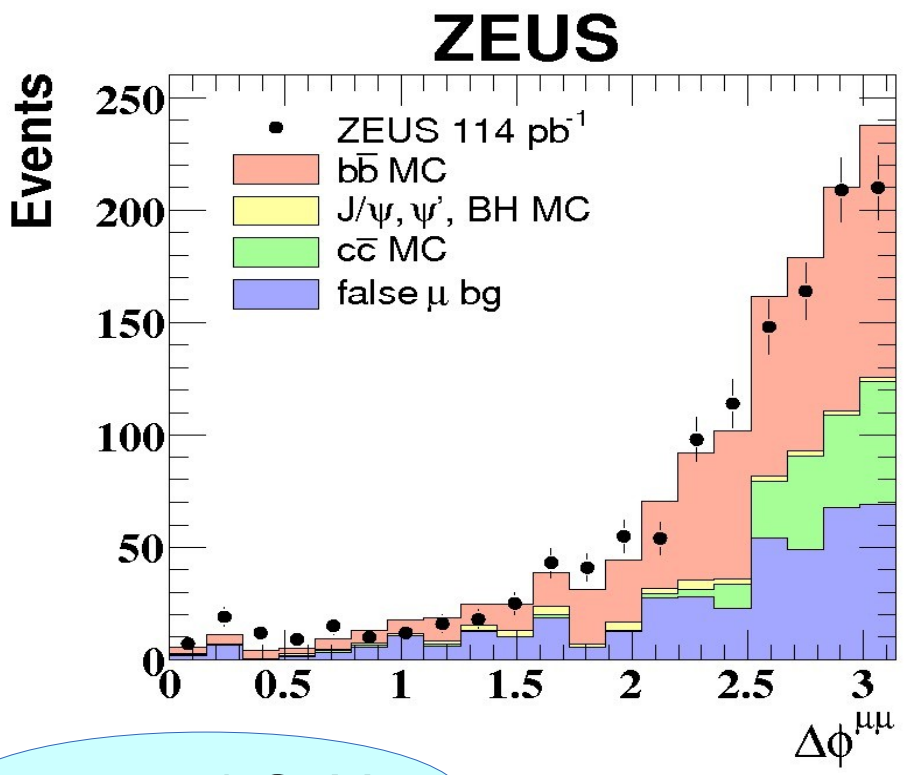
$b\bar{b}$ production

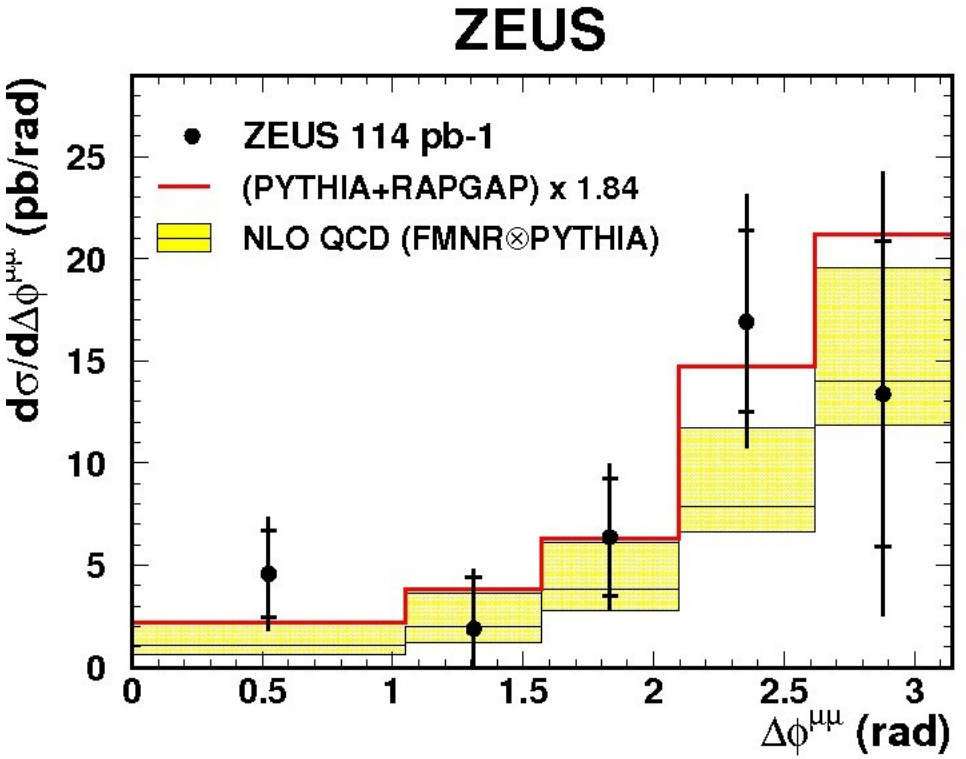
- HERA I (114 pb^{-1})
- Double tag events
  - Low background ☺
  - Larger kinematic range ☺
  - Low statistics ☹
- Two identified muons
- PhP + DIS
  - E_T > 8 GeV
- Measure *bb* correlations
  - Probe NLO effects



DESY 08-129, JHEP02 (2009) 032

$b\bar{b}$ production



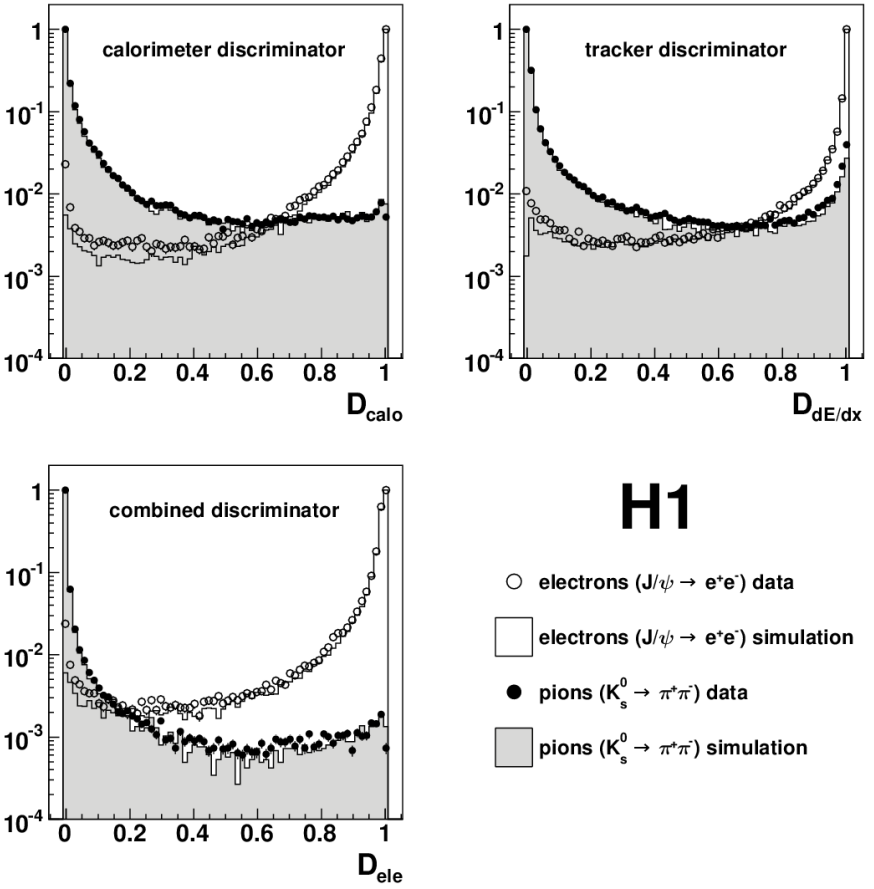


$m_{\mu\mu} > 4$ GeV

- $\Delta\varphi$ between muons from different quarks
- Correlations reasonably well described

$b\bar{b}$ production

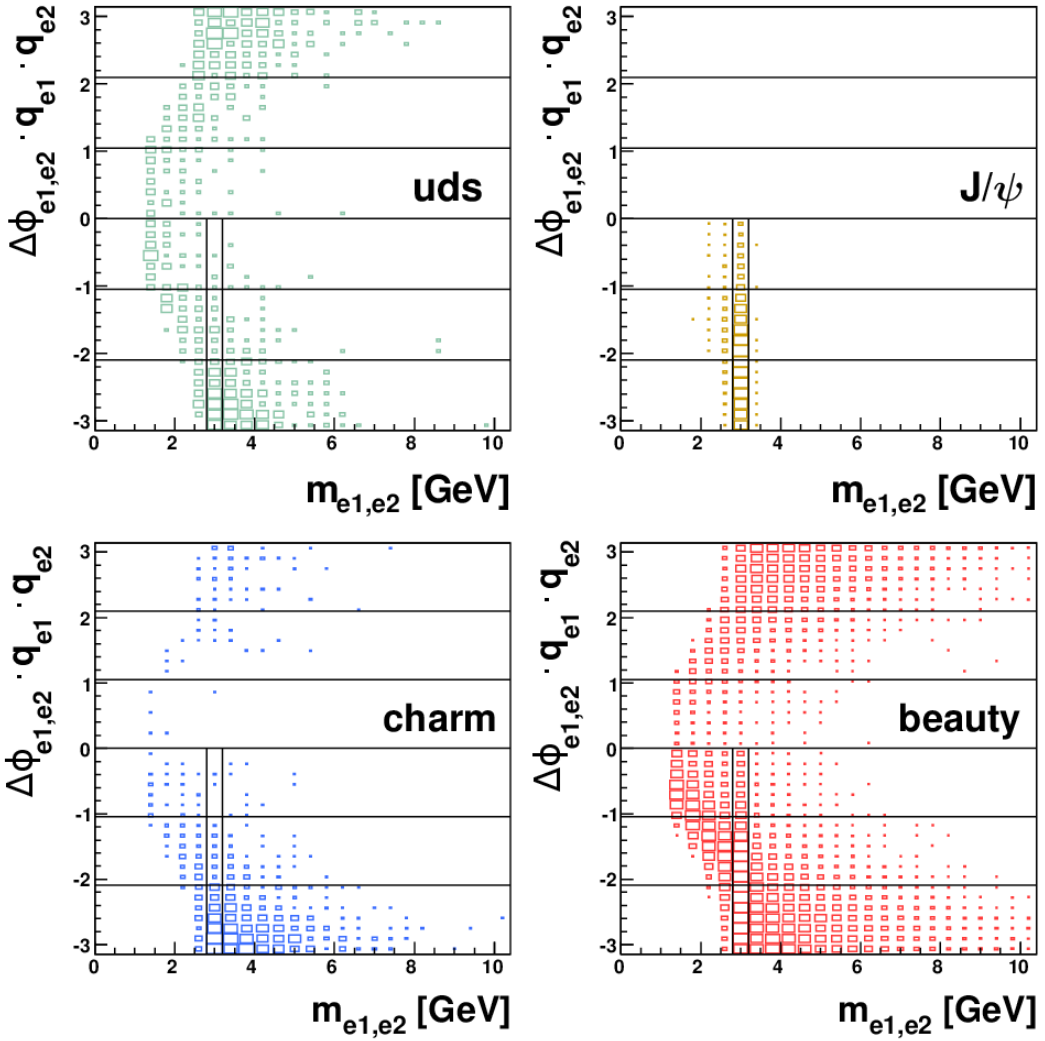
- HERA II
  - 48 pb^{-1} (2007)
- Use 2 identified electrons
  - $p_T^e > 1$ GeV
  - Use neural network to identify electrons
  - Validate with J/ψ and K_S^0 decays
- Aim for very low p_T^b



DESY 12-072, Eur. Phys. J. C72 (2012) 2148

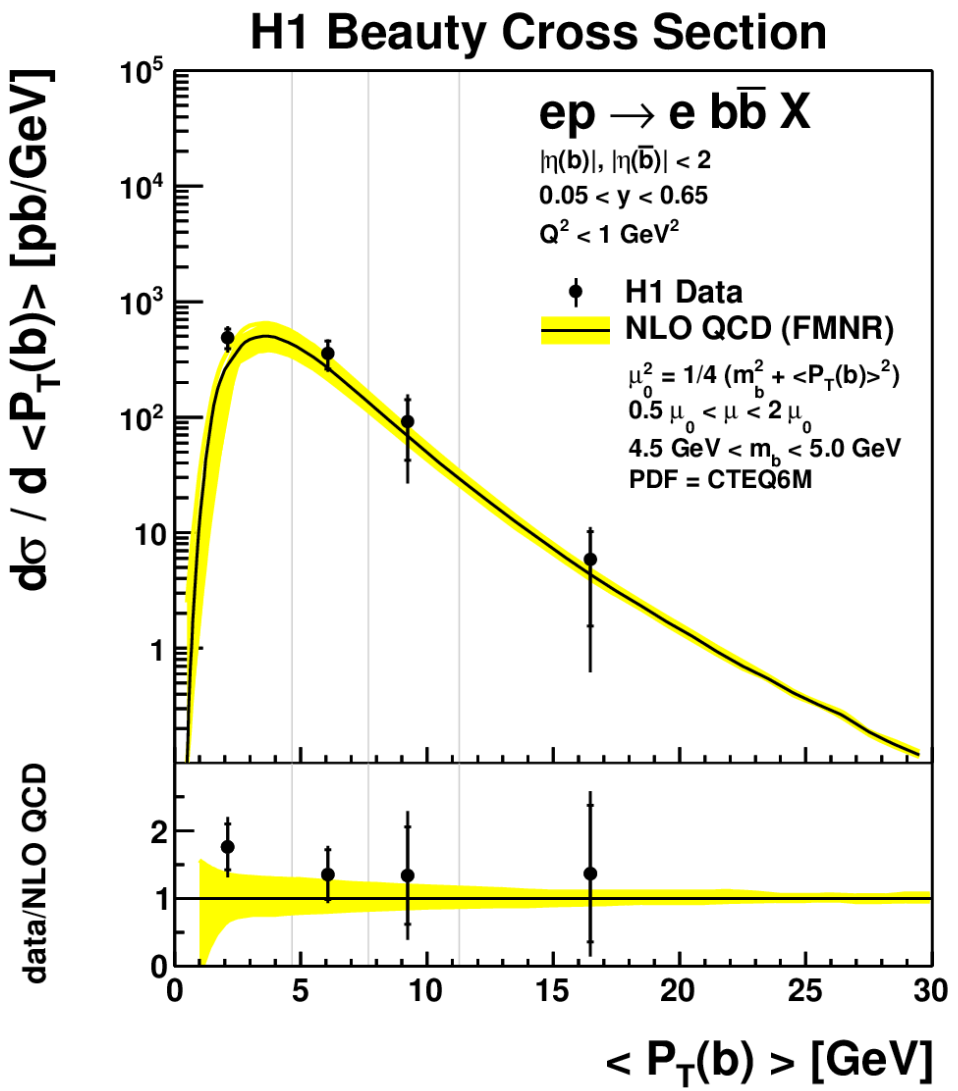
$b\bar{b}$ production

- Separate into categories



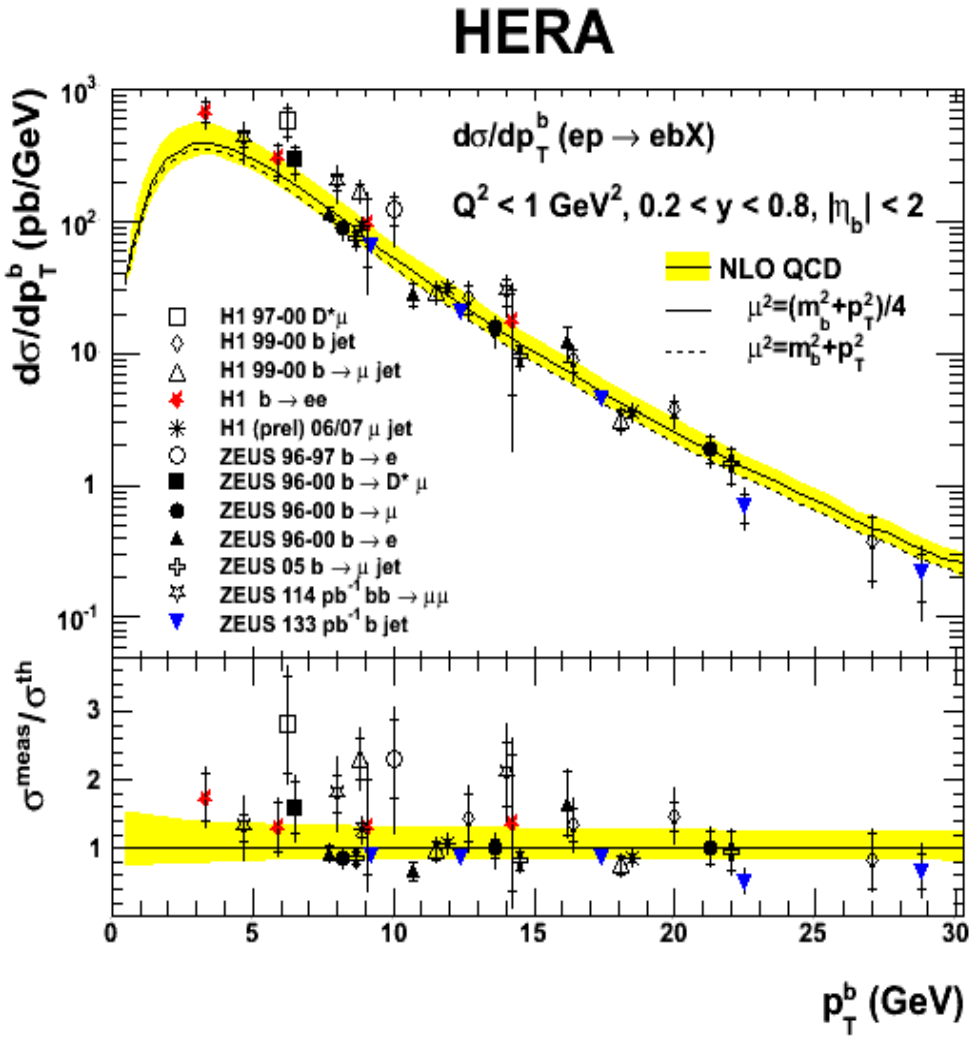
- Clear J/ψ region
- Charm mostly in $q_{e1}q_{e2}\Delta\varphi < 0$
- Beauty at higher masses

bb production



- Use thrust axis to divide event into hemispheres and calculate $<p_T^b>$
- Extract cross-section and compare with NLO prediction
- Good agreement, but data higher than prediction at small p_T^b

Summary of *b* photoproduction



- Good agreement between ZEUS and H1 measurements
  - Large $p_T{}^b$ range covered
- Good agreement with NLO QCD predictions
  - Better agreement with scale $\mu^2 = (m^2 + p_T{}^2)/4$ than $(m^2 + p_T{}^2)$

Conclusions

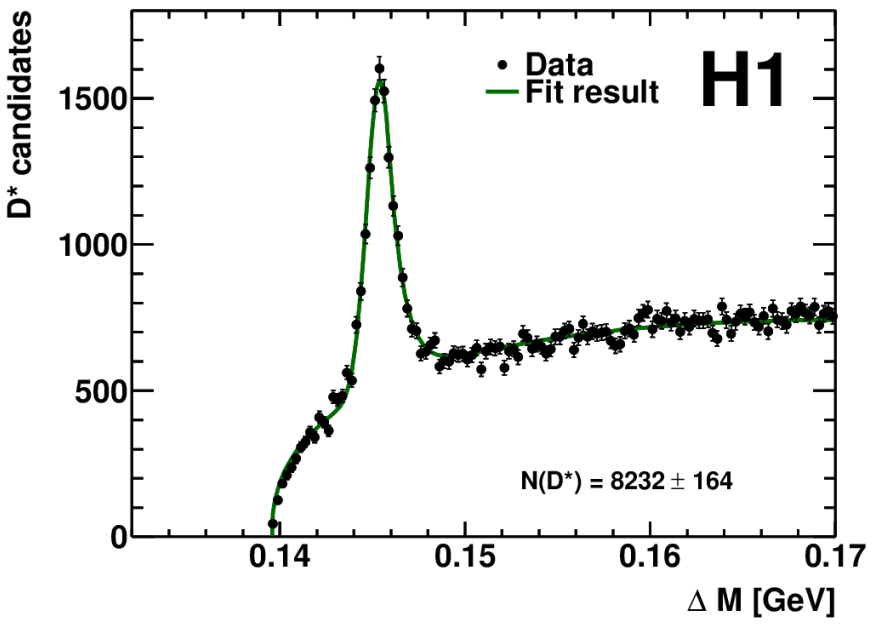
- *b* and *c* quark photoproduction measured in a variety of ways at HERA
- Data is usually more precise than the predictions
- General agreement between data and both LO MC and NLO calculations, although some shape differences are seen

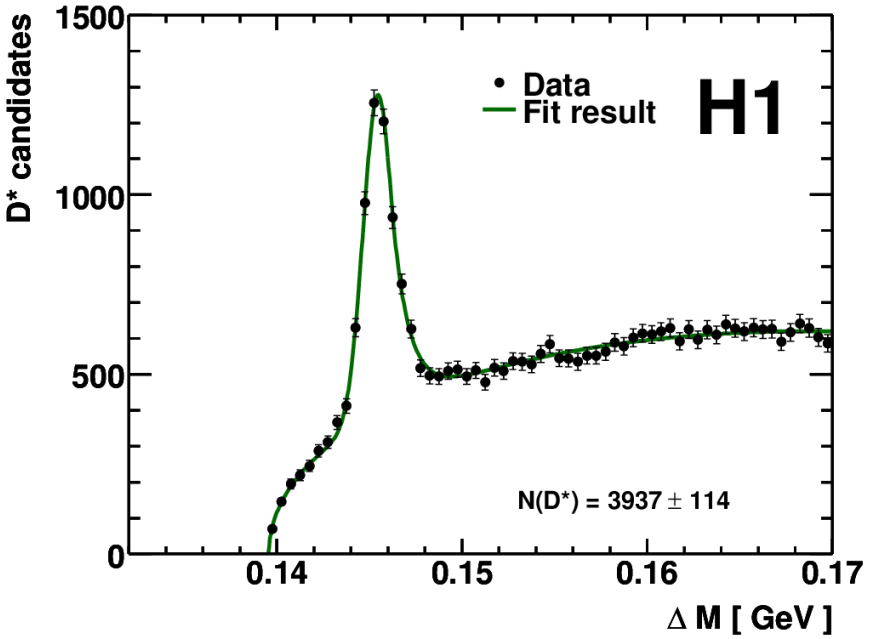
Backup

H1 DESY 11-248
D*

c production using *D**

- Inclusive
  - $p_T(D^*) > 1.8$ GeV
  - Cut on dE/dx for *K*
- Dijet
  - $p_T(\text{jet}) > 3.5$ GeV
  - $p_T(D^*) > 2.1$ GeV





$$D^{*-} \to \bar{D}^0 \pi^- \to K^+ \pi^- \pi^-$$

Kinematic range

inclusive D^* meson and D^*-tagged dijet production	
Photon virtuality	$Q^2 < 2\ \mathrm{GeV}^2$
γp centre-of-mass energy	$100 < W_{\gamma p} < 285\ \mathrm{GeV}$
Pseudorapidity of $D^{*\pm}$	$\lvert\eta(D^*)\rvert < 1.5$
inclusive D^* meson production	
Transverse momentum of $D^{*\pm}$	$p_T(D^*) > 1.8\ \mathrm{GeV}$
D^*-tagged dijet production	
Transverse momentum of $D^{*\pm}$	$p_T(D^*) > 2.1\ \mathrm{GeV}$
Transverse momentum of D^* jet	$p_T(D^*\ \mathrm{jet}) > 3.5\ \mathrm{GeV}$
Pseudorapidity of D^* jet	$\lvert\eta(D^*\ \mathrm{jet})\rvert < 1.5$
Transverse momentum of other jet	$p_T(\mathrm{other\ jet}) > 3.5\ \mathrm{GeV}$
Pseudorapidity of other jet	$-1.5 < \eta(\mathrm{other\ jet}) < 2.9$
Dijet invariant mass M_{jj}	$M_{jj} > 6\ \mathrm{GeV}$

Table 3: Definition of the kinematic range of the measurements.

Systematic uncertainties

Uncertainty source	D^*	D^*-tagged dijet
Uncorrelated uncertainties		
Trigger efficiency	7.5%	3.1%
Signal extraction	1.5%	1.5%
D^0 meson mass cut	2.0%	2.0%
Reflections	1.0%	1.0%
Background from deep-inelastic scattering	1.0%	1.0%
$\mathrm{d}E/\mathrm{d}x$ cut	0.5%	–
Hadronic energy scale	0.6%	2.0%
Model	2.0%	1.5%
Fragmentation	2.5%	2.0%
Track finding efficiency (half)	2.9%	2.9%
Total uncorrelated	9.2%	6.0%
Normalisation uncertainties		
Track finding efficiency (half)	2.9%	2.9%
Luminosity	5.0%	5.0%
Branching ratio	1.5%	1.5%
Total normalisation	6.0%	6.0%
Total	10.9%	8.5%

Table 4: Summary of all sources of systematic uncertainties and their effect on the total D^* and the D^*-tagged dijet production cross section with the breakdown into sources leading to bin-to-bin uncorrelated uncertainties and sources leading to normalisation uncertainties.

ZEUS DESY 12-144
Excited charm

Decay modes

- $D^{*+} \rightarrow D^0\pi^+ \rightarrow (K^-\pi^+)\pi^+$
- $D^{*+} \rightarrow D^0\pi^+ \rightarrow (K^-\pi^+\pi^-\pi^+)\pi^+$
- $D^+ \rightarrow K^-\pi^+\pi^+$
- $D^0 \rightarrow K^-\pi^+$

$D_1(2420)^0$ and $D_2^*(2460)^0$

- $D^{*+}\pi^-$
  - $p_T(\pi_a) > 0.15$ GeV;
  - $\eta(\pi_a) < 1.1$;
  - $p_T(D^{*+}\pi_a)/E_\perp^{\theta>10^\circ} > 0.25$ (0.30) for the $D^0 \to K\pi$ ($D^0 \to K\pi\pi\pi$) channel;
  - $\cos\theta^*(D^{*+}) < 0.9$, where $\theta^*(D^{*+})$ is the angle between the D^{*+} in the $D^{*+}\pi_a$ rest frame and the $D^{*+}\pi_a$ line of flight in the laboratory frame;
  - the cut $l_\pi > 0.01$ was applied for π_a.
- $D^+\pi^-$ ($D_2^*(2460)^0$)
  - $p_T(\pi_a) > 0.3$ GeV;
  - $\eta(\pi_a) < 1.5$;
  - $p_T(D^+\pi_a)/E_\perp^{\theta>10^\circ} > 0.35$;
  - $\cos\theta^*(D^+) < 0.8$, where $\theta^*(D^+)$ is the angle between the D^+ in the $D^+\pi_a$ rest frame and the $D^+\pi_a$ line of flight in the laboratory frame;
  - the cut $l_\pi > 0.01$ was applied for π_a.

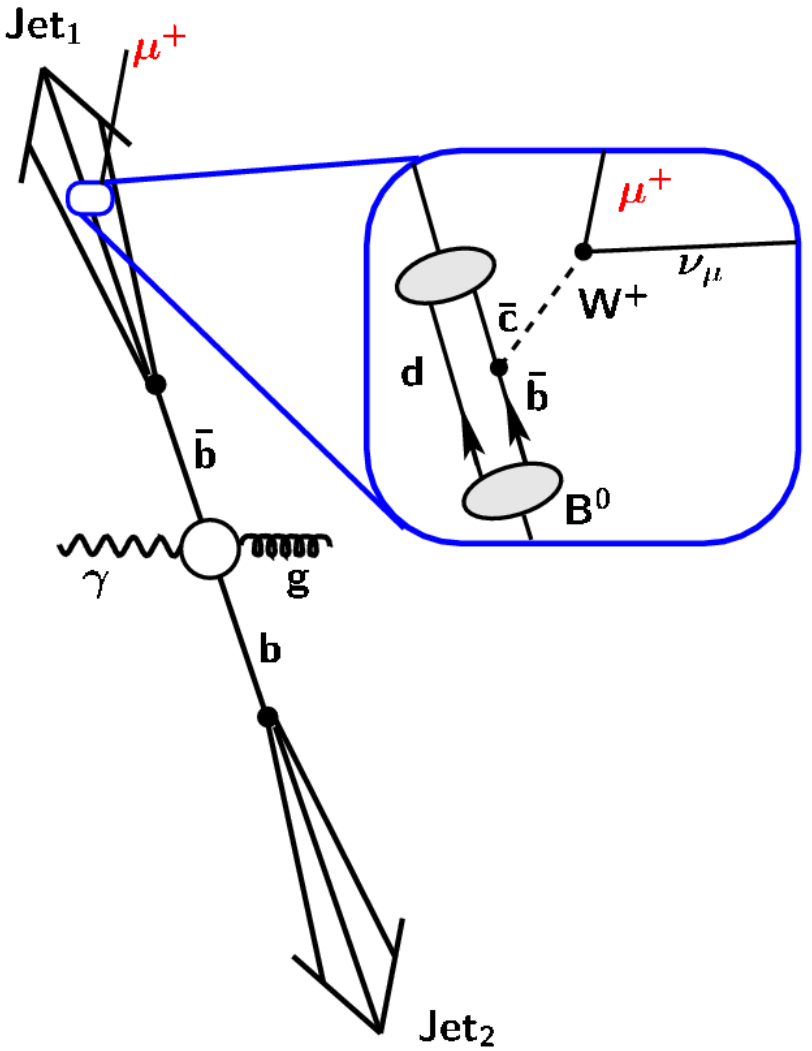
$D_1(2420)^+$ and $D_2^*(2460)^+$

- $p_T(\pi_a) > 0.35$ GeV;
- $\eta(\pi_a) < 1.6$;
- $p_T(D^0\pi_a)/E_\perp^{\theta>10^\circ} > 0.3$;
- $\cos\theta^*(D^0) < 0.85$, where $\theta^*(D^0)$ is the angle between the D^0 in the $D^0\pi_a$ rest frame and the $D^0\pi_a$ line of flight in the laboratory frame;
- the cut $l_\pi > 0.01$ was applied for π_a.

ZEUS DESY 08-210
b with muons

b in photoproduction using muons

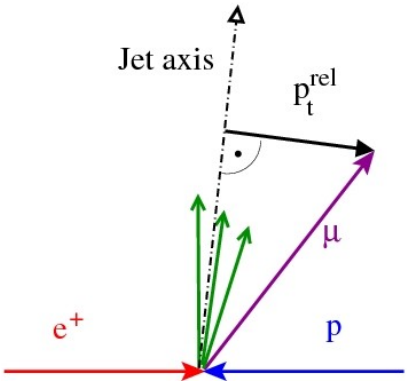
- HERA II data
  - 126 pb^{-1} (2005)
- Photoproduction
- Dijet events
  - $p_T^{jet} > 7(6)$ GeV
- Semileptonic decays to muons
  - ($p_T^{\mu} > 2.5$ (1.5) GeV)
- Include lifetime information



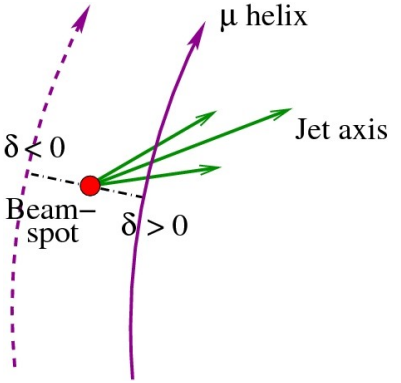
DESY 08-210, JHEP04 (2009) 133

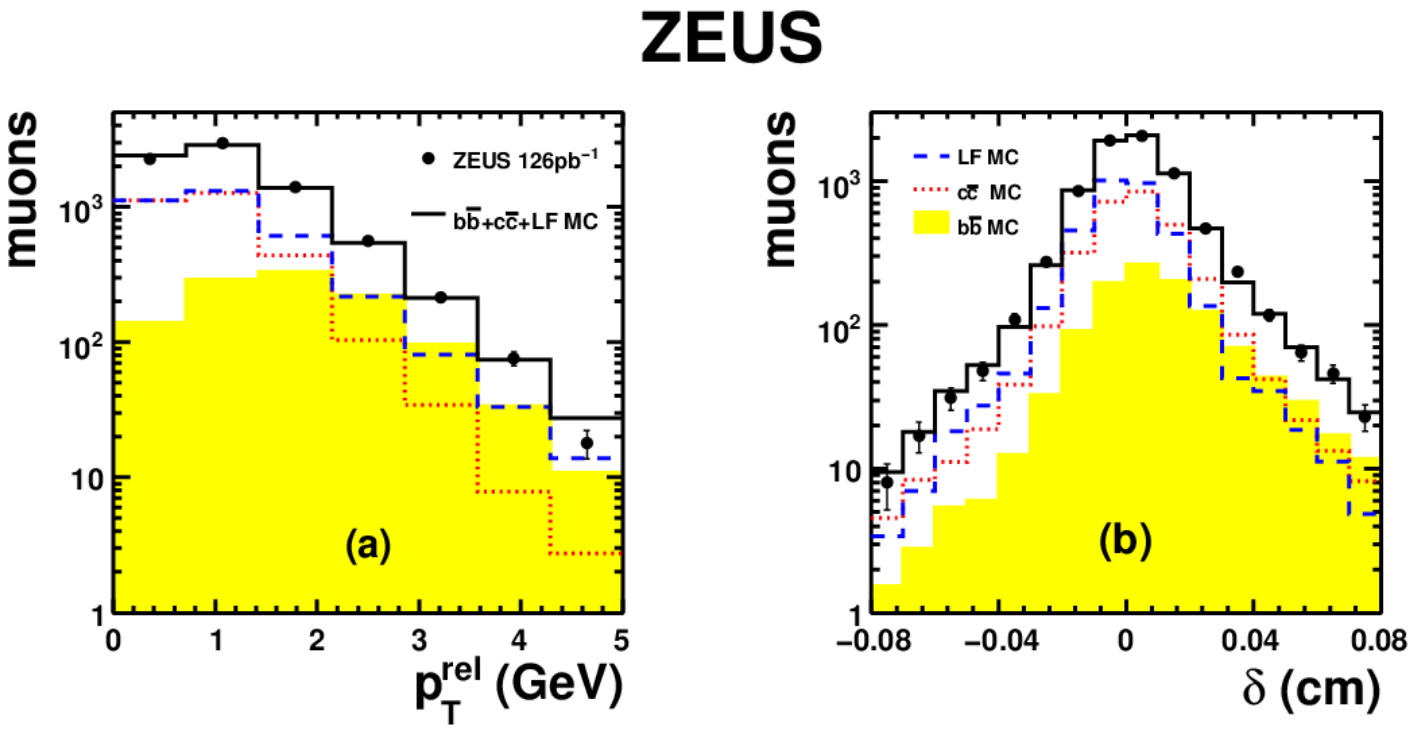
b in photoproduction using muons

- p_T^{rel}

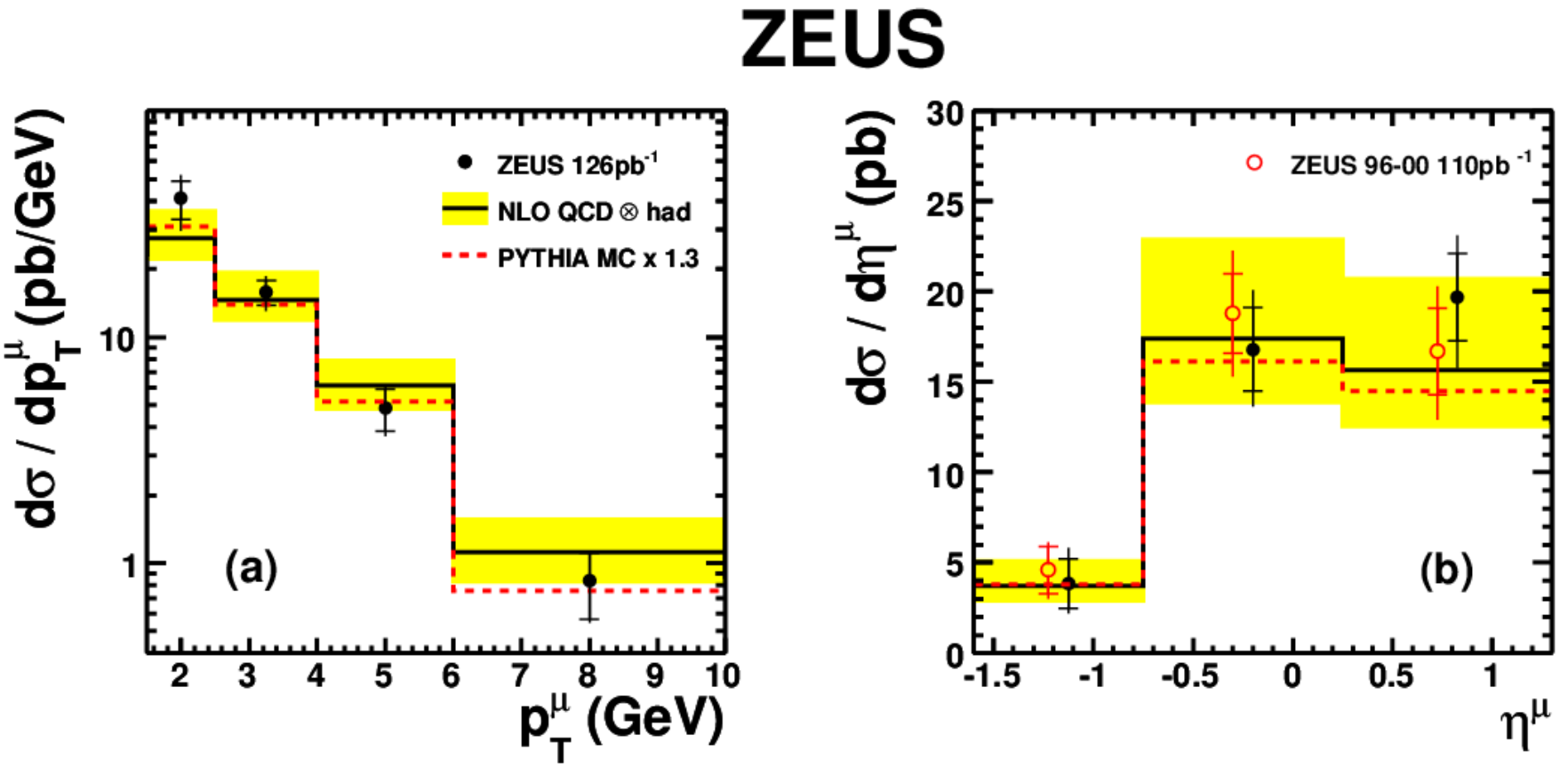


- Impact parameter





b in photoproduction using muons



$p_T^\mu > 1.5$ GeV

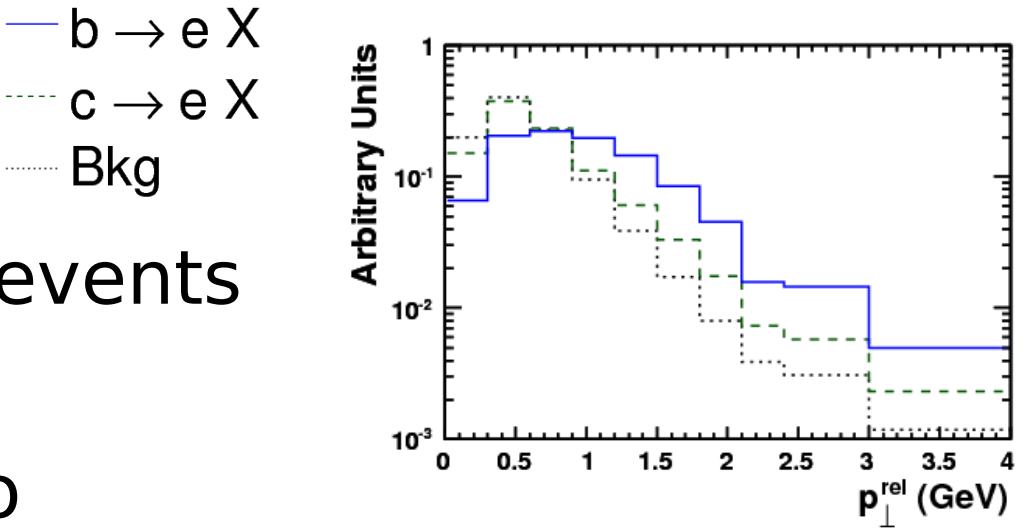
Good agreement between HERA I and HERA II cross-sections

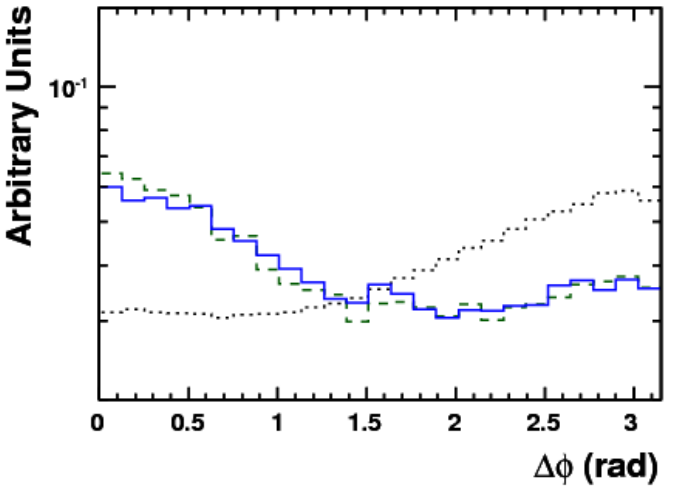
$p_T^\mu > 2.5$ GeV

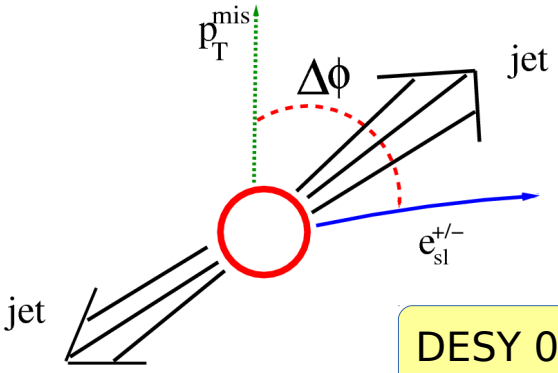
ZEUS DESY 08-056
b & c with electrons

b & c in photoproduction using electrons

- HERA I data
  - 120 pb^{-1} (1996-2000)
- Dijet photoproduction events
  - $E_T^{jet} > 7(6)$ GeV
- Semileptonic decays to electrons ($p_T^e > 0.9$ GeV)
- Look for more variables to determine b and c quark fractions separately



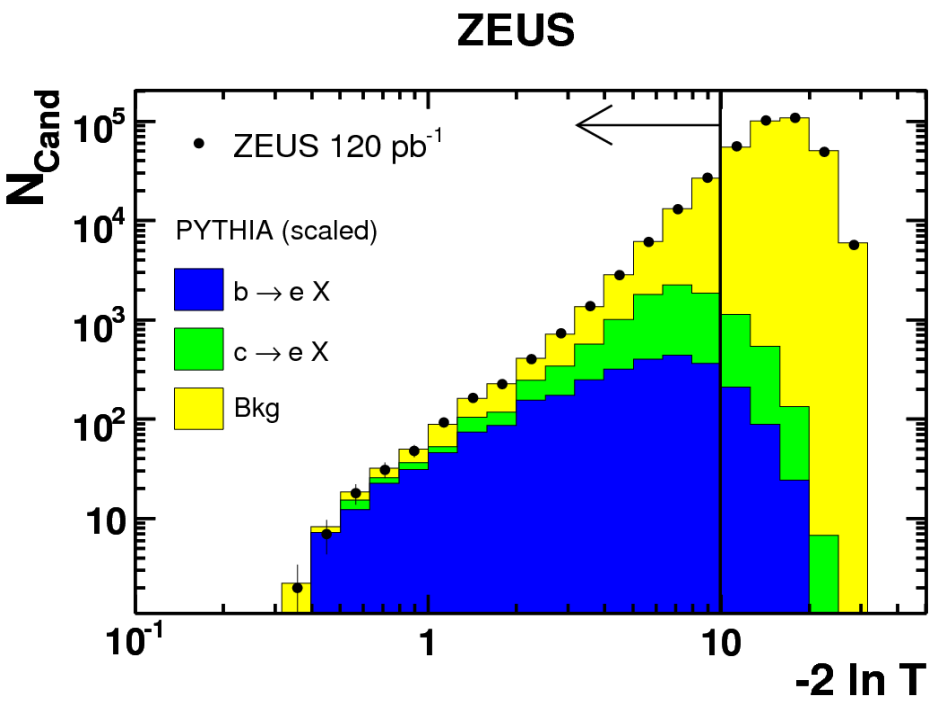




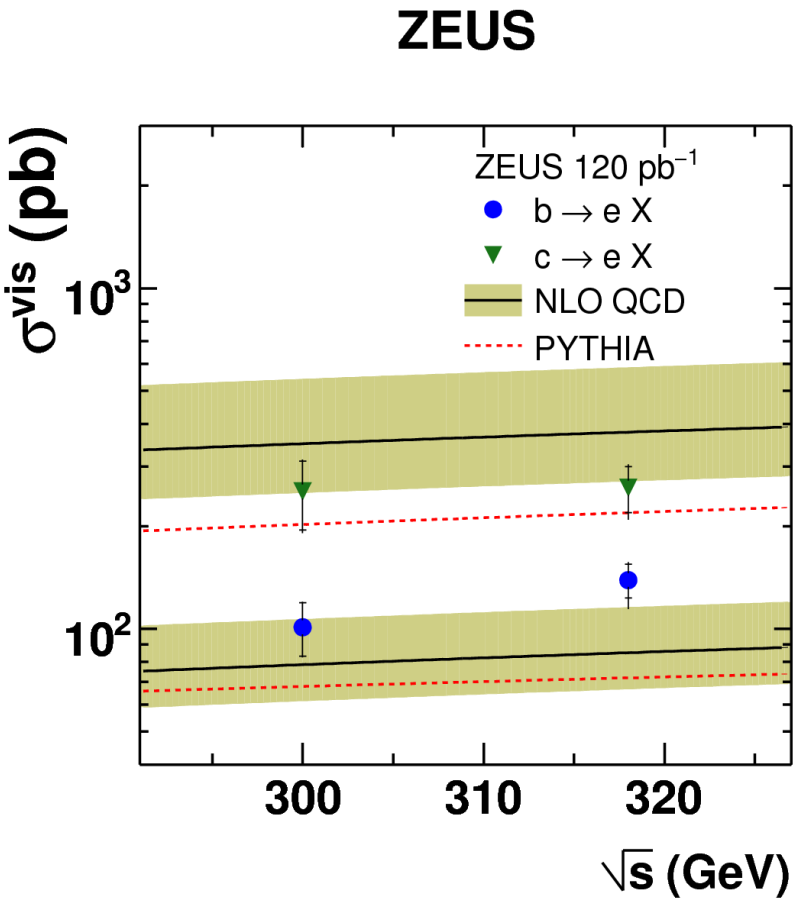
DESY 08-056, Phys. Rev. D 78 (2008) 072001

b & c in photoproduction using electrons

- Use a likelihood ratio method to separate b,c and light flavour



- Visible cross-section



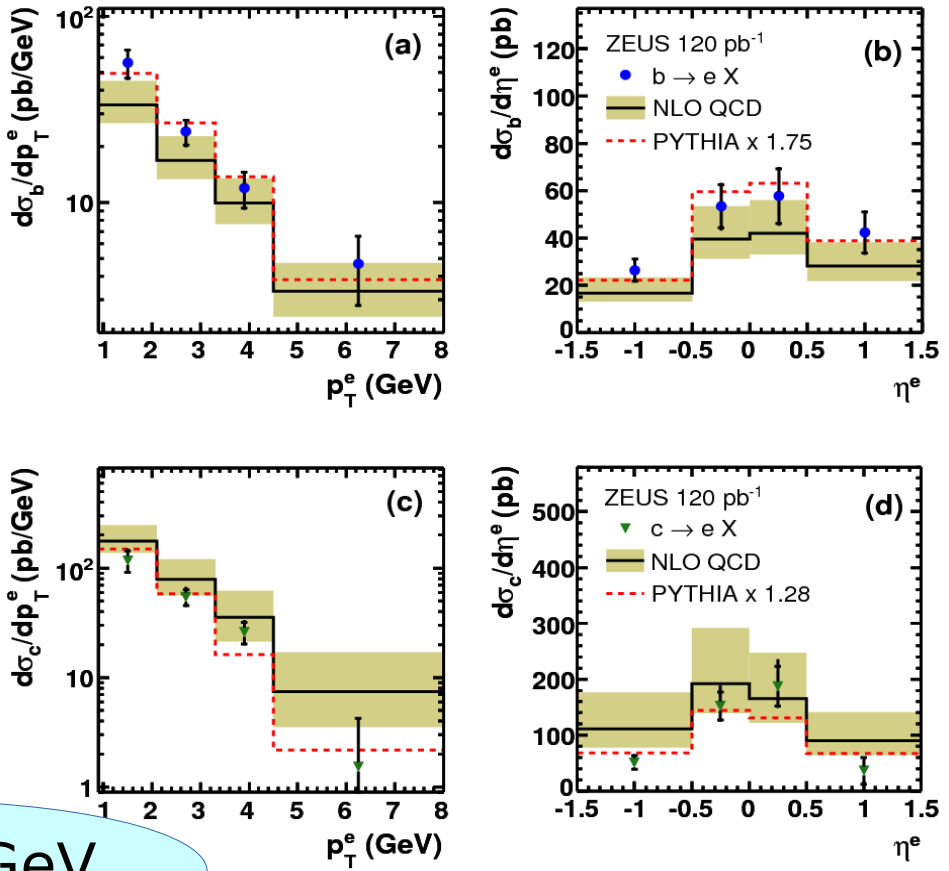
b & c in photoproduction using electrons

p_T^e

η^e

Beauty

Charm



$p_T^e > 0.9$ GeV

- LO Monte Carlo scale factors:
  - b x 1.75
  - c x 1.28
- NLO absolute predictions

H1 DESY 12-059
b & c with muons

Cuts & Calculations

- Cuts
- $-1.5 < \eta_{jet} < 2.5$
- $Q^2 < 2.5\ \text{GeV}^2$
- $0.2 < y < 0.8$
- $p_t^{\mu} > 2.5\ \text{GeV}$
- $-1.3 < \eta^{\mu} < 1.5$

- MC@NLO
  - $m_b = 4.75\ \text{GeV}$
  - $m_c = 1.5\ \text{GeV}$
  - $\mu_R = \sqrt{(m_Q^2 + p_T^2)}$
  - $\mu_F = 2\mu_R$

Systematic uncertainties

Systematic error source	Beauty $\Delta\sigma/\sigma[\%]$	Charm $\Delta\sigma/\sigma[\%]$
Trigger efficiency	4	4
Muon identification	4	4
Track finding efficiency	3	3
Luminosity	4	4
δ Resolution	3	2
Jet axis	4	2
Hadronic energy scale	3	5
Physics model	3	1
Fragmentation	3	4
Fake muon background	1	1
Total	10.5	10.4

Table 3: Summary of the systematic uncertainties of the beauty and charm cross sections.

Cross-sections

	$\sigma_{\text{vis}}(ep \to eb\bar{b}X \to ejj\mu X')$ [pb]	$\sigma_{\text{vis}}(ep \to ec\bar{c}X \to ejj\mu X')$ [pb]
H1 Data	43.3 ± 2.1 (stat.) ± 4.5 (sys.)	81.3 ± 4.3 (stat.) ± 8.5 (sys.)
PYTHIA	35.3	94.3
CASCADE	29.0	76.8
HERWIG	20.6	58.5
MC@NLO	$33.4^{+7.1}_{-9.2}$	$58.6^{+29.5}_{-11.2}$

Table 4: Total visible measured beauty and charm cross sections along with their statistical and systematic errors. The total predictions from PYTHIA, CASCADE, HERWIG, and MC@NLO are also shown. The MC@NLO predictions are given with their theoretical uncertainties.

ZEUS DESY 11-067
b & c inclusive

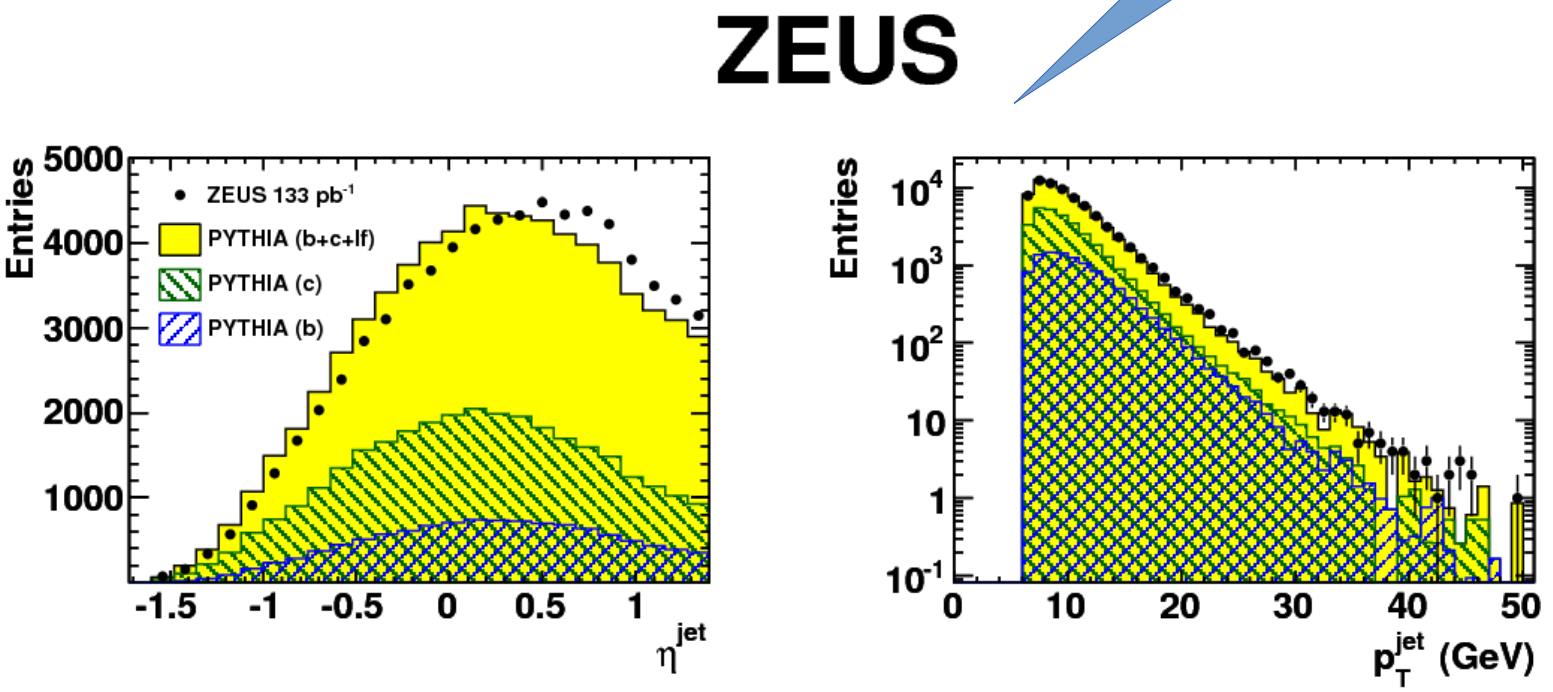
b & c in photoproduction inclusive analysis

- Data and MC samples
  - 2005 $e^{-}p$ data – 133 pb^{-1}
  - Monte Carlo (MC):
    - b, c samples (high statistics)
      - PYTHIA with CTEQ5L + GRV-G LO
      - m_b = 4.75 GeV, m_c = 1.5 GeV
      - Generate direct, resolved and excitation samples
    - Light flavour (lf) sample (1x data)
      - PYTHIA with CTEQ4L + GRV-G LO

Event selection

- No scattered electron
- $0.2 < y < 0.8$
- Two highest p_T jets
  - $|\eta| < 2.5$, $p_T > 7(6)$ GeV

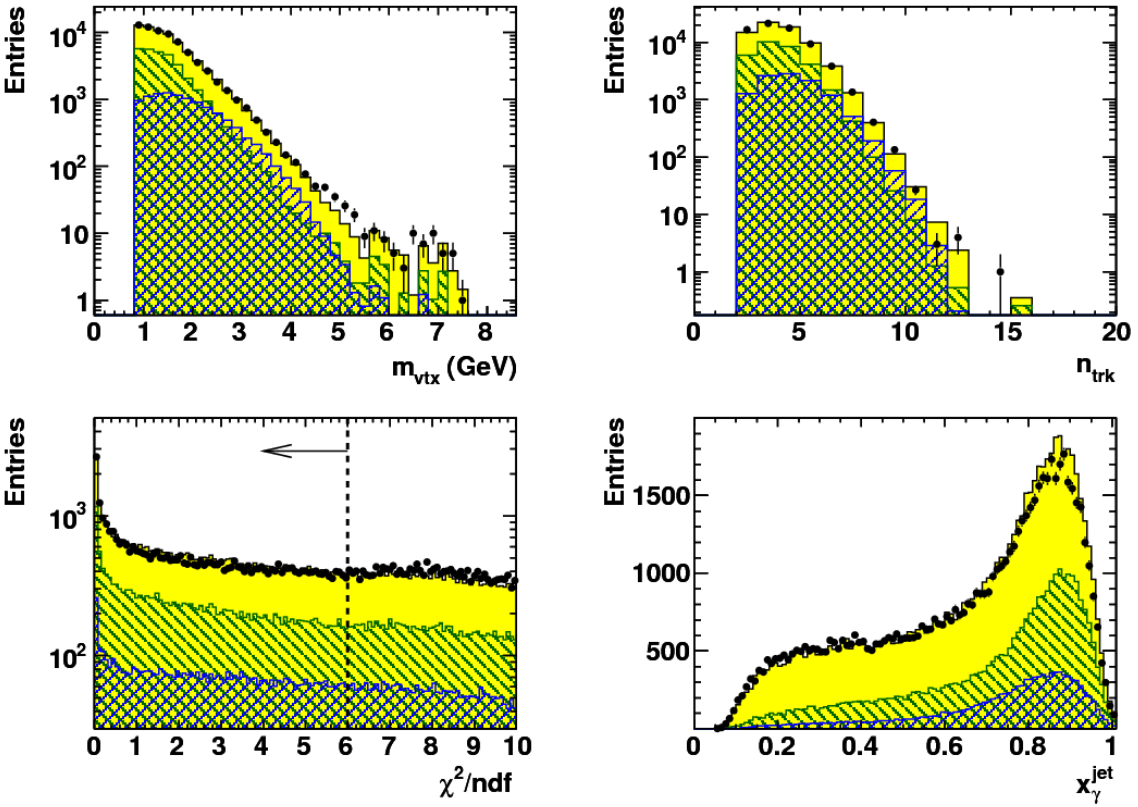
Secondary vertex with |significance| > 3 required



universitätbonn

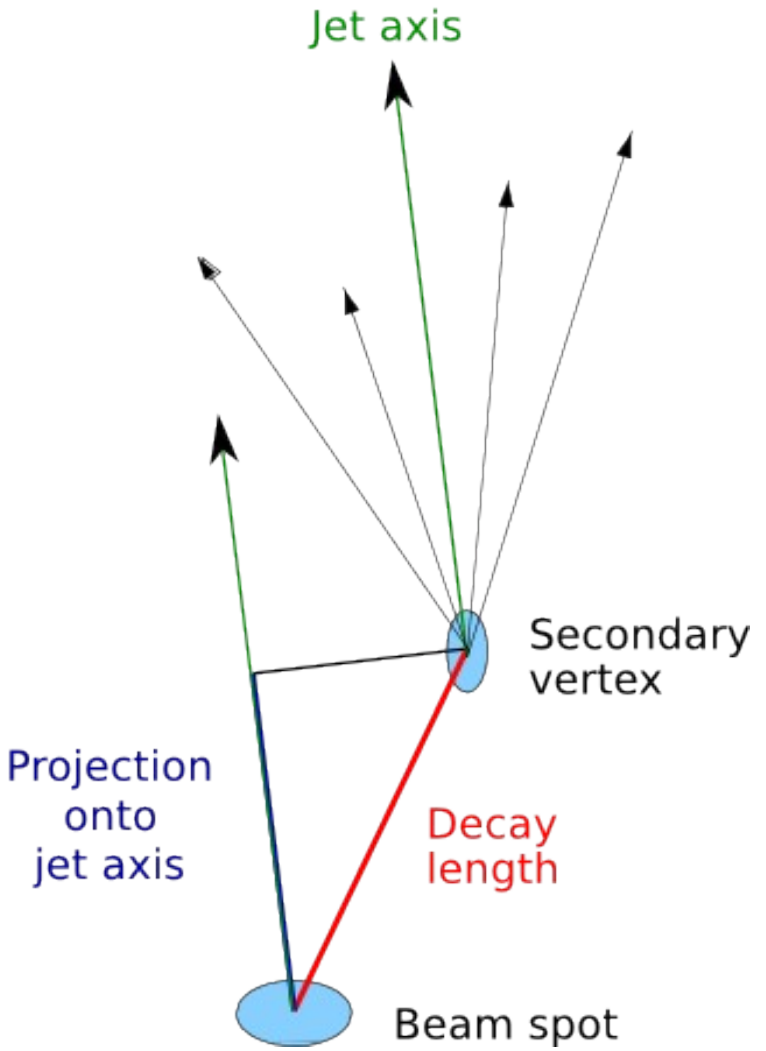
Control distributions

- Jets with associated secondary vertices used for cross-section
  - $-1.6 < \eta < 1.4$
  - $|S| > 3$
  - 70 433 jets remain



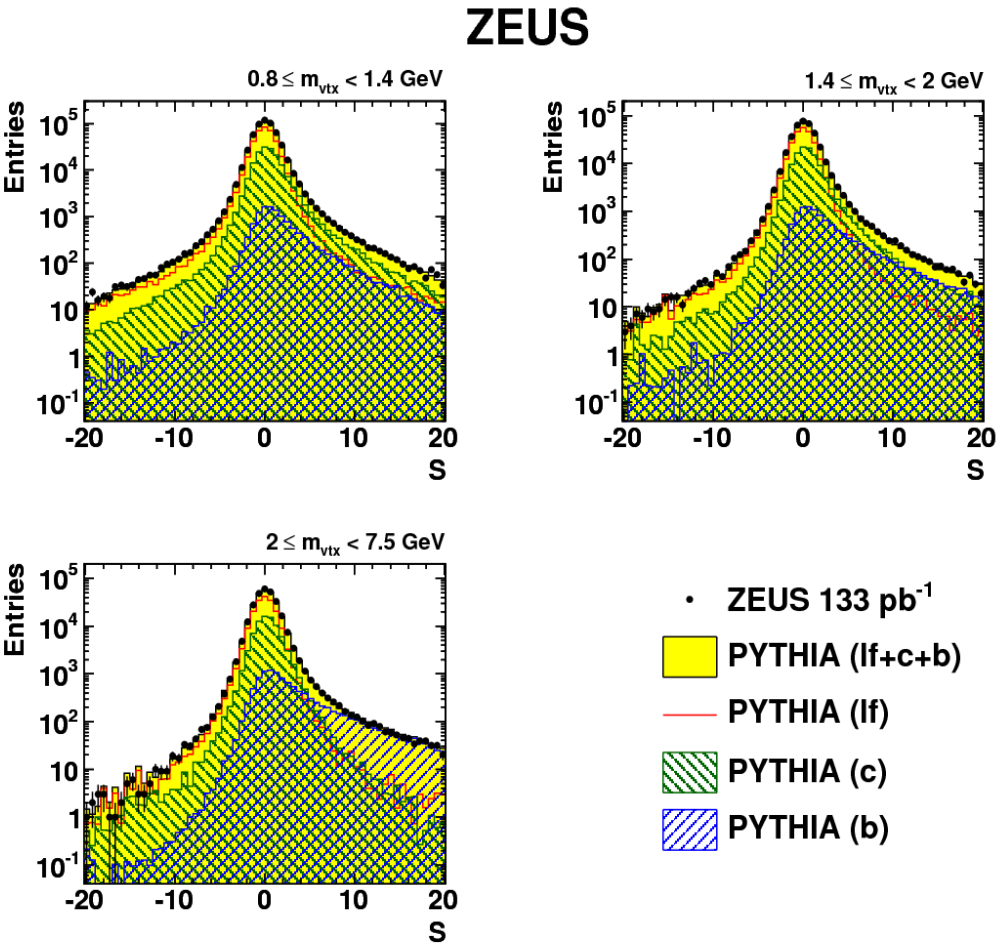
Secondary vertex

- Secondary vertex:
  - Find 3-D vertex
  - Project onto XY plane
  - Project onto jet axis
- Also calculate invariant mass of tracks associated to vertex, m_{vtx}



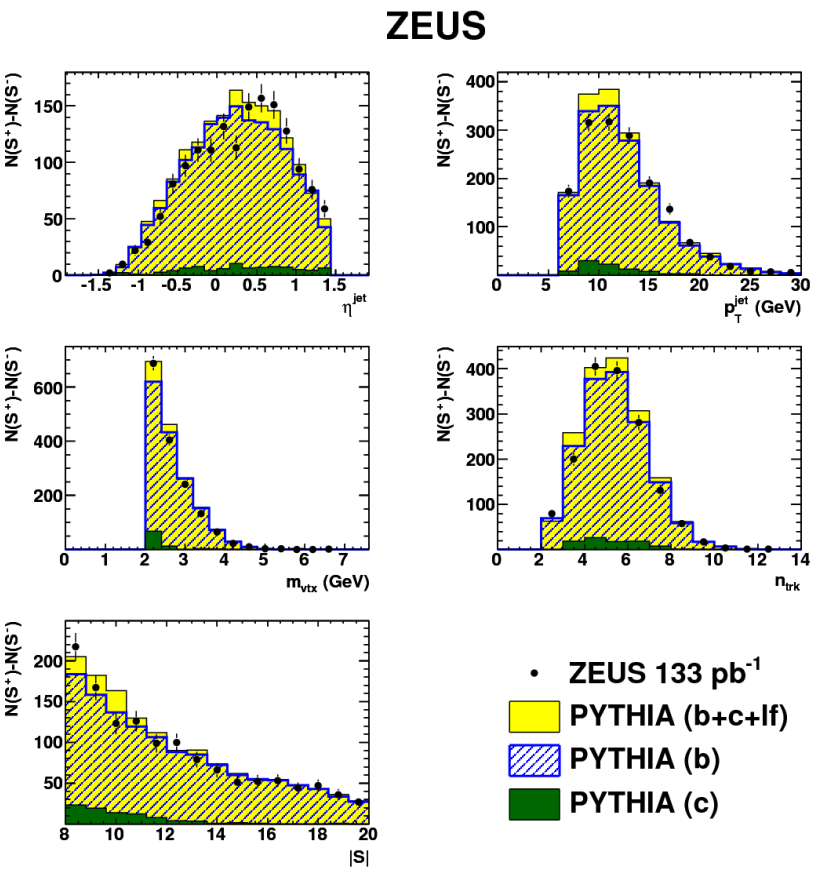
Significance distributions

- Use negative significance to check and tune MC resolution
- b, c, lf dominate in different mass bins and significance regions
- Subtract negative from positive significance to (almost) remove light flavour contribution



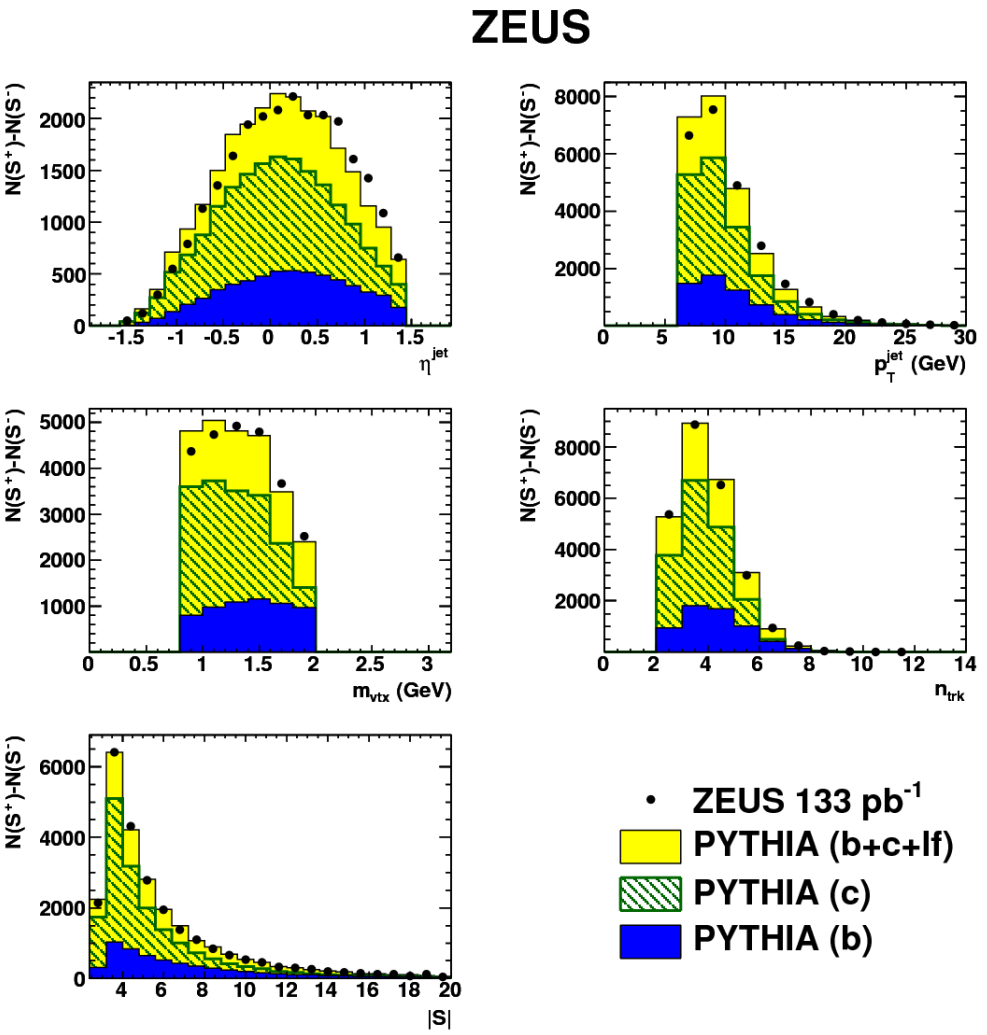
b-enriched sample

- As a cross-check, enrich b:
  - m_{vtx} > 2.0 GeV
  - |S| > 8
- Pure sample
  - >90%
- Good agreement with Monte Carlo



c-enriched sample

- As a cross-check, enrich c:
  - $0.8 < m_{vtx} < 2.0$ GeV
- Sample purity
  - ~70%
- Good agreement with Monte Carlo
  - Ongoing studies to improve m_{vtx}



Systematic uncertainties

- Uncertainties for total cross-section

Parameter	Uncertainty (%)	
	b	c
Trigger efficiency	+4.2/-3.9	+4.5/-3.2
Jet energy scale	±0.6	±4.3
Tracking/Decay length	+6.0/-1.0	+1.2/-0.7
Jet reweighting	-5.6	-1.5
Charm mesons	-1.8	+0.6/-2.2
Fragmentation	+1.8/-2.1	+1.2/-1.3
Luminosity	±1.8	±1.8
Total	+7.8/-7.7	+6.7/-7.0

- No single dominant contribution

NLO QCD predictions

- Use FMNR program for predictions
  - $m_b = 4.75$ GeV, $m_c = 1.5$ GeV
  - $\mu_F = \mu_R = 0.5 \sqrt{(m_Q^2 + p_T^2)}$
- Vary masses and scales (by a factor of 2) to get theory uncertainty
- Dominant uncertainty comes from scale variation

ZEUS DESY 08-129
b with dimuons

H1 DESY 12-072
b with dielectrons

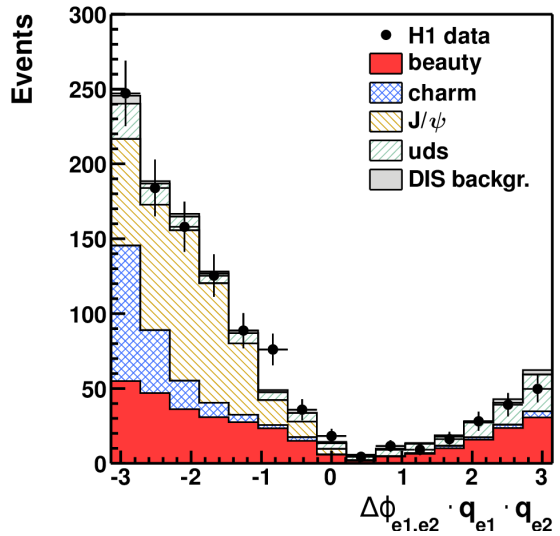
Selection cuts

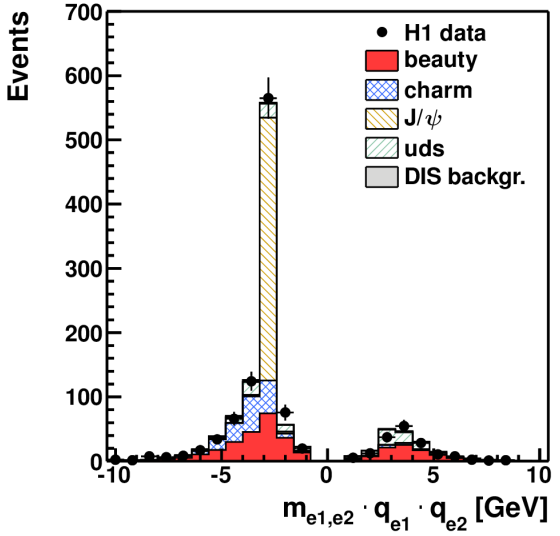
Overview of the Selection Cuts
Trigger selection
• track multiplicity cuts • 1 or 2 online identified electrons
Offline electron selection
• 2 electron candidates with: – $D_{\mathrm{ele}} > 0.825$, $R_{\mathrm{E,cone}} < 350\%$ – $P_T(e) > 1\,\mathrm{GeV}$, $20^\circ < \vartheta(e) < 140^\circ$ – verification of the L3 $P_T(e)$-thresholds 100 MeV above the $P_T(e)$-threshold of the respective subtrigger which recorded the event (see table 1 and text)
Background rejection and further cuts
Rejection of non ep-background: • good vertex, timing vetoes Rejection of DIS events: • no identified scattered beam positron • $0.05 < y_{\mathrm{h}} < 0.65$ Rejection of photon conversions and Dalitz decays: • $m_{e1,e2} > 1.2\,\mathrm{GeV}$ • no converted photon • $\mathrm{dca}_e < 0.2\,\mathrm{cm}$

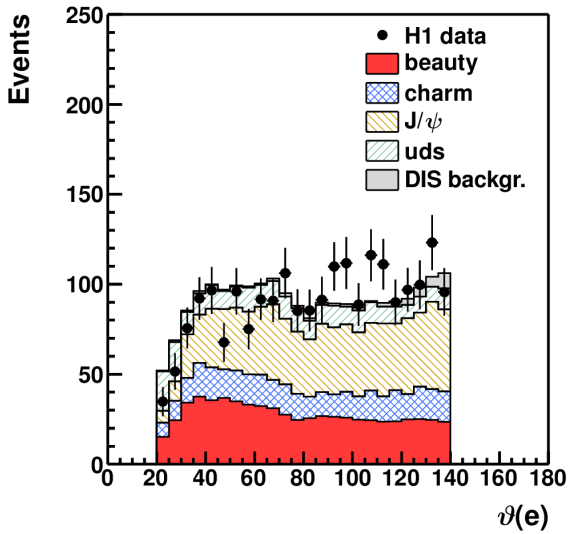
Table 2: Overview of the online and offline selection cuts. More details on the selection procedure can be found in [47].

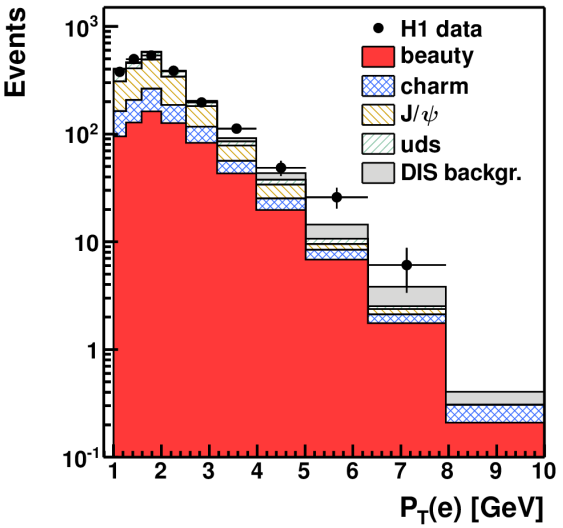
bb production

- Separate into categories









bb production