Heavy Flavour Photoproduction Measurements at HERA

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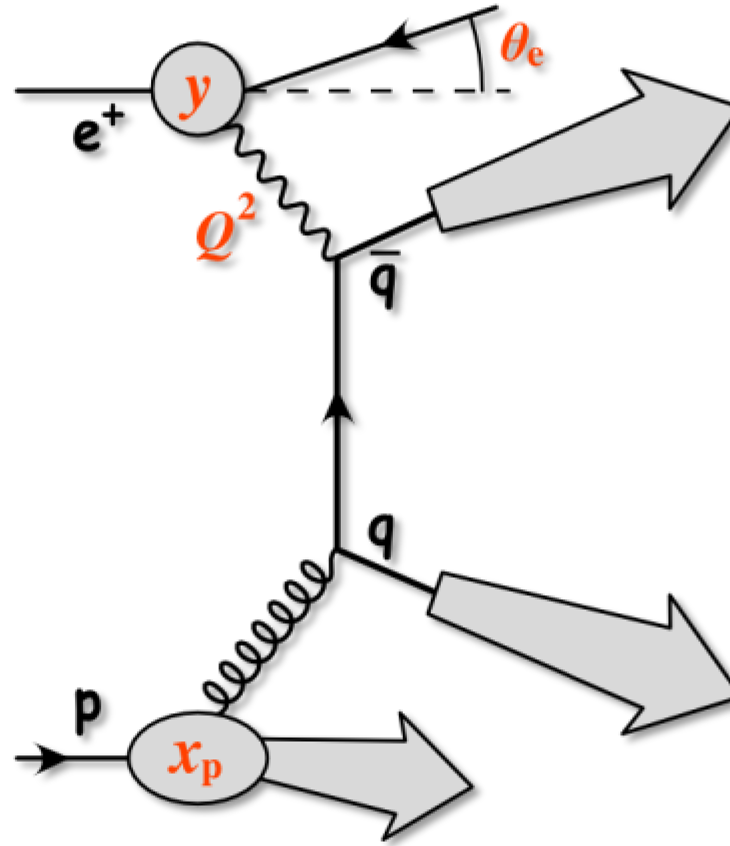
on behalf of the

H1 and ZEUS collaborations

Hadron Structure

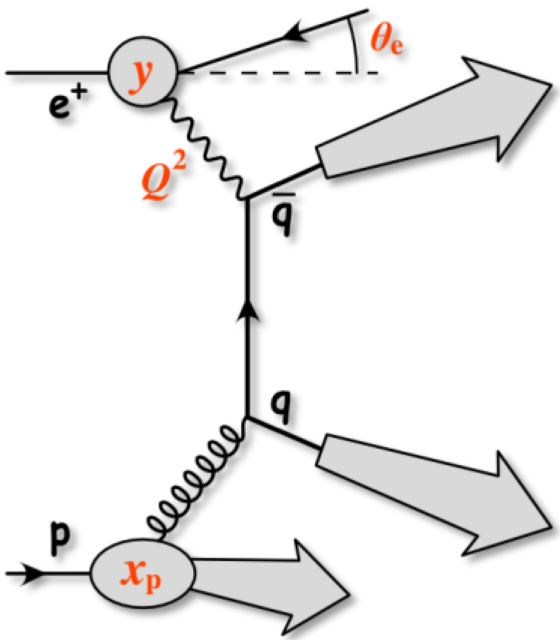
1 July 2013

- $e^{\pm}p$ scattering at $\sqrt{s} = 320$ GeV
- charm and beauty predominantly produced via boson–gluon fusion
- test pQCD
  - multiple hard scales involved: $Q^2, p_{\mathrm{T}}, m_{\mathrm{q}}$
- probe proton structure
- measure fragmentation fractions



E_{p} = 920 GeV
E_{e} = 27.5 GeV

Photoproduction at HERA



- photoproduction (PhP)

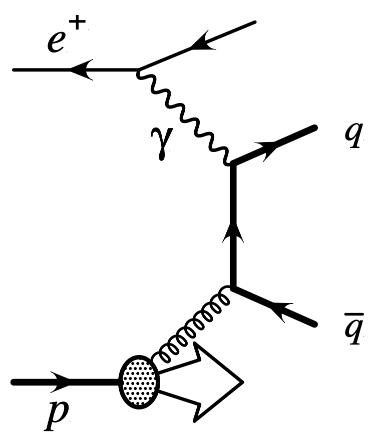
$$Q^2 \approx 0$$

  - γp scattering with quasi-real γ
  - $e^{\pm}$ escapes at small θ_e

- deep inelastic scattering

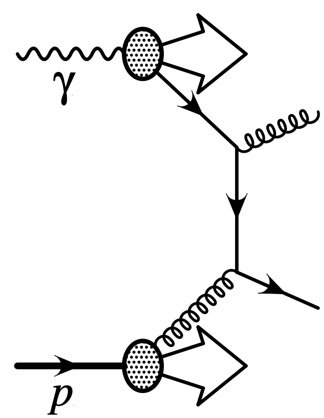
  → talk on recent results by A. Geiser

point-like photon



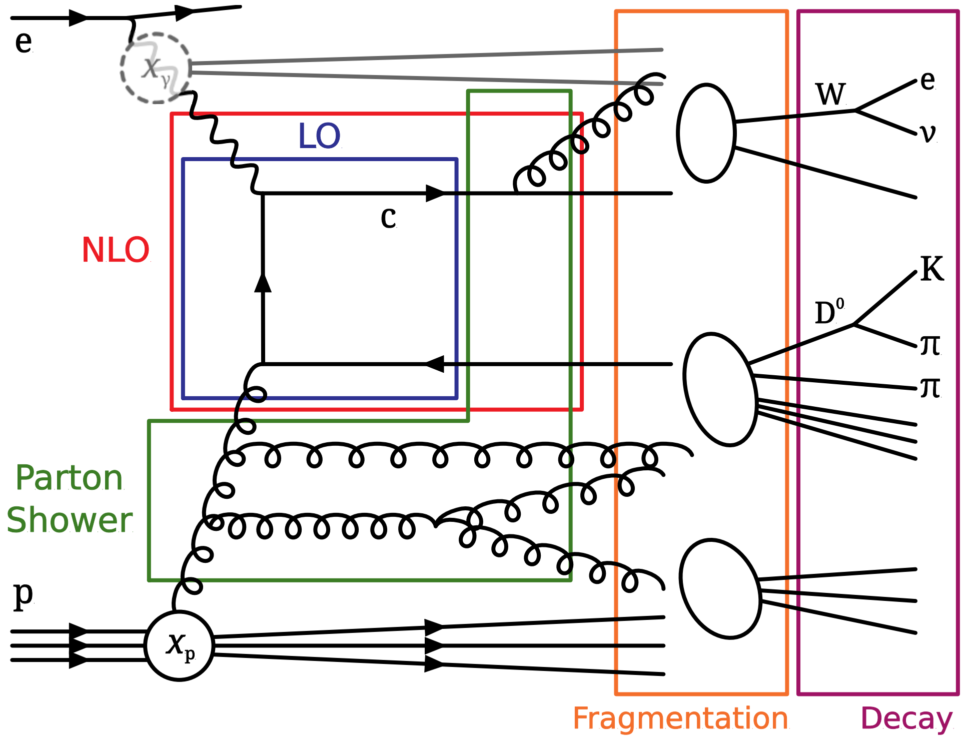
photon–gluon fusion

hadron-like photon



flavour excitation in photon

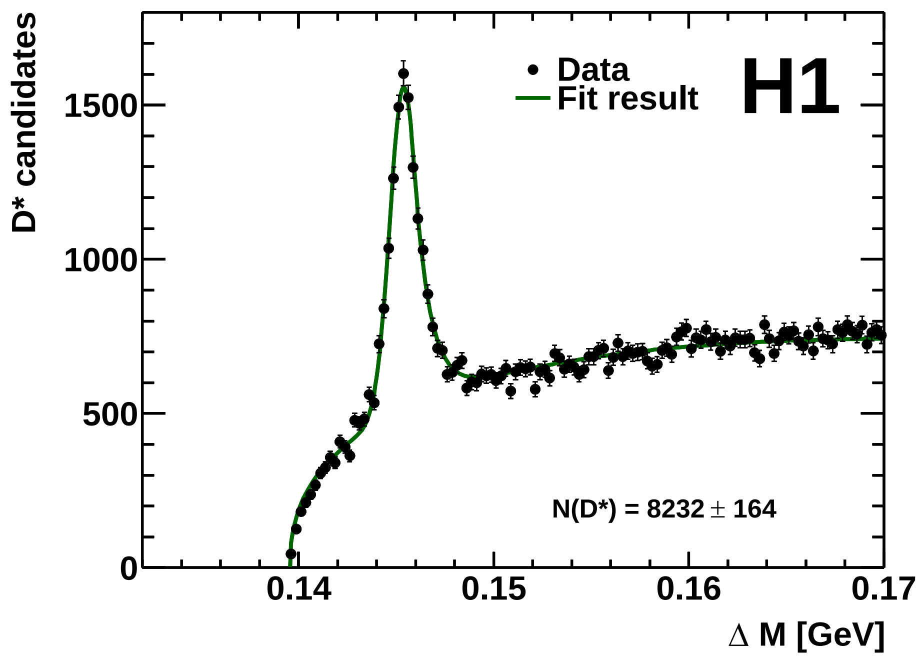
Theory & Experiment



- LO QCD + PS MC generators
  - PYTHIA
  - CASCADE
  - HERWIG
  - RAPGAP (DIS)
- NLO QCD calculation
  - FMNR
  - apply hadronisation corrections from LO MC to compare with data
- NLO QCD + PS MC generator
  - MC@NLO + HERWIG (H1)

Inclusive and Dijet Charm from D*

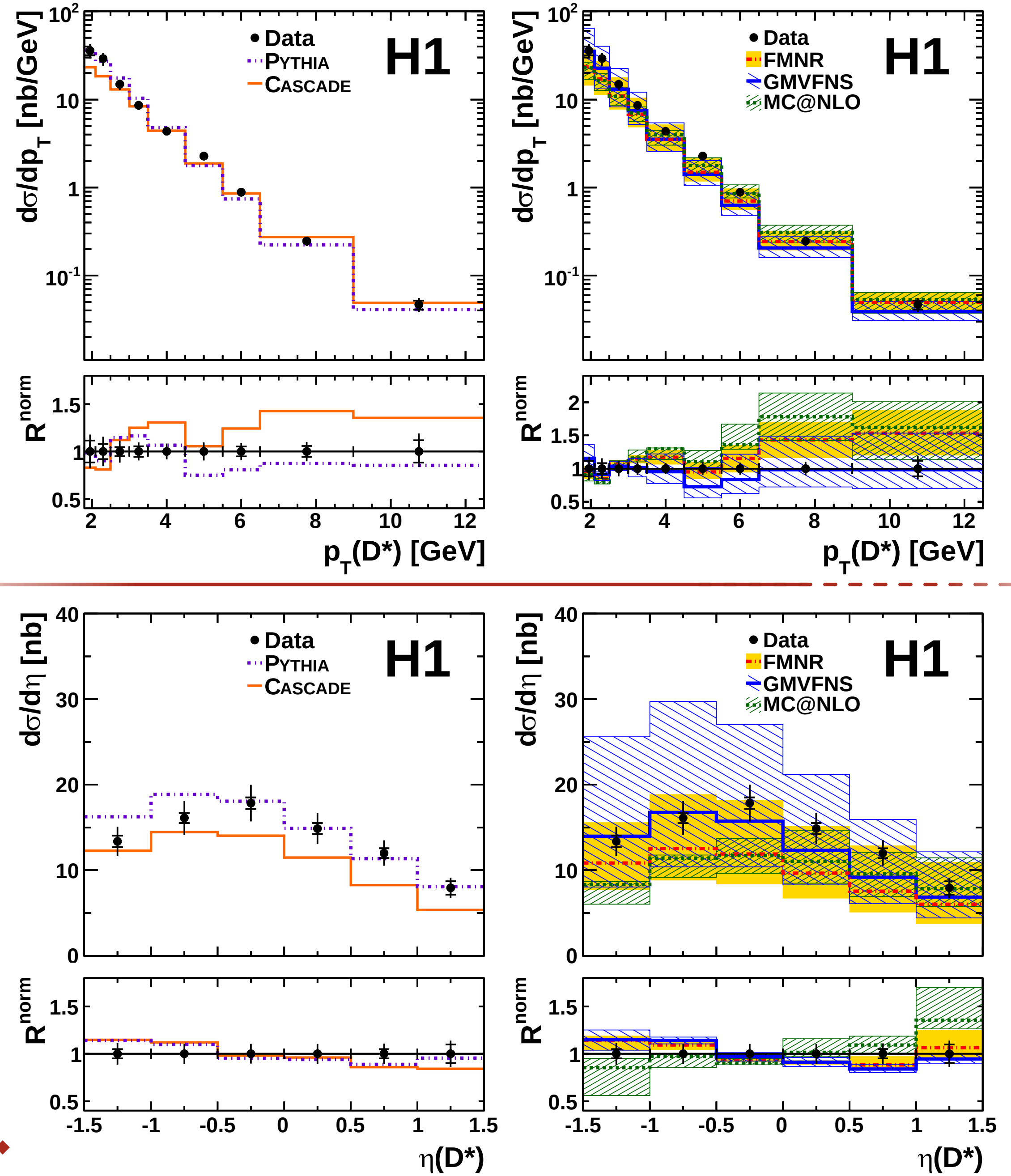
- c in (dijet) PhP events
- reconstruct $D^{*+} \to D^0 \pi^+_{\mathrm{slow}}$
  $\to K^- \pi^+ \pi^+_{\mathrm{slow}}$
  - $p_\mathrm{T}(\mathrm{D}^*) > 1.8\ \mathrm{GeV}$
- $0.1 \lesssim y \lesssim 0.8$
- $\mathcal{L} = 93\ \mathrm{pb}^{-1}$ (2006/07)



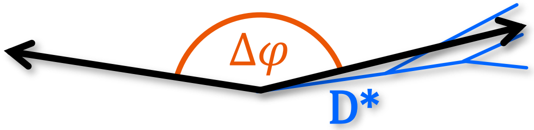
Eur. Phys. J. C72 (2012) 1995

D* Inclusive Cross-Sections

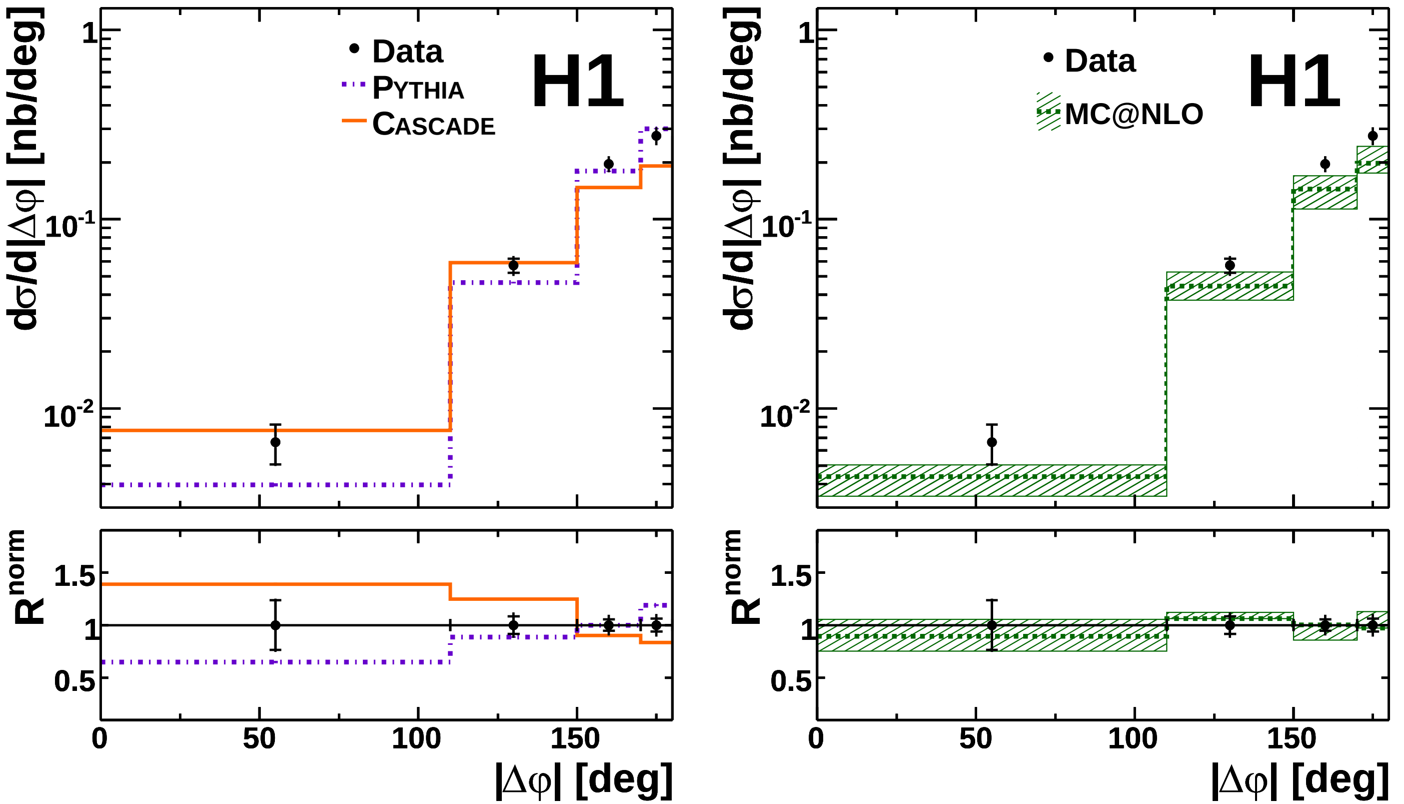
- very precise measurement
- PYTHIA: describes all distributions quite well
- MC@NLO: large normalisation uncertainty
- MC@NLO: undershoots data low $p_{\mathrm{T}}(\mathrm{D}^{*})$



D*-Tagged Dijet Correlations

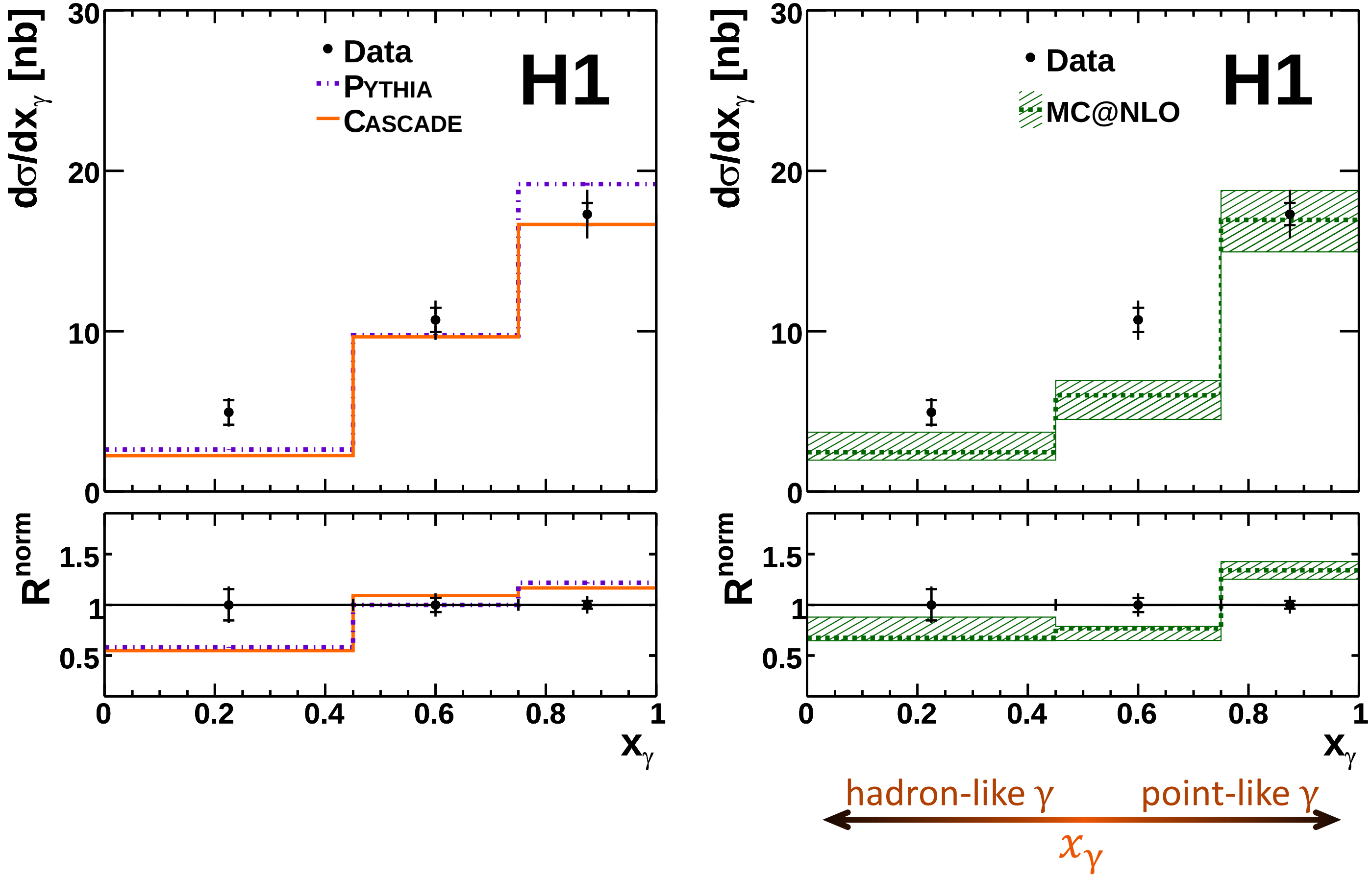


- use D* to tag charm jets
  - $p_T(D^*) > 2.1$ GeV, $p_T(\text{jet}) > 3.5$ GeV



- LO+PS: cannot model hard radiation well
- MC@NLO: good modelling

D*-Tagged Dijet Correlations

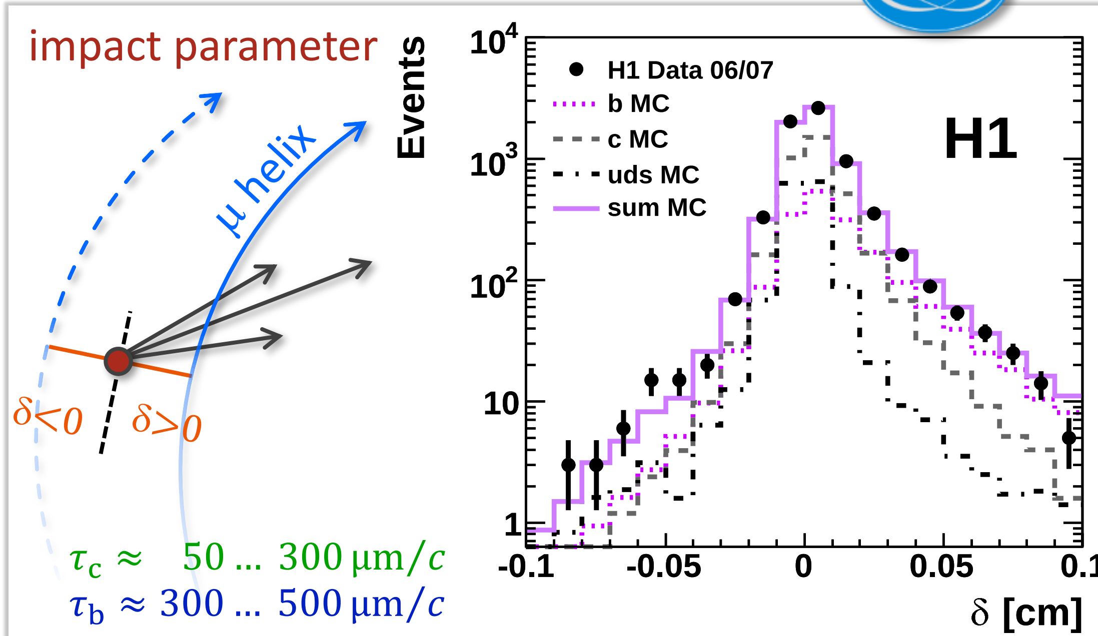


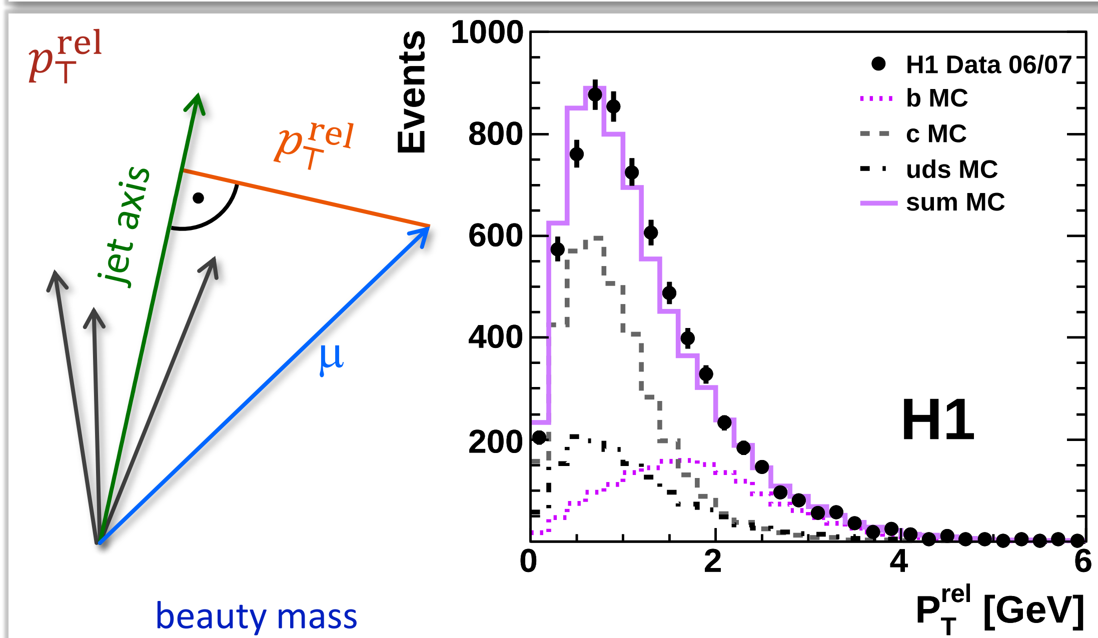
- LO+PS: reasonable modelling
- MC@NLO: underestimates hadron-like γ enriched

Heavy Flavour Photoproduction from Muons

- c and b in dijet PhP
- semi-leptonic decay to $\mu^{\pm}$
  - $p_{\mathrm{T}}^{\mu} > 2.5$ GeV
- ≥ 2 jets
  - $p_{\mathrm{T}}(\text{jet 1}) > 7$ GeV, $p_{\mathrm{T}}(\text{jet 2}) > 6$ GeV
- $0.2 < y < 0.8$
- $\mathcal{L} = 179\ \mathrm{pb}^{-1}$ (2006/07)

2D template fit

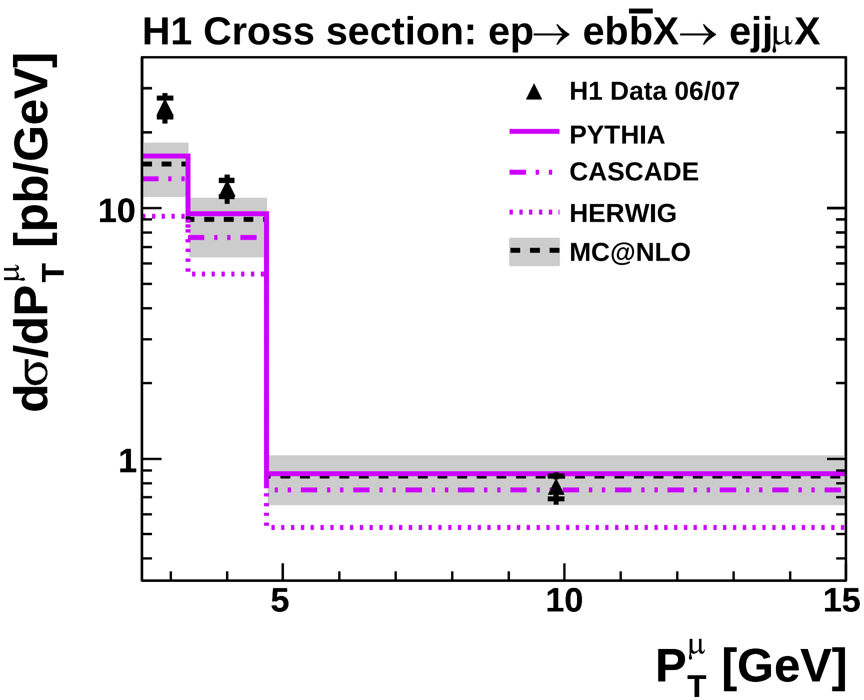




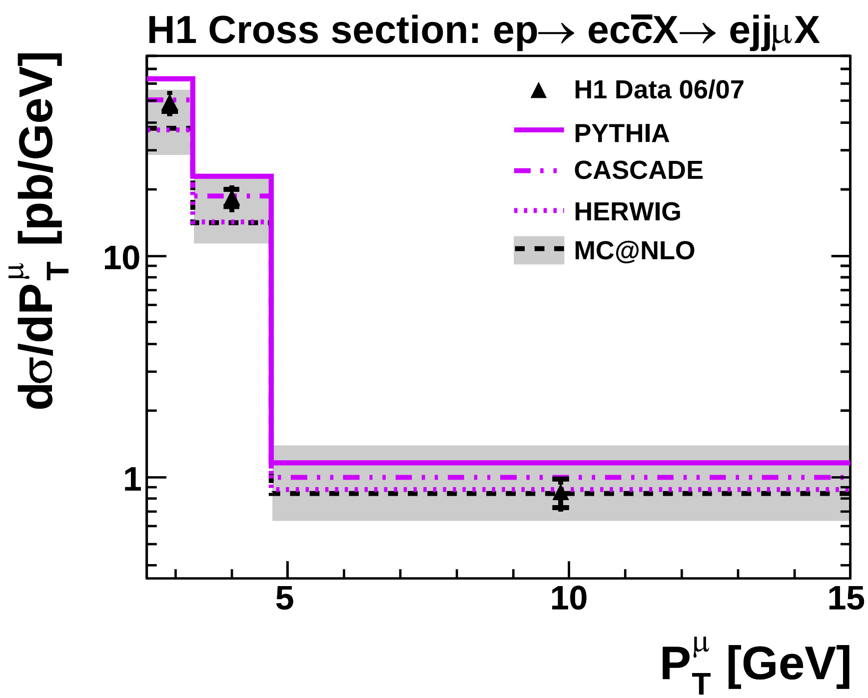
Eur. Phys. J. C72 (2012) 2047

Charm / Beauty Cross-Sections

beauty



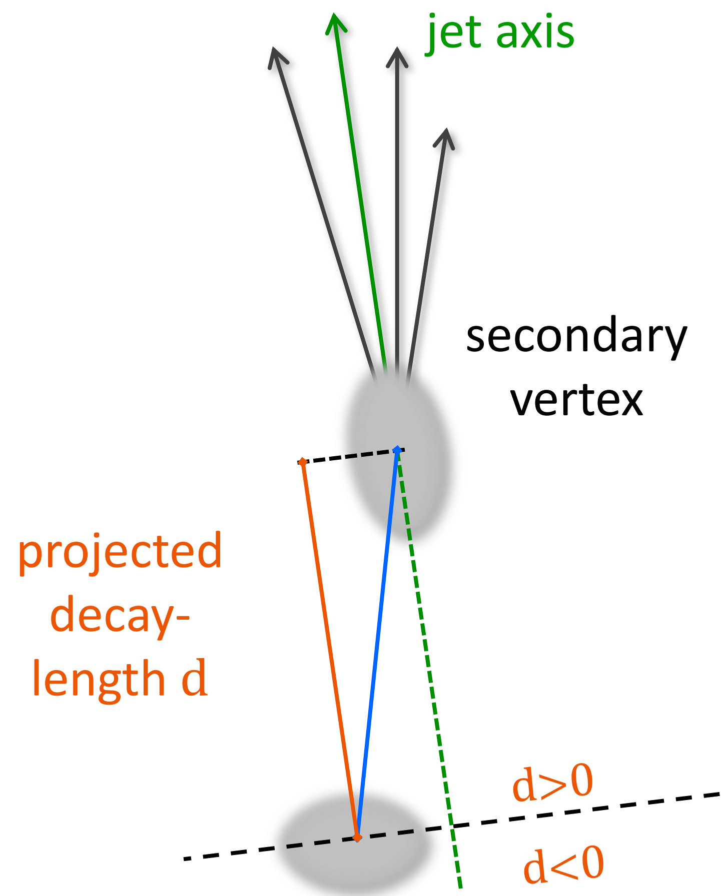
charm



- data more precise than predictions
- slight b data excess in 1st p_T^μ bin
- MC@NLO, CASCADE, HERWIG: (slightly) below data
- c well modelled

Heavy Quark Jets from Secondary Vertices

- c and b in dijet PhP events
- tag jets via secondary vertex
- ≥ 2 jets
  - $p_{\mathrm{T}}(\text{jet } 1) > 7 \text{ GeV}$, $p_{\mathrm{T}}(\text{jet } 2) > 6 \text{ GeV}$
- $0.2 < y < 0.8$
- $\mathcal{L} = 133 \text{ pb}^{-1}$ (2005)

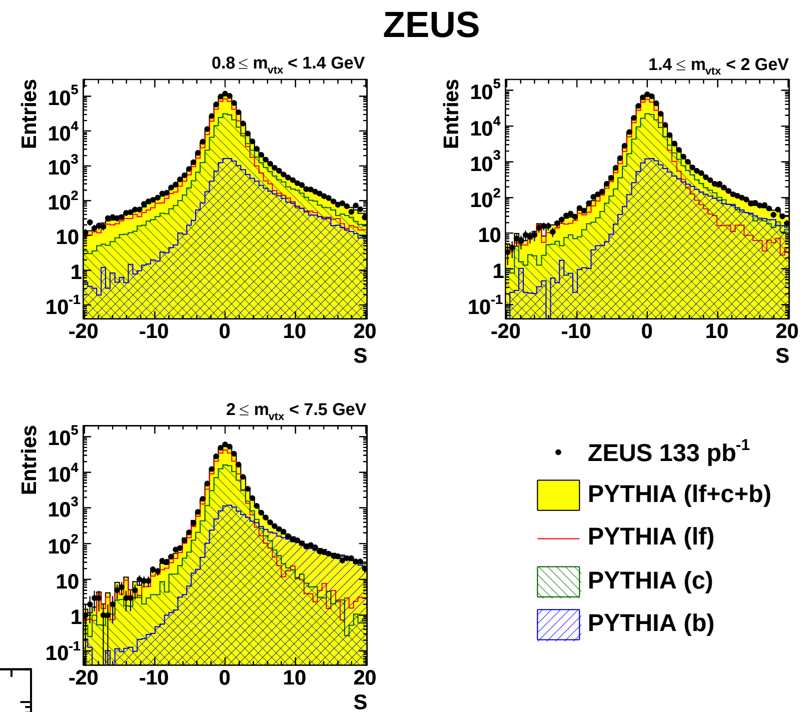


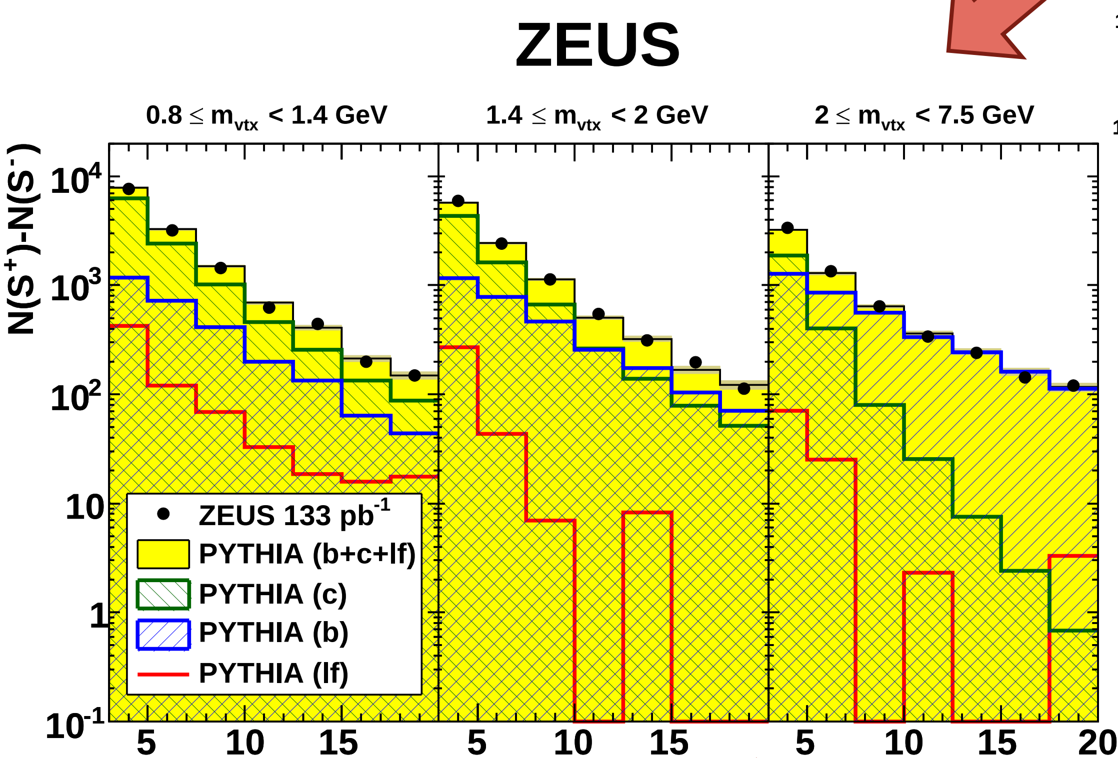
$$S = d/\delta d$$

Eur. Phys. J. C71 (2011) 1659

Signal Extraction

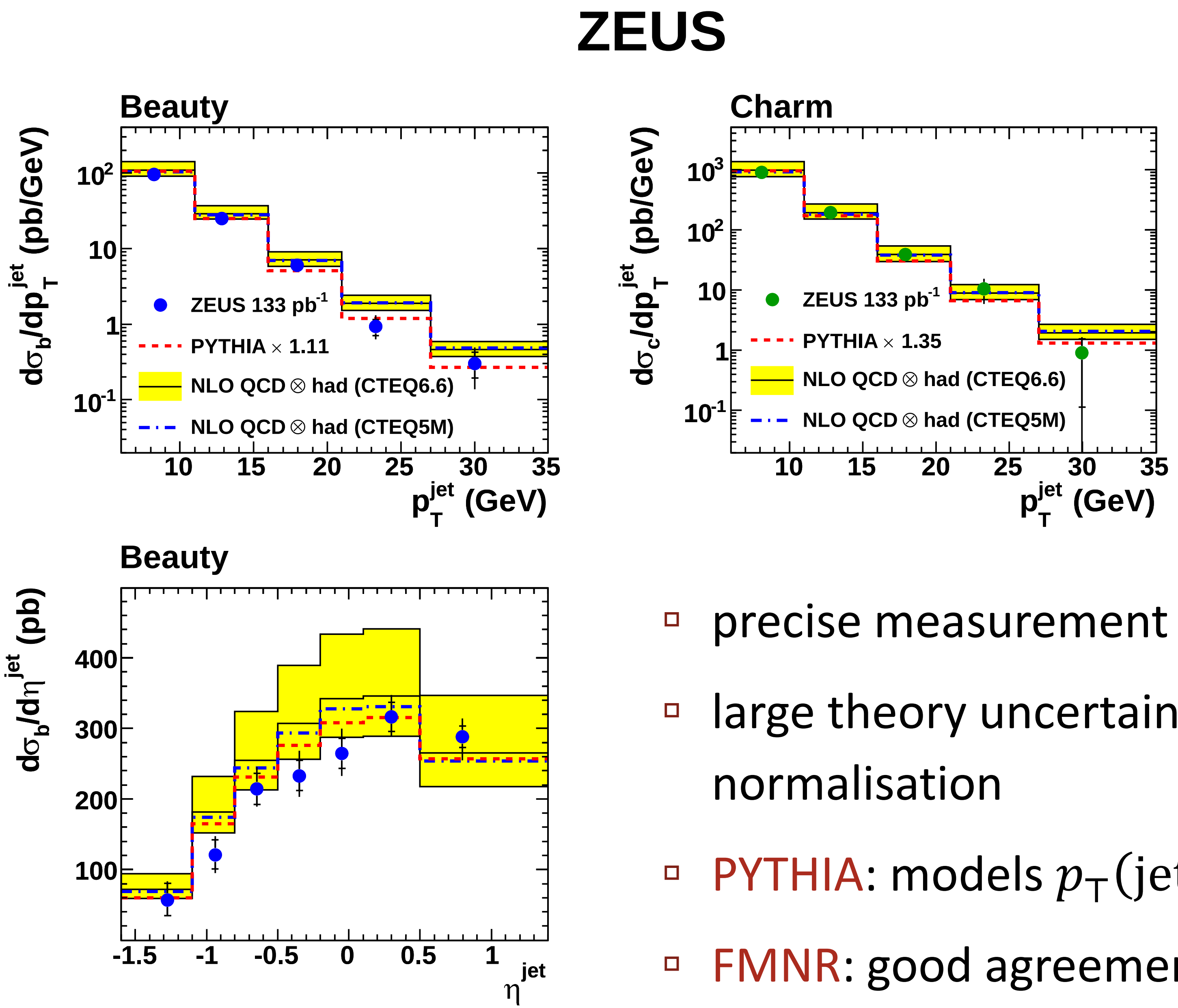
- subtract $N\{S < -3\}$ from $N\{S > 3\}$ to suppress symmetric uds
- fit b, c, and uds templates for $|S| \otimes m_{\mathrm{vtx}}$ to data





inclusive fit result

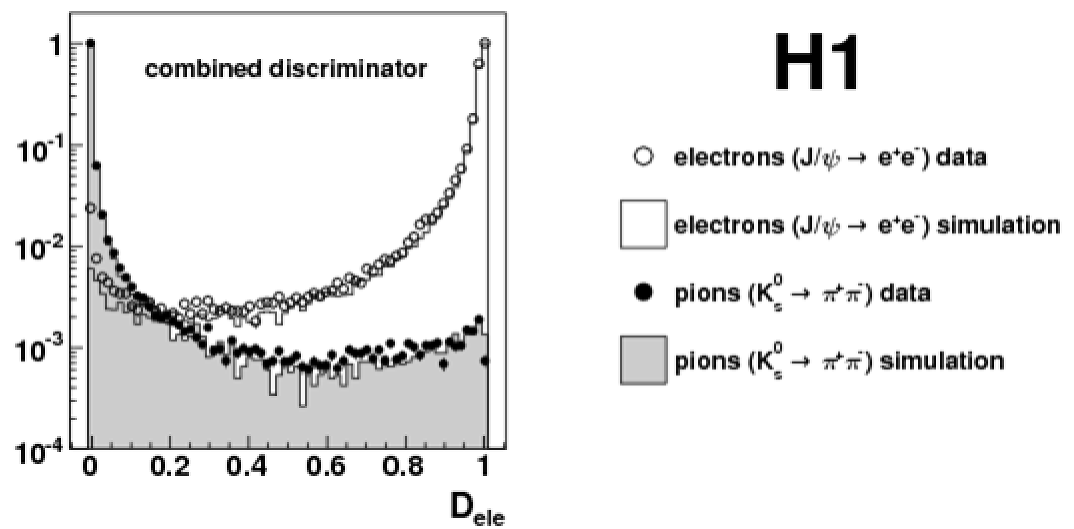
$$k_{\mathrm{c}} = 1.35$$
$$k_{\mathrm{b}} = 1.1$$



- precise measurement
- large theory uncertainty on normalisation
- PYTHIA: models p_T(jet) very well
- FMNR: good agreement for both PDFs

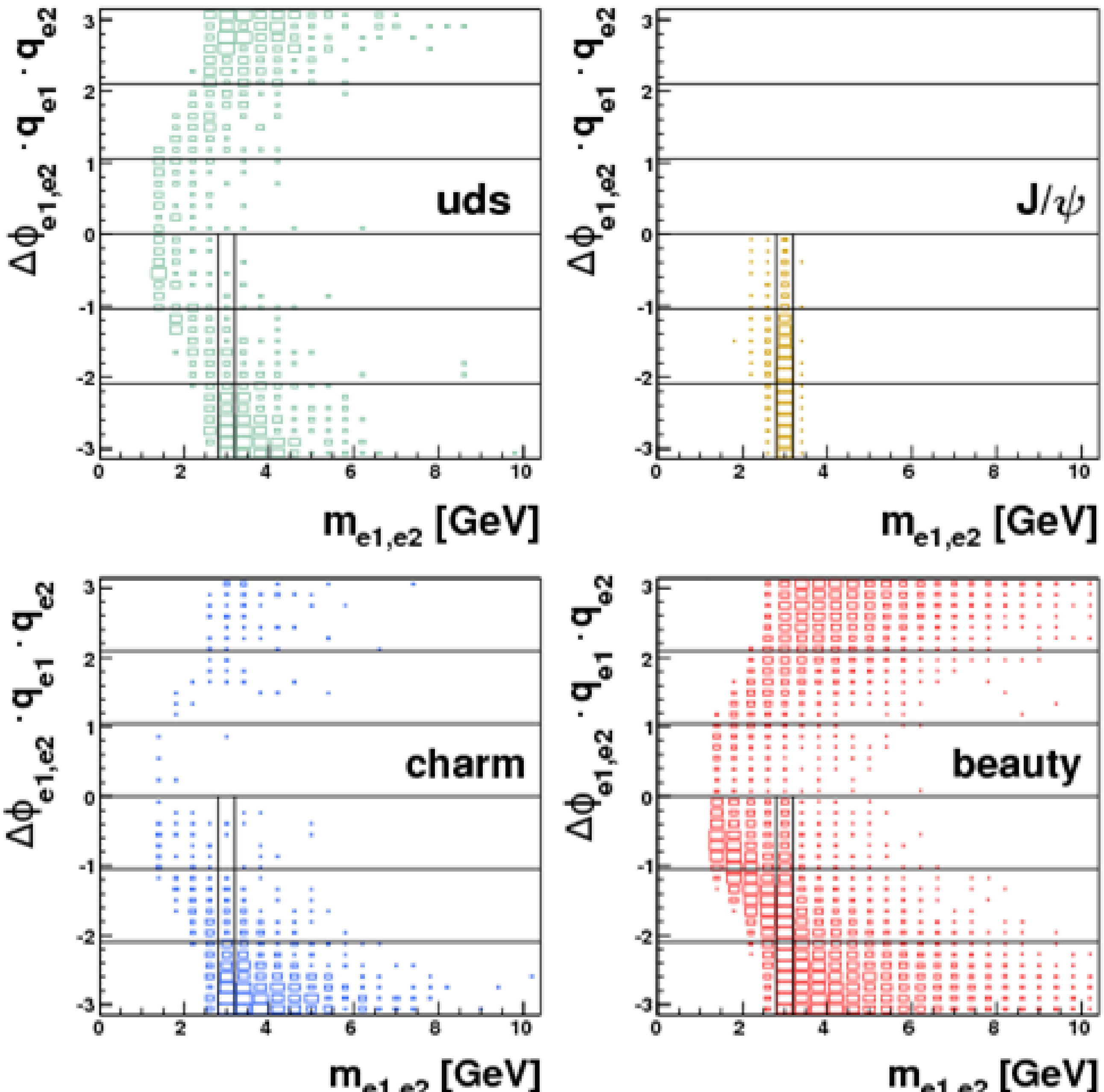
- probe b in PhP near $p_T^b = 0$
  - dominant scale m_b
- 2 semi-leptonic decays to $e^\pm$
  - $p_T^e > 1$ GeV (!)
- hemispheres
- $0.05 < y < 0.65$
- $\mathcal{L} = 48\ \text{pb}^{-1}$ (2007)

novel low-momentum electron identification

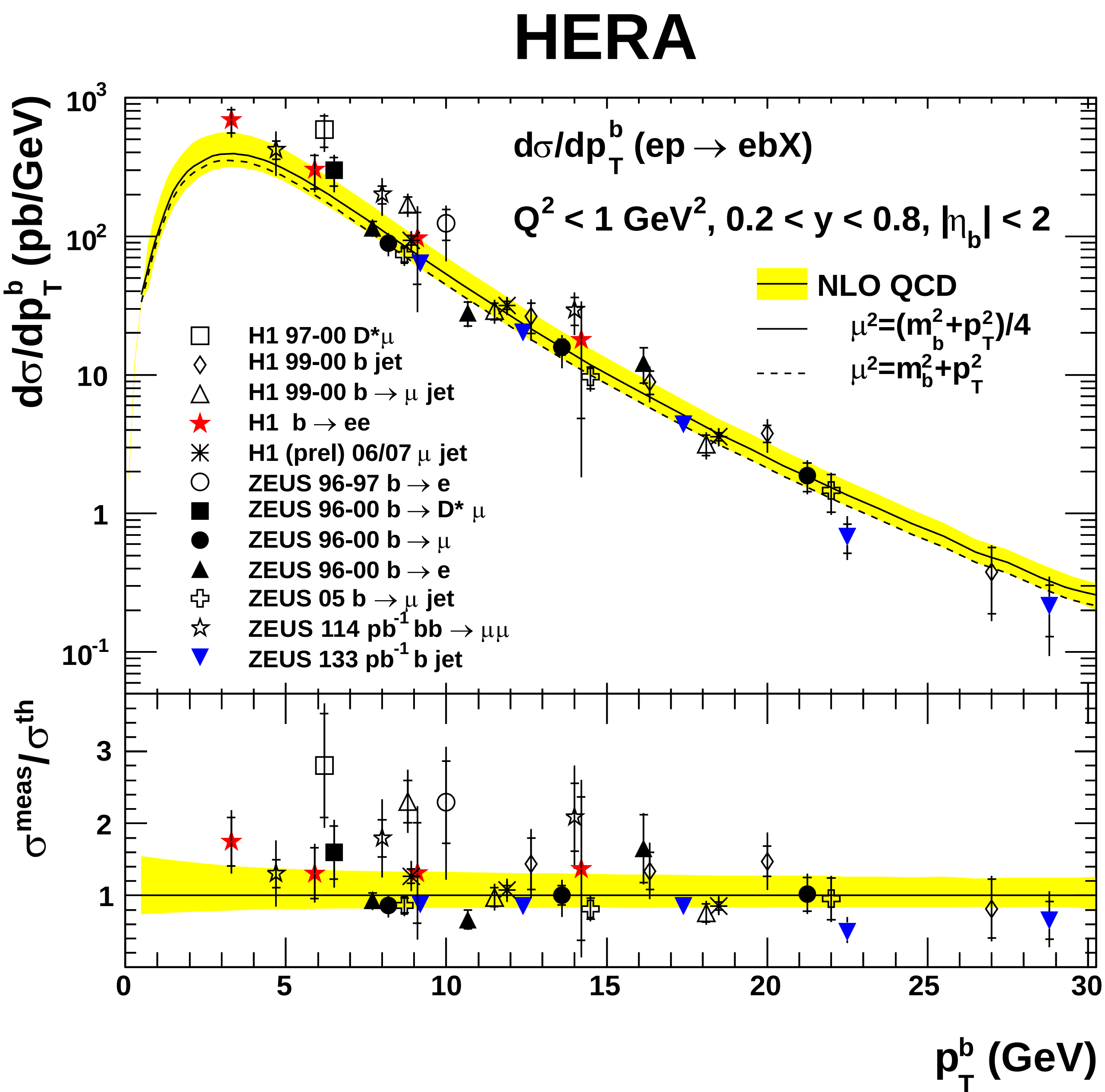


Eur. Phys. J. C72 (2012) 2148

Signal Extraction

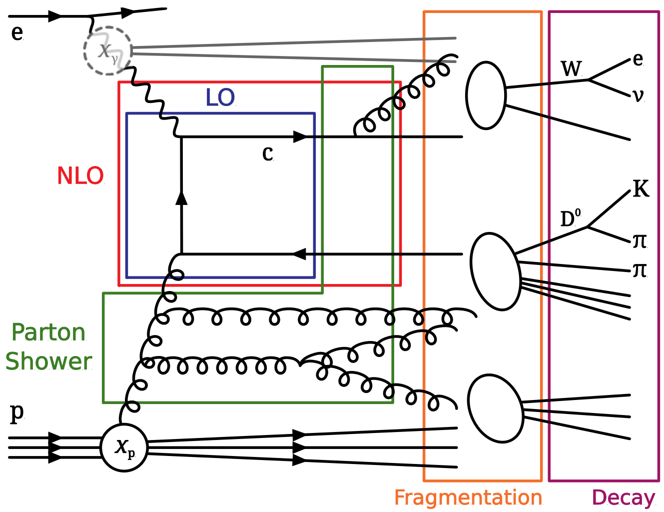


use $\Delta\phi_{ee}$, m_{ee}, charge for separation



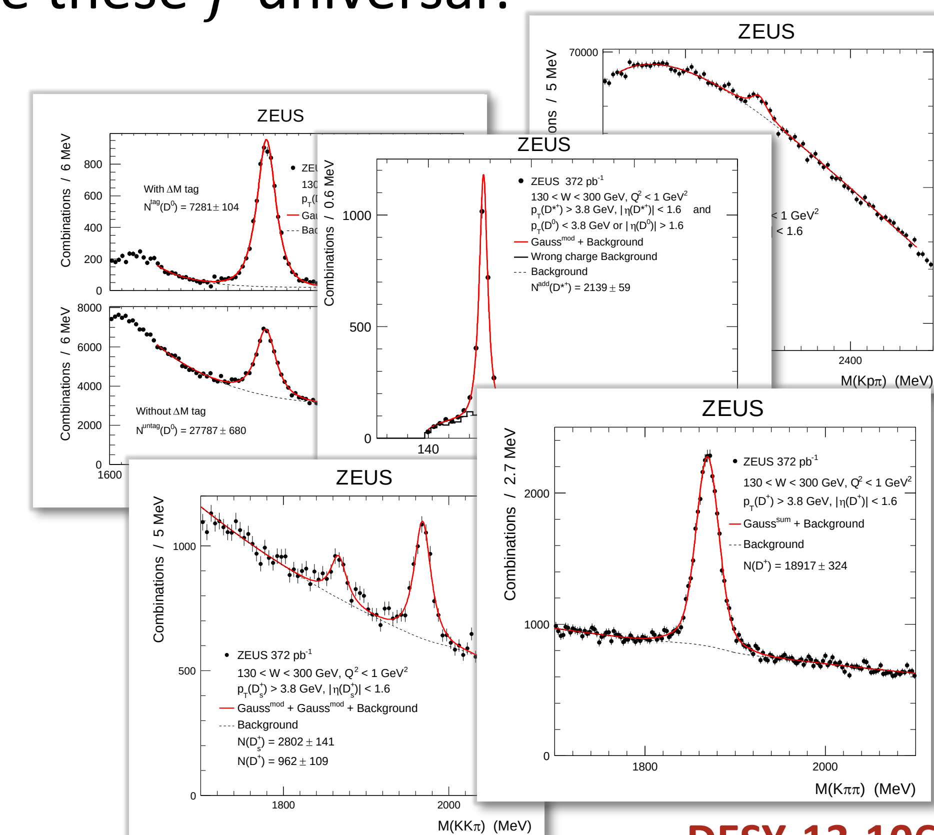
- b production probed at HERA over wide $p_{\mathrm{T}}^{\mathrm{b}}$ range
- measurements complement and confirm each other
- in general good agreement with FMNR prediction

Charm Fragmentation Fractions



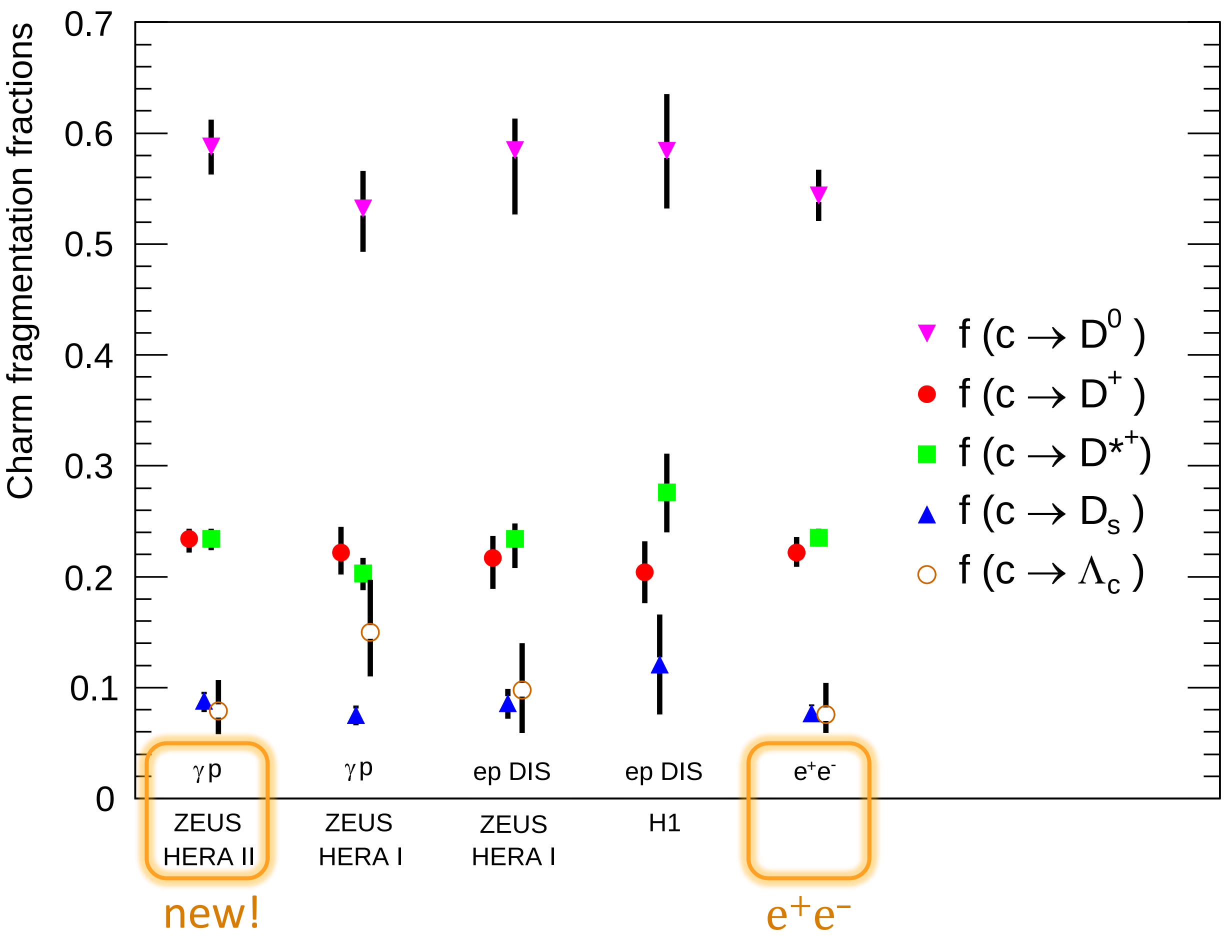
- fragmentation fractions
  $f(c \rightarrow D^{*+}, D^0, D_s^+, D^+, \Lambda_c^+, \ldots)$
  probability for c-quark to produce a particular c-hadron
- are these f universal?

- exclusive reconstruction
  - $[D^{*+} \rightarrow] \cdot D^0\pi^+ \rightarrow K^-\pi^+\pi^+$
  - $D_s^+ \rightarrow \phi\pi^+ \rightarrow K^-K^+\pi^+$
  - $D^+ \rightarrow K^-\pi^+\pi^+$ (veto $\phi \rightarrow K^-K^+$)
  - $\Lambda_c^+ \rightarrow K^-p\pi^+$
- $\mathcal{L} = 372\ \mathrm{pb}^{-1}$



DESY-13-106

Charm Fragmentation Fractions



- precise measurement
- consistent results in PhP, DIS and e^+e^-
- supports universality of fragmentation

arXiv:1306.4862 – to be published in JHEP

Summary

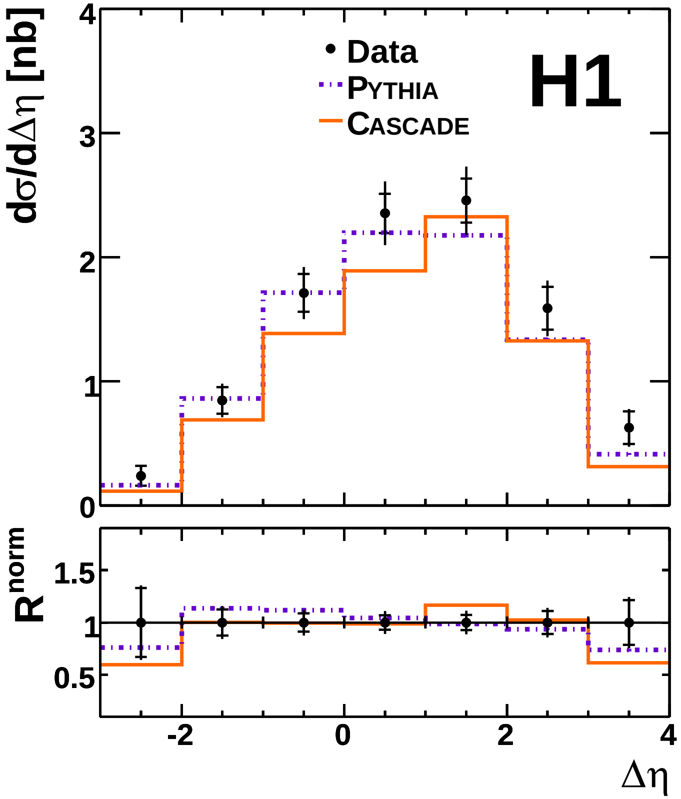
- various experimental techniques employed by H1 and ZEUS to measure charm and beauty photoproduction at HERA
  - experimental uncertainties often smaller than theory ones!
- measured cross-sections and predictions agree
  - room for improvement esp. for certain “difficult” variables (sensitivity to higher-order effects)
- measurement of fragmentation fractions supports universality

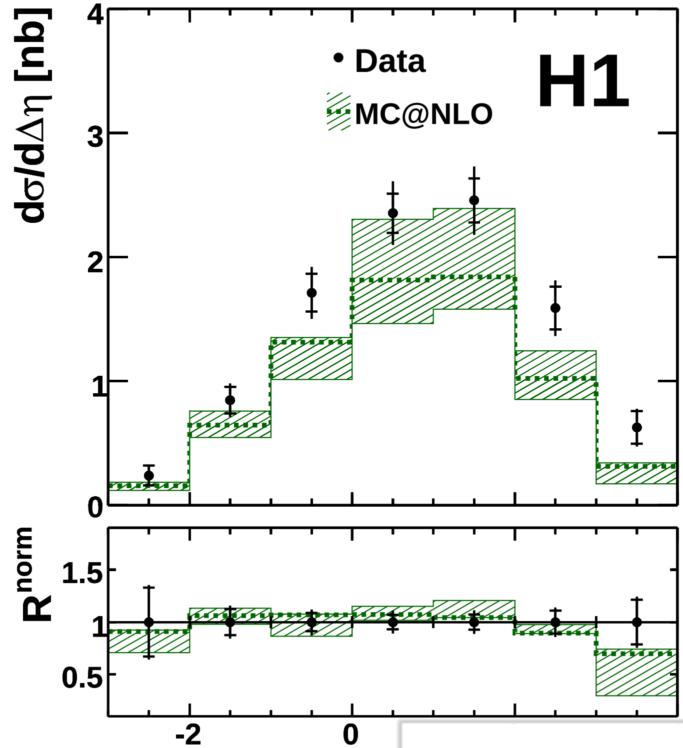
Backup

Backup: DESY-11-067

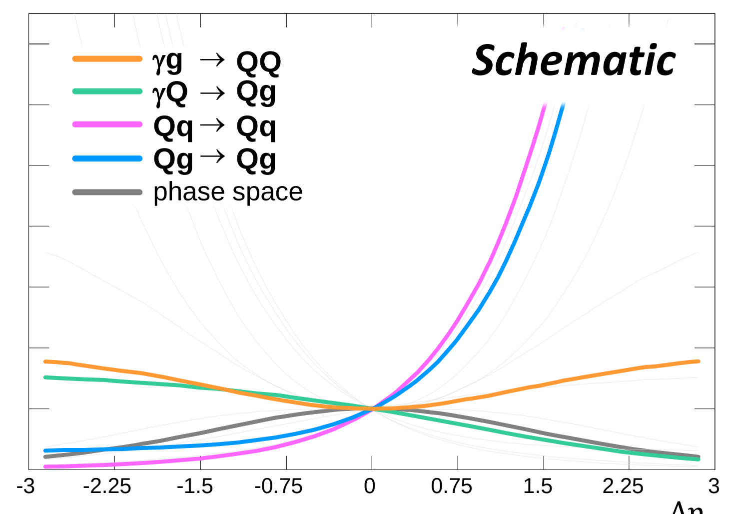
Uncertainty source	D	D -tagged dijet
Uncorrelated uncertainties		
Trigger efficiency	7.5%	3.1%
Signal extraction	1.5%	1.5%
D^0 meson mass cut	2.0%	2.0%
Reflections	1.0%	1.0%
Background from deep-inelastic scattering	1.0%	1.0%
dE / dx cut	0.5%	-
Hadronic energy scale	0.6%	2.0%
Model	2.0%	1.5%
Fragmentation	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%

$$\Delta\eta = \eta(\text{other jet}) - \eta(\text{D}^* \text{ jet})$$

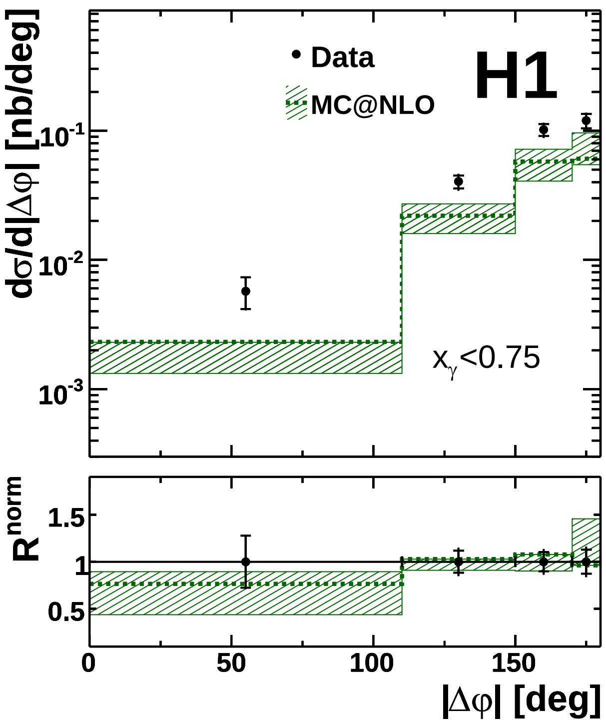




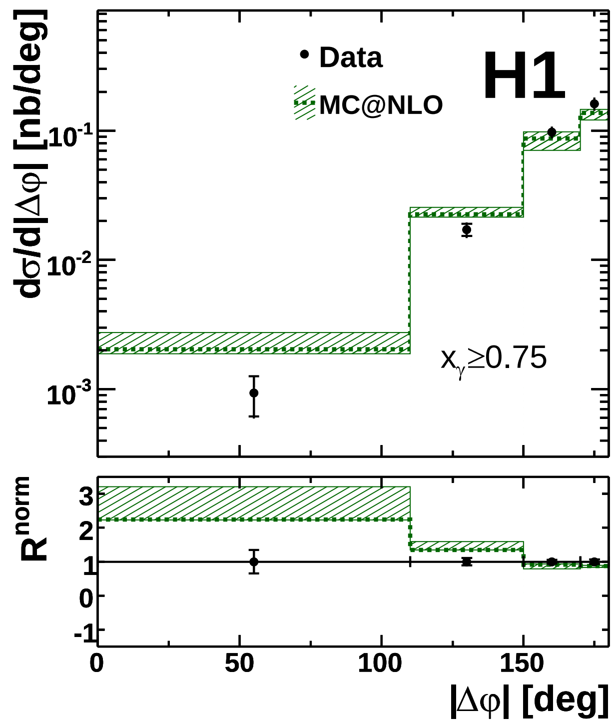
- sensitivity to matrix element
- predictions below data at high $\Delta\eta$, where charm leaves hard scatter along $e^{\pm}$ beam, esp. for MC@NLO



LO MEs as function of Δη in arbitrary units hadron-like γ enriched



point-like γ enriched



- MC@NLO: $\Delta\varphi$ shape ok for hadron-like γ, but a bit off for point-like γ

Backup: DESY-12-059

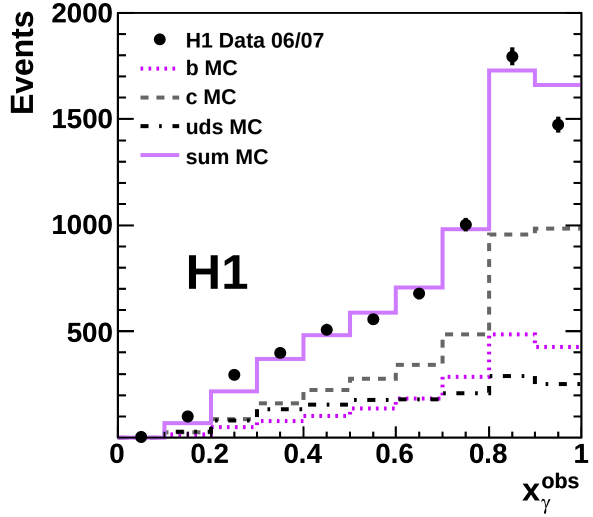
	Photoproduction of $b(c) \rightarrow \mu j j X$
Kinematic range	$Q^2 < 2.5\,\mathrm{GeV}^2$ $0.2 < y < 0.8$
Event selection	$P_T^{\mu} > 2.5\,\mathrm{GeV}$ $-1.3 < \eta^{\mu} < 1.5$ $P_T^{jet1} > 7\,\mathrm{GeV}$ $P_T^{jet2} > 6\,\mathrm{GeV}$ $-1.5 < \eta^{jet} < 2.5$
Event sample	$N_{events} = 6807$ $L = 179\,\mathrm{pb}^{-1}$

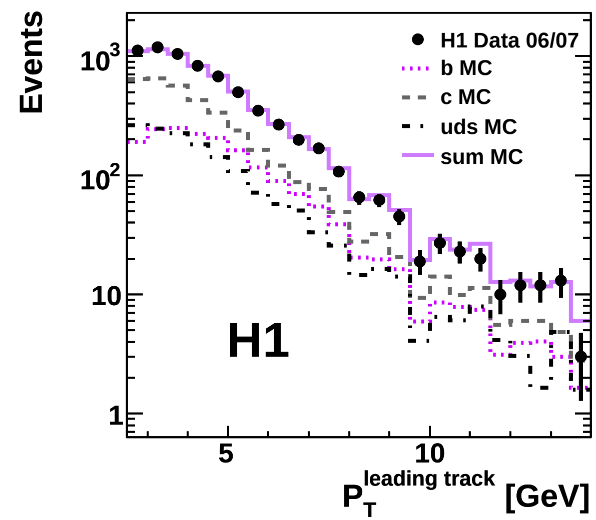
Table 1: Def nition of the kinematic range of the measurement and event yield for the data sample collected in the years 2006 and 2007. The variables are measured in the laboratory frame.

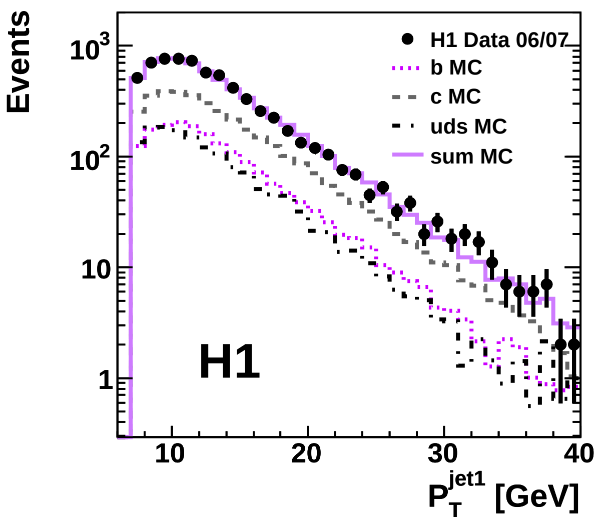
Systematic error source	Beauty $\Delta\sigma/\sigma[\%]$	Charm $\Delta\sigma/\sigma[\%]$
Trigger eff ciency	4	4
Muon identif cation	4	4
Track f nding eff ciency	3	3
Luminosity	4	4
δ Resolution	3	2
Jet axis	4	2
Hadronic energy scale	3	5
Physics model	3	1
Fragmentation	3	4
Fake muon background	1	1
Total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

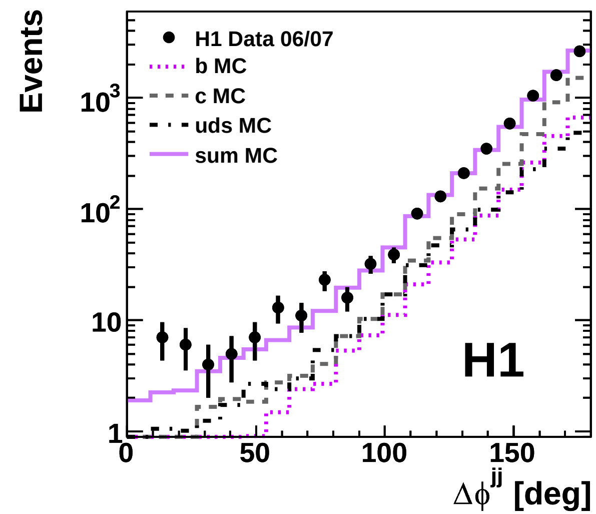
Table 2: Summary of the systematic uncertainties of the beauty and charm cross sections.

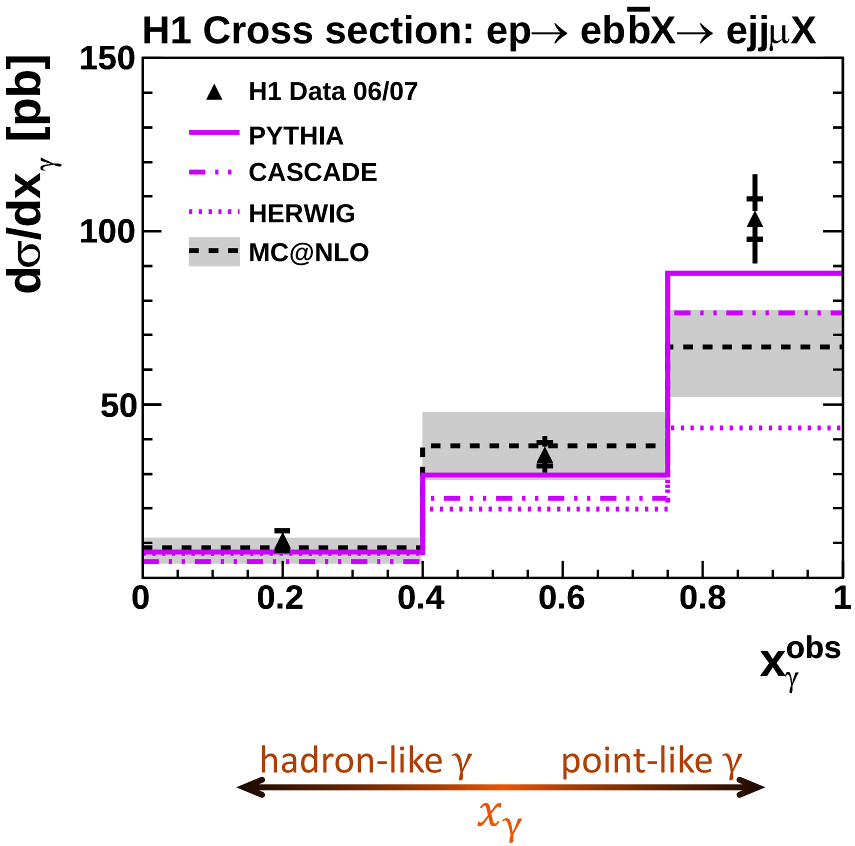
Backup: DESY-12-059





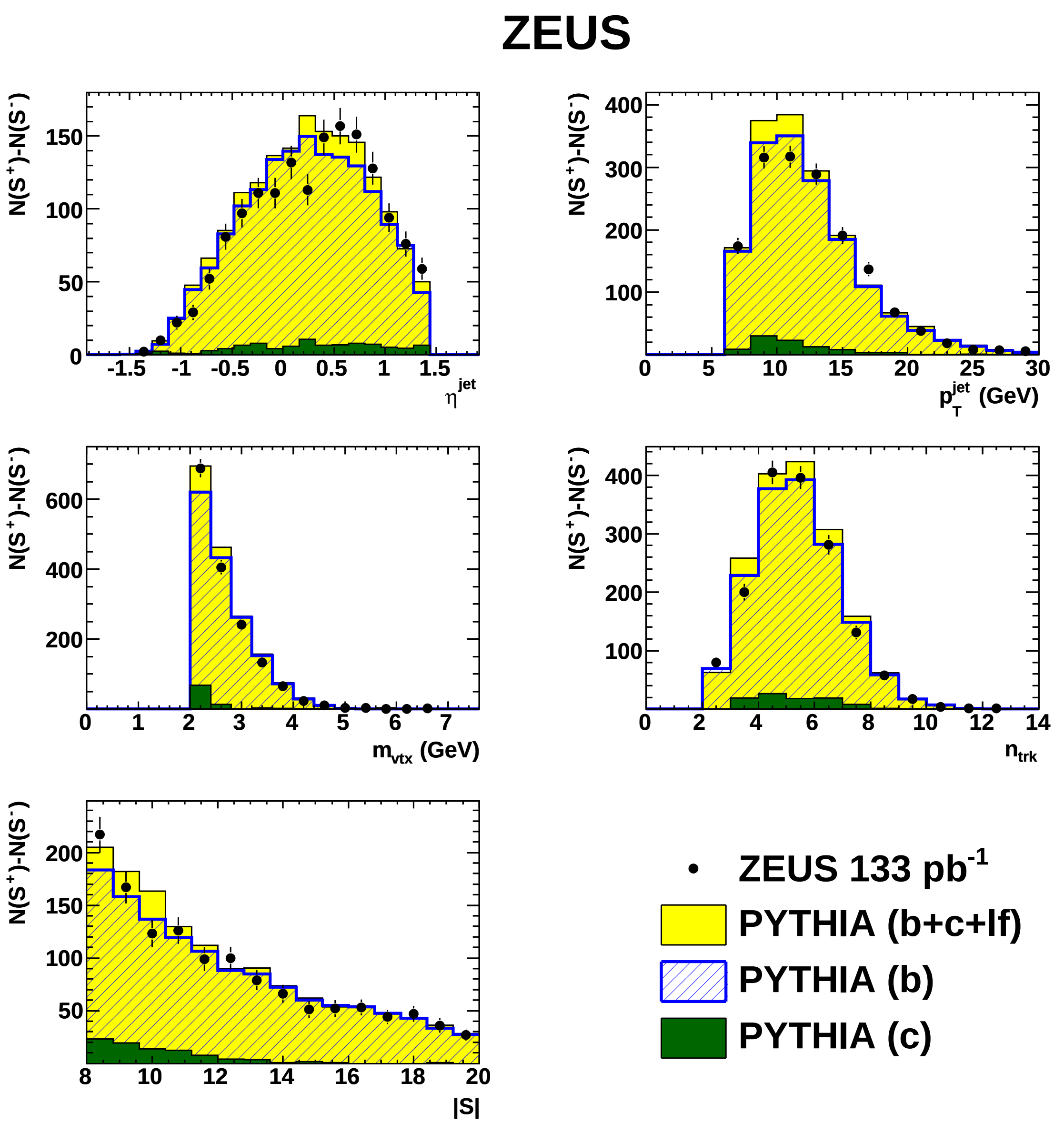


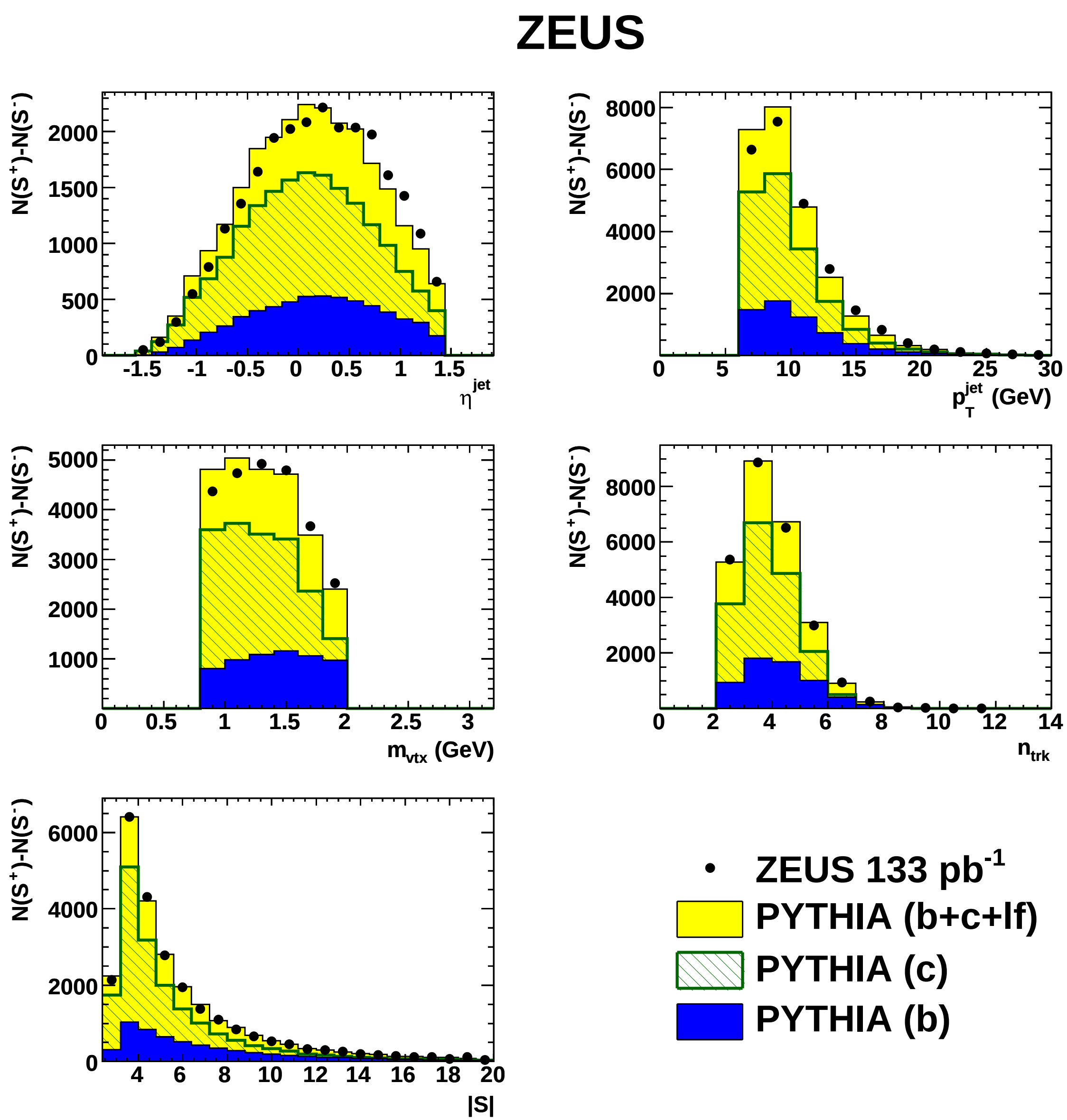


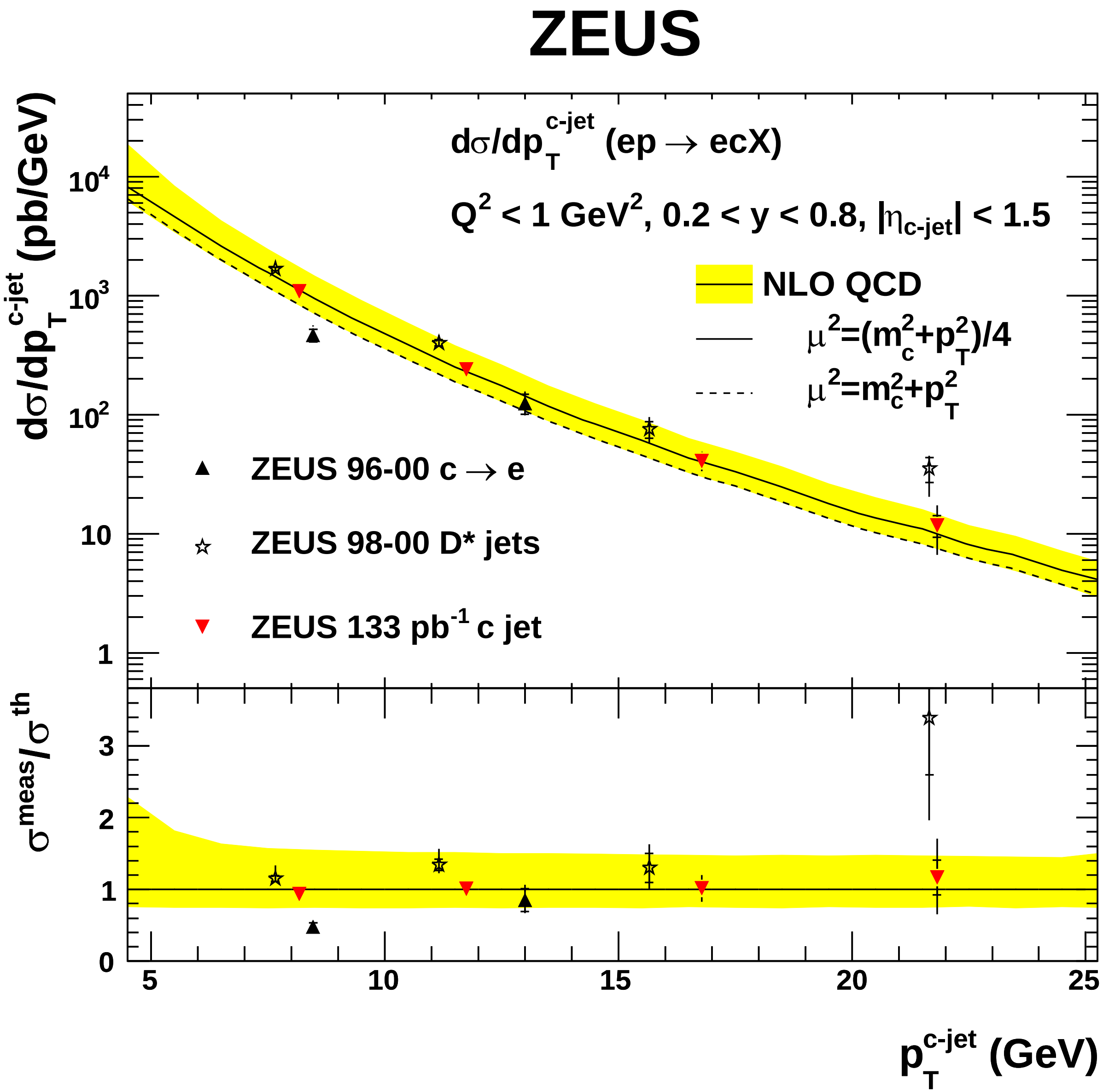


- LO+PS: dijet correlations well-described
- MC@NLO: dijet correlations ok, point-like γ a bit underestimated compared to hadron-like

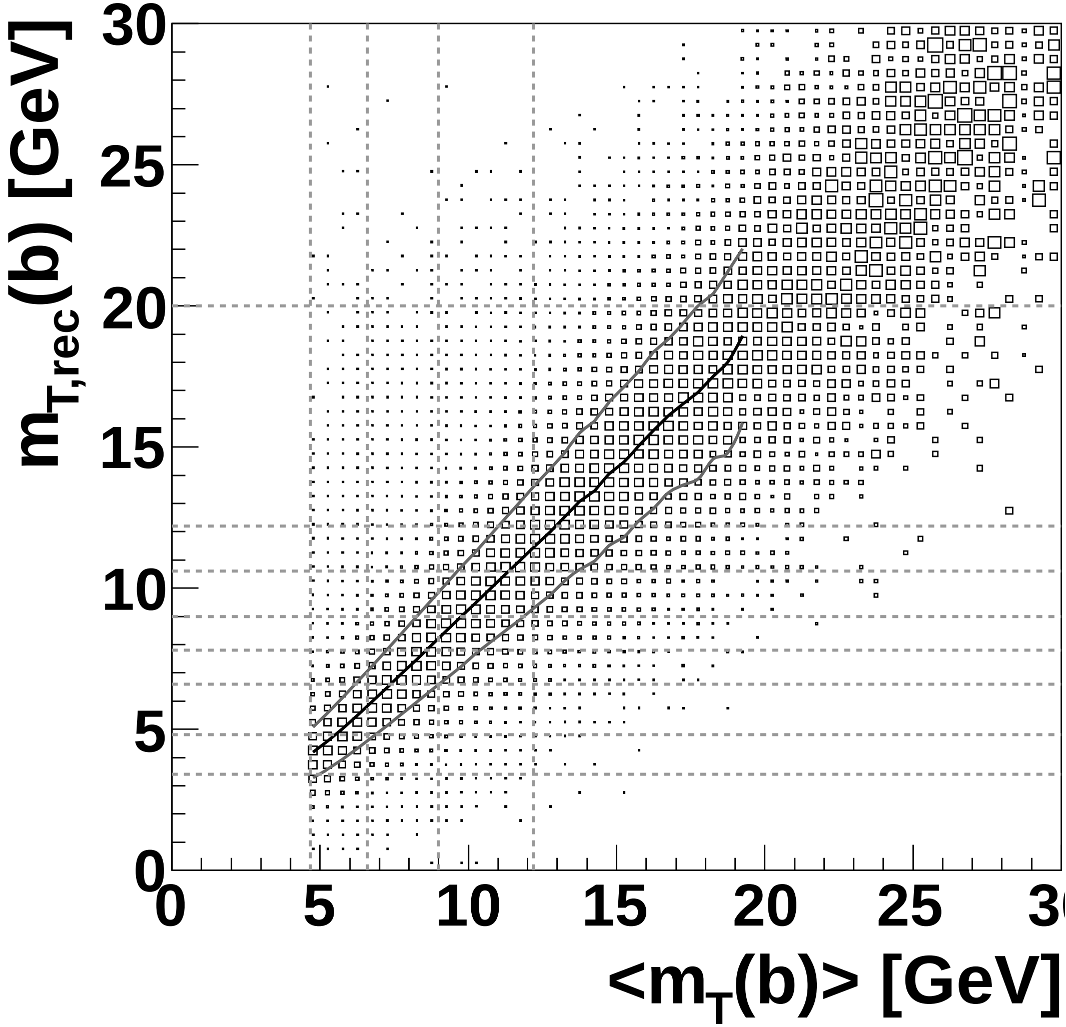
	Source	Beauty / Charm (%)
1a)	TLT trigger e ciency	± 0.8 / ± 2.0
1b)	FLT trigger e ciency	$^{+4.1}_{-3.8}$ / $^{+4.0}_{-3.7}$
2)	CAL hadronic energy scale	± 0.6 / ± 4.3
3)	Track-finding uncertainty	+ 5.9 / + 1.0
4)	Decay-length smearing	± 1.0 / ± 0.7
5)	Light-flavour asymmetry	± 0.2 / ± 0.7
6a)	^{jet} reweighting	- 1.2 / - 1.0
6b)	p_T^{jet} reweighting	- 5.5 / - 1.1
7a)	$D^{\pm} / D^{0}$ ratio	$^{+0}_{-1.3}$ / $^{+0.6}_{-1.8}$
7b)	$D^{\pm} / D_s^{\pm}$ ratio	$^{+0}_{-1.2}$ / $^{+0.1}_{-1.3}$
8)	Charm fragmentation	$^{+0.3}_{-0.3}$ / $^{+1.2}_{-1.3}$
9)	Beauty fragmentation	$^{+1.8}_{-2.1}$ / $^{+0.1}_{-0.1}$
10)	Luminosity measurement	± 1.8 / ± 1.8
	Total	$^{+7.8}_{-7.7}$ / $^{+6.7}_{-7.0}$

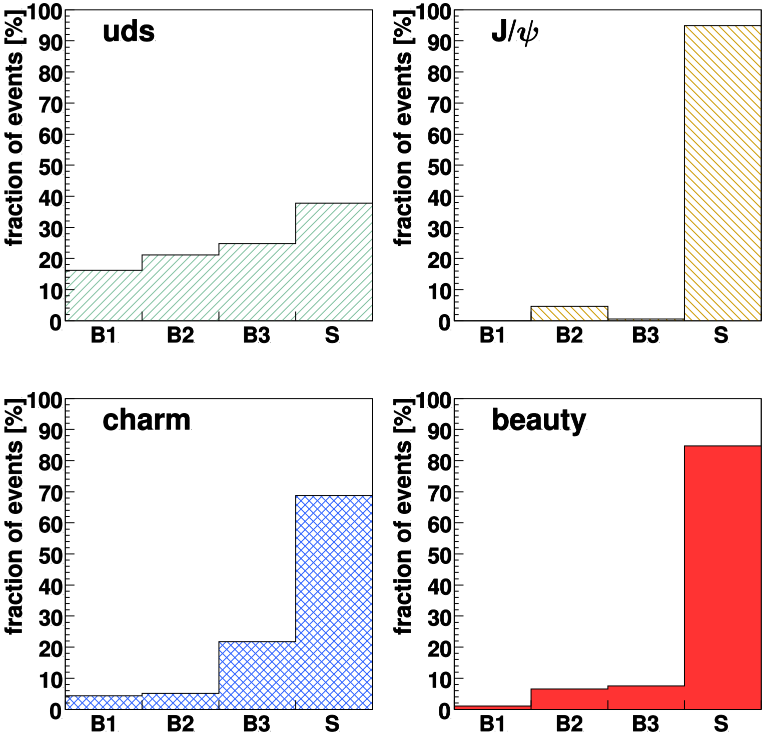

ZEUS
N(S⁺)-N(S⁻)
η^{jet}
p_T^{jet} (GeV)
m_{vtx} (GeV)
n_{trk}
|S|
ZEUS 133 pb^{-1}
PYTHIA (b+c+lf)
PYTHIA (b)
PYTHIA (c)

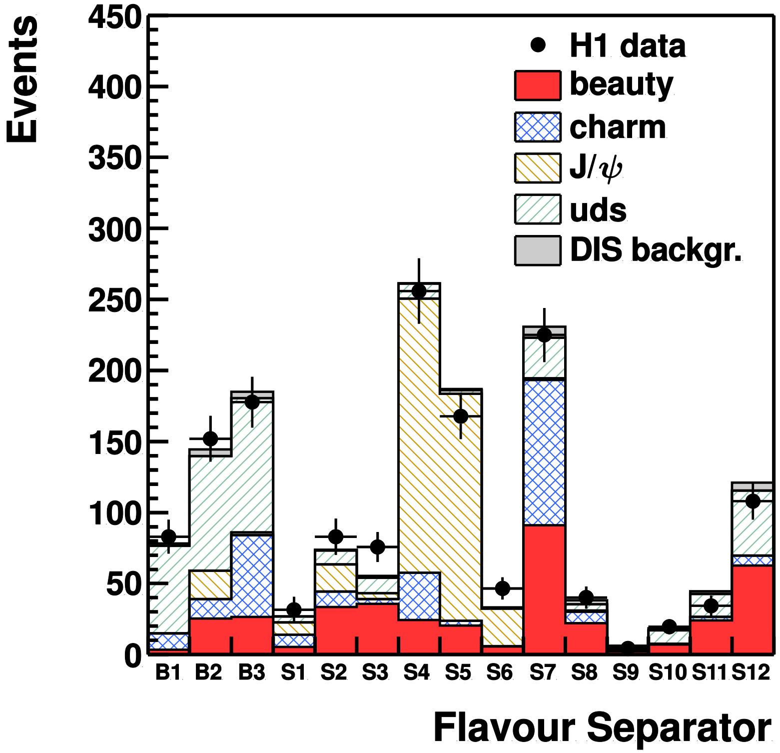

ZEUS
N(S+)-N(S-)
η^jet
p_T^jet (GeV)
m_vtx (GeV)
n_trk
|S|
ZEUS 133 pb-1
PYTHIA (b+c+lf)
PYTHIA (c)
PYTHIA (b)

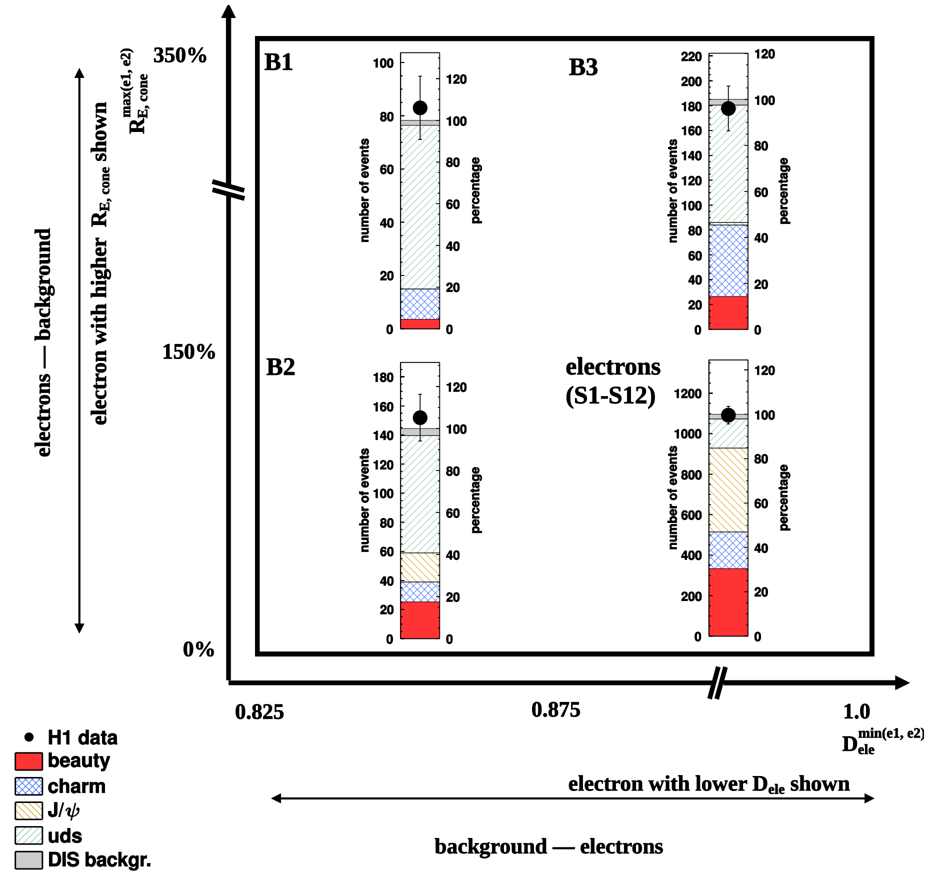

ZEUS
dσ/dp_T^c-jet (ep → ecX)
Q² < 1 GeV², 0.2 < y < 0.8, |η_c-jet| < 1.5
NLO QCD
μ²=(m_c²+p_T²)/4
μ²=m_c²+p_T²
ZEUS 96-00 c → e
ZEUS 98-00 D* jets
ZEUS 133 pb⁻¹ c jet
dσ/dp_T^c-jet (pb/GeV)
σ^meas/σ^th
p_T^c-jet (GeV)
10⁴
10³
10²
10
1
3
2
1
0
5
10
15
20
25

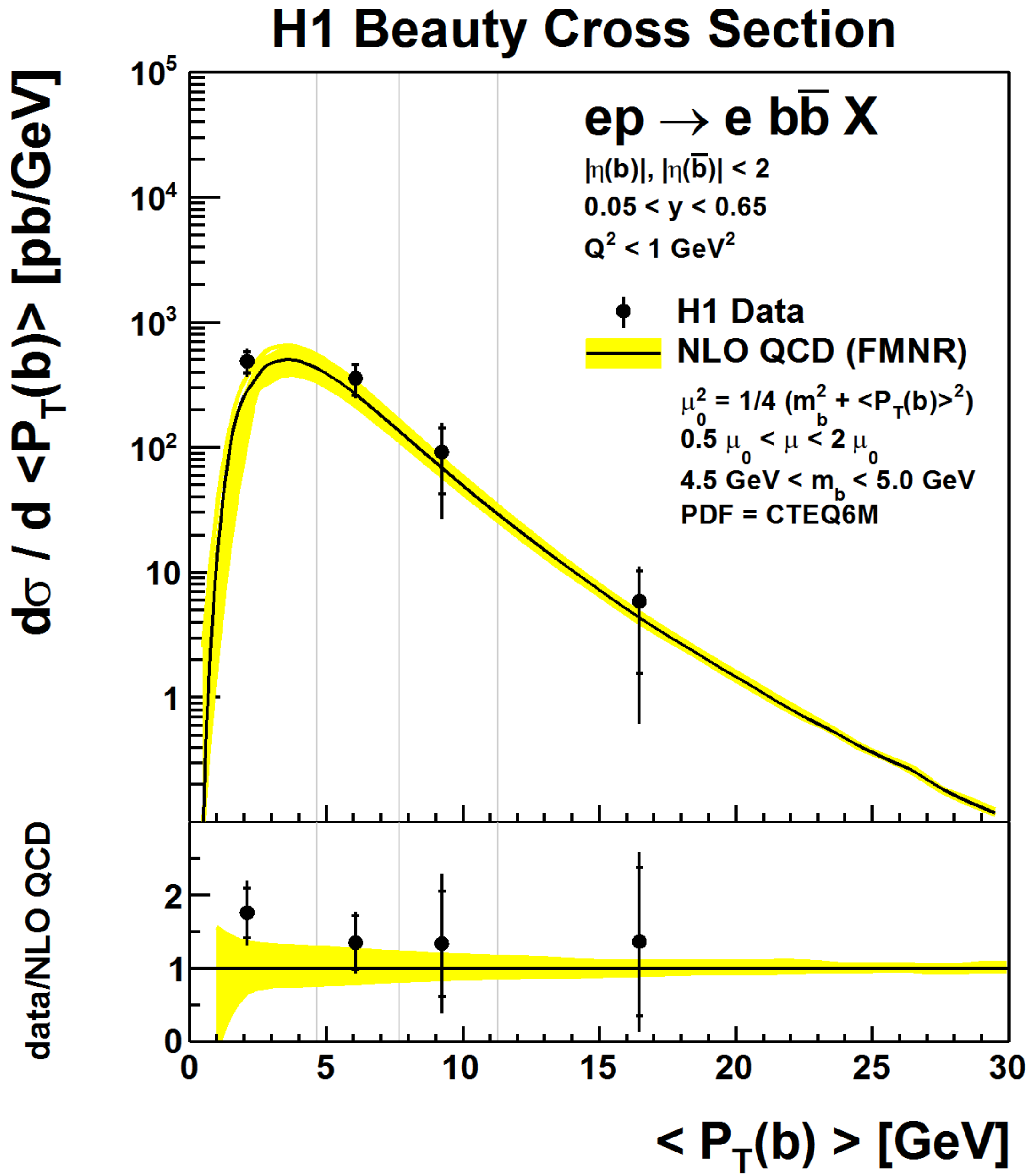
Overview of the Selection Cuts
Trigger selection
* track multiplicity cuts * 1 or 2 online identified electrons
Offline electron selection
* 2 electron candidates with: - $D_{ele} > 0.825$, $R_{E,cone} < 350\%$ - $P_T(e) > 1$ GeV, $20 < \#(e) < 140$ - verification of the L3 $P_T(e)$-thresholds 100 MeV above the $P_T(e)$-threshold of the respective subtrigger which recorded the event (see table ?? 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 * $0.05 < y_h < 0.65$ Rejection of photon conversions and Dalitz decays: * $m_{e1,e2} > 1.2$ GeV * no converted photon * $dca_e < 0.2$ cm


$m_{T,rec}(b)$ [GeV]
30
25
20
15
10
5
0
0
5
10
15
20
25
30
$<m_T(b)>$ [GeV]


fraction of events [%]
uds
J/ψ
charm
beauty
B1
B2
B3
S


Events
H1 data
beauty
charm
J/ψ
uds
DIS backgr.
B1 B2 B3 S1 S2 S3 S4 S5 S6 S7 S8 S9 S10 S11 S12
Flavour Separator


electrons — background
electron with higher R_E, cone shown
350%
150%
0%
B1
B2
B3
electrons (S1-S12)
number of events
percentage
0.825
0.875
1.0
electron with lower D_ele shown
background — electrons
H1 data
beauty
charm
J/ψ
uds
DIS backgr.


H1 Beauty Cross Section
ep → e bb̄ X
|η(b)|, |η(b̄)| < 2
0.05 < y < 0.65
Q² < 1 GeV²
H1 Data
NLO QCD (FMNR)
μ₀² = 1/4 (m_b² + <P_T(b)>²)
0.5 μ₀ < μ < 2 μ₀
4.5 GeV < m_b < 5.0 GeV
PDF = CTEQ6M
dσ / d <P_T(b)> [pb/GeV]
data/NLO QCD
< P_T(b) > [GeV]

$$\sigma_{gs} = \sigma^{eq}(D^+) + \sigma^{eq}(D^0) + \sigma(D_s^+) + \sigma(\Lambda_c^+) \cdot 1.14$$

$$\begin{aligned}
f(c \to D^+) &= \sigma^{eq}(D^+)/\sigma_{gs} = [\sigma(D^+) + \sigma^{add}(D^{*+}) \cdot (1 - B_{D^{*+} \to D^0\pi^+})]/\sigma_{gs}, \\
f(c \to D^0) &= \sigma^{eq}(D^0)/\sigma_{gs} \\
&= [\sigma^{untag}(D^0) + \sigma^{tag}(D^0) + \sigma^{add}(D^{*+}) \cdot (R_{u/d} + B_{D^{*+} \to D^0\pi^+})]/\sigma_{gs}, \\
f(c \to D_s^+) &= \sigma(D_s^+)/\sigma_{gs}, \\
f(c \to \Lambda_c^+) &= \sigma(\Lambda_c^+)/\sigma_{gs}, \\
f(c \to D^{*+}) &= \sigma^{kin}(D^{*+})/\sigma_{gs} = [\sigma^{tag}(D^0)/B_{D^{*+} \to D^0\pi^+} + \sigma^{add}(D^{*+})]/\sigma_{gs}.
\end{aligned}$$

$p_T(D, D^*, \Lambda_c) > 3.8\,\text{GeV}$, $|\eta(D, D^*, \Lambda_c)| < 1.6$, $130 < W < 300\,\text{GeV}$, $Q^2 < 1\,\text{GeV}^2$

	total (%)	b (%)	qqq (%)	f t (%)	c (%)	trg (%)	trk (%)	CAL (%)	S_l (%)
$f(c \to D^+)$	$^{+1.8}_{-2.7}$	$^{+0.3}_{-0.3}$	$^{+0.4}_{-0.4}$	$^{+1.4}_{-2.0}$	$^{+0.3}_{-0.3}$	$^{+0.6}_{-0.6}$	$+1.0$	$^{+0.2}_{-1.6}$	$^{+0.2}_{-0.1}$
$f(c \to D^0)$	$^{+1.7}_{-1.0}$	$^{+0.2}_{-0.2}$	$^{+0.4}_{-0.4}$	$^{+1.6}_{-0.6}$	$^{+0.1}_{-0.1}$	$^{+0.3}_{-0.3}$	-0.7	$+0.8$	$^{+0.2}_{-0.1}$
$f(c \to D_s^+)$	$^{+2.1}_{-8.0}$	$^{+0.4}_{-0.4}$	$^{+0.4}_{-0.3}$	$^{+1.3}_{-7.6}$	$^{+0.1}_{-0.1}$	$^{+0.8}_{-0.9}$	$+1.1$	$^{+0.3}_{-1.9}$	$^{+0.2}_{-0.1}$
$f(c \to \Lambda_c^+)$	$^{+6.4}_{-11.7}$	$^{+0.1}_{-0.1}$	$^{+0.4}_{-0.3}$	$^{+6.1}_{-11.6}$	$^{+0.2}_{-0.1}$	$^{+1.1}_{-0.4}$	$+1.0$	$^{+0.5}_{-0.9}$	-0.7
$f(c \to D^{*+})$	$^{+1.9}_{-1.9}$	$^{+1.0}_{-1.0}$	$^{+0.4}_{-0.4}$	$^{+1.5}_{-1.6}$	$^{+0.2}_{-0.1}$	$^{+0.4}_{-0.4}$	-0.4	$^{+0.3}_{-0.1}$	$+0.2$