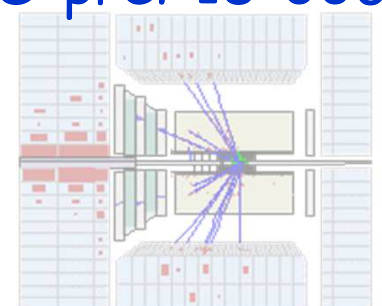
1st paper presentation

Measurement of beauty production from dimuon events in ep interactions at HERA and search for QCD instanton contributions

A. Geiser, N. Stefaniuk, D. Bot, I. Bloch
ZEUS coll. Meeting, 16.2.2021

- main physics goal: total beauty cross section at HERA
- secondary physics goals:
  - differential cross sections
  - world-wide first look at/search for heavy-flavour induced instanton final states
- history and content of paper
  - beauty cross sections
  - instanton search

ZEUS-prel-18-006



apologies for 'remnant' footers

beauty cross sections

- Introduction/history
- Event Selection
- Signal & background signatures / normalisation
- Total and differential cross sections
- Systematics
- Conclusions

Outline of paper

Measurement of beauty production from dimuon events at HERA II

Reminder

A. Geiser, N. Stefaniuk, I. Bloch
ZAF 30.1.2018

- main physics goal: total beauty cross section at HERA

History: (long term project ☺)

- **HERA I analysis**, PhD thesis, I. Bloch, 2005 **-> reuse same analysis strategy**
- FMNRxPYTHIA **NLO calculations**, E. Nuncio-Quiroz, PhD thesis 2008, **still valid**
- paper on **total and differential b cross sections**, ZEUS, 2008 (HERA I)
  http://www-zeus.desy.de/~ibloch/bbbar/bbbar_ibl_paper_master.html
- **muon efficiency calculations** for HERA II, K. Most, Master thesis 2011
- basic **HERA II** analysis, PhD thesis, D. Bot, 2011
- add **MVD secondary vertex analysis**, PhD thesis, N. Stefaniuk, 2017
- write **HERA II paper**, A.G., 2018 **-> outline today,** **all HERA II plots from N.S. thesis**

2nd preliminary request for

Measurement of beauty production from dimuon events at HERA II

Reminder

A. Geiser, N. Stefaniuk, I. Bloch

ZEUS meeting 2.7.2018

- only minor changes with respect to 1st preliminary presentation:

- tentative extra 15% systematic uncertainty on total cross sections removed as decided at 1st preliminary presentation
- figure cosmetics kindly updated by Iris
- systematics very slightly streamlined (all quoted uncertainties taken from already public sources: theses N. Stefaniuk or D. Bot, or HERA I paper; cross section numbers unchanged)
- writeup provided (ZEUS-prel-18-006, for ICHEP 2018)

- answers to questions by E. Lohrmann, P. Bussey, et al.

+ status update 4.9.2018, no further changes since then

Developments since preliminary release

Reminder

- minor cosmetic issues in preliminary plots kindly fixed by Iris

- resolution of question (Sasha et al.):
  why does the data/NLO ratio look larger for differential cross sections than for total cross section?
  -> explanation: Nazar picked up the NLO predictions with
  central QCD scale $\mu = \mu_0$ for the figures
  (used for the HERA I preliminary)
  rather than those with $\mu=\mu_0/2$ (used for the HERA I paper)

not wrong, but (unfortunately) different scale choice for total and differential predictions -> added statement to preliminary writeup

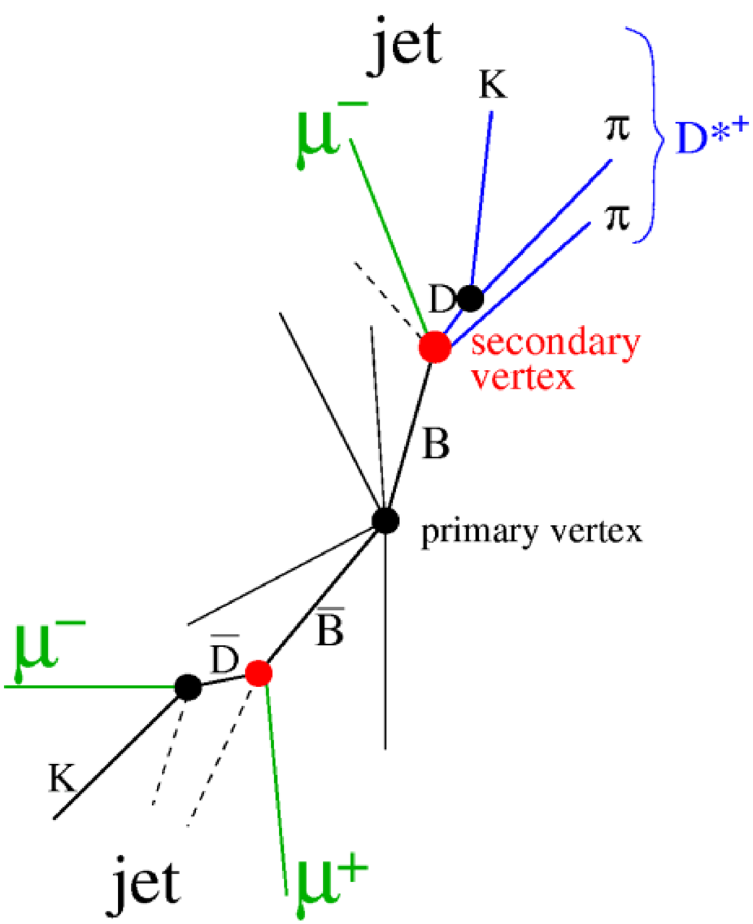
-> will be made consistent for paper
(Ingo is investigating how to redo the plots)

$\boxed{\text{not yet}}$

Goals of the μμ analysis

multi-tagged $b\bar{b}$ events

here: **two muons**



- tag both b´s
  → **explicitly measure $b\bar{b}$ correlations**
- dimuon signature has low background
  → low muon p_T cuts
  → sensitive even to B mesons at the kinematic threshold (low p_T)
- almost full rapidity coverage (rear and forward muon chambers)
  → **directly measure total $b\bar{b}$ cross section without any additional cuts**

Selection cuts and MC

same as in ZEUS-prel-18-006
(and similar to HERA I)

data samples:

- **HERA II, 03-07, L ~ 377 pb^{-1}** (t.b.c., muon chamber qual. requirement?)
  Common Ntuples version v02d (data), v02e/f (MC); cannot use v06/v08 since muon efficiency corrections not available

event selection:

- **CAL E_T > 8 GeV** ($\approx 2\, m_b$ - missing neutrinos, proton remnant and DIS e cand. removed)
- cut on muon E_T fraction ($0.1 < p_T^{\mu\mu}/E_T < 0.7_{\text{high m}} / 0.5_{\text{low m}}$)
- $|zvtx| < 30$ cm, $\sqrt{(xvtx^2+yvtx^2)} < 3$ cm, muon p_T asym. < 0.7, $\Delta\eta^{\mu\mu} < 3$, anti-cosmic cuts
- 'or' of muon, hadronic charm, and dijet triggers (trigger eff. ?)

muon selection:

- **two muons, $m^{\mu\mu}$ > 1.5 GeV**
- **p_T^{μ} > 0.75 GeV** for muon quality ≥ 5, **p_T^{μ} > 1.5 GeV** for muon quality ≥ 4
- simplified for differential cross sections: **p_T^{μ} >1.5 GeV** for both muons

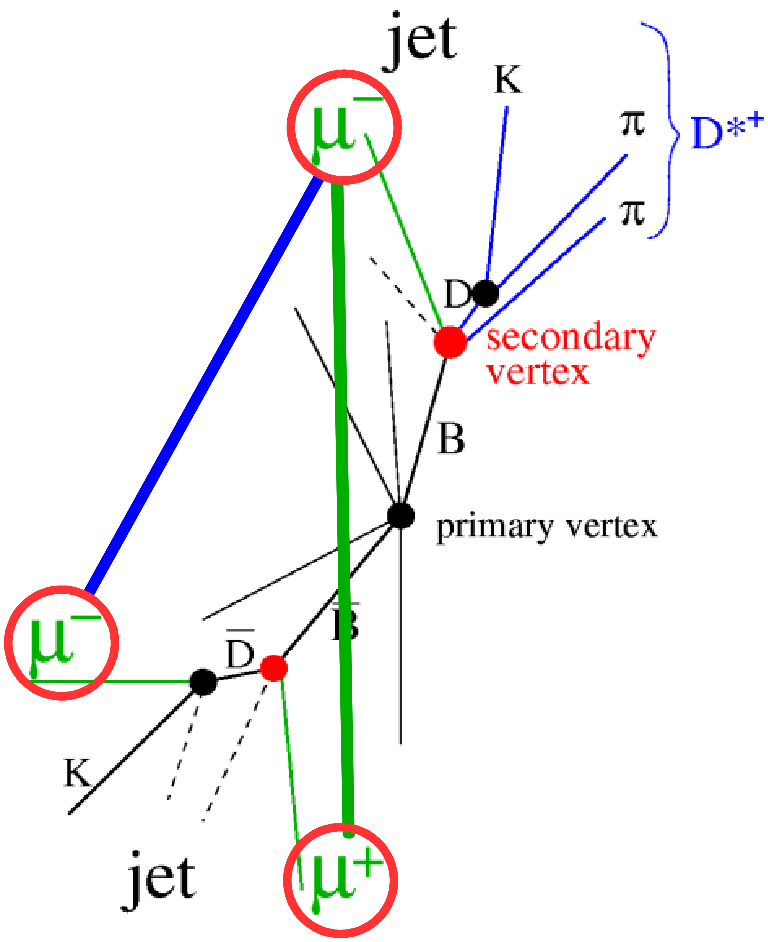
MC samples:

- **beauty and charm:** **RAPGAP** (Q^2>1 GeV^2) and **PYTHIA** (Q^2<1 GeV^2)
- J/ψ, ψ', Upsilon, Bethe-Heitler, each DIS/γp from various generators
- J/ψ (p_T) and Upsilon (Q^2) MCs reweighted to data distributions
- muon efficiency corrections applied (from independent data set)

Signal topologies: dimuon mass, charge

multi-tagged $b\bar{b}$ events

here: **two muons**



- **muons from different b´s**

  → like or unlike sign

  (secondary c decays or $B^0\bar{B}^0$ mixing)

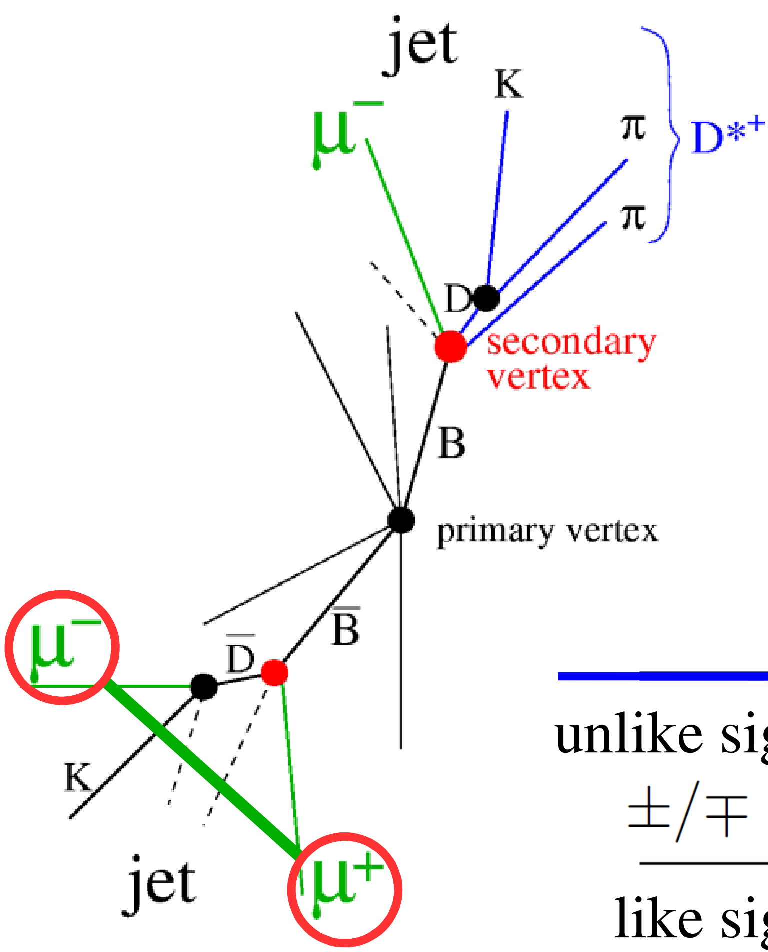
  opposite hemispheres

  high dimuon mass

- **suited to measure $b\bar{b}$ correlations**

Signal topologies: dimuon mass, charge

multi-tagged $b\bar{b}$ events



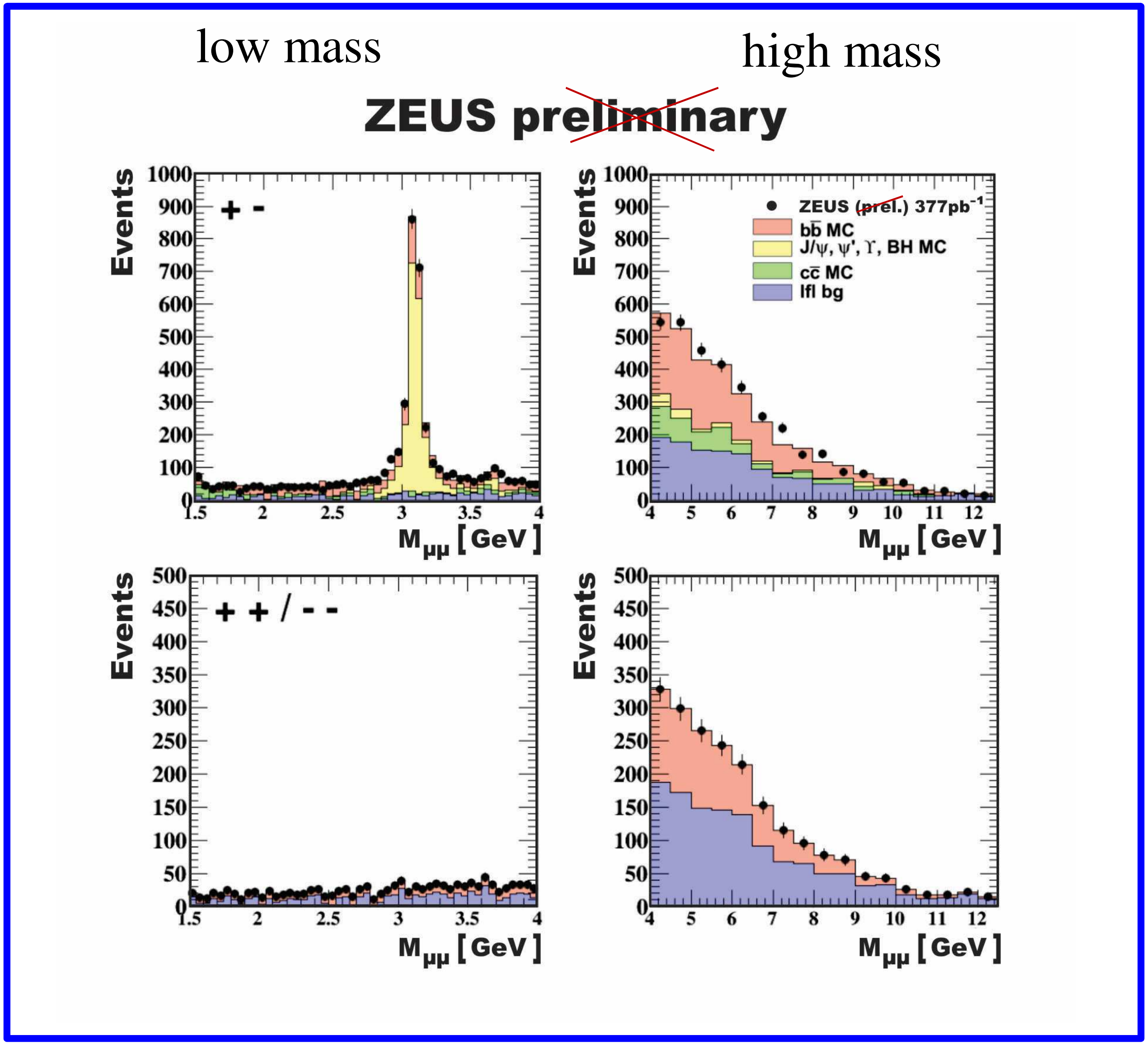
here: **two muons**

- **muons from same b** (including $b \rightarrow J/\psi$)
  - $\rightarrow$ **unlike sign**
  - **same hemisphere**
  - **dimuon mass < 4 GeV**
  - (B mass - hadrons/neutrinos)
- **useful contribution to total cross section**

$\rightarrow$ classify data into subsamples:

	low mass (< 4 GeV)	high mass (> 4 GeV)
unlike sign $\pm/\mp$	muons from same b J/ψ, ψ' + light-flavour bg	muons from diff. b or c Υ, Bethe Heitler + light-flavour bg
like sign $++/--$	light flavour bg + few muons from diff. b	muons from diff. b + light-flavour bg

Dimuon mass distributions

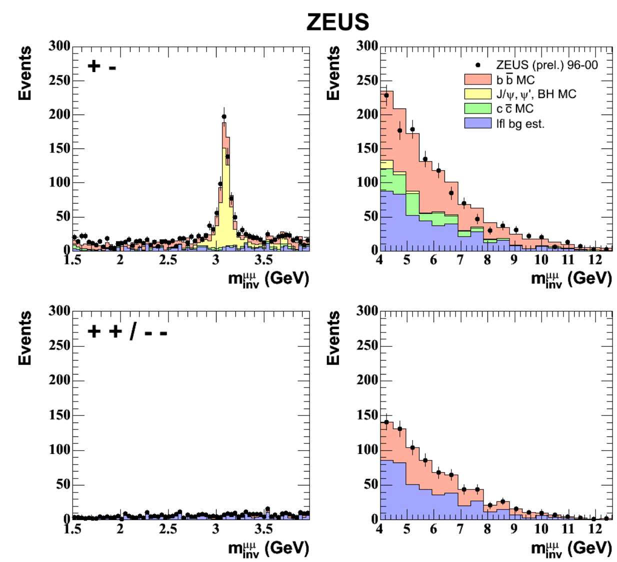


paper plot

data well
described by MC.

beauty contribution:
~5200 events

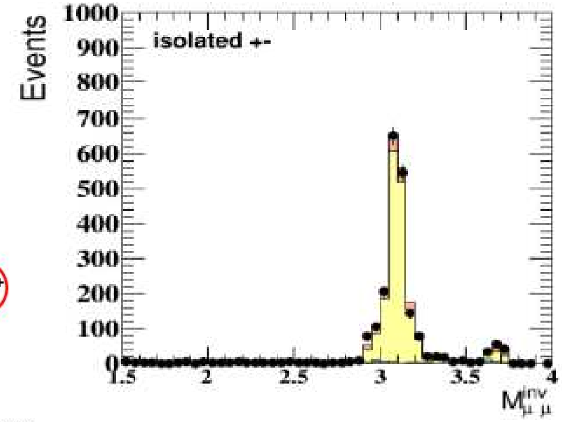
(Hera I: 1900 ± 210 events)



Normalisations

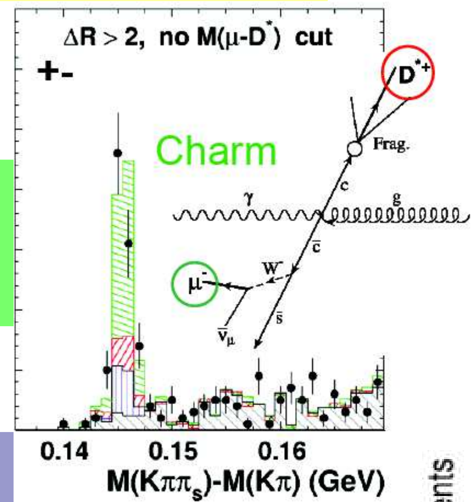
Short summary - **normalisation procedure identical to HERA I paper**:

J/ψ, ψ, BH: Normalised on sub sample **of isolated dimuons**



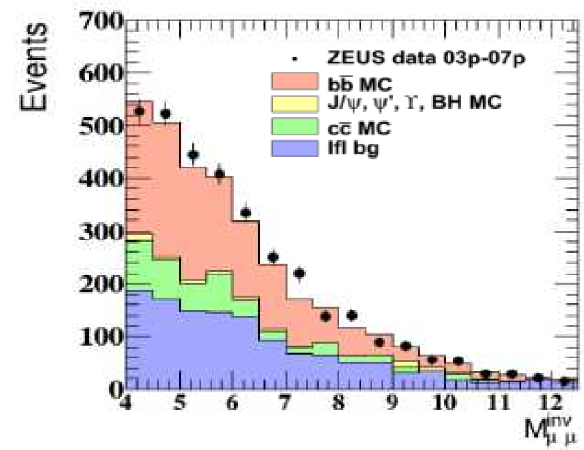
Charm: Normalised using **b→D*μ charm normalisation**

$S_c = 1.37 \pm 0.20$



will be adjusted/rechecked later

Light flavour background: Difference of like sign(data - beauty)



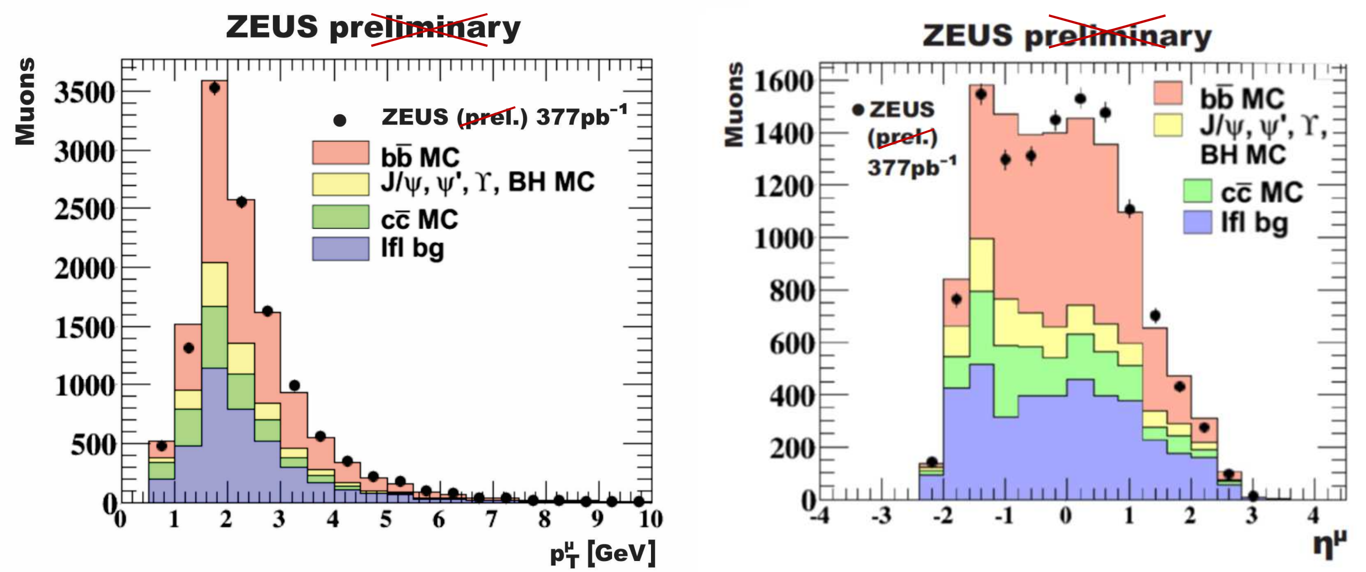
Beauty: Determined using **difference of like and unlike sign dimuon events**.

$$d^u = b^u + bg^u_{lfl} + c^u + J/\psi^u + \psi'^u + BH^u$$

Muon p_T and η distributions

nonisolated unlike sign muon pairs

paper plots



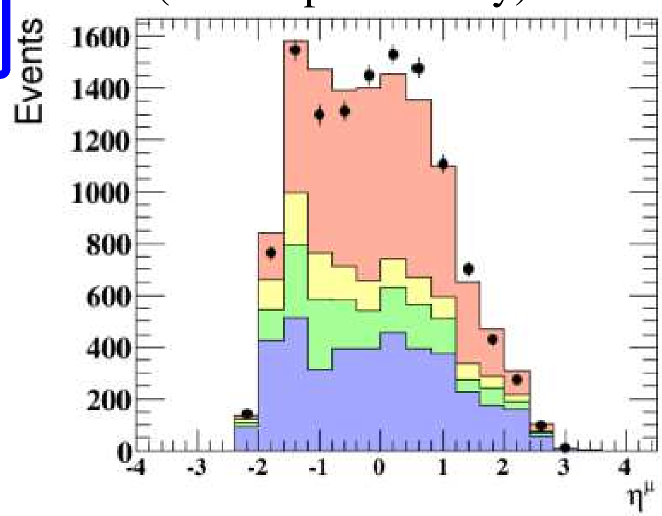
acceptance down to **very low p_T**

very **large η range** (-2.2 to +2.5)

b MC (x 1.85) **agrees with data**

Nazar's plot

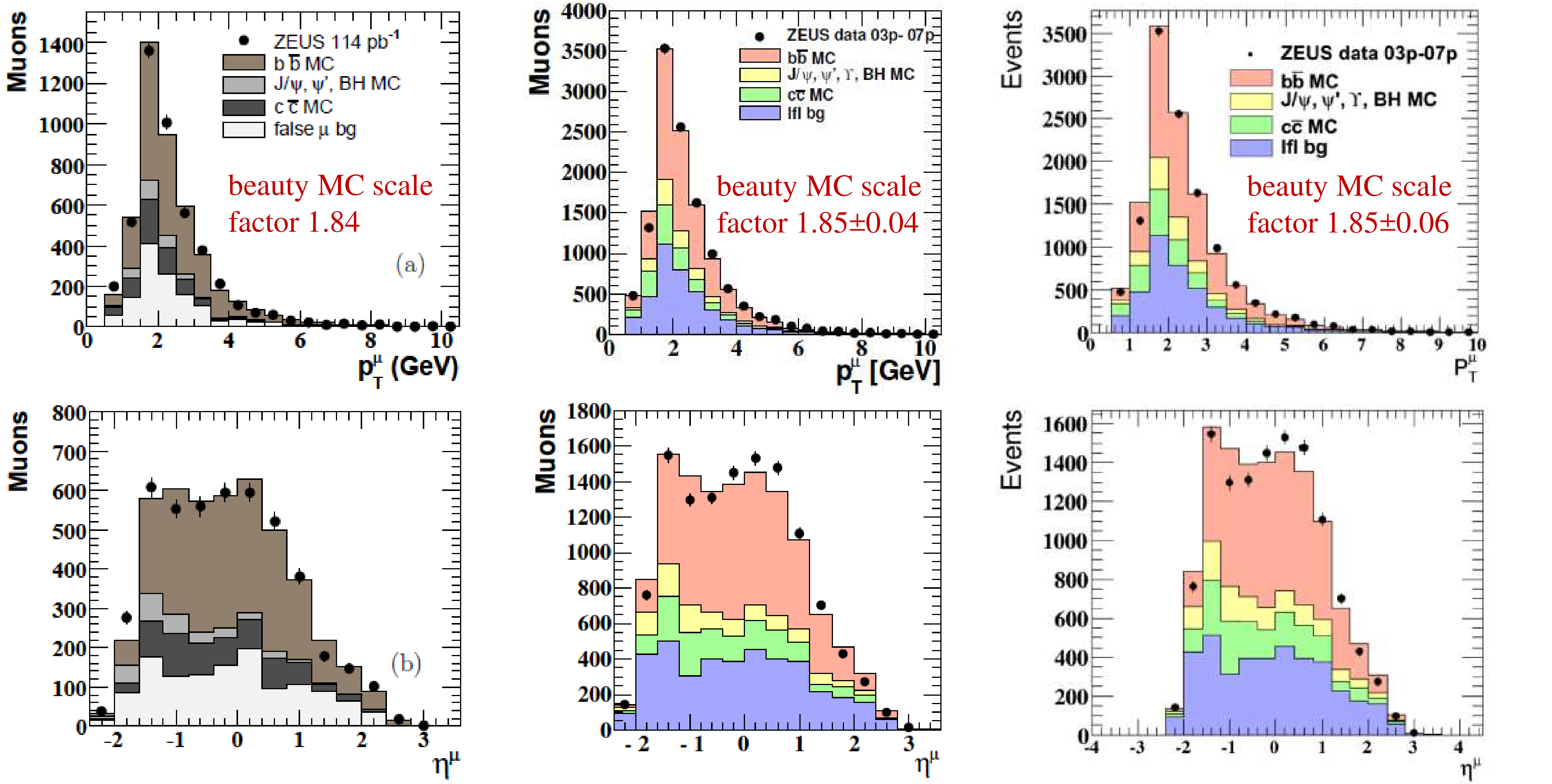
(not for preliminary)



Recheck self-consistency: data and MC

- e.g. nonisolated unlike sign muon pairs: **data and MC consistent !**

Ingo/HERA I paper | Danny/HERA II thesis | Nazar/HERA II thesis



Theoretical tools

identical to HERA I

FMNR

- **Fixed order NLO in the massive mode (PHP regime)**
- **Mass of the b quark** $m_b = 4.75$ **GeV,** **(4.5 - 5.0)**
- μ_R **and** μ_F **:** $\mu^2 = m_b^2 + p_{Tb}^2$ **($\mu/2 - 2\mu$)**
- **Proton: CTEQ5M** **Photon: GRV-G-HO**
  (PDF error << scale/mass error $\rightarrow$ **neglected)**

For visible cross sections - identical procedure as for b->D*μ paper:

FMNR + Pythia

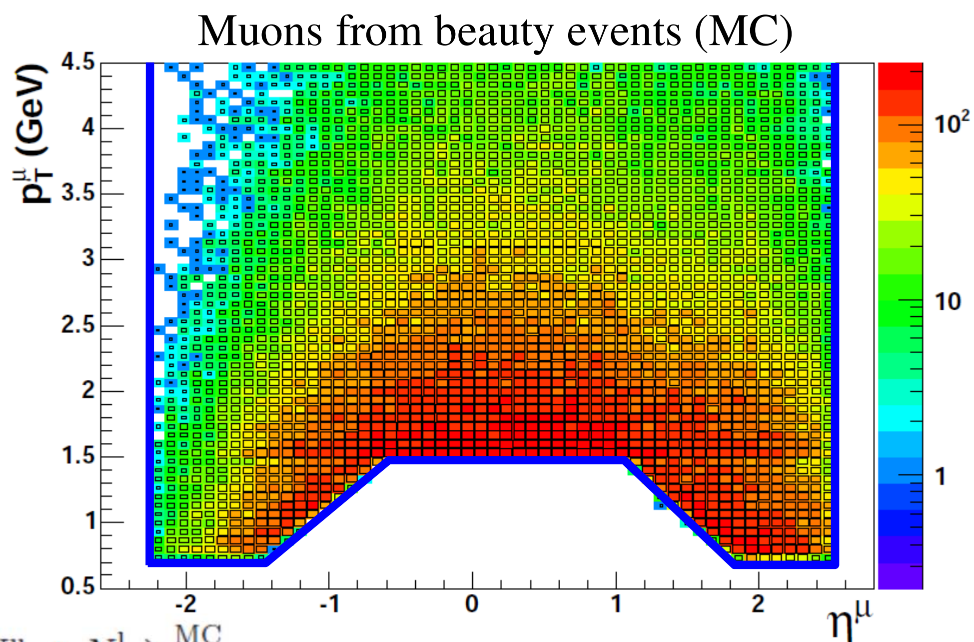
http://www-zeus.desy.de/~nuncio/ZEUS_ONLY/dis2006.html

- **In FMNR weighted events with positive and negative weights spanning over 8 orders of magnitude -> "naive" interface very inefficient, not practical**
- **Use weight range reduction (REDSTAT) to ~ 1 order of magnitude preserving NLO accuracy**
  - **events with large + and – weights but similar topologies are "averaged"**

Visible cross section

Definition of the visible cross section, guided by detector efficiency, to yield minimum extrapolation factor.

Visible range defined by blue line:



$1^{st}\ \mu$: $p_T > 1.5$ GeV

$2^{nd}\ \mu$: ($p > 1.8$ GeV for $\eta < 0.6$

$p > 2.5$ *or* $p_T > 1.5$ GeV for $\eta > 0.6$)

and $p_T > 0.75$ GeV

both μ: $-2.2 < \eta < 2.5$

$$N_{b\bar{b}\to\mu\mu} = \left(N^{\rm u}_{\rm data} - N^{\rm l}_{\rm data} - (N_{\rm charm} + N_{\rm VM} + N_{\rm BH})\right) \times \left(\frac{N^{\rm u}_{b\bar{b}} + N^{\rm l}_{b\bar{b}}}{N^{\rm u}_{b\bar{b}} - N^{\rm l}_{b\bar{b}}}\right)_{\rm MC}$$

identical to HERA I (reminder: no lf bg MC!)

Visible cross section:

σ_{vis} ep→bbX→μμX' = 43 ± 3 (stat.) $^{+13}_{-11}$ (syst.) pb **HERA II paper**

σ_{vis} ep→$b\bar{b}X$→μμX' = 55 ± 7 (stat.) $^{+14}_{-15}$ (syst.) pb **HERA I paper**

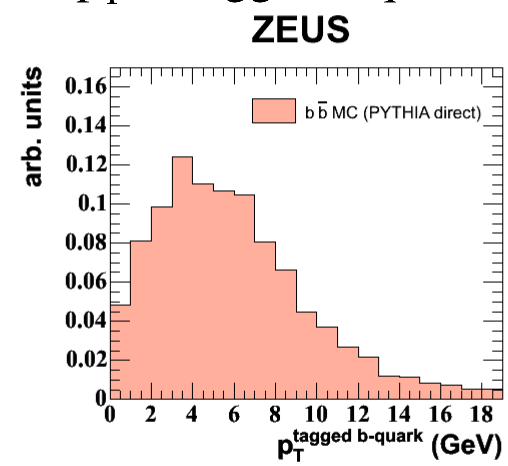
NLO: (FMNR⊗PYTHIA): 33^{+18}_{-8} pb

consistent

Total $b\bar{b}$ cross section

Measurement directly sensitive to total beauty cross section.

p_T of tagged b quark:



Scale MC cross sections:

γp: Pythia $\sigma_b(318\text{ GeV}) = 6.56$ nb
DIS: Rapgap $\sigma_b(318\text{ GeV}) = 0.91$ nb
γp+DIS = 7.47 nb

with measured MC scale factor: 1.85 ± 0.06 (stat.)

alternatively divide visible cross section by efficiency, 0.38% (tbc)

=> Total cross section for $b\bar{b}$ production in HERA ep collisions:

$\sigma_{b\,tot}$ $ep \to b\bar{b}X$ (318 GeV) = 11.4 ± 0.8 (stat.) $^{+3.5}_{-2.9}$ (syst.) nb **HERA II paper**
$\sigma_{b\,tot}$ $ep \to b\bar{b}X$ (318 GeV) = 13.1 ± 1.5 (stat.) $^{+4.0}_{-4.3}$ (syst.) nb **HERA I paper**

NLO QCD predictions:
FMNR+HVQDIS

$7.5^{+4.5}_{-2.1}$ nb

$4.5 < m_b < 5.0$
$0.5 < \mu/\mu_0 < 2$

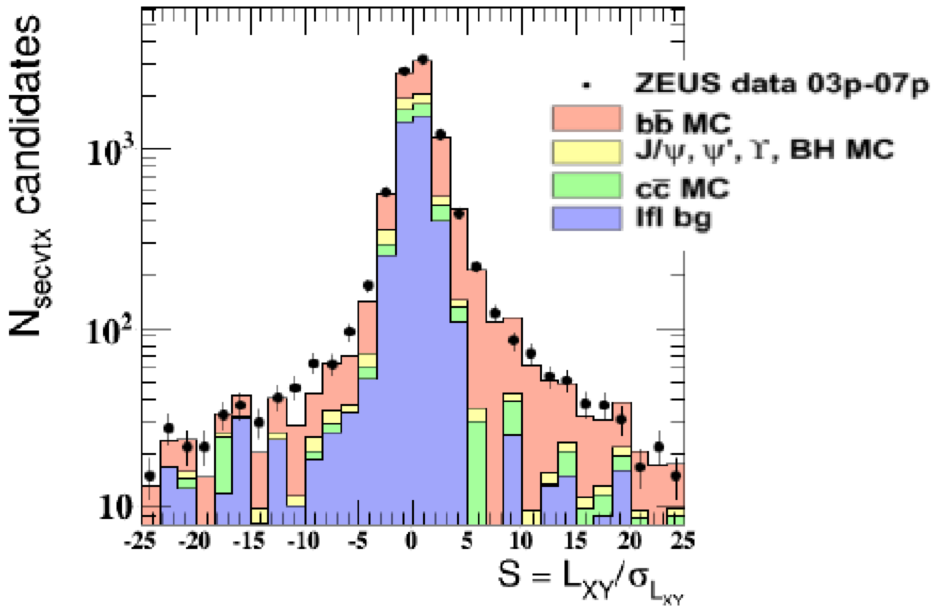
a bit less consistent, but (hopefully) still OK

Checking the charm, beauty and light flavour fractions using the MVD

In order to define secondary vertex signed decay length, need jets
-> require >= 1 jet E_T > 2.5 GeV

-> 20% efficiency loss, concentrated at low p_T
many higher p_T events have two entries, further reduces weight of low p_T

decay length significance distribution for all nonisolated events:



lf distribution obtained from ‘subtraction procedure’ as for all other plots (no l.f. bg MC)

Should be symmetric ?

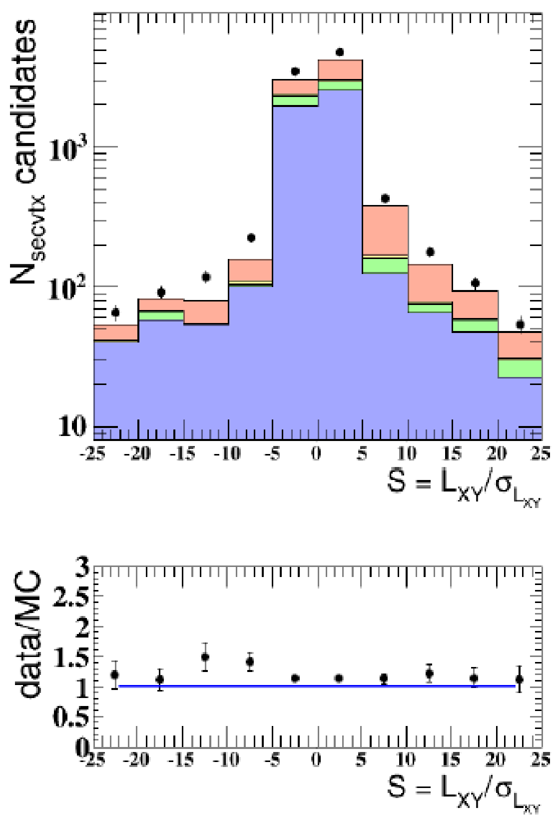
reasonable, but not perfect -> improve by fitting

Refitting the charm, beauty and light flavour fractions using the MVD

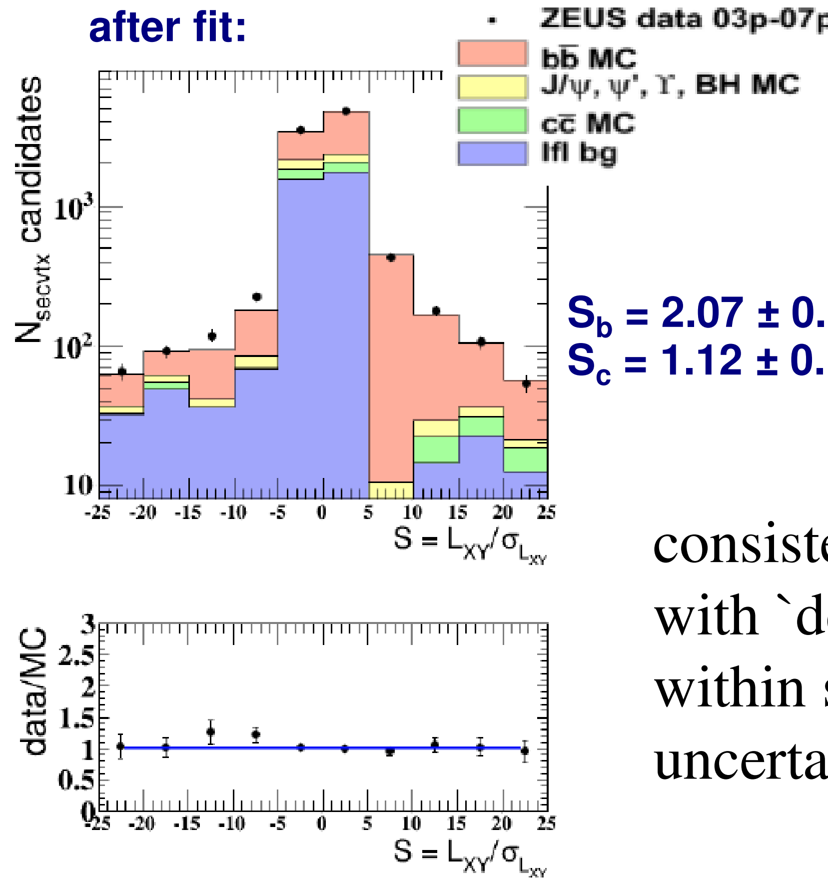
Impose constraint that light flavour contribution should be (statistically) symmetric, use charm and beauty decay lengthy distributions from MC

Fit decay length distribution with charm, beauty and l.f. normalisation free, l.f. shape free except (statistical) symmetry constraint

before fit: (S_c=S_b=1)



after fit:



S_b = 2.07 ± 0.08 (stat)
S_c = 1.12 ± 0.14 (stat)

consistent with `default' within systematic uncertainties

Refitting the charm, beauty and light flavour fractions using the MVD

Issues:

- it is not clear whether the assumption that the l.f. background be symmetric is justified in the low significance region, which was cut away in the inclusive charm in DIS analysis in order to avoid the corresponding (large) systematics

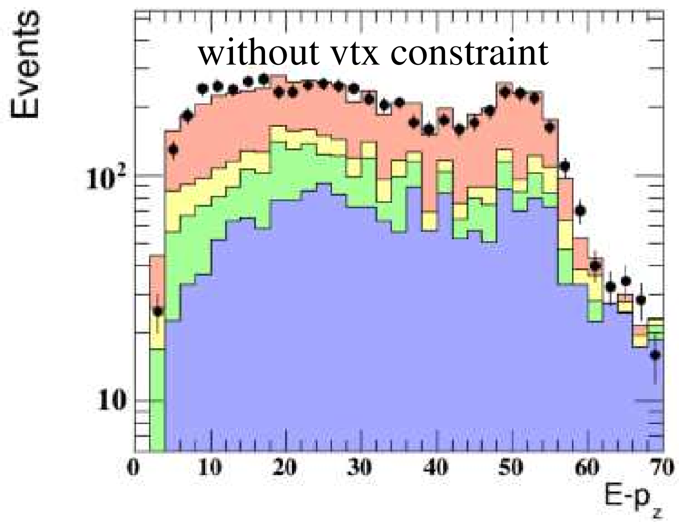
- it is not clear whether the new factor covers the low p_T region which was removed

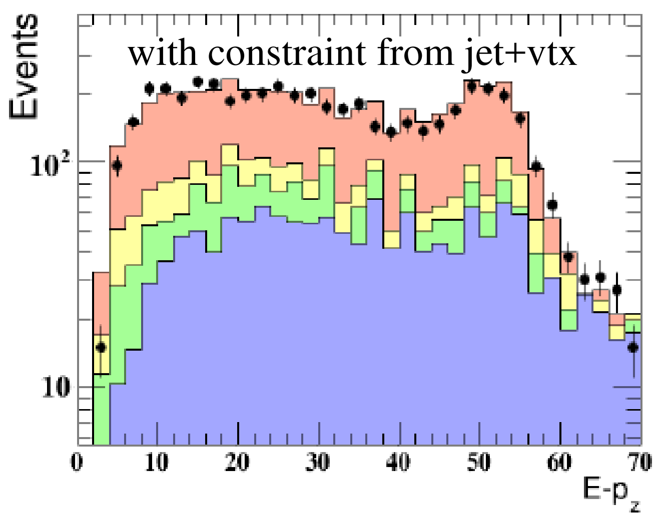
- there is not enough statistics for a meaningful bin-by-bin vertex significance fit for the differential cross sections (next slides)

- the new charm scale factor (1.12 ± 0.14) is consistent with the `old one' (1.37 ± 0.20) but the old one has a more conservative uncertainty

- reapplying the new fitted charm scale factor to the control plots of the data without jet requirement indicates that this might lead to a slight (systematic?) overestimate of the total beauty contribution

e.g.:



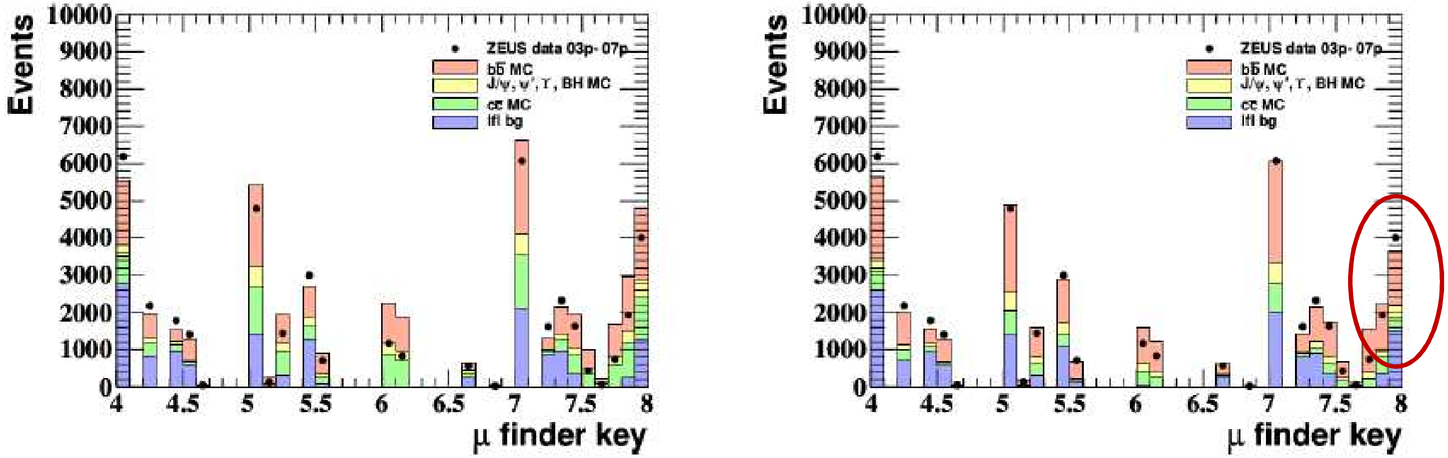


-> decision for preliminary release: use charm fraction fit from MVD as part of (successful) systematic checks only + refer to thesis Nazar for details -> stick to that for paper

Summary of systematic uncertainties (visible cross section)

Muon efficiency correction:		Nazar/Danny paper	**HERA I**
Use BRMUON only or BAC only; Trigger		**+20% -18%; +-5%**	**+-15%; +-5%**
(D. Bot, 11.1.2012: should actually be	slide	**+14.2% -11.4%)**	
Dimuon isolation; vary cut by 500 MeV (data and MC):		**+-3%** Nazar/Danny	**+-2%**
CAL ET; vary cut by 1 GeV (data and MC):		**+-3%** Nazar/Danny	**+-2%**
Bethe Heitler and Quarkonia contributions;		Nazar	
change normalisation of nonisolated fraction by +-50%:		**+10% -3%**	**+-10%**
Charm contribution; vary by +-20%:	slides	Danny **+6% -10%**	**+-12%**
Charm and beauty spectral shape;			
Variation of direct and nondirect fractions	slide		
charm:		**+-2%** Nazar/Danny	**+0/-4%**
beauty:		**+-12%**	**+4/-12%**
BBbar oscillations; other b model uncertainties		paper **+-4%; +-10%**	**+-4%; +-10%**
Variation of like/unlike sign light flavour ratio by 3%:		Nazar/Danny **+3% -1%**	**+-3%**
Luminosity:	slide	**+-2%** Nazar/Danny	**+-2%**
		-------	---------
		+30% -26% Nazar	**+25% -28%**

Muon finder distributions before/after efficiency corrections



(a) (b)

Figure 3.2: Distribution of muon finder combinations for dimuon events left: before and right: after applying the muon efficiency corrections.[99]. The μ finder key description is shown in table 7.2.

Definition of the bin contents of Fig. 3.2

x-axis number	Finder	Description
4 = quality 4		
4.2	BREMAT	inner chambers
4.4	BAC	
4.5	BAC/BREMAT + MV	not vertex assosiated or low quality muon
4.6	MPMATCH or MUFO	low probability that is mutched with track
4.7	MUFO	assosited tracks not found
5 = quality 5		
5.1	BREMAT + MV	outer chambers low probability (BREMAT)
5.2	BREMAT + MV	inner chambers (BREMAT), $\lvert\eta^\mu\rvert > 0.6$ (MV)
5.4	BAC + MV	$\lvert\eta^\mu\rvert > 0.6$
5.5	BREMAT + BAC + MV	inner chambers (BREMAT), $\lvert\eta^\mu\rvert < 0.6$ (MV)
5.6	MPMATCH/MUFO	lower quality forward muon
6 = quality 6		
6.1	BREMAT + MV	outer chambers
6.6	MPMATCH or MUFO	with tracks
6.8	MPMATCH/MUFO + MV	lower probability (MPMATCH/MUFO)
7 = quality 7		
7.2	quality 4 & 4	
7.3	quality 5 & 4	
7.4	quality 6 & 4 or quality 5 & 5	
7.5	quality 6 & 5	
7.6	quality 6 & 6	
7.8	muon chambers only	MPMATCH, MUFO or BREMAT
7.9	BAC only & 4	

Table 7.2: μ finder key bin meaning[99].

4 = quality 4

- 4.2: BREMAT 4dof
- 4.4: BAC
- 4.5: BAC/BREMAT+MV, Bad quality or not vtx-assoc.
- 4.6: MPMATCH or MUFO, low prob, with track
- 4.7: MUFO w/o track

5 = quality 5

- 5.1: BREMAT 5dof low prob + MV
- 5.2: BREMAT 4dof + MV, |η|>0.6
- 5.4: BAC+MV, |η|>0.6
- 5.5: BREAMT 4dof + BAC + MV, |η|<0.6
- 5.6: lower quality MPMATCH/MUFO

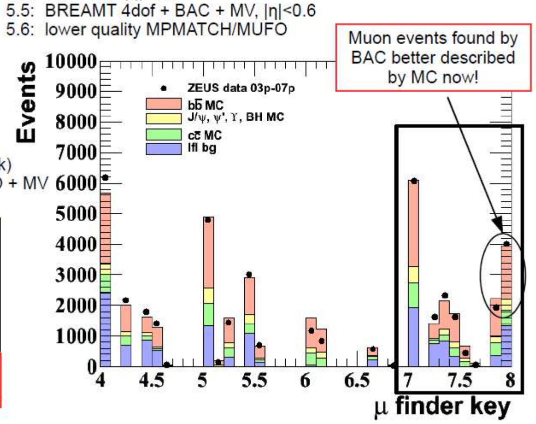
6 = quality 6

- 6.1: BREMAT 5dof
- 6.6: MPMATCH or MUFO (with track)
- 6.8: lower quality MPMATCH/MUFO + MV

7.0: all dimuons

7.2: quality 4+4
7.3: quality 5+4
7.4: quality 6+4, 5+5
7.5: quality 6+5
7.6 quality 6+6

7.8: muon chambers only
7.9: BAC only



with "new" K. Most efficiency corrections
D. Bot, 11.01.12

Recheck consistency: visible beauty cross sections

visible phase space:

$1^{st}\ \mu$: p_T > 1.5 GeV
$2^{nd}\ \mu$: (p > 1.8 GeV for $\eta < 0.6$
p > 2.5 *or* $p_T > 1.5$ GeV for $\eta > 0.6$)
and p_T > 0.75 GeV
both μ: $-2.2 < \eta < 2.5$

Visible cross section: using lumi + MC acceptance + corrections

- Ingo/HERA I paper:

  $\boldsymbol{\sigma_{vis}\ ep \to bbX \to \mu\mu X' = 55 \pm 7\ (stat.)\ {}^{+14}_{-15} (syst.)\ pb}$ (prel: 63)

- Danny/HERA II thesis:

  $\boldsymbol{\sigma_{vis}\ ep \to bbX \to \mu\mu X' = 50 \pm 4\ (stat.)\ {}^{+14}_{-13} (syst.)\ pb}$

- Nazar/HERA II thesis:

  $\boldsymbol{\sigma_{vis}\ ep \to bbX \to \mu\mu X' = 43 \pm 3\ (stat.)\ {}^{+13}_{-11} (syst.)\ pb}$

~~clarify difference~~ in central value between Danny and Nazar

NLO QCD:

$\boldsymbol{\sigma_{vis}\ ep \to bbX \to \mu\mu X' = 33\ {}^{+14}_{-8} (NLO)\ {}^{+5}_{-3} (frag+Br)\ pb}$

Recheck consistency: total beauty cross sections

Total cross section: using MC cross section x scale factor + corrections

- Ingo/HERA I paper:

  $\sigma_{b\ tot}$ **ep→bbX (318 GeV) = 13.1 ± 1.5 (stat.)** $^{+4.0}_{-4.3}$ **(syst.) pb** (prel: 16.1)

- Danny/HERA II thesis:

  $\sigma_{b\ tot}$ **ep→bbX (318 GeV) = 12.6 ± 1.0 (stat.)** $^{+3.6}_{-3.3}$ **(syst.) nb**

- Nazar/HERA II thesis:

  $\sigma_{b\ tot}$ **ep→bbX (318 GeV) = 11.4 ± 0.8 (stat.)** $^{+3.5}_{-2.9}$ **(syst.) nb**

clarify ~~difference~~ difference in central value between Danny and Nazar

NLO QCD predictions:

FMNR+HVQDIS **7.5** $^{+4.5}_{-2.1}$ **nb** (prel: 6.8)

Recheck consistency: double ratios

data/theory (total) / data/theory (vis):

- Ingo/HERA I paper: 1.05
- Danny/HERA II thesis: 1.11
- Nazar/HERA II thesis: 1.17 and paper

~~clarify differences~~

extra systematic differences of non fully clarified origin
are of same order as known
overestimate of muon efficiency systematic (bad argument ...)

acceptable?

Investigation of reported ~10-15% internal inconsistencies

- had two successful investigation sessions with Ingo in 2018/19

- muon efficiency corrections: (confirmation)
  the HERA II corrections were applied (as it should be)
  but the (too large) uncertainties were propagated from the HERA I correction numbers obtained earlier by Danny (uncertainties would shrink)

- luminosity:
  the quoted luminosity (377 pb^{-1}) refers to the number WITHOUT MBTAKE. The number WITH MBTAKE is smaller.
  The muon efficiency corrections are probably those WITH MBTAKE (would increase cross section)

- Branching ratio corrections for b->c->mu vs. b->mu:
  probably not (yet) applied (would reduce cross section)

- extrapolation from visible to total phase space:
  used the HERA I MC corrected number for total cross section
  used uncorrected HERA II MC for total (would need to recheck MCs)

Investigation of reported ~10-15% internal inconsistencies, part II

- further effects were under investigation
  -> did not find time for additional iterations

- already investigated effects partially cancel and net effect is within total systematic errors quoted

- all will ~~be~~ fixed for final paper

Conclusion from consistency checks:

Some as yet only partially clarified systematic differences at the level of ~10-15%, i.e. about 1/3-1/2 of total systematic uncertainty

Reminds differences of the same order between HERA I preliminary and HERA I paper

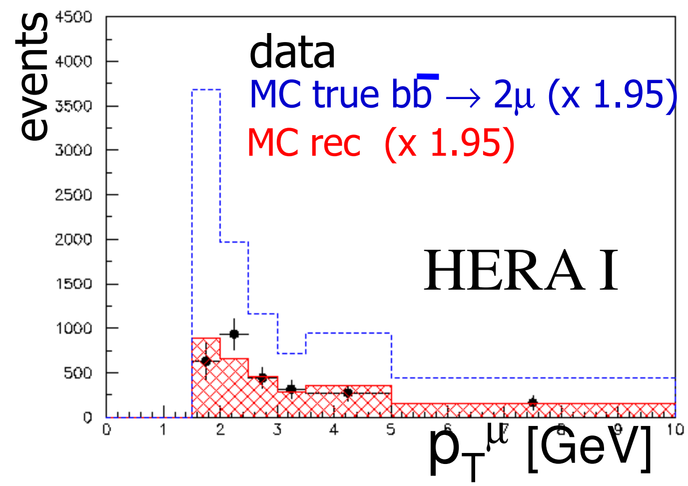
Some time invested with Ingo to investigate origin of differences. Partially successful in locating issues, but no valence (time) found to fix them (very difficult since limited access to original material).

Options:

- **A) ~~clarify and proceed with paper~~**
- **B) ~~as A), but make preliminary prerelease for ICHEP 2018 and add 15% extra systematic uncertainty~~**
- **C) keep values and systematics as is and make preliminary release for ICHEP 2018**
  decision of collaboration in 2018
- **D) keep as is also for paper** **decide today**

Muon differential cross sections - p_T^μ

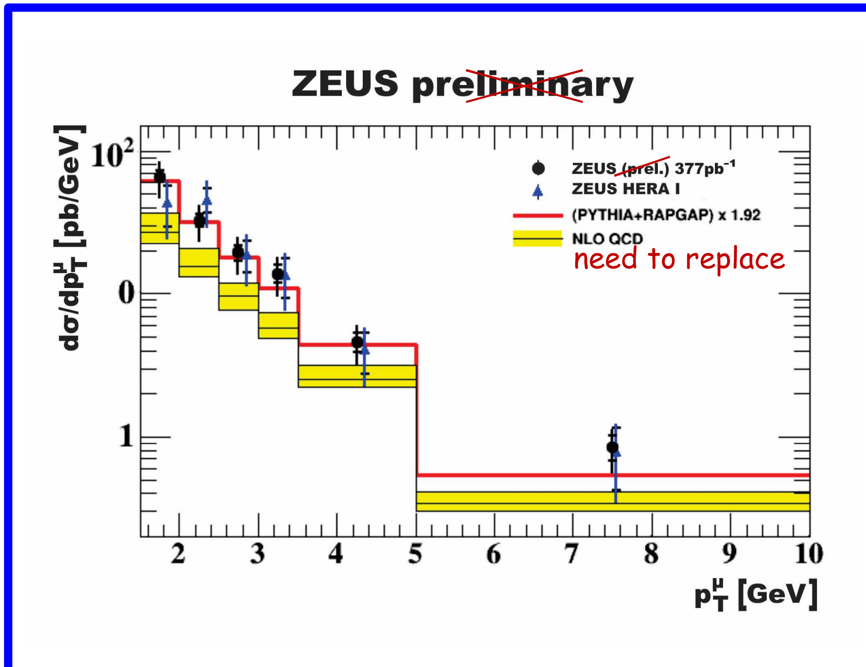
- restrict both μ to
  $p_T^\mu > 1.5$ GeV
  and **$-2.2 < \eta^\mu < 2.5$**
  -> average factor $S_b = 1.92$ (was 1.95 in HERA I)



- extract b signal bin-by-bin
  from unlike vs. like sign contributions:

$$N_{b\bar{b}\to\mu\mu} = \left(N^{\mathrm{u}}_{\mathrm{data}} - N^{\mathrm{l}}_{\mathrm{data}} - (N_{\mathrm{charm}} + N_{\mathrm{VM}} + N_{\mathrm{BH}})\right) \times \left(\frac{N^{\mathrm{u}}_{b\bar{b}} + N^{\mathrm{l}}_{b\bar{b}}}{N^{\mathrm{u}}_{b\bar{b}} - N^{\mathrm{l}}_{b\bar{b}}}\right)^{\mathrm{MC}}$$

$\rightarrow$ cross section in p_T^μ

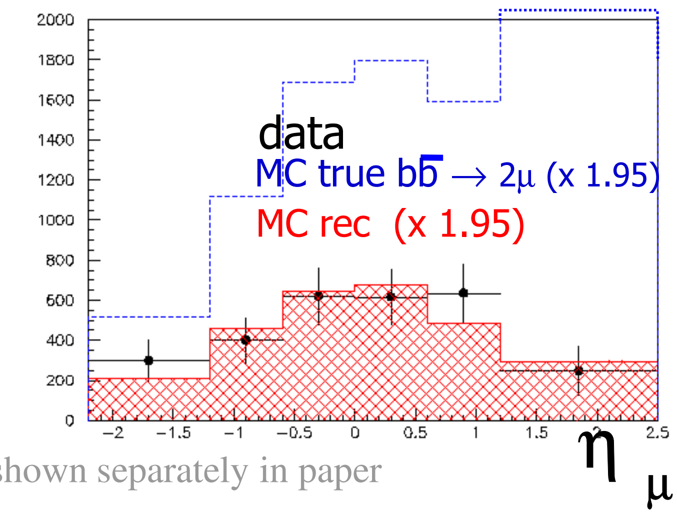


paper plot

Very good description of the p_T shape by the LO+PS MC and NLO (FMNR+PYTHIA)

Muon differential cross sections - η^μ

- restrict both μ to
  $p_T^\mu > 1.5$ GeV
  and **$-2.2 < \eta^\mu < 2.5$**

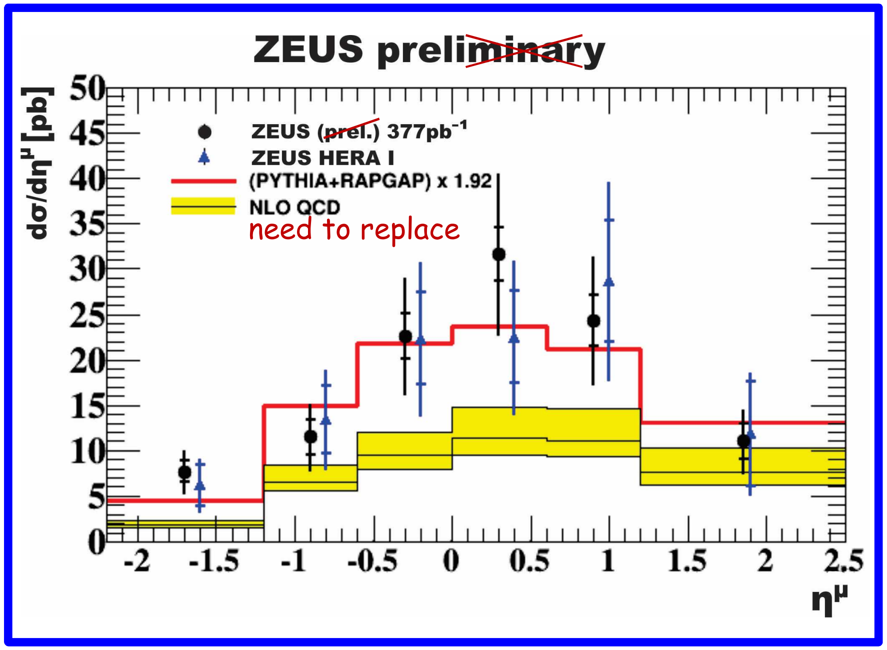


LO+PS and NLO shown separately in paper

- extract b signal bin-by-bin
from unlike vs. like sign contributions:

$$N_{b\bar{b}\to\mu\mu} = \left(N^{\mathrm{u}}_{\mathrm{data}} - N^{\mathrm{l}}_{\mathrm{data}} - (N_{\mathrm{charm}} + N_{\mathrm{VM}} + N_{\mathrm{BH}})\right) \times \left(\frac{N^{\mathrm{u}}_{b\bar{b}} + N^{\mathrm{l}}_{b\bar{b}}}{N^{\mathrm{u}}_{b\bar{b}} - N^{\mathrm{l}}_{b\bar{b}}}\right)^{\mathrm{MC}}$$

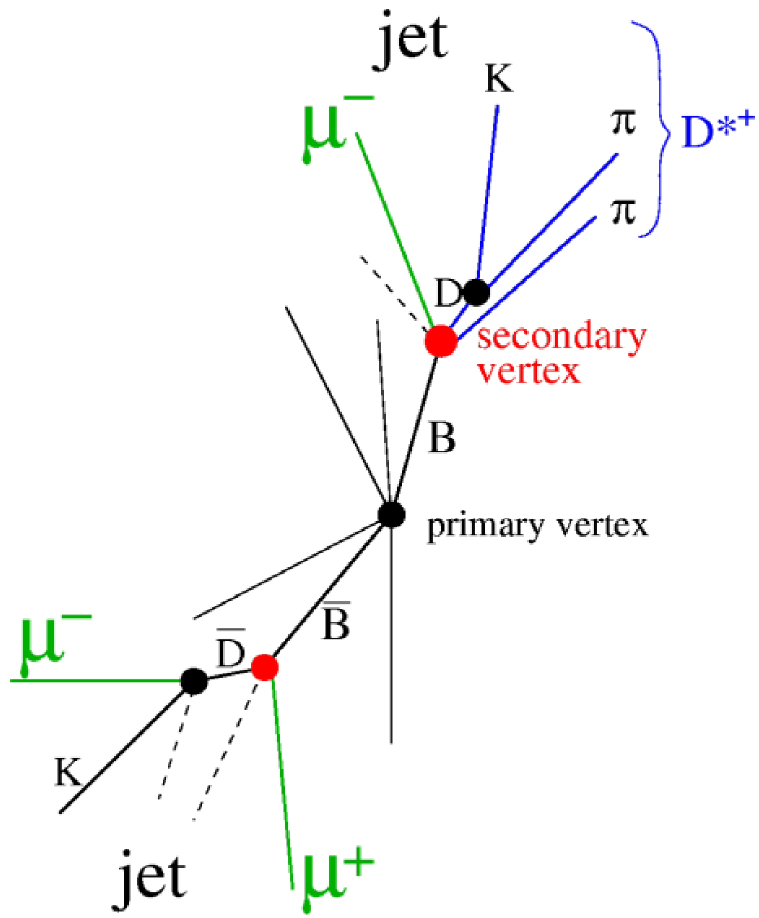
$\rightarrow$ cross section in η^μ

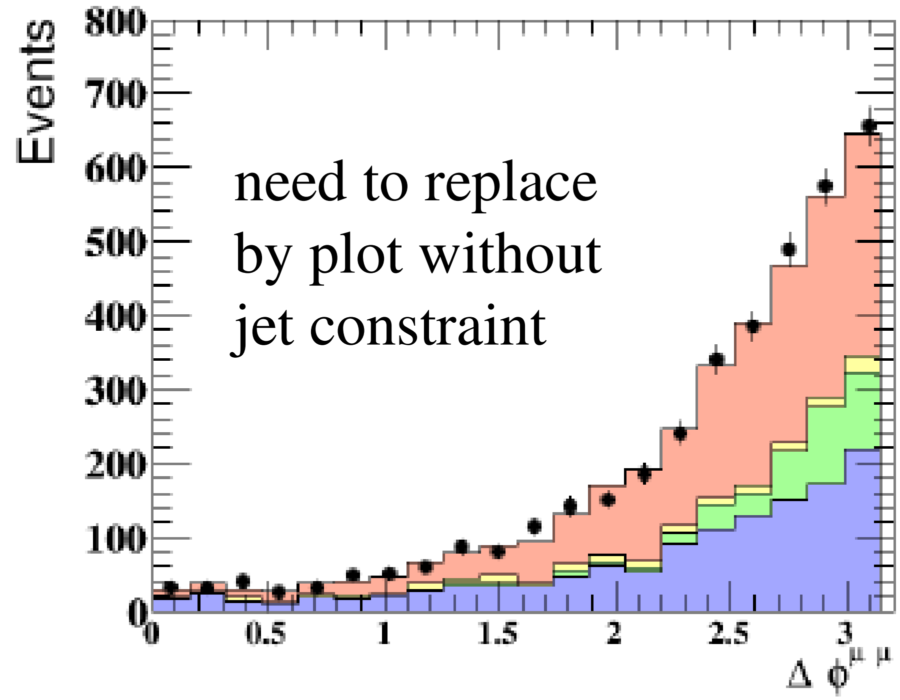


Very good description in shape by the LO+PS MC and NLO in full η and p_T range. NLO low but consistent.

paper plot

Angular correlation distribution - $\Delta\phi^{\mu\mu}$



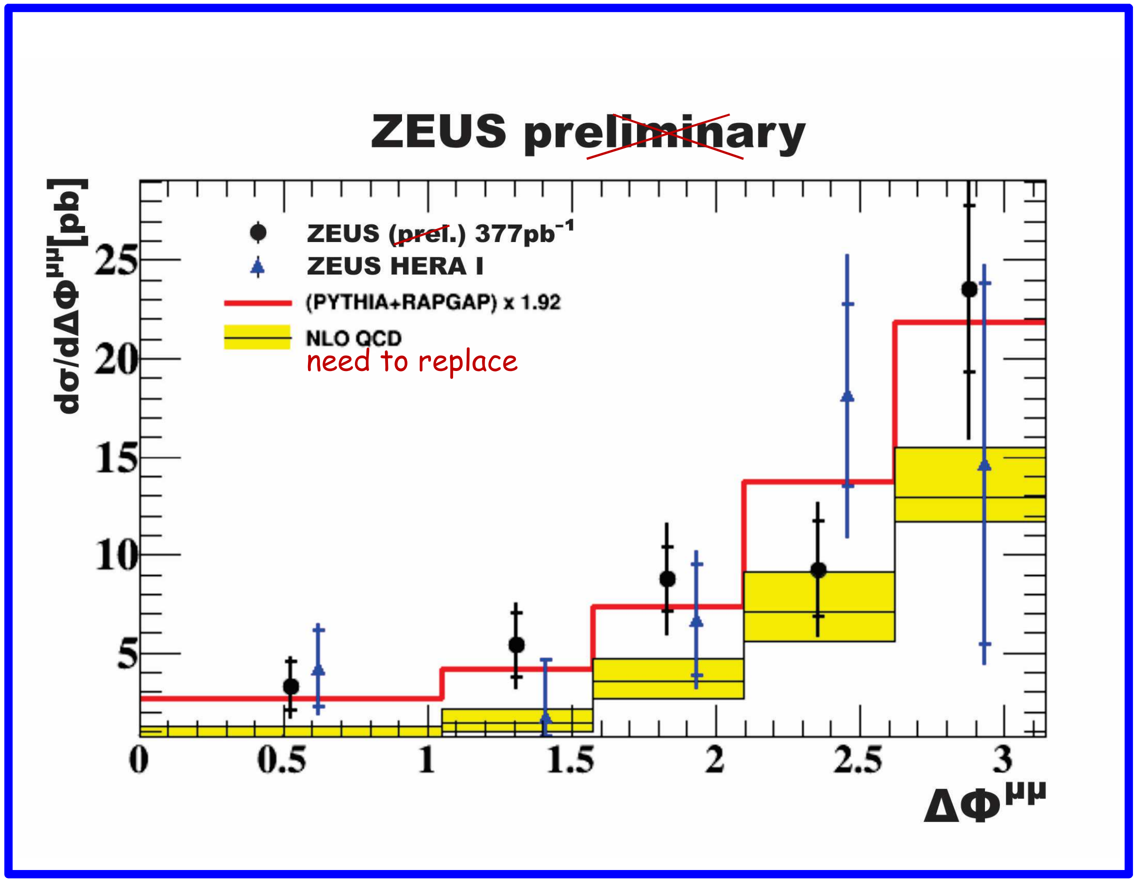


Reconstructed $\Delta\phi^{\mu\mu}$: with $m^{\mu\mu} > 3.25$ GeV

Muon angular correlations - $\Delta\phi^{\mu\mu}$

- restrict both μ to
  $p_T^{\mu} > 1.5$ GeV
  and **$-2.2 < \eta^{\mu} < 2.5$**

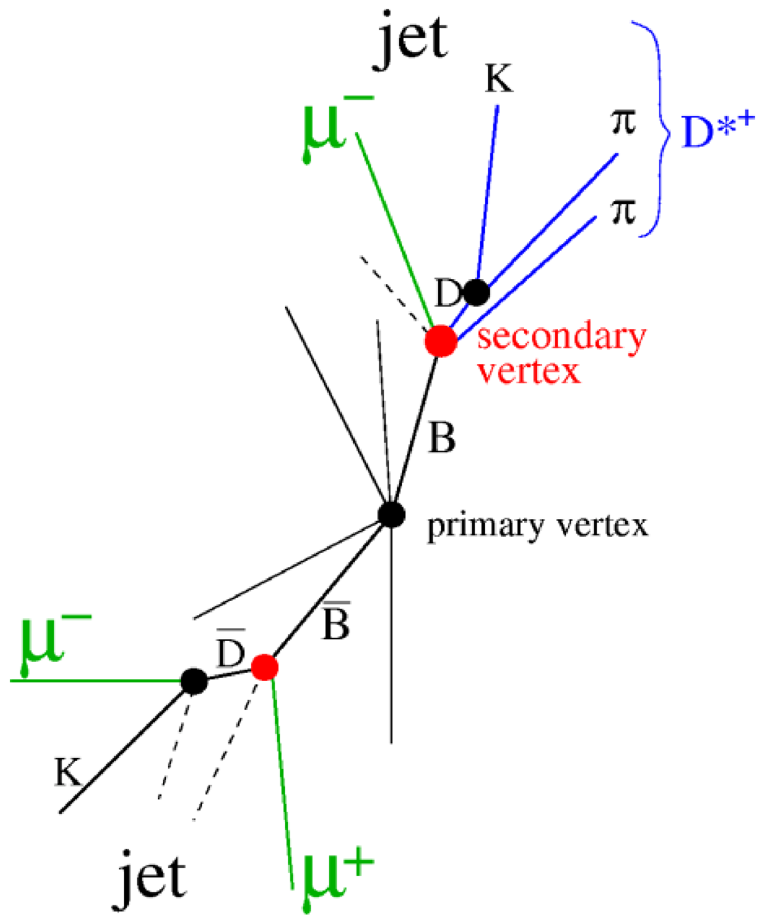
→ **cross section in $\Delta\phi^{\mu\mu}$ for muons from diff. b**

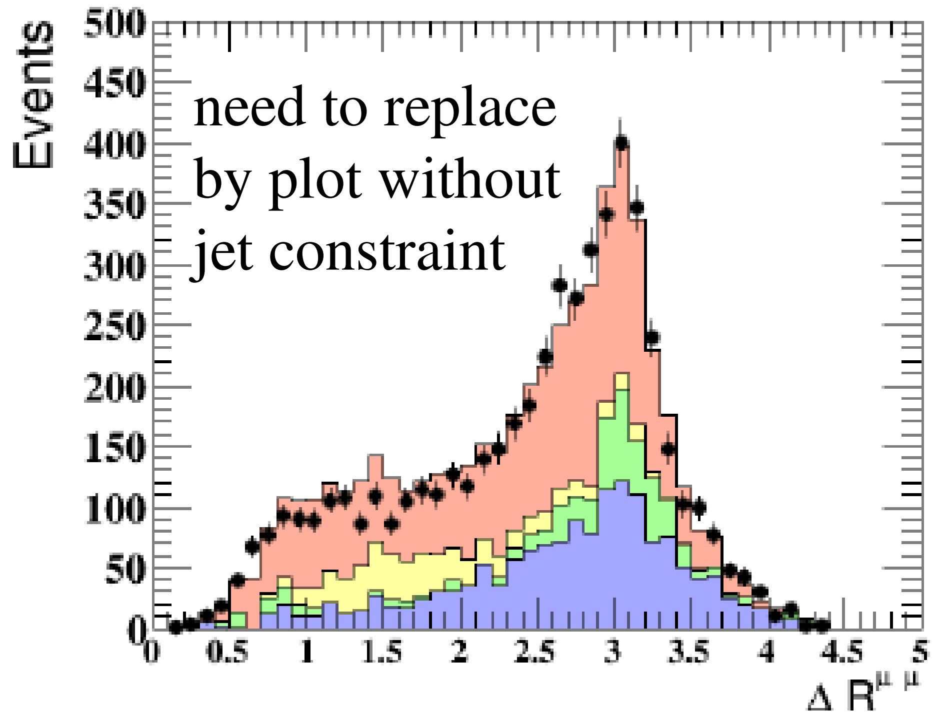


paper plot

reasonable agreement within large errors

Angular correlation distribution - $\Delta R^{\mu\mu}$

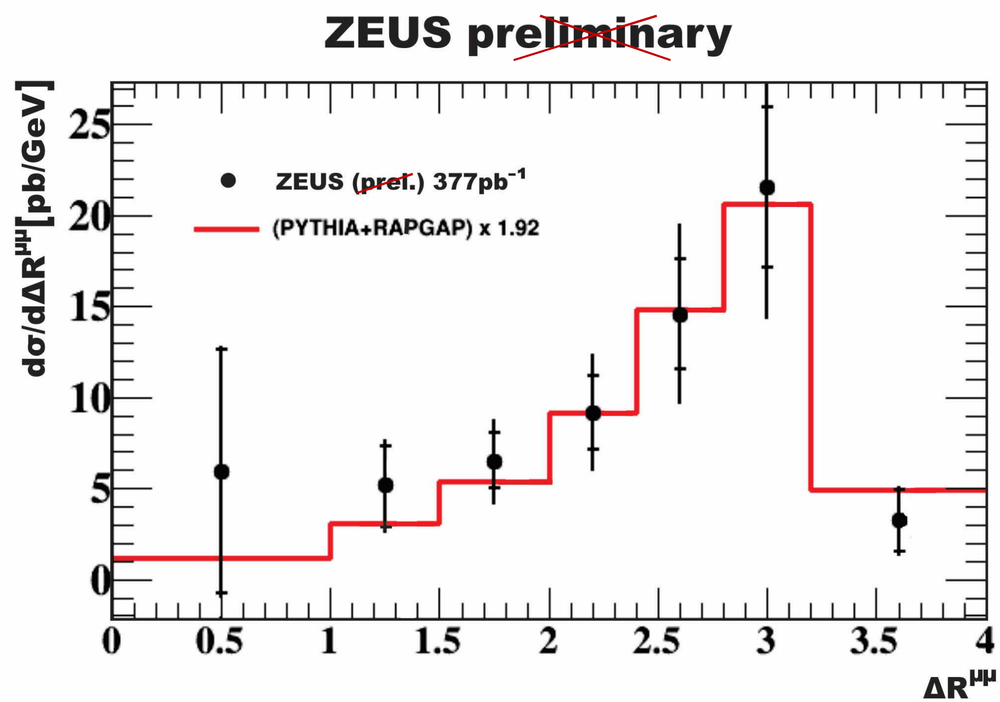




Reconstructed $\Delta R^{\mu\mu}$: (all masses)

Muon angular correlations - $\Delta R^{\mu\mu}$

- restrict both μ to
  $p_T^{\mu} > 1.5$ GeV
  and $-2.2 < \eta^{\mu} < 2.5$



paper plot

→ **cross section in $\Delta R^{\mu\mu}$ for muons from diff. b**

was not published previously (statistics)
-> NLO prediction was not calculated

Conclusion for cross sections

- Measured **Beauty cross sections with**
  - **large acceptance** (extended η^{μ} and p_T^{μ} range) / **low extrapolation**
  - **sensitive to very low p_T^b**
  - **high beauty purity of ~ 50%**
- Confirmation of measurement of **total beauty cross section** at HERA
- **Differential cross sections**
  - good agreement in shape **with LO+PS and HERA I, smaller uncertainties**
- **Reasonable agreement with NLO**, generally slightly lower than data
  - **no particular trend in p_T or η** (as before)
- New distribution: Delta R (not enough statistics in HERA I)

Search for QCD instanton contribution

- Introduction/history
- Signal signatures
- Results
- Conclusions

Why/how to look for QCD instantons in ep collisions at HERA? More in talk tomorrow !

- **Chirality** (all left or all right)
  … difficult to access experimentally
- **Flavour democracy !?**

relates pion and proton masses
-> understand mass of
visible part of the universe

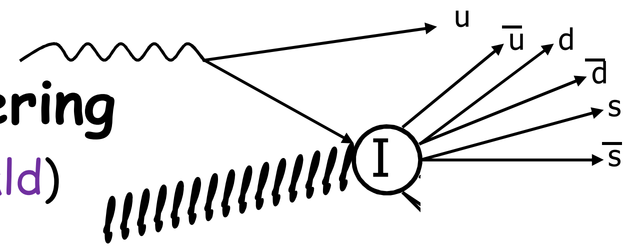
  - 2 flavours: pion propagation through instanton-antiinstanton hopping

    $u_L + \bar{d}_L$ -> $u_R + \bar{d}_R$ -> $u_L + \bar{d}_L$ -> … -> calculate pion mass on lattice

  - 3 flavours:

    light instantons in Deep Inelastic Scattering

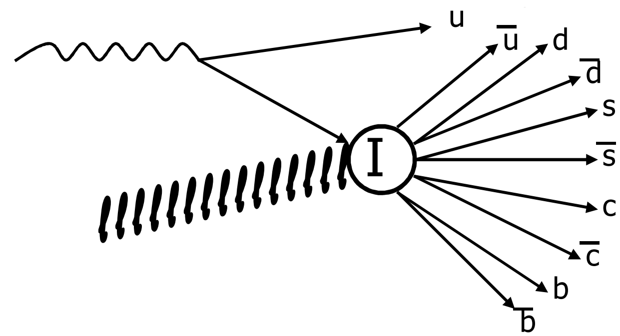
    (DIS needed to provide virtuality, see talk A. Ringwald)



  - 4 or 5 flavours: "new"

    "heavy" instantons in photoproduction

    (minimum virtuality provided by heavy quarks)



  - up to 6 flavours?: LHC

Search for QCD instanton contribution to beauty cross section from dimuon events at HERA II

- physics goal: first ever check of heavy-flavour-induced QCD instanton production (untested part of Standard Model)

History: (long term project ☺)

- Diploma Thesis D. Bot 2008: **adapt QCDINS program** (for prediction of QCD instantons in DIS at HERA with ddbar + uubar + ssbar final states) to prediction of ddbar+ uubar + ssbar + ccbar + bbbar final states in photoproduction, with kind support from F. Schrempp.
- basic **HERA II** analysis, PhD thesis, D. Bot, 2011, sections 5.12 and
  (but bug in instanton MC sample, e and p directions interchanged)
- **redo analysis** with correct MC sample, PhD thesis, N. Stefaniuk, 2017, appendix D
- **revival of interest** through instanton and sphaleron workshop, december 2020

"Heavy flavour" instantons at HERA II

N. Stefaniuk, **DESY-THESIS-2017-038 Appendix D, using ZEUS data**

With the support of F. Schrempp, modified QCDINS to work for N_F=5 also in photoproduction
(Diplom thesis D. Bot, DESY-THESIS-2008-014, in German)
photon virtuality -> incoming heavy quark virtuality

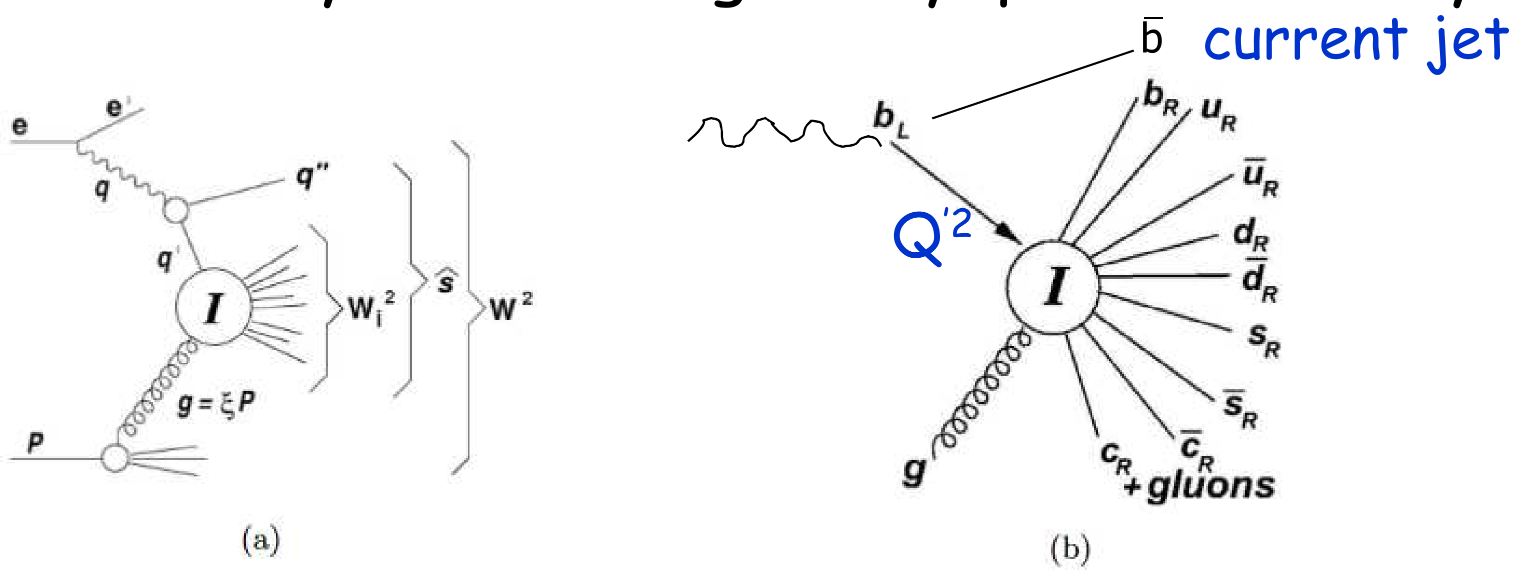


Figure 7.24: QCD instanton-induced events production diagram.

-> correct kinematics, unknown normalization (mass effects)
"mass unsuppressed" N_F=5 prediction:
16% of total bbar cross section -> try 8% +- 8%

“Heavy flavour” instantons at HERA

D. Bot, DESY-THESIS-2011-032, section 5.12

5.12 Reconstruction of instanton kinematics

For the experimental verification of instanton-induced events at HERA, the reconstruction of both, the kinematic variable Q'^2, which is the virtuality of the quark entering the instanton-subprocess, and the *instanton band*, a limited area in the $\eta - \phi$ plane, in which the particles of the instanton-decay are distributed, is essential. In Fig. 5.23, the kinematics of the instanton process in ep collisions is shown: The photon with four-momentum q fluctuates into a $q\bar{q}$ pair, one of which with four-momentum q' enters the instanton subprocess and the other quark with four-momentum q'', referred to as *current quark*, forms a jet with high transverse energy. Analogous to the photon virtuality Q^2, the virtuality of the quark q' is given by

$$Q'^2 = -q'^2 = -(q - q'')^2 \tag{5.33}$$

Several instanton analyses have shown [7–10,15], that the current quark q'' and the hadronic jet with highest transverse energy, E_T^{Jet}, are well correlated. Using this identity and the Jacquet-Blondel method (cf. Sec. 5.10) yields for the reconstructed quark virtuality Q'^2 [8,15]:

$$\boxed{Q'^2_{rec} = \sum(E_i - p_{z,i}) \cdot (E_{Jet} + p_{z,Jet}) - m^2_{Jet}.} \tag{5.34}$$

“Heavy flavour” instantons at HERA

D. Bot, DESY-THESIS-2011-032, section 5.12

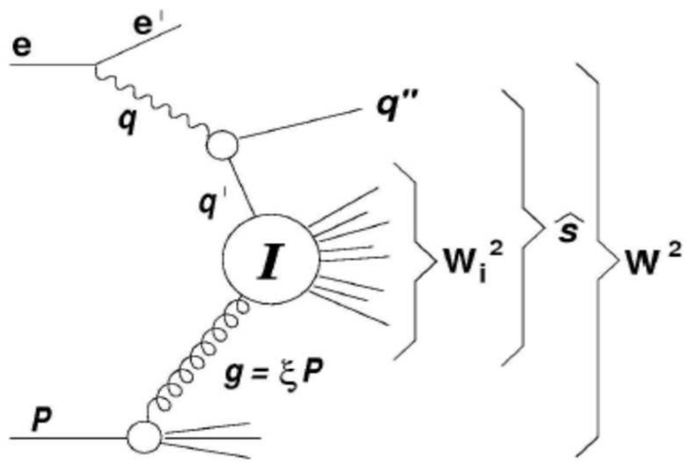


Figure 5.23: Reminder: Feynman diagram of instanton-induced processes in *ep* collisions at HERA.

All EFOs, which are neither part of the proton remnant nor of the jet with highest E_T, "form" the instanton. As a consequence of the homogeneous energy and parton distribution in the instanton rest-frame, a band structure in the $\eta - \phi$ plane is expected, referred to as instanton band. The band is defined to have a width of ± 1.1 units in η around a mean $\bar{\eta}$, the middle of the instanton band [7]:

$$\bar{\eta} = \frac{\sum E_{T,h}\eta_h}{\sum E_{T,h}}. \tag{5.35}$$

The sum of all EFOs in this band will be defined as *particle multiplicity* N_{Band}. Since heavy-flavour instantons contain both, a $b\bar{b}$ and $c\bar{c}$ pair, the expected parton multiplicity in instanton-induced events should be higher than in charm or beauty events,

“Heavy flavour” instantons at HERA

D. Bot, DESY-THESIS-2011-032, section 5.12

5.12.1 Separation from beauty quark events

Besides the reconstruction of the kinematic variables of instanton-induced events, so-called *event shape variables* [163], e.g. the (pseudo) thrust, sphericity, isotropy, oblateness, aplanarity etc., have proven to be very useful for the separation of instanton events from normal DIS and photoproduction events. In principle, instantons are expected to "decay" isotropically in their rest-frame. As a result, hadrons from the instanton-subprocess should be distributed homogeneously in the instanton-band and in the detector. Event shape variables are quanitities sensitive to the distribution of particles in the lab- and specific center-of-mass frames, allowing to separate isotropic events from dijet-systems (e.g. charm and partially beauty) events. Three of these quantities, which are used in this analysis, are described in the following.

Sphericity

The sphericity *Sph* [164, 165] is calculated for all EFOs in the lab frame which are neither part of the proton remnant nor of the current jet. The diagonalised *sphericity tensor*, given by

$$Sph^{\alpha\beta} = \frac{\sum_i p_i^\alpha p_i^\beta}{\sum_i |p_i^2|}, \quad \alpha, \beta = x, y, z \tag{5.36}$$

yields three different positive eigenvalues $\lambda_{1,2,3}$ fulfilling the following relations:

$$0 \leq \lambda_1 \leq \lambda_2 \leq \lambda_3 \quad \text{and} \quad \lambda_1 + \lambda_2 + \lambda_3 = 1. \tag{5.37}$$

Then the sphericity quantity can be defined as:

$$\boxed{Sph = \frac{3}{2}(\lambda_1 + \lambda_2).} \tag{5.38}$$

In the case of (di)jet-like events, the sphericity has values close to 0, in the case of isotropic events values close to 1.

"Heavy flavour" instantons at HERA

D. Bot, **DESY-THESIS-2011-032, section 5.12**

Isotropy

The isotropy Δ_B [166] is calculated for all EFOs within the reconstructed instanton band after a Lorentz-boost into the instanton rest-frame. This quantity is defined as:

$$\boxed{\Delta_B = \frac{E_{\mathrm{in,B}} - E_{\mathrm{out,B}}}{E_{\mathrm{in,B}}},} \tag{5.39}$$

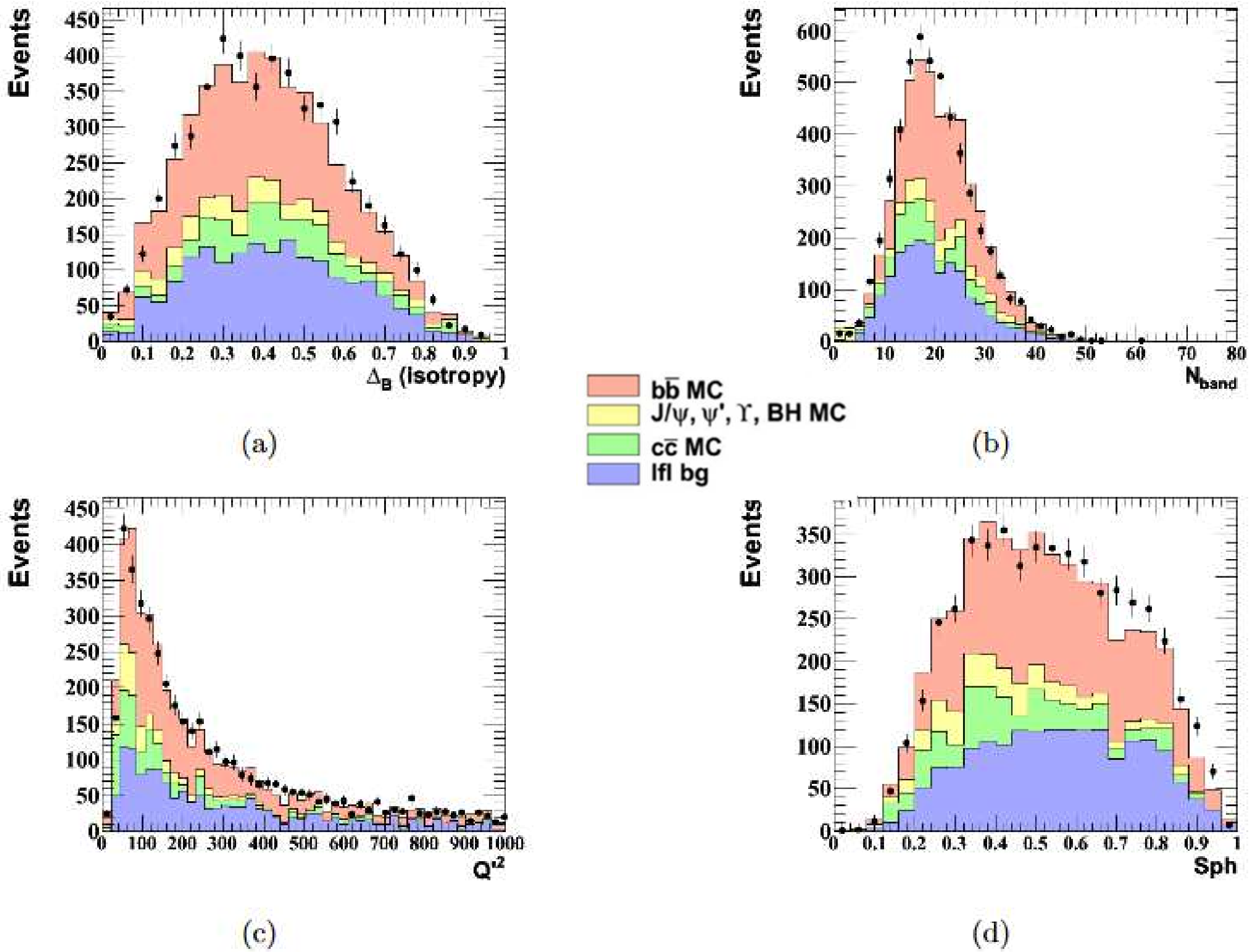
with

$$E_{\mathrm{in,B}} = \max \sum_h |\vec{p_h} \cdot \vec{i}| \quad \text{and} \quad E_{\mathrm{out,B}} = \min \sum_h |\vec{p_h} \cdot \vec{i}|, \tag{5.40}$$

where h denotes the EFOs in the instanton band and $\vec{p_h}$ their momenta. The maximum of $E_{\mathrm{in,B}}$ and the minimum of $E_{\mathrm{out,B}}$, respectively, are obainted by trying out all orientations of the unit-vectors $\vec{i}$. For (di)jet-like events, the isotropy variable has values close to 1 and approaches 0 for isotropic events.

Heavy flavour instantons at HERA II

N. Stefaniuk, **DESY-THESIS-2017-038 Appendix D, using ZEUS data**



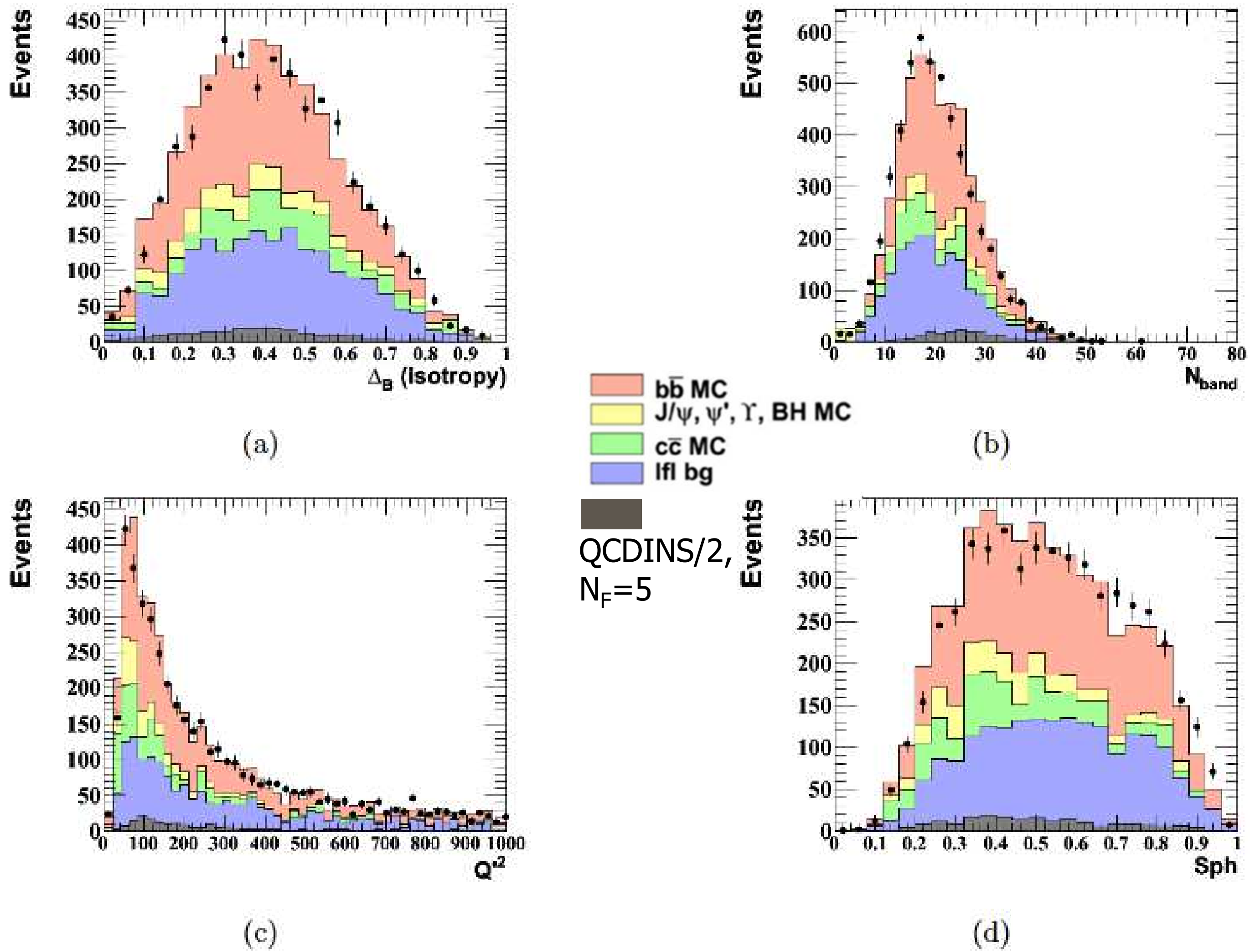
instanton-sensitive variables

same dimuon event selection as for beauty cross section

Figure 7.25: The isotropy(a), instanton band(b), quark virtuality(c) and sphericity(d) without instanton events included.

Heavy flavour instantons at HERA II

N. Stefaniuk, **DESY-THESIS-2017-038 Appendix D, using ZEUS data**



no improvement
->
no indication for sizeable instanton contribution

(qualitative only)

Figure 7.26: The isotropy(a), instanton band(b), quark virtuality(c) and sphericity(d) variables with instanton events included.

Conclusion for potential instanton contribution

- first investigation ever of instanton induced contribution to **beauty cross section** (or any other heavy flavour cross section)
  - **mass-unsuppressed prediction of QCDINS ~16%**
    (upper limit, actual mass-suppressed contribution presumably much lower, but suppression factor unknown)
  - **-> test contribution of 8+-8%**
- **no indication for presence of such a contribution at HERA**
  (might just be much smaller)
- **presented at sphaleron and instanton workshop, december 2021**
- **qualitative result only, but might contribute to stimulate searches for a corresponding contribution at LHC** (much larger cross section, much larger luminosity, better flavour tagging, theory calculations ongoing, analyses in preparation)