Status of paper

Measurement of beauty production from dimuon events at HERA II

A. Geiser, N. Stefaniuk, I. Bloch
ZAF 19.6.2018

- 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
- basic **HERA II** analysis, PhD thesis, D. Bot, 2011 (with HERA I muon corrections)
- **muon efficiency calculations** for HERA II, K. Most, Master thesis 2011
- add **MVD secondary vertex analysis**, PhD thesis, N. Stefaniuk, 2017
- write **HERA II paper**, A.G., 2018 -> **status today** (see also presentation 30.1.18)
- **Possibly preliminary request for ICHEP18 (to be decided)**

ZAF 30.1.18: To do for paper

- paper writing started
- recheck self-consistency of all numbers
- recheck and possibly complete list of systematics

- preliminary prerelease for summer conferences?

Ingo will help on conceptual checks (with limited time)
meeting scheduled for Jul 3

not yet and
Nazar is reachable but response to requests will probably be slow

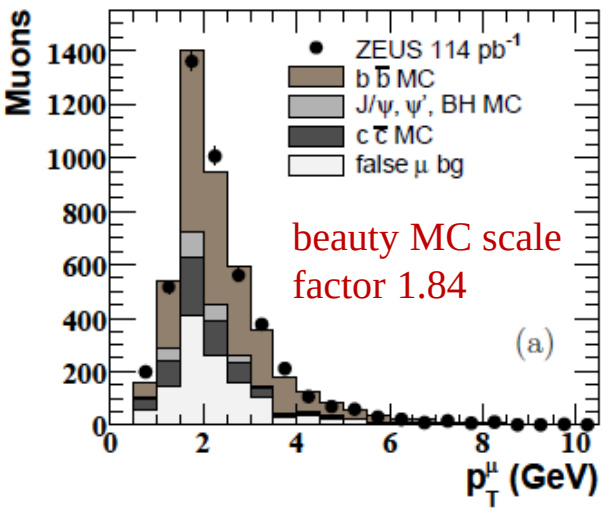
Feedback?

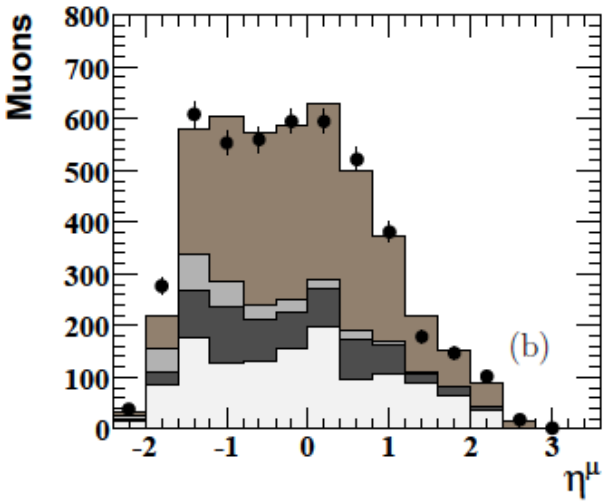
-> **decision: use charm fraction fit from MVD as part of systematic checks only + refer to thesis Nazar for details**

Recheck self-consistency: data and MC

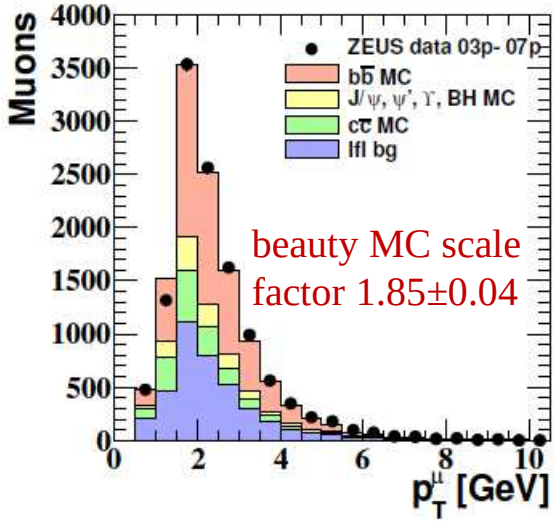
- e.g. nonisolated unlike sign muon pairs: **data and MC consistent !**

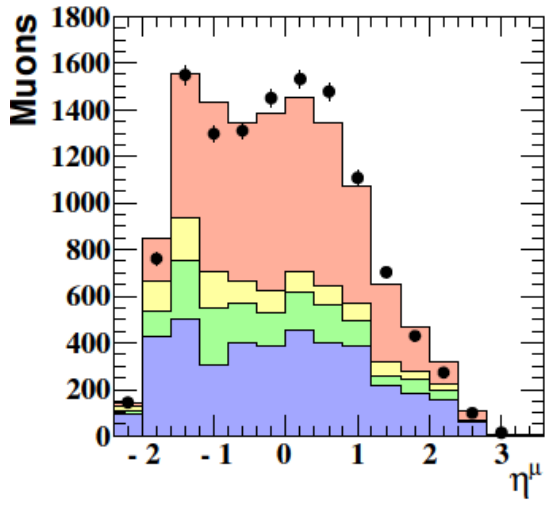
Ingo/HERA I paper



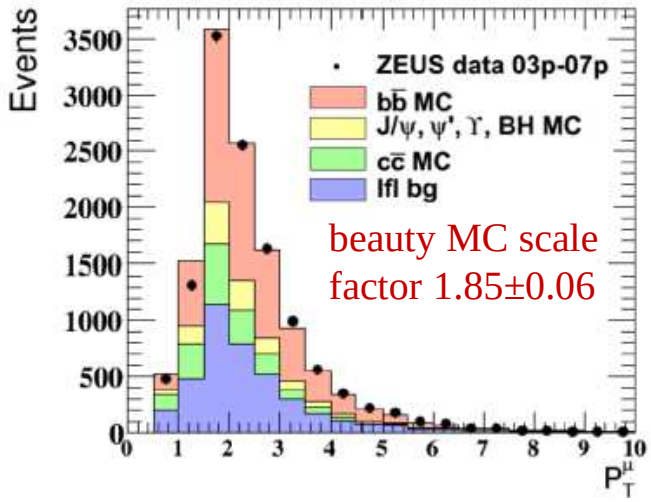


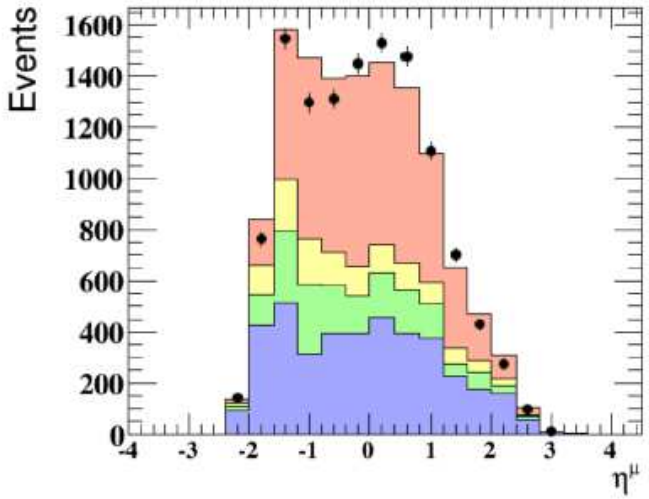
Danny/HERA II thesis





Nazar/HERA II thesis





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:
  σ_{vis} **ep→bbX→μμX' = 55 ± 7 (stat.) $^{+14}_{-15}$ (syst.) pb** (prel: 63)

- Danny/HERA II thesis:
  σ_{vis} **ep→bbX→μμX' = 50 ± 4 (stat.) $^{+14}_{-13}$ (syst.) pb**

- Nazar/HERA II thesis:
  σ_{vis} **ep→bbX→μμX' = 43 ± 3 (stat.) $^{+13}_{-11}$ (syst.) pb** (± extra 15%?)

Need to clarify difference in central value between Danny and Nazar

NLO QCD:
σ_{vis} **ep→bbX→μμX' = 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** (± extra 15%?)

Need to clarify 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

Need to clarify differences

Summary of systematic uncertainties (visible cross section)

Muon efficiency correction:		**HERA I**
Use BRMUON only or BAC only; Trigger	**+20.2% -18.4%; --**	**+-15%; +-5%**
D. Bot, 11.1.2012: should actually be	**+14.2% -11.4%; +-5%?**	
Dimuon isolation; vary cut by 500 MeV (data and MC):	**+2.7% -3.0%**	**+-2%**
CAL ET; vary cut by 1 GeV (data and MC):	**+3.5% -2.2%**	**+-2%**
Bethe Heitler and Quarkonia contributions; change normalisation of nonisolated fraction by +-50%:	**+10% -3%**	**+-10%**
Charm contribution; vary by +-20% (to be revisited):	**+6% -10%**	**+-12%**
Charm and beauty spectral shape; Variation of direct and nondirect fractions		
charm:	**+-2%**	**+0/-4%**
beauty:	**+-12%**	**+4/-12%**
BBbar oscillations; other b model uncertainties	**+-4%; +-12%**	**+-4%; +-12%**
Variation of like/unlike sign light flavour ratio by 3%:	**+3% -1%**	**+-3%**
Luminosity:	**+-2%**	**+-2%**
	-------	**---------**
	+30% -28%	**+26% -28%**
Clarification of differences in cross section calculations:	**(+-15%) ?**	

	+34% -32%	

Muon finder distributions before/after efficiency corrections

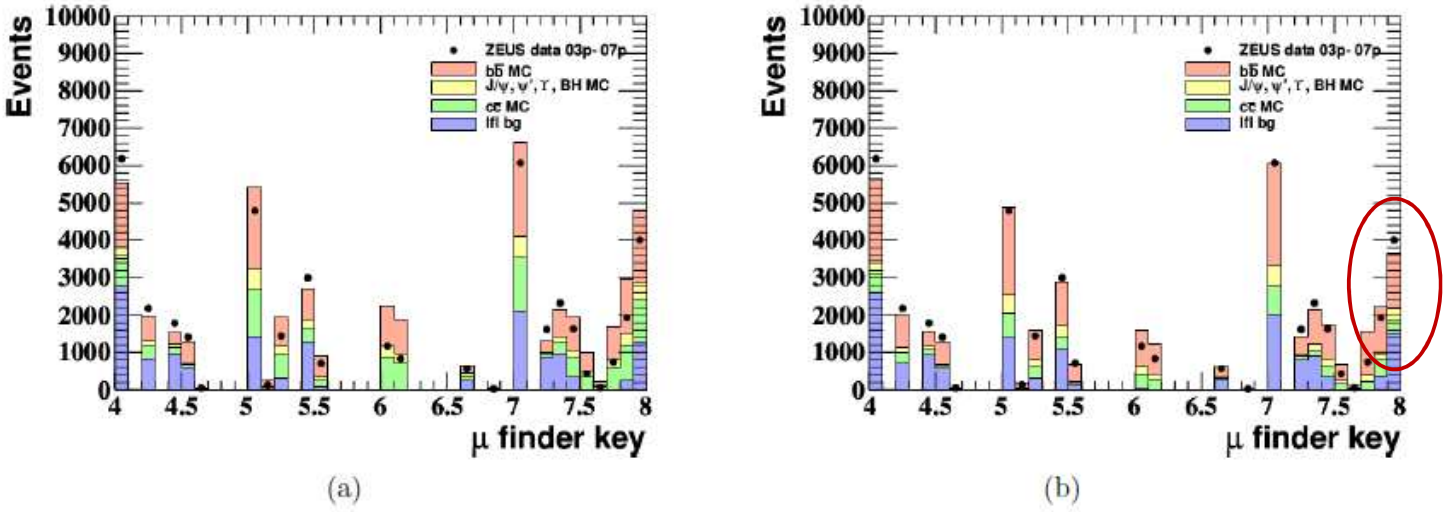


Figure 3.2: Distribution of muon finder combinations for dimuon events left: before and right: after applying the muon efficiency corrections.[99]. The μ finder key description is shown in table 7.2.

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	

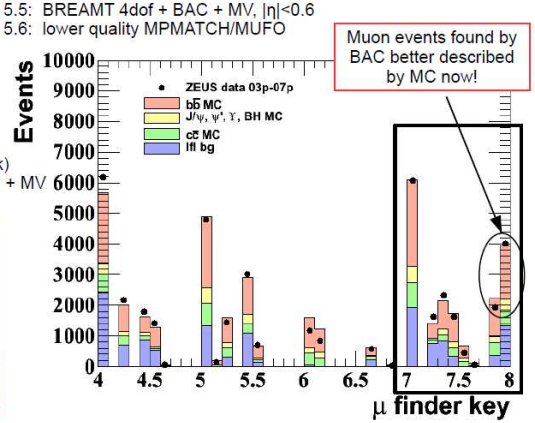
Table 7.2: μ finder key bin meaning[99].

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 efficiency corrections
D. Bot, 11.01.12

Conclusion from consistency checks:

Some as yet not 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

Appointment with Ingo on July 3 to look into this further (not in time for ICHEP)

Options: A) clarify and proceed with paper
B) as A), but make preliminary prerelease for ICHEP and add 15% extra systematic uncertainty

Do we still want to go for preliminary? (very tight)

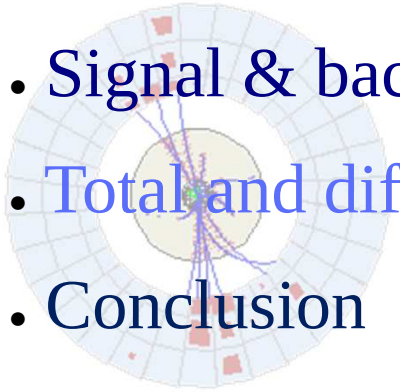
Also technical problem: currently no access to figures
(-> no document, no cosmetics)

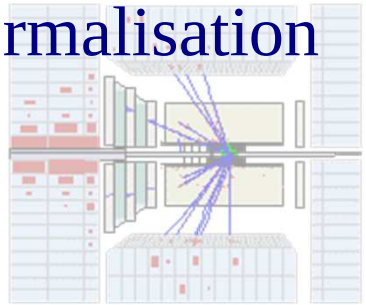
If not (directly go for paper) talk ends here, and remainder is backup (essentially copy of presentation of 30.1.18)

Outline of potential preliminary request

Measurement of beauty production from dimuon events at HERA II

- Introduction
- Event Selection
- Signal & background signatures / normalisation
- Total and differential cross sections
- Conclusion
- To do

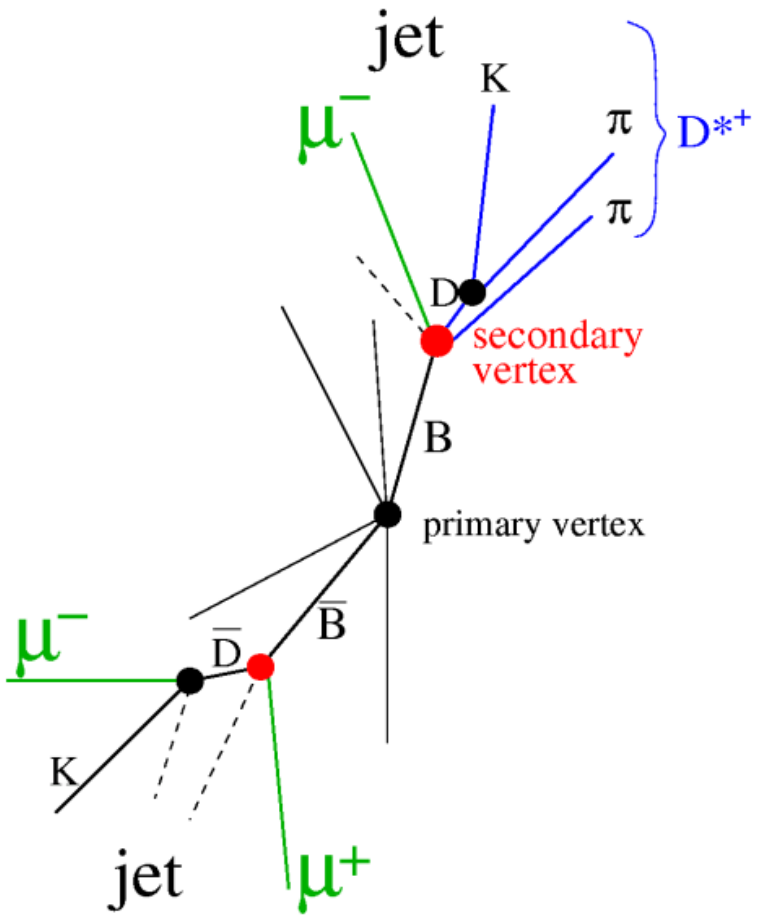




Goals of the μμ analysis

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

data samples:

- **HERA II, 03-07, $L \sim 377\ pb^{-1}$** (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**
- **$p_T^{\mu} > 0.75$ GeV** for muon quality ≥ 5, **$p_T^{\mu} > 1.5$ GeV** for muon quality ≥ 4
- simplified for differential cross sections: **$p_T^{\mu} > 1.5$ GeV** for both muons

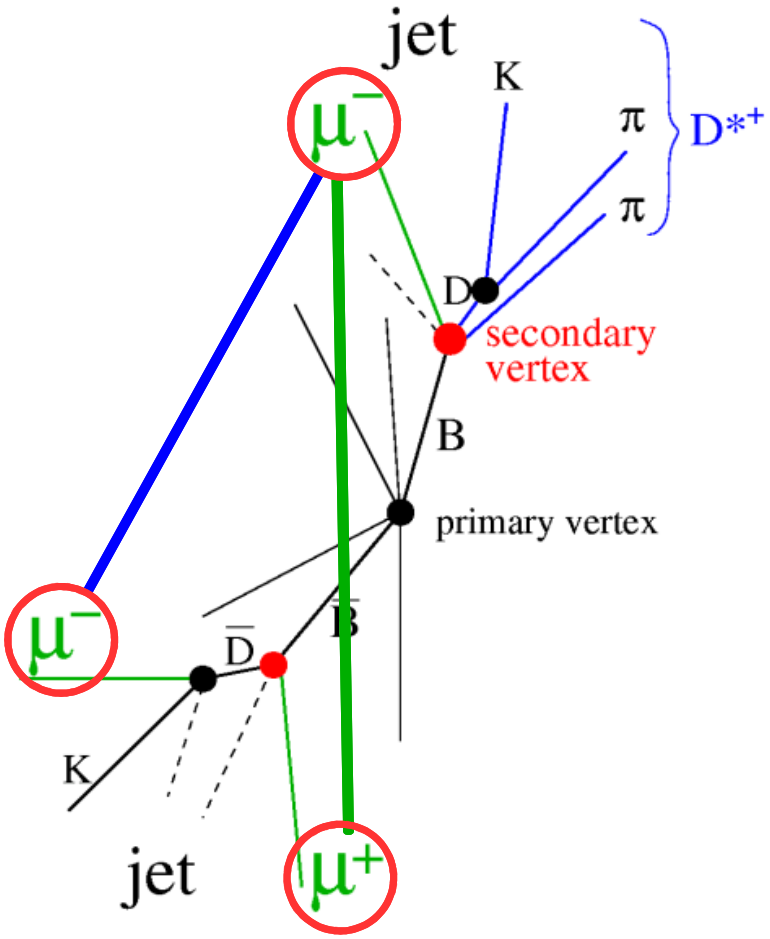
MC samples:

- **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**

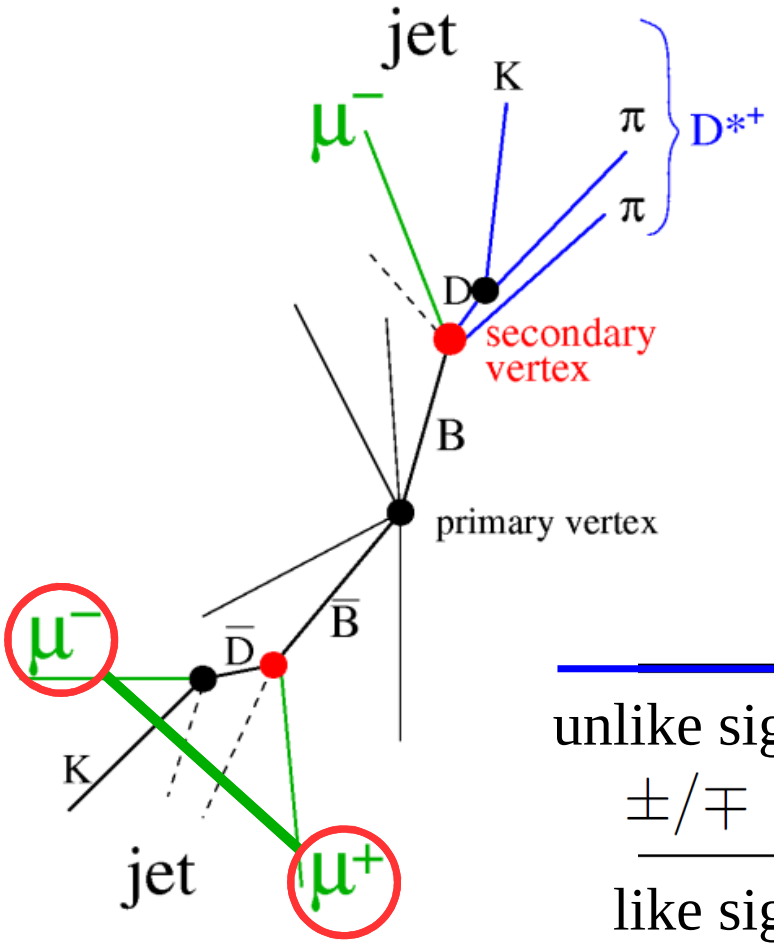


- **muons from different b´s**
  - → **like or unlike sign**
    (secondary c decays or $B^0\bar{B}^0$ mixing)
    opposite hemispheres
    high dimuon mass

- **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 $b \to J/\psi$)

  → **unlike sign**

  same hemisphere

  dimuon mass < 4 GeV

  (B mass - hadrons/neutrinos)

- **useful contribution to total cross section**

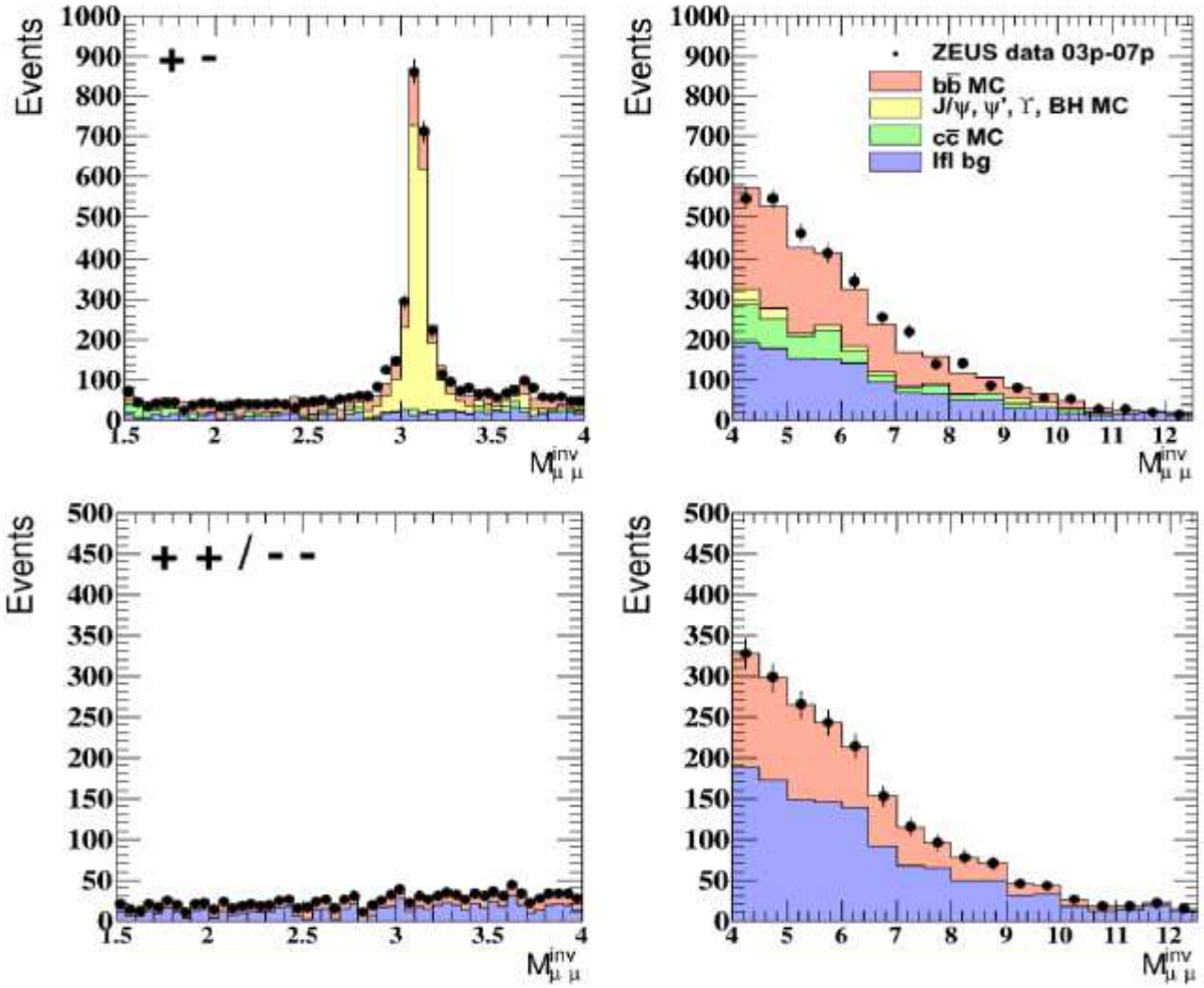
→ **classify data into subsamples:**

	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

low mass

high mass

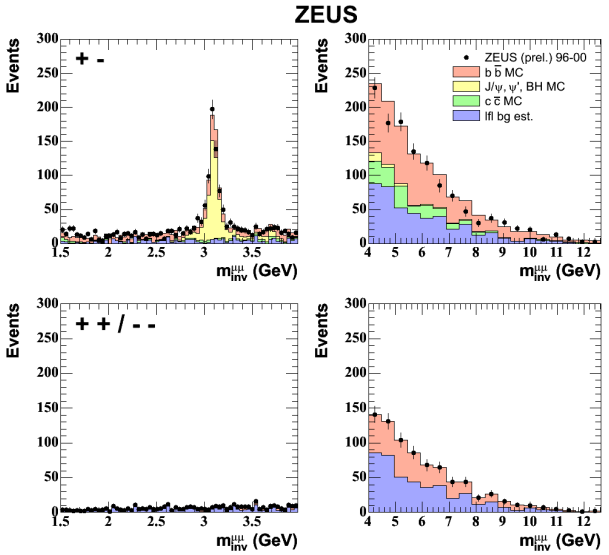


prospective preliminary plot

data well described by MC.

beauty contribution:
~5200 events

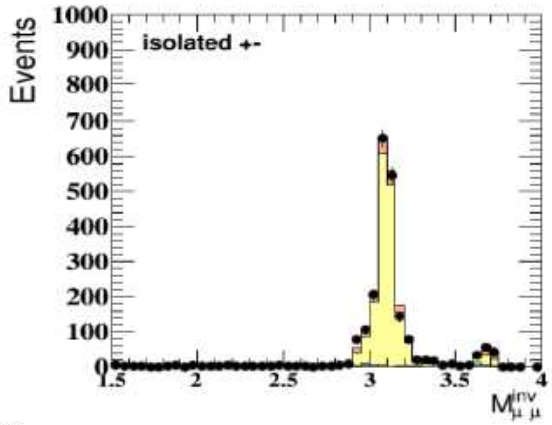
(Hera I: 1900 ± 210 events)



Normalisations

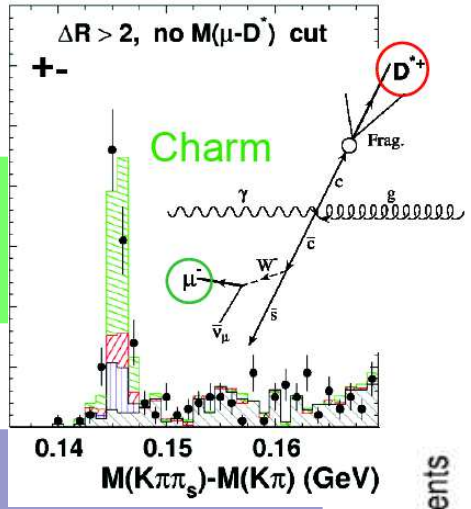
Short summary - normalisation procedure identical to HERA I paper:

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



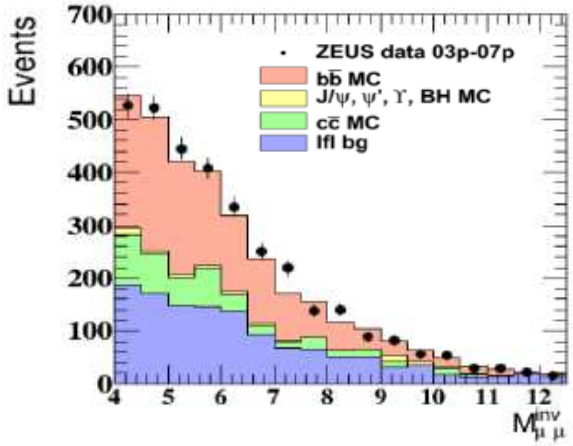
Charm: Normalised using **b→D*μ charm normalisation**

$S_c = 1.37 \pm 0.20$



will be adjusted/rechecked later

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



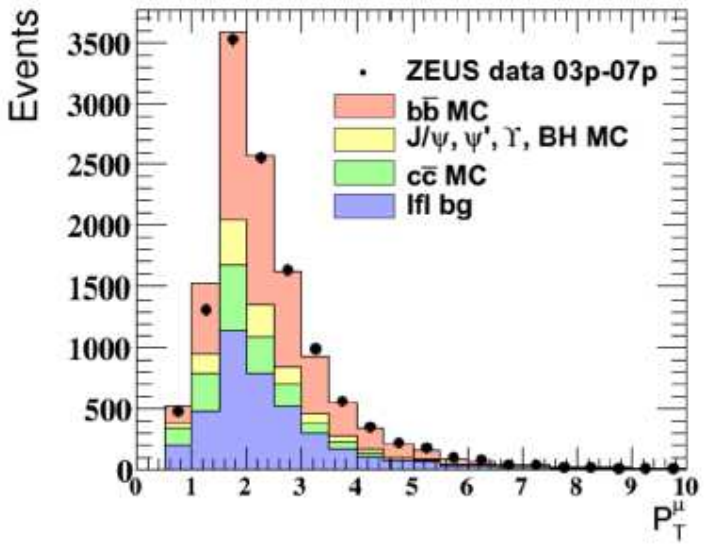
Beauty: Determined using **difference of like and unlike sign dimuon events**.

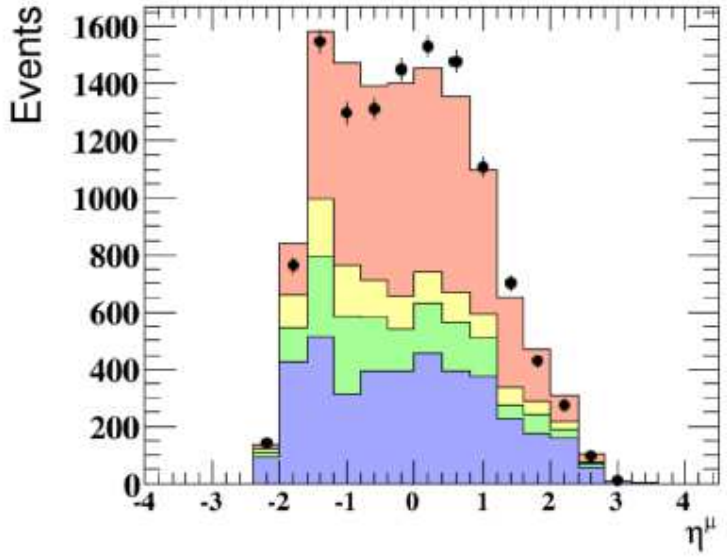
$$d^u = b^u + bg^u_{lfl} + c^u + J/\psi^u + \psi'^u + BH^u$$

Muon p_T and η distributions

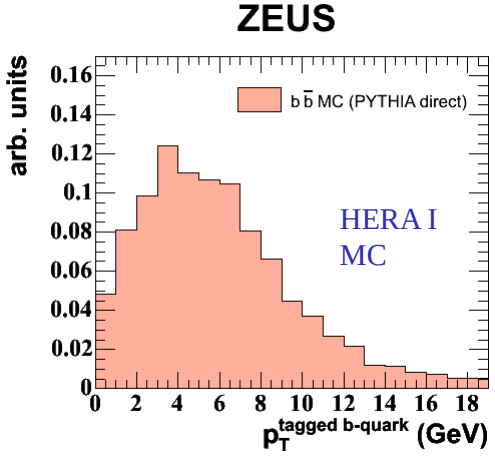
nonisolated unlike sign muon pairs

prospective preliminary plots





p_T of tagged b quark:



acceptance down to **very low p_T**

very **large η range** (-2.2 to +2.5)

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

sensitive to total $b\bar{b}$ cross section!

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"

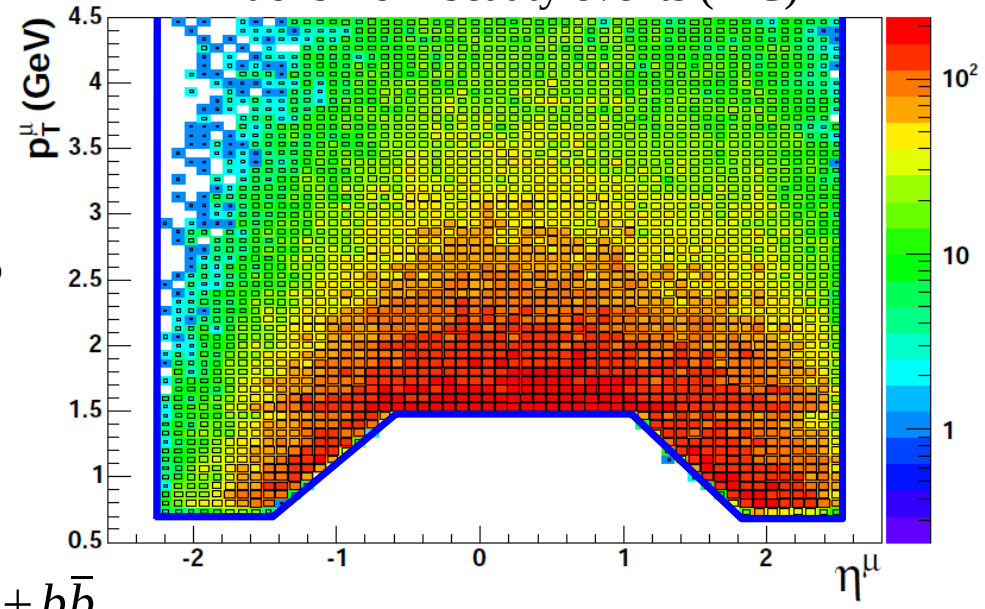
Visible cross section

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: $-2.2 < \eta < 2.5$

Muons from beauty events (MC)



$$N_{b\bar{b}\to\mu\mu} = [data_{unl} - data_{like} - \{charm/BH/\psi/\Upsilon\}] \cdot \frac{b\bar{b}_{unl} + b\bar{b}_{like}}{b\bar{b}_{unl} - b\bar{b}_{like}}$$

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

Visible cross section:

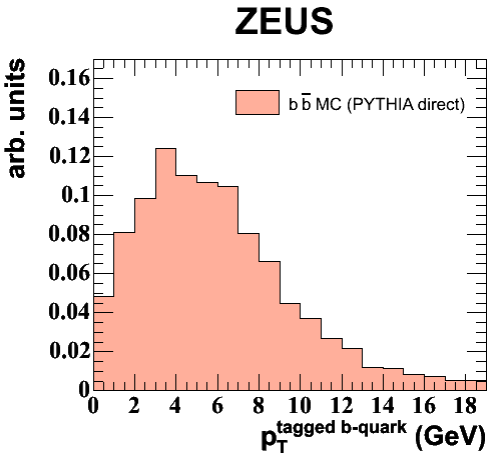
σ_{vis} **ep→bbX→μμX'**	= **43 ± 3 (stat.)**	$^{+13}_{-11}$ **(syst.) pb**	**HERA II** ±15%
σ_{vis} **ep→bb̄X→μμX'**	= **55 ± 7 (stat.)**	$^{+14}_{-15}$ **(syst.) pb**	**HERA I paper**

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:

* to be rechecked *

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** **±15%**

$\sigma_{b\ tot}$ $ep \to b\bar{b}X$ (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**

$4.5 < m_b < 5.0$

$0.5 < \mu/\mu_0 < 2$

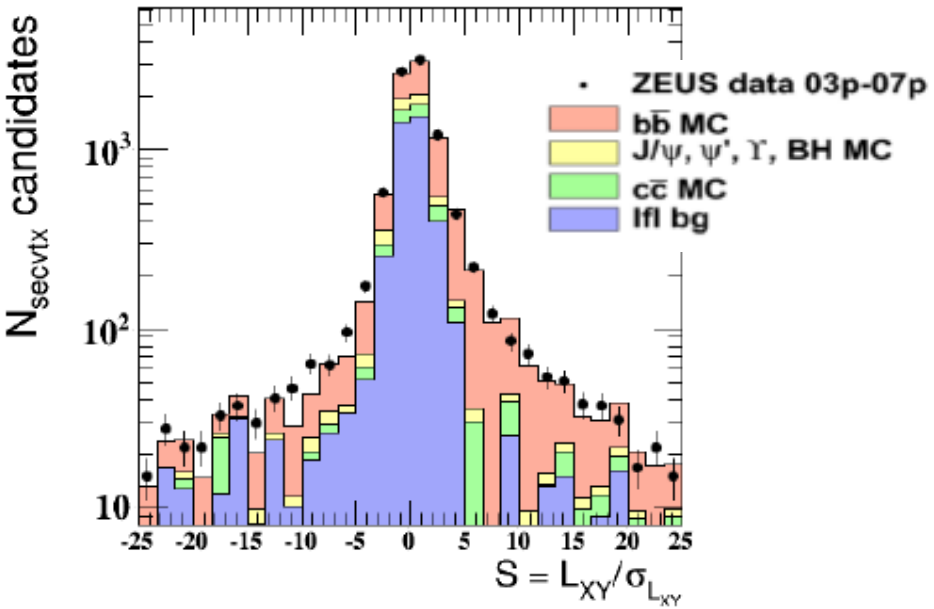
Some consistency checks still needed

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 ?

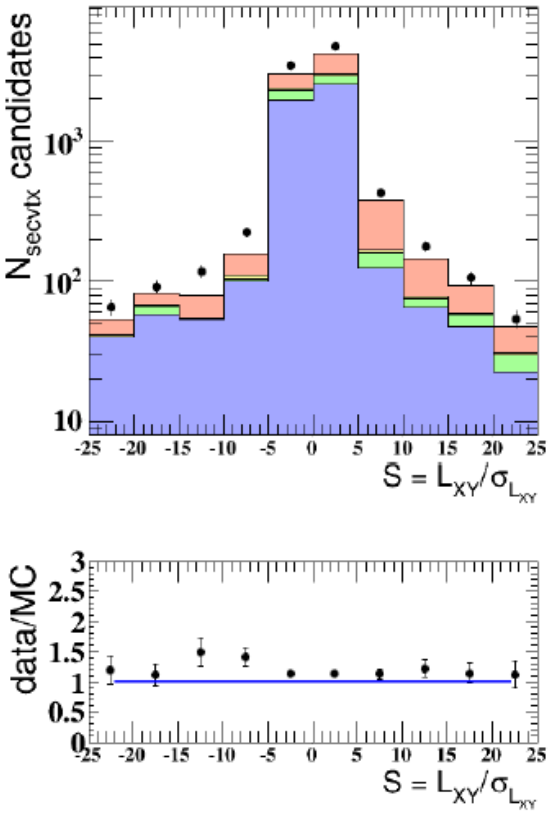
reasonable, but not perfect -> improve by fitting

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

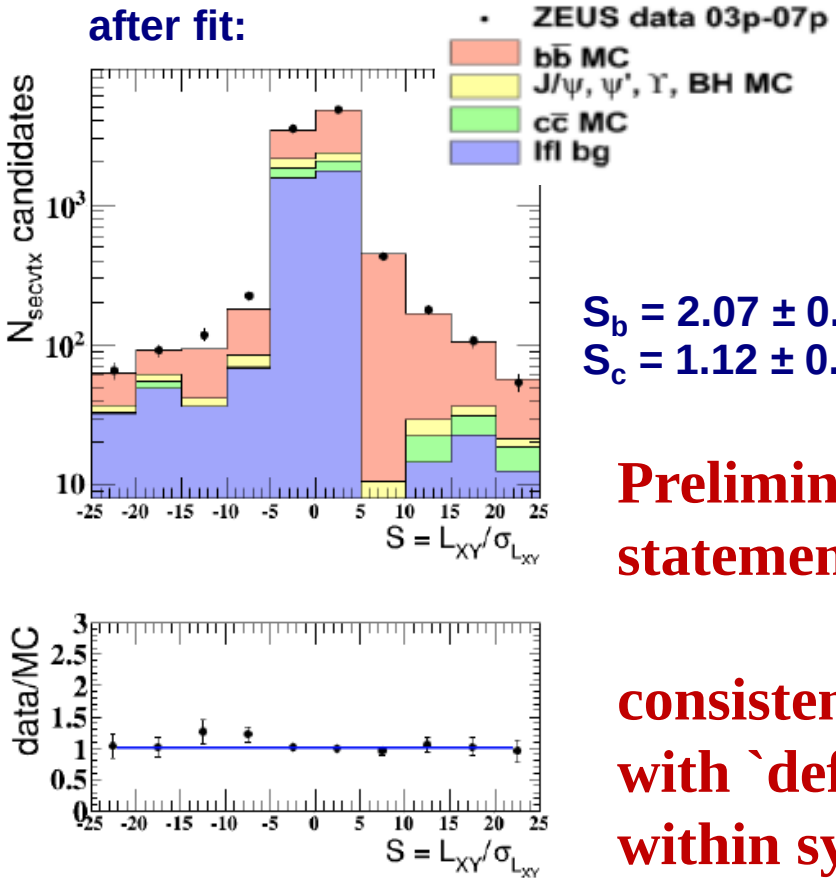
Impose constraint that light flavour contribution should be (statistically) symmetric, use charm and beauty decay lengthy distributions from MC

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)

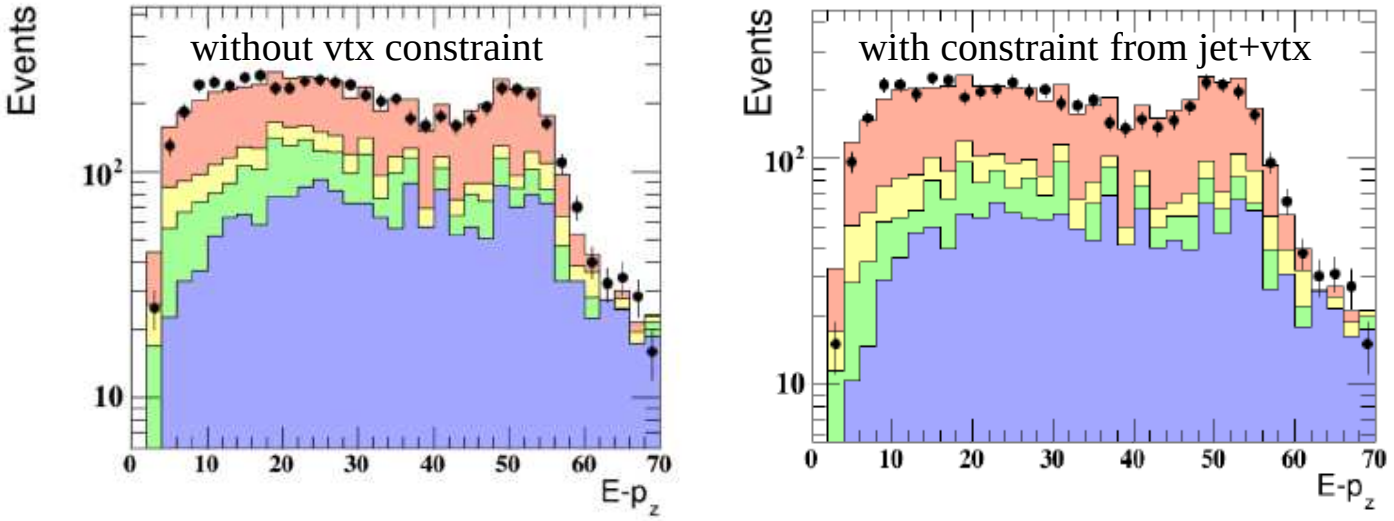
Preliminary statement:

consistent with `default' within systematic Uncertainties (no plots)

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

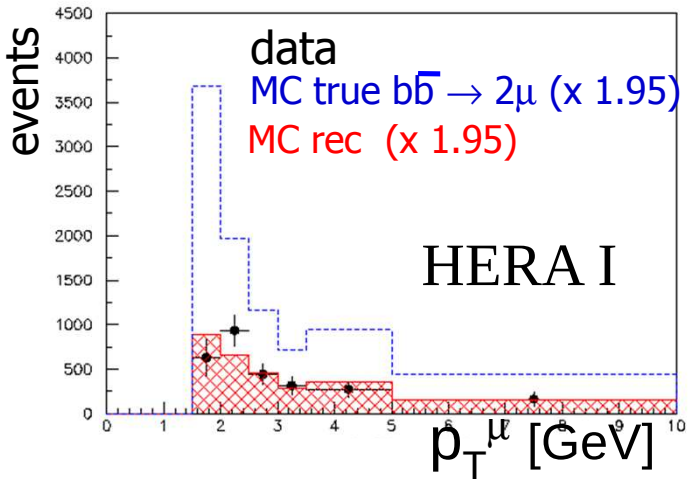
e.g.:



-> use the secondary vertex study as a (successful) cross check only, and stick to the 'classical' method for the core results (conservative approach)

Muon differential cross sections - p_T^μ

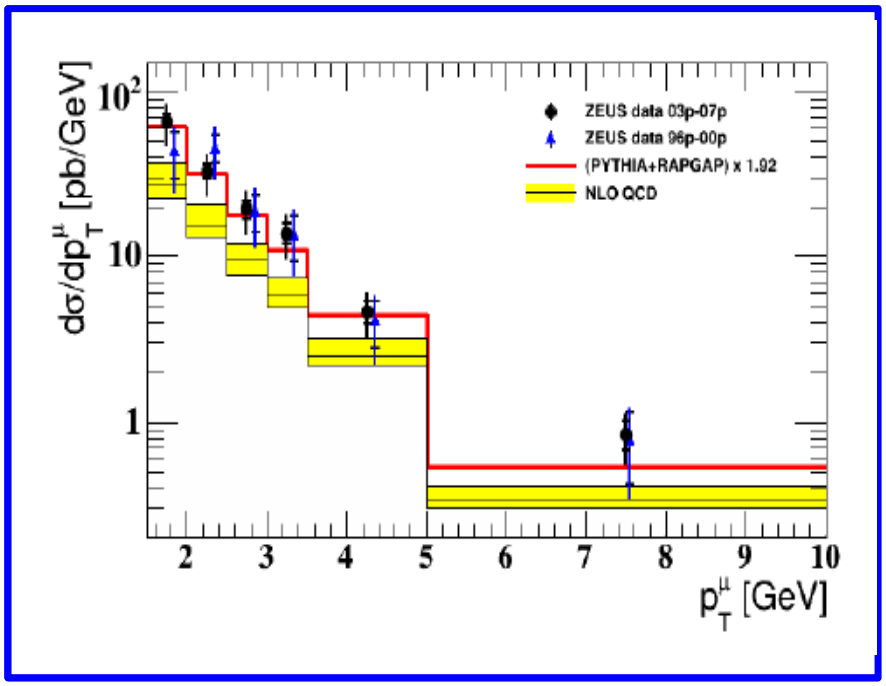
- restrict both μ to
  $p_T^\mu > 1.5$ GeV
  and **$-2.2 < \eta^\mu < 2.5$**
  -> average factor $S_b = 1.92$ (was 1.95 in HERA I)



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

$$N_{b\bar{b}\to\mu\mu} = \left[data_{unl} - data_{like} - \{ charm/BH/\psi/\Upsilon \} \right] \cdot \frac{b\bar{b}_{unl} + b\bar{b}_{like}}{b\bar{b}_{unl} - b\bar{b}_{like}}$$

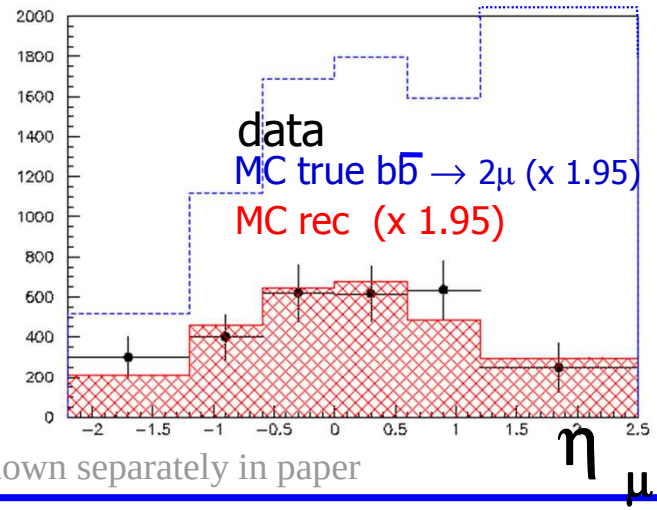
→ cross section in p_T^μ



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 $-2.2 < \eta^{\mu} < 2.5$

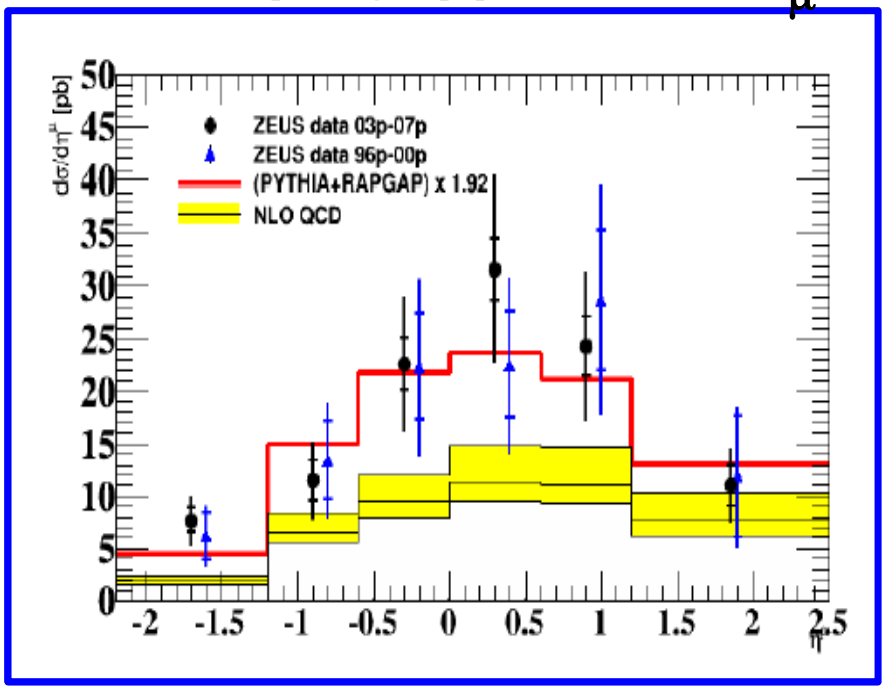


LO+PS and NLO shown separately in paper

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

$$N_{b\bar{b}\rightarrow\mu\mu} = [data_{unl} - data_{like} - \{charm/BH/\psi/\Upsilon\}] \cdot \frac{b\bar{b}_{unl} + b\bar{b}_{like}}{b\bar{b}_{unl} - b\bar{b}_{like}}$$

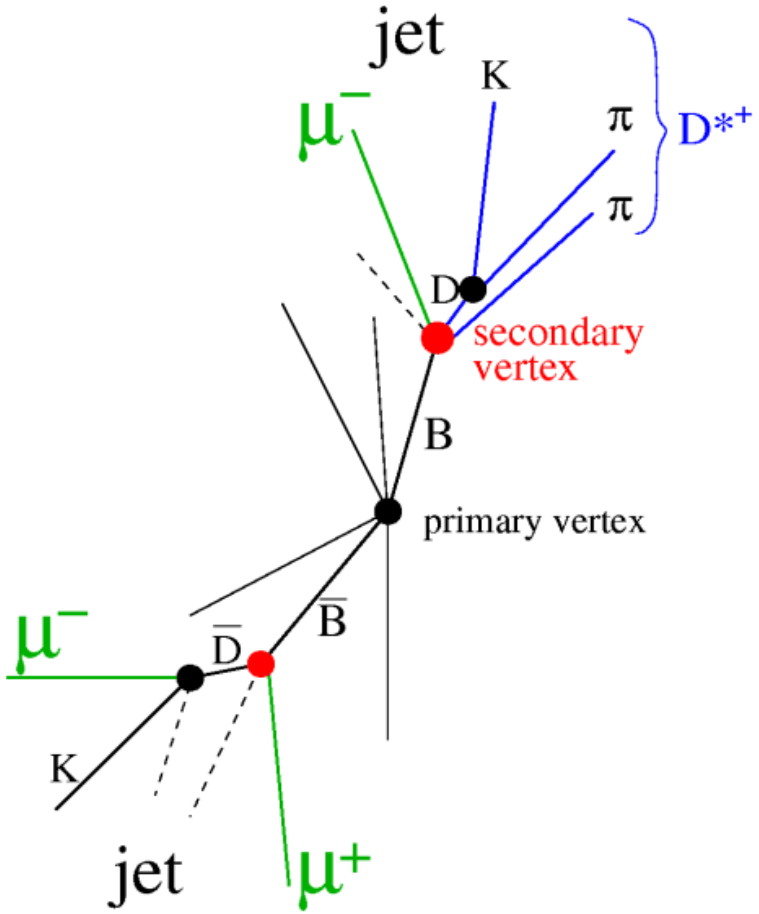
→ **cross section in η^{μ}**

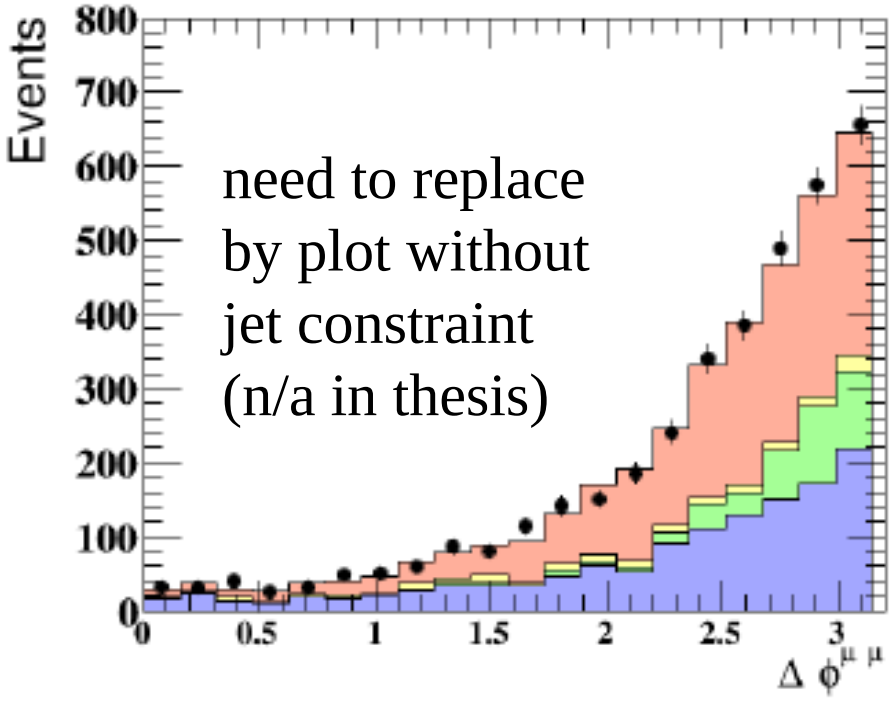


Very good description in shape by the LO+PS MC and NLO in full η and p_T range. NLO low but consistent.

prel. plot

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

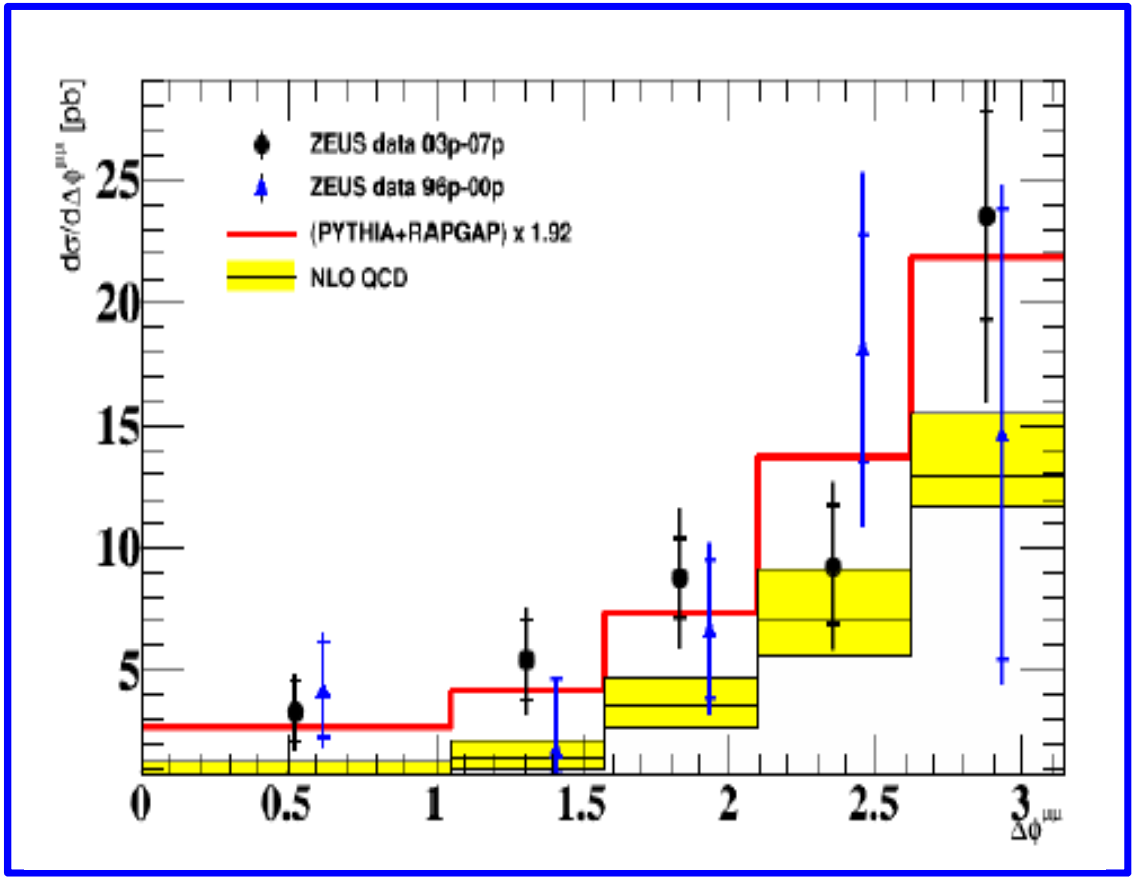




Reconstructed $\Delta\phi^{\mu\mu}$: with $m^{\mu\mu} > 3.25$ GeV

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

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

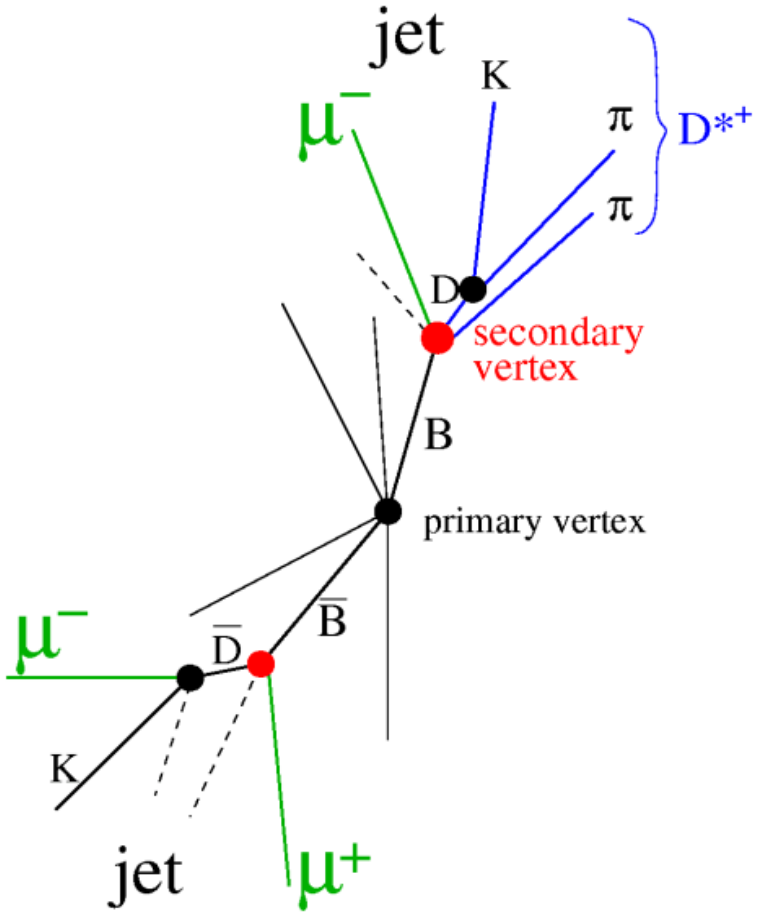


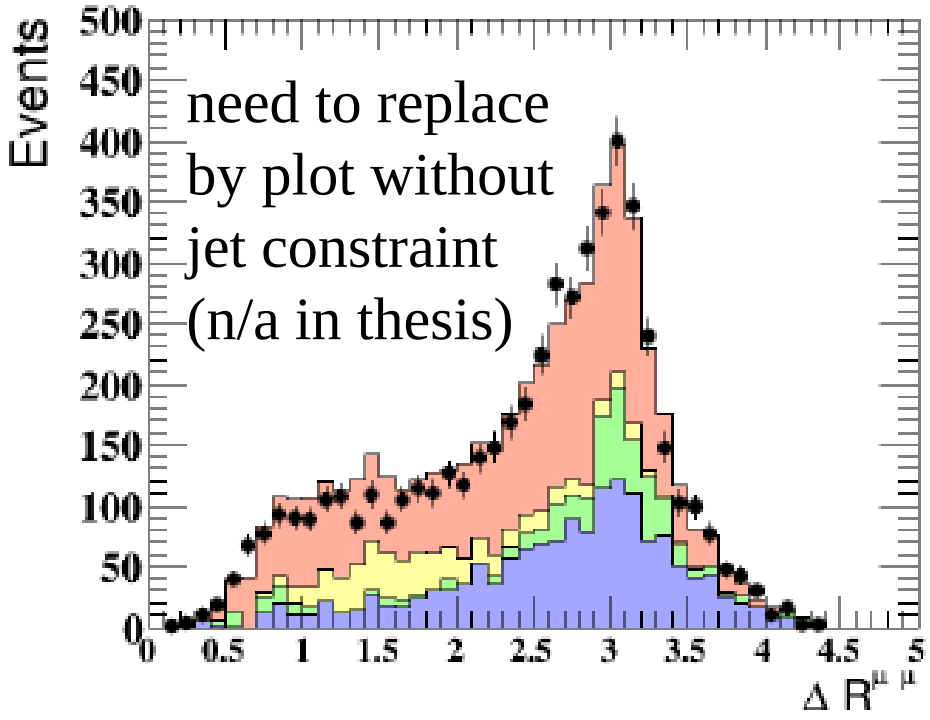
prospective preliminary plot

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

reasonable agreement within large errors

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

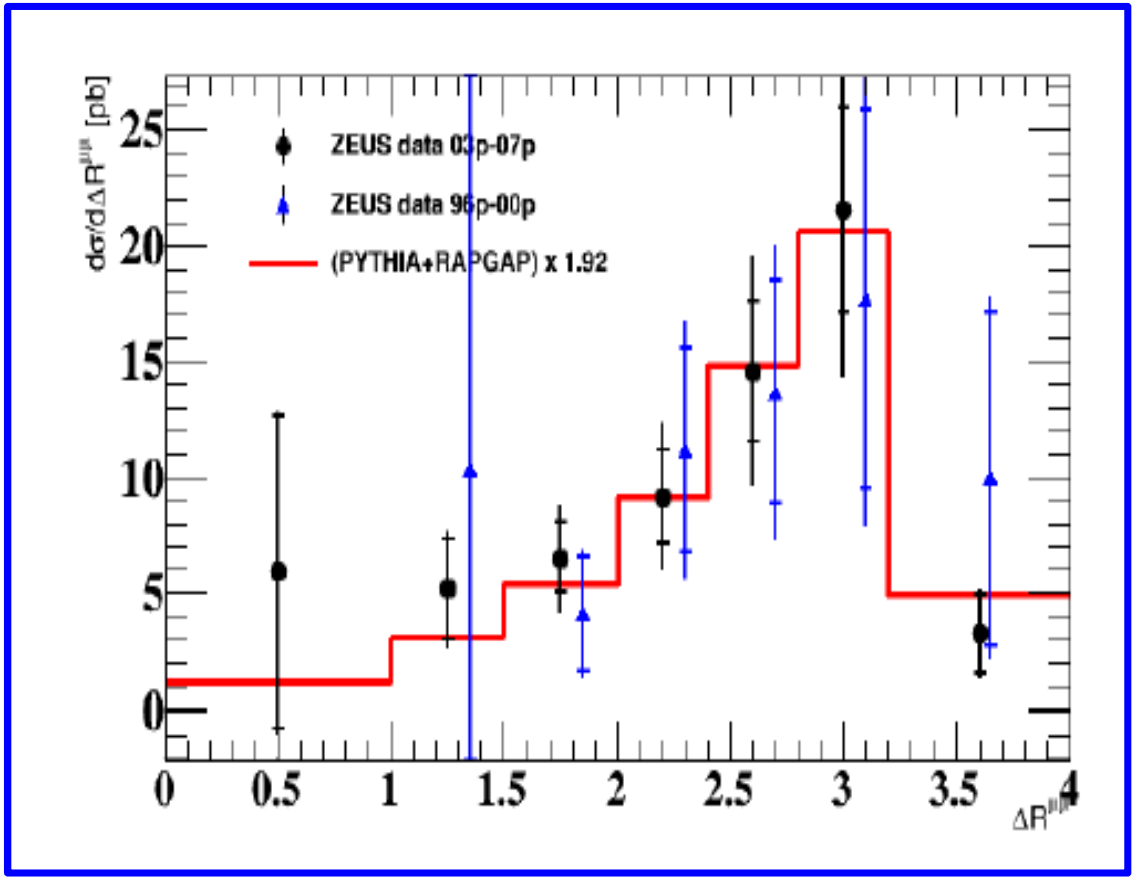




Reconstructed $\Delta R^{\mu\mu}$: (all masses)

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

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



prospective prel. plot **(without HERA I)**

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

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

Conclusion

- 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 slighly lower than data
  - no particular trend in p_T or η (as before)
- New distribution: Delta R (not enough statistics in HERA I)