Measurement of beauty production from dimuon events (and other heavy flavour results) at HERA

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on behalf of the ZEUS collaboration

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Deep Inelastic Scattering
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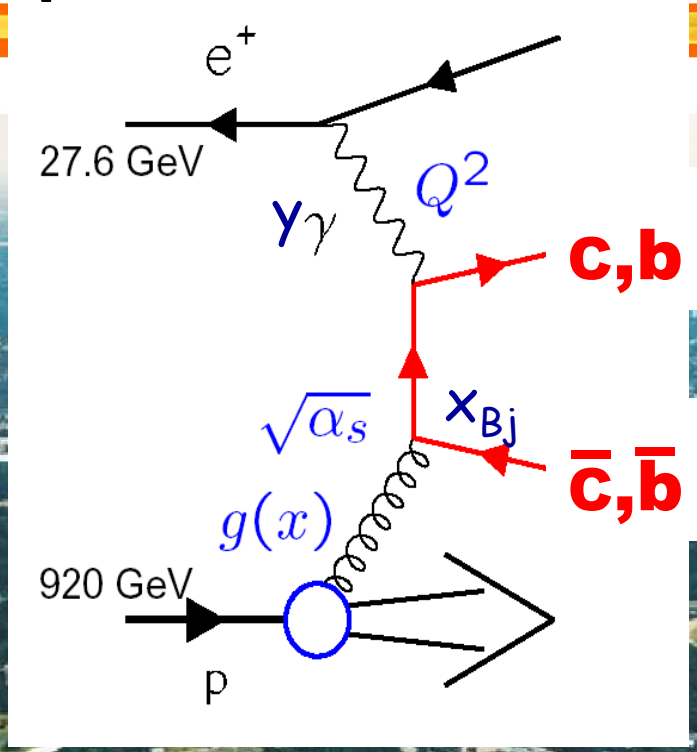
- Introduction
- Beauty tags at HERA
- Beauty from dimuons ZEUS-prel-18-006
- Reminder: combination of charm and beauty data in NC DIS
- Cross-reference: charm in CC DIS -> see talk J. Nam in WG1
- Conclusions

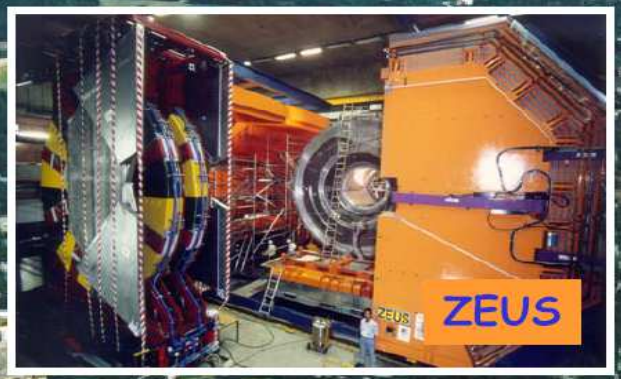
The HERA ep collider and experiments

DESY, Hamburg



up to 30% (3%)

of cross section for c,b



HERA I: ~ 130 pb^{-1} (physics)

HERA II: ~ 380 pb^{-1} (physics)

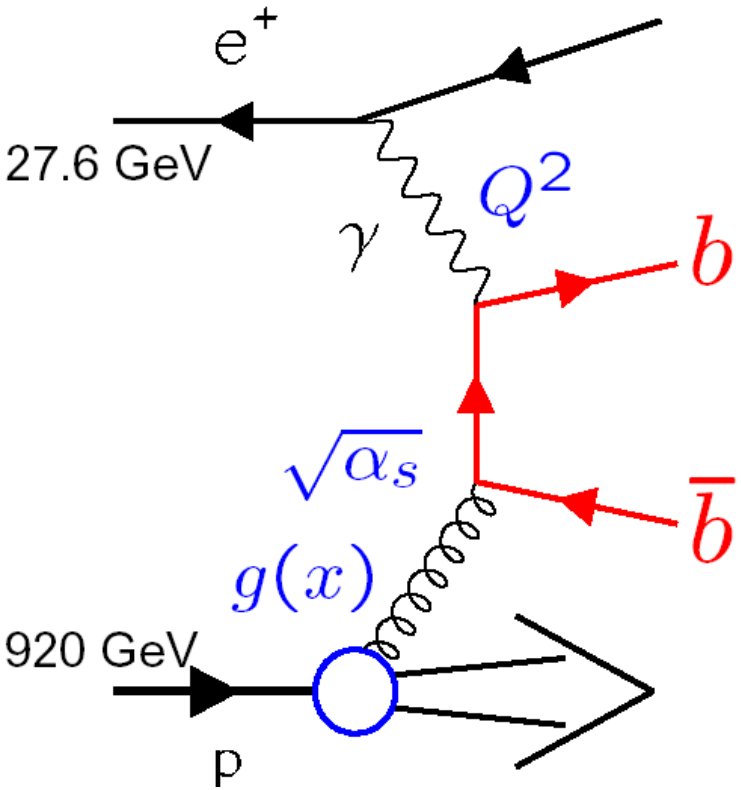
combined: ~ 2 x 0.5 fb^{-1}

HERA:

p (920 GeV) e (27.6 GeV)

Open beauty production in ep scattering

Dominant production process in ep-collisions: Boson-Gluon -Fusion



- Driven by gluons in the proton
- Relevant scales:

$m_b \sim 5$ GeV

$Q^2 \lesssim 1$ GeV$^2 \rightarrow \gamma p$

> 1 GeV$^2 \rightarrow$ DIS

p_T^b

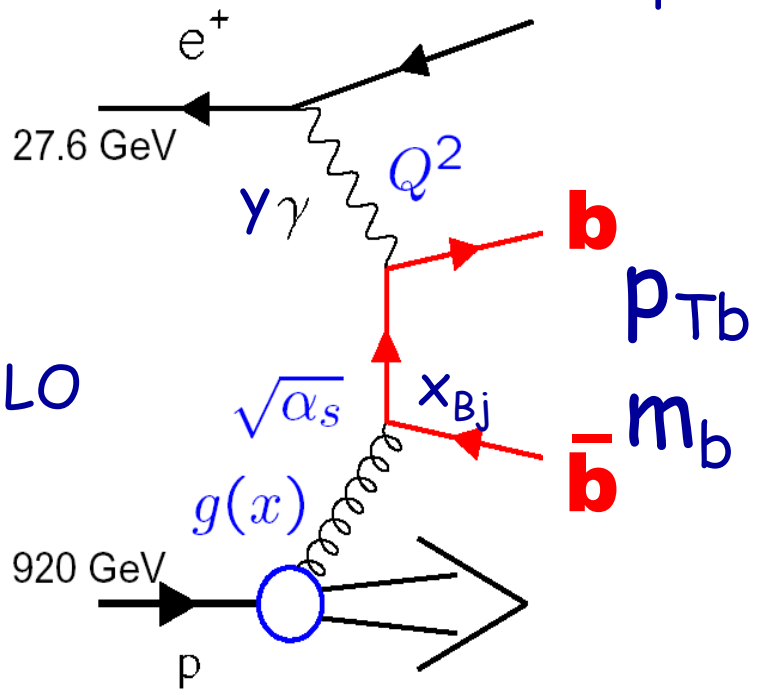
multiscale problem

-> terms $[\alpha_s \ln (Q^2/m_b^2)]^n$, $[\alpha_s \ln (p_T^2/m_b^2)]^n$, etc.

in perturbative expansion -> potentially large th. errors

Fixed Flavour Number Scheme (FFNS)

example: beauty



+ NLO corrections,

"natural" scales:

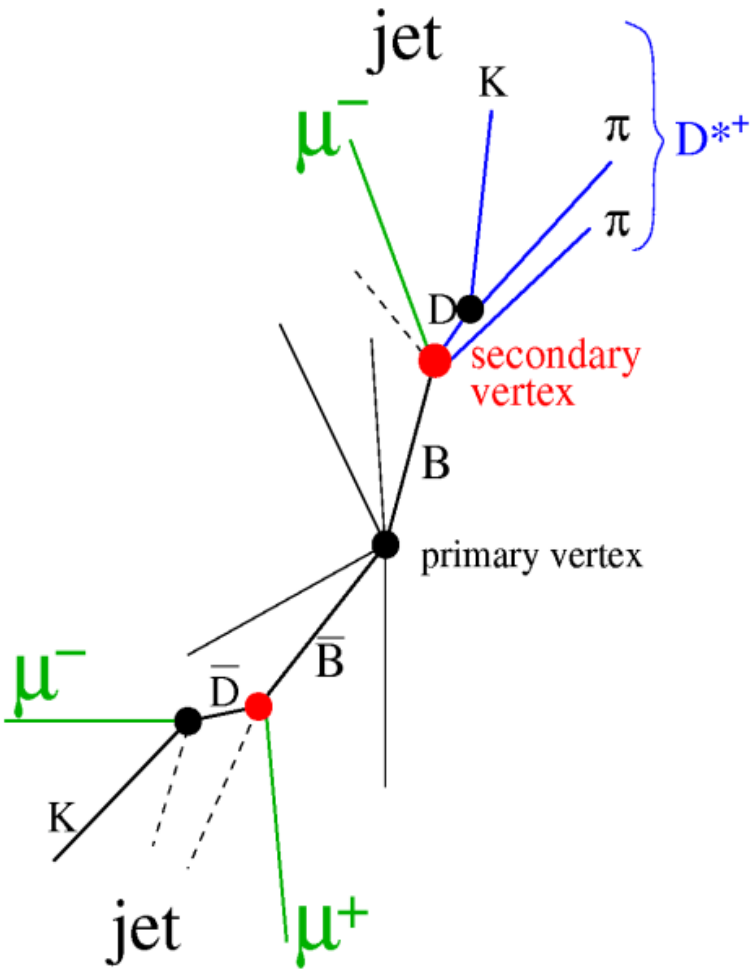
$\mu^2 = m_b^2 + p_T^2$ (γp)

$\mu^2 = Q^2 + 4m_b^2$ (DIS)

- no beauty in proton
- full kinematical treatment of beauty quark mass ☺
  (multi-scale problem: Q^2, p_T, m_b -> logs of ratios)
- no resummation of logs ☹
- no extra matching parameters ☺

Beauty double-tagging

multi-tagged $b\bar{b}$ events here: **two muons**



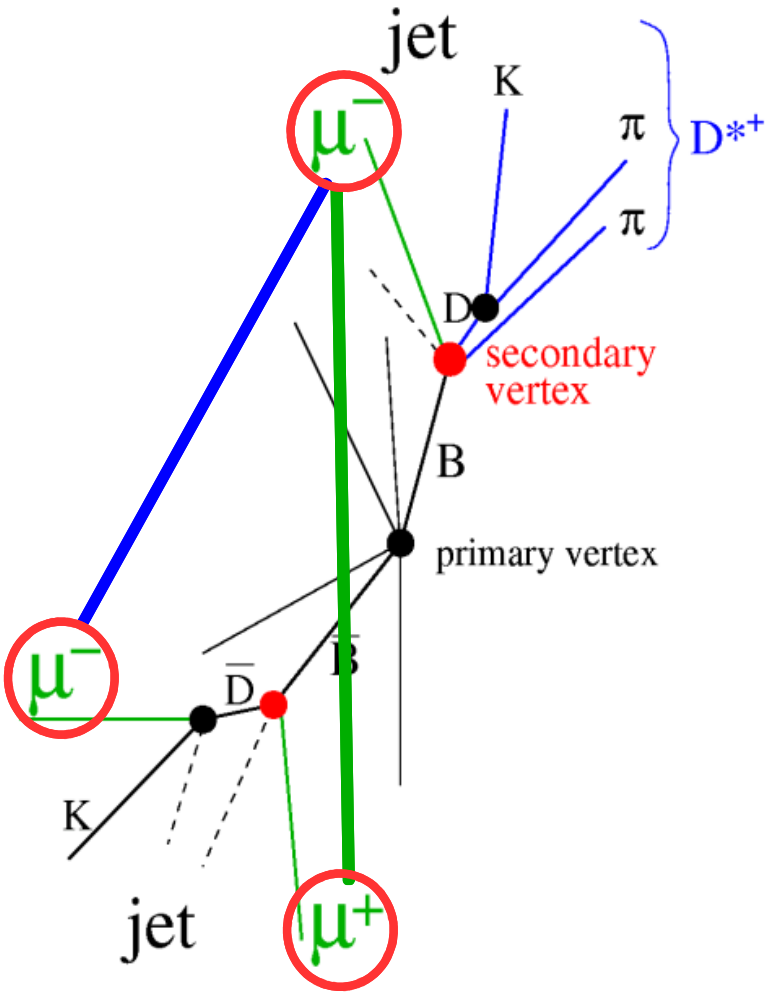
- tag both b´s
  → **explicitly measure $b\bar{b}$ correlations**

- 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 (DIS + γp)**

Signal topologies: 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

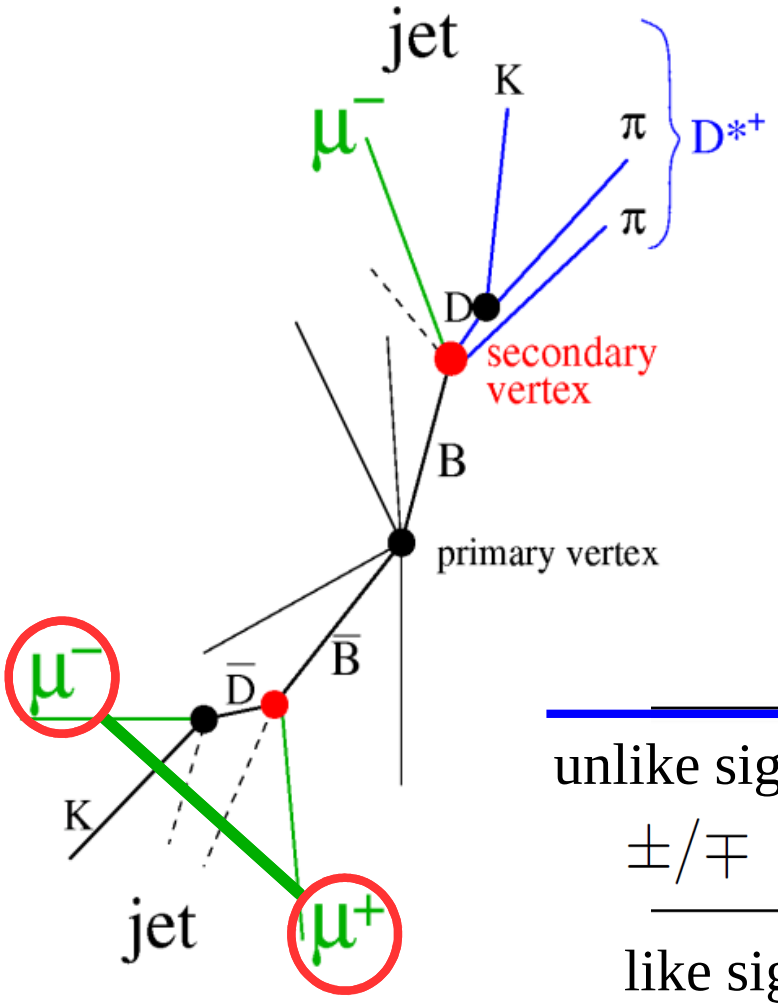
    high dimuon mass

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

Signal topologies: mass, charge

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

here: **two muons**



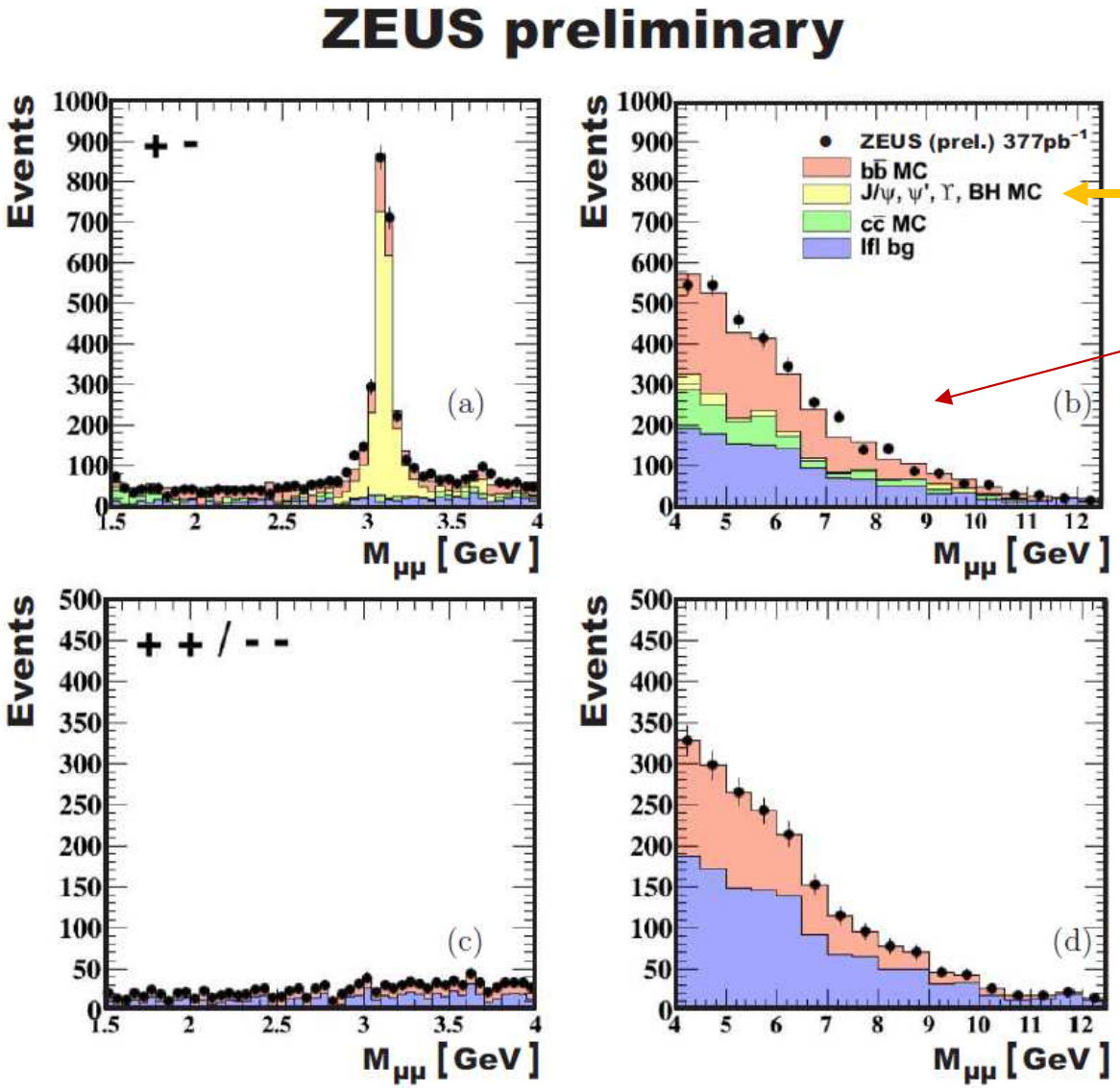
- **muons from same b** (including b→J/ψ)
  - → **unlike sign**
  - **same hemisphere**
  - **dimuon mass < 4 GeV**
  - (B mass - hadrons/neutrinos)
- **useful contribution to total cross section**

→ **classify data into subsamples:**

	low mass (< 4 GeV)	high mass (> 4 GeV)
unlike sign ±/∓	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 spectrum

ZEUS-prel-18-006



muons mostly isolated

signal mainly nonisolated

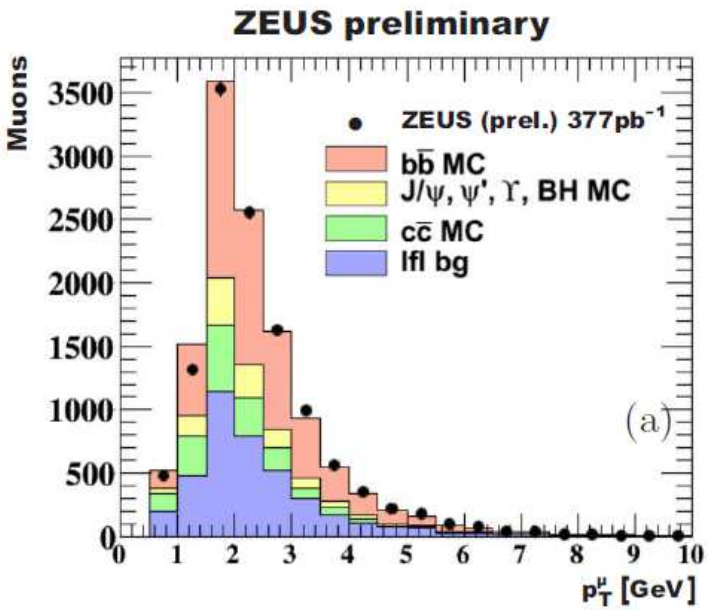
very similar to HERA I analysis
JHEP02 (2009) 032

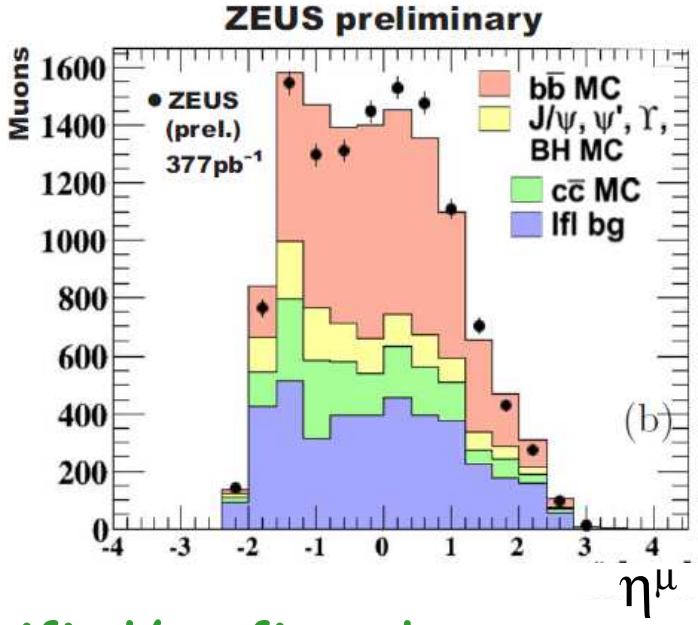
almost 3 times larger statistics

Muon p_T and η distributions

ZEUS-prel-18-006

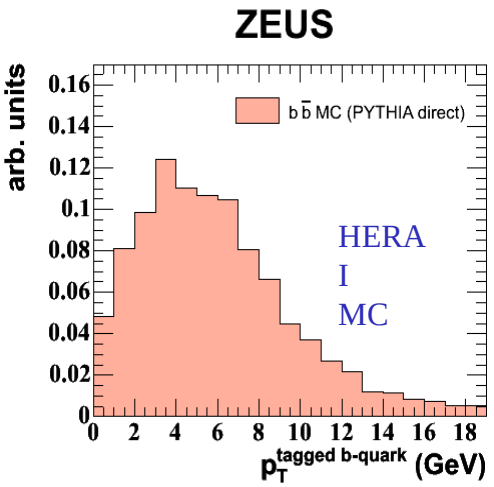
nonisolated unlike sign muon pairs (low+high mass)





~50% beauty

p_T of tagged b quark:



Charm bg fraction verified/confirmed
by fit of inclusive secondary vertices (not shown)

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!

Total visible bb->μμ+X cross section

ZEUS-prel-18-006

visible phase space:

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

Visible cross section: using lumi + MC acceptance + corrections

- HERA I paper: JHEP02 (2009) 032

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

- HERA II preliminary: **ZEUS-prel-18-006**

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

NLO QCD (same as HERA I paper):

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

scale $\mu^2 = \frac{1}{4}(m^2+p_T^2)$ details see backup

-> agreement within uncertainties

Total beauty cross section in ep @ 318 GeV

ZEUS-prel-18-006

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

- HERA I paper: JHEP02 (2009) 032

$\sigma_{b\,tot}$ **ep→bbX (318 GeV) = 13.9 ± 1.5 (stat.) $^{+\,4.0}_{-\,4.3}$ (syst.) nb**

- HERA II preliminary: **ZEUS-prel-18-006**

$\sigma_{b\,tot}$ **ep→bbX (318 GeV) = 11.4 ± 0.8 (stat.) $^{+\,3.9}_{-\,2.9}$ (syst.) nb**

NLO QCD predictions (same as HERA I paper):

FMNR+HVQDIS **7.5 $^{+\,4.5}_{-\,2.1}$ nb** scale $\mu^2 = ¼(m^2+p_T^2+Q^2)$

for theory-inspired motivation of QCD scale choice see doi:10.3360/dis.2007.163

-> agreement within (large) uncertainties

only measurement of its kind so far

any chance to get NNLO prediction?

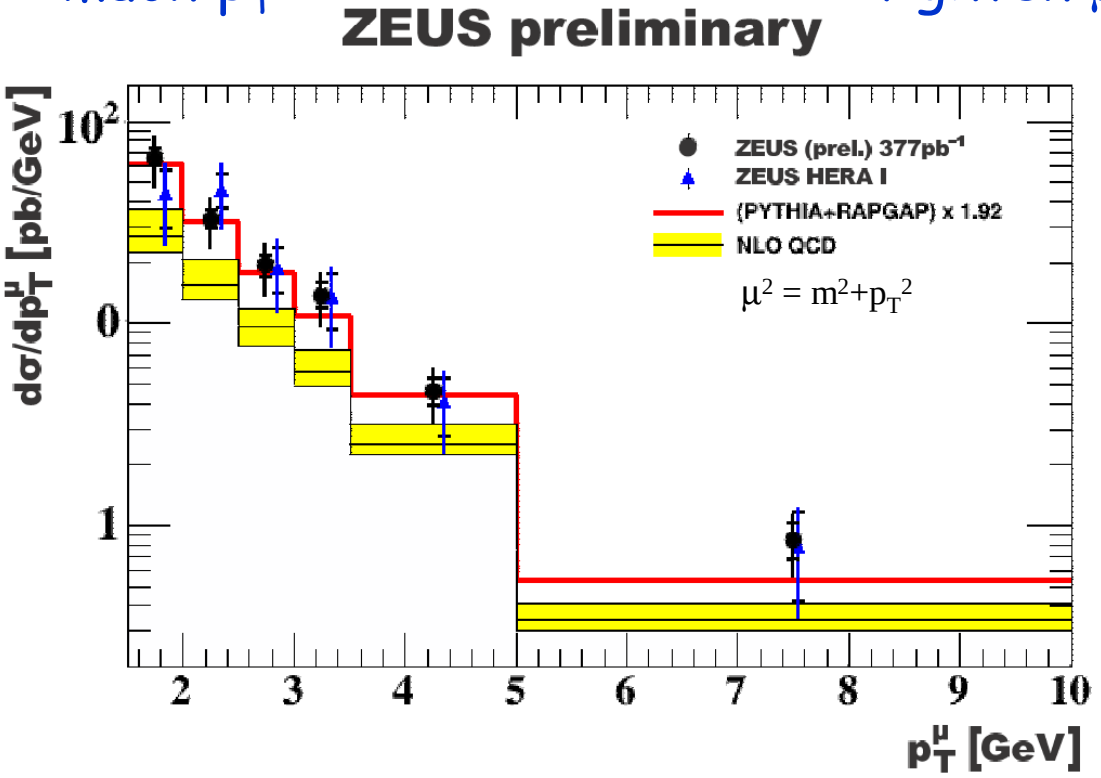
(exists for pp and (almost) for DIS)

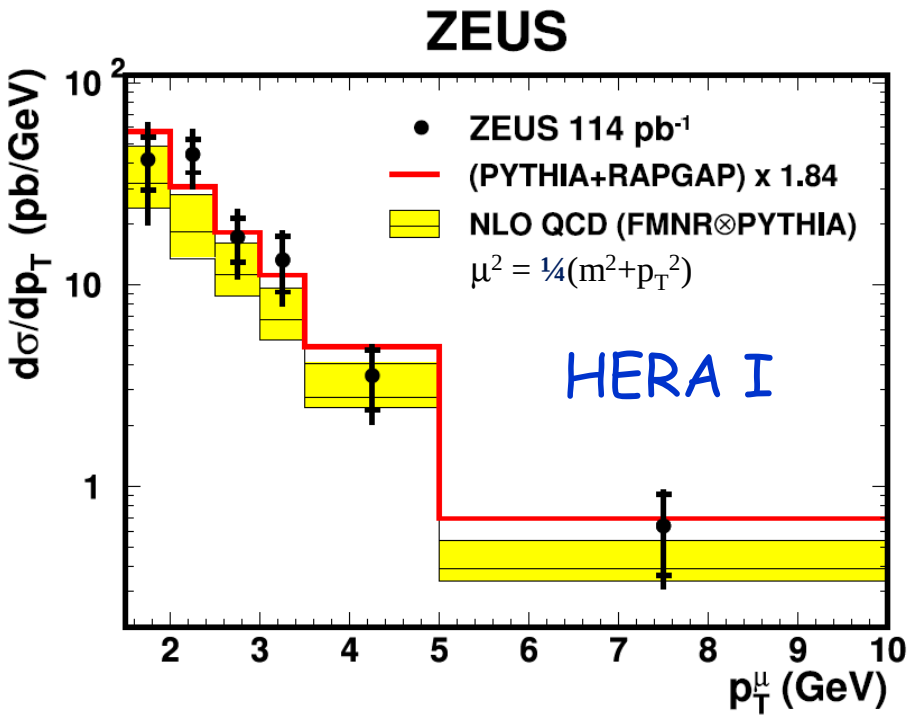
Differential cross sections bb->μμ+X

ZEUS-prel-18-006

muon p_T

tighten μ p_T cut to 1.5 GeV





Good agreement with HERA I result, smaller data uncertainties.

Shape of NLO prediction agrees well with data.

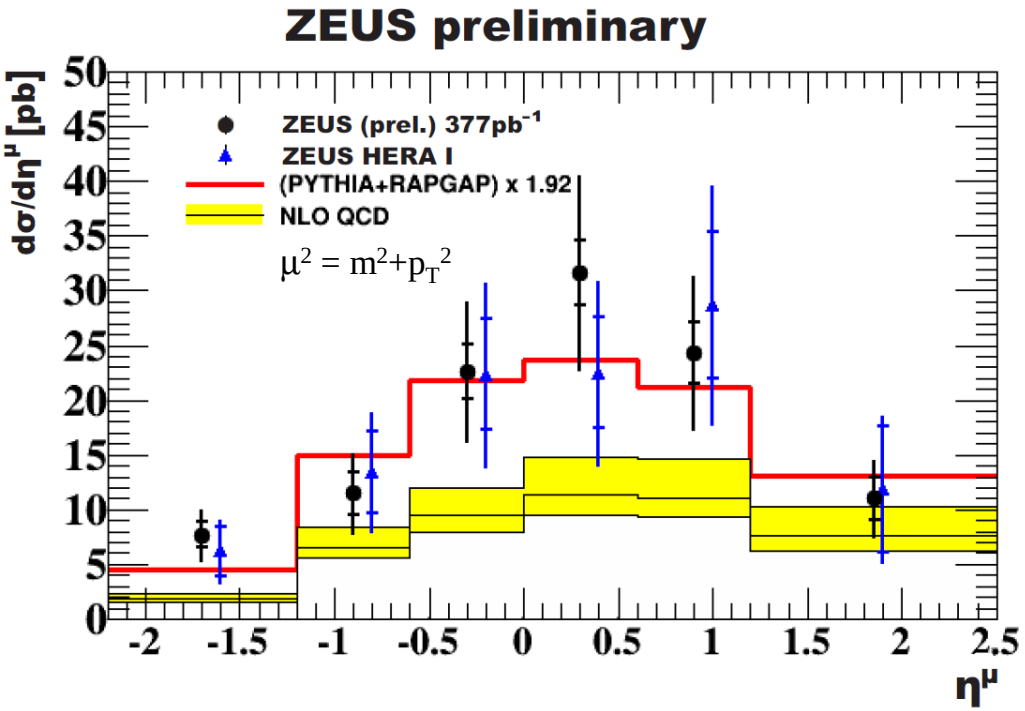
Normalisation agreement better for reduced QCD scale

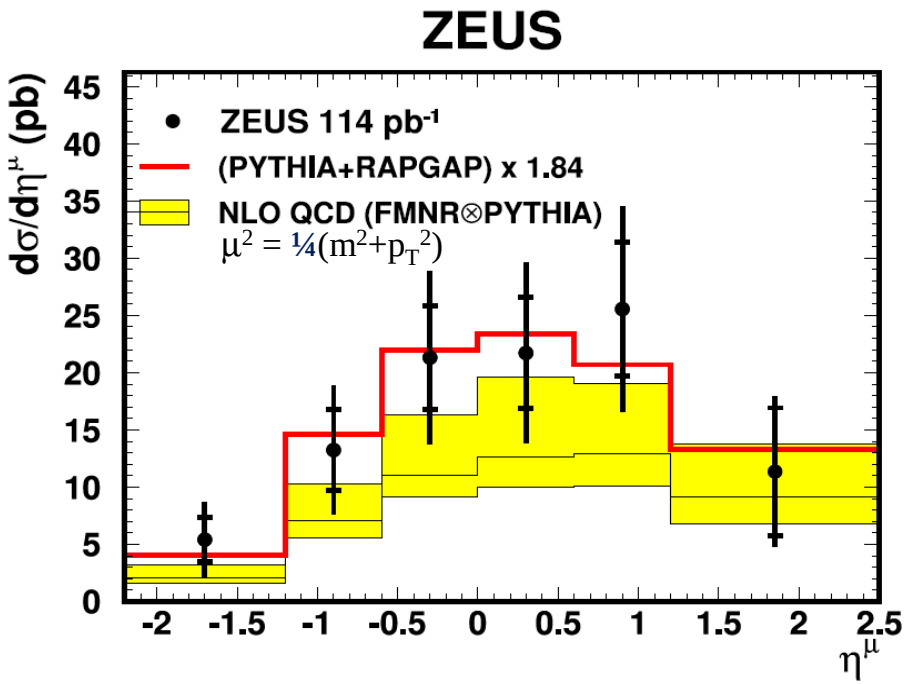
(NNLO corrections, also to bb correlations, potentially large)

Differential cross sections bb->μμ+X

ZEUS-prel-18-006

muon pseudorapidity





in general: similar conclusions as for muon p_T

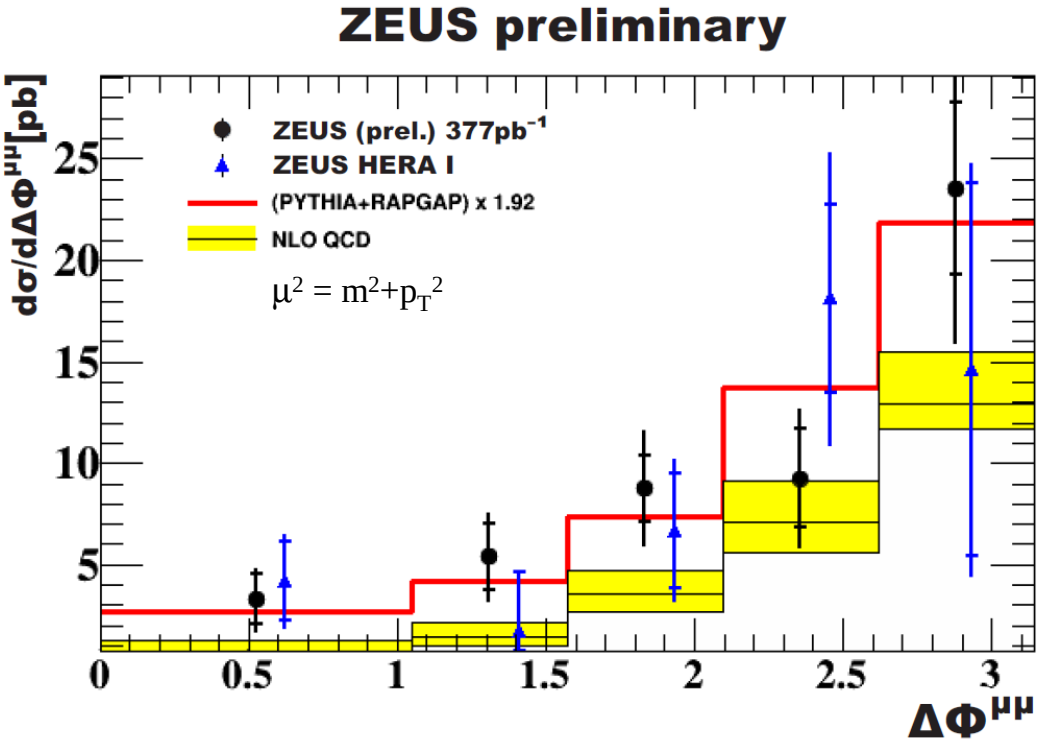
LO+PS MC describes shape slightly better than NLO

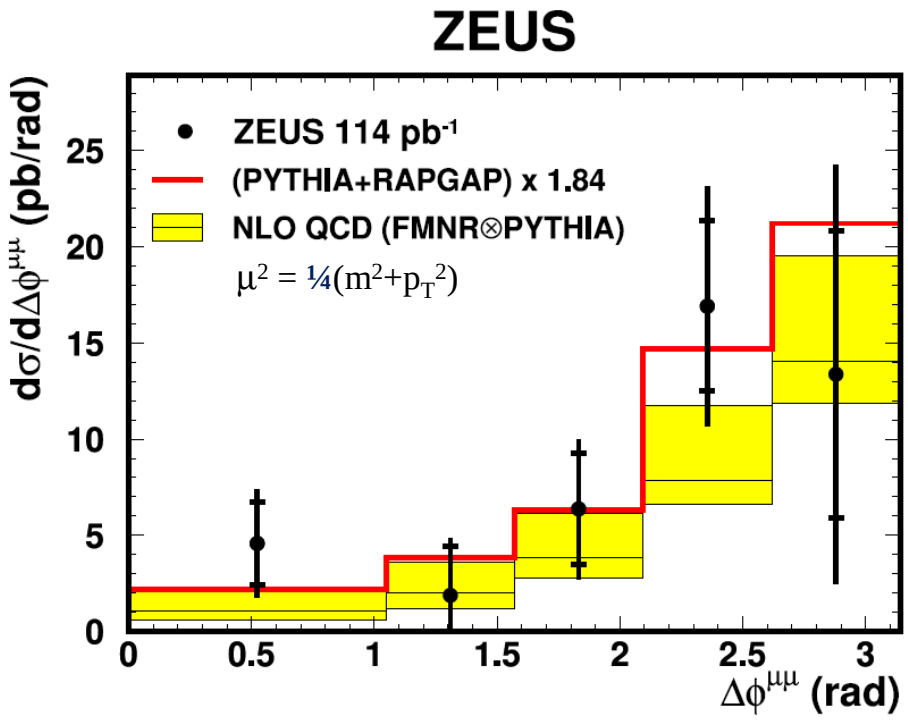
Differential cross sections bb->μμ+X

ZEUS-prel-18-006

$\Delta\phi^{\mu\mu}$ for $m^{\mu\mu}$ > 3.25 GeV (μ's from different b's)

-> directly sensitive to bbbar correlations

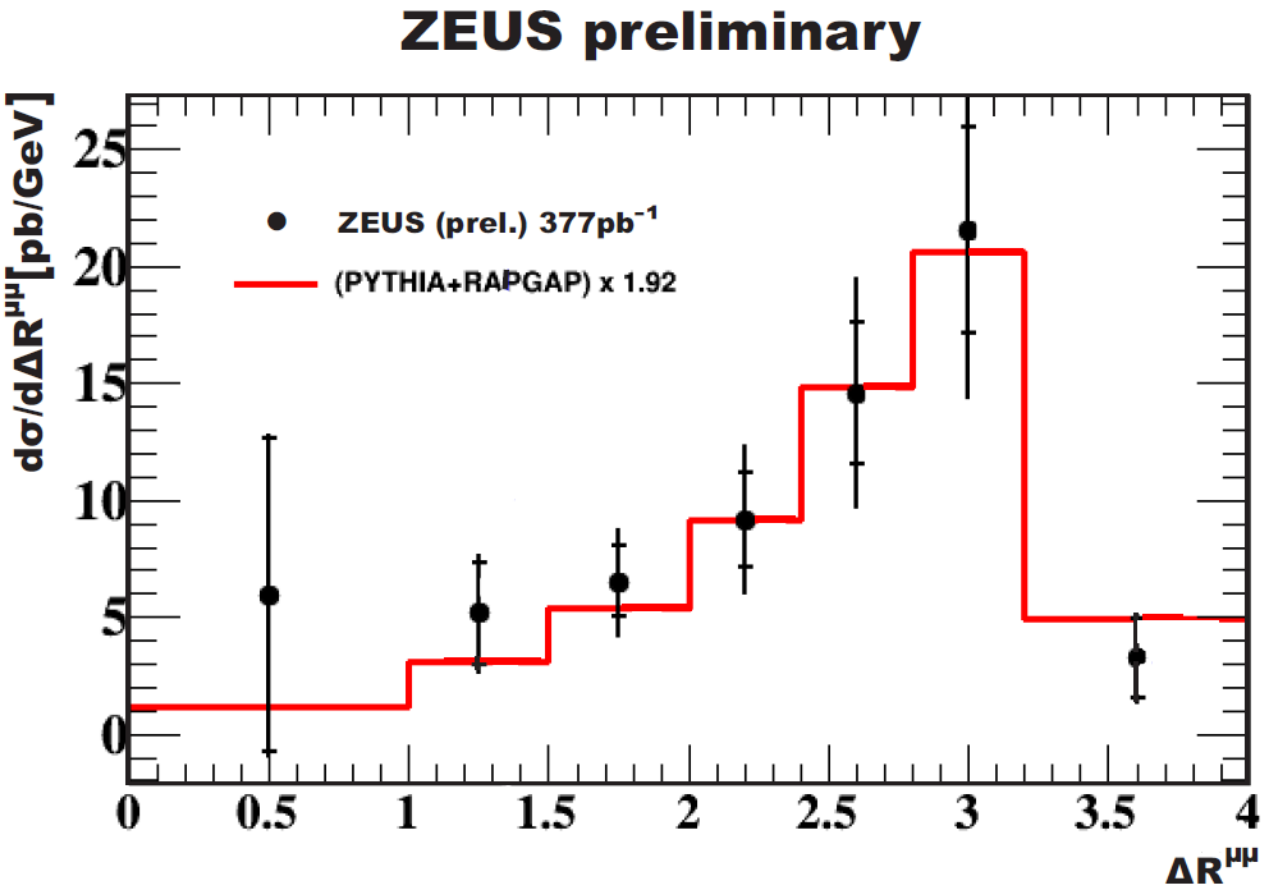




Lower scale NLO prediction agrees better in both shape and normalisation

Differential cross sections bb->μμ+X

ZEUS-prel-18-006

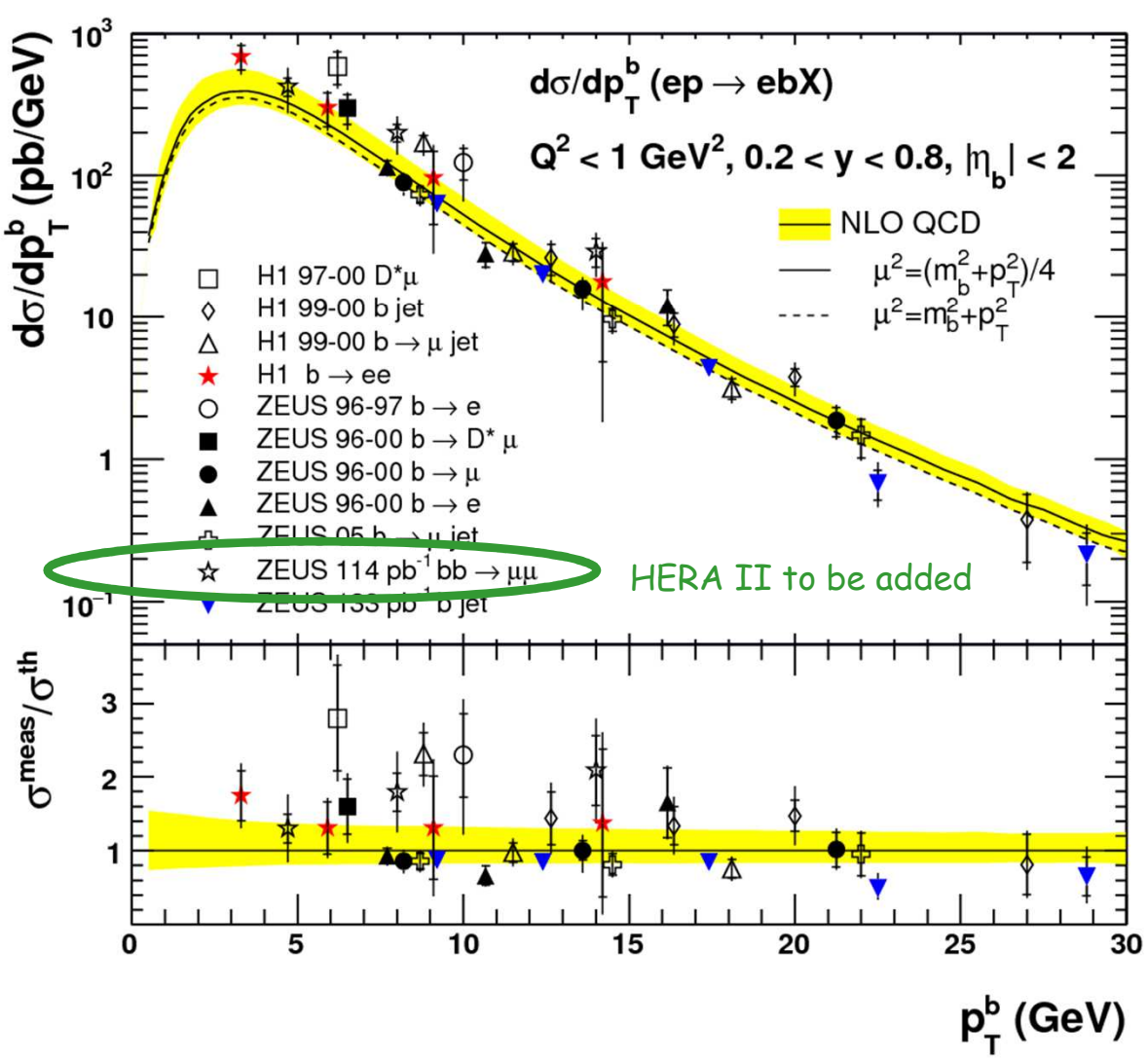


no previous measurement (statistics)

agrees with LO+PS MC, NLO prediction not calculated yet

Beauty in photoproduction: summary

b quark



Data vs. NLO QCD:

reasonable agreement

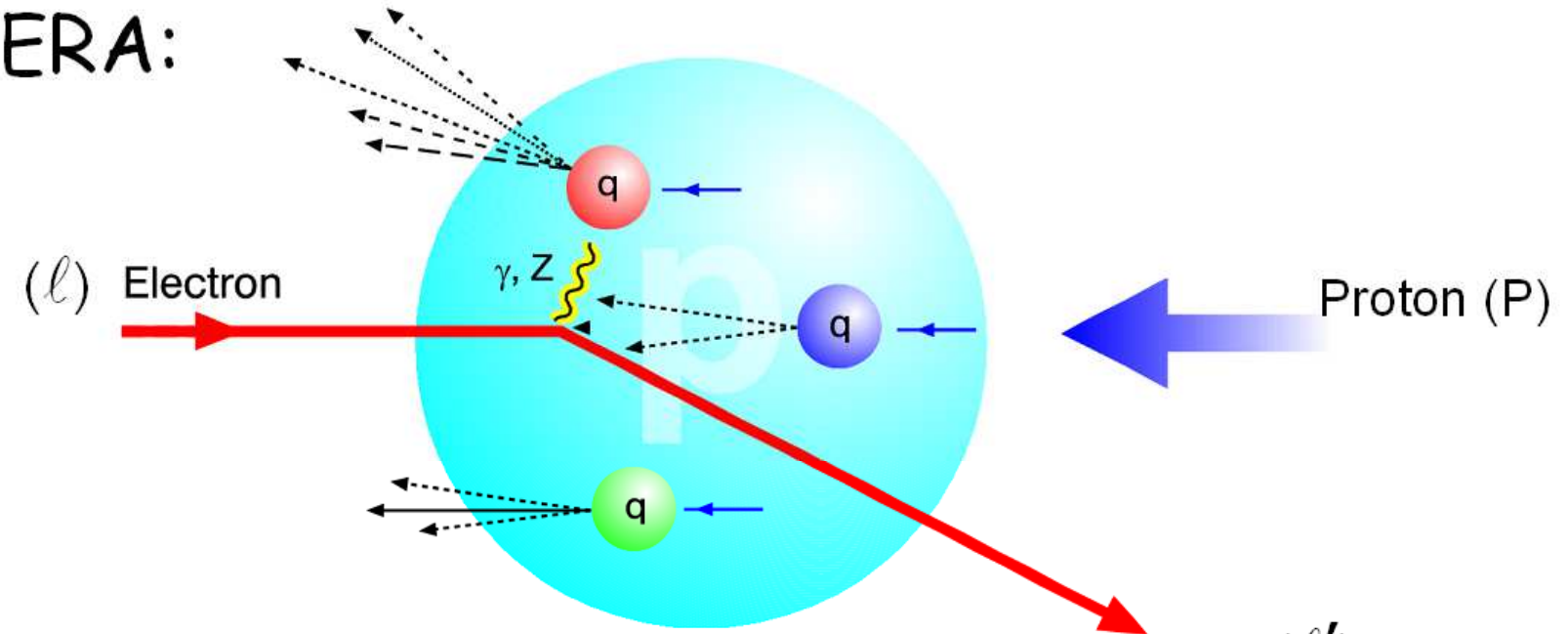
for theory-inspired motivation of QCD scale choice see

doi:10.3360/dis.2007.163

double-tag measurements have tendency to come out higher than single tag

Deep Inelastic ep Scattering at HERA

HERA:



kinematic variables:

$Q^2 = -q^2$ photon (or Z) virtuality, squared momentum transfer

$x_{Bj} = \frac{Q^2}{2Pq}$ Bjorken scaling variable

for $Q^2 \gg (2m_q)^2$: momentum fraction of p constituent

(equivalent in LO QPM only)

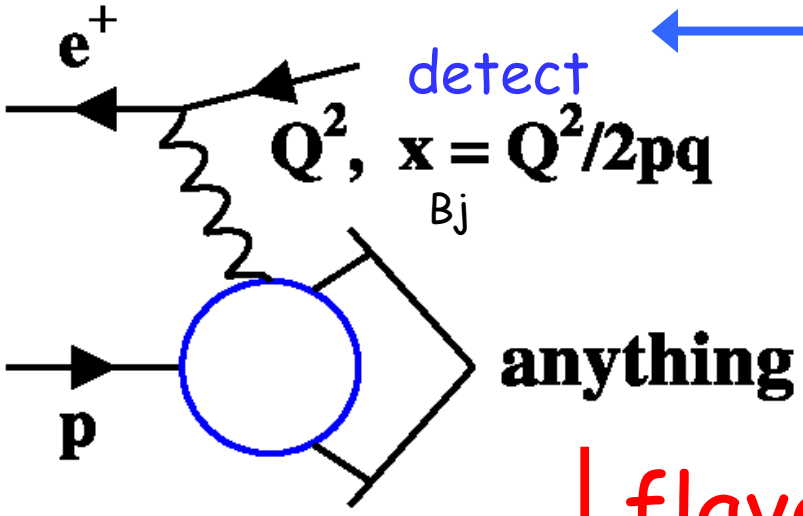
$y = \frac{qP}{\ell P}$ inelasticity,

γ momentum fraction (of e)

$Q^2 \lesssim 1$ GeV^2: photoproduction

$Q^2 \gtrsim 1$ GeV^2: DIS

Heavy flavour contributions to σ_r



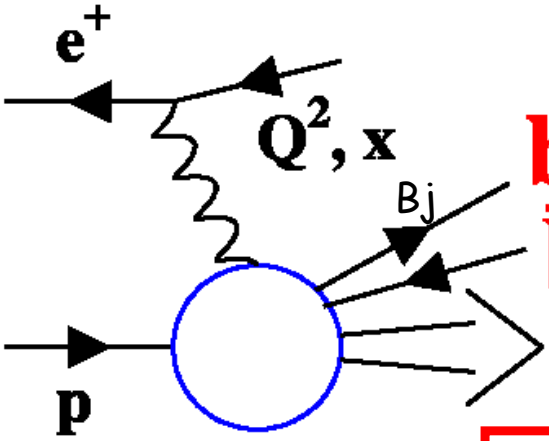
detect

Measure cross section

$$\frac{d^2\sigma}{dx_{Bj}\,dQ^2} \approx \frac{2\pi\alpha^2}{Q^4 x_{Bj}}\left[1+(1-y)^2\right]\sigma_r(x_{Bj},Q^2)$$

Combine 16 H1+ZEUS input data sets!

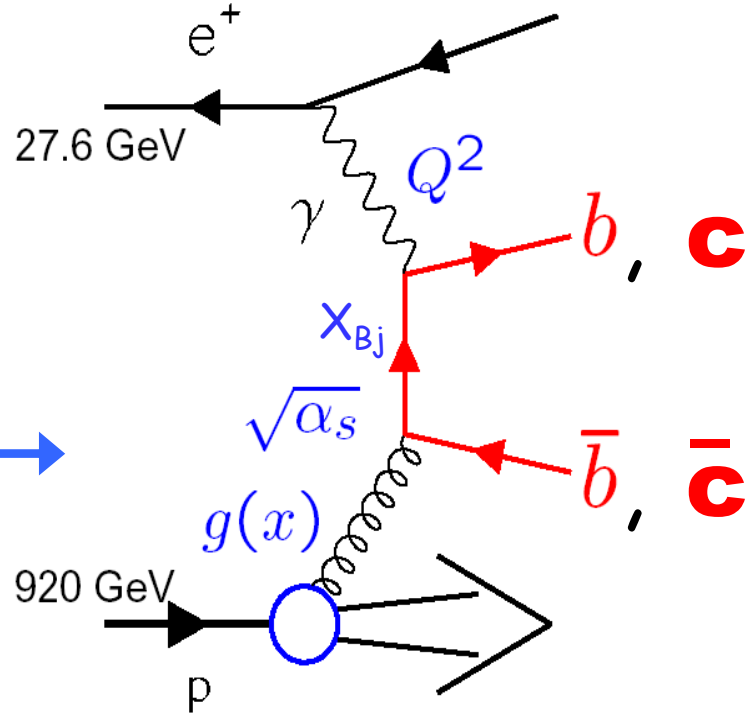
flavour tagging



$\mathbf{b}\,\bar{\mathbf{b}}$ or $\mathbf{c}\,\bar{\mathbf{c}}$

→ $\sigma_r^{b\bar{b}}$, $\sigma_r^{c\bar{c}}$

QCD



QCD fit (DIS incl.+c+b): charm subset

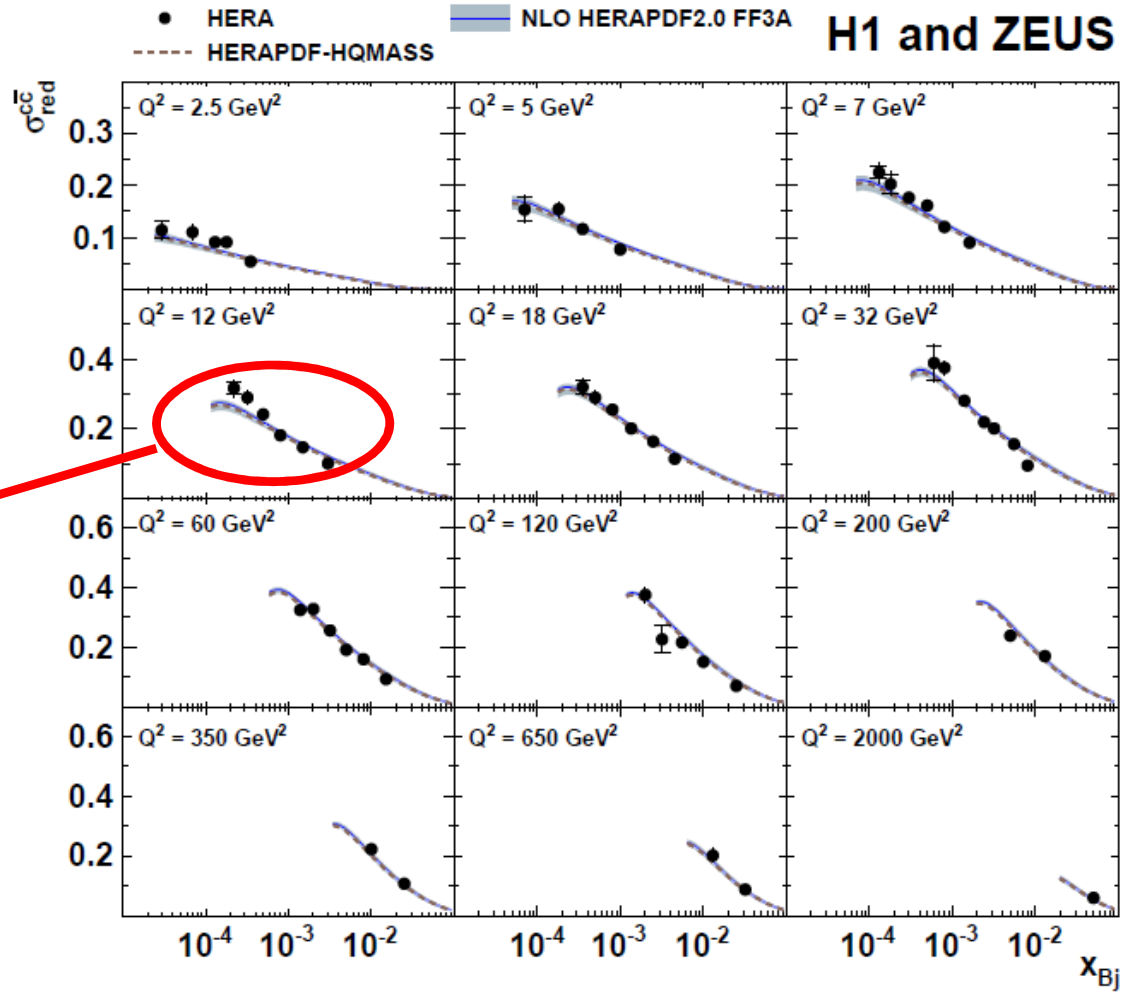
arXiv:1804.01019

already presented at DIS18

fully consistent with HERAPDF2.0 FF3A

under discussion in context of low x resummation

(see backup and talks J. Rojo and R. Yoshida)



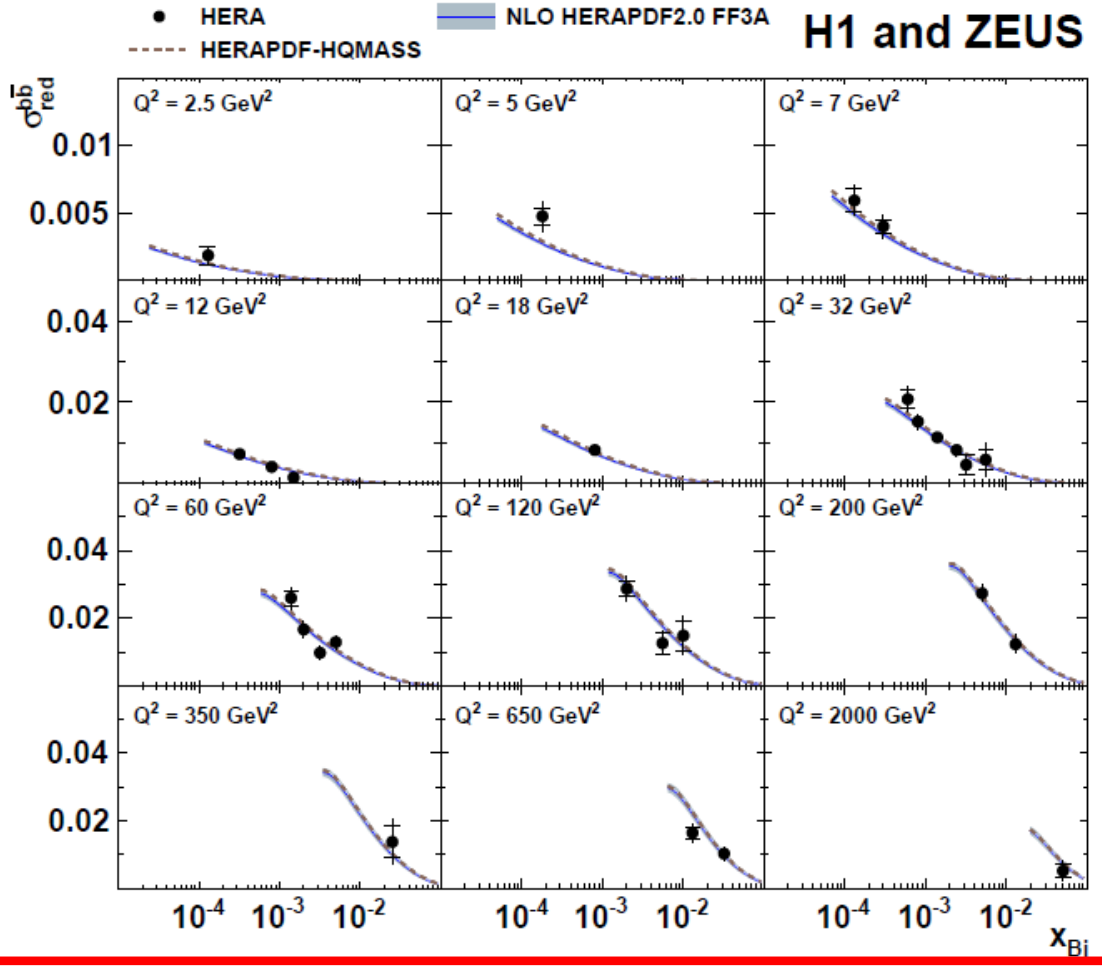
$m_c(m_c) = 1.29\ ^{+0.05}_{-0.04\ exp/fit}\ ^{+0.06}_{-0.01\ mod/scale}\ ^{+0.00}_{-0.03\ par}$ GeV

PDG: 1.27 ±0.03 GeV (lattice QCD + time-like processes)

QCD fit (DIS incl.+c+b): beauty subset

arXiv:1804.01019

fully consistent with HERAPDF FF3A



new: $m_b(m_b) = 4.05\ ^{+0.10}_{-0.11\ exp/fit}\ ^{+0.09}_{-0.03\ mod/scale}\ ^{+0.00}_{-0.03\ par}$ GeV

ZEUS: $m_b(m_b) = 4.07 \pm 0.14_{exp/fit}\ ^{+0.08}_{-0.08\ mod/scale}\ ^{+0.05}_{-0.00\ par}$ GeV

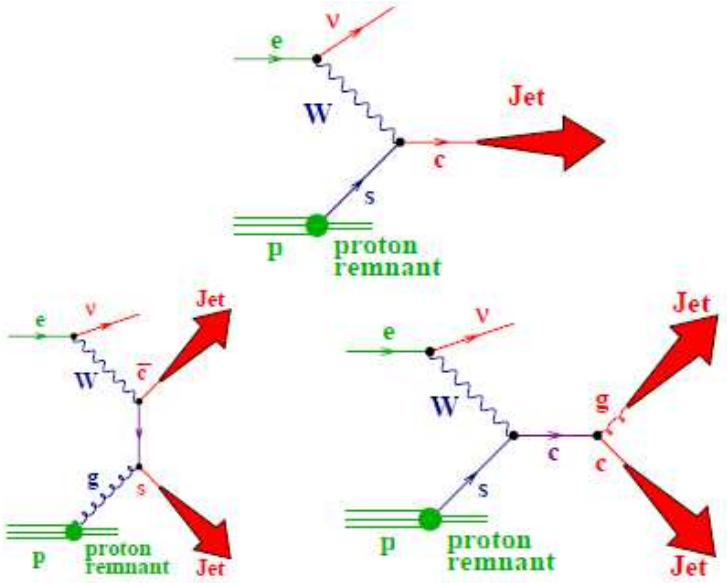
PDG: 4.18 ± 0.03 GeV (lattice QCD + time-like processes)

Charm in ep CC

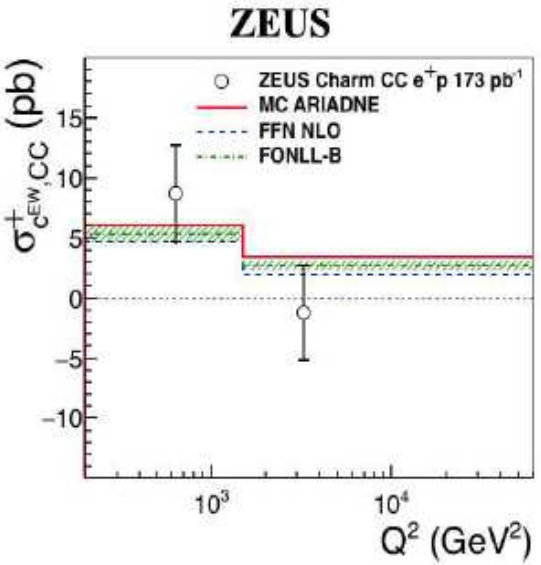
DESY 19-054, arXiv:1904.03261

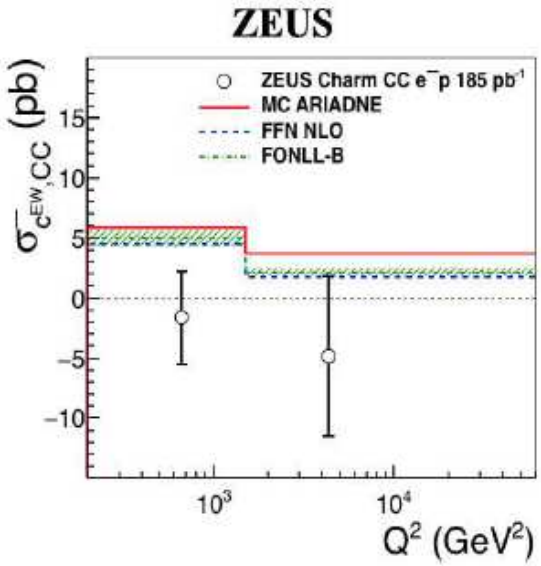
First ever collider measurement, large uncertainties

already advertised in talk C. Glasman:



$ep \to \nu$+jet(s)+X (c tag), $\sqrt{s} = 318$ GeV, $\mathcal{L} = 358$ pb^{-1}





- **Visible cross section:**

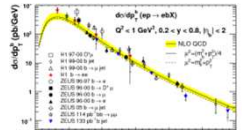
$$\sigma^{+}_{c,\mathrm{vis}} = 4.0 \pm 2.8\ (\mathrm{stat})\ ^{+0.1}_{-0.6}\ (\mathrm{syst})\ \mathrm{pb}$$
$$\sigma^{-}_{c,\mathrm{vis}} = -3.0 \pm 3.8\ (\mathrm{stat})\ ^{+0.5}_{-0.1}\ (\mathrm{syst})\ \mathrm{pb}$$

Sets the stage for future measurements at EIC/LHeC/…

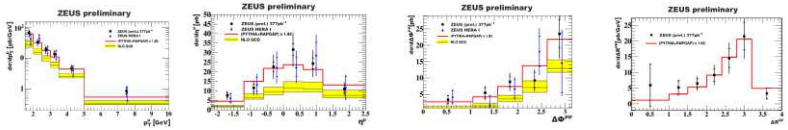
Details see dedicated talk J. Nam tomorrow in WG1

Summary and conclusions

- **Beauty cross sections in ep collisions have been measured from dimuons**
  dimuon tag covers full phase space -> allows **extraction of total b cross section**
- **good agreement with earlier measurements**



- **total cross section** somewhat larger than but **in agreement with NLO QCD**
- **differential cross sections in muon p_T, η, $\Delta\phi$ and ΔR** test bbbar correlations, agree very well with LO+PS MC shape
  NLO prediction: good agreement in shape
  normalisation agrees better with lower scale choice (motivated by theory)



- large NLO uncertainties (mainly b mass + QCD scale dependence) suggest **significant NNLO corrections**
  -> any chance for NNLO calculations soon?
- Other HERA heavy flavour results include **H1+ZEUS charm and beauty data combination in DIS** (presented in detail last year) and **charm in CC by ZEUS** (see dedicated talk J. Nam)
- In general, 6 new ZEUS preliminaries and 2 new papers since last DIS (2 on HFL)

-> **ZEUS team is small, but alive and well, new collaborators and ideas welcome**

Backup slides

Selection cuts and MC

data samples:

- **HERA II, 03-07, L ~ 377 pb^{-1}**

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

muon selection:

- **two muons, $m^{\mu\mu} > 1.5$ GeV**
- **$p_T^{\mu} > 0.75$ GeV** for high muon quality ≥ 5, **$p_T^{\mu} > 1.5$ GeV** for low muon quality
- 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)

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 **:** $\mu^2 = m_b^2 + p_{Tb}^2$ **(μ/2 – 2μ)**
- **Proton: CTEQ5M Photon: GRV-G-HO**
  (PDF error << scale/mass error → neglected)

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

FMNR + Pythia

A G and A E Nuncio Quiroz 2008 J. Phys.: Conf. Ser.110 022036

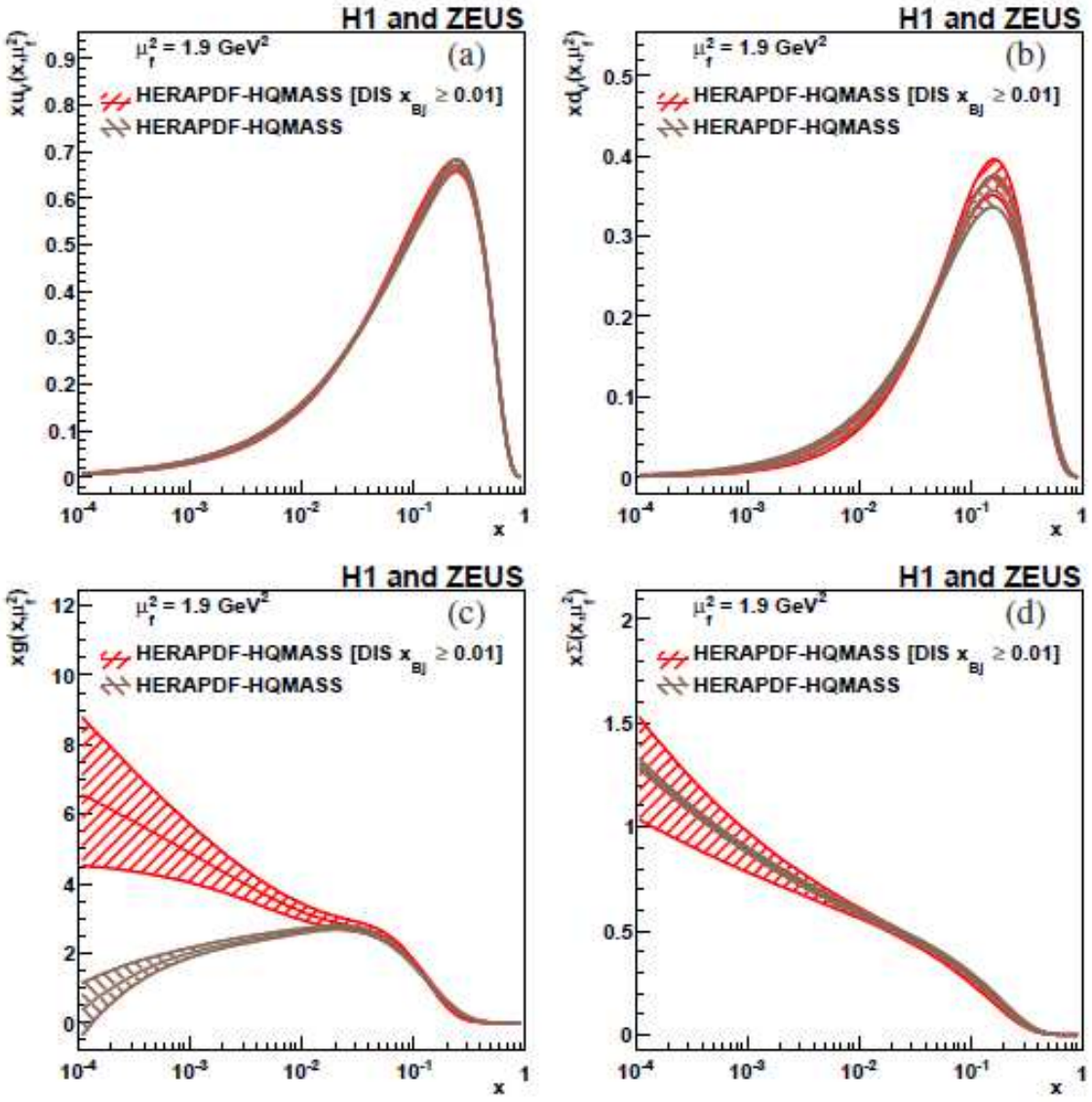
- **In FMNR weighted events with positive and negative weights spanning over 8 orders of magnitude -> "naive" interface very inefficient, not practical**
- **Use weight range reduction (REDSTAT) to ~ 1 order of magnitude preserving NLO accuracy**
  - **events with large + and – weights but similar topologies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

QCD fit with $x_{Bj} > 0.01$ for inclusive data

arXiv:1804.01019

charm and beauty mass floating

gluon at $x < 0.01$ inconsistent with inclusive fit



FONLL-C fit of inclusive data

arXiv:1802.00064 (XFitter team):

FONLL-C inclusive fit with and without NLLx resummation

personal remark:

FONLL-C inclusive fit with NLLx qualitatively consistent with FF charm

+ x > 0.01 inclusive fit (compare previous slide)

-> combine both worlds by applying NLLx to light flavours only in FF scheme?

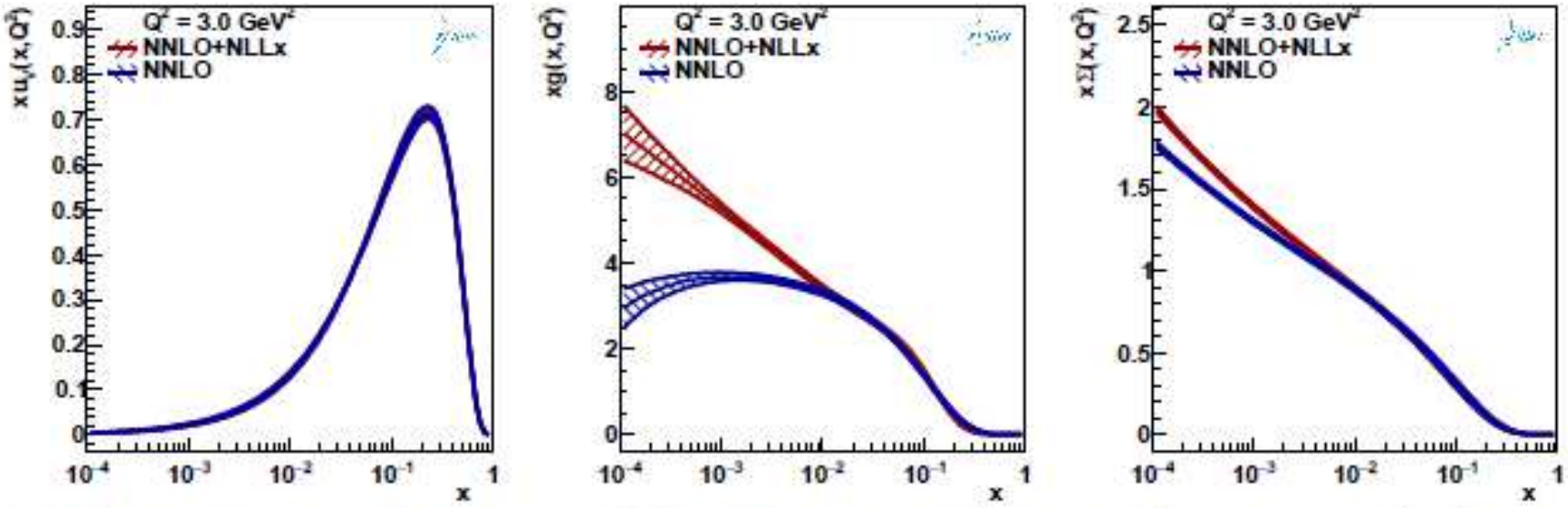
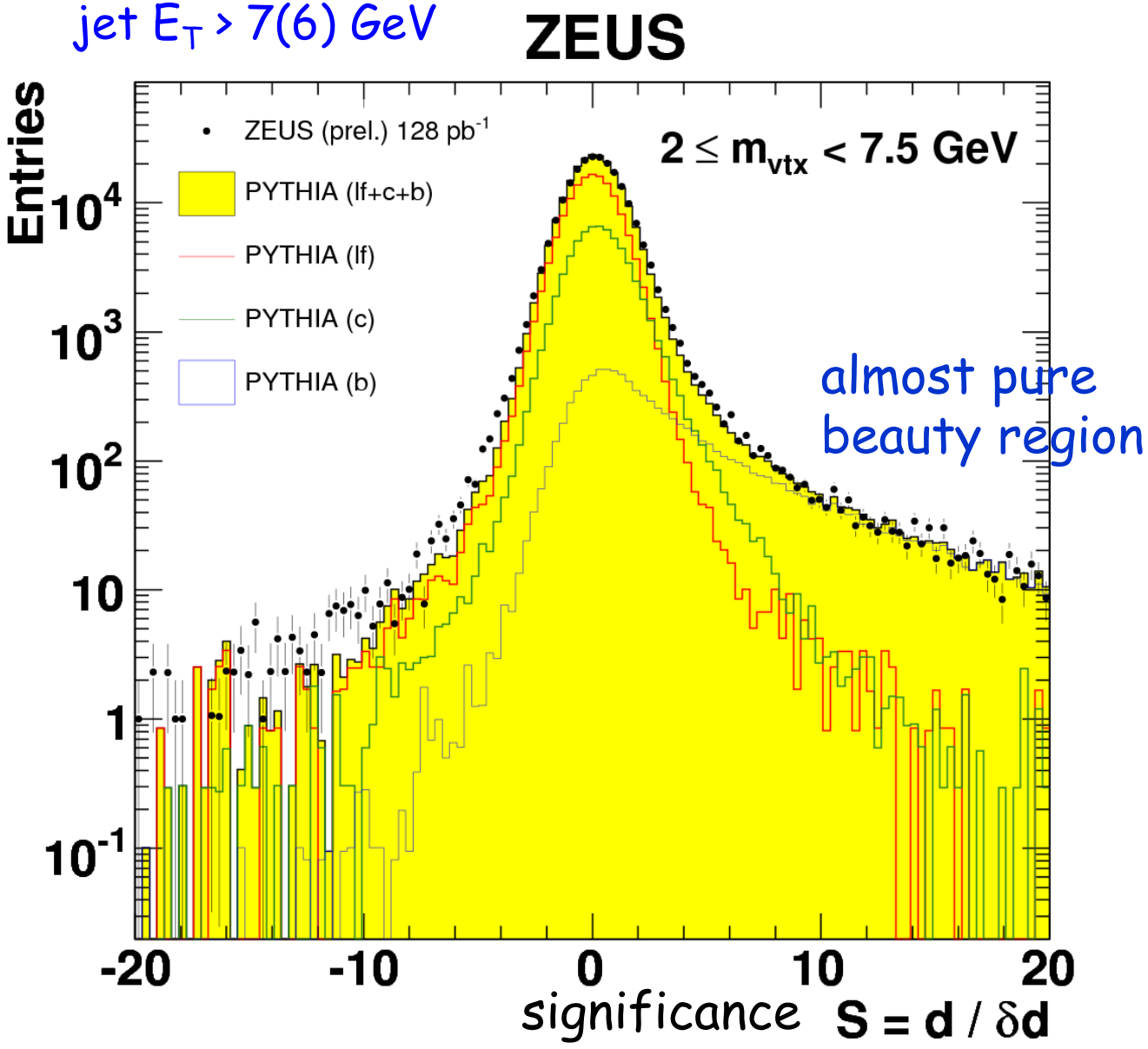


Figure 3 The up valence PDF xu_v, the gluon PDF xg and the total singlet PDF $x\Sigma$ for the final fits with (NNLO+NLLx) and without (NNLO) $\ln(1/x)$ resummation.

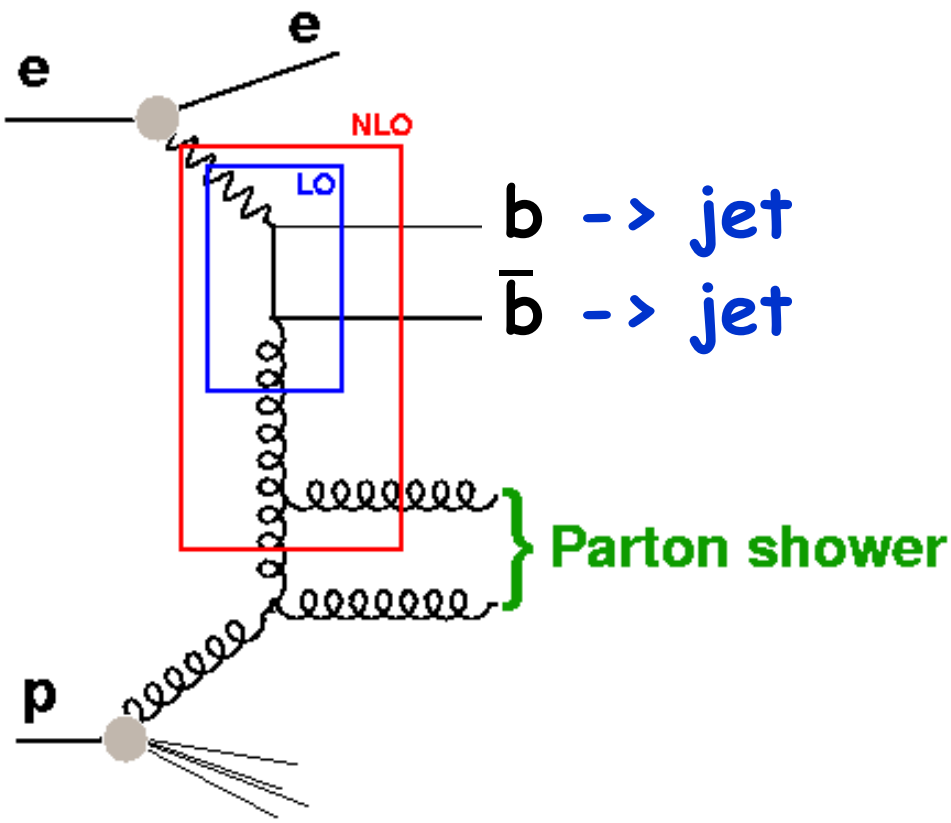
beauty from inclusive dijets + vtx

use significance of secondary vertex

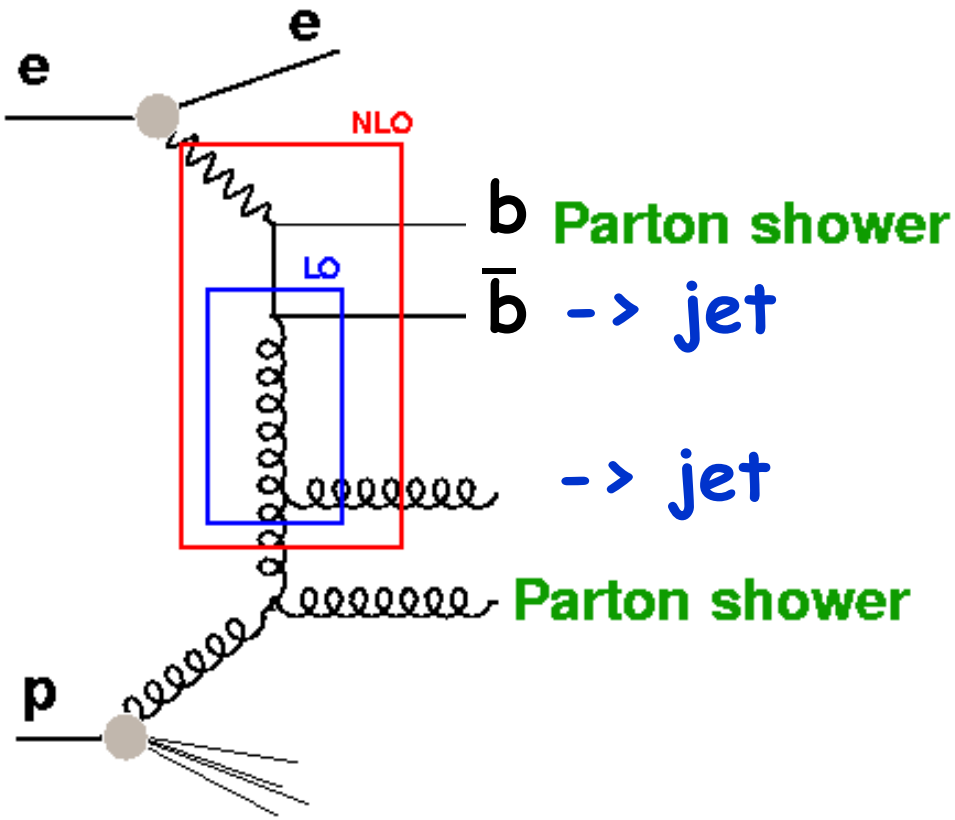
simultaneous fit of mirorred significance for three different mass ranges



NLO vs. LO + parton shower



"direct γ"



"resolved γ"