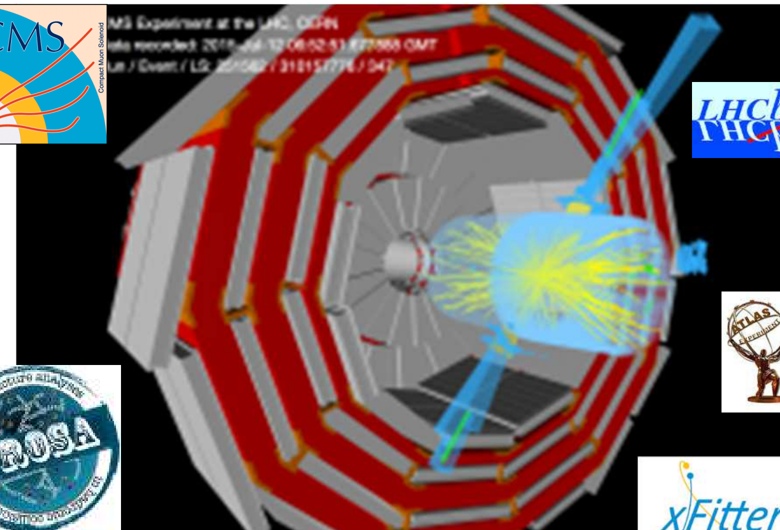
Heavy flavour production in CMS and outlook on combined treatment of heavy flavour measurements at HERA, LHC and elsewhere

Achim Geiser

DESY Hamburg

(member of the CMS, ZEUS and PROSA collaborations)



HQHP19 workshop, Mainz, 3. 10. 2019

- Selected heavy flavour results from CMS (and other LHC exp.)
- Charm/beauty and proton structure from HERA (+LHCb)
- (MSbar quark masses and running Higgs Yukawa couplings)
- HQHP Projects for discussion

Open Heavy Flavour production in CMS

other LHC collaborations covered in separate dedicated talks on tuesday -> see e.g. nice introduction in ATLAS talk

CMS forward covered by talk R. Ulrich on tuesday

CMS has **rich program of heavy flavour measurements**:
- BPH, TOP, HIN, SMP, hundreds of CMS papers

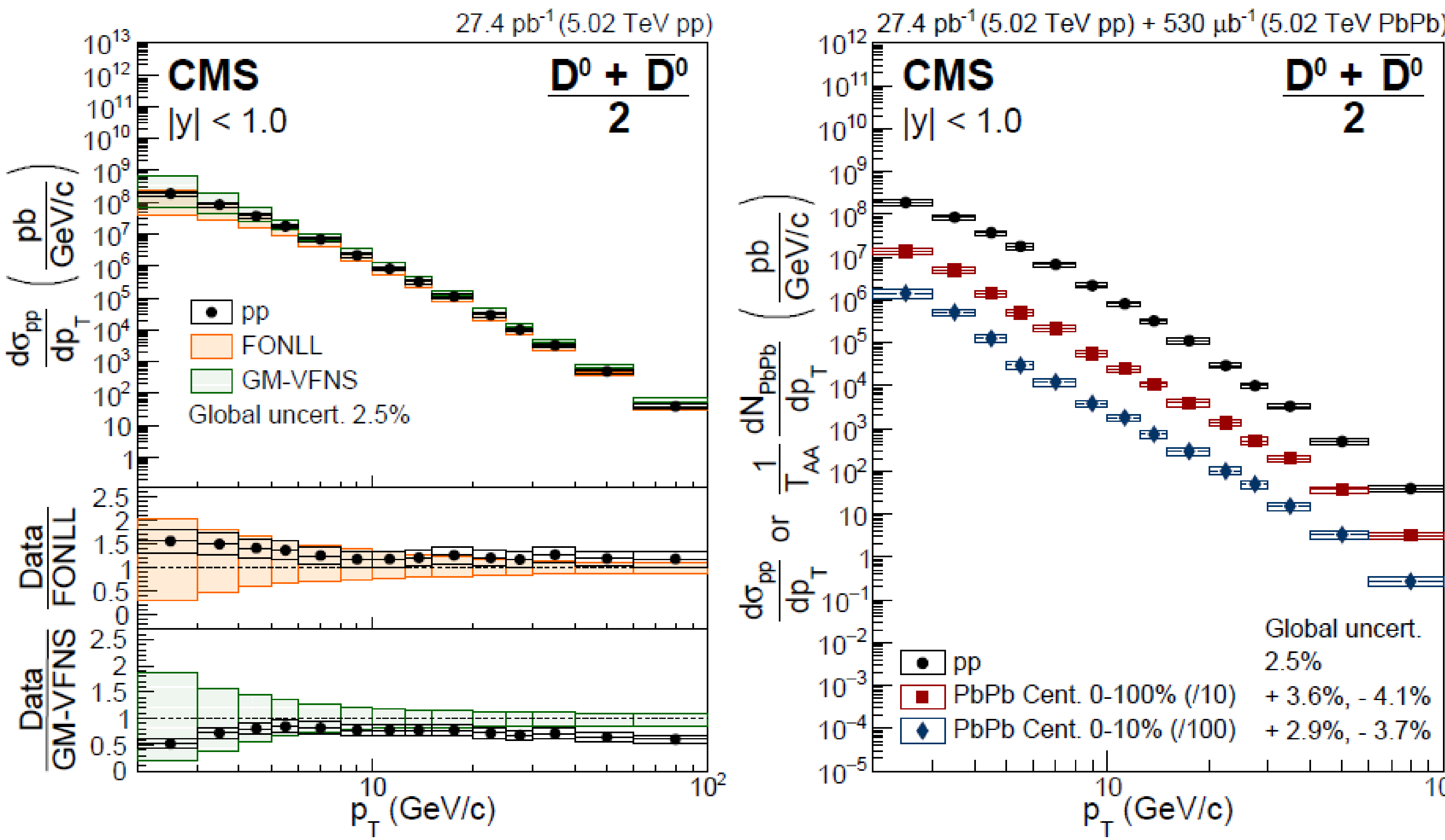
(maybe not true, talk Masip?)

Onia (J/ψ, Υ, …) and **rare decays** barely contribute to cosmic ray physics -> concentrate on **open heavy flavour production**

Cosmic ray interactions are **pA** and **AA** interactions
-> concentrate on **selected pp vs pA vs AA comparisons**

Charm in pp and PbPb @ 5.02 TeV

arXiv:1708.04962 Phys.Lett. B782 (2018)



same conclusions as for ATLAS, ALICE and LHCb results:
data and theory are consistent, but theory unc. >> data unc.

D^0 nuclear modification factor

arXiv:1708.04962 Phys.Lett. B782 (2018)

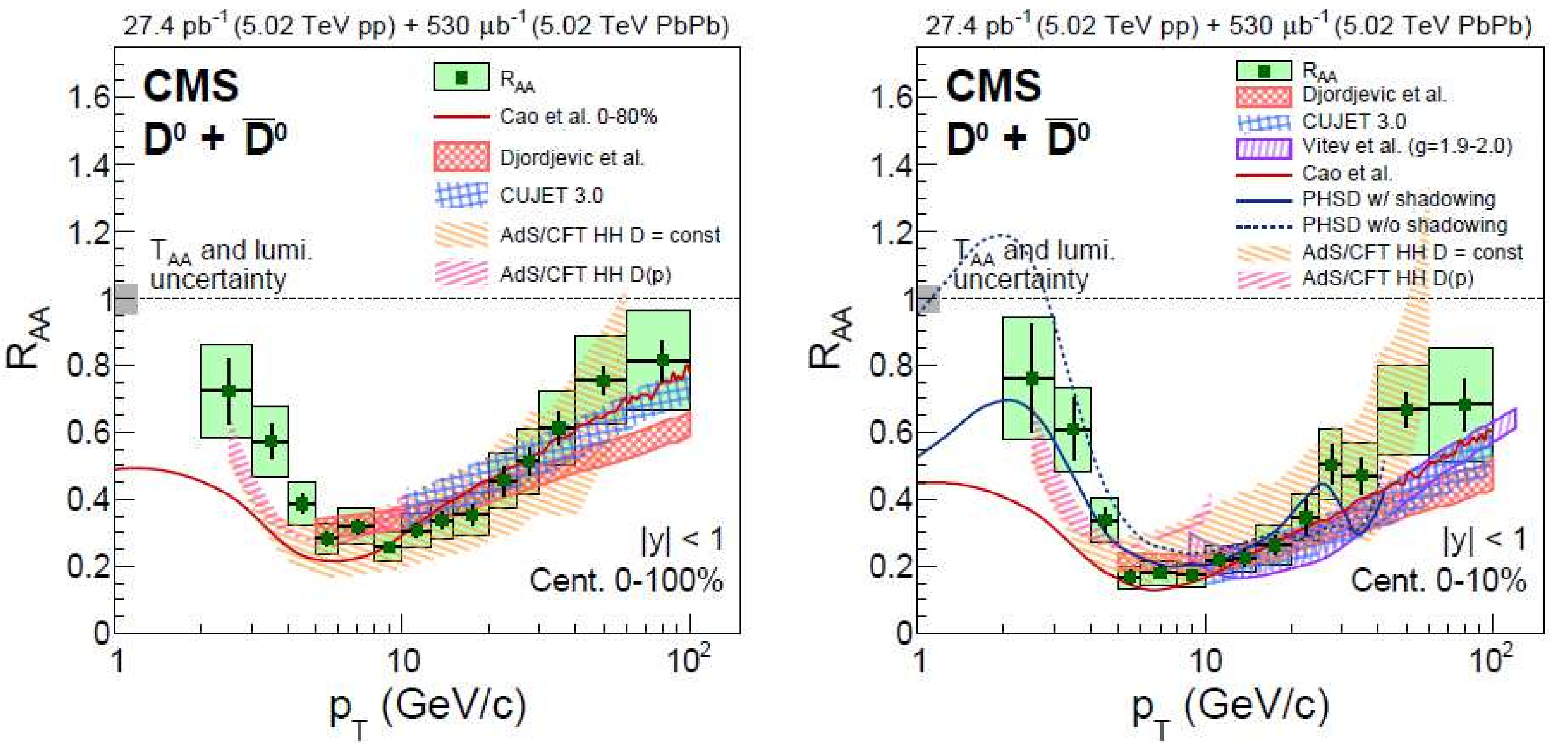


Figure 3: R_{AA} as a function of p_T in the centrality range 0–100% (left) and 0–10% (right). The vertical bars (boxes) correspond to statistical (systematic) uncertainties. The global systematic uncertainty, represented as a grey box at $R_{AA} = 1$, comprises the uncertainties in the integrated luminosity measurement and T_{AA} value. The D^0 R_{AA} values are also compared to calculations from various theoretical models [37–47].

Project for discussion 1:

Sven: Which further collider and/or fixed-target measurements would we suggest to decrease present uncertainties ?

- combine LHC charm measurements in central region with very forward measurements (e.g. TOTEM, CASTOR, ...) ?

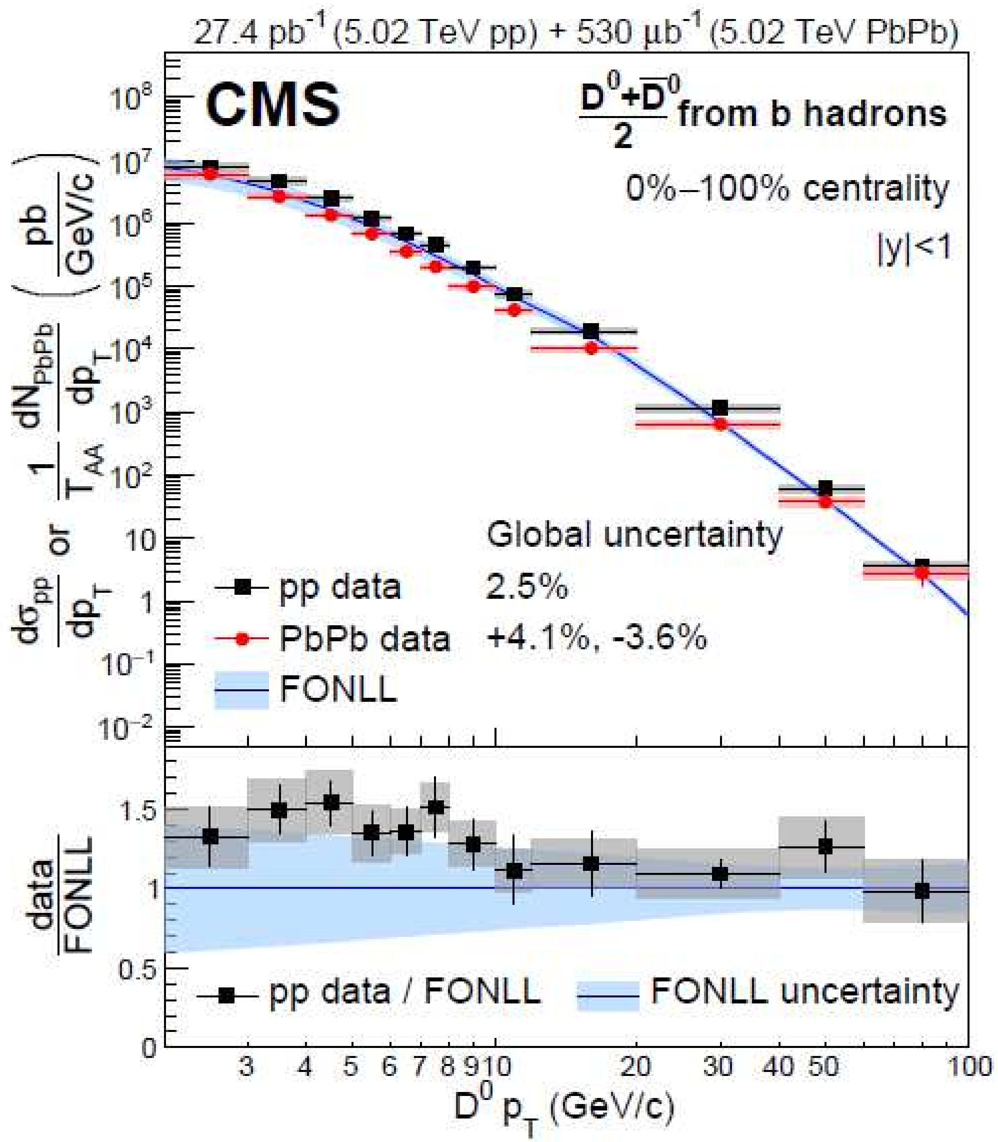
e.g. 7 TeV Minimum Bias + CASTOR data

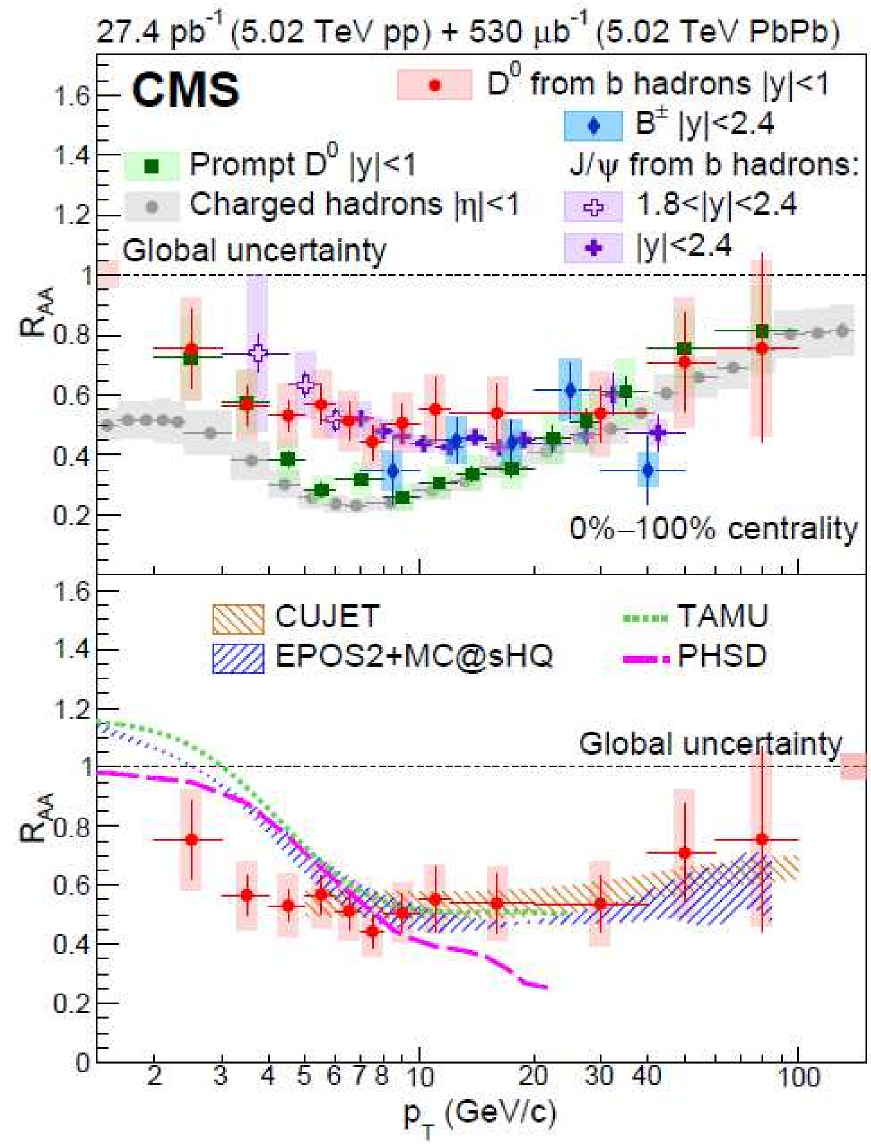
(available as CMS Open Data)

Can we learn something for cosmic rays?

D^0 from b decays

arXiv:1810.11102, Phys.Rev.Lett. 123 (2019) 022001





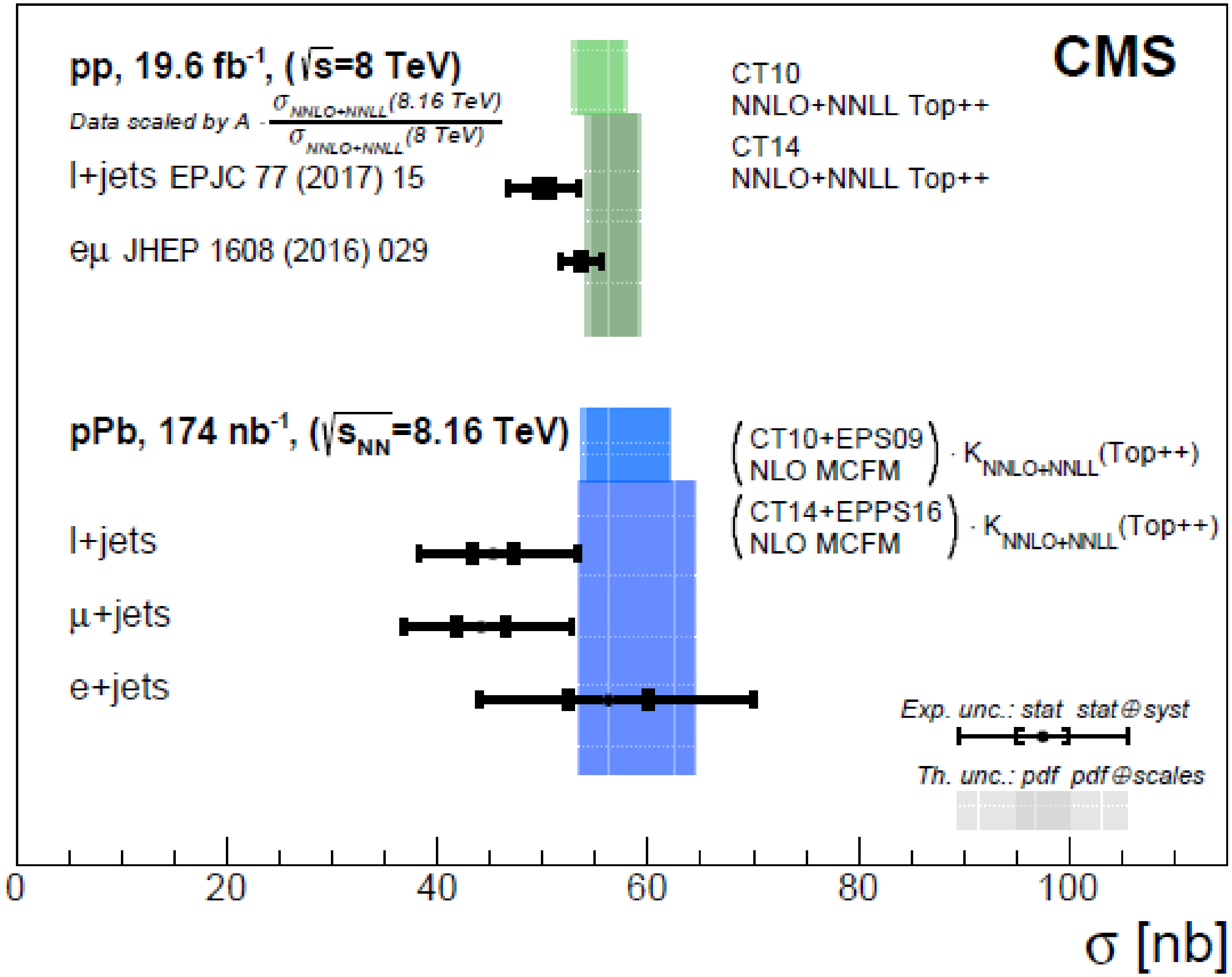
also beauty dominated by NLO theory uncertainty

Project for discussion 2:

- Combine pp and pA heavy flavour measurements to p-air?

Top in p-Pb vs. pp

arXiv:1709.07411, Phys.Rev.Lett. 119 (2017) 242001

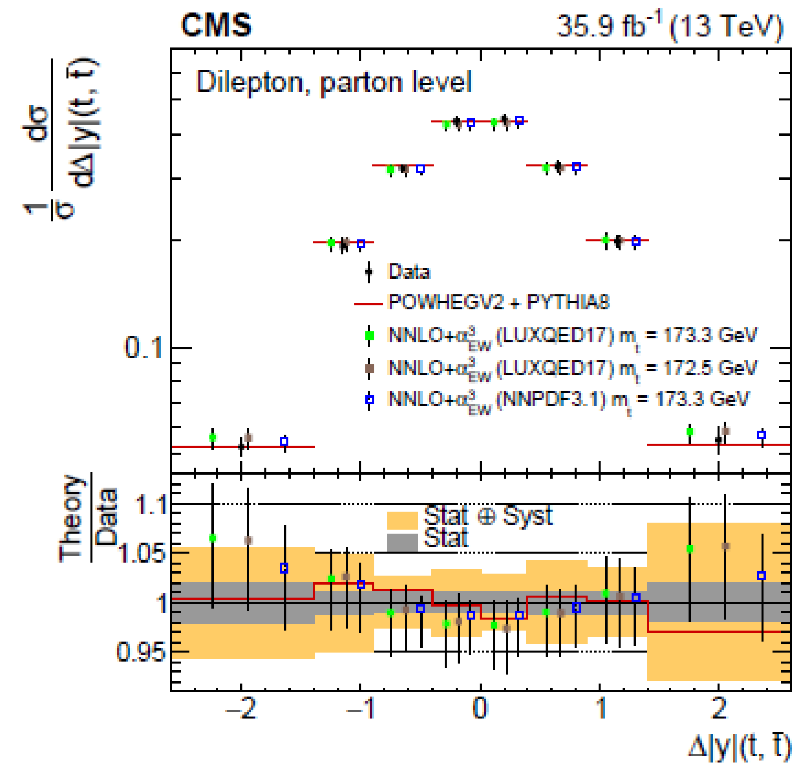


cross sections/nucleon are the same within uncertainties

Project for discussion 3:

Sven: "How can we reduce theory uncertainties?"

- get existing differential NNLO cross section predictions for top to work for charm and beauty?



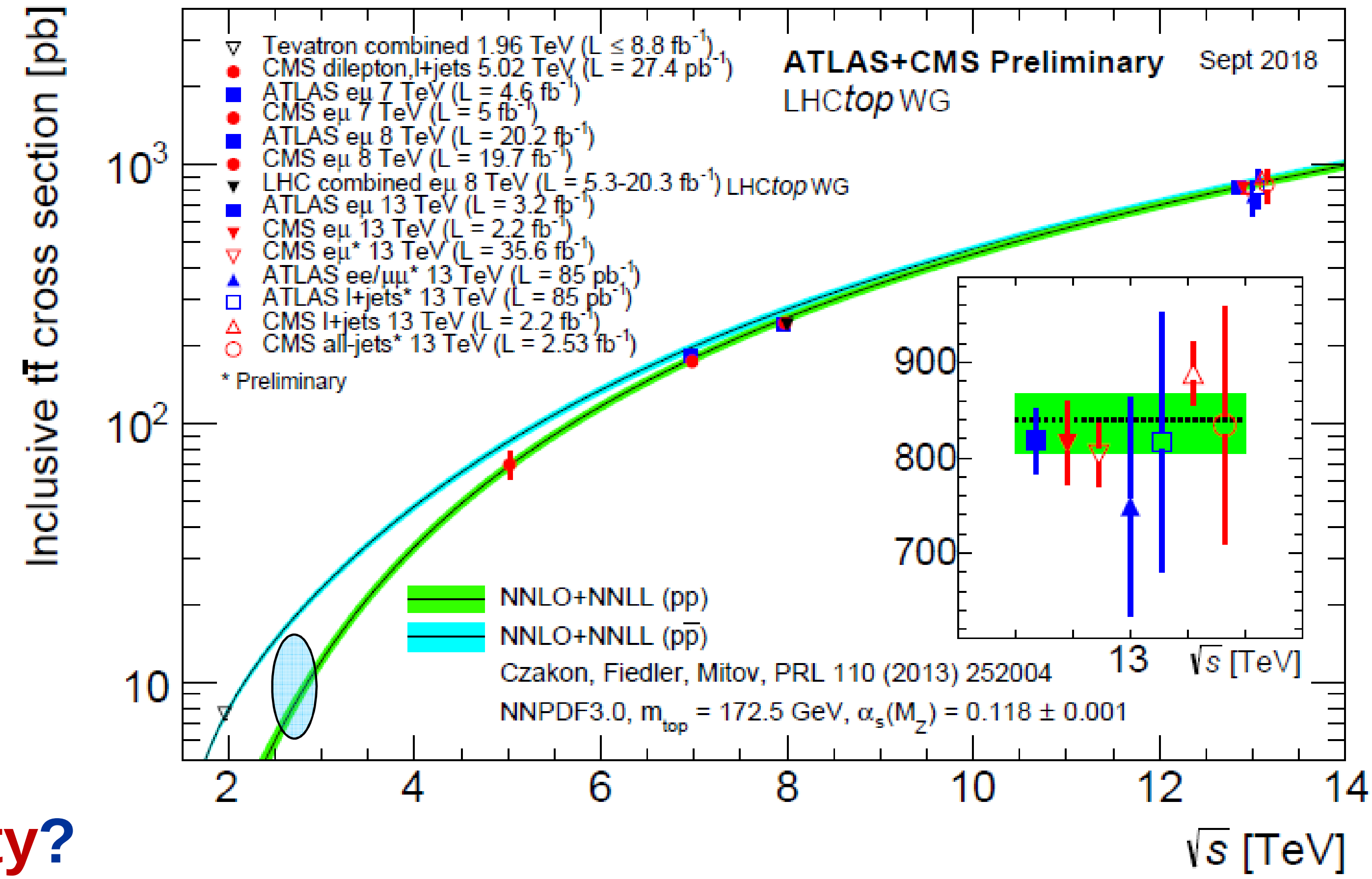
-> expect general reduction of theory uncertainties by ~factor 2 w.r.t. NLO, also for extrapolation to cosmic ray predictions

Total ttbar pp cross section vs. NNLO+NNLL

see also talk Schwinn

Measured at almost all available CMS energies

(missing:
measurement
at 2.76 TeV)

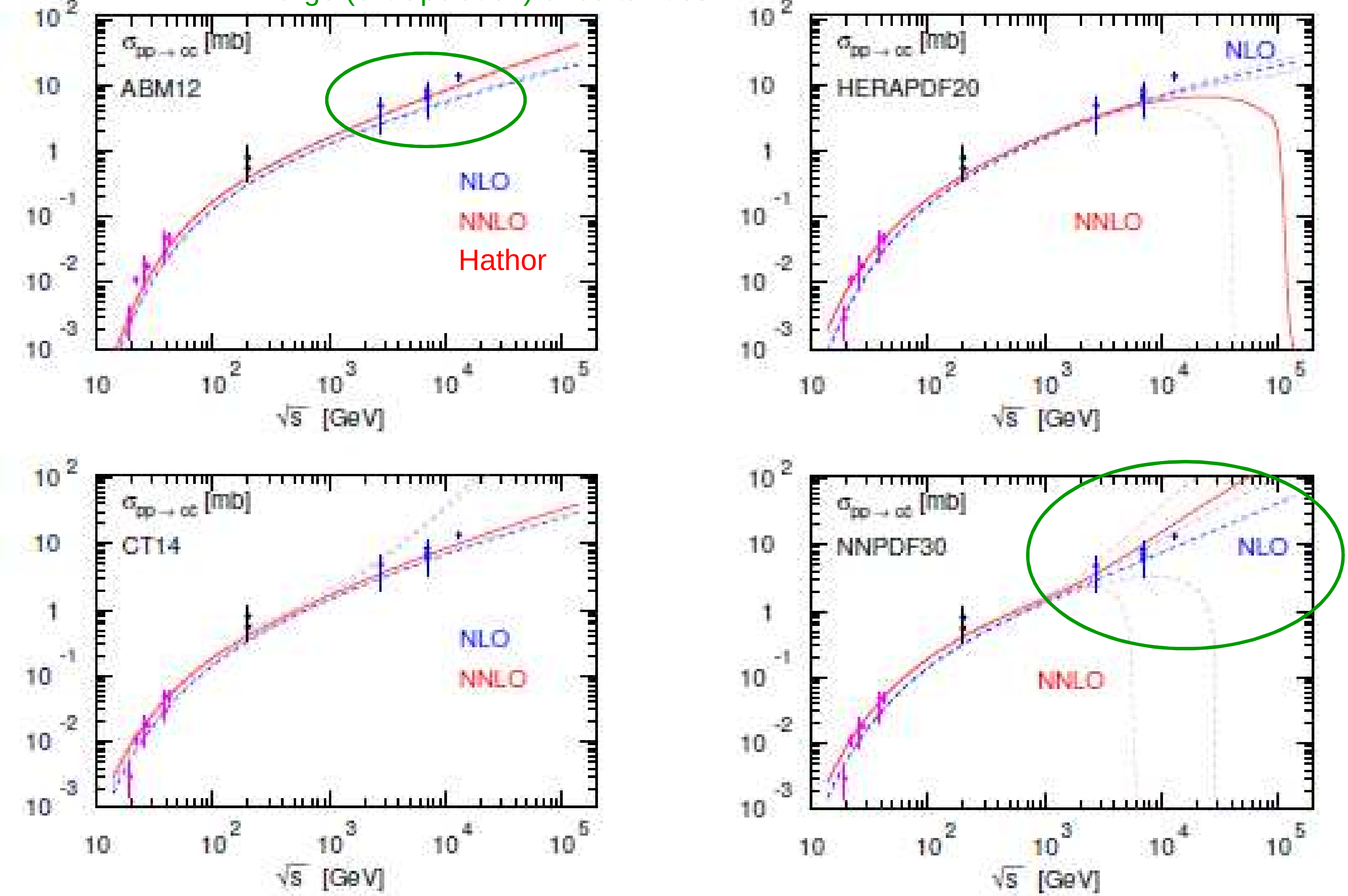


produce the same
for charm and beauty?

(so far “unmeasured” at LHC; only strong extrapolations available)

NNLO total charm cross section: A. Accardi et al., Eur.Phys.J. C76 (2016) no.8, 471

large (extrapolation) uncertainties



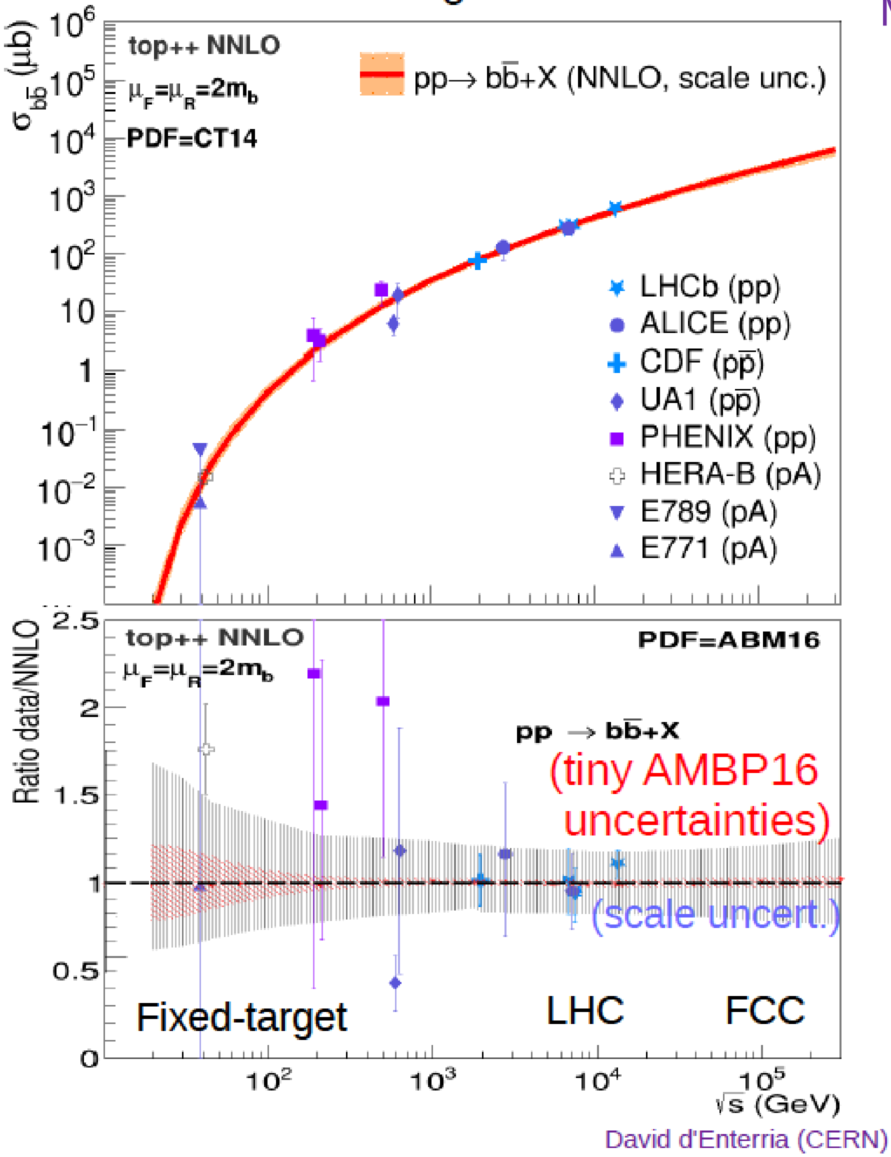
can constrain PDFs

(and cosmic rays)

Similar considerations for total beauty cross section

- Bottom: Very good agreement at all √s within large uncertainties

D. D'Enterria
Moriond QCD 2017



Compared to Charm, Beauty has:

smaller cross section

smaller branching fractions

longer lifetime, larger mass

Data and NNLO theory precision comparable,

~30%

Project for discussion 4:

Sven: Which further collider and/or fixed-target measurements would we suggest to decrease present uncertainties ?

- data points for c and b total cross sections at LHC so far dominated by extrapolation uncertainties
- close experimental "white spots" in LHC phase space?

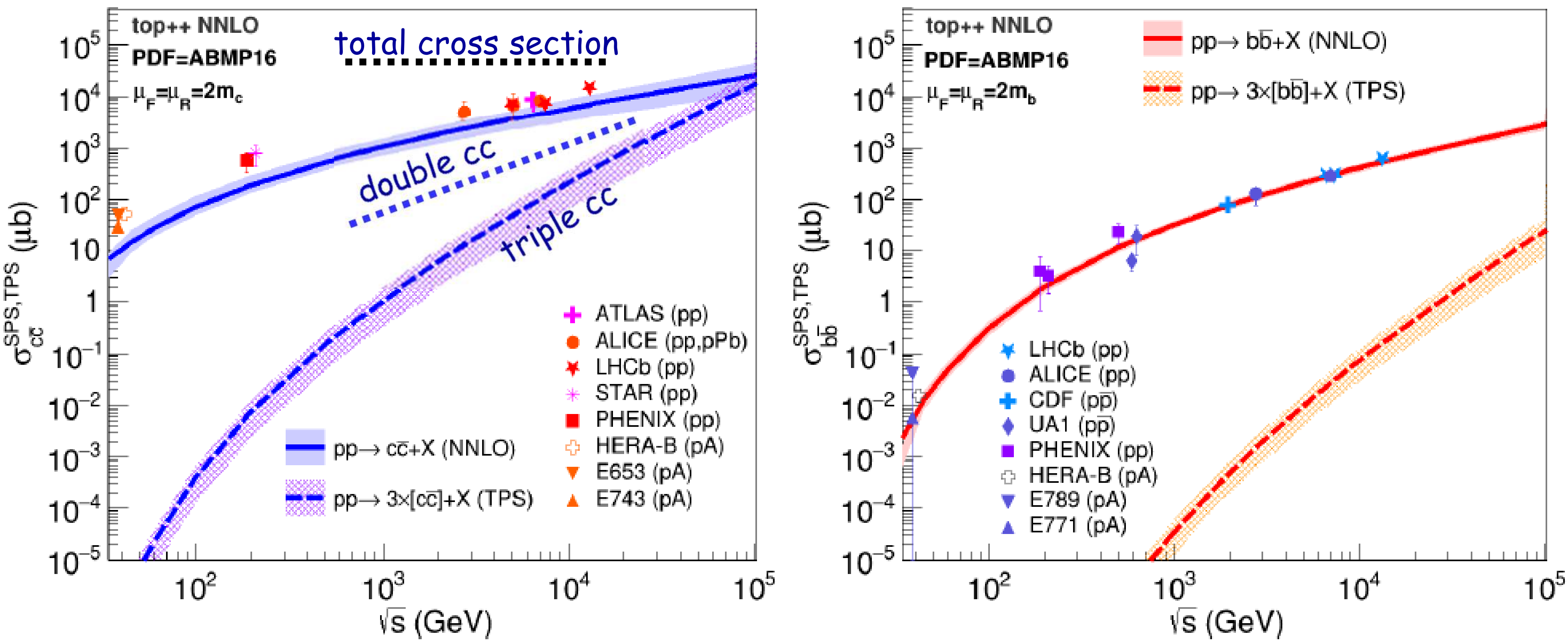
-> reduce extrapolation uncertainty to negligible level?

-> constrain PDFs, α_s, m_c and m_b to NNLO also from LHC total charm and beauty cross sections, as already done for top?

Double and triple cc and bb pair production

arXiv:1612.05582, Phys.Rev.Lett. 118 (2017) 122001
D. D'Enterria, S. Snigirev

pp



(data/theory agreement improves with scale $\mu=m_Q$)

around $\sqrt{s}$=100 TeV, charm cross section equates total cross section!

p-Pb interactions

arXiv:1612.08112, Eur.Phys.J. C78 (2018) 359
D. D'Enterria, S. Snigirev

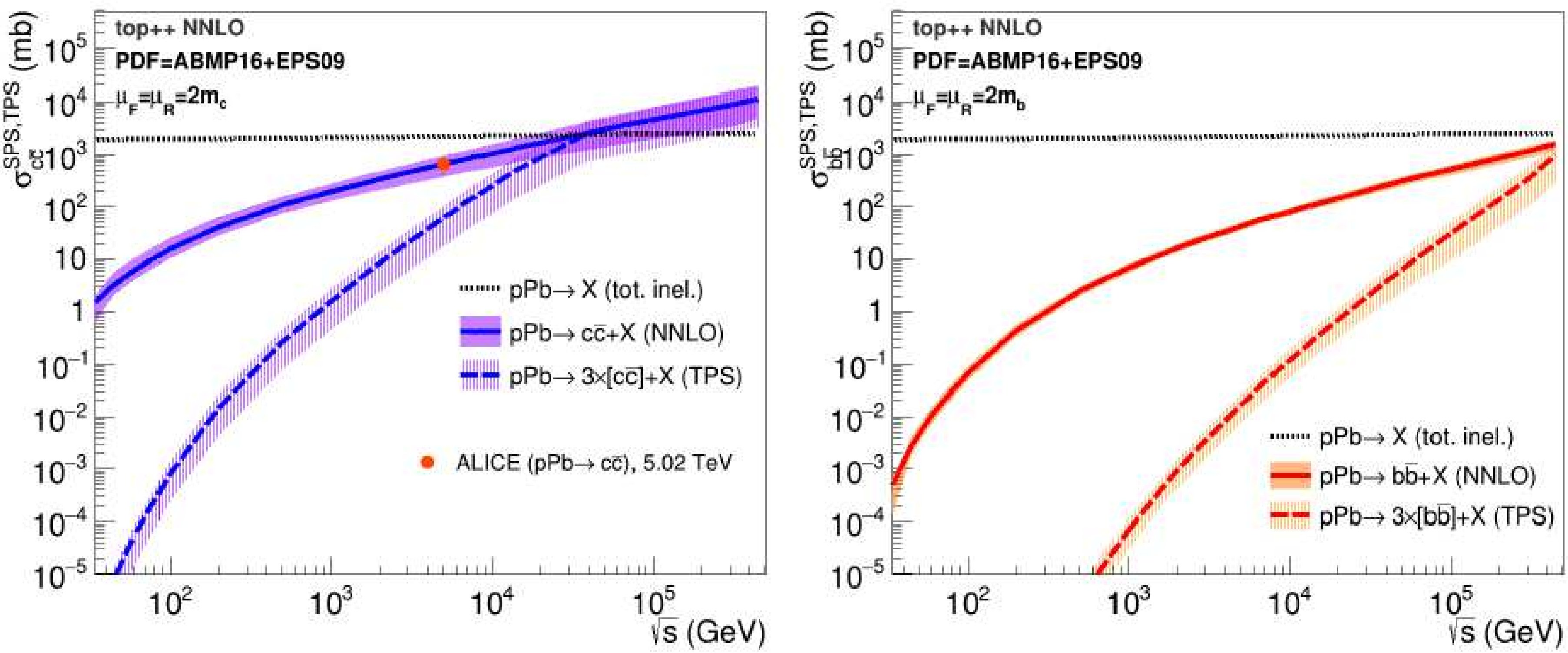


FIG. 1: Charm (left) and bottom (right) cross sections in pPb collisions as a function of c.m. energy, in single-parton (solid line) and triple-parton (dashed line) parton scatterings, compared to the total inelastic pPb cross section (dotted line). Bands around curves indicate scale, PDF (and $\sigma_{\rm eff,TPS}$, in the TPS case) uncertainties added in quadrature. The pPb $\rightarrow c\bar{c} + X$ charm data on the left plot has been derived from [29].

p-air interactions

arXiv:1612.08112, Eur.Phys.J. C78 (2018) 359
D. D'Enterria, S. Snigirev

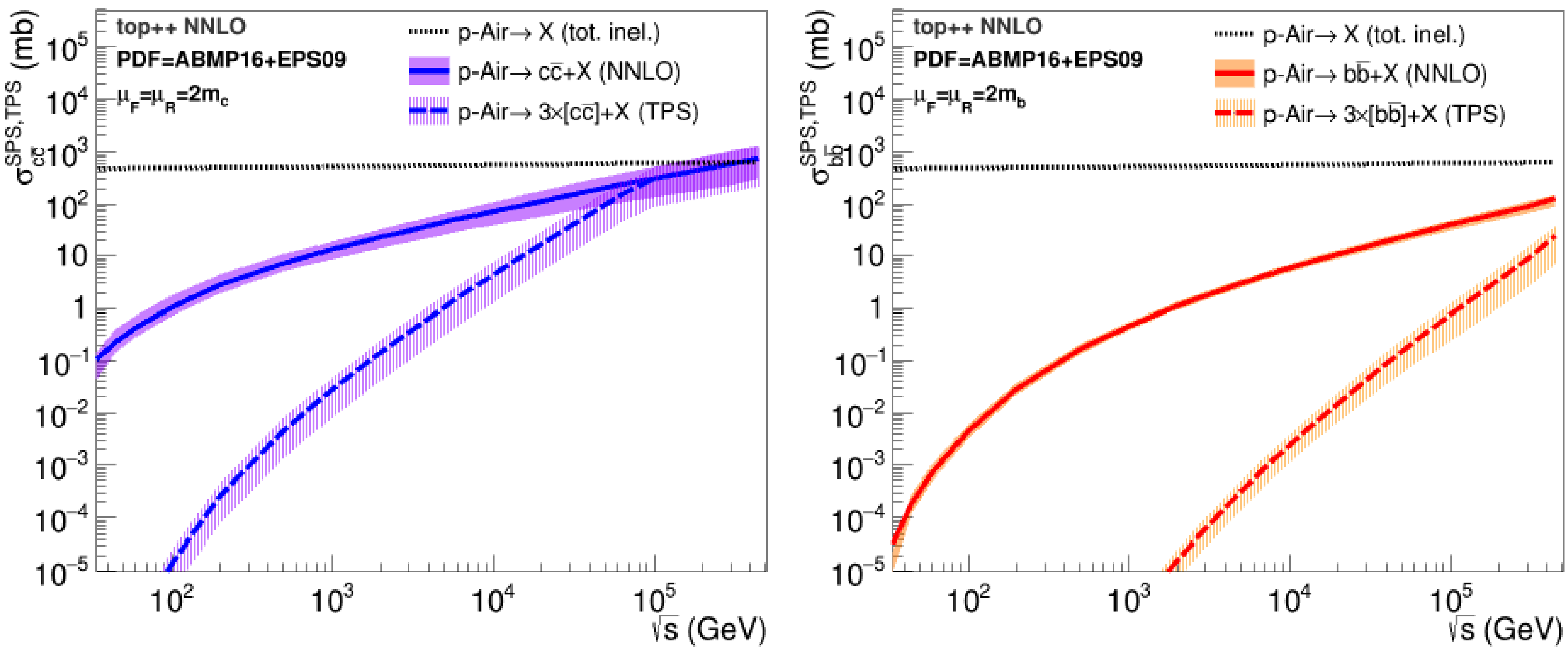


FIG. 2: Charm (left) and bottom (right) cross sections in p-Air collisions as a function of c.m. energy, in single-parton (solid line) and triple-parton (dashed line) parton scatterings, compared to the total inelastic p-Air cross section (dotted line). Bands around curves indicate scale, PDF (and $\sigma_{\mathrm{eff,TPS}}$, in the TPS case) uncertainties added in quadrature.

above E~10^{10} GeV, every cosmic ray interaction may contain (multiple) charm pairs already from the first interaction!

-> significant energy loss to neutrinos?

Project for discussion 5:

Sven: "How can we reduce theory uncertainties?"

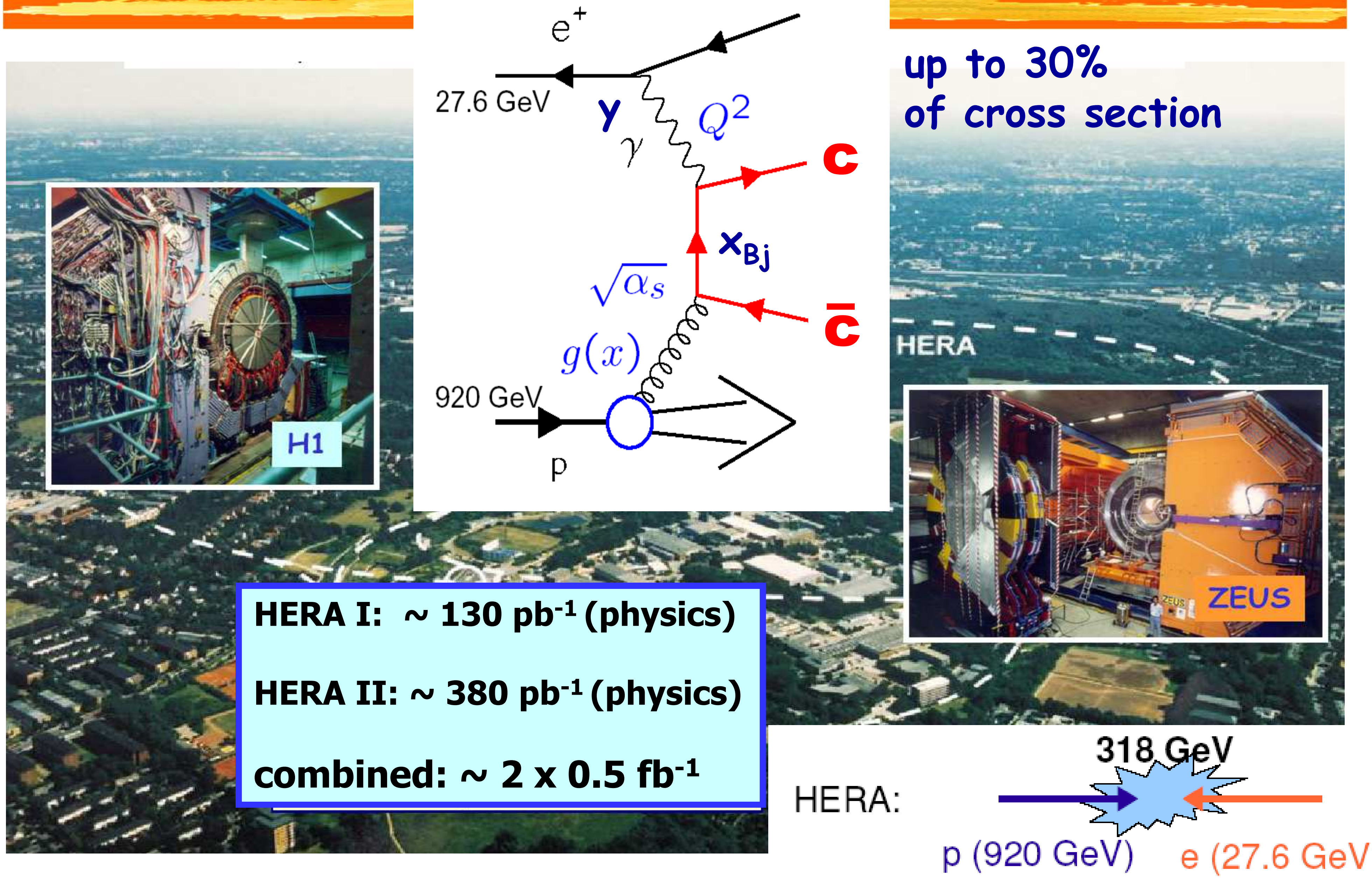
- further improve evaluation of multi-HQ production

  (beyond simple effective cross section approach)

  + improve measurements of multiple heavy flavour final states at LHC

-> improve predictions for multi-heavy-flavour pairs also in cosmic ray interactions

The HERA ep collider and experiments



up to 30% of cross section

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

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

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

Review of open charm at HERA

arXiv:1506.07519

discussion of ~60 papers by H1 and ZEUS + theory, 1995-2015

Progress in Particle and Nuclear Physics 84 (2015) 1–72

ELSEVIER

Contents lists available at ScienceDirect

Progress in Particle and Nuclear Physics

journal homepage: www.elsevier.com/locate/ppnp

Review

Charm, beauty and top at HERA

O. Behnke, A. Geiser *, M. Lisovyi [1]

DESY, Hamburg, Germany

CrossMark

ARTICLE INFO

Keywords:
Charm
Beauty
Top
HERA
DIS
Photoproduction

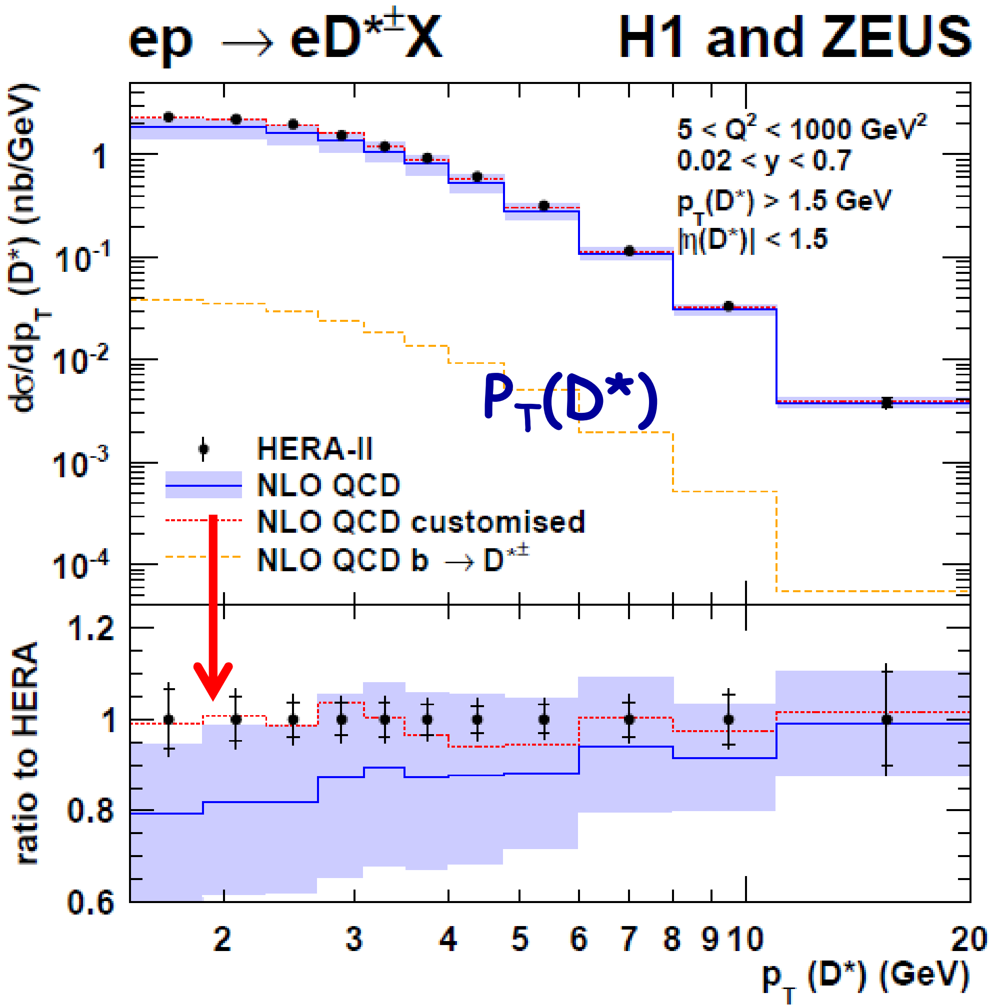
ABSTRACT

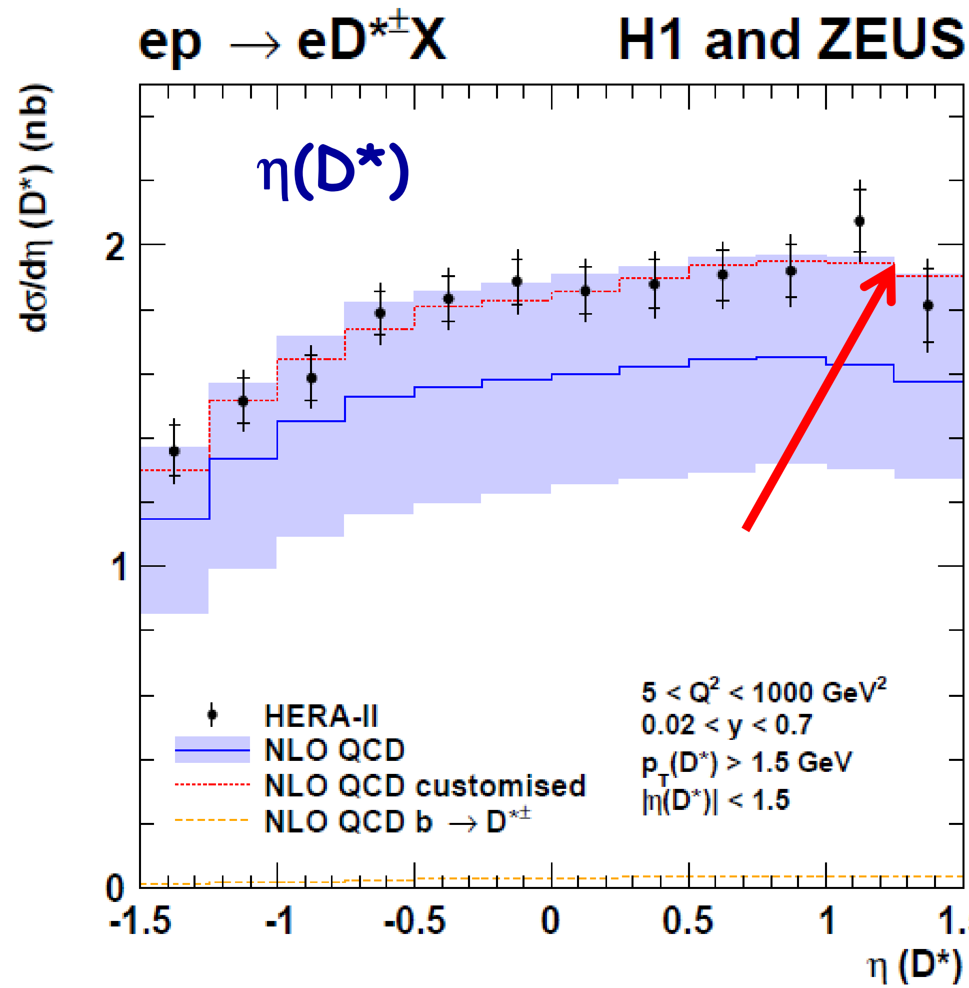
Results on open charm and beauty production and on the search for top production in high-energy electron–proton collisions at HERA are reviewed. This includes a discussion of relevant theoretical aspects, a summary of the available measurements and measurement techniques, and their impact on improved understanding of QCD and its parameters, such as parton density functions and charm- and beauty-quark masses. The impact of these results on measurements at the LHC and elsewhere is also addressed.

(also includes discussion of different heavy flavour schemes)

Combined D* cross sections in DIS

arXiv:1503.06042, JHEP 1509 (2015) 149

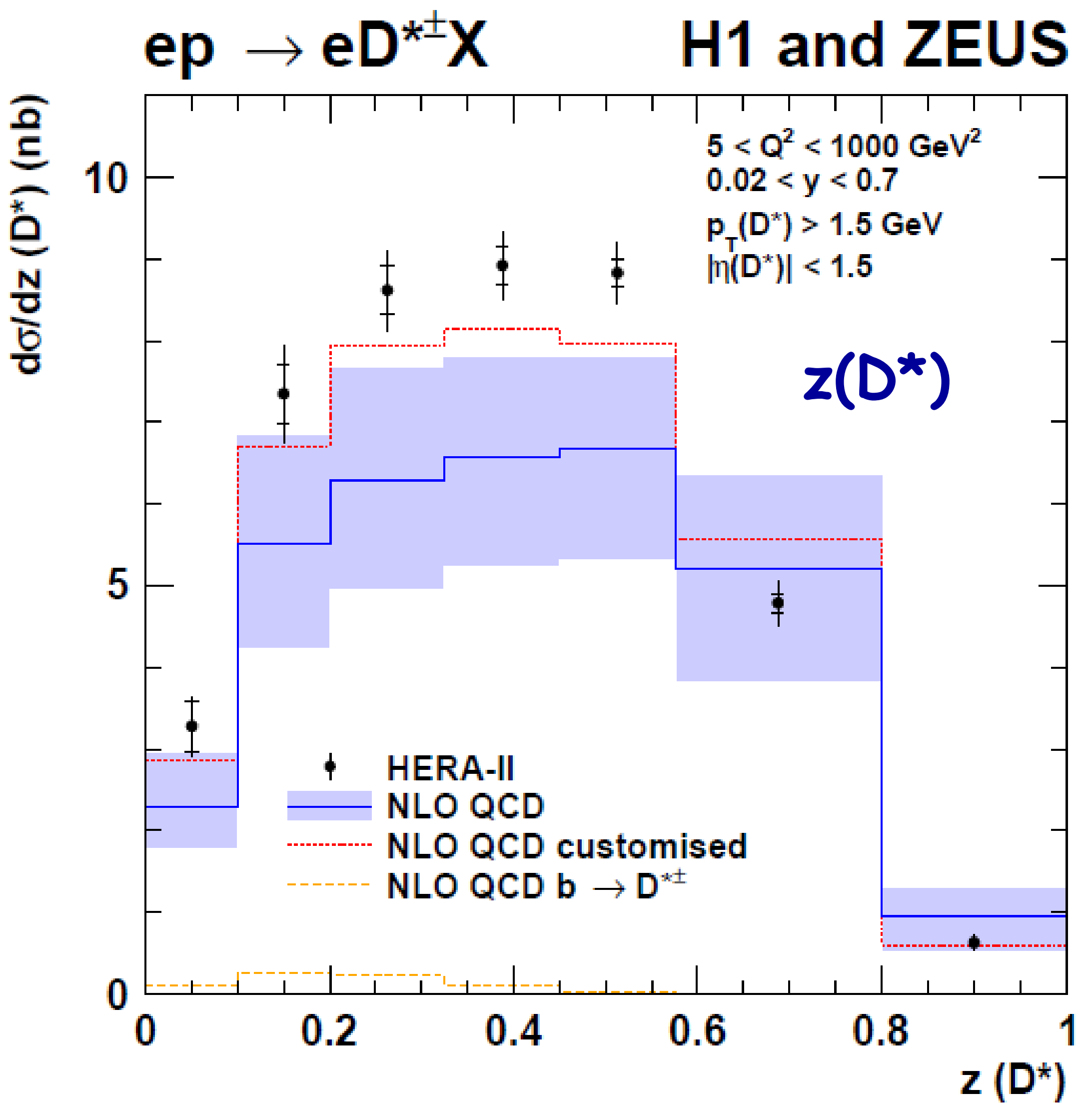




customised choice: - reduced renormalisation scale
- modified scale dependence of fragmentation
- slightly lower charm mass (all within uncertainty)

Charm fragmentation function

arXiv:1503.06042, JHEP 1509 (2015) 149



Combination of H1 and ZEUS D* measurements

example: z
(energy/momentum fraction taken by D*) ,
shape directly sensitive to fragmentation parameters

more work on theory needed

Project for discussion 6:

- NLO theory uncertainties much larger than experimental uncertainties

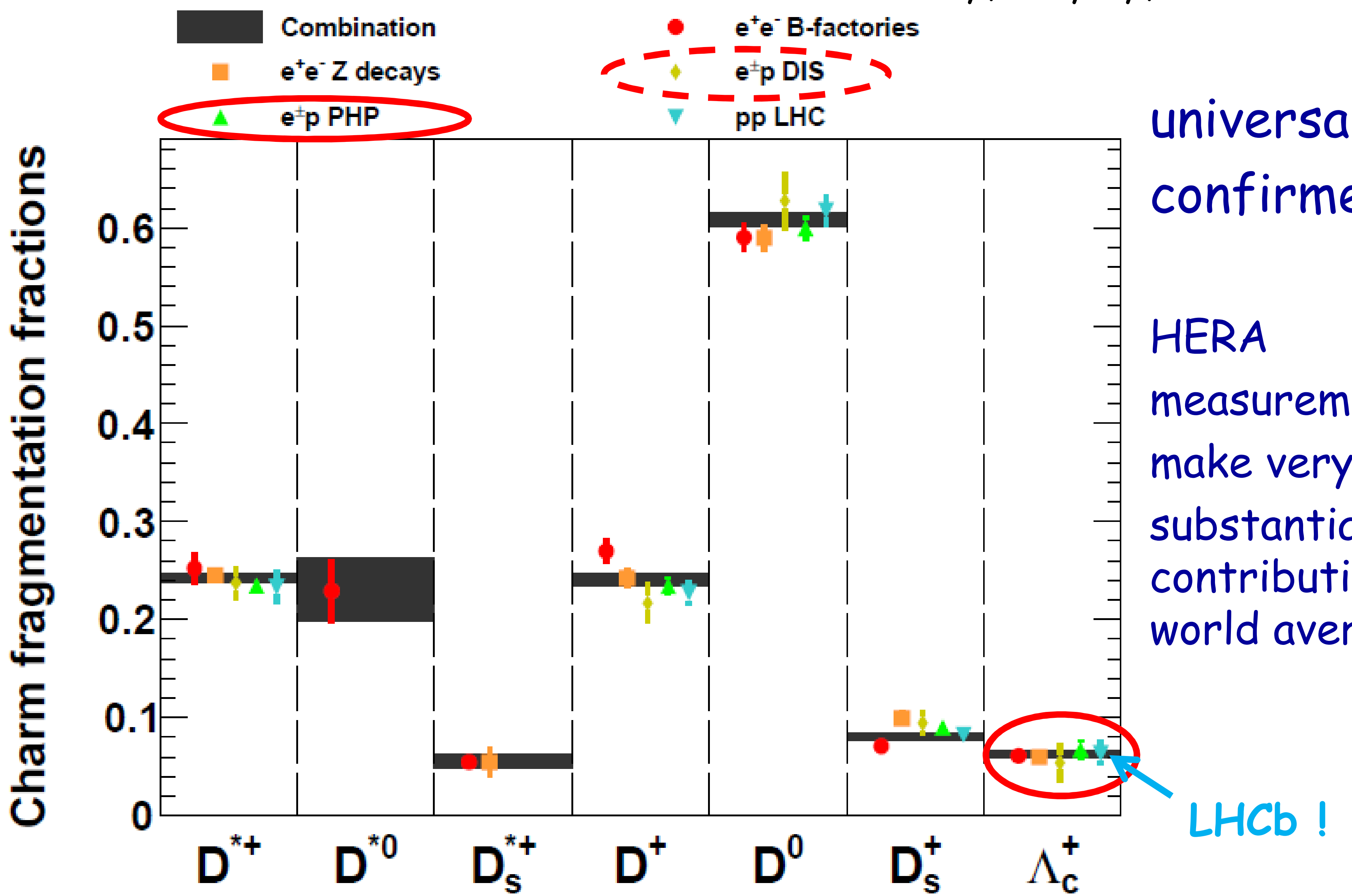
Sven: "How can we reduce theory uncertainties?"

- evaluate 'customized choice' of NLO theory parameters (scales, fragmentation & m_c), within uncertainties, also for LHC charm & beauty predictions? (LHCb, ALICE, ATLAS, CMS)

-> data driven uncertainty reduction on predictions for cosmic ray physics?

Charm fragmentation fractions

arXiv 1509.01061, EPJC 76 (2016) 397
Lisovyi, Verbytskyi, Zenaiev

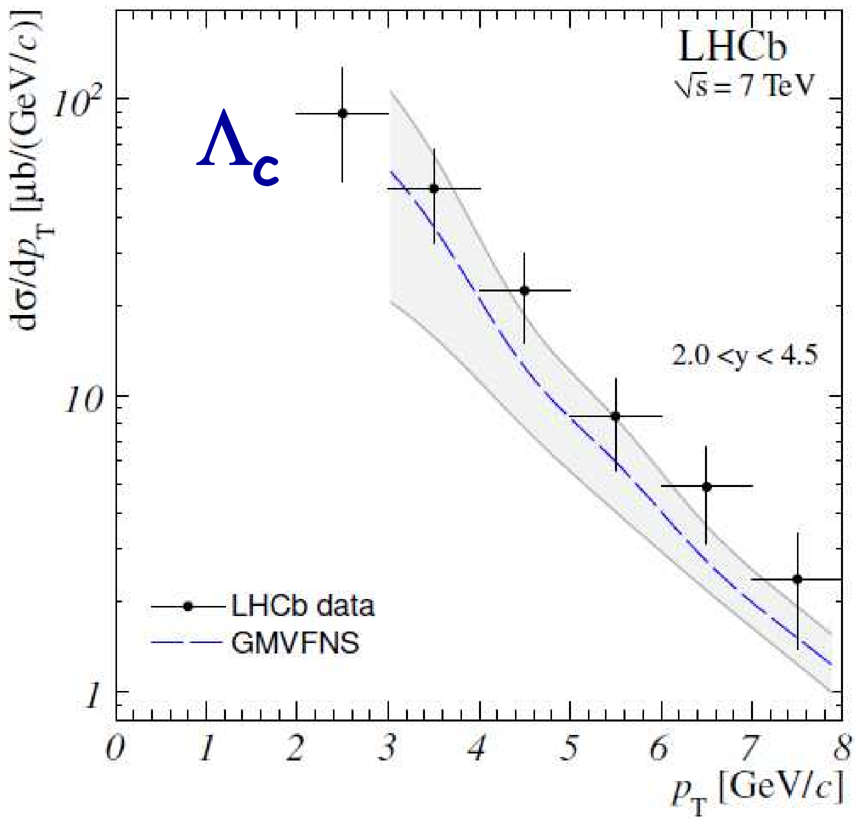


universality confirmed

HERA measurements make very substantial contribution to world average

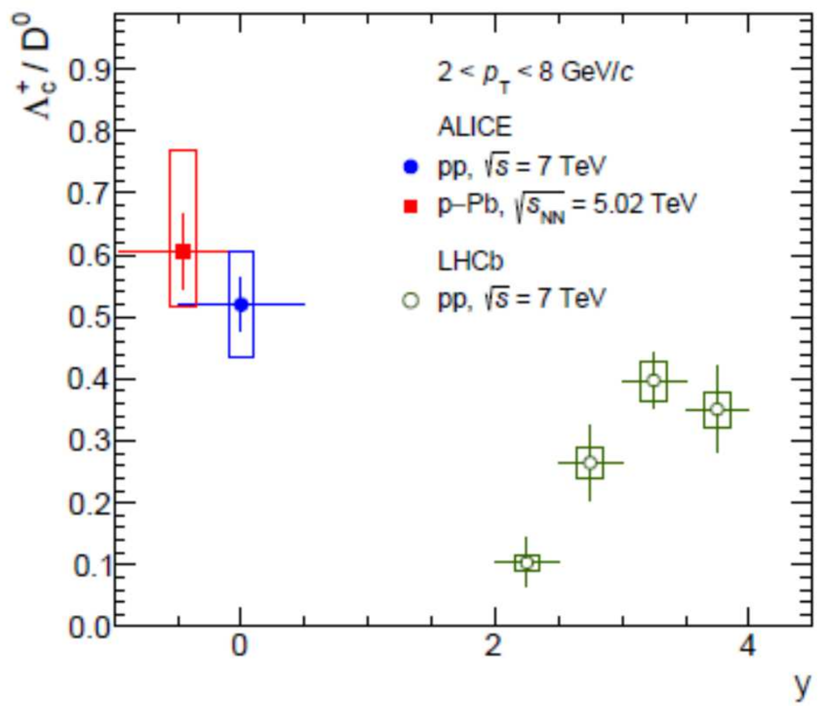
Lambda_c production in LHCb

arXiv:1302.2864, Nucl.Phys. B871 (2013) 1



- consistent with e+e- and ep !

arXiv:1712.09581



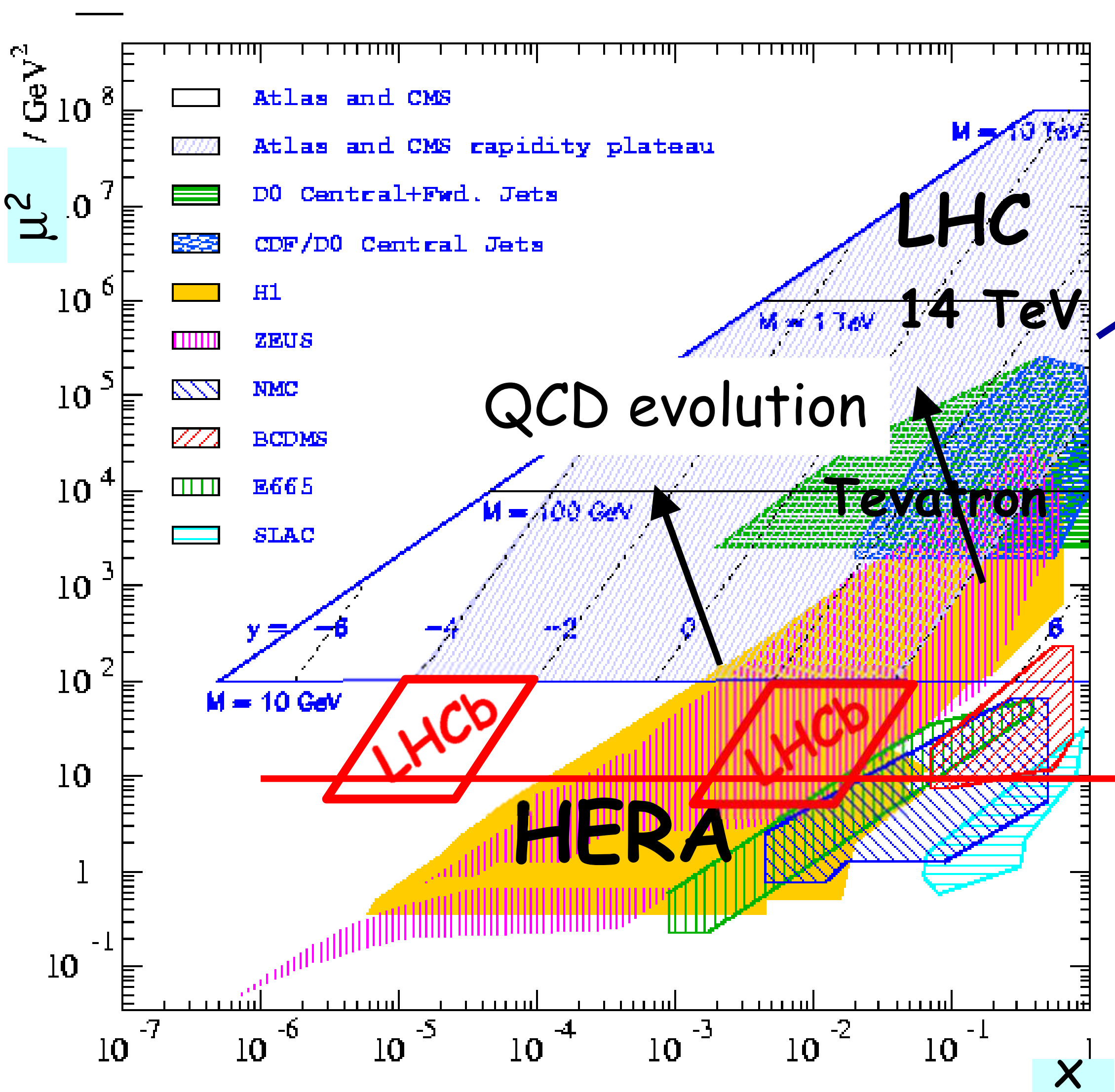
inconsistent with ALICE observation of nonuniversality at mid-rapity !?

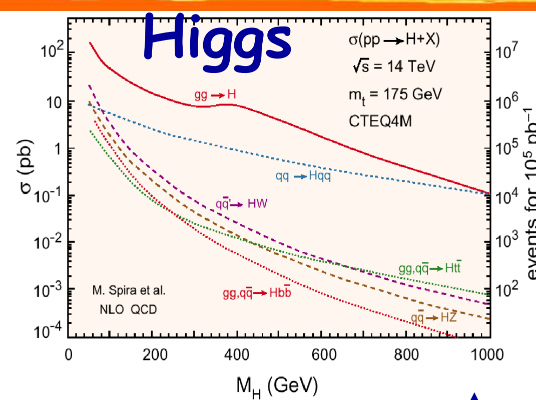
Project for discussion 7:

- Lambda_c fragmentation fraction from LHCb (and e+e-, HERA, ...) seems in contradiction with findings by ALICE

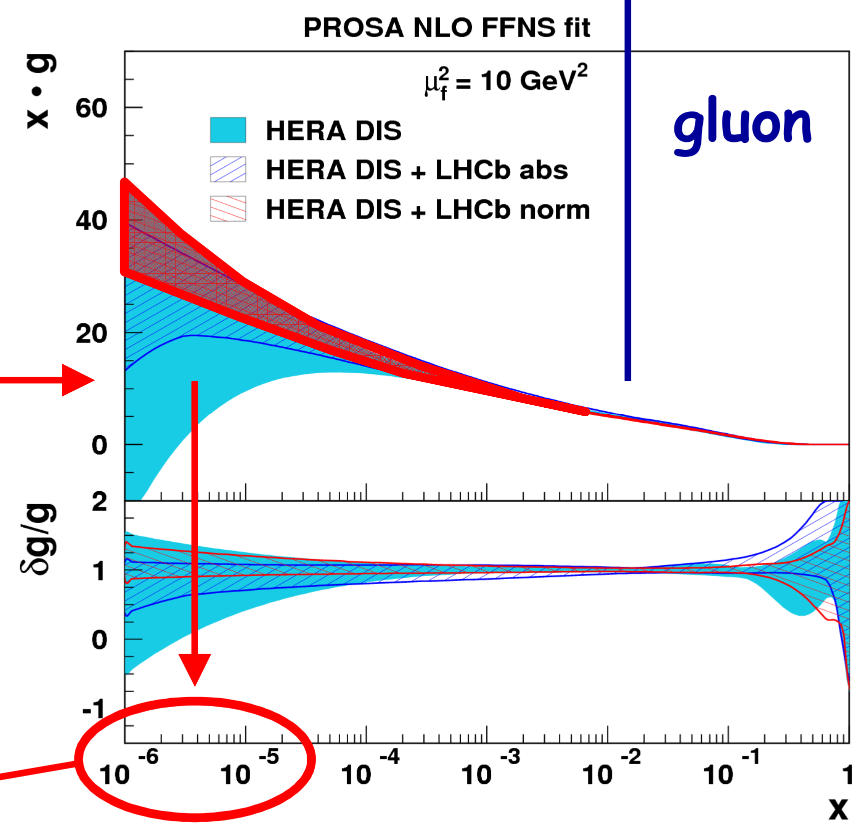
-> clarify discrepancy ?

Parton density functions (PDF)





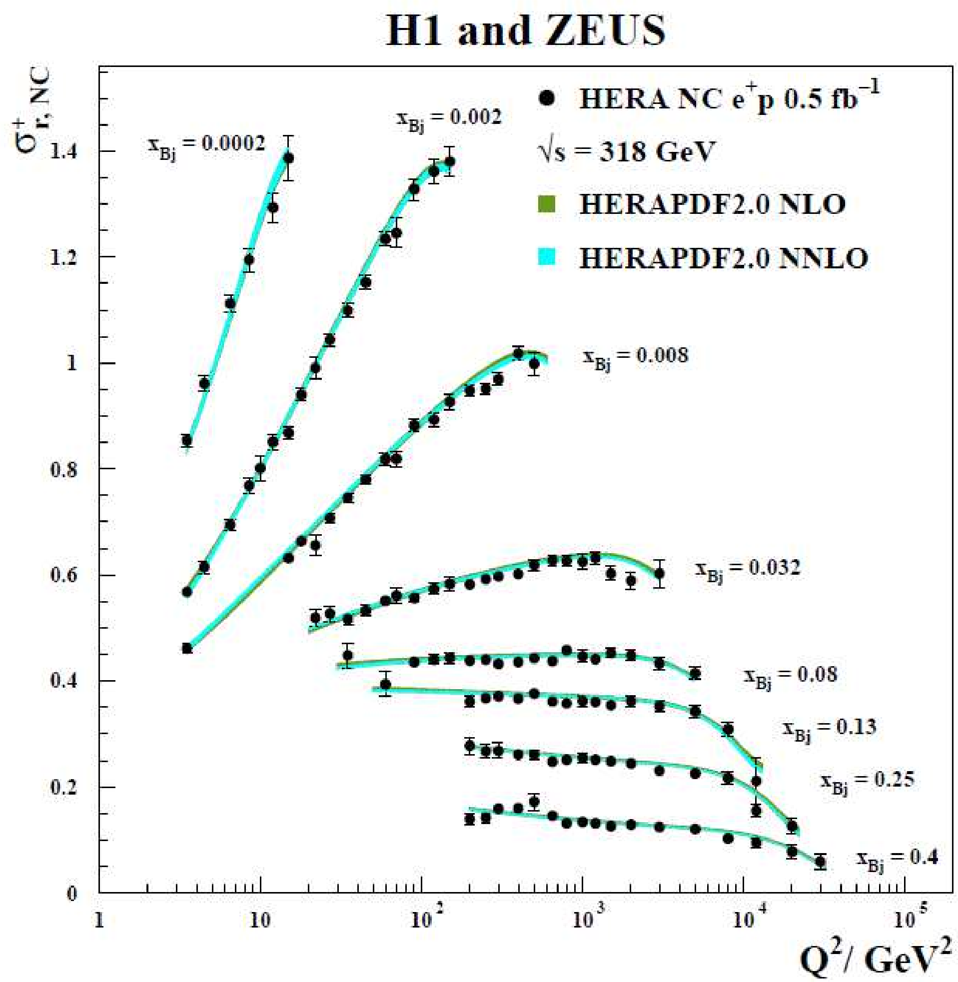
top, jets, ...

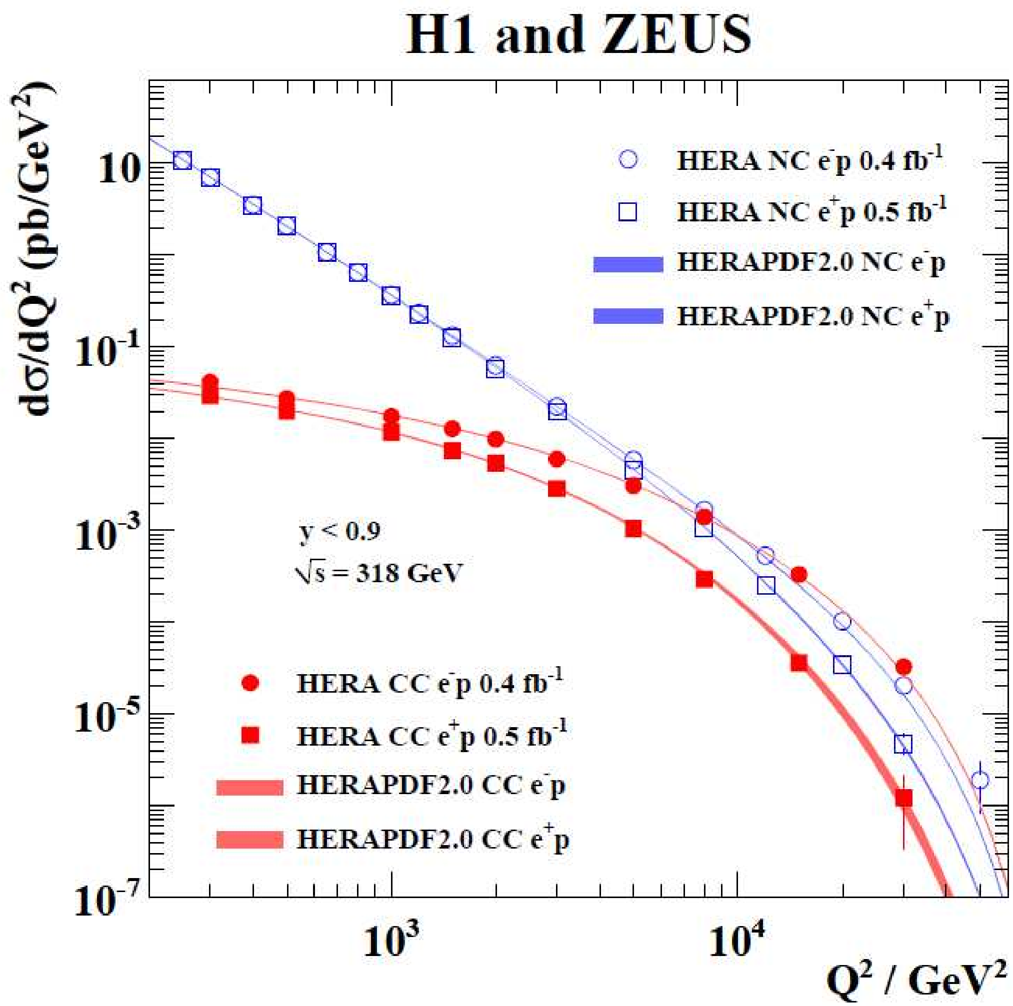


parton densities from HERA and LHC data
-> cross sections at LHC, cosmic rays, ...

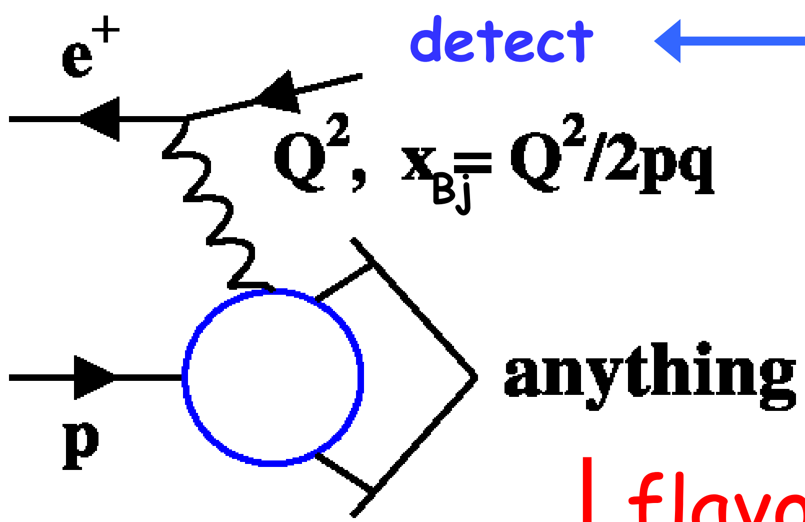
Final HERA inclusive DIS combination and PDF fit

arXiv 1506.06042, EPJC 75 (2015) 580





Heavy flavour contributions to σ_r

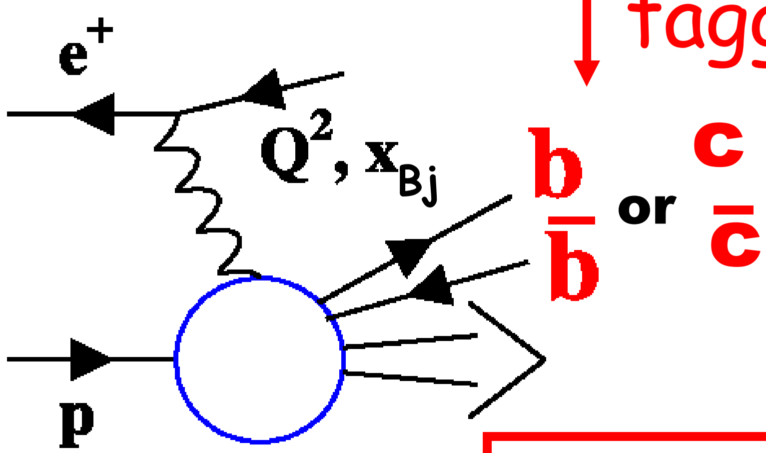


detect ⟷

Measure cross section

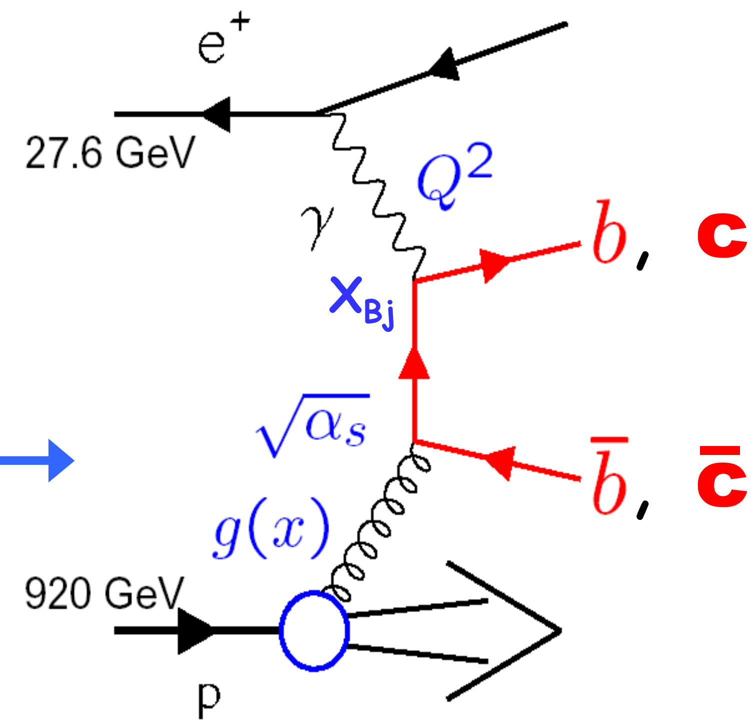
$$\frac{d^2\sigma}{dx_{Bj}\,dQ^2} \simeq \frac{2\pi\alpha^2}{Q^4 x_{Bj}} \left[1 + (1-y)^2\right] \sigma_r(x_{Bj}, Q^2)$$

flavour tagging



-> $\sigma_r^{b\bar{b}}$, $\sigma_r^{c\bar{c}}$

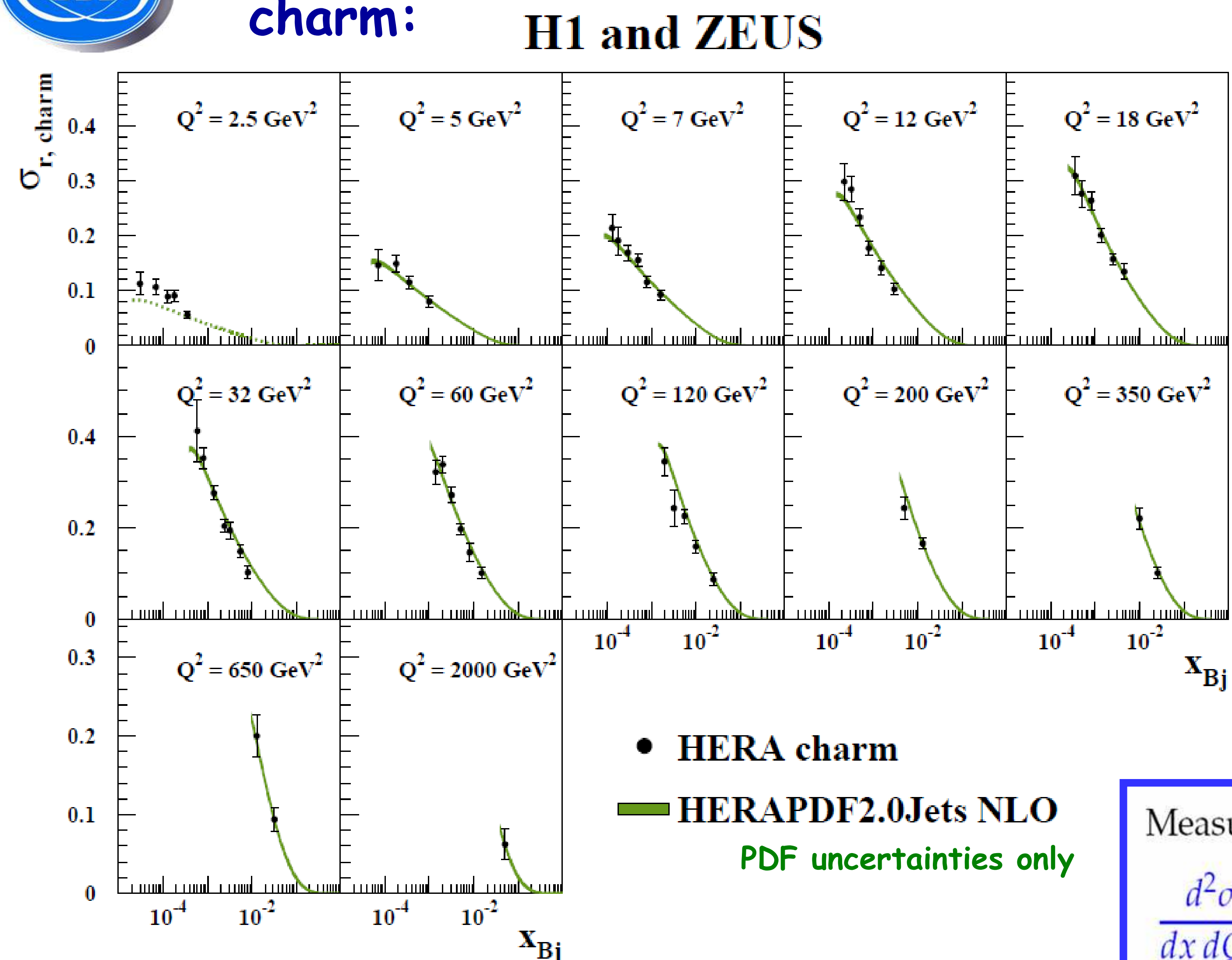
QCD ⟷



includes fit of inclusive charm + jet DIS data

arXiv 1506.06042, EPJC 75 (2015) 580

charm:



well described by fit

Measure cross section

$$\frac{d^2\sigma}{dx\,dQ^2} = \frac{2\pi\alpha^2}{Q^4 x}\left\{\left[1+(1-y)^2\right]\sigma_{red}^{cc}\right.$$

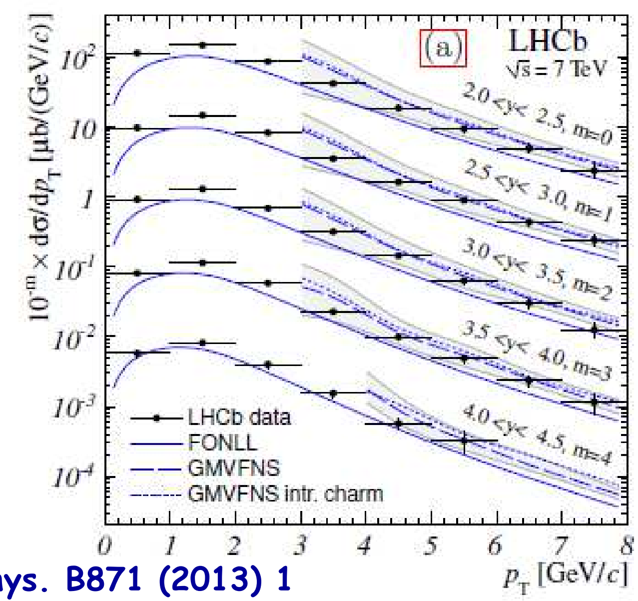
Constraint of gluon at very low x

arXiv 1503.04581, Eur.Phys.J. C75 (2015) 396

Combined fit of

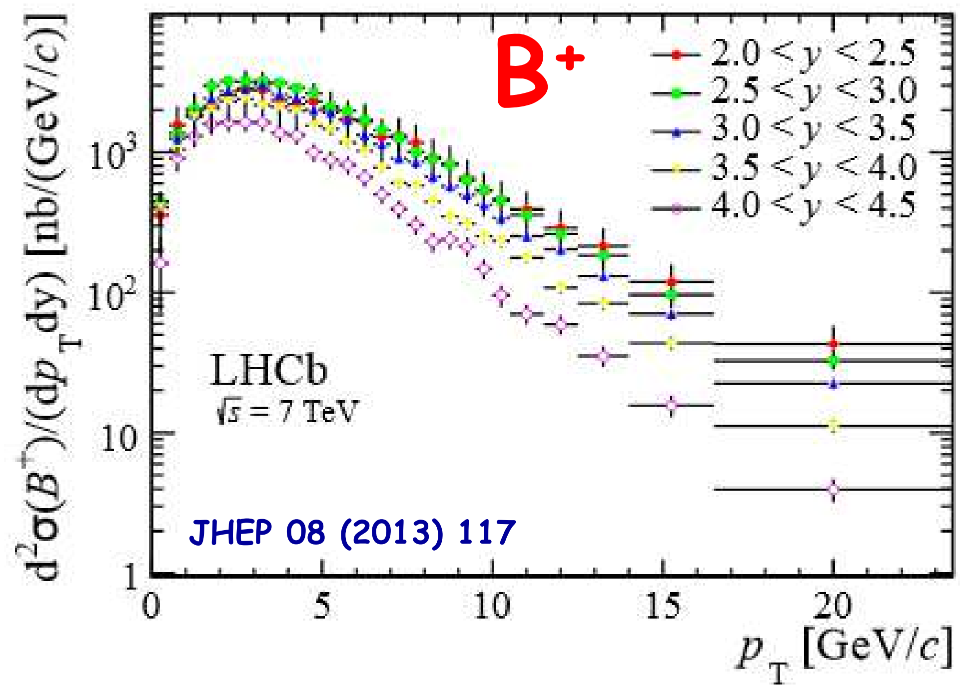
- HERA I inclusive data: main PDF constraint
- HERA charm and beauty data: constrain m_c, m_b and gluon at low x: 10^{-2} -10^{-4}
- **LHCb charm and beauty data**, constrain gluon at very low x: 10^{-3}- 10^{-6}

D^0



Nucl.Phys. B871 (2013) 1

B^+



JHEP 08 (2013) 117

Input data sets

HERA I combined inclusive + HERA combined charm + ZEUS beauty + LHCb charm + LHCb beauty

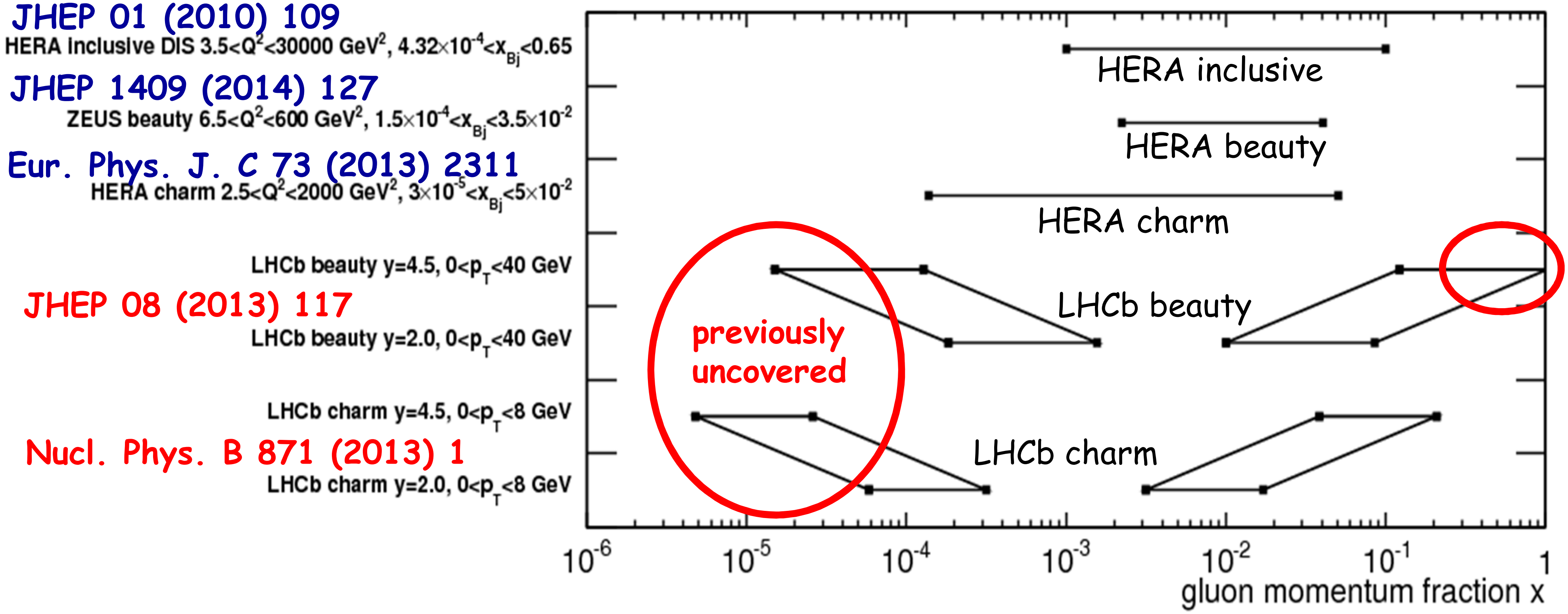
JHEP 01 (2010) 109

JHEP 1409 (2014) 127

Eur. Phys. J. C 73 (2013) 2311

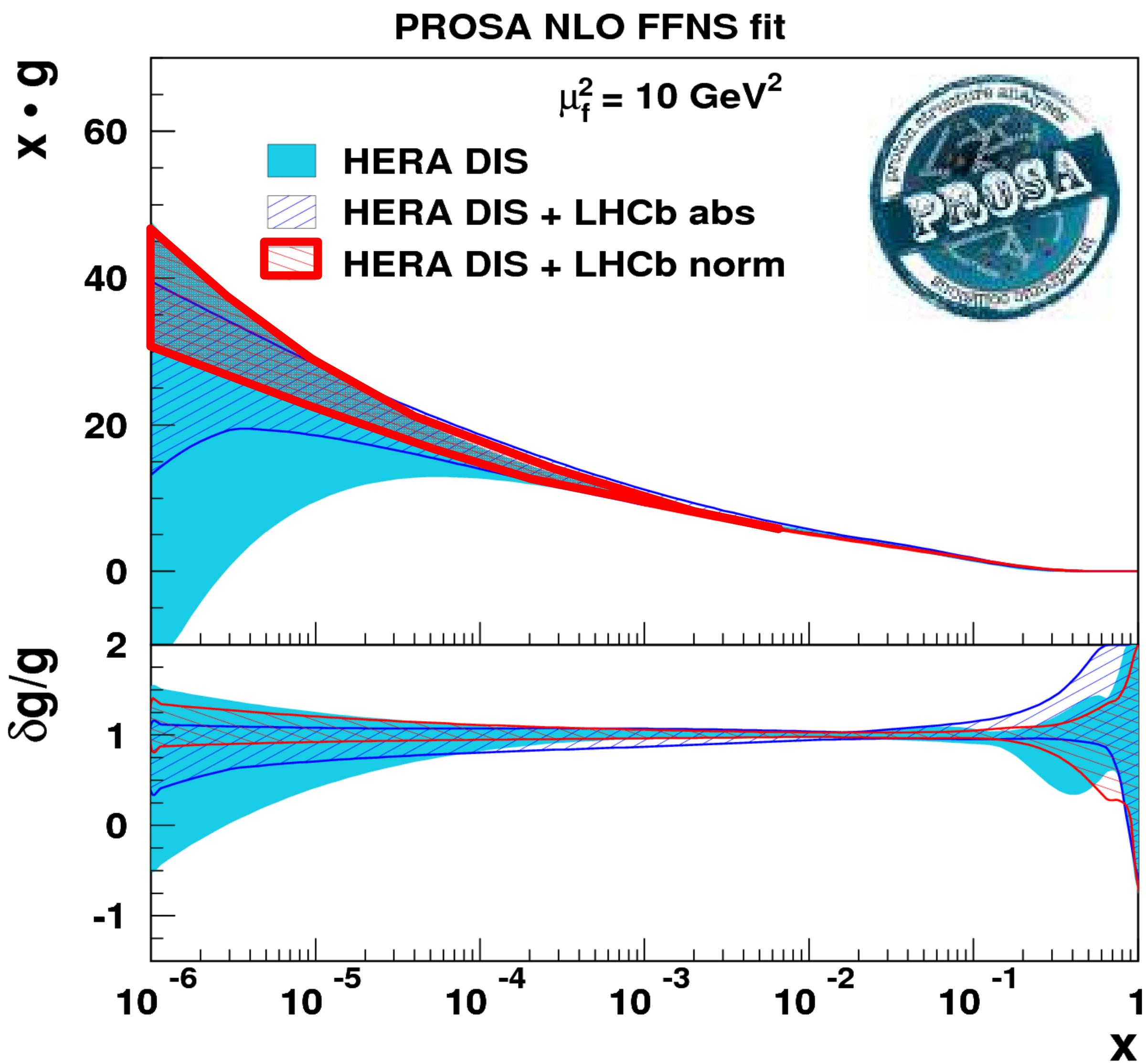
JHEP 08 (2013) 117

Nucl. Phys. B 871 (2013) 1



combination of data sets "bridges" complete x range

Final comparison of gluon fits



gluon positive and well constrained down to $x \sim 10^{-6}$

first constraint from data

(March 2015)

for $x \ll 10^{-4}$

now many more

already in use to constrain

cosmic ray prompt neutrino spectrum (e.g. Ice Cube)

-> talk O. Zenaiev

Project for discussion 8:

- extend PROSA HERA+LHCb fit (see talk O. Zenaiev next week) to include also ALICE (central low p_T) + ATLAS (7 TeV) + CMS (5 TeV) charm, as well as ATLAS+CMS+LHCb top (large x!)
  -> further improve low x and high x gluon
  -> improved cosmic ray predictions

(PROSA = open collaboration of theorists and experimentalists)

Conclusions and outlook (part I)

- explore potential to improve heavy flavour theory predictions for cosmic ray physics by going to NNLO and/or by "tuning" NLO theory parameters to LHC + HERA data within uncertainties;
  explore synergies between c,b,t
- explore potential to further close "white spots" in measurements of heavy flavour measurements, in particular at LHC;
  relate central to forward measurements?
- further explore potential arising from combination of heavy flavour and non-heavy flavour measurements in pp, pA, AA and ep
- … more ideas/projects/discussions later in the workshop?

Part II (no time today)

- detection of beauty, W,Z, top in cosmic rays through internal structure of air showers + lepton detection ?

- application of low x gluon resummation including proper treatment of heavy flavour masses

- proper treatment of heavy flavour masses in NLO + NNLO jet predictions (so far all jet predictions still use massless approximation)

- measurement of c,b,t running masses, mass running, and running of corresponding Higgs Yukawa couplings

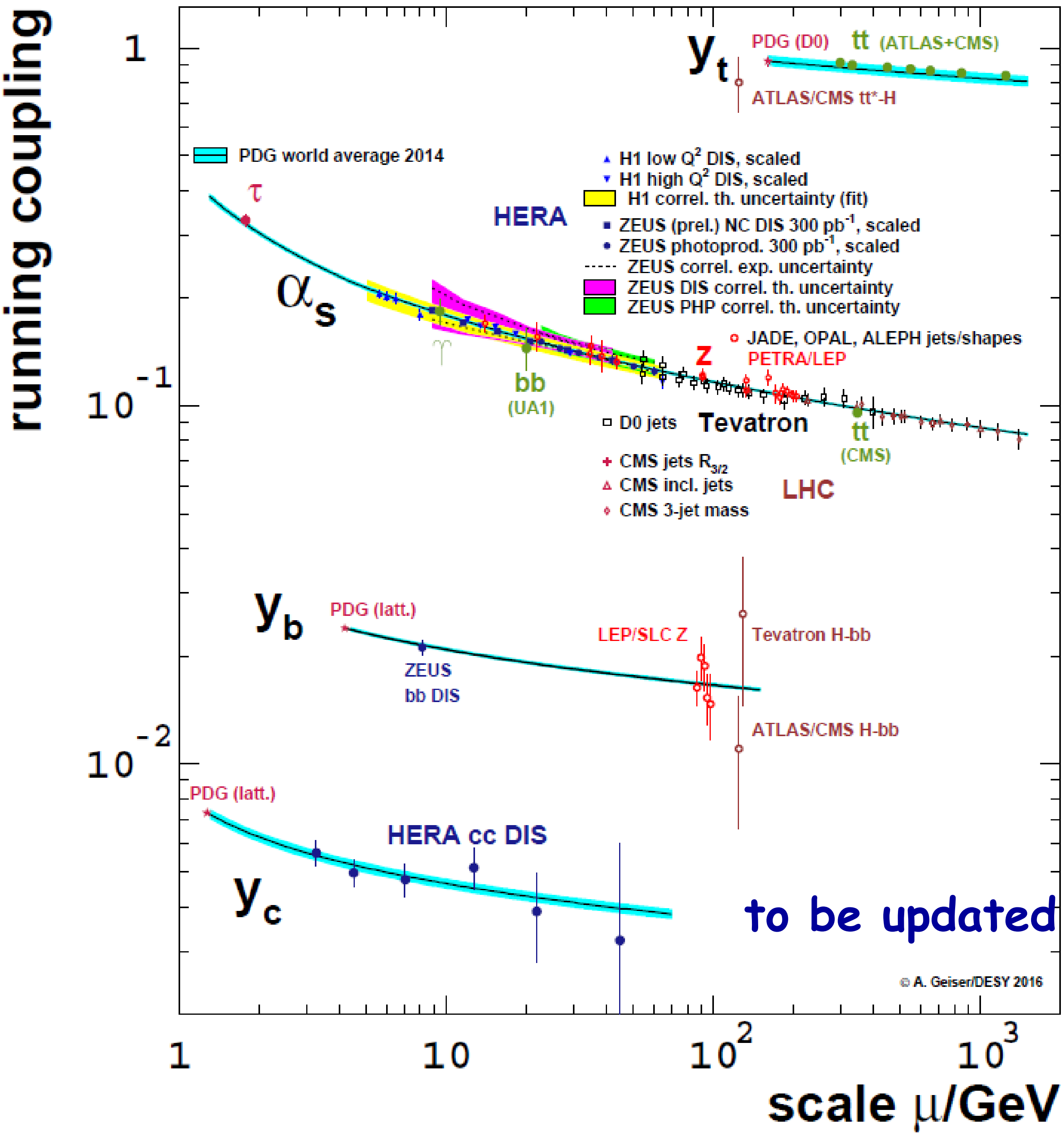
Conclusion

Part II

experimental representation of running Yukawa couplings obtained for the first time

heavy quark physics is also QCD + Higgs physics

so far, Higgs couplings and their running as obtained from quark masses are consistent with directly measured Higgs couplings



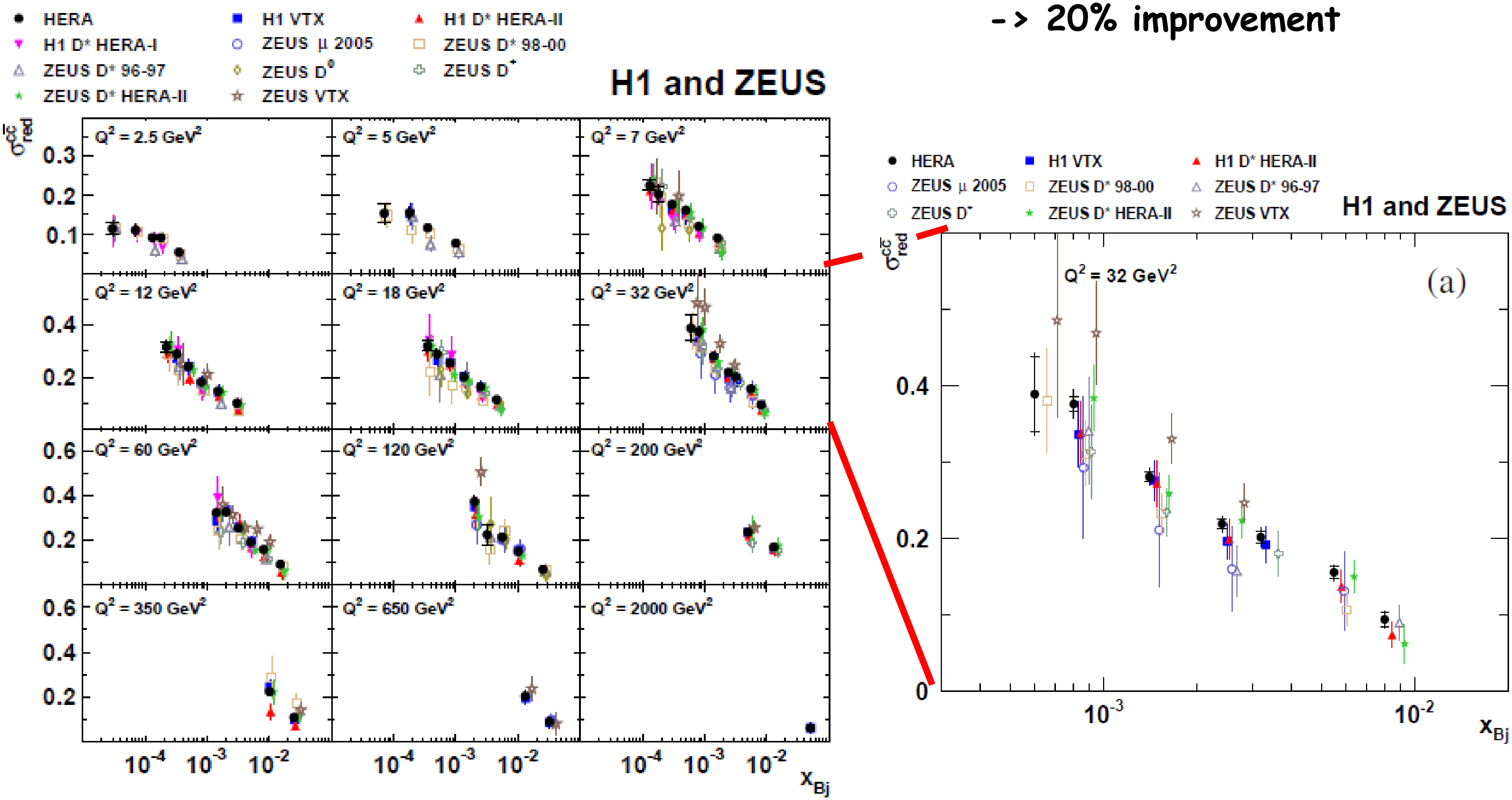
Backup

Final HERA Charm combination

arXiv:1804.01019

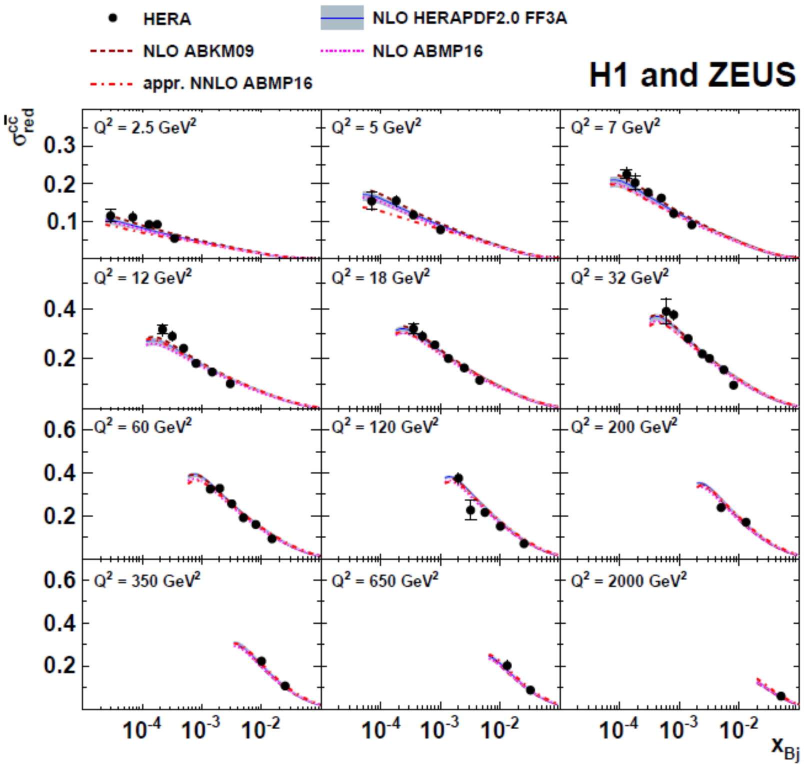
209 -> 52 data points

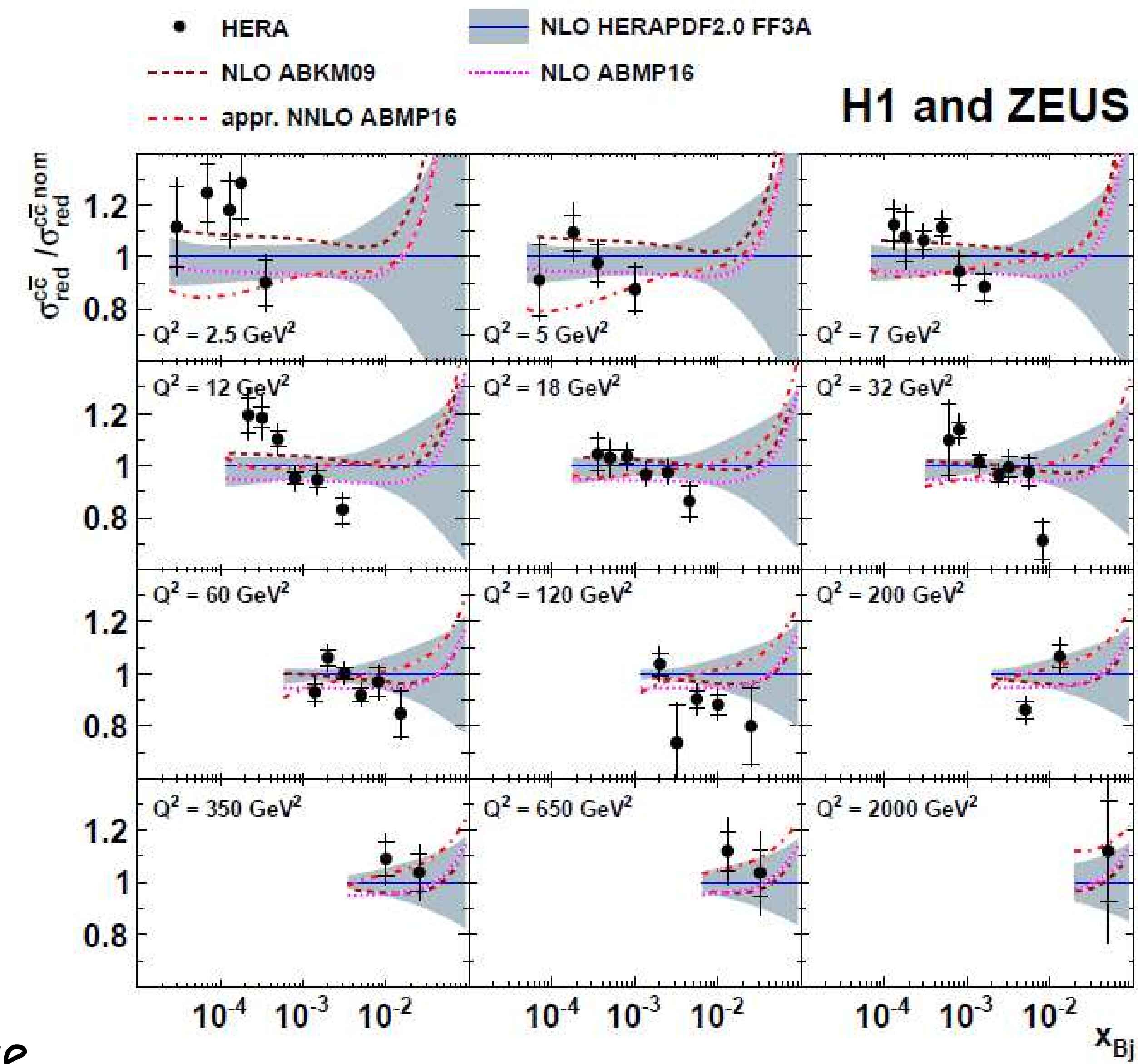
3 HERA II data sets added
-> 20% improvement



Comparison to FFNS QCD predictions

arXiv:1804.01019





data reasonably described

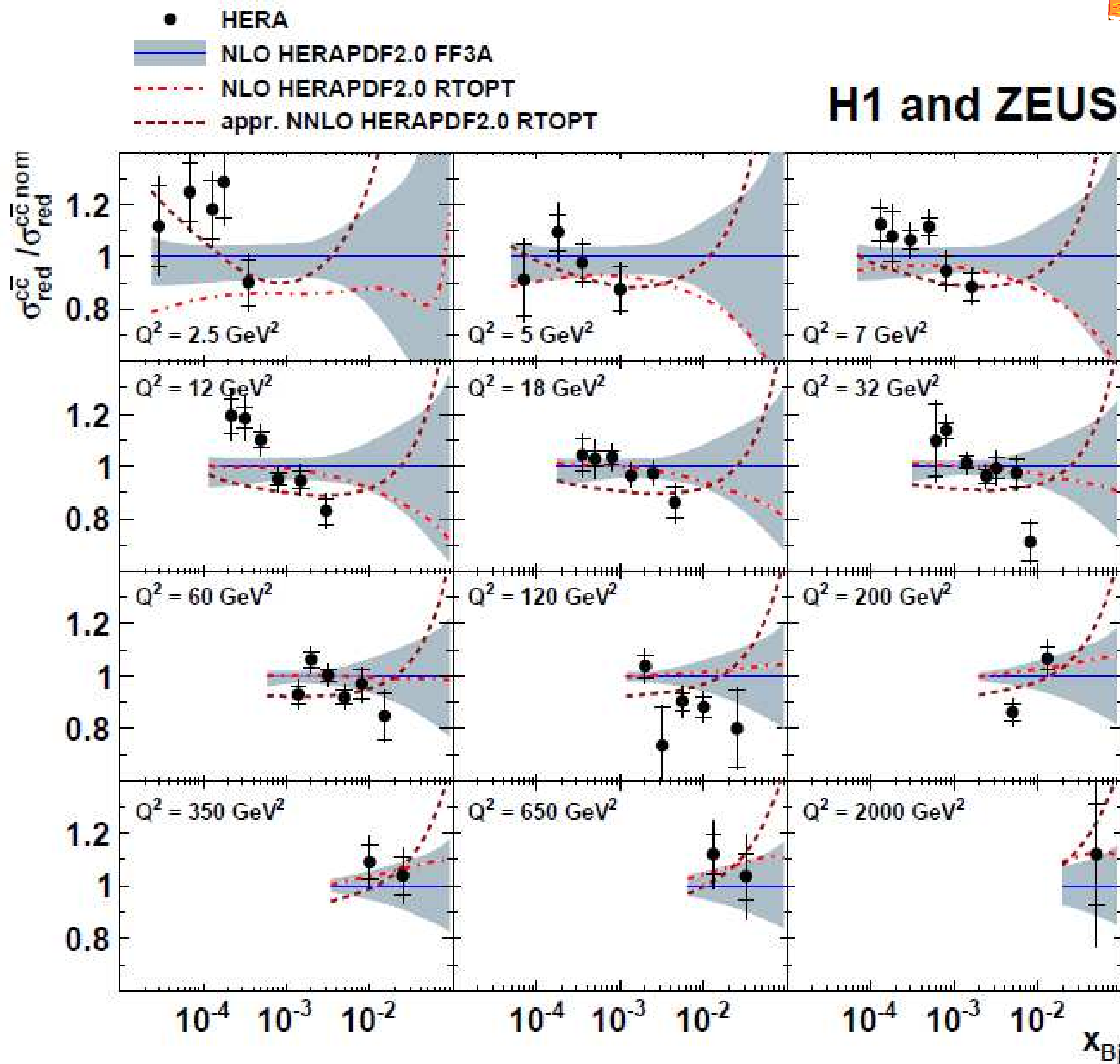
best: HERAPDF2.0 FF and ABKM09NLO

~3σ tension with x_{Bj} slope

appr. NNLO does not improve

Comparison to VFNS QCD predictions

arXiv:1804.01019



data description reasonable but **not better than FF**

overall, **NLO better than appr. NNLO**

beauty in backup:
larger uncertainties
-> all consistent

QCD fit: charm x slope

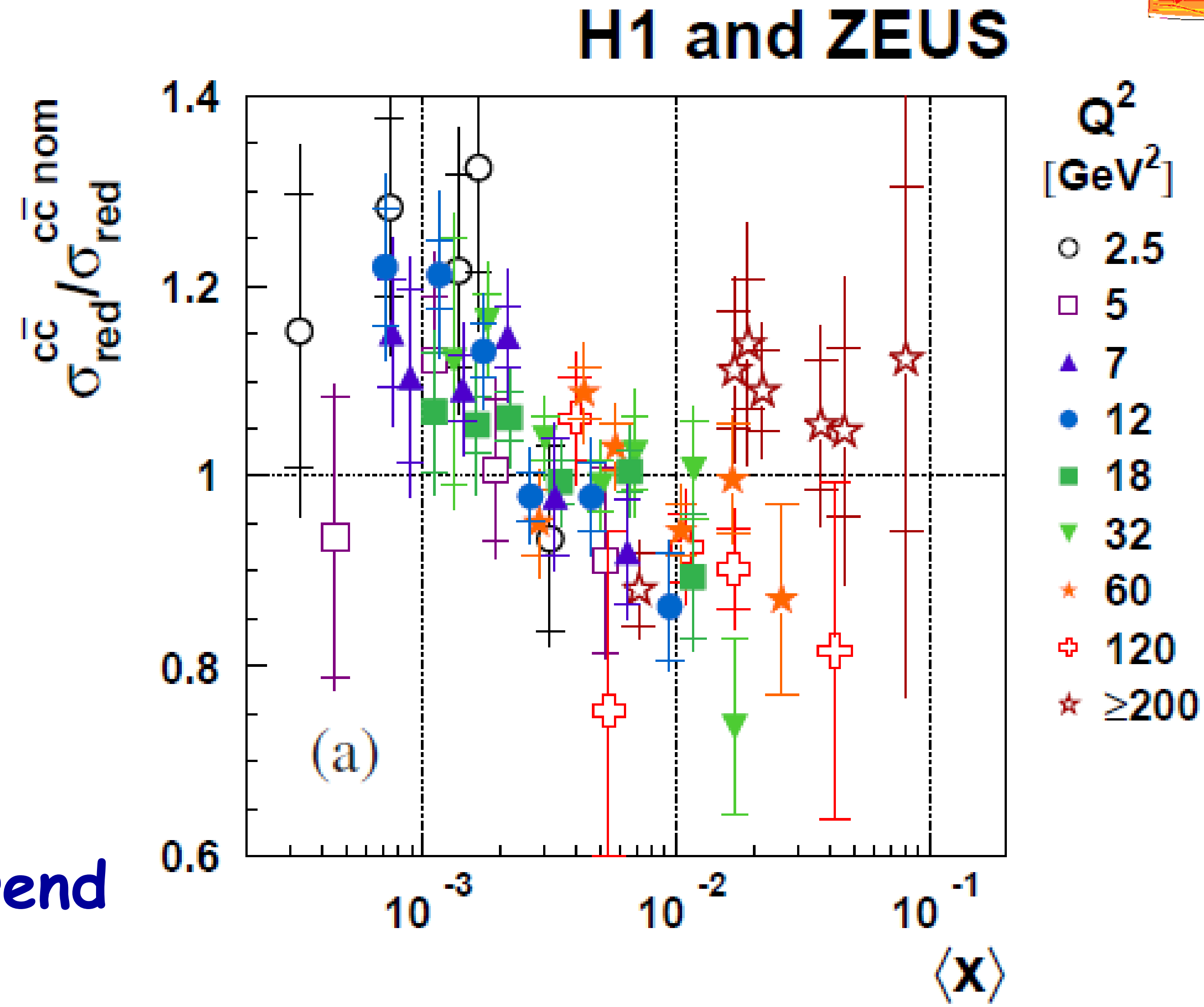
arXiv:1804.01019

plot **data/fit**
vs. <x> of
incoming partons
(rather than x_{Bj})
for each data point

LO: $x = x_{Bj} \cdot \left(1 + \frac{\hat{s}}{Q^2}\right)$

<x> calculated at **NLO**
using HVQDIS

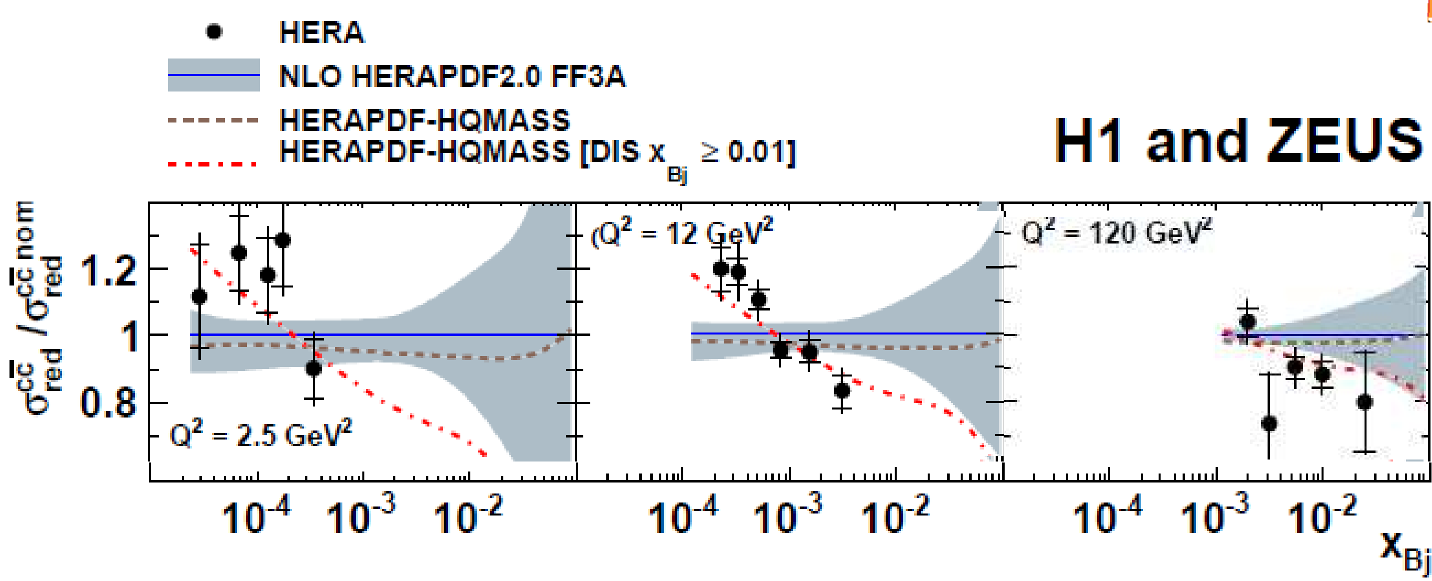
-> common <x> trend
for all Q^2



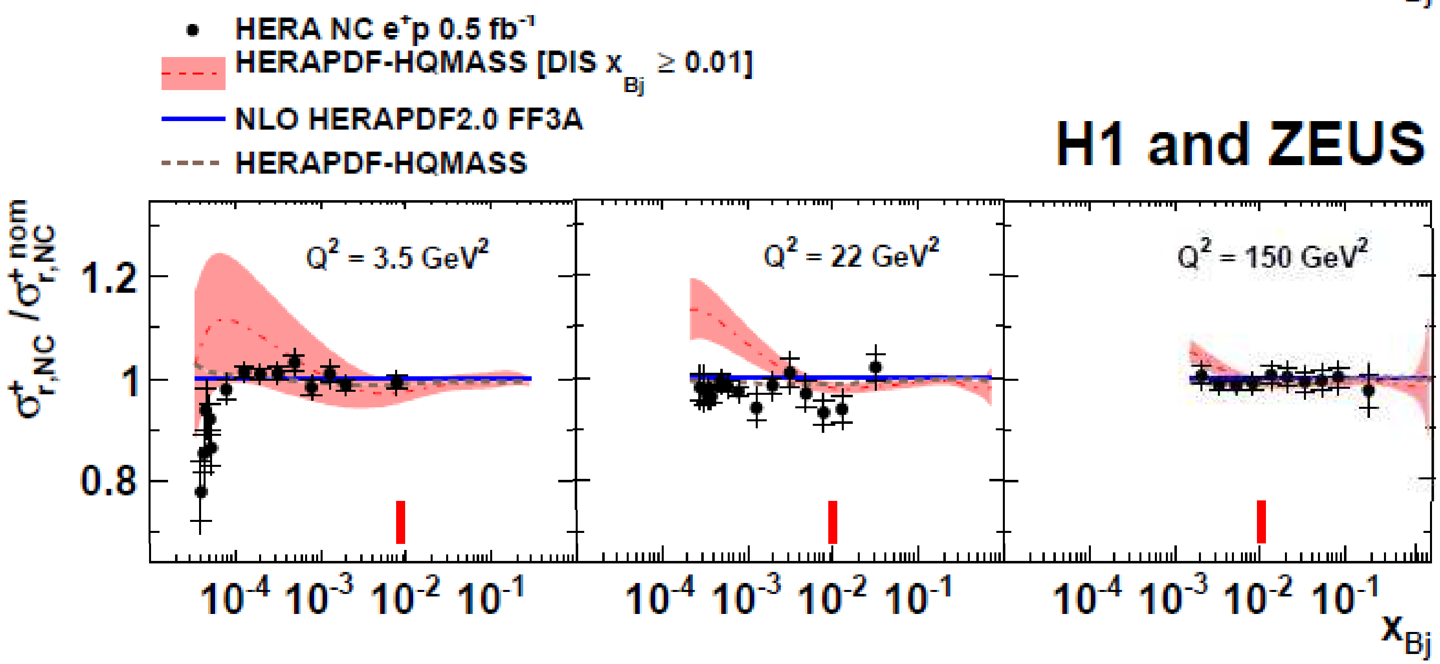
further discussion (gluon shape (?), low x resummation (?), …) **see backup**

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

can **improve low x charm slope**
(no longer constrained by inclusive)



but **fails to describe low x inclusive data**



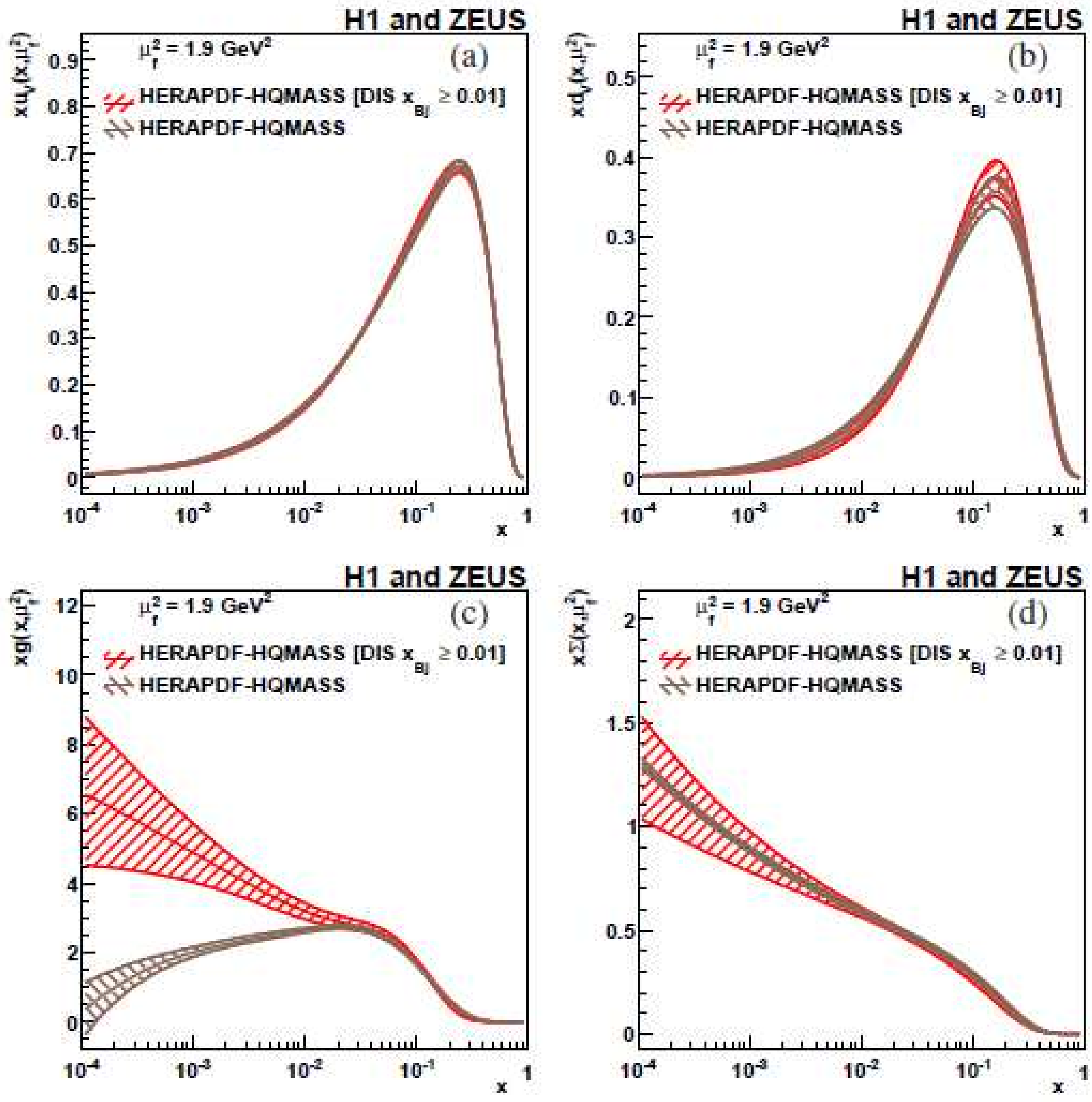
-> not a solution (but hint)

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 (no charm) 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?

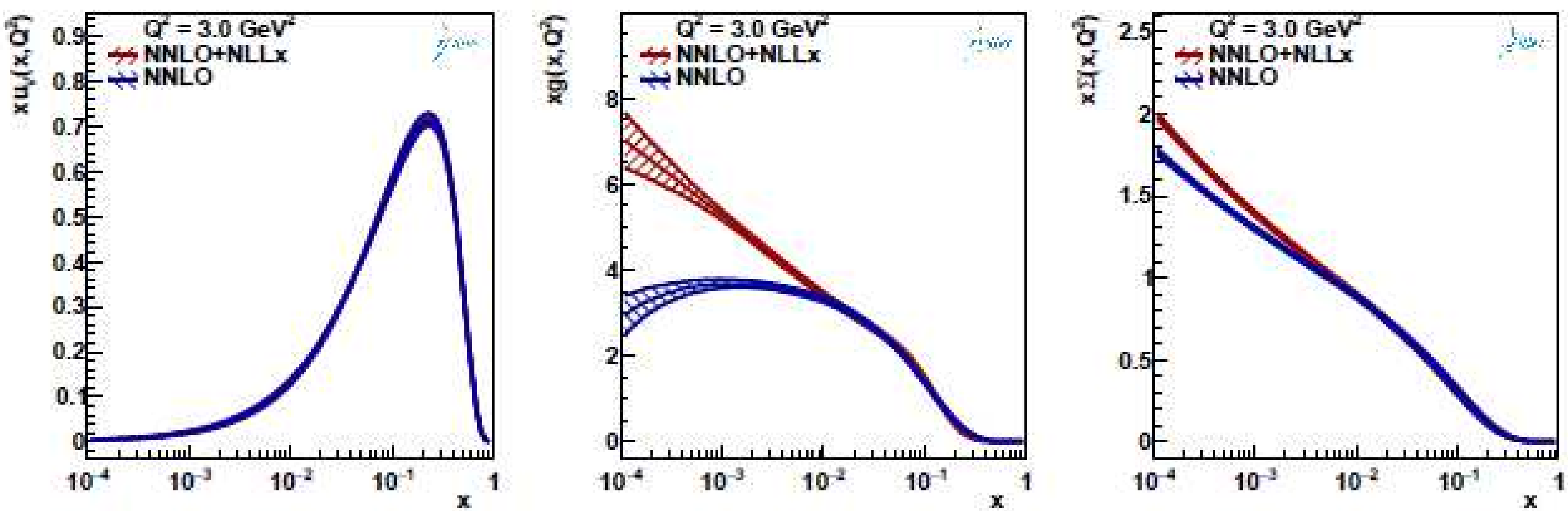


Figure 3 The up valence PDF xu_v, the gluon PDF xg and the total singlet PDF $x\Sigma$ for the final fits with (NNLO+NLLx) and without (NNLO) $\ln(1/x)$ resummation.

Project for discussion 9:

- Clarify treatment of low-x resummation for HERA light and heavy flavour data?

Resummation formula cannot be correct for massive quarks -> use FFNS approach:

Proposal: combine nf=3 prediction with resummation (FF PDF + matrix elements)
with heavy flavour predictions w/o resummation

-> improve consistency and reduce uncertainty for low-x gluon (relevant for cosmic ray predictions)

QCD fit

arXiv:1804.01019

simultaneous NLO QCD fit of

- combined **inclusive DIS** data (arXiv:1506.06042), Q^2_{min}=3.5 GeV^2
- new combined **charm and beauty DIS** data

simultaneously fit **PDF's** (a la **HERAPDF** FF) in FFNS at NLO and **charm quark and beauty quark "running" masses** in MSbar scheme

- using xFitter [www.xfitter.org], 14 parameters (±1)
- NLO DGLAP [QCDNUM] and matrix elements [OPENQCDRAD], nf = 3
- $\mu_F = \mu_R = \sqrt{Q^2 + 4m_Q^2}$, varied by factor 2 (for heavy flavour part only)
- **free $m_c(m_c)$, $m_b(m_b)$**
- $\alpha_s(M_Z)^{nf=3} = 0.106$, equivalent to $\alpha_s(M_Z)^{nf=5} = 0.118 \pm 0.002$
- fit uncertainty using $\Delta\chi^2 = 1$

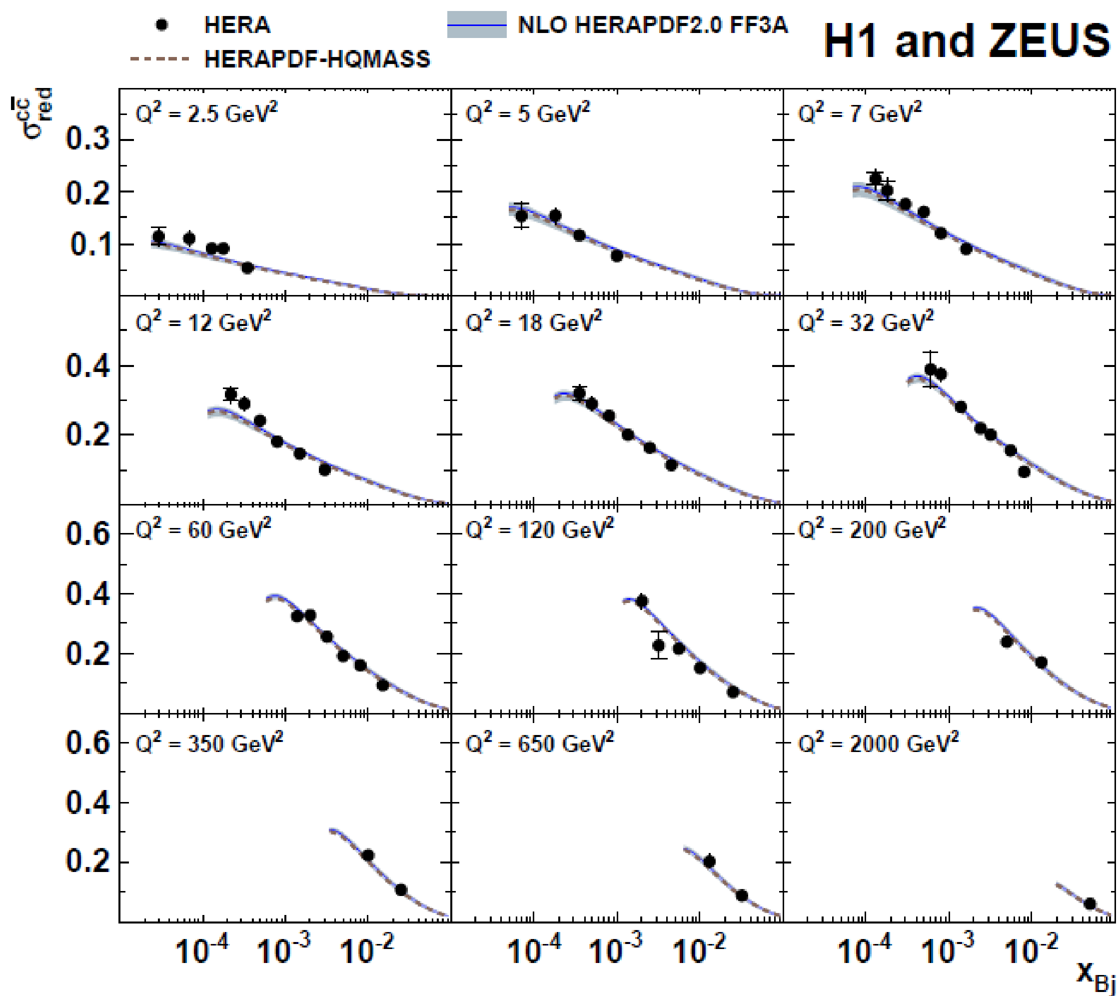
-> HERAPDF-HQMASS

QCD fit: charm subset

arXiv:1804.01019

fully consistent
with HERAPDF2.0 FF3A

uncertainty breakdown
in backup



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

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

Comparison with other $m_c(m_c)$ determinations

arXiv:1804.01019

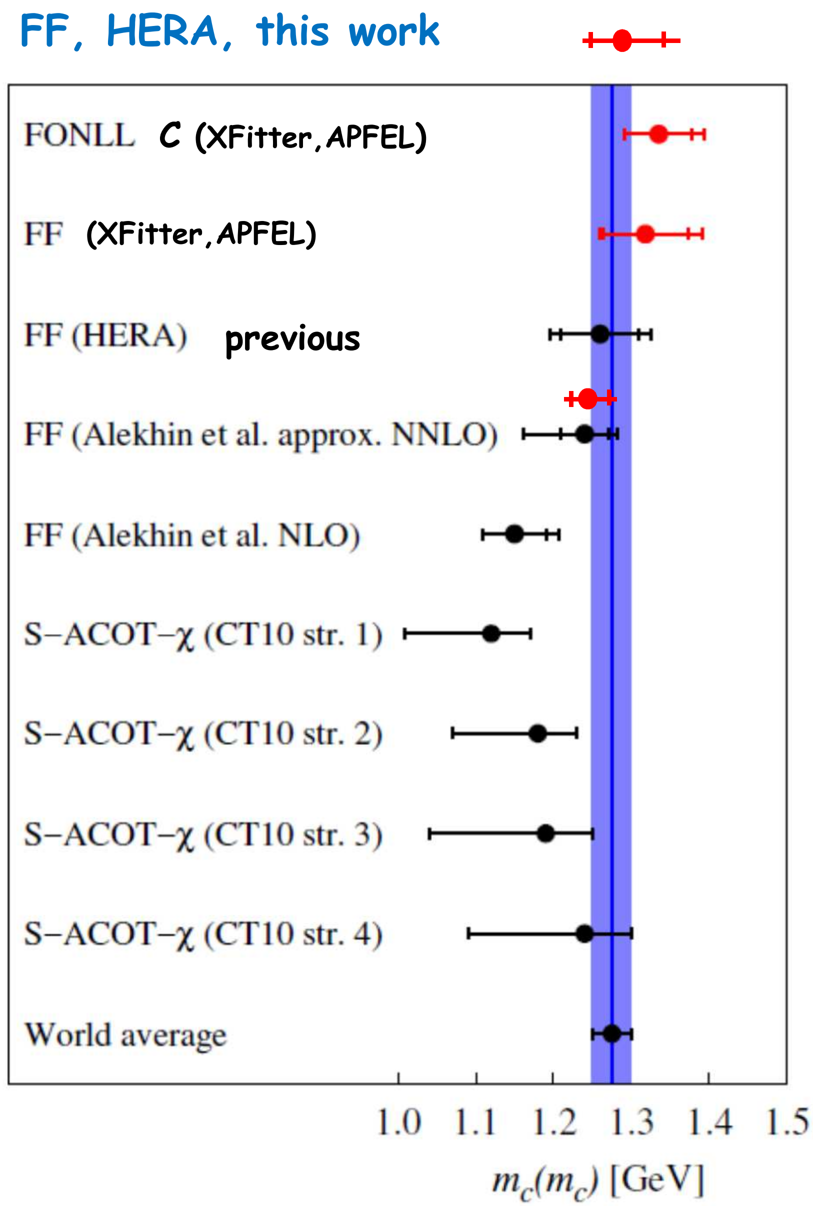
this work:

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

latest ABMP16 result: $m_c(m_c) = 1.252 \pm 0.018 \pm 0.032$ GeV
S. Alekhin et al., arXiv:1701.05383,
Phys. Rev. D96 (2017) 014011

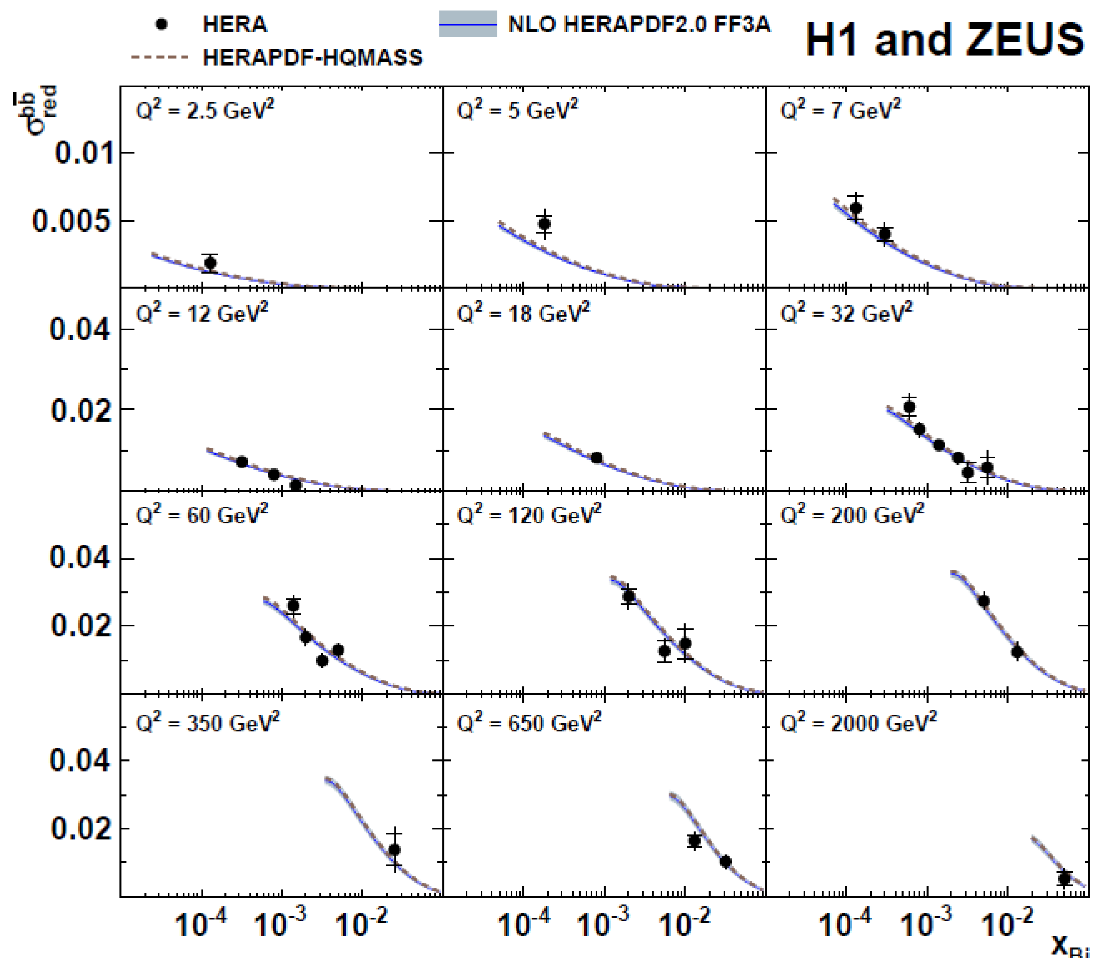
previous results summarized in
V. Bertone et al., arXiv:1605.01946,
JHEP 1608 (2016) 050 :

scheme	$m_c(m_c)$ [GeV]
FONLL (this work)	$1.335 \pm 0.043(\text{exp})^{+0.019}_{-0.000}(\text{param})^{+0.011}_{-0.008}(\text{mod})^{+0.033}_{-0.008}(\text{th})$
FFN (this work)	$1.318 \pm 0.054(\text{exp})^{+0.011}_{-0.010}(\text{param})^{+0.015}_{-0.019}(\text{mod})^{+0.045}_{-0.004}(\text{th})$
FFN (HERA) [9]	$1.26 \pm 0.05(\text{exp}) \pm 0.03(\text{mod}) \pm 0.02(\text{param}) \pm 0.02(\alpha_s)$
FFN (Alekhin *et al.*) [24]	$1.24 \pm 0.03(\text{exp})^{+0.03}_{-0.02}(\text{scale})^{+0.00}_{-0.07}(\text{th})$ (approx. NNLO)
	$1.15 \pm 0.04(\text{exp})^{+0.04}_{-0.00}(\text{scale})$ (NLO)
S-ACOT-χ (CT10) [29]	$1.12^{+0.05}_{-0.11}$ (strategy 1)
	$1.18^{+0.05}_{-0.11}$ (strategy 2)
	$1.19^{+0.06}_{-0.15}$ (strategy 3)
	$1.24^{+0.06}_{-0.15}$ (strategy 4)
World average [53]	1.275 ± 0.025



QCD fit: beauty subset

arXiv:1804.01019



fully consistent with HERAPDF FF3A

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

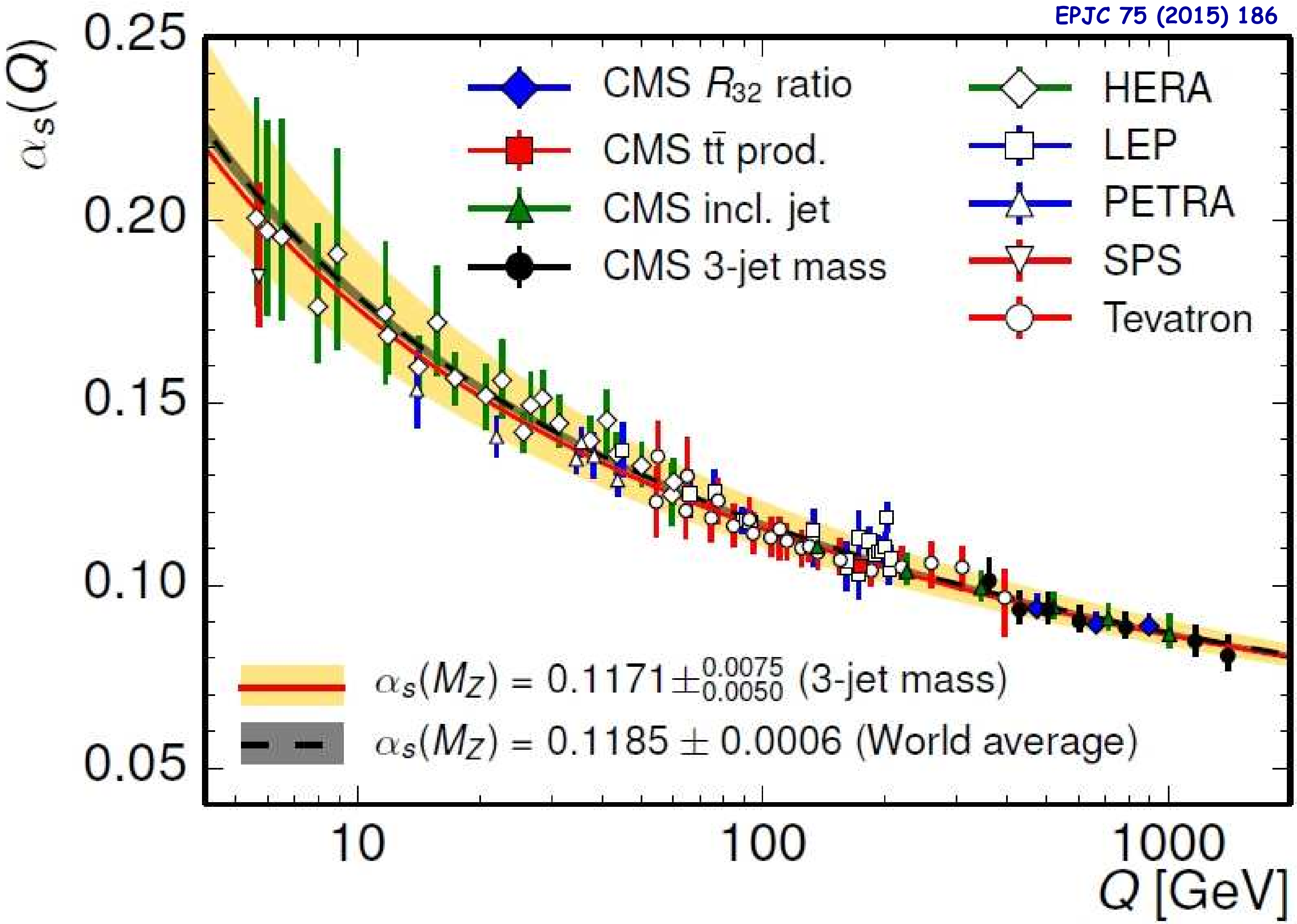
ZEUS: $m_b(m_b) = 4.07 \pm 0.14_{\text{exp/fit}}\ ^{+0.08}_{-0.08}\ \text{mod/scale}\ ^{+0.05}_{-0.00}\ \text{par}$ GeV

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

Running strong coupling „constant“ α_s

e.g. from jet production at e+e-, ep, and pp at DESY, Fermilab and CERN

EPJC 75 (2015) 186



Yes, it runs!

running of α_s and quark masses

- α_s running depends on number of coulours N_C and number of quark flavours N_F

$$\alpha_s(Q^2) = \frac{\alpha_s(Q_0^2)}{1 + \alpha_s\,(11N_C-2N_F)/12\pi\ \ln(Q^2/Q_0^2)}$$

leading order QCD formulae

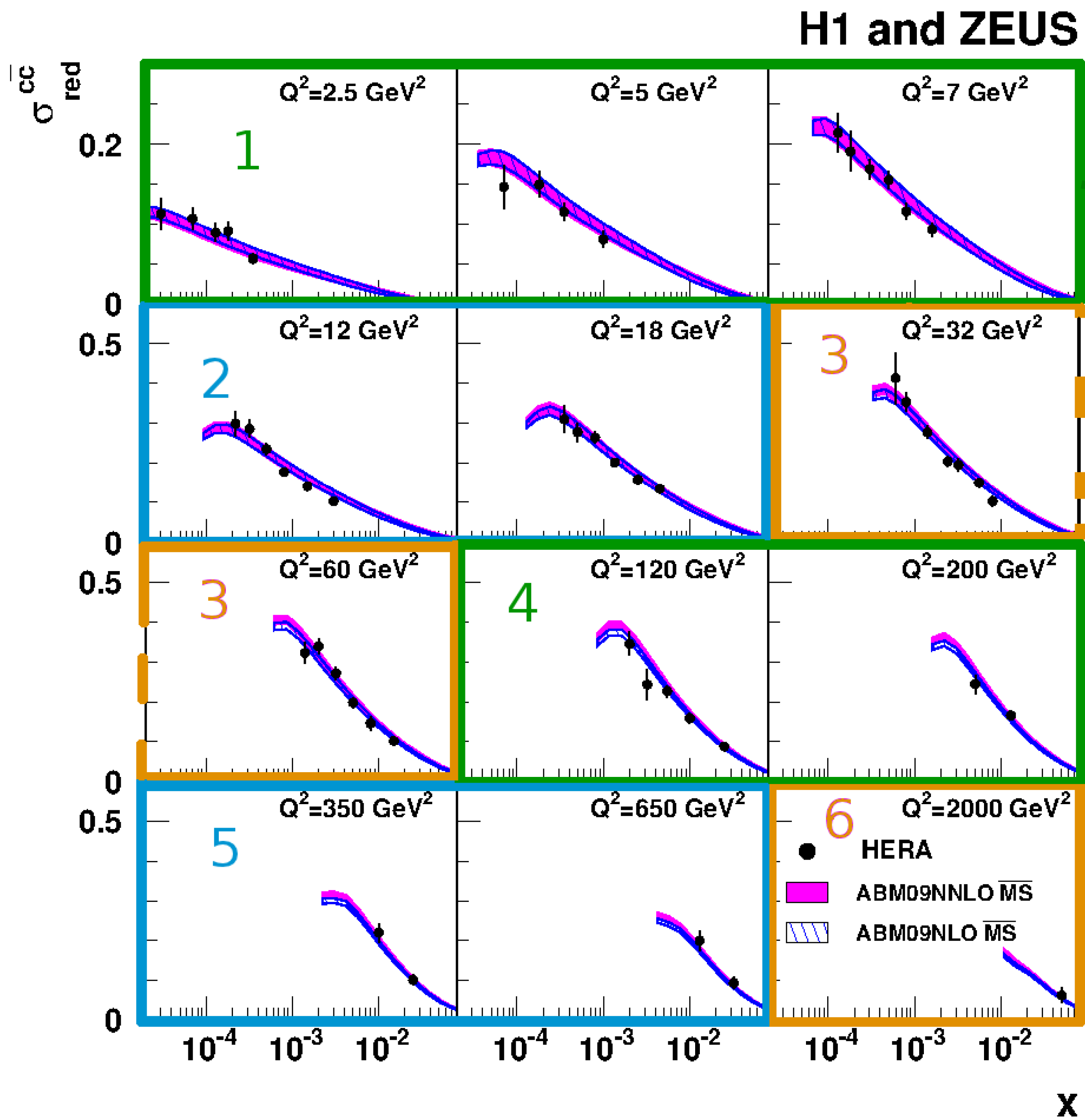
- quark mass running depends on α_s , e.g.

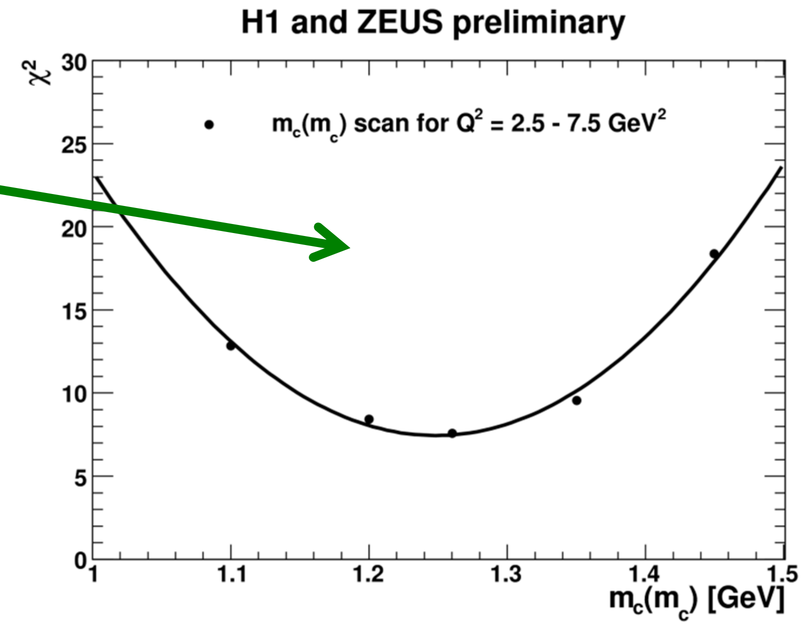
$$m(\text{pole}) = m(m)\,(1 + 4/3\ \alpha_s/\pi)$$
$$= m(Q)\,(1 + \alpha_s/\pi\,(4/3+\ln(Q^2/m_c^2)))$$

- part of gluon field around quark not 'visible' any more when 'looking' at smaller distances/larger energy scales -> **effective mass decreases**

measurement of m_c running

Update reference





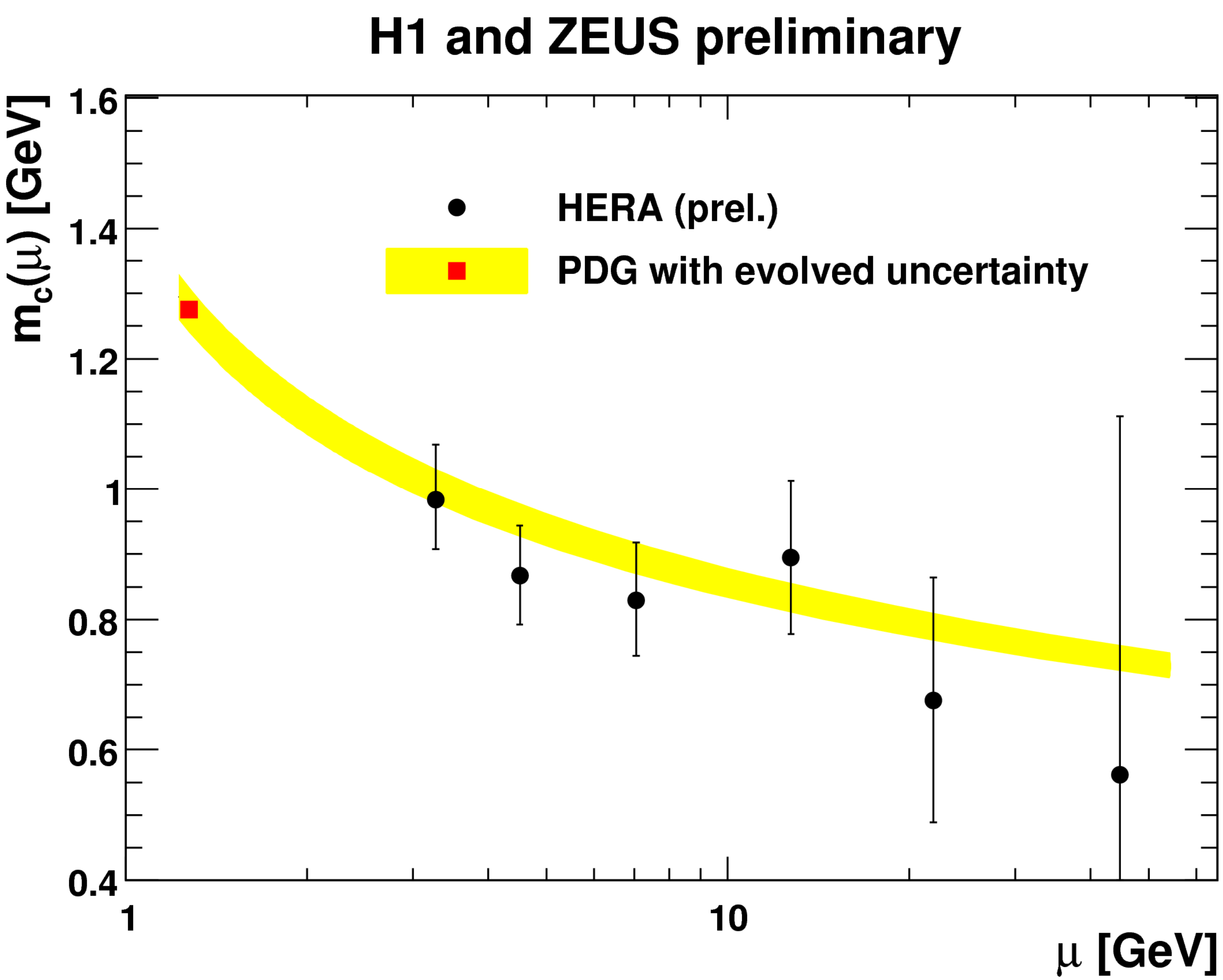
extract $m_c(\mu)$ separately for 6 different kinematic ranges in $\mu^2 = Q^2+4m_c^2$

(take log average for central scale)

the running charm quark mass

H1-prelim-14-071, ZEUS-prel-14-006, + S. Moch

Prog. Part. Nucl. Phys. 84 (2015) 1



running mass
concept in QCD
is self-consistent !

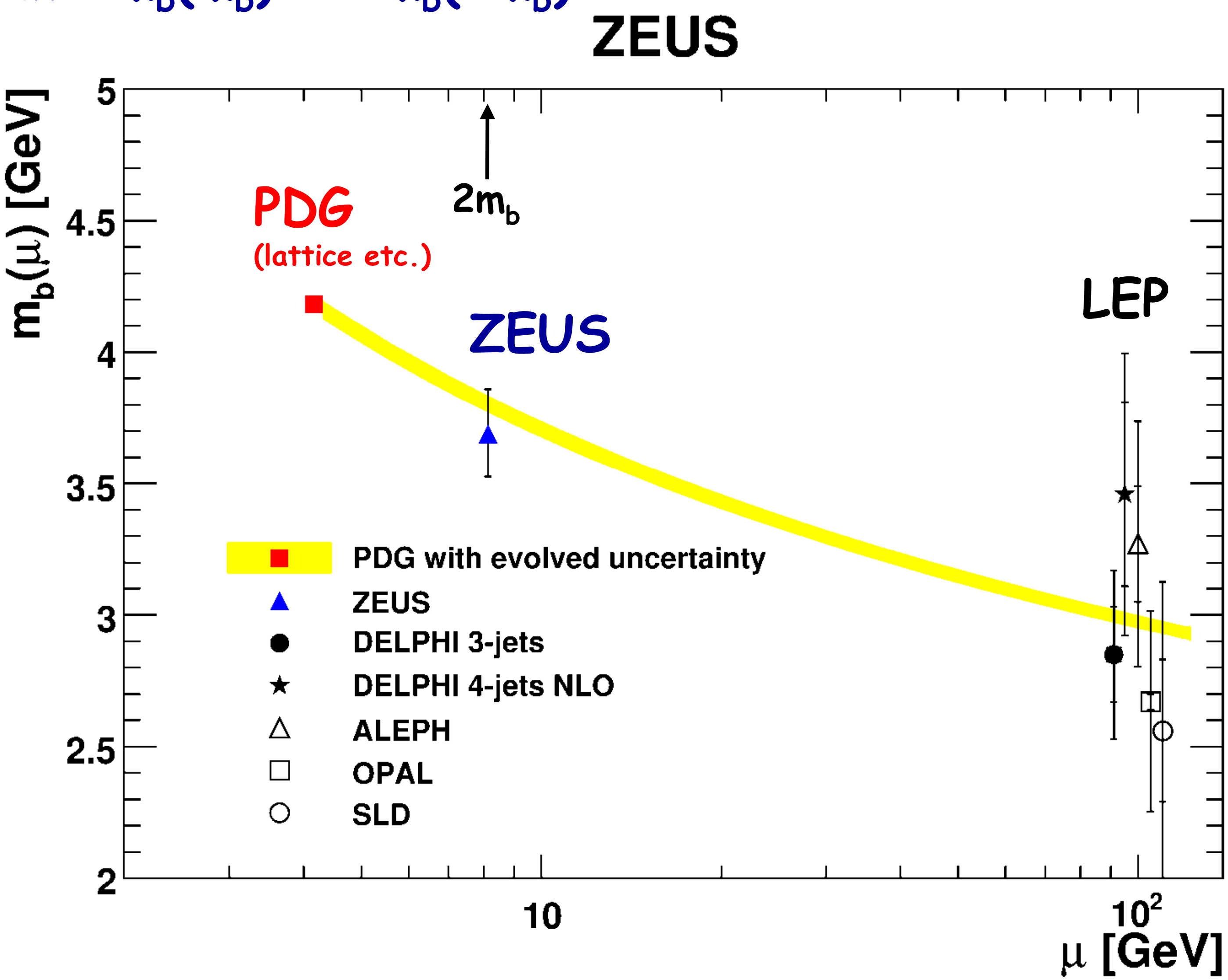
but mass is also
manifestation of
Higgs Yukawa
couplings !
$y_Q = \sqrt{2}m_Q/v$

the running beauty quark mass

arXiv:1506.07519

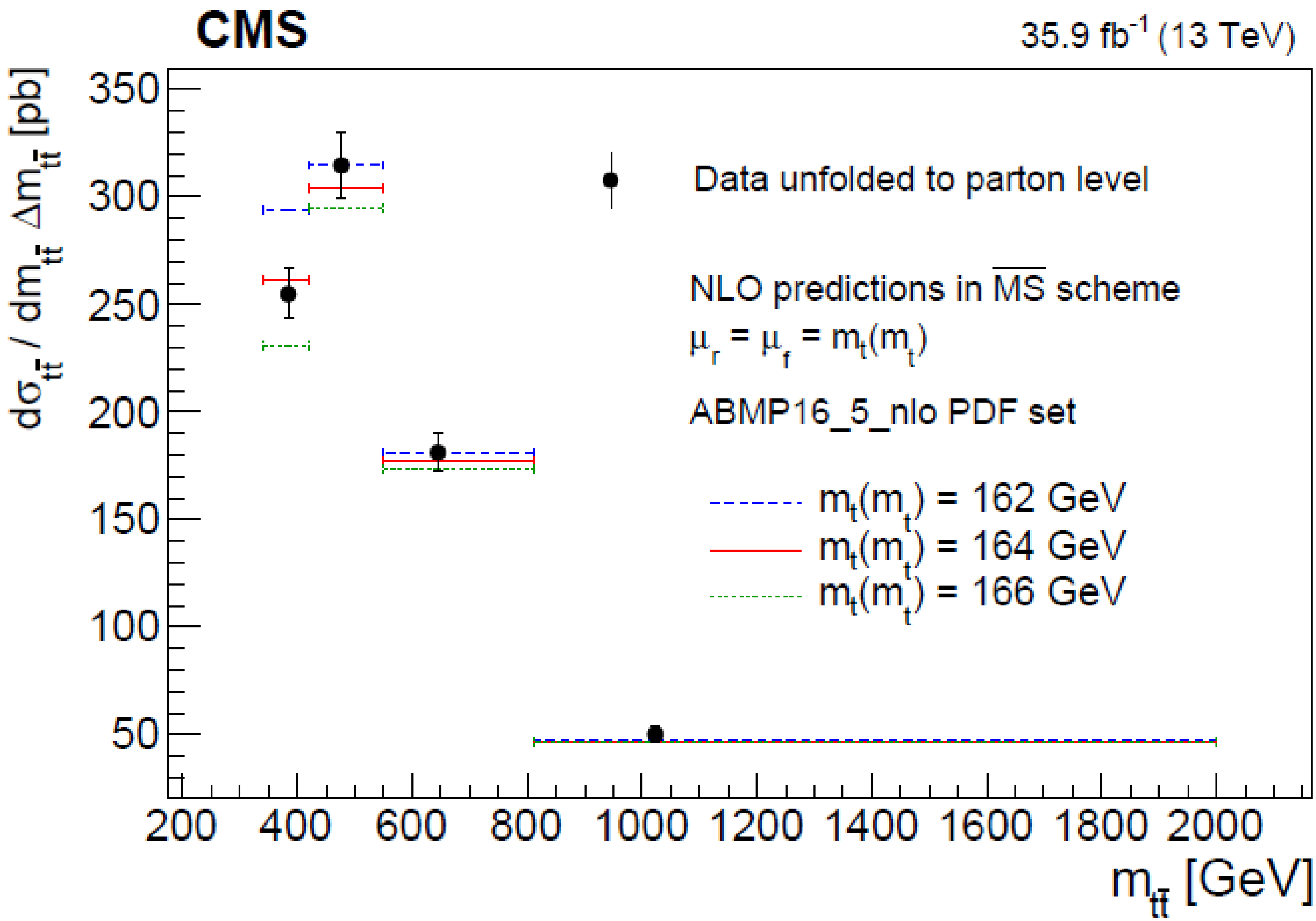
translate $m_b(m_b) \to m_b(2m_b)$

Prog. Part. Nucl. Phys. 84 (2015) 1

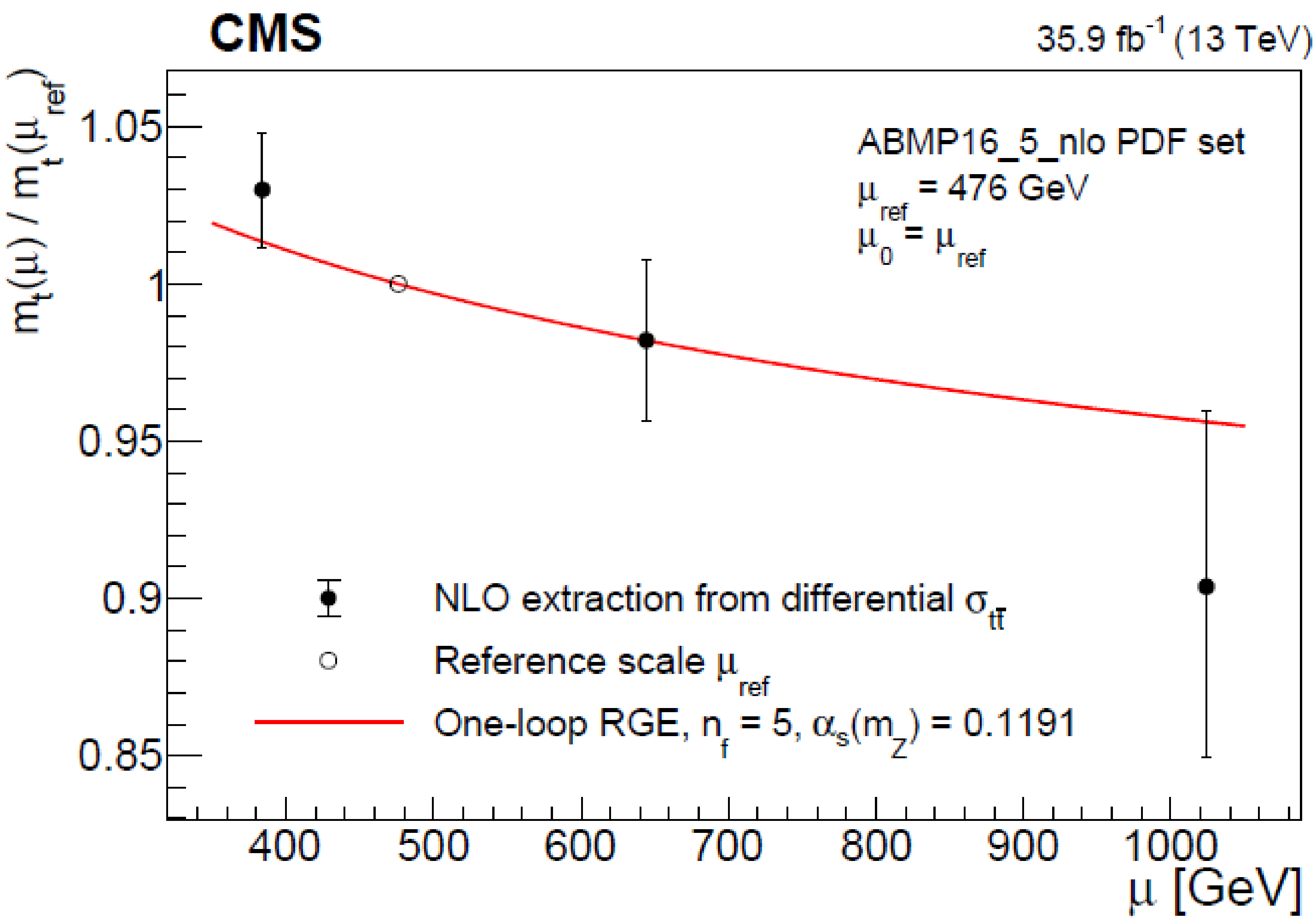


add extrapolated H1/ZEUS point

Top cross section vs. m_{tt}

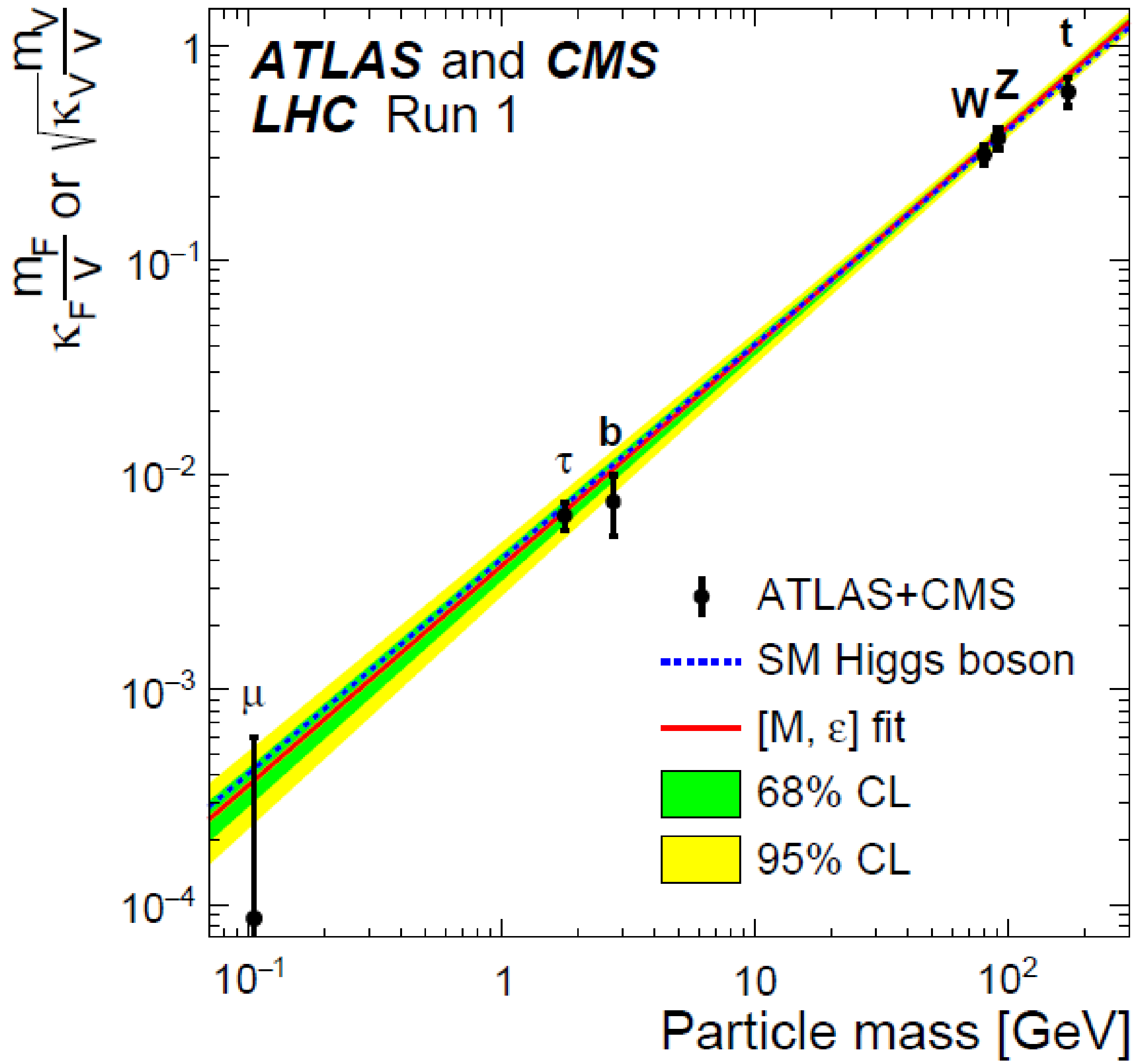


Top quark mass running



Direct measurements of Higgs Yukawa couplings

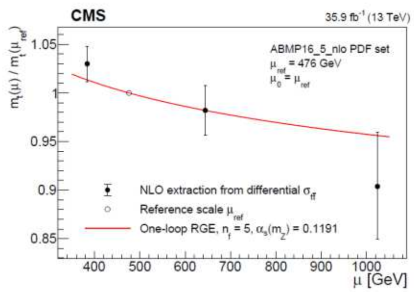
ATLAS and CMS, JHEP08 (2016) 045



Running of α_s and quark Yukawa couplings

update of PoS CHARM2016 (2017) 012

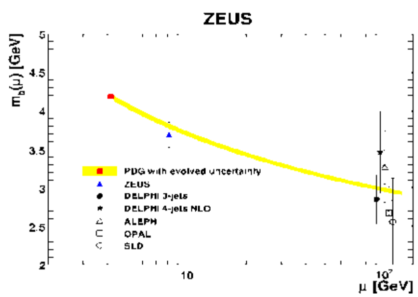
relate m_t, m_b, m_c to associated Higgs Yukawa couplings

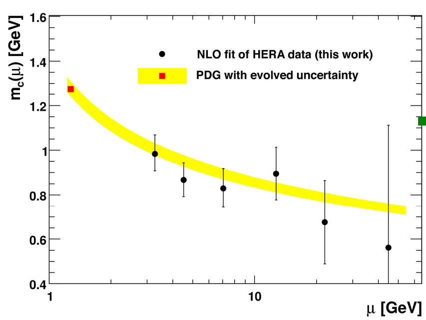


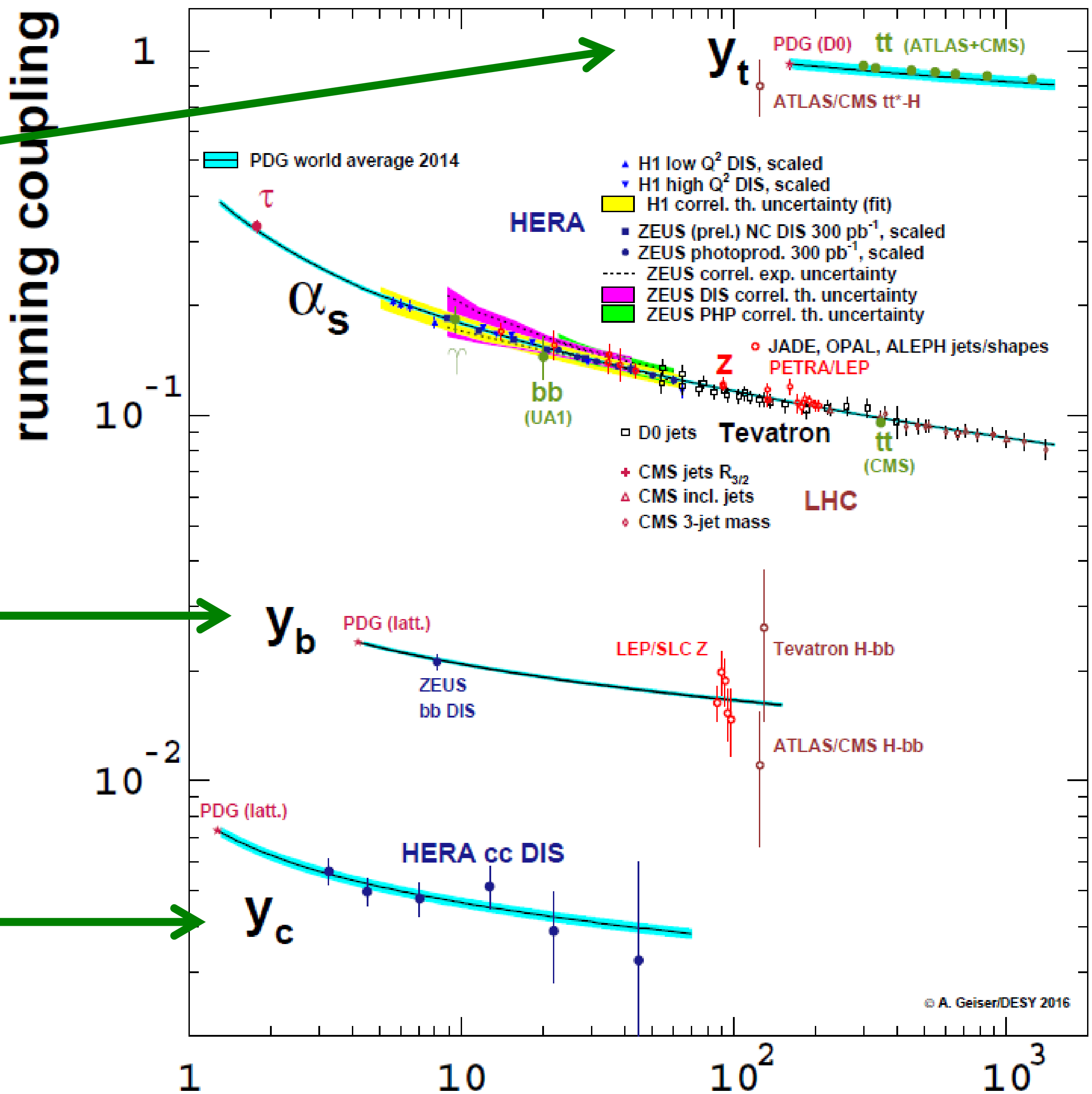
LO EW (+NLO QCD) formula:

$$y_Q = \sqrt{2} m_Q / v$$

(choose scheme in which formula is exact)







Project for discussion 10:

- Update and finalize this plot

so far, Higgs couplings and their running
as obtained from quark masses are consistent
with directly measured Higgs couplings

Project for discussion 10:

- improve heavy flavour treatment in NLO and NNLO jet predictions at HERA and LHC

NLO/NNLO jet fits in DIS at HERA

At HERA, have

massless NLO inclusive DIS, O(alphas), NF=3 (5) (1 loop)

massive NLO inclusive DIS HQ, O(alphas^2) (1 loop)

combine -> 3F FFNS (NLO for both inclusive and HQ) fit mQ

combine -> FONLL-B (additional free damping parameter)

massless NNLO inclusive DIS, O(alphas^2), NF=5 (2 loop)

massive NLO inclusive DIS HQ, O(alphas^2) (1 loop)

combine -> FONLL-C (NNLO for inclusive, NLO for HQ) fit mQ

massless NNLO inclusive DIS, O(alphas^2), NF=3 (2 loop)

massive NNLO inclusive DIS HQ (appr.), O(alphas^3) (2 loop)

combine -> 3F FFNS (NNLO for both inclusive and HQ)

fit mQ + alphas

NLO/NNLO jet fits at HERA in DIS and PhP

At HERA, have

massless NLO jets in DIS differential, NF=5 O(alphas^2) 1-loop

-> fit alphas

massive NLO differential DIS HQ (HVQDIS) O(alphas^2) 1-loop

-> can produce jets at 1 loop

combine! -> evaluate correction to alphas fit w.r.t. massless only

massless NLO jets in PhP differential, NF=5 O(alphas^2) 1-loop

-> fit alphas

massive NLO differential HQ (FMNR) O(alphas^2) 1-loop

-> can produce jets at 1 loop

combine!

massless NNLO jets in DIS differential, NF=5 O(alphas^4) 2-loop

-> fit alphas

combine with massive ???

NLO/NNLO jet fits at LHC

At LHC, have

massless NLO jets, O(alphas^3), NF=5 O(alphas^3) 1-loop

massive NLO differential HQ (MNR), O(alphas^3) 1-loop

-> can produce jets at 1 loop

-> combine

FONLL (collinear resummation, single differential only)

massless NNLO jets O(alphas^4), NF=5 O(alphas^4) 2-loop

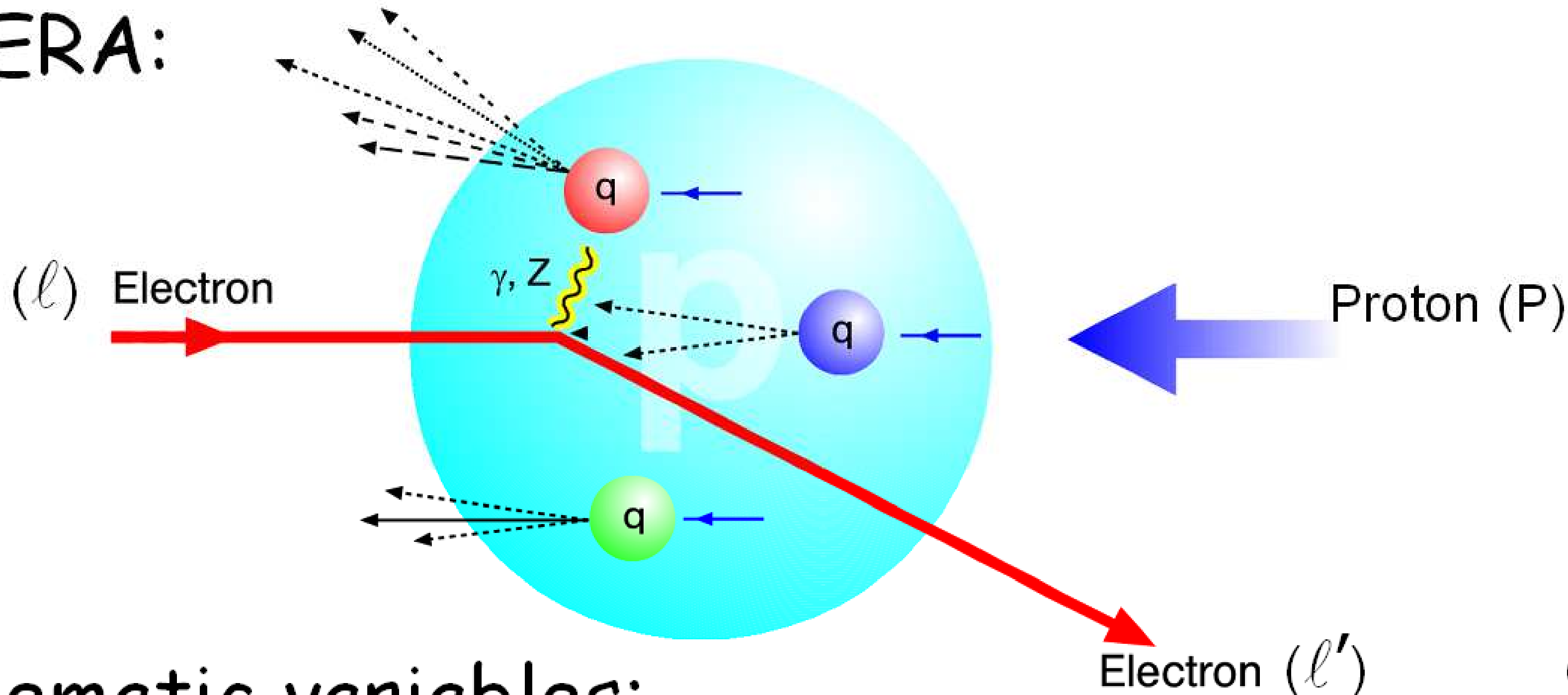
massive NNLO differential HQ (top only!) O(alphas^4) 2-loop

-> get to work for c and b and combine

- rule of thumb for cc, bb and tt pair production collisions at LHC energies (~10 TeV, E_cosmic ray ~ 10^8 GeV):
- cc: ~ 10% of total cross section
- bb: ~ 1% of total cross section
- tt: ~ 0.01% of total cross section

Deep Inelastic ep Scattering at HERA

HERA:



$q = \ell - \ell'$

kinematic variables:

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

$x = \frac{Q^2}{2Pq}$ Bjorken scaling variable,
for $Q^2 \gg (2m_q)^2$: momentum fraction of p constituent

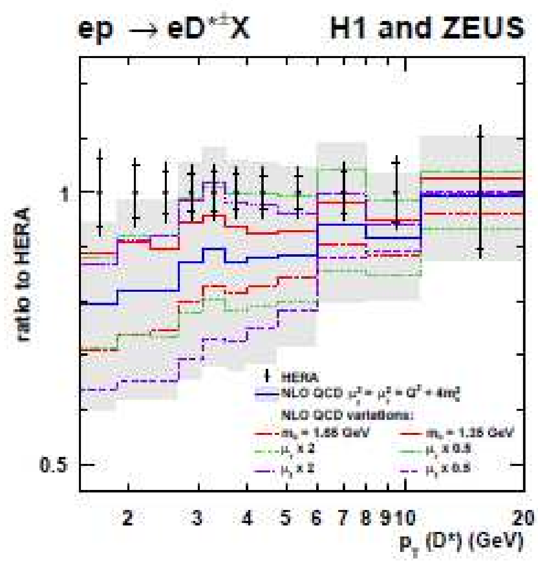
$y = \frac{qP}{\ell P}$ inelasticity,
γ momentum fraction (of e)

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

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

Comparison to NLO QCD

detailed study of theory uncertainties



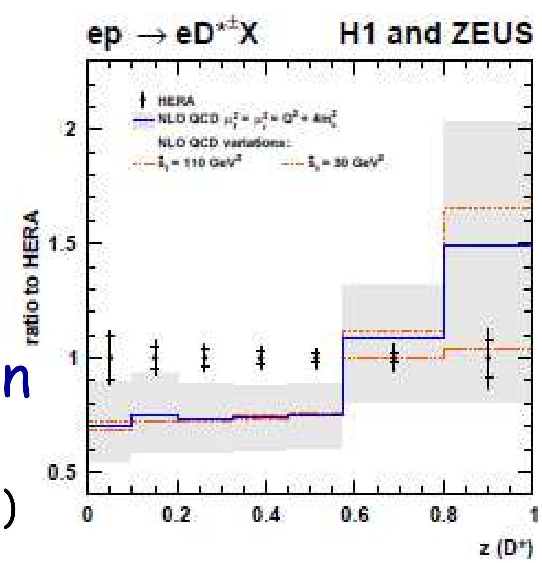
is it possible to customise (choose parameters) such that all distributions are described simultaneously?

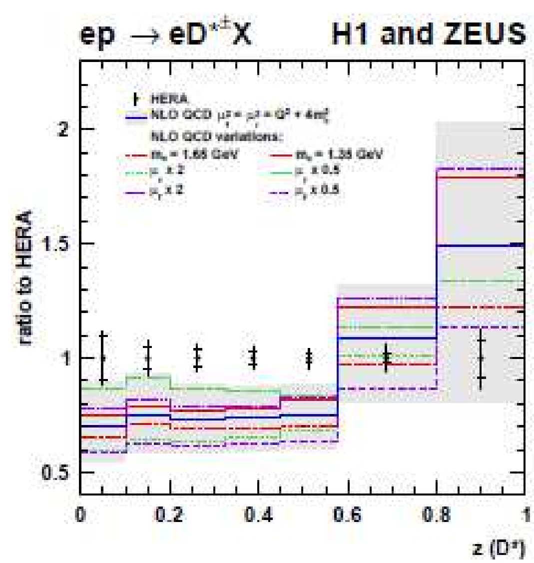
largest:

QCD scales

fragmentation

(Kartvelishvili as measured at HERA)

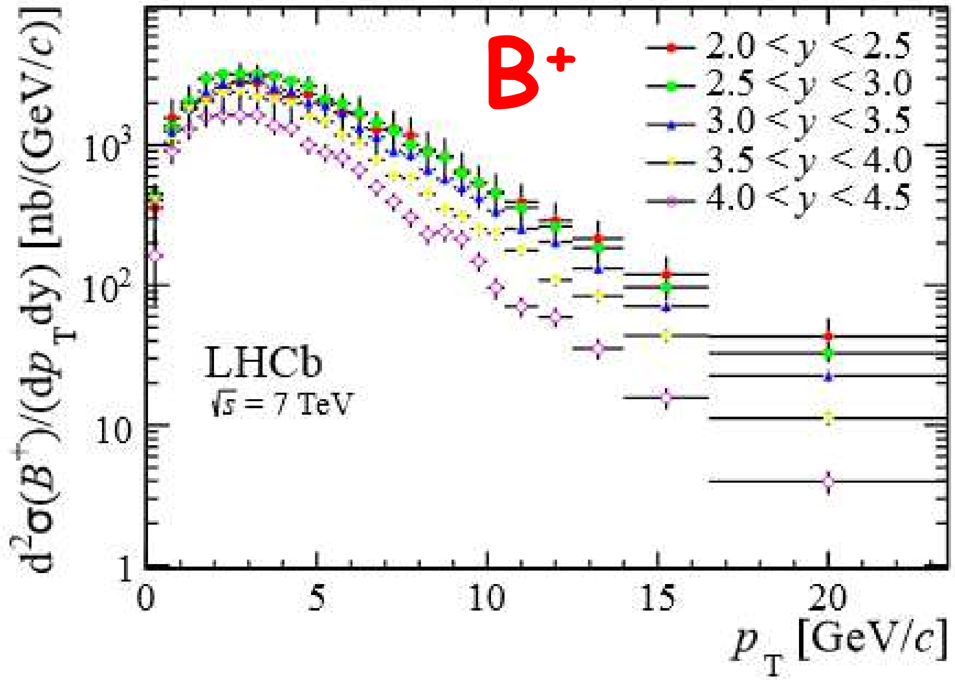


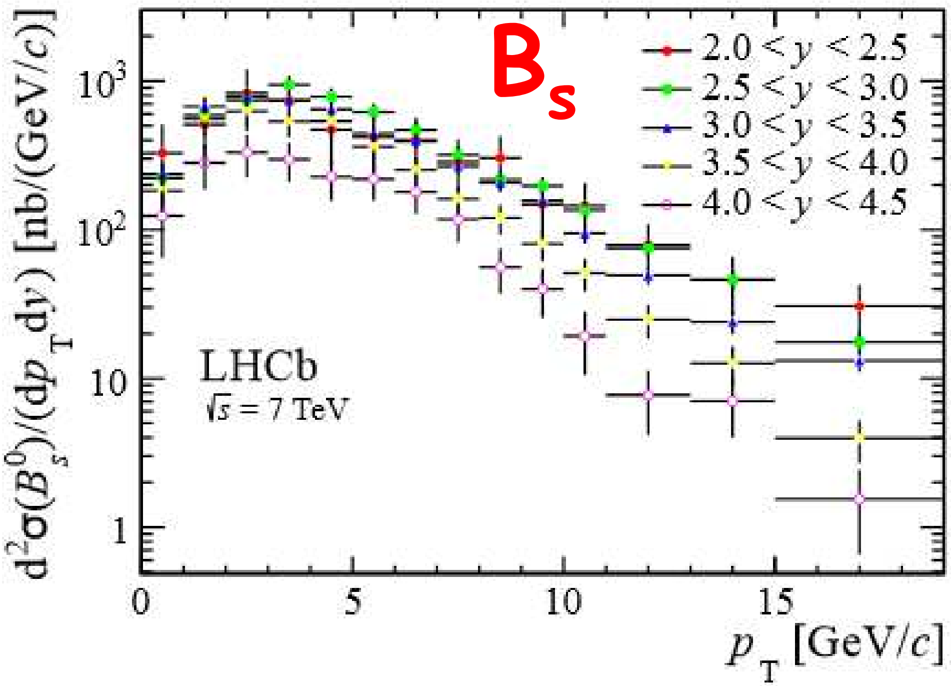


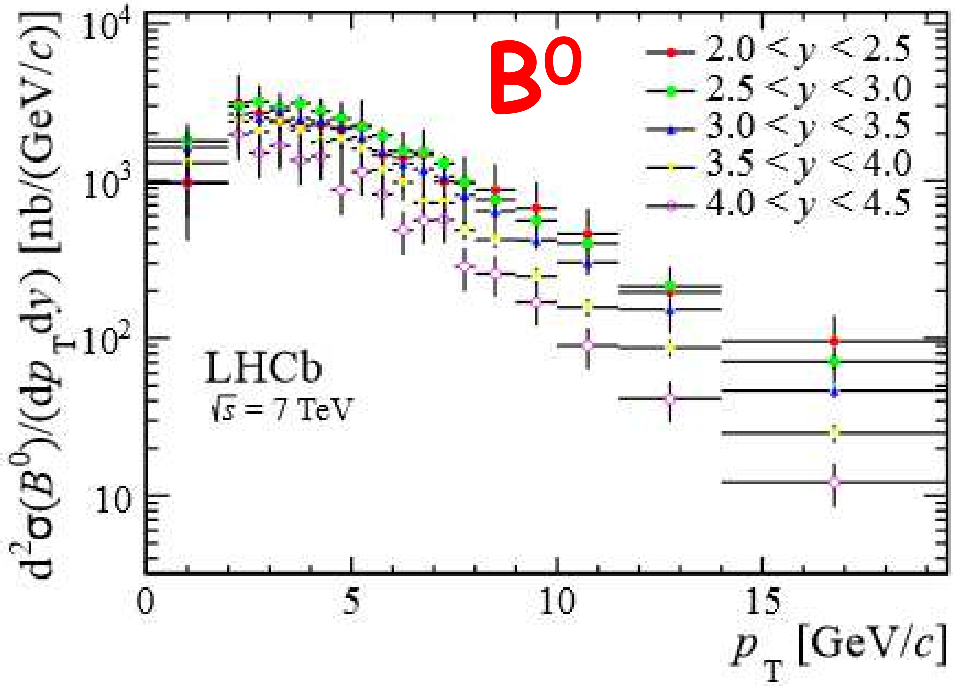
it is!

Beauty at LHCb

JHEP 08 (2013) 117







Charm

at LHCb

Nucl.Phys. B871 (2013) 1-20

down to p_T = 0 GeV

large theory uncertainty at NLO (~factor 2) but also strong m_c dependence

directly sensitive to gluon down to x~10^{-5} !

FONLL fits well (factor 2 scale uncertainty not shown)

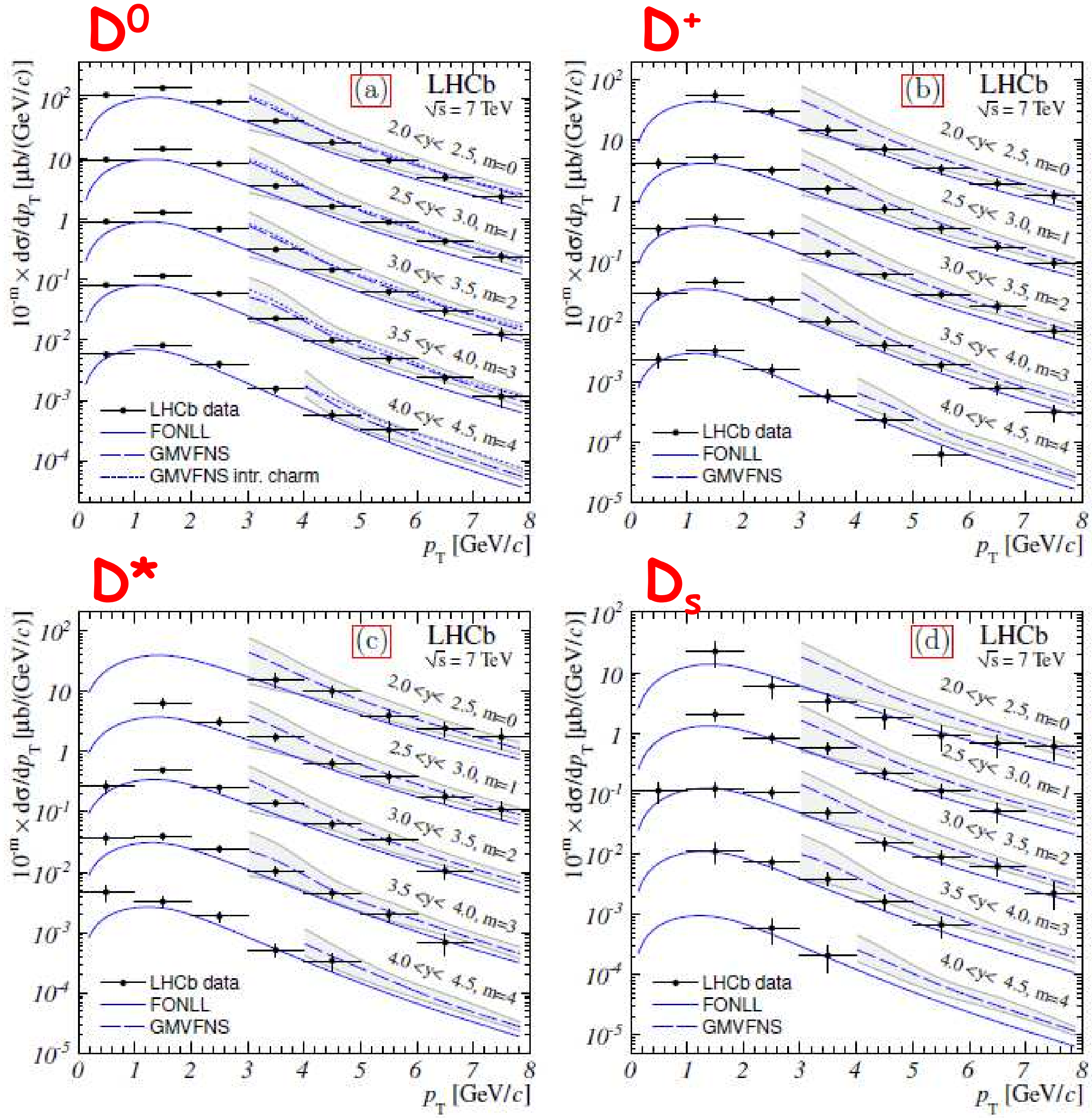
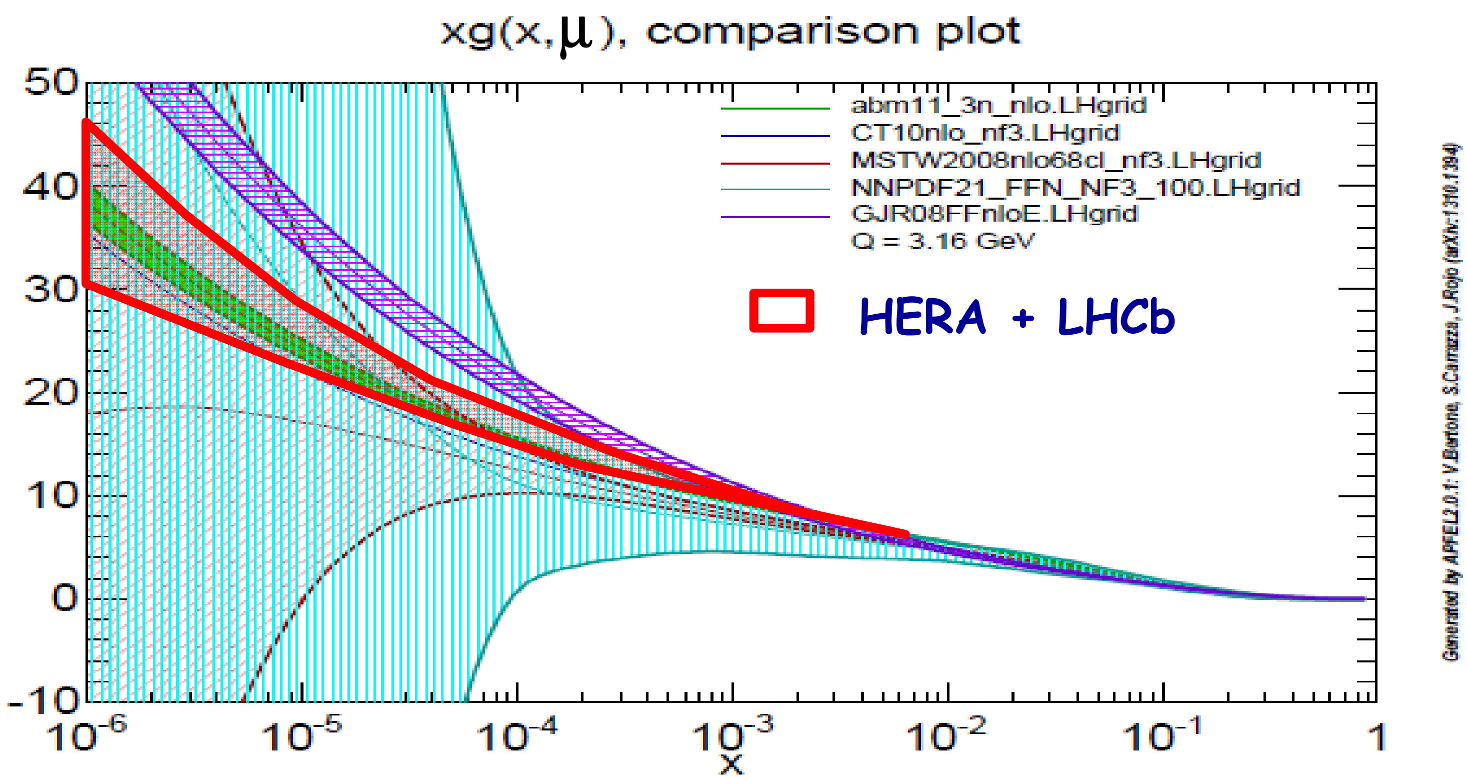


Figure 4: Differential cross-sections for (a) D^0, (b) D^+, (c) D^{*+}, and (d) D_s^+ meson production compared to theoretical predictions. The cross-sections for different y regions are shown as functions of p_T. The y ranges are shown as separate curves and associated sets of points scaled by factors 10^{-m}, where the exponent m is shown on the plot with the y range. The error bars associated with the data points show the sum in quadrature of the statistical and total systematic uncertainty. The shaded regions show the range of theoretical uncertainties for the GMVFNS prediction.

Comparison to 'old' global PDFs

HERAPDF style parameterization with sizeable \`negative gluon ' term (but net positive gluon)

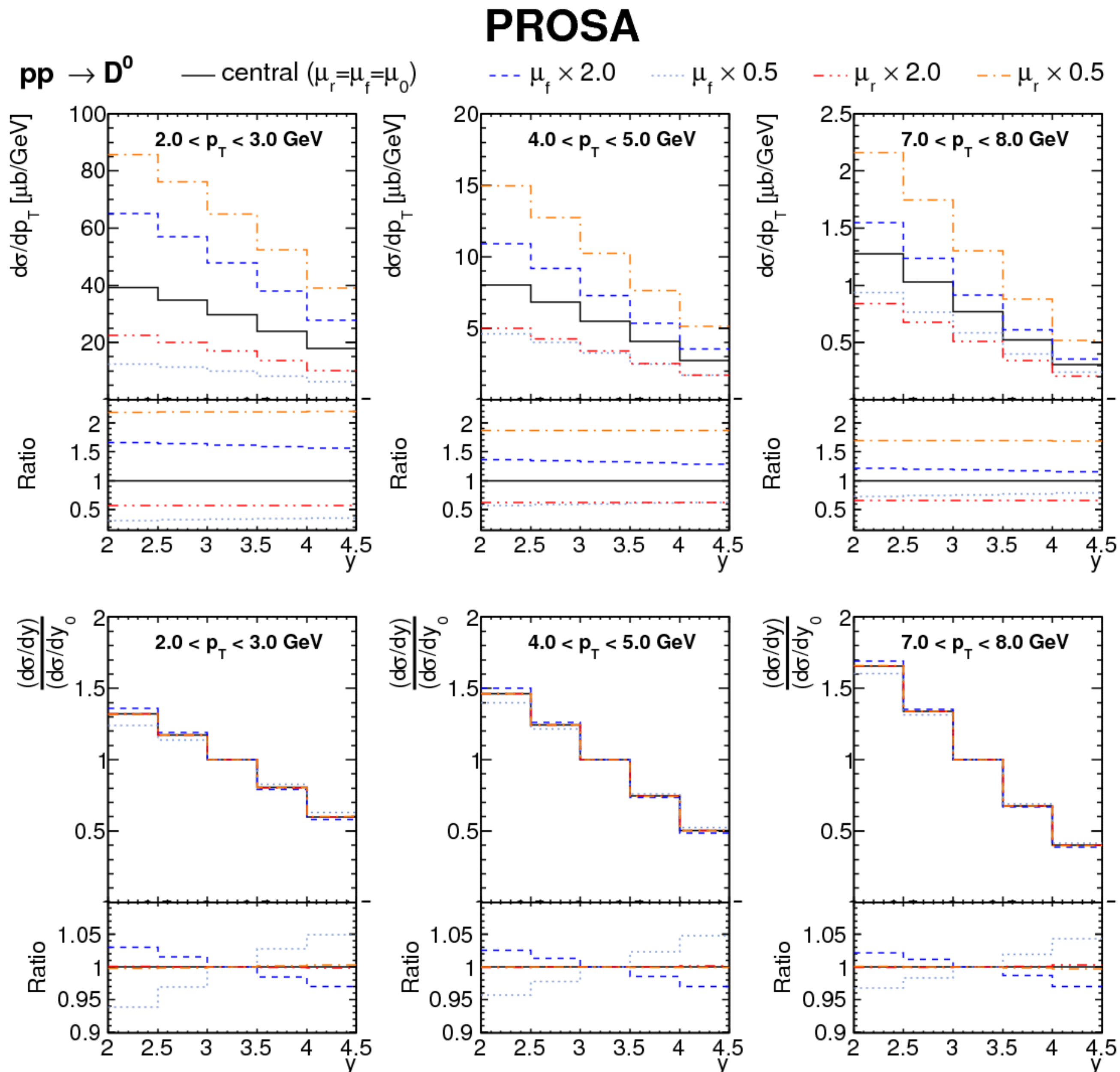


in good agreement with constrained ABM11 parameterization at low x

NLO scale dependence

charm at LHCb

(similar
for beauty,
see backup)



absolute cross section:

~factor 2

p_T-normalized cross section:

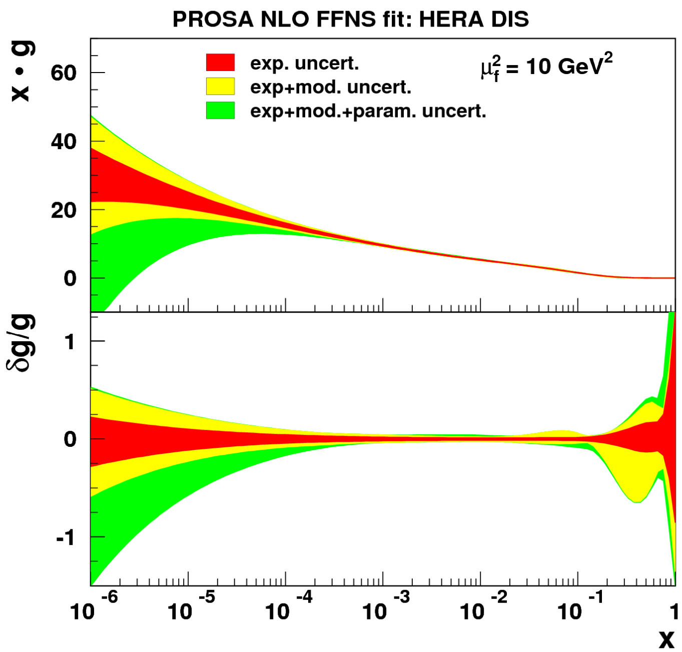
(use shape in
y for each p_T bin,
normalized to
central y bin)

~ few %

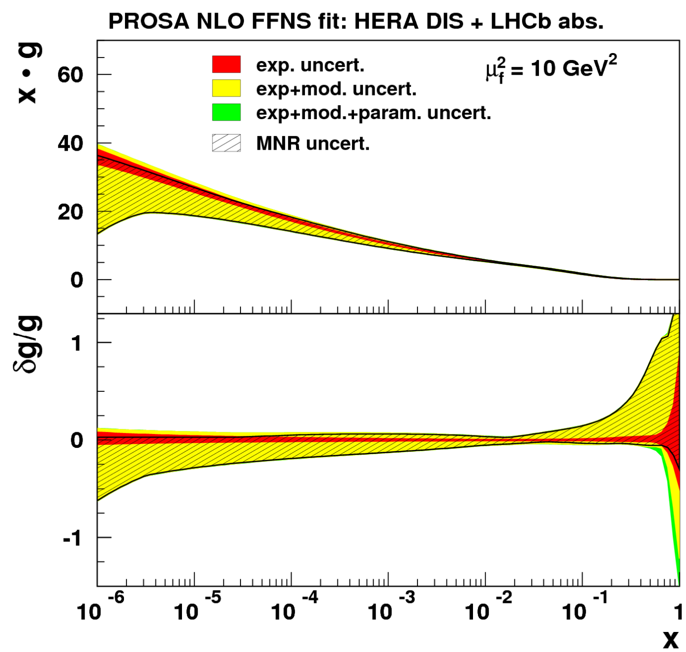
Comparison of uncertainties

Example: gluon PDF

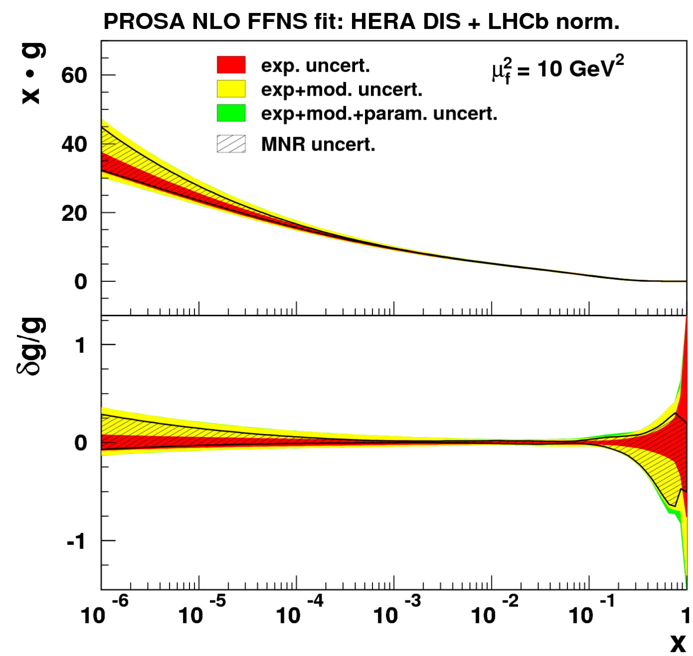
HERA only



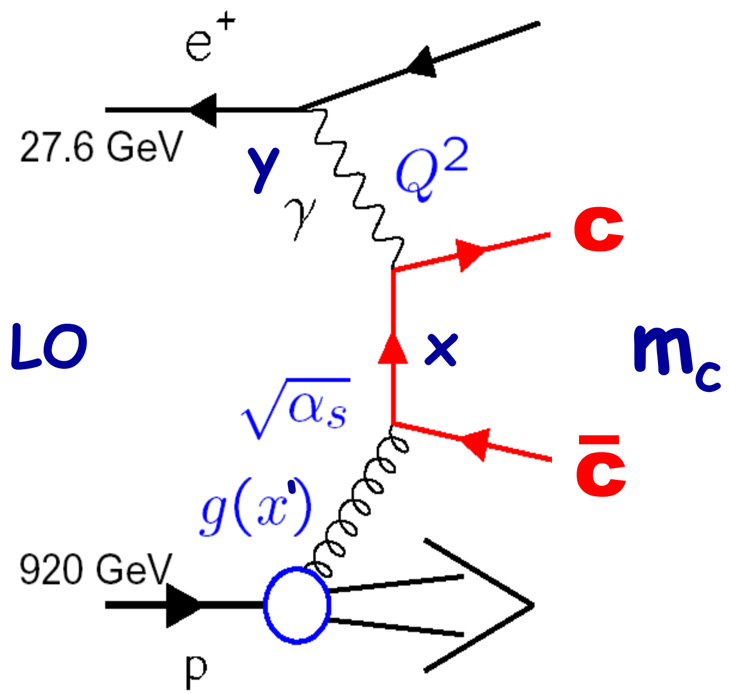
HERA + LHCb absol.



HERA absol. + LHCb norm.



fixed flavour number scheme (FFNS)



+ NLO (+partial NNLO) corrections,

"natural" scale:
$Q^2 + 4m_c^2$

- no charm in proton
- full kinematical treatment of charm mass (multi-scale problem: Q^2, p_T, m_c -> logs of ratios)
- no resummation of logs

m_c fit and uncertainties

H1-prelim-14-071, ZEUS-prel-14-006, + S. Moch

use appropriate PDF set for each mass (from inclusive DIS data only), fit charm data

Fit uncertainty

- Was estimated by taking $\Delta\chi^2 = 1$ (dominant uncertainty)

Parametrisation

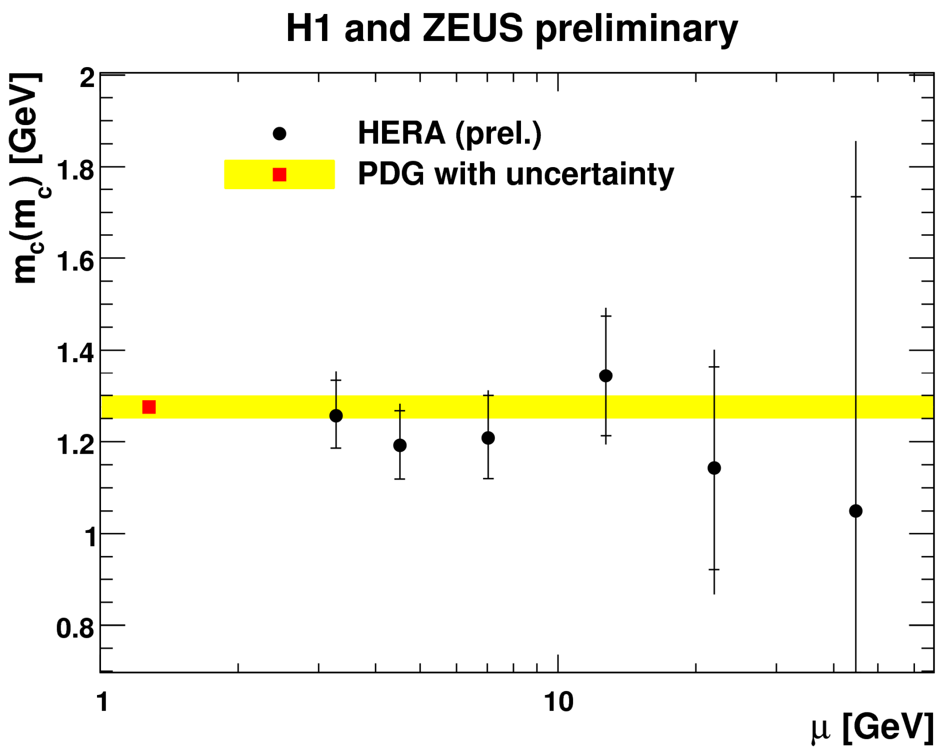
- Adding extra parameter in the PDF parametrisation

Model uncertainty

- Variation of the strangeness supression factor
- Lower cut on Q^2 for inclusive data
- The evolution starting scale
- The b-quark mass

Theory

- Variation of α_s
- Variation of the factorisation and renormalization scales of heavy quarks by factor 2



-> outer error bar

sensitivity to $m_c(m_c)$ decreases with increasing scale $\mu^2 = Q^2+4m_c^2$

'in reality', have measured $m_c(\mu)$ at each scale

the running b quark mass at LEP

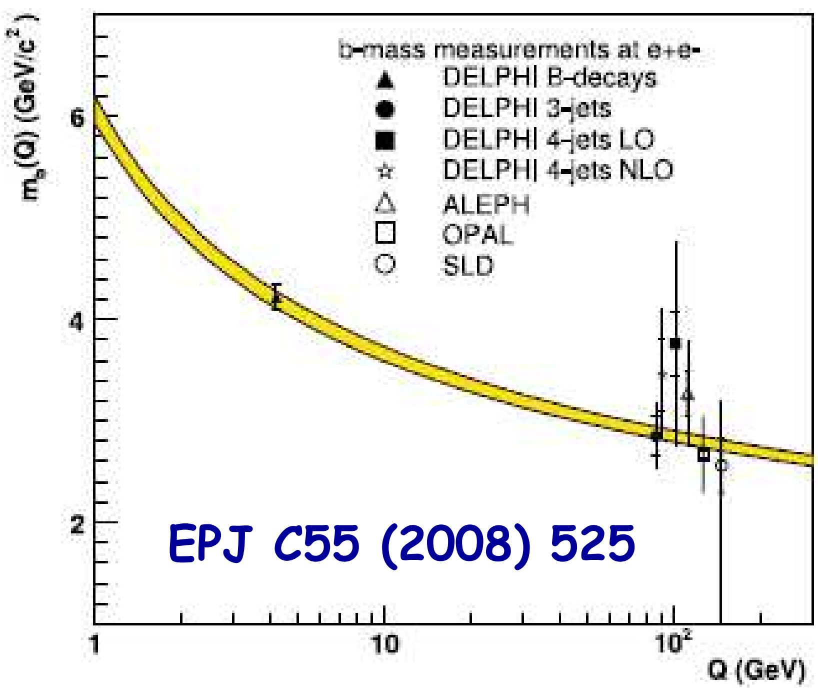


Fig. 6. The energy evolution of the $\overline{MS}$-running b-quark mass $m_b(Q)$ as measured at LEP. DELPHI results from $R_3^{b\ell}$ [7] at the M_Z scale and from semileptonic B-decays [31] at low energy are shown together with results from other experiments (ALEPH [4], OPAL [5] and SLD [6]). The masses extracted from LO and approximate NLO calculations of $R_4^{b\ell}$ are found to be consistent with previous experimental results and with the reference value $m_b(Q)$ (*grey band*) obtained from evolving the average $m_b(m_b) = 4.20 \pm 0.07$ GeV$/c^2$ from [17] using QCD RGE (with a strong coupling constant value $\alpha_s(M_Z) = 0.1202 \pm 0.0050$ [30])

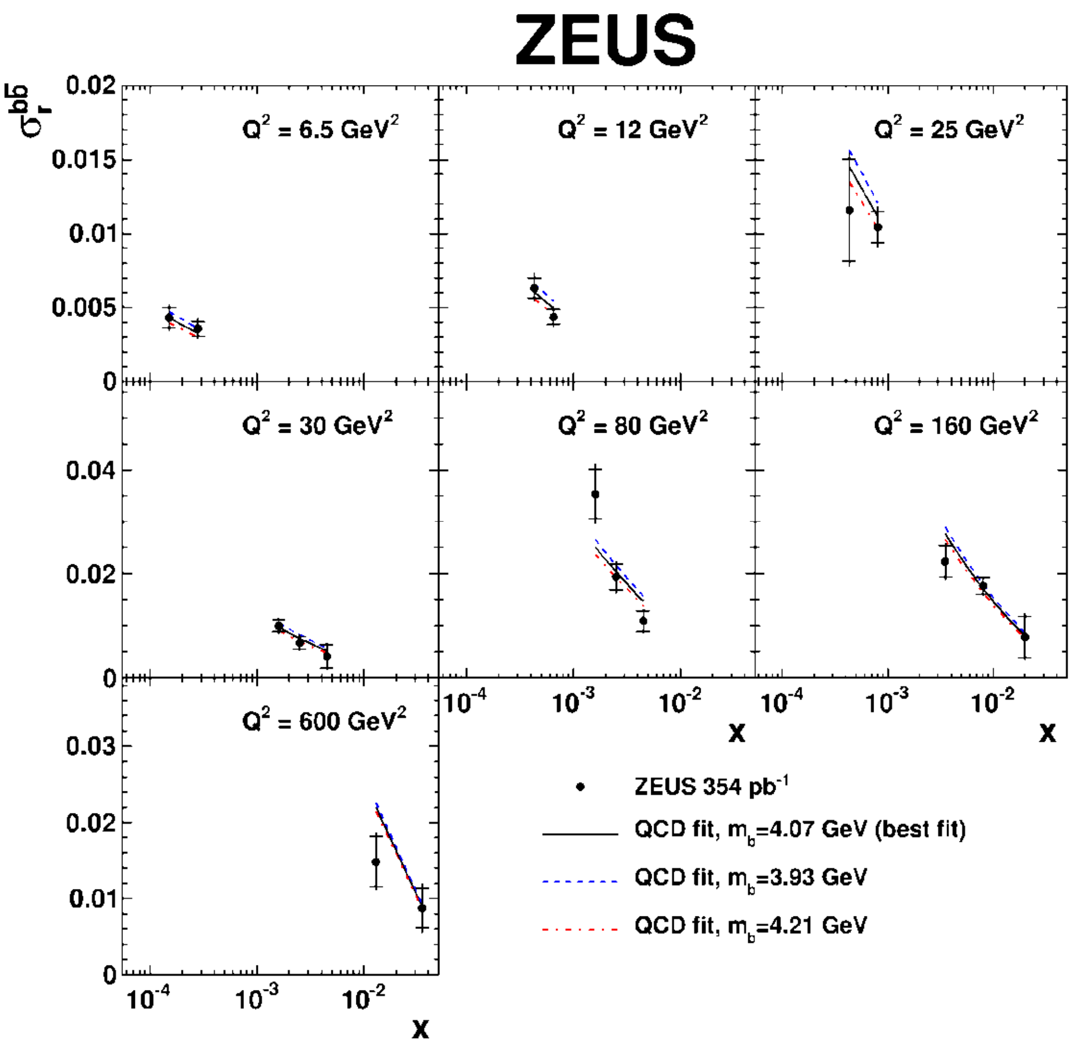
LEP: Z -> bb + gluons, measurement of phase space/ angular distributions

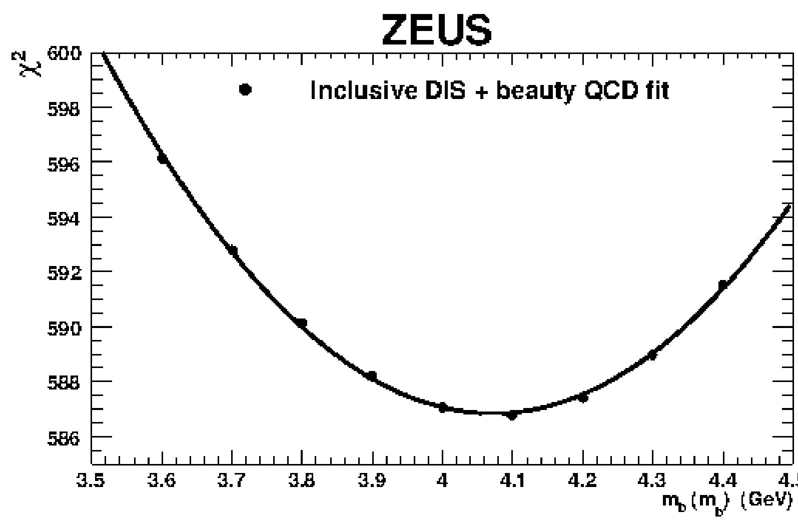
$$m_{(Q)} = m_{(Q_0)} \, (1 - \alpha_s/\pi \, \ln(Q^2/Q_0^2))$$

charm and top mass running not explicitly measured (so far)

m_b from reduced beauty cross section

JHEP 1409 (2014) 127





uncertainty evaluation
similar to charm running case

$m_b(m_b) = 4.07 \pm 0.14_{fit}\ {}^{+0.01}_{-0.07}{}_{mod}\ {}^{+0.05}_{-0.00}{}_{par}\ {}^{+0.08}_{-0.05}{}_{th}$ GeV

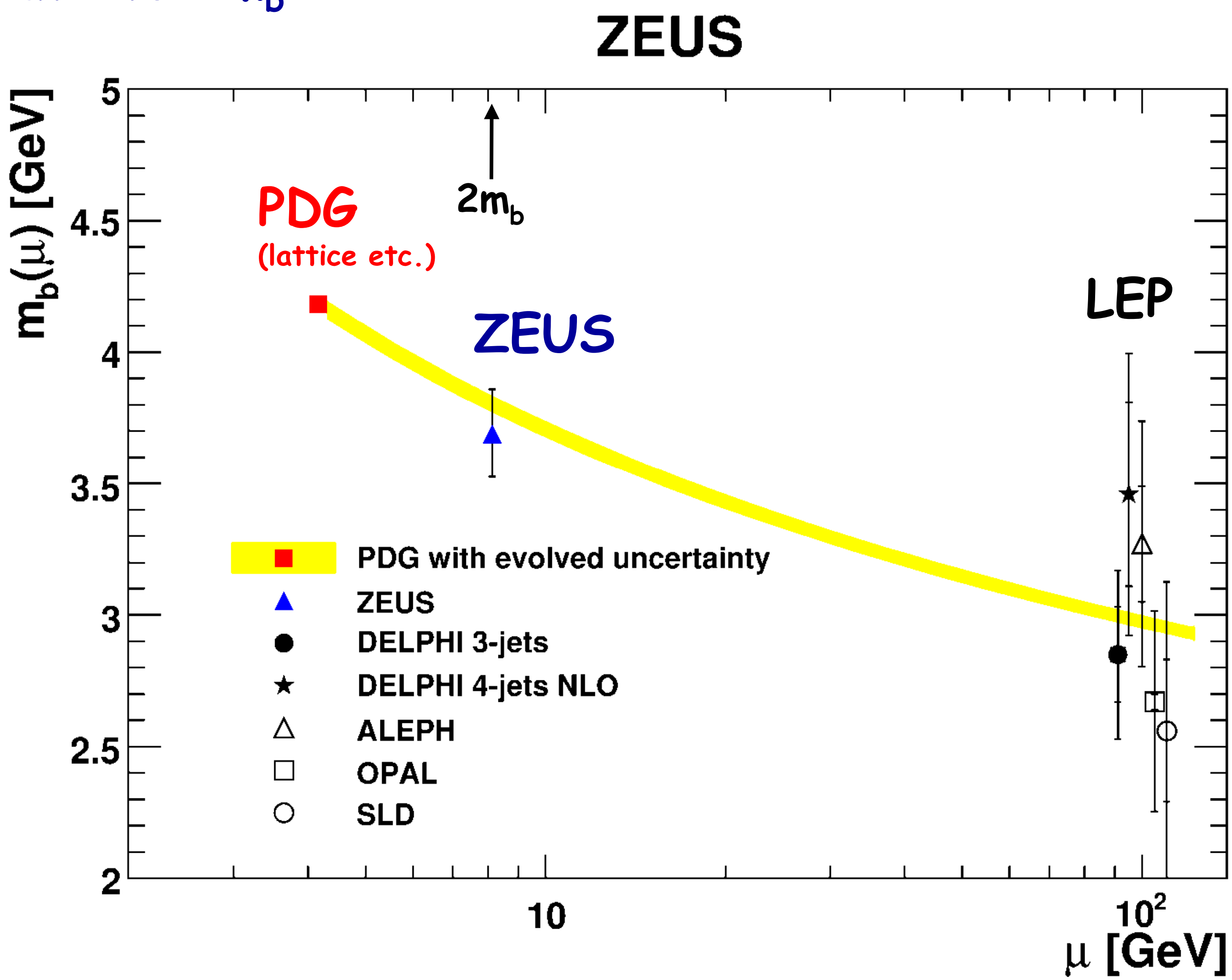
PDG: 4.18 ± 0.03 GeV (lattice QCD + time-like processes)

the running beauty quark mass

arXiv:1506.07519

translate to $2m_b$

Prog. Part. Nucl. Phys. 84 (2015) 1



Higgs couplings

relate m_t, m_b, m_c to associated Higgs Yukawa couplings

LO EW (+NLO QCD) formula:

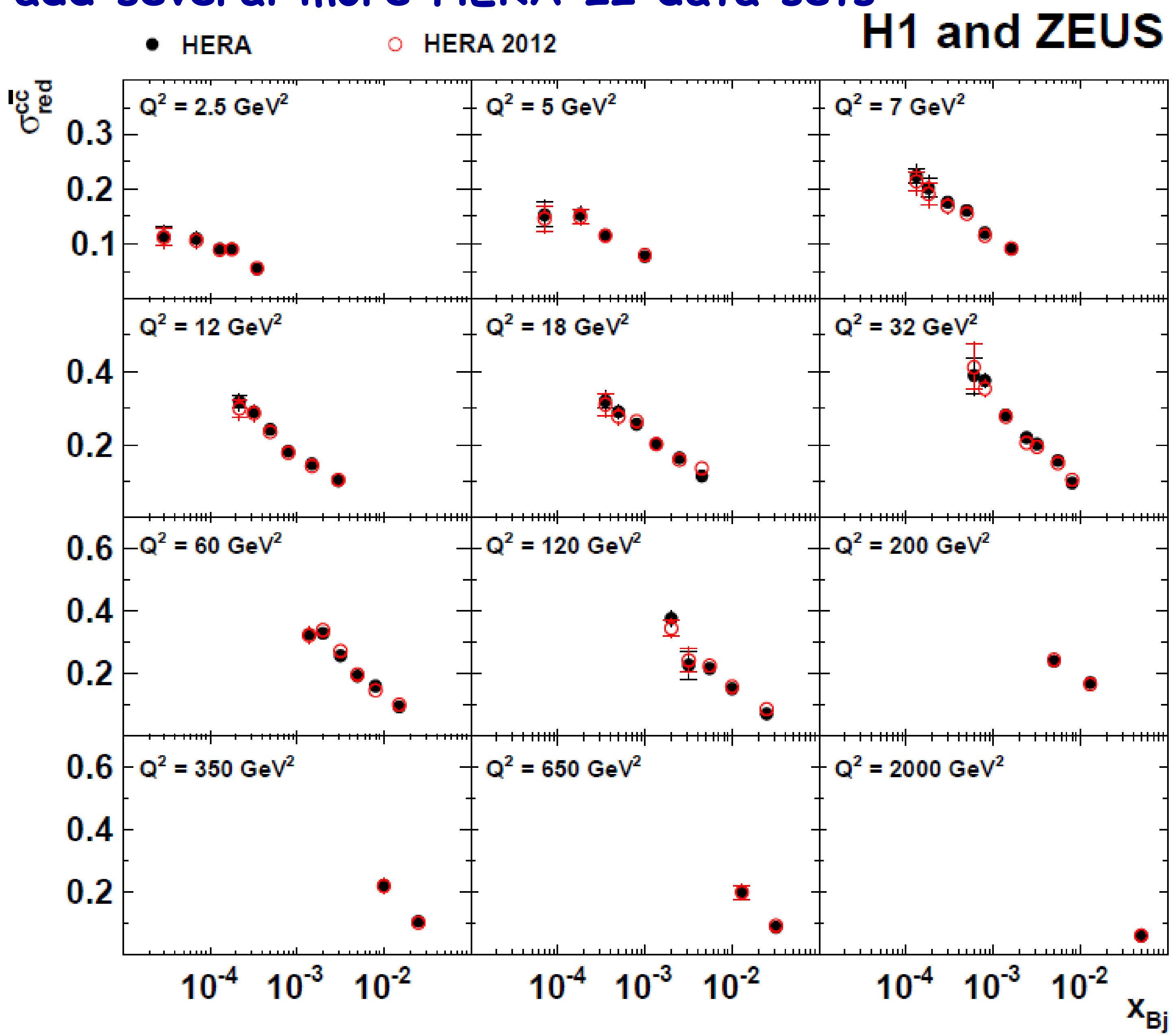
$$y_Q = \sqrt{2} m_Q / v$$

source: viXra blog

Final HERA charm (and beauty) combinations in DIS

arXiv:1804.01019

add several more HERA II data sets



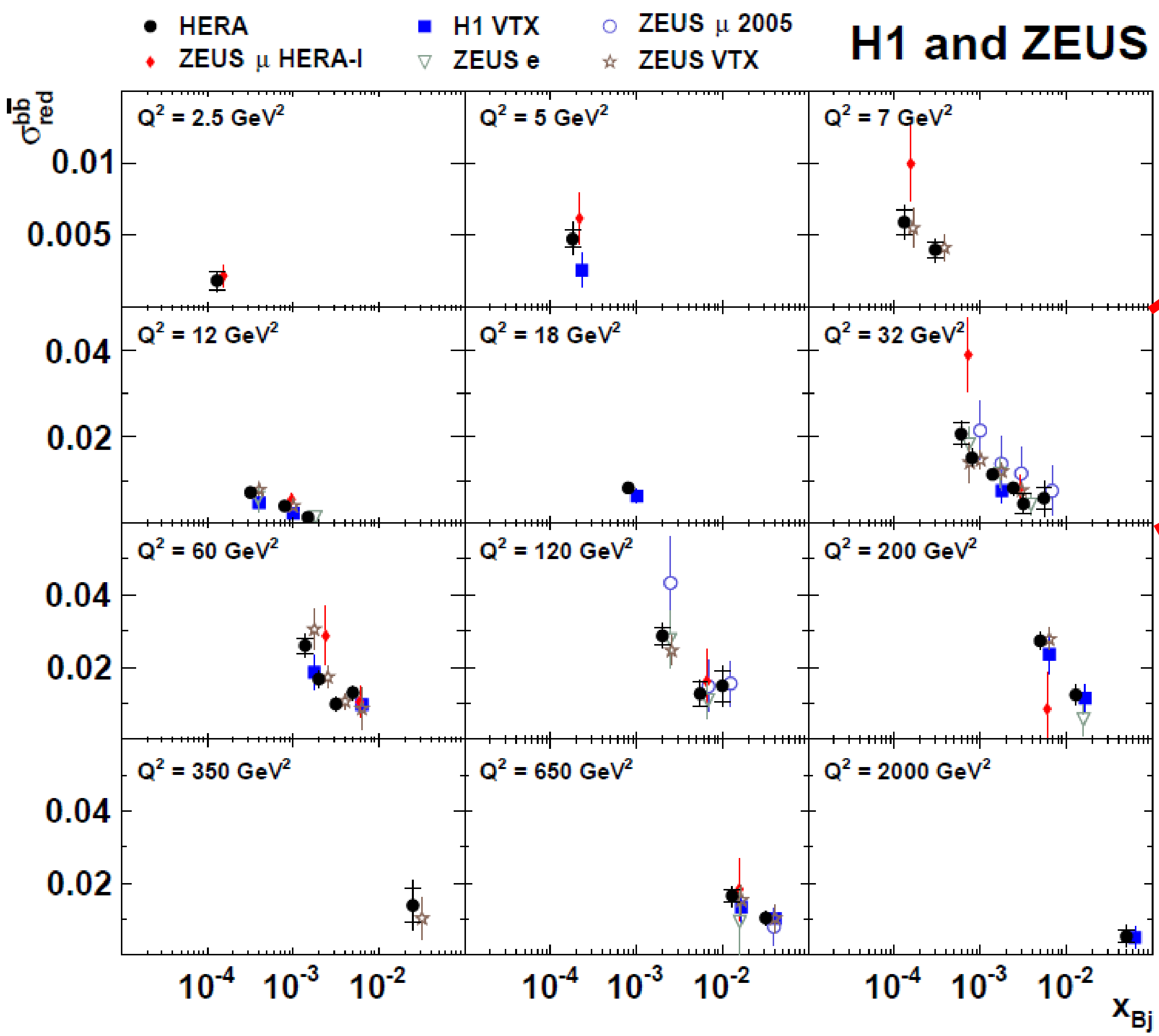
~20% improvement

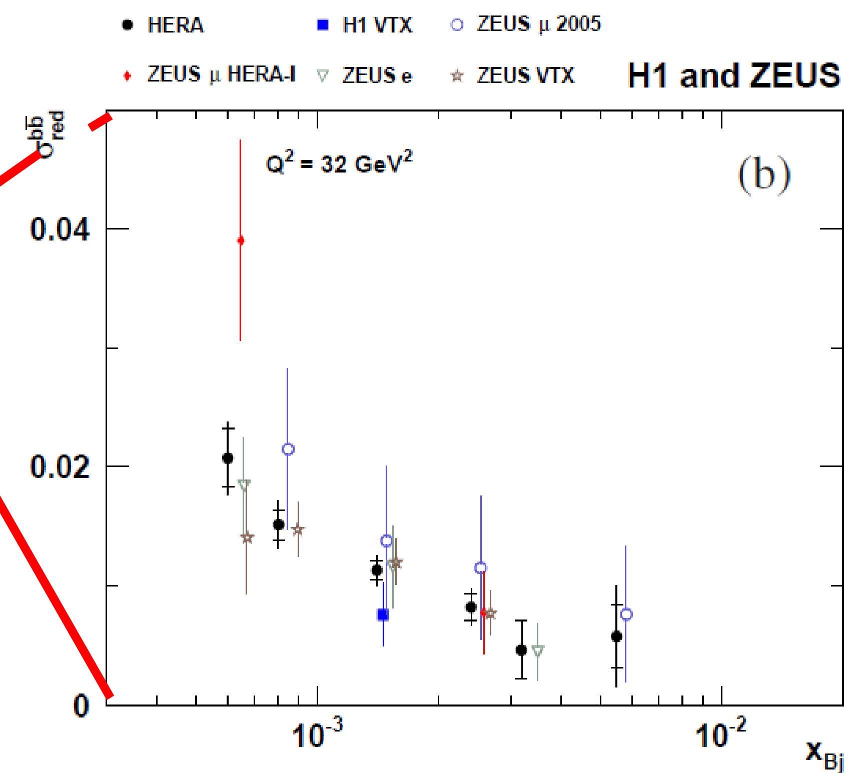
Beauty combination

arXiv:1804.01019

57 -> 27 data points

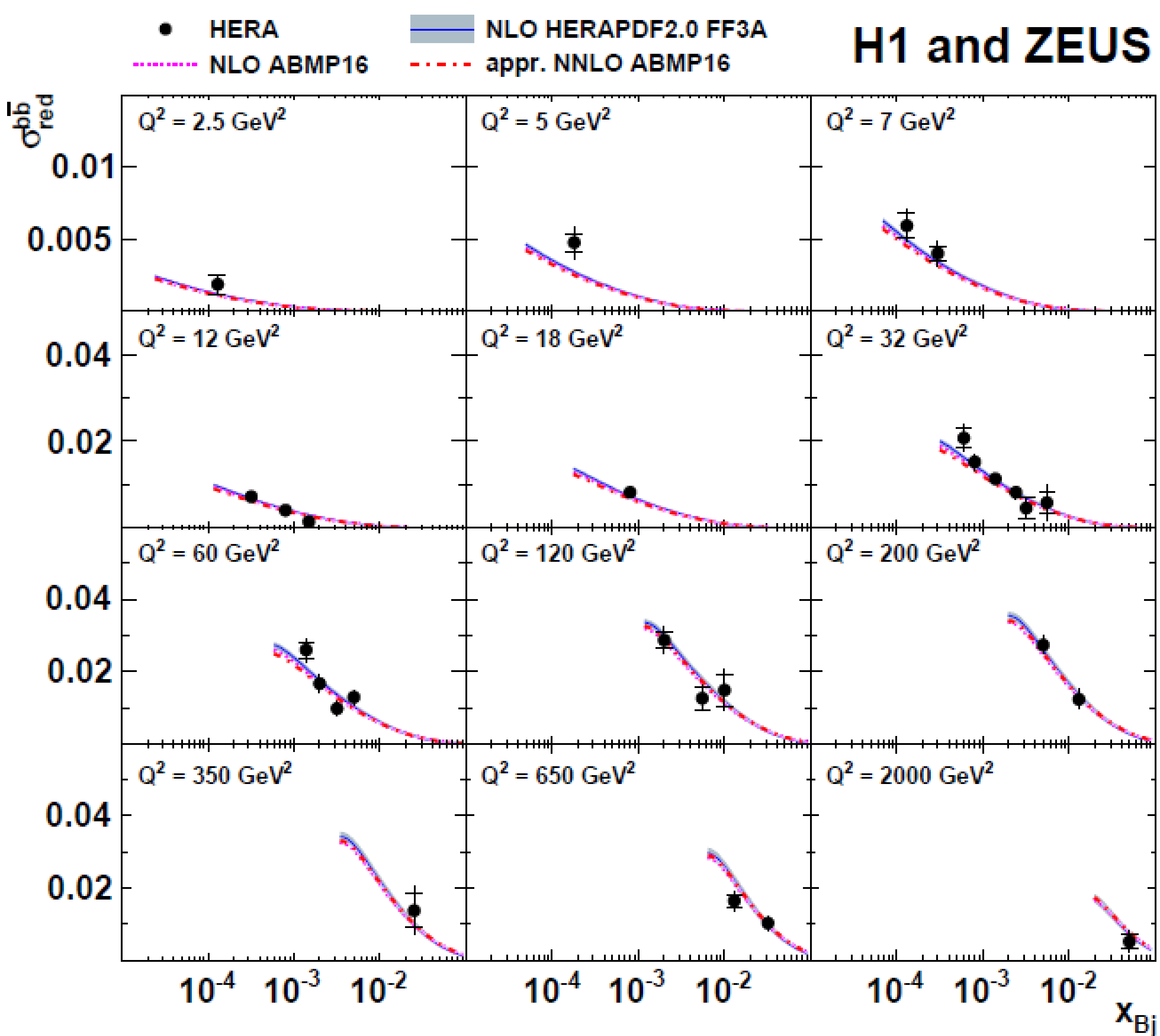
combined for the first time





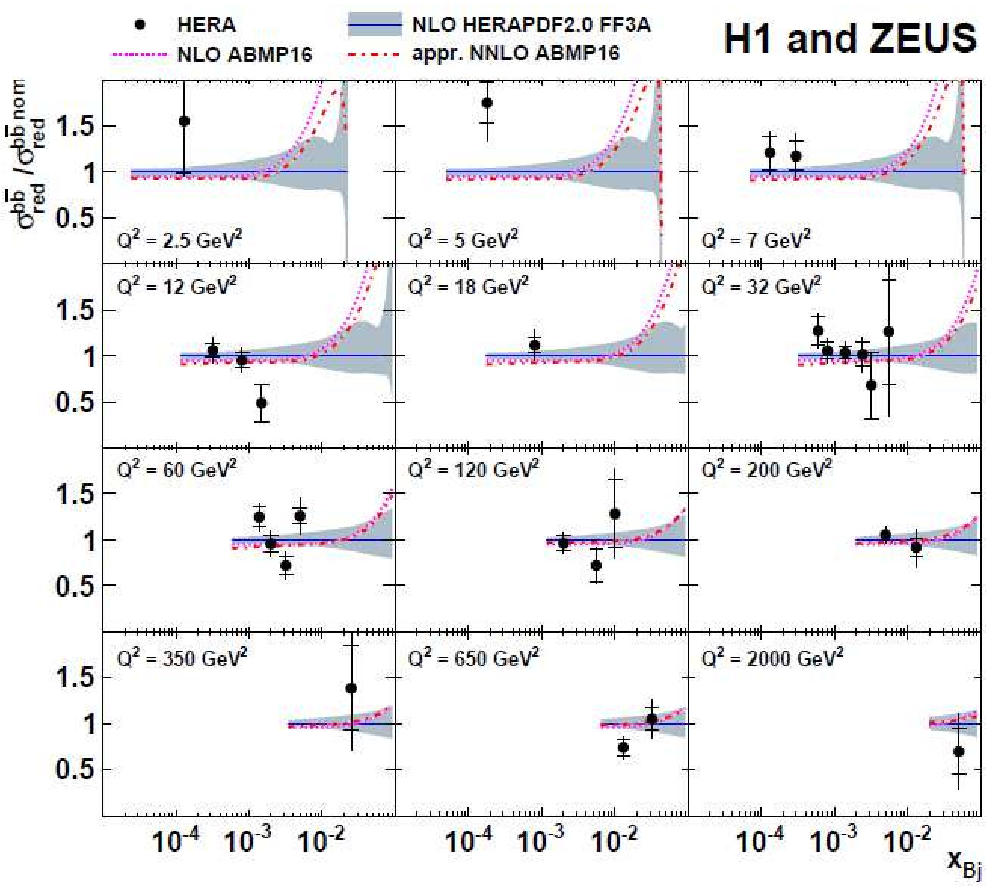
Comparison to FFNS predictions

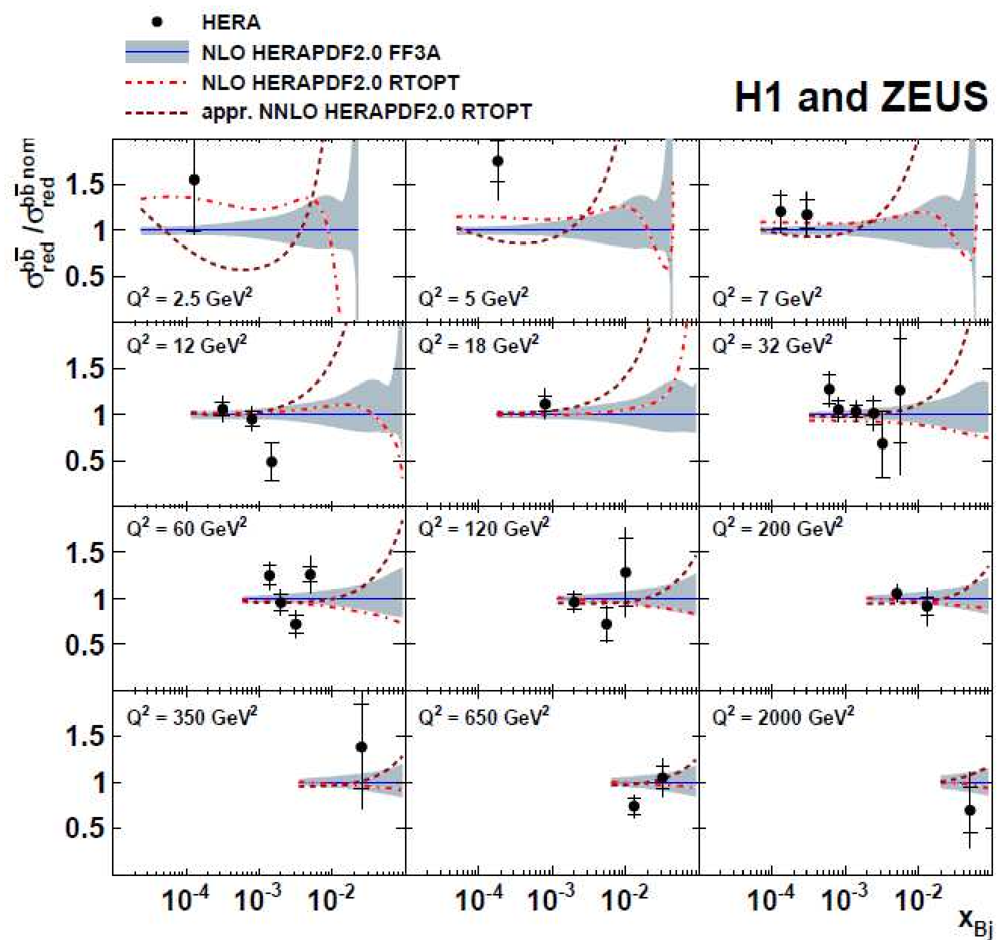
beauty:



Comparison to FFNS and VFNS predictions

Beauty:





Predictions w/o and with log 1/x resummation

arXiv:1804.01019

NLL resummation of log 1/x terms improves x_{Bj} slope but deteriorates normalisation

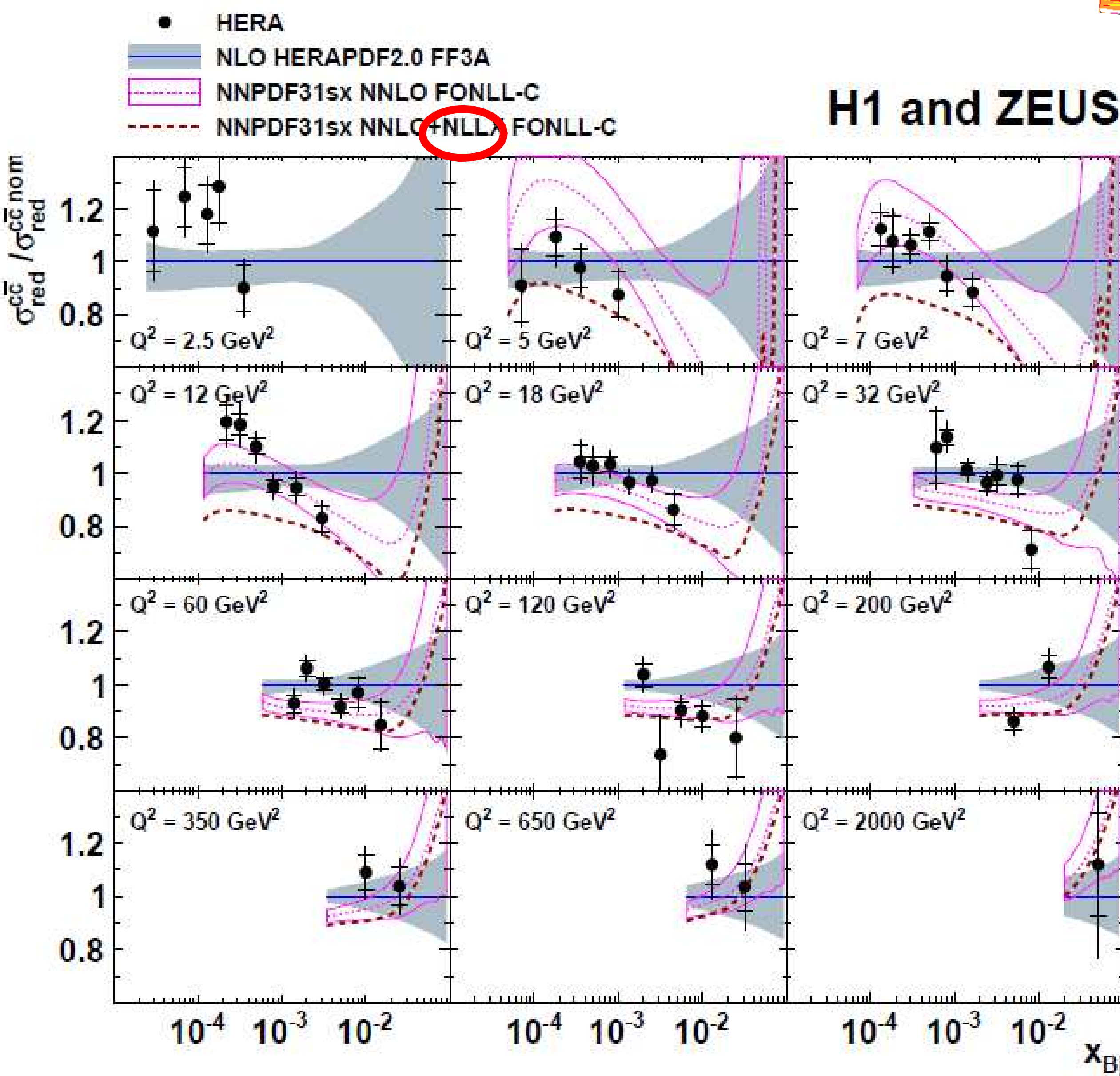
overall, NNPDF3.1sx

(fitted charm, arXiv:1710.05935)

either with or w/o log 1/x resummation

not better than HERAPDF

(FONLL-C + NLLx see below)



χ^2 and p-values for various QCD predictions

arXiv:1804.01019

central predictions

Dataset	PDF (scheme)	χ^2 [p-value]
charm [38]	HERAPDF20_NLO_FF3A (FFNS)	59 [0.23]
	ABKM09 (FFNS)	59 [0.23]
	ABMP16_3_nlo (FFNS)	61 [0.18]
	ABMP16_3_nnlo (FFNS)	70 [0.05]
	HERAPDF20_NLO_EIG (RTOPT)	71 [0.04]
(N_{data} = 52)	HERAPDF20_NNLO_EIG (RTOPT)	66 [0.09]
	NNPDF31sx NNLO (FONLL-C)	106 [$1.5 \cdot 10^{-6}$]
(N_{data} = 47)	NNPDF31sx NNLO+NLLX (FONLL-C)	71 [0.013]
	HERAPDF20_NLO_FF3A (FFNS)	86 [0.002]
	ABKM09 (FFNS)	82 [0.005]
charm,	ABMP16_3_nlo (FFNS)	90 [0.0008]
this analysis	ABMP16_3_nnlo (FFNS)	109 [$6 \cdot 10^{-6}$]
	HERAPDF20_NLO_EIG (RTOPT)	99 [$9 \cdot 10^{-5}$]
(N_{data} = 52)	HERAPDF20_NNLO_EIG (RTOPT)	102 [$4 \cdot 10^{-5}$]
	NNPDF31sx NNLO (FONLL-C)	140 [$1.5 \cdot 10^{-11}$]
(N_{data} = 47)	NNPDF31sx NNLO+NLLX (FONLL-C)	114 [$5 \cdot 10^{-7}$]
	HERAPDF20_NLO_FF3A (FFNS)	33[0.20]
beauty,	ABMP16_3_nlo (FFNS)	37 [0.10]
this analysis	ABMP16_3_nnlo (FFNS)	41 [0.04]
	HERAPDF20_NLO_EIG (RTOPT)	33 [0.20]
(N_{data} = 27)	HERAPDF20_NNLO_EIG (RTOPT)	45 [0.016]

previous combined charm

new combined charm

beauty

Table 4: The χ^2, p-values and number of data points of the charm and beauty data with respect to the NLO and approximate NNLO calculations using various PDFs as described in the text. The measurements at $Q^2 = 2.5$ GeV^2 are excluded in the calculations of the χ^2 values for the NNPDF3.1sx predictions, by which the number of data points is reduced to 47, as detailed in the caption of figure 12.

QCD fit: systematic uncertainties

arXiv:1804.01019

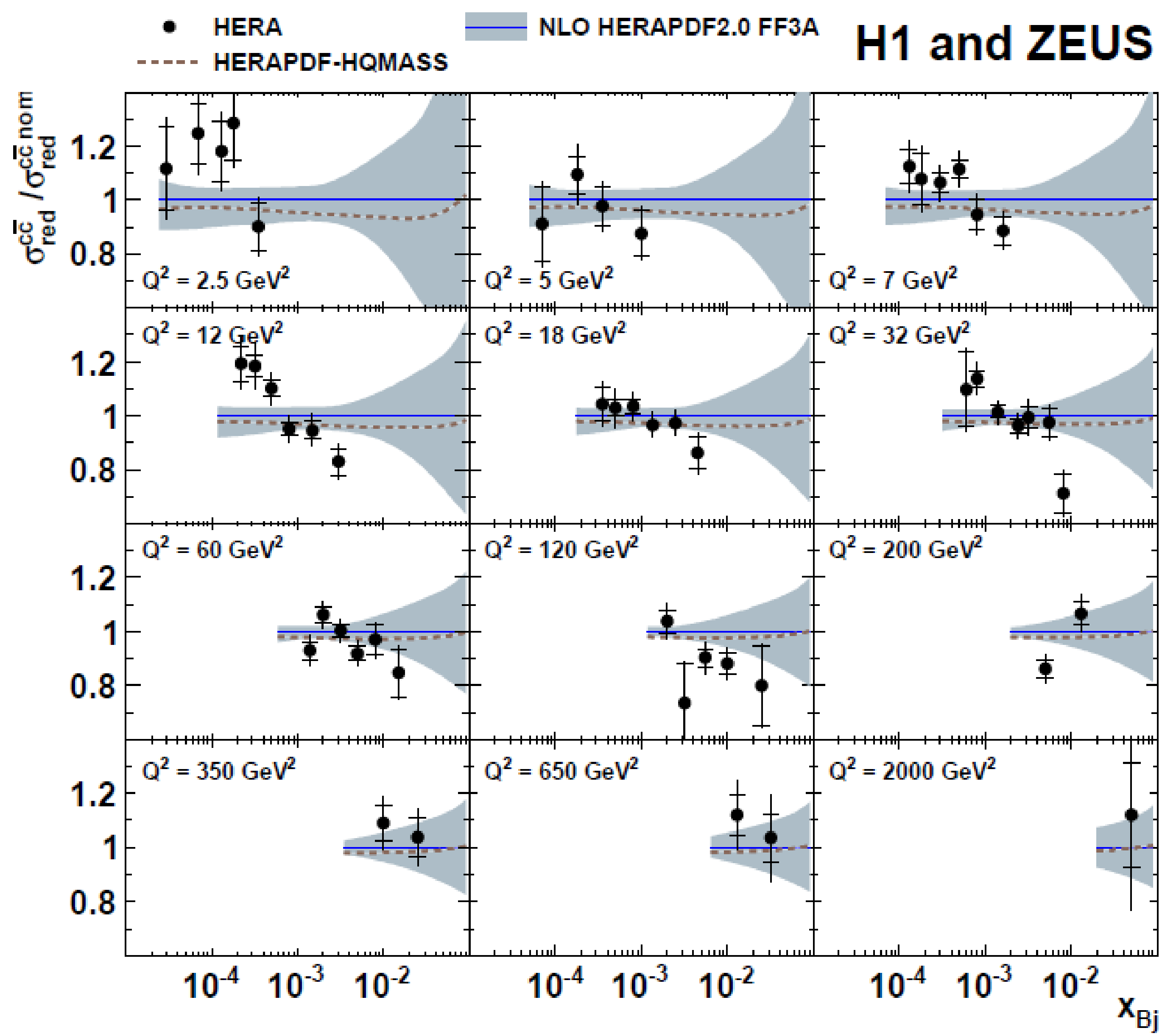
Parameter	Variation	$m_c(m_c)$ uncertainty [GeV]	$m_b(m_b)$ uncertainty [GeV]
	Experimental / Fit uncertainty		
Total	$\Delta\chi^2 = 1$	$^{+0.046}_{-0.041}$	$^{+0.104}_{-0.109}$
	Model uncertainty		
f_s	$0.4^{+0.1}_{-0.1}$	$^{-0.003}_{+0.004}$	$^{-0.001}_{+0.001}$
$Q^2_{\rm min}$	$3.5^{+1.5}_{-1.0}$ GeV^2	$^{-0.001}_{+0.007}$	$^{-0.005}_{+0.007}$
$\mu_{r,f}$	$\mu_{r,f}{}^{\times 2.0}_{\times 0.5}$	$^{+0.030}_{+0.060}$	$^{-0.032}_{+0.090}$
$\alpha_s^{n_f=3}(M_Z)$	$0.1060^{+0.0015}_{-0.0015}$	$^{-0.014}_{+0.011}$	$^{+0.002}_{-0.005}$
Total		$^{+0.062}_{-0.014}$	$^{+0.090}_{-0.032}$
	PDF parameterisation uncertainty		
$\mu^2_{f,0}$	1.9 ± 0.3 GeV^2	$^{+0.003}_{-0.001}$	$^{-0.001}_{+0.001}$
E_{u_v}	set to 0	-0.031	-0.031
Total		$^{+0.003}_{-0.031}$	$^{+0.001}_{-0.031}$

Table 5: List of uncertainties for the charm- and beauty-quark mass determination. The PDF parameterisation uncertainties not shown have no effect on $m_c(m_c)$ and $m_b(m_b)$.

QCD fit: charm

arXiv:1804.01019

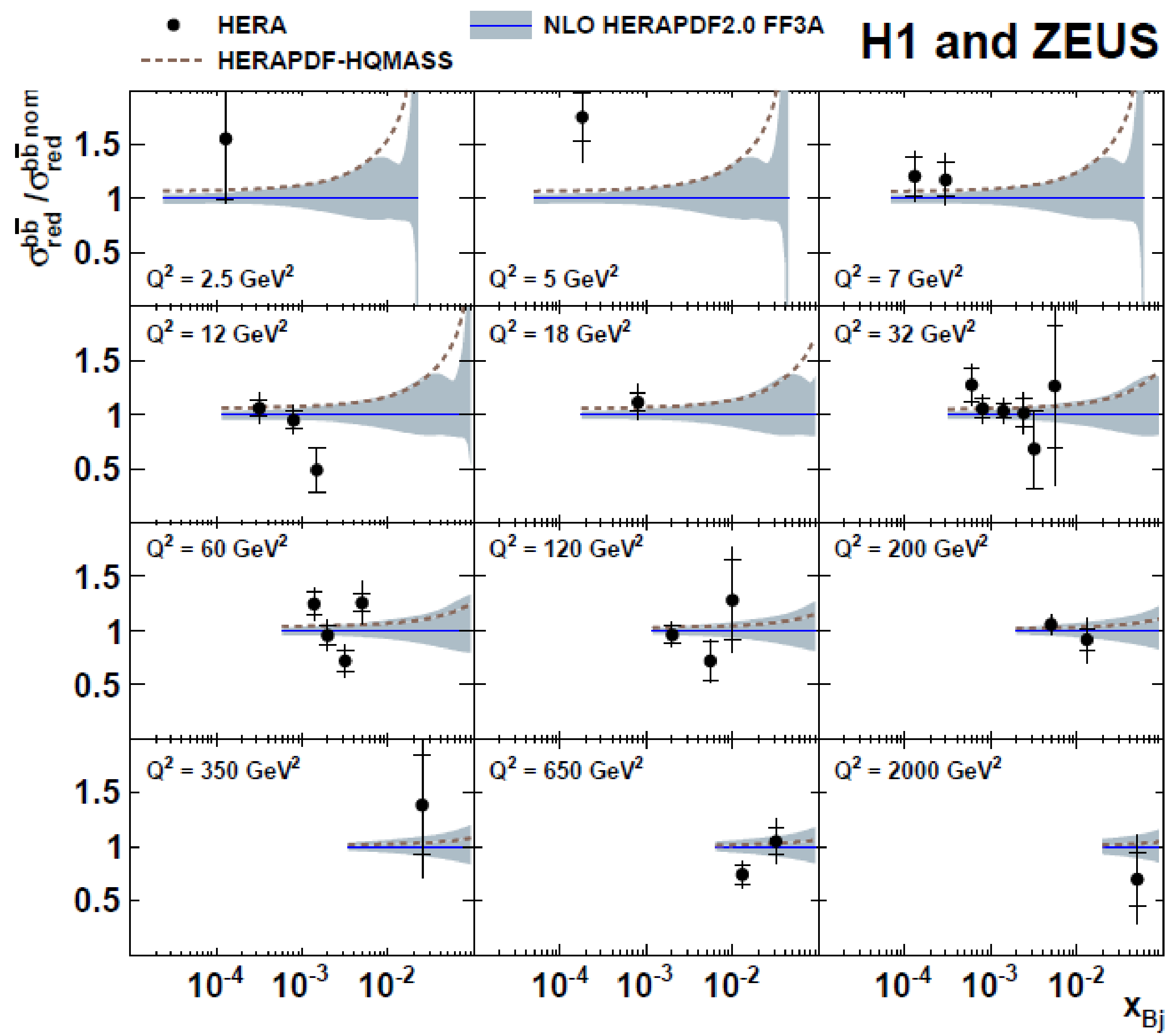
fully consistent with HERAPDF2.0FF3A



QCD fit: beauty

arXiv:1804.01019

fully consistent with HERAPDF2.0FF3A

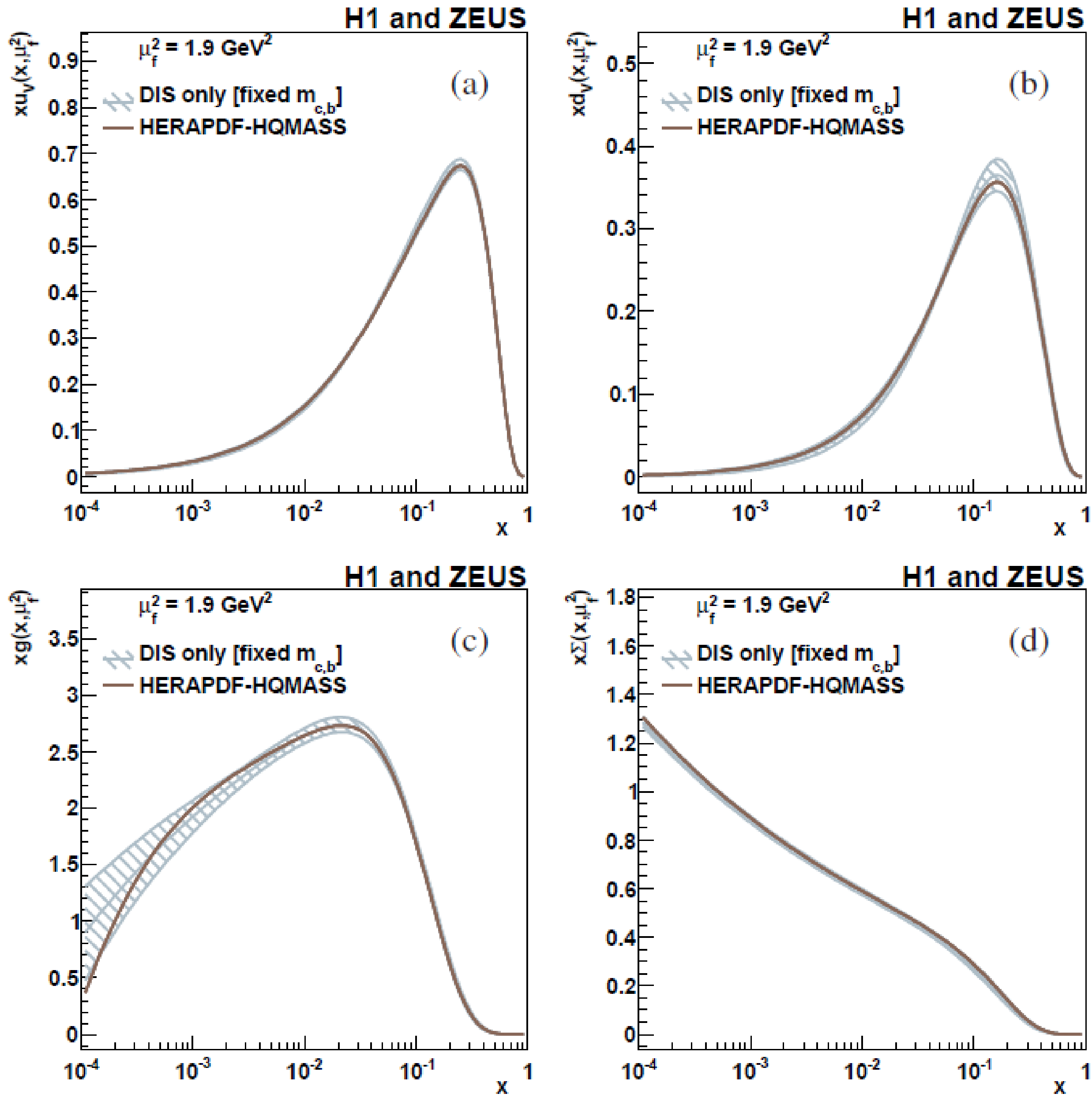


QCD fit: inclusive data subset

arXiv:1804.01019

PDFs consistent with those of inclusive data only
(and c, b masses fixed to PDG)

-> **inclusive data**
(and c,b mass values)
dominate in fixing PDF



QCD fit: inclusive data, parametrisation uncert.

Reminder, **full fit**: $\Delta\chi^2=1$ scale dom 14p->15p,13p

- **$m_c(m_c)$ = 1290 $^{+46}_{-41}$(exp/fit) $^{+62}_{-14}$(mod) $^{+3}_{-31}$(par) MeV**
- **$m_b(m_b)$ = 4049 $^{+104}_{-109}$(exp/fit) $^{+90}_{-32}$(mod) $^{+1}_{-31}$(par) MeV**

Using **inclusive HERA data only** (14p)**:**

- $m_c(m_c)$ = 1798 $^{+144}_{-134}$ (exp/fit) MeV
- $m_b(m_b)$ = 8450 $^{+2280}_{-1810}$(fit) MeV

no full uncertainty evaluation, but large sensitivity to **PDF parametrisation** (-> 13p):

- $m_c(m_c)$ = 1798 -> 1450 MeV,
- $m_b(m_b)$ = 8450 -> 3995 MeV

dominant effect:

$$xg(x) = A_g x^{B_g}(1-x)^{C_g} - A'_g x^{B'_g}(1-x)^{C'_g}$$
$$xu_v(x) = A_{u_v} x^{B_{u_v}}(1-x)^{C_{u_v}}(1+E_{u_v}x^2)$$
$$xd_v(x) = A_{d_v} x^{B_{d_v}}(1-x)^{C_{d_v}}$$
$$x\bar{U}(x) = A_{\bar{U}} x^{B_{\bar{U}}}(1-x)^{C_{\bar{U}}}(1+D_{\bar{U}}x)$$
$$x\bar{D}(x) = A_{\bar{D}} x^{B_{\bar{D}}}(1-x)^{C_{\bar{D}}}$$

13p: $E_{u_v} = 0$

-> inclusive HERA data alone cannot constrain HQ masses reliably

-> interplay of PDFs and HQ masses needs careful treatment

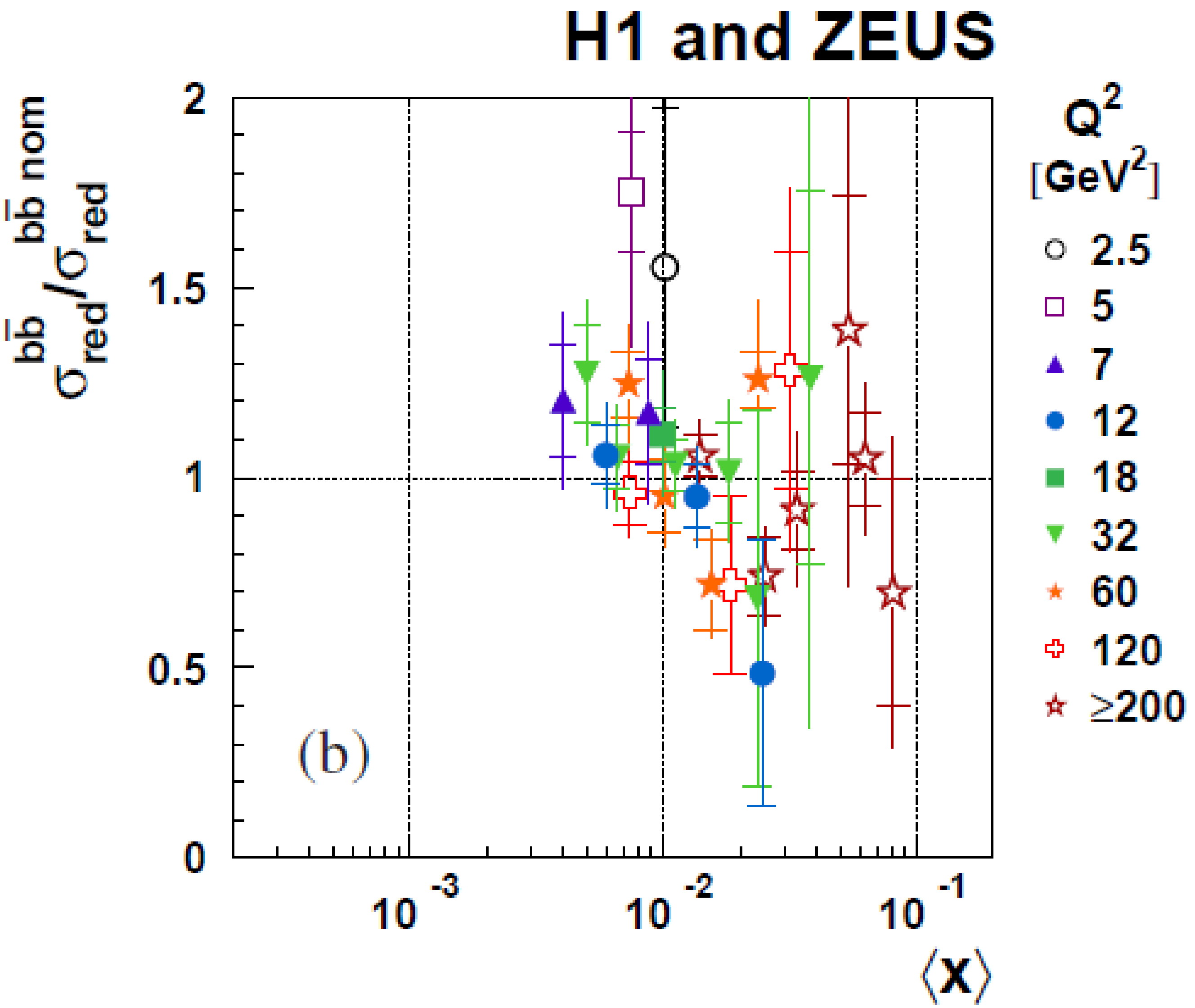
QCD fit: beauty x slope

arXiv:1804.01019

plot data/fit
vs. <x> of
incoming partons
(rather than x_{Bj})
for each data point

LO: $x = x_{\mathrm{Bj}} \cdot \left(1 + \frac{\hat{s}}{Q^2}\right)$

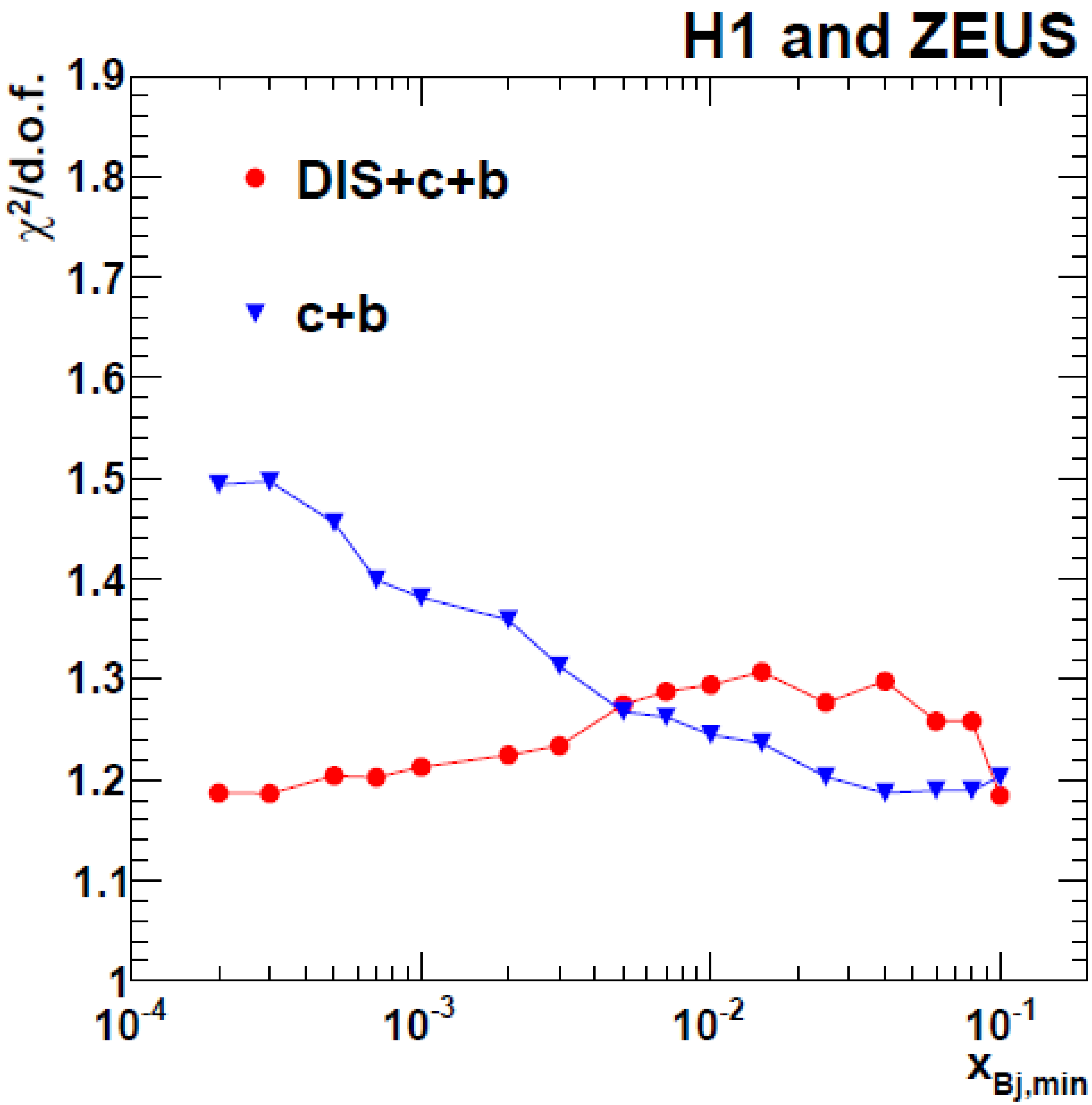
<x> calculated at NLO
using HVQDIS



-> beauty consistent with charm but does not add information

χ^2 as function of min. x_{Bj} cut

arXiv:1804.01019



Comparison of HERAPDF with FONLL-C + NLLx

for inclusive data only

from
arXiv:1802.00064 :

	Step-1	Step-2	Step-3	Step-4
	HERAPDF2.0 NNLO	FONLL-C	Move Q_0^2 and charm threshold	include NLLx resummation
HERA χ^2/d.o.f	1363/1131	1387/1131	1389/1131	1316/1131

Table 1 The χ^2 per degree of freedom (d.o.f.) for the PDF fits under different conditions, starting from the settings for the HERAPDF2.0 NNLO.

from
arXiv:1506.06042:

HERAPDF	Q^2_{min}[GeV^2]	χ^2	d.o.f.	χ^2/d.o.f
2.0 NLO	3.5	1357	1131	1.200
2.0HiQ2 NLO	10.0	1156	1002	1.154
2.0 NNLO	3.5	1363	1131	1.205
2.0HiQ2 NNLO	10.0	1146	1002	1.144
2.0 AG NLO	3.5	1359	1132	1.201
2.0HiQ2 AG NLO	10.0	1161	1003	1.158
2.0 AG NNLO	3.5	1385	1132	1.223
2.0HiQ2 AG NNLO	10.0	1175	1003	1.171
2.0 NLO FF3A	3.5	1351	1131	1.195
2.0 NLO FF3B	3.5	1315	1131	1.163
2.0Jets $\alpha_s(M_Z^2)$ fixed	3.5	1568	1340	1.170
2.0Jets $\alpha_s(M_Z^2)$ free	3.5	1568	1339	1.171

Table 4: The values of χ^2 per degree of freedom for HERAPDF2.0 and its variants.

inclusion of NLLx resummation with FONLL-C achieves similar performance as HERAPDF2.0 FF3B