# Lessons from heavy flavour production at HERA


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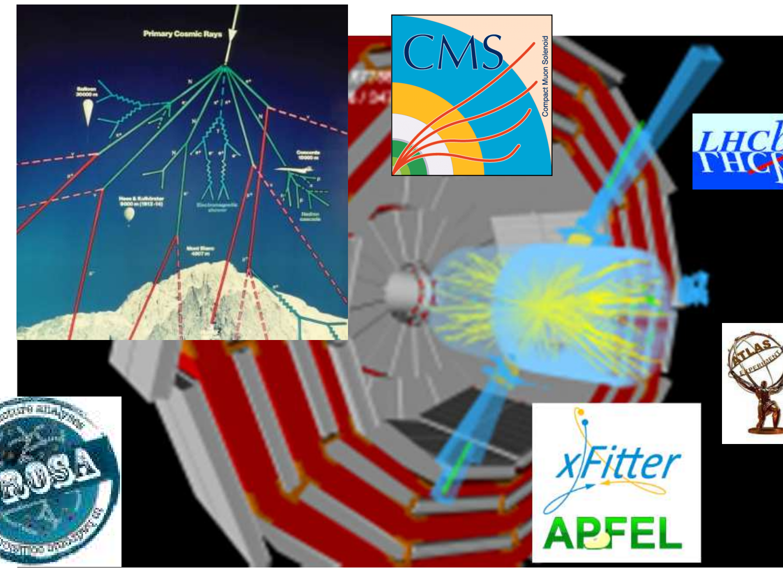
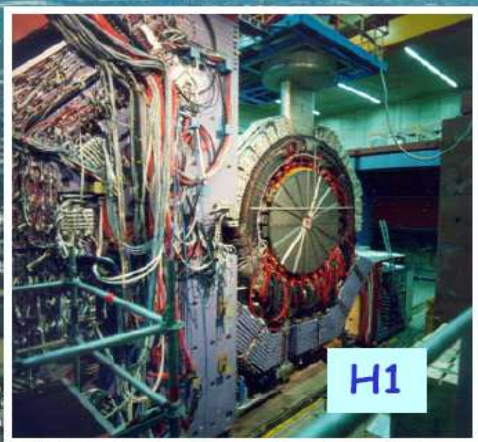
(member of the
ZEUS, CMS and PROSA
collaborations)

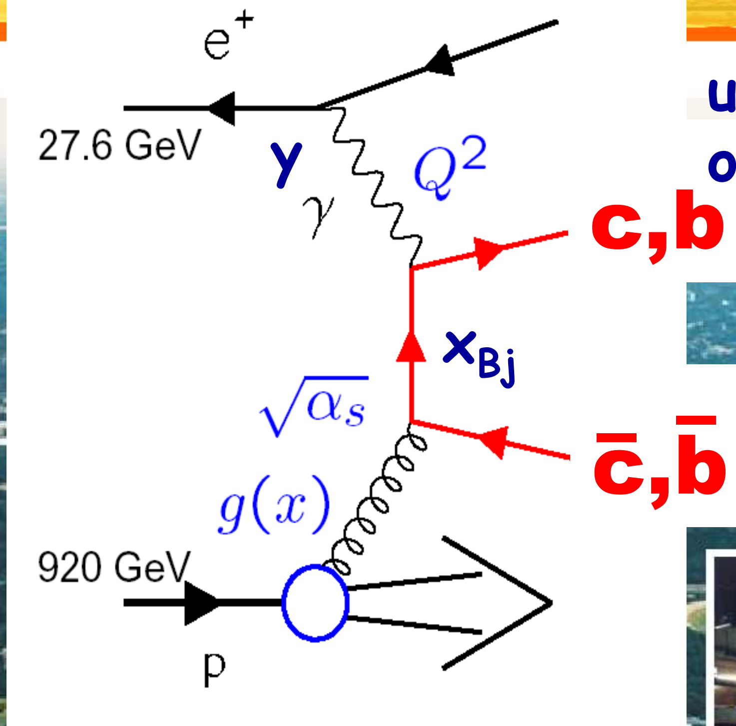


**Workshop on Opportunities with Heavy Flavour at the EIC, online, 4. 11. 2020**

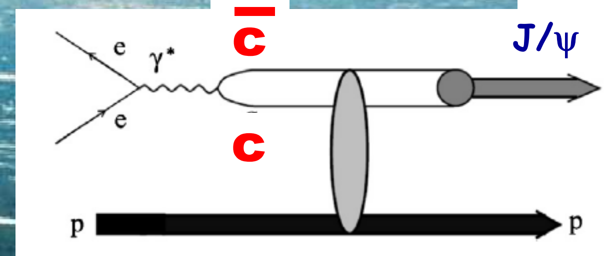
- Introduction, relation to EIC, HERA data preservation + Lessons
- HERA Heavy Flavour review + Lessons
- Recent HERA Heavy Flavour results + Lessons
- Conclusions and outlook

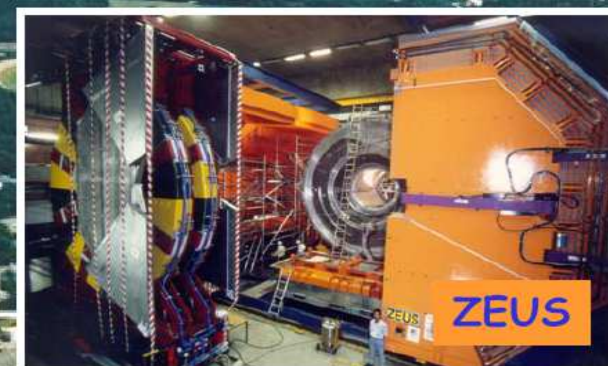
# The HERA ep collider and experiments




**up to 30% of cross section**




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

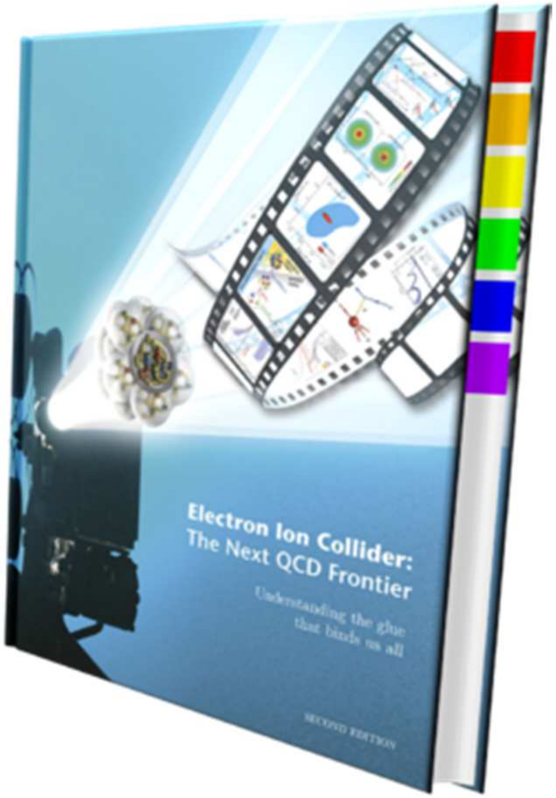
**HERA II: ~ 380 pb$^{-1}$(physics)**

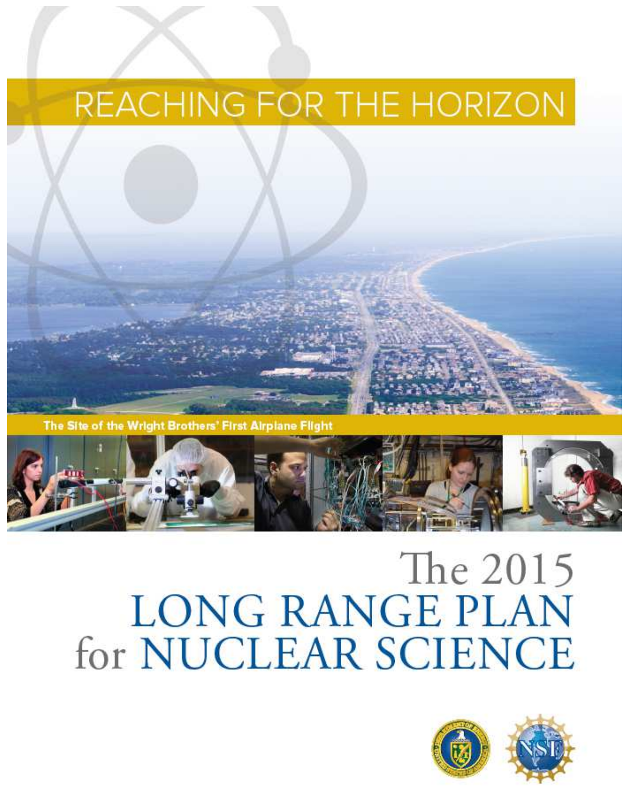
**combined: ~ 2 x 0.5 fb$^{-1}$**

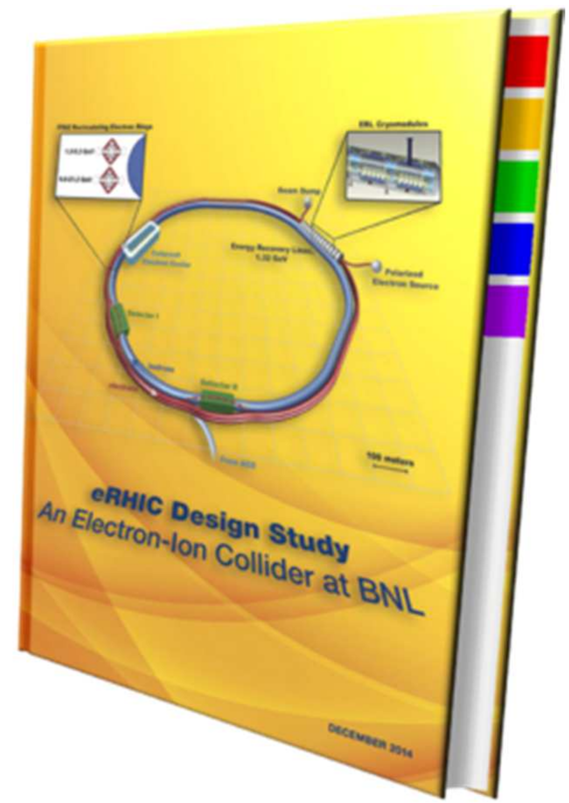
HERA:

# Synergy with future experiments: EIC

- many EIC topics common with HERA



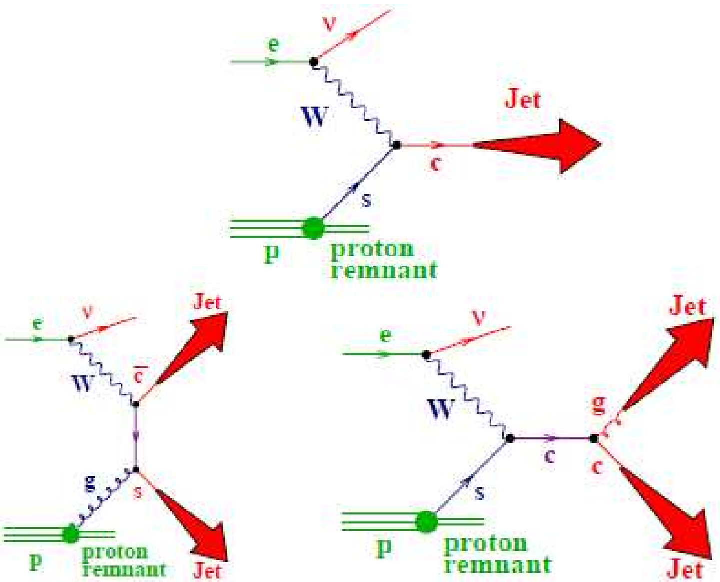

- some EIC members have recently joined ZEUS or H1 to work on common analysis topics with real ZEUS or H1 data, more welcome!

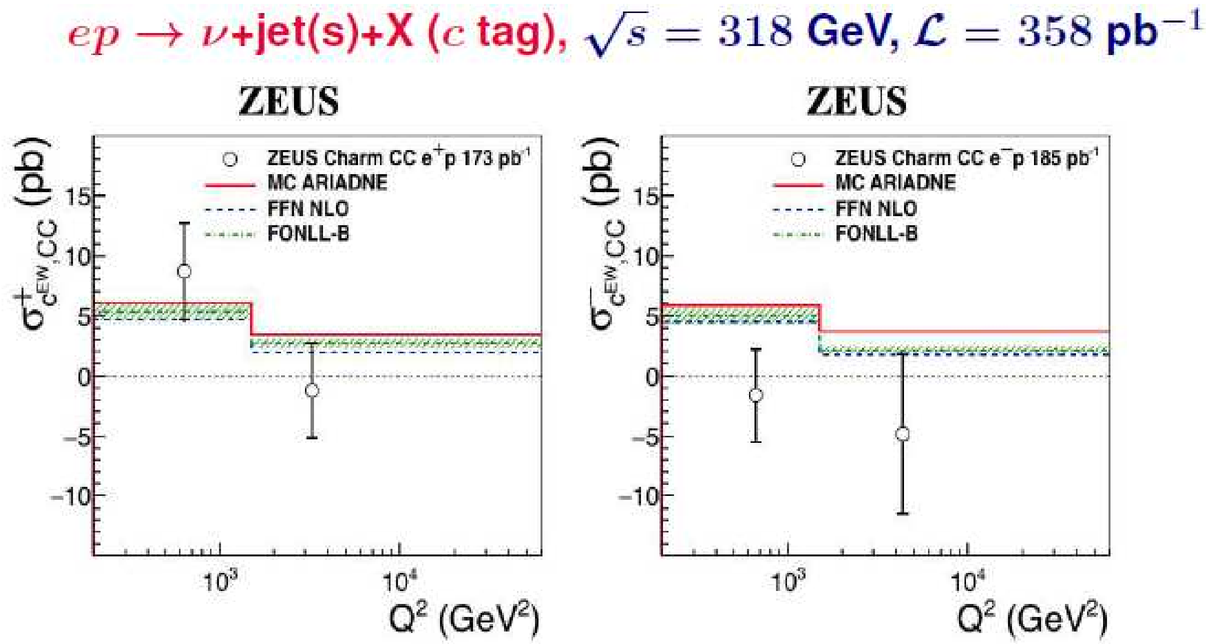
# Charm in ep Charged Current reactions

*JHEP* 05 (2019) 201, arXiv:1904.03261

First ever collider measurement, large uncertainties

**PhD project of J. Nam, temple university**




- **Visible cross section:**

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

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

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

**-> see next presentation (S. Sekula)**

# Lesson: HERA relevance for EIC

- Many of the HERA heavy flavour physics topics remain relevant, in particular in the context of EIC
- The full HERA data remain available for analysis (in simplified format for ZEUS, in original format for H1)
- Many important physics topics which can be addressed with the existing HERA data have not yet been addressed, due to lack of person power; a publishable result can be produced (e.g. in ZEUS) by a master student or a part-time PhD student within ~ a year

->

Additional person power from the EIC community is most welcome

# How to get access to the HERA data

**ZEUS:** (common ntuples, flat root ntuples, only software needed: plain root, almost any version); both HERA I and HERA II data

contact Matthew.Wing@desy.de (ZEUS spokesperson) (or me)

- either access for specific single project/paper for common publication, or
- become full ZEUS member (no fees/chores beyond working on the physics) and participate in all papers

**H1:** (dedicated OO framework)

contact Stefan.Schmitt@desy.de (H1 spokesperson)

to become H1 member (no fees fees/chores beyond working on the physics)

**HERMES:** contact Gunar.Schnell@desy.de (HERMES spokesperson)

for more details, see also
https://indico.bnl.gov/event/9287/contributions/41457/attachments/30600/48033/EIC_2020.pdf

# Review of open charm & beauty 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

Contents lists available at ScienceDirect

Progress in Particle and Nuclear Physics

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

ELSEVIER

Review

## Charm, beauty and top at HERA

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CrossMark

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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)

# Example:
# all charm photoproduction cross section measurements

| No. | Analysis | c-Tag | Ref. | Exp. | Data | $\mathcal{L}$ [$pb^{-1}$] | $Q^2$ [$GeV^2$] | $y$ | Particle | $p_T$ [GeV] | $\eta$ | Events | effect. s:b | bgfree events |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | $D^*$ incl. | $K\pi\pi_s$ | [166] | ZEUS | 93 | 0.5 | $< 4$ | [0.15, 0.84] | $D^*$ | $> 1.7$ | [−1.5, 1.5] | $48 \pm 11$ | 1 : 1.5 | 19 |
| 2 | $D^*$ tagged incl. | $K\pi\pi_s$ | [167] | H1 | 94 | 2.8 | $< 0.01$ | [0.28, 0.65] | $D^*$ | $> 2.5$ | [−1.5, 1.0] | $119 \pm 16$ | 1 : 1.2 | 55 |
| | | | | | | 1.3 | $< 4$ | [0.10, 0.80] | | | | $97 \pm 15$ | 1 : 1.3 | 42 |
| 3 | $D^*$ incl. | $K\pi\pi_s$ | [168] | ZEUS | 94 | 3.0 | $< 4$ | [0.15, 0.87] | $D^*$ | $> 3$ | [−1.5, 1.0] | $152 \pm 16$ | 1 : 0.7 | 90 |
| | | $K3\pi\pi_s$ | | | | | | | | | | $199 \pm 29$ | 1 : 3.2 | 17 |
| 4 | $D^*$ tagged | $K\pi\pi_s$ | [169] | H1 | 95-96 | 10.2 | $< 0.009$ | [0.02, 0.32] | $D^*$ | $> 2$ | [−1.5, 1.5] | $299 \pm 75$ | n.a. | 16 |
| | | | | | 94-96 | 10.7 | $< 0.01$ | [0.29, 0.62] | | $> 2.5$ | $(\hat{y}(D^*))$ | $489 \pm 92$ | n.a. | 28 |
| 5 | $D^*$ incl. | $K\pi\pi_s$ | [170] | ZEUS | 96-97 | 37 | $< 1$ | [0.19, 0.87] | $D^*$ | $> 2$ | [−1.5, 1.5] | $3702 \pm 136$ | 1 : 4.0 | 741 |
| | | $K3\pi\pi_s$ | | | | | | | | $> 4$ | | $1397 \pm 108$ | 1 : 7.3 | 167 |
| | $D^*$ + dijet | $K\pi\pi_s$ | | | | | | | $D^*$ Jet1(2) | $> 3$ $> 7(6)$ | [−1.5, 1.5] [−2.4, 2.4] | $587 \pm 41$ | 1 : 1.9 | 205 |
| 6 | $D^*$ incl. | $K\pi\pi_s$ | [171] | ZEUS | 98-00 | 79 | $< 1$ | [0.17, 0.77] | $D^*$ | [1.9, 20] | [−1.6, 1.6] | $10350 \pm 190$ | 1 : 2.5 | 2970 |
| 7 | $D^*$ tagged +jet +dijet | $K\pi\pi_s$ | [172] | H1 | 99-00 | 51 | $< 0.01$ | [0.29, 0.65] | $D^*$ | $> 2$ | [−1.5, 1.5] | $1166 \pm 82$ | 1 : 4.8 | 202 |
| | | | | | | | | | Jet | $> 3$ | [−1.5, 1.5] | $592 \pm 57$ | 1 : 4.5 | 108 |
| | | | | | | | | | Jet 1(2) | $> 4(3)$ | [−1.5, 1.5] | $496 \pm 53$ | 1 : 4.7 | 88 |
| 8 | $D^*$ + dijet | $K\pi\pi_s$ | [173] | ZEUS | 96-00 | 120 | $< 1$ | [0.17, 0.77] | $D^*$ Jet1(2) | $> 3$ $> 7(6)$ | [−1.5, 1.5] [−1.9, 1.9] | $1092 \pm 43$ | 1 : 0.7 | 650 |
| 9 | $D^*$ + jet + dijet | $K\pi\pi_s$ | [174] | ZEUS | 98-00 | 79 | $< 1$ | [0.17, 0.77] | $D^*$ | $> 3$ | [−1.5, 1.5] | $4891 \pm 113$ | 1 : 1.6 | 1870 |
| | | | | | | | | | Jet1(2) | $> 6(7)$ | [−1.5, 2.4] | $1692 \pm 70$ | 1 : 1.6 | 584 |
| 10 | lifet.+dijet | imp.par. | [141] | H1 | 99-00 | 57 | $< 1$ | [0.15, 0.80] | Track Jet1(2) | $> 0.5$ $> 11(8)$ | [−1.3, 1.3] [−0.9, 1.3] | $4600 \pm 460$ | 1 : 45 | 100 |
| 11 | $D^*$ + $\mu$ | $K\pi\pi_s$ + $\mu$ | [175] | H1 | 98-00 | 89 | $< 1$ | [0.05, 0.75] | $D^*$ $\mu$ | $> 1.5$ $p > 2$ | [−1.5, 1.5] [−1.74, 1.74] | $53 \pm 13$ | 1 : 2.2 | 17 |
| 12 | $e$ + dijet | $e + \not{E}_T$ | [176] | ZEUS | 96-00 | 120 | $< 1$ | [0.2, 0.8] | $e$ Jet1(2) | $> 0.9$ $> 7(6)$ | [−1.5, 1.5] [−2.5, 2.5] | $\sim 8000$ | n.a. | 70 |
| 13 | lifet.+dijet | sec. vtx. | [177] | ZEUS | 05 | 133 | $< 1$ | [0.2, 0.8] | tracks Jet1(2) | $> 0.5$ $> 7(6)$ | [−1.6, 1.4] [−2.5, 2.5] | $\sim 20000$ | n.a. | 2320 |
| 14 | $\mu$ + dijet | $\mu$ + imp.par. | [178] | H1 | 06-07 | 179 | $< 2.5$ | [0.2, 0.8] | $\mu$ Jet1(2) | $> 2.5$ $> 7(6)$ | [−1.3, 1.5] [−1.5, 2.5] | $3315 \pm 170$ | 1 : 7.7 | 380 |
| 15 | $D^*$ incl +dijet | $K\pi\pi_s$ | [179] | H1 | 06-07 | 31 − 93 | $< 2$ | [0.1, 0.8] | $D^*$ | $> 1.8$ | [−1.5, 1.5] | $8232 \pm 164$ | 1 : 2.3 | 2520 |
| | | | | | | | | | Jet1(2) | $> 3.5$ | [−1.5, 2.9] | $3937 \pm 114$ | 1 : 2.3 | [illegible] |
| 16 | $D^*$ incl | $K\pi\pi_s$ | [180] | ZEUS | 06-07 | 144 | $< 1$ | [0.167, 0.802] | $D^*$ | [1.9, 20] | [−1.6, 1.6] | $12256 \pm 191$ | 1 : 2.0 | 4120 |
| | MER | | | | 07 | 6.3 | | | | | | $417 \pm 37$ | 1 : 2.3 | 127 |
| | LER | | | | 07 | 13.4 | | | | | | $859 \pm 49$ | 1 : 1.8 | 307 |

**similar for DIS**

**-> "work horse": D*   (and lifetime-tagged jets)**

# Lesson: Tracking

- Tracking is crucial for the reconstruction of charm and beauty final states
- The D* is the `workhorse', *if* you can reconstruct the `slow pion' from $D^* \rightarrow D^0\pi$ decay (complements secondary vertex/impact parameter reconstruction)
- Most of the charm cross section is forward and/or at low $p_T$ (beauty more central)
- Statistics is the limitation for beauty studies

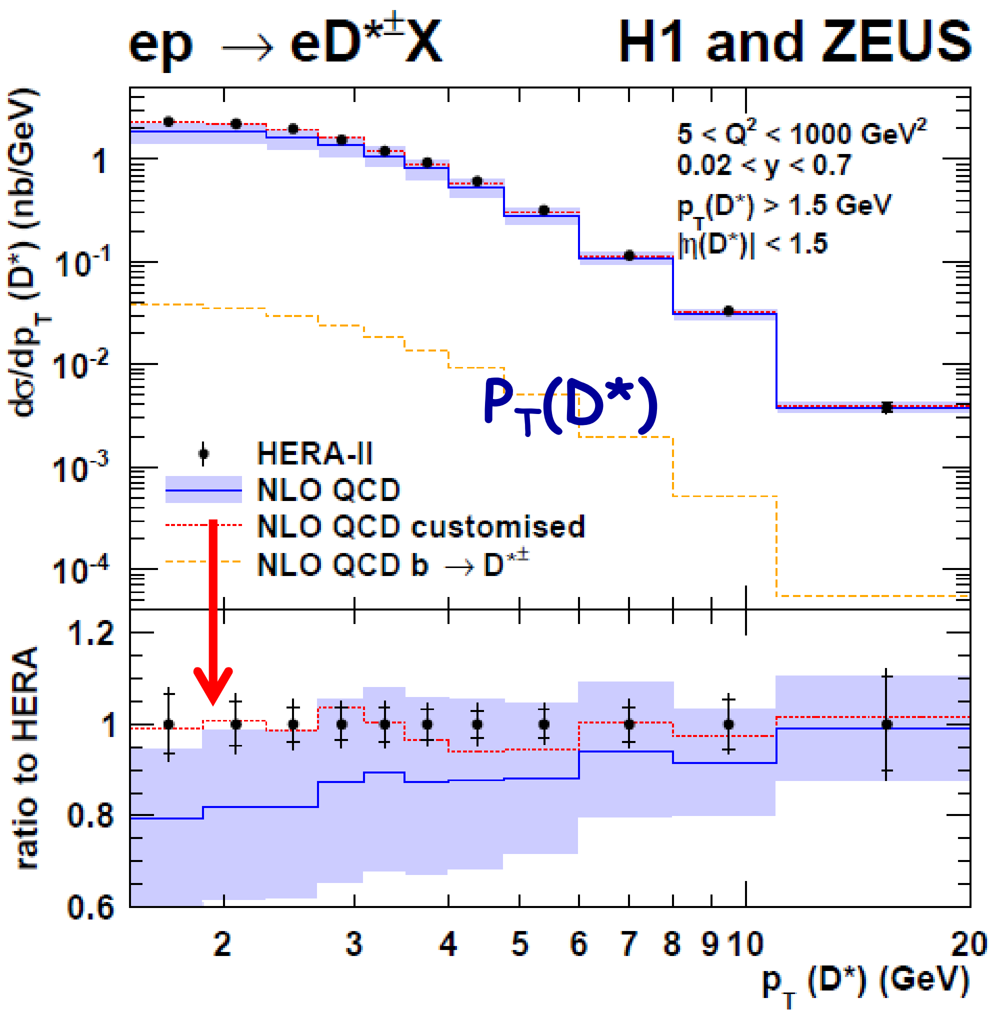
->

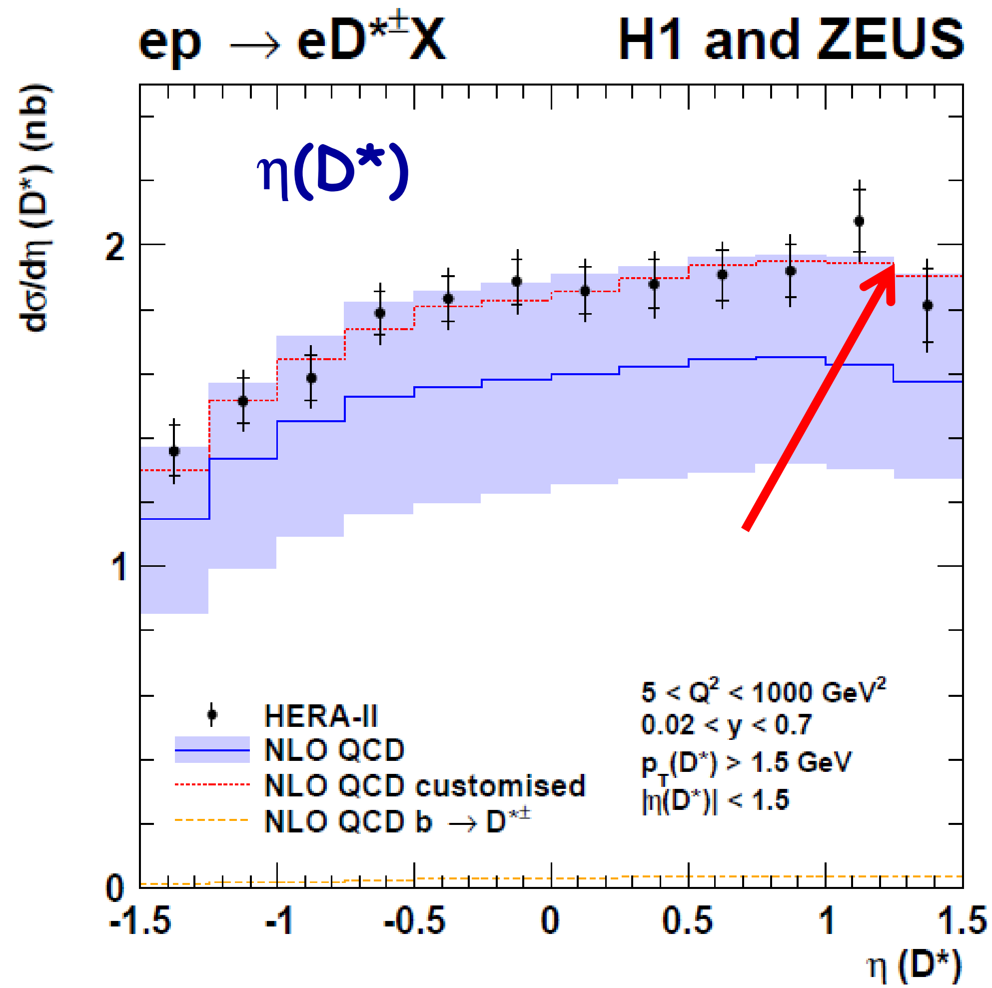
Forsee widest possible fiducial coverage for tracking, as much forward as you can, and down to 50 MeV pions, on largest possible statistics

-> compare detector session on Friday

# 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)

# Lesson: Phenomenological calculations

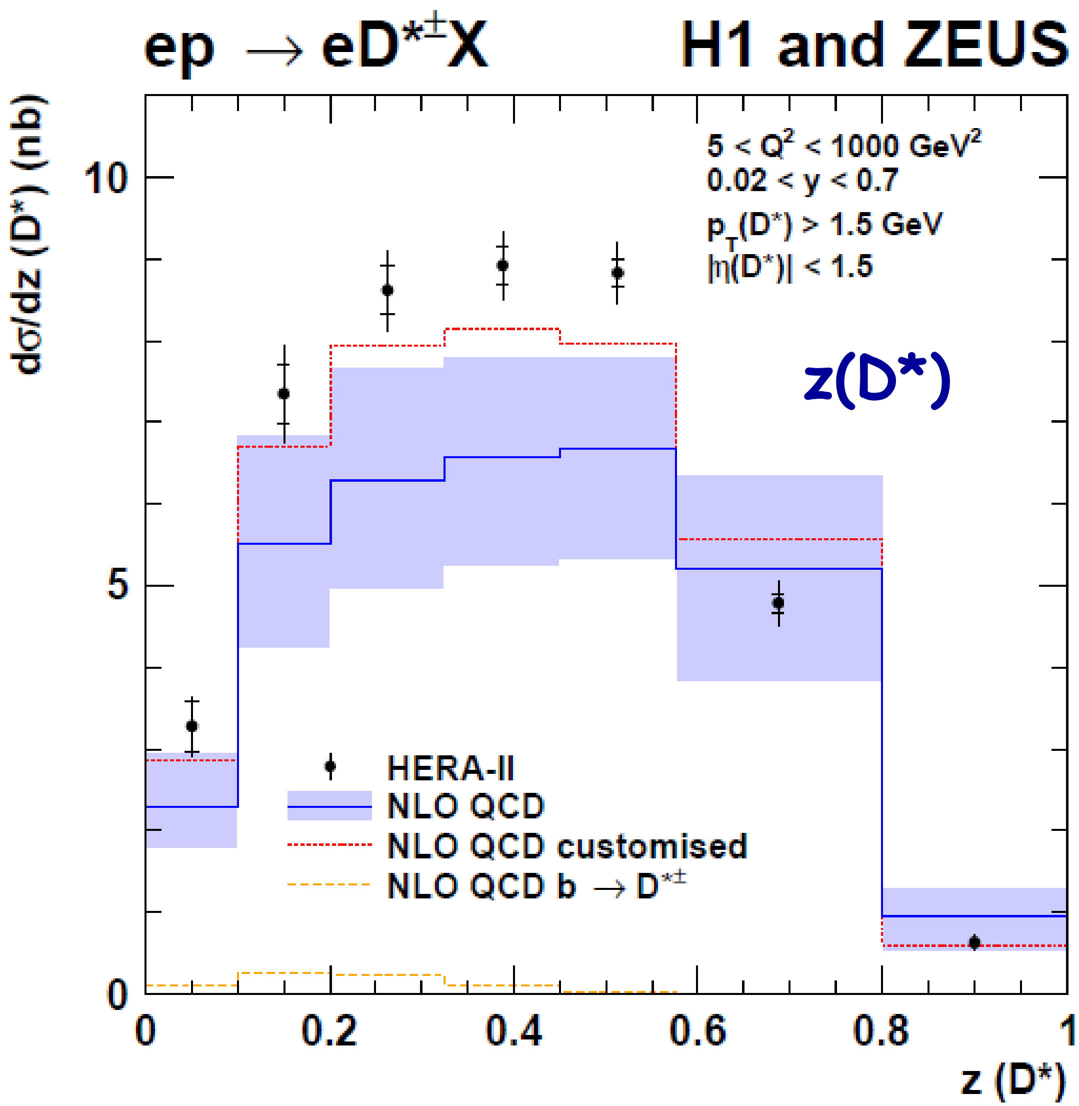
- **Phenomenological QCD (+EW) theory calculations are essential, but not entirely trivial.**
- **Only few theorists are currently active e.g. in differential NNLO predictions for heavy flavours in ep/gamma p/eN/gamma N collisions,**
  (ep total see talk S. Moch, pp differential see talk A. Mitov, PDF talks see P. Nadolsky, J. Rojo, V. Guzey)
  **or in NLO+NLL PS MC predictions for such processes**
  (with the exception of those present at this workshop, of course ☺)

**->**

**Encourage your theory collegues to get involved in such calculations, both for photoproduction and DIS, and both for proton and nuclear collisions, well before EIC starts.**

# Charm fragmentation function

arXiv:1503.06042, JHEP 1509 (2015) 149



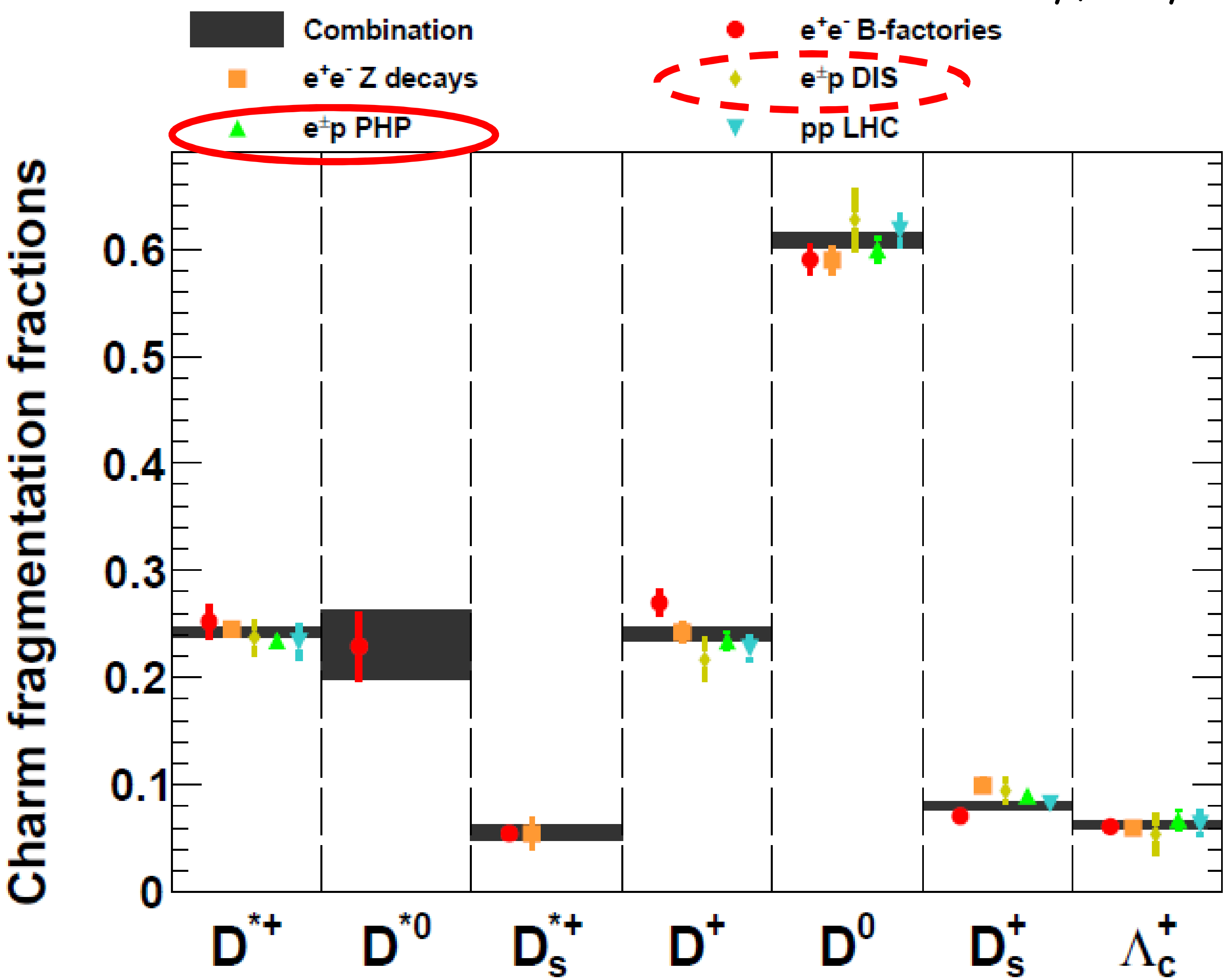

**Combination of H1 and ZEUS D* measurements**

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

more work on theory needed

# Charm fragmentation fractions

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




universality confirmed

HERA measurements make very substantial contribution to world average

# Lesson: Fragmentation

- ep collisions are a great environment to study heavy flavour fragmentation fractions and functions
- lately nonuniversality found at LHC for in both pp and heavy ion collisions, in particular for baryons (need proton particle id)

  see also talk I. Schienbein tomorrow
- restudy in ep: need to access lowest possible $p_T$ and highest possible rapidities

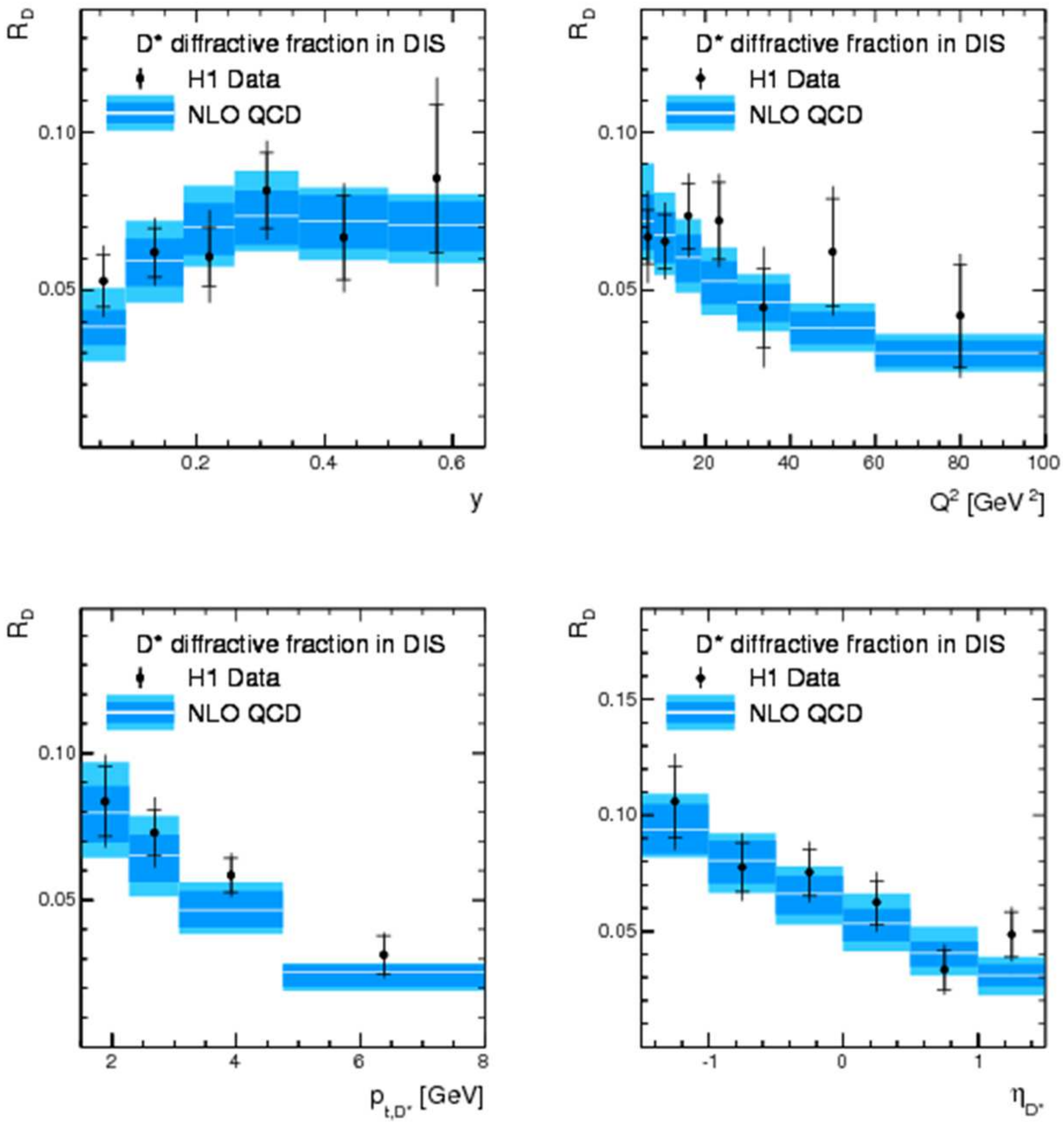
->

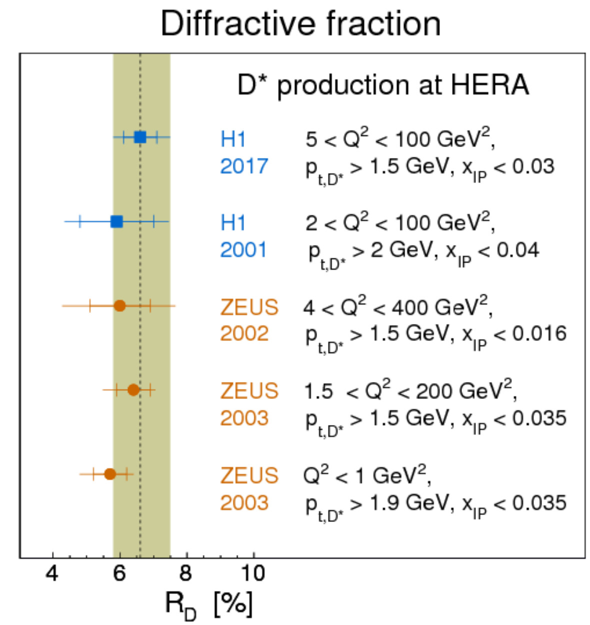
Forsee widest possible fiducial coverage for heavy flavour reconstruction, with particle id

see also detector session on Friday

# Diffractive D* production in DIS

*Eur.Phys.J.C 77 (2017) 5, 340, arXiv:1703.09476*




diffractive fraction in DIS well described using diffractive PDF (from DIS data)

(H1/ZEUS discussion about diffractive charm in PhP remains open)

# Lesson: Heavy flavours in Diffraction

- Diffractive production of heavy flavours remains a hot topic, in particular for photoproduction
  (corresponding HERA II data not yet analyzed)
- Universality of diffractive PDF is known to be badly broken when going to pp ("gap survival factor")
- Comparison with ultra-peripheral Pb p (i.e. gamma p) collisions at LHC would be possible and desirable

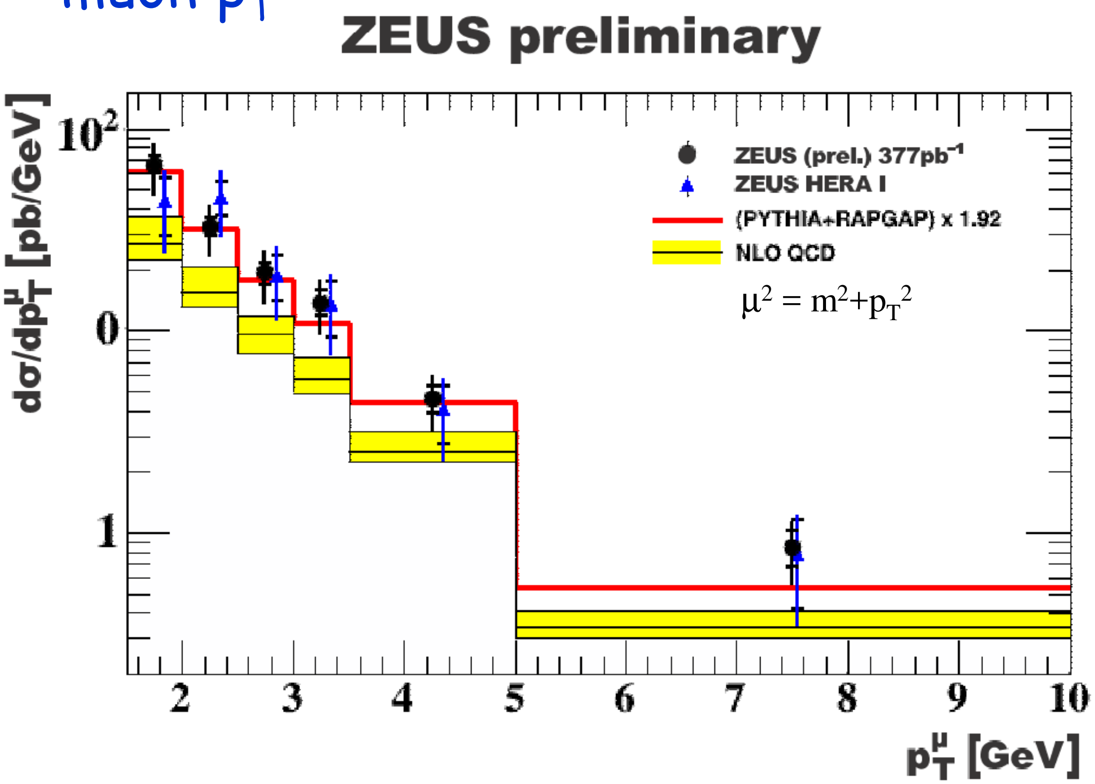
->

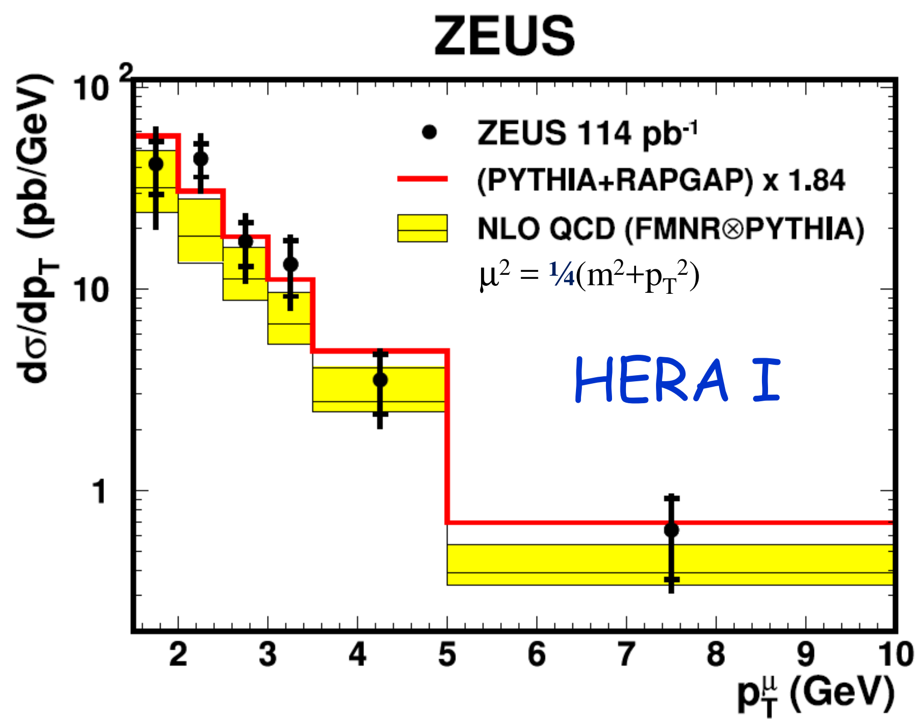
Encourage your experimental collegues to get involved in such measurements (with HERA or LHC data, later with EIC)

# Differential cross sections bb->μμ+X

ZEUS-prel-18-006

muon $p_T$




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)

# 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

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

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

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

**NLO QCD predictions (same as HERA I paper):**

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

**FMNR+HVQDIS** $7.5\ ^{+4.5}_{-2.1}$ nb

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

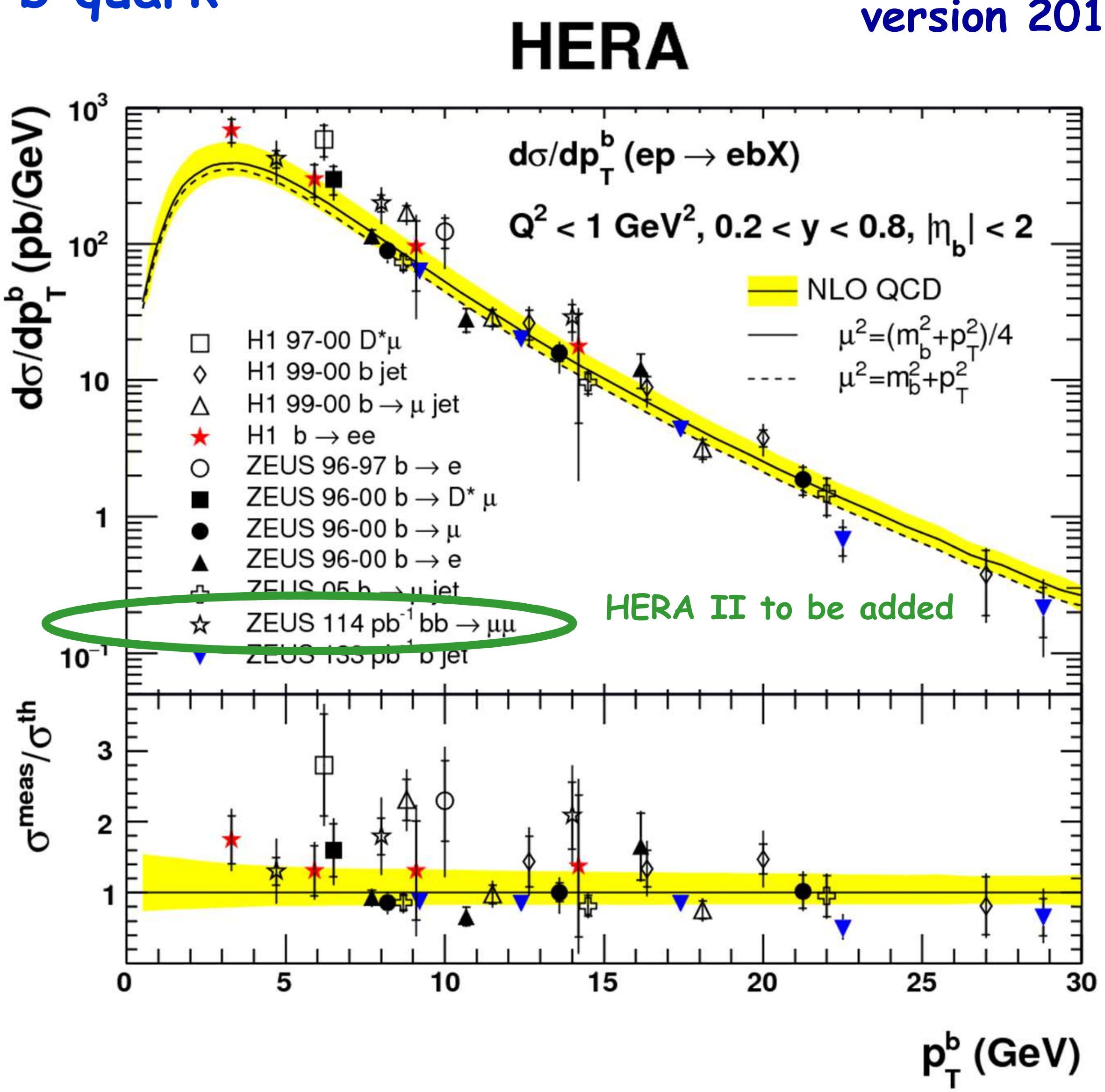
any chance to get NNLO prediction?

(exists for pp and (almost) for DIS)

# Beauty in photoproduction: summary

b quark

version 2012




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

# Lesson: beauty

- Total as well as differential beauty cross sections fully experimentally accessible
- Limited by statistics (b cross section 1 order of magnitude smaller than charm)
- Limited by non-availability of NNLO QCD corrections

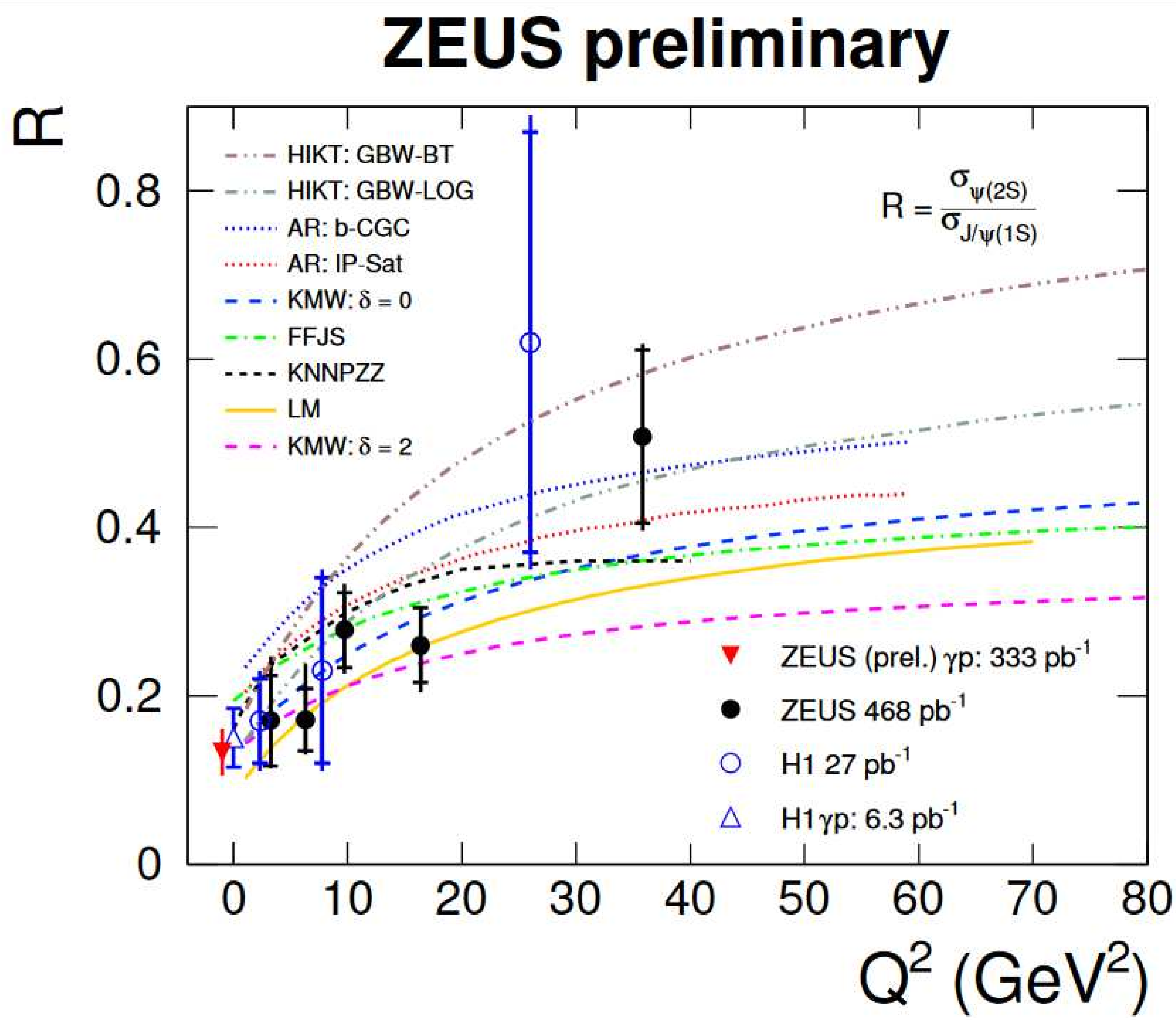
->

Collect maximum statistics, improve theory.

# Measurement of the cross-section ratio $\sigma_{\psi(2S)}/\sigma_{J/\psi(1S)}$

arXiv:1605.01946, Nucl. Phys. B909 (2016) 934

+ ZEUS-prel-18-003




results start to discriminate between different theory predictions

# Lesson: J/psi production

- J/psi production is a great tool to study many aspects of QCD

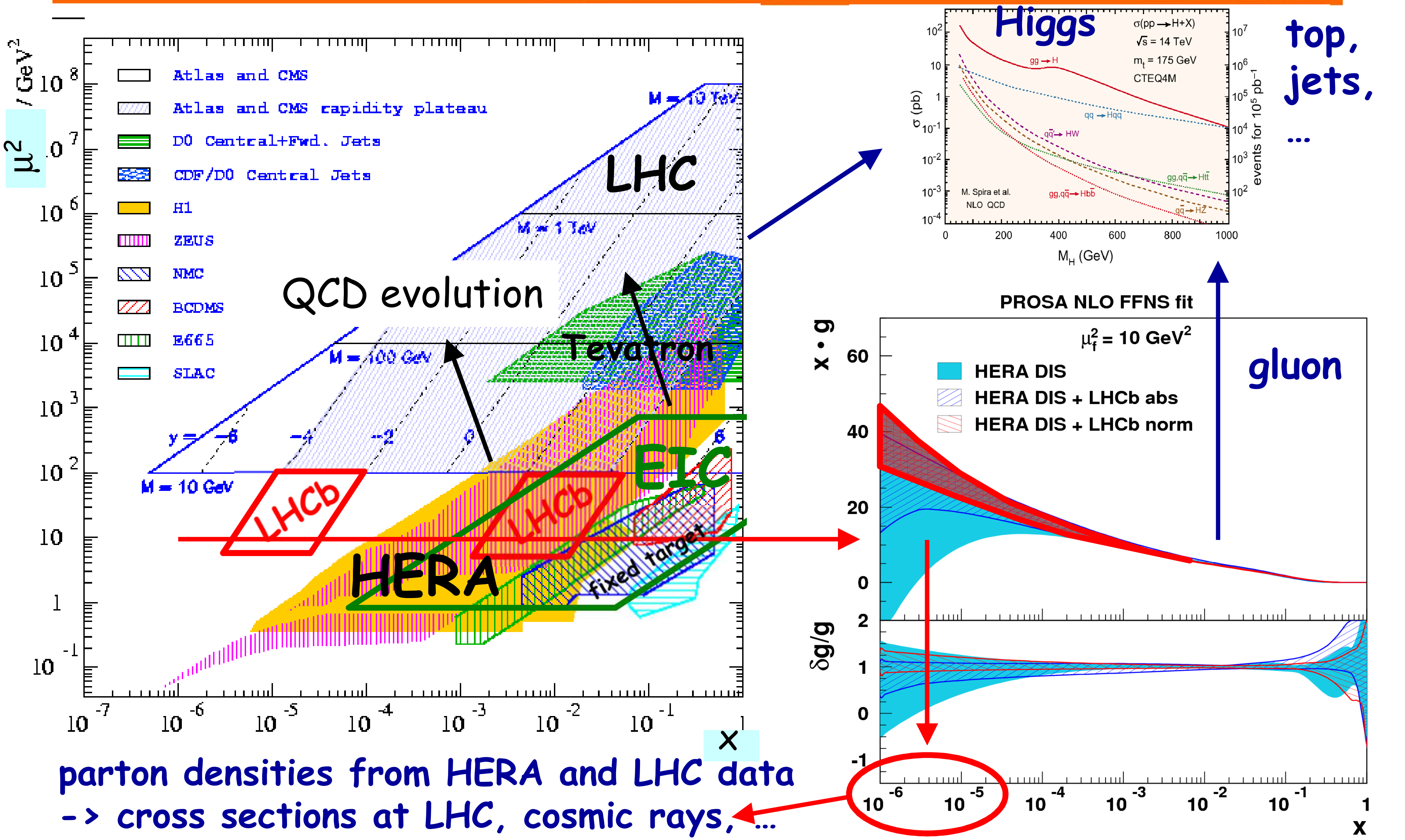
see also talk Y. Makris tomorrow

->

For full fiducial coverage, need muon reconstruction down to ~1-1.5 GeV

(HERA: $p_T$ > 1.5 GeV for nonisolated muons,
p > 1 GeV for isolated muons)

# Parton density functions (PDF)

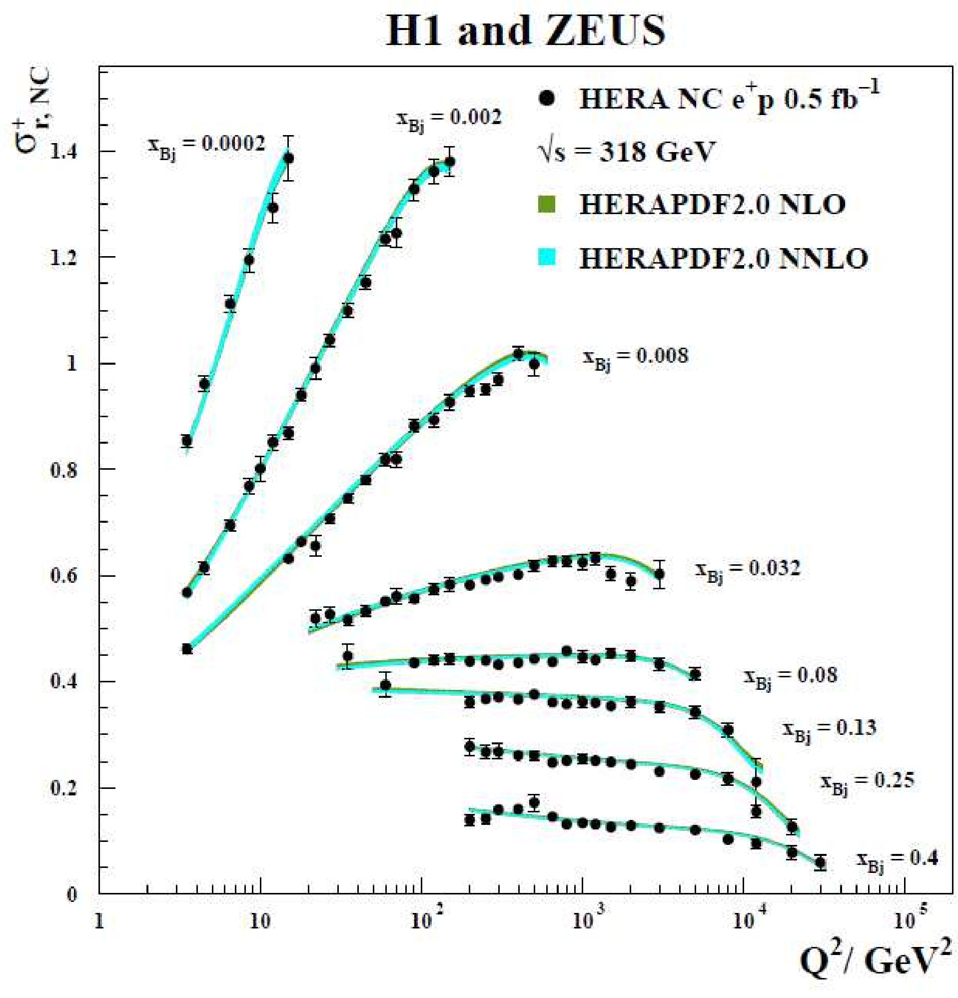


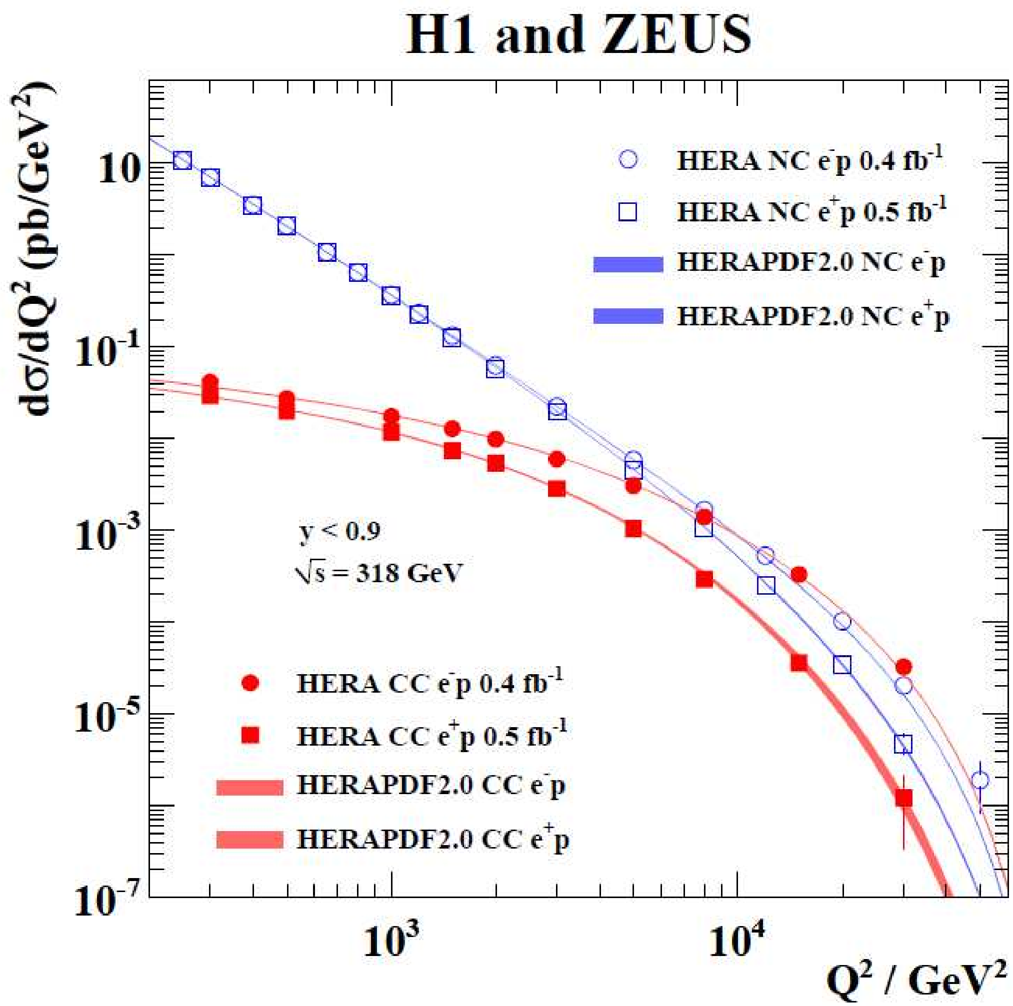

parton densities from HERA and LHC data
-> cross sections at LHC, cosmic rays, ...

# Final HERA inclusive DIS combination and PDF fit

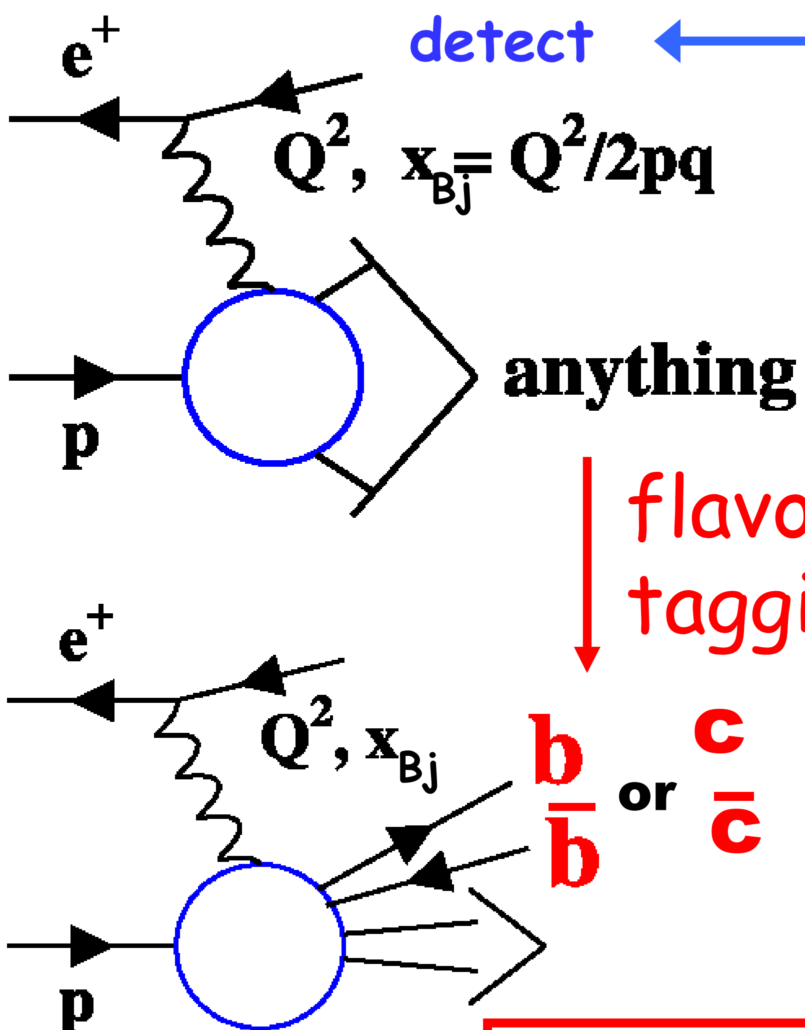
arXiv 1506.06042, EPJC 75 (2015) 580

**already >500 citations**



# Heavy flavour contributions to $\sigma_r$




detect ⟷

Measure cross section

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

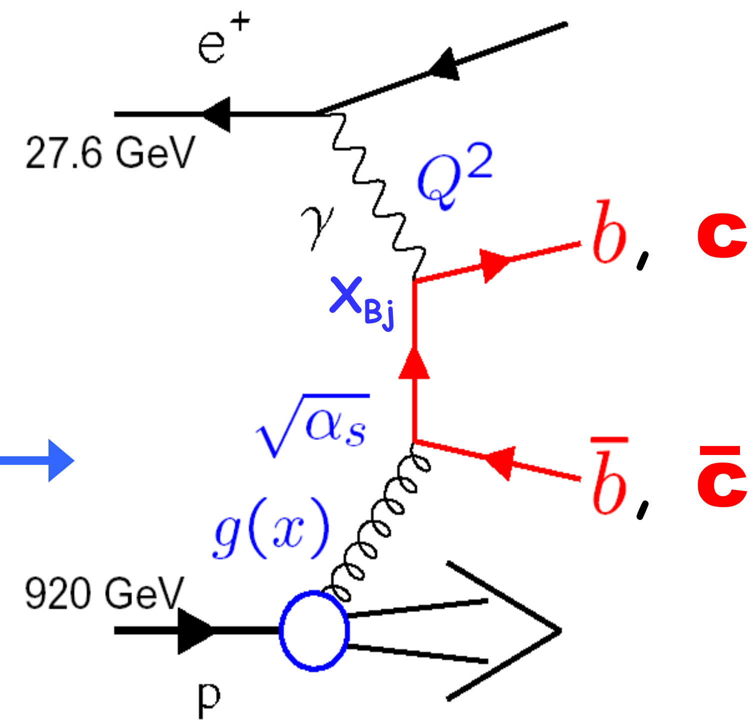
flavour tagging

**b** **$\bar{b}$** or **c** **$\bar{c}$**

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

see also talk R. Thorne

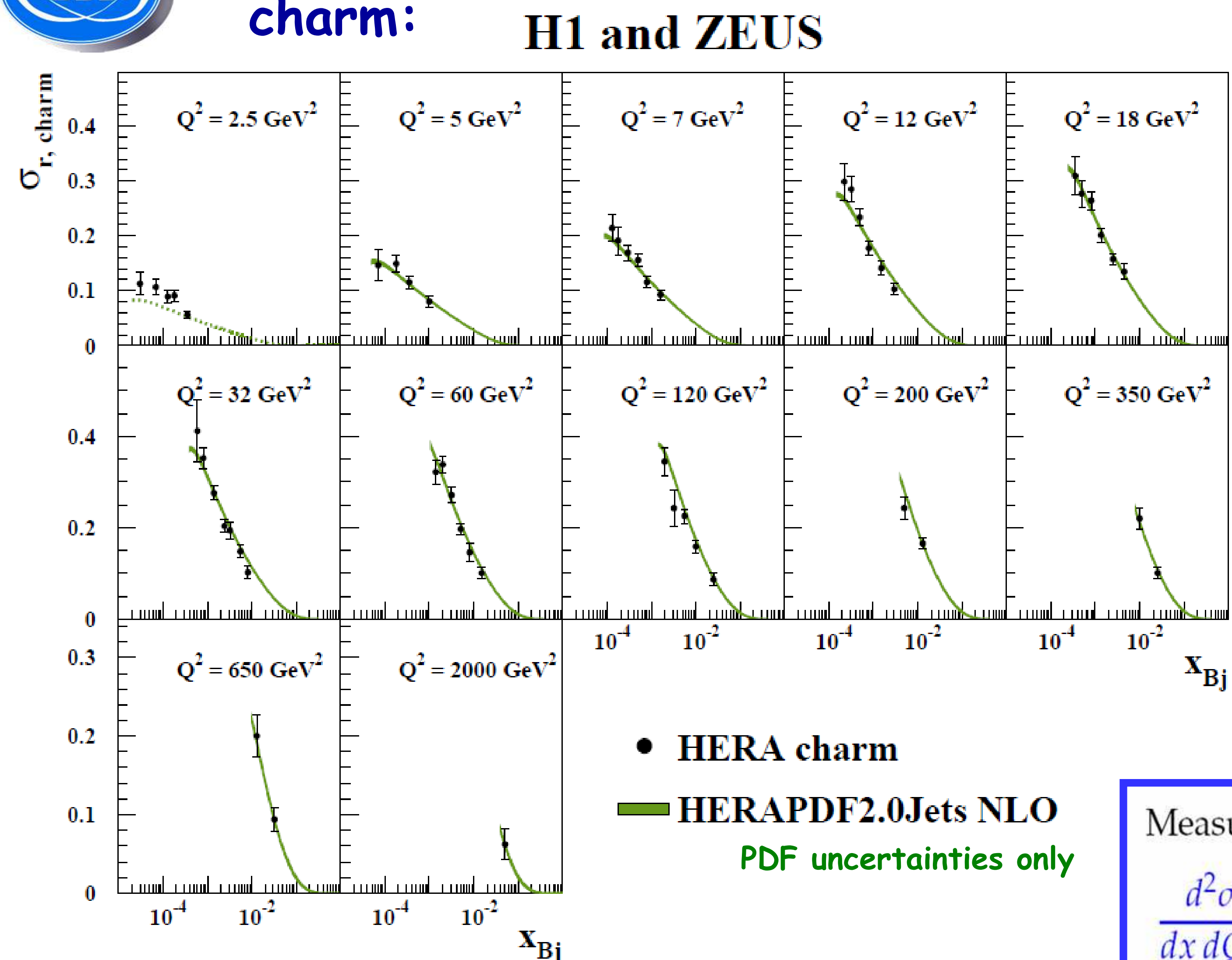
QCD ⟷



# includes fit of inclusive charm + jet DIS data

arXiv 1506.06042, EPJC 75 (2015) 580

charm:




PDF uncertainties only

well described by fit

Measure cross section

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

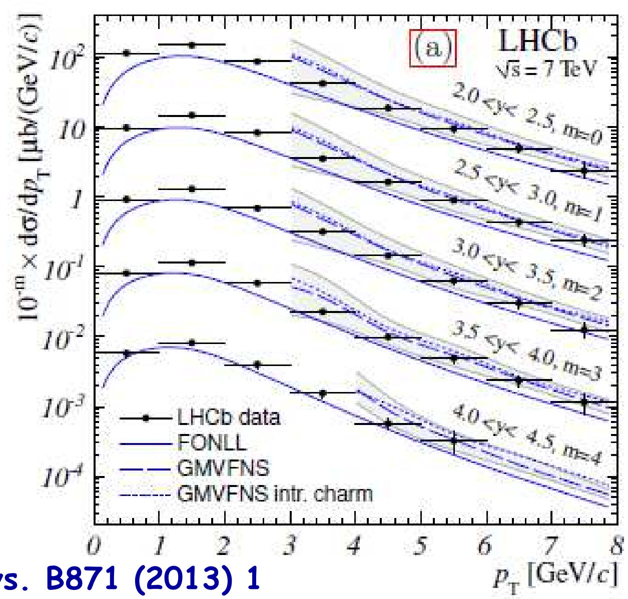
# Constraint of gluon at very low x

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

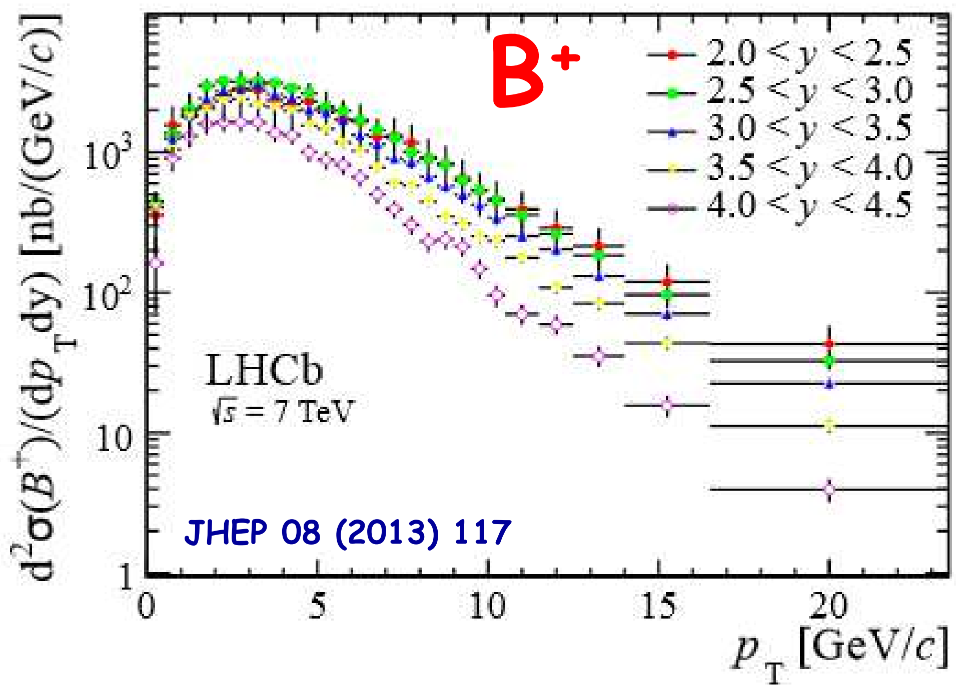
Combined fit of

- 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: $10^{-3}$- $10^{-6}$

D0




Nucl.Phys. B871 (2013) 1




JHEP 08 (2013) 117

# Input data sets

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

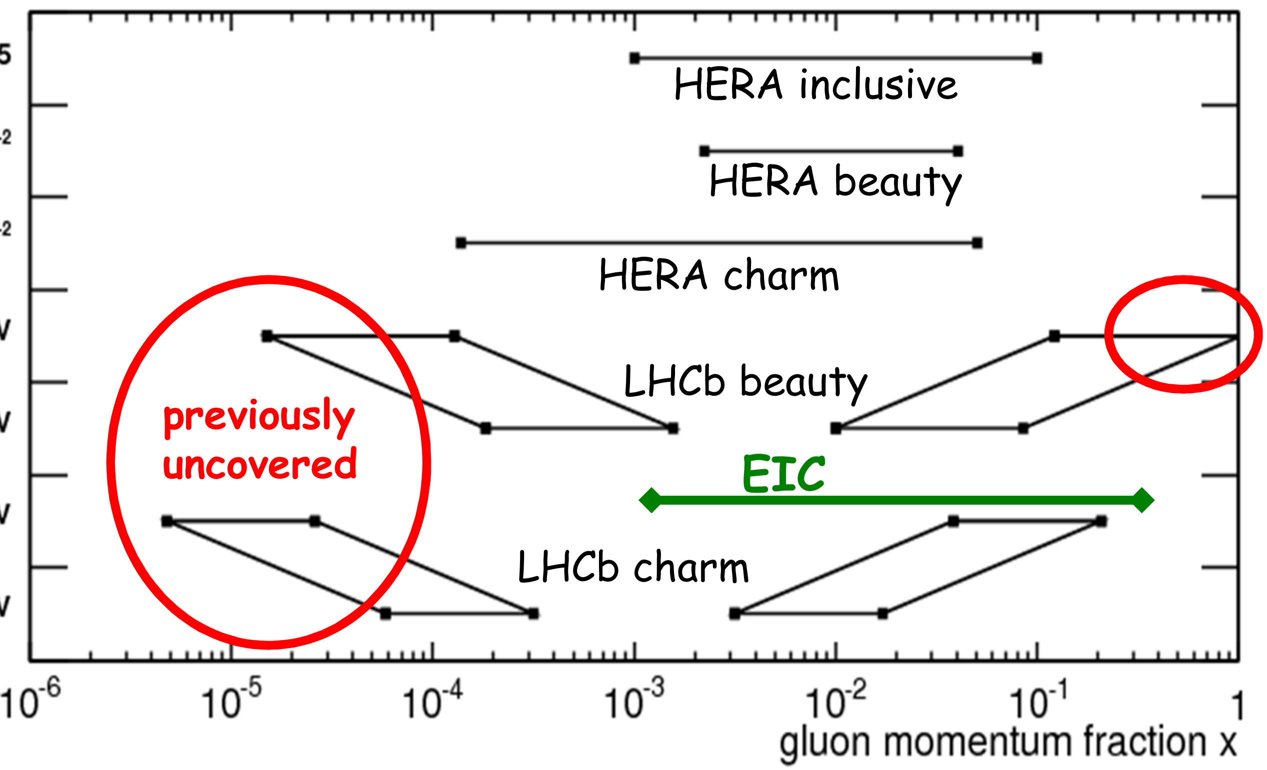
JHEP 01 (2010) 109
HERA inclusive DIS $3.5<Q^2<30000$ GeV$^2$, $4.32\times10^{-4}<x_{Bj}<0.65$

JHEP 1409 (2014) 127
ZEUS beauty $6.5<Q^2<600$ GeV$^2$, $1.5\times10^{-4}<x_{Bj}<3.5\times10^{-2}$

Eur. Phys. J. C 73 (2013) 2311
HERA charm $2.5<Q^2<2000$ GeV$^2$, $3\times10^{-5}<x_{Bj}<5\times10^{-2}$

LHCb beauty $y=4.5$, $0<p_T<40$ GeV
JHEP 08 (2013) 117
LHCb beauty $y=2.0$, $0<p_T<40$ GeV

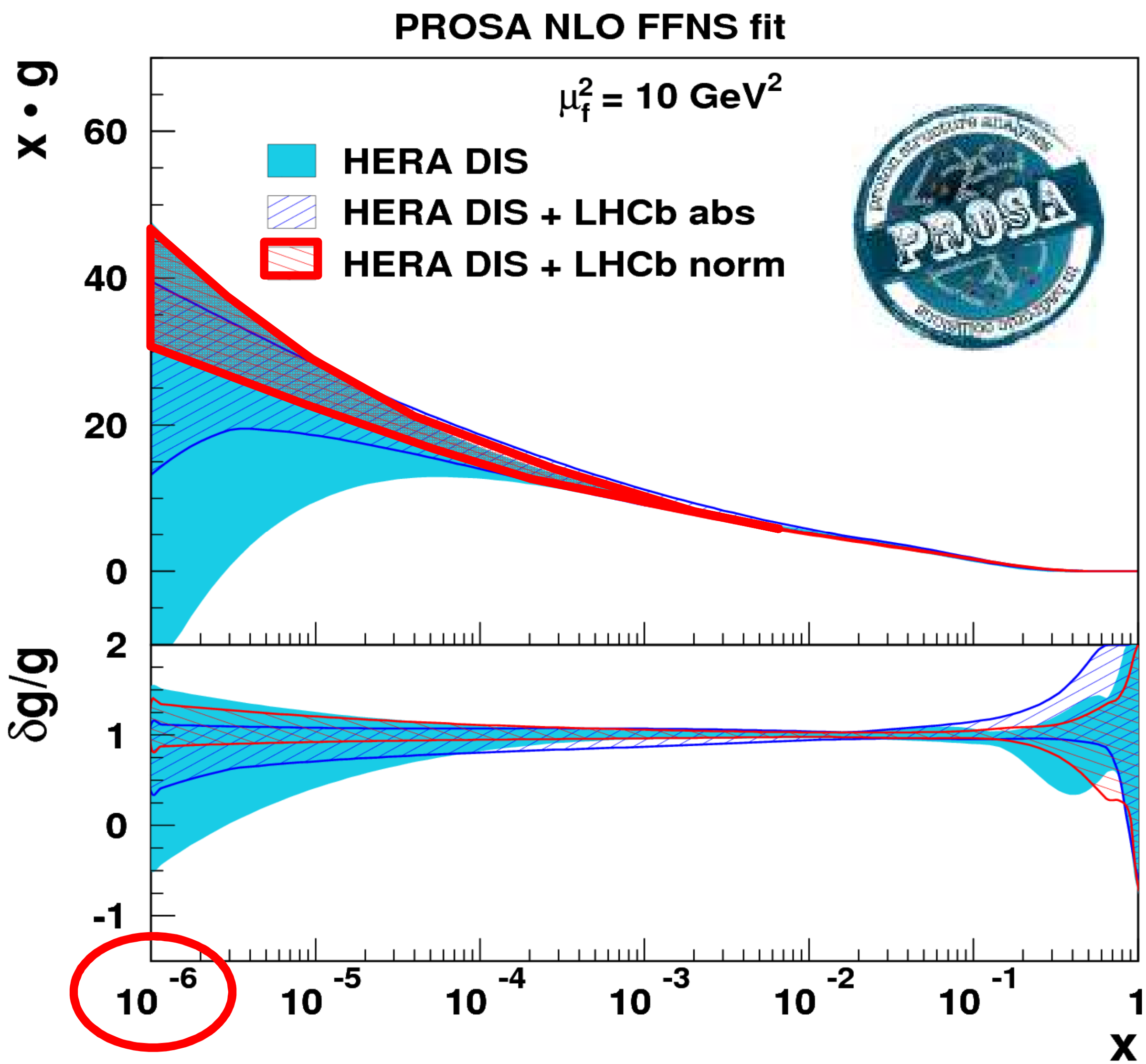
LHCb charm $y=4.5$, $0<p_T<8$ GeV
Nucl. Phys. B 871 (2013) 1
LHCb charm $y=2.0$, $0<p_T<8$ GeV




**combination of data sets "bridges" complete x range**

# final comparison of gluon fits

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




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

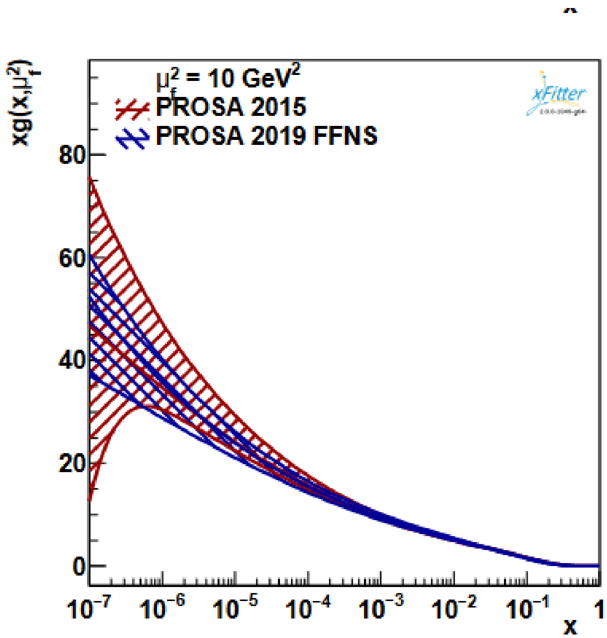
**first constraint from data for $x << 10^{-4}$**

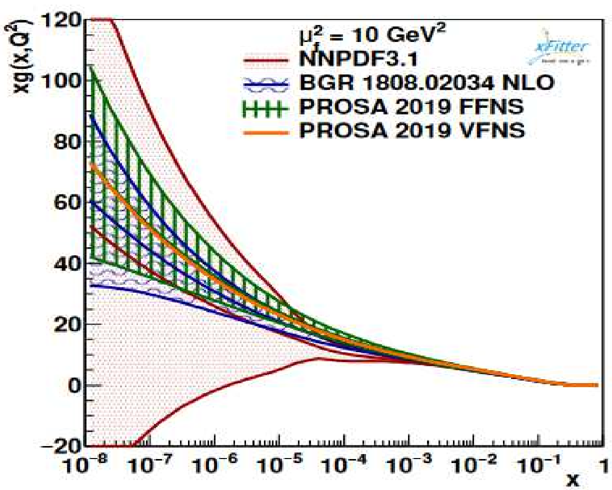
already in use to constrain

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

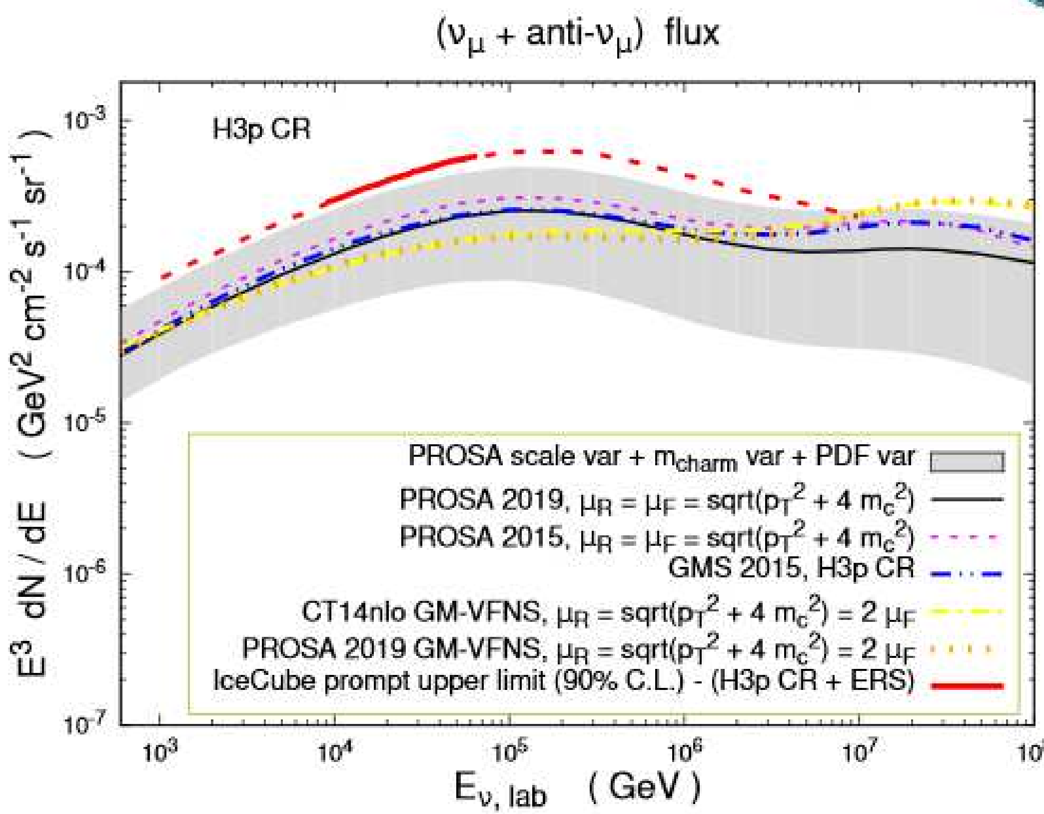
# update, and cosmic ray predictions

arXiv 1611.03815, JHEP 05 (2017) 004 arXiv 1911.13164, JHEP 04 (2020) 118




**use final HERA data, include more LHCb data, and ALICE data -> constrain cosmic ray prompt neutrino spectrum (e.g. Ice Cube)**



# Lesson: low x physics

- The EIC kinematic coverage strongly overlaps with HERA, fixed target, and forward coverage at the LHC (LHCb, also e.g. CMS after high luminosity upgrade)
- HERA data were/are essential to disentangle and calibrate the two x `branches' at LHCb
- The result can be used to study e.g. the cosmic ray neutrino spectrum at Ice Cube

->

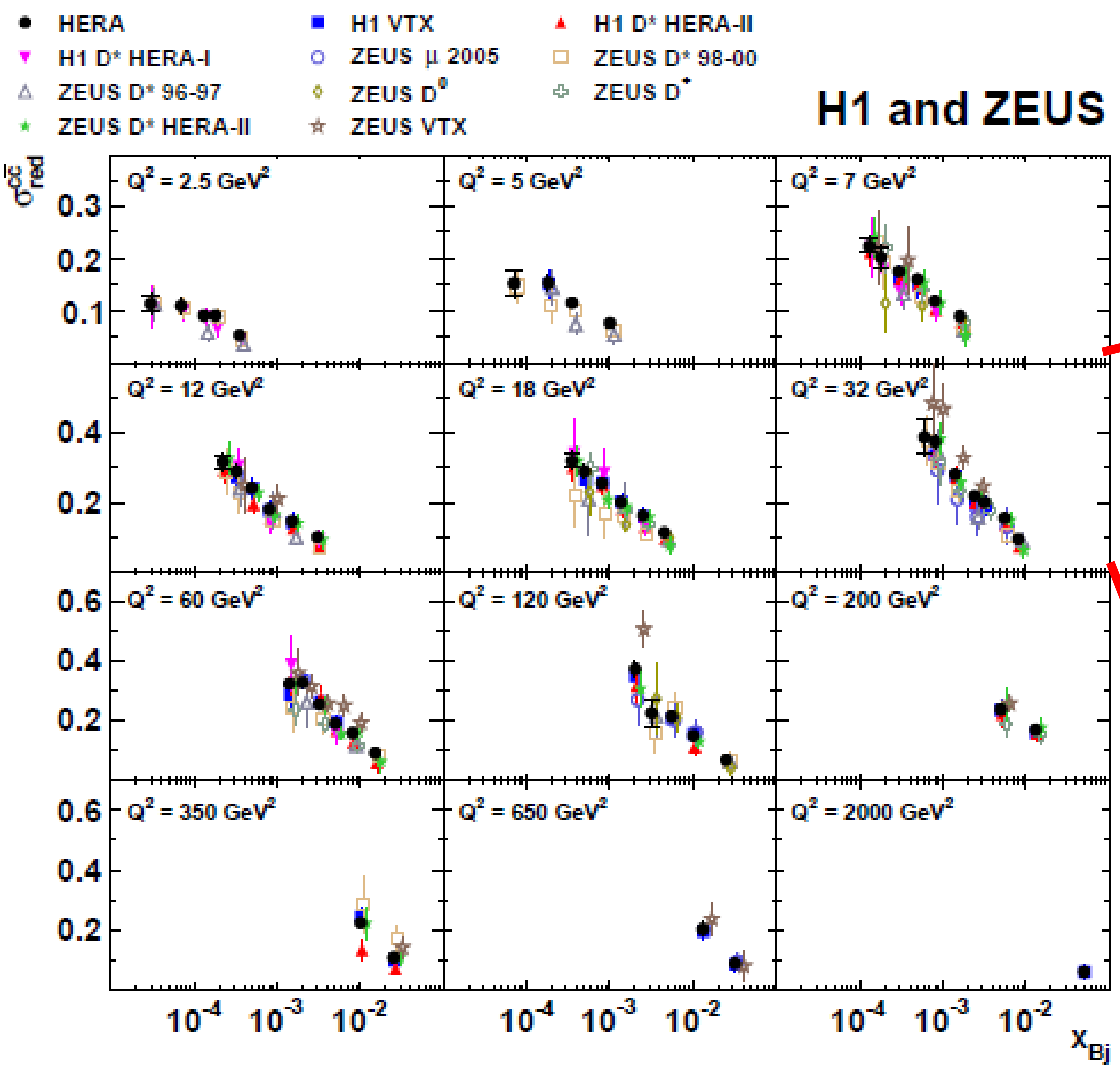
EIC data will have a similar essential role w.r.t. phase 2 LHC data; further enhanced by the availability of 'nuclear' data vs. heavy ion collisions

# Final HERA Charm combination

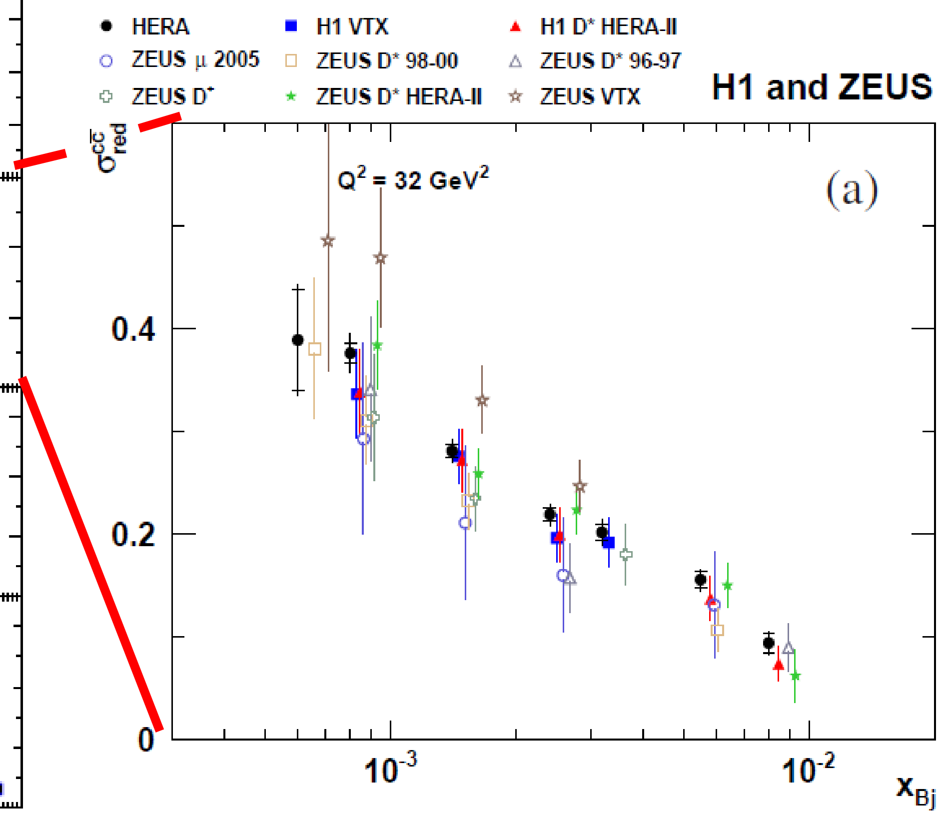
*Eur.Phys.J.C 78 (2018) 473, arXiv:1804.01019*

209 -> 52 data points

(+ beauty combination, see backup)




3 HERA II data sets added
-> 20% improvement



# QCD fit: charm x slope

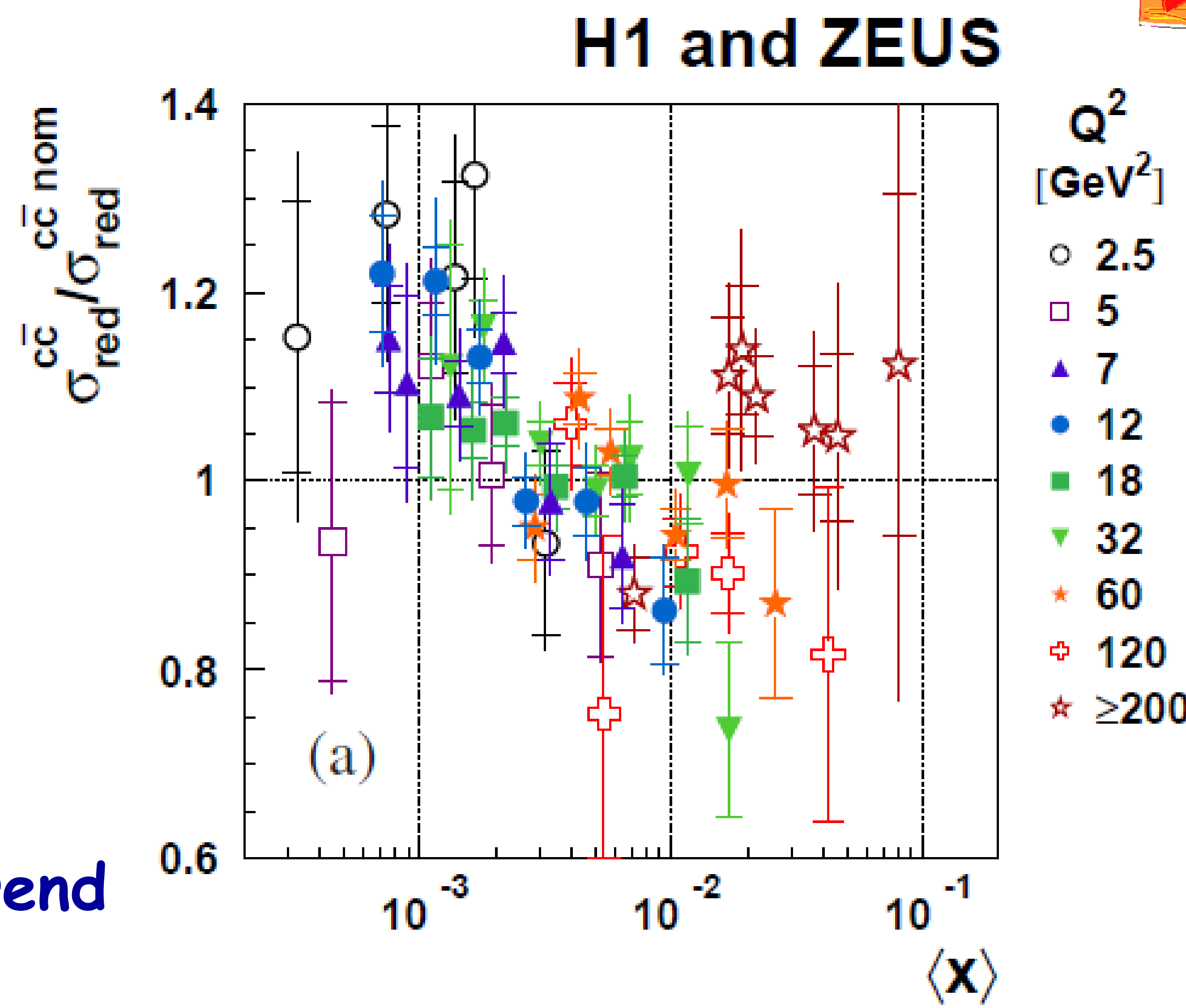
*Eur.Phys.J.C 78 (2018) 473, arXiv:1804.01019*

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 $Q^2$**



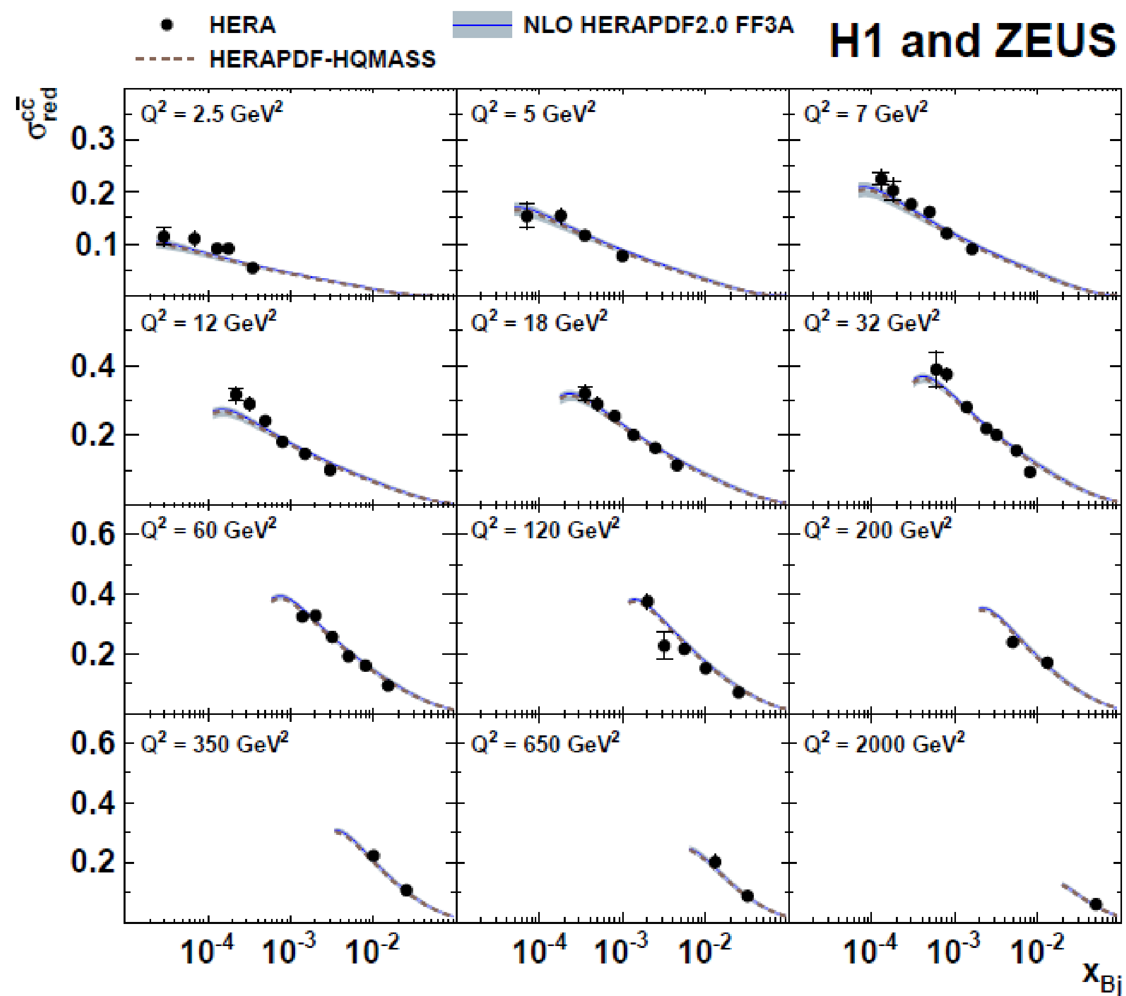

**further discussion** (gluon shape (?), low x resummation (?), ...) **see backup**

# QCD fit:  charm subset

*Eur.Phys.J.C 78 (2018) 473,  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

Eur.Phys.J.C 78 (2018) 473, arXiv:1804.01019

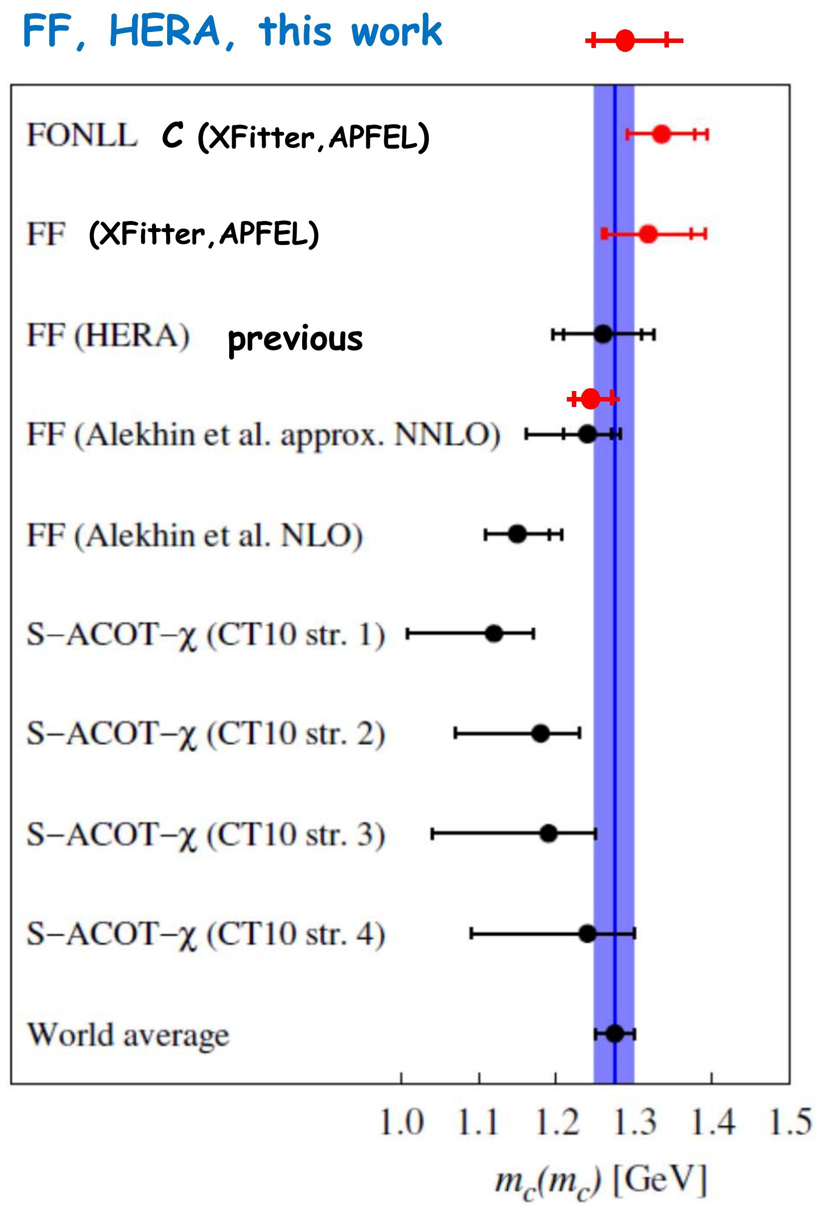
**this work:**

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

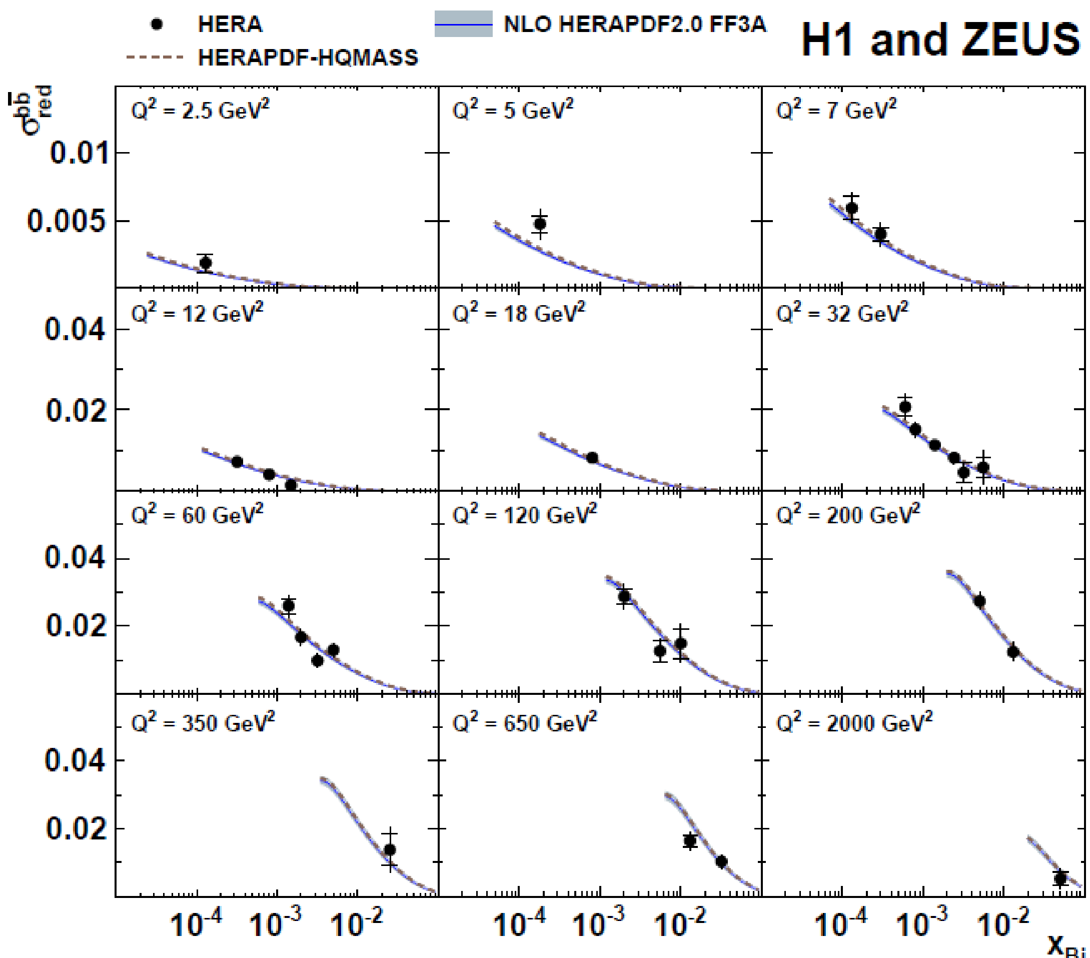
| scheme | $m_c(m_c)$ [GeV] |
|---|---|
| FONLL (this work) | $1.335 \pm 0.043(\text{exp})^{+0.019}_{-0.000}(\text{param})^{+0.011}_{-0.008}(\text{mod})^{+0.033}_{-0.008}(\text{th})$ |
| FFN (this work) | $1.318 \pm 0.054(\text{exp})^{+0.011}_{-0.010}(\text{param})^{+0.015}_{-0.019}(\text{mod})^{+0.045}_{-0.004}(\text{th})$ |
| 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-$\chi$ (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] | $1.275 \pm 0.025$ |



# QCD fit: beauty subset

*Eur.Phys.J.C* 78 (2018) 473, 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)

# Lesson: QCD studies, coverage

- Deep inelastic scattering is a both experimentally and theoretically very clean environment for heavy flavour production and the measurement of related QCD parameters.

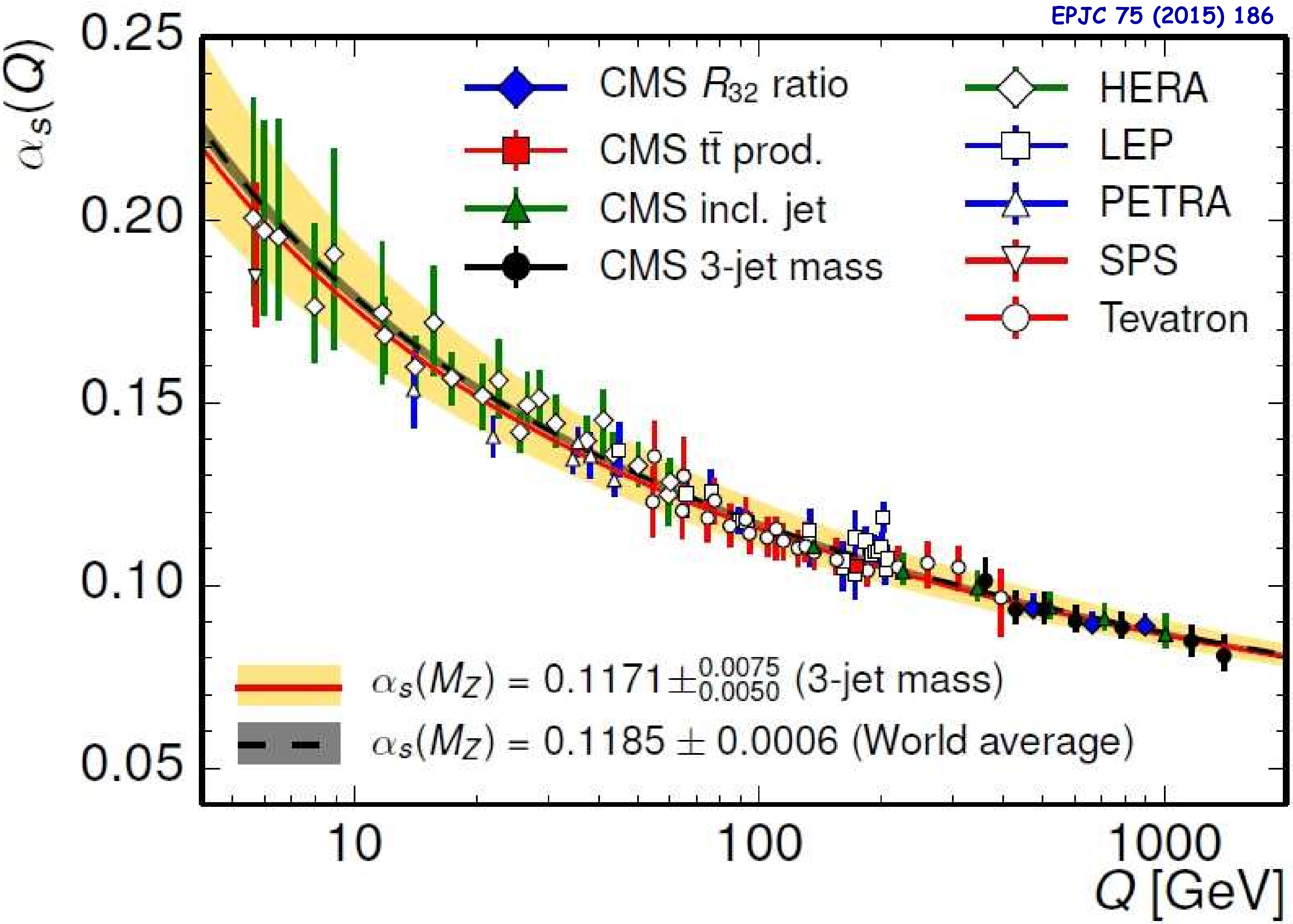
->

Make sure you have full trigger coverage for inclusive charm and beauty production in DIS, best through an inclusive DIS trigger, possibly complemented by dedicated heavy flavour triggers.

# Running strong coupling „constant“ $\alpha_s$

**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 $\alpha_s$ and quark masses

- **$\alpha_s$ 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 $\alpha_s$ , e.g.**

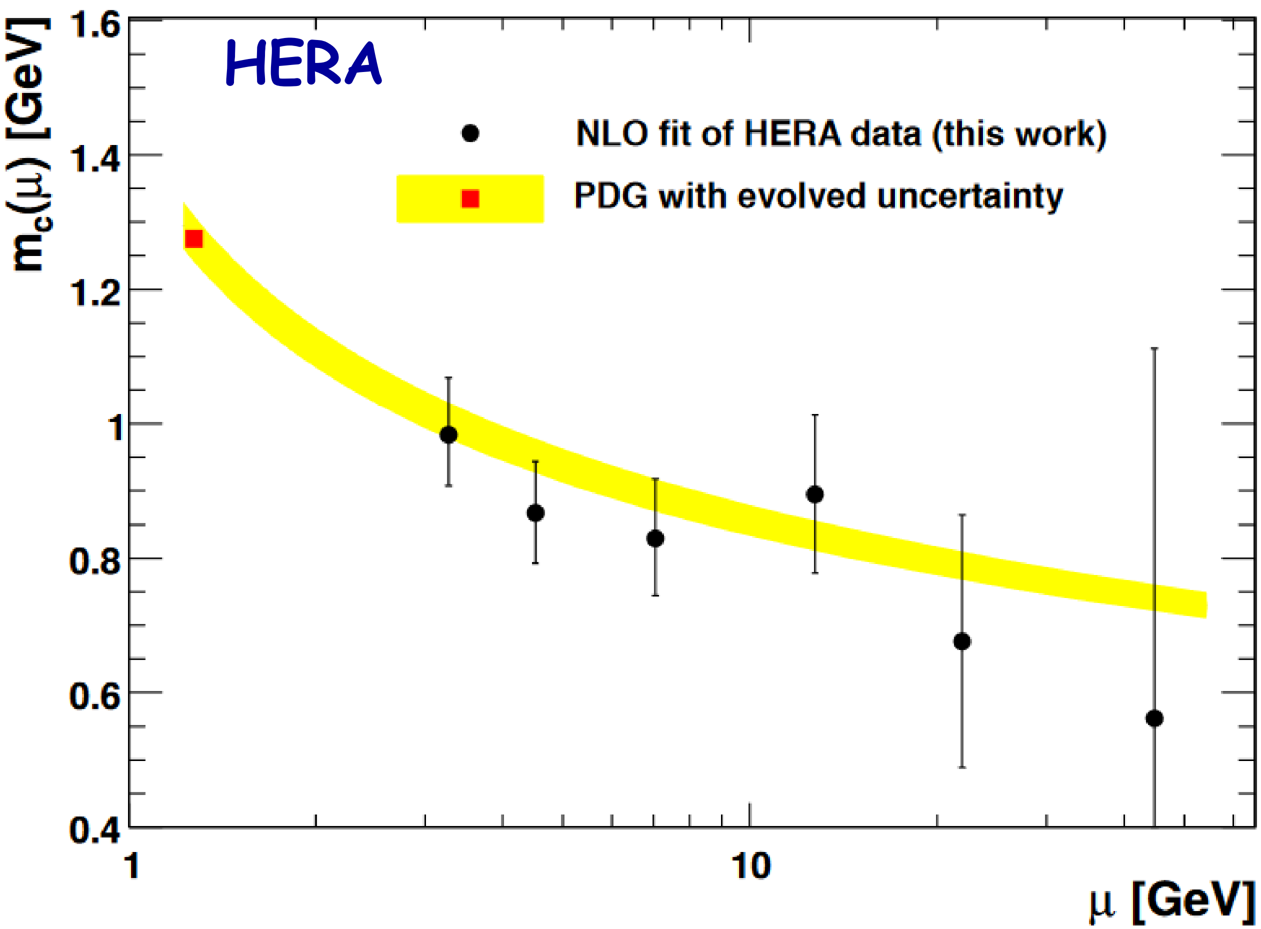
$$m(pole) = m(m)\,(1 + 4/3\;\alpha_s/\pi)$$
$$= m(Q)\,(1 + \alpha_s/\pi\,(4/3+\ln(Q^2/m_c^2))$$

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

# the running charm quark mass

*Phys.Lett.B 775 (2017) 233-238, arxiv:1705.08863*

Do mass determination separately for different $Q^2+4m^2$




running mass concept in QCD is self-consistent !

but mass is also manifestation of Higgs Yukawa couplings !

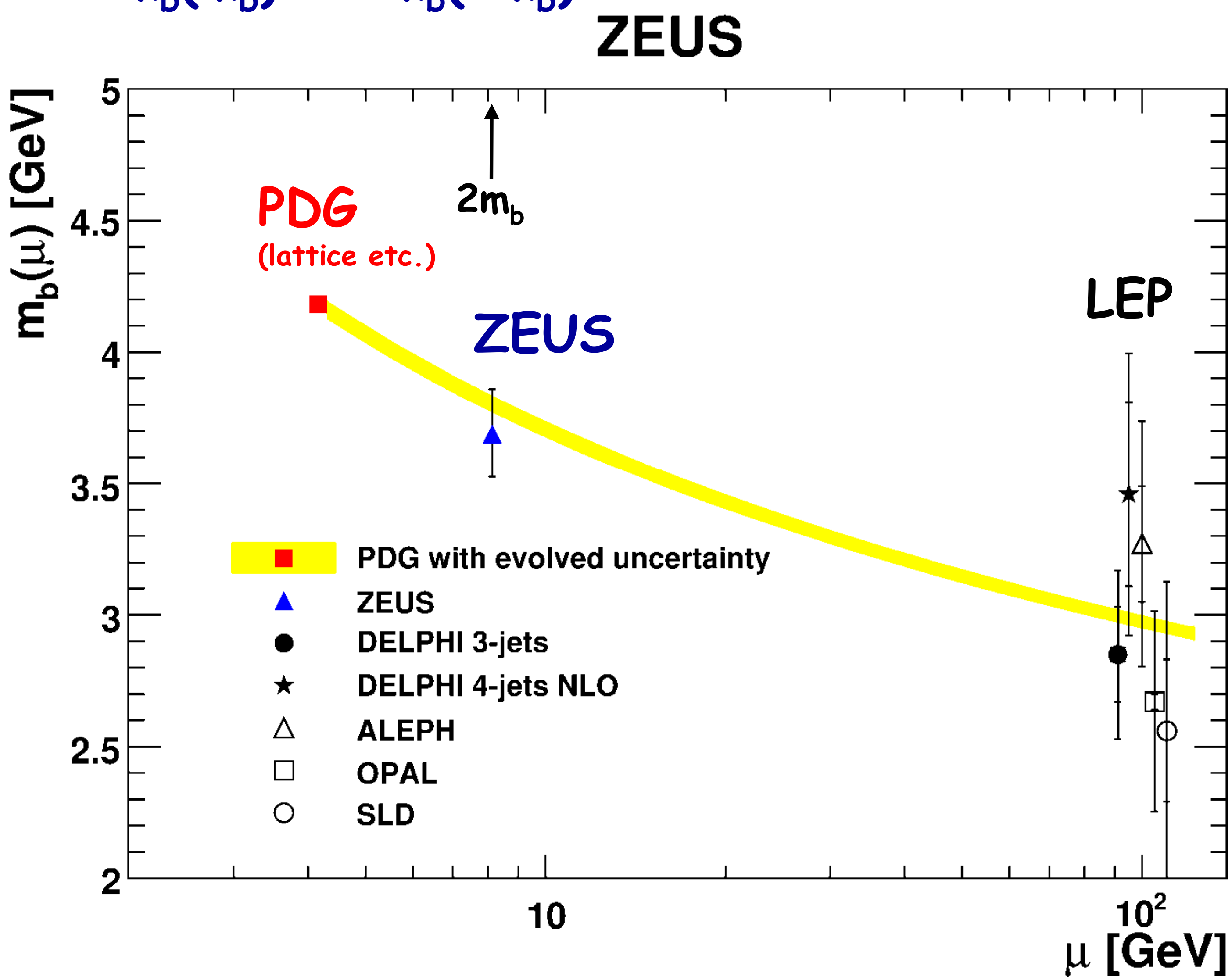
$y_Q = \sqrt{2}m_Q/v$

# the running beauty quark mass

arXiv:1506.07519

translate $m_b(m_b)$ -> $m_b(2m_b)$

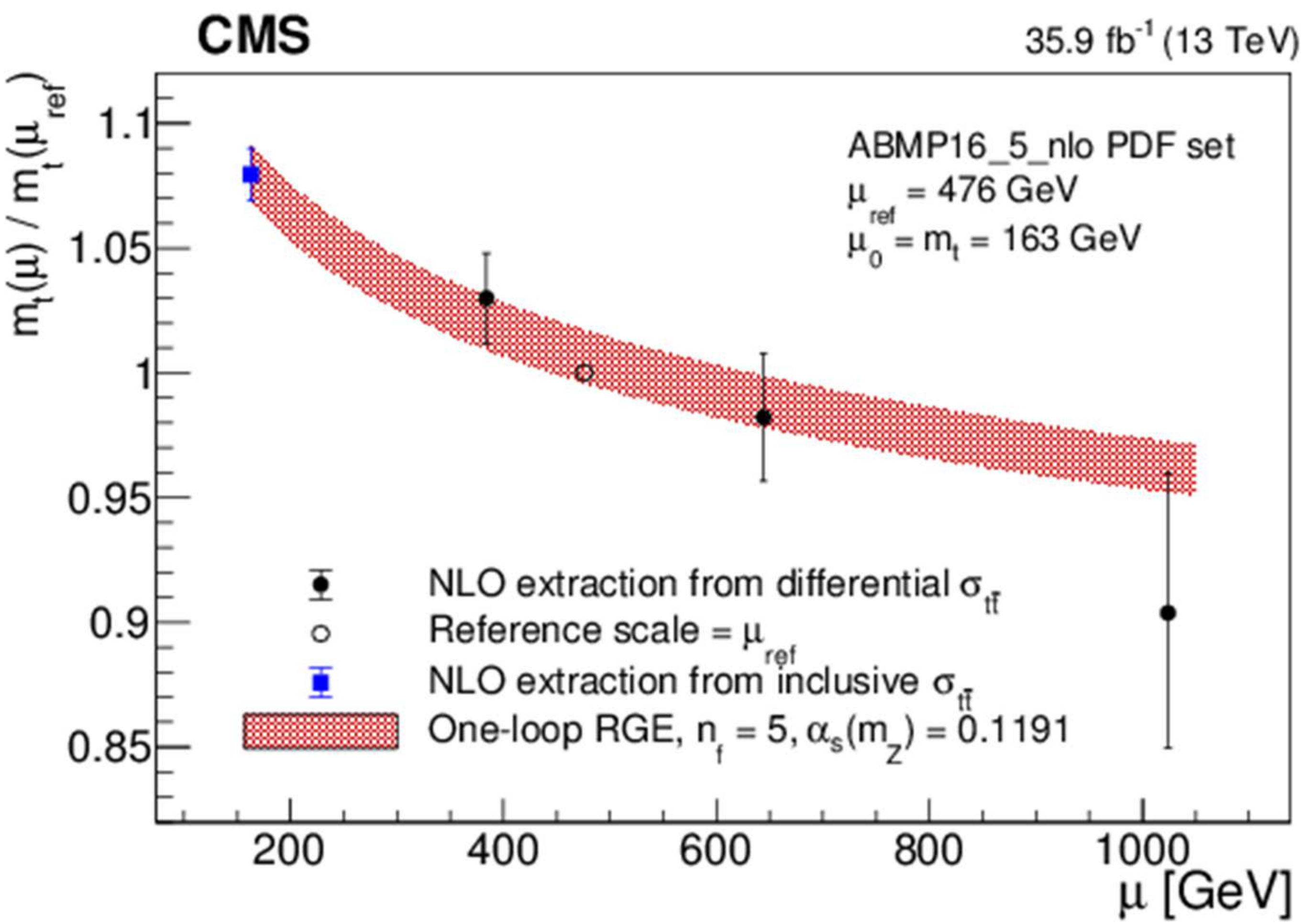
Prog. Part. Nucl. Phys. 84 (2015) 1



# Top quark mass running

*Phys.Lett.B* 803 (2020) 135263, arXiv:1909.09193

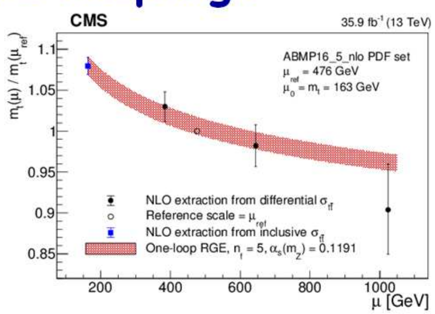
extract top mass from CMS cross sections at different scales



# Running of $\alpha_s$ and quark Yukawa couplings

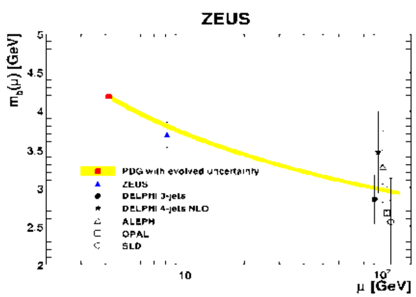
update of PoS CHARM2016 (2017) 012

relate $m_t$, $m_b$, $m_c$ to associated Higgs Yukawa couplings

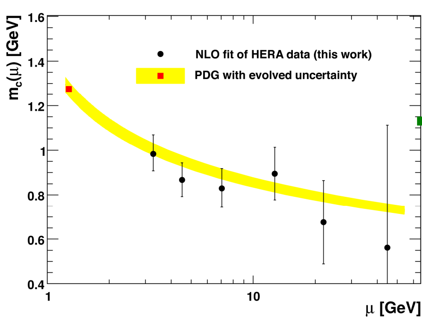


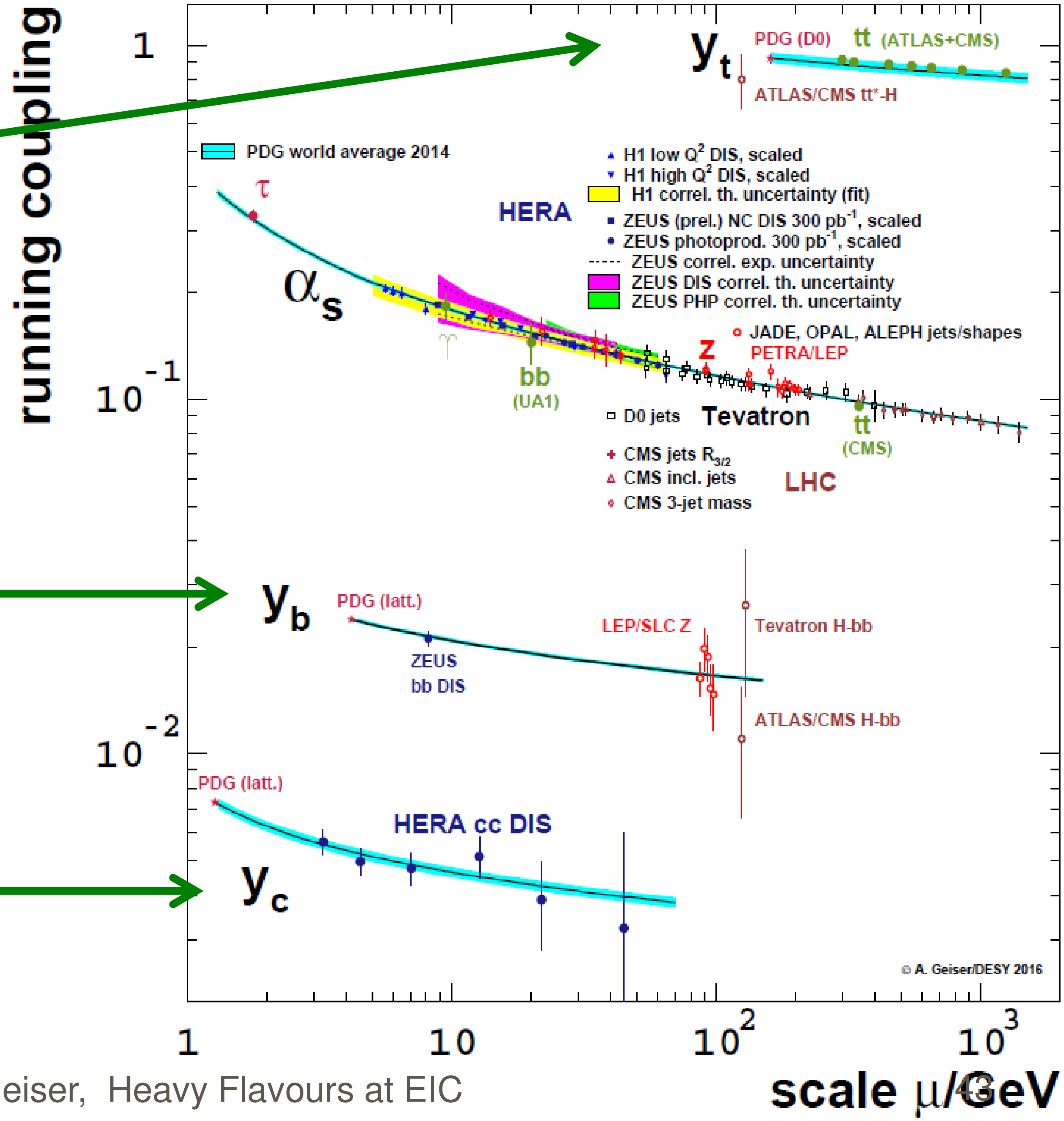
LO EW (+NLO QCD) formula:

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



(choose scheme in which formula is exact)





# Lesson: HERA/EIC and Higgs

- measuring heavy quark masses
  (within the standard model)
  is equivalent to measuring Higgs Yukawa couplings

->

Heavy quark physics is also QCD + Higgs physics, even at EIC

# Conclusion and Outlook

- EIC has a great future in taking over the relay from HERA concerning ep collisions plus go well beyond

- Meanwhile, the HERA data remain available, and only about half the analyses known that could be done with the HERA II data have actually been done (lack of person power).

  Synergy with EIC person power might alleviate this.

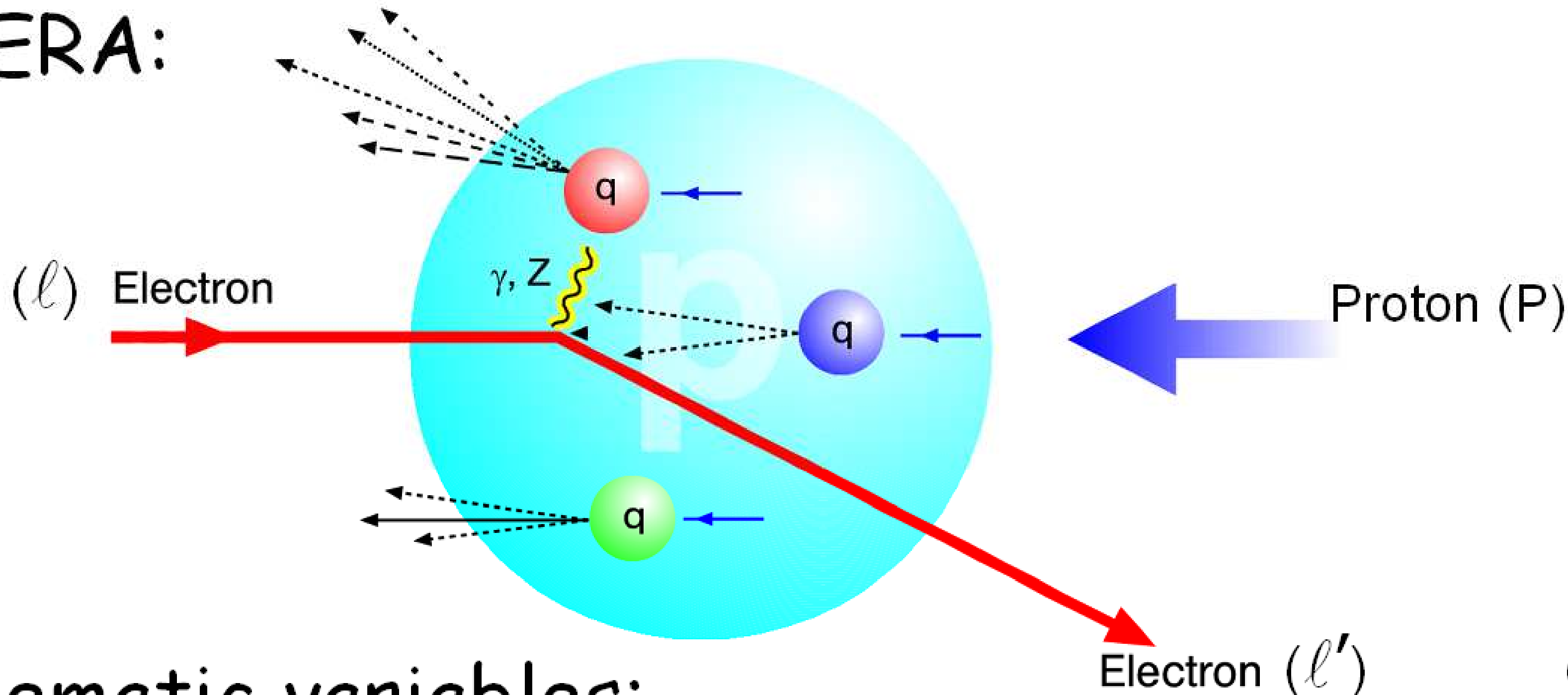
- Theory improvements would/will greatly boost the significance of these HERA results.

- Hopefully the outlook towards EIC will motivate theorists to already provide the corresponding improvements now, rather than waiting for EIC to start.

# Backup

# Deep Inelastic ep Scattering at HERA

HERA:




$q = \ell - \ell'$

kinematic variables:

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

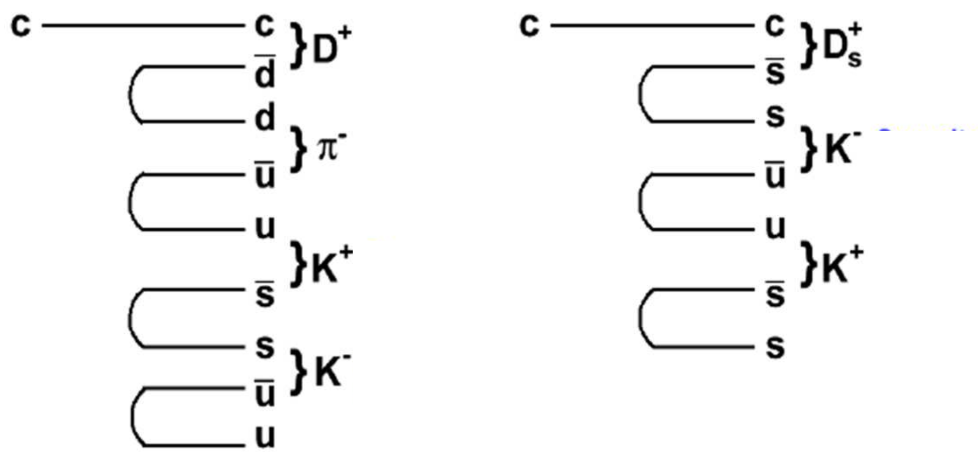
$x = \frac{Q^2}{2Pq}$ Bjorken scaling variable,
for $Q^2 \gg (2m_q)^2$: momentum fraction of p constituent

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

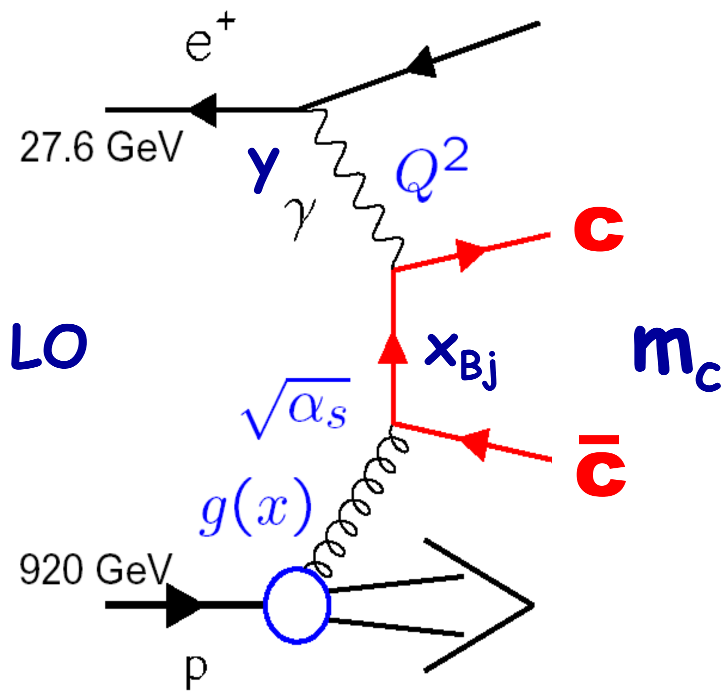
$Q^2 \lesssim 1\ GeV^2$: photoproduction

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

# Charm Fragmentation



# fixed flavour number scheme (FFNS)




+ NLO (+partial NNLO) corrections,

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

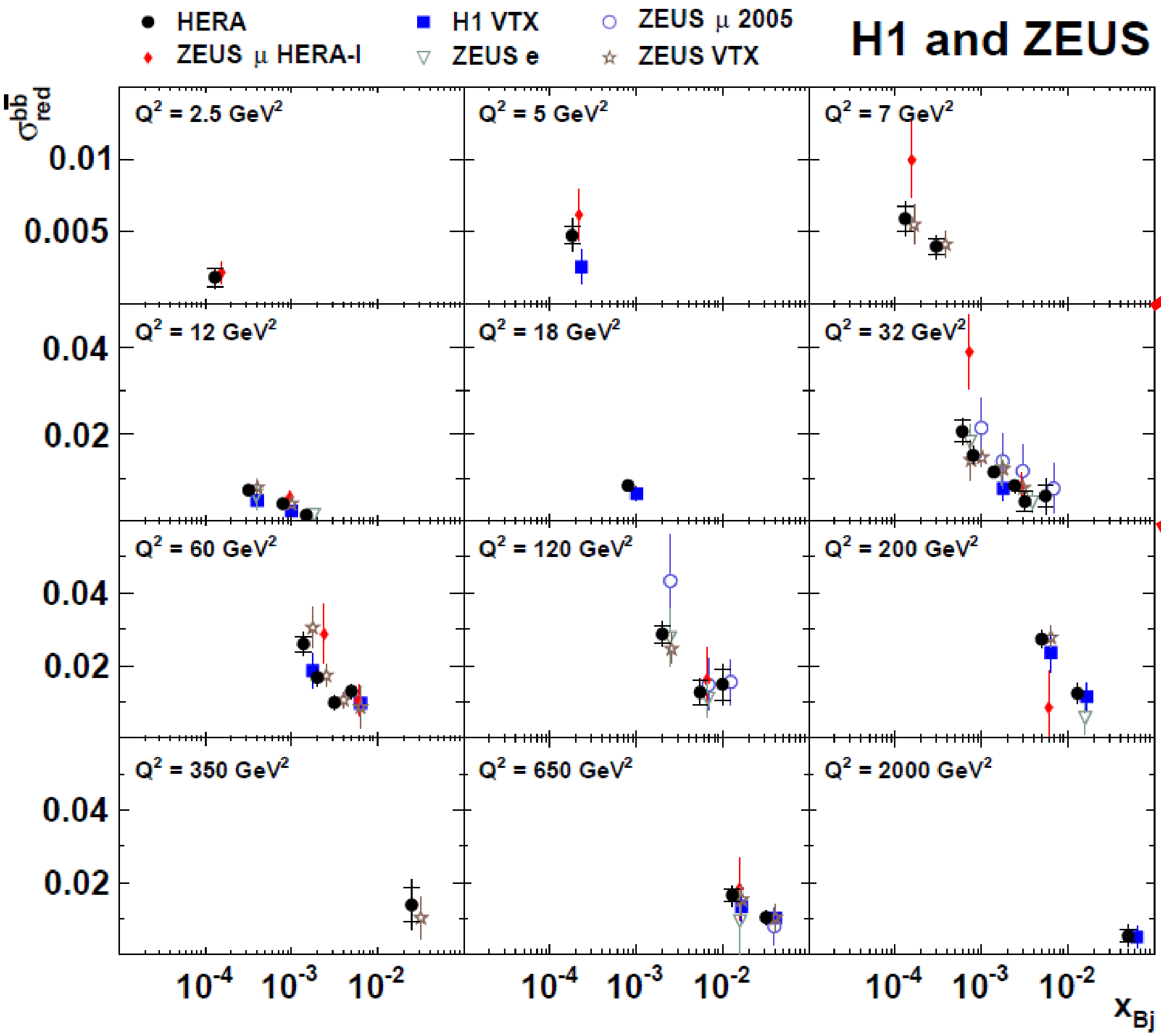
- no charm in proton
- full kinematical treatment of charm mass (multi-scale problem: $Q^2$, $p_T$, $m_c$ -> logs of ratios)
- no resummation of logs

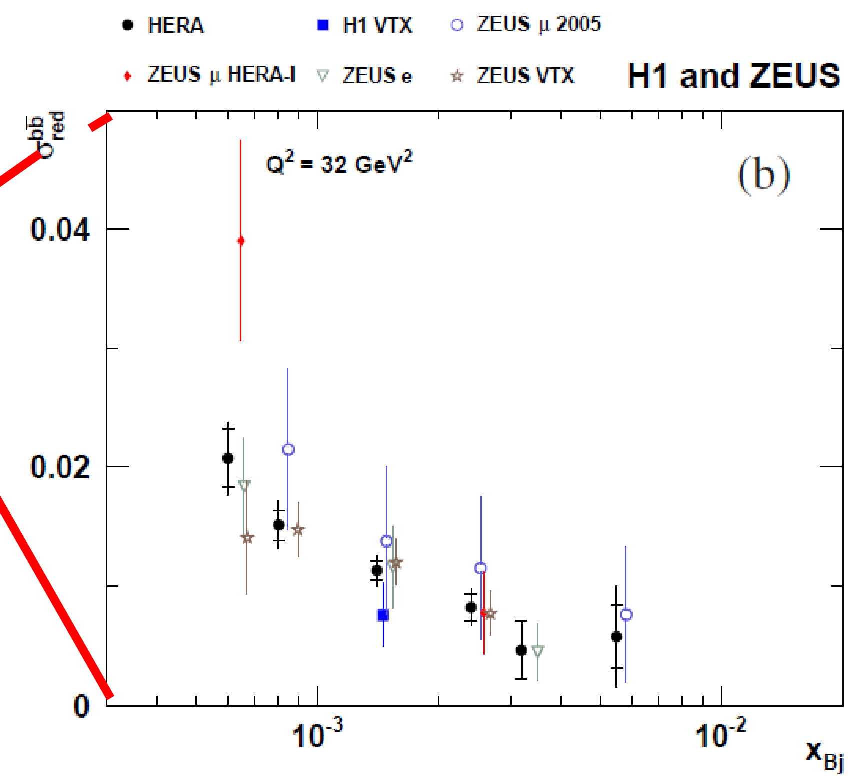
# Beauty combination

arXiv:1804.01019

## 57 -> 27 data points

combined for the first time



# 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 $x \sim 10^{-5}$ !**

**FONLL fits well (factor 2 scale uncertainty not shown)**

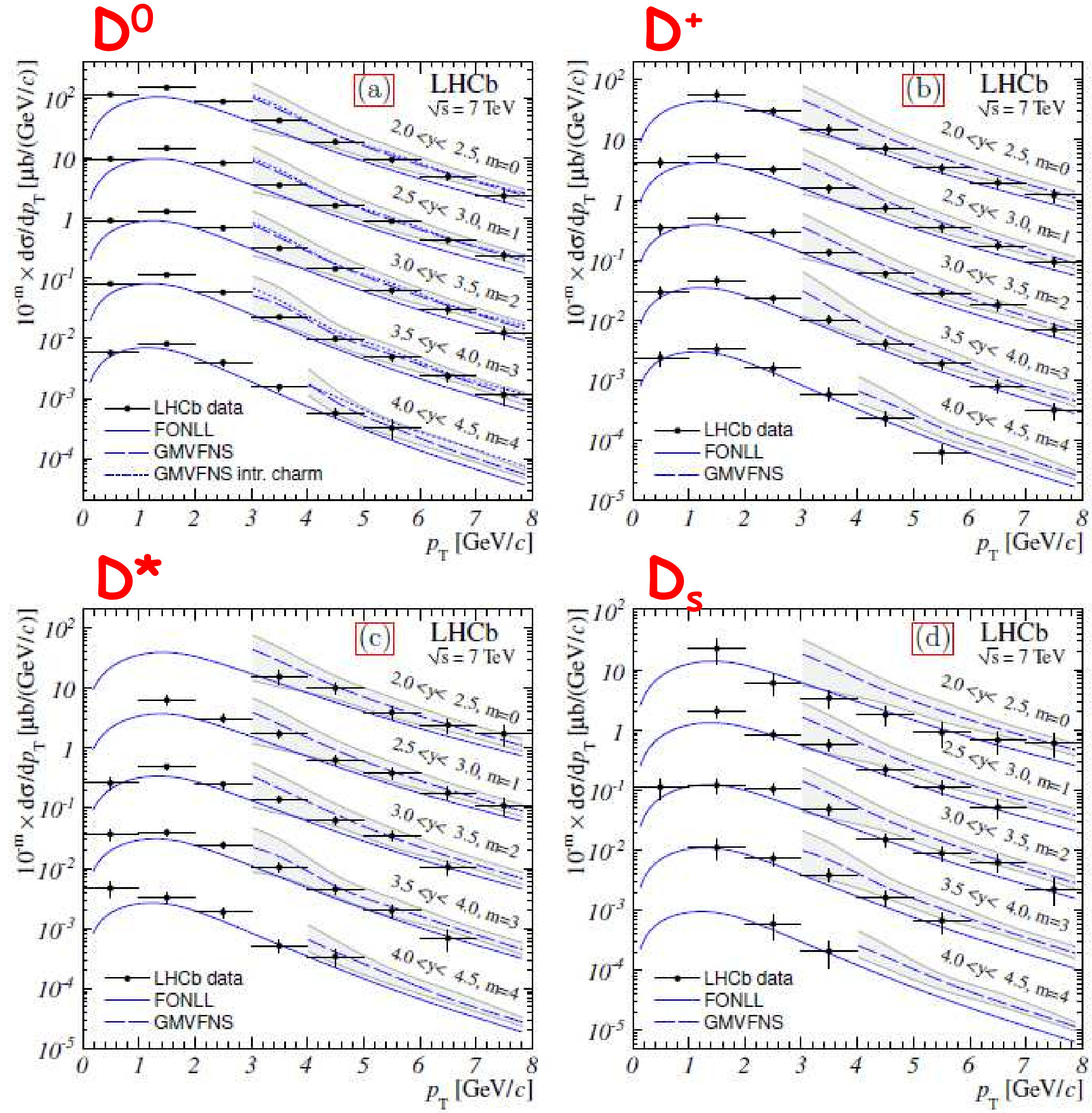
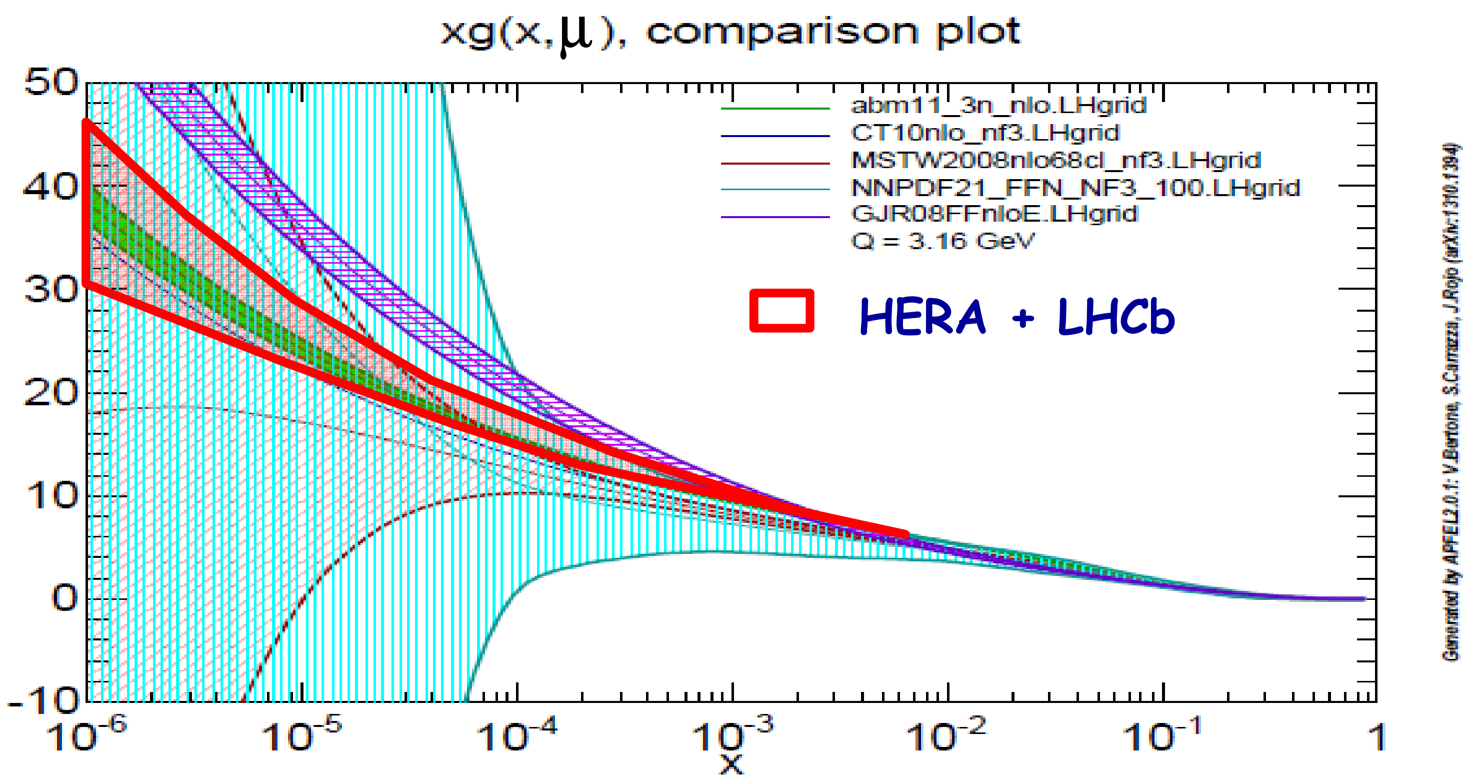



Figure 4: Differential cross-sections for (a) $D^0$, (b) $D^+$, (c) $D^{*+}$, and (d) $D_s^+$ meson production compared to theoretical predictions. The cross-sections for different $y$ regions are shown as functions of $p_T$. The $y$ ranges are shown as separate curves and associated sets of points scaled 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

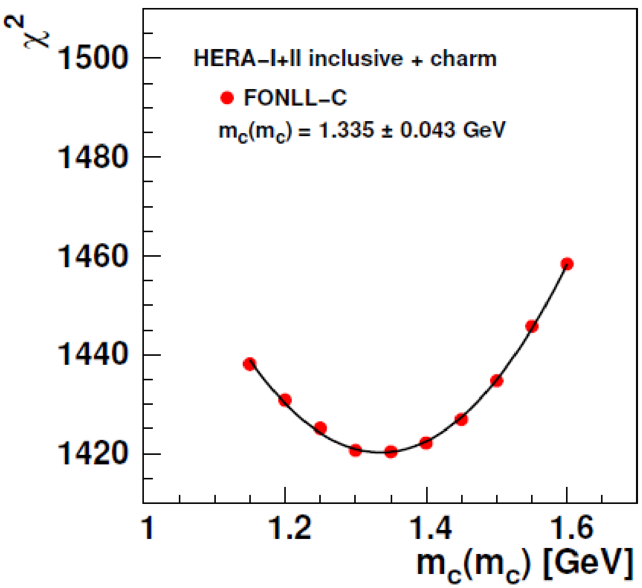
HERAPDF style parameterization with sizeable \`negative gluon ' term (but net positive gluon)




in good agreement with constrained ABM11 parameterization at low x

# $m_c(m_c)$ from FONLL fit of HERA data

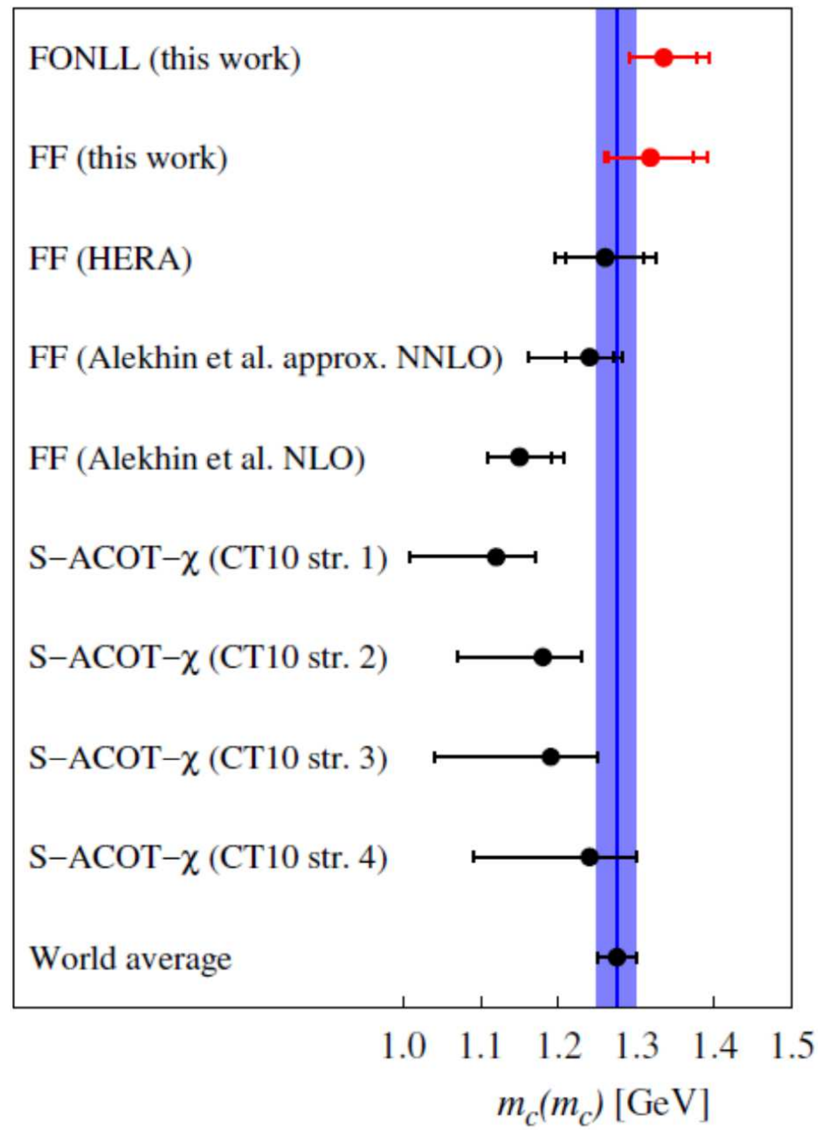
V. Bertone et al., arXiv 1605.01946, JHEP 1608 (2016) 050




xFitter

APFEL

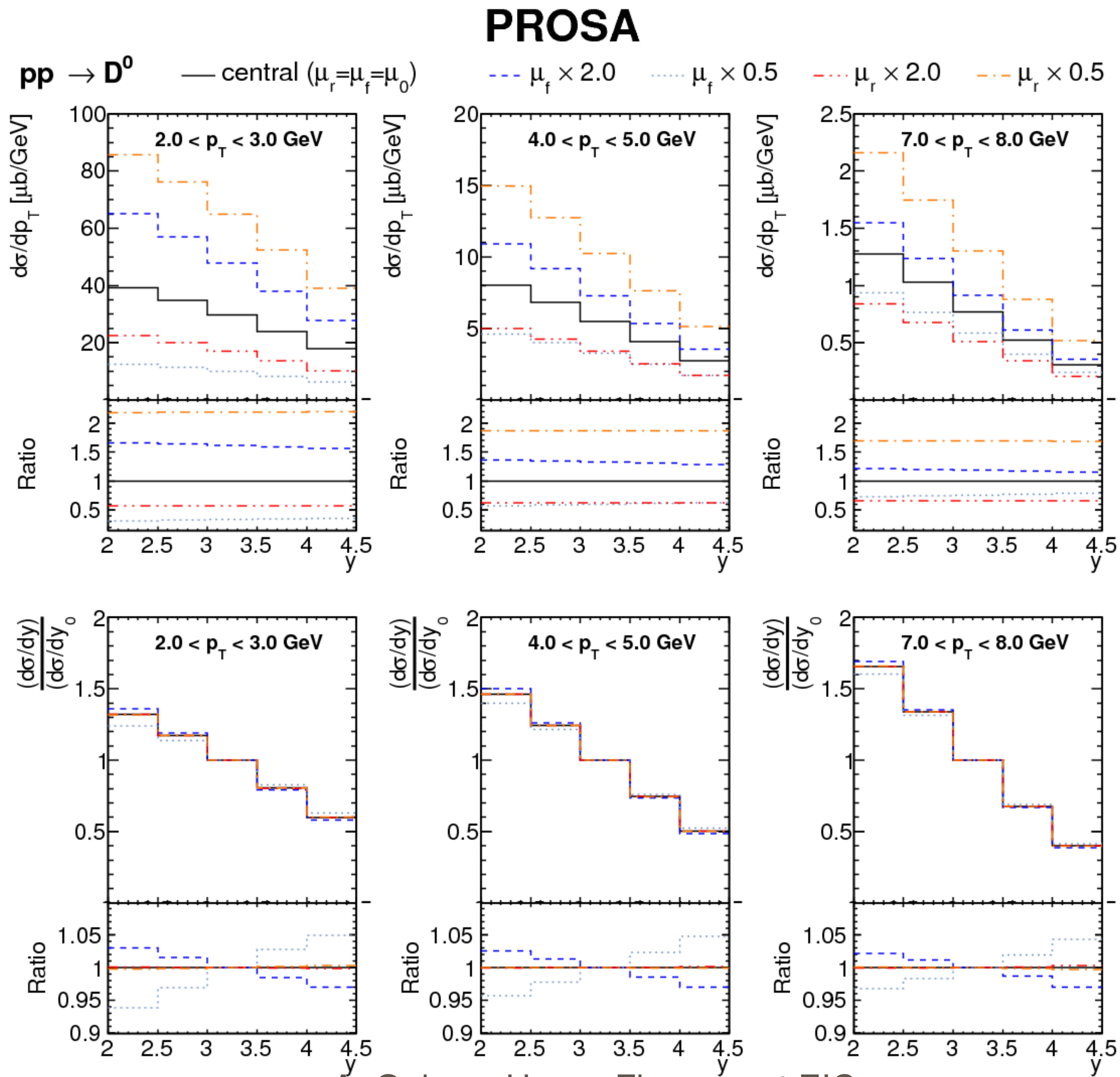
| scheme | $m_c(m_c)$ [GeV] |
|---|---|
| FONLL (this work) | $1.335 \pm 0.043(\text{exp})^{+0.019}_{-0.000}(\text{param})^{+0.011}_{-0.008}(\text{mod})^{+0.033}_{-0.008}(\text{th})$ |
| FFN (this work) | $1.318 \pm 0.054(\text{exp})^{+0.011}_{-0.010}(\text{param})^{+0.015}_{-0.019}(\text{mod})^{+0.045}_{-0.004}(\text{th})$ |
| 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-$\chi$ (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] | $1.275 \pm 0.025$ |



# NLO scale dependence

charm at LHCb

(similar for beauty, see backup)




absolute cross section:

~factor 2

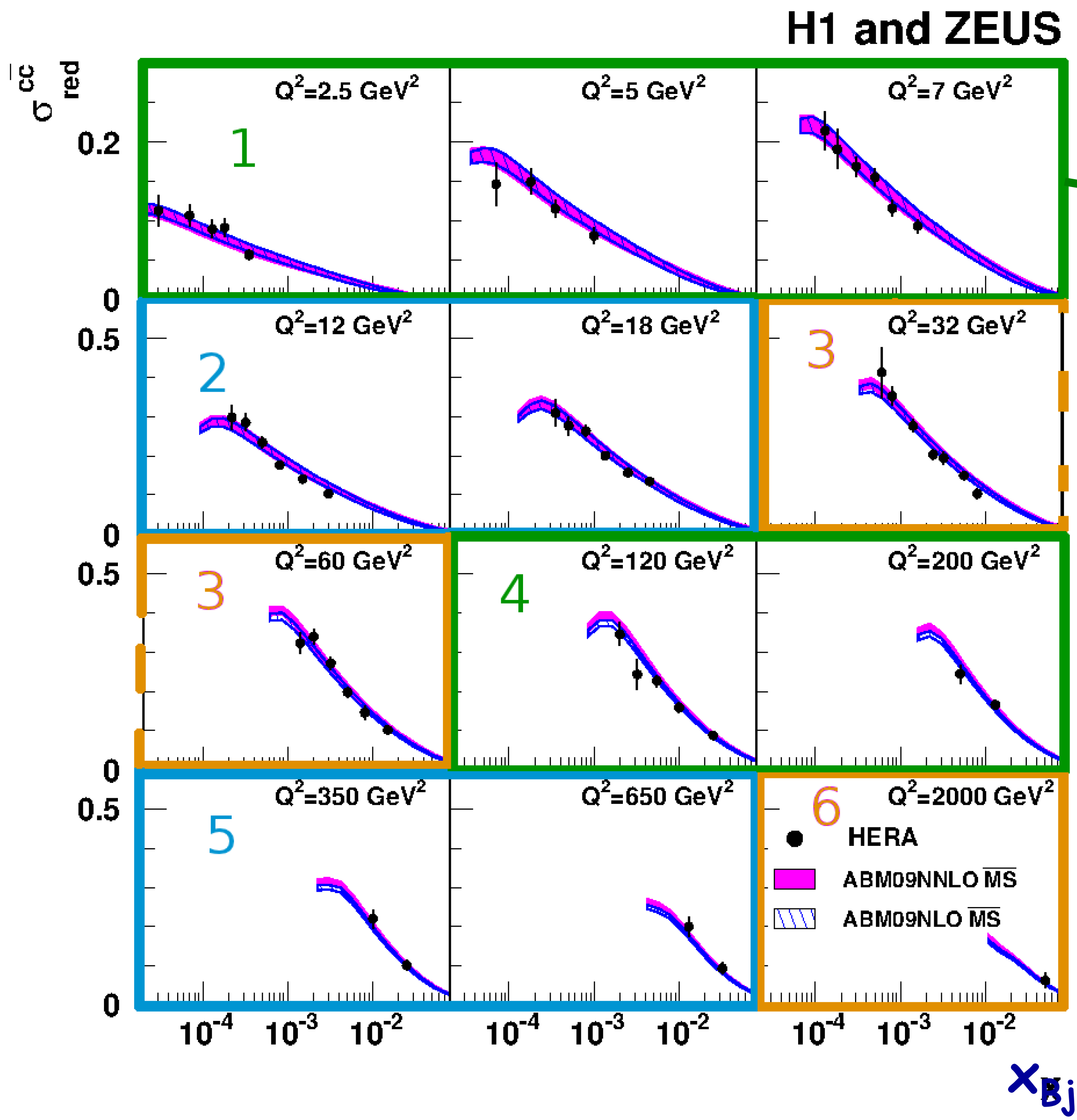
$p_T$-normalized cross section:

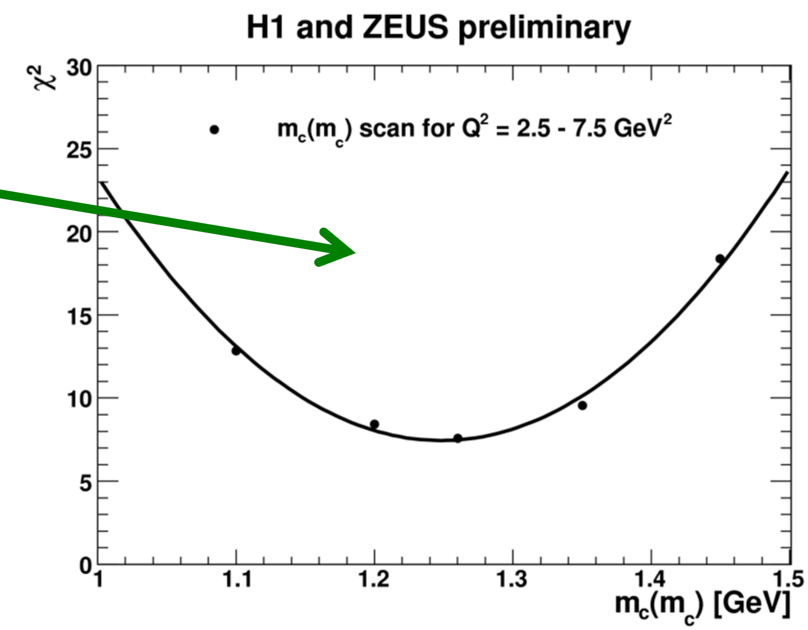
(use shape in y for each $p_T$ bin, normalized to central y bin)

~ few %

# measurement of $m_c$ running

*Phys.Lett.B 775 (2017) 233-238, arxiv:1705.08863*




**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 b quark mass at LEP

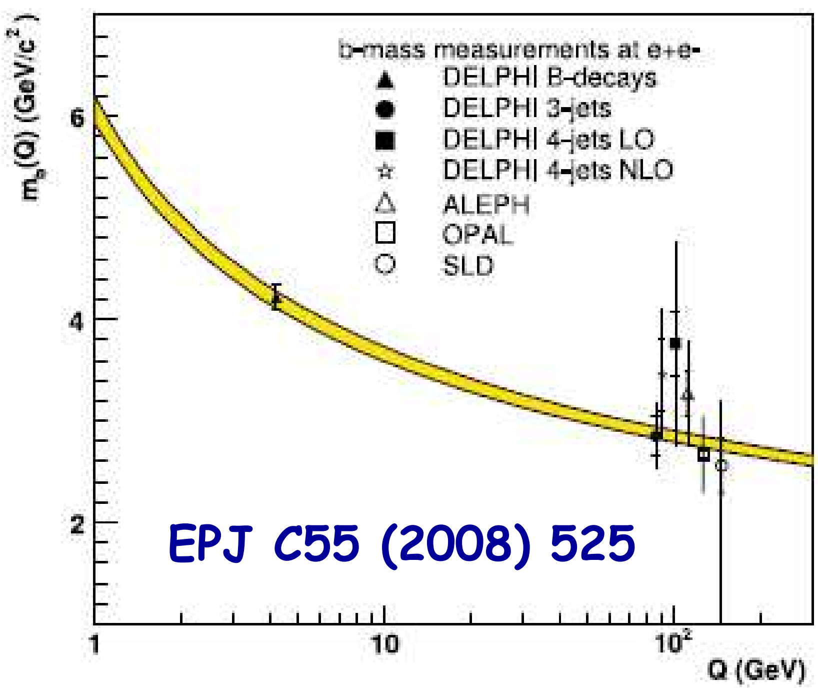



Fig. 6. The energy evolution of the $\overline{MS}$-running $b$-quark mass $m_b(Q)$ as measured at LEP. DELPHI results from $R_3^{b\ell}$ [7] at the $M_Z$ scale and from semileptonic $B$-decays [31] at low energy are shown together with results from other experiments (ALEPH [4], OPAL [5] and SLD [6]). 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**

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

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

# Higgs couplings

**relate $m_t$, $m_b$, $m_c$ to associated Higgs Yukawa couplings**

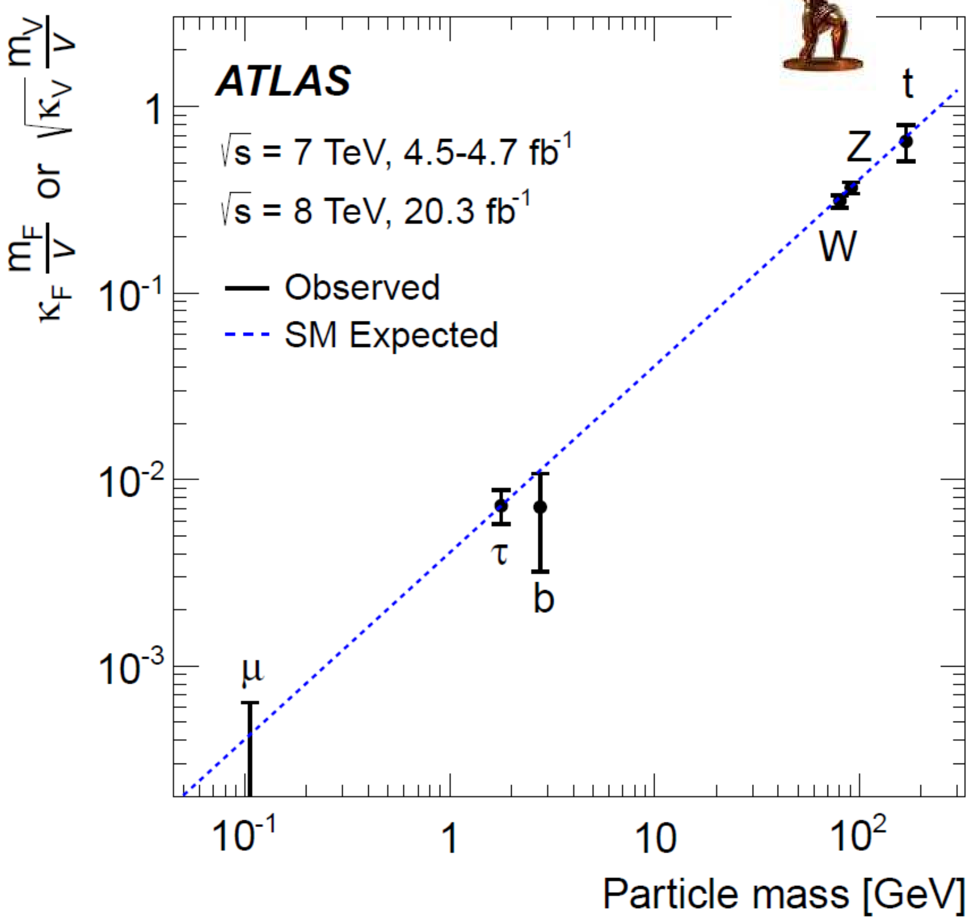
**LO EW (+NLO QCD) formula:**

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

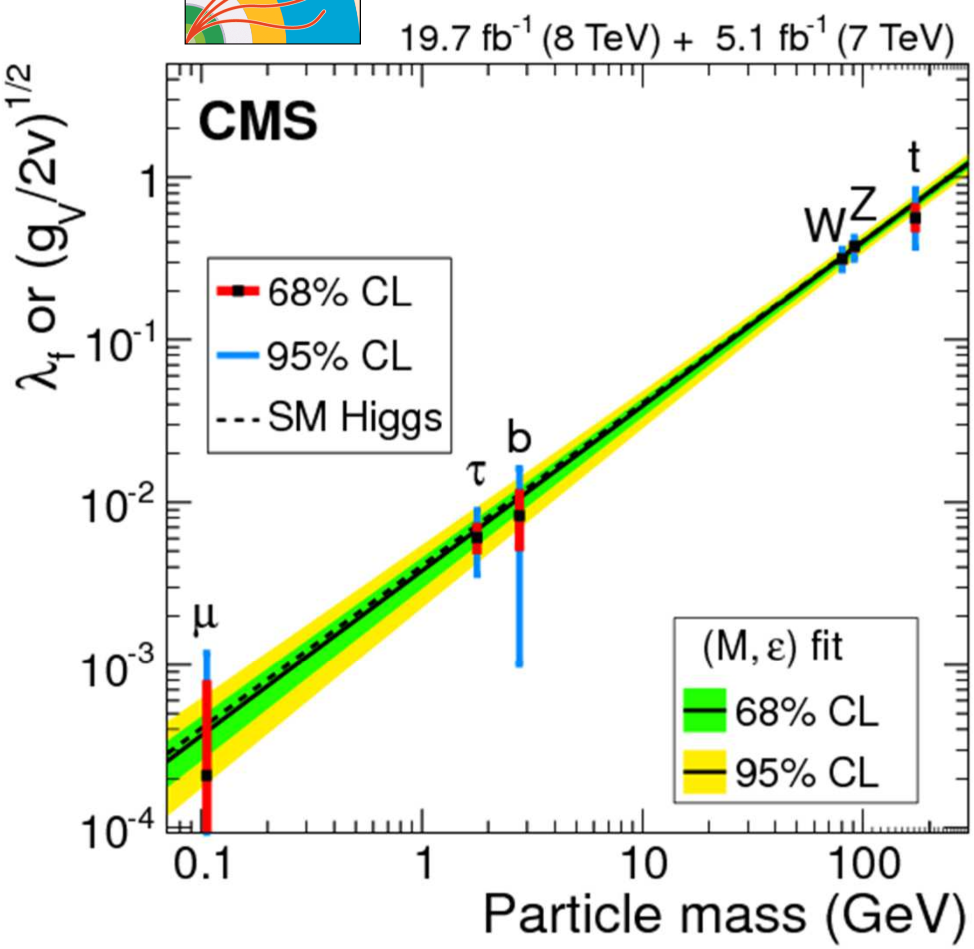
# Direct measurements of Higgs Yukawa couplings

**vs. mass**

arXiv: 1507.04548, EPJC 76 (2016) 6




EPJC 75 (2015) 212




Hbb updated from PRD 92 (2015) 032008

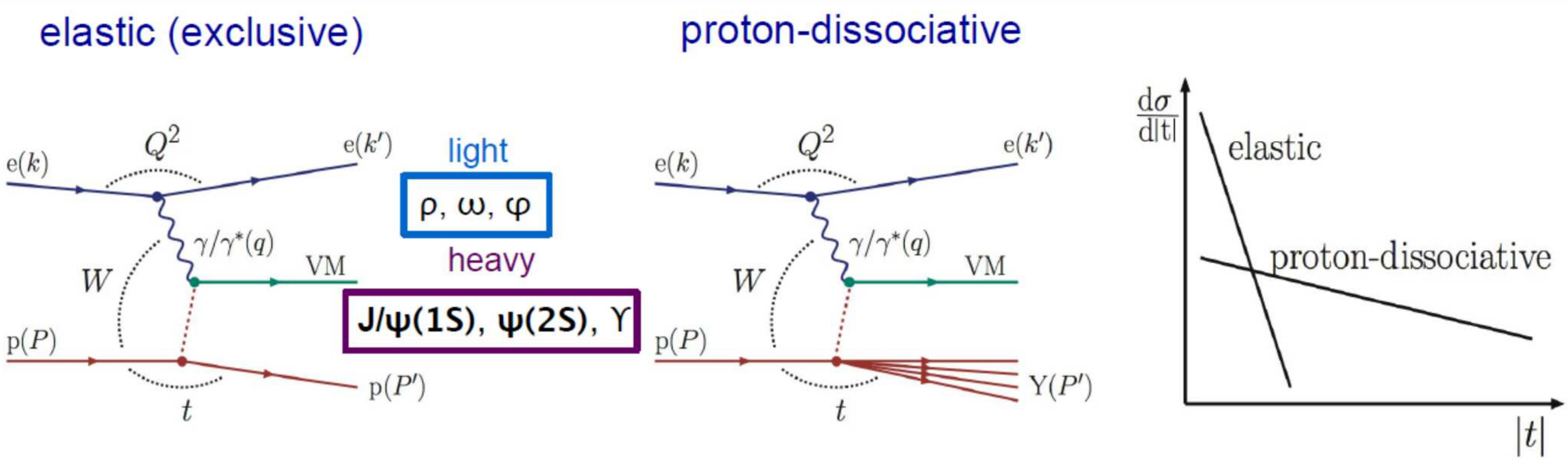
to be updated from JHEP08 (2016) 045

# Measurement of the cross-section ratio $\sigma_{\psi(2S)}/\sigma_{J/\psi(1S)}$ in deep inelastic exclusive ep scattering at HERA

## Diffractive vector meson (VM) production at HERA

arXiv 1605.01946

courtesy N. Kovalchuk



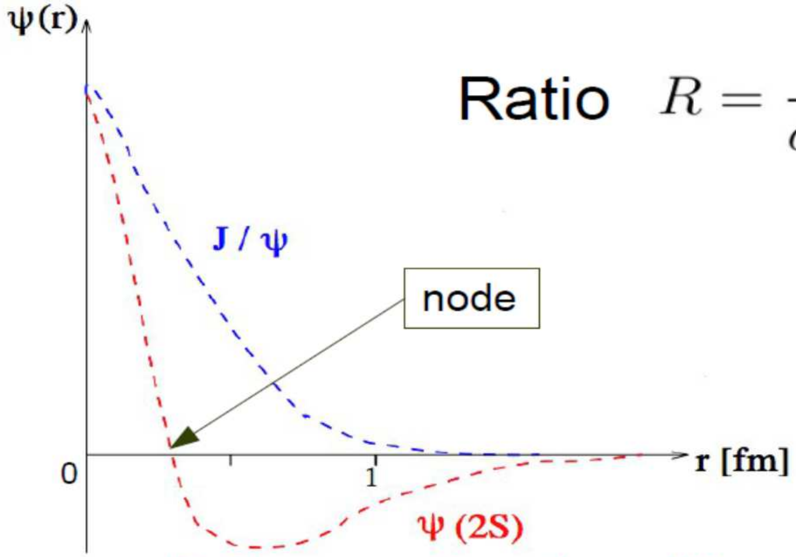

### Kinematics of the process

| | | |
|---|---|---|
| $Q^2$ — photon virtuality | $Q^2 < 1$ GeV$^2$ — γp<br>$Q^2 \gtrsim 1$ GeV$^2$ — **DIS** | $Q^2 = -q^2 = -(k - k')^2$ |
| W — photon-proton CMS energy | | $W^2 = (q + P)^2$ |
| t — 4-mom. transfer squared at proton vertex | | $t = (P - P')^2$ |

# Measurement of the cross-section ratio $\sigma_{\psi(2S)}/\sigma_{J/\psi(1S)}$

## $\sigma_{\psi(2S)}/\sigma_{J/\psi(1S)}$ in DIS

courtesy N. Kovalchuk




Ratio $R = \frac{\sigma_{\gamma p \to \psi(2S) p}}{\sigma_{\gamma p \to J/\psi\, p}}$ gives information about the dynamics of hard process

sensitive to radial wave function of charmonium

ψ(2S) wave function different from J/ψ wave function:

- Has a node at ≈ 0.35 fm
- $<r^2_{\psi(2S)}> \approx 2 <r^2_{J/\psi(1S)}>$

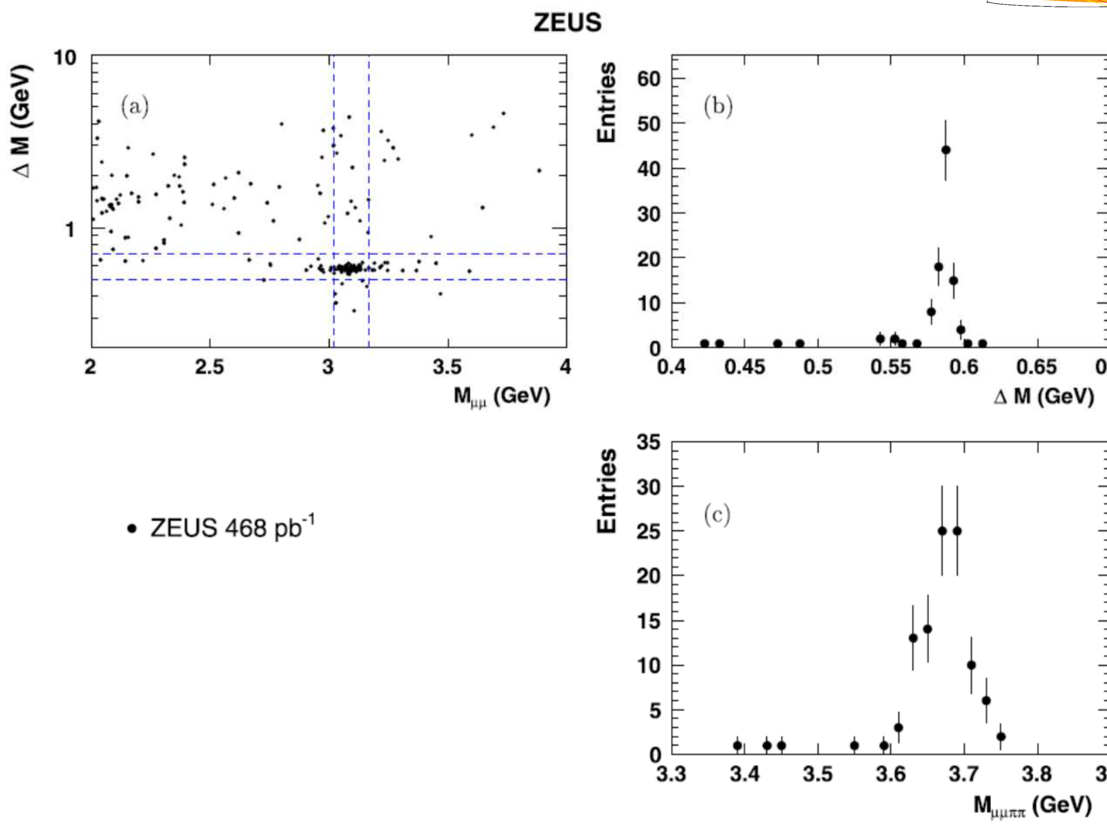
pQCD model calculations predicts R ~ 0.17 (PhP)
and rise of R with $Q^2$ (DIS)

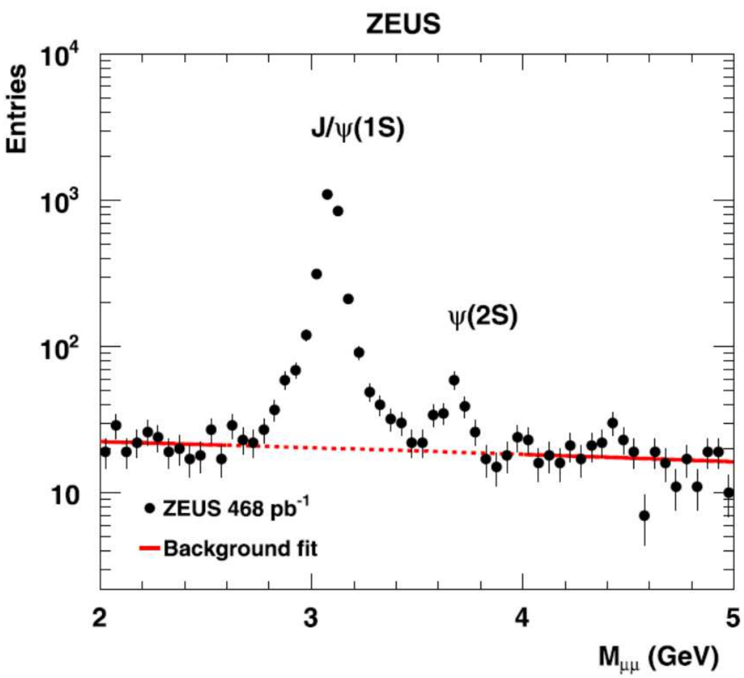
4

# Measurement of the cross-section ratio $\sigma_{\psi(2S)}/\sigma_{J/\psi(1S)}$

arXiv:1605.01946, Nucl. Phys. B909 (2016) 934

simultaneous measurement of $J/\psi$, $\psi' \to \mu\mu$

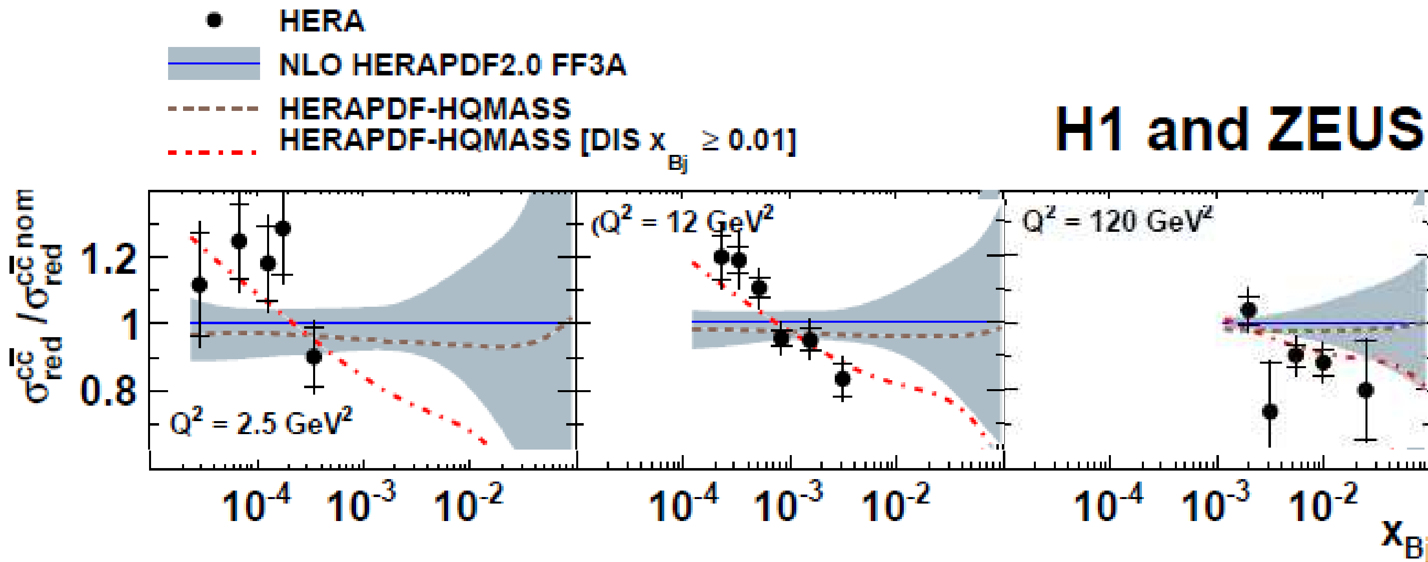


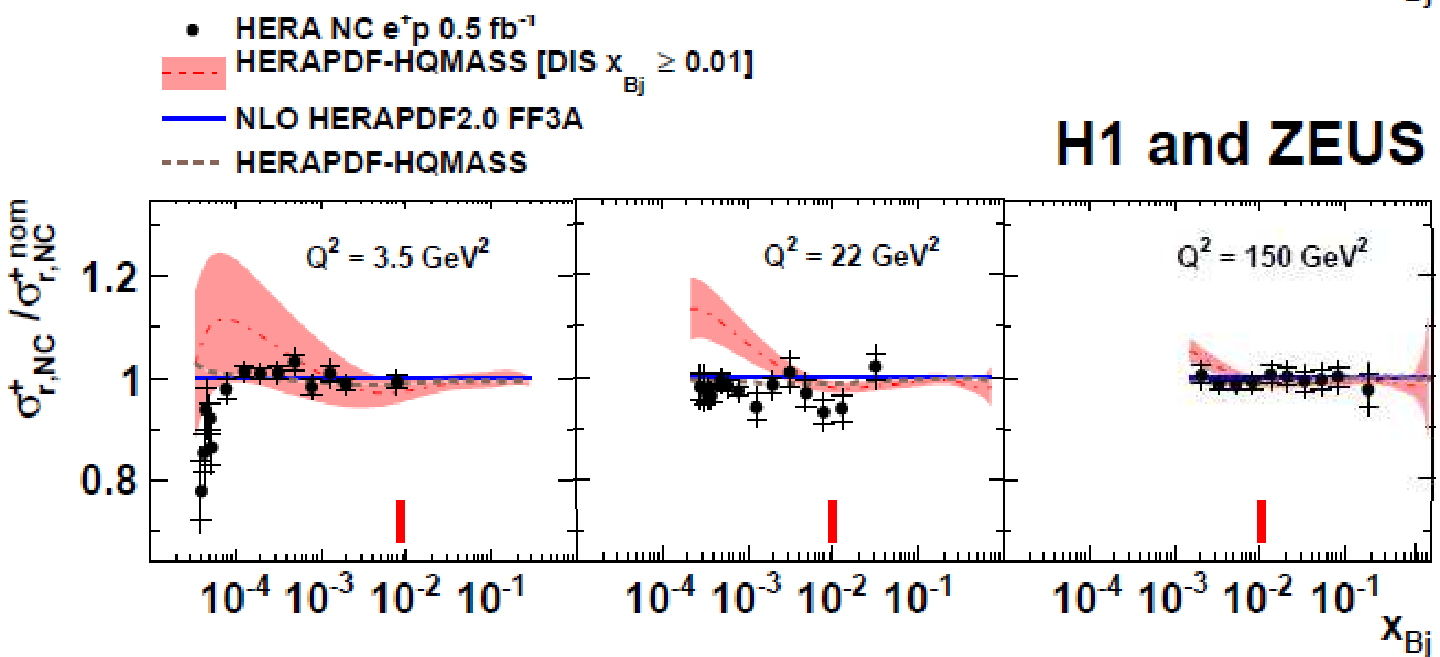

$\psi' \to J/\psi\ \pi\pi \to \mu\mu\pi\pi$

# 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**



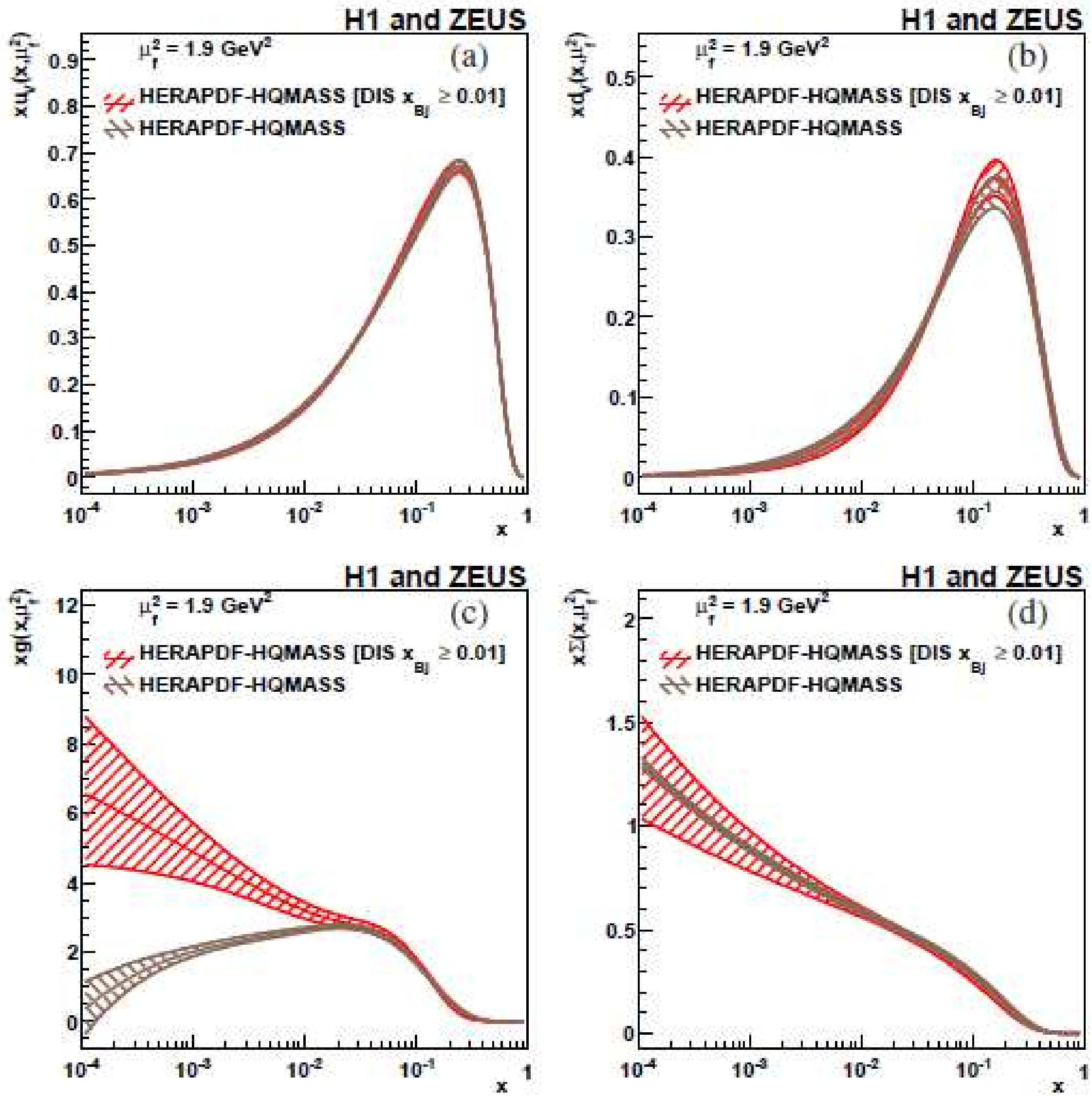

-> not a solution (but hint)

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

*Eur.Phys.J.C* 78 (2018) 473, 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?

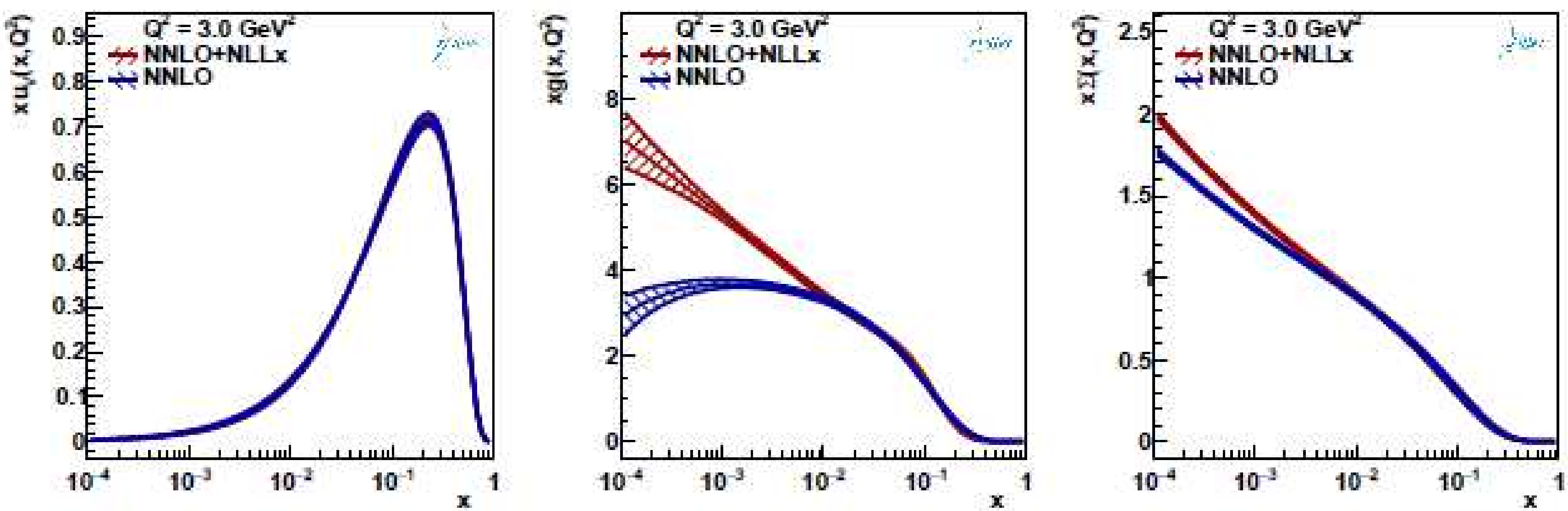



**Figure 3** The up valence PDF $xu_v$, the gluon PDF $xg$ and the total singlet PDF $x\Sigma$ for the final fits with (NNLO+NLL$x$) and without (NNLO) $\ln(1/x)$ resummation.

# QCD fit

Eur.Phys.J.C 78 (2018) 473, 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**

# Lesson: kinematic coverage

- The EIC kinematic coverage strongly overlaps with HERA, fixed target, and forward coverage at the LHC (LHCb, also e.g. CMS after high luminosity upgrade)

- HERA data were/are essential to disentangle and calibrate the two x `branches' at LHCb

->

EIC data will have a similar essential role w.r.t. phase 2 LHC data; further enhanced by the availability of 'nuclear' data vs. heavy ion collisions