

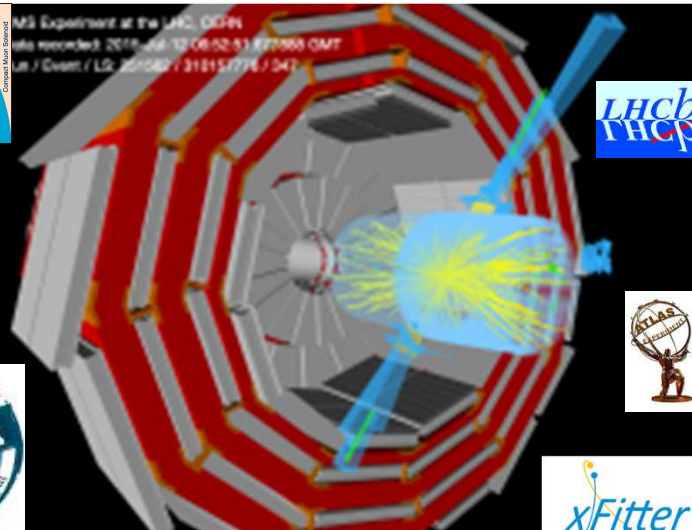
Charm production at HERA, proton structure, the charm mass, and Higgs Yukawa couplings

Achim Geiser
DESY Hamburg

(member of the

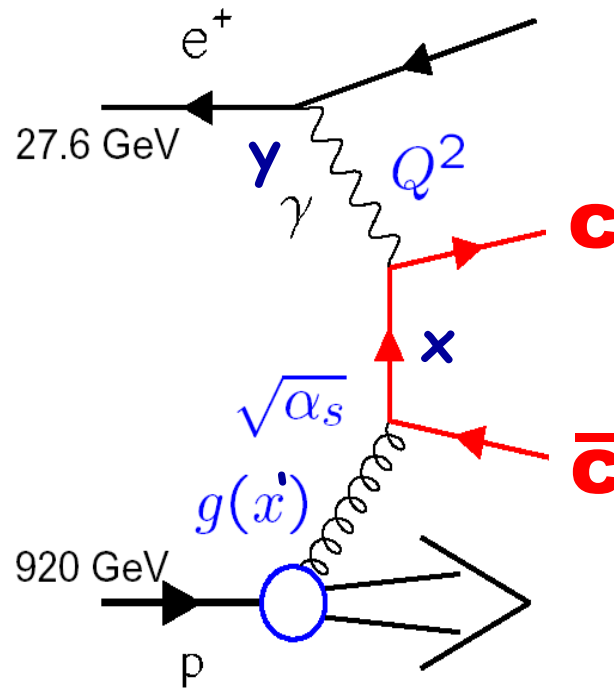
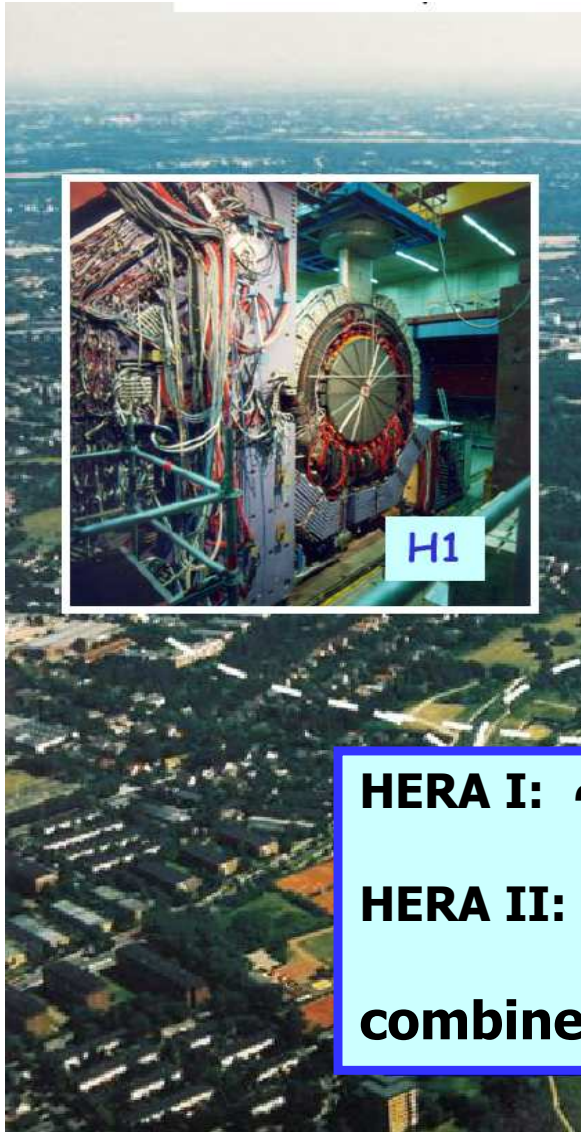
ZEUS, CMS and PROSA
collaborations)

Charm workshop, Bologna, 8. 9. 2016

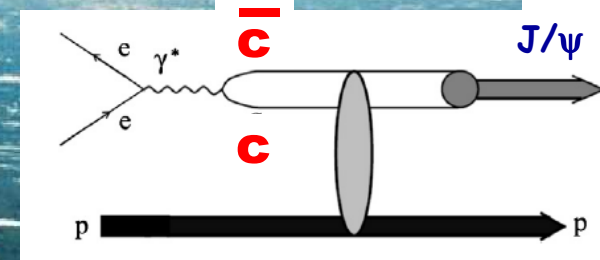


- Summary of and latest results on charm production at HERA  
- Charm and proton structure    
- Recent charm quark mass measurements   
- Running quark masses and Higgs Yukawa couplings    

The HERA ep collider and experiments



up to 30%
of cross section

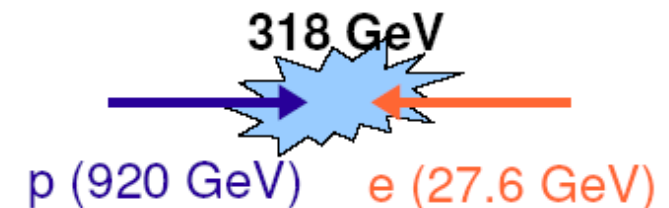


HERA I: $\sim 130 \text{ pb}^{-1}$ (physics)

HERA II: $\sim 380 \text{ pb}^{-1}$ (physics)

combined: $\sim 2 \times 0.5 \text{ fb}^{-1}$

HERA:



Review of open charm at HERA

arXiv:1506.07519

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

recent
review:

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



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. Lisovyi¹
DESY, Hamburg, Germany

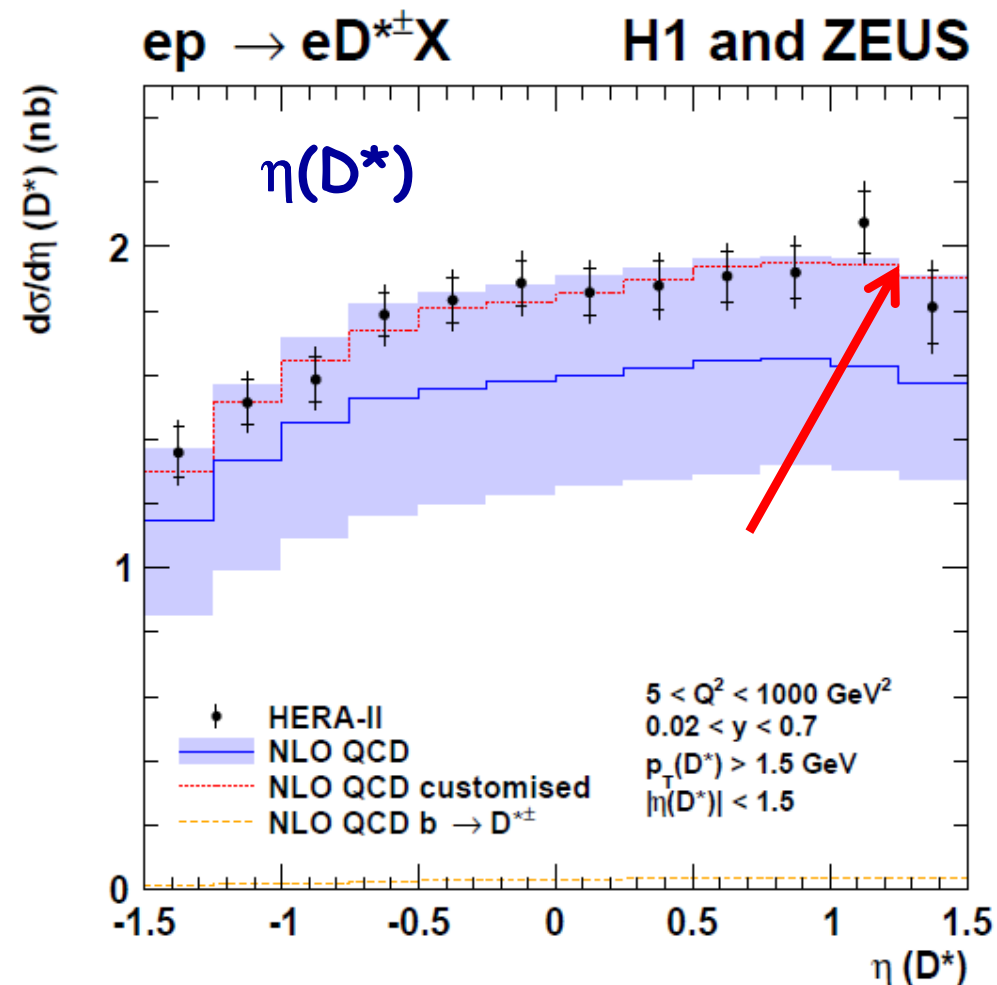
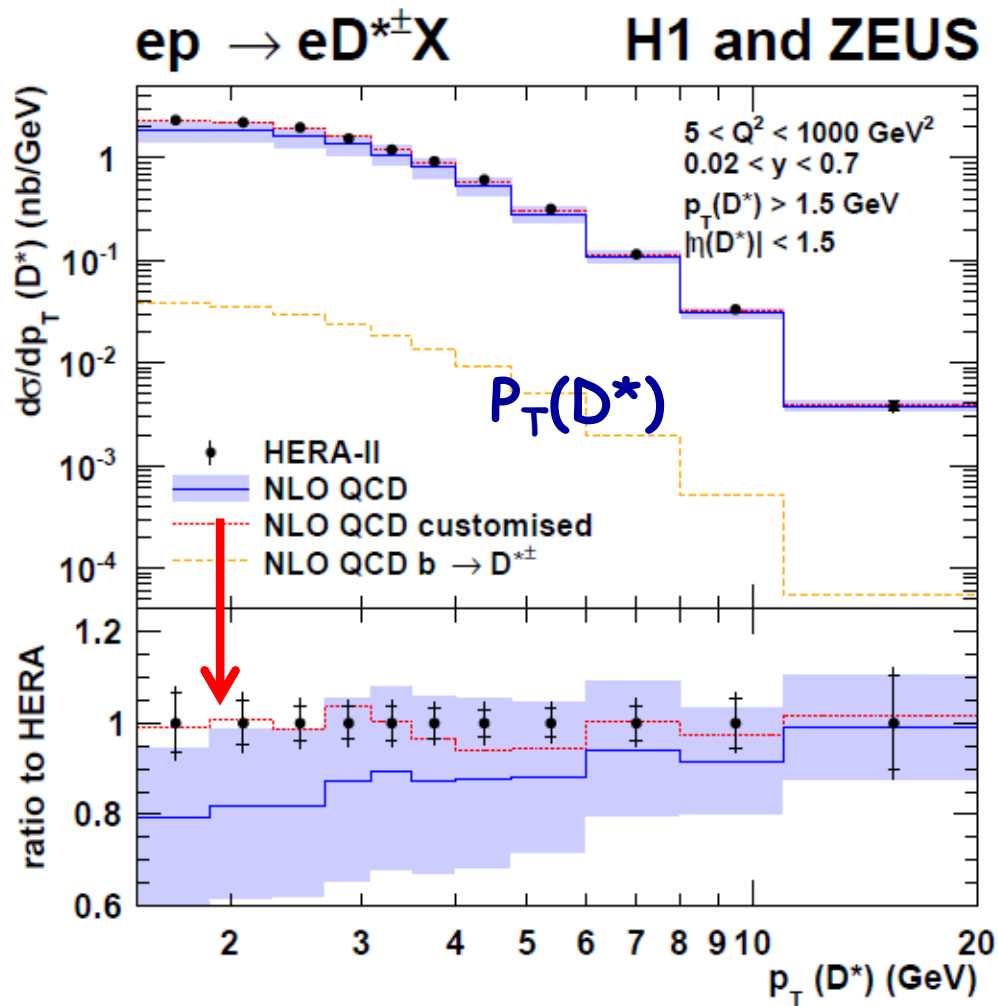
 CrossMark

ARTICLE INFO	ABSTRACT
Keywords: Charm Beauty Top HERA DIS Photoproduction	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. © 2015 Elsevier B.V. All rights reserved.



Combined D^* cross sections in DIS

arXiv:1503.06042, JHEP 1509 (2015) 149

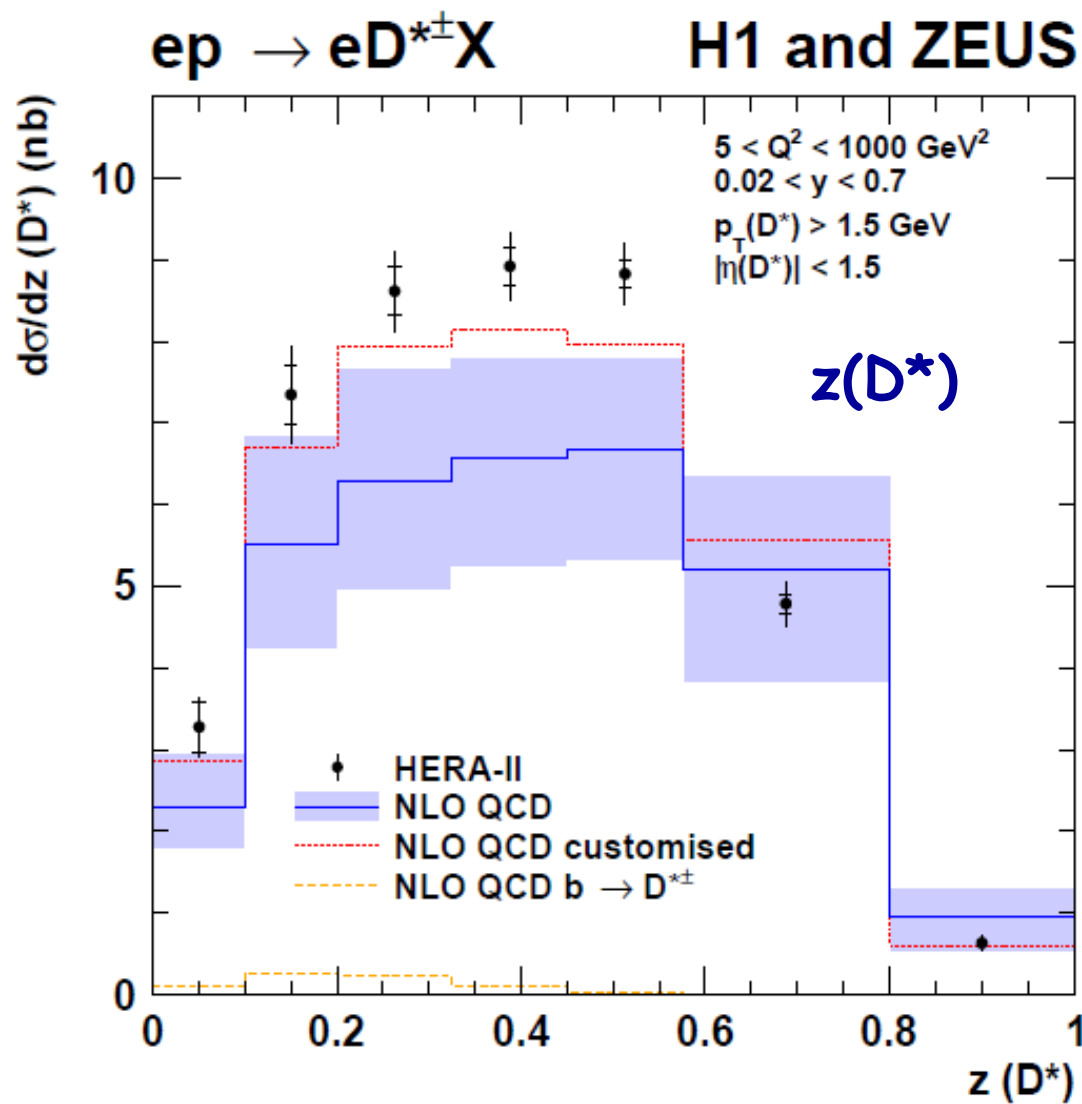


customised choice: - reduced renormalisation scale
 - modified scale dependence of fragmentation
 - slightly lower charm mass
 (all within uncertainty)



Charm fragmentation function

arXiv:1503.06042, JHEP 1509 (2015) 149



Combination of
H1 and ZEUS
 D^* measurements

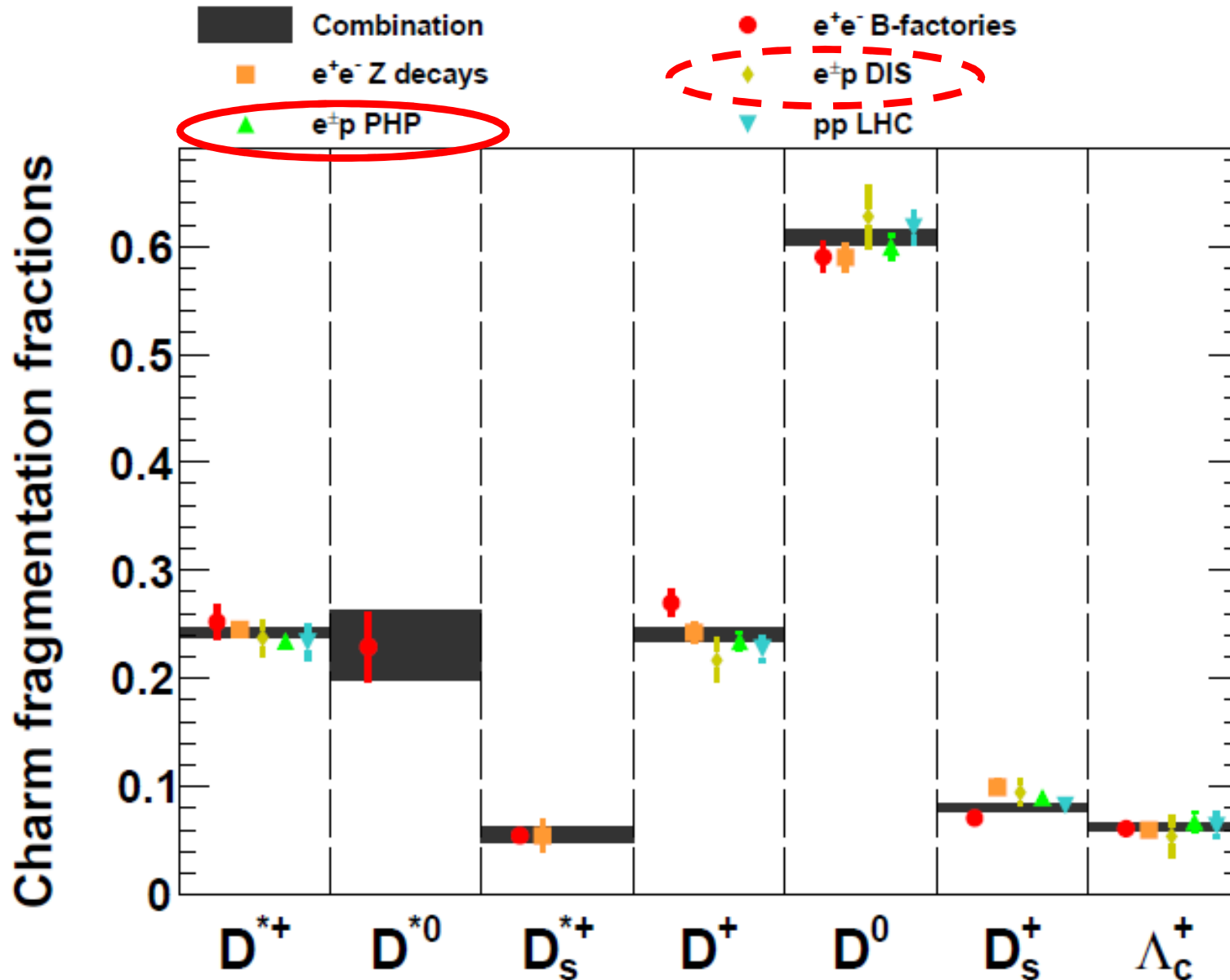
example: z
(energy/momentum fraction
taken by D^*),
shape directly sensitive
to fragmentation
parameters

more work on theory
needed

Charm fragmentation fractions

arXiv 1509.01061, EPJC 76 (2016) 397

Lisovsky, Verbytskyi, Zenaiev



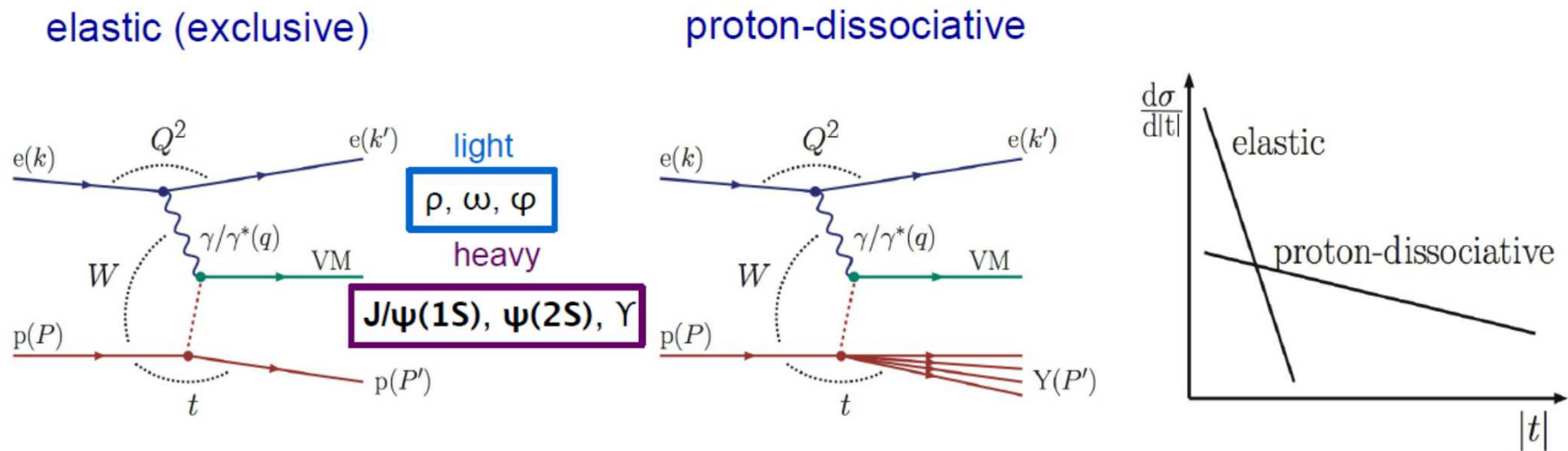
universality
confirmed

HERA
measurements
make very
substantial
contribution
to world
average

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 $Q^2 < 1 \text{ GeV}^2$ — γp
 $Q^2 \gtrsim 1 \text{ GeV}^2$ — **DIS**

W — photon-proton CMS energy

t — 4-mom. transfer squared at proton vertex

$$Q^2 = -q^2 = -(k - k')^2$$

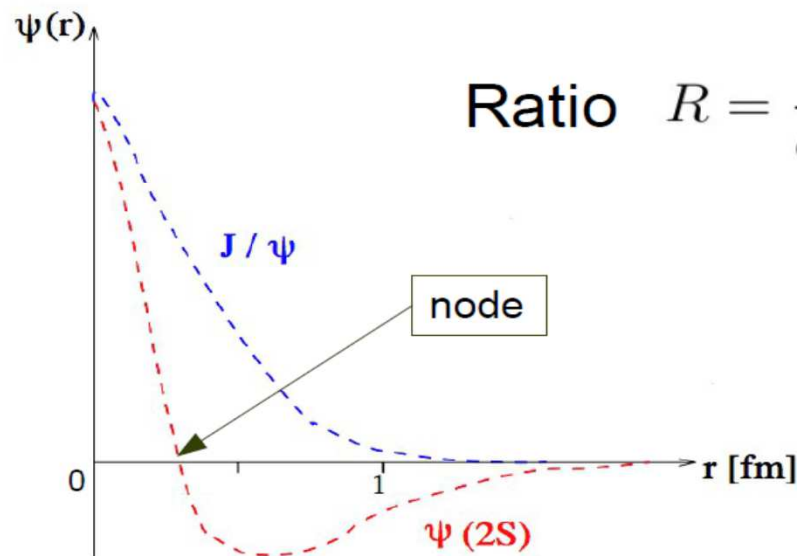
$$W^2 = (q + P)^2$$

$$t = (P - P')^2$$

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

sensitive to radial wave function of charmonium

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

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

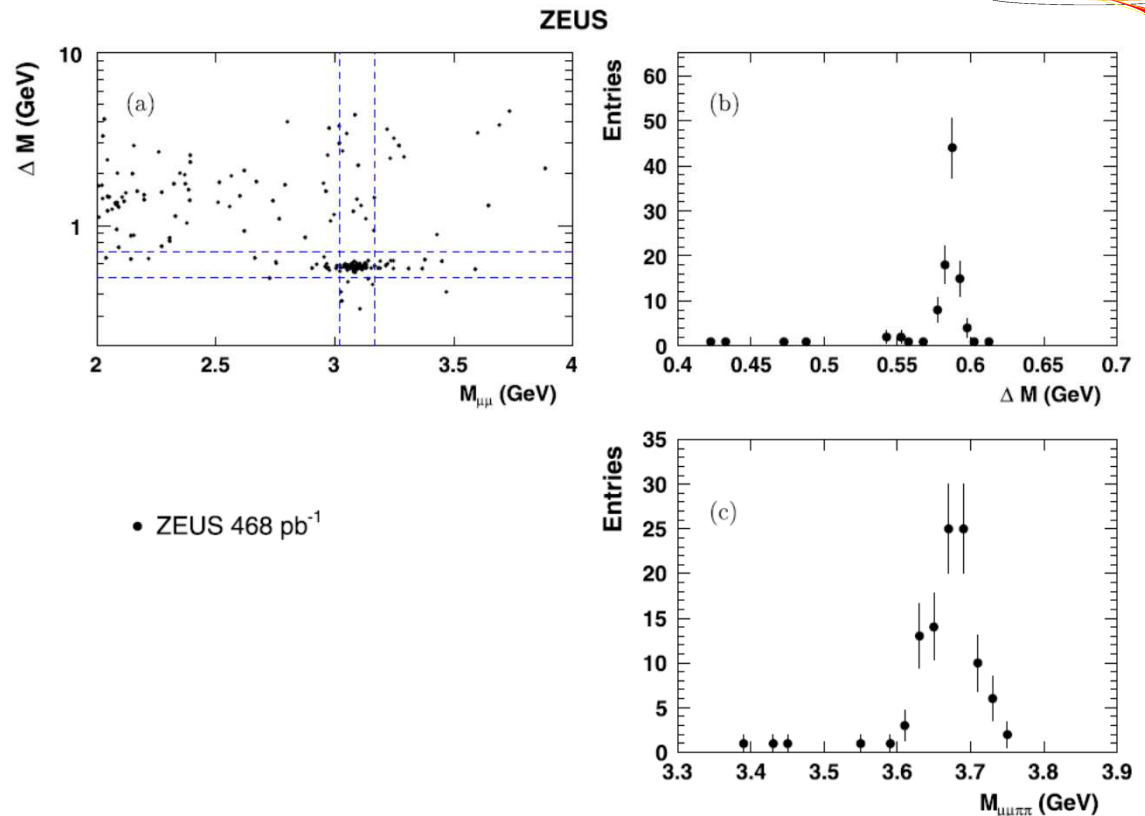
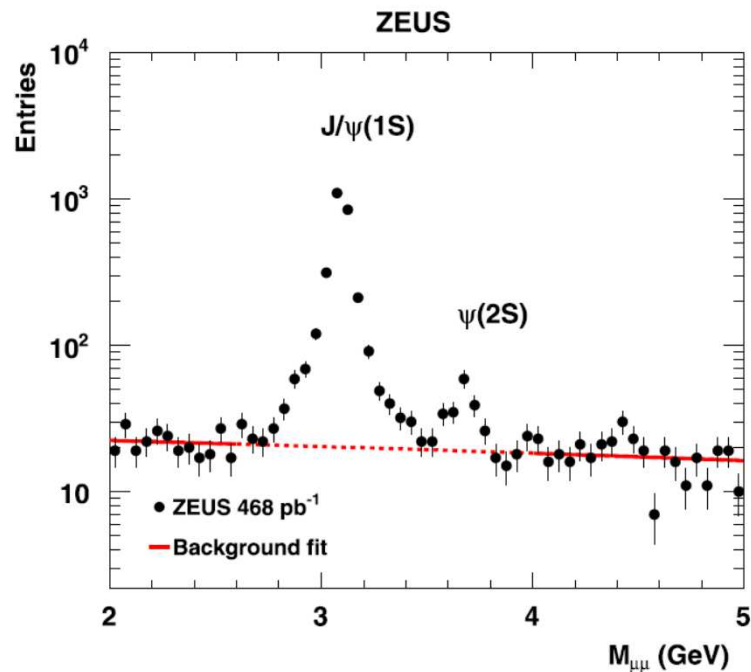
pQCD model calculations predicts $R \sim 0.17$ (PhP)
and rise of R with Q^2 (DIS)

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

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



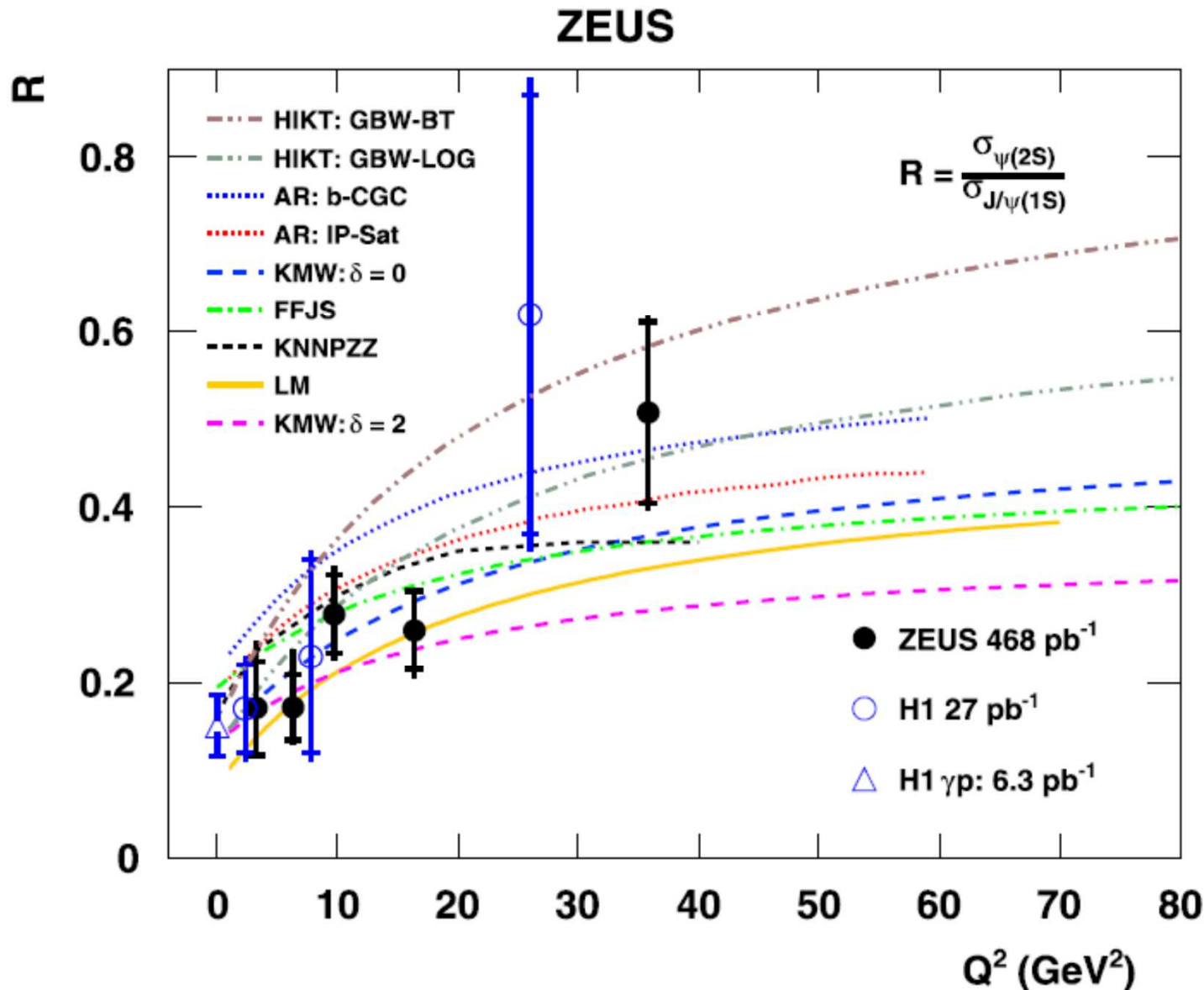
simultaneous
measurement of
 $J/\psi, \psi' \rightarrow \mu\mu$



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

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

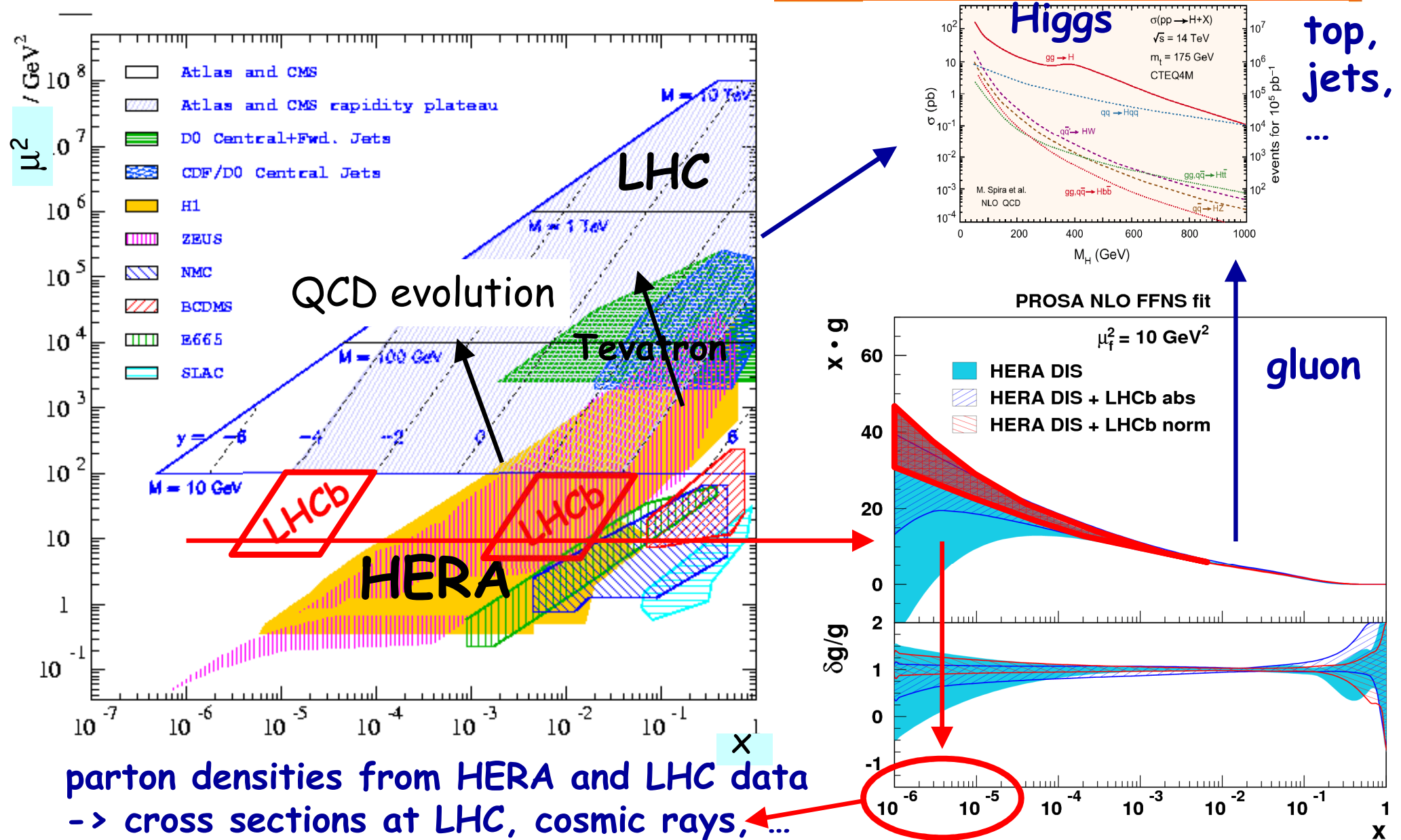
arXiv:1605.01946, Nucl. Phys. B909 (2016) 934



result starts
to discriminate
between
different
theory
predictions

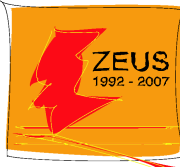
(for more details
see N. Kovalchuk,
DIS16)

Parton density functions (PDF)

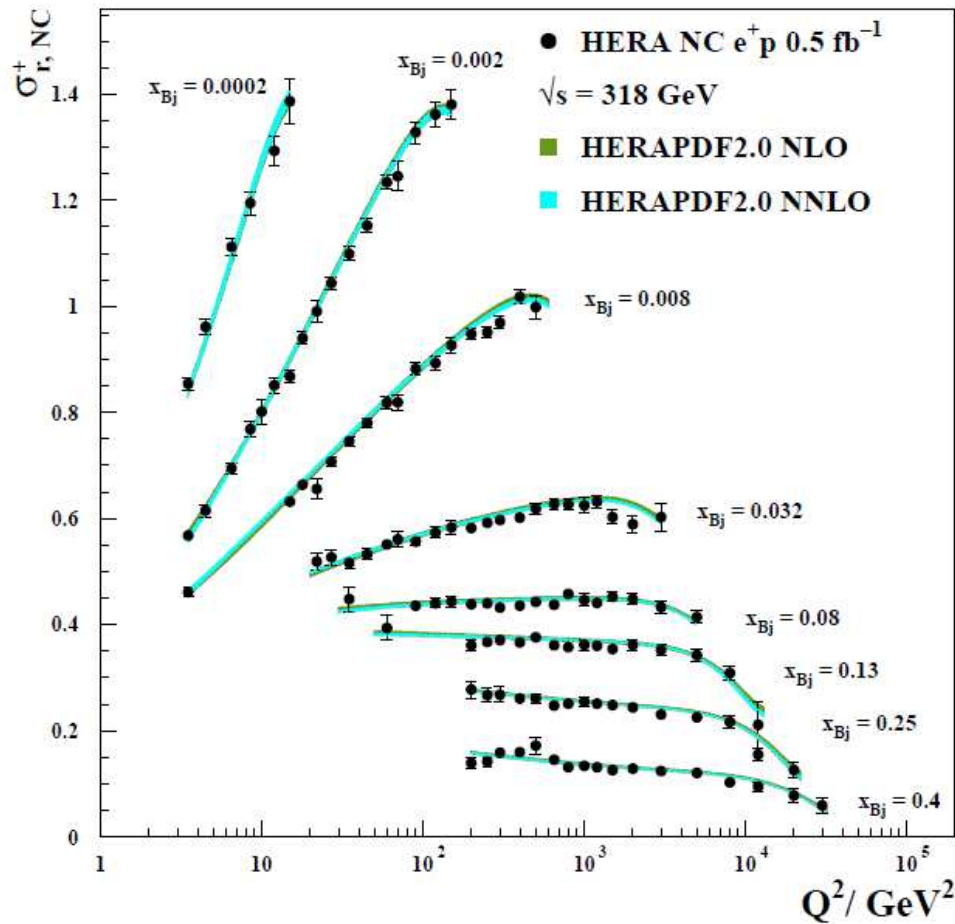


Final HERA inclusive DIS combination and PDF fit

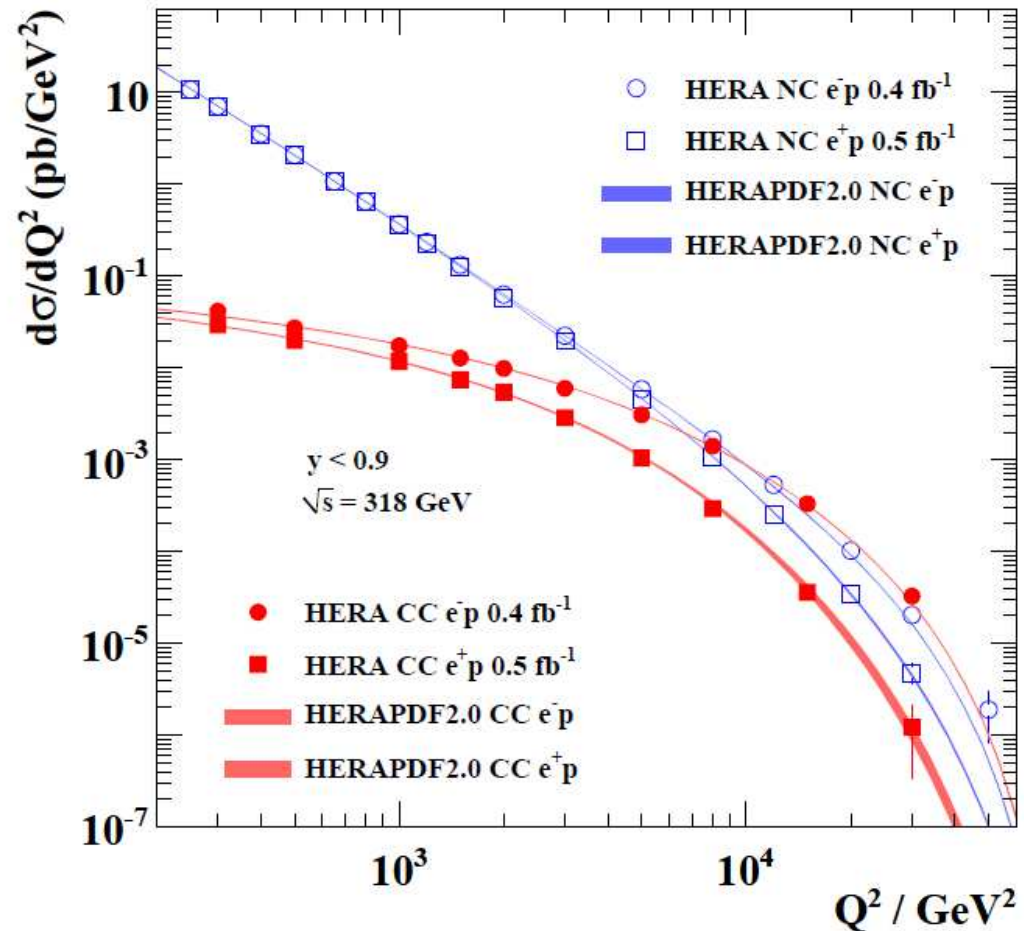
arXiv 1506.06042, EPJC 75 (2015) 580



H1 and ZEUS



H1 and ZEUS



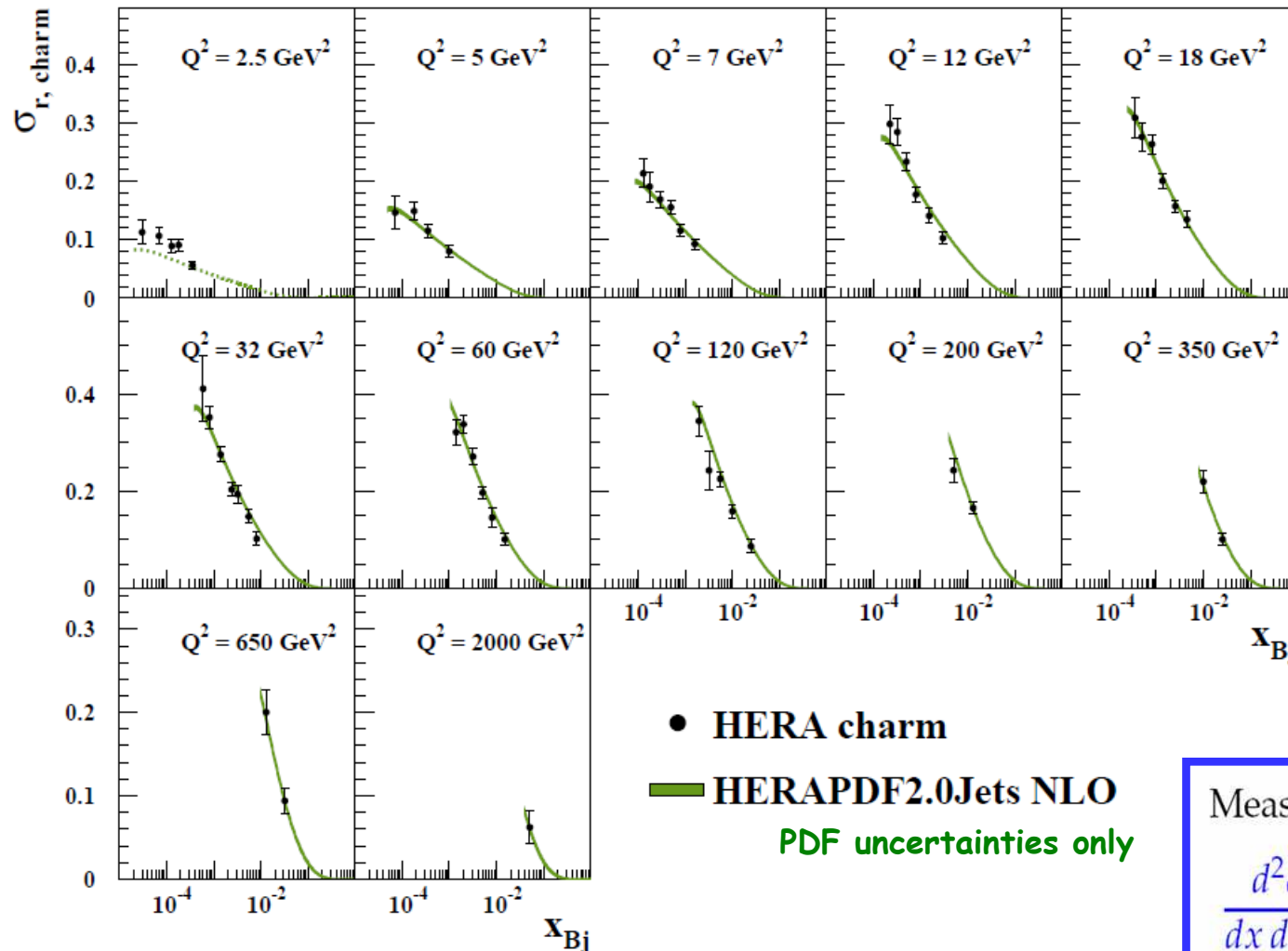
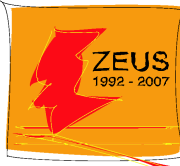
includes fit of inclusive charm + jet DIS data

arXiv 1506.06042, EPJC 75 (2015) 580



charm:

H1 and ZEUS



well
described
by fit

Measure cross section

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

Constraint of gluon at very low x

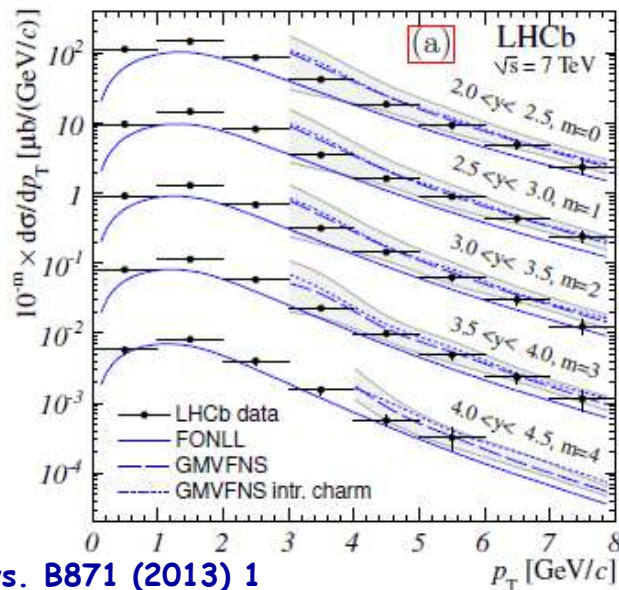
arXiv 1503.04581, Eur.Phys.J. C75 (2015) 396



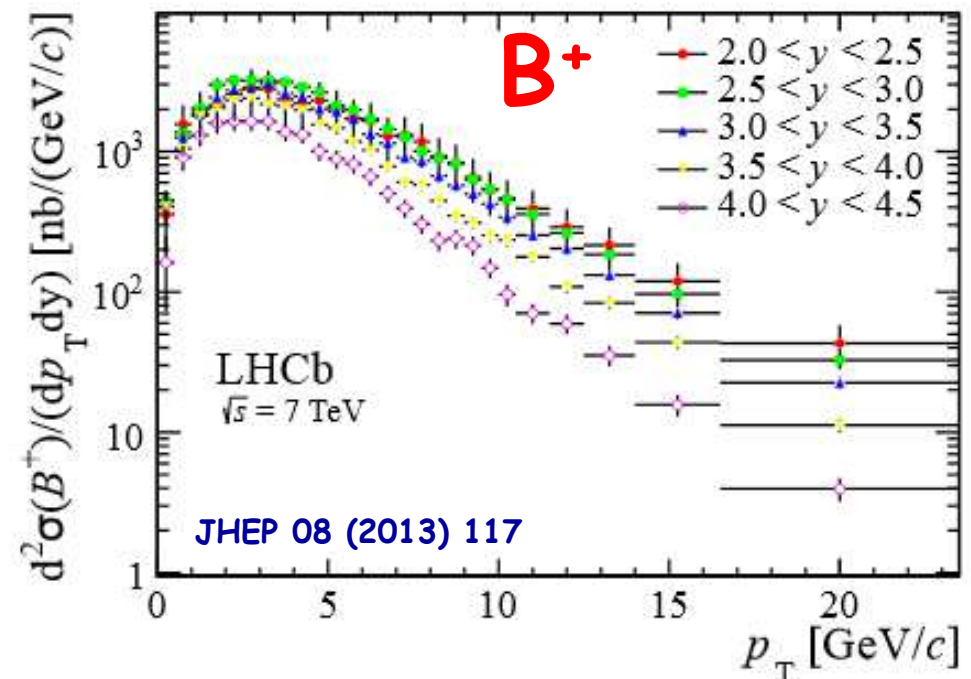
Combined fit of

- 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

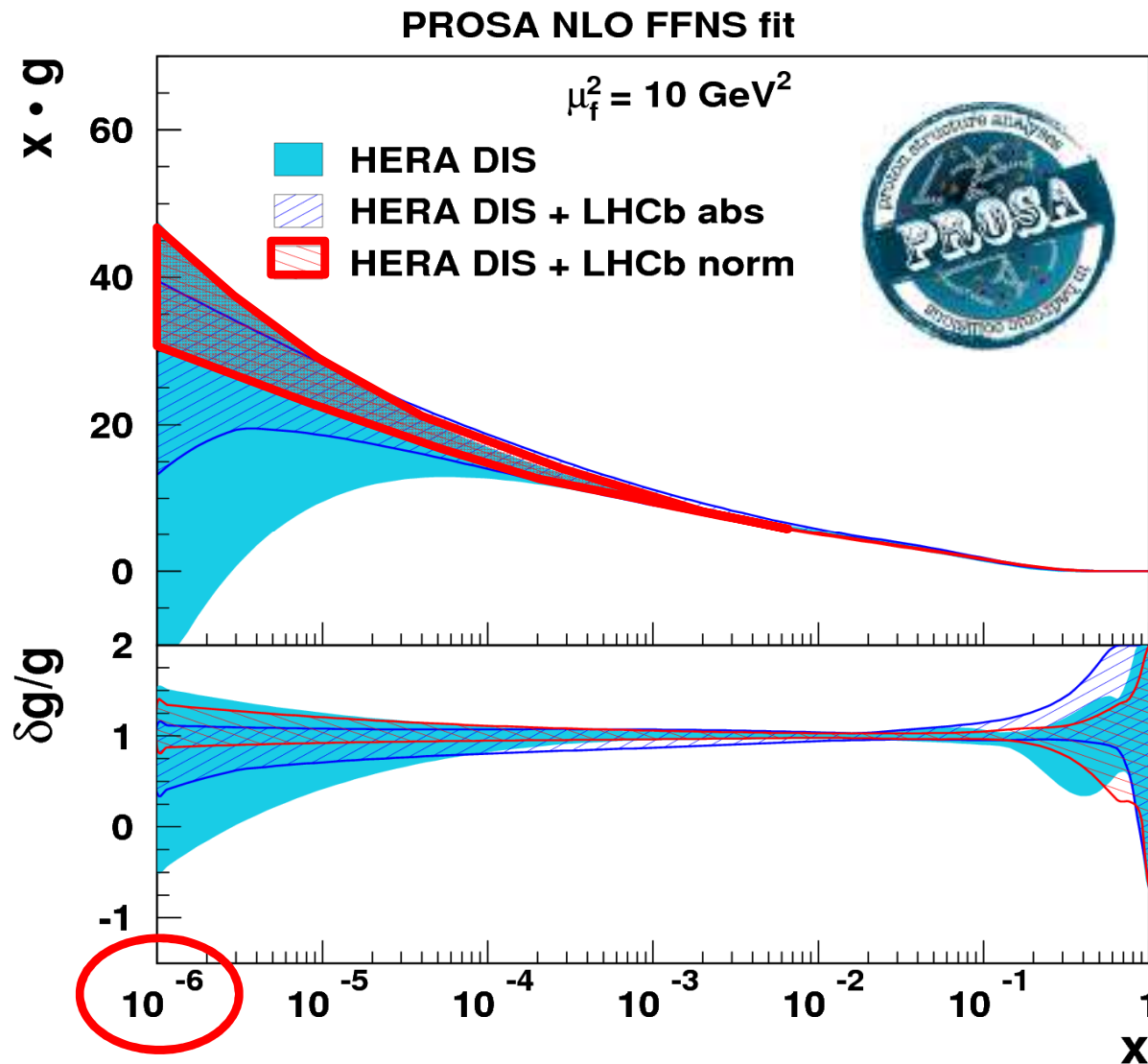


Nucl.Phys. B871 (2013) 1



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 $x \ll 10^{-4}$

already in use to constrain
cosmic ray prompt
neutrino spectrum
(e.g. Ice Cube)

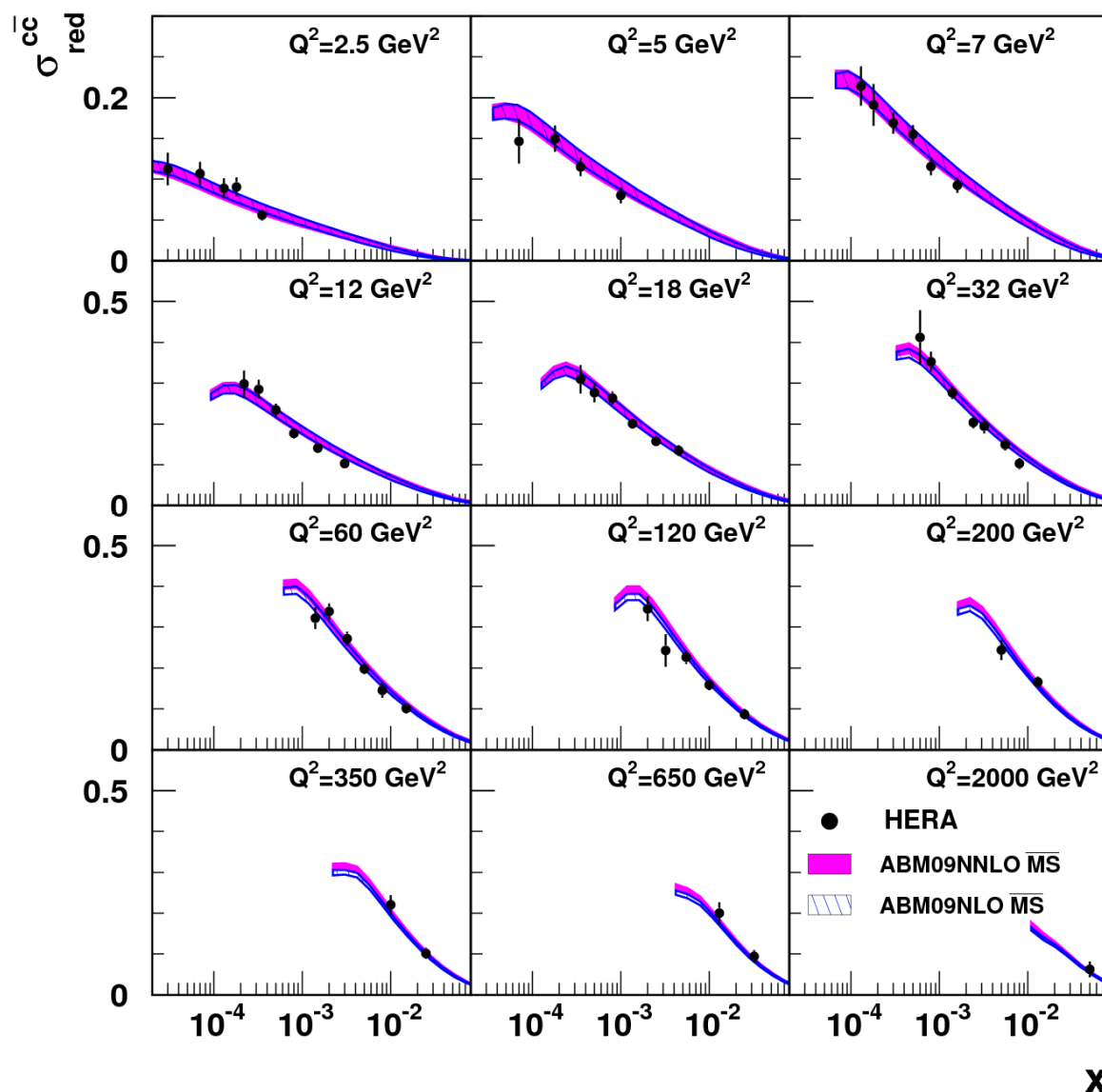


Combined HERA charm data



EPJC 73 (2013) 2311

H1 and ZEUS



comparison to ABM FFNS

very good description
of data
in full kinematic range

unambiguous treatment
of m_c in all terms of
calculation

here: $\overline{MS}$ running mass

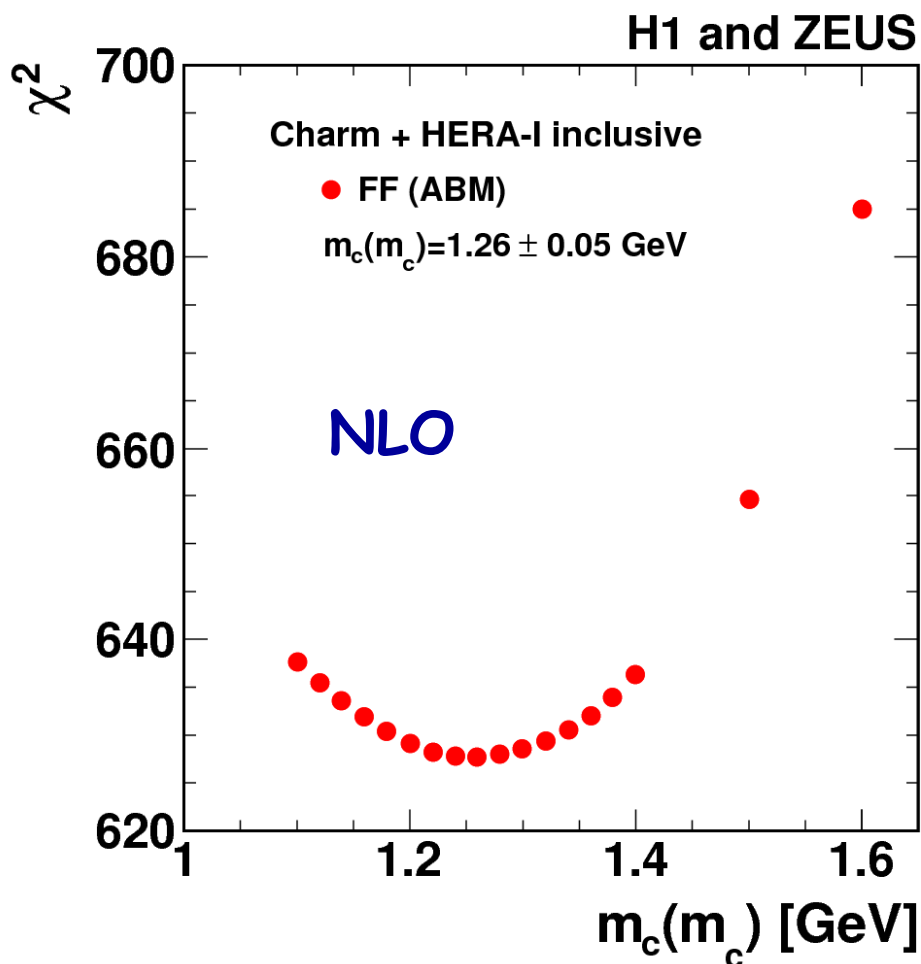
(similar predictions for
pole mass)



measurement of $\overline{MS}$ charm mass



EPJC 73 (2013) 2311



simultaneous fit of
combined charm data
and inclusive HERA I
DIS data

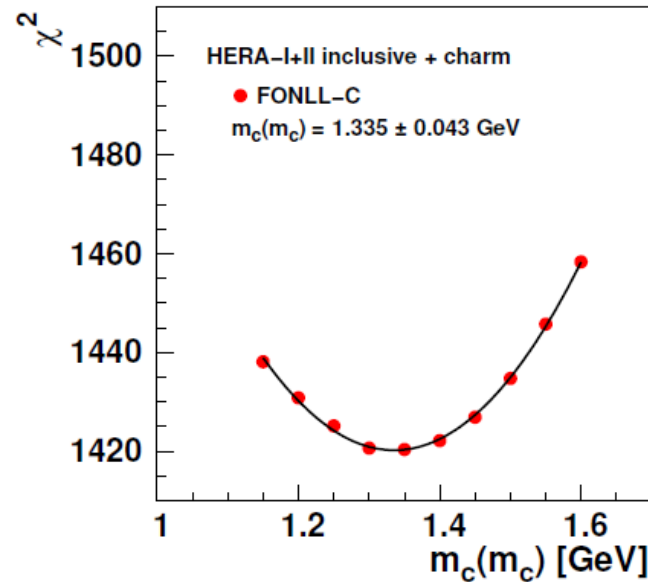


$$m_c(m_c) = 1.26 \pm 0.05_{\text{exp}} \pm 0.03_{\text{mod}} \pm 0.02_{\alpha_s} \text{ GeV}$$

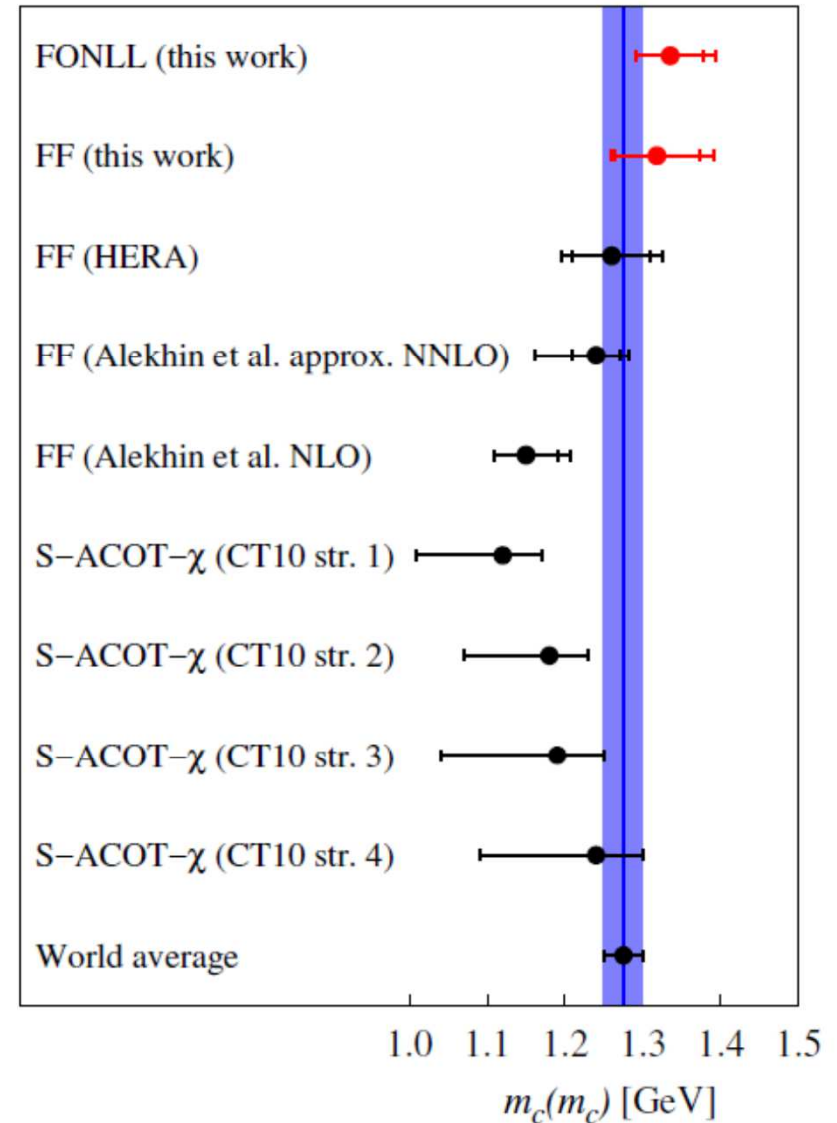
PDG: 1.275 ± 0.025 GeV (lattice QCD + time-like processes)

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

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 <i>et al.</i>) [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



running of α_s and quark masses

- α_s running depends on number of colours 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.

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

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

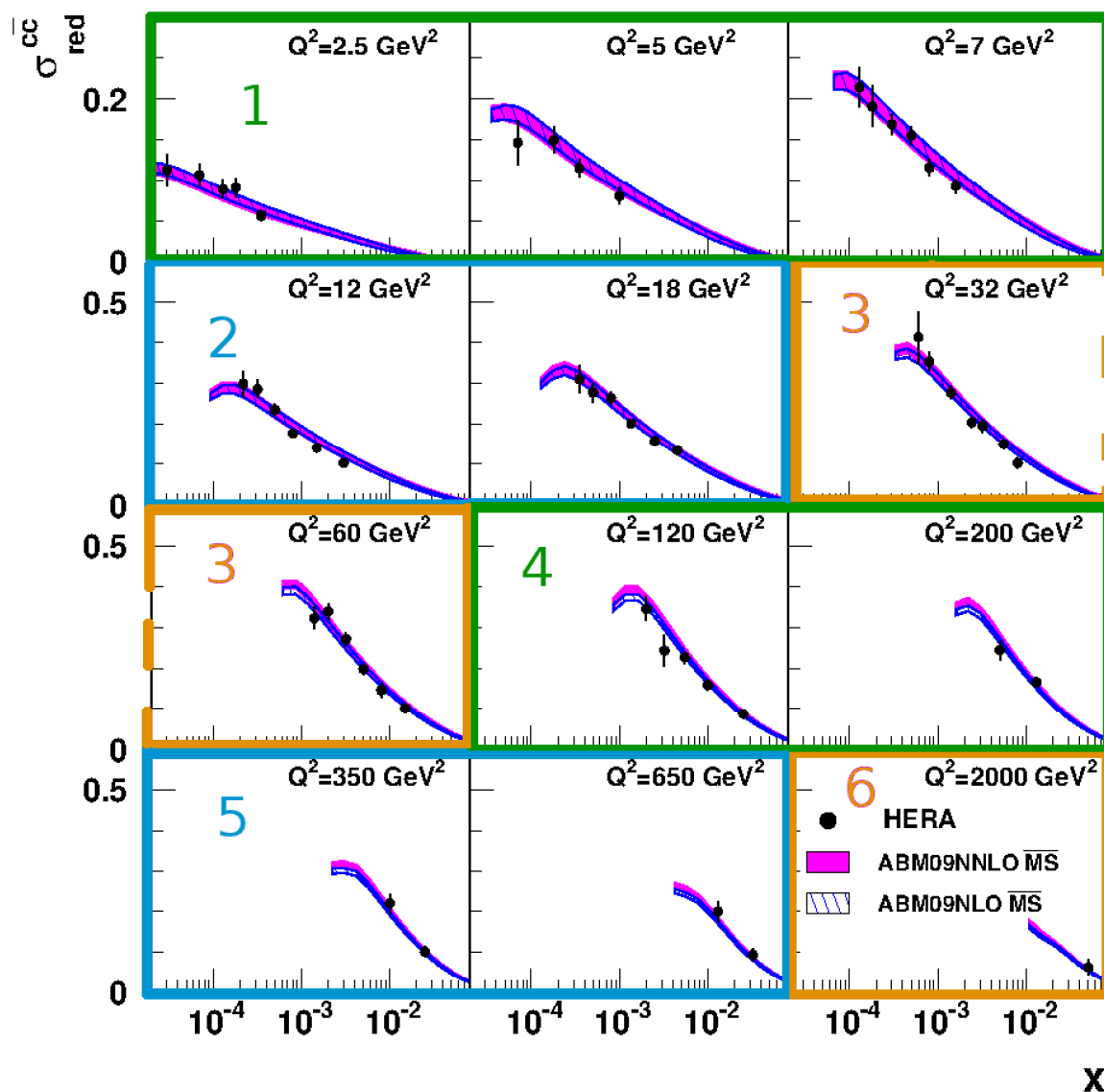


measurement of m_c running

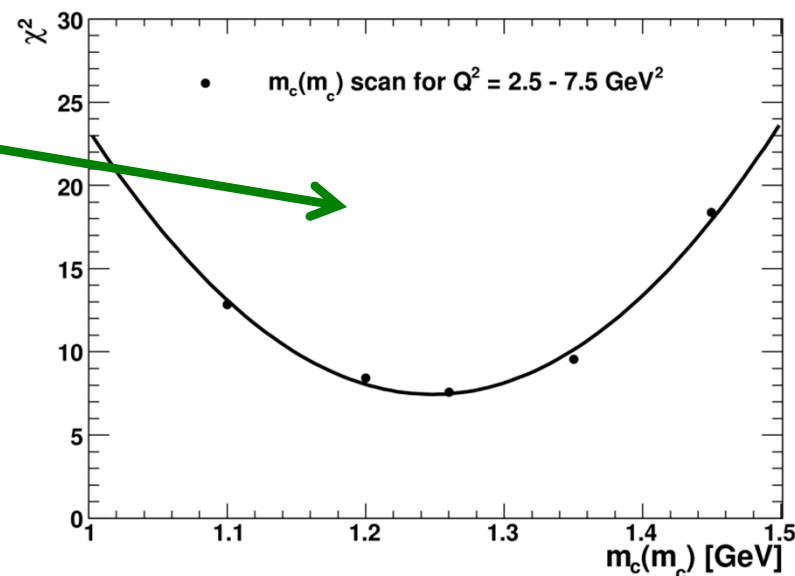


H1-prelim-14-071, ZEUS-prel-14-006, + S. Moch

H1 and ZEUS



H1 and ZEUS preliminary



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

(take log average for central scale)



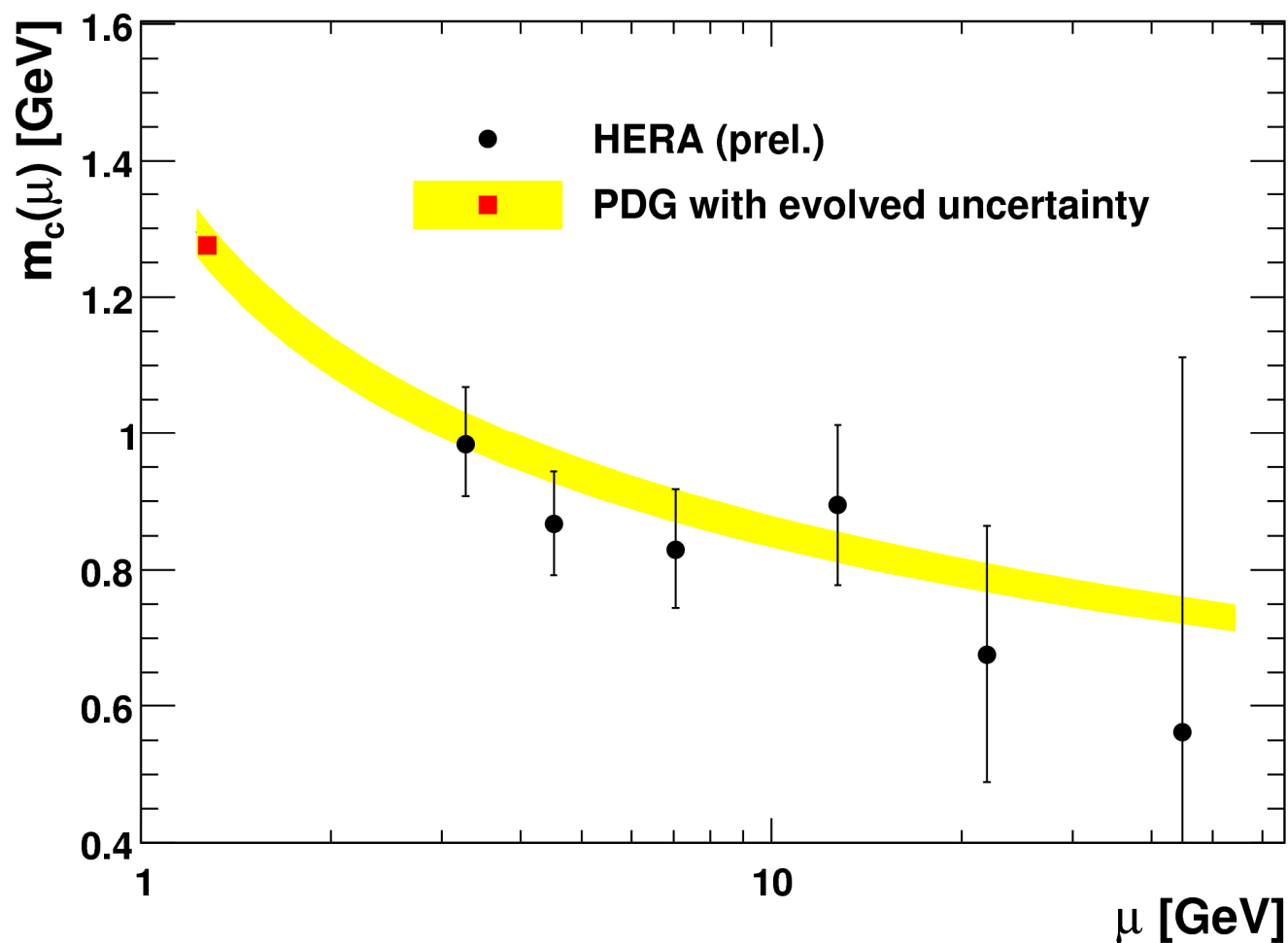
the running charm quark mass



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

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

H1 and ZEUS preliminary



running mass
concept in QCD
is self-consistent !

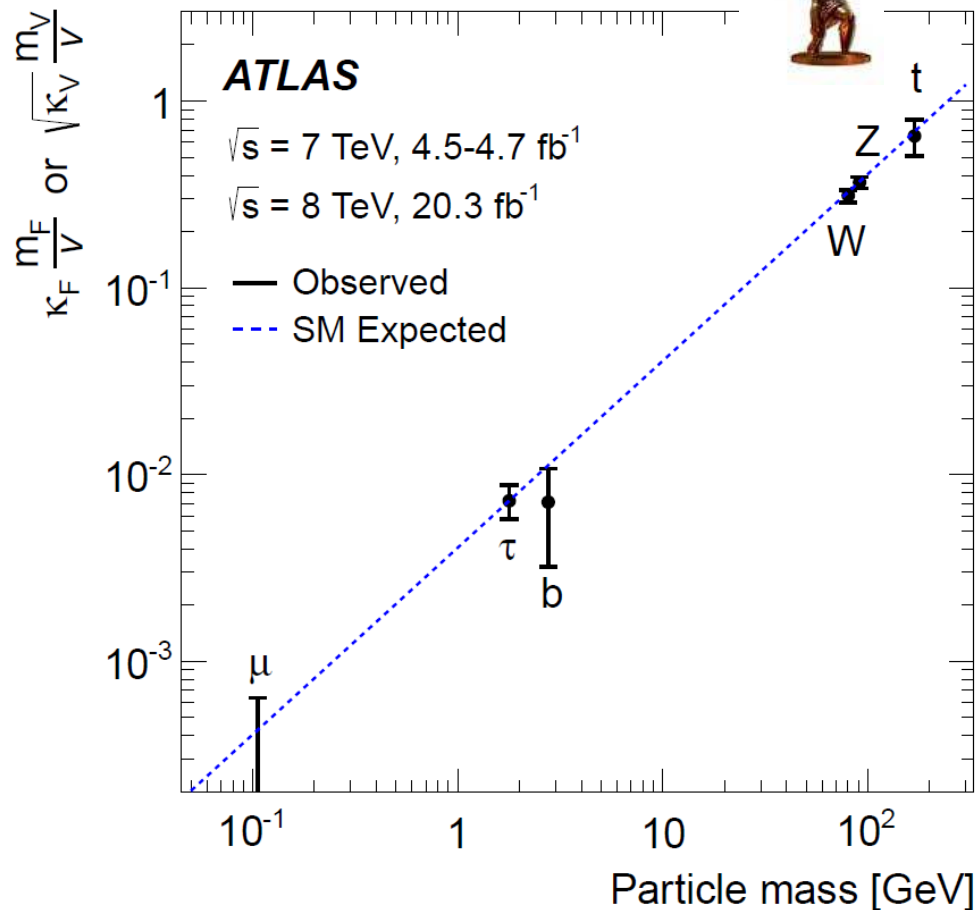
but mass is also
manifestation of
Higgs Yukawa
couplings !

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

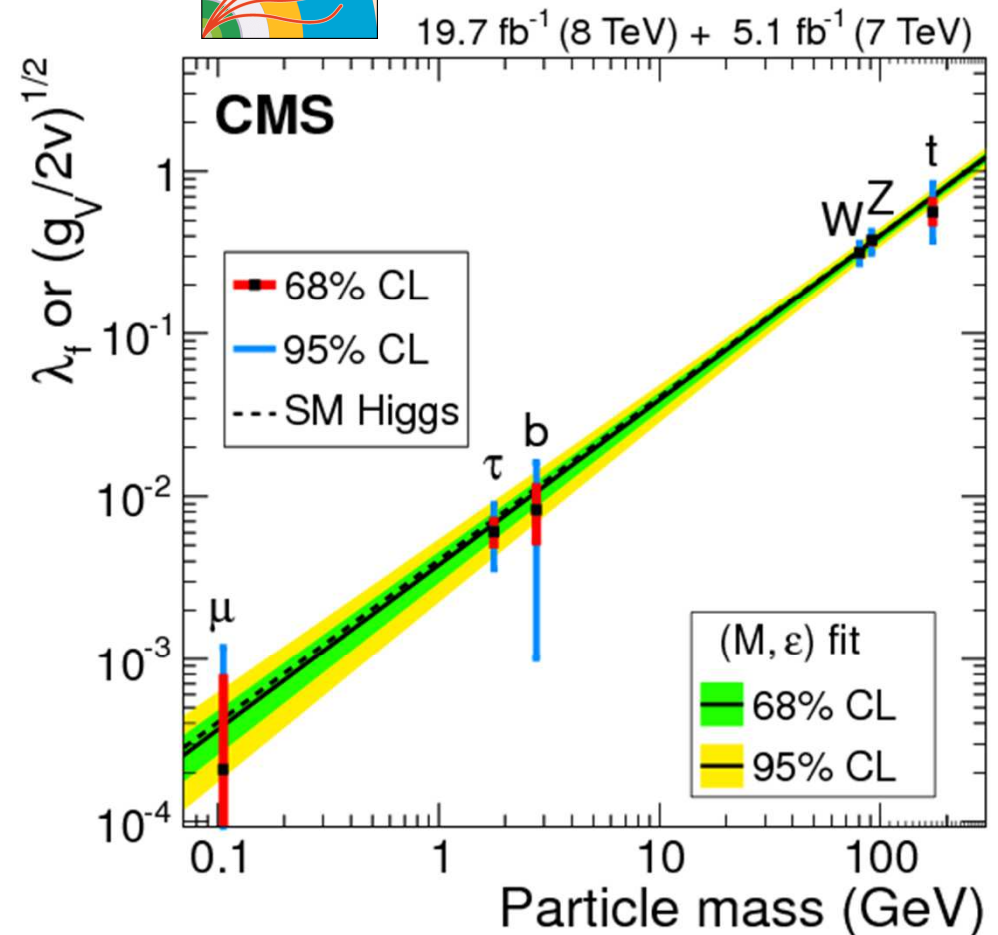
Direct measurements of Higgs Yukawa couplings

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

Running

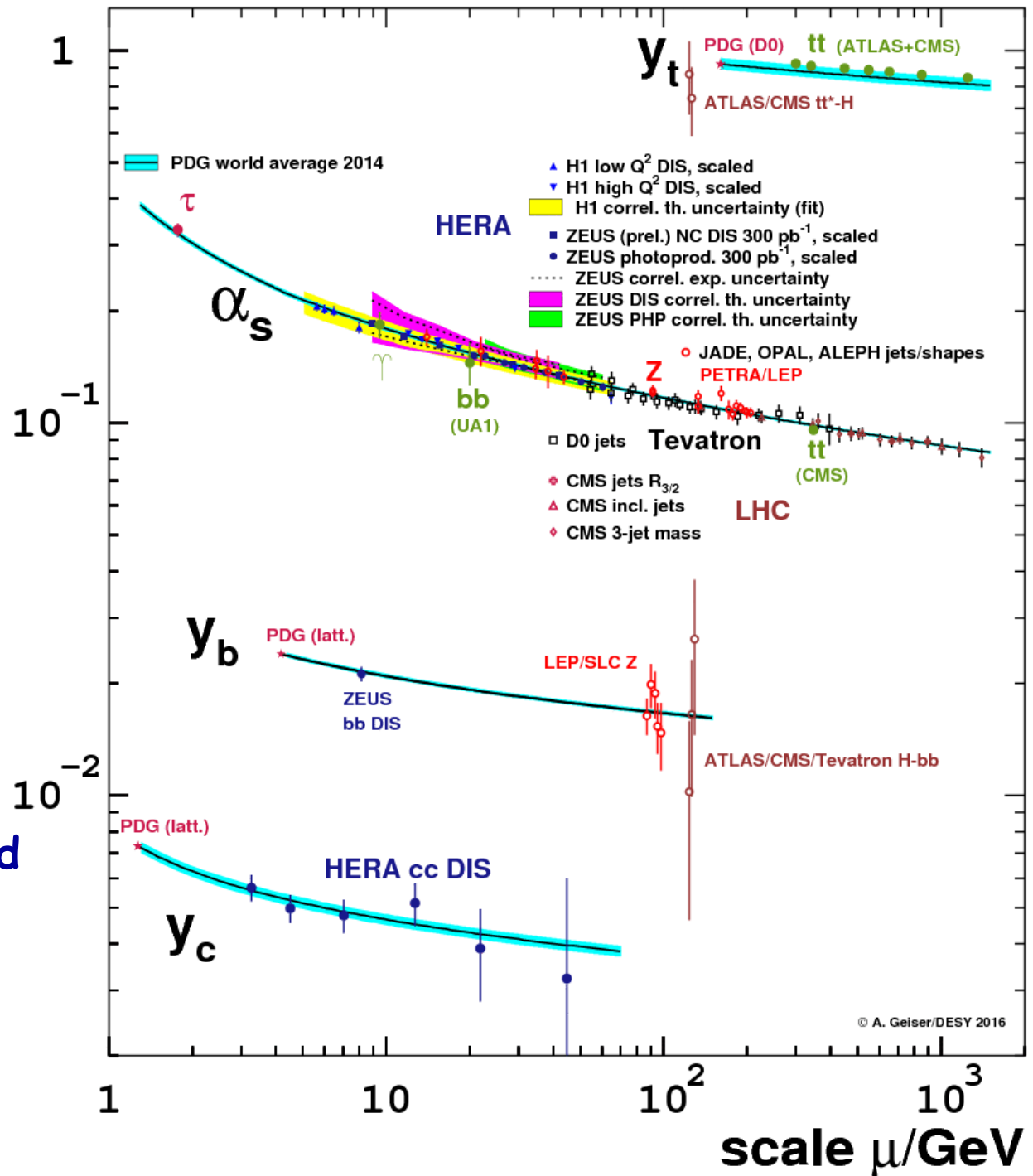
of
strong coupling
and
heavy quark
Yukawa couplings
(very preliminary)

relate m_t , m_b , m_c to associated
Higgs Yukawa couplings

LO EW (+NLO QCD) formula:

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

running coupling



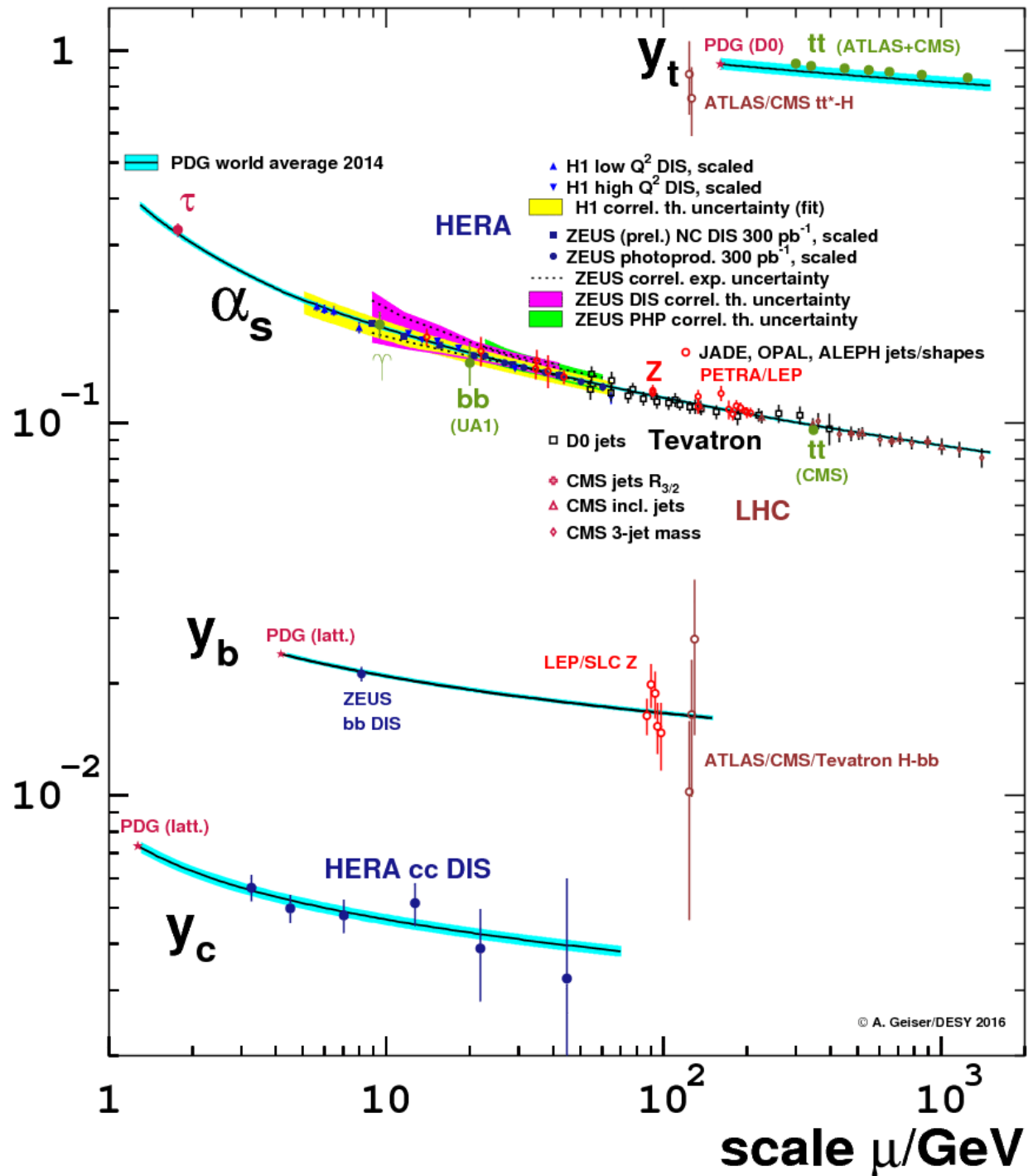
Conclusion

HERA can measure almost all aspects of charm production

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

running coupling

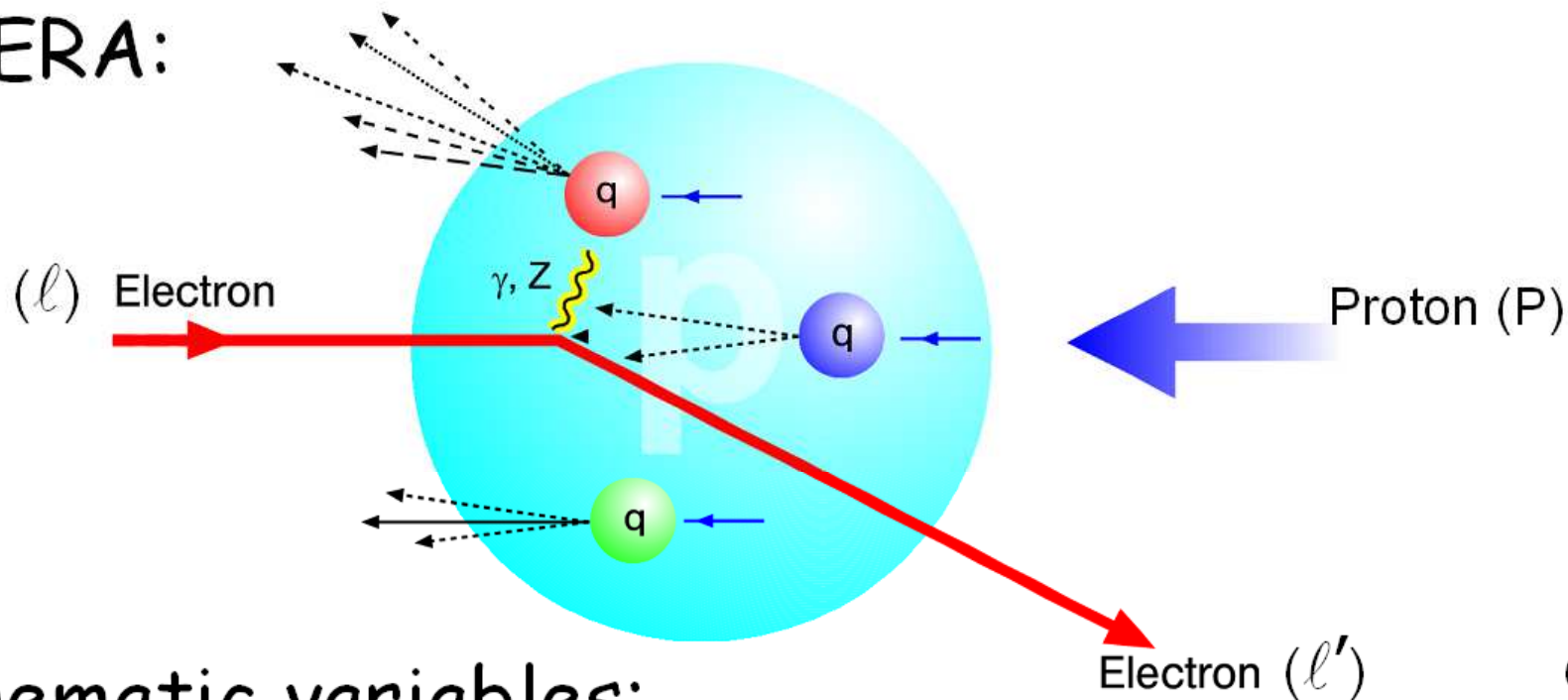




Backup

Deep Inelastic ep Scattering at HERA

HERA:



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

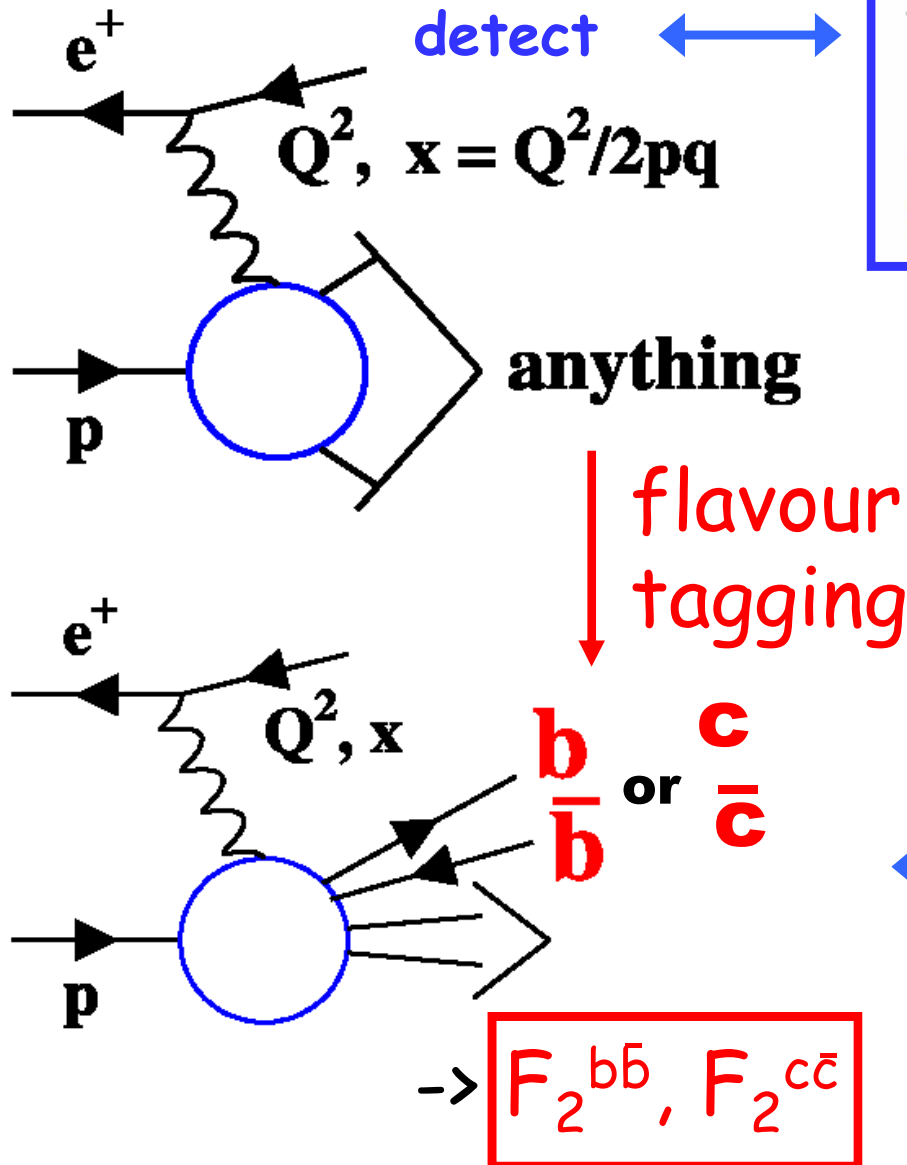
$$Q^2 \lesssim 1 \text{ GeV}^2:$$

photoproduction

$$Q^2 \gtrsim 1 \text{ GeV}^2:$$

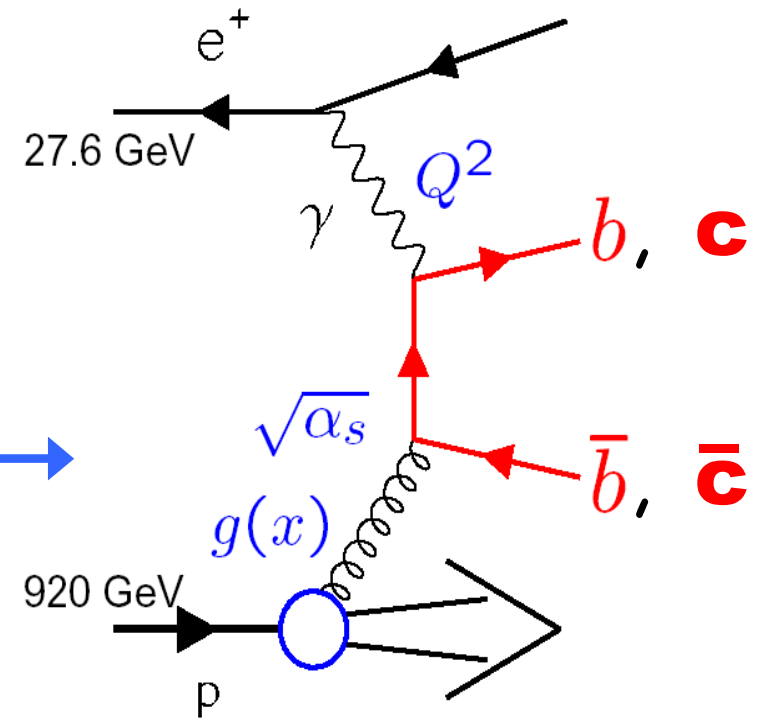
DIS

Heavy flavour contributions to F_2

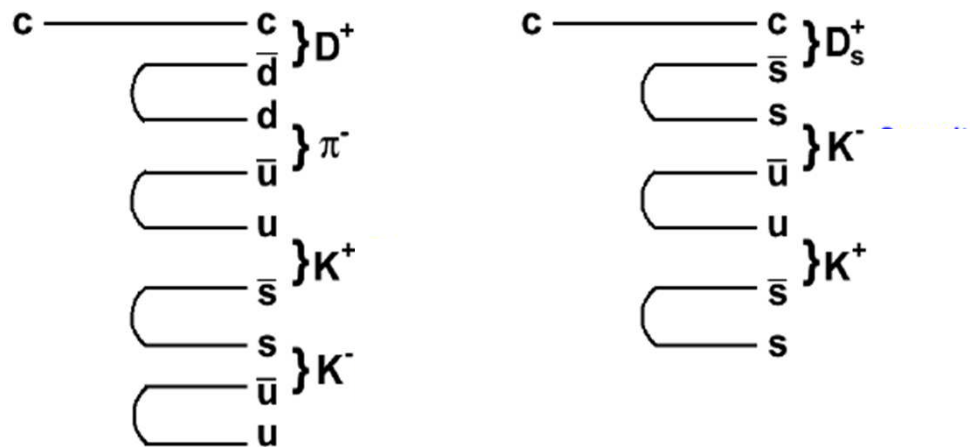


Measure cross section

$$\frac{d^2\sigma}{dx dQ^2} \approx \frac{2\pi\alpha^2}{Q^4 x} \left\{ \left[1 + (1-y)^2 \right] F_2(x, Q^2) \right\}$$



Charm Fragmentation

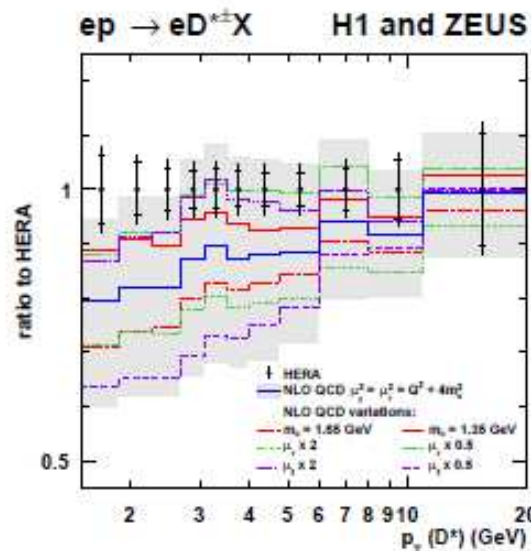




Comparison to NLO QCD



detailed
study of
theory
uncertainties



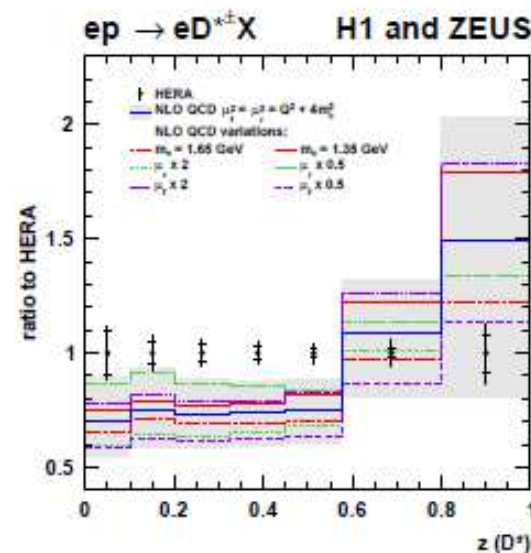
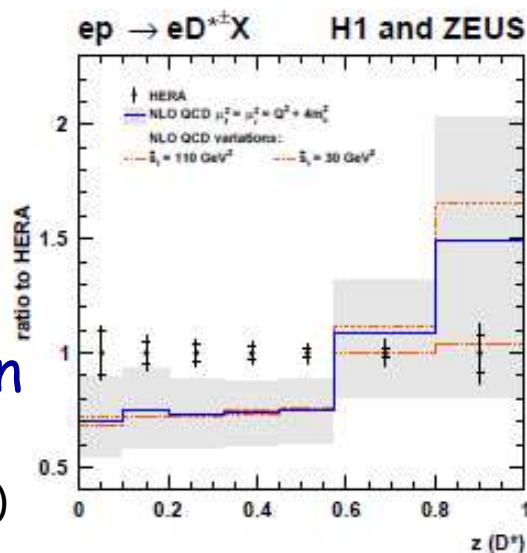
is it possible to
customise (choose
parameters)
such that all
distributions are
described
simultaneously?

largest:

QCD scales

fragmentation

(Kartvelishvili as
measured at HERA)



it is!

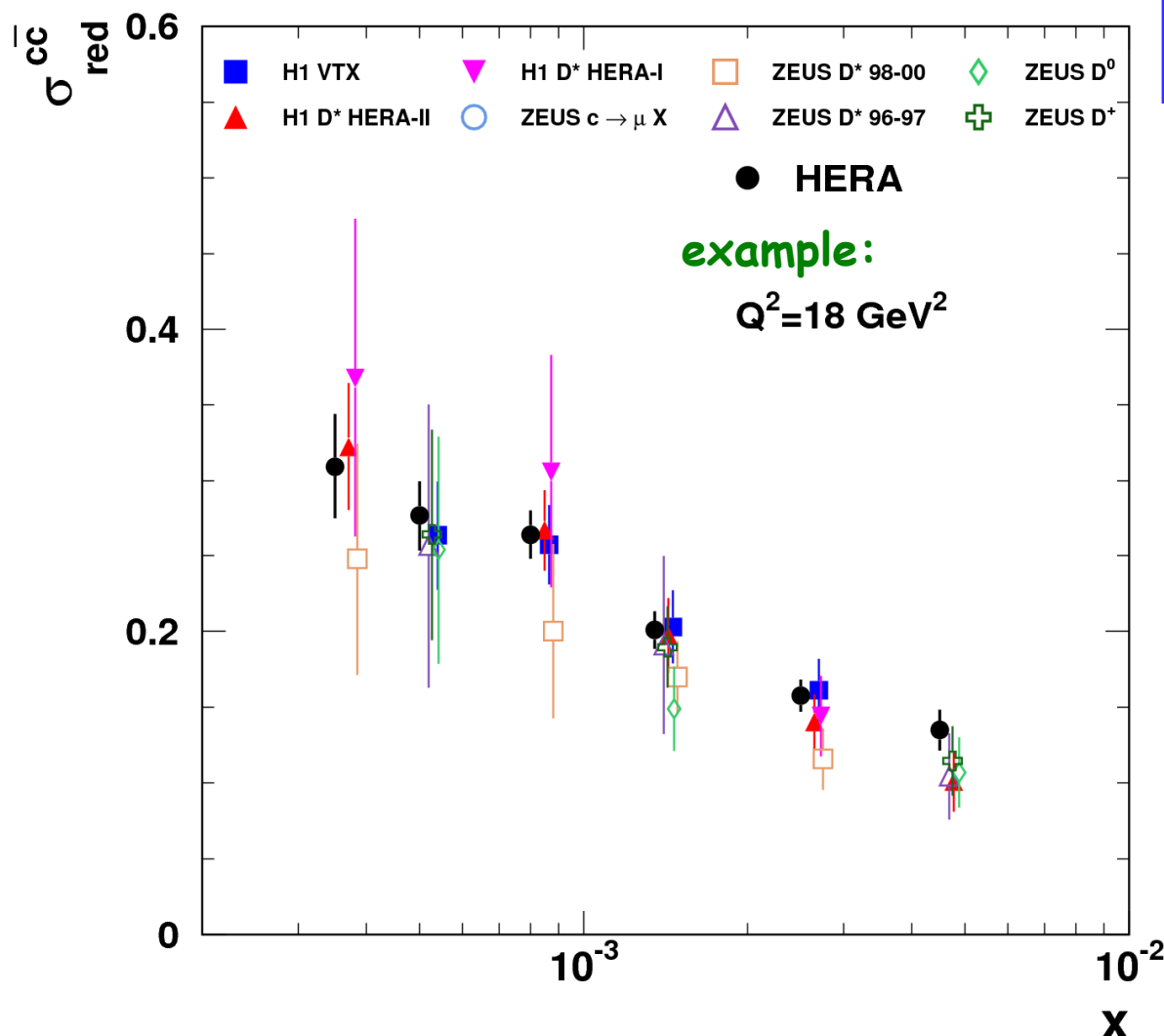


HERA charm data combination



EPJ C73 (2013) 2311

H1 and ZEUS



Measure cross section

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

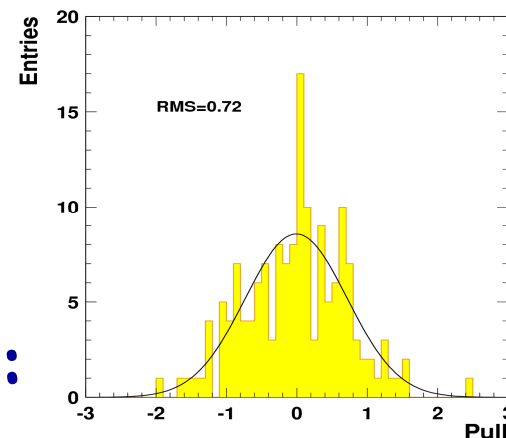
9 data sets
(HERA I, HERA II)

5 charm tagging methods

155 → 52 data points

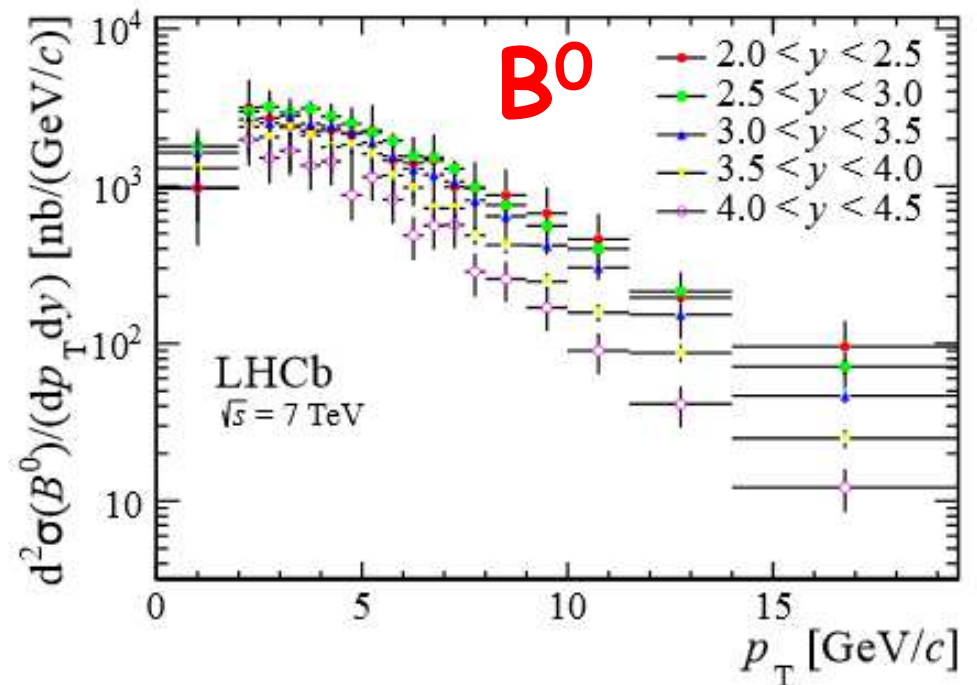
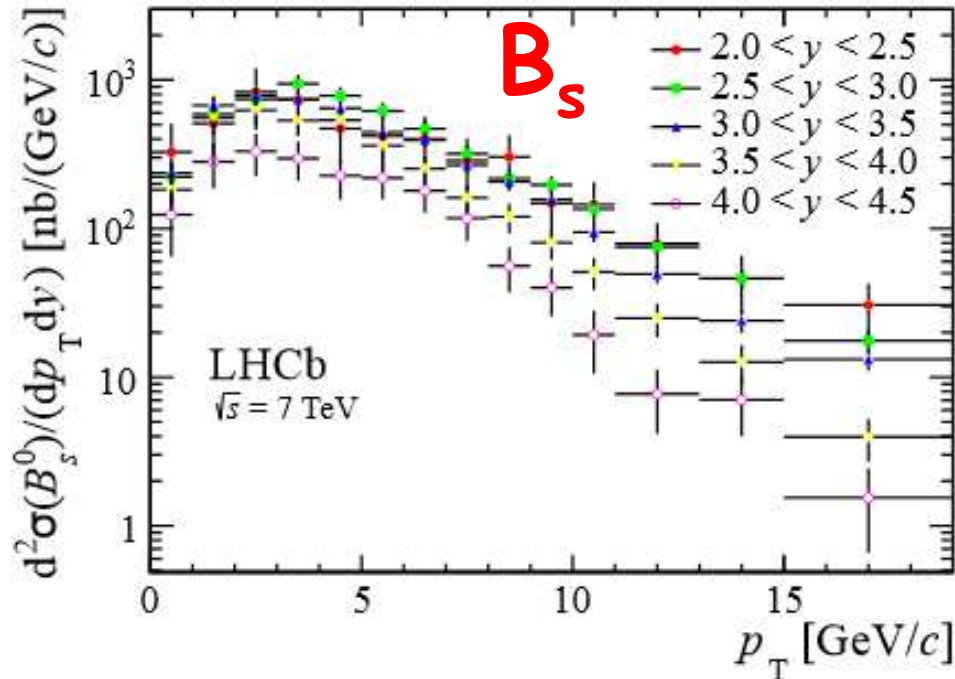
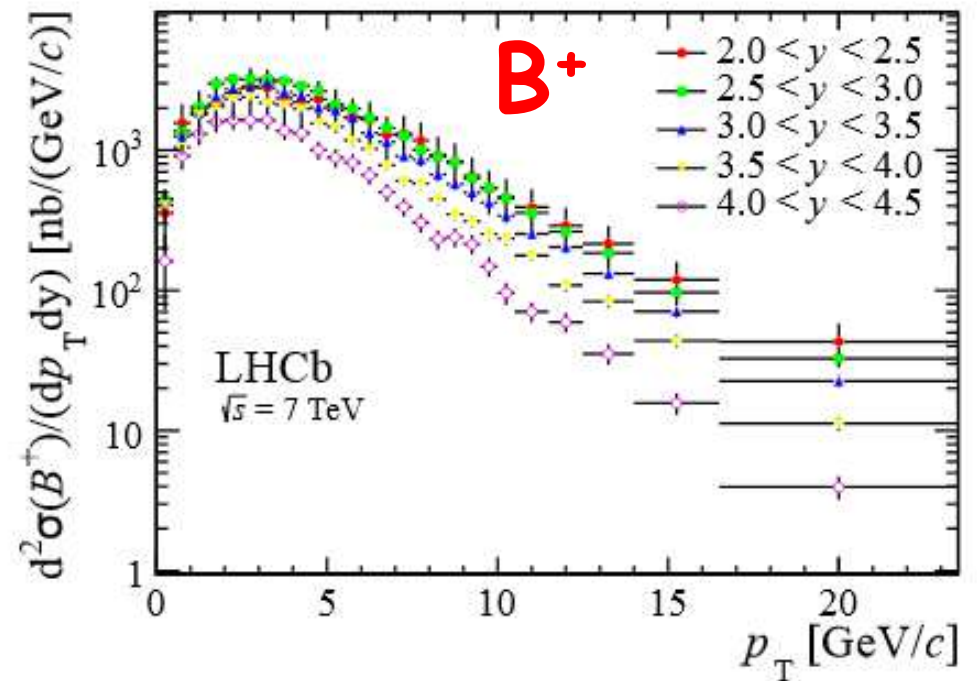
48 correlated systematic
uncertainties

very good selfconsistency of data:



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

FONLL fits well (factor 2
scale uncertainty not shown)

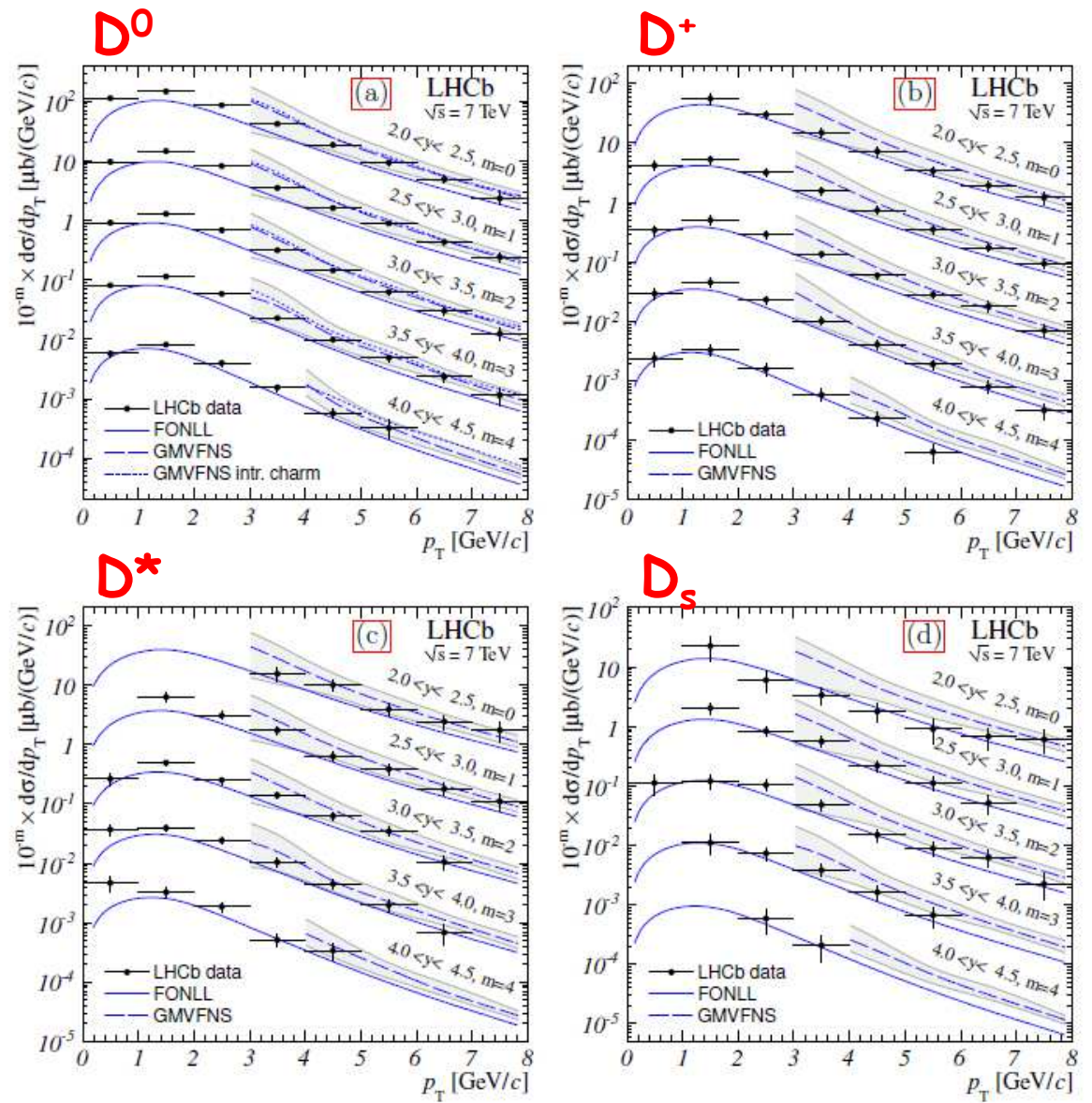
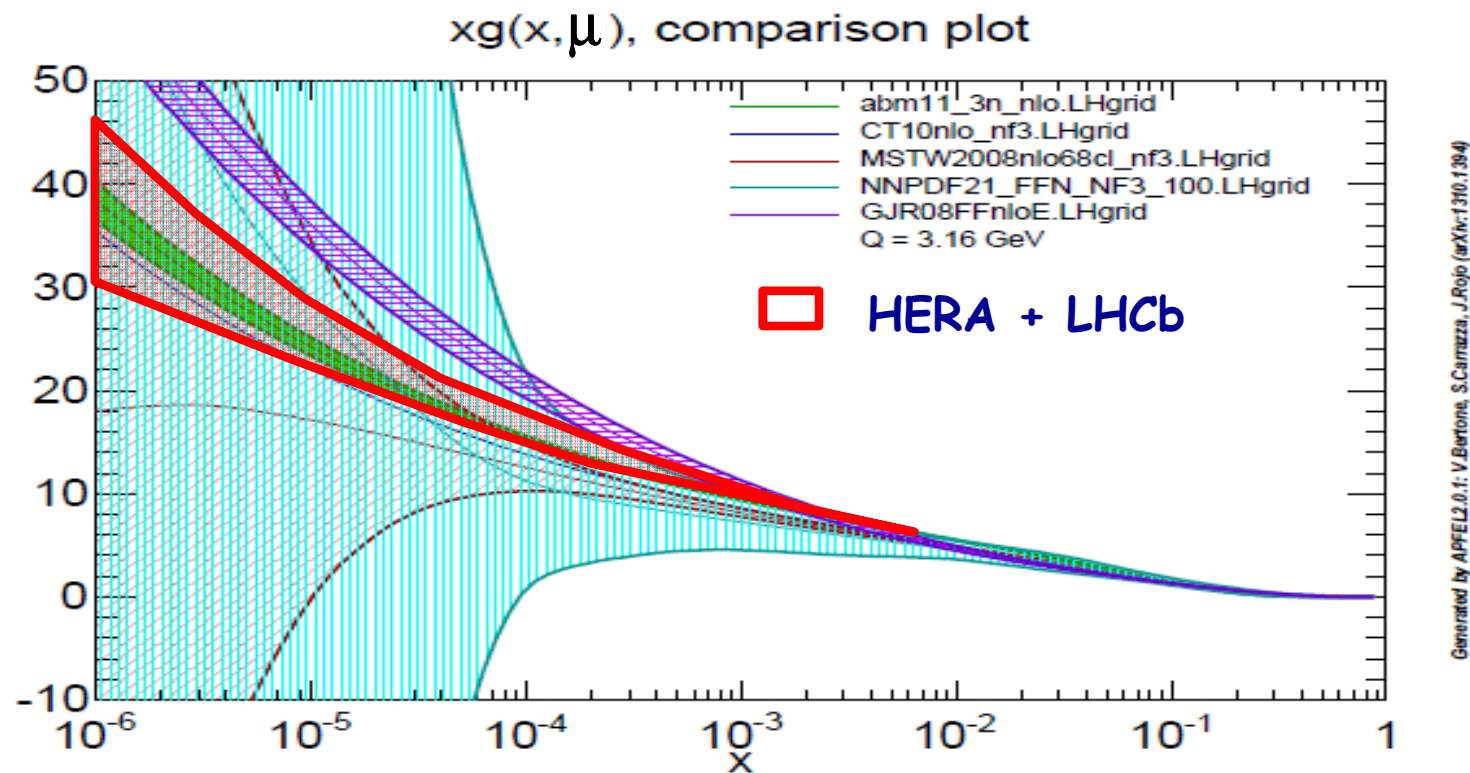


Figure 4: Differential cross-sections for (a) D^0 , (b) D^+ , (c) D^{*+} , and (d) D_s^+ meson production compared to theoretical predictions. The cross-sections for different y regions are shown as functions of p_T . The y ranges are shown as separate curves and associated sets of points scaled by factors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

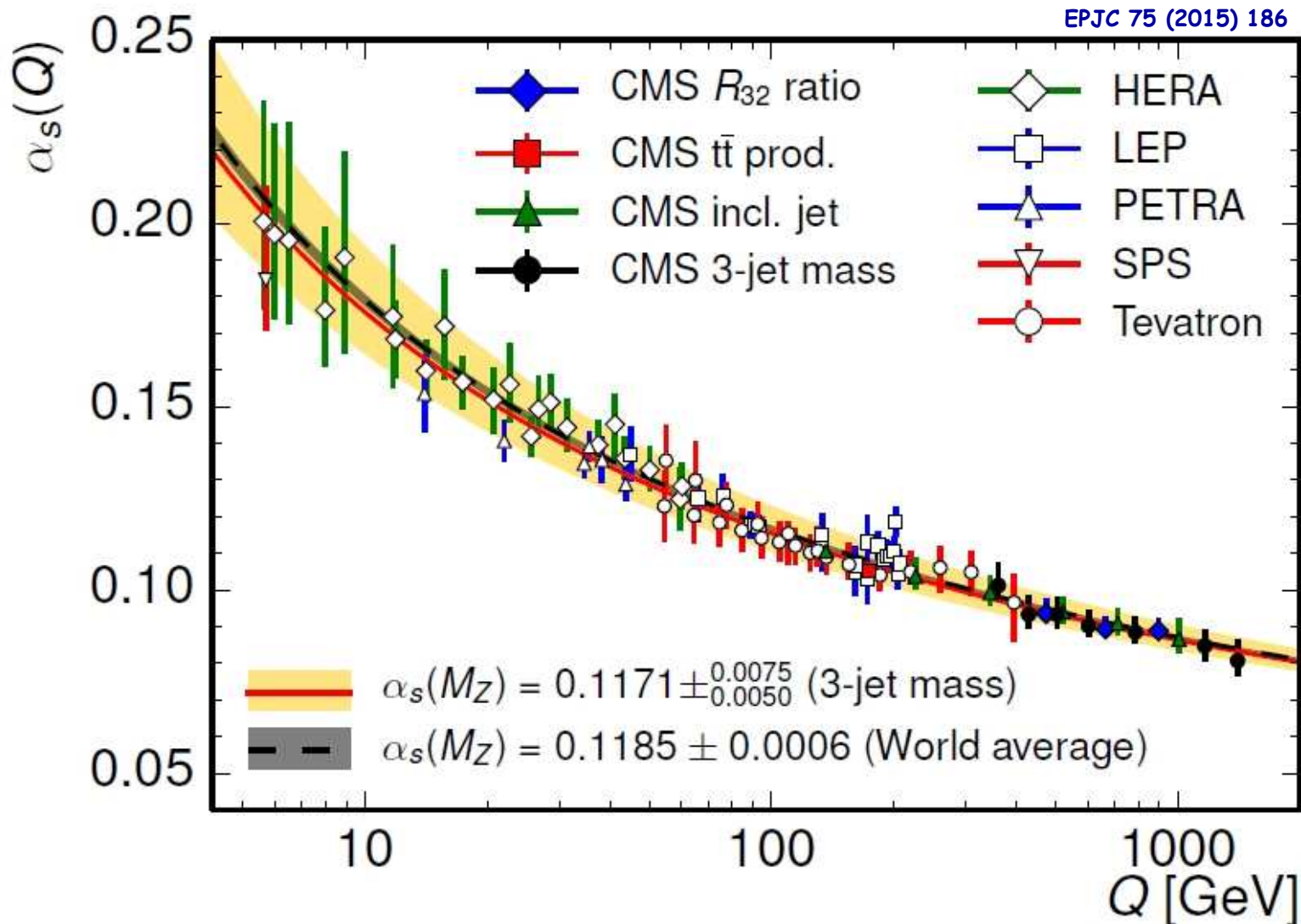
HERAPDF style parameterization with sizeable
'negative gluon' term (but net positive gluon)



in good agreement with constrained ABM11
parameterization at low x

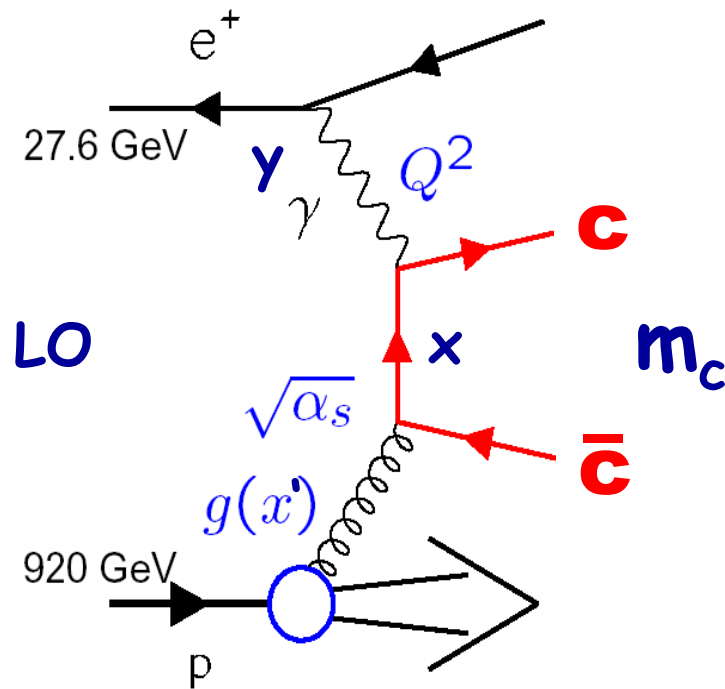
Running strong coupling „constant“ α_s

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



**Yes,
it runs!**

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: $Q^2, p_T, m_c \rightarrow \text{logs of ratios}$)
- 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

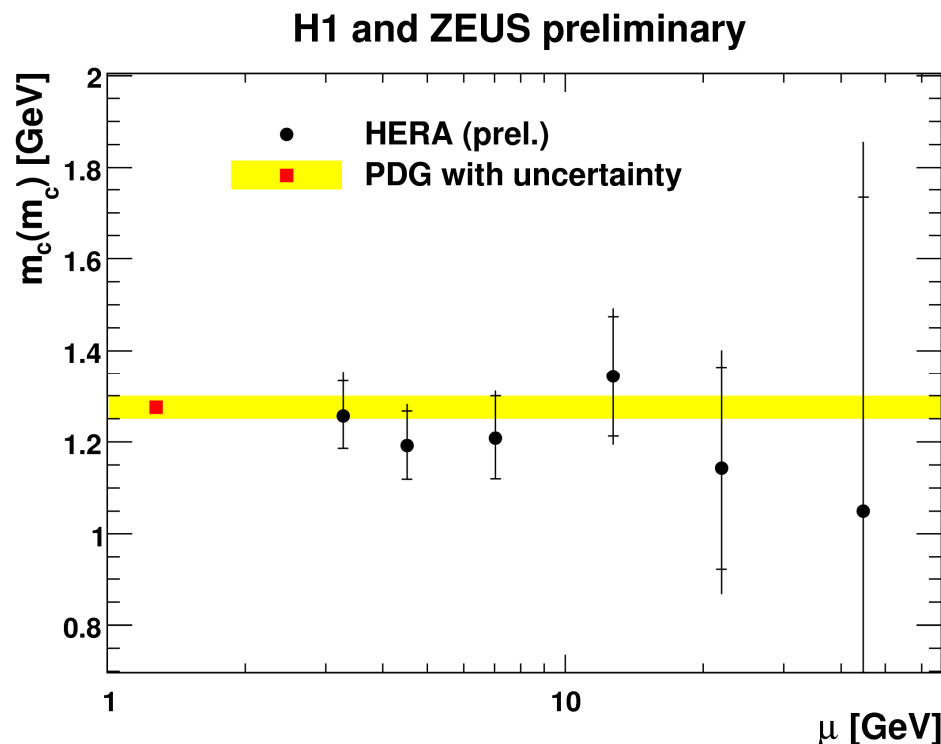
- Adding extra parameter in the PDF parametrisation

Model uncertainty

- Variation of the strangeness suppression 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

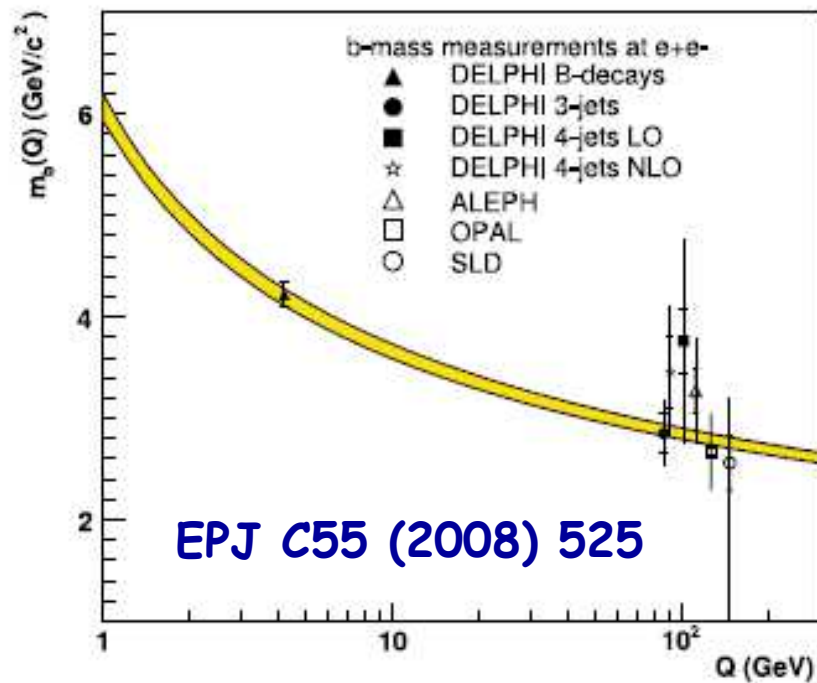


Fig. 6. The energy evolution of the $\overline{MS}$ -running b -quark mass $m_b(Q)$ as measured at LEP. DELPHI results from $R_3^{b\ell}$ [7] at the M_Z scale and from semileptonic B -decays [31] at low energy are shown together with results from other experiments (ALEPH [4], OPAL [5] and SLD [6]). The 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 $m_b(m_b) = 4.20 \pm 0.07 \text{ GeV}/c^2$ from [17] using QCD RGE (with a strong coupling constant value $\alpha_s(M_Z) = 0.1202 \pm 0.0050$ [30])

LEP: $Z \rightarrow b\bar{b} + \text{gluons}$,
measurement of phase space/
angular distributions

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

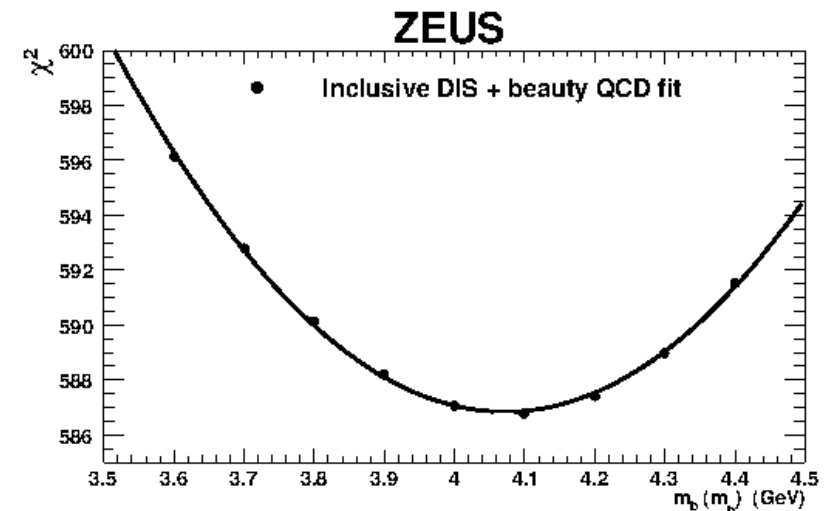
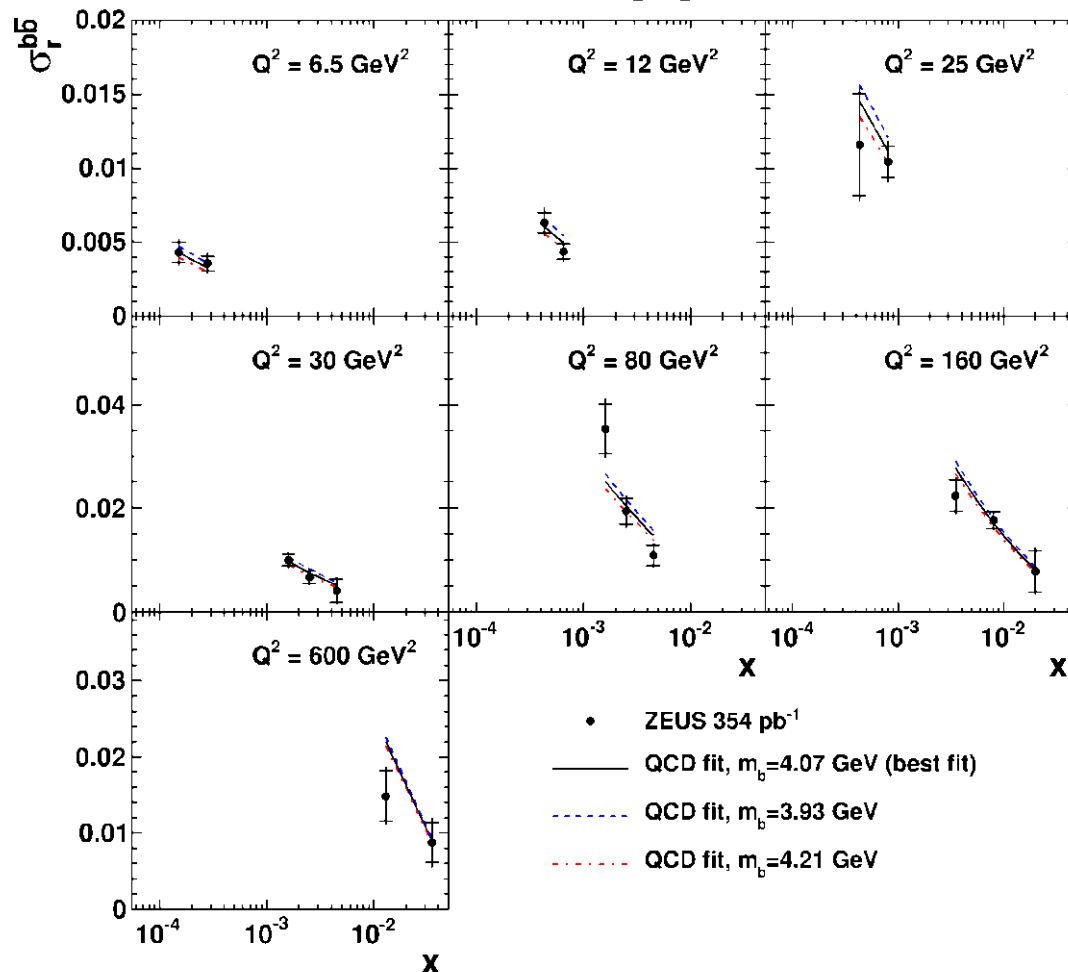
charm and top mass running
not explicitly measured
(so far)

m_b from reduced beauty cross section



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ZEUS



uncertainty evaluation
similar to charm running case

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

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

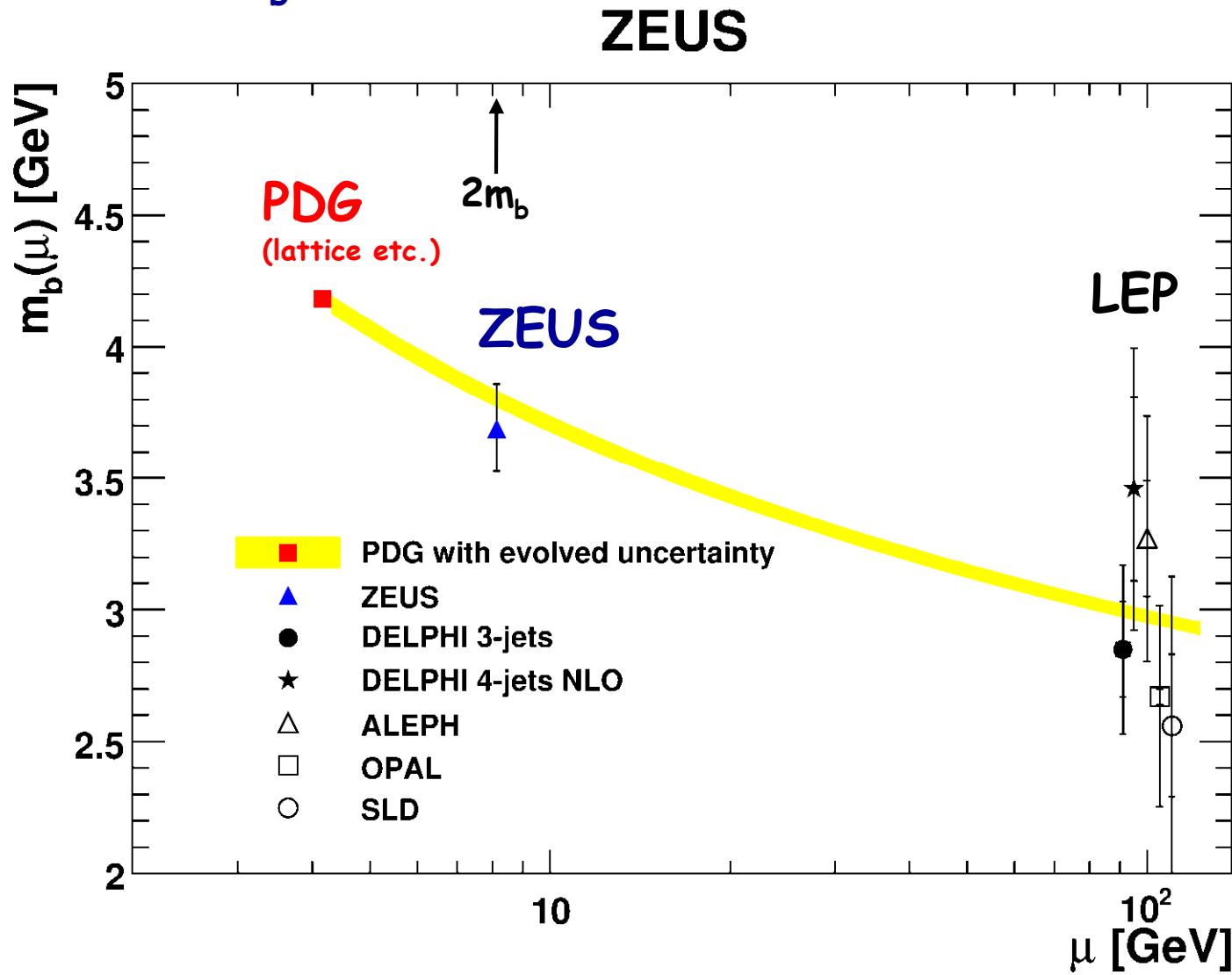
the running beauty quark mass



arXiv:1506.07519

translate to $2m_b$

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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