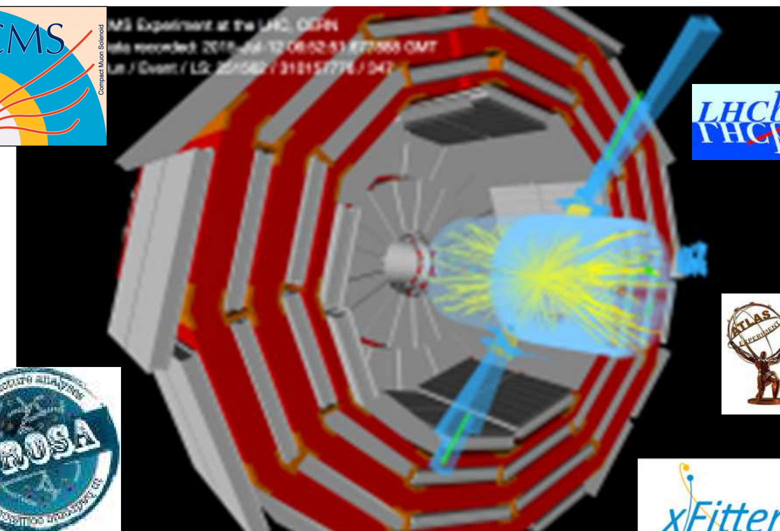
Charm production at HERA, proton structure, the charm mass, and Higgs Yukawa couplings

Achim Geiser

DESY Hamburg

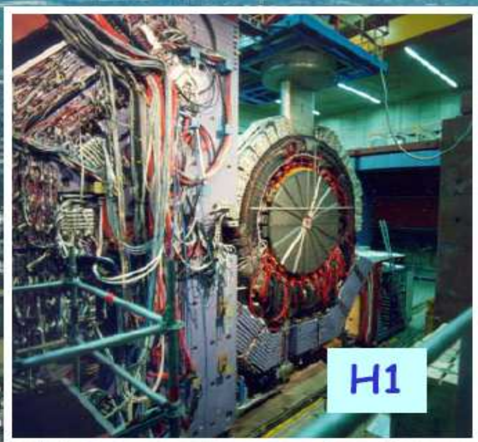
(member of the ZEUS, CMS and PROSA collaborations)

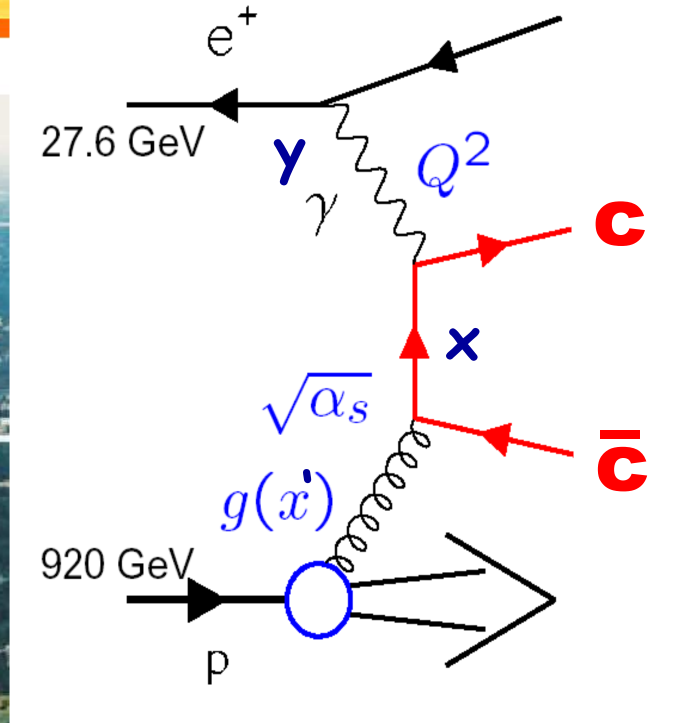


Charm workshop, Bologna, 8. 9. 2016

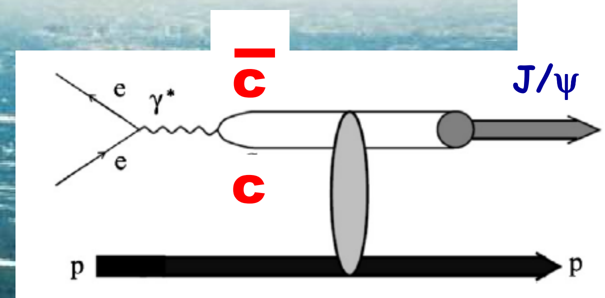
- **Summary of and latest results on charm production at HERA**
- **Charm and proton structure** — **$\psi'/J/\psi$ cross section ratio**
- **Recent charm quark mass measurements**
- **Running quark masses and Higgs Yukawa couplings**

The HERA ep collider and experiments

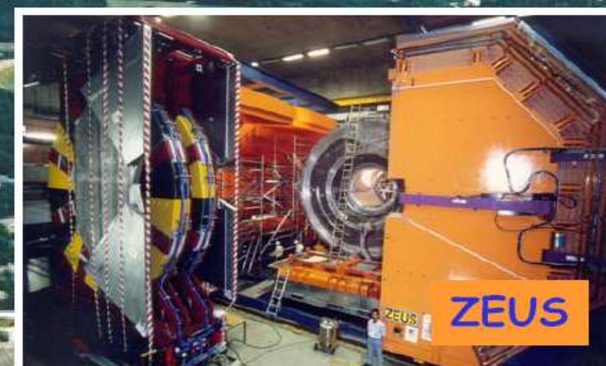




up to 30% of cross section



HERA

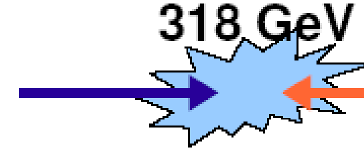


HERA I: ~ 130 pb^{-1} (physics)

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

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

HERA:



p (920 GeV) e (27.6 GeV)

Review of open charm at HERA

arXiv:1506.07519

recent review:

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

Review

Charm, beauty and top at HERA

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

DESY, Hamburg, Germany

ARTICLE INFO

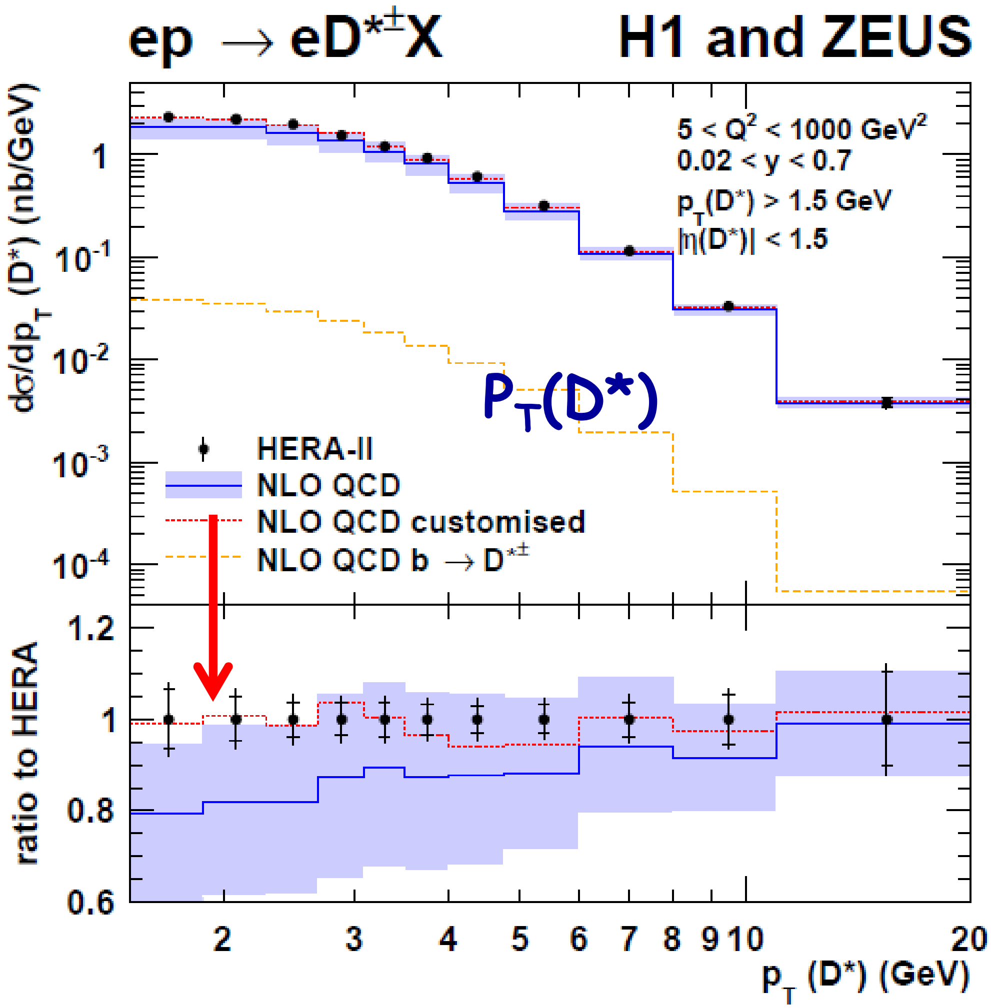
Keywords:
Charm
Beauty
Top
HERA
DIS
Photoproduction

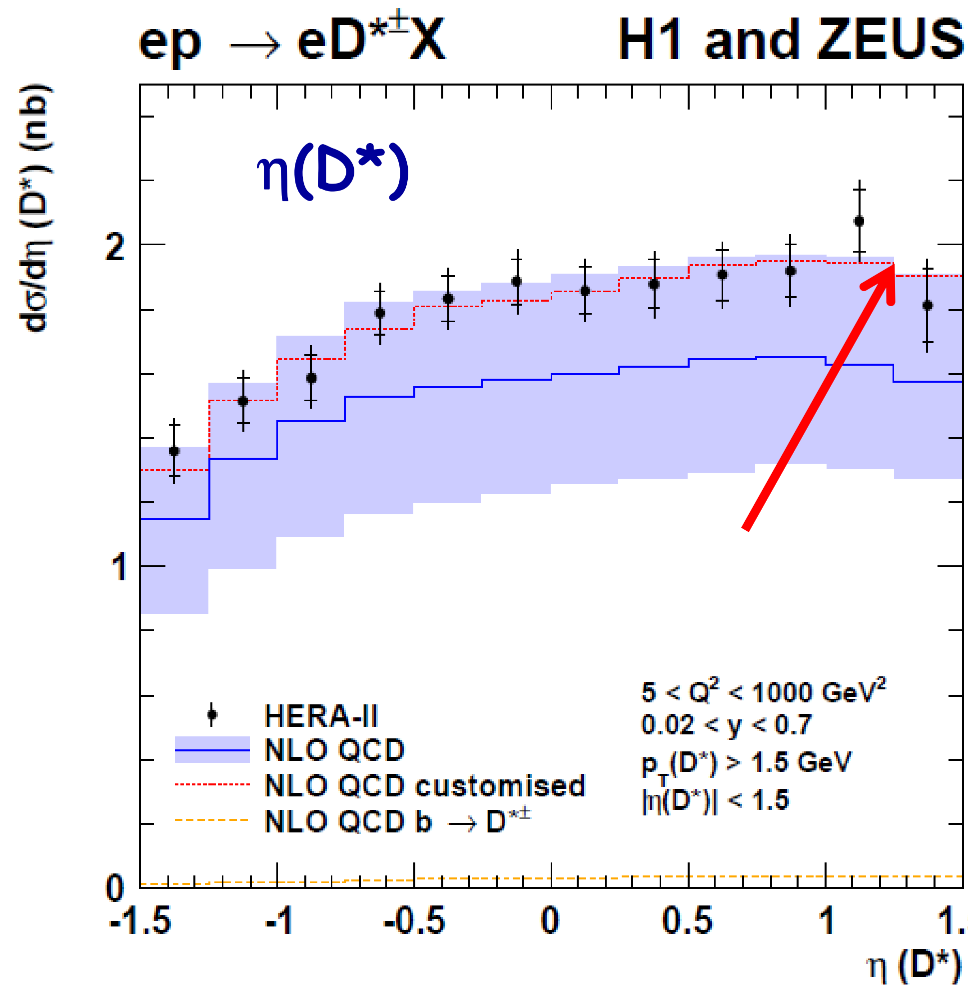
ABSTRACT

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.

Combined D* cross sections in DIS

arXiv:1503.06042, JHEP 1509 (2015) 149

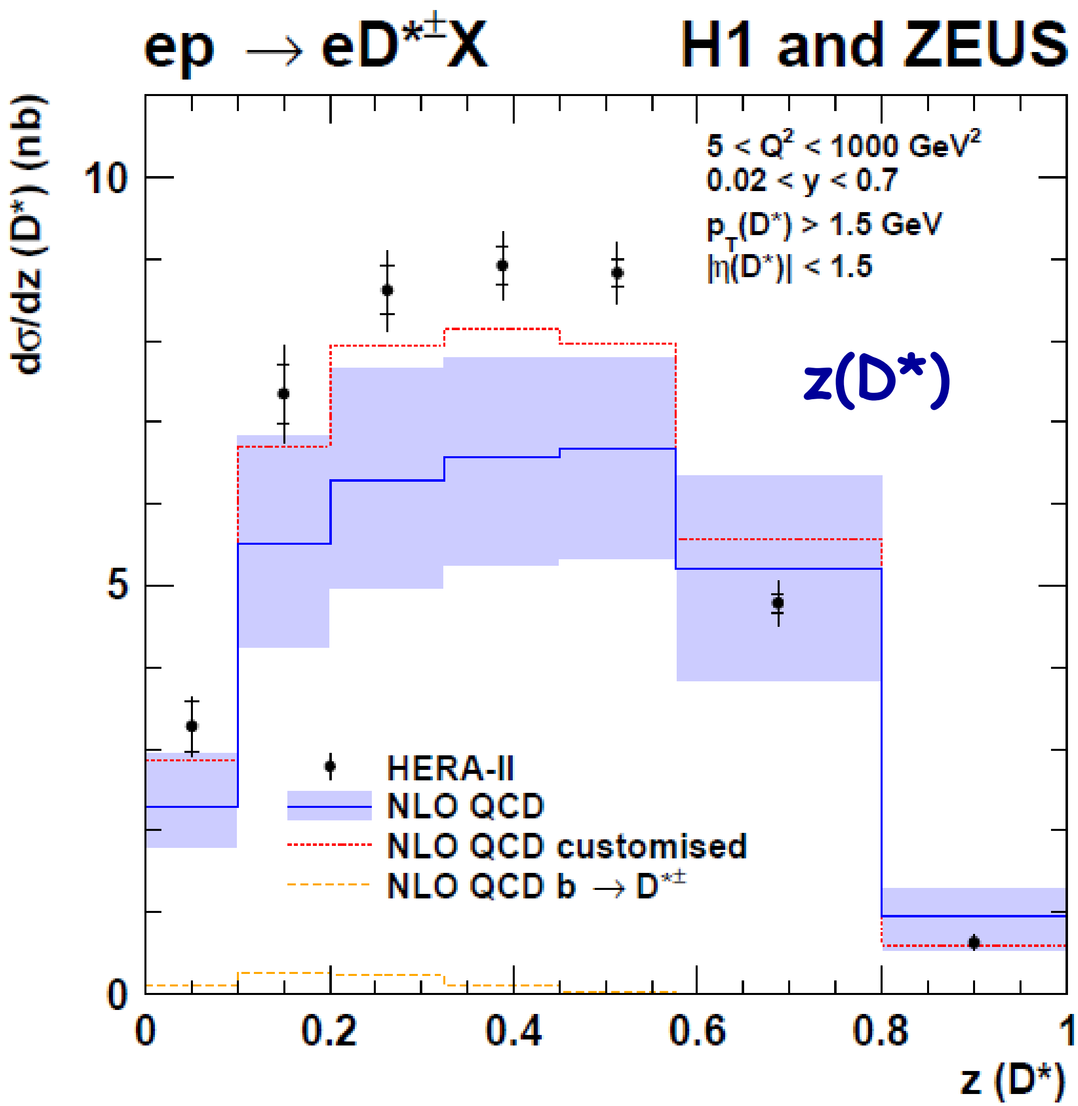




customised choice: - reduced renormalisation scale
- modified scale dependence of fragmentation
- slightly lower charm mass (all within uncertainty)

Charm fragmentation function

arXiv:1503.06042, JHEP 1509 (2015) 149



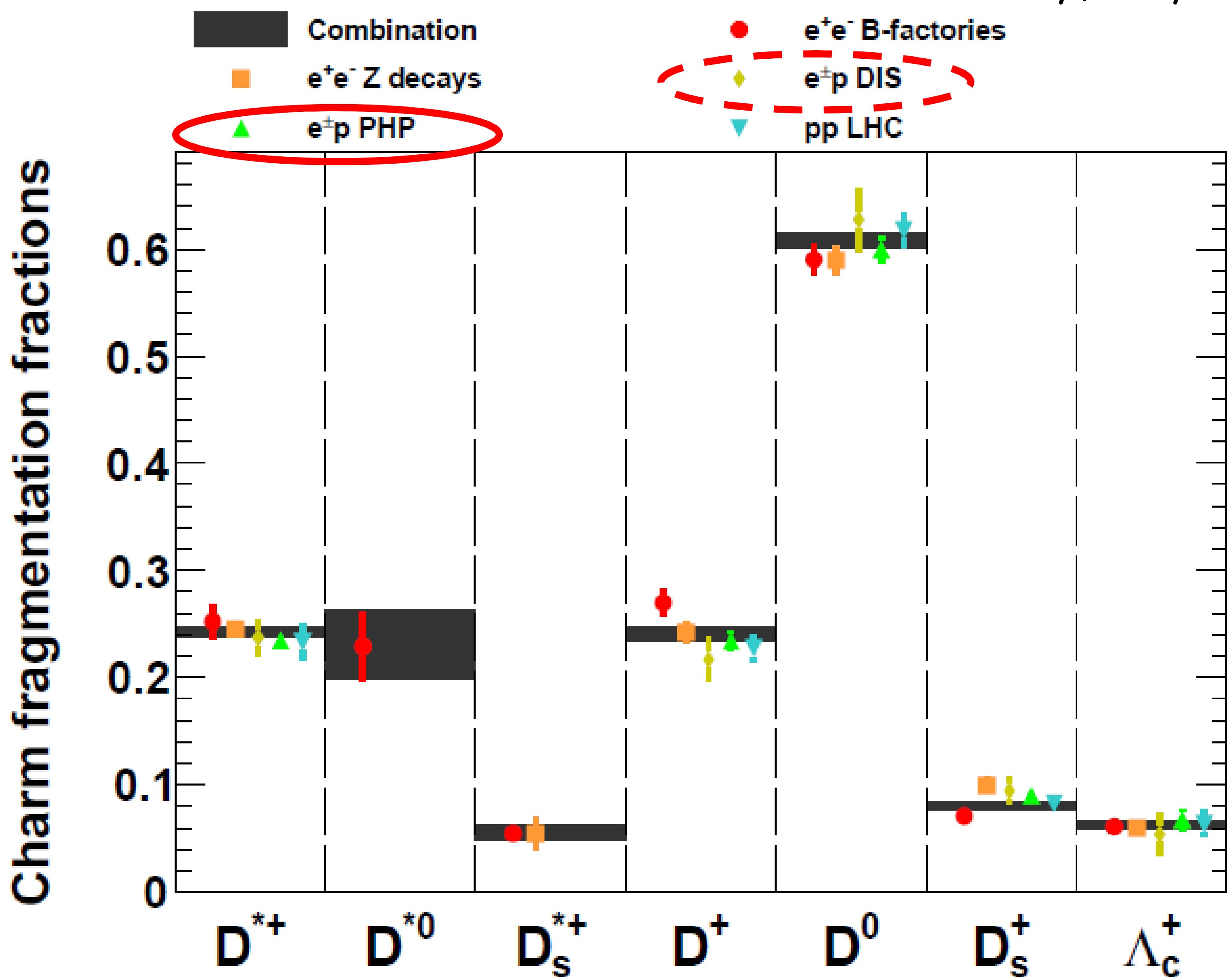
Combination of H1 and ZEUS D* measurements

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
Lisovyi, Verbytskyi, Zenaiev



universality confirmed

HERA measurements make very substantial contribution to world average

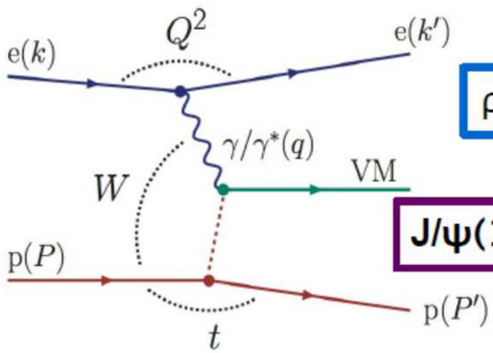
Measurement of the cross-section ratio $\sigma_{\psi(2S)}/\sigma_{J/\psi(1S)}$ in deep inelastic exclusive ep scattering at HERA

arXiv 1605.01946

Diffractive vector meson (VM) production at HERA

courtesy N. Kovalchuk

elastic (exclusive)



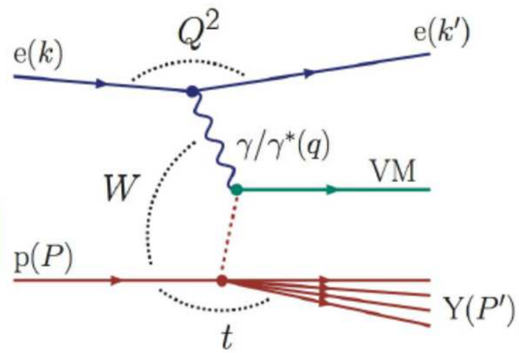
light

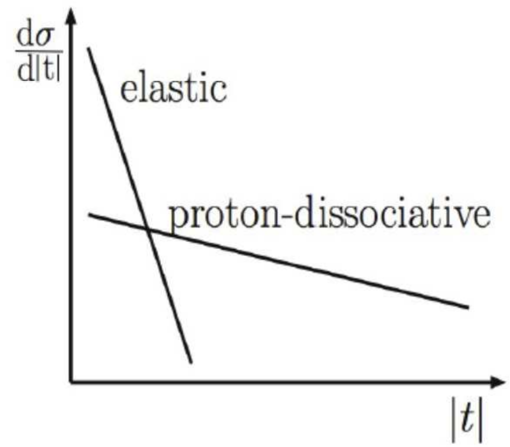
ρ, ω, φ

heavy

J/ψ(1S), ψ(2S), Υ

proton-dissociative





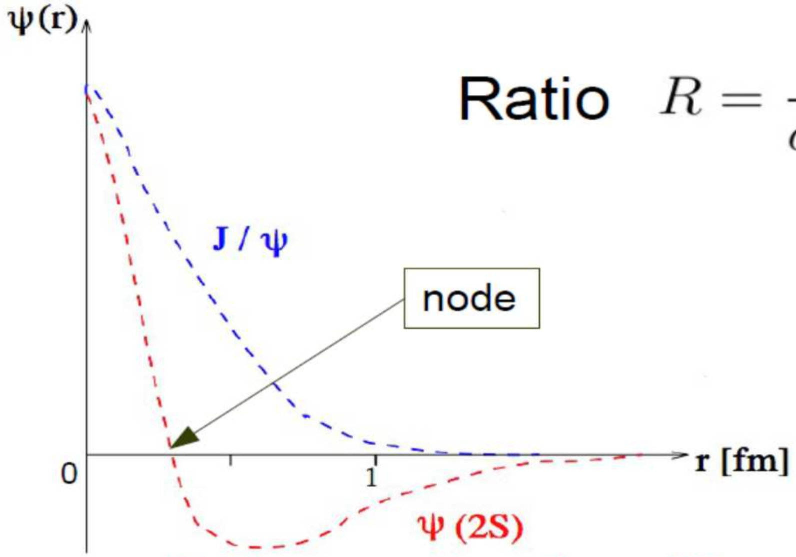
Kinematics of the process

Q^2 — photon virtuality	$Q^2 < 1$ GeV^2 — γp $Q^2 \gtrsim 1$ 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
- $<r^2_{\psi(2S)}> \approx 2 <r^2_{J/\psi(1S)}>$

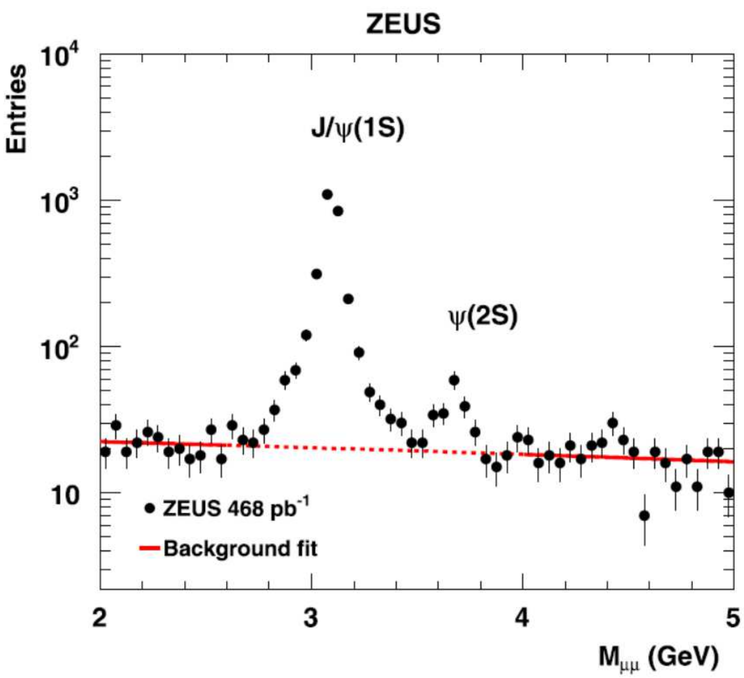
pQCD model calculations predicts R ~ 0.17 (PhP) and rise of R with Q^2 (DIS)

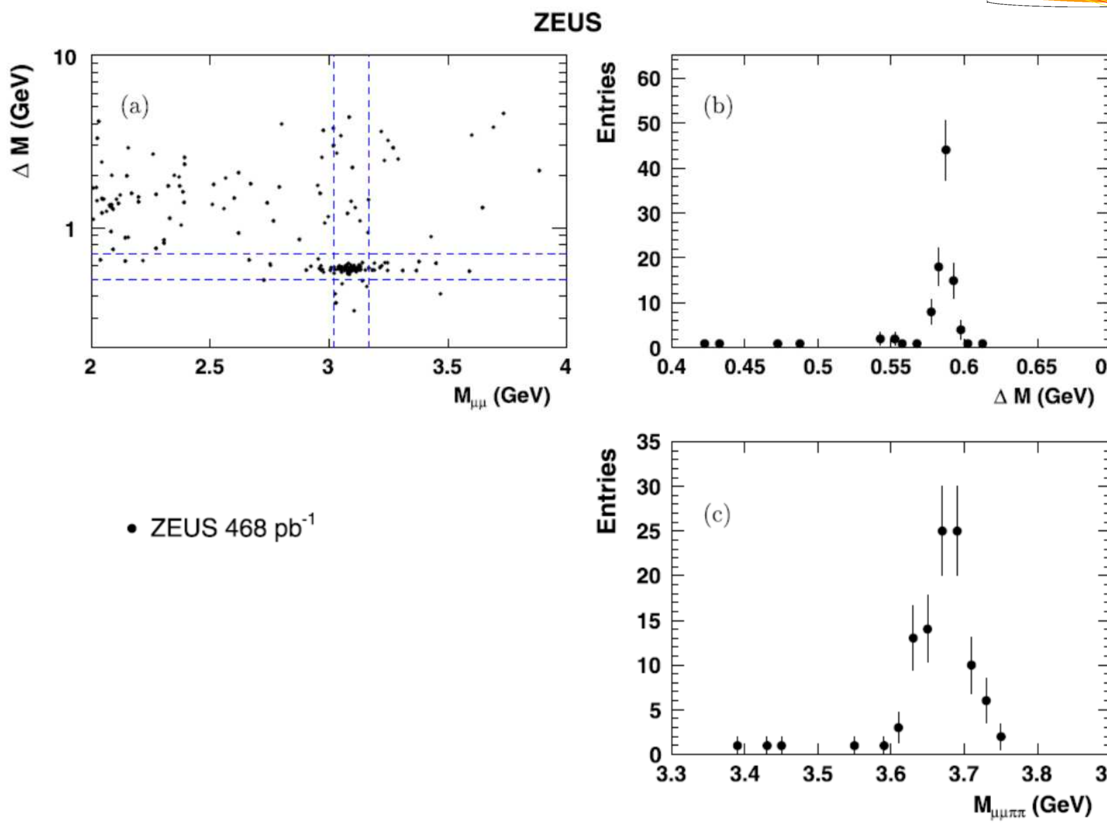
4

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/ψ, ψ' -> $\mu\mu$

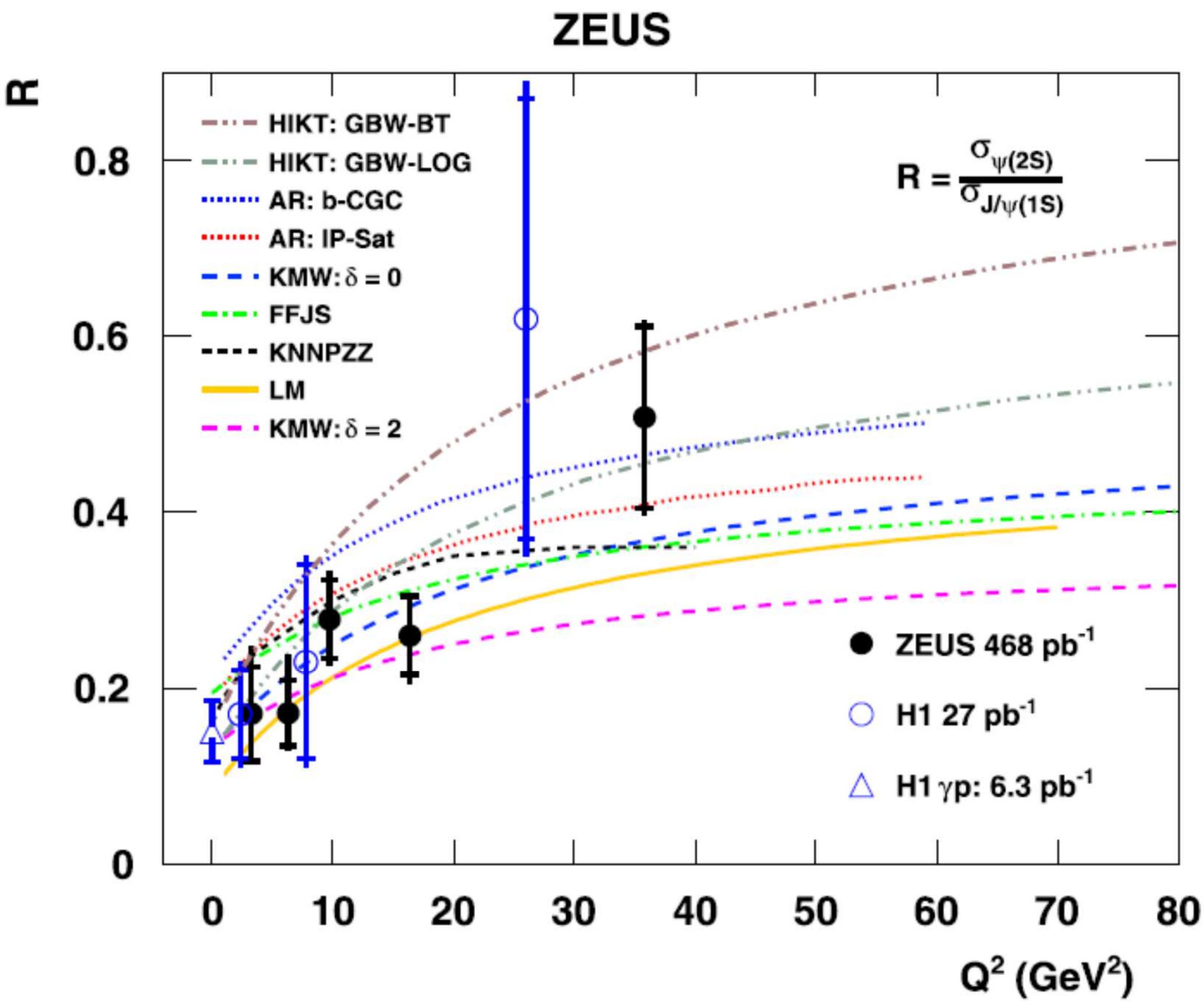




ψ' -> $J/\psi\ \pi\pi$ -> $\mu\mu\pi\pi$

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

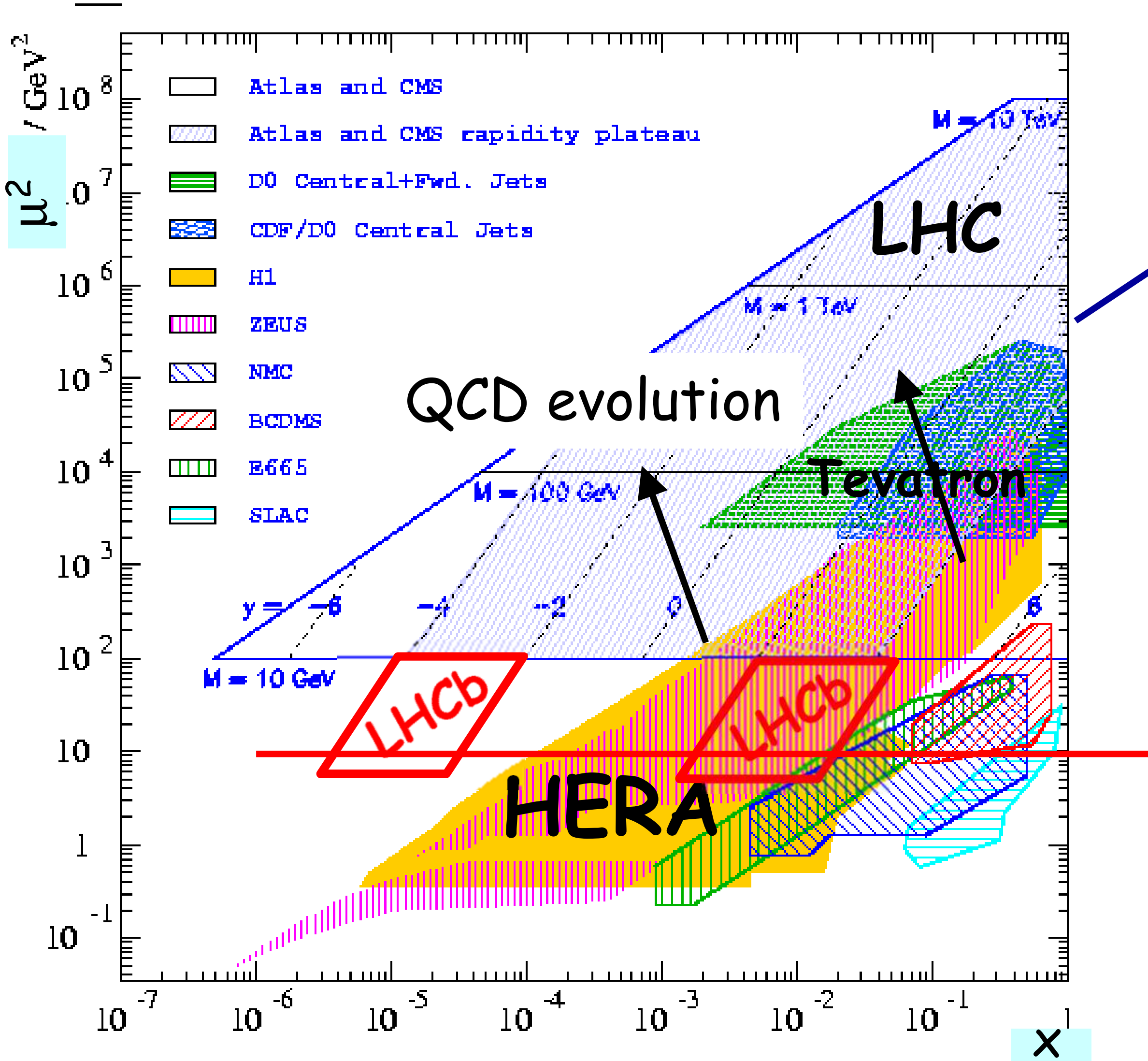
arXiv:1605.01946, Nucl. Phys. B909 (2016) 934

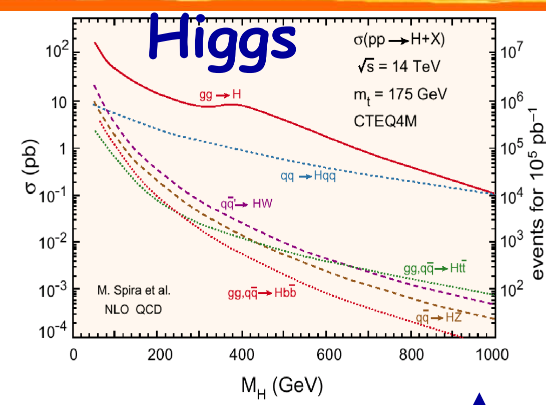


result starts to discriminate between different theory predictions

(for more details see N. Kovalchuk, DIS16)

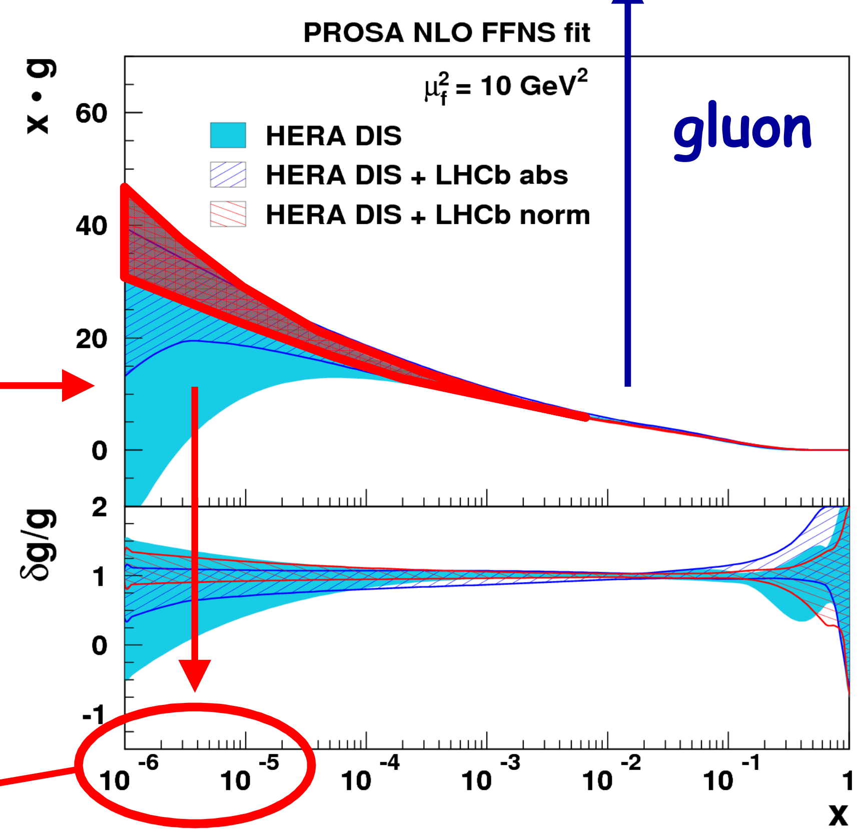
Parton density functions (PDF)





top, jets, ...

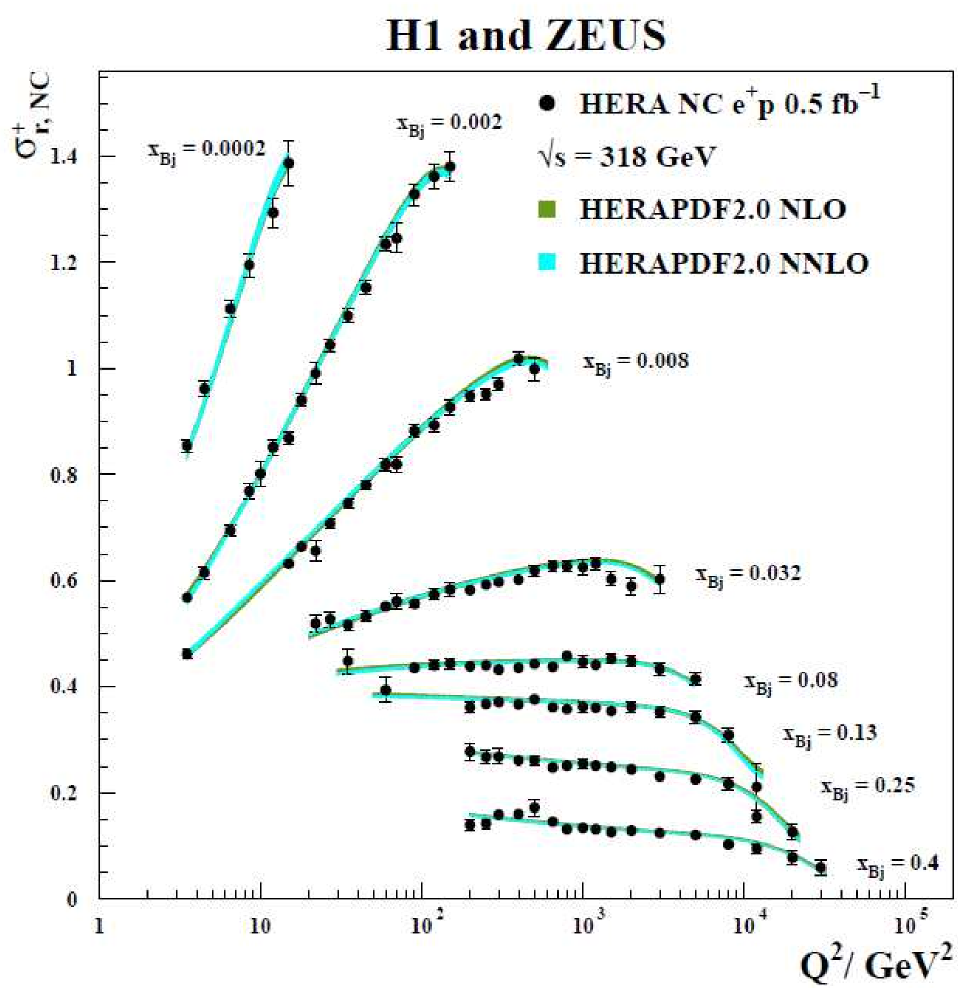
gluon

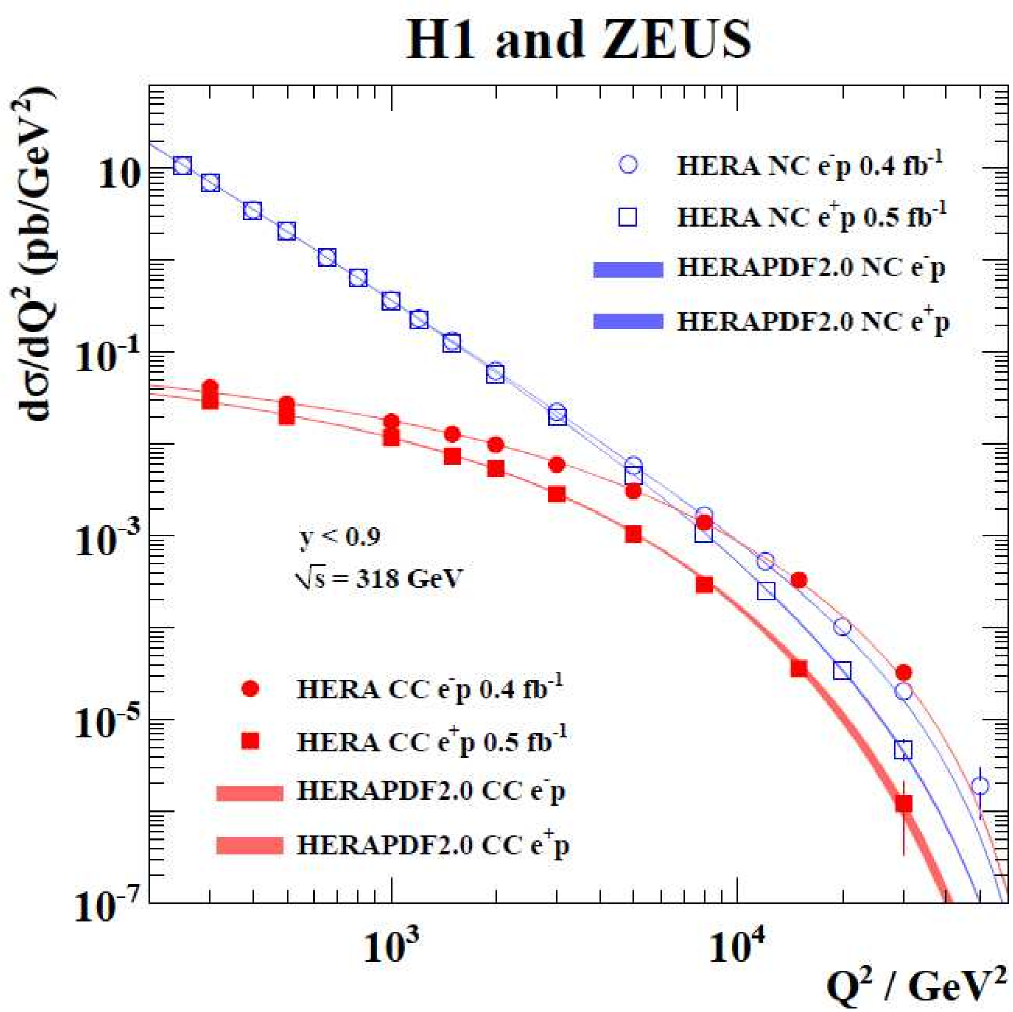


parton densities from HERA and LHC data
-> cross sections at LHC, cosmic rays, ...

Final HERA inclusive DIS combination and PDF fit

arXiv 1506.06042, EPJC 75 (2015) 580

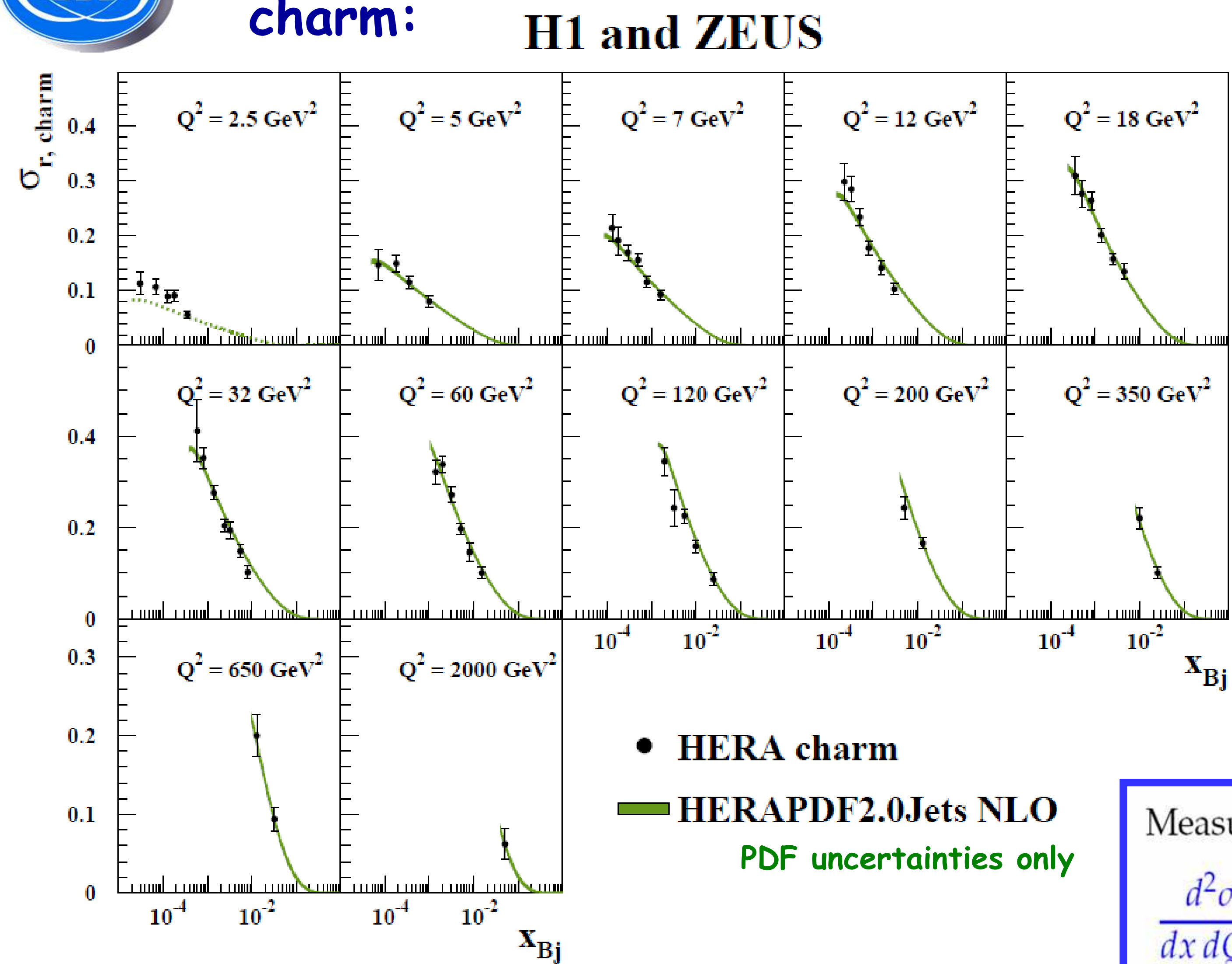




includes fit of inclusive charm + jet DIS data

arXiv 1506.06042, EPJC 75 (2015) 580

charm:



well described by fit

Measure cross section

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

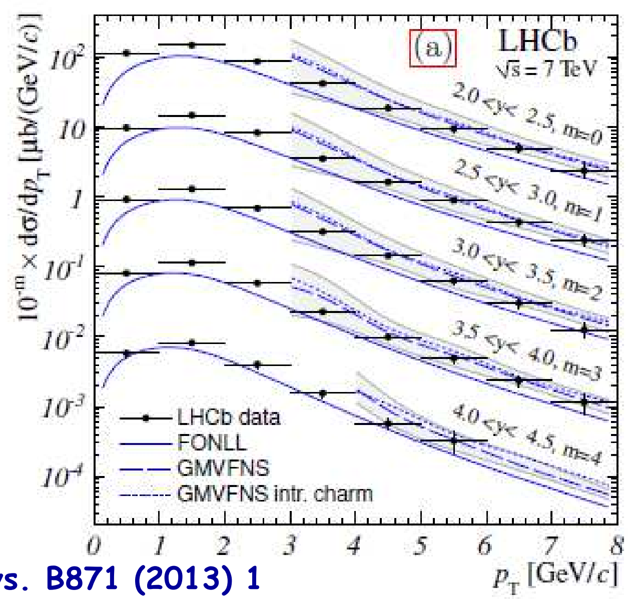
Constraint of gluon at very low x

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

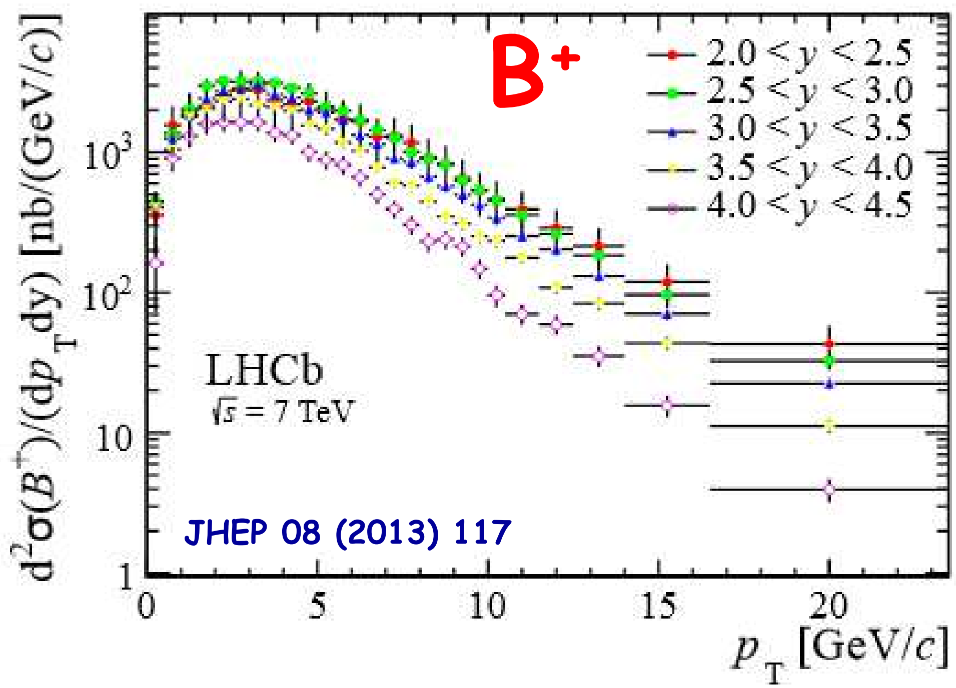
Combined fit of

- 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

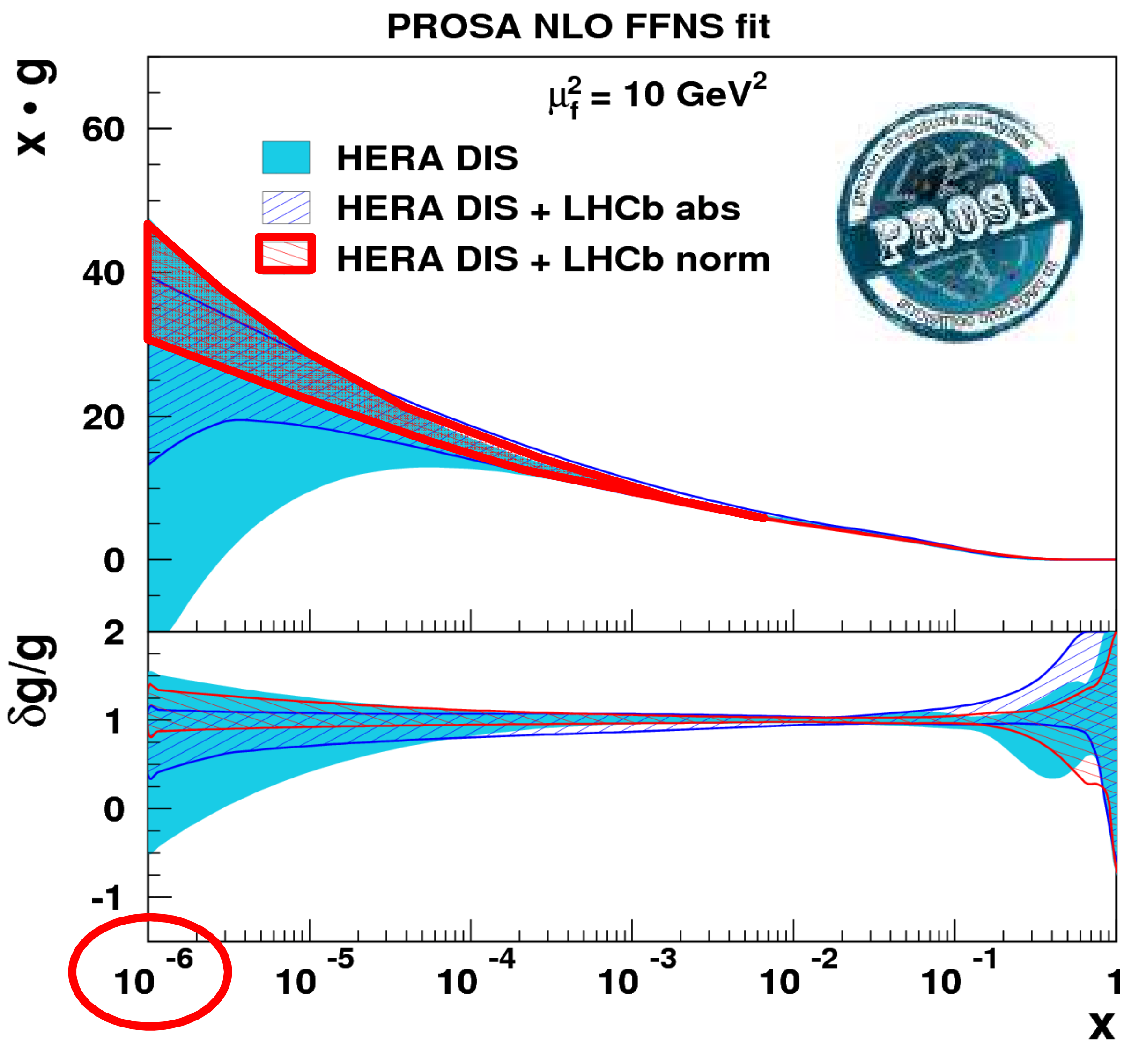


Nucl.Phys. B871 (2013) 1



final comparison of gluon fits

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



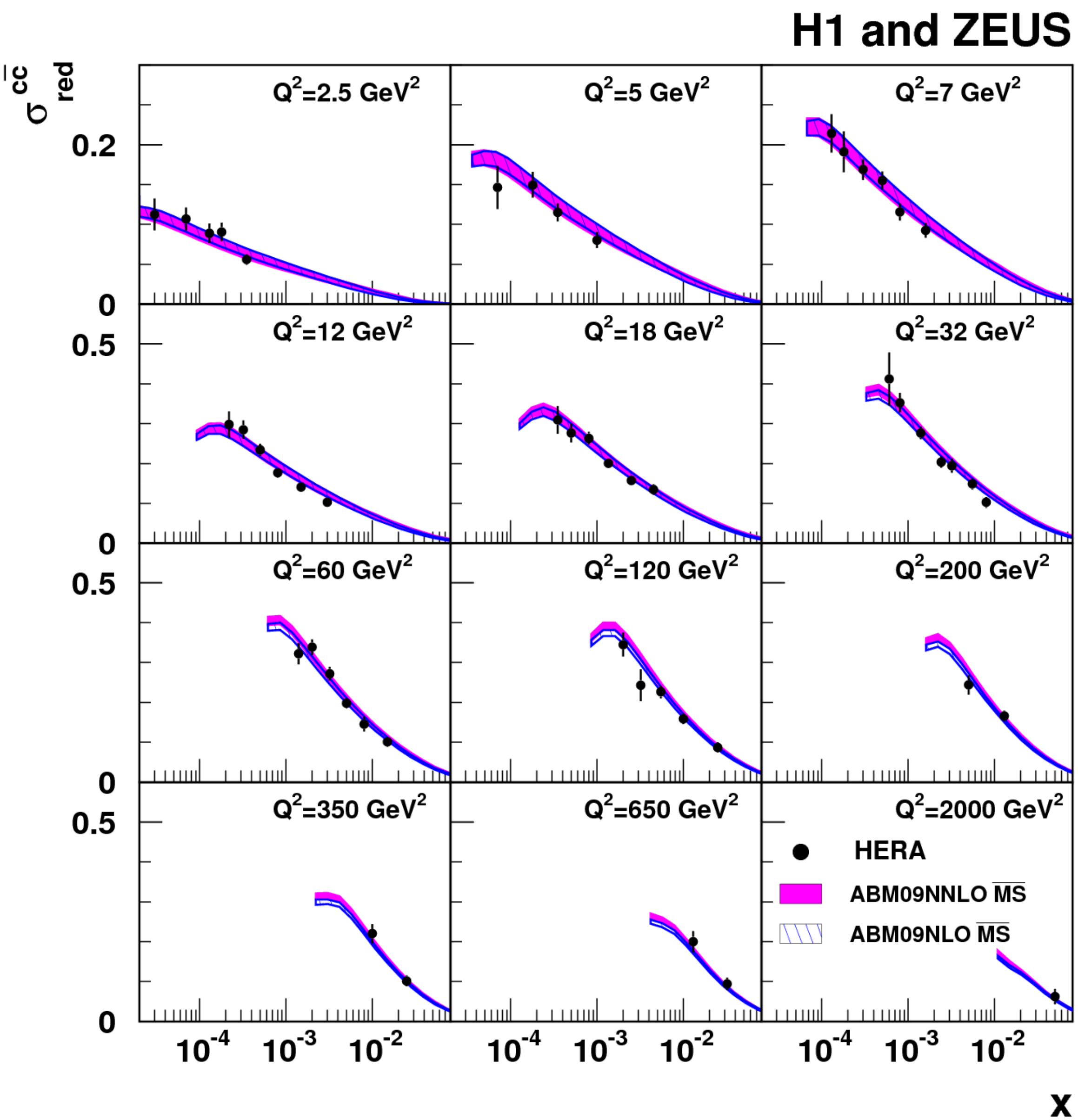
gluon positive and well constrained down to x ~ 10^{-6}

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

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

Combined HERA charm data

EPJC 73 (2013) 2311



comparison to ABM FFNS

very good description of data in full kinematic range

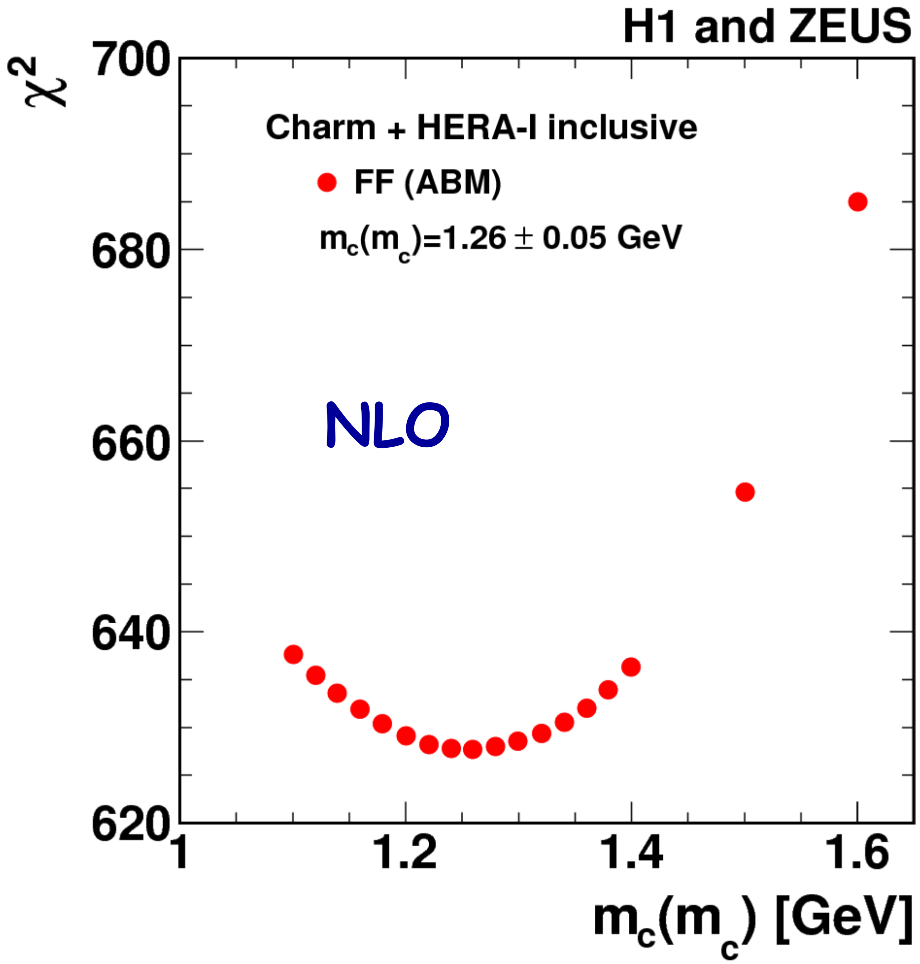
unambigous treatment of m_c in all terms of calculation

here: $\overline{MS}$ running mass

(similar predictions for pole mass)

measurement of $\overline{\text{MS}}$ charm mass

EPJC 73 (2013) 2311



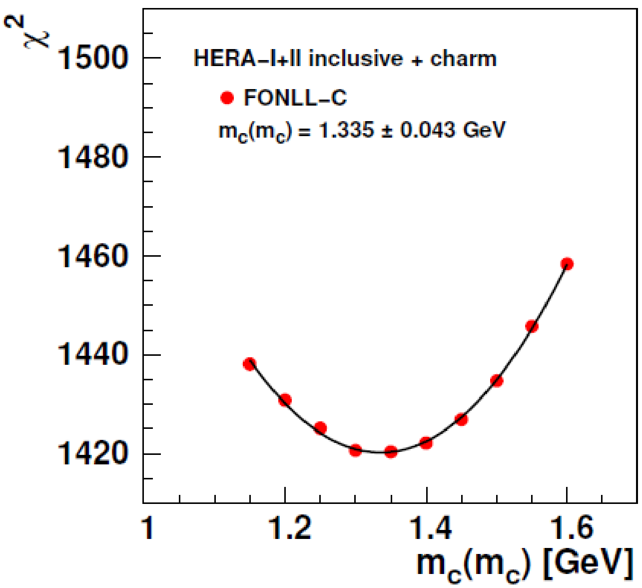
simultaneous fit of combined charm data and inclusive HERA I DIS data

$m_c(m_c)$ = 1.26 $\pm0.05_{exp}$ $\pm0.03_{mod}$ $\pm0.02_{\alpha s}$ GeV

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

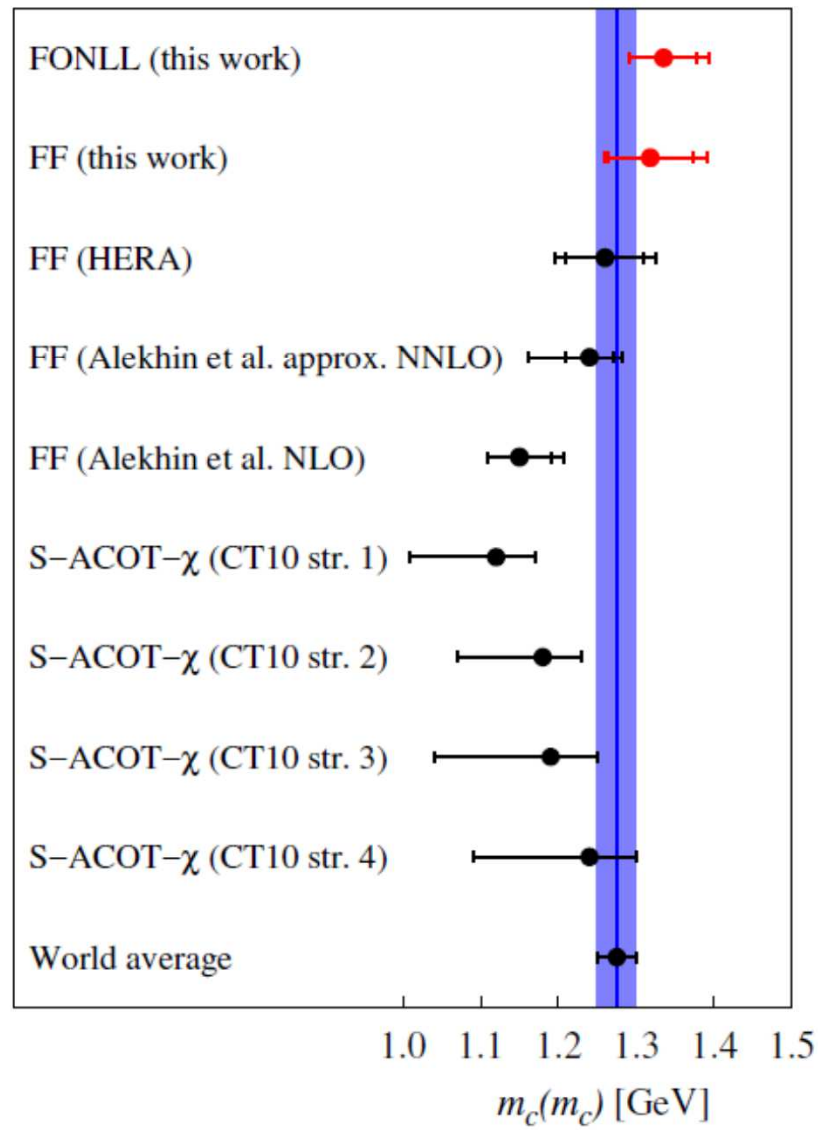
$m_c(m_c)$ from FONLL fit of HERA data

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



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-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 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

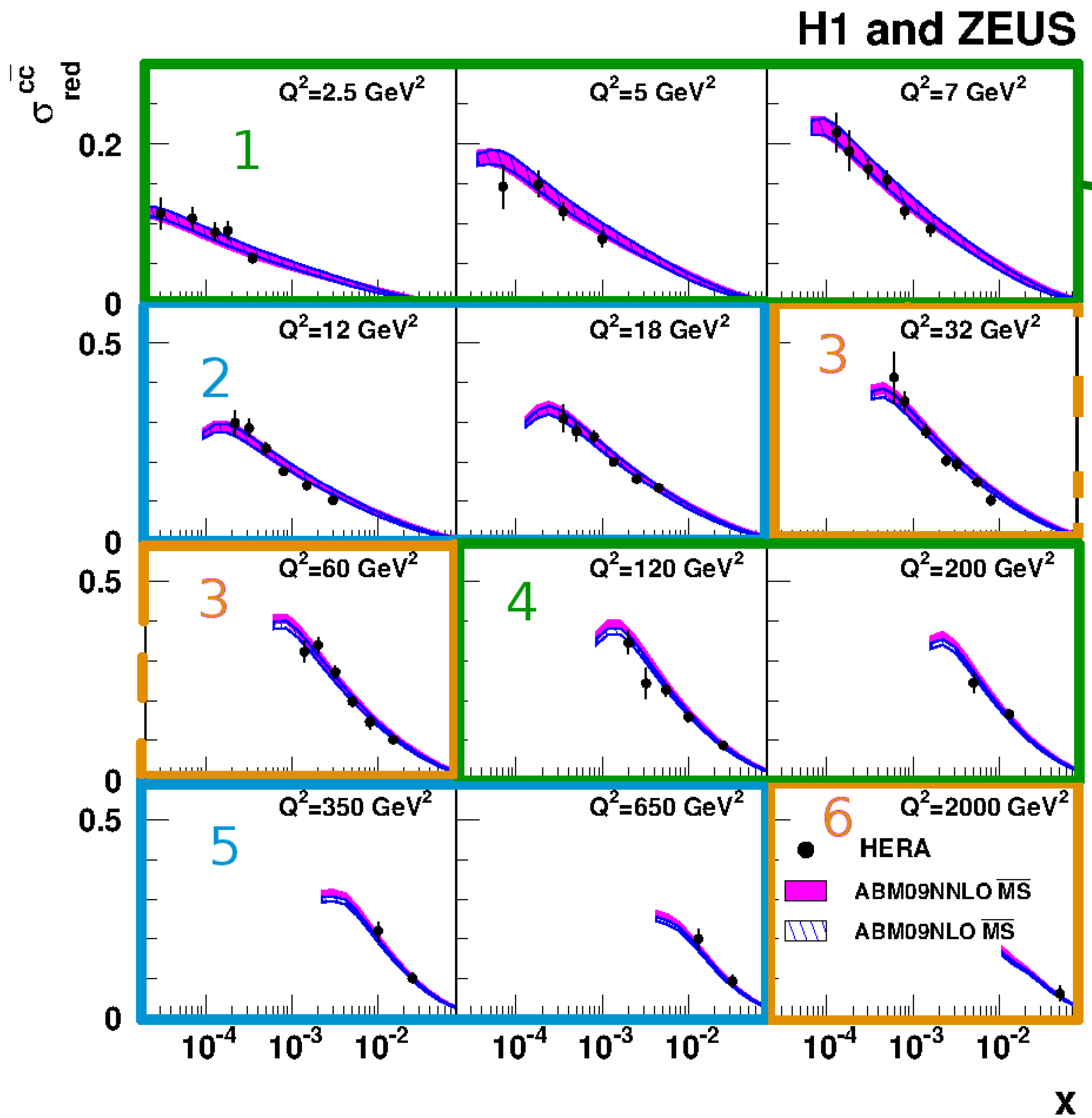
- **quark mass running depends on α_s , e.g.**

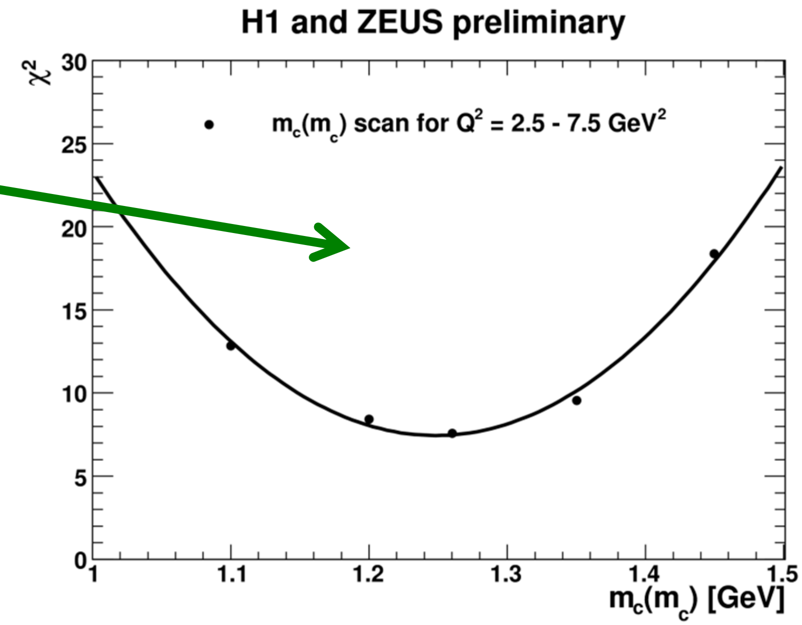
$$m(pole) = m(m) (1 + 4/3 \ \alpha_s/\pi)$$
$$= m(Q) (1 + \alpha_s/\pi (4/3+\ln(Q^2/m_c^2)))$$

- 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

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





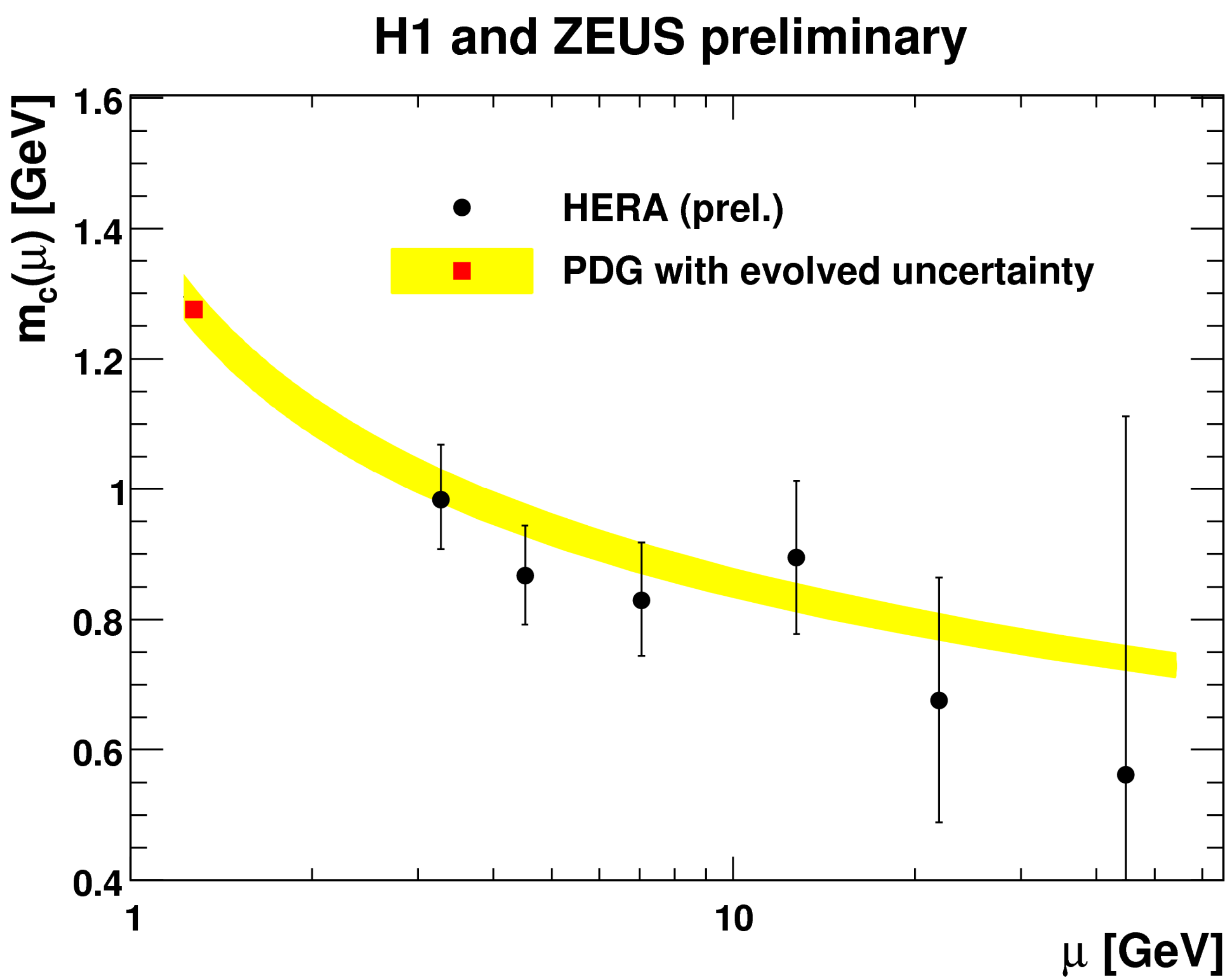
extract $m_c(\mu)$ separately for 6 different kinematic ranges in $\mu^2 = Q^2+4m_c^2$

(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 !

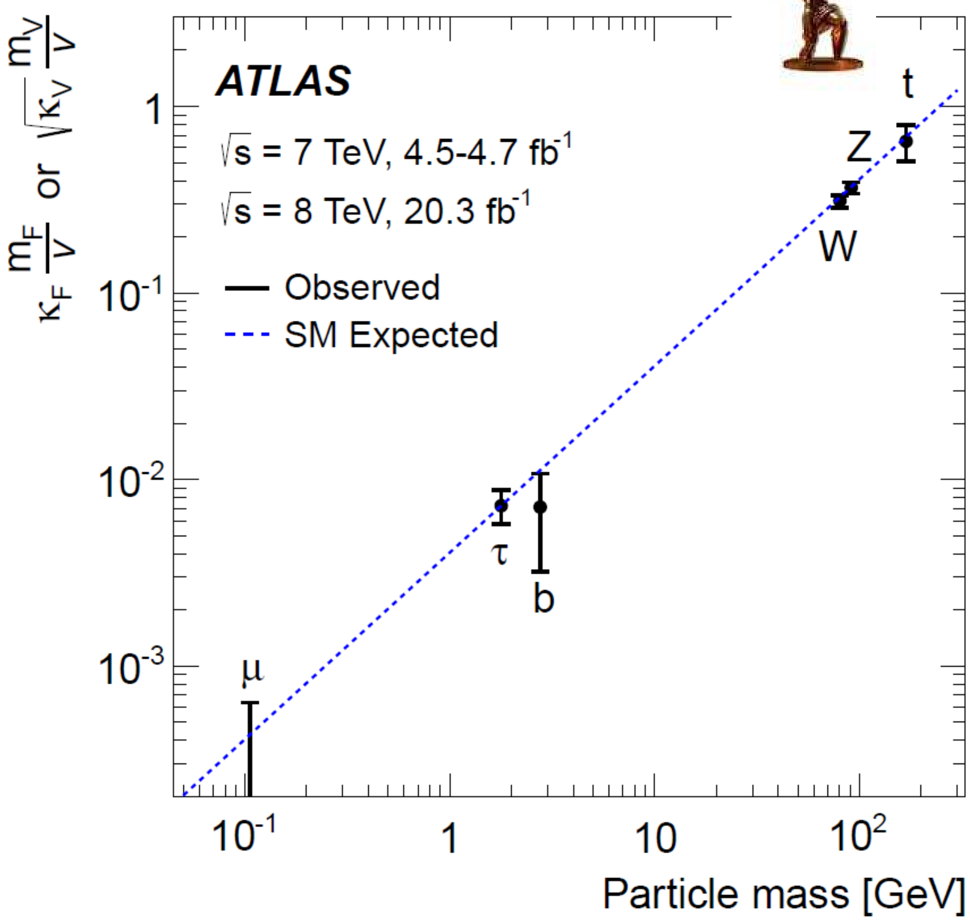
but mass is also
manifestation of
Higgs Yukawa
couplings !

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

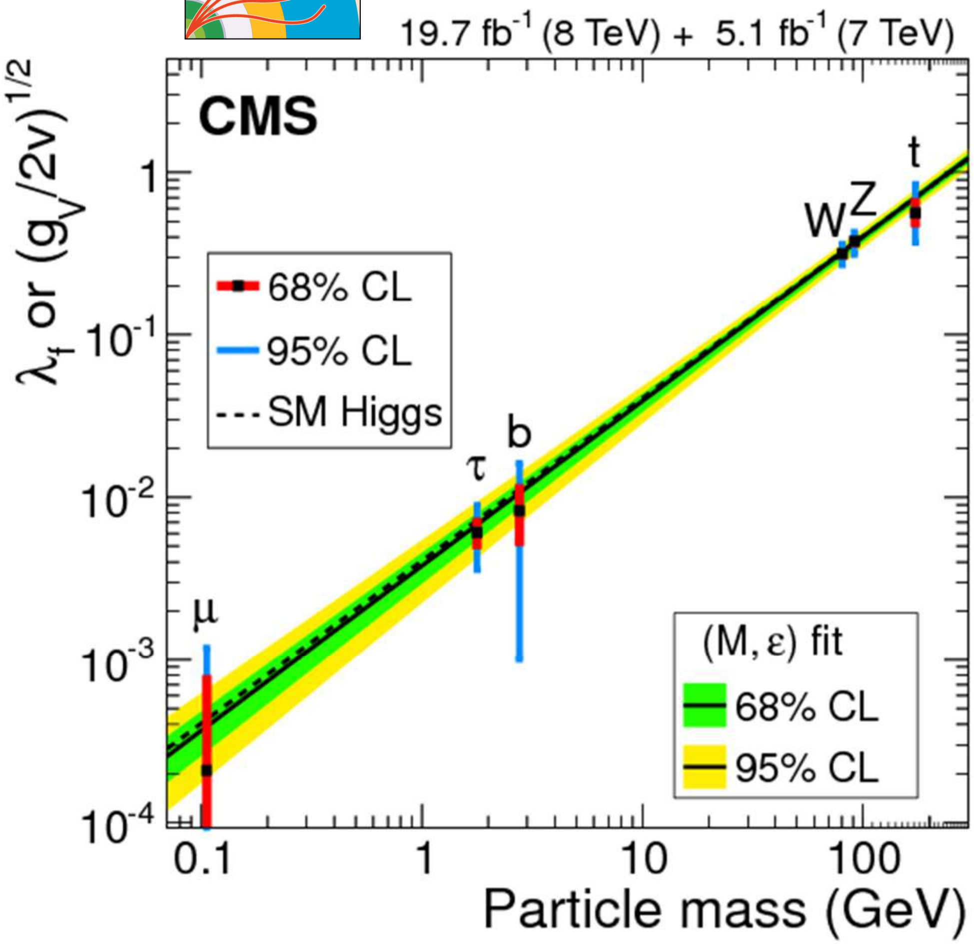
Direct measurements of Higgs Yukawa couplings

vs. mass

arXiv: 1507.04548, EPJC 76 (2016) 6



EPJC 75 (2015) 212

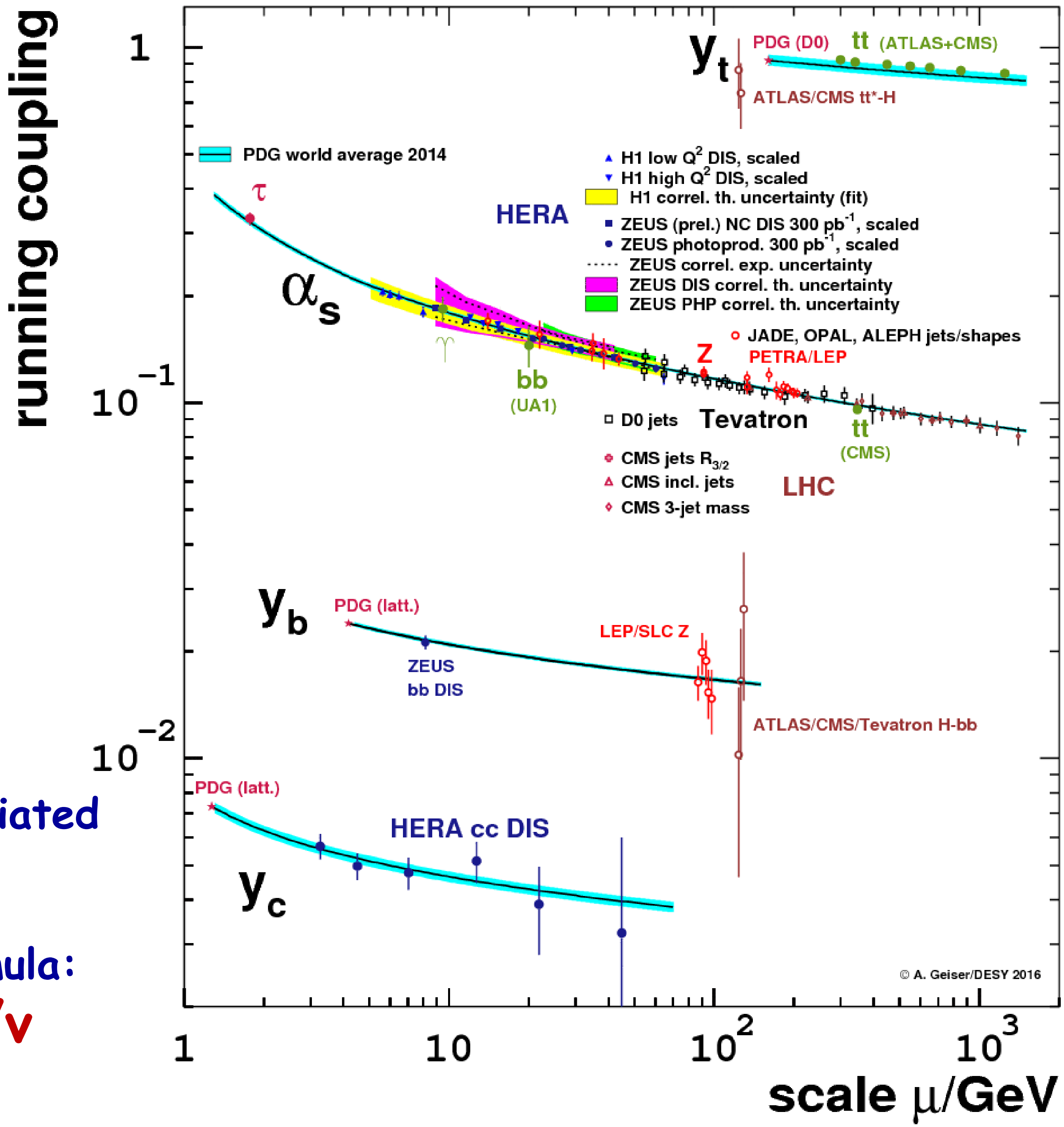


Hbb updated from PRD 92 (2015) 032008

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:

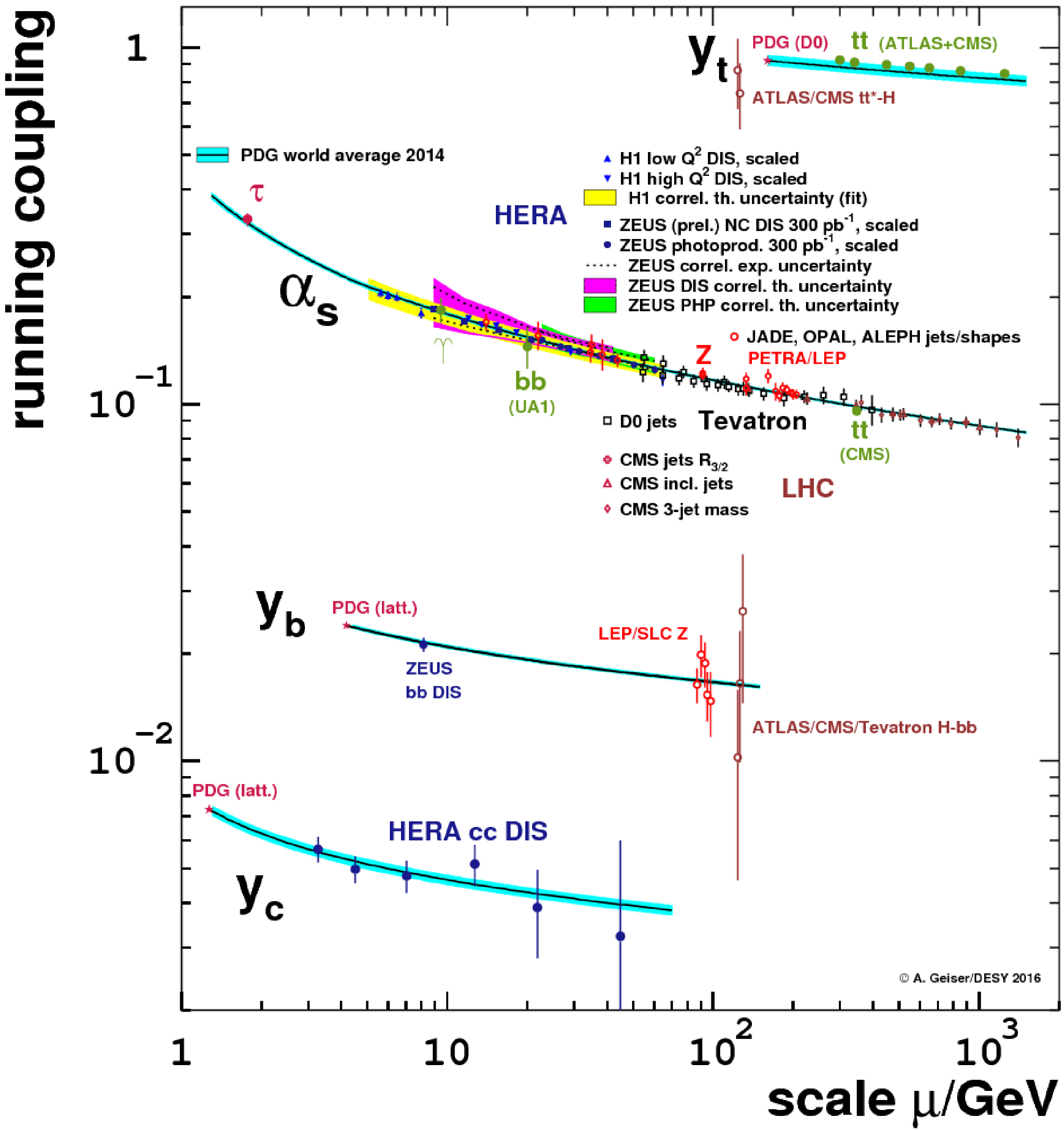
$$y_Q = \sqrt{2} m_Q / v$$

Conclusion

HERA can measure almost all aspects of charm production

Heavy Quark physics is also QCD + Higgs physics

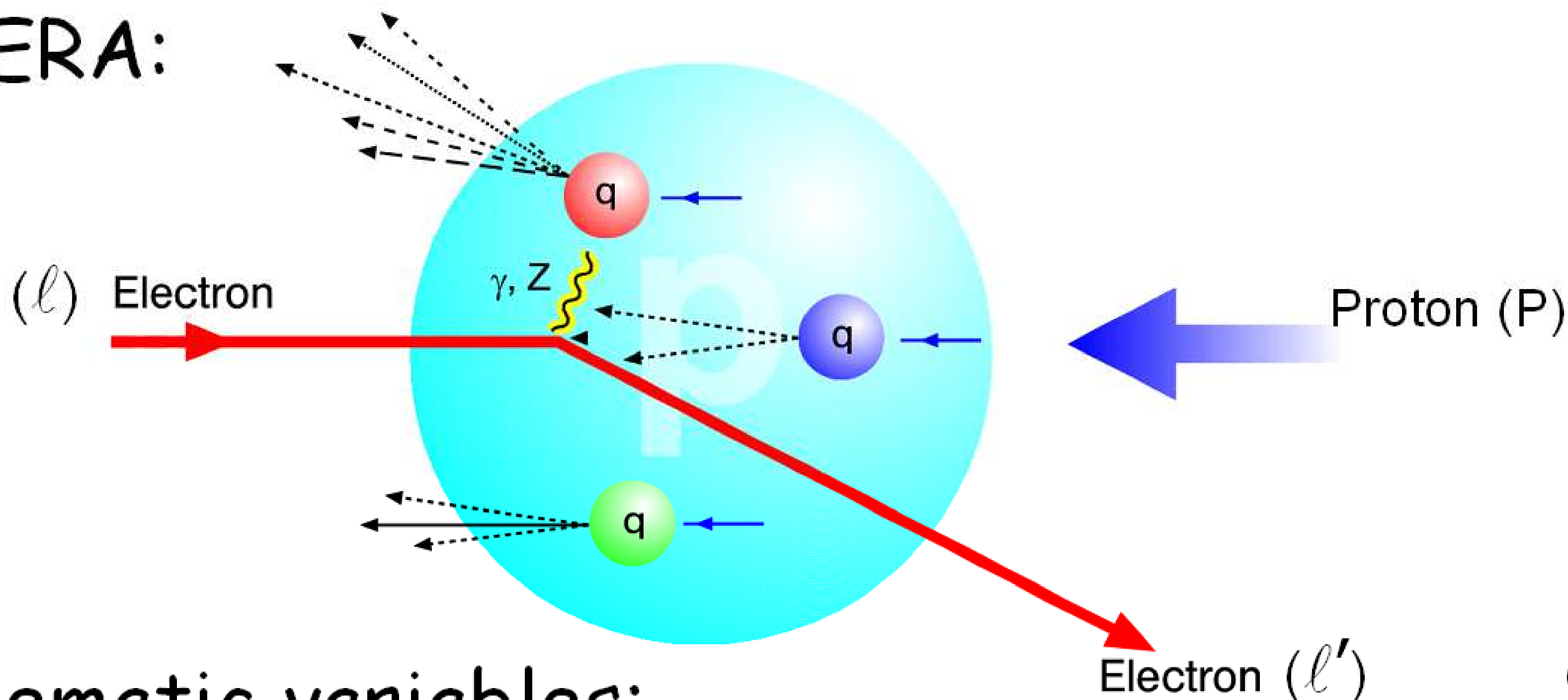
so far, Higgs couplings and their running as obtained from quark masses are consistent with directly measured Higgs couplings



Backup

Deep Inelastic ep Scattering at HERA

HERA:



$q = \ell - \ell'$

kinematic variables:

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

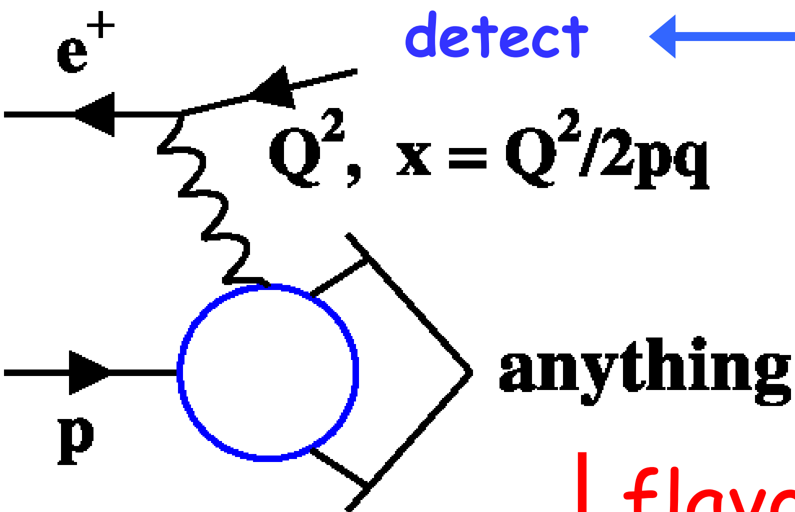
$x = \frac{Q^2}{2Pq}$ Bjorken scaling variable,
for $Q^2 \gg (2m_q)^2$: momentum fraction of p constituent

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

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

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

Heavy flavour contributions to F_2

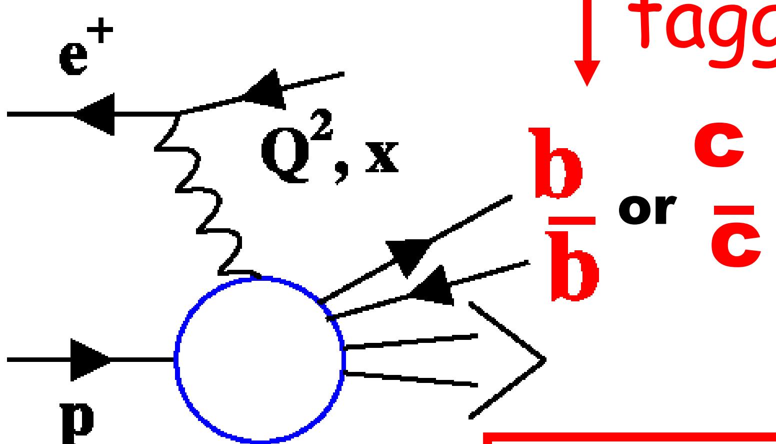


detect ⟷

Measure cross section

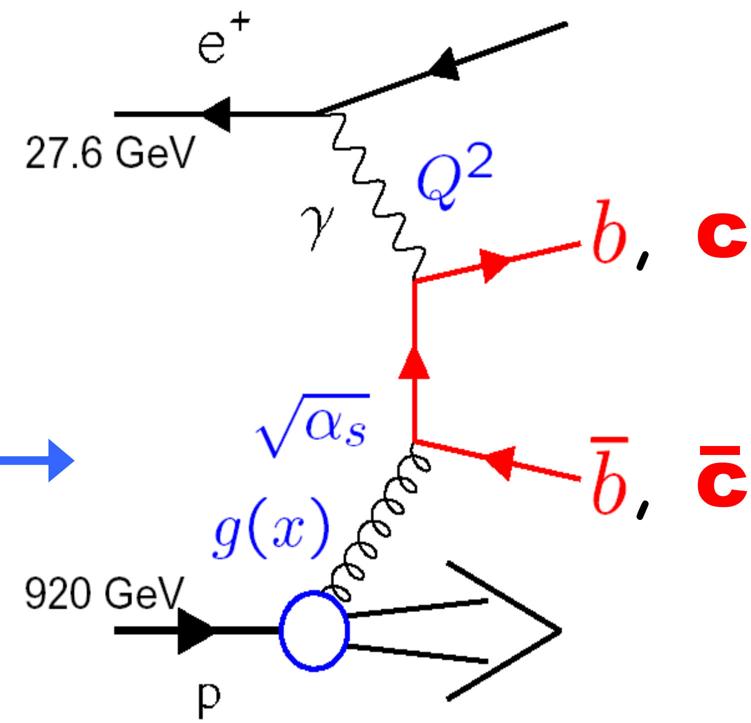
$$\frac{d^2\sigma}{dx\,dQ^2} \cong \frac{2\pi\alpha^2}{Q^4 x}\left\{\left[1+(1-y)^2\right]F_2(x,Q^2)\right)$$

↓ flavour tagging

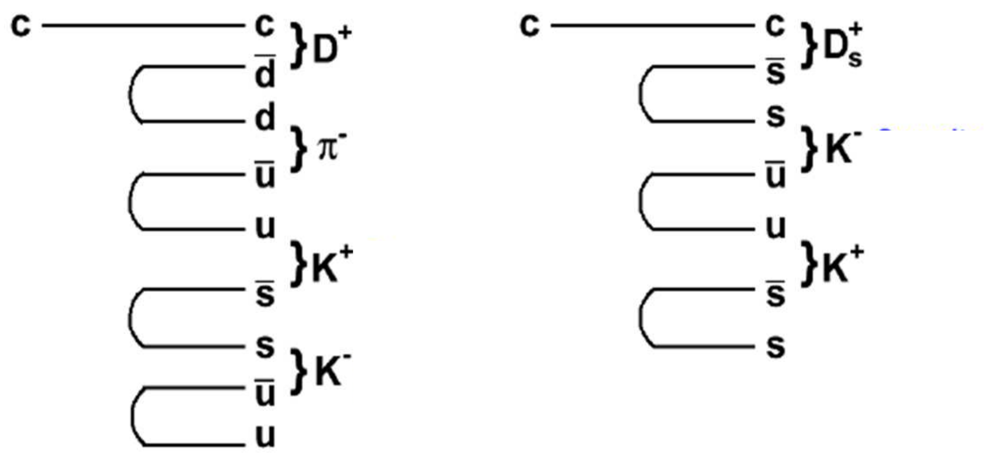


-> $F_2^{b\bar{b}}$, $F_2^{c\bar{c}}$

QCD ⟷

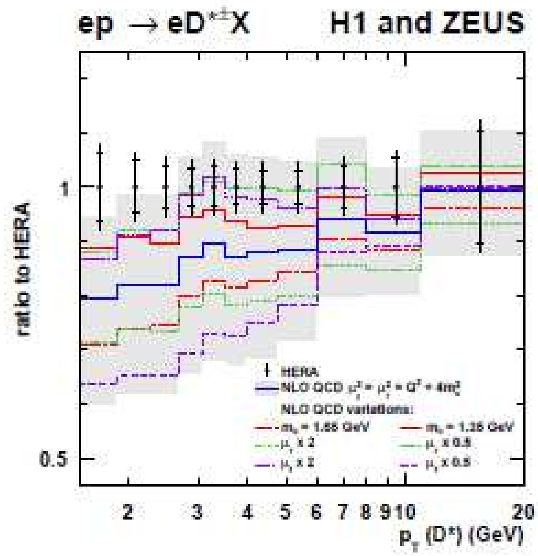


Charm Fragmentation



Comparison to NLO QCD

detailed study of theory uncertainties



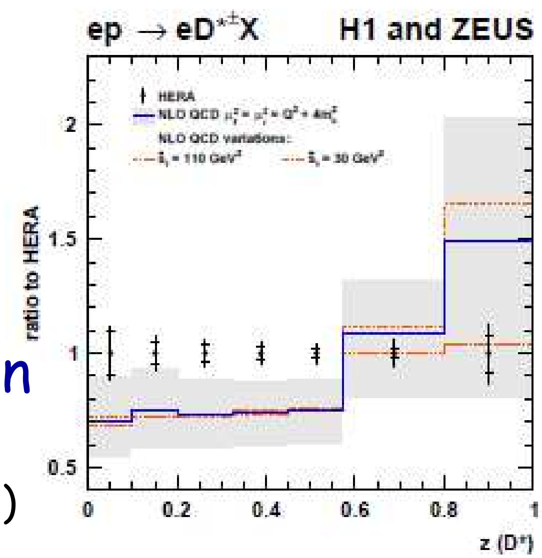
is it possible to customise (choose parameters) such that all distributions are described simultaneously?

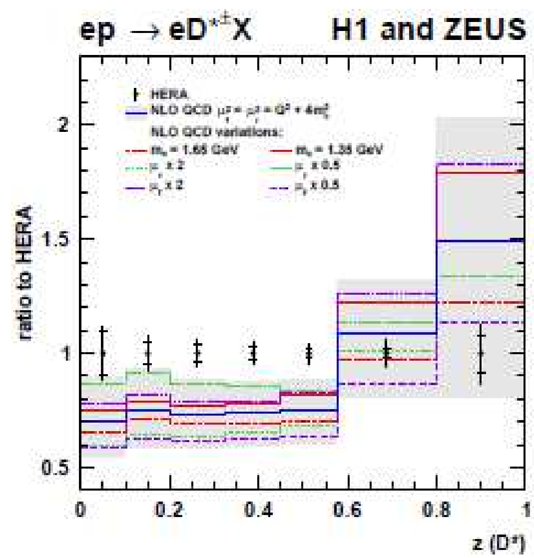
largest:

QCD scales

fragmentation

(Kartvelishvili as measured at HERA)

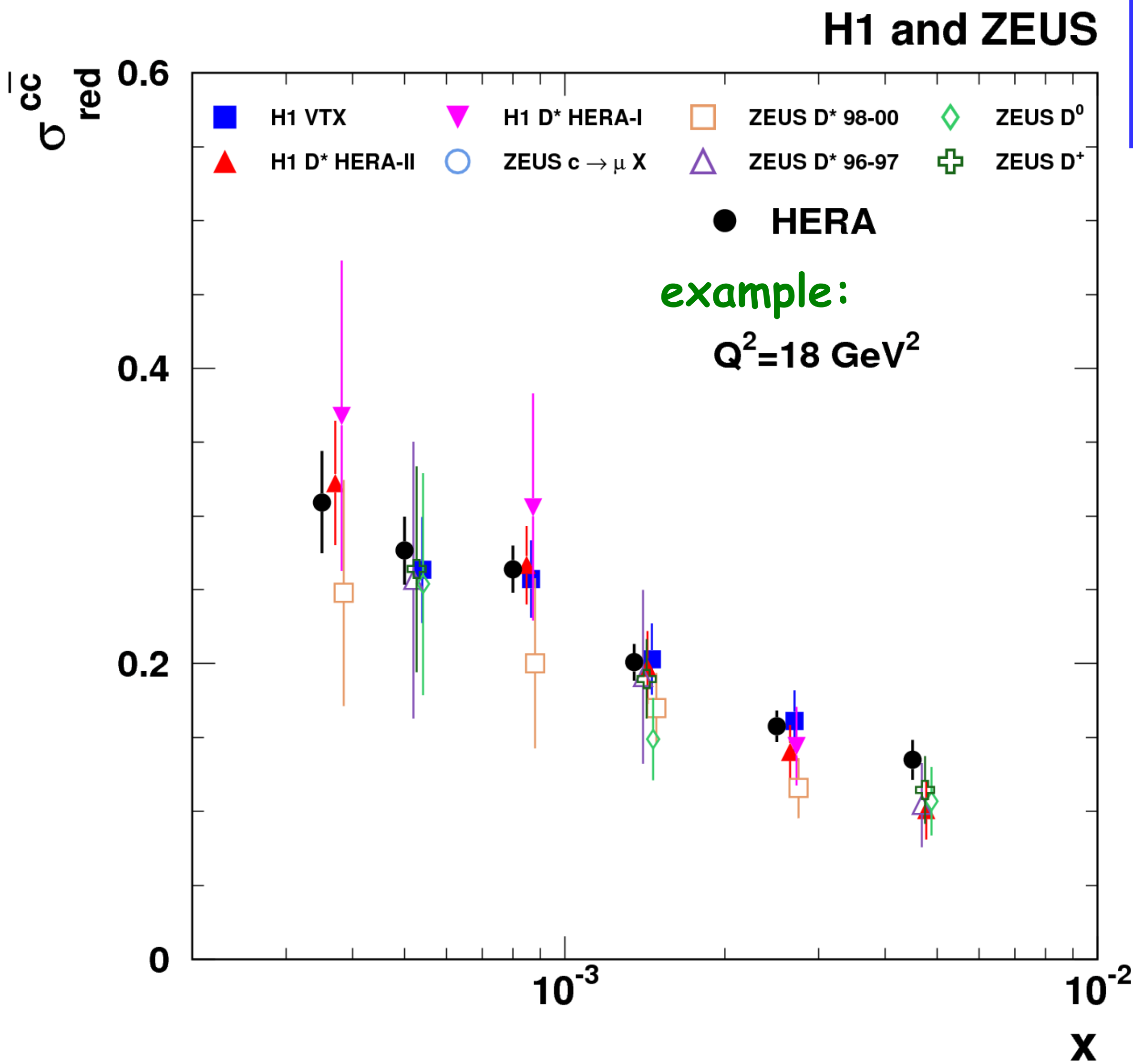




it is!

HERA charm data combination

EPJ C73 (2013) 2311



Measure cross section

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

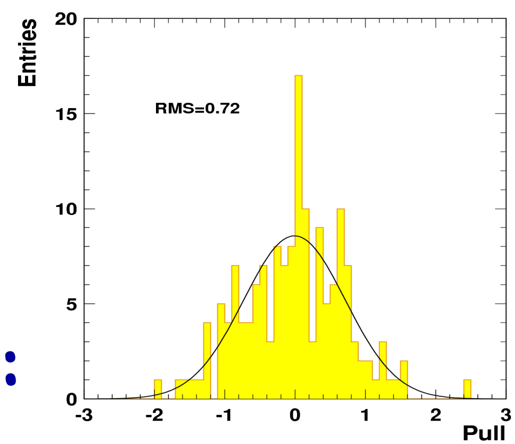
9 data sets
(HERA I, HERA II)

5 charm tagging methods

155 -> 52 data points

48 correlated systematic uncertainties

very good selfconsistency of data:



Beauty at LHCb

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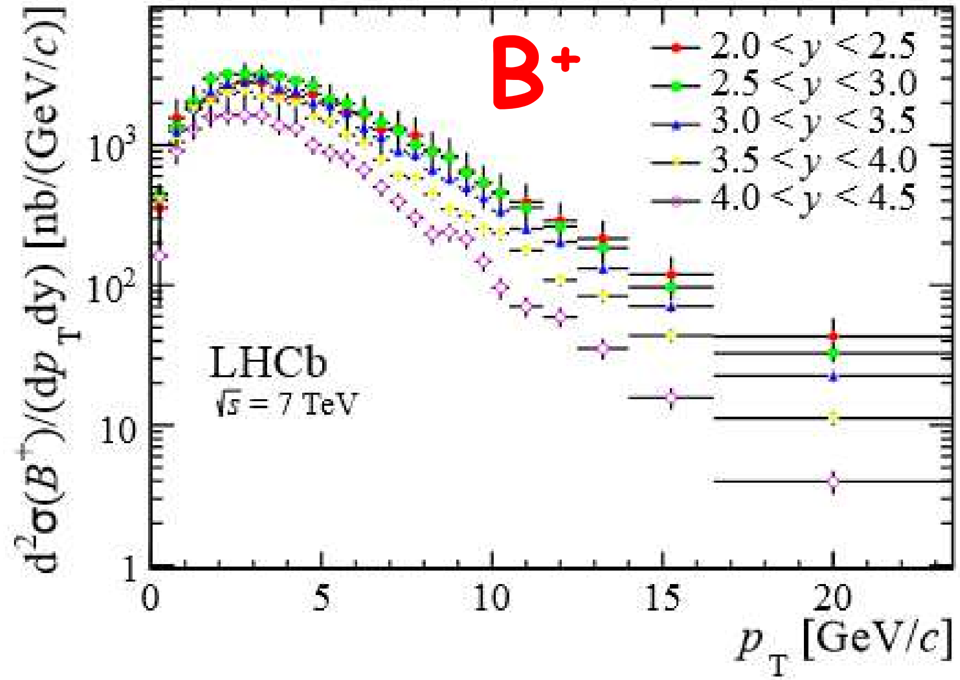
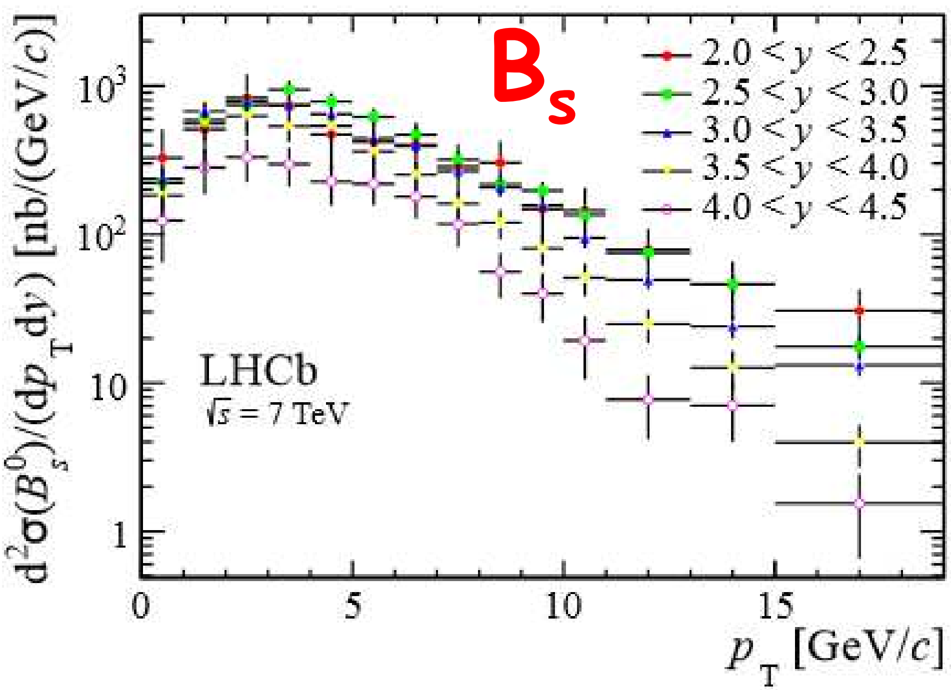
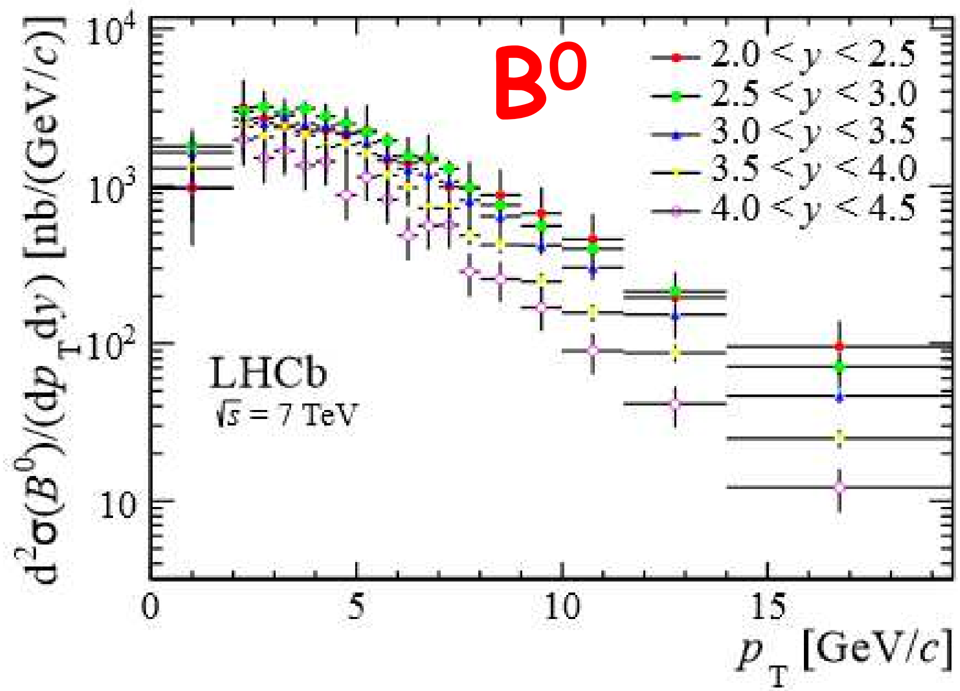






Charm

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)

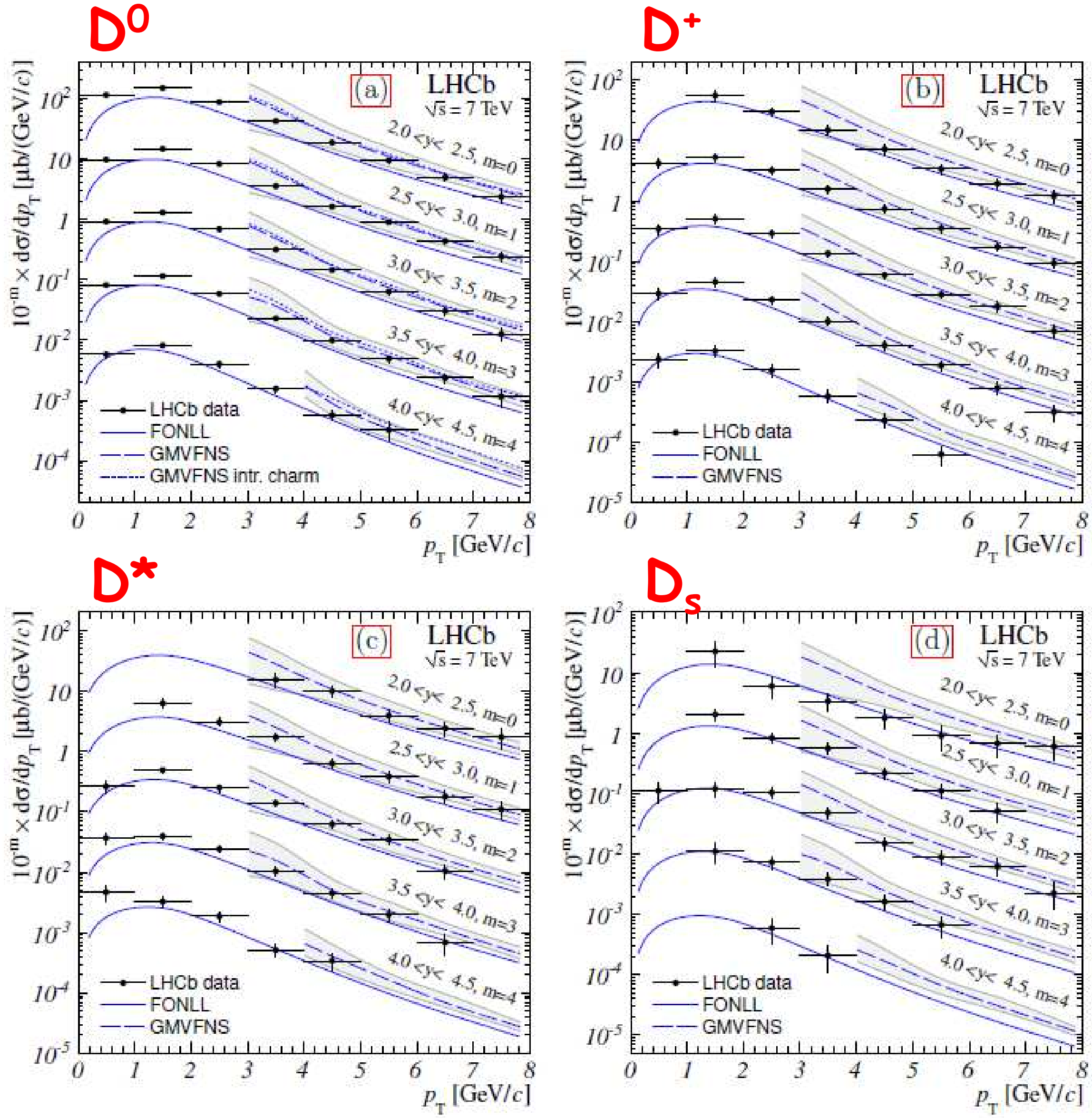
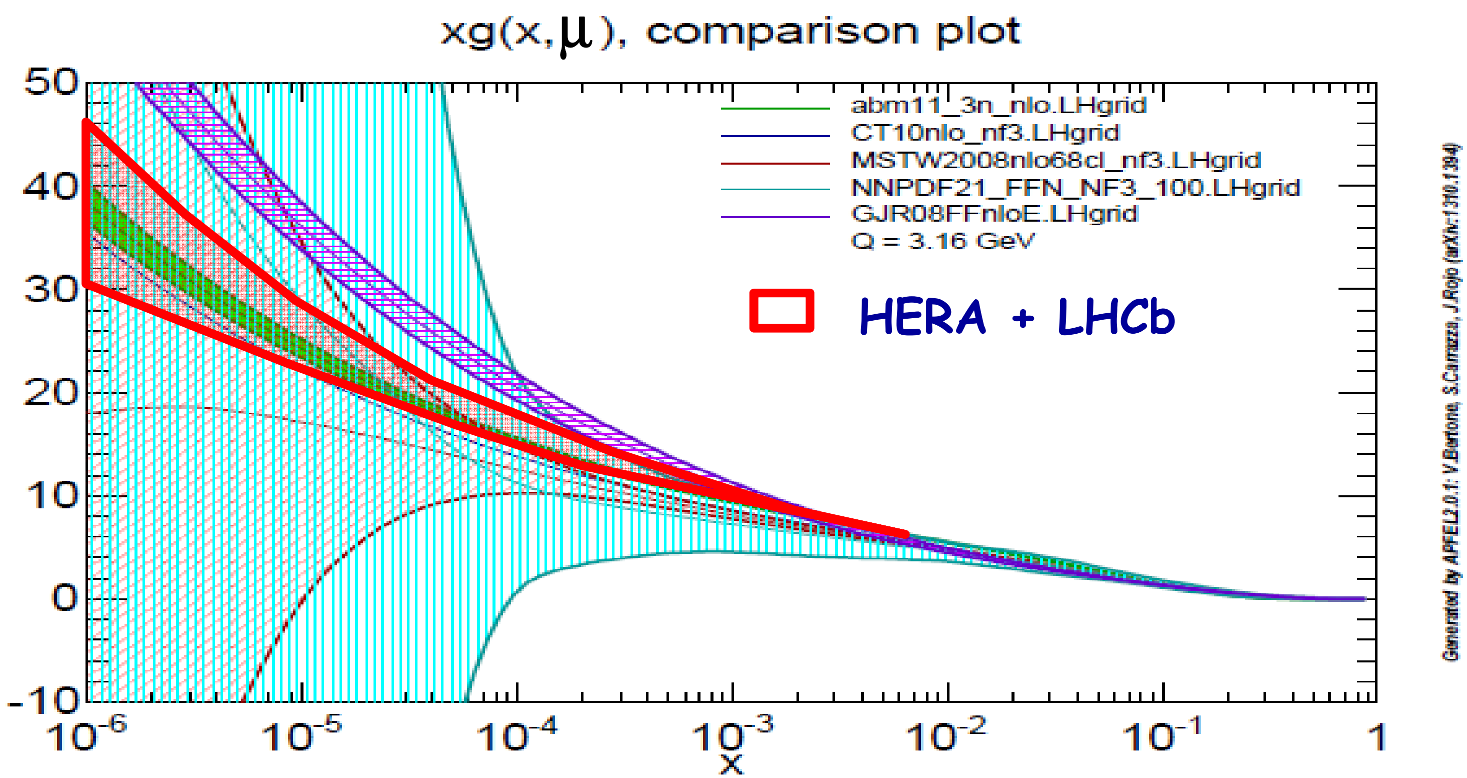


Figure 4: Differential cross-sections for (a) D^0, (b) D^+, (c) D^{*+}, and (d) D_s^+ meson production compared to theoretical predictions. The cross-sections for different y regions are shown as functions of p_T. The y ranges are shown as separate curves and associated sets of points scaled by factors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

Running strong coupling „constant“ α_s

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

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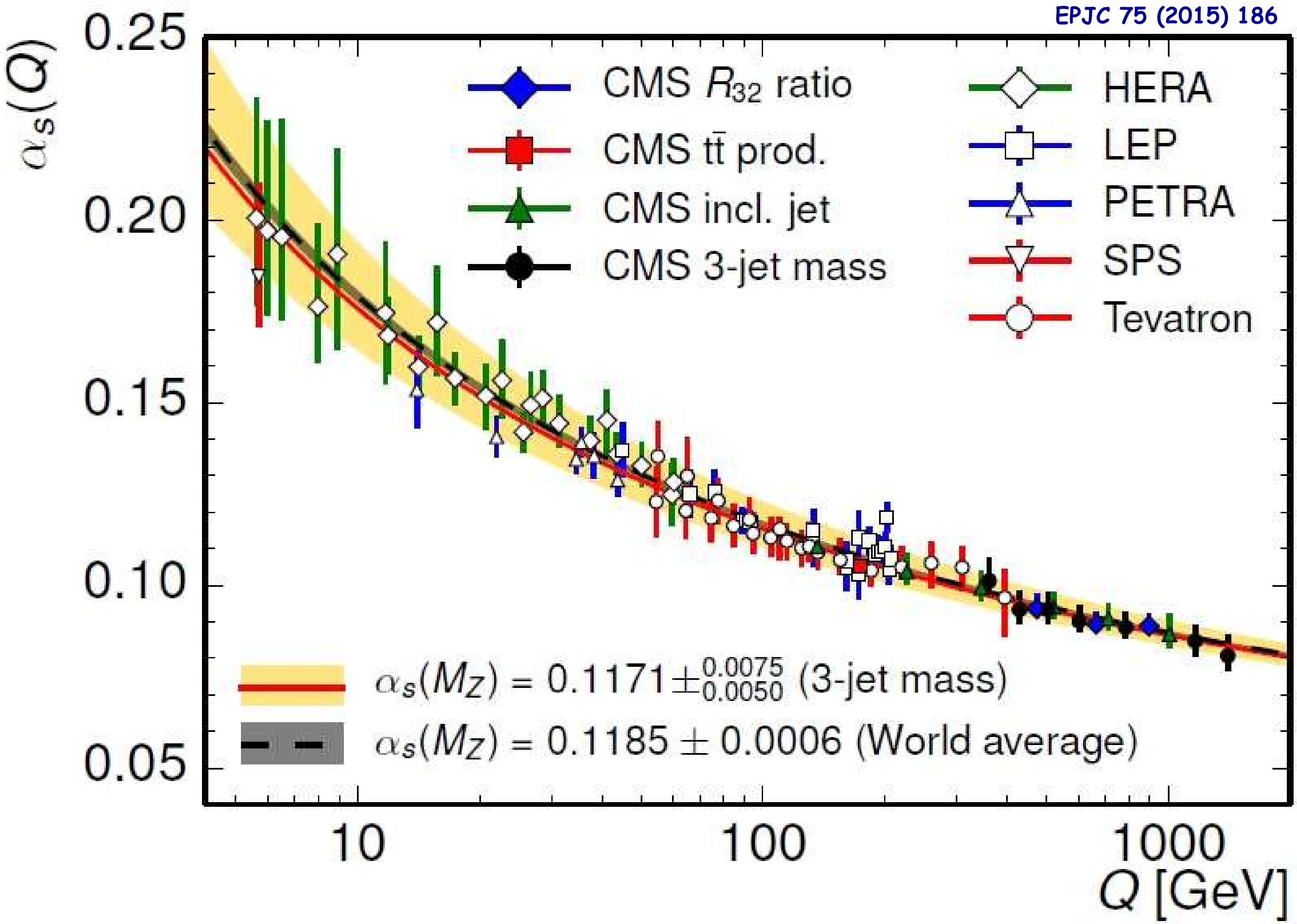
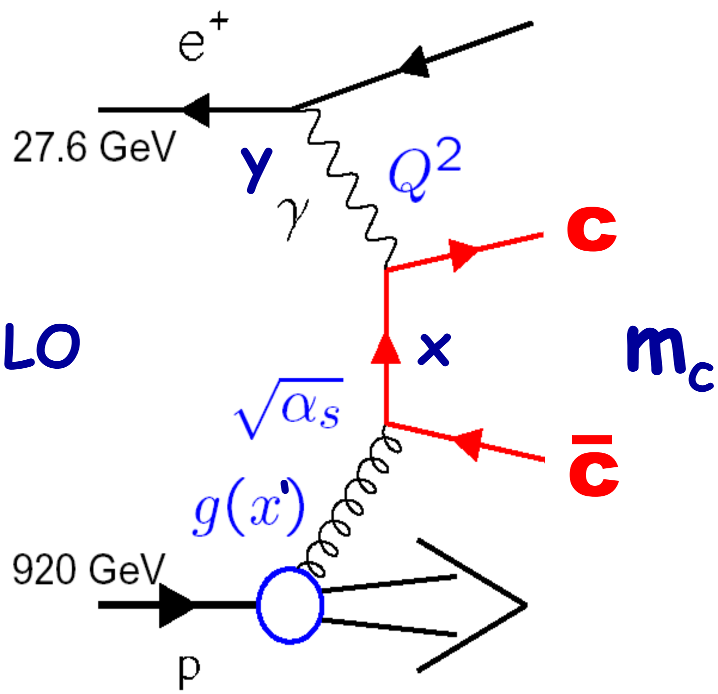


Yes, it runs!

fixed flavour number scheme (FFNS)



LO

+ 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 $\triangle\chi^2 = 1$ (dominant uncertainty)

Parametrisation

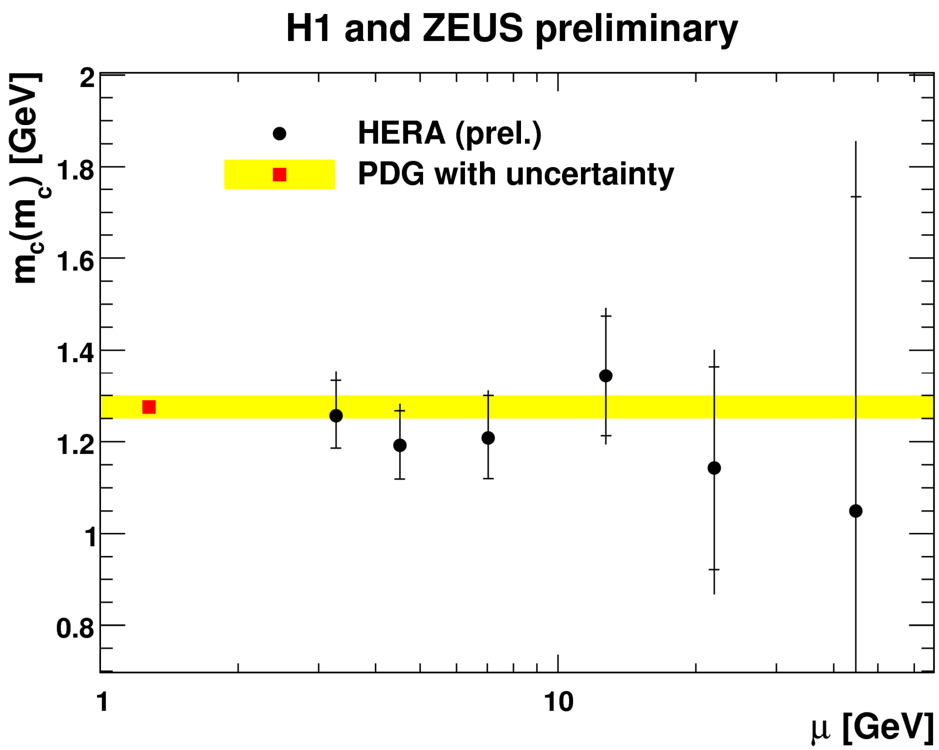
- Adding extra parameter in the PDF parametrisation

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

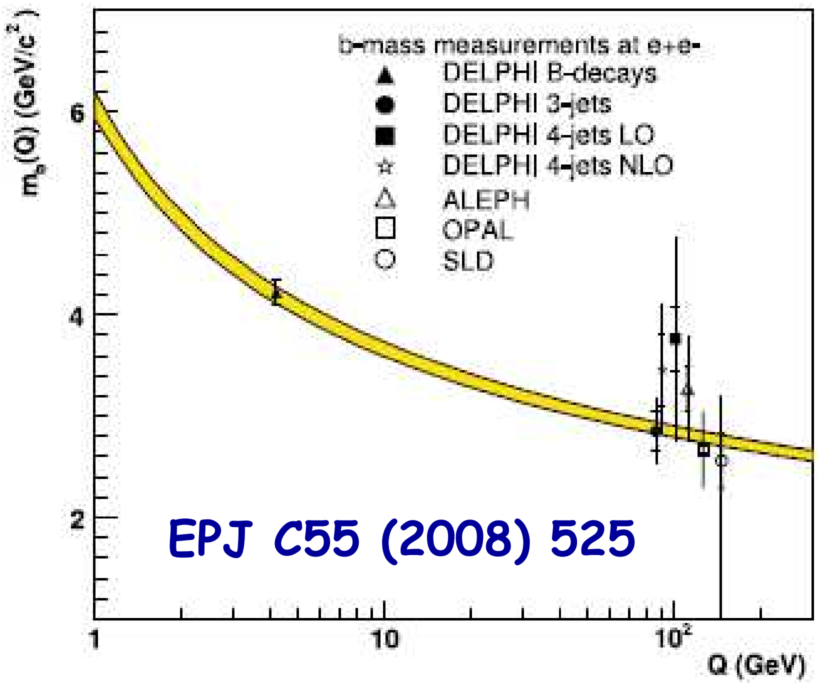


Fig. 6. The energy evolution of the $\overline{MS}$-running b-quark mass $m_b(Q)$ as measured at LEP. DELPHI results from $R_3^{b\ell}$ [7] at the M_Z scale and from semileptonic B-decays [31] at low energy are shown together with results from other experiments (ALEPH [4], OPAL [5] and SLD [6]). The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

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

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

m_b from reduced beauty cross section

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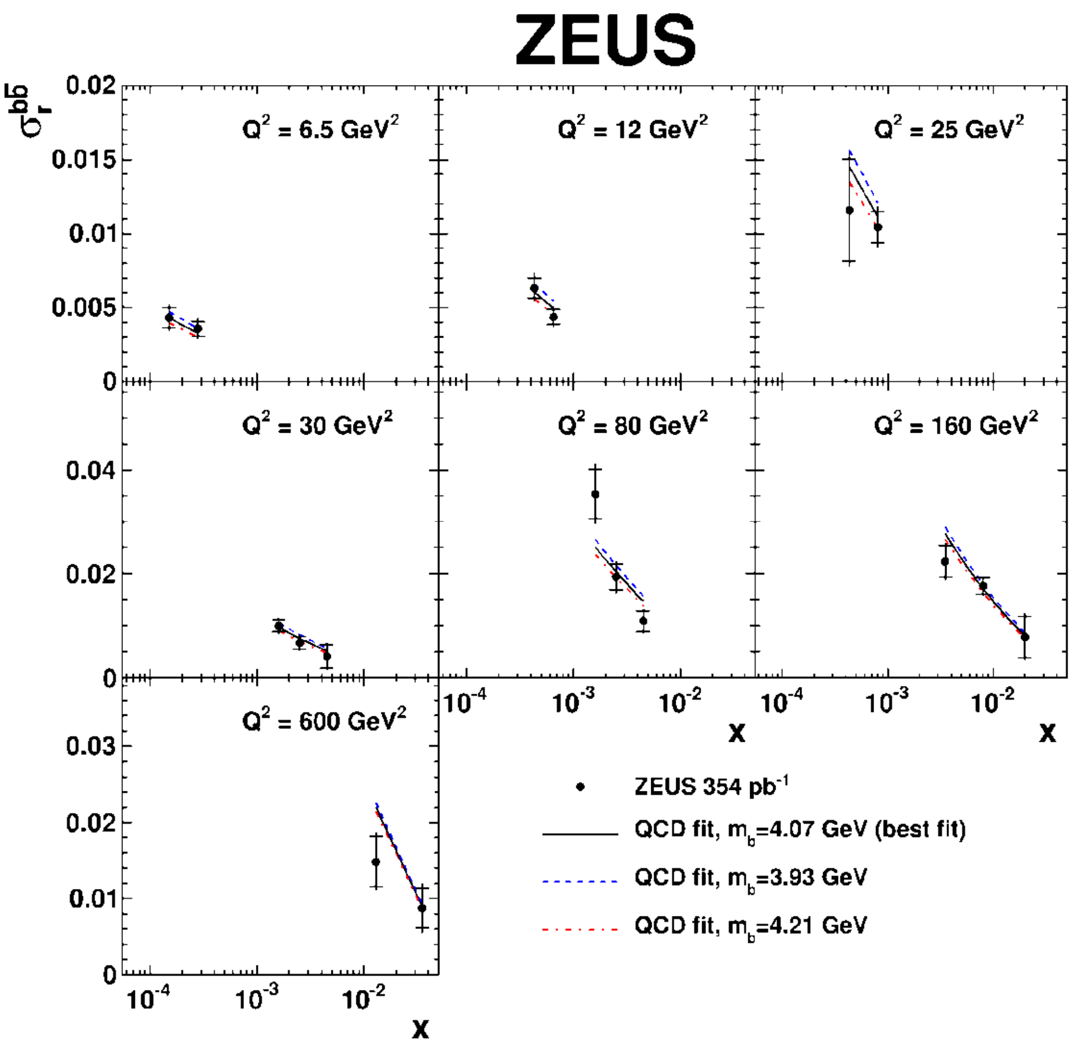

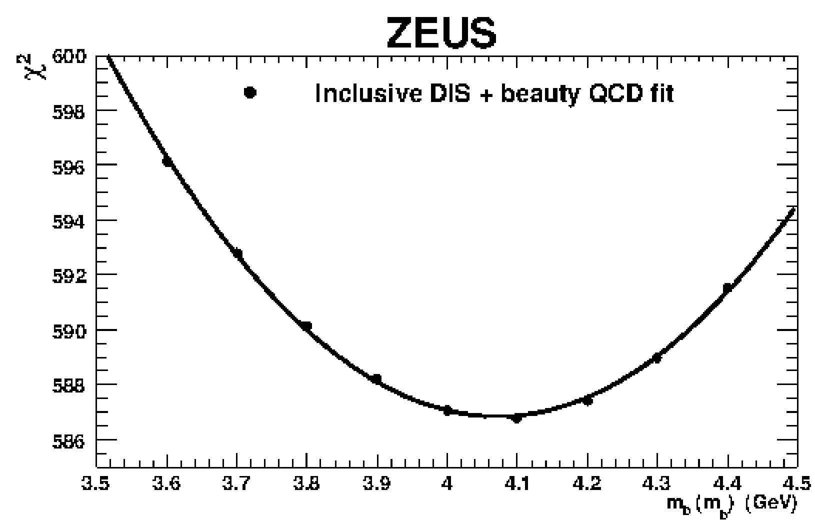

uncertainty evaluation
similar to charm running case

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

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

the running beauty quark mass

arXiv:1506.07519

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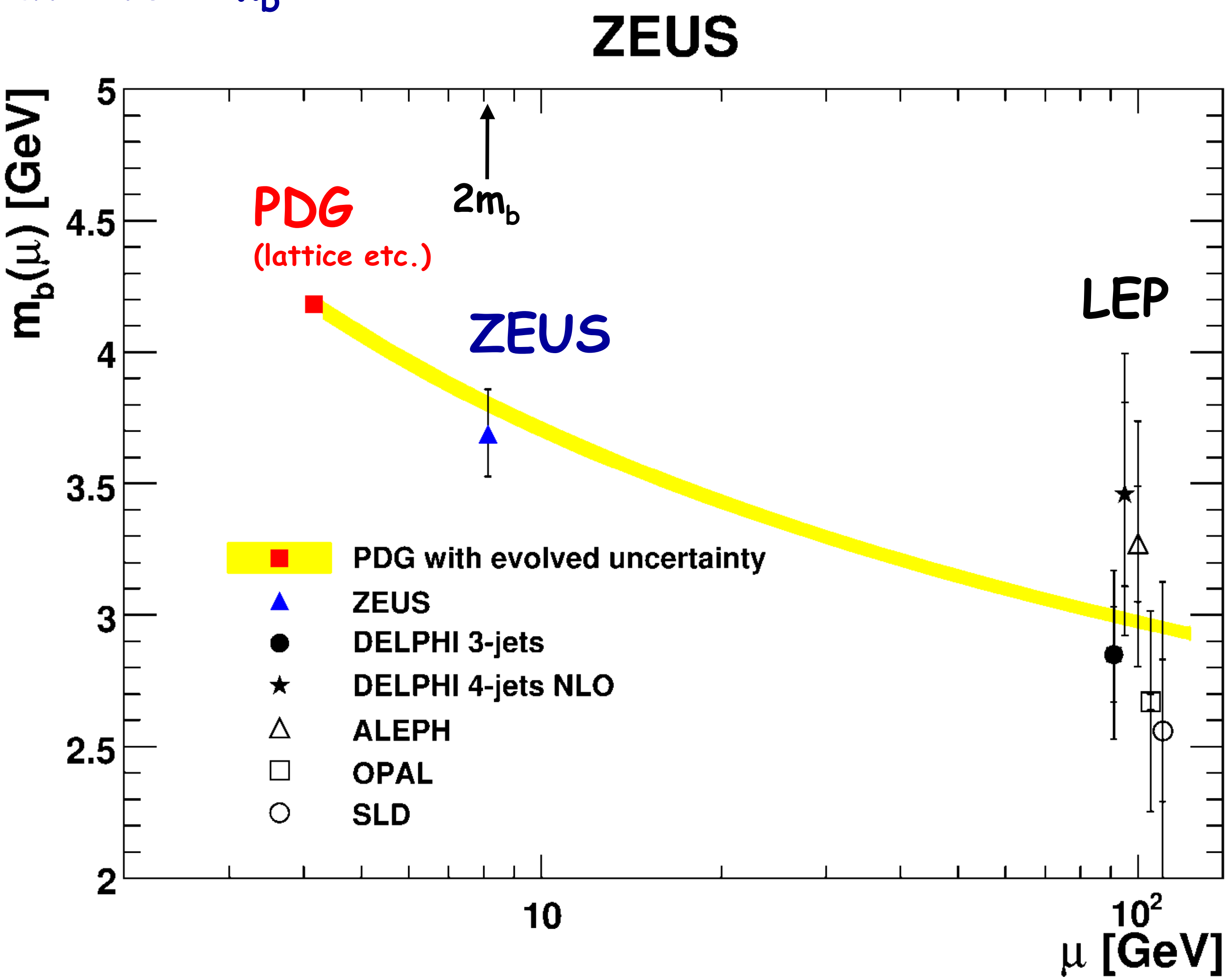
translate to $2m_b$



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