A determination of $m_c(m_c)$ from HERA data using a matched heavy flavor scheme

Valerio Bertone

University of Oxford

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Main contributors: V.B., Achim Geiser, Ringaile Placakyte, Voica Radescu, and Juan Rojo

Motivation

- The **mass of the charm quark** is one of the fundamental parameters of the Standard Model.
- A precise and faithful determination is relevant:
  - in principle: as a **fundamental test** of the Standard Model,
  - in practice: as a requirement for accurate **phenomenology at the LHC**.
- The current global-average value of the charm mass in the $\overline{\mathrm{MS}}$ renormalization scheme is $\mathbf{m_c(m_c) = 1.275 \pm 0.025}$ **GeV**:
  - dominated by the high-precision $e^+e^- \to Q\overline{Q}$ data,
  - interesting to provide **alternative determinations** from other processes:
    - to test the robustness of the global average,
    - to attempt to further reduce the present uncertainty.
- **Charm production in DIS** is directly sensitive to the charm mass:
  - precise HERA data available,
- Also the new inclusive **combined HERA 1+2** data provide a constraint.

Current Status

- A competitive determination of the charm mass from DIS data has already been achieved in the context of PDF fits to HERA DIS data:
    - **H1-ZEUS** and **Alehkin et al.** determinations are included in the PDG value.
    - both obtained in the so-called **FFNS** with of $\overline{\mathrm{MS}}$ heavy quark masses.
- Employing **$\overline{\mathbf{MS}}$ heavy quark masses** is **crucial** in this context:
    - improvement of **perturbative convergence**,
    - direct handle on $m_c(m_c)$.
- So far, **GM-VFNSs** (e.g. FONLL, ACOT, TR) have mostly employed the **pole mass** definition for heavy quark masses:
    - difficult to determine $m_c(m_c)$ even indirectly because of the **poor convergence** of the perturbative relation that connects $\overline{\mathrm{MS}}$ and pole mass definitions.
    - pole mass definition intrinsically affected by **non-perturbative $\mathbf{O(\Lambda_{QCD})}$ corrections** (renormalons).

What's new (Theory)

- We have formulated the **FONLL scheme in terms of the $\overline{\mathrm{MS}}$ masses**:
    - first step towards a **direct determination of $m_c(m_c)$** in the FONLL scheme,
    - **alternative/complementary** mass scheme to the FFNS.
- Two main steps required:
    1. re-expressing the **massive coefficient functions**, usually given in terms of pole masses, in terms of $\overline{\mathrm{MS}}$ masses:
        - similar to what has been done by S. Alehkin and S.O. Moch with a relevant difference regarding the RG running of the masses.
    2. **Matching conditions** of the running quantities (PDFs, α_s, and masses):
        - needed by the FONLL scheme as a VFNS (not needed in the FFNS).
- All the formalism is implemented in **APFEL** ⇒ **available in xFitter**:

ready to attempt a determination of $m_c(m_c)$

Analysis Settings

- The **dataset**:
  - combined HERA 1+2 charm production cross sections,
  - combined HERA 1+2 inclusive DIS cross sections,
  - cut on data with $Q^2 < Q_{min}^2 = 3.5$ GeV^2.
- The **parametrization**:

$$
\begin{aligned}
xg(x) &&= A_g x^{B_g}(1-x)^{C_g} - A'_g x^{B'_g}(1-x)^{25}, \quad & B_{\bar{U}} = B_{\bar{D}}, \\
xu_v(x) &= xu(x) - x\overline{u}(x) &= A_{u_v} x^{B_{u_v}}(1-x)^{C_{u_v}}(1+E_{u_v}x^2), \quad & A_{\bar{U}} = A_{\bar{D}}(1-f_s) \\
xd_v(x) &= xd(x) - x\overline{d}(x) &= A_{d_v} x^{B_{d_v}}(1-x)^{C_{d_v}}, & \\
x\bar{U}(x) &= x\overline{u}(x) &= A_{\bar{U}} x^{B_{\bar{U}}}(1-x)^{C_{\bar{U}}}(1+D_{\bar{U}}x), & \\
x\bar{D}(x) &= x\overline{d}(x) + x\overline{s}(x) &= A_{\bar{D}} x^{B_{\bar{D}}}(1-x)^{C_{\bar{D}}}. &
\end{aligned}
$$

- and its variations:
  - strangeness fraction: $f_s = 0.4 \pm 0.1$,
  - initial scale: $Q_0^2 = 1$ - 1.5 GeV^2 (bound to be below te charm mass),
  - functional form variation: inclusion of the D_{uv} linear term in $xu_v(x)$.

Analysis Settings

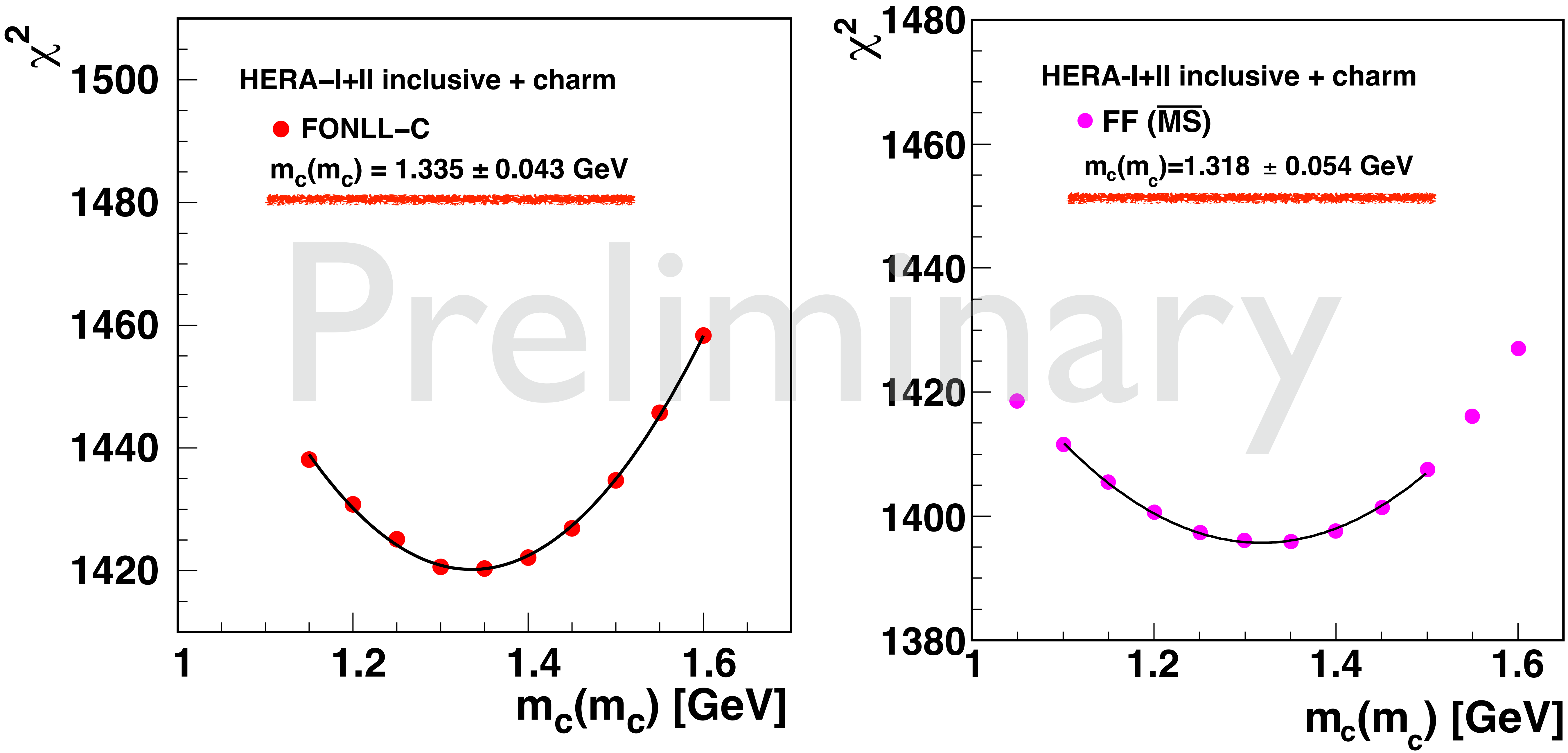
- The **model (QCD) settings** and their variations:
  - strong coupling: $\alpha_s(M_Z) = 0.118 \pm 0.0015$,
  - all heavy quark masses are defined in the $\overline{\mathrm{MS}}$ renormalization scheme:
    - charm mass: $m_c(m_c)$ scan in the range [1.10 - 1.60] GeV with steps of 0.05 GeV,
    - bottom mass: $m_b(m_b) = 4.18 \pm 0.25$ GeV (PDG value and conservative variation),
    - top mass: $m_t(m_t) = 160$ GeV (PDG value and no variation).
- The **theory settings** and their variations:
  - central scales: $\mu_R^2 = \mu_F^2 = Q^2$,
  - scale variations: $\mu_R^2 = \mu_F^2 = Q^2 / 2$ and $\mu_R^2 = \mu_F^2 = 2\, Q^2$,
  - variation of the damping factor (only for FONLL).

Analysis Settings

- Main result based on the **FONLL-C scheme**:
  - FONLL-C is nominally a NNLO scheme but accurate at NLO in the massive sector.
  - Consequently, the **accuracy** of our determination of $m_c(m_c)$ is formally **NLO**.
  - **model**, **parametrization**, and **theory uncertainties** are estimated by applying the variations described in the previous slides,
  - the impact of the so-called FONLL "**damping factor**", which is an artifice to suppress unwanted higher-order terms in the low-energy region, is also considered as a source of the theoretical uncertainty.
- The FONLL determination is accompanied by a determination in the **FFNS at NLO**:
  - same model, parametrization, and theory variations,
  - complements previous determinations.

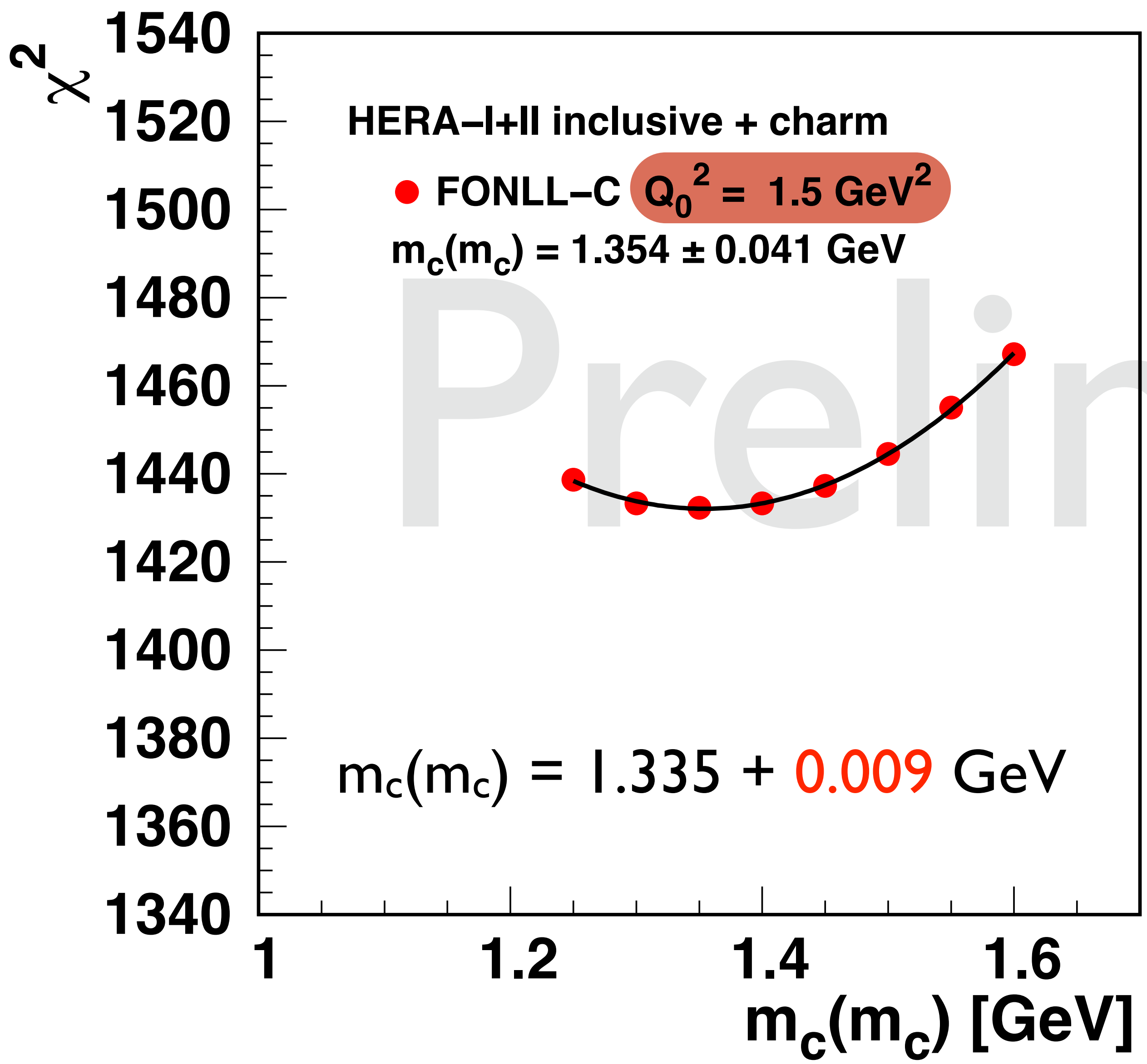
Results: Central Value

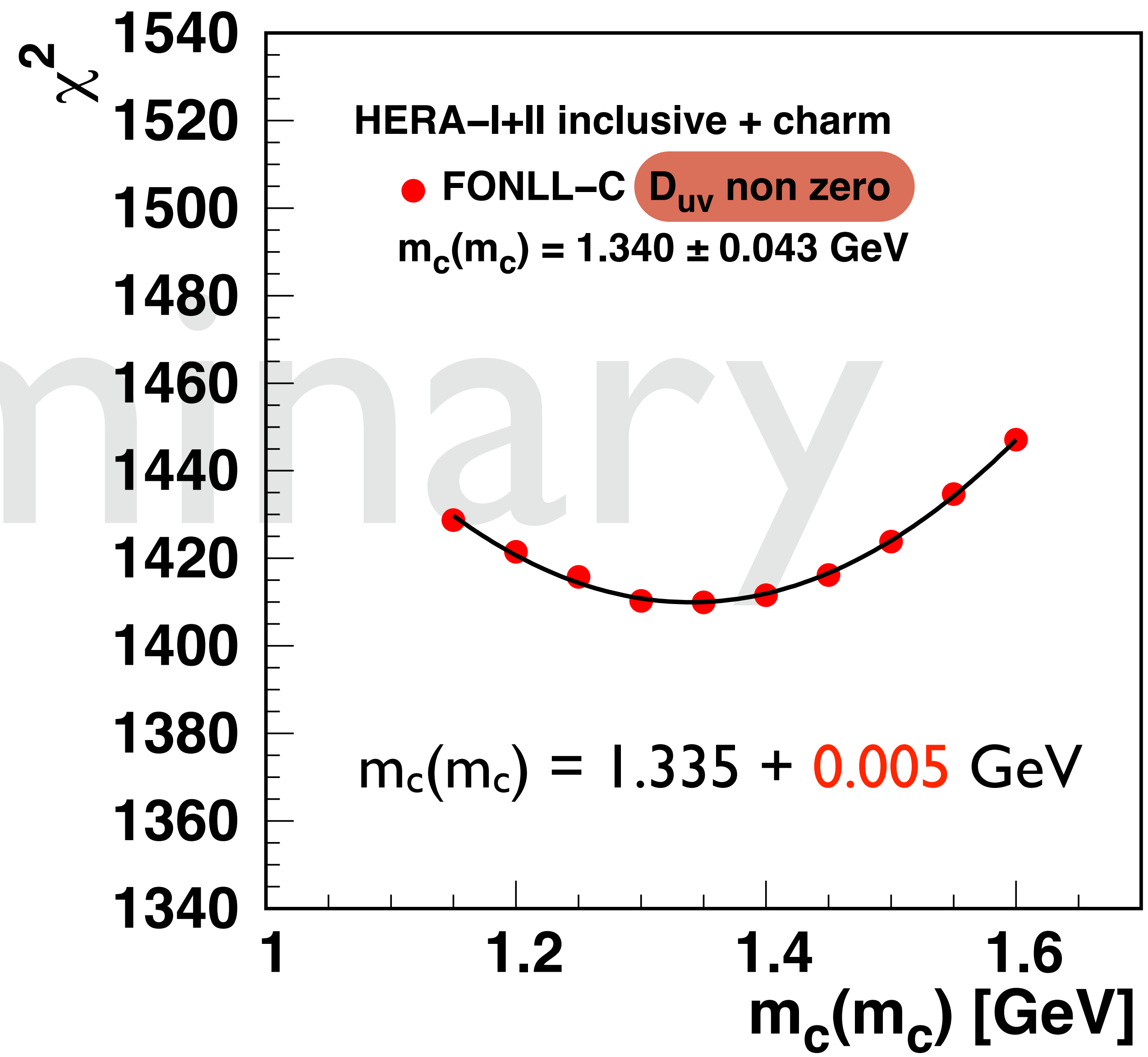
- The **best fit** values of $m_c(m_c)$ is determined as the minimum of a parabolic fit to the global χ^2 vs. $m_c(m_c)$,
- the **1-σ experimental uncertainty** is determined as $\Delta\chi^2 = 1$ variation around the minimum.



Results: Param Uncertainty

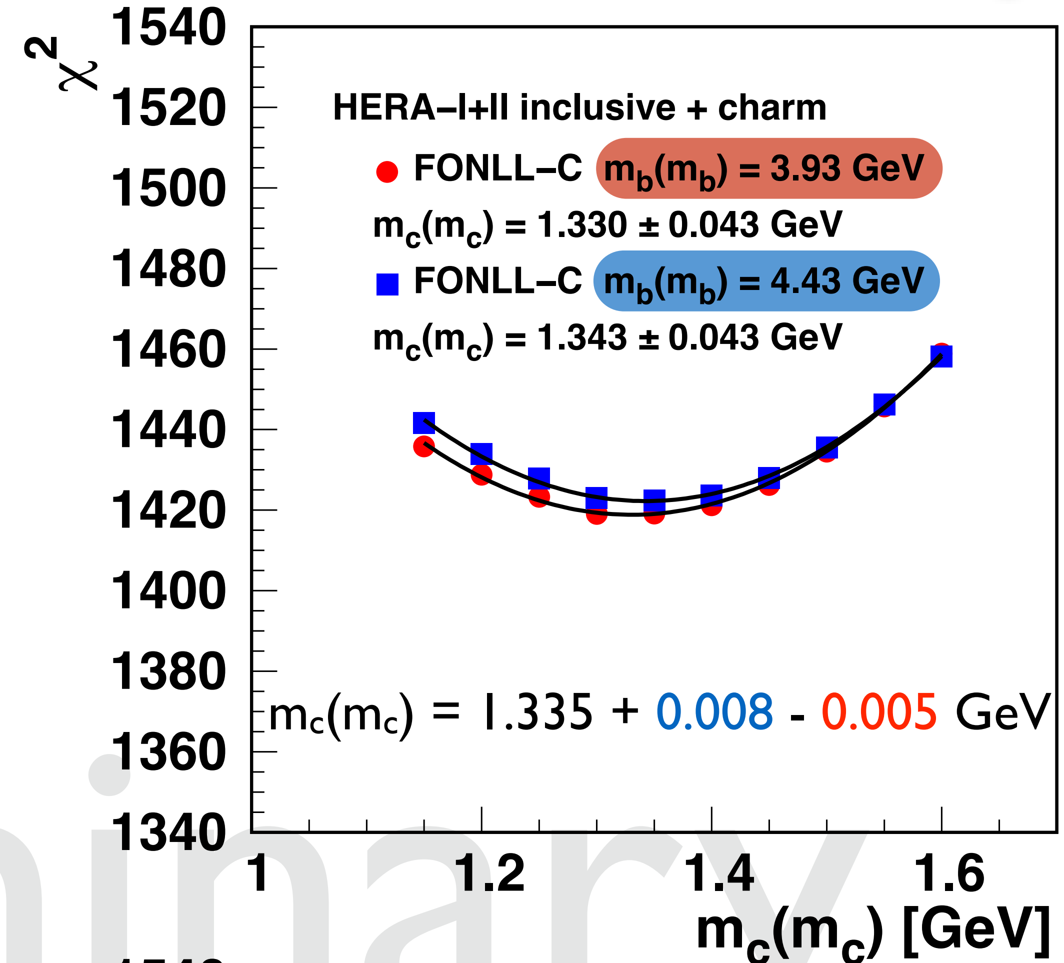
- The parametric uncertainty is estimated varying:
  - the initial scale Q_0^2 from 1 to 1.5 GeV^2,
  - including the linear proportional D_{uv} into the $xu_v(x)$ distribution (variation with the largest impact).

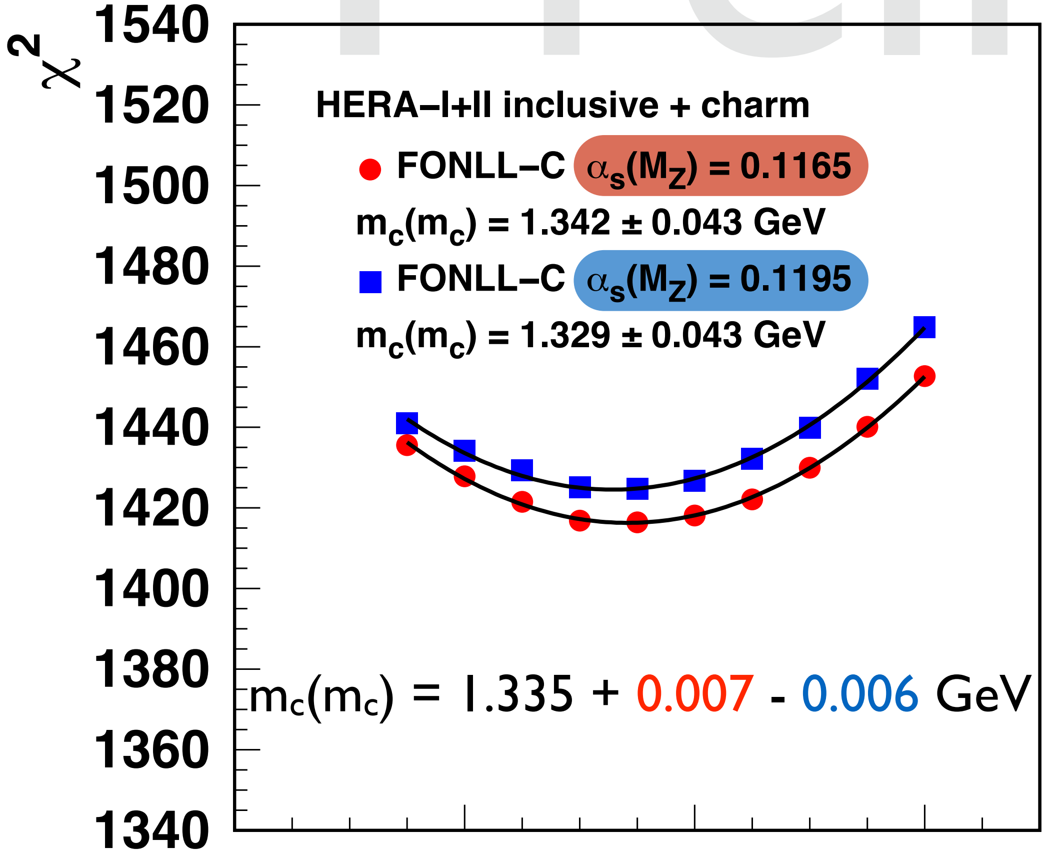


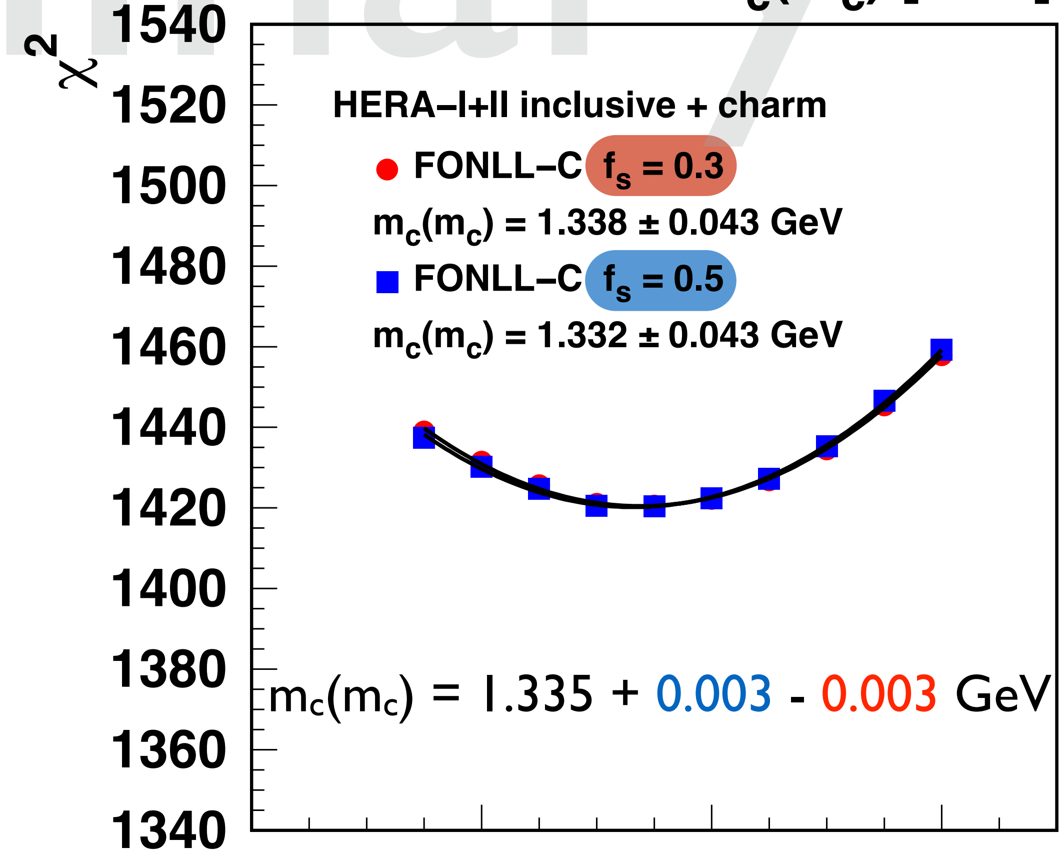


Results: Model Uncertainty

- The model uncertainty is estimated varying:
  - $\alpha_s(M_Z)$ by 0.0015 around 0.118,
  - $m_b(m_b)$ by 0.25 GeV around 4.18 GeV,
  - f_s by 0.1 around 0.4.

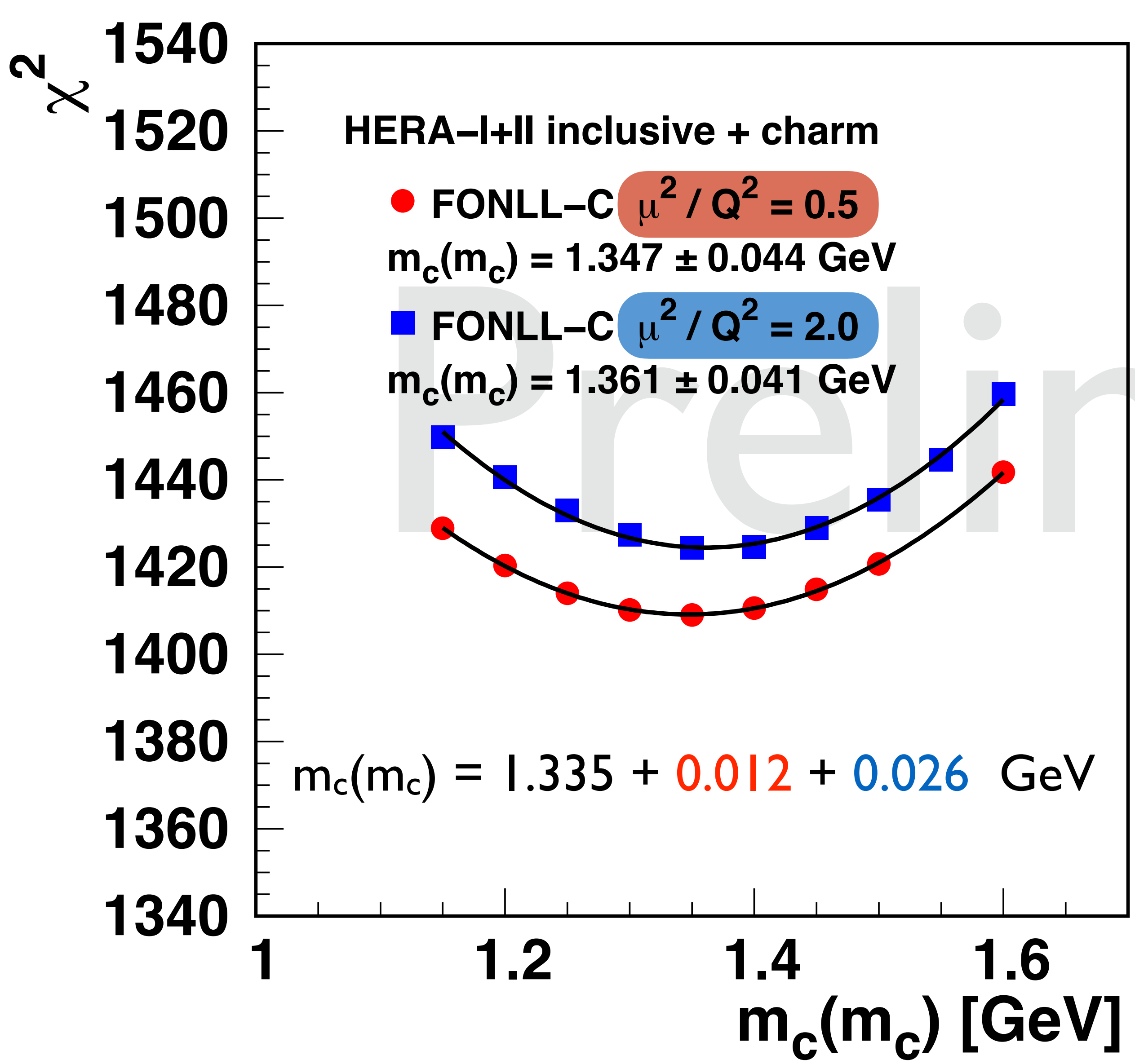


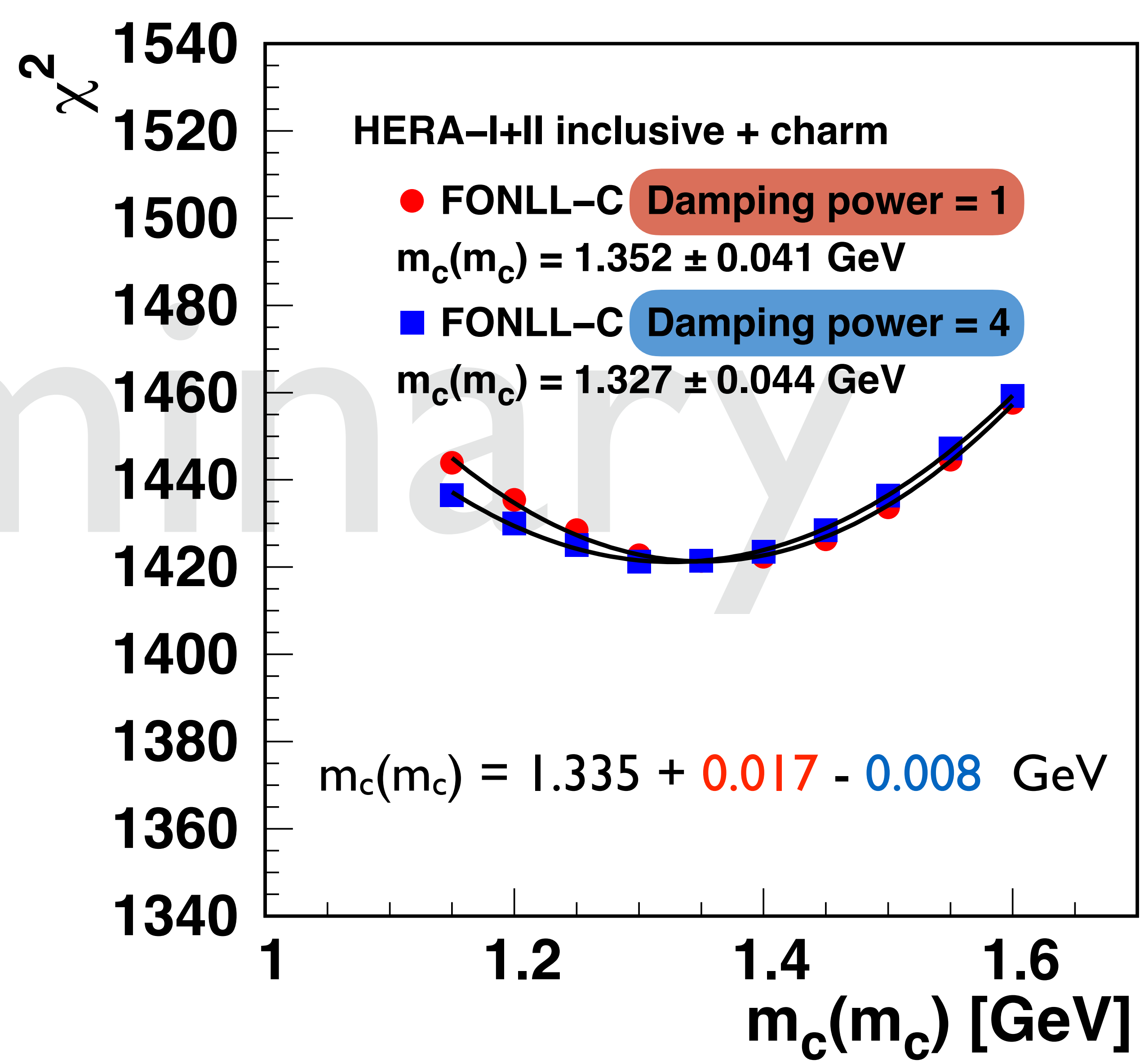




Results: Theory Uncertainty

- The theoretical uncertainty is estimated varying:
  - μ_R^2 and μ_F^2 by a factor two up and down around $\mu_R^2 = \mu_F^2 = Q^2$ (only in the heavy quark contributions),
  - the suppression power of the FONLL damping factor from 2 to 1 and 4.





Results: Final Combinations

- FONLL-C:

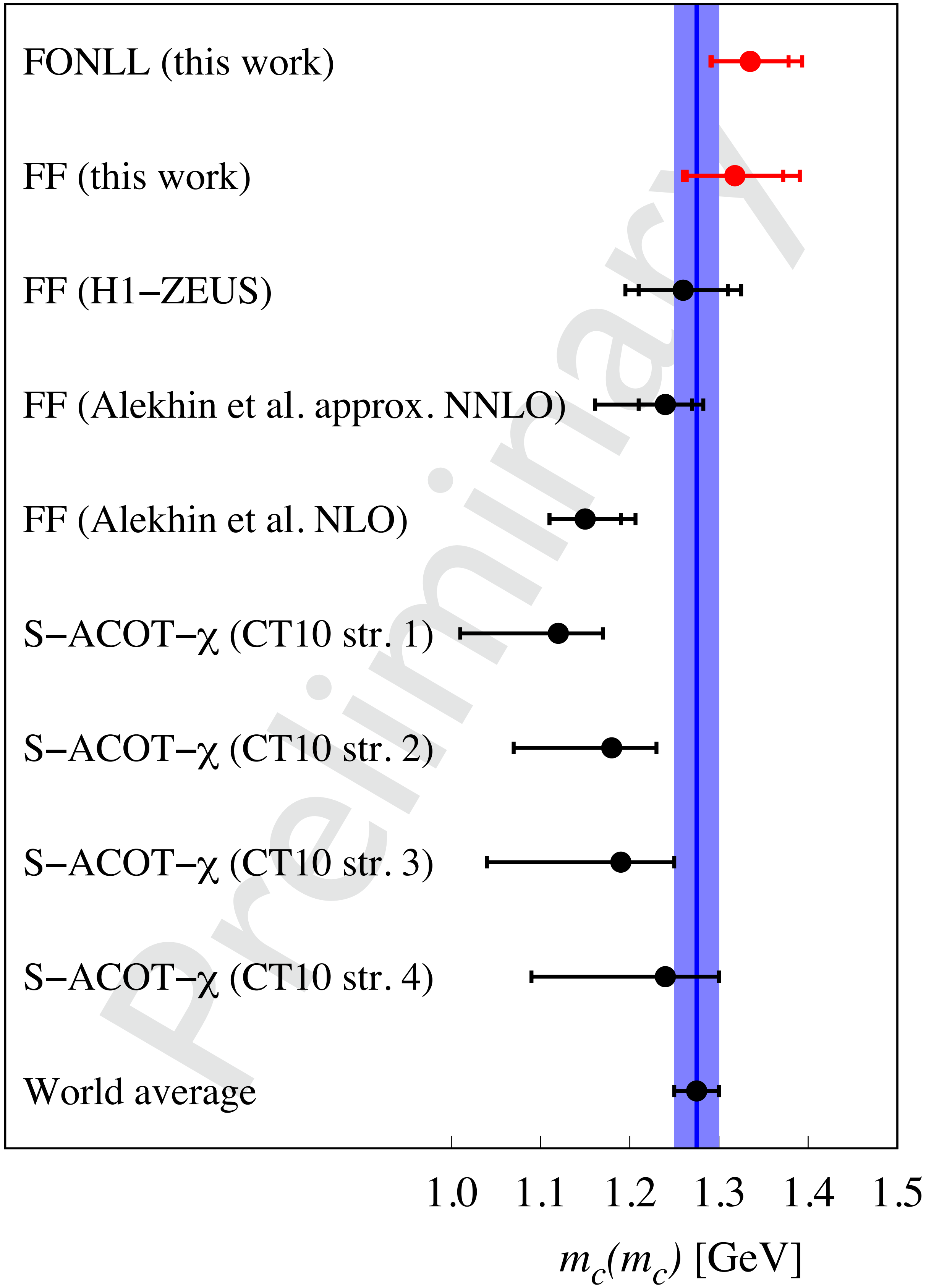
$$m_c(m_c) = 1.335 \pm 0.043(\text{exp})^{+0.019}_{-0.000}(\text{param})^{+0.011}_{-0.008}(\text{mod})^{+0.033}_{-0.008}(\text{th})\ \text{GeV}$$

- FF@NLO (same variations as FONLL):

$$m_c(m_c) = 1.318 \pm 0.054(\text{exp})^{+0.011}_{-0.010}(\text{param})^{+0.015}_{-0.019}(\text{mod})^{+0.045}_{-0.004}(\text{th})\text{GeV}$$

Results: Comparisons

- Our determinations are **compatible** with each other.
- Compatible with the **PDG world average**.
- **Competitive uncertainty**.
- General agreement with most of the **past determinations**.
- Differently from the other determinations, ours tend to be **above the PDG value**:
    - main difference: fit to the recent **combined HERA 1+2 inclusive cross sections**.
    - Is there any correlation?

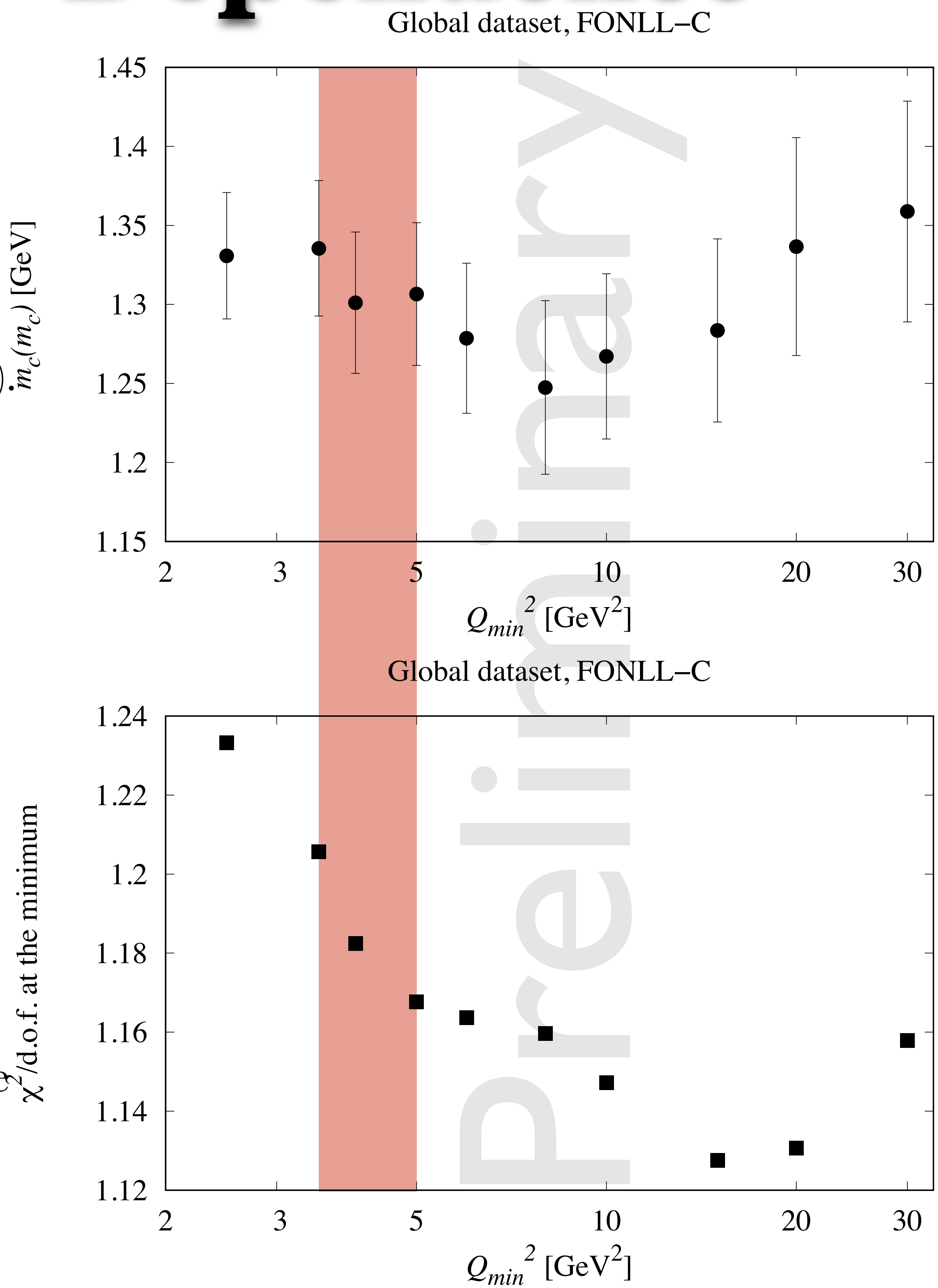


Results: Q_{min}^2 Dependence

- Criteria to choose the value of Q_{min}^2:

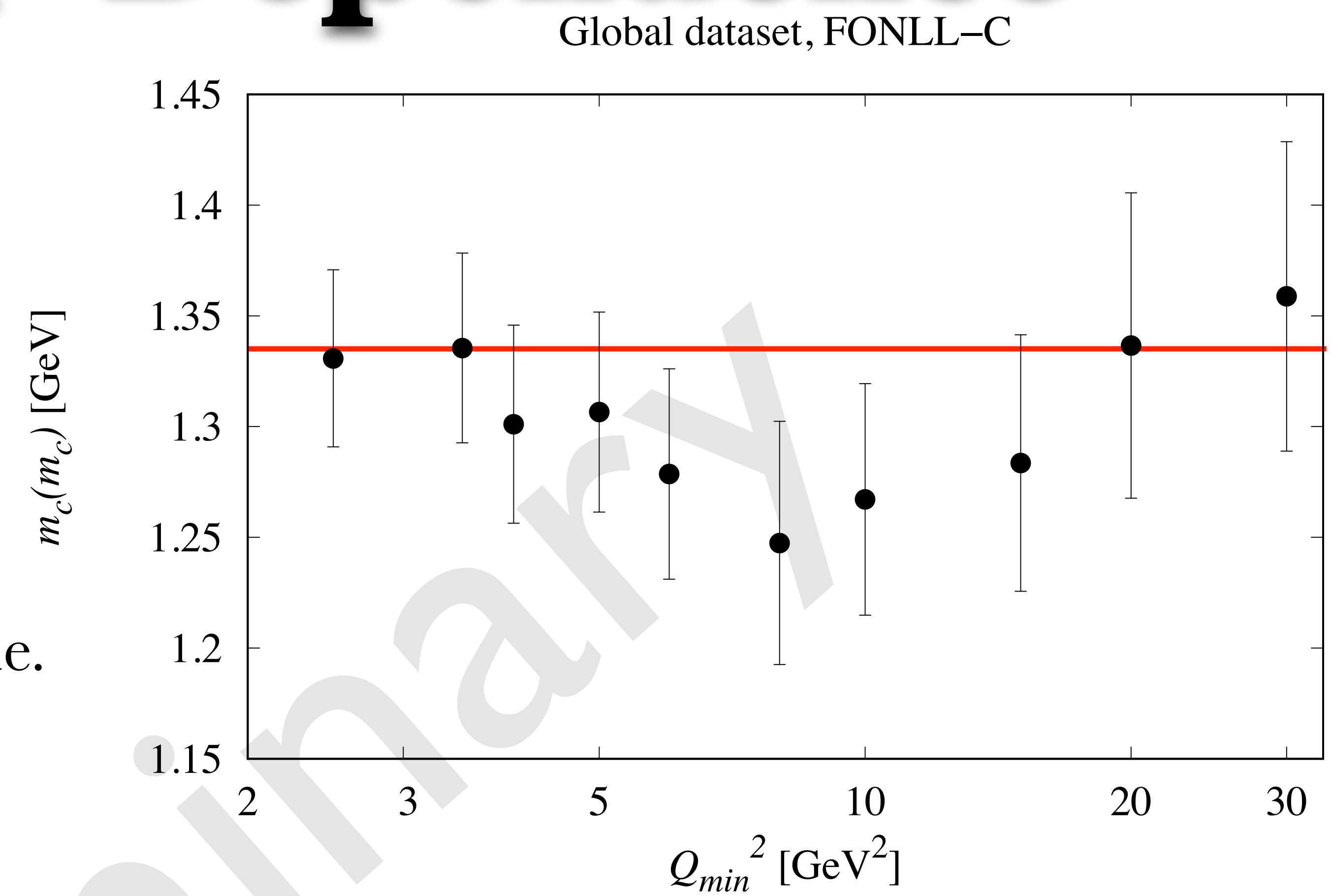
1) as **high sensitivity** to $m_c(m_c)$ as possible:
   - small experimental uncertainty on $m_c(m_c)$.
2) **Good description** of the full dataset:
   - low value of the χ^2.
3) Fit as many points as possible:
   - Q_{min}^2 reasonably small.

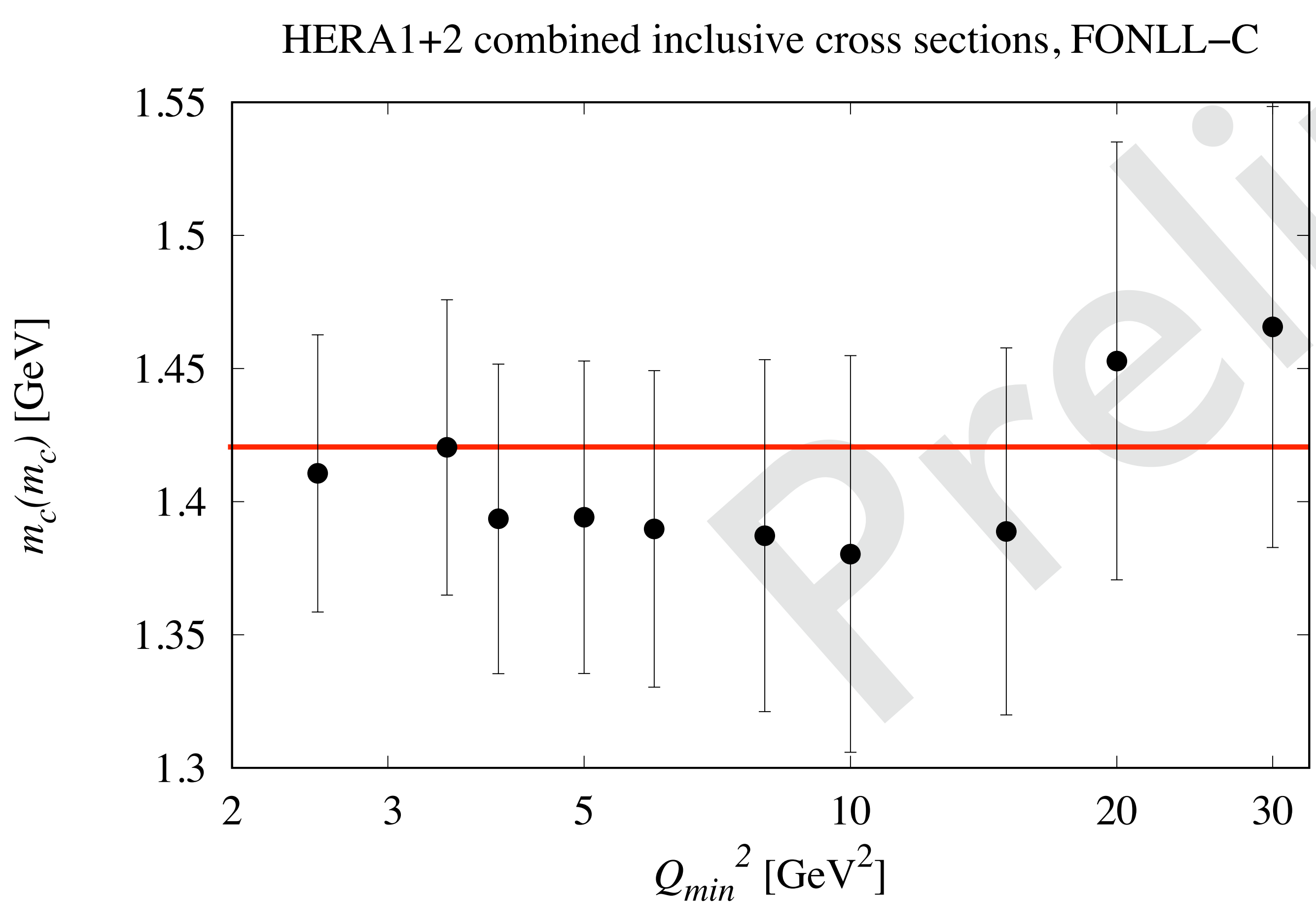
- This suggests $Q_{min}^2 \in [3.5:5]$ GeV^2:
  - $Q_{min}^2 = 3.5$ GeV^2 is a conservative choice in line with previous studies.

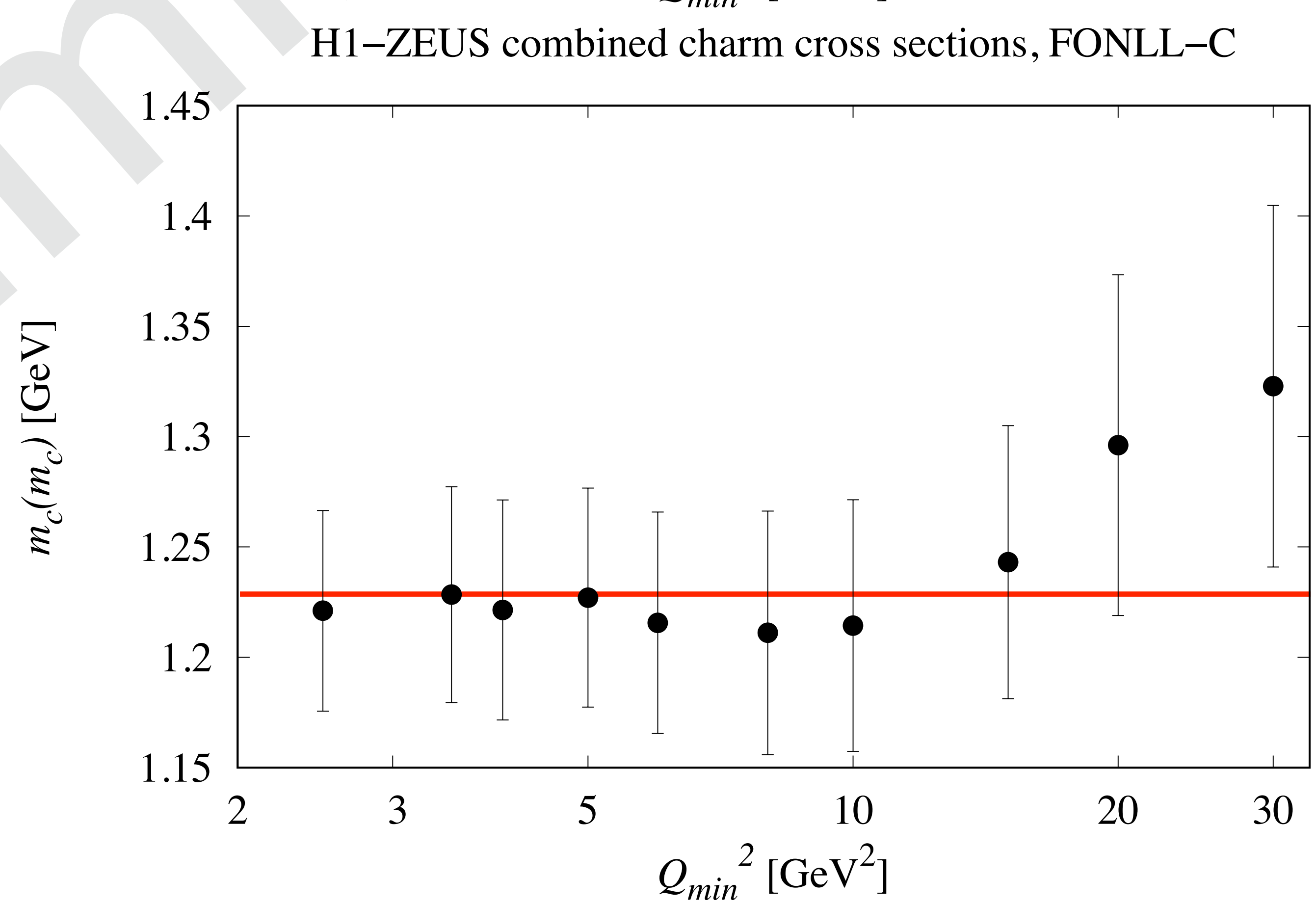


Results: Q_{min}^2 Dependence

- The global results is a compromise:
  - charm data prefer $m_c(m_c)\sim 1.23$ GeV,
  - inclusive data prefer $m_c(m_c)\sim 1.42$ GeV.
  - **Inclusive data pull up** the global value.







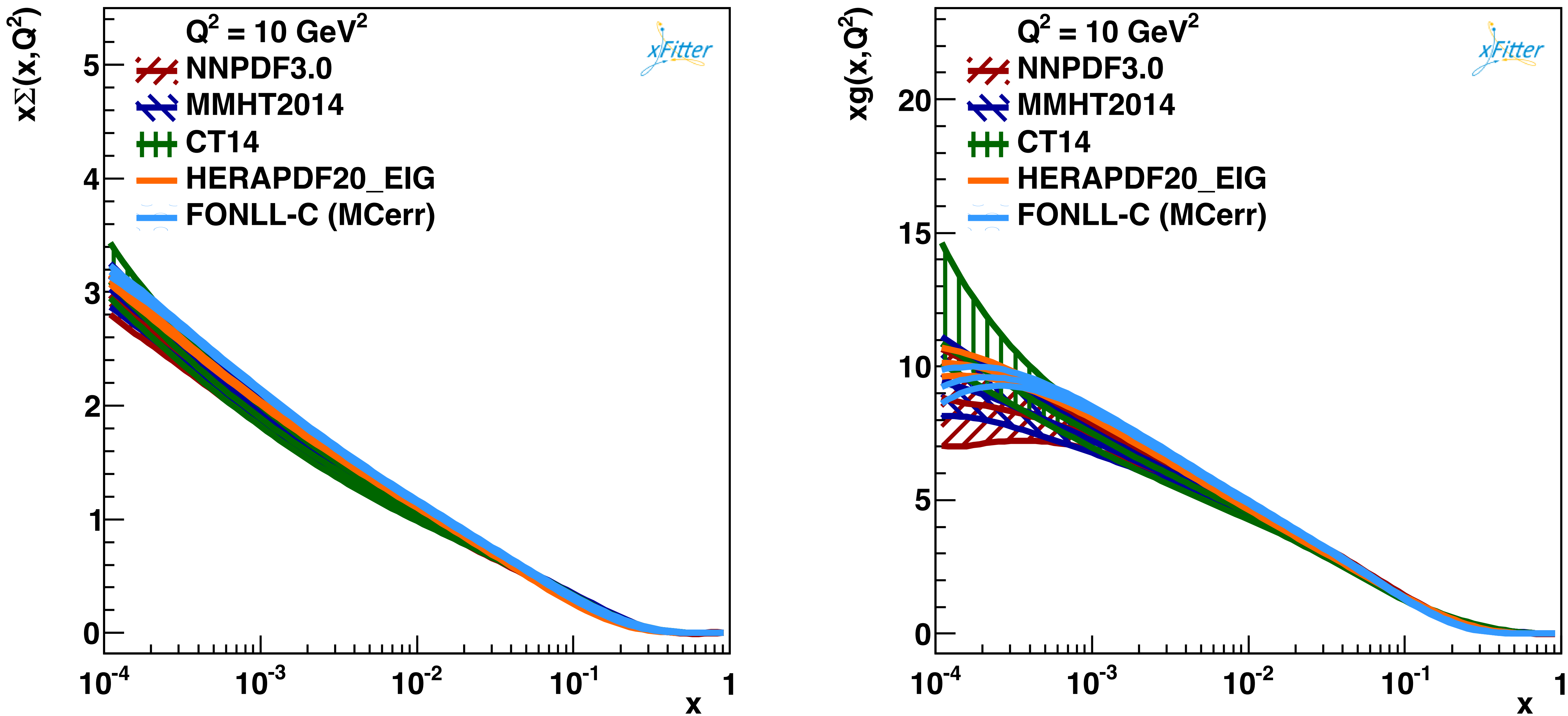
Conclusions and Summary

- First **direct** determination of the $\overline{\mathrm{MS}}$ charm mass $m_c(m_c)$ from a fit to inclusive and charm production DIS data from HERA based on the **FONLL scheme**:
  - accompanied by the formulation of the FONLL scheme in terms of the $\overline{\mathrm{MS}}$ masses.
- Solid and competitive determination **complementary** and in **good agreement** with the previous determinations based on the FFNS:
  - our study also provides FFNS determination with a full characterization of the uncertainties which is in good agreement with the FONLL value.
- Ours is the first determination of $m_c(m_c)$ that uses the recent **combined HERA 1+2 inclusive cross sections**:
  - these new measurements seem to prefer a value of $m_c(m_c)$ larger than the charm cross sections **pulling up** the global value.

Backup Slides

Results: PDFs

- Comparison with other PDF sets based on a GM-VFNS:



- General good agreement,
- A detailed study at the level of PDFs is beyond the scope of this work.