# The xFitter Project

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on behalf of the xFitter developers team

# Motivation

The **factorization theorem** for a hadronic cross section reads:

$$d\sigma_{\text{had}} = W_{ij} \otimes f_i \otimes f_j \, d\Phi$$

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- High-energy dominated
- Computable in perturbation theory

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- Universal (for a given hadronic species)
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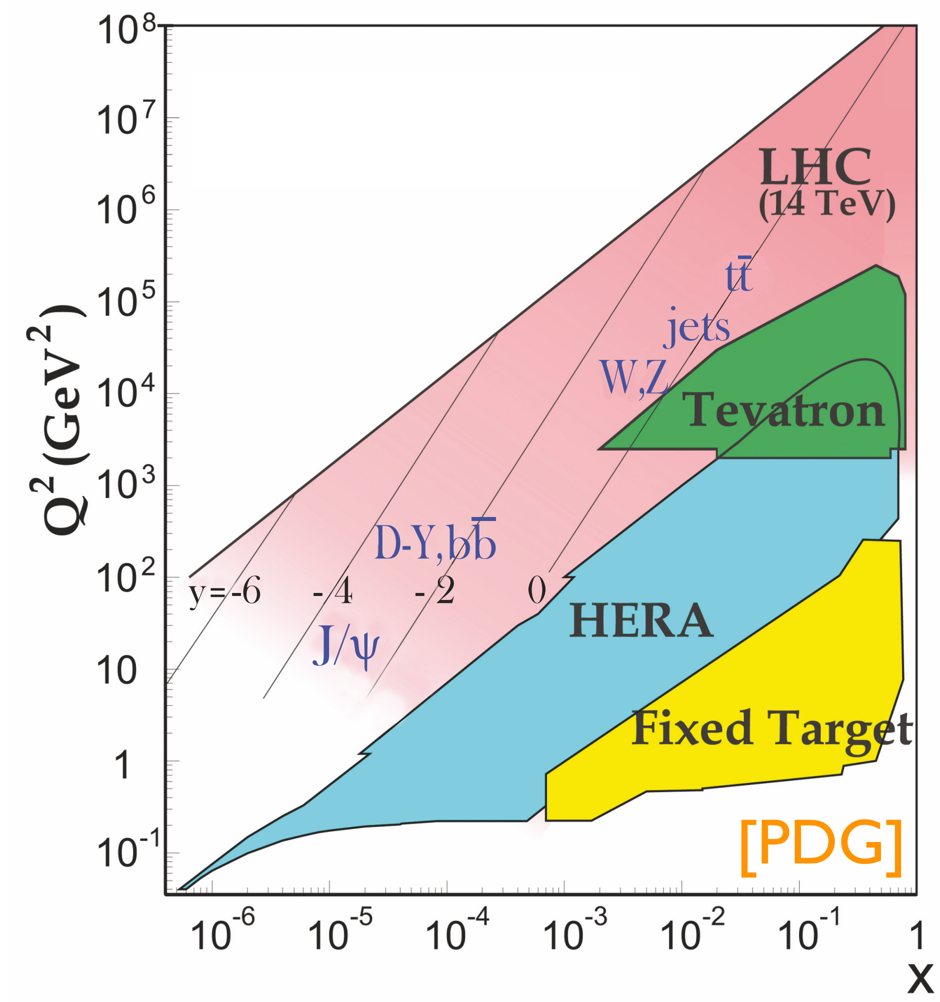
How do we determine parton distribution functions (PDFs)?

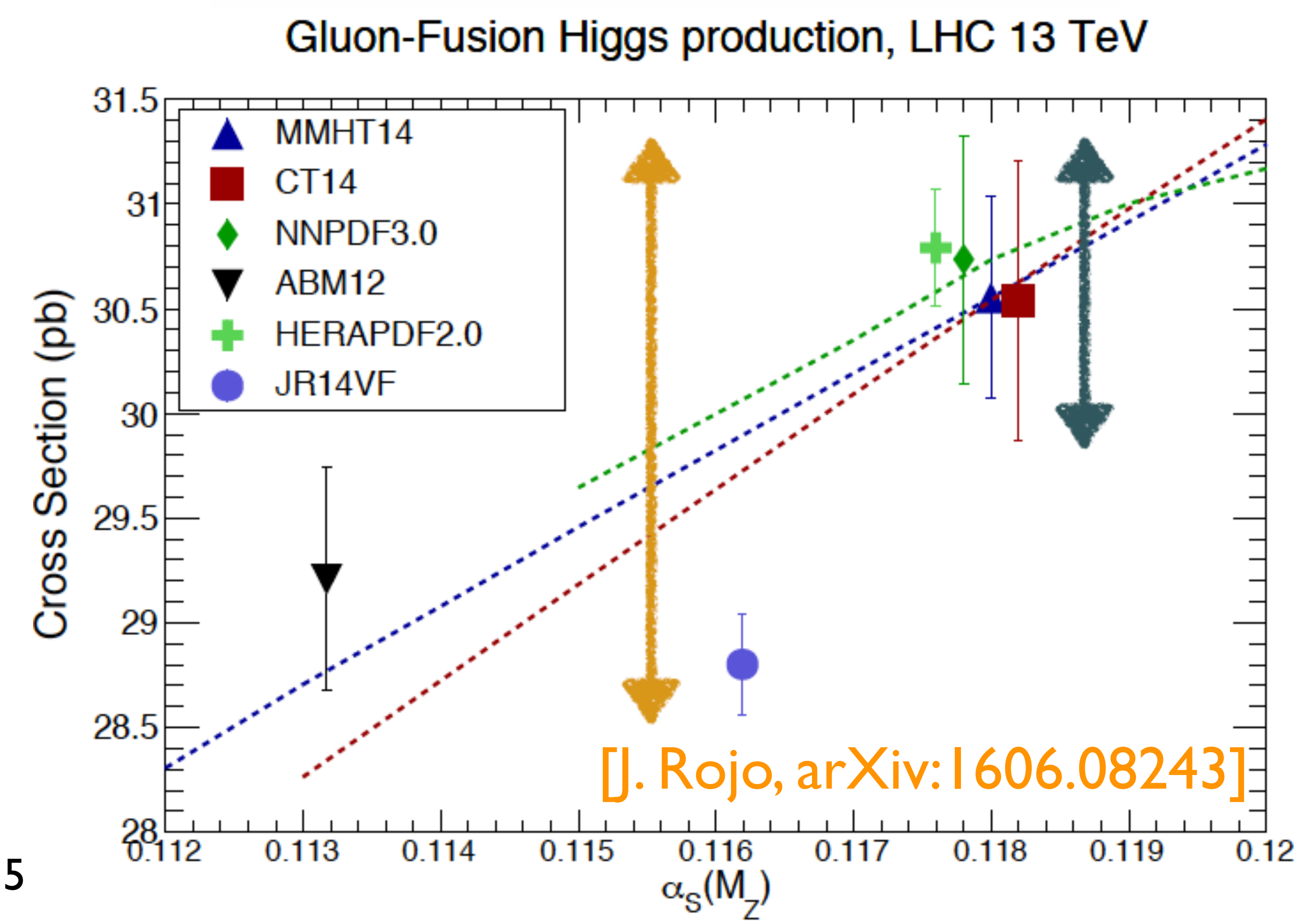
Presently, the most accurate and reliable way is through **fits to data**

# Motivation

Fitting PDFs is a **complex** task.

- **Dataset**:
  - as large and varied as possible,
  - spanning a wide kinematic range.
- Estimate of the **uncertainty**:
  - include full experimental uncertainties,
  - ensure a faithful representation.
- Choice of the **parametrization**:
  - avoid parametrization biases.
- **Theoretical inputs**:
  - higher order corrections,
  - heavy-quark mass effects,
  - …
- **Different choices** may lead to substantially **different results**.



# Motivation

**xFitter** (former HERAFitter) provides a **unique open-source** framework available from:

https://www.xfitter.org/xFitter

that allows the users to:

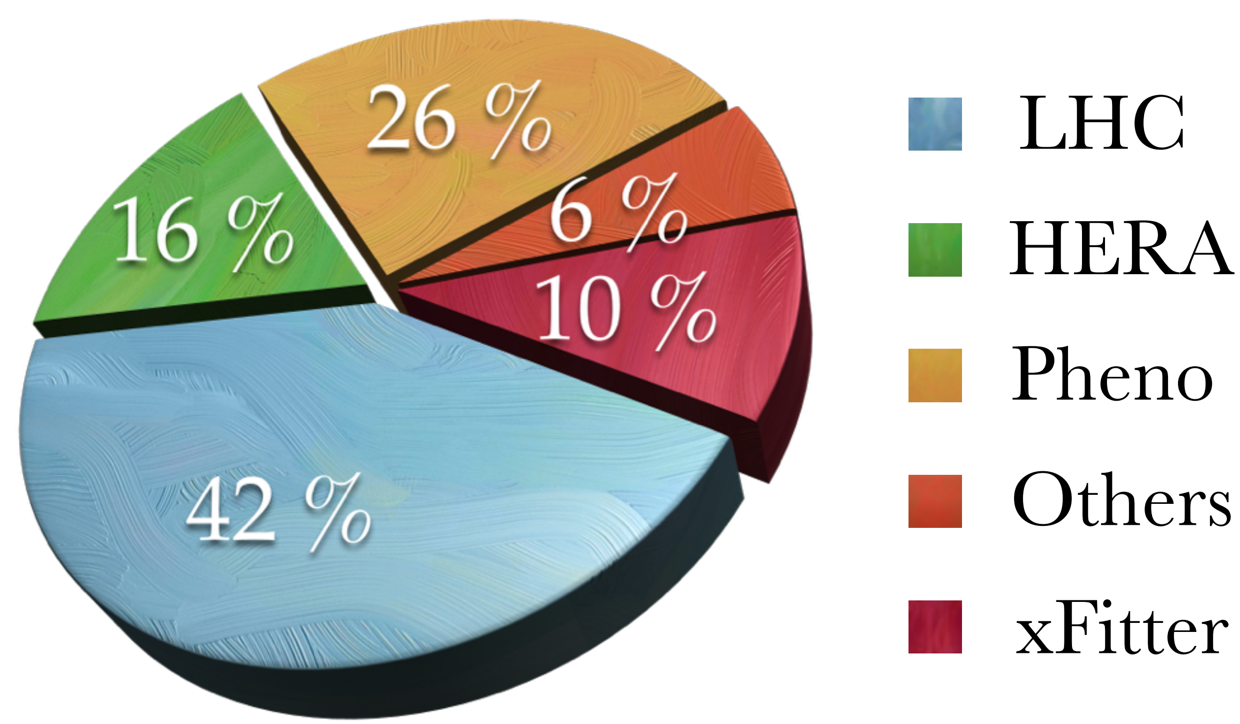
- **extract PDFs** from a large variety of experimental data,
- assess the **impact** of data **on PDFs**,
- check the **consistency** of experimental data,
- test different **theoretical assumptions**.

Around **30 active developers**:

- theorists and experimentalists.

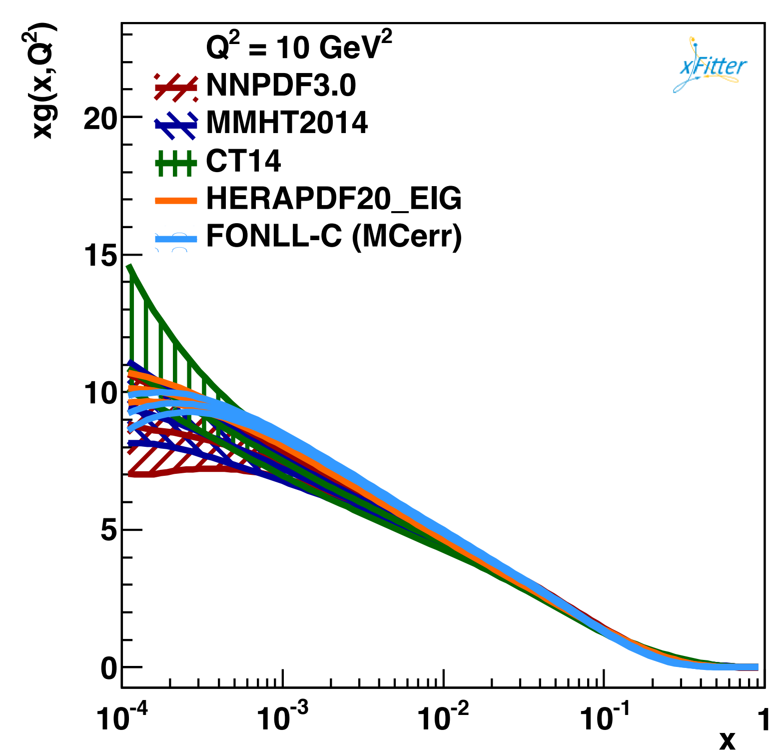
More than **30 publications** based on xFitter:

- I will discuss one of them on which I worked directly.



# xFitter in a Nutshel

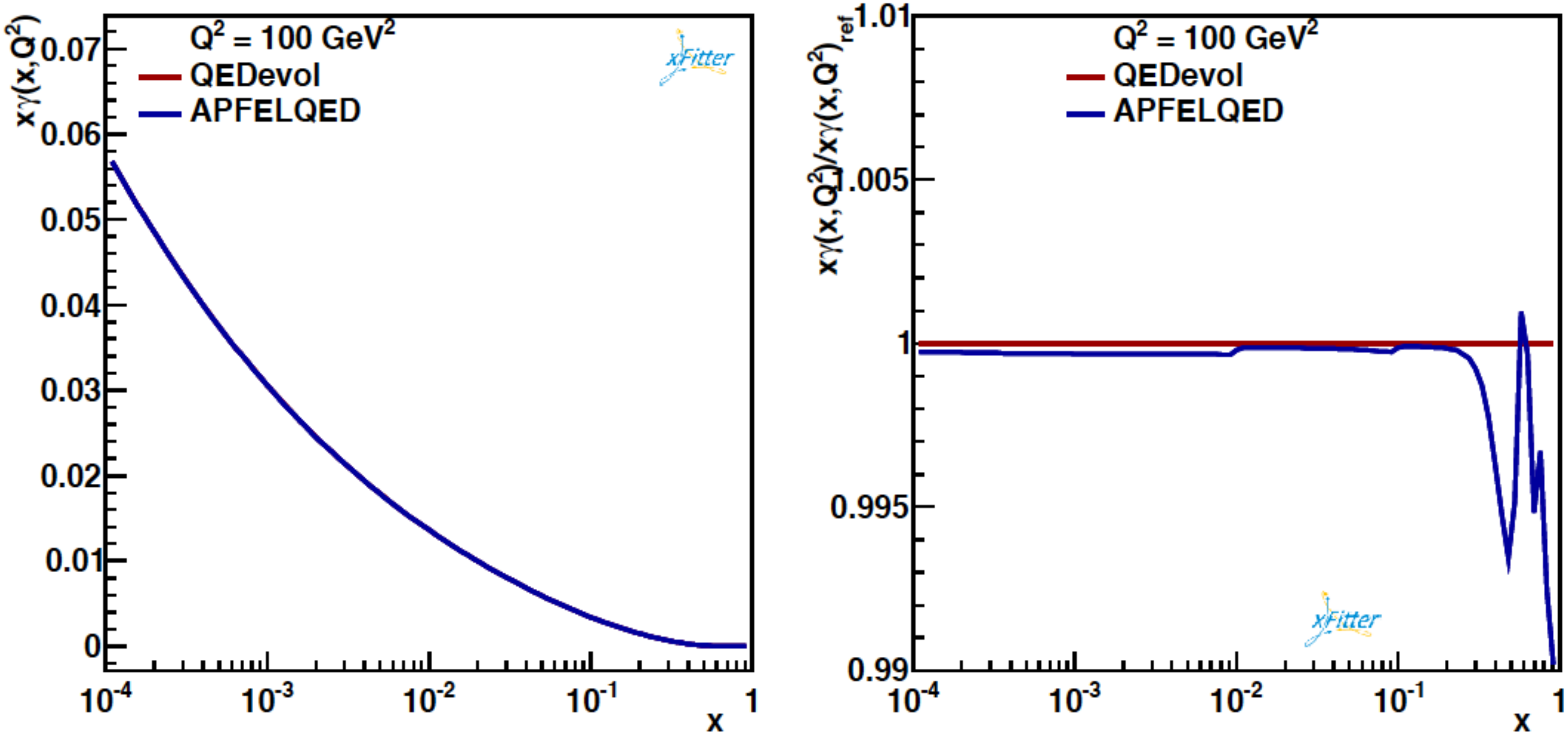
- **Parametrize** PDFs at the initial scale:
  - several functional forms available ("standard", Chebyshev, etc.),
  - define parameters to be fitted.
- **Evolve** PDFs to the scales of the fitted data points:
  - DGLAP evolution up to NNLO in QCD (QCDNUM, APFEL, MELA),
  - non-DGLAP evolutions (dipole, CCFM, ABF).
- Compute **predictions** for the data points:
  - several mass schemes available in DIS (ZM-VFNS, ACOT, FONLL, RT, FFNS),
  - predictions for hadron-collider data through fast interfaces (APPLgrid, FastNLO).
- **Comparison data-predictions** via $\chi^2$:
  - multiple definitions available,
  - consistent treatment of the systematic uncertainties.
- **Minimize** the $\chi^2$ w.r.t. the fitted parameters.
  - using MINUIT or by Bayessian reweighing.
- Useful **drawing tools**.



# xFitter 1.2: what's new?

- **QED corrections**:
  - LO QED corrections as implemented in **APFEL**, [Bertone, Carrazza and Rojo, arXiv:1310.1394]
  - LO QED corrections as implemented in **QEDevol** (QCDNUM plugin), [Sadykov, arXiv:1401.1133]

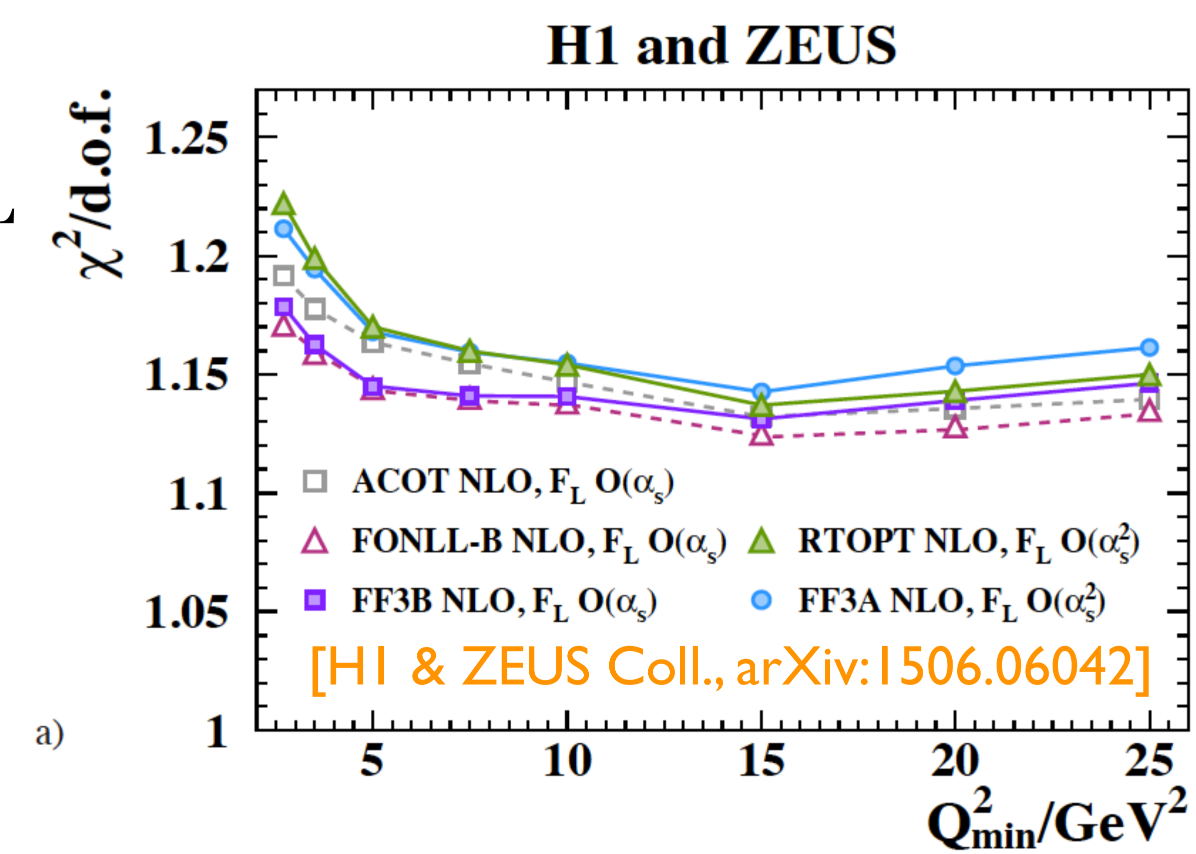
[plots produced by R. Sadykov]




  - possibility to determine the **photon PDFs** from fits to data.

# xFitter 1.2: what's new?

- **Heavy-quark schemes**:
  - **FONLL** general-mass scheme via APFEL up to NNLO in QCD:
    - available with pole and $\overline{\text{MS}}$ definitions of the heavy quark masses,
    - complete the set of heavy quark schemes available in xFitter.




  - **FFNS**:
    - for DIS structure functions updated to OPENQCDRAD v2.0b4,
    - interface to Mangano-Nason-Ridolfi code for heavy-quark production at hadron colliders [Mangano, Nason and Ridolfi, Nucl. Phys. B373 (1992) 295].
  - Implementation of the **Hybrid VFNS** [Olness et al., arXiv:1306.6553]:
    - optimize the treatment of the single experiments independently from one another.
  - VFNS with **displaced thresholds**: [Bertone, Glazov, Mitov, Papanastasiou, Ubiali, in preparation]
    - possibility to set heavy-quark masses and thresholds independently.

# xFitter 1.2: what's new?

- **Fast interfaces**:
  - interface to the **APFELgrid** code that allows optimize the computation of hadronic observables in the context of PDF fits:
    [Bertone, Carrazza and Hartland, arXiv:1605.02070]
    - much **faster** than APPLgrid,
    - reduction of the memory footprint.
- **Mellin transform method** via interface to the MELA code:
  [Bertone, Carrazza and Nocera, arXiv:1501.00494]
  - **complementary** to the more common $x$-space method,
  - **more analytical** (*e.g.* the DGLAP equation can be solve exactly),
  - suitable to implement, *e.g.*, threshold **resummation**.
- New **reweighting** option using the Giele-Keller method.
  [Giele and Keller, hep-ph/9803393]

# Latest Results

## List of analyses by xFitter

The link to the list of analyses using former HERAFitter can be accessed here

| | | | | |
|---|---|---|---|---|
| 32 | 03.2016 | xFitter and APFEL teams and A. Geiser | arXiv:1605.01946 | A determination of mc(mc) from HERA data using a matched heavy flavor scheme |

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| 25 | 07.2015 | PDF4LHC | accepted by Journal of Physics G | The PDF4LHC report on PDFs and LHC data:Results from Run I and preparation for Run II |
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… more in preparation.

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[V. Bertone et al., arXiv:1605.01946]

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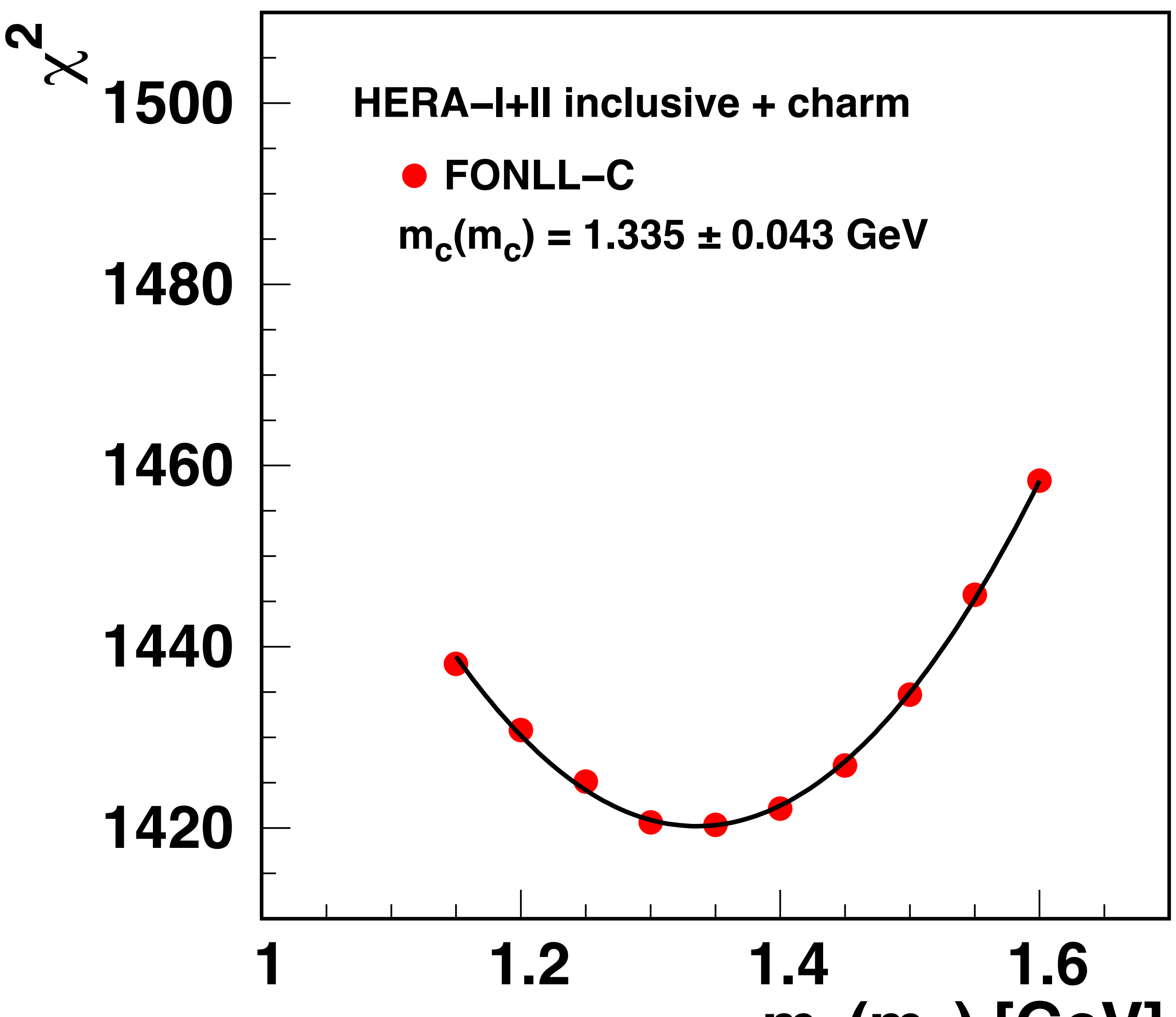
# Charm Mass Determination

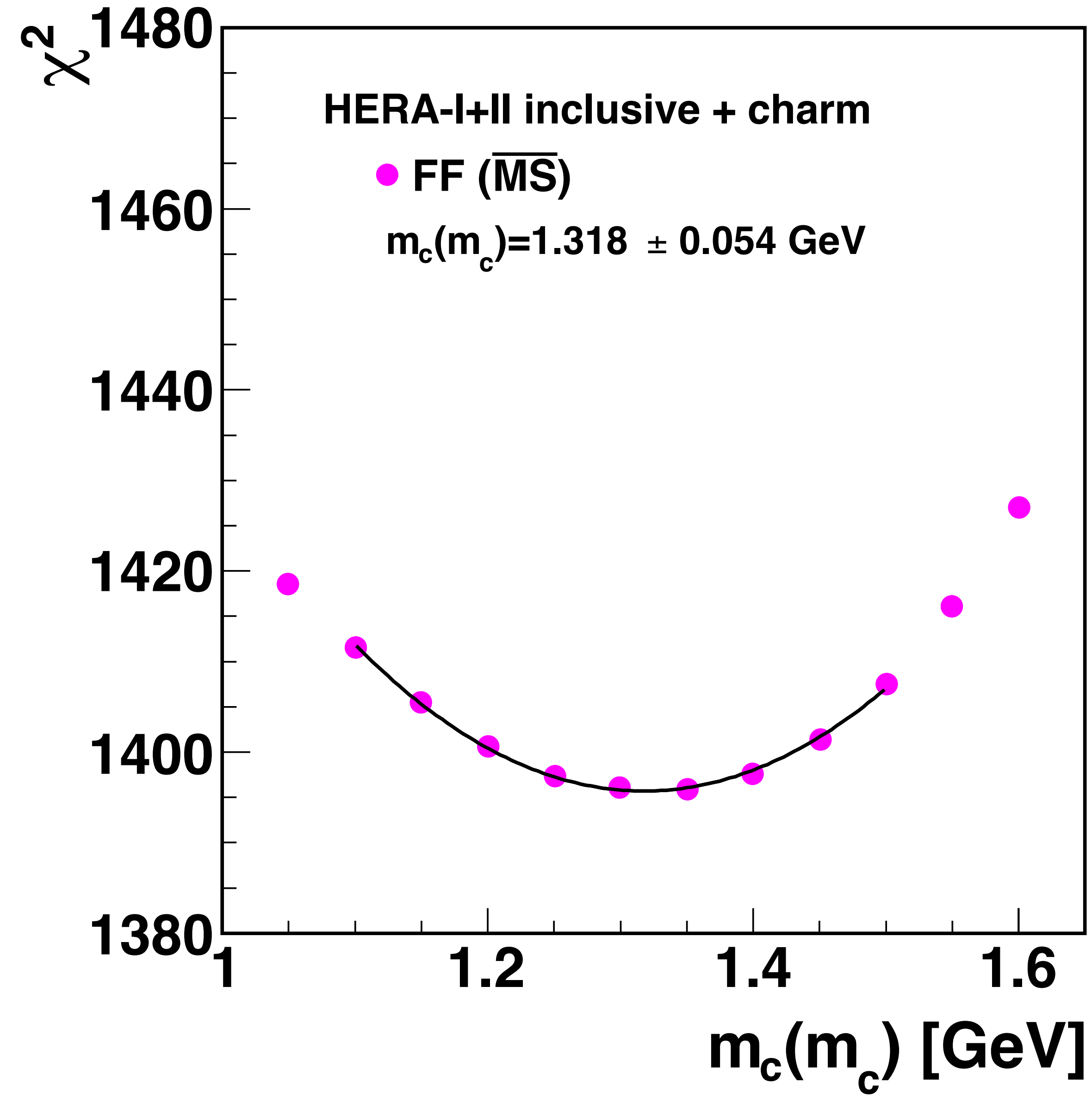
- A precise and faithful determination of the **charm mass** is relevant:
  - in principle: as a **fundamental test** of the Standard Model,
  - in practice: as a requirement for accurate **phenomenology at the LHC**.
- The PDG value of the charm mass is $\mathbf{m_c(m_c) = 1.275 \pm 0.025}$ **GeV**:
  - dominated by the high-precision $e^+e^- \to Q\overline{Q}$ data,
  - interesting to provide **alternative determinations** from other processes.
- **Inclusive** and **charm data in DIS** is directly sensitive to the charm mass:
  - exploit the precise **HERA1+2 combined** data to extract the charm mass.
- Employing the $\overline{\mathbf{MS}}$ **definition** for the heavy quark masses is **crucial**:
  - improvement of **perturbative convergence** w.r.t. the pole mass definition,
  - direct handle on $m_c(m_c)$.

# Charm Mass Determination

- Determination obtained using the **FONLL general mass scheme**:
  - first time in the context of the FONLL scheme,
  - alternative/complementary to the past determinations in the FFNS.
- Formulation of the **FONLL scheme in terms of the $\overline{\mathrm{MS}}$ masses**.
- All the formalism is implemented in **APFEL** ⇒ **available in xFitter**.
- Our value of $m_c(m_c)$ is determined as:
  - the minimum of the best fit parabola of the $\boldsymbol{\chi^2}$ **scan vs.** $\mathbf{m_c(m_c)}$:
    - for each value of $m_c(m_c)$ **PDFs were fitted** to data.
  - **1-σ exp.** uncertainty estimated as $\boldsymbol{\Delta\chi^2 = 1}$ variation around the minimum.
  - **Model**, **parametrization**, and **theory uncertainties** also estimated.
- The FONLL determination is accompanied by an analogous determination in the **FFNS.**

# Charm Mass Determination




- FONLL:

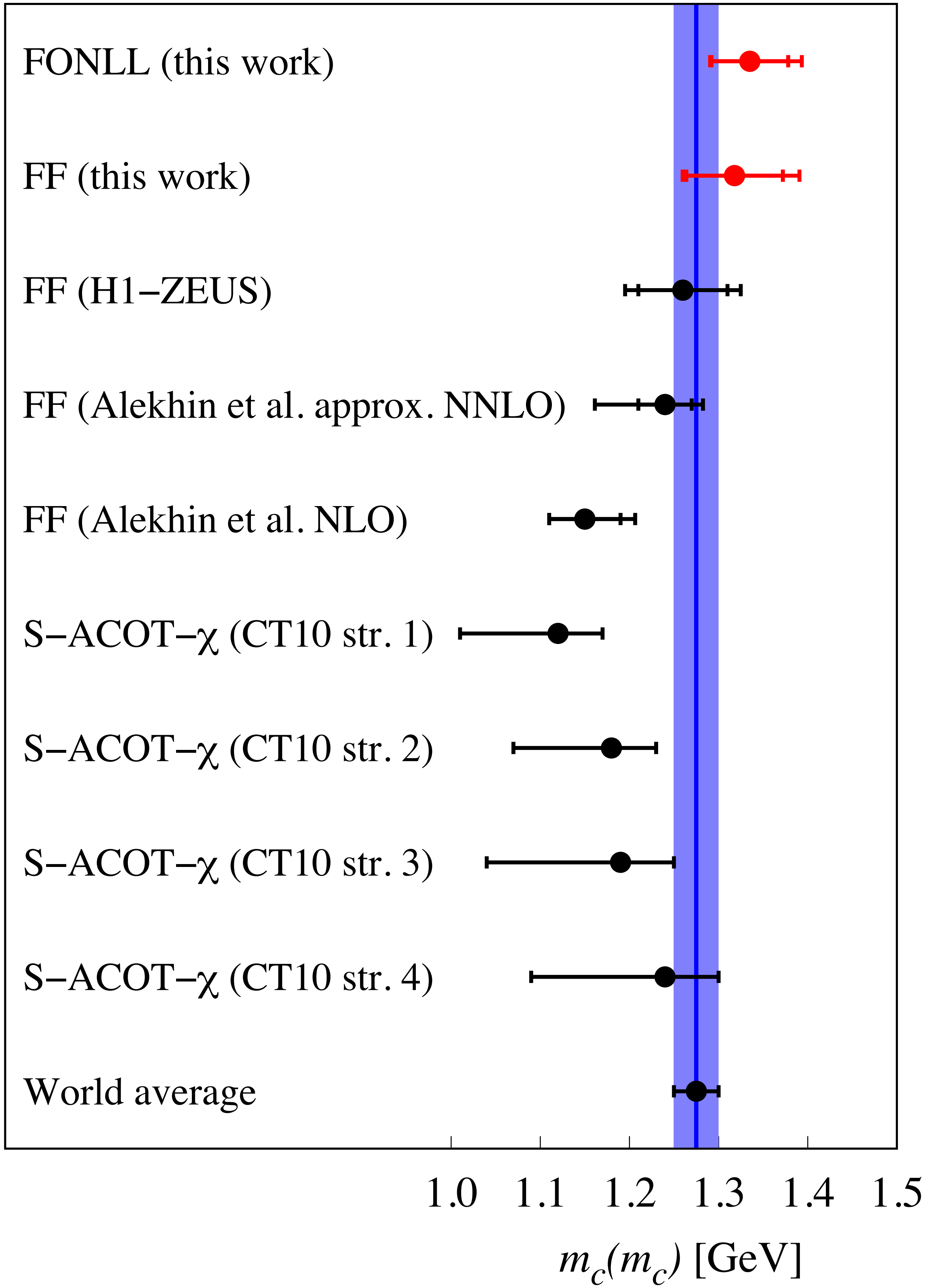
$$m_c(m_c) = 1.335 \pm 0.043(\text{exp})^{+0.019}_{-0.000}(\text{param})^{+0.011}_{-0.008}(\text{mod})^{+0.033}_{-0.008}(\text{th})\ \text{GeV}$$

- FFNS:

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

# Charm Mass Determination

- 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**:
  - the recent **combined HERA1+2 inclusive cross sections** tend to pull the value of $m_c(m_c)$ up.



# Summary

- **xFitter** (former HERAFitter) is a unique **open-source** package oriented to fits of PDFs that provides a framework for the **interpretation** and the **analysis** of the experimental data.

- xFitter is presently widely used for many analyses of the **LHC data** to quantify the **constraints on PDFs**.

- The new release of xFitter provides a number of **new features** that allow the users to perform even more accurate analyses,

- I presented one of the many recent results obtained with xFitter.

# Outlook

- Many new developments are foreseen:
  - full NLO QCD+QED (EW) corrections,
  - nuclear PDFs,
  - small-*x* resummation,
  - higher twists,
  - …

# Backup Slides

# xFitter 1.2: QED corrections

- **QED corrections**:
  - LO QED corrections as implemented in **APFEL**,
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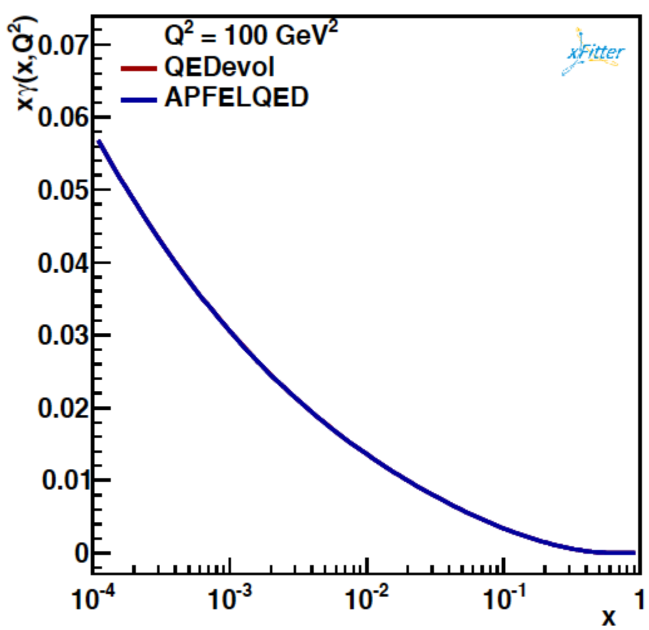
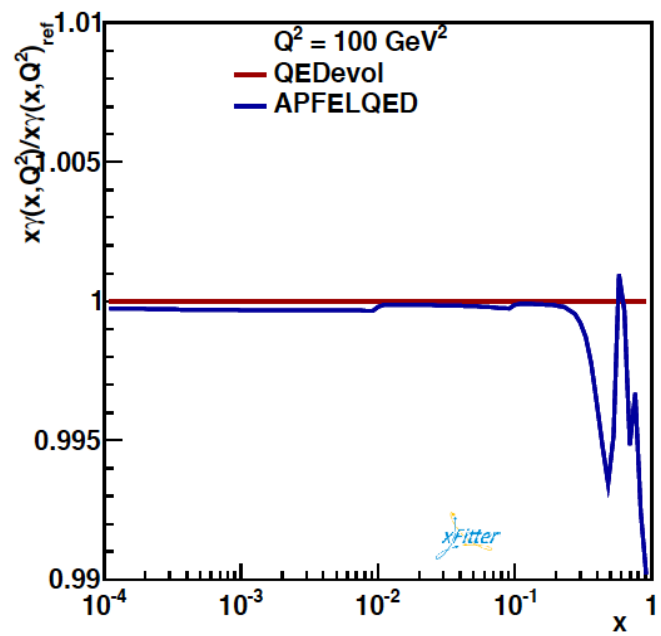
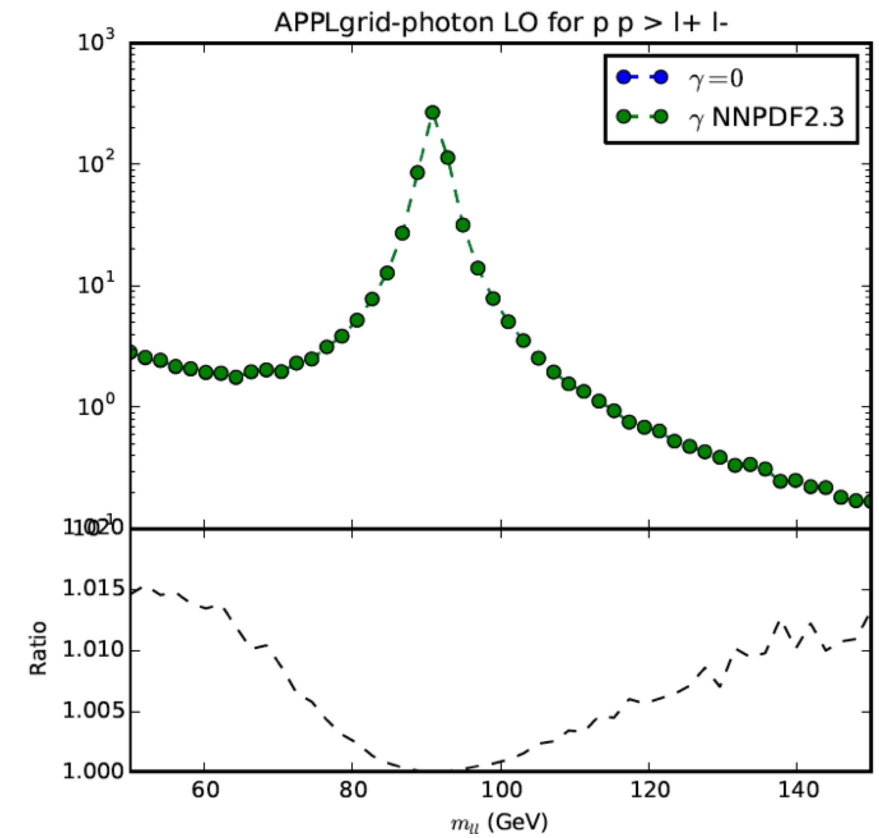
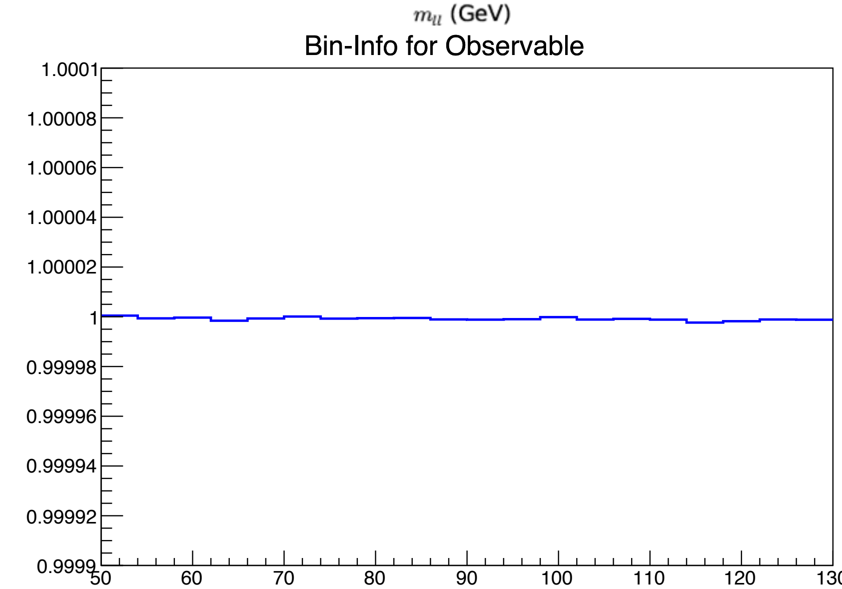



  - Plan to include **full NLO QCD+QED** (EW) corrections:
    - to DGLAP and DIS structure functions through APFEL,
    - to hadron-collider processes through MG5_aMC@NLO and SANC.

# 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**:

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

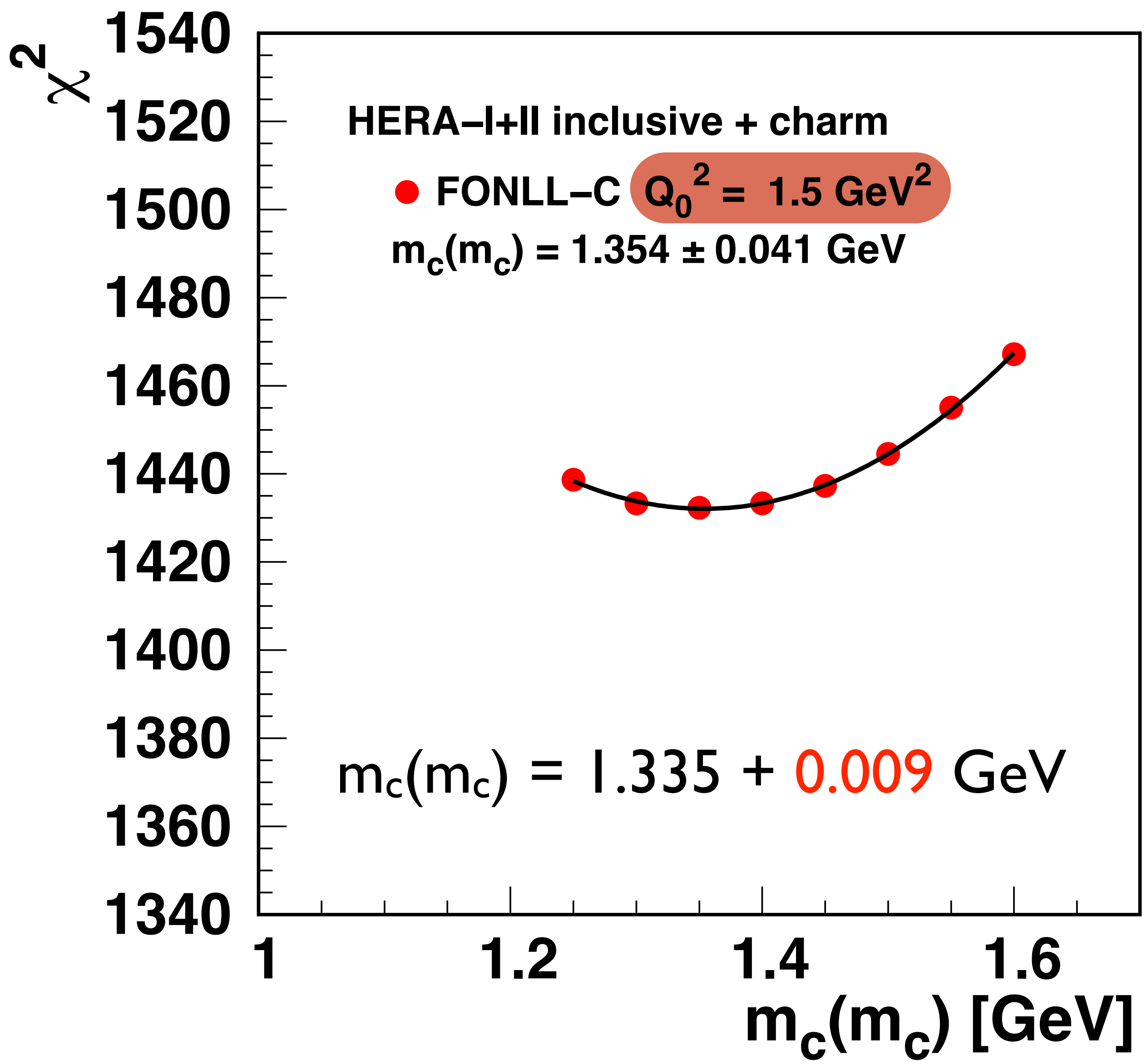
- and its variations:
  - strangeness fraction: $f_s = 0.4 \pm 0.1$,
  - initial scale: $Q_0^2 = 1 - 1.5$ GeV$^2$ (bound to be below te charm mass),
  - functional form variation: inclusion of the $D_{uv}$ linear term in $xu_v(x)$.

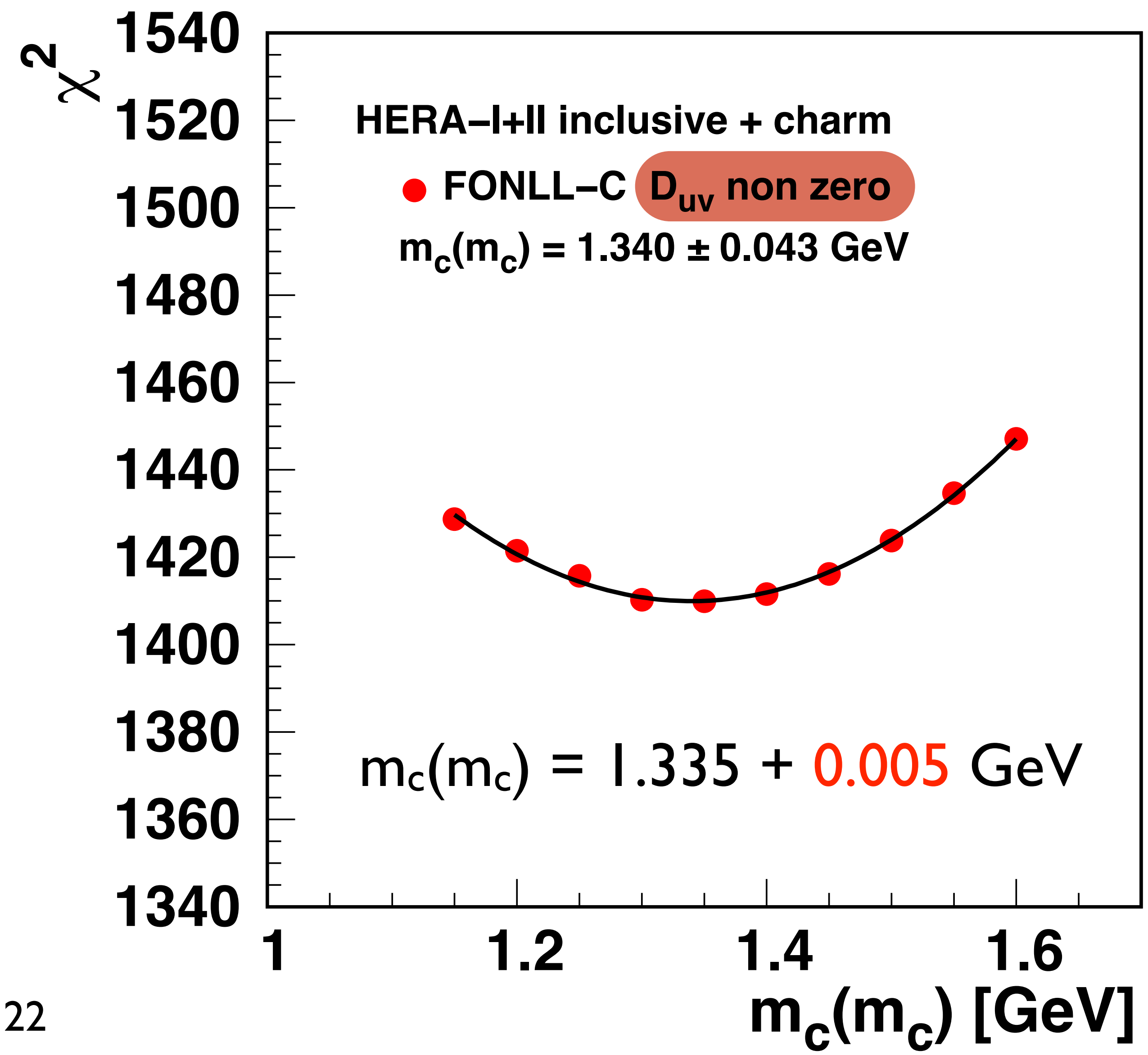
# Analysis Settings

- 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 $\overline{\text{MS}}$ 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).

# Results: Param Uncertainty

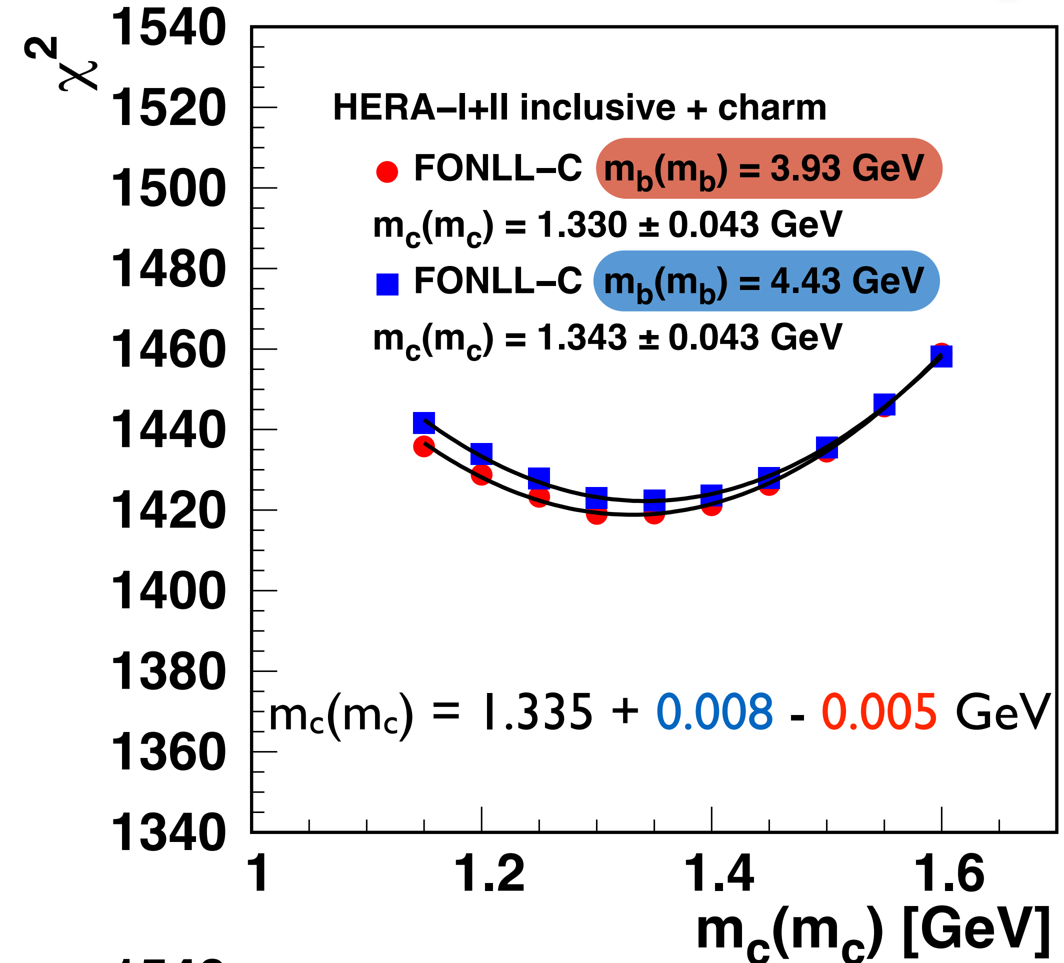
- The parametric uncertainty is estimated varying:
  - the initial scale $Q_0^2$ from 1 to 1.5 $GeV^2$,
  - including the linear proportional $D_{uv}$ into the $xu_v(x)$ distribution (variation with the largest impact).

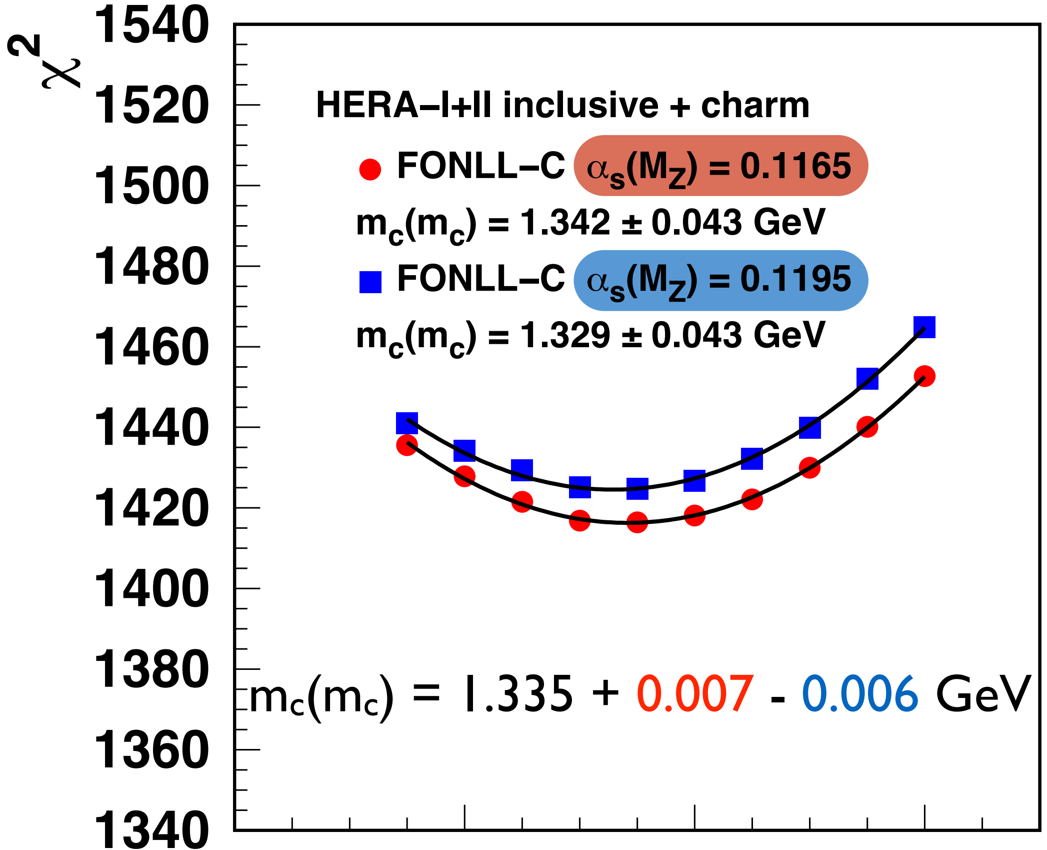


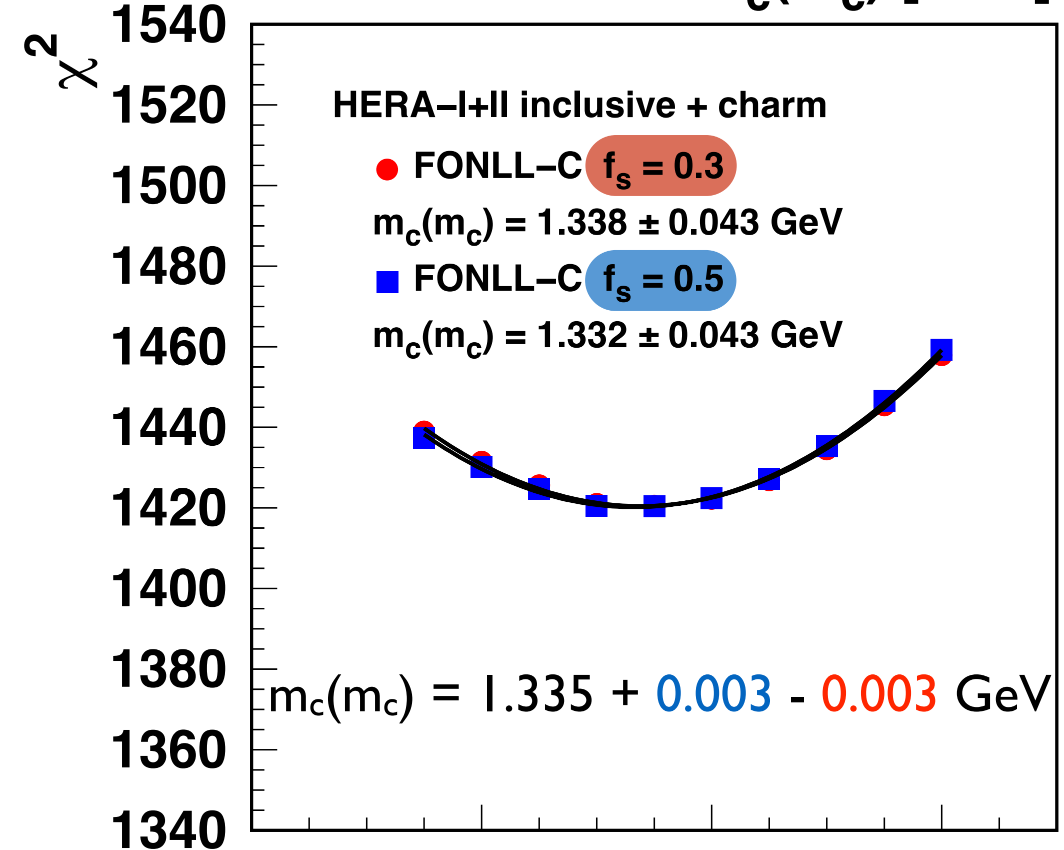



# Results: Model Uncertainty

- 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.

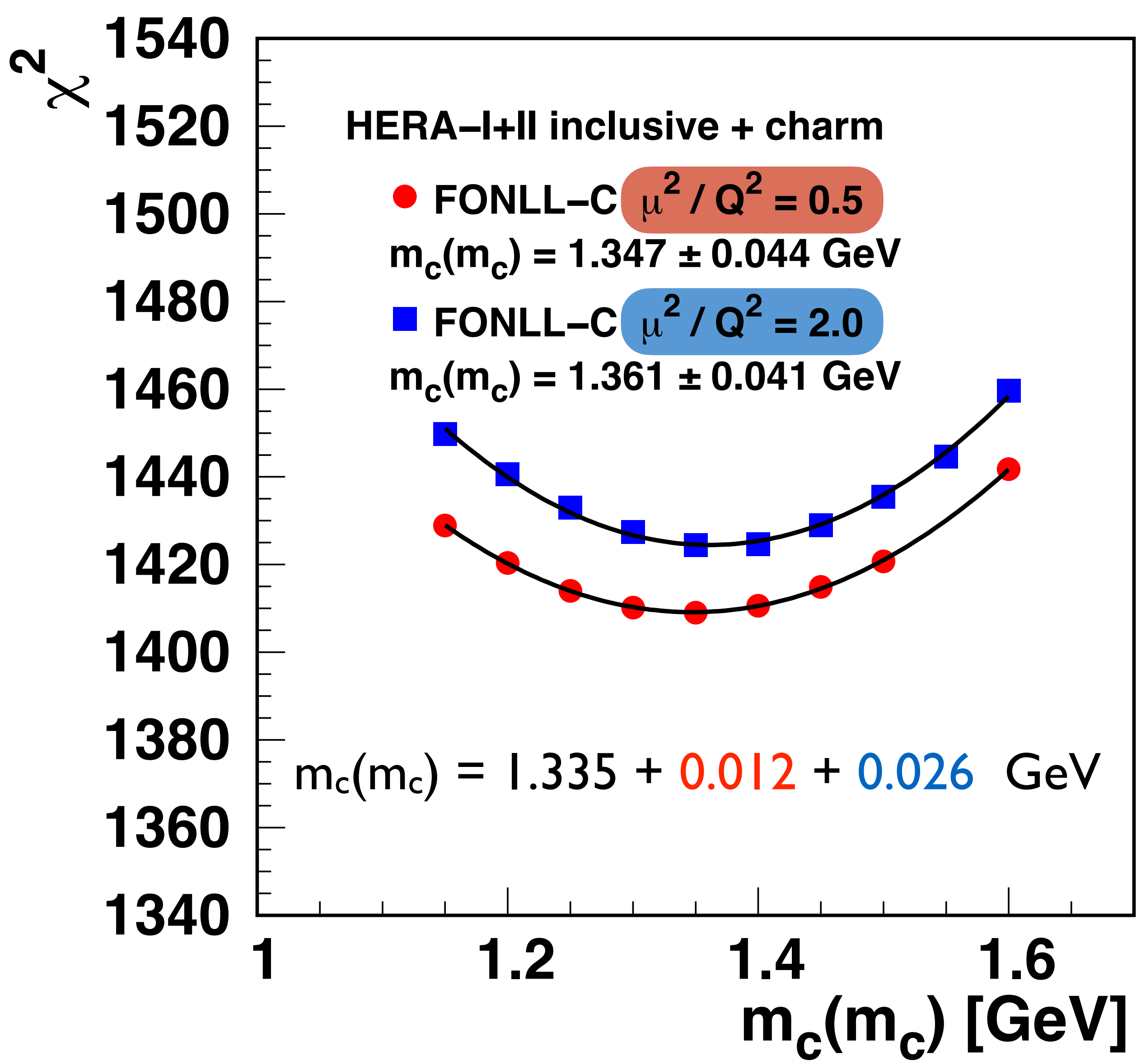


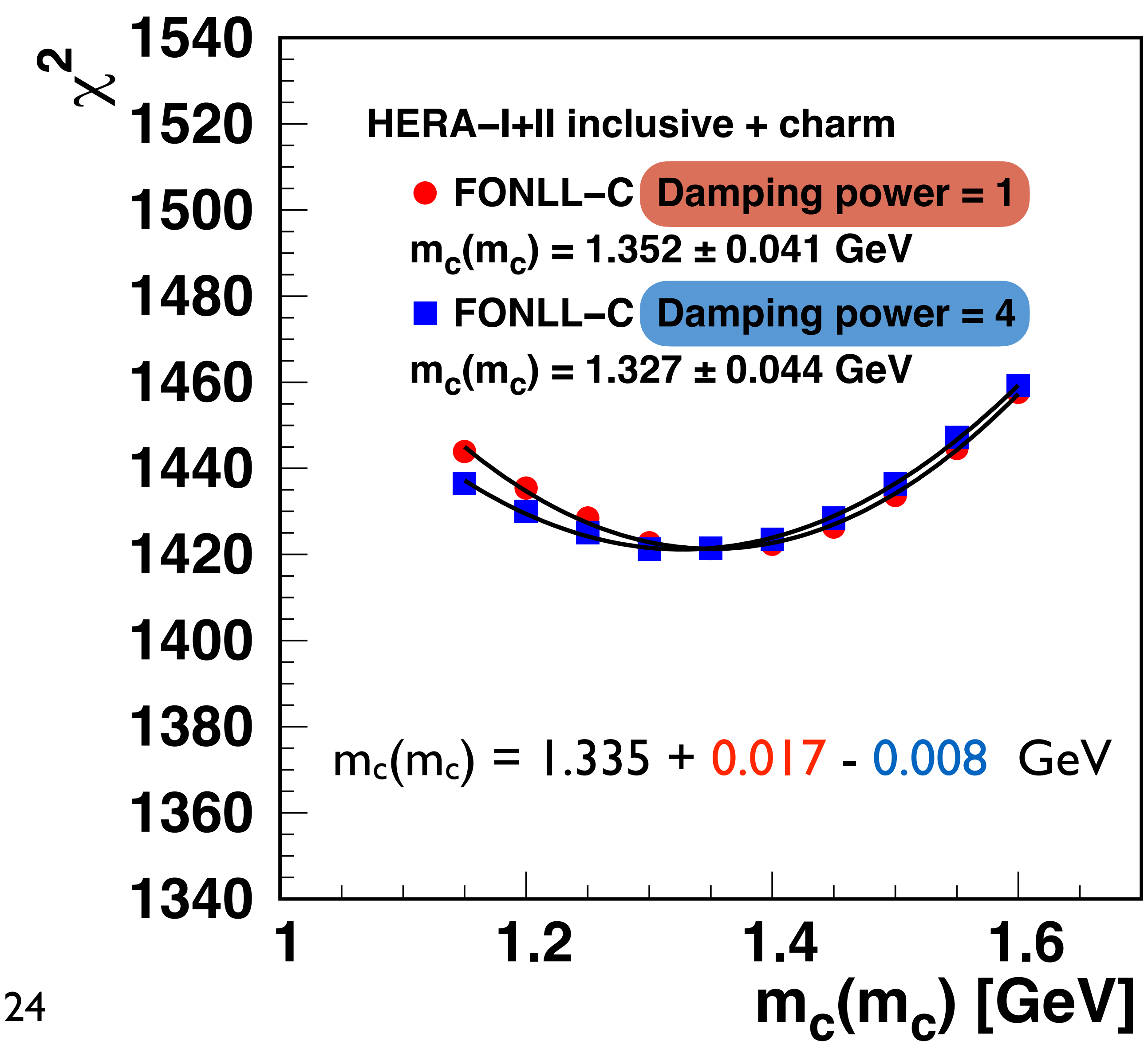



# Results: Theory Uncertainty

- The theoretical uncertainty is estimated varying:
  - $\mu_R^2$ and $\mu_F^2$ 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.



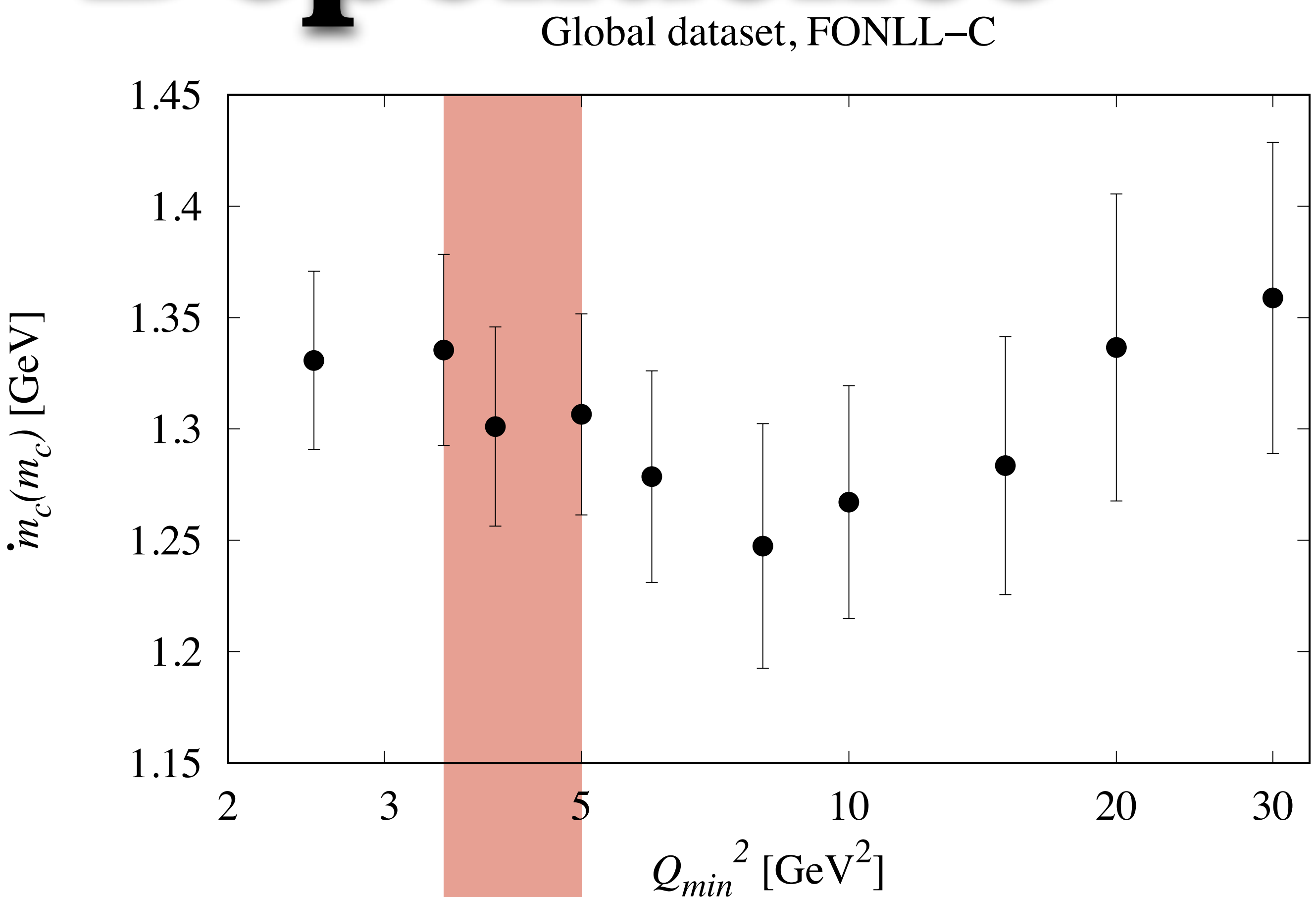



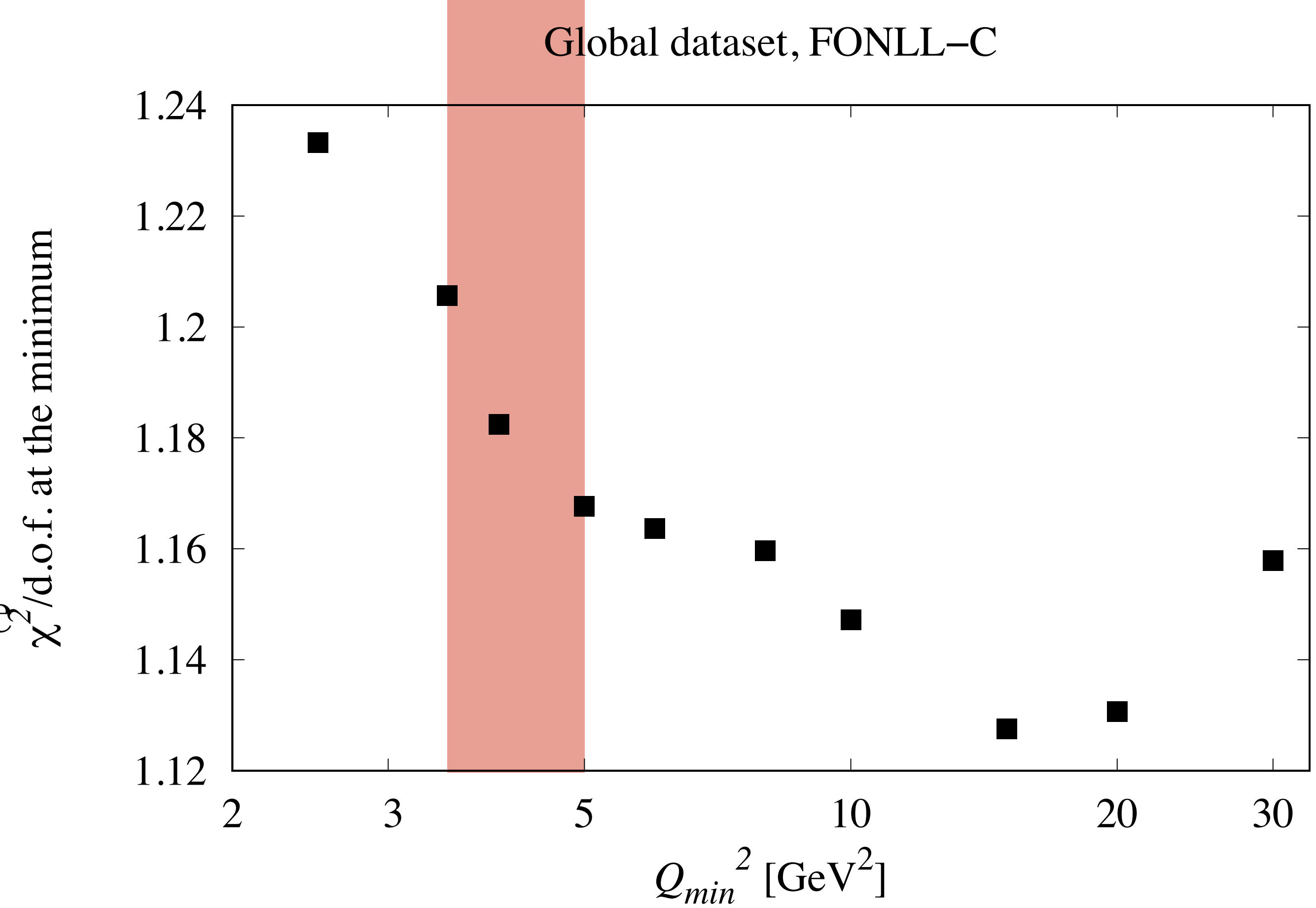
# Results: $Q_{min}^2$ Dependence

- 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 $\chi^2$.
3) Fit as many points as possible:
   - $Q_{min}^2$ reasonably small.

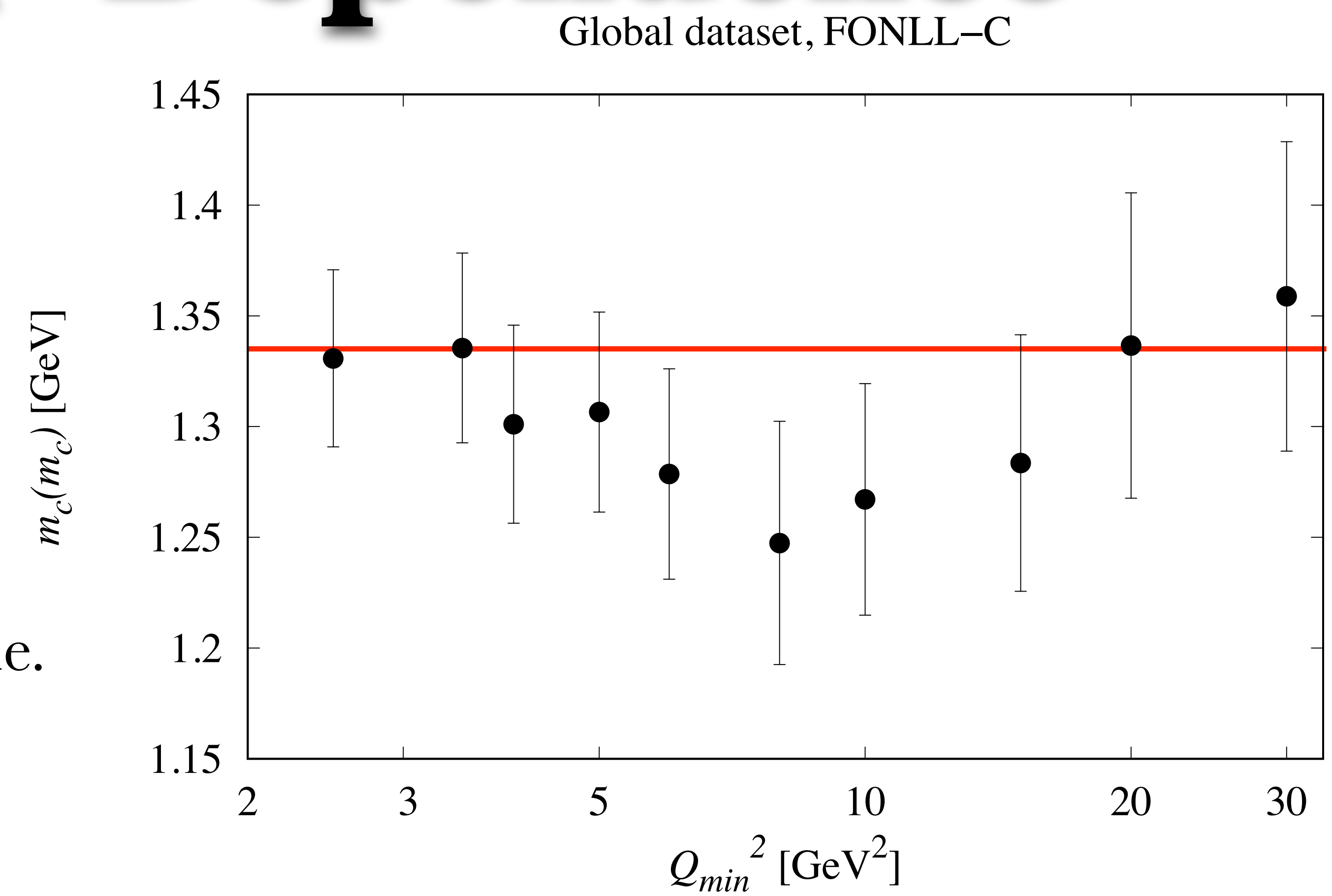
- This suggests $Q_{min}^2 \in [3.5:5]$ GeV$^2$:
   - $Q_{min}^2 = 3.5$ GeV$^2$ is a conservative choice in line with previous studies.

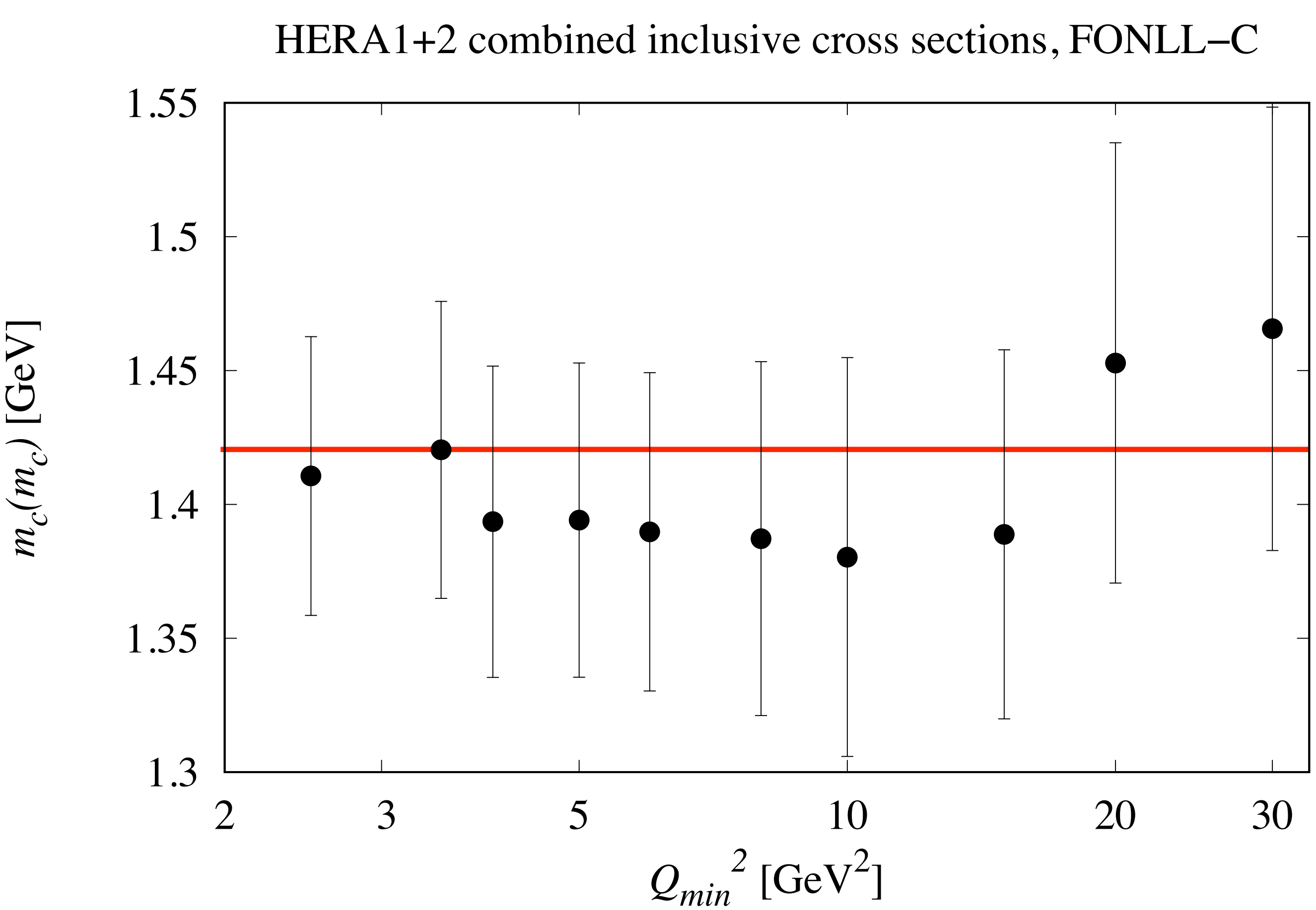


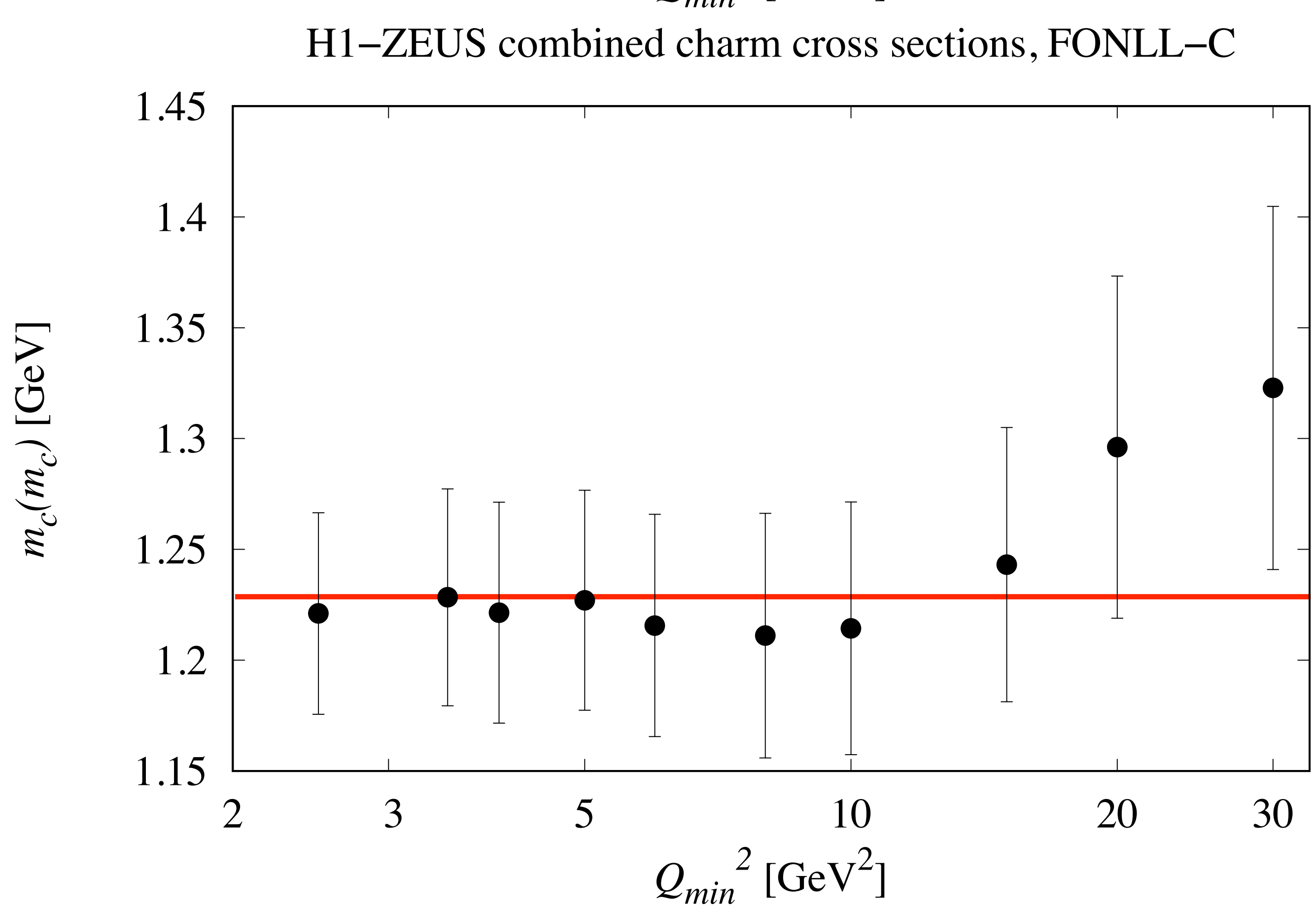



# Results: $Q_{min}^2$ Dependence

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

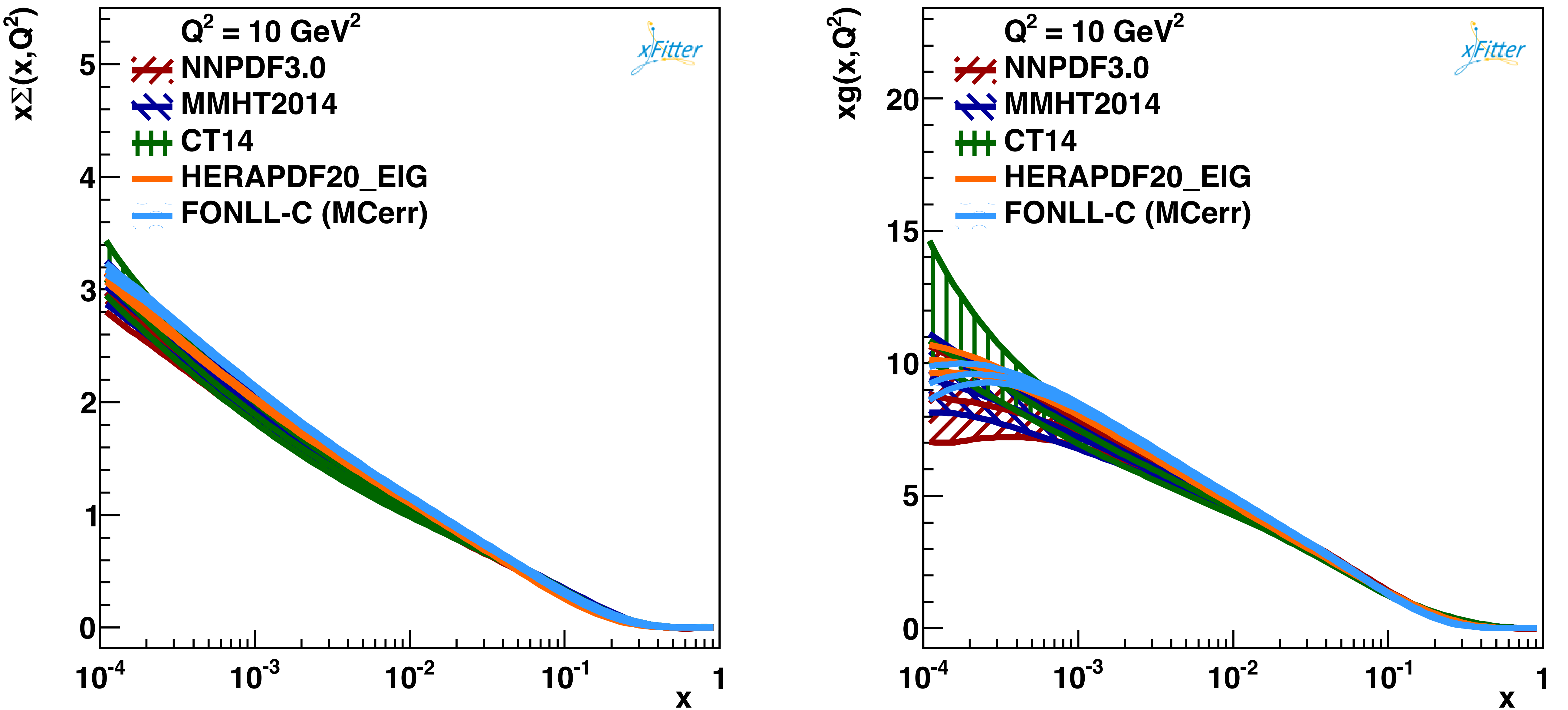


# Results: PDFs

- 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.