QCD + SMEFT analyses with xFitter

Workshop on top quark mass measurements

Valencia, May 21th, 2024

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based on ongoing work in collaboration with:
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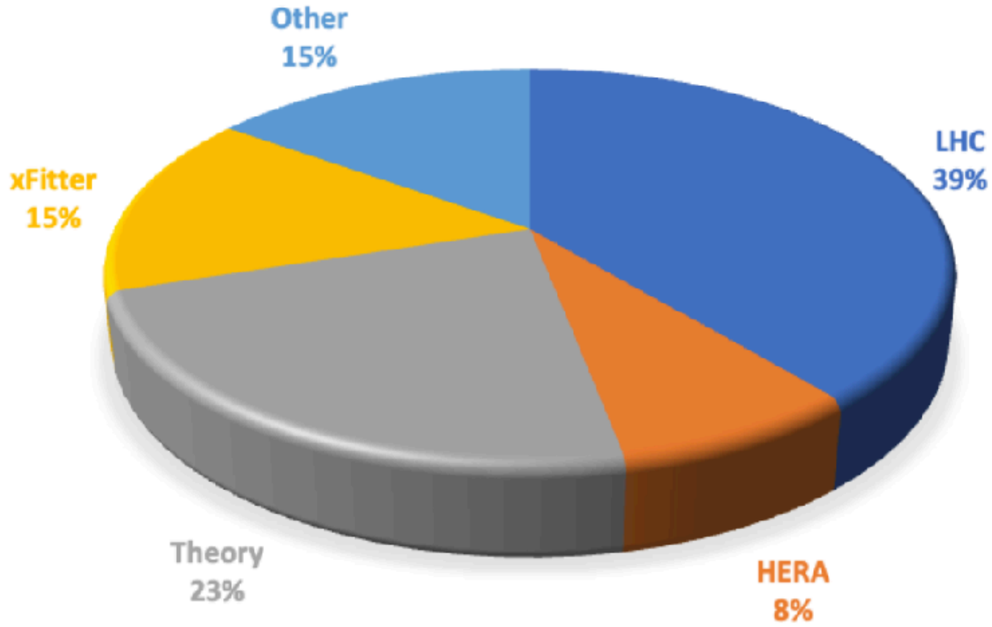
The xFitter project



- **xFitter** (former HERAFitter) an open-source QCD fitting framework

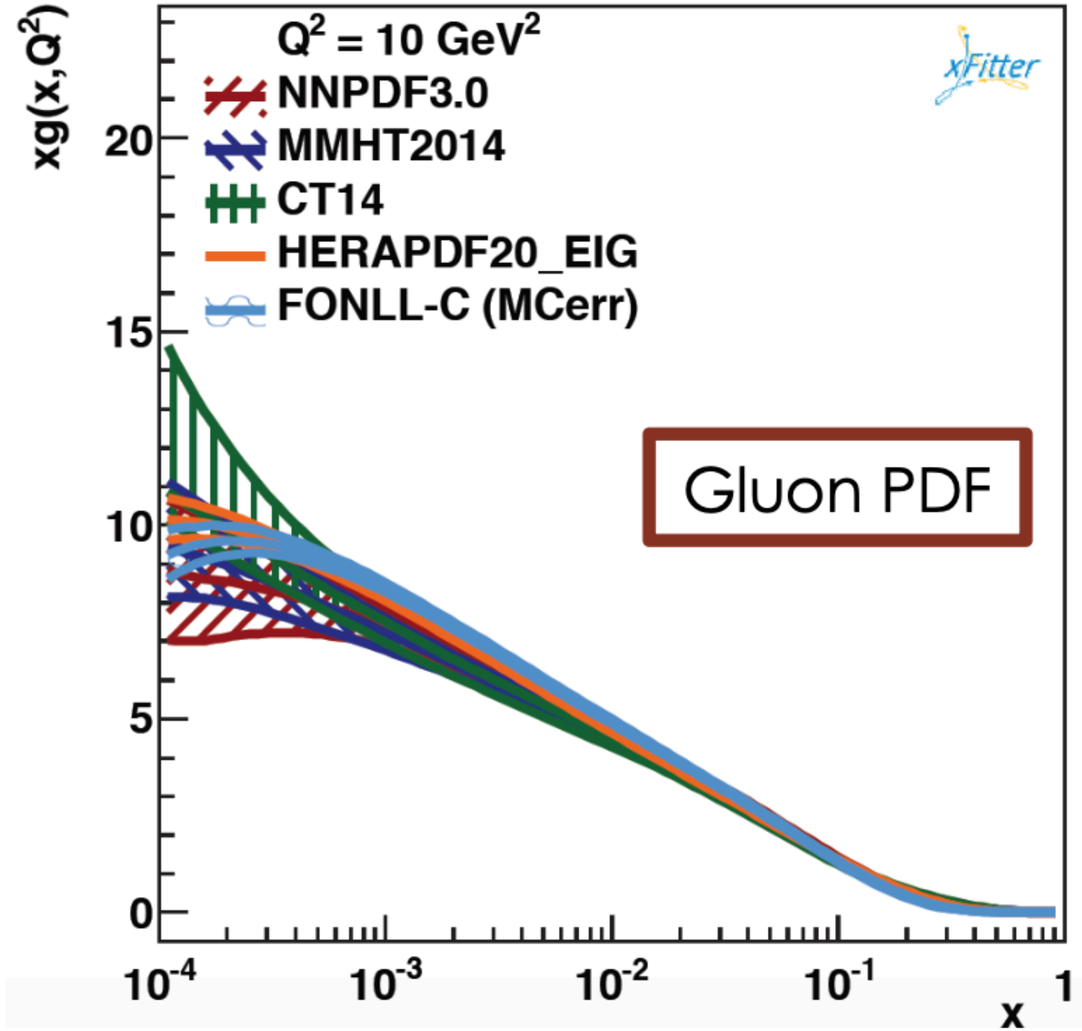
  https://gitlab.cern.ch/fitters/xfitter

- Designed to
  - Evaluate **consistency between data and theoretical predictions**
  - **Perform inference** on theoretical model parameters (m_t, α_S, $\sin^2\theta$, …)
  - **Extract Parton Distribution Functions**

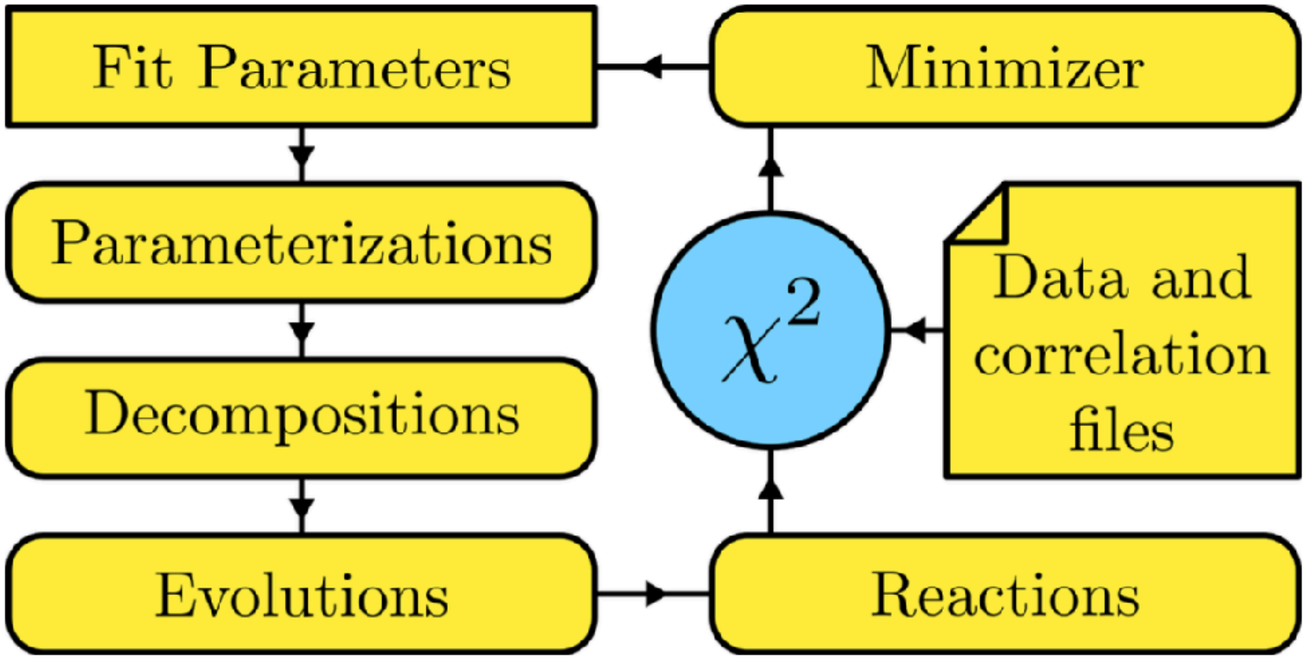
- Developers community of both **experimentalists and theorists**
- Used in more than **100 publications** so far

What is xFitter - I

- **Parametrise PDFs** at a given scale
  - Several parametrisations and decompositions
- **Evolve them** at the scale of the measured data
  - DGLAP evolution up to N3LO QCD and NLO QED with APFEL/APFEL++/QCDNUM
- **Compute theory** predictions:
  - DIS at NNLO with different mass schemes: ZM-VFNS,ACOT, FONLL, TR
  - Fast interfaces: APPLgrid, FastNLO, pineAPPL
- **Compare with data** using a χ^2:
  - Systematics are linearized: “profiling” as a trivial matrix inversion
  - For unconstrained minimisation: MINUIT, ceres-solver

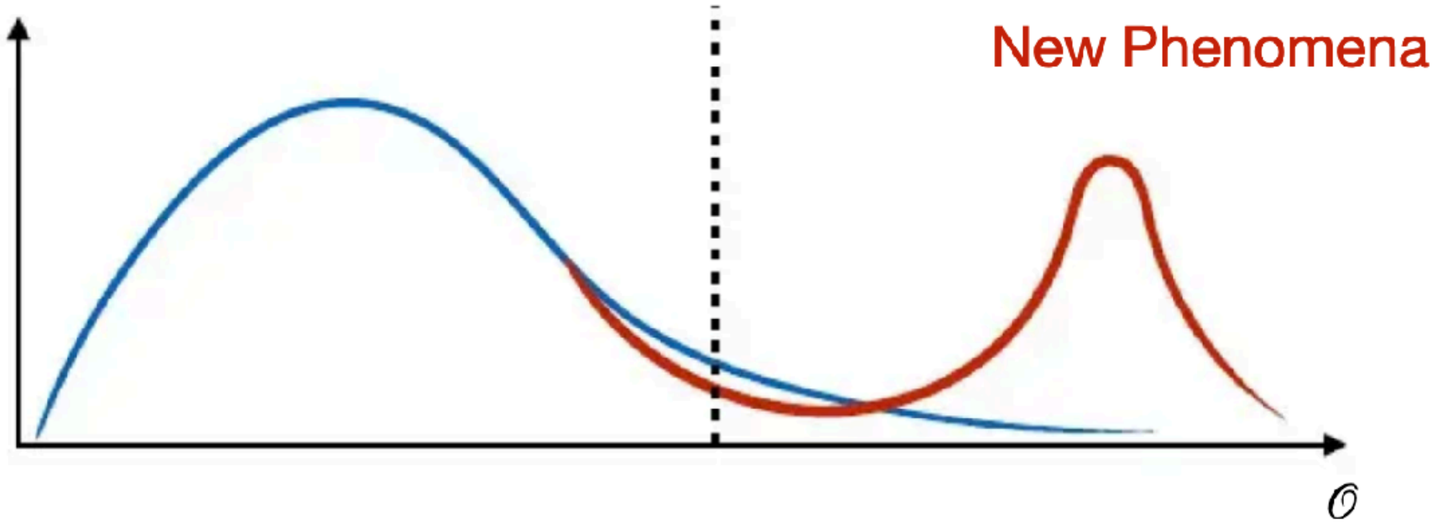


What is xFitter - II



- Significant **overhauling of the code** starting from version 2.0
- **Flexible interfaces** to minimizers, PDF parameterisation and decomposition, evolution and many new theory reactions
- Many example of analyses available as a starting point
- For a nice overview talk xFitterIntroduction

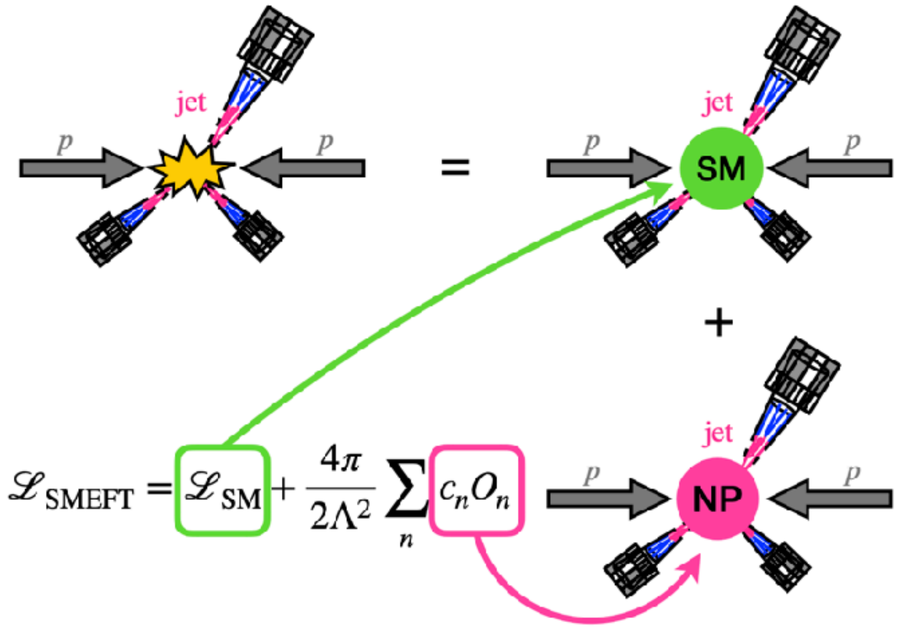
PDF and SMEFT interplay



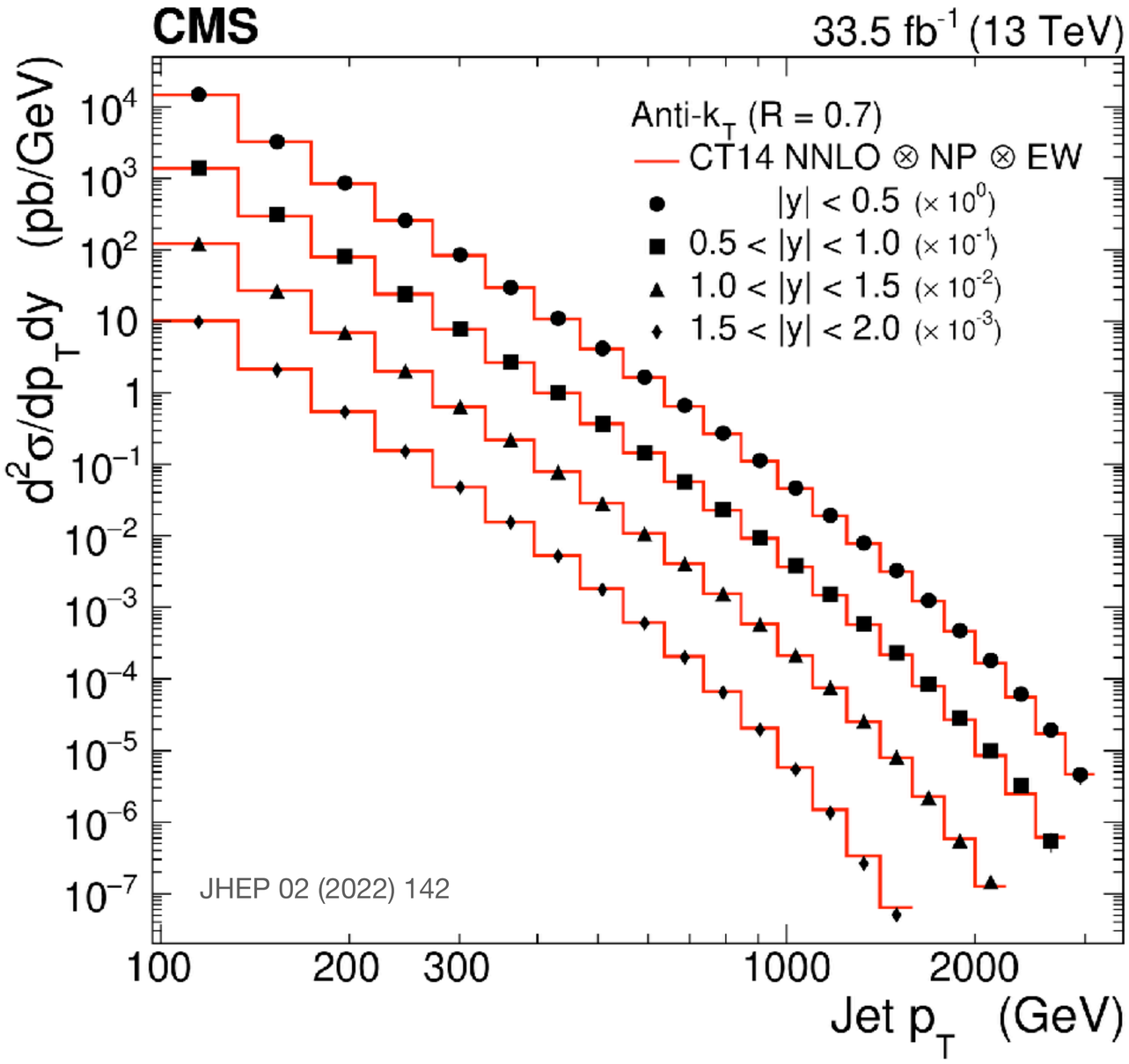
- Can EFT constraints be washed away by a refit of Parton Distribution Functions?
  - Few studies on this by the PDF fitting groups (NNPDF, CTEQ)
  - A more and more relevant question as our measurements improve in accuracy
- **Simultaneous determinations** of PDFs and SMEFT the consistent way out

CMS Inclusive jets at 13 TeV

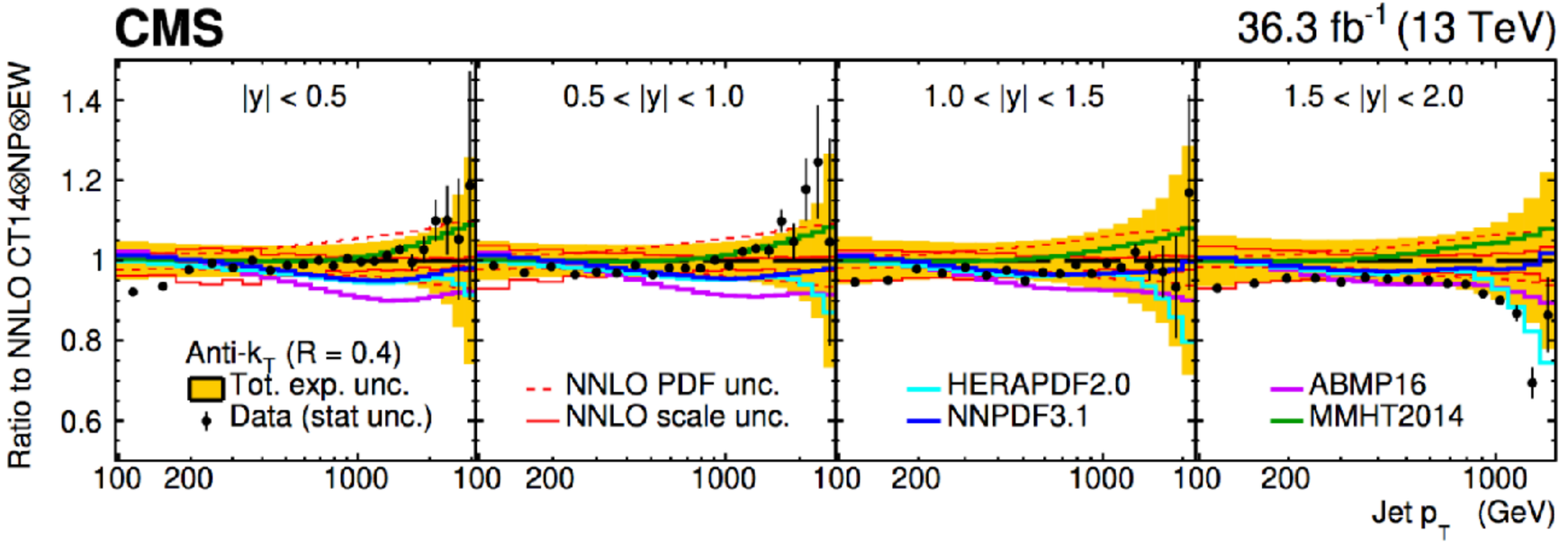
- 13 TeV inclusive jet cross-sections using 36 fb^{-1} of data
  - PDF, PDF+SMEFT analyses and strong coupling measurement
  - NNLO theory using NLO fast grids and NNLO k-factors

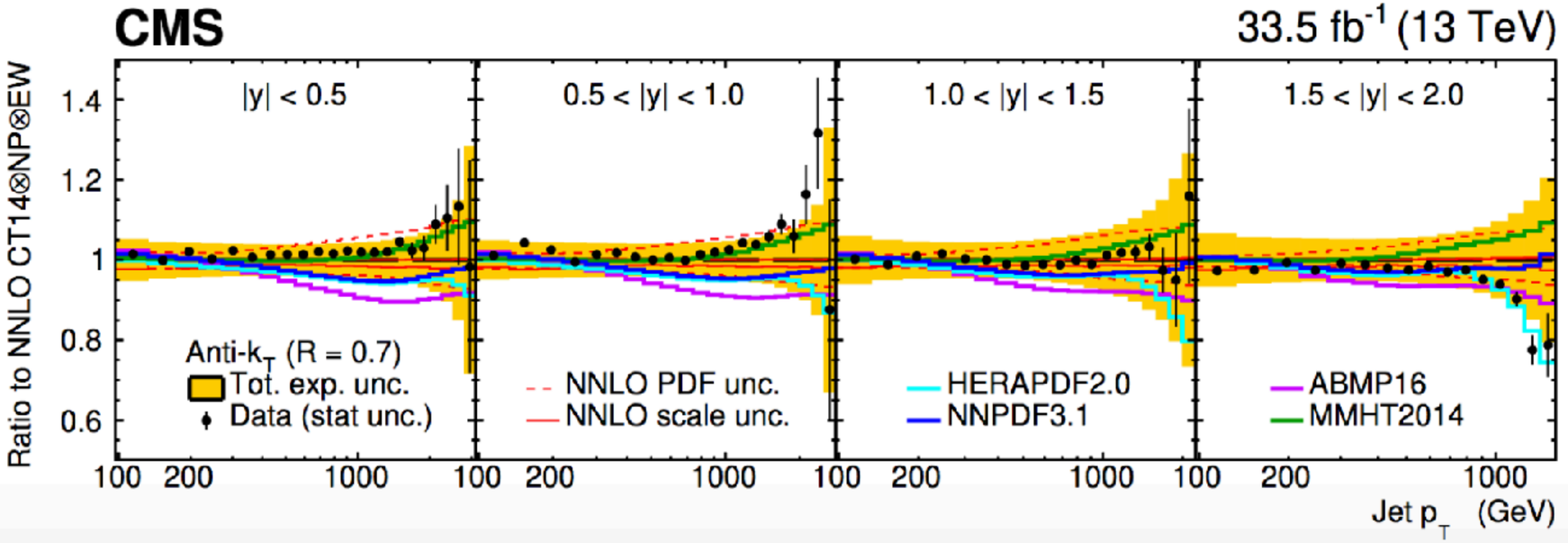


CI: contact interaction operators

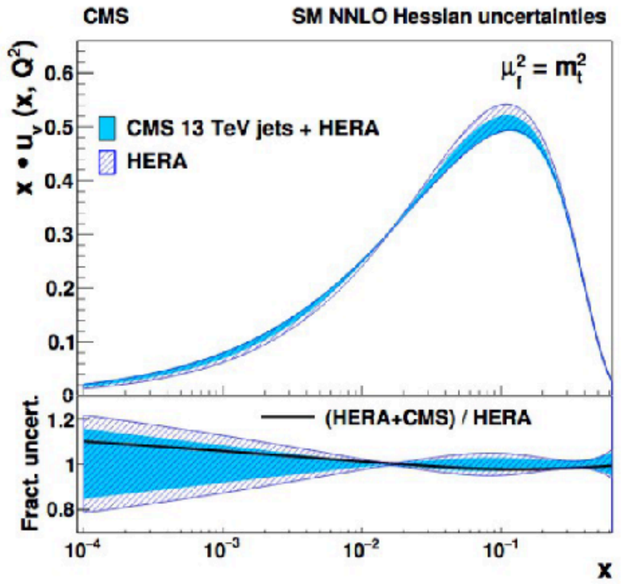


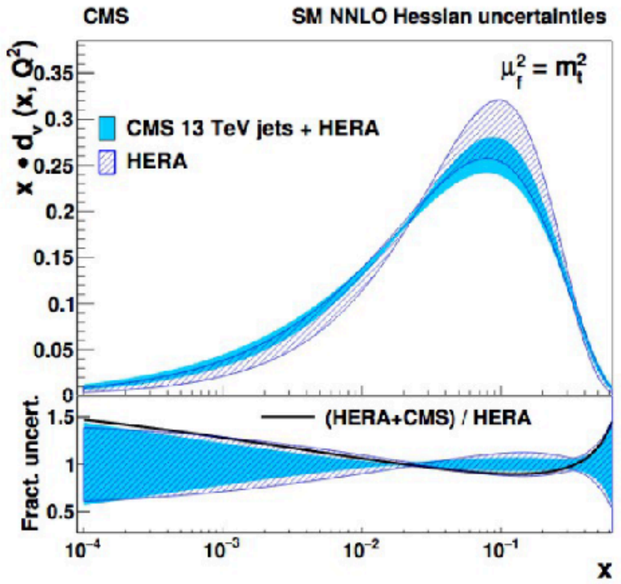
Data / predictions comparison

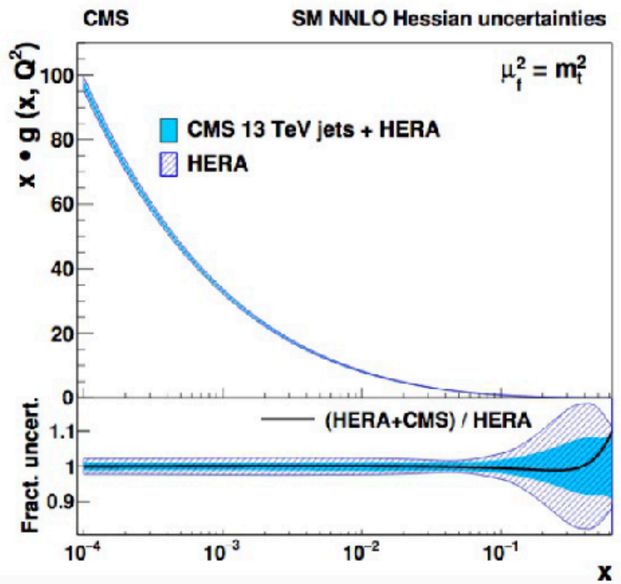


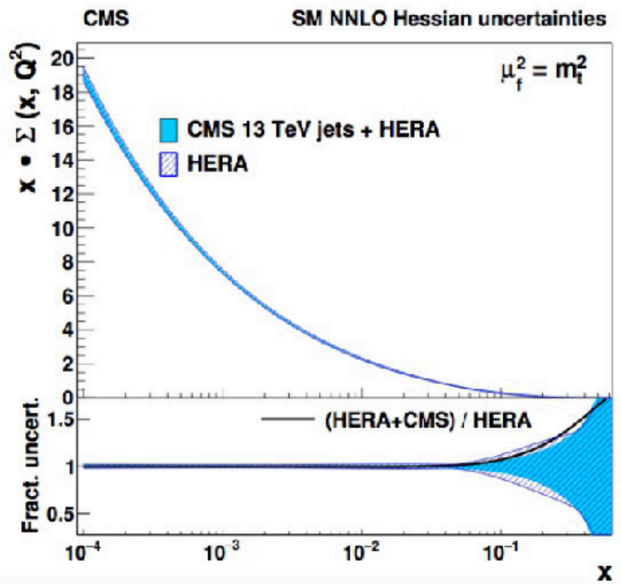


Determination of PDFs and strong coupling









- **Improved gluon constraints** in the “usual” HERA+X fit
- **Reduction in the MHOU** on the strong coupling constant using the NNLO grids

With NNLO k-factors

$$\alpha_S(m_Z) = 0.1170 \pm 0.0014\,(\text{fit}) \pm 0.0007\,(\text{model}) \pm 0.0008\,(\text{scale}) \pm 0.0001\,(\text{param.})$$

With NNLO grids

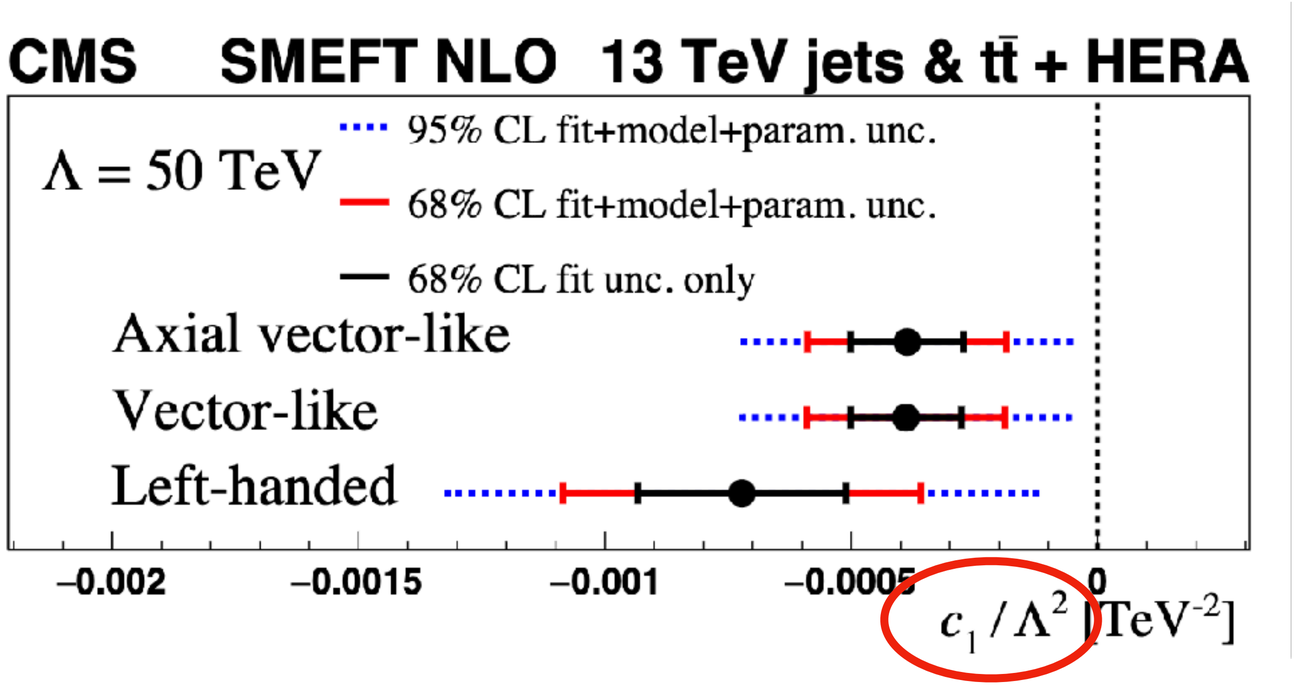
$$\alpha_S(m_Z) = 0.1166 \pm 0.0014\,(\text{fit}) \pm 0.0007\,(\text{model}) \pm 0.0004\,(\text{scale}) \pm 0.0001\,(\text{param.})$$

SMEFT INTERPRETATION

- Effect of **Contact Interactions** (CI) added to the fit using an interface to CIJET
  - **CIJET**: Incorporate exact CI dependence at NLO accuracy into fast grids [1301.7263]
- Simultaneous determination of PDFs, the strong coupling and Wilson coefficients
- Fit of of **jets and top-quark pair data** at NLO QCD (for consistency with SM)

$$\mathcal{L}_{\mathrm{SMEFT}} = \mathcal{L}_{\mathrm{SM}} + \frac{2\pi}{\Lambda^2} \sum_{n \in \{1,3,5\}} c_n O_n.$$

95% CL on Λ with $c_1 = -1$:
Axial vector-like: 24 TeV
Vector-like: 31 TeV
Left-handed: 31 TeV

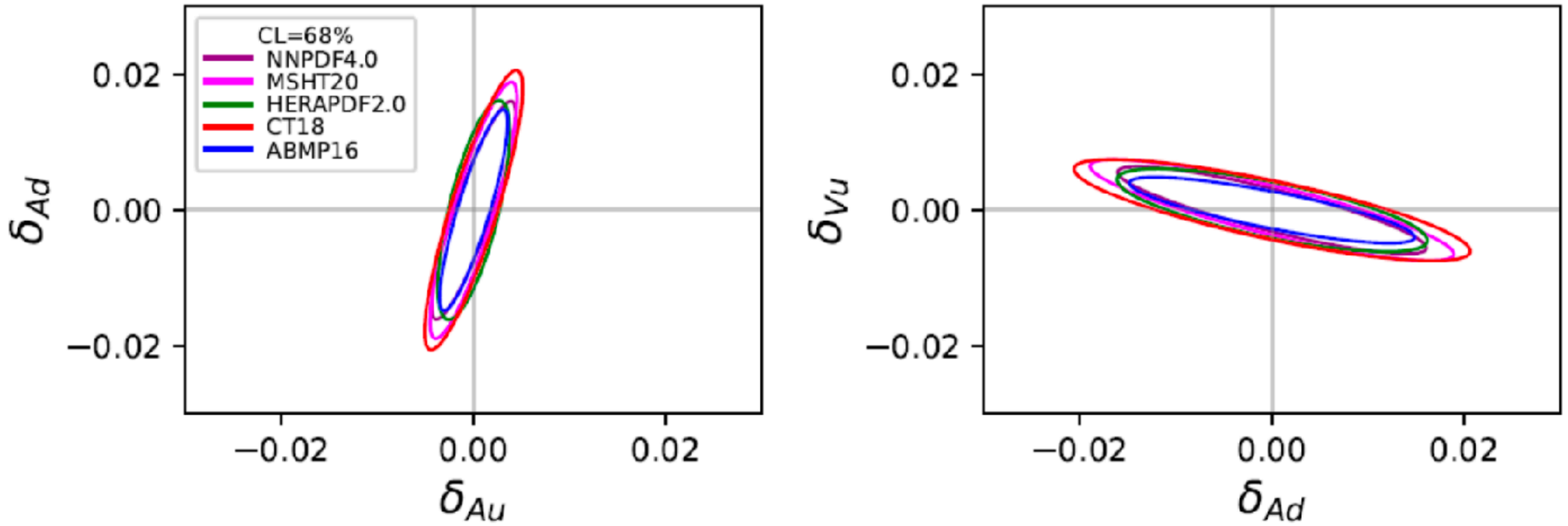


Drell-Yan A_{FB} in the SMEFT

- Drell-Yan forward-backward asymmetry is sensitive to **anomalous Z couplings to fermions**
  - Z coupling to leptons very well constrained by LEP measurements
  - LEP **constraints on quark couplings much weaker** (some constraints by HERA, Tevatron)

- Evaluated the sensitivity of HL-LHC Drell-Yan measurements to vector/axial coupling to quarks
  - Fast LO computation of Drell-Yan cross-sections with anomalous couplings
  - In this exercise PDFs are simultaneously constrained (but not refitted)

https://arxiv.org/abs/2310.19638



Extensions to arbitrary EFT operators

- The two previous examples of PDF+SMEFT analyses relied on interfaces specific to a given process or set of operators

- We aim to develop a **flexible interface** allowing us to parametrize the theory dependence on **arbitrary operators** and for **any process**

- **Two approaches** considered, both using SMEFT@NLO model in mg5_aMC@NLO:
  - **Tabulate the cross-section predictions** for linear and quadratic variations of a given set of operators (using reweighting), **interpolate them** for each bin, and pass the interpolation to xFitter to minimize the Wilson coefficients
  - Incorporate the EFT dependence into **fast grids** (pineAPPL).
    Consider the exact dependence of the EFT modifications on the PDFs

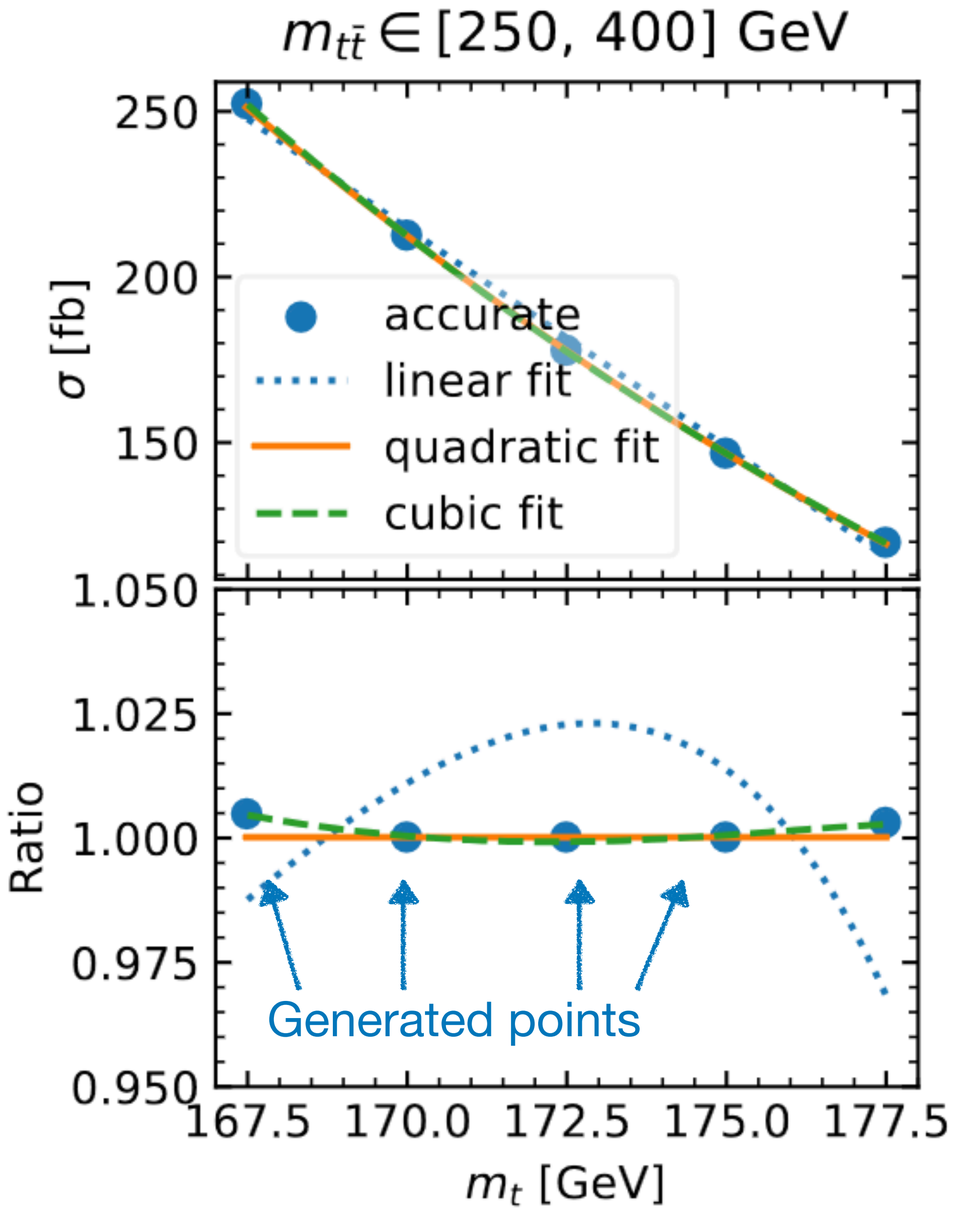
Parametrisation of EFT/m_{top} dependence

- New xFitter reaction able to derive a polynomial dependence of a measurement σ on a parameter $\boldsymbol{c}$

$$\sigma^{(\alpha)}(\mathbf{c}) = \sigma_0^{(\alpha)} + \sum_i c_i \sigma_i^{(\alpha)} + \sum_{i \leqslant j} c_i c_j \sigma_{ij}^{(\alpha)}$$

$$= \sigma_0^{(\alpha)} \left(1 + \sum_i c_i K_i^{(\alpha)} + \sum c_i c_j K_{ij}^{(\alpha)} \right).$$

- Requires the computation of the linear and quadratic $\boldsymbol{K}$-factors: $K_i = \sigma_i/\sigma_0$, $K_{ij} = \sigma_{ij}/\sigma_0$
- The $\boldsymbol{K}$ can either provided as tabulated numbers or through interpolation grids
- Example application to the interpolation of the top mass dependence for a cross-section measurement in the $m_{t\bar{t}}$ threshold region



HL-LHC projection study

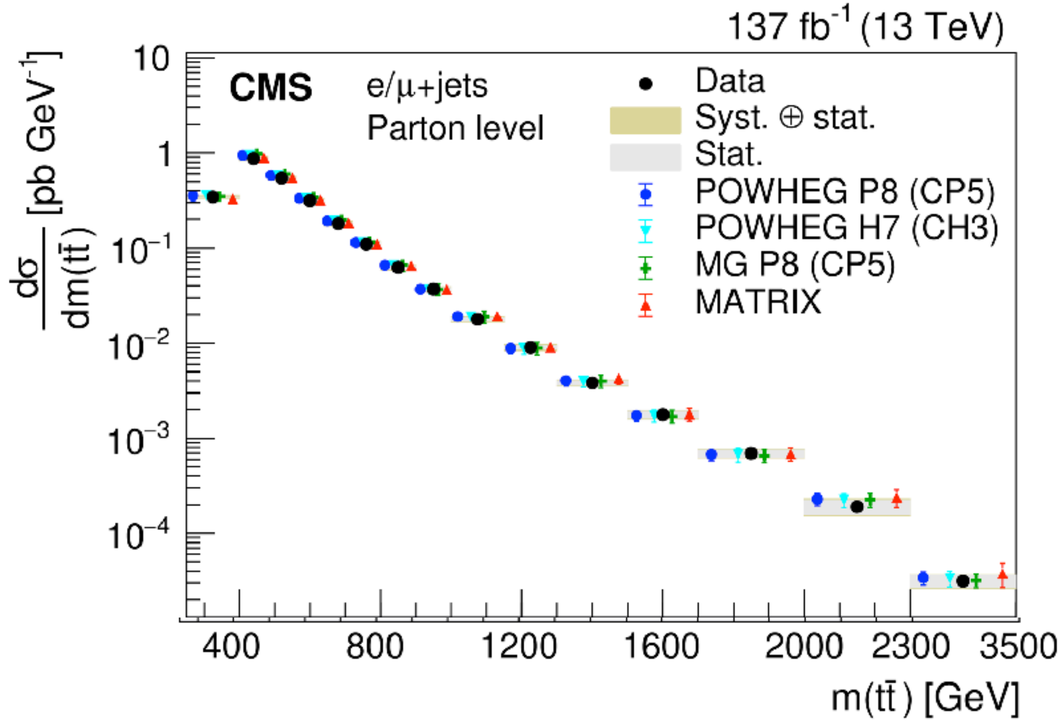
- We illustrate the capabilities and functionality of the new reaction in a sensitivity study using High Luminosity LHC projections of the invariant mass of the top-quark pairs, $m_{t\bar{t}}$

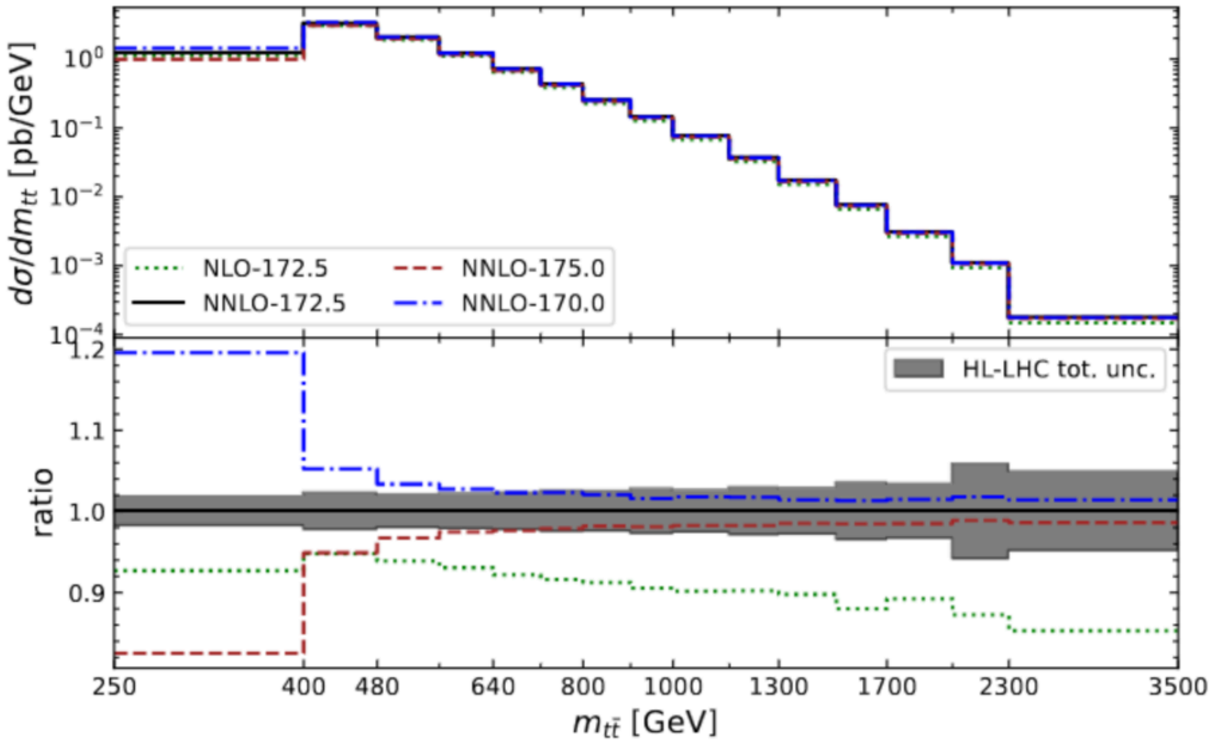
- Consider a simultaneous determination of the PDFs, the top-quark mass and of four relevant EFT operators

- To properly determine PDFs, the HL-LHC pseudo-data are used in conjunction with the HERA-II combination of inclusive DIS cross-sections

HL-LHC Pseudodata generation

- We generated HL-LHC pseudodata starting from a CMS measurement of the $m_{t\bar{t}}$ distribution at 13 TeV (TOP-20-001) and rescaling its uncertainties
  - **Statistical uncertainties**: Rescaled to 3 ab^{-1} of integrated luminosity
  - **Systematic Uncertainties**: Rescaled by a factor of two wrt existing uncertainties
  - **Luminosity**: Consider a 1% luminosity uncertainty (following Yellow Report)





SMEFT fit to 13 TeV top data

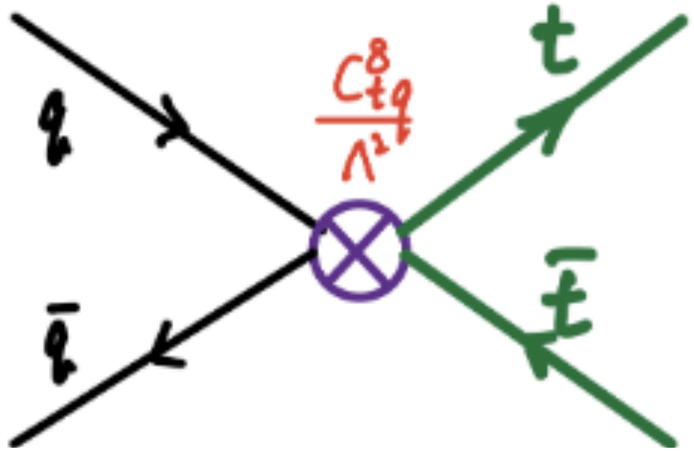
- Four representative dim-6 SMEFT operators considered:

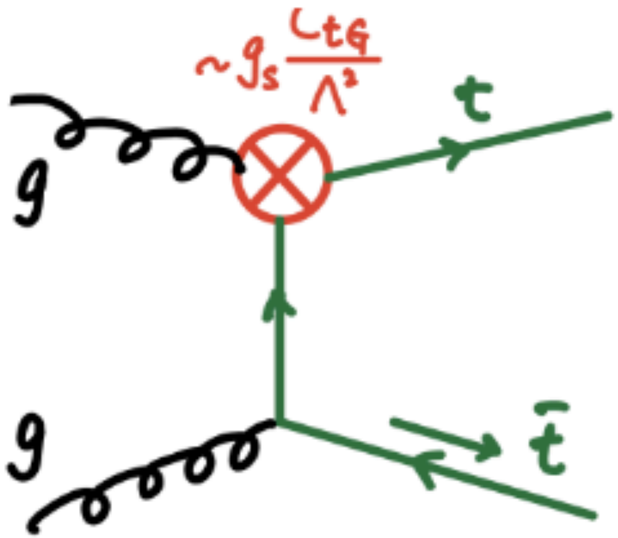
$$O_{tu}^{1} = \sum_{i=1}^{2} (\bar{t}\gamma_{\mu}t)\,(\bar{u}_{i}\gamma^{\mu}u_{i}) \;,$$

$$O_{td}^{1} = \sum_{i=1}^{3} (\bar{t}\gamma^{\mu}t)\,(\bar{d}_{i}\gamma_{\mu}d_{i}) \;,$$

$$O_{tG} = ig_{s}(\bar{q}_{L3}\tau^{\mu\nu}T^{A}t)\tilde{\varphi}G_{\mu\nu}^{A} + \text{h.c.}\,,$$

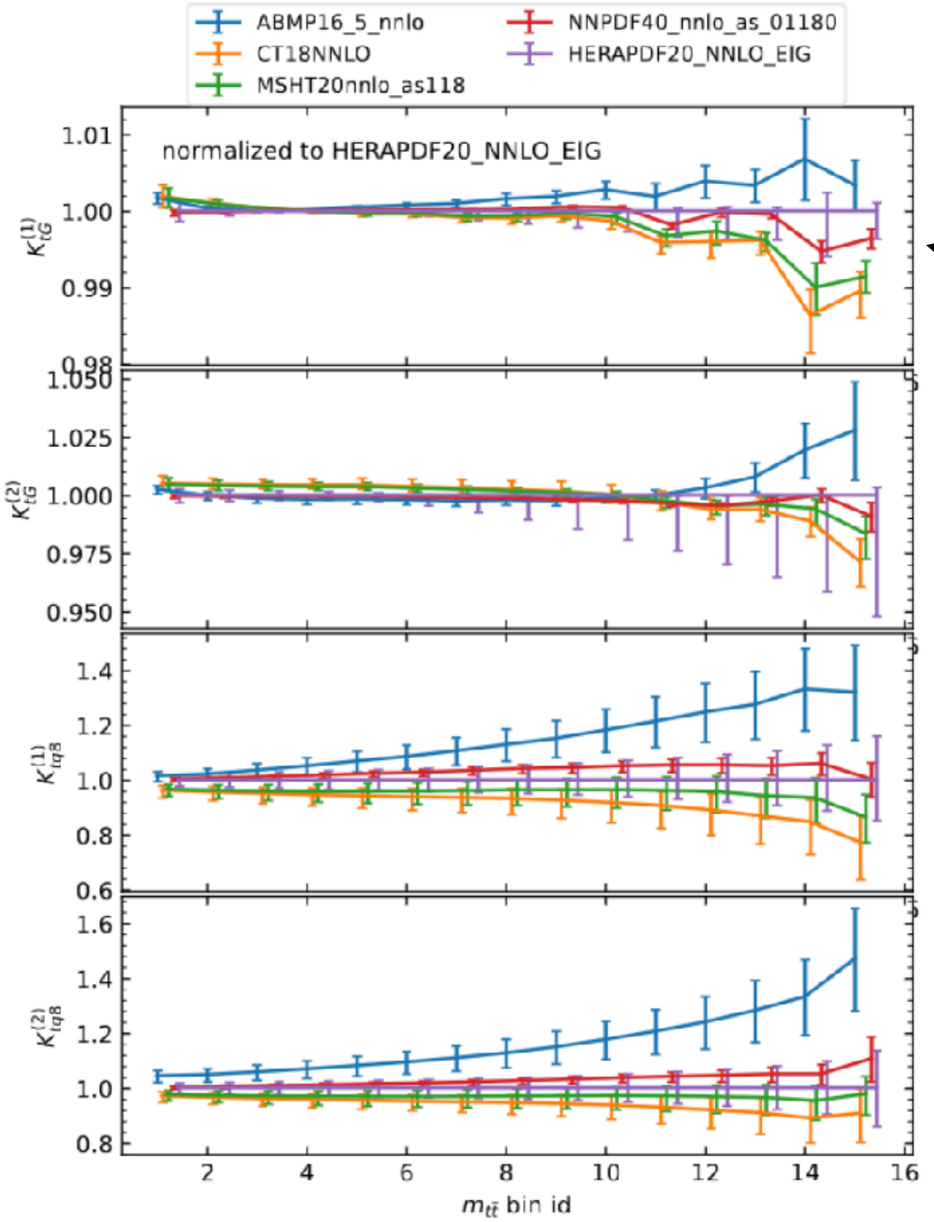
$$O_{tq}^{8} = \sum_{i=1}^{2} (\bar{q}_{Li}\gamma_{\mu}T^{A}q_{L,i})(\bar{t}\gamma^{\mu}T^{A}t)\,,$$





- Predictions for varied Wilson coefficients obtained at NLO QCD using mg5_aMC@NLO and SMEFT@NLO

PDF dependence of EFT contributions



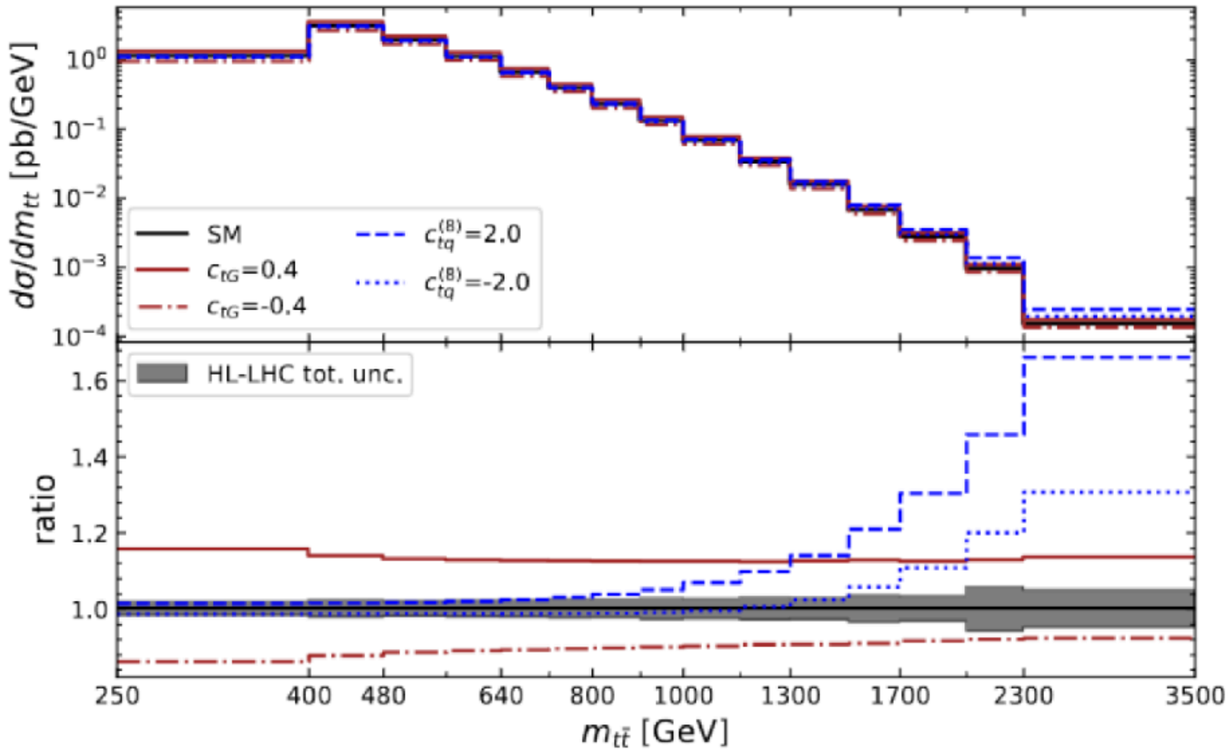
$$\sigma_{\mathrm{EFT}} = \sigma_{\mathrm{SM}} + (c_{tG}\,\sigma_{tG,I} + c_{tG}^2\,\sigma_{tG,Q}) + (c_{tq8},\sigma_{tq8,I} + c_{tq8}^2\sigma_{tq8,Q}) + c_{tq8}c_{tG}\sigma_{tG,tq}$$

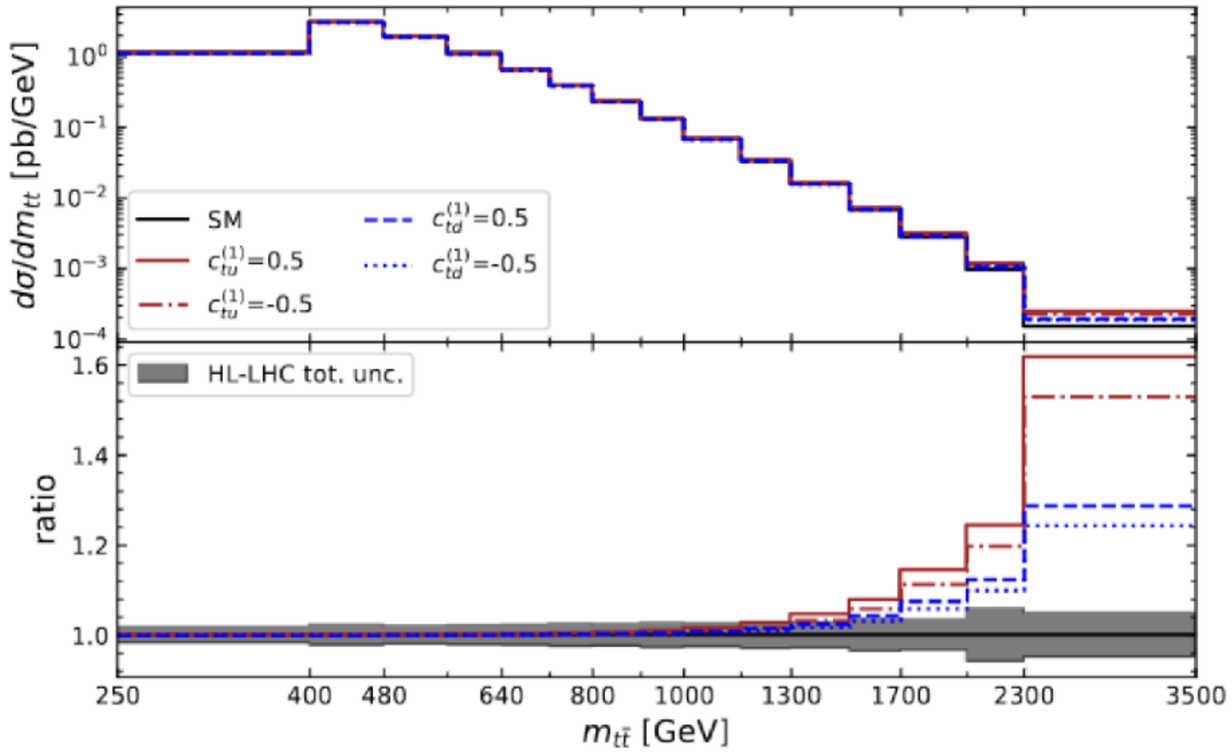
Error bars indicate the PDF dependence using a given PDF error set

- K-factors to evaluate linear/quadratic dependence on EFT operators are always assumed not to depend on other QCD parameters such as the PDF
- New xFitter reaction can test this assumption
  - PDF dependence of the EFT contributions is typically small compared to the accuracy of existing measurements
  - But can be as large as 10% if we consider ABMP16
  - Motivates the use of grids rather than tabulated K-factors

Impact of EFT operators

- We can now look at the effect of each individual operator on the cross-sections
  - C_{tg} has a large effect on the overall cross-section
  - Other operators mostly affect the high-$m_{t\bar{t}}$ region
  - Quadratic terms cannot be neglected for C_{tu}^{1}, C_{td}^{1}





PDF FIT CONFIGURATION

- QCD analysis is performed at NNLO in QCD following the HERAPDF2 fit
  - DIS cross-sections calculated at NNLO in the RT VFNS
  - Quark masses are set to m_b=4.5 GeV, m_c=1.43 GeV and $\alpha_s(m_Z)$=0.118
  - The value of m_{top} and of the Wilson coefficients are interpolated using the new reaction and left free in the fit

- We parametrise the gluon, u- and d-valence and Ubar and Dbar PDFs
  - Strangeness fraction $f_s = \bar{s}/(\bar{d}+\bar{s})$ fixed to 0.4 following HERAPDF
  - PDFs parametrized at a starting scale of Q^2_0=1.9 GeV^2

$$xf(x) = A_f x^{B_f}(1-x)^{C_f}(1+D_f x+E_f x^2)$$

Preliminary results

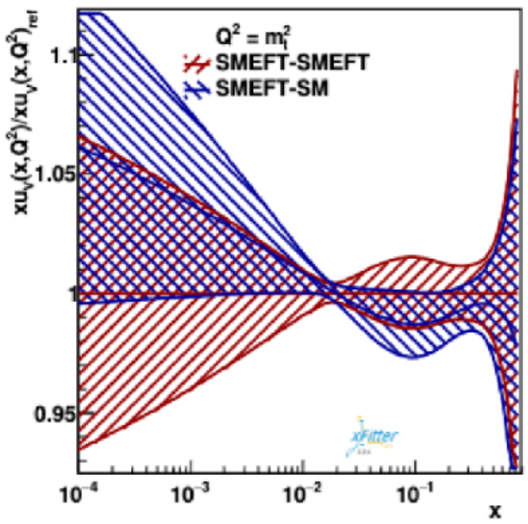
- In our nominal fit, we inject some non-zero values for the Wilson coefficients close to their current experimental bounds
  - The fit can retrieve injected values within quoted fit uncertainties

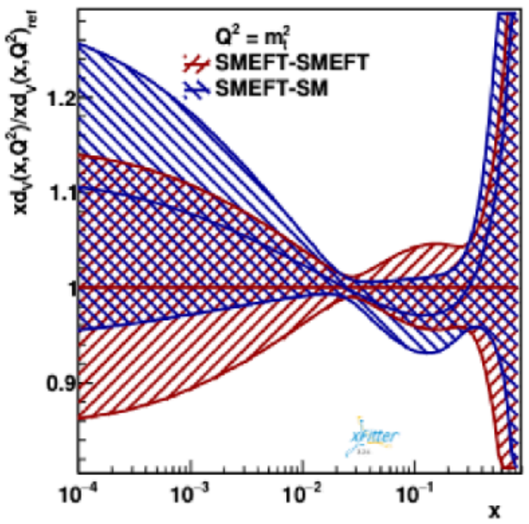
	m_t	C_{tG}	$C_{tq}^{(8)}$	$C_{tu}^{(1)}$	$C_{td}^{(1)}$
input parameters	172.5	-0.1	1.0	0	0
quadratic EFT fit	172.50 ± 0.37	-0.11 ± 0.08	1.00 ± 0.25	-0.01 ± 0.37	0.01 ± 1.14
linear EFT fit	172.47 ± 0.36	-0.07 ± 0.39	0.35 ± 12.22	-0.35 ± 3.46	8.36 ± 53.34
fixed PDF	172.41 ± 0.35	-0.14 ± 0.08	0.93 ± 0.50	-0.01 ± 1.05	-0.09 ± 1.69

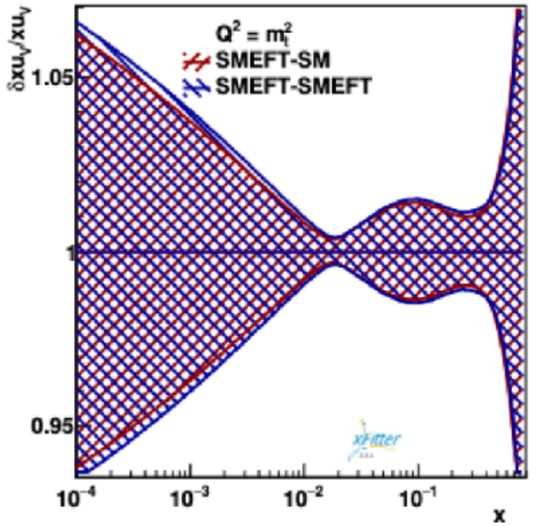
- Good sensitivity to both m_{top} and the EFT parameters
  - Large dependence on the quadratic corrections for C_{tu}^{1}, C_{td}^{1}

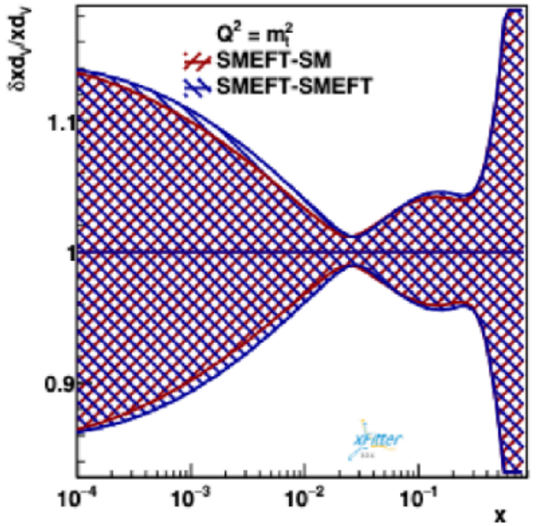
PDF uncertainties and Biases

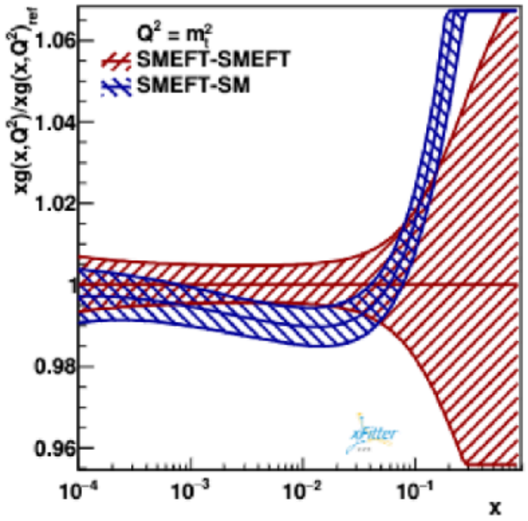
- Can further compare the resulting PDFs when we fit pseudodata with non-zero Wilson coefficients with (SMEFT-SMEFT) or without (SMEFT-SM) fitting the EFT

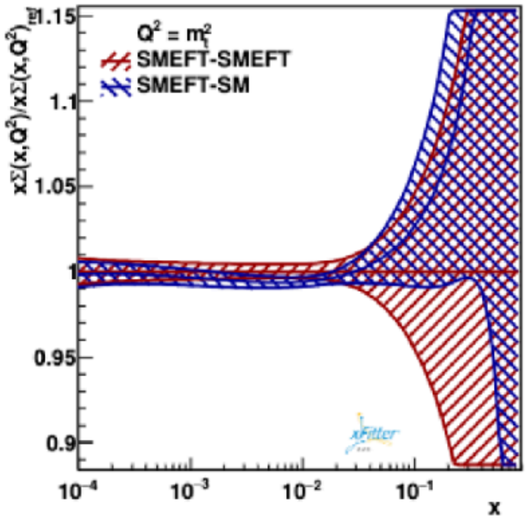


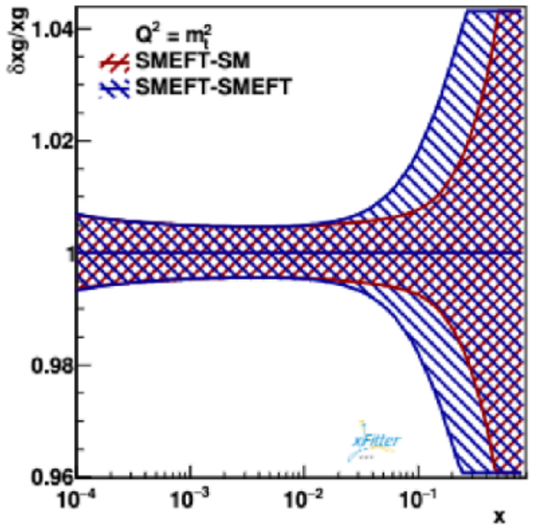


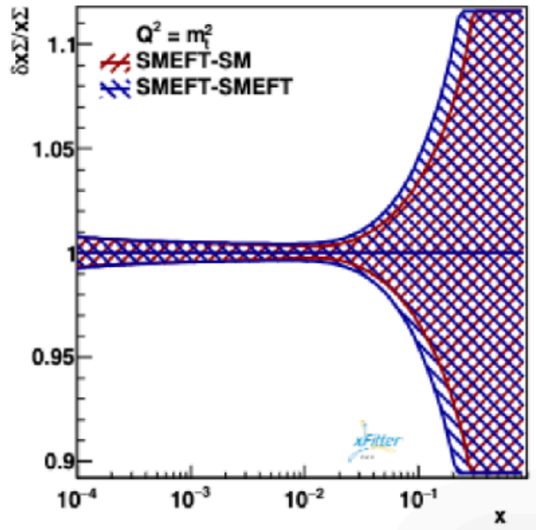












Conclusions

- Increased accuracy of LHC measurements sensitive to EFT effect, makes it important to avoid possible biases due to the interplay with PDF and SM parameters

- The xFitter framework has been extended to allow incorporating a parametrization of EFT effects with an easy and flexible approach

- Highlighted a possible neglected bias due to the PDF dependence of the EFT

- Showcased its capabilities by performing a sensitivity study for the simultaneous determination of PDF, SMEFT and m_{top} on an HL-LHC 13 TeV projected measurement of $m_{t\bar{t}}$

- Potential for many interesting applications for (HL-)LHC analyses

Summary

- **xFitter** the “go-to” choice for QCD/PDF analyses by LHC experiments

- Recently extended to allow **PDF+X fits** (X=SMEFT, but also EW parameters, …)
- New reactions allowing for fast evaluation of the effect of SMEFT operators, exploiting SMEFT@NLO in mg5_aMC@NLO:
  - Interpolate **tabulated cross-sections** predictions with varied Wilson coefficients
  - Through **pineAPPL grids** at fixed-order for varied Wilson coefficients

- Plan to use them for a **simultaneous CMS fit of PDFs, SM parameters and SMEFT operators** to inclusive **jets and top quark pair** production data at 13 TeV
  - Many more potential applications, limited by available person power

Backup