EFT reaction: SMEFT+PDF extraction in the xFitter framework

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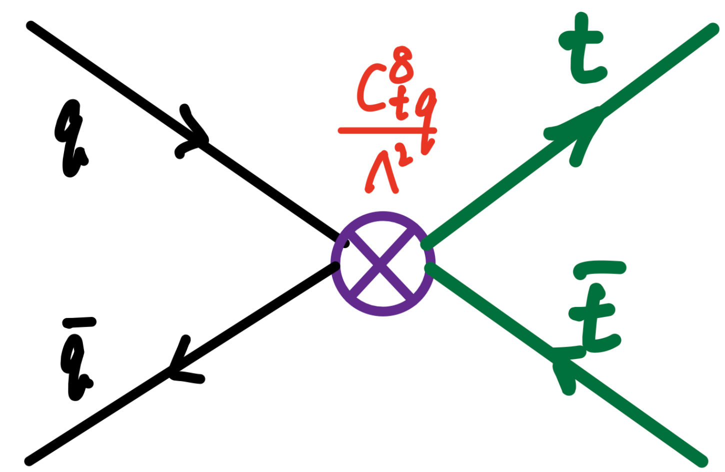
Indirect BSM search in framework of SMEFT

- The SM Effective Field Theory (SMEFT)
  - symmetries: $SU(3)_C \times SU(2)_L \times U(1)_Y$ (+ L conservation + …)
  - expanded in Λ_{NP} ($\gg \Lambda_{\text{EW}}$)

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \frac{c_i^{(6)}}{\Lambda^2}\mathcal{O}_i^{(6)} + \frac{c_i^{(8)}}{\Lambda^4}\mathcal{O}_i^{(8)} + \cdots$$



- Wilson coefficients determined by minimizing

$$\chi^2(\text{PDF}, \text{SMEFT}) = \sum_{i,j=1}^{N_{\text{pt}}} (T_i - D_i)(\text{cov}^{-1})_{ij}\,(T_j - D_j)$$

$$T(c_{\text{EFT}}) = \text{PDF} \otimes \hat{\sigma}(c_{\text{EFT}})$$

Motivation for joint SMEFT-PDF fits

$$T(c_{\mathrm{EFT}}) \sim \mathrm{PDF}(c_{\mathrm{EFT}} = 0) \otimes \hat{\sigma}(c_{\mathrm{EFT}})$$

- SMEFT analyses may be biased using SM PDFs
  - NP may be absorbed by PDFs, and escape subsequent NP hunting.
  - a more and more relevant question as our measurements improve in accuracy

- Simultaneous determination of PDFs and SMEFT

$$T(\theta_{\mathrm{PDF}}, c_{\mathrm{EFT}}) = \mathrm{PDF}(\theta) \otimes \hat{\sigma}(c_{\mathrm{EFT}})$$

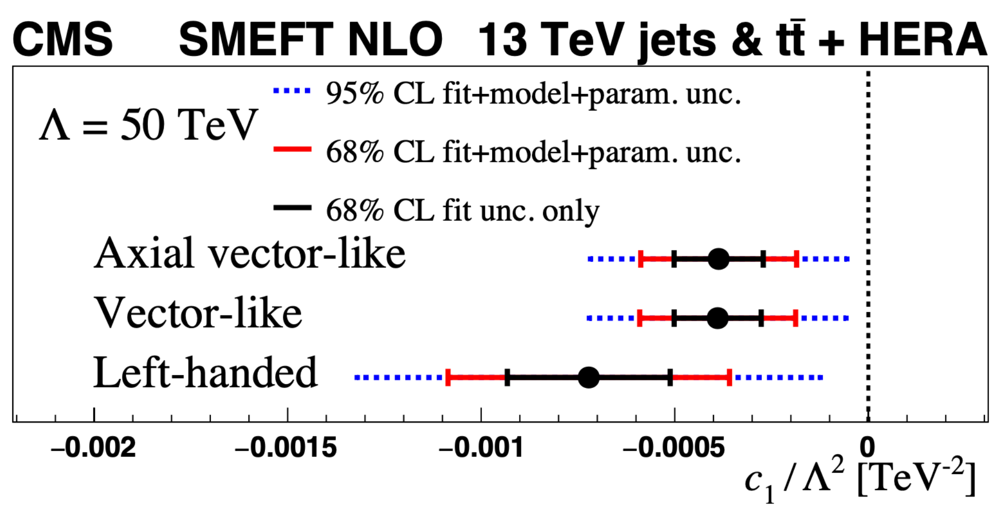
  - few studies by the PDF fitting groups: SIMUnet (NNPDF4.0), CT18

this work —> develop a new xFitter reaction for SMEFT-PDF fit

Fit in the xFitter framework

- xFitter is a powerful tool for
  - extracting PDFs
  - evaluating consistency between data and theory
  - performing inference on theoretical model parameters (m_t, α_s, $\theta_{\rm EW}$ etc.)

- EFT fits in the xFitter framework



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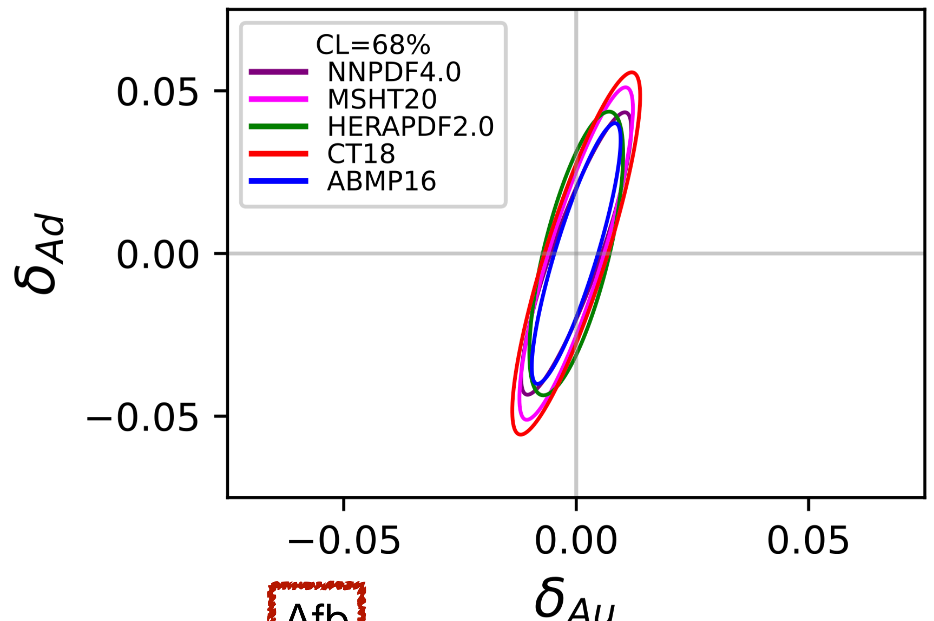


Afb [2310.19638]

Ingredients for PDF+SMEFT fit

- Global anaysis: various parameters and processes
  - flexible interface allowing us to parametrize the theory dependence on various **operators** for a wide variety of **processes**

- incorpolate EFT contribution by **fast grids** (APPLgrid, PineAPPL)
  - ensure both the precision and the speed
  - incorporate full dependence of EFT corrections on PDFs

$$\sigma\left(c_{tG}=0\right) \equiv \sigma_{\mathrm{SM}}$$
$$\sigma\left(c_{tG}=-30/\mathrm{TeV}^2\right) = \sigma_{\mathrm{SM}} - 30 \cdot l_{c_{tG}} + 30^2 \cdot q_{c_{tG}}$$
$$\sigma\left(c_{tG}=40/\mathrm{TeV}^2\right) = \sigma_{\mathrm{SM}} + 40 \cdot l_{c_{tG}} + 40^2 \cdot q_{c_{tG}}$$

3 PineAPPL grids are generated to determine EFT corrections for the CtG parameter

quadratic dependence

Parameterization of EFT dependence

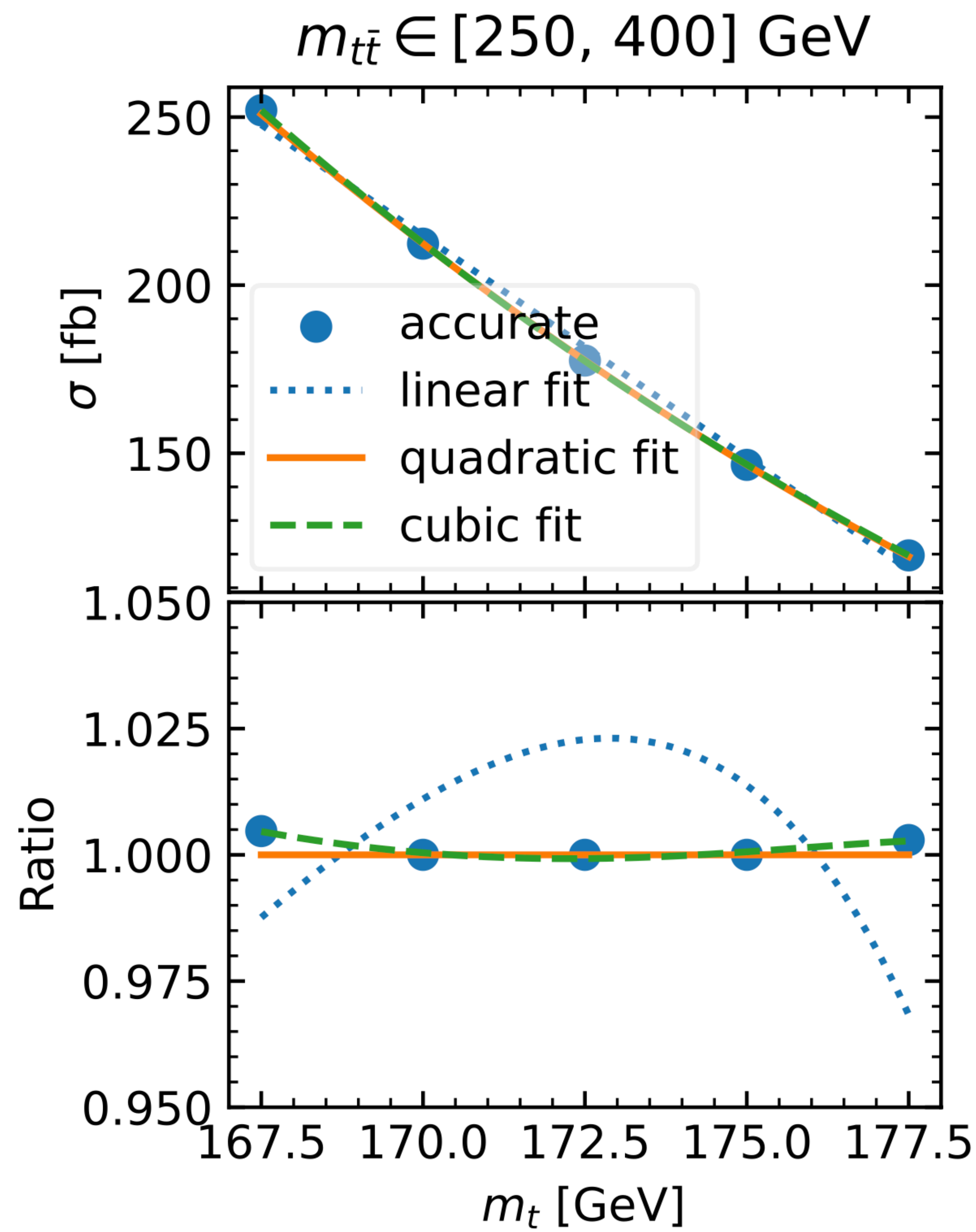
- quadratic polynomial dependence

$$\sigma^{(\alpha)}(\boldsymbol{c}; \alpha_s, \mathrm{PDF}) \stackrel{?}{=} \sigma^{(\alpha)}_{\boldsymbol{c}=0} \times \left(1 + \sum_i c_i K_i^{(\alpha)} + \sum_{i \leqslant j} c_i c_j K_{ij}^{(\alpha)} \right)$$

Examples of parameters c:

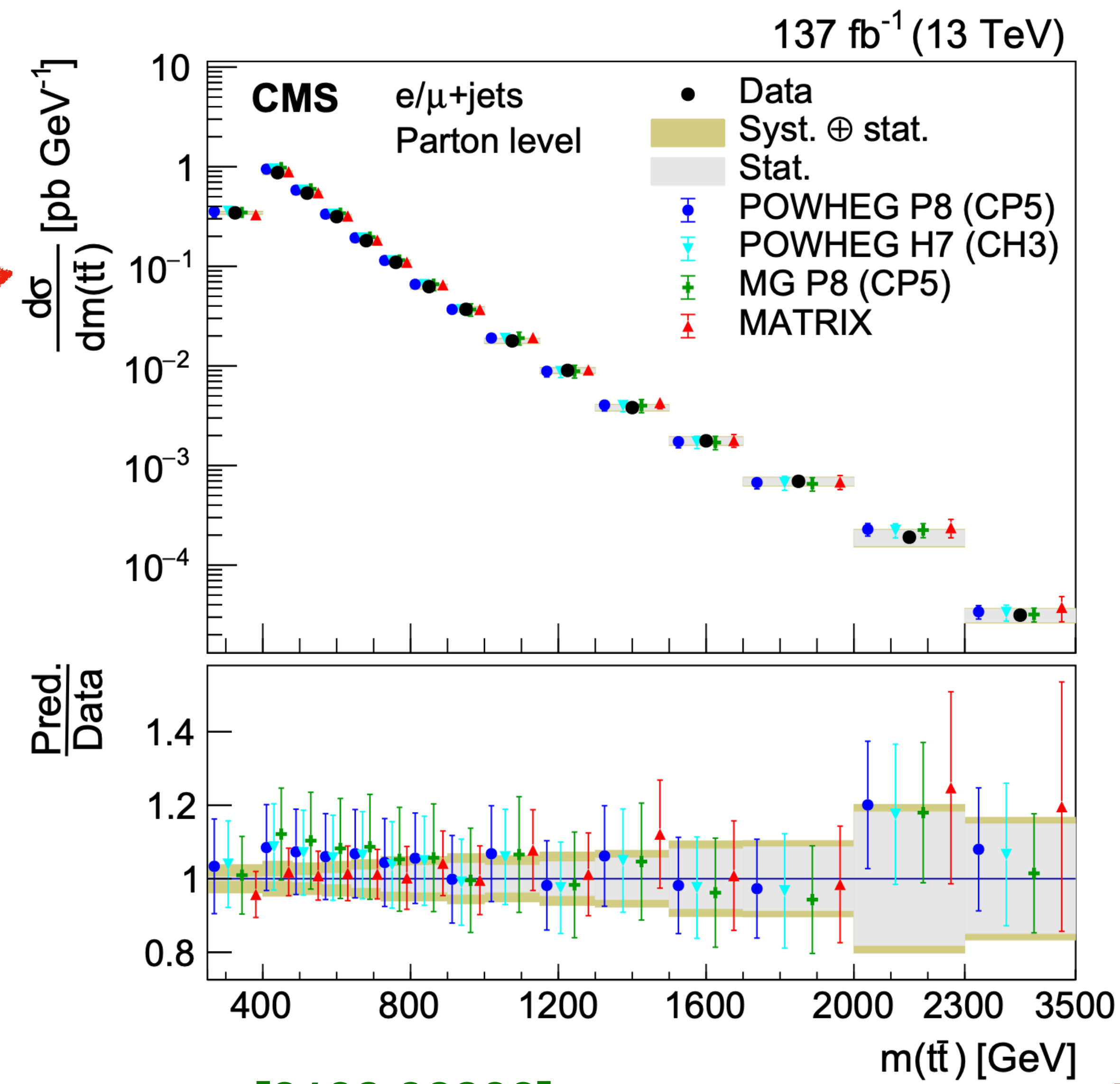
- SMEFT Wilson coefficient: c_i
- SM parameters: $\delta m_t \equiv m_t - 172.5\mathrm{GeV}$

- linear/quadratic BSM K factors
  - have to be firstly calculated outside xFitter EFT reaction



HL-LHC projection study

- illustrate the functionality of the EFT reaction
  - simultaneous determination of HERAPDF + m_t + SMEFT $xf(x) = Ax^B(1-x)^C(1+Dx+Ex^2)$
- HL-LHC projection of $m_{t\bar{t}}$
  - CMS measurement of $m_{t\bar{t}}$ at 13 TeV with rescaled uncertainties
- HERA-II combination of DIS
  - to properly determine PDFs



[2108.02803]

Theoretical predictions

- 4 representative dim-6 SMEFT operators

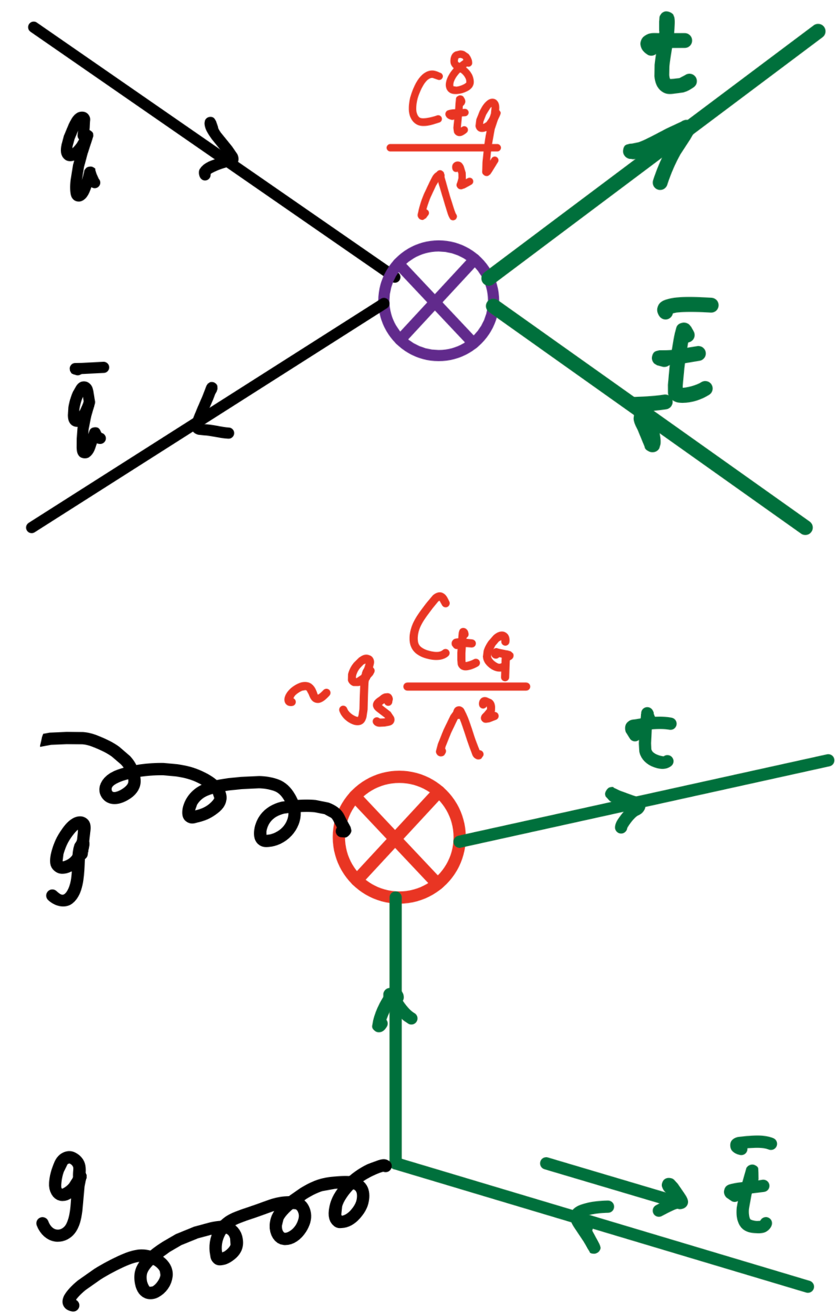
$$O_{tu}^{1} = \sum_{i=1}^{2} (\bar{t}\,\gamma_\mu\, t_R)\,(\bar{u}_{Ri}\,\gamma^\mu\, u_i)$$

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

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

$$O_{tG} = i\, g_s\, (\bar{Q}\,\tau^{\mu\nu}\, T_A\, t)\,\tilde{\varphi}\, G_{\mu\nu}^{A} + \text{h.c.}$$

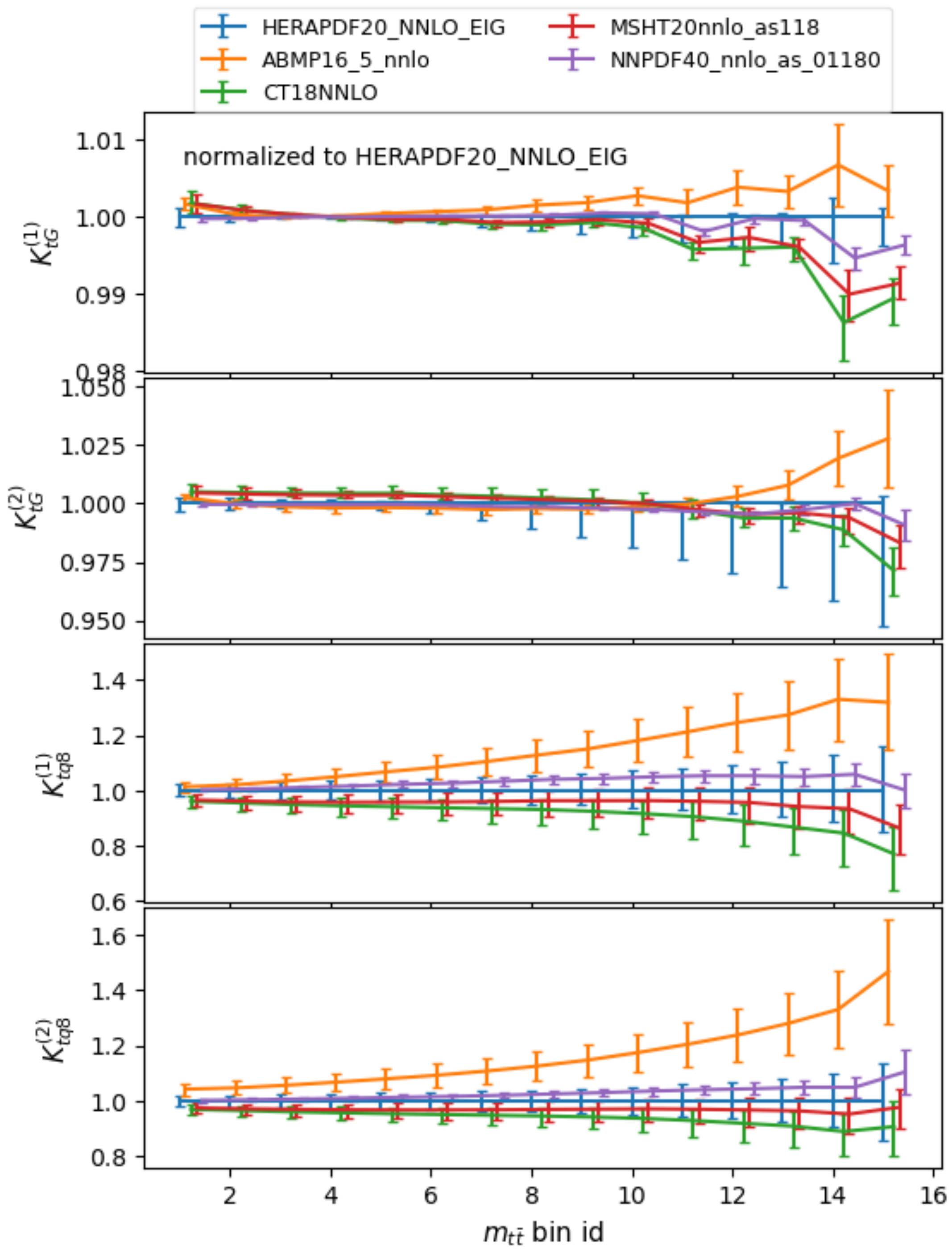
- EFT contributions to m_{tt} calculated at NLO QCD
  - MG5_aMC@NLO + SMEFT@NLO + PineAPPL
  - quadratic dependence and BSM K factors



$$\sigma = \sigma_{\text{SM}} \times (1 + K_{\text{tq8}}^{(1)} c_{\text{tq8}} + K_{\text{tq8}}^{(2)} c_{\text{tq8}}^{2} + K_{\text{tG}}^{(1)} c_{\text{tG}} + \cdots)$$

PDF dependence of EFT contributions

$$\sigma(c_{\mathrm{tq8}}, c_{\mathrm{tG}}) = \sigma_{\mathrm{SM}} \times (1 + K^{(1)}_{\mathrm{tq8}} c_{\mathrm{tq8}} + K^{(2)}_{\mathrm{tq8}} c^2_{\mathrm{tq8}} + K^{(1)}_{\mathrm{tG}} c_{\mathrm{tG}} + \cdots)$$



- BSM K factors for linear/quadratic dependence on EFT operators are often assumed to **independent** of PDFs
  - PDF dependence of EFT contribution is typically small
  - can be as large as 10% for ABMP and HERAPDF
  - motivates the use of grids instead of tabulated BSM K factors

Results

- pseudo data generated with non-zero SMEFT parameters
  - The fit can retrieve injected values within quoted fit uncertainties

	m_t [GeV]	c_{tG} [TeV^{-2}]	$c_{tq}^{(8)}$ [TeV^{-2}]	$c_{tu}^{(1)}$ [TeV^{-2}]	$c_{td}^{(1)}$ [TeV^{-2}]
generated	172.5	-0.1	1.0	0	0
SMEFT-SMEFT (full)	172.50 ± 0.37	-0.11 ± 0.08	1.00 ± 0.25	-0.01 ± 0.37	0.01 ± 1.14
SMEFT-SMEFT (linear)	172.47 ± 0.36	-0.07 ± 0.39	0.35 ± 12.22	-0.35 ± 3.46	8.36 ± 53.34
SMEFT-SM	172.83 ± 0.23	-	-	-	-
fixed-PDF SMEFT	172.41 ± 0.35	-0.14 ± 0.08	0.93 ± 0.50	-0.01 ± 1.05	-0.09 ± 1.69

- The Wilson coefficients are not well constrained if **only linear** EFT corrections are included in the fit.

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

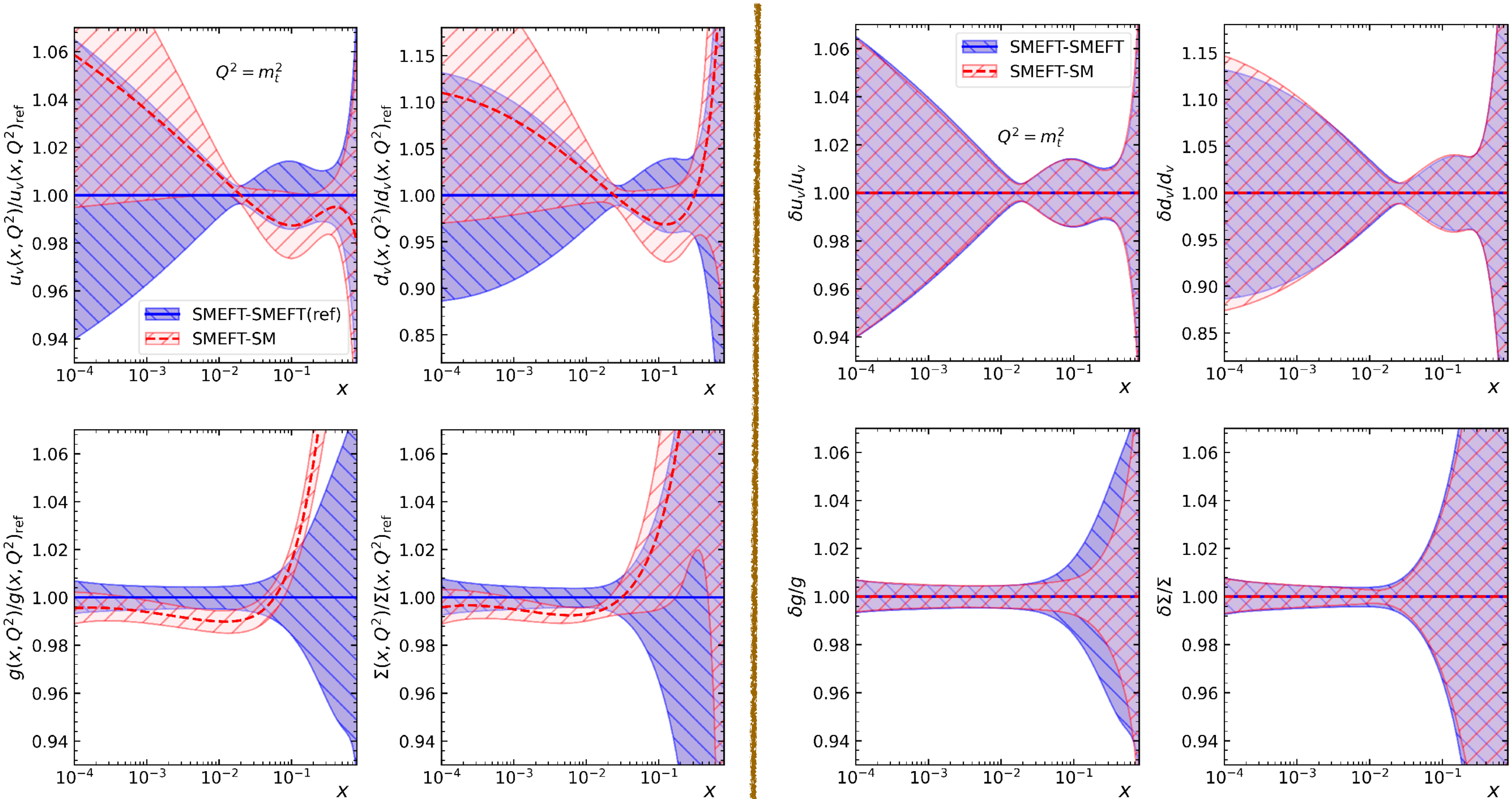
$$O_{td}^1 = \sum_{i=1}^{3} (\bar{t}\,\gamma^\mu\, t)\,(\bar{d}_{Ri}\,\gamma_\mu\, d_i)$$

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

$$O_{tG} = i\, g_s\,(\bar{Q}\,\tau^{\mu\nu}\, T_A\, t)\,\tilde{\varphi}\, G_{\mu\nu}^A + \text{h.c.}$$

PDF uncertainties and biases

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



Summary

- joint SMEFT+PDF fits are more self-consistent
  - simultaneous determination of PDFs and SMEFT may become more relevant as our measurements improve in accuracy
  - SMEFT analyses may be biased if SM PDFs are used

- a new xFitter EFT reaction is developed
  - designed for **SMEFT+PDF** fit
  - also suitable for fitting **SM/SMEFT** parameters with **fixed PDFs**
  - **quadratic polynomial** (+ limited support for **higher power corrections**)
  - include BSM K factors via **fast grids** or **tabulated cross-sections**

backup

Install the EFT reaction

- Download the source
  - https://gitlab.cern.ch/fitters/xfitter/-/tree/reaction-smeft/reactions/EFT

- and then recompile xFitter

appending a new line **`add_subdirectory(reactions/EFT)`** to **`/path_to_xfitter/xfitter_master/CMakeLists.txt`** ;
recompiling xFitter by executing

```
cd /path_to_xfitter
source setup.sh
cd xfitter_master
./make.sh install .
```

Main arguments of the EFT reaction

```
TermName   = 'SMNNLO',    'KEFT'
TermSource = 'PineAPPL', 'EFT'
TermInfo   =
  'GridName=/path/to/PineAPPL_grid.pineappl',
  'ListEFTParam=deltamt,ctg,ctq8:FileName=/path/to/EFT_file.yaml
:xiF=1.0:xiR=1.0'
TheorExpr  = 'SMNNLO*KEFT'
```

- mandatory arguments
  - FileName: 10 linear + 10 quadratic + 45 mixed terms for 10 parameters
  - ListEFTParam

- controlling the reaction output

AbsOutput	**NoCentral**	reaction output
False	False	$\sigma(\mathbf{c})/\sigma(\mathbf{c}=0)$
False	True	$\sigma(\mathbf{c})/\sigma(\mathbf{c}=0) - 1$
True	False	$\sigma(\mathbf{c})$
True	True	$\sigma(\mathbf{c}) - \sigma(\mathbf{c}=0)$

EFT YAML file for fitting one EFT parameter

```yaml
# The EFT YAML file for fitting ctg
SM_NLO: # name of the entry is almost arbitrary
  type: C # Central predictions (sigma_0 in Eq.(A1))
  format: PineAPPL # xsec are PineAPPL tables
  xsec: [ /path/to/SM_NLO.pineappl ]
Linear_ctg: # This starts a new entry
  type: L # predictions up to Linear corrections
  param: ctg # name of the parameter (in ListEFTParam)
  param_value: 20.0 # value of ctg used to generate the grid
  format: PineAPPL
  xsec: [ /path/to/ctg1.pineappl ] # SM_NLO + 20.0*l_ctg
Quadratic_ctg: # SM_NLO + 40.0*l_ctg + 40.0^2*q_ctg
  type: Q # predictions up to Quadratic corrections
  param: ctg
  param_value: 40.0
  format: PineAPPL
  xsec: [ /path/to/ctg2.pineappl ]
```

$$\sigma(c_{tG} = 0) \equiv \sigma_0$$

$$\sigma_{\text{lin.}}(c_{tG} = 20) = \sigma_0 + 20 \cdot l_{c_{tG}}$$

$$\sigma(c_{tG} = 40) = \sigma_0 + 40 \cdot l_{c_{tG}} + 40^2 \cdot q_{c_{tG}}$$

Types of the entries

$$\begin{aligned}\sigma^{(\alpha)}(\boldsymbol{c};\alpha_s,\mathrm{PDF}) &= \sigma_0^{(\alpha)} + \sum_i c_i\,\sigma_i^{(\alpha)} + \sum_{i\leqslant j} c_i\,c_j\,\sigma_{ij}^{(\alpha)} \\ &= \sigma_0^{(\alpha)}\left(1 + \sum_i c_i\,K_i^{(\alpha)} + \sum_{i\leqslant j} c_i\,c_j\,K_{ij}^{(\alpha)}\right)\end{aligned}$$

type	param	param_value	xsec
C	-	-	σ_0
l	i	-	$l_i \equiv \sigma_i$
q	i	-	$q_i \equiv \sigma_{ii}$
m	$[i, j]$	-	$m_{ij} \equiv \sigma_{ij}$
L	i	c_i	$\sigma_0 + c_i\sigma_i$
Q	i	c_i	$\sigma_0 + c_i l_i + c_i^2 q_i$
M	$[i, j]$	$[c_i, c_j]$	$\sigma_0 + c_i l_i + c_j l_j + c_i^2 q_i + c_j^2 q_j + c_i c_j m_{ij}$

Format of entires

- format=
  - PineAPPL, APPLgrid
  - xsection (xsec for each bin)
  - ratio (K factors for each bin)

```
ctg_ctq8: # theoretical predictions for ctg=20, ctq8=40
  type: M # include the Mixing between ctg and ctq8
  param: [ctg, ctq8] # both ctg and ctq8 are non-zero
  param_value: [20.0, 40.0] # ctg=20, ctq8=40
  format: PineAPPL
  xsec: [ /path/to/ctg_ctq8.pineappl ]
Kfactor_mt_linear: # l_deltamt / Central
  type: l
  param: deltamt
  format: ratio # xsec is an array of ratios
  xsec: [-0.10349132, -0.02400355, -0.01317847, ... ]
```

- using other xFitter reactions instead?
  - PineAPPL, APPLgrid
  - KFactor

Including higher power corrections via monomials

$$\sigma^{(\alpha)}(\boldsymbol{c};\alpha_s,\mathrm{PDF}) = \sigma_0^{(\alpha)} + \sum_i c_i\,\sigma_i^{(\alpha)} + \sum_{i\leqslant j} c_i\,c_j\,\sigma_{ij}^{(\alpha)}$$

$$= \sigma_0^{(\alpha)}\left(1 + \sum_i c_i\,K_i^{(\alpha)} + \sum_{i\leqslant j} c_i\,c_j\,K_{ij}^{(\alpha)}\right)$$

```yaml
mt_cubic: # contribution proportional to deltamt^3
  type: monomial
  format: ratio
  param: [deltamt]
  power: [3]
  xsec:  [0.0001, ...]
mt3_ctg: # contribution proportional to deltamt^3 * ctg
  type: monomial
  format: ratio
  param: [deltamt, ctg]
  power: [3, 1]
  xsec:  [0.0002, ...]
```