A global interpretation of particle physics data in the SMEFT

SMEFiT

Juan Rojo
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Theory Group Seminar

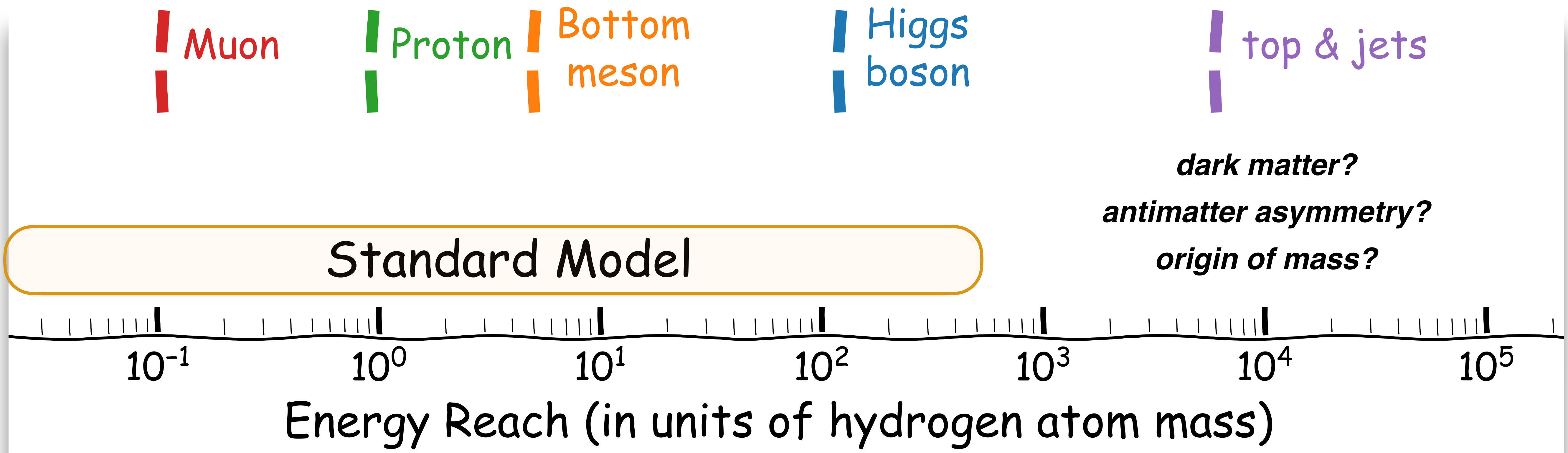
IFAE, UAB, 4/3/2022

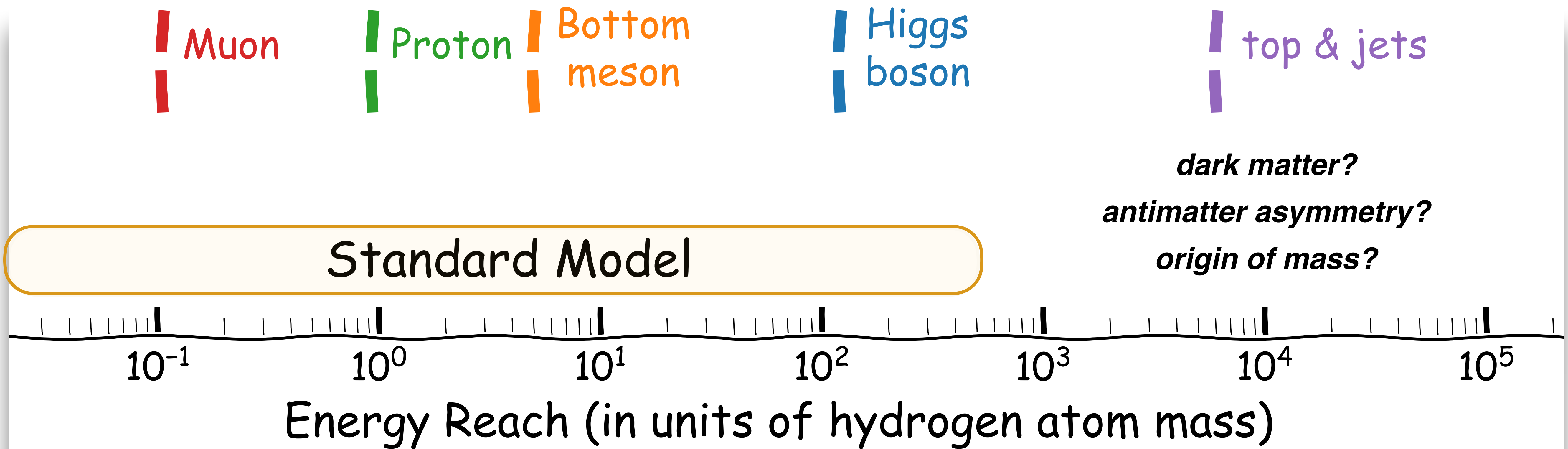
Outline

- The Standard Model as an Effective Field Theory
- Combined SMEFT analysis of Higgs, diboson, and top quark data
- Parton Distributions in the SMEFT
- Statistically optimal observables with ML & Bounds on BSM models

SMEFiT

SMEFT: the new Standard Model


Muon
Proton
Bottom meson
Higgs boson
top & jets
dark matter?
antimatter asymmetry?
origin of mass?
Standard Model
10^-1
10^0
10^1
10^2
10^3
10^4
10^5
Energy Reach (in units of hydrogen atom mass)



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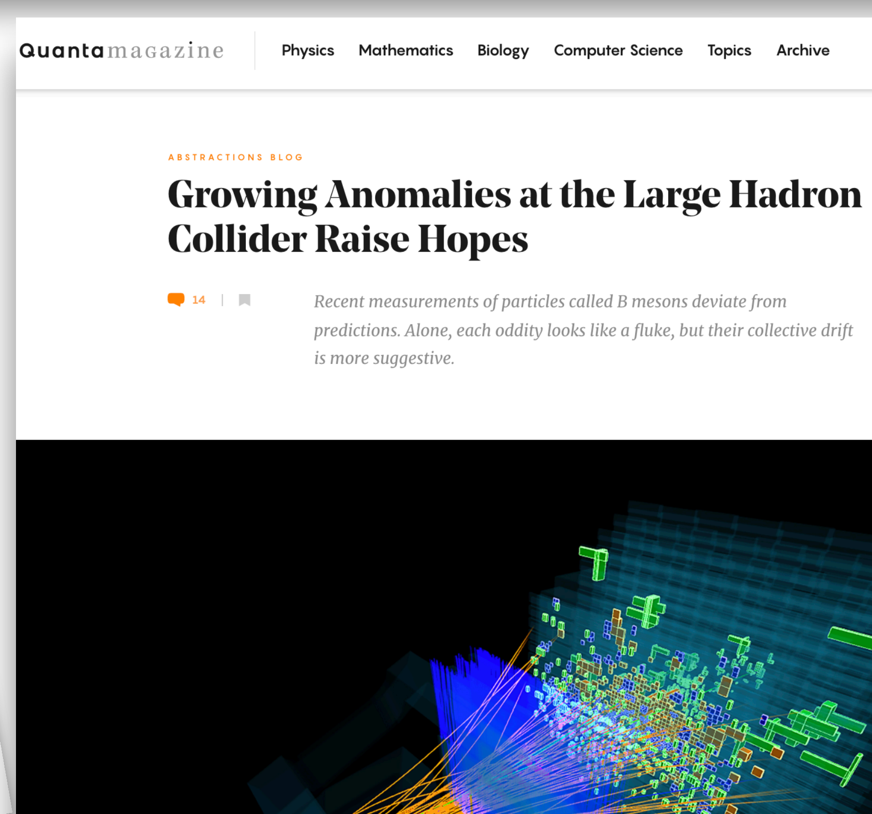
NIEUWS

Natuurkundigen van Cern vinden aanwijzing die ons begrip van de werkelijkheid op zijn kop kan zetten

different interactions of electrons and muons !

George van Hal 23 maart 2021, 09:00



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ABSTRACTIONS BLOG

Growing Anomalies at the Large Hadron Collider Raise Hopes

14

Recent measurements of particles called B mesons deviate from predictions. Alone, each oddity looks like a fluke, but their collective drift is more suggestive.

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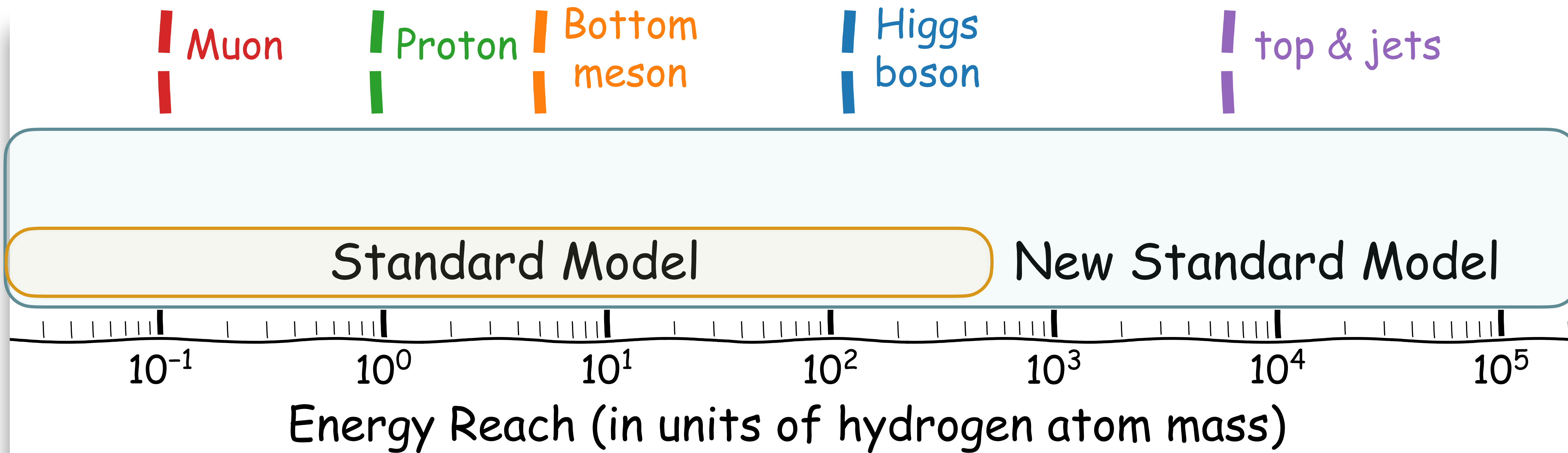


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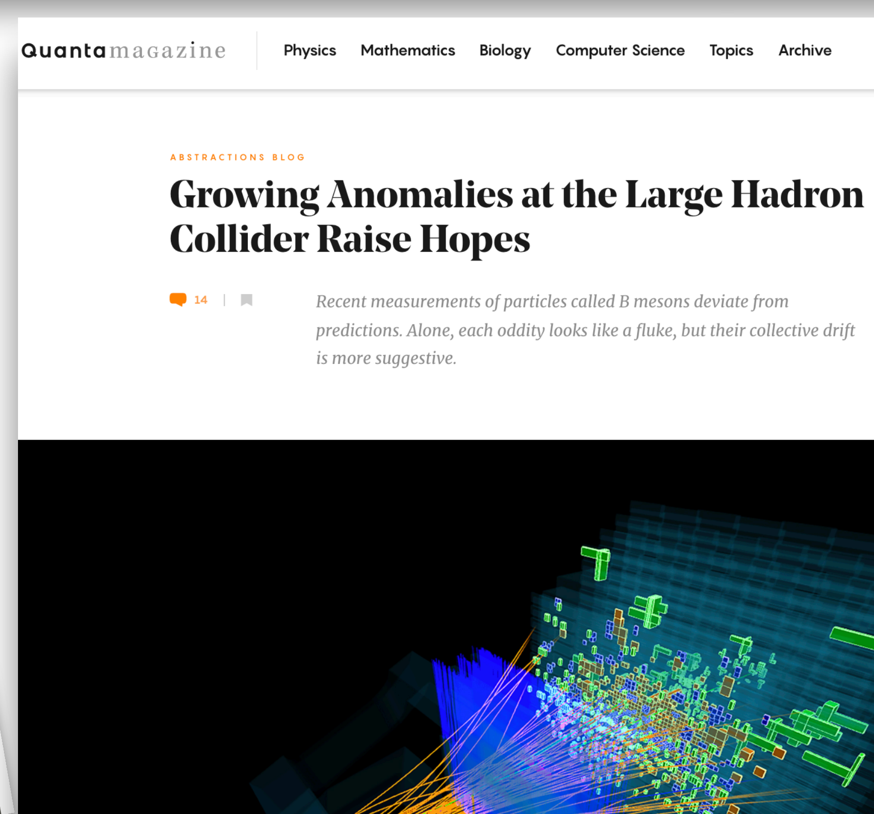
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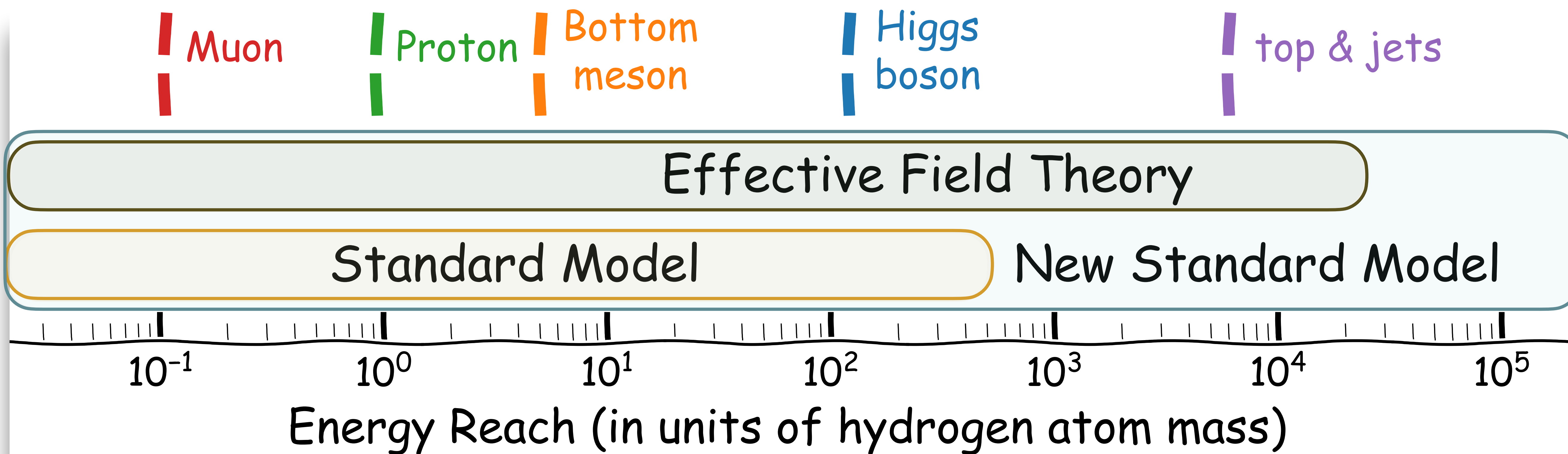


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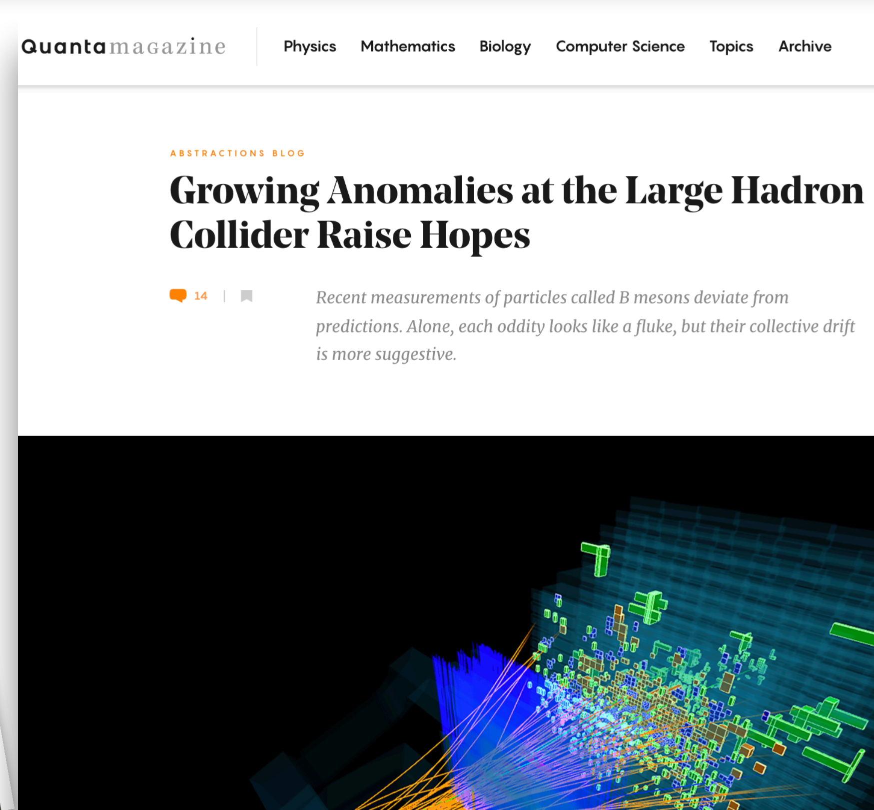
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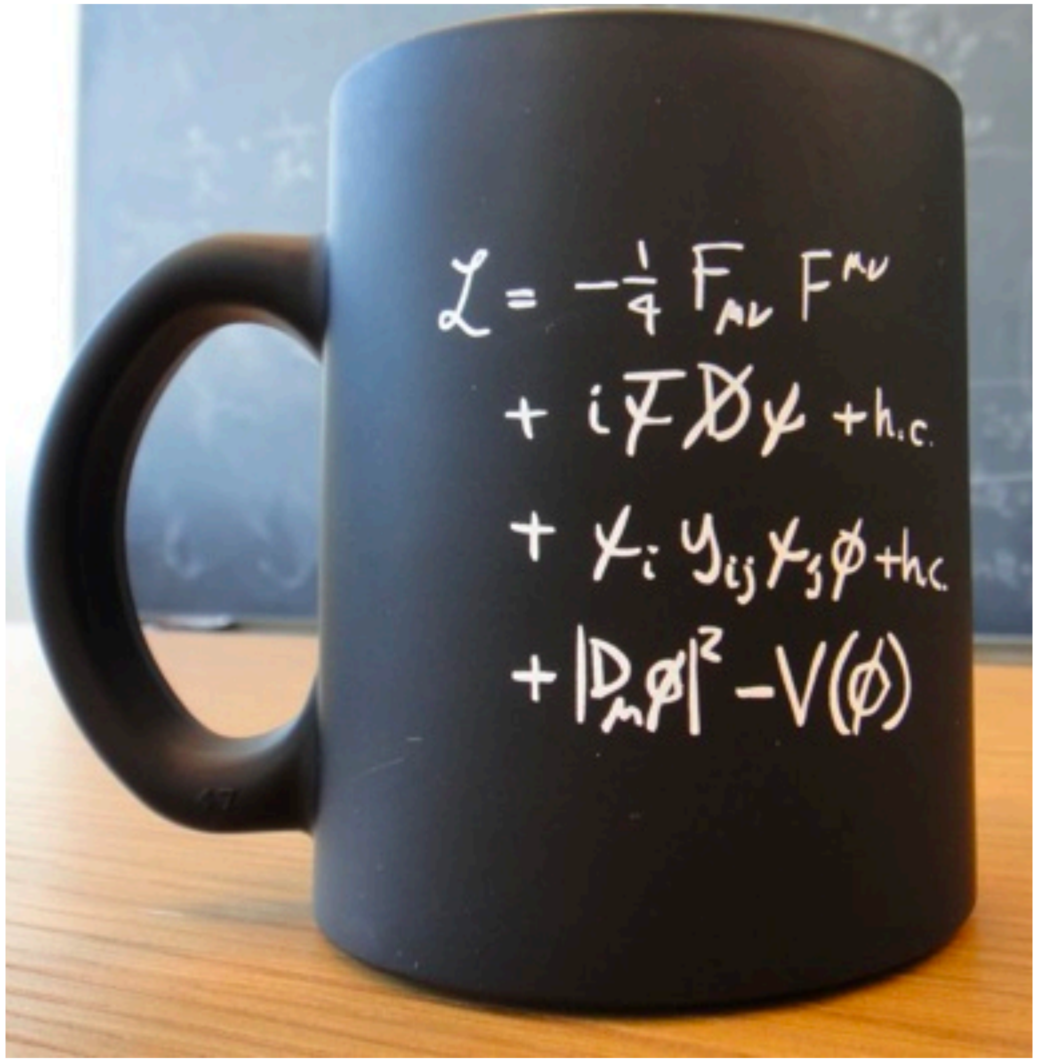
The Standard Model

The Standard Model is defined by:

- **Particle (matter) content**: quarks and leptons
- **Gauge** (local) symmetries and their eventual breaking mechanisms
- **Lorentz** invariance and other global symmetries
- Linearly realized SU(2)L EWSB
- Renormalizablity: validity up to **arbitrarily high scales**



$$\mathscr{L}_{\rm SM} = \sum_i c_i \mathscr{O}_i^{(d=4)}$$

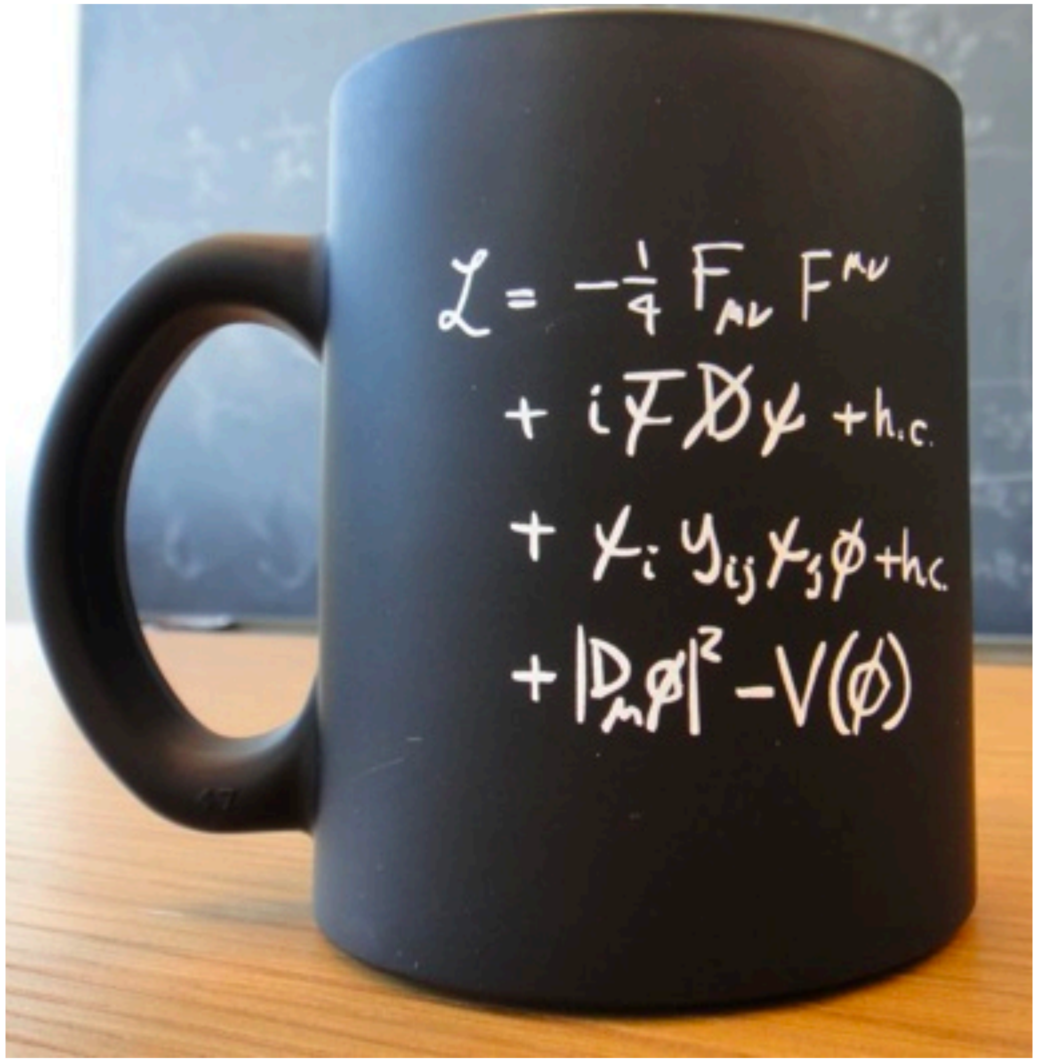
dimensionless couplings (before EWS breaking)

All possible operators of **mass-dimension <=4** consistent with above requirements

The Standard Model as an EFT

The Standard Model EFT is defined by:

- **Particle (matter) content**: quarks and leptons
- **Gauge** (local) symmetries and their eventual breaking mechanisms
- **Lorentz** invariance and other global symmetries
- Linearly-realized SU(2)_L EWSB
- **Validity only up to certain energy scale Λ**



$$\mathscr{L}_{\rm SMEFT} = \mathscr{L}_{\rm SM} + \sum_{i}^{N_{d6}} \frac{c_i}{\Lambda^2} \mathcal{O}_i^{(6)} + \sum_{j}^{N_{d8}} \frac{b_j}{\Lambda^2} \mathcal{O}_i^{(8)} + \dots$$

All possible operators of **mass-dimension 6** consistent with above requirements

All possible operators of **mass-dimension 8** consistent with above requirements

Why the SMEFT?

$$\mathscr{L}_{\rm SMEFT} = \mathscr{L}_{\rm SM} + \sum_i^{N_{d6}} \frac{c_i}{\Lambda^2}\mathcal{O}_i^{(6)} + \sum_j^{N_{d8}} \frac{b_j}{\Lambda^2}\mathcal{O}_i^{(8)} + \ldots$$

- ☑ **Low-energy limit** of generic UV-complete theories (with linearly realized EWSB)
- ☑ **Complete basis** at any given mass-dimension: systematic parametrisation of BSM effects
- ☑ **Fully renormalizable**, full-fledged QFT: compute higher orders in QCD and EW
- ☑ Matched to a large number of **BSM models** that reduce to the SM at low energies: exploits the full power of **SM measurements** for model-independent BSM searches
- ☑ Some operators induce **growth with the partonic centre-of-mass energy**: increased sensitivity in LHC cross-sections in the TeV region

$$\sigma(E) = \sigma_{\rm SM} \times (E)\left(1 + \sum_i^{N_{d6}} \omega_i \frac{c_i\, v^2}{\Lambda^2} + \sum_i^{N_{d6}} \widetilde{\omega}_i \frac{c_i\, E^2}{\Lambda^2} + \mathcal{O}\left(\Lambda^{-4}\right)\right)$$

related considerations apply to other EFTs with the SM as low-energy limits, such as HEFT

The Standard Model EFT

- The number of SMEFT operators is large: **59 non-redundant operators at dimension 6** for one fermion generation, **2499 operators** without any flavour assumption
- A global SMEFT analysis needs to explore a **huge complicated parameter space**

pure bosonic

X^3	
Q_G	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$
$Q_{\widetilde G}$	$f^{ABC} \widetilde G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$
Q_W	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$
$Q_{\widetilde W}$	$\varepsilon^{IJK} \widetilde W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$
φ^6	
Q_φ	$(\varphi^\dagger \varphi)^3$
$\varphi^4 D^2$	
$Q_{\varphi\Box}$	$(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$
$Q_{\varphi D}$	$(\varphi^\dagger D^\mu \varphi)^* (\varphi^\dagger D_\mu \varphi)$

$X^2\varphi^2$	
$Q_{\varphi G}$	$\varphi^\dagger \varphi G^A_{\mu\nu} G^{A\mu\nu}$
$Q_{\varphi B}$	$\varphi^\dagger \varphi B_{\mu\nu} B^{\mu\nu}$
$Q_{\varphi W}$	$\varphi^\dagger \varphi W^I_{\mu\nu} W^{I\mu\nu}$
$Q_{\varphi WB}$	$\varphi^\dagger \tau^I \varphi W^I_{\mu\nu} B^{\mu\nu}$
$Q_{\varphi\widetilde G}$	$\varphi^\dagger \varphi \widetilde G^A_{\mu\nu} G^{A\mu\nu}$
$Q_{\varphi\widetilde B}$	$\varphi^\dagger \varphi \widetilde B_{\mu\nu} B^{\mu\nu}$
$Q_{\varphi\widetilde W}$	$\varphi^\dagger \varphi \widetilde W^I_{\mu\nu} W^{I\mu\nu}$
$Q_{\varphi\widetilde W B}$	$\varphi^\dagger \tau^I \varphi \widetilde W^I_{\mu\nu} B^{\mu\nu}$

four-fermion operators

bosonic-fermionic

$(\bar L L)(\bar L L)$		$(\bar L L)(\bar R R)$	
$Q_{\ell\ell}$	$(\bar\ell\gamma_\mu\ell)(\bar\ell\gamma^\mu\ell)$	$Q_{\ell e}$	$(\bar\ell\gamma_\mu\ell)(\bar e\gamma^\mu e)$
$Q_{qq}^{(1)}$	$(\bar q\gamma_\mu q)(\bar q\gamma^\mu q)$	$Q_{\ell u}$	$(\bar\ell\gamma_\mu\ell)(\bar u\gamma^\mu u)$
$Q_{qq}^{(3)}$	$(\bar q\gamma_\mu\tau^I q)(\bar q\gamma^\mu\tau^I q)$	$Q_{\ell d}$	$(\bar\ell\gamma_\mu\ell)(\bar d\gamma^\mu d)$
$Q_{\ell q}^{(1)}$	$(\bar\ell\gamma_\mu\ell)(\bar q\gamma^\mu q)$	Q_{qe}	$(\bar q\gamma_\mu q)(\bar e\gamma^\mu e)$
$Q_{\ell q}^{(3)}$	$(\bar\ell\gamma_\mu\tau^I\ell)(\bar q\gamma^\mu\tau^I q)$	$Q_{qu}^{(1)}$	$(\bar q\gamma_\mu q)(\bar u\gamma^\mu u)$

$\psi^2\varphi^3$		$\psi^2\varphi^2 D$	
$Q_{u\varphi}$	$(\varphi^\dagger\varphi)(\bar q u\widetilde\varphi)$	$Q_{\varphi\ell}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar\ell\gamma^\mu\ell)$
$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar q d\varphi)$	$Q_{\varphi\ell}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}^I_\mu\varphi)(\bar\ell\tau^I\gamma^\mu\ell)$
$Q_{e\varphi}$	$(\varphi^\dagger\varphi)(\bar\ell e\varphi)$	$Q_{\varphi e}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar e\gamma^\mu e)$
$\psi^2 X\varphi$		$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar q\gamma^\mu q)$
Q_{eW}	$(\bar\ell\sigma^{\mu\nu}e)\tau^I\varphi W^I_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}^I_\mu\varphi)(\bar q\tau^I\gamma^\mu q)$
Q_{eB}	$(\bar\ell\sigma^{\mu\nu}e)\varphi B_{\mu\nu}$	$Q_{\varphi u}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar u\gamma^\mu u)$
Q_{uG}	$(\bar q\sigma^{\mu\nu}T^A u)\widetilde\varphi G^A_{\mu\nu}$	$Q_{\varphi d}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar d\gamma^\mu d)$
Q_{uW}	$(\bar q\sigma^{\mu\nu}u)\tau^I\widetilde\varphi W^I_{\mu\nu}$	$Q_{\varphi ud}$	$(\widetilde\varphi^\dagger iD_\mu\varphi)(\bar u\gamma^\mu d)$

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φ^6		$Q_{\varphi\widetilde G}$	$\varphi^\dagger\varphi\,\widetilde G^A_{\mu\nu}G^{A\mu\nu}$

pure bosonic

four-fermion operators

bosonic-fermionic

Fulfilling the potential of the SMEFT framework demands global analyses based on **a wide range of process** such that most (all?) **directions in the EFT parameter space** are covered

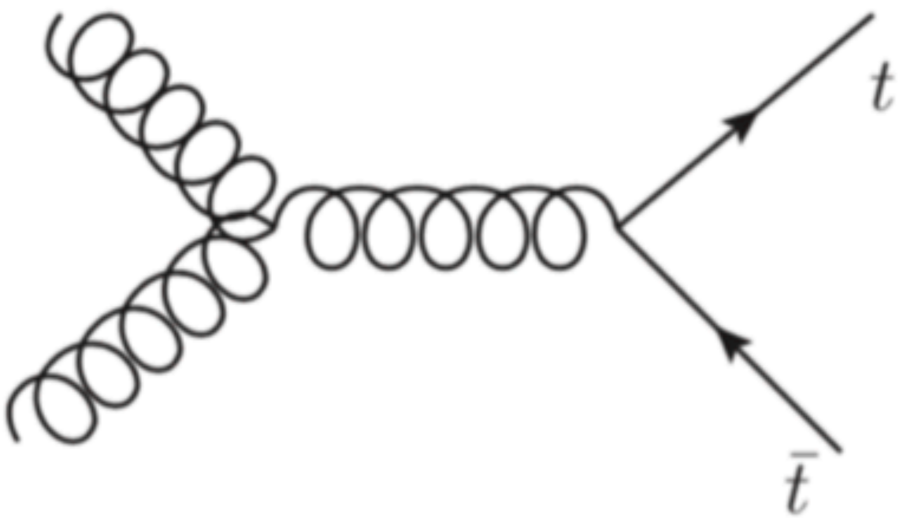
$Q_{\ell\ell}$	$(\bar\ell\gamma_\mu\ell)(\bar\ell\gamma^\mu\ell)$	$Q_{\ell e}$	$(\bar\ell\gamma_\mu\ell)(\bar e\gamma^\mu e)$
$Q_{qq}^{(1)}$	$(\bar q\gamma_\mu q)(\bar q\gamma^\mu q)$	$Q_{\ell u}$	$(\bar\ell\gamma_\mu\ell)(\bar u\gamma^\mu u)$
$Q_{qq}^{(3)}$	$(\bar q\gamma_\mu\tau^I q)(\bar q\gamma^\mu\tau^I q)$	$Q_{\ell d}$	$(\bar\ell\gamma_\mu\ell)(\bar d\gamma^\mu d)$
$Q_{\ell q}^{(1)}$	$(\bar\ell\gamma_\mu\ell)(\bar q\gamma^\mu q)$	Q_{qe}	$(\bar q\gamma_\mu q)(\bar e\gamma^\mu e)$
$Q_{\ell q}^{(3)}$	$(\bar\ell\gamma_\mu\tau^I\ell)(\bar q\gamma^\mu\tau^I q)$	$Q_{qu}^{(1)}$	$(\bar q\gamma_\mu q)(\bar u\gamma^\mu u)$

Q_{eW}	$(\bar\ell\sigma^{\mu\nu}e)\tau^I\varphi W^I_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}^I_\mu\varphi)(\bar q\tau^I\gamma^\mu q)$
Q_{eB}	$(\bar\ell\sigma^{\mu\nu}e)\varphi B_{\mu\nu}$	$Q_{\varphi u}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar u\gamma^\mu u)$
Q_{uG}	$(\bar q\sigma^{\mu\nu}T^A u)\widetilde\varphi G^A_{\mu\nu}$	$Q_{\varphi d}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar d\gamma^\mu d)$
Q_{uW}	$(\bar q\sigma^{\mu\nu}u)\tau^I\widetilde\varphi W^I_{\mu\nu}$	$Q_{\varphi ud}$	$(\widetilde\varphi^\dagger iD_\mu\varphi)(\bar u\gamma^\mu d)$

SMEFT effects in top quark pair production

Standard Model

$^{\ddagger}O_{uG}^{(ij)} = (\bar{q}_i \sigma^{\mu\nu} T^A u_j)\, \tilde{\varphi} G_{\mu\nu}^A\,,$



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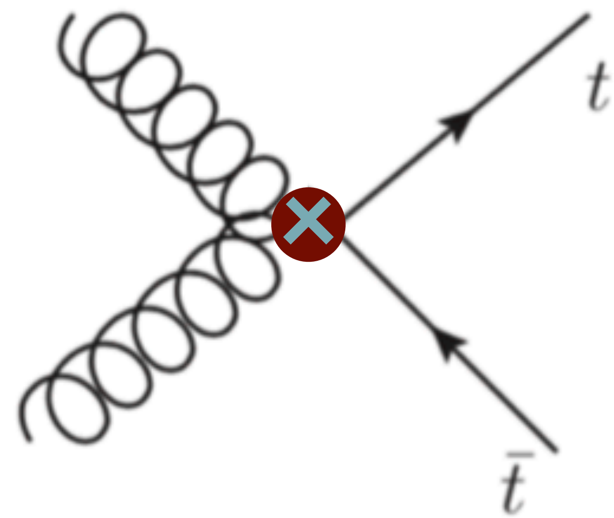


new interactions between SM fields

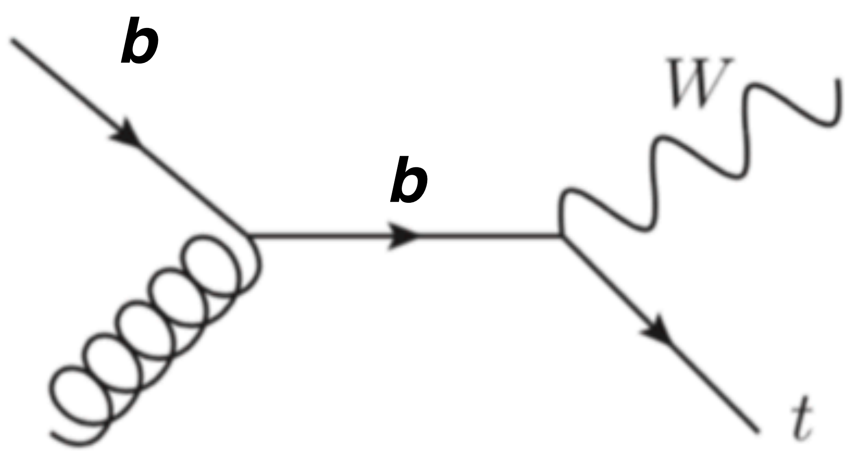
$$= \sigma_{SM} \times \left(1 + a\frac{c_{tG}}{\Lambda^2} + b\frac{c_{tG}^2}{\Lambda^4} \right)$$

SM: N(NLO) QCD **interference** **squared**

SMEFT effects in single top production

Standard Model

$$O_{uW}^{(ij)} = (\bar{q}_i \sigma^{\mu\nu} \tau^I u_j)\, \tilde{\varphi} W_{\mu\nu}^I$$



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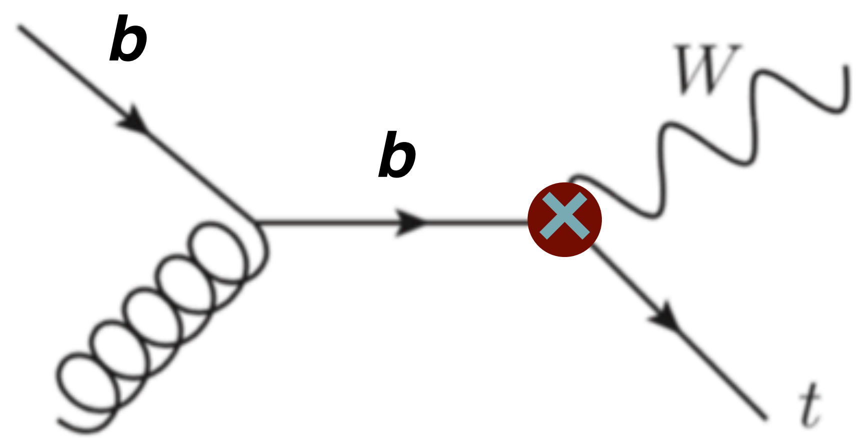
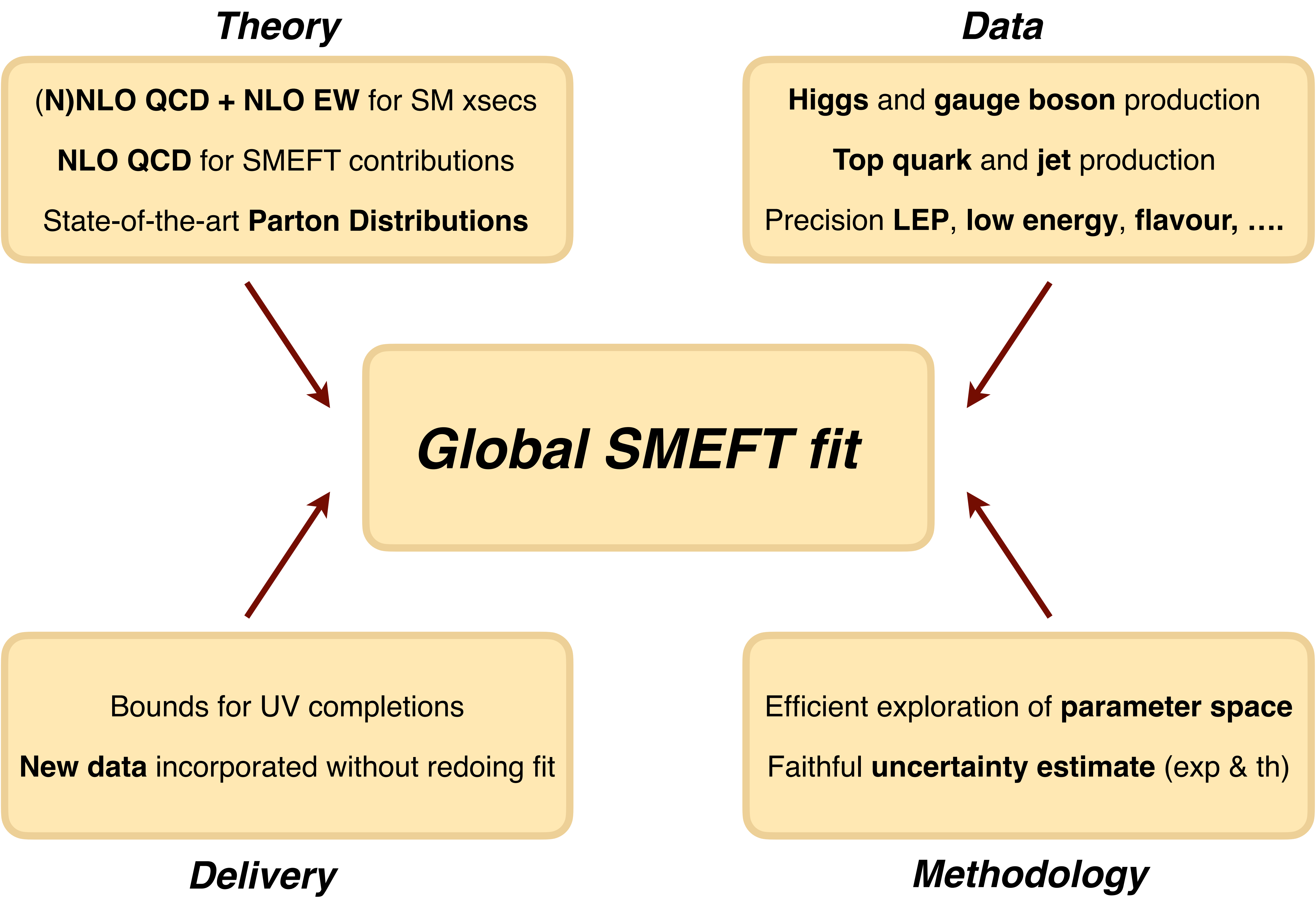


modifications of the SM interactions

$$= \sigma_{SM} \times \left(1 + a\frac{c_{tW}}{\Lambda^2} + b\frac{c_{tW}^2}{\Lambda^4}\right)$$

SM: N(NLO) QCD **interference** **squared**

Towards a global SMEFT analysis



A combined interpretation of Higgs and top quark data in the SMEFT

N. P. Hartland et al. ``A Monte Carlo global analysis of the Standard Model Effective Field Theory: the top quark sector,'' JHEP 04 (2019), 10 [arXiv:1901.05965 [hep-ph]].

J. J. Ethier et al. [SMEFiT Collaboration], ``Combined SMEFT interpretation of Higgs, diboson, and top quark data from the LHC,'' JHEP 11 (2021), 089, [arXiv:2105.00006 [hep-ph]].

The SMEFiT framework

Theory

(N)NLO QCD + NLO EW for SM xsecs

NLO QCD, both linear and quadratic terms, **with SMEFT@NLO**

State-of-the-art **parton distributions** (avoid double counting)

Data

Higgs data (signal strengths, diff, STXS), diboson LEP and LHC, all available **top quark data** from Runs I+II, VBS, more in progress

Full experimental **correlations** included

SMEFiT

Validation

Extensive **statistical toolbox** to validate results: information geometry, PCA, closure testing, …

Full **posterior probabilities** in the EFT coefficients available, likelihoods WIP

Methodology

Two independent fitting methods, **MCfit** and **NestedSampling** (no reliance on linear approx) cross-check each other

Modular structure facilitates adding new datasets of better theory calculations

Fitting methodology

MCfit generate a large sample of **Monte Carlo replicas** to construct the **probability distribution** in the space of experimental data accounting for all uncertainties

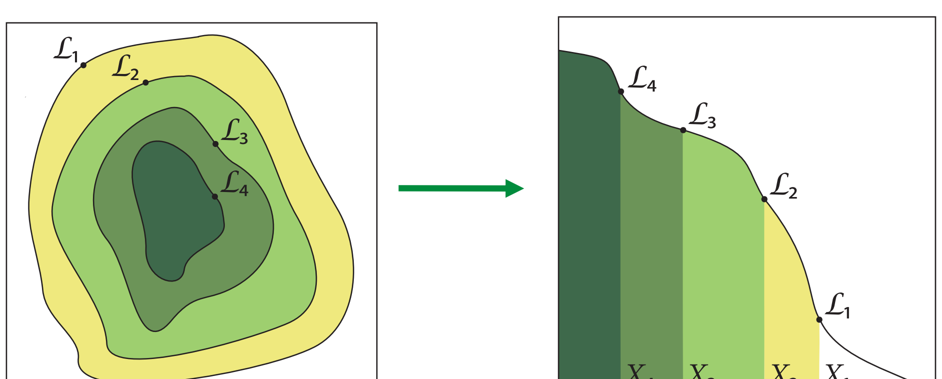
Determine the SMEFT coefficients **replica-by-replica** by minimising a cost function

$$E(\{c_l^{(k)}\}) \equiv \frac{1}{N_{\rm dat}} \sum_{i,j=1}^{N_{\rm dat}} \left(\mathcal{O}_i^{(\rm th)}\left(\{c_n^{(k)}\}\right) - \mathcal{O}_i^{({\rm art})(k)} \right) ({\rm cov}^{-1})_{ij} \left(\mathcal{O}_j^{(\rm th)}\left(\{c_n^{(k)}\}\right) - \mathcal{O}_j^{({\rm art})(k)} \right)$$

where covariance matrix includes **all sources of experimental + theory errors**

Nested Sampling statistical mapping of the *N*-dimensional likelihood profile to 1D

$$Z = \int d^N c \mathscr{L}\left({\rm data} \,|\, \vec{c}\right) \pi(\vec{c}) = \int_0^1 dX \mathscr{L}(X)$$



- Samples directly from prior space to locate **regions of maximum likelihood**
- Main advantage: **no need for optimiser** (fitting)
- Exponential increase in runtime as prior volume increases

Theory calculations in the SMEFT

from Lagrangian …

$$\mathscr{L}_{\text{SMEFT}} = \mathscr{L}_{\text{SM}} + \sum_{m=1}^{N_6} \frac{c_m}{\Lambda^2} \mathscr{O}_i^{(6)} + \sum_{n=1}^{N_8} \frac{b_j}{\Lambda^4} \mathscr{O}_i^{(8)} + \dots$$

SM **EFT$_{\text{d6}}$** **EFT$_{\text{d8}}$**

Theory calculations in the SMEFT

from Lagrangian …

$$\mathscr{L}_{\rm SMEFT} = \mathscr{L}_{\rm SM} + \sum_{m=1}^{N_6} \frac{c_m}{\Lambda^2}\mathcal{O}_i^{(6)} + \sum_{n=1}^{N_8} \frac{b_j}{\Lambda^4}\mathcal{O}_i^{(8)} + \ldots$$

SM **EFT$_{d6}$** **EFT$_{d8}$**

Linear EFT cross-sections: interference SM-EFT$_{d6}$

Quadratic EFT cross-sections: squares EFT$_{d6}$

to cross-sections ….

$$\sigma_{\rm SMEFT}\left(\boldsymbol{c},\boldsymbol{\Lambda}\right) \simeq \sigma_{\rm SM} \times \left(1 + \sum_{m=1}^{N_6} \frac{c_m}{\Lambda^2}\sigma_m^{(\rm eft)} + \sum_{m,n=1}^{N_6} \frac{c_m c_n}{\Lambda^4}\sigma_{m,n}^{(\rm eft)}\right)$$

evaluate at (N)NLO QCD + NLO EW

evaluate at NLO QCD with **SMEFT@NLO**

Theory calculations in the SMEFT

… to constraints on the EFT parameters

$$\chi^2(\boldsymbol{c}, \Lambda) = \frac{1}{n_{\rm dat}} \sum_{i,j=1}^{n_{\rm dat}} \left(\sigma_{\rm i,SMEFT}(\boldsymbol{c}, \Lambda) - \sigma_{\rm i,exp}\right) \left(\mathrm{cov}^{-1}\right)_{ij} \left(\sigma_{\rm j,SMEFT}(\boldsymbol{c}, \Lambda) - \sigma_{\rm j,exp}\right)$$

log-likelihood minimisation

Linear EFT cross-sections:

interference SM-EFT$_{\rm d6}$

Quadratic EFT cross-sections:

squares EFT$_{\rm d6}$

to cross-sections ….

$$\sigma_{\rm SMEFT}\left(\boldsymbol{c}, \boldsymbol{\Lambda}\right) \simeq \sigma_{\rm SM} \times \left(1 + \sum_{m=1}^{N_6} \frac{c_m}{\Lambda^2} \sigma_m^{\rm (eft)} + \sum_{m,n=1}^{N_6} \frac{c_m c_n}{\Lambda^4} \sigma_{m,n}^{\rm (eft)}\right)$$

evaluate at (N)NLO QCD + NLO EW

evaluate at NLO QCD

with **SMEFT@NLO**

The SMEFiT framework

SMEFiT

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OVERVIEW:

Features

Available Datasets

THEORY:

SMEFT

References

TALKS AND LECTURES:

Talks and seminars

IMPLEMENTATION:

Fitting strategies

Nested Sampling

MCFit

RESULTS:

SMEFiT Top

SMEFiT RW

SMEFiT VBS

SMEFiT2.0

Welcome to the SMEFiT website!

SMEFiT is a Python package for global analyses of particle physics data in the framework of the Standard Model Effective Field Theory (SMEFT). The SMEFT represents a powerful model-independent framework to constrain, identify, and parametrise potential deviations with respect to the predictions of the Standard Model (SM). A particularly attractive feature of the SMEFT is its capability to systematically correlate deviations from the SM between different processes. The full exploitation of the SMEFT potential for indirect New Physics searches from precision measurements requires combining the information provided by the broadest possible dataset, namely carrying out extensive global analysis which is the main purpose of SMEFiT.

Project description

The SMEFiT framework has been used in the following **scientific publications**:

- *A Monte Carlo global analysis of the Standard Model Effective Field Theory: the top quark sector*, N. P. Hartland, F. Maltoni, E. R. Nocera, J. Rojo, E. Slade, E. Vryonidou, C. Zhang [HMN+19].
- *Constraining the SMEFT with Bayesian reweighting*, S. van Beek, E. R. Nocera, J. Rojo, and E. Slade [vBNRS19].
- *SMEFT analysis of vector boson scattering and diboson data from the LHC Run II* , J. Ethier, R. Gomez-Ambrosio, G. Magni, J. Rojo [EGAMR21].
- *Combined SMEFT interpretation of Higgs, diboson, and top quark data from the LHC*, J. Ethier, F. Maltoni, L. Mantani, E. R. Nocera, J. Rojo, E. Slade, E. Vryonidou, C. Zhang [EMM+21] **arXiv:2105.00006**

Results from these publications, including driver and analysis scripts, are available in the **Results** section.

Team description

The **SMEFiT collaboration** is currently composed by the following members:

- Jaco ter Hoeve, *VU Amsterdam and Nikhef Theory Group*
- Giacomo Magni, *VU Amsterdam and Nikhef Theory Group*
- Fabio Maltoni, *Centre for Cosmology, Particle Physics and Phenomenology Louvain and University of Bologna*
- Luca Mantani, *Centre for Cosmology, Particle Physics and Phenomenology Louvain*
- Emanuele Roberto Nocera, *Higgs Center for Theoretical Physics, University of Edinburgh*
- Juan Rojo, *VU Amsterdam and Nikhef Theory Group*
- Eleni Vryonidou, *University of Manchester*

https://lhcfitnikhef.github.io/SMEFT/

Quantifying EFT sensitivity

Quantify impact in fit using **information geometry** (Fisher discriminant)

linear

$$I_{ij} = \sum_{m=1}^{n_{\rm dat}} \frac{\sigma_{m,i}^{(\rm eft)} \sigma_{m,j}^{(\rm eft)}}{\delta^2_{{\rm exp},m}}$$

n.b. operator normalisation is arbitrary, thus absolute values of Fisher unphysical

normalise to the sum over a given operator: relative Fisher is physical

quadratic

$$I_{ij} = {\rm E}\left[\sum_{m=1}^{n_{\rm dat}} \frac{1}{\delta^2_{{\rm exp},m}} \left(\sigma_{m,ij}\left(\sigma_m^{(\rm th)} - \sigma_m^{(\rm exp)}\right) + \left(\sigma_{m,i}^{(\rm eft)} + \sum_{l=1}^{n_{\rm op}} c_l \sigma_{m,il}^{(\rm eft)}\right)\left(\sigma_{m,j}^{(\rm eft)} + \sum_{l'=1}^{n_{\rm op}} c_{l'} \sigma_{m,jl'}\right)\right)\right]$$

Determine **most sensitive directions** and identify possible flat directions using Principal Component Analysis (PVA) & Singular Value Decomposition (SVD)

$$\sigma_m^{(\rm th)}(\boldsymbol{c}) = \sigma_m^{(\rm sm)} + \sum_{i=1}^{n_{\rm op}} c_i \sigma_{m,i}^{(\rm eft)}$$

$$K = UWV^\dagger$$

singular value decomposition

$$K_{mi} = \sigma_{m,i}^{(\rm eft)} / \delta_{\rm exp,m};$$

$$\mathrm{PC}_k = \sum_{i=1}^{n_{\rm op}} a_{ki} c_i \,, \quad k = 1, \ldots, n_{\rm op} \,, \qquad \left(\sum_{i=1}^{n_{\rm op}} a_{ki}^2 = 1 \;\; \forall k\right)$$

n.b. within our approach flat directions are not a problem, and can also be identified *a posteriori*

Operator basis and flavour assumptions

Class	$N_{\rm dof}$	Independent DOFs	DoF in EWPOs
four-quark (two-light-two-heavy)	14	$c_{Qq}^{1,8}$, $c_{Qq}^{1,1}$, $c_{Qq}^{3,8}$, $c_{Qq}^{3,1}$, c_{tq}^{8}, c_{tq}^{1}, c_{tu}^{8}, c_{tu}^{1}, c_{Qu}^{8}, c_{Qu}^{1}, c_{td}^{8}, c_{td}^{1}, c_{Qd}^{8}, c_{Qd}^{1}	
four-quark (four-heavy)	5	c_{QQ}^{1}, c_{QQ}^{8}, c_{Qt}^{1}, c_{Qt}^{8}, c_{tt}^{1}	
four-lepton	1		$c_{\ell\ell}$
two-fermion (+ bosonic fields)	23	$c_{t\varphi}$, c_{tG}, $c_{b\varphi}$, $c_{c\varphi}$, $c_{\tau\varphi}$, c_{tW}, c_{tZ}, $c_{\varphi Q}^{(3)}$, $c_{\varphi Q}^{(-)}$, $c_{\varphi t}$	$c_{\varphi\ell_1}^{(1)}$, $c_{\varphi\ell_1}^{(3)}$, $c_{\varphi\ell_2}^{(1)}$, $c_{\varphi\ell_2}^{(3)}$, $c_{\varphi\ell_3}^{(1)}$, $c_{\varphi\ell_3}^{(3)}$, $c_{\varphi e}$, $c_{\varphi\mu}$, $c_{\varphi\tau}$, $c_{\varphi q}^{(3)}$, $c_{\varphi q}^{(-)}$, $c_{\varphi u}$, $c_{\varphi d}$
Purely bosonic	7	$c_{\varphi G}$, $c_{\varphi B}$, $c_{\varphi W}$, $c_{\varphi d}$, c_{WWW}	$c_{\varphi WB}$, $c_{\varphi D}$
Total	50 (36 independent)	34	16 (2 independent)

- **Dim-6 SMEFT operators** modifying Higgs, dibosons, and top quark properties: **36** (14) **independent** (dependent) **DoFs**
- Flavour assumption is **MFV**, with $\mathrm{U}(2)_q \times \mathrm{U}(2)_u \times \mathrm{U}(3)_d$ in quark sector (special role for top quark) and $\left(\mathrm{U}(1)_\ell \times \mathrm{U}(1)_e\right)^3$ in lepton sector
- Constraints from **LEP EWPOs** imposed via restrictions in parameter space

$$\begin{pmatrix} c_{\varphi\ell_i}^{(3)} \\ c_{\varphi\ell_i}^{(1)} \\ c_{\varphi e/\mu/\tau} \\ c_{\varphi q}^{(-)} \\ c_{\varphi q}^{(3)} \\ c_{\varphi u} \\ c_{\varphi d} \\ c_{\ell\ell} \end{pmatrix} = \begin{pmatrix} -\frac{1}{t_W} & -\frac{1}{4t_W^2} \\ 0 & -\frac{1}{4} \\ 0 & -\frac{1}{2} \\ \frac{1}{t_W} & \frac{1}{4s_W^2}-\frac{1}{6} \\ -\frac{1}{t_W} & -\frac{1}{4t_W^2} \\ 0 & \frac{1}{3} \\ 0 & -\frac{1}{6} \\ 0 & 0 \end{pmatrix} \begin{pmatrix} c_{\varphi WB} \\ c_{\varphi D} \end{pmatrix}$$

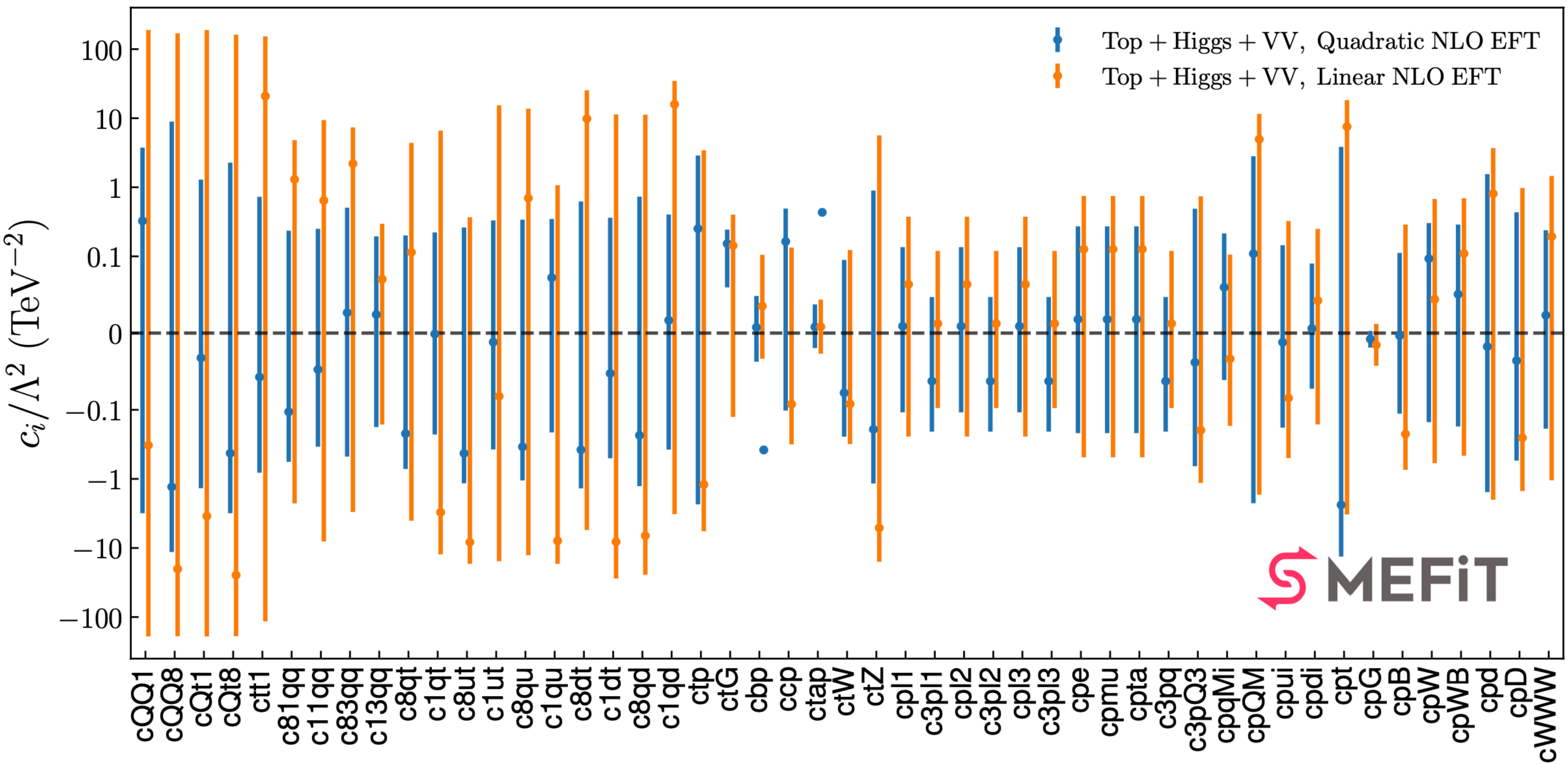
Experimental data

Category	Processes	n_{dat}
Top quark production	$t\bar{t}$ (inclusive) **(incl LHC charge asy)**	94
	$t\bar{t}Z$, $t\bar{t}W$ **(incl ptZ in ttZ)**	14
	single top (inclusive)	27
	tZ, tW	9
	$t\bar{t}t\bar{t}$, $t\bar{t}b\bar{b}$	6
	Total	**150**
Higgs production and decay	Run I signal strengths	22
	Run II signal strengths	40
	Run II, differential distributions & STXS	35
	Total	**97**
Diboson production	LEP-2 **(WW)**	40
	LHC **(WW & WZ)**	30
	Total	**70**
Baseline dataset	**Total**	**317**

+ systematic assessment of fit results **wrt dataset variations**:

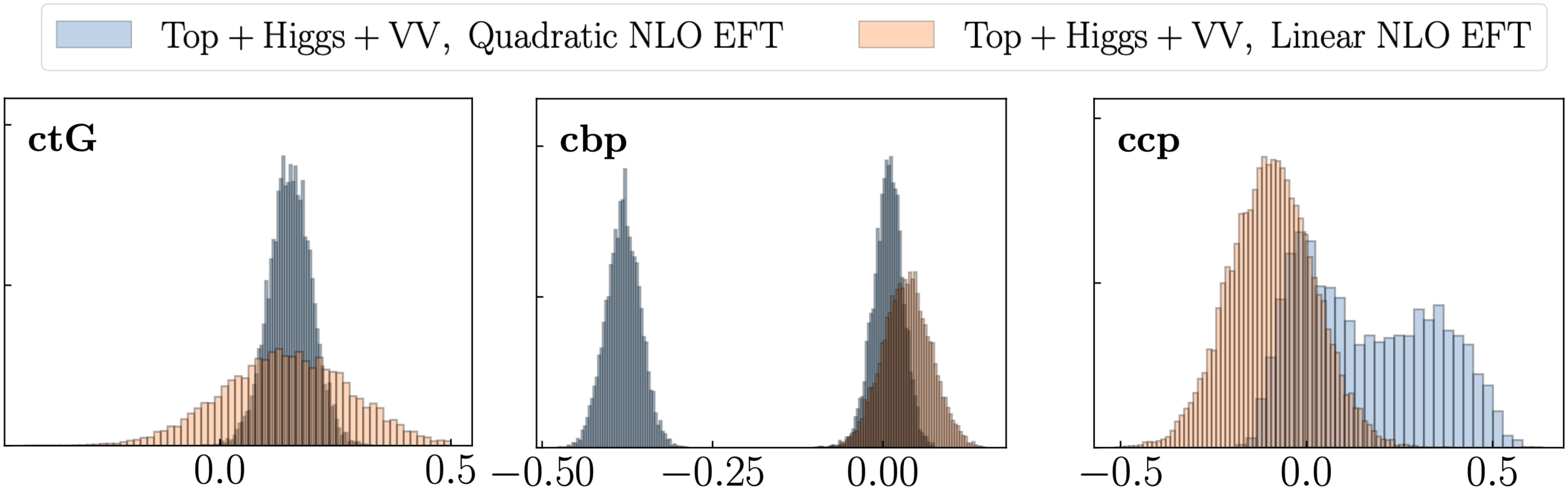
Higgs-only fit, top-only fit, no high-E data, no diboson data …

Results: global fit



- Agreement with SM at 95% CL for all EFT coefficients except for **ctG** in quadratic fit
- Quadratic corrections bring in sensitivity (more stringent bounds) *e.g.* for four-fermion operators
- Some DoFs exhibit a second ``BSM-like” solution in the quartic fit

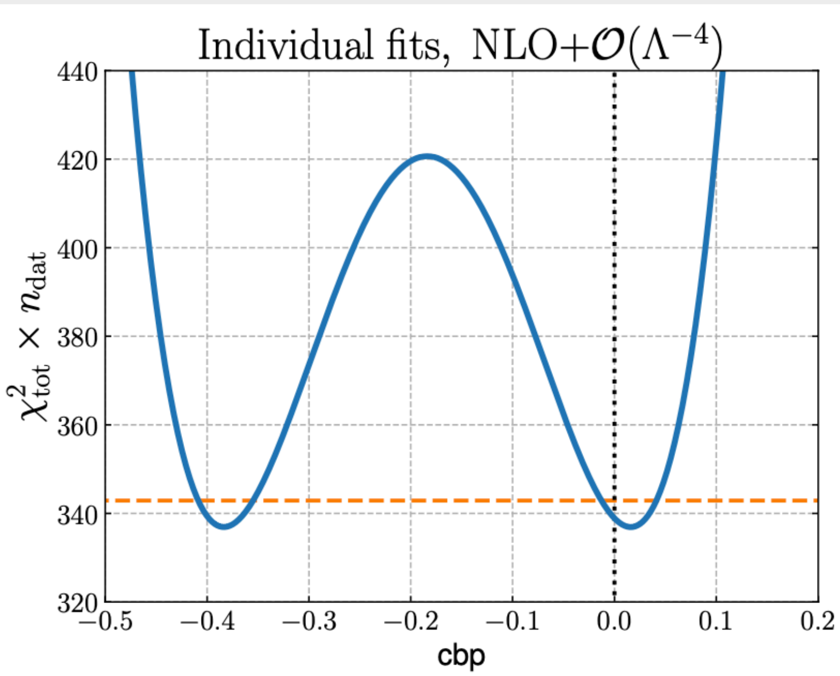
Results: global fit

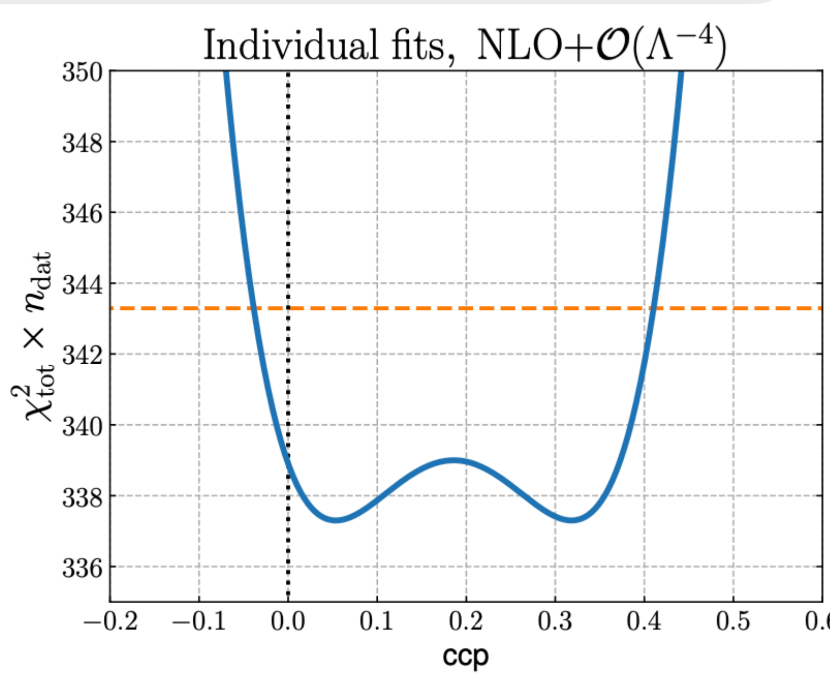


chromo-magnetic operator ***bottom Yukawa*** ***charm Yukawa***

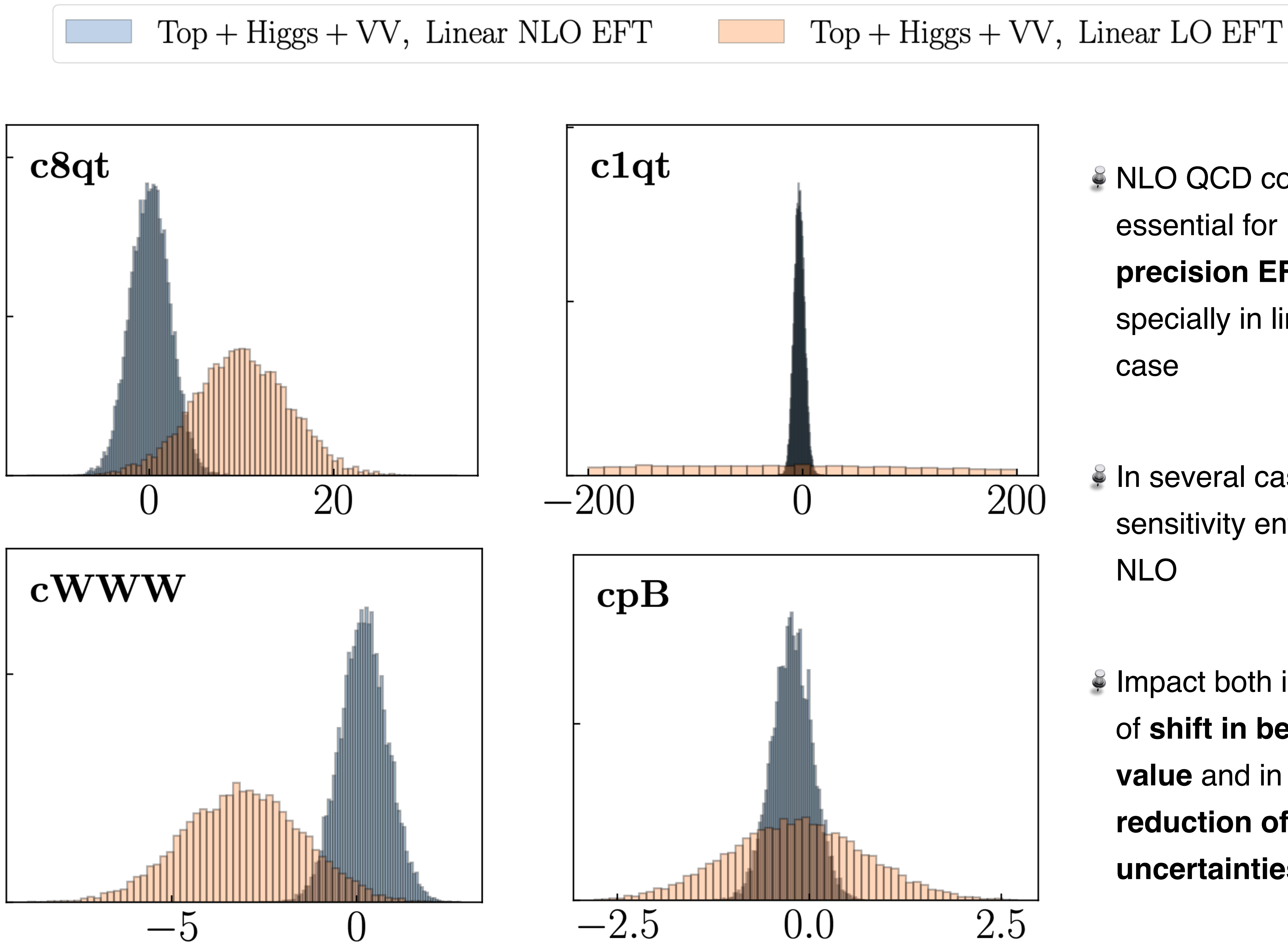
in general, sensitivity of fit results to inclusion of **quadratic EFT corrections**

1-parameter fits



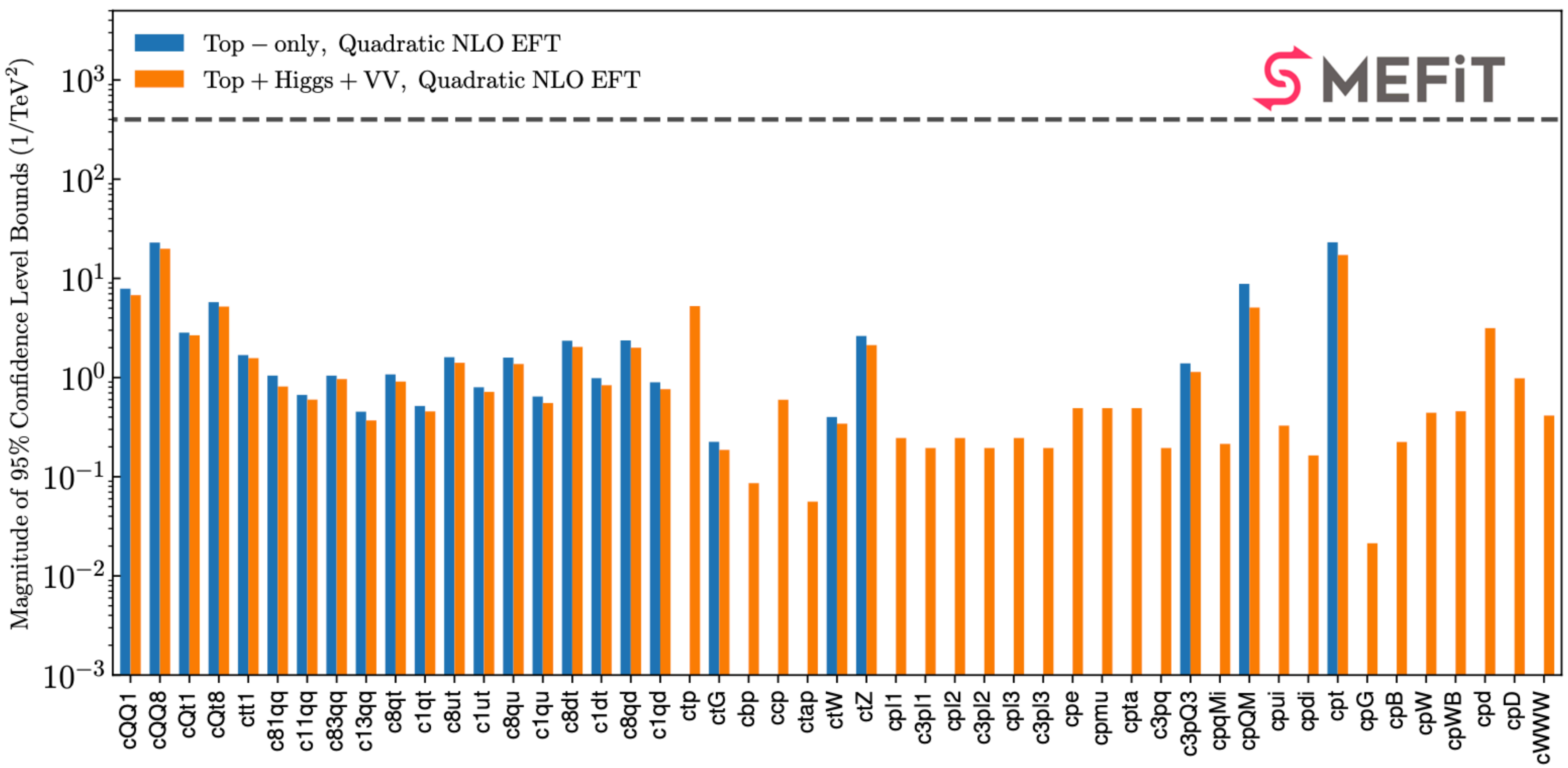


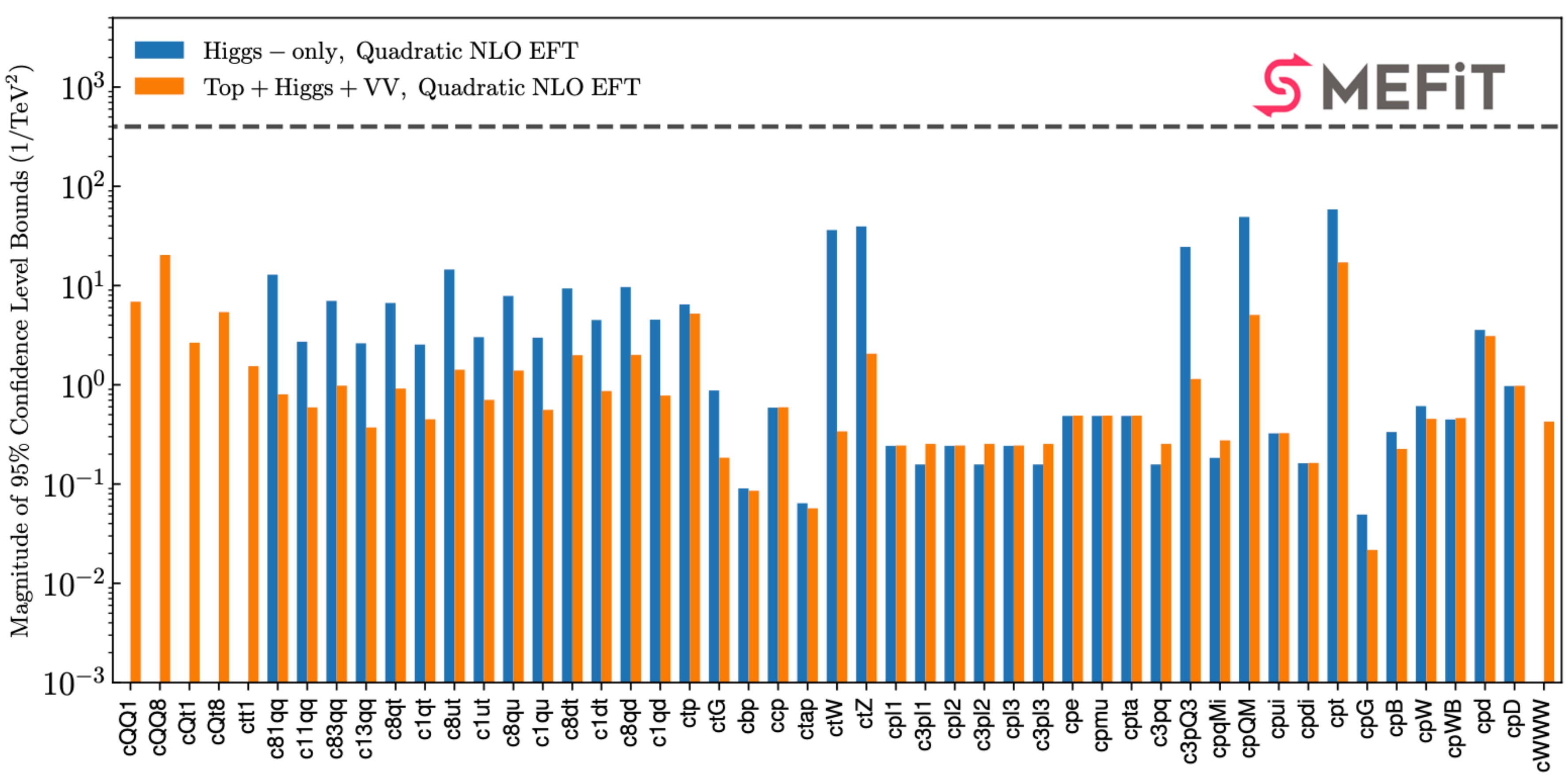
Results: impact of NLO corrections



- NLO QCD corrections essential for **precision EFT fits**, specially in linear case
- In several cases new sensitivity enters at NLO
- Impact both in terms of **shift in best-fit value** and in **reduction of fit uncertainties**

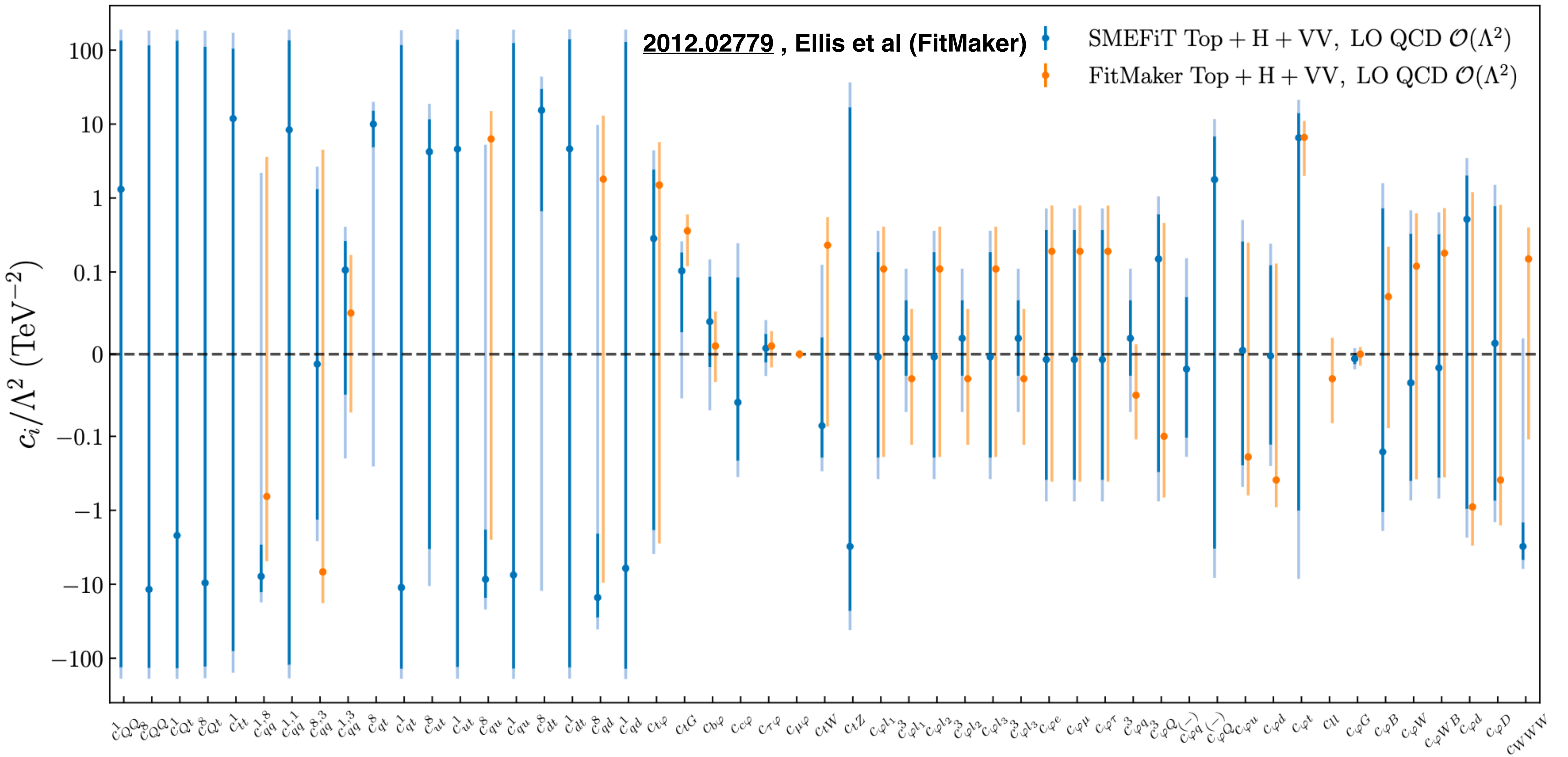
Results: dataset dependence





- Global fits consistent, but **more accurate**, with top-only or Higgs-only fit
- Top data **boosts the Higgs EFT fit** all across the board
- Diboson data only constraints **cWWW**
- Fit results stable upon **removal of high energy bins** (E > 1 TeV)

Comparison with FitMaker



Global (marginalised) fits, 68% and 95% CL ranges (*nb not a tuned comparison*)

Reasonable consistency but also noticeable differences: need **benchmark comparisons!**

ongoing efforts in LHC EFT WG

Can New Physics Hide Inside the Proton?

S. Carrazza et al,``Can New Physics hide inside the proton?,'' Phys. Rev. Lett. 23 (2019) no.13, 132001, [arXiv:1905.05215 [hep-ph]].

A. Greljo et al, ``Parton distributions in the SMEFT from high-energy Drell-Yan tails,'' JHEP \textbf{07} (2021), 122 [arXiv:2104.02723 [hep-ph]].

Can New Physics hide inside the proton?

``How can you be sure you are not reabsorbing BSM physics into your PDF fits?"

perhaps most frequent question I am asked in talks!

Assuming the **SM**, the theory calculations that enter a global PDF fit are:

$$\sigma_{\rm LHC}(\boldsymbol{\theta}) \propto \sum_{ij=u,d,g,\ldots} \int_{M^2}^{s} d\hat{s}\; \mathcal{L}_{ij}(\hat{s}, s, \boldsymbol{\theta})\, \widetilde{\sigma}_{{\rm SM},ij}(\hat{s}, \alpha_s(M))$$

SM PDFs

However in the case of BSM physics, here parametrised by the **SMEFT,** the correct expression is:

SMEFT PDFs

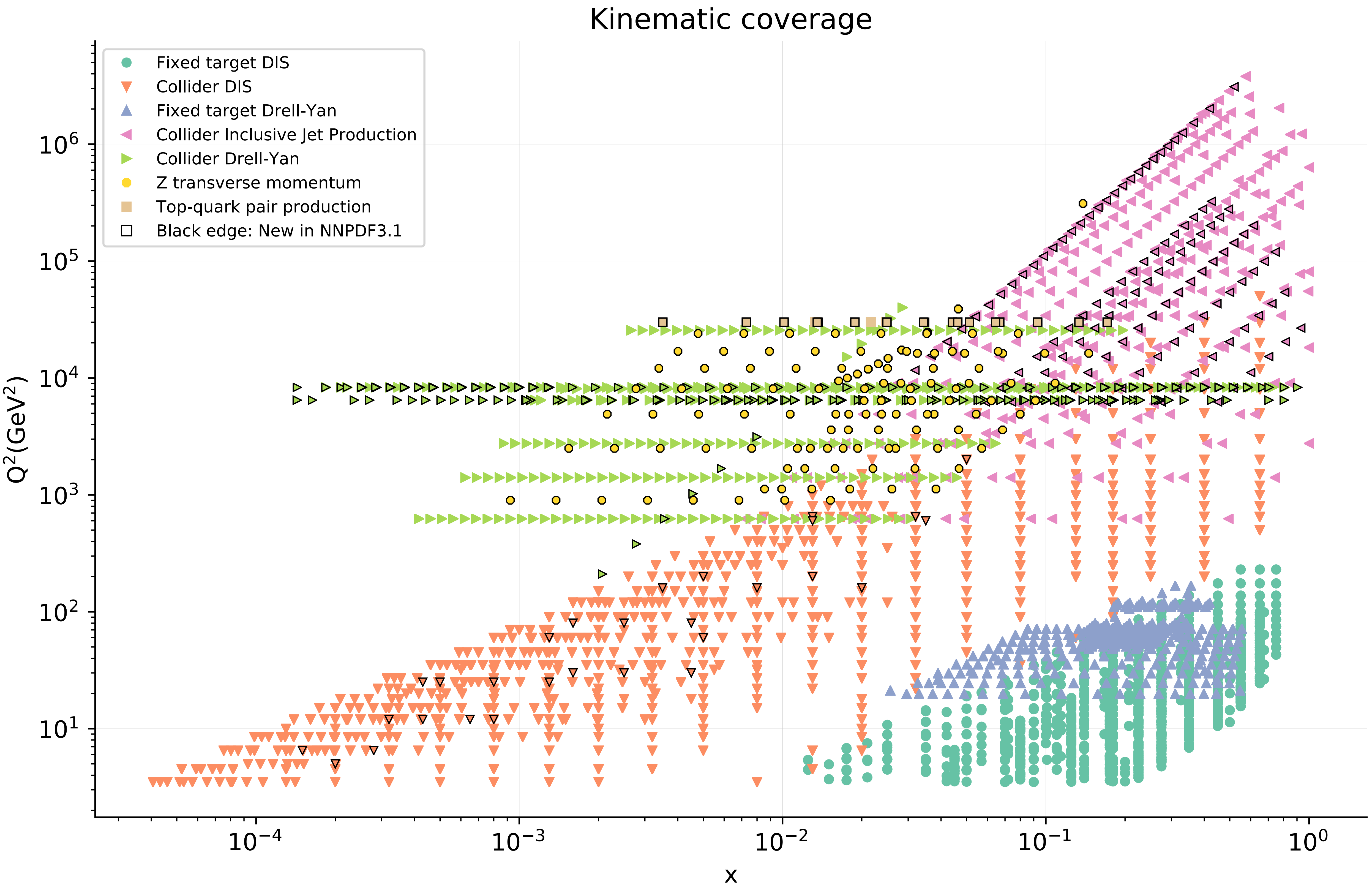
$$\sigma_{\rm LHC}\left(\boldsymbol{c}, \Lambda, \boldsymbol{\theta}\right) \simeq \left(\int_{M^2}^{s} d\hat{s}\; \mathcal{L}_{ij}(\hat{s}, s, \boldsymbol{\theta})\, \widetilde{\sigma}_{{\rm SM},ij}(\hat{s}, \alpha_s(M)) \right) \times \left(1 + \sum_{m=1}^{N_6} c_m \frac{\kappa_m}{\Lambda^2} + \sum_{m,n=1}^{N_6} c_m c_n \frac{\kappa_{mn}}{\Lambda^4} \right),$$

PDF parameters

SMEFT coefficients

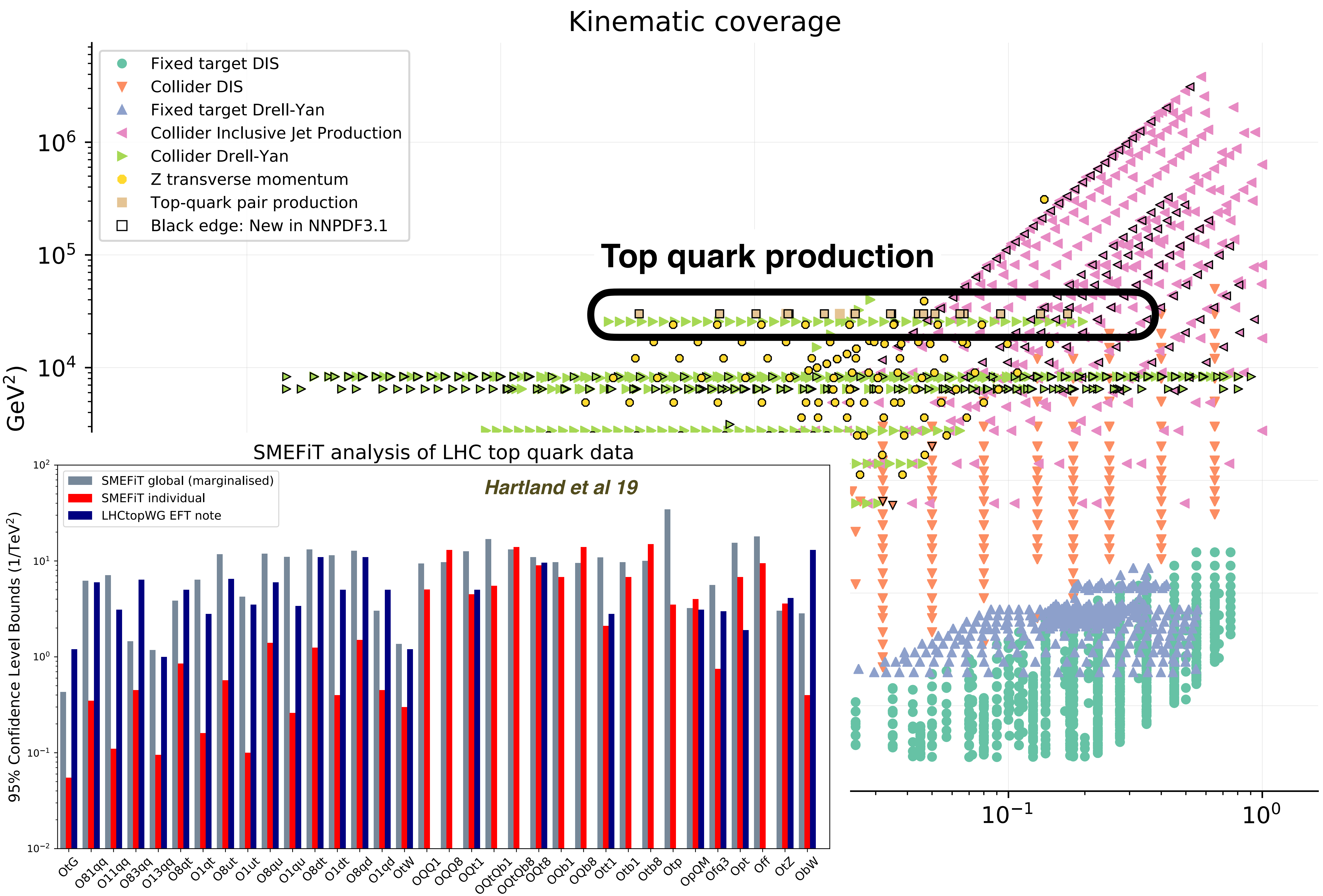
How different are ``SM PDFs" & ``SMEFT PDFs"? Can we quantify the risk of **fitting away BSM** in PDFs?

SMEFT & PDFs

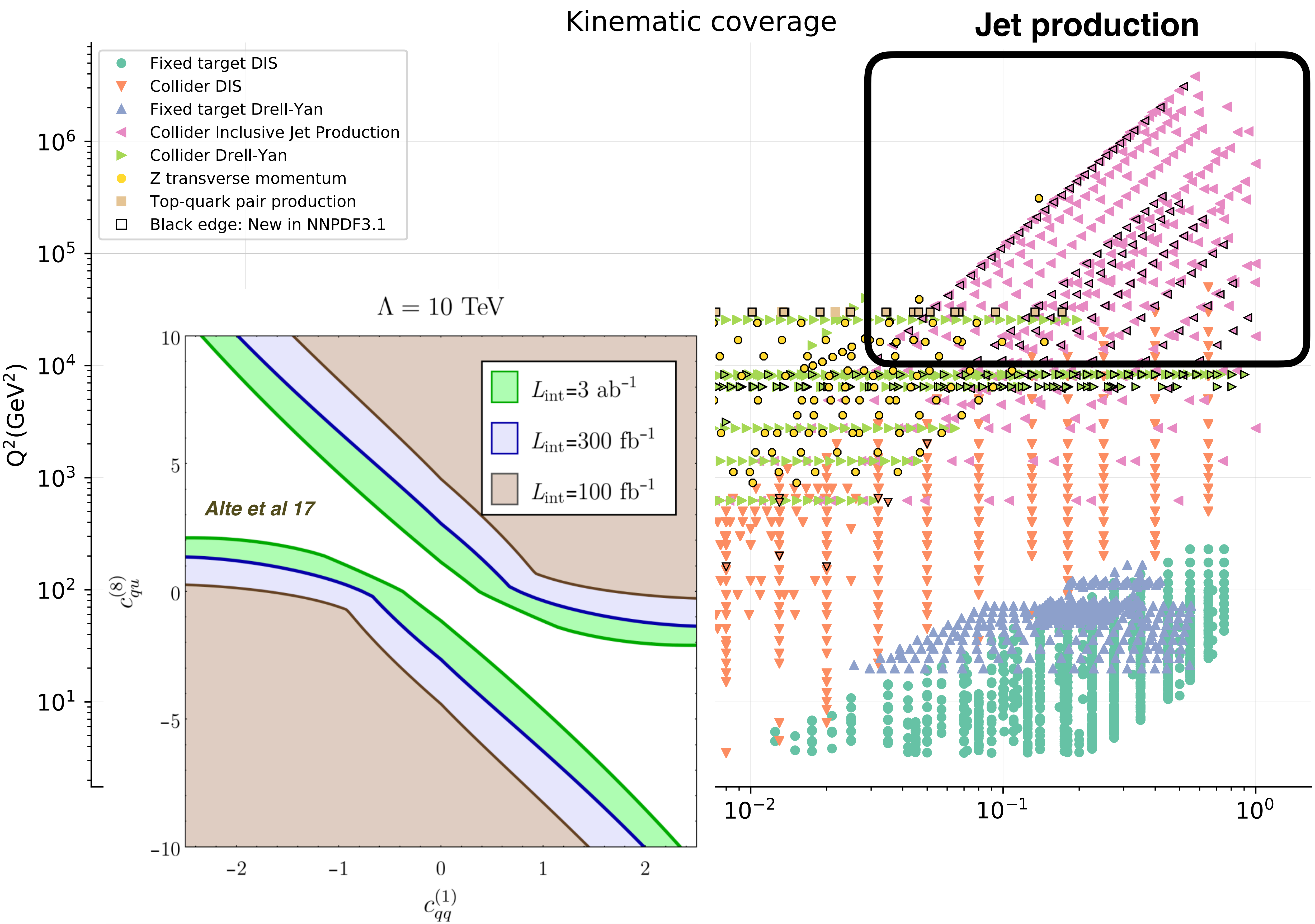


Kinematic coverage
Fixed target DIS
Collider DIS
Fixed target Drell-Yan
Collider Inclusive Jet Production
Collider Drell-Yan
Z transverse momentum
Top-quark pair production
Black edge: New in NNPDF3.1
$Q^2(\mathrm{GeV}^2)$
10^6
10^5
10^4
10^3
10^2
10^1
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^0
x

SMEFT & PDFs

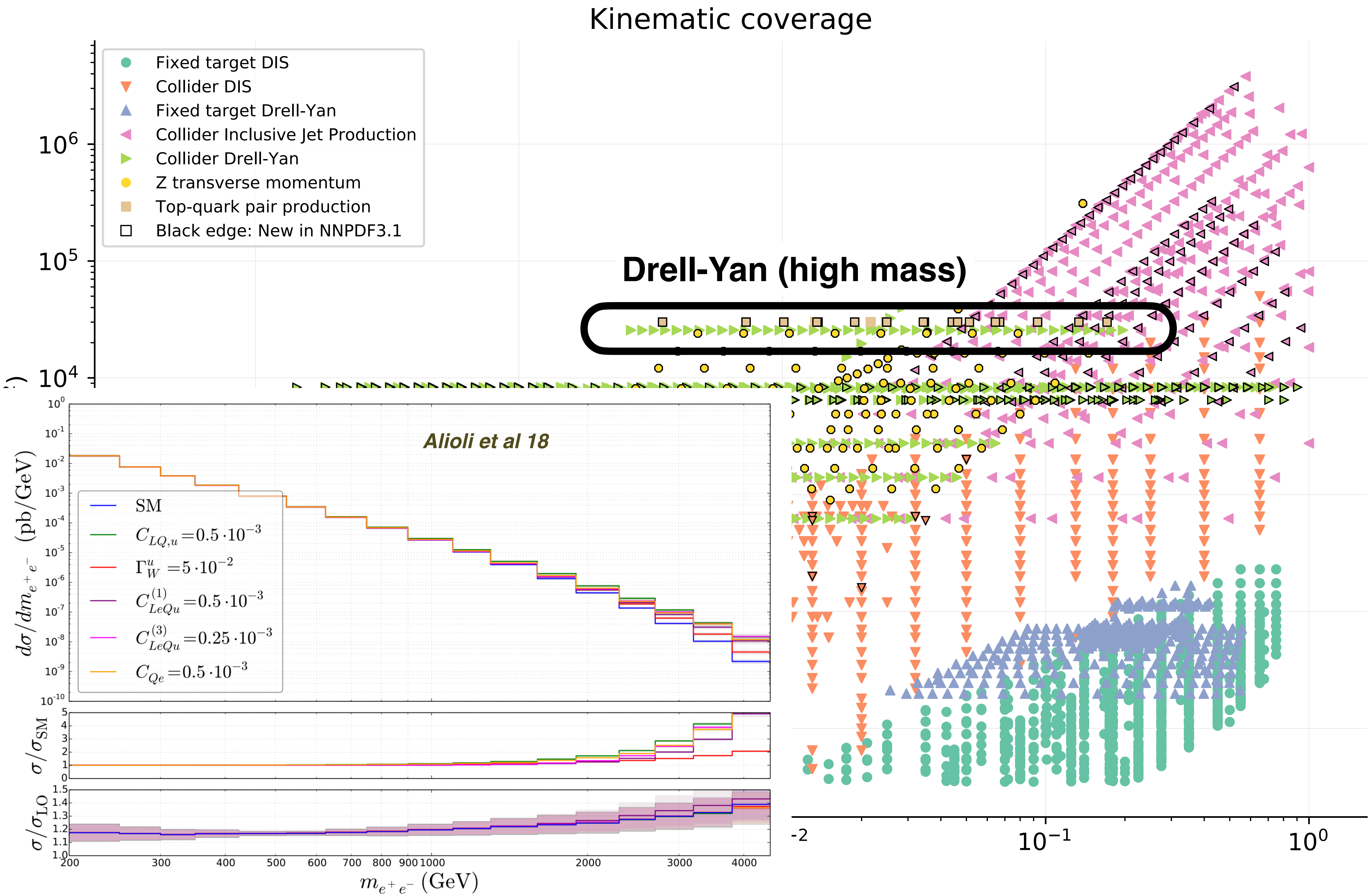

Kinematic coverage
Fixed target DIS
Collider DIS
Fixed target Drell-Yan
Collider Inclusive Jet Production
Collider Drell-Yan
Z transverse momentum
Top-quark pair production
Black edge: New in NNPDF3.1
Top quark production
10^6
10^5
10^4
GeV^2)
10^{-1}
10^0
SMEFiT analysis of LHC top quark data
SMEFiT global (marginalised)
SMEFiT individual
LHCtopWG EFT note
Hartland et al 19
95% Confidence Level Bounds (1/TeV^2)
10^2
10^1
10^0
10^{-1}
10^{-2}
OtG O81qq O11qq O83qq O13qq O8qt O1qt O8ut O1ut O8qu O1qu O8dt O1dt O8qd O1qd OtW OQQ1 OQQ8 OQt1 OQtQb1 OQtQb8 OQt8 OQb1 OQb8 Ott1 Otb1 Otb8 Otp OpQM Ofq3 Opt Off OtZ ObW

SMEFT & PDFs



Kinematic coverage
Jet production
Fixed target DIS
Collider DIS
Fixed target Drell-Yan
Collider Inclusive Jet Production
Collider Drell-Yan
Z transverse momentum
Top-quark pair production
Black edge: New in NNPDF3.1
$Q^2(\mathrm{GeV}^2)$
10^1
10^2
10^3
10^4
10^5
10^6
10^{-2}
10^{-1}
10^0
$\Lambda = 10$ TeV
$L_{\rm int}$=3 ab^{-1}
$L_{\rm int}$=300 fb^{-1}
$L_{\rm int}$=100 fb^{-1}
Alte et al 17
$c_{qu}^{(8)}$
$c_{qq}^{(1)}$
10
5
0
−5
−10
−2
−1
0
1
2

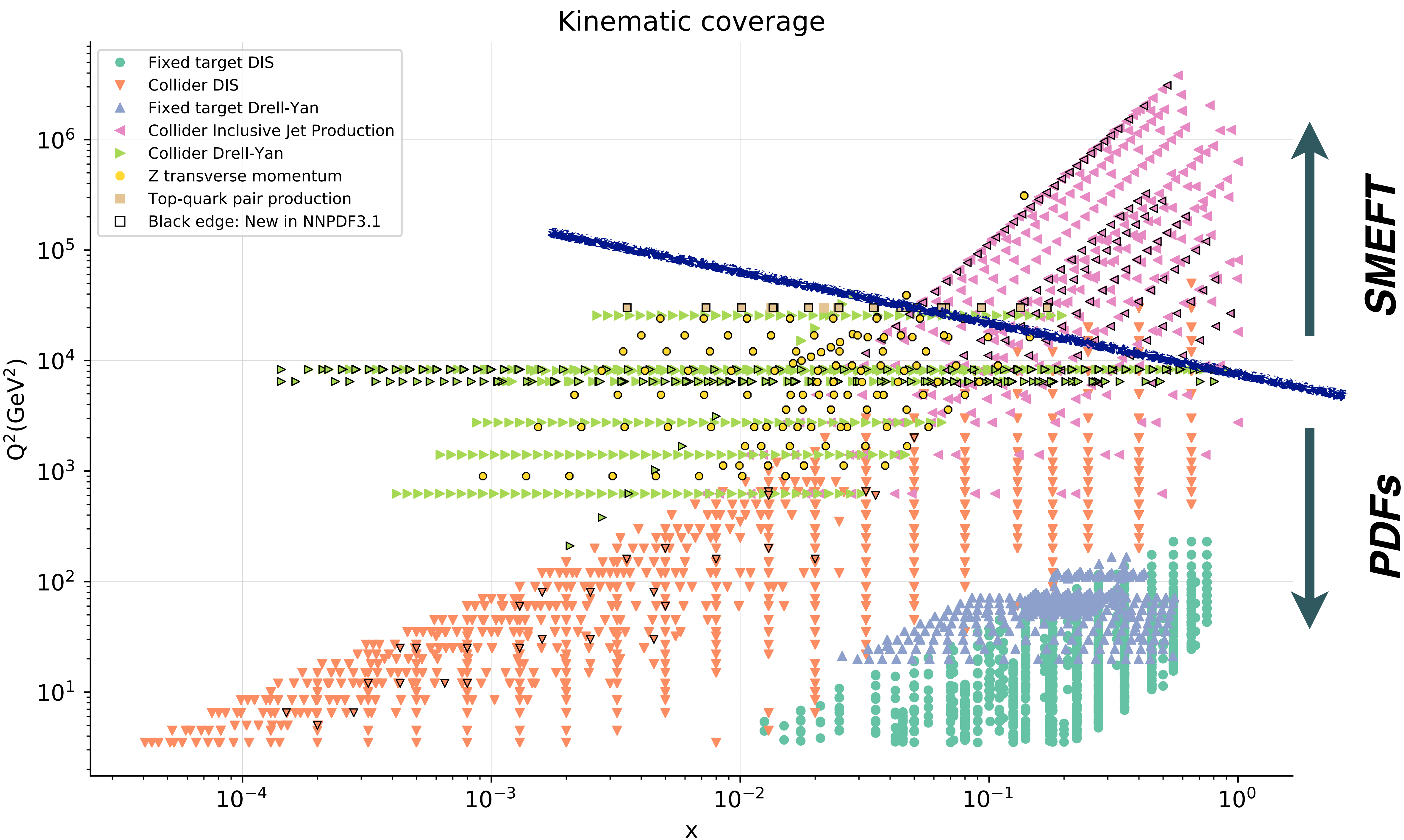
SMEFT & PDFs



Kinematic coverage
Fixed target DIS
Collider DIS
Fixed target Drell-Yan
Collider Inclusive Jet Production
Collider Drell-Yan
Z transverse momentum
Top-quark pair production
Black edge: New in NNPDF3.1
Drell-Yan (high mass)
Alioli et al 18
SM
$C_{LQ,u} = 0.5 \cdot 10^{-3}$
$\Gamma_W^u = 5 \cdot 10^{-2}$
$C_{LeQu}^{(1)} = 0.5 \cdot 10^{-3}$
$C_{LeQu}^{(3)} = 0.25 \cdot 10^{-3}$
$C_{Qe} = 0.5 \cdot 10^{-3}$
$d\sigma/dm_{e^+e^-}$ (pb/GeV)
σ/σ_{SM}
σ/σ_{LO}
$m_{e^+e^-}$ (GeV)

SMEFT & PDFs

Separate LHC data into **input for PDF fits** and **input for SMEFT studies?**



significant **information loss on PDFs**, specially in crucial large-x region

SMEFT PDFs from high-E Drell-Yan

Exp.	$\sqrt{s}$ (TeV)	Ref.	$\mathcal{L}$ (fb^{-1})	Channel	1D/2D	$n_{\rm dat}$	$m_{\ell\ell}^{\rm max}$ (TeV)
ATLAS	7	[120]	4.9	e^-e^+	1D	13	[1.0, 1.5]
ATLAS (*)	8	[86]	20.3	$\ell^-\ell^+$	2D	46	[0.5, 1.5]
CMS	7	[121]	9.3	$\mu^-\mu^+$	2D	127	[0.2, 1.5]
CMS (*)	8	[87]	19.7	$\ell^-\ell^+$	1D	41	[1.5, 2.0]
CMS (*)	13	[122]	5.1	e^-e^+, $\mu^-\mu^+$ $\ell^-\ell^+$	1D	43, 43 43	[1.5, 3.0]
Total						**270 (313)**	

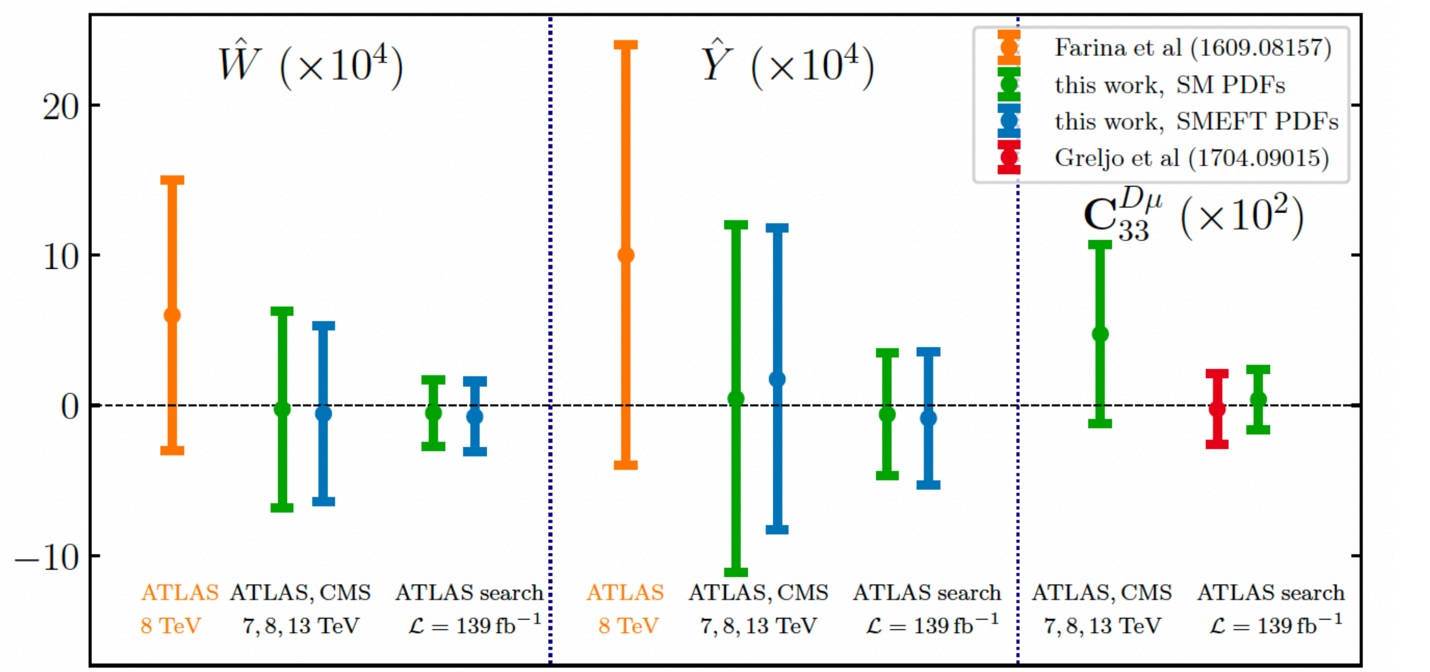
Extract PDFs from global fit where **high-mass DY cross-sections** account for EFT effects in two benchmark scenarios

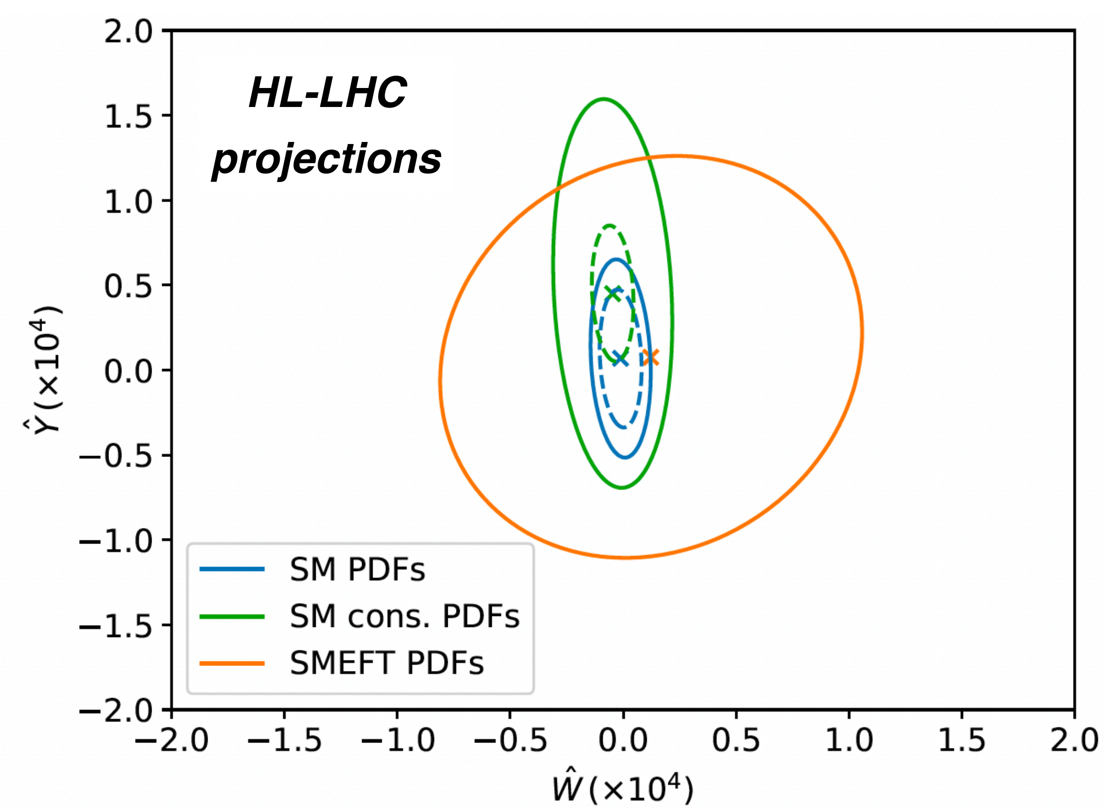
$$d\sigma_{\rm SMEFT} = d\sigma_{\rm SM} \times K_{\rm EFT}$$

$$K_{\rm EFT} = 1 + \sum_{n=1}^{n_{\rm op}} c_n R^{(n)}_{\rm SMEFT} + \sum_{n,m=1}^{n_{\rm op}} c_n c_m R^{(n,m)}_{\rm SMEFT}$$

Available data: limited interplay between PDF and EFT fits, best constraints from **searches**

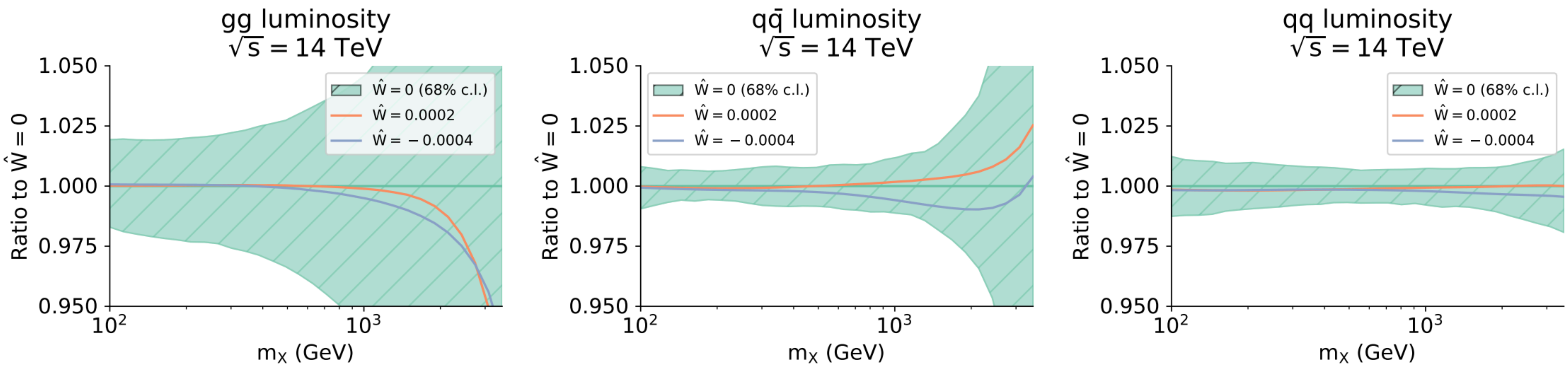
HL-LHC: EFT effects, if present, would be **reabsorbed into PDFs**



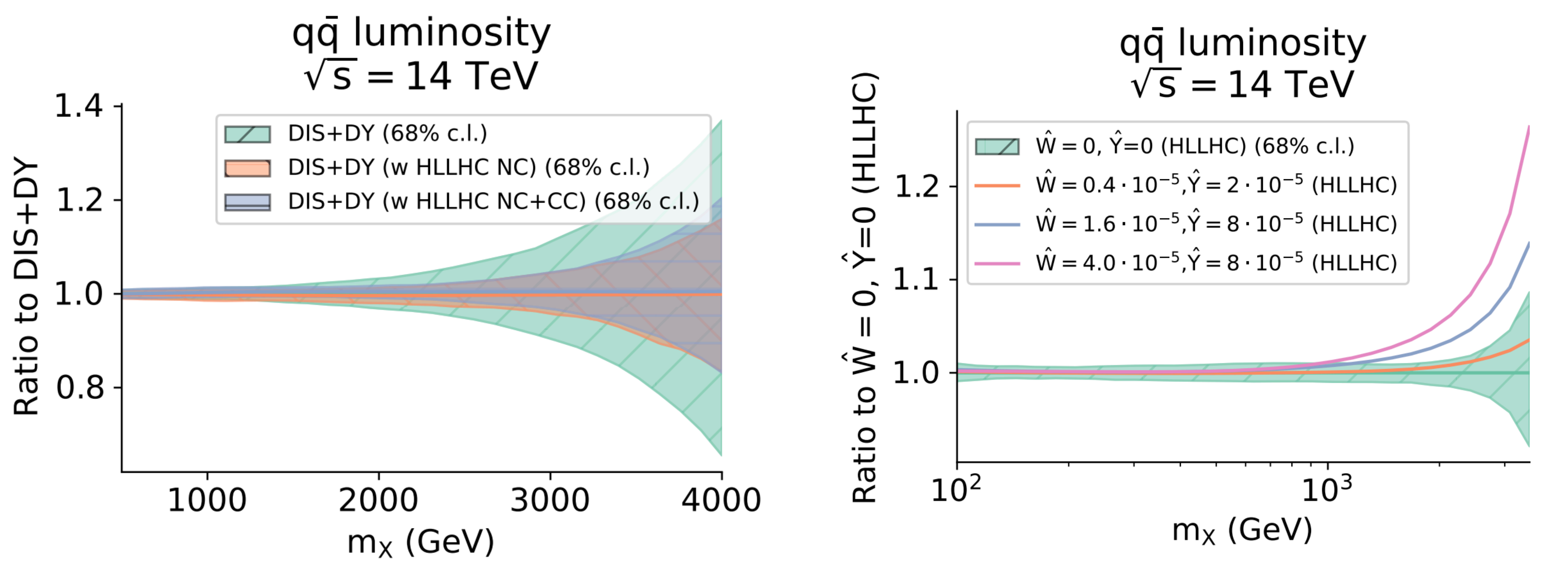


SMEFT PDFs from high-E Drell-Yan

with current (published) DY data, interplay between PDF and EFT effects **moderate ….**

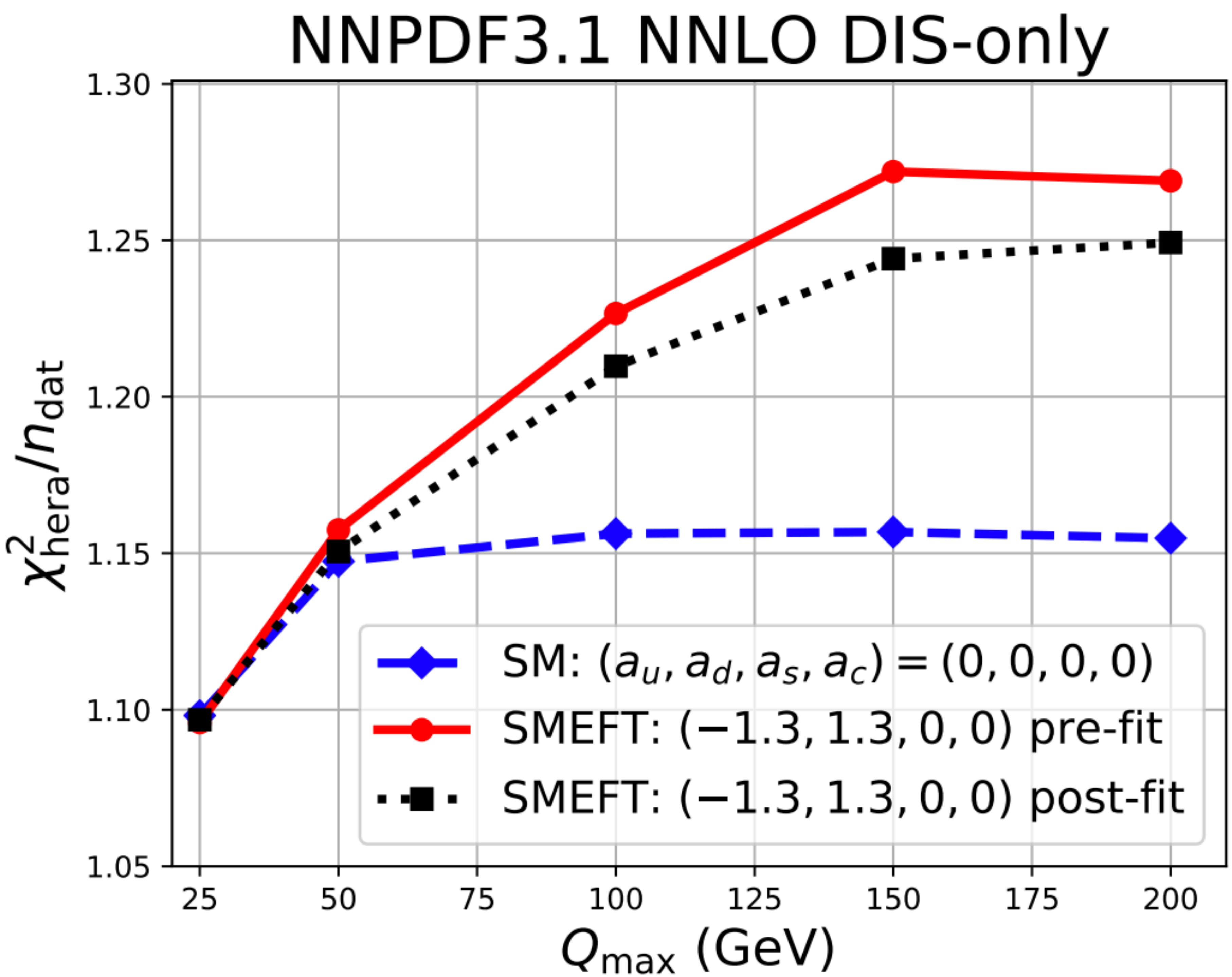


… while at the HL-LHC EFT effects may be **reabsorbed into the PDFs**: careful separation required



Fingerprinting EFT effects

Tell-tale sign of SMEFT effects: **rapid variation with *Q*** (with QCD evolution slower)



What’s next?

Statistically optimal observables from ML

Which kind of measurement is **most sensitive to SMEFT operators?**

Difficult question to answer in general, since SMEFT-sensitive measurements can be:

- Inclusive or (1,2,3, …)-differential (in which specific variables?)
- Binned (choice of binning?) or unbinned
- Unfolded at parton level, at particle level, or at detector level

Also applies to other cases i.e. PDF determinations

topic of heated discussions i.e. STXS in Higgs analyses

Our goal: deploy **unbinned measurements** to determine the ``optimal'' sensitivity that a given process can have on SMEFT operators by means of **machine learning techniques**

carry out EFT analysis with different variants of the same measurement

$$\log \mathcal{L}(c) = -\frac{1}{2}\sum_i \frac{(n_i - \nu_i)^2}{\nu_i} = -\frac{\chi^2}{2}.$$

Binned Gaussian likelihood

$$\log \mathcal{L}(c) = \sum_i n_i \log \nu_i - \nu_i$$

Binned Poisson likelihood

Unbinned extended likelihood

sum over events

$$\log \mathcal{L}(\nu, c) = -\nu(c) + \sum_i^n \log \nu(c) f(x_i, c) \qquad f(x_i, c) \equiv \frac{1}{\sigma(X, c)} \frac{d\sigma(x, c)}{dx}$$

event kinematics

Statistically optimal observables from ML

dependence of cross-section on **all (independent) kinematic variables and all EFT coefficients**

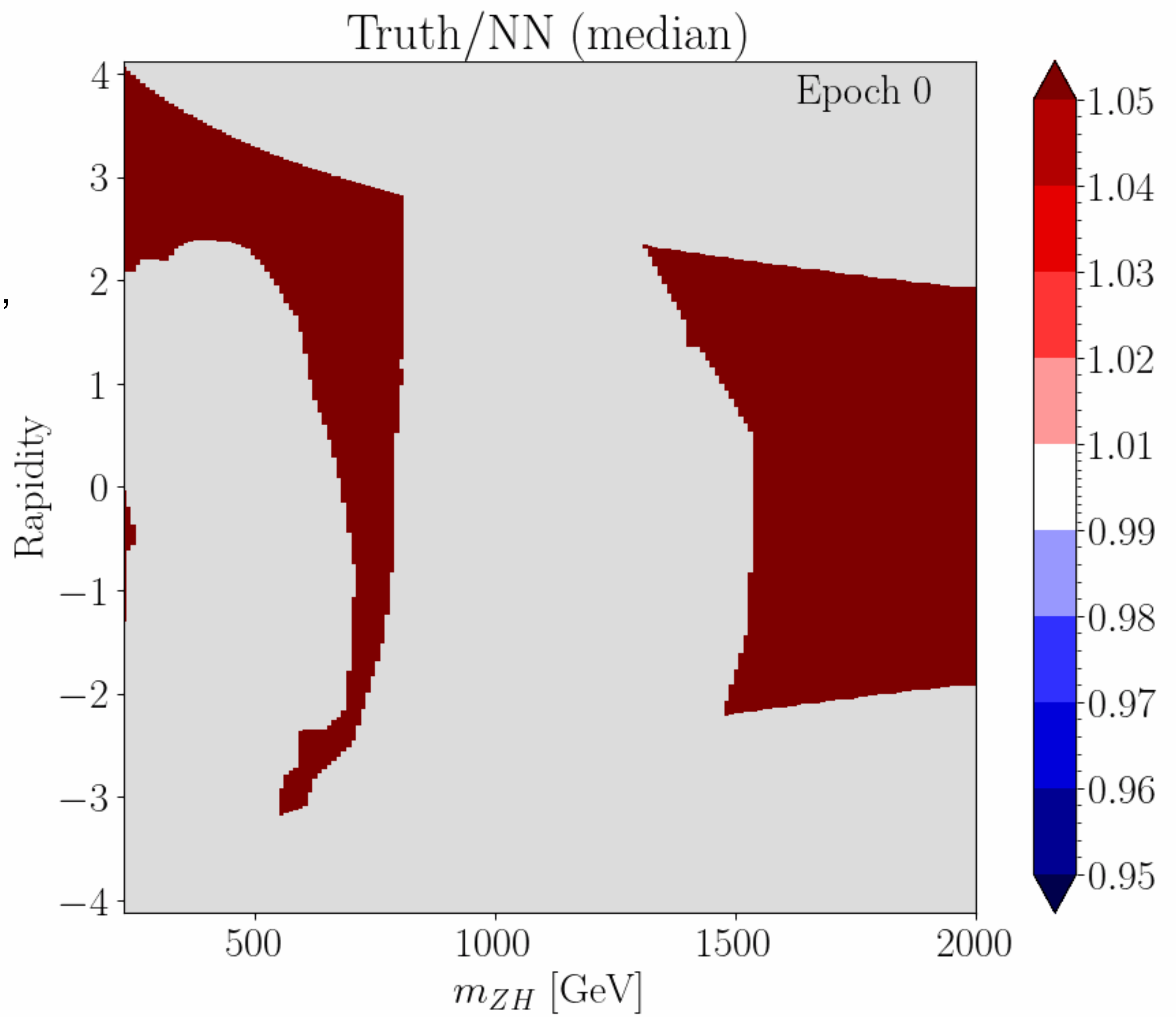
$$f(x_i, c) \equiv \frac{1}{\sigma(X,c)} \frac{d\sigma(x,c)}{dx}$$

is parametrised with **feed-forward neural networks** trained to Monte Carlo simulations, benchmarked with analytical calculations

extendable to **arbitrary number** of kinematic variables and EFT coefficients (NN training can be parallelised)

challenge: correctly describing tails of distributions (low-states)

$$pp \to hZ \to b\bar{b}\ell^+\ell^-$$

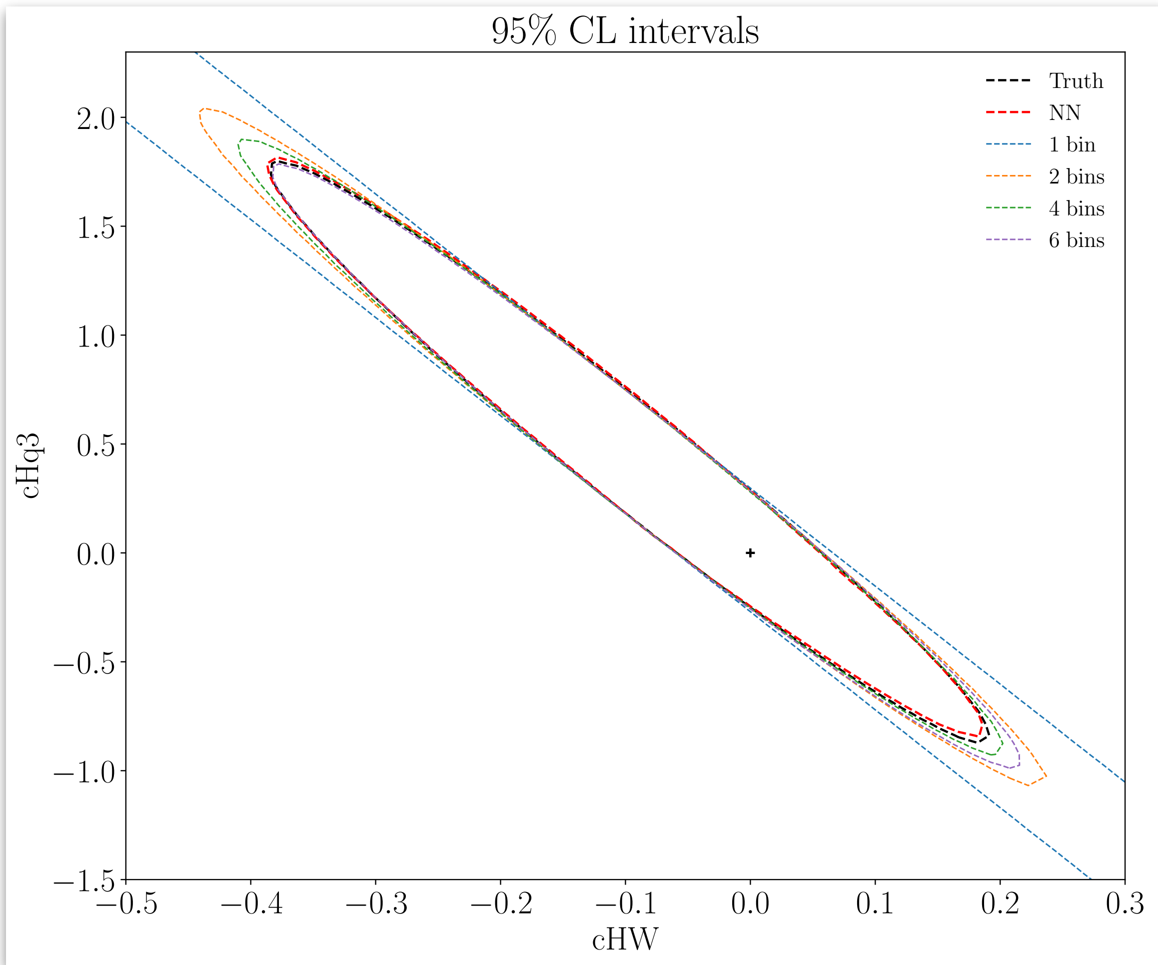


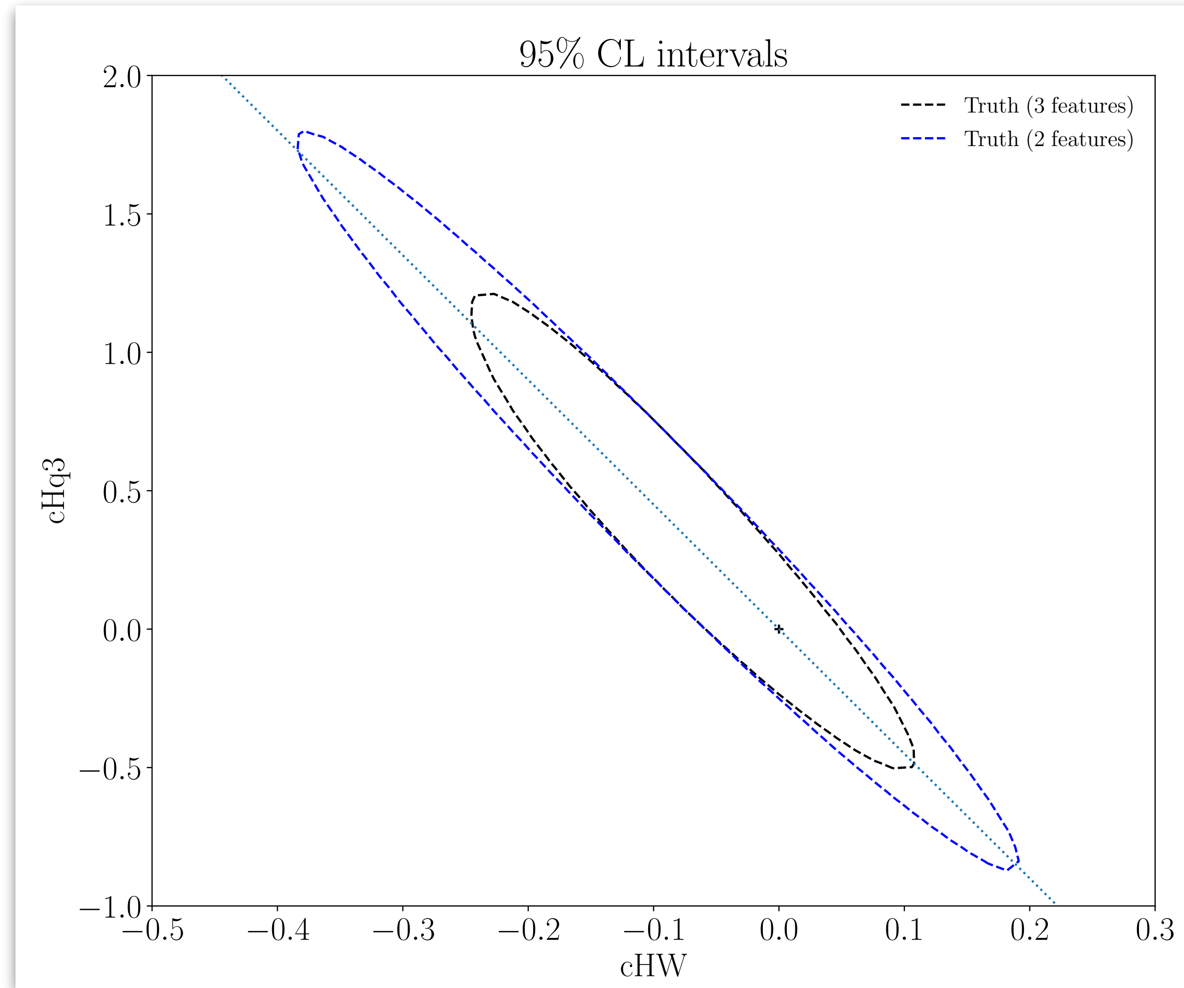
ML model uncertainties assessed using the Monte Carlo replica method

Statistically optimal observables from ML

Proof of concept: sensitivity to SMEFT coefficients in **h+V** and **top quark pair** production

$$pp \to hZ \to b\bar{b}\ell^+\ell^-$$





- Sensitivity improves with **number of bins** (eventually saturating)
- Sensitivity improves when **adding new features** (eventually saturating)

Inform **future measurements** optimising the reach of LHC data for EFT constraints

``Unbinned measurements in global SMEFT fits from machine learning'', R. Gomez-Ambrosio, J. ter Hoeve, M. Madigan, J. Rojo, and V. Sanz, in preparation

Matching to UV-complete models

The global SMEFT analysis framework can be deployed to provide bounds on the **parameters of UV-complete BSM theories**, provided the matching relations are known

For illustration: extend the SM with a **complex scalar** $\varphi \sim (1,2)_{1/2}$

$$\mathcal{L}_{int} = \left(y^e_\varphi\right)_{ij}\, \bar{e}_{R,i}\varphi^\dagger \ell_{L,j} + \left(y^d_\varphi\right)_{ij}\, \bar{d}_{R,i}\varphi^\dagger q_{L,j} + \left(y^u_\varphi\right)_{ij}\, i\bar{u}_{R,i}\varphi^\dagger \sigma_2 q_{L,j} + \lambda_\varphi \varphi^\dagger H H^\dagger H + \text{h.c.},$$

Upon integrating out the heavy field, the following **SMEFT operators** are generated

$$\mathcal{O}_{\ell e},\ \mathcal{O}^{(1)}_{qu},\ \mathcal{O}^{(8)}_{qu},\ \mathcal{O}^{(1)}_{qd},\ \mathcal{O}^{(8)}_{qd},\ \mathcal{O}_{ledq},\ \mathcal{O}^{(1)}_{quqd},\ \mathcal{O}^{(1)}_{lequ},\ \mathcal{O}_{H},\ \mathcal{O}_{eH},\ \mathcal{O}_{dH},\ \mathcal{O}_{uH}$$

whose **Wilson coefficients** are related to mass and couplings of heavy scalar by

$$\frac{c_{bH}}{\Lambda^2} = \frac{\lambda_\varphi \left(y^d_\varphi\right)_{33}}{m^2_\varphi}, \quad \frac{c_{cH}}{\Lambda^2} = -\frac{\lambda_\varphi \left(y^u_\varphi\right)_{22}}{m^2_\varphi}, \quad \frac{c^{(1)}_{Qd}}{\Lambda^2} = -\frac{\left(\left(y^d_\varphi\right)_{33}\right)^2}{6\, m^2_\varphi}, \quad \frac{c^{(8)}_{Qd}}{\Lambda^2} = -\frac{\left(\left(y^d_\varphi\right)_{33}\right)^2}{m^2_\varphi},$$

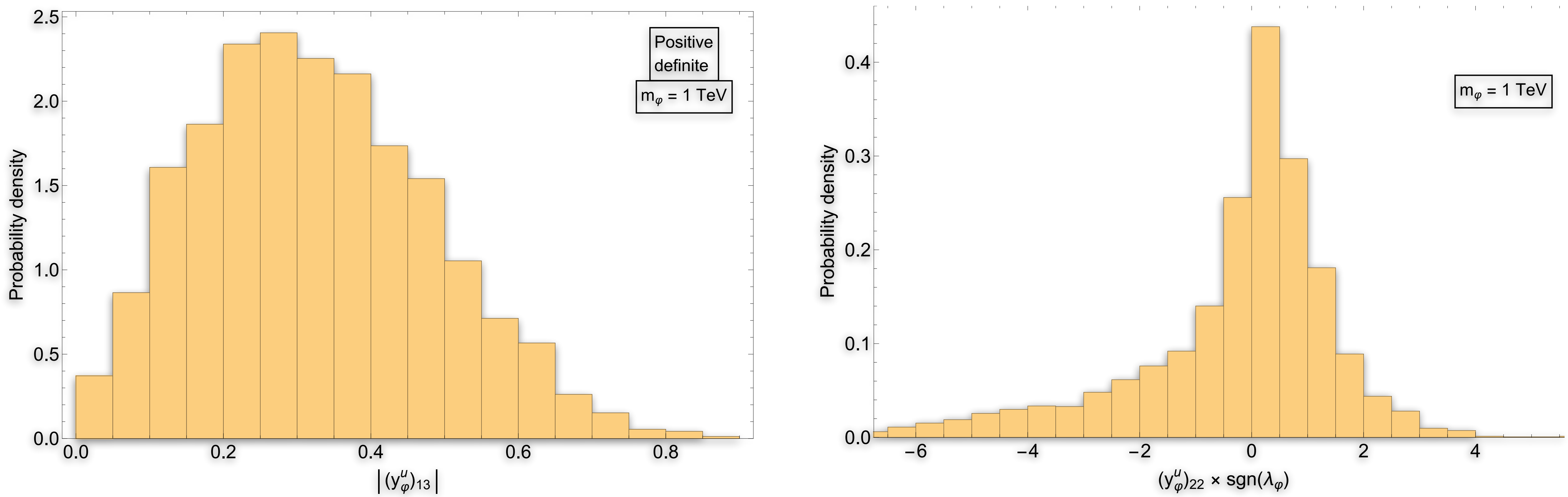
$$\frac{c^{(1)}_{Qt}}{\Lambda^2} = -\frac{\left(\left(y^u_\varphi\right)_{33}\right)^2}{6\, m^2_\varphi}, \quad \frac{c^{(8)}_{Qt}}{\Lambda^2} = -\frac{\left(\left(y^u_\varphi\right)_{33}\right)^2}{m^2_\varphi}, \quad \frac{c^{(1)}_{Qu}}{\Lambda^2} = -\frac{\left(\left(y^u_\varphi\right)_{31}\right)^2}{6\, m^2_\varphi}, \quad \frac{c^{(8)}_{Qu}}{\Lambda^2} = -\frac{\left(\left(y^u_\varphi\right)_{31}\right)^2}{m^2_\varphi},$$

$$\frac{c^{(1)}_{tq}}{\Lambda^2} = -\frac{\left(\left(y^u_\varphi\right)_{13}\right)^2}{6\, m^2_\varphi}, \quad \frac{c^{(8)}_{tq}}{\Lambda^2} = -\frac{\left(\left(y^u_\varphi\right)_{13}\right)^2}{m^2_\varphi}, \quad \frac{c_{tH}}{\Lambda^2} = -\frac{\left(y^u_\varphi\right)_{33}\lambda_\varphi}{m^2_\varphi}, \quad \frac{c_{\tau H}}{\Lambda^2} = \frac{\left(y^e_\varphi\right)_{33}\lambda_\varphi}{m^2_\varphi},$$

depends on flavour assumptions, must be consistent in EFT and in UV-complete theory

Matching to UV-complete models

Repeat global SMEFT analysis framework with matching conditions **built in** and derive bounds on UV-complete theory parameters



positive-definite UV couplings require dedicated statistical interpretation

key advantage: the SMEFT fit already includes constraints from a **very large and diverse** number of experimental measurements

WIP: **automating the procedure** as much as possible, so that for a general UV-complete Lagrangian one can efficiently derive **SMEFT-based bounds**

``Bounds on UV-complete models from global SMEFT fits", G. Magni, J. Rojo, A. Rossia, E. Vryodinou, in preparation

Summary and outlook

- The EFT framework provides a robust strategy to interpret particle physics data in terms of new BSM phenomena while **minimising model assumptions**

- Only within a **global SMEFT interpretation** it is possible to compare with largest possible class of UV-complete theories and to reduce assumptions i.e. concerning flavour structure

- The SMEFiT framework has been successfully deployed for the **most extensive SMEFT analysis of LHC data** to date based on state-of-the-art EFT calculations

- Ongoing work includes adding more processes, constructing optimally-sensitive observables with ML, matching to UV complete models, accounting for flavour and low-energy constraints …

- We also need a fitting methodology that scales to **hundreds of EFT coefficients**

Summary and outlook

- The EFT framework provides a robust strategy to interpret particle physics data in terms of new BSM phenomena while **minimising model assumptions**

- Only within a **global SMEFT interpretation** it is possible … st possible class of UV-complete theories and to reduce a… structure

- The SMEFiT framew… **…ve SMEFT analysis** o… …ations

- On… …esses, constructing optimally-sensitive observables with … …plete models, accounting for flavour and low-energy constraints …

- We also need a fitting methodology that scales to **hundreds of EFT coefficients**

Thanks for your attention!

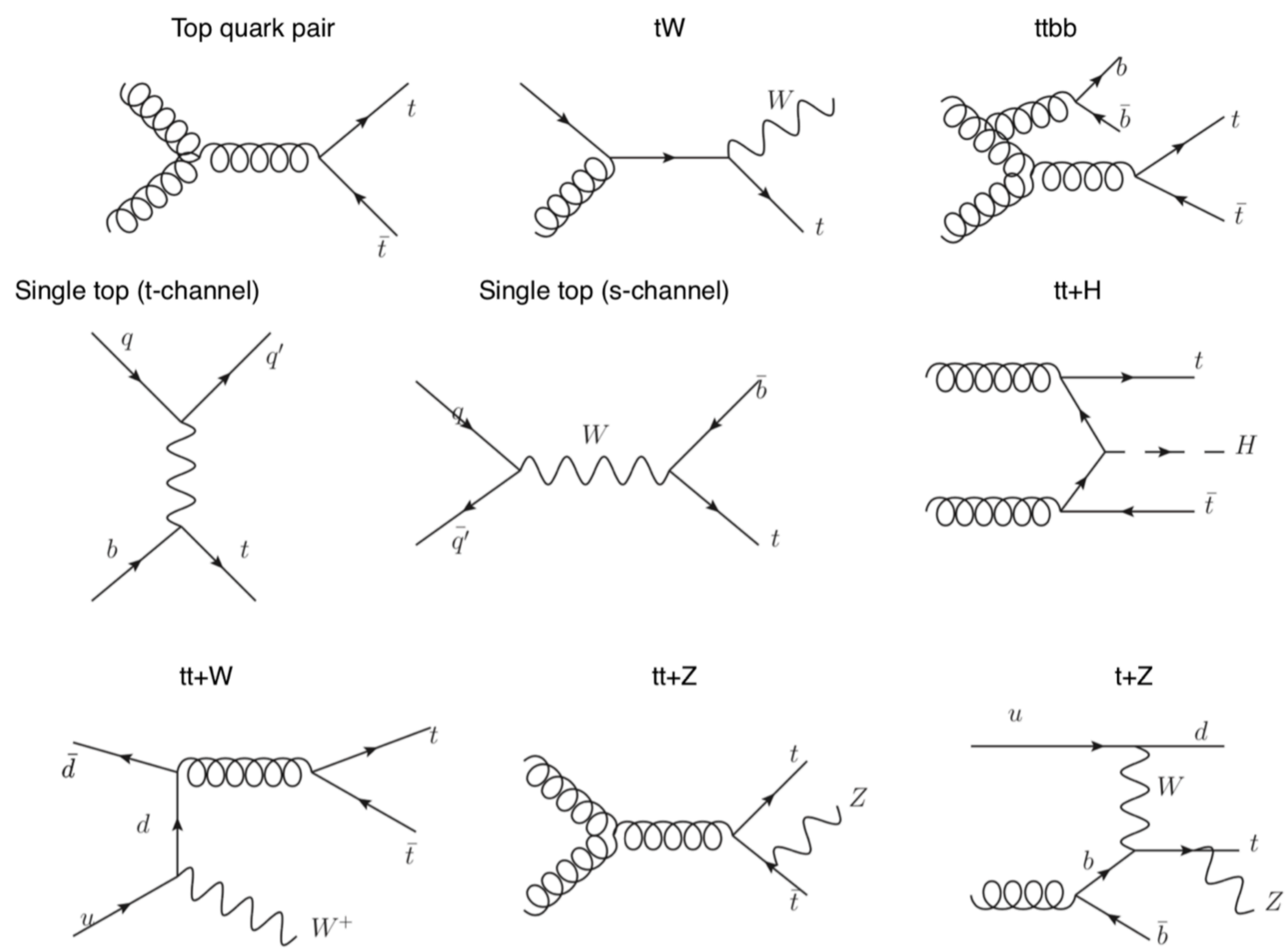
Extra Material

SMEFiT analysis of top quark sector

Notation	Sensitivity at $\mathcal{O}(\Lambda^{-2})$ ($\mathcal{O}(\Lambda^{-4})$)								
	$t\bar{t}$	single-top	tW	tZ	$t\bar{t}W$	$t\bar{t}Z$	$t\bar{t}H$	$t\bar{t}t\bar{t}$	$t\bar{t}b\bar{b}$
OQQ1								✓	✓
OQQ8								✓	✓
OQt1								✓	✓
OQt8								✓	✓
OQb1								(✓)	✓
OQb8								(✓)	✓
Ott1								✓	✓
Otb1								(✓)	✓
Otb8								✓	✓
OQtQb1									
OQtQb8									
O81qq	✓				✓	✓	✓	✓	✓
O11qq	✓				(✓)	(✓)	(✓)	✓	✓
O83qq	✓	✓		(✓)	✓	✓	✓	✓	✓
O13qq	✓	✓		✓	(✓)	(✓)	(✓)	✓	✓
O8qt	✓				✓	✓	✓	✓	✓
O1qt	✓				(✓)	(✓)	(✓)	✓	✓
O8ut	✓					✓	✓	✓	✓
O1ut	✓					(✓)	(✓)	✓	✓
O8qu	✓					✓	✓	✓	✓
O1qu	✓					(✓)	(✓)	✓	✓
O8dt	✓					✓	✓	✓	✓
O1dt	✓					(✓)	(✓)	✓	✓
O8qd	✓					✓	✓	✓	✓
O1qd	✓					(✓)	(✓)	✓	✓
OtG	✓				✓	✓	✓	✓	✓
OtW		✓	✓	✓					
ObW		(✓)	(✓)						
OtZ				✓		✓			
Off		(✓)	(✓)	(✓)					
Ofq3		✓	✓	✓		✓			
OpQM				✓		✓			
Opt				✓		✓	✓		
Otp							✓		

A large number of different dimension-6 SMEFT operators modify **top production at LHC**

$$\sigma_i^{\rm th}\left(\{c_n\}\right) = \sigma_{{\rm SM},i} + \sum_{n=1}^{N_{\rm op}} \widetilde{\sigma}_{i,n}\frac{c_n}{\Lambda^2}\left(+ \sum_{n,m=1}^{N_{\rm op}} \widetilde{\sigma}_{i,nm}\frac{c_n c_m}{\Lambda^4}\right)$$



SMEFiT analysis of top quark sector

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OQQ8								✓	✓
OQt1								✓	✓
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OQb1								(✓)	✓
OQb8								(✓)	✓
Ott1								✓	✓
Otb1								(✓)	✓
Otb8								✓	✓
OQtQb1									
OQtQb8									
O81qq	✓				✓	✓	✓	✓	✓
O11qq	✓				(✓)	(✓)	(✓)	✓	✓
O83qq	✓	✓		(✓)	✓	✓	✓	✓	✓
O13qq	✓	✓		✓	(✓)	(✓)	(✓)	✓	✓
O8qt	✓				✓	✓	✓	✓	✓
O1qt	✓				(✓)	(✓)	(✓)	✓	✓
O8ut	✓					✓	✓	✓	✓
O1ut	✓					(✓)	(✓)	✓	✓
O8qu	✓					✓	✓	✓	✓
O1qu	✓					(✓)	(✓)	✓	✓
O8dt	✓					✓	✓	✓	✓
O1dt	✓					(✓)	(✓)	✓	✓
O8qd	✓					✓	✓	✓	✓
O1qd	✓					(✓)	(✓)	✓	✓
OtG	✓				✓	✓	✓	✓	✓
OtW		✓	✓	✓					
ObW		(✓)	(✓)						
OtZ				✓		✓			
Off		(✓)	(✓)	(✓)					
Ofq3		✓	✓	✓		✓			
OpQM				✓		✓			
Opt				✓		✓	✓		
Otp							✓		

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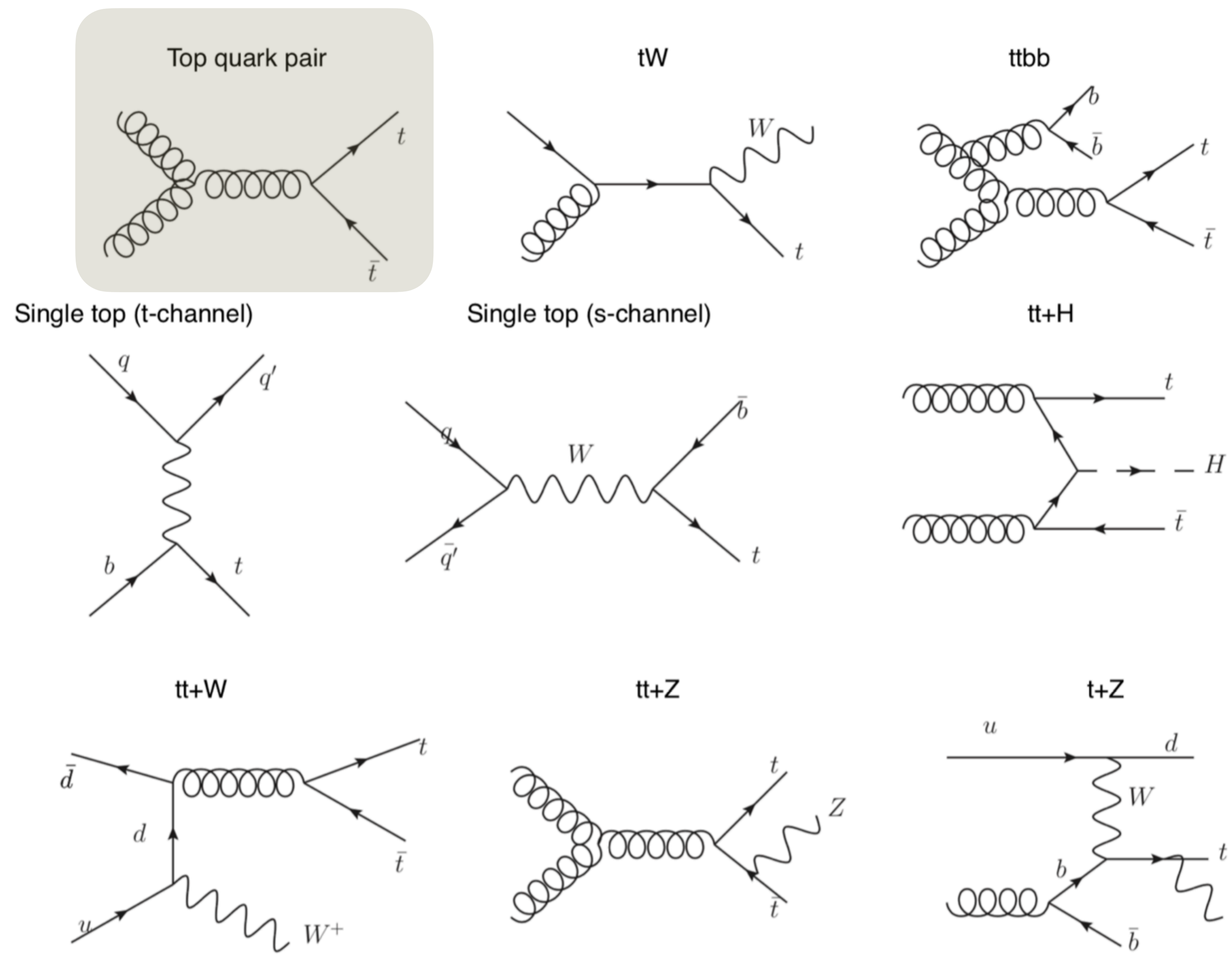
$$\sigma_i^{\rm th}\left(\{c_n\}\right) = \sigma_{{\rm SM},i} + \sum_{n=1}^{N_{\rm op}} \widetilde{\sigma}_{i,n}\frac{c_n}{\Lambda^2} + \sum_{n,m=1}^{N_{\rm op}} \widetilde{\sigma}_{i,nm}\frac{c_n c_m}{\Lambda^4}$$



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OQb8								(✓)	✓
Ott1								✓	✓
Otb1								(✓)	✓
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O8qt	✓				✓	✓	✓	✓	✓
O1qt	✓				(✓)	(✓)	(✓)	✓	✓
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O1ut	✓					(✓)	(✓)	✓	✓
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O1qu	✓					(✓)	(✓)	✓	✓
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O1dt	✓					(✓)	(✓)	✓	✓
O8qd	✓					✓	✓	✓	✓
O1qd	✓					(✓)	(✓)	✓	✓
OtG	✓				✓	✓	✓	✓	✓
OtW		✓	✓	✓					
ObW		(✓)	(✓)						
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Ofq3		✓	✓	✓		✓			
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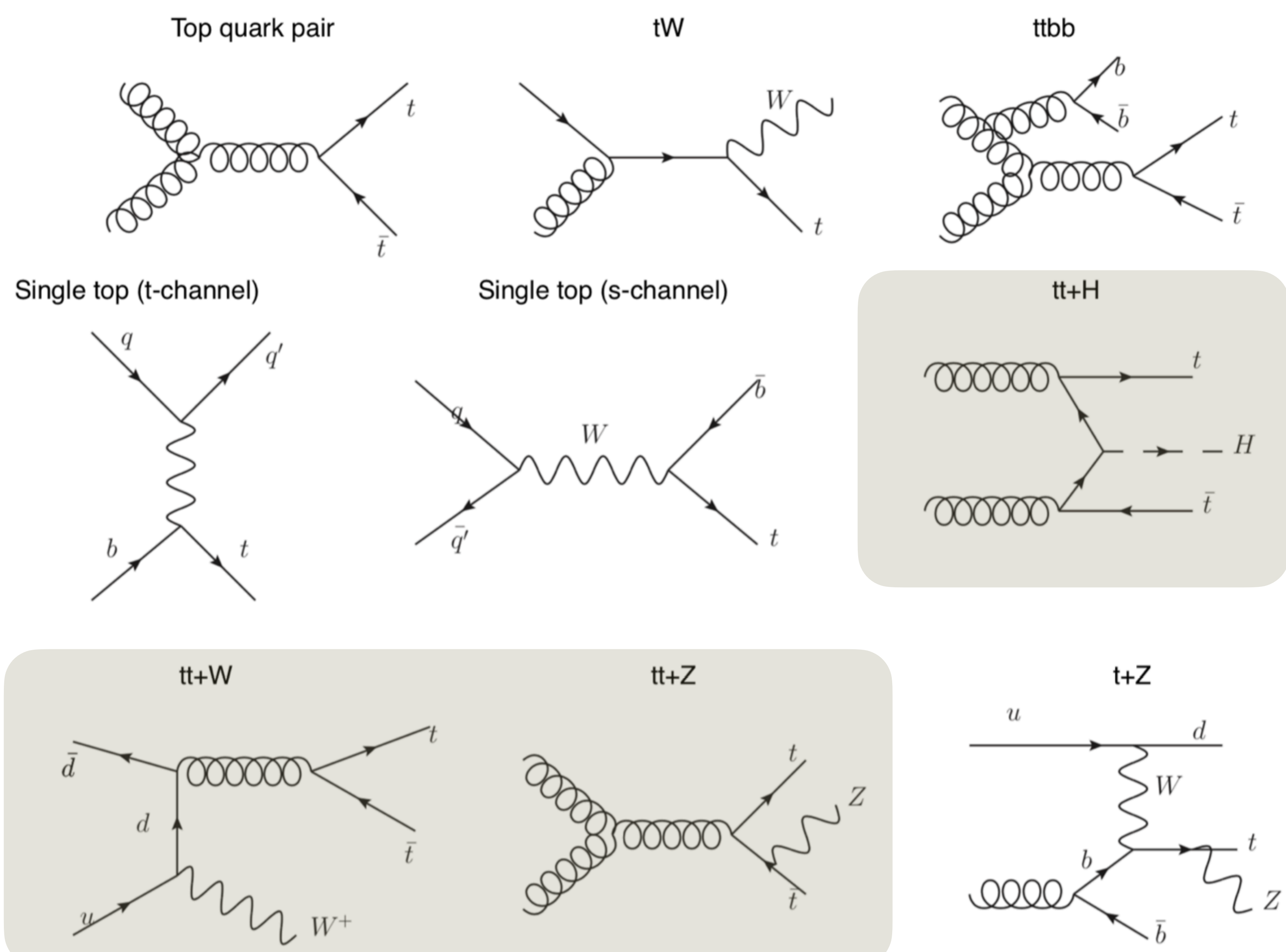

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Otb1								(✓)	✓
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O1qd	✓					(✓)	(✓)	✓	✓
OtG	✓				✓	✓	✓	✓	✓
OtW		✓	✓	✓					
ObW		(✓)	(✓)						
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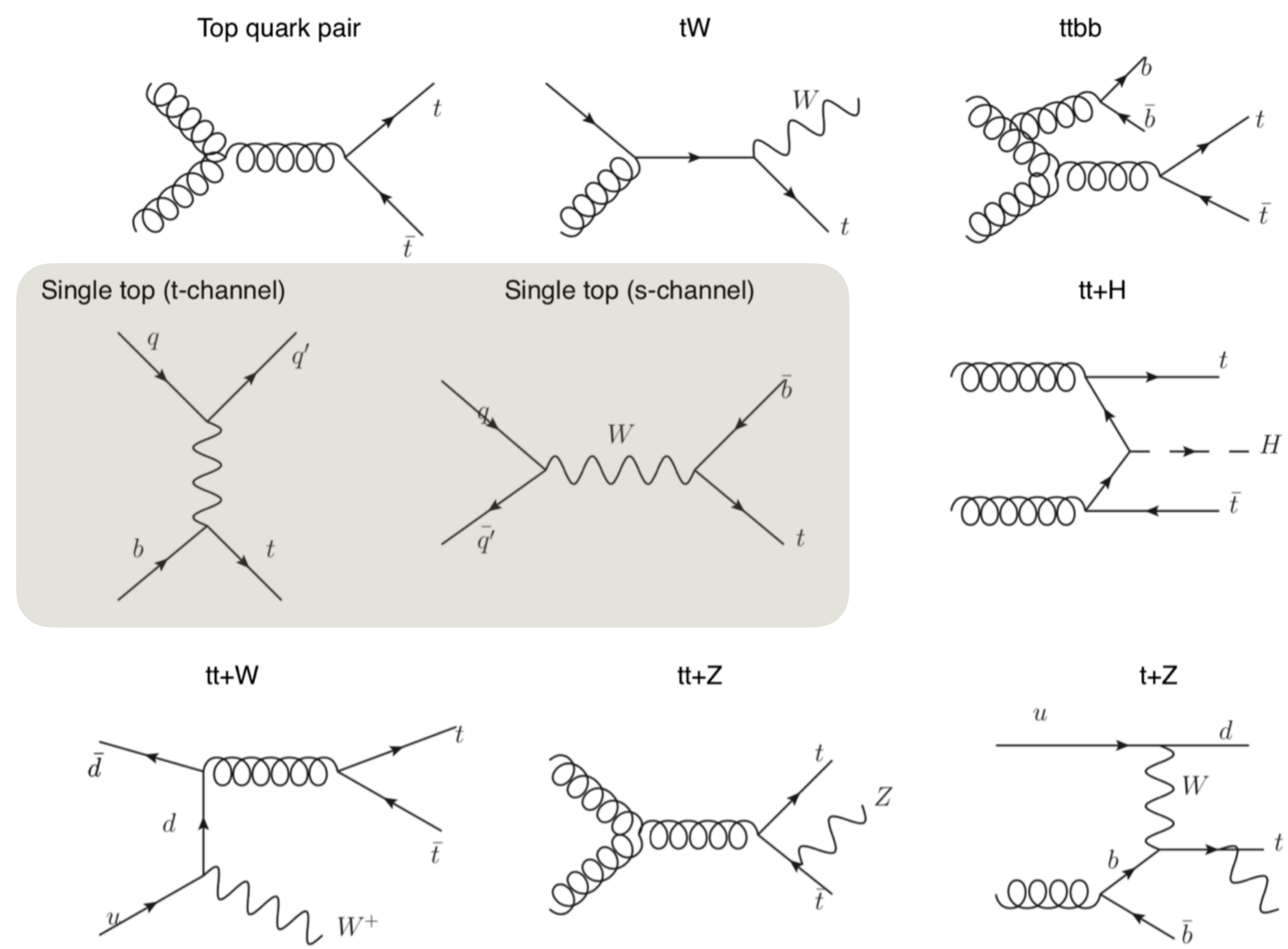
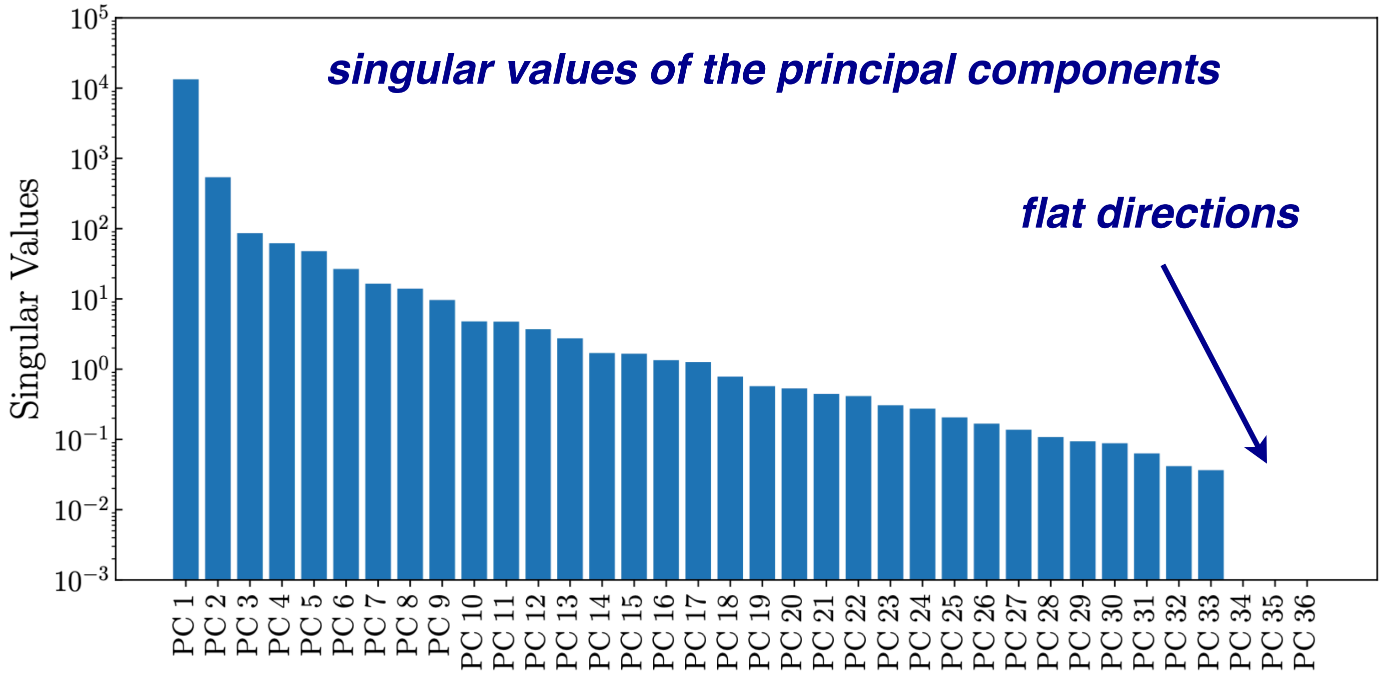
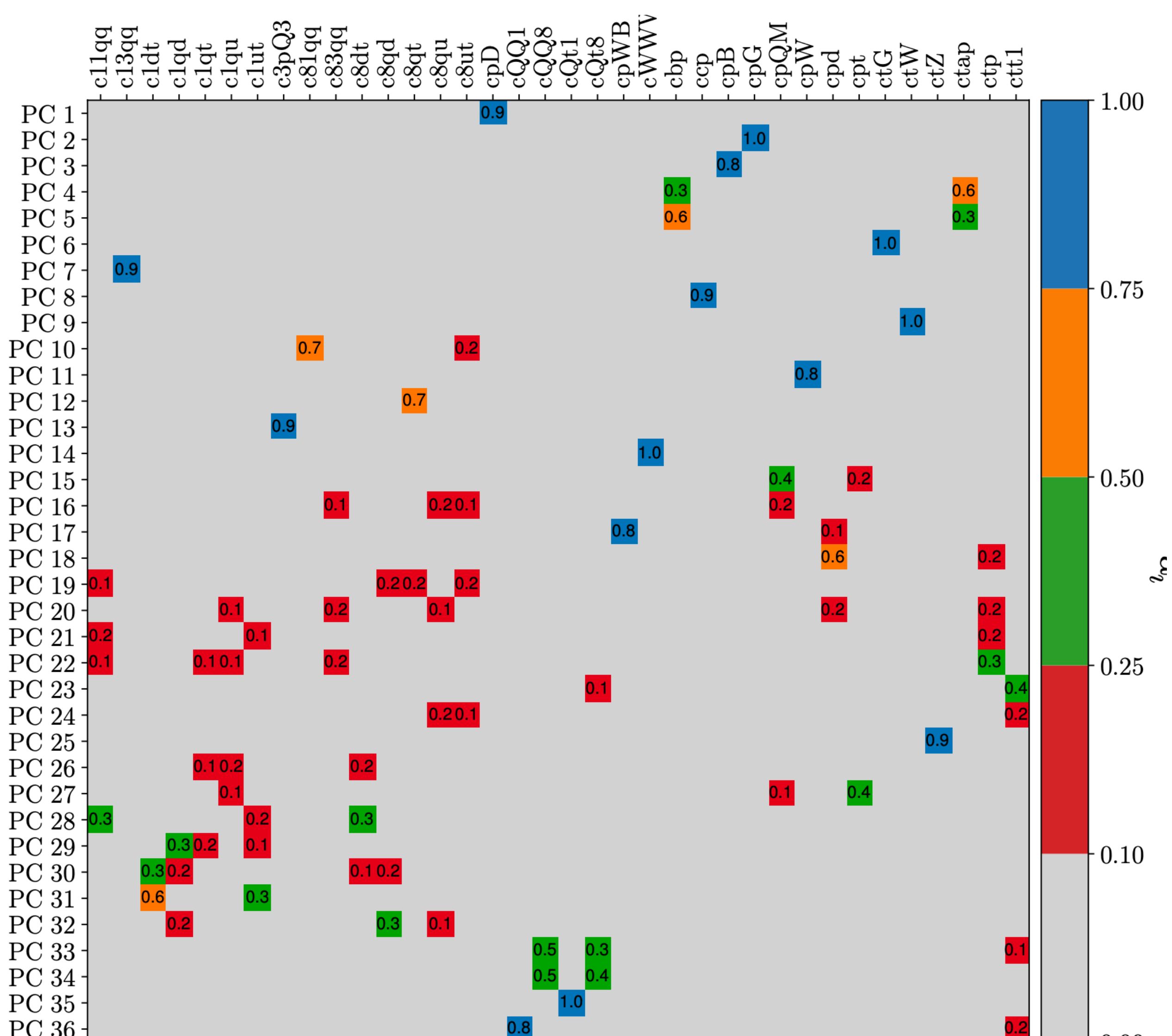


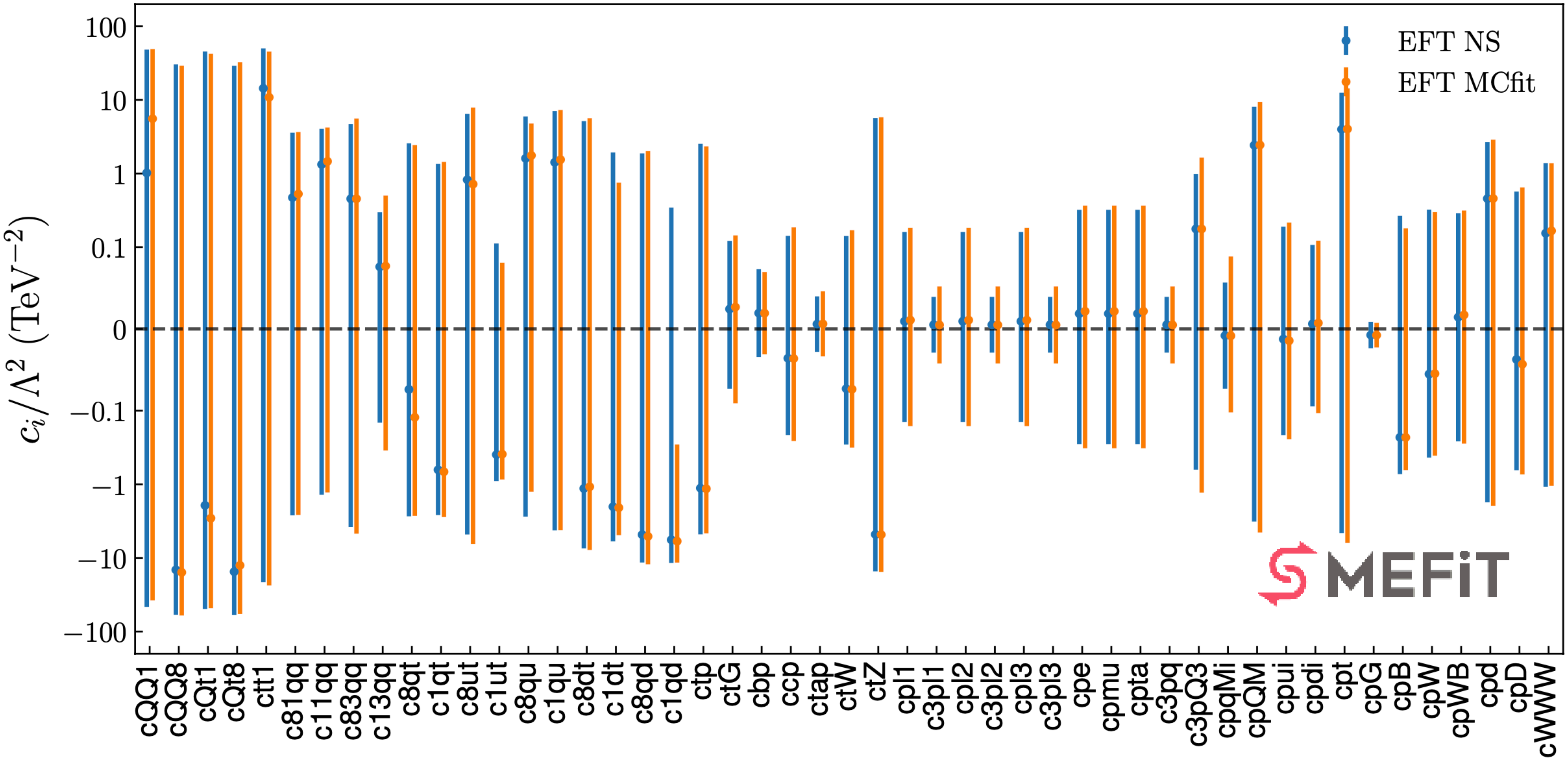
Quantifying EFT sensitivity





- Identify **flat directions** (in linear EFT fit) and which coefficient combinations have the higher variance
- Determine which coefficients are determined by one or a few processes, and which ones only enter at the level of linear combinations of many coefficients
- Some EFT parameters represent ``**natural directions**'', other always appear in combination with several other coefficients
- Powerful tool to understand fit results, eventually could be used to **fit in the PCA basis** (though this is not required)

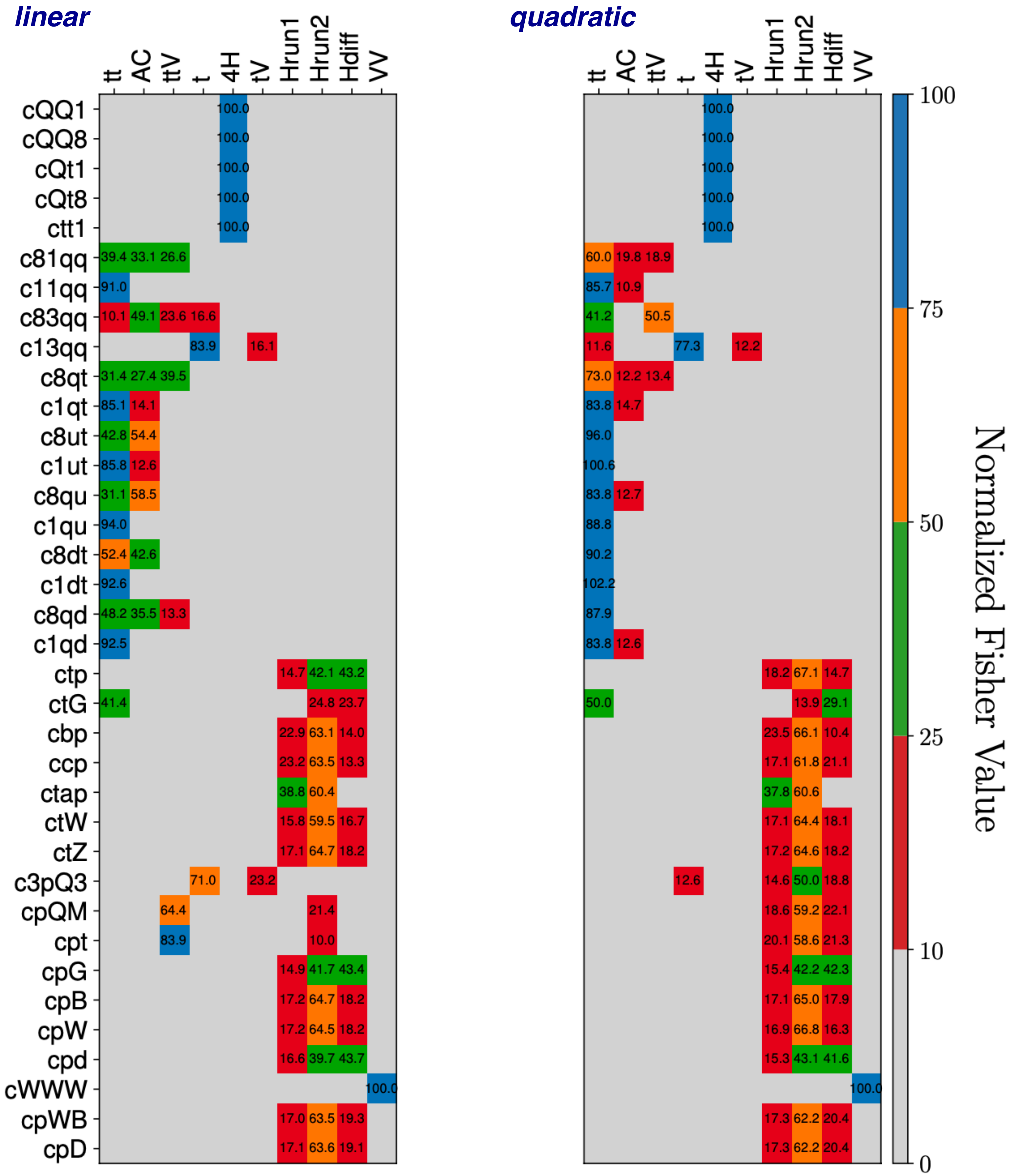
Fitting methodology



Median and 95% CL intervals for the **50 EFT parameters** considered in this analysis in linear fit

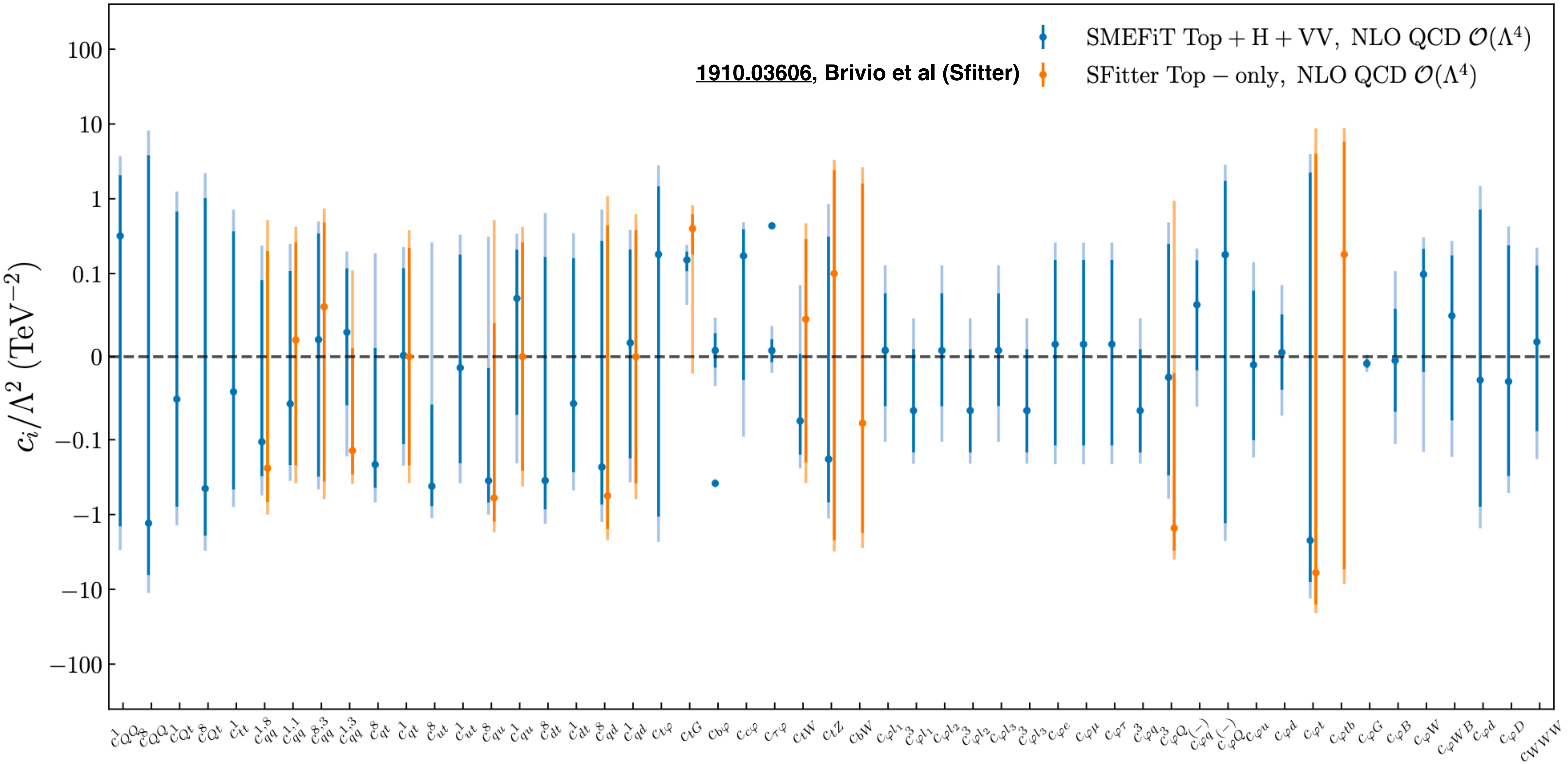
Equivalent results obtained with **MCfit** and **NS**: mutual validation of fit outcome

Quantifying EFT sensitivity



- Compare **relative impact of each process** on a given EFT coefficient
- Four-fermion operators constrained (mostly) by top data, two-fermion and purely bosonic (mostly) by Higgs
- **Sensitivity** depends on linear vs quadratic, but also LO vs NLO EFT
- Can be used at a finer level, *e.g.* identify **which differential distribution** of a given measurement carries more weight in the EFT fit

Comparison with SFitter (top-only)



global fit marginalised, 68% and 95% CL ranges (*not a tuned comparison*)