The Standard Model EFT:

The top quark sector

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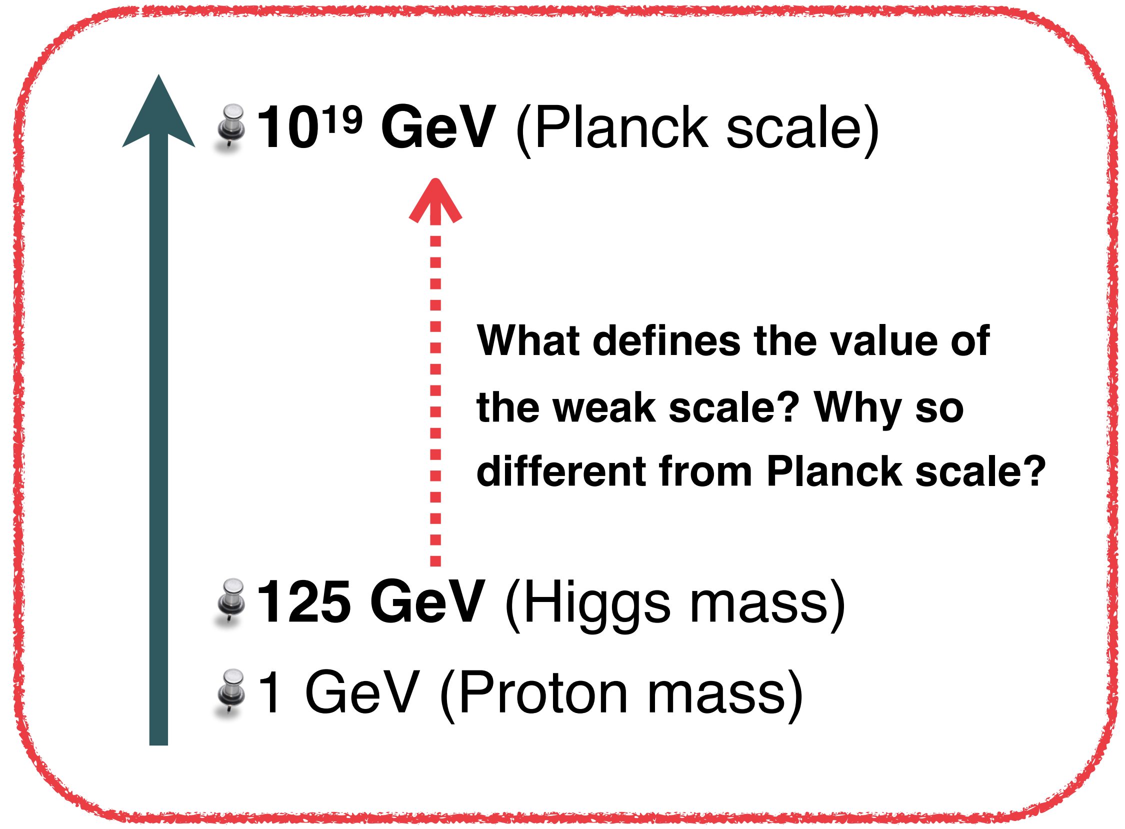
Nikhef Topical Lectures on Flavour Physics and CP violation

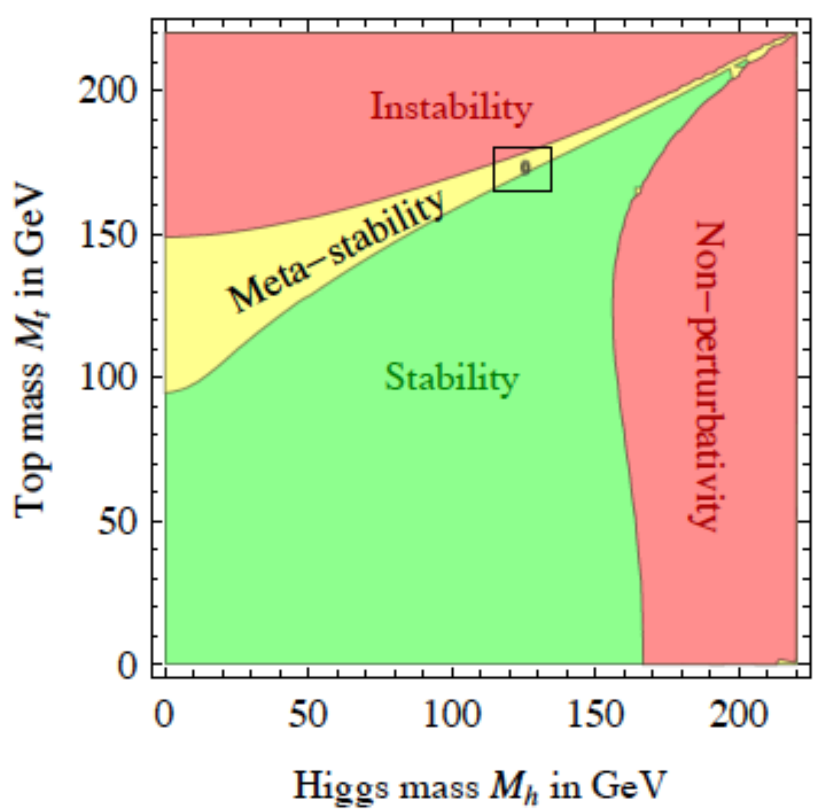
14th June 2019

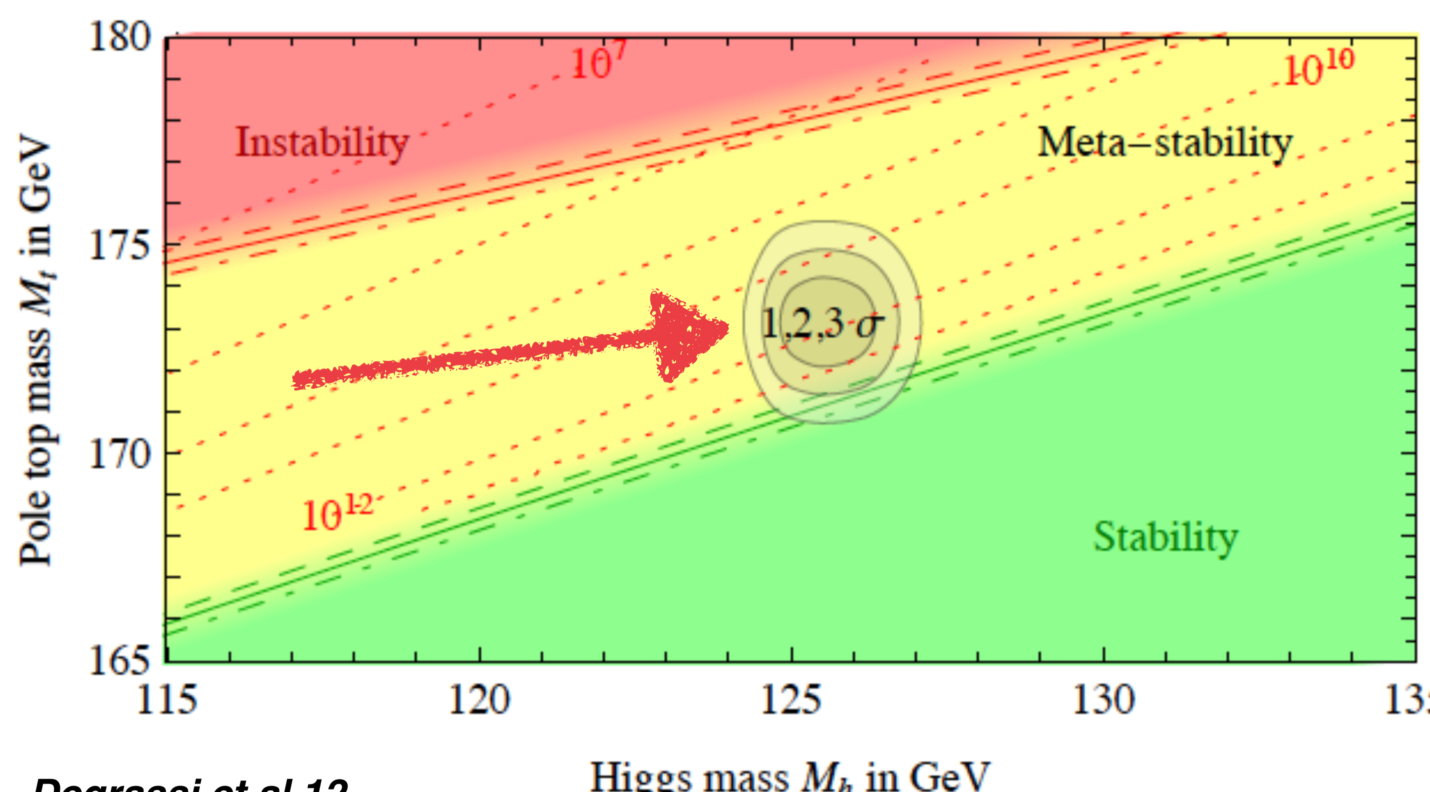
Open questions in particle physics

The Higgs boson

- Huge gap between **weak** and **Plank scales?**
- **Compositeness**? Non-minimal Higgs sector?
- Coupling to **Dark Matter**? Role in cosmological phase transitions?
- Is the **vacuum state of the Universe** stable?







Degrassi et al 12

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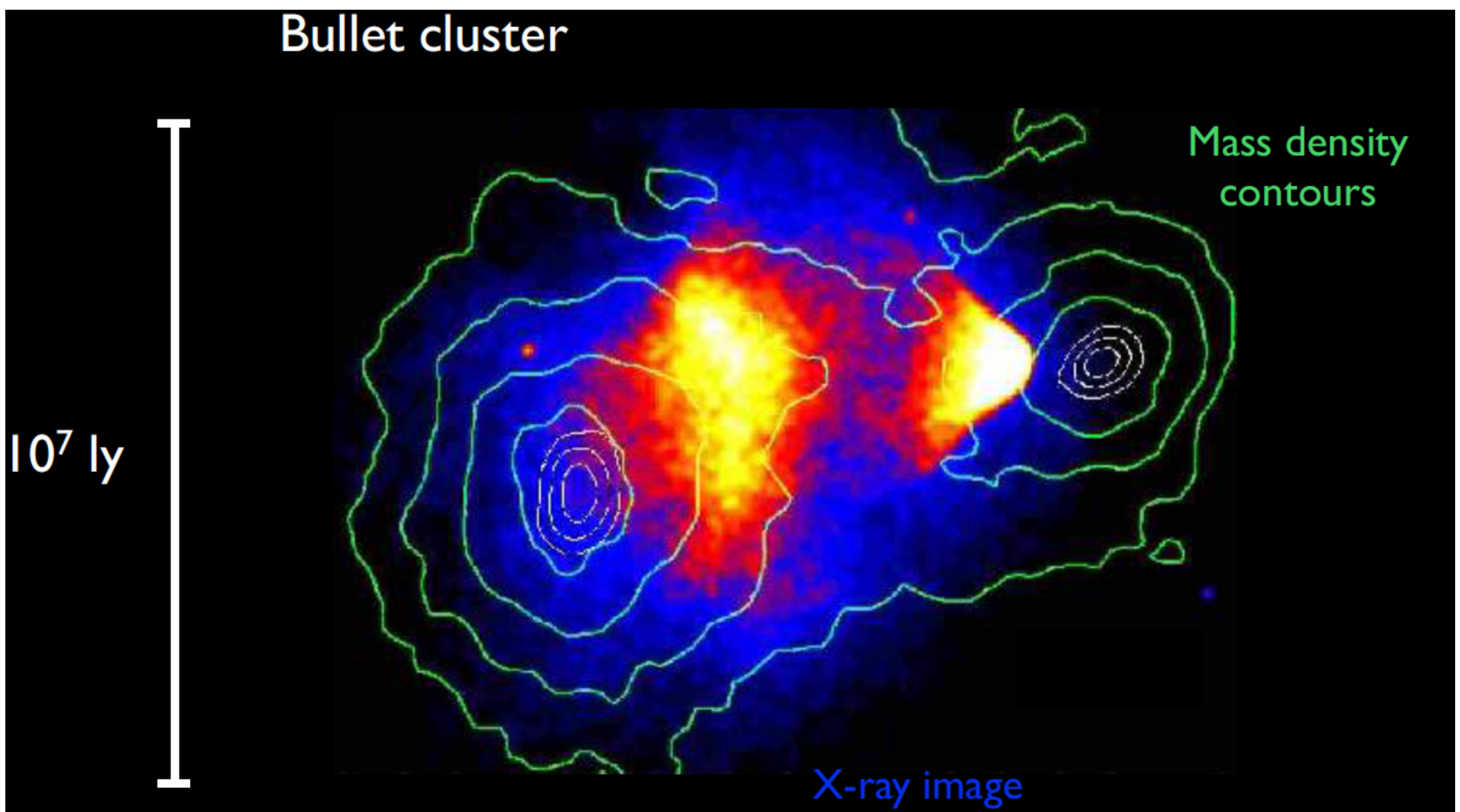
Dark matter

- **Weakly interacting massive particles**? Neutrinos? Ultralight particles (axions)?
- **Interactions** with SM particles? Self-interactions?
- **Structure** of the Dark Sector?



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Quarks and leptons

- Why **3 families?** Origin of **masses, mixings**?
- Origin of **Matter-Antimatter asymmetry?**
- Origin of **neutrino masses? Are neutrinos Majorana or Dirac**? CP violation in the lepton sector?

Dark matter

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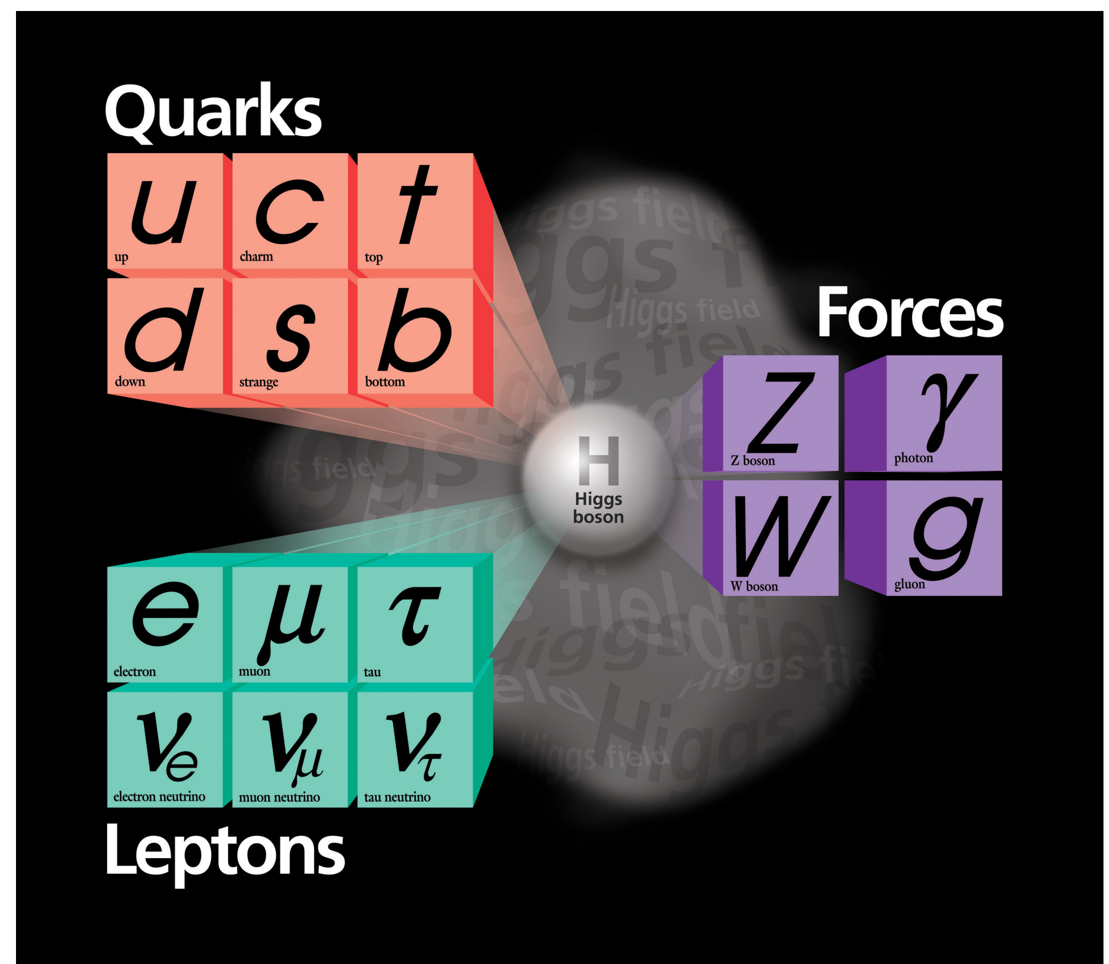
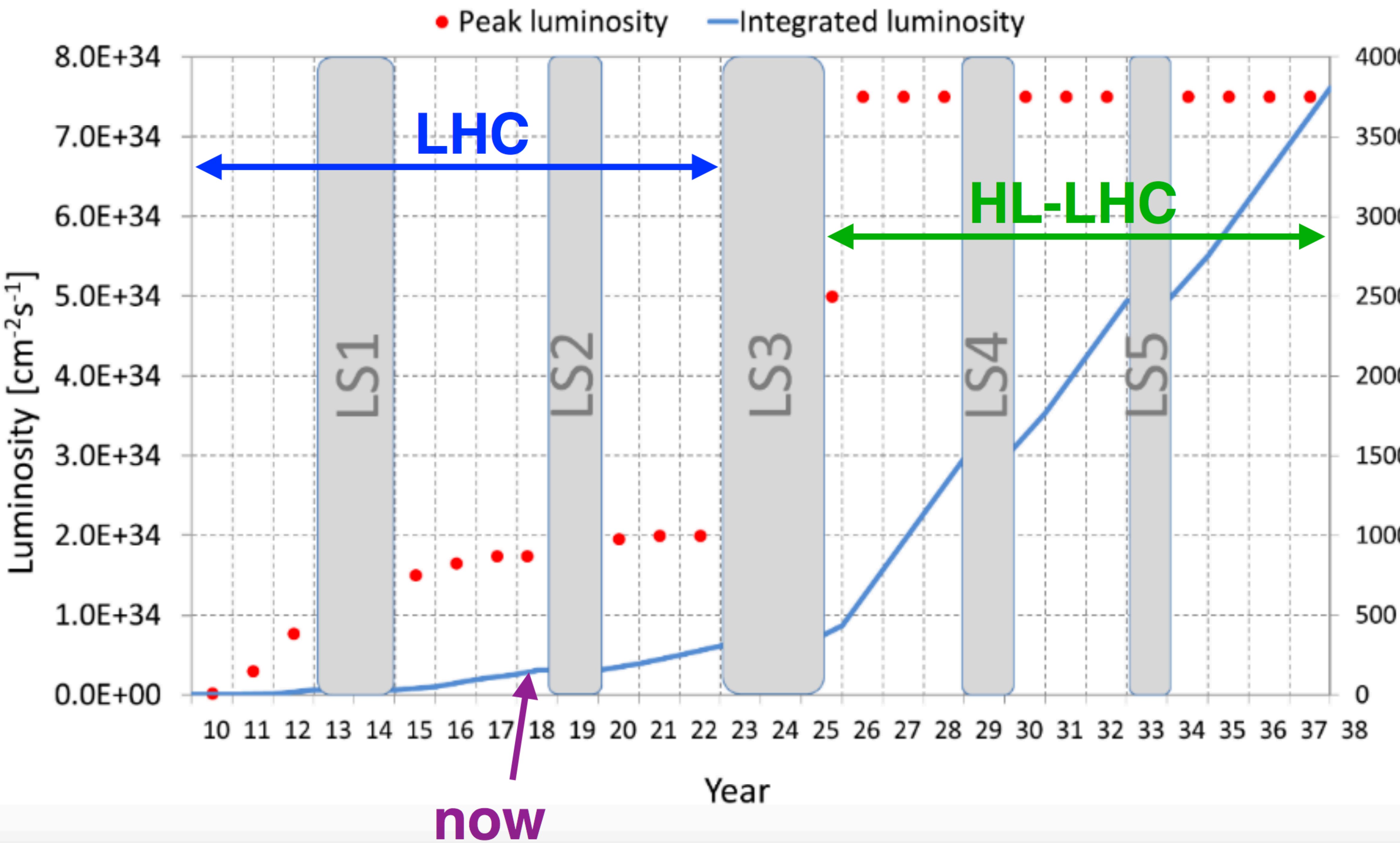


Open questions in particle physics

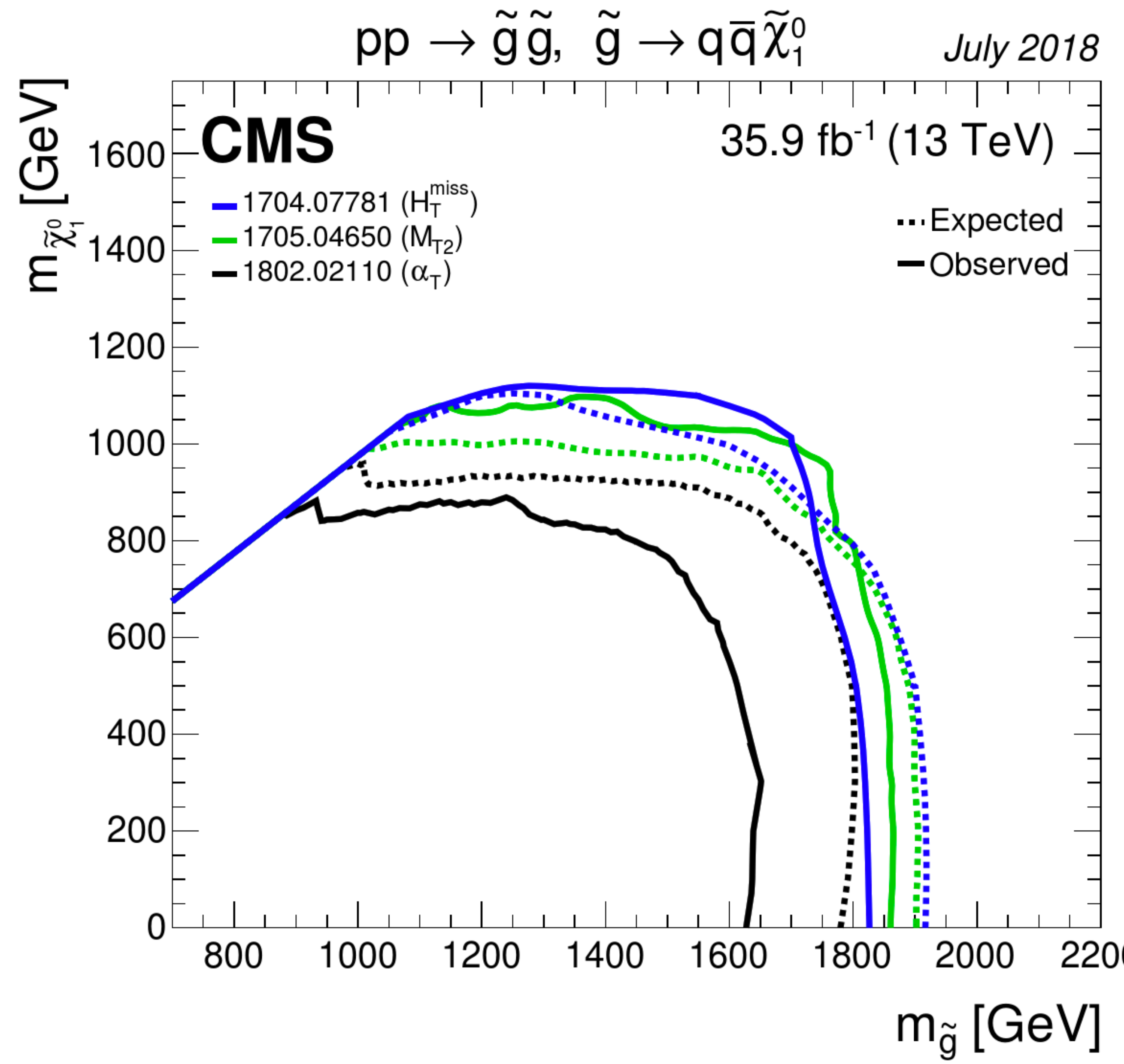


Crucial information on these fundamental questions will be provided by the LHC: the **exploration of the high-energy frontier** has just started!

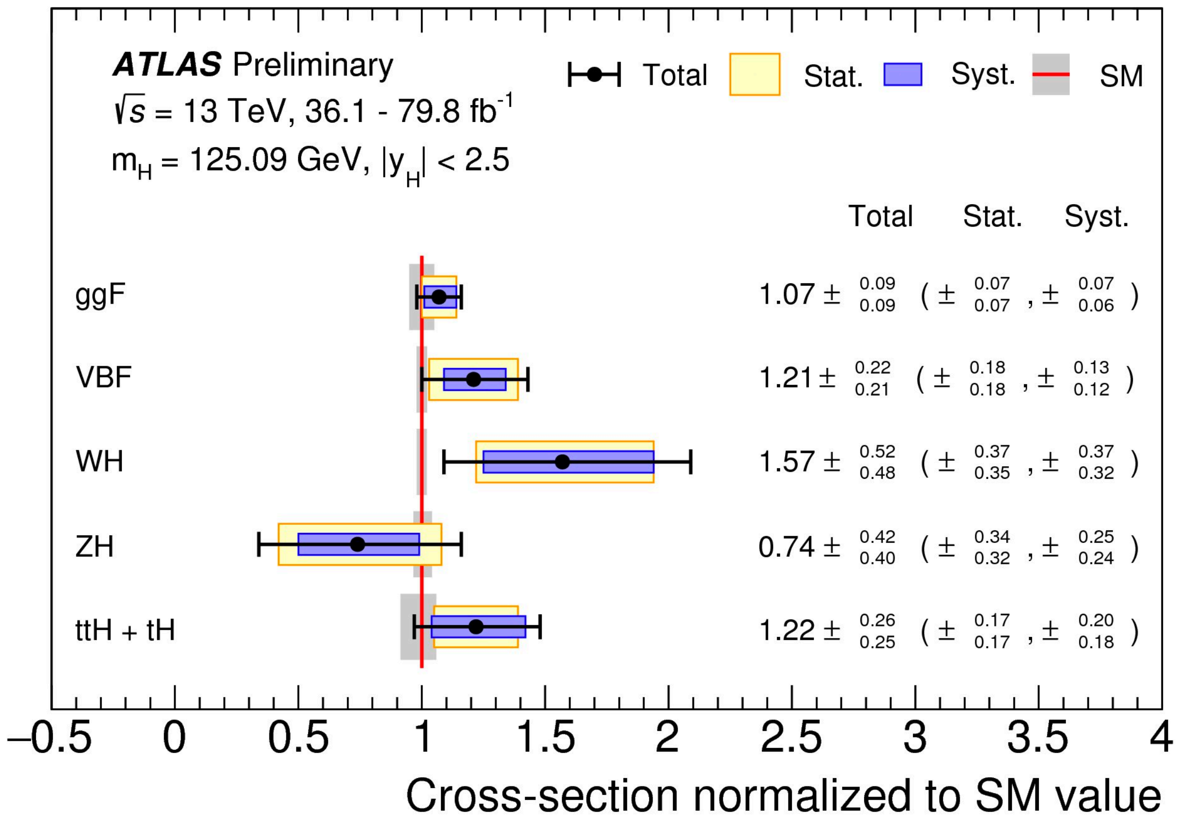
The quest for New Physics at the LHC

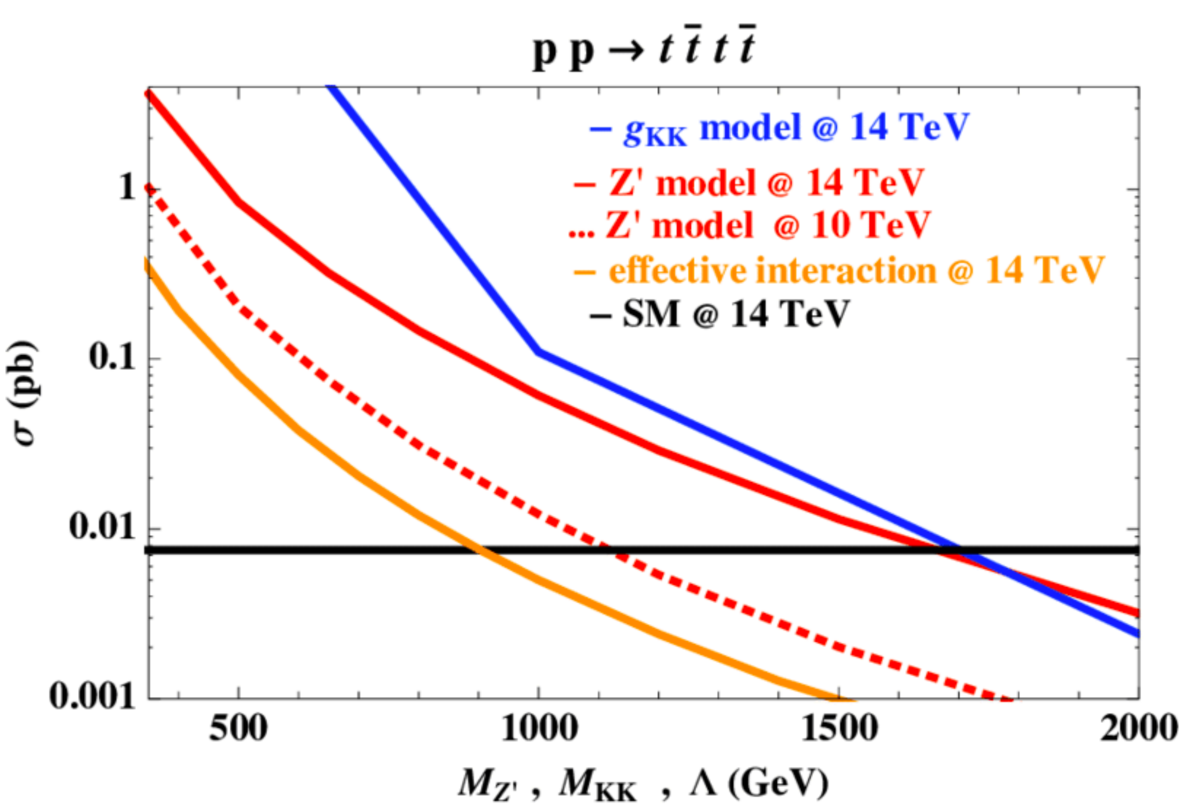
Model-Dependent Searches

- Map parameter space of **specific theories**, or specific realisations of theories (SUSY, Higgs compositeness, …)
- **Reinterpretation/recasting** challenging, since requires Monte Carlo showering, detector simulation, …
- Ad-hoc **restrictions of the BSM parameter space** to facilitate interpretation
- Sensitive to **O(1) deviations**



The quest for New Physics at the LHC





Model-Independent Searches

- ``**SM" measurements** to constrain BSM
- Allows the use of **highest possible precision** in theory calculations
- Interpreted in **multiple BSM frameworks** (including those not thought of yet!)
- In the long-term, measurements have the **largest impact** in the HEP community
- Sensitive to **O(0.1) or O(0.01) deviations**

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The Standard Model Effective Field Theory

The Standard Model EFT

Systematic parametrisation of the **theory space** in vicinity of Standard Model

$$\mathcal{L}_{\rm SMEFT} = \mathcal{L}_{\rm SM} + \sum_i^{N_{d6}} \frac{c_i}{\Lambda^2}\mathcal{O}_i^{(6)} + \sum_j^{N_{d8}} \frac{b_j}{\Lambda^4}\mathcal{O}_j^{(8)} + \ldots$$

- ☑ SMEFT: **low-energy limit** of generic UV-complete theories at high energies
- ☑ Assumes **SM field content and symmetries** (except the accidental ones!)
- ☑ **Complete basis** at any given mass-dimension
- ☑ **Fully renormalizable**, full-fledged QFT: can compute higher orders in QCD and EW
- ☑ Can be matched to **any BSM model** that reduces to the SM at low energies

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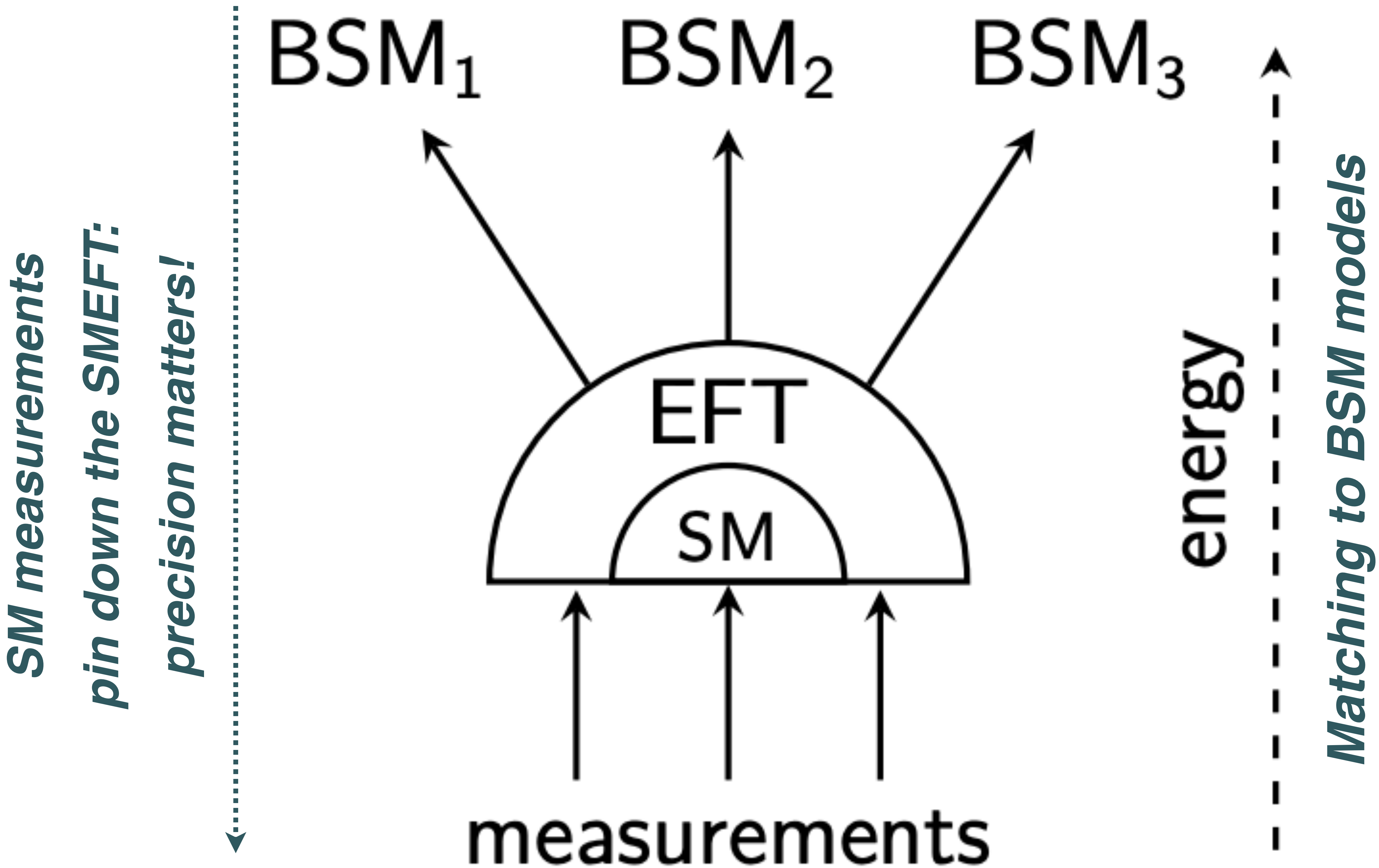
(...) if one writes down the most general possible Lagrangian, including all *terms consistent with assumed symmetry principles, (...) the result will simply be the most general possible S-matrix consistent with analyticity, perturbative unitarity, cluster decomposition and the assumed symmetry.* [*Phenomenological Lagrangians*, Weinberg '79]

The Standard Model EFT



The Standard Model EFT

- Heavy bSM physics beyond the direct reach of the LHC can be **parametrised in a model-independent** in terms of complete basis of **higher-dimensional operators**

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- Some operators induce **growth with the partonic centre-of-mass energy**: increased sensitivity in LHC cross-sections in the TeV region

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

enhanced sensitivity from ***TeV-scale processes:***
unique feature of LHC

The Standard Model EFT

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- The number of SMEFT operators is large: **59 non-redundant operators at dimension 6** with Minimal Flavour Violation, **> 2000 operators** without any flavour assumption

- A global SMEFT analysis needs to explore a **huge complicated parameter space**

The Standard Model EFT

Operators involving up-type quarks in the *Warsaw* basis: [Grzadkowski et al '10]

Four-quark operators (11)

$$O_{qq}^{1(ijkl)} = (\bar{q}_i\gamma^\mu q_j)(\bar{q}_k\gamma_\mu q_l),$$
$$O_{qq}^{3(ijkl)} = (\bar{q}_i\gamma^\mu\tau^I q_j)(\bar{q}_k\gamma_\mu\tau^I q_l),$$
$$O_{qu}^{1(ijkl)} = (\bar{q}_i\gamma^\mu q_j)(\bar{u}_k\gamma_\mu u_l),$$
$$O_{qu}^{8(ijkl)} = (\bar{q}_i\gamma^\mu T^A q_j)(\bar{u}_k\gamma_\mu T^A u_l),$$
$$O_{qd}^{1(ijkl)} = (\bar{q}_i\gamma^\mu q_j)(\bar{d}_k\gamma_\mu d_l),$$
$$O_{qd}^{8(ijkl)} = (\bar{q}_i\gamma^\mu T^A q_j)(\bar{d}_k\gamma_\mu T^A d_l),$$
$$O_{uu}^{(ijkl)} = (\bar{u}_i\gamma^\mu u_j)(\bar{u}_k\gamma_\mu u_l),$$
$$O_{ud}^{1(ijkl)} = (\bar{u}_i\gamma^\mu u_j)(\bar{d}_k\gamma_\mu d_l),$$
$$O_{ud}^{8(ijkl)} = (\bar{u}_i\gamma^\mu T^A u_j)(\bar{d}_k\gamma_\mu T^A d_l),$$
$$O_{quqd}^{1(ijkl)} = (\bar{q}_i u_j)\,\varepsilon\,(\bar{q}_k d_l),$$
$$O_{quqd}^{8(ijkl)} = (\bar{q}_i T^A u_j)\,\varepsilon\,(\bar{q}_k T^A d_l),$$

Two-quark operators (9)

$$O_{u\varphi}^{(ij)} = \bar{q}_i u_j \tilde{\varphi}\,(\varphi^\dagger\varphi),$$
$$O_{\varphi q}^{1(ij)} = (\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{q}_i\gamma^\mu q_j),$$
$$O_{\varphi q}^{3(ij)} = (\varphi^\dagger i\overleftrightarrow{D}^I_\mu\varphi)(\bar{q}_i\gamma^\mu\tau^I q_j),$$
$$O_{\varphi u}^{(ij)} = (\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{u}_i\gamma^\mu u_j),$$
$$O_{\varphi ud}^{(ij)} = (\tilde{\varphi}^\dagger iD_\mu\varphi)(\bar{u}_i\gamma^\mu d_j),$$
$$O_{uW}^{(ij)} = (\bar{q}_i\sigma^{\mu\nu}\tau^I u_j)\,\tilde{\varphi}\,W^I_{\mu\nu},$$
$$O_{dW}^{(ij)} = (\bar{q}_i\sigma^{\mu\nu}\tau^I d_j)\,\varphi\,W^I_{\mu\nu},$$
$$O_{uB}^{(ij)} = (\bar{q}_i\sigma^{\mu\nu} u_j)\quad\tilde{\varphi}\,B_{\mu\nu},$$
$$O_{uG}^{(ij)} = (\bar{q}_i\sigma^{\mu\nu} T^A u_j)\,\tilde{\varphi}\,G^A_{\mu\nu},$$

Two-quark-two-lepton operators (8)

$$O_{lq}^{1(ijkl)} = (\bar{l}_j\gamma^\mu l_j)(\bar{q}_k\gamma^\mu q_l),$$
$$O_{lq}^{3(ijkl)} = (\bar{l}_j\gamma^\mu\tau^I l_j)(\bar{q}_k\gamma^\mu\tau^I q_l),$$
$$O_{lu}^{(ijkl)} = (\bar{l}_j\gamma^\mu l_j)(\bar{u}_k\gamma^\mu u_l),$$
$$O_{eq}^{(ijkl)} = (\bar{e}_j\gamma^\mu e_j)(\bar{q}_k\gamma^\mu q_l),$$
$$O_{eu}^{(ijkl)} = (\bar{e}_j\gamma^\mu e_j)(\bar{u}_k\gamma^\mu u_l),$$
$$O_{lequ}^{1(ijkl)} = (\bar{l}_i e_j)\,\varepsilon\,(\bar{q}_k u_l),$$
$$O_{lequ}^{3(ijkl)} = (\bar{l}_i\sigma^{\mu\nu} e_j)\,\varepsilon\,(\bar{q}_k\sigma_{\mu\nu} u_l),$$
$$O_{ledq}^{(ijkl)} = (\bar{l}_i e_j)(\bar{d}_k q_l),$$

$\not{B}$ and $\not{L}$ operators (5)

$$O_{duq}^{(ijkl)} = (\overline{d^c}_{i\alpha} u_{j\beta})(\overline{q^c}_{k\gamma}\varepsilon l_l)\,\epsilon^{\alpha\beta\gamma},$$
$$O_{qqu}^{(ijkl)} = (\overline{q^c}_{i\alpha}\varepsilon q_{j\beta})(\overline{u^c}_{k\gamma} e_l)\,\epsilon^{\alpha\beta\gamma},$$
$$O_{qqq}^{1(ijkl)} = (\overline{q^c}_{i\alpha}\varepsilon q_{j\beta})(\overline{q^c}_{k\gamma}\varepsilon l_l)\,\epsilon^{\alpha\beta\gamma},$$
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$$O_{duu}^{(ijkl)} = (\overline{d^c}_{i\alpha} u_{j\beta})(\overline{u^c}_{k\gamma} e_l)\,\epsilon^{\alpha\beta\gamma}.$$

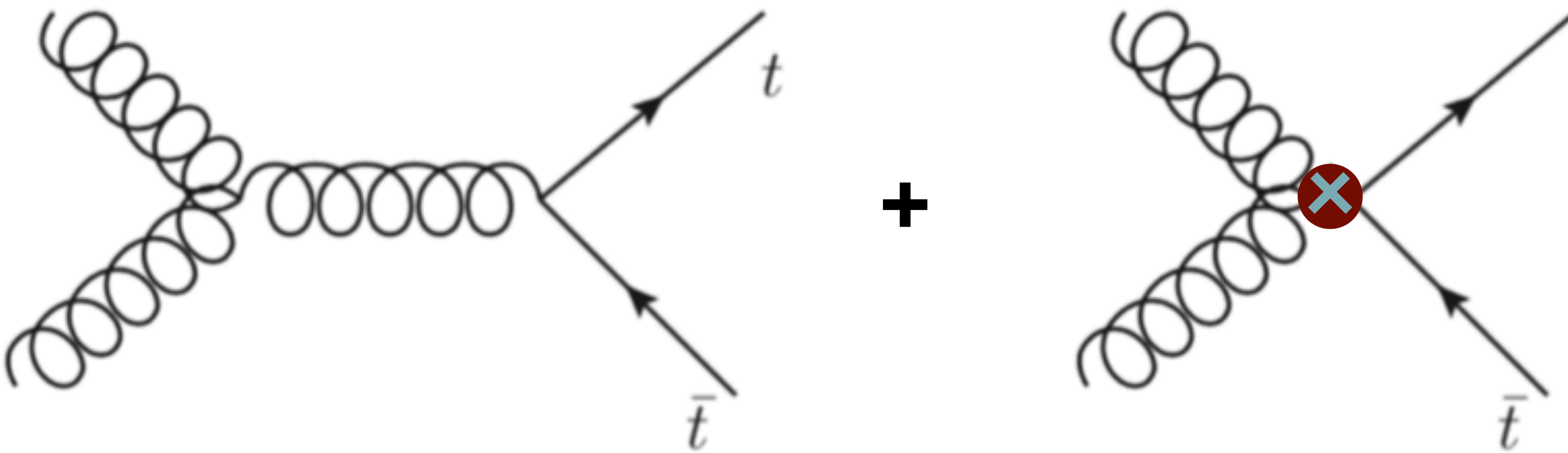
+ *ijkl* generation index assignments

q, l: left-handed doublets
u, d, e: right-h. singlets

SMEFT effects

Standard Model

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



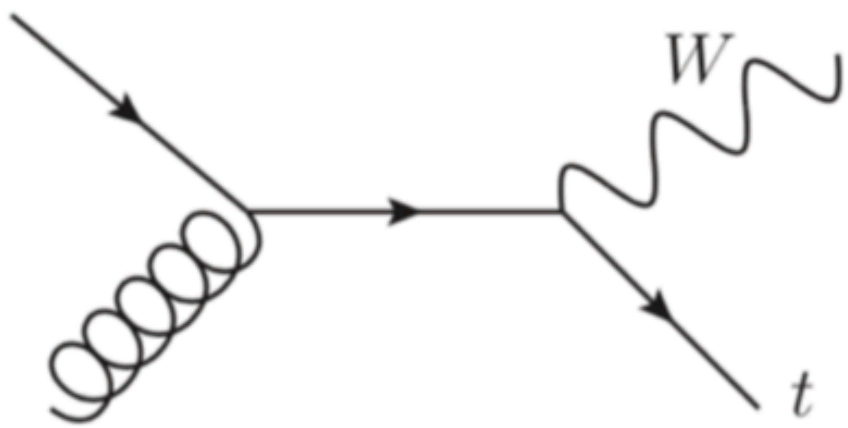
$$= \sigma_{SM} \times \left(1 + a\frac{c_{tG}}{\Lambda^2} + b\frac{c_{tG}^2}{\Lambda^4} \right)$$

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

SMEFT effects

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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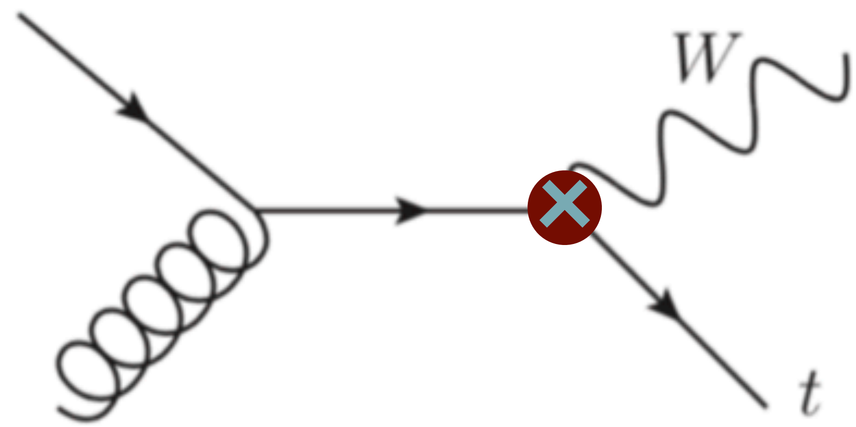

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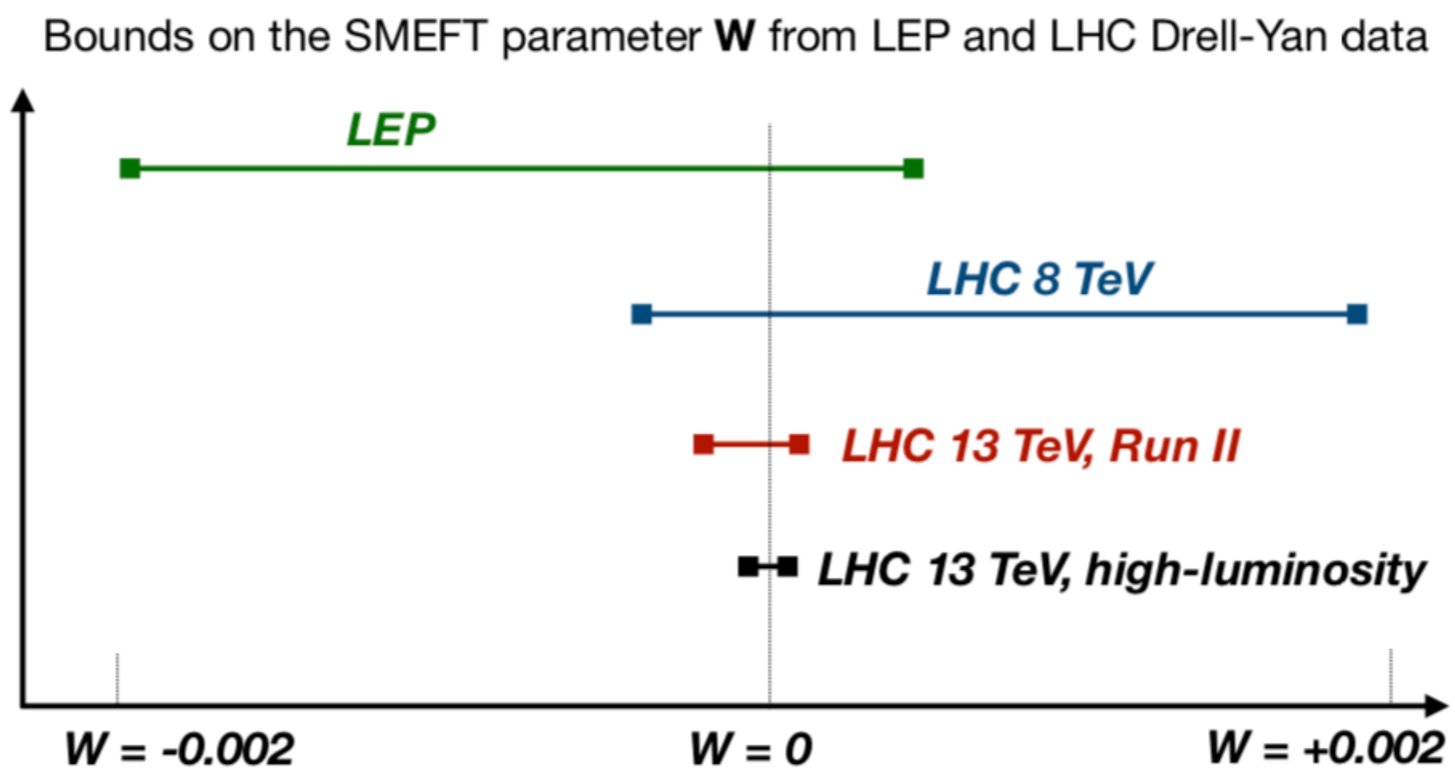
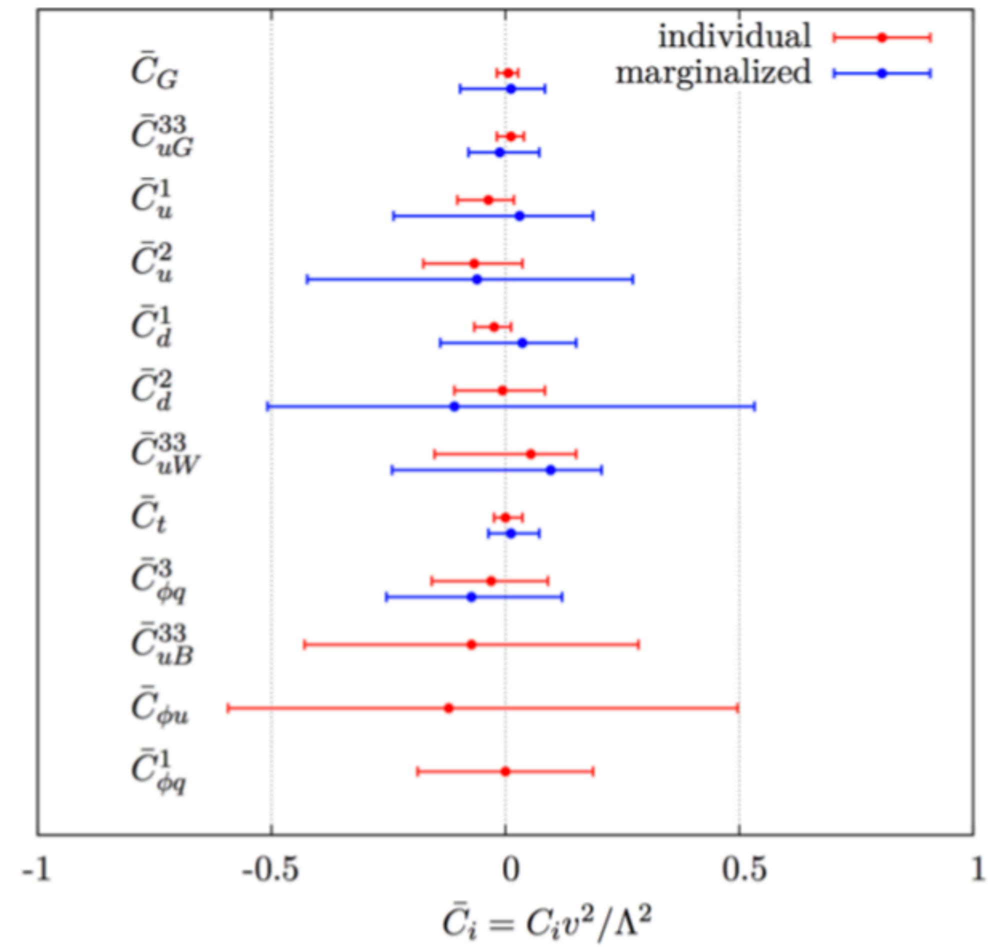
SMEFT constraints from LHC





- LHC data can markedly improve the LEP bounds on SMEFT coefficients: **Precision Electroweak Tests at hadron colliders**

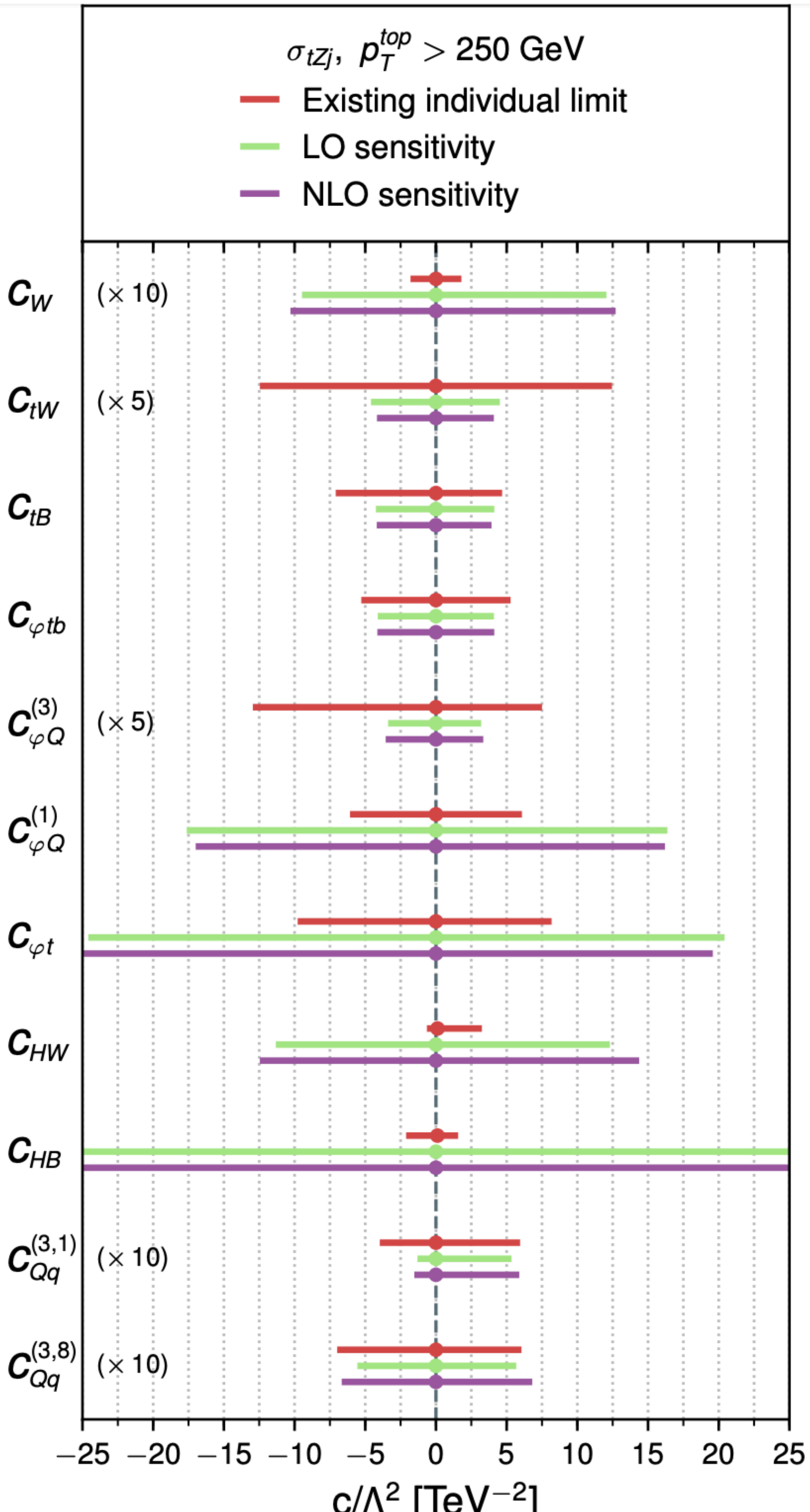
Farina et al PLB (16)

- Varying all parameters simultaneously results in **looser bounds** that varying a few parameters at a time due to degeneracies in parameter space

TopFitter, Buckley et al, JHEP (15)

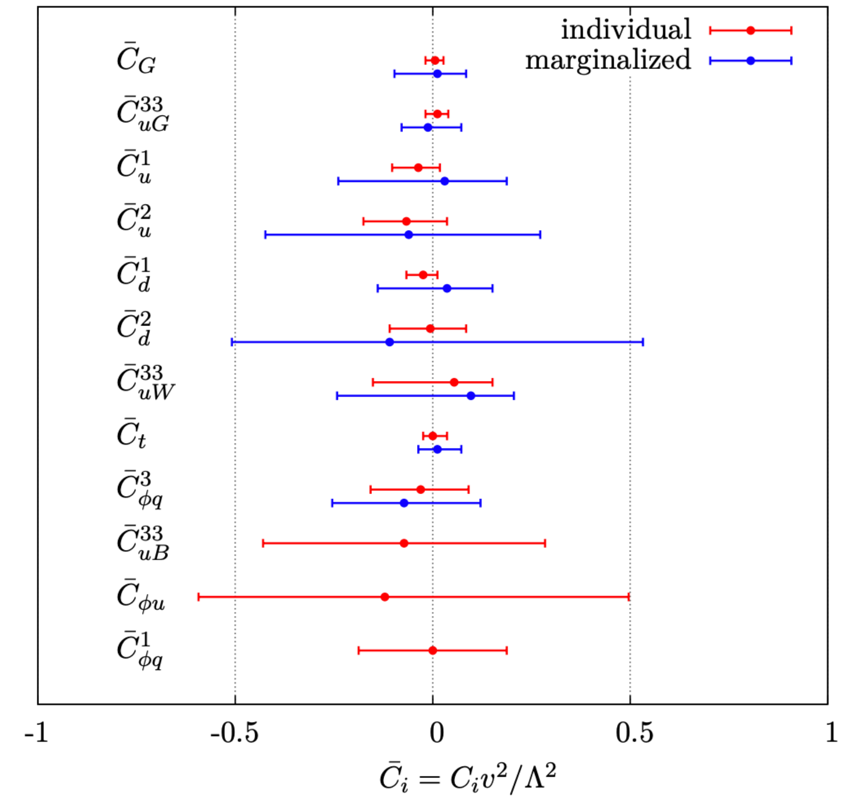
SMEFT constraints from LHC

Exploit **rarer processes** at LHC eg ***t+Z+j***



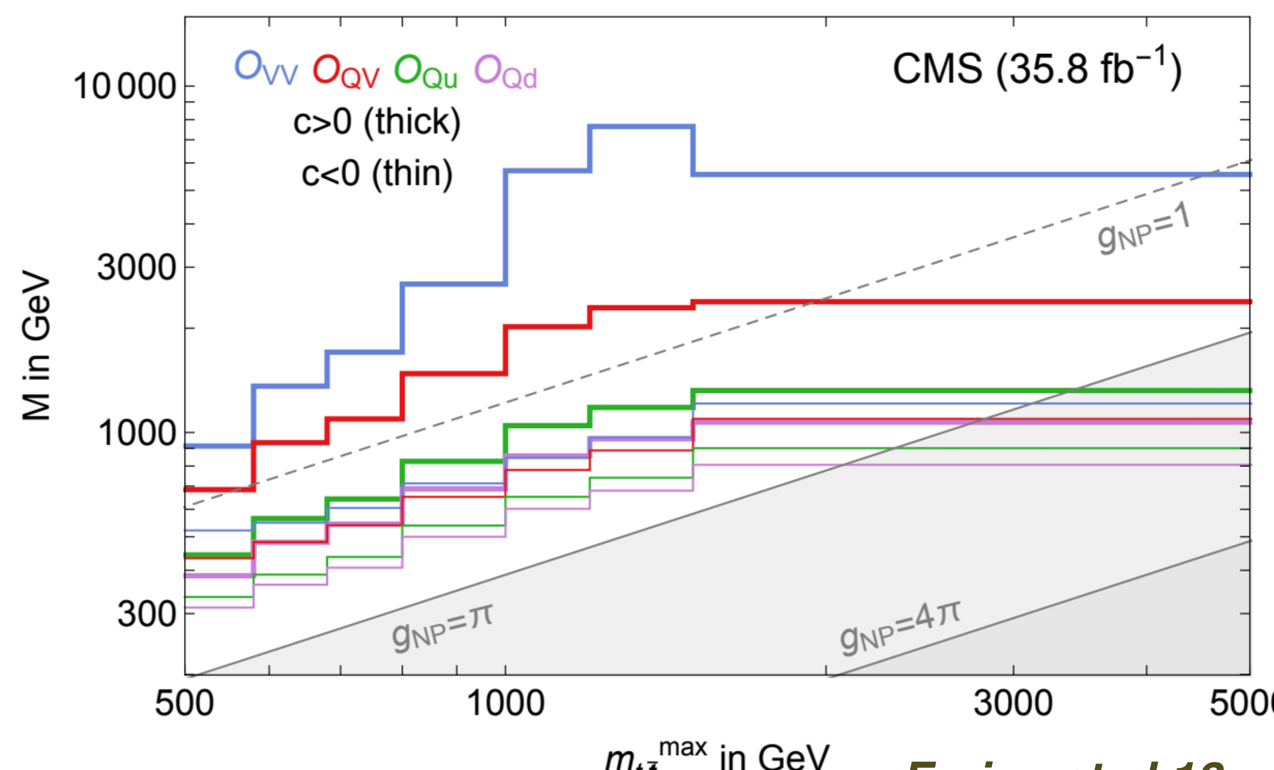
Degrande et al 18

Combine **different processes** in global fit



TopFitter 15

Enhance sensitivity from **high-energy m_{tt} tail**



Farina et al 18

Recipe for a global SMEFT analysis

Theory

(N)NLO QCD + NLO EW for SM xsecs

NLO QCD for SMEFT contributions

State-of-the-art Parton Distributions

Data

Higgs and **gauge boson** production

Top quark and **jet** production

Precision LEP, low energies, **flavour**

Global SMEFT fit

Bounds can be compared with

specific UV completions

New data incorporated without redoing fit

Delivery

Efficient exploration of **parameter space**

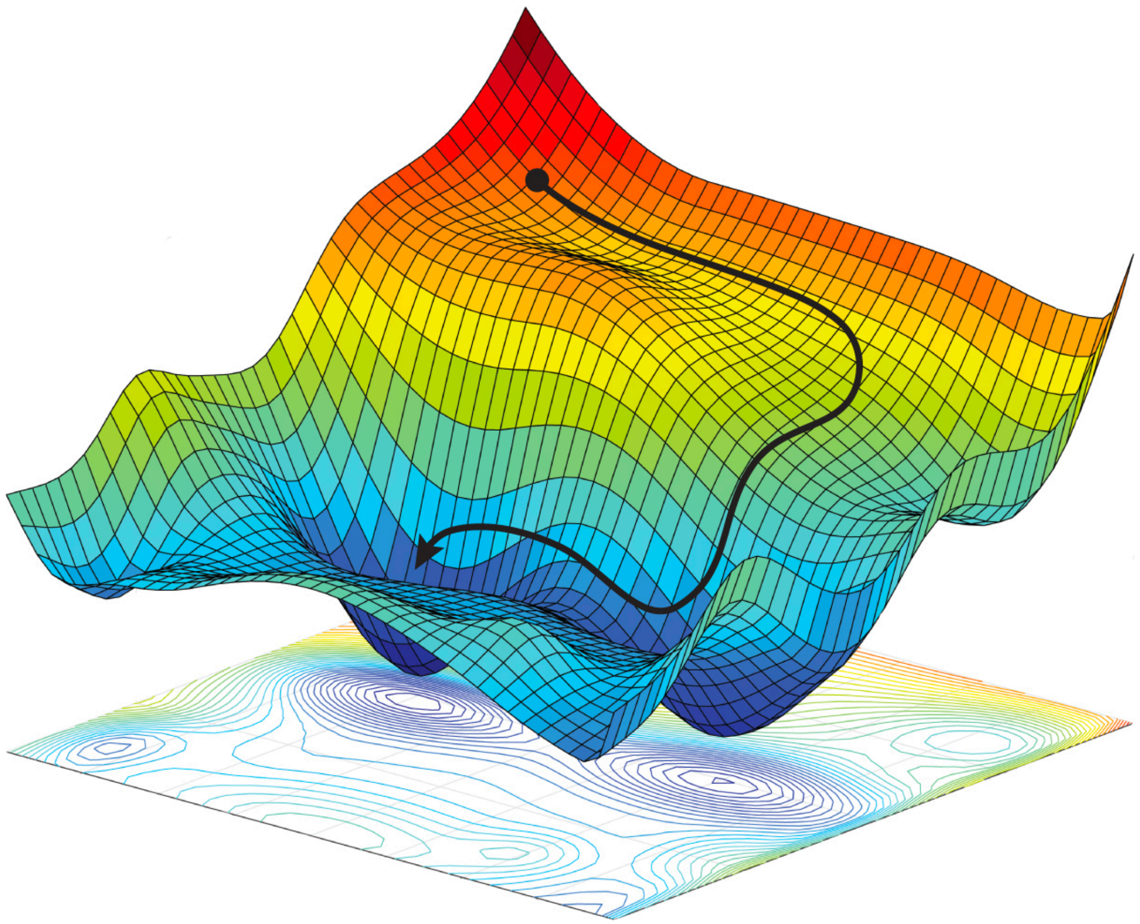
Faithful **uncertainty estimate**

Avoiding under- and over-fitting

Methodology

The optimisation conundrum

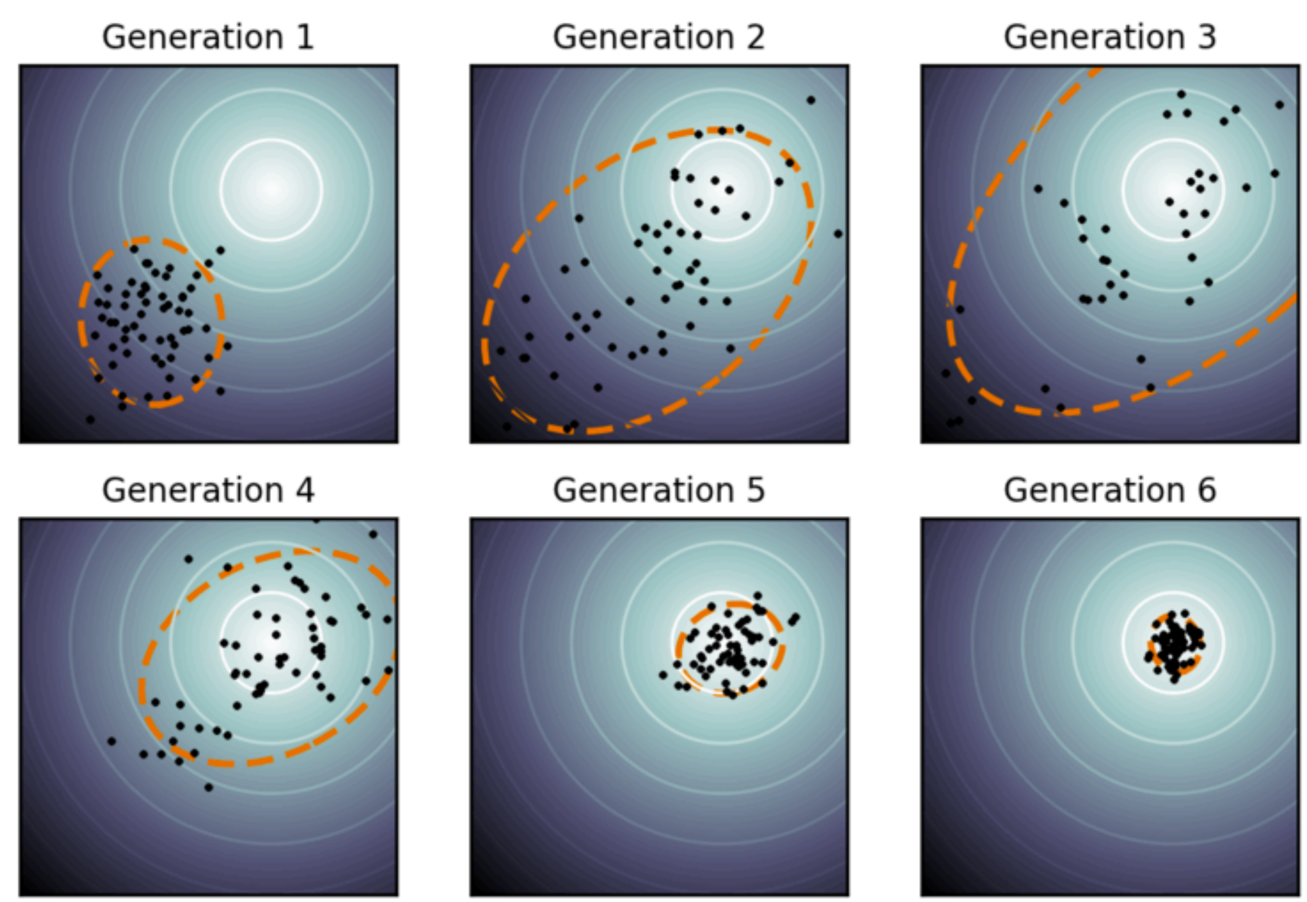
(Stochastic) Gradient Descent



- A challenge for any SMEFT global analysis is the efficient exploration of the **huge parameter space**

- Several pitfalls to be avoided: under-fitting, over-fitting, **local minima**, saddle points, ….

Genetic Algorithms



- **Deterministic algorithms**: follow the gradient of the cost function

- **Evolutionary algorithms**: act on population of solutions with random mutations and selection

The optimisation conundrum

https://www.youtube.com/watch?v=RiWc0ZDSTyY

The SMEFiT framework

A Monte Carlo global analysis of the Standard Model Effective Field Theory: the top quark sector*,*

Nathan P. Hartland, Fabio Maltoni, Emanuele R. Nocera, Juan Rojo,

Emma Slade, Eleni Vryonidou, Cen Zhang, arXiv:1901.05965, JHEP in press

The SMEFiT method

- Generate a large sample of **Monte Carlo replicas** to construct the **probability distribution** in the space of experimental data

$$\mathcal{O}_i^{(\mathrm{art})(k)} = S_{i,N}^{(k)} \mathcal{O}_i^{(\mathrm{exp})} \left(1 + \sum_{\alpha=1}^{N_{\mathrm{sys}}} r_{i,\alpha}^{(k)} \sigma_{i,c}^{(\mathrm{sys})} + r_i^{(k)} \sigma_i^{(\mathrm{stat})} \right) , \quad k = 1, \ldots, N_{\mathrm{rep}}$$

cross-section for k-th replica

central value (data)

correlated systematic uncertainties

statistical uncertainties

 # MC replicas

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- Construct theory calculations where the SM is **extended by SMEFT corrections**

to be determined from the data

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

SM: compute at (N)NLO QCD

SMEFT: compute at (N)LO QCD with aMC@NLO

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

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

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- The covariance matrix includes **all sources of experimental errors** + some theory errors

t_0 prescription

$$({\rm cov}_{t_0})_{ij}^{\rm (exp)} \equiv \left(\sigma_i^{\rm (stat)} \right)^2 \delta_{ij} + \left(\sum_{\alpha=1}^{N_{\rm sys}} \sigma_{i,\alpha}^{\rm (sys)} \sigma_{j,\alpha}^{\rm (sys)} \mathcal{O}_i^{\rm (exp)} \mathcal{O}_j^{\rm (exp)} + \sum_{\beta=1}^{N_{\rm norm}} \sigma_{i,\beta}^{\rm (norm)} \sigma_{j,\beta}^{\rm (norm)} \mathcal{O}_i^{\rm (th,0)} \mathcal{O}_j^{\rm (th,0)} \right)$$

$${\rm cov}_{ij} = {\rm cov}_{ij}^{\rm (exp)} + {\rm cov}_{ij}^{\rm (th)}$$

th uncertainties: PDFs

can be extended to MHOUs

$${\rm cov}_{ij}^{\rm (th)} = \left\langle \mathcal{O}_i^{\rm (th)(r)} \mathcal{O}_j^{\rm (th)(r)} \right\rangle_{\rm rep} - \left\langle \mathcal{O}_i^{\rm (th)(r)} \right\rangle_{\rm rep} \left\langle \mathcal{O}_j^{\rm (th)(r)} \right\rangle_{\rm rep} ,$$

The SMEFiT method

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

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

- The covariance matrix includes **all sources of experimental errors** + some theory errors

$${\rm cov}_{ij} = {\rm cov}_{ij}^{(\rm exp)} + {\rm cov}_{ij}^{(\rm th)}$$

- The ensemble of coefficients $\{c_l^{(k)}\}$ then provides a sampling of the **probability density** in the **SMEFT parameter space**

$$\langle c_l \rangle \equiv \frac{1}{N_{\rm rep}} \sum_{k=1}^{N_{\rm rep}} c_l^{(k)} \qquad \rho\left(c_i, c_j\right) = \frac{\frac{1}{N_{\rm rep}} \sum_{k=1}^{N_{\rm rep}} c_i^{(k)} c_j^{(k)} - \langle c_i \rangle \langle c_j \rangle}{\delta c_i \delta c_j} .$$

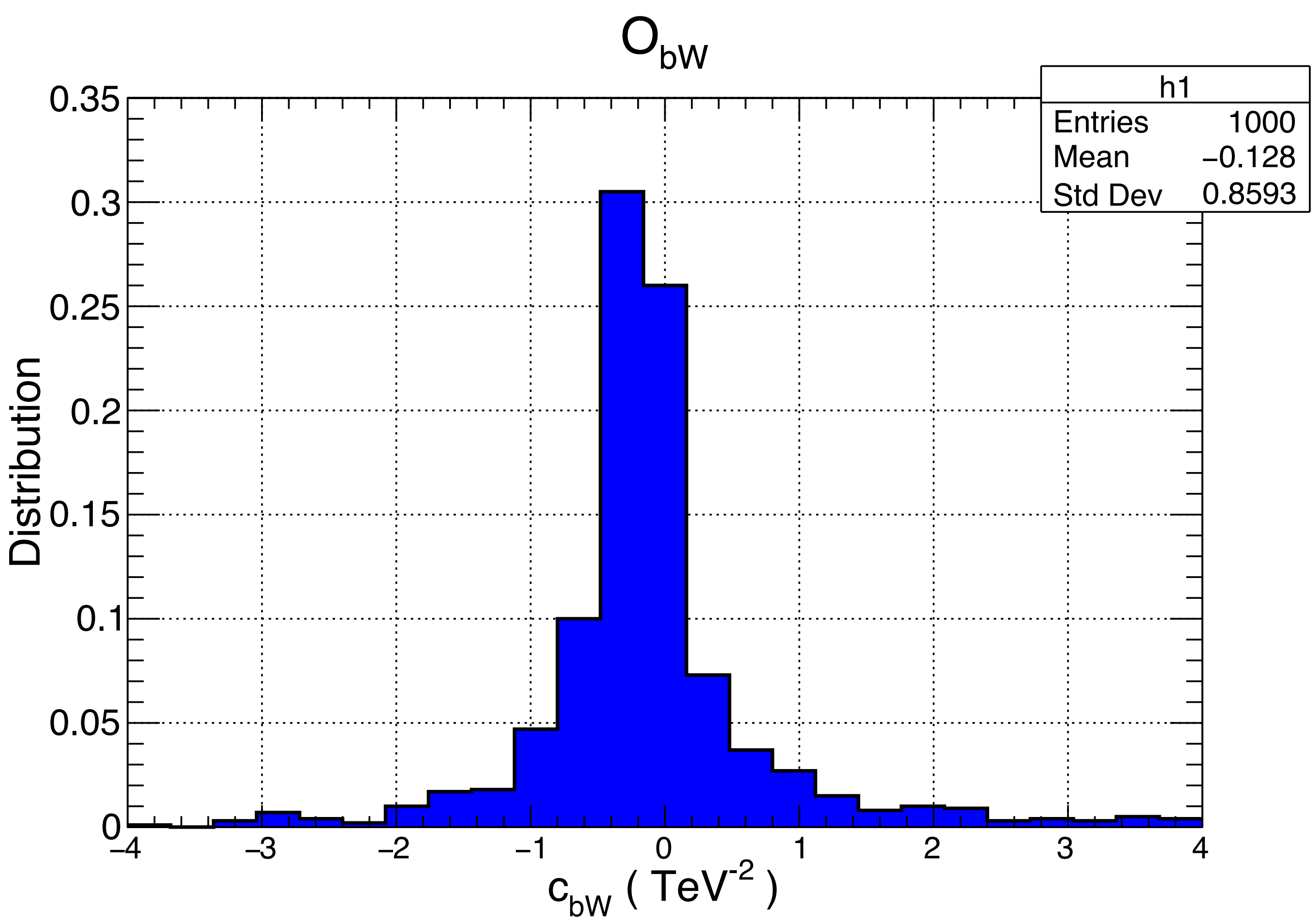
Sampling the SMEFT probability distribution

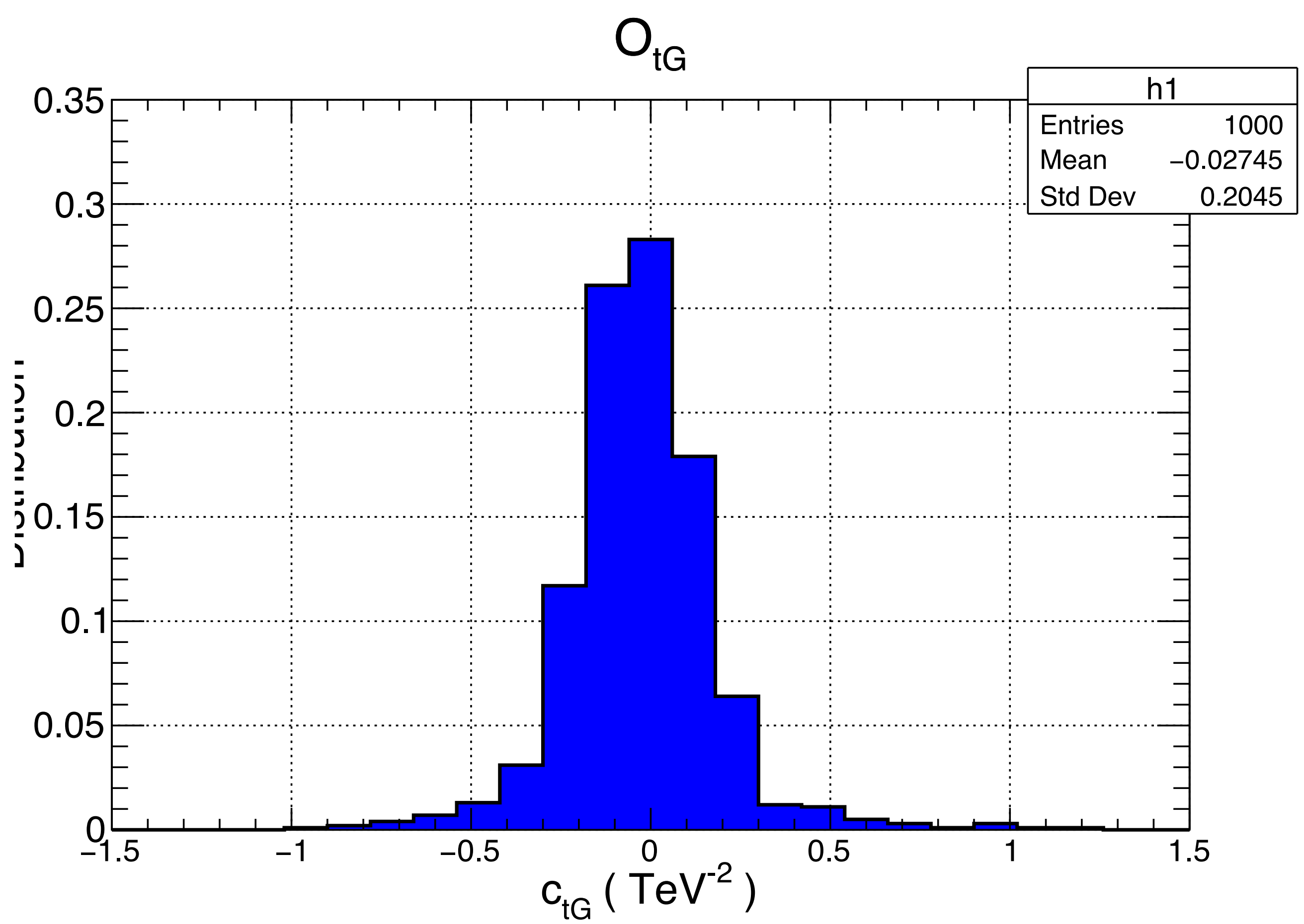
- The output of SMEFiT is a sampling of the **probability distribution** in the SMEFT space

$$\left\{ c_n^{(k)} \right\}, \quad n = 1 \ldots, N_{\rm op}, \quad k = 1 \ldots, N_{\rm rep}$$

- Used to **evaluate statistical estimators** such as variances, correlations, higher moments, …

- Distributions are **reasonably Gaussian** for well-constrained degrees of freedom ….





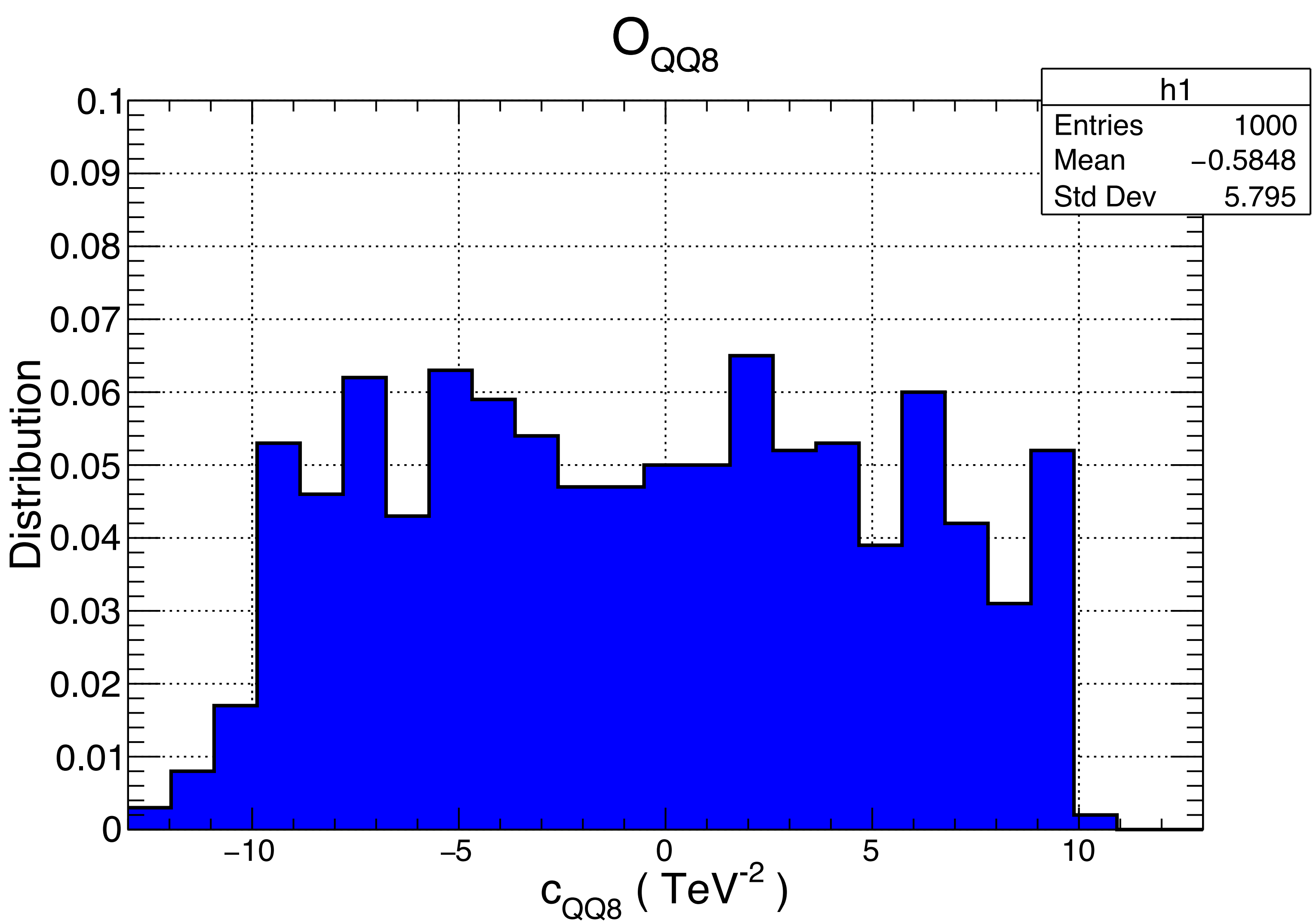
Sampling the SMEFT probability distribution

- The output of SMEFiT is a sampling of the **probability distribution** in the SMEFT space

$$\left\{ c_n^{(k)} \right\}, \quad n = 1 \ldots, N_{\rm op}\,, \quad k = 1 \ldots, N_{\rm rep}$$

- Used to **evaluate statistical estimators** such as variances, correlations, higher moments, …

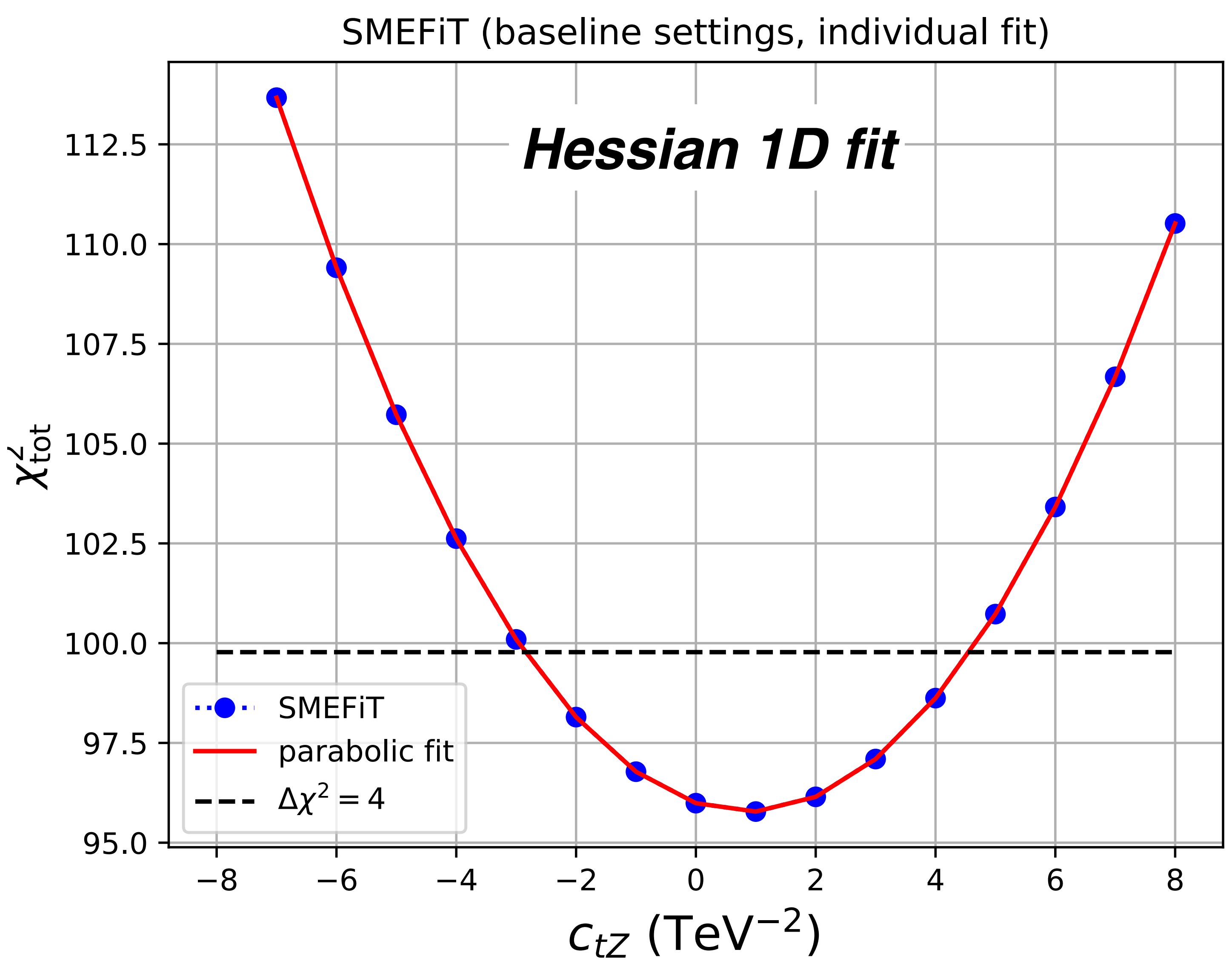
- …. but much less so for **under-constrained** or **redundant** operators



The SMEFiT method

- Uncertainties on the SMEFT degrees of freedom evaluated from **variance of MC sample**

$$\left(\delta c_n\right)^2 = \frac{1}{N_{\rm rep}} \sum_{k=1}^{N_{\rm rep}} \left(c_n^{(k)}\right)^2 - \left\langle c_n \right\rangle^2$$



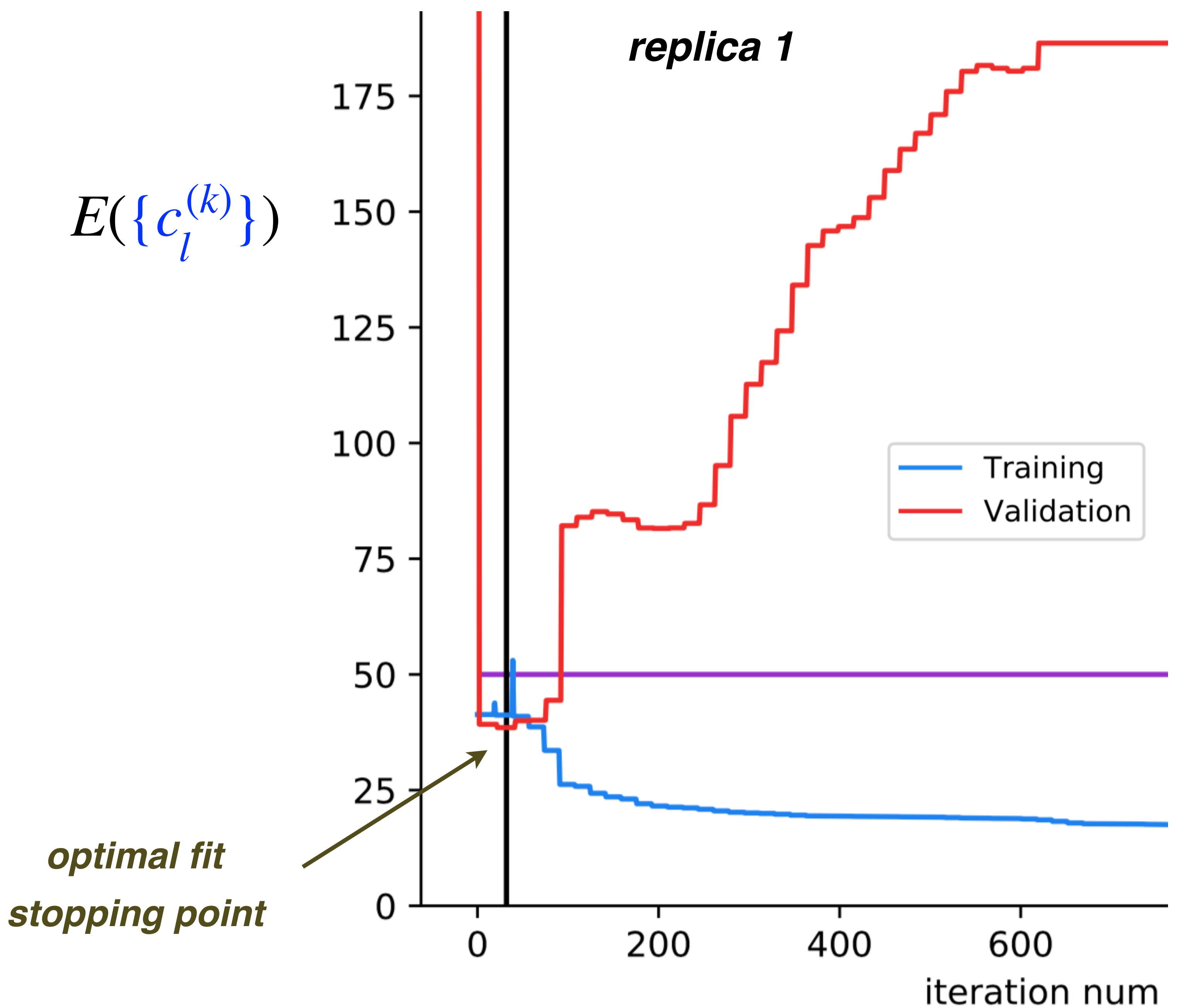
- For single-parameter fits, **Monte Carlo results** benchmarked with **Hessian method**, finding good agreement

- The Hessian method **numerically less stable** as dimensionality of parameter space increases

The SMEFiT method

- Since in general there will be **unconstrained/degenerate directions** in the parameter space, it is crucial to avoid overfitting (that is, fitting statistical fluctuations)

- Achieved by the **cross-validation look-back validation stopping** method



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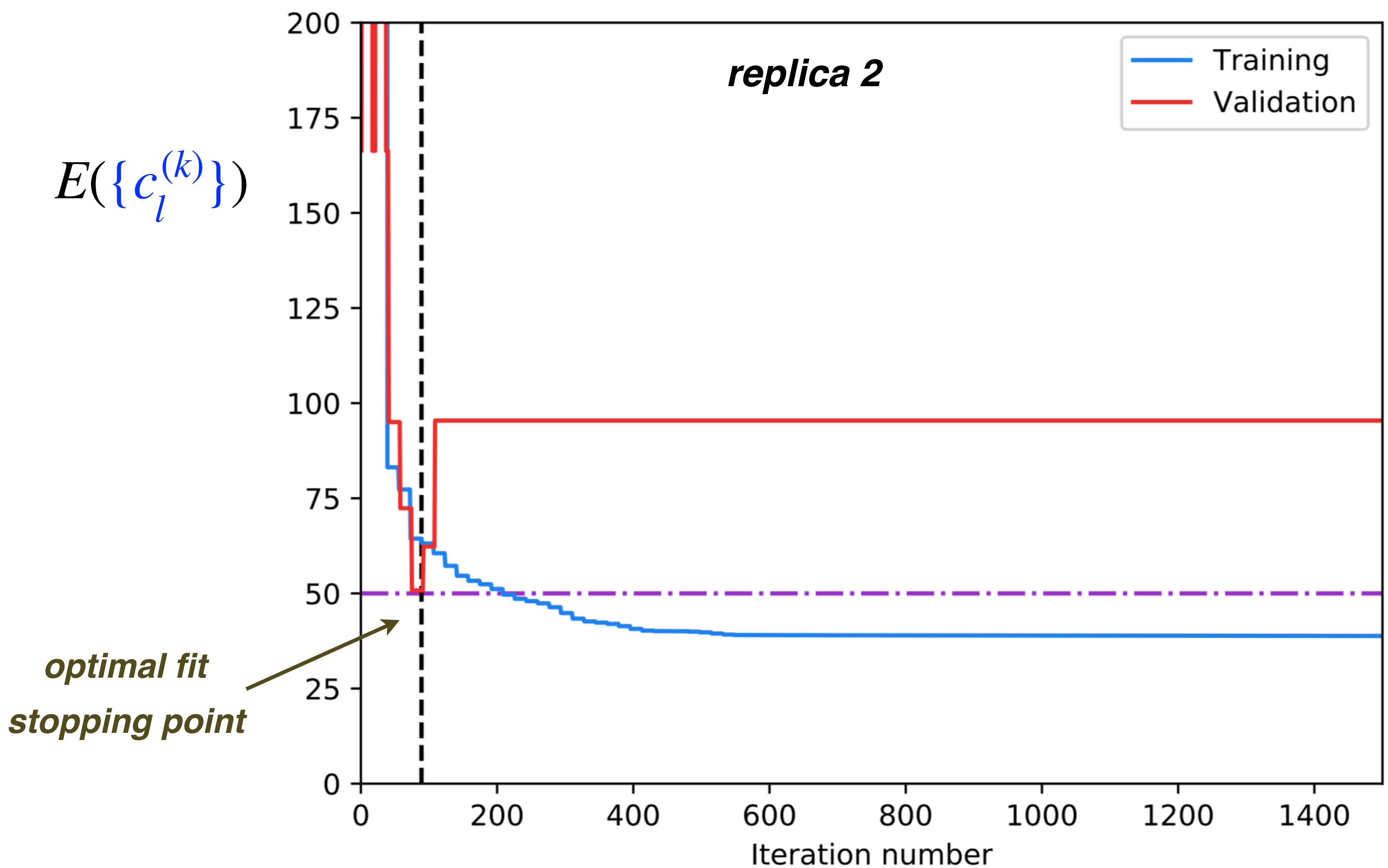


SMEFiT code structure

Stand-alone **Python code**, which exploits functionalities of the **NNPDF framework**

NNPDF code

- **Experimental data** and covariance matrices
- **NLO** APPLgrids + **NNLO** C-factors (for processes used in PDF fit)

aMC@NLO

- NLO **QCD** (benchmark)
- LO, NLO **SMEFT**
- Both $\mathbf{O(\Lambda^{-2})}$ and $\mathbf{O(\Lambda^{-4})}$ from ***d=6*** **operators**

MCFM

- NLO **QCD** (consistent choice of PDFs)
- Cross-checks of **aMC@NLO**

Python analysis code

- Assemble **theory predictions** for generic SMEFT Wilson coefficients
- **Optimisation** with Sequential Quadratic Programming (**SciPy**)
- Look-back **cross-validation stopping**
- **Monte Carlo replicas** for uncertainty propagation

SMEFiT:

the top quark case

***A Monte Carlo global analysis of the Standard Model Effective Field Theory: the top quark sector**,*

Nathan P. Hartland, Fabio Maltoni, Emanuele R. Nocera, Juan Rojo,

Emma Slade, Eleni Vryonidou, Cen Zhang, arXiv:1901.05965, JHEP in press

Operator basis

- We follow the same flavour assumptions as in the **LHC Top WG note**
- Minimal Flavour Violation (MFV), diagonal CKM, zero Yukawas for first two quark gens, CP conservation assumed
- Include those SMEFT dimension-6 operators of Warsaw basis with **at least one top quark**
- The fit includes a total of **34 independent degrees of freedom**
- Include both **interference** and **quadratic contributions** from these operators

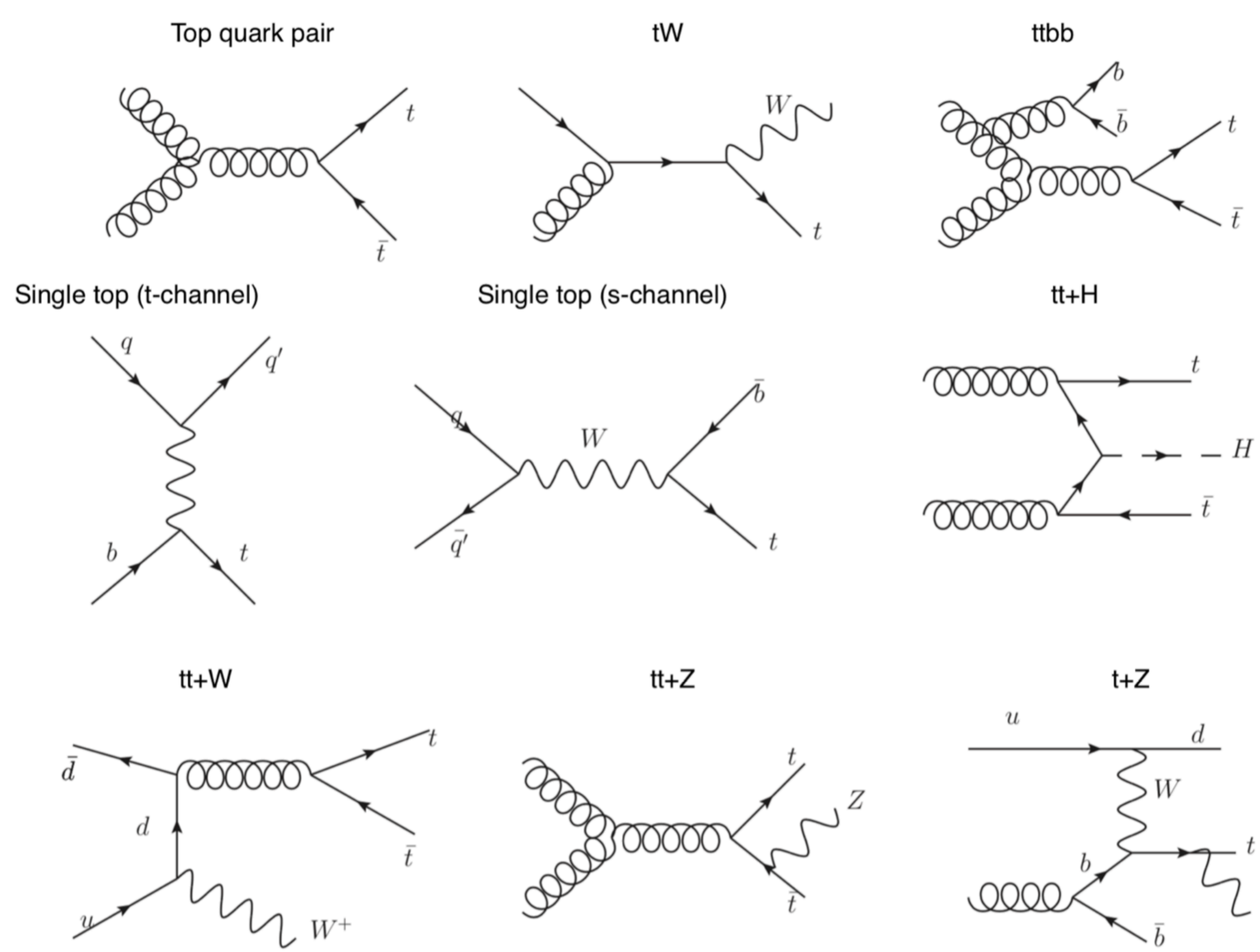
Class	Notation	Degree of Freedom	Operator Definition
	OQQ1	c^{1}_{QQ}	$2C_{qq}^{1(3333)} - \frac{2}{3}C_{qq}^{3(3333)}$
	OQQ8	c^{8}_{QQ}	$8C_{qq}^{3(3333)}$
	OQt1	c^{1}_{Qt}	$C_{qu}^{1(3333)}$
	OQt8	c^{8}_{Qt}	$C_{qu}^{8(3333)}$
$QQQQ$	OQb1	c^{1}_{Qb}	$C_{qd}^{1(3333)}$
	OQb8	c^{8}_{Qb}	$C_{qd}^{8(3333)}$
4-heavy	Ott1	c^{1}_{tt}	$C_{uu}^{(3333)}$
	Otb1	c^{1}_{tb}	$C_{ud}^{1(3333)}$
	Otb8	c^{8}_{tb}	$C_{ud}^{8(3333)}$
	OQtQb1	c^{1}_{QtQb}	$C_{quqd}^{1(3333)}$
	OQtQb8	c^{8}_{QtQb}	$C_{quqd}^{8(3333)}$
	O81qq	$c^{1,8}_{Qq}$	$C_{qq}^{1(i33i)} + 3C_{qq}^{3(i33i)}$
	O11qq	$c^{1,1}_{Qq}$	$C_{qq}^{1(ii33)} + \frac{1}{6}C_{qq}^{1(i33i)} + \frac{1}{2}C_{qq}^{3(i33i)}$
	O83qq	$c^{3,8}_{Qq}$	$C_{qq}^{1(i33i)} - C_{qq}^{3(i33i)}$
	O13qq	$c^{3,1}_{Qq}$	$C_{qq}^{3(ii33)} + \frac{1}{6}(C_{qq}^{1(i33i)} - C_{qq}^{3(i33i)})$
	O8qt	c^{8}_{tq}	$C_{qu}^{8(ii33)}$
	O1qt	c^{1}_{tq}	$C_{qu}^{1(ii33)}$
	O8ut	c^{8}_{tu}	$2C_{uu}^{(i33i)}$
$QQqq$	O1ut	c^{1}_{tu}	$C_{uu}^{(ii33)} + \frac{1}{3}C_{uu}^{(i33i)}$
	O8qu	c^{8}_{Qu}	$C_{qu}^{8(33ii)}$
2-heavy-2-light	O1qu	c^{1}_{Qu}	$C_{qu}^{1(33ii)}$
	O8dt	c^{8}_{td}	$C_{ud}^{8(33ii)}$
	O1dt	c^{1}_{td}	$C_{ud}^{1(33ii)}$
	O8qd	c^{8}_{Qd}	$C_{qd}^{8(33ii)}$
	O1qd	c^{1}_{Qd}	$C_{qd}^{1(33ii)}$
	OtG	c_{tG}	$\mathrm{Re}\{C_{uG}^{(33)}\}$
	OtW	c_{tW}	$\mathrm{Re}\{C_{uW}^{(33)}\}$
	ObW	c_{bW}	$\mathrm{Re}\{C_{dW}^{(33)}\}$
	OtZ	c_{tZ}	$\mathrm{Re}\{-s_W C_{uB}^{(33)} + c_W C_{uW}^{(33)}\}$
$QQ+V,G,\varphi$	Off	$c_{\varphi tb}$	$\mathrm{Re}\{C_{\varphi ud}^{(33)}\}$
	Ofq3	$c^{3}_{\varphi Q}$	$C_{\varphi q}^{3(33)}$
2-heavy + V/h	OpQM	$c^{-}_{\varphi Q}$	$C_{\varphi q}^{1(33)} - C_{\varphi q}^{3(33)}$
	Opt	$c_{\varphi t}$	$C_{\varphi u}^{(33)}$
	Otp	$c_{t\varphi}$	$\mathrm{Re}\{C_{u\varphi}^{(33)}\}$

The top quark sector of the SMEFT

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**

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



The top quark sector of the SMEFT

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							✓		

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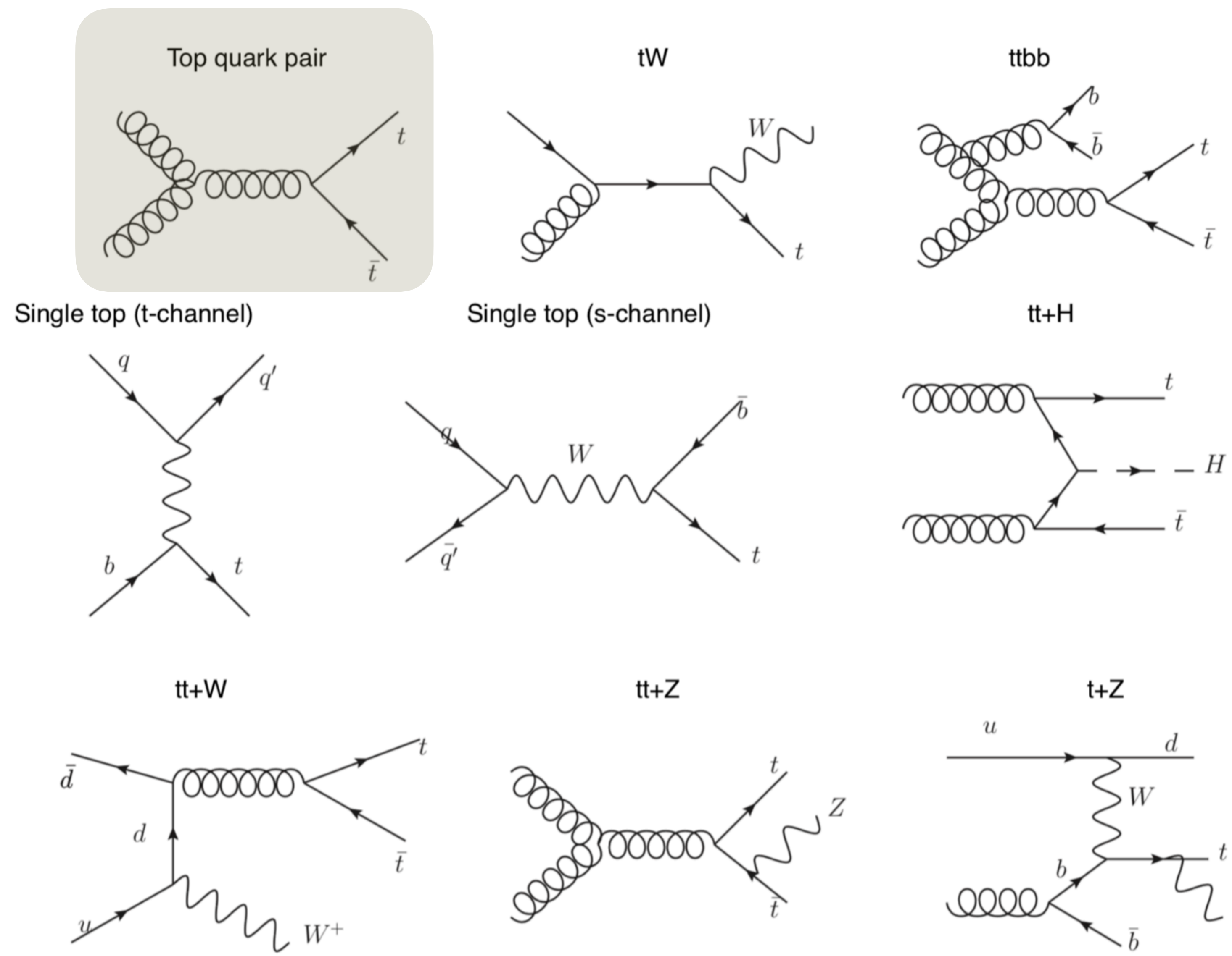
$$\sigma_i^{\rm th}\left(\{c_n\}\right) = \sigma_{{\rm SM},i} + \sum_{n=1}^{N_{\rm op}} \widetilde{\sigma}_{i,n}\frac{c_n}{\Lambda^2} + \sum_{n,m=1}^{N_{\rm op}} \widetilde{\sigma}_{i,nm}\frac{c_n c_m}{\Lambda^4}$$



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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							✓		

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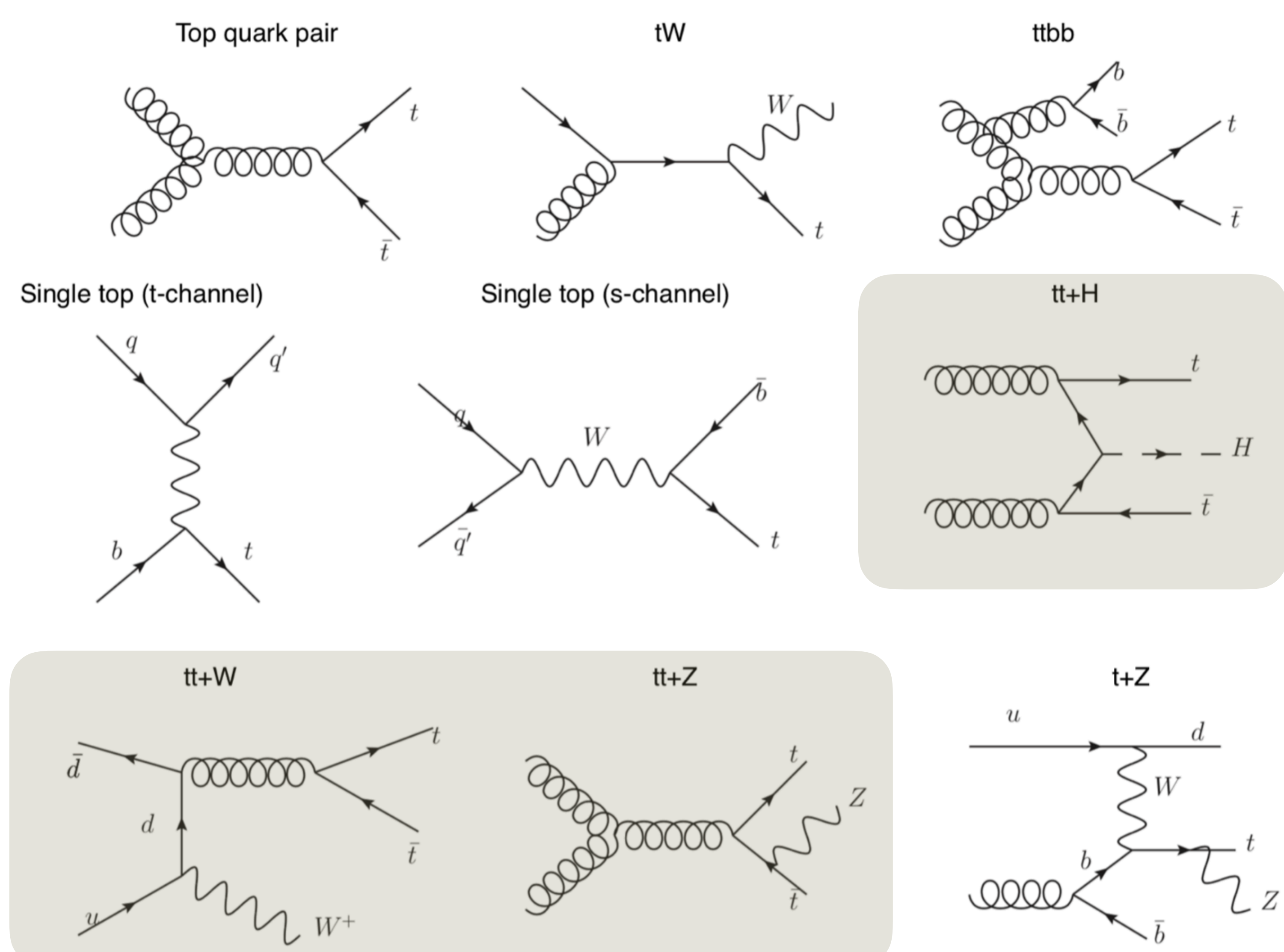

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OQQ1								✓	✓
OQQ8								✓	✓
OQt1								✓	✓
OQt8								✓	✓
OQb1								(✓)	✓
OQb8								(✓)	✓
Ott1								✓	✓
Otb1								(✓)	✓
Otb8								✓	✓
OQtQb1									
OQtQb8									
O81qq	✓				✓	✓	✓	✓	✓
O11qq	✓				(✓)	(✓)	(✓)	✓	✓
O83qq	✓	✓		(✓)	✓	✓	✓	✓	✓
O13qq	✓	✓		✓	(✓)	(✓)	(✓)	✓	✓
O8qt	✓				✓	✓	✓	✓	✓
O1qt	✓				(✓)	(✓)	(✓)	✓	✓
O8ut	✓					✓	✓	✓	✓
O1ut	✓					(✓)	(✓)	✓	✓
O8qu	✓					✓	✓	✓	✓
O1qu	✓					(✓)	(✓)	✓	✓
O8dt	✓					✓	✓	✓	✓
O1dt	✓					(✓)	(✓)	✓	✓
O8qd	✓					✓	✓	✓	✓
O1qd	✓					(✓)	(✓)	✓	✓
OtG	✓				✓	✓	✓	✓	✓
OtW		✓	✓	✓					
ObW		(✓)	(✓)						
OtZ				✓		✓			
Off		(✓)	(✓)	(✓)					
Ofq3		✓	✓	✓		✓			
OpQM				✓		✓			
Opt				✓		✓	✓		
Otp							✓		

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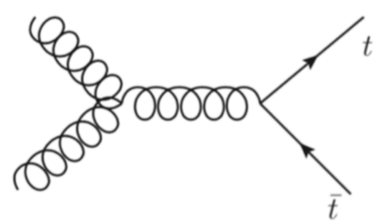
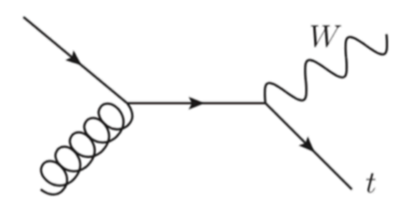
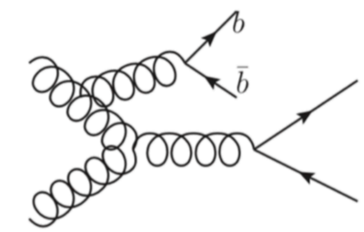
Top quark pair



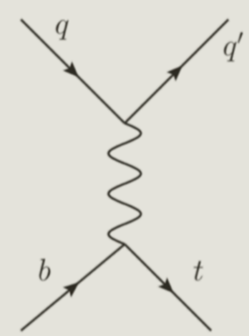
tW



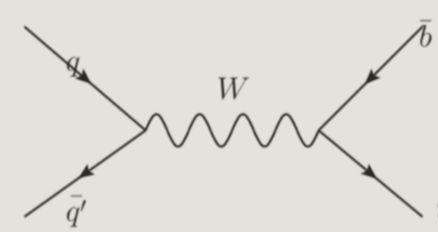
ttbb



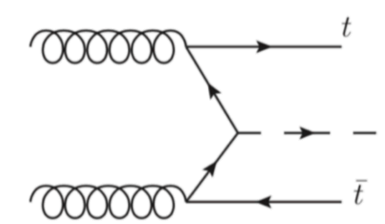
Single top (t-channel)



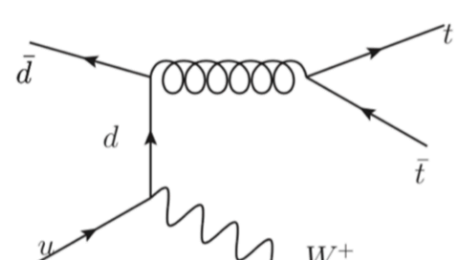
Single top (s-channel)



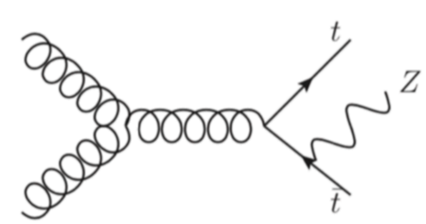
tt+H



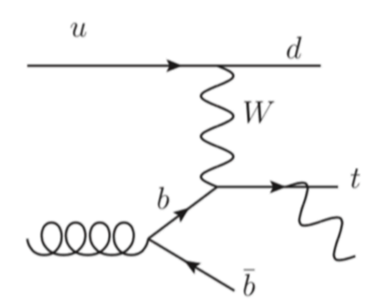
tt+W



tt+Z



t+Z



Input dataset (I)

Process	Dataset	$\sqrt{s}$	Info	Observables	$N_{\rm dat}$	Ref
$t\bar{t}$	`ATLAS_tt_8TeV_ljets`	**8 TeV**	lepton+jets	$d\sigma/d\|y_t\|$, $d\sigma/dp_t^T$, $d\sigma/dm_{t\bar{t}}$, $d\sigma/d\|y_{t\bar{t}}\|$	5, 8, 7, 5	[77]
$t\bar{t}$	`CMS_tt_8TeV_ljets`	**8 TeV**	lepton+jets	$d\sigma/dy_t$, $d\sigma/dp_t^T$, $d\sigma/dm_{t\bar{t}}$, $d\sigma/dy_{t\bar{t}}$	10, 8, 7, 10	[78]
$t\bar{t}$	`CMS_tt2D_8TeV_dilep`	**8 TeV**	dileptons	$d^2\sigma/dy_t dp_t^T$, $d^2\sigma/dy_t dm_{t\bar{t}}$, $d^2\sigma/dp_{t\bar{t}}^T dm_{t\bar{t}}$, $d^2\sigma/dy_{t\bar{t}} dm_{t\bar{t}}$	16, 16, 16, 16	[79]
$t\bar{t}$	`CMS_tt_13TeV_ljets`	**13 TeV**	lepton+jets	$d\sigma/d\|y_t\|$, $d\sigma/dp_t^T$, $d\sigma/dm_{t\bar{t}}$, $d\sigma/d\|y_{t\bar{t}}\|$	7, 9, 8, 6	[83]
$t\bar{t}$	`CMS_tt_13TeV_ljets2`	**13 TeV**	lepton+jets	$d\sigma/d\|y_t\|$, $d\sigma/dp_t^T$, $d\sigma/dm_{t\bar{t}}$, $d\sigma/d\|y_{t\bar{t}}\|$	11, 12, 10, 10	[85]
$t\bar{t}$	`CMS_tt_13TeV_dilep`	**13 TeV**	dileptons	$d\sigma/dy_t$, $d\sigma/dp_t^T$, $d\sigma/dm_{t\bar{t}}$, $d\sigma/dy_{t\bar{t}}$	8, 6, 6, 8	[86]
$t\bar{t}$	`ATLASCMS_AcMtt_8TeV`	**8 TeV**	Asymm comb	$A_C(m_{t\bar{t}})$, Eq. (3.1)	6	[80]
$t\bar{t}$	`ATLAS_WhelF_8TeV`	**8 TeV**	W helicity fract	F_0, F_L, F_R	3	[81]
$t\bar{t}$	`CMS_WhelF_8TeV`	**8 TeV**	W helicity fract	F_0, F_L, F_R	3	[82]

Input dataset (II)

Process	Dataset	$\sqrt{s}$	Info	Observables	$N_{\rm dat}$	Ref
Single t	CMS_t_tch_8TeV_inc	**8 TeV**	t-channel	$\sigma_{\rm tot}(t), \sigma_{\rm tot}(\bar{t})$ (R_t)	2 (1)	[95]
Single t	CMS_t_sch_8TeV	**8 TeV**	s-channel	$\sigma_{\rm tot}(t+\bar{t})$	1	[96]
Single t	ATLAS_t_sch_8TeV	**8 TeV**	s-channel	$\sigma_{\rm tot}(t+\bar{t})$	1	[97]
Single t	ATLAS_t_tch_8TeV	**8 TeV**	t-channel	$d\sigma(tq)/dp_T^t, d\sigma(\bar{t}q)/dp_T^{\bar{t}}$ $d\sigma(tq)/dy_t, d\sigma(\bar{t}q)/dy_t$	5, 4 4, 4	[98]
Single t	ATLAS_t_tch_13TeV	**13 TeV**	t-channel	$\sigma_{\rm tot}(t), \sigma_{\rm tot}(\bar{t})$ (R_t)	2 (1)	[99]
Single t	CMS_t_tch_13TeV_inc	**13 TeV**	t-channel	$\sigma_{\rm tot}(t+\bar{t})$ (R_t)	1 (1)	[100]
Single t	CMS_t_tch_8TeV_dif	**8 TeV**	t-channel	$d\sigma/dp_T^{(t+\bar{t})}$, $d\sigma/d\lvert y^{(t+\bar{t})}\rvert$	6 6	[101]
Single t	CMS_t_tch_13TeV_dif	**13 TeV**	t-channel	$d\sigma/dp_T^{(t+\bar{t})}$, $d\sigma/d\lvert y^{(t+\bar{t})}\rvert$	4 4	[102]
tW	ATLAS_tW_inc_8TeV	**8 TeV**	inclusive	$\sigma_{\rm tot}(tW)$	1	[103]
tW	CMS_tW_inc_8TeV	**8 TeV**	inclusive	$\sigma_{\rm tot}(tW)$	1	[104]
tW	ATLAS_tW_inc_13TeV	**13 TeV**	inclusive	$\sigma_{\rm tot}(tW)$	1	[105]
tW	CMS_tW_inc_13TeV	**13 TeV**	inclusive	$\sigma_{\rm tot}(tW)$	1	[106]
tZ	CMS_tZ_inc_13TeV	**13 TeV**	inclusive	$\sigma_{\rm fid}(Wbl^+l^-q)$	1	[107]
tZ	ATLAS_tZ_inc_13TeV	**13 TeV**	inclusive	$\sigma_{\rm tot}(tZq)$	1	[108]

Input dataset (III)

Process	Dataset	$\sqrt{s}$	Info	Observables	$N_{\rm dat}$	Ref
$t\bar{t}b\bar{b}$	`CMS_ttbb_13TeV`	**13 TeV**	total xsec	$\sigma_{\rm tot}(t\bar{t}b\bar{b})$	1	[87]
$t\bar{t}t\bar{t}$	`CMS_tttt_13TeV`	**13 TeV**	total xsec	$\sigma_{\rm tot}(t\bar{t}t\bar{t})$	1	[88]
$t\bar{t}Z$	`CMS_ttZ_8_13TeV`	**8+13 TeV**	total xsec	$\sigma_{\rm tot}(t\bar{t}Z)$	2	[89, 90]
$t\bar{t}Z$	`ATLAS_ttZ_8_13TeV`	**8+13 TeV**	total xsec	$\sigma_{\rm tot}(t\bar{t}Z)$	2	[91, 92]
$t\bar{t}W$	`CMS_ttW_8_13TeV`	**8+13 TeV**	total xsec	$\sigma_{\rm tot}(t\bar{t}W)$	2	[89, 90]
$t\bar{t}W$	`ATLAS_ttW_8_13TeV`	**8+13 TeV**	total xsec	$\sigma_{\rm tot}(t\bar{t}W)$	2	[91, 92]
$t\bar{t}H$	`CMS_tth_13TeV`	**13 TeV**	signal strength	$\mu_{t\bar{t}H}$	1	[93]
$t\bar{t}H$	`ATLAS_tth_13TeV`	**13 TeV**	total xsec	$\sigma_{\rm tot}(t\bar{t}H)$	1	[94]

The fit includes more than **100 cross-section measurements** at 8 and 13 TeV from **10 different top-quark production processes**

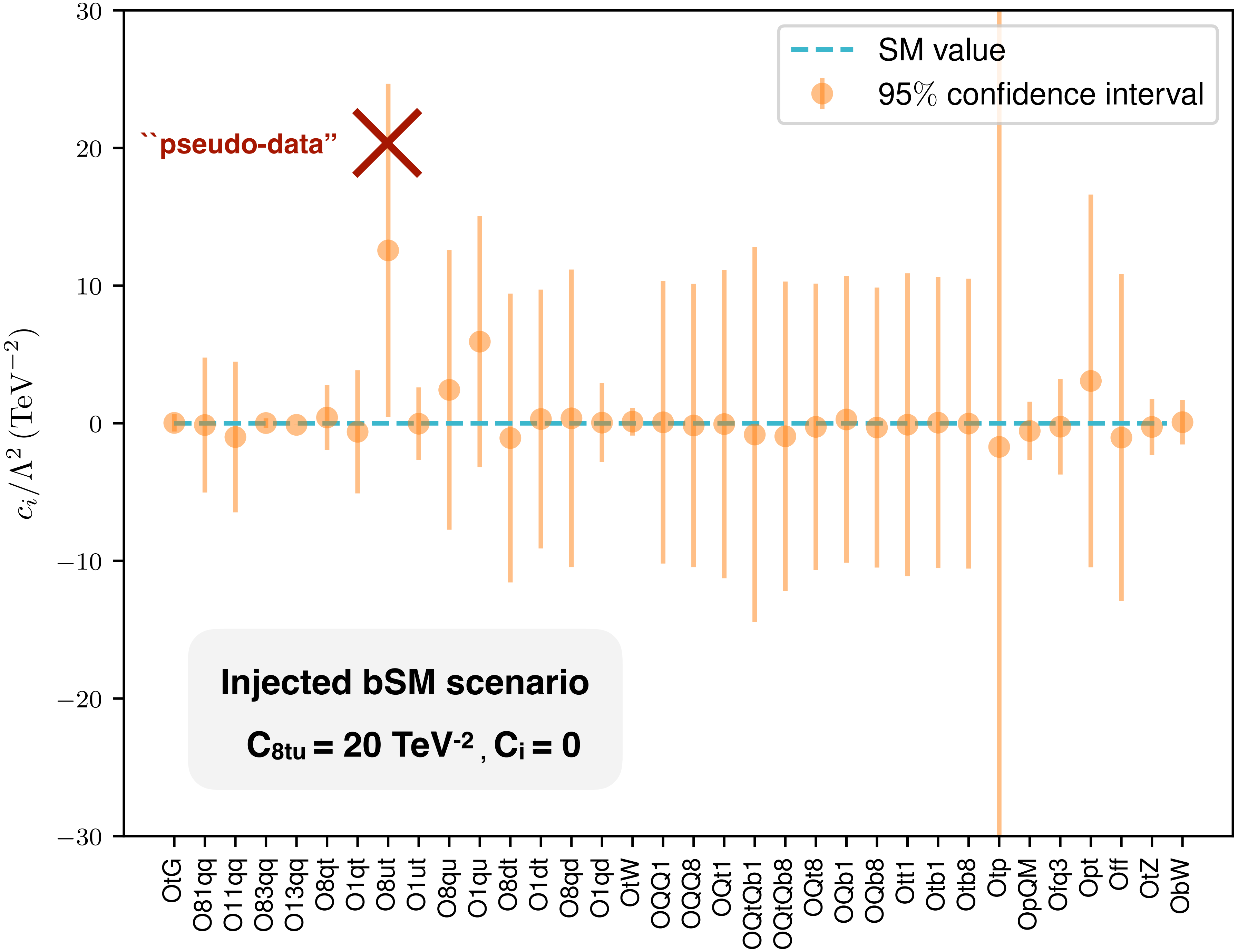
Theory calculations

Process	SM	Code	SMEFT	Code
$t\bar{t}$	NNLO QCD	MCFM/SHERPA NLO + NNLO K-factors	NLO QCD	MG5_aMC
single-t (t-ch)	NNLO QCD	MCFM NLO + NNLO K-factors	NLO QCD	MG5_aMC
single-t (s-ch)	NLO QCD	MCFM	NLO QCD	MG5_aMC
tW	NLO QCD	MG5_aMC	NLO QCD	MG5_aMC
tZ	NLO QCD	MG5_aMC	LO QCD + NLO SM K-factors	MG5_aMC
$t\bar{t}W(Z)$	NLO QCD	MG5_aMC	LO QCD + NLO SM K-factors	MG5_aMC
$t\bar{t}h$	NLO QCD	MG5_aMC	LO QCD + NLO SM K-factors	MG5_aMC
$t\bar{t}t\bar{t}$	NLO QCD	MG5_aMC	LO QCD + NLO SM K-factors	MG5_aMC
$t\bar{t}b\bar{b}$	NLO QCD	MG5_aMC	LO QCD + NLO SM K-factors	MG5_aMC

PDF set: **NNPDF3.1 NNLO no-top**

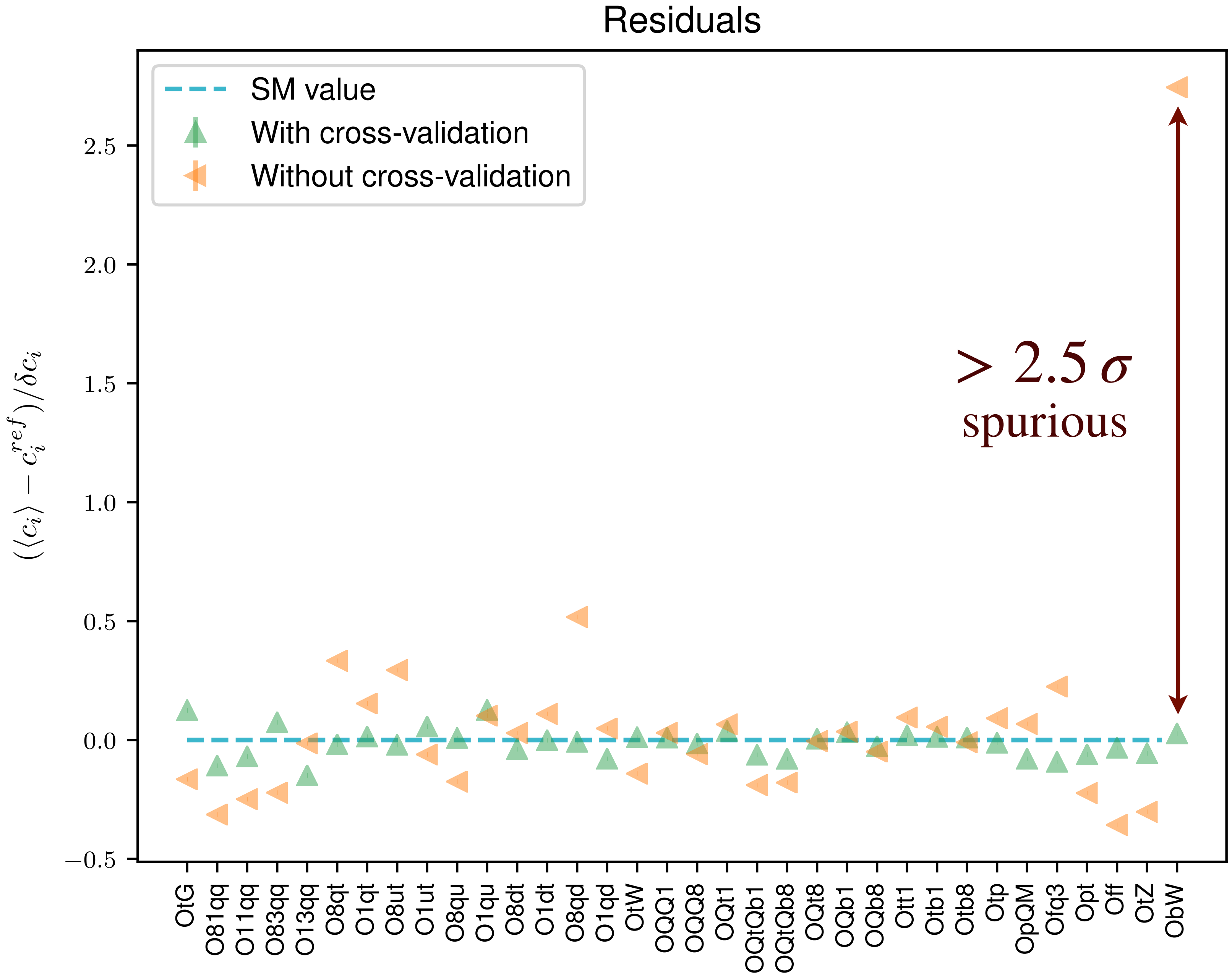
Closure Tests

- Generate **pseudo-data based** on a given scenario (SM or BSM) and check that the correct (known) results are reproduced after the fit
- Allows quantifying the **expected statistical significance** for BSM deviations



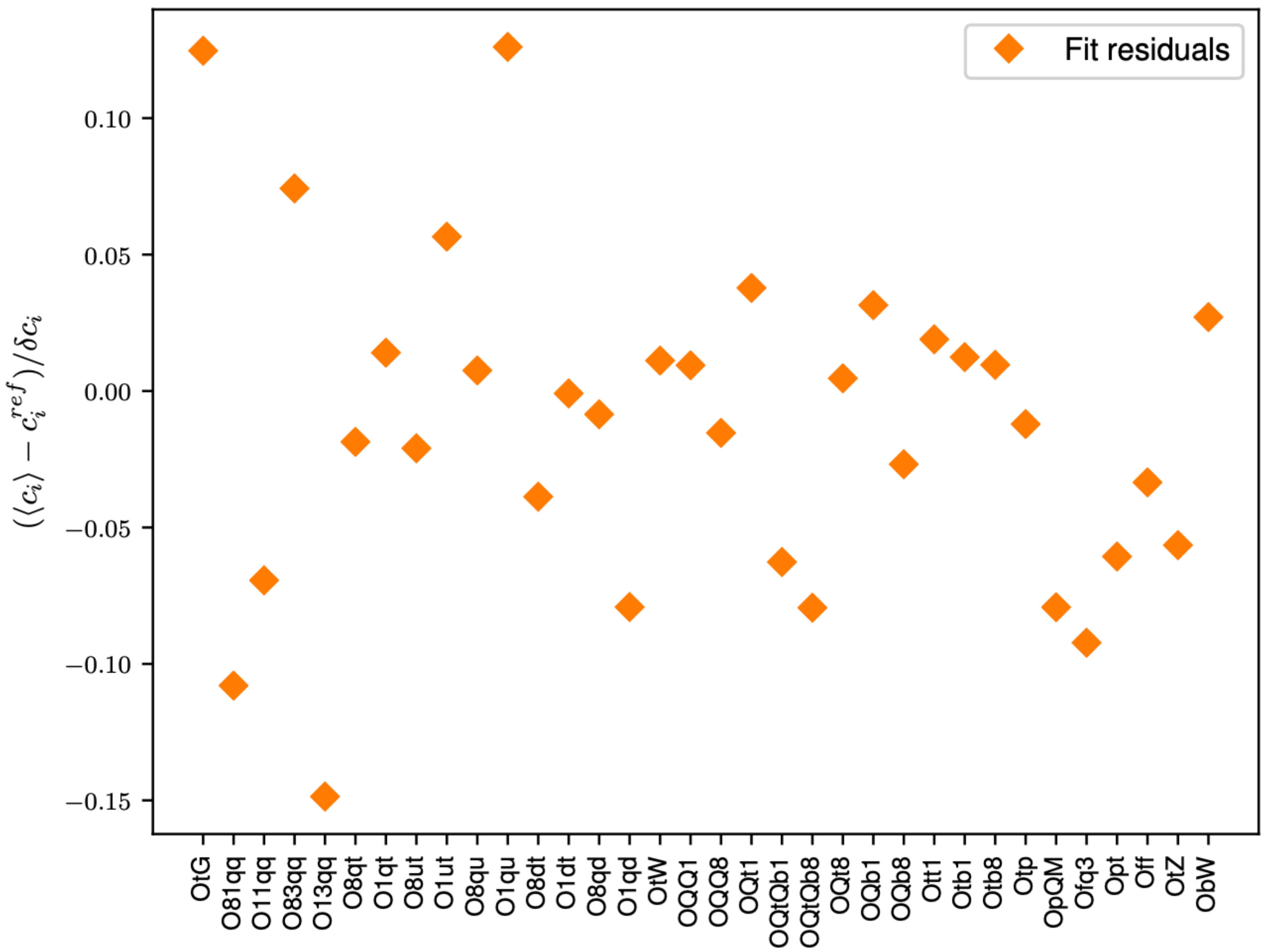
Cross-validation

- Since N_{par} is not too different from N_{dat}, overfitting will take place for an efficient optimiser
- **Artificial tensions with the SM** are likely to be generated by overfitting!
- Fit residuals **consistent with true result (SM)** only with cross-validation

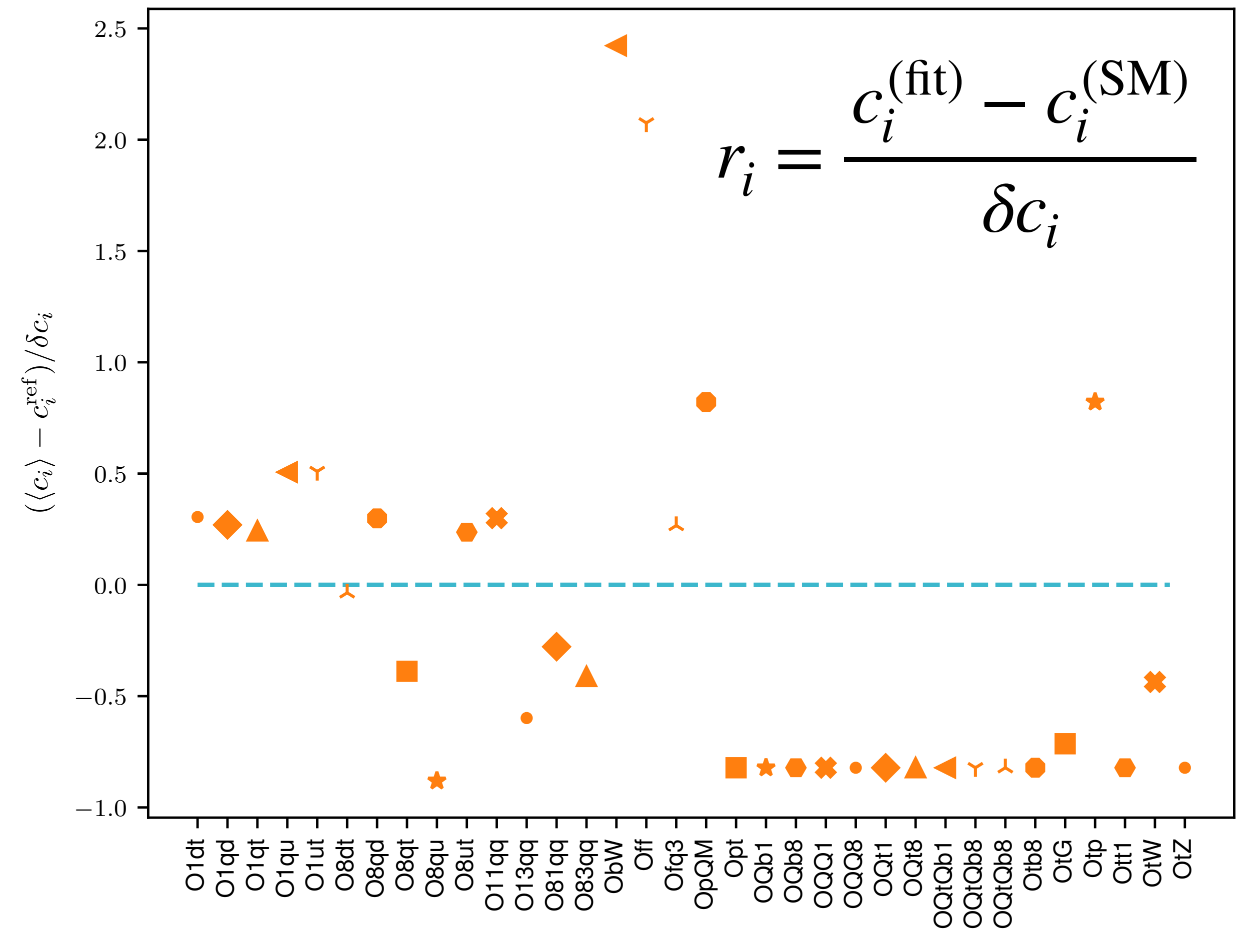


Global vs individual fits

Global fits (all params fitted)



Individual fits (one param at a time)



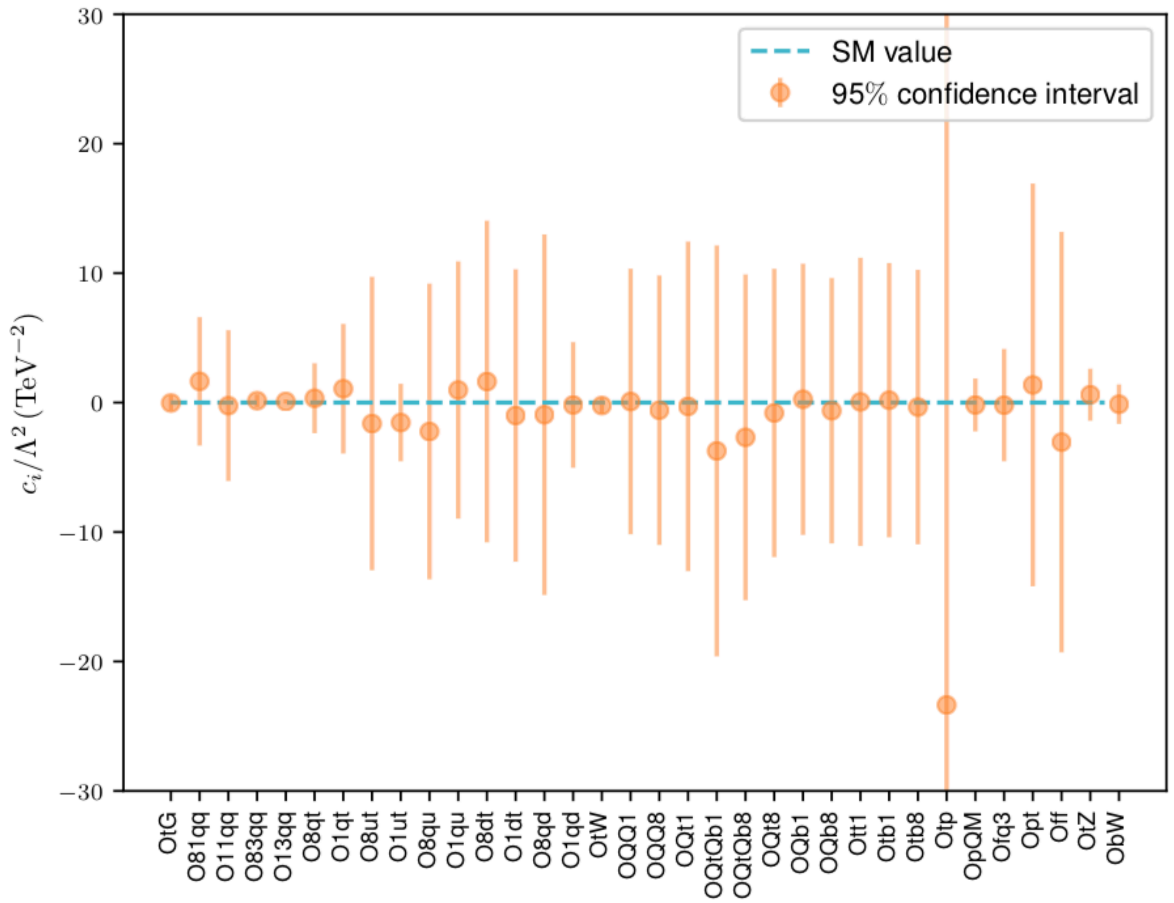
- If each operator was a truly **independent random variable**, we would expect that at least **2 operators** have residuals **|r| > 1** (bounds are 95% CL)
- This is far from being the case when all operators are fitted simultaneously
- Explained by **correlations between operators + degeneracies in parameter space**: much larger fluctuations if we fit one operator at a time

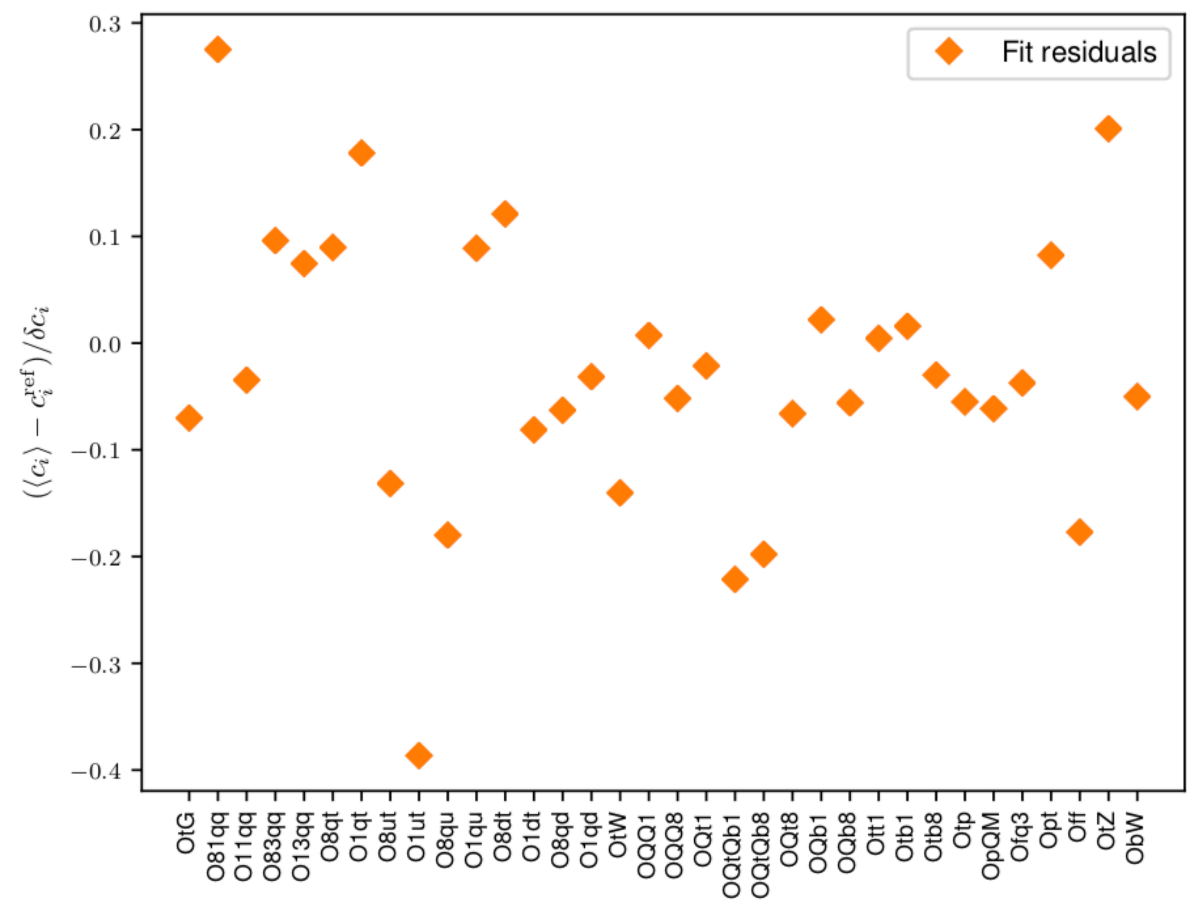
Fit quality

- **Good agreement** between theory (SM and SMEFT) and data for most datasets
- For the **103 fitted cross-sections**, we find ***χ^2/n_{dat}*** *of* **1.11 (1.06)** before (after) fit
- Including SMEFT effects improves agreement with data: need to quantify how **significant** this improvement is

Dataset	$\chi^2/n_{\rm dat}$ (prior)	$\chi^2/n_{\rm dat}$ (fit)	$n_{\rm dat}$
ATLAS_tt_8TeV_ljets [$m_{t\bar{t}}$]	1.51	1.25	7
CMS_tt_8TeV_ljets [$y_{t\bar{t}}$]	1.17	1.17	10
CMS_tt2D_8TeV_dilep [$(m_{t\bar{t}}, y_t)$]	1.38	1.38	16
CMS_tt_13TeV_ljets2 [$m_{t\bar{t}}$]	1.09	1.28	8
CMS_tt_13TeV_dilep [$m_{t\bar{t}}$]	1.34	1.42	6
CMS_tt_13TeV_ljets_2016 [$m_{t\bar{t}}$]	1.87	1.87	10
ATLAS_WhelF_8TeV	1.98	0.27	3
CMS_WhelF_8TeV	0.31	1.18	3
CMS_ttbb_13TeV	5.00	1.29	1
CMS_tttt_13TeV	0.05	0.02	1
ATLAS_tth_13TeV	1.61	0.55	1
CMS_tth_13TeV	0.34	0.01	1
ATLAS_ttZ_8TeV	1.32	5.29	1
ATLAS_ttZ_13TeV	0.01	1.06	1
CMS_ttZ_8TeV	0.04	0.06	1
CMS_ttZ_13TeV	0.90	0.67	1
ATLAS_ttW_8TeV	1.34	0.27	1
ATLAS_ttW_13TeV	0.82	0.65	1
CMS_ttW_8TeV	1.54	0.54	1
CMS_ttW_13TeV	0.03	0.09	1
CMS_t_tch_8TeV_dif	0.11	0.32	6
ATLAS_t_tch_8TeV [y_t]	0.91	0.43	4
ATLAS_t_tch_8TeV [$y_{\bar{t}}$]	0.39	0.45	4
ATLAS_t_sch_8TeV	0.08	1.92	1
ATLAS_t_tch_13TeV	0.02	0.09	2
CMS_t_tch_13TeV_dif [y_t]	0.46	0.49	4
CMS_t_sch_8TeV	1.26	0.76	1
ATLAS_tW_inc_8TeV	0.02	0.06	1
CMS_tW_inc_8TeV	0.00	0.07	1
ATLAS_tW_inc_13TeV	0.52	0.82	1
CMS_tW_inc_13TeV	4.29	1.68	1
ATLAS_tZ_inc_13TeV	0.00	0.00	1
CMS_tZ_inc_13TeV	0.66	0.34	1
Total	**1.11**	**1.06**	**103**

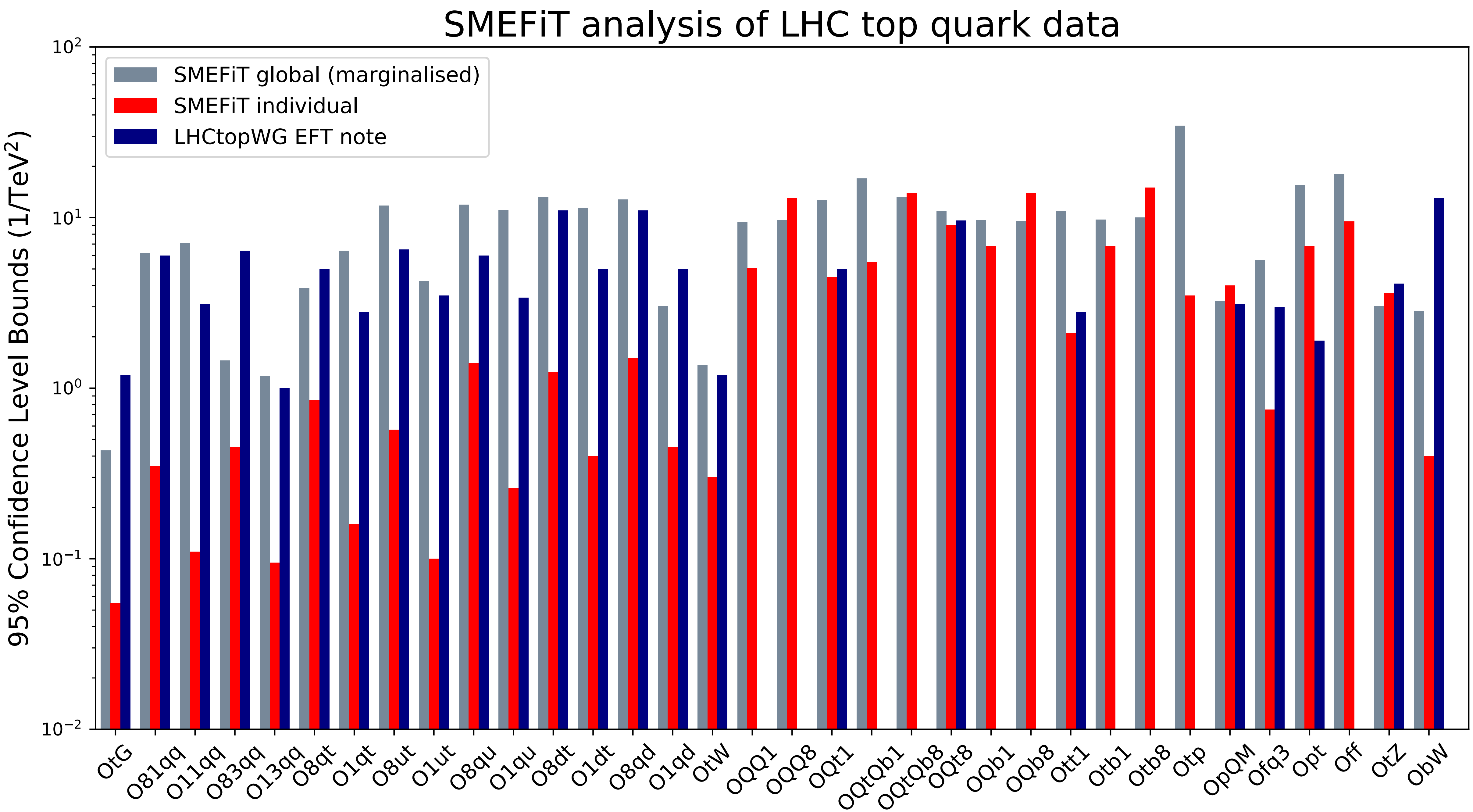
SMEFiT results





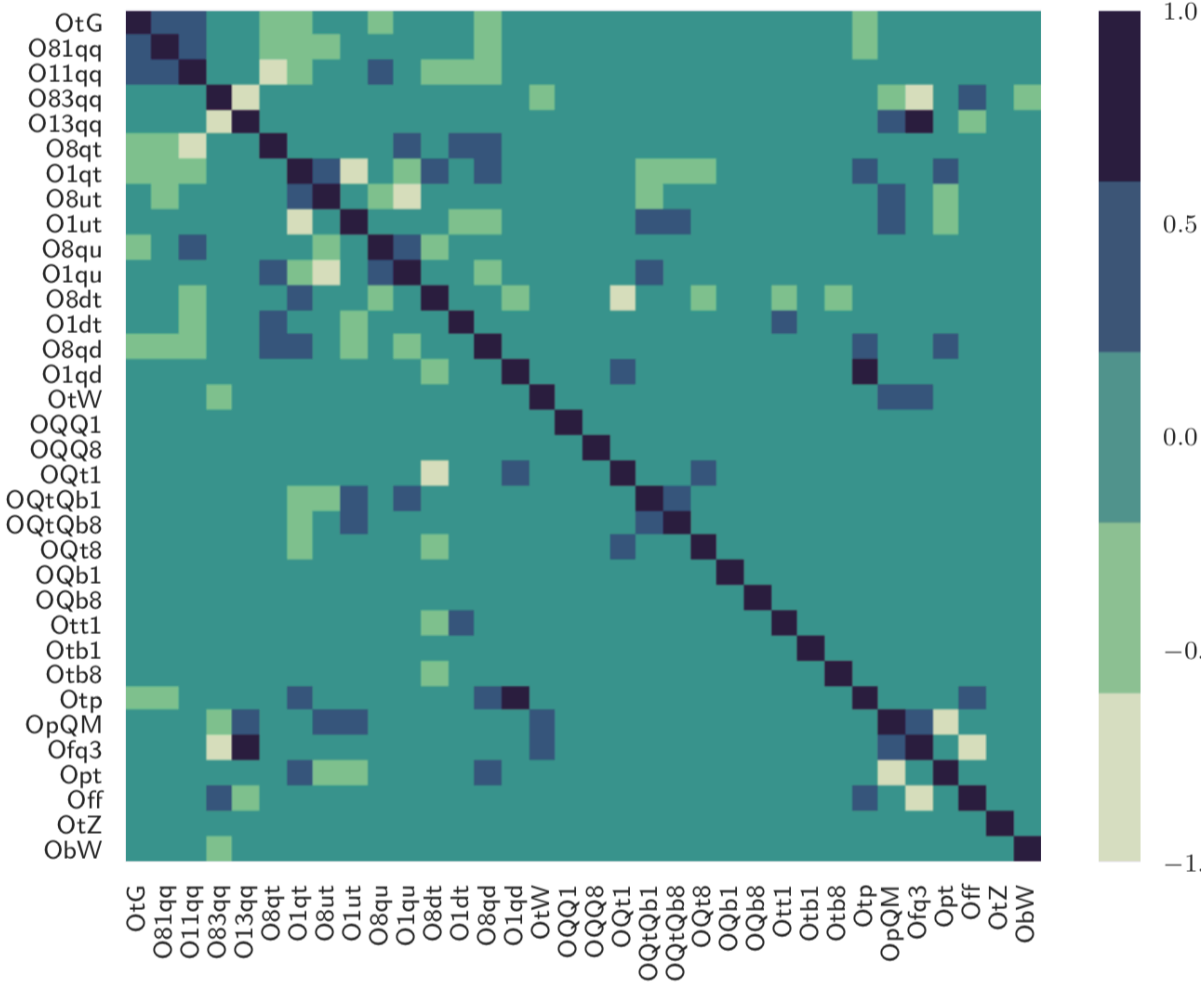
- Agreement with the SM expectation **within uncertainties**
- Bounds on individual operators are in general largely **correlated among them**
- Large differences between the bounds obtained from each operator

Comparison with 1D fits and previous bounds

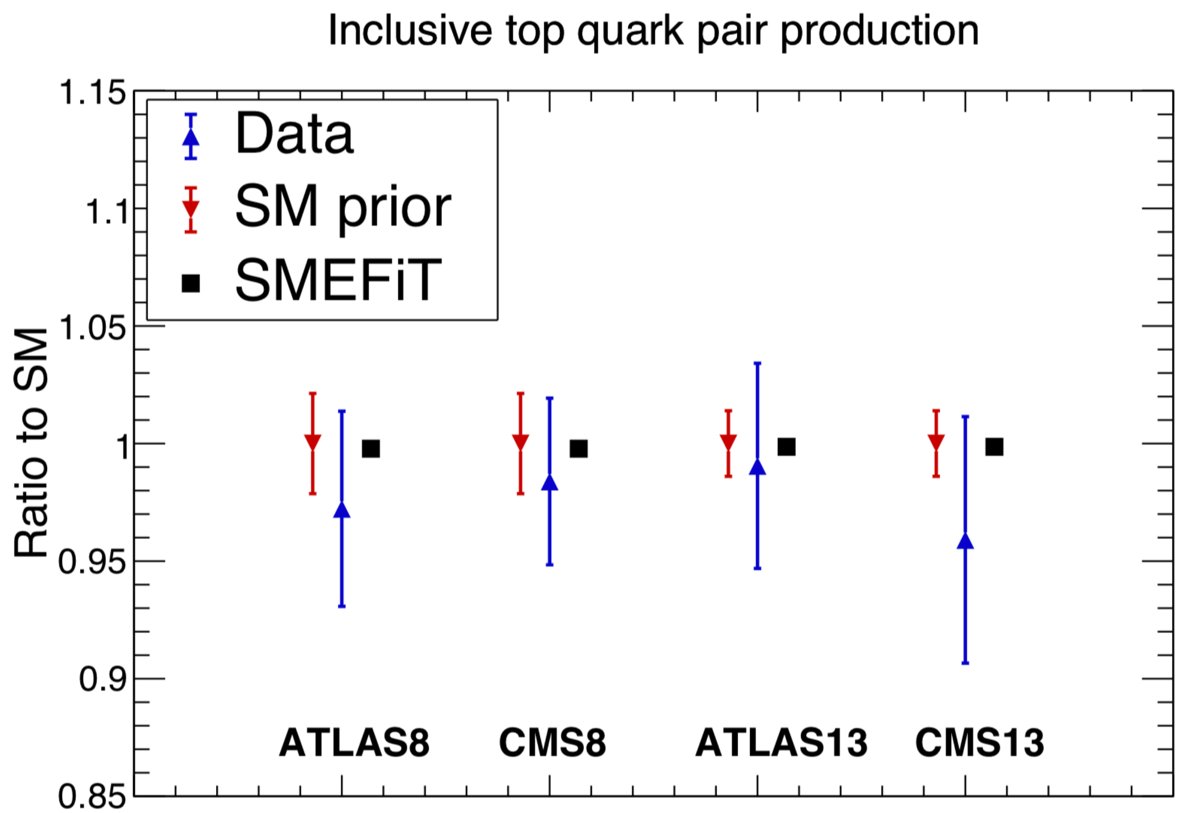


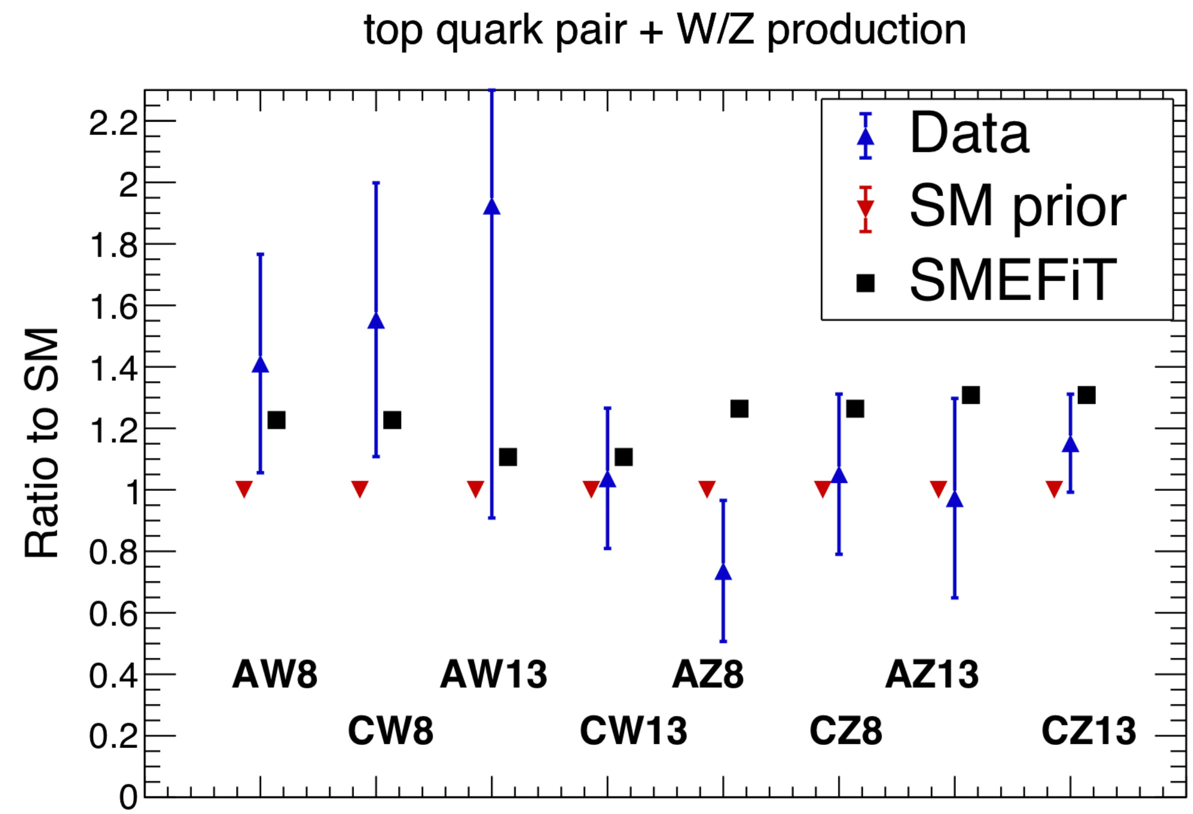
- **Improvement** found (more stringent bounds) in most fitted degrees of freedom
- For some specific operators **our bounds are the first ones** to be reported
- Individual bounds can dramatically **overestimate** the actual (marginalised) bounds

Correlation map

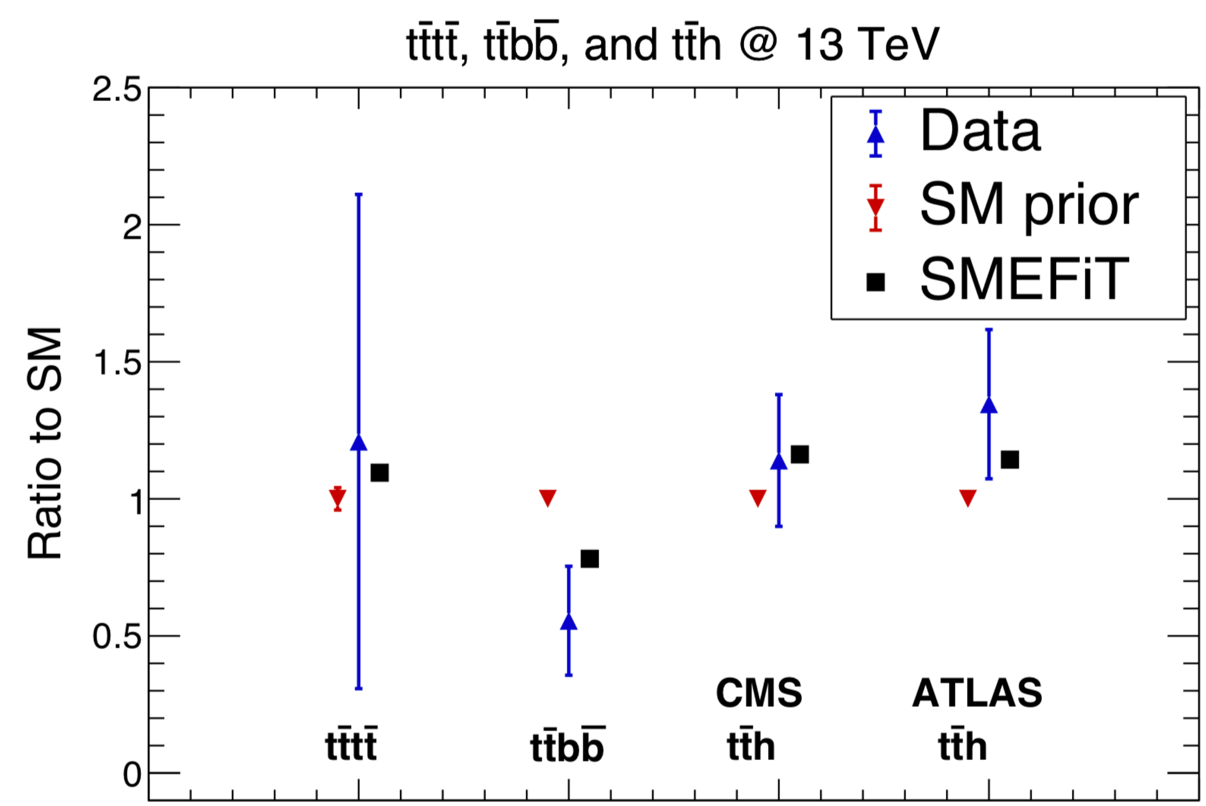


Comparison with data

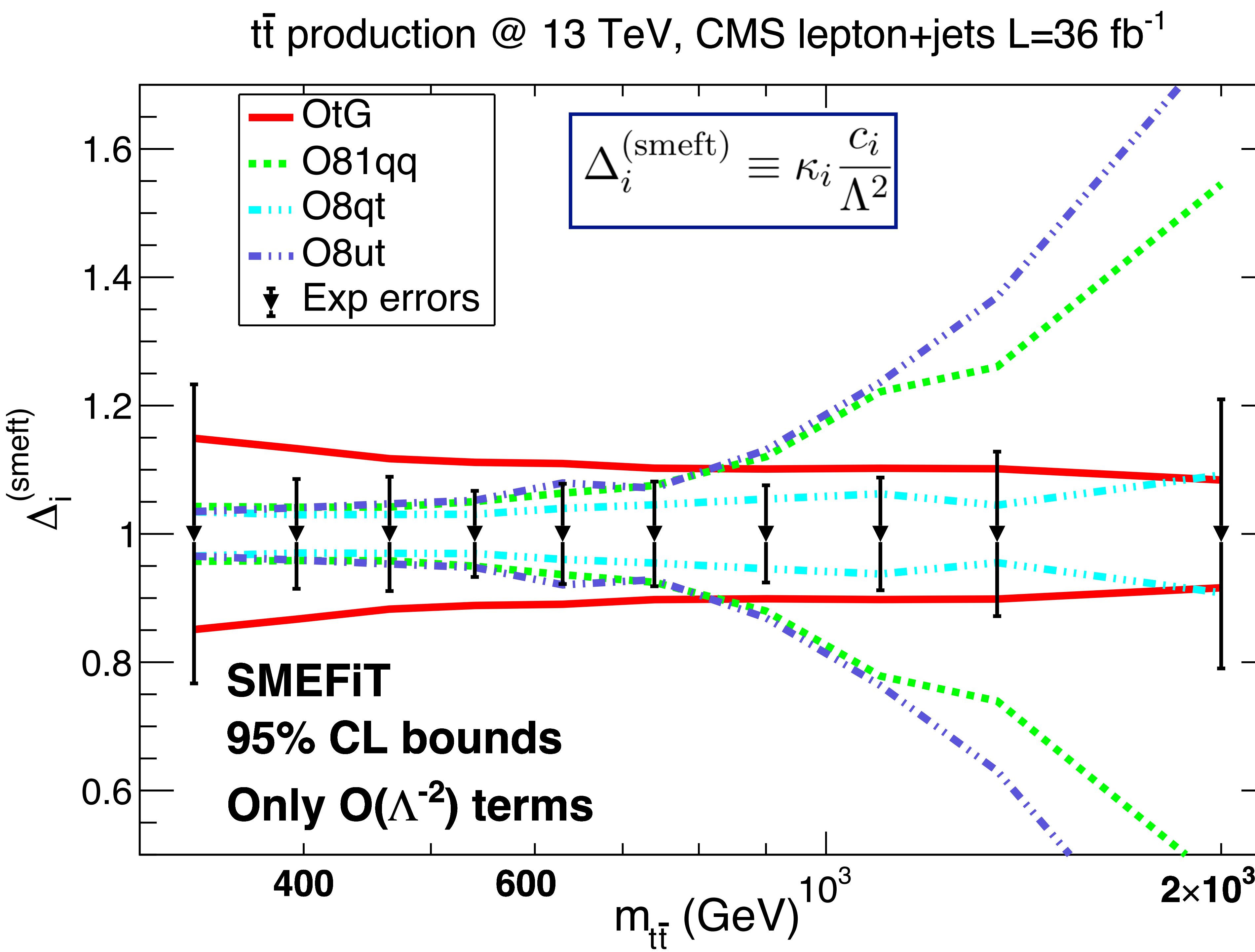




- The **best-fit SMEFT-induced shift** wrt the SM calculation depends on the process
- For inclusive top quark pair and single top, the SMEFT shifts are $< 2\%$
- For ***tttt, ttbbb***, and ***tth*** the SMEFT shifts can be as large as 20% (reflecting the larger experimental errors)

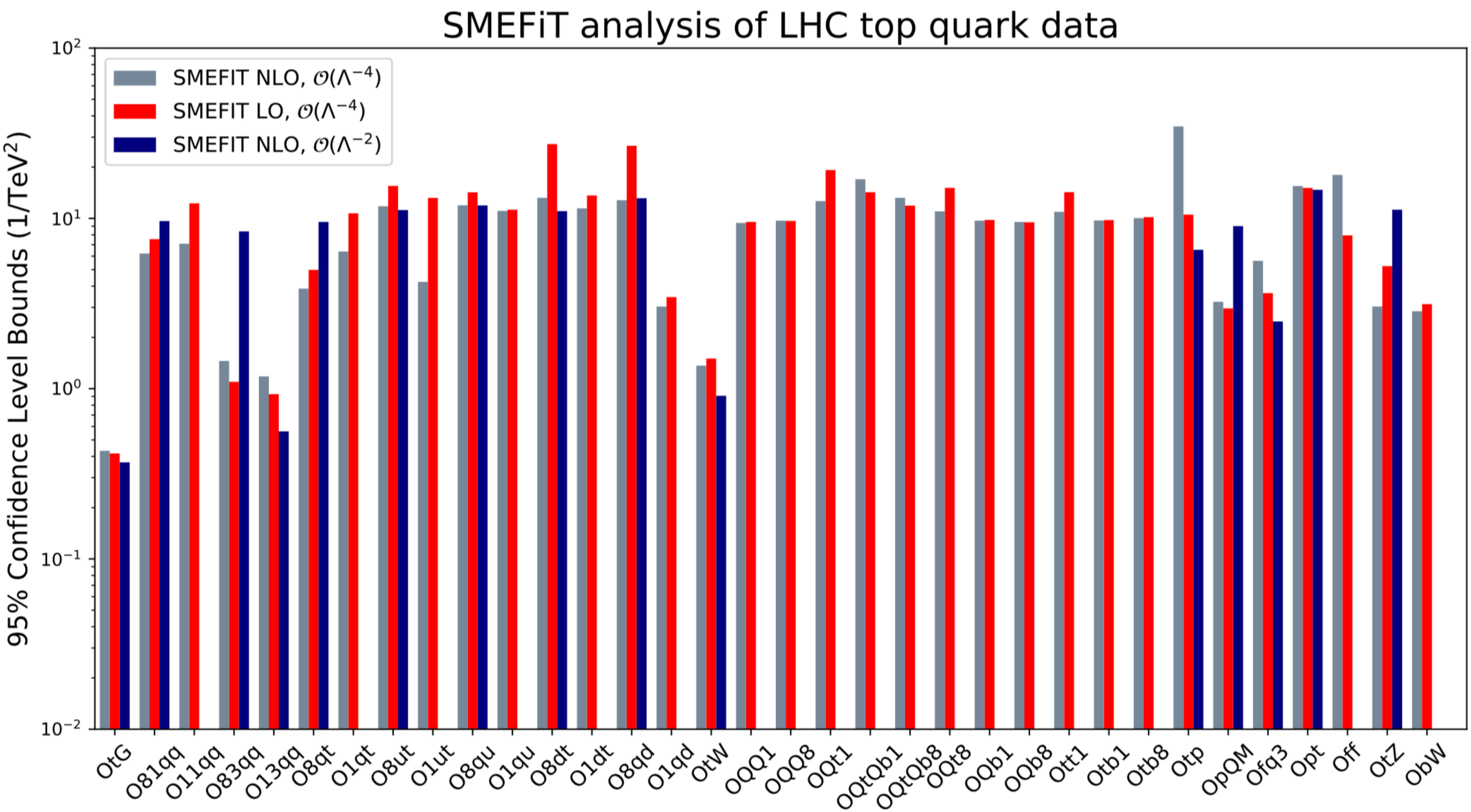


High-energy behaviour



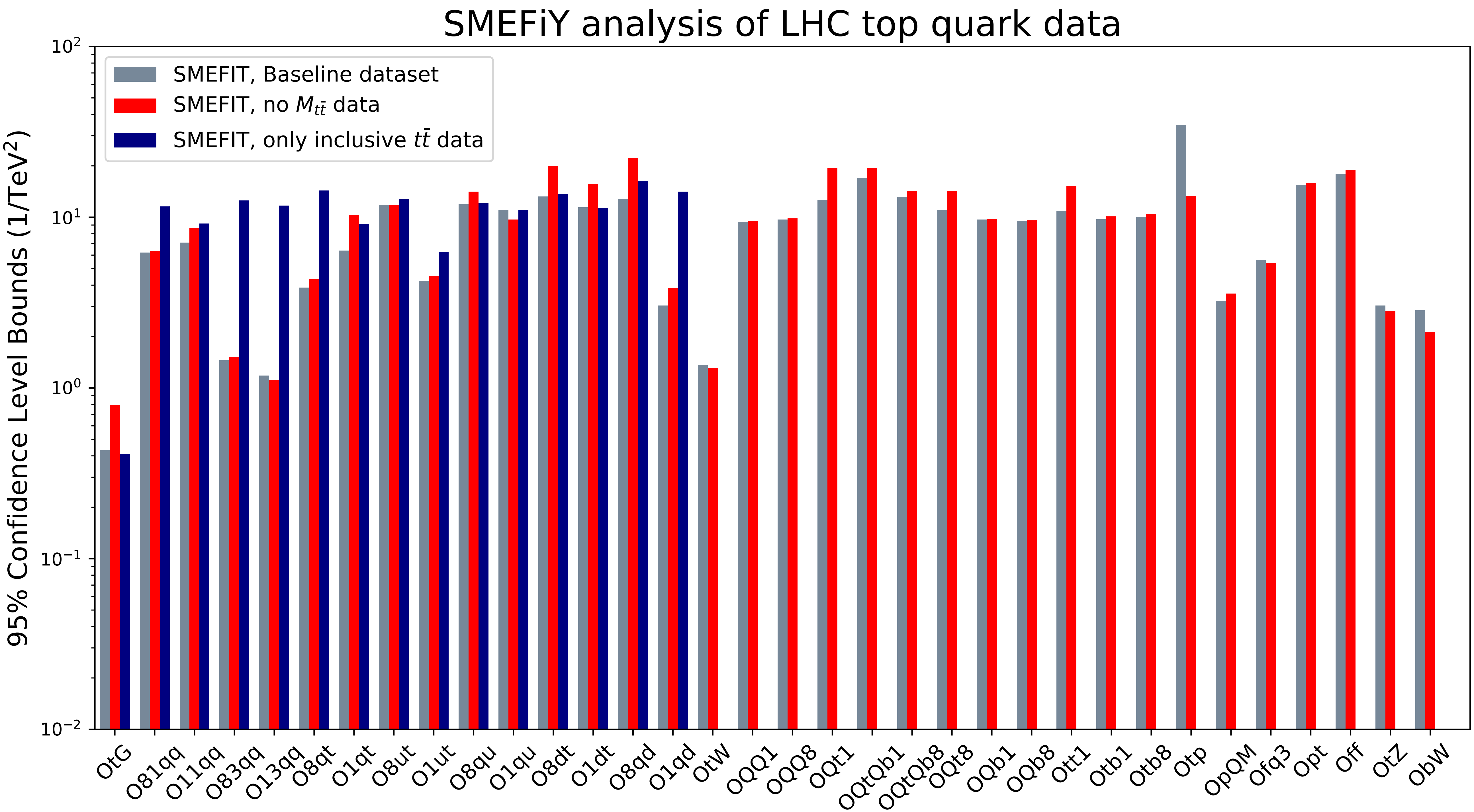
Energy-growing effects enhance sensitivity to SMEFT effects with **TeV-scale cross-sections** but need to be careful to ensure **validity of EFT description**

Dependence on theory settings



Accounting for the **quadratic O(Λ^{-4}) terms** strengthens bounds for several operators

Dependence on dataset



Reasonable stability of the fit results with respect to the **choice of dataset**

Summary and outlook

- Presented a novel framework, **SMEFiT,** suitable for global analyses of the SMEFT, which exploit expertise inherited from global PDF fits

- As a proof-of-concept, applied this framework to the exploration of the constraints in the SMEFT parameter space provided by **LHC top quark data**

- **Improved constraints** compared to previous studies (first-even bounds in some cases)

- Demonstrated **Bayesian reweighting** for the *a posteriori* inclusion of the constraints from new measurements on SMEFiT without need of redoing fit

- Next steps: enlarge the operator fitting basis and include **additional LHC cross-sections** (Higgs, electroweak, jets) as well as flavour and low-energy observables, and explore implications for specific **UV-complete models**