Staying on Top of Likelihood Analyses with *SFitter*

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Based on 2312.12502 with N. Elmer, T. Plehn & N. Schmal

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Global SMEFT interpretations

The SMEFT: a powerful framework for capturing deviations from the SM:

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \frac{C^{(5)}}{\Lambda}\mathcal{O}^{(5)} + \sum_i \frac{C_i^{(6)}}{\Lambda^2}\mathcal{O}_i^{(6)} + \ldots$$

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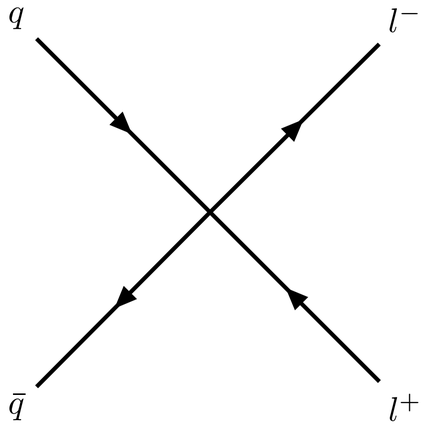

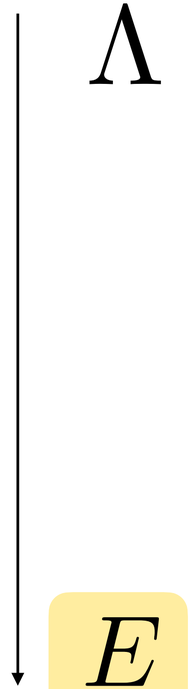

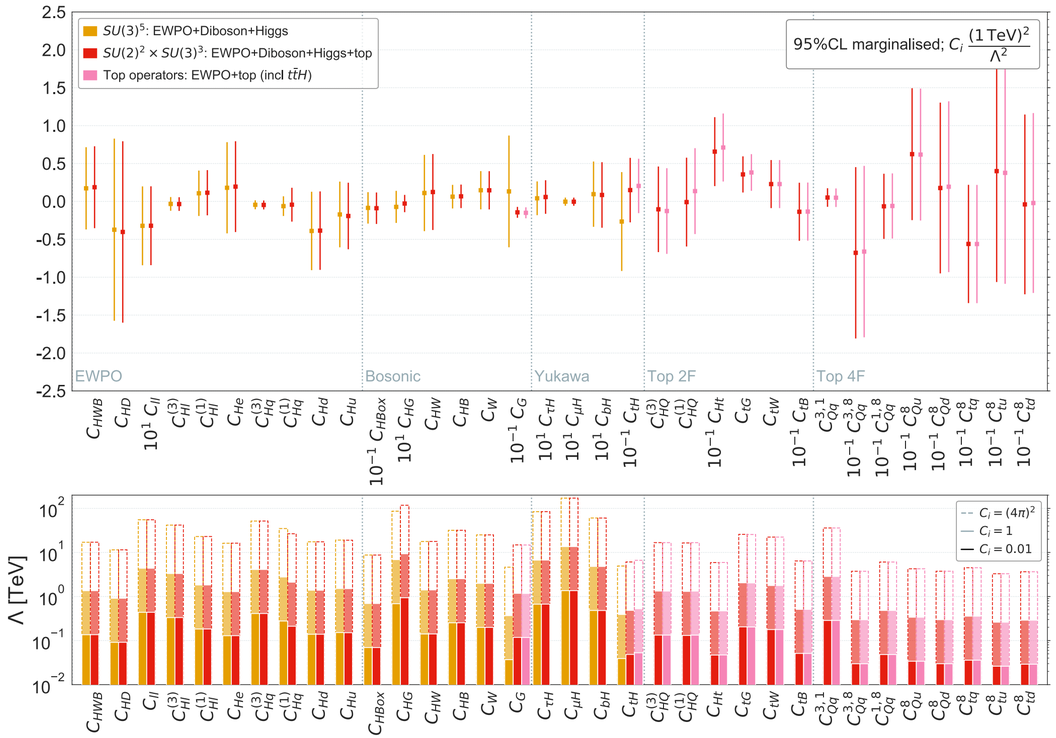

2012.02779, J. Ellis, MM, K. Mimasu, V. Sanz, T. You

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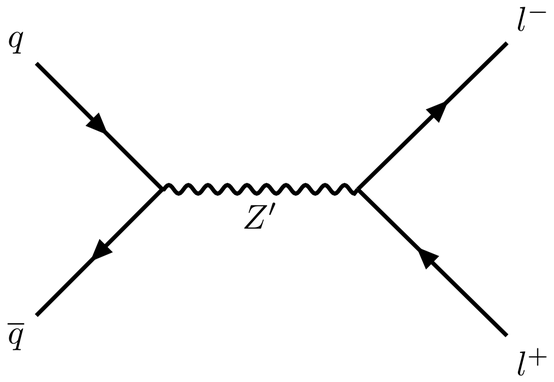

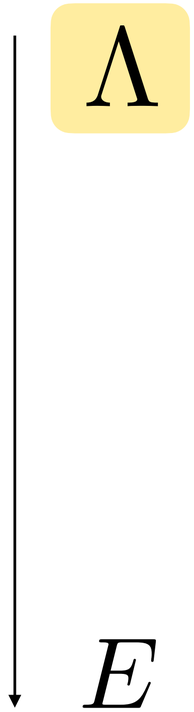

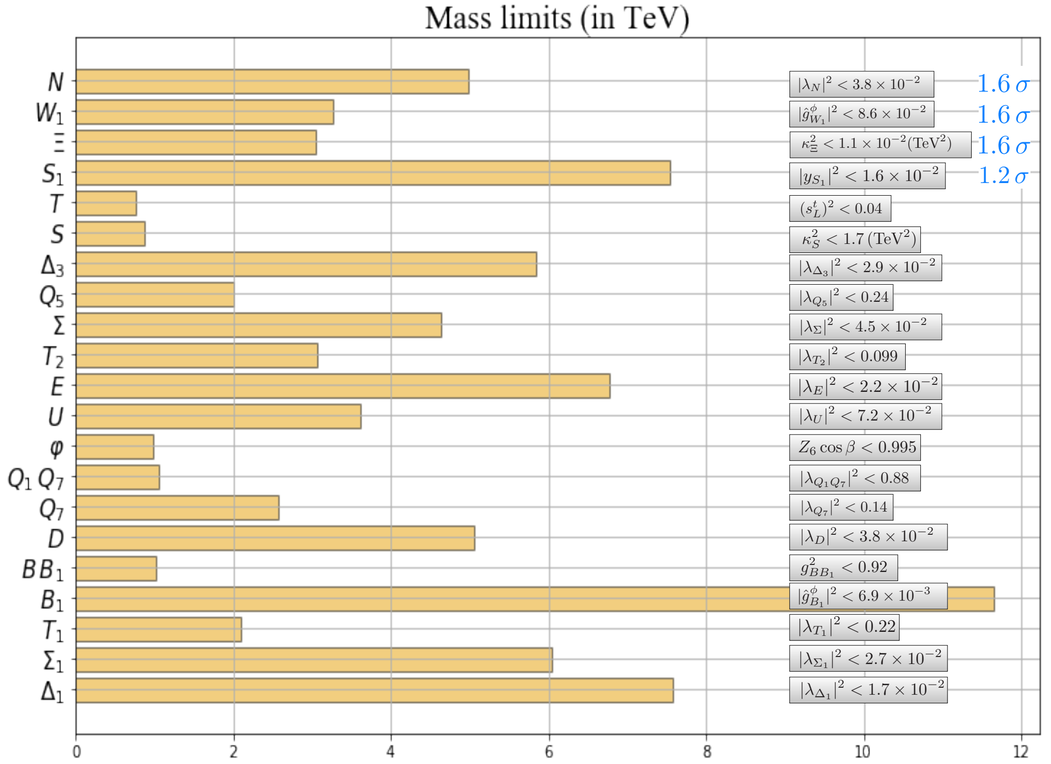

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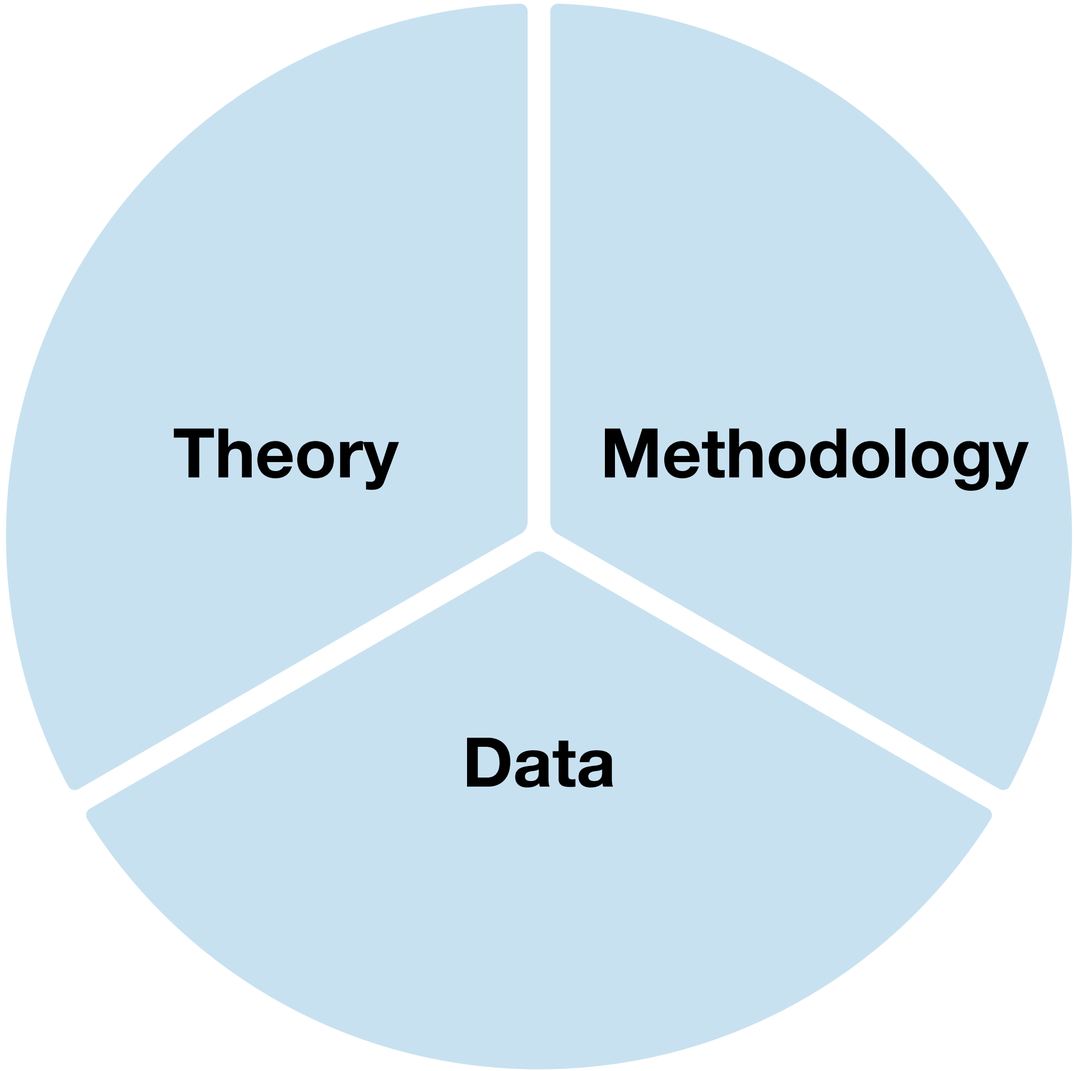
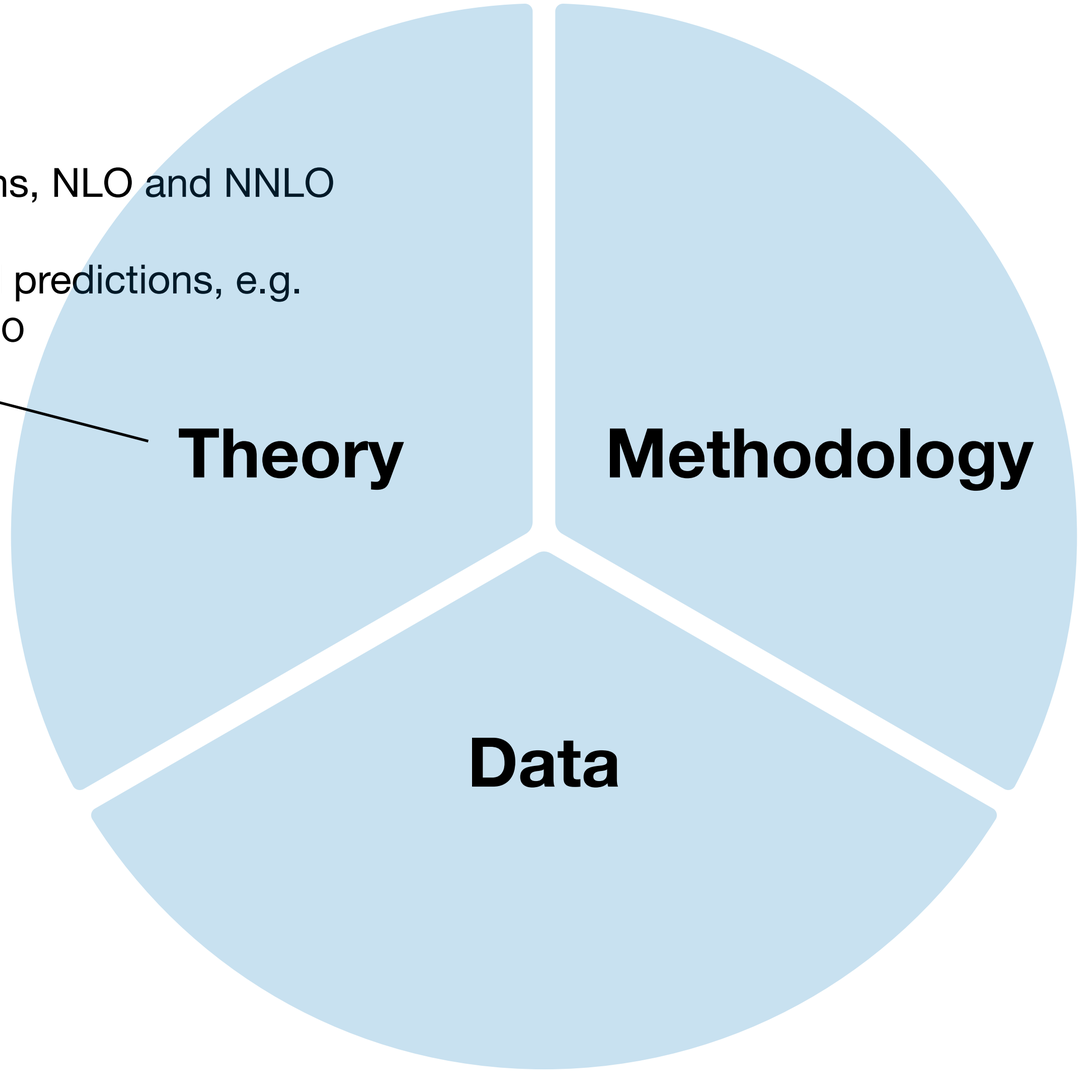


Global SMEFT interpretations

- Precision SM calculations, NLO and NNLO
- PDFs
- SMEFT calculations and predictions, e.g. `SMEFTsim, SMEFT@NLO`



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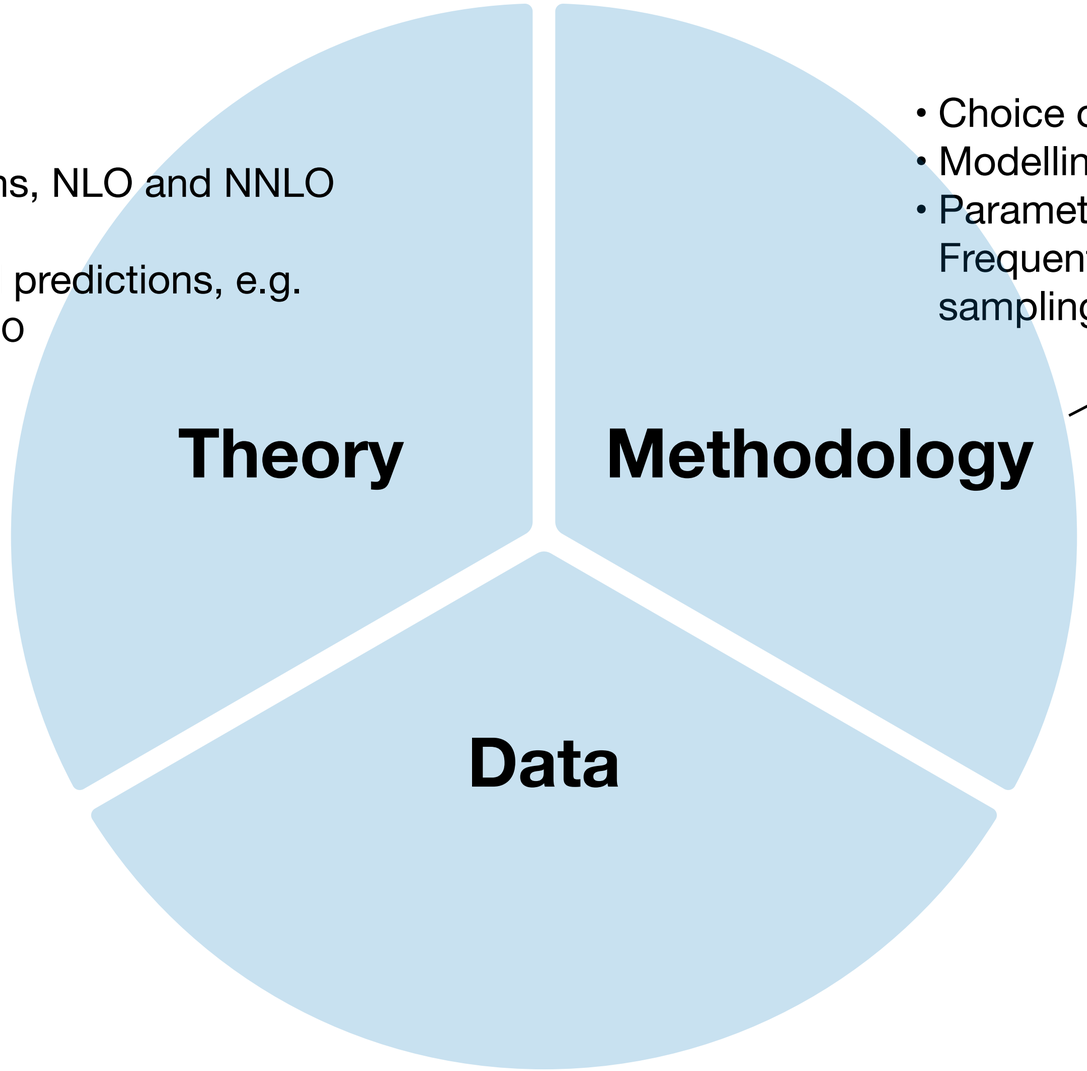

- Choice of likelihood
- Modelling of uncertainties
- Parameter estimation: Bayesian vs Frequentist, grid scan vs MCMC vs Nested sampling vs profiling vs …

Global SMEFT interpretations

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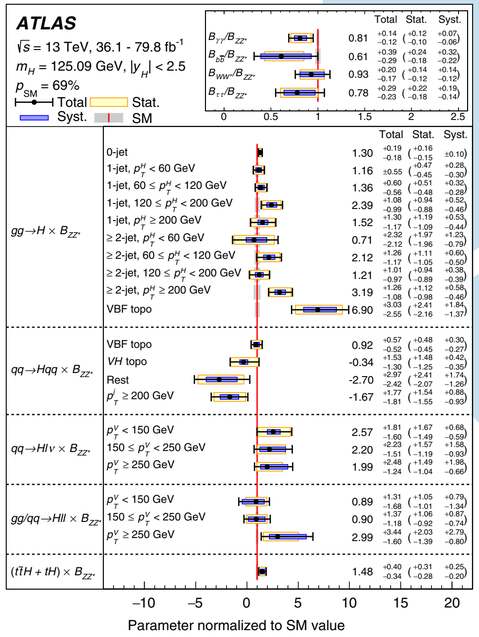
Theory

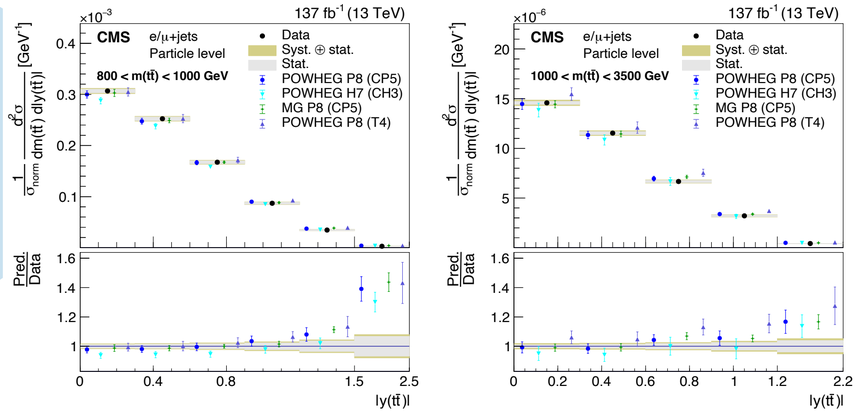
Methodology

- Choice of likelihood
- Modelling of uncertainties
- Parameter estimation: Bayesian vs Frequentist, grid scan vs MCMC vs Nested sampling vs profiling vs …

Data



[ATLAS, Phys. Rev. D 101 (2020) 012002]

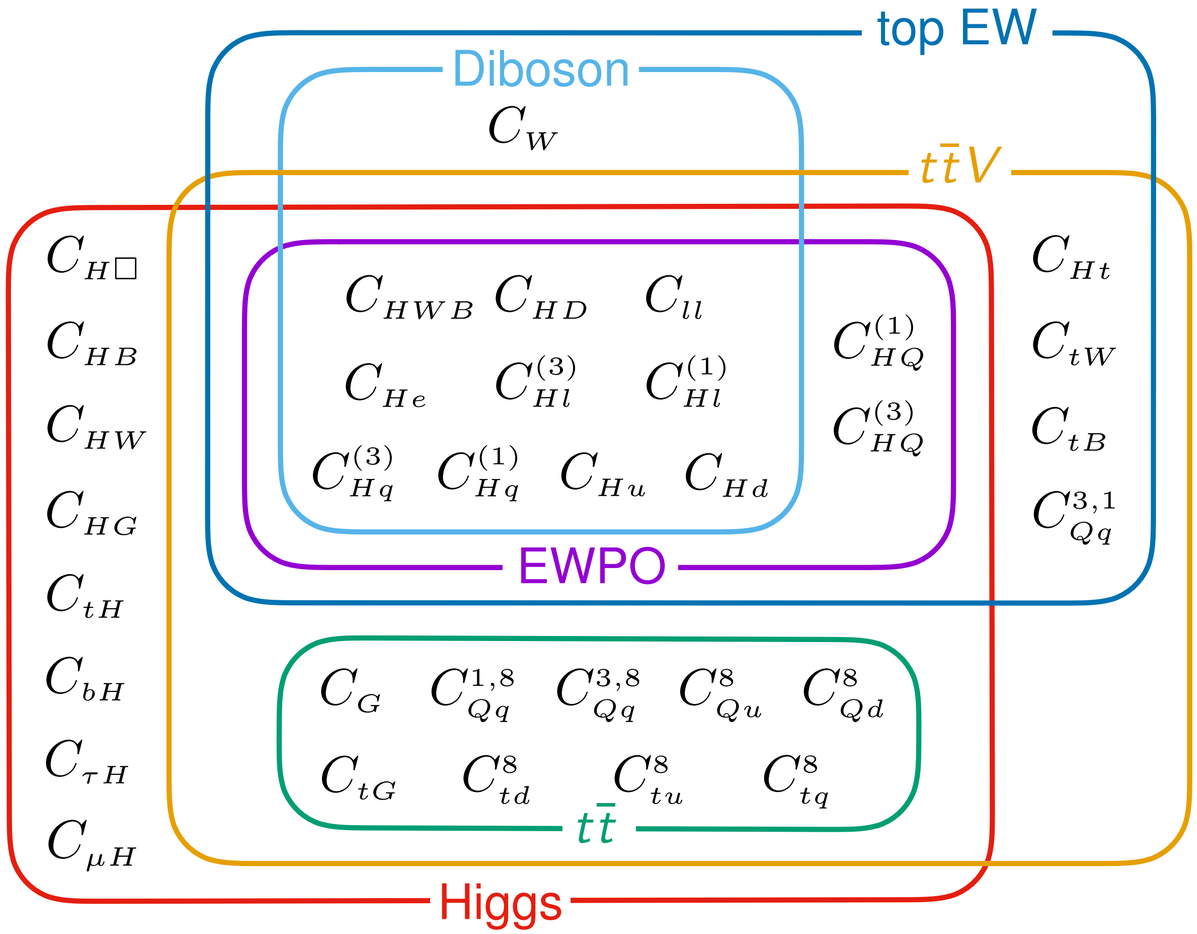


[CMS, Phys. Phys. Rev. D 104 (2021) 092013]

Global SMEFT interpretations: Data

Global: as much data constraining as many processes as possible

Data: the use of data in SMEFT fits depends on *how the data is presented*



2012.02779, J. Ellis, MM, K. Mimasu, V. Sanz, T. You

Published likelihoods

from https://twiki.cern.ch/twiki/bin/view/AtlasPublic

Observation of the tgamma production	TOPQ	Accepted by PRL	2023-02-02	13	140 fb^{-1}	Documents | 2302.01283 Inspire | HepData Internal
Search for gluinos in multi-b final states	SUSY	Eur. Phys. J. C 83 (2023) 561	2022-11-15	13	139 fb^{-1}	Documents | 2211.08028 Inspire | HepData Internal
Measurement of the s-channel single top cross-section at 13 TeV	TOPQ	JHEP 06 (2023) 191	2022-09-19	13	139 fb^{-1}	Documents | 2209.08990 Inspire | HepData Internal
Search for flavor-changing neutral-current couplings between the top-quark and the photon at 13 TeV	TOPQ	Phys. Lett. B 842 (2023) 137379	2022-05-05	13	139 fb^{-1}	Documents | 2205.02537 Inspire | HepData Internal
Search for SUSY in events with 2 leptons, jets and MET	SUSY	Eur. Phys. J. C 83 (2023) 515	2022-04-27	13	139 fb^{-1}	Documents | 2204.13072 Inspire | HepData Internal
Search BSM H→hh→bb gamma gamma and hh→bb gamma gamma	HDBS	Phys. Rev. D 106 (2022) 052001	2021-12-22	13	139 fb^{-1}	Documents | 2112.11876 Inspire | HepData Internal
Search for charginos and neutralinos in all-hadronic final states	SUSY	Phys. Rev. D 104 (2021) 112010	2021-08-17	13	139 fb^{-1}	Documents | 2108.07586 Inspire | HepData Briefing | Internal
4-top xsec measurement	TOPQ	JHEP 11 (2021) 118	2021-06-22	13	139 fb^{-1}	Documents | 2106.11683 Inspire | HepData Internal
Search for gluinos, stops and electroweakinos in RPV models in final states with 1L and many jets	SUSY	Eur. Phys. J. C 81 (2021) 1023	2021-06-17	13	139 fb^{-1}	Documents | 2106.09609 Inspire | HepData Briefing | Internal

Many more likelihoods being published alongside measurements 🥳

Goal: **to assess the impact of published likelihoods on global SMEFT interpretations with SFitter**

Outline:

- SFitter
- SMEFT fits in the top sector
- SFitter and likelihoods

SFitter

Likelihood: $p(d|c,\theta)$

d: data

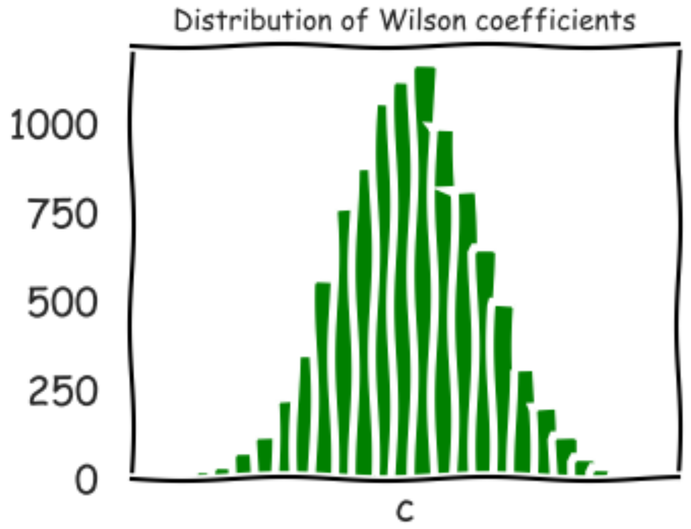
c: Wilson coefficient

θ: nuisance parameter

SFitter

Likelihood: $p(d|c,\theta)$

sample using MCMC



SFitter

Likelihood: $p(d|c,\theta)$

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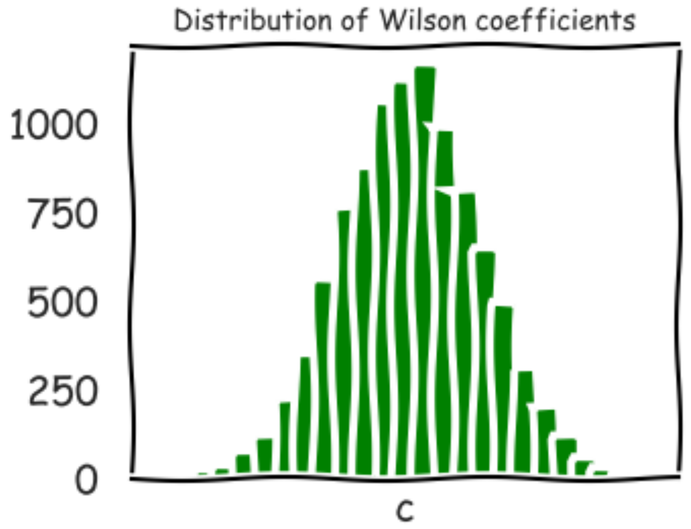
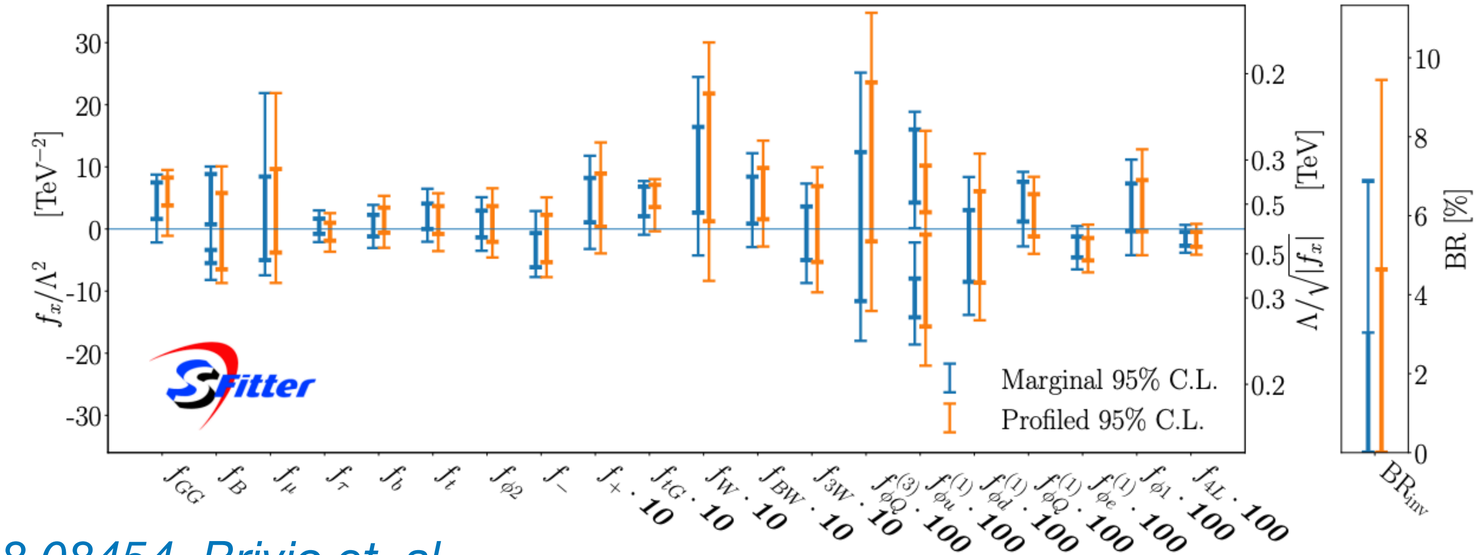


marginalise/profile



2208.08454, Brivio et. al

SFitter: likelihood construction

Accurate reconstruction of the likelihood is crucial:

$$p(d|c,\theta) = \mathrm{Pois}(d|m(c,\theta,b))\,\mathrm{Pois}(b_{\mathrm{CR}}|b\,k)\prod_i \mathcal{C}_i(\theta_i,\sigma_i)$$

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signal regions

control regions

nuisance parameters determine the impact of uncertainties

SFitter: theory uncertainties

Theory uncertainties follow a flat distribution:

$$\theta_{\mathrm{th}} \sim \mathcal{F}(\sigma_{\mathrm{th}})$$

e.g. QCD scale uncertainties, PDF uncertainties

Theory uncertainties are correlated between measurements of the same observable

SFitter: systematic uncertainties

Systematic uncertainties follow a Gaussian distribution:

$$\theta_{\mathrm{syst}} \sim \mathcal{N}(0, \sigma_{\mathrm{syst}})$$

Published likelihoods will allow us to validate this approximation

σ_{syst} approximated from experimental publications, HEPData and published likelihoods

SFitter: correlated systematic uncertainties

Systematic uncertainties are grouped into categories:

example:

$$\left.\begin{aligned}&\theta_{\text{jet energy scale}}\\&\theta_{\text{jet energy resolution}}\\&\theta_{\text{other jet reconstruction}}\end{aligned}\right\}\ \theta_{\text{jets}}$$

SFitter: correlated systematic uncertainties

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example:

$\theta_{\text{jet energy scale}}$

$\theta_{\text{jet energy resolution}}$

$\theta_{\text{other jet reconstruction}}$

$\Big\}$ θ_{jets}

θ_{jets} is 100% correlated between measurements

Different categories are uncorrelated: e.g. θ_{jets}, θ_{lumi}, θ_{leptons} .....

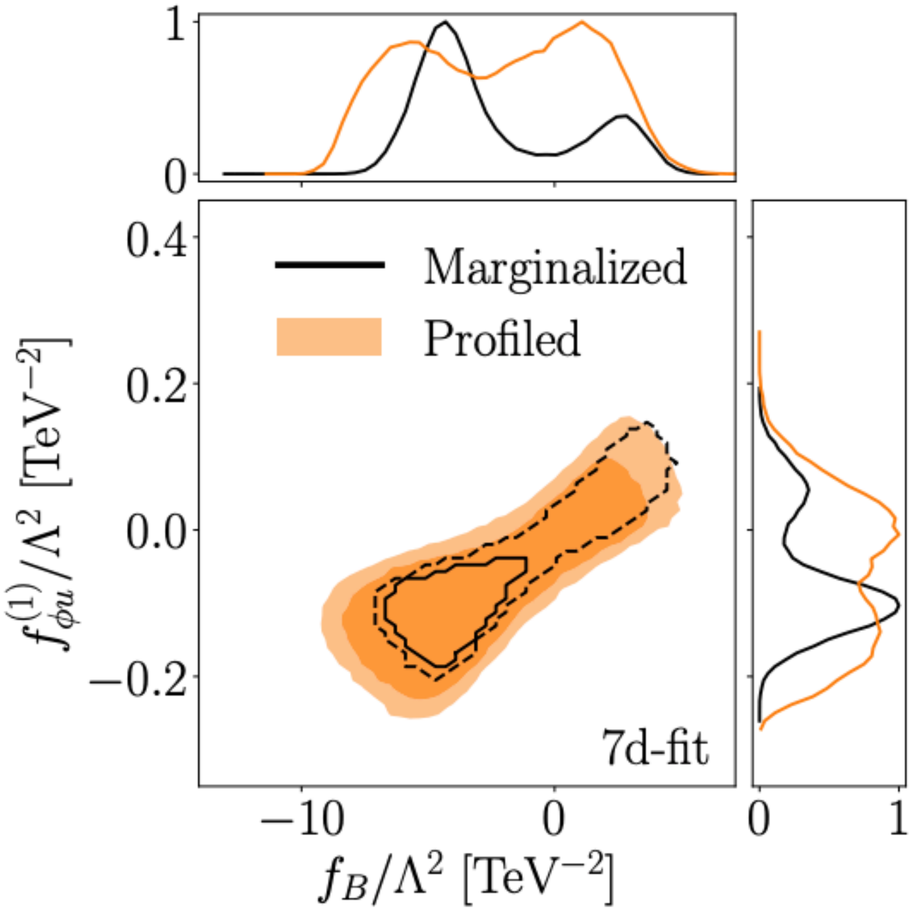
Published likelihoods will allow us to validate this approximation

SFitter: profiling and marginalisation

Constraints on parameters of interest are obtained by **profiling** or **marginalisation**

Profiling: $\mathcal{L}_{\text{prof}}(c) = \max_{\theta} \mathcal{L}_{\text{excl}}(c, \theta)$

Marginalisation: $\mathcal{L}_{\text{marg}}(c) = \int d\theta \mathcal{L}_{\text{excl}}(c, \theta)$



2208.08454, Brivio et. al, Higgs + diboson global fit

SMEFT fits in the top sector

The top sector of the SMEFT

Operator	Definition	Operator	Definition
$O_{Qq}^{3,8}$	$(\bar{Q}\gamma_\mu T^A \tau^I Q)(\bar{q}_i \gamma^\mu T^A \tau^I q_i)$	$O_{Qq}^{3,1}$	$(\bar{Q}\gamma_\mu \tau^I Q)(\bar{q}_i \gamma^\mu \tau^I q_i)$
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We will constrain 22 operators of the dimension-6 SMEFT

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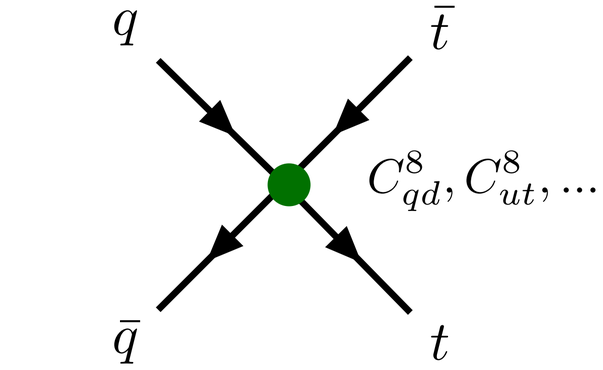
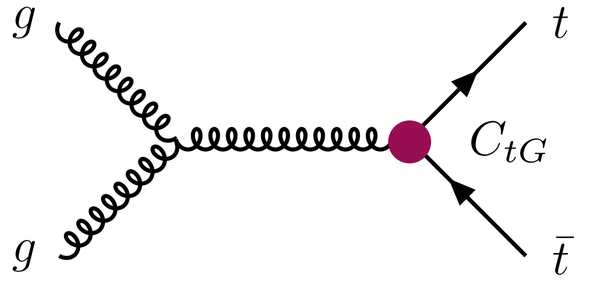
$t\bar{t}$ production:





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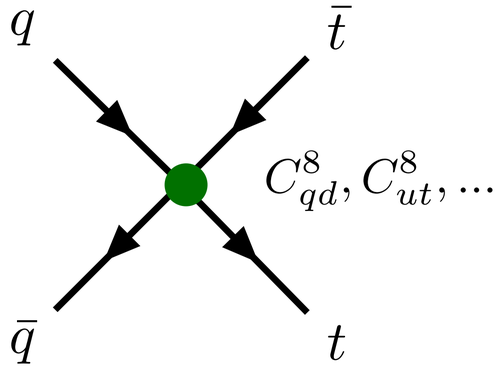
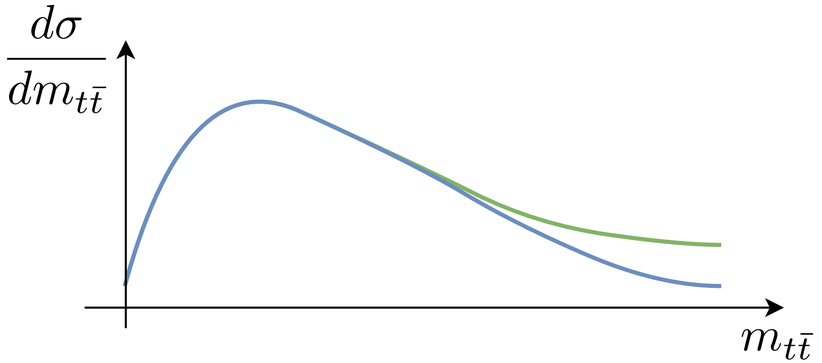


Energy growing effect in **kinematic distributions**



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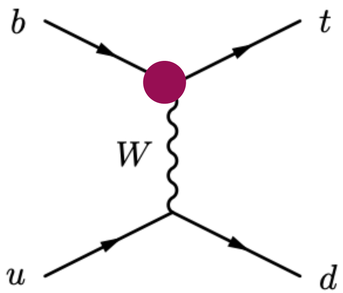
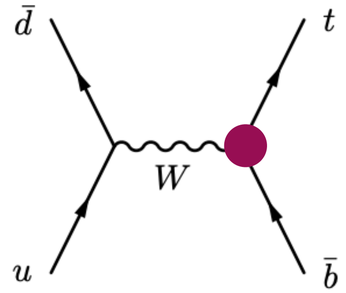
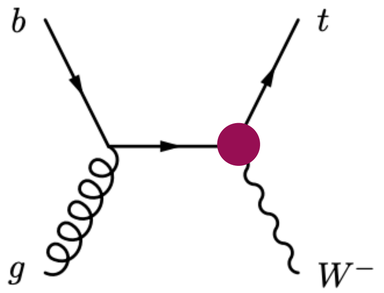
Single top production



(t-channel)



(s-channel)



(tW)

1910.03606, Brivio et. al

The top sector of the SMEFT

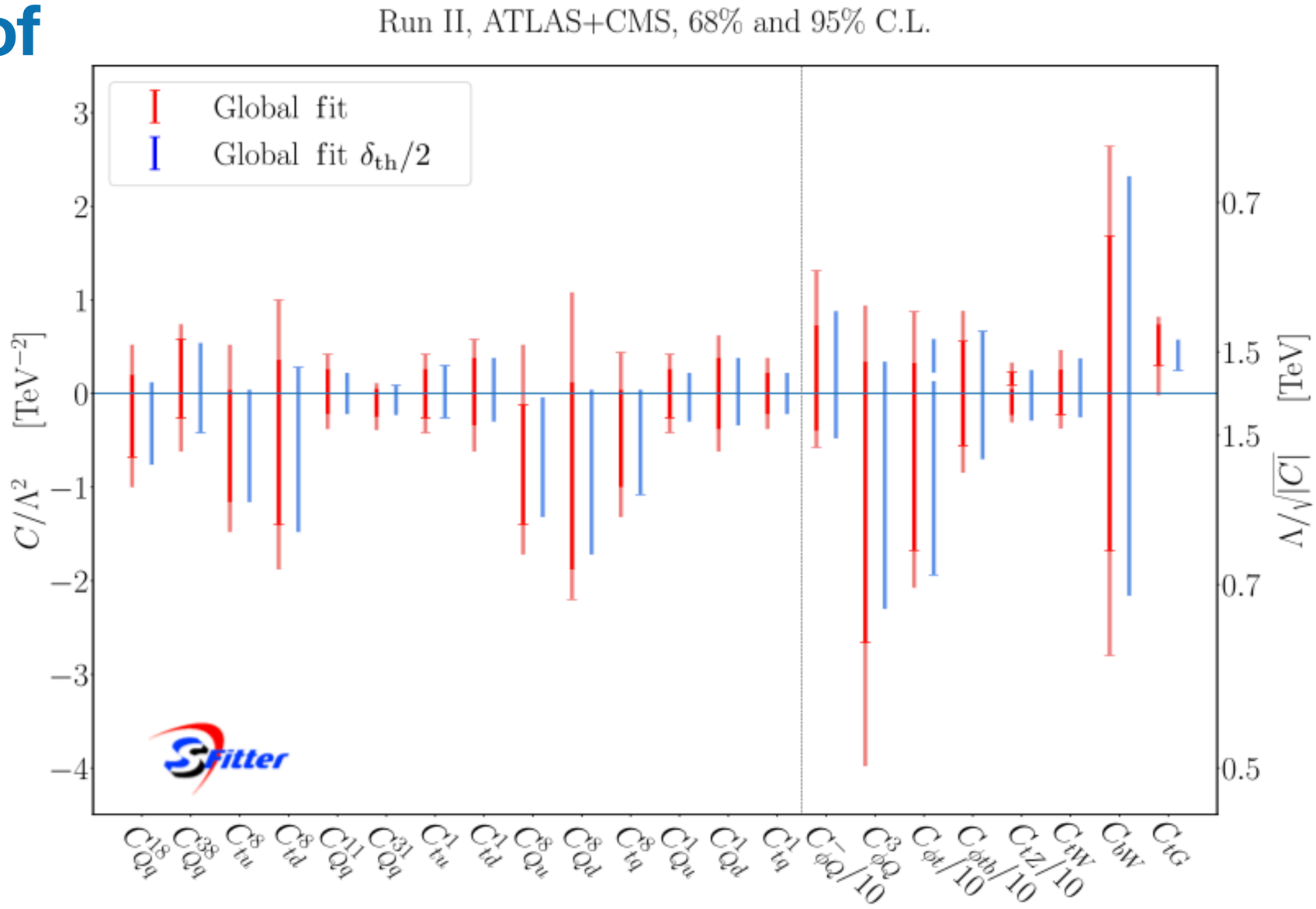
Operator	Definition	Operator	Definition
$O_{Qq}^{3,8}$	$(\bar{Q}\gamma_\mu T^A \tau^I Q)(\bar{q}_i \gamma^\mu T^A \tau^I q_i)$	$O_{Qq}^{3,1}$	$(\bar{Q}\gamma_\mu \tau^I Q)(\bar{q}_i \gamma^\mu \tau^I q_i)$
$O_{Qq}^{1,8}$	$(\bar{Q}\gamma_\mu T^A Q)(\bar{q}_i \gamma^\mu T^A q_i)$	$O_{Qq}^{1,1}$	$(\bar{Q}\gamma_\mu Q)(\bar{q}_i \gamma^\mu q_i)$
O_{tu}^{8}	$(\bar{t}\gamma_\mu T^A t)(\bar{u}_i \gamma^\mu T^A u_i)$	O_{tu}^{1}	$(\bar{t}\gamma_\mu t)(\bar{u}_i \gamma^\mu u_i)$
O_{td}^{8}	$(\bar{t}\gamma_\mu T^A t)(\bar{d}_i \gamma^\mu T^A d_i)$	O_{td}^{1}	$(\bar{t}\gamma_\mu t)(\bar{d}_i \gamma^\mu d_i)$
O_{Qu}^{8}	$(\bar{Q}\gamma^\mu T^A Q)(\bar{u}_i \gamma_\mu T^A u_i)$	O_{Qu}^{1}	$(\bar{Q}\gamma^\mu Q)(\bar{u}_i \gamma_\mu u_i)$
O_{Qd}^{8}	$(\bar{Q}\gamma^\mu T^A Q)(\bar{d}_i \gamma_\mu T^A d_i)$	O_{Qd}^{1}	$(\bar{Q}\gamma^\mu Q)(\bar{d}_i \gamma_\mu d_i)$
O_{tq}^{8}	$(\bar{q}_i \gamma^\mu T^A q_i)(\bar{t}\gamma_\mu T^A t)$	O_{tq}^{1}	$(\bar{q}_i \gamma^\mu q_i)(\bar{t}\gamma_\mu t)$
$O_{\phi Q}^{3}$	$(\phi^\dagger i\overleftrightarrow{D}_\mu \phi)(\bar{Q}\gamma^\mu \tau^I Q)$	$O_{\phi Q}^{1}$	$(\phi^\dagger i\overleftrightarrow{D}_\mu \phi)(\bar{Q}\gamma^\mu Q)$
$O_{\phi t}$	$(\phi^\dagger i\overleftrightarrow{D}_\mu \phi)(\bar{t}\gamma^\mu t)$	$O_{\phi tb}$	$(\tilde{\phi}^\dagger i D_\mu \phi)(\bar{t}\gamma^\mu b)$
O_{tB}	$(\bar{Q}\sigma^{\mu\nu} t)\tilde{\phi} B_{\mu\nu}$	O_{tW}	$(\bar{Q}\sigma^{\mu\nu} t)\tau^I \tilde{\phi} W^I_{\mu\nu}$
O_{bW}	$(\bar{Q}\sigma^{\mu\nu} b)\tau^I \phi W^I_{\mu\nu}$	O_{tG}	$(\bar{Q}\sigma_{\mu\nu} T^A t)\tilde{\phi} G^A_{\mu\nu}$

+ contributions to

$t\bar{t} + X(Z, W, \gamma)$

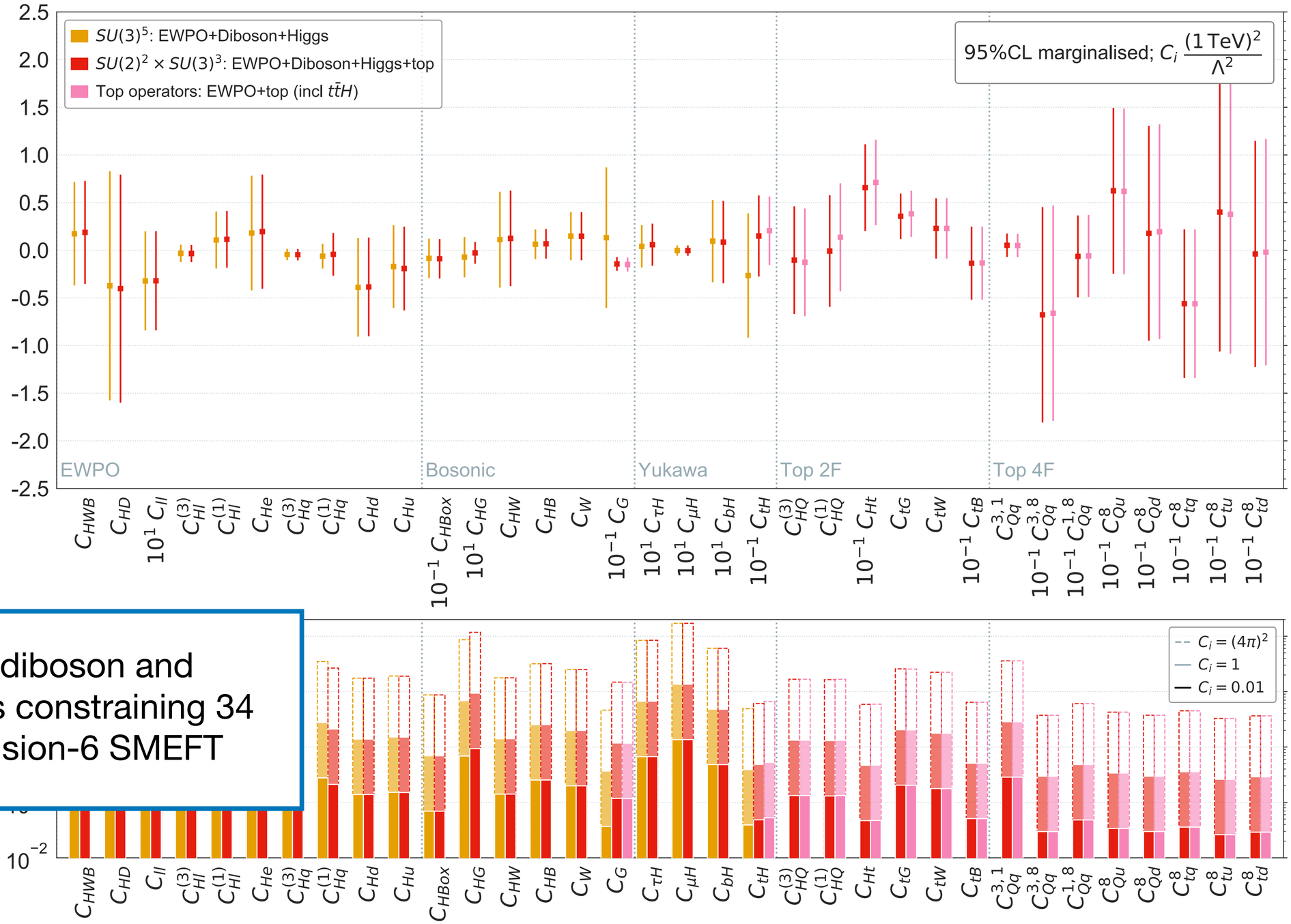
single top $+ X(Z, W)$

SFitter global fit of the top sector

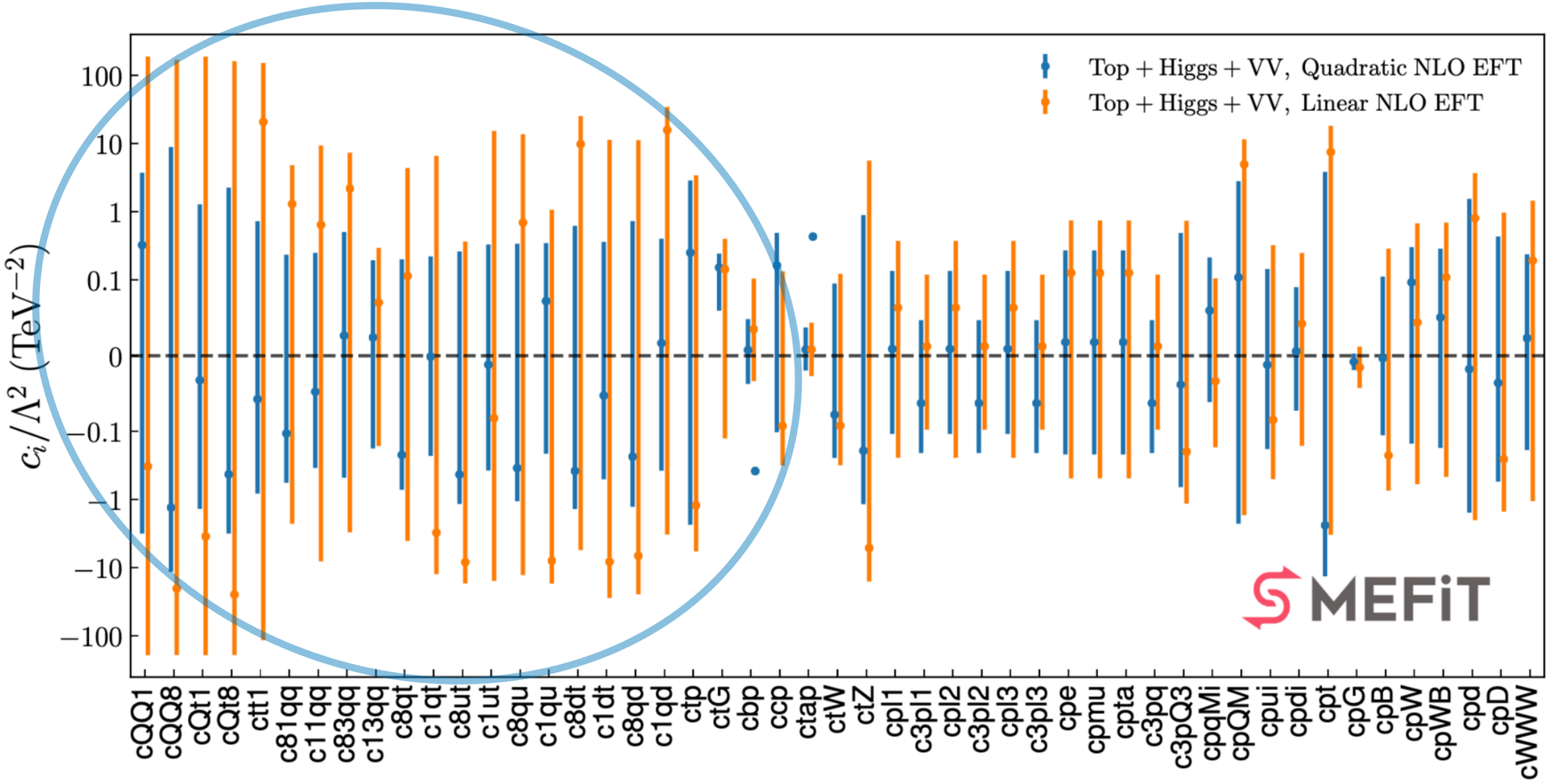


1910.03606, Brivio et. al

2012.02779, J. Ellis, MM, K. Mimasu, V. Sanz, T. You



Global fit of Higgs, top, diboson and electroweak observables constraining 34 coefficients of the dimension-6 SMEFT



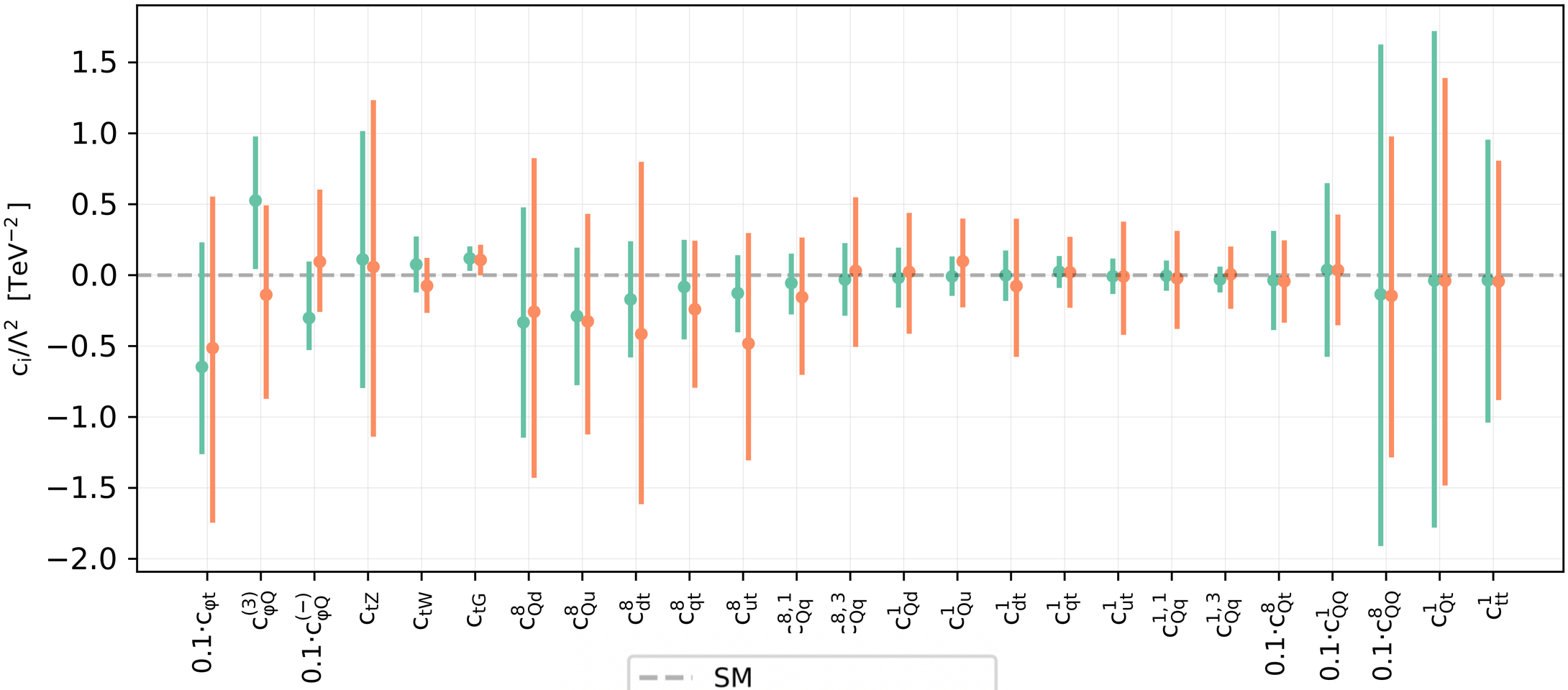
J. Ethier et. al, 2105.00006

Impact of higher order EFT terms and NLO calculations in the SMEFT

$$\sigma = \sigma_{\rm SM} + \frac{C}{\Lambda^2}\sigma_{\rm lin} + \frac{C^2}{\Lambda^4}\sigma_{\rm quad}$$

The top sector after Run II

Z. Kassabov et. al , 2303.06159



Top quark data available in 2023

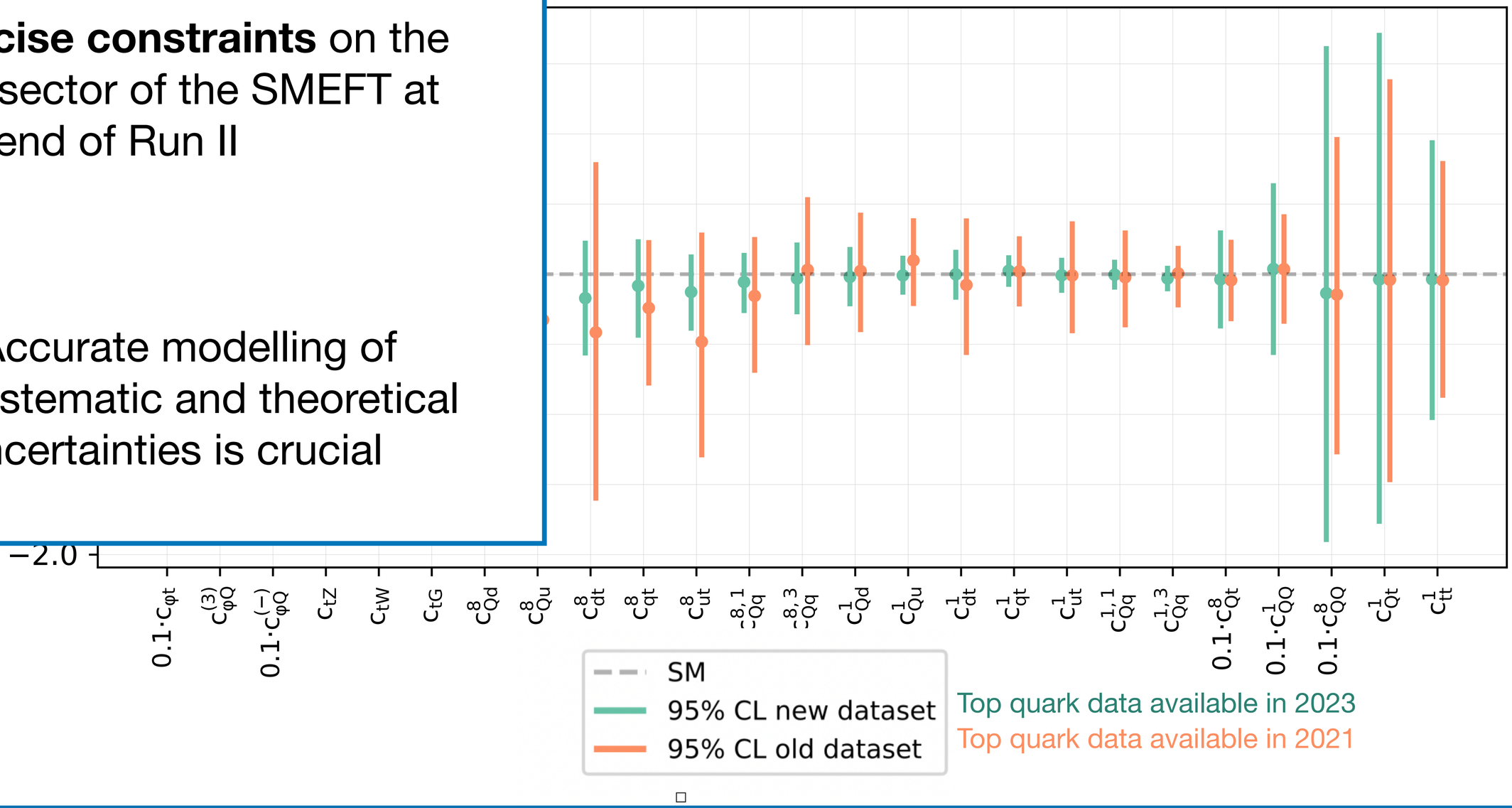
Top quark data available in 2021

The top sector after Run II

Z. Kassabov et. al , 2303.06159

Precise constraints on the top sector of the SMEFT at the end of Run II

➡ Accurate modelling of systematic and theoretical uncertainties is crucial



SFitter and likelihoods

SFitter and published likelihoods

Recall:

$$p(d|c,\theta) = \mathrm{Pois}(d|m(c,\theta,b))\ \mathrm{Pois}(b_{\mathrm{CR}}|b\,k)\ \prod_i \mathcal{C}_i(\theta_i,\sigma_i)$$

signal regions

control regions

nuisance parameters determine the impact of uncertainties

SFitter and published likelihoods

Recall:

$$p(d|c,\theta) = \mathrm{Pois}(d|m(c,\theta,b))\,\mathrm{Pois}(b_{\mathrm{CR}}|b\,k)\prod_i \mathcal{C}_i(\theta_i,\sigma_i)$$

Published likelihoods allow us to accurately reconstruct this:

- json format specifying parameters of the statistical model
- can be read and analysed using **pyhf** *pyhf.readthedocs.io*
- visualisation with **cabinetry** *cabinetry.readthedocs.io*

SFitter and published likelihoods

We will make use of three published likelihoods in SFitter:

ATLAS measurement of the
$t\bar{t}$ **total cross section**
at 13 TeV

2006.13076

ATLAS measurement of the
$t\bar{t}Z$ **total cross section**
at 13 TeV

2103.12603

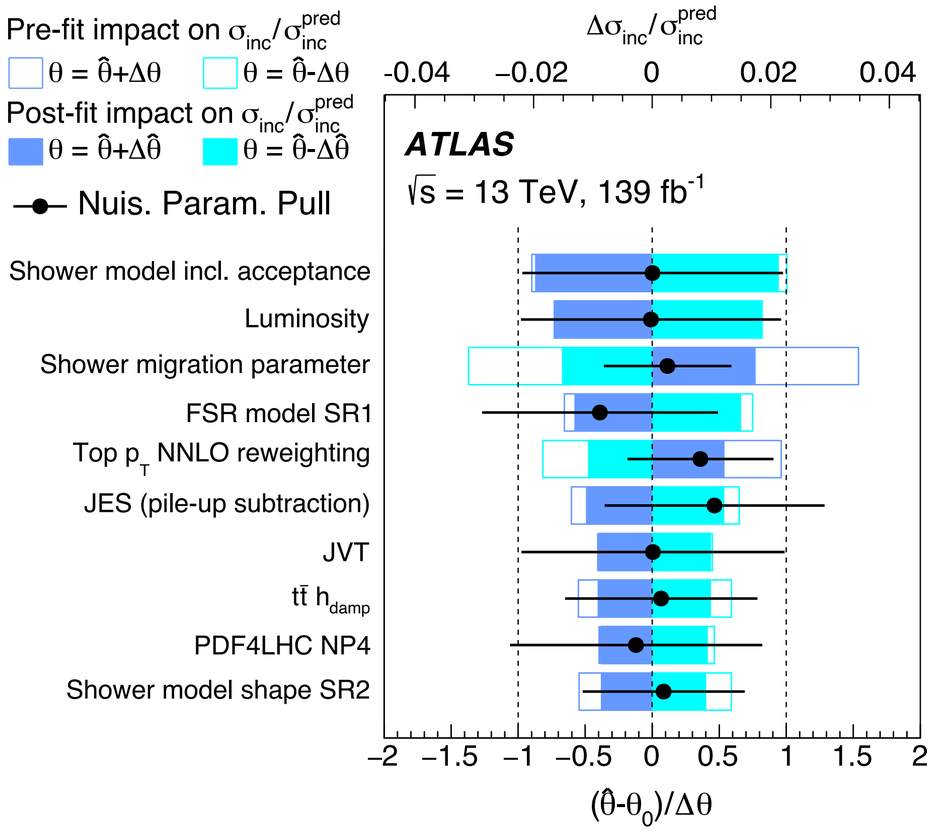
ATLAS measurement of the
s-channel single top
total cross section
at 13 TeV

2209.08990

Added to an **updated global fit** of the top sector: 122 measurements from $t\bar{t}, t\bar{t} + X(Z, W, \gamma)$, single top

Case 1: $t\bar{t}$ production

ATLAS measurement of the $t\bar{t}$ total cross section at 13 TeV, 2006.13076



detailed information on systematic uncertainties

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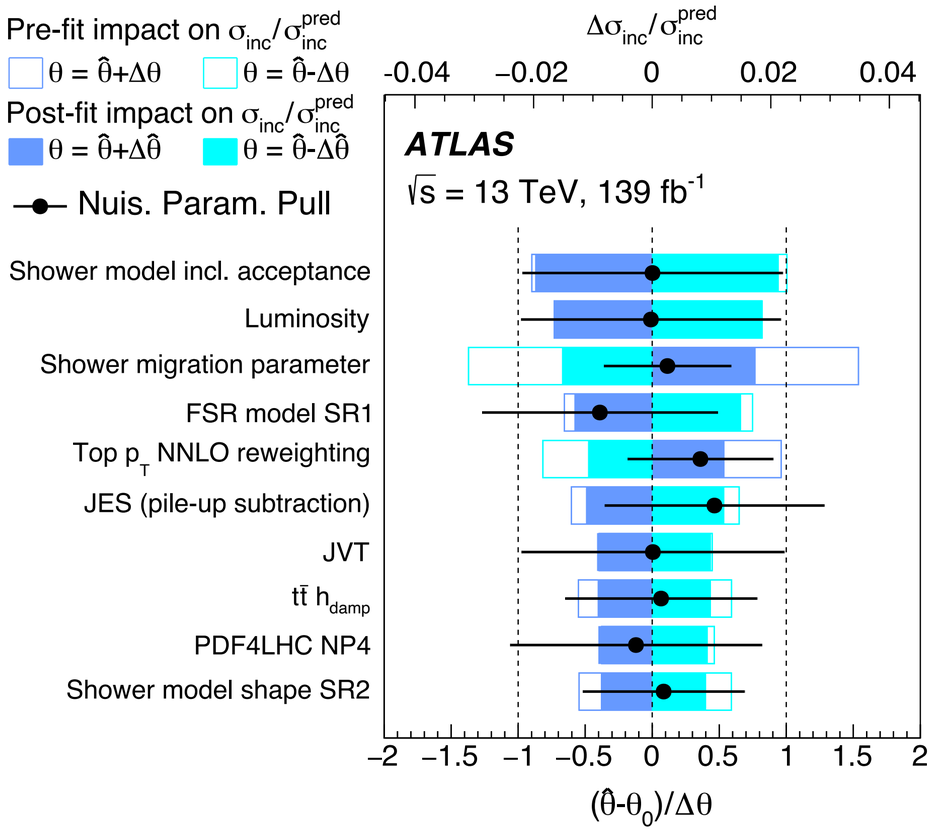

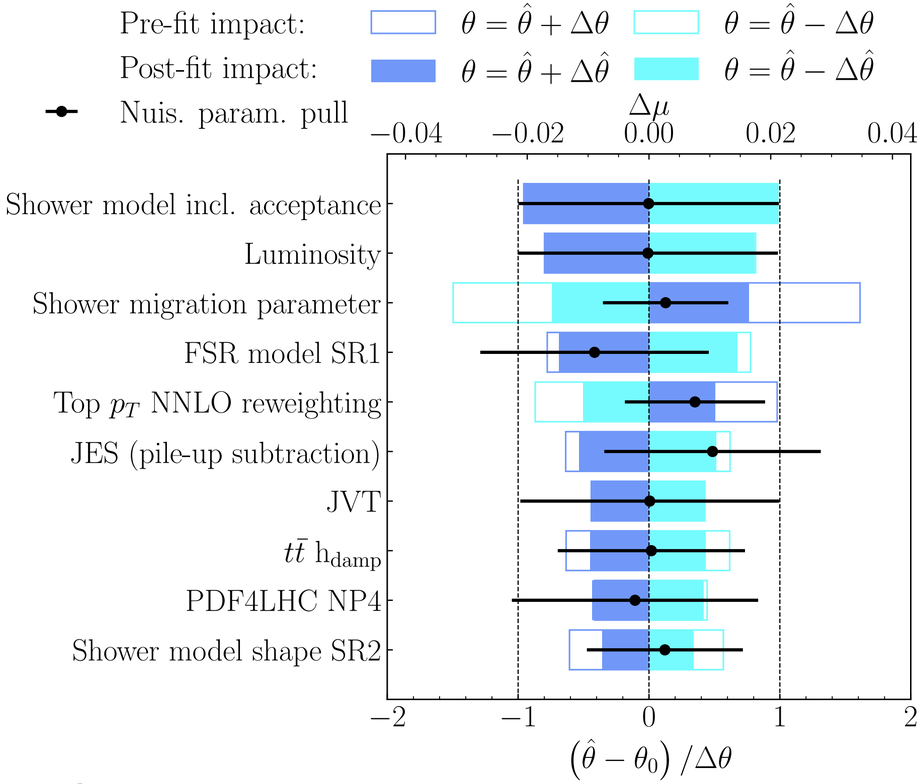

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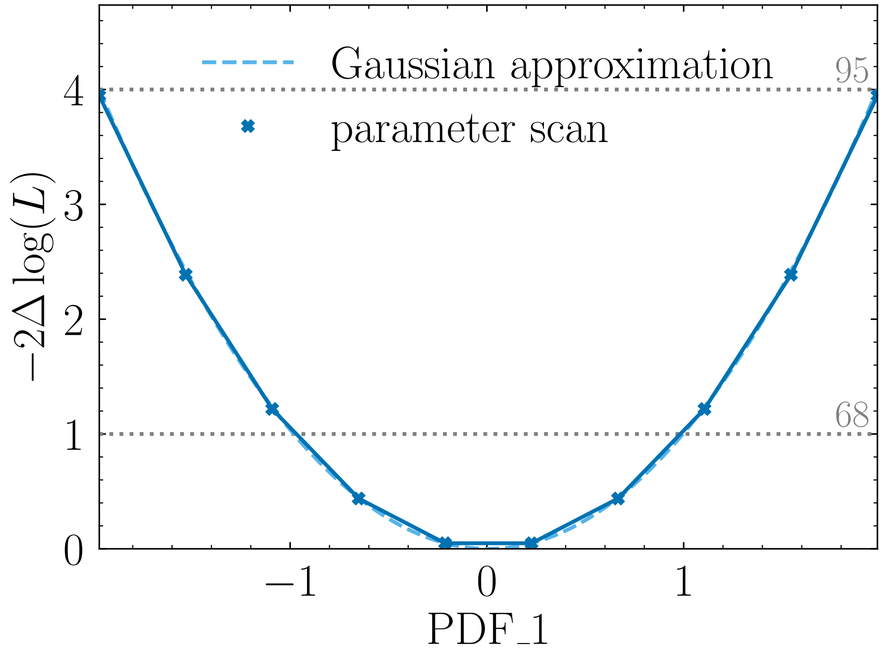

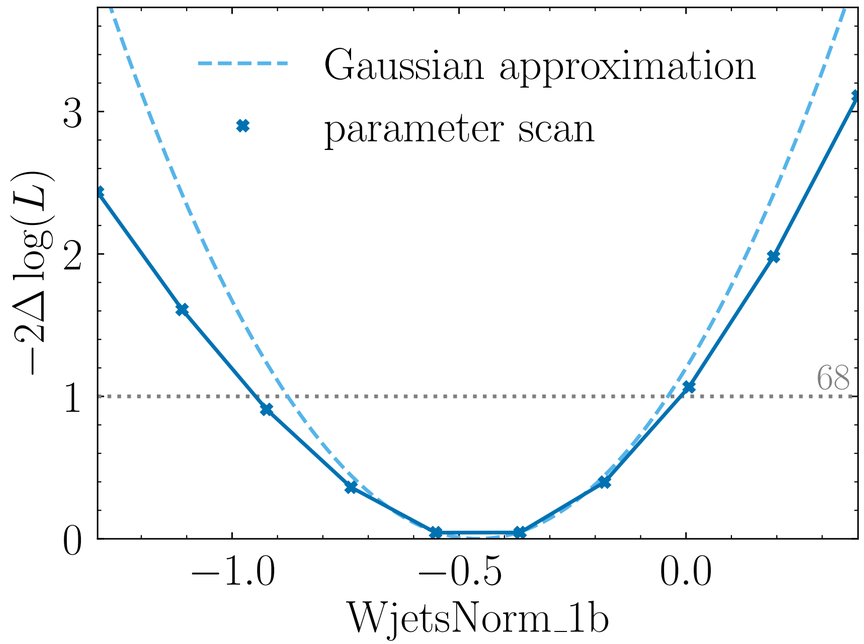

Assumption of gaussian distributions for systematic uncertainties is validated ✅

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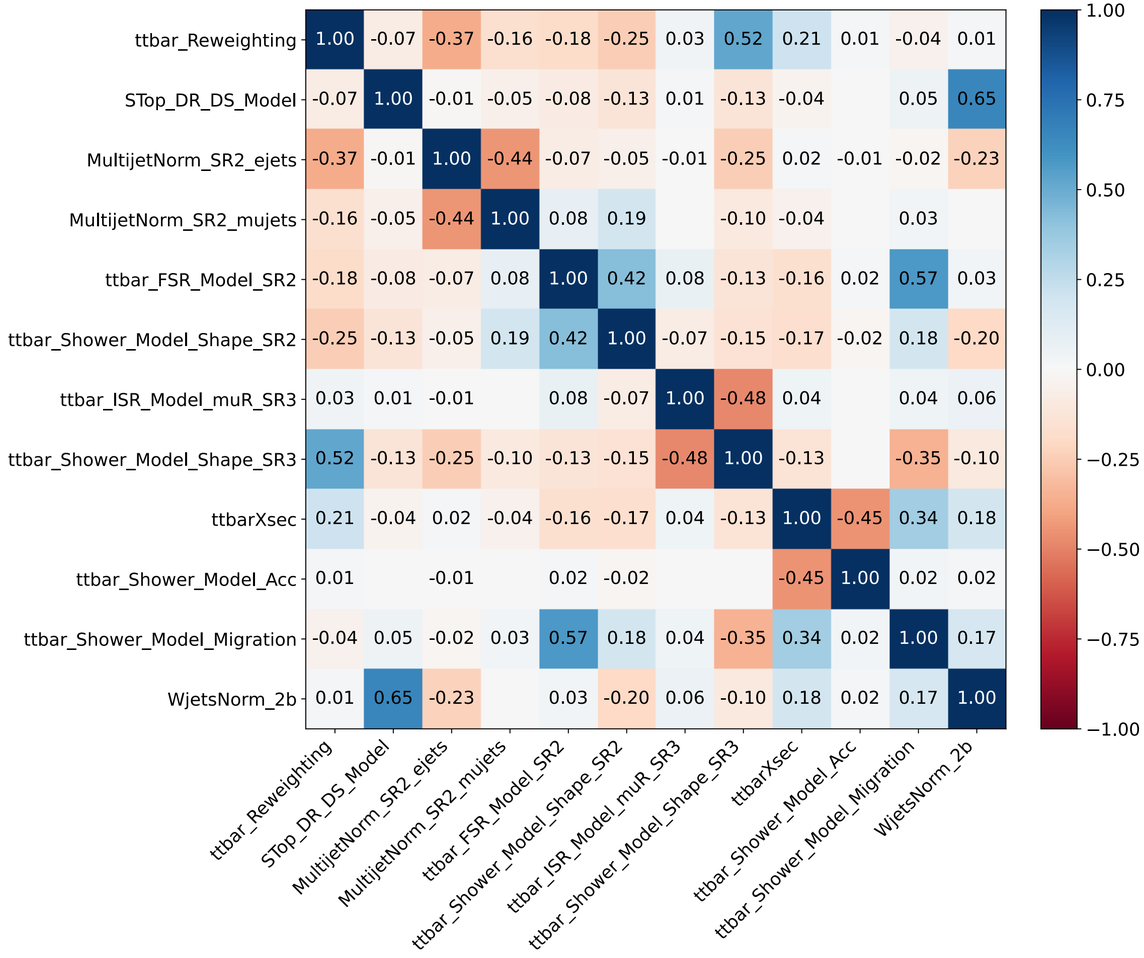

We can analyse the correlations between systematic uncertainties **before** and after grouping in to SFitter categories

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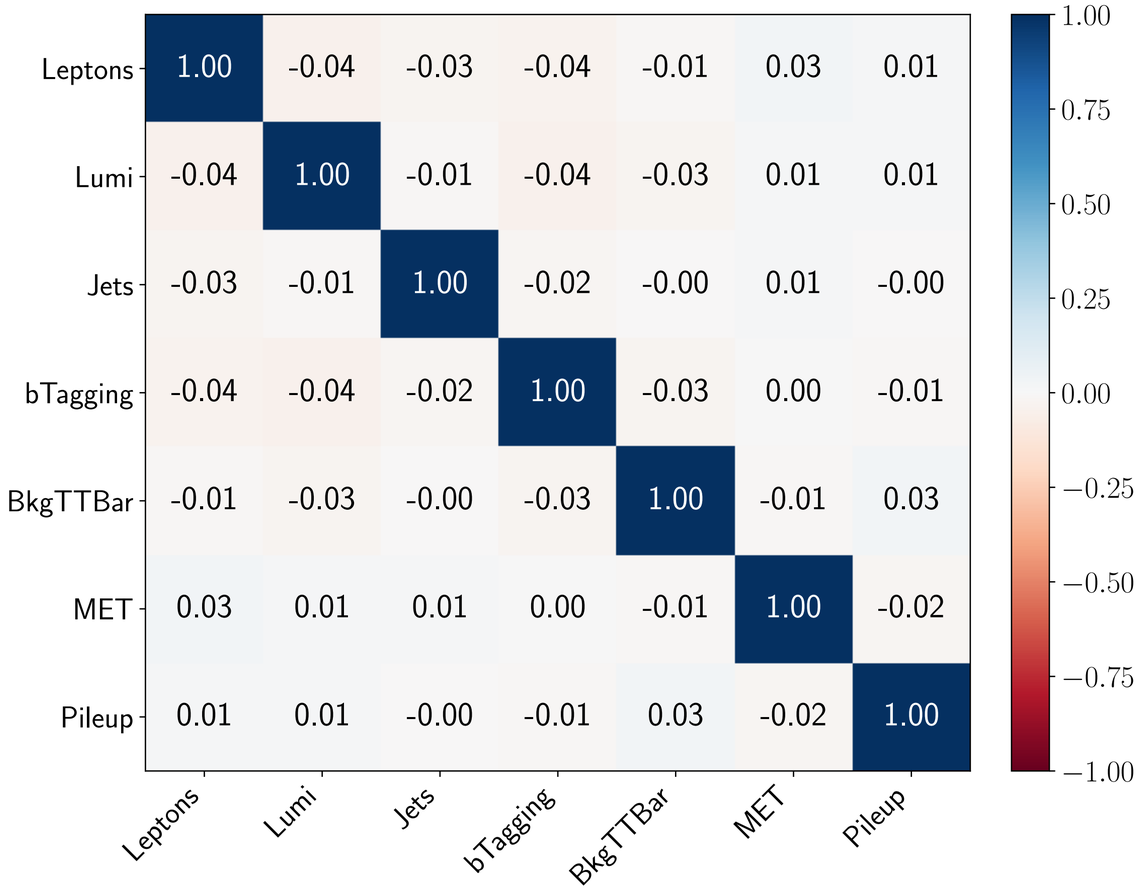

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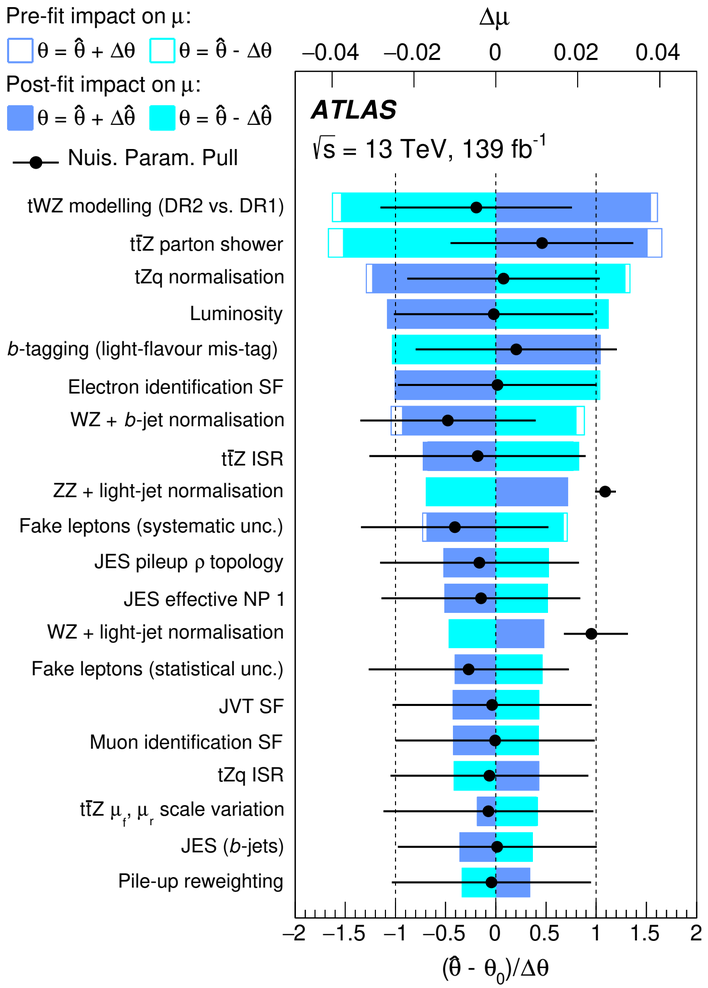
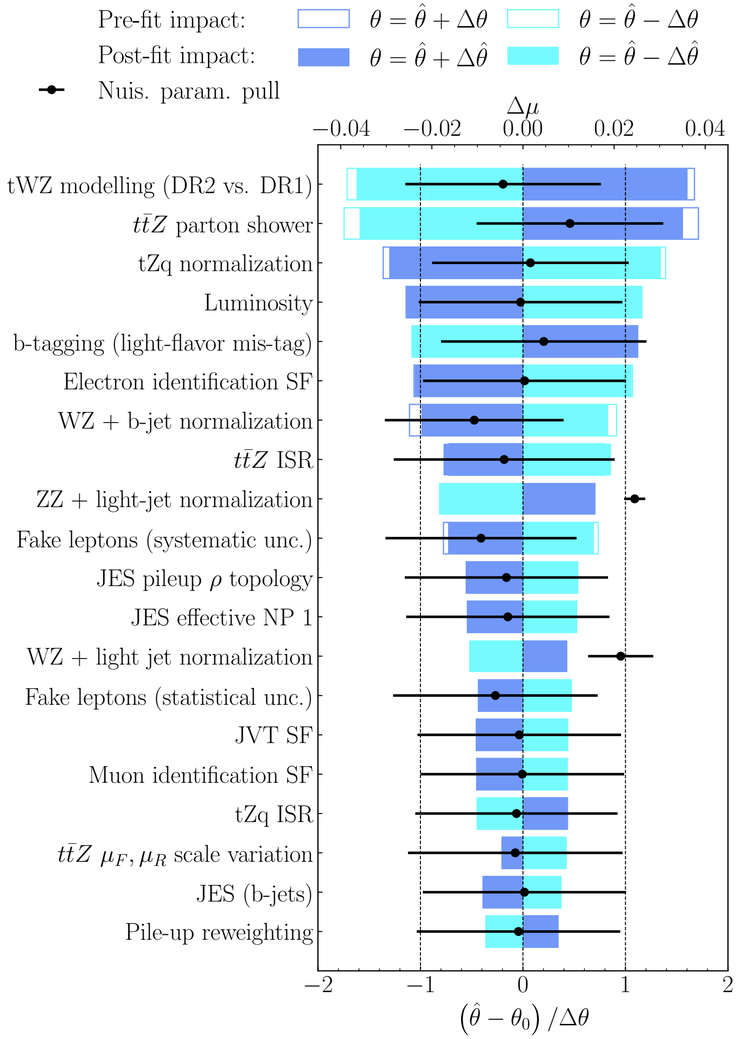
Case 2: $t\bar{t}Z$ production

ATLAS measurement of the $t\bar{t}Z$ total cross section at 13 TeV, 2103.12603





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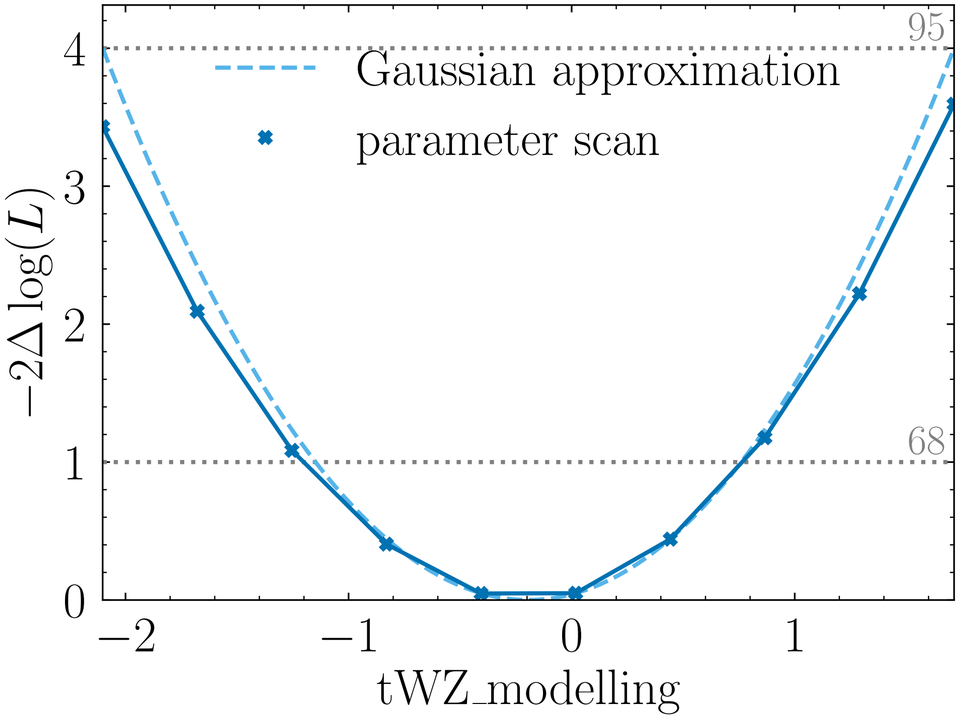

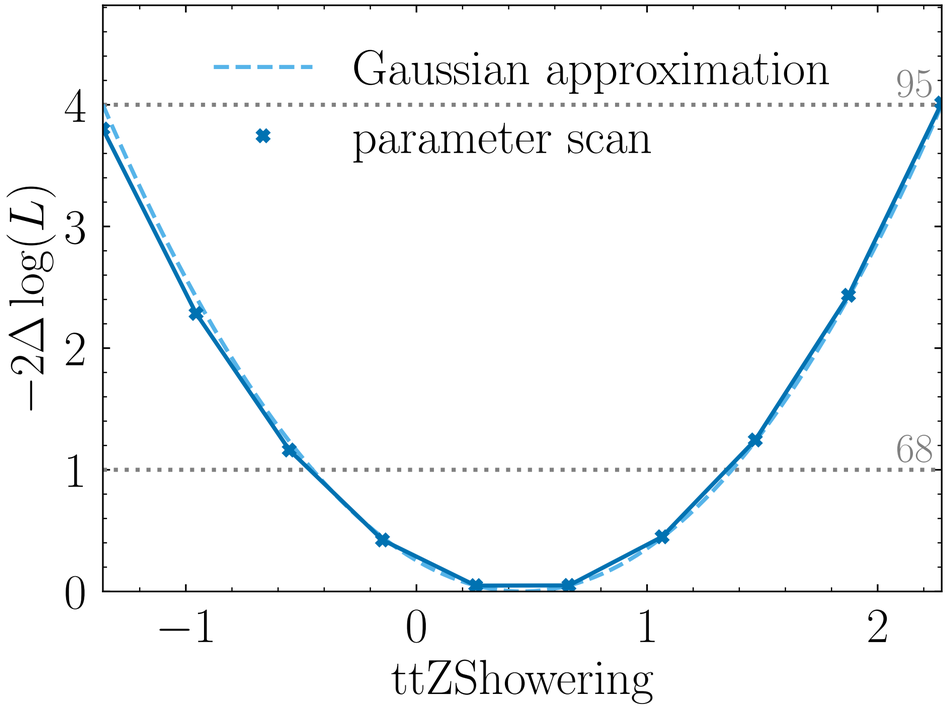

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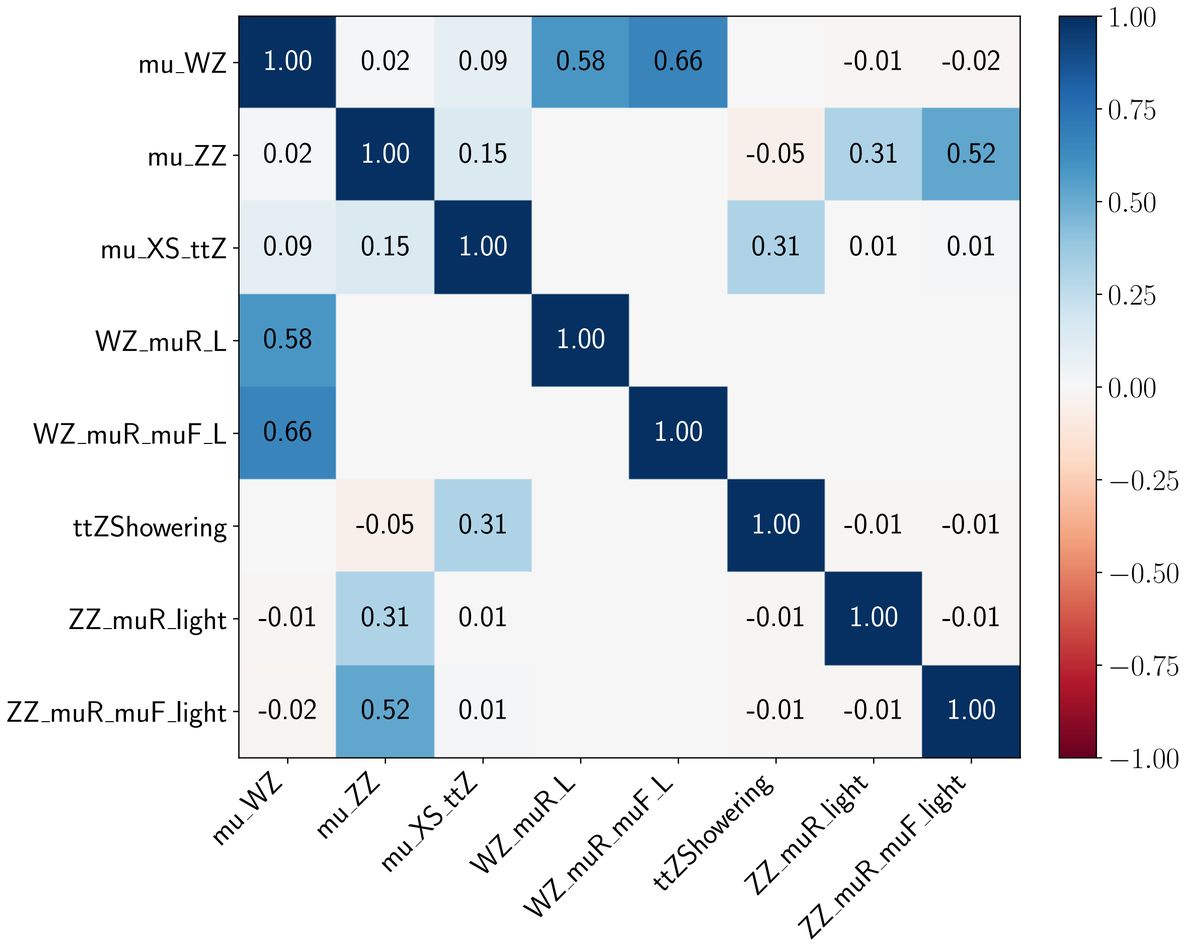

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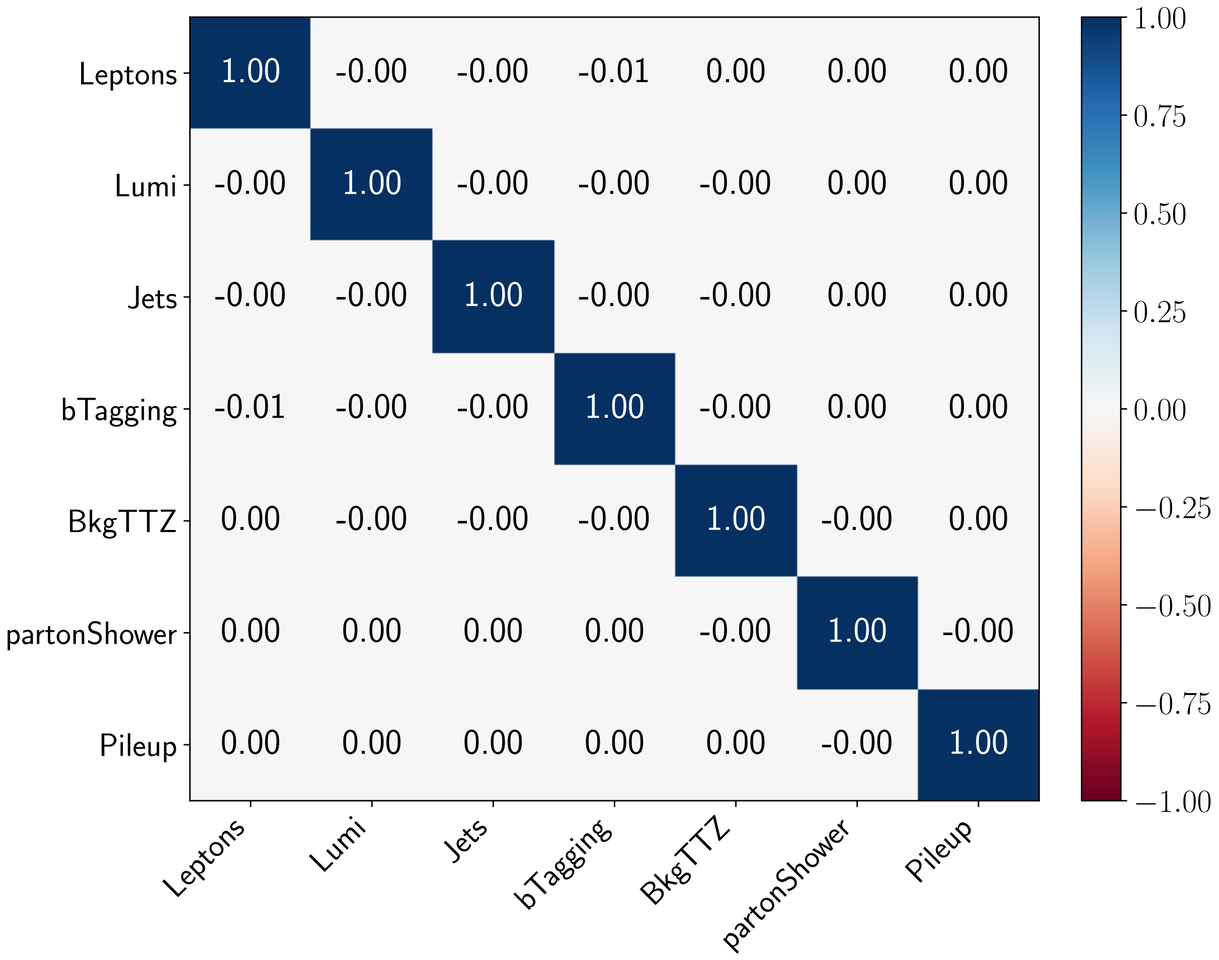

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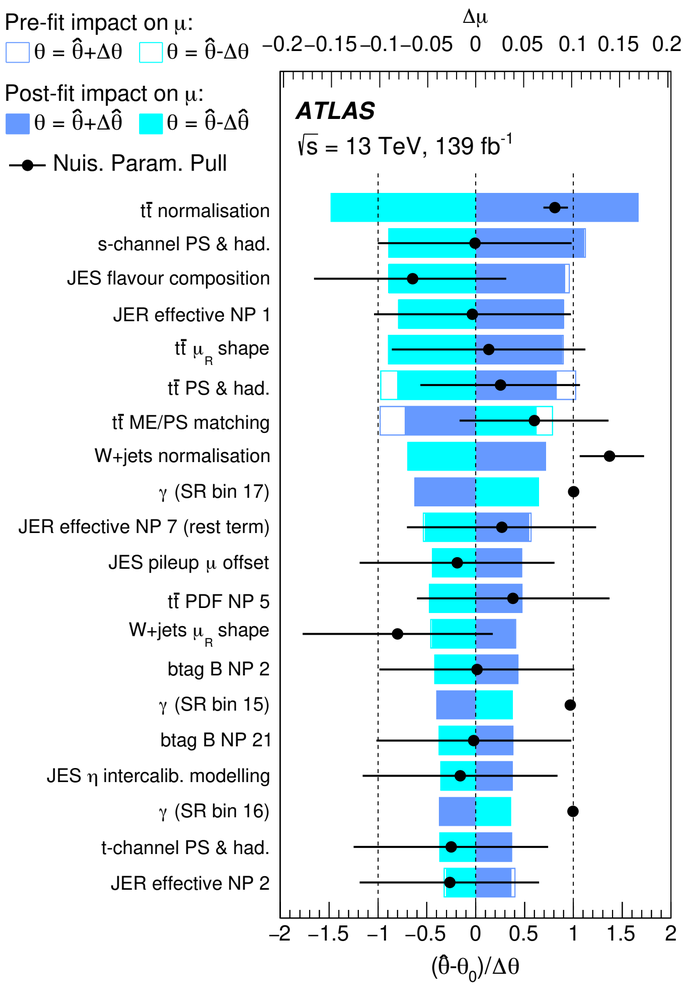
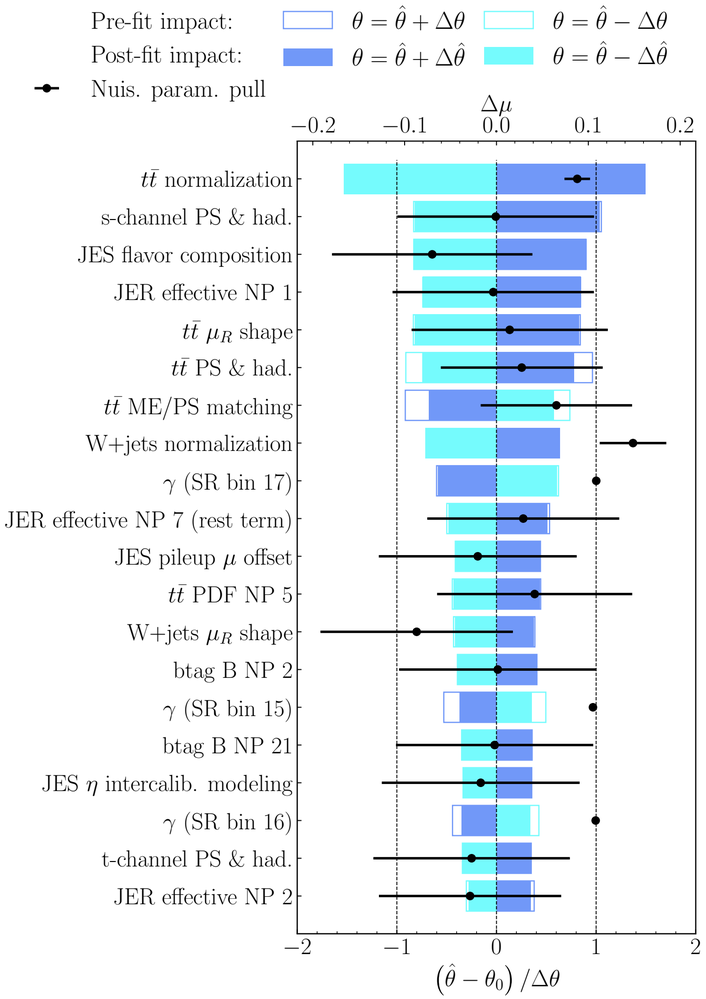
Case 3: *s*-channel single top production

ATLAS measurement of the s-channel single top production total cross section at 13 TeV, 2209.08990





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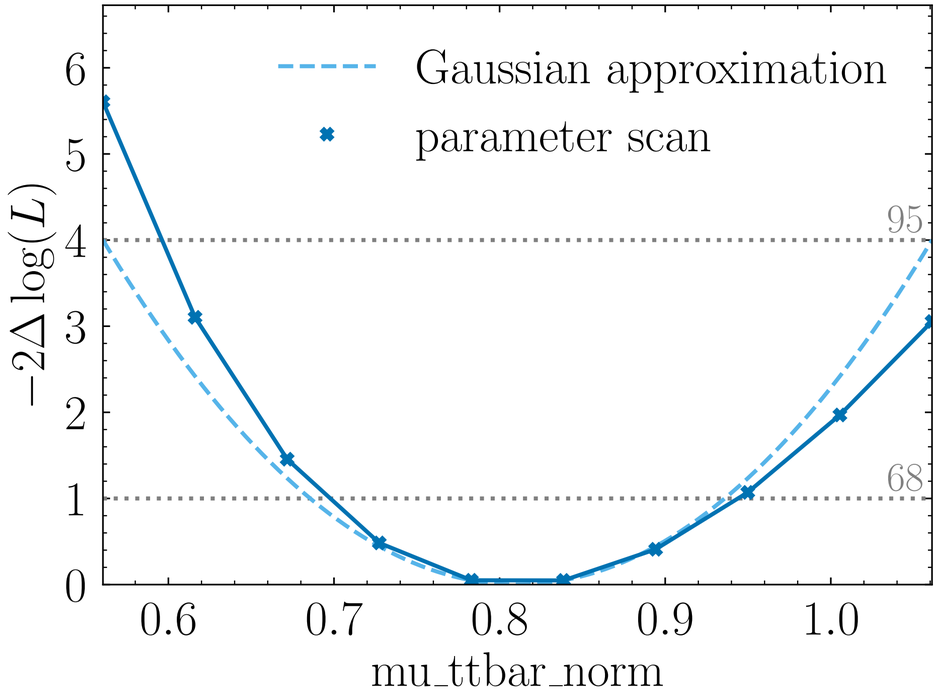

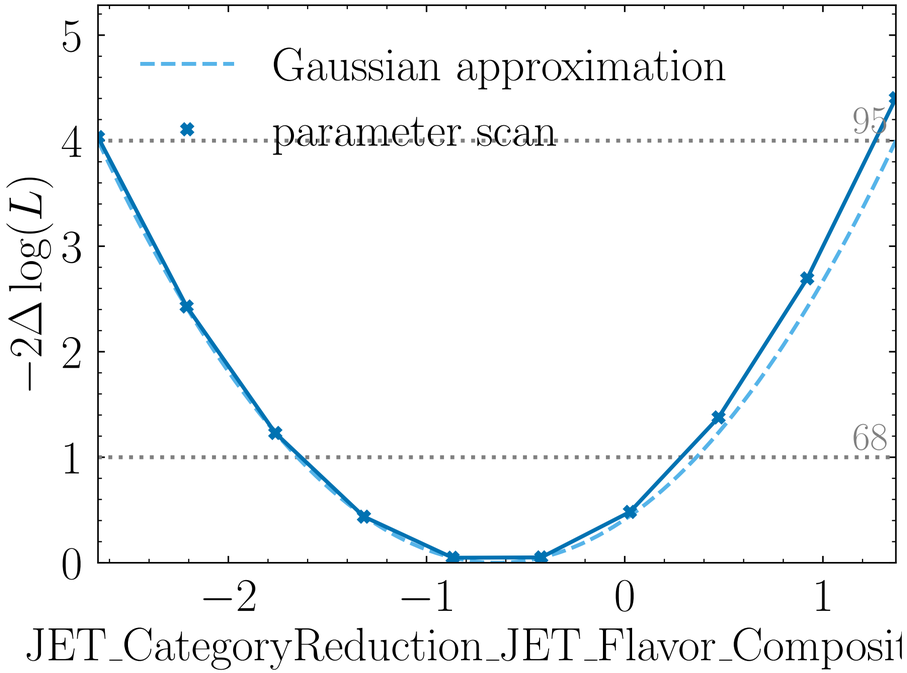

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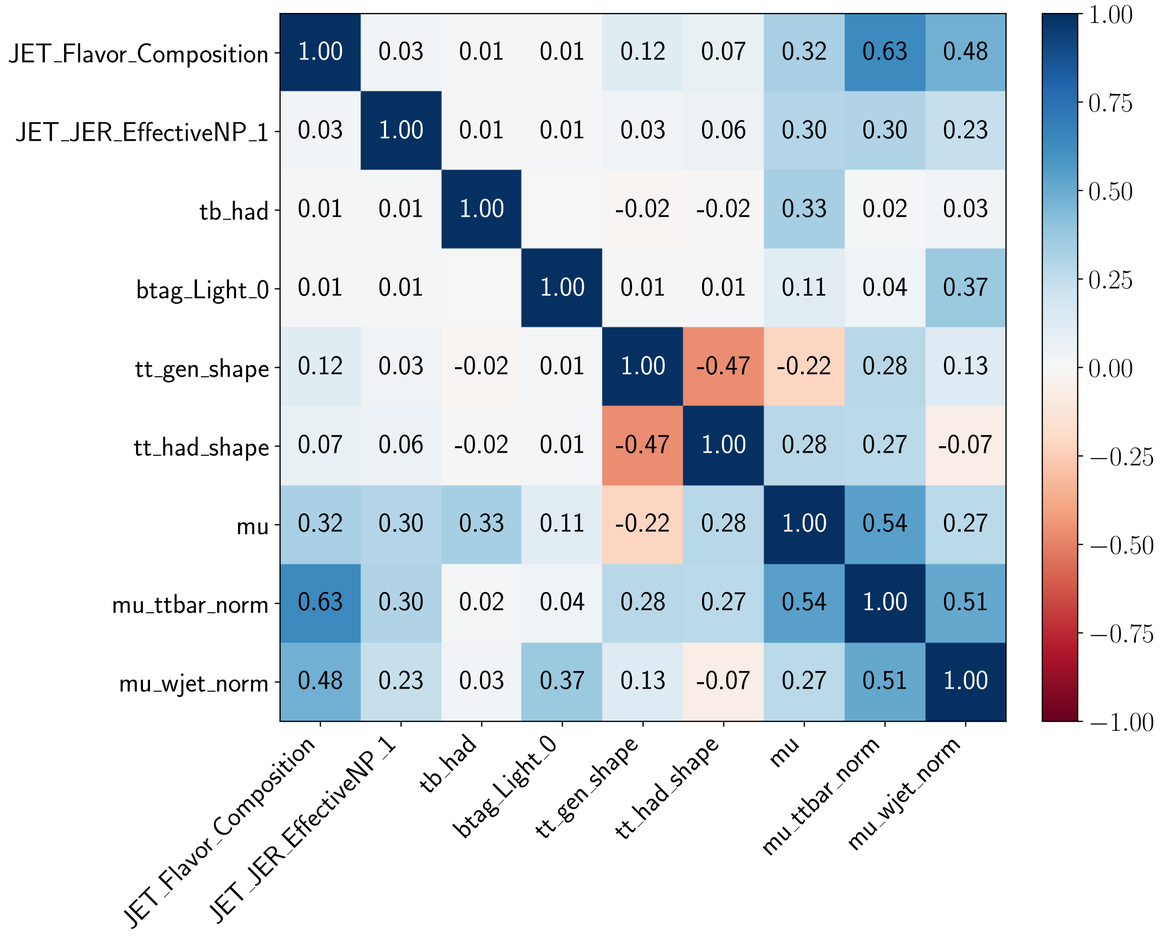

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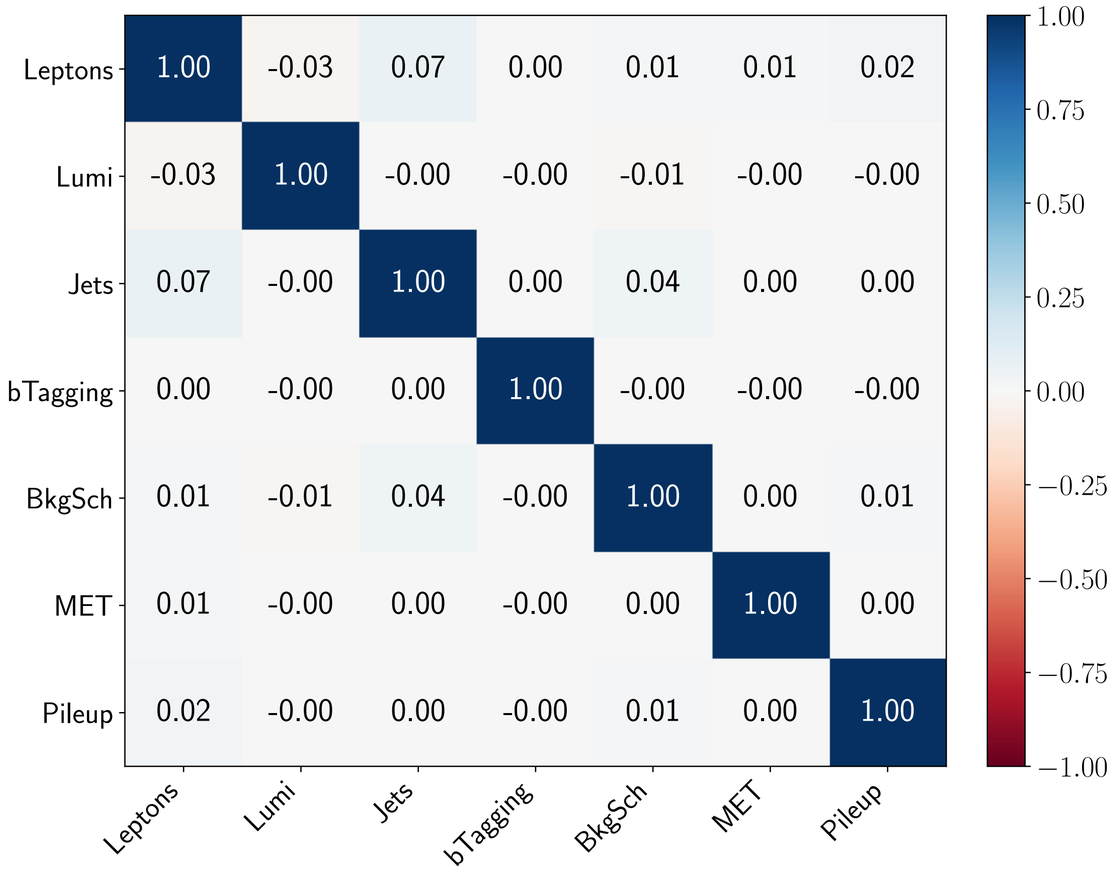

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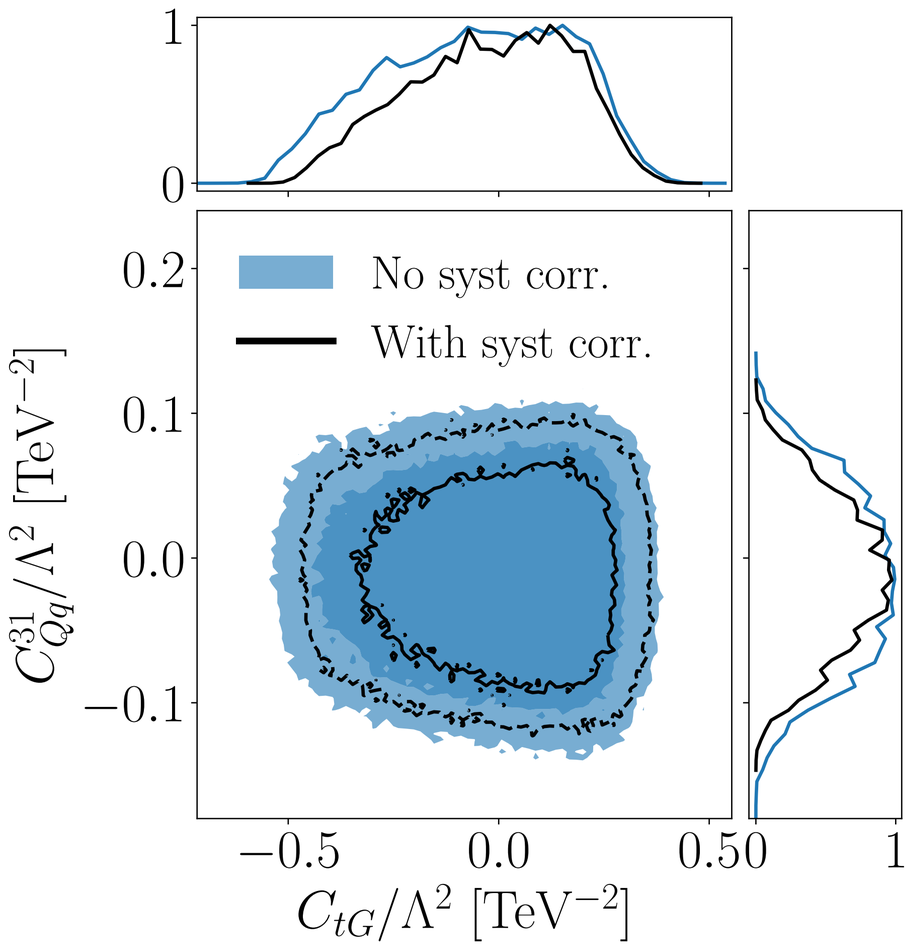
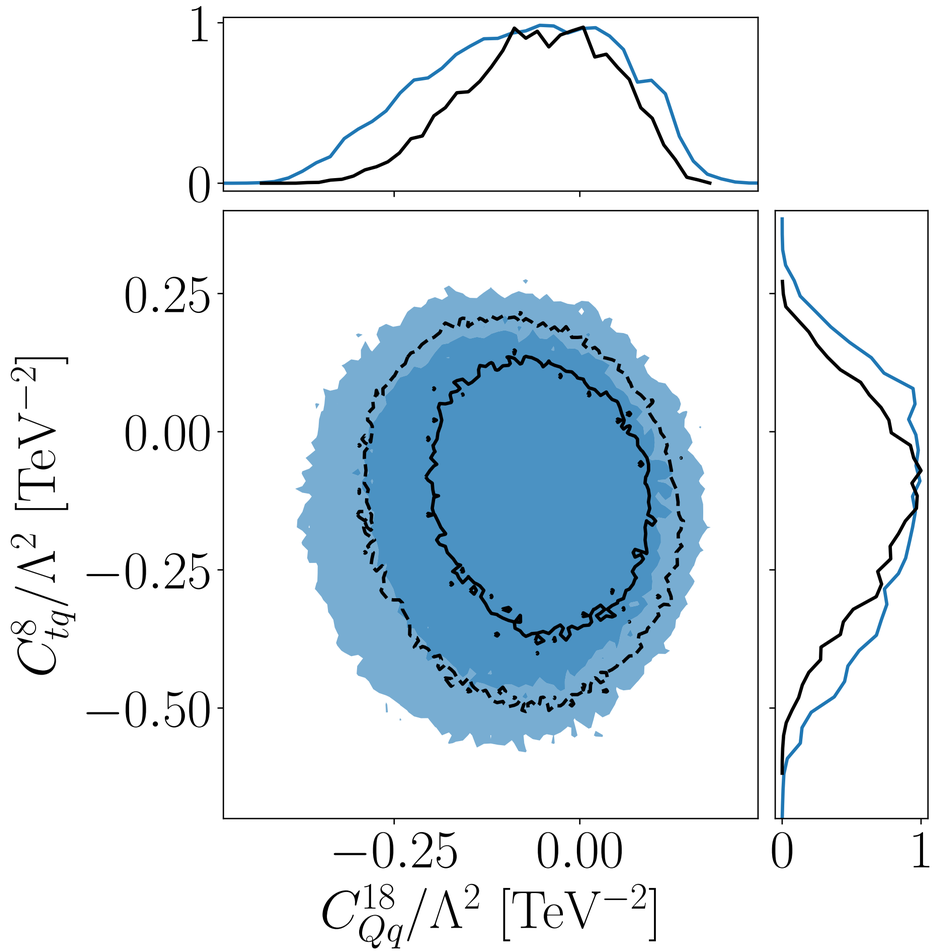
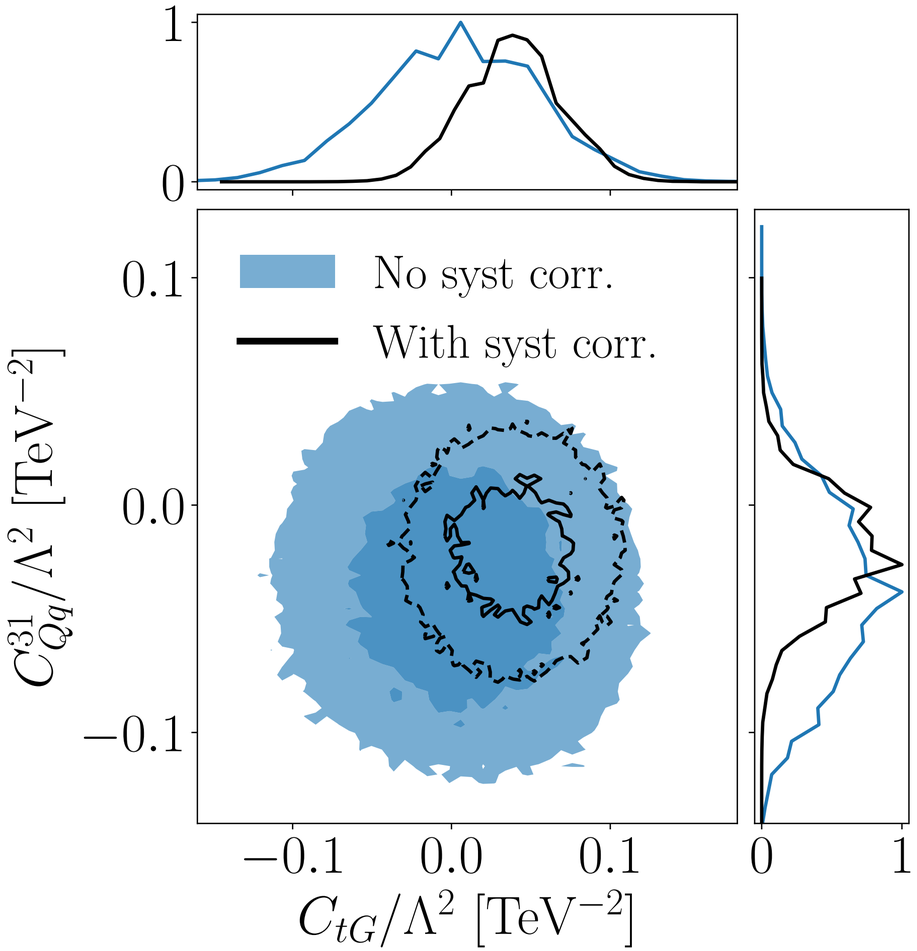
Results: impact of correlated systematic uncertainties

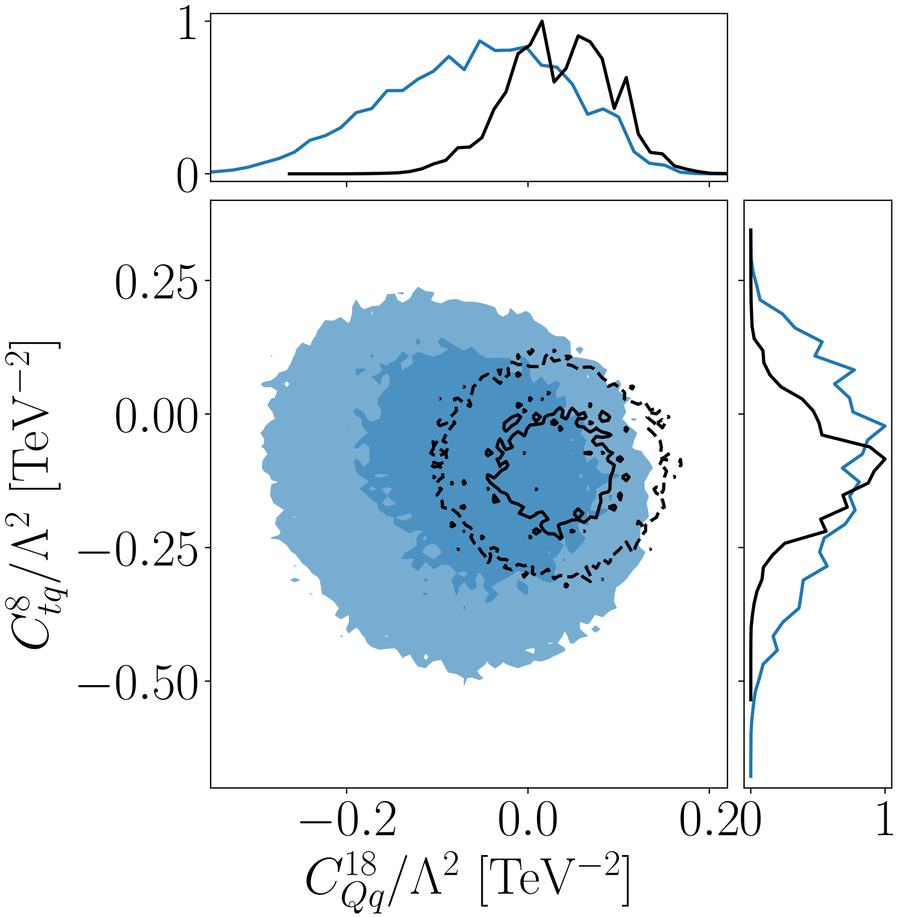




Results: impact of correlated systematic uncertainties

Theory uncertainties set to zero

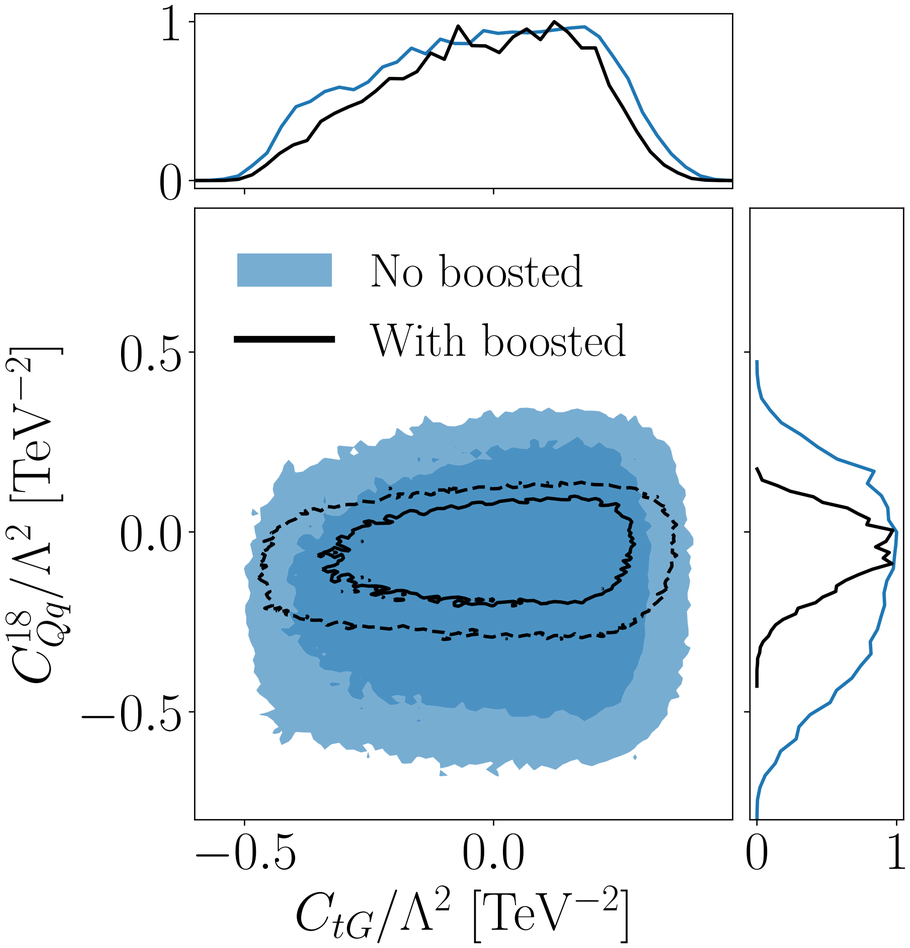


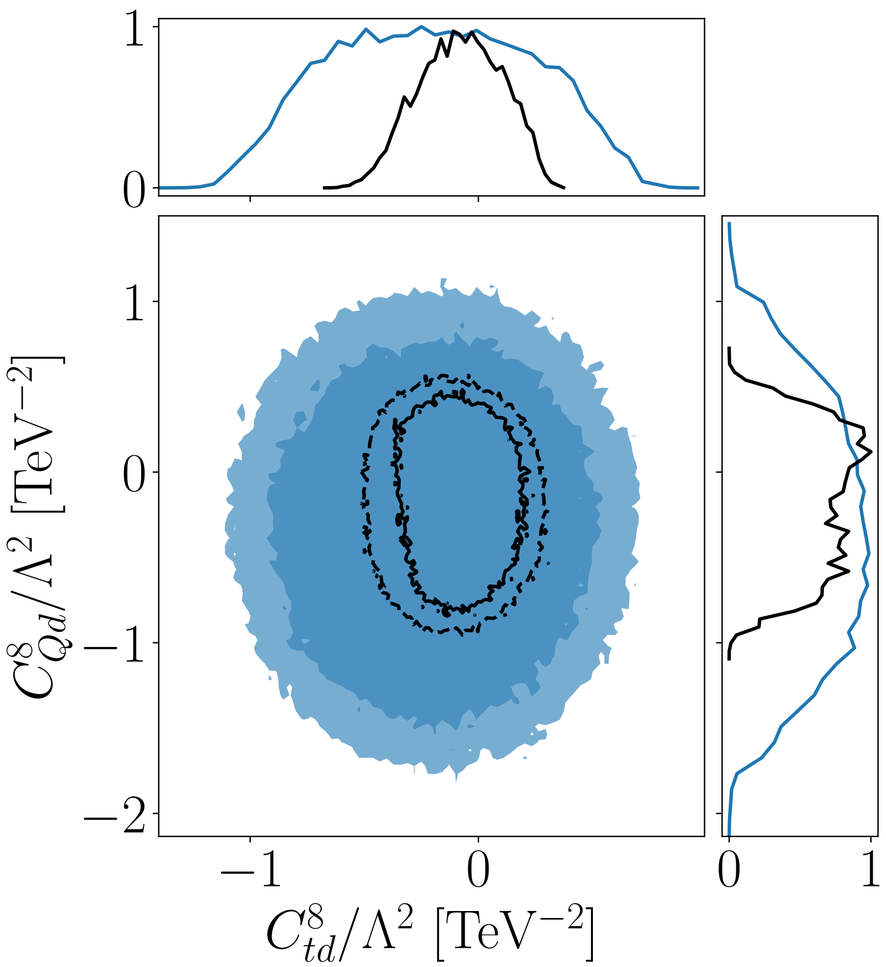


More SFitter results

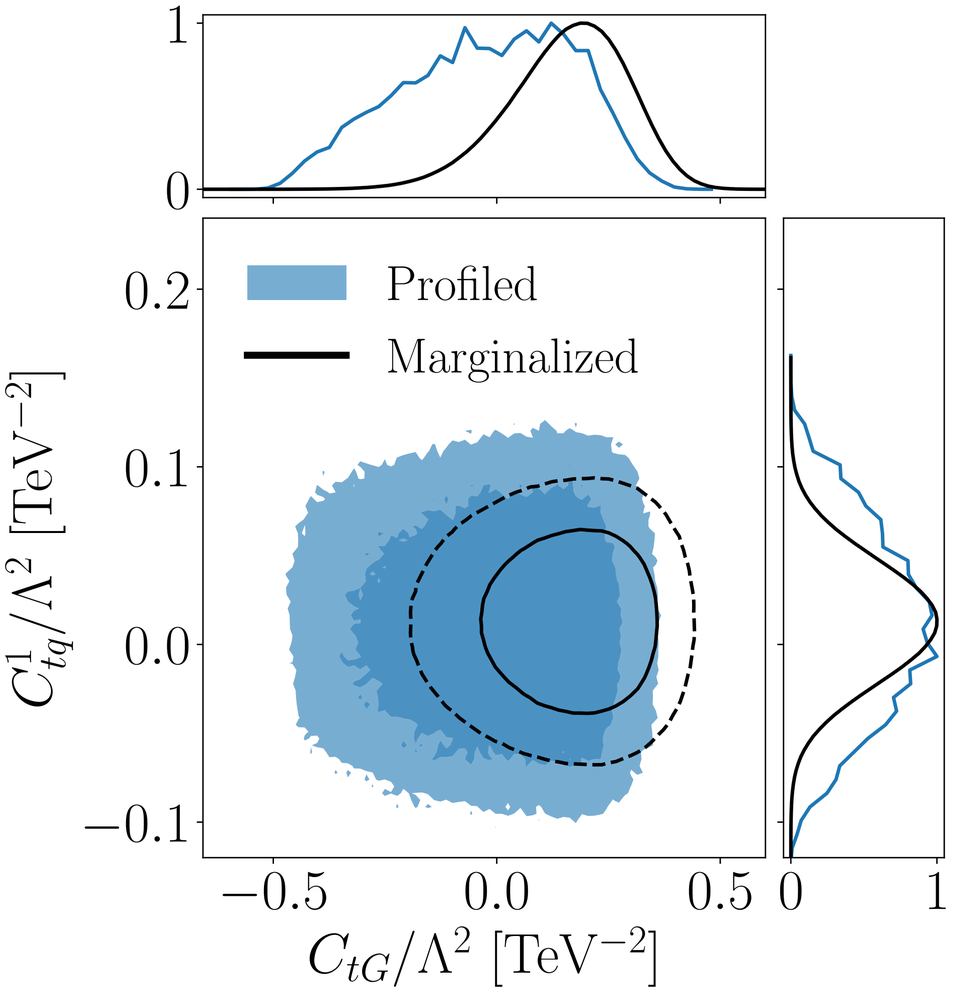
Boosted tops

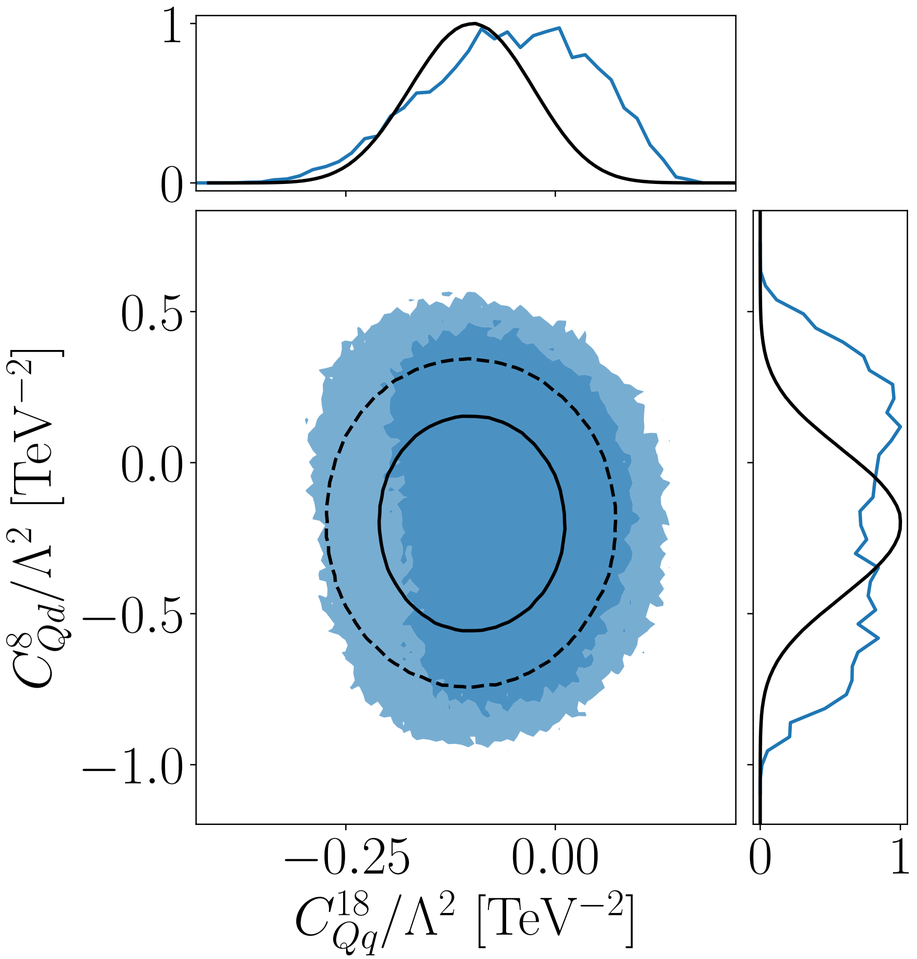
ATLAS measurement of top quark pair production using boosted top quarks at 13 TeV, *2205.02817*



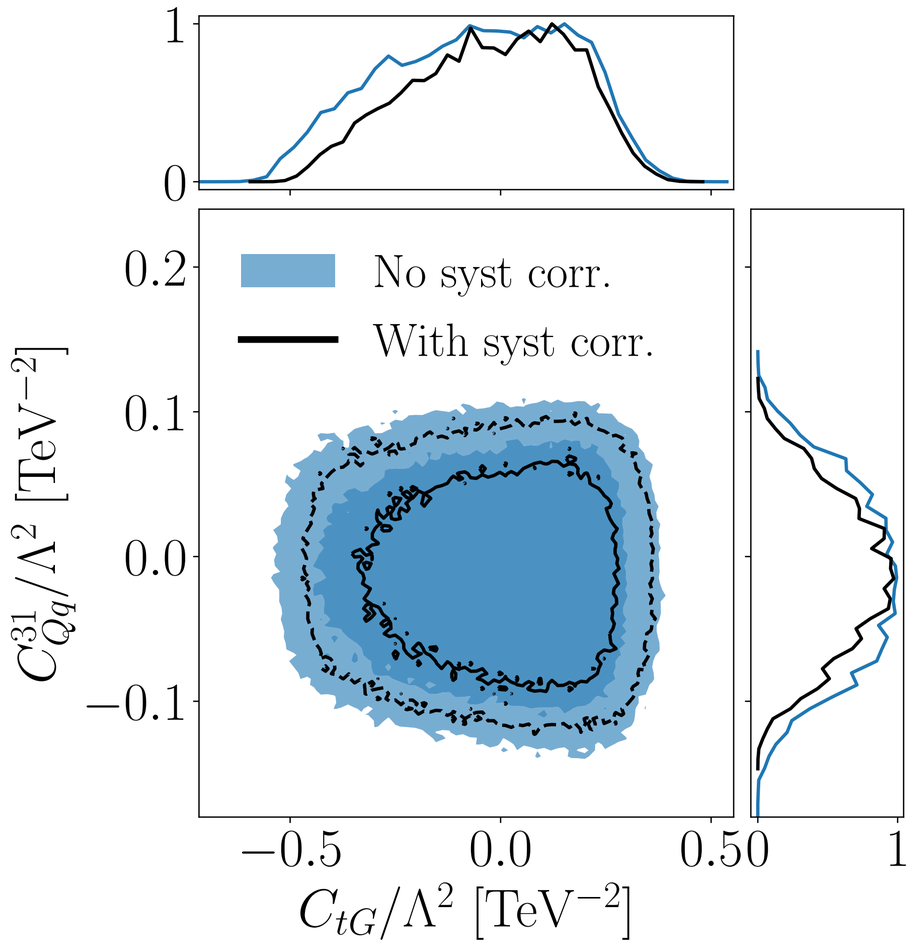


Marginalisation vs profiling





Conclusions



Likelihoods can now be implemented in SFitter.
These allow us to

- validate our methodology
- accurately model the effect of systematic uncertainties on the SMEFT

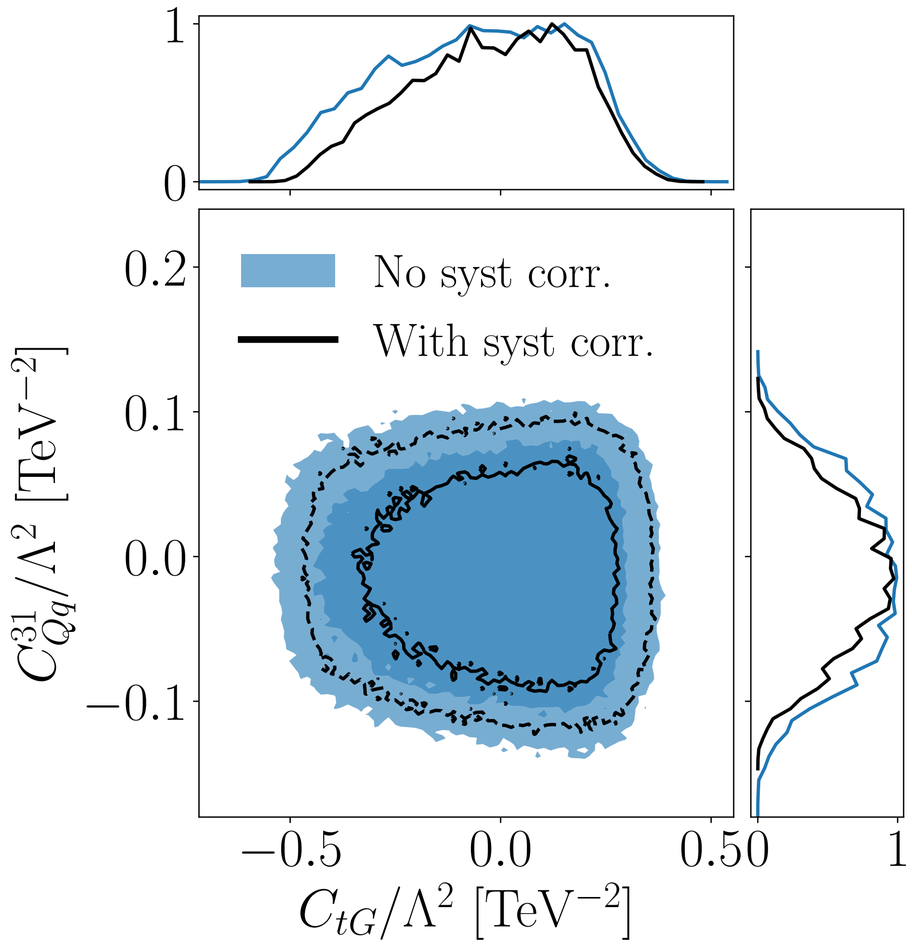
However, the impact of likelihoods is **limited** by:

- theory uncertainties, which dominate in the top sector

- availability of likelihoods for differential measurements

Conclusions

Thank you for listening!



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