STAYING ON TOP OF SMEFT-LIKELIHOOD ANALYSES

A global SMEFT analysis in the top sector including public likelihoods

Nikita Schmal

Collaborators: Nina Elmer, Maeve Madigan, Tilman Plehn

Based on arXiv:2312.12502 [hep-ph]

Outline

- **Intro:** Standard Model Effective Field Theory
- **Part I:** Statistical analysis using SFitter
- **Part II:** SFitter analyses with public likelihoods
- **Part III:** The Global SMEFT analysis
- **Conclusion**

Standard Model Effective Field Theory

SMEFT

- Well established model agnostic approach in searches for BSM physics

$$\mathcal{L}_{SMEFT} = \mathcal{L}_{SM} + \sum_{d=5}^{n} \frac{C_i^{(d)}}{\Lambda^{d-4}} O_i^{(d)}$$

- Up to **quadratic order** SMEFT contributions included i.e.

$$\sigma = \sigma_{SM} + \frac{c_6}{\Lambda^2}\sigma_6 + \frac{c_6^2}{\Lambda^4}\sigma_{6\times 6} + \frac{c_8}{\Lambda^4}\sigma_8 + \mathcal{O}(\Lambda^5)$$

Standard Model Effective Field Theory

SMEFT

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- Restrict ourselves to operators of **dimension 6**

Standard Model Effective Field Theory

Updated dataset

- Update of arXiv:1910.03606 [hep-ph]

  (SFitter global Top fit, 2019)

- Impose $U(2)_q \times U(2)_u \times U(2)_d$ symmetry
  - Consider a total of **22 Operators**
- Includes $t\bar{t}$, $t\bar{t}Z$, $t\bar{t}W$ and single top data
  - Total of **122 datapoints**

arXiv:2312.12502 [hep-ph]

Wilson coeff		$t\bar{t}$	single t	tW	tZ	t-decay	$t\bar{t}Z$	$t\bar{t}W$
$C_{Qq}^{1,8}$		Λ^{-2}	–	–	–	–	Λ^{-2}	Λ^{-2}
$C_{Qq}^{3,8}$		Λ^{-2}	$\Lambda^{-4}\,[\Lambda^{-2}]$	–	$\Lambda^{-4}\,[\Lambda^{-2}]$	$\Lambda^{-4}\,[\Lambda^{-2}]$	Λ^{-2}	Λ^{-2}
C_{tu}^{8}, C_{td}^{8}	Eq.(3)	Λ^{-2}	–	–	–	–	Λ^{-2}	–
$C_{Qq}^{1,1}$		$\Lambda^{-4}\,[\Lambda^{-2}]$	–	–	–	–	$\Lambda^{-4}\,[\Lambda^{-2}]$	$\Lambda^{-4}\,[\Lambda^{-2}]$
$C_{Qq}^{3,1}$		$\Lambda^{-4}\,[\Lambda^{-2}]$	Λ^{-2}	–	Λ^{-2}	Λ^{-2}	$\Lambda^{-4}\,[\Lambda^{-2}]$	$\Lambda^{-4}\,[\Lambda^{-2}]$
C_{tu}^{1}, C_{td}^{1}		$\Lambda^{-4}\,[\Lambda^{-2}]$	–	–	–	–	$\Lambda^{-4}\,[\Lambda^{-2}]$	–
C_{Qu}^{8}, C_{Qd}^{8}		Λ^{-2}	–	–	–	–	Λ^{-2}	–
C_{tq}^{8}	Eq.(4)	Λ^{-2}	–	–	–	–	Λ^{-2}	Λ^{-2}
C_{Qu}^{1}, C_{Qd}^{1}		$\Lambda^{-4}\,[\Lambda^{-2}]$	–	–	–	–	$\Lambda^{-4}\,[\Lambda^{-2}]$	–
C_{tq}^{1}		$\Lambda^{-4}\,[\Lambda^{-2}]$	–	–	–	–	$\Lambda^{-4}\,[\Lambda^{-2}]$	$\Lambda^{-4}\,[\Lambda^{-2}]$
$C_{\phi Q}^{-}$		–	–	–	Λ^{-2}	–	Λ^{-2}	–
$C_{\phi Q}^{3}$		–	Λ^{-2}	Λ^{-2}	Λ^{-2}	Λ^{-2}	Λ^{-2}	–
$C_{\phi t}$		–	–	–	Λ^{-2}	–	Λ^{-2}	–
$C_{\phi tb}$	Eq.(5)	–	Λ^{-4}	Λ^{-4}	Λ^{-4}	Λ^{-4}	–	–
C_{tZ}		–	–	–	Λ^{-2}	–	Λ^{-2}	–
C_{tW}		–	Λ^{-2}	Λ^{-2}	Λ^{-2}	Λ^{-2}	–	–
C_{bW}		–	Λ^{-4}	Λ^{-4}	Λ^{-4}	Λ^{-4}	–	–
C_{tG}		Λ^{-2}	$[\Lambda^{-2}]$	Λ^{-2}	–	$[\Lambda^{-2}]$	Λ^{-2}	Λ^{-2}

What is our tool of choice?

SFitter

- Used for various global SMEFT analyses (Higgs, Di-Boson, EWPO, **Top**)
- Comprehensive treatment of **uncertainties**
- **Fully correlated** systematic uncertainties within experiments
- Allows for both **profiling and marginalization** methods
- Mapping of likelihood using **MCMC**

- **Goal of this part:** Explain what exactly all this means

What is SFitter?

The exclusive likelihood

- Likelihood for a **single measurements** modelled as

$$\mathcal{L}_{excl} = \mathrm{Pois}(d|p(\alpha_n, \theta_i, b))\mathrm{Pois}(b_{CR}|b\,k)\prod_i \mathcal{C}(\theta_i, \sigma_i)$$

- SMEFT contributions are incorporated into **model parameters** α_n
- Uncertainties included via **nuisance parameters (NP)** θ_i
- **Constraint term** $\mathcal{C}(\theta_i, \sigma_i)$ depends on uncertainty considered

What is SFitter?

Uncertainty constraints

$$\mathcal{C}(\theta_i, \sigma_i)$$

- Systematic unc. $\mathcal{N}(x|\mu,\sigma) = \frac{1}{\sqrt{2\pi}\sigma} \exp\left(-\frac{(x-\mu)^2}{2\sigma^2}\right)$
- Statistical unc. $\text{Pois}(n|\nu) = \frac{\nu^n e^{-\nu}}{n!}, \quad \nu > 0$
- Theory unc. $\mathcal{F}(x|\mu,\sigma) = \frac{1}{2\sigma}\Theta\left[x-(\mu-\sigma)\right]\Theta\left[(\mu+\sigma)-x\right]$

- Choice of constraint is **motivated by physical intuition**
  - **However:** They are a choice and could technically be chosen differently

What is SFitter?

Generalization to multiple measurements

- Global analyses study numerous different processes

$$\mathcal{L}_{\text{excl,full}} = \prod_c \text{Pois}(d_c|p_c)\text{Pois}(b_{CR_c}|b_c\, k_c) \prod_i \mathcal{C}(\theta_{i,c}, \sigma_{i,c})$$

- Take into consideration correlations between these measurements

$$\mathcal{N}(\theta_{syst,i}|0, \sigma_i) \longrightarrow \mathcal{N}(\vec{\theta}_{syst,i}|\vec{0}, \Sigma_i)$$

- **Assumption:** Systematics are **fully correlated** between measurements

What is SFitter?

Systematic uncertainties

- Each category of systematic is **fully correlated** within CMS and ATLAS
- Luminosity correlated between both experiments

Systematic uncertainties
Beam
Background (Separate for each channel)
ETmis
Jets
Leptons
LightTagging
Luminosity
Pileup
Trigger
Tune
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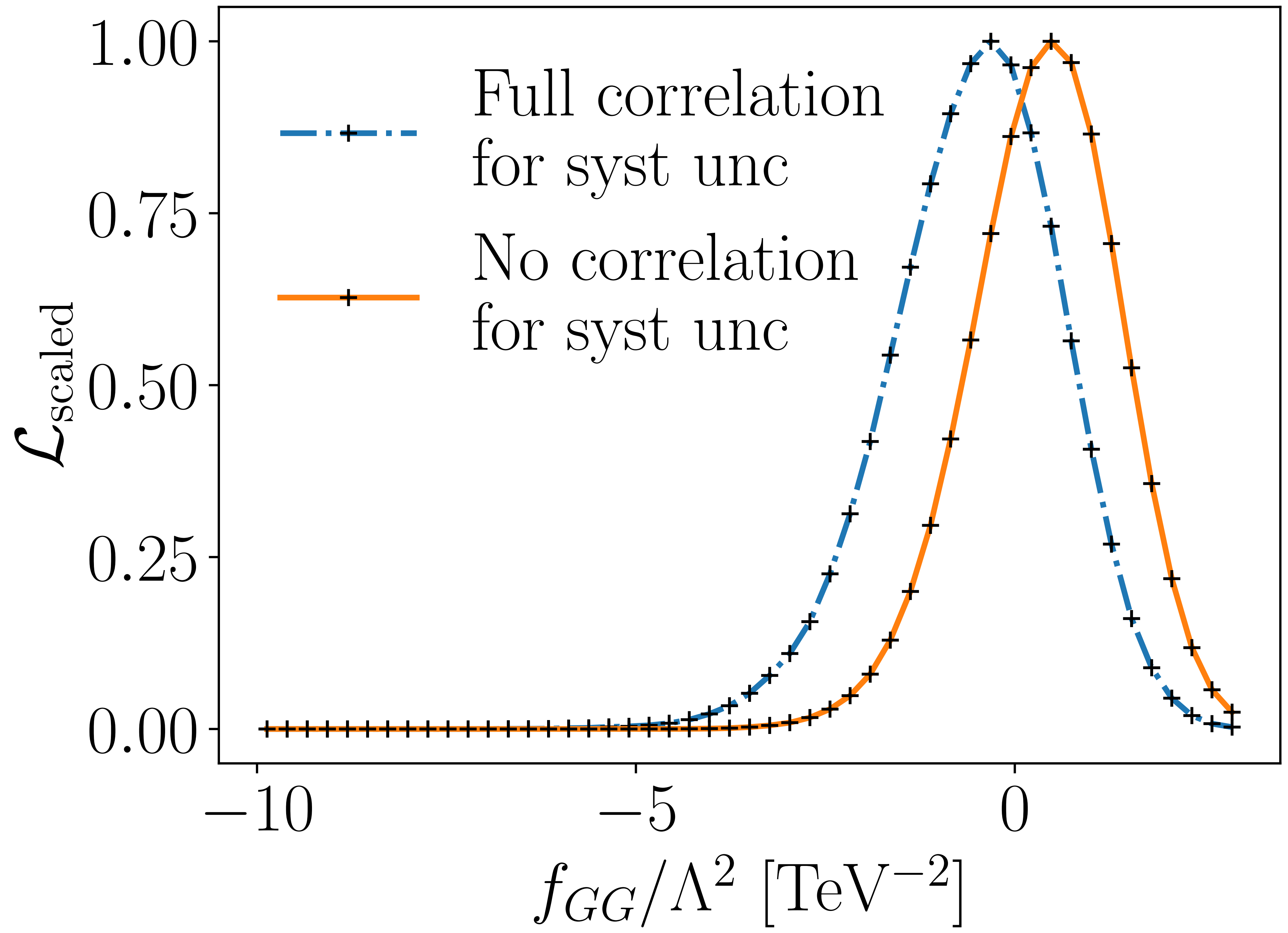
partonShower
tTagging
tauTagging

What is SFitter?

Systematic uncertainties

- Each category of systematic is **fully correlated** within CMS and ATLAS
- Luminosity correlated between both experiments
- Clear shift in the likelihoods **due to correlations** between systematics

arXiv:2208.08454 [hep-ph]



What is SFitter?

To profile or to marginalize

- Common exclusive likelihood constructed

$$\mathcal{L}_{excl} = \mathrm{Pois}(d|p(\alpha_n, \theta_i, b))\mathrm{Pois}(b_{CR}|b\,k)\prod_i \mathcal{C}(\theta_i, \sigma_i)$$

- The nuisance parameters θ_i are **not physically interesting**

What is SFitter?

To profile or to marginalize

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$$\mathcal{L}_{excl} = \text{Pois}(d|p(\alpha_n, \theta_i, b))\text{Pois}(b_{CR}|b\,k)\prod_i \mathcal{C}(\theta_i, \sigma_i)$$

- The nuisance parameters θ_i are **not physically interesting**
    - **Decision:** How do we handle the nuisance parameters?

Profiling:

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

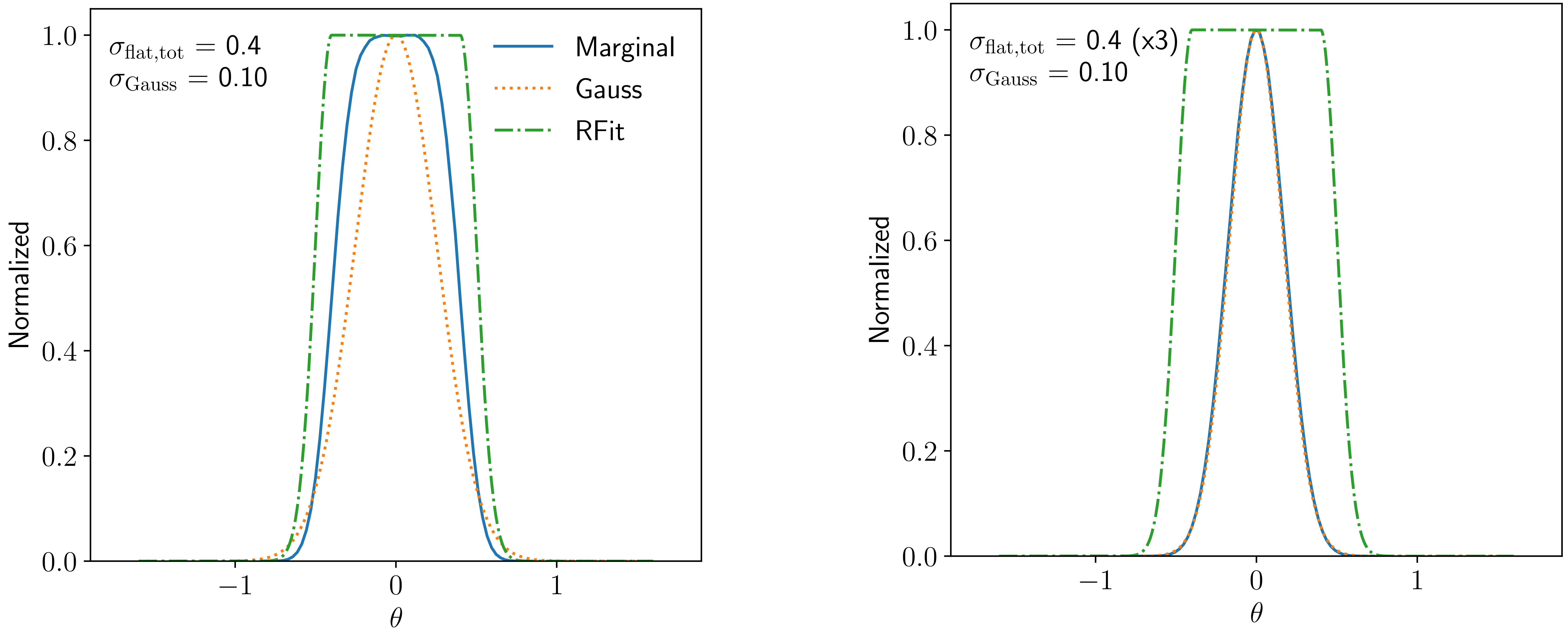
Marginalization:

$$\mathcal{L}_{marg}(\alpha) = \int d\theta \mathcal{L}_{excl}(\alpha, \theta)$$

What is SFitter?

To profile or to marginalize

arXiv:2208.08454 [hep-ph]



- Comparison for the product of Gaussian and uniform distributions
  - Marginalization over multiple flat unc. gives **Gaussian** results

What is SFitter?

Takeaway

- **Uncertainty treatment** essential to our SFitter analysis
  - Implementation of theory, statistical and systematic uncertainties
  - Furthermore: **Correlated systematics** of the same type

- Theory prediction and uncertainties done by us
  - However: The systematics have to be provided **by experiment**
  - How is this data provided and **how can we use it?**

Published Likelihoods

Quick overview

- Likelihoods published in the **HistFactory** format

$$\mathcal{L}(n_{cb}, a_\chi | \eta, \chi) = \prod_{c \in \text{channels}} \prod_{b \in \text{bins}} \text{Pois}(n_{cb} | \nu_{cb}(\eta, \chi)) \prod_{\chi \in \vec{\chi}} c_\chi(a_\chi | \chi)$$

- Provides effect of **individual NPs** via $\nu_{cb} = \sum_{s \in \text{samples}} \left(\prod_{\kappa \in \vec{\kappa}} \kappa_{scb} \right) \left(\nu^0_{scb} + \sum_{\Delta \in \vec{\Delta}} \Delta_{scb} \right)$

Description	Modification	Constraint $\mathcal{C}$
Luminosity ('lumi')	$\kappa_{sb} = \lambda$	$\mathcal{N}(l = \lambda_0 \| \lambda, \sigma_\lambda)$
Normalization unc. ('normsys')	$\kappa_{sb} = g_p(\alpha \| \kappa_{sb,\alpha=\pm 1})$	$\mathcal{N}(a = 0 \| \alpha, \sigma = 1)$
Correlated Shape ('histosys')	$\Delta_{sb} = f_p(\alpha \| \Delta_{sb,\alpha=\pm 1})$	$\mathcal{N}(a = 0 \| \alpha, \sigma = 1)$
MC Stat. ('staterror')	$\kappa_{sb} = \gamma_b$	$\prod_b \mathcal{N}(a_{\gamma_b} = 1 \| \gamma_b, \delta_b)$
Uncorrelated Shape ('shapesys')	$\kappa_{sb} = \gamma_b$	$\prod_b \text{Pois}(\sigma_b^{-2} \| \sigma_b^{-2} \gamma_b)$
Normalization ('normfactor')	$\kappa_{sb} = \mu_b$	

Published Likelihoods

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$$\mathcal{L}(n_{cb}, a_\chi | \eta, \chi) = \prod_{c \in \text{channels}} \prod_{b \in \text{bins}} \text{Pois}(n_{cb} | \nu_{cb}(\eta, \chi)) \prod_{\chi \in \vec{\chi}} \mathcal{C}_\chi(a_\chi | \chi)$$

- There are many **different nuisance parameters** (hundreds)
- Analysed using dedicated python libraries such as **pyhf** and **cabinetry**
  - **Question:** How to make use of this in SFitter analyses?

Likelihoods published by ATLAS

arXiv:2006.13076 [hep-ex]

EUROPEAN ORGANISATION FOR NUCLEAR RESEARCH (CERN)

Phys. Lett. B 810 (2020) 135797
DOI: 10.1016/j.physletb.2020.135797

CERN-EP-2020-096
10th November 2020

Measurement of the $t\bar{t}$ production cross-section in the lepton+jets channel at $\sqrt{s}$ = 13 TeV with the ATLAS experiment

The ATLAS Collaboration

arXiv:2209.08990 [hep-ex]

Eur. Phys. J. C (2021) 81:737
https://doi.org/10.1140/epjc/s10052-021-09439-4

THE EUROPEAN PHYSICAL JOURNAL C

Check for updates

Regular Article - Experimental Physics

Measurements of the inclusive and differential production cross sections of a top-quark–antiquark pair in association with a Z boson at $\sqrt{s}$ = 13 TeV with the ATLAS detector

ATLAS Collaboration*
CERN, 1211 Geneva 23, Switzerland

arXiv:2103.12603 [hep-ex]

EUROPEAN ORGANISATION FOR NUCLEAR RESEARCH (CERN)

JHEP 06 (2023) 191
DOI: 10.1007/JHEP06(2023)191

CERN-EP-2022-116
6th July 2023

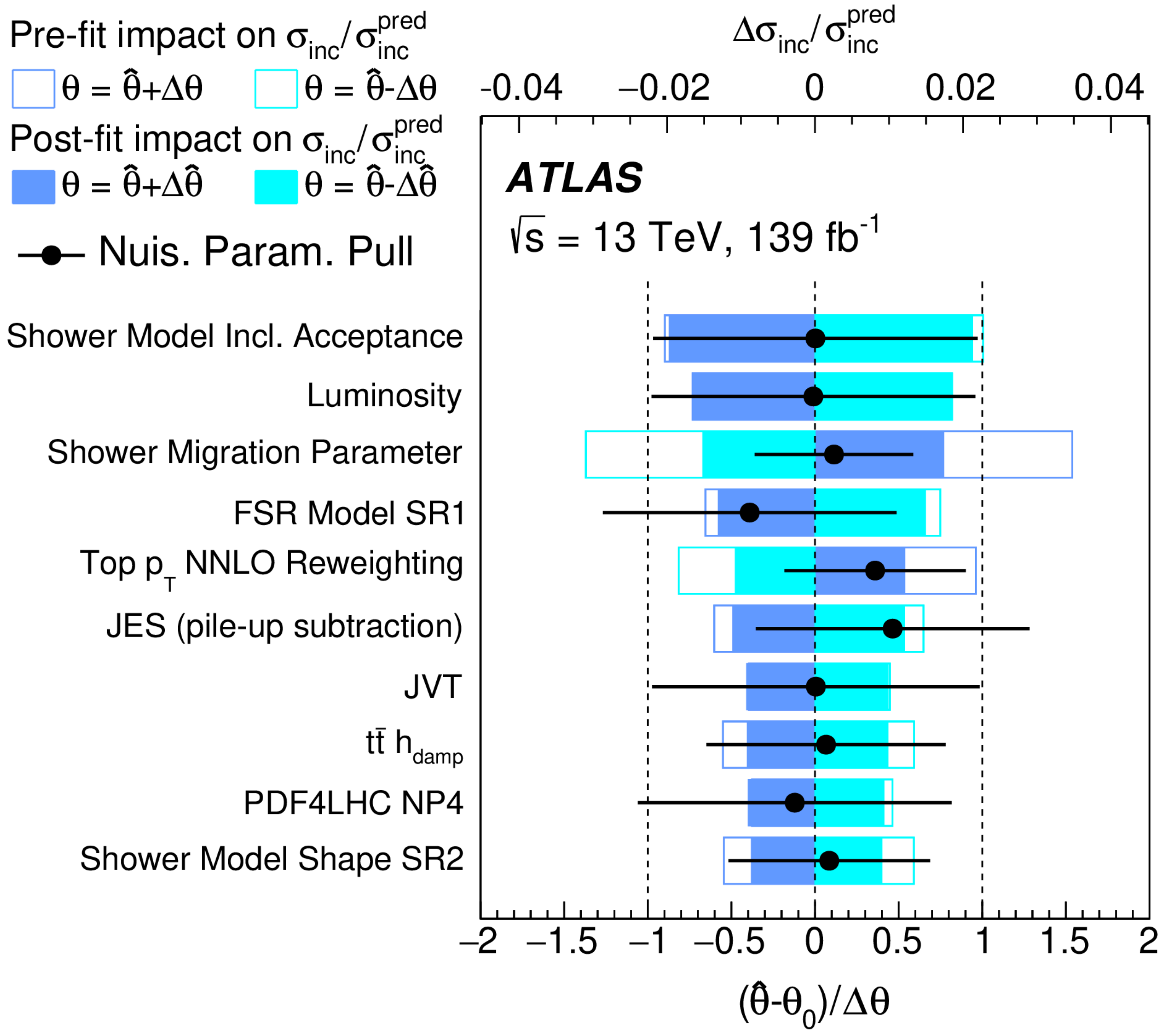
Measurement of single top-quark production in the s-channel in proton–proton collisions at $\sqrt{s}$ = 13 TeV with the ATLAS detector

The ATLAS Collaboration

➤ Full likelihoods **publicly available** on HEPData

Published Likelihoods

Quick overview (Reproduction)



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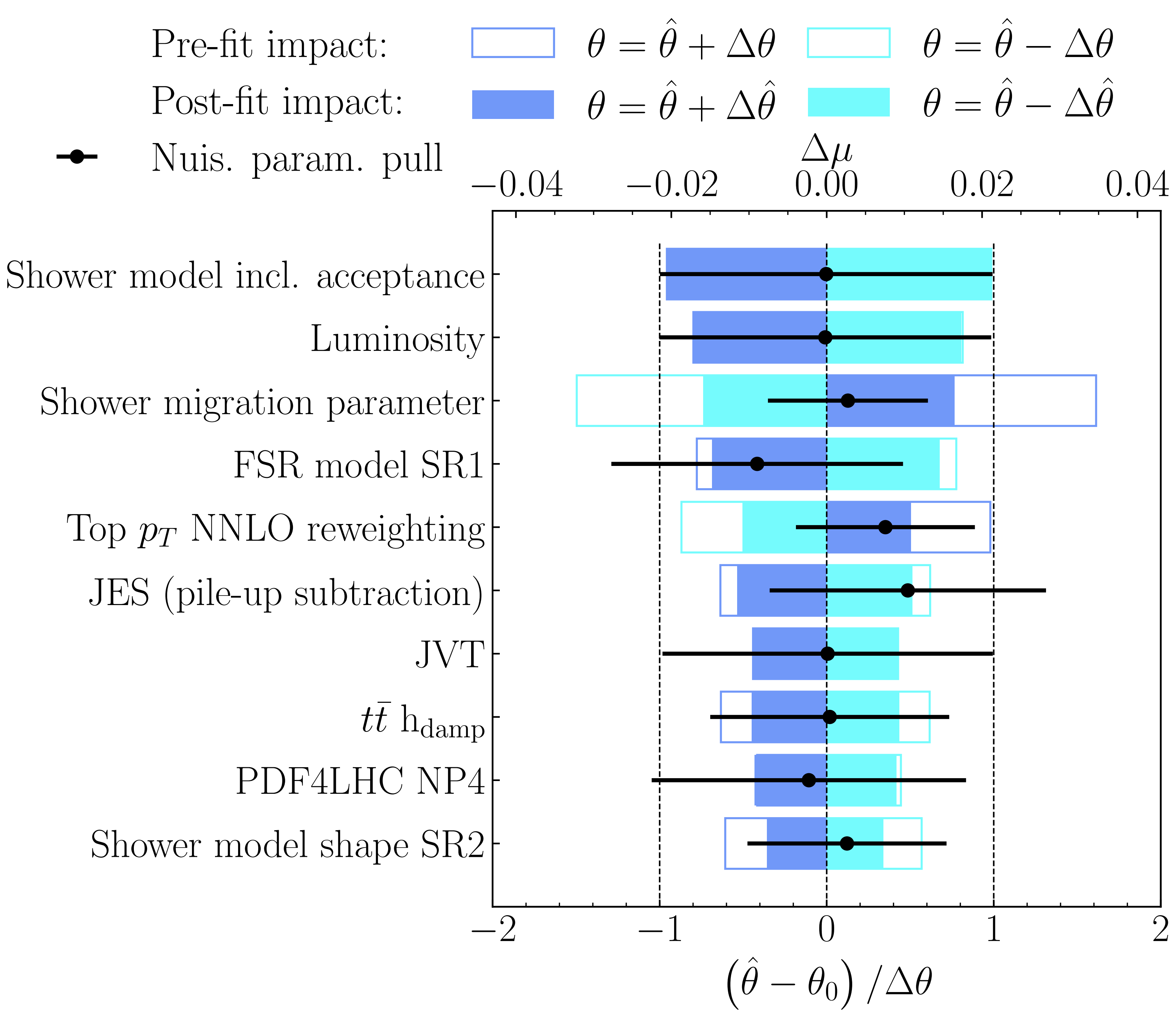

arXiv:2312.12502 [hep-ph]

cabinetry

pyhf ∂ifferentiable ℒikelihoods

Published Likelihoods

Uncertainties

- **Previously:** Uncertainties taken as given in the paper
- **Now:** Uncertainties extracted from profiling fit via pyhf
  - Implemented into SFitter using the constraints terms $\mathcal{C}(\theta_i, \sigma_i)$
- **Problem:** Difficult to automate due to inconsistent naming conventions

Uncertainty	Reproduced $\frac{\Delta\sigma_{t\bar{t}Z}}{\sigma_{t\bar{t}Z}}$ [%]	Paper $\frac{\Delta\sigma_{t\bar{t}Z}}{\sigma_{t\bar{t}Z}}$ [%]
ttZ parton shower	3.1	3.1
tWZ modeling	2.9	2.9
b-tagging	2.9	2.9
WZ/ZZ + jets modeling	2.7	2.8
tZq modeling	2.6	2.6
Lepton	2.3	2.3
Luminosity	2.2	2.2
Jets + E_T^{miss}	2.1	2.1
Fake leptons	2.1	2.1
$t\bar{t}Z$ ISR	1.7	1.6
$t\bar{t}Z\mu_F$ and μ_r scales	0.9	0.9
Other backgrounds	0.8	0.7
Pile-up	0.7	0.7
$t\bar{t}Z$ PDF	0.2	0.2
Stat	5.2	5.2

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➤ **Previously:** Possibly incompatible groups, how to correlate?

Published Likelihoods

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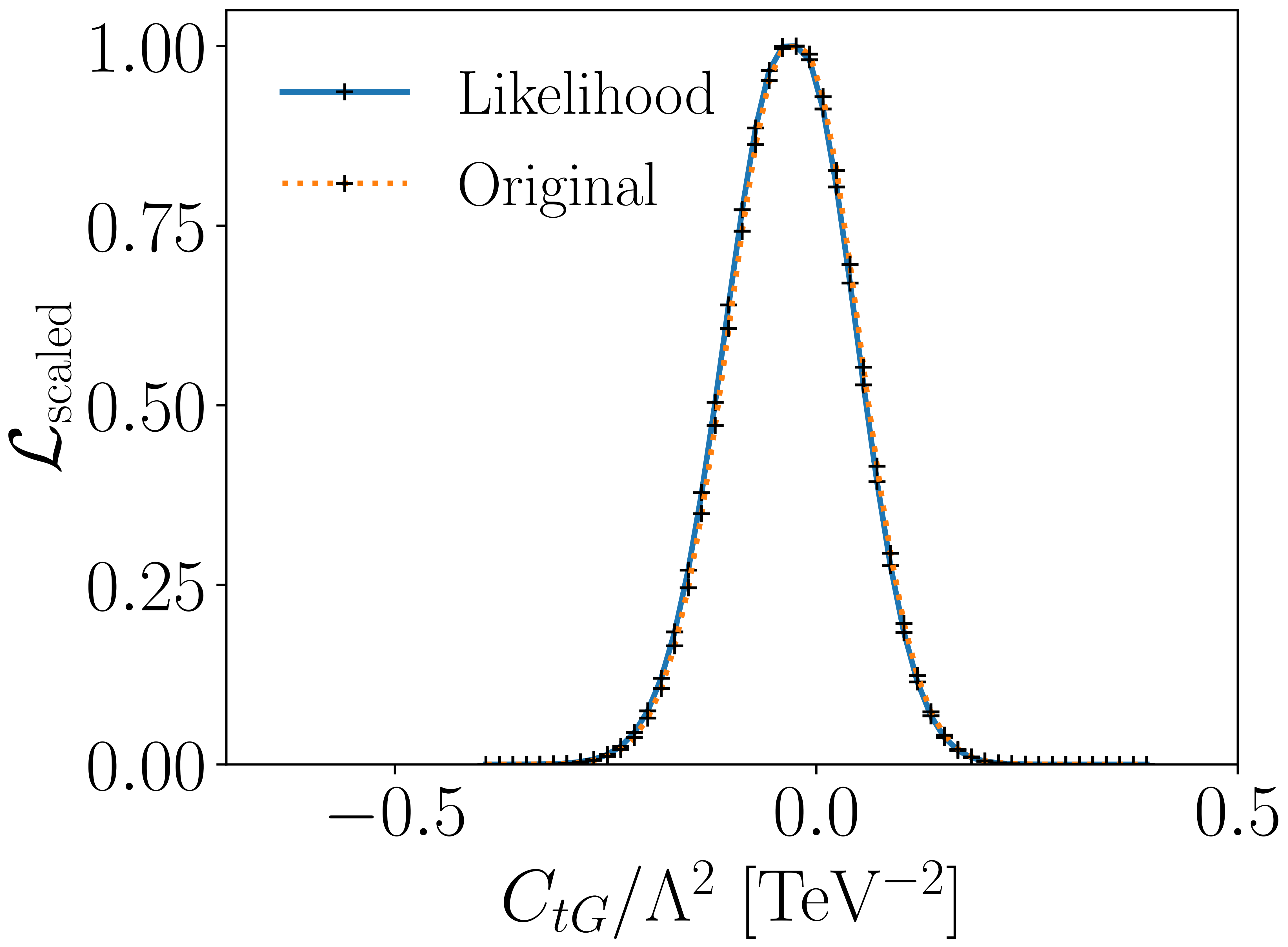
➤ **Now:** Simply separate the nuisance parameters in profile likelihood fit

Published Likelihoods

Testing Implementation

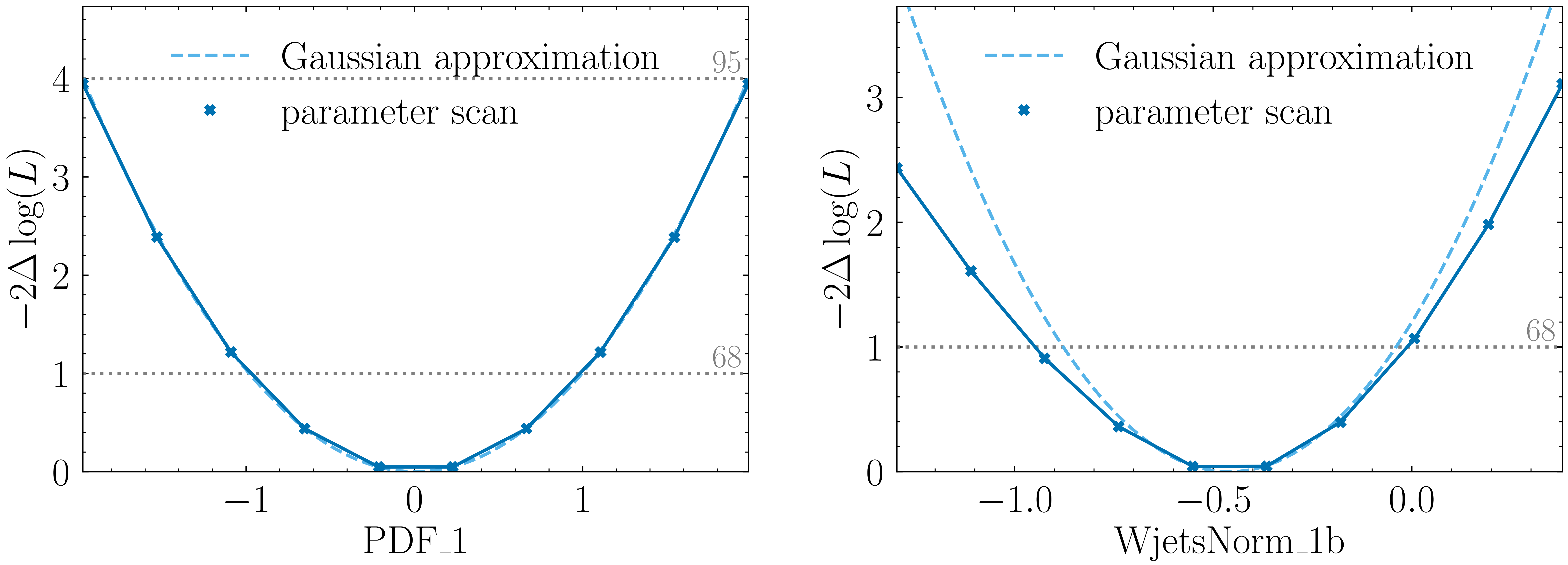
- Low dimensional fit to **only** C_{tG} and total cross section measurements
- Neglect theory uncertainties
- **Excellent agreement** between both methods of implementation



Published Likelihoods

Parameter scans with cabinetry

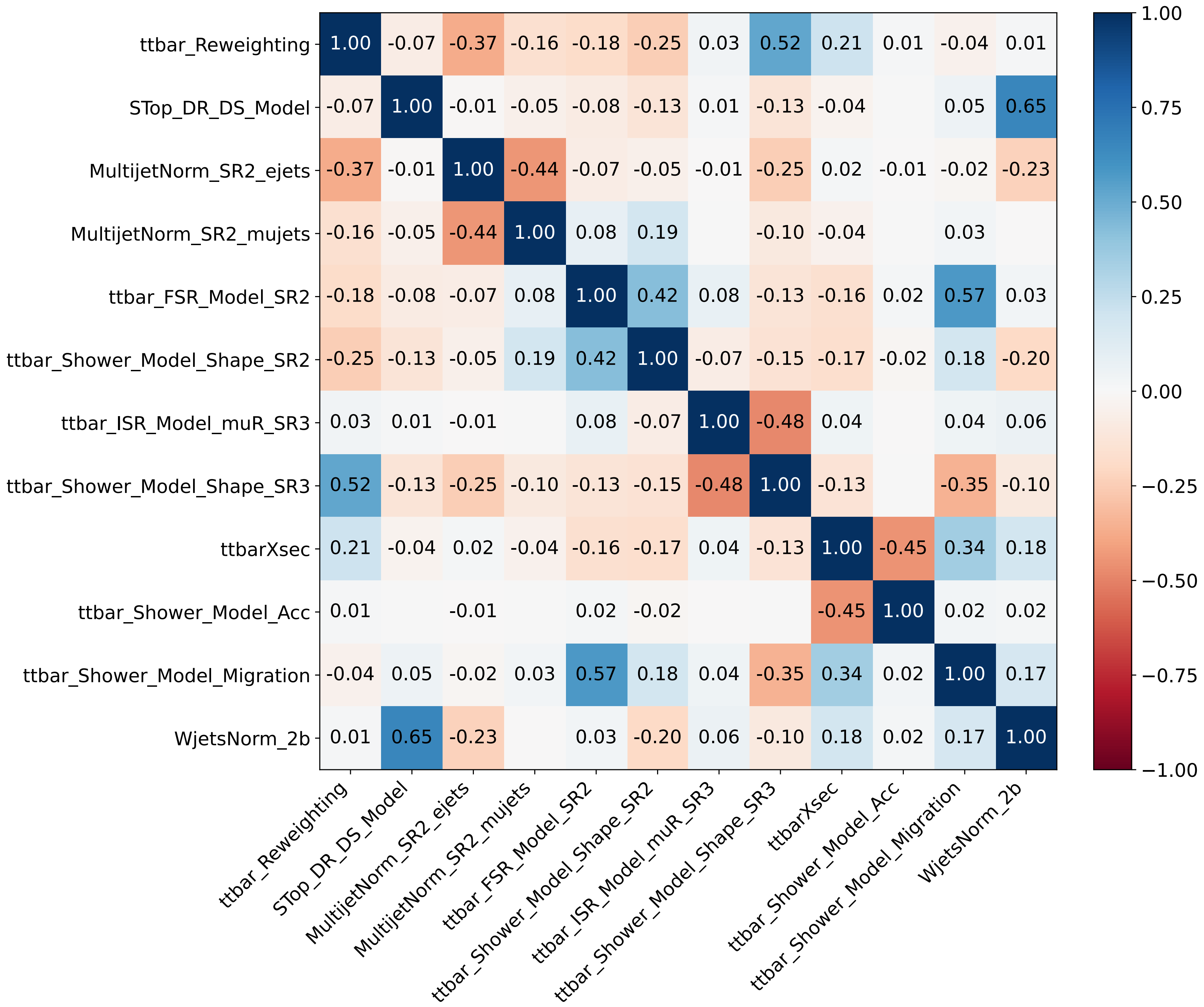
arXiv:2312.12502 [hep-ph]



- NPs are all very Gaussian, only small number of exceptions
  - Validates **Gaussian** constraint term $\mathcal{C}(\theta_i, \sigma_i)$ for systematics

Published Likelihoods

Concerning Correlations

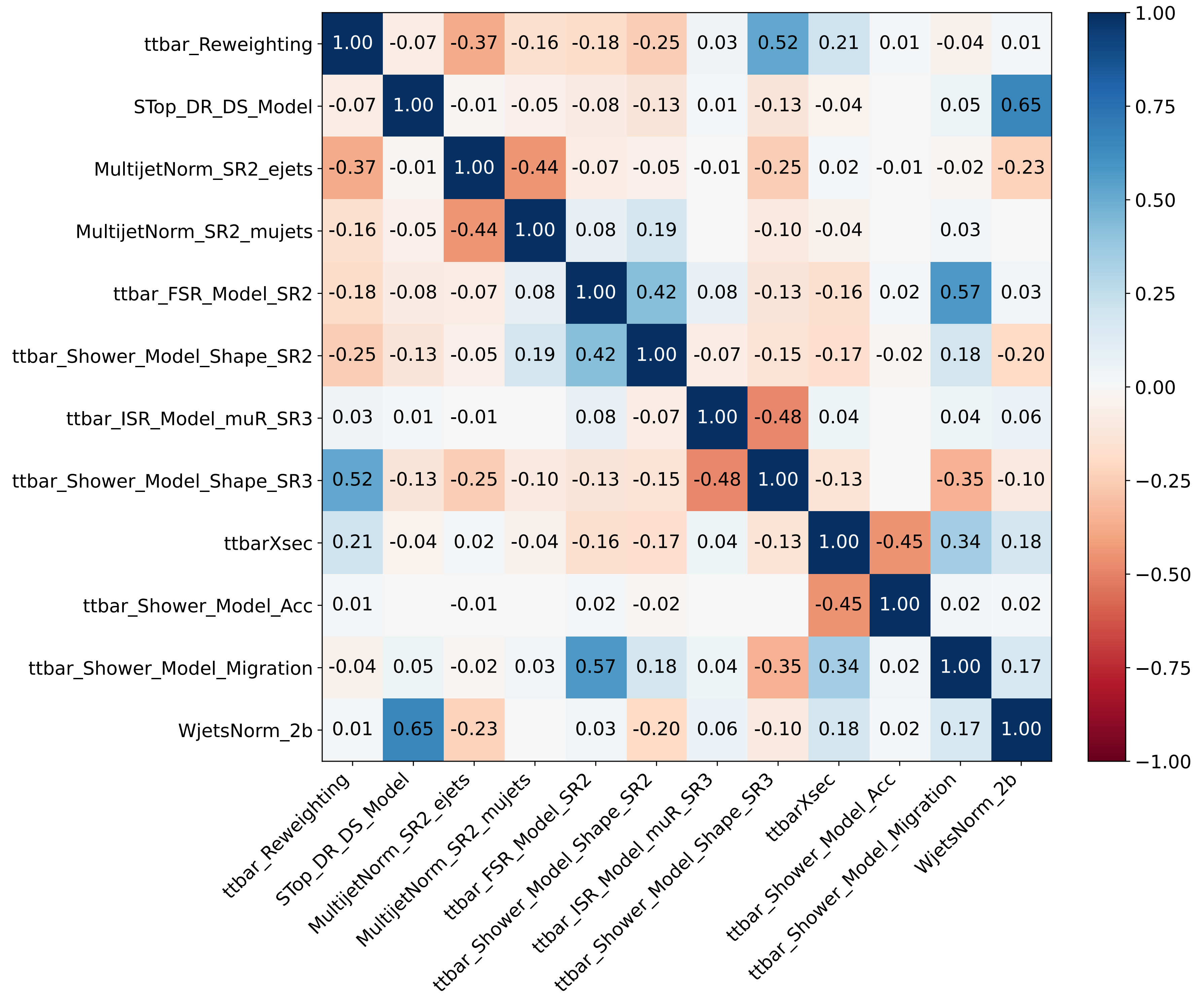


➤ **Currently:** No correlations between uncertainties within a measurement

Published Likelihoods

Concerning Correlations

[arXiv:2312.12502 hep-ph]

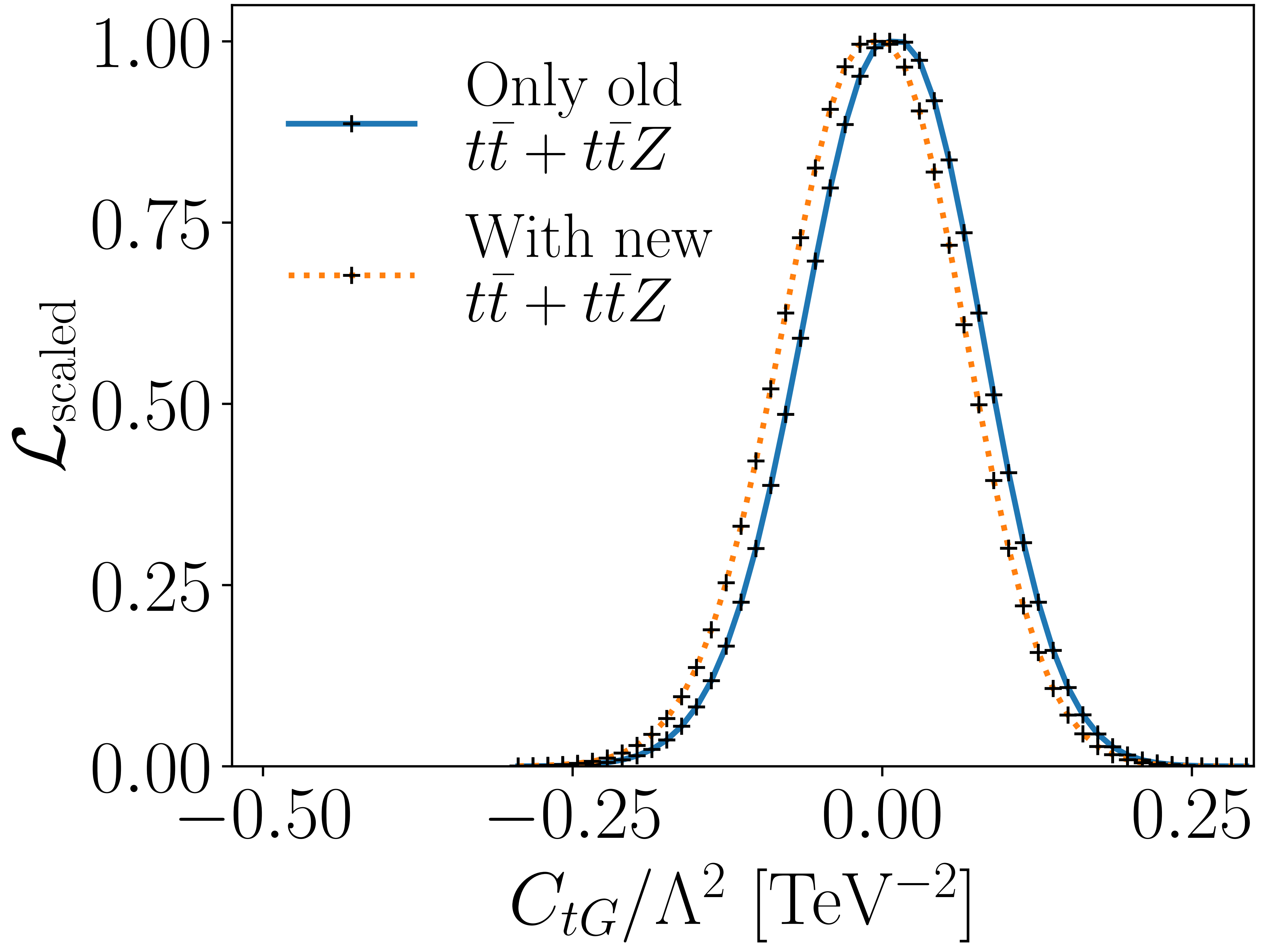


- ➤ **Currently:** No correlations between uncertainties within a measurement
  - ➤ Correlations of systematics included in SFitter are **negligibly small**

Published Likelihoods

Constraints

- Visible shift from new measurements
- Constraints **shift slightly** after including both new measurements
- Measurements of **total cross sections** barely affect constraints

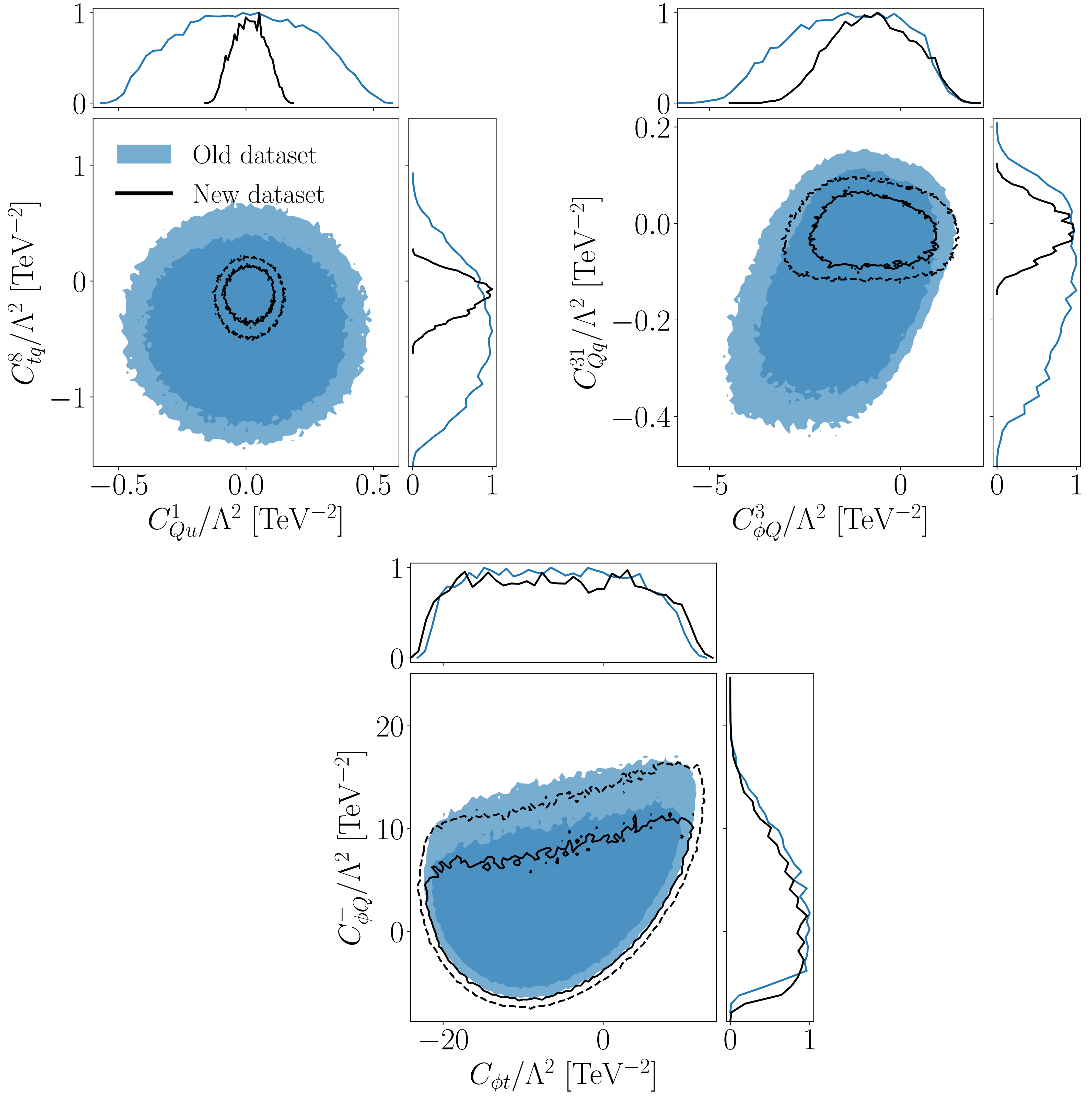


Global SMEFT analysis

Results (New dataset)

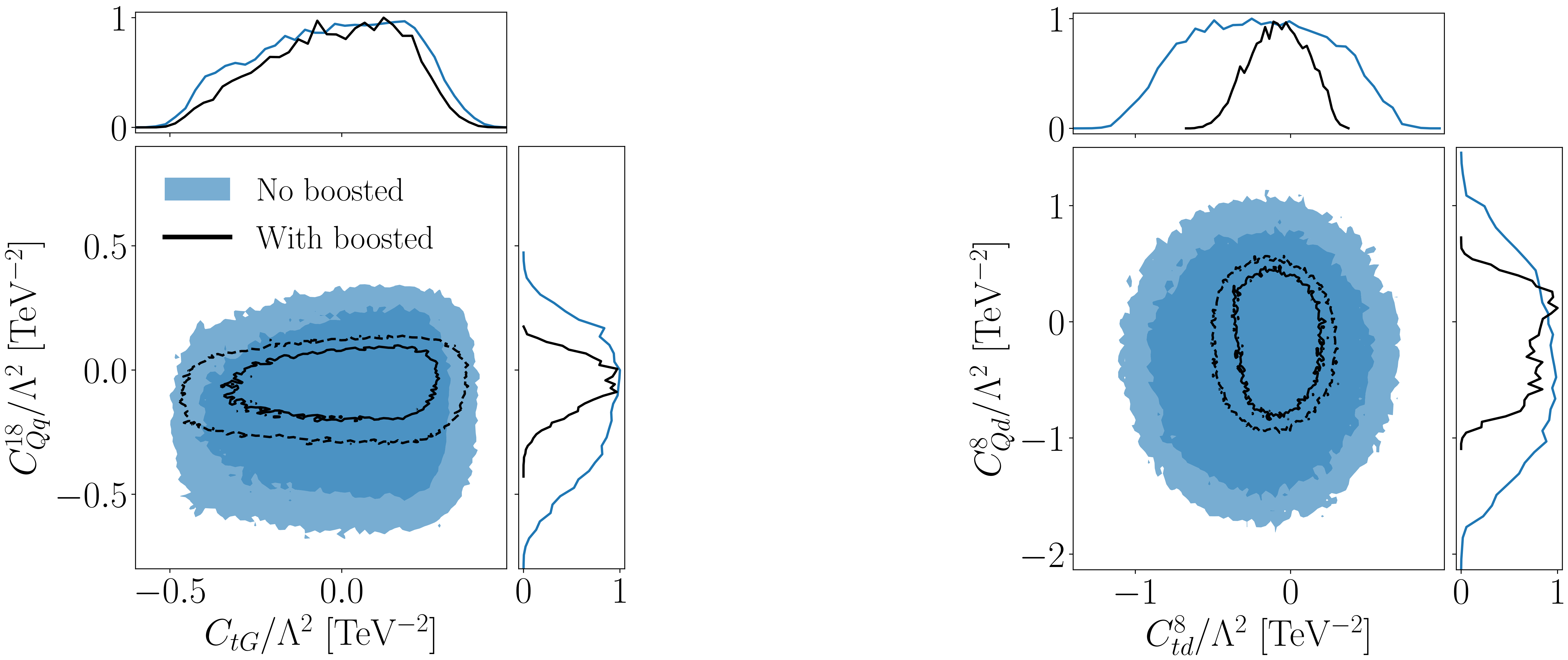
- Shown operators are all constrained by one of the public likelihoods
- Visibly **stronger constraints**, especially for four-fermion operators
- **However:** Constraints barely affected by measurements with likelihoods

arXiv:2312.12502 [hep-ph]



Global SMEFT analysis

Results (Boosted measurement)

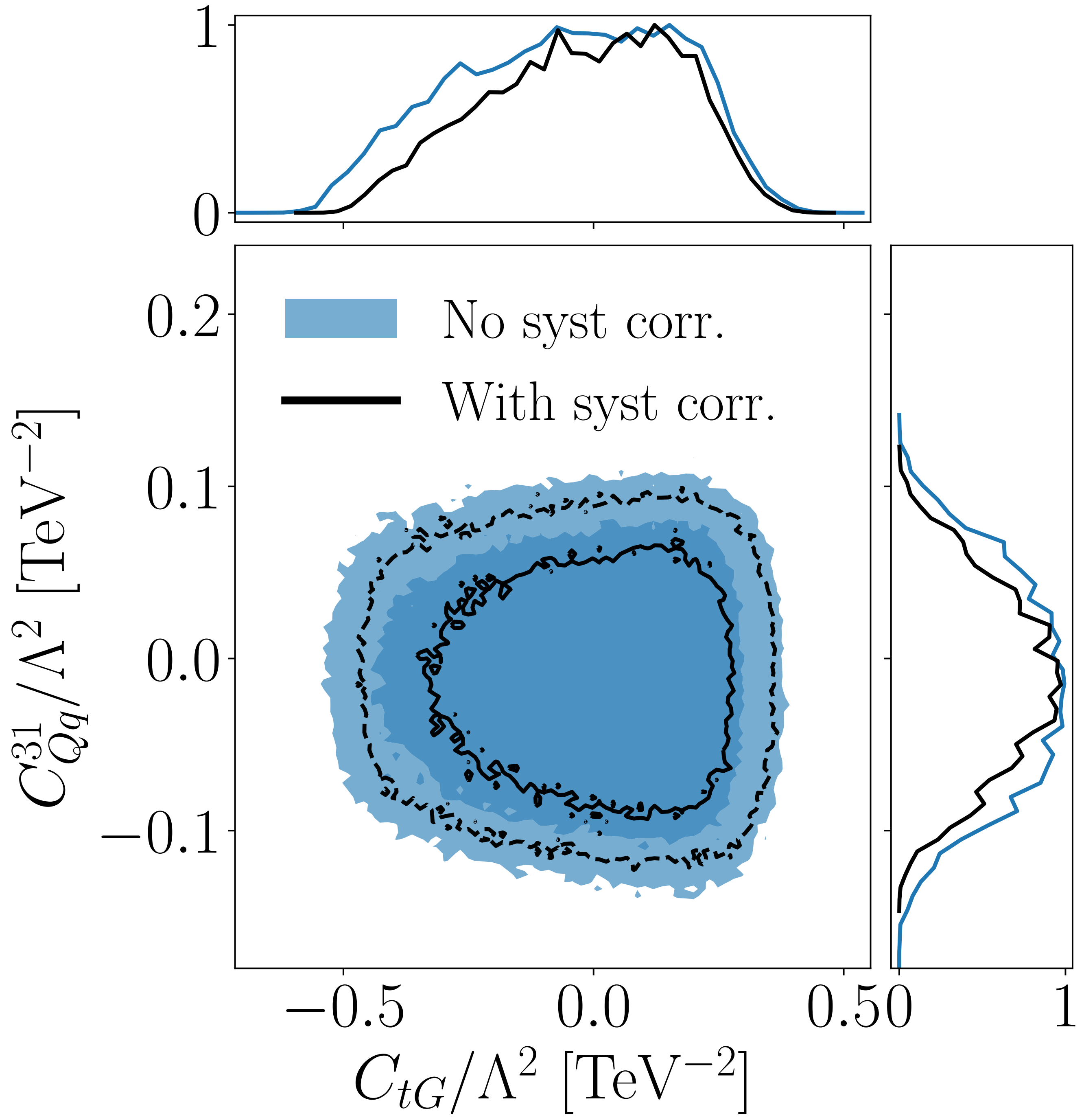


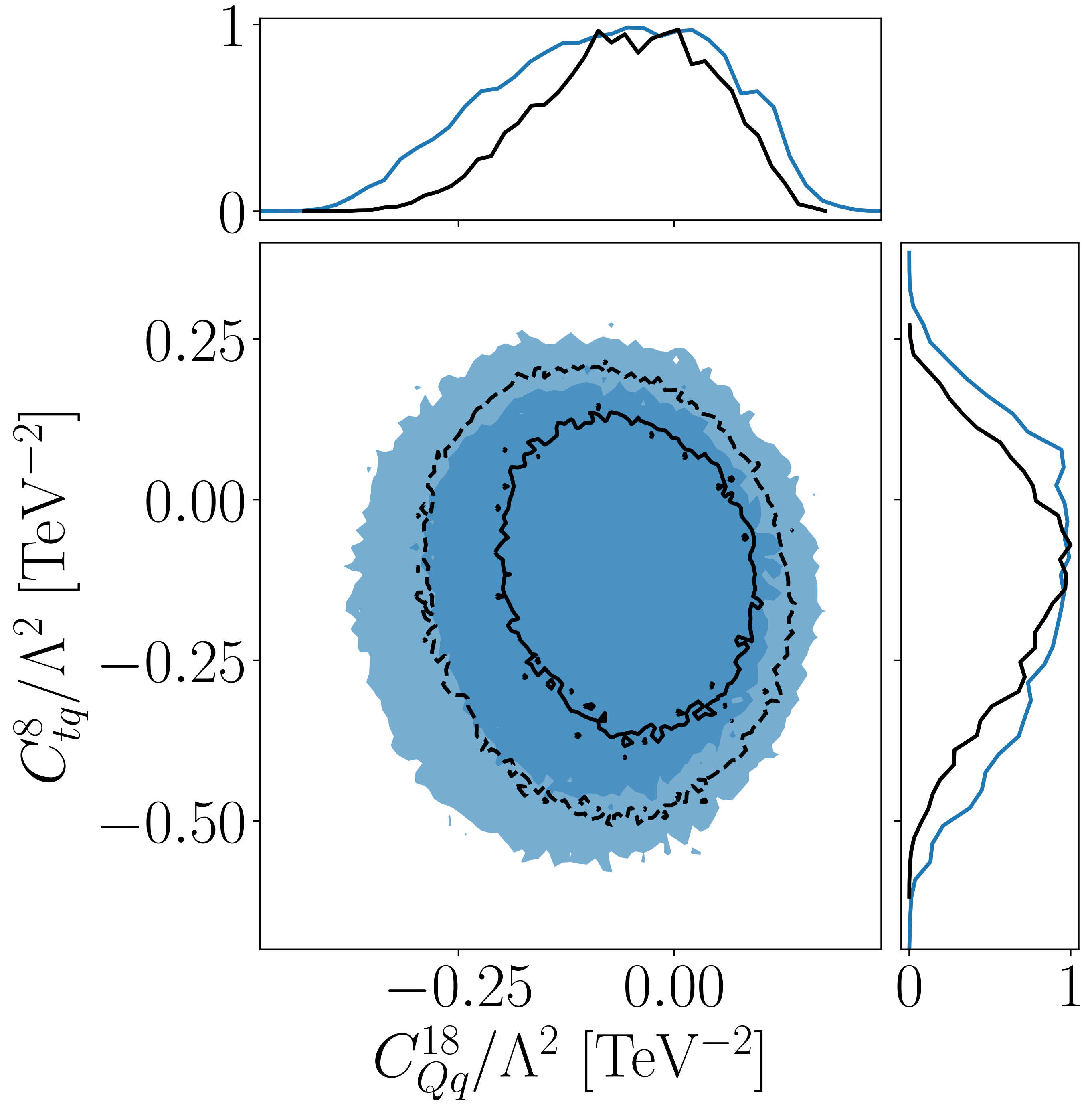
arXiv:2312.12502 [hep-ph]

- **Boosted measurement** strongly affect constraints for four-fermion operators

Global SMEFT analysis

Results (Correlations)



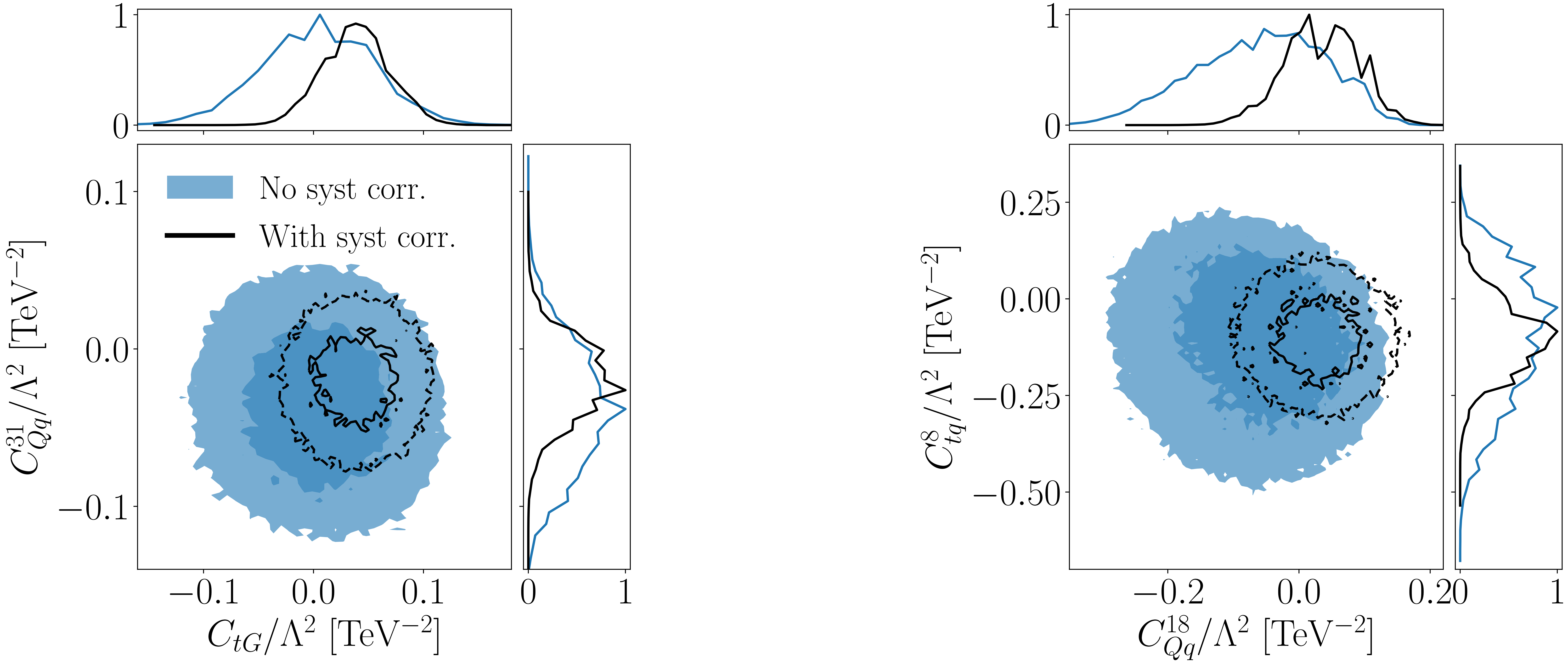


arXiv:2312.12502 [hep-ph]

- **Correlations** lead to **slightly stronger** constraints

Global SMEFT analysis

Results (Correlations, neglecting theory)



arXiv:2312.12502 [hep-ph]

➤ **Correlations** lead to **significantly different** results also in the Top sector

Concluding

- **Summary:** Uncertainties and correlations are essential to SFitter constraints
  - Large effect of **theory uncertainties** in the top sector
  - Published likelihoods provide an alternative way to use experimental data
    - **Validates assumptions** made in previous analyses

- **However:** Currently included likelihoods not particularly SMEFT sensitive
  - Publication of more **differential measurements** would be useful
  - **Global SMEFT analysis** requires data from all kinds of processes

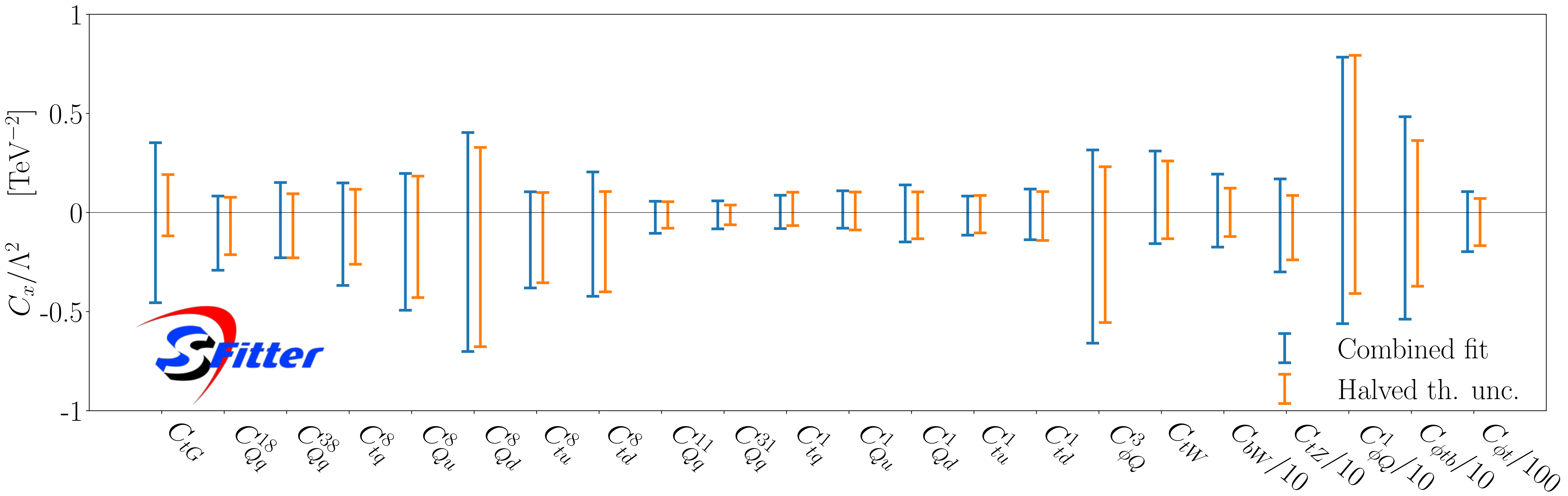
The full dataset

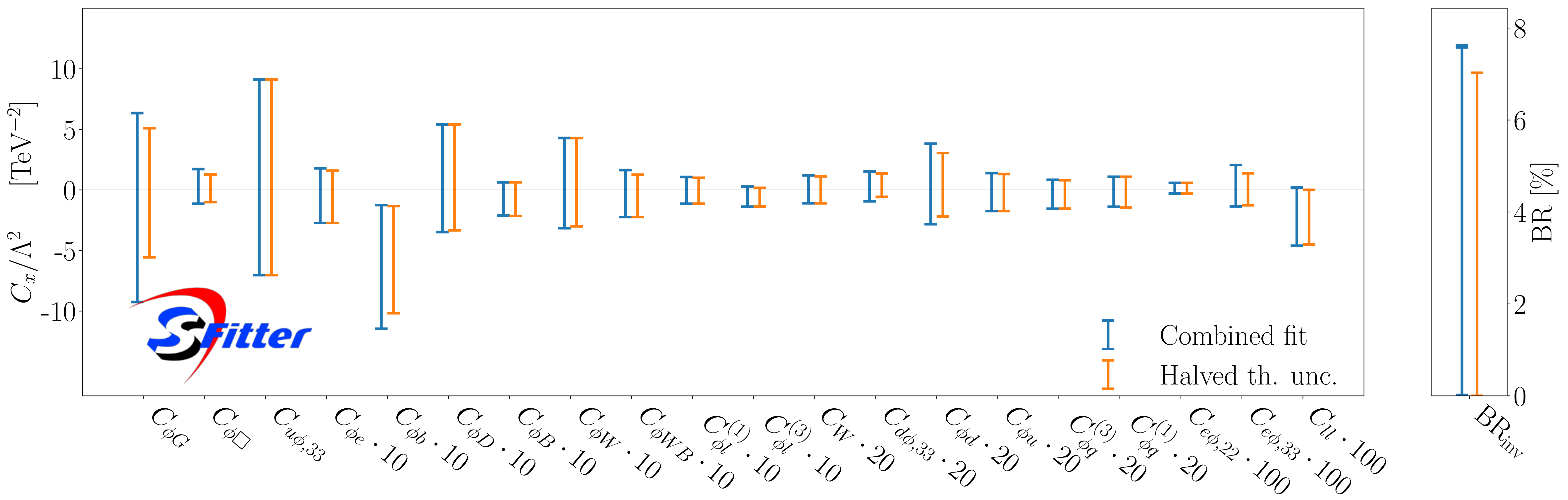
Experiment	Energy [TeV]	$\mathcal{L}$ [fb^{-1}]	Channel	Observable	# Bins	New	Likelihood	QCD k-factor
CMS [79]	8	19.7	$e\mu$	$\sigma_{t\bar{t}}$				[80]
ATLAS [81]	8	20.2	lj	$\sigma_{t\bar{t}}$				[80]
CMS [82]	13	137	lj	$\sigma_{t\bar{t}}$		✓		[80]
CMS [83]	13	35.9	ll	$\sigma_{t\bar{t}}$				[80]
ATLAS [84]	13	36.1	ll	$\sigma_{t\bar{t}}$		✓		[80]
ATLAS [85]	13	36.1	aj	$\sigma_{t\bar{t}}$		✓		[80]
ATLAS [47]	13	139	lj	$\sigma_{t\bar{t}}$		✓	✓	[80]
CMS [86]	13.6	1.21	ll, lj	$\sigma_{t\bar{t}}$		✓		[86]
CMS [87]	8	19.7	lj	$\frac{1}{\sigma}\frac{d\sigma}{dp_T^t}$	7			[88–90]
CMS [87]	8	19.7	ll	$\frac{1}{\sigma}\frac{d\sigma}{dp_T^t}$	5			[88–90]
ATLAS [91]	8	20.3	lj	$\frac{1}{\sigma}\frac{d\sigma}{dm_{t\bar{t}}}$	7			[88–90]
CMS [82]	13	137	lj	$\frac{1}{\sigma}\frac{d\sigma}{dm_{t\bar{t}}}$	15	✓		[45]
CMS [92]	13	35.9	ll	$\frac{1}{\sigma}\frac{d\sigma}{d\Delta y_{t\bar{t}}}$	8			[88–90]
ATLAS [93]	13	36	lj	$\frac{1}{\sigma}\frac{d\sigma}{dm_{t\bar{t}}}$	9	✓		[45]
ATLAS [94]	13	139	aj, high-p_T	$\frac{1}{\sigma}\frac{d\sigma}{dm_{t\bar{t}}}$	13	✓		
CMS [95]	8	19.7	lj	A_C				[96]
CMS [97]	8	19.5	ll	A_C				[96]
ATLAS [98]	8	20.3	lj	A_C				[96]
ATLAS [99]	8	20.3	ll	A_C				[96]
CMS [100]	13	138	lj	A_C		✓		[96]
ATLAS [101]	13	139	lj	A_C		✓		[96]
ATLAS [48]	13	139		$\sigma_{t\bar{t}Z}$		✓	✓	[102]
CMS [103]	13	77.5		$\sigma_{t\bar{t}Z}$				[102]
CMS [104]	13	35.9		$\sigma_{t\bar{t}W}$				[102]
ATLAS [105]	13	36.1		$\sigma_{t\bar{t}W}$		✓		[102]
CMS [106]	8	19.7		$\sigma_{t\bar{t}\gamma}$		✓		
ATLAS [107]	8	20.2		$\sigma_{t\bar{t}\gamma}$		✓		

Exp.	$\sqrt{s}$ [TeV]	$\mathcal{L}$ [fb^{-1}]	Channel	Observable	# Bins	New	Likelihood	QCD k-factor
ATLAS [108]	7	4.59	t-ch	$\sigma_{tq+\bar{t}q}$				
CMS [109]	7	1.17 (e), 1.56 (μ)	t-ch	$\sigma_{tq+\bar{t}q}$				
ATLAS [110]	8	20.2	t-ch	σ_{tq}, $\sigma_{\bar{t}q}$				
CMS [111]	8	19.7	t-ch	σ_{tq}, $\sigma_{\bar{t}q}$				
ATLAS [112]	13	3.2	t-ch	σ_{tq}, $\sigma_{\bar{t}q}$				[113]
CMS [114]	13	2.2	t-ch	σ_{tq}, $\sigma_{\bar{t}q}$				[113]
CMS [115]	13	35.9	t-ch	$\frac{1}{\sigma}\frac{d\sigma}{d\lvert p_{T,t}\rvert}$	5	✓		
CMS [116]	7	5.1	s-ch	$\sigma_{t\bar{b}+\bar{t}b}$				
CMS [116]	8	19.7	s-ch	$\sigma_{t\bar{b}+\bar{t}b}$				
ATLAS [117]	8	20.3	s-ch	$\sigma_{t\bar{b}+\bar{t}b}$				
ATLAS [49]	13	139	s-ch	$\sigma_{t\bar{b}+\bar{t}b}$		✓	✓	
ATLAS [118]	7	2.05	tW (2l)	$\sigma_{tW+\bar{t}W}$				
CMS [119]	7	4.9	tW (2l)	$\sigma_{tW+\bar{t}W}$				
ATLAS [120]	8	20.3	tW (2l)	$\sigma_{tW+\bar{t}W}$				
ATLAS [121]	8	20.2	tW (1l)	$\sigma_{tW+\bar{t}W}$		✓		
CMS [122]	8	12.2	tW (2l)	$\sigma_{tW+\bar{t}W}$				
ATLAS [123]	13	3.2	tW (1l)	$\sigma_{tW+\bar{t}W}$				
CMS [124]	13	35.9	tW ($e\mu j$)	$\sigma_{tW+\bar{t}W}$				
CMS [125]	13	36	tW (2l)	$\sigma_{tW+\bar{t}W}$		✓		
ATLAS [126]	13	36.1	tZ	σ_{tZq}				
ATLAS [127]	7	1.04		F_0,F_L				
CMS [128]	7	5		F_0,F_L				
ATLAS [129]	8	20.2		F_0,F_L				
CMS [130]	8	19.8		F_0,F_L				
ATLAS [131]	13	139		F_0,F_L		✓		

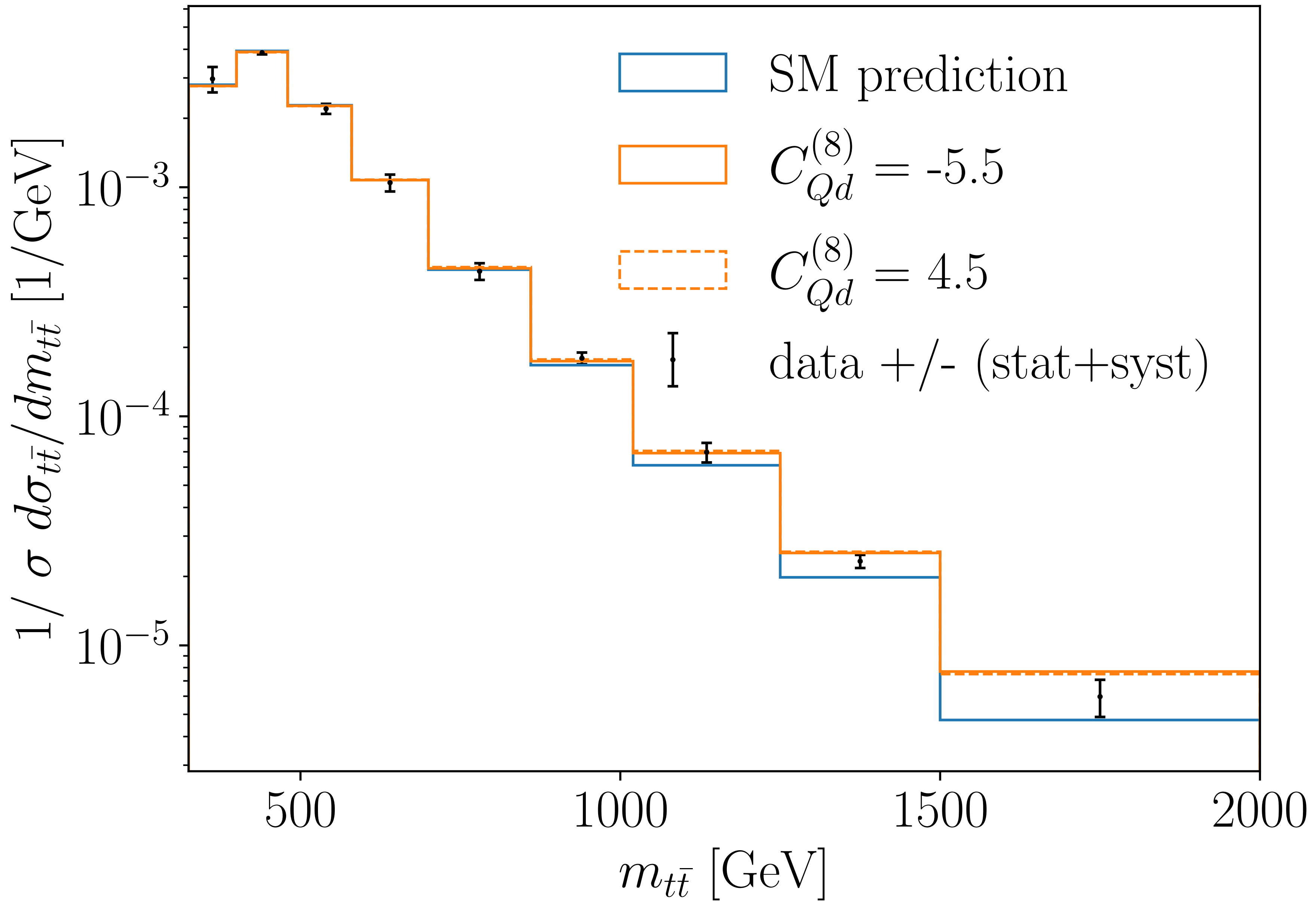
Global SMEFT analysis

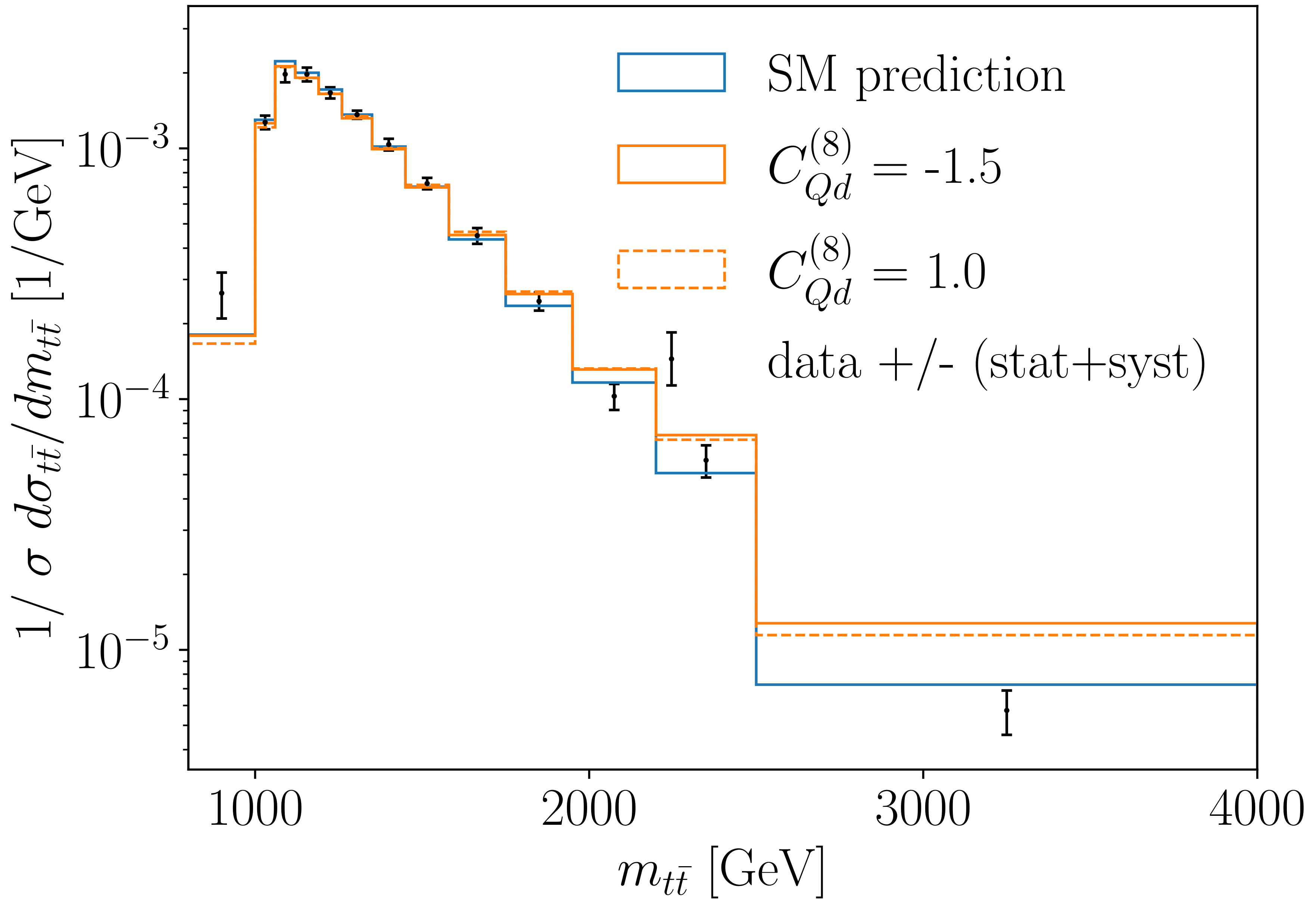
Combined fit for Higgs, EWPO, Di-Boson and Top data





Boosted measurements





➤ **Sensitivity** of boosted measurement for a single four-fermion operator