UNIVERSITÄT
HEIDELBERG
ZUKUNFT
SEIT 1386

STAYING ON TOP OF LIKELIHOOD ANALYSES

Using pyhf for global SMEFT analyses with SFitter

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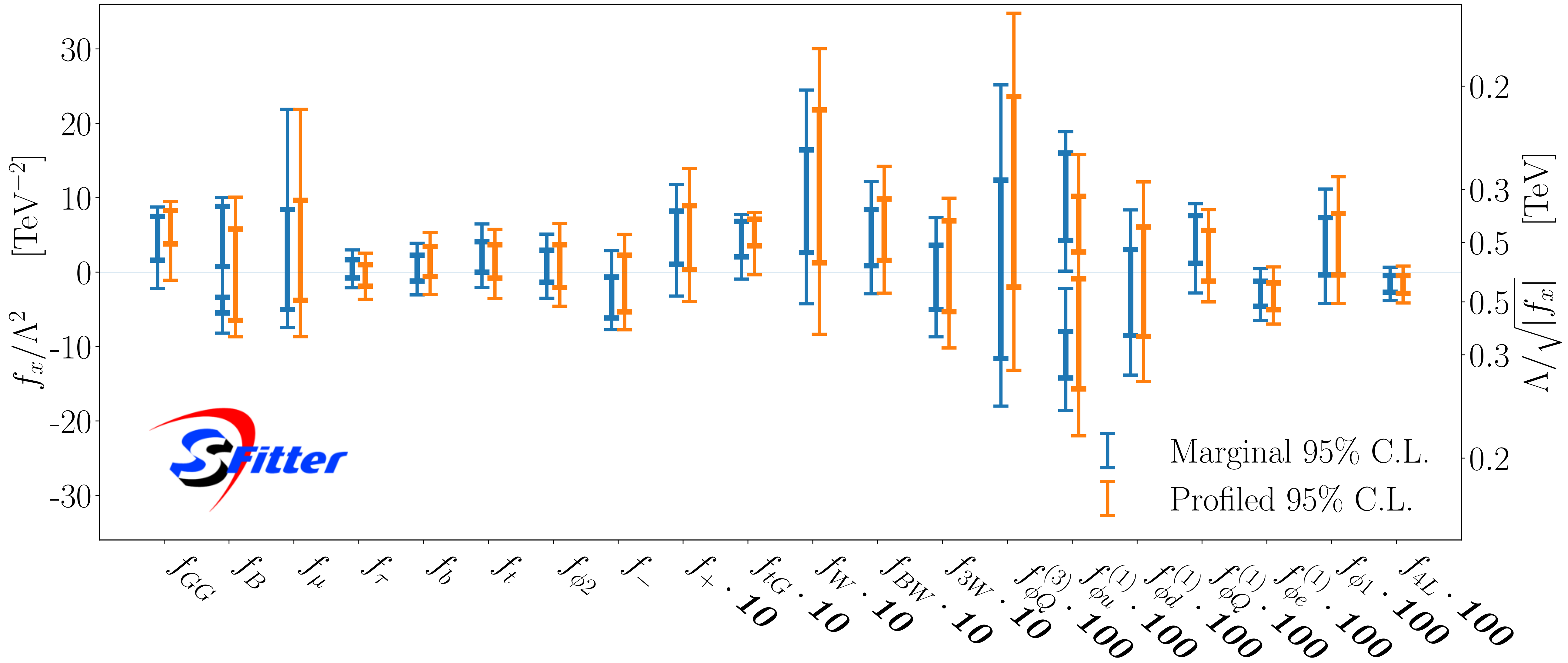
What’s the purpose of this talk?

- **Problem:** Large number of observations cannot be explained by the SM alone
- **What we do:** Global SMEFT analyses using **SFitter**
- **Goal:** Put constraints on physics beyond the Standard Model

arXiv:2208.08454 [hep-ph]



Outline

- **Intro:** Standard Model Effective Field Theory
- **Part I:** Statistical analysis using SFitter
- **Part II:** SFitter analyses with pyhf
- **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

Model and dataset

arXiv:1910.03606 [hep-ph]

- Restrict ourselves to the Top sector
  - Include $t\bar{t}$, $t\bar{t}Z$, $t\bar{t}W$ and single top data
    - Total **~116 datapoints**
- Impose $U(2)_q \times U(2)_u \times U(2)_d$ symmetry
  - Consider a total of **22 Operators**

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}	$(\bar{Q}\sigma^{\mu\nu} t)\tau^I \tilde{\phi} W_{\mu\nu}^I$
O_{bW}	$(\bar{Q}\sigma^{\mu\nu} b)\tau^I \phi W_{\mu\nu}^I$	O_{tG}	$(\bar{Q}\sigma_{\mu\nu} T^A t)\tilde{\phi} G_{\mu\nu}^A$

PART I

Statistical analysis with SFitter

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 we mean with all of this

What is SFitter?

The exclusive likelihood

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

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

- 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. $\mathrm{Pois}(n|\nu) = \frac{\nu^n e^{-\nu}}{n!}, \quad \nu > 0$
- 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
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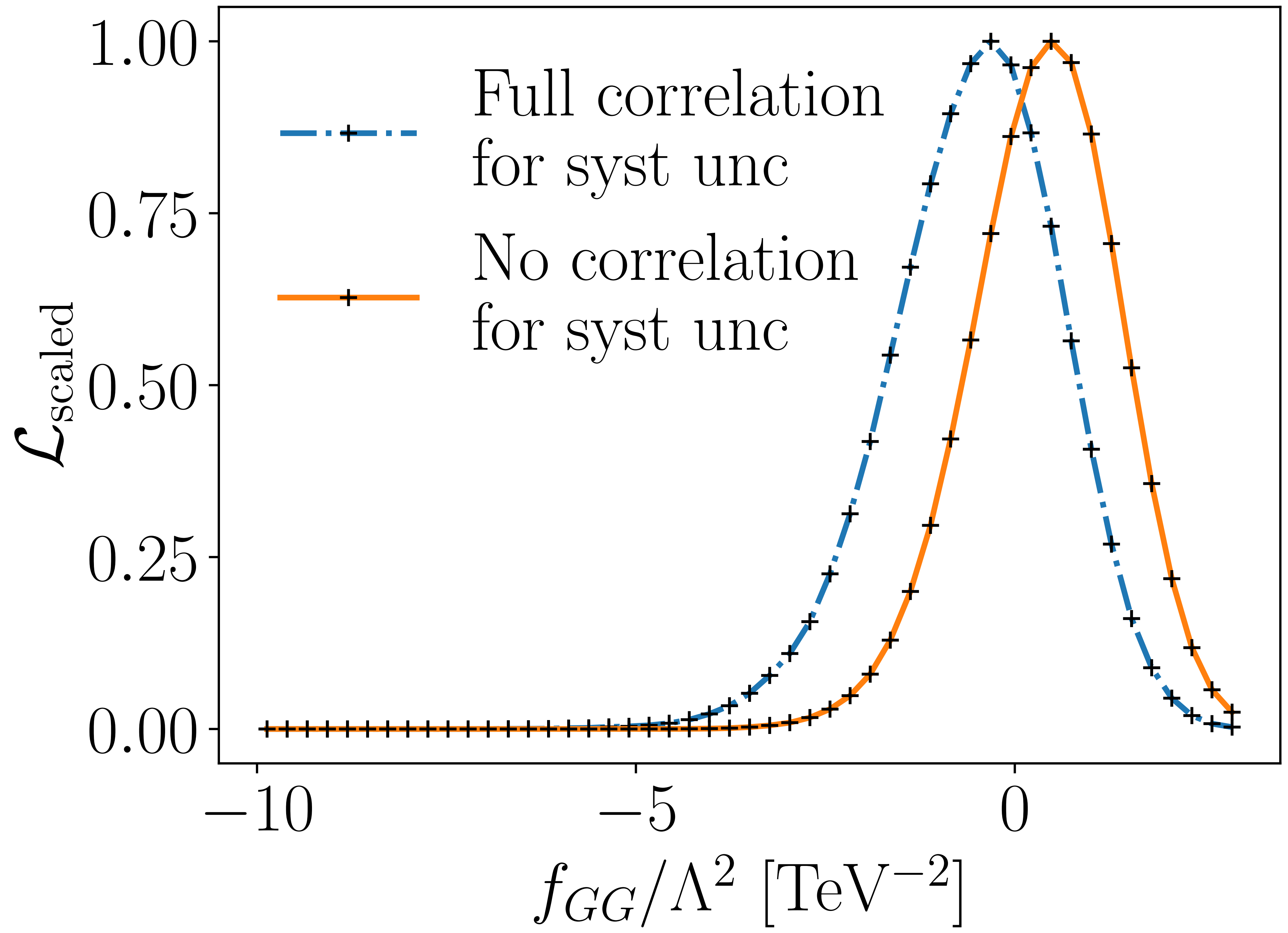
What is SFitter?

Systematic uncertainties

arXiv:2208.08454 [hep-ph]

- ➤ 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



What is SFitter?

To profile or to marginalize

- Common exclusive likelihood constructed

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

- The NPs θ_i are not physically interesting

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To profile or to marginalize

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

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

Profiling:

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

Marginalization:

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

What is SFitter?

To profile or to marginalize

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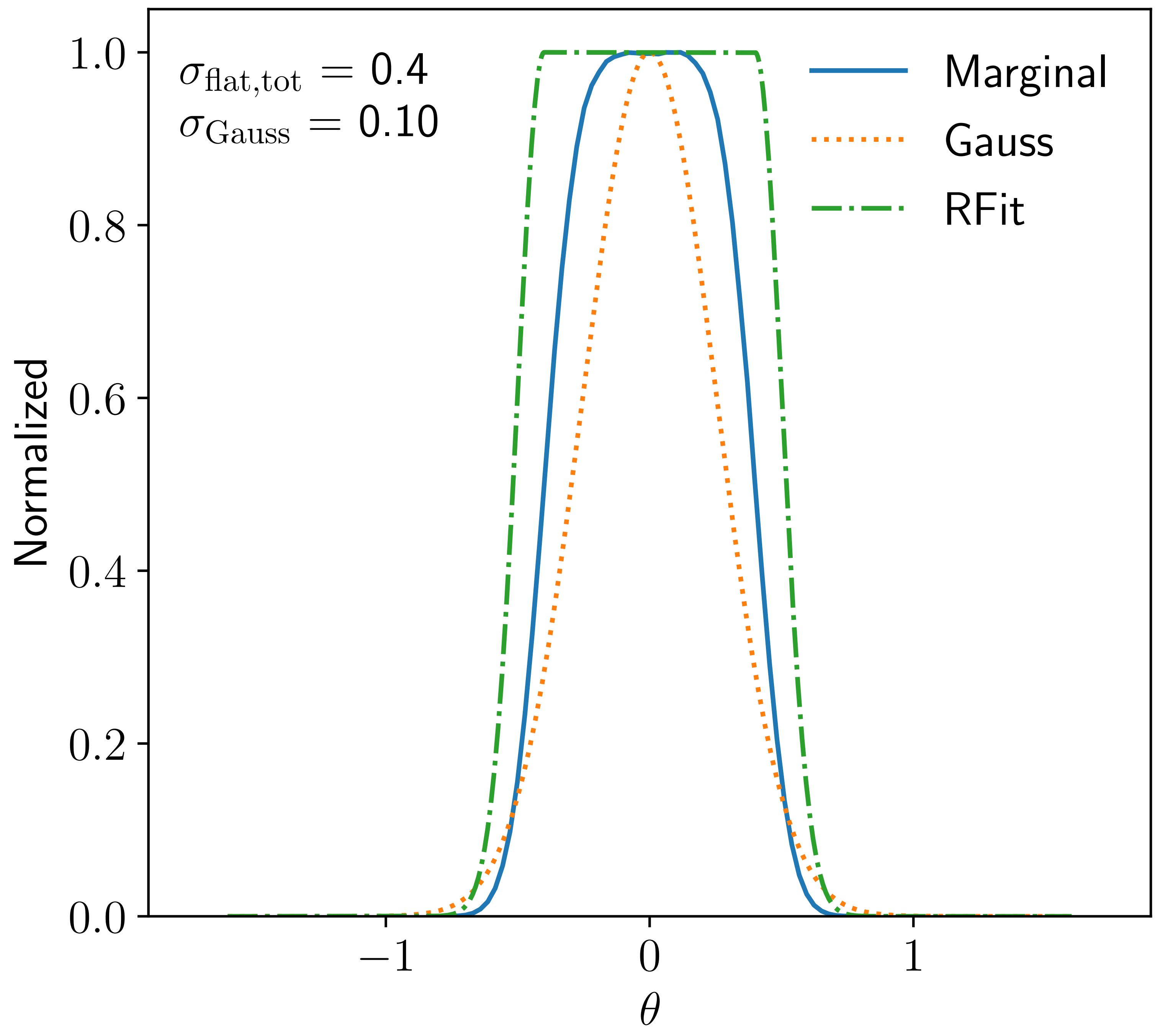
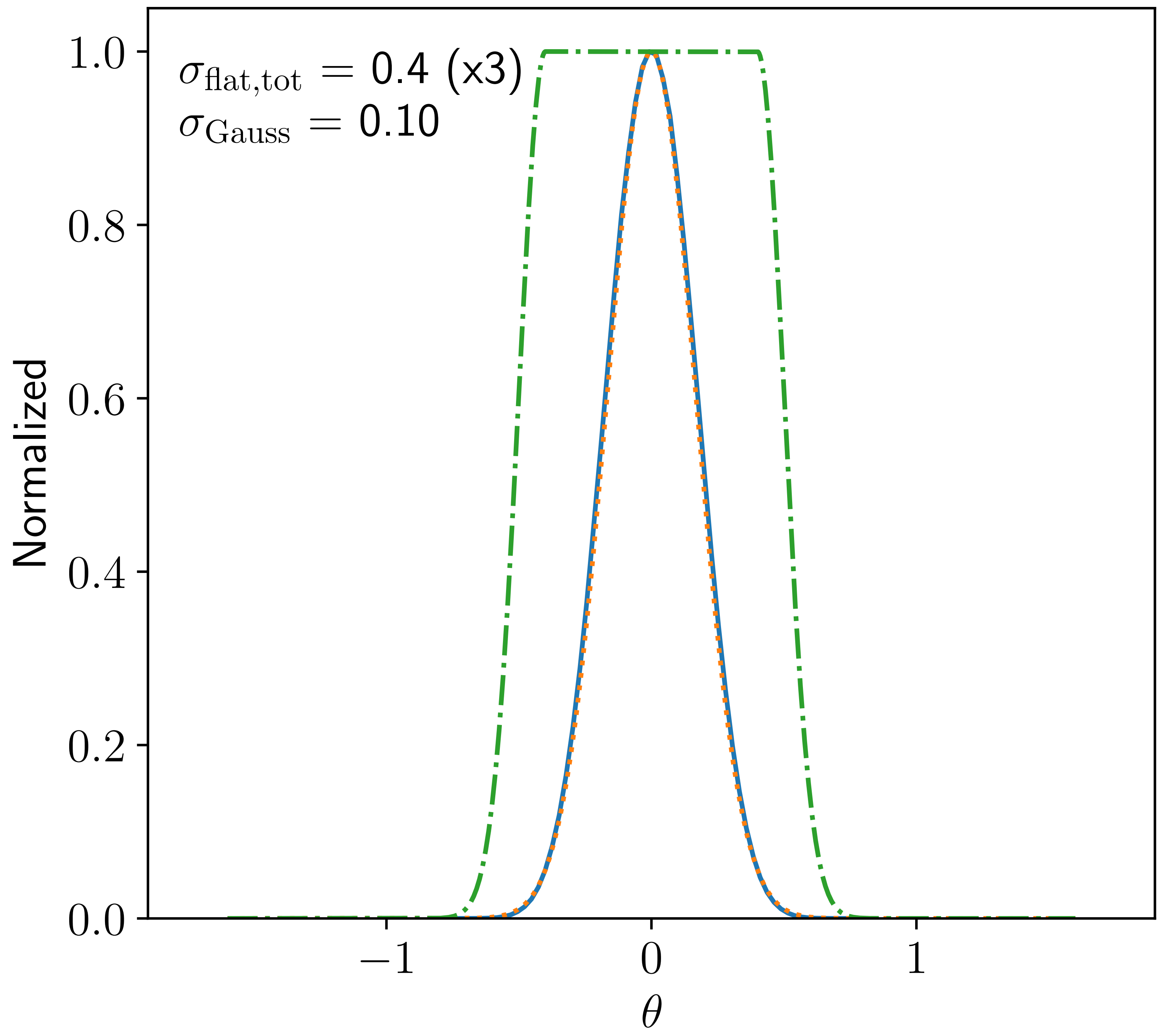
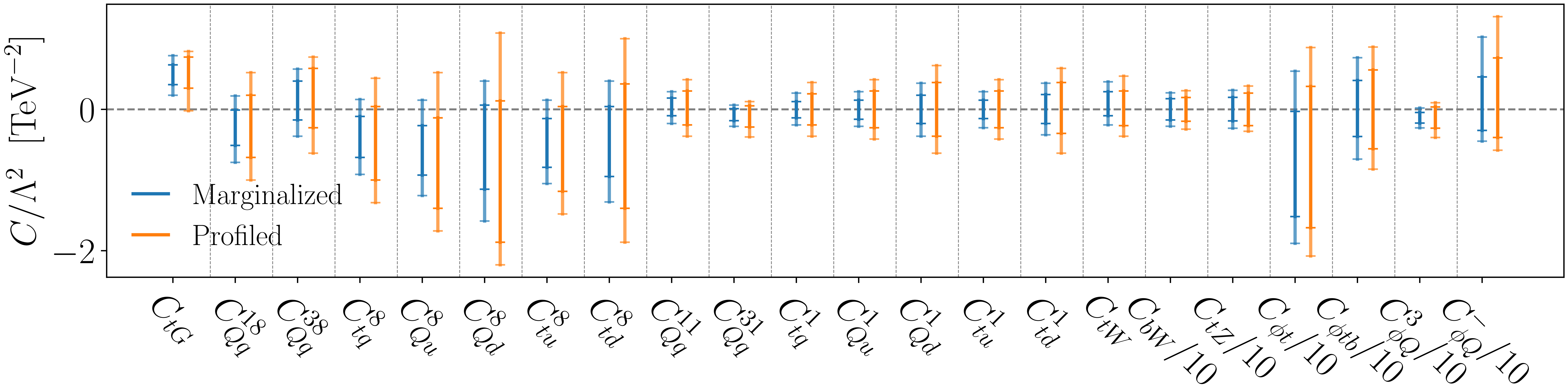




- Comparison for the product of Gaussian and uniform distributions
  - Marginalization over multiple flat unc. gives **Gaussian** results

Some Results

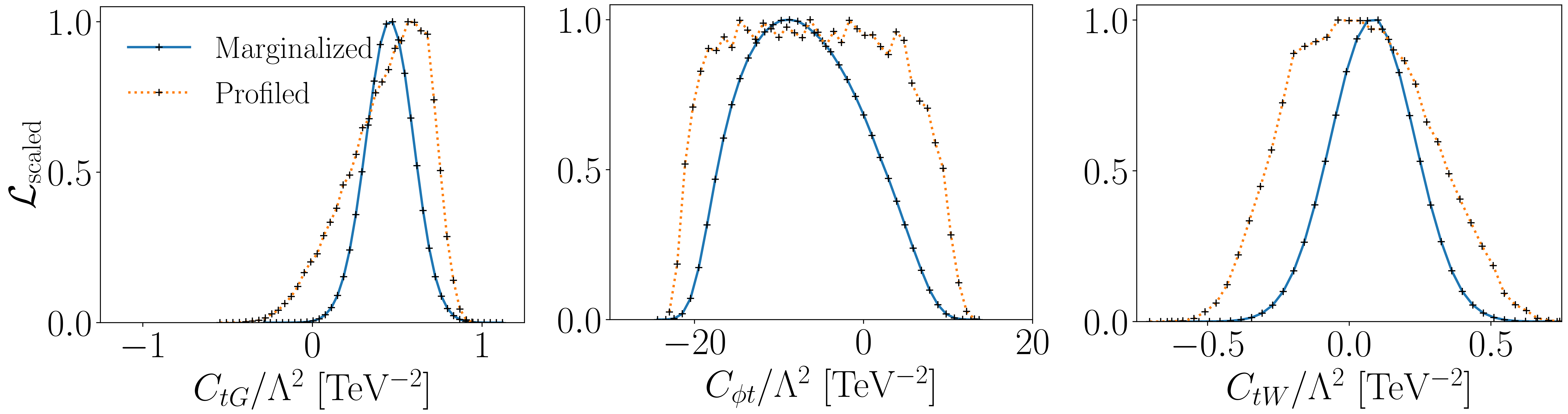
Profiling vs Marginalization



➤ Stronger constraints for marginalized likelihood as a result of **large theory uncertainties**

Some Results

Profiling vs Marginalization



- ➤ Expected behaviour due to marginalization of **flat theory uncertainties**

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?

PART II

SFitter analyses with pyhf

∂ifferentiable
ℒikelihoods

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 large number of **individual NPs**
- 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:2103.12603 [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

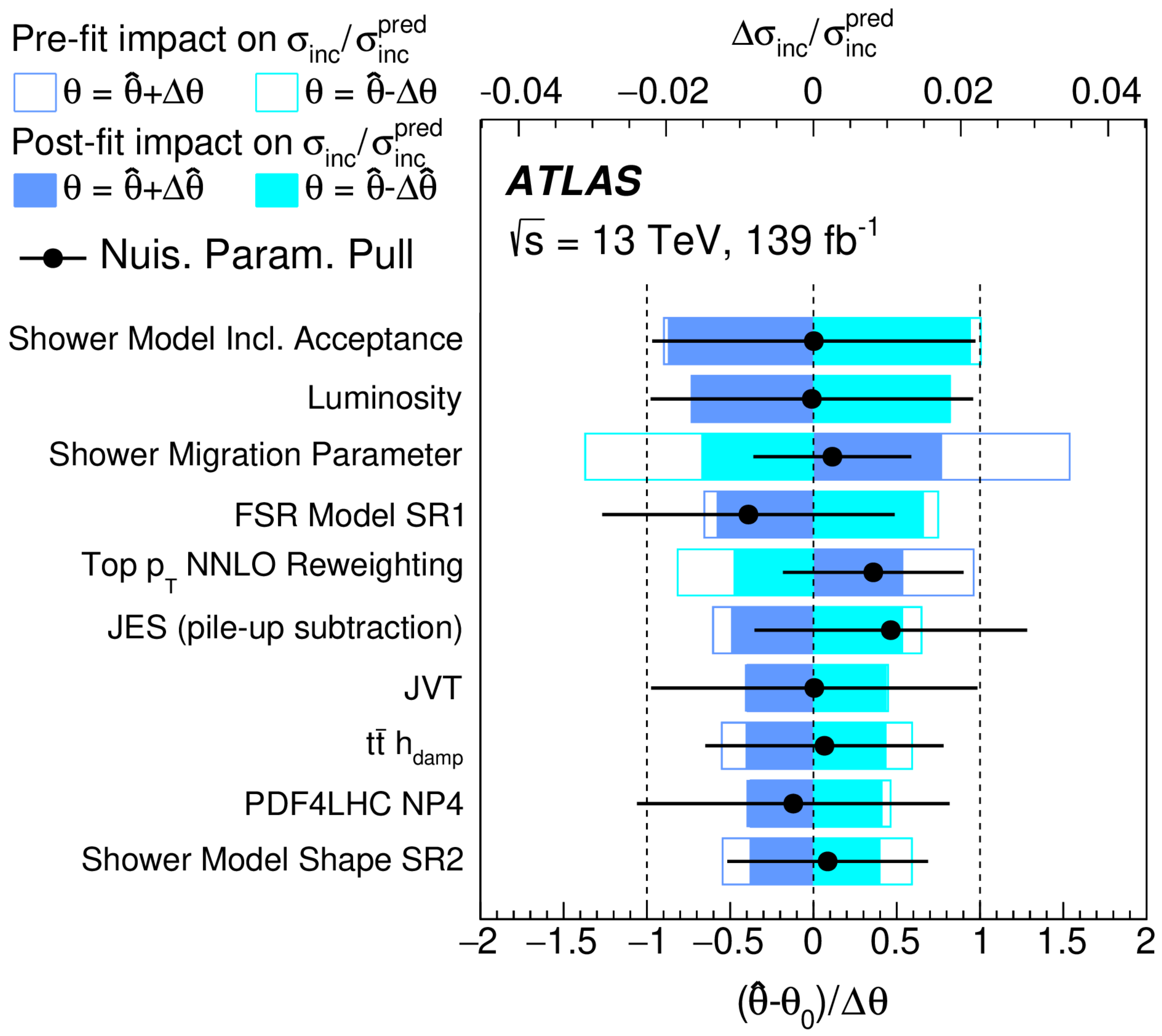
ATLAS Collaboration*
CERN, 1211 Geneva 23, Switzerland

Received: 24 March 2021 / Accepted: 10 July 2021 / Published online: 16 August 2021

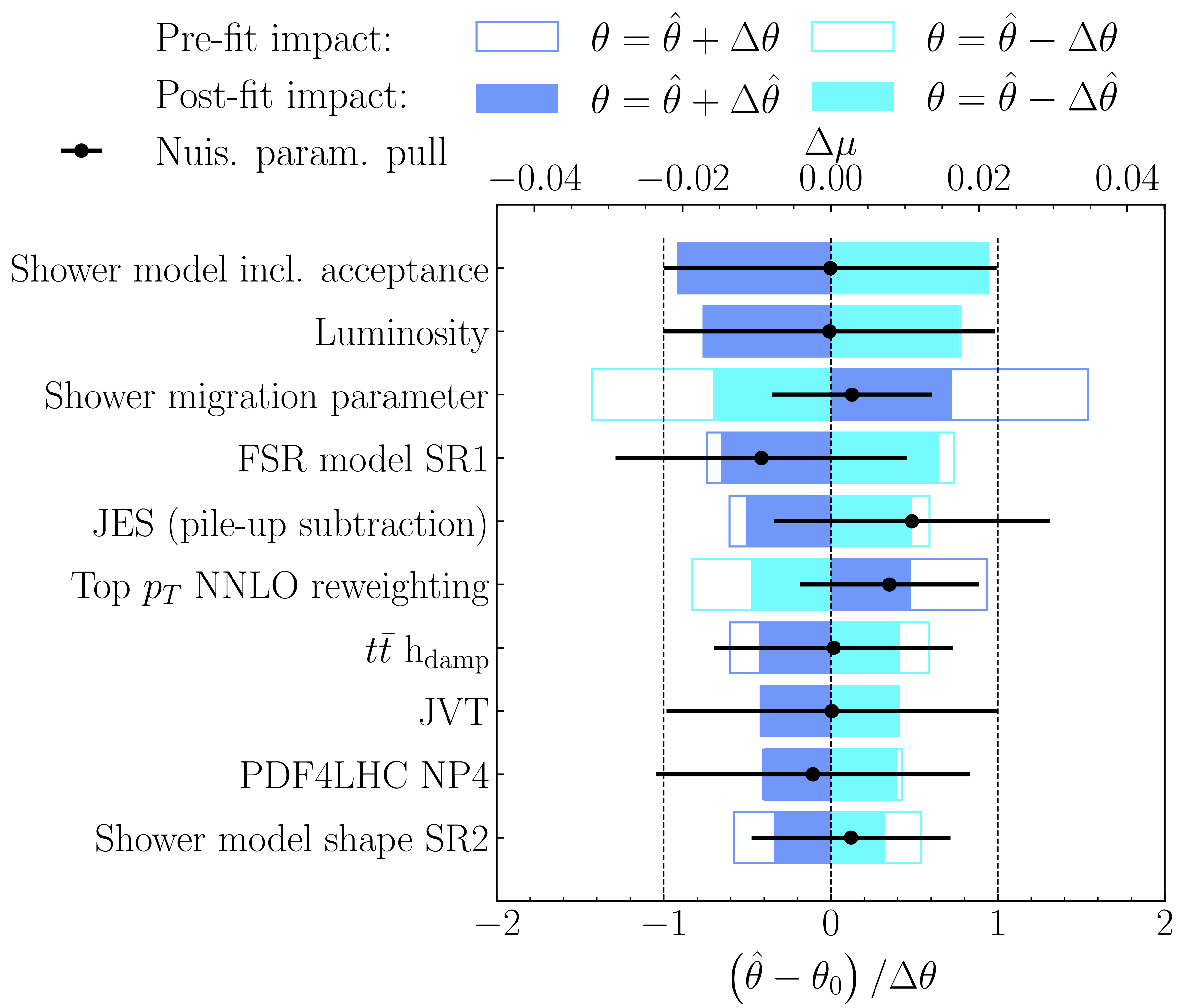
➤ Full likelihoods **publicly available** on HEPData

Published Likelihoods

Quick overview (Reproduction)



From [arXiv:2006.13076](https://arxiv.org/abs/2006.13076) [hep-ex]



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

Published Likelihoods

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?

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

Published Likelihoods

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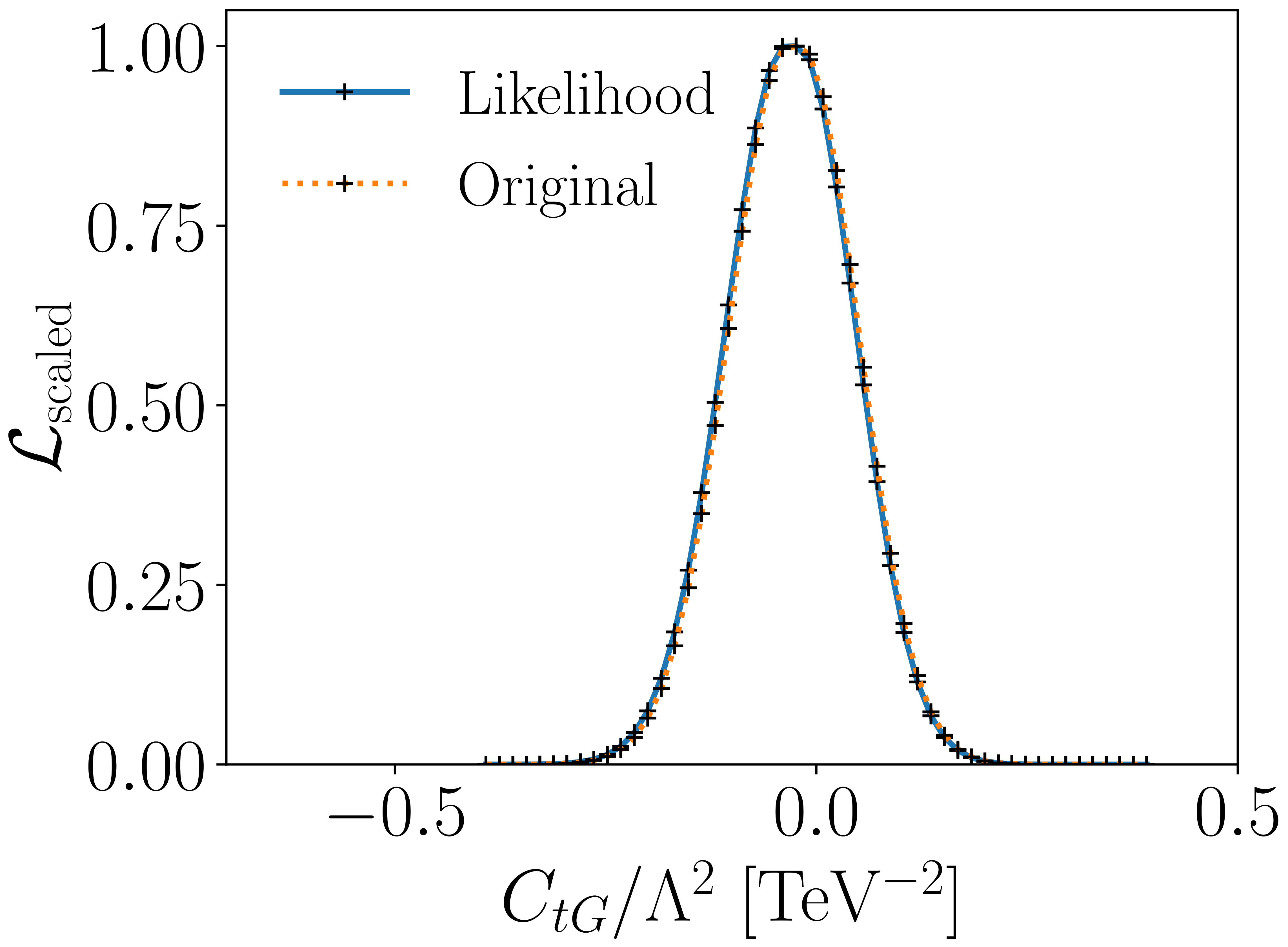
?

➤ **Now:** Simply separate the NPs in profile likelihood fit

Published Likelihoods

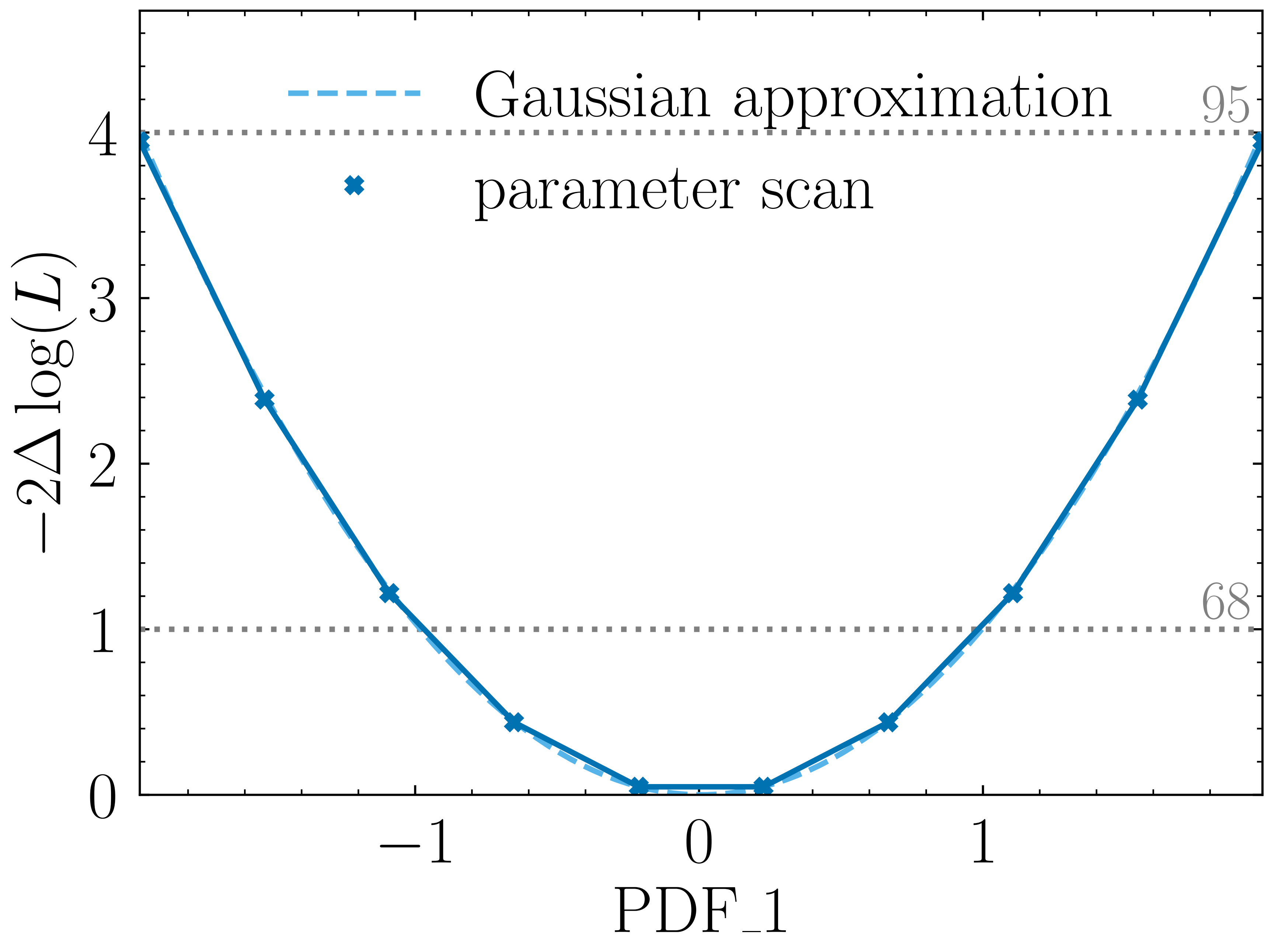
Implementation

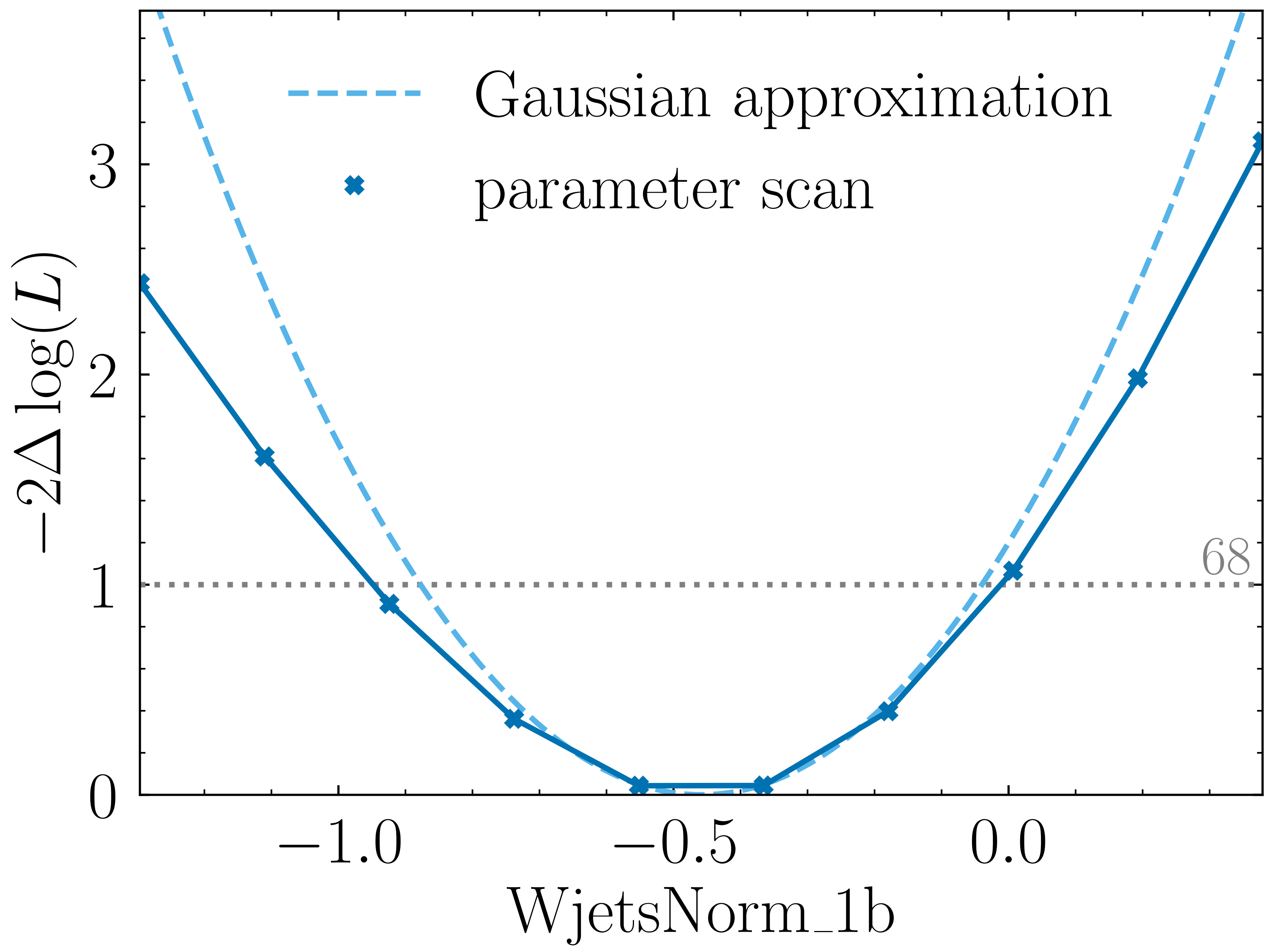
- Low dimensional fit to **only** C_{tG} and total cross section measurements
- Neglect theory uncertainties
- **Excellent agreement** between both methods of implementation



Published Likelihoods

Parameter scans with cabinetry

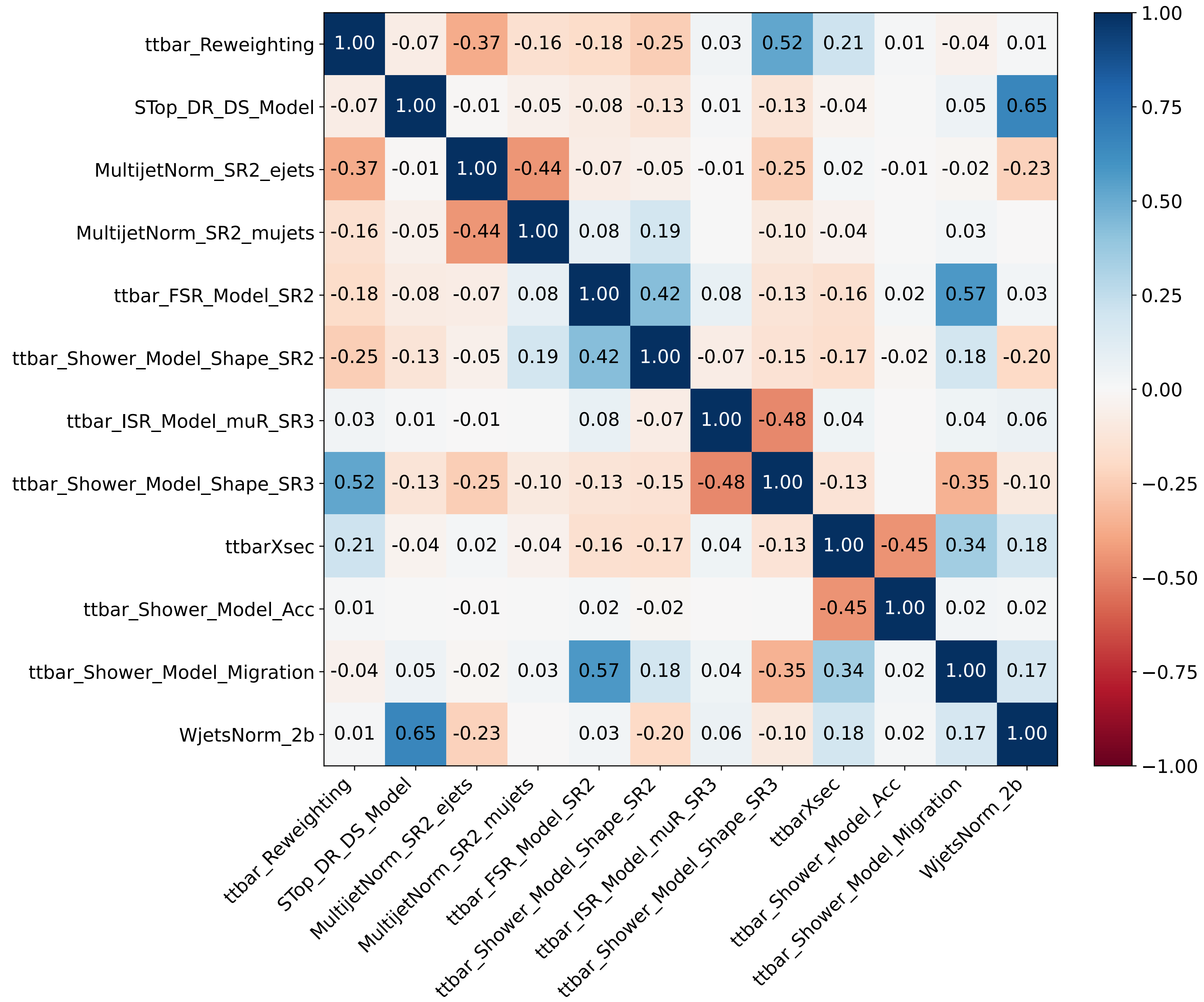




- NPs are all very Gaussian, only small number of exceptions
  - Validates **Gaussian** constraint term $\mathcal{C}(\theta_i, \sigma_i)$ for systematics

Published Likelihoods

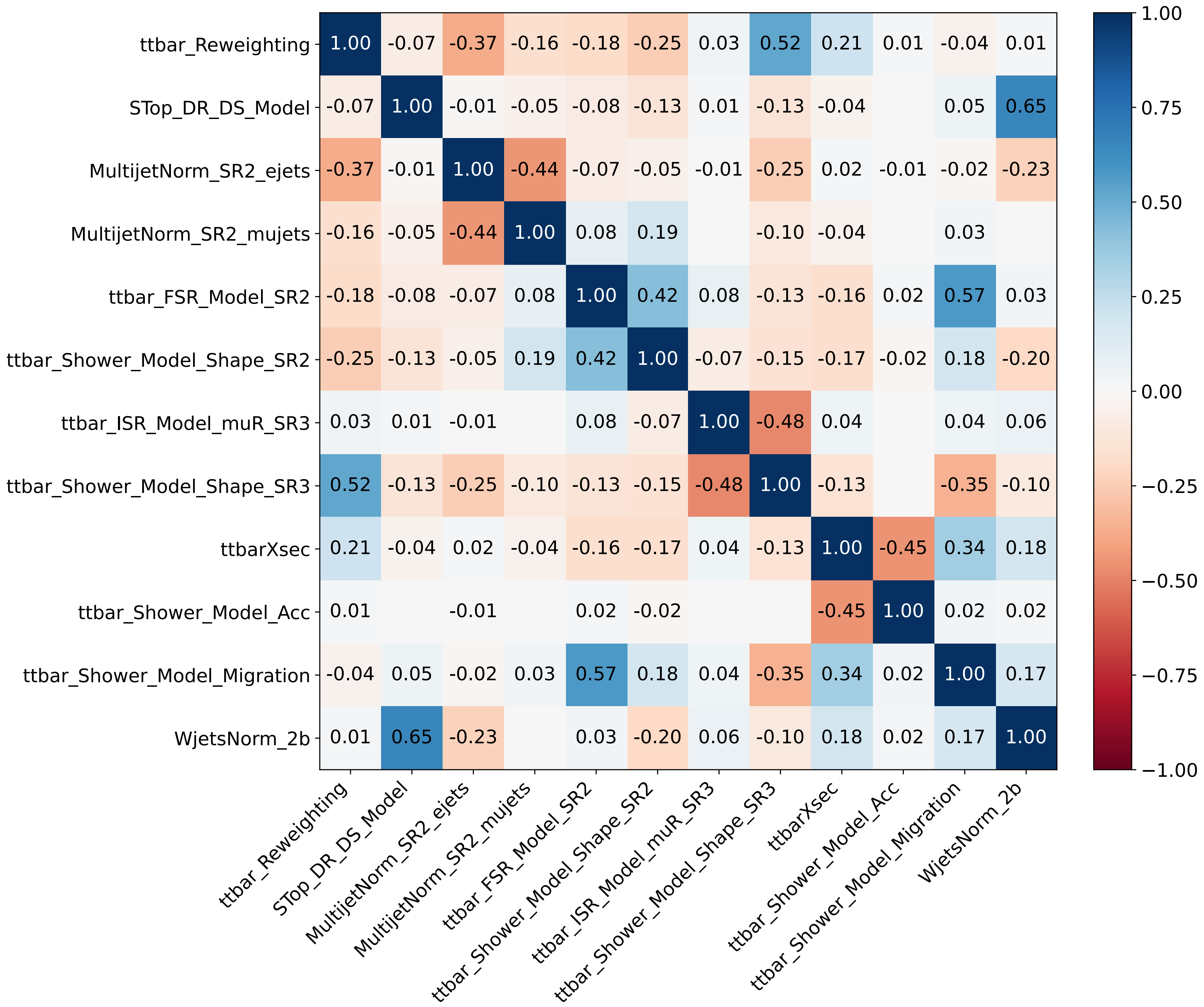
Concerning Correlations

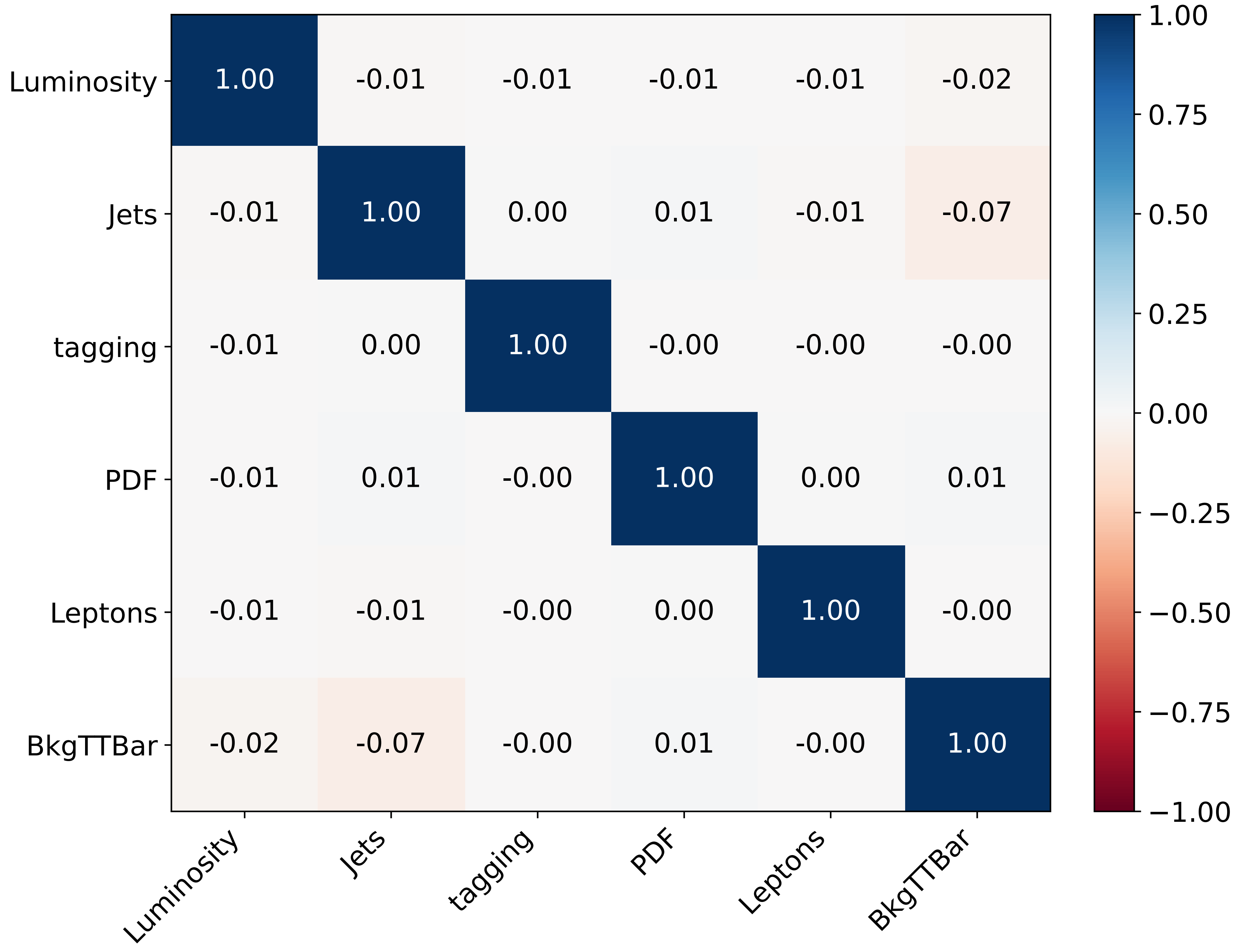


➤ **Currently:** No correlations between uncertainties in SFitter

Published Likelihoods

Concerning Correlations





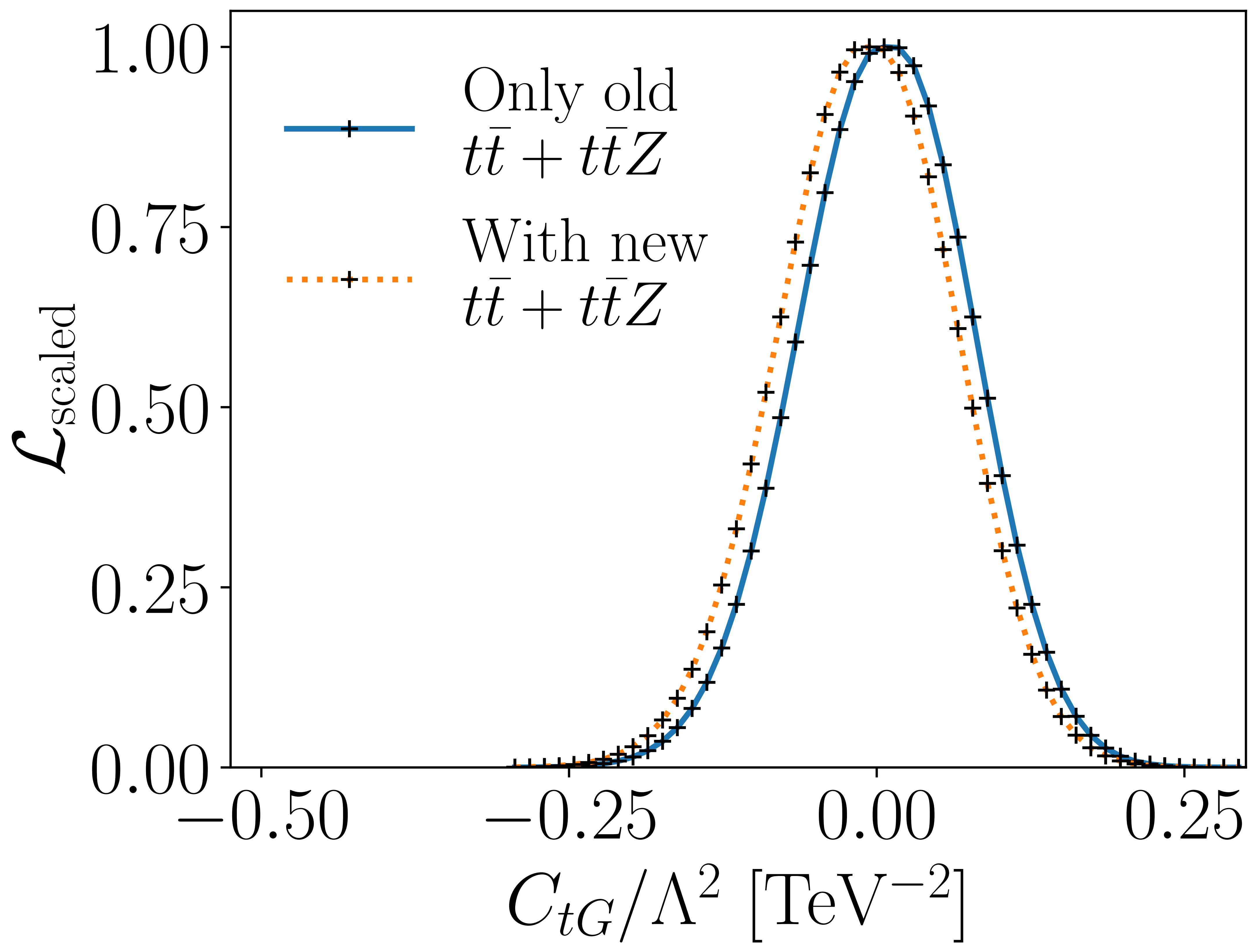
➤ **Currently:** No correlations between uncertainties in SFitter

  ➤ 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



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