technische universität dortmund

Fakultät Physik

From Top to Bottom

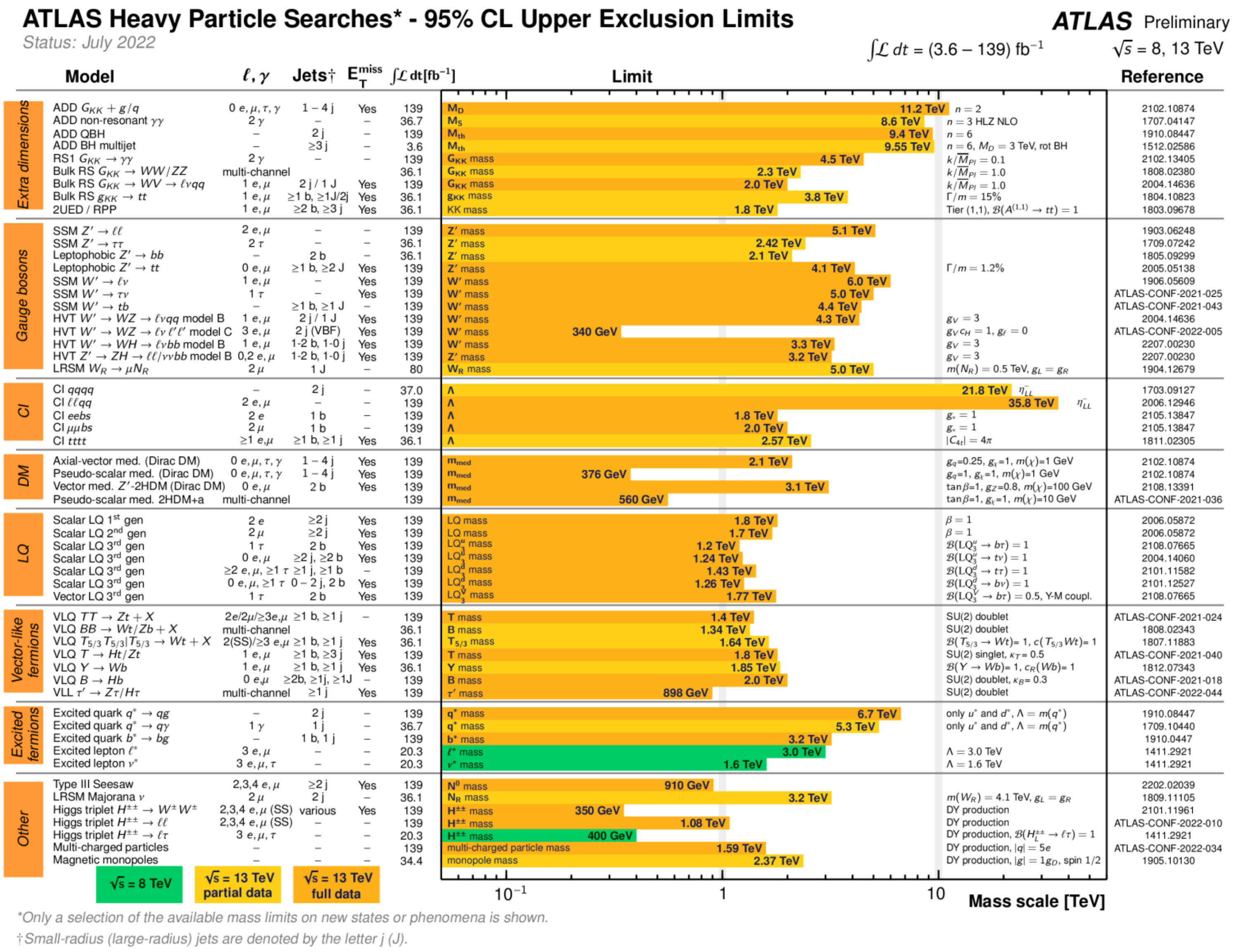
An effective approach to connecting the members of the third family

(from an experimentalists point of view)

Kevin Kröninger – TU Dortmund
(in collaboration with Gudrun Hiller's group)

EFT Mini-Workshop, Bologna, July 5th 2023

Motivation



So what now?

→ Indirect searches in different sectors

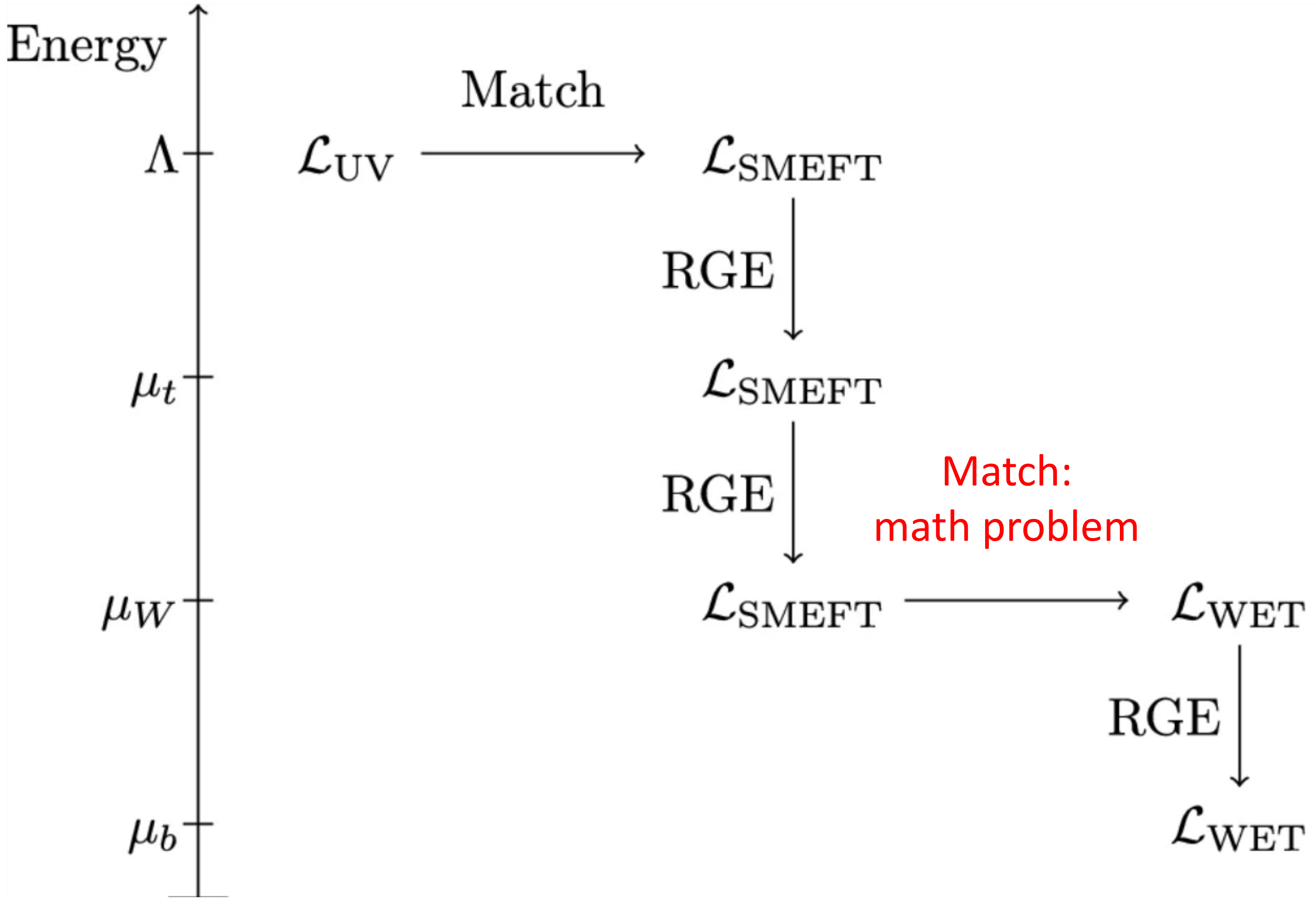
Concrete aims

- Interpret data in terms of effective field theory

  - Which data? — Measurements from the realms of top-quark and bottom-quark physics
  - What for? — Constrain values of the Wilson coefficents
  - How? — Formulate a proper statistical problem (Bayesian interpretation)
  - Why? — See if there is a synergy effect

Formulation of the problem

Running couplings



$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{C_i^{(6)}}{\Lambda^2} O_i^{(6)} + \mathcal{O}\left(\Lambda^{-4}\right)$$

Match:
experimental problem

$$\mathcal{L}_{\text{WET}} = \frac{4G_F}{\sqrt{2}} V_{ts}^* V_{tb} \sum_{i=1}^{8} \bar{C}_i Q_i$$

The inference process

Expression	Meaning
Parameters	Here: the scaled Wilson coefficients $\tilde{C}_i = C_i \frac{v^2}{\Lambda^2}$
Observables	Things one can measure, e.g. σ_{meas}, and for which there is a prediction as a function of the parameters, e.g. $\sigma_{\text{pred}} = \sigma(\tilde{C}_1, \tilde{C}_2)$
Likelihood	The statistical model, i.e. the probability for obtaining a certain measurement given a specific set of parameters, e.g. $p(\sigma_{\text{meas}} \mid \sigma_{\text{pred}}, \tilde{C}_1, \tilde{C}_2)$
Prior probability	Knowledge available about the parameters before the inference, e.g. $p(\tilde{C}_1, \tilde{C}_2)$
Posterior probability	The probability of the parameter values given a specific measurement, e.g. $p(\tilde{C}_1, \tilde{C}_2 \mid \sigma_{\text{meas}})$
Bayes' Theorem	Connects likelihood, prior probability and posterior probability: $$p(\tilde{C}_1, \tilde{C}_2 \mid \sigma_{\text{meas}}) = \frac{p(\sigma_{\text{meas}} \mid \sigma_{\text{pred}}, \tilde{C}_1, \tilde{C}_2) \cdot p(\tilde{C}_1, \tilde{C}_2)}{\text{Normalization}}$$

The inference process

BAT.jl

- Julia-based tool for evaluating posterior probabilities
- Strong in sampling high-dimensional and multi-model spaces
- Available on github: https://github.com/bat/BAT.jl

[O. Schulz, ..., KK *et al.*, SN Comput. Sci. **2** (2021) 210]

EFTfitter.jl

- BAT.jl-based tool
- Combination and interpretation of several measurements
- Multivariate statistical model

$$-2\ln p(\mathbf{x}|\mathbf{y}) = \sum_{i=1}^{n}\sum_{j=1}^{n}[\mathbf{x}-U\mathbf{y}]_i\,\mathcal{M}^{-1}_{ij}\,[\mathbf{x}-U\mathbf{y}]_j$$

$$\mathcal{M}_{ij} = \mathrm{cov}[x_i, x_j]$$

$$\mathrm{cov}[x_i, x_j] = \sum_{k=1}^{M}\mathrm{cov}^{(k)}[x_i, x_j]$$

[N. Castro, ..., KK *et al.*, Eur. Phys. J. C **76** (2016) 432]

Example 1: Top-Photon-Coupling

Eur. Phys. J. C (2020) 80:136
https://doi.org/10.1140/epjc/s10052-020-7680-9

THE EUROPEAN PHYSICAL JOURNAL C

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Regular Article - Theoretical Physics

Constraining top-quark couplings combining top-quark and *B* decay observables

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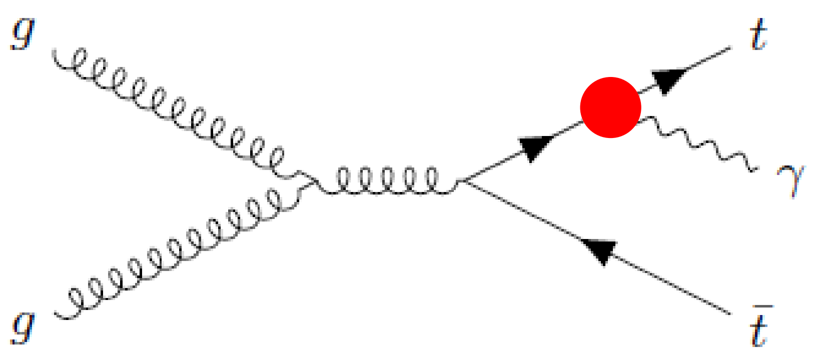
Aims:

- Set up the machinery
- Check for benefits

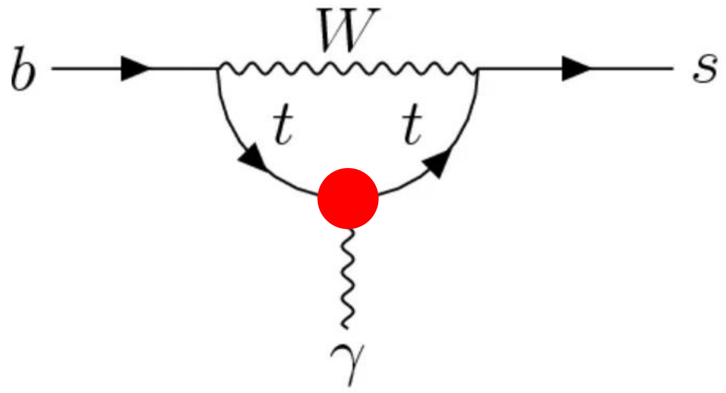
Example 1: Top-Photon-Coupling

- Consider two processes which probe the top-quark coupling to photons

Production of a top-quark pair plus a photon (tt+gamma)



Bottom-to-Strange plus photon decays



Example 1: Top-Photon-Coupling

- Consider three relevant Wilson coefficents

SMEFT operators

$$O_{uB} = (\bar{q}_L \sigma^{\mu\nu} u_R)\, \tilde{\varphi} B_{\mu\nu}\,,$$
$$O_{uG} = (\bar{q}_L \sigma^{\mu\nu} T^A u_R)\, \tilde{\varphi} G^A_{\mu\nu}\,,$$
$$O_{uW} = (\bar{q}_L \sigma^{\mu\nu} \tau^I u_R)\, \tilde{\varphi} W^I_{\mu\nu}\,,$$

Matched WET operators

$$\Delta \bar{C}_7^{(0)} = \frac{\sqrt{2} m_t}{m_W} \left[\tilde{C}_{uW} E_7^{uW}(x_t) + \tilde{C}^*_{uW} F_7^{uW}(x_t) + \frac{\cos\theta_w}{\sin\theta_w} \left(\tilde{C}_{uB} E_7^{uB}(x_t) + \tilde{C}^*_{uB} F_7^{uB}(x_t) \right) \right],$$

$$\Delta \bar{C}_8^{(0)} = \frac{\sqrt{2} m_t}{m_W} \left[\tilde{C}_{uW} E_8^{uW}(x_t) + \tilde{C}^*_{uW} F_8^{uW}(x_t) - \frac{g}{g_s} \left(\tilde{C}_{uG} E_8^{uG}(x_t) + \tilde{C}^*_{uG} F_8^{uG}(x_t) \right) \right],$$

Example 1: Top-Photon-Coupling

- Consider two observables

Measurements

$$\sigma^{\text{fid}}_{\text{ATLAS}}(t\bar{t}\gamma, 1\ell) = 521 \pm 9\,(\text{stat.}) \pm 41\,(\text{syst.})\,\text{fb}\,,$$
$$\sigma^{\text{fid}}_{\text{ATLAS}}(t\bar{t}\gamma, 2\ell) = 69 \pm 3\,(\text{stat.}) \pm 4\,(\text{syst.})\,\text{fb}\,.$$

Measurement from EPJC **79** (2019) 382

$$\text{BR}(\bar{B} \to X_s\gamma) = (332 \pm 15) \times 10^{-6}$$

Combination from HFLAV Collaboration

Predictions

$$\sigma^{\text{fid}}_{\text{SM,NLO}}(t\bar{t}\gamma, 1\ell) = 495 \pm 99\,\text{fb}\,,$$
$$\sigma^{\text{fid}}_{\text{SM,NLO}}(t\bar{t}\gamma, 2\ell) = 63 \pm 9\,\text{fb}\,.$$

NLO QCD calculation from PRD **83** (2011) 074013

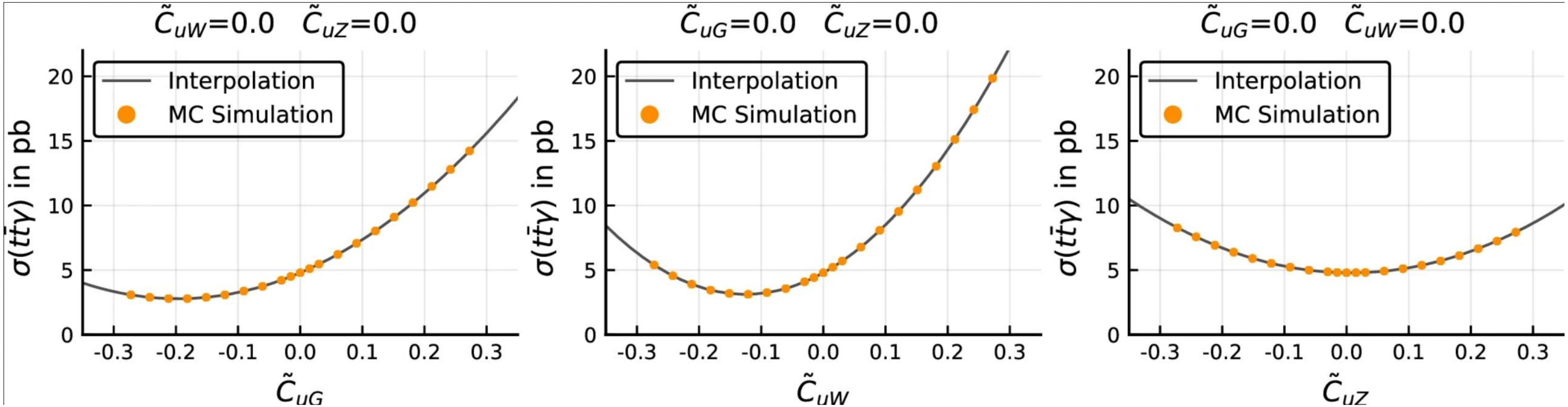
$$\text{BR}_{\text{SM}}(\bar{B} \to X_s\gamma) = (336 \pm 23) \times 10^{-6}$$

NNLO calculation from PRL **114** (2015) 221801

Example 1: Top-Photon-Coupling

Top-quark pair + photon production as a function of the parameters

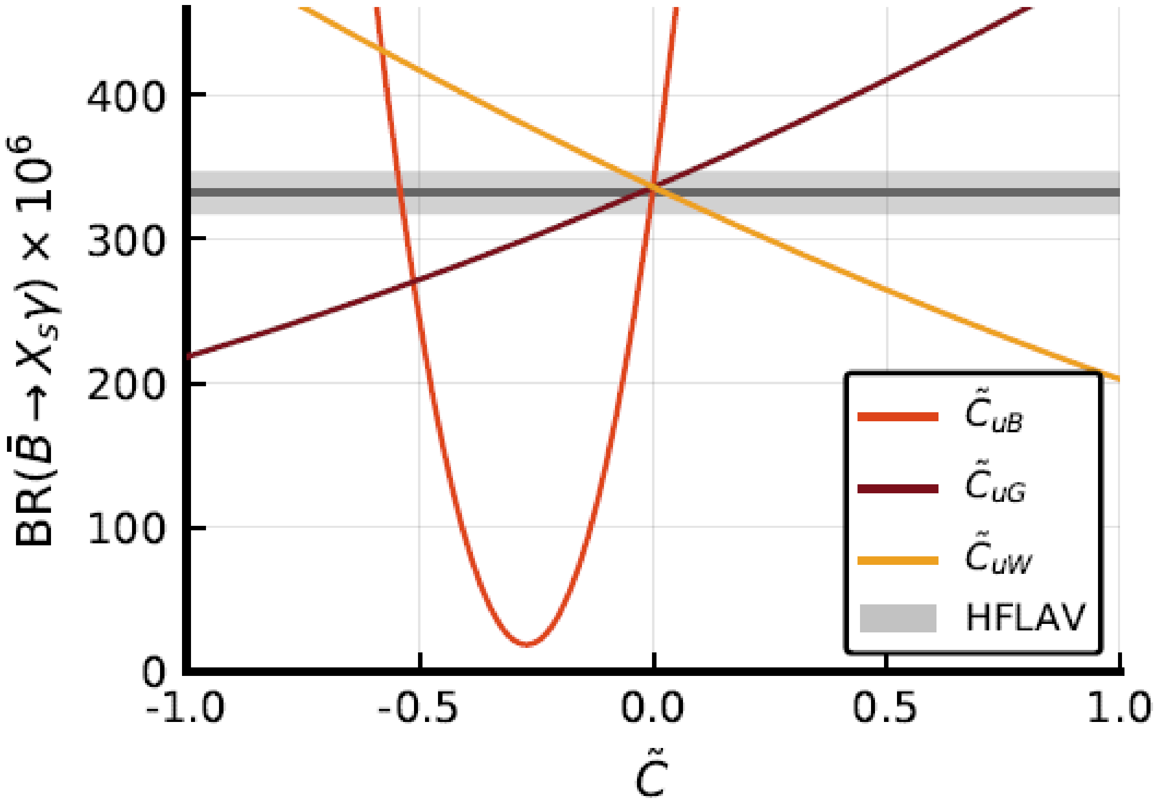
- Generation of MC using MadGraph5_aMC@NLO with the dim6top_LO UFO model
- Scale SM prediction to NLO QCD prediction
- Interpolate between sampling points
- Calculate fiducial acceptances by adding parton showering and particle-level analysis with MadAnalysis



Example 1: Top-Photon-Coupling

Branching ratio as a function of the parameters

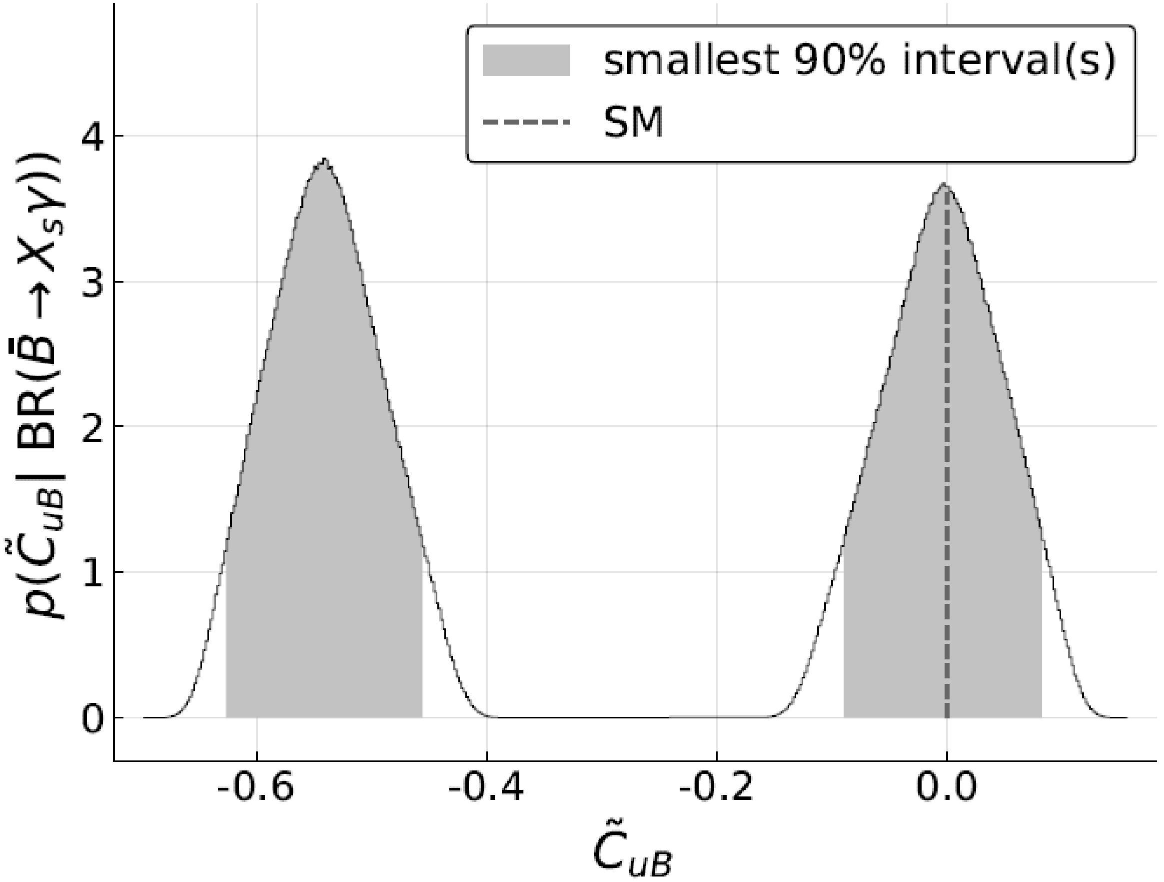
- Calculate „by hand“
- Use „flavio“ for flavor phenomenology and „wilson“ for the running and matching



Example 1: Top-Photon-Coupling

Constraining parameters (b-physics only)

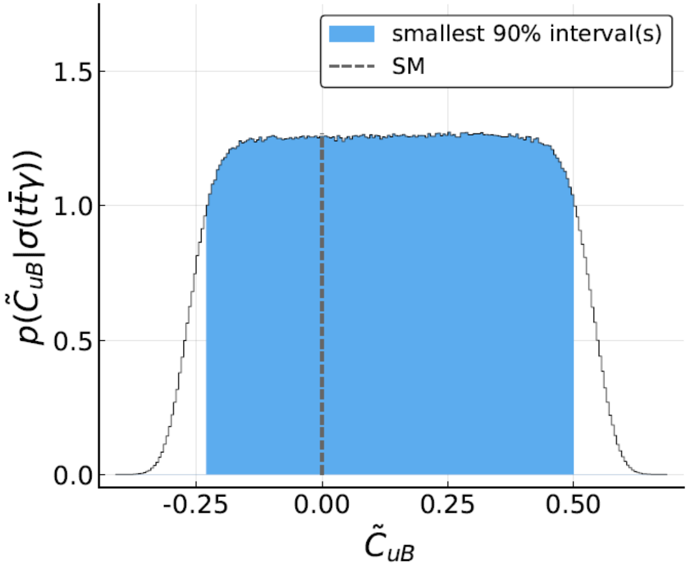
- Fit includes only branching ratio
- Uniform prior for all three parameters in the region [-1, 1]
- Almost not sensitivity to $\tilde{C}_{uW}$ and $\tilde{C}_{uG}$
- Marginalized posterior for $\tilde{C}_{uB}$ shows two regions with high probability

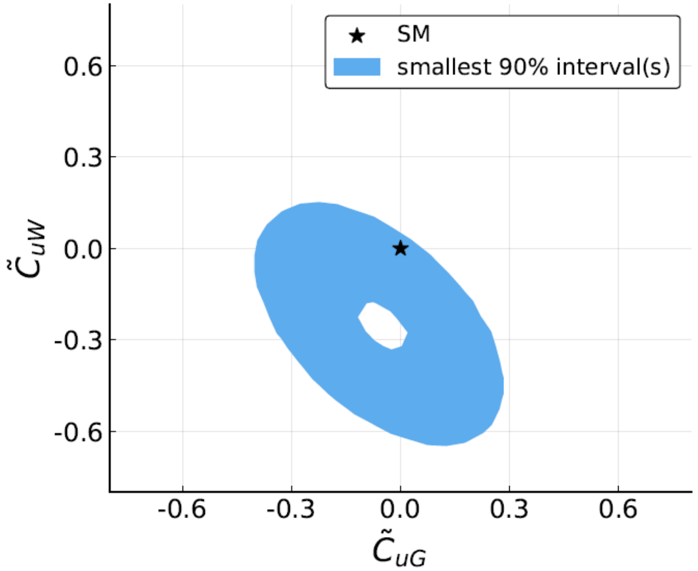


Example 1: Top-Photon-Coupling

Constraining parameters (top-quark-physics only)

- Fit includes only cross-section
- Uniform prior for all three parameters in the region [-1, 1]
- Similar sensitivities to all three parameters





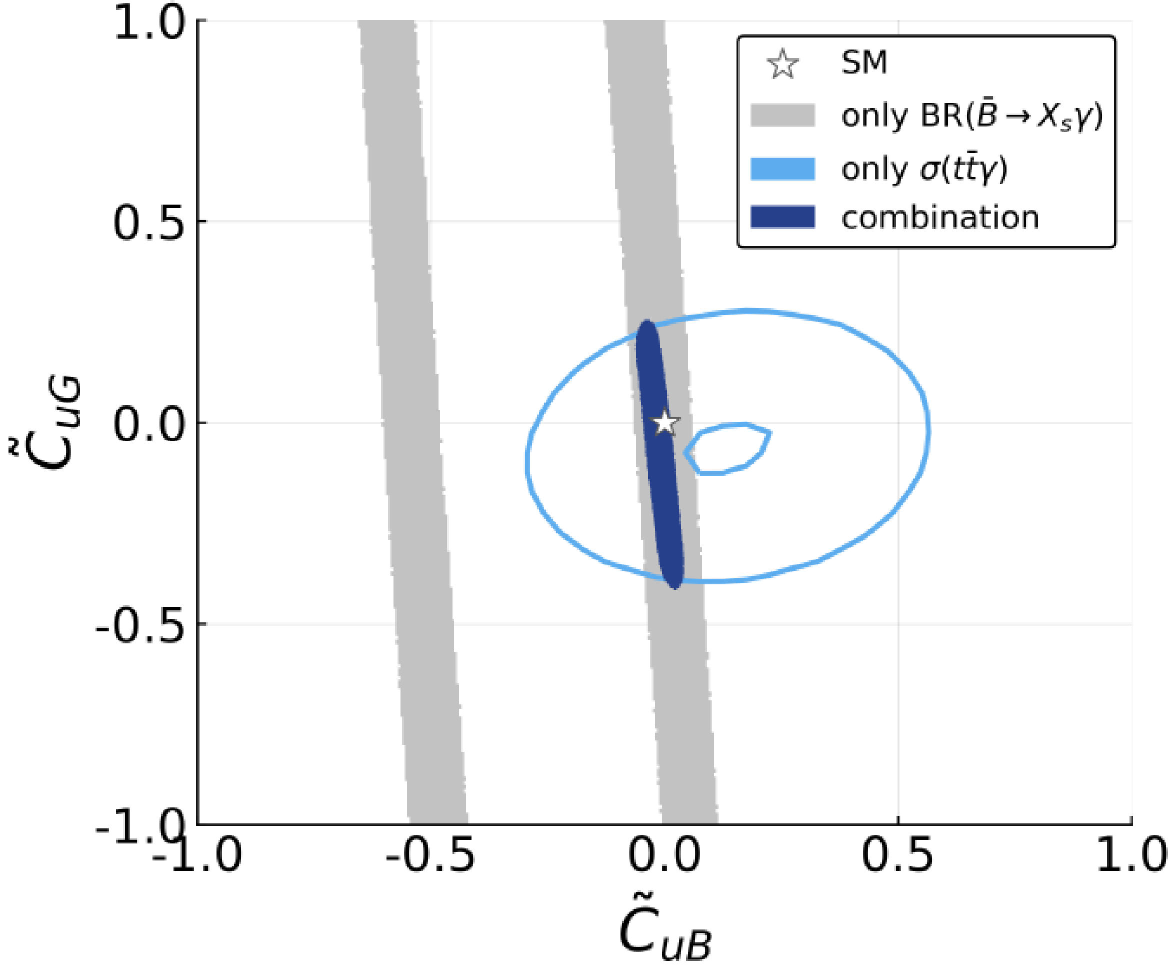
Example 1: Top-Photon-Coupling

Constraining parameters (combined analysis)

- Fit includes all measurements
- Uniform prior for all three parameters in the region [-1, 1]

→ Resolves ambiguity in $\tilde{C}_{uB}$

→ Orthorgonality of observables leads to significantly reduced allowed phase space



Example 2: Systematic studies

PHYSICAL REVIEW D **102,** 115019 (2020)

Correlating uncertainties in global analyses within standard model EFT matters

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(Received 19 December 2019; accepted 18 November 2020; published 16 December 2020)

We investigate the impact of correlations between (theoretical and experimental) uncertainties on multi-experiment, multi-observable analyses within the standard model effective field theory (SMEFT). To do so, we perform a model-independent analysis of t-channel single top-quark production and top-quark decay data from ATLAS, CMS, CDF, and D0. We show quantitatively how the fit changes when different experimental or theoretical correlations are assumed. Scaling down statistical uncertainties according to the luminosities of future colliders with 300 fb^{-1} and higher, we find that this effect becomes a matter of life and death: assuming no correlations returns a fit in agreement with the standard model while a "best guess"-ansatz taking into account correlations would observe new physics. At the same time, modeling the impact of higher order SMEFT-corrections the latter turn out to be a subleading source of uncertainty only.

DOI: 10.1103/PhysRevD.102.115019

Aim:

- Test the impact of correlations among measurements

Observables

Process	$\sqrt{s}$	Luminosity	Experiment	Observable	Reference
Single top	7 TeV	4.59 fb^{-1}	ATLAS	$\sigma(tq)$, $\sigma(\bar{t}q)$, $d\sigma(tq)/dp_T$, $d\sigma(\bar{t}q)/dp_T$	[26]
		1.17 fb^{-1} (μ)	CMS	$\sigma(tq+\bar{t}q)$	[41]
		1.56 fb^{-1} (e)	CMS	$\sigma(tq+\bar{t}q)$	[41]
Single top	8 TeV	20.2 fb^{-1}	ATLAS	$\sigma(tq)$, $\sigma(\bar{t}q)$, $d\sigma(tq)/dp_T$, $d\sigma(\bar{t}q)/dp_T$	[27]
		19.7 fb^{-1}	CMS	$\sigma(tq)$, $\sigma(\bar{t}q)$, $\sigma(tq+\bar{t}q)$, $d\sigma/d\|y(t/\bar{t})\|$	[28,42]
Single top	13 TeV	3.2 fb^{-1}	ATLAS	$\sigma(tq)$, $\sigma(\bar{t}q)$	[37]
		2.2 fb^{-1}	CMS	$\sigma(tq)$, $\sigma(\bar{t}q)$, $\sigma(tq+\bar{t}q)$	[43]
		2.3 fb^{-1}	CMS	$d\sigma/d\|y(t/\bar{t})\|$	[29]
Top decay	1.96 TeV	2.7 fb^{-1}	CDF	F_0	[47]
		8.7 fb^{-1}	CDF	F_0	[48]
		5.4 fb^{-1}	D0	F_0	[49]
Top decay	7 TeV	1.04 fb^{-1}	ATLAS	F_0, F_L	[39]
		5.0 fb^{-1}	CMS	F_0, F_L	[44]
Top decay	8 TeV	20.2 fb^{-1}	ATLAS	Γ_t	[38]
		20.2 fb^{-1}	ATLAS	F_0, F_L	[40]
		19.7 fb^{-1}	CMS	F_0, F_L	[45]
Top decay	13 TeV	19.8 fb^{-1}	CMS	F_0, F_L	[46]

Example 2: Systematic studies

4 Operators

$$O_{\phi q}^{(3)} = i(\phi^\dagger \overset{\leftrightarrow}{D}{}^I_\mu \phi)(\bar{q}_L \gamma^\mu \tau^I q_L),$$

$$O_{tW} = (\bar{q}_L \sigma^{\mu\nu} \tau^I t_R)\tilde{\phi} W^I_{\mu\nu},$$

$$O_{qq}^{(1)} = (\bar{q}_L \gamma_\mu q_L)(\bar{q}_L \gamma^\mu q_L),$$

$$O_{qq}^{(3)} = (\bar{q}_L \gamma_\mu \tau^I q_L)(\bar{q}_L \gamma^\mu \tau^I q_L)$$

3 Parameters

$$\tilde{C}_{\phi q}^{(3)}, \quad \tilde{C}_{tW}, \quad \tilde{C}_{qq} = \tilde{C}_{qq}^{(3)1133} + \frac{1}{6}(\tilde{C}_{qq}^{(1)1331} - \tilde{C}_{qq}^{(3)1331})$$

(neglecting other linear combinations with smaller mass terms)

Correlations

- Calculating a global covariance matrix

$$\mathcal{M}_{ij} = \mathrm{cov}[x_i, x_j] = \sum_k \mathrm{cov}^{(k)}[x_i, x_j] = \sum_k \rho_{ij}^{(k)} \sigma_i^{(k)} \sigma_j^{(k)}$$

- Covariance matrix has dimension 55x55
- Use statistical correlation if published
- Parameterize (experimental) systematic and theory uncertainties with a single parameter each, ρ_{sys} and ρ_{th}

Correlations

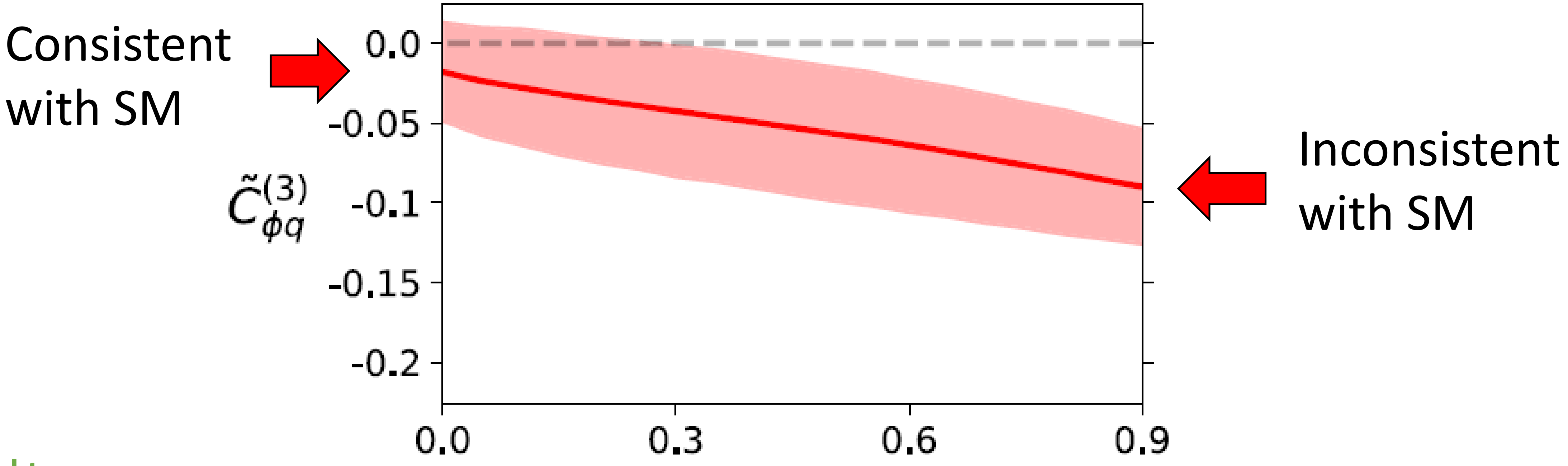
- Illustration:

$$
\begin{array}{c} \\ \sigma(tq)_7^A \\ \sigma(\bar{t}q)_7^A \\ \sigma(tq)_8^A \\ \sigma(tq)_8^C \\ \Gamma_t \end{array}
\begin{array}{c} \sigma(tq)_7^A \quad \sigma(\bar{t}q)_7^A \quad \sigma(tq)_8^A \quad \sigma(tq)_8^C \quad \Gamma_t \\
\begin{pmatrix} 1 & \rho_{\mathrm{sys}} & \frac{\rho_{\mathrm{sys}}}{2} & 0 & 0 \\ \rho_{\mathrm{sys}} & 1 & \frac{\rho_{\mathrm{sys}}}{2} & 0 & 0 \\ \frac{\rho_{\mathrm{sys}}}{2} & \frac{\rho_{\mathrm{sys}}}{2} & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{pmatrix} \end{array}
$$

$$
\begin{array}{c} \\ \sigma(tq)_7^A \\ \sigma(\bar{t}q)_7^A \\ \sigma(tq)_8^A \\ \sigma(tq)_8^C \\ \Gamma_t \end{array}
\begin{array}{c} \sigma(tq)_7^A \quad \sigma(\bar{t}q)_7^A \quad \sigma(tq)_8^A \quad \sigma(tq)_8^C \quad \Gamma_t \\
\begin{pmatrix} 1 & \rho_{\mathrm{th}} & \frac{\rho_{\mathrm{th}}}{2} & \frac{\rho_{\mathrm{th}}}{2} & 0 \\ \rho_{\mathrm{th}} & 1 & \frac{\rho_{\mathrm{th}}}{2} & \frac{\rho_{\mathrm{th}}}{2} & 0 \\ \frac{\rho_{\mathrm{th}}}{2} & \frac{\rho_{\mathrm{th}}}{2} & 1 & \rho_{\mathrm{th}} & 0 \\ \frac{\rho_{\mathrm{th}}}{2} & \frac{\rho_{\mathrm{th}}}{2} & \rho_{\mathrm{th}} & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{pmatrix} \end{array}
$$

- Define three scenarios:
  - No correlation: $\rho_{\mathrm{sys}} = \rho_{\mathrm{th}} = 0$
  - Best guess: $\rho_{\mathrm{sys}} = \rho_{\mathrm{th}} = 0.9$
  - Variation: $\rho_{\mathrm{sys}} = \rho_{\mathrm{th}} = 0.0 \ldots 0.9$

Example 2: Systematic studies



Results

→ Correlations can have a strong impact on the constraints

→ Even more important in future measurements (small statistical uncertainties)

Example 3: towards a global fit

Top and beauty synergies in SMEFT-fits at present and future colliders

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ABSTRACT: We perform global fits within Standard Model Effective Field Theory (SMEFT) combining top-quark pair production processes and decay with $b \to s$ flavor changing neutral current transitions and $Z \to b\bar{b}$ in three stages: using existing data from the LHC and B-factories, using projections for the HL-LHC and Belle II, and studying the additional new physics impact from a future lepton collider. The latter is ideally suited to directly probe $\ell^+\ell^- \to t\bar{t}$ transitions. We observe powerful synergies in combining both top and beauty observables as flat directions are removed and more operators can be probed. We find that a future lepton collider significantly enhances this interplay and qualitatively improves global SMEFT fits.

JHEP06(2021)010

Aims:

- Get the most out of current data
- Estimate the sensitivity of future experiments to global fits

Example 4: MFV

More Synergies from Beauty, Top, Z and Drell-Yan Measurements in SMEFT

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[2] *Department of Physics and Astronomy, University of Sussex, Brighton, BN1 9QH, U.K.*

We perform a global analysis of Beauty, Top, Z and Drell-Yan measurements in the framework of the Standard Model effective theory (SMEFT). We work within the minimal flavor violation (MFV) hypothesis, which relates different sectors and generations beyond the $SU(2)_L$-link between left-handed top and beauty quarks. We find that the constraints on the SMEFT Wilson coefficients from the combined analysis are stronger than the constraints from a fit to the individual sectors, highlighting synergies in the global approach.

[arXiv:2304.12837]

Aims:

- Study MFV scenario for stronger synergy effects
- Study impact of Drell-Yan data

Observables and parameters

- Consider 14 operators

$$O_{uG} = (\bar{q}_L \sigma^{\mu\nu} T^A u_R)\, \tilde{\varphi} G^A_{\mu\nu}\,, \qquad O_{uW} = (\bar{q}_L \sigma^{\mu\nu} u_R)\, \tau^I \tilde{\varphi} W^I_{\mu\nu}\,, \qquad O_{uB} = (\bar{q}_L \sigma^{\mu\nu} u_R)\, \tilde{\varphi} B_{\mu\nu}\,,$$

$$O_{qe} = (\bar{q}_L \gamma_\mu q_L)\,(\bar{e}_R \gamma^\mu e_R)\,, \qquad O^{(1)}_{lq} = (\bar{l}_L \gamma_\mu l_L)\,(\bar{q}_L \gamma^\mu q_L)\,, \qquad O^{(3)}_{lq} = (\bar{l}_L \gamma_\mu \tau^I l_L)\,(\bar{q}_L \gamma^\mu \tau^I q_L)$$

$$O_{eu} = (\bar{e}_R \gamma_\mu e_R)\,(\bar{u}_R \gamma^\mu u_R)\,, \qquad O_{ed} = (\bar{e}_R \gamma_\mu e_R)\,(\bar{d}_R \gamma^\mu d_R)\,, \qquad O_{lu} = (\bar{l}_L \gamma_\mu l_L)\,(\bar{u}_R \gamma^\mu u_R)\,,$$

$$O_{ld} = (\bar{l}_L \gamma_\mu l_L)\,(\bar{d}_R \gamma^\mu d_R)\,, \qquad O^{(1)}_{\varphi q} = \left(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi\right)(\bar{q}_L \gamma^\mu q_L)\,, \qquad O^{(3)}_{\varphi q} = \left(\varphi^\dagger i \overleftrightarrow{D}^I_\mu \varphi\right)(\bar{q}_L \tau^I \gamma^\mu q_L)$$

$$O_{\varphi u} = \left(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi\right)(\bar{u}_R \gamma^\mu u_R)\,, \qquad O_{\varphi d} = \left(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi\right)(\bar{d}_R \gamma^\mu d_R)\,.$$

- All Wilson coefficients are assumed to have real values
- RG-induced effects of additional operators neglected (percent level)

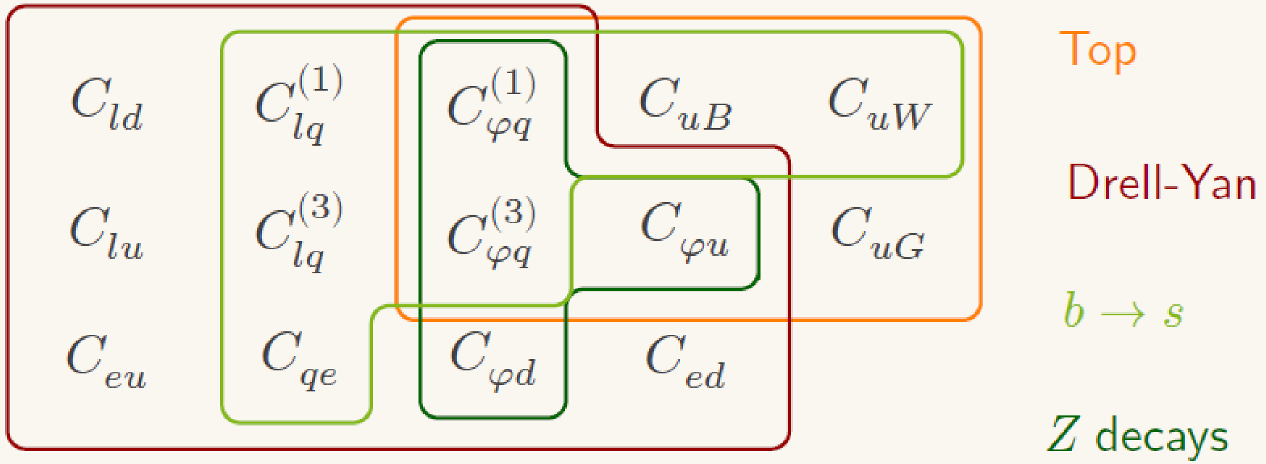
Minimal flavor violation

- Impose flavor structure of the SM onto new physics
- Formal approach: SMEFT Lagrangian obeys an $U(3)^5$ symmetry
- This implies constraints on the flavor structure of the Lagrangian
- Quark bilinears are expanded, e.g.

$$\bar{q}_L q_L : \quad C_{ij} = \left(a_1 1 + a_2 Y_u Y_u^\dagger + a_3 Y_d Y_d^\dagger + \ldots\right)_{ij}$$

- Rotate to mass basis and only consider top Yukawa
- Rescale Wilson coefficients, e.g.
  - LH up-type 1st and 2nd generation bilinears: $\tilde{C}_{q\bar{q}} = \frac{v^2}{\Lambda^2}\, a_1$
  - LH top quarks: $\tilde{C}_{q\bar{q}} \left(1 + \frac{a_2 y_t^2}{a_1} + \frac{a_4 y_t^4}{a_1} + \ldots\right) = \tilde{C}_{q\bar{q}}\,(1 + \gamma_a)$

Observables and parameters



14 Wilson coefficients and $\gamma_{a/b} \to$ 16 degrees of freedom

$\sigma_{t\bar{t}}$ $\sigma_{t\bar{t}Z}$ $\sigma_{t\bar{t}\gamma}$ $\sigma_{t\bar{t}W}$
$\sigma_{t\bar{t}H}$ Γ_t f_0 f_L

R_b A_{FB}^b R_c A_{FB}^c

e^+e^- $e\nu$
$\mu^+\mu^-$ $\mu\nu$
$\tau^+\tau^-$ $\tau\nu$

$\mathcal{B}_{\bar{B}\to X_s\gamma}$ $\mathcal{B}_{B^0\to K^*\gamma}$ $\mathcal{B}_{B^+\to K^{*+}\gamma}$ $\mathcal{B}_{\bar{B}\to X_s l^+ l^-}$ $\mathcal{B}_{\bar{B}\to X_s l^+ l^-}$
$\mathcal{B}_{B_s\to\mu^+\mu^-}$ $\mathrm{F}_{L\,B^0\to K^*\mu^+\mu^-}$ $\mathrm{P}^{(\prime)}_{i\,B^0\to K^*\mu^+\mu^-}$ $\mathcal{B}_{B^0\to K\mu^+\mu^-}$ $\mathcal{B}_{B^+\to K^+\mu^+\mu^-}$
$\mathcal{B}_{B^+\to K^{+*}\mu^+\mu^-}$ $\mathrm{F}_{L\,B_s\to\phi\mu^+\mu^-}$ $\mathrm{S}_{i\,B_s\to\phi\mu^+\mu^-}$ $\mathcal{B}_{\Lambda_b\to\Lambda\mu^+\mu^-}$ $\Delta M_{s\,B_s/\bar{B}_s}$

L. Nollen

Example 3: towards a global fit

Global fit

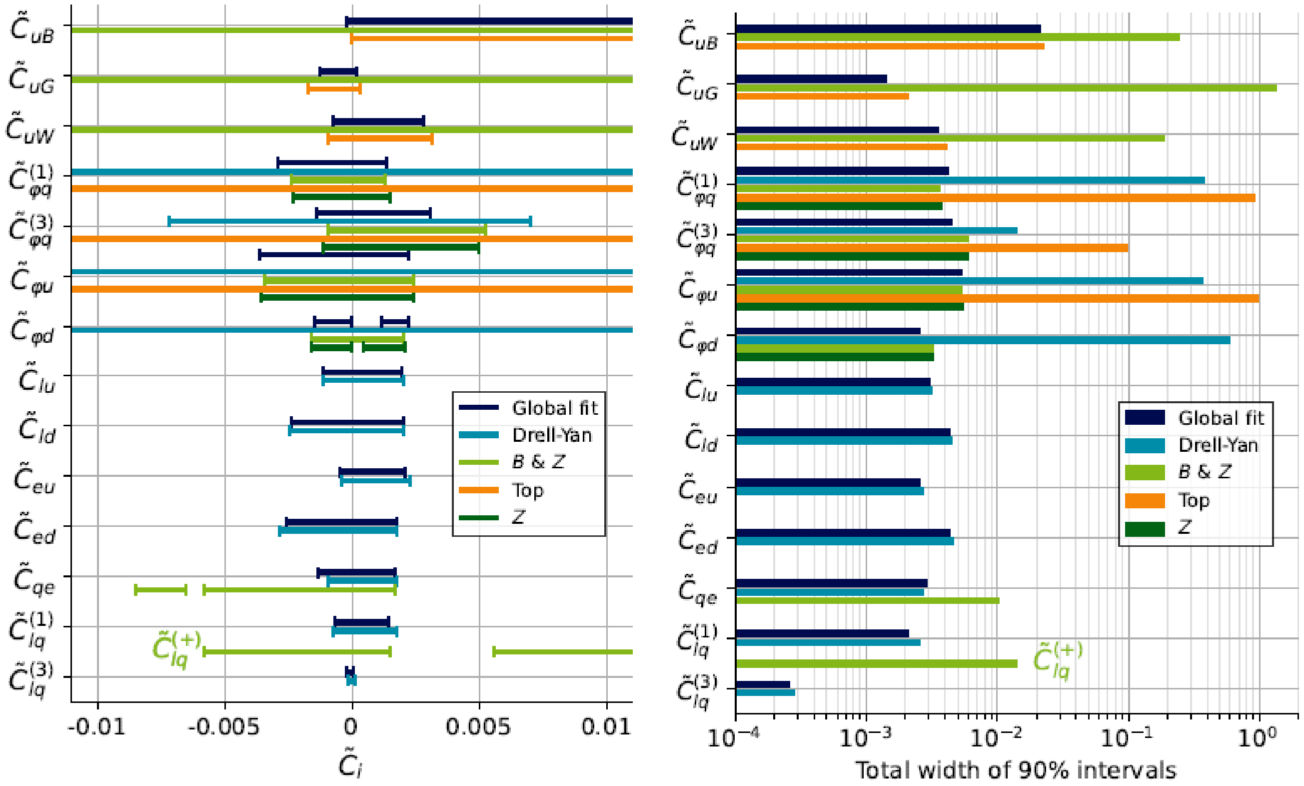
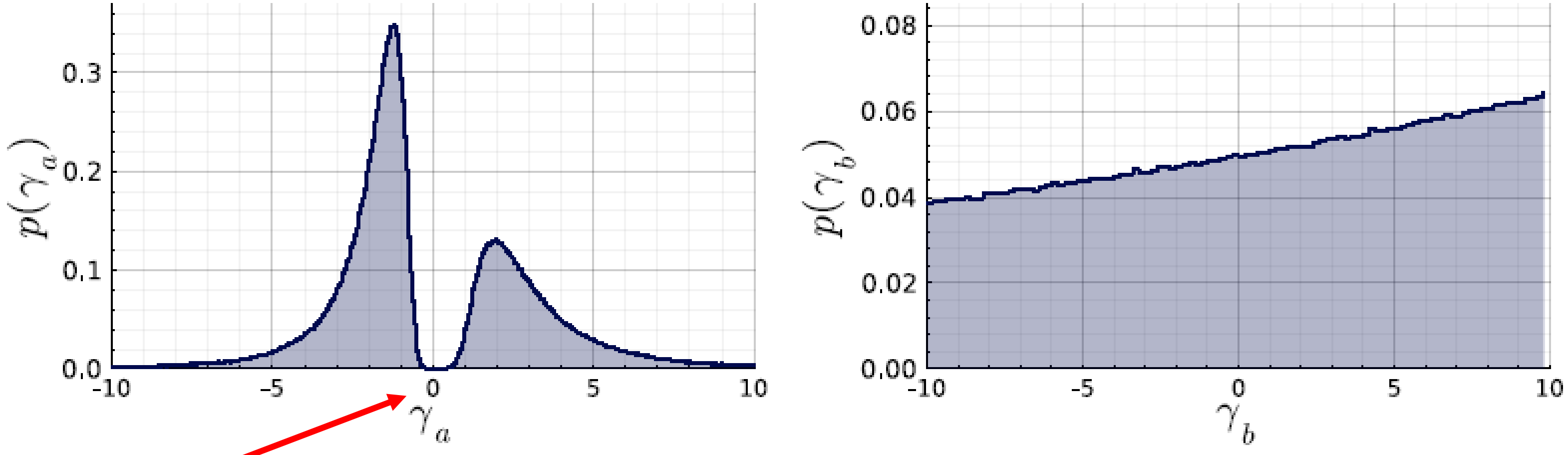


FIG. 7: Constraints on the SMEFT Wilson coefficients $\tilde{C}_i$ assuming Λ =10 TeV and a flat prior in the range [-1, 1] for $\tilde{C}_i$. Shown are the 90% credible intervals (left) and the total width of these intervals (right). We compare the result of the global fit including top, B-physics, Z-decay and Drell-Yan measurements to the fit results of the individual sectors. For the global fit, we simultaneously fit $\gamma_{a,b}$ with a flat prior in the range $-10 \leq \gamma_{a,b} \leq 10$, whereas this parameter is set to $\gamma_{a,b}$=1 for the individual fits. In the $B + Z$ fit, we can only constrain C^{+}_{lq}. See text for details.

Example 3: towards a global fit

Global fit



Minimum at 0 due to b→sμμ observables

FIG. 8: Marginalized posterior probability distributions of the MFV parameters γ_a and γ_b defined in Eqs. (29), (31) for $\Lambda = 10$ TeV obtained from the global fit including top, B-physics, Z-decay and Drell-Yan measurements. We choose a uniform distribution in the interval $-10 \leq \gamma_{a,b} \leq 10$ as the prior probability distribution.

What have we learned?

- Combining top-quark and bottom-quark measurements in a global fit significantly tightens the constraints on Wilson coefficients
- Important aspects
  - Running of couplings and matching
  - Correlations among measurements
  - Statistical interpretation (bi-modal and funny-shaped distributions)
  - Sampling the high-dimensional parameter spaces is not trivial

What will we do next?

- Estimation of the impact of FCC-ee measurements on a global fit
- Extend the fit by charm measurements

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