

New Results from TopFitter

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What is TopFitter?

- ▶ global fits of Wilson coefficients in the top quark sector of the standard model effective field theory (SMEFT) to experimental data
- ▶ earlier publications: [1506.08845, 1512.03360]
 - ▶ $t\bar{t}$ production and single-top data fitted separately
 - ▶ 12 operators were fitted (up to 6 simultaneously)
 - ▶ used up to 226 degrees of freedom (observables and bins) for the fit (datasets from Tevatron and LHC mostly Run I)
- ▶ work on improved version of TopFitter
 - ▶ first application: *Electroweak Top Couplings, Partial Compositeness and Top Partner Searches* [2006.09112, Brown, Englert, PG, Stylianou]
- ▶ other groups performing global top fits, for example:
SMEFiT[1901.05965], Durieux et al.[1907.10619], SFitter[1910.03606]
- ▶ goals for an updated global fit:
 - ▶ including a comprehensive data set from Tevatron and LHC Run I+II
 - ▶ extending the set of included top quark operators
 - ▶ study the impact of double operator insertions on the fit
 - ▶ including observables at the level of decayed top quarks
 - ▶ including fiducial measurements

Standard Model Effective Field Theory (SMEFT)

- ▶ nature of BSM physics unknown → use EFT in a bottom-up approach
- ▶ write down all possible operators satisfying Lorentz and Gauge invariance

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$$\begin{aligned}\mathcal{L}_{\text{SMEFT}} &= \mathcal{L}_{\text{SM}} + \sum_{n=5}^{\infty} \frac{1}{\Lambda^{4-n}} \sum_i C_i^{(n)} O_i^{(n)} \\ &= \mathcal{L}_{\text{SM}} + \frac{1}{\Lambda} \sum_i C_i^{(5)} O_i^{(5)} + \frac{1}{\Lambda^2} \sum_i C_i^{(6)} O_i^{(6)} + \dots\end{aligned}$$

Λ : scale of New Physics, $C_i^{(n)}$: Wilson coefficients, $O_i^{(n)}$: dim.- n operators

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SMEFT: parametrize high-scale New Physics in terms of Wilson coefficients.

This is a **very general approach** to New Physics and allows to constrain a large class of high-scale BSM models.

SMEFT

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \frac{1}{\Lambda} \sum_i C_i^{(5)} O_i^{(5)} + \frac{1}{\Lambda^2} \sum_i C_i^{(6)} O_i^{(6)} + \dots$$

dim 5 operators are
lepton number (LN) violating
⇒ not considered if
LN conservation is assumed

dim-6 operators
usually considered the first
term in the EFT expansion

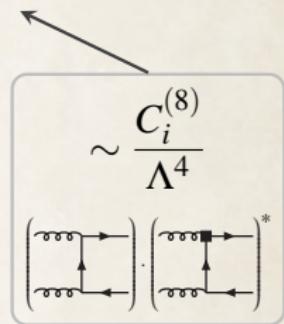
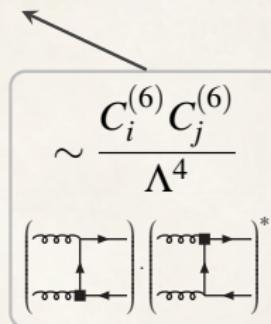
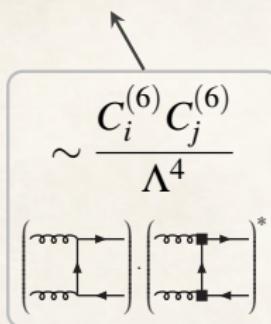
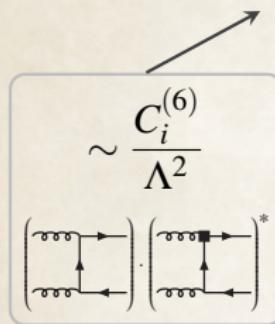
- ▶ There are **59 independent (B and L conserving) dim-6 operators** in the SMEFT
- ▶ counting all possible flavour configurations using 3 fermion generations: 2499
- ▶ additional 4 \cancel{B} operators possible (flavour not counted)
- ▶ alternative counting counts CPC and CPV operators separately: $76 + 8 (\cancel{B})$
- ▶ different operator bases are used in the literature,
e.g. **Warsaw basis** [Grzadkowski et al. 2010], **HISZ basis** [Hagiwara et al. 1993]
- ▶ operators of odd mass dimension violate B and/or L [Kobach 2016]
- ▶ next-to-leading EFT order of L-conserving operators is dim 8
- ▶ dim 8 operators often neglected due to large number ($895 + 98 (\cancel{B})$) [Henning et al. 2015];
exceptions exist, e.g. [1308.6323, 1603.03064, 1804.08688, 1808.00442, 1808.00010]

SMEFT at the Matrix Element Level

$$|\mathcal{M}_{\text{SM}} + \mathcal{M}_{\text{dim6}} + \mathcal{M}_{\text{dim8}}|^2$$

consider terms up to $\mathcal{O}(1/\Lambda^4)$

$$= |\mathcal{M}_{\text{SM}}|^2 + 2\text{Re} [\mathcal{M}_{\text{SM}} \mathcal{M}_{\text{dim6}}^*] + |\mathcal{M}_{\text{dim6}}|^2 + 2\text{Re} [\mathcal{M}_{\text{SM}} \mathcal{M}_{\text{dim8}}^*] + \dots$$



This expansion is reflected in the (differential) cross section

$$\sigma = \sigma_{\text{SM}} + \sum_i \frac{C_i^{(6)}}{\Lambda^2} \sigma_i^{(6)} + \sum_{ij} \frac{C_i^{(6)} C_j^{(6)}}{\Lambda^4} \sigma_{ij}^{(6)} + \sum_k \frac{C_k^{(8)}}{\Lambda^4} \sigma_k^{(8)} + \mathcal{O}(\Lambda^{-6})$$

This simple structure is broken by top decay

Top Effective Field Theory

2-Fermion Operators (top-gauge-Higgs)

$$\psi^2 X H$$

dipole

$$\psi^2 D H^2$$

neutral/charged current

$$\psi^2 H^3$$

Yukawa

$$C_{uB}^{33} (\bar{Q} \sigma^{\mu\nu} u) \tilde{\phi} B_{\mu\nu}$$

$$C_{\phi q}^{(1)33} (\phi^\dagger i \overleftrightarrow{D}_\mu \phi) (\bar{Q} \gamma^\mu Q)$$

$$C_{u\phi}^{33} (\phi^\dagger \phi) (\bar{Q} u \tilde{\phi})$$

$$C_{uG}^{33} (\bar{Q} \sigma^{\mu\nu} T^A u) \tilde{\phi} G_{\mu\nu}^A$$

$$C_{\phi u}^{33} (\phi^\dagger i \overleftrightarrow{D}_\mu \phi) (\bar{u} \gamma^\mu u)$$



$$C_{uW}^{33} (\bar{Q} \sigma^{\mu\nu} \tau^I u) \tilde{\phi} W_{\mu\nu}^I$$

$$C_{\phi q}^{(3)33} (\phi^\dagger i \overleftrightarrow{D}_\mu^I \phi) (\bar{Q} \tau^I \gamma^\mu Q)$$

$$C_{dW}^{33} (\bar{Q} \sigma^{\mu\nu} \tau^I d) \phi W_{\mu\nu}^I$$

$$C_{\phi ud}^{33} i(\tilde{\phi}^\dagger D_\mu \phi) (\bar{u} \gamma^\mu d)$$



Warsaw
Basis



Flavour assumption: $U(2)_q \times U(2)_u \times U(2)_d$

Top Effective Field Theory

4-Fermion Operators

$(\bar{L}L)(\bar{L}L)$, $(\bar{L}L)(\bar{R}R)$, $(\bar{R}R)(\bar{R}R)$, $(\bar{L}R)(\bar{L}R)$

$$C_{qq}^{(1)} (\bar{Q} \gamma_\mu Q) (\bar{Q} \gamma^\mu Q)$$

$$C_{qq}^{(3)} (\bar{Q} \tau^I \gamma_\mu Q) (\bar{Q} \tau^I \gamma^\mu Q)$$

$$Qq$$

$$QQ$$

$$Q\ell$$

$$C_{qu}^{(1)} (\bar{Q} \gamma_\mu Q) (\bar{u} \gamma^\mu u)$$

$$C_{qu}^{(8)} (\bar{Q} \gamma_\mu T^A Q) (\bar{u} \gamma^\mu T^A u)$$

ii33, i33i

3333

$$C_{qd}^{(1)} (\bar{Q} \gamma_\mu Q) (\bar{d} \gamma^\mu d)$$

$$C_{qd}^{(8)} (\bar{Q} \gamma_\mu T^A Q) (\bar{d} \gamma^\mu T^A d)$$

33ii

3333

$$C_{ud}^{(1)} (\bar{u} \gamma_\mu u) (\bar{d} \gamma^\mu d)$$

$$C_{ud}^{(8)} (\bar{u} \gamma_\mu T^A u) (\bar{d} \gamma^\mu T^A d)$$

33ii

3333

$$C_{uu} (\bar{u} \gamma_\mu u) (\bar{u} \gamma^\mu u)$$

ii33, i33i

3333

~~CP~~
$$C_{quqd}^{(1)} (\bar{Q}^j u) \epsilon_{jk} (\bar{Q}^k d)$$

$$C_{quqd}^{(8)} (\bar{Q}^j T^A u) \epsilon_{jk} (\bar{Q}^k T^A d)$$

3333

4-quark operators

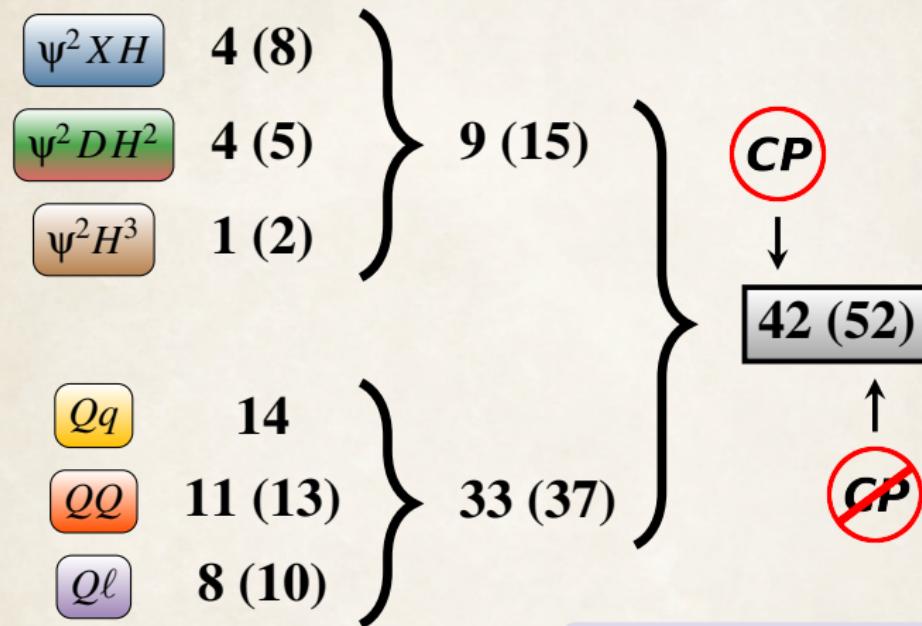
Warsaw
Basis

Flavour assumption: $U(2)_q \times U(2)_u \times U(2)_d$

~~CP~~
$$C_{lequ}^{(1)ii33} (\bar{\ell}^j e) \epsilon_{jk} (\bar{Q}^k u)$$

~~CP~~
$$C_{lequ}^{(3)ii33} (\bar{\ell}^j \sigma_{\mu\nu} e) \epsilon_{jk} (\bar{Q}^k \sigma^{\mu\nu} u)$$

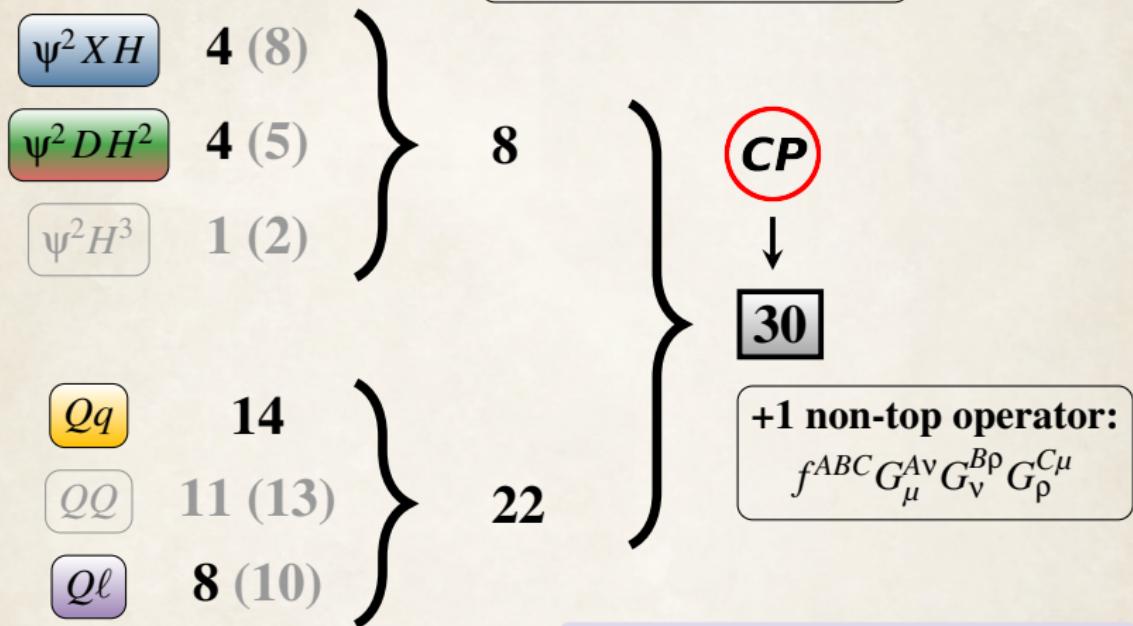
Top EFT: Number of operators



Flavour assumption: $U(2)_q \times U(2)_u \times U(2)_d$

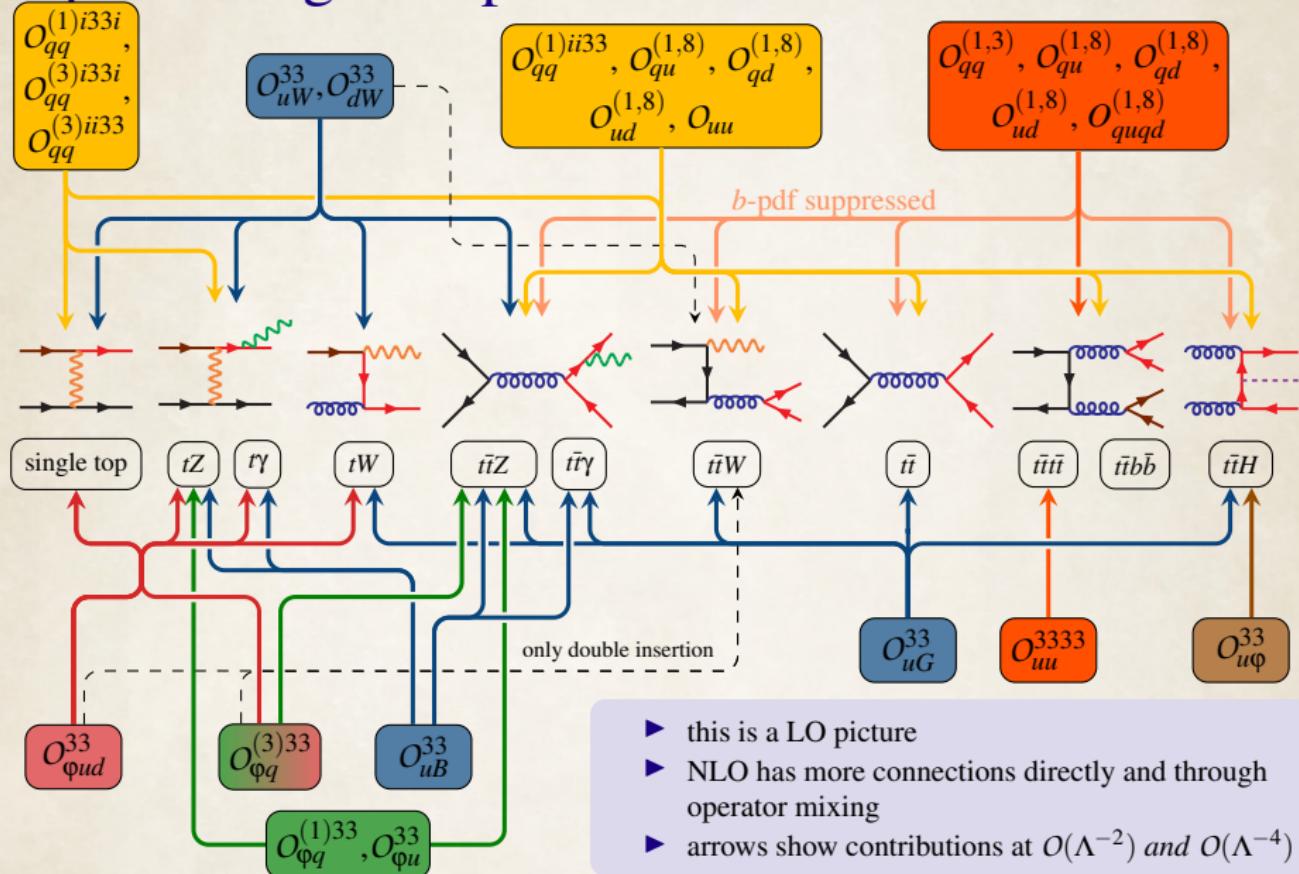
Top EFT: Number of operators

Operators in TopFitter



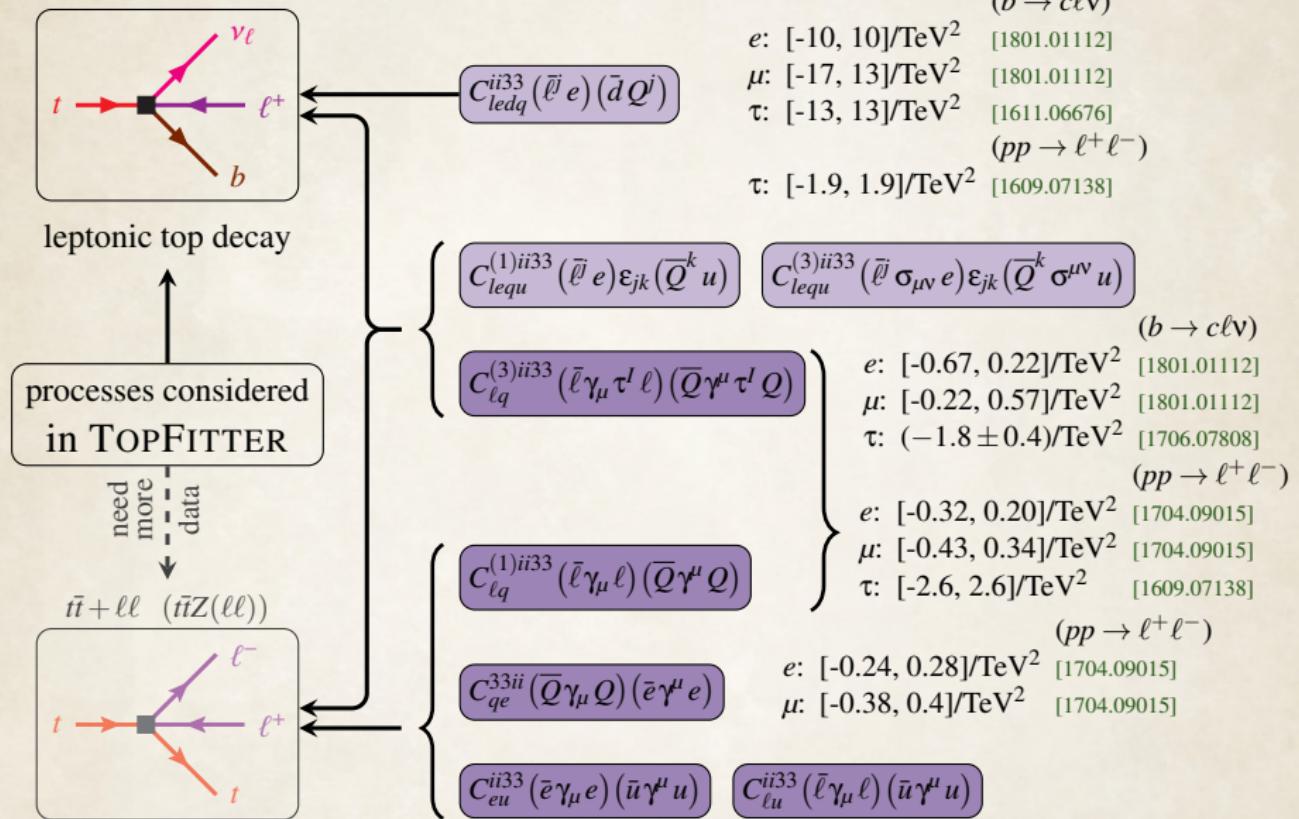
Flavour assumption: $U(2)_q \times U(2)_u \times U(2)_d$

Top EFT: a global picture

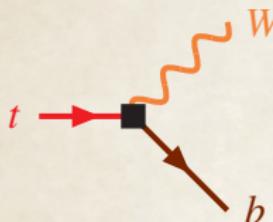


Top-Lepton Operators

existing constraints from non-top processes [1802.07237]



EFT in Top Quark Decay

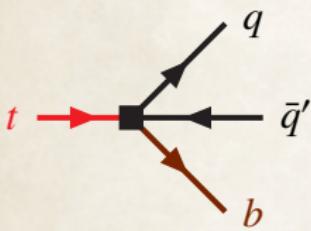


$$C_{uW}^{33} (\bar{Q} \sigma^{\mu\nu} \tau^I u) \tilde{\phi} W_{\mu\nu}^I$$

$$C_{dW}^{33} (\bar{Q} \sigma^{\mu\nu} \tau^I d) \phi W_{\mu\nu}^I$$

$$C_{\phi q}^{(3)33} (\phi^\dagger i \overleftrightarrow{D}_\mu \phi) (\bar{Q} \tau^I \gamma^\mu Q)$$

$$C_{\phi ud}^{33} i (\bar{\phi}^\dagger D_\mu \phi) (\bar{u} \gamma^\mu d)$$



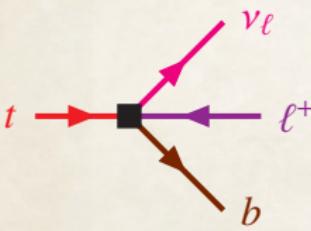
$$C_{qq}^{(1)} (\bar{Q} \gamma_\mu Q) (\bar{Q} \gamma^\mu Q)$$

i33i

$$C_{qq}^{(3)} (\bar{Q} \tau^I \gamma_\mu Q) (\bar{Q} \tau^I \gamma^\mu Q)$$

ii33, i33i

- decay gives add. constraints on operators in t production
- decay gives access to new operators
- decay provides access to new observables sensitive to production and decay



$$C_{\ell q}^{(3)ii33} (\bar{\ell} \gamma_\mu \tau^I \ell) (\bar{Q} \gamma^\mu \tau^I Q)$$

$$C_{ledq}^{ii33} (\bar{\ell}^j e) (\bar{d} Q^j)$$

$$C_{lequ}^{(1)ii33} (\bar{\ell}^j e) \epsilon_{jk} (\bar{Q}^k u)$$

$$C_{lequ}^{(3)ii33} (\bar{\ell}^j e) \epsilon_{jk} (\bar{Q}^k \sigma^{\mu\nu} u)$$

EFT in Top Quark Decay: generating predictions

remember:

$$\sigma = \sigma_{\text{SM}} + \sum_i \frac{C_i^{(6)}}{\Lambda^2} \sigma_i^{(6)} + \sum_{ij} \frac{C_i^{(6)} C_j^{(6)}}{\Lambda^4} \sigma_{ij}^{(6)} + \dots$$

This simple structure is broken by top quark decay, e.g.

$$\sigma(pp \rightarrow t\bar{t} \rightarrow b\bar{b}\ell^+\ell^- v_\ell \bar{v}_\ell) \stackrel{\text{NWA}}{\equiv} \frac{\tilde{\sigma}(\{C_i\})}{\Gamma_t^2(\{C_i\})}$$

However, numerator and denominator exhibit the same polynomial structure as the cross section, in particular the top quark decay width is given by

$$\Gamma = \Gamma_{\text{SM}} + \sum_i \frac{C_i^{(6)}}{\Lambda^2} \Gamma_i^{(6)} + \sum_{ij} \frac{C_i^{(6)} C_j^{(6)}}{\Lambda^4} \Gamma_{ij}^{(6)} + \dots$$

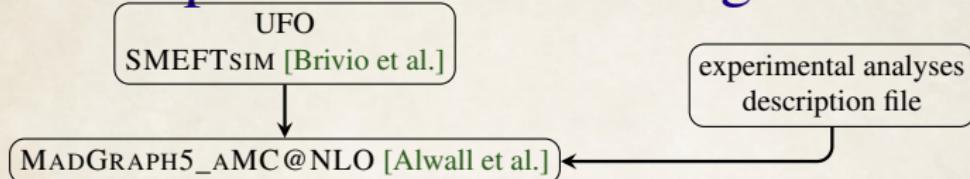
Hence, in addition to $\tilde{\sigma}_i$, $\tilde{\sigma}_{ij}$ one has to determine Γ_i , Γ_{ij} to construct the cross section including top quark decay

Theoretical predictions and fitting

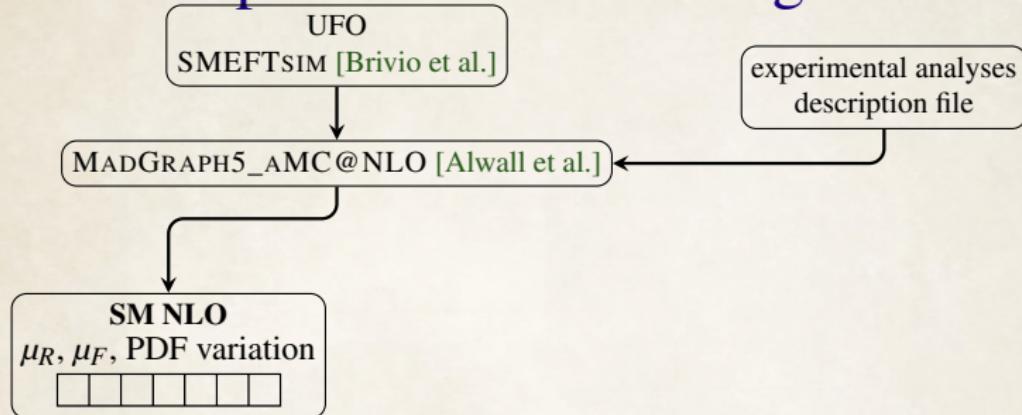
UFO

SMEFTSIM [Brivio et al.]

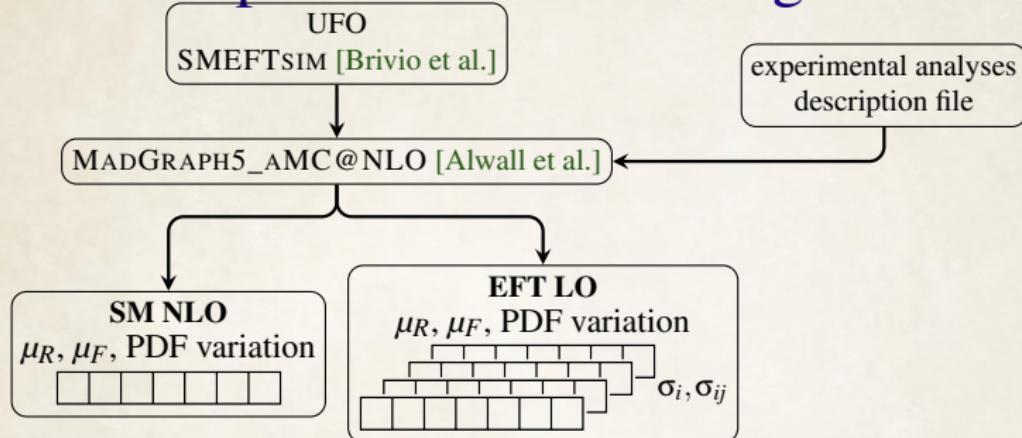
Theoretical predictions and fitting



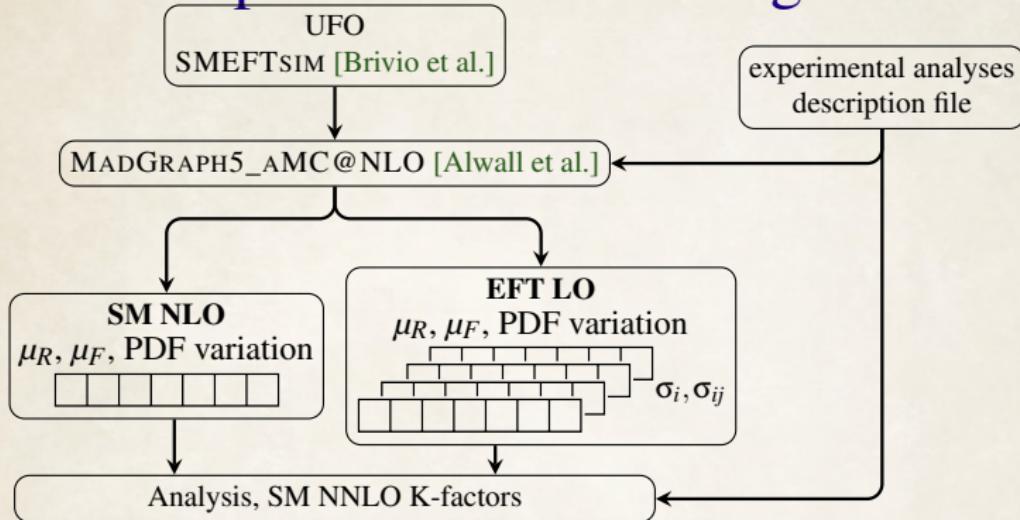
Theoretical predictions and fitting



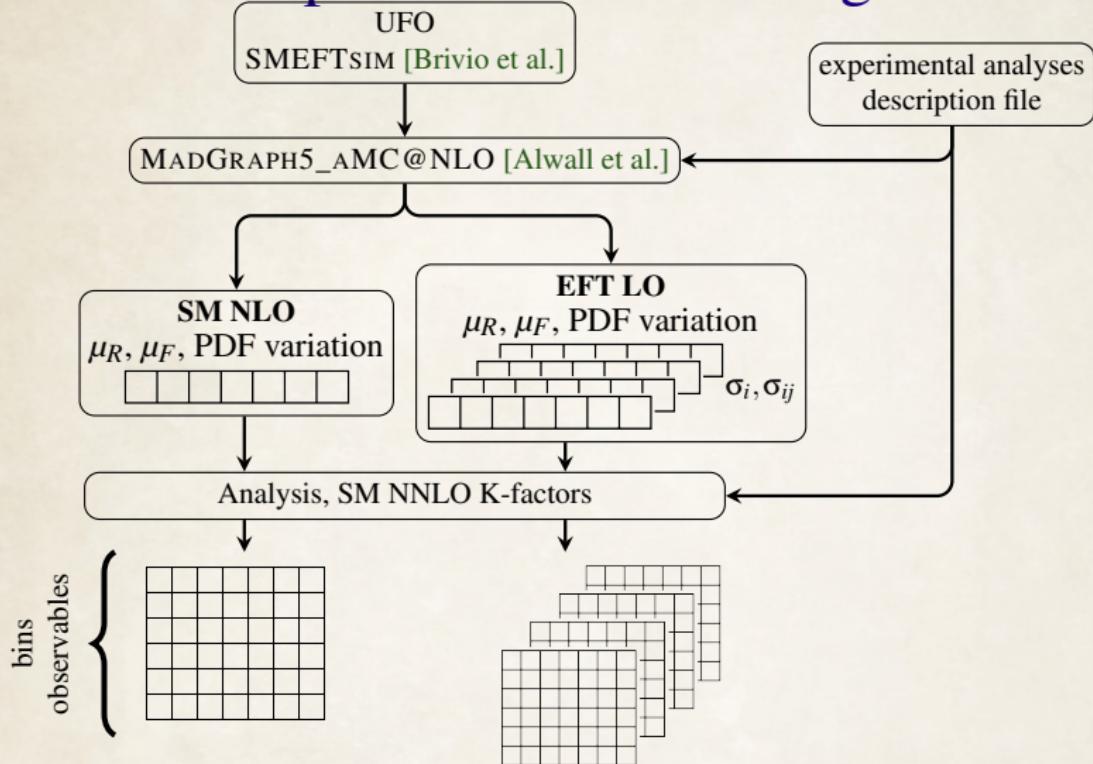
Theoretical predictions and fitting



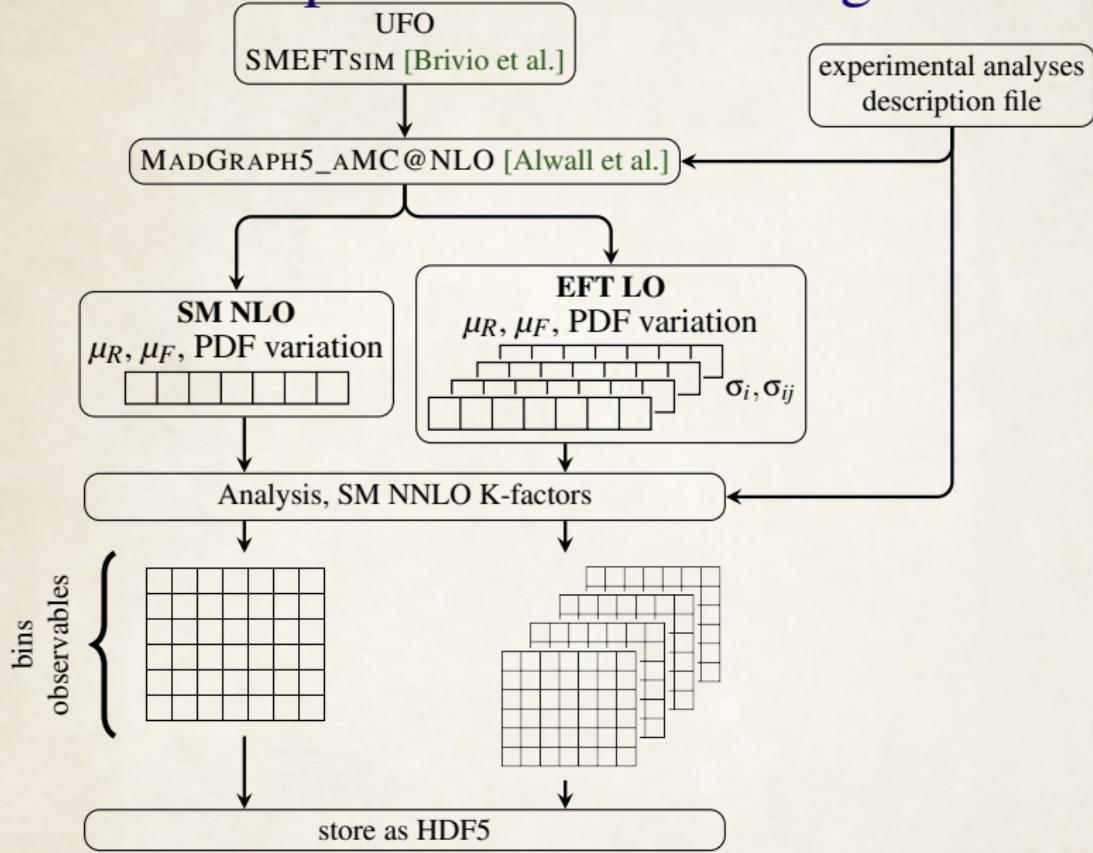
Theoretical predictions and fitting



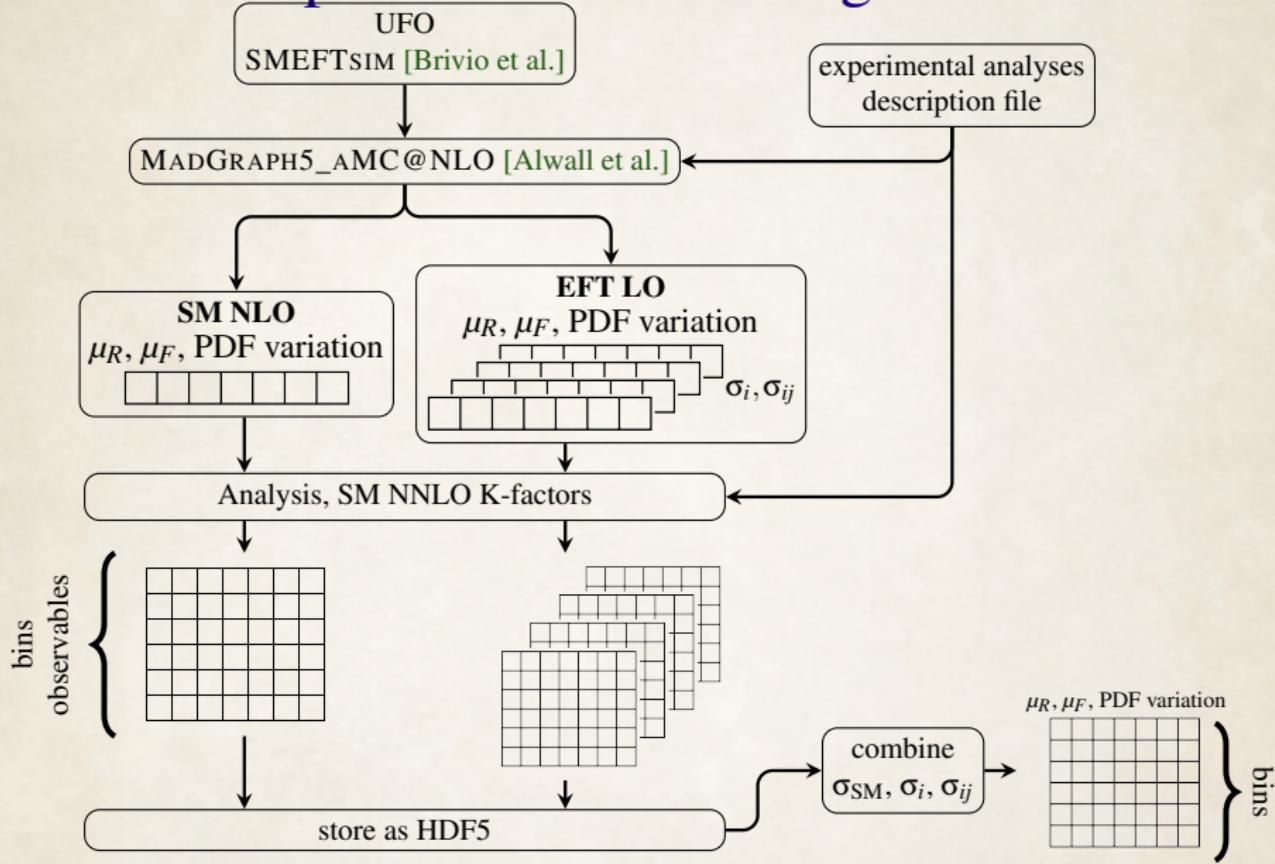
Theoretical predictions and fitting



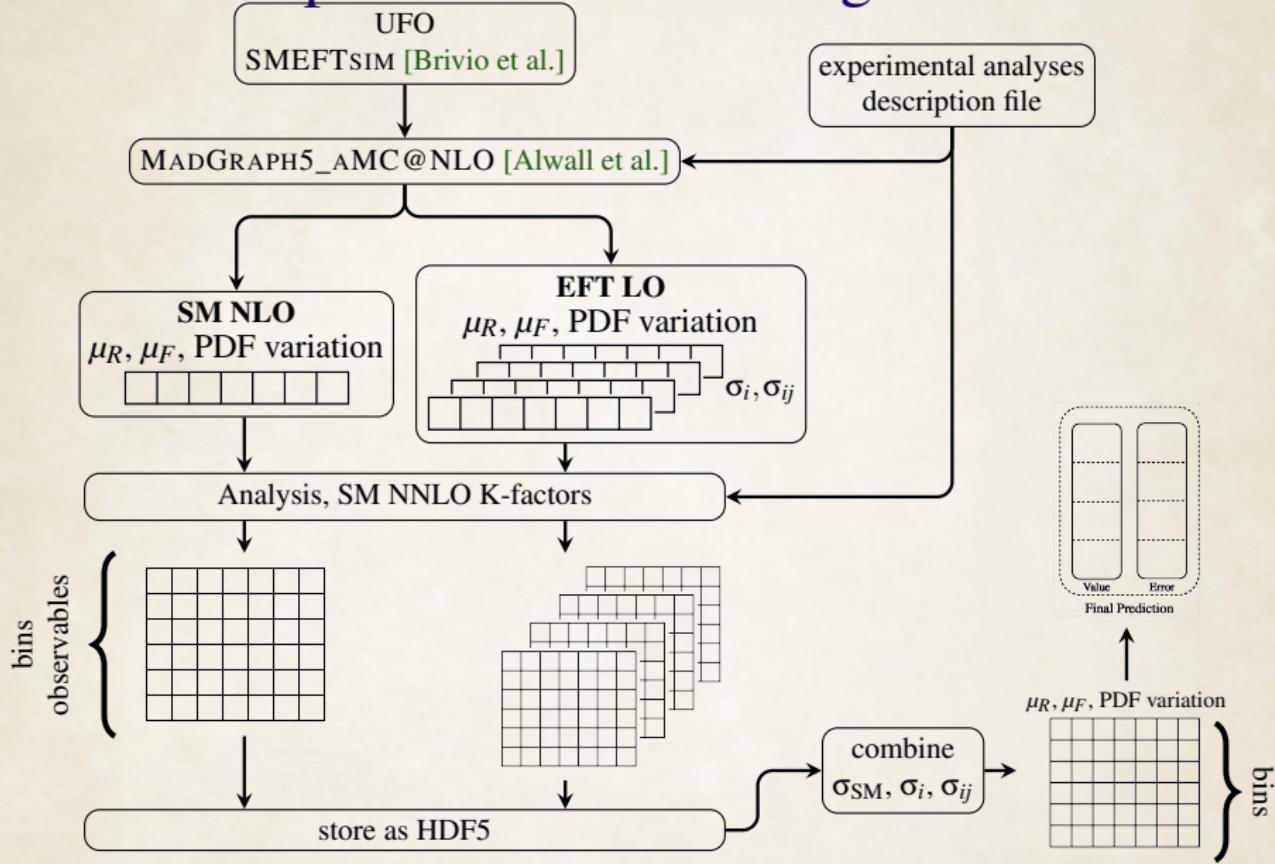
Theoretical predictions and fitting



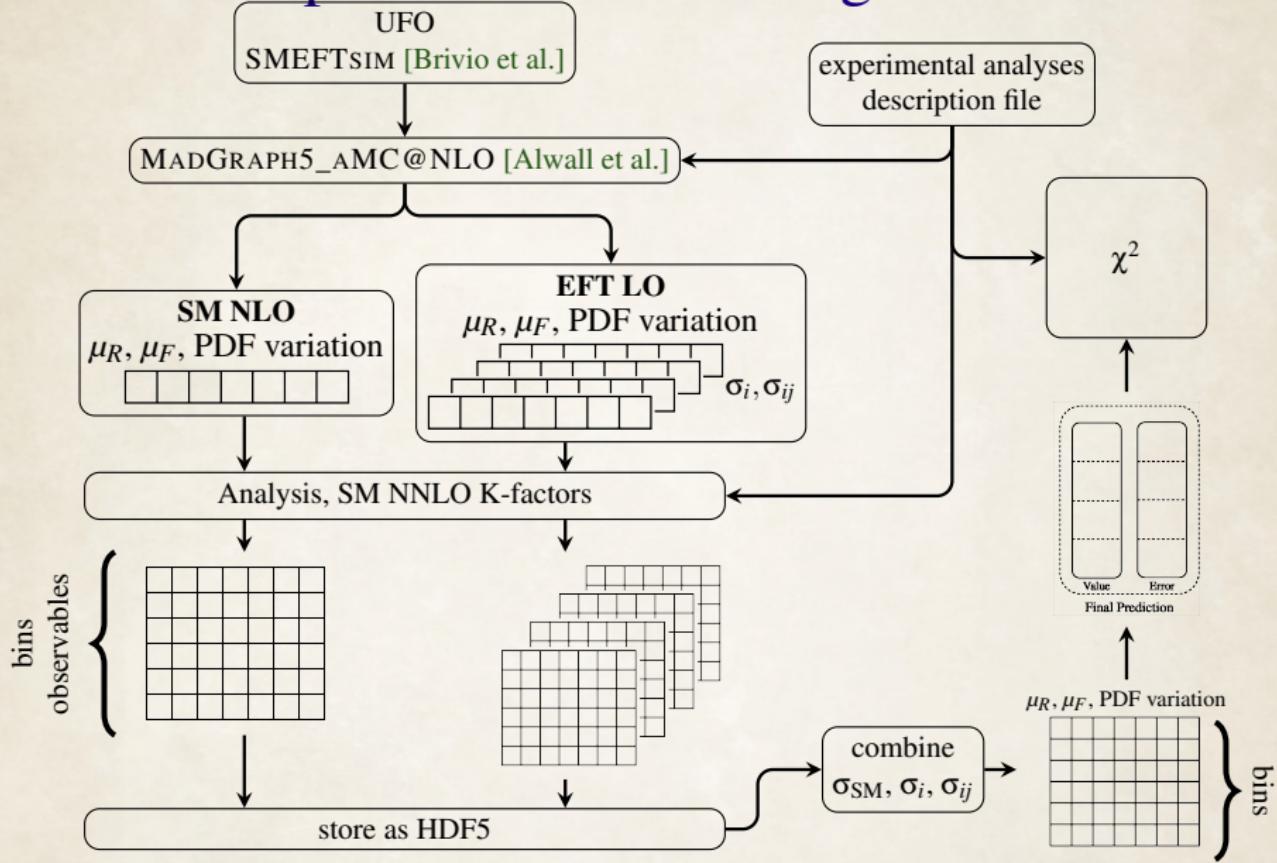
Theoretical predictions and fitting



Theoretical predictions and fitting



Theoretical predictions and fitting



Experimental input: target

	TEV		LHC7		LHC8		LHC13	
process	observables	d.o.f.	observables	d.o.f.	observables	d.o.f.	observables	d.o.f.
$t\bar{t}$	Whel, σ , diff		Whel, σ , A_C (diff)		Whel, σ , A_C (diff)		σ , diff, 2-diff	(110)
	Γ_t , A_{FB} , a_l	(52)	diff, A_C , 2-diff	(82)	diff, Γ_t , A_C , 2-diff	(108)		
$t\bar{t}W$					σ	(2)	σ	(2)
					σ	(2)	$\cos\theta_Z^*, p_{T,Z}, \sigma$	(9)
$t\bar{t}(\ell\ell)$	A_{FB}^ℓ (diff), A_{FB}^ℓ , P_t	(8)	A_C , spin corr.		2-diff	(108)	spin corr., diff	(130)
	A_{FB}^ℓ (diff), A_{FB}^ℓ , P_t	(12)						
tj	Γ_t , σ	(2)	σ , R_t , diff	(17)	Whel, σ	(3)	σ , R_t	(4)
tb	σ	(1)			σ	(2)		
tW			σ	(1)	σ	(1)	σ	(2)
$tj(\ell)$					A_{FB} , P_t	(17)		
tjZ							σ	(1)
$tjZ(\ell\ell)$							σ	(2)

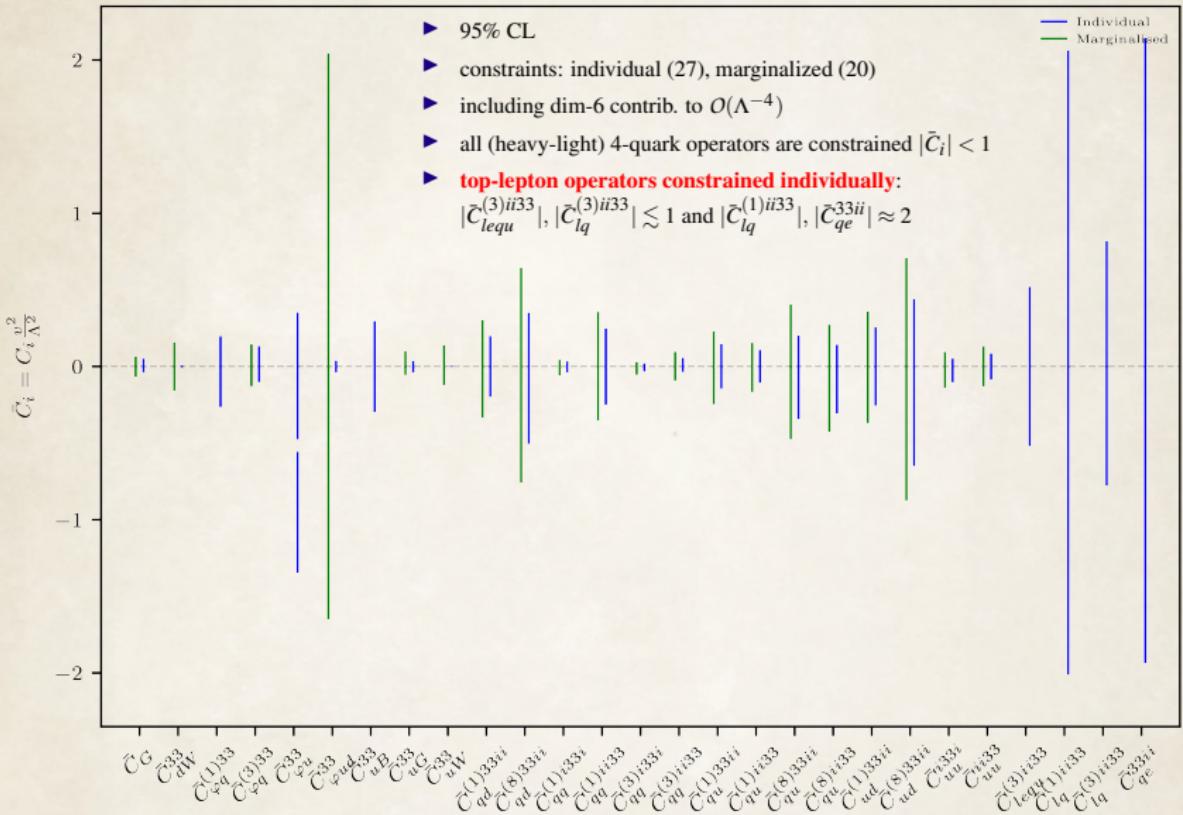
- ▶ 78 analyses
- ▶ >600 degrees of freedom
- ▶ 11 processes
- ▶ including top quark decay

Experimental input: preliminary

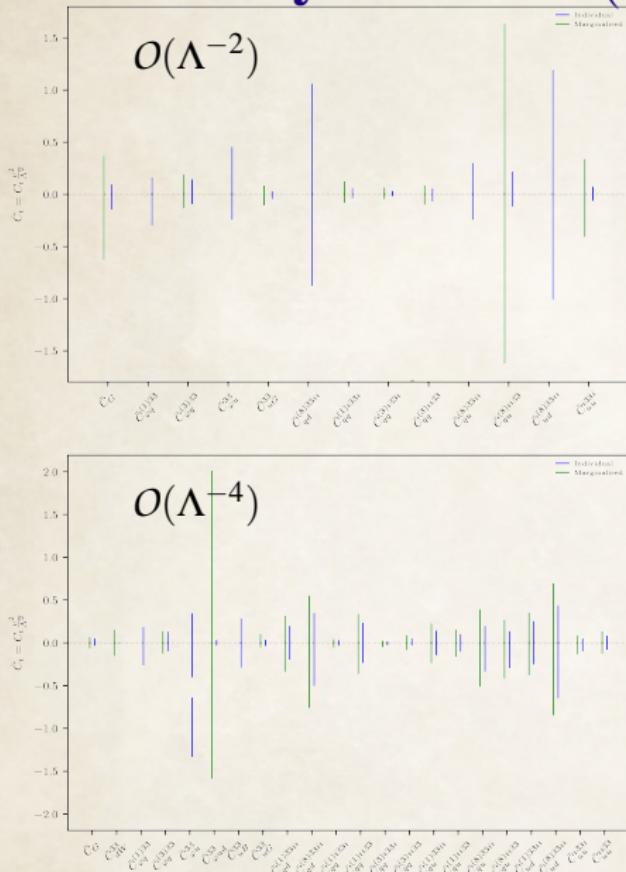
process	TEV		LHC7		LHC8		LHC13	
	observables	d.o.f.	observables	d.o.f.	observables	d.o.f.	observables	d.o.f.
$t\bar{t}$	$\Gamma_t, \sigma, \text{diff}$				2-diff, σ, Γ_t			
	$W\text{-hel}$	(14)	$\sigma, \text{diff}, W\text{-hel}$	(45)	$W\text{-hel}$	(62)	σ	(2)
$t\bar{t}W$					σ	(2)	σ	(2)
					σ	(2)	$p_{T,Z}, \cos\theta_Z^*, \sigma$	(9)
$t\bar{t}(\ell\ell)$			spin corr.	(7)				
tj	σ, Γ_t	(2)	σ, diff, R_t	(17)	$W\text{-hel}$	(1)	σ, R_t	(4)
tb	σ	(1)			σ	(2)		
tW			σ	(1)	σ	(1)	σ	(2)
tjZ							σ	(1)
$tjZ(\ell\ell)$							σ	(2)

- ▶ 45 analyses
- ▶ 179 degrees of freedom
- ▶ 9 processes
- ▶ including top quark decay

Preliminary results



Preliminary results: $O(\Lambda^{-2})$ vs. $O(\Lambda^{-4})$



- ▶ 95% CL
 - ▶ here: top-lepton operators not fitted
 - ▶ some operators only contribute at $O(\Lambda^{-4})$ (at LO)
 - ▶ impact of $O(\Lambda^{-4})$ strong on some operators
 - ▶ inclusion of full target data set expected to reduce impact

Conclusion

goals for an updated global fit:

- ▶ including a comprehensive data set from Tevatron and LHC Run I+II
promising results with preliminary data set
- ▶ extending the set of included top quark operators
extension w.r.t. previous TOPFITTER results
lepton-top operators
- ▶ study the impact of double operator insertions on the fit
double operator insertions included, comparison with single insertion
only need to be done
- ▶ including observables at the level of decayed top quarks
prelim. data set already includes some observables, more to be included
in the target set
- ▶ including fiducial measurements
not in this talk, work in progress

Thank you for your attention!