Global EFT fits in the top sector

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TOP WG meeting
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Top-quark operators & how to look for them

$$O_{\varphi Q}^{(3)} = i\frac{1}{2}y_t^2\left(\varphi^\dagger \overleftrightarrow{D}^I_\mu \varphi\right)(\bar{Q}\gamma^\mu \tau^I Q)$$

$$O_{\varphi Q}^{(1)} = i\frac{1}{2}y_t^2\left(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi\right)(\bar{Q}\gamma^\mu Q)$$

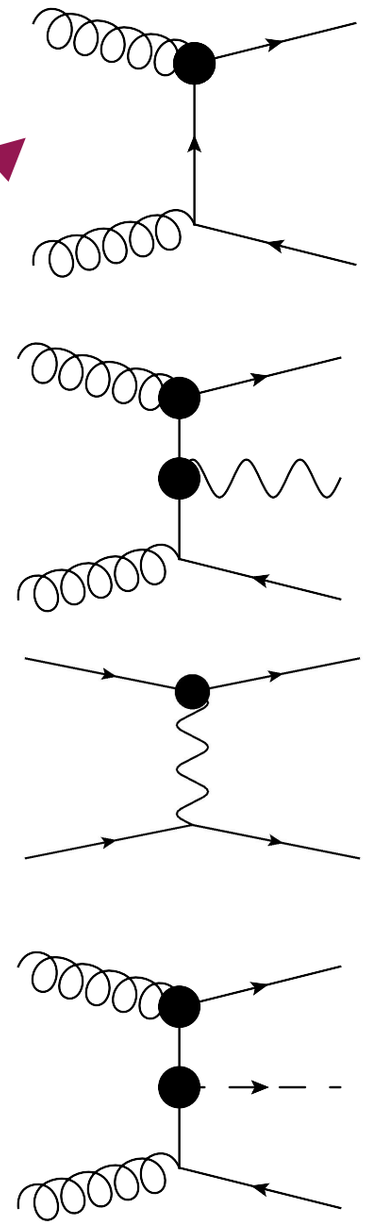
$$O_{\varphi t} = i\frac{1}{2}y_t^2\left(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi\right)(\bar{t}\gamma^\mu t)$$

$$O_{tW} = y_t g_w (\bar{Q}\sigma^{\mu\nu}\tau^I t)\tilde{\varphi} W^I_{\mu\nu}$$

$$O_{tB} = y_t g_Y (\bar{Q}\sigma^{\mu\nu} t)\tilde{\varphi} B_{\mu\nu}$$

$$O_{tG} = y_t g_s (\bar{Q}\sigma^{\mu\nu} T^A t)\tilde{\varphi} G^A_{\mu\nu}\,,$$

$$O_{t\phi} = y_t^3\left(\phi^\dagger\phi\right)(\bar{Q}t)\,\tilde{\phi}$$



see for example: Aguilar-Saavedra (arXiv:0811.3842)
Zhang and Willenbrock (arXiv:1008.3869)

+four-fermion operators

+non-top operators (mixing)

Operators entering various processes: Global approach needed

Top EFT in Monte Carlo@NLO

Aim to obtain a complete Monte Carlo implementation based on:

- Warsaw basis
- Degrees of freedom for top operators as in arXiv:1802.07237 (LHCTopWG)

Current status:

- 73 degrees of freedom (top, Higgs, gauge):
  - CP-conserving
  - Flavour assumption: $U(2)_Q \times U(2)_u \times U(3)_d \times U(3)_L \times U(3)_e$
- 0/2F@NLO operators validated (with previous partial NLO implementations) → **http://feynrules.irmp.ucl.ac.be/wiki/SMEFTatNLO**
- 4F@NLO operators validation: on-going

Future plans

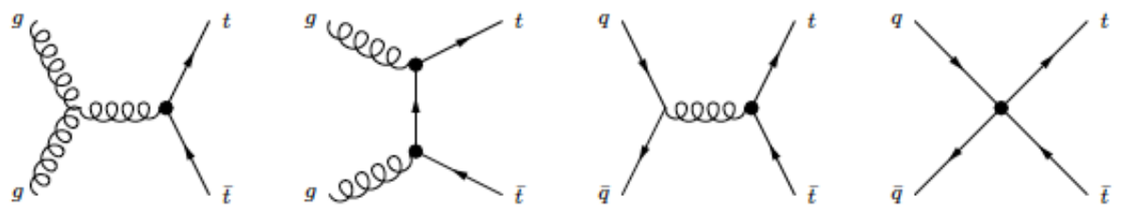
- Full NLO model release (4F@NLO)
- Other flavour assumptions
- CP-violating effects

Work in progress with: C. Degrande, G. Durieux, F. Maltoni, K. Mimasu, C. Zhang

EFT in top physics

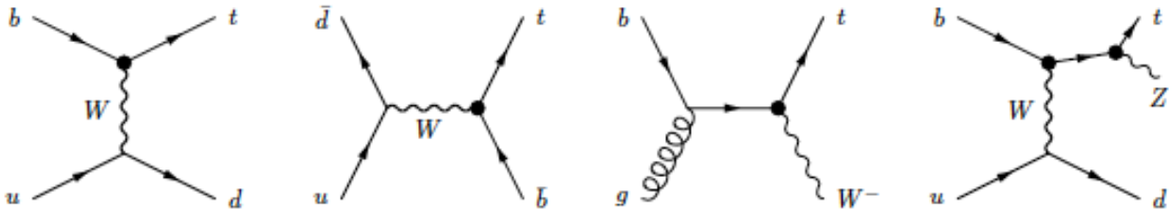
- 8 four-quark operators with LL and RR chiral structure

$$O_{Qq}^{1,8} = (\bar{Q}\gamma_\mu T^A Q)(\bar{q}_i\gamma^\mu T^A q_i) \qquad O_{Qq}^{1,1} = (\bar{Q}\gamma_\mu Q)(\bar{q}_i\gamma^\mu q_i)$$
$$O_{Qq}^{3,8} = (\bar{Q}\gamma_\mu T^A \tau^I Q)(\bar{q}_i\gamma^\mu T^A \tau^I q_i) \qquad O_{Qq}^{3,1} = (\bar{Q}\gamma_\mu \tau^I Q)(\bar{q}_i\gamma^\mu \tau^I q_i)$$
$$O_{tu}^{8} = (\bar{t}\gamma_\mu T^A t)(\bar{u}_i\gamma^\mu T^A u_i) \qquad O_{tu}^{1} = (\bar{t}\gamma_\mu t)(\bar{u}_i\gamma^\mu u_i)$$
$$O_{td}^{8} = (\bar{t}\gamma^\mu T^A t)(\bar{d}_i\gamma_\mu T^A d_i) \qquad O_{td}^{1} = (\bar{t}\gamma^\mu t)(\bar{d}_i\gamma_\mu d_i)\ ;$$



- 6 four-quark operators with LR and RL chiral structure

$$O_{Qu}^{8} = (\bar{Q}\gamma^\mu T^A Q)(\bar{u}_i\gamma_\mu T^A u_i) \qquad O_{Qu}^{1} = (\bar{Q}\gamma^\mu Q)(\bar{u}_i\gamma_\mu u_i)$$
$$O_{Qd}^{8} = (\bar{Q}\gamma^\mu T^A Q)(\bar{d}_i\gamma_\mu T^A d_i) \qquad O_{Qd}^{1} = (\bar{Q}\gamma^\mu Q)(\bar{d}_i\gamma_\mu d_i)$$
$$O_{tq}^{8} = (\bar{q}_i\gamma^\mu T^A q_i)(\bar{t}\gamma_\mu T^A t) \qquad O_{tq}^{1} = (\bar{q}_i\gamma^\mu q_i)(\bar{t}\gamma_\mu t)\ ;$$

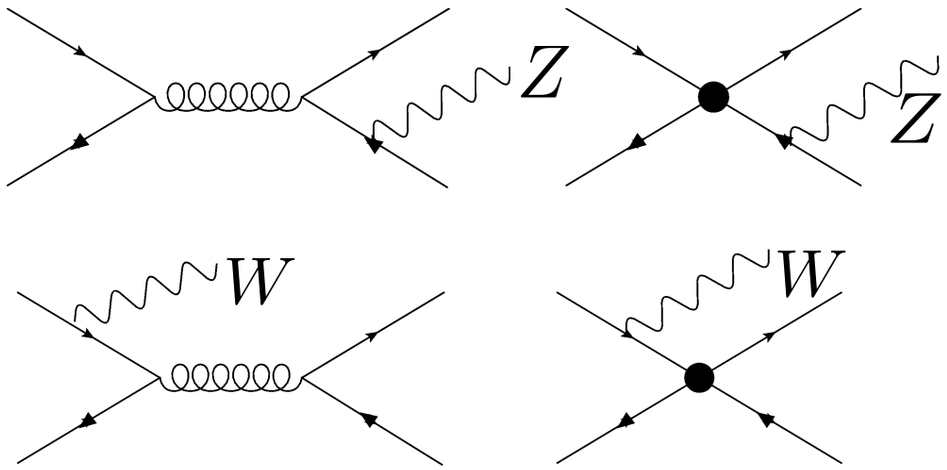


- 8 operators with two heavy quarks and bosons [40]

$$O_{\phi Q}^{1} = (\phi^\dagger i \overleftrightarrow{D_\mu} \phi)(\bar{Q}\gamma^\mu Q) \qquad {}^\ddagger O_{tB} = (\bar{Q}\sigma^{\mu\nu} t)\,\tilde{\phi}\, B_{\mu\nu}$$
$$O_{\phi Q}^{3} = (\phi^\dagger i \overleftrightarrow{D_\mu^I} \phi)(\bar{Q}\gamma^\mu \tau^I Q) \qquad {}^\ddagger O_{tW} = (\bar{Q}\sigma^{\mu\nu} t)\,\tau^I \tilde{\phi}\, W_{\mu\nu}^I$$
$$O_{\phi t} = (\phi^\dagger i \overleftrightarrow{D_\mu} \phi)(\bar{t}\gamma^\mu t) \qquad {}^\ddagger O_{bW} = (\bar{Q}\sigma^{\mu\nu} b)\,\tau^I \phi\, W_{\mu\nu}^I$$
$${}^\ddagger O_{\phi tb} = (\tilde{\phi}^\dagger i D_\mu \phi)(\bar{t}\gamma^\mu b) \qquad {}^\ddagger O_{tG} = (\bar{Q}\sigma^{\mu\nu} T^A t)\,\tilde{\phi}\, G_{\mu\nu}^A\ .$$

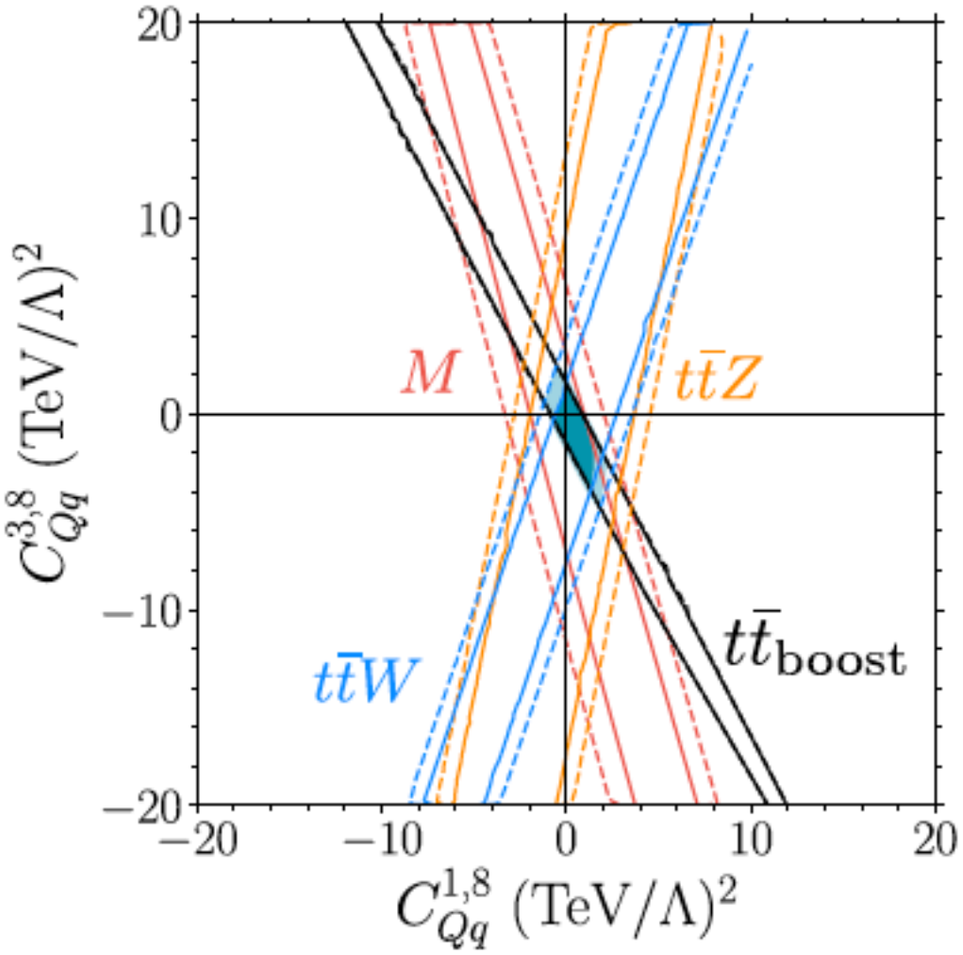
22 d.o.f.
CP-conserving

(34 d.o.fs if 4-heavy contributions and Yukawa: arXiv:1901.05965)

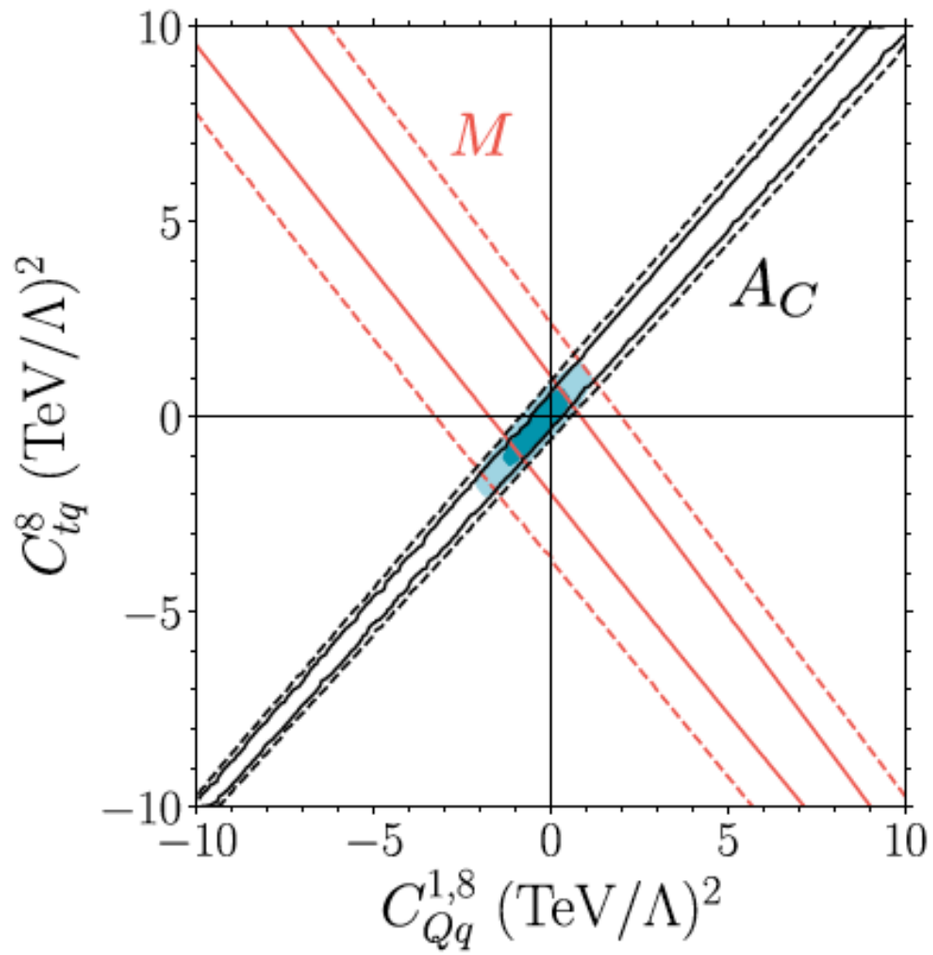


Rich phenomenology

The impact of multiple measurements



$$O_{Qq}^{1,8} = (\bar{Q}\gamma_\mu T^A Q)(\bar{q}_i\gamma^\mu T^A q_i)$$
$$O_{Qq}^{3,8} = (\bar{Q}\gamma_\mu T^A \tau^I Q)(\bar{q}_i\gamma^\mu T^A \tau^I q_i)$$



$$O_{tq}^{8} = (\bar{q}_i\gamma^\mu T^A q_i)(\bar{t}\gamma_\mu T^A t)$$
$$O_{Qq}^{1,8} = (\bar{Q}\gamma_\mu T^A Q)(\bar{q}_i\gamma^\mu T^A q_i)$$

Brivio, Bruggisser, Maltoni, Moutafis, Plehn, EV, Westhoff, Zhang arXiv:1910.03606

Some considerations for a fit

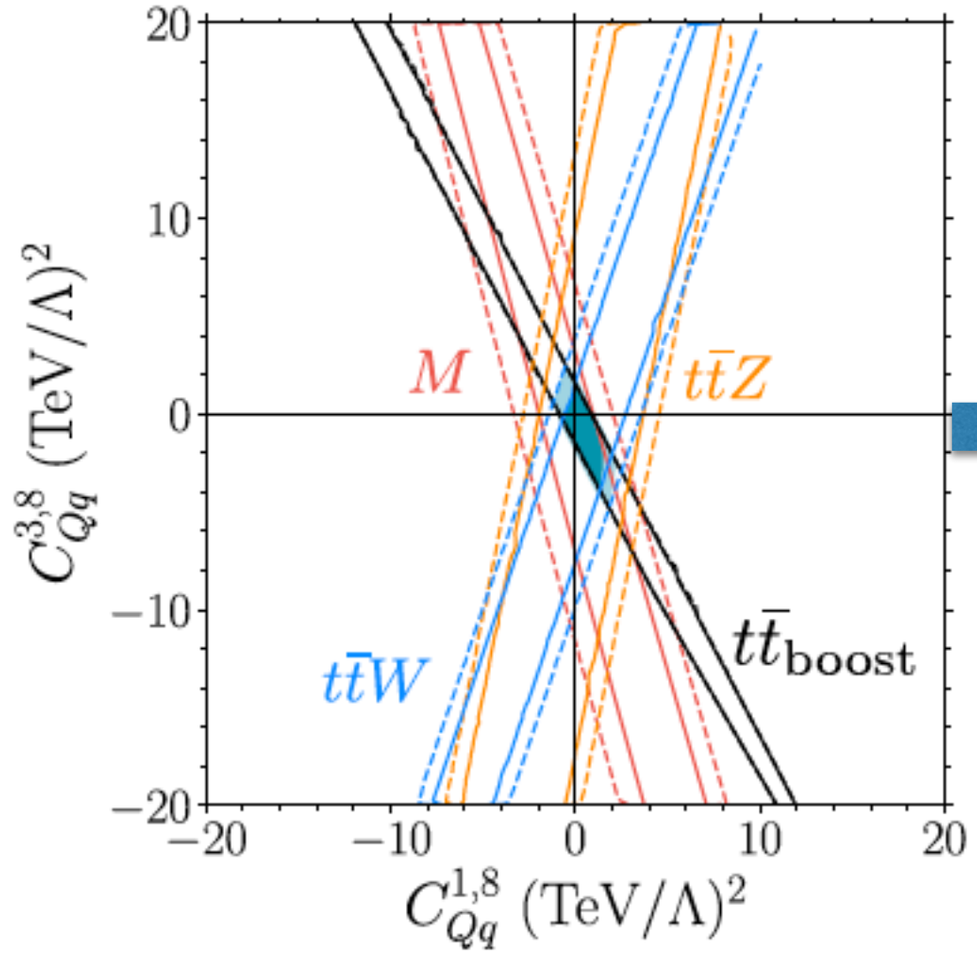
- Validity of the EFT expansion: E<Λ
  - Ensure results are not dominated by high energy regions
  - report limits as a function of the max scale probed Contino et al arXiv: 1604.06444

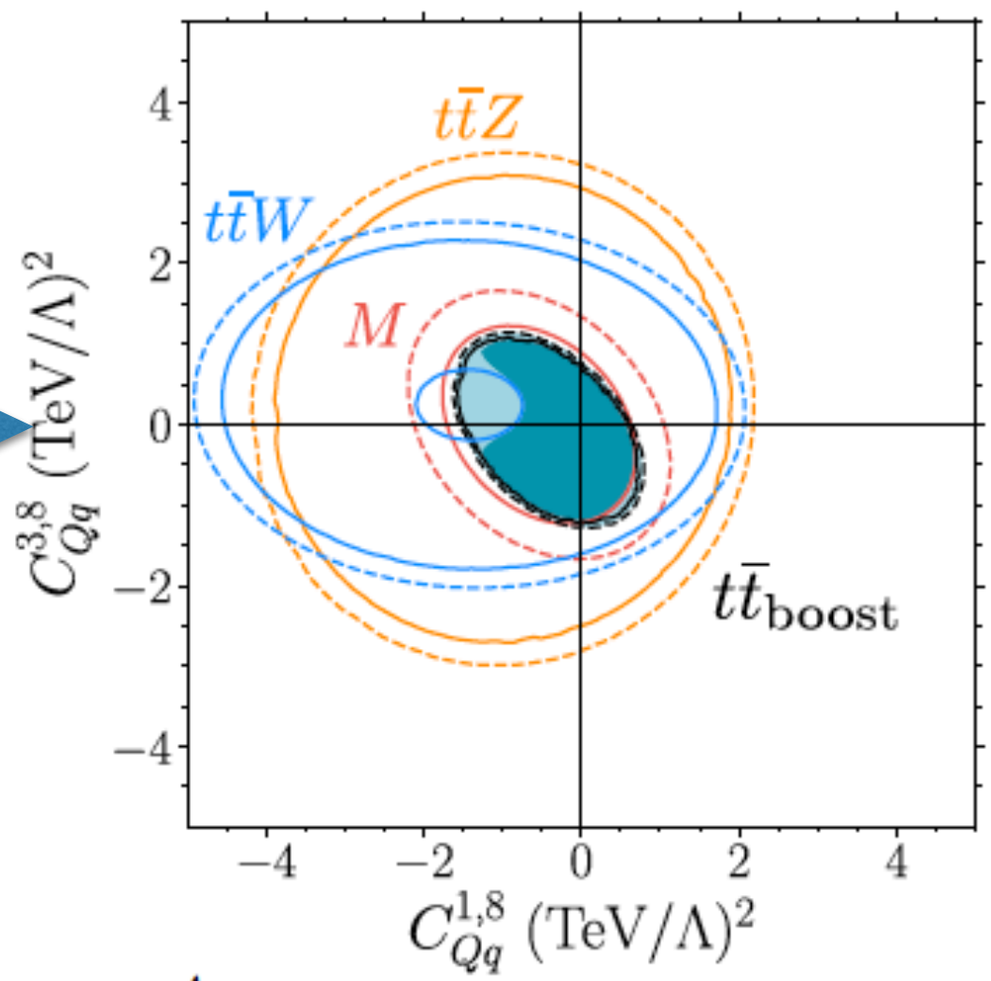
- $1/\Lambda^2$ vs $1/\Lambda^4$ contributions
  - $1/\Lambda^2$ suppressed due to helicity Azatov et al arXiv:1607.05236
  - $1/\Lambda^4$ can be large for loosely constrained operator coefficients/strongly coupled theories

$$C_i^2 \frac{E^4}{\Lambda^4} > C_i \frac{E^2}{\Lambda^2} > 1 > \frac{E^2}{\Lambda^2}$$

E<Λ satisfied but $O(1/\Lambda^4)$ large for large operator coefficients

Impact of quadratic terms in top production





$$O_{Qq}^{1,8} = (\bar{Q}\gamma_\mu T^A Q)(\bar{q}_i \gamma^\mu T^A q_i)$$
$$O_{Qq}^{3,8} = (\bar{Q}\gamma_\mu T^A \tau^I Q)(\bar{q}_i \gamma^\mu T^A \tau^I q_i)$$

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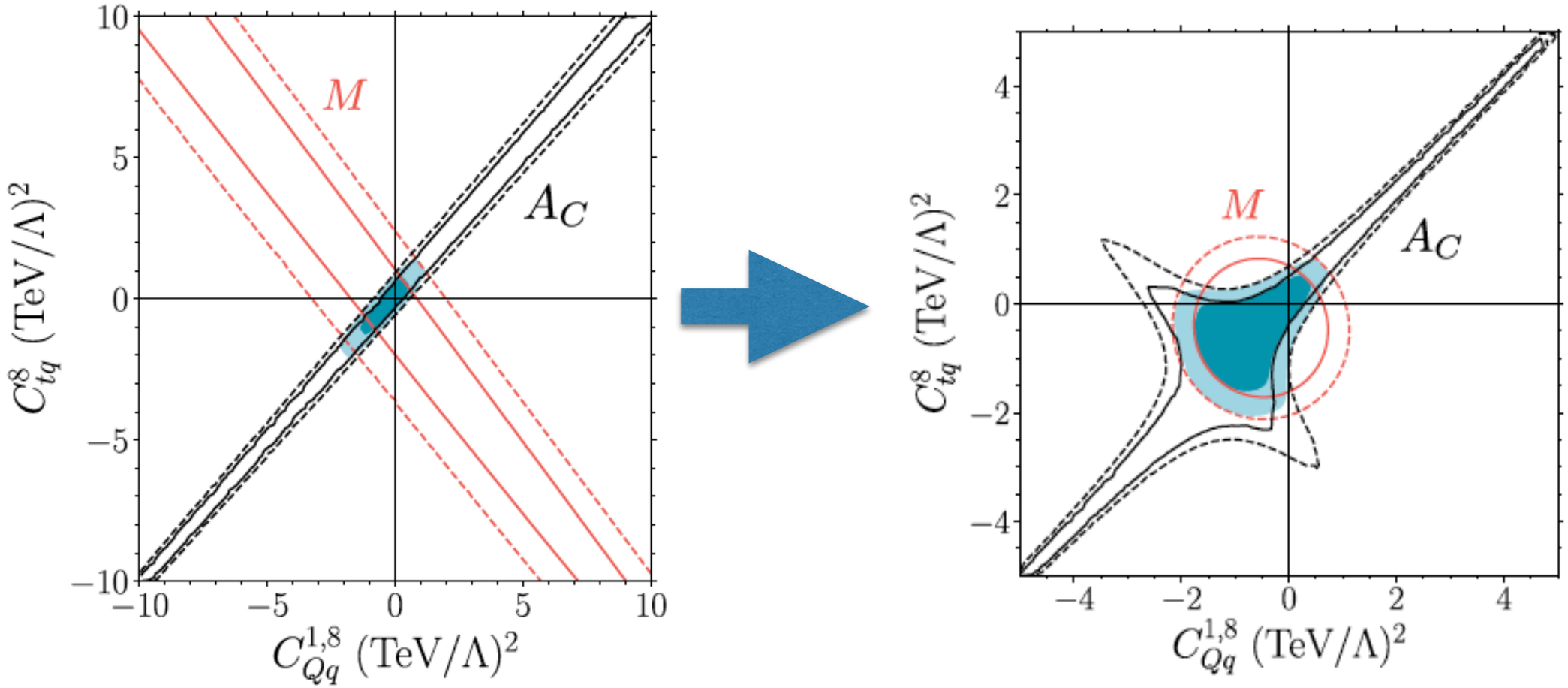
Impact of quadratic terms in top production



$$O_{tq}^8 = (\bar{q}_i \gamma^\mu T^A q_i)(\bar{t} \gamma_\mu T^A t)$$

$$O_{Qq}^{1,8} = (\bar{Q} \gamma_\mu T^A Q)(\bar{q}_i \gamma^\mu T^A q_i)$$

Brivio, Bruggisser, Maltoni, Moutafis, Plehn, EV, Westhoff, Zhang arXiv:1910.03606

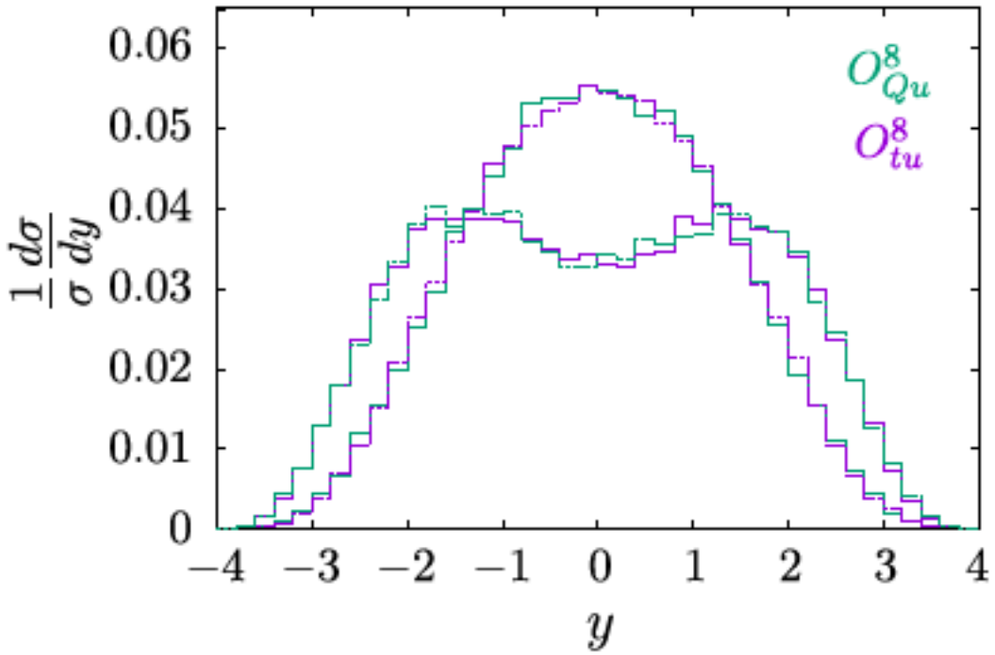
Can NLO matter?

$$O^8_{tu} = (\bar{t}\gamma_\mu T^A t)(\bar{u}_i \gamma^\mu T^A u_i)$$

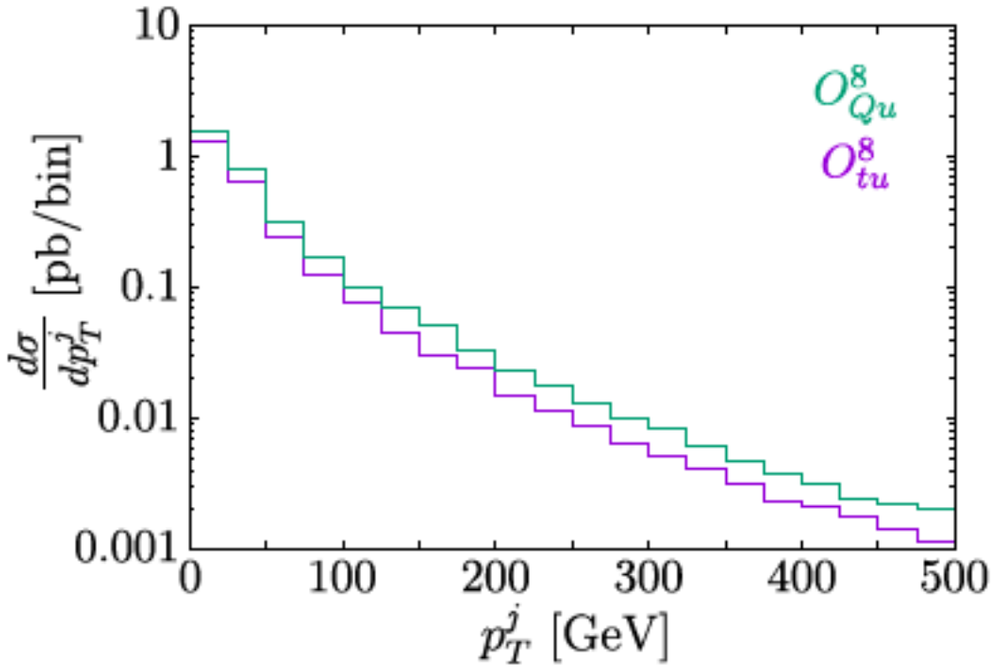
$$O^8_{Qu} = (\bar{Q}\gamma^\mu T^A Q)(\bar{u}_i \gamma_\mu T^A u_i)$$

Only differ in top quark chirality

Degenerate at LO for charge symmetric observables



Different rapidity distributions
RR operator: forward
LR operator: backward

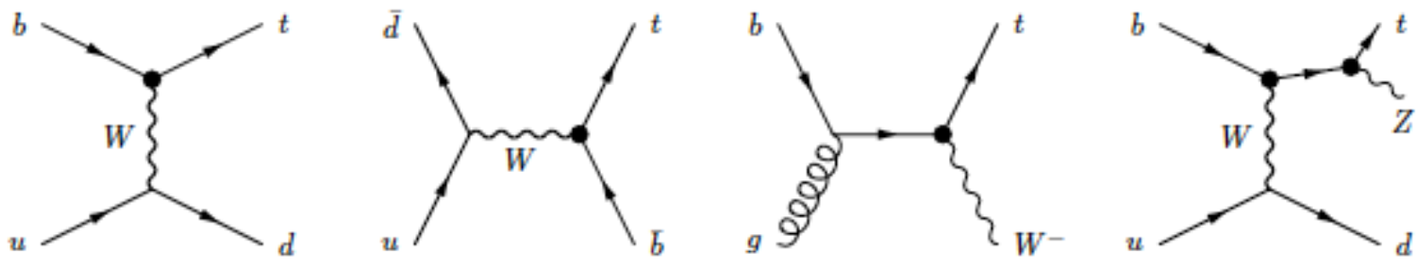


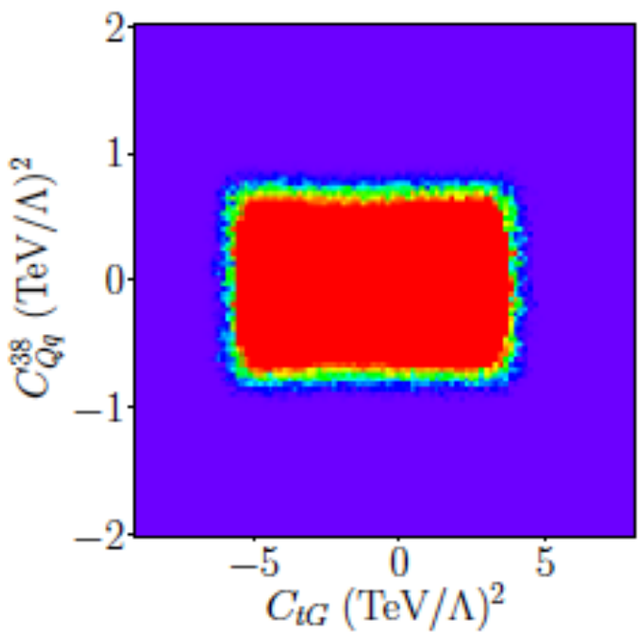
Stronger acceleration of colour
more QCD radiation for backwards tops

See also P. Skands, B. Webber and J. Winter, arXiv: 1205.1466

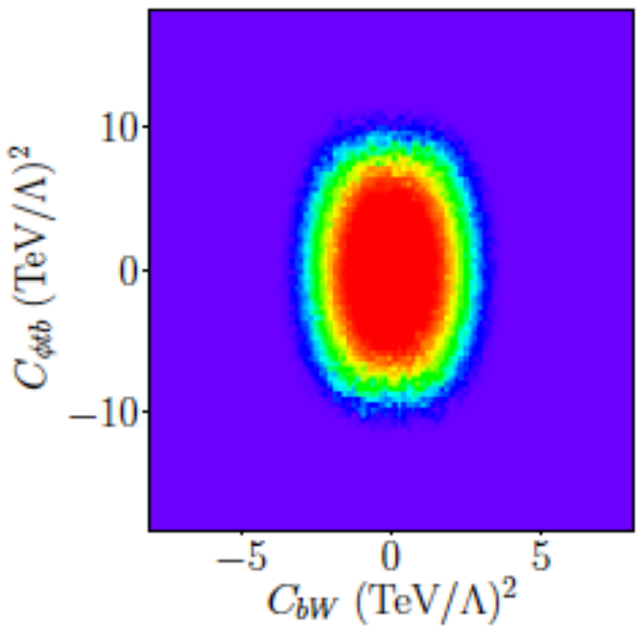
Correlations between operators

Single top:

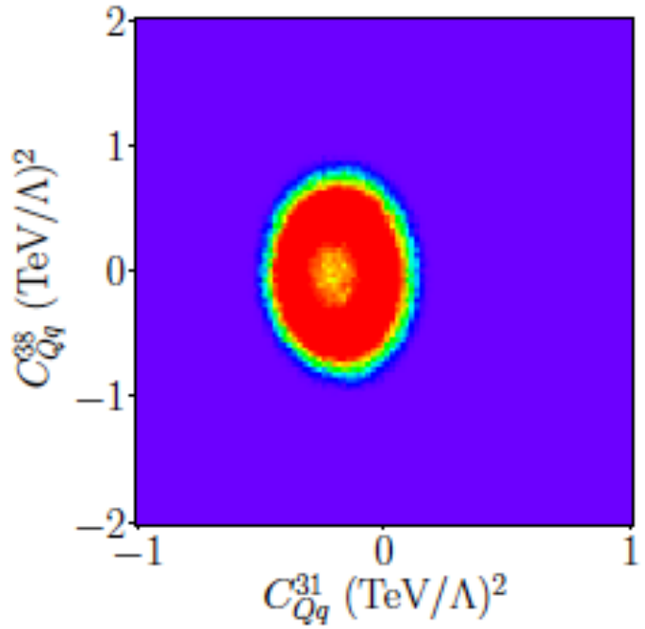




constraints from different processes



constraints from squared terms



constraints from linear and squared terms

Global fit Setup

Theory

(N)NLO QCD for SM
NLO QCD for SMEFT

Data

Top pair production and single top (differential)
Associated production with W,Z
W helicity fractions
Parton-level

Global SMEFT fit
of the top-quark sector

Methodology

Sfitter framework
Theoretical and experimental
uncertainties/Correlations

Output

Fit results can be used to bound
specific UV complete models
New data can be straightforwardly added

See also: Hartland, Maltoni, Nocera, Rojo, Slade, EV and Zhang, arXiv:1901.05965 (SMEFiT analysis)

Observables and theory predictions

Data

- Top-pair production
- W-helicities
- Single top: t-channel, s-channel
- tW, tZ

experiment	$\sqrt{S}$ (TeV)	$\mathcal{L}$ (fb^{-1})	channel	observable & K-fi
$pp \to t\bar{t}$				
CMS [52]	8	19.7	$e\mu$	$\sigma_{t\bar{t}}$
ATLAS [54]	8	20.02	lj	$\sigma_{t\bar{t}}$
CMS [55]	13	2.3	lj	$\sigma_{t\bar{t}}$
CMS [56]	13	3.2	ll	$\sigma_{t\bar{t}}$
ATLAS [57]	13	3.2	$e\mu$	$\sigma_{t\bar{t}}$
ATLAS [58]	8	20.3	lj	$\sigma^{-1}(d\sigma/dm_{t\bar{t}})$
CMS [62]	8	19.7	lj	$\sigma^{-1}(d\sigma/dp_{T,t})$
			ll	$\sigma^{-1}(d\sigma/dp_{T,1})$
CMS [63]	8	19.7	$e\mu$	$\sigma^{-1}(d^2\sigma/dm_{t\bar{t}}dy_{t}$
CMS [65]	8	19.7	lj high p_T	$d\sigma/dp_{T,t}$
CMS [66]	13	2.3	lj	$\sigma^{-1}(d\sigma/dm_{t\bar{t}})$
CMS [67]	13	35.8	lj	$\sigma^{-1}(d\sigma/dp_T(t_h))$
CMS [68]	13	2.1	ll	$\sigma^{-1}(d\sigma/dp_{T,t})$
CMS [69]	13	35.9	ll	$\sigma^{-1}(d\sigma/d\Delta y_{t\bar{t}})$
ATLAS [70]	13	36.1	aj high p_T	$\sigma^{-1}(d\sigma/dm_{t\bar{t}})$
CMS [71]	8	19.7	lj	A_C
CMS [73]	8	19.7	ll	A_C
ATLAS [74]	8	20.3	lj	A_C
ATLAS [75]	8	20.3	ll	A_C
ATLAS [76]	13	139	lj	A_C
$pp \to t\bar{t}Z$				
CMS [77]	13	77.5	multi lept.	$\sigma_{t\bar{t}Z}$
ATLAS [79]	13	3.2	multi lept.	$\sigma_{t\bar{t}Z}$
$pp \to t\bar{t}W$				
CMS [80]	13	35.9	multi lept.	$\sigma_{t\bar{t}W}$
ATLAS [79]	13	3.2	multi lept.	$\sigma_{t\bar{t}W}$

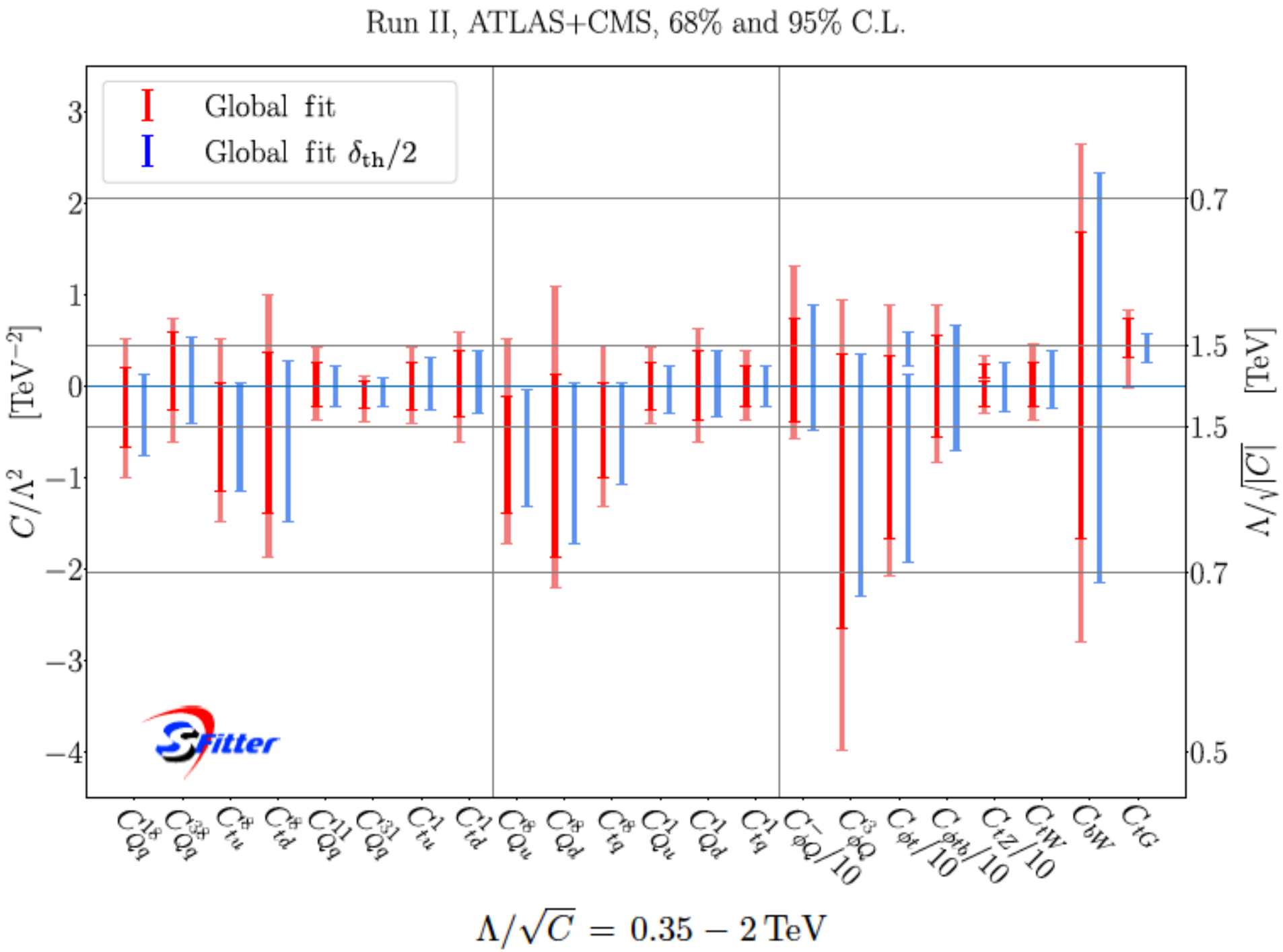
experiment	$\sqrt{S}$ (TeV)	$\mathcal{L}$ (fb^{-1})	channel	observable
$t-$channel				
CMS [81]	7	1.17 (μ), 1.56 (e)	$e+\mu$	$\sigma_{tq+\bar{t}q}$
ATLAS [82]	7	4.59	$e+\mu$	$\sigma_{tq+\bar{t}q}$
ATLAS [83]	8	20.2	$e+\mu$	$\sigma_{tq}, \sigma_{\bar{t}q}$
CMS [84]	8	19.7	$e+\mu$	$\sigma_{tq}, \sigma_{\bar{t}q}$
ATLAS [85]	13	3.2	$e+\mu$	$\sigma_{tq}, \sigma_{\bar{t}q}$
CMS [87]	13	2.3	μ	$\sigma_{tq}, \sigma_{\bar{t}q}$
$s-$channel				
CMS [88]	7	5.1	μ	$\sigma_{t\bar{b}+\bar{t}b}$
	8	19.7	$e+\mu$	$\sigma_{t\bar{b}+\bar{t}b}$
ATLAS [89]	8	20.3	$e+\mu$	$\sigma_{t\bar{b}+\bar{t}b}$
tW channel				
ATLAS [90]	7	2.05	$2lj$	$\sigma_{tW+\bar{t}W}$
CMS [91]	7	4.9	$2lj$	$\sigma_{tW+\bar{t}W}$
ATLAS [92]	8	20.3	$2lj$	$\sigma_{tW+\bar{t}W}$
CMS [93]	8	12.2	$2lj$	$\sigma_{tW+\bar{t}W}$
ATLAS [94]	13	3.2	$2lj$	$\sigma_{tW+\bar{t}W}$
CMS [95]	13	35.9	$e\mu j$	$\sigma_{tW+\bar{t}W}$
tZ channel				
ATLAS [96]	13	36.1	$3l2j$	σ_{tZq}
W helicities in top decays				
ATLAS [97]	7	1.04		F_0, F_L
CMS [98]	13	5.0		F_0, F_L
ATLAS [99]	8	20.2		F_0, F_L
CMS [100]	8	19.8		F_0, F_L

Theoretical predictions

- Best available SM predictions
- NLO EFT predictions
- O(1/Λ^4) terms

See also: Hartland, Maltoni, Nocera, Rojo, Slade, EV and Zhang, arXiv:1901.05965

Global fit results



Brivio, Bruggisser, Maltoni, Moutafis, Plehn, EV, Westhoff, Zhang arXiv:1910.03606

Outlook

- Global top EFT fits results available
- Combining as many processes as possible crucial to extract maximal information
- NLO EFT predictions can play a role in breaking degeneracies between operators
- More precise measurements of associated production will help improve the bounds for operators of the electroweak couplings of the top

Thank you for your attention