Top-quark physics: challenges and opportunities

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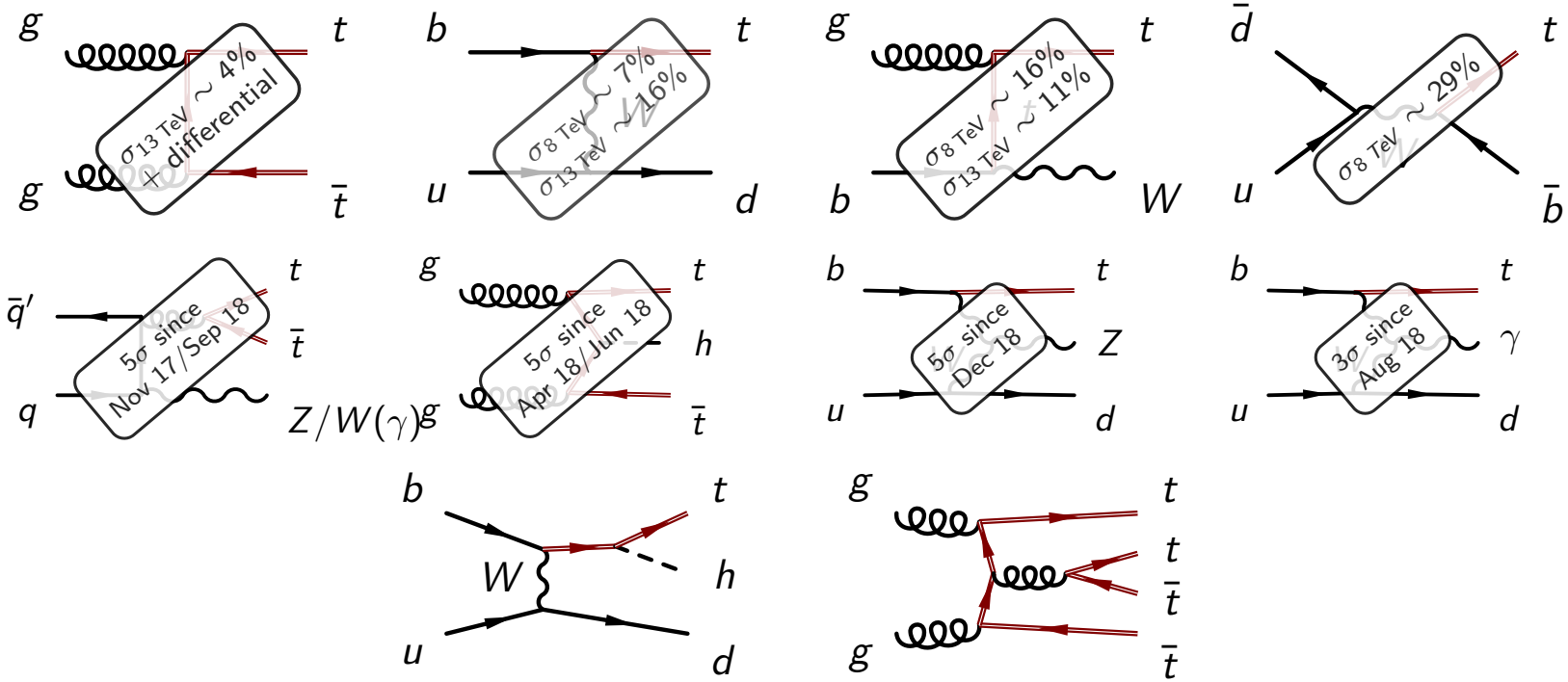
The SM top quark

- is 24 years old and remains a prime target
- has $y_t \simeq 1$, $V_{tb} \simeq 1$, $\Gamma_t \simeq 1.4$ GeV $> \Lambda_{\mathrm{QCD}}$
- has only been produced at hadron colliders



+ mass, spin correlation, W helicity fractions + exotica
[more in Clement Helsens' talk]

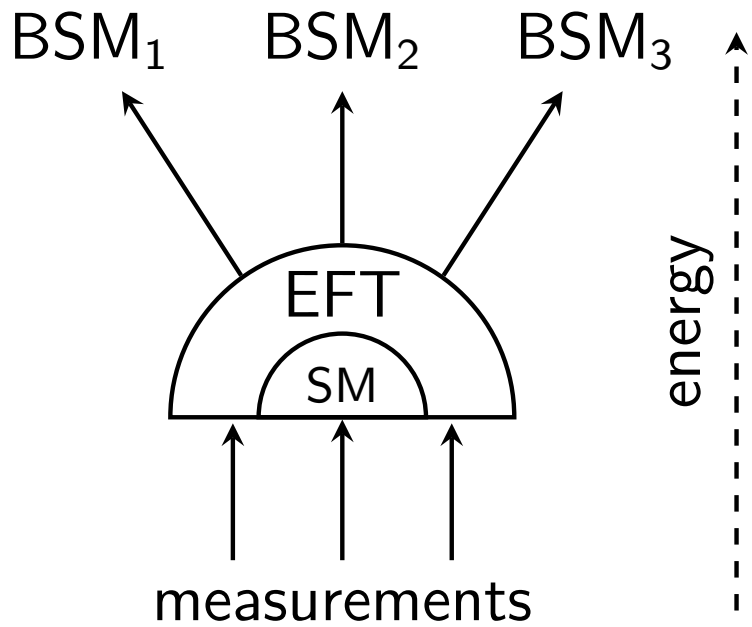
Beyond SM measurements

The SM effective field theory (SMEFT)

systematically parametrizes the theory space
in direct vicinity of the SM

- in a low-energy limit
- assuming SM fields and symmetries
- systematic and renormalizable when global

(...) if one writes down the most general possible Lagrangian, including all *terms consistent with assumed symmetry principles, (...) the result will simply be the most general possible S-matrix consistent with analyticity, perturbative unitarity, cluster decomposition and the assumed symmetry.* [*Phenomenological Lagrangians*, Weinberg '79]



The up-type sector at dim-6

Operators involving up-type quarks in the *Warsaw* basis: [Grzadkowski et al '10]

Four-quark operators (11)

$$O_{qq}^{1(ijkl)} = (\bar{q}_i\gamma^\mu q_j)(\bar{q}_k\gamma_\mu q_l),$$
$$O_{qq}^{3(ijkl)} = (\bar{q}_i\gamma^\mu \tau^I q_j)(\bar{q}_k\gamma_\mu \tau^I q_l),$$
$$O_{qu}^{1(ijkl)} = (\bar{q}_i\gamma^\mu q_j)(\bar{u}_k\gamma_\mu u_l),$$
$$O_{qu}^{8(ijkl)} = (\bar{q}_i\gamma^\mu T^A q_j)(\bar{u}_k\gamma_\mu T^A u_l),$$
$$O_{qd}^{1(ijkl)} = (\bar{q}_i\gamma^\mu q_j)(\bar{d}_k\gamma_\mu d_l),$$
$$O_{qd}^{8(ijkl)} = (\bar{q}_i\gamma^\mu T^A q_j)(\bar{d}_k\gamma_\mu T^A d_l),$$
$$O_{uu}^{(ijkl)} = (\bar{u}_i\gamma^\mu u_j)(\bar{u}_k\gamma_\mu u_l),$$
$$O_{ud}^{1(ijkl)} = (\bar{u}_i\gamma^\mu u_j)(\bar{d}_k\gamma_\mu d_l),$$
$$O_{ud}^{8(ijkl)} = (\bar{u}_i\gamma^\mu T^A u_j)(\bar{d}_k\gamma_\mu T^A d_l),$$
$$O_{quqd}^{1(ijkl)} = (\bar{q}_i u_j)\,\varepsilon\,(\bar{q}_k d_l),$$
$$O_{quqd}^{8(ijkl)} = (\bar{q}_i T^A u_j)\,\varepsilon\,(\bar{q}_k T^A d_l),$$

Two-quark operators (9)

$$O_{u\varphi}^{(ij)} = \bar{q}_i u_j \tilde{\varphi}\,(\varphi^\dagger\varphi),$$
$$O_{\varphi q}^{1(ij)} = (\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar{q}_i\gamma^\mu q_j),$$
$$O_{\varphi q}^{3(ij)} = (\varphi^\dagger i\overleftrightarrow{D}^I_\mu \varphi)(\bar{q}_i\gamma^\mu \tau^I q_j),$$
$$O_{\varphi u}^{(ij)} = (\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar{u}_i\gamma^\mu u_j),$$
$$O_{\varphi ud}^{(ij)} = (\tilde{\varphi}^\dagger iD_\mu \varphi)(\bar{u}_i\gamma^\mu d_j),$$
$$O_{uW}^{(ij)} = (\bar{q}_i\sigma^{\mu\nu}\tau^I u_j)\,\tilde{\varphi}\,W^I_{\mu\nu},$$
$$O_{dW}^{(ij)} = (\bar{q}_i\sigma^{\mu\nu}\tau^I d_j)\,\varphi\,W^I_{\mu\nu},$$
$$O_{uB}^{(ij)} = (\bar{q}_i\sigma^{\mu\nu} u_j)\quad\tilde{\varphi}\,B_{\mu\nu},$$
$$O_{uG}^{(ij)} = (\bar{q}_i\sigma^{\mu\nu} T^A u_j)\,\tilde{\varphi}\,G^A_{\mu\nu},$$

Two-quark-two-lepton operators (8)

$$O_{lq}^{1(ijkl)} = (\bar{l}_j\gamma^\mu l_j)(\bar{q}_k\gamma^\mu q_l),$$
$$O_{lq}^{3(ijkl)} = (\bar{l}_j\gamma^\mu \tau^I l_j)(\bar{q}_k\gamma^\mu \tau^I q_l),$$
$$O_{lu}^{(ijkl)} = (\bar{l}_j\gamma^\mu l_j)(\bar{u}_k\gamma^\mu u_l),$$
$$O_{eq}^{(ijkl)} = (\bar{e}_j\gamma^\mu e_j)(\bar{q}_k\gamma^\mu q_l),$$
$$O_{eu}^{(ijkl)} = (\bar{e}_j\gamma^\mu e_j)(\bar{u}_k\gamma^\mu u_l),$$
$$O_{lequ}^{1(ijkl)} = (\bar{l}_i e_j)\,\varepsilon\,(\bar{q}_k u_l),$$
$$O_{lequ}^{3(ijkl)} = (\bar{l}_i\sigma^{\mu\nu} e_j)\,\varepsilon\,(\bar{q}_k\sigma_{\mu\nu} u_l),$$
$$O_{ledq}^{(ijkl)} = (\bar{l}_i e_j)(\bar{d}_k q_l),$$

$\not{B}$ and $\not{L}$ operators (5)

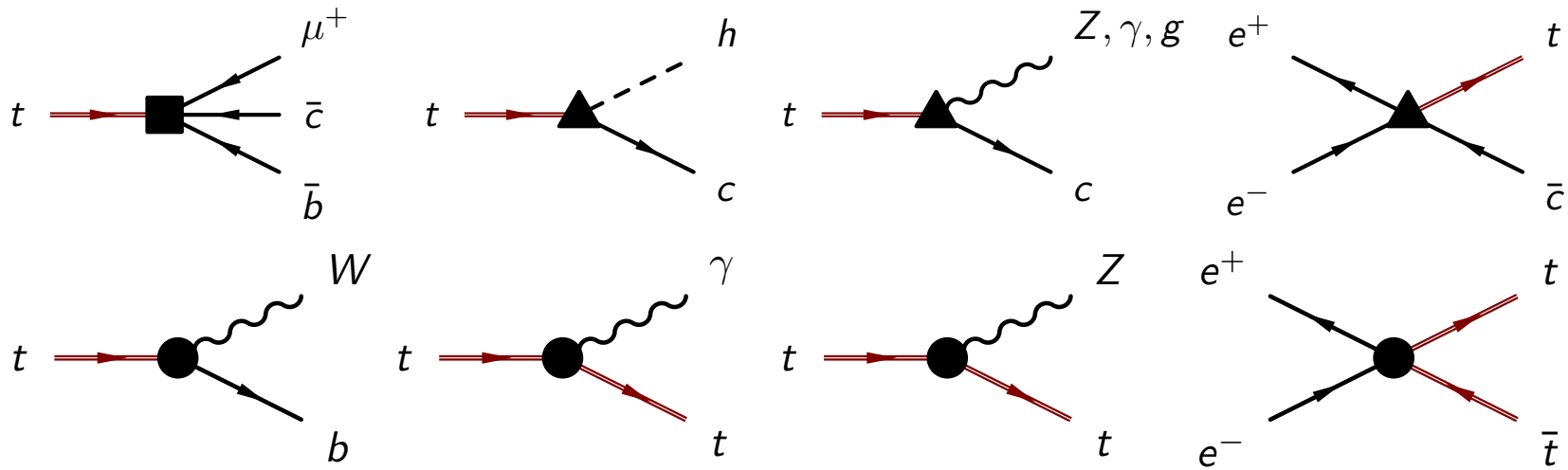
$$O_{duq}^{(ijkl)} = (\overline{d^c}_{i\alpha} u_{j\beta})(\overline{q^c}_{k\gamma}\varepsilon l_l)\,\epsilon^{\alpha\beta\gamma},$$
$$O_{qqu}^{(ijkl)} = (\overline{q^c}_{i\alpha}\varepsilon q_{j\beta})(\overline{u^c}_{k\gamma} e_l)\,\epsilon^{\alpha\beta\gamma},$$
$$O_{qqq}^{1(ijkl)} = (\overline{q^c}_{i\alpha}\varepsilon q_{j\beta})(\overline{q^c}_{k\gamma}\varepsilon l_l)\,\epsilon^{\alpha\beta\gamma},$$
$$O_{qqq}^{3(ijkl)} = (\overline{q^c}_{i\alpha}\tau^I\varepsilon q_{j\beta})(\overline{q^c}_{k\gamma}\tau^I\varepsilon l_l)\,\epsilon^{\alpha\beta\gamma},$$
$$O_{duu}^{(ijkl)} = (\overline{d^c}_{i\alpha} u_{j\beta})(\overline{u^c}_{k\gamma} e_l)\,\epsilon^{\alpha\beta\gamma}.$$

\+ *ijkl* generation index assignments

q, l: left-handed doublets
u, d, e: right-h. singlets

The SMEFT top quark

- could violate B at the quark level [1107.3805]
- could have sizeable FCNCs [1310.1618]
- could have four-point interactions
- could have modified vector or dipole couplings



Striving for global EFT analyses

Striving for global EFT analyses

$><$ considering one operator at the time *(individual sensitivity)*

i.e. including simultaneously all contributing operators, and combining various measurements

- up to contributions already sufficiently well constrained
- up to consistent theory assumption (e.g. flavour symmetry)

- because BSM do generically not generate one single op.
- because operators mix under RG flow

  $\rightarrow$ to preserve systematic theory-space coverage

  $\rightarrow$ to ensure renormalizability, order by order

Challenges in global EFT analyses

- cover multi-dimensional parameter spaces
  - adapt EXP simulation practices: morphing, re-weighting, ...
- combine measurements, processes, and sectors
  - coordinate analyses meant to be combined
  - overcome the separation in top, Higgs, EW,... EXP groups
- gather the info. needed to establish EFT validity range

LHC TOP WG standards

by the TH community, with extensive feedback from EXP [1802.07237]

- Fixing normalization and notation,
  for convenient linear
  dedicat
  outputs

- Indicative direct & indirect constraints

Interpreting top-quark LHC measurements in the standard-model effective field theory [here]

J. A. Aguilar Saavedra,[1] C. Degrande,[2] G. Durieux,[3] F. Maltoni,[4] E. Vryonidou,[2] C. Zhang[5] (editors), D. Barducci,[6] I. Brivio,[7] V. Cirigliano,[8] W. Dekens,[8,9] J. de Vries,[10] C. Englert,[11] M. Fabbrichesi,[12] C. Grojean,[3,13] U. Haisch,[2,14] Y. Jiang,[7] J. Kamenik,[15,16] M. Mangano,[2] D. Marzocca,[12] E. Mereghetti,[8] K. Mimasu,[4] L. Moore,[4] G. Perez,[17] T. Plehn,[18] F. Riva,[2] M. Russell,[18] J. Santiago,[19] M. Schulze,[13] Y. Soreq,[20] A. Tonero,[21] M. Trott,[7] S. Westhoff,[18] C. White,[22] A. Wulzer,[2,23,24] J. Zupan.[25]

LHC TOP WG standards

by the TH community, with extensive feedback from EXP [1802.07237]

- Fixing normalization and notation,
  for convenient linear combinations,
  dedicated implementation for MC simulation [here]

- General guiding principle for EFT use,
  and conventional assumptions about BSM flavour
  to prioritize explorations

- Specific example of global analysis strategy,
  identifying useful EXP outputs

- Indicative direct & indirect constraints

Combining observables and processes

Top operators in top processes (loosely defined)

Tevatron & LHC run-I [TopFitter 1512.03360]

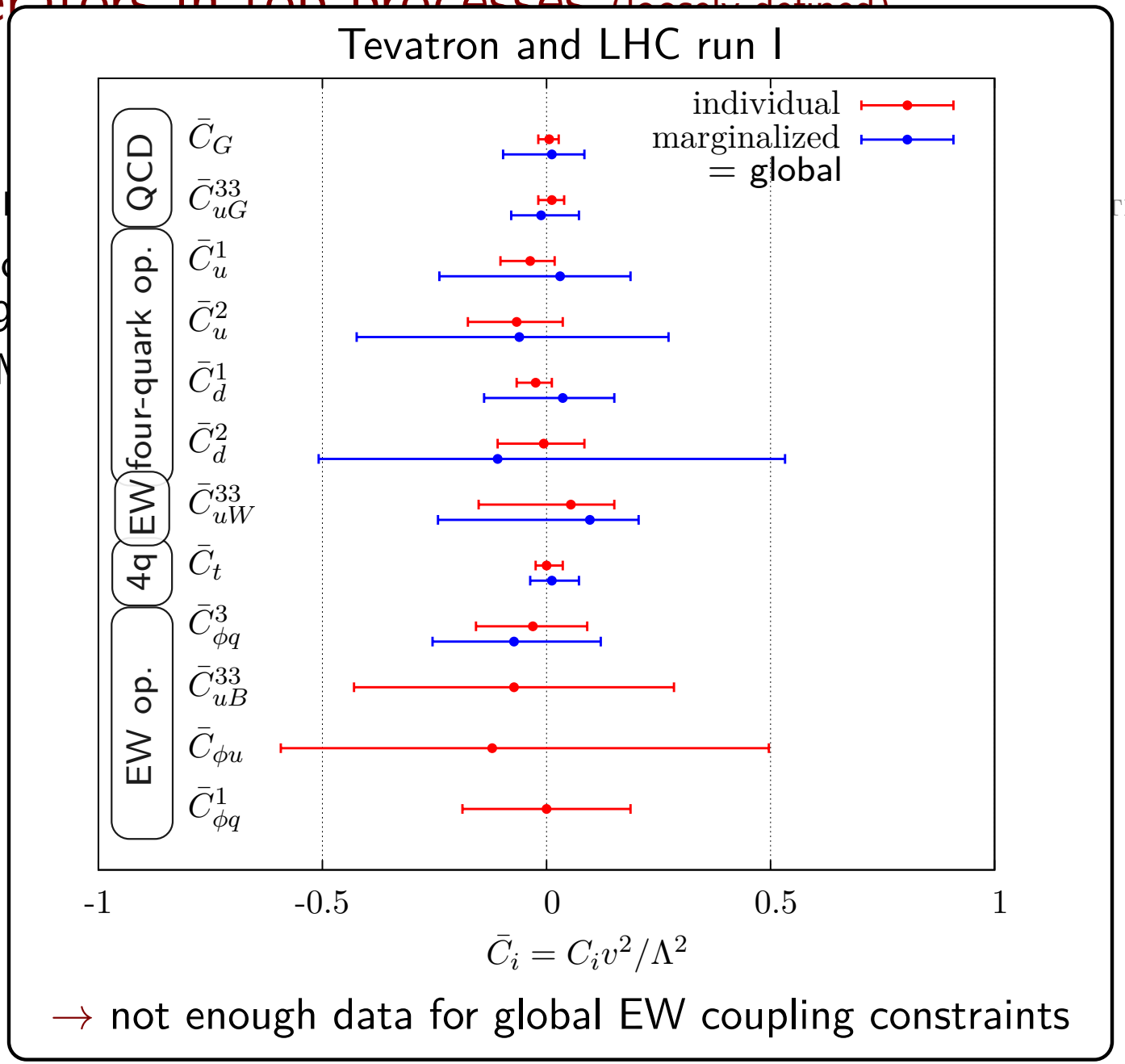
- global constraints on 9 op. (12 considered)
- 195 observables ($t\bar{t}$, single t, associated prod., decay)
- SM (N)NLO k-factors in each bin

Top operators in top processes (loosely defined)

Tevatr

- gl
- 19
- SM

TER 1512.03360]



→ not enough data for global EW coupling constraints

Top operators in top processes (loosely defined)

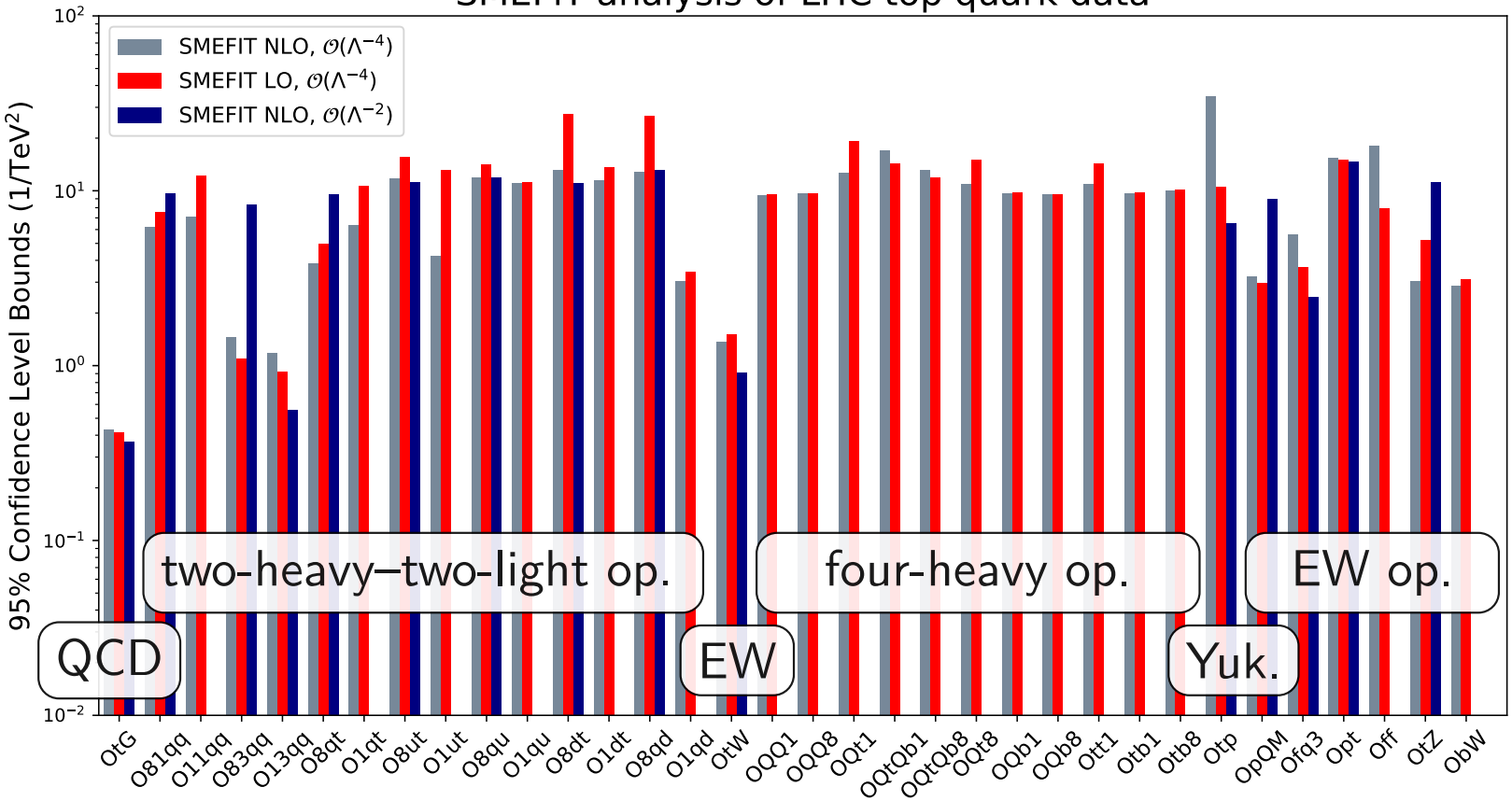
Tevatron & LHC run-I [TopFitter 1512.03360]

- global constraints on 9 op. (12 considered)
- 195 observables ($t\bar{t}$, single t, associated prod., decay)
- SM (N)NLO k-factors in each bin

+ LHC run-2 [SMEFiT 1901.05965]

- global constraints on 34 op. (CP-conserving, $U(2)_q \times U(2)_u \times U(2)_d$-symmetric)
- most EFT predictions at NLO in QCD
- PDF set excluding top data
- study of C_6/Λ^2 and C_6^2/Λ^4 relative relevance
- variation of probed energy

Top operators in top processes (loosely defined)



3360]

5965]

$\rightarrow$ C_6^2/Λ^4 terms often dominate C_6/Λ^2 ones

$\rightarrow$ NLO QCD EFT have sizeable effects

$\rightarrow$ constaints midly affected by $m_{t\bar{t}}$ or $m_{t\bar{t}t\bar{t}} < 3\,\text{TeV}$ information

$\rightarrow$ global constraints still far from individual ones

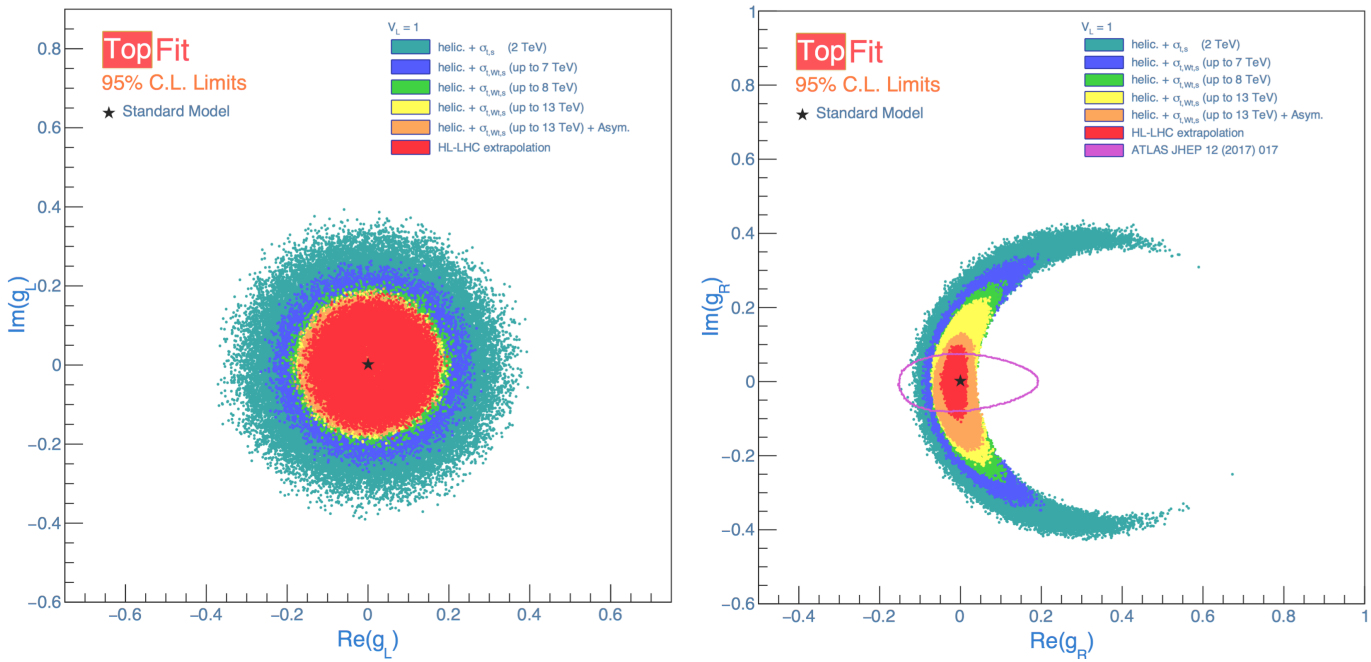
Future prospects

HL-LHC

[Yellow Rept. WG1]

- factor $\mathcal{O}$(1-10) improvement on individual sensitivities
- fighting against systematics

W-helicity fractions, single top production, $t\bar{t}$ asymmetries [Déliot et al. 1811.02492]



$g_L \equiv \frac{v^2}{\Lambda^2} c^*_{bW}$, $g_R \equiv \frac{v^2}{\Lambda^2} c_{tW}$ in LHC TOP WG conventions,

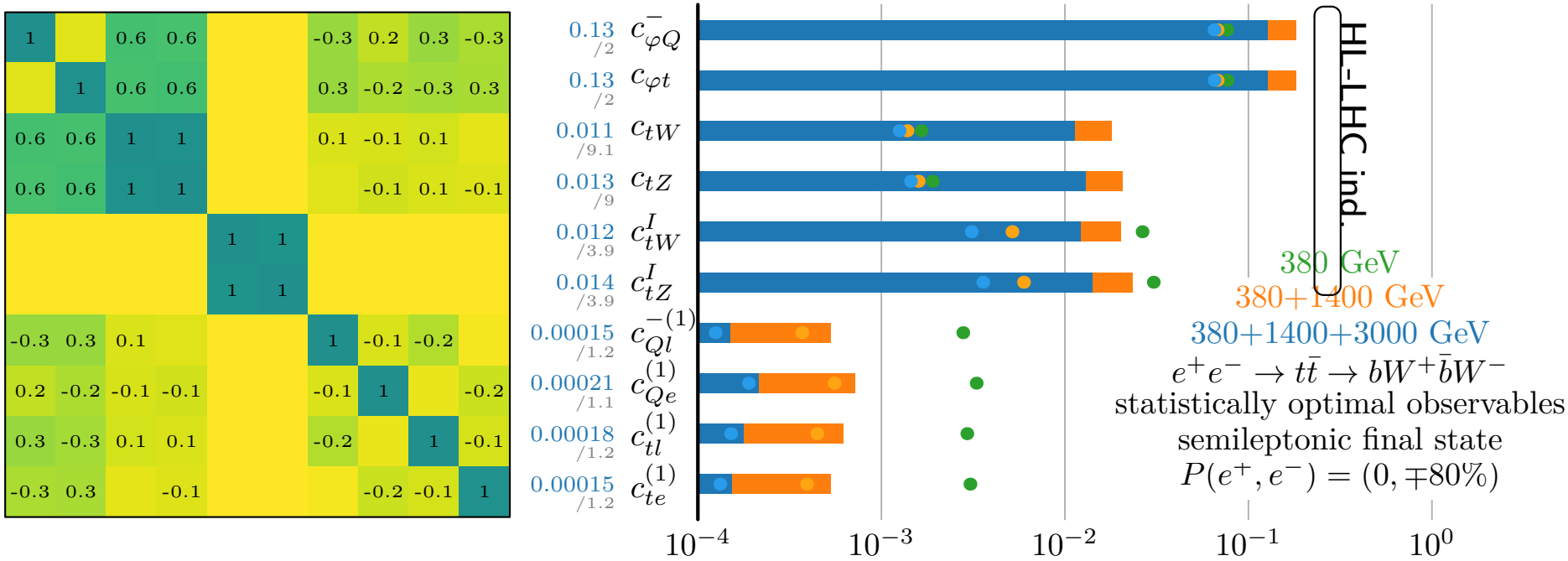
$\rightarrow$ limited improvement between current and HL-LHC

Future prospects

Future lepton colliders

- global analysis of $e^+e^- \to t\bar{t} \to bW^+\bar{b}W^-$ (all 10 op.) [1807.02121]
- with powerful *statistically optimal observables*
- factor $\mathcal{O}$(10-1000) improvement on individual sensitivities

CLIC scenario (1, 2.5, and 5 ab^{-1}), 1σ, in TeV^{-2}, bars: global, blobs: individual

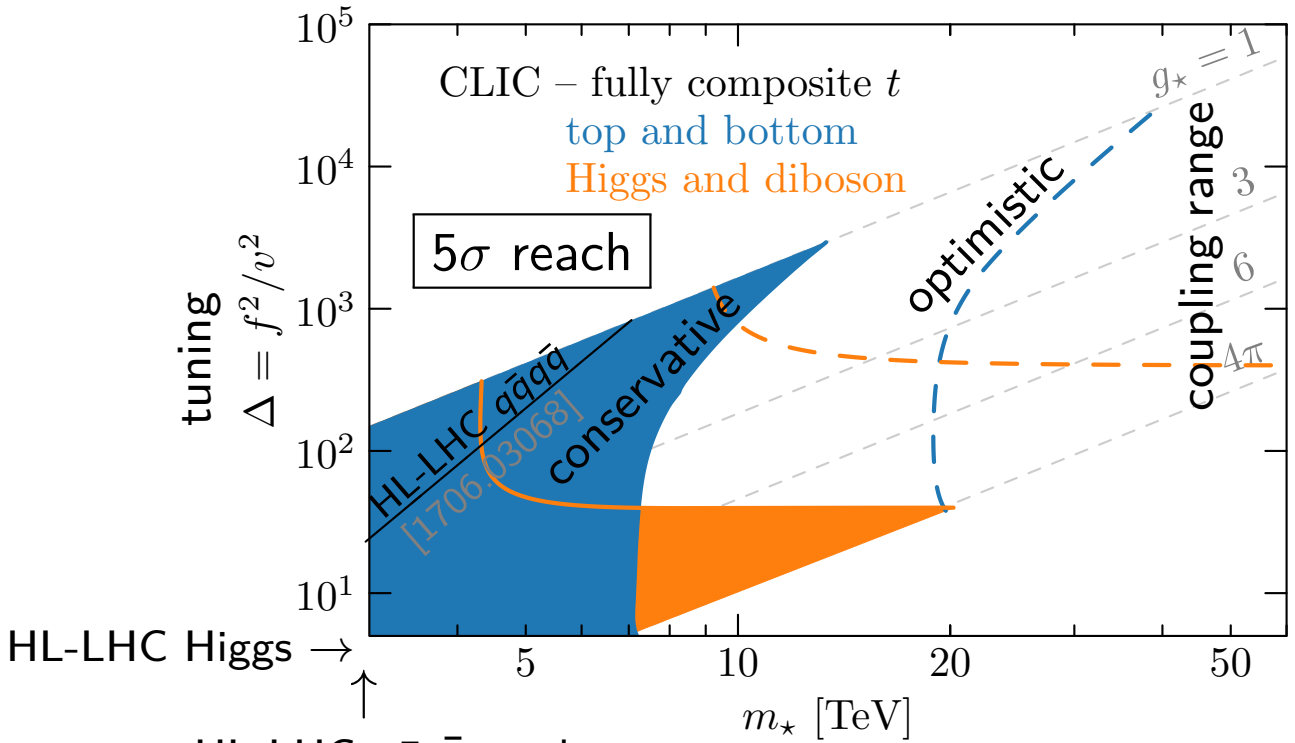


→ two centre-of-mass energies are needed

→ high-energy helps constraining four-fermion operators

Future prospects

... and four-fermion operators drive top limits on compositeness



[1807.10273]

→ Higgs probes fine tuning

→ top probes composite partner masses

→ high-energy helps constraining four-fermion operators

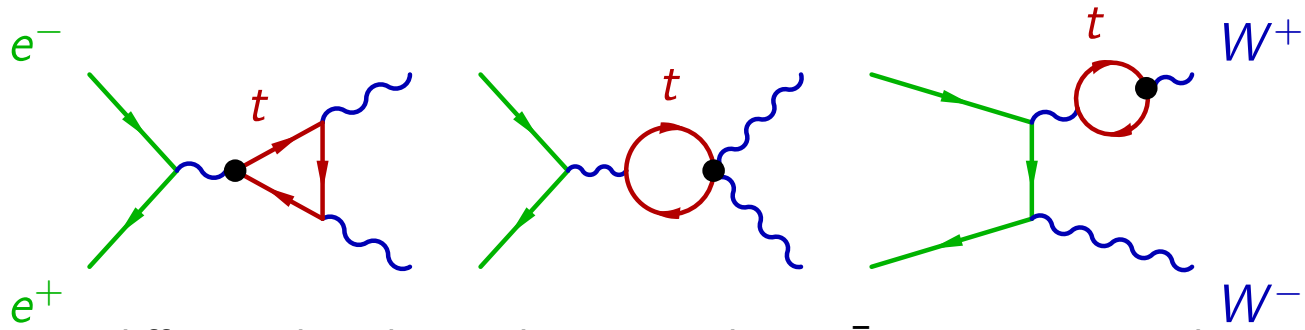
Combining sectors

Top operators in EW processes

Comprehensive loop calculations

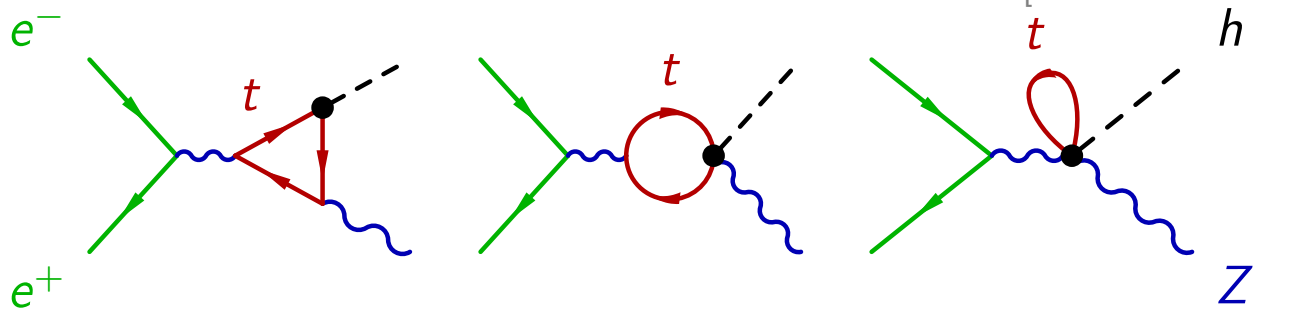
E.g. for lepton colliders:

- At the Z pole [Zhang, Greiner, Willenbrock '12]
- In diboson production [GD, Gu, Vrionidou, Zhang '18]



differential in the production angle, $e\bar{e}t\bar{t}$ operators omited

- In Higgs [Vrionidou, Zhang, '18] [see also Boselli et al '18]



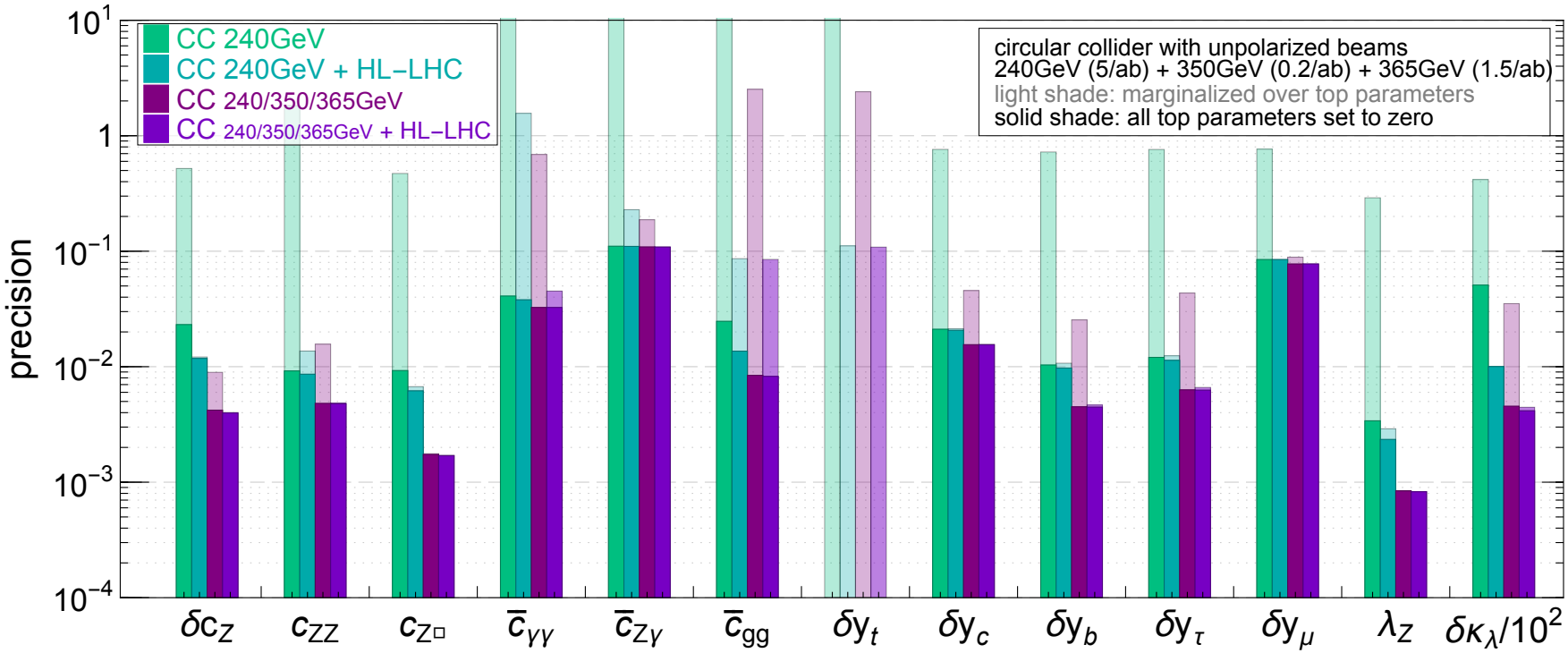
- Higgsstrahlung and W-fusion through reweighing in MG5/aMC@NLO
- Higgs decays

Top operators in EW processes

Future circular lepton collider prospects

[1809.03520]

light shades: 12 Higgs op. floated, 6 top op. floated
dark shades: 12 Higgs op. floated, 6 top op. $\to$ 0



$\to$ uncertainties on top meas. contaminate Higgs meas.:
i.e. need $e^+e^- \to t\bar{t}$ and HL-LHC constraints for Higgs precision

Top-quark physics: challenges and opportunities

The top quark has been in the spotlight for 20^+ years
but retains shadows to be explored.

The standard-model effective field theory
helps covering the theory space systematically.

Challenging global analyses are needed,
spanning multi-dimensional parameter spaces,
combining observables, processes and sectors.

A lot remains to be learned about the top quark,
covering BSM parameter space along the way.

Backup

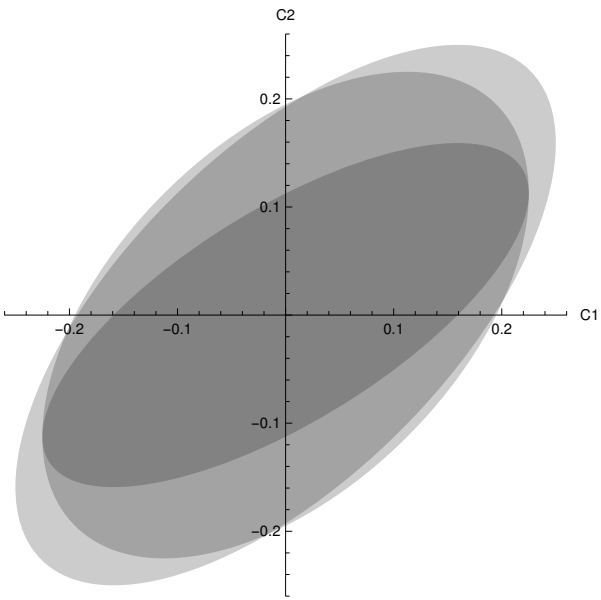
Statistically optimal observables

[Atwood,Soni '92]
[Diehl,Nachtmann '94]

minimize the one-sigma ellipsoid in EFT parameter space

(*joint efficient* set of estimators, saturating the Cramér-Rao bound: $V^{-1} = I$,like MEM)

For small C_i, with a phase-space distribution $\sigma(\Phi) = \sigma_0(\Phi) + \sum_i C_i\, \sigma_i(\Phi)$, the stat. opt. obs. are the average values of $O_i(\Phi) = \sigma_i(\Phi)/\sigma_0(\Phi)$.



e.g. $\sigma(\phi) = 1 + \cos(\phi) + C_1 \sin(\phi) + C_2 \sin(2\phi)$

1. asymmetries: $O_i \sim \text{sign}\{\sin(i\phi)\}$
2. moments: $O_i \sim \sin(i\phi)$
3. statistically optimal: $O_i \sim \dfrac{\sin(i\phi)}{1 + \cos\phi}$

$\Longrightarrow$ area ratios 1.9 : 1.7 : 1

Previous applications in $e^+e^- \to t\,\bar{t}$, on different distributions:
[Grzadkowski, Hioki '00] [Janot '15] [Khiem et al '15]

Conventional BSM flavour assumptions (FCNCs treated separately)

To prioritize the study of flavour structures

Lepton sector (not critical)

- rather loose $[U(1)_{l+e}]^3$ aka flavour diagonality
- could easily be restricted to $U(3)_{l+e}$, $U(3)_l \times U(3)_e$, or ...

Quark sector (baseline and variants)

mostly restrict the large number of four-quark operators

Baseline: $U(2)_q \times U(2)_u \times U(2)_d$ among first two generations

$\equiv$ SM flavour symmetry in the limit $y_{u,d,s,c} \to 0$, $V_{\rm CKM} \to \mathbb{I}$

forces the first two generations to appear as $\sum_{i=1,2} \bar{q}_i q_i$, $\bar{u}_i u_i$, $\bar{d}_i d_i$

Extended: $U(2)_{q+u+d}$ [sugg. by J.A.Aguilar-Saavedra]

- allows light right-handed charged currents $\sum_{i=1,2} \bar{u}_i d_i$
- allows light chirality flipping currents $\sum_{i=1,2} \bar{q}_i u_i$, $\bar{q}_i d_i$

Restricted: *top-philic* scenario [sugg. by A.Wulzer]

- assumes NP generates all operators with tops and bosons
- then project that over-complete set on the Warsaw basis with EOM, etc.

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Baseline: $U(2)_q \times U(2)_u \times U(2)_d$ among first two generations

d.o.f. counting

	baseline	extended	restricted
four heavy quarks	$11 + 2$ CPV		5
two light and two heavy quarks	14	$+10 + 10$ CPV	} 5
two heavy quarks and two leptons	$(8 + 3$ CPV$)\times 3$		}
two heavy quarks and bosons	$9 + 6$ CPV		$9 + 6$ CPV

- assumes NP generates all operators with tops and bosons
- then project that over-complete set on the Warsaw basis with EOM, etc.