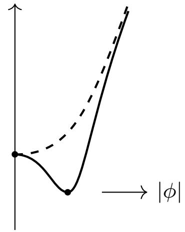
Probing new physics systematically with effective field theories

Gauthier Durieux
(CERN)

Be.HEP meeting, 22 Dec 2021

Electroweak symmetry breaking

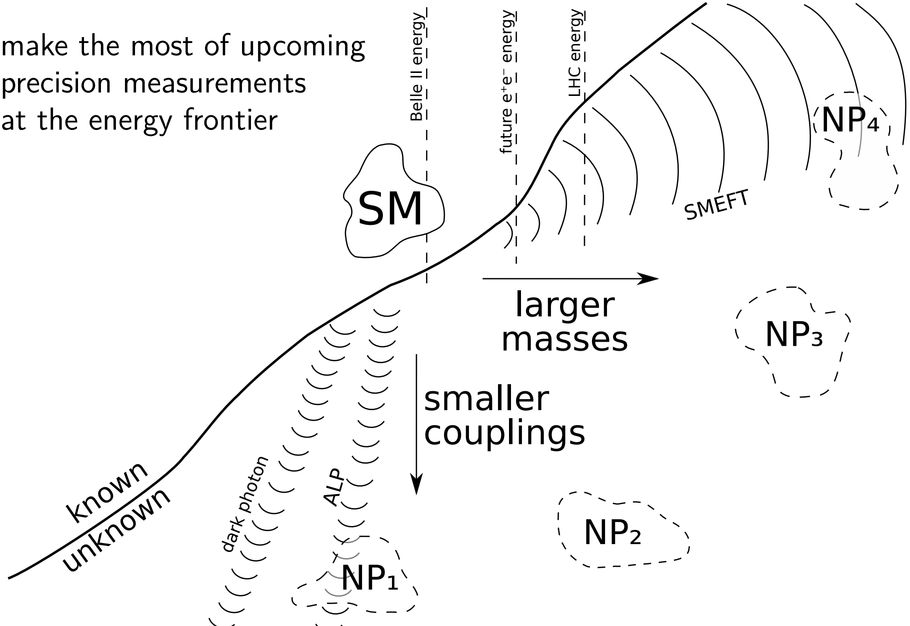
Microscopic dynamics behind
Ginzburg-Landau-like phenomenological description?



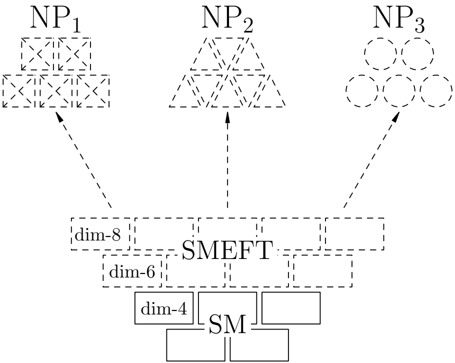
$V(\phi) = \pm\mu^2|\phi|^2 + \lambda|\phi|^4$

Systematic indirect exploration

make the most of upcoming
precision measurements
at the energy frontier

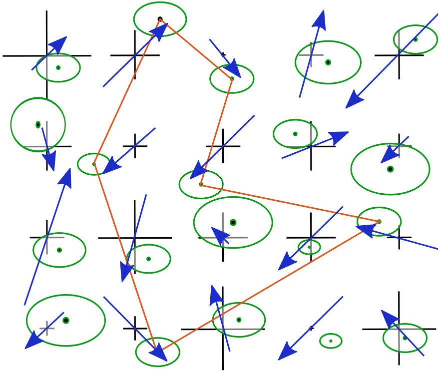


Taking the SM to higher dimensions



- using established bricks (fields and symmetries)
- extension organised by relevance (dimension)
- including all deformations (theory space coverage)

Isolating patterns of new physics



array of sensitive observables

- precise SM predictions
- precise SMEFT predictions
- precise measurements

→ correlate deviations

SMEFT challenges

1. improved sensitivity (develop powerful and complementary obs.)
2. more global picture (combine sectors)
3. precise data interpretation (include quantum corrections)
4. new-physics implications (map to models)
5. framework understanding (leverage on-shell methods)

1. Improved sensitivity

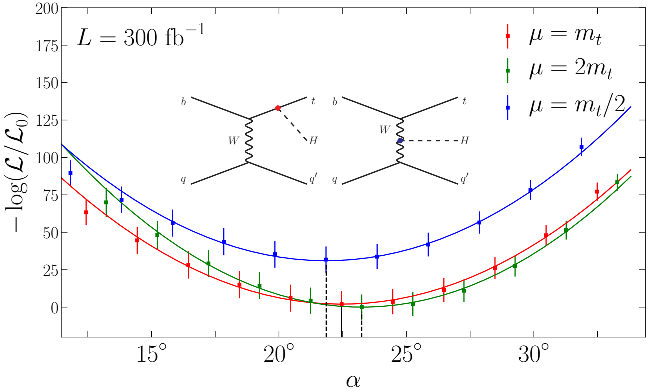
Matrix element method

[Kondo '88], [...]
[Kraus, Martini, Peitzsch, Uwer '19]

$$L(\theta|\{x_n\}) = \prod_{n=1}^{N} p(x_n|\theta) \qquad \text{with} \qquad p(x|\theta) = \frac{1}{\sigma(\theta)} \int dz \frac{d\sigma(z|\theta)}{dz} W(z,x)$$

possibly adding total rate information

Demanding – beyond 1D parameter space
– if partial or imperfect measurements ($W(z,x) \neq \delta(z,x)$)

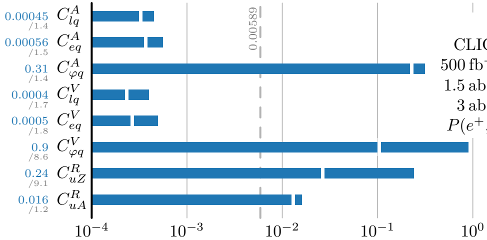


Statistically optimal observables

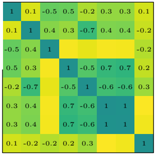
- in TeV^{-2}, $\Delta\chi^2 = 1$
- white marks: individual constraints
- gray numbers: global/individual ratios

[GD, Perelló, Vos, Zhang '18]

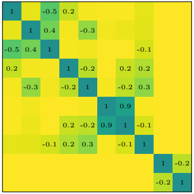
$\sigma + A^{\mathrm{FB}}$:



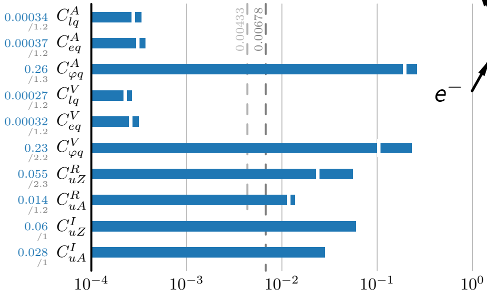
σ and A^{FB}
CLIC-like run scenario
$500\,\mathrm{fb}^{-1}$ at $\sqrt{s} = 380\,\mathrm{GeV}$
$1.5\,\mathrm{ab}^{-1}$ at $\sqrt{s} = 1.4\,\mathrm{TeV}$
$3\,\mathrm{ab}^{-1}$ at $\sqrt{s} = 3\,\mathrm{TeV}$
$P(e^+, e^-) = (0\%, \mp 80\%)$

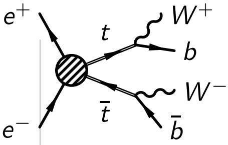


correlation matrices



Statistically optimal observables:



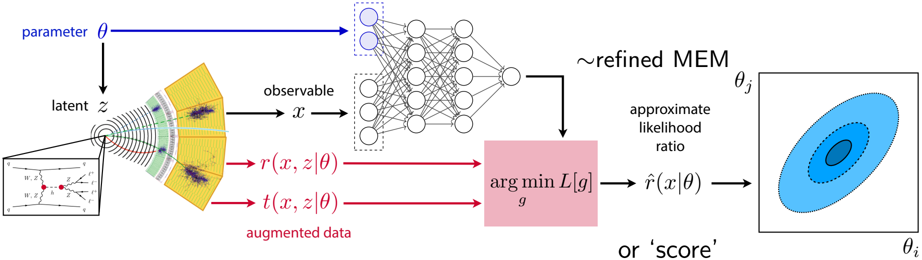


reduced sensitivity to quadratic dependences

Machine-learning enhancement

[DNN integration for MEM: Bury, Delaere '20]
[K. Cranmer 11 Jan '21]

- extrapolate from theory to experiment
- avoid integration over unmeasured particles and resolutions
- include shower, hadronization and detector effects



or 'score'

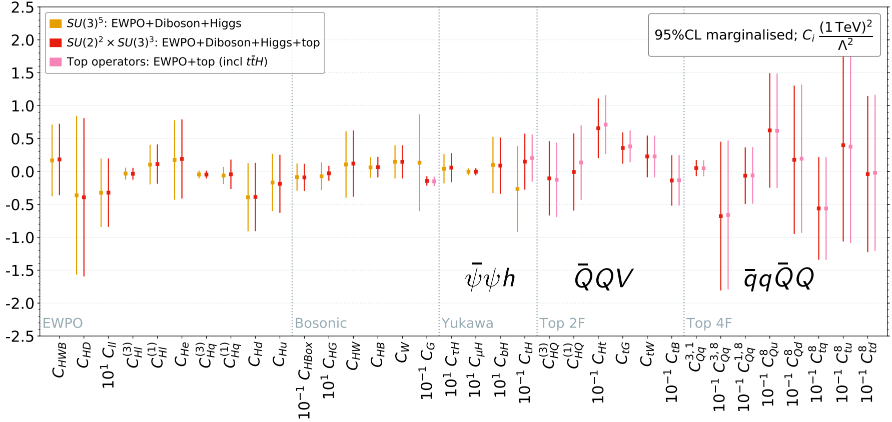
$$t(x) = \nabla_\theta \log p(x|\theta)\big|_{\theta_{\rm SM}}$$

∼ refined optimal observables: $\langle t(x) \rangle_{\{x_n\}}$

2. More global picture

Fitmaker: EW+Higgs+top

[Ellis, Madigan, Mimasu, Sanz, You '20]

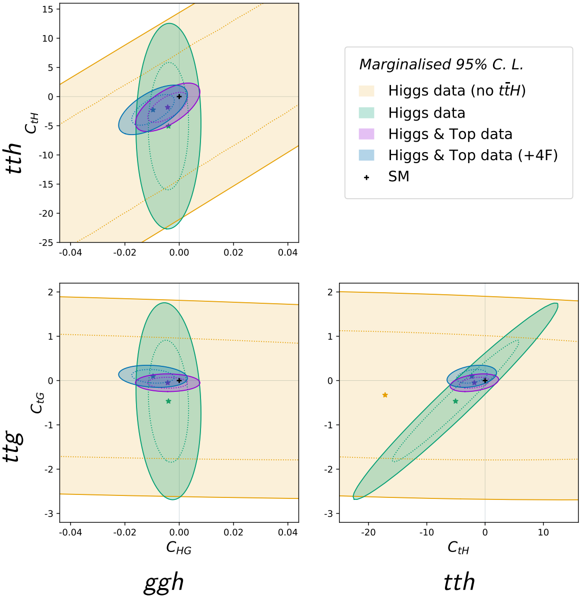


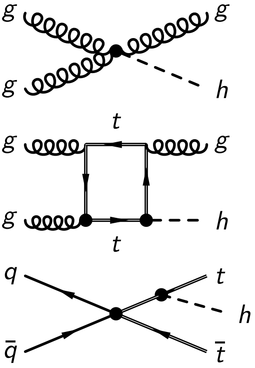
- tension in various observables but no large deviation consistent overall

e.g. obs.	ttW	$m_{tt}\&y_{tt}$	$p_T^{\text{t-chan}}$
χ^2/ndf	2	1.5	5

- largest correlations btw EW and Higgs, no significant degradation from top

Fitmaker: EW+Higgs+top



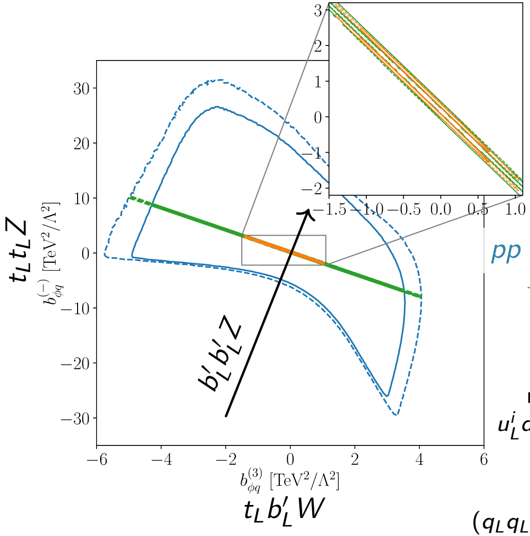


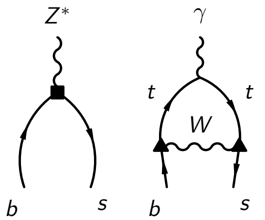
- Higgs/top complementarity among C_{HG}, C_{tH}, C_{tG}
- in subset of 9 operators $C_{H\Box}$, C_{HG}, C_{HW}, C_{HB}, C_{tG}, C_{tH}, C_{bH}, $C_{\tau H}$, $C_{\mu H}$
- robust against $\bar{q}q\bar{t}t$ op.

Sfitter: top+bottom

$B_s \to \mu^+\mu^-$: $b'_L b'_L Z$ current
$B \to X_s\gamma$: $t_L b'_L W$ current

with $b'_L \equiv V_{td} d_L + V_{ts} s_L + V_{tb} b_L$





$pp \to ttZ, tZ, tW, tj$
$+ B_s \to \mu^+\mu^-$
$+ B \to X_s\gamma$
(no $Z \to bb$)

marginalized over
$u_L^i d_L^i W / u_L^i u_L^i Z / d_L^i d_L^i Z$,
$\Delta\chi^2 = 2.3$ & 6

($q_L q_L q_L q_L$ op. also studied)

EFTfitter: top+bottom

[Bißmann et al. '20]

Operators [8]

- top dipoles [3]
- top currents [3]
- $b'_L b'_L \ell\ell$ [2]

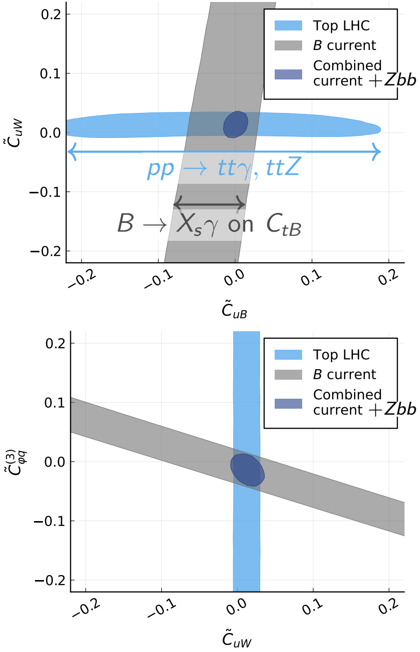
Constraints

- $t\bar{t}$, $t\bar{t}\gamma$, $t\bar{t}Z$ rates
- W helicity fractions
- $Z \to b\bar{b}$ (at tree level)
- $b \to s\gamma$, $b \to s\ell\ell$ (`flavio+wilson`)
- B_s mixing, $b \to s\nu\bar{\nu}$

\+ future $e^+e^- \to t\,\bar{t}$ (σ,$A_{\rm FB}$)

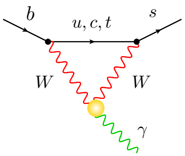
Improvements from b

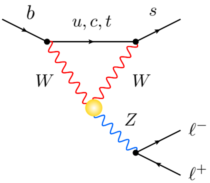
- mostly on C_{uB}, $C^3_{\varphi q}$ ($b \to s\gamma$)
- not much in $C_{\varphi u}$
- none in C_{tW}, C_{tG}

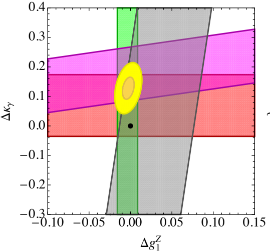


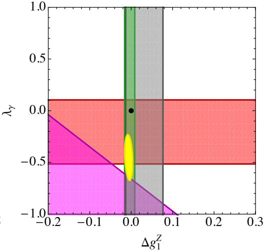
EW+bottom

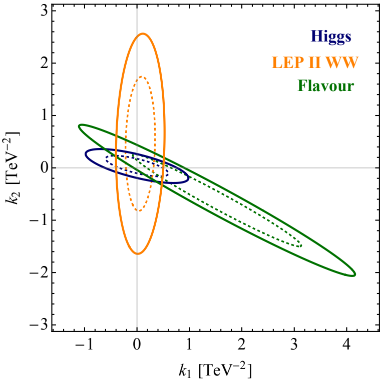
[Bobeth, Haisch '15]
[Aoude, Hurth, Renner, Shepherd '20]











10 EWPO operators (no λ_γ)
ran to $\Lambda = 1\,\text{TeV}$
excl. $b \to s\mu\mu$ angular obs.

ΔC_7 : $B \to X_s\gamma$
ΔC_9 : $B \to K^*\mu\mu$
ΔC_{10} : $B_s \to \mu\mu, \ldots$
δg_L^b : $Z \to bb$

3 TGC analysis
ran to $\Lambda = 2\,\text{TeV}$
2D individual, 68(95)%CL

3. Precise data interpretation

SMEFT at one loop

- $pp \to jj$ ($q\bar{q}q\bar{q}$) [Gao, Li, Wang, Zhu, Yuan '11]
- $pp \to t\bar{t}$ ($q\bar{q}t\bar{t}$) [Shao, Li, Wang, Gao, Zhang, Zhu '11]
- $pp \to VV$ [Dixon, Kunszt, Signer '99] [Melia, Nason, Röntsch, Zanderighi '11] [Baglio, Dawson, Lewis '17, '18, '19] [Chiesa, Denner, Lang '18]
- EWPO (top) [Zhang, Greiner, Willenbrock '12]
- top decays [Zhang '14] [Boughezal, Chen, Petriello, Wiegand '19]
- top FCNCs UFO [Degrande, Maltoni, Wang, Zhang '14] [GD, Maltoni, Zhang '14]
- $pp \to t\bar{t}$ (chromo-dipole) [Franzosi, Zhang '15]
- $h \to \gamma\gamma$, VV, γZ [Hartmann, Trott '15] [Ghezzi, Gomez-Ambrosio, Passarino, Uccirati '15] [Dawson, Giardino '18] [Dedes, Paraskevas, Rosiek, Suxho, Trifyllis '18] [Dawson, Giardino '18] [Dedes, Suxho, Trifyllis '19]
- $h \to f\bar{f}$ [Gauld, Pecjak, Scott '15, '16] [Cullen, Pecjak, Scott '19, '20]
- $pp \to tj$ [Zhang '16] [de Beurs, Laenen, Vreeswijk, Vryonidou '18]
- $pp \to t\bar{t}Z$, $gg \to ZH$ [Röntsch, Markus Schulze '14] [Bylund, Maltoni, Vryonidou, Zhang '16]
- $pp \to t\bar{t}H$, $gg \to Hj, HH$ [Maltoni, Vryonidou, Zhang '16]
- $pp \to HV$ [Degrande, Fuks, Mawatari, Mimasu, Sanz '16] [Alioli, Dekens, Girard, Mereghetti '18]
- Z, W poles [Hartmann, Shepherd, Trott '16] [Dawson, Ismail, Giardino '18, '18, '19]
- $pp \to h$ [Grazzini, Ilnicka, Spira, Wiesemann '16] [Deutschmann, Duhr, Maltoni, Vryonidou '17]
- $pp \to tjZ, tjh$ [Degrande, Maltoni, Mimasu, Vryonidou, Zhang '18]
- $pp \to$ jets (triple gluon) UFO [Hirshi, Maltoni, Tsinikos, Vryonidou '18]
- Higgs self-coupling [McCullough '13] [Gorbahn, Haisch '16] [Degrassi et al. '16, '17] [Bizon et al. '16] [Kribs et al. '16] [Maltoni, Pagani, Shivaji, Zhao '17] [Di Vita, GD, Grojean, Gu, Liu, Panico, Riembau, Vantalon '17]
- EW Higgs & WW (top) [Vryonidou, Zhang '18] [GD, Gu, Vryonidou, Zhang '18] [Boselli, Hunter, Mitov '18]
- EW $pp \to t\bar{t}$ (ttZ,tth) [Martini, Schulze '19] [Martini, Pan, Schulze, Xiao '21]
- all QCD and four-quarks UFO [Degrande, GD, Maltoni, Mimasu, Vryonidou, Zhang '20]
- EW $pp \to \ell^+\ell^-$ [Dawson, Giardino '21]

SMEFT at one loop: automation

CP and flavour symmetries

compatible with 5FS

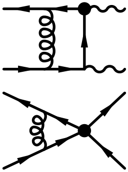
- $U(2)_q \times U(2)_u \times U(3)_d$ — no light-quark right-handed CC, or chiral flip
- $[U(1)_l \times U(1)_e]^3$ — 'diagonality' without LFU, no chiral flips

Bosonic and top operators [67]

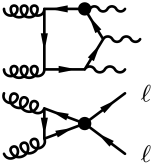
- Higgs, electroweak, bosonic [8]
- $\bar{Q}Q, \bar{q}q, \bar{\ell}\ell$ currents $+W, Z$ $(+h)$ [16]
- $\bar{Q}Q$ dipoles (W, Z, γ) and Yukawa [4]
- $\bar{Q}Q + (\bar{Q}Q, \bar{q}q, \bar{\ell}\ell)$ [5+17+17]

Counterterms [UV & R2, up to 5pt] for:

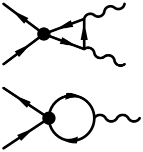
NLO QCD corr. (reals + virtuals)



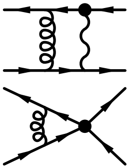
Loop-induced with g_s



Loop-induced with four-quarks



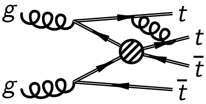
Mixed QCD/EW in single top $(+\, Z, W, h)$

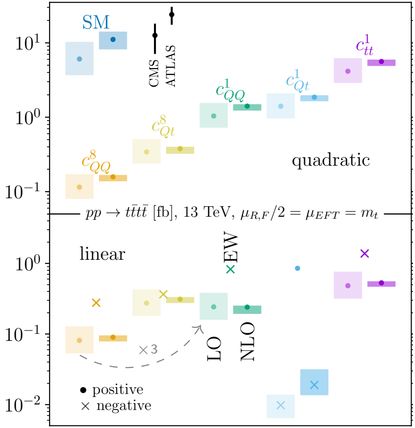


[Degrande, GD, Maltoni, Mimasu, Vryonidou, Zhang '20]

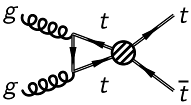
SMEFT at one loop: automation

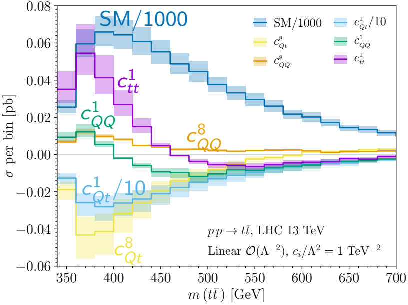
Better accuracy and uncertainties





New sensitivities



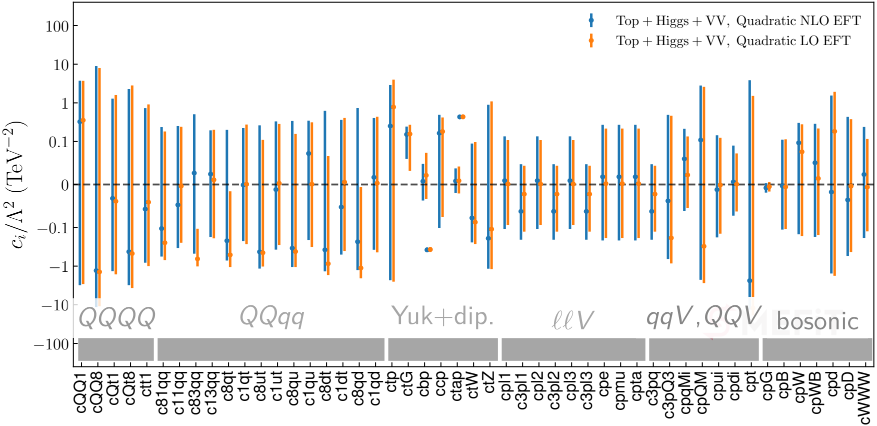


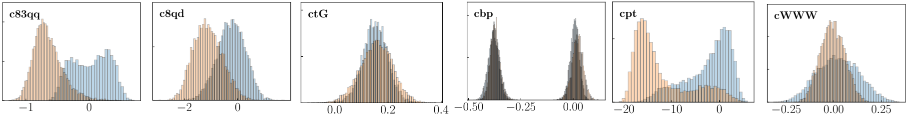
technicalities:

- anomaly cancellation
- evanescent operators

SMEFiT: diboson+Higgs+top

NLO SMEFT in $t\bar{t}$, single top, $gg \to h$, hV, tth, $h \to bb$, diboson



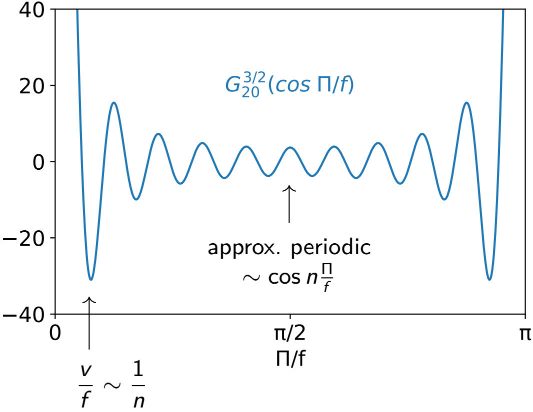


4. New-physics implications

Gegenbauer composite Higgs

[GD, McCullough, Salvioni '21]

Gegenbauer potentials $G_n^{(N-1)/2}(\cos\frac{\Pi}{f})$ are radiatively stable for pseudo-Nambu-Goldstone bosons of $SO(N+1) \to SO(N)$.

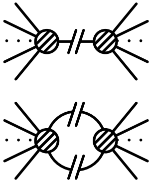


They naturally yield SM-like couplings for a pNGB Higgs, with deviations scaling as v^2/f^2, except for the Higgs trilinear.

5. Framework understanding

On-shell perspective on SMEFT

factorization/unitarity



construct amplitudes from particles

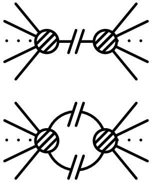
instead of operators from fields

→ avoiding gauge and field-redefinition redundancies

→ better understanding & more efficient computations

On-shell perspective on SMEFT

factorization/unitarity



c

graviton Feynman rules

[De Witt '67]

$$\frac{\delta^3 S}{\delta\varphi_{\mu\nu}\delta\varphi_{\sigma'\tau'}\delta\varphi_{\rho''\lambda''}} \longrightarrow$$

$$\mathrm{Sym}\big[-\tfrac{1}{4}P_3(p\cdot p'\eta^{\mu\nu}\eta^{\sigma\tau}\eta^{\rho\lambda})-\tfrac{1}{4}P_6(p^\sigma p^\tau\eta^{\mu\nu}\eta^{\rho\lambda})+\tfrac{1}{4}P_3(p\cdot p'\eta^{\mu\sigma}\eta^{\nu\tau}\eta^{\rho\lambda})+\tfrac{1}{2}P_6(p\cdot p'\eta^{\mu\nu}\eta^{\sigma\rho}\eta^{\tau\lambda})+P_3(p^\sigma p^\lambda\eta^{\mu\nu}\eta^{\tau\rho})$$
$$-\tfrac{1}{2}P_3(p^\tau p'^\mu\eta^{\nu\sigma}\eta^{\rho\lambda})+\tfrac{1}{2}P_3(p^\rho p'^\lambda\eta^{\mu\sigma}\eta^{\nu\tau})+\tfrac{1}{2}P_6(p^\rho p^\lambda\eta^{\mu\sigma}\eta^{\nu\tau})+P_6(p^\sigma p'^\lambda\eta^{\tau\mu}\eta^{\nu\rho})+P_3(p^\sigma p'^\mu\eta^{\tau\rho}\eta^{\lambda\nu})$$
$$-P_3(p\cdot p'\eta^{\nu\sigma}\eta^{\tau\rho}\eta^{\lambda\mu})\big],$$

$$\frac{\delta^4 S}{\delta\varphi_{\mu\nu}\delta\varphi_{\sigma'\tau'}\delta\varphi_{\rho''\lambda''}\delta\varphi_{\iota'''\kappa'''}} \longrightarrow$$

$$\mathrm{Sym}\big[-\tfrac{1}{8}P_6(p\cdot p'\eta^{\mu\nu}\eta^{\sigma\tau}\eta^{\rho\lambda}\eta^{\iota\kappa})-\tfrac{1}{8}P_{12}(p^\sigma p^\tau\eta^{\mu\nu}\eta^{\rho\lambda}\eta^{\iota\kappa})-\tfrac{1}{4}P_6(p^\sigma p'^\mu\eta^{\nu\tau}\eta^{\rho\lambda}\eta^{\iota\kappa})+\tfrac{1}{8}P_6(p\cdot p'\eta^{\mu\sigma}\eta^{\nu\tau}\eta^{\rho\lambda}\eta^{\iota\kappa})$$
$$+\tfrac{1}{4}P_6(p\cdot p'\eta^{\mu\nu}\eta^{\sigma\tau}\eta^{\rho\iota}\eta^{\lambda\kappa})+\tfrac{1}{4}P_{12}(p^\sigma p^\tau\eta^{\mu\nu}\eta^{\rho\iota}\eta^{\lambda\kappa})+\tfrac{1}{2}P_6(p^\sigma p'^\mu\eta^{\nu\tau}\eta^{\rho\iota}\eta^{\lambda\kappa})-\tfrac{1}{4}P_6(p\cdot p'\eta^{\mu\sigma}\eta^{\nu\tau}\eta^{\rho\iota}\eta^{\lambda\kappa})$$
$$+\tfrac{1}{4}P_{24}(p\cdot p'\eta^{\mu\nu}\eta^{\sigma\rho}\eta^{\tau\lambda}\eta^{\iota\kappa})+\tfrac{1}{4}P_{24}(p^\sigma p^\tau\eta^{\mu\rho}\eta^{\nu\lambda}\eta^{\iota\kappa})+\tfrac{1}{4}P_{12}(p^\rho p'^\lambda\eta^{\mu\sigma}\eta^{\nu\tau}\eta^{\iota\kappa})+\tfrac{1}{2}P_{24}(p^\sigma p'^\rho\eta^{\tau\mu}\eta^{\nu\lambda}\eta^{\iota\kappa})$$
$$-\tfrac{1}{2}P_{12}(p\cdot p'\eta^{\nu\sigma}\eta^{\tau\rho}\eta^{\lambda\mu}\eta^{\iota\kappa})-\tfrac{1}{2}P_{12}(p^\sigma p'^\mu\eta^{\tau\rho}\eta^{\lambda\nu}\eta^{\iota\kappa})+\tfrac{1}{2}P_{12}(p^\sigma p^\rho\eta^{\tau\lambda}\eta^{\mu\nu}\eta^{\iota\kappa})-\tfrac{1}{2}P_{24}(p\cdot p'\eta^{\mu\nu}\eta^{\tau\rho}\eta^{\lambda\iota}\eta^{\kappa\sigma})$$
$$-P_{12}(p^\sigma p^\tau\eta^{\nu\rho}\eta^{\lambda\iota}\eta^{\kappa\mu})-P_{12}(p^\rho p'^\lambda\eta^{\nu\iota}\eta^{\kappa\sigma}\eta^{\tau\mu})-P_{24}(p_\sigma p'^\rho\eta^{\tau\iota}\eta^{\kappa\mu}\eta^{\nu\lambda})-P_{12}(p^\rho p'^\iota\eta^{\lambda\sigma}\eta^{\tau\mu}\eta^{\nu\kappa})$$
$$+P_6(p\cdot p'\eta^{\nu\rho}\eta^{\lambda\sigma}\eta^{\tau\iota}\eta^{\kappa\mu})-P_{12}(p^\sigma p^\rho\eta^{\mu\nu}\eta^{\tau\iota}\eta^{\kappa\lambda})-\tfrac{1}{2}P_{12}(p\cdot p'\eta^{\mu\rho}\eta^{\nu\lambda}\eta^{\sigma\iota}\eta^{\tau\kappa})-P_{12}(p^\sigma p^\rho\eta^{\tau\lambda}\eta^{\mu\iota}\eta^{\nu\kappa})$$
$$-P_6(p^\rho p'^\iota\eta^{\lambda\kappa}\eta^{\mu\sigma}\eta^{\nu\tau})-P_{24}(p^\sigma p'^\rho\eta^{\tau\mu}\eta^{\nu\iota}\eta^{\kappa\lambda})-P_{12}(p^\sigma p'^\mu\eta^{\tau\rho}\eta^{\lambda\iota}\eta^{\kappa\nu})+2P_6(p\cdot p'\eta^{\nu\sigma}\eta^{\tau\rho}\eta^{\lambda\iota}\eta^{\kappa\mu})\big].$$

171 & 2850 terms

vs.

$$\left([12]^3/[23][31]\right)^2 \;\&\; [12]^4\langle 34\rangle^4/stu$$

→ avoiding ... ies

→ better u ... tions

On-shell perspective on SMEFTs

operator bases from massless amplitudes

[Shadmi, Weiss '18], [Ma, Shu, Xiao '19], [Falkowski '19], [GD, Machado '19], [Li, Ren, et al. '20, '20, '20]

massive amplitude enumeration

spin spinors: [Arkani-Hamed, Huang, Huang '17]

SM: [Christensen, Field '18], [Bachu, Yelleshpur '19],

SMEFT: [Aoude, Machado '19], [GD, Kitahara, Shadmi, Weiss '19], [GD et al. '20], [Dong, Ma, Shu '21], [Balkin, GD, Kitahara, Shadmi, Weiss '21]

non-renormalizations, non-interferences, anomalous dim.

[Cheung, Shen '15], [Azatov et al. '16], [Bern et al. '19, '20], [Jiang et al. '20], [Elias Miró et al. '20], [Baratella et al. '20, '20], [Baratella et al. '21], [Accettulli Huber, De Angelis '21]

...

Double copy of EFTs

[Bonnefoy, GD, Grojean, Machado, Roosmale-Nepveu '21]

$\otimes$	BAS	NLSM	YM
BAS	BAS	NLSM	YM
NLSM		sGal	BI
YM			GR

'theory multiplications'

e.g. $f^{abc}\frac{[12]^3}{[13][23]} \to \left(\frac{[12]^3}{[13][23]}\right)^2$

Colour-Kinematics (CK)

$$\sum_i \frac{n_i c_i}{d_i} \longrightarrow \sum_i \frac{n_i n_i'}{d_i}$$

constructive rules for valid n_i^{EFT}

[Carrasco, Rodina, Yin, Zekioglu '19, '21]

Kawai-Lewellen-Tye (KLT)

$$\sum_{\alpha,\beta} A_\alpha\, S_{\alpha\beta}\, A'_\beta$$

bootstrap equations for valid S^{EFT}

[Chi, Elvang, Herderschee, Jones, Paranjape '21]

What EFTs are allowed as double-copy inputs?

What EFTs are obtained as outputs?

Probing new physics systematically with EFTs

EFTs are privileged tools to make the most of upcoming precision measurements.

Observables offering high sensitivities and complementarities are required.

A global approach preserves the systematic new-physics theory-space coverage.

Precise EFT predictions yield sharper new-physics patterns.

Model interpretations put landmarks in the explored territory.

The theory understanding of EFTs is still progressing.

Extras

Statistically optimal observables

minimize the one-sigma ellipsoid in target parameter space

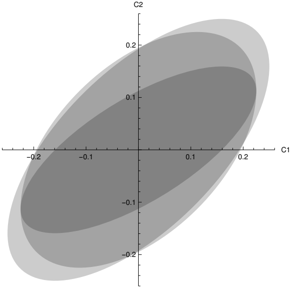
(*joint efficient* set of estimators, saturating the Cramér-Rao bound: $V^{-1} = I$)

For small C_i, with a phase-space distribution $\sigma(x) = \sigma_{\text{SM}}(x) + \sum_i C_i \, \sigma_i(x)$,

The stat. optimal observables: $OO_i \equiv \Big\langle n \, \sigma_i(x)/\sigma_{\text{SM}}(x) \Big\rangle_{\{x_n\}}$

The associated covariance:

$$\text{cov}(C_i, C_j)^{-1} = \epsilon\mathcal{L} \int \! \text{d}x \, \frac{\sigma_i(x)\sigma_j(x)}{\sigma_{\text{SM}}(x)} + \mathcal{O}(C_k).$$



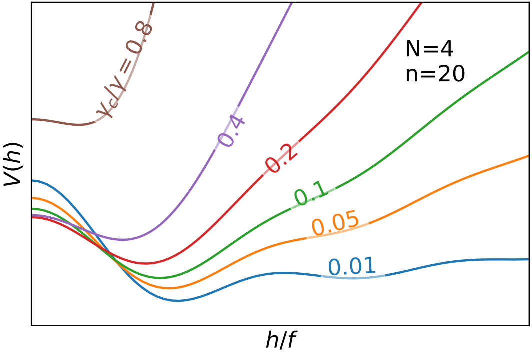
e.g. $\sigma(\phi) = 1 + \cos(\phi) + C_1 \sin(\phi) + C_2 \sin(2\phi)$

1. asymmetries $\sim \big\langle \, \text{sign}\{\sin(i\phi)\} \big\rangle$
2. moments $\sim \big\langle \, \sin(i\phi) \big\rangle$
3. statistically optimal $\sim \Big\langle \dfrac{\sin(i\phi)}{1 + \cos\phi} \Big\rangle$

$\Longrightarrow$ area ratios 1.9 : 1.7 : 1

Top+Gegenbauer potential

$$V(h) = \kappa \frac{N_c y_t^2}{16\pi^2} f^2 M_T^2 \left[\sin^2 \frac{h}{f} + \gamma\, G_n^{3/2}\left(\cos\frac{h}{f}\right)\right]$$



$$v/f \searrow 0 \quad \text{as} \quad \gamma \searrow \gamma_c$$

$$\frac{m_h^2}{\kappa \frac{N_c y_t^2}{16\pi^2} M_T^2} \searrow \quad \text{as} \quad \gamma \searrow \gamma_c \quad \text{relaxing} \quad \kappa \nearrow$$

Benchmark phenomenology

$n = 10$ and $f \sim M_T \sim 2\,\mathrm{TeV}$

$\rightarrow$ both v/f and m_h tunings $\sim 30\%$, so $\sim 10\%$ total

$\rightarrow$ top partners just escape HL-LHC searches

$\rightarrow$ Higgs coupling modifications $\frac{v^2}{f^2} \lesssim 1\%$ $\qquad \lesssim 2.6\%$ @HL-LHC, 2σ

$\rightarrow$ Higgs self-coupling modification $\lesssim 10\%$ $\qquad \lesssim 100\%$ @HL-LHC, 2σ

[ECFA '19]