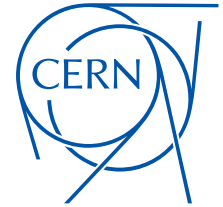
"EFT highlights"
personnal comments on where we stand and go

Gauthier Durieux
(CERN)

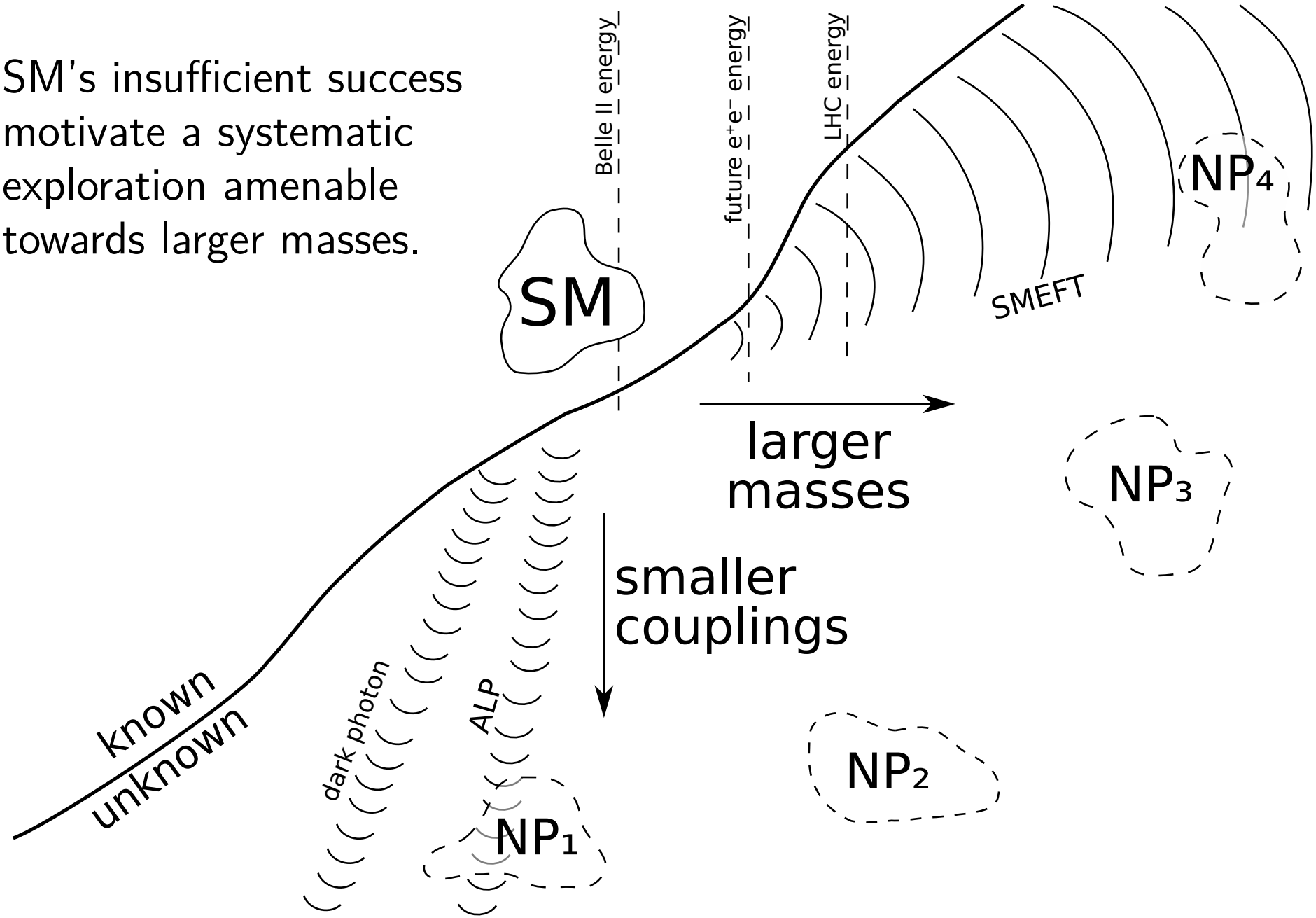
usual disclamer and apologies in order
complaints are welcome



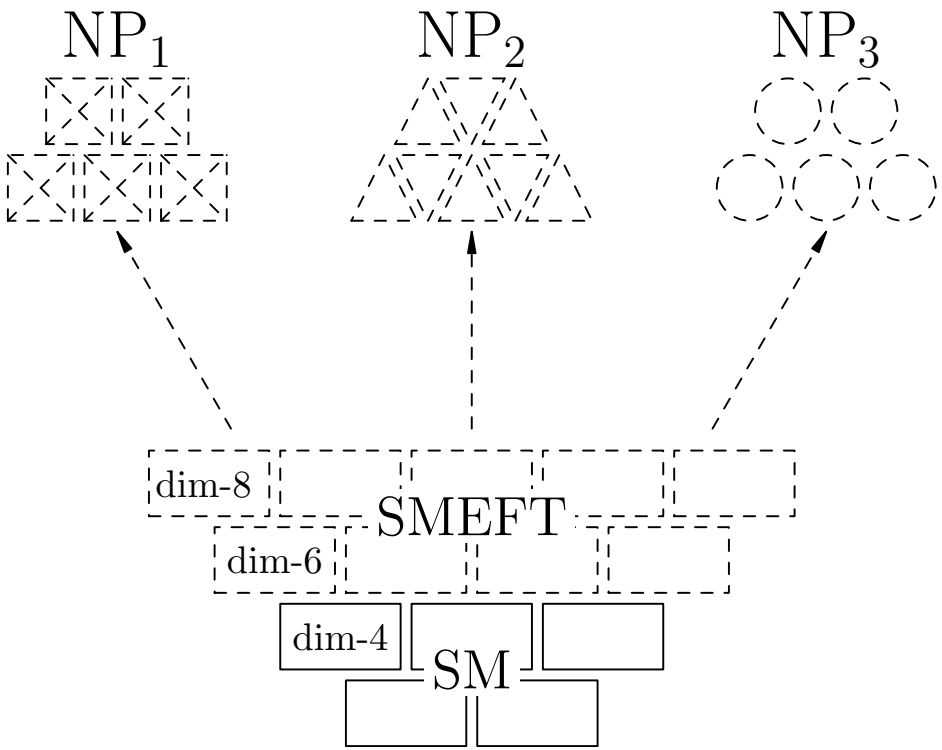
HEFT – Manchester – 19 June 2023

Particle physics' landscape

SM's insufficient success motivate a systematic exploration amenable towards larger masses.

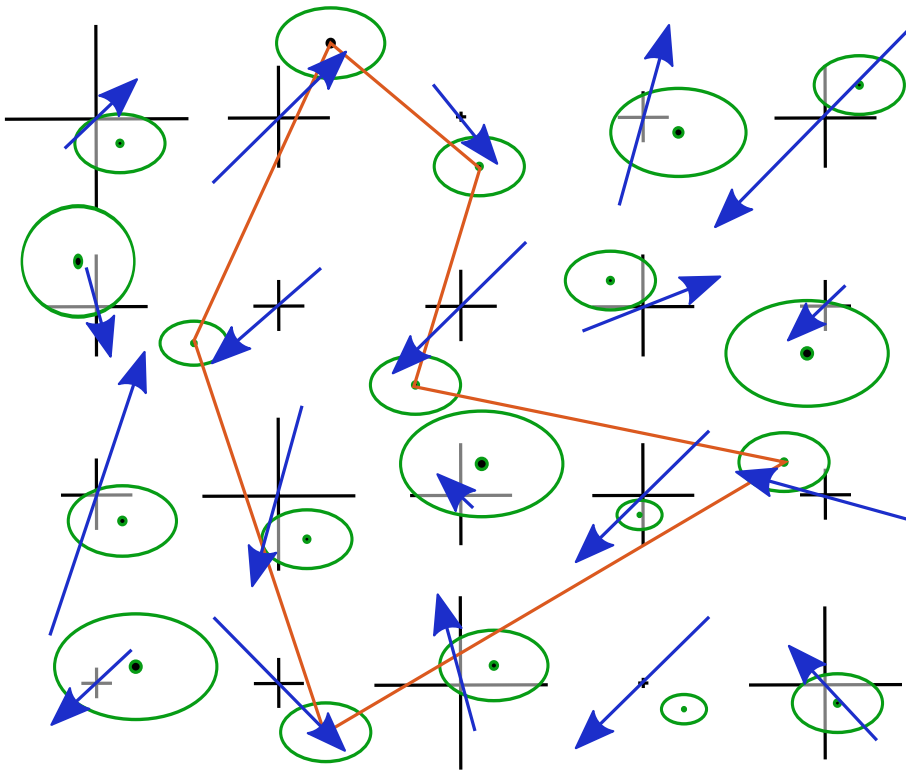


Taking the SM to higher dimensions



- 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-EFT predictions
- precise measurements

$\rightarrow$ correlate deviations

SMEFT progresses

1. Improved sensitivity (powerful observables, multidimensionally)
2. Global picture (parameterisation, sector combinations, fits)
3. Precise interpretation (higher-order SM/EFT corrections)
4. Models' connection (charting, matching, positiving, bootstraping)
5. New techniques & understanding (amplitudes, geometry)

1. Improved sensitivity

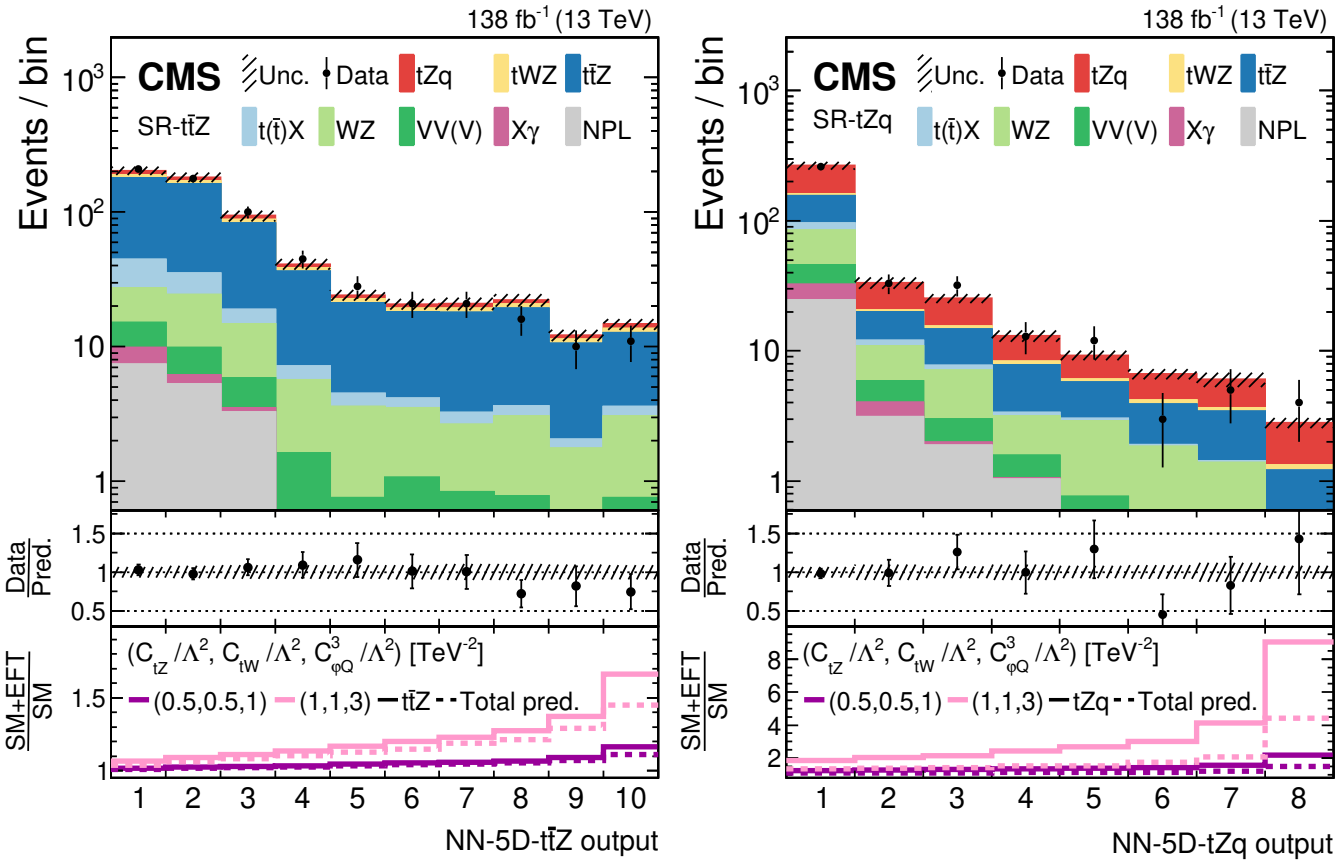
- matrix element method defines the theoretical optimal
- ML for invisible PS integration, shower, hadronisation, detector
- multidimensionality curse [Atwood, Soni '92] [Diehl, Nachtmann '94] [Gomez Ambrosio, ter Hoeve, Madigan, Rojo, Sanz '22]
- ease, understanding, and control

ML optimisation for SMEFT

[CMS '21]

- $tZ + X$ process in the three-lepton signal region
- 1. discriminate $t\bar{t}Z$, tZj signals and backgrounds
- 2. train SM vs. $(c_{tZ}, c_{tW}, c^3_{\phi q})$ from reweighted samples

WG studies



Fixed-order NLO weights

[Kraus, Martini, Uwer '19]
[see also Figy, Giele '18]

- NLO = Born + Virtual + Real

  with virtual and real occupying different phase-spaces (n vs. $n+1$)
  and IR divergences cancelling between them

- 'jet events' instead of parton events

  intrinsic inclusiveness guaranteeing IR safety
  for a given jet clustering algorithm
  integrating over soft and collinear radiations

$$\frac{d^r\sigma^{\mathrm{NLO}}}{dx_1\dots dx_r} = \frac{d^r\sigma^{\mathrm{BV}}}{dx_1\dots dx_r} + \sum_i \sum_{\substack{j \\ j\neq i}} \frac{d^r\sigma^{\mathrm{R}}_{\mathcal{R}_{ij}}}{dx_1\dots dx_r} + \sum_i \frac{d^r\sigma^{\mathrm{R}}_{\mathcal{R}_i}}{dx_1\dots dx_r} + \sum_i \frac{d^r\sigma^{\mathrm{R}}_{\tilde{\mathcal{R}}_i}}{dx_1\dots dx_r}$$

- phase space parametrization with variables

  already non-trivial at LO
  not allowing reconstruction of
  - jet invariant masses
  - overall transverse momentum

Fixed-order NLO weights

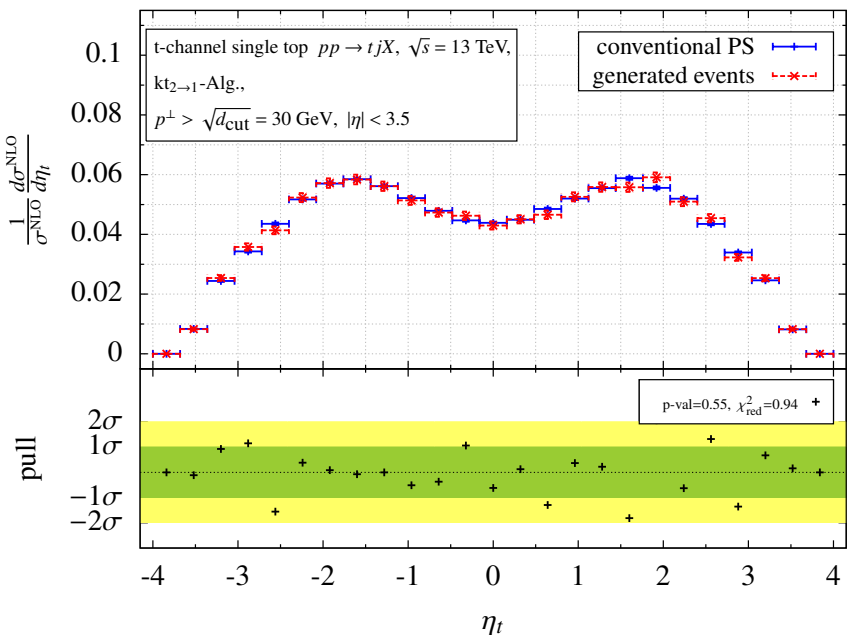
[Kraus, Martini, Uwer '19]

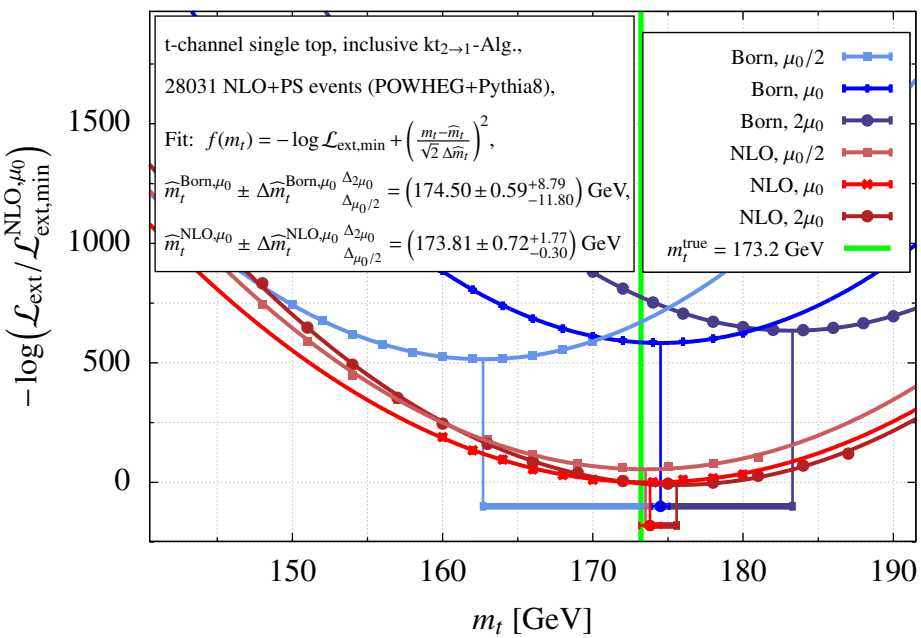
e.g. in $pp \to t\,j$ use $x = \{\eta_t,\, E_j,\, \eta_j,\, \phi_j\}$

$$J_t = \left(E_t,\, -J^\perp \cos\phi_j,\, -J^\perp \sin\phi_j,\, J^\perp \sinh\eta_t\right)$$
$$J_j = \left(E_j,\, J^\perp \cos\phi_j,\, J^\perp \sin\phi_j,\, J^\perp \sinh\eta_j\right)$$

with

$$J^\perp = J_t^\perp = J_j^\perp = \frac{\sqrt{E_j{}^2 - J_j{}^2}}{\cosh\eta_j}$$
$$E_t = \sqrt{J^{\perp 2}\cosh^2\eta_t + J_t{}^2}$$





2. Global picture

Fitmaker EW+Higgs+top, linear

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

SMEFiT diboson+Higgs+top, NLO

[Ethier, Magni, Maltoni, Mantani, Nocera, Rojo, Slade, Vryonidou, Zhang '21]

HEPfit EW, flavour, [illegible]

[de Blas, Pierini, Reina, Silvestrini '22]

EFTfitter top+B+EW, 14 op.

[Grunwald, Hiller, Kröninger, Nollen '23]

SFitter EW+diboson diff.+Higgs, top+B

[BFMO, Bruggisser, Elmer, Geoffray, Luchmann, Plehn '22]

OptEx EW+diboson diff.+Higgs+diHiggs, 23 op, no 4f, linear

[Anisha, Das, Banerjee, Biekötter, Chakrabortty, Patra, Spannowsky '21]

more observables

less restrictive flavour assumptions

better predictions

facilitated interpretations

$\longrightarrow$ build LHC legacy

[see the more comprehensive table by Anke]

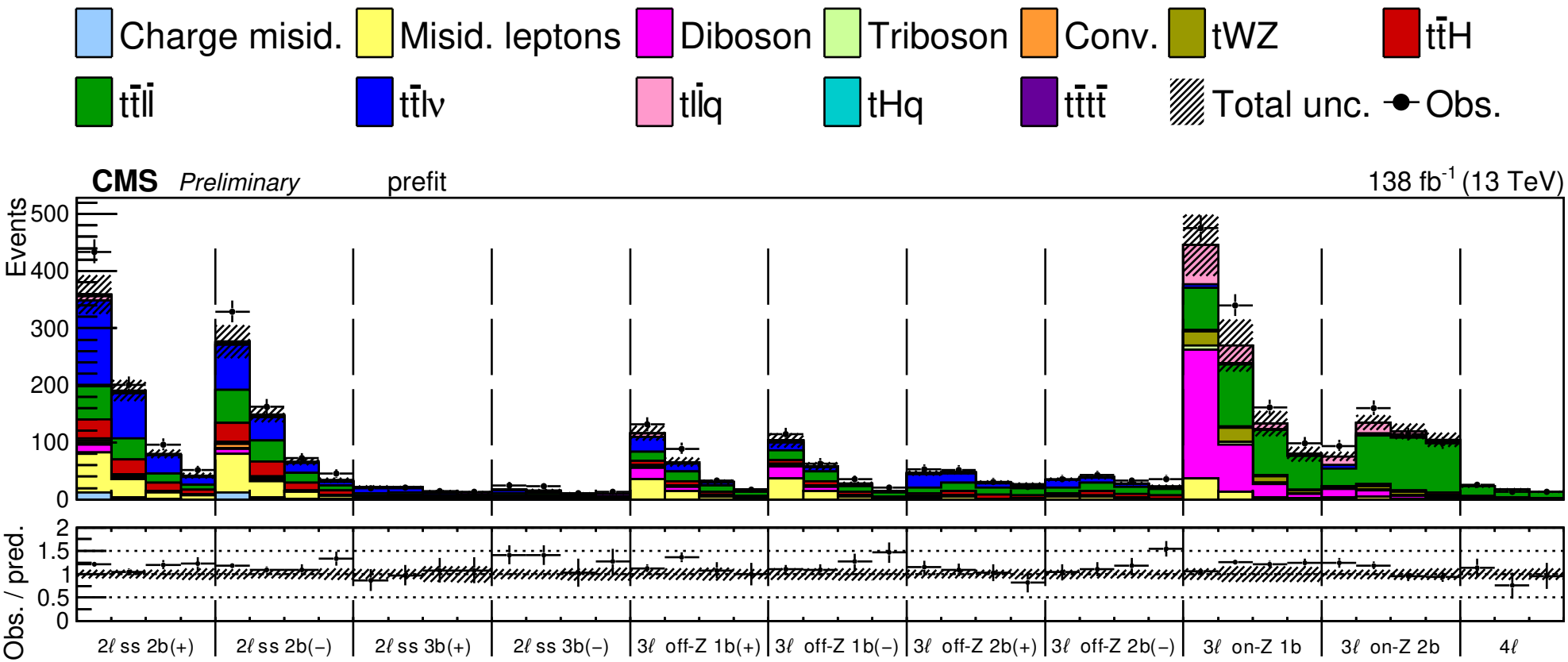
- shared predictions: validated, consistent, state-of-the-art [WG studies]
- cross-validation of fitting machineries
- uncertainties on EFT parameterisation [Altmannshofer, Stangl '21]
- EFT in backgrounds, in PDFs

[Kassabov, Madigan, Mantani, Moore, Morales Alvarado, Rojo, Ubiali '23]

Abolishing the 'signal' definition

[CMS '20]
[CMS '23]

- leptons+b's+jets final state, p_T bins, 178 data points
- contains tth, ttZ, ttW, tZq, tHq, diboson, etc.
- 26 top operator contributions to all processes [reweighting!]

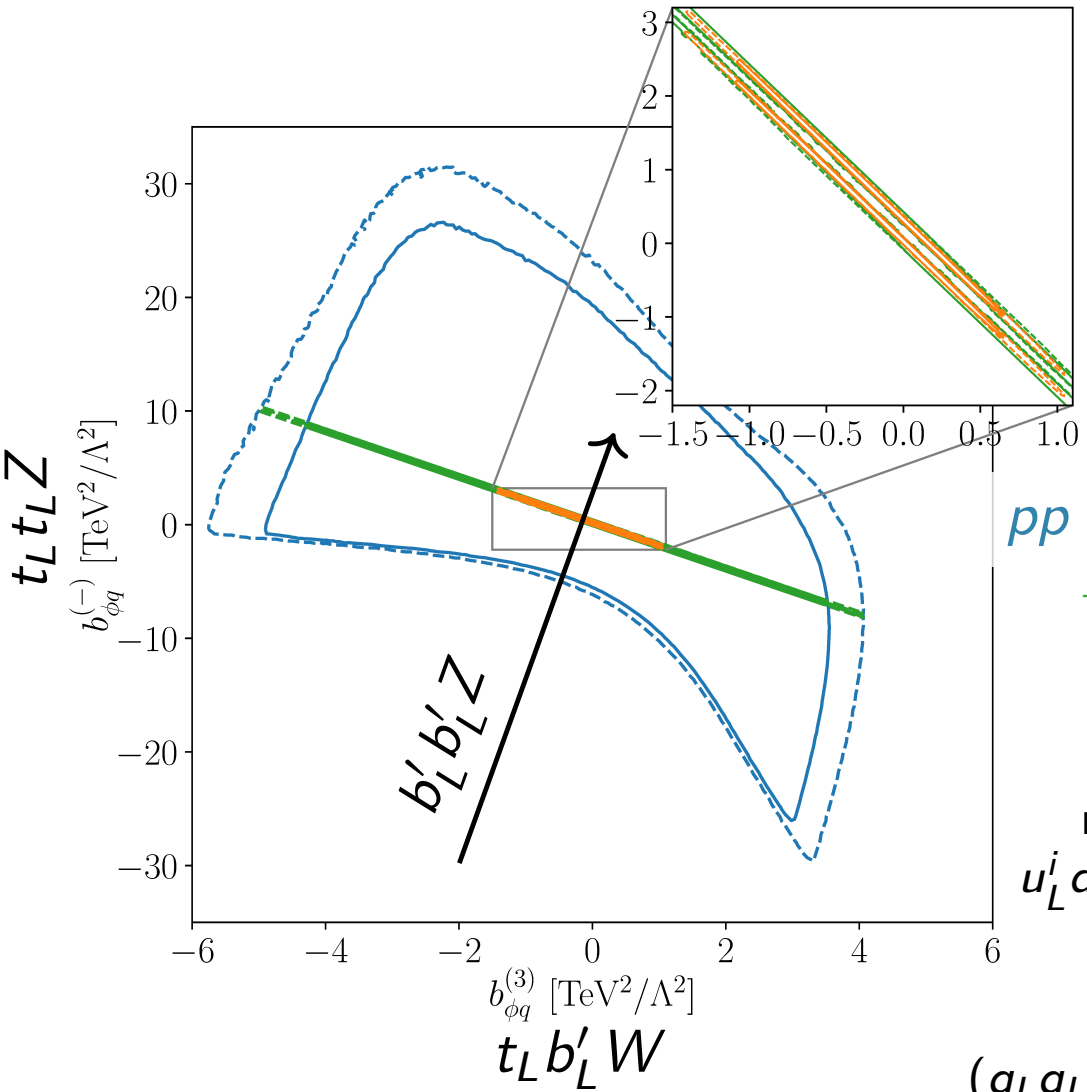


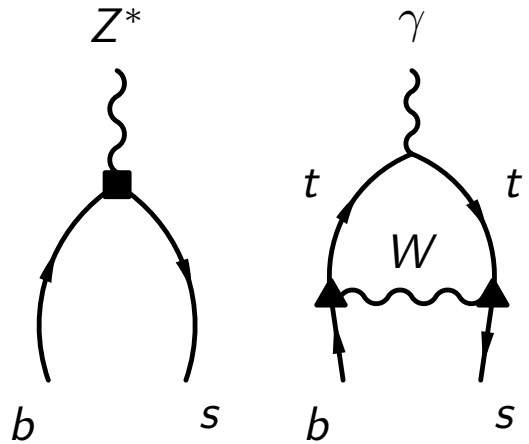
Bottom for top: $b \to s\gamma$ helps $c_{\phi Q}^{1,3}$

[Bruggisser et al. '21]
[see also Brod et al. '14]

$B_s \to \mu^+\mu^-$: $b'_L b'_L Z$ 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)

Bottom for top: $b \to s\gamma$ helps c_{tB}

[Bißmann et al. '20]

Operators [8]

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

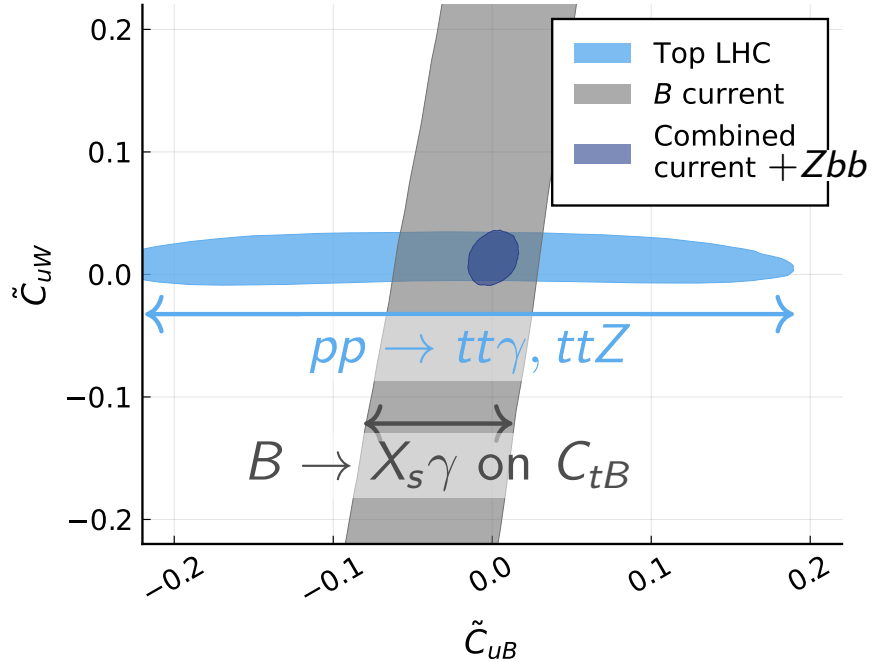
Constraints

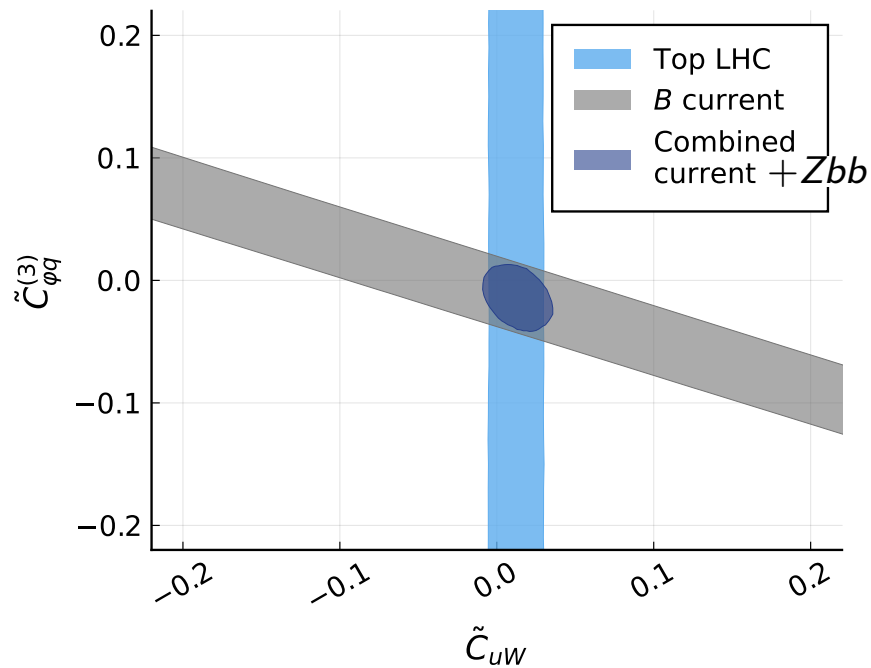
- $t\bar{t}$, $t\bar{t}\gamma$, $t\bar{t}Z$ rates
- W helicity fractions
- $Z \to b\bar{b}$ (at tree level)
- $b \to s\gamma$, $b \to s\ell\ell$ (`flavio+wilson`)
- B_s mixing, $b \to s\nu\bar{\nu}$

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

Improvements from b

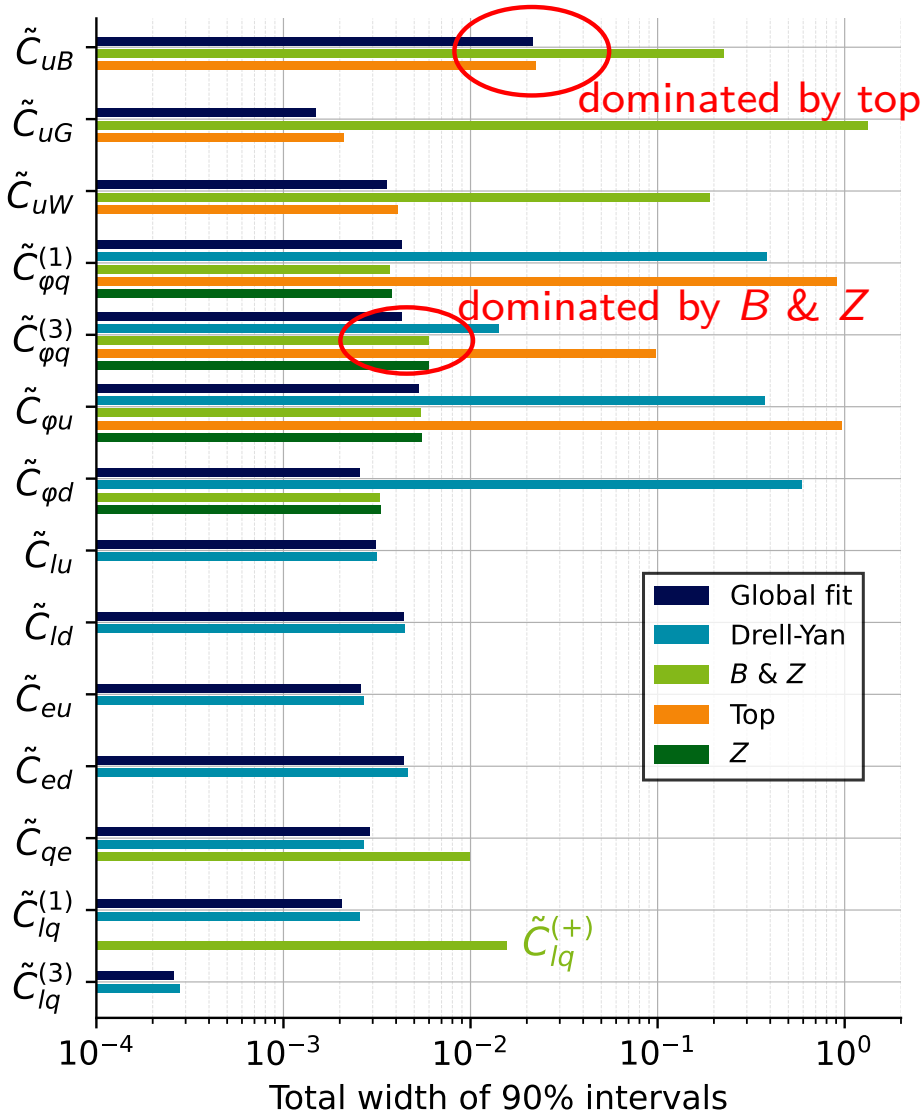
- mostly on C_{uB}, $C^3_{\varphi q}$ ($b \to s\gamma$)
- not much in $C_{\varphi u}$
- none in C_{tW}, C_{tG}





Bottom for top

[Grunwald, Hiller, Kröninger, Nollen '23]



leading MFV + resummed y_t corrections to $\bar{q}q$ and $\bar{u}u$ currents

complementarity of $b \to s\gamma$ for c_{tB} seems to have disappeared

complementarity of $b \to s\gamma$ for $c^{1,3}_{\phi Q}$ may still be there (light flavours appear too)

3. Precise interpretation

- deploy NLO QCD, systematise NLO EW [Biekötter, Pecjak, Scott, Smith '23] [Bellafronte, Dawson, Giardino '23]
- gain new sensitivities + handle new degeneracies
- account for RG running, go beyond one-loop [Aoude, Maltoni, Mattelaer, Severi, Vryonidou '22] [Bern, Parra-Martinez, Sawyer '20] [Cao, Herzog, Melia, Roosmale Nepveu '23]
- explore dim>6, benchmark dim-6 truncation validity [Ellis, Mimasu, Zampedri '23] [Degrande, Li '23] [Heinrich, Lang '22]

SMEFT loops

- $pp \to jj$ $(q\bar{q}q\bar{q})$ [Gao, Li, Wang, Zhu, Yuan '11]
- $pp \to t\bar{t}$ $(q\bar{q}t\bar{t})$ [Shao, Li, Wang, Gao, Zhang, Zhu '11]
- $pp \to V\,V$ [Dixon, Kunszt, Signer '99] [Melia, Nason, Röntsch, Zanderighi '11] [Baglio, Dawson, Homiller, Lane, Lewis '17, '18, '19, '20] [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]

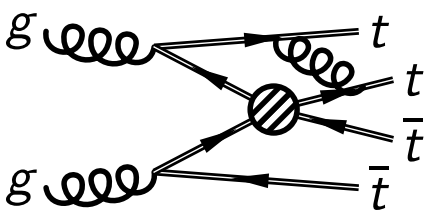
- $h \to f\bar{f}$ [Gauld, Pecjak, Scott '15, '16] [Cullen, Pecjak, Scott '19, '20]
- $pp \to tj$ [Zhang '16] [de Beurs, Laenen, Vreeswijk, Vryonidou '18]
- $pp \to t\bar{t}Z$, $gg \to ZH$ [Röntsch, Markus Schulze '14] [Bylund, Maltoni, Vryonidou, Zhang '16]
- $pp \to t\bar{t}H$, $gg \to Hj, HH$ [Maltoni, Vryonidou, Zhang '16]
- $pp \to HV$ [Degrande, Fuks, Mawatari, Mimasu, Sanz '16] [Alioli, Dekens, Girard, Mereghetti '18]
- Z, W poles [Hartmann, Shepherd, Trott '16] [Bellafronte, Dawson, Ismail, Giardino '18, '18, '19, '22, '23]
- $pp \to h$ [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]

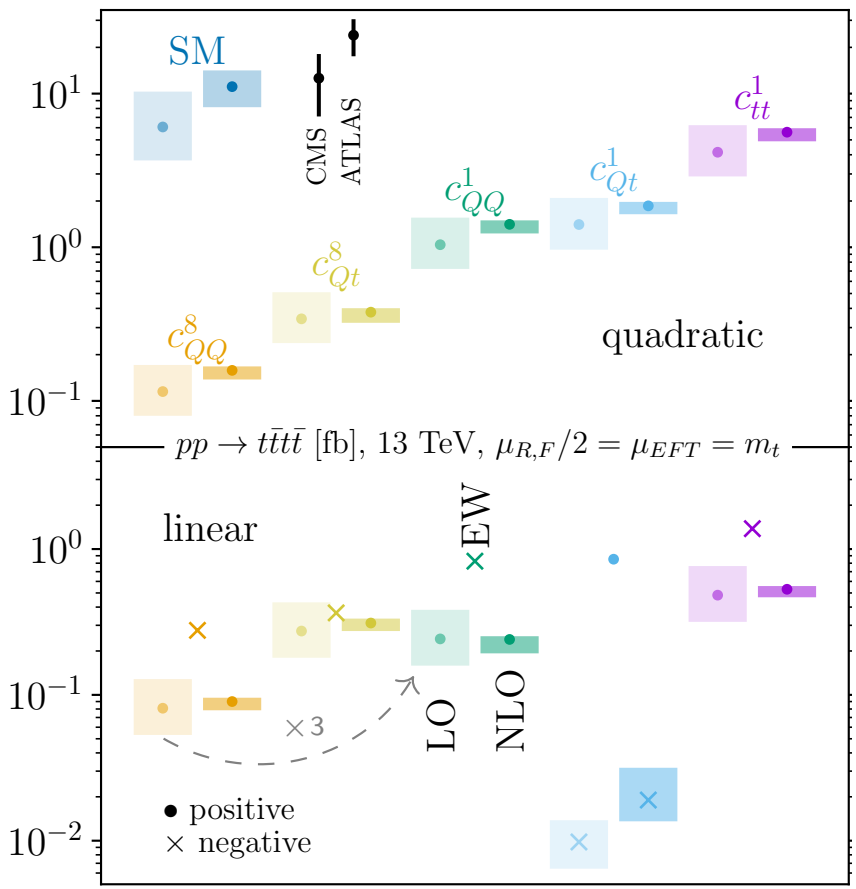
- EW Higgs & WW (top) [Vryonidou, Zhang '18] [GD, Gu, Vryonidou, Zhang '18] [Boselli, Hunter, Mitov '18]
- EW $pp \to t\bar{t}$ (ttZ,tth) [Martini, Schulze '19] [Martini, Pan, Schulze, Xiao '21]
- all QCD and four-quarks UFO [Degrande, GD, Maltoni, Mimasu, Vryonidou, Zhang '20]
- EW $pp \to \ell^+\ell^-$ [Dawson, Giardino '21, '22]
- EW $QQQQ$ in $gg \to h$, $h \to bb$, $pp \to tth$ [Alasfar, de Blas, Gröber '22]
- NNLO $pp \to Zh \to \ell^+\ell^- b\bar{b}$ [Haisch, Scott, Wiesemann, Zanderighi, Zanoli '22]
- NNLO VBF [Asteriadis, Caola, Melnikov, Röntsch '22]

SMEFT at one loop

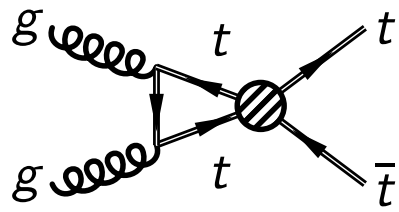
[Degrande, GD, Maltoni, Mimasu, Vryonidou, Zhang '20]

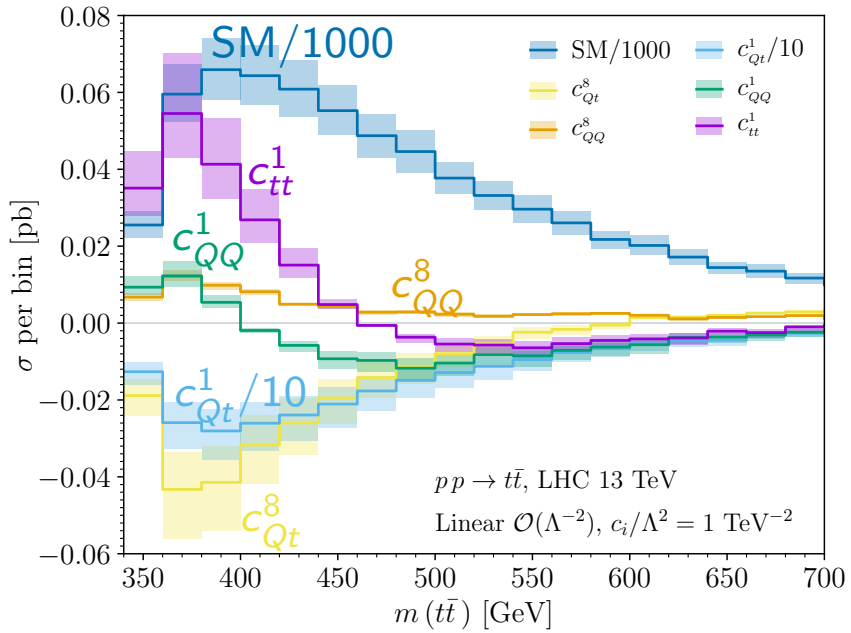
Better accuracy and uncertainties





New sensitivities





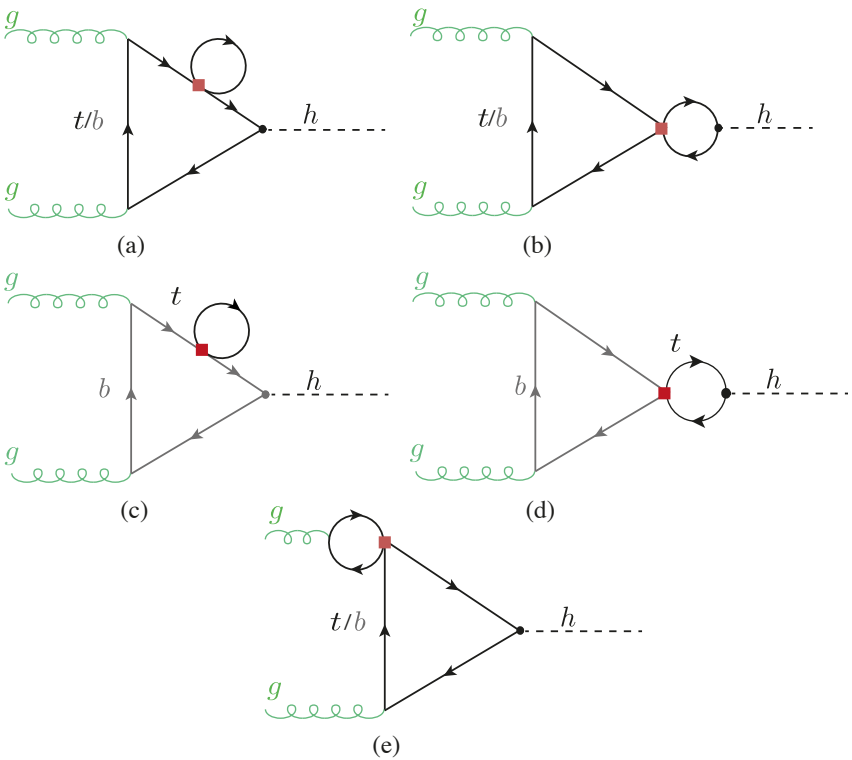
technicalities:

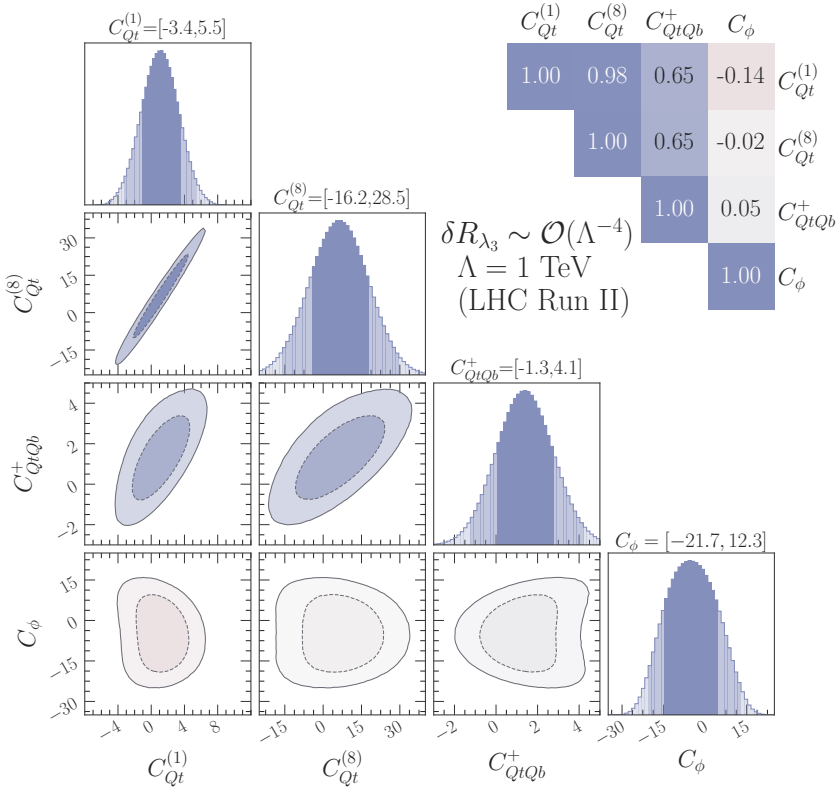
- anomaly cancellation
  [Bonnefoy et al. '20] [Feruglio '20]
- evanescent operators

$t\bar{t}Q\bar{Q}$ in Higgs processes

[Alasfar, de Blas, Gröber '22]

- sensitivity in $gg \to h$, $h \to \gamma\gamma$, $pp \to t\bar{t}h$ comparable to $pp \to t\bar{t}t\bar{t}$ and $t\bar{t}b\bar{b}$
- spoils the loop sensitivity to the Higgs self-coupling

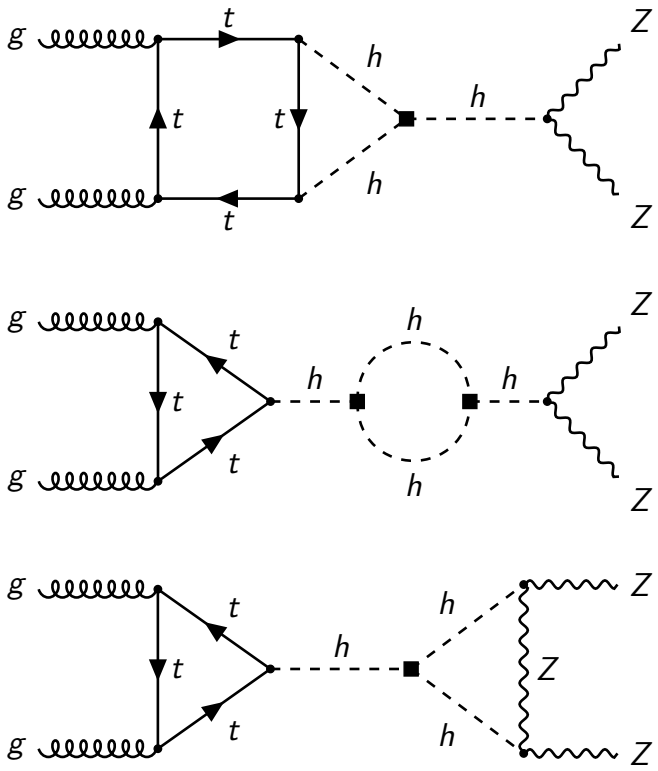


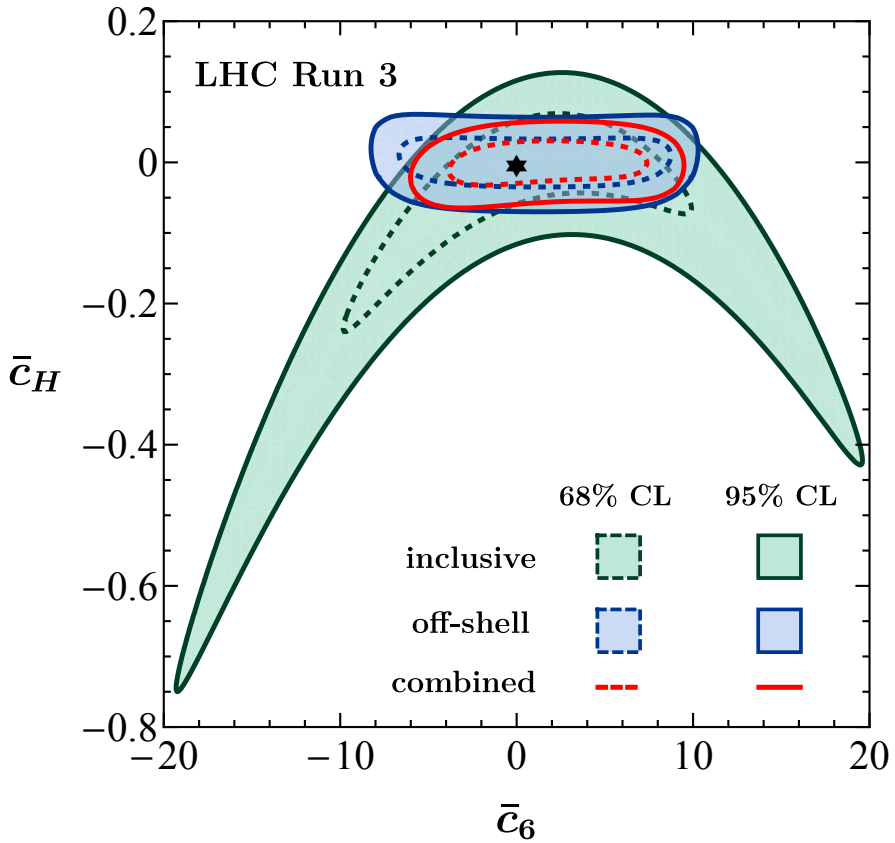


Self-coupling in off-shell $gg \to 4\ell$

[Haisch, Koole '21]

- extra discriminating power in differential distributions
- leveraged with matrix-element based observable





4. Models' connexion

- charting

  EFT space populated by models

- matching [LHC EFT WG note '22]
  - CoDEx (func) [Bakshi, Chakrabortty, Patra '18]
  - Matchmakereft (diag) [Carmona, Lazopoulos, Olgoso, Santiago '21]
  - Matchete (func) [Fuentes-Martín, König, Pagès, Thomsen, Wilsch '22]

  - specific models [Dawson, Fontes, Quezada-Calonge, Sanz-Cillero '23] [Banta, Cohen, Craig, Lu, Sutherland '23]

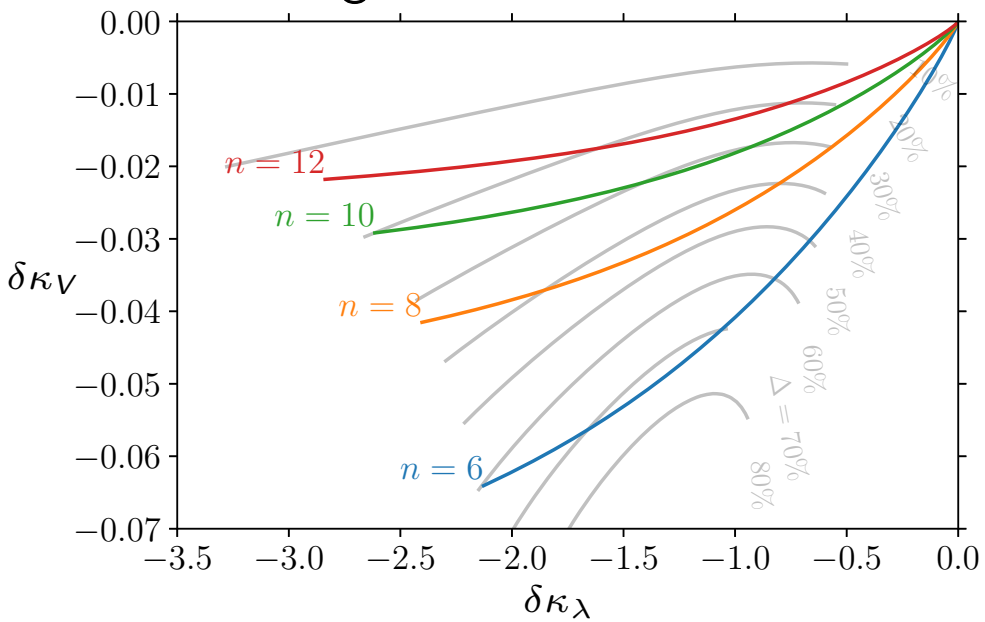
  - subtleties [Fuentes-Martín, König, Pagès, Thomsen, Wilsch '22]

- positiving and bootstraping [Riembau '22] [Miro, Guerrieri, Gumus '22]
  - BSM starts at dim-8
  - pheno starts at dim-8 [Bellazzini, Riva '18] [Gu, Wang, Zhang '20]
  - sum rules apply at dim-6 [Remmen, Rodd '22]

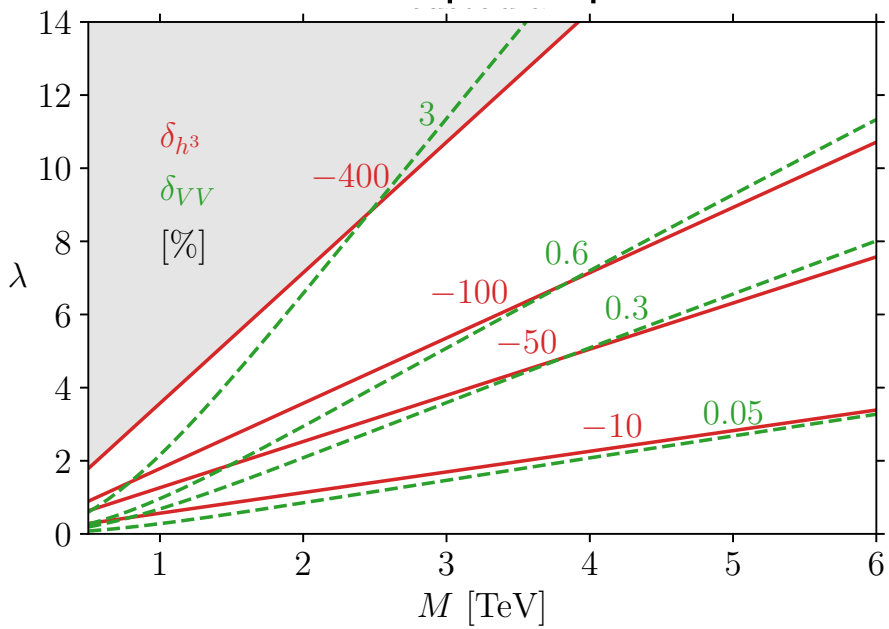
Charting $\delta\kappa_\lambda/\delta\kappa_V$ space

[GD, McCullough, Salvioni '21, '22, '22]
see also: [Di Luzio, Gröber, Spannowsky '17]
[Gupta, Rzehak, Wells '13] [Falkowski, Rattazzi '19]
[Logan, Rentala '15] [Chala, Krause, Nardini '18] [etc.]

Gegenbauer's Twin



custodial weak-quadruplet scalar



$$\lambda\, H^* H^* (\epsilon H) \Phi + \lambda \frac{1}{\sqrt{3}} H^* H^* H^* \widetilde{\Phi}$$

- a loop factor allowed dimensionally (or v^2/M_X^2 if dim-6/dim-8)
- dim$\gg$6 operators may be very relevant
- vacuum stability as limiting constraint

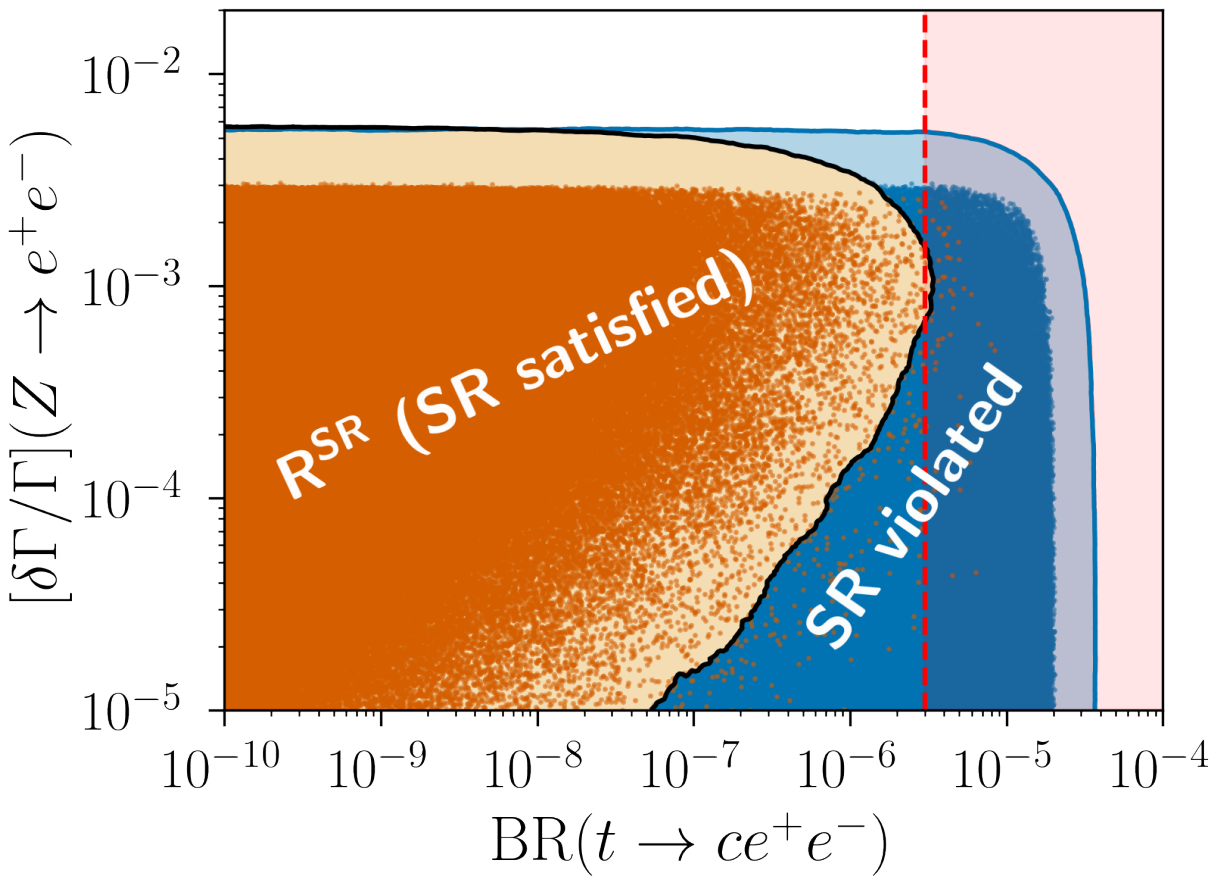
Top FCNC sum rules

[Altmannshofer, Gori, Lehmann, Zuo '23]

If UV dominated either by scalars or vectors: [Remmen, Rodd '20, '22]

$$|C_{tcee}|^2 < C_{ttee}\, C_{ccee}$$

C_{tcee}: $e^+e^- \to tc$ — C_{ttee}: $Z \to e^+e^-$ — C_{ccee}: $pp \to e^+e^-$



5. New techniques & understanding

- on-shell anomalous dimensions and selection rules

[Cheung, Shen '15], [Azatov et al. '16], [Bern et al. '19, '20]
[Jiang et al. '20], [Elias Miró et al. '20, '21], [Baratella et al. '20, '20, '21]
[Accettulli Huber, De Angelis '21], [Delle Rose et al. '22], [Baratella '22]
[Machado, Renner, Sutherland '22], [Chala '23]

- on-shell operator enumeration

[Shadmi, Weiss '18], [Ma, Shu, Xiao '19], [Falkowski '19], [GD, Machado '19]
[Li, Ren, et al. '20, '20], [Harlander, Kempkens, Schaaf '23]

- Hilbert series

[Kondo, Murayama, Okabe '22] [Sun, Wang, Yu '22]
[Gráf, Henning, Lu, Melia, Murayama '22]

- on-shell EFT amplitude construction

[Aoude, Machado '19], [GD, Kitahara, Shadmi, Weiss '19], [GD et al. '20]
[Balkin et al. '21], [Dong, Ma, Shu, Zheng '21, '22], [De Angelis '22]
[Bradshaw, Chang, Chen, Liu, Luty '22, '23], [Liu, Ma, Shadmi, Waterbury '23]

- on-shell matching

[Delle Rose, von Harling, Pomarol '22]
[De Angelis, GD 'xx]

- field geometry

[Corbett, Martin '23] [Martin, Trott '23]
[Craig, Lee, Lu, Sutherland '23] [Helset, Jenkins, Manohar '22]
[Brivio, Davighi, Alminawi 'xx]

- double copy

[ask Jasper and Quentin!]

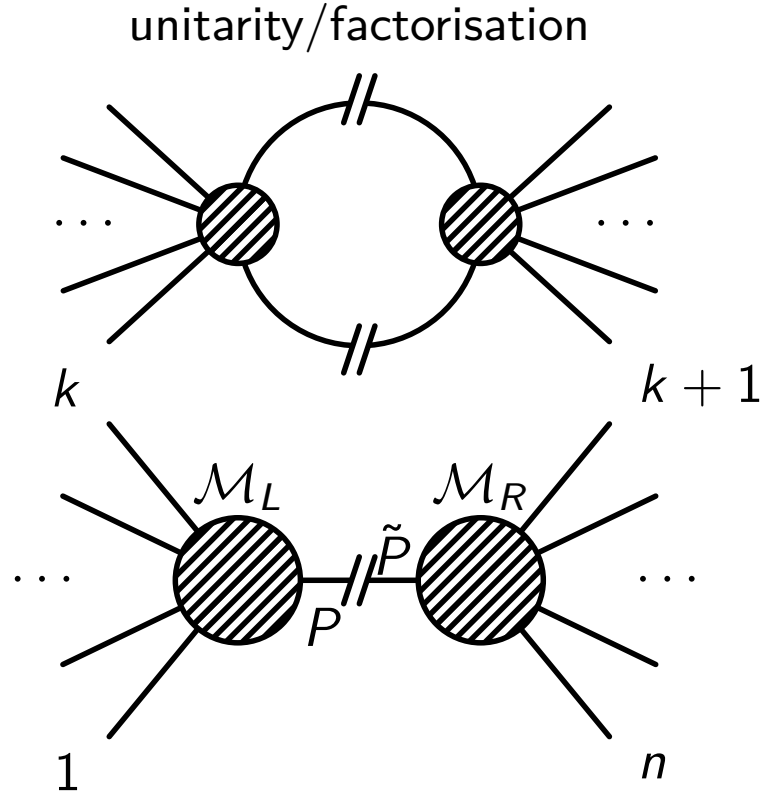
On-shell: recursive amplitude construction

- loops cut into trees

  + rational terms

- trees cut into trees

  + contact terms

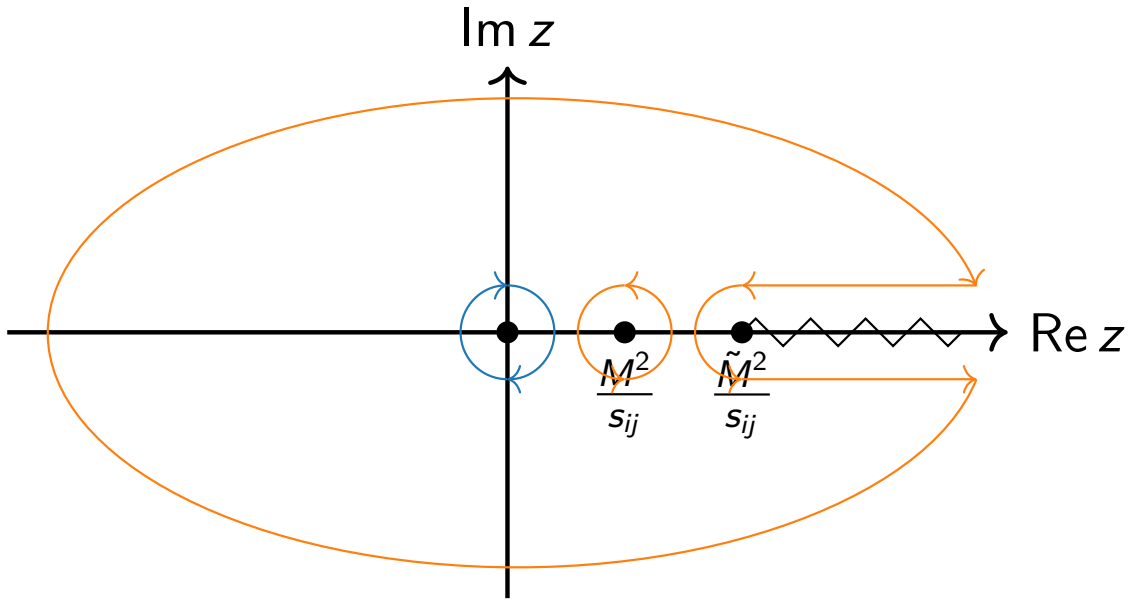


$$\mathcal{M}^{\text{tree}}(1,\dots k,\dots n) = \sum_{\text{channels}} \frac{\mathcal{M}_L^{\text{tree}}(1,\dots k,P)\,\mathcal{M}_R^{\text{tree}}(\tilde{P},k+1,\dots n)}{P^2-m^2} + \mathcal{M}^{\text{contact}}(1,\dots k,\dots n)$$

On-shell matching

[De Angelis, GD 'xx]

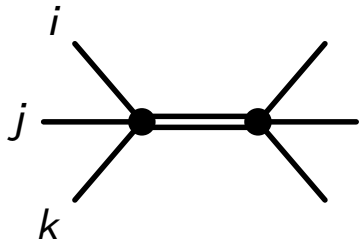
- phrase matching as $A^{\text{EFT}} = A^{\text{UV}}$ for $p_i \to 0$ (assume massless EFT for simplicity)
- introduce 'dilatation' $p_i \to \sqrt{z}\, p_i$ and equate powers of z at $z \to 0$
- use $\left.\dfrac{\partial^n A}{\partial z^n}\right|_{z=0} = \oint \mathrm{d}z \dfrac{A(z)}{z^{n+1}}$ around $z = 0$ and deforme it



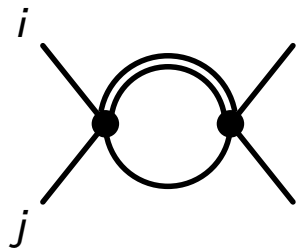
- reduce residues and 1-loop cuts to trees by factorisation / unitarity $T - T^\dagger = iT^\dagger \cdot T$
- get new insight / sum rules?

[Delle Rose, von Harling, Pomarol '22]

On-shell matching: $\Phi\phi^3$ example



$$: \sum_{z=M^2/s_{ijk}} \frac{1}{s_{ijk} z^{n+1}} |A(\phi\phi\phi \to \Phi)|^2 = \frac{g^2}{M^2} \sum_{\text{channels}} \left(\frac{s_{ijk}}{M^2}\right)^n$$



$$\begin{aligned}
: &\frac{1}{2\pi} \sum_{\text{channels}} \int_{M^2/s_{ij}}^{\infty} \frac{\mathrm{d}z}{z^{n+1}} \int \text{dLIPS}\, |A(\phi\phi \to \phi\Phi)|^2 \\
= &\frac{1}{2\pi} \sum_{\text{channels}} \int_{M^2/s_{ij}}^{\infty} \frac{\mathrm{d}z}{z^{n+1}} \frac{1}{8\pi} \left(1 - \frac{M^2}{z s_{ij}}\right) g^2 \\
= &\frac{g^2}{16\pi^2 n(n+1)} \sum_{\text{channels}} \left(\frac{s_{ij}}{M^2}\right)^n
\end{aligned}$$

- all EFT orders obtained at once
- nothing to compute on the EFT side (i.e. hard expansion obtained)
- phase-space integral can be complicated and require dimreg

SMEFT progresses

1. Improved sensitivity (powerful observables, multidimensionally)
2. Global picture (parameterisation, sector combinations, fits)
3. Precise interpretation (higher-order SM/EFT corrections)
4. Models' connection (charting, matching, positiving+bootstraping)
5. New techniques & understanding (amplitudes, geometry)