SMEFT@NLO for e^+e^-

Anders Eller Thomsen

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^{b} UNIVERSITÄT BERN
AEC
ALBERT EINSTEIN CENTER
FOR FUNDAMENTAL PHYSICS

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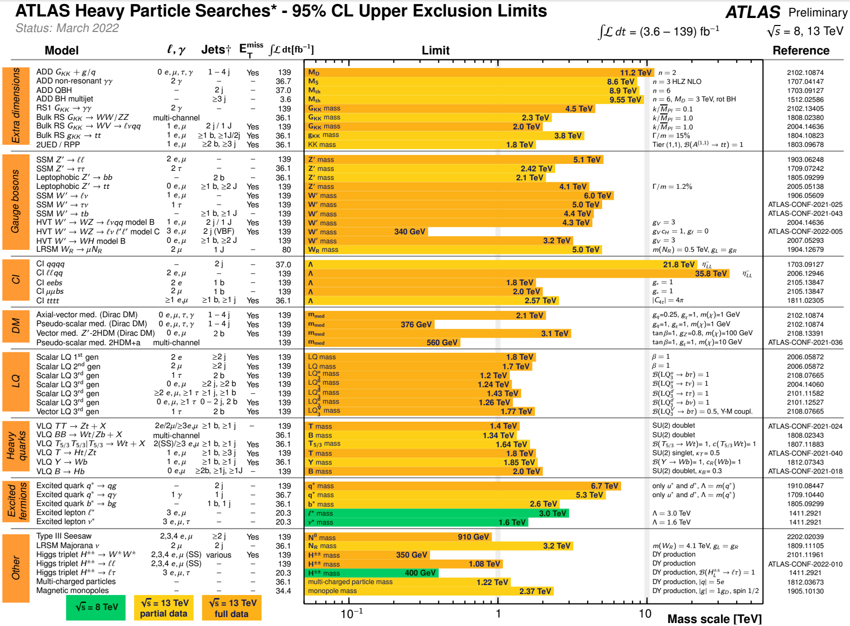
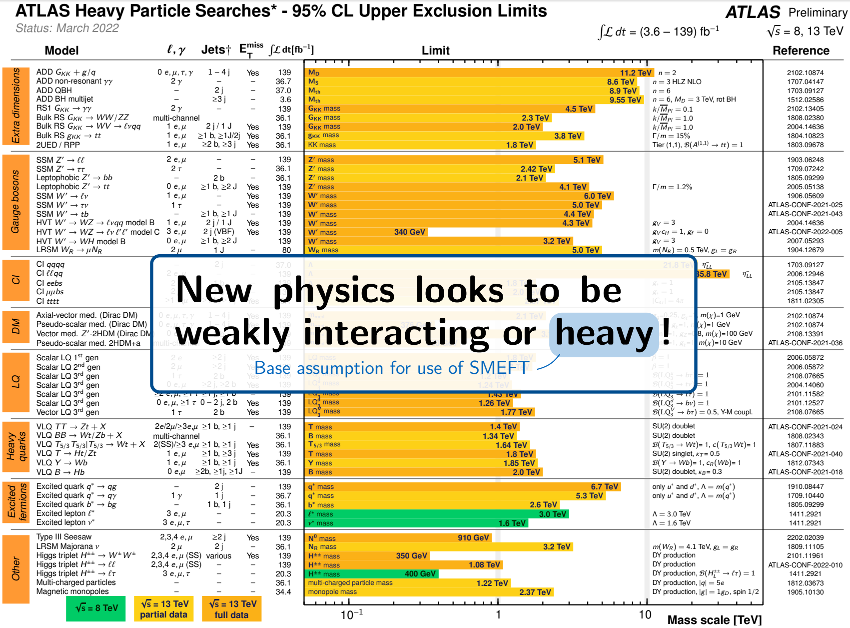

ATLAS Heavy Particle Searches* - 95% CL Upper Exclusion Limits
Status: March 2022
ATLAS Preliminary
$\int\mathcal{L}\,dt = (3.6 - 139)\ \mathrm{fb}^{-1}$
$\sqrt{s} = 8,\ 13$ TeV
Model
ℓ,γ
Jets†
E_T^{miss}
$\int\mathcal{L}\,dt[\mathrm{fb}^{-1}]$
Limit
Reference
Extra dimensions
ADD $G_{KK}+g/q$ | 0 e,μ,τ,γ | 1 – 4 j | Yes | 139 | M_D | 11.2 TeV | $n=2$ | 2102.10874
ADD non-resonant $\gamma\gamma$ | 2 γ | – | – | 36.7 | M_S | 8.6 TeV | $n=3$ HLZ NLO | 1707.04147
ADD QBH | – | 2 j | – | 37.0 | M_{th} | 8.9 TeV | $n=6$ | 1703.09127
ADD BH multijet | – | ≥3 j | – | 3.6 | M_{th} | 9.55 TeV | $n=6$, $M_D=3$ TeV, rot BH | 1512.02586
RS1 $G_{KK}\to\gamma\gamma$ | 2 γ | – | – | 139 | G_{KK} mass | 4.5 TeV | $k/\overline{M}_{Pl}=0.1$ | 2102.13405
Bulk RS $G_{KK}\to WW/ZZ$ | multi-channel | | | 36.1 | G_{KK} mass | 2.3 TeV | $k/\overline{M}_{Pl}=1.0$ | 1808.02380
Bulk RS $G_{KK}\to WV\to\ell\nu qq$ | 1 e,μ | 2 j / 1 J | Yes | 139 | G_{KK} mass | 2.0 TeV | $k/\overline{M}_{Pl}=1.0$ | 2004.14636
Bulk RS $g_{KK}\to tt$ | 1 e,μ | ≥1 b, ≥1J/2j | Yes | 36.1 | g_{KK} mass | 3.8 TeV | $\Gamma/m=15\%$ | 1804.10823
2UED / RPP | 1 e,μ | ≥2 b, ≥3 j | Yes | 36.1 | KK mass | 1.8 TeV | Tier (1,1), $\mathcal{B}(A^{(1,1)}\to tt)=1$ | 1803.09678
Gauge bosons
SSM $Z'\to\ell\ell$ | 2 e,μ | – | – | 139 | Z' mass | 5.1 TeV | | 1903.06248
SSM $Z'\to\tau\tau$ | 2 τ | – | – | 36.1 | Z' mass | 2.42 TeV | | 1709.07242
Leptophobic $Z'\to bb$ | – | 2 b | – | 36.1 | Z' mass | 2.1 TeV | | 1805.09299
Leptophobic $Z'\to tt$ | 0 e,μ | ≥1 b, ≥2 J | Yes | 139 | Z' mass | 4.1 TeV | $\Gamma/m=1.2\%$ | 2005.05138
SSM $W'\to\ell\nu$ | 1 e,μ | – | Yes | 139 | W' mass | 6.0 TeV | | 1906.05609
SSM $W'\to\tau\nu$ | 1 τ | – | Yes | 139 | W' mass | 5.0 TeV | | ATLAS-CONF-2021-025
SSM $W'\to tb$ | – | ≥1 b, ≥1 J | – | 139 | W' mass | 4.4 TeV | | ATLAS-CONF-2021-043
HVT $W'\to WZ\to\ell\nu qq$ model B | 1 e,μ | 2 j / 1 J | Yes | 139 | W' mass | 4.3 TeV | $g_V=3$ | 2004.14636
HVT $W'\to WZ\to\ell\nu\ell'\ell'$ model C | 3 e,μ | 2 j (VBF) | Yes | 139 | W' mass | 340 GeV | $g_V c_H=1$, $g_f=0$ | ATLAS-CONF-2022-005
HVT $W'\to WH$ model B | 0 e,μ | ≥1 b, ≥2 J | | 139 | W' mass | 3.2 TeV | $g_V=3$ | 2007.05293
LRSM $W_R\to\mu N_R$ | 2 μ | 1 J | – | 80 | W_R mass | 5.0 TeV | $m(N_R)=0.5$ TeV, $g_L=g_R$ | 1904.12679
CI
CI $qqqq$ | – | 2 j | – | 37.0 | Λ | 21.8 TeV | η_{LL}^- | 1703.09127
CI $\ell\ell qq$ | 2 e,μ | – | – | 139 | Λ | 35.8 TeV | η_{LL}^- | 2006.12946
CI $eebs$ | 2 e | 1 b | – | 139 | Λ | 1.8 TeV | $g_*=1$ | 2105.13847
CI $\mu\mu bs$ | 2 μ | 1 b | – | 139 | Λ | 2.0 TeV | $g_*=1$ | 2105.13847
CI $tttt$ | ≥1 e,μ | ≥1 b, ≥1 j | Yes | 36.1 | Λ | 2.57 TeV | $|C_{4t}|=4\pi$ | 1811.02305
DM
Axial-vector med. (Dirac DM) | 0 e,μ,τ,γ | 1 – 4 j | Yes | 139 | m_{med} | 2.1 TeV | g_q=0.25, g_χ=1, $m(\chi)$=1 GeV | 2102.10874
Pseudo-scalar med. (Dirac DM) | 0 e,μ,τ,γ | 1 – 4 j | Yes | 139 | m_{med} | 376 GeV | g_q=1, g_χ=1, $m(\chi)$=1 GeV | 2102.10874
Vector med. Z'-2HDM (Dirac DM) | 0 e,μ | 2 b | Yes | 139 | m_{med} | 3.1 TeV | $\tan\beta$=1, g_Z=0.8, $m(\chi)$=100 GeV | 2108.13391
Pseudo-scalar med. 2HDM+a | multi-channel | | | 139 | m_{med} | 560 GeV | $\tan\beta$=1, g_χ=1, $m(\chi)$=10 GeV | ATLAS-CONF-2021-036
LQ
Scalar LQ 1st gen | 2 e | ≥2 j | Yes | 139 | LQ mass | 1.8 TeV | $\beta=1$ | 2006.05872
Scalar LQ 2nd gen | 2 μ | ≥2 j | Yes | 139 | LQ mass | 1.7 TeV | $\beta=1$ | 2006.05872
Scalar LQ 3rd gen | 1 τ | 2 b | Yes | 139 | LQ_3^u mass | 1.2 TeV | $\mathcal{B}(LQ_3^u\to b\tau)=1$ | 2108.07665
Scalar LQ 3rd gen | 0 e,μ | ≥2 j, ≥2 b | Yes | 139 | LQ_3^u mass | 1.24 TeV | $\mathcal{B}(LQ_3^u\to t\nu)=1$ | 2004.14060
Scalar LQ 3rd gen | ≥2 e,μ, ≥1 τ | ≥1 j, ≥1 b | – | 139 | LQ_3^d mass | 1.43 TeV | $\mathcal{B}(LQ_3^d\to t\tau)=1$ | 2101.11582
Scalar LQ 3rd gen | 0 e,μ, ≥1 τ | 0 – 2 j, 2 b | Yes | 139 | LQ_3^d mass | 1.26 TeV | $\mathcal{B}(LQ_3^d\to b\nu)=1$ | 2101.12527
Vector LQ 3rd gen | 1 τ | 2 b | Yes | 139 | LQ_3^V mass | 1.77 TeV | $\mathcal{B}(LQ_3^V\to b\tau)=0.5$, Y-M coupl. | 2108.07665
Heavy quarks
VLQ $TT\to Zt+X$ | 2e/2μ/≥3e,μ | ≥1 b, ≥1 j | – | 139 | T mass | 1.4 TeV | SU(2) doublet | ATLAS-CONF-2021-024
VLQ $BB\to Wt/Zb+X$ | multi-channel | | | 36.1 | B mass | 1.34 TeV | SU(2) doublet | 1808.02343
VLQ $T_{5/3}T_{5/3}|T_{5/3}\to Wt+X$ | 2(SS)/≥3 e,μ | ≥1 b, ≥1 j | Yes | 36.1 | $T_{5/3}$ mass | 1.64 TeV | $\mathcal{B}(T_{5/3}\to Wt)$= 1, $c(T_{5/3}Wt)$= 1 | 1807.11883
VLQ $T\to Ht/Zt$ | 1 e,μ | ≥1 b, ≥3 j | Yes | 139 | T mass | 1.8 TeV | SU(2) singlet, $\kappa_T=0.5$ | ATLAS-CONF-2021-040
VLQ $Y\to Wb$ | 1 e,μ | ≥1 b, ≥1 j | Yes | 36.1 | Y mass | 1.85 TeV | $\mathcal{B}(Y\to Wb)$= 1, $c_R(Wb)$= 1 | 1812.07343
VLQ $B\to Hb$ | 0 e,μ | ≥2b, ≥1j, ≥1J | – | 139 | B mass | 2.0 TeV | SU(2) doublet, $\kappa_B=0.3$ | ATLAS-CONF-2021-018
Excited fermions
Excited quark $q^*\to qg$ | – | 2 j | – | 139 | q^* mass | 6.7 TeV | only u^* and d^*, $\Lambda=m(q^*)$ | 1910.08447
Excited quark $q^*\to q\gamma$ | 1 γ | 1 j | – | 36.7 | q^* mass | 5.3 TeV | only u^* and d^*, $\Lambda=m(q^*)$ | 1709.10440
Excited quark $b^*\to bg$ | – | 1 b, 1 j | – | 36.1 | b^* mass | 2.6 TeV | | 1805.09299
Excited lepton ℓ^* | 3 e,μ | – | – | 20.3 | ℓ^* mass | 3.0 TeV | $\Lambda=3.0$ TeV | 1411.2921
Excited lepton ν^* | 3 e,μ,τ | – | – | 20.3 | ν^* mass | 1.6 TeV | $\Lambda=1.6$ TeV | 1411.2921
Other
Type III Seesaw | 2,3,4 e,μ | ≥2 j | Yes | 139 | N^0 mass | 910 GeV | | 2202.02039
LRSM Majorana ν | 2 μ | 2 j | – | 36.1 | N_R mass | 3.2 TeV | $m(W_R)=4.1$ TeV, $g_L=g_R$ | 1809.11105
Higgs triplet $H^{\pm\pm}\to W^\pm W^\pm$ | 2,3,4 e,μ (SS) | various | Yes | 139 | $H^{\pm\pm}$ mass | 350 GeV | DY production | 2101.11961
Higgs triplet $H^{\pm\pm}\to\ell\ell$ | 2,3,4 e,μ (SS) | – | – | 139 | $H^{\pm\pm}$ mass | 1.08 TeV | DY production | ATLAS-CONF-2022-010
Higgs triplet $H^{\pm\pm}\to\ell\tau$ | 3 e,μ,τ | – | – | 20.3 | $H^{\pm\pm}$ mass | 400 GeV | DY production, $\mathcal{B}(H_L^{\pm\pm}\to\ell\tau)=1$ | 1411.2921
Multi-charged particles | – | – | – | 36.1 | multi-charged particle mass | 1.22 TeV | DY production, $|q|=5e$ | 1812.03673
Magnetic monopoles | – | – | – | 34.4 | monopole mass | 2.37 TeV | DY production, $|g|=1g_D$, spin 1/2 | 1905.10130
$\sqrt{s}$ = 8 TeV
$\sqrt{s}$ = 13 TeV partial data
$\sqrt{s}$ = 13 TeV full data
10^{-1}
1
10
Mass scale [TeV]

Direct searches for new physics

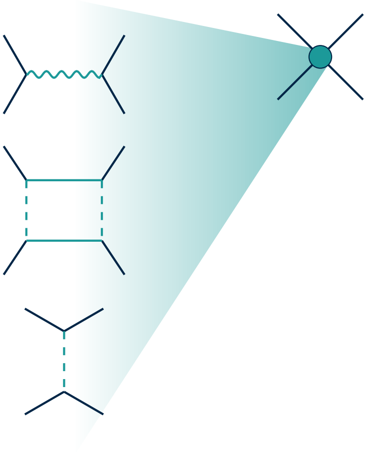


New physics looks to be weakly interacting or heavy!

Base assumption for use of SMEFT

Effective field theory

High-energy physics manifests as contact interactions in EFTs



UV Physics

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_{D=5} \sum_{k} \frac{C_{D,k}}{\Lambda^{D-4}} \mathcal{O}_{D,k}$$

Effective field theory

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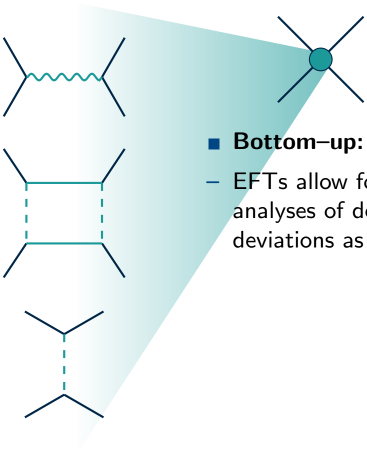


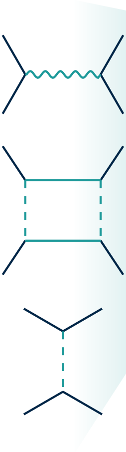
$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_{D=5} \sum_{k} \frac{C_{D,k}}{\Lambda^{D-4}} \mathcal{O}_{D,k}$$

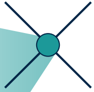
UV Physics

- **Bottom–up:**
  - EFTs allow for **model-comprehensive** ("model-independent") analyses of deviations from the SM, quantifying possible deviations as an expansion in E/Λ

Effective field theory

High-energy physics manifests as contact interactions in EFTs



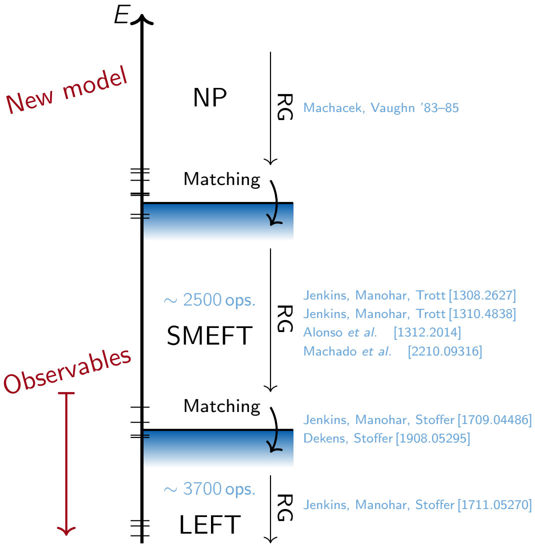


UV Physics

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_{D=5} \sum_{k} \frac{C_{D,k}}{\Lambda^{D-4}} \mathcal{O}_{D,k}$$

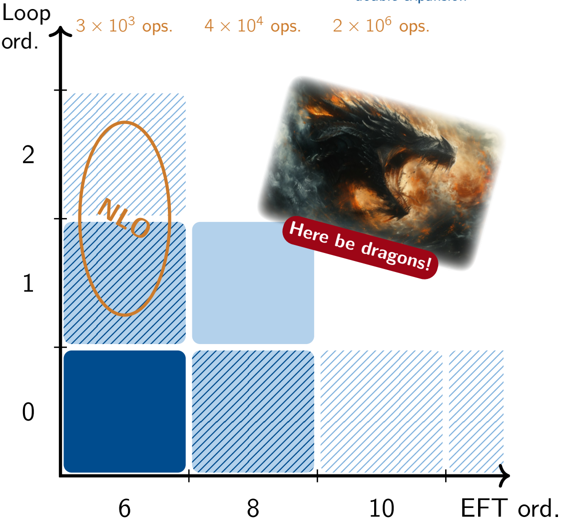
- **Bottom–up:**
  - EFTs allow for **model-comprehensive** ("model-independent") analyses of deviations from the SM, quantifying possible deviations as an expansion in E/Λ
- **Top–down:**
  - **Precision calculations** necessitates the use of EFTs to separate the large BSM energy scales
  - Many BSM models result in the same EFT and **calculations can be recycled**: you only need to compute once in the EFT

BSM EFT workflow

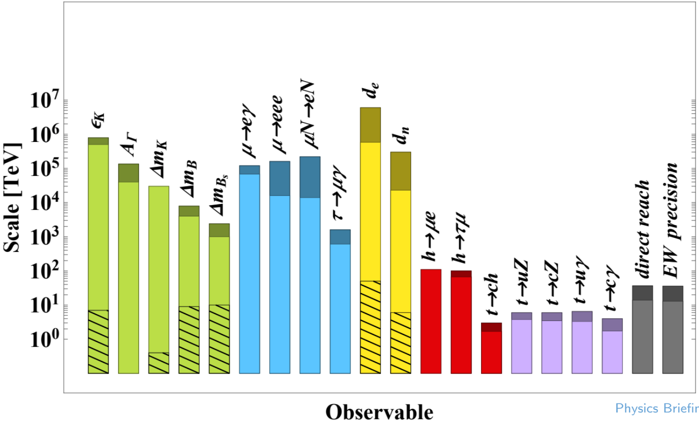


How advanced are SMEFT calculations?

$$\mathcal{L}_{\mathrm{SMEFT}}(\phi) = \mathcal{L}_{\mathrm{SM}}(\phi) + \sum_{d=5}^{\infty} \sum_{\ell=0}^{\infty} \sum_{k} \underbrace{\frac{C_{d,k}^{(\ell)}}{(16\pi^2)^{\ell}\, \Lambda^{d-4}}}_{\text{double expansion}} \mathcal{O}_{d,k}^{(\ell)}(\phi)$$



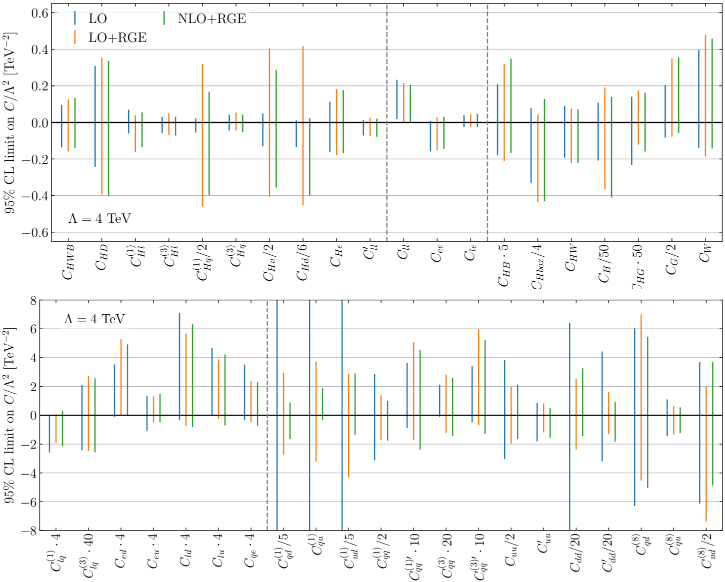
Why SMEFT at the FCC?



Physics Briefing Book [1910.11775]

- Indirect searches very competitive with direct BSM searches (see talk by L. Allwicher)
- FCC to improve sensitivity to NP in rare-decays, Higgs physics, top physics, EW precision

Operator mixing, a SMEFT loop effect



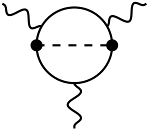
Global fit with $U(3)^5$ flavor symmetry

Figure from Bartocci, Biekötter, Hurth [2412.09674]

Why we need NLO

- Sizable radiative QCD + top Yukawa effects
- Qualitatively new effects at 2-loop order

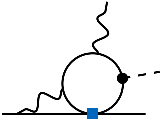
Das Bakshi *et al.* [2103.15861]



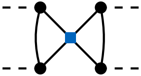
Heavy fermions producing CP-odd triple gauge boson interactions

- Surprisingly large 2-loop effects

Ardu, Davidson [2103.07212]; Allwicher *et al.* [2302.11584]



LFV 4-fermion operator contributing to $\mu \to e\gamma$



4-top operator contributing to m_W

- Restoration of scheme invariance $\rightsquigarrow$ minimizes theory uncertainties

SMEFT@NLO: current status

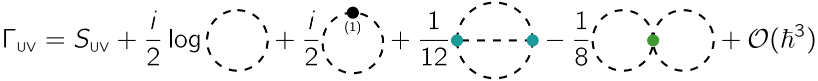
	LO	NLO	Automated	
MC generators	✓	✓	✓	QCD effects only
Higgs physics	✓	✓		Many decay and production channels
EWP	✓	✓	✓ (LO)	Lacking full flavor dependence
RG (anomalous dims.)	✓	✗	✓	Very partial 2-loop results
SMEFT→LEFT matching	✓	✓	✓	
UV→SMEFT matching	✓	✓	✓	Broken gauge symmetries largely untested

Computational challenges

- Mature multi-loop EFT techniques have been developed for SM calculations (WEH). A basis for SMEFT calculations @ NLO
- **Continuation of $\boldsymbol{\gamma}_5$** to $d = 4 - 2\epsilon$ dimensions
  - Semi-naive implementation (case by case validity)
  - BMHV-scheme (gauge-restoring counterterms)

$$\mathrm{Tr}\left[\gamma_\alpha \gamma_\mu \gamma_\nu \gamma_\rho \gamma_\sigma \gamma^\alpha \gamma_5\right] = \ldots ?!$$

- **Evanescent operators** become relevant @ NLO
- Experimentation with new computational framework (functional methods, heat-kernel, etc.)



Two-loop SMEFT RGEs

- Implementation based on `Matchete`
- Using newly developed functional methods
- Bosons are handled, fermions are WIP

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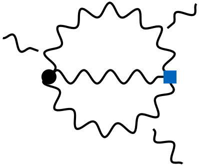


```
L = FreeLag[] + cGt[] Gtilde;
L // NiceForm
```

iceForm=

$$-\frac{1}{4} G^{\mu\nu x 2} + \left(D_\mu \bar{c}_G{}^x \cdot D_\mu c_G{}^x\right) + g\, G^{\mu y} \left(\bar{c}_G{}^x \cdot D_\mu c_G{}^z\right) f^{xyz} + \frac{1}{6}\, \mathrm{cGt}\, G^{\mu\rho y} G^{\nu\rho z} G^{\sigma\kappa x} f^{xyz} \varepsilon^{\mu\nu\sigma\kappa}$$

```
ctlag = CountertermLagrangian[L, EFTOrder → 6] // EchoTiming;
ctlag // NiceForm
```

» Added new CG cg1 with indices {SU3c[adj], SU3c[adj], SU3c[adj], SU3c[adj]}

» Added new CG cg2 with indices {SU3c[adj], SU3c[adj], SU3c[adj], SU3c[adj], SU3c[adj]}

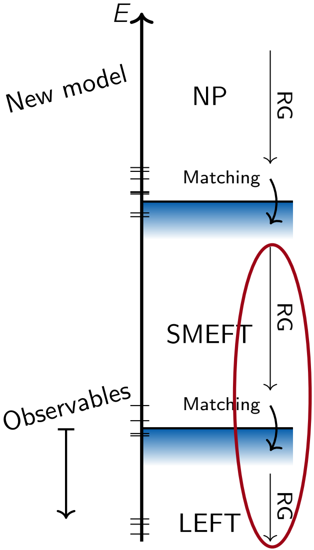
13 695.1 — Mathematica, single core

'/NiceForm=

$$-\frac{11}{4} \hbar \frac{1}{\epsilon} g^2 G^{\mu\nu x 2} - \frac{51}{4} \hbar^2 \frac{1}{\epsilon} g^4 G^{\mu\nu x 2} - 3\hbar \frac{1}{\epsilon} \mathrm{cGt}\, g^2 G^{\mu\nu x} G^{\rho\sigma y} G^{\sigma\kappa z} f^{xyz} \varepsilon^{\mu\nu\rho\kappa} - \frac{21}{2} \hbar^2 \frac{1}{\epsilon^2} \mathrm{cGt}\, g^4 G^{\mu\nu x} G^{\rho\sigma y} G^{\sigma\kappa z} f^{xyz} \varepsilon^{\mu\nu\rho\kappa} - \frac{425}{24} \hbar^2 \frac{1}{\epsilon} \mathrm{cGt}\, g^4 G^{\mu\nu x} G^{\rho\sigma y} G^{\sigma\kappa z} f^{xyz} \varepsilon^{\mu\nu\rho\kappa}$$

Born, Fuentes-Martín, Kvedaraitė, **AET** [2410.07320]+WIP

Software tools



Evolving SMEFT coefficients:

DsixTools
Fuentes-Martín *et al.* [2010.16341]

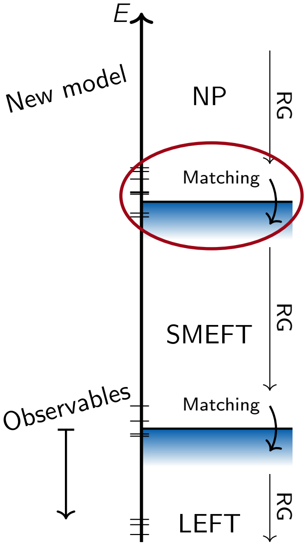
wilson
Aebischer *et al.* [1804.05033]

RGEsolver
Di Noi, Silvestrini [2210.06838]

Common interface format:

WCxf
Aebischer *et al.* [1712.05298]

Software tools



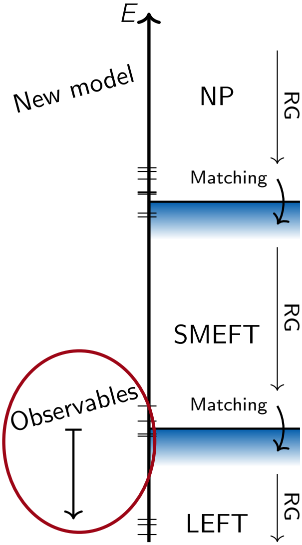
One-loop matching tools:

MATCHETE — **AET** *et al.* [2212.04510]

Carmona *et al.* [2112.10787]

One-loop dictionaries:

SOLD — Guedes *et al.* [2303.16965]



SMEFT in event generators:

SMEFT@NLO
Degrande *et al.* [2008.11743]

SmeftFR
Dedes *et al.* [2302.01353]

SMEFTsim
Brivio [2012.11343]

Fitting tools:

Staub [1810.08132]

EOS
van Dyk *et al.* [2111.15428]

Aebischer *et al.* [1810.07698]

HEPfit
de Blas *et al.* [1910.14012]

SMEFiT
Ellis *et al.* [2012.02779]

HighPT
Allwicher *et al.* [2207.10756]

Fitmaker
Ellis *et al.* [2012.02779]

Summary and outlook

- Comprehensive SMEFT analyses benefit from inclusion of higher order effects
- New computational/QFT challenges
- Software packages $\rightsquigarrow$ new flexibility!
- Great progress and . . . much more to come before the 2040's

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Thank you!