The Standard Model effective field theory at low energies

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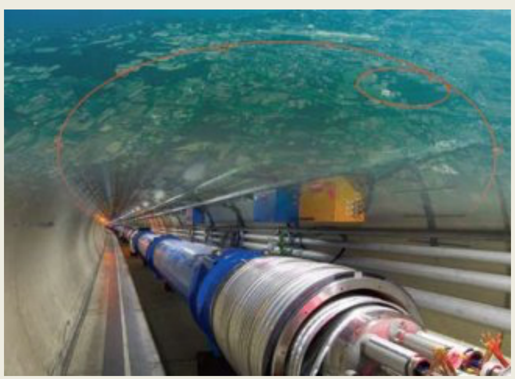
SM-EFT at low energy

- **Tautology:** *the saying of the same thing twice in different words*
- By construction: SM-EFT approximates some UV-complete theory at a high-energy scale ~ $\mathbf{\Lambda}$
- **All experiments are low-energy experiments.**
- Of course: SM-EFT might break down @LHC if $\mathbf{\Lambda}$ close to EW scale
- That being said: in general a split is made



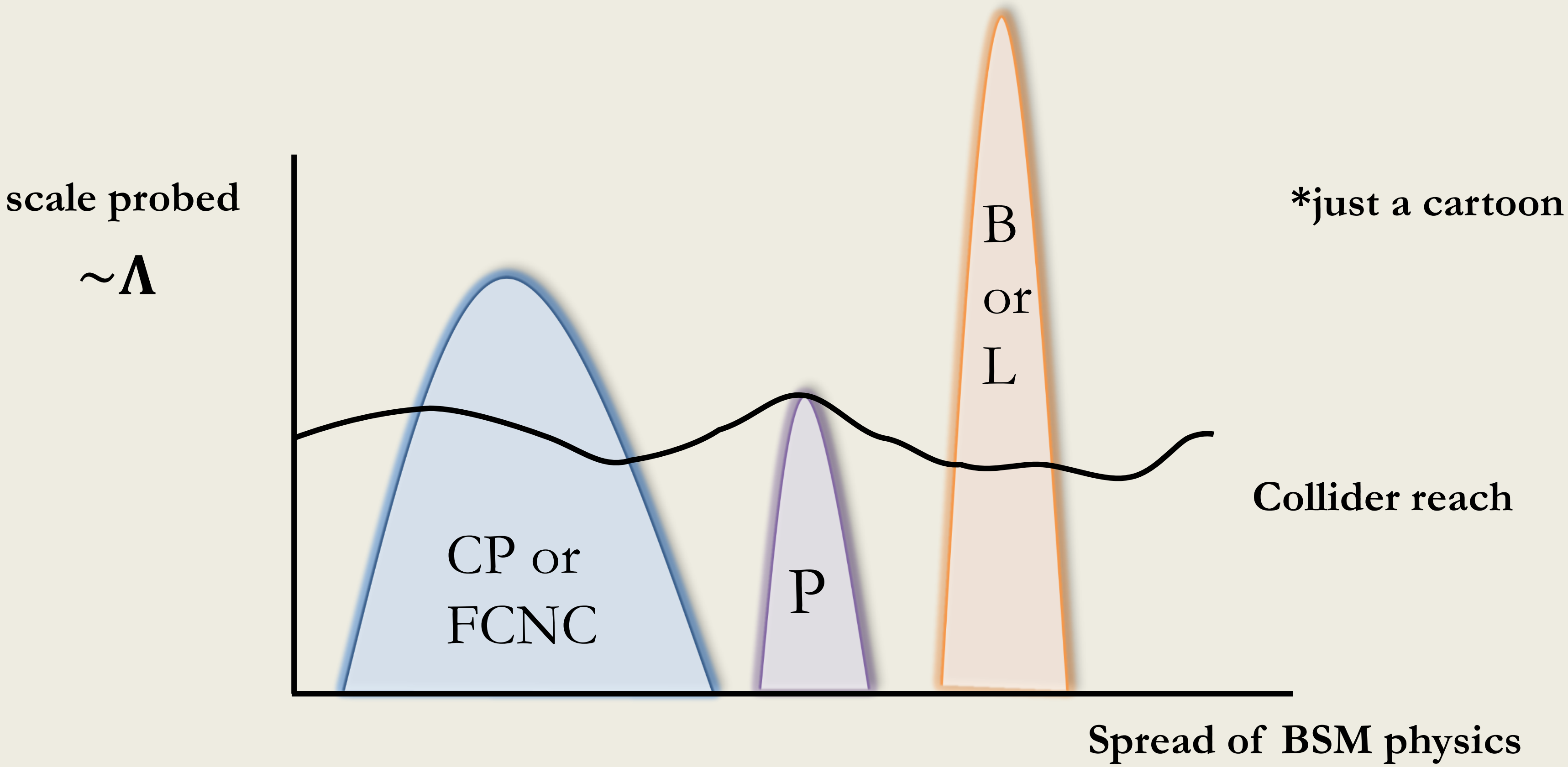
Large Hadron Collider and beyond

Everything else at lower energies (might include LEP)

Split is understandable from community point of view but of course artificial

Large number of low-energy SM tests

- Proton decay (dim 6^2)
- neutron-antineutron oscillations (dim-9)
- Neutrinoless double beta decay (dim-5^2)
- Lepton flavor violation (dim-6^2)
- Electric dipole moments (theta + dim-6)
- Pion, neutron, nuclear beta decay (dim 6)
- Electron/muon g-2 (dim 6)
- Flavor physics (dim 6)
- Coherent neutrino scattering (dim 6)
- ……………………………

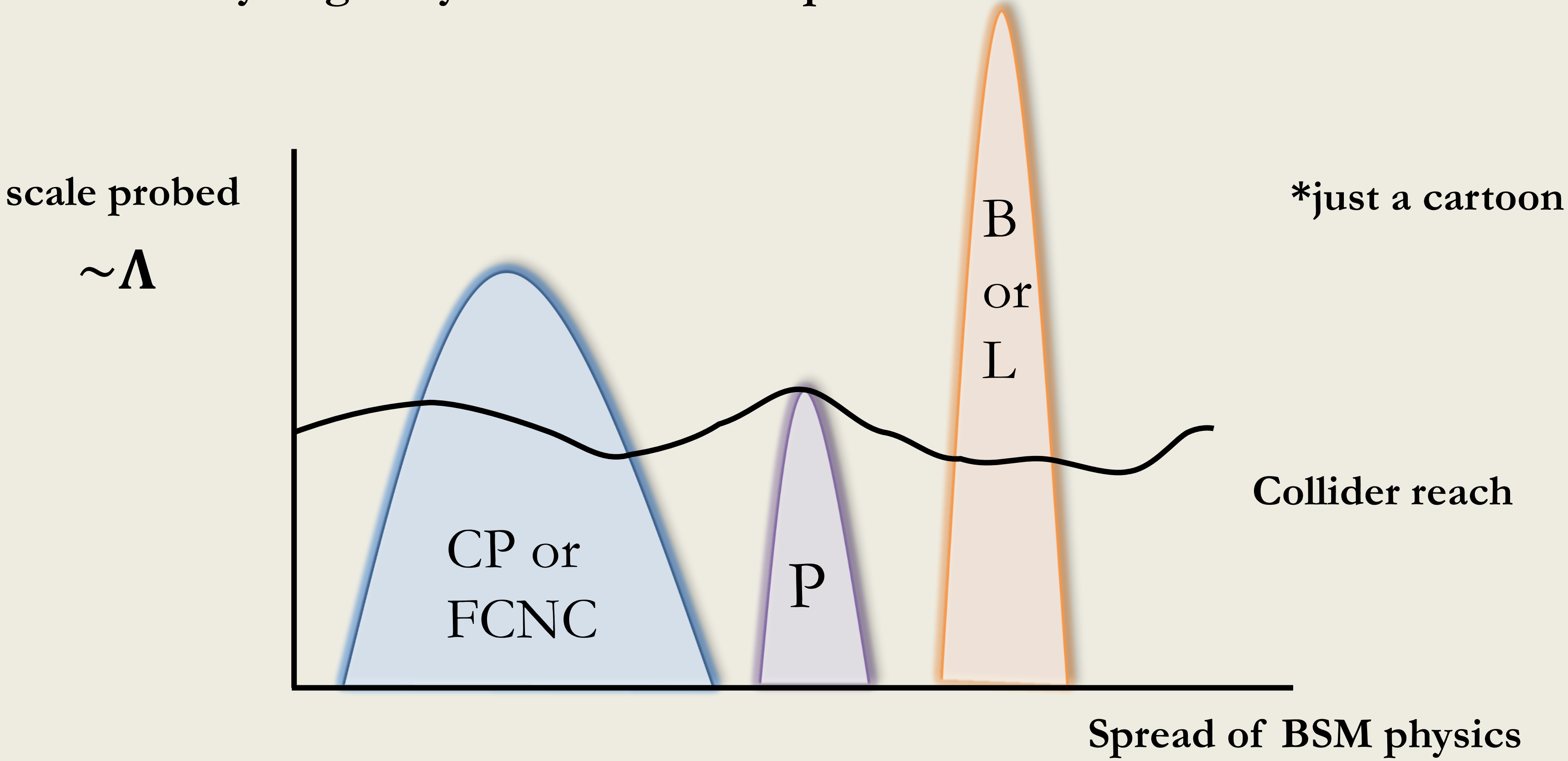


Large number of low-energy SM tests

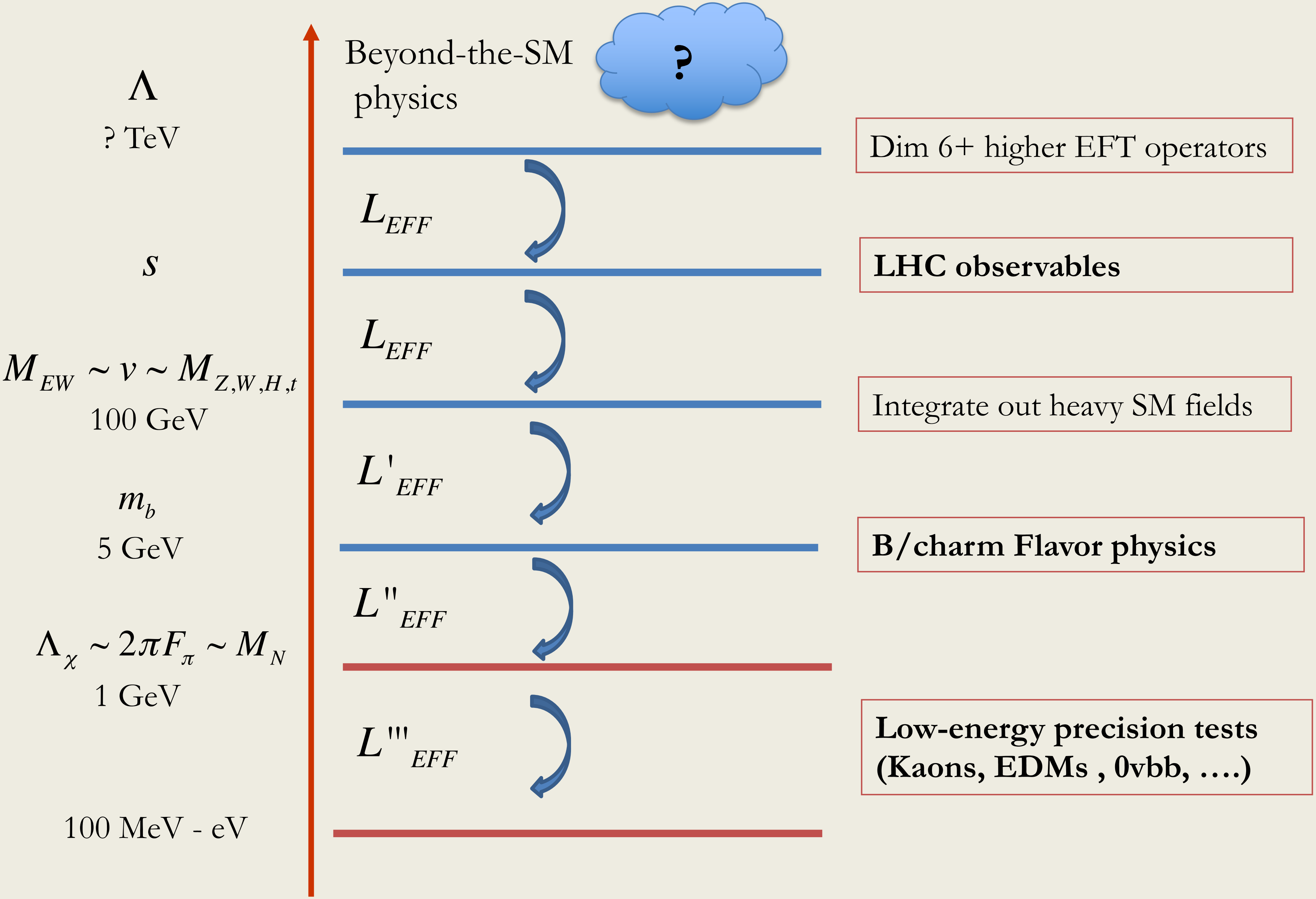
- For BSM physics to be observable at the LHC, we need to avoid the 'peaks'

1. Avoid FCNC and CP by hand or via Minimal Flavor Violation
2. Assume B+L conservation (accidental in SM)

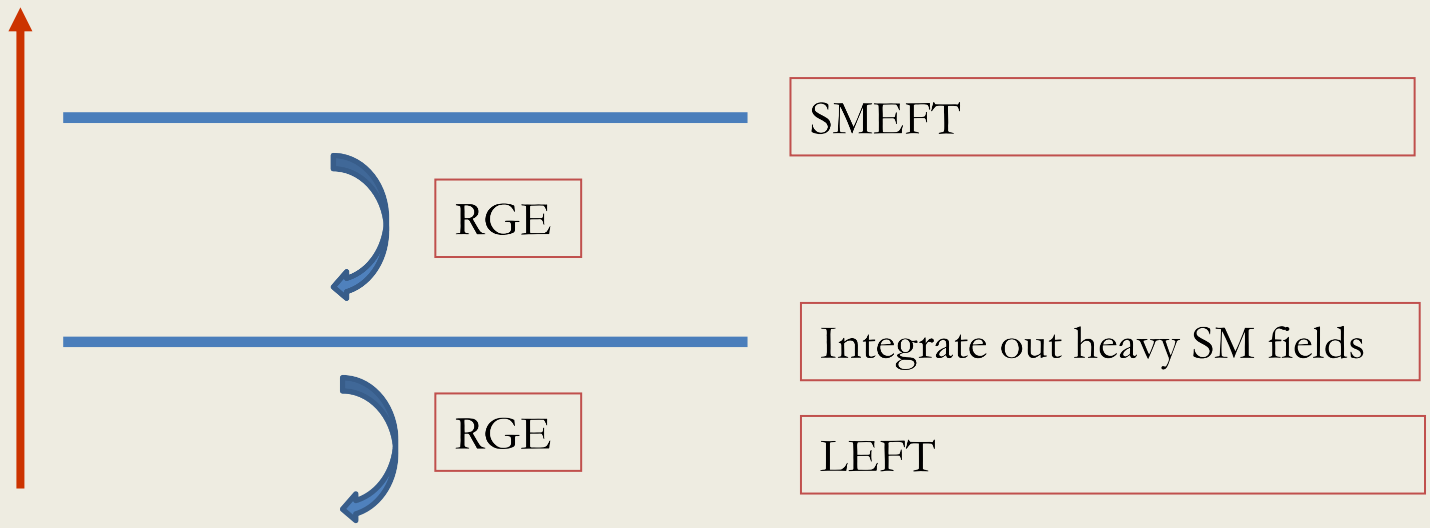
- Reasonable: but of course strong assumptions on BSM models
- **Best way to go beyond these assumptions ?**



The road to incorporate low-energy tests



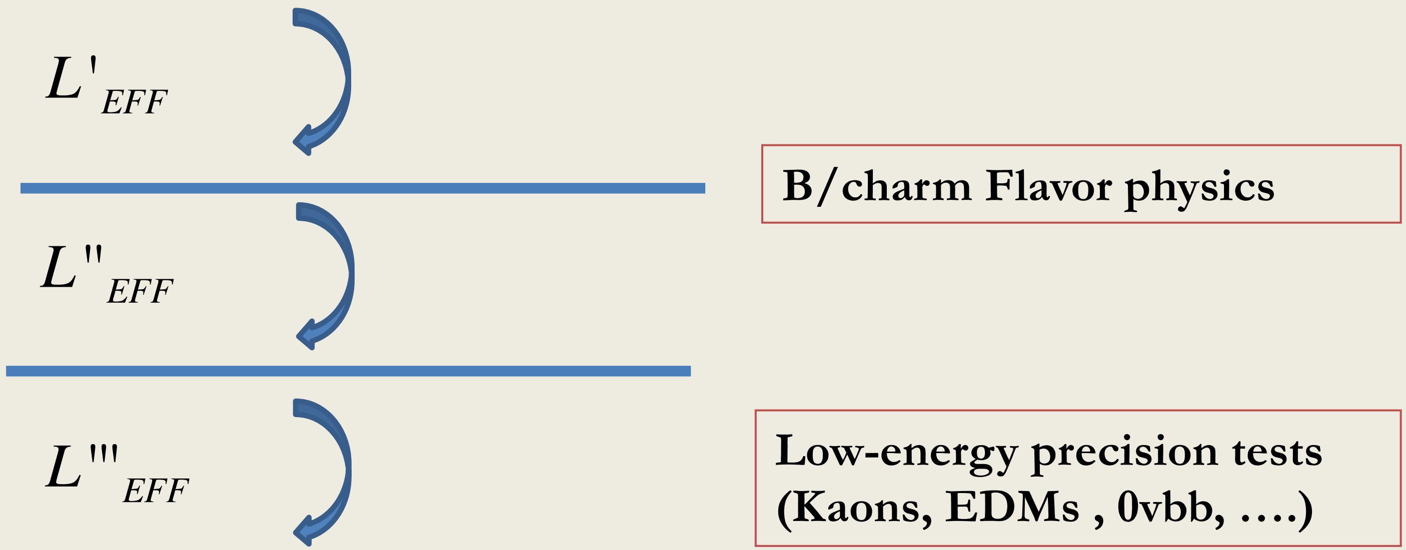
Connecting to low-energy scales



- **Renormalization-group equations** to evolve to low energies
- Full 1 loop below and above EW scale known (Jenkins et al '13 '14 '17)
- 2- or 3-loop known for subset of operators (e.g. 1907.04923)

- Matching to **LEFT** below EW scales (integrate out top, Higgs, W-Z)
- **Full one-loop matching by Dekens/Stoffer: 1908.05295**
- Some cases 2-loop matters (e.g. Barr-Zee diagrams)

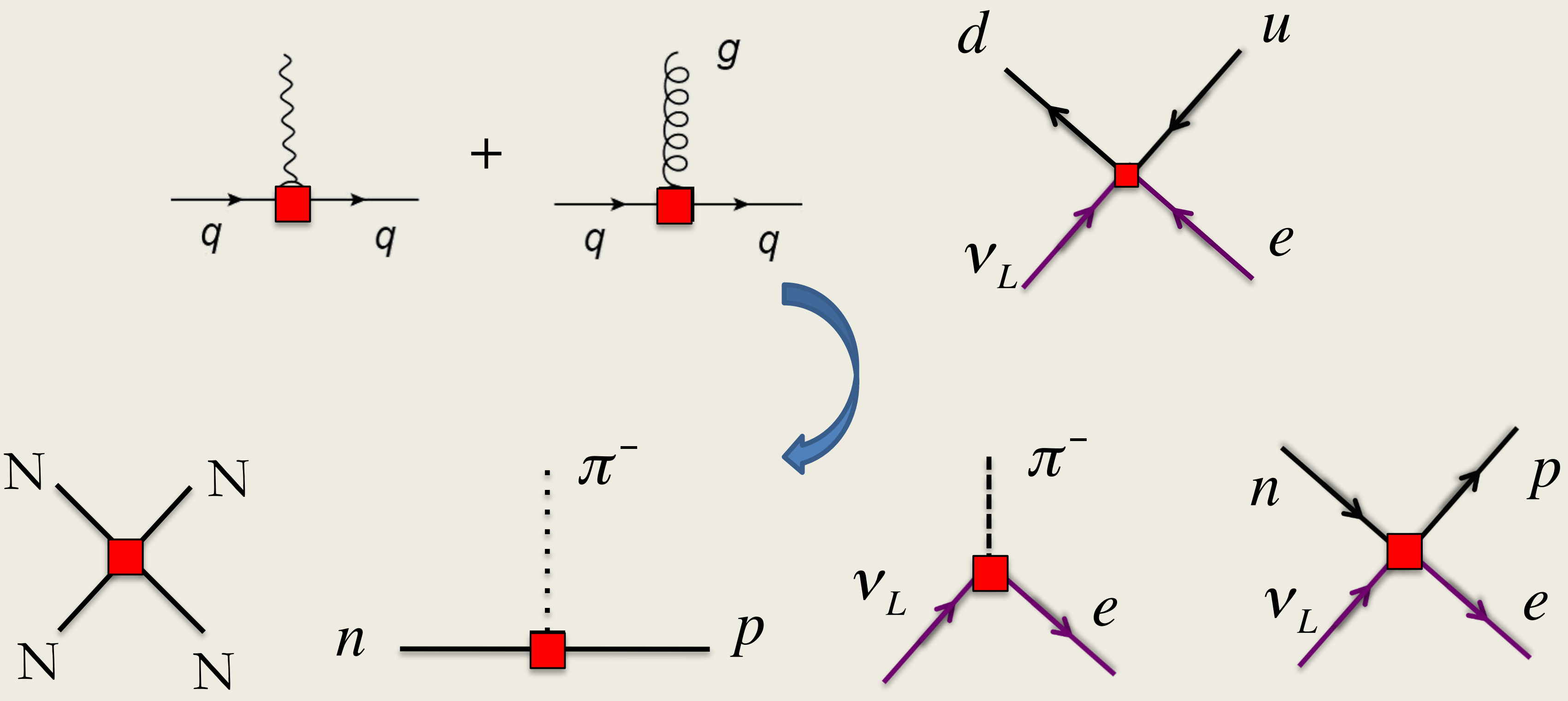
Challenges of non-perturbative QCD



- SM-EFT can be matched to EFTs for non-perturbative QCD

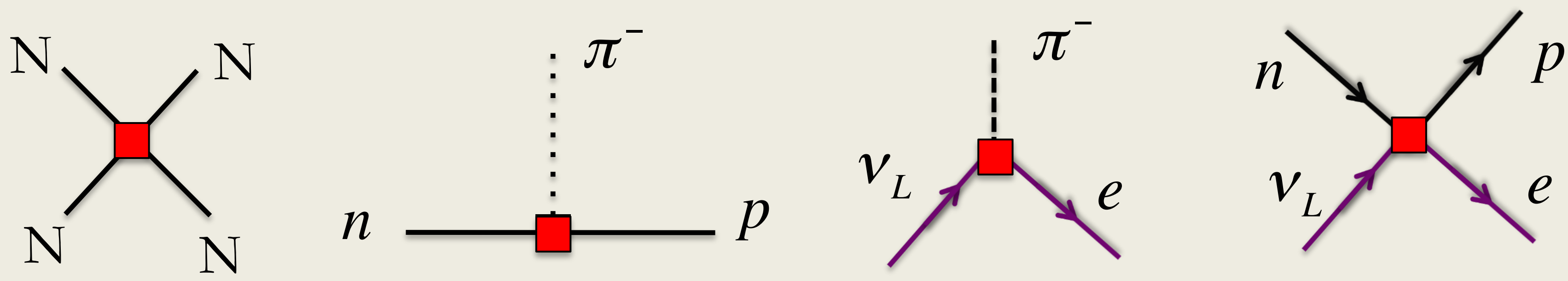
1. Heavy Quark EFT (bottom, charm)
2. **Chiral Perturbation Theory (nucleons, pions, kaons)**
3. **Chiral EFT (nuclei)**

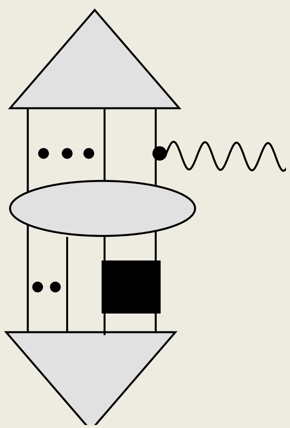
From LEFT to ChPT



- ChPT to translate LEFT to hadrons. **Power counting identifies leading terms.**
- Matrix elements ideally from lattice QCD
- Great progress for nucleon form factors, LNV, CPV, g-2 QCD corrections
- But still 100% uncertainties for many cases (e.g. 0vbb, EDMs)

From LEFT to ChEFT





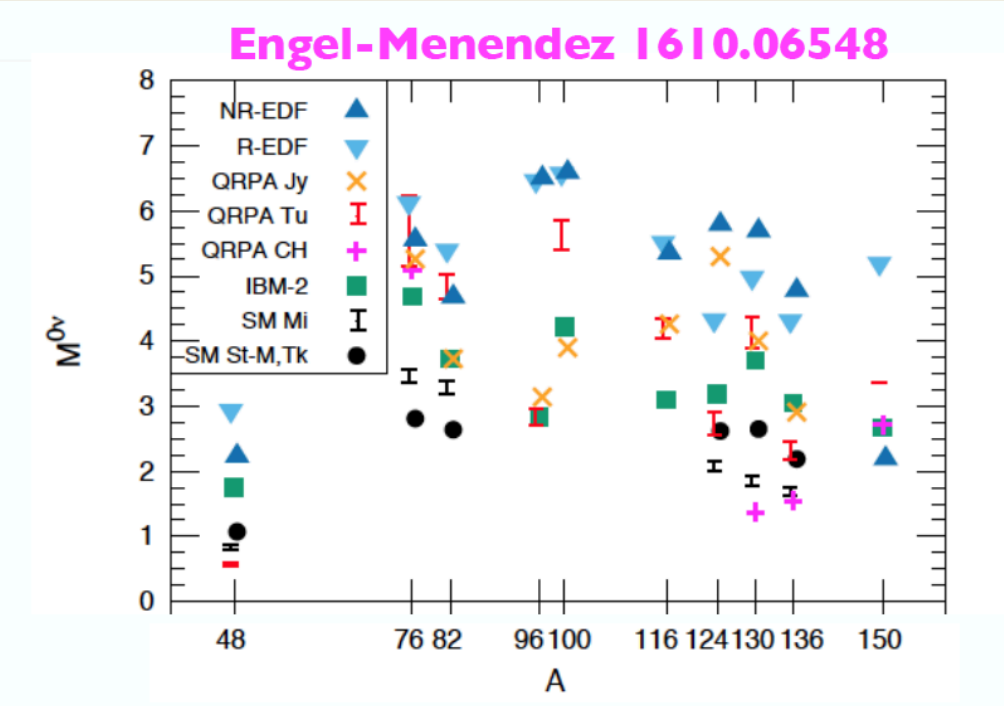
ChEFT to systematiccaly calculate nuclear BSM observables

EDMs, 0vbb, mu-to-e conversion, DM direct detection, ….

- Chiral EFT for both **wave functions and BSM currents**.
- **First-principle** for light nuclei (tremendous progress last few years)
- Nuclear approximations for heavier systems (e.g. Shell Model)

- **Works great in some cases, for others still big problem**

Open problems

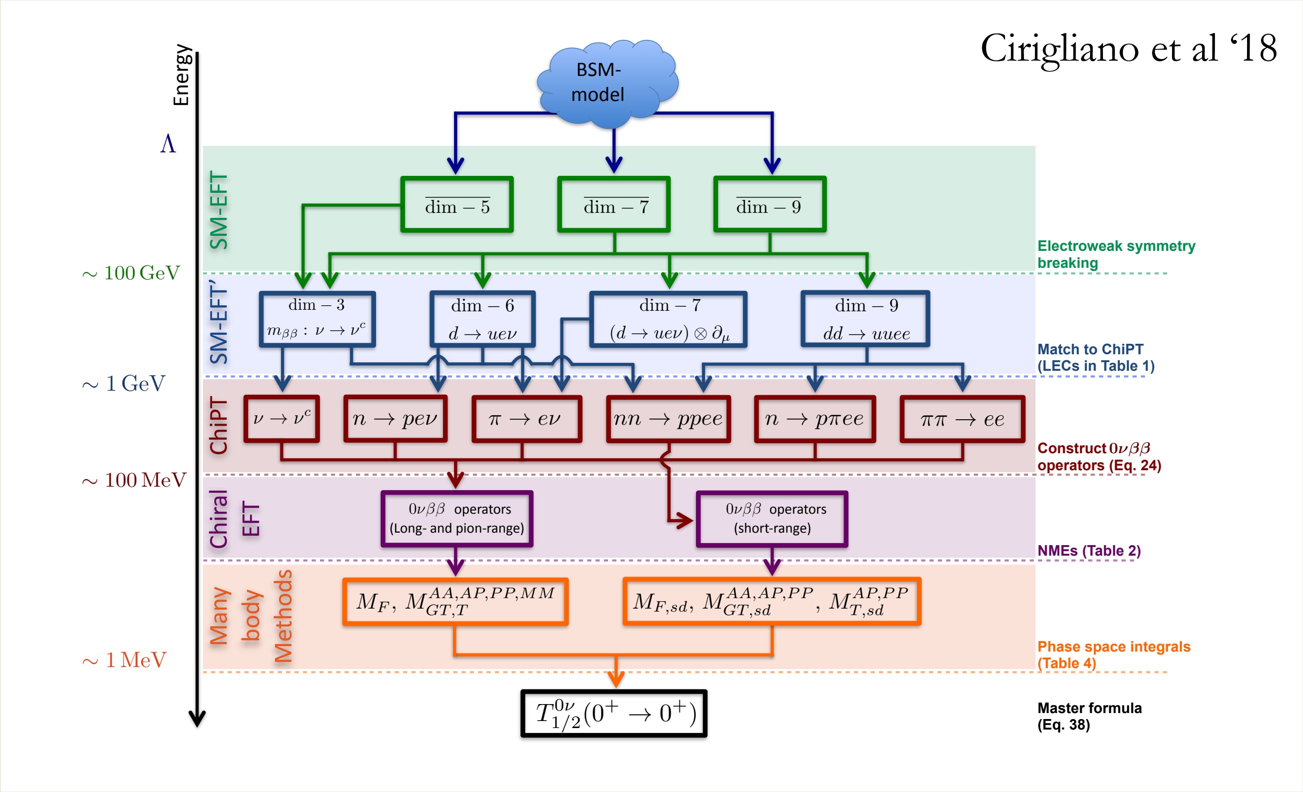


EDMs	a_1 range (best)
^{199}Hg	0.030±0.060
^{225}Ra	14±12
^{129}Xe	-0.03±0.025

- Nuclear observables that depend on two-nucleon processes (neutrinoless double beta decay, CPV nuclear force, Hadronic Parity Violation) are **problematic**
- **Power counting** not always understood (*do we even know what is leading order?)*

- **Chiral EFT is rich topic: benefits from closer particle-nuclear connection and the EFT experts in the hep-ph community**
- See for instance 2020 INT program: BSM physics with nucleons and nuclei

End-to-End EFT framework



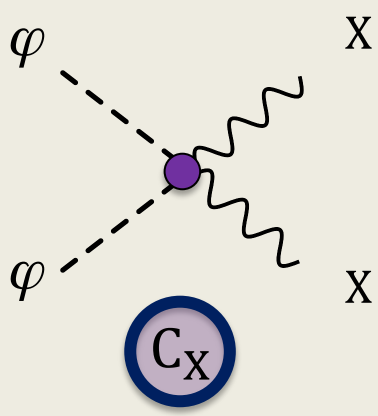
- Cascade of EFTs to connect low-energy observables to SMEFT at high scales
- Exists e.g. for 0vbb, EDMs, beta decay, coherent scattering, many flavor observables

- **How to deal with hadronic/nuclear uncertainties in fits ?**
- **How to truncate operator basis to make fit managable ?**
- Automization tools would be very welcomes (a la **flavio** for flavor physics)

An explicit example: CPV in Higgs sector

- CP violation typically ignored in fits of Higgs, top, EW global fits
- Lot of interest in CPV in higgs and top physics (e.g. for EW baryogenesis)
- *See also: Snowmass-2021 CPV Higgs couplings by Andrei Gritsan*
- 4 gauge-Higgs operators exist (B, W, BW, G)

$\varphi^{+}\varphi\, X\tilde{X}$



After EW symmetry breaking

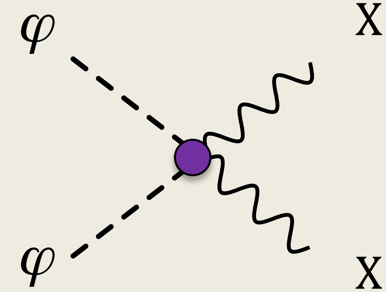
- **h-gluon-gluon**
- **h-gamma-gamma**
- **h-gamma-Z**
- **W-W-gamma**
- **h-Z-Z (not independent)**

- Evades flavor constraints (MFV automatic). Scale can be relatively low
- Motivated by universal theories (BSM couples to SM bosons/fermions through SM currents)

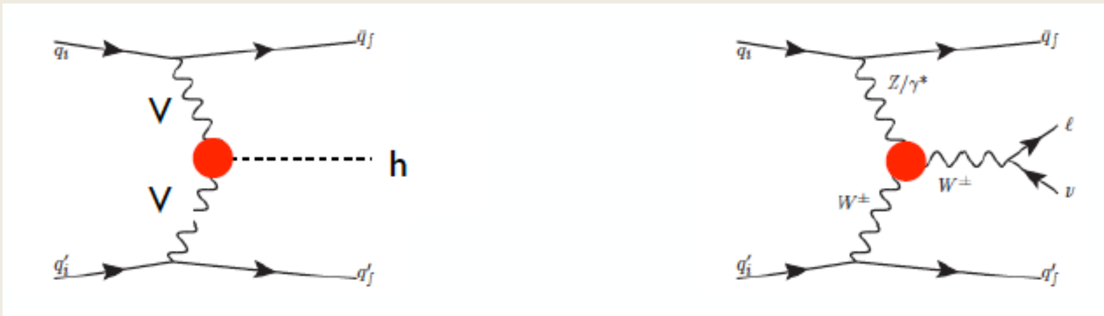
Peskin, Takeuchi '90
Barbieri et al '04
Ferreira et al '17

Collider and low-energy probes

$\varphi^{+}\varphi\, X\tilde{X}$



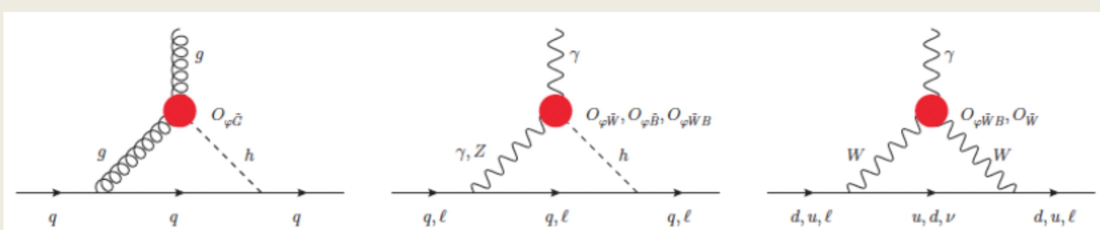
- Induce CPV angular distribution in pp → h/V + 2 jets



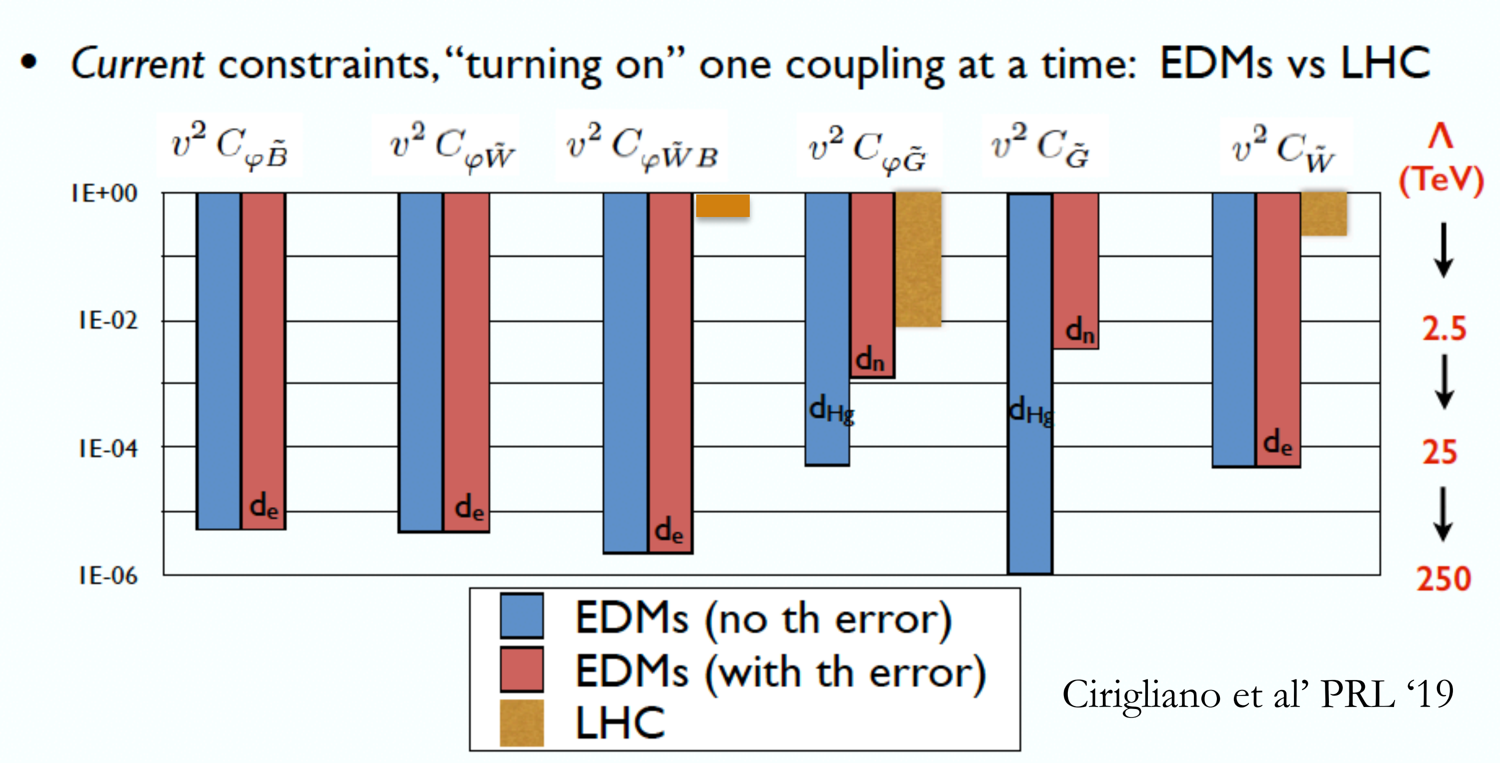
e.g. ATLAS 2006.15458 $0.23 < \tilde{C}_{HWB}/\Lambda^2 < 2.34\ (TeV^{-2})$

Bernlochner et al '19 $-0.19 < \tilde{C}_{HGG}/\Lambda^2 < 0.03\ (TeV^{-2})$

- Same couplings induce CPV fermionic operators at one loop
- Also induce CPV in B → s gamma transitions

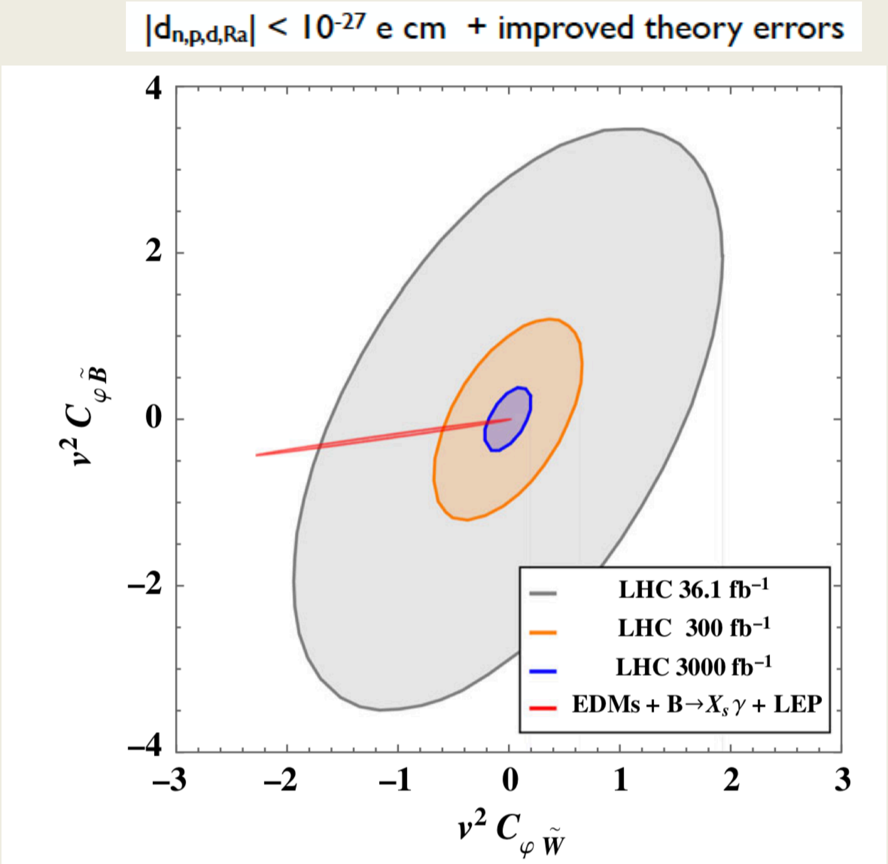


Low-energy constraints are stringent



- EDM constraints are very stringent for single couplings
- Theory errors are relevant for nuclear CP violation (very severe!)
- **But EDMs suffer from 'free directions'** $0.17\, C_{\varphi\tilde{B}} + 0.86\, C_{\varphi\tilde{W}} + 0.48\, C_{\varphi\tilde{W}B}$
- **Unconstrained direction: appears in global fits**

CP violation in ‘universal theories’



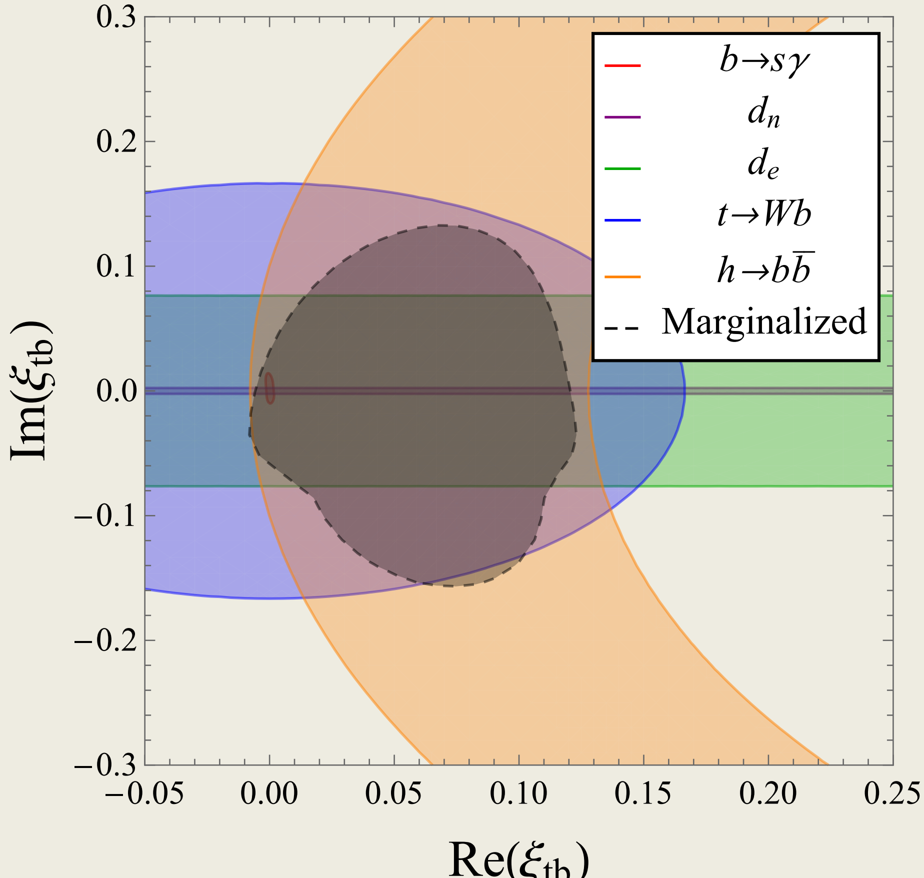
Cirigliano et al PRL ‘19

HL-LHC projections from Bernlochner et al ‘18

- Low-energy limits avoided in global fits (free directions)
- Strong constraints on possible UV completion (must point in free direction or appear at high scales only)
- **Low- and high-energy data together will close parameter space**

Another example: modified Wtb vertices

Real	Individual	Marginalized	Imaginary	Individual	Marginalized
ξ_{tb}	$[-1.4, 1.5] \cdot 10^{-3}$	$[-0.01, 0.12]$	ξ_{tb}	$[-2.4, 2.4] \cdot 10^{-3}$	$[-0.16, 0.13]$
δ_{LL}	$[-0.03, 0.04]$	$[-0.03, 0.04]$	–		
$v^2 C_{Wt}$	$[-0.09, 0.05]$	$[-0.10, 0.04]$	$v^2 C_{Wt}$	$[-6.0, 6.0] \cdot 10^{-4}$	$[-1.0, 0.9] \cdot 10^{-3}$
$v^2 C_{Wb}$	$[-0.04, 0.05]$	$[-3.5, 0.4]$	$v^2 C_{Wb}$	$[-3.5, 3.5] \cdot 10^{-2}$	$[-1.9, 2.2]$



Alioli, Cirigliano, Dekens, JdV, Mereghetti ‘17

de Beurs, Laenen, Vreeswijk, Vryonidou ‘18

These are just examples

- **All experiments are low-energy experiments in SMEFT**
- Even if low-energy constraints 'disappear' from global limits they still enforce non-trivial constraints on UV models
- We should include as much data as we can

- Benefit from **closer connection between communities** (e.g collider versus fundamental symmetries) who are looking for the same thing!

- **Personal interests for future of SMEFT@low energies**
  1. Hopefully more global analyses including low-energy data
  2. Better understanding of chiral EFT power counting for BSM
  3. Go beyond SM-EFT by adding light d.o.f.: e.g. sterile neutrinos or scalars
  4. Theta term not protected in SMEFT (unlike SM): new hierarchy problem. CP-odd observables could provide indirect evidence for Peccei-Quinn mechanism in nature *Draper, Kozaczuk et al' 18*
  5. Potential of new experiments (e.g. EIC) (see talk by Daniel Wiegand)
  6. ……………………..