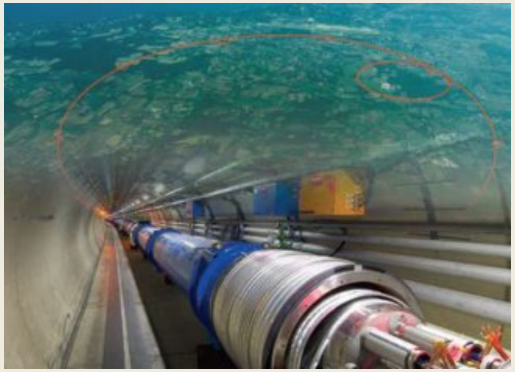
The Standard Model effective field theory at low energies

Jordy de Vries, University of Amsterdam, Nikhef

SM-EFT at low energy

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



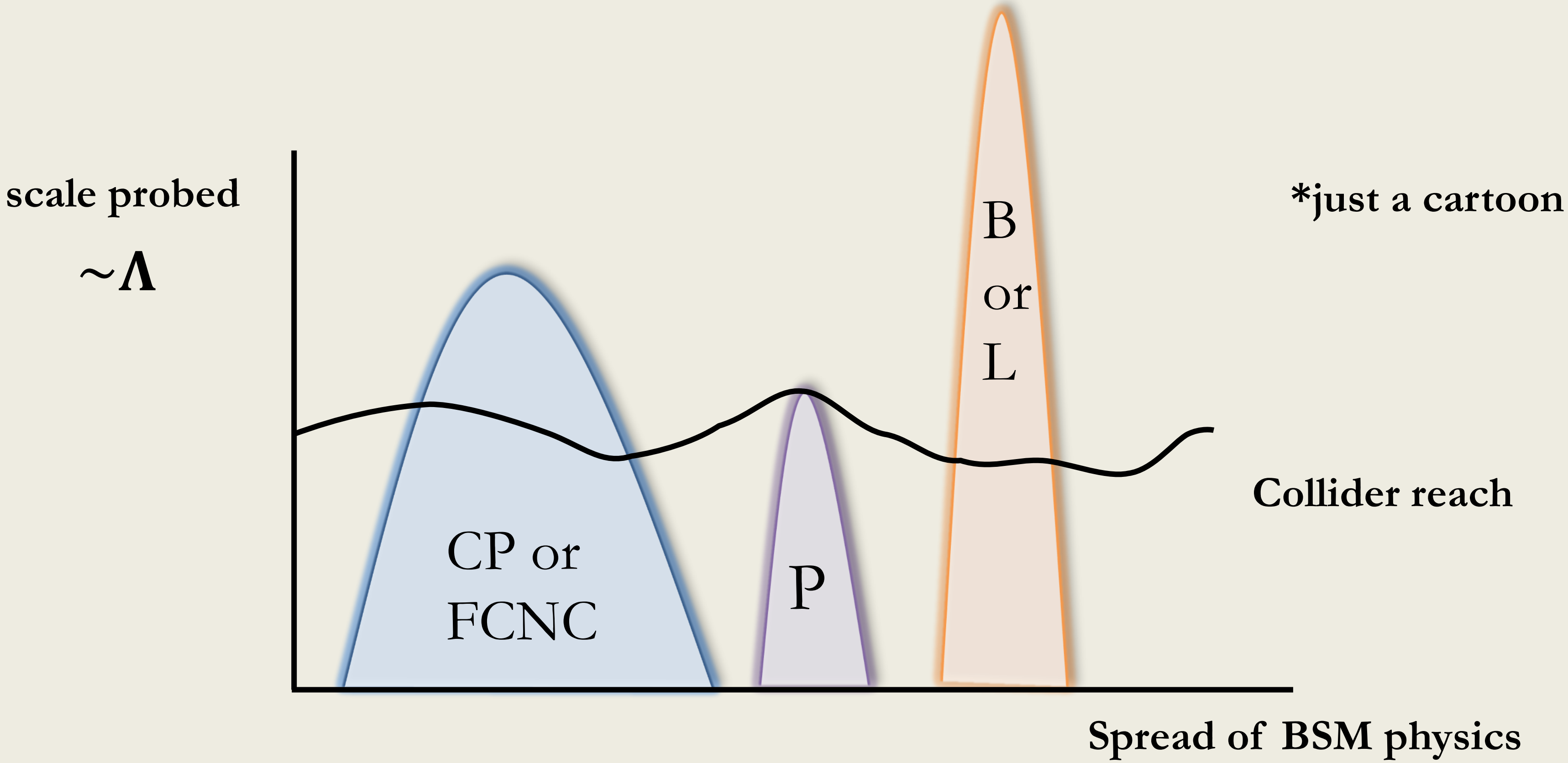
Large Hadron Collider and beyond

Everything else at lower energies

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)
- ....

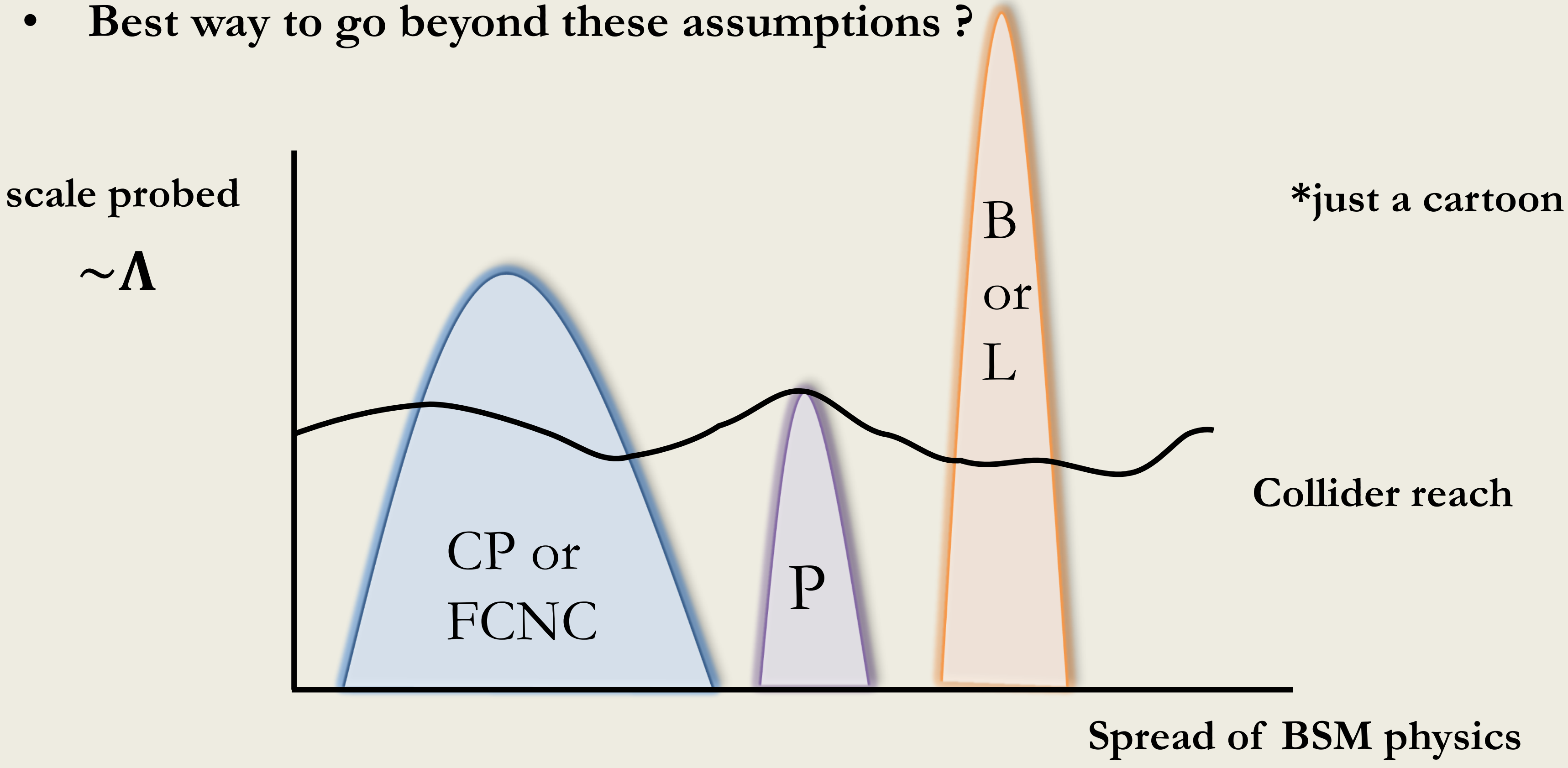


Large number of low-energy SM tests

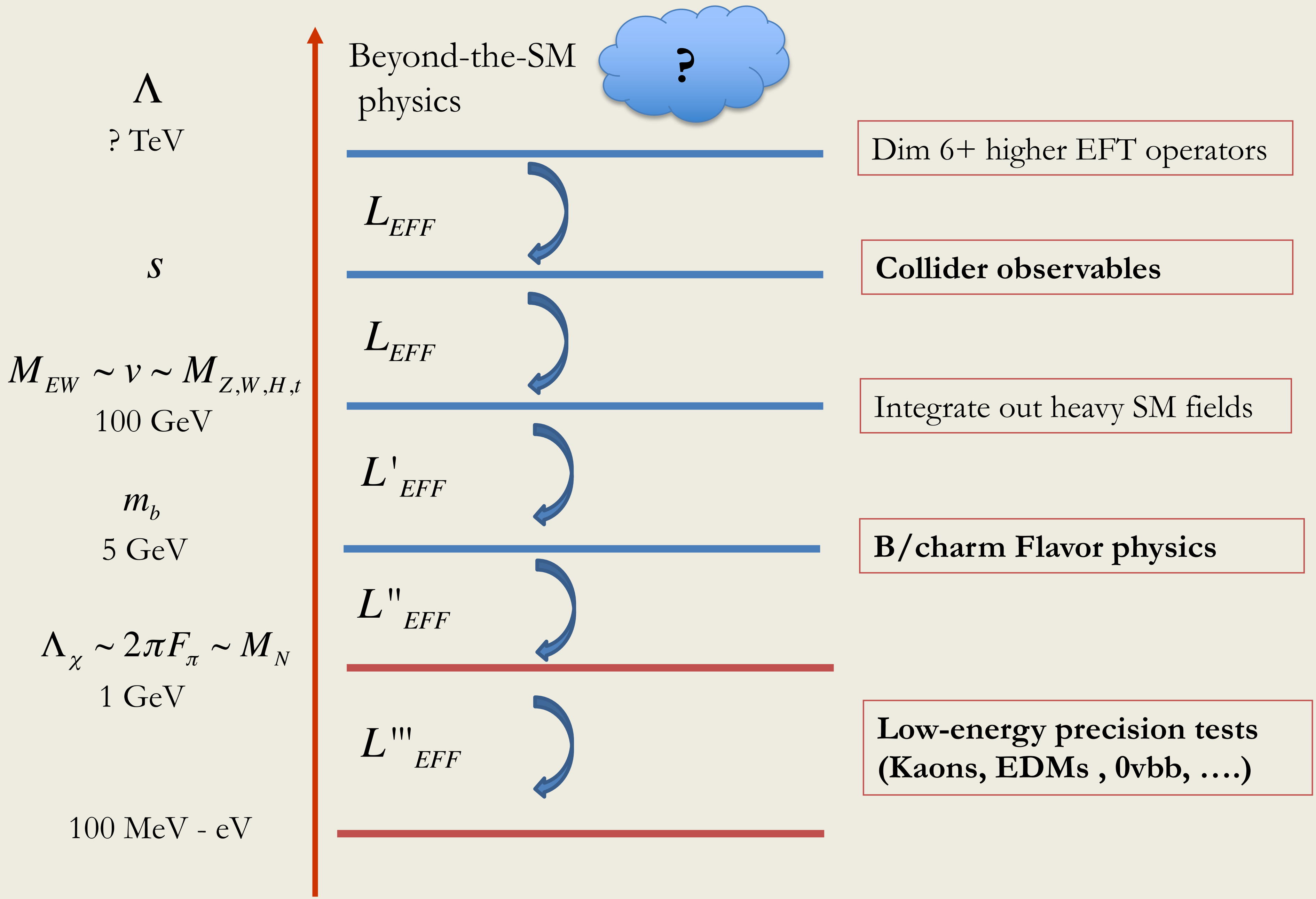
- For BSM physics to be relatively low scale, must avoid the 'peaks'

1. Avoid FCNC and CP by hand or via Minimal Flavor Violation
2. Assume B+L conservation (accidental in SM)
3. Or aim for free directions left behind by low-energy measurements

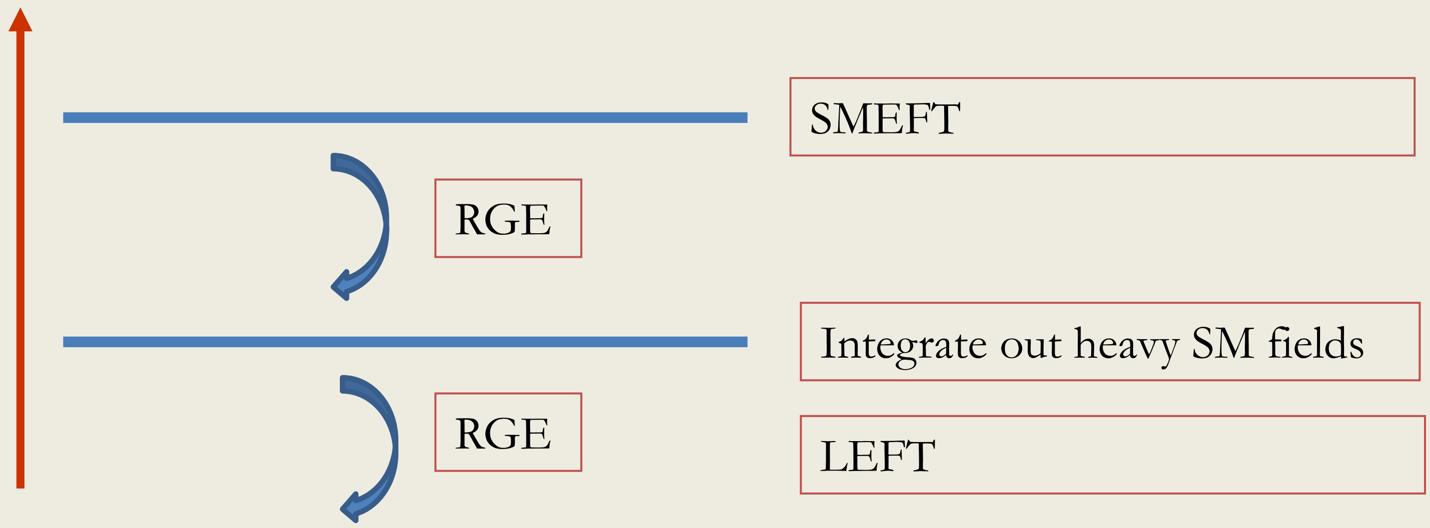
- Reasonable: but strong assumptions on BSM models
- **Best way to go beyond these assumptions ?**



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

L'_{EFF}

B/charm Flavor physics

L''_{EFF}

L'''_{EFF}

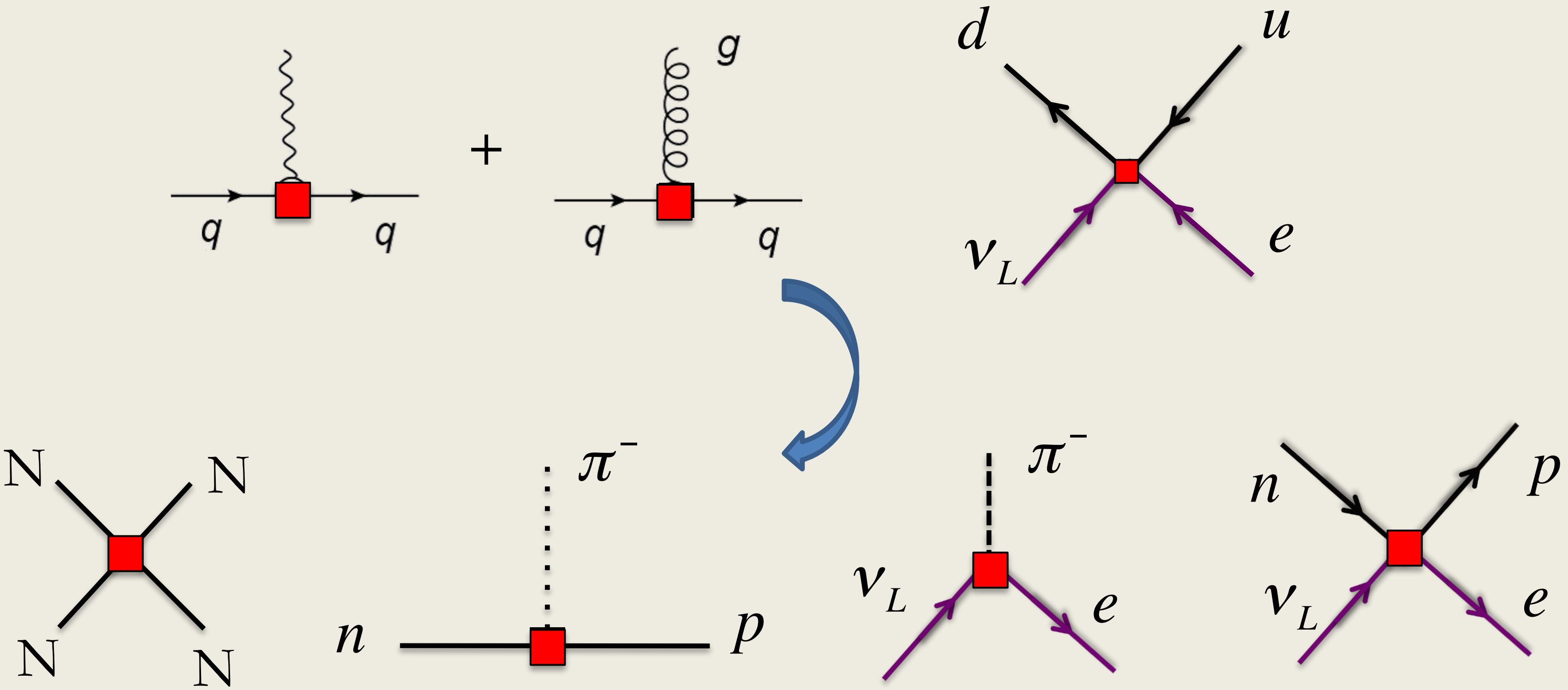
Low-energy precision tests (Kaons, EDMs , 0vbb, ….)

- 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)

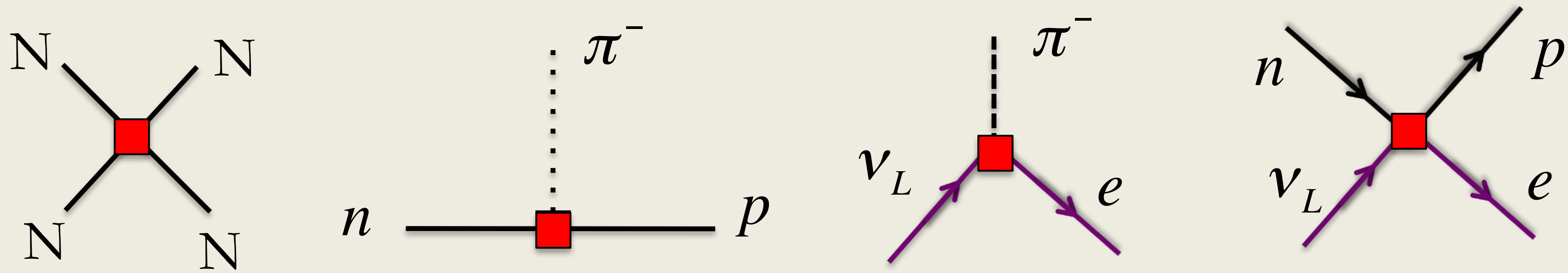
- Systematic incorporation of low-energy data requires development of low-energy EFTs, lattice QCD, and many-body calculations

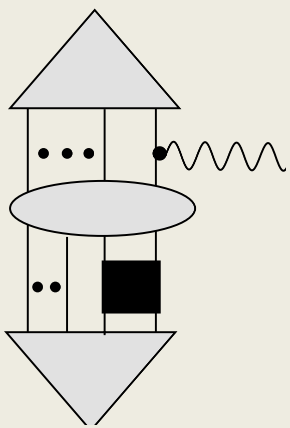
From LEFT to ChPT



- 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, muon g-2
- But still 100% uncertainties for many cases (e.g. 0vbb, EDMs)

From LEFT to ChEFT





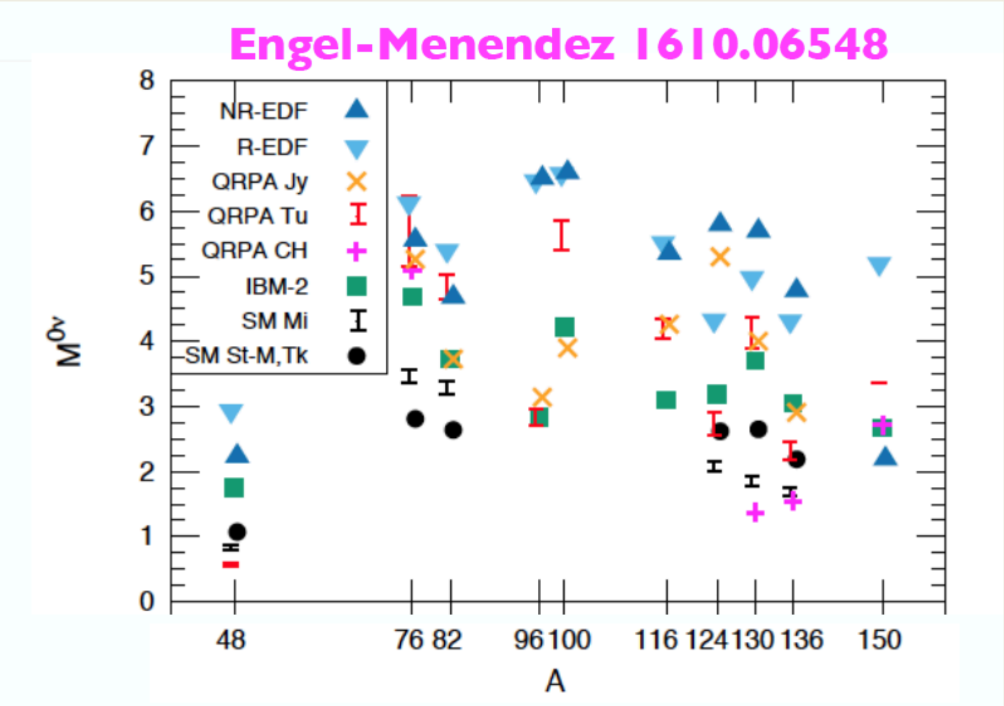
ChEFT to systematiccaly calculate nuclear BSM observables

EDMs, 0vbb, mu-to-e conversion, neutrino scattering, …. …

- 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 open problems**

Open problems



Engel, van Kolck, Ramsey-Musolf '13

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?*)

- **This is a 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

EWBG and CPV Yukawa's

- CP violation typically ignored in fits of Higgs, top, EW global fits
- *But see progress in e.g. Ethier et al 2101.03180*
- Potential connection to **electroweak baryogenesis**
- Example: CP-odd Yukawa couplings at dim-6.

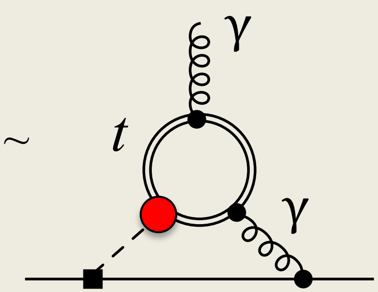
$$L = -y_f \bar{f} f\, h - \frac{y_f}{\Lambda_f^2}\, \bar{f} i\gamma^5 f\, (v^2 h + \cdots)$$

- Assuming a first-order EWPT occurs (not today) we require about 5% CPV in top-Yukawa → $\Lambda_t \lesssim 1$ TeV

- Seems ruled out by electron EDM measurements

Lower in global analysis…

Electron EDM ~



$\Lambda_t \geq 7$ TeV

Bian et al PRL '14

EWBG and CPV Yukawa's

- CP violation typically ignored in fits of Higgs, top, EW global fits
- *But see progress in e.g. Ethier et al 2101.03180*
- Potential connection to electroweak baryogenesis
- Example: CP-odd Yukawa couplings at dim-6.

$$L = -y_f \bar{f} f\, h - \frac{y_f}{\Lambda_f^2}\, \bar{f} i\gamma^5 f\, (v^2 h + \cdots)$$

- **Tau to the rescue!** A 10% CPV in tau-Yukawa works too!
- Measure $h \to \tau + \bar{\tau}$ at 1% accuracy (dim-8).

JdV, Postma, van de Vis, '18
Fuchs et al '19 '20

Coupling modifier (precision in %)	HL-LHC + CLIC$_{380}$	HL-LHC + FCC-ee$_{365}$
κ_W	0.73	0.41
κ_Z	0.44	0.17
κ_g	1.5	0.90
κ_γ	1.4 *	1.3
$\kappa_{Z\gamma}$	10 *	10 *
κ_c	4.1	1.3
κ_t	3.2	3.1
κ_b	1.2	0.64
κ_μ	4.4 *	3.9
κ_τ	1.4	0.66

Charting the European Course to the High-Energy Frontier 1912:13466

But not a direct probe of CPV

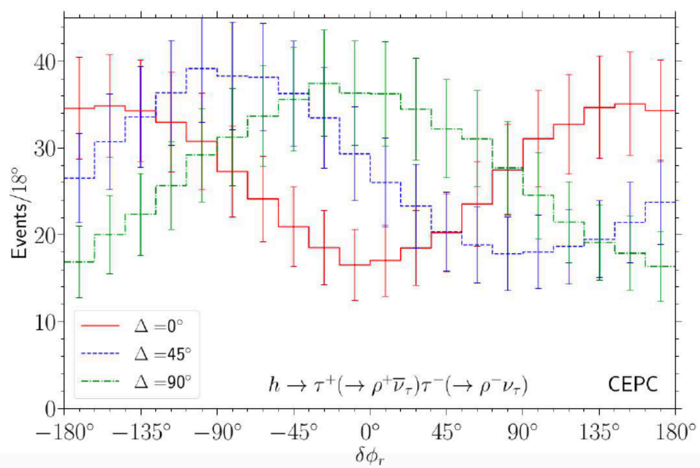
EWBG and CPV Yukawa's

- Angular correlations in $h \to \tau + \bar{\tau} \to X^+ \upsilon X^- \bar{\upsilon}$
- Cleaner environment at e^+e^- colliders
- Determined Higgs rest frame ($e^+e^- \to Zh$)

Bergem Bernreuther, Spiesberger '13
Chen, Wu '17
Ge, Li, Pasquini, Ramsey-Musolf '20
Many other papers

$$\mathcal{L}_{h\tau\tau} = -\kappa_\tau \frac{m_\tau}{v} \bar{\tau}(\cos\Delta + i\gamma_5 \sin\Delta)\tau h$$

- Ge et al '20 studied several CP-sensitive observables to find optimal one



	68% C.L. for $m = 1$	95% C.L. for $m = 1$
CEPC	2.9°	5.6°
FCC-ee	3.2°	6.3°
ILC	3.8°	7.4°

Limit on Δ

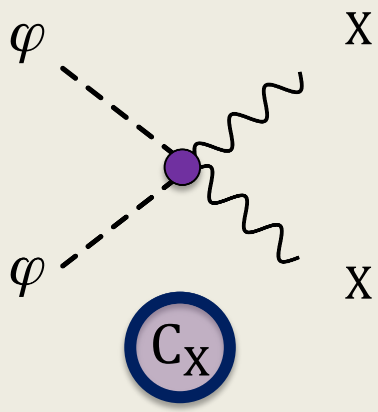
- Asymmetries probe CPV couplings ~ Λ >1 TeV
- **Could rule out/indentify tau-induced EWBG**

Slide from Gang Li (thanks!)

Higgs-gauge interactions

- CP violation typically ignored in fits of Higgs, top, EW global fits
- Potential connection to electroweak 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

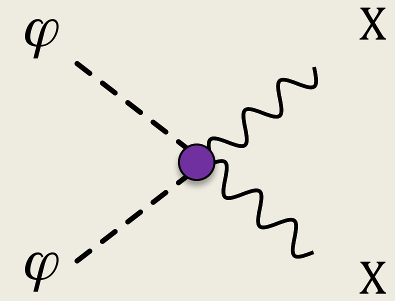
- **h-gluon-gluon**
- **h-gamma-gamma**
- **h-gamma-Z**
- **W-W-gamma**
- **h-Z-Z (not independent)**

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

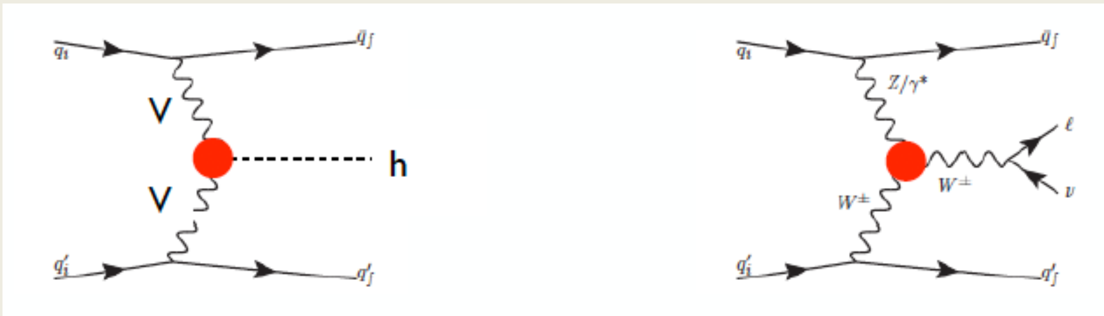
Peskin, Takeuchi '90
Barbieri et al '04
Ferreira et al '17

Collider and low-energy probes

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



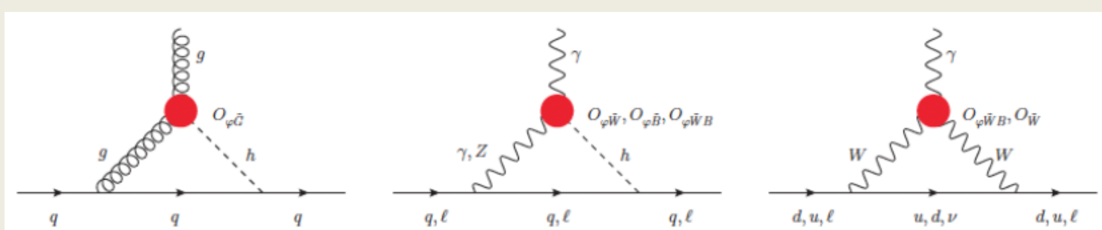
- Induce CPV angular distribution in pp → h/V + 2 jets



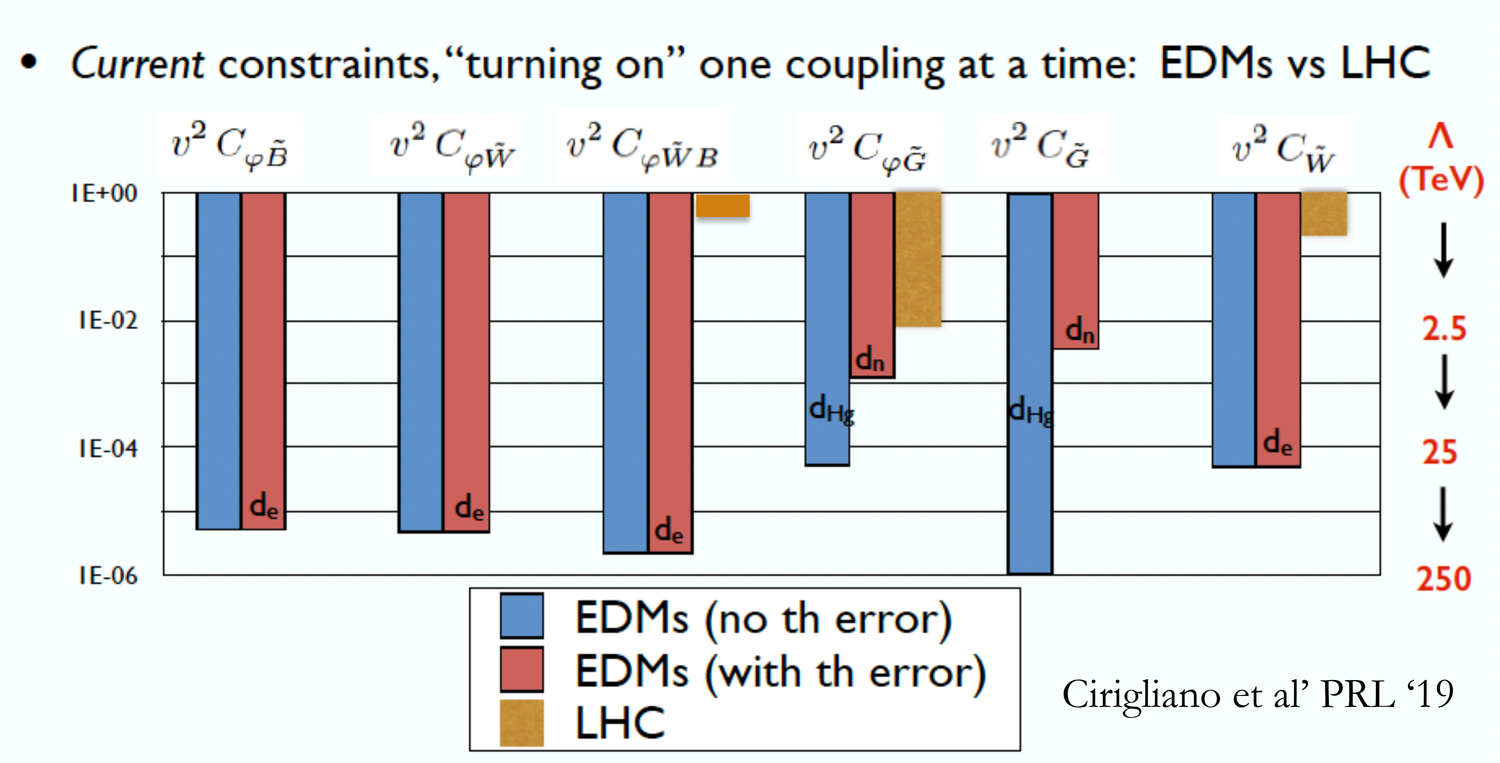
e.g. ATLAS 2006.15458 $\quad 0.23 < \tilde{C}_{HWB}/\Lambda^2 < 2.34\ (TeV^{-2})$

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

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

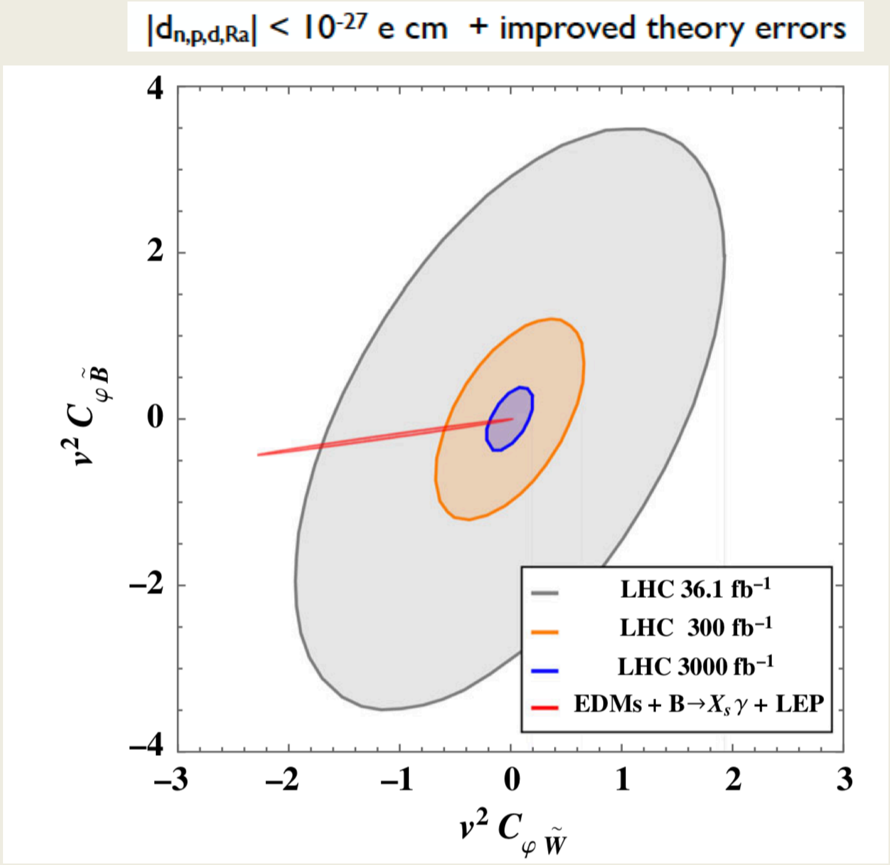


Low-energy constraints are stringent



- 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’



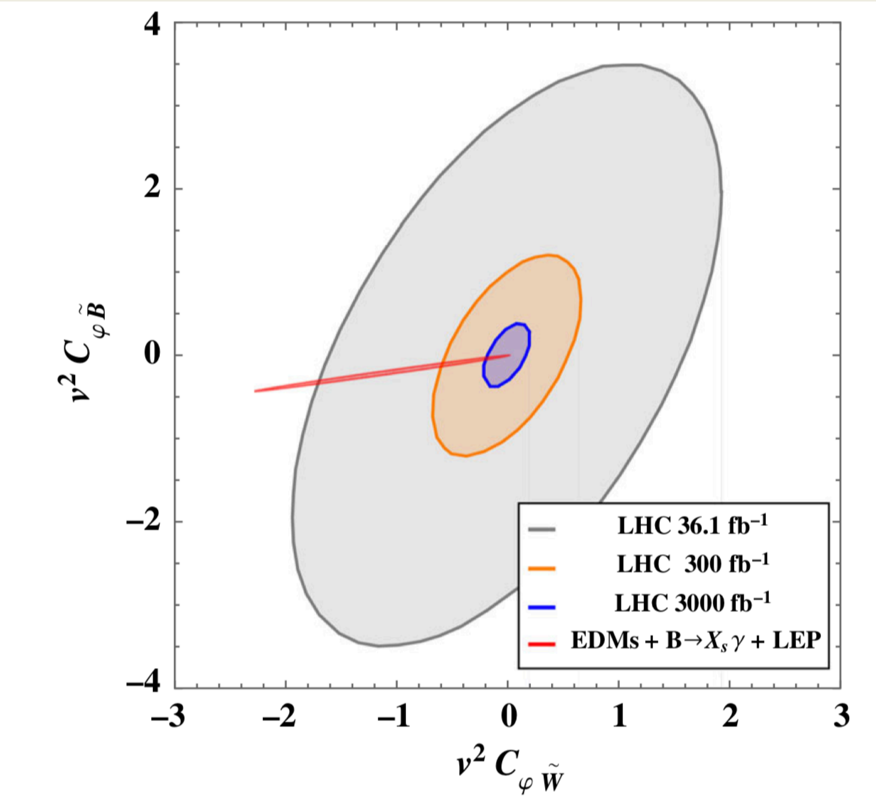
JdV et al PRL ‘19

HL-LHC projections from Bernlochner et al ’18

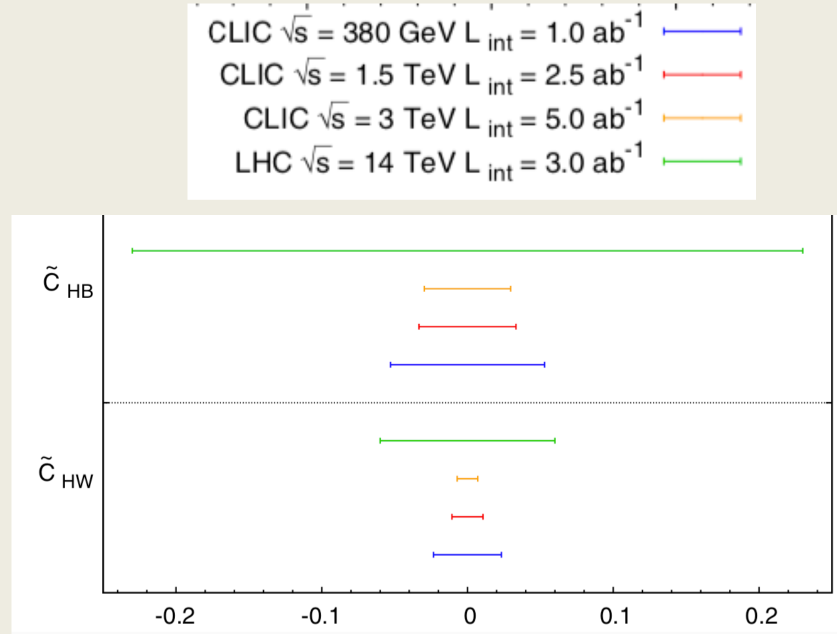
- Low-energy limits avoided in global fits (free directions)
- Strong constraints on possible UV completion (must point in free direction or appear at high scales only)

CP violation in 'universal theories'

$|d_{n,p,d,Ra}| < 10^{-27}$ e cm + improved theory errors



Karadeniz et al '19



- 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)
- **Linear e^+e^- machines very complementary. Global analysis interesting.**

Other interplays not discussed here

1. Non-standard interactions in beta decay + coherent neutrino scattering versus eeZ , evW, modifications at linear colliders *(Falkowski et al 2010.13797, Hoferichter et al 2007.08529, De Blas et al 1907.04311)*

2. Top-Higgs interactions at low-energy + LHC . *(Cirigliano et al 1605.03409)* versus linear colliders (*Bernreuther et al 1710.06737*)

3. Neutrinoless double beta *(JdV et al 1806.02780)* versus heavy neutrinos searches at e^+e^- versus linear colliders (*Cai et al 1711.02180*)

4. Atomic Parity violation *(Arcadi et al 1906.04755)* versus eeqq modifications

5. Muon g-2 versus muon colliders (*Aebischer et al 2102.08954* , *Capdevilla et al 2101.10334)*

6. …….

Lots of low-energy + high-energy interplay
Global analyses benefit from including all data