CP and Flavour Violation as a probe for New Phenomena

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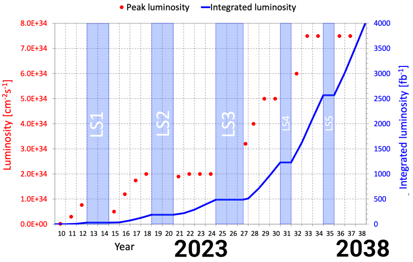
The next decade at the particle-physics frontier

LHC



Bottom

Kaons

Charm

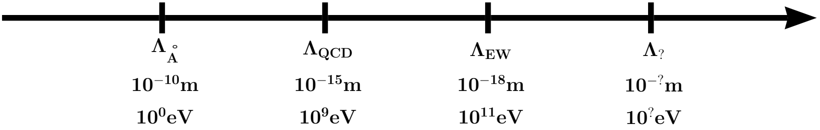
Beam-dump

SHiP
Search for Hidden Particles

EDMs, $(g-2)_\mu$ (FNAL/J-PARC), **neutrino facilities** (DUNE),
Dark-Matter direct detection (XENONnT), **axion searches** (BabyIAXO),...

Huge amount of data – combine, maximize impact & guide future

(Some) open questions



- $H \equiv H_{\text{SM}}$?

- New CP violating sources for baryogenesis?
  SM ➜ not sufficient $\not{C}\not{P}$

- Have we missed d.o.f. at any scale?
  Dark matter, QCD axion, …

- Next "fundamental" scale, $\Lambda_?$

Dynamics Beyond the Standard Model must exist

Baryogenesis / Dark Matter / ν masses-oscillations / gravity

Hierarchy Problem / Strong-CP Problem / Flavour Puzzle / …

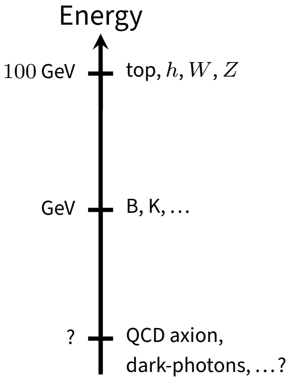
Not clear which BSM

can be probed with ongoing/future experiments

Key Strategies

data-driven questions, model-independent interpretations, precision

Outline



today's talk

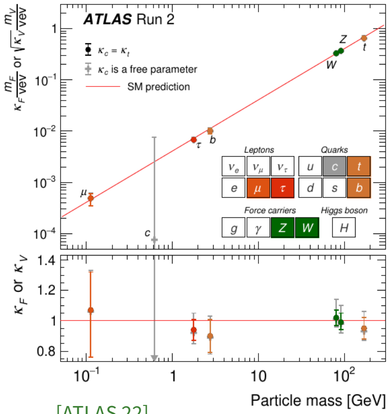
Anomalous Higgs couplings

Higgs CP violation & EDMs

Flavour probes of light NP

Flavoured QCD-axions and dark-photons

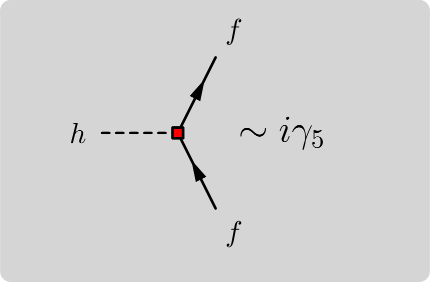
Higgs



[ATLAS 22]

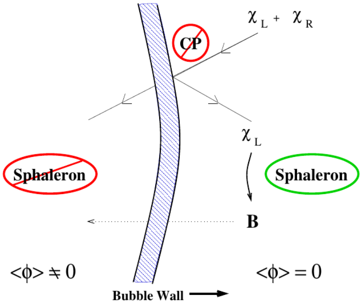
- couplings in SM CP conserving $\propto m/v$
- only subset of properties measured
- CP properties key for **EW Baryogenesis**

Why focus on CP-violating Yukawas?



- **Phenomenology:** Still room for large deviations from SM
- **Theory:** Relevant for models of EW Baryogenesis

Electroweak Baryogenesis



Minimally two EFT operators

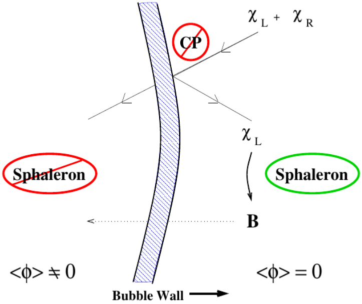
$$\mathcal{L} = \frac{1}{\Lambda_{\text{CP}}^2}(H^\dagger H)^3 + \frac{1}{\Lambda_{\not{\text{CP}}}^2}(H^\dagger H)\bar{Q}_3\tilde{H}t_R + \text{h.c.}$$

[see Huber, Pospelov, Ritz 06, review Morrisey, Ramsey-Musolf 12 and refs. therein]

- extra sources of $\not{\text{CP}}$ & allow for a 1$^{\text{st}}$-order EW phase transition

➜ $\Lambda_{\text{CP}}, \Lambda_{\not{\text{CP}}} \approx 1$ TeV for correct photon-baryon ratio

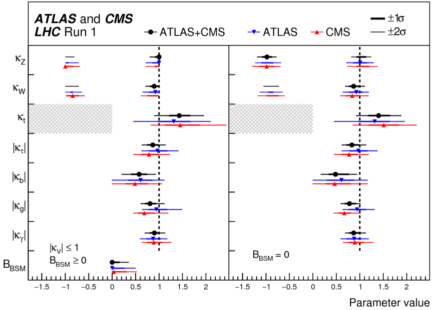
Electroweak Baryogenesis



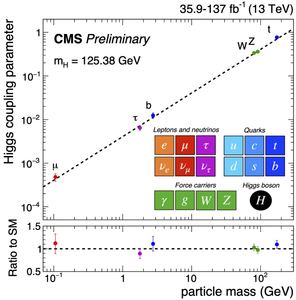
➜ Natural expectation
$\not{CP}$ in Higgs Yukawas

➜ Look for all $\not{CP}$ Higgs Yukawas

Higgs at LHC



[ATLAS+CMS combination of Run I]



[$H \to \mu\mu$ CMS 20]

- Couplings to gauge bosons, 3rd gen. fermions, and 2nd gen. muons (charm)
- **Only a subset of Higgs couplings/properties**
- ✗ Weak constraints on light-fermion Yukawas and $\not{CP}$

Novel search strategies for LHC

- **exclusive Higgs decays**

  [Bodwin et at 13; Kagan et al 14; Perez et al 15; König, Neubert 15;...]

- **charm-tagging**

  [Perez et al 15, 16] [ATLAS/CMS search]

- **Higgs kinematics / distributions**

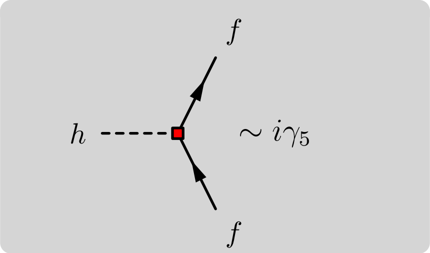
  [Bishara et al 16; Soreq et al 16]

Limited (direct) sensitivity to CP violation

(Example $h \to \tau\tau$ [Harnik et al 13] [CMS 22])

EDMs: complementary, indirect info on Higgs ~~CP~~

Why focus on *flavour-conserving* ~~CP~~ Yukawas?



- Typically ~~CP~~ accompanied by **flavour violation strongly constrained** by FCNC searches

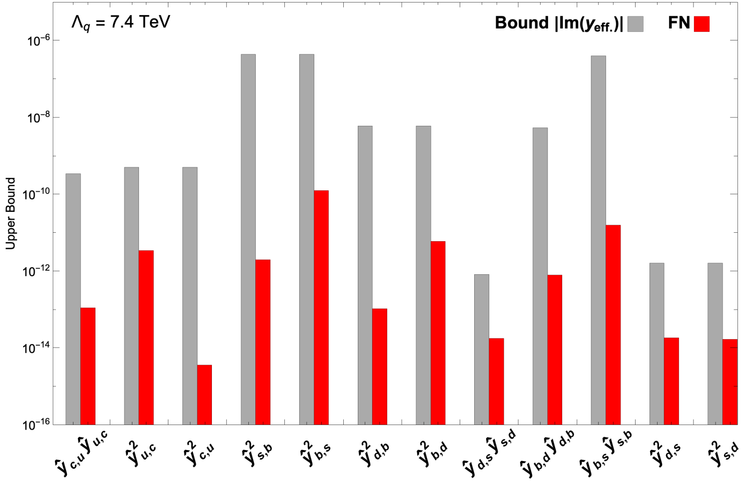
  (ϵ_K, $K_L \to \pi^0 \nu\nu$, CP-asymmetries of B decays, etc)

- Theoretically **possible** to have new (low-energy) sources of ~~CP~~ *without* flavor-violation beyond the SM

  (requires some type of flavour alignment)

(Typically) flavour- and CP-violation is correlated

example from Froggatt-Nielsen-type models



[Alonso-Gonzalez et at 2103.16569 ; see also Alonso-Gonzalez et al 2109.07490]

Theory setup (EFT)

Require a proper setup to accurately **correlate signals** of $\not{CP}$ from observables of **different energy scales**

Higgs EFTs

- **SMEFT**
  Linear realisation of electroweak symmetry breaking, $\Lambda \gg 100$ GeV

- **HEFT/chiral electroweak theory**
  Also non-linear realisation of electroweak symmetry breaking possible

- **κ-framework?**
  Intuitive interpretation, widely used by experimental collaborations

SMEFT and BSM Yukawas

- Only one type of dim.-6 operator modifies Higgs Yukawas

$$\mathscr{L}_{\text{Yukawa}} = -\bar{F}_L \hat{H} Y_f f_R + \frac{1}{\Lambda^2}(H^\dagger H)\bar{F}_L \hat{H} C'_{fH} f_R + \text{h.c.}\,.$$

- Y_f and C'_{fH} generic, complex 3×3 matrices
- rewrite in broken phase, rotate to mass-eigenstate basis

UV assumption

CP-violation without flavour-violation Setup

$\equiv$

$C_{fH} \equiv U_f^\dagger C'_{fH} W_f$ diagonal with phases

SMEFT Yukawa operators in mass-basis

$$C_{fH} = \underbrace{C_{fH+}}_{\textbf{CP-even}} + i \underbrace{C_{fH-}}_{\textbf{CP-odd}}$$

$$\mathscr{L}_f = \left(-m_f - m_f \frac{h}{v} + \frac{v^3}{2\sqrt{2}\Lambda^2} \boldsymbol{C_{fH+}} \left(2\frac{h}{v} + 3\frac{h^2}{v^2} + \frac{h^3}{v^3} \right) \right) \bar{f} f \\ + \frac{v^3}{2\sqrt{2}\Lambda^2} \boldsymbol{C_{fH-}} \left(2\frac{h}{v} + 3\frac{h^2}{v^2} + \frac{h^3}{v^3} \right) \bar{f} i\gamma_5 f$$

(Unitarity gauge)

(Goldstone-boson contributions required for gauge-invariant computations)

➜ Place direct and indirect constraints on $\boldsymbol{C_{fH\pm}/\Lambda^2}$ ($f = u, c, t, d, s, b, e, \mu, \tau$)

SMEFT / HEFT

$$\mathscr{L}_f = \left(-m_f - m_f\frac{h}{v} + \frac{v^3}{2\sqrt{2}\Lambda^2}\boldsymbol{C_{fH+}}\left(2\frac{h}{v} + 3\frac{h^2}{v^2} + 1\frac{h^3}{v^3}\right)\right)\bar{f}f + \frac{v^3}{2\sqrt{2}\Lambda^2}\boldsymbol{C_{fH-}}\left(2\frac{h}{v} + 3\frac{h^2}{v^2} + 1\frac{h^3}{v^3}\right)\bar{f}i\gamma_5 f$$

- Difference between SMEFT and HEFT
  ➜ coefficients of $\boldsymbol{(h/v)^n}$ are uncorrelated

- If leading effects controlled by the h/v-term the analysis also applies for HEFT

(this is the case in our analysis)

SMEFT / κ-framework

$$\mathscr{L}_f = \left(-m_f - m_f\frac{h}{v} + \frac{v^3}{2\sqrt{2}\Lambda^2}\boldsymbol{C_{fH+}}\left(2\frac{h}{v} + 3\frac{h^2}{v^2} + 1\frac{h^3}{v^3}\right)\right)\bar{f}f + \frac{v^3}{2\sqrt{2}\Lambda^2}\boldsymbol{C_{fH-}}\left(2\frac{h}{v} + 3\frac{h^2}{v^2} + 1\frac{h^3}{v^3}\right)\bar{f}i\gamma_5 f$$

(Unitarity gauge)

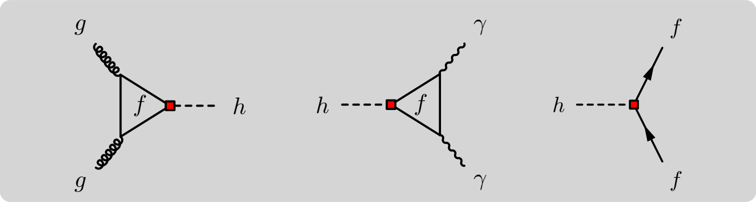
- κ-framework is "$n = 1$" HEFT in unitarity gauge

$$\mathscr{L}_f^\kappa = -\frac{y_f^{\text{SM}}}{\sqrt{2}}\boldsymbol{\kappa_f}\bar{f}\left(\cos\boldsymbol{\phi_f} + i\gamma_5\sin\boldsymbol{\phi_f}\right)f\,,$$

$$\kappa_f\cos\phi_f \mathrel{\hat{=}} 1 - \frac{v}{\sqrt{2}m_f}\frac{v^2}{\Lambda^2}C_{fH,+} \qquad \kappa_f\sin\phi_f \mathrel{\hat{=}} -\frac{v}{\sqrt{2}m_f}\frac{v^2}{\Lambda^2}C_{fH,-}$$

$\hat{=}$ means "only the h/v term contributes"

LHC observables



Main effects captured by modifications in:

- $gg \to h$ & $h \to \gamma\gamma$ (hWW / hZZ / $hZ\gamma$ numerically less relevant)
- **BR**$(h \to b\bar{b})$
- **total width** Γ_h
- $t\bar{t}$ **and single-**t **production**

Use collider likelihoods from `HiggsSignals2.5.0` & `HiggsBounds5.8.0` interfaced with `GAMBIT`

[Bechtle et al 06,12 and Athron et al 17]

EDMs = stringent tests of flavour-diagonal $\not{CP}$

Multiple experimental targets

[e cm]	d_e	d_n	$d_{p,D}$
current	1.1×10^{-29}	2.9×10^{-26}	–
expected	10^{-34}	1.0×10^{-28}	1.0×10^{-29}

	d_{Hg}	d_{Xe}	d_{Ra}
current	7.4×10^{-30}	5.5×10^{-27}	4.2×10^{-22}
expected	1.0×10^{-29}	5.0×10^{-29}	1.0×10^{-27}

[Hewett et al 12; Baker et al 06; ACME 18, Graner et al 16; EDM3 collaboration]

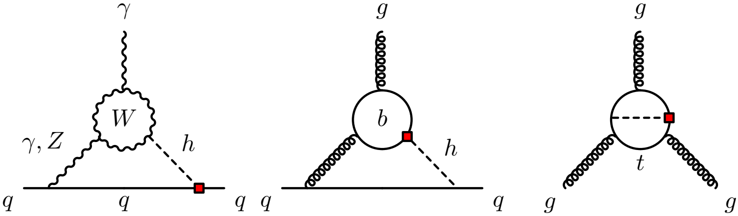
✓ Impressive improvements expected

✓ Progress in lattice-QCD

➜ *Indirect* probes of “low-scale” **$\not{CP}$ in Higgs Yukawas**

Higgs $\not{CP}$ affects EDMs

induce eEDM, qEDM, qC(hromo)EDM, $\not{CP}$-Weinberg operators



- **Often main focus only on single-flavour cases**

  (electrons [Panico et al 18; Altmannshofer et al 15], 3rd gen [Fuchs et al 20, Brod et al 13], b/c [Brod, ES 18], light-quarks [Brod, Skodras 18], ...)

- **First steps towards global picture**

  [Brod et al 22 and Bahl et al 22]

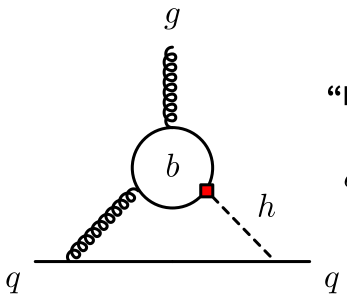
  ➜ *Precision in theory predictions*

  ➜ *Cross-correlations/cancellations*

  ➜ *Global SMEFT analysis and fit to LHC*

Precision

(an example: bottom Yukawa)



“Naive” Barr–Zee type computation

$$\tilde{d}_q = g_s^3 \left(\# + \# \log \frac{m_b}{m_h} \right) \frac{v^2}{\Lambda^2} C_{bH-}$$

- Naive computation is a **bad** approximation
  ➜ factor 5 uncertainty in qCEDM

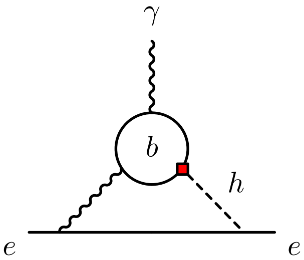
- Reason: multi-scale problem, $\alpha_s \log(m_b/m_h) \sim 1$!

➜ **Precision:** use EFT to resum the large logs and estimate uncertainties (@LL [Brod et al 13] and @NLL [Brod, ES 18])

Precision

(large logarithms in leptonic EDMs)

Typically RGE effects are assumed to be small and neglected for leptonic operators



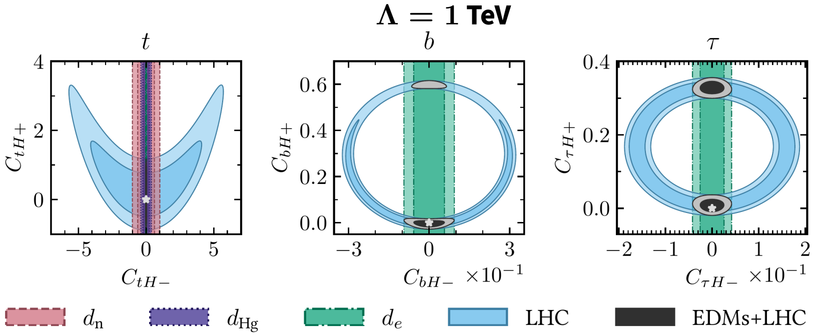
“Naive” Barr–Zee type computation

$$d_e = e^3(\# + \# \log \frac{m_b}{m_h}) \frac{v^2}{\Lambda^2} C_{bH-}$$

- Factor of 2 uncertainty from QCD ambiguity ($m_b(M_H)$ vs $m_b(2\text{ GeV})$)
- Difficulty: $\alpha_s \log$ resummation within a 2-loop electromagnetic contribution

[Brod, Polonsky, ES 23]

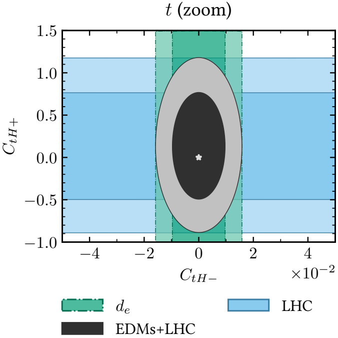
2 parameter scan – single flavour – 3rd generation



- EDM–LHC complementarity [see also recent CMS $h \to \tau\tau$ analysis]
- EDMs only sensitive to C_{fH-}
- electron EDM constraint dominates over quark EDMs
- Caveat of eEDM constraint: relies on electron coupling to Higgs

2 parameter scan – top (magnification)

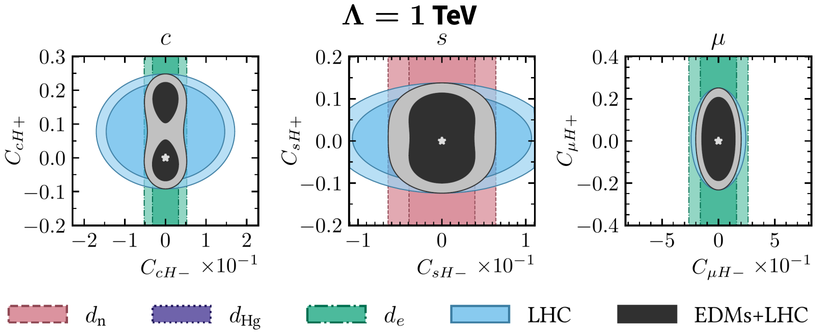
$\Lambda = 1$ **TeV**



- possible to relax strong eEDM constraints by turning on other C_{fH-} couplings

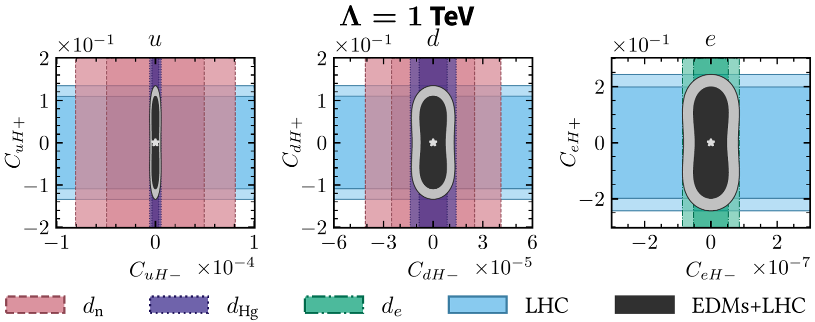
➜ need global analysis to expose cancellations in EDMs

2 parameter scan – single flavour – 2nd generation



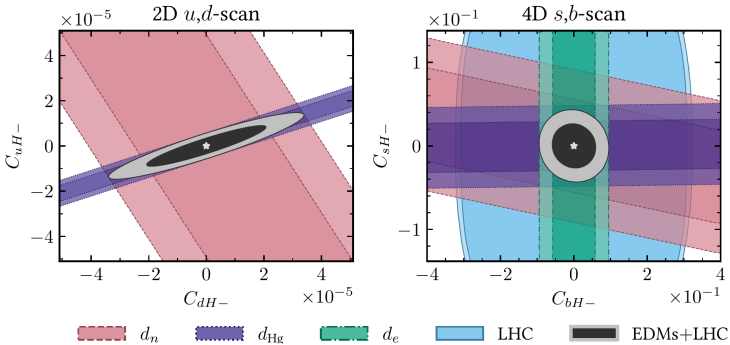
- EDM proportional to fermion mass ➜ for s qEDM main constraint
- c-tagging at LHC, μ CMS search, s total width

2 parameter scan – single flavour – 1st generation



- LHC constraints only from Γ_h
- qEDMs dominant constraint on quark Yukawas
- eEDM dominant constraint on electron Yukawa

Beyond single-flavour – two-flavour survey



[Brod et al 22, see also Chien et al 15]

- profiled over not-plotted directions

➜ complementarity of EDMs (d_n vs d_{Hg} vs d_e)

➜ global picture requires precise measurements and predictions in multiple EDMs

Flavour-diagonal Higgs $\not{CP}$ (take-away messages)

Phenomenologically attractive setup

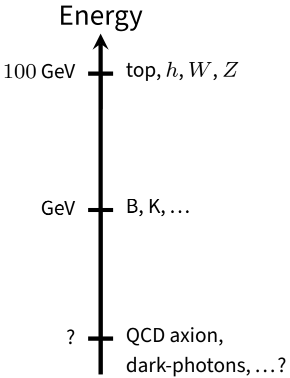
- Low-scale NP effects still possible, excellent prospects
- Relevant for models of EW Baryogenesis

→ Accurate EFT computations important in light of expected progress

Cancellations / Correlations

- Global picture required to assess Higgs $\not{CP}$
- Complementarity of LHC and EDM constraints persists in multi-param. surveys

Outline



today's talk

Anomalous Higgs couplings

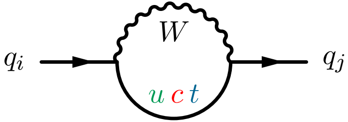
Higgs CP violation & EDMs

Flavour probes of light NP

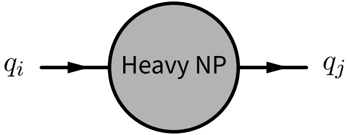
Flavoured QCD-axions and dark-photons

Flavour Changing Neutral Currents: SM vs NP

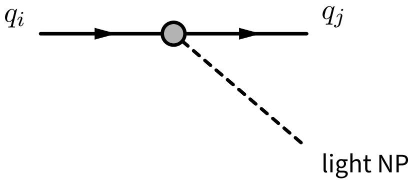
SM
loop induced, precision



Heavy NP
virtual, indirect probe
SUSY, Composite Higgs, Extra Dimensions, …



Light NP
decays to “invisible”
Axions, Dark Photons, …



Flavour – the answer to all?

- Exp. data have **potential** to provide at least some answers.
- However, there are **no guarantees**.

  ➜FV in NP may be fully aligned to FV in SM

  ➜D.o.f. associated to BSM FV may be too heavy for discovery

  ➜our experiments may have blind spots (compressed spectra, missing energy, ...)

➜ **Two (semi-orthogonal) strategies:**

- Expose deviations through precision and global fits
  (golden observables: EDMs, clean FCNCs, ...; EFTs: WET, SMEFT, ...)
- Go beyond established interpretation of data and observables
  (radiative modes, distributions, light-NP interpretations,...)

Light-NP & flavour – example QCD Axion

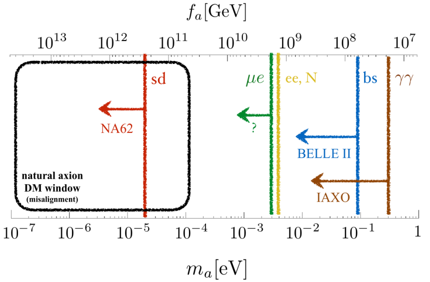
$$\Gamma_K^{\text{tot}} \sim M_K^5/M_W^4 \qquad\qquad \Gamma_B^{\text{tot}} \sim M_B^5/M_W^4$$

- Dimension-5 QCD axion couplings: $\frac{\partial^\mu a}{f_a}\,\bar{q}_i\gamma_\mu(\gamma_5)q_j$

$$\text{BR}(K \to \pi a) \propto \frac{M_W^4}{\boldsymbol{M_K^2} f_a^2}$$

$$\text{BR}(B \to \pi a) \propto \frac{M_W^4}{\boldsymbol{M_B^2} f_a^2}$$

➜ High sensitivity to light NP



(for $C_i = 1$)

[from R. Ziegler @ La Thuille]

Light NP

- **Scalars**
  QCD axion (best motivated light NP scenario), ALPs,…
- **Fermions**
  light sterile neutrinos, fermionic DM, …
- **Vectors**
  dark Photons, light Z', …

Phenomenology depends strongly on:
masses, lifetimes, and couplings to SM

Most promising search strategies may differ!

example for this talk: light vectors

EFTs for light, flavoured vectors V'

– Dipole interaction

$$\mathscr{L}^{D}_{\text{FCNC}} = \frac{C^{D}_{ij}}{\Lambda}\bar{f}_i\sigma^{\mu\nu}f_jF'_{\mu\nu} + \frac{C^{D5}_{ij}}{\Lambda}\bar{f}_i i\sigma^{\mu\nu}\gamma_5 f_jF'_{\mu\nu}$$

$*$ $SU(2)_L$ gauge invariance ➜ $\bar{Q}_L H\sigma^{\mu\nu}q_R F'_{\mu\nu}$ ➜dim-6 counting

– Vector interaction

$$\mathscr{L}^{V}_{\text{FCNC}} = \frac{m_{V'}}{\Lambda}C^{V}_{ij}\,\bar{f}_i\gamma^{\mu}f_jV'_{\mu} + \frac{m_{V'}}{\Lambda}C^{V5}_{ij}\,\bar{f}_i\gamma^{\mu}\gamma_5 f_jV'_{\mu}$$

$*$ gauge invariance ➜ no flavour violation for $m_{V'} = 0$ at dim-4

$*$ power, n, of $(m_{V'}/\Lambda)^n$ model dependent

Flavour phenomenology of light Vectors

- dependence on mass of light Vector (& Form Factors)
  ➜recast of searches required

- multiple channels and experiments required to probe all couplings

Two-body decays to invisible V'

Pseudoscalar$\to$Pseudoscalar$+V'$

Pseudoscalar$\to$Vector$+V'$

Baryon$\to$Baryon$+V'$

	C_{ij}^{D}	C_{ij}^{D5}	C_{ij}^{V}	C_{ij}^{V5}
sd				
cu	depend on V' mass			
bs				
bd				

[Folch et al 24]

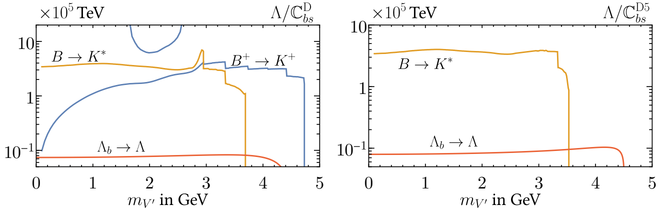
Summary of searches included

Quark Transition	Hadronic Process	Form Factors	Experimental Limit
$s \to d$	$K^+ \to \pi^+ + V'$	[65, 66]	NA62 [17, 38, 39]
	$\Sigma^+ \to p + V'$	[34, 67–69]	BES III [70], Lifetime$_r$[22, 63]
	$\Xi^- \to \Sigma^- + V'$	[34, 67–69]	Lifetime$_r$[22, 63]
	$\Xi^0 \to \Sigma^0 + V'$	[34, 67–69]	Lifetime$_r$[22, 63]
	$\Xi^0 \to \Lambda + V'$	[34, 67–69]	Lifetime$_r$[22, 63]
	$\Lambda \to n + V'$	[34, 67–69]	Lifetime$_r$[22, 63]
$b \to s$	$B^+ \to K^+ + V'$	[71, 71]	BaBar$_r$ [41], Belle II$_r$ [44, 62]
	$B \to K^* + V'$	[71, 71]	BaBar$_r$ [41, 62]
	$\Lambda_b \to \Lambda + V'$	[72, 72]	Lifetime$_r$[22, 63]
$b \to d$	$B^+ \to \pi^+ + V'$	[71, 73]	BaBar$_r$ [40]
	$B \to \rho + V'$	[71, 71]	LEP$_r$ [60, 61]
	$\Lambda_b \to n + V'$	[72, 74]	Lifetime$_r$ [22, 63]
$c \to u$	$D^+ \to \pi^+ + V'$	[75, 76]	CLEO$_r$ [22, 42]
	$\Lambda_c \to p + V'$	[77, 77]	BES III [45], Lifetime$_r$ [22, 63]

[Folch et al 24]

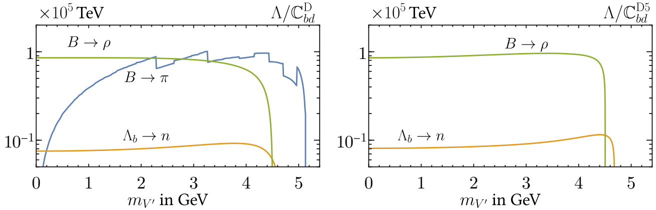
Dipole interaction — B sector

$b - s$ transition



$* \sim 2\sigma$ excess in 2023 $B \to K\nu\nu$ Belle2 measurement [recast from Altmannshofer et al 23]

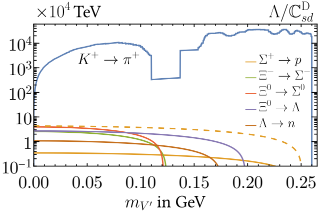
$b - d$ transition

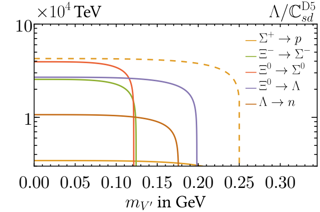


pseudoscalar→pseudoscalar decays **insensitive to dipoles** for small $m_{V'}$!

Dipole interaction — K, D sector

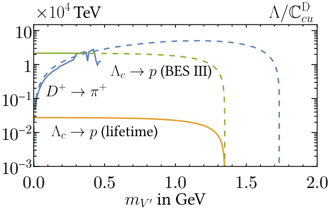
$s - d$ transition

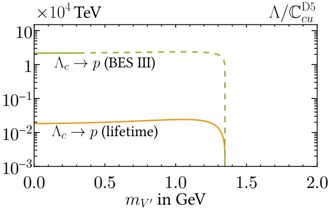




$*$ not including a recast of the new NA62 measurement of $K^+ \to \pi^+\nu\nu$

$c - u$ transition

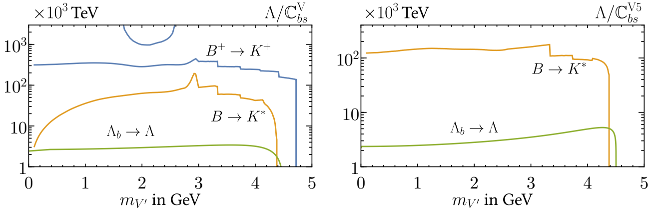




pseudoscalar→pseudoscalar decays **insensitive to dipoles** for small $m_{V'}$!

Vector interaction — B sector

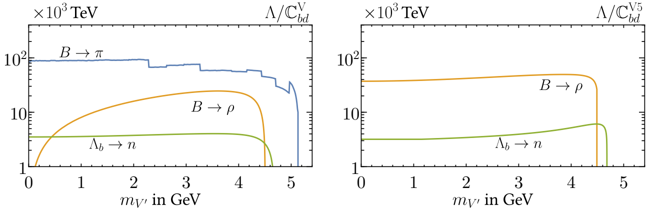
$b - s$ transition



pseudoscalar→pseudoscalar limits **survive for $m_{V'} \to 0$**

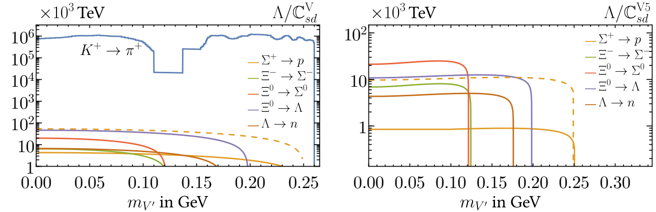
analogous to $t \to W d$ decay in gauge-less limit in SM

$b - d$ transition



Vector interaction — K, D sector

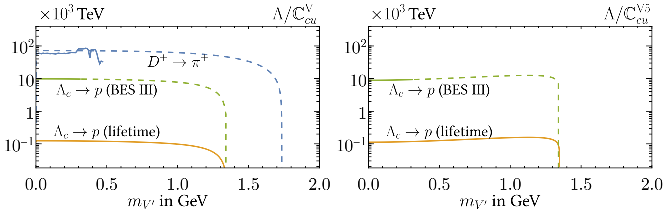
$s - d$ transition



pseudoscalar→pseudoscalar limits **survive for $m_{V'} \to 0$**

analogous to $t \to W d$ decay in gauge-less limit in SM

$c - u$ transition

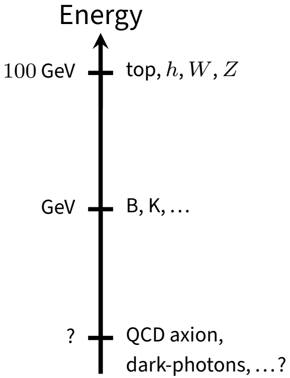


Flavour and light NP (take-away messages)

- Possible to hide NP with **Light NP**
  ➜ QCD axions, sterile ν's, and dark-photons/light dark vectors
  ➜ Quark-flavour can provide competitive tests
  ➜ Look for interpretations of invisible signatures

- **Light Dark Vectors**
  ➜ Rich flavour phenomenology
  ➜ Considered vector- and dipole-type couplings
  ➜ Multiple channels and dedicated analyses needed for full picture

Conclusions



Anomalous Higgs couplings

Higgs CP violation & EDMs

Flavour probes of light NP

Flavoured QCD-axions and dark-photons

- Even if heavy particles are experimentally **not directly accessible**, they can leave their **imprints in low-energy** observables.
- **Precision** and **broad/novel interpretation** of data important to disentagle such NP.