Flavour Summary

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Why flavour?

Open questions related to Flavour dynamics

- "*The flavour Puzzle*"
  Is there a dynamical origin for the observed masses and mixings?

- "*The New Physics flavour Problem*"
  If New Physics is light it must have non-trivial flavour structure

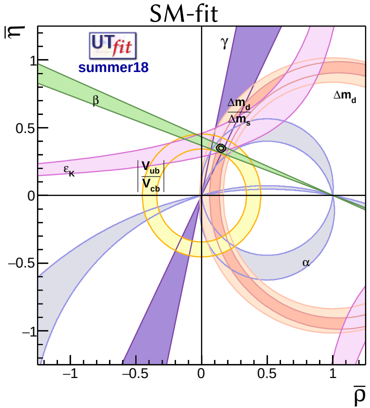
- "*Baryogenesis*"
  Where are the CP violating sources beyond the CKM phase necessary for Baryogenesis?

- "*Strong CP Problem*"
  Why is the QCD vacuum CP conserving?

FCNCs & CKM unitarity triangle: Traditional Flavour

- Quark-sector provides multiple observables, overconstrained system

➜ test the SM by testing the CKM unitarity triangle

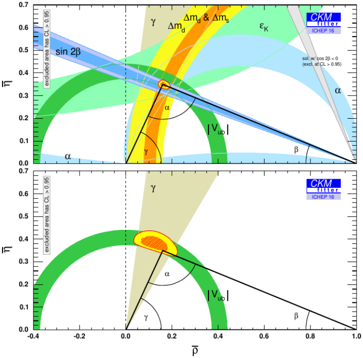


[UTfit 18]

Very successful program so far

Learned a lot, plenty of room for new physics

- Spectacular progress in last 20 years
- The implications of the consistency of measurements is often overstated
- Larger allowed region if there is NP
- Compare tree-level (lower plot) and loop-dominated measurements
- LHCb: constraints in the B_s sector (2nd–3rd gen.) caught up with B_d

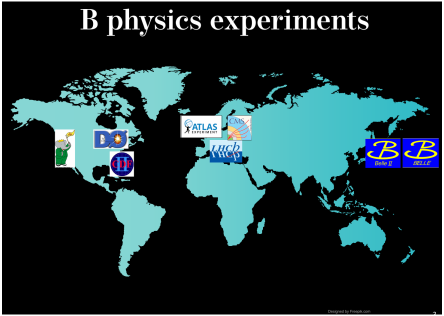


- $\mathcal{O}(20\%)$ NP contributions to most loop-level processes (FCNC) are still allowed

[talk by Z. Ligeti]

- Still not sensitive to many observables (FCNCs/CP-violation with τ's, $B_q \to ee/\tau\tau, \ldots$)
- Experimental efforts continue

The B-factory legacy continues



[talk by N. Taniguchi]

Kaon experiments

Searches for $K \to \pi\nu\nu$

[@CERN]

[@J-PARC]

Flavour program at a future Z-factory, FCC-ee, CEPC?

(Few sensitivity studies, ongoing progress, but flavour community busy with LHCb upgrades and Belle2)

LHCb — LHC at CERN

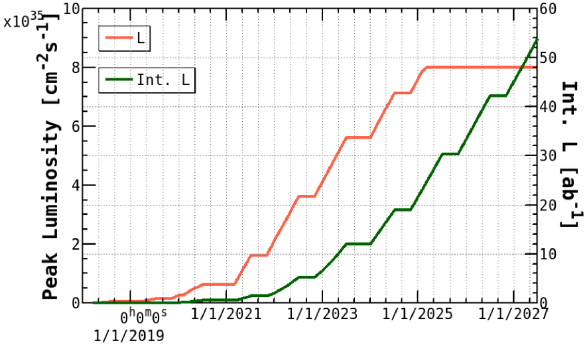
	LHC era			HL-LHC era	
	Run 1 (2010-12)	Run 2 (2015-18)	Run 3 (2021-24)	Run 4 (2027-30)	Run 5+ (2031+)
ATLAS, CMS	25 fb^{-1}	150 fb^{-1}	300 fb^{-1}	$\longrightarrow$	3000 fb^{-1}
LHCb	3 fb^{-1}	9 fb^{-1}	23 fb^{-1}	50 fb^{-1}	*300 fb^{-1}

* assumes a future LHCb upgrade to raise the instantaneous luminosity to $2\text{x}10^{34}$ $cm^{-2}s^{-1}$

- Major LHCb upgrade in LS2 (raise instantaneous luminosity to $2 \times 10^{33}/\text{cm}^2/\text{s}$)
  Major ATLAS and CMS upgrades in LS3, for HL-LHC
- LHCb, 2017, Expression of Interest for an upgrade in LS4 to $2 \times 10^{34}/\text{cm}^2/\text{s}$
  To me, this is obviously an integral part of the full exploitation of the LHC

[talk by Z. Ligeti]

Belle II — SuperKEKB at Tsukuba



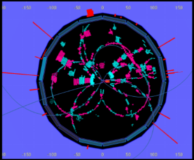
- First collisions 2018 (unfinished detector), with full detector starting spring 2019
  Goal: $50\times$ the Belle and nearly $100\times$ the BaBar data set [See: N. Taniguchi's talk, Thursday]
- Discussions started about physics case and feasibility of a factor ~ 5 upgrade, similar to LHCb Phase-II upgrade aiming 50/fb $\to$ 300/fb, in LHC LS4

[talk by Z. Ligeti]

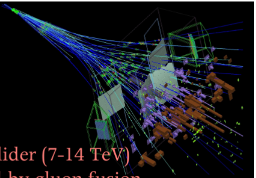
Complementarity of LHCb and Belle 2

[talk by N. Taniguchi]

Belle II



LHCb



electron -positron collider

$e^- e^+ \to \Upsilon(4S) \to B\bar{B}$

proton -ptoron collider (7-14 TeV)
b quarks produced by gluon fusion

Exclusive production

$B_d \bar{B}_d$

All b-hadron varieties produced

B_d, B_s, B_c, Λ_b

$\sigma_{bb} \sim 1\text{nb}$; $\sim 1 \times 10^6$ $b\bar{b}$ pairs/fb^{-1}

$\sigma_{bb} \sim \mathcal{O}(100)\mu\text{b}$; $\sim 1 \times 10^{11}$ $b\bar{b}$ pairs/fb^{-1}

low multiplicity and clean environment

high multiplicity and not clean environment

B mesons almost at rest in lab frame
asymmetric beam energies boost for decay vertex separation

Highly boosted topology gives excellent decay vertex separation.

Hermetic 4π detector

Longitudinally boosted bb pairs

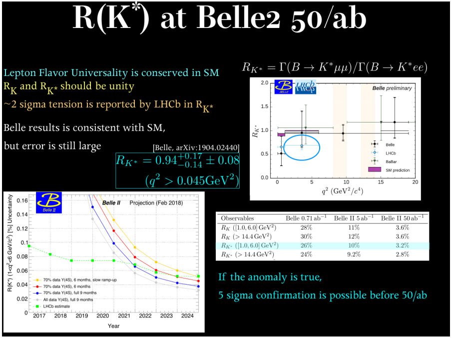
Advantage in modes including γ, π^0, ν (missing)

Advantage in charged particles modes and Bs decays

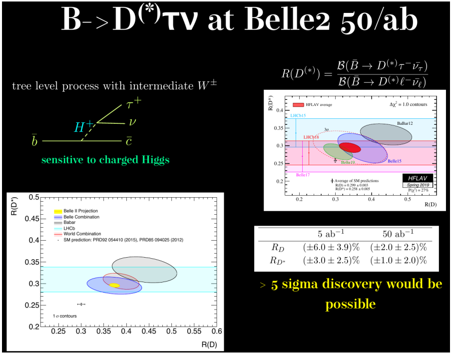
different systematics

Two experiments are required to establish NP

- Belle 2 will shed light in present anomalies ($R_{K^{(*)}}, R_{D^{(*)}}$)



Observables	Belle 0.71 ab^{-1}	Belle II 5 ab^{-1}	Belle II 50 ab^{-1}
R_K ([1.0, 6.0] GeV^2)	28%	11%	3.6%
R_K (> 14.4 GeV^2)	30%	12%	3.6%
R_{K^*} ([1.0, 6.0] GeV^2)	26%	10%	3.2%
R_{K^*} (> 14.4 GeV^2)	24%	9.2%	2.8%



	5 ab^{-1}	50 ab^{-1}
R_D	$(\pm 6.0 \pm 3.9)\%$	$(\pm 2.0 \pm 2.5)\%$
R_{D^*}	$(\pm 3.0 \pm 2.5)\%$	$(\pm 1.0 \pm 2.0)\%$

[talk by N. Taniguchi]

- $> 5\sigma$ discoveries possible
- typically, "deviation" implies a NP scale, example $R_K \to Z'$ with mass 2 TeVZ'
- confirmation of these or any new deviations can inform the discussion for future colliders

Going beyond: flavour at Z factories (FCC-ee/CEPC)

Tera-Z at FCC-ee or CEPC

- **production of 10^{12} Z's**
- ✓ no phase-space limitations like at Belle-2
- ✓ LEP environment, less hadronic activity than at LHCb
- ✘ larger $\sqrt{s}$ than at Belle-2, more hadronic activity
- ✓ decay products of Z **more boosted** than at Belle 2
  more separation in lab-frame, better experimental resolution?

It is **not clear (and process specific)** whether the combination of higher **hadronic activity** but larger **boost** is **beneficial** for the tera-Z. Input and dedicated studies needed.

Tera-Z vs Belle 2 and LHCb

Particle	@ Tera-Z	@ Belle II		@ LHCb
***b* hadrons**				
B^+	6×10^{10}	3×10^{10}	$(50\,\mathrm{ab}^{-1}$ on $\Upsilon(4S))$	3×10^{13}
B^0	6×10^{10}	3×10^{10}	$(50\,\mathrm{ab}^{-1}$ on $\Upsilon(4S))$	3×10^{13}
B_s	2×10^{10}	3×10^{8}	$(5\,\mathrm{ab}^{-1}$ on $\Upsilon(5S))$	8×10^{12}
b baryons	1×10^{10}			1×10^{13}
Λ_b	1×10^{10}			1×10^{13}
***c* hadrons**				
D^0	2×10^{11}			
D^+	6×10^{10}			
D_s^+	3×10^{10}			
Λ_c^+	2×10^{10}			
τ^+	3×10^{10}	5×10^{10}	$(50\,\mathrm{ab}^{-1}$ on $\Upsilon(4S))$	

From CEPC's CDR using fragmentation ratios from Amhis et al, 17

- Similar statistical sample of $B^{0,\pm}$, τ's at Belle 2 and a tera-Z
- Two orders of magnitude more B_s at tera-Z wrt to Belle 2
- b-baryon physics possible
- Limited possibilities for charm physics at Belle 2

Flavour at a tera-Z factory: summary [from CEPC CDR]

Observable	Current sensitivity	Future sensitivity	Tera-Z sensitivity
$\mathrm{BR}(B_s \to ee)$	2.8×10^{-7} (CDF) [10]	$\sim 7 \times 10^{-10}$ (LHCb) [18]	$\sim$ few $\times 10^{-10}$
$\mathrm{BR}(B_s \to \mu\mu)$	0.7×10^{-9} (LHCb) [8]	$\sim 1.6 \times 10^{-10}$ (LHCb) [18]	$\sim$ few $\times 10^{-10}$
$\mathrm{BR}(B_s \to \tau\tau)$	5.2×10^{-3} (LHCb) [9]	$\sim 5 \times 10^{-4}$ (LHCb) [18]	$\sim 10^{-5}$
R_K, R_{K^*}	$\sim 10\%$ (LHCb) [5, 4]	$\sim$few% (LHCb/Belle II) [18, 40]	$\sim$few %
$\mathrm{BR}(B \to K^* \tau\tau)$	–	$\sim 10^{-5}$ (Belle II) [40]	$\sim 10^{-8}$
$\mathrm{BR}(B \to K^* \nu\nu)$	4.0×10^{-5} (Belle) [44]	$\sim 10^{-6}$ (Belle II) [40]	$\sim 10^{-6}$
$\mathrm{BR}(B_s \to \phi\nu\bar{\nu})$	1.0×10^{-3} (LEP) [15]	–	$\sim 10^{-6}$
$\mathrm{BR}(\Lambda_b \to \Lambda\nu\bar{\nu})$	–	–	$\sim 10^{-6}$
$\mathrm{BR}(\tau \to \mu\gamma)$	4.4×10^{-8} (BaBar) [24]	$\sim 10^{-9}$ (Belle II) [40]	$\sim 10^{-9}$
$\mathrm{BR}(\tau \to 3\mu)$	2.1×10^{-8} (Belle) [37]	$\sim$ few $\times 10^{-10}$ (Belle II) [40]	$\sim$ few $\times 10^{-10}$
$\frac{\mathrm{BR}(\tau \to \mu\nu\bar{\nu})}{\mathrm{BR}(\tau \to e\nu\bar{\nu})}$	3.9×10^{-3} (BaBar) [23]	$\sim 10^{-3}$ (Belle II) [40]	$\sim 10^{-4}$
$\mathrm{BR}(Z \to \mu e)$	7.5×10^{-7} (ATLAS) [3]	$\sim 10^{-8}$ (ATLAS/CMS)	$\sim 10^{-9} - 10^{-11}$
$\mathrm{BR}(Z \to \tau e)$	9.8×10^{-6} (LEP) [17]	$\sim 10^{-6}$ (ATLAS/CMS)	$\sim 10^{-8} - 10^{-11}$
$\mathrm{BR}(Z \to \tau\mu)$	1.2×10^{-5} (LEP) [13]	$\sim 10^{-6}$ (ATLAS/CMS)	$\sim 10^{-8} - 10^{-10}$

- At the moment mostly based on rescaling limits from LEP
- Important to perform (non-trivial) sensitivity studies, including backgrounds and detector simulation. **(FCC-ee and CEPC advocates should combine efforts)**

Flavour at a tera-Z factory: highlights

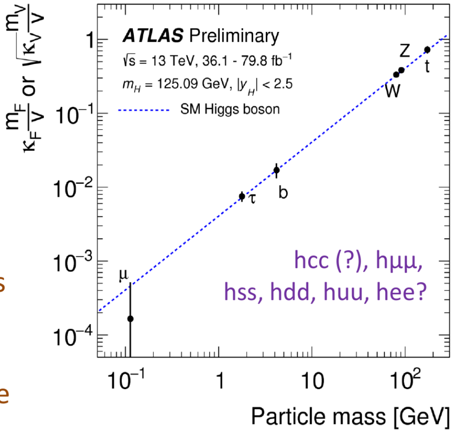
- Simulation-wise the study of flavour at FCC-ee or CEPC has only just begun
- Given the statistics, the tera-Z will compete well with both Belle-2 and LHCb

- **But in some cases tera-Z is expected to outperform both:**
  - τ **Physics**
    BRs and lifetime, lepton-flavour violating decays [FCC-ee study by M. Dam]
  - **lepton flavour violating Z decays** [FCC-ee study by M. Dam, and CEPC CDR]
  - $\boldsymbol{B_0 \to K^* \tau\tau}$ and $\boldsymbol{B_s \to \tau\tau}$ [FCC-ee study by Kamenik et al 17]
  - $\boldsymbol{b \to s\nu\nu}$ transition
    access to $B_s \to \phi\nu\nu$ and $\Lambda_b \to \Lambda\nu\nu$ [ongoing CEPC study]
  - $\boldsymbol{B_c}$ **physics**
    so far uncharted territory, determination of V_{cb}, relation to R_{D^*} anomaly
    [ongoing CEPC study]
- The full potential is not yet explored, significant work still required.

"The flavour of Higgs", a new era for Flavour

Flavour is more than the test of CKM unitarity

- Mass-coupling degeneracy well-supported by Higgs data
  - Nevertheless, should continue program as far as we can go and cover all SM fermions possible



[talk by F. Yu]

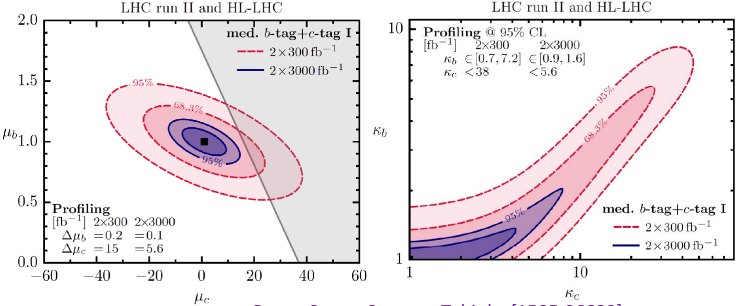
- Test the SM by probing the flavour and CP properties of the Higgs

→ A new "unitarity triangle"

Probing Higgs Yukawas: beyond standard approaches I

- Search for exclusive Higgs decays, $H \to J/\psi\gamma$, $H \to \phi\gamma$,...
-
  - Directly measure in $q\bar{q}$ decays
    - Use bottom and charm tagging in tandem, profile over enhanced c content in Higgs decays

	ϵ_b	ϵ_c	ϵ_l
b-tagging	70%	20%	1.25%
c-tagging I	13%	19%	0.5%
c-tagging II	20%	30%	0.5%
c-tagging III	20%	50%	0.5%



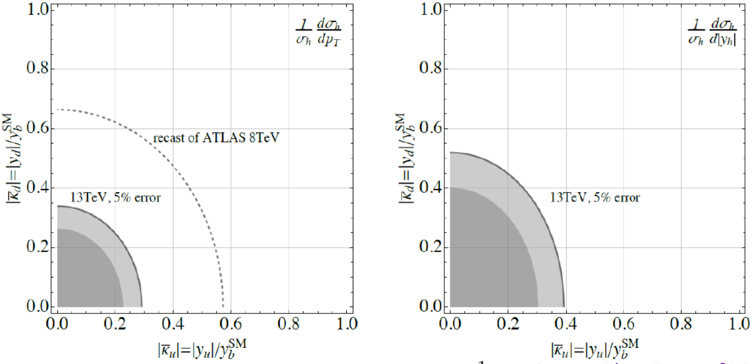
Perez, Soreq, Stamou, Tobioka [1505.06689]

[talk by F. Yu]

- Probe light-quark Yukawas in Higgs distributions

– Use normalized $p_{T,\,h}$ and y_h distributions

- Continuing theory calculations needed to push uncertainties



$$p_T : \quad \bar{\kappa}_u < 0.27, \bar{\kappa}_d < 0.31 \quad 2\ \text{ab}^{-1}$$

$$y : \quad \bar{\kappa}_u < 0.36, \bar{\kappa}_d < 0.47 \quad 2\ \text{ab}^{-1}$$

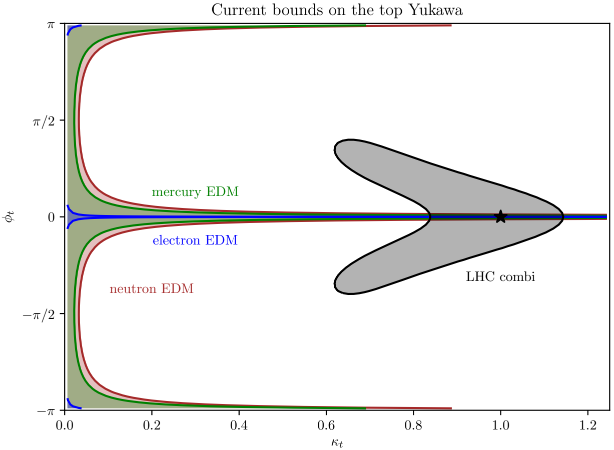
Soreq, Zhu, Zupan [1606.09621]

[talk by F. Yu]

CP properties of the Higgs Yukawas

- EDM measurements sensitive to CP violation in Higgs Yukawas
- Complementarity of high-energy and high-intensity frontier
- Probing models for eletroweak Baryogenesis

Example: top-quark

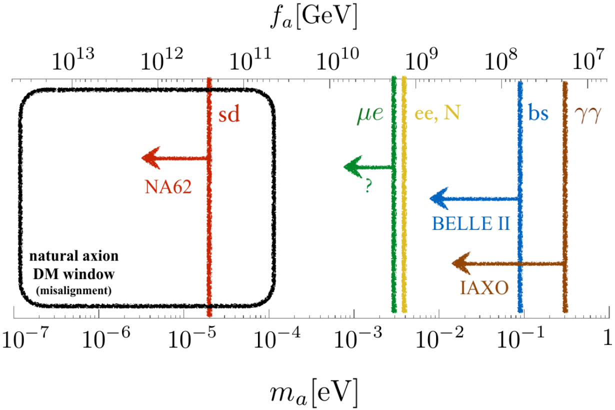


Flavour and light New Physics

- Often emphasis is laid on testing high-energy scales for NP
- Flavour also probes light-NP scenarios that weakly interact with SM particles

Example: probing the QCD axion via flavour-violating coupling

From R. Ziegler @ La Thuille 2019



- Kaon sector, $K^+ \to \pi^+ \nu\nu$ already probes the Axion DM window
- Improvements expected in the future (Belle 2, NA62, KOTO)

Conclusions and Outlook

Traditional Flavour (FCNCs)

- FCNC processes probe scales $\gg 1$ TeV
- Rich ongoing and planned experimental program (20% NP effects still possible)
- Tensions in data will be resolved, 5σ discoveries possible

➜ useful input for decision on future colliders

Flavour is more than FCNCs

Higgs Flavour

- Large NP effects may be hiding in Higgs Yukawas
- Important target measurements for LHC and future colliders
- Probe flavour and CP structure, complementary info from high-intensity data (FCNCs, EDMs)

Flavour and light NP

- FCNCs probe also light but weakly interacting NP scenarios (example QCD axion)
- Improvements expected from Belle 2, NA62, …, but tera-Z would probe new relevant channels

Final thoughts

- Without tensions/deviations from the SM the scale of BSM Flavour dynamics is unknown

➜ Models most useful in order to correlate predictions in light of anomalies

- Future-collider discussion should learn but not heavily rely on current tensions in data

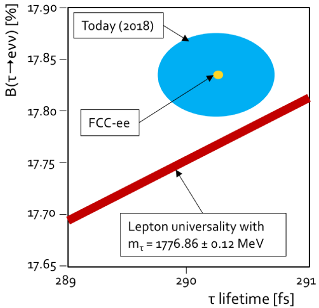
➜ Prioritize i) probing weakly constrained channels, ii) identifying new experimental methods/observables, and iii) pursuing reliable theory predictions

Zoltan's flowchart

Evidence for BSM?		FLAVOR yes	FLAVOR no
ATLAS & CMS	yes	complementary information	distinguish models
	no	tells us where to look next	flavor is the best microscope

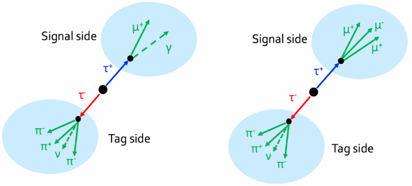
Appendix

τ's and LFV at the tera-Z



- lifetime measurement, 3 orders of magnitude better than LEP
- Lepton flavour universality tests
- Z limits from rescaling LEP, 3 orders of magnitude improvement
- τ limits 1-2 orders of magnitude improvement [FCC-ee study by M. Dam]

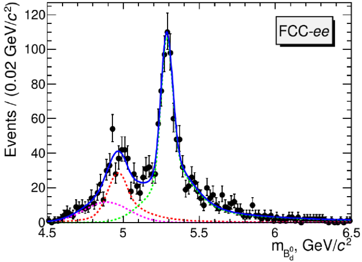
Decay	Present bound	FCC-ee sensitivity
$Z \to \mu e$	0.75×10^{-6}	10^{-10}–10^{-8}
$Z \to \tau\mu$	12×10^{-6}	10^{-9}
$Z \to \tau e$	9.8×10^{-6}	10^{-9}
$\tau \to \mu\gamma$	4.4×10^{-8}	2×10^{-9}
$\tau \to 3\mu$	2.1×10^{-8}	10^{-10}



[FCC-ee study by M. Dam with some simulation, see also CEPC-CDR]

$B_0 \to K^*\tau\tau$ at the tera-Z

- Expected sensitivities from LHCb and Belle II far from SM expectations
- Important test of LFU violation given present R_K and R_{K^*} tensions
- **$B \to K^*\tau\tau$ a golden mode for the tera-Z**



- Fully reconstruct the decay
  Z vertex from primary tracks, B vertex from $K\pi$, τ vertices from 3 prong decays
- Expect $\mathcal{O}(10^3)$ reconstructed events
  [Kamenik et al 17]
- Angular analysis possible

- Thus $B_s \to \tau\tau$ also accessible for the first time at the tera-Z
- Together with $B_s \to \phi\nu\nu$ and $\Lambda_b \to \Lambda\nu\nu$ possible to disentangle chiral-structure of operators

Origin of axion–fermion couplings

- axion couples to PQ current
- PQ basis $\neq$ mass basis

$$C^{V,A}_{u_i,u_j} = (V^\dagger_{UL} \mathrm{PQ}_q V_{UL})_{ij} \pm (V^\dagger_{UR} \mathrm{PQ}_u V_{UR})_{ij}$$

- **If PQ charge non-universal ➜flavor violating couplings**
  e.g., non-universal DFSZ models [Celis et al 14; di Luzio et al 17]
  e.g., PQ = FN (“axiflavon”/“flaxion”) [Wilczek 82; Calibbi et al 16; Ema et al 16]

➜**Flavor violating couplings** offer another way to search for the **QCD axion**

➜Need (often neglected) dedicated analyses