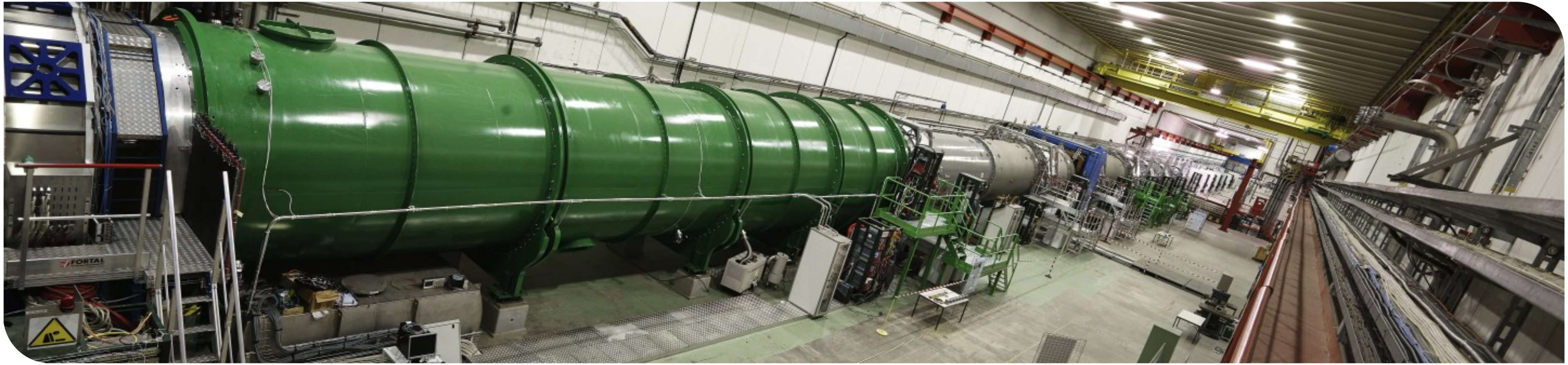
Physics reach of future ECN3 experiments:
General considerations and preliminary results

Felix Kahlhoefer

Physics Beyond Colliders Annual Workshop, 7-9 November 2022



Two challenges for studying physics reach

- Aim: Enable experiments to present their science case in a robust and balanced way that allows for external assessment

- Part 1: Towards fair sensitivity comparisons
  - Example: Sensitivity to light and long-lived dark scalars in beam dumps

- Part 2: Towards fair interpretation
  - Example: Sensitivity to lepton flavour universality violation in kaon decays

Towards fair sensitivity comparisons

- Step 1: Define benchmark scenarios
  - **For feebly-interacting particles:** Set of 11 benchmark scenarios agreed upon by PBC experiments

    → New BCs under development

  - **For heavy new physics:** Natural framework is Effective Field Theory, but need to focus on specific (sets of) operators

9.1 Vector Portal
- 9.1.1 Minimal Dark Photon model (BC1)
- 9.1.2 Dark Photon decaying to invisible final states (BC2)
- 9.1.3 Milli-charged particles (BC3)

9.2 Scalar Portal
- 9.2.1 Dark scalar mixing with the Higgs (BC4 and BC5)

9.3 Neutrino Portal
- 9.3.1 Neutrino portal with electron-flavor dominance (BC6)
- 9.3.2 Neutrino portal with muon-flavor dominance (BC7)
- 9.3.3 Neutrino portal with tau-flavor dominance (BC8)

9.4 Axion Portal
- 9.4.1 Axion portal with photon-coupling (BC9)
- 9.4.2 Axion portal with fermion-coupling (BC10)
- 9.4.3 Axion portal with gluon-coupling (BC11)

Towards fair sensitivity comparisons

- Step 2: Agree on signal simulation
  - **Example: FIPs produced in B meson decays**
    - All experiments should use the same B meson spectra (obtained e.g. from Pythia 8)
    - All experiments should use the same cross sections for proton-proton scattering and bb production
    - Ideally, codes used to simulate subsequent FIPs decays (e.g. three-body decays of HNLs) should be made publicly available

WORK IN PROGRESS

Towards fair sensitivity comparisons

- Step 3: Clearly state assumptions & level of sophistication
  - Assumed data set (integrated luminosity, POT, …) and corresponding timescales
  - Detector simulation (fast/full, assumed resolution, acceptances, …)
  - Background study (simulated, extrapolated from data, …)

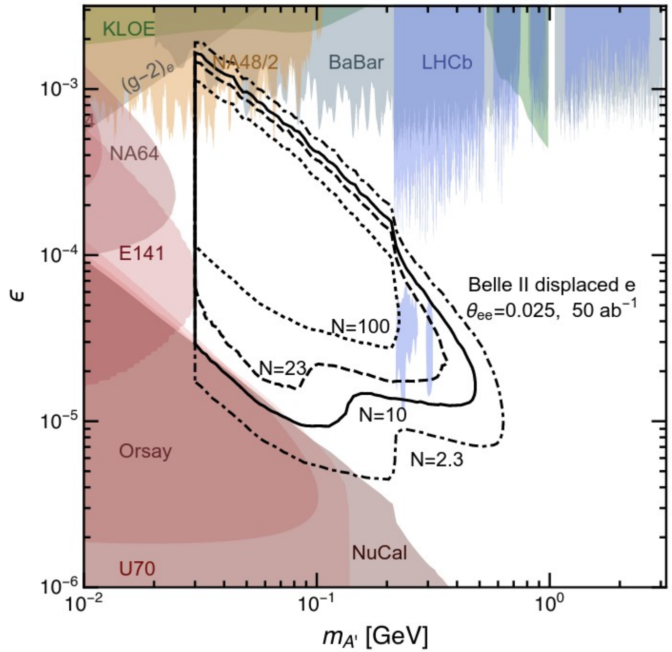
- Goals:
  - Store sensitivity projections together with documentation in central repository
  - Graphically represent maturity level using different line styles in summary plots

Towards fair sensitivity comparisons

- What about experiments that are not part of PBC?
  - Many groups worldwide adopt PBC conventions and benchmarks
  - New proposals often have low level of sophistication (detector simulation and background estimates are very challenging and time-consuming)
  - Vastly varying timescales and level of realism
  - Need to decide which experiments to include on case-by-case basis

Towards fair sensitivity comparisons

- Possible solution: Three types of plots
  - Contour plot of predicted new-physics events
    - No background estimates needed
  - Standard sensitivity projections (90% CL)
    - Requires estimate of background *rate*
  - Plot of discovery potential
    - Requires estimate of background *uncertainty*



Ferber et al., arXiv:2202.03452

Benchmark model: Light dark scalars

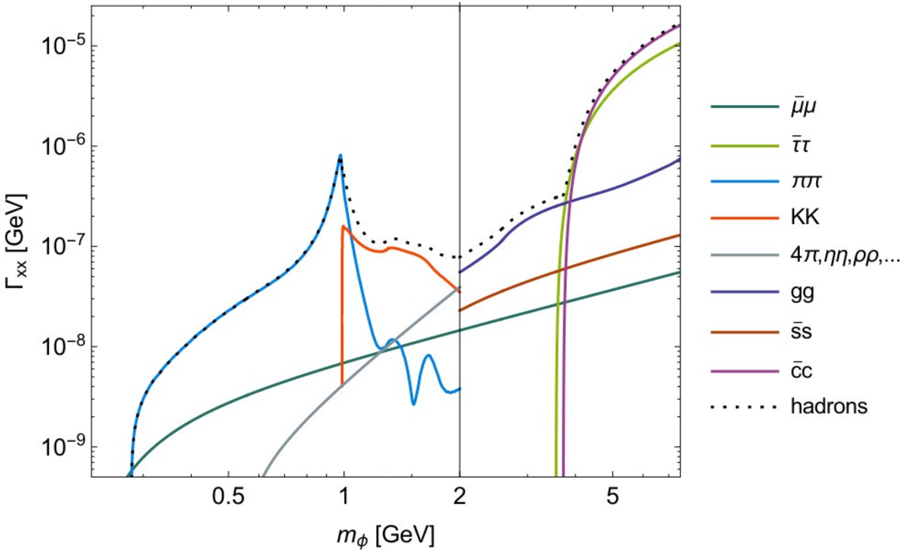
$$\mathcal{L}_{\text{scalar}} = \mathcal{L}_{\text{SM}} + \mathcal{L}_{\text{DS}} - (\mu S + \lambda S^2) H^\dagger H.$$

- Simplest version (BC4): λ = 0, μ≠0
  → Mixing with SM Higgs boson

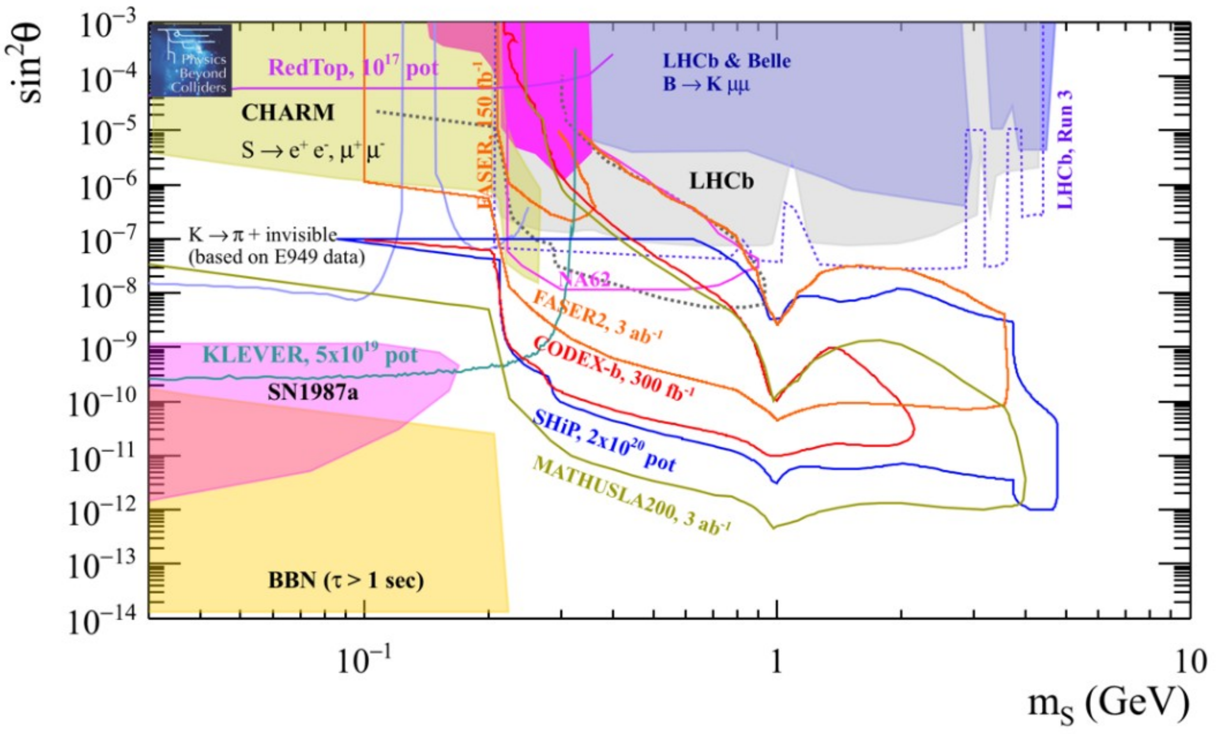
$$\theta = \frac{\mu v}{m_h^2 - m_S^2}$$

- Production through rare meson decays: B → K + S, K → π + S
- Various different decay modes

Winkler, arXiv:1809.01876

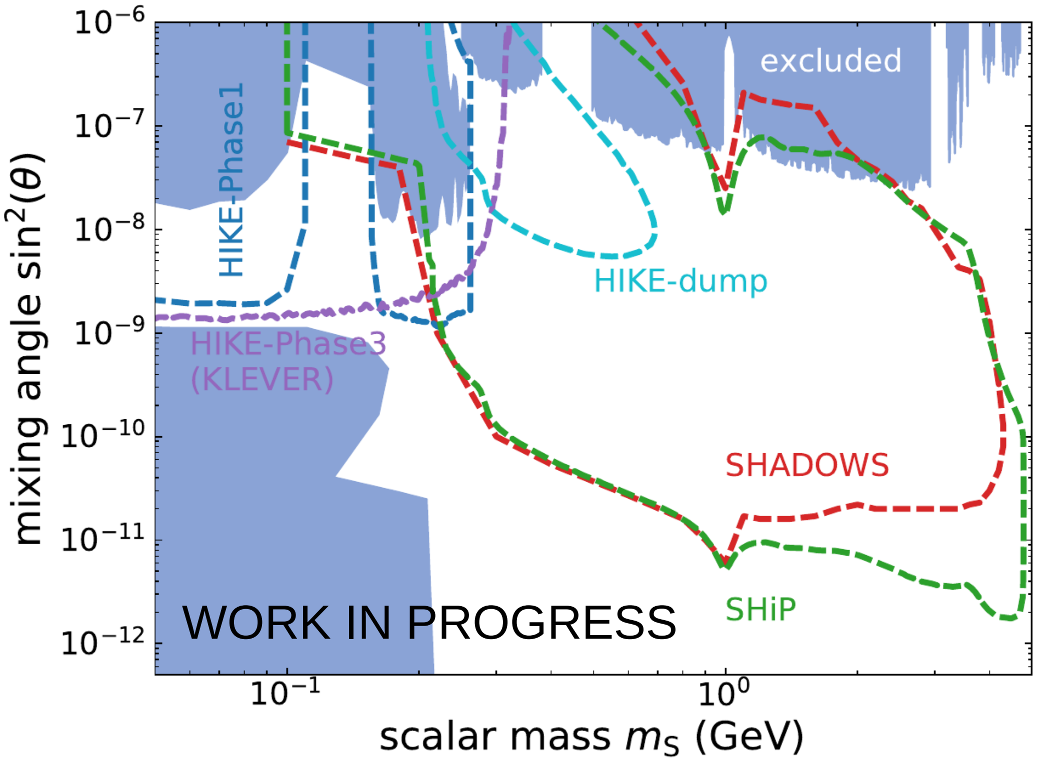


Sensitivity projections (2019)



Beacham et al., arXiv:1901.09966

Sensitivity projections (ECN3)



- HIKE-Phase1: $K^+ \to \pi^+ + S$
  (40x NA62 Run1 2016-2018)
- HIKE-Phase3: $K_L \to \pi^0 + S$
  (assume 60 events in $K \to \pi\nu\nu$)
- HIKE-dump: $5*10^{19}$ POT
  (no background)
- SHADOWS: $5*10^{19}$ POT
  (no background)
- SHiP: $2*10^{20}$ POT
  (no background)

Towards fair interpretation

- In many cases different experiments achieve best sensitivity for different benchmarks
  - SHADOWS much better than HIKE (in dump mode) for FIPs produced in B meson decays (BC4, BC6-8, BC10)
  - SHADOWS looses sensitivity for FIPs produced in the forward direction (BC1, BC9, BC11)
  - Only SHiP (with scattering detector) is sensitive to invisibly decaying dark photons (BC2)
- No well-defined method to compare size of different parameter regions
- Certainly no way of comparing relative merit of different BCs
- Even less clear how to compare searches for light new particles to kaon decays

Towards fair interpretation

- Possible strategy: How much knowledge can be gained by each experiment?
- Given existing exclusions, how strong a signal can be expected?
- How much could be learned from such a signal in terms of underlying models?
  - Reconstruction of particle mass and branching ratios
  - Discrimination between models?
- Would a null result imply any qualitative changes in our understanding?

Heavy new physics in K decays

HIKE will not only improve measurement of **BR($K^+ \to \pi^+\nu\nu$)** but also measure **BR($K_L \to \pi^0\nu\nu$)**, **BR($K_L \to \mu^+\mu^-$), BR($K_L \to \pi^0\mu^+\mu^-$)** and **BR($K_L \to \pi^0 e^+e^-$)**

- Given existing constraints on these decays, can we hope for **new physics to be revealed** with statistical significance?
- Answer requires **combination of different decay modes**, which relies on **model-specific assumptions**
- Of particular interest: **Lepton flavour universality violation**

  → **BR($K^+ \to \pi^+ e^+ e^-$)/BR($K^+ \to \pi^+\mu^+\mu^-$)** and **BR($K^+ \to e^+\nu$)/BR($K^+ \to \mu^+\nu$)**

EFT for lepton flavour universality violation

$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}}\lambda_t^{sd}\frac{\alpha_e}{4\pi}\sum_k C_k^\ell O_k^\ell$$

- Many different possible Lorentz structures
- Focus on those of particular interest for B physics:

$$O_9^\ell = (\bar{s}\gamma_\mu P_L d)\,(\bar{\ell}\gamma^\mu \ell)\,, \qquad O_{10}^\ell = (\bar{s}\gamma_\mu P_L d)\,(\bar{\ell}\gamma^\mu \gamma_5 \ell)$$

- Additional assumptions: $\delta C_L^\ell \equiv \delta C_9^\ell = -\delta C_{10}^\ell$ (only left-handed)

$\delta C_L^\tau = \delta C_L^\mu$ (reduce dimensions)

Three steps towards a global picture

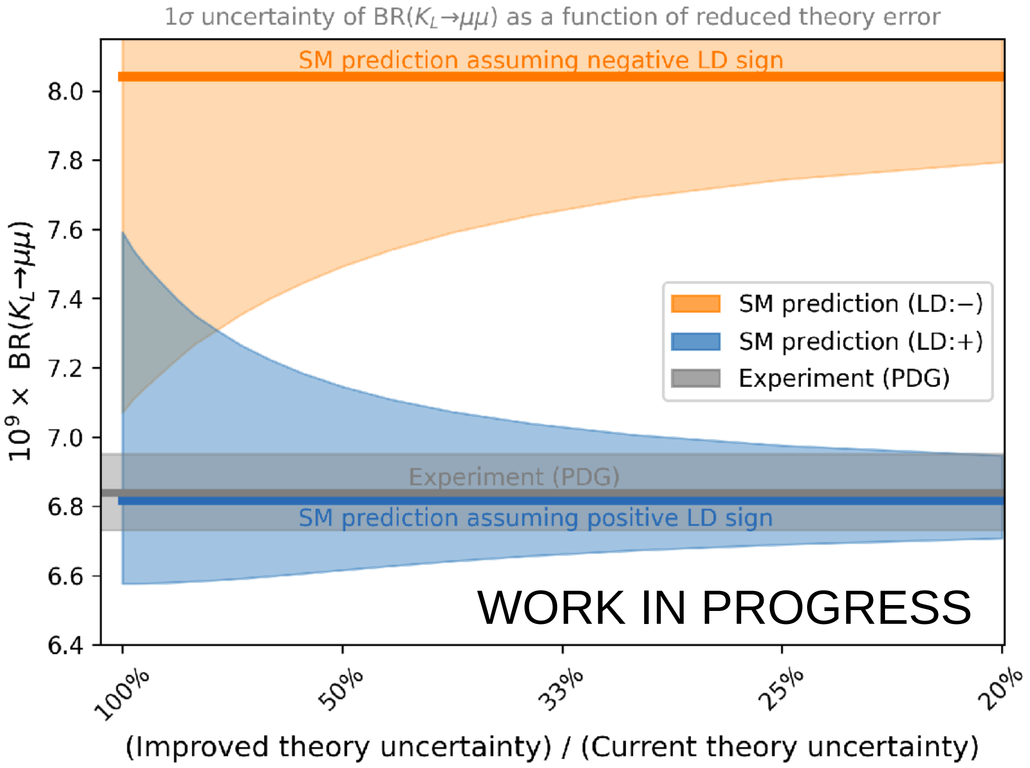
- Obtain current best-fit point by fitting all available data
- Shrink error bars according to expected improvements
- Quantify deviation from the Standard Model

Observable	SM prediction	Exp results	Ref.	Experimental Err. Projections
$\mathrm{BR}(K^+ \to \pi^+ \nu\nu)$	$(7.86 \pm 0.61) \times 10^{-11}$	$(10.6^{+4.0}_{-3.5} \pm 0.9) \times 10^{-11}$	[15]	10%(@2025) 5%(CERN; long-term) [109]
$\mathrm{BR}(K^0_L \to \pi^0 \nu\nu)$	$(2.68 \pm 0.30) \times 10^{-11}$	$< 3.0 \times 10^{-9}$ @90% CL	[17]	20%(CERN; long-term [109]) 15% (KOTO [112])
$\mathrm{LFUV}(a_+^{\mu\mu} - a_+^{ee})$	0	-0.031 ± 0.017	[16, 60]	± 0.007 (assuming ± 0.005 for each mode)
$\mathrm{BR}(K_L \to \mu\mu)$ (+)	$(6.82^{+0.77}_{-0.29}) \times 10^{-9}$	$(6.84 \pm 0.11) \times 10^{-9}$	[62]	experimental uncertainty kept to current value
$\mathrm{BR}(K_L \to \mu\mu)$ (−)	$(8.04^{+1.47}_{-0.98}) \times 10^{-9}$			
$\mathrm{BR}(K_S \to \mu\mu)$	$(5.15 \pm 1.50) \times 10^{-12}$	$< 2.1(2.4) \times 10^{-10}$ @90(95)% CL	[63]	$< 8 \times 10^{-12}$ @95% CL (CERN; long-term [77])
$\mathrm{BR}(K_L \to \pi^0 ee)(+)$	$(3.46^{+0.92}_{-0.80}) \times 10^{-11}$	$< 28 \times 10^{-11}$ @90% CL	[107]	observation (CERN; long-term [109]) (we assume 100% error)
$\mathrm{BR}(K_L \to \pi^0 ee)(-)$	$(1.55^{+0.60}_{-0.48}) \times 10^{-11}$			
$\mathrm{BR}(K_L \to \pi^0 \mu\mu)(+)$	$(1.38^{+0.27}_{-0.25}) \times 10^{-11}$	$< 38 \times 10^{-11}$ @90% CL	[108]	
$\mathrm{BR}(K_L \to \pi^0 \mu\mu)(-)$	$(0.94^{+0.21}_{-0.20}) \times 10^{-11}$			

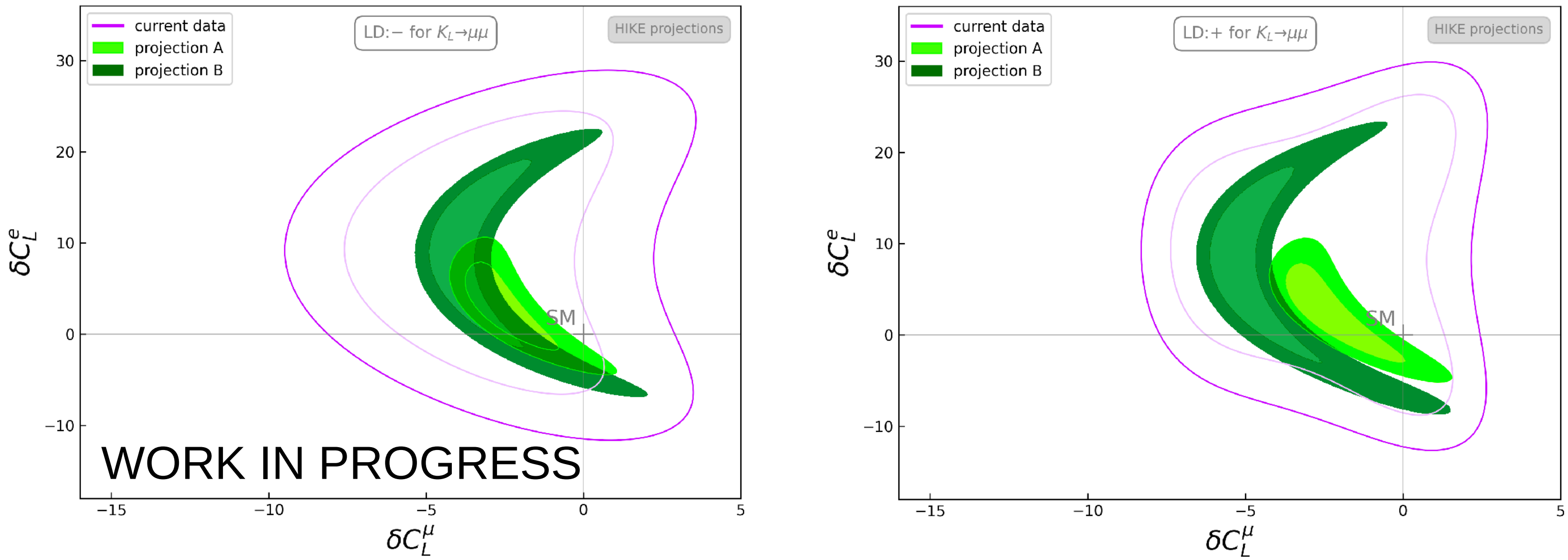
Table and analysis strategy taken from "Anatomy of kaon decays and prospects for lepton flavour universality violation" by G. D'Ambrosio, A.M. Iyer, F. Mahmoudic and S. Neshatpour, arXiv:2206.14748

Theoretical uncertainties

- Essential to have theoretical uncertainties under control
- Particularly challenging: $K_L \rightarrow \mu^+\mu^-$
- Unknown sign of long-distance contribution from $K_L \rightarrow \gamma\gamma$
- Mitigation strategy: Repeat fit twice for different assumptions



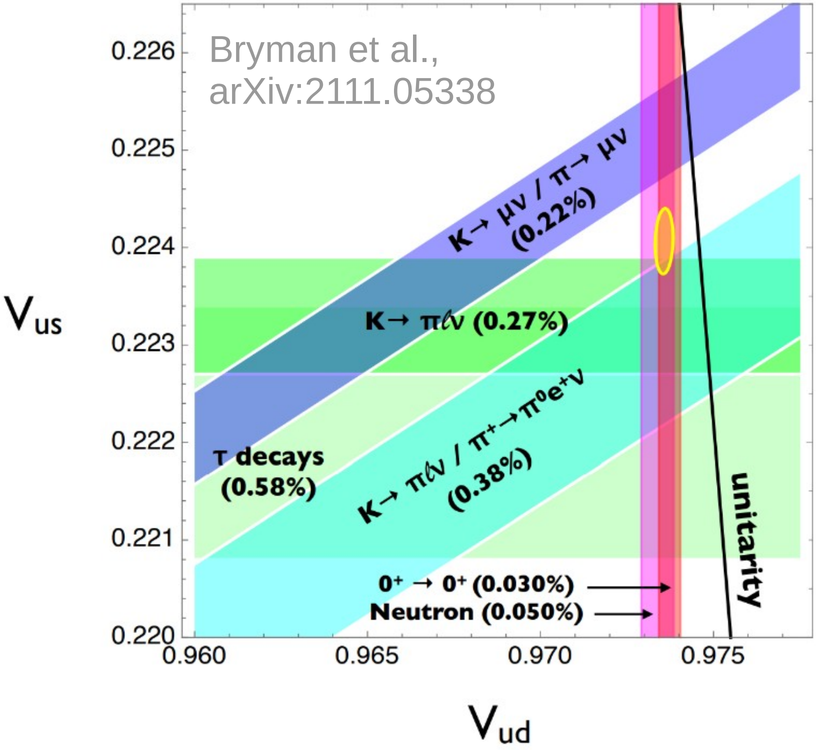
Results



- Projection A: New modes agree with SM → Overall consistency with SM at 3σ
- Projection B: New modes agree with best-fit point → Clear departure from SM at 3σ

Next steps

- Apply similar strategy also to fit of CKM matrix elements
- Current data hints at unitarity violation (“Cabibbo angle anomaly”)
- Study international competition
  - BR($K_L \to \pi^0 \nu\nu$) at KOTO
  - BR($K_S \to \mu^+\mu^-$) at LHCb



Felix Kahlhoefer
Institute for Theoretical Particle Physics (TTP)

Conclusions

- Exciting opportunities to search for new physics beyond the Standard Model with future experiments at ECN3

- Challenge 1: Fair comparison of sensitivity projections
  - Unify model/simulation assumptions, clearly label level of maturity

- Challenge 2: Fair interpretation of physics case
  - Quantify information gain / statistical significance

- Huge discovery potential for both light and heavy new physics