SM tests with Kaons & pions

Radoslav Marchevski (École Polytechnique Fédérale de Lausanne)

on behalf of the Flavour Physics WG

Why kaon and pion physics?

- Important questions we still haven't answered: what is origin of the SM flavour structure?
  - hierarchies of the fermion Yukawa couplings and mixing parameters, observed matter-antimatter asymmetry, etc…

Motivation for kaon and pion physics

- Large sensitivity to NP through precisely calculable (rare) observables
- Complementarity with beauty and charm sectors to uncover the flavour structure of NP
- Precision tests of the SM (CKM unitarity)
- Tests of low-energy hadronic theories (latticle, ChPT, dispersive analysis, …)

Main players

	γ	quarks	μ	e	τ	ν
$2_q \; 1_q \rightarrow 1_q$	$s \rightarrow d\,\gamma$	$K \leftrightarrow \bar{K}$	$s \rightarrow d\,\mu\mu$ $s \rightarrow u\,\mu\nu$ $d \rightarrow s\,\mu\nu$	$R_{sd}(e/\mu)$ $R_{su}(e/\mu)$ $R_{du}(e/\mu)$		$s \rightarrow d\nu\nu$

- Kaon and pion physics offers precision tests of the SM and is highly sensitive to the flavour structure of NP
- Several **gold-plated** observables dominated dominated by *short-distance dynamics* ↔ *precise theoretical control*
  - $s \rightarrow d\nu\nu$ → main goal of the NA62 experiment
  - $s \rightarrow d\,\mu\mu$ through $K_S - K_L \rightarrow\ \mu\mu$ interference effects
  - LFU ratios $(R_{qq'})$

Main players

Long-term plans:

- one or more dedicated projects (green)
- clean mode lacking dedicated project (purple)

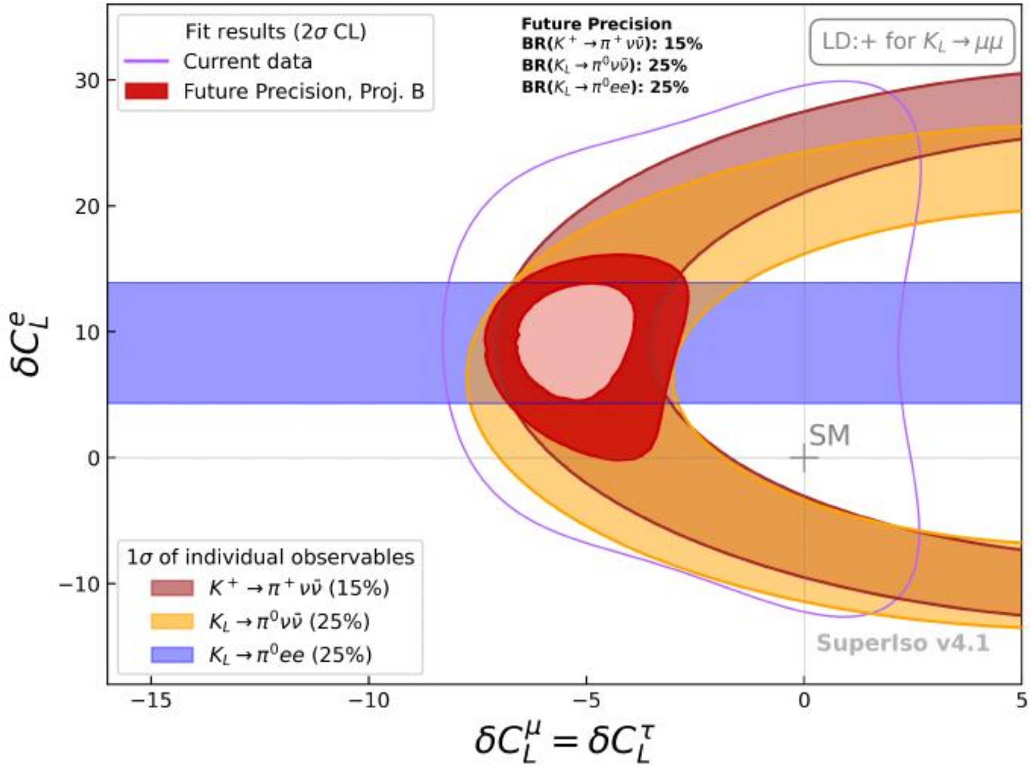
	γ	quarks	μ	e	τ	ν
2_q $1_q \to 1_q$	$s \to d\gamma$	$K \leftrightarrow \bar{K}$	$K_{L,S} \to \mu\mu$ $s \to u\,\mu\nu$ $d \to s\,\mu\nu$	$R_{sd}(e/\mu)$ $R_{su}(e/\mu)$ $R_{du}(e/\mu)$ $\pi^+ \to \pi^0 e\nu$		$K_L \to \pi^0\nu\nu$ $K^+ \to \pi^+\nu\nu$

- NA62 is the present state-of-the-art K^+ experiment and will take data until 2026
- Ongoing effort by KOTO at J-PARC in Japan to measure $K_L \to \pi^0\nu\nu$ to 25% in the late 2030s
- The newly approved PIONEER experiment will tackle
  - pion LFU tests @10^{-4} at PSI in the late 2020s/early 2030s
  - sub one per mill level $|V_{ud}|$ extraction from $\pi^+ \to \pi^0 e\nu$ decays
- LHCb will study $K_S - K_L \to \mu\mu$ interference with Upgrade II
- No next-generation K^+ experiment (post NA62) foreseen → *clear hole in the program* which *must be addressed*

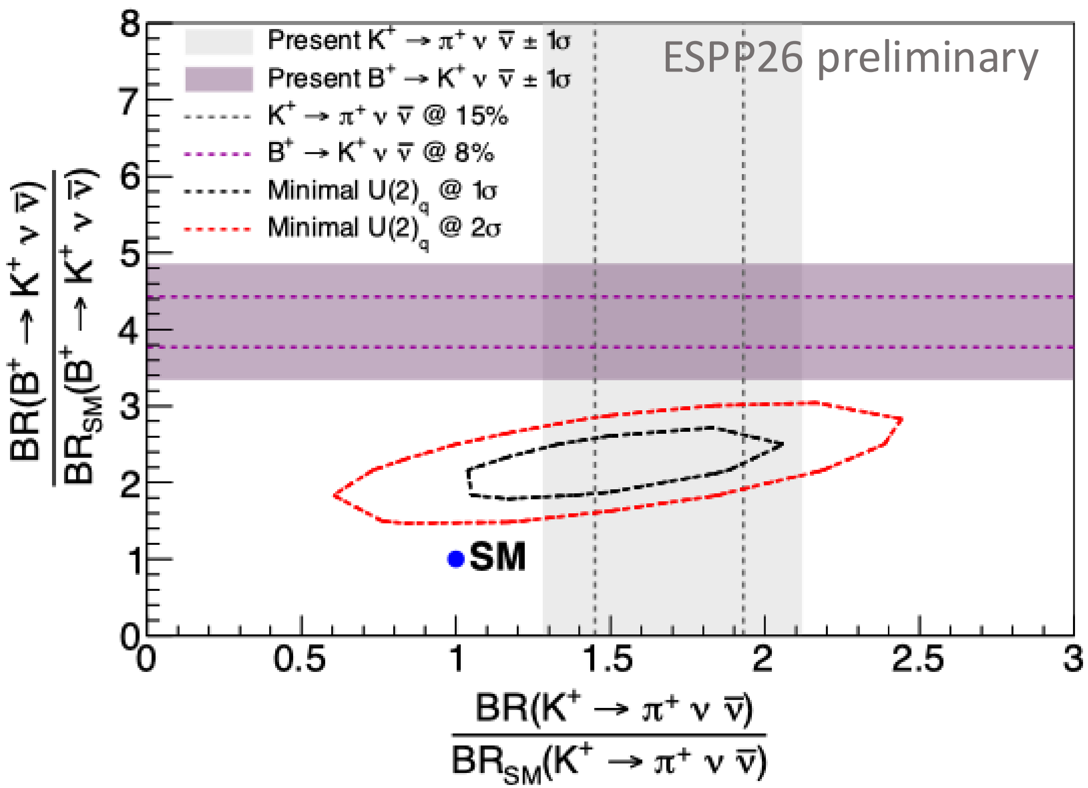
BSM reach and complementarity

- Kaon physics offers complementarity between different decay modes and sectors
- Complementarity is important to investigate the flavour structure of NP

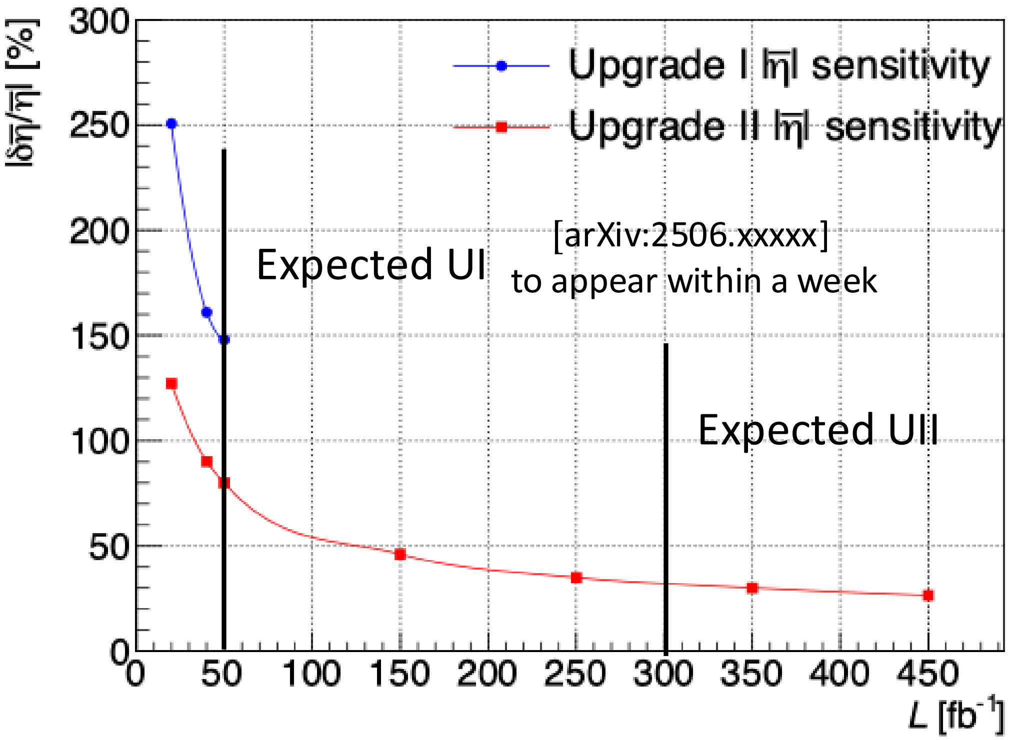
Impact on LFUV tests
$s \to d\ell\ell + s \to d\nu\bar{\nu}$



NP aligned to 3rd generation +
approximate $U(2)^5$ flavour symmetry
$s \to d\ell\ell + b \to s\nu\bar{\nu}$



$K \to \mu^+\mu^-$ interference



Time-dependent rate

$$\frac{1}{\mathcal{N}}\frac{d\Gamma(\overset{(-)}{K}{}^0 \to \mu^+\mu^-)}{dt} = C_L\, e^{-\Gamma_L t} + C_S\, e^{-\Gamma_S t} \pm 2\, C_{\text{Int.}} \cos(\Delta M_K t - \varphi_0) e^{-\Gamma t}$$

Short-distance CPV contribution

$$\begin{aligned} C_L &= |A(K_L)_{\ell=0}|^2\,, \\ C_S &= |A(K_S)_{\ell=0}|^2 + \beta_\mu^2 |A(K_S)_{\ell=1}|^2\,, \\ C_{\text{Int.}} &= |A(K_S)_{\ell=0}||A(K_L)_{\ell=0}|\,, \\ \varphi_0 &= \arg\left[A(K_S)^*_{\ell=0}\, A(K_L)_{\ell=0}\right]. \end{aligned}$$

$$\Rightarrow \quad C_{\text{Int.}} = C_L \sqrt{\frac{\tau_L}{\tau_S}\frac{\mathcal{B}(K_S \to \mu^+\mu^-)_{l=0}}{\mathcal{B}(K_L \to \mu^+\mu^-)}}$$

$$\Downarrow$$

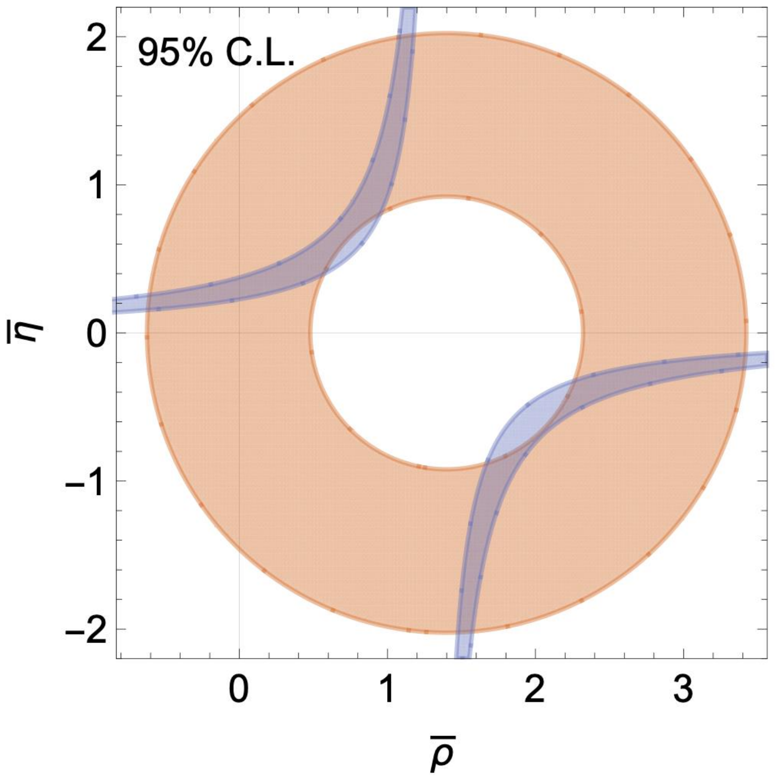
$$\mathcal{B}(K_S)_{\ell=0} = \frac{\beta_\mu \tau_S}{16\pi m_K}\left|\frac{2\, G_F^2 m_W^2}{\pi^2} f_K m_K m_\mu Y_t\right|^2 \cdot (\lambda^5 A^2 \bar{\eta})^2$$

- Measuring $K \to \mu^+\mu^-$ interference can give direct access to the short-distance component of $K_S \to \mu^+\mu^-$
- Prospects to measure the interference using a tagged analysis at LHCb with Upgrade II!
- **Measurement of $C_{\text{Int.}}(|A(K_S)_{\ell=0}|)$ is a direct measurement of η**

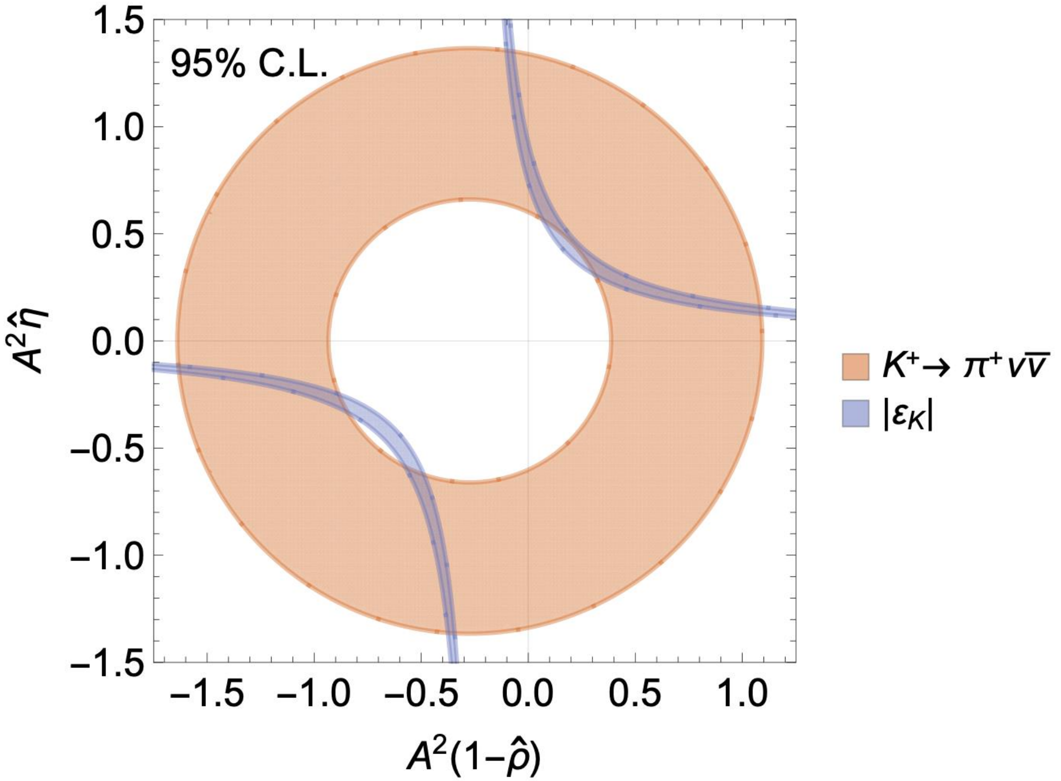
CKM tests with kaons

- The $s \to d$ CKM unitarity triangles can be constrained using kaon observables alone
- Avoids using B-physics input ($|V_{cb}|$) and use the $(\mathrm{A}^2(1-\bar{\rho}), A\bar{\eta})$ plane instead ⇒ better constrains

UT constraints with B physics input (PNN + ε_K)
present



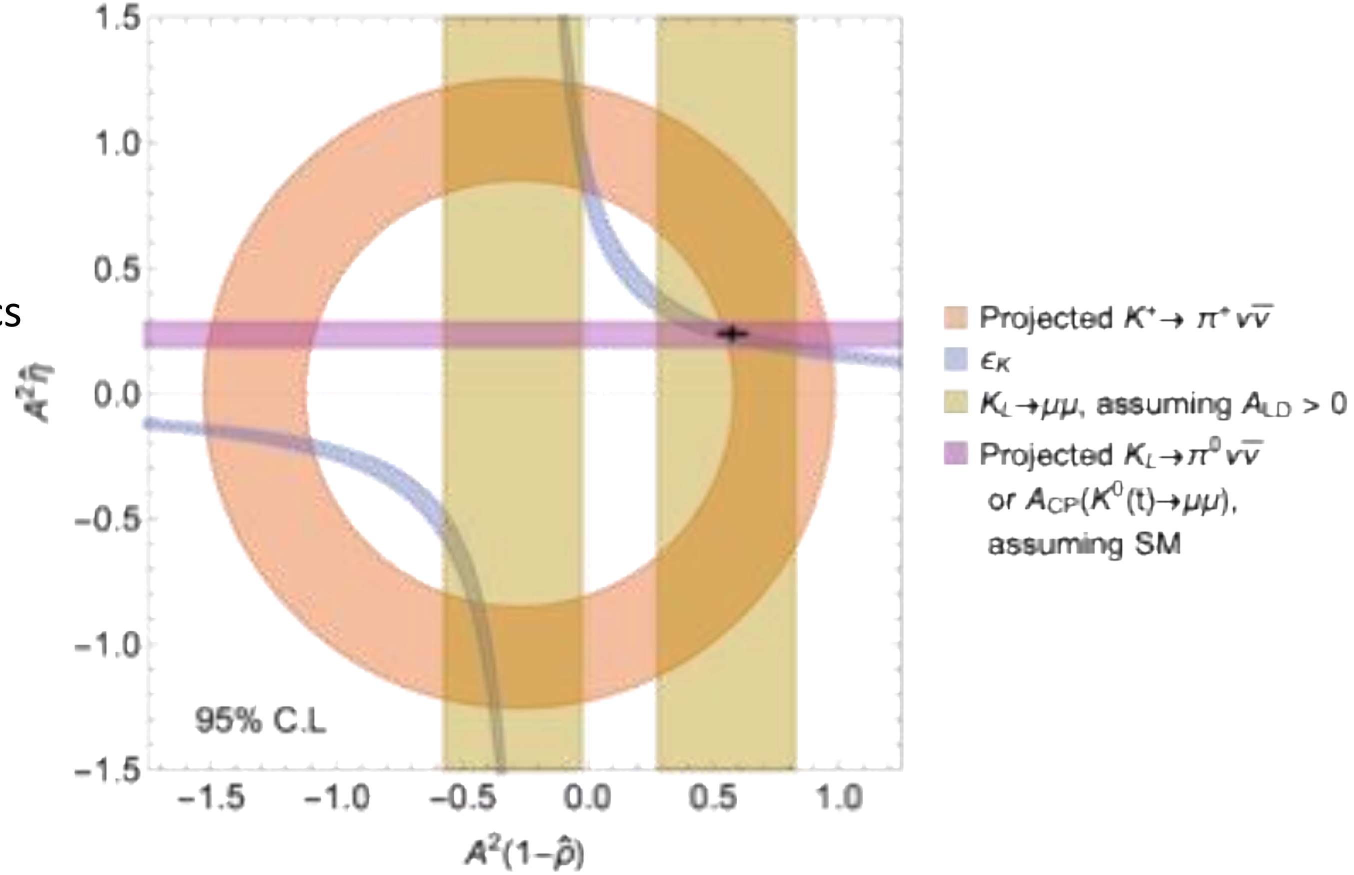
UT constraints w/o B physics (PNN + ε_K)
present



CKM tests with kaons

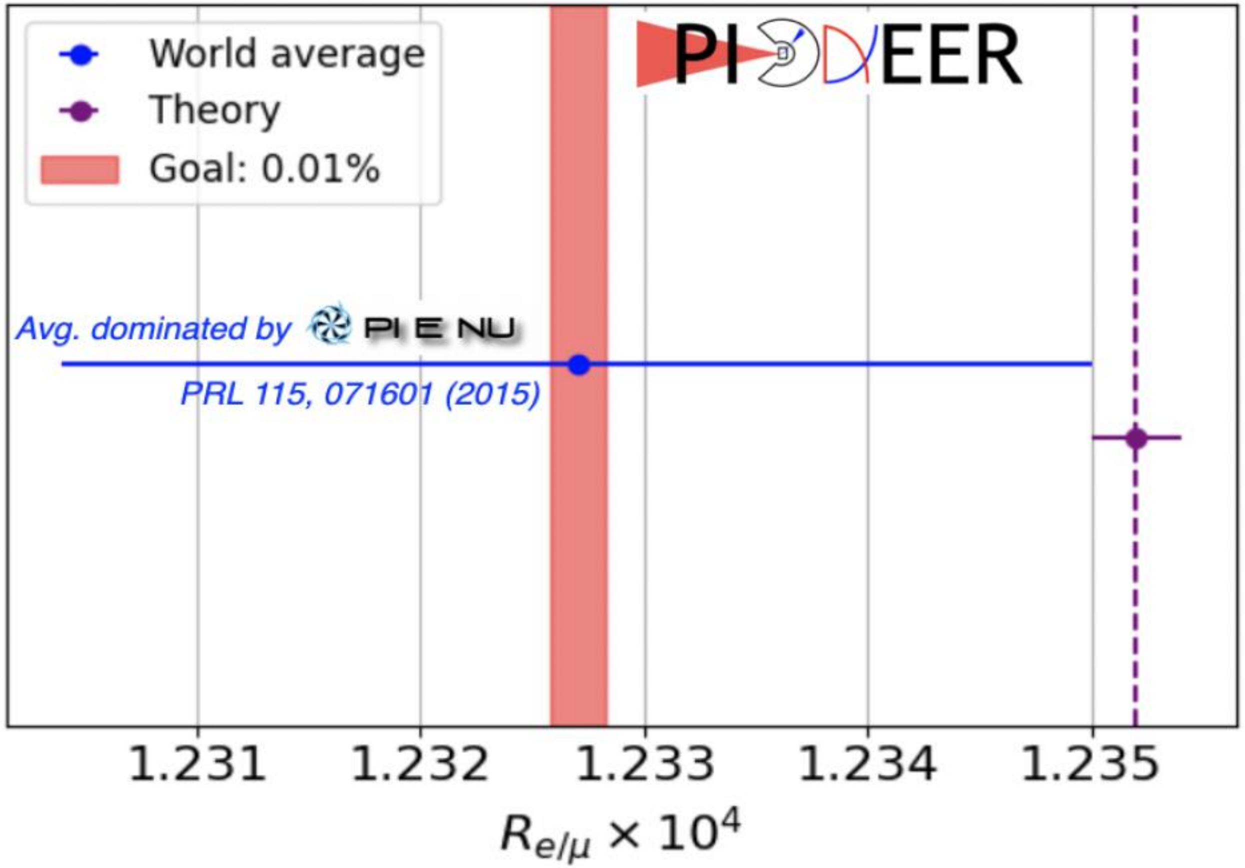
- Combining all kaon-related observables can provide a powerful CKM test using exclusively loop-level observables
- The discrete ambiguity in $K_L \to \mu\mu$ can be resolved if the sign of the A_{CP} in $K \to \mu\mu$ is determined by LHCb
- An improved measurement of $K^+ \to \pi^+ \nu\bar{\nu}$ could strengthen the constraints significantly

UT constraints w/o B physics
future



LFU tests with pions

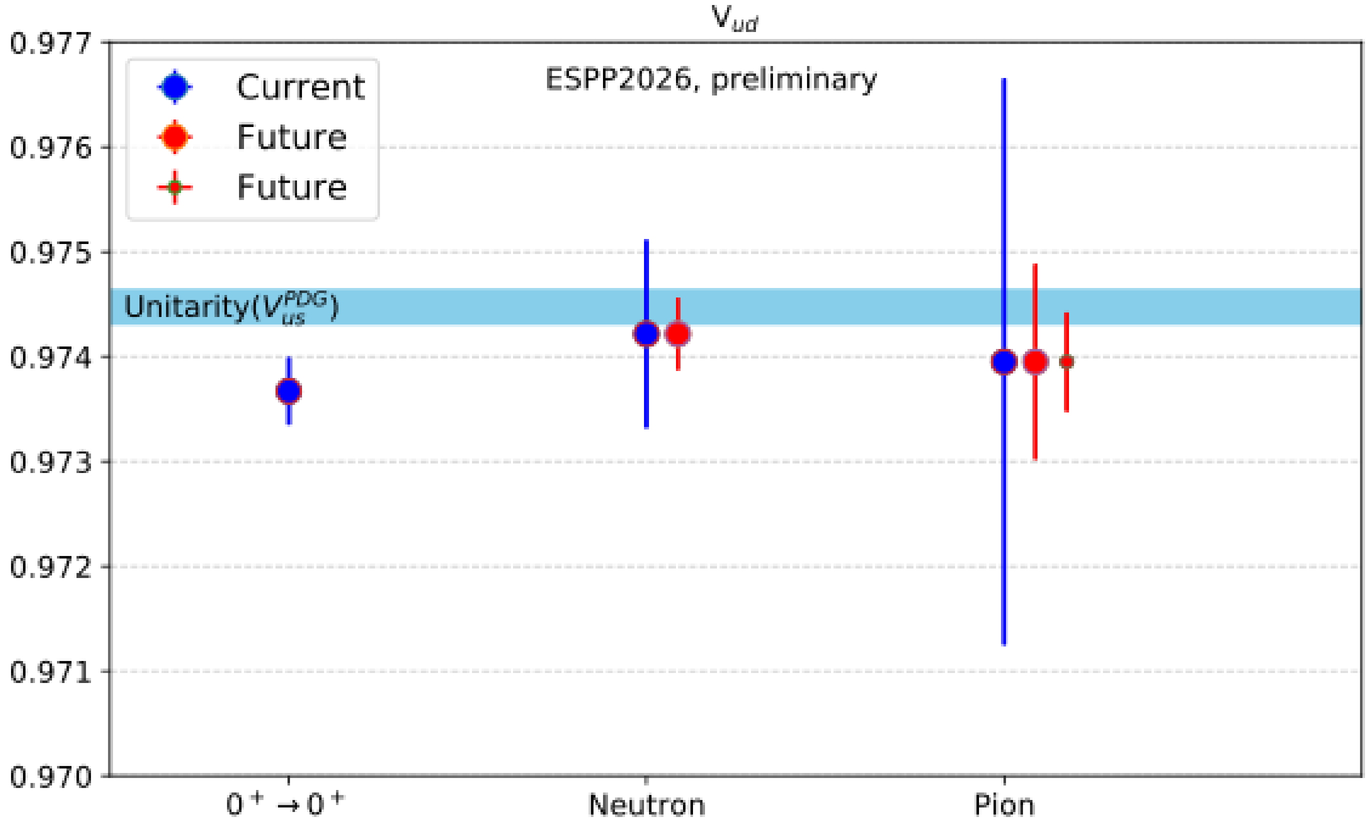
- LFU in the pion sector: the most precisely known observable involving quarks in the SM(1.2×10^{-4})
  - experimental sensitivity will be improved by a factor of 15 to match the theory uncertainty



(a) PIONEER Phase I goal

CKM tests with pions

- Precision CKM unitarity tests with $\pi^+ \to \pi^0 e^+ \nu(\gamma)$ decays
  - very challenging measurement: $\mathcal{B}\left(\pi^+ \to \pi^0 e^+ \nu(\gamma)\right) = (1.036 \pm 0.006) \times 10^{-8}$ $\to \times$ 6 *better precision expected*
  - cleanest extraction of V_{ud}: *expected precision to reach* 0.05%
  - comparable uncertainty to extractions from superallowed nuclear beta decays



Conclusions

- Kaon and pion physics remains a powerful tests of the SM paradigm offerring high sensitivity to the NP flavour structure through the precision measurement of rare decays, CKM parameters, and LFU tests

Request from the kaon and pion physics community

- Protect and amplify the European kaon physics programme, exploring opportunities for:
  - $K^+ \to \pi^+ \nu \bar{\nu}$ (successor of NA62), $K_{S,L} \to \mu^+ \mu^-$ decay and interference
- Facilitate and support European contribution for KOTO II for $K_L \to \pi^0 \nu \bar{\nu}$ and $K_L \to \pi^0 \ell^+ \ell^-$ as well as participation in PIONEER
- Maintain European leadership on theory computations for kaon and pion physics (phenomenology, dispersion theory, effective theory, lattice QCD)