CEPC Physics/Detector Workshop, August 2023

New directions in kaon physics

Avital Dery

AD, Ghosh, Grossman, Schacht, [arXiv: 2104.06427]

AD, Ghosh, [arXiv:2112.05801]

AD, Ghosh, Grossman, Kitahara, Schacht [arXiv:2211.03804]

Reviews: **AD** [arXiv:2211.06446], Schacht [arXiv:2305.06267]

Motivation -

Reminder: The Wolfenstein parameterization of the CKM

$$-\frac{g}{\sqrt{2}}\begin{pmatrix}\bar{u}_L & \bar{c}_L & \bar{t}_L\end{pmatrix}\begin{pmatrix}1-\frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho-i\eta) \\ -\lambda & 1-\frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1\end{pmatrix} W^{+}{}_{\mu}\gamma^{\mu}\begin{pmatrix}d_L \\ s_L \\ b_L\end{pmatrix} + \mathcal{O}(\lambda^4)$$

Assuming SM: 4 physical parameters: A , λ , ρ , η

First 4 indep. measurements - calibration,
From 5th measurement on - test of the SM

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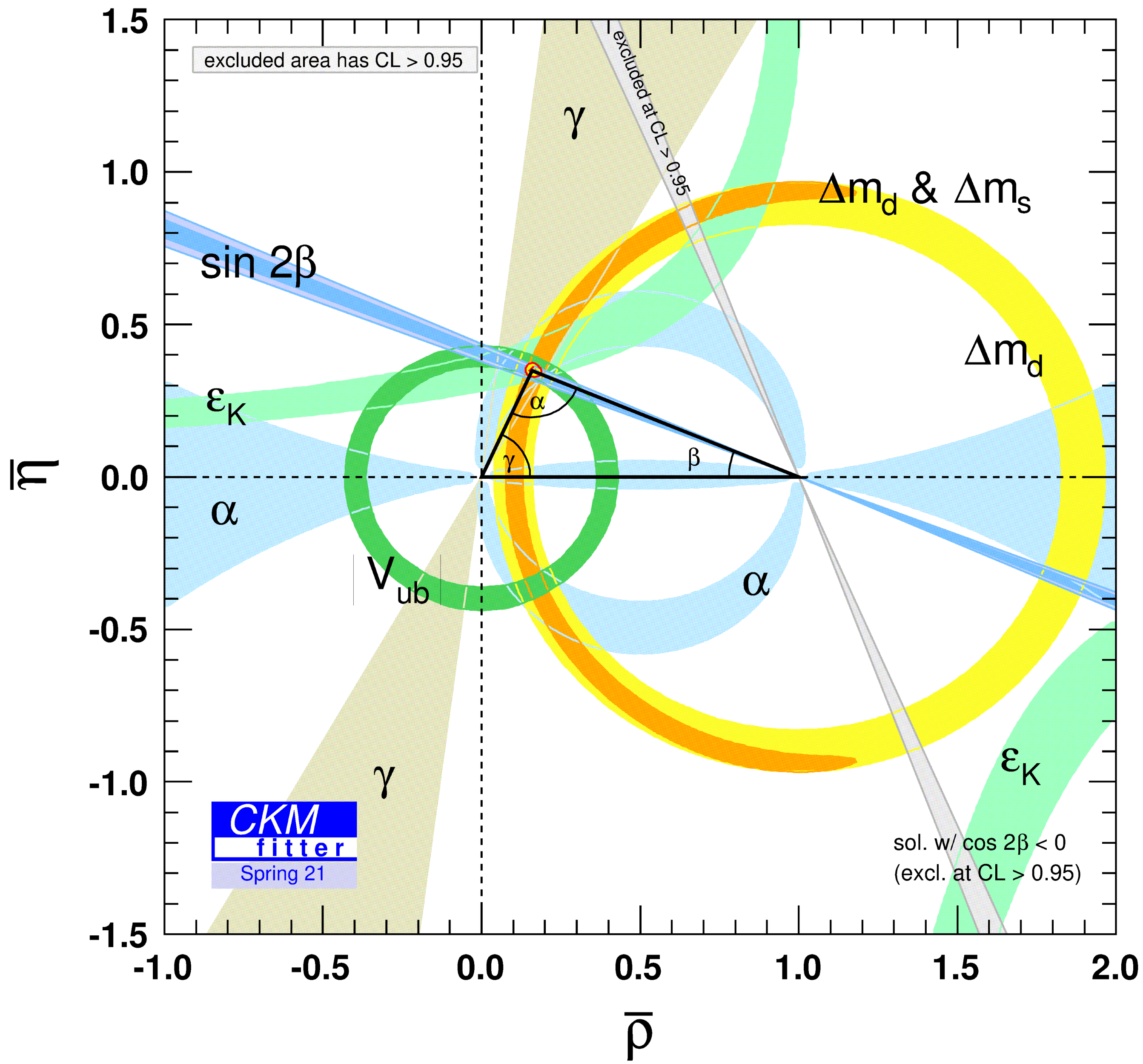
Assuming SM: 4 physical parameters: A, λ, ρ, η

First 4 indep. measurements - calibration,
From 5th measurement on - test of the SM

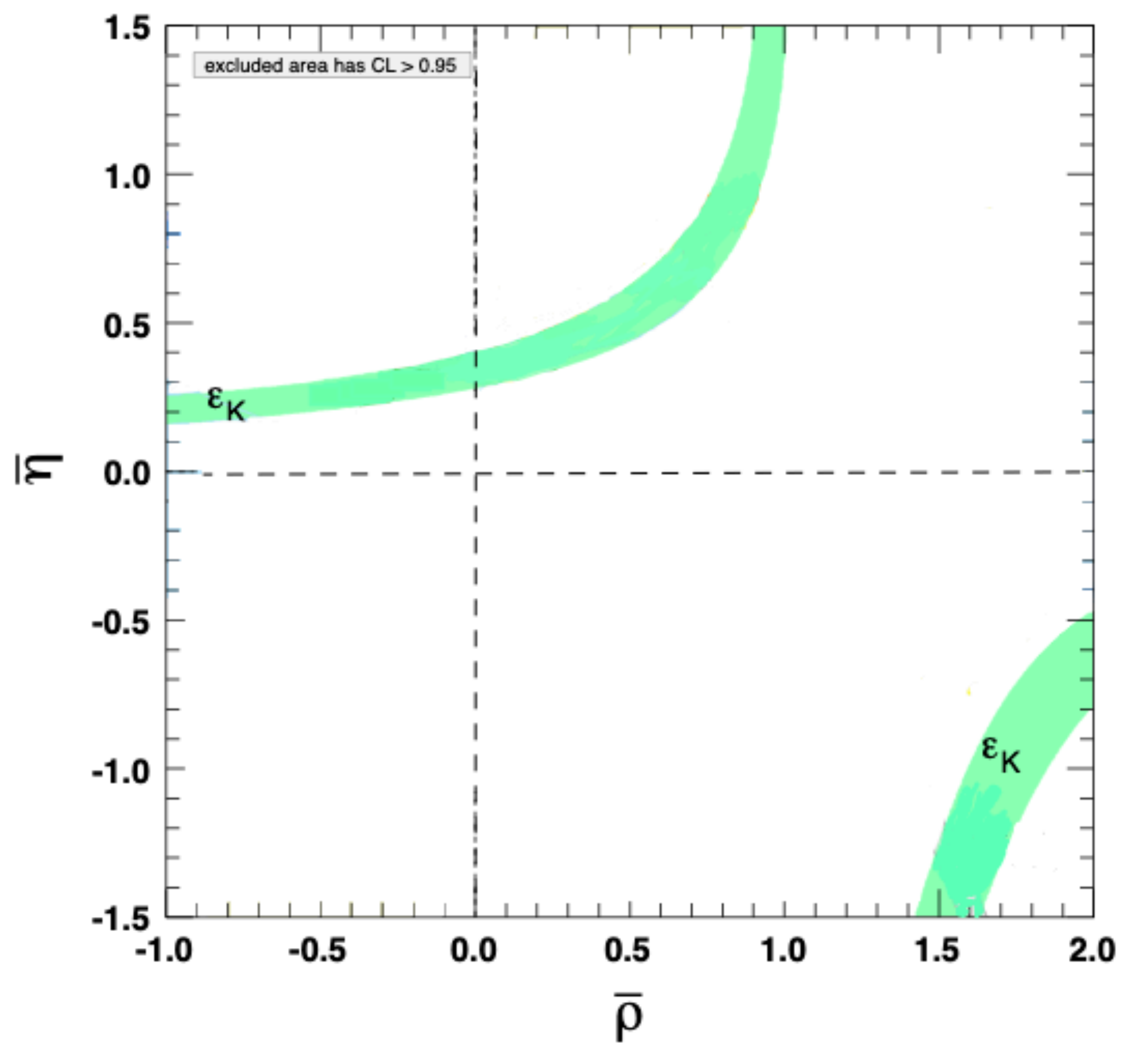
Current status: CKM picture verified in dozen of processes,

$$\frac{\delta A}{A}=2\,\%, \quad \frac{\delta\lambda}{\lambda}=0.2\,\%, \quad \frac{\delta\rho}{\rho}=12\,\%, \quad \frac{\delta\eta}{\eta}=3\,\%.$$

CPV



Cross-checks from **kaon physics** would be a unique and crucial test of the CKM paradigm.



Cross-checks from **kaon physics** would be a unique and crucial test of the CKM paradigm.

Kaon CKM measurements provide a valuable independent test.

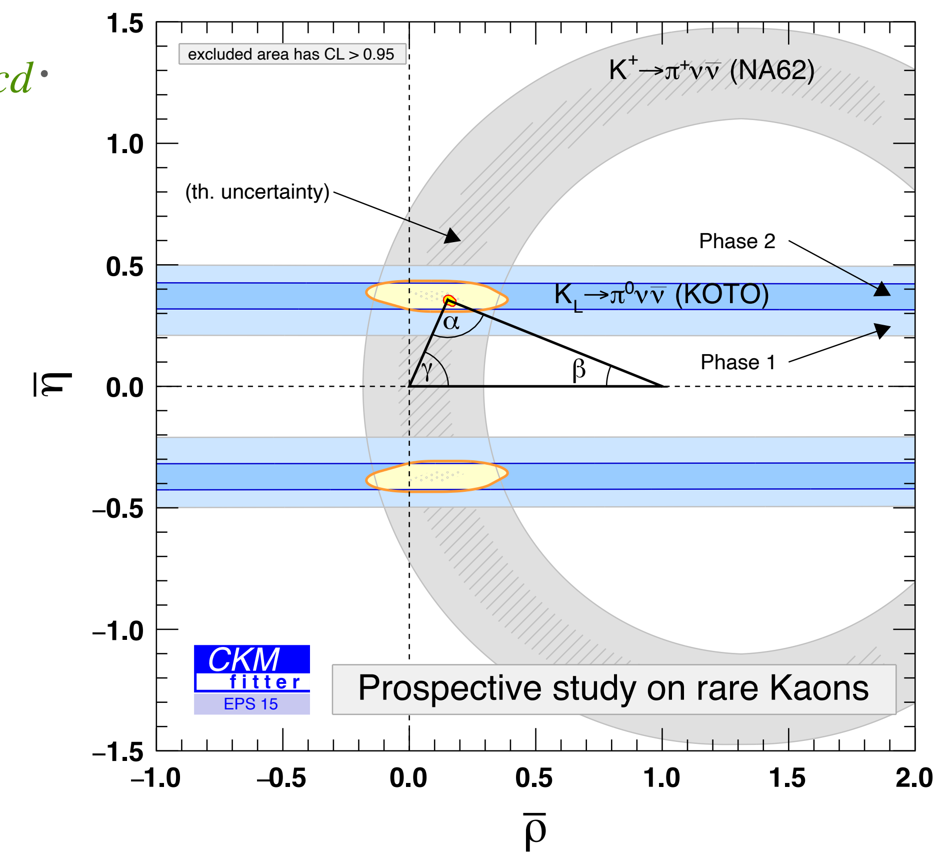
- Employ a different set of experimental techniques
- Require a different set of theoretical tools
- Sensitive to different New Physics scenarios

Two *golden modes* identified in the *1990's*

$K^+ \to \pi^+ \nu \bar{\nu}$ $\quad$ $K_L \to \pi^0 \nu \bar{\nu}$

Theoretically: Clean, sensitive to functions of $V_{ts}^* V_{td}, V_{cs}^* V_{cd}$.

The combination of <u>both</u> measurements would enable determination of $\{\rho, \eta\}$ from kaon physics.



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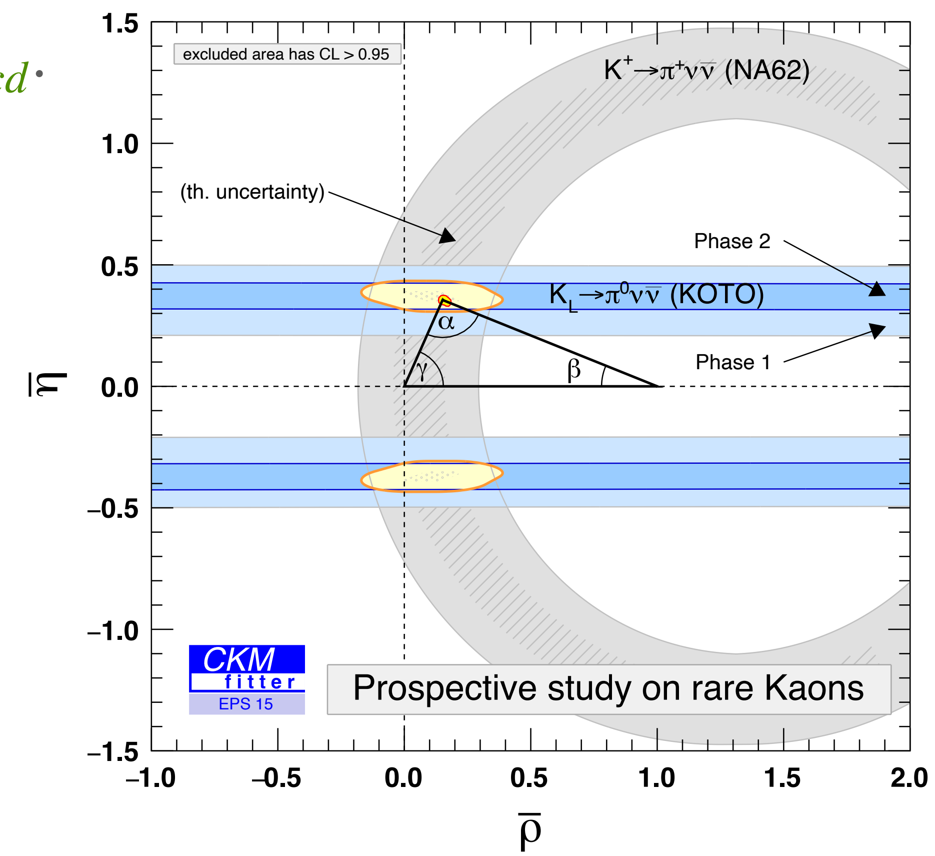
The combination of both measurements would enable determination of $\{\rho, \eta\}$ from kaon physics.

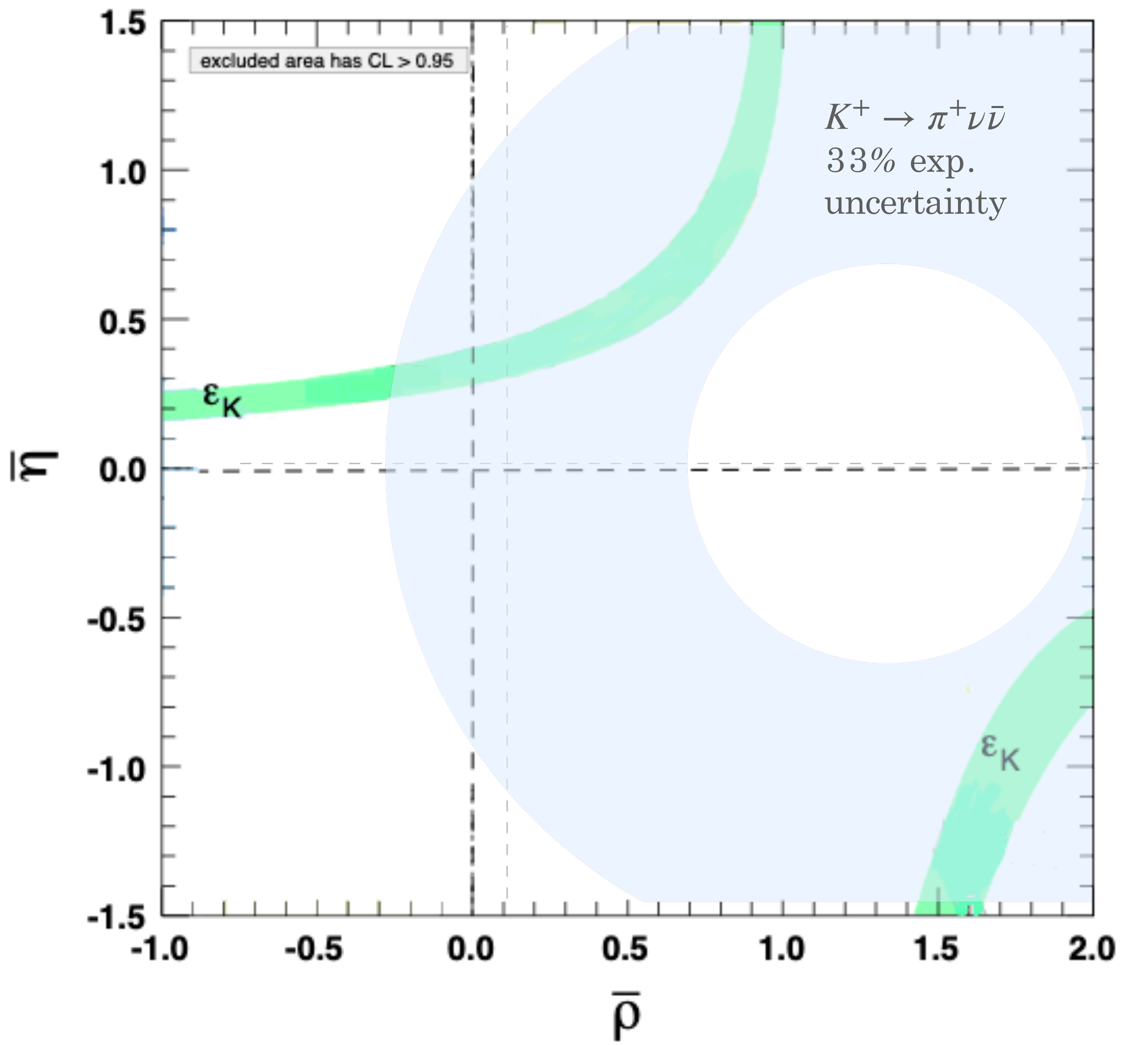
Experimentally: Extremely challenging.
Very rare decays, invisible particles in the final state.



Current status: $\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu}) = \left(1.06^{+0.41}_{-0.34}\right) \cdot 10^{-10}$ 2021: First evidence observed by **NA62 !**

$\mathcal{B}(K_L \to \pi^0 \nu\bar{\nu}) < 4.9 \cdot 10^{-9}$ 2021: Latest bound by **KOTO**

$\mathcal{B}(K_L \to \pi^0 \nu\bar{\nu})_{SM} = 2.6 \cdot 10^{-11}$ Extremely challenging to approach SM sensitivity



Cross-checks from **kaon physics** would be a unique and crucial test of the CKM paradigm.

What about

$$K_{L,S} \to \mu^+\mu^- \ ?$$

$K_{L,S} \to \mu^+\mu^-$ - Measurement vs. SM prediction

$$\mathcal{B}(K_L \to \mu^+\mu^-) = (6.84 \pm 0.11) \cdot 10^{-9}$$

$$\mathcal{B}(K_S \to \mu^+\mu^-)_{\text{LHCb 2020}} < 2.1 \cdot 10^{-10}$$

Hadronic uncertainty

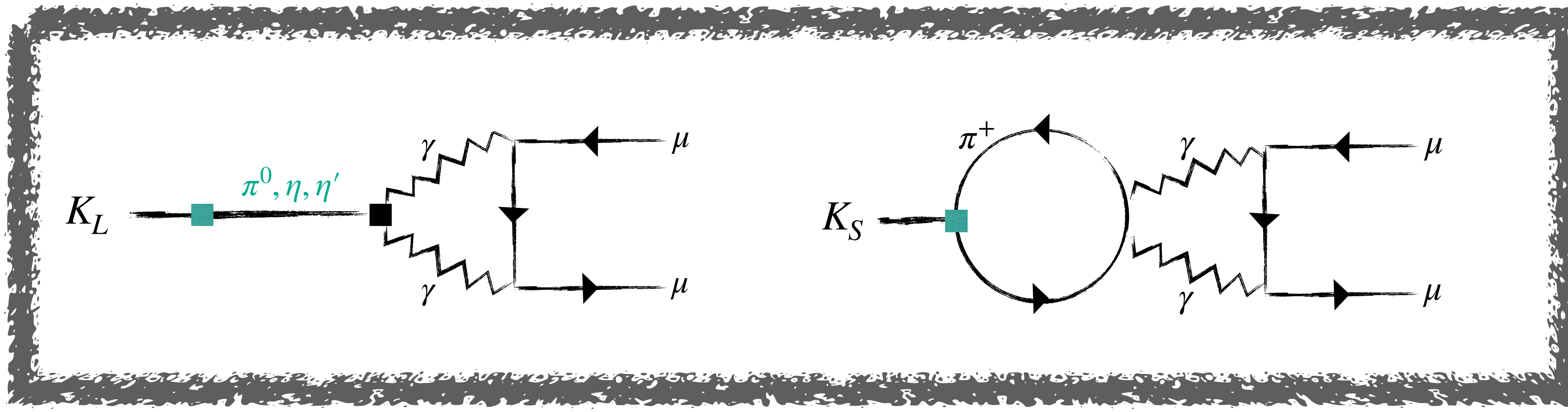
$$\mathcal{B}(K_L \to \mu^+\mu^-)_{\text{SM}} = \begin{cases} (6.85 \pm 0.80 \pm 0.06) \times 10^{-9}\,(+) \\ (8.11 \pm 1.49 \pm 0.13) \times 10^{-9}\,(-) \end{cases}$$

Hadronic uncertainty

$$\mathcal{B}(K_S \to \mu^+\mu^-)_{\text{SM}} = (5.18 \pm 1.50 \pm 0.02) \times 10^{-12}$$

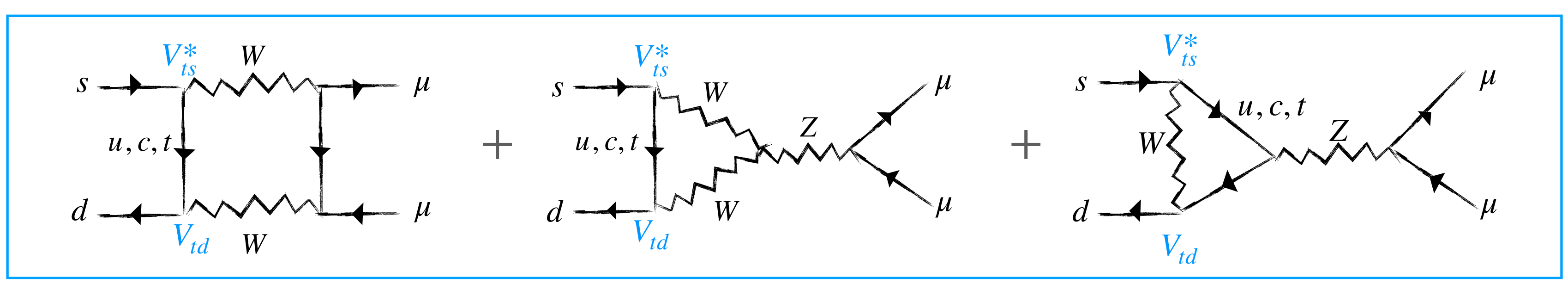
$K_{L,S} \to \mu^+\mu^-$ - leading and sub-leading contributions

Total (time integrated) rates severely dominated by non-perturbative effects



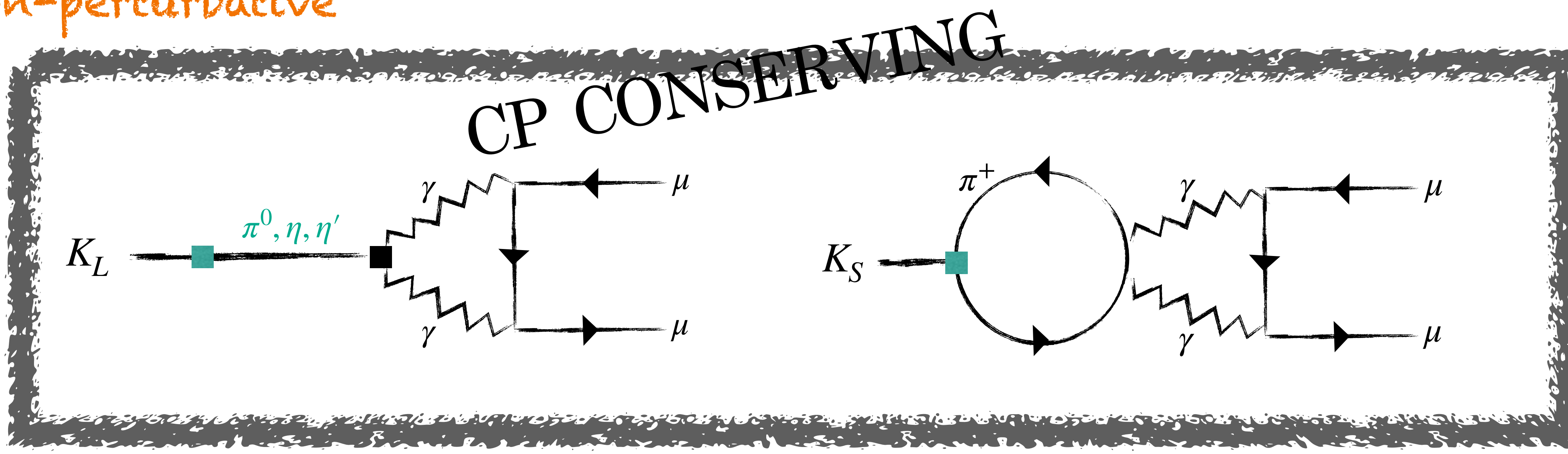
Sub-dominant contributions contain the desired clean CKM dependence

+

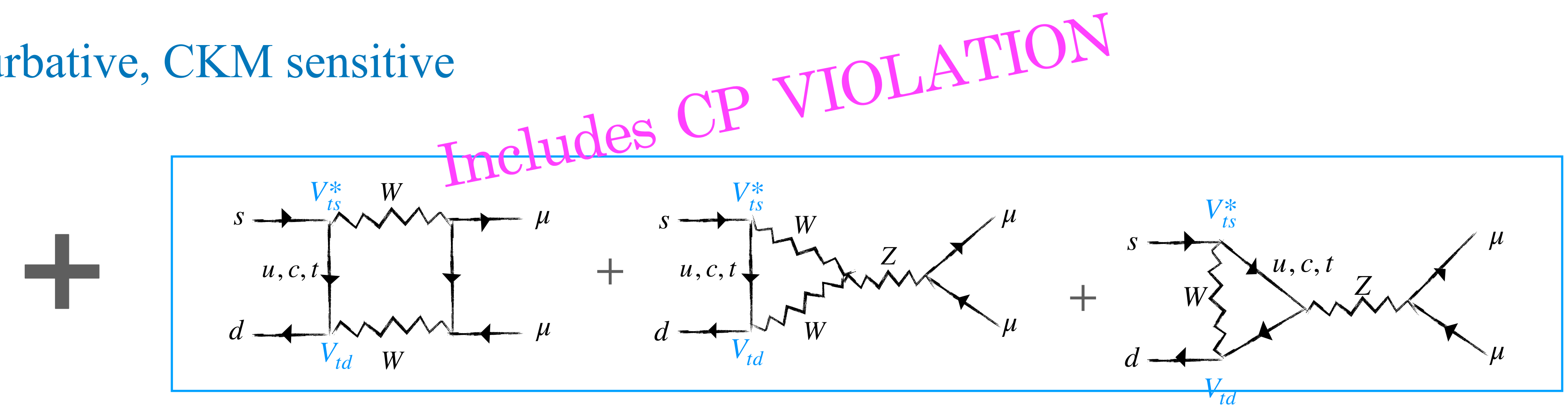


: CP Violation

Non-perturbative



Perturbative, CKM sensitive



Approximations used in the analysis

We work under the following 3 assumptions -

1. CPV in mixing is negligible, $\mathcal{O}(\varepsilon_K) \sim 10^{-3}$
2. No scalar operators are relevant, in the SM good to $\mathcal{O}(m_K^2/m_W^2) \sim 10^{-4}$
3. CPV in the non-perturbative contributions is negligible, of $\mathcal{O}(\lambda^4) \sim 10^{-3}$

All fulfilled in the SM to $\mathcal{O}(10^{-3})$

CP analysis of $K \to \mu^+\mu^-$

Initial state: kaon mass eigenstates are CP eigenstates, (Up to $\mathcal{O}(10^{-3})$ corrections)

K_L ,	K_S
CP-odd	CP-even

Final state: since the kaon has $J = 0$, the dimuon state can have either $S = 0, \ell = 0$ or $S = 1, \ell = 1$

corresponding to final states:

$(\bar{\mu}\mu)_{\ell=0}$,	$(\bar{\mu}\mu)_{\ell=1}$
CP-odd	CP-even

In practice, we measure the incoherent sums,

$$\Gamma(K_S \to \mu^+\mu^-)_{meas.} = \Gamma(K_S \to (\mu^+\mu^-)_{\ell=0}) + \Gamma(K_S \to (\mu^+\mu^-)_{\ell=1})$$

$$\Gamma(K_L \to \mu^+\mu^-)_{meas.} = \Gamma(K_L \to (\mu^+\mu^-)_{\ell=0}) + \Gamma(K_L \to (\mu^+\mu^-)_{\ell=1})$$

If we could extract the CPV modes, we would have a similar situation (theoretically) to $K_L \to \pi^0 \nu\bar{\nu}$

Time dependent rate - naive parameter counting

$$\left(\frac{d\Gamma}{dt}\right) = N_f\, f(t)\,, \qquad f(t) = C_L\, e^{-\Gamma_L t} + C_S\, e^{-\Gamma_S t} + 2\, C_{Int.} \cos(\Delta m t - \varphi_0) e^{-\Gamma t}\,,$$

4 Experimental parameters

$\{C_L, C_S, C_{Int.}, \varphi_0\}$

Experimental

Theory parameters: 4 amplitudes and 2 phases

CPV $|A(K_S \to (\mu^+\mu^-)_{\ell=0})|$

$|A(K_S \to (\mu^+\mu^-)_{\ell=1})|$

$|A(K_L \to (\mu^+\mu^-)_{\ell=0})|$

CPV $|A(K_L \to (\mu^+\mu^-)_{\ell=1})|$

$$\varphi_0 \equiv \arg(A(K_S)_0^* A(K_L)_0)$$
$$\varphi_1 \equiv \arg(A(K_S)_1^* A(K_L)_1)$$

Theoretical

A priori, 6 theory parameters

Time dependent rate - naive parameter counting

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CPV $|A(K_S \to (\mu^+\mu^-)_{\ell=0})|$

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$|A(K_L \to (\mu^+\mu^-)_{\ell=0})|$

~~CPV $|A(K_L \to (\mu^+\mu^-)_{\ell=1})|$~~

$\varphi_0 \equiv \arg(A(K_S)_0^* A(K_L)_0)$

~~$\varphi_1 \equiv \arg(A(K_S)_1^* A(K_L)_1)$~~

Theoretical

Under our approximations two are negligible

A priori, ~~6~~ theory parameters

4, 1 of which is CP odd

Entire system can be solved.

4 Experimental parameters

4 theory parameters

$$\{C_L, C_S, C_{Int.}, \varphi_0\} \longleftrightarrow \{\,|A(K_S)_0|, |A(K_L)_0|, |A(K_S)_1|, \arg(A(K_S)_0^* A(K_L)_0)\}$$

$$\begin{aligned} C_L &= |A(K_L)_0|^2 \\ C_S &= |A(K_S)_0|^2 + \beta_\mu^2 |A(K_S)_1|^2 \\ C_{Int.} &= D\,|A(K_S)_0 A(K_L)_0| \\ \varphi_0 &= \arg\left(A(K_S)_0 A(K_L)_0\right) \end{aligned}$$

$$D = \frac{N_{K^0} - N_{\overline{K}^0}}{N_{K^0} + N_{\overline{K}^0}}$$

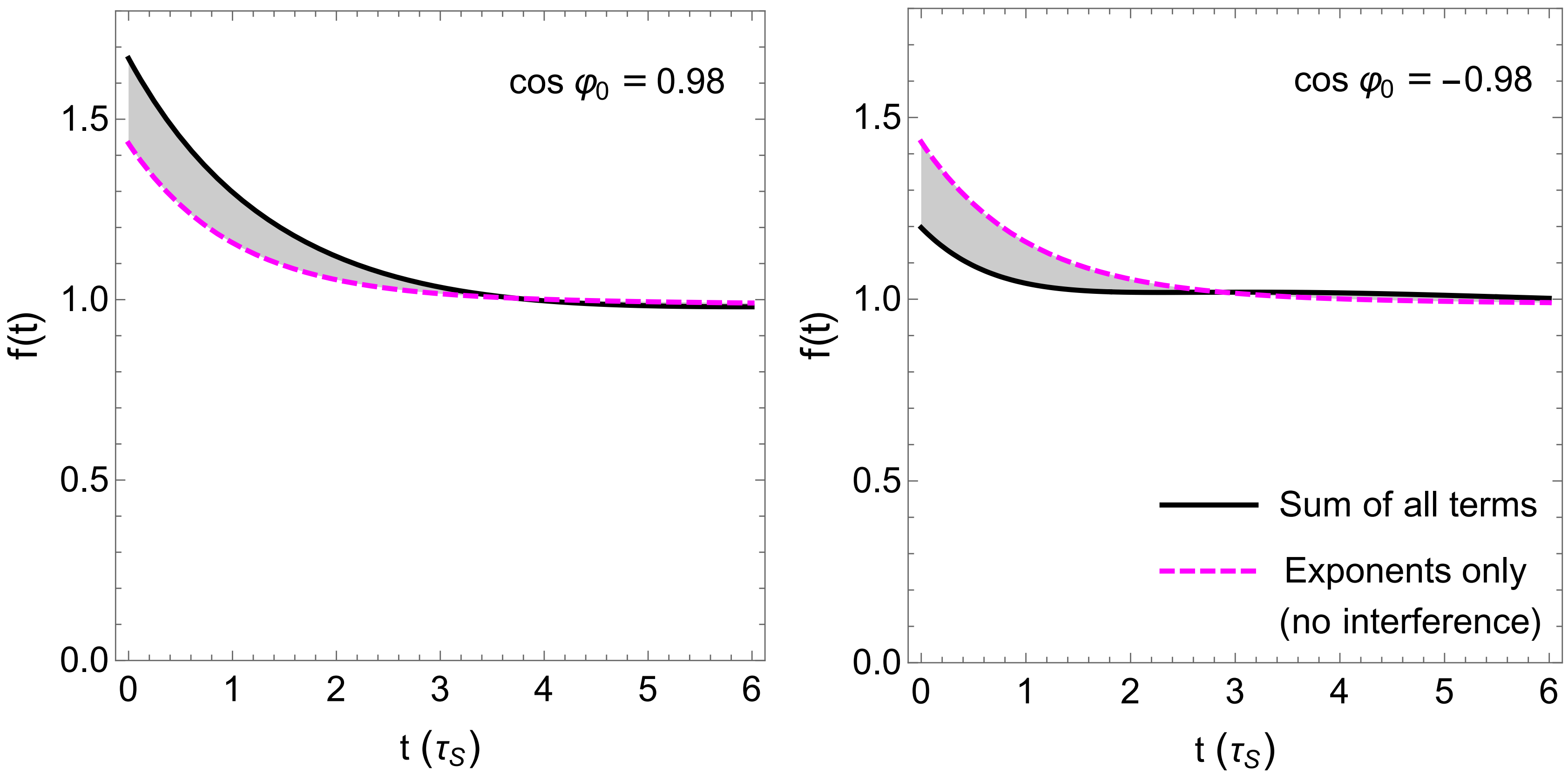
In particular, we can solve for the CPV amplitude $|A(K_S)_0|$

$$\frac{1}{D^2}\frac{C_{Int.}^2}{C_L} = |A(K_S)_0|^2$$

Time dependence - measuring $C_{\text{Int.}}$

$$f(t) = C_L\, e^{-\Gamma_L t} + C_S\, e^{-\Gamma_S t} + 2\, C_{Int.} \cos(\Delta m t - \varphi_0) e^{-\Gamma t},$$

Pure K^0 beam



$$\frac{1}{D^2}\frac{C_{Int.}^2}{C_L} = |A(K_S)_0|^2$$

SM prediction

AD, M. Ghosh, Y. Grossman, S. Schacht [arXiv:2104.06427]
J. Brod and E. Stamou [arXiv:2209.07445]

$$\mathcal{B}(K_S \to \mu^+\mu^-)_{\ell=0} = \frac{\tau_S \beta_\mu}{16\pi m_K} \left| A(K_S)_{\ell=0} \right|^2$$

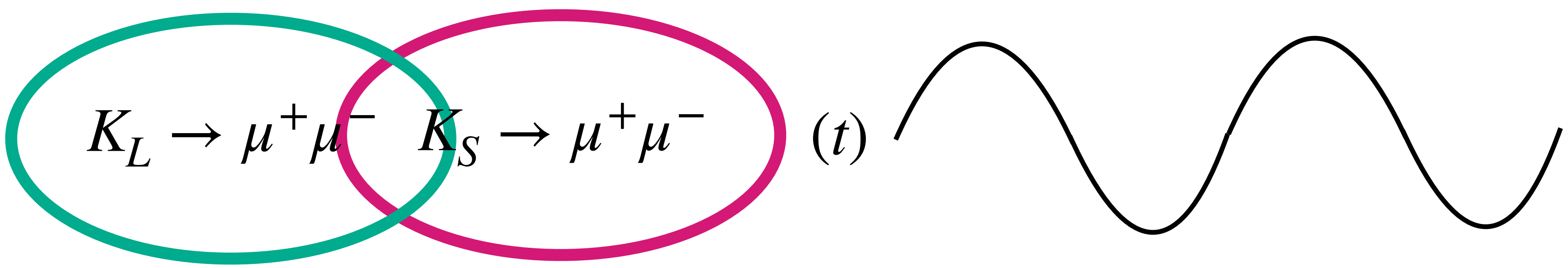
$$\mathcal{B}(K_S \to \mu^+\mu^-)_{\ell=0} = \frac{\tau_S \beta_\mu}{16\pi m_K} \left| \frac{2G_F^2 m_W^2}{\pi^2} m_K m_\mu Y_t \times f_K \times \underbrace{A^2\lambda^5\bar{\eta}} \right|^2$$

Only hadronic parameter, $\mathcal{O}(1\%)$ uncertainty from isospin breaking

Desired CKM dependence

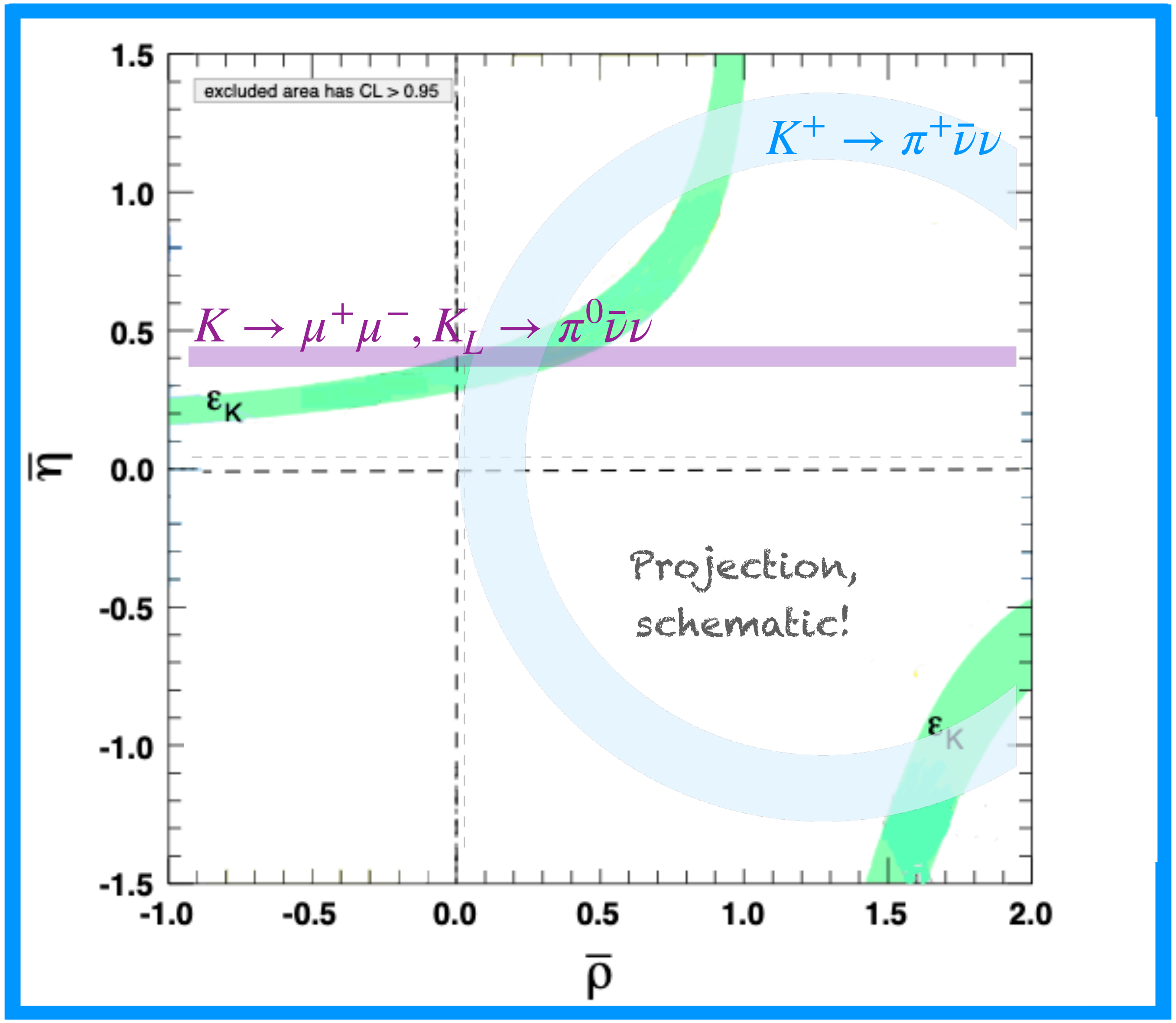
Time dependent rate - $K(t) \to \mu^+\mu^-$

Third golden mode



$K_L - K_S$ interference in a measurement of the **time dependent rate** can be used to extract a clean CPV observable, measuring η from kaon physics with <u>$\lesssim 1\,\%$ theory uncertainty</u>

Third kaon golden mode.



The experimental challenge

Zeroth order requirements:

1. Neutral kaons with non-zero dilution factor, $D = \frac{N_{K^0} - N_{\overline{K}^0}}{N_{K^0} + N_{\overline{K}^0}}$
2. Sensitivity to K_S lifetimes

@ CEPC?

- A yield of $\mathcal{O}(10^{13})$ neutral kaons expected.
- Naively, QCD production => same number of K^0 and $\overline{K}^0$, $D = 0$.

  => would need to explore creating an artificial non-zero D via post-selection.
- Time scales?

Summary

✦ Recent progress in kaon physics, in particular
third kaon golden mode: $K(t) \to \mu^+\mu^-$

✦ Requires exploration of feasibility in relevant future experimental facilities.

✦ Theory avenues for future exploration: related decay modes (e.g., $K \to \pi\ell\ell, K \to \pi\pi\ell\ell$),

Thank you for your attention!

Supplemental

A lot of recent attention in the literature

Theory developments: SM aspects -

D'Ambrosio and Kitahara [1707.06999]
AD, Ghosh, Grossman and Schacht [2104.06427]
Buras and Venturini [2109.11032]
Brod and Stamou [2209.07445]
AD, Ghosh, Grossman, Kithara and Schacht [2211.03804]

Beyond the SM -

Chobanova et al. [1711.11030]
Endo et al. [1712.04959]
AD and Ghosh [2112.05801]
D'Ambrosio et al. [2206.14748]

Lattice QCD:

Christ, Feng, Jin, Tu and Zhao (2020)
Zhao and Christ (2022)
Christ, Feng, Jin, Tu and Zhao [2208.03834]

Experimental:

LHCb [2001.10354]
LHCb $K \to 4\mu$ (talk at Kaon 2022)

Some remarks

- This CKM combination is almost identical to that appearing in $\mathcal{B}(K_L \to \pi^0 \nu\bar{\nu})$. We have

[A. J. Buras and E. Venturini, [arXiv:2109.11032]]

$$\left[\frac{\mathcal{B}(K_S \to \mu^+\mu^-)_{\ell=0}}{\mathcal{B}(K_L \to \pi^0 \nu\bar{\nu})}\right]^{\mathrm{SM}} = 1.55 \cdot 10^{-2} \left(\frac{\lambda}{0.225}\right)^2 \left(\frac{Y_t}{X_t}\right)^2$$

- The current numeric SM prediction reads

[J. Brod and E. Stamou [arXiv:2209.07445]]

$$\mathcal{B}(K_S \to \mu^+\mu^-)^{\mathrm{SM}}_{\ell=0} = 1.70(02)_{\mathrm{QCD/EW}}(01)_{f_K}(19)_{\mathrm{param.}} \times 10^{-13}$$

where the non-parametric uncertainties are of $\mathcal{O}(1\%)$.

- Including effects of CPV in mixing ($\varepsilon_K \neq 0$) results in an additional (parametric) uncertainty of order 3 % .

[J. Brod and E. Stamou [arXiv:2209.07445]]

Additional SM test - the phase shift φ_0

[**AD**, Ghosh, Grossman, Kitahara, Schacht [arXiv:2211.03804]]

One of the four parameters of $K \to \mu^+\mu^-$,

$$\varphi_0 \equiv \arg(A(K_S)_0^* A(K_L)_0)$$

How can we estimate it?

Additional SM test - the phase shift φ_0

[**AD**, Ghosh, Grossman, Kitahara, Schacht [arXiv:2211.03804]]

One of the four parameters of $K \to \mu^+\mu^-$,

$$\varphi_0 \equiv \arg(A(K_S)_0^* A(K_L)_0)$$

Closely related to the ratio of K_L decay rates, $R_{K_L} \equiv \frac{\mathcal{B}(K_L \to \mu^+\mu^-)}{\mathcal{B}(K_L \to \gamma\gamma)}$

To see this, we write

absorptive (on-shell)

$$\cos^2\varphi_0 = \frac{\mathrm{I}m[A(K_S)^*_{\ell=0}A(K_L)_{\ell=0}]^2}{|A(K_S)_{\ell=0}|^2|A(K_L)_{\ell=0}|^2} = \frac{\mathrm{I}m[A(K_L)_{\ell=0}]^2}{|A(K_L)_{\ell=0}|^2}$$

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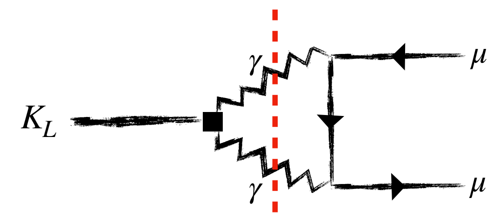


$$\cos^2\varphi_0 = \frac{Im[A(K_L)_{\ell=0}]^2}{|A(K_L)_{\ell=0}|^2} = \frac{[\text{diagram}]}{\mathcal{B}(K_L \to \mu^+\mu^-)} = \frac{C_{\text{QED}}}{R_{K_L}}$$

Model independent prediction -

$$\cos^2\varphi_0 = 0.96 \pm 0.02_{\text{exp.}} \pm 0.02_{\text{th.}}$$

$\mathscr{B}(K_S \to \mu^+\mu^-)_{\ell=0}$ beyond the SM

[**AD**, M. Ghosh [arXiv:2112.05801]]

Current upper bound leaves much room for possible NP,

[LHCb [arXiv:2001.10354]]

$$\mathscr{B}(K_S \to \mu^+\mu^-) = \mathscr{B}(K_S \to \mu^+\mu^-)_{\ell=0} + \mathscr{B}(K_S \to \mu^+\mu^-)_{\ell=1} \leq 2.1 \cdot 10^{-10}$$

$$\mathscr{B}(K_S \to \mu^+\mu^-)_{\ell=0} \leq 2.1 \cdot 10^{-10}$$

$$\to \quad \frac{\mathscr{B}(K_S \to \mu^+\mu^-)_{\ell=0}}{\mathscr{B}(K_S \to \mu^+\mu^-)^{\rm SM}_{\ell=0}} \lesssim 10^3$$

Model independent effective operator analysis

[**AD**, M. Ghosh [arXiv:2112.05801]]

$$\mathcal{H}^{|\Delta S|=1}_{eff.} = \sum_i C_i O_i,$$

Vectorial	$O_{VLL} = (\overline{Q}_L\gamma^\mu Q_L)(\overline{L}_L\gamma_\mu L_L)$;	$O_{VLR} = (\overline{Q}_L\gamma^\mu Q_L)(\overline{e}_R\gamma_\mu e_R)$,
	$O_{VRL} = (\overline{d}_R\gamma^\mu d_R)(\overline{L}_L\gamma_\mu L_L)$;	$O_{VRR} = (\overline{d}_R\gamma^\mu d_R)(\overline{e}_R\gamma_\mu e_R)$,
Scalar	$O_{SLR} = (\overline{Q}_L d_R)(\overline{e}_R L_L)$,	$O_{SRL} = (\overline{d}_R Q_L)(\overline{L}_L e_R)$

$$R(K_S \to \mu^+\mu^-)_{\ell=0} = \left(1 + \frac{1}{|C^{\rm SM}_{VLL}|\sin\theta_{ct}}\left[A_S\left(|C^{\rm NP}_{SLR}|\sin\Theta_{SLR} + |C^{\rm NP}_{SRL}|\sin\Theta_{SRL}\right)\right.\right.$$
$$\left.\left. + |C^{\rm NP}_{VLL}|\sin\Theta_{VLL} - |C^{\rm NP}_{VRL}|\sin\Theta_{VRL} - |C^{\rm NP}_{VLR}|\sin\Theta_{VLR} + |C^{\rm NP}_{VRR}|\sin\Theta_{VRR}\right]\right)^2$$

$$R(K_L \to \pi^0\bar{\nu}\nu) = \frac{1}{3}\sum_{i=e,\mu,\tau}\left(1 + \frac{|(C^{\rm NP}_{VLL})_i|\sin\Theta_{VLL,i} + |(C^{\rm NP}_{VRL})_i|\sin\Theta_{VRL,i}}{|C^{\rm SM}_{VLL}|\sin\theta_{ct}}\right)^2$$

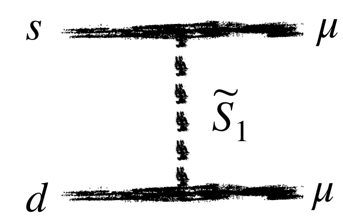
Additionally sensitive to RH currents and scalar operators

Example NP toy models

[**AD**, M. Ghosh [arXiv:2112.05801]]

A. Scalar Leptoquark $\tilde{S}_1 \sim (\bar{3},1)_{4/3}$

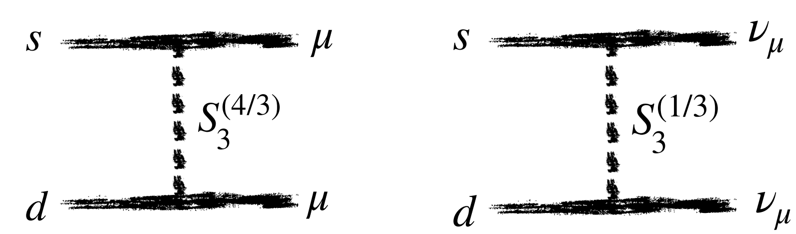
Generates the effective operator $\mathcal{O}_{VRR}$



Can saturate the current bound while satisfying all existing constraints, $R(K_S \to \mu^+\mu^-)_{\ell=0} \sim 10^3$

B. Scalar Leptoquark $S_3 \sim (\bar{3},3)_{1/3}$

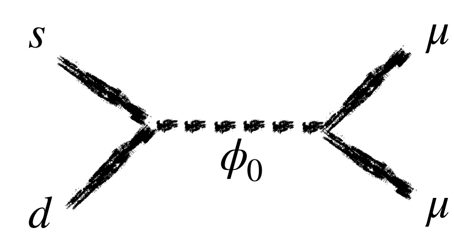
Generates the effective operator $\mathcal{O}_{VLL}$



Bounded by the GN bound on $R(K_L \to \pi^0 \bar{\nu}\nu)$, $R(K_S \to \mu^+\mu^-)_{\ell=0} \lesssim 26$

C. 2HDM $\Phi \sim (1,2)_{1/2} = \begin{pmatrix} \phi^+ \\ \phi_0 \end{pmatrix}$

Generates the effective operators $\mathcal{O}_{SLR}, \mathcal{O}_{SRL}$



Can saturate the current bound while satisfying all existing constraints, $R(K_S \to \mu^+\mu^-)_{\ell=0} \sim 10^3$

Relevant New Physics scales

[**AD**, M. Ghosh [arXiv:2112.05801]]

Assuming SM sensitivity -

Vectorial operators: $\Lambda_{\rm NP} \sim 300\,\text{TeV}$

Scalar operators: $\Lambda_{\rm NP} \sim 1000\,\text{TeV}$

[Direct searches, EW precision tests: $\Lambda_{\rm NP} \sim 10\,\text{TeV}$]

The experimental challenge

Zeroth order requirements:

1. Neutral kaons with non-zero dilution factor, $D = \frac{N_{K^0} - N_{\overline{K}^0}}{N_{K^0} + N_{\overline{K}^0}}$
2. Sensitivity to K_S lifetimes

Current experiments:

LHCb -

1. Roughly the same number of $K^0, \overline{K}^0$ particles, $D = 0$.

   Can induce an artificial non-zero D by tagging (post-selection).
2. YES

Bkgs such as $K_S \to \pi\pi$ may be difficult to control

KOTO -

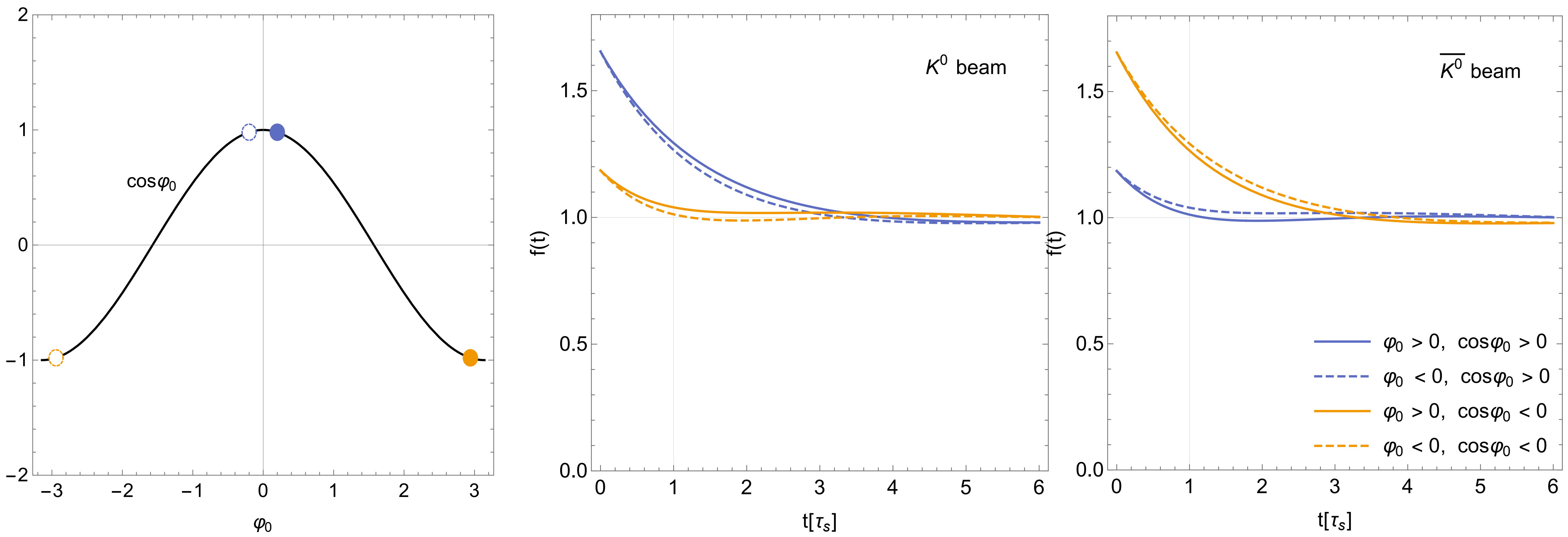
1. YES
2. Basically a K_L beam (detectors far from target)

   Can in principle use matter regeneration to induce a K_S component.

NA62 - Charged beam

Additional SM test - the phase shift φ_0

[**AD**, Ghosh, Grossman, Kitahara, Schacht [arXiv:2211.03804]]



Model independent prediction -

$$\cos^2\varphi_0 = 0.96 \pm 0.02_{\text{exp.}} \pm 0.02_{\text{th.}}$$

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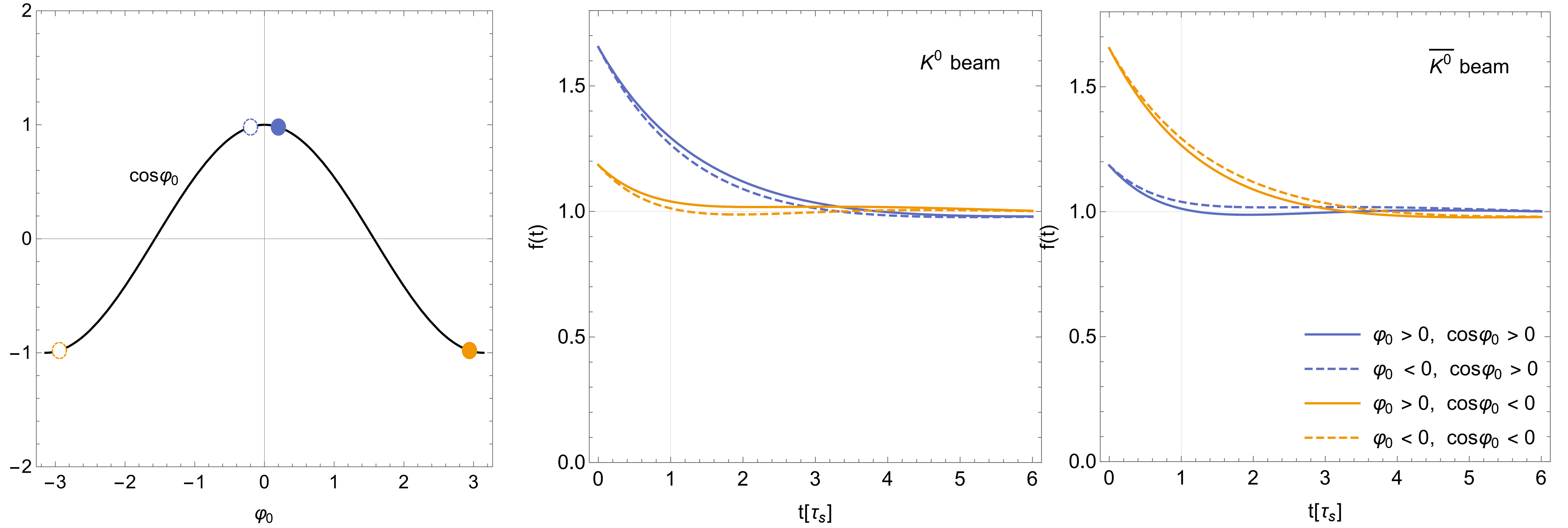

Model independent prediction -

$$\cos^2\varphi_0 = 0.96 \pm 0.02_{\text{exp.}} \pm 0.02_{\text{th.}} \xrightarrow{\text{ChPT, large}\, N_C} \cos\varphi_0 < 0$$