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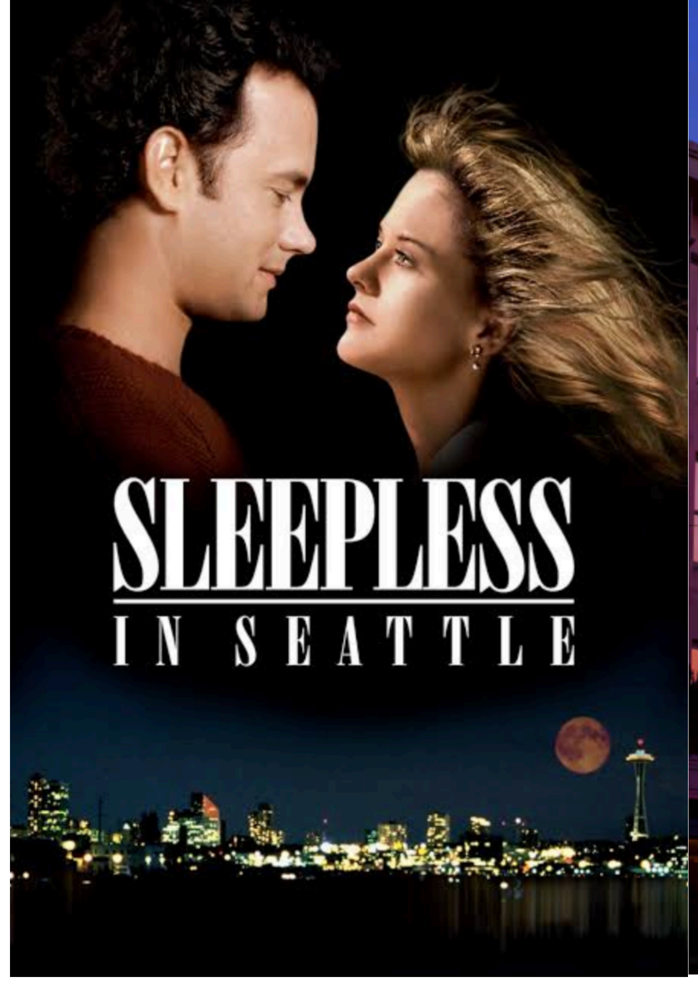


INT, Seattle, 15th January 2026

Impact for Rare Kaon decays of Testing the Standard Model in Charged-Weak Decays

Predictions for the rare kaon decays
from QCD in the limit of a large number of colour
With M. Knecht and S.Neshatpour

e-Print: 2409.08568 [hep-ph] MDPI

THANKS to Collaborations Nazila Iyer Neshatpour
- 2311.04878 2404.03643

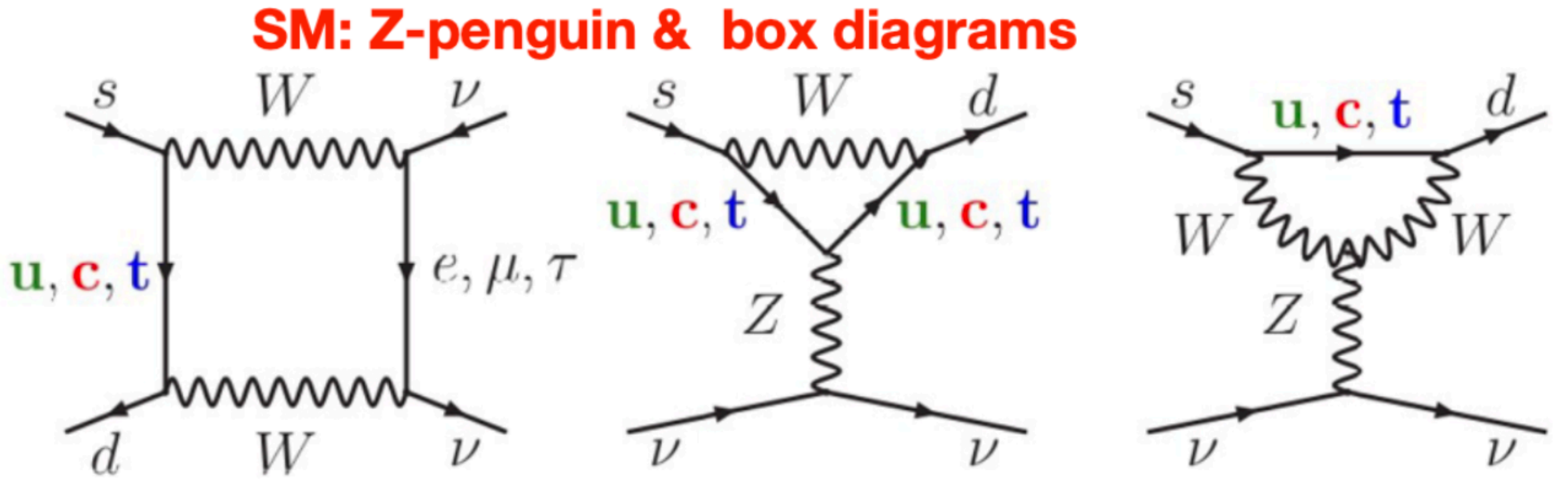
THANKS to NA48 HIKE LHCB KOTO
T. Kitahara

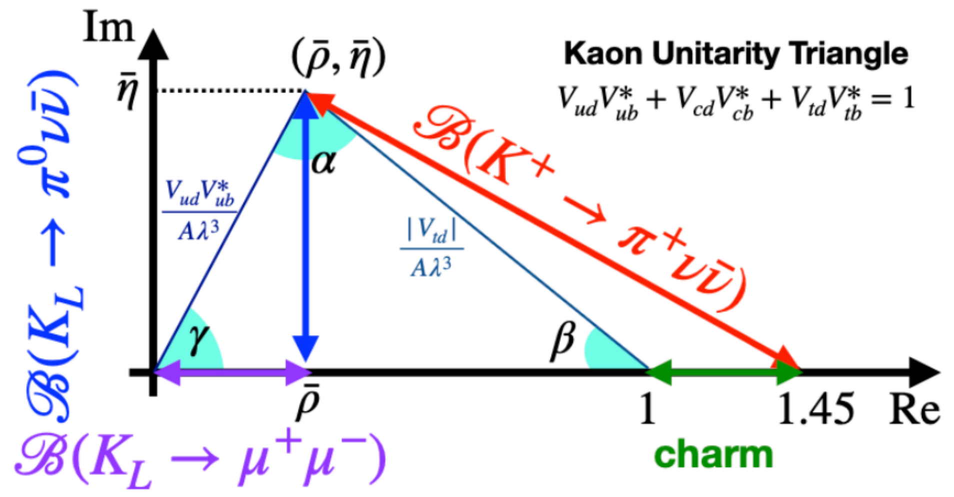
CP violation in $K \to \mu^+\mu^-$ with and without time dependence through a tagged analysis
Giancarlo D'Ambrosio (INFN, Naples), Avital Dery (CERN), Yuval Grossman (Cornell U., LEPP), Teppei Kitahara (Chiba U. and KMI, Nagoya and Nagoya U.), Radoslav Marchevski (EPFL, Lausanne, LPPC) et al. (Jul 17, 2025)
e-Print: 2507.13445 [hep-ph]

Giancarlo D'Ambrosio
INFN Sezione di Napoli

Outline

- Discussion of the Golden modes $K \to \pi \nu \bar{\nu}$





A lot of recent activity

Theory

- D'Ambrosio Kitahara, 1707.06999
- Dery Ghosh Grossman Schacht, 2104.06427
- Buras Venturini, 2109.11032
- Dery Ghosh, 2112.05801
- D'Ambrosio Iyer Mahmoudi Neshatpour 2206.14748
- Brod Stamou, 2209.07445
- Dery Ghosh Grossman Kitahara Schacht, 2211.03804
- D'Ambrosio Dery Grossman Kitahara Marchevski Martinez Santos Schacht, 2507.13445

Experiment

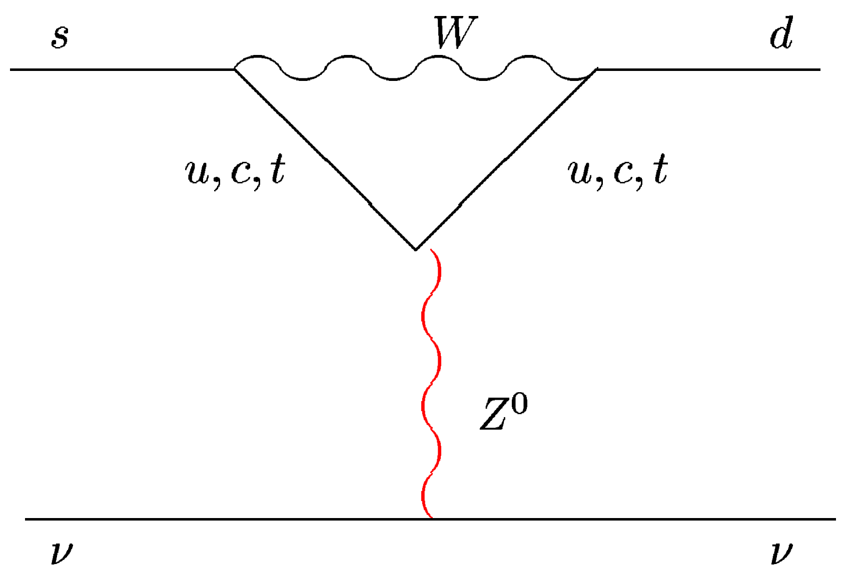
- NA62, 2412.12015, 5σ observation of $K^+ \to \pi^+ \nu \bar{\nu}$: $\mathcal{B} = (13.0^{+3.3}_{-3.0}) \cdot 10^{-11}$.
- KOTO, 2012.07571: Improved upper limit on $K_L \to \pi^0 \nu \bar{\nu}$.
- Proposal for KOTO II: 2501.14827.
- LHCb, 2001.10354: Upper limit on $K_S \to \mu^+ \mu^-$.
- LHCb, 2212.04977: Upper limits on $K_{S,L} \to 2(\mu^+ \mu^-)$.

- Role of LHCB: $K_{S,L} \to \mu \mu$

$K \to \pi \nu \overline{\nu}$

NEED KOTO/KOTO II NA62 AND LHCB

$$A(s \to d\nu\overline{\nu})_{\mathrm{SM}} \sim \overline{s}_L \gamma_\mu d_L \quad \overline{\nu}_L \gamma^\mu \nu_L \times \left[\sum_{q=c,t} V_{qs}^* V_{qd}\, m_q^2\right]$$



$$\sim \qquad \left[A^2\lambda^5\ (1-\rho-i\eta)m_t^2 + \lambda m_c^2\right]$$

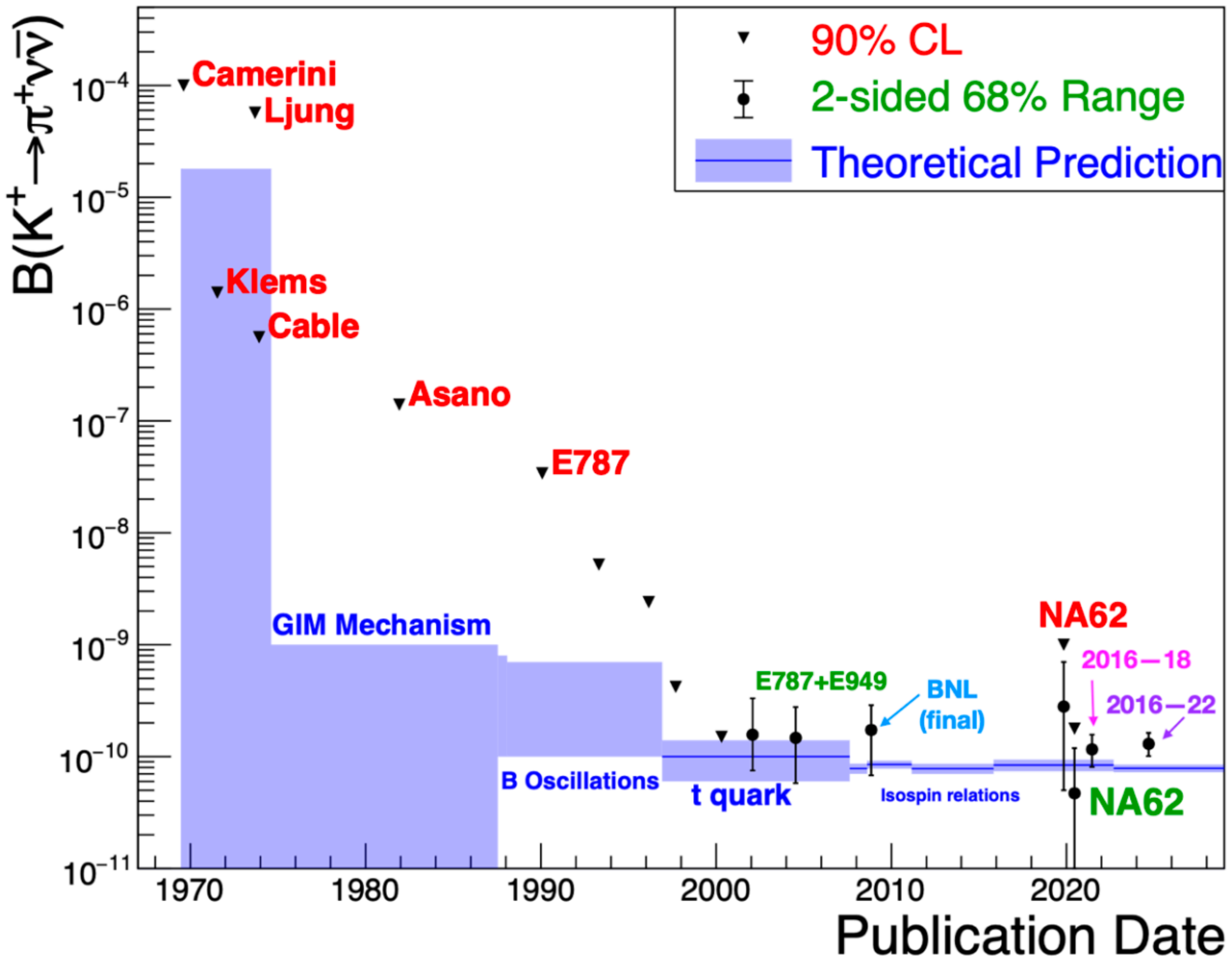
SM $\quad \underbrace{V - A \otimes V - A}$ $\Downarrow$ Littenberg

$$\Gamma(K_L \to \pi^0 \nu\overline{\nu}) \quad \begin{cases} \text{CP violating} \\ \Rightarrow\ J = A^2\lambda^6\eta \\ \text{Only } top \end{cases}$$

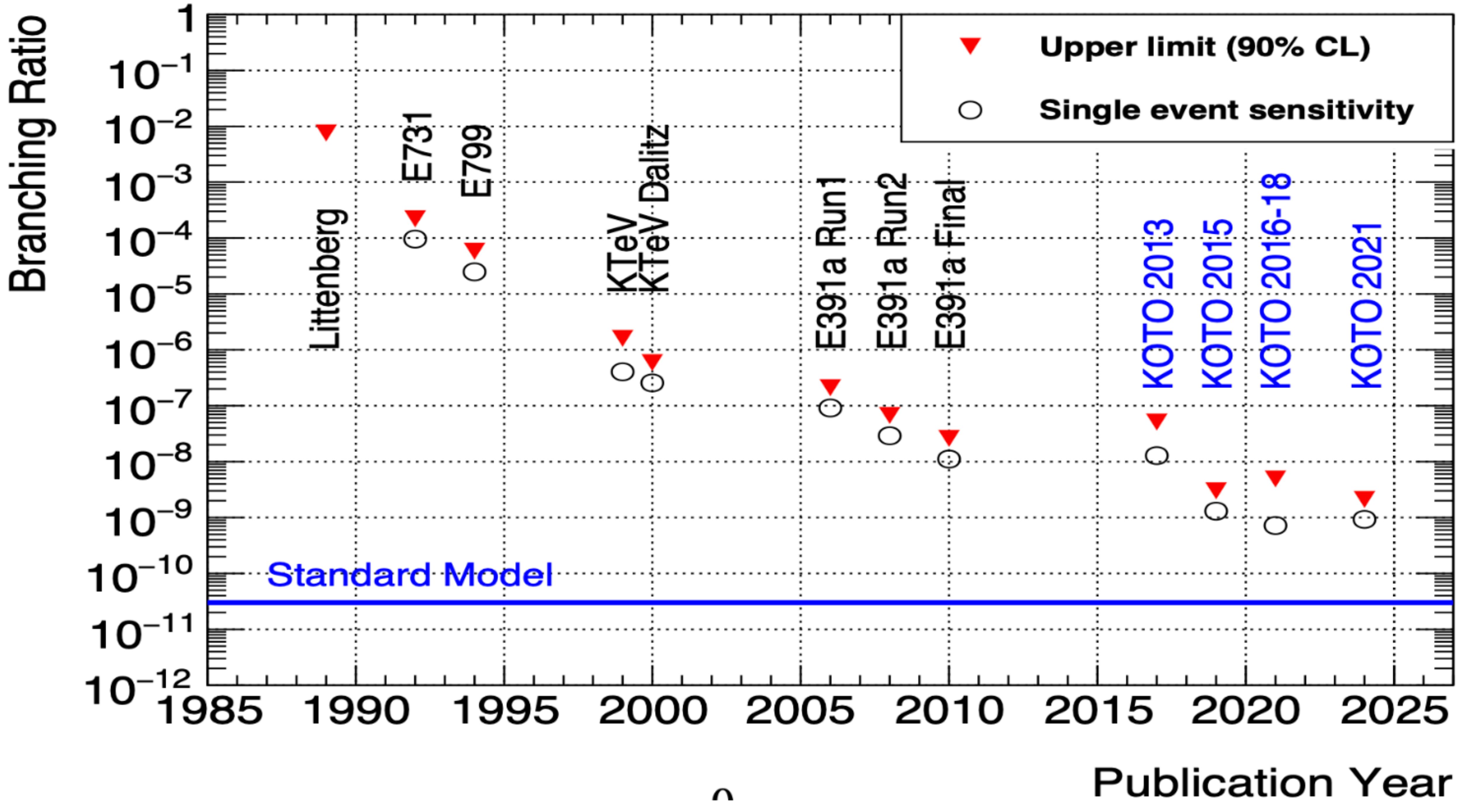
SM

Buchalla and Buras, hep-ph/9308272, Buras et al, 1503.02693.

$K \rightarrow \pi\nu\bar{\nu}$ (PNN): A Long Game...



Joel Swallow @KAON25

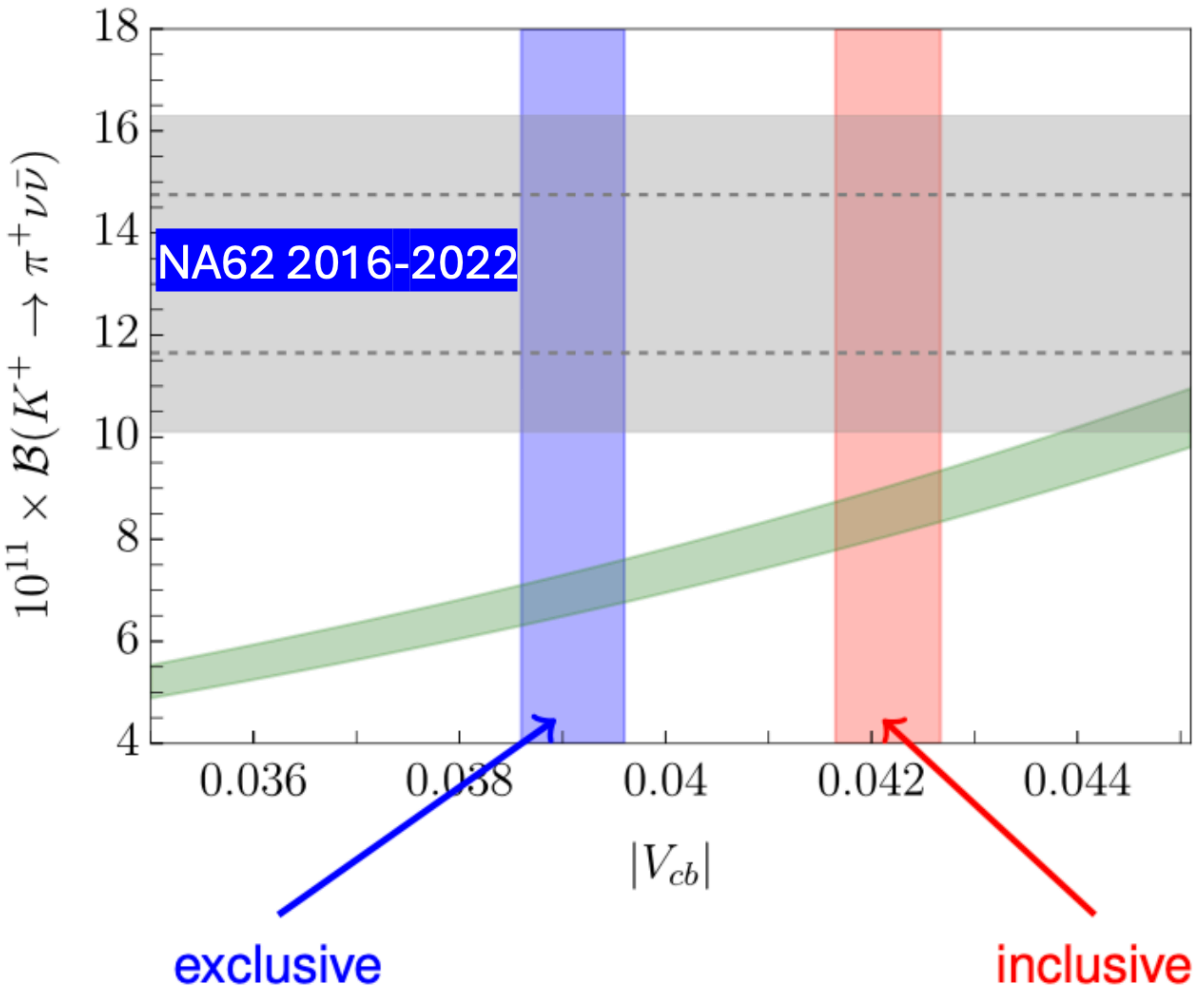


Keita Ono @KAON25

$$\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu}) \propto |\lambda_{ts}|^2 \quad \lambda_{ts} \equiv \lambda |V_{cb}|^2 \left[(\bar{\rho} - 1) \left(1 - \frac{\lambda^2}{2}\right) + i\bar{\eta} \left(1 + \frac{\lambda^2}{2}\right) \right] + \mathcal{O}(\lambda^4)$$

Marzia Bordone@KAON2025

...beginning to provide quantitative tests



NA62 Projection, Karim Massri @KAON2025

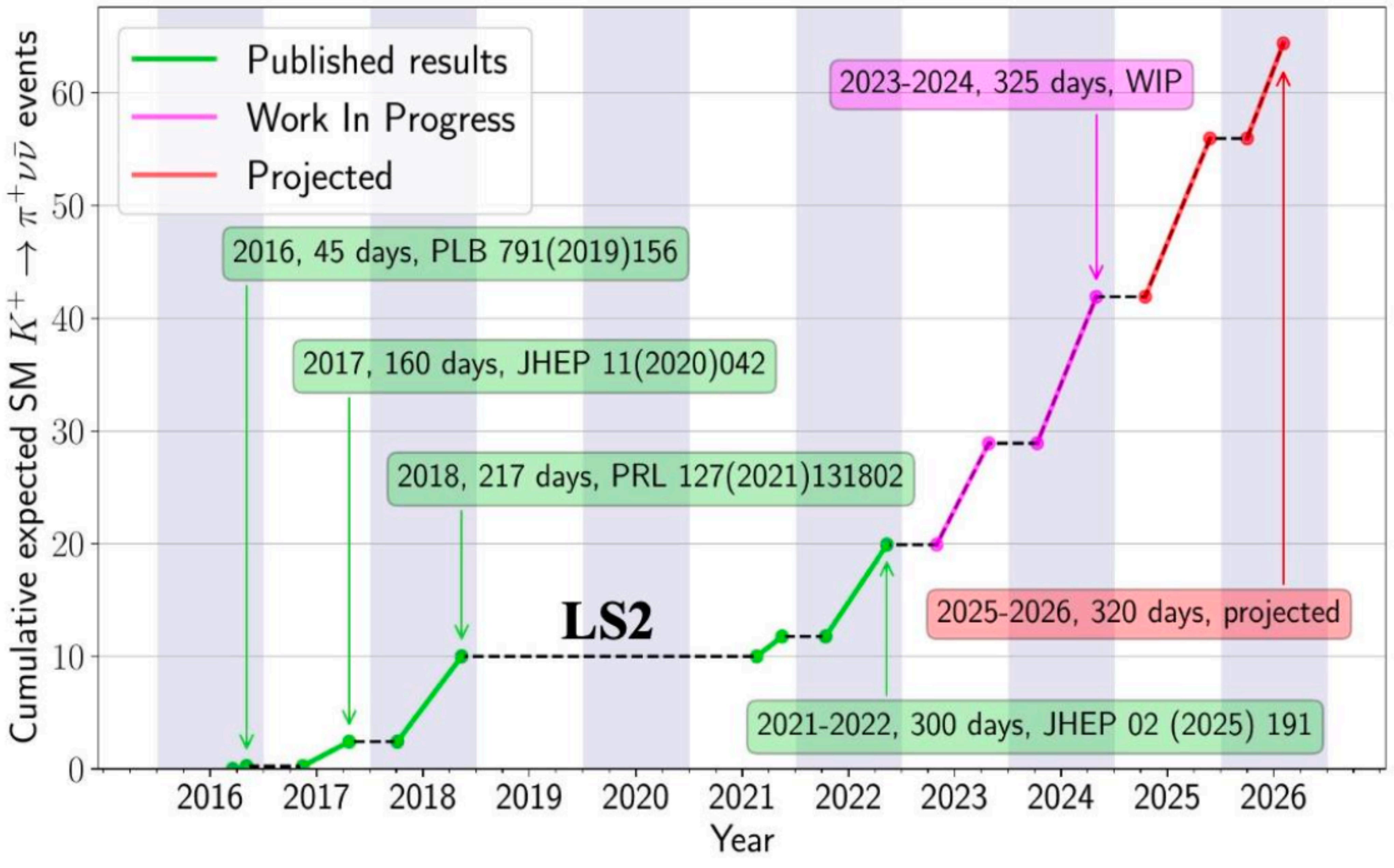
$K^+ \to \pi^+ \nu\bar{\nu}$: Final dataset projection

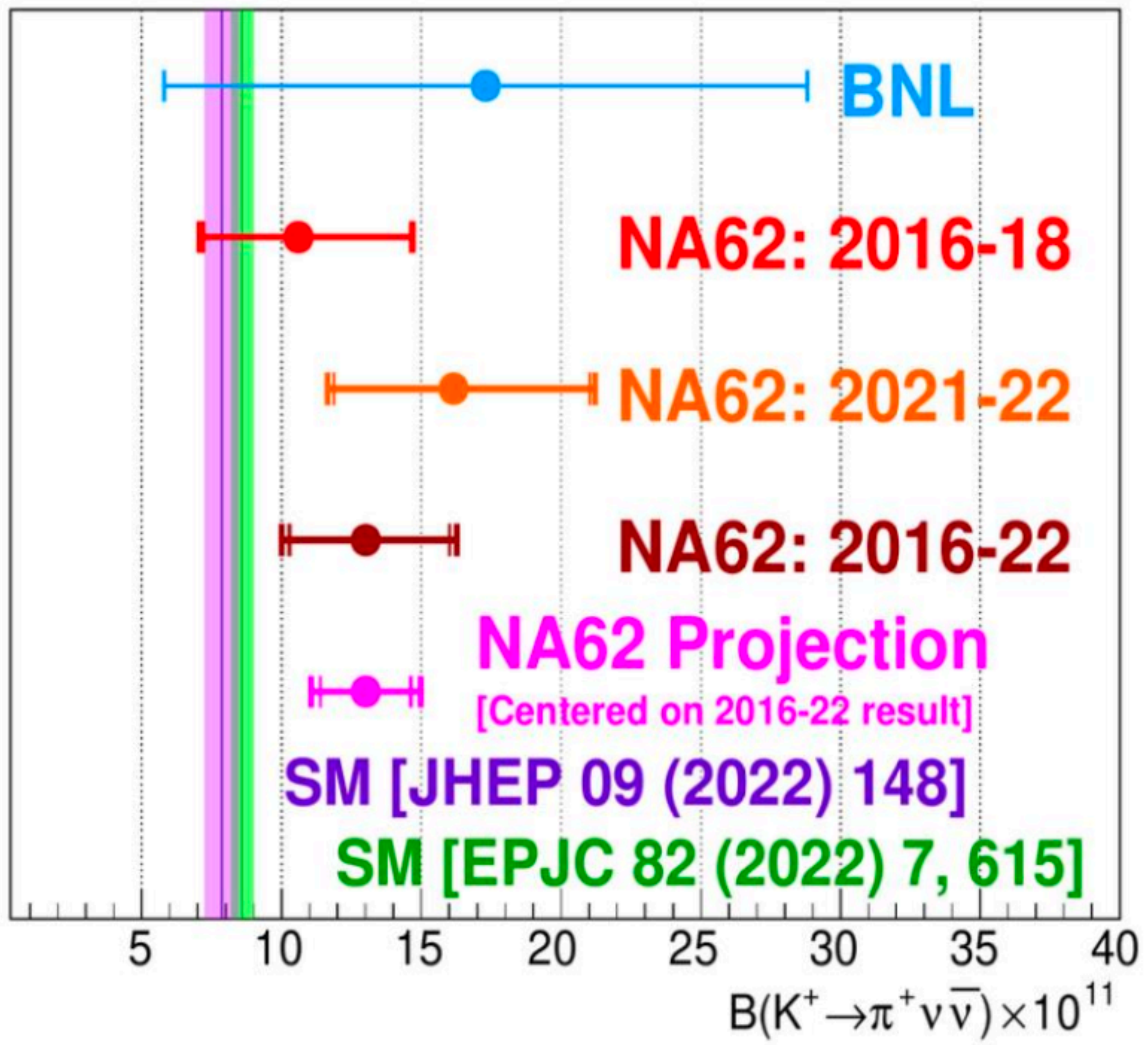
NA62

Latest $K^+ \to \pi^+ \nu\bar{\nu}$ result (2016-2022 data) discussed in detail **M. Zamkovsky**

Final dataset (2016-2026) projection

- Projected to be ~ 3x the 2016-2022 statistics (> 60 SM $K^+ \to \pi^+ \nu\bar{\nu}$)
- Assume same $N_{\pi\nu\nu}$ /day as 2024, assume same B/S as 2021-2022



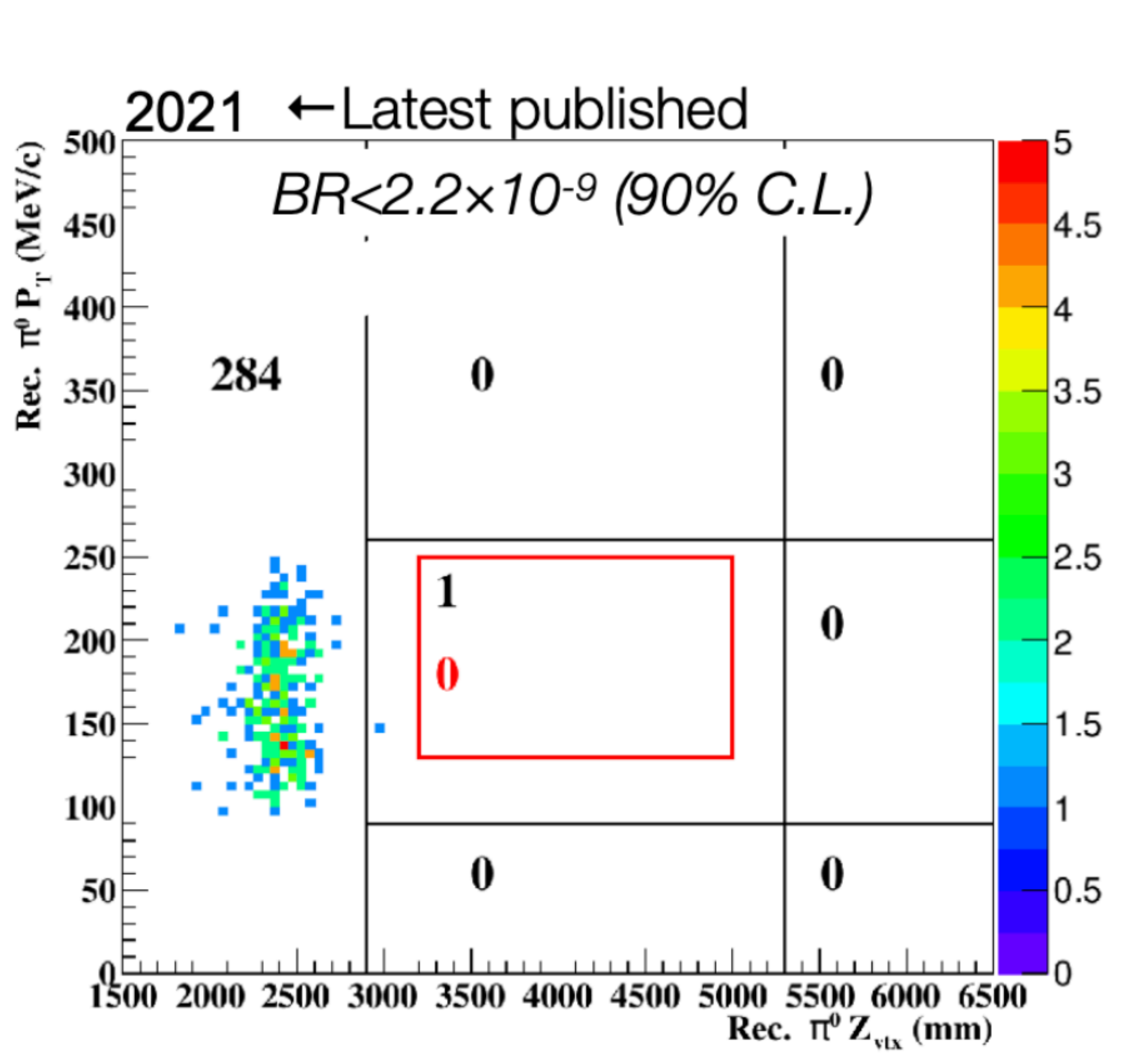


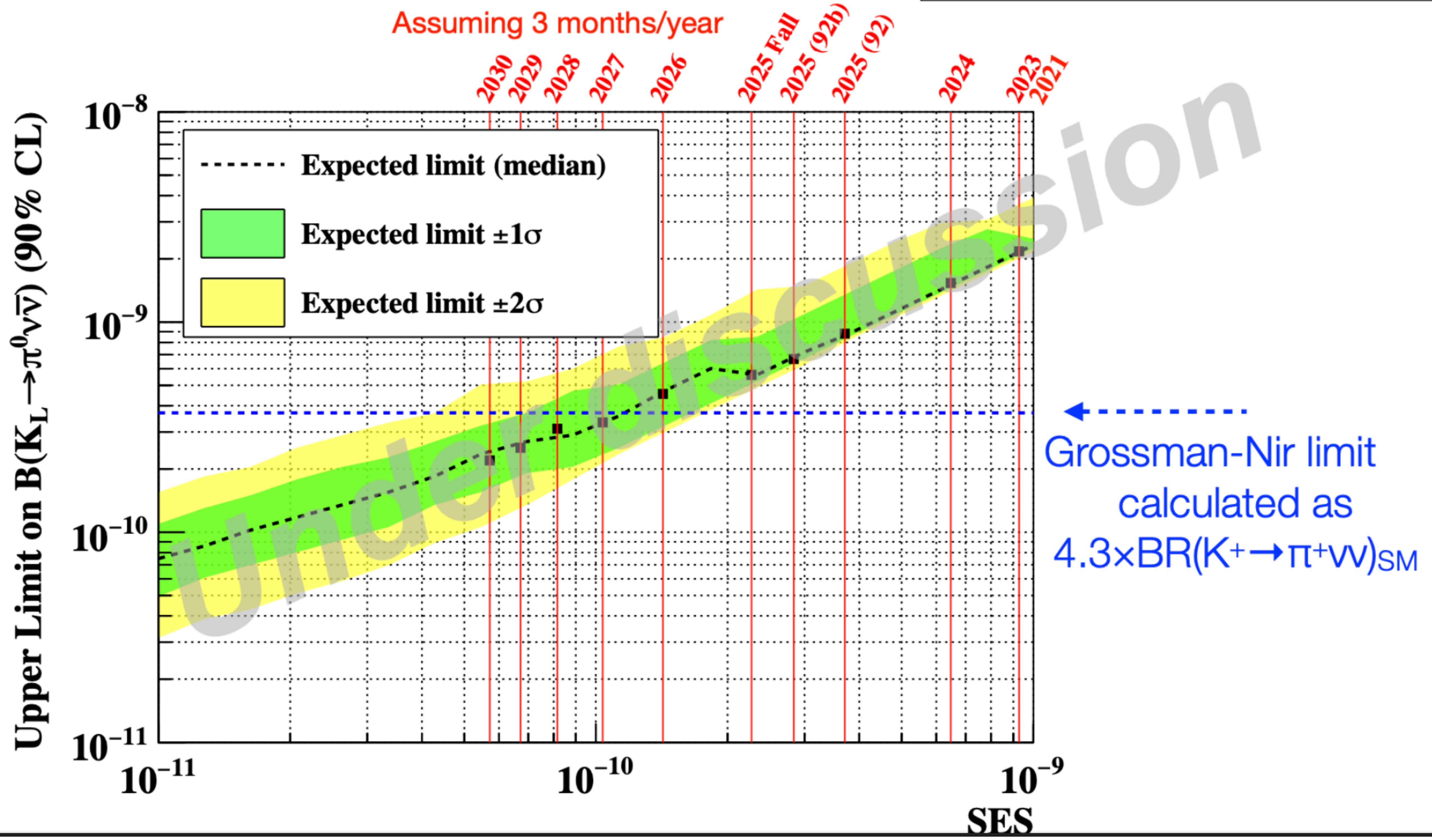
Expect BR($K^+ \to \pi^+ \nu\bar{\nu}$) uncertainty < 20% (stats + analysis improvements)

KOTO Projection, Tadashi Nomura @KAON2025

Limit vs SES considering BGL

[Example]
Discussion based on modified-frequentist method (CL_s method)





Kaon UT: testing the SM across flavor sectors

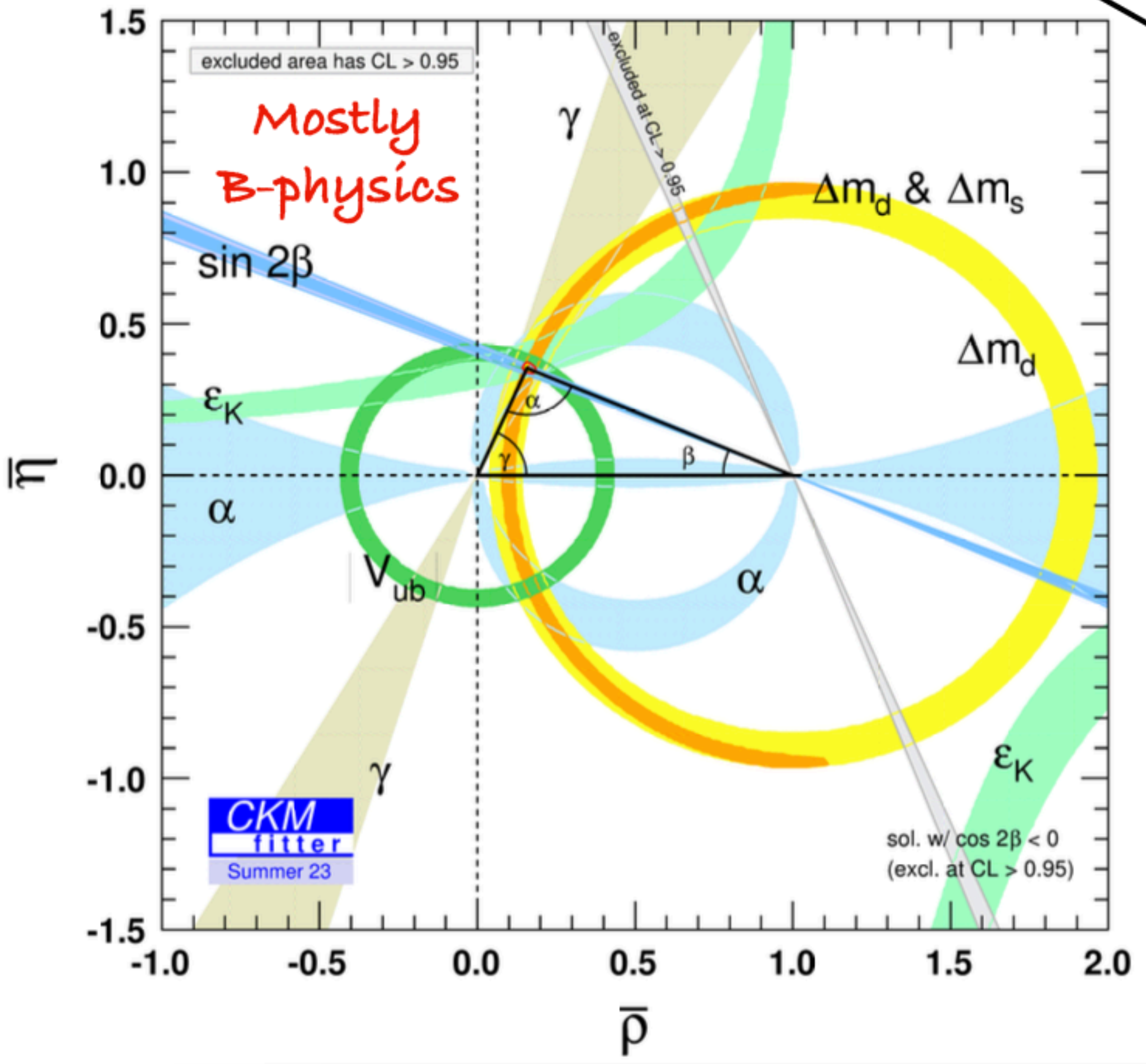
NA62: $\mathcal{B}(K^+ \to \pi^+ \nu \bar{\nu}) = (13.0^{+3.3}_{-3.0}) \times 10^{-11}$

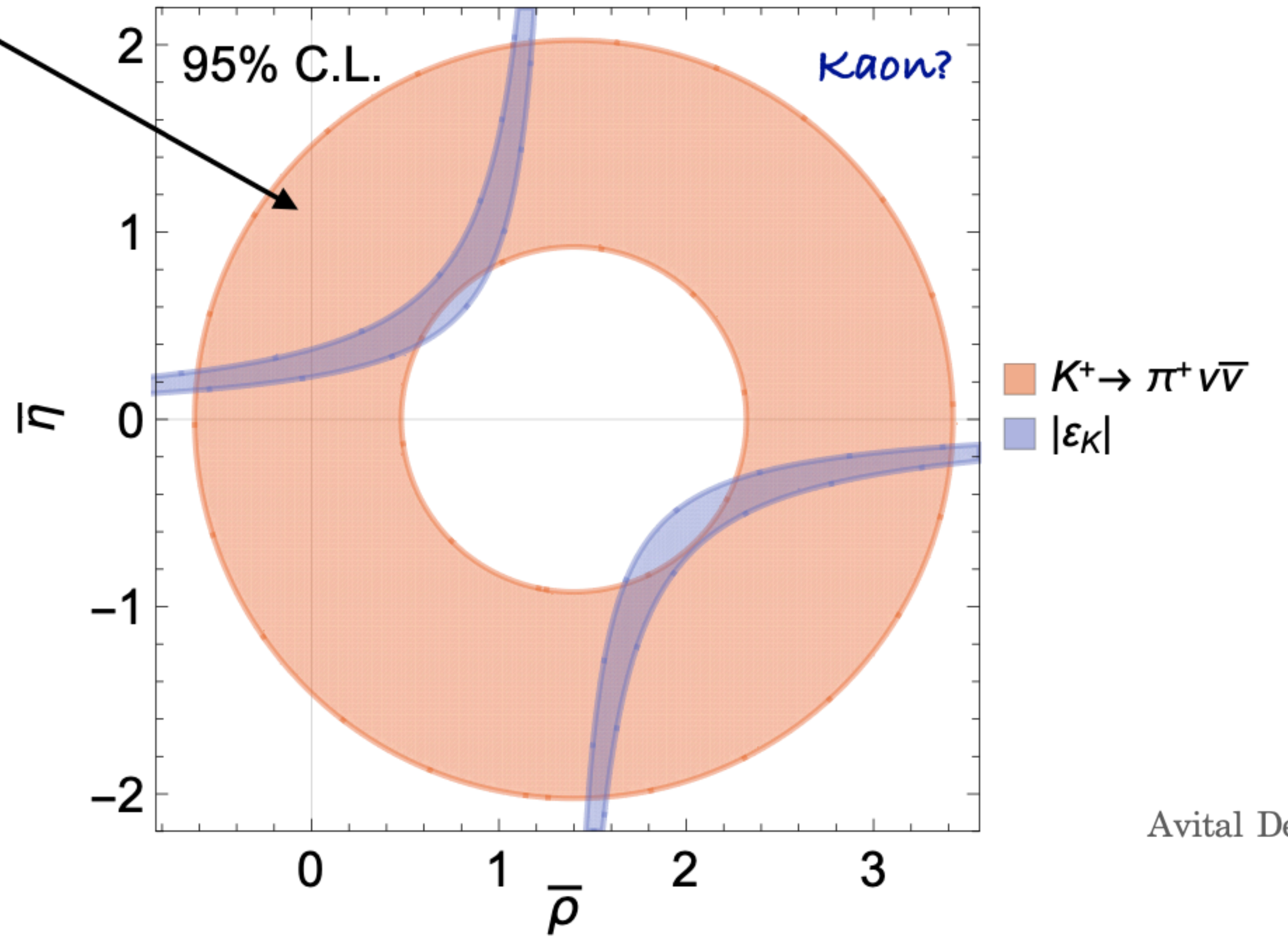
[arXiv:2412.12015]

Does the plot rely purely on kaon information?

NO. B-physics input needed,

e.g. $\varepsilon_K \sim |V_{cb}|^4$

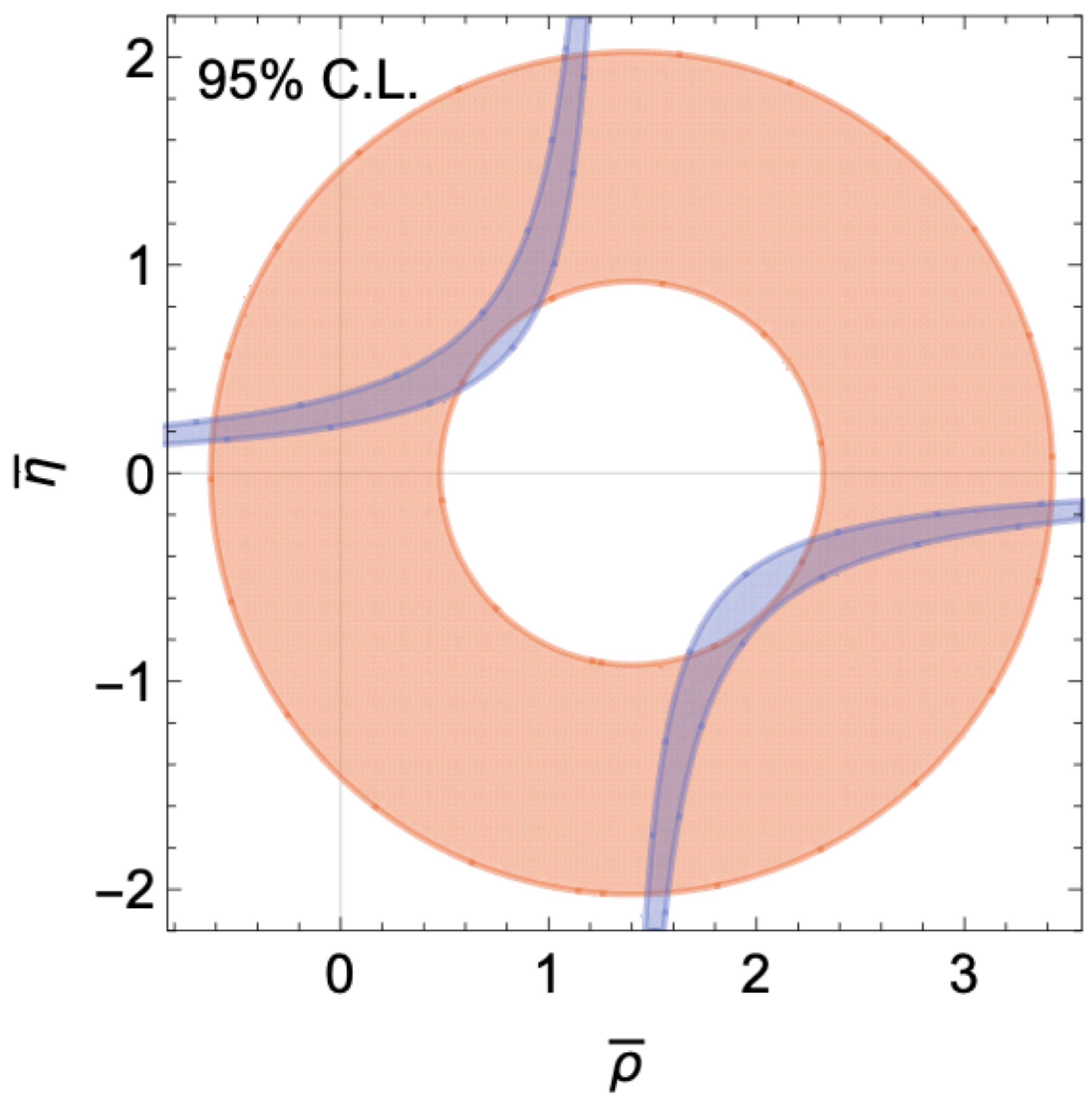




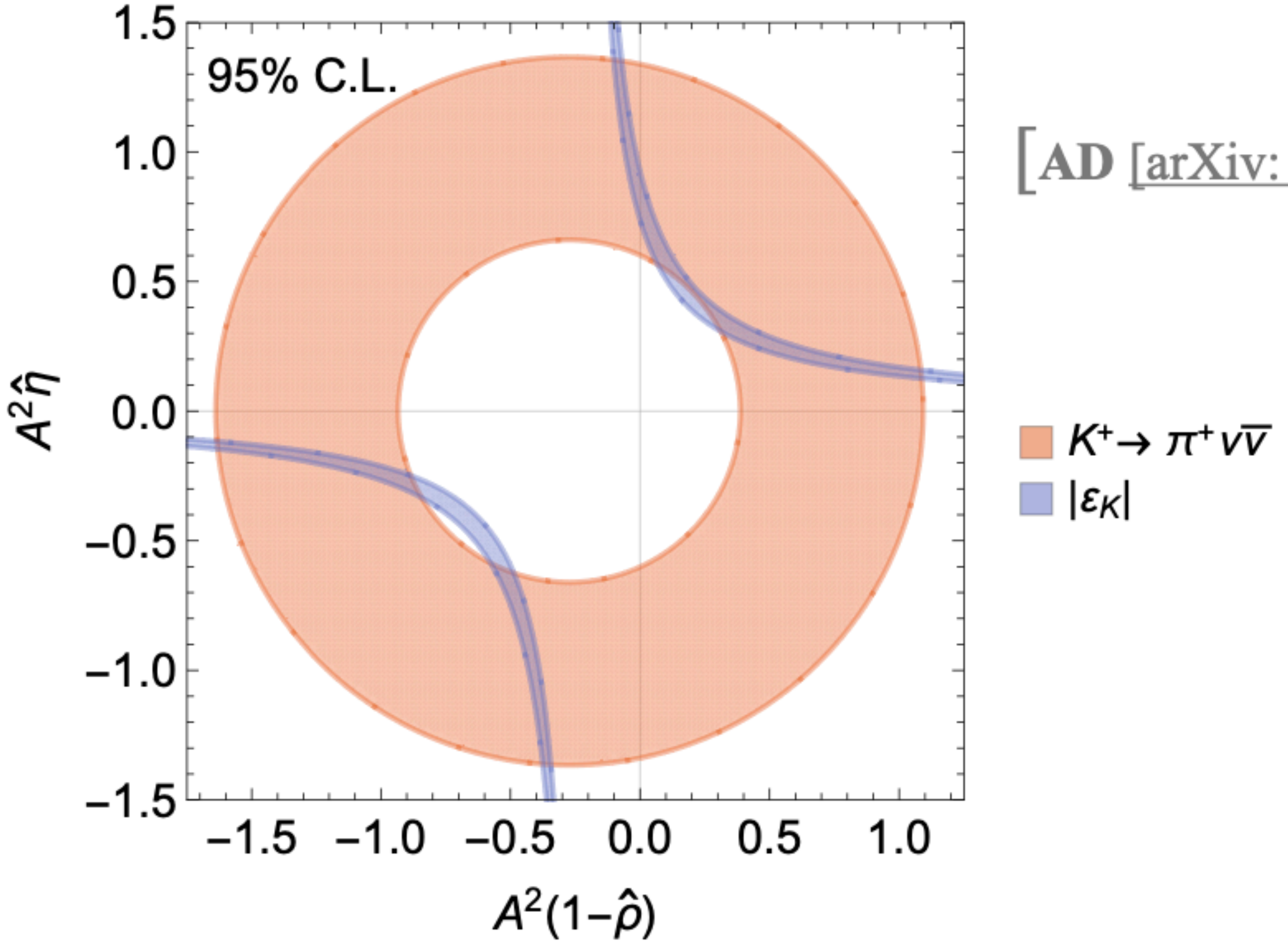
Avital Dery

Shift to the (ds)-triangle picture

Before



After



[AD [arXiv: 2504.12386]]

uncertainty artificially inflated.

dependent on B input ($|V_{cb}|$)

parametric uncertainty shrinks

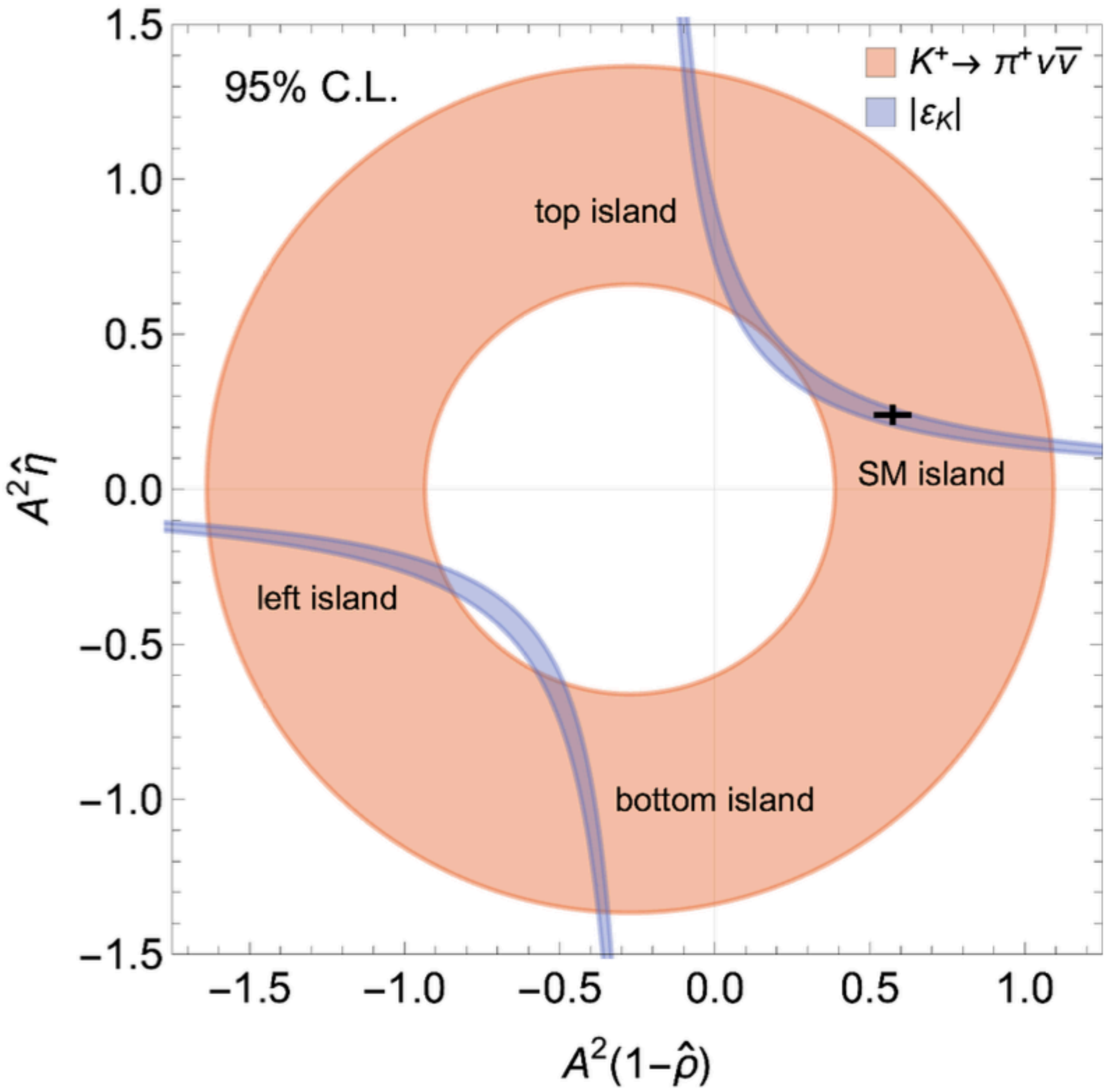
purely kaon-physics determined

The four islands

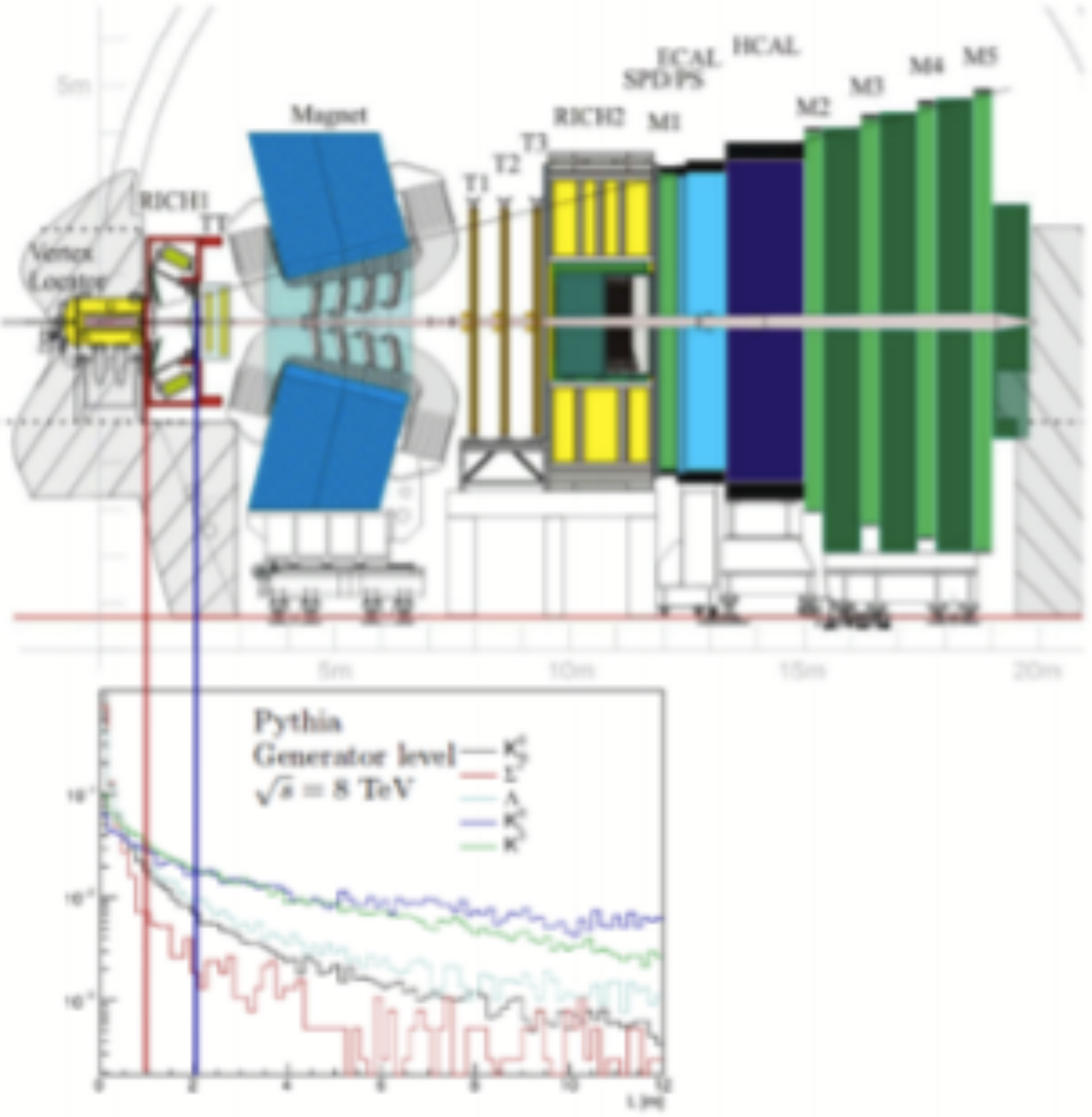
Four (almost) disconnected regions

Approximately symmetric around

$$\approx (-0.3,\ 0)$$



Kaon in LHCb



- LHCb experiment has been designed for efficient reconstructions of ***b*** and ***c***
- Huge production of strangeness [$O(10^{13})/\mathrm{fb}^{-1}$ $K^0{}_S$] is suppressed by its trigger efficiency [ε~1-2%@LHC Run-I, ε~18%@LHC Run-II]
- LHCb upgrade (LS2=Phase I upgrade, LS4=Phase II upgrade) could realize high efficiency for $K^0{}_S$ [ε~90%@LHC Run-III] [M. R. Pernas, HL/HE LHC meeting, Fermilab, 2018]
- In LHC Run-III and HL-LHC, we could probe the *ultra* rare decay $\mathrm{Br}{\sim}O(10^{-11\sim-12})$

Rare Kaon decay program at LHCB

	PDG	Prospects
$K_S \to \mu\mu$	$< 9 \times 10^{-9}$ at 90% CL	$(\mathrm{LD})(5.0 \pm 1.5) \cdot 10^{-12}$ $\quad$ NP $< 10^{-11}$
$K_S \to \mu\mu\mu\mu$	–	SM LD $\sim 2 \times 10^{-14}$
$K_S \to ee\mu\mu$	–	$\sim 10^{-11}$
$K_S \to eeee$	–	$\sim 10^{-10}$
$K_S \to \pi^0\mu\mu$	$(2.9 \pm 1.3) \cdot 10^{-9}$	$\sim 10^{-9}$
$K_S \to \pi^+\pi^-e^+e^-$	$(4.79 \pm 0.15) \cdot 10^{-5}$	SM LD $\sim 10^{-5}$
$K_S \to \pi^+\pi^-\mu^+\mu^-$	–	SM LD $\sim 10^{-14}$

Prospects for Measurements with Strange Hadrons at LHCb

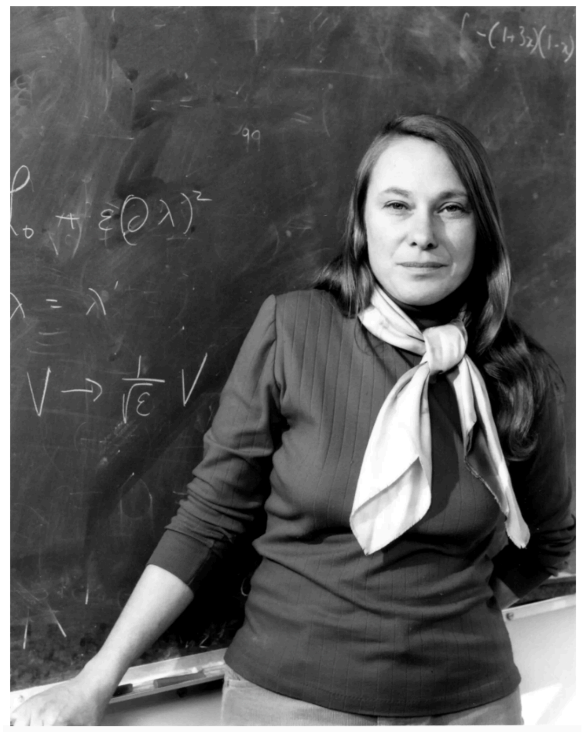
A.A. Alves Junior (Santiago de Compostela U., IGFAE), M.O. Bettler (Cambridge U.), A. Brea Rodríguez (Santiago de Compostela U., IGFAE), A. Casais Vidal (Santiago de Compostela U., IGFAE), V. Chobanova (Santiago de Compostela U., IGFAE) et al. (Aug 10, 2018)

Published in: *JHEP* 05 (2019) 048 • e-Print: 1808.03477 [hep-ex]

Rare n Strange 2017: strange physics at LHCb

$$K_{L,S} \to \mu\mu$$

$K_L \to \mu\mu$



Mary K. Gaillard in 1985, four years after she became the first woman hired by the physics department at the University of California, Berkeley. University of California, Berkeley

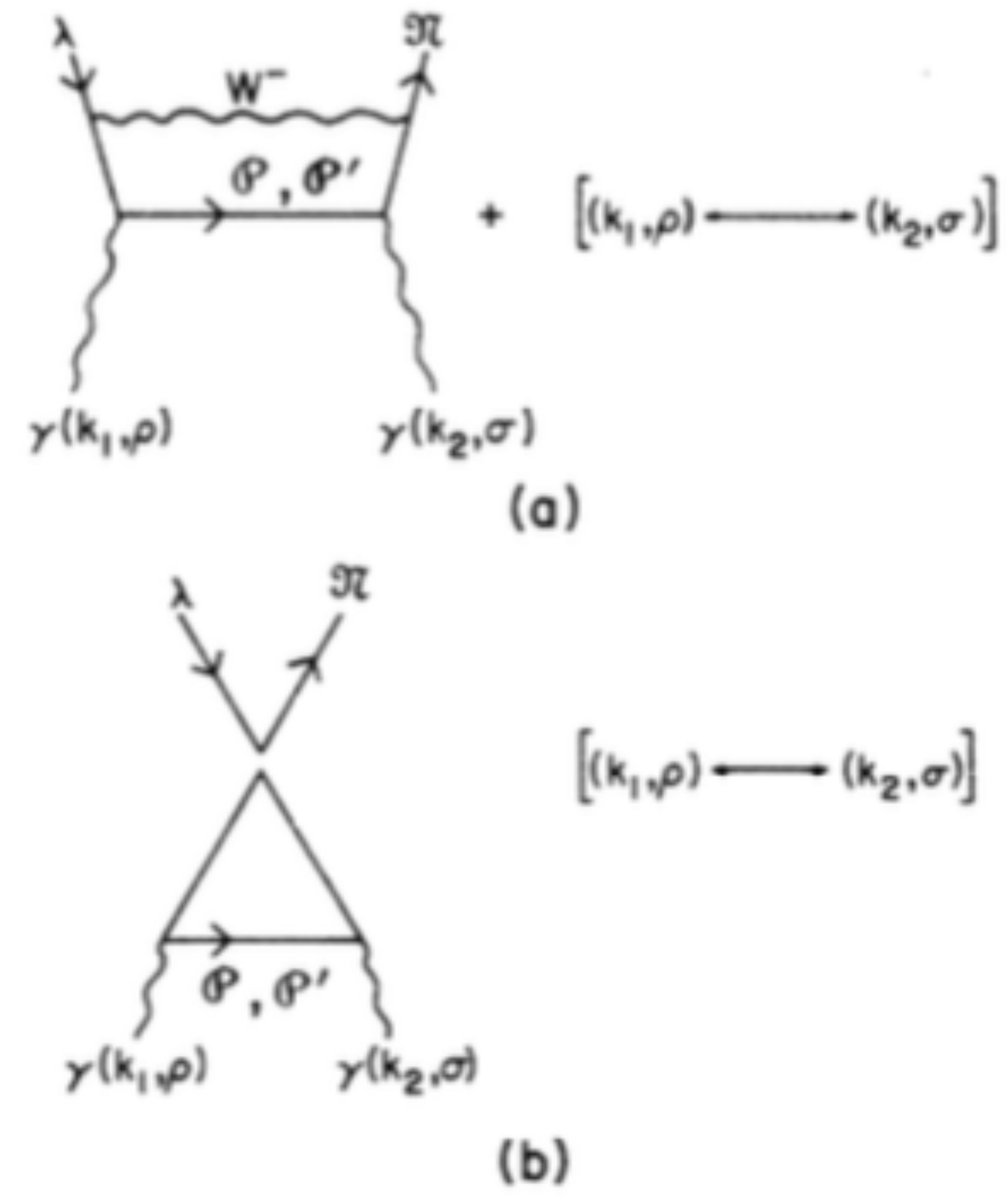


FIG. 7. Leading contributions to $\lambda + \bar{\mathfrak{N}} \to \gamma + \gamma$. To leading order in M_W^{-2}, the diagrams in (a) reduce to those of (b).

Gaillard Lee

$\Gamma(K_L^0 \to \mu^+\mu^-)/\Gamma(K_L^0 \to \pi^+\pi^-)$

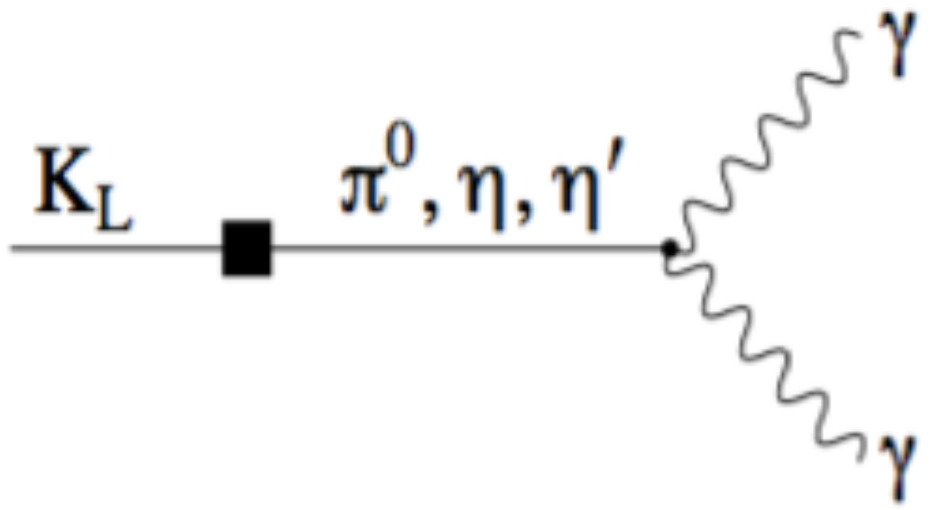
VALUE (10^{-6})	EVTS	DOCUMENT ID	TECN	COMMENT
3.48 ± 0.05	**OUR AVERAGE**			
3.474 ±0.057	6210	AMBROSE 2000	B871	
3.87 ±0.30	179	[1] AKAGI 1995	SPEC	
3.38 ±0.17	707	HEINSON 1995	B791	
• • • We do not use the following data for averages, fits, limits, etc. • • •				
3.9 ±0.3 ±0.1	178	[2] AKAGI 1991B	SPEC	In AKAGI 1995

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

$K_L \to \gamma\gamma\,|_{\rm exp}$ known

Dispersive calculation: Re A, Im A

We do not know the sign of $A(K_L \to \gamma\gamma)$

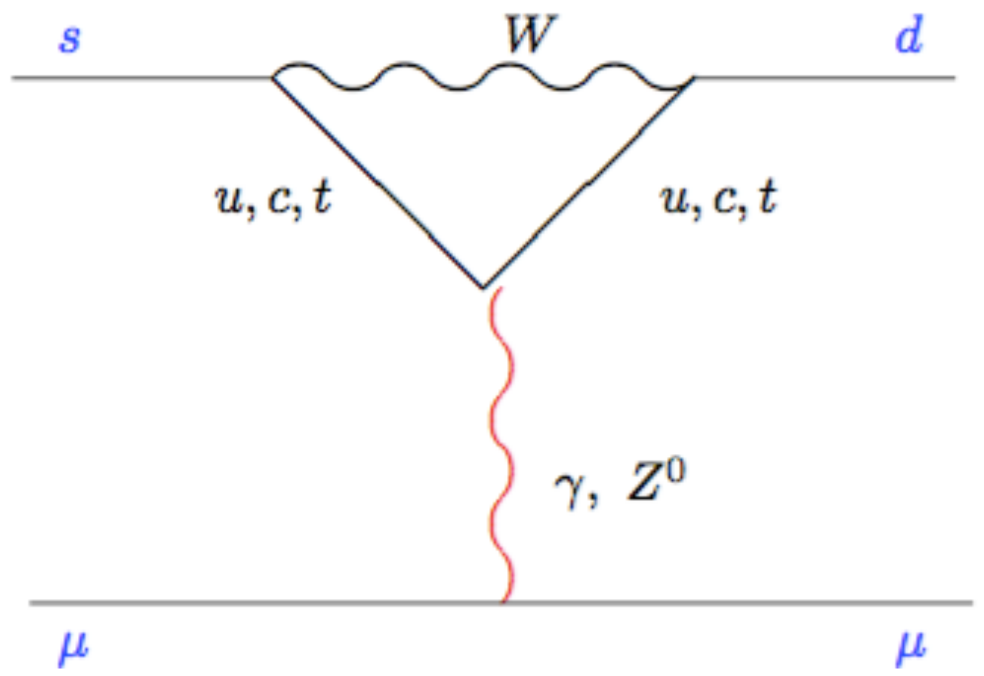


$$
\begin{aligned}
A(K_L \to 2\gamma_\perp)_{O(p^4)} &= A(K_L \to \pi^0 \to 2\gamma_\perp) + A(K_L \to \eta_8 \to 2\gamma_\perp) \\
&= A(K_L \to \pi^0) A(\pi^0 \to 2\gamma_\perp) \left[\frac{1}{M_K^2 - M_\pi^2} + \frac{1}{3} \cdot \frac{1}{M_K^2 - M_8^2} \right] \simeq 0
\end{aligned}
$$

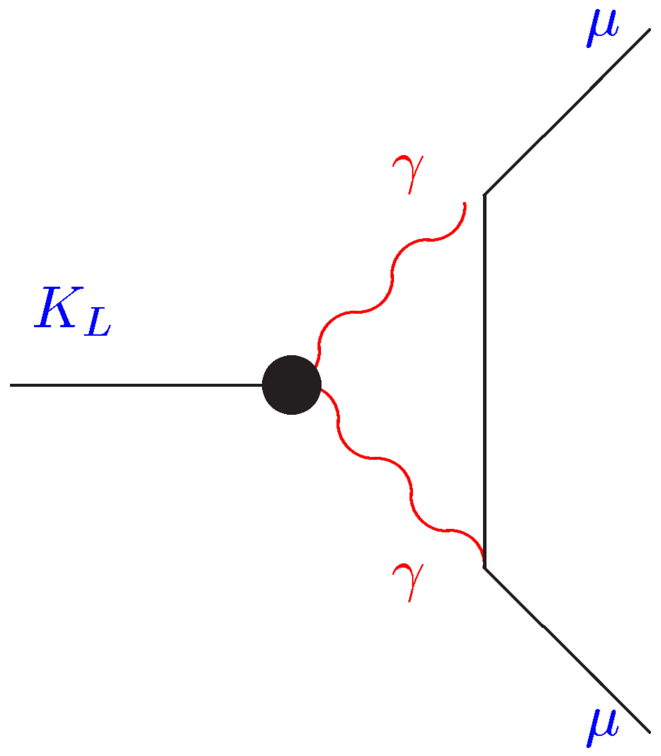
Kaon Decays in the Standard Model
Vincenzo Cirigliano (Los Alamos), Gerhard Ecker, Helmut Neufeld (Vienna U.), Antonio Pich, Jorge Portoles, refs therein

$K_L \to \mu\mu$

GD Espriu 86
GD Isidori Portoles
Isidori Unterdorfer 04
[Hoferichter, Hoid, de Elvira arXiv:2310.17689]



$<<$



$$\frac{\Gamma(K_L \to \mu\bar{\mu})}{\Gamma(K_L \to \gamma\gamma)} \sim \quad |ReA|^2 + |ImA|^2$$

Absorptive calculation
model independent

$$27.14$$

Subtracting from expt. the Absorptive contribution

$$0.98 \pm 0.55 = |ReA|^2 = (\chi_{\gamma\gamma}(M_\rho) + \chi_{\text{short}} - 5.12)^2$$

$$|\chi_{\text{short}}^{\text{SM}}| = 1.96(1.11 - 0.92\bar{\rho})$$

Additional constraints

Neutral kaon decays -

Fundamentally different from B physics, as K_L and K_S are also (approximate) CP eigenstates

CP-even transitions result in vertical bands

$K_L \to \mu^+\mu^-$

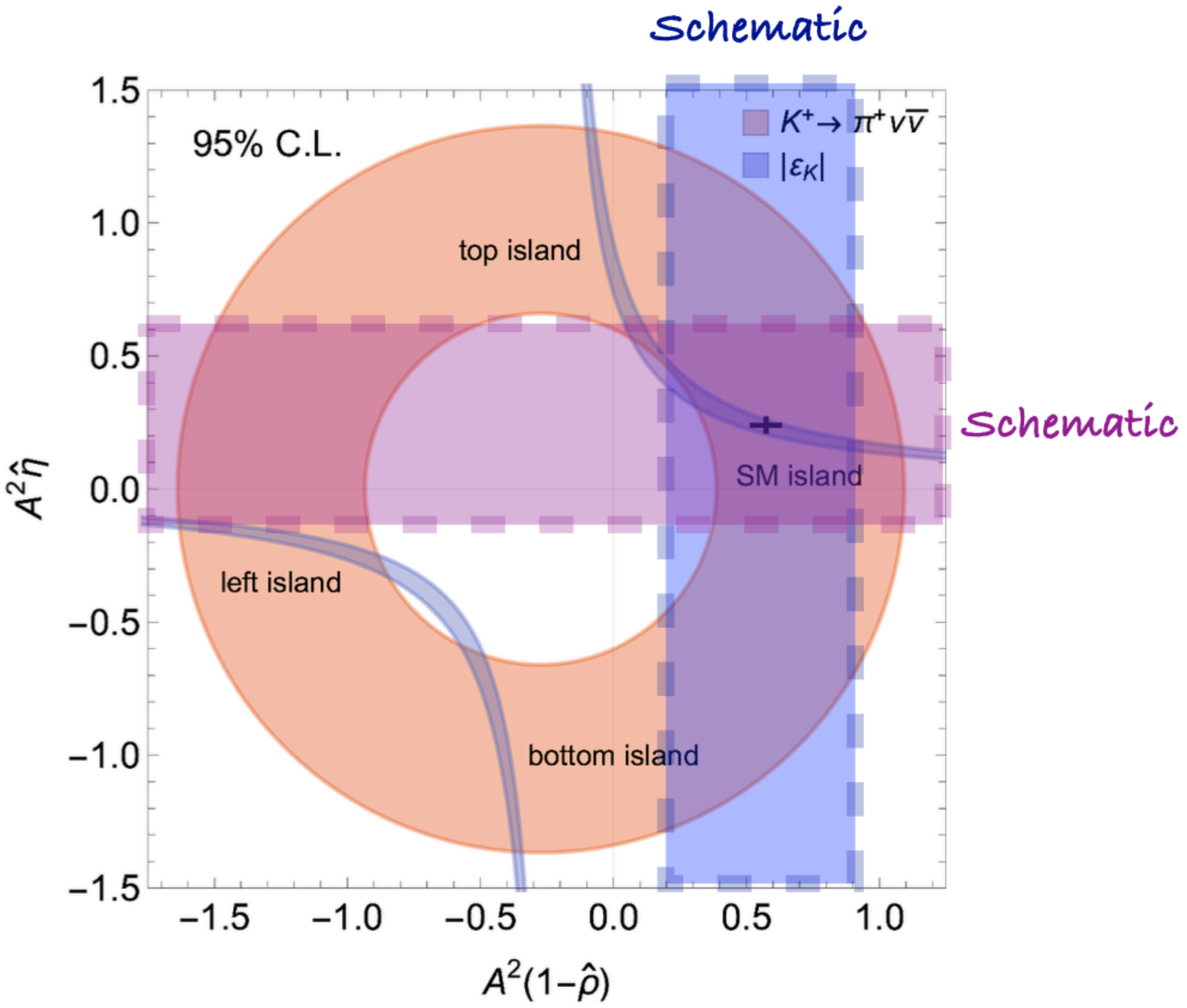
CP-odd transitions result in horizontal bands

$K_L \to \pi^0 \nu\bar{\nu}$

ε'/ε

$A_{\mathrm{CP}}(K^0 \to \mu^+\mu^-)$

...



Magically comes LHCB

measuring $K_S \to \mu\mu$

Mostly K_L decays outside fiducial volume

$K_S \to \mu\mu$

Dr. Gaillard at Berkeley in the early 1980s. AIP Emilio Segrè Visual Archives, Physics Today Collection

PHYSICAL REVIEW D VOLUME 10, NUMBER 3 1 AUGUST 1974

Rare decay modes of the K mesons in gauge theories

M. K. Gaillard* and Benjamin W. Lee†
National Accelerator Laboratory, Batavia, Illinois 60510‡
(Received 4 March 1974)

Rare decay modes of the kaons such as $K \to \mu\bar{\mu}$, $K \to \pi\nu\bar{\nu}$, $K \to \gamma\gamma$, $K \to \pi\gamma\gamma$, and $K \to \pi e\bar{e}$ are of theoretical interest since here we are observing higher-order weak and electromagnetic interactions. Recent advances in unified gauge theories of weak and electromagnetic interactions allow in principle unambiguous and finite predictions for these processes. The above processes, which are "induced" $|\Delta S| = 1$ transitions, are a good testing ground for the cancellation mechanism first invented by Glashow, Iliopoulos, and Maiani (GIM) in order to banish $|\Delta S| = 1$ neutral currents. The experimental suppression of $K_L \to \mu\bar{\mu}$ and nonsuppression of $K_L \to \gamma\gamma$ must find a natural explanation in the GIM mechanism which makes use of extra quark(s). The procedure we follow is the following: We deduce the effective interaction Lagrangian for $\lambda + \mathfrak{N} \to l + \bar{l}$ and $\lambda + \bar{\mathfrak{N}} \to \gamma + \gamma$ in the free-quark model; then the appropriate matrix elements of these operators between hadronic states are evaluated with the aid of the principles of conserved vector current and partially conserved axial-vector current. We focus our attention on the Weinberg-Salam model. In this model, $K \to \mu\bar{\mu}$ is suppressed due to a fortuitous cancellation. To explain the small K_L-K_S mass difference and nonsuppression of $K_L \to \gamma\gamma$, it is found necessary to assume $m_{\mathcal{P}}/m_{\mathcal{P}'} \ll 1$, where $m_{\mathcal{P}}$ is the mass of the proton quark and $m_{\mathcal{P}'}$ the mass of the charmed quark, and $m_{\mathcal{P}'} < 5$ GeV. We present a phenomenological argument which indicates that the average mass of charmed pseudoscalar ... sti- ... sup- ... very ... has the ... l upper ... tion

$K_S^0 \to \mu^+\mu^-$

INSPIRE search

$\Gamma(K_S^0 \to \mu^+\mu^-)/\Gamma_{total}$ Γ_{11}/Γ

Test for $\Delta S = 1$ weak neutral current. Allowed by first-order weak interaction combined with electromagnetic interaction.

VALUE	*CL%*	*DOCUMENT ID*		*TECN*
$< 2.1 \times 10^{-10}$	90	[1] AAIJ	2020AE	LHCB
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$< 8 \times 10^{-10}$	90	[2] AAIJ	2017BQ	LHCB
$< 9 \times 10^{-9}$	90	[3] AAIJ	2013G	LHCB
$< 3.2 \times 10^{-7}$	90	GJESDAL	1973	ASPK

$BR(K_S^0 \to \mu^+\mu^-)_{theo} \sim 10^{-12}$

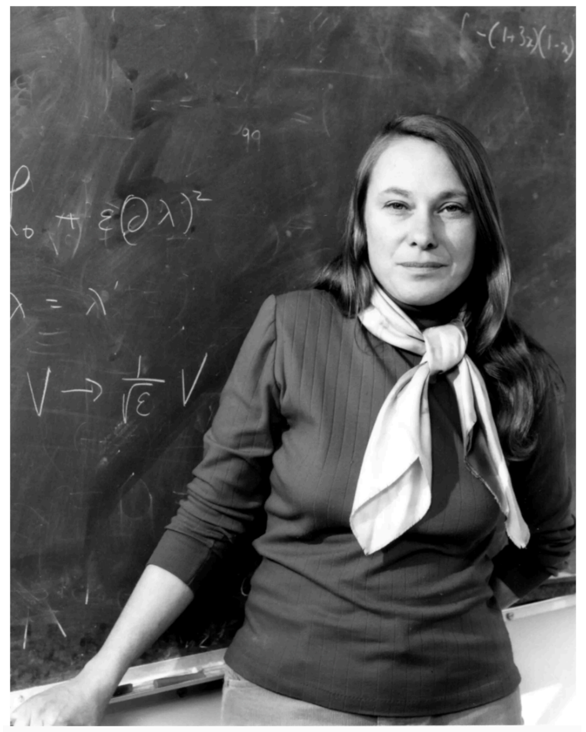
$\boxed{BR(K_S^0 \to \mu^+\mu^-) < 2.2 \times 10^{-10} @ 90\% \text{ CL}}$

PRL 125 (2020) 231801

- prospects to reach $O(10^{-11})$ sensitivity with Run 3 data (analysis ongoing)

  JHEP 05 (2019) 048

Impressive limit, opening the way to phenomenological implications (see next)



Mary K. Gaillard in 1985, four years after she became the first woman hired by the physics department at the University of California, Berkeley. University of California, Berkeley

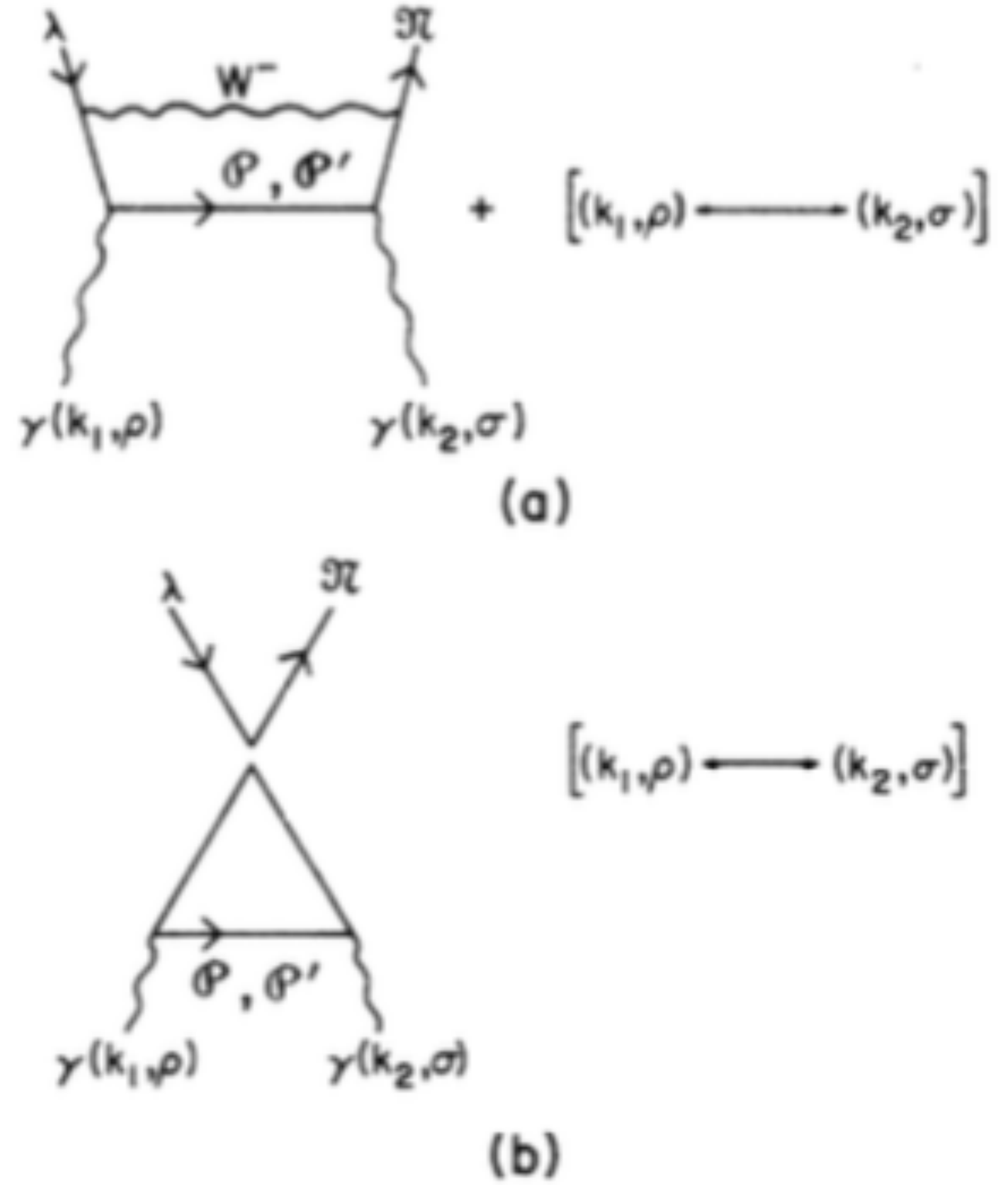


FIG. 7. Leading contributions to $\lambda + \bar{\mathfrak{N}} \to \gamma + \gamma$. To leading order in M_W^{-2}, the diagrams in (a) reduce to those of (b).

Gaillard Lee

To good approximation:

- LD effects are CP conserving. $\Rightarrow$ CP violating amplitudes are purely SD.

Short-distance (SD) and long-distance (LD) physics

- CP-conserving decays: SD and LD

$$\underset{\text{CP-odd}}{K_L} \to \underset{\text{CP-odd}}{(\mu\mu)_{l=0}} \qquad \underset{\text{CP-even}}{K_S} \to \underset{\text{CP-even}}{(\mu\mu)_{l=1}}$$

- CP-violating decays: Only SD

$$\underset{\text{CP-even}}{K_S} \to \underset{\text{CP-odd}}{(\mu\mu)_{l=0}} \qquad \underset{\text{CP-odd}}{K_L} \to \underset{\text{CP-even}}{(\mu\mu)_{l=1}}$$

- We can cleanly calculate it in the SM.

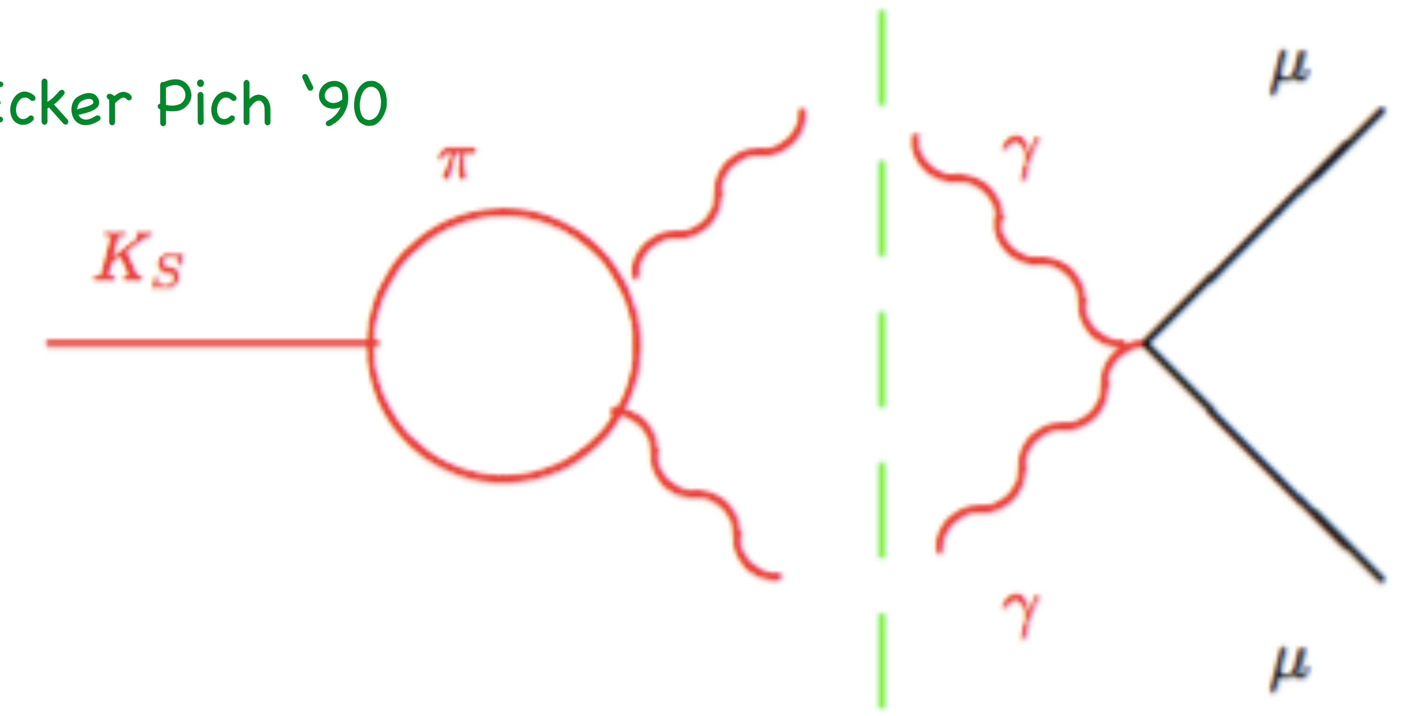
$$\mathcal{B}(K_S \to (\mu\mu)_{l=0}) = 1.7 \cdot 10^{-13} \times \left(\frac{A^2 \lambda^5 \bar{\eta}}{1.3 \times 10^{-4}}\right)$$

[Inami Lim 1981, Isidori Unterdorfer hep-ph/0311084, Dumm Pich hep-ph/9801298, Brod Stamou 2209.07445]

- Hadronic uncertainties from $f_K \lesssim 1\%$

$K_S \to \mu\mu$

Ecker Pich '90



No CP conserving Short Distance due to Furry Theorem

Gaillard Lee

LD 5×10^{-12} 20% TH err

Dispersive treatment of $K_S \to \gamma\gamma$ and $K_S \to \gamma l^+ l^-$

Gilberto Colangelo, Ramon Stucki, and Lewis C. Tunstall

Short Distance

SM $10^{-5} |\Im(V_{ts}^* V_{td})|^2 \sim 10^{-13}$

NP few 10^{-11} allowed

Summarizing

$$\mathcal{B}\left(\mathrm{K}_S^0 \to \mu^+\mu^-\right)_{\mathrm{SM}} = (5.18 \pm 1.50_{\mathrm{LD}} \pm 0.02_{\mathrm{SD}}) \times 10^{-12}$$

$$\parallel$$

$$(4.99_{\mathrm{LD}} + 0.19_{\mathrm{SD}})$$

[Ecker, Pich '91; Isidori, Unterdorfer '04; Chobanova, D'Ambrosio, TK, Martínez, Santos, Fernández, Yamamoto '18]

SD??

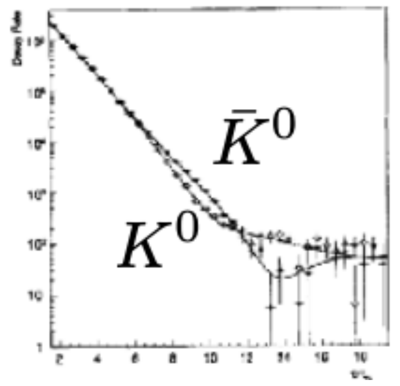
{

CPLEAR Flavor tagging

Such an interference has been discussed from ’67 [Sehgal and Wolfenstein], and has been observed/ utilized in many processes: e.g., $K^0 \to \pi\pi$, $K^0 \to 3\pi^0$, $K^0 \to \pi^+\pi^-\pi^0$, and $K^0 \to \pi^0 e^+ e^-$

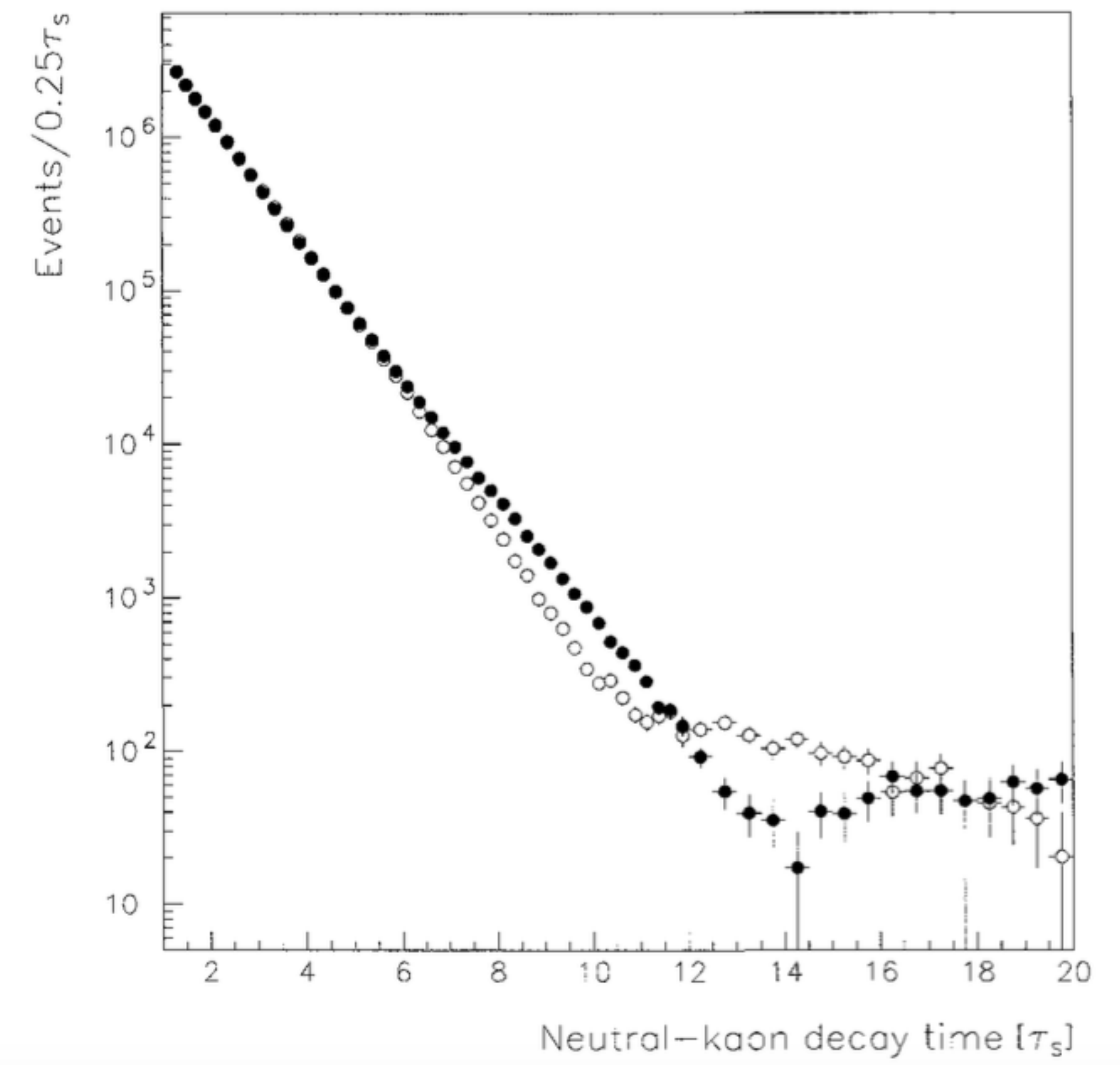
cf. CPLEAR experiment (1990-99@CERN)

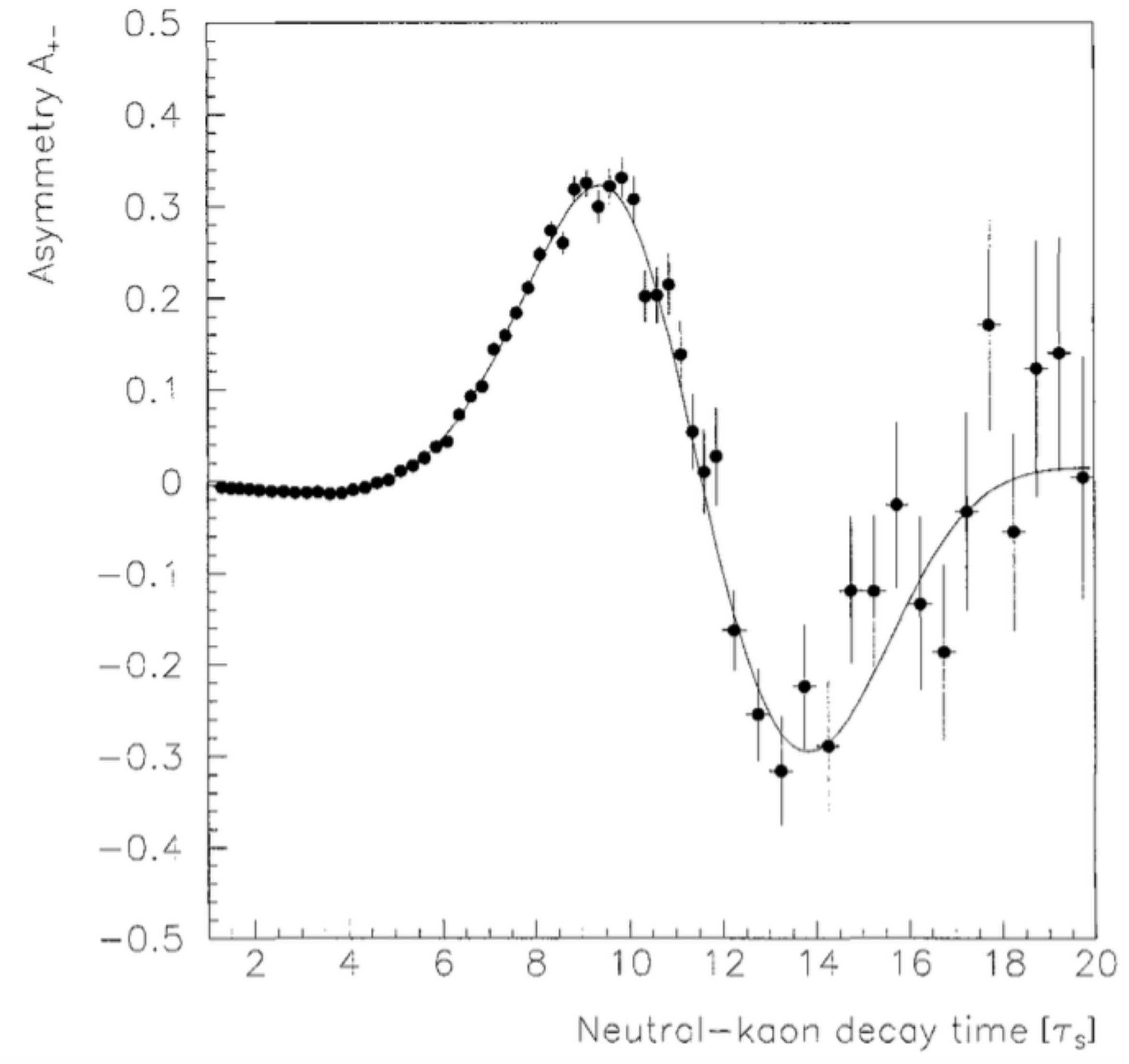
$$p\bar{p} \to \begin{bmatrix} K^0 K^- \pi^+ \\ \bar{K}^0 K^+ \pi^- \end{bmatrix}$$



$\{K_S, K_L\} \to \pi^+\pi^-$

measured the interference between K_L and K_S [CPLEAR collaboration ’95]





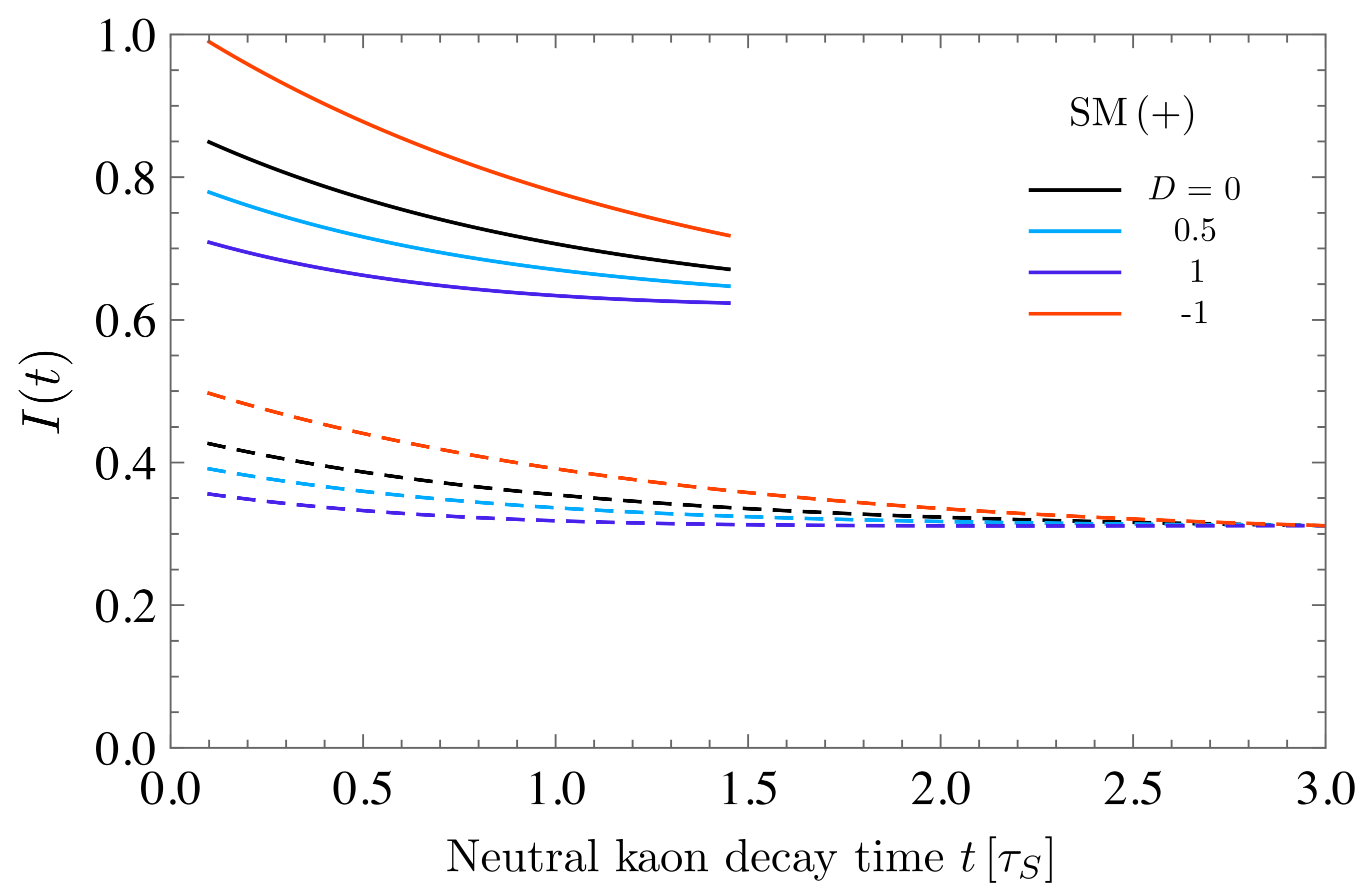
}

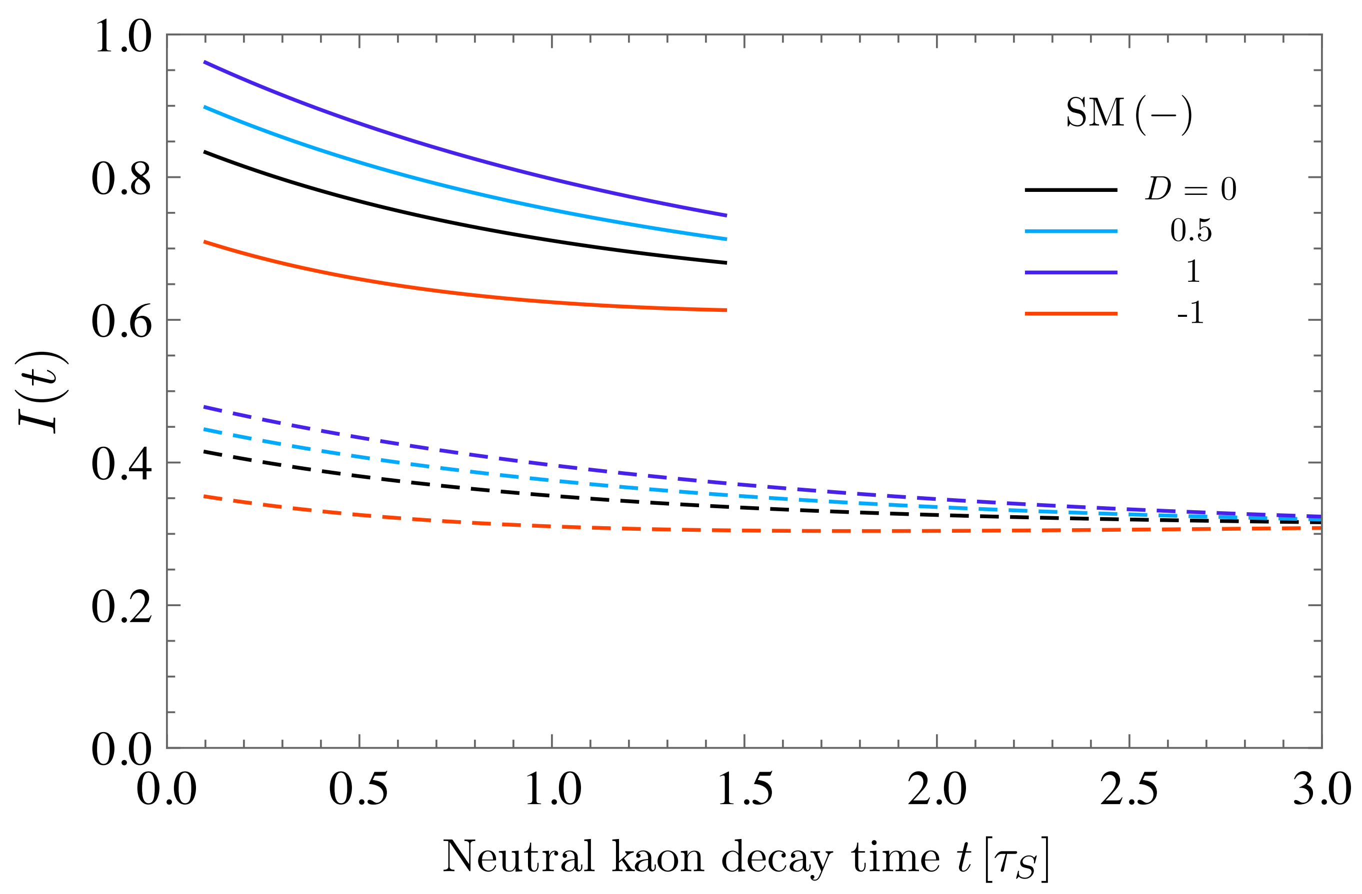
Can we study $K^0(t)$?

GD , Kitahara
1707.06999 PRL

$$pp \to K^0 K^- X$$

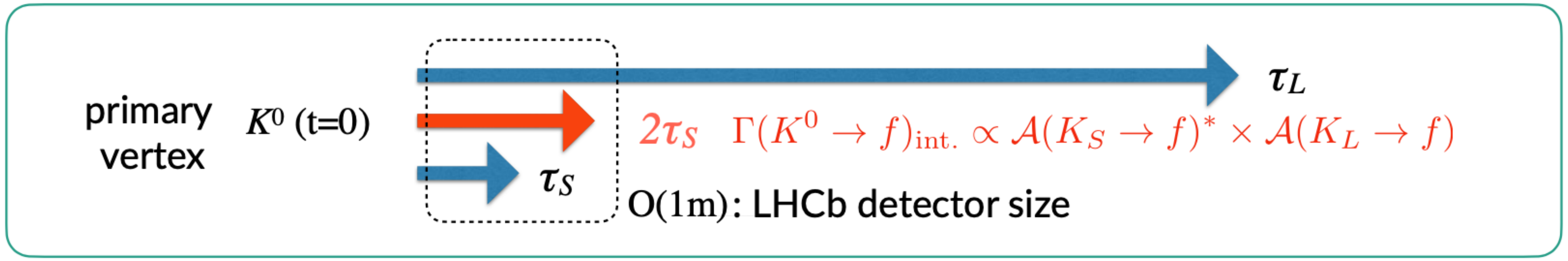
$$pp \to K^{*+} X \to K^0 \pi^+ X$$



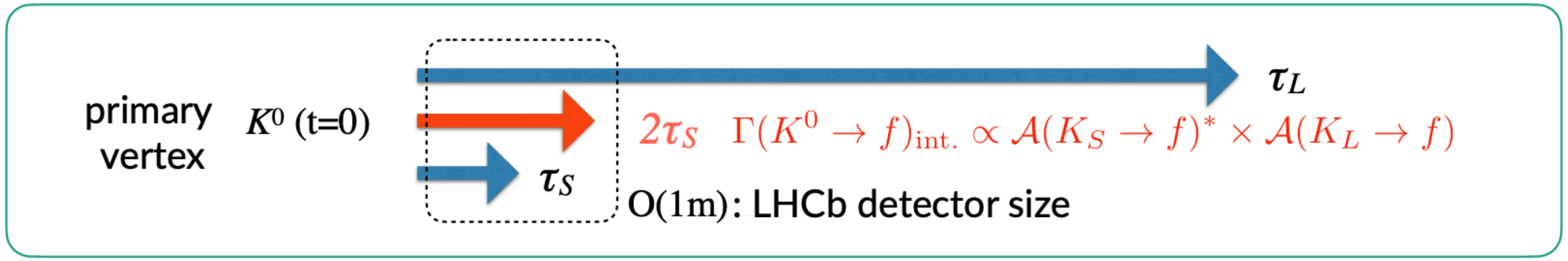


$$|\overset{(-)}{K}{}^0(t)\rangle = \frac{1}{\sqrt{2}(1 \pm \bar{\epsilon})}\left[e^{-iH_S t}\left(|K_1\rangle + \bar{\epsilon}|K_2\rangle\right) \pm e^{-iH_L t}\left(|K_2\rangle + \bar{\epsilon}|K_1\rangle\right)\right]$$

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



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



Interference $\tau \sim 2\tau_S$

$$I(t) = \frac{1}{2}\left|\mathcal{A}\left(K_S\right)\right|^2 e^{-\Gamma_S t} + \frac{1}{2}\left|\mathcal{A}\left(K_L\right)\right|^2 e^{-\Gamma_L t} + D\,\mathrm{Re}\left[e^{-i\Delta M_K t}\mathcal{A}\left(K_S\right)^* \mathcal{A}\left(K_L\right)\right] e^{-\frac{\Gamma_B+\Gamma_L}{2}t} + \mathcal{O}(\bar{\epsilon})$$

$$\mathcal{H}_{\rm eff} = \frac{G_F \alpha}{\sqrt{2}}\lambda_t y'_{7A}\left(\bar{s}\gamma_\mu\gamma_5 d\right)\left(\bar{\mu}\gamma^\mu\gamma_5\mu\right) + \mathrm{h.c.}$$

$$\sum_{spin}\mathcal{A}\left(K_1 \to \mu^+\mu^-\right)^* \mathcal{A}\left(K_2 \to \mu^+\mu^-\right)$$

$$= \frac{16 i G_F^4 M_W^4 F_K^2 M_K^2 m_\mu^2 \sin^2\theta_W}{\pi^3}\mathrm{Im}\left[\lambda_t\right] y'_{7A}\left\{\underbrace{A^\mu_{L\gamma\gamma}}_{\gamma\gamma\text{ loop}} - 2\pi\sin^2\theta_W\left(\mathrm{Re}\left[\lambda_t\right] y'_{7A} + \mathrm{Re}\left[\lambda_c\right] y_c\right)\right\}$$

Coefficient is pure imaginary

Leading contribution is proportional to $D \times \mathrm{Im}[\lambda_t] \times \mathrm{Im}[A(K_L \to \gamma\gamma \to \mu\mu)]$

It looks like [weak phase] × [strong phase], namely **the direct CPV in meson decay**

$K(t) \to \mu^+\mu^-$

[D'Ambrosio, Kitahara, [arXiv: 1707.06999]]

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

The $K \to \mu^+\mu^-$system can be described by four parameters:

$\lvert A(K_L)_{\text{CP-even}} \rvert$	$C_L = \lvert A(K_L)_{\text{CP-even}} \rvert^2$
$\lvert A(K_S)_{\text{CP-odd}} \rvert$ $\propto A^2\lambda^4\bar{\eta}$	$C_S = \lvert A(K_S)_{\text{CP-odd}} \rvert^2 + \beta_\mu^2 \lvert A(K_S)_{\text{CP-even}} \rvert^2$
$\lvert A(K_S)_{\text{CP-even}} \rvert$	$C_{\text{Int.}} = \lvert A(K_S)_{\text{CP-odd}} A(K_L)_{\text{CP-even}} \rvert$
$\varphi_0 = \arg\left(A(K_S)^*_{\text{CP-odd}} A(K_L)_{\text{CP-even}}\right)$	φ_0

$$\frac{d\Gamma(K^0(\overline{K}^0))}{dt} = C_L e^{-i\Gamma_L t} + C_S e^{-i\Gamma_S t} \pm 2\, C_{\text{Int.}} \cos\left(\Delta M_K t - \varphi_0\right) e^{-i\Gamma t}$$

Interference term holds the CPV (SD) information

$$\frac{C^2_{\text{Int.}}}{C_L} = \lvert A(K_S)_{\text{CP-odd}} \rvert^2$$

Theoretically clean

The same effect induces A_{CP}: the difference between K^0 and $\overline{K}^0$ rates.

A new way to access η

$K_S \to \mu^+\mu^-$: Prospects

arXiv:2507.13445

See A. Dery's talk

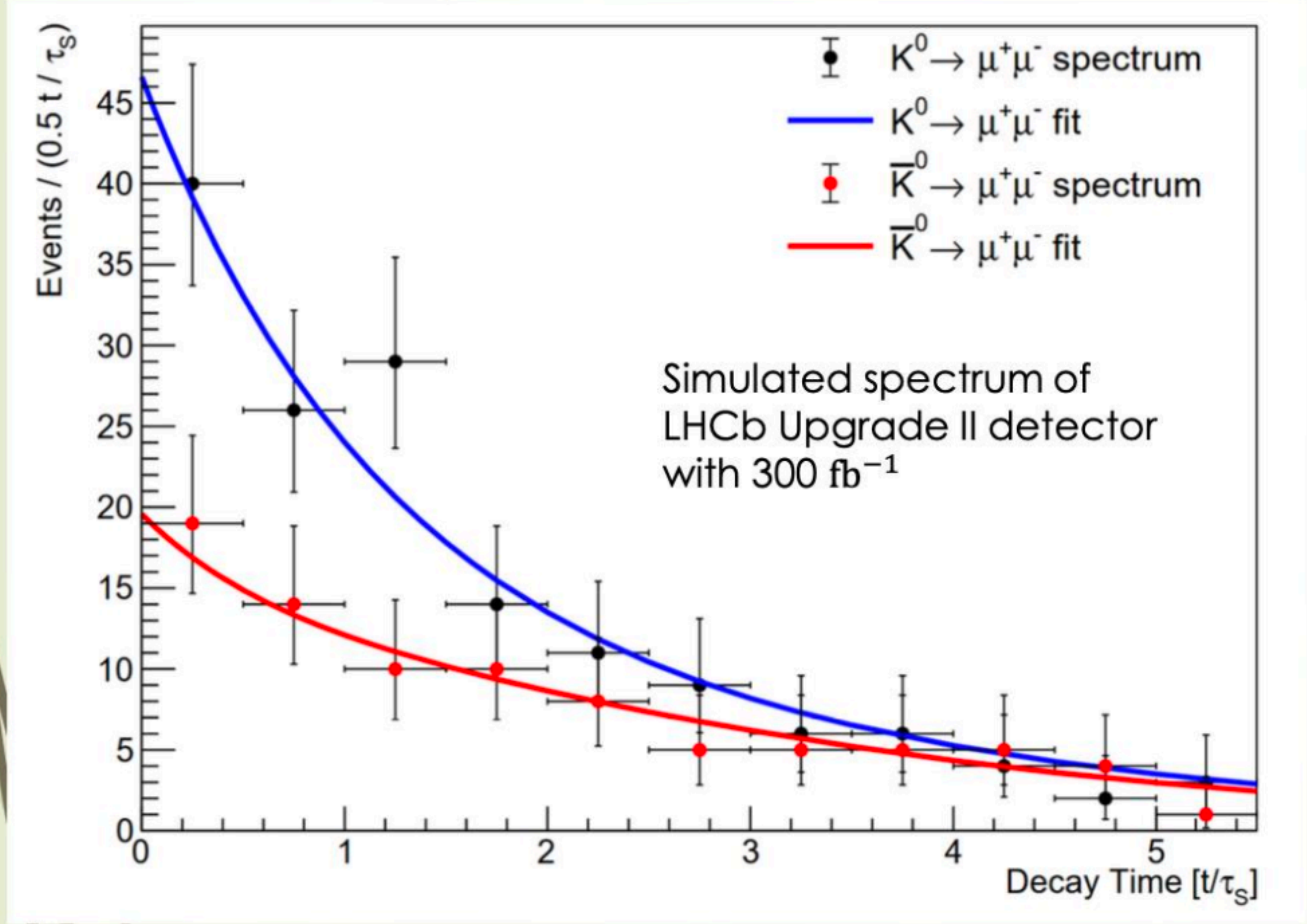
- $K^0 \to \mu^+\mu^-$ interference grants access to SD

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

$$\begin{aligned} C_L &= |A(K_L)_{\ell=0}|^2\,, \\ C_S &= \boxed{|A(K_S)_{\ell=0}}|^2 + \beta_\mu^2 |A(K_S)_{\ell=1}|^2\,, \\ C_{\text{Int.}} &= \boxed{|A(K_S)_{\ell=0}|}\,|A(K_L)_{\ell=0}| \end{aligned}$$



- Also grants access to CKM η
- Time-dependence and Tagging required
- Benefit from extending acceptance (Downstream tracks)

KAON2025

LHCb Upgrade II might be able to achieve:
- $\delta\eta/\eta \sim 35\%$
- Sign of $A^{\mu}_{L\gamma\gamma}$ with at least 3σ

$A_{CP}(K^0 \to \mu^+\mu^-)$ at LHCb

[D'Ambrosio, Dery, Grossman, Kitahara, Marchevski, Martinez Santos, Schacht: 2507.13445]

$$A_{CP} = \frac{\int \frac{d\Gamma}{dt}(\overline{K}^0)dt - \int \frac{d\Gamma}{dt}(K^0)dt}{\int \frac{d\Gamma}{dt}(\overline{K}^0)dt + \int \frac{d\Gamma}{dt}(K^0)dt} = -\frac{2C_{Int.}I_{Int.}}{C_L I_L + C_S I_S}$$

$$C_L \sim \mathcal{B}(K_L \to \mu^+\mu^-) \quad \textbf{(known)}$$
$$C_S \sim \mathcal{B}(K_S \to \mu^+\mu^-) \quad \text{(unknown)}$$

$$\left.\begin{aligned} I_L(t) &\equiv \int_0^t F^{\text{eff}}(t')\, e^{-\Gamma_L t'} dt' \\ I_S(t) &\equiv \int_0^t F^{\text{eff}}(t')\, e^{-\Gamma_S t'} dt' \\ I_{\text{Int.}}(t) &\equiv \int_0^t F^{\text{eff}}(t') \cos(\Delta M_K t' - \varphi_0) e^{-\Gamma t'} dt' \end{aligned}\right\} \textbf{known} \text{ (4-fold ambiguity in } \varphi_0\text{)}$$

Possible future

Avital Dery @Kaon25

[arXiv: 2504.12386]

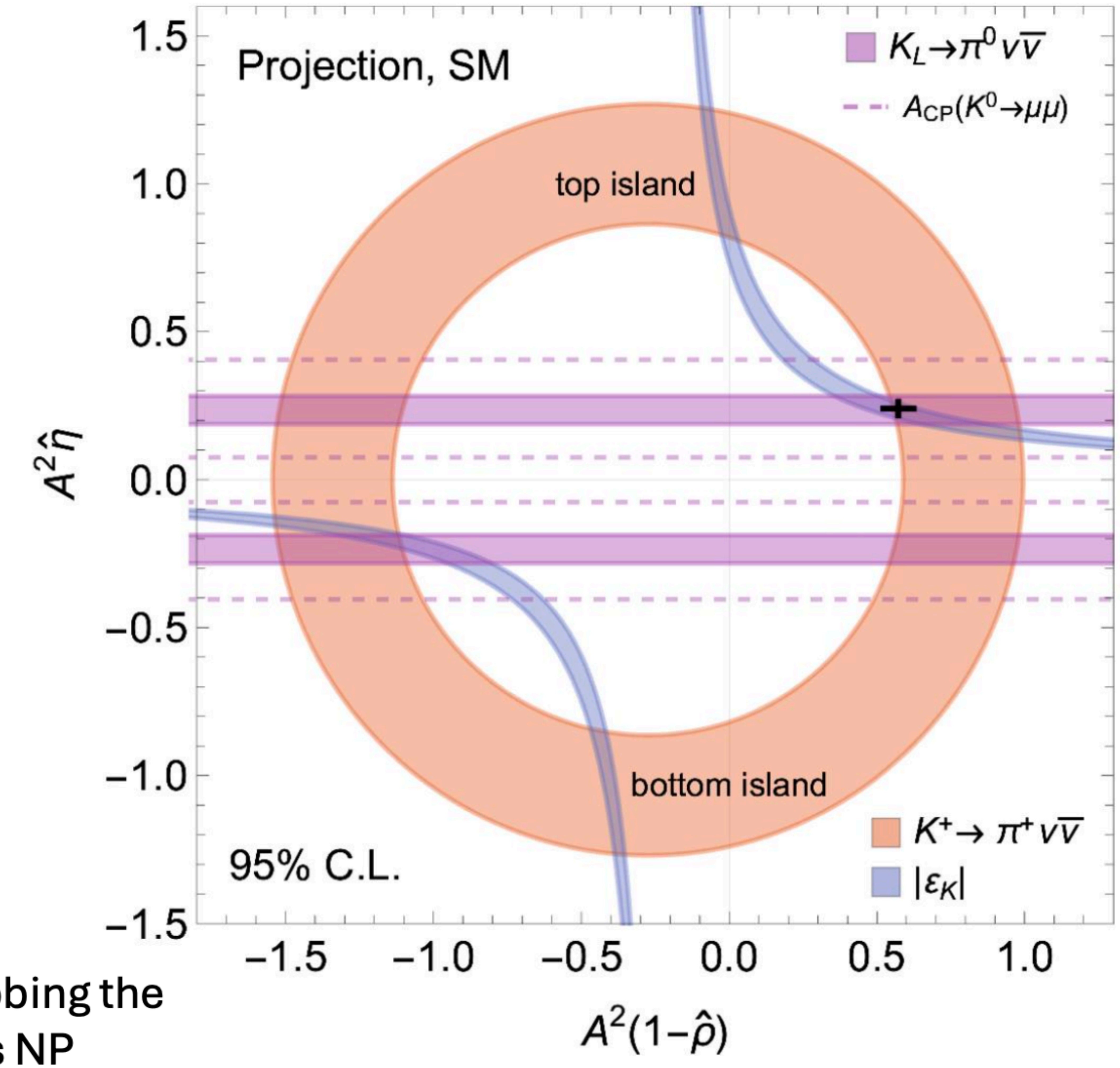
NA62 expectation:

15 % uncertainty on $\mathscr{B}(K^+ \to \pi^+ \nu \bar{\nu})$

Planned KOTO II projection:

20 % uncertainty on $\mathscr{B}(K_L \to \pi^0 \nu \bar{\nu})$
=> A measurement of $(A^2 \hat{\eta})$

Complementary measurement of $(A^2 \hat{\eta})$ via $A_{\rm CP}(K^0 \to \mu^+ \mu^-)$ at LHCb



“Progress in rare kaon decays (exp+pheno+dispersion+Lattice) allows to start probing the kaon UT plane, with constraints sensitive to various NP operators, using vastly different experimental and theory techniques, complementing the B-physics CKM picture in a unique and crucial way”

KAONS: RICH POTENTIAL

Rare Kaon decay program at LHCB

	PDG	Prospects
$K_S \to \mu\mu$	$< 9 \times 10^{-9}$ at 90% CL	(LD)$(5.0 \pm 1.5) \cdot 10^{-12}$ NP $< 10^{-11}$
$K_S \to \mu\mu\mu\mu$	–	SM LD $\sim 2 \times 10^{-14}$
$K_S \to ee\mu\mu$	–	$\sim 10^{-11}$
$K_S \to eeee$	–	$\sim 10^{-10}$
$K_S \to \pi^0\mu\mu$	$(2.9 \pm 1.3) \cdot 10^{-9}$	$\sim 10^{-9}$
$K_S \to \pi^+\pi^-e^+e^-$	$(4.79 \pm 0.15) \cdot 10^{-5}$	SM LD $\sim 10^{-5}$
$K_S \to \pi^+\pi^-\mu^+\mu^-$	–	SM LD $\sim 10^{-14}$

HIKE

$K^+ \to \pi^+\nu\bar{\nu}$	$\sigma_{\mathcal{B}}/\mathcal{B} \sim 5\%$	BSM physics, LFUV
$K^+ \to \pi^+\ell^+\ell^-$	Sub-% precision on form-factors	LFUV
$K^+ \to \pi^-\ell^+\ell^+$, $K^+ \to \pi\mu e$	Sensitivity $\mathcal{O}(10^{-13})$	LFV / LNV
Semileptonic K^+ decays	$\sigma_{\mathcal{B}}/\mathcal{B} \sim 0.1\%$	V_{us}, CKM unitarity
$R_K = \mathcal{B}(K^+ \to e^+\nu)/\mathcal{B}(K^+ \to \mu^+\nu)$	$\sigma(R_K)/R_K \sim \mathcal{O}(0.1\%)$	LFUV
Ancillary K^+ decays (e.g. $K^+ \to \pi^+\gamma\gamma$, $K^+ \to \pi^+\pi^0 e^+e^-$)	% – ‰	Chiral parameters (LECs)
$K_L \to \pi^0\ell^+\ell^-$	$\sigma_{\mathcal{B}}/\mathcal{B} < 20\%$	Imλ_t to 20% precision, BSM physics, LFUV
$K_L \to \mu^+\mu^-$	$\sigma_{\mathcal{B}}/\mathcal{B} \sim 1\%$	Ancillary for $K \to \mu\mu$ physics
$K_L \to \pi^0(\pi^0)\mu^\pm e^\mp$	Sensitivity $\mathcal{O}(10^{-12})$	LFV
Semileptonic K_L decays	$\sigma_{\mathcal{B}}/\mathcal{B} \sim 0.1\%$	V_{us}, CKM unitarity
Ancillary K_L decays (e.g. $K_L \to \gamma\gamma$, $K_L \to \pi^0\gamma\gamma$)	% – ‰	Chiral parameters (LECs), SM $K_L \to \mu\mu$, $K_L \to \pi^0\ell^+\ell^-$ rates

LHCb Sensitivity to Strange particles

(I am adapting material from the presentation of Luis Miguel Garcia Martin @KAON25)

Channel	$\mathcal{R}$	ϵ_L	ϵ_D	$\sigma_L(\mathrm{MeV}/c^2)$	$\sigma_D(\mathrm{MeV}/c^2)$
$K^0_S \to \mu^+\mu^-$	1	1.0 (1.0)	1.8 (1.8)	~ 3.0	~ 8.0
$K^0_S \to \pi^+\pi^-$	1	1.1 (0.30)	1.9 (0.91)	~ 2.5	~ 7.0
$K^0_S \to \pi^0\mu^+\mu^-$	1	0.93 (0.93)	1.5 (1.5)	~ 35	~ 45
$K^0_S \to \gamma\mu^+\mu^-$	1	0.85 (0.85)	1.4 (1.4)	~ 60	~ 60
$K^0_S \to \mu^+\mu^-\mu^+\mu^-$	1	0.37 (0.37)	1.1 (1.1)	~ 1.0	~ 6.0
$K^0_L \to \mu^+\mu^-$	~ 1	2.7 (2.7) $\times 10^{-3}$	0.014 (0.014)	~ 3.0	~ 7.0
$K^+ \to \pi^+\pi^+\pi^-$	~ 2	9.0 (0.75) $\times 10^{-3}$	41 (8.6) $\times 10^{-3}$	~ 1.0	~ 4.0
$K^+ \to \pi^+\mu^+\mu^-$	~ 2	6.3 (2.3) $\times 10^{-3}$	0.030 (0.014)	~ 1.5	~ 4.5
$\Sigma^+ \to p\mu^+\mu^-$	~ 0.13	0.28 (0.28)	0.64 (0.64)	~ 1.0	~ 3.0
$\Lambda \to p\pi^-$	~ 0.45	0.41 (0.075)	1.3 (0.39)	~ 1.5	~ 5.0
$\Lambda \to p\mu^-\bar{\nu}_\mu$	~ 0.45	0.32 (0.31)	0.88 (0.86)	–	–
$\Xi^- \to \Lambda\mu^-\bar{\nu}_\mu$	~ 0.04	39 (5.7) $\times 10^{-3}$	0.27 (0.09)	–	–
$\Xi^- \to \Sigma^0\mu^-\bar{\nu}_\mu$	~ 0.03	24 (4.9) $\times 10^{-3}$	0.21 (0.068)	–	–
$\Xi^- \to p\pi^-\pi^-$	~ 0.03	0.41(0.05)	0.94 (0.20)	~ 3.0	~ 9.0
$\Xi^0 \to p\pi^-$	~ 0.03	1.0 (0.48)	2.0 (1.3)	~ 5.0	~ 10
$\Omega^- \to \Lambda\pi^-$	~ 0.001	95 (6.7) $\times 10^{-3}$	0.32 (0.10)	~ 7.0	~ 20

Channel	$\mathcal{R}$	ϵ_L	ϵ_D	$\sigma_L(\mathrm{MeV}/c^2)$	$\sigma_D(\mathrm{MeV}/c^2)$
$K^0_S \to \pi^+\pi^-e^+e^-$	1	1.0 (0.18)	2.83 (1.1)	~ 2.0	~ 10
$K^0_S \to \mu^+\mu^-e^+e^-$	1	1.18 (0.48)	2.93 (1.4)	~ 2.0	~ 11
$K^+ \to \pi^+e^+e^-$	~ 2	0.04 (0.01)	0.17 (0.06)	~ 3.0	~ 13
$\Sigma^+ \to pe^+e^-$	~ 0.13	1.76 (0.56)	3.2 (1.3)	~ 3.5	~ 11
$\Lambda \to p\pi^-e^+e^-$	~ 0.45	$< 2.2 \times 10^{-4}$	~ 17 (< 2.2) $\times 10^{-4}$	–	–

Channel	$\mathcal{R}$	ϵ_L	ϵ_D	$\sigma_L(\mathrm{MeV}/c^2)$	$\sigma_D(\mathrm{MeV}/c^2)$
$K^0_S \to \mu^+e^-$	1	1.0 (0.84)	1.5 (1.3)	~ 3.0	~ 8.0
$K^0_L \to \mu^+e^-$	1	3.1 (2.6) $\times 10^{-3}$	13 (11) $\times 10^{-3}$	~ 3.0	~ 7.0
$K^+ \to \pi^+\mu^+e^-$	~ 2	3.1 (1.1) $\times 10^{-3}$	16 (8.5) $\times 10^{-3}$	~ 2.0	~ 8.0

$\mathcal{R}$ – ratio of production w.r.t. K^0_S

ϵ – ratio of efficiencies w.r.t. $K^0_S \to \mu^+\mu^-$

JHEP05(2019)048

It was realised that a strong kaon programme can be realized in LHCb

Conclusion

- LHCB has a chance to test short distance physics in a
- Golden Channel complementing NA62 and KOTO

Prospects

Crivellin, GD, Hoferichter, Tunstall '16

GD Iyer Mahmoudi Neshatpour 2206.14748

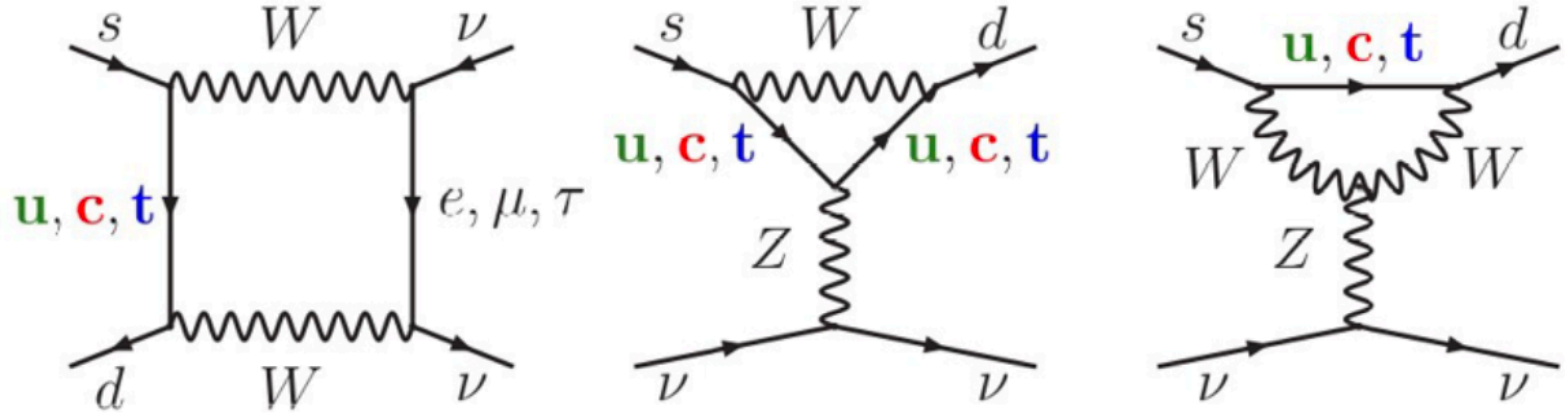
$K^+ \to \pi^+ l^+ l^-$ LFUV test $a_+^{\mu\mu} - a_+^{ee}$

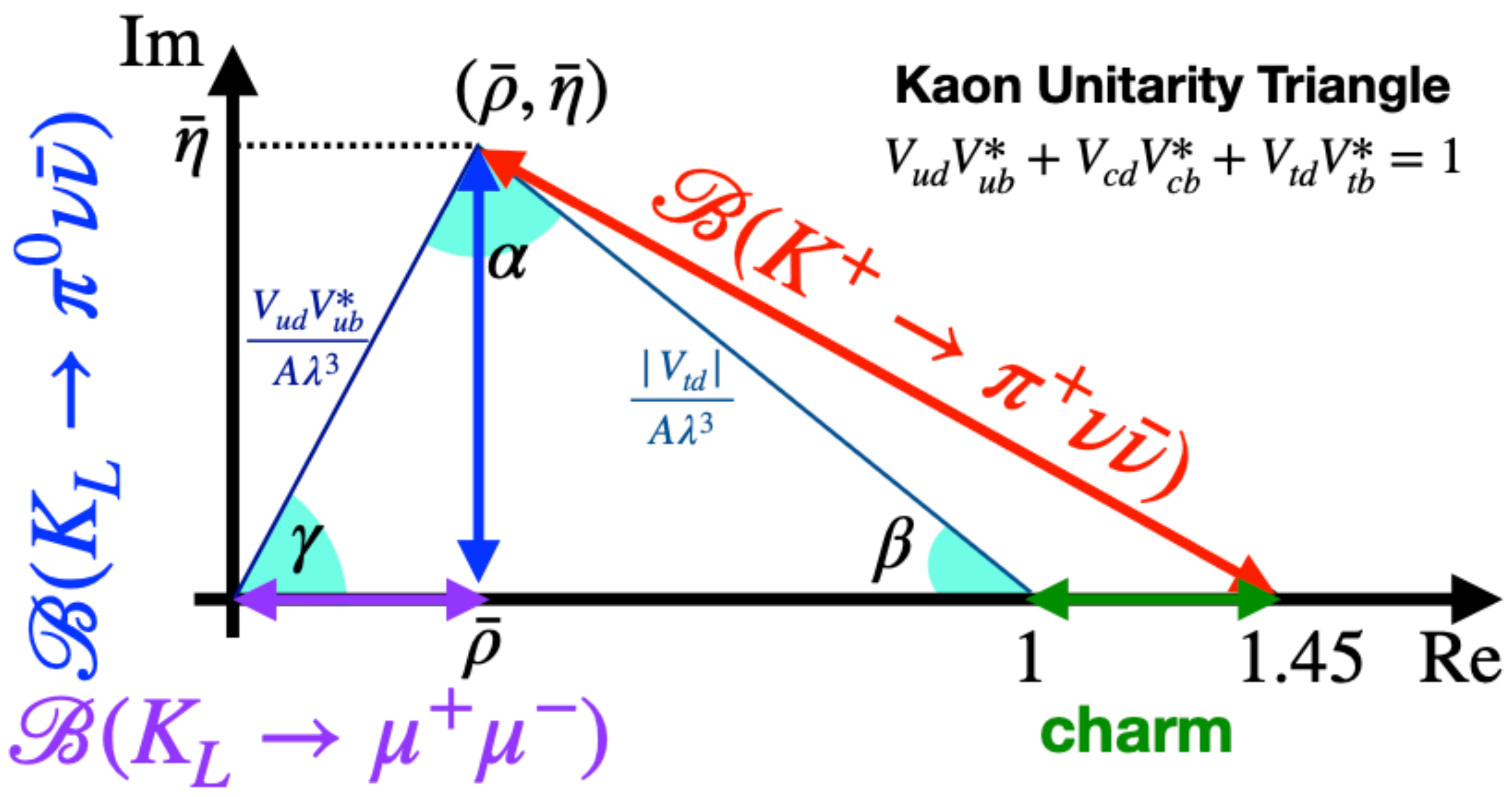
- Global tests lepton flavour universality violation

- Scalar and tensor couplings Phys. Lett. B 855 (2024) 138824 GD Iyer Mahmoudi Neshatpour

$K \to \pi\nu\bar{\nu}$: Precision test of the Standard Model

SM: Z-penguin & box diagrams





- $\mathscr{B}(K \to \pi\nu\bar{\nu})$ **highly suppressed** in SM
  - GIM mechanism & maximum CKM suppression $s \to d$ transition: $\sim \frac{m_t}{m_W}\left|V^*_{ts}V_{td}\right|$
- Theoretically clean $\Rightarrow$ high precision SM predictions
  - Dominated by short distance contributions.
  - Hadronic matrix element extracted from $\mathscr{B}(K \to \pi^0\ell^+\nu_\ell)$ decays via isospin rotation.

Mode	SM Branching Ratio [1]	SM Branching Ratio [2]	Experimental Status
$K^+ \to \pi^+\nu\bar{\nu}$	$(8.60 \pm 0.42) \times 10^{-11}$	$(7.86 \pm 0.61) \times 10^{-11}$	$(10.6 \pm 4.0) \times 10^{-11}$ NA62 16−18
$K_L \to \pi^0\nu\bar{\nu}$	$(2.94 \pm 0.15) \times 10^{-11}$	$(2.68 \pm 0.30) \times 10^{-11}$	$< 2 \times 10^{-9}$ KOTO (2021 data)

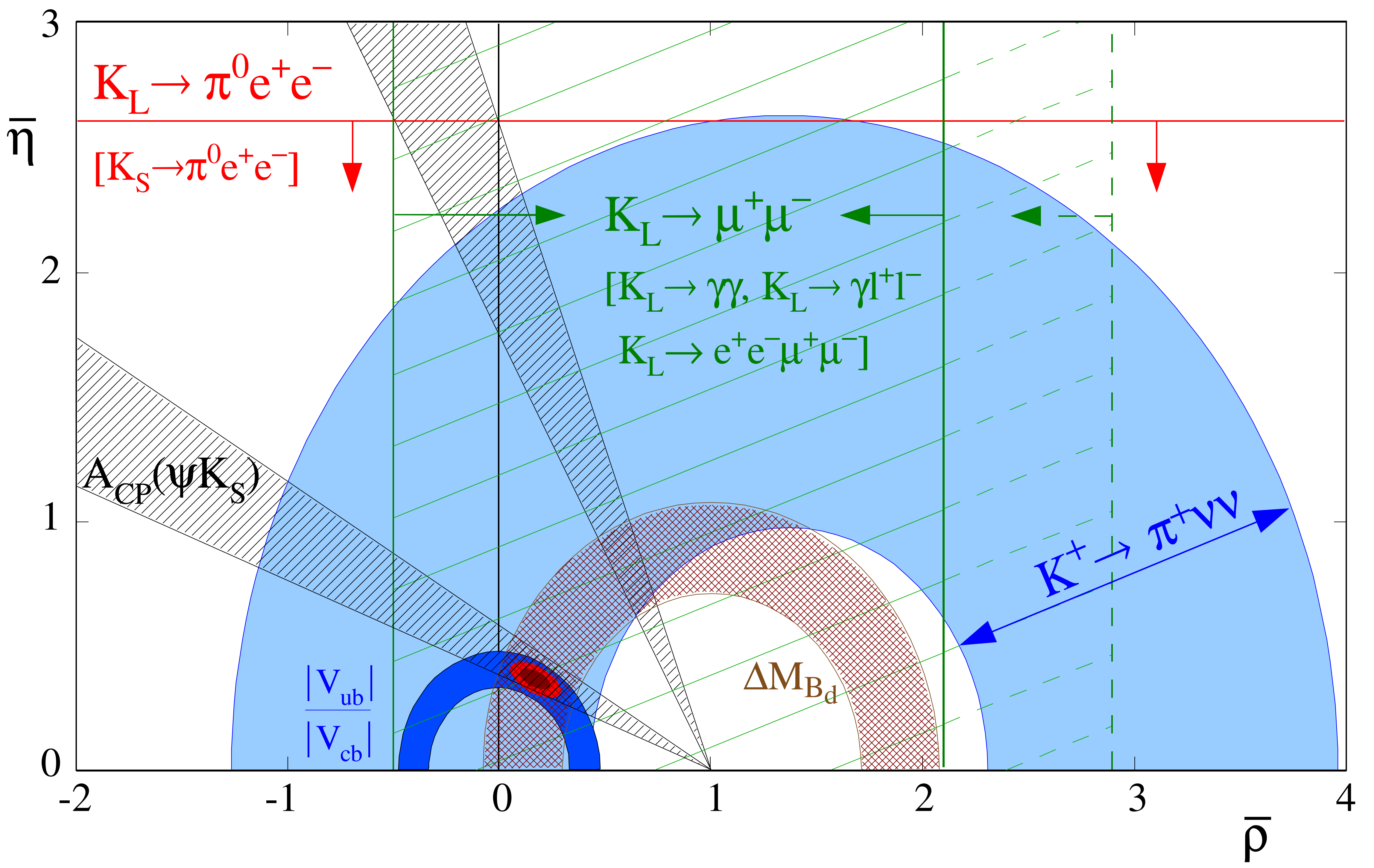
^Recent SM calculations [1:Buras et al. EPJC 82 (2022) 7, 615][2:D'Ambrosio et al. JHEP 09 (2022) 148]
(Differences in SM calculations from choice of CKM parameters: see [Eur.Phys.J.C 84 (2024) 4, 377])

NA62 16-22 $(13.0)^{+3.3}_{-3.0} \times 10^{-11}$ 18^{+3}_{-2}

Bkg

Isidori Unterdorfer

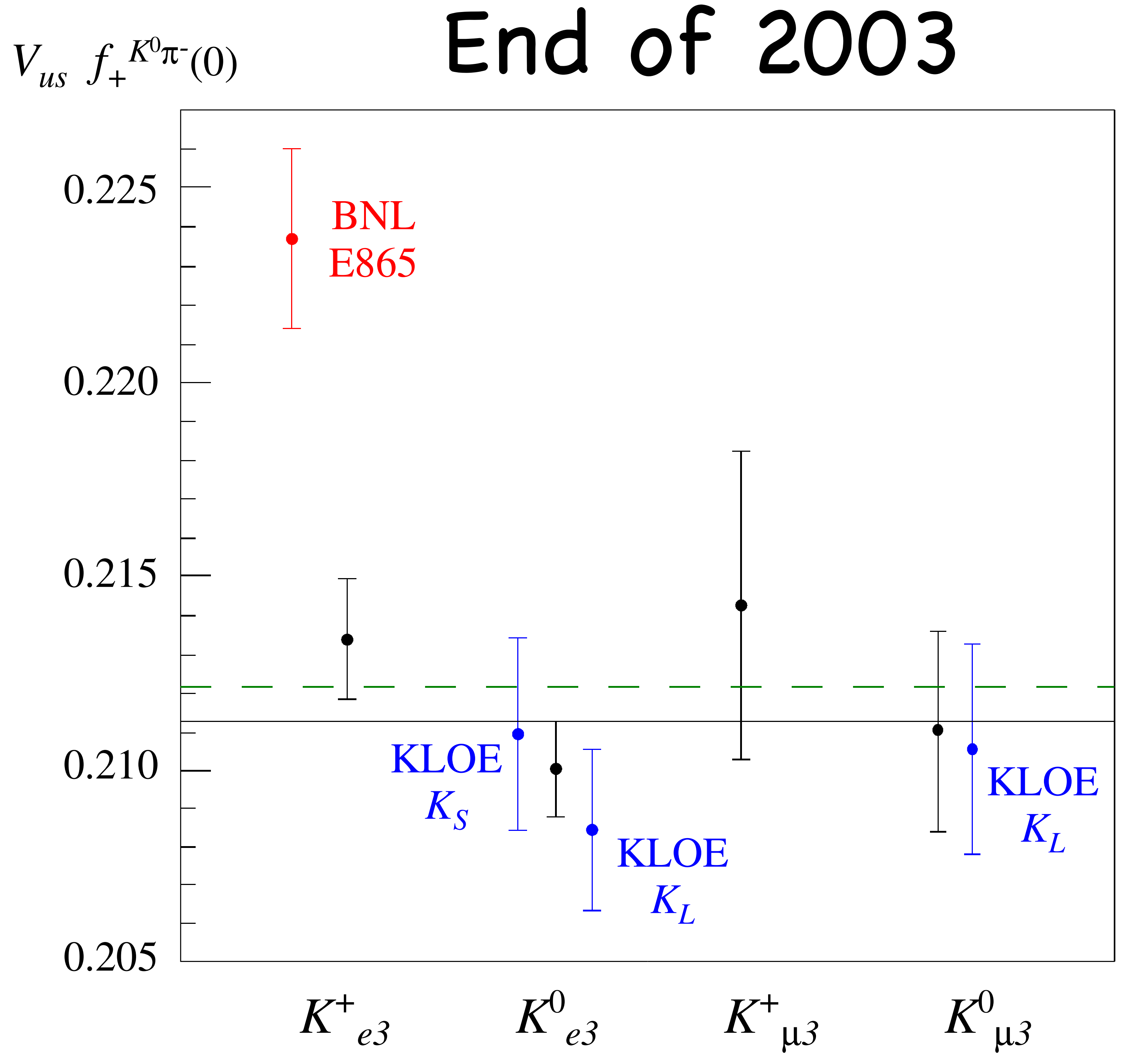
$K_L \to \mu\mu$: our sign ignorance



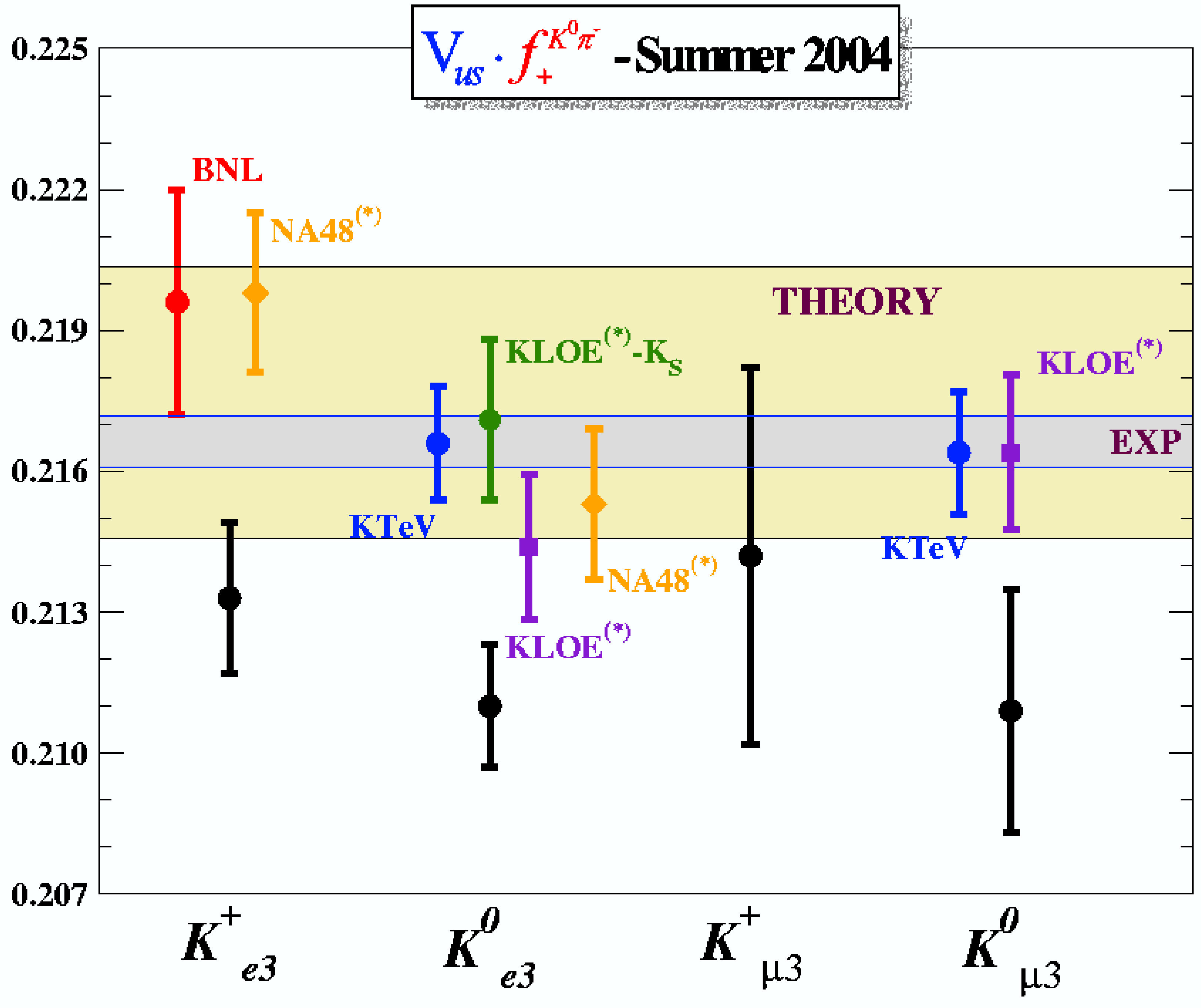
We do not know the sign

We know the sign

End of 2003



$V_{us}\ f_+^{K^0\pi^-}(0)$
0.225
0.220
0.215
0.210
0.205
BNL
E865
KLOE
K_S
KLOE
K_L
KLOE
K_L
K^+_{e3}
K^0_{e3}
$K^+_{\mu 3}$
$K^0_{\mu 3}$



$V_{us} \cdot f_+^{K^0\pi^-}$ -Summer 2004
0.225
0.222
0.219
0.216
0.213
0.210
0.207
BNL
NA48(*)
THEORY
KLOE(*)-K_S
KLOE(*)
EXP
KTeV
NA48(*)
KLOE(*)
KTeV
K^+_{e3}
K^0_{e3}
$K^+_{\mu 3}$
$K^0_{\mu 3}$