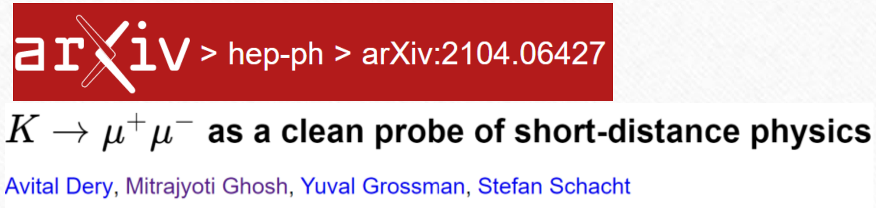
# $K_S \to \mu^+\mu^-$

The ultimate rags to riches story



arXiv > hep-ph > arXiv:2104.06427

$K \to \mu^+\mu^-$ **as a clean probe of short-distance physics**

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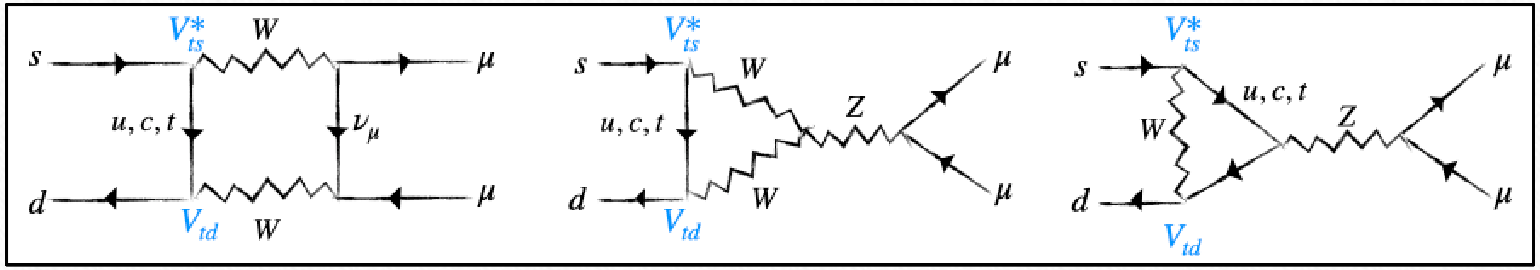
# An introduction to $K_L \to \mu^+\mu^-$ and $K_S \to \mu^+\mu^-$

Flavor Changing Neutral Current (FCNC), loop-suppressed in the SM

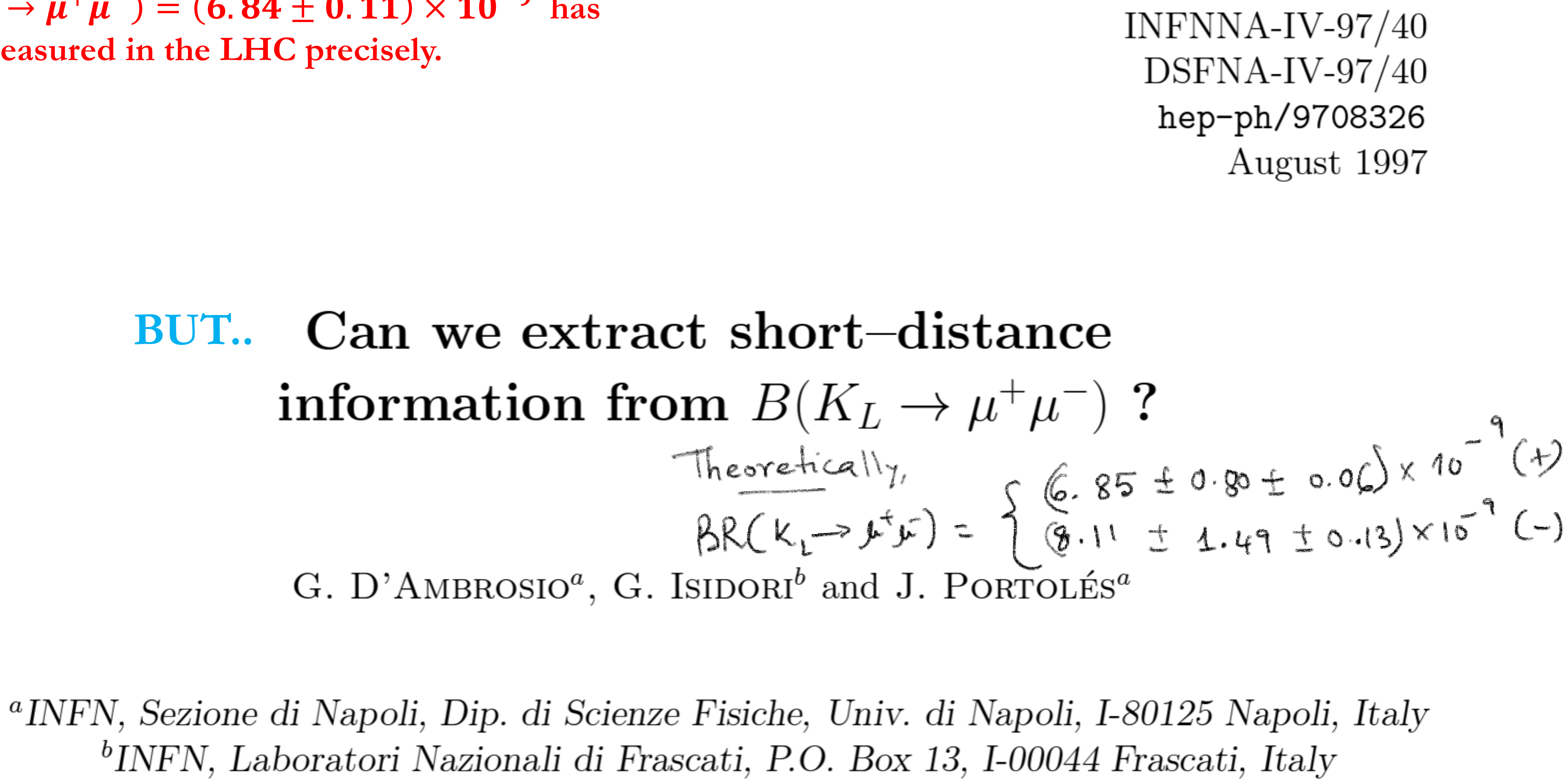


Short Distance Perturbative physics (can be calculated accurately)

**Dominating** Long Distance physics (large errors in calculation)

(by around 25 times)

**$BR(K_L \to \mu^+\mu^-) = (6.84 \pm 0.11) \times 10^{-9}$ has been measured in the LHC precisely.**



INFNNA-IV-97/40
DSFNA-IV-97/40
hep-ph/9708326
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**BUT..**

# Can we extract short–distance information from $B(K_L \to \mu^+\mu^-)$ ?

Theoretically,

$$BR(K_L \to \mu^+\mu^-) = \begin{cases} (6.85 \pm 0.80 \pm 0.06) \times 10^{-9} & (+) \\ (8.11 \pm 1.49 \pm 0.13) \times 10^{-9} & (-) \end{cases}$$

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# The fairy godmother arrives – CP violation!

CP properties of the final state depend on the relative angular momentum $l=0,1$

$CP(\mu^+\mu^-)_{l=0} = -1$

$CP(\mu^+\mu^-)_{l=1} = +1$

$CP(K_L) = -1$

$CP(K_S) = +1$

CP conserving : $K_S \to (\mu^+\mu^-)_{l=1}$, $K_L \to (\mu^+\mu^-)_{l=0}$

CP violating : $K_S \to (\mu^+\mu^-)_{l=0}$, $K_L \to (\mu^+\mu^-)_{l=1}$

# “Bibbity Babbity Boo”-ing some parameters

⇛ Long Distance Physics Does not violate CP.

“Before CP-violation”:

We start off with 6 parameters

$A_L^0, \quad A_s^0, \quad A_L^1, \quad A_s^1$

$\arg(A_L^{0*} A_s^0)$

$\arg(A_L^{1*} A_s^1)$

$(\bar{s}\gamma_\mu\gamma_5 d)(\bar{\mu}\gamma_\mu\gamma^5\ell)$

Can show this using CPT

“After CP-violation”:

Left with just 4!

$A_L^0$ ✓, $A_s^0$ ✓, $\cancel{A_L^1}$, $A_s^1$ ✓

$\arg(A_L^{0*} A_s^0)$ ✓

$\cancel{\arg(A_L^{1*} A_s^1)}$

# Time dependence measurements

A clever way to measure 4 unknowns!

$$\left(\frac{\mathrm{d}\Gamma}{\mathrm{d}t}\right) = \mathcal{N}_f f(t) \longrightarrow |\langle f|\mathcal{H}|K^0(t)\rangle|^2$$

$$f(t) = \underbrace{C_L e^{-\Gamma_L t} + C_S\, e^{-\Gamma_S t}}_{\text{related to } K_L \text{ and } K_S \text{ decays}} + 2\,\underbrace{[C_{sin}\sin(\Delta m t) + C_{cos}\cos(\Delta m t)]}_{\text{interference of } K_L \text{ and } K_S}\, e^{-\Gamma t}$$

The four coefficients are functions of $A_L^0$, $A_S^0$, $A_S^1$ and $\arg(A_L^{*0} A_S^0)$ ....

# The big reveal!

$$\boxed{|A_S^0|^2 = \frac{C_{\cos}^2 + C_{\sin}^2}{C_L}}$$

Corresponds to

$$Br(K_S \to \mu^+\mu^-)_{\ell=0} = Br(K_L \to \mu^+\mu^-) \times \frac{\tau_S}{\tau_L} \times \left(\frac{C_{\cos}^2 + C_{\sin}^2}{C_L}\right)$$

# In the Standard Model…

$$\mathcal{H}_{\text{eff}} = -\frac{G_F}{\sqrt{2}}\frac{\alpha}{2\pi\sin^2\theta_W}\left[V_{cs}^*V_{cd}Y_{NL} + V_{ts}^*V_{td}Y(x_t)\right]\left[(\bar{s}d)_{V-A}(\bar{\mu}\mu)_{V-A}\right] + h.c.$$

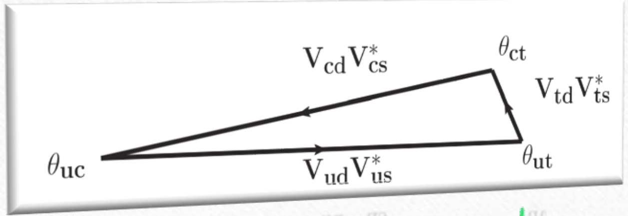
$$\beta_\mu = \left(1 - \frac{4m_\mu^2}{m_K^2}\right)^{1/2}$$

kaon decay constant

$$\mathcal{B}(K_S \to (\mu^+\mu^-)_{\ell=0}) = \frac{\beta_\mu \tau_S}{16\pi m_K} 4|\tilde{g}_{\text{SM}}|^2 f_K^2 m_\mu^2 m_K^2 \sin^2\theta_{ct}$$
$$= \frac{\beta_\mu \tau_S}{16\pi m_K}\left|\frac{G_F}{\sqrt{2}}\frac{2\alpha_{em}}{\pi\sin^2\theta_W} m_K m_\mu \times Y(x_t) \times f_K \times V_{ts}V_{td}\sin\theta_{ct}\right|^2$$

$$\mathcal{B}(K_S \to (\mu^+\mu^-)_{\ell=0}) \approx 1.64 \cdot 10^{-13} \times \left|\frac{V_{ts}V_{td}\sin\theta_{ct}}{(A^2\lambda^5\bar{\eta})_{\text{best fit}}}\right|^2,$$

$$(A^2\lambda^5\bar{\eta})_{\text{best fit}} = 1.33 \cdot 10^{-4}.$$



d-s unitarity triangle

# The Main Takeaway

## Before:

The decay $K_S \to \mu^+\mu^-$ was considered to be:

- Theoretically unclean
- Experimentally challenging

## After:

Our claim is that this decay is:

Experimentally challenging, but..

**Theoretically Clean**

(a property shared with the decay $K_L \to \pi\bar{\nu}\nu$)

# New Physics Sensitivity?

From a SM calculation,

$$\mathrm{Br}\left(K_S \to (\mu^+\mu^-)_{\ell=0}\right) = 1.6 \times 10^{-13}$$

Bounds from experiment

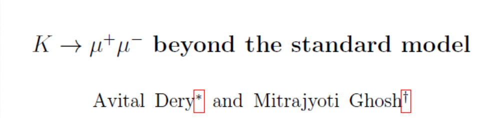
$$\mathrm{Br}\left(K_S \to \mu^+\mu^-\right) < 2.1 \times 10^{-9}$$

4 ORDERS OF MAGNITUDE ENCHANCEMENT POSSIBLE DUE TO NEW PHYSICS !!

# What next?

## On the theoretical side

- New Physics (NP) sensitivity of the $K_S \to \mu\mu$ decay rate?



$K \to \mu^+\mu^-$ **beyond the standard model**

Avital Dery[*] and Mitrajyoti Ghosh[†]

(2112.05801)

- Other decays such as $K \to \pi l^+ l^-$, $K \to \pi\pi l^+ l^-$ could also have a similar rags to riches moment?

## Some issues on the experimental front..

- Experimentally, in order to see time dependence, need around $10^{13}$ events per year
- It is difficult to produce a pure $K^0$ beam, current experiments produce either $K^+$, or a mixture of $K^0$ and $\overline{K^0}$.