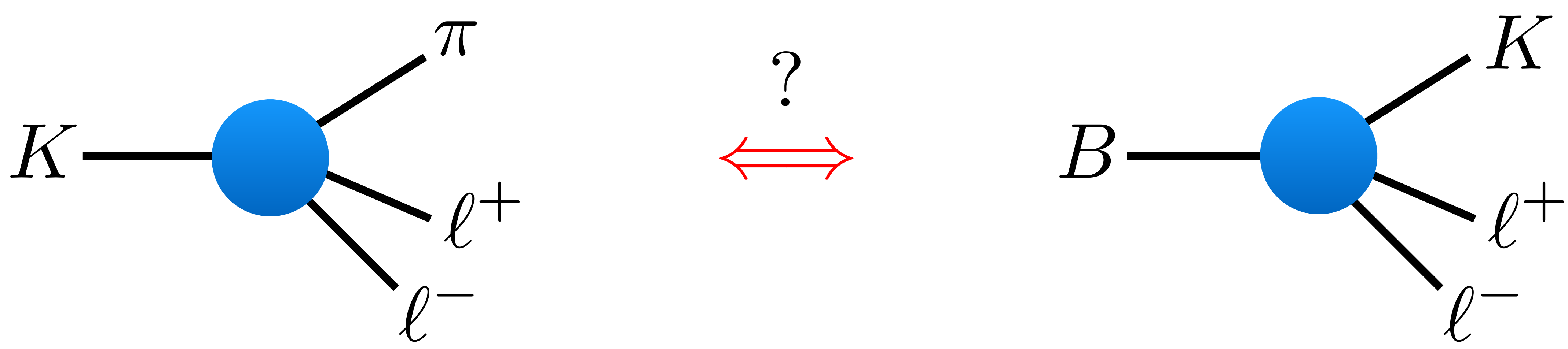
Lepton Flavour (Universality) Violation in Rare Kaon Decays



In collaboration with A. Crivellin, G. D'Ambrosio & M. Hoferichter [arXiv:1601.00970]

UNIVERSITÄT BERN

AEC
ALBERT EINSTEIN CENTER FOR FUNDAMENTAL PHYSICS

Lewis C. Tunstall
Albert Einstein Centre for Fundamental Physics
Institute for Theoretical Physics
University of Bern

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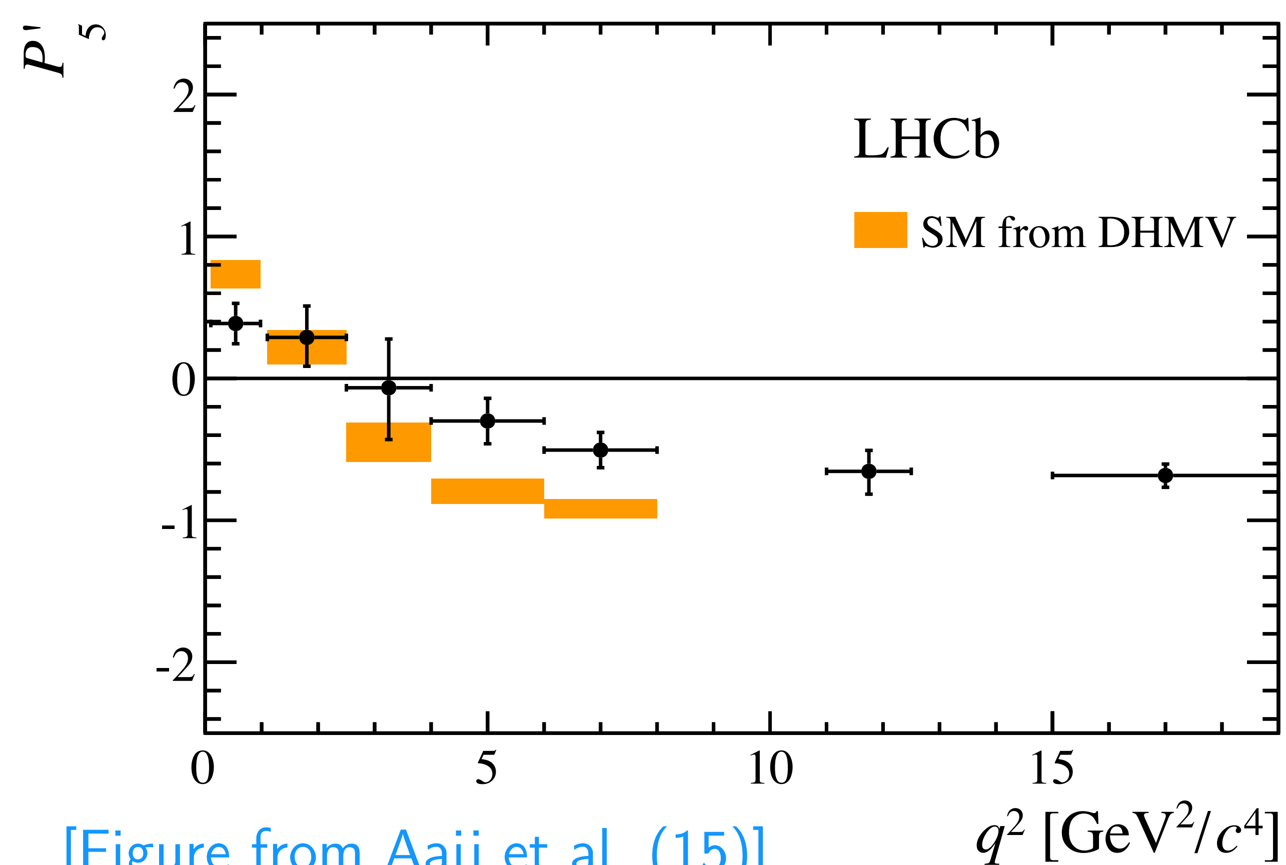
0 | Motivation

Is New Physics lurking in semi-leptonic B-decays?

Among several recent flavour anomalies, three at Belle, BaBar and LHCb have received considerable attention: [Discussed in detail in Siim Tolk's talk]

1. measured value of angular observable P_5' in $B \to K^* \mu^+ \mu^-$ deviates from SM at 2-3σ level

[Descotes-Genon et al. (13 & 14); Altmannshofer & Straub (15); Jäger & Martin Camalich (16)]



[Figure from Aaij et al. (15)]

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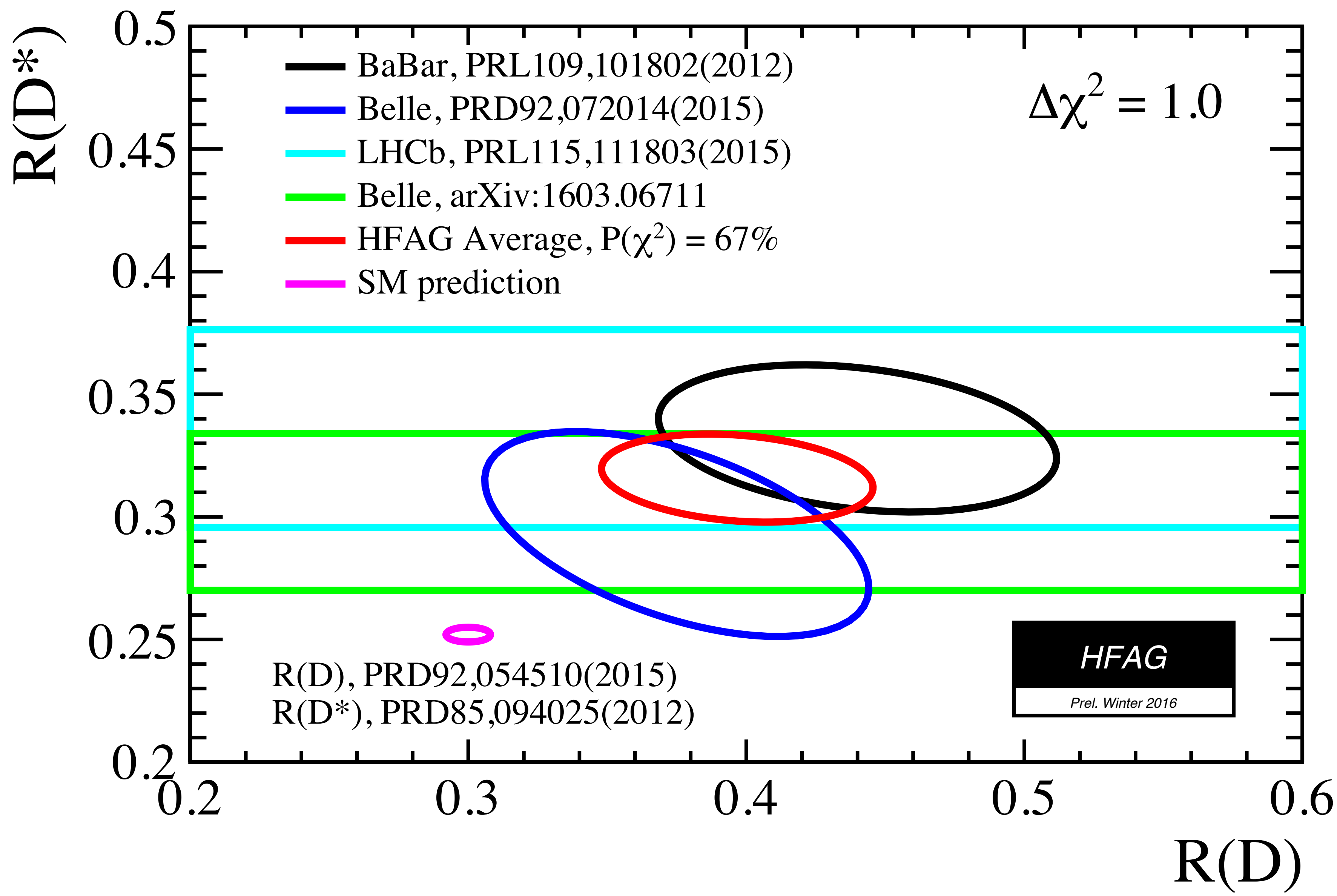
Is New Physics lurking in semi-leptonic B-decays?

2. Measured rates for $B \to D\tau\nu_\tau$ and $B \to D^*\tau\nu_\tau$ are enhanced relative to SM predictions: combination $\Rightarrow$ **tension** with SM at 3.9σ level**



(**) does the tension survive at Belle?

[Figure from Heavy Flavor Averaging Group (16)]

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Is New Physics lurking in semi-leptonic B-decays?

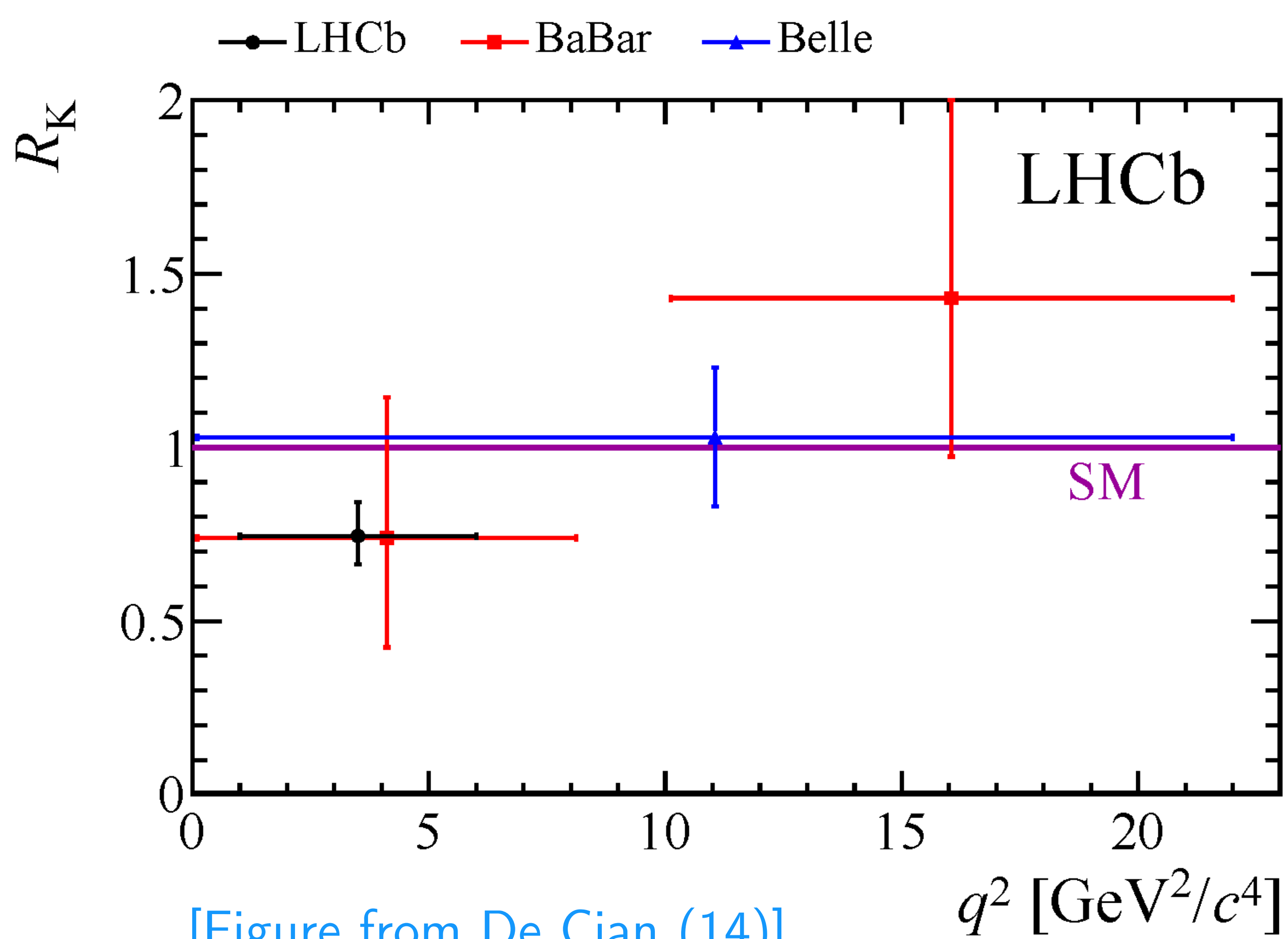
3. a 2.6σ signal of **L**epton **F**lavour **U**niversality **V**iolation (**LFUV**) in $B \to K\ell^+\ell^-$ decays

$$R_K = \frac{\mathrm{Br}[B^+ \to K^+\mu^+\mu^-]_{[1,6]}}{\mathrm{Br}[B^+ \to K^+e^+e^-]_{[1,6]}} = 0.745 \cdot (1 \pm 13\%)$$ [LHCb (14)]

vs.

$$R_K^{\mathrm{SM}} = 1.003 \pm 0.0001$$

[Bobeth, Hiller, Piranishvili (07)]



[Figure from De Cian (14)]

0 | Motivation

Each deviation at most a 3σ effect, but ... global fits with other $b \to s$ transitions indicate [Altmannshofer & Straub (15); Descotes-Genon et al. (15)]

- **N**ew **P**hysics (**NP**) is preferred over SM by 4-5σ
- The effect is in μμ modes only

Expressed in terms of the effective ΔB=1 Hamiltonian

$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_i C_i^B(\mu) Q_i^B(\mu)$$

potential NP interpreted as contributions to Wilson coefficients $C_{9,10}^B$ of

$$Q_9^B = \frac{e^2}{32\pi^2} [\bar{s}\gamma^\mu(1-\gamma_5)b] \sum_{\ell=e,\mu} [\bar{\ell}\gamma_\mu \ell] \qquad \text{(vector)}$$

$$Q_{10}^B = \frac{e^2}{32\pi^2} [\bar{s}\gamma^\mu(1-\gamma_5)b] \sum_{\ell=e,\mu} [\bar{\ell}\gamma_\mu \gamma_5 \ell] \qquad \text{(axial-vector)}$$

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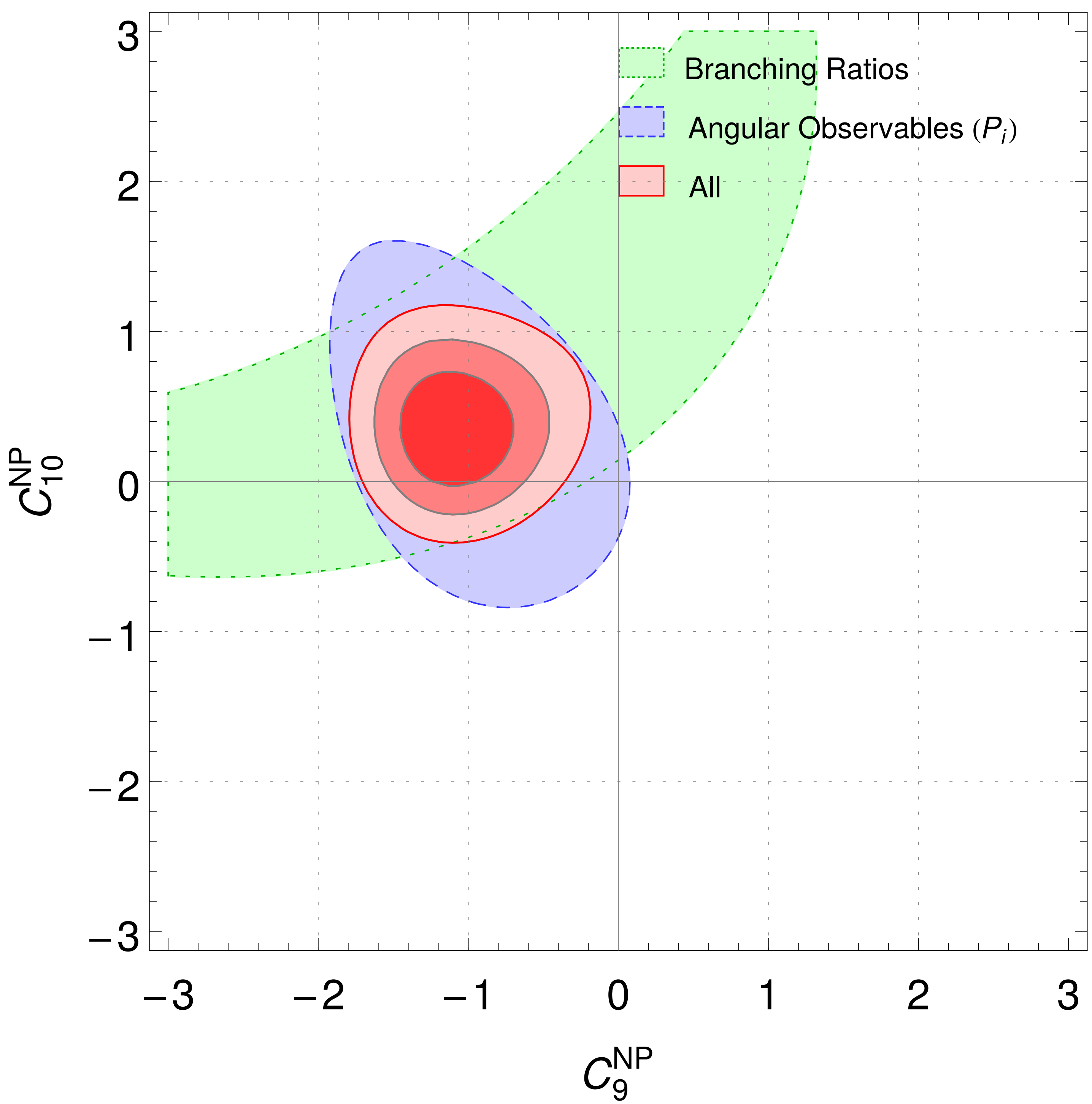
An explanation of the B-anomalies typically requires pulls of $C_{9,10}^{\text{NP}} \sim O(1)$

$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_i C_i^B(\mu) Q_i^B(\mu)$$

$$Q_9^B = \frac{e^2}{32\pi^2} \left[\bar{s}\gamma^\mu (1-\gamma_5) b\right] \sum_{\ell=e,\mu} \left[\bar{\ell}\gamma_\mu \ell\right]$$

$$Q_{10}^B = \frac{e^2}{32\pi^2} \left[\bar{s}\gamma^\mu (1-\gamma_5) b\right] \sum_{\ell=e,\mu} \left[\bar{\ell}\gamma_\mu \gamma_5 \ell\right]$$

[Figure from Descotes-Genon et al. (15)]



1 | Kaon probes of LFUV

This talk: examine complementary role that **rare kaon decays** can provide in testing NP explanations of the B-anomalies

Key idea & outline

1. Consider low energy scales $\mu \ll m_{t,b,c}$ and decouple heavy quarks

$$\mathcal{L}_{\rm eff} = -\frac{G_F}{\sqrt{2}} V_{ud} V_{us}^* \sum_i C_i(\mu) Q_i(\mu) \qquad (\Delta S = 1)$$

Observe that the semi-leptonic operators

$$Q_{7V} = [\bar{s}\gamma^\mu(1-\gamma_5)d] \sum_{\ell=e,\mu} [\bar{\ell}\gamma_\mu \ell]$$

$$Q_{7A} = [\bar{s}\gamma^\mu(1-\gamma_5)d] \sum_{\ell=e,\mu} [\bar{\ell}\gamma_\mu \gamma_5 \ell]$$

are the $s \to d$ **analogues** of the $b \to s$ operators $Q^B_{9,10}$

1 | Kaon probes of LFUV

2. Assuming **M**inimal **F**lavour **V**iolation (**MFV**) in the **quark sector** observe that

$$C_{7V,7A} \text{ are correlated with } C^B_{9,10}$$

$\Rightarrow$ convert knowledge of $C_{7V,7A}$ into **bounds** on $C^B_{9,10}$

Problem: quality of bounds limited by non-perturbative effects from QCD

$\Rightarrow$ parameterise ignorance via low-energy constants (**LECs**) of χPT

3. Focus on **experimental determination** of LECs in rare kaon decays

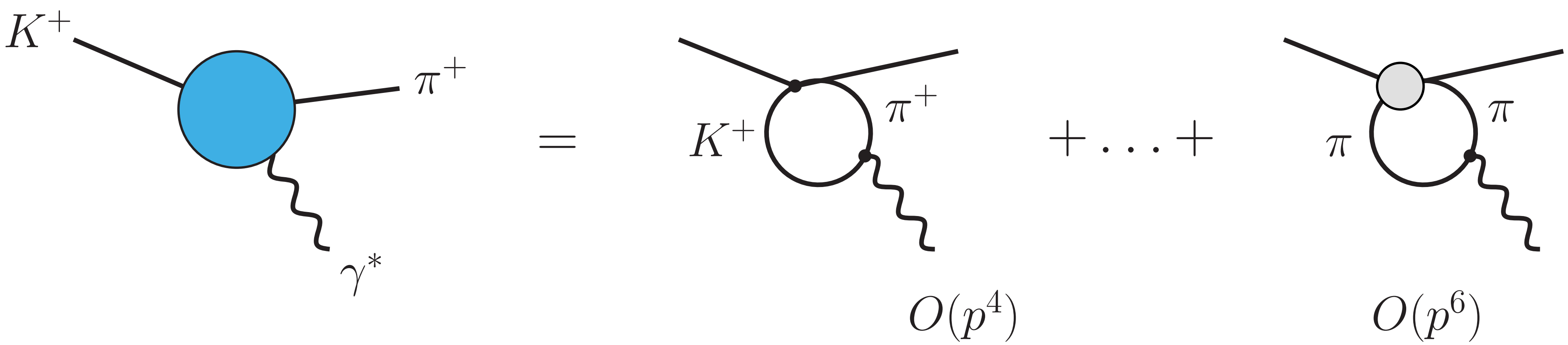
$$K^\pm \to \pi^\pm \ell^+ \ell^- \qquad \text{and} \qquad K_L \to \ell^+ \ell^-$$

NB. Measurements at **NA62** may improve the resulting limits on $C^B_{9,10}$

4. Similar strategy adopted to obtain bounds on **LFV** in B-meson sector

2 | LFUV and $K^\pm \to \pi^\pm \ell^+ \ell^-$

Dominant contribution to $K^\pm \to \pi^\pm \ell^+ \ell^-$ due to $K^\pm \to \pi^\pm \gamma^*$ transition:



[Ecker et al. (87)] [D'Ambrosio et al. (98)]

Chiral dynamics contained in vector form factor:

$$V_+(z) = a_+ + b_+ z + V_+^{\pi\pi}(z)\,, \qquad z = q^2/m_K^2$$

Chiral symmetry alone does not constrain value of LECs a_+ and b_+

[Recent lattice determinations at unphysical kinematics, Christ et al. (15 & 16 & 16); See also Chris Sachrajda's talk]

$\Rightarrow$ consider **measurements** of spectrum $d\Gamma/dz \propto |V_+(z)|^2$

2 | LFUV and $K^\pm \to \pi^\pm \ell^+ \ell^-$

Fits to E865 and NA48/2 spectra yield

$$a_+^{ee} = -0.584 \pm 0.008 \qquad a_+^{\mu\mu} = -0.575 \pm 0.039$$

Key point: if LFU applies $\Rightarrow$ $a_+^{ee} \equiv a_+^{\mu\mu}$ (valid in SM)

$\therefore$ LFUV can be probed in differences such as $a_+^{ee} - a_+^{\mu\mu} \neq 0$

One can show that $C_{7V}^{\mu\mu} - C_{7V}^{ee} = \alpha \dfrac{a_+^{\mu\mu} - a_+^{ee}}{2\pi\sqrt{2} V_{ud} V_{us}^*}$

$\Rightarrow$ In MFV framework, difference converted into constraint

$$C_9^{B,\mu\mu} - C_9^{B,ee} = -\frac{a_+^{\mu\mu} - a_+^{ee}}{\sqrt{2} V_{ts}^* V_{td}} \approx -19 \pm 79$$

2 | LFUV and $K^\pm \to \pi^\pm \ell^+ \ell^-$

Conclude?

$$C_9^{B,\mu\mu} - C_9^{B,ee} = -\frac{a_+^{\mu\mu} - a_+^{ee}}{\sqrt{2} V_{ts}^* V_{td}} \approx -19 \pm 79$$

- NP parameter space relevant for B-anomalies involves $C_{9,10}^B = O(1)$

$\Rightarrow$ Determination of $a_+^{\mu\mu} - a_+^{ee}$ needs (at least) order of magnitude improvement to probe NP explanations of B-anomalies

- Remarkably, improvements of this size may be possible at the NA62 experiment:

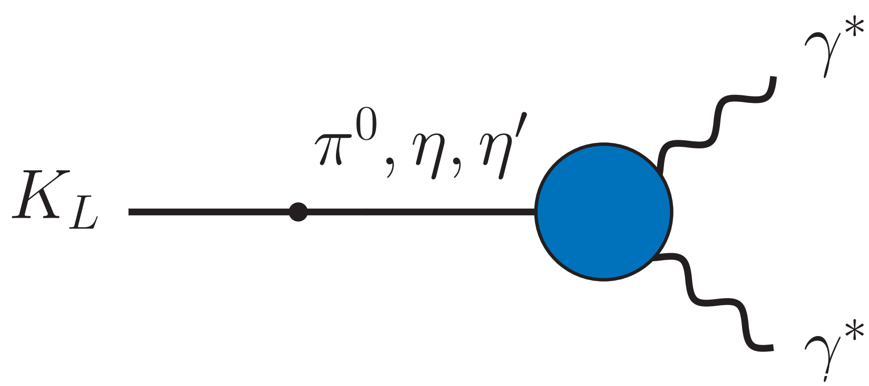
High statistics: nominal # of decays $\approx$ 50 times greater than NA48/2

$\Rightarrow$ **Proposal:** measure $K^\pm \to \pi^\pm \ell^+ \ell^-$ spectrum to extract $a_+^{\mu\mu}$ at high precision (currently has largest uncertainty)

3 | LFUV and $K_L \to \ell^+\ell^-$

Complementary to $K^\pm \to \pi^\pm \ell^+\ell^-$ since probes LFUV effects due to **axial-vector** interactions

Dominant long-distance contribution due to $K_L \to \gamma^*\gamma^* \to \ell^+\ell^-$



[Gomez Dumm & Pich (98); Knecht et al. (99); Isidori & Unterdorfer (03)]

Dispersive component of amplitude (normalised to $K_L \to \gamma\gamma$):

$$F_{\ell,\text{disp}} = \frac{1}{4\beta_\ell}\log^2\left(\frac{1-\beta_\ell}{1+\beta_\ell}\right) + \frac{1}{\beta_\ell}\text{Li}_2\left(\frac{\beta_\ell - 1}{\beta_\ell + 1}\right) + \frac{\pi^2}{12\beta_\ell} + 3\log\frac{m_\ell}{\mu} + \chi(\mu)$$

LECs strike again!

$$\chi(\mu) = \chi_{\gamma\gamma}(\mu) + \chi_{\text{SD}}$$

3 | LFUV and $K_L \to \ell^+\ell^-$

Same argument as for $K^\pm \to \pi^\pm \ell^+\ell^-$: if LFU applies $\Rightarrow$ $\chi_{ee} \equiv \chi_{\mu\mu}$

$\therefore$ LFUV can be probed by considering the difference

$$C_{7A}^{\mu\mu} - C_{7A}^{ee} = \underbrace{-\frac{\alpha}{F_K G_F V_{ud} V_{us}^*} \left(\frac{2\Gamma_{\gamma\gamma}}{\pi m_K^3} \right)^{1/2}}_{\text{measured quantities}} (\chi_{\mu\mu} - \chi_{ee})$$

$\Rightarrow$ In MFV framework, difference related to **axial-vector** coefficients

$$C_{10}^{B,\mu\mu} - C_{10}^{B,ee} = 2.6 \left(\frac{3.5 \times 10^{-4}}{V_{ts}^* V_{td}} \right) (\chi_{\mu\mu} - \chi_{ee})$$

Quality of bounds on $C_{10}^{B,\ell\ell}$ depends on **precision** with which $\chi_{\ell\ell}$ can be determined

3 | LFUV and $K_L \to \ell^+\ell^-$

Extract $\chi_{\ell\ell}$ from data?

The present situation is as follows:

- Fit to measured rates yields two solutions per channel

Channel	χ (Solution 1)	χ (Solution 2)
ee	$5.1^{+15.4}_{-10.3}$	$-(57.5^{+15.4}_{-10.3})$
$\mu\mu$	3.75 ± 0.20	1.52 ± 0.20

- Suppose uncertainty can be reduced at future K_L experiment (e.g. side programme at **NA62**) by factor of ≈ 10:

$$\chi_{\mu\mu} - \chi_{ee} \approx 1.3 \pm 1.3 \qquad \Leftrightarrow \qquad C_{10}^{B,\mu\mu} - C_{10}^{B,ee} \approx 3.5 \pm 3.5$$

$\Rightarrow$ Improvement required to obtain competitive bounds on $C_{10}^{B,\ell\ell}$ of similar magnitude to that found for $C_9^{B,\ell\ell}$ in $K^\pm \to \pi^\pm \ell^+\ell^-$

4 | Lepton flavour violating decays

Adopt similar strategy to analysis of LFUV in $K \to \pi\ell\ell$ and $K_L \to \ell\ell$:

$$\{\text{Limits on kaon sector } C^{\mu e}_{7V,7A}\} \overset{\text{MFV}}{\Longleftrightarrow} \{\text{Bounds on } b \to s \text{ transitions}\}$$

Analysis simplified by absence of LFV in SM (modulo ν oscillations)

$\Rightarrow$ amplitude factorises so **no problem with LECs**

Key modes

$$\mathrm{Br}[K^+ \to \pi^+ \mu^\pm e^\mp] \propto \{|C^{\mu e}_{7V}|^2 + |C^{\mu e}_{7A}|^2\} \quad \textbf{(NA62)}$$

$$\mathrm{Br}[K_L \to \mu^\pm e^\mp] \propto \{|C^{\mu e}_{7V}|^2 + |C^{\mu e}_{7A}|^2\} \quad \textbf{(NA62?)}$$

	$K_L \to \mu^\pm e^\mp$	$K^+ \to \pi^+ \mu^\pm e^\mp$	$K_L \to \pi^0 \mu^\pm e^\mp$	$K^+ \to \pi^+ \mu^\pm e^\mp$ (NA62 projection)
$\left(\lvert C^{\mu e}_{7V}\rvert^2 + \lvert C^{\mu e}_{7A}\rvert^2\right)^{1/2}$	$< 1.3 \times 10^{-6}$	$< 2.2 \times 10^{-5}$		$< 5.1 \times 10^{-6}$
$\left(\lvert y^{\mu e}_{7V}\rvert^2 + \lvert y^{\mu e}_{7A}\rvert^2\right)^{1/2}$			< 0.040	
$\left(\lvert C^{B,\mu e}_{9}\rvert^2 + \lvert C^{B,\mu e}_{10}\rvert^2\right)^{1/2}$	< 0.71	< 12	< 35	< 2.7

Strongest bound from $K_L \to \mu e$ ... but remove GigaTracker at NA62?

5 | Remarks and future prospects

Rare kaon decays offer probe into NP explanations of anomalies @ LHCb

Within framework of MFV in the **quark sector** have discussed how

$$\{\text{Limits on LFUV \& LFV in K decays}\} \quad \Leftrightarrow \quad \{\text{Bounds on } C^{B}_{9,10}\}$$

Potential NP may not satisfy MFV $\Rightarrow$ 3 possibilities to test at **NA62**:

1. NP explanation of B-anomalies consistent with MFV [e.g. Crivellin et al. (15)]
   $\Rightarrow$ should see **signal** at projected sensitivities

2. Kaon searches at MFV-expected sensitivity turn out negative
   $\Rightarrow$ any NP explanation of B-anomalies requires departures from MFV

3. Signal observed at current or slightly improved sensitivity
   $\Rightarrow$ can rule out NP explanations of B-anomalies based on MFV