

# Flavour Physics (of quarks)

## Part 4: Flavour Changing Neutral Currents

Matthew Kenzie

**Cavendish HEP Graduate Lectures**

February 2024

## Lecture 1: Flavour in the SM

- ▶ Flavour in the SM
- ▶ Quark Model History
- ▶ The CKM matrix

## Lecture 2: Mixing and $CP$ violation

- ▶ Neutral Meson Mixing (no CPV)
- ▶  $B$ -meson production and experiments
- ▶  $CP$  violation

## Lecture 3: Measuring the CKM parameters

- ▶ Measuring CKM elements and phases
- ▶ Global CKM fits
- ▶  $CPT$  and  $T$ -reversal
- ▶ Dipole moments

## Lecture 4: Flavour Changing Neutral Currents (Today)

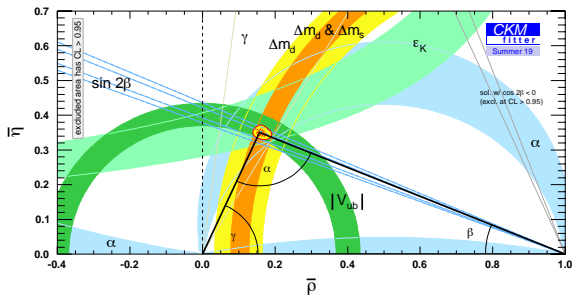
- ▶ Effective Theories
- ▶ New Physics in  $B$  mixing
- ▶ New Physics in rare  $b \rightarrow s$  processes
- ▶ Lepton Flavour Violation

## 1. Recap

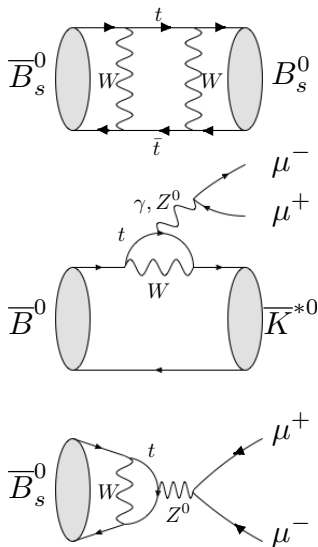
# Recap

Last time we looked at

- ▶ Measurements of the CKM matrix elements
- ▶ Measurements of the CKM matrix phases
- ▶ Recall from Lecture 1 the lack of tree-level flavour-changing-neutral-currents (FCNCs) in the SM



- ▶ FCNC processes can probe incredibly high mass scales (well beyond those directly accessible at the LHC)
  - ▶ If there are new particles at the TeV-scale, why don't they manifest themselves in FCNC processes (the so-called "flavour problem")
- ▶ There are two types of FCNC process:
  - ▶  $\Delta F = 2$ : meson anti-meson mixing
  - ▶  $\Delta F = 1$ : "rare decays" e.g.  $B_s^0 \rightarrow \mu^+ \mu^-$  or  $B^0 \rightarrow K^{*0} \mu^+ \mu^-$
- ▶ In the SM these processes are heavily suppressed
  - ▶ They are loop processes that are CKM suppressed and (depending on the process) can also be GIM suppressed and/or helicity suppressed

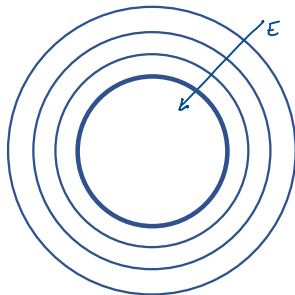


## 3. Effective Theories

# It is all about scale

- *Why is unnatural fine-tuning such a big deal?*

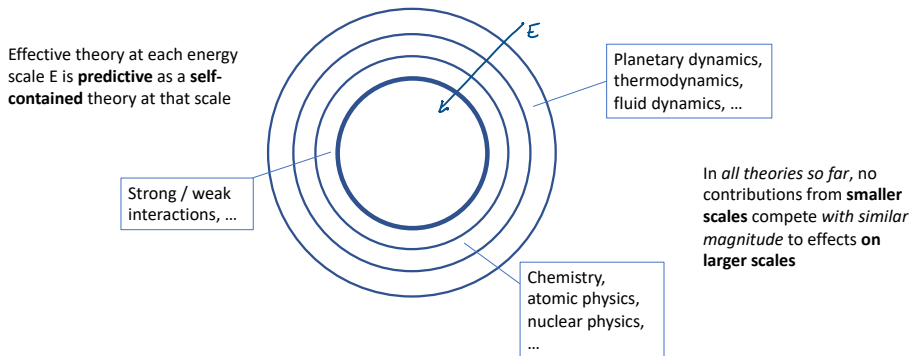
Effective theory at each energy scale  $E$  is **predictive** as a **self-contained** theory at that scale



[Slide stolen from T. You](#)

# It is all about scale

- *Why is unnatural fine-tuning such a big deal?*

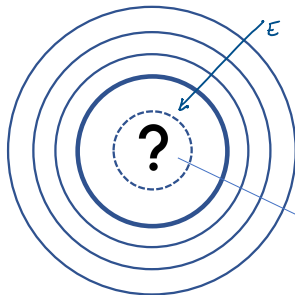


[Slide stolen from T. You](#)

# It is all about scale

- *Why is unnatural fine-tuning such a big deal?*
- Indicates an *unprecedented breakdown* of the **effective theory** structure of nature

Effective theory at each energy scale  $E$  is **predictive** as a **self-contained** theory at that scale



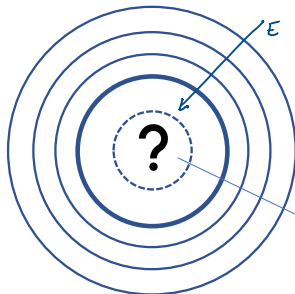
**Unnatural Higgs** means the next layer *is no longer predictive* without including contributions from much smaller scales

[Slide stolen from T. You](#)

# It is all about scale

- *Why is unnatural fine-tuning such a big deal?*
- Indicates an *unprecedented breakdown* of the **effective theory** structure of nature

Effective theory at each energy scale  $E$  is **predictive** as a **self-contained** theory at that scale



**Unnatural Higgs** means the next layer *is no longer predictive* without including contributions from much smaller scales

- Are we missing a **fundamentally new** “*post-naturalness*” principle? c.f. null results in search for aether

[Slide stolen from T. You](#)

# Effective Theories

- ▶ In meson/baryon decays there is a clear separation of scales which we can “decouple”
  - ▶  $b$  quark states have  $m \sim 5$  GeV while particles in loops ( $W^\pm, t$ ) have  $m \sim 100$  GeV

$$m_W \gg m_b > \Lambda_{\text{QCD}} \quad (1)$$

- ▶ We want to study the physics of the mixing/decay at or below a scale,  $\Lambda_{\text{NP}}$ , in a theory which has contributions from particles at a scale **below and above**  $\Lambda_{\text{NP}}$
- ▶ We can replace the full theory with an effective theory (which is renormalisable) valid at  $\Lambda$

$$\mathcal{L}(\phi_L, \phi_H) \rightarrow \mathcal{L}(\phi_L) + \mathcal{L}_{\text{eff}} = \mathcal{L}(\phi_L) + \underbrace{\sum_i C_i \mathcal{O}_i(\phi_L)}_{\text{operator product expansion}} \quad (2)$$

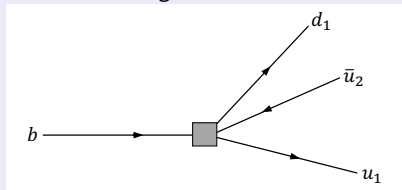
- ▶ In other words for interactions originating at a high scale (*i.e.* SM+NP) we get an effective matrix element

$$\langle f | H_{\text{eff}} | i \rangle = \sum_k \frac{1}{\Lambda^k} \sum_i \underbrace{C_{k,i}}_{\substack{\text{short distance} \\ \text{contribution} \\ \text{(physics} > \Lambda)}} \underbrace{\langle f | \mathcal{O}_k | i \rangle}_\Lambda_{\substack{\text{"Local operators"} \\ \text{long distance} \\ \text{contribution} \\ \text{(physics} < \Lambda)}} \quad (3)$$

- ▶ The so-called “**Wilson coefficients**” are independent of  $\Lambda$

## Non-leptonic $b$ decay

e.g.  $b \rightarrow u\bar{c}s$



$$H_{\text{eff}}(b \rightarrow u_1 \bar{u}_2 d_1) =$$

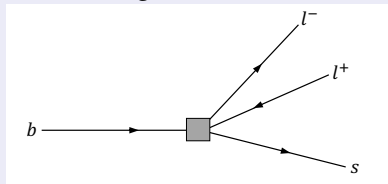
$$\frac{G_F}{\sqrt{2}} V_{u_1 b} V_{u_2 d_1}^* [\mathcal{C}_1 \mathcal{O}_1^{u_1 \bar{u}_2 d_1} + \mathcal{C}_2 \mathcal{O}_2^{u_1 \bar{u}_2 d_1}]$$

$$\mathcal{O}_1^{u_1 \bar{u}_2 d_1} = (\bar{u}_1^\alpha \gamma_\mu (1 - \gamma_5) b^\beta) (\bar{d}_1^\beta \gamma^\mu (1 - \gamma_5) u_2^\alpha)$$

$$\mathcal{O}_2^{u_1 \bar{u}_2 d_1} = (\bar{u}_1^\alpha \gamma_\mu (1 - \gamma_5) b^\alpha) (\bar{d}_1^\beta \gamma^\mu (1 - \gamma_5) u_2^\beta)$$

## EW penguin

e.g.  $b \rightarrow s \ell^+ \ell^-$



$$H_{\text{eff}}(b \rightarrow s \ell^+ \ell^-) =$$

$$\frac{2G_F}{\sqrt{2}} V_{ts} V_{tb}^* \sum_{i=9,10} c_i \mathcal{O}_i$$

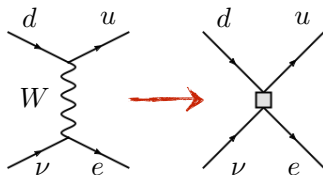
$$\mathcal{O}_9 = (\bar{s}_L \gamma_\mu b_L) (\bar{\ell} \gamma^\mu \ell)$$

$$\mathcal{O}_{10} = (\bar{s}_L \gamma_\mu b_L) (\bar{\ell} \gamma^\mu \gamma_5 \ell)$$

$$\mathcal{C} = \mathcal{C}_{\text{SM}} + \mathcal{C}_{\text{NP}} \quad \text{and is complex}$$

# Fermi's theory

- ▶ In the Fermi model of the weak interaction, the full electroweak Lagrangian (which was unknown at the time) is replaced by a low-energy theory (QED) plus a single operator with an effective coupling constant

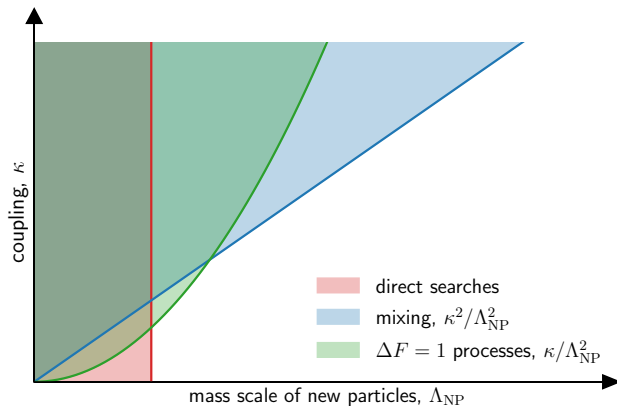


- ▶ At low energies the full theory can be replaced by a 4-fermion operator and a single coupling constant,  $G_F$ , as

$$\lim_{q^2 \rightarrow 0} \left( \frac{g^2}{m_W^2 - q^2} \right) = \frac{g^2}{m_W^2} \quad (4)$$

- ▶ The Lagrangian simplifies to

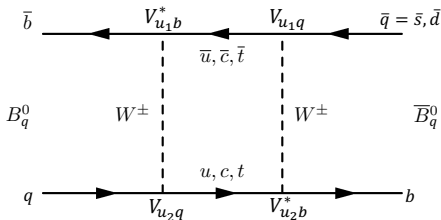
$$\mathcal{L}_{EW} \rightarrow \mathcal{L}_{QED} + \frac{G_F}{\sqrt{2}} (\bar{u}d)(e\bar{\nu}) \quad (5)$$



- ▶ In reality the direct searches do have *some* dependence on  $\kappa$  as you need a coupling to SM particles in order to produce the new particles in  $pp$  collisions

4.  $\Delta F = 2$  processes (NP in  $B$  mixing)

- ▶ Take neutral  $B$  mixing diagram as an example



- ▶ Have an amplitude (summed over up-type quarks in the loop,  $u_1, u_2$ )

$$\mathcal{A}(B_q^0 \rightarrow \bar{B}_q^0) = \sum_{u_1, u_2} (V_{u_1 b}^* V_{u_1 q})(V_{u_2 b}^* V_{u_2 q}) A_{u_1 u_2} \quad \text{where} \quad A_{u_1 u_2} \propto m_{u_1} m_{u_2} / m_W^2 \quad (6)$$

- ▶ Inserting the known CKM constraint  $V_{ub}^* V_{ud} + V_{cb}^* V_{cd} + V_{tb}^* V_{td} = 0$  gives

$$\mathcal{A}(B_q^0 \rightarrow \bar{B}_q^0) = \sum_{u_1} (V_{u_1 b}^* V_{u_1 d} [V_{tb}^* V_{td} (A_{tu_1} - A_{uu_1}) + V_{cb}^* V_{cd} (A_{cu_1} - A_{uu_1})]) \quad (7)$$

so for the  $B$  system the top totally dominates as  $A_{tu_1} \gg A_{cu_1} \gg A_{uu_1}$

- ▶ Introducing new physics at some higher scale,  $\Lambda_{\text{NP}}$ , with coupling,  $\kappa_{\text{NP}}$

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{\kappa_{\text{NP}}^2}{\Lambda_{\text{NP}}^{d-4}} \mathcal{O}_i^{(d)} \quad (8)$$

- ▶ With the **SM contribution** from the box diagram

$$(V_{tb}^* V_{td})^2 \frac{g^4 m_t^2}{16\pi^2 m_W^4}$$

- ▶ and a **NP contribution** (at dimension 6)

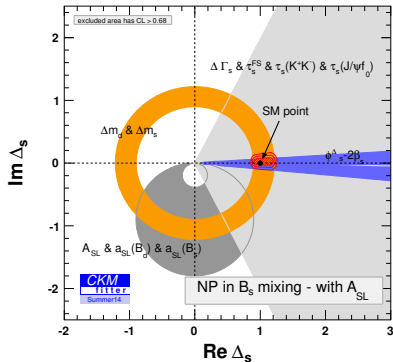
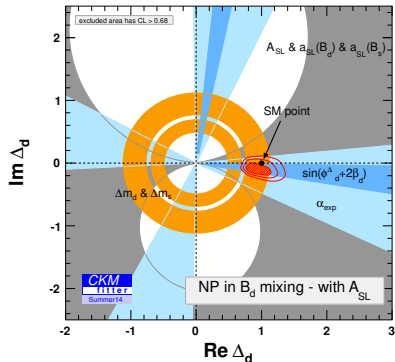
$$\frac{\kappa_{\text{NP}}^2}{\Lambda_{\text{NP}}^2}$$

# New physics in $B$ mixing

- ▶ Quantify the NP contribution to  $B$  mixing with a multiplicative factor such that

$$M_{12} = M_{12,SM} \cdot \Delta_q \quad (9)$$

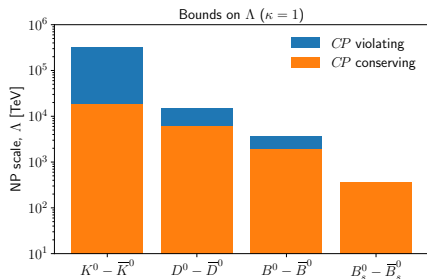
- ▶ Constraints provided by CKM fitter show that the result is consistent with the SM (i.e.  $\text{Re}(\Delta) = 1$  and  $\text{Im}(\Delta) = 0$ )



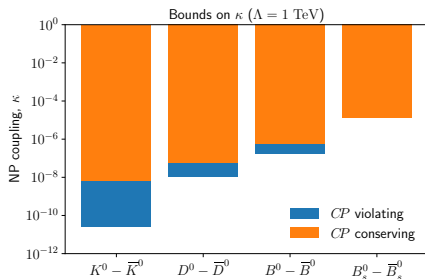
# New physics constraints from neutral mixing

- ▶ So far everything shows consistency with the SM
- ▶ We can use this to set limits on the size of the NP scale ( $\Lambda$ ) or coupling to SM ( $\kappa$ )

Plots produced using [\[arXiv:1002.0900\]](https://arxiv.org/abs/1002.0900)



Scale of NP if  $\kappa = 1$



Size of  $\kappa$  if  $\Lambda = 1$  TeV

## Small couplings?

- ▶ New flavour violating sources (if there are any) must be highly tuned
  - ▶ Either come with a very small coupling constant
  - ▶ Or must have a very large mass
- ▶ For an  $\mathcal{O}(1)$  effect:

- ▶ generic tree-level

$$\kappa_{\text{NP}} \sim 1 \quad \longrightarrow \quad \Lambda_{\text{NP}} \gtrsim 10^4 \text{ TeV}$$

- ▶ generic loop-order

$$\kappa_{\text{NP}} \sim \frac{1}{(4\pi)^2} \quad \longrightarrow \quad \Lambda_{\text{NP}} \gtrsim 10^3 \text{ TeV}$$

- ▶ tree-level with “alignment”

$$\kappa_{\text{NP}} \sim (y_t V_{ti}^* V_{tj})^2 \quad \longrightarrow \quad \Lambda_{\text{NP}} \gtrsim 5 \text{ TeV}$$

- ▶ loop-order with “alignment”

$$\kappa_{\text{NP}} \sim \frac{(y_t V_{ti}^* V_{tj})^2}{(4\pi)^2} \quad \longrightarrow \quad \Lambda_{\text{NP}} \gtrsim 0.5 \text{ TeV}$$

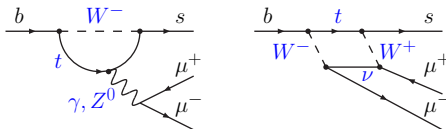
# Minimal Flavour Violation

- ▶ One way of achieving small couplings is to build models that have a flavour structure which is “aligned” with the CKM matrix
  - ▶ Require that the Yukawa couplings are also the unique source of flavour breaking beyond the SM
- ▶ This is referred to as **minimal flavour violation** (MFV)
- ▶ The couplings to new particles are naturally suppressed by the Hierarchy of CKM elements
- ▶ Clearly this massively degrades the sensitivity to finding it

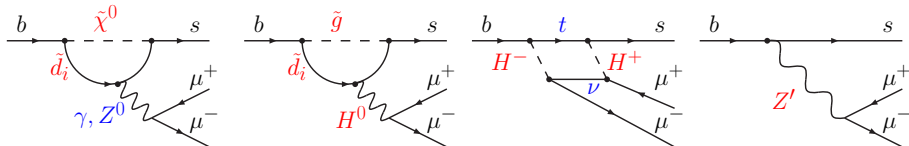
5.  $\Delta F = 1$  processes (Rare  $B$  decays)

# $\Delta F = 1$ FCNC decays

- ▶ FCNC transitions only occur at loop order (and beyond) in the SM
- ▶ The SM diagrams involve the charged current interaction ( $W^\pm$ )



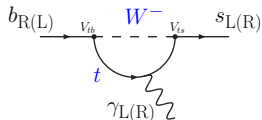
- ▶ New particles can also contribute (at either tree or loop level depending on the NP characteristics)



- ▶ The effect of the NP amplitudes can be to enhance (or suppress) decays, introduce new sources of  $CP$  violation or modify angular distributions of final-state particles (as their spin structure and coupling will be different to the SM)

## Properties of $\Delta F = 1$ processes

- ▶ There are a large number of other observables that can be considered
- ▶ In the SM, photons from  $b \rightarrow s\gamma$  decays are predominantly left-handed ( $C_7/C_7' \sim m_b/m_s$ ) due to the charged current interaction



- ▶ The flavour structure of the SM implies that the rate of  $b \rightarrow d$  processes is suppressed by  $|V_{td}/V_{ts}|^2$  relative to  $b \rightarrow s$  processes
- ▶ In the SM

$$\Gamma(B \rightarrow M\mu^+\mu^-) \approx \Gamma(B \rightarrow Me^+e^-)$$

due to the universal couplings of the gauge bosons (except the Higgs) to the different lepton flavours (known as **lepton universality**). The only differences in the rate come down to phase-space considerations

- ▶ Direct lepton flavour violation is unobservable **in the SM** at any conceivable experiment due to the small size of the neutrino mass

# The effective theory for rare $b \rightarrow s$ decays

- ▶ Can write an effective theory Hamiltonian as

$$H_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \frac{\alpha_e}{4\pi} \sum_i C_i(\mu) \mathcal{O}_i(\mu) \quad (10)$$

Weak decay,  $(1/m_W)^2$

CKM suppression

Loop suppression,  $(1/4\pi)^2$

Wilson coefficient (integrating out scales above  $\mu$ )

Local operator with different Lorentz structure (vector, axial vector etc.)

- ▶ Then introduce new particles that give rise to corrections

$$\Delta H_{\text{eff}} = \frac{\kappa_{\text{NP}}}{\Lambda_{\text{NP}}^2} \mathcal{O}_{\text{NP}} \quad (11)$$

NP scale

local operator

- ▶ The constant  $\kappa$  can share some, all or none of the suppression of the SM process

# Leptonic decay operators

- ▶ Have already seen some of the non-leptonic operators (and the  $b \rightarrow sl^+\ell^-$  operators  $\mathcal{O}_9$  and  $\mathcal{O}_{10}$ )

$$\mathcal{O}_7 = \frac{m_b}{e} \bar{s} \sigma^{\mu\nu} P_R b F_{\mu\nu}$$

EW penguin

$$\mathcal{O}_8 = g_s \frac{m_b}{e^2} \bar{s} \sigma^{\mu\nu} P_R T^\alpha b G_{\mu\nu}^\alpha$$

gluonic penguin

$$\mathcal{O}_9 = \bar{s} \gamma_\mu P_L b \bar{\ell} \gamma^\mu \ell$$

vector current

$$\mathcal{O}_{10} = \bar{s} \gamma_\mu P_L b \bar{\ell} \gamma^\mu \gamma_5 \ell$$

axial-vector current

$$\mathcal{O}'_7 = \frac{m_b}{e} \bar{s} \sigma^{\mu\nu} P_L b F_{\mu\nu}$$

$$\mathcal{O}'_8 = g_s \frac{m_b}{e^2} \bar{s} \sigma^{\mu\nu} P_L T^\alpha b G_{\mu\nu}^\alpha$$

$$\mathcal{O}'_9 = \bar{s} \gamma_\mu P_R b \bar{\ell} \gamma^\mu \ell$$

$$\mathcal{O}'_{10} = \bar{s} \gamma_\mu P_R b \bar{\ell} \gamma^\mu \gamma_5 \ell$$

right handed currents  
(suppressed in the SM)

- ▶ Scalar and pseudo-scalar operators (e.g. from Higgs penguins)

$$\begin{aligned}\mathcal{O}_S &= \bar{s}P_R b \bar{\ell} \ell, & \mathcal{O}'_S &= \bar{s}P_L b \bar{\ell} \ell \\ \mathcal{O}_P &= \bar{s}P_R b \bar{\ell} \gamma_5 \ell, & \mathcal{O}'_P &= \bar{s}P_L b \bar{\ell} \gamma_5 \ell\end{aligned}$$

- ▶ Tensor operators

$$\mathcal{O}_T = \bar{s} \sigma_{\mu\nu} b \bar{\ell} \sigma^{\mu\nu} \ell, \quad \mathcal{O}'_T = \bar{s} \sigma_{\mu\nu} b \bar{\ell} \sigma^{\mu\nu} \ell$$

- ▶ All of these are vanishingly small in the SM
- ▶ **In principle one could also introduce LFV versions of every operator**

- ▶ In the effective theory we then have

$$\mathcal{A}(B \rightarrow f) = V_{tb}^* V_{tq} \sum_i C_i(M_W) U(\mu, m_W) \langle f | \mathcal{O}_i(\mu) | B \rangle \quad (12)$$

had. mat. elem.

- ▶ For **inclusive processes** the sum over exclusive states is related to the quark level decays

$$\mathcal{B}(B \rightarrow X_s \gamma) = \mathcal{B}(b \rightarrow s \gamma) + \mathcal{O}(\Lambda_{\text{QCD}}^2 / m_B^2) \quad (13)$$

- ▶ For **exclusive processes** we need to compute form-factors / decay constants
- ▶ In leptonic decays the matrix element can be factorised into a leptonic current and a  $B$  meson decay constant,  $f_{B_q}$

$$\langle \ell^+ \ell^- | j_\ell j_q | B_q \rangle = \langle \ell^+ \ell^- | j_\ell | 0 \rangle \langle 0 | j_q | B_q \rangle \approx \langle \ell^+ \ell^- | j_\ell | 0 \rangle \cdot f_{B_q} \quad (14)$$

- ▶ In semi-leptonic decays the matrix element can be factorised into a leptonic current times a form-factor

$$\langle \ell^+ \ell^- M | j_\ell j_q | B_q \rangle = \langle \ell^+ \ell^- | j_\ell | 0 \rangle \langle M | j_q | B_q \rangle \approx \langle \ell^+ \ell^- | j_\ell | 0 \rangle \cdot F(q^2) + \mathcal{O}(\Lambda_{\text{QCD}} / m_B) \quad (15)$$

although, due to hadronic contributions, this factorisation is not exact

## 6. FCNC Experimental Results

# FCNC Experimental Results

- ▶ Will mainly focus on recent measurements of  $B$  decay processes, predominantly involving  $b \rightarrow s$  transitions
- ▶ These are some of the less well tested (only recently had sufficient samples of  $B$  decays for many of these measurements)
- ▶ FCNC decays of charm and strange can also be studied however the GIM mechanism is much more effective (*i.e.* there is a larger natural cancellation) for them
  - ▶ For the charm mesons the masses and mass differences are small (*i.e.*  $m_c - m_s$ )
  - ▶ For strange the top contribution is considerably suppressed relative to the  $B$  decays because  $V_{ts} \ll V_{tb}$
- ▶ These are some of the arguments that make  $B$  physics so compelling (at least to some)

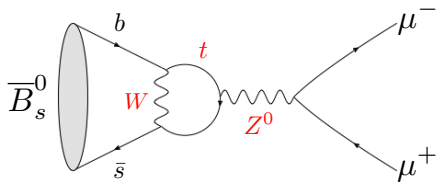
# The $B_{(s)}^0 \rightarrow \mu^+ \mu^-$ decay

- ▶  $B_s^0 \rightarrow \mu^+ \mu^-$  is the golden channel for study of FCNC decays
- ▶ It is highly suppressed in the SM
  1. Loop suppressed
  2. CKM suppressed
  3. Helicity suppressed (pseudo-scalar  $B$  to two spin- $\frac{1}{2}$  muons)

## SM process

with neutral current (axial-vector)

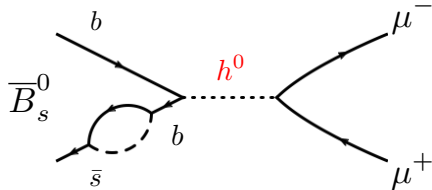
There is also a contribution from  $W^\pm$  box diagrams



## Possible NP process

with scalar operators

No helicity suppression e.g. SUSY at high  $\tan(\beta)$



# $B_s^0 \rightarrow \mu^+ \mu^-$ in the SM

- ▶ Nice and clean because only one operator contributes in the SM

$$\mathcal{O}_{10} = (\bar{s}\gamma_\mu b)(\bar{\mu}\gamma^\mu\gamma_5\mu) \quad (16)$$

- ▶ The branching fraction in the SM is

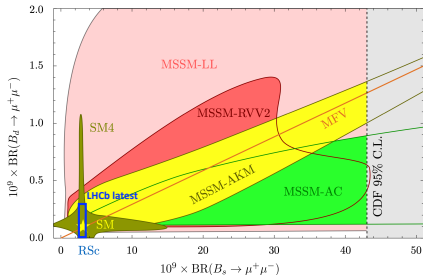
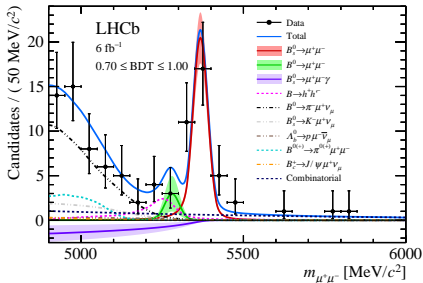
$$\mathcal{B}(B_s^0 \rightarrow \mu^+ \mu^-) = \underbrace{|V_{tb}^* V_{ts}|^2}_{\text{CKM factors}} \frac{G_F^2 \alpha_e^2}{16\pi^3 \Gamma_H} M_B M_\mu^2 \underbrace{f_B^2}_{\text{Decay constant } \langle 0 | \bar{s}\gamma^\mu\gamma_5 b | B \rangle = i f_B p^\mu} \sqrt{1 - \frac{4M_\mu^2}{M_B^2}} |\mathcal{C}_{10}(m_b)|^2 \underbrace{\left(\frac{M_\mu^2}{M_B^2}\right)}_{\text{helicity suppression}}$$

- ▶ Beyond the SM

$$\frac{\mathcal{B}(B_s^0 \rightarrow \mu^+ \mu^-)_{\text{NP}}}{\mathcal{B}(B_s^0 \rightarrow \mu^+ \mu^-)_{\text{SM}}} = \frac{1}{|\mathcal{C}_{\text{SM}}|^2} \left[ \left(1 - 4 \frac{m_\mu^2}{m_B^2}\right) \left| \frac{m_B}{2m_\mu} (\mathcal{C}_S - \mathcal{C}'_S) \right|^2 + \left| \frac{m_B}{2m_\mu} (\mathcal{C}_P - \mathcal{C}'_P) + (\mathcal{C}_{10} - \mathcal{C}'_{10}) \right|^2 \right]$$

# $B_s^0 \rightarrow \mu^+ \mu^-$ experimental results

- ▶ Observation is the end of a long road of searches
- ▶  $B_s^0 \rightarrow \mu^+ \mu^-$  ( $B^0 \rightarrow \mu^+ \mu^-$ ) now observed at  $> 7\sigma$  ( $\sim 3\sigma$ ). Both are consistent with the SM predictions
- ▶ No sign of NP here (unfortunately) but this does set some very strong constraints on many models



# Photon polarisation

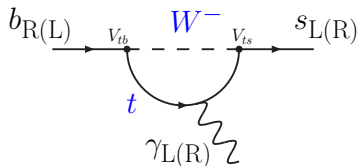
- ▶ In radiative  $B$  decays allows both

$$b_L \rightarrow s_R \gamma_R \quad (17)$$

$$b_R \rightarrow s_L \gamma_L \quad (18)$$

- ▶ However the charged current interaction **only** couples to left-handed quarks
- ▶ Need a helicity flip (boost into suitable frame) to either the  $b$  or  $s$  quark
- ▶ The right-handed contribution is therefore suppressed by

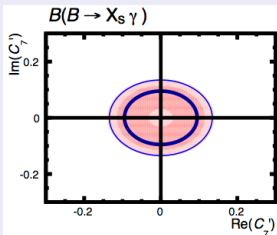
$$\frac{\mathcal{A}(b_L \rightarrow s_R \gamma_R)}{\mathcal{A}(b_R \rightarrow s_L \gamma_L)} \sim \frac{m_s}{m_b}$$



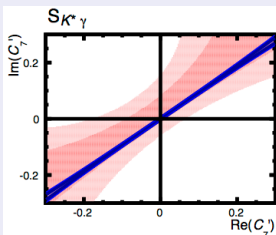
# Radiative decays

- ▶ Constraints on right-handed currents in  $b \rightarrow s\gamma$  decays
- ▶ Results are consistent with the LH polarisation expected in the SM

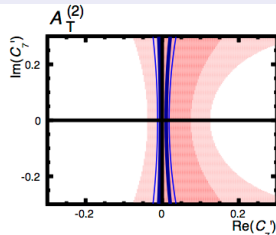
## Inclusive branching fraction



## Time-dependent $CP$ violation in $B \rightarrow [K_S^0 \pi^0] \gamma$



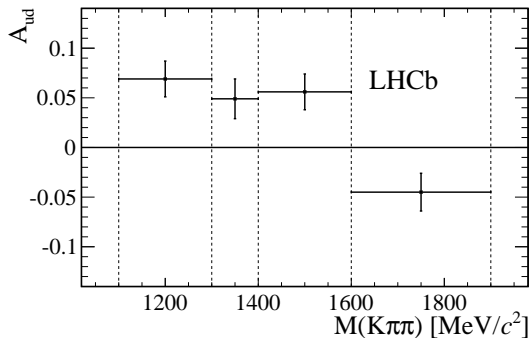
## Angular distribution of $B \rightarrow K^* e^+ e^-$



## Is the photon polarised?

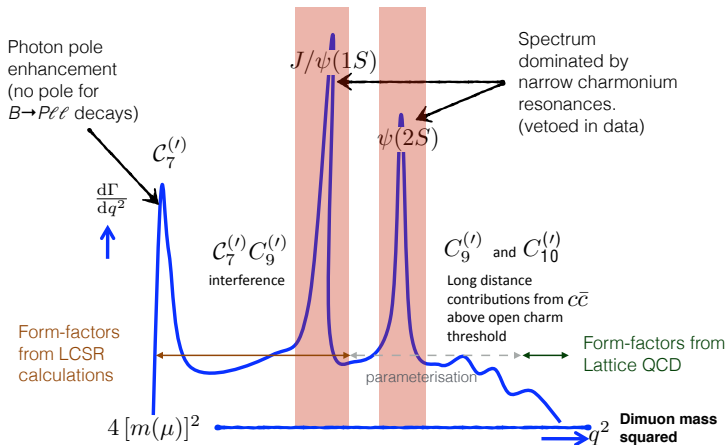
- ▶ Yes, in  $B^+ \rightarrow K^+ \pi^- \pi^+ \gamma$  decays the photon has a preferred direction with respect to the  $K^+ \pi^- \pi^+$  decay plane
- ▶ This can only happen if the photon is polarised

[arXiv:1402.6852]



$$b \rightarrow s \ell^+ \ell^-$$

- ▶ A very important class of decays for FCNC limits are  $b \rightarrow s \ell^+ \ell^-$  transitions
- ▶ Understanding distributions with respect to the invariant mass of the di-lepton spectrum ( $q^2$ ) is vital

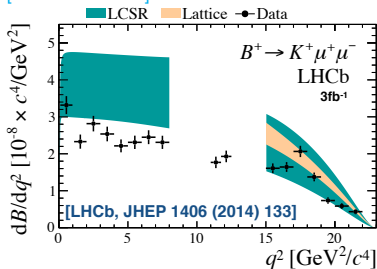


slide from Tom Blake

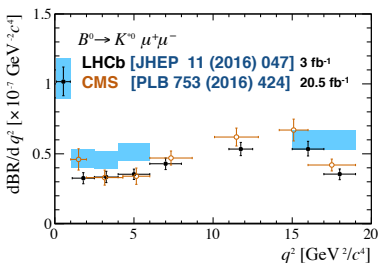
# Branching fractions in $b \rightarrow s\mu^+\mu^-$

- ▶ The LHCb (and CMS) Run 1 datasets already have precise measurements of differential branching fractions with at least comparable precision to the SM theory expectations

[arXiv:1403.8044]



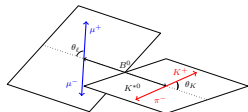
[arXiv:1606.04731], [arXiv:1507.08126]



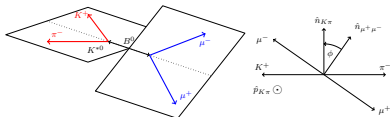
- ▶ SM predictions have large theory uncertainties from the hadronic form-factors (of which there are 3 for  $B^\pm \rightarrow K^\pm$  and 7 for  $B \rightarrow K^*$ )
- ▶ Details of theory predictions in [arXiv:1111.2558], [arXiv:1306.0434] and [arXiv:1411.3161]

# The $B^0 \rightarrow K^{*0} \mu^+ \mu^-$ angular basis

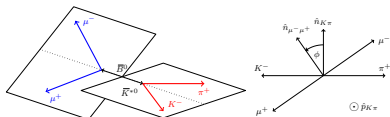
- ▶ We have a four-body final state (as  $K^{*0} \rightarrow K^+ \pi^-$ )
  - ▶ The angular distribution provides many observables that are sensitive to new physics
  - ▶ The branching fraction might not be affected (or affected at a very small level) however angular distributions can be affected by different spin structure of NP particles
  - ▶ For example, at low  $q^2$ , the angle between the two decay planes,  $\phi$ , is sensitive to the photon polarisation
- ▶ The four-body system is described by three decay angles (defined in the helicity basis) and the dimuon invariant mass squared,  $q^2$ 
  - ▶  $\phi$  angle between the two decay planes in the  $B$  rest-frame
  - ▶  $\theta_\ell, \theta_K$  angle between the  $B$  momentum in the  $B$  frame and the  $K\pi$  or  $\ell^+ \ell^-$  momentum in their decay frame



(a)  $\theta_K$  and  $\theta_\ell$  definitions for the  $B^0$  decay



(b)  $\phi$  definition for the  $B^0$  decay



(c)  $\phi$  definition for the  $\bar{B}^0$  decay

## The $B^0 \rightarrow K^{*0} \mu^+ \mu^-$ angular distribution

- ▶ A rather complex angular distribution with many observables (which depend on form-factors for the  $B \rightarrow K^*$  transition plus the Wilson coefficients)
- ▶ The  $CP$ -averaged angular decay rate (where  $\Omega = (\theta_K, \theta_\ell, \phi)$ ) is

$$\begin{aligned} \frac{1}{d(\Gamma + \bar{\Gamma})/dq^2} \frac{d^3(\Gamma + \bar{\Gamma})}{d\vec{\Omega}} \Big|_P &= \frac{9}{32\pi} \left[ \frac{3}{4}(1 - F_L) \sin^2 \theta_K + F_L \cos^2 \theta_K \right. \\ &\quad + \frac{1}{4}(1 - F_L) \sin^2 \theta_K \cos 2\theta_\ell \\ &\quad - F_L \cos^2 \theta_K \cos 2\theta_\ell + S_3 \sin^2 \theta_K \sin^2 \theta_\ell \cos 2\theta \\ &\quad + S_4 \sin 2\theta_K \sin 2\theta_\ell \cos \phi + S_5 \sin 2\theta_K \sin \theta_\ell \cos \phi \\ &\quad + \frac{4}{3} A_{FB} \sin^2 \theta_K \cos \theta_\ell + S_7 \sin 2\theta_K \sin \theta_\ell \sin \phi \\ &\quad \left. + S_8 \sin 2\theta_K \sin 2\theta_\ell \sin \phi + S_9 \sin^2 \theta_K \sin^2 \theta_\ell \sin 2\phi \right] \end{aligned}$$

$F_L$

fractional longitudinal polarisation of the  $K^{*0}$

$A_{FB}$

forward-backward asymmetry of the dilepton system

$S_5$

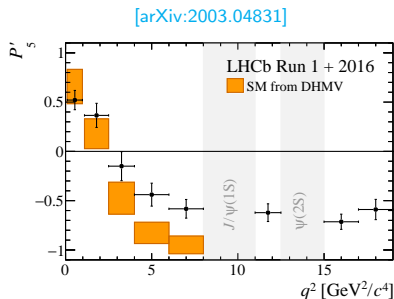
particularly sensitive to  $C_9$

## Form-factor “free” observables

- ▶ Several experiments have produced such an angular analysis (LHCb is the most sensitive)
- ▶ In QCD factorisation / SCET there are only two form factors
  - ▶ One is associated with  $A_0$  and the other with  $A_{\parallel}$  and  $A_{\perp}$
- ▶ Can then construct ratios of observables which are independent of the form-factors (at least to leading order) e.g.

$$P'_5 = S_5 / \sqrt{F_L(1 - F_L)}$$

- ▶ Historically there has been quite a bit of tension between predictions and measurement of  $P'_5$ . In the latest LHCb measurement ([arXiv:]) this specific tension is a bit reduced but there remains an overall considerable tension with the SM (arising from discrepancies in  $P'_5$  and  $A_{FB}$  and  $F_L$ )

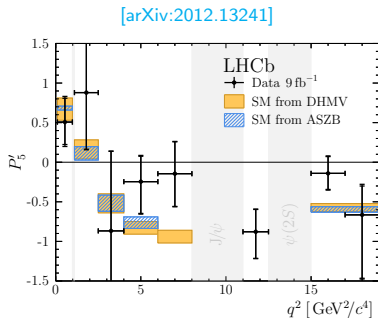


# Form-factor “free” observables

- ▶ Several experiments have produced such an angular analysis (LHCb is the most sensitive)
- ▶ In QCD factorisation / SCET there are only two form factors
  - ▶ One is associated with  $A_0$  and the other with  $A_{\parallel}$  and  $A_{\perp}$
- ▶ Can then construct ratios of observables which are independent of the form-factors (at least to leading order) e.g.

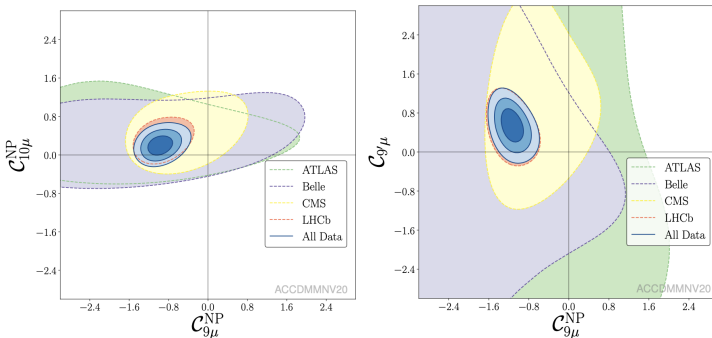
$$P'_5 = S_5 / \sqrt{F_L(1 - F_L)}$$

- ▶ Historically there has been quite a bit of tension between predictions and measurement of  $P'_5$ . In the latest LHCb measurement ([arXiv:]) this specific tension is a bit reduced but there remains an overall considerable tension with the SM (arising from discrepancies in  $P'_5$  and  $A_{FB}$  and  $F_L$ )
- ▶ Also see it in the charged mode,  
 $B^+ \rightarrow K^{*+} \mu^+ \mu^-$



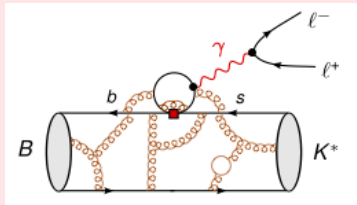
- ▶ These measurements then lead to some very nice interpretations in terms of the Wilson coefficients with global fits to  $b \rightarrow s$  data
- ▶ Note a general pattern of consistency between experiments/measurements **and data** seems to favour a modified vector coupling ( $C_9^{NP} \neq 0$ ) at  $\sim 4 - 5\sigma$  (if you entirely trust the theory assumptions)

[arXiv:1903.09578] (updated 2020)



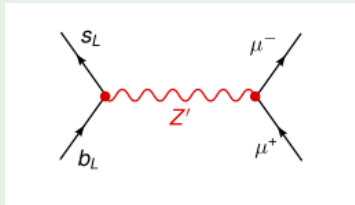
# Interpretation of global fits

## Pessimist's view point



- ▶ A vector-like contribution could point to a problem with our understanding of QCD
- ▶ e.g. are we correctly estimating the contribution from charm loops that produce dimuon pairs via a virtual photon?

## Optimist's view point



- ▶ Vector-like contribution could come from a new tree-level contribution (e.g.  $Z'$  with  $m \sim O(1)$  TeV)
- ▶ A  $Z'$  should also give effects elsewhere (e.g. particularly in mixing, which it doesn't) so a challenge for model builders who need to suppress this

Which one are you?

Further work is needed from both experiment and theory to establish what is going on here

- ▶ In the SM ratios like

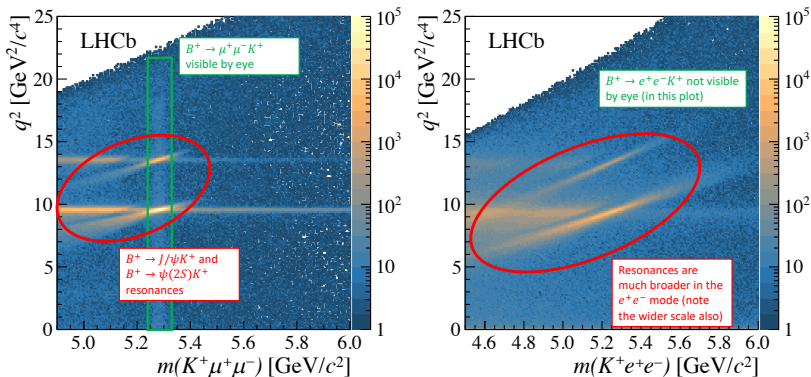
$$R_K = \frac{\int d\Gamma(B^+ \rightarrow K^+ \mu^+ \mu^-)/dq^2 \cdot dq^2}{\int d\Gamma(B^+ \rightarrow K^+ e^+ e^-)/dq^2 \cdot dq^2} \quad (19)$$

should only differ from unity by phase space

- ▶ The dominant SM processes couple equally to the different lepton flavour (apart from the Higgs)
- ▶ Incredibly theoretically clean since hadronic uncertainties cancel in the ratio (they have the same hadronic matrix element). The only consideration is from small electroweak corrections as  $q^2$  approaches 0
- ▶ Experimentally these are much more challenging, primarily due to differences in muon/electron reconstruction
  - ▶ In particular Bremsstrahlung radiation from the electrons
  - ▶ LHCb does not have a high resolution ECAL
  - ▶ Electron efficiency is much poorer than muon efficiency at LHCb (trigger and reconstruction)

# $B^+ \rightarrow K^+ l^+ l^-$ candidates

- ▶ Have to correct electrons for energy loss due to Bremsstrahlung (look for ECAL clusters (*i.e.* photons) associated with the electron track)
- ▶ This is successful to some extent but even after Bremsstrahlung recovery there are significant differences in mass resolution between the dielectron and dimuon final states

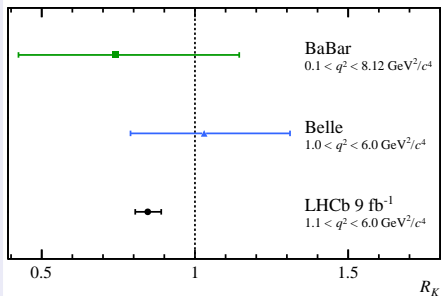


# Lepton universality results

Status in early 2022

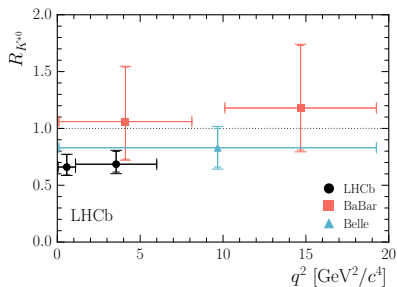
$R_K$  from  $B^\pm \rightarrow K^\pm \ell^+ \ell^-$

[arXiv:2103.11769]



$R_{K^{*0}}$  from  $B^0 \rightarrow K^{*0} \ell^+ \ell^-$

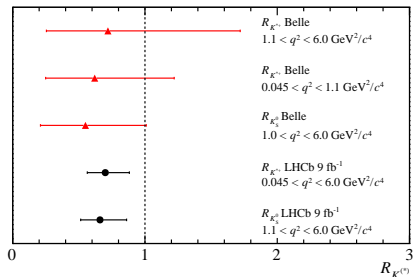
[arXiv:1705.05802]



Status in early 2022

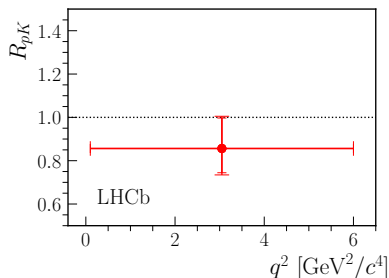
$R_{K_S^0}$  and  $R_{K^{*+}}$

[arXiv:2110.09501]



$R_{pK}$  from  $\Lambda_b^0 \rightarrow pK^- \ell^+ \ell^-$

[arXiv:1912.08139]

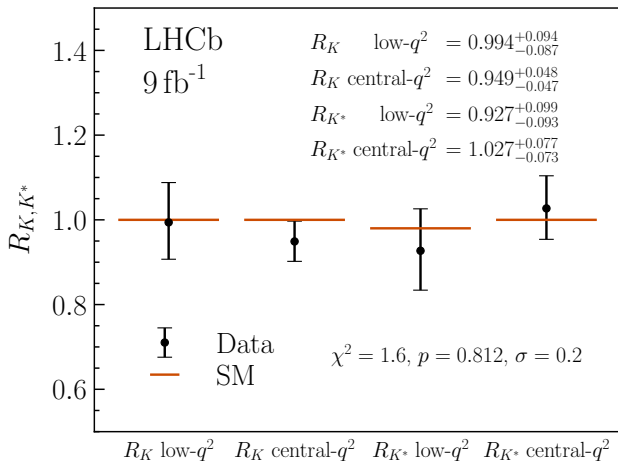


# Lepton universality results

Status in late 2022 (insert *extremely sad face*)

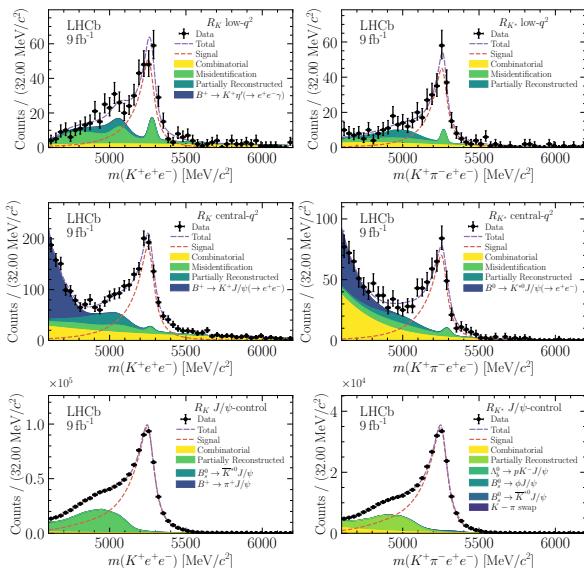
$R_K$  and  $R_{K^*}$

[arXiv:2212.09153]



# Lepton universality results

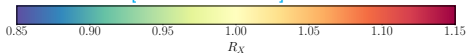
[arXiv:2212.09153]



# Lepton universality results

[arXiv:2212.09153]

LHCb



$R_K$  low- $q^2$

DLL(e) > 7	0.960 ± 0.097	0.971 ± 0.099	0.988 ± 0.102	0.997 ± 0.102	0.982 ± 0.100	0.973 ± 0.099	0.967 ± 0.099	0.967 ± 0.099	0.977 ± 0.102
DLL(e) > 5	0.961 ± 0.086	0.964 ± 0.086	0.969 ± 0.088	0.983 ± 0.090	0.973 ± 0.089	0.981 ± 0.091	0.979 ± 0.092	0.961 ± 0.090	0.985 ± 0.095
DLL(e) > 2	0.873 ± 0.073	0.904 ± 0.078	0.908 ± 0.079	0.958 ± 0.087	0.950 ± 0.086	0.954 ± 0.087	0.938 ± 0.086	0.940 ± 0.087	0.969 ± 0.093
	> 0.20	> 0.25	> 0.30	> 0.35	> 0.40	> 0.45	> 0.50	> 0.55	> 0.60

ProbNN(e)

$R_K$  central- $q^2$

DLL(e) > 7	0.948 ± 0.051	0.944 ± 0.051	0.944 ± 0.051	0.939 ± 0.051	0.939 ± 0.051	0.941 ± 0.051	0.934 ± 0.051	0.935 ± 0.051	0.937 ± 0.052
DLL(e) > 5	0.941 ± 0.044	0.938 ± 0.044	0.942 ± 0.044	0.933 ± 0.044	0.939 ± 0.045	0.951 ± 0.046	0.946 ± 0.046	0.953 ± 0.047	0.949 ± 0.048
DLL(e) > 2	0.906 ± 0.040	0.902 ± 0.040	0.907 ± 0.040	0.895 ± 0.040	0.904 ± 0.041	0.916 ± 0.042	0.920 ± 0.043	0.925 ± 0.044	0.919 ± 0.044
	> 0.20	> 0.25	> 0.30	> 0.35	> 0.40	> 0.45	> 0.50	> 0.55	> 0.60

ProbNN(e)

$R_{K^*}$  low- $q^2$

DLL(e) > 7	0.985 ± 0.112	0.982 ± 0.112	0.966 ± 0.109	0.952 ± 0.107	0.971 ± 0.111	0.975 ± 0.112	0.984 ± 0.114	0.970 ± 0.112	0.960 ± 0.111
DLL(e) > 5	0.980 ± 0.097	0.993 ± 0.100	0.978 ± 0.099	0.979 ± 0.100	1.007 ± 0.103	1.014 ± 0.105	1.010 ± 0.106	1.010 ± 0.108	1.019 ± 0.110
DLL(e) > 2	0.855 ± 0.080	0.848 ± 0.079	0.830 ± 0.076	0.847 ± 0.080	0.883 ± 0.086	0.901 ± 0.088	0.915 ± 0.089	0.925 ± 0.092	0.934 ± 0.117
	> 0.20	> 0.25	> 0.30	> 0.35	> 0.40	> 0.45	> 0.50	> 0.55	> 0.60

ProbNN(e)

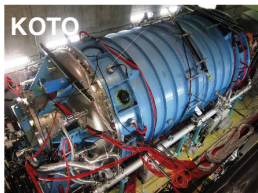
$R_{K^*}$  central- $q^2$

DLL(e) > 7	1.127 ± 0.100	1.119 ± 0.099	1.116 ± 0.099	1.103 ± 0.098	1.097 ± 0.097	1.083 ± 0.095	1.097 ± 0.099	1.113 ± 0.101	1.119 ± 0.103
DLL(e) > 5	1.021 ± 0.074	1.016 ± 0.074	1.016 ± 0.075	0.997 ± 0.073	1.016 ± 0.076	1.001 ± 0.075	1.012 ± 0.077	1.035 ± 0.081	1.049 ± 0.084
DLL(e) > 2	0.965 ± 0.066	0.990 ± 0.069	0.986 ± 0.069	0.993 ± 0.071	1.024 ± 0.075	1.006 ± 0.073	1.014 ± 0.075	1.038 ± 0.079	1.039 ± 0.081
	> 0.20	> 0.25	> 0.30	> 0.35	> 0.40	> 0.45	> 0.50	> 0.55	> 0.60

ProbNN(e)

# Rare kaon decays

- ▶ Two new rare kaon decay experiments
  - ▶ KOTO at J-PARC, searching for  $K_L^0 \rightarrow \pi^0 \nu \bar{\nu}$
  - ▶ NA62 at CERN, searching for  $K^+ \rightarrow \pi^+ \nu \bar{\nu}$
- ▶ The advantage (theoretically) of final states with neutrinos is that there is no contribution from quark loops involving light quarks (which can annihilate to produce charged leptons e.g. charm loops)
- ▶ The challenge experimentally is these are incredibly rare (and contain just one charged track in the final state)

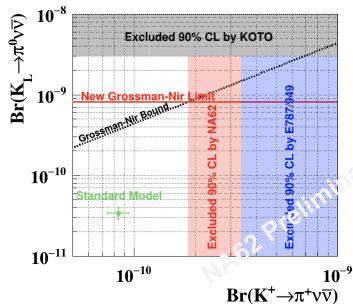
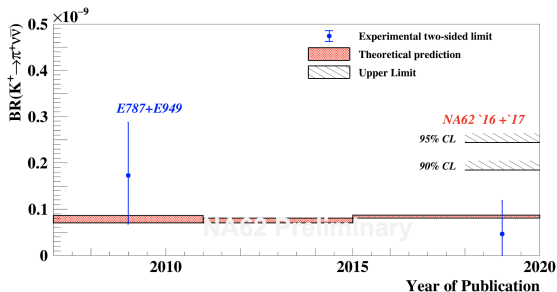


- ▶ Aim to collect a dataset of  $\sim 100 K^+ \rightarrow \pi^+ \nu \bar{\nu}$  decays
- ▶ Currently have  $\sim 3$  events in analysed data (2016+2017) giving

$$\mathcal{B}(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = (4.7^{+7.2}_{-4.7}) \times 10^{-11}$$

*i.e.* consistent with zero

- ▶ Also search for lepton number violating  $K^\pm \rightarrow \pi^\mp \ell^\pm \ell^\pm$  decays



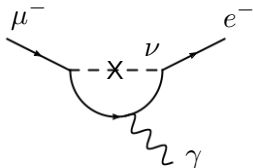
## 7. Lepton Flavour Violation

# Lepton Flavour Violation

- ▶ Essentially forbidden in the SM by the smallness of the neutrino mass

$$\mathcal{B}(\mu \rightarrow e\gamma) \propto \frac{m_\nu^4}{m_W^4} \sim 10^{-54} \quad (20)$$

- ▶ Very powerful null test of the SM
- ▶ **Any** visible signal is a clear sign of New Physics

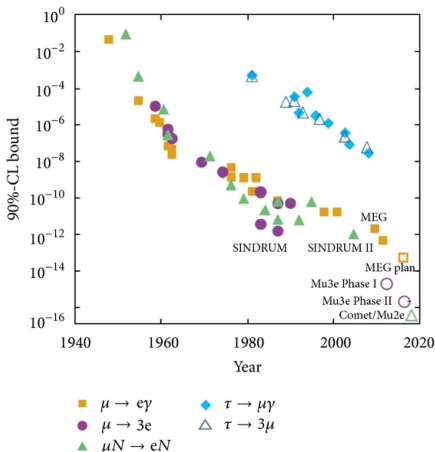


- ▶ Different signatures include
  1.  $\mu \rightarrow e\gamma$  at rest (MEG at PSI, Mu2E at PSI)
  2.  $\mu \rightarrow 3e$  (Mu3e at PSI)
  3.  $\mu$  conversion in field of Au nucleus (SINDRUM II at PSI)



# Charged LFV future

- ▶ Data taking has begun at MEG-II (aiming for  $O(10^{-14})$ )
- ▶ New  $\mu \rightarrow 3e$  experiment (Mu3e) at PSI
- ▶ Two new conversion experiments (Mu2e) at PSI and (COMET) at J-PARC
- ▶ Expect improvements for LFV  $\tau$  decays from Belle 2



## 8. Recap

# New Physics?

- ▶ We have seen in these lectures the incredible success of the CKM matrix as a predictive tool for properties of flavour decays
- ▶ Our various measurements which constrain the CKM picture are all consistent with the SM predictions
- ▶ However, there are some very tantalising hints that could suggest New Physics
  - ▶ Tension in  $V_{ub}$  (and to a lesser extent  $V_{cb}$ )
  - ▶ Enhancement / tension in  $B \rightarrow D^{(*)}\tau\nu\tau$
  - ▶ (Still some) differential anomalies in  $B \rightarrow K^{(*)}\ell^+\ell^-$  decays
  - ▶ Muon  $g-2$
- ▶ These should all be resolved in the next 5-10 years
- ▶ **It's an exciting time to be a flavour physicist!**

} all at  $\gtrsim 3\sigma$

In this lecture we have covered

- ▶ Effective theories
- ▶ Flavour Changing Neutral Current processes
- ▶ Experimental constraints on new particles in  $\Delta F = 1$  and  $\Delta F = 2$  FCNCs
- ▶ Minimal Flavour Violation
- ▶ Lepton Flavour Violation
- ▶ Future Flavour Violation Experiments

End of Lecture 4

# GAME OVER

Thanks for playing (listening)!