# The Mysteries of Flavour

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RAL Academic Lectures

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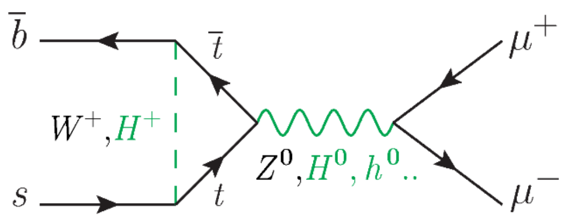
# HEAVY FLAVOUR AND RARE DECAYS

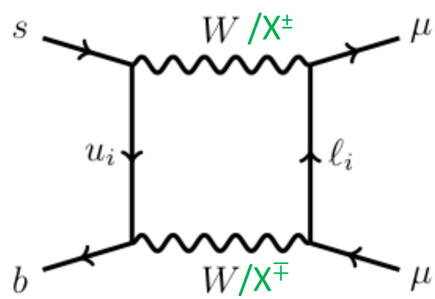
# Heavy Flavour – precision search for New Physics

Requirements:
- A decay that is predicted to be unlikely in the Standard Model but possible with New Physics extensions.
- A decay that is theoretically clean.

=> "Flavour Changing Neutral Currents"

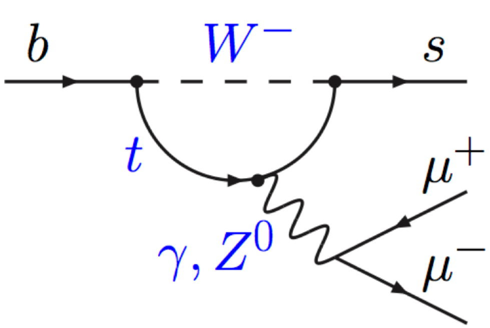
Fully Leptonic

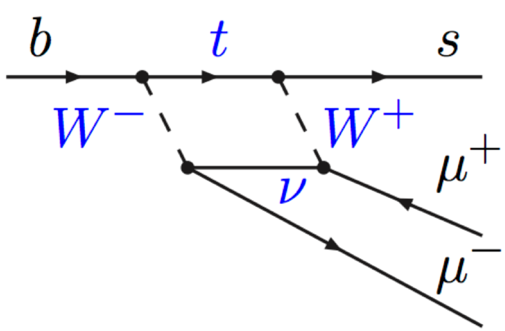


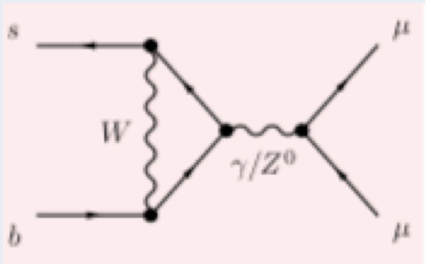
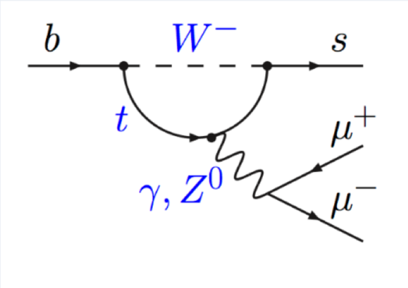
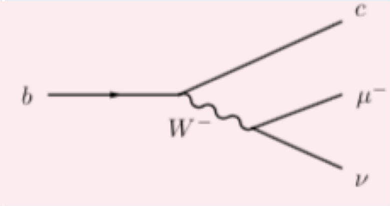

New Physics can:
1. Change Branching Fraction
2. Change Differential Branching Fraction
3. Change Angular Distributions

Half Leptonic



# Where to look:

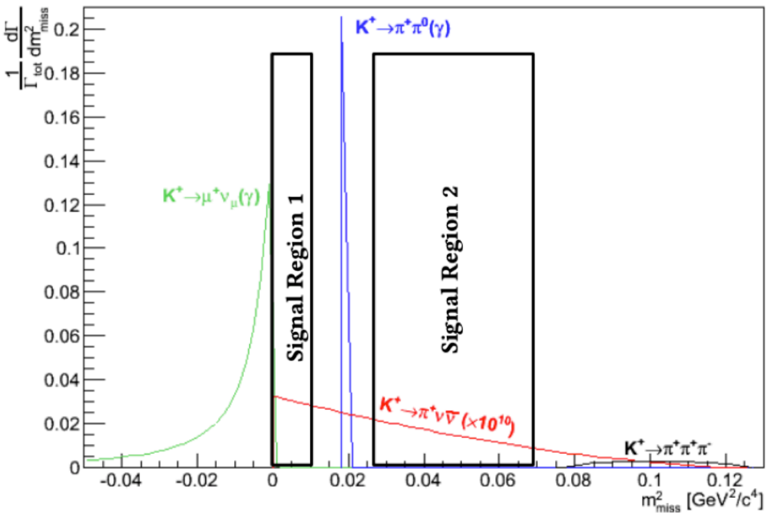
| | Flavour Changing Neutral Current | | | Charged Current |
|---|---|---|---|---|
| | Leptonic | Mesonic | Baryonic | Semi-leptonic |
| |   |   | |   |
| | | | | |
| Strange | $K^0_s \to \mu^+\mu^-$ | $K^+ \to \pi^+ \bar{\nu}\nu$<br>$K^0 \to \pi^0 \bar{\nu}\nu$ | $\Sigma^+ \to p\mu^+\mu^-$ | |
| Charm | $D^0 \to \mu^+\mu^-$<br>$D^0 \to e^+\mu^-$ | $D^0 \to h^+h^- \mu^+\mu^-$<br>$J/\psi \to D^0e^+e^-$ | $\Lambda_c^+ \to p\mu^+\mu^-$ | |
| Beauty | $B^0{}_{(s)} \to \mu^+\mu^-$<br>$B^0{}_{(s)} \to \tau^+\tau^-$ | $B^0 \to K^{(*)0} \mu^+ \mu^-/e^+e^-$<br>$B^+ \to K^{(*)+} \mu^+ \mu^-/e^+e^-$<br>$B^0_s \to \phi\ \mu^+ \mu^-$<br>$B^0_s \to K^* \mu^+ \mu^-$ | $\Lambda_b \to \Lambda\ \mu^+\mu^-$ | $B^0 \to D^{(*)}\tau^+\nu/\mu^+\nu$<br>$B^+_c \to J/\psi\ \tau^+\nu/\mu^+\nu$ |

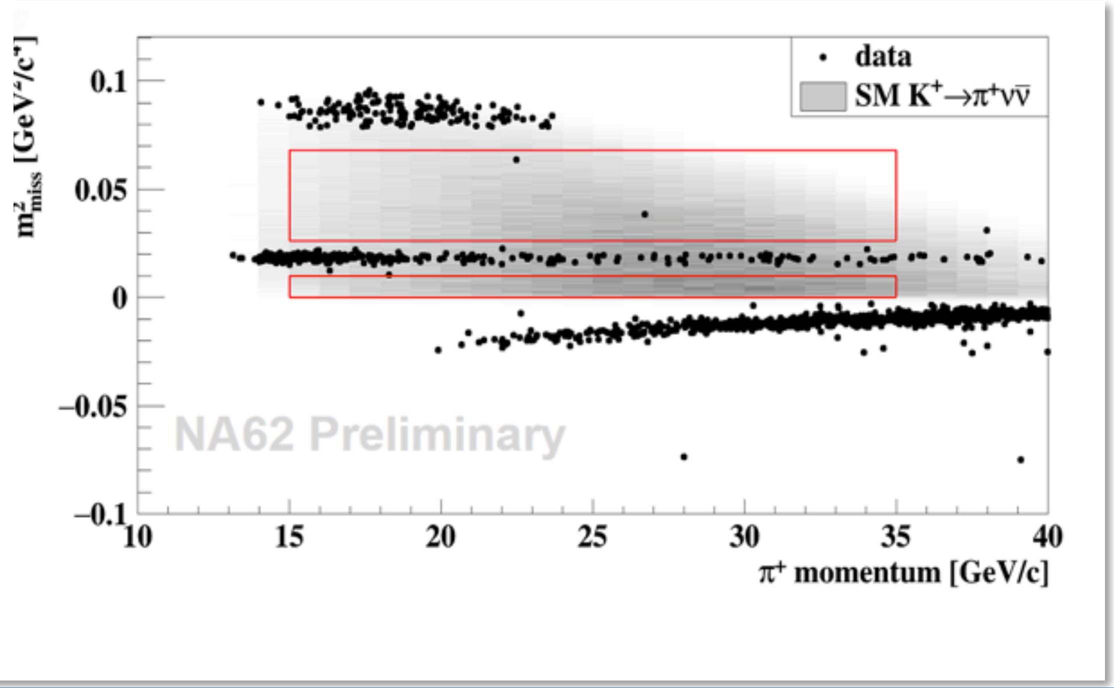
See next slides for decays in red

# STRANGE

# Kaon decays – Mesonic FCNC

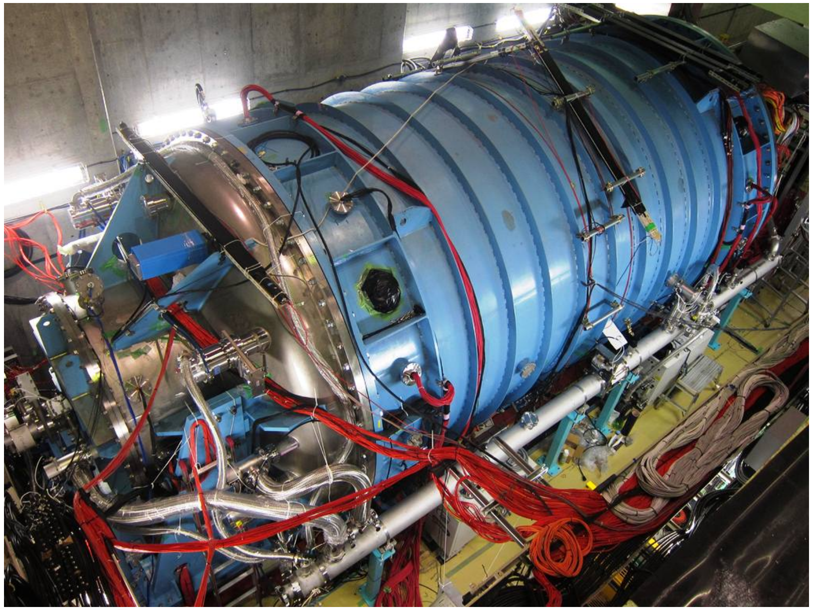
- NA62 (KAON2019 result): $K^+ \to \pi^+ \bar{\nu}\nu$
  - $B_{E949} = (1.73 \pm 1.1) \times 10^{-10}$
  - NA62 found 2 events.
  - $B_{NA62} < 1.85 \times 10^{-10}$ at 90% CL UL
  - $B_{SM} = (7.81^{+0.80}_{-0.71} \pm 0.29) \times 10^{-11}$

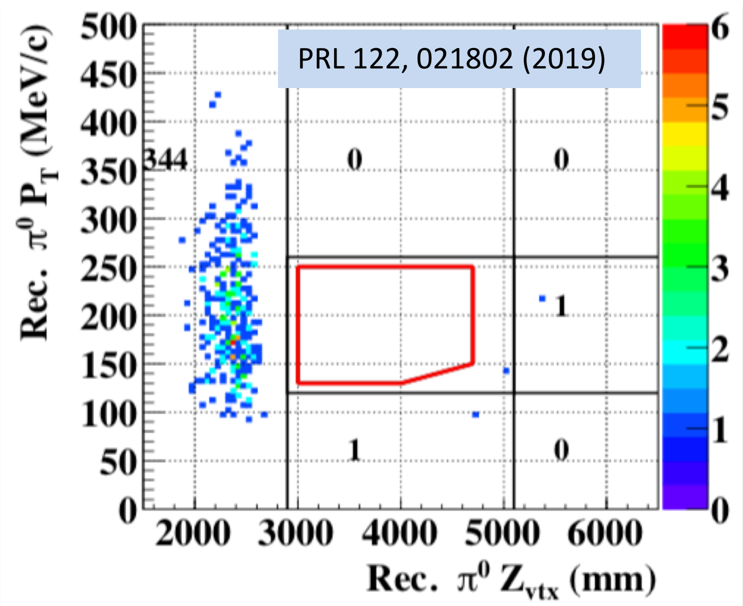


# Kaon decays – Mesonic FCNC

- KOTO (J-PARC) $K^0_L \rightarrow \pi^0 \bar{\nu}\nu$
  - 2015 data
  - $B_{E391a} < 2.6 \times 10^{-8}$ at 90% CL UL
  - KOTO found 0 events.
  - $B_{KOTO} < 3 \times 10^{-9}$ at 90% CL UL
  - $B_{SM} = (2.43^{+0.40}_{-0.37} \pm 0.06) \times 10^{-11}$





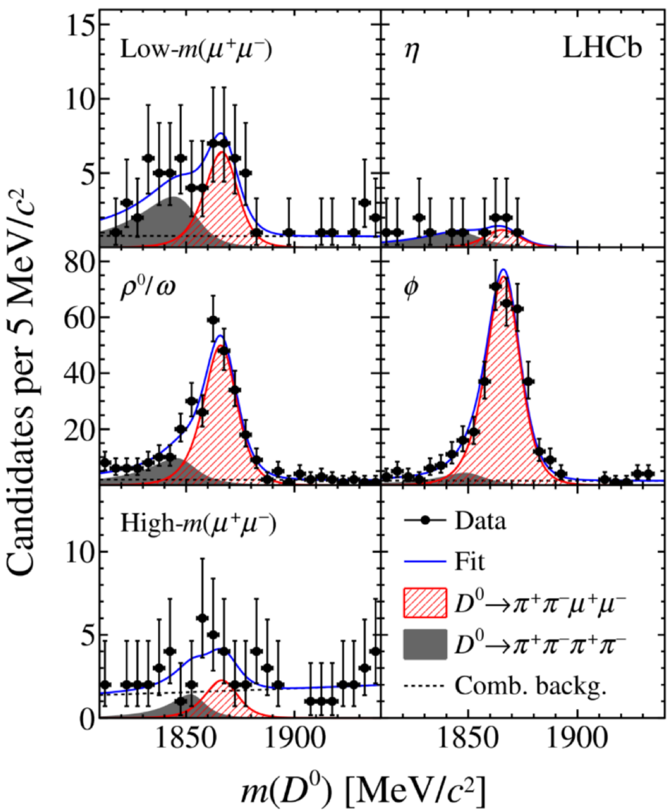
# CHARM

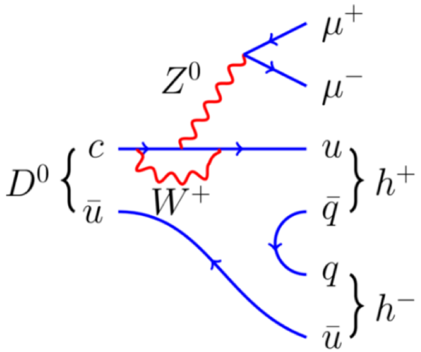
# Rarest charm hadron decay $D^0 \rightarrow h^-h^+l^+l^-$

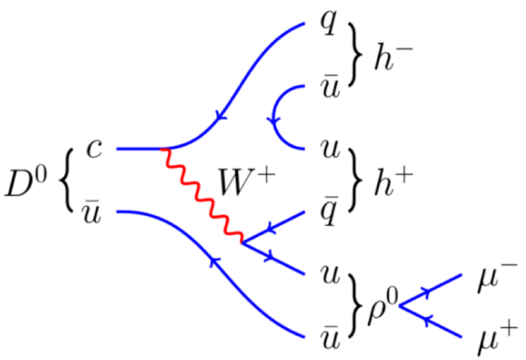
PRL 119, 181805 (2017)

Until recently, only upper limits on branching fractions measured.
Decay suppressed by GIM mechanism and loop-processes.
Now have the rarest charm hadron decays:

$$B(D^0 \rightarrow \pi^+\pi^-\mu^-\mu^+) = (9.64 \pm 0.48 \pm 0.51 \pm 0.97)\times 10^{-7}$$
$$B(D^0 \rightarrow K^+K^-\mu^-\mu^+) = (1.54 \pm 0.27 \pm 0.09 \pm 0.16)\times 10^{-7}$$

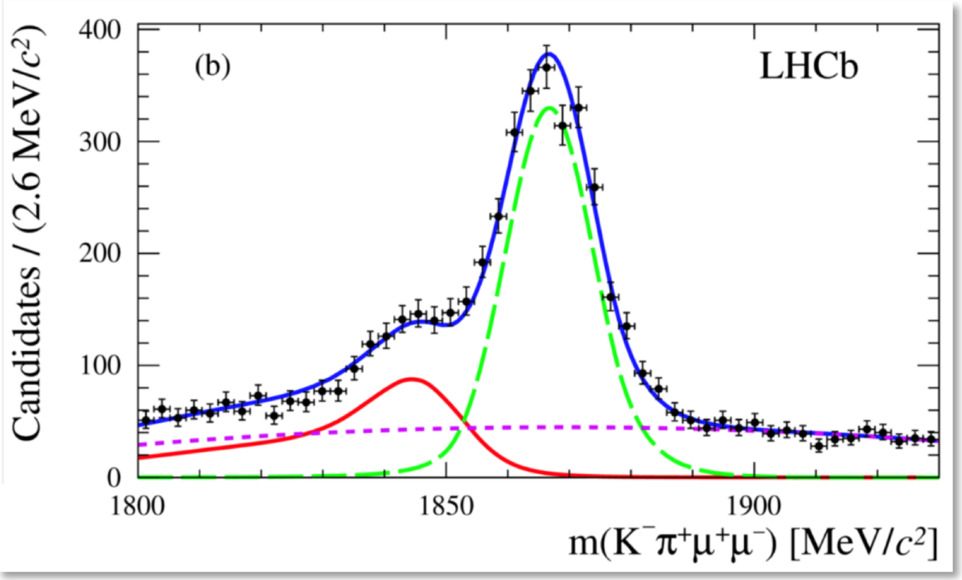


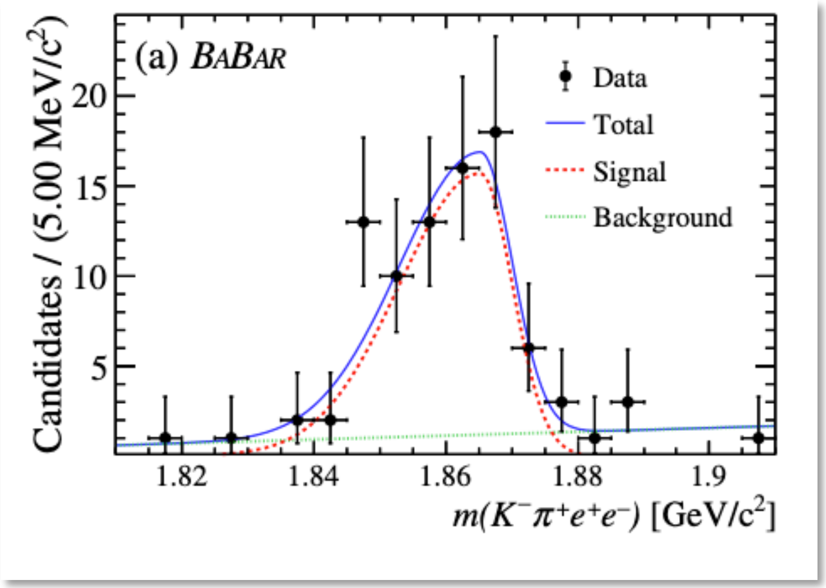



# Charm decay $D^0 \to K^-\pi^+l^+l^-$

PRL 122, 081802 (2019)




$B(D^0 \to K^-\pi^+\mu^+\mu^-) = (4.17 \pm 0.12 \pm 0.40) \times 10^{-6}$

$B(D^0 \to K^-\pi^+e^+e^-) = (4.0 \pm 0.5 \pm 0.2 \pm 0.1) \times 10^{-6}$

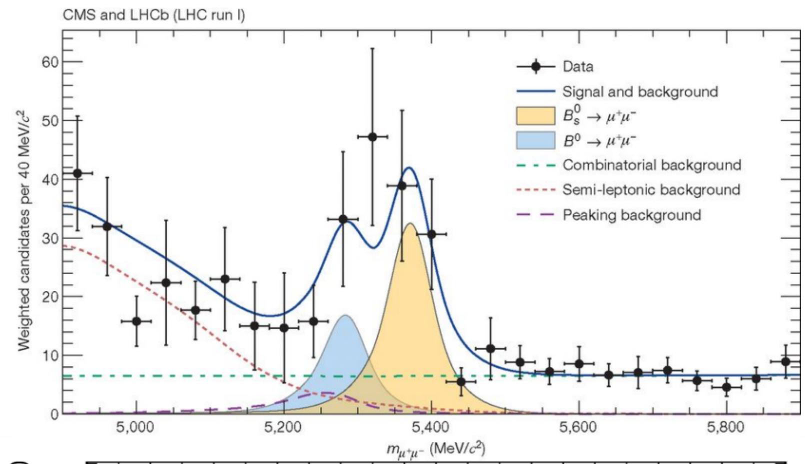
$$\frac{B(D^0 \to K^-\pi^+\mu^+\mu^-)}{B(D^0 \to K^-\pi^+e^+e^-)} = 1.05 \pm 0.18$$

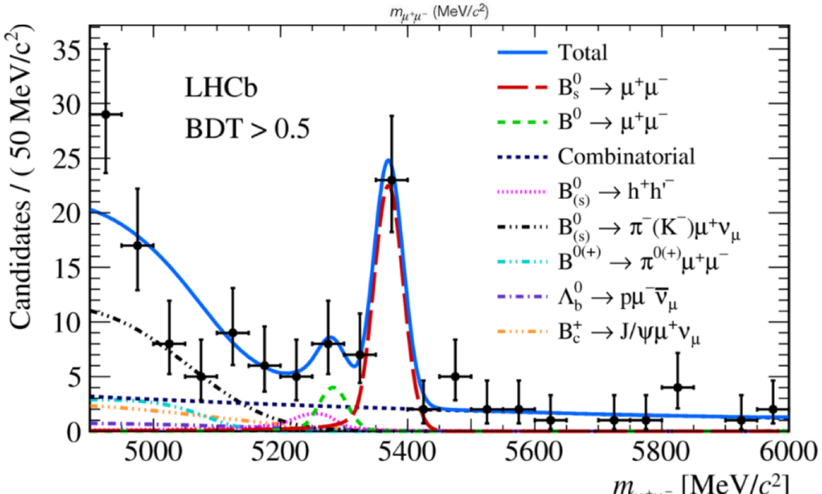
We are entering the era where it may be possible to test Lepton Universality in rare charm decays.

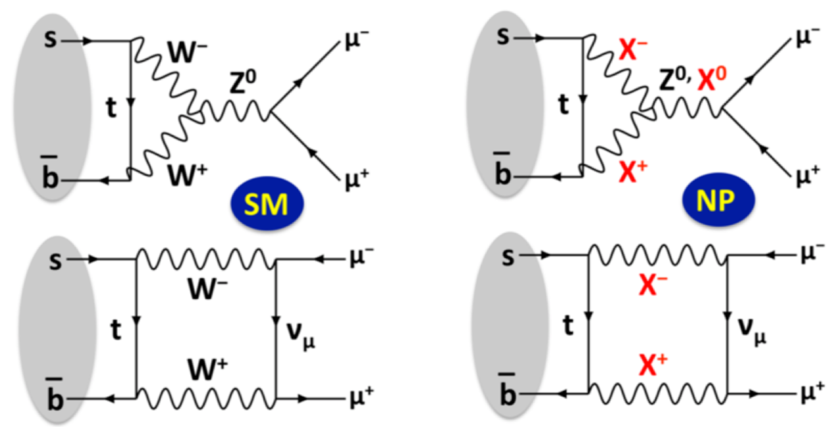
# BEAUTY

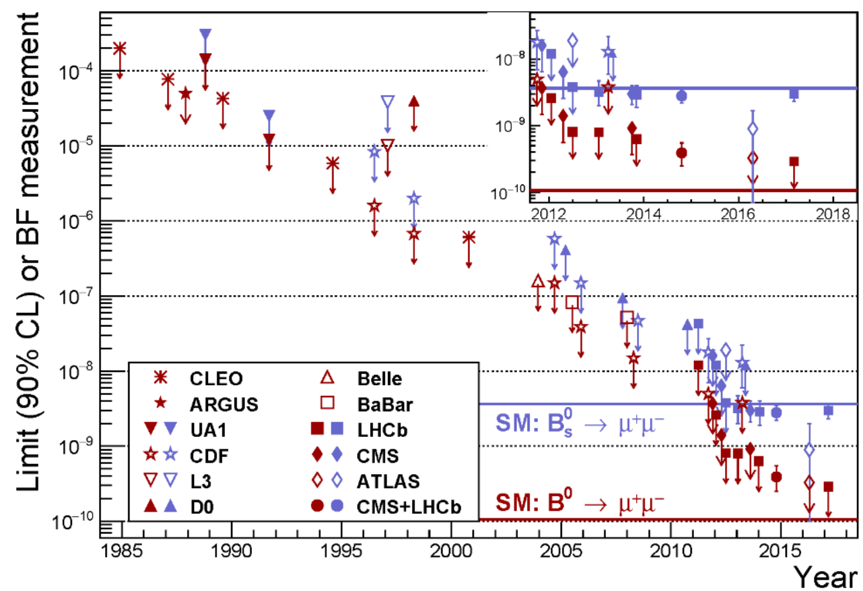
# $B^0_{(s)} \rightarrow \mu^+\mu^-$

PRL 118, 191801 (2017)



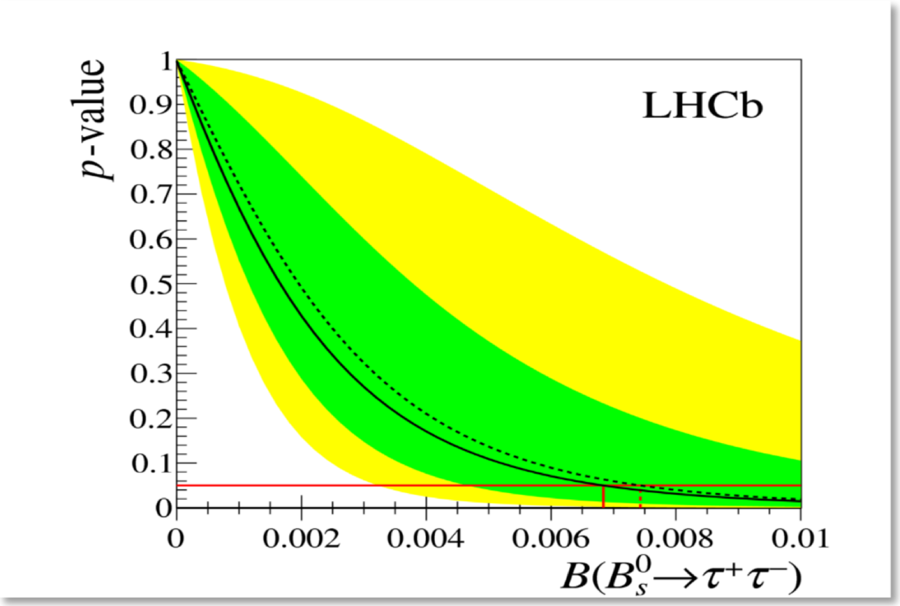




$$B_{SM}(B^0_s \rightarrow \mu^+\mu^-) = (3.65 \pm 0.23)\times 10^{-9}$$
$$B(B^0_s \rightarrow \mu^+\mu^-) \quad = (3.0 \quad \pm 0.6^{+0.3}_{-0.2})\times 10^{-9}$$

$$B_{SM}(B^0 \rightarrow \mu^+\mu^-) = (1.06 \pm 0.09)\times 10^{-10}$$
$$B(B^0 \rightarrow \mu^+\mu^-) \quad < 3.4\times 10^{-9}\ (95\%\ CL)$$

# $B^0_{(s)} \rightarrow \tau^+\tau^-$




$B_{SM}(B_s^0 \rightarrow \tau^+\tau^-) = (2.22 \pm 0.19)\times 10^{-8}$

$B(B_s^0 \rightarrow \tau^+\tau^-) \quad < 6.8 \times 10^{-3}$ (95% CL)

$B_{SM}(B^0 \rightarrow \tau^+\tau^-) = (7.73 \pm 0.49)\times 10^{-7}$

$B(B^0 \rightarrow \tau^+\tau^-) \quad < 2.1\times 10^{-3}$ (95% CL)

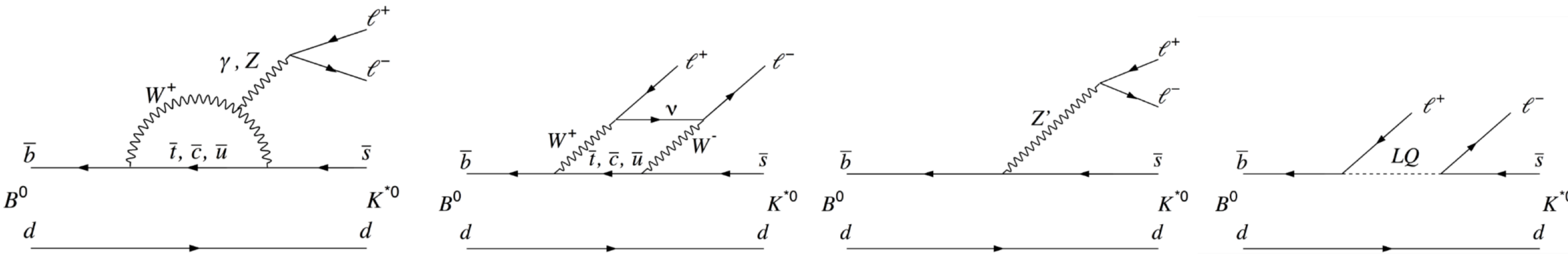
LHCb: $B\left(B_s^0 \rightarrow \tau^+\tau^-\right) < 5.2\times 10^{-3}$ (90% CL)

LHCb: $B\left(B^0 \rightarrow \tau^+\tau^-\right) < 1.6\times 10^{-3}$ (90% CL)

BaBar: $B\left(B^0 \rightarrow \tau^+\tau^-\right) < 4.1\times 10^{-3}$ (90% CL)

# THE R(X) ANOMALIES

# Introduction: $b \to s l^+ l^-$




Effective Hamiltonian can be expressed via Operator Product Expansion (OPE) in terms of operators *O* and Wilson coefficients *C*.

$$H_{eff} = -\frac{4G_F}{\sqrt{2}} V_{tq}^* V_{tb} \sum_{i=1} C_i^{(\prime)}(\mu) O_i^{(\prime)}(\mu) + \sum_i \frac{C_i^{NP}}{\Lambda^2} O_i^{NP}$$

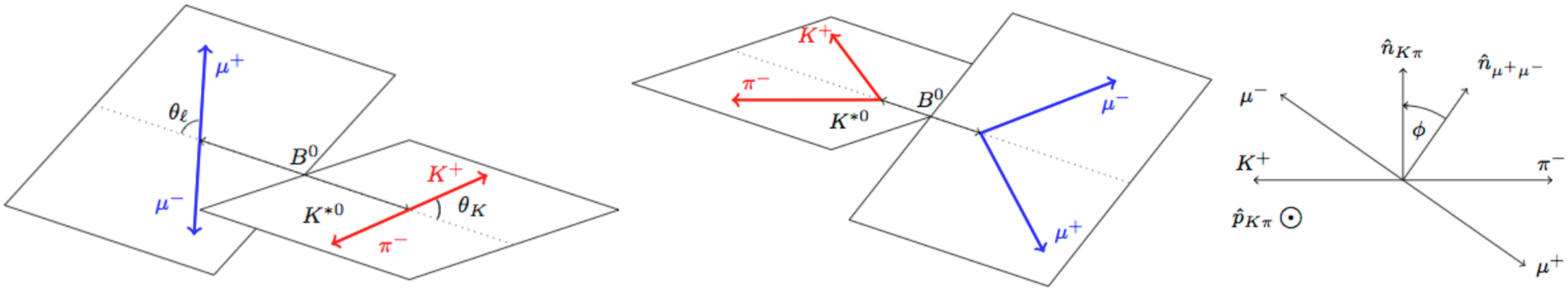
| | |
|---|---|
| $i = 1,2$ | Tree |
| $i = 3-6,8$ | Gluon Penguin |
| $i = 7$ | Photon Penguin |
| $i = 9$ | EW Penguin (axial) |
| $i = 10$ | EW Penguin (vector) |
| $i = S$ | Scalar Penguin |
| $i = P$ | Pseudoscalar Penguin |

New Physics (NP) can enter e.g. via new particles in loops:

- Modify magnitude and phase of Standard Model (SM) $C_i$
- Introduce new couplings $C^{NP}$.
- Potentially different couplings to the leptons.

Look for changes in branching fractions, angular distributions, and lepton universality.

# Angular analysis example: $B^0 \to K^{*0}\mu^+\mu^-$




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

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

$$
\frac{1}{\mathrm{d}(\Gamma+\bar{\Gamma})/\mathrm{d}q^2}\frac{\mathrm{d}^3(\Gamma+\bar{\Gamma})}{\mathrm{d}\vec{\Omega}}\Bigg|_{\mathrm{P}} = \frac{9}{32\pi}\Big[\tfrac{3}{4}(1-F_{\mathrm{L}})\sin^2\theta_K + F_{\mathrm{L}}\cos^2\theta_K
+\tfrac{1}{4}(1-F_{\mathrm{L}})\sin^2\theta_K\cos 2\theta_l
-F_{\mathrm{L}}\cos^2\theta_K\cos 2\theta_l + S_3\sin^2\theta_K\sin^2\theta_l\cos 2\phi
+S_4\sin 2\theta_K\sin 2\theta_l\cos\phi + S_5\sin 2\theta_K\sin\theta_l\cos\phi
+\tfrac{4}{3}A_{\mathrm{FB}}\sin^2\theta_K\cos\theta_l + S_7\sin 2\theta_K\sin\theta_l\sin\phi
+S_8\sin 2\theta_K\sin 2\theta_l\sin\phi + S_9\sin^2\theta_K\sin^2\theta_l\sin 2\phi\Big].
$$

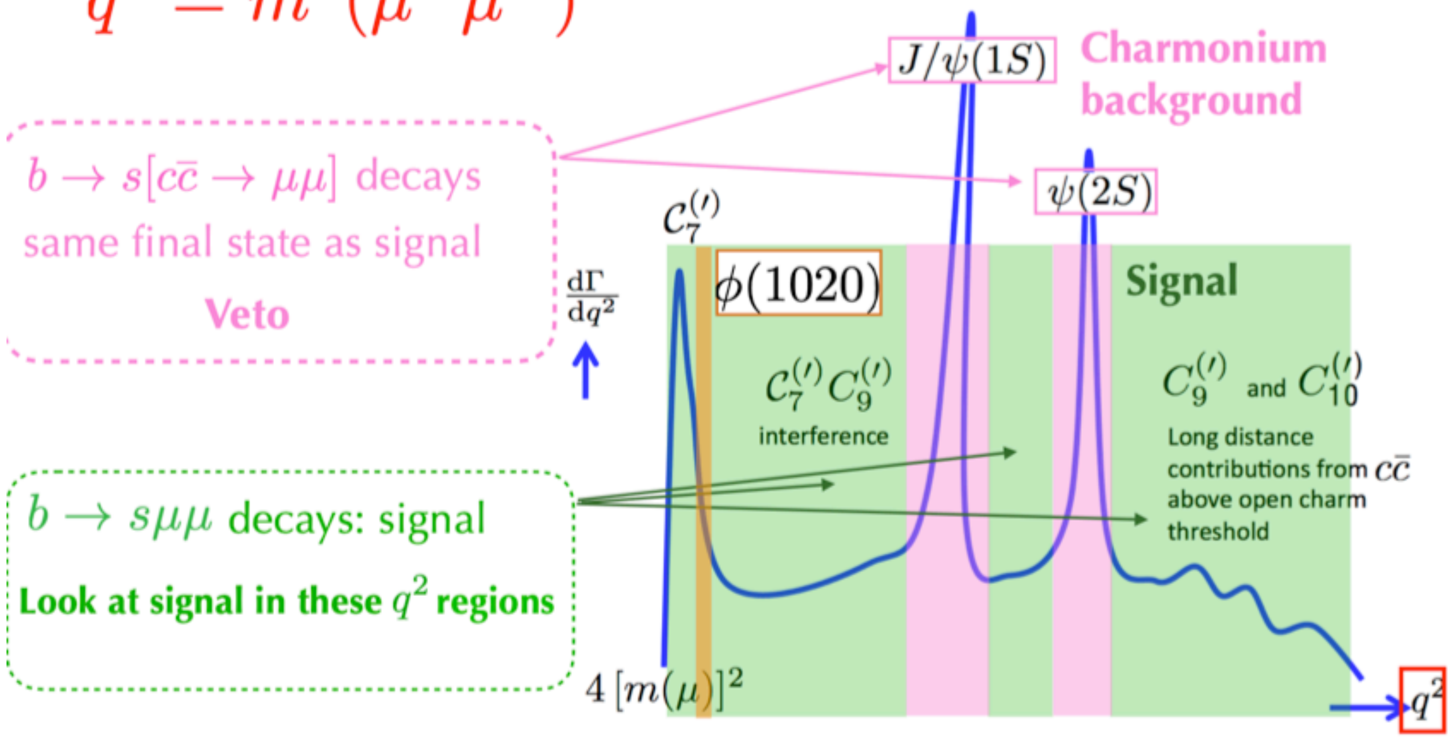
$q^2$ invariant mass squared of $l^+l^-$ system.
$\theta_k$ between $K^+$ & $B^0$ in K* rest frame.
$\theta_l$ between $l^+(l^-)$ & $B(\bar{B})$ in $l^+l^-$ rest frame.
$\phi$ between the di-lepton and $K\pi$ plane in B rest frame.
$F_L$: Longitudinal Polarization.
$A_{FB}$: Forward-Backward di-lepton asymmetry.

Formula is different for different decays

$$P'_{4,5,6,8} = S_{4,5,7,8} / \sqrt{F_L(1-F_L)}$$ [JHEP 01 (2013) 048]

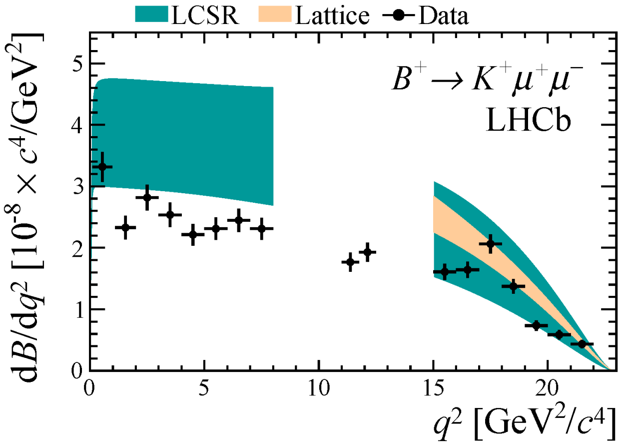
SM theoretical predictions exist for $F_L$, $A_{FB}$, P', $S_{3,4,5}$ as a function of $q^2$.
Other $S_i$ are expected to be ~zero in the SM.

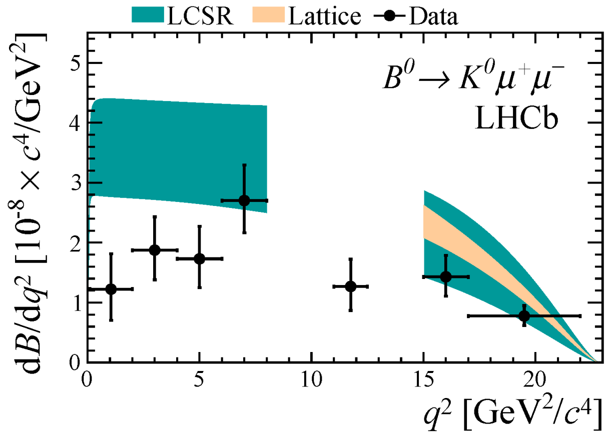
$$q^2 = m^2(\mu^+\mu^-)$$

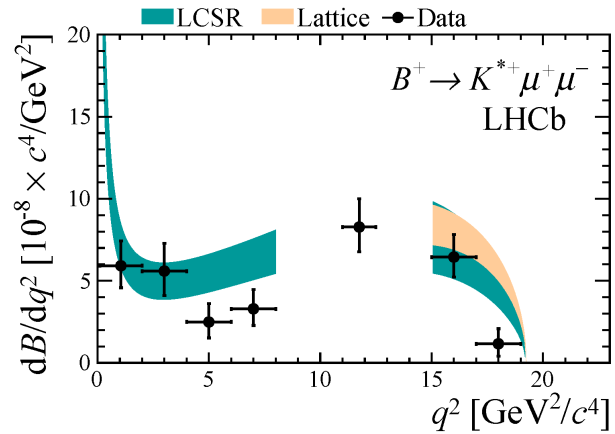


# $b \rightarrow s\, l^+ l^-$ decay rates

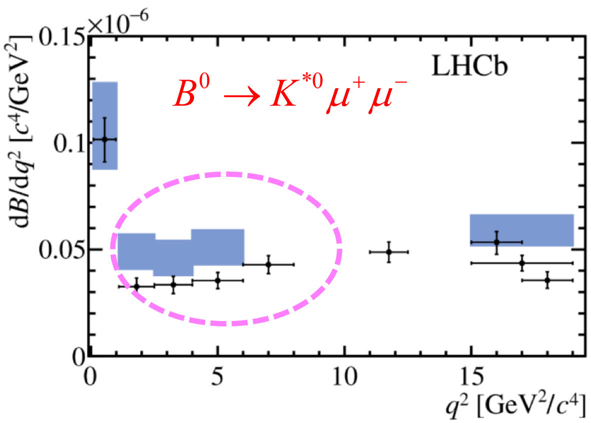
JHEP 06 (2014) 133; JHEP 09 (2014) 177

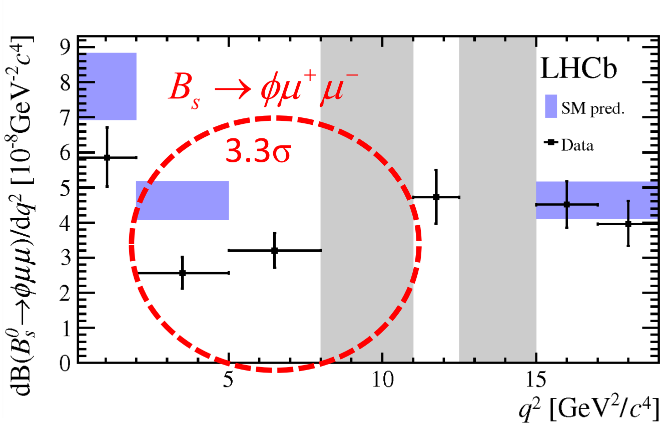


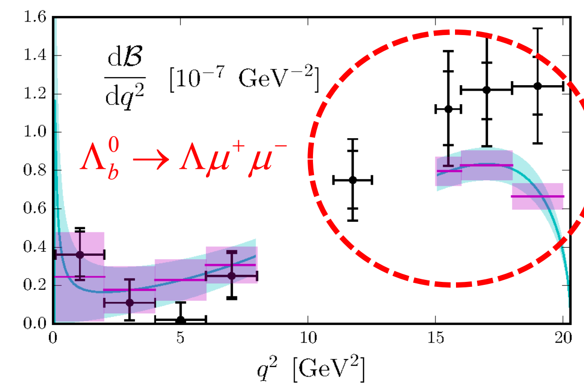




Branching fractions seem to be consistently lower than SM predictions



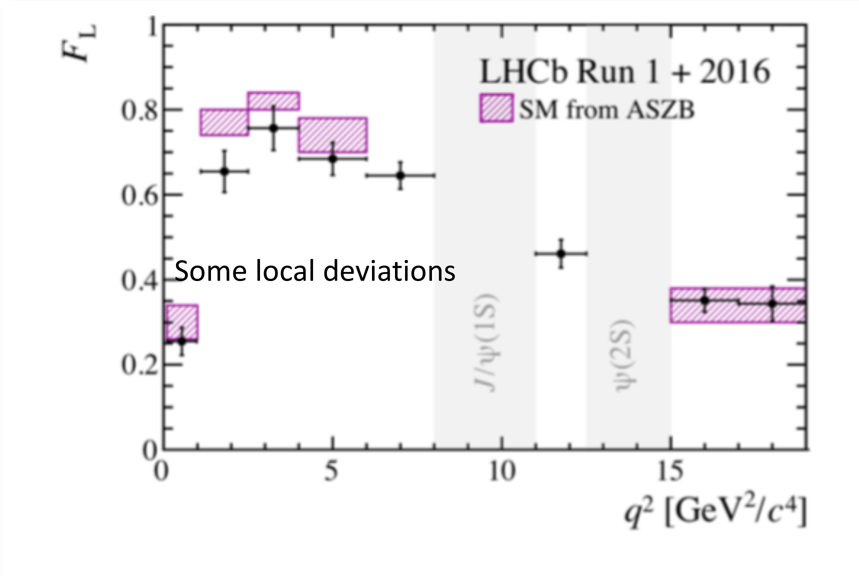



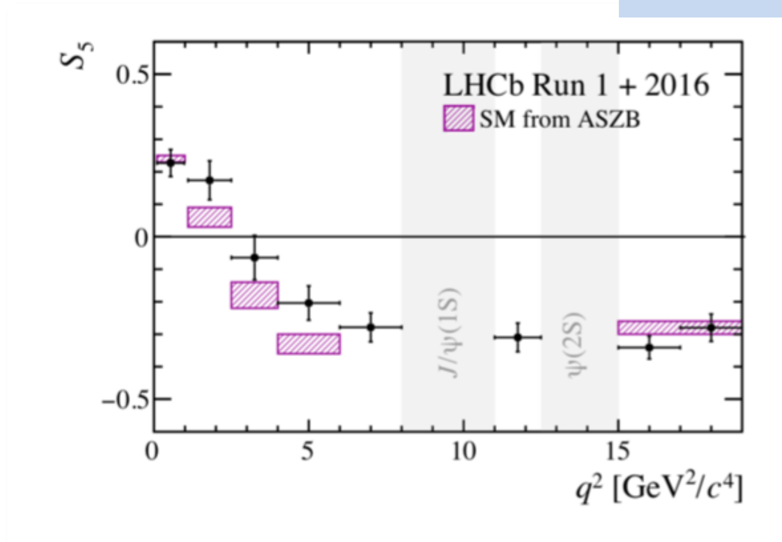



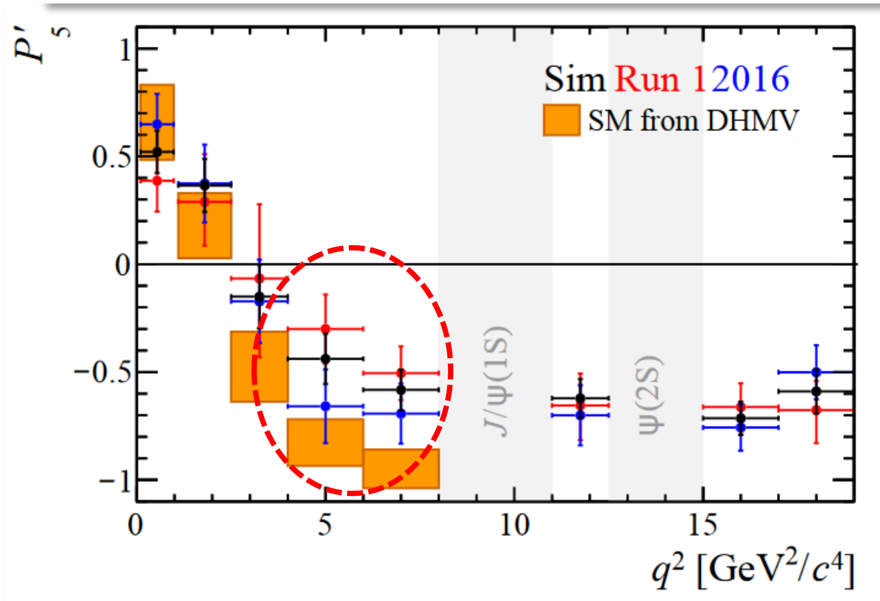

Differential branching fractions seem to differ from SM predictions in some places

# Angular analysis: $B^0 \to K^{*0}\mu^+\mu^-$

LHCb-PAPER-2020-002




Black – LHCb result.
Orange - SM DHMV JHEP 12 (2014) 129.
Purple - SM ASZB EPJC 74 (2015) 382.

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

Tension in $P_5'$ (LHCb data only):
[4.0-6.0] and [6.0-8.0] GeV$^2/c^4$ bin 2.5σ and 2.9σ.
The combined deviation is 3.3σ.
Other coefficients *C* compatible with SM.

# Lepton Universality R(K): $B^+ \to K^+ l^+ l^-$ (l=e,μ)

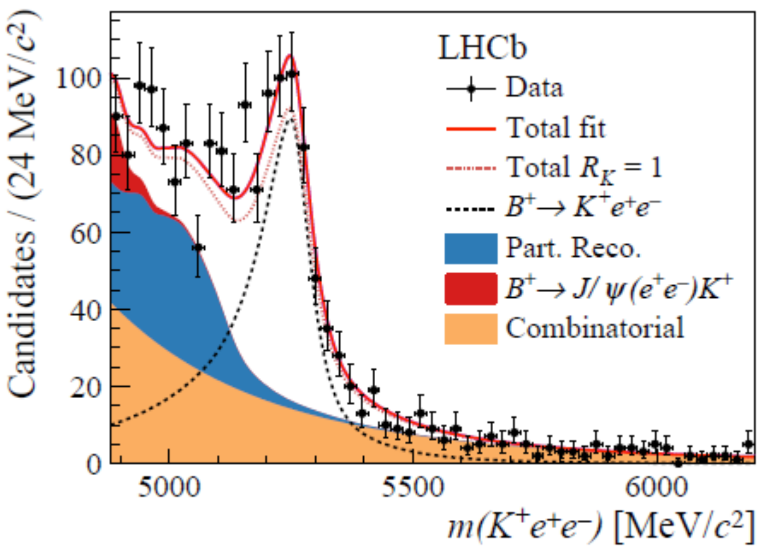
PRL 113, 151601 (2014)
PRL 122, 191801 (2019)

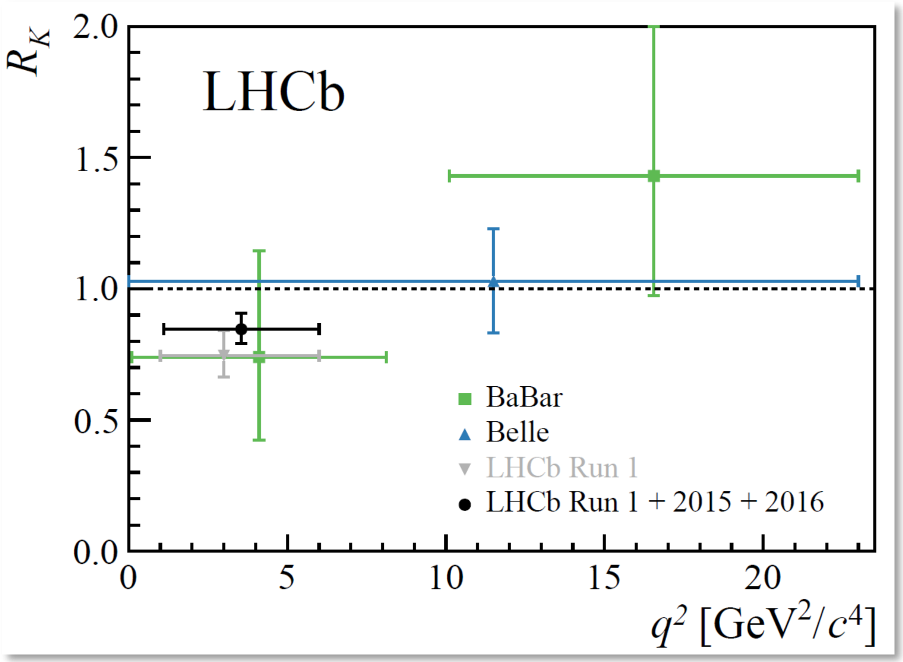
Theoretical uncertainties in branching fraction mostly cancel in ratios.

SM prediction $R_K \approx 1.0 \pm (0.001\text{-}0.01)$ depending on corrections.

Extract yields from fit to $m(K^+l^+l^-)$ mass spectrum

Use range $1.0 < q^2 < 6.0$ GeV$^2$ as theoretical uncertainties lowest here and for comparison with other experiments.



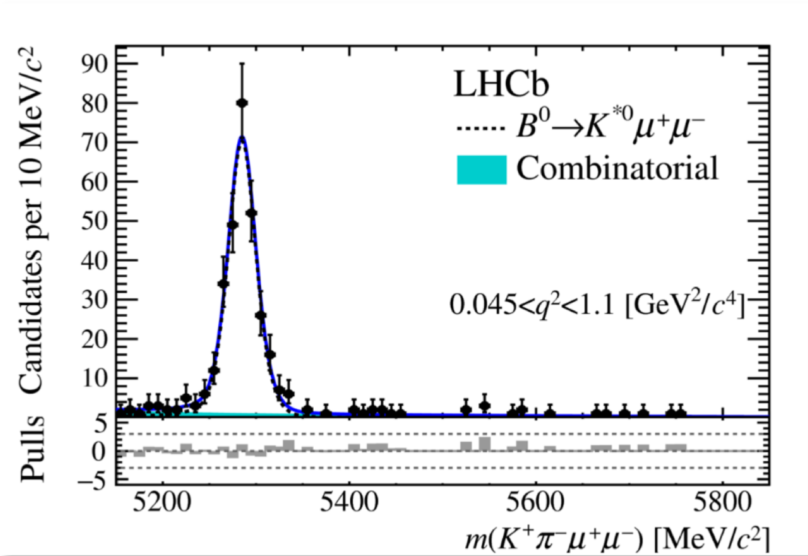



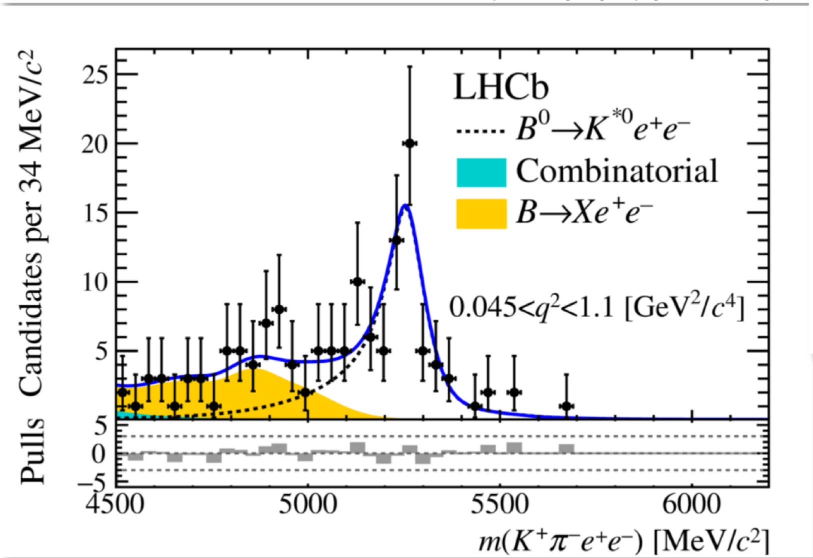

$$R_k = 0.846^{+0.060+0.015}_{-0.054-0.014}$$

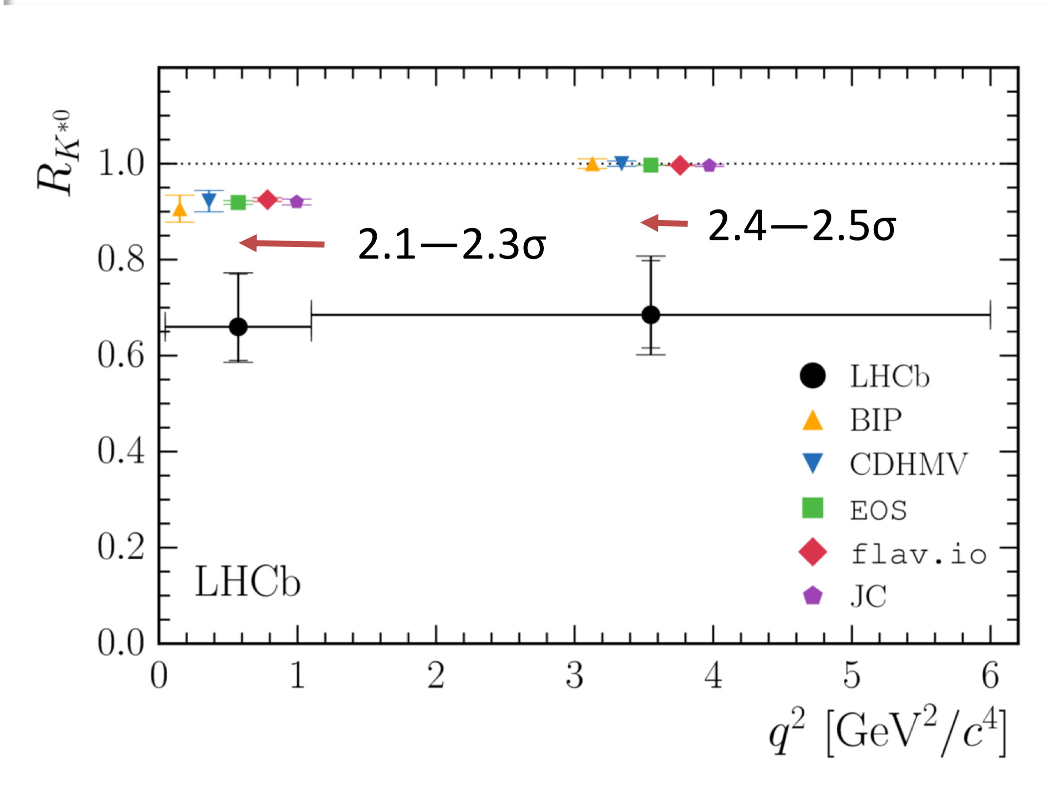
Ratio is 2.5σ from SM prediction.

# Lepton Universality R($K^{*0}$): $B^0 \to K^{*0} l^+ l^-$ ($l = e, \mu$)

JHEP 08 (2017) 055



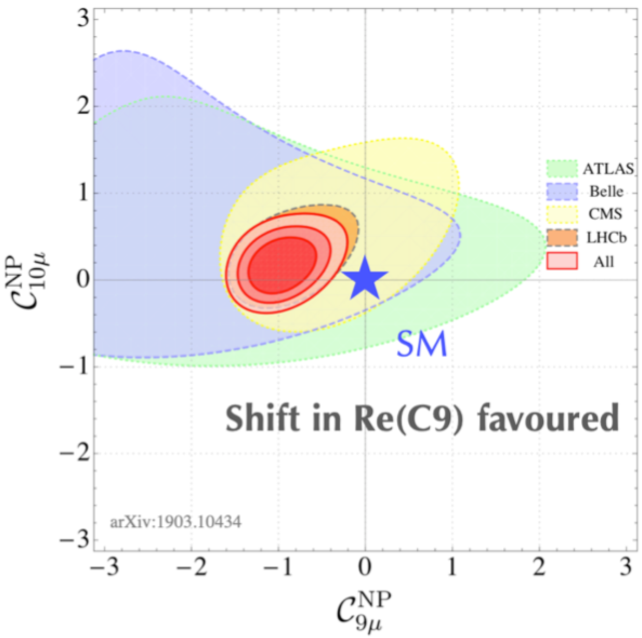




$$R_{K^{*0}} = 0.66^{+0.11}_{-0.07} \pm 0.03 \text{ (low } q^2\text{)}$$

$$R_{K^{*0}} = 0.69^{+0.11}_{-0.07} \pm 0.05 \text{ (central } q^2\text{)}$$

# Possible explanations for $b \rightarrow s l^+ l^-$




$$H_{eff} = -\frac{4G_F}{\sqrt{2}} V_{tq}^* V_{tb} \sum_{i=1} C_i^{(\prime)}(\mu) O_i^{(\prime)}(\mu) + \sum_i \frac{C_i^{NP}}{\Lambda^2} O_i^{NP}$$

Fit to differential branching fractions and angular observables.

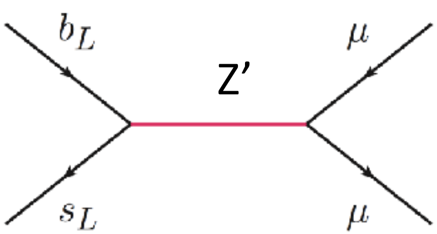
3-5$\sigma$ deviation from SM.

Best fit prefers negative $C_{9\mu}$.

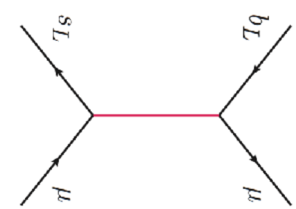
Suggests New Physics in the couplings of the muons but not the electrons.

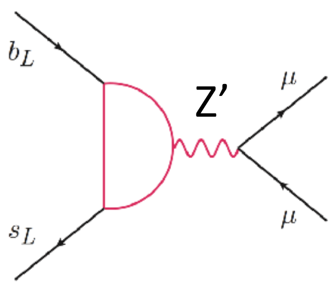
Prefers left-handed currents and not right-handed

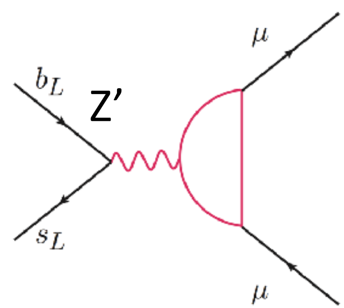
Front Runners:



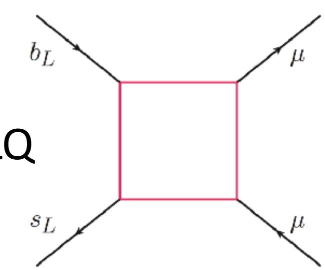

Leptoquarks (LQ)



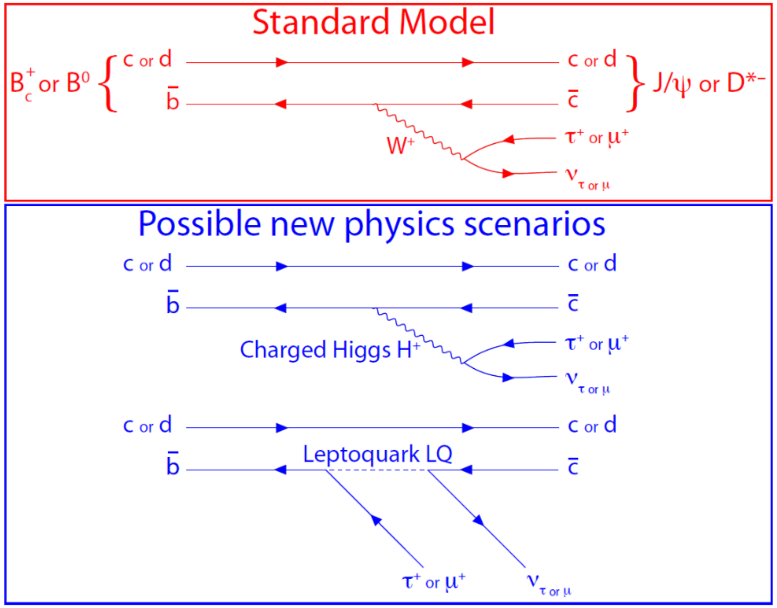



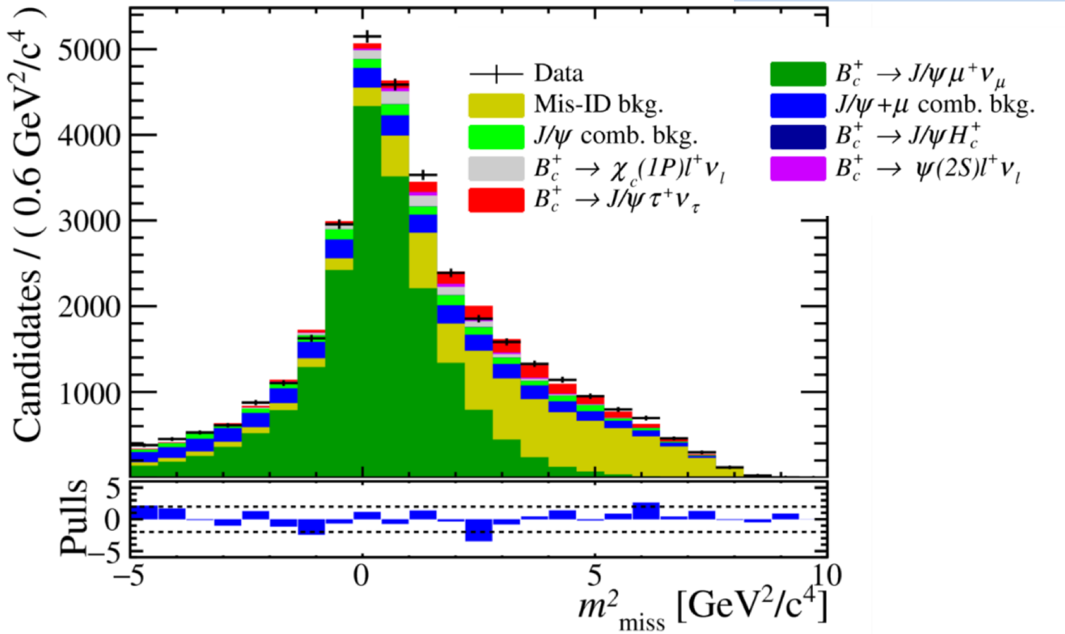

LQ



# Lepton Universality R($J/\psi$): $B_c^+ \to J/\psi l^+ \nu$ ($l=\tau,\mu$)

PRL 120 (2018) 121801



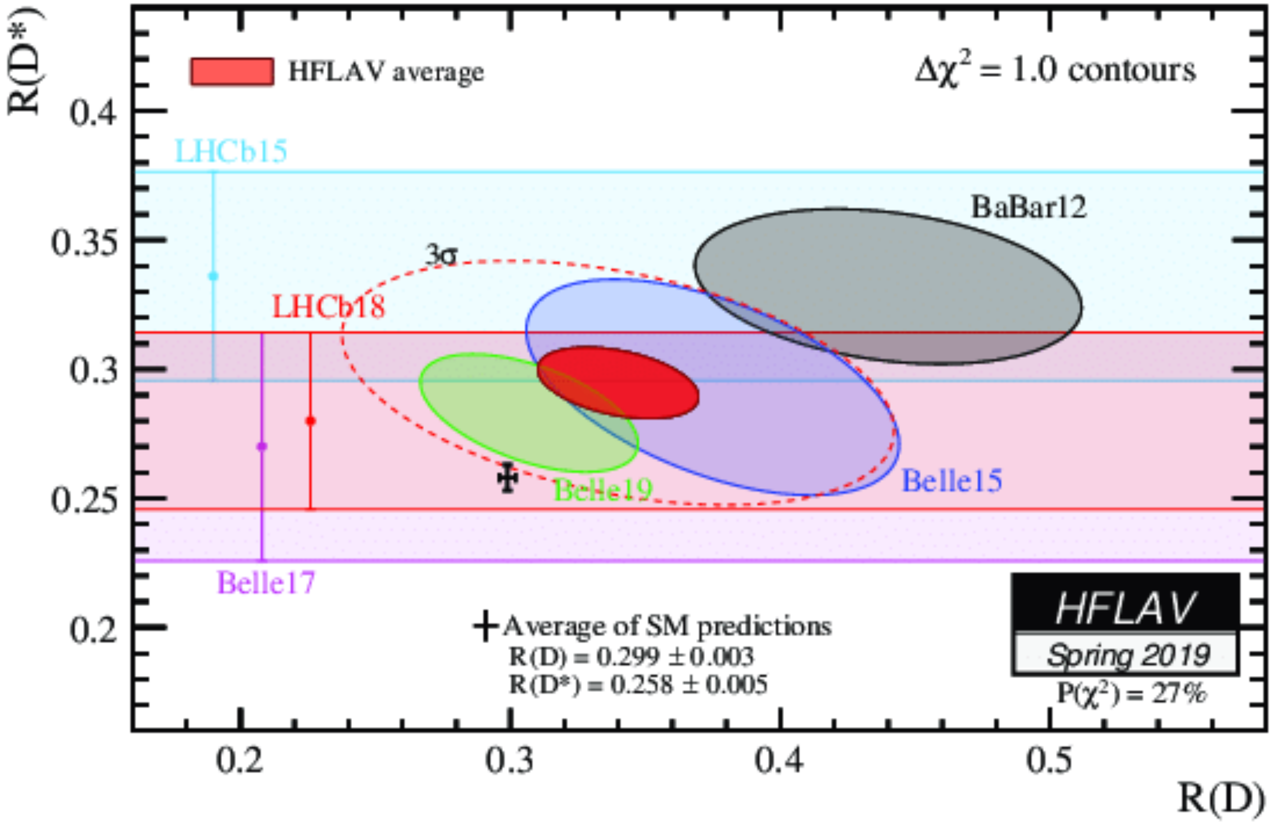




$$R_{J/\psi} = \frac{B(B_c^+ \to J/\psi \tau^+ \bar{\upsilon}_\tau)}{B(B_c^+ \to J/\psi \mu^+ \bar{\upsilon}_\mu)} = 0.71 \pm 0.17 \pm 0.18$$

$R^{SM}_{J/\psi} = 0.25 - 0.28$ (due to form factor uncertainty)

Result is within 2σ of Standard Model

# Lepton Universality $R(D^{(*)})$: $B^0 \to D^{(*)-} l^+ \nu_l$ ($l=\tau,\mu$)



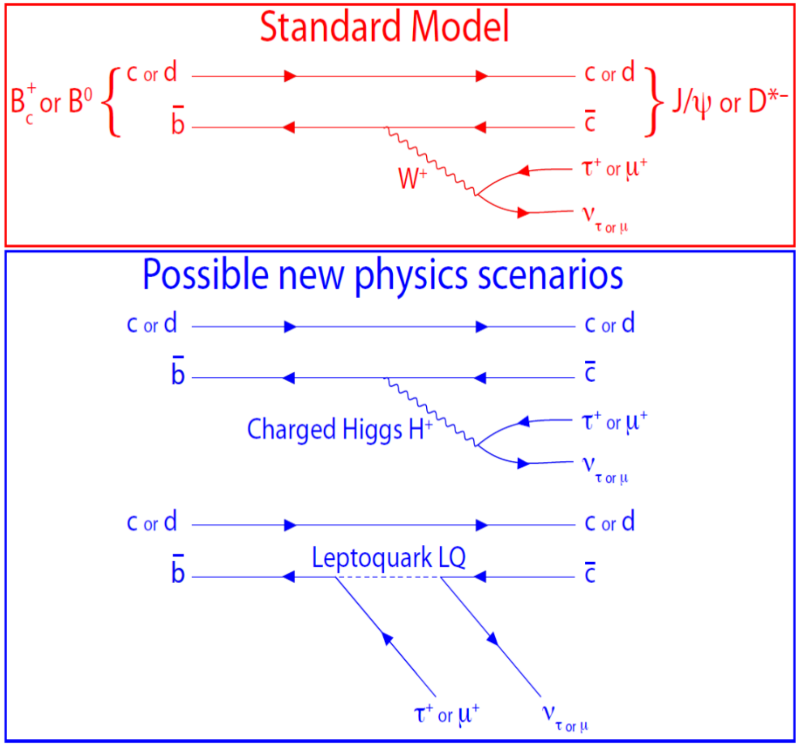

$$Average\ R_{D^{*-}} = \frac{B(B^0 \to D^{*-}\tau^+\nu_\tau)}{B(B^0 \to D^{*-}\mu^+\nu_\mu)}$$ = 0.306 ± 0.013 (stat) ± 0.007 (syst)

$$Average\ R_{D^{-}} = \frac{B(B^0 \to D^{-}\tau^+\nu_\tau)}{B(B^0 \to D^{-}\mu^+\nu_\mu)}$$ = 0.407 ± 0.039 (stat) ± 0.024 (syst)

Numbers are out of date

When all R(D) and R(D*) measurements are combined, the discrepancy is ~3σ

# Possible explanations for b $\rightarrow c\tau\nu$




Some candidates potentially ruled out:

- $H^+$ ruled out by constraints from $B_c$ lifetime, b $\rightarrow c\tau\nu$ $q^2$ distributions, pp$\rightarrow$ ττ
- W' ruled out by pp$\rightarrow$ ττ
- But W' can work if there is new RH neutrino: (Greljo, Robinson, Shakya, JZ, 1804.04642)

Some candidates still going strong:

- Vector LQ explains both b $\rightarrow c\tau\nu$ and $b \rightarrow s l^+ l^-$
- Also possible if more than one scalar LQ (Crivellin, Muller, Ota, 1703.09226)

# Lepton Universality R(pK): $B^0 \rightarrow \Lambda_b(\rightarrow pK^-)l^+l^-$

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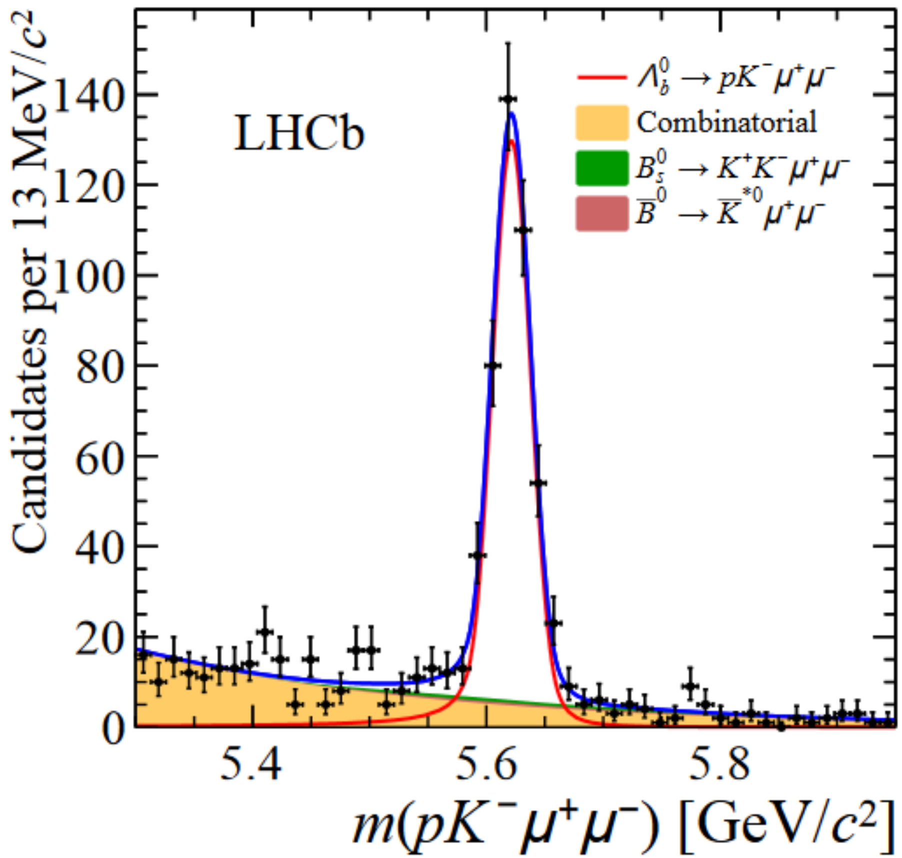
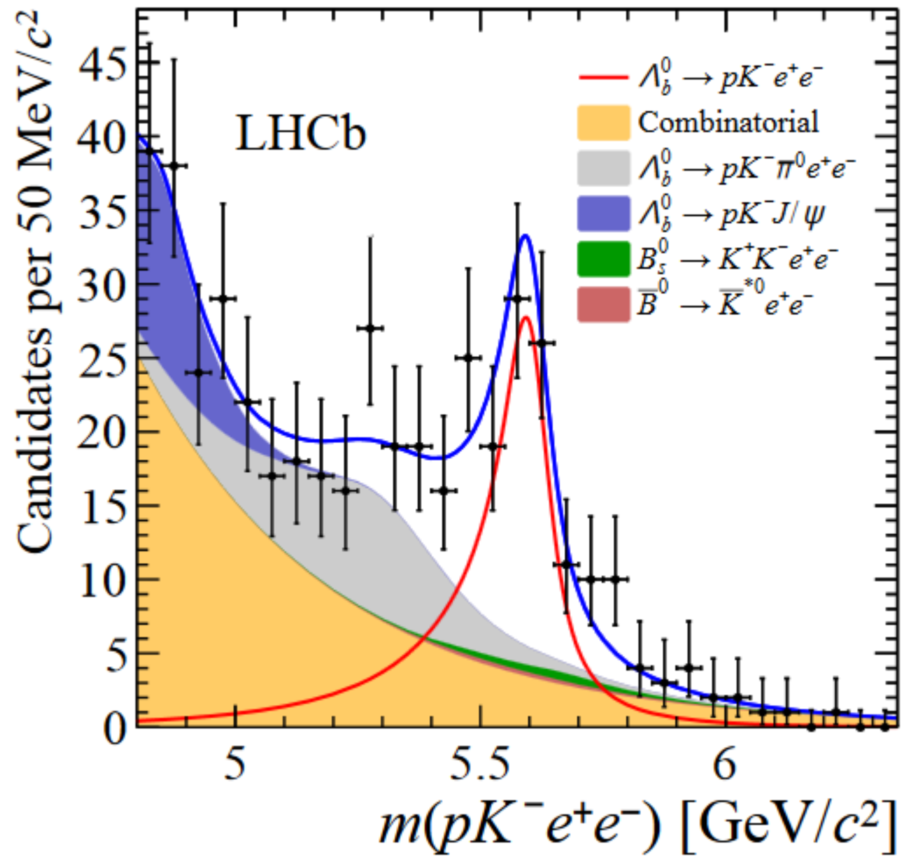
Example of LUV in a baryon decay

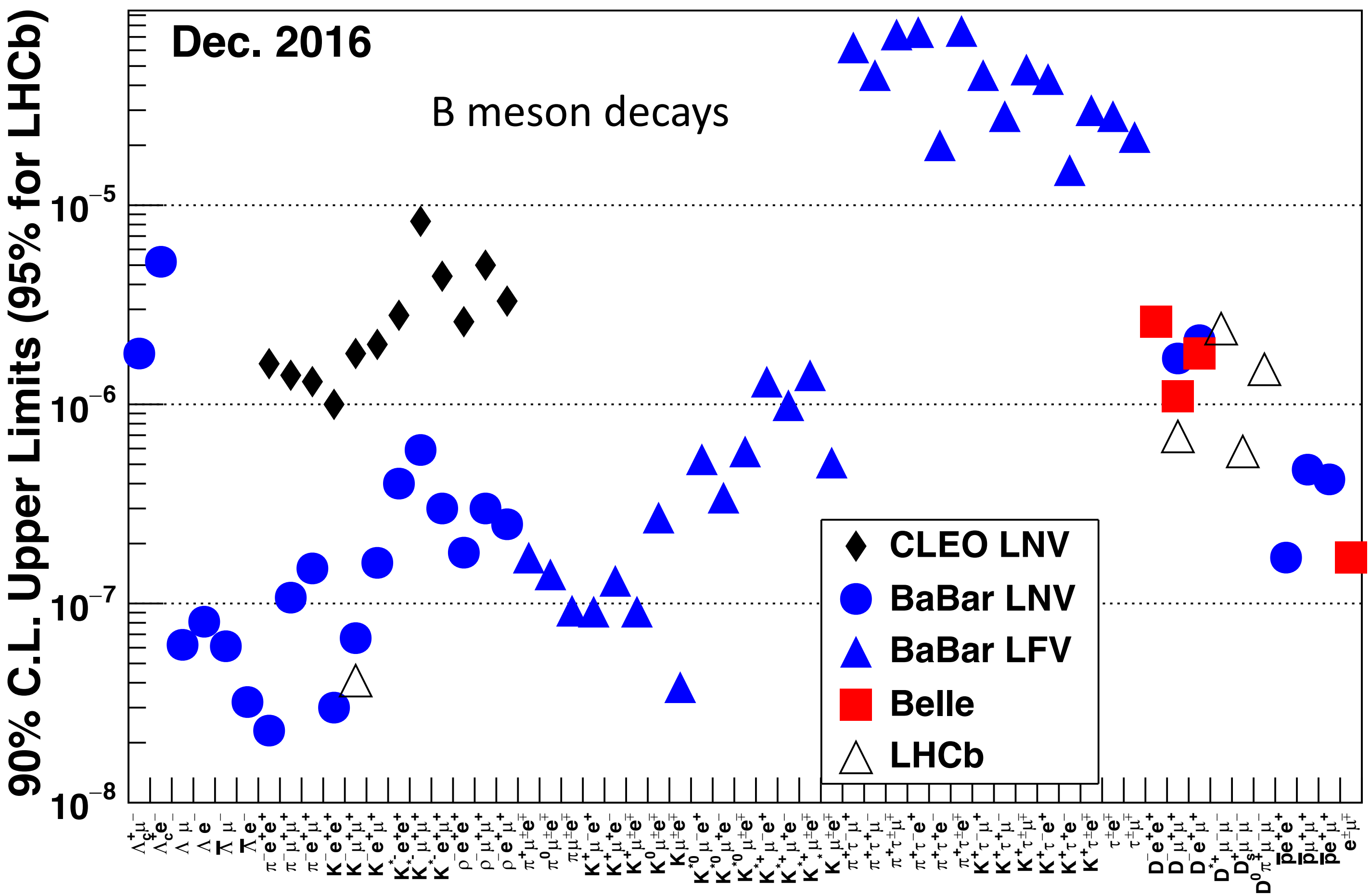



$R_{pk}^{-1} = 1.17^{+0.18}_{-0.16} \pm 0.07$

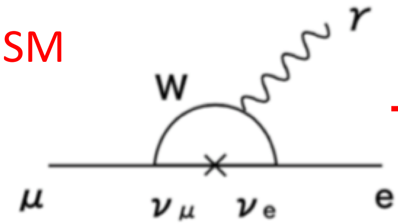
# (UN)DEDICATED CLFV EXPERIMENTS

# Lepton Flavour and Number Violation



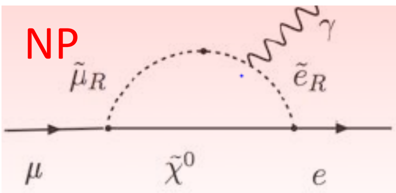
# Charged Lepton Flavour Violation

SM

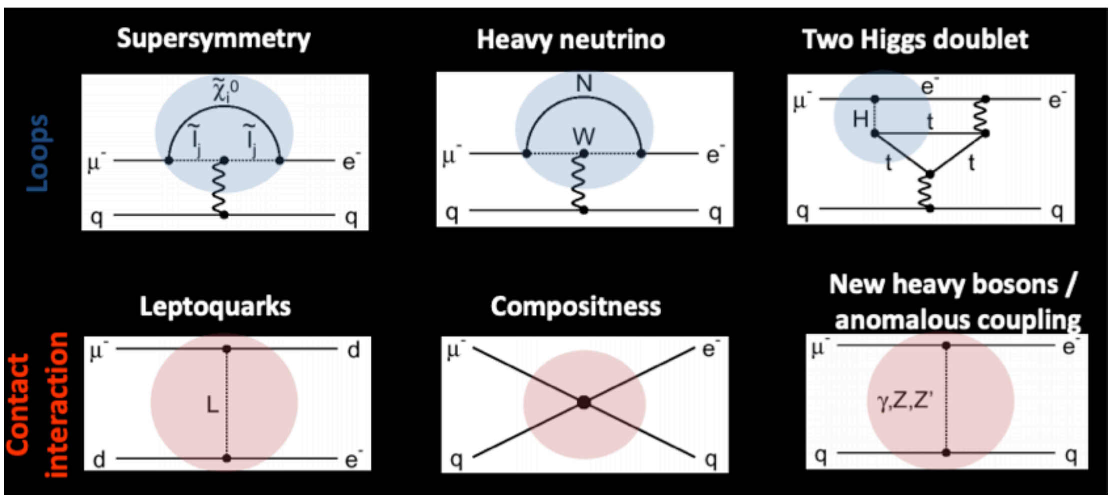


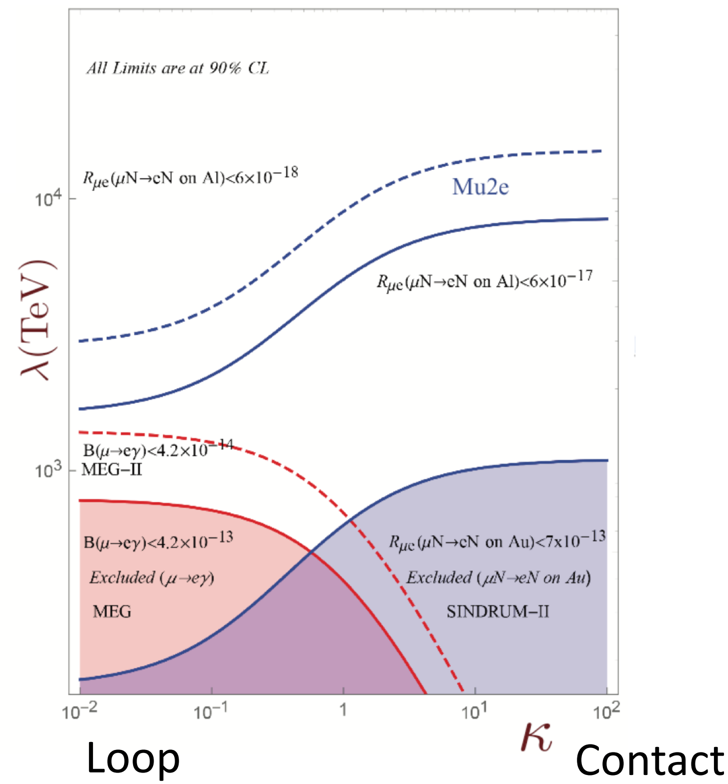

$$\Gamma(\mu \to e\gamma) = \frac{\alpha G_F^2 m_\mu^5}{384\pi^4} \sin^2 2\theta \sin^2\left(\frac{\Delta m^2 L}{4E}\right) \longrightarrow B(\mu^+ \to e^+\gamma) < 10^{-54}$$

NP

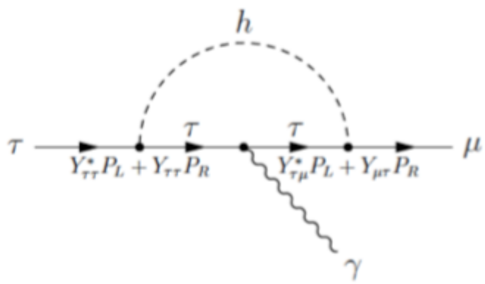


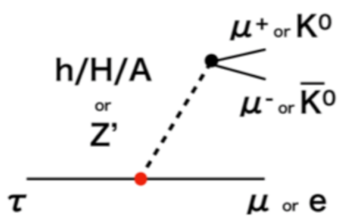

$$\Gamma(l_1 \to l_2\gamma) = \frac{\alpha G_F^2 m_{l_1}^5}{2048\pi^4}(|D_R|^2 + |D_L|^2) \longrightarrow 10^{-14} < B(\mu^+ \to e^+\gamma) < 10^{-11}$$

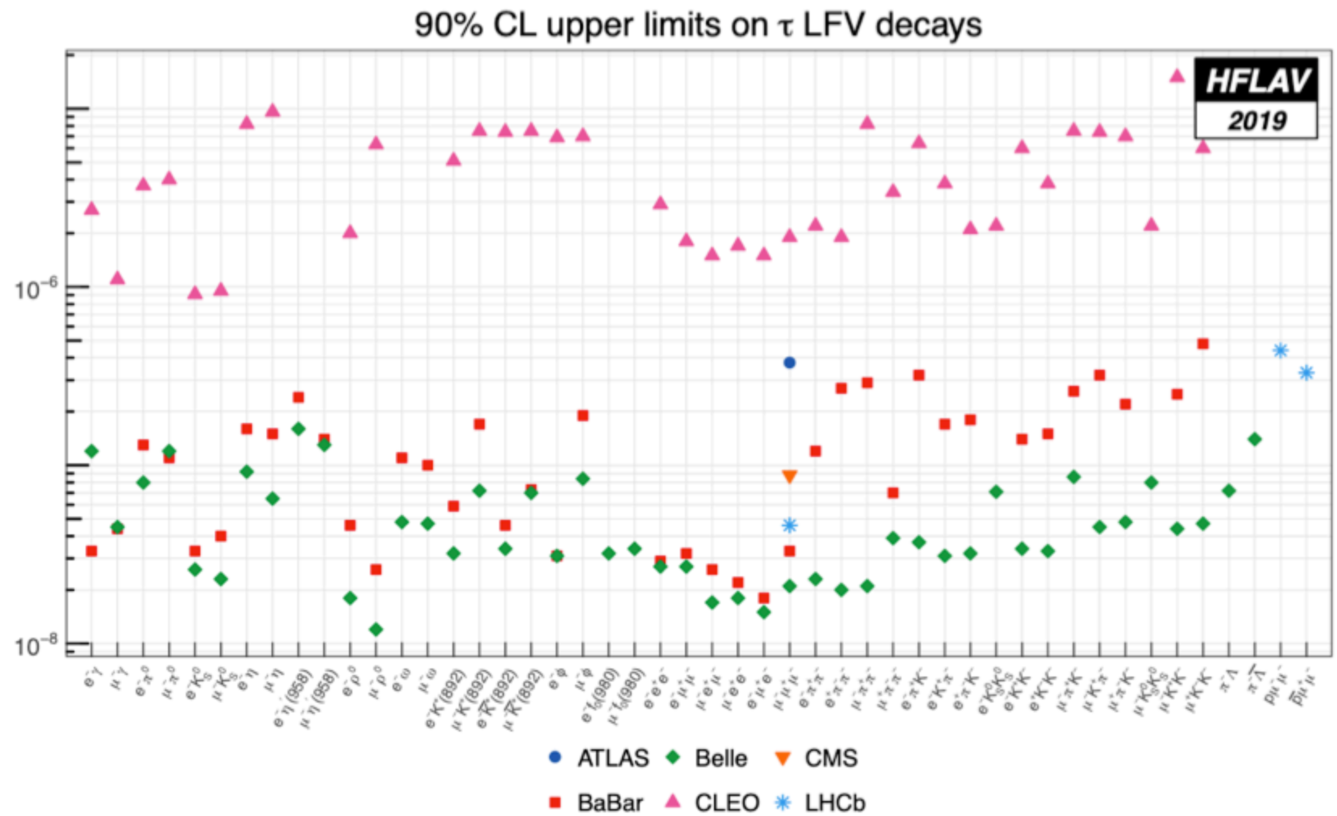


# τ Lepton Flavour Violation

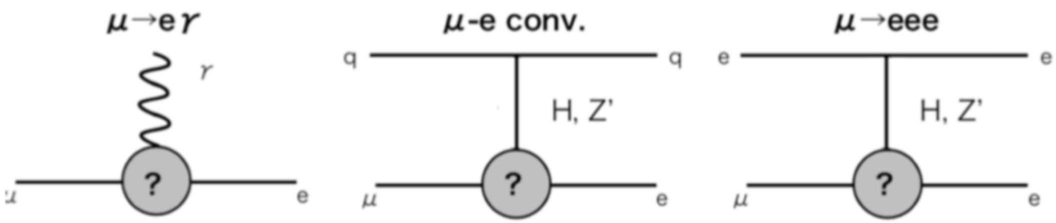


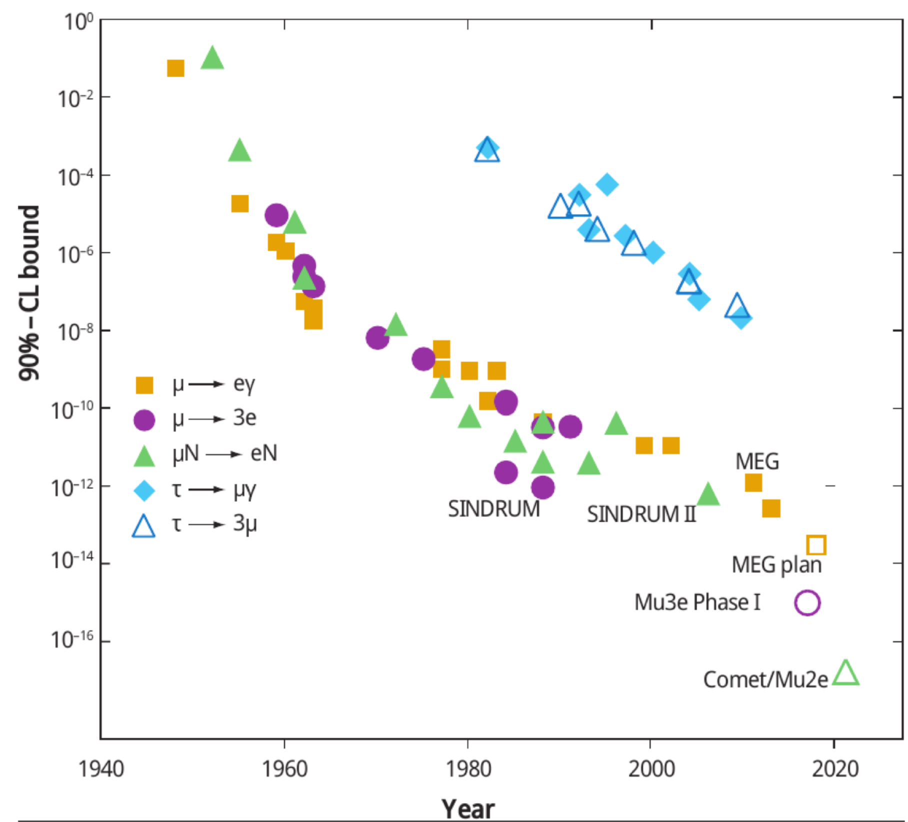
# μ Lepton Flavour Violation

MEG/MEG2 SINDRUM-II/mu2e SINDRUM/mu3e



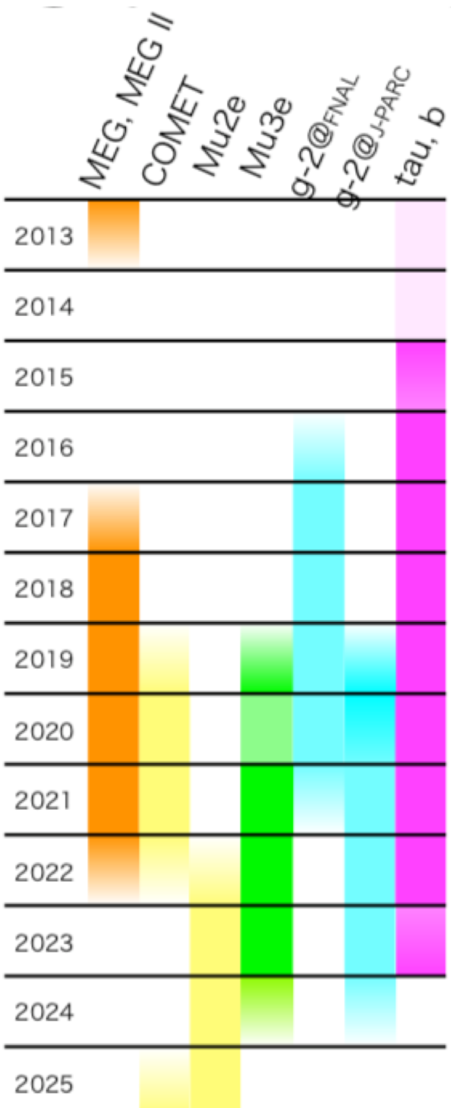

$\mu^+ \rightarrow e^+e^-e^+$ and $\mu^-N \rightarrow e^-N$ can also have BSM tree-level Leptoquarks and Z' processes.

| Process | Experiment | Upper limit |
|---|---|---|
| $\mu^+ \rightarrow e^+\gamma$ | MEG | $4.2 \times 10^{-13}$ |
| $\mu^+ \rightarrow e^+e^-e^+$ | SINDRUM | $1.0 \times 10^{-12}$ |
| $\mu^-N \rightarrow e^-N$ | SINDRUM II | $4.3 \times 10^{-12}$ (Ti)<br>$7.1 \times 10^{-13}$ (Au) |

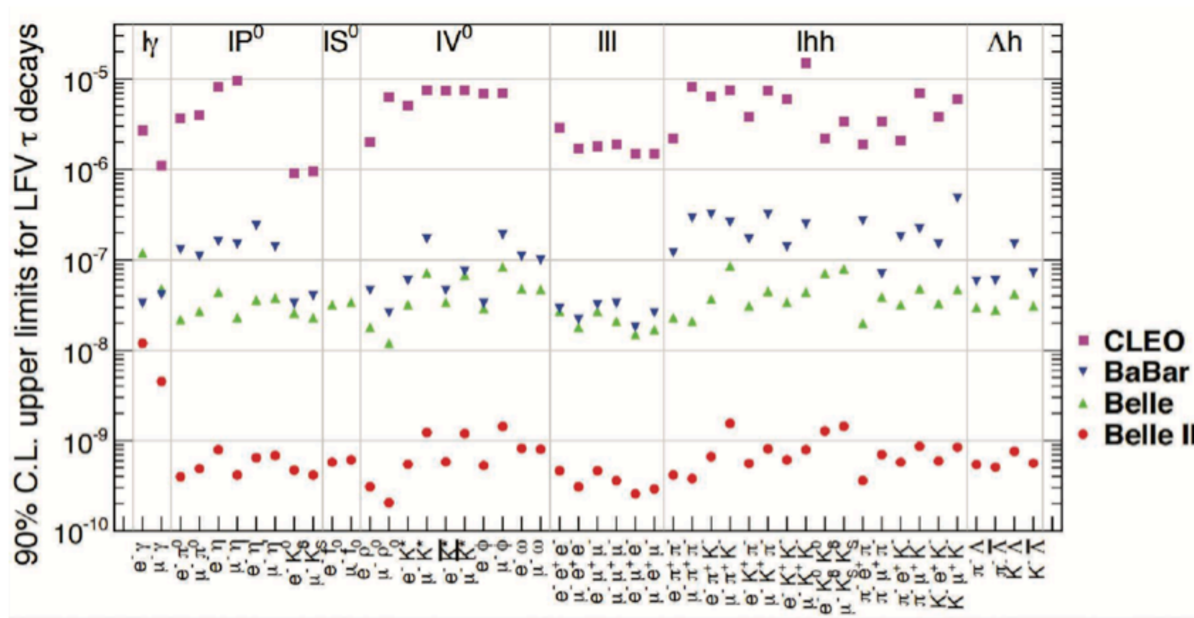


# THE FUTURE

# Dedicated cLFV experiments



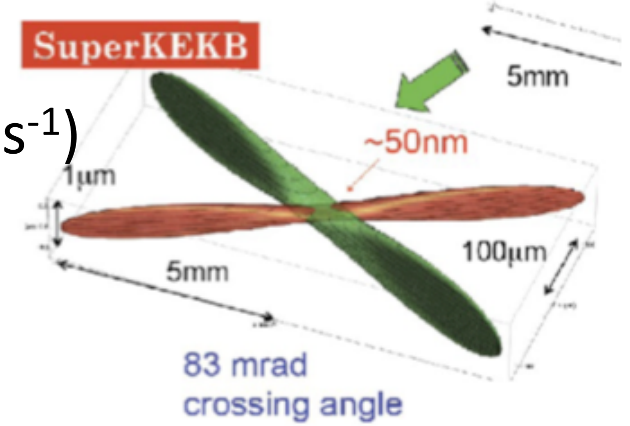

- MEG2: sensitivity < 4 x $10^{-14}$ (>2022?)
- Mu2e: sensitivity < 6 x $10^{-17}$(>2023)
- Mu3e: sensitivity < 2 x $10^{-15}$ (>2021), < $10^{-16}$ (>2025)
- Belle II/LHCb (τ decays): ~$10^{-10}$

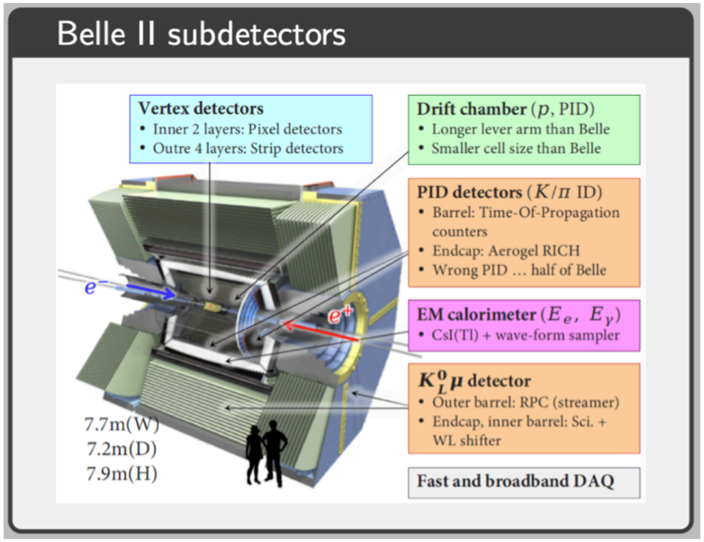


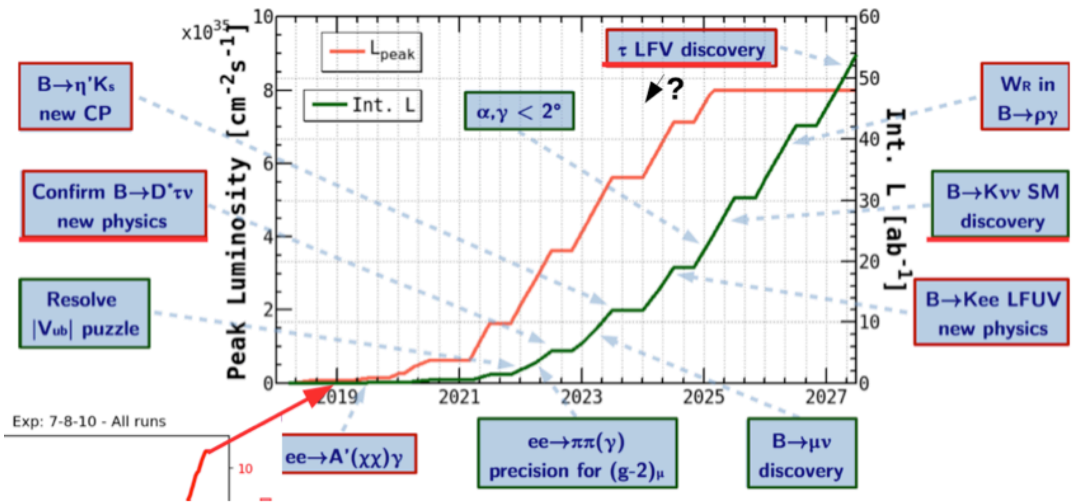
# Belle II and SuperKEKB

Nano-beam scheme working:

- 1.2 x $10^{34}$ $cm^{-2}s^{-1}$ achieved (goal: 8 x $10^{35}$ $cm^{-2}s^{-1}$)
- 10.4 $fb^{-1}$ collected (goal: 50 $ab^{-1}$).



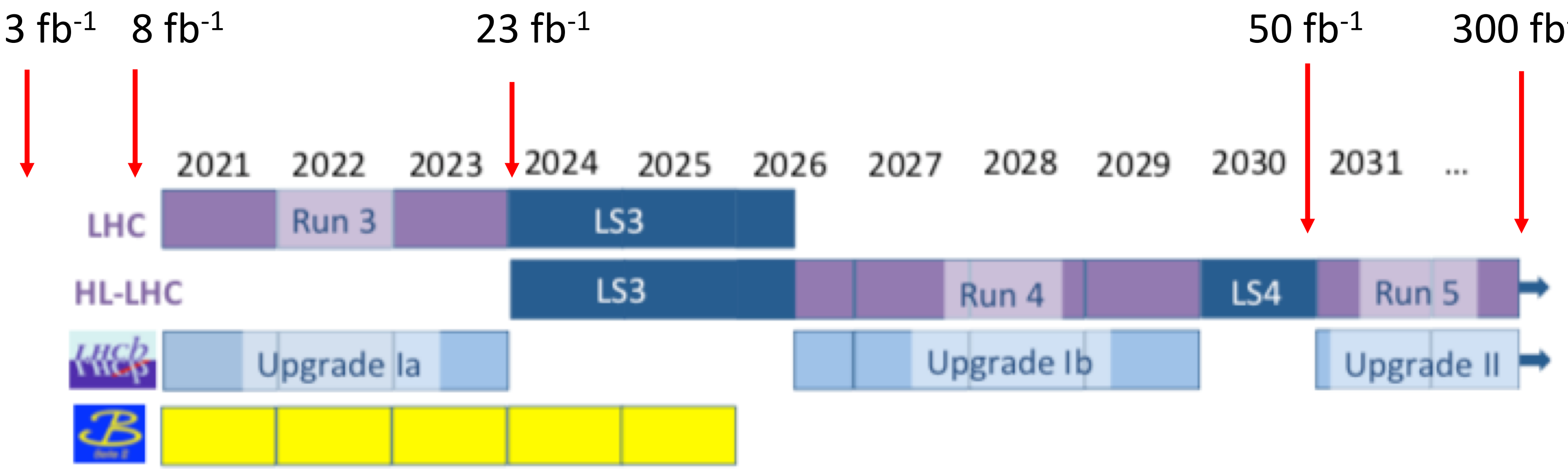



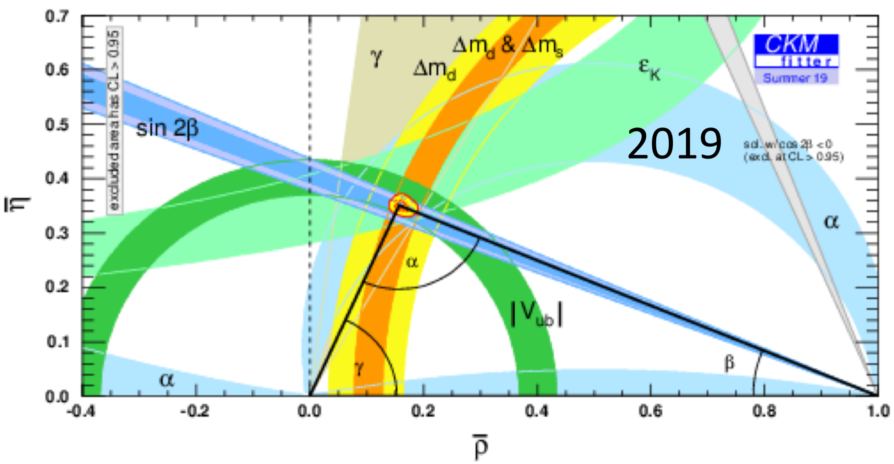



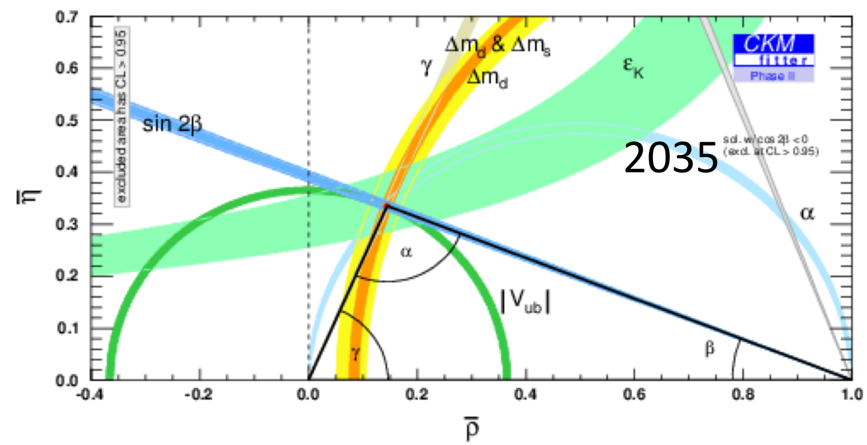

Add at least a year to this schedule

# LHC(b)

Multiply luminosity by 10 for ATLAS/CMS, shift everything after Run 3 by 1 year, delay by X months for covid-19



# Conclusion of Flavour "Mysteries"

- Summary of deviations presented today:
  - 2-3σ deviations from Standard Model in some $B^0 \rightarrow K^{*0}\mu^+\mu^-$ angular observables and in some $q^2$ ranges.
  - Some deviations in $dB/dq^2$ for $B \rightarrow Kl^+l^-$ decays.
  - 2.6σ deviation in Lepton Universality in $B^+ \rightarrow K^+l^+l^-$ decays.
  - 2.2-2.5σ deviation in Lepton Universality in $B^0 \rightarrow K^{*0}l^+l^-$ decays.
  - When combined with other measurements, 4.1σ deviation in Lepton Universality in $B \rightarrow D^{(*)}l^+\nu_l$ .
- Results from other experiments, e.g. Belle and BaBar, point in the same direction e.g. $R(D^{(*)})$.
- You can write the conclusion by voting on:

"This house believes the tensions between experimental measurements and Standard Model predictions shown today are indications of New Physics processes"