what is lepton universality and what do we know about it ?

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Fakultät Physik

Einführung

Lepton Universality in the Standard Modell

Lepton Universality Tests

- The Electroweak Sector
- Pseudoscalar Mesons
- Meson Mixing

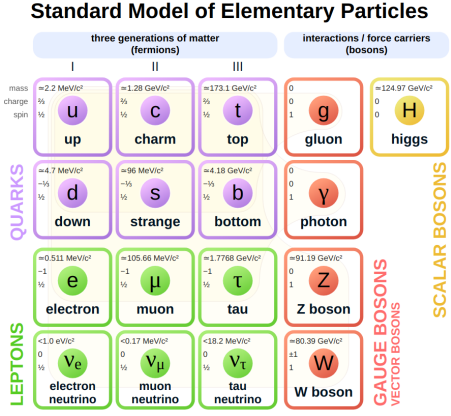
Beyond Standard Model: Leptoquarks

Conclusion

Lepton Universality in the Standard Modell

Standard Model (SM)

- gauge theory
- $SU(3)_C \otimes SU(2)_L \otimes U(1)_y$



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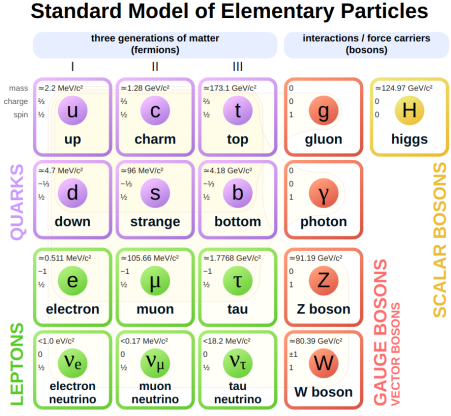

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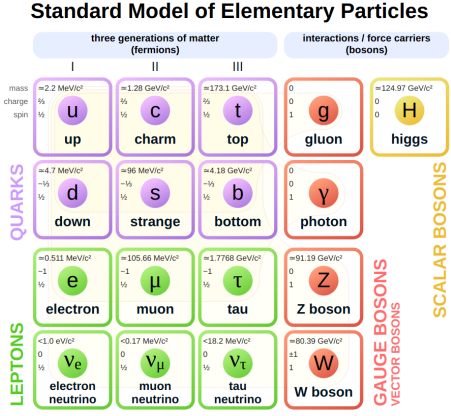
- twelve elementary fermions
  - six quarks
  - six leptons
  - three generations



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Standard Model (SM)

- gauge theory
- $SU(3)_C \otimes SU(2)_L \otimes U(1)_y \overset{SSB}{\rightarrow} SU(3)_C \otimes U(1)_{\text{QED}}$
  - Masses generated
  - Higgs-Boson
- twelve elementary fermions
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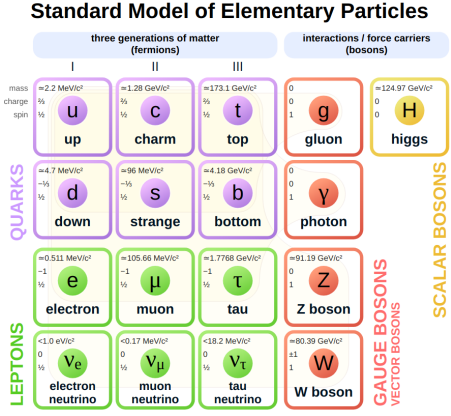

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Leptons in the Standard Model

Particle	**Q** / e	**Mass** / MeV
electron (e)	-1	0.511
neutrino (ν_e)	0	0
muon (μ)	-1	105.66
neutrino (ν_μ)	0	0
tau (τ)	-1	1776.86
neutrino (ν_τ)	0	0

Electroweak Interaction

- Charged Currents (CC)
- $W^{\pm}$-Boson interactions
  - left handed fermions
  - right handed anti-fermions
  - → violates **C** and **P**

- Neutral Currents (NC)
- Z-Boson, Photon
  - decays into $l\bar{l}$
  - never observed: $Z \rightarrow e^{\pm}\mu^{\mp}$

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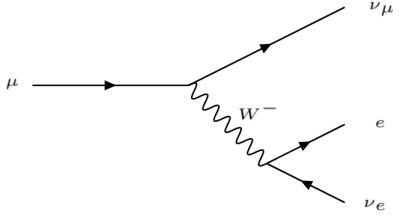

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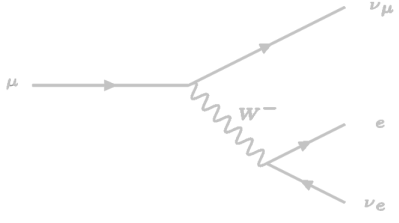

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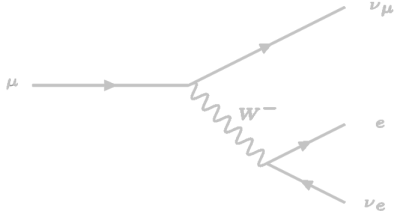

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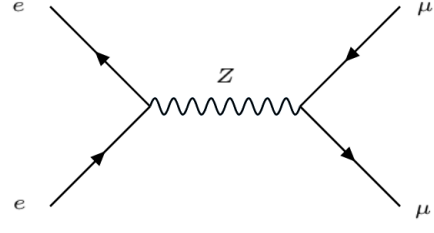
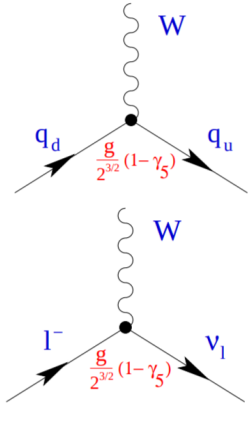


Charged Current [2]

In the SM, the lagrangian for the charged current is

$$\mathcal{L}_{CC} = \frac{g_1}{2\sqrt{2}} \left\{ W_\mu^\dagger \left[\bar{u}\gamma^\mu(1-\gamma^5)d + \bar{\nu}_e\gamma^\mu(1-\gamma^5)e \right] \right\}$$

- $g_1 = \frac{e}{sin(\theta_W)}$
- independent of mass



[1] arXiv:hep-ph/0502010

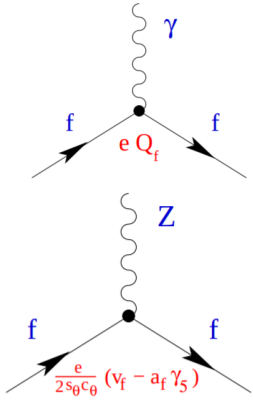
Neutral Current

In the SM, the lagrangian for the neutral current is

$$\mathcal{L}_{\text{NC}} = \frac{g_2}{2\sin(\theta_W)} Z_\nu \sum_f \bar{f}\gamma^\mu \left(\nu_f - a_f\gamma_5\right) f$$

- $g_2 = \frac{e}{cos(\theta_W)}$
- independent of mass

	u	d	ν_e	e
$2\,v_f$	$1 - \frac{8}{3}\sin^2\theta_W$	$-1 + \frac{4}{3}\sin^2\theta_W$	1	$-1 + 4\sin^2\theta_W$
$2\,a_f$	1	-1	1	-1



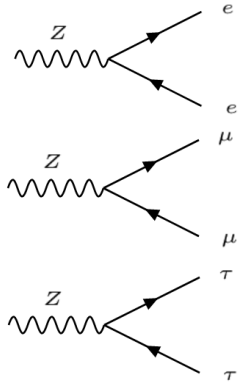
Lepton Universality

- charged and neutral currents studied:
  - inpependent of mass
  - constant coupling to all leptons

→ lepton flavour does not matter

Partial Width of the Z-Boson

- compare partial widths →ratios
  - no favoured flavour
  - → expect ratios near 1
- measurements [3] [4] :



[5] arXiv:hep-ex/0509008
[6] arXiv:1612.03016

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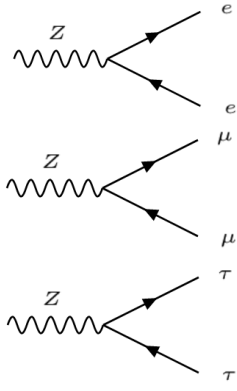

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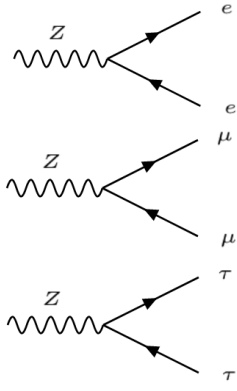

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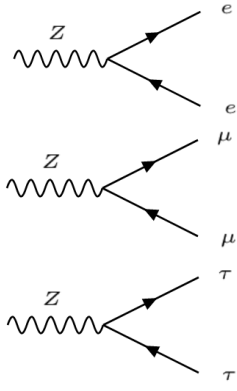

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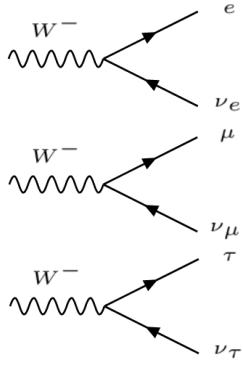

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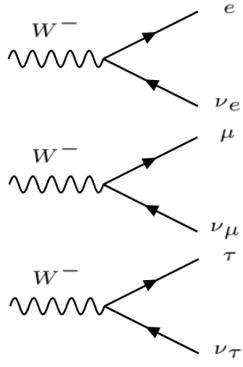

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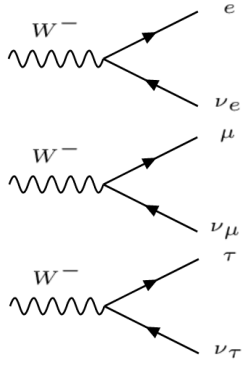

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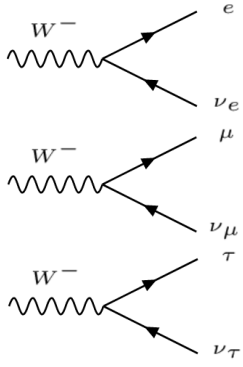

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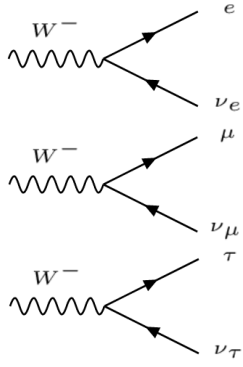
- $\approx 2.3\sigma$ deviation!



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Difficulty: tau reconstruction

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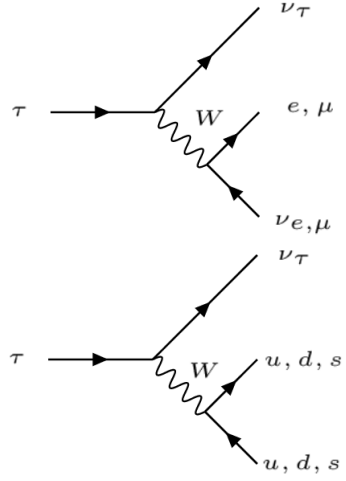
  - τ_l
  - τ_{had}

Branching Ratios of the $W^{\pm}$-Boson



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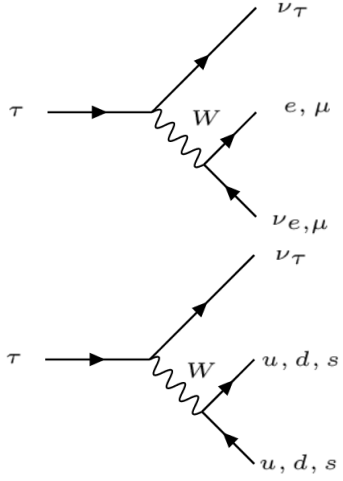

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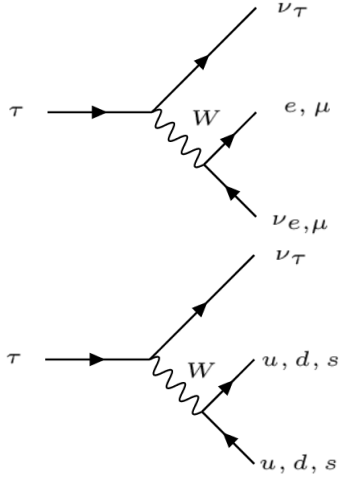

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- may be cause of deviation

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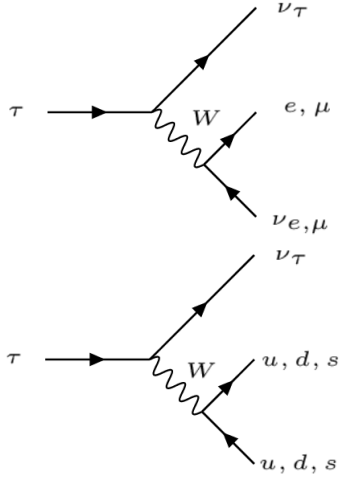
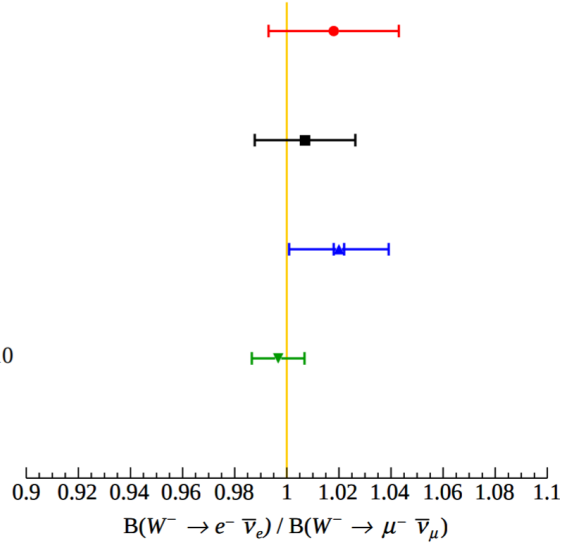


CDF : 1.018 ± 0.025
J. Phys. G34 (2007) 2457

LEP : 1.007 ± 0.019
Phys. Rept. 532 (2013) 119

LHCb : 1.020 ± 0.019
JHEP 10 (2016) 030

ATLAS : 0.997 ± 0.010
Eur. Phys. J. C77 (2017) 367



Pseudoscalar Mesons

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  - composed of $d, \bar{u}$
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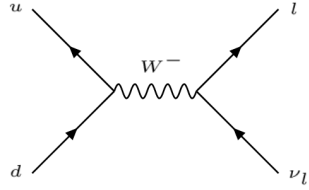

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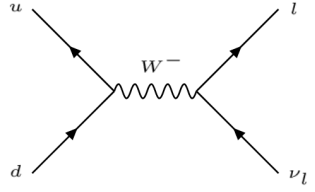

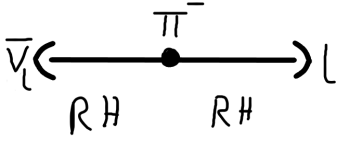

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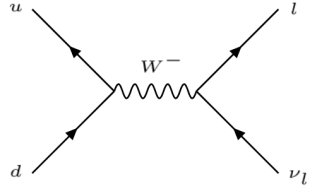

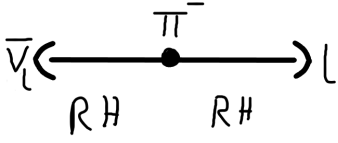

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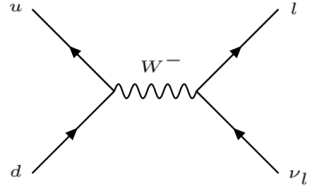

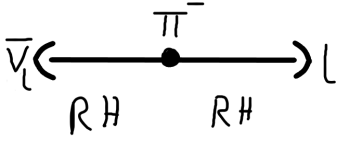

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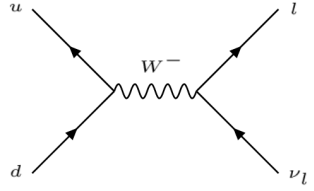

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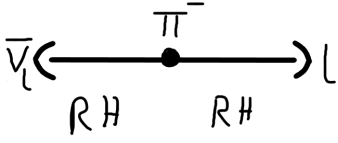
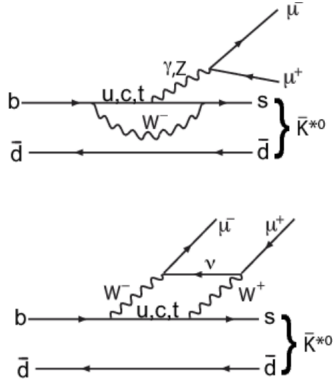


- measured :
  - $\frac{\Gamma_{\pi^-\to e^-\bar{\nu}_e}}{\Gamma_{\pi^-\to\mu^-\bar{\nu}_\mu}} = (1.230 \pm 0.004)\cdot 10^{-4}$

R_K and R_{K^*}

- anomalies in $\bar{B}^0 \to \bar{H} l \bar{l}$
  - $H = K, K^*$



[10] arXiv:1406.6482

R_K and R_{K^*}

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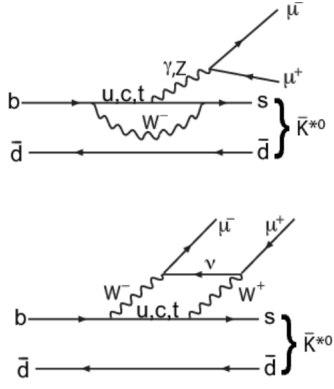

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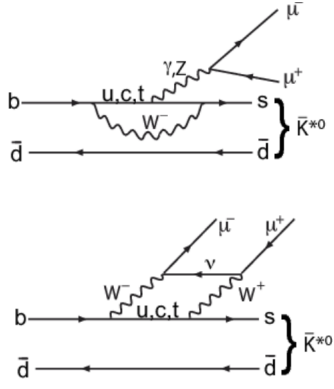

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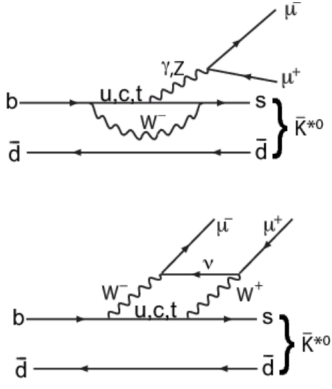
- Potential lepton flavour-violation (2.6σ)
- Leptoquarks may be the answer to this!



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Beyond the Standard Modell: Leptoquarks

- Theories: supersymmetry, grand unification
  - imply: scalars with colour and different quantum numbers
  - → Leptoquarks
- Leptoquarks (LQs)
  - spin 0 or spin 1
  - lepton number (L) $\neq 0$
  - baryon number (B) $\neq 0$
  - mass $\mathcal{O}(TeV)$
  - Three generations of LQs:
    - Generation X of LQs couples to Generation X of the SM $X \in \{1, 2, 3\}$
  - Coupling across generations possible

[11]

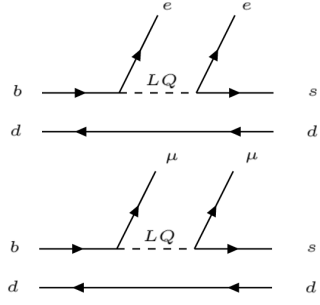
Possible Leptoquarks and their quantum numbers[10]

Spin	$3B+L$	$SU(3)_c$	$SU(2)_W$	$U(1)_Y$	Allowed coupling
0	-2	$\bar{3}$	1	$1/3$	$\bar{q}_L^c \ell_L$ or $\bar{u}_R^c e_R$
0	-2	$\bar{3}$	1	$4/3$	$\bar{d}_R^c e_R$
0	-2	$\bar{3}$	3	$1/3$	$\bar{q}_L^c \ell_L$
1	-2	$\bar{3}$	2	$5/6$	$\bar{q}_L^c \gamma^\mu e_R$ or $\bar{d}_R^c \gamma^\mu \ell_L$
1	-2	$\bar{3}$	2	$-1/6$	$\bar{u}_R^c \gamma^\mu \ell_L$
0	0	3	2	$7/6$	$\bar{q}_L e_R$ or $\bar{u}_R \ell_L$
0	0	3	2	$1/6$	$\bar{d}_R \ell_L$
1	0	3	1	$2/3$	$\bar{q}_L \gamma^\mu \ell_L$ or $\bar{d}_R \gamma^\mu e_R$
1	0	3	1	$5/3$	$\bar{u}_R \gamma^\mu e_R$
1	0	3	3	$2/3$	$\bar{q}_L \gamma^\mu \ell_L$

[11] Phys. Lett. B 191 (1987) 442

How LQs can contribute to R_K and R_{K^*}

- $R_K < 1$



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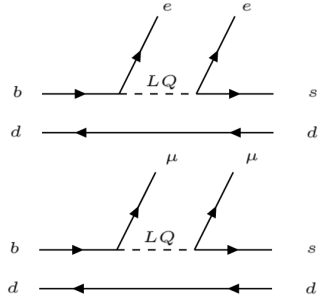
  - too many electrons
  - too few muons
  - combination of both?



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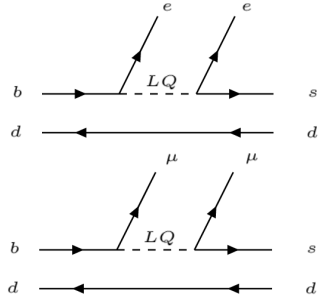
- LQs have tcouple differently to different lepton generations



Conclusion

- Lepton Universality:
  - Interaction of gauge bosons and leptons is flavour-independent
- Most tests correspond to LU
- R_K and R_{K^*}: 2.6σ deviaton
- Leptoquarks may explain R_K and R_{K^*}