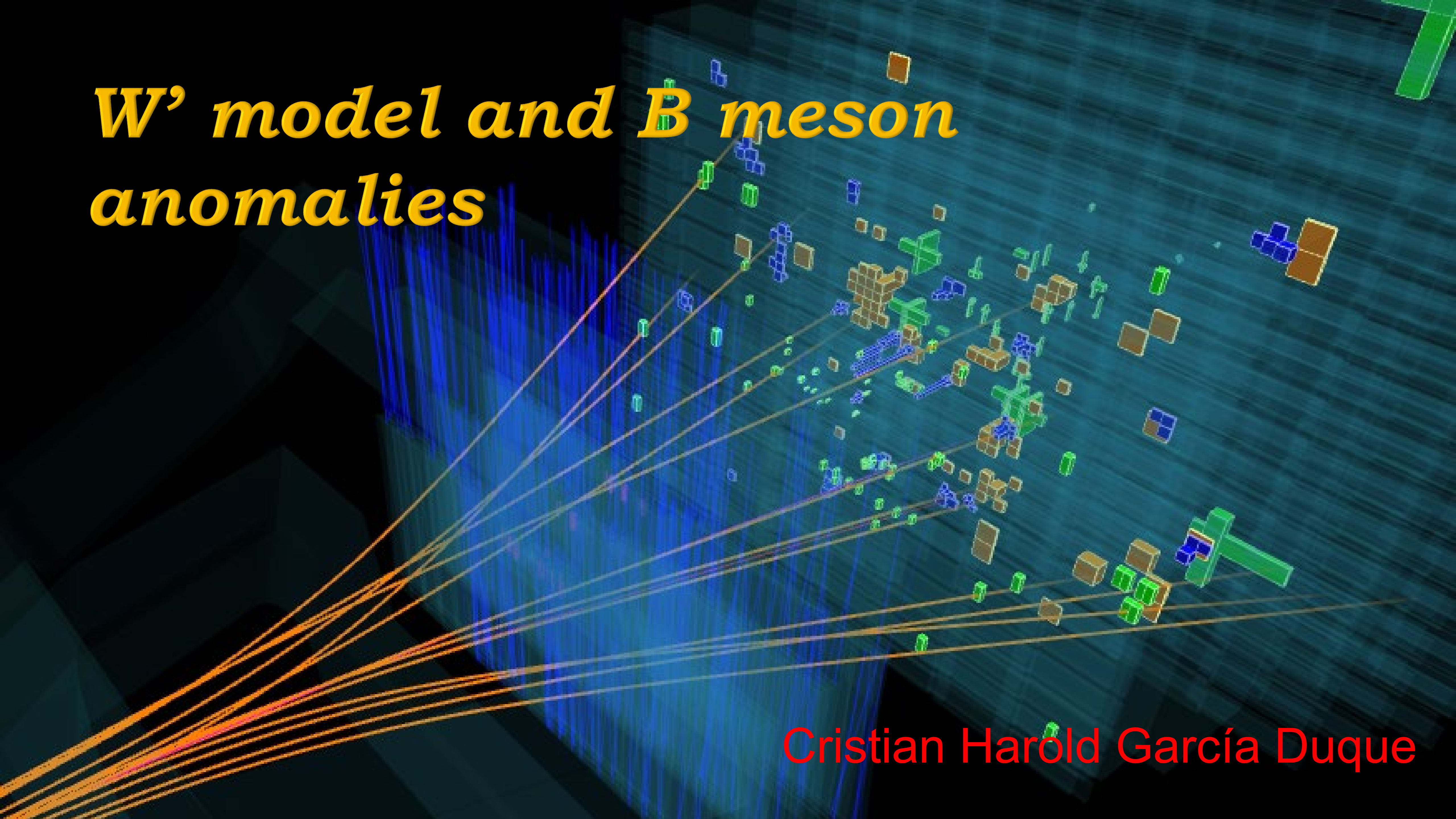

W' model and B meson anomalies

Cristian Harold García Duque

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    - LFUV, *R(D)* and *R(D*)*
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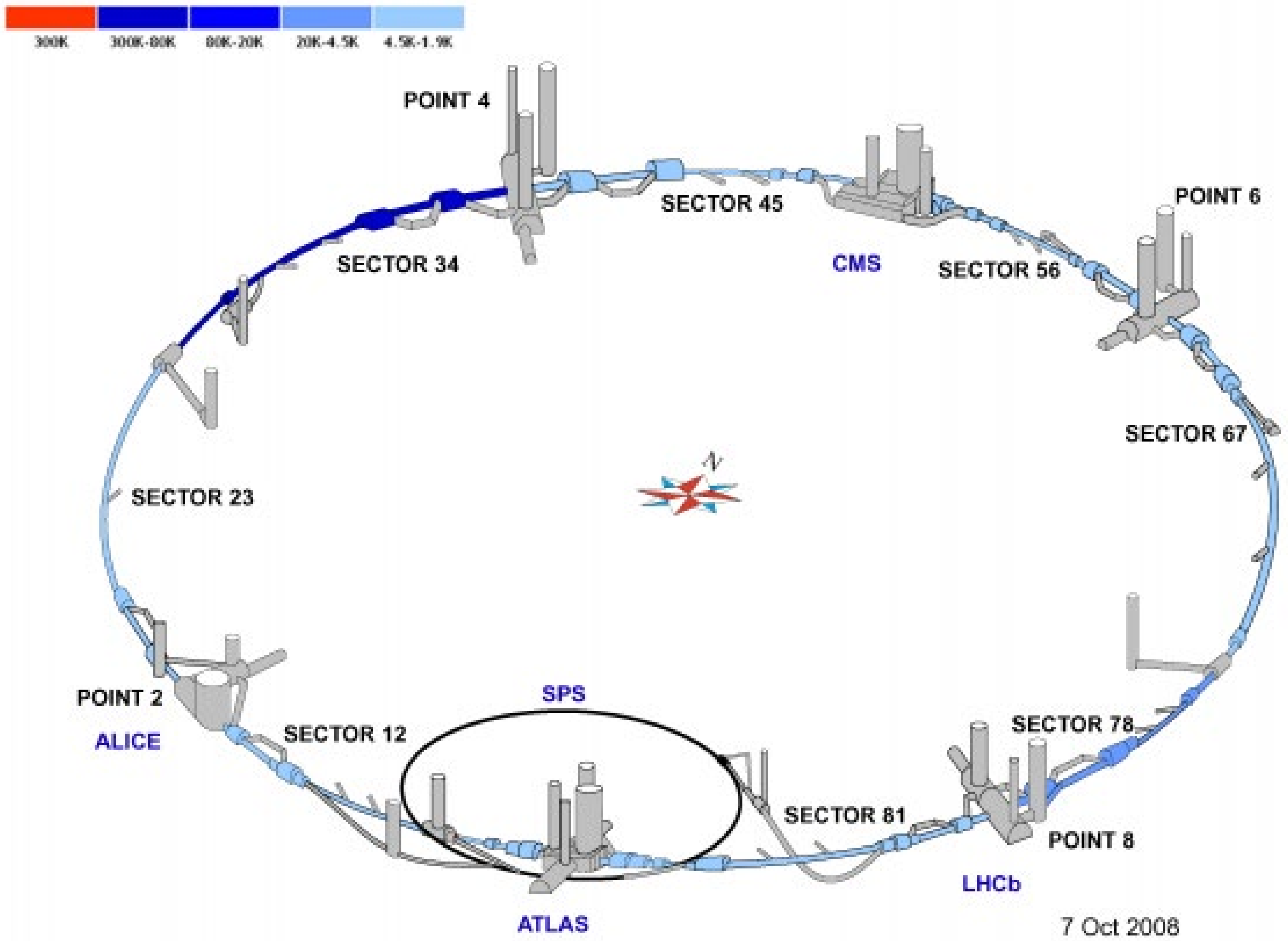


Image taken from CERN (2008), https://home.cern

1. Introduction: Standard Model

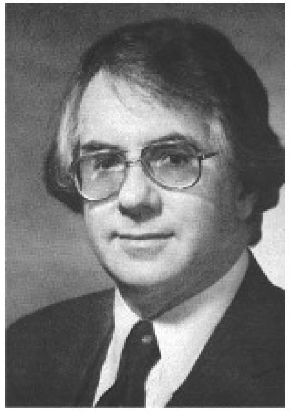
It is a theory that describes the structure and functioning of matter.

This is based on quantum field theory and includes three fundamental interactions [1]:

Electromagnetic
Weak nuclear
Strong nuclear
Does not include gravity!!!

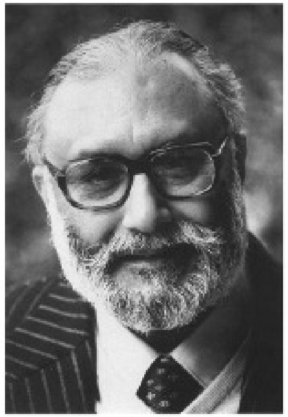
The gauge symmetry of the SM:

$$SU(3)_C \times SU(2)_L \times U(1)_Y$$

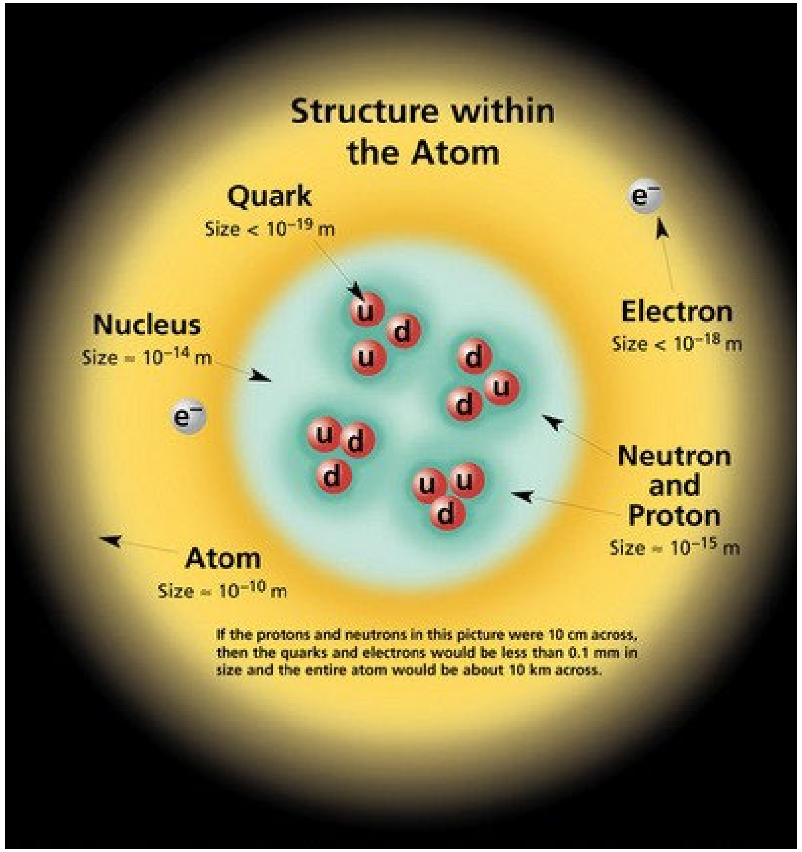


Sheldon L. Glashow

Steven Weinberg



Abdus Salam



Photos: Wikipedia https://es.m.wikipedia.org/ and The Nobel Foundation https://www.nobelprize.org/
Image taken from: https://www.particleadventure.org

[1] S.L. Glashow, *Partial-symmetries of weak interactions*, Nucl. Phys. 22 (4), 579–588 (1961); S. Weinberg, *A Model of Leptons*, Phys. Rev. Lett. 19 (21): 1264–1266 (1967); A. Salam (1968), *Elementary Particle Physics: Relativistic Groups and Analyticity*, Eighth Nobel Symposium. Stockholm: Almquvist and Wiksell. p. 367(1968).

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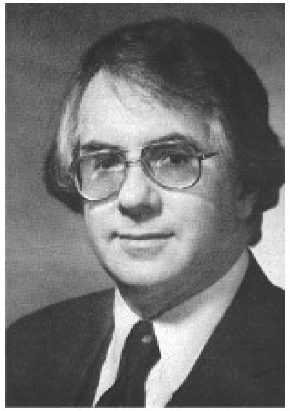
Electroweak-lepton couplings are **UNIVERSAL!!!**



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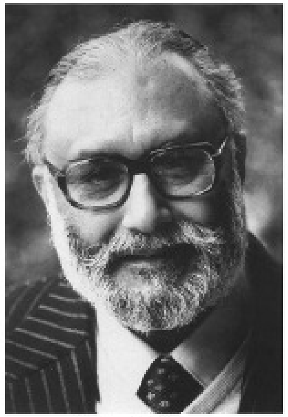

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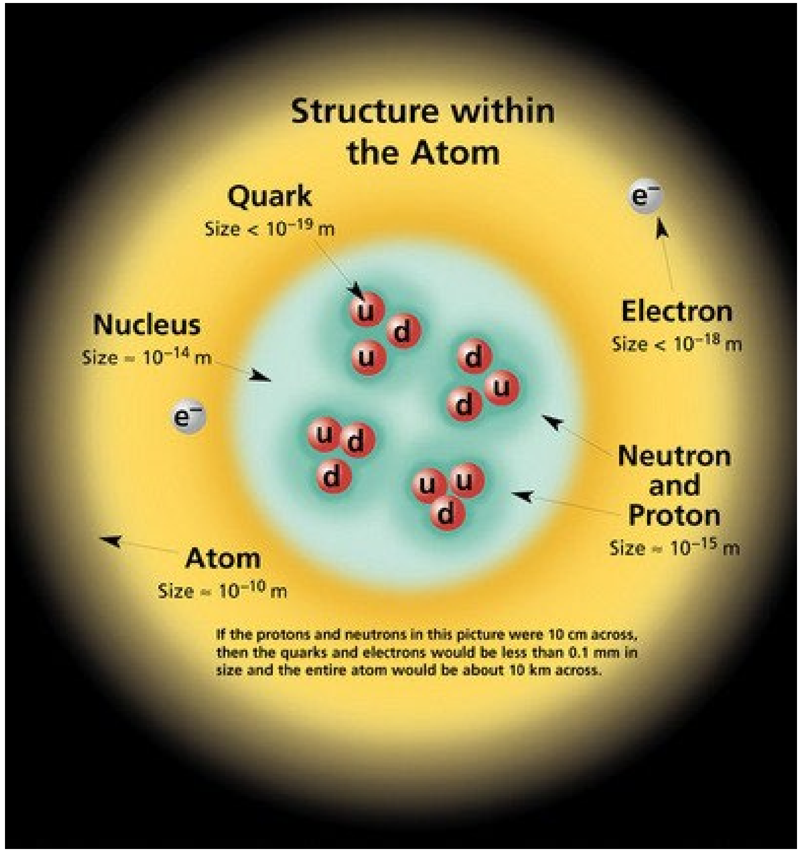

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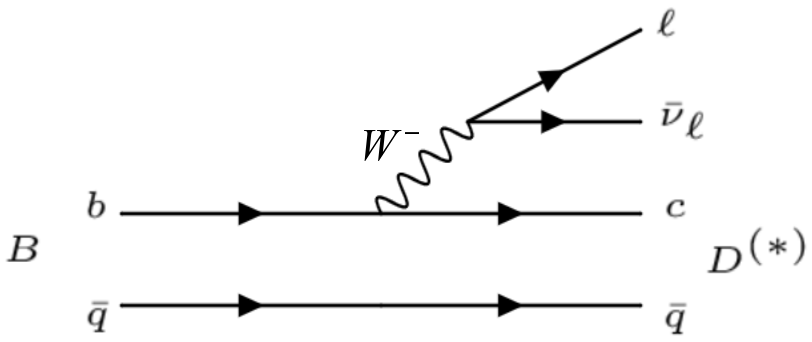
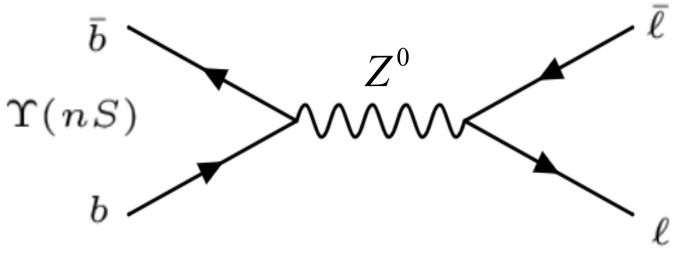
1. Introduction: LFUV

We can test the **L**epton **F**lavor **U**niversality (LFU), by studying semi-leptonic or leptonic decays, such as the $b \to cl\bar{\nu}$ and $b\bar{b} \to l\bar{l}$ processes:





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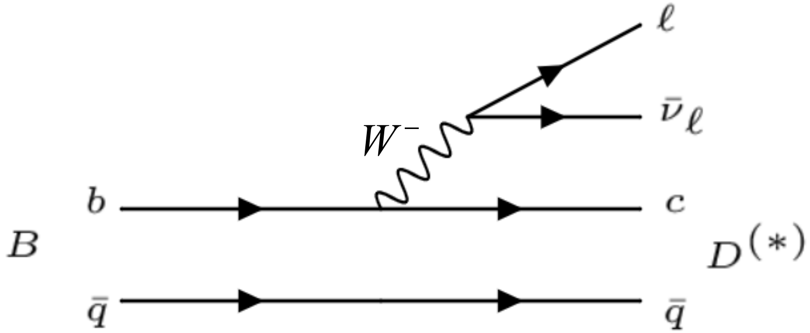
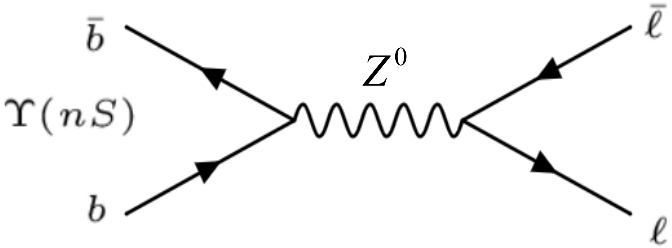




Hints of **LFU-V**iolation in the measurements of the ratio of semileptonic *B* meson decays:

$$R(M) = \frac{Br(B \to M\tau\bar{\nu}_\tau)}{Br(B \to Ml\bar{\nu}_l)},$$

where,

$$l = e, \mu$$

$$M = D, D^*(\bar{q}c)$$

Different experimental facilities observed an excess of the a τ-lepton on $b \to cl\bar{\nu}$ processes.

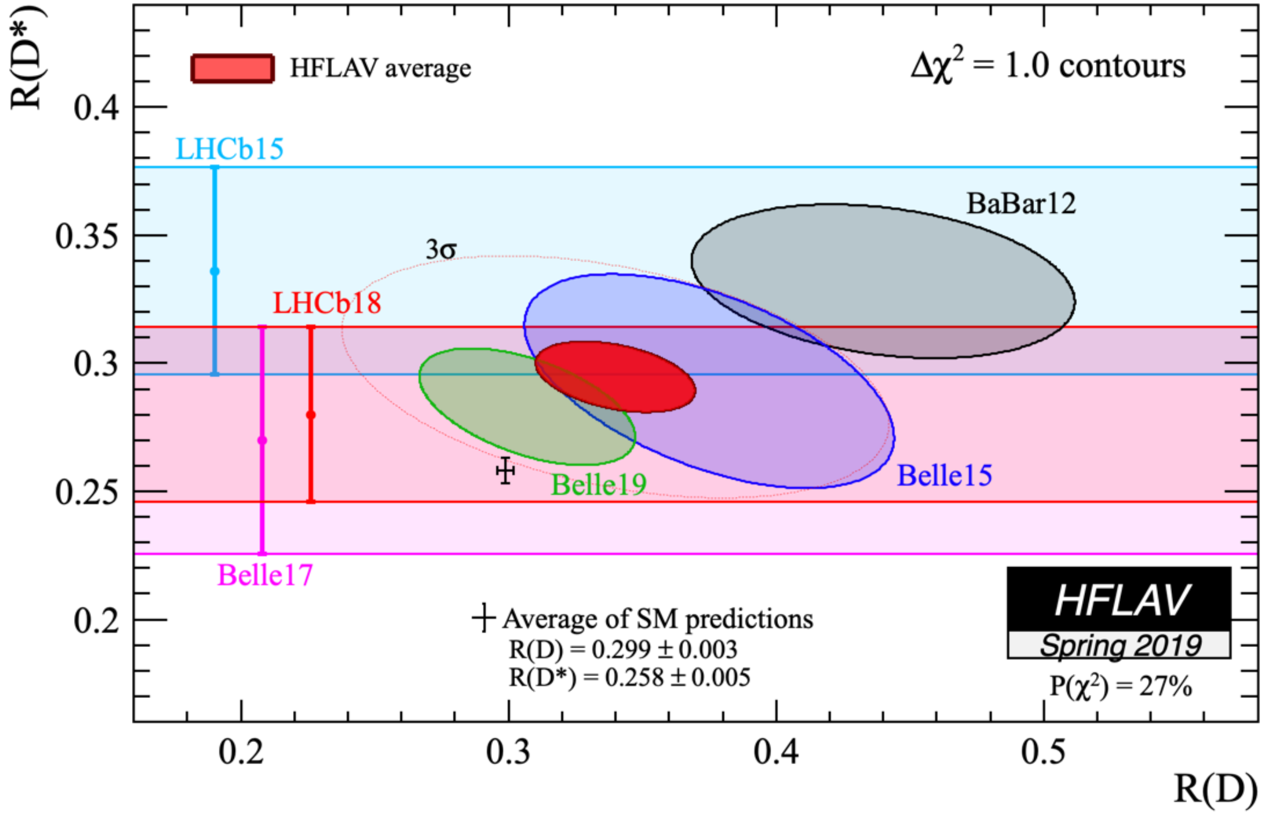
[1] A. Greljo, G. Isidori, and D. Marzocca, *On the breaking of lepton flavor universality in B decays*, J. High Energy Phys. 07 (2015) [arXiv:1506.01705]

1. Introduction: *R(D*)* and *R(D)*

These were called *R(D)* and *R(D*)* anomalies.

Experiment	***R(D*)***	***R(D)***
BaBar12 [2]	0.332±0.024±0.018	0.440±0.058±0.042
Belle15 [3]	0.293±0.038±0.015	0.375±0.064±0.026
LHCb15 [4]	0.336±0.027±0.030	
Belle17 [5]	0.270±0.035±0.026	
LHCb18 [6]	0.280±0.018±0.029	
Belle19 [7]	0.283±0.018±0.014	0.307±0.037±0.016
HFLAV average [1]	**0.295±0.011±0.008**	**0.340±0.027±0.013**
SM prediction [1]	**0.258±0.005**	**0.299±0.003**

Image taken from HFLAV (2019) [1], https://hflav-eos.web.cern.ch/hflav-eos/semi/



[1] (HFLAV Collaboration) Y Amhis *et al.*, *Averages of b-hadron, c-hadron, and τ-lepton properties as of 2018.* (2019) [arXiv:1909.12524]
[2] (BaBar Collaboration) J. P. Lees *et al.*, Phys.Rev.Lett 109, 101802 (2012) [arXiv:1205.5442] and Phys.Rev.D 88, 072012 (2013) [arXiv:1303.0571]
[3] (Belle Collaboration) M. Huschle *et al.*, Phys.Rev. D92, 072014 (2015) [arXiv:1507.03233]
[4] (LHCb collaboration) R. Aaij *et al.*, Phys.Rev.Lett. 115, 111803 (2015), Erratum: Phys.Rev.Lett. 115, 159901 (2015) [arXiv:1506.08614]
[5] (Belle Collaboration) S. Hirose *et al.*, Phys.Rev.Lett. 118, 211801 (2017) [arXiv:1612.00529] and Phys.Rev.D 97, 012004 (2018) [arXiv:1709.00129]
[6] (LHCb Collaboration) R. Aaij *et al.*, Phys.Rev.Lett. 120, 171802 (2018) [arXiv:1708.08856] and Phys.Rev.D 97, 072013 (2018) [arXiv:1711.02505]
[7] (Belle Collaboration) A. Abdesselam *et al.*, Preliminary result presented at Moriond EW 2019 [arXiv:1904.08794]

2. Standard Model: The Particle Zoo

	Fermions			Gauge Bosons	
	I	II	III		
Quarks	2.3 MeV 2/3 1967 u up	1.275 GeV 2/3 1974 c charm	173.07 GeV 2/3 1995 t top	0 0 1979 g gluon	126 GeV 0 2012 H Higgs boson
	4.8 MeV -1/3 1967 d down	95 MeV -1/3 1968 s strange	4.18 GeV -1/3 1977 b bottom	0 0 γ photon	$1\ \text{eV}=1,6\times10^{-19}\ \text{J}$ $m_p = 938\ \text{MeV}$
Leptons	0.511 MeV -1 1897 e electron	105.7 MeV -1 1936 μ muon	1.777 GeV -1 1975 τ tau	91.2 GeV 0 1983 Z^0 Z boson	Mass Charge Year Flavor Name
	< 2.2 eV 0 1956 ν_e e. neutrino	< 0.17 MeV 0 1962 ν_μ m. neutrino	<15.5 MeV 0 2000 ν_τ t. Neutrino	80.4 GeV ±1 1983 $W^\pm$ W boson	

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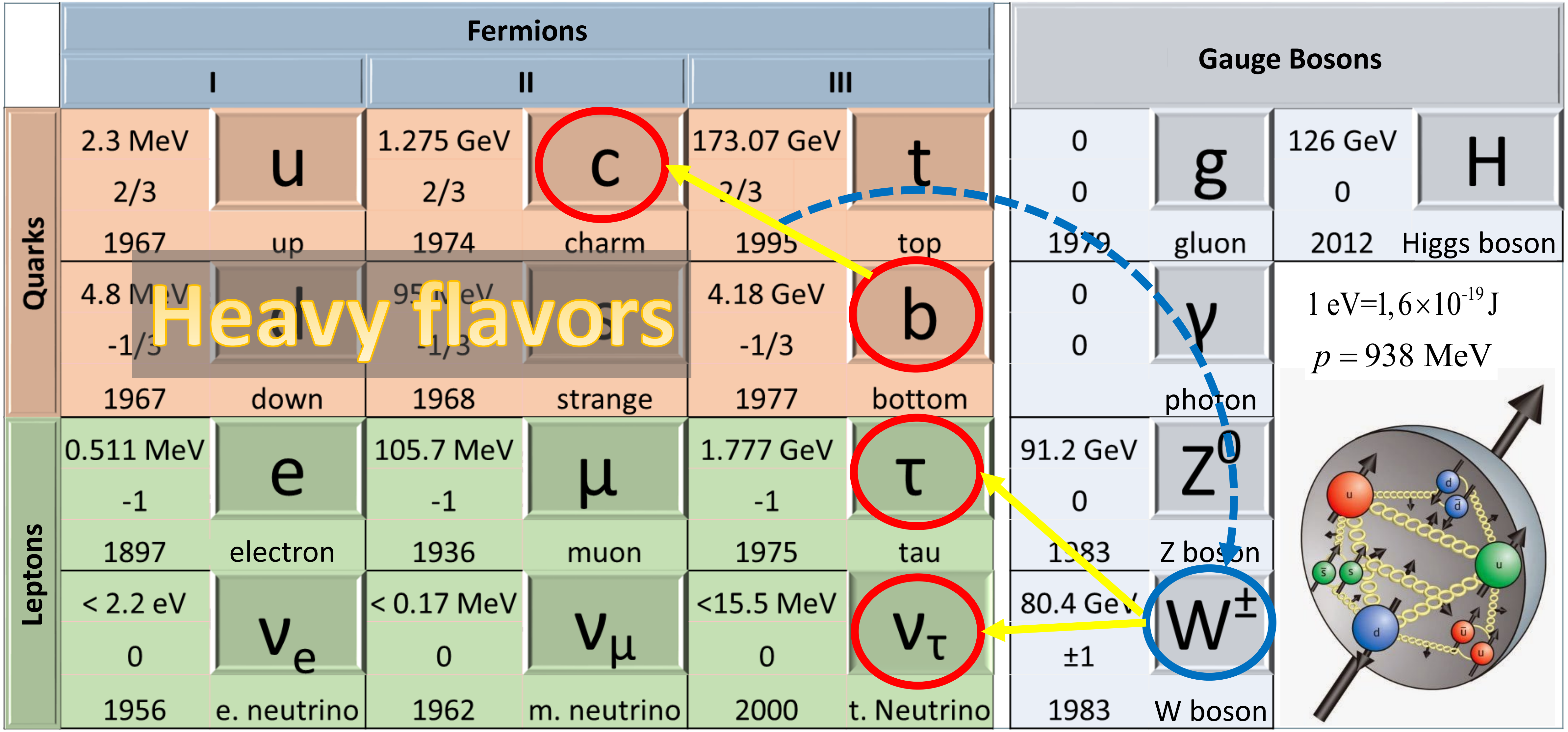

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$$1\ \text{eV}=1,6\times10^{-19}\ \text{J}$$

$$p = 938\ \text{MeV}$$

Image taken from https://www2.cose.isu.edu/

2. Standard Model: Why not?

Advantages [1]:

Subatomic particles
Forces and interactions
Links Quantum Chromodynamics, Quantum Electrodynamics and Electroweak theories
50 years of predictions

Disadvantages [2]:

Graviton
19 arbitrary parameters
Massless neutrinos
Plank scale inconsistence
Mass hierarchy
Matter–antimatter asymmetry
No dark mater
No dark energy

Illustration by Francisco Doug Grundy
http://douggrundycartoons.blogspot.com/

New Physics - beyond the SM:

Grand unification theories SU(5), SO(10)
Supersymmetry SU(3)xSU(2)xU(2)
String theory

SM extensions:

Multiple Higgs
Extra gauge bosons (W’, Z’)
Seesaw mechanism
Leptoquarks
Fourth fermion family

[1] S. Weinberg, *Essay: Half a Century of the Standard Model*, Phys. Rev. Lett. 121, 220001 (2018).
[2] O. Miyamoto, *Five mysteries the Standard Model can’t explain*, https://www.symmetrymagazine.org (2018); E. Boos, *Quantum Field Theory and the Electroweak Standard Model,* ESHEP 2013, 1-64 (2013). [arXiv:1608.02382]

2. Standard Model: Lagrangian

The SM’s lagrangian can be written[1]

$$\mathcal{L} = \mathcal{L}_{Kinetic} + \mathcal{L}_{Higgs} + \mathcal{L}_{Yukawa}$$

$$-\mathcal{L}_K(Q_L) = i\overline{Q}_L^I \gamma_\mu \left(\partial^\mu + \tfrac{i}{2} g_s G_a^\mu \lambda_a + \tfrac{i}{2} g W_b^\mu \tau_b + \tfrac{i}{2} g' B^\mu\right) Q_L^I$$

$$-\mathcal{L}_K(L_L) = i\overline{L}_L^I \gamma_\mu \left(\partial^\mu + \tfrac{i}{2} g W_b^\mu \tau_b + \tfrac{i}{2} g' B^\mu\right) L_L^I$$

$$\mathcal{L}_H = \mu^2 \phi^\dagger \phi - \lambda\left(\phi^\dagger \phi\right)^2 \qquad \phi = \frac{1}{\sqrt{2}}\begin{pmatrix}0\\ v\end{pmatrix}.$$

$$-\mathcal{L}_{Yuk} = Y_{ij}^e \overline{L}_{Li}^I \phi E_{Rj}^I + Y_{ij}^d \overline{Q}_{Li}^I \phi D_{Rj}^I + Y_{ij}^u \overline{Q}_{Li}^I \tilde{\phi} U_{Rj}^I + h.c.,$$

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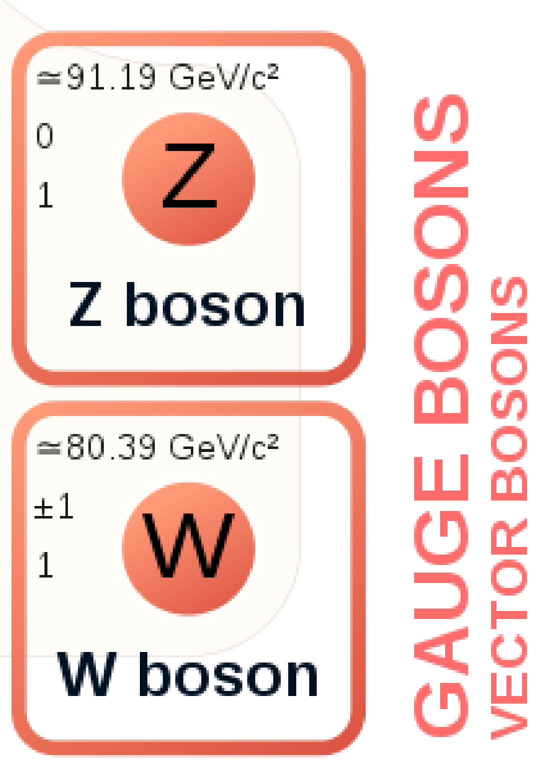

Image taken and edited from MissMJ and Cush, Wikimedia Commons (2017), https://commons.wikimedia.org/wiki/File:Standard_Model_of_Elementary_Particles.svg

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3. W’ Bosons Model:

Revising the **semileptonic** decay ratios[1]

$$R(M)=\frac{Br(B\to M\tau\overline{\nu}_{\tau})}{Br(B\to Ml\overline{\nu}_{l})},\ l=e,\mu\ \text{ and }\ M=D,D^{*}(\overline{q}c),$$

We can observe two possibilities

$$R(M)=\frac{Br(B\to M\tau\overline{\nu}_{\tau})_{SM}+Br(B\to M\tau\overline{\nu}_{\tau})_{NP}}{Br(B\to Ml\overline{\nu}_{l})_{SM}-Br(B\to Ml\overline{\nu}_{l})_{NP}}.$$

So we choose a third generation interaction.

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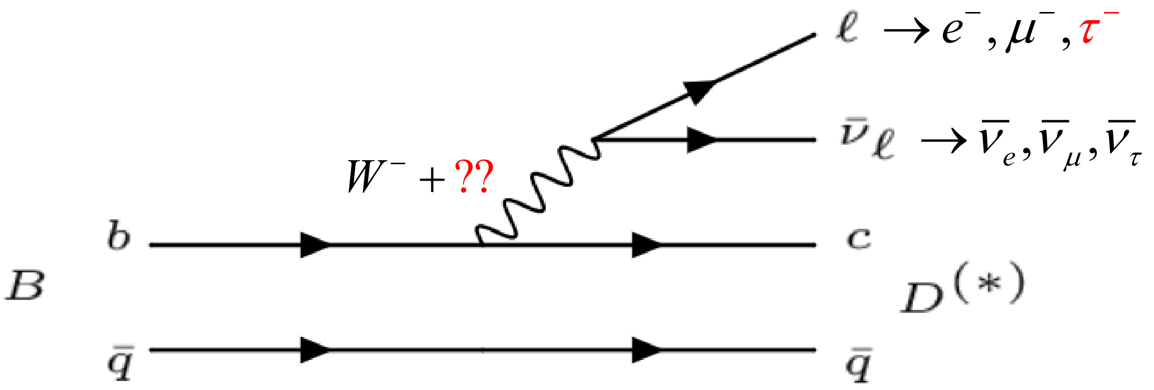
$$B^-\to D^0\tau^-\bar{\nu}_\tau,\quad \boxed{b\to c\ell\bar{\nu}_\ell\;,\;\ell=e,\mu,\tau}$$



We can explain the τ-lepton excess on $b\to cl\bar{\nu}$ processes.

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3. W' Bosons Model: From SMEFT

New physics comes from the non-renormalizable effective field theory (EFT) Lagrangian [1]:

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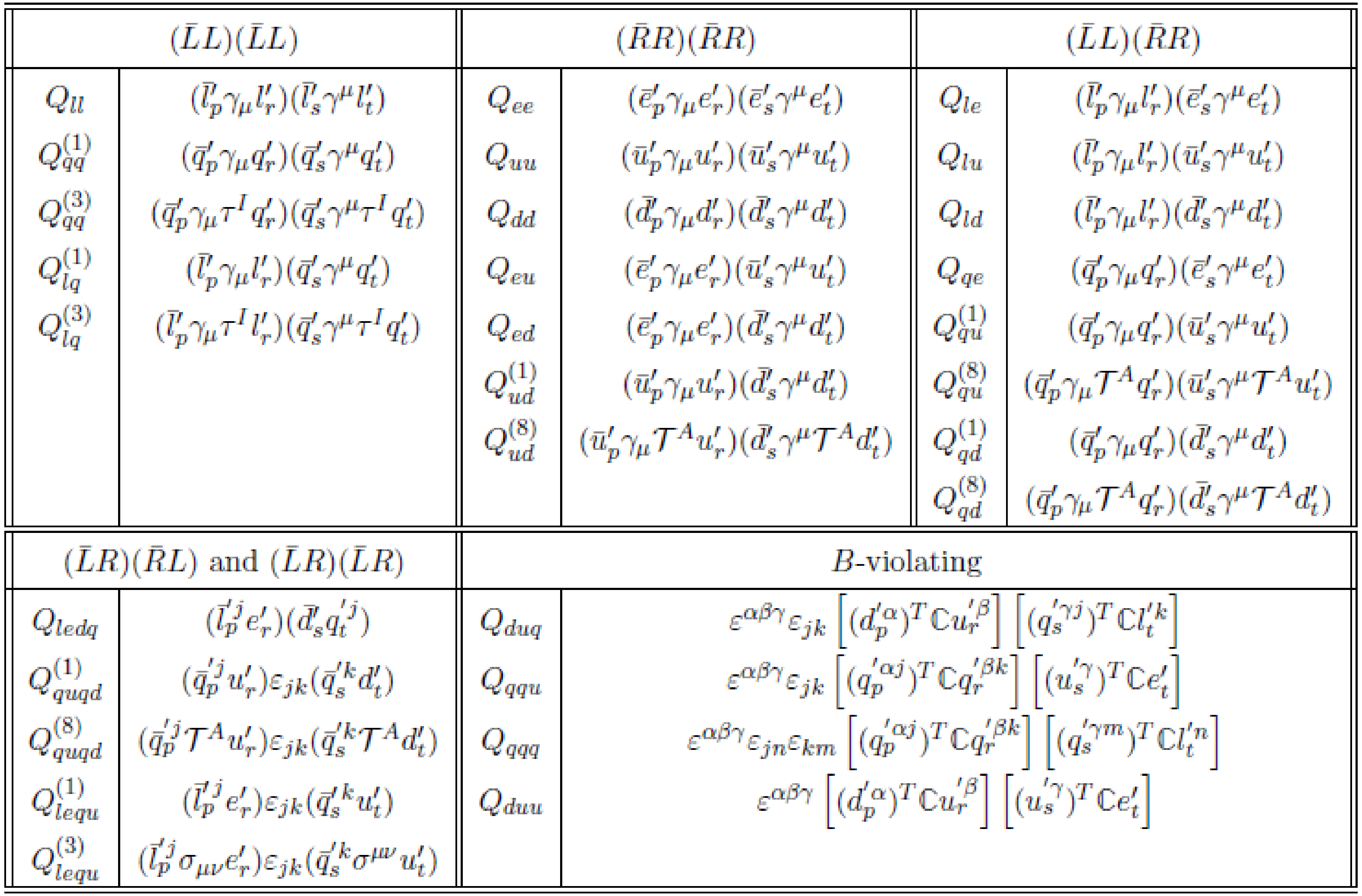
$$\mathcal{L}_{NP} = \sum_f C^f Q_f .$$



$(\bar{L}L)(\bar{L}L)$		$(\bar{R}R)(\bar{R}R)$		$(\bar{L}L)(\bar{R}R)$	
Q_{ll}	$(\bar{l}'_p\gamma_\mu l'_r)(\bar{l}'_s\gamma^\mu l'_t)$	Q_{ee}	$(\bar{e}'_p\gamma_\mu e'_r)(\bar{e}'_s\gamma^\mu e'_t)$	Q_{le}	$(\bar{l}'_p\gamma_\mu l'_r)(\bar{e}'_s\gamma^\mu e'_t)$
$Q_{qq}^{(1)}$	$(\bar{q}'_p\gamma_\mu q'_r)(\bar{q}'_s\gamma^\mu q'_t)$	Q_{uu}	$(\bar{u}'_p\gamma_\mu u'_r)(\bar{u}'_s\gamma^\mu u'_t)$	Q_{lu}	$(\bar{l}'_p\gamma_\mu l'_r)(\bar{u}'_s\gamma^\mu u'_t)$
$Q_{qq}^{(3)}$	$(\bar{q}'_p\gamma_\mu\tau^I q'_r)(\bar{q}'_s\gamma^\mu\tau^I q'_t)$	Q_{dd}	$(\bar{d}'_p\gamma_\mu d'_r)(\bar{d}'_s\gamma^\mu d'_t)$	Q_{ld}	$(\bar{l}'_p\gamma_\mu l'_r)(\bar{d}'_s\gamma^\mu d'_t)$
$Q_{lq}^{(1)}$	$(\bar{l}'_p\gamma_\mu l'_r)(\bar{q}'_s\gamma^\mu q'_t)$	Q_{eu}	$(\bar{e}'_p\gamma_\mu e'_r)(\bar{u}'_s\gamma^\mu u'_t)$	Q_{qe}	$(\bar{q}'_p\gamma_\mu q'_r)(\bar{e}'_s\gamma^\mu e'_t)$
$Q_{lq}^{(3)}$	$(\bar{l}'_p\gamma_\mu\tau^I l'_r)(\bar{q}'_s\gamma^\mu\tau^I q'_t)$	Q_{ed}	$(\bar{e}'_p\gamma_\mu e'_r)(\bar{d}'_s\gamma^\mu d'_t)$	$Q_{qu}^{(1)}$	$(\bar{q}'_p\gamma_\mu q'_r)(\bar{u}'_s\gamma^\mu u'_t)$
		$Q_{ud}^{(1)}$	$(\bar{u}'_p\gamma_\mu u'_r)(\bar{d}'_s\gamma^\mu d'_t)$	$Q_{qu}^{(8)}$	$(\bar{q}'_p\gamma_\mu T^A q'_r)(\bar{u}'_s\gamma^\mu T^A u'_t)$
		$Q_{ud}^{(8)}$	$(\bar{u}'_p\gamma_\mu T^A u'_r)(\bar{d}'_s\gamma^\mu T^A d'_t)$	$Q_{qd}^{(1)}$	$(\bar{q}'_p\gamma_\mu q'_r)(\bar{d}'_s\gamma^\mu d'_t)$
				$Q_{qd}^{(8)}$	$(\bar{q}'_p\gamma_\mu T^A q'_r)(\bar{d}'_s\gamma^\mu T^A d'_t)$

$(\bar{L}R)(\bar{R}L)$ and $(\bar{L}R)(\bar{L}R)$		B-violating	
Q_{ledq}	$(\bar{l}'^j_p e'_r)(\bar{d}'_s q'^j_t)$	Q_{duq}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(d'^{\alpha}_p)^T C u'^{\beta}_r\right]\left[(q'^{\gamma j}_s)^T C l'^k_t\right]$
$Q_{quqd}^{(1)}$	$(\bar{q}'^j_p u'_r)\varepsilon_{jk}(\bar{q}'^k_s d'_t)$	Q_{qqu}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(q'^{\alpha j}_p)^T C q'^{\beta k}_r\right]\left[(u'^{\gamma}_s)^T C e'_t\right]$
$Q_{quqd}^{(8)}$	$(\bar{q}'^j_p T^A u'_r)\varepsilon_{jk}(\bar{q}'^k_s T^A d'_t)$	Q_{qqq}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jn}\varepsilon_{km}\left[(q'^{\alpha j}_p)^T C q'^{\beta k}_r\right]\left[(q'^{\gamma m}_s)^T C l'^n_t\right]$
$Q_{lequ}^{(1)}$	$(\bar{l}'^j_p e'_r)\varepsilon_{jk}(\bar{q}'^k_s u'_t)$	Q_{duu}	$\varepsilon^{\alpha\beta\gamma}\left[(d'^{\alpha}_p)^T C u'^{\beta}_r\right]\left[(u'^{\gamma}_s)^T C e'_t\right]$
$Q_{lequ}^{(3)}$	$(\bar{l}'^j_p\sigma_{\mu\nu}e'_r)\varepsilon_{jk}(\bar{q}'^k_s\sigma^{\mu\nu}u'_t)$		

[1] B. Grzadkowski, M. Iskrzynski, M. Misiak, and J. Rosiek, *Dimension-Six Terms in the Standard Model Lagrangian*, JHEP 10 (2010) 085 [arXiv:1008.4884].

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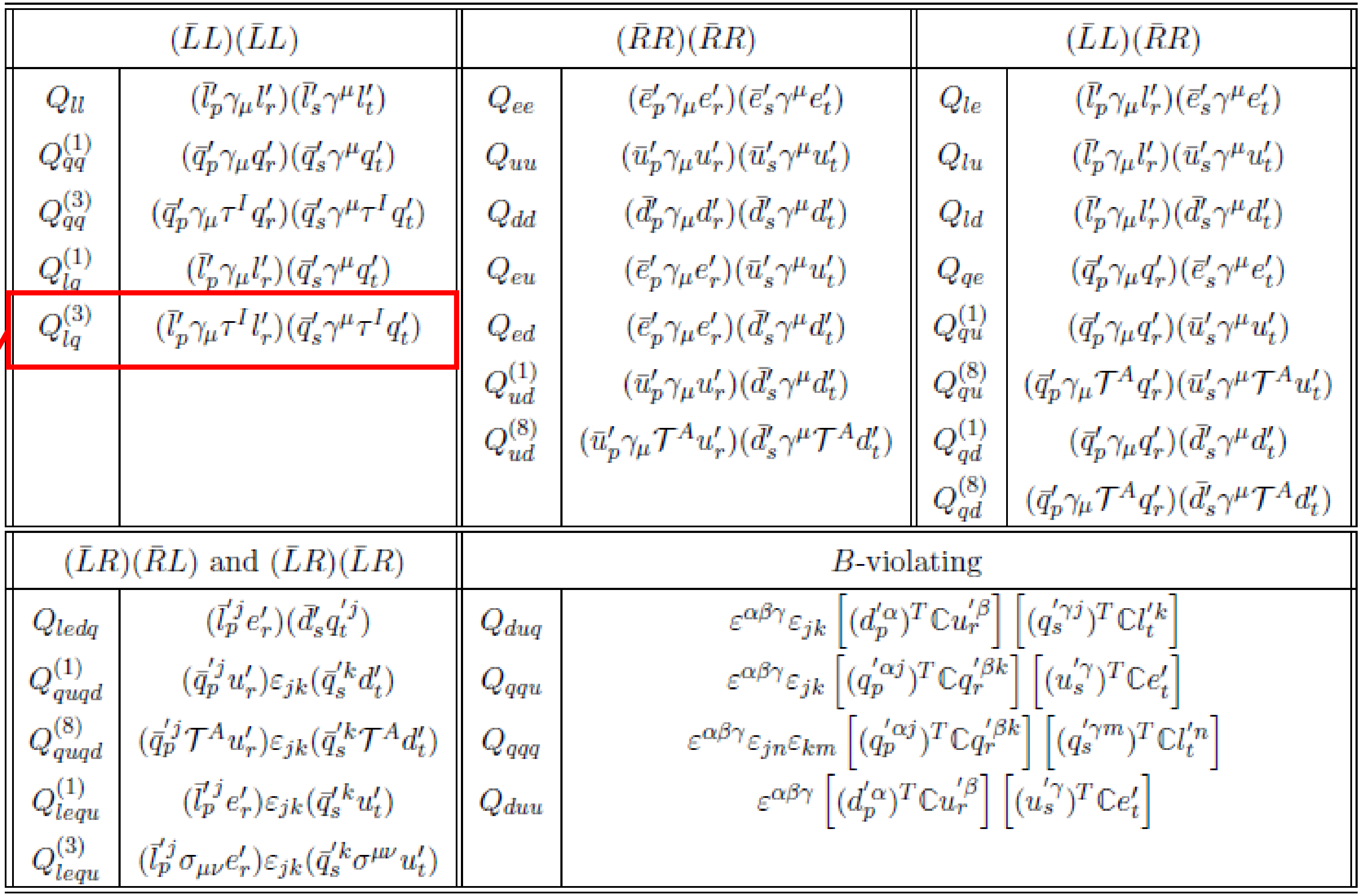
$$\mathcal{L}_{NP} = \sum_{f} C^{f} Q_{f}.$$

The purely Left handed vector NP operators are:

$$\mathcal{L}_{NP} = \sum_{prst} C^{prst}\left(\bar{l}_p \gamma_\mu \tau^I l_r\right)\left(\bar{q}_s \gamma^\mu \tau^I q_t\right)$$



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$Q_{qq}^{(1)}$	$(\bar{q}'_p\gamma_\mu q'_r)(\bar{q}'_s\gamma^\mu q'_t)$	Q_{uu}	$(\bar{u}'_p\gamma_\mu u'_r)(\bar{u}'_s\gamma^\mu u'_t)$	Q_{lu}	$(\bar{l}'_p\gamma_\mu l'_r)(\bar{u}'_s\gamma^\mu u'_t)$
$Q_{qq}^{(3)}$	$(\bar{q}'_p\gamma_\mu\tau^I q'_r)(\bar{q}'_s\gamma^\mu\tau^I q'_t)$	Q_{dd}	$(\bar{d}'_p\gamma_\mu d'_r)(\bar{d}'_s\gamma^\mu d'_t)$	Q_{ld}	$(\bar{l}'_p\gamma_\mu l'_r)(\bar{d}'_s\gamma^\mu d'_t)$
$Q_{lq}^{(1)}$	$(\bar{l}'_p\gamma_\mu l'_r)(\bar{q}'_s\gamma^\mu q'_t)$	Q_{eu}	$(\bar{e}'_p\gamma_\mu e'_r)(\bar{u}'_s\gamma^\mu u'_t)$	Q_{qe}	$(\bar{q}'_p\gamma_\mu q'_r)(\bar{e}'_s\gamma^\mu e'_t)$
$Q_{lq}^{(3)}$	$(\bar{l}'_p\gamma_\mu\tau^I l'_r)(\bar{q}'_s\gamma^\mu\tau^I q'_t)$	Q_{ed}	$(\bar{e}'_p\gamma_\mu e'_r)(\bar{d}'_s\gamma^\mu d'_t)$	$Q_{qu}^{(1)}$	$(\bar{q}'_p\gamma_\mu q'_r)(\bar{u}'_s\gamma^\mu u'_t)$
		$Q_{ud}^{(1)}$	$(\bar{u}'_p\gamma_\mu u'_r)(\bar{d}'_s\gamma^\mu d'_t)$	$Q_{qu}^{(8)}$	$(\bar{q}'_p\gamma_\mu T^A q'_r)(\bar{u}'_s\gamma^\mu T^A u'_t)$
		$Q_{ud}^{(8)}$	$(\bar{u}'_p\gamma_\mu T^A u'_r)(\bar{d}'_s\gamma^\mu T^A d'_t)$	$Q_{qd}^{(1)}$	$(\bar{q}'_p\gamma_\mu q'_r)(\bar{d}'_s\gamma^\mu d'_t)$
				$Q_{qd}^{(8)}$	$(\bar{q}'_p\gamma_\mu T^A q'_r)(\bar{d}'_s\gamma^\mu T^A d'_t)$

$(\bar{L}R)(\bar{R}L)$ and $(\bar{L}R)(\bar{L}R)$		B-violating	
Q_{ledq}	$(\bar{l}'^j_p e'_r)(\bar{d}'_s q'^j_t)$	Q_{duq}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(d'^\alpha_p)^T C u'^\beta_r\right]\left[(q'^{\gamma j}_s)^T C l'^k_t\right]$
$Q_{quqd}^{(1)}$	$(\bar{q}'^j_p u'_r)\varepsilon_{jk}(\bar{q}'^k_s d'_t)$	Q_{qqu}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(q'^{\alpha j}_p)^T C q'^{\beta k}_r\right]\left[(u'^\gamma_s)^T C e'_t\right]$
$Q_{quqd}^{(8)}$	$(\bar{q}'^j_p T^A u'_r)\varepsilon_{jk}(\bar{q}'^k_s T^A d'_t)$	Q_{qqq}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jn}\varepsilon_{km}\left[(q'^{\alpha j}_p)^T C q'^{\beta k}_r\right]\left[(q'^{\gamma m}_s)^T C l'^n_t\right]$
$Q_{lequ}^{(1)}$	$(\bar{l}'^j_p e'_r)\varepsilon_{jk}(\bar{q}'^k_s u'_t)$	Q_{duu}	$\varepsilon^{\alpha\beta\gamma}\left[(d'^\alpha_p)^T C u'^\beta_r\right]\left[(u'^\gamma_s)^T C e'_t\right]$
$Q_{lequ}^{(3)}$	$(\bar{l}'^j_p \sigma_{\mu\nu} e'_r)\varepsilon_{jk}(\bar{q}'^k_s \sigma^{\mu\nu} u'_t)$		

[1] B. Grzadkowski, M. Iskrzynski, M. Misiak, and J. Rosiek, *Dimension-Six Terms in the Standard Model Lagrangian*, JHEP 10 (2010) 085 [arXiv:1008.4884].

3. W’ Bosons Model:

So, we choose an **extension** of the SM that is a color-neutral real $SU(2)_L$ triplet of massive **vectors** W’ and Z’ that coupled predominantly to **left-handed** fermions from **the third generation** [1].

The Lagrangian that describes the interactions between fermions and the new vector bosons, in the interaction basis, is [2]:

$$\mathcal{L}_{W'+Z'} = g_b \bar{Q}_3 \frac{\sigma_a}{2} \gamma^\mu W^a_\mu Q_3 + g_\tau \bar{L}_3 \frac{\sigma_a}{2} \gamma^\mu W^a_\mu L_3$$

The mass of the new bosons has been taken as $M_{W'}=M_{Z'}=1\text{TeV}$.

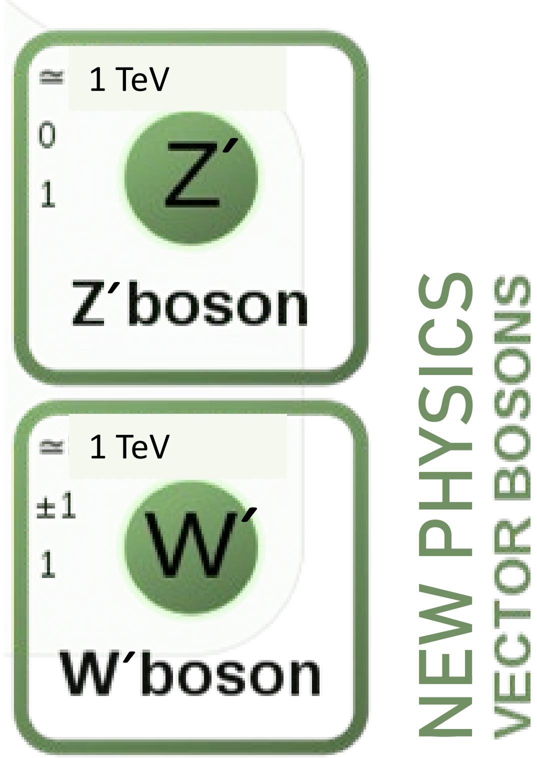


Image taken and edited from MissMJ and Cush, Wikimedia Commons (2017), https://commons.wikimedia.org/wiki/File:Standard_Model_of_Elementary_Particles.svg

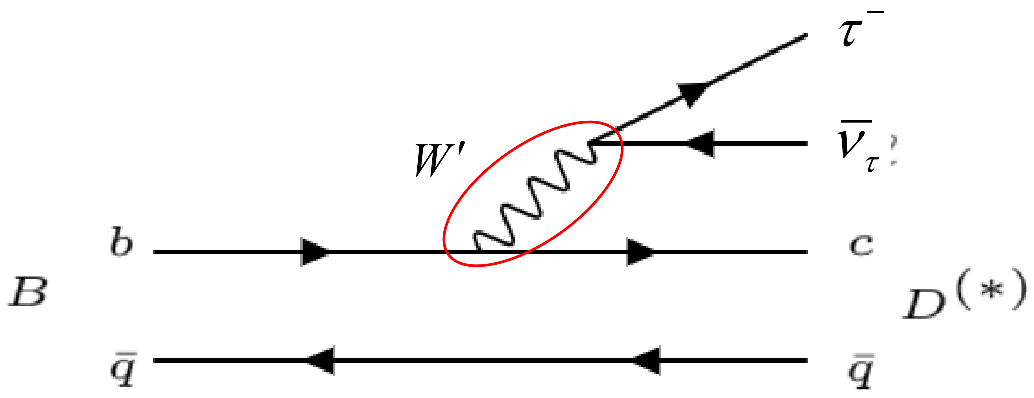
[1] A. Greljo, G. Isidori, and D. Marzocca, *On the breaking of lepton flavor universality in B decays*, J. High Energy Phys. 07 (2015) [arXiv:1506.01705]

[2] D. A. Faroughy, A. Greljo, and J. F. Kamenik, *Confronting lepton flavor universality violation in B decays with high-pT tau lepton searches at LHC*, Phys. Lett. B 764, 126 (2017). [arXiv:1609.07138]

3. W’ Bosons Model: Charged and Neutral Decays

Charged Current: Semileptonic decay [1]

$B^- \to D^0 \tau^- \overline{\nu}_\tau ,$ $\boxed{b \to c\ell \overline{\nu}_\ell \ , \ \ell = e, \mu, \tau}$



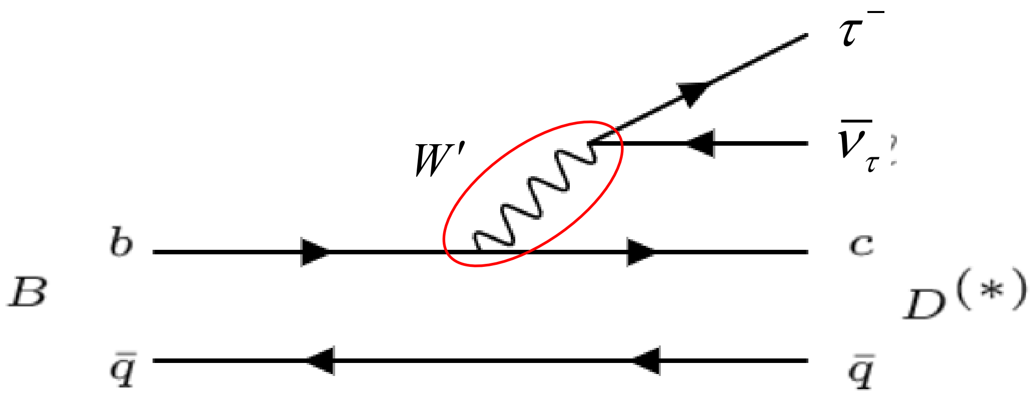
$$\mathcal{L}_{CC} = -\frac{g_b g_\tau}{2M_{W'}^2} V_{cb} \left(\overline{c} \gamma_\mu P_L b \right) \left(\overline{\tau} \gamma^\mu P_L \nu_\tau \right) + H.c.$$

[1] A. Greljo, G. Isidori, and D. Marzocca, *On the breaking of lepton flavor universality in B decays*, J. High Energy Phys. 07 (2015) [arXiv:1506.01705]

3. W' Bosons Model: Charged and Neutral Decays

Charged Current: Semileptonic decay [1]

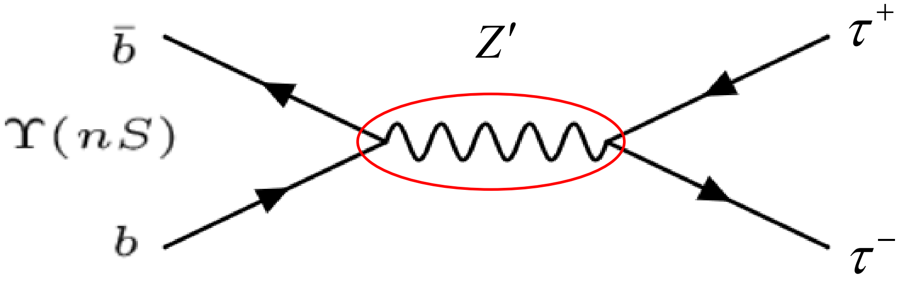
$B^- \to D^0\tau^-\bar{\nu}_\tau,$ $\boxed{b \to c\ell\bar{\nu}_\ell\ ,\ \ell = e,\mu,\tau}$



$$\mathcal{L}_{CC} = -\frac{g_b g_\tau}{2M_{W'}^2}V_{cb}\left(\bar{c}\gamma_\mu P_L b\right)\left(\bar{\tau}\gamma^\mu P_L \nu_\tau\right) + H.c.$$

Neutral Current: Leptonic decay [1]

$\Upsilon(nS)\to\tau^-\tau^+,$ $\boxed{b\bar{b}\to\ell\bar{\ell}\ ,\ \ell=e,\mu,\tau}$



$$\mathcal{L}_{NC} = -\frac{g_b g_\tau}{4M_{W'}^2}V_{cb}\left(\bar{b}\gamma_\mu P_L b\right)\left(\bar{\tau}\gamma^\mu P_L \tau\right)$$

[1] A. Greljo, G. Isidori, and D. Marzocca, *On the breaking of lepton flavor universality in B decays*, J. High Energy Phys. 07 (2015) [arXiv:1506.01705]

4. *R(M)* Anomalies: Charged Observables

$$b \to c\ell\bar{\nu}_\ell \qquad \Longrightarrow \qquad R(M)=\frac{Br(B\to M\tau\bar{\nu}_\tau)}{Br(B\to M\ell\bar{\nu}_\ell)},\quad \text{with:}\quad \begin{array}{l}\ell=e,\mu\\ M=\bar{q}c\end{array}$$

Experimental observables:

Observable	Experimental measure	SM Prediction	References
***R*(*D**)**	0.295±0.011±0.008	0.258±0.005	2019[1]
***R*(*D*)**	0.340±0.027±0.013	0.299±0.003	2019[1]
***R*(*J/ψ*)**	0.71±0.17±0.18	0.283±0.048	2018[2], 2018[3]
$R(X_c)$	0.223±0.030	0.216±003	2019[4]
$P_\tau(D^*)$	$-0.38\pm0.51^{+0.21}_{-0.16}$	-0.497±0.013	2017[5], 2013[6]
$F_L(D^*)$	0.60±0.08±0.04	0.216±0.003	2019[7], 2017[8]
$BR(B_c\to\tau\nu)$	≲10%		2017[9]

[1] (HFLAV Collaboration) Y Amhis *et al.*, *Averages of b-hadron, c-hadron, and τ-lepton properties as of 2018.* (2019) [arXiv:1909.12524]

[2] (LHCb C0llaboration) R. Aaij *et al.,Measurement of the ratio of branching fractions B(Bc→J/ψ τν)/B(Bc→J/ψ lν),* Phys. Rev. Lett. 120, 121801 (2018) [arXiv:1711.05623]

[3] R. Watanabe, *New Physics effect on Bc→J/ψ τν in relation to the RD(*) anomaly*, Phys. Lett. B 776, 5 (2018) [arXiv:1709.08644]

[4] S. Kamali, *New physics in inclusive semileptonic B decays including nonperturbative corrections*, Int. J. Mod. Phys. A 34, 1950036 (2019) [arXiv:1811.07393]

[5] (Belle Collaboration) S. Hirose *et al.*, Phys.Rev.Lett. 118, 211801 (2017) [arXiv:1612.00529] and Phys.Rev.D 97, 012004 (2018) [arXiv:1709.00129]

[6] M. Tanaka and R. Watanabe, *New physics in the weak interaction of B→D(*)τν*, Phys. Rev. D 87, 034028 (2013) [arXiv:1212.1878]

[7] (Belle Collaboration) A. Abdesselam *et al.*, *Measurement of the D* polarization in the decay B→D*τν*, (2019) [arXiv:1903.03102]

[8] A. K. Alok *et al.*, *D* polarization as a probe to discriminate new physics in B→D*τν*, Phys. Rev. D 95, 115038 (2017) [arXiv:1606.03164]

[9] A. G. Akeroyd and C. H. Chen, *Constraint on the branching ratio of Bc → τν from LEP1 and consequences for R(D(*)) anomaly*, Phys. Rev. D 96, 075011 (2017).

4. *R(M)* Anomalies: Neutral Observables

$$b\bar{b} \to \ell\bar{\ell}$$

⇨

$$R_{\Upsilon(nS)} = \frac{Br(\Upsilon(nS) \to \tau^-\tau^+)}{Br(\Upsilon(nS) \to \ell^-\ell^+)}, \quad \text{with:} \quad \begin{array}{c} \ell = e, \mu \\ n = 1, 2, 3 \end{array}$$

Experimental observables:

Observable	Experimental measure	SM Prediction	References
***R*(Υ(1S))**	1.005±0.013±0.022	0.9924 ± 10^{-5}	2010 [1,2]
***R*(Υ(2S))**	1.04±0.04±0.05	0.9940 ± 10^{-5}	2007 [3,2]
***R*(Υ(3S))**	1.05±0.08±0.05	0.9948 ± 10^{-5}	2007 [3,2]
***R*(Υ(3S)) 2020**	0.966±0.008±0.014	same	2020 [4]
***R*(Υ(3S)) comb**	0.968±0.016	same	

[1] (BABAR Collaboration) P. del Amo Sanchez *et al.*, *Test of lepton universality in Upsilon(1S) decays at BABAR,* Phys. Rev. Lett. 104:191801 (2010) [arXiv:1002.4358]

[2] Daniel Aloni, Aielet Efrati, Yuval Grossman and Yosef Nir, *Y and ψ leptonic decays as probes of solutions to the $R^{(*)}$D puzzle*, Journal of High Energy Physics, 2017(6), 1-27 (2017) [arXiv:1702.07356]

[3] (CLEO Collaboration) D. Besson *et al., First Observation of Υ(3S) -> ττ and Tests of Lepton Universality in Upsilon Decays,* Phys. Rev. Lett. 98:052002 (2007) [arXiv:hep-ex/0607019]

[4] (BABAR Collaboration) P. del Amo Sanchez *et al., Precision measurement of the $B(Y(3S)\to\tau^+\tau^-)/B(Y(3S)\to\mu^+\mu^-)$ ratio* Phys. Rev. Lett. 125, 241801 (2020) [arXiv:2005.01230]

5. 3G-LH-W’ Model: Charged Observables

The model [1,2]:

$$R(M) = R(M)_{MS}\left(\left|1 + C_{VLL}^{bc\tau\nu}\right|^2\right), \quad M = D, D^*, J/\psi$$

$$R(X_c) = R(X_c)_{SM}\left(1 + 1.147\left|C_{VLL}^{bc\tau\nu}\right|^2\right),$$

$$F_L(D^*) = F_L(D^*)_{MS}\, r_{D^*}^{-1}\left(\left|1 + C_{VLL}^{bc\tau\nu}\right|^2\right),$$

$$P_\tau(D^*) = P_\tau(D^*)_{MS}\, r_{D^*}^{-1}\left(\left|1 + C_{VLL}^{bc\tau\nu}\right|^2\right),$$

$$\mathrm{BR}(B_c^- \to \tau^-\overline{\nu}_\tau) = \mathrm{BR}(B_c^- \to \tau^-\overline{\nu}_\tau)_{SM}\left(\left|1 + C_{VLL}^{bc\tau\nu}\right|^2\right),$$

where $r_{D^*} = \dfrac{R(D^*)}{R(D^*)_{SM}}.$

$$\boxed{C_{VLL}^{bc\tau\nu} = \frac{\sqrt{2}}{4G_F}\frac{g_b g_\tau}{M_{W'}^2}.}$$

[1] J. D. Gómez, N. Quintero, and E. Rojas, *Charged current b → cτ¯ντ anomalies in a general W0 boson scenario*, Phys. Rev. D 100, 093003 (2019). [arXiv:1907.08357]

[2] S. Kamali, *New physics in inclusive semileptonic B decays including nonperturbative corrections*, Int. J. Mod. Phys. A 34, 1950036 (2019). [arXiv:1811.07393]

5. 3G-LH-W’ Model: Neutral Observables

The model [1]:

$$R_{\Upsilon(ns)} = \frac{\left(1-4x_\tau^2\right)^{1/2}}{\left|A_V^{SM}\right|^2}\left[\left|A_V^{b\tau}\right|^2\left(1+2x_\tau^2\right)+\left|B_V^{b\tau}\right|^2\left(1-4x_\tau^2\right)\right],$$

$$\left|A_V^{SM}\right| = -4\pi\alpha Q_b$$

$$A_V^{b\tau} = \left|A_V^{SM}\right| + \frac{m_{\Upsilon(ns)}^2}{4}C_{VLL}^{bb\tau\tau},$$

$$B_V^{b\tau} = -\frac{m_{\Upsilon(ns)}^2}{2}C_{VLL}^{bb\tau\tau},$$

where $x_\tau^2 = \dfrac{m_\tau}{m_{\Upsilon(ns)}},$

$$\boxed{C_{VLL}^{bb\tau\tau} = \frac{g_b g_\tau}{4M_{W'}^2}.}$$

[1] D. Aloni, A. Efrati, Y. Grossman and Y. Nir, *Υ and ψ leptonic decays as probes of solutions to the R(D$^{(*)}$) puzzle*, HEP 06, 019 (2017). [arXiv:1702.07356]

6. Phenomenological Study: BFP Analysis

Best Fit Points, χ^2_{min}/N_{dof}, p-value and Pull$_{\mathrm{SM}}$:

Dataset	g_b	g_τ	χ^2_{min}/N_{dof}	p-value [%]	Pull$_{\mathrm{SM}}$
$b \to c\tau\nu$	2.99	1.54	1.04	39.0	3.72
$b \to c\tau\nu + R(\Upsilon)2010$	3.05	1.52	0.79	61.3	3.75
$b \to c\tau\nu + R(\Upsilon)2020$	3.27	1.39	1.20	29.3	3.68
$b \to c\tau\nu + R(\Upsilon)combined$	3.05	1.52	1.11	35.3	3.68

Setting $M_{W'} = M_{Z'} = 1$ TeV, and using:

$$\mathrm{pull}_{\mathrm{SM}} = \sqrt{\chi^2_{\mathrm{SM}} - \chi^2_{\min}}$$

Dataset 1: $b \to c\tau\nu$:
$R(D)+R(D^*)+R(J/\psi)+R(X_c)+P_\tau(D^*)+F_L(D^*)+\mathrm{BR}(B_c\to\tau\nu)$, $\boldsymbol{N_{dof}=5}$

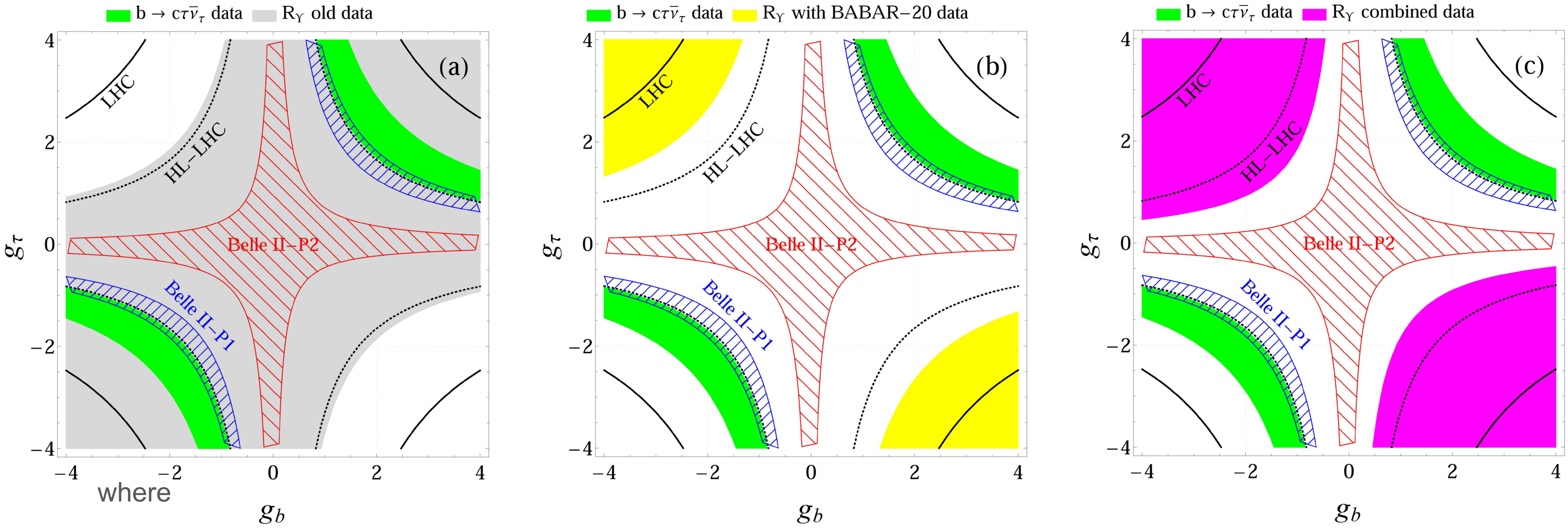
Dataset 2: $b \to c\tau\nu + R(\Upsilon)2010$:
$R(D)+R(D^*)+R(J/\psi)+R(X_c)+P_\tau(D^*)+F_L(D^*)+\mathrm{BR}(B_c\to\tau\nu)+R(\Upsilon(1S))+R(\Upsilon(2S))+R(\Upsilon(3S))2010$, $\boldsymbol{N_{dof}=8}$

Dataset 3: $b \to c\tau\nu + R(\Upsilon)2020$:
$R(D)+R(D^*)+R(J/\psi)+R(X_c)+P_\tau(D^*)+F_L(D^*)+\mathrm{BR}(B_c\to\tau\nu)+R(\Upsilon(1S))+R(\Upsilon(2S))+R(\Upsilon(3S))2020$, $\boldsymbol{N_{dof}=8}$

Dataset 4: $b \to c\tau\nu + R(\Upsilon)$combined :
$R(D)+R(D^*)+R(J/\psi)+R(X_c)+P_\tau(D^*)+F_L(D^*)+\mathrm{BR}(B_c\to\tau\nu)+R(\Upsilon(1S))+R(\Upsilon(2S))+R(\Upsilon(3S))2010+R(\Upsilon(3S))2020$, $\boldsymbol{N_{dof}=9}$

6. Phenomenological Study: Plot Analysis

We show our results, using 1σ allowed parameter space, Belle-II future prospects [1] and LHC bounds [2]:



where

[1] (Belle-II Collaboration) E. Kou *et al.*, *The Belle II physics book*, Prog. Theor. Exp. Phys. 2019, 123C01 (2019); Erratum, Prog. Theor. Exp. Phys. 2020, 029201 (2020). [arXiv:1808.10567]

[2] D. Marzocca, U. Min, and M. Son, *Bottom-flavored mono-tau tails at the LHC*, J. High Energy Phys. 12 (2020) 035. [arXiv:2008.07541]

7. Concluding Remarks

NP scenarios that explain LFUV anomalies for $b \to c\tau\nu$ observables **induce** effects $bb \to \tau\tau$ observables.

An extra massive 3G-LH-W’ leptons is a **viable** solution to the for $b \to c\tau\nu$ anomalies.

We performed a **robust** phenomenological analysis of the parametric space of gauge couplings using $b \to c\tau\nu$ and $bb \to \tau\tau$ data.

The BABAR measurement of $R(\Upsilon(3S))$ **cannot be explained** simultaneously with $b \to c\tau\nu$ data within the 3G-LH-W’ model and future $R(\Upsilon(nS))$ measurements will be important to confirm or refute this model.

Next step will be exploring a leptoquark scenario including *R(K$^{(*)}$)* and g-2 observables.

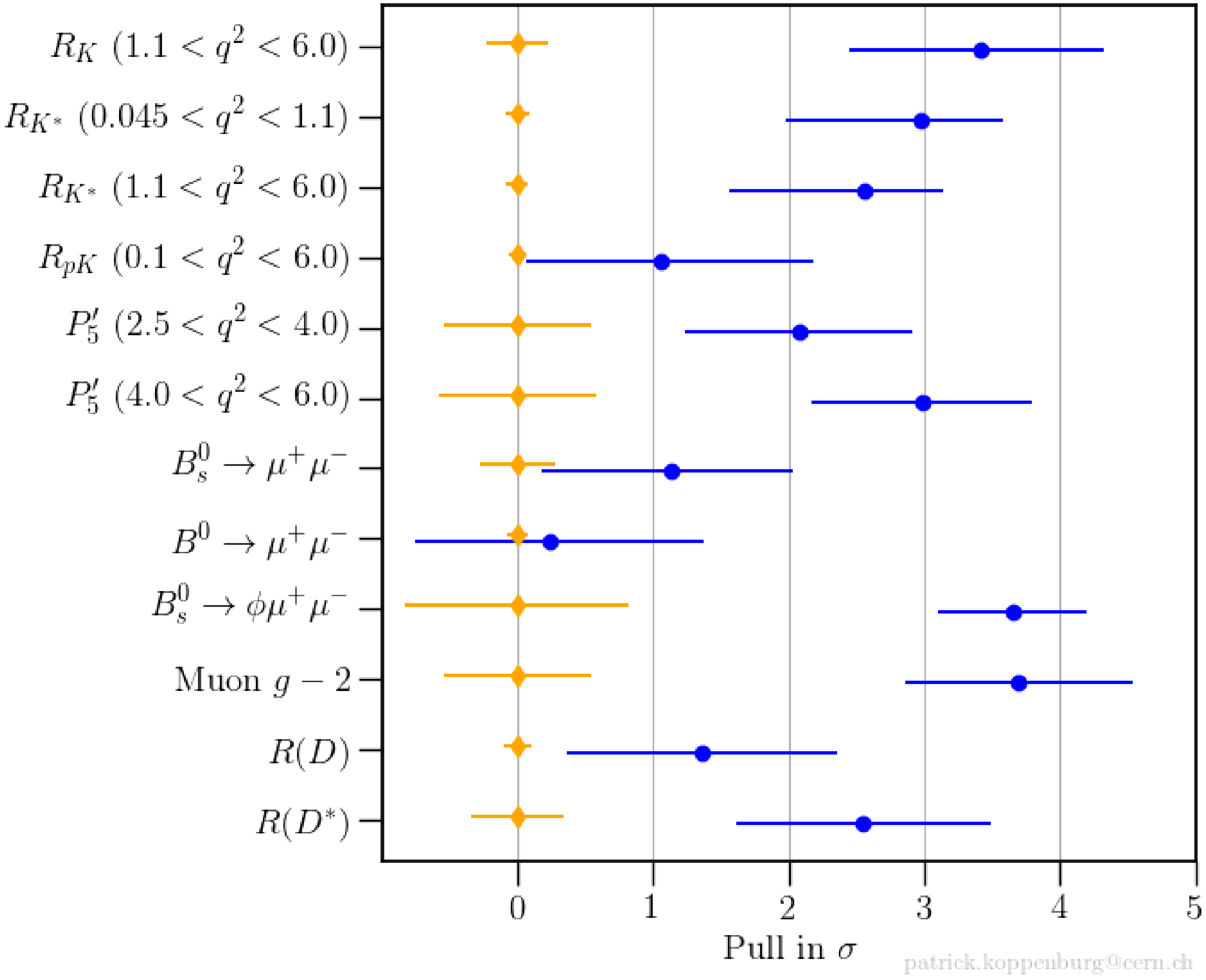


Image taken form Patrick Koppenburg, Scholarpedia (2021), http://www.scholarpedia.org/article/Rare_decays_of_b_hadrons#LHCb-PAPER-2021-004

8. Products

PHYSICAL REVIEW D **103**, 073003 (2021)

Extra gauge bosons and lepton flavor universality violation in Υ and B meson decays

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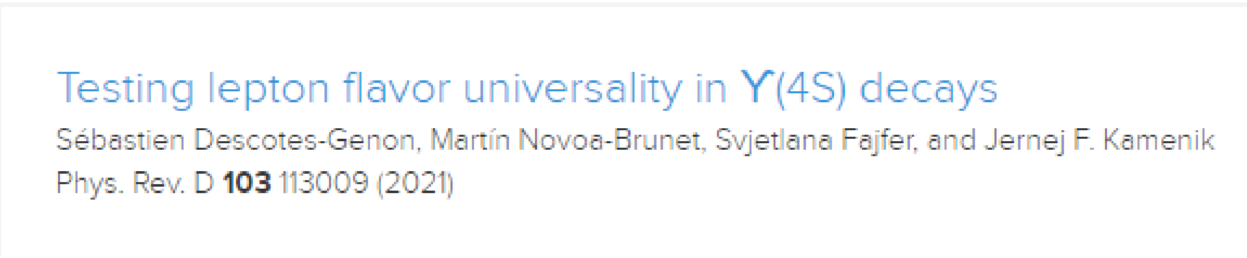

Testing lepton flavor universality in $\Upsilon(4S)$ decays

Sébastien Descotes-Genon, Martín Novoa-Brunet, Svjetlana Fajfer, and Jernej F. Kamenik

Phys. Rev. D **103** 113009 (2021)

UNIVERSIDAD DEL QUINDÍO

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PERTINENTE
CREATIVA
INTEGRADORA

MUCHAS GRACIAS

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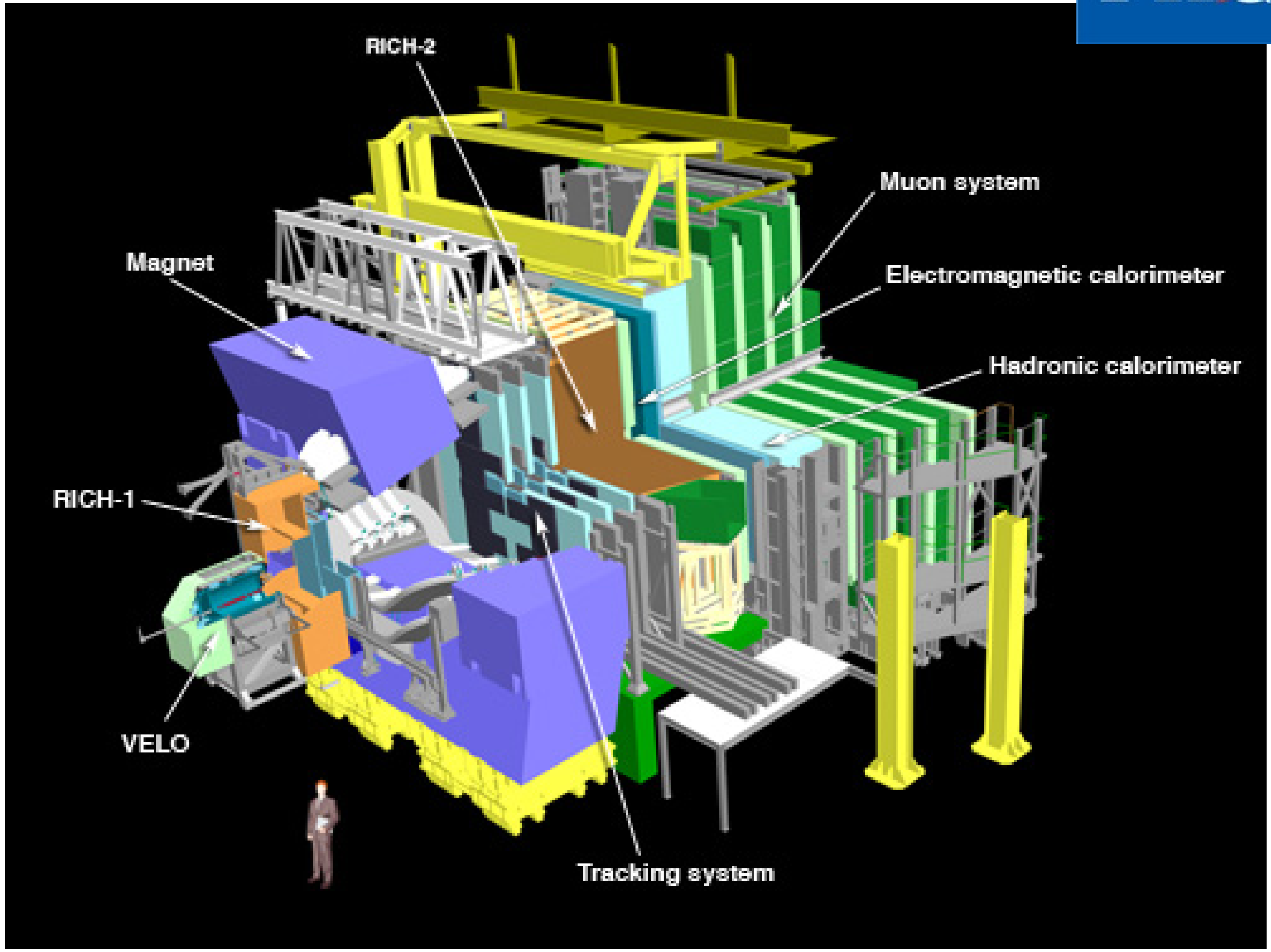
Collider: LHC

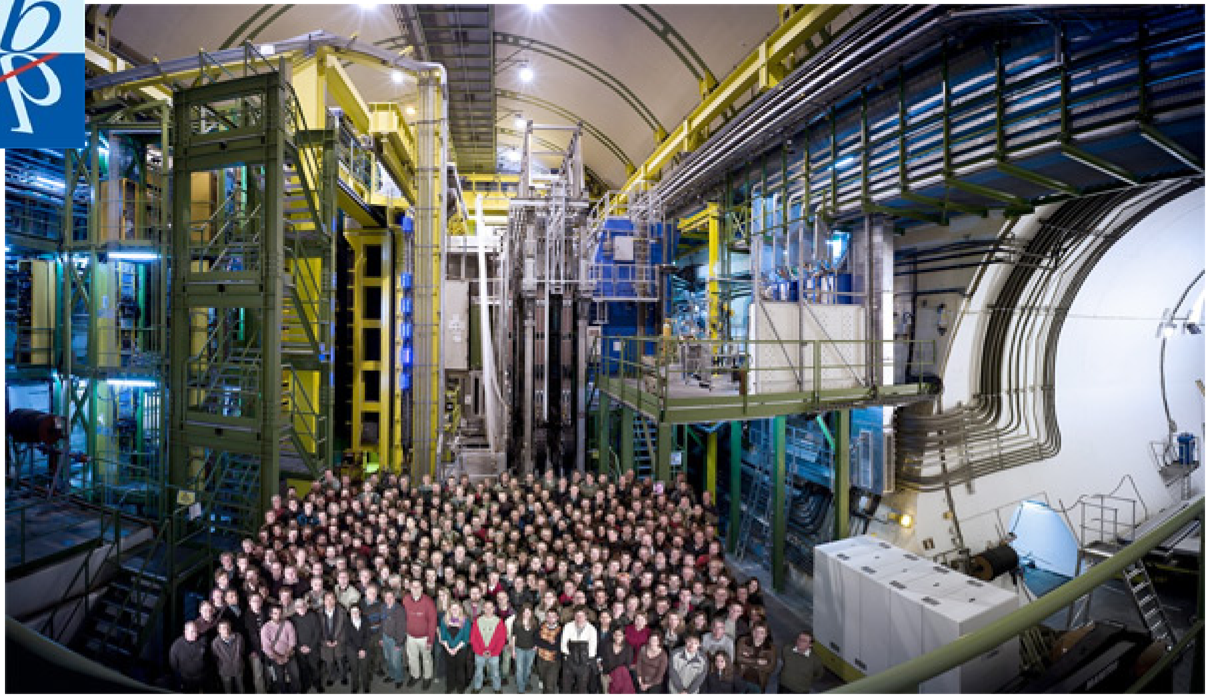
- Cyclotron
- Circumference 27 Km
- Proton-proton 13 TeV

CERN 2008 - video capture

Experiment: LHCb



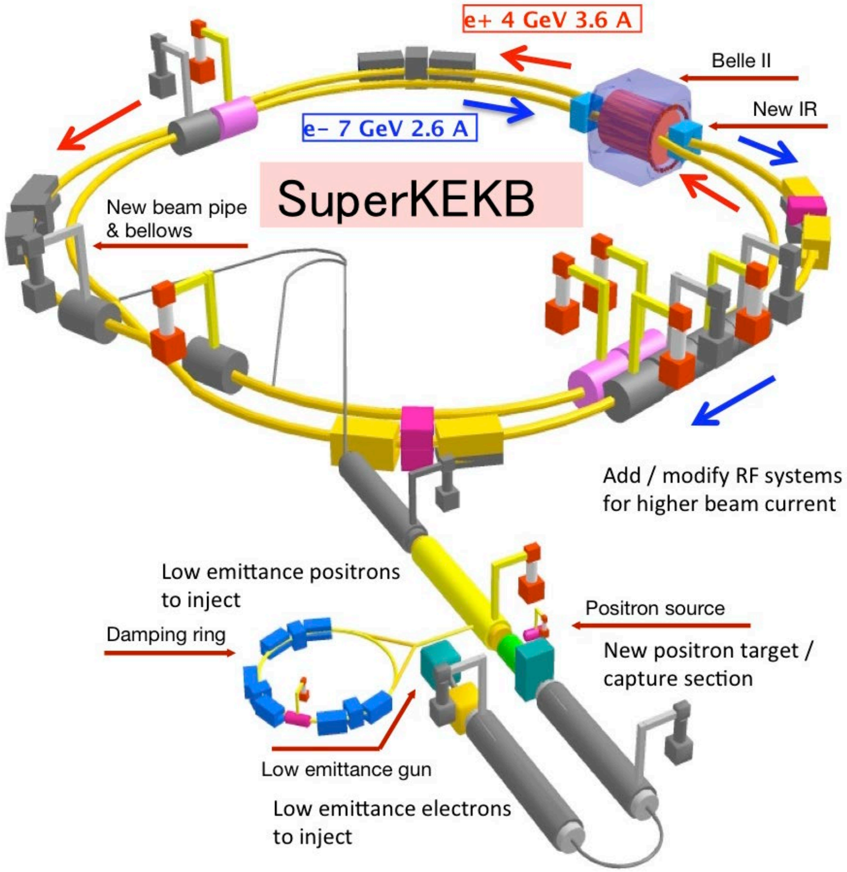
CERN 2008 - LHCb Experiment



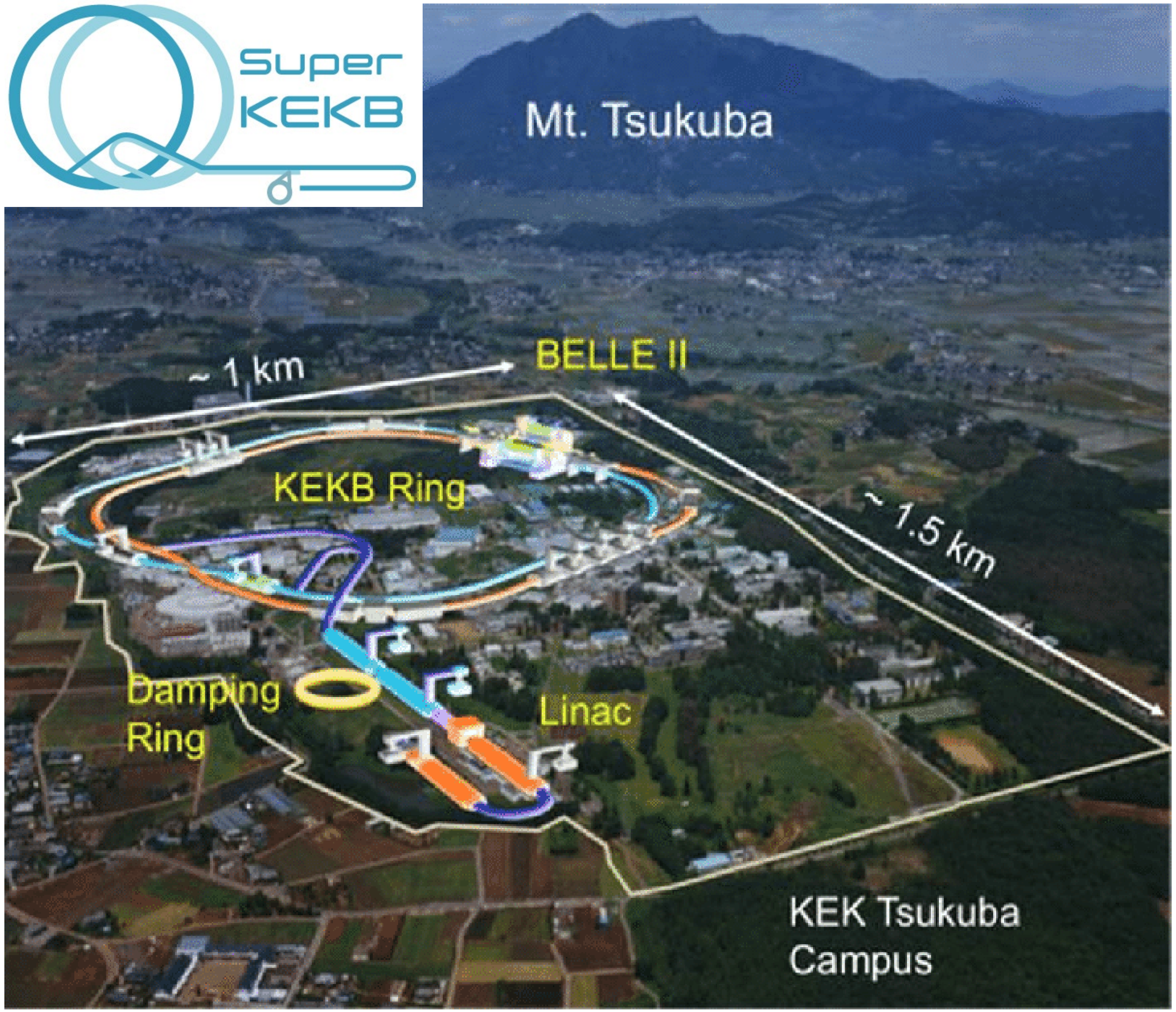
- Length 20m
- Height 5m
- Weight 45000 ton

Collider: SuperKEKB

- Cyclotron
- Circumference 3km
- Electron-positron 11GeV (7-4)

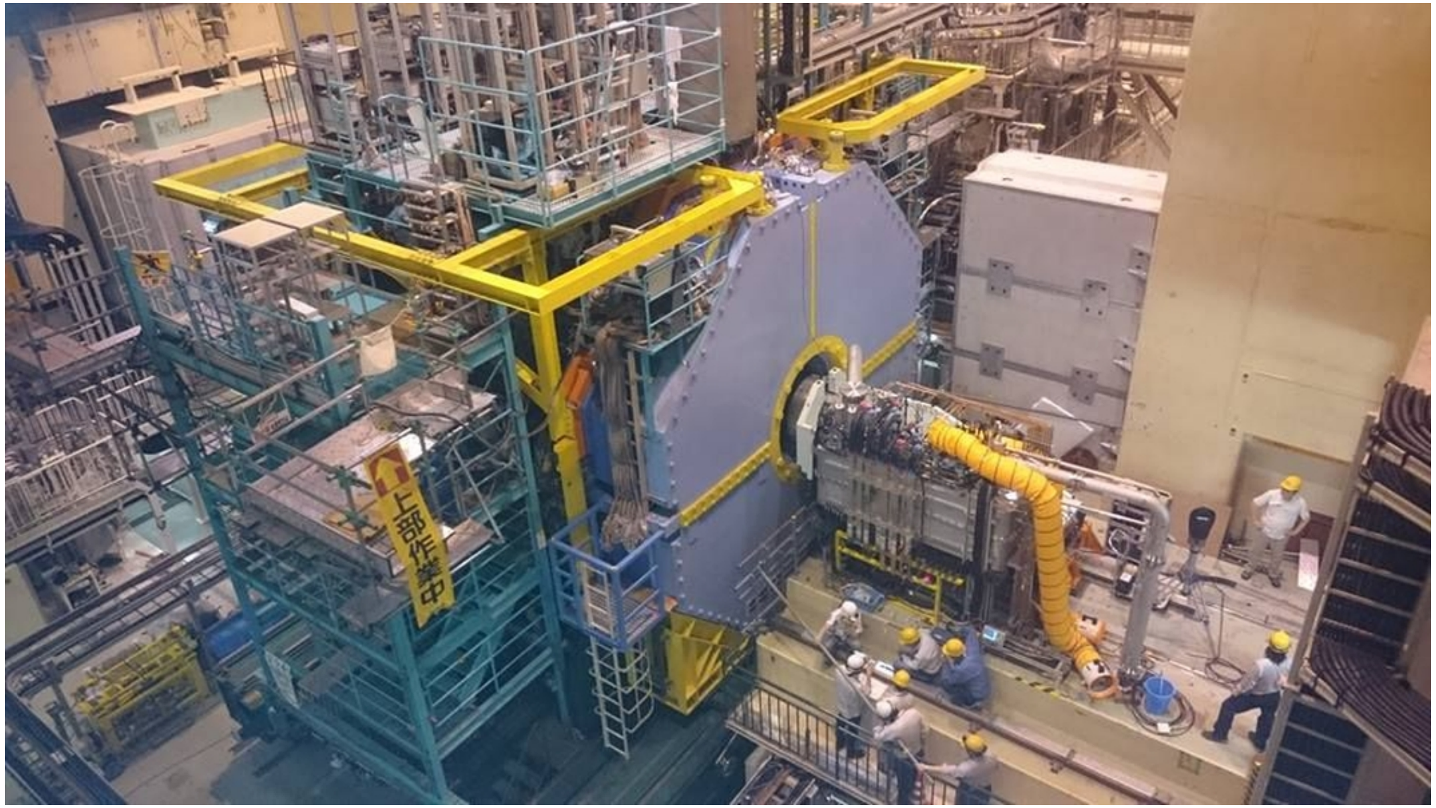


2011, HIGH ENERGY ACCELERATOR RESEARCH ORGANIZATION, KEK



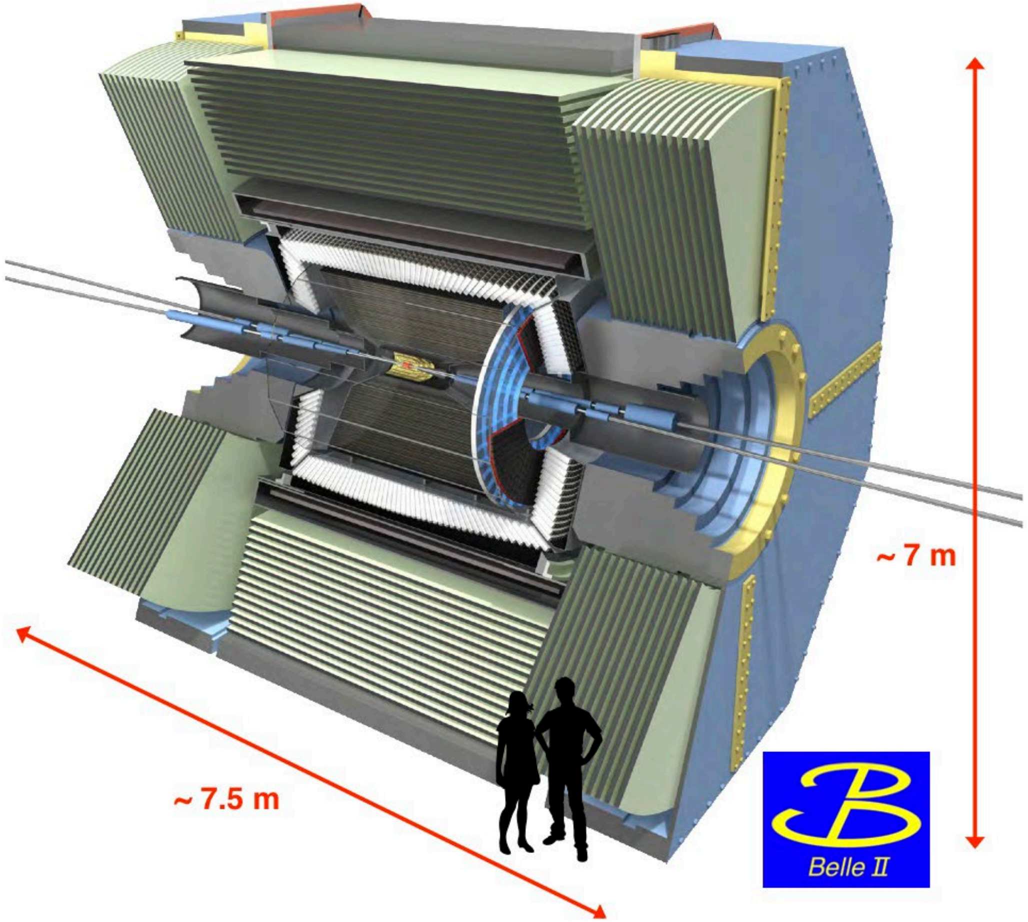
10.1103/PhysRevAccelBeams.19.121001

Experiment: Belle II



McGill Physics - McGill University

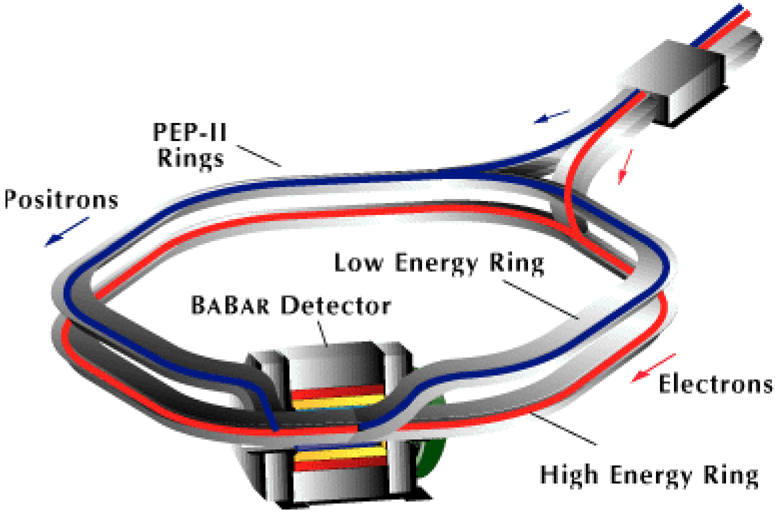
- Length 7.5m
- Height 7m
- Weight 1400 ton



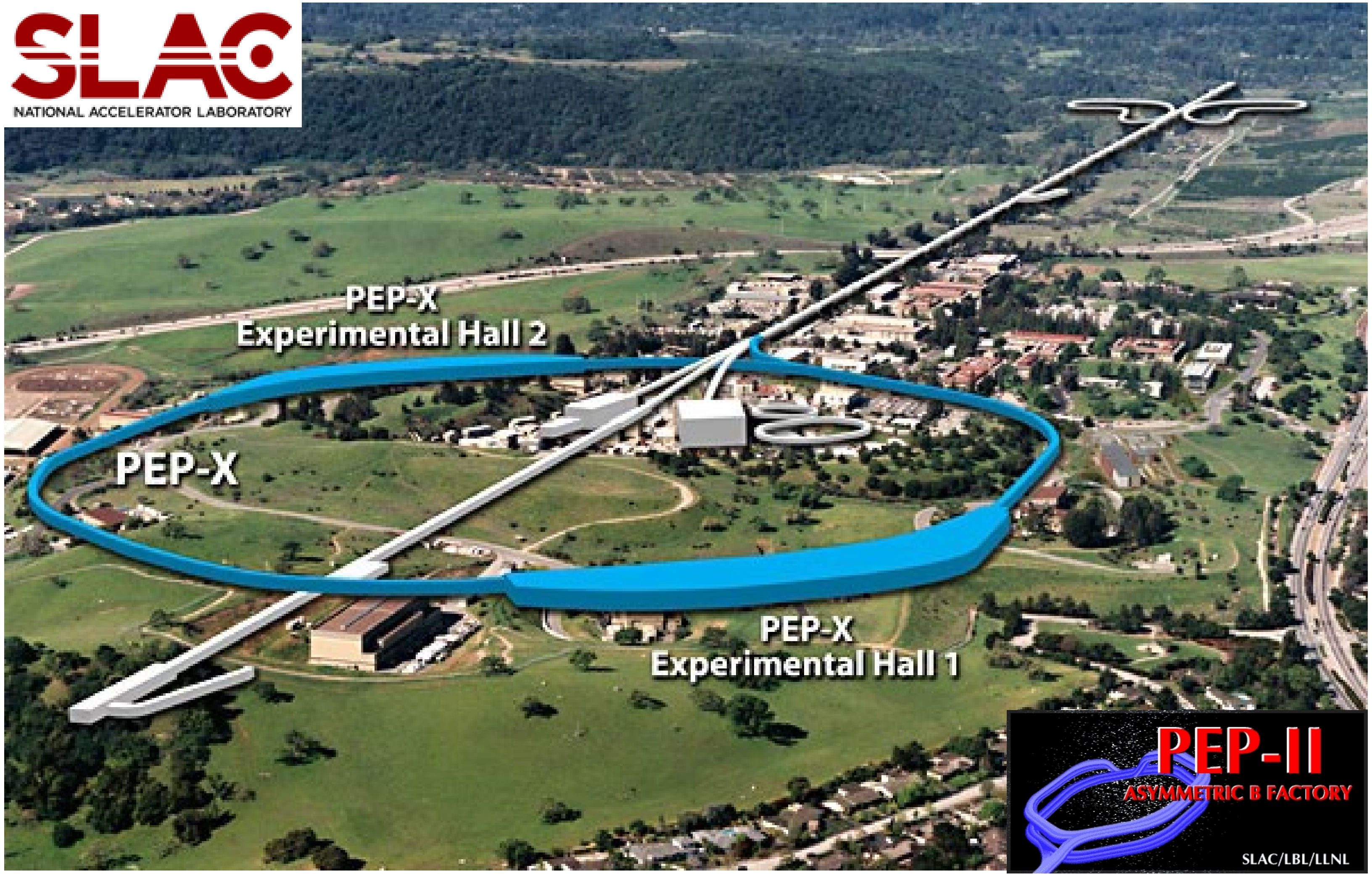
2011, HIGH ENERGY ACCELERATOR RESEARCH ORGANIZATION, KEK

Collider: PEP-II

- Lineal
- 3.2Km
- Electron-Positron 10.58GeV



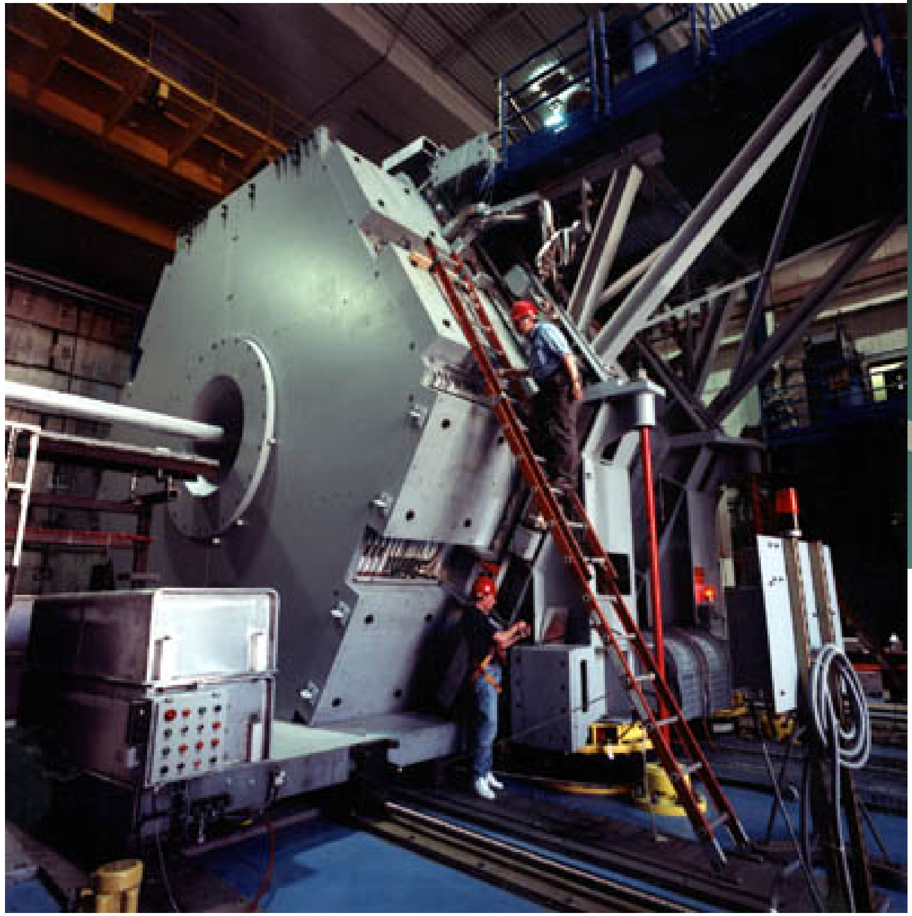
SLAC NATIONAL ACCELERATOR LABORATORY

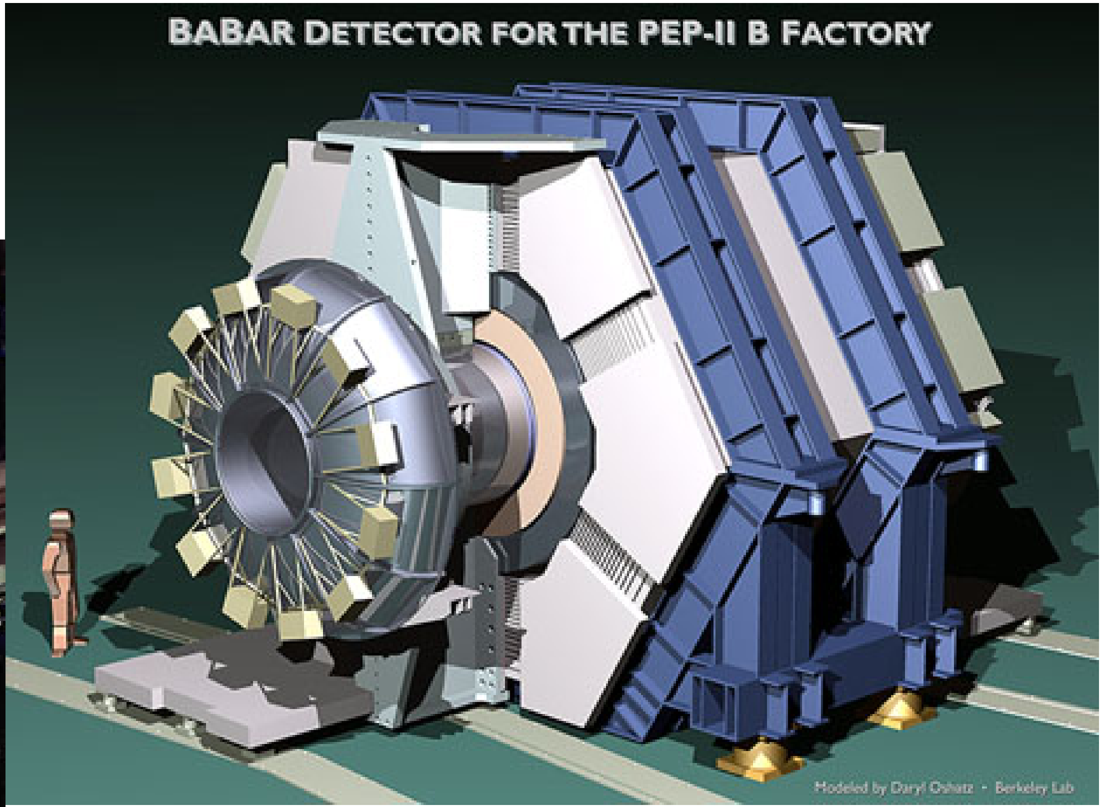


SLAC NATIONAL ACCELERATOR LABORATORY

Collider: BaBar

Length 6.2m
Height 6.6m





https://www.slac.stanford.edu/BFROOT/

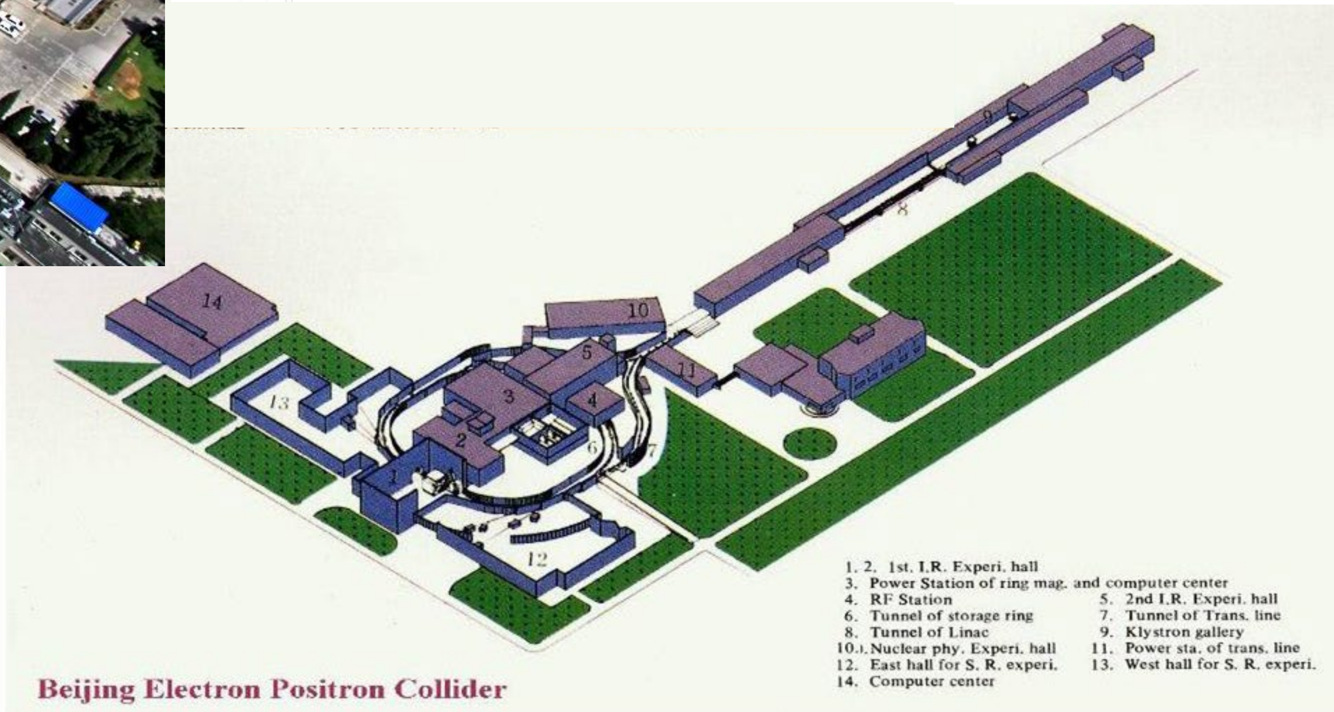
Collider: BEPC II

2002-2020, Institute of High Energy Physics, CAS

- Cyclotron
- Circumference 240m
- Electron-positron 4.6 GeV (symmetric)

Institute of High Energy Physics

Chinese Academy of Sciences



EPICS 2008, Shanghai

Experiment: BES III

2002-2020, Institute of High Energy Physics, CAS

- Length 6m
- Diameter 7m