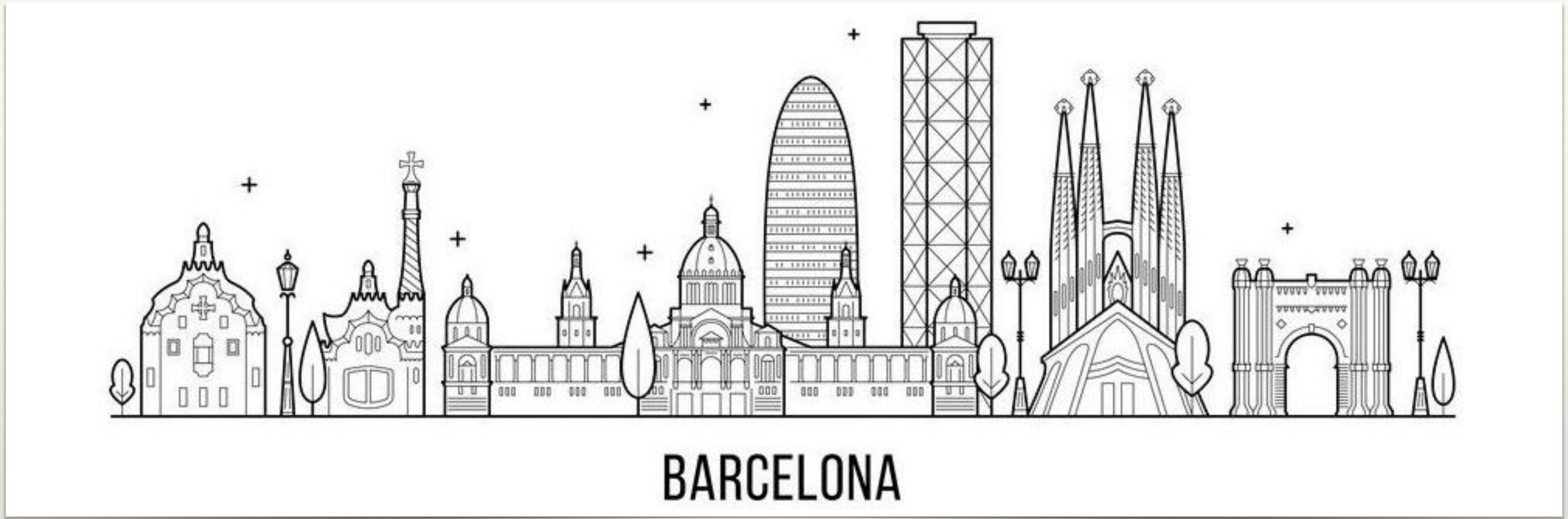


Claudio Andrea Manzari

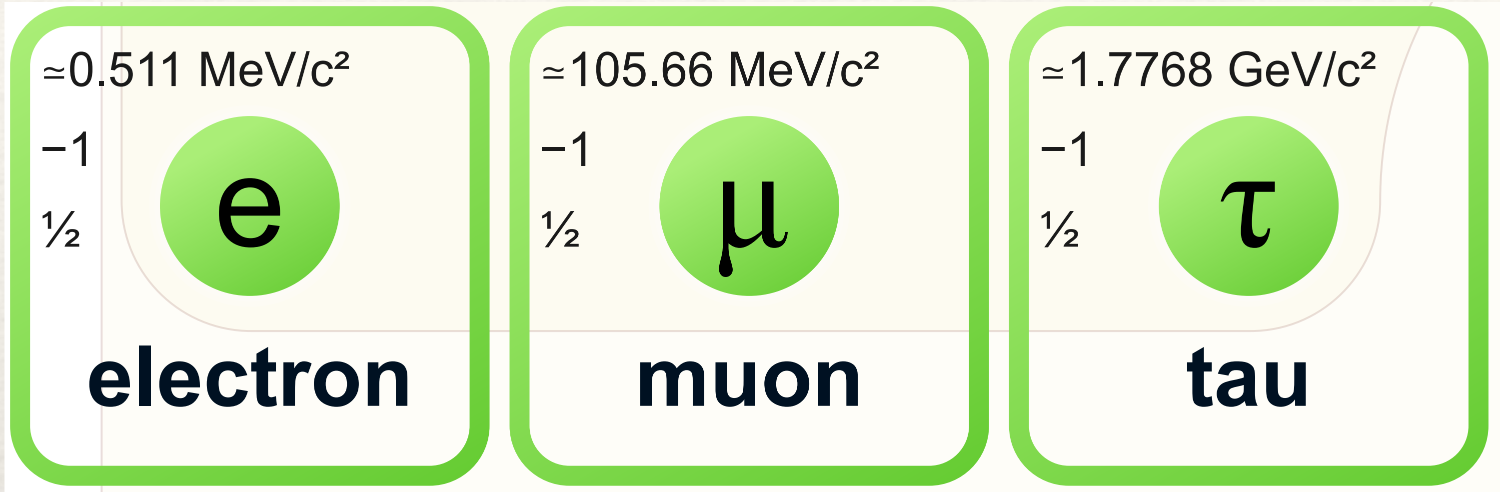
Lepton Flavour Universality Violation: new hints from the Cabibbo Angle Anomaly?

I.F.A.E. 18.10.2021

University of Zurich[UZH]
PAUL SCHERRER INSTITUT PSI

Lepton Flavour Universality

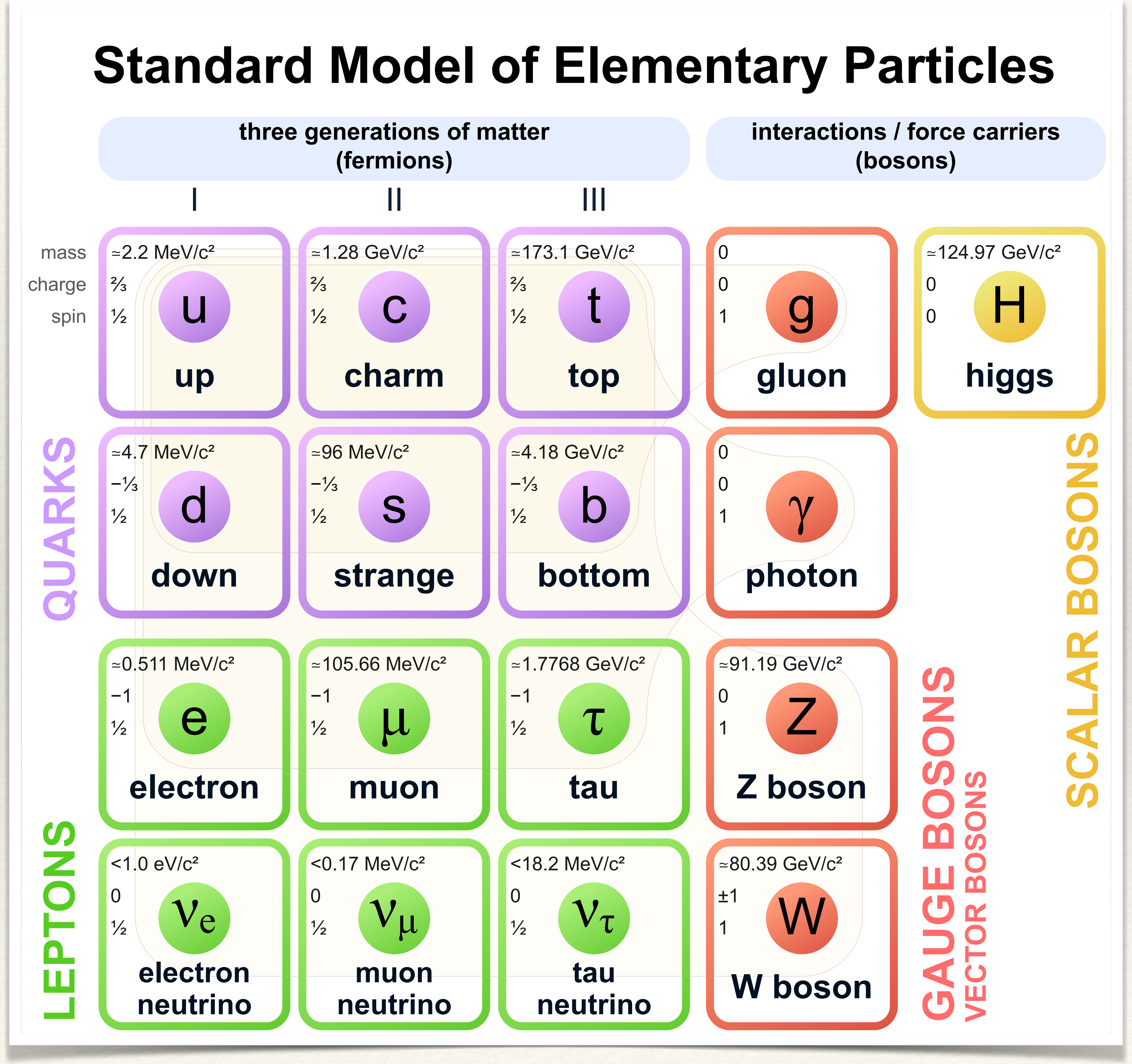
In the SM there are 3 lepton families



- The only distinctions at the fundamental level are…

…<u>the Couplings with H!</u>

$$\mathscr{L}_{\mathrm{YUK}} = -Y_e \bar{e}_L e_R H - Y_\mu \bar{\mu}_L \mu_R H - Y_\tau \bar{\tau}_L \tau_R H$$



Lepton Flavour Universality

- Small Yukawas…

$$Y_e \approx 2 \times 10^{-6} \quad Y_\mu \approx 4 \times 10^{-4} \quad Y_\tau \approx 7 \times 10^{-3}$$

at high energies, the differences are negligible

E.g.:

$$\sigma(Z \to \ell\ell) \propto |\mathcal{M}|^2 \sqrt{1 - 4\frac{m_\ell^2}{m_Z^2}}$$

$$\mathrm{Br}(Z \to e^+e^-) \approx (3.3632 \pm 0.0042)\,\%$$

$$\mathrm{Br}(Z \to \mu^+\mu^-) \approx (3.3662 \pm 0.0066)\,\%$$

$$\mathrm{Br}(Z \to \tau^+\tau^-) \approx (3.3696 \pm 0.0083)\,\%$$

- …but large ratios!

$$Y_e : Y_\mu : Y_\tau \;\approx\; 1 : 212 : 3560$$

responsible for the large visible breaking of LFU:

1. Different masses $m_e \simeq 0.5$ MeV $\quad m_\mu \simeq 106$ MeV $\quad m_\tau \simeq 1780$ MeV

2. Different decay channels

e is STABLE!

μ decays to "$e\,\bar{\nu}_e\,\nu_\mu$" only
$\tau_\mu \simeq 2 \times 10^{-6} s$

τ has several decays channel into leptons and hadrons: e, μ, π, K, η, etc . $\quad \tau_\tau \simeq 3 \times 10^{-13} s$

Lepton Flavour Universality

In the SM **LFUV** arises only from the Higgs sector. Can we test this property of the SM?

$\boxed{b \to s\ell\ell \text{ data}}$

$\boxed{b \to c\ell\nu \text{ data}}$

$\boxed{\textit{Cabibbo Angle Anomaly}}$

$\boxed{(g-2)_\mu \text{ vs } (g-2)_e}$

$\boxed{\ell \to \ell'\nu\nu \text{ data}}$

$\boxed{\Delta A_{\mathrm{FB}}}$

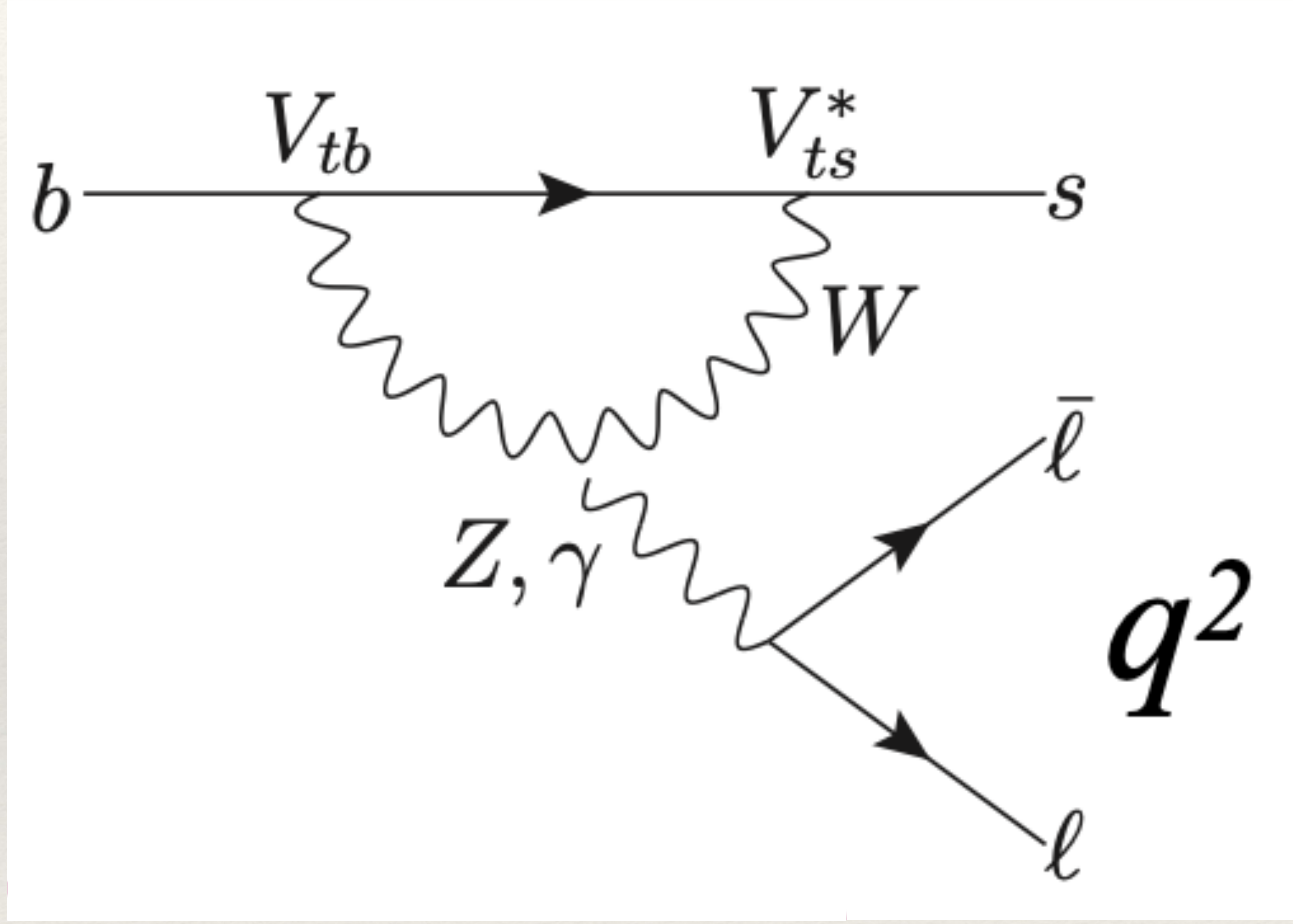
Neutral Current B decays

A perfect environment to search for LFUV are the flavour-changing neutral-current transitions in semileptonic B decays

Due to their suppression in the SM, they have a high sensitivity to potential NP contributions.

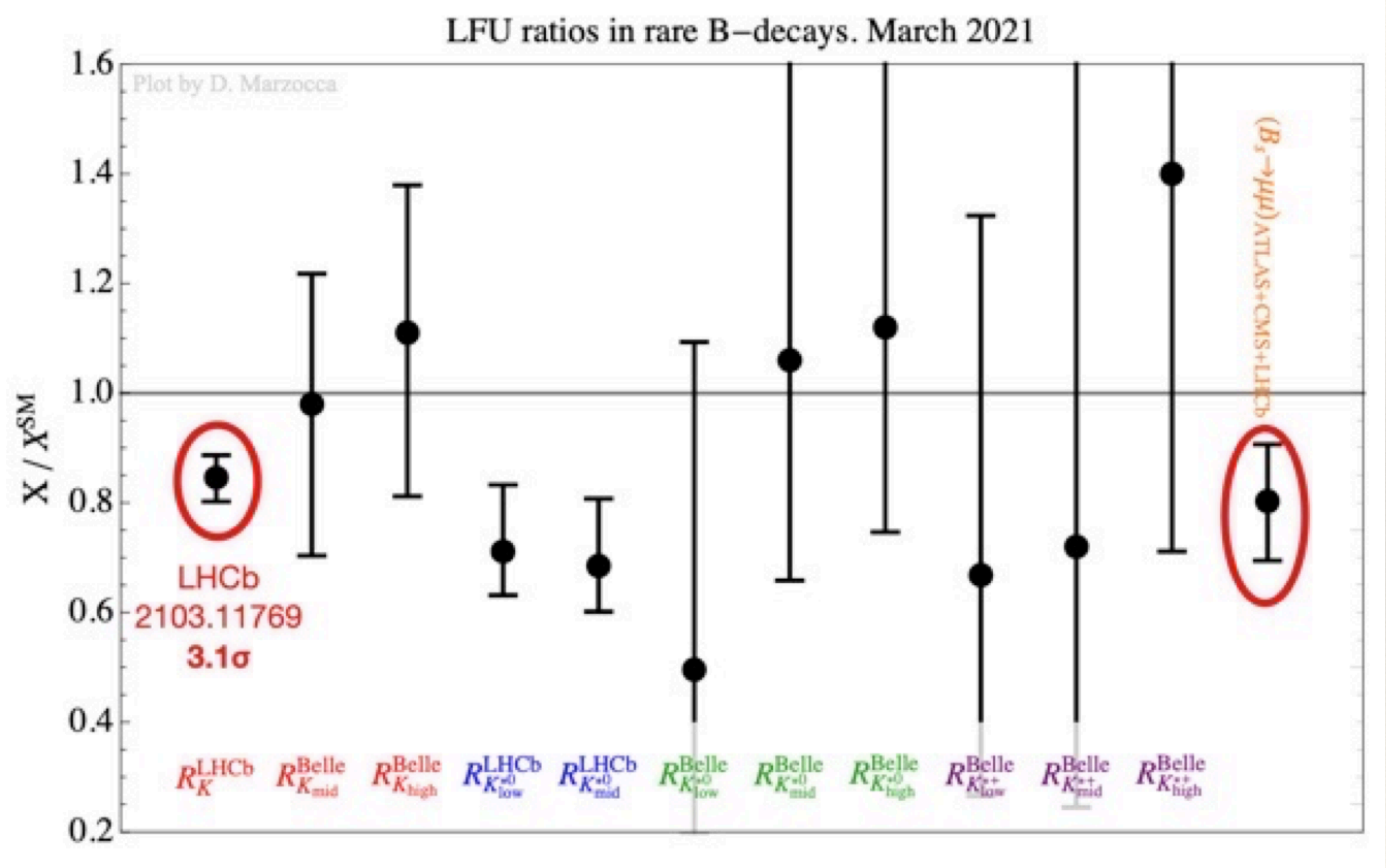
$$\boxed{b \to s\mu^+\mu^- \text{ vs } b \to se^+e^-}$$

Huge experimental effort from LHCb and Belle



Neutral Current B decays

Clean SM predictions



$$R(A) = \frac{\int \frac{d\mathcal{B}}{dq^2}(B \to A\mu^+\mu^-)dq^2}{\int \frac{d\mathcal{B}}{dq^2}(B \to Ae^+e^-)dq^2}$$

$B_s \to \mu^+\mu^-$ theoretically very clean but chirality suppress

There is a coherent pattern of deviations from the SM

This is a first hint of LFUV

Neutral Current B decays

We need to study systematically the possible NP contributions

$$\mathscr{L}_{\mathrm{NP}} = \frac{c_i}{\Lambda^2} O_i$$

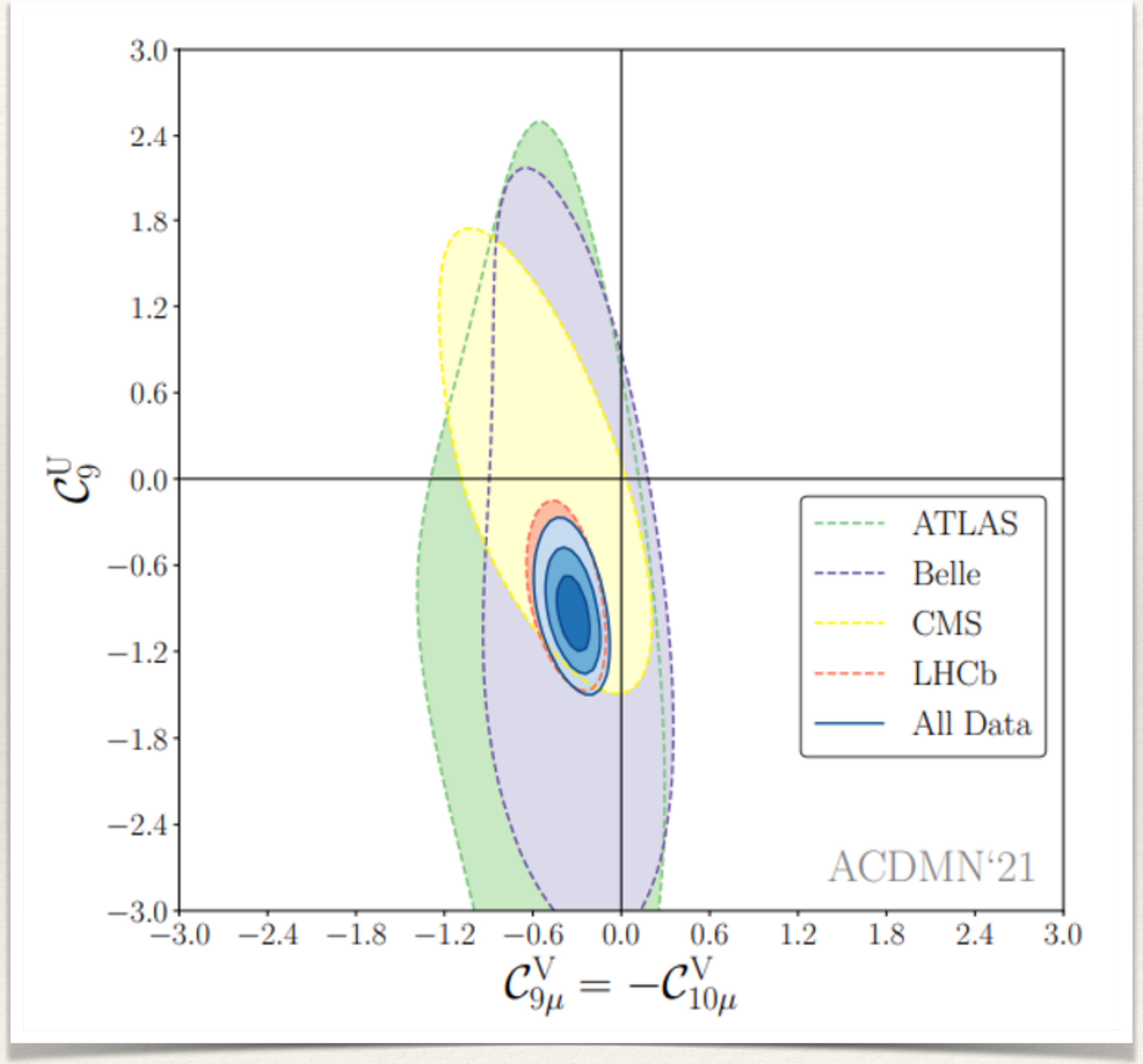
$$O_9 = \left(\bar{s}\gamma_\mu P_L b\right)\left(\bar{\ell}\gamma^\mu \ell\right) \qquad O_{10} = \left(\bar{s}\gamma_\mu P_L b\right)\left(\bar{\ell}\gamma^\mu \gamma^5 \ell\right)$$

Global Fits to all observables strongly prefers NP hypothesis over SM.

2103.13370 2103.12738 2104.08921

Scenario		Best-fit point	1 σ	2 σ	$\mathrm{Pull}_{\mathrm{SM}}$	p-value
Scenario 6	$\mathcal{C}_{9\mu}^{\mathrm{V}} = -\mathcal{C}_{10\mu}^{\mathrm{V}}$	-0.52	$[-0.60, -0.44]$	$[-0.68, -0.36]$	6.8	40.1 %
	$\mathcal{C}_9^{\mathrm{U}} = \mathcal{C}_{10}^{\mathrm{U}}$	-0.41	$[-0.54, -0.28]$	$[-0.66, -0.15]$		
Scenario 7	$\mathcal{C}_{9\mu}^{\mathrm{V}}$	-0.76	$[-1.00, -0.52]$	$[-1.25, -0.30]$	6.9	41.7 %
	$\mathcal{C}_9^{\mathrm{U}}$	-0.39	$[-0.68, -0.09]$	$[-0.94, +0.19]$		
Scenario 8	$\mathcal{C}_{9\mu}^{\mathrm{V}} = -\mathcal{C}_{10\mu}^{\mathrm{V}}$	-0.30	$[-0.39, -0.21]$	$[-0.47, -0.13]$	7.3	53.8 %
	$\mathcal{C}_9^{\mathrm{U}}$	-0.92	$[-1.10, -0.72]$	$[-1.27, -0.51]$		

Algueró, Capdevilla, Descotes-Genon, Matias, Novoa-Brunet '21

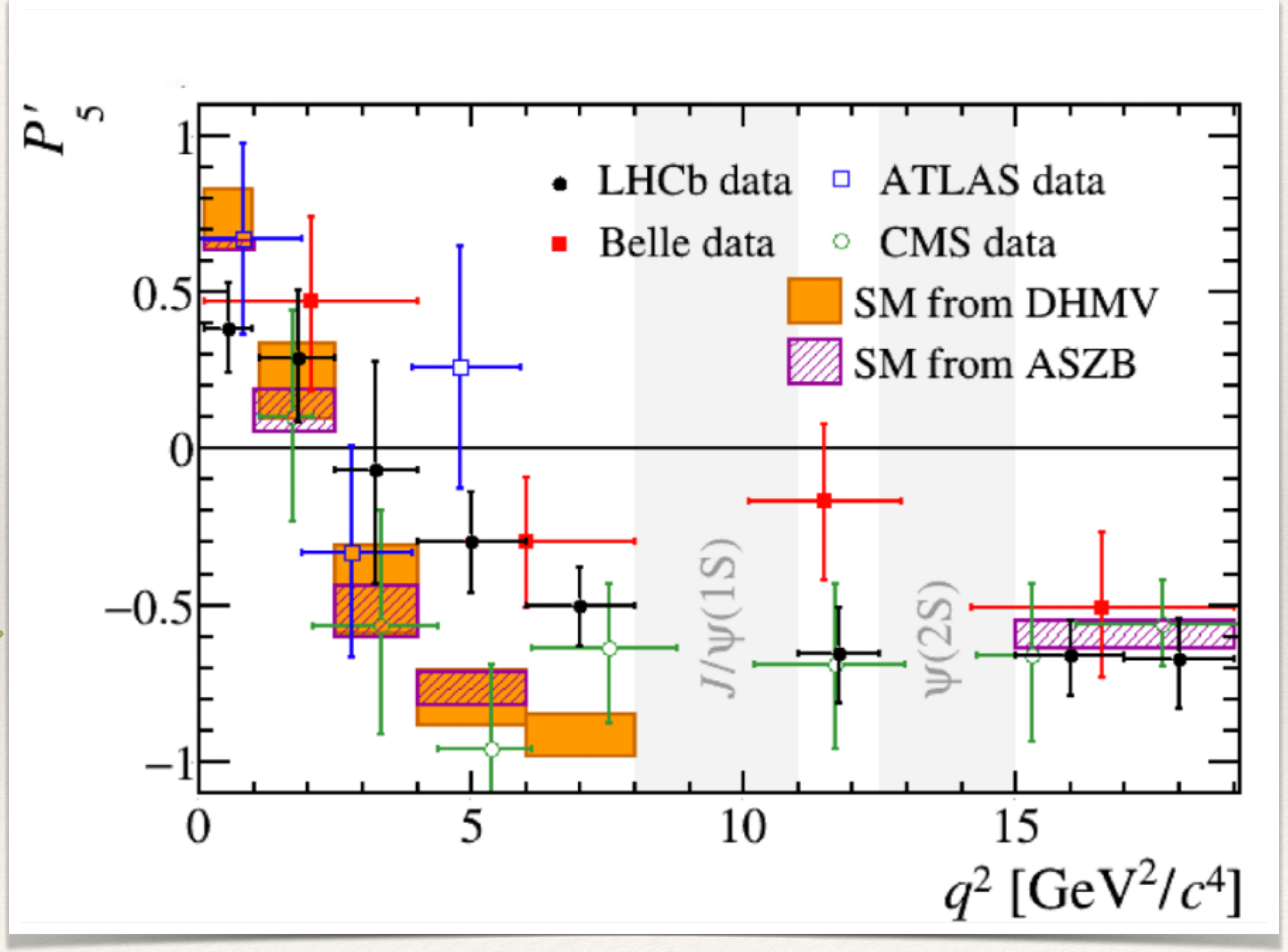


$\Lambda \sim 30$ TeV

P_5'

Angular observable in $B \to K^*\mu\mu$, constructed in such a way that the form factor dependence is minimized

1303.5794 Descotes-Genon, Hurth, Matias, Virto



STRONG SUPPORT FOR $R(K)$ & $R(K^*)$

With C_9 fitted from $R(K)$ and $R(K^*)$, the prediction for P_5' is in perfect agreement with measurements!

- Data consistently below SM prediction
- Confirmed by latest LHCb analysis for the charged mode

Charged Current B decays

- Tree level processes in the SM, suppressed by V_{cb}

- Processes measured so far:

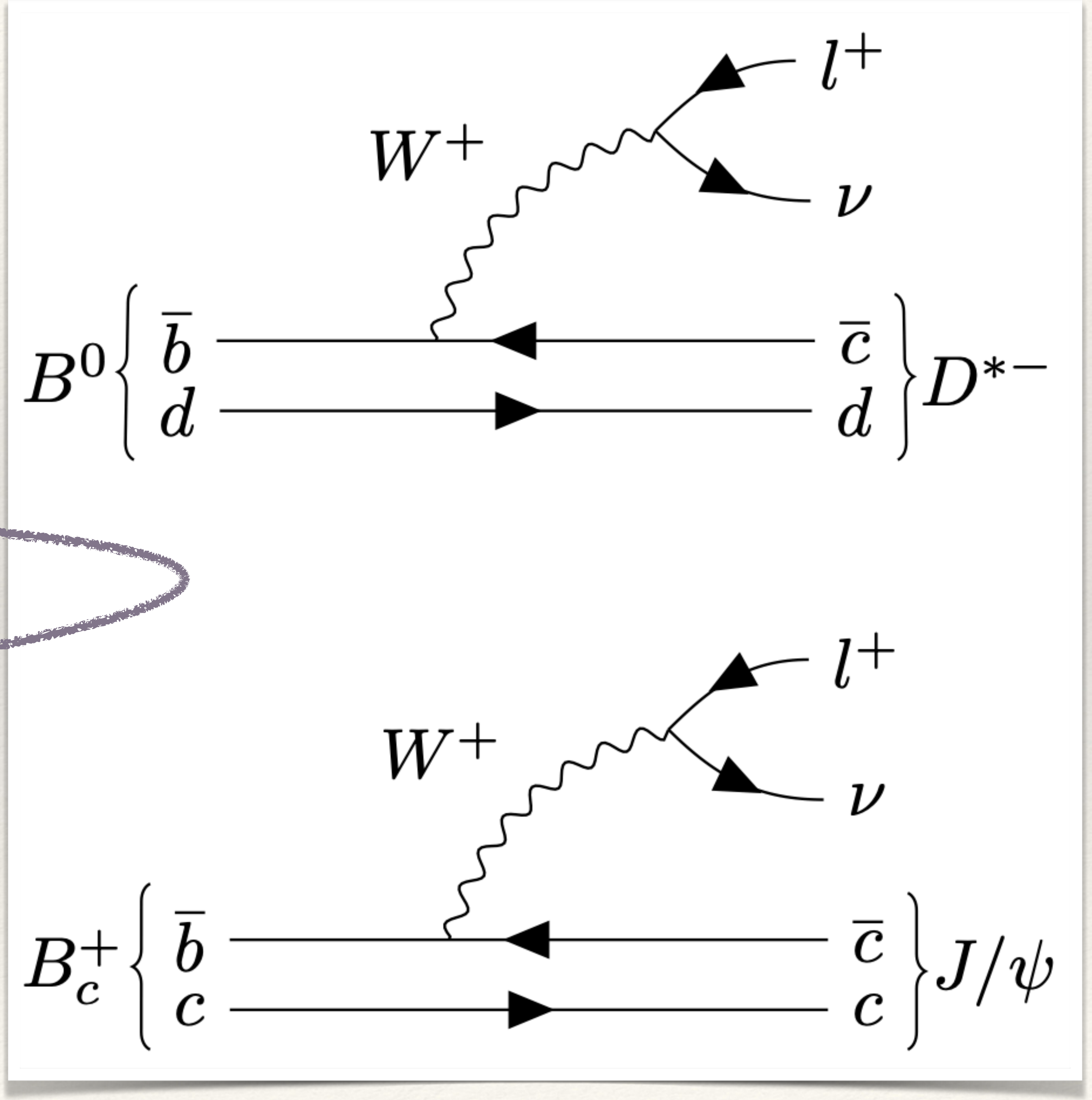
$$B \to D^{-}\tau^{+}\nu_{\tau}, \quad B \to D^{*-}\tau^{+}\nu_{\tau}, \quad B \to J/\Psi\tau^{+}\nu_{\tau}$$

- Form factors needed for SM predictions

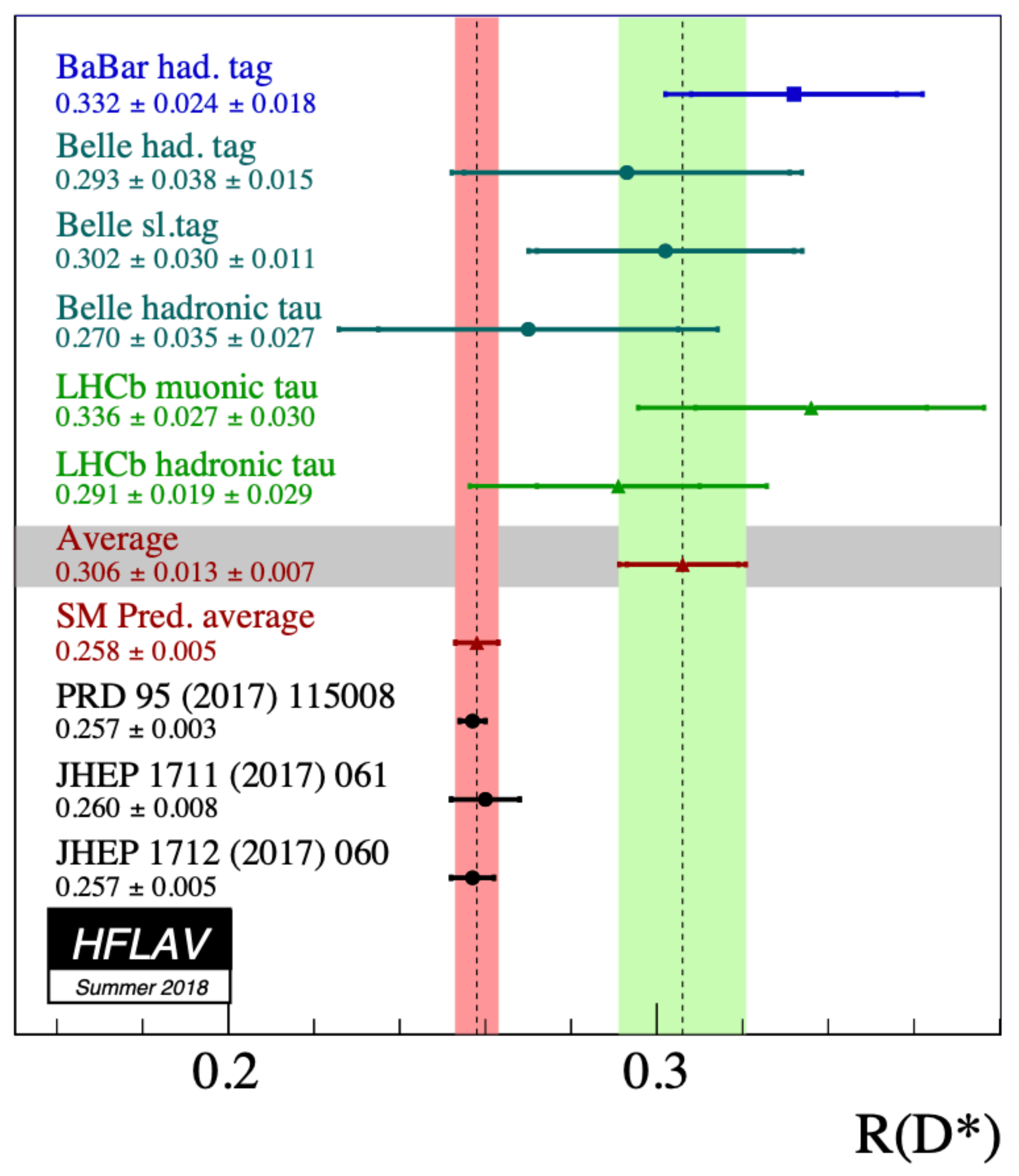
LFU Testing Ratios to reduce QCD uncertainties

$$R(A) = \frac{\mathscr{B}(B^0 \to A^{+}\tau\nu)}{\mathscr{B}(B^0 \to A^{+}\ell\nu)}$$

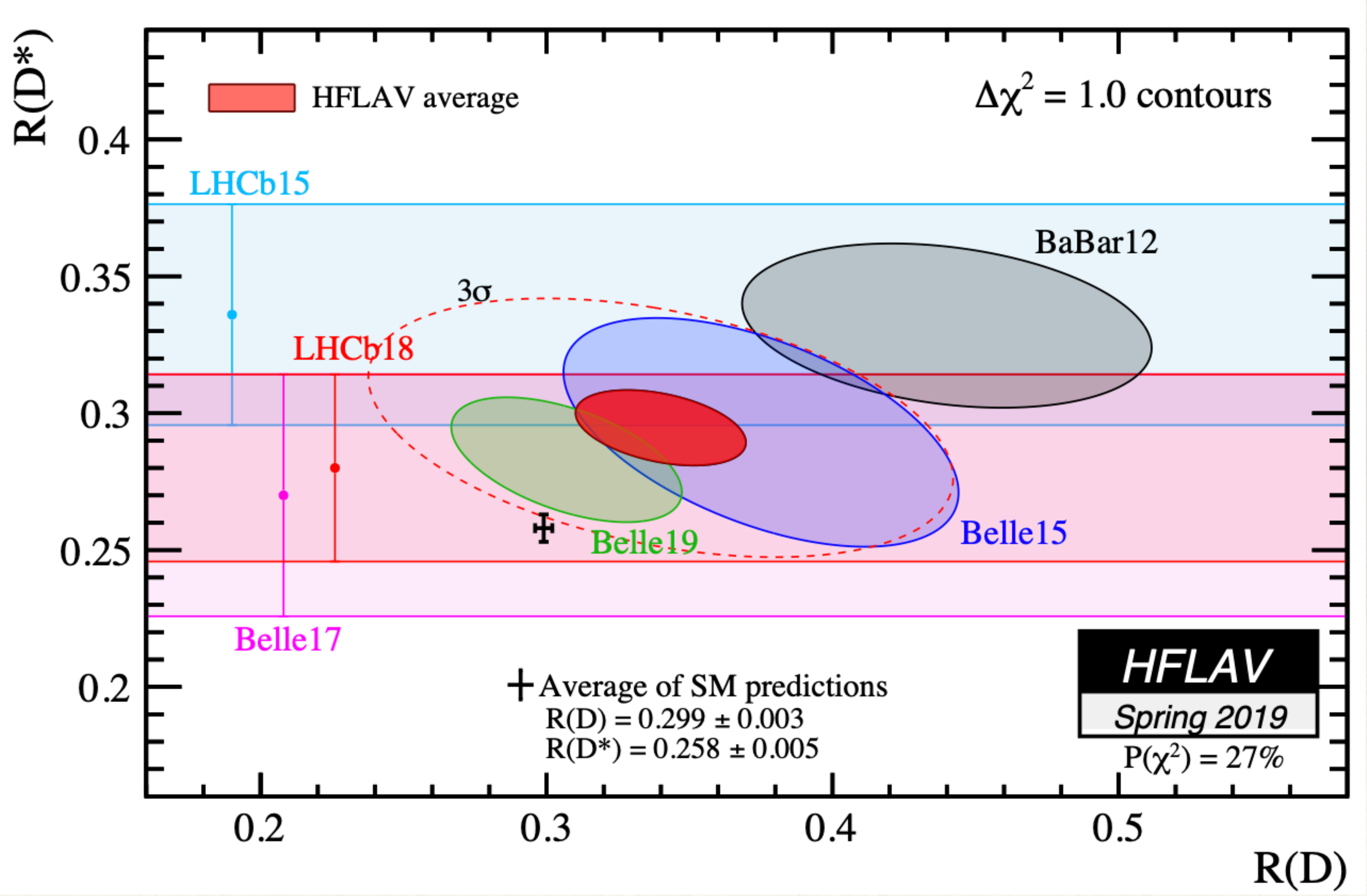
- Sensitive to NP coupling with 3rd generation leptons



Charged Current B decays



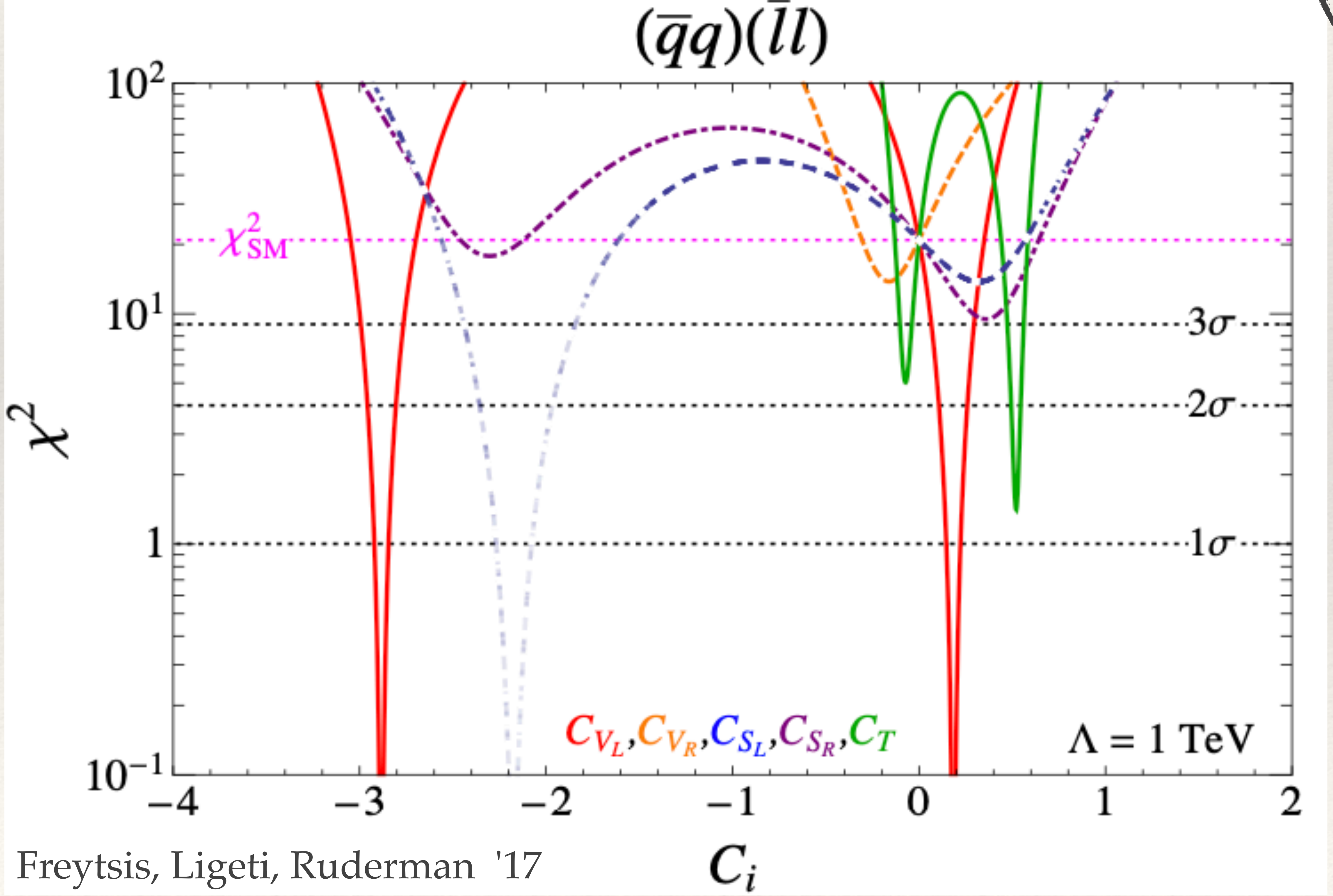
- All measurements lie consistently above the SM!
- $R(J/\Psi)$ known with less precision but support $R(D)$ and $R(D^*)$
- $O(10\%)$ constructive effect needed



Charged Current B decays

EFT analysis: $\mathcal{H} = \frac{4G_F}{\sqrt{2}} V_{cb} \left(\bar{c}\gamma_\mu P_L b\right)\left(\bar{\tau}\gamma^\mu P_L \nu_\tau\right) + \sum_i \frac{c_i}{\Lambda^2} O_i$

SM contribution



Freytsis, Ligeti, Ruderman '17

1506.08896

Coefficient(s)	Best fit value(s) ($\Lambda = 1$ TeV)
C_{V_L}	0.18 ± 0.04, $\quad -2.88 \pm 0.04$

New Physics: The same operator as in the SM gives the best fit

Future Improvements

Analysis of different channels: $B \to D^{**}\tau\nu$, $\quad B_s \to D_s^*\tau\nu$

Analysis of Baryonic Counterparts: $\Lambda_b \to \Lambda_c \tau\nu$

More Statistics:

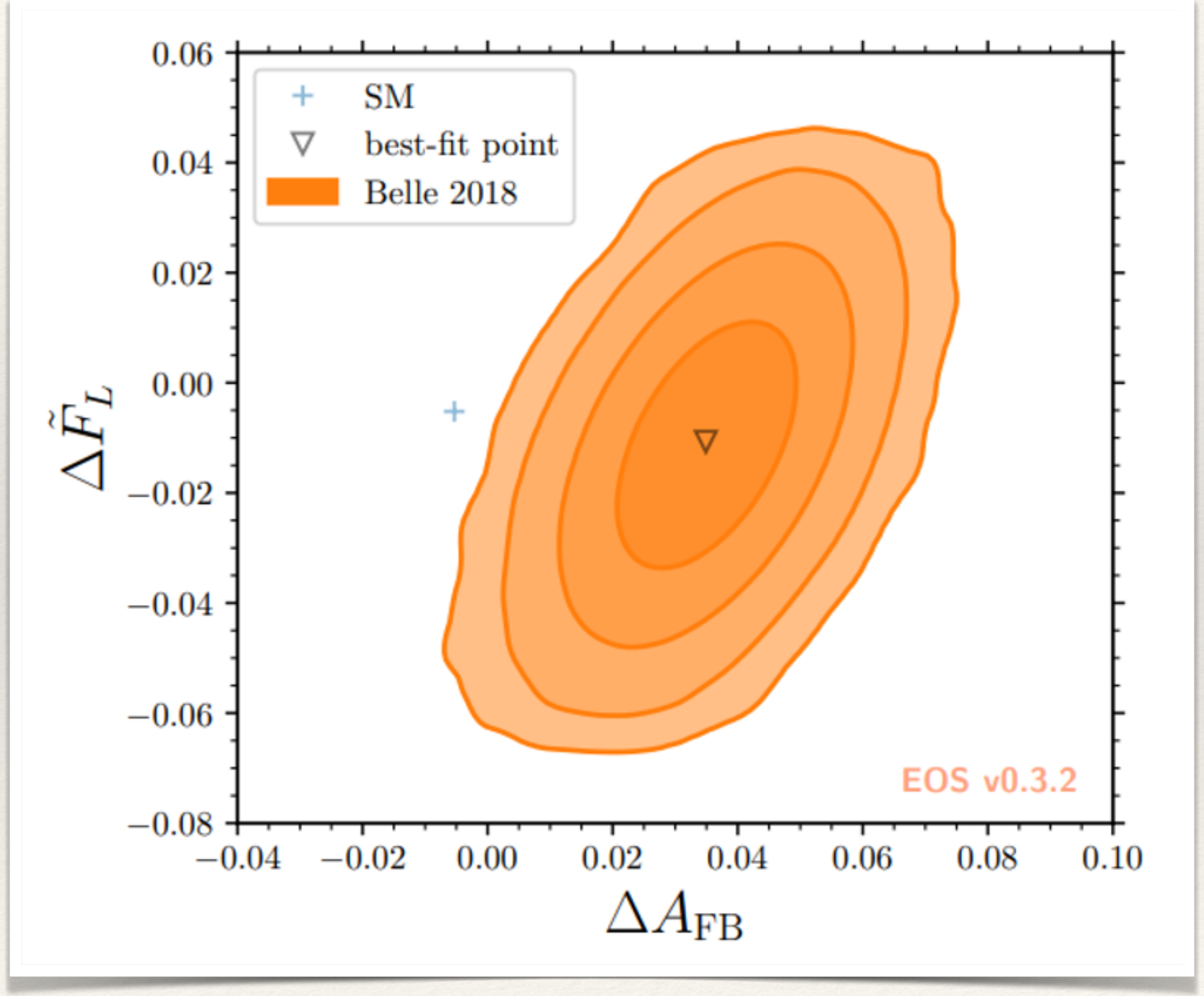
Belle II	2023	2030
	5 ab^{-1}	50 ab^{-1}
R_D	$(\pm 6.0 \pm 3.9)\%$	$(\pm 2.0 \pm 2.5)\%$
R_{D^*}	$(\pm 3.0 \pm 2.5)\%$	$(\pm 1.0 \pm 2.0)\%$

Charged Current B decays

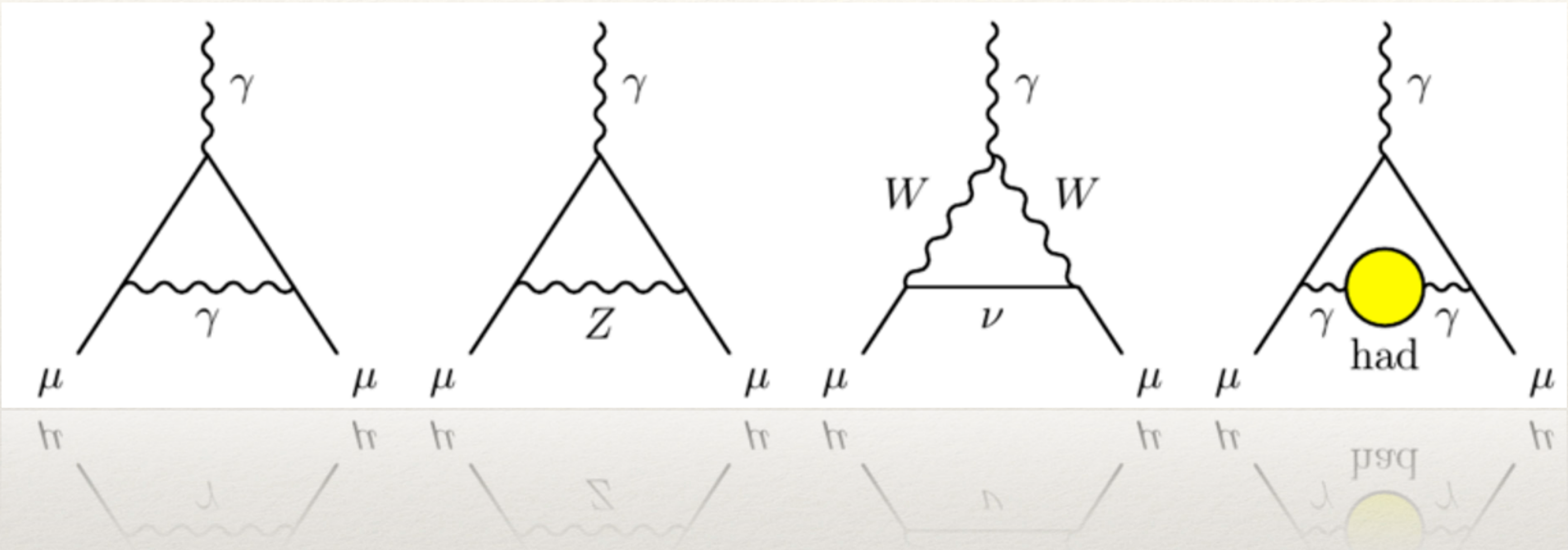
$$\Delta A_{FB} \equiv A_{FB}(b \to c\mu\nu) - A_{FB}(b \to ce\nu)$$

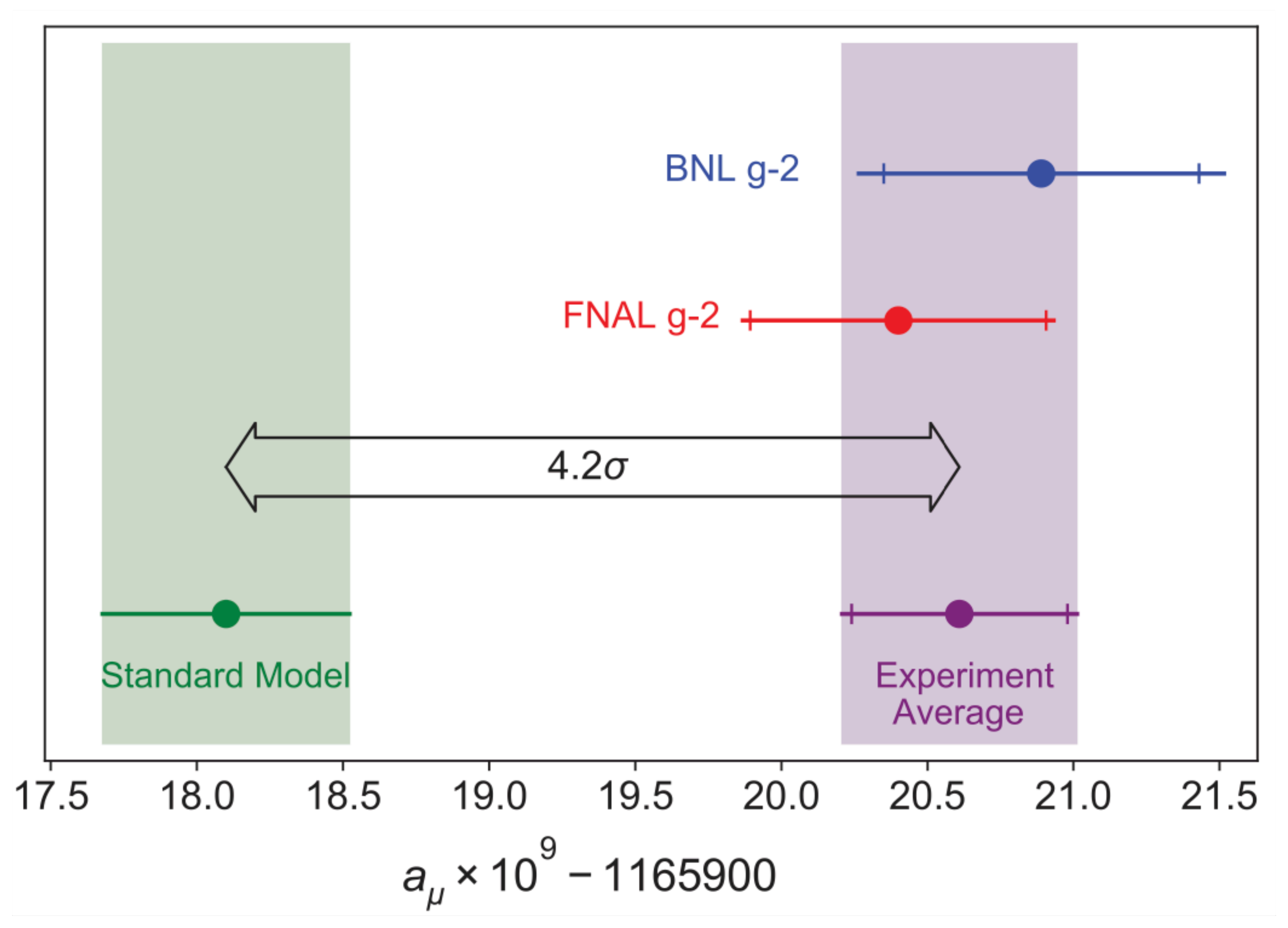
Another hint of LFUV between muons and electrons but in charged current B decays!

- 4 σ tension found by 2104.02094, studying Belle data 1809.03290
- Tensor operators needed to explain angular asymmetry
- Upcoming LHCb analysis on the muon mode will give more insights



Anomalous Magnetic Moment of the Muon





- Theory prediction challenging because of hadronic effects
- A contribution fo the same order of the SM EW one is needed
- Chiral enhancement necessary for heavy NP

A LFU effect would be in strong disagreement with $(g-2)_e$ measurements! → **LFUV required**

$\tau \to \mu\nu\nu$

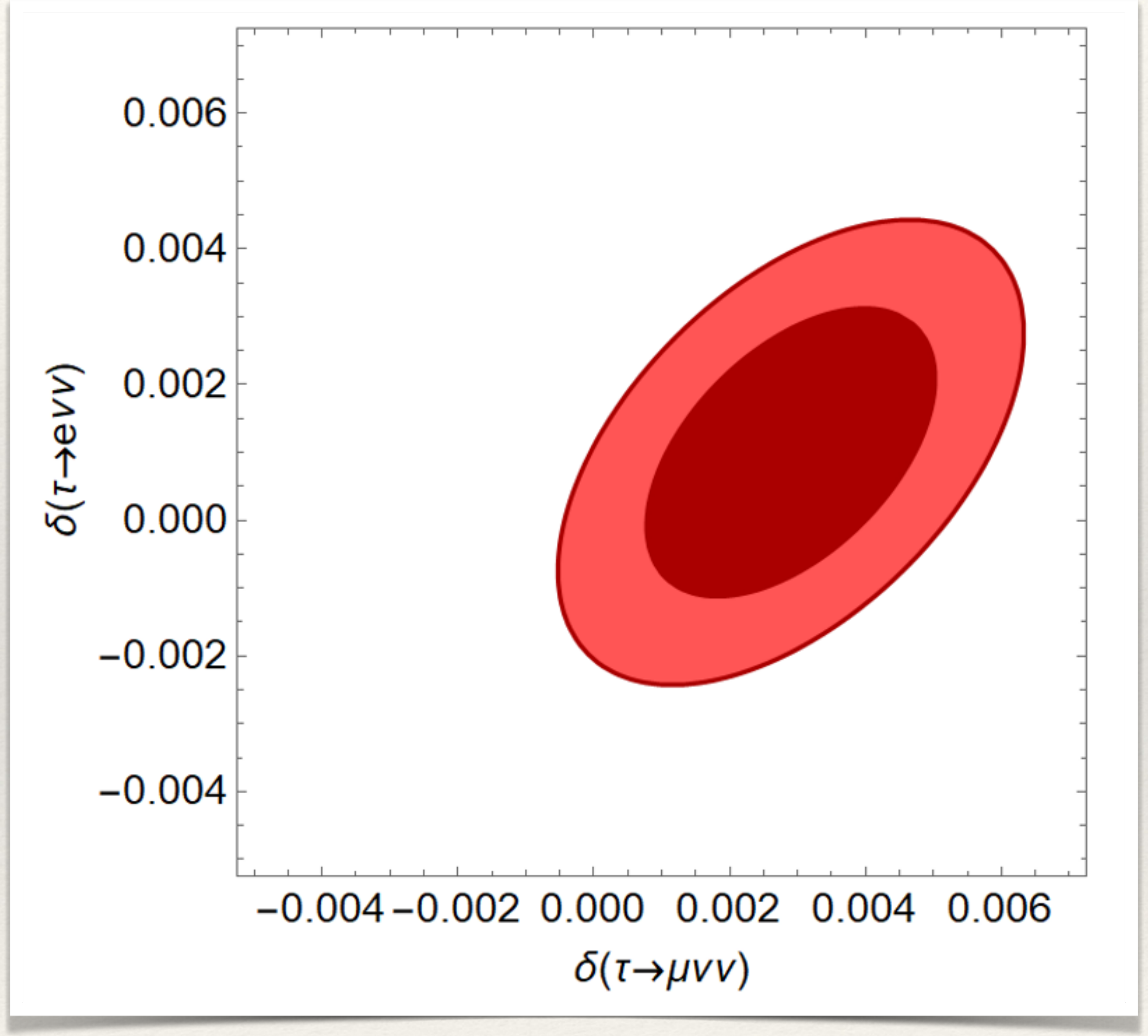
Leptonic tau decays are the simplest processes to test LFU

$$\left.\frac{\mathcal{A}\left[\tau \to \mu\nu\bar{\nu}\right]}{\mathcal{A}\left[\mu \to e\nu\bar{\nu}\right]}\right|_{\mathrm{EXP}} = 1.0029 \pm 0.0014\,,$$

$$\left.\frac{\mathcal{A}\left[\tau \to \mu\nu\bar{\nu}\right]}{\mathcal{A}\left[\tau \to e\nu\bar{\nu}\right]}\right|_{\mathrm{EXP}} = 1.0018 \pm 0.0014\,,$$

$$\left.\frac{\mathcal{A}\left[\tau \to e\nu\bar{\nu}\right]}{\mathcal{A}\left[\mu \to e\nu\bar{\nu}\right]}\right|_{\mathrm{EXP}} = 1.0010 \pm 0.0014\,,$$

At the amplitude level! In the SM they all = 1.



$\mu \to e\nu\nu$ **very well constrained by experiments therefore NP in** τ **sector needed**

So far…

$\boxed{b \to s\ell\ell \text{ data } (R(K), RK^*, P_5')}$

$\boxed{\Delta A_{\mathrm{FB}} \text{ data}}$ $\boxed{(g-2)_\mu}$

LFUV required between e and μ.

$\boxed{b \to c\ell\nu \text{ data}}$ $\boxed{\tau \to \mu\nu\nu \text{ data}}$

LFUV required between τ and e, μ.

New Physics in the lepton sector →

- **Large effects in τ** $\Lambda_\tau \sim 3\,\mathrm{TeV}$
- **Smaller effect in μ** $\Lambda_\mu \sim 30\,\mathrm{TeV}$
- **Negligible effect in e**

Very similar to SM fermion mass pattern!

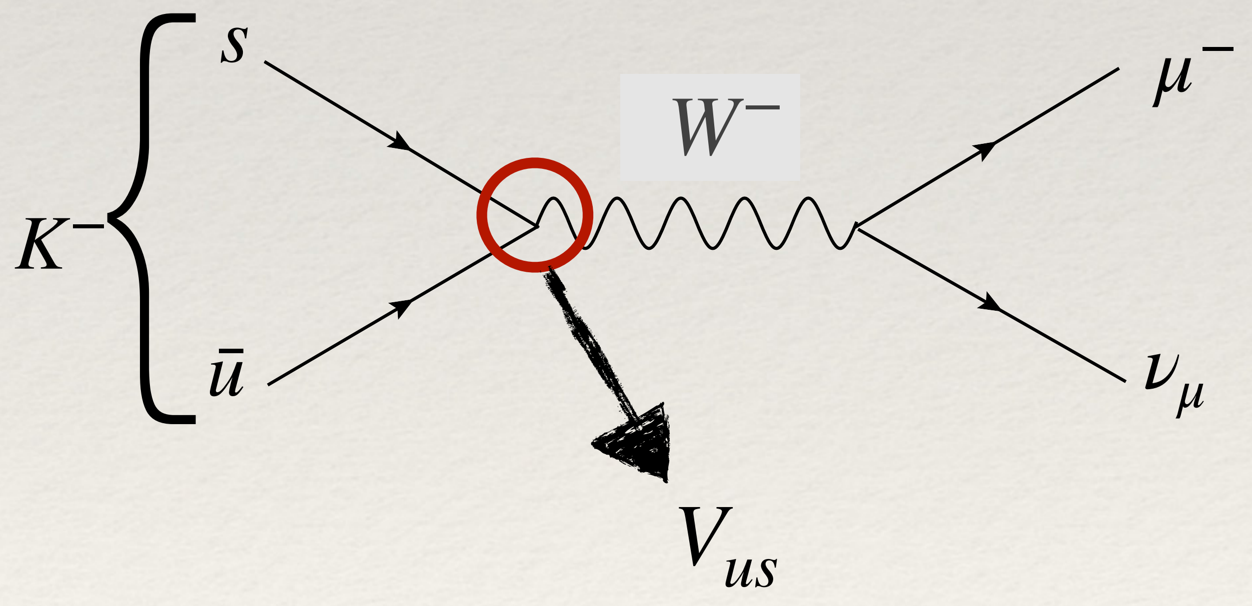
The Cabibbo Angle Anomaly

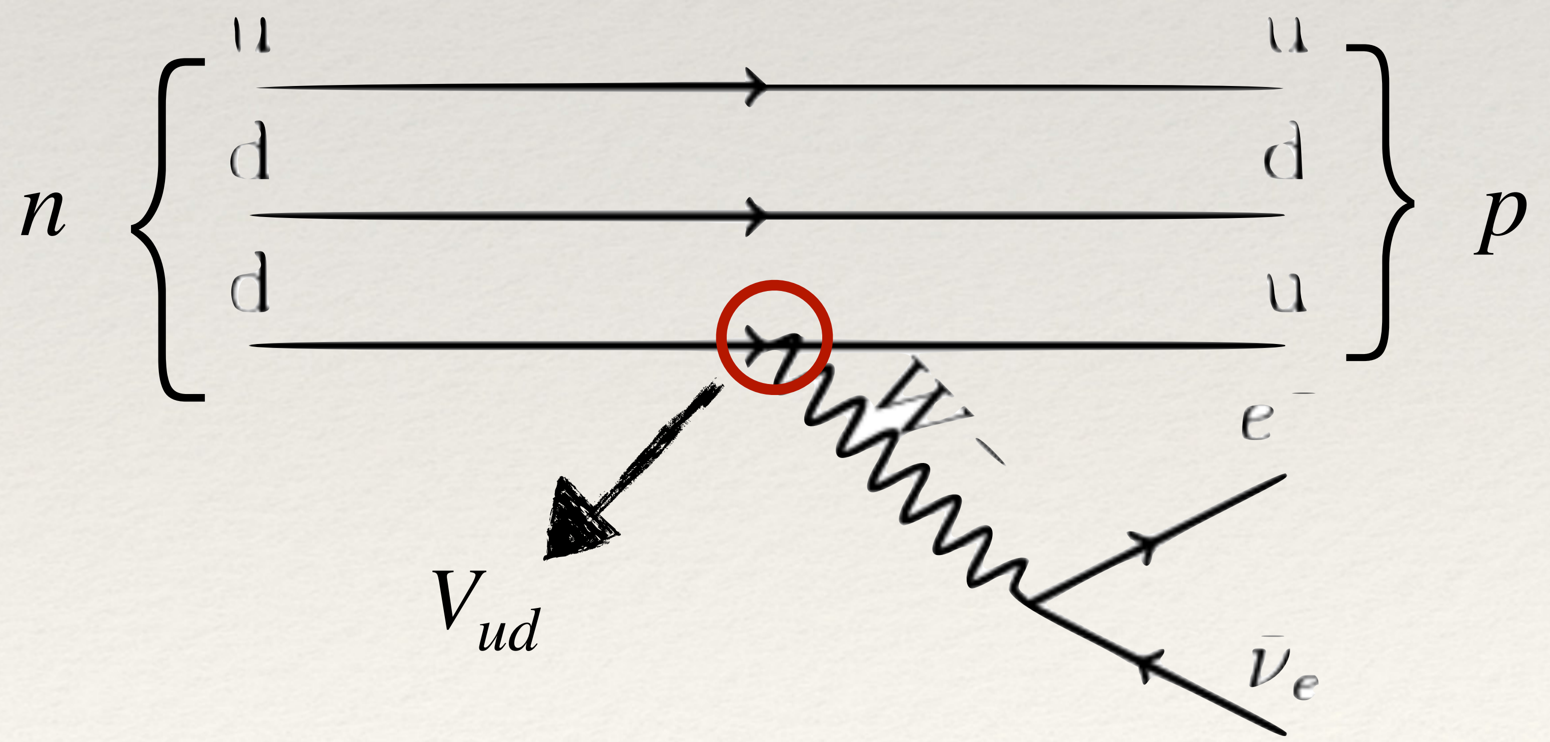
The unitary Cabibbo-Kobayashi-Maskawa (CKM) matrix parametrizes the misalignment between interaction and mass bases in the quark sector.

$$\mathscr{J}^{\lambda}_{CC} = (\bar{\nu}_{eL}, \bar{\nu}_{\mu L}, \bar{\nu}_{\tau L})\gamma^{\lambda}\begin{pmatrix} \mathbf{e}_L \\ \mu_L \\ \tau_L \end{pmatrix} + (\bar{\mathbf{u}}_L, \bar{\mathbf{c}}_L, \bar{\mathbf{t}}_L)\gamma^{\lambda}\begin{pmatrix} \mathbf{d}'_L \\ \mathbf{s}'_L \\ \mathbf{b}'_L \end{pmatrix}$$

$$= (\bar{\nu}_{eL}, \bar{\nu}_{\mu L}, \bar{\nu}_{\tau L})\gamma^{\lambda}\begin{pmatrix} \mathbf{e}_L \\ \mu_L \\ \tau_L \end{pmatrix} + (\bar{\mathbf{u}}_L, \bar{\mathbf{c}}_L, \bar{\mathbf{t}}_L)\gamma^{\lambda}\mathbf{V}\begin{pmatrix} \mathbf{d}_L \\ \mathbf{s}_L \\ \mathbf{b}_L \end{pmatrix}$$

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

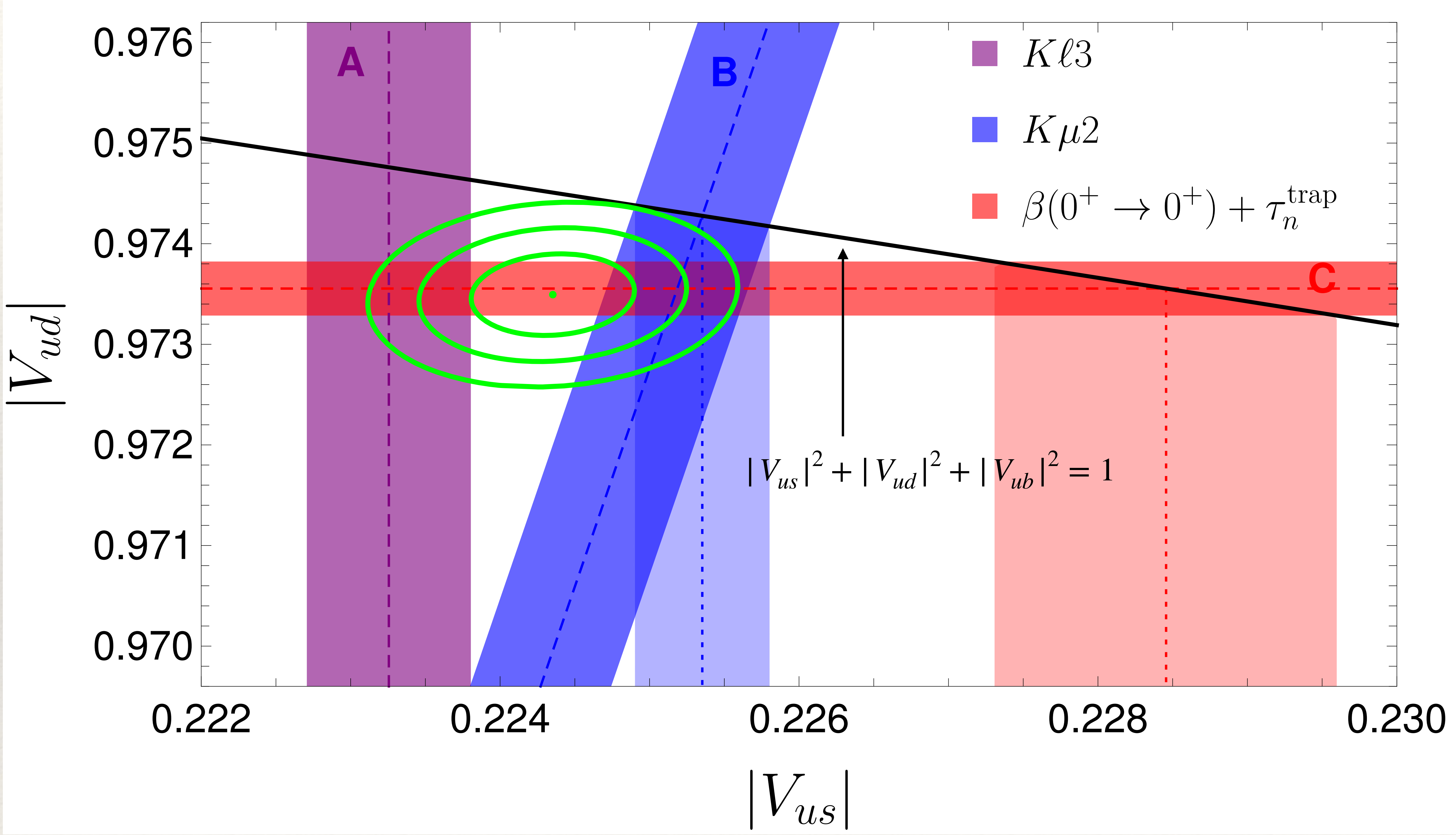




The Cabibbo Angle Anomaly

In the SM $|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1$

- V_{ud} from super-allowed β decays
- V_{us} from semileptonic K decays
- $\frac{V_{us}}{V_{ud}}$ from $\frac{K \to \mu\nu}{\pi \to \mu\nu}$



$$|V_{ud}^{\beta}|^2 + |V_{us}^{K,\pi}|^2 + |V_{ub}|^2 = 0.9985(5)$$

A DEFICIT IN THE FIRST ROW CKM UNITARITY RELATION

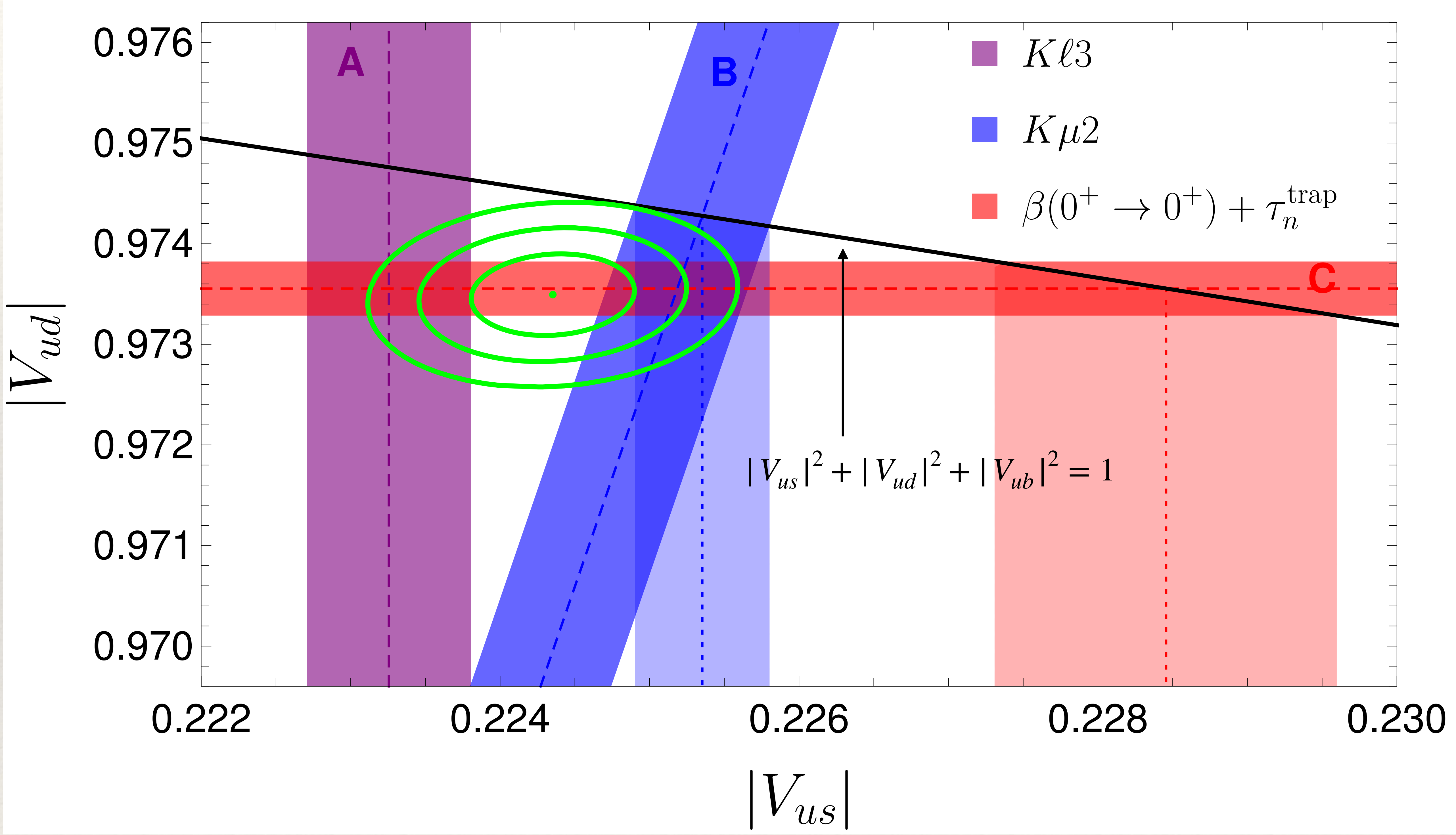
The Cabibbo Angle Anomaly

$$|V_{ud}^{\beta}|^2 + |V_{us}^{K,\pi}|^2 + |V_{ub}|^2 = 0.9985(5)$$

$$\left|\frac{V_{ud}}{V_{us}}\right|^2 \sim 20$$

≈ 0.0037
negligible error

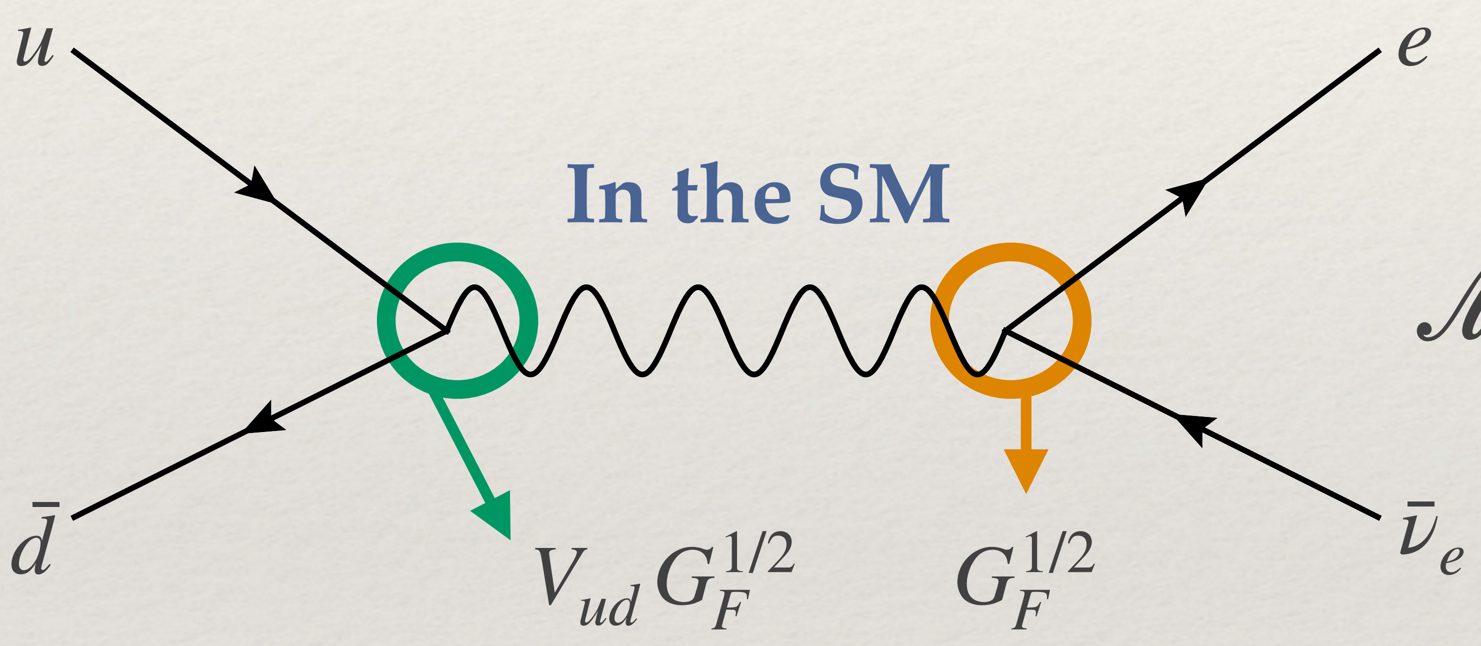
$$|V_{ud}|^2(1-\varepsilon)^2 + |V_{us}|^2 + |V_{ub}|^2 = 0.9985(5)$$



Note: there is also a (less significant) deficit in the first column of the CKM unitarity relation. This further strengthen the idea of a modification in V_{ud} from β decays.

The Cabibbo Angle Anomaly

$$|V_{ud}|^2(1-\varepsilon)^2 + |V_{us}|^2 + |V_{ub}|^2 = 0.9985(5)$$



$$\mathcal{M}_\beta \propto x\, V_{ud}\, G_F$$

To extract V_{ud}

In the SM

$$\frac{\mathcal{M}_\beta}{G_F^\mu} \propto \overset{1}{x}\, V_{ud} \overset{1}{\frac{G_F}{G_F^\mu}} \equiv V_{ud}^\beta$$

Two possibilities:

NP in β decay

$$x = (1-\epsilon)$$

$$G_F^\mu = G_F$$

NP in μ decay

$$x = 1$$

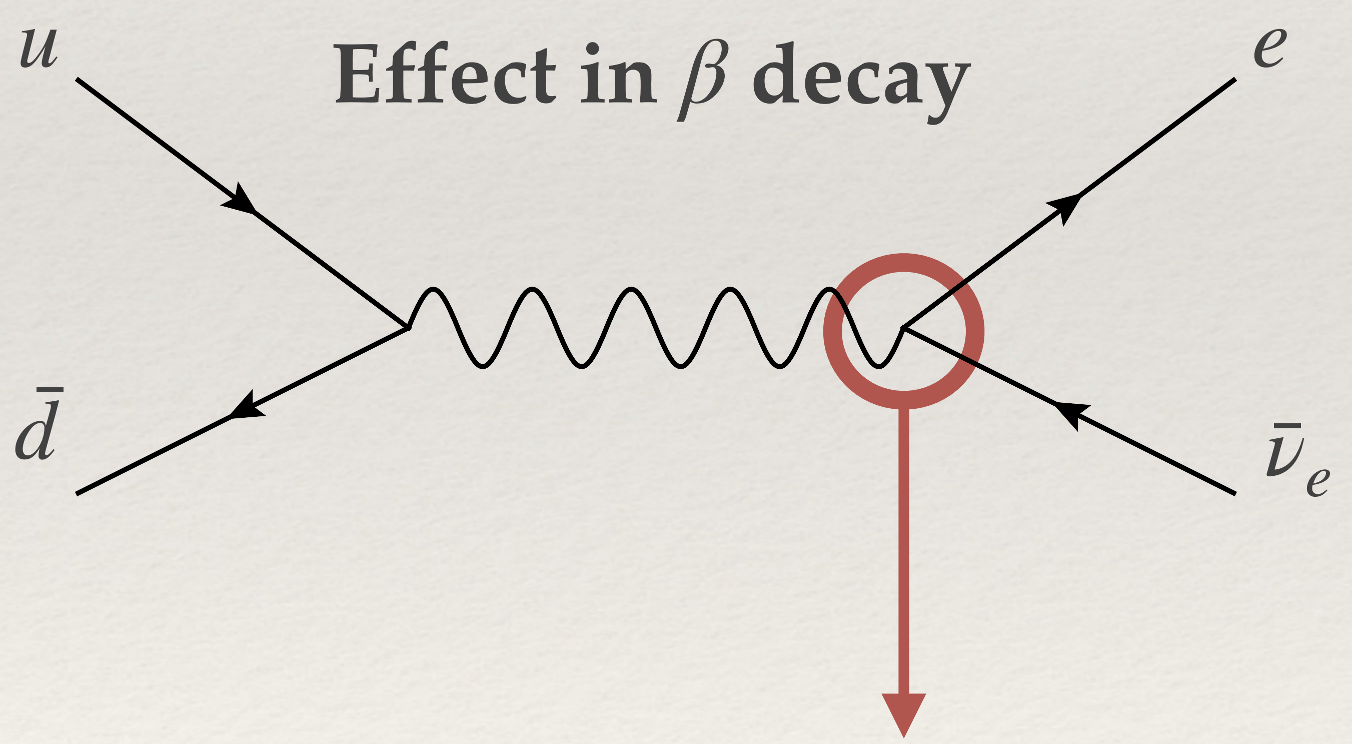
$$G_F^\mu = G_F(1+\epsilon)$$

The Cabibbo Angle Anomaly

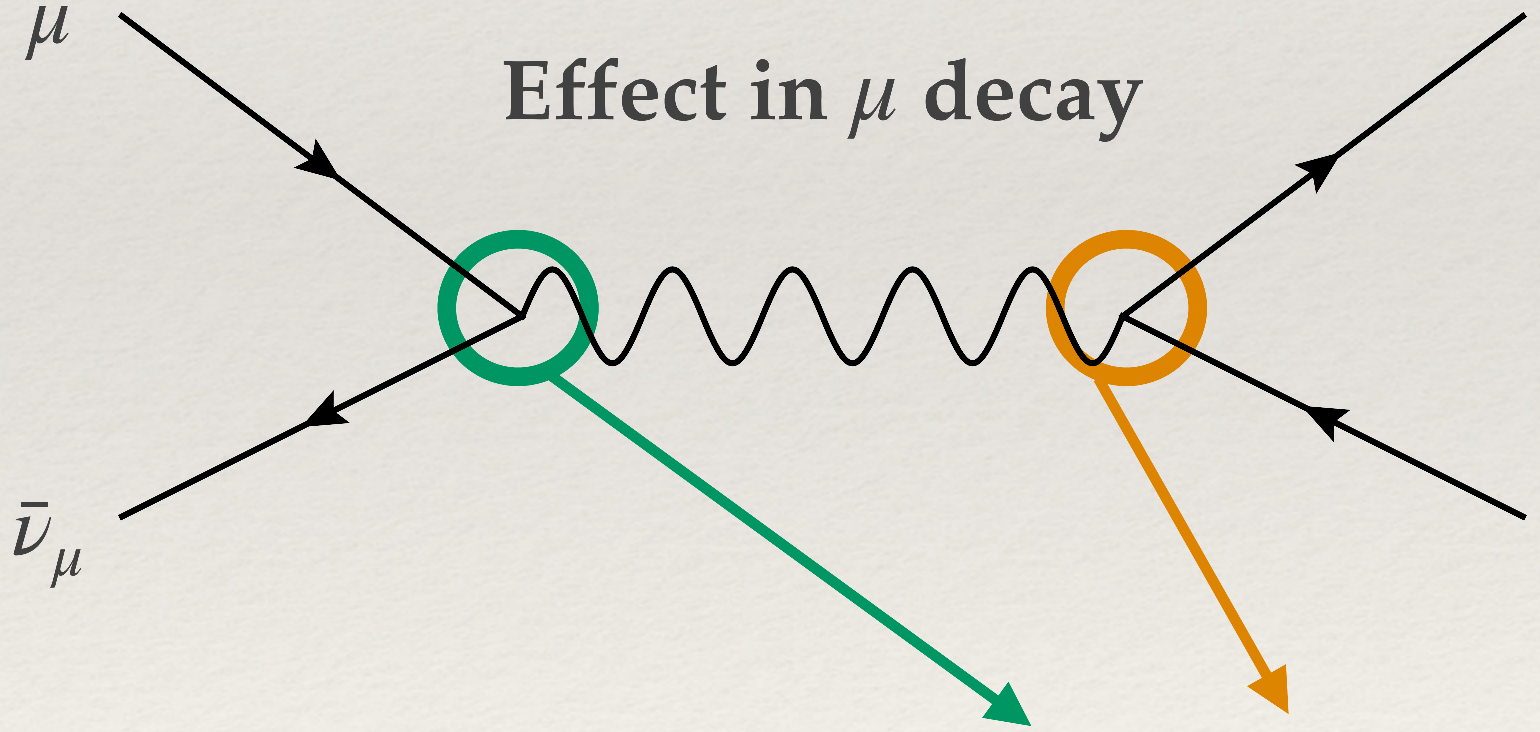
1912.08823 *A.Coutinho, A.Crivellin, C.A.M.*

- **WE RECENTLY PROPOSED TO STUDY THIS ANOMALY AS A HINT OF LFUV**
- **MINIMAL SCENARIO: WE MODIFY ONLY THE COUPLINGS OF W TO LEPTONS**

$$\mathscr{L} = i\frac{g_2}{\sqrt{2}}\bar{\nu}_f \gamma^\mu P_L \ell_i W_\mu (\delta_{fi} + \varepsilon_{fi})$$



$$\mathscr{M}_\beta \propto V_{ud}(1+\varepsilon_{ee})\,G_F$$



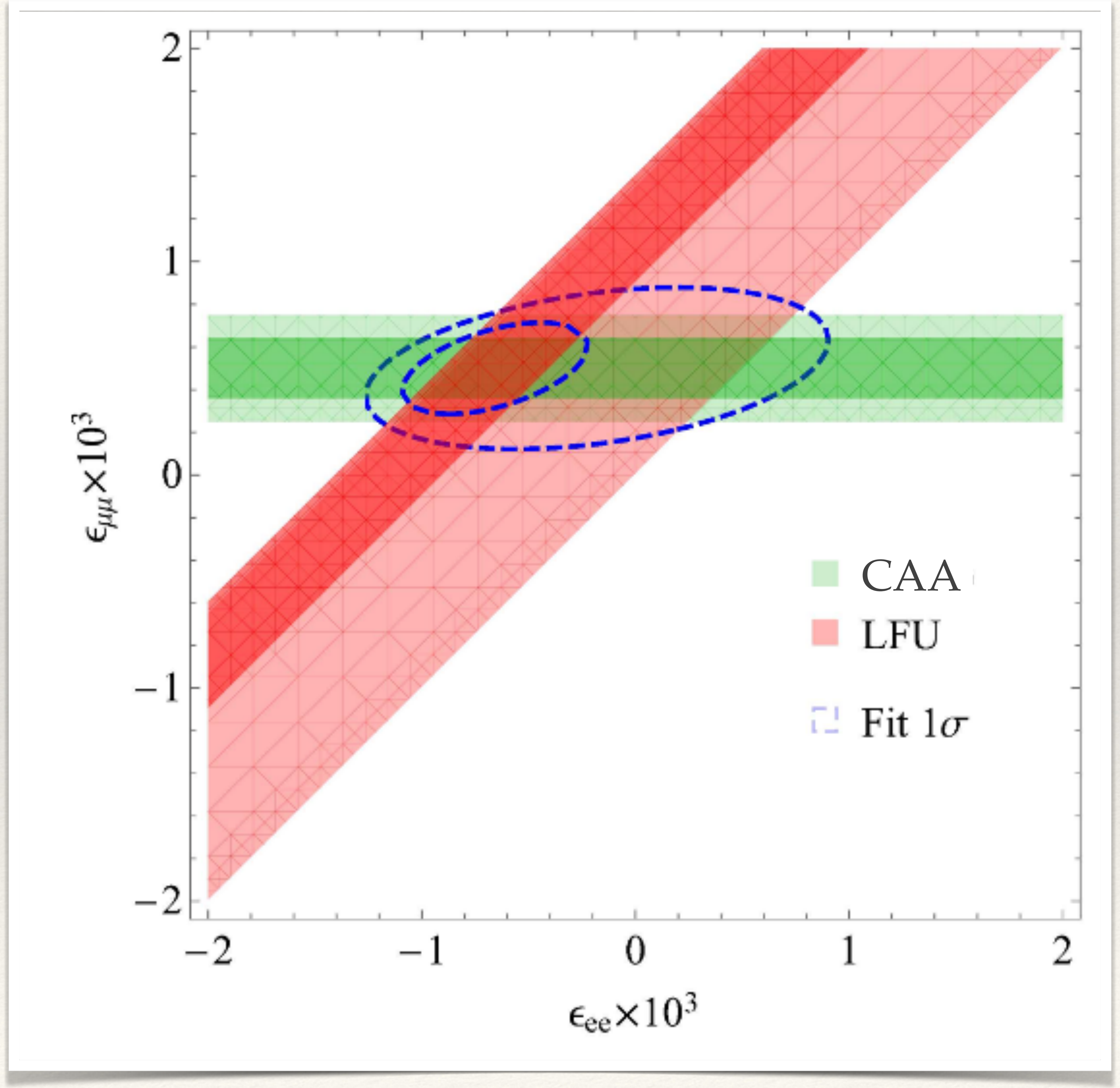
$$G_F^\mu = G_F\left(1+\varepsilon_{\mu\mu}+\varepsilon_{ee}\right)$$

induces very important indirect modifications in several observables

The Cabibbo Angle Anomaly

$$\left|V_{ud}^{\beta}\right| \simeq \left|V_{ud}^{\mathscr{L}}\right| \frac{\left(1+\varepsilon_{ee}\right)}{\left(1+\varepsilon_{ee}+\varepsilon_{\mu\mu}\right)} \simeq \left|V_{ud}^{\mathscr{L}}\right| \left(1-\varepsilon_{\mu\mu}\right)$$

- Modified electron couplings do not affect the CAA!
- <u>**LFUV needed**</u>
- Necessary to consider LFU tests: $\frac{\pi \to \mu\nu}{\pi \to e\nu}, \frac{W \to \tau\nu}{W \to \mu\nu}, \ldots$
- The global fit prefers also non zero electron couplings, with opposite sign than for muons



The Cabibbo Angle Anomaly

EFT APPROACH

1912.08823 *A.Coutinho, A.Crivellin, C.A.M.*

- IN GENERAL $SU(2)_L$ HAS TO BE TAKEN INTO ACCOUNT
- MINIMAL SCENARIO: ONLY OPERATORS WHICH MODIFY THE COUPLINGS OF W AND Z TO LEPTONS
- THERE ARE 3 OPERATORS AT THE DIM-6 LEVEL IN SMEFT

$$Q_{\phi\ell}^{(1)ij} = \phi^\dagger i \overleftrightarrow{D}_\mu \phi \bar{\ell}^i \gamma^\mu \ell^j \qquad Q_{\phi\ell}^{(3)ij} = \phi^\dagger i \overleftrightarrow{D}_\mu^I \phi \bar{\ell}^i \tau^I \gamma^\mu \ell^j \qquad Q_{\phi e}^{ij} = \phi^\dagger i \overleftrightarrow{D}_\mu \phi \bar{e}^i \gamma^\mu e^j$$

$$Z \to \ell\ell \propto C_{\phi\ell}^{(1)} + C_{\phi\ell}^{(3)} \qquad Z \to ee \propto C_{\phi e}$$

$$Z \to \nu\nu \propto C_{\phi\ell}^{(3)} - C_{\phi\ell}^{(1)} \qquad W \to \ell\nu \propto C_{\phi\ell}^{(3)}$$

EW precision observables

Also Z couplings to leptons are modified. Strong constraints from Electroweak measurements performed at the Z resonance with the e^+e^- colliders SLC & LEP

High precision test of the SM!

Observable	Measurement	Observable	Measurement
M_W [GeV]	80.379(12)	σ_h^0 [nb]	41.541(37)
Γ_W [GeV]	2.085(42)	R_e^0	20.804(50)
$\mathrm{BR}(W \to \mathrm{had})$	0.6741(27)	R_μ^0	20.785(33)
$\sin^2\theta^e_{\mathrm{eff(CDF)}}$	0.23248(52)	R_τ^0	20.764(45)
$\sin^2\theta^e_{\mathrm{eff(D0)}}$	0.23146(47)	$A_{\mathrm{FB}}^{0,e}$	0.0145(25)
$\sin^2\theta^\mu_{\mathrm{eff(CDF)}}$	0.2315(20)	$A_{\mathrm{FB}}^{0,\mu}$	0.0169(13)
$\sin^2\theta^\mu_{\mathrm{eff(CMS)}}$	0.2287(32)	$A_{\mathrm{FB}}^{0,\tau}$	0.0188(17)
$\sin^2\theta^\mu_{\mathrm{eff(LHCb)}}$	0.2314(11)	R_b^0	0.21629(66)
P_τ^{pol}	0.1465(33)	R_c^0	0.1721(30)
A_e	0.1516(21)	$A_{\mathrm{FB}}^{0,b}$	0.0992(16)
A_μ	0.142(15)	$A_{\mathrm{FB}}^{0,c}$	0.0707(35)
A_τ	0.136(15)	A_b	0.923(20)
Γ_Z [GeV]	2.4952(23)	A_c	0.670(27)

EW precision observables

EW sector completely parametrized by 3 parameters (+ fermion masses)

$$\mathscr{L}_{\text{EW}} = \sum_i \bar{\psi}_i(\not{D} - \frac{m_i}{v}H)\psi_i + (D_\mu H)(D^\mu H)$$

$$D_\mu = \partial_\mu - i g_1 B_\mu - i g_2 \tau^a W^a_\mu$$

For practical purposes better to trade them with the most precise parameters

$$G_F = 1.1663787(6) \times 10^{-5}\,\text{GeV}^{-2}$$

$$M_Z = 91.1875(21)\,\text{GeV}$$

$$\alpha = 7.2973525664 \times 10^{-3}$$

+

Parameter	Prior
$\Delta\alpha_{\text{had}} \times 10^4$ [16, 17]	276.1(1.1)
$\alpha_s(M_Z)$ [8, 33]	0.1179(10)
M_H [GeV] [8, 38–40]	125.10(14)
m_t [GeV] [8, 41–44]	172.76(30)

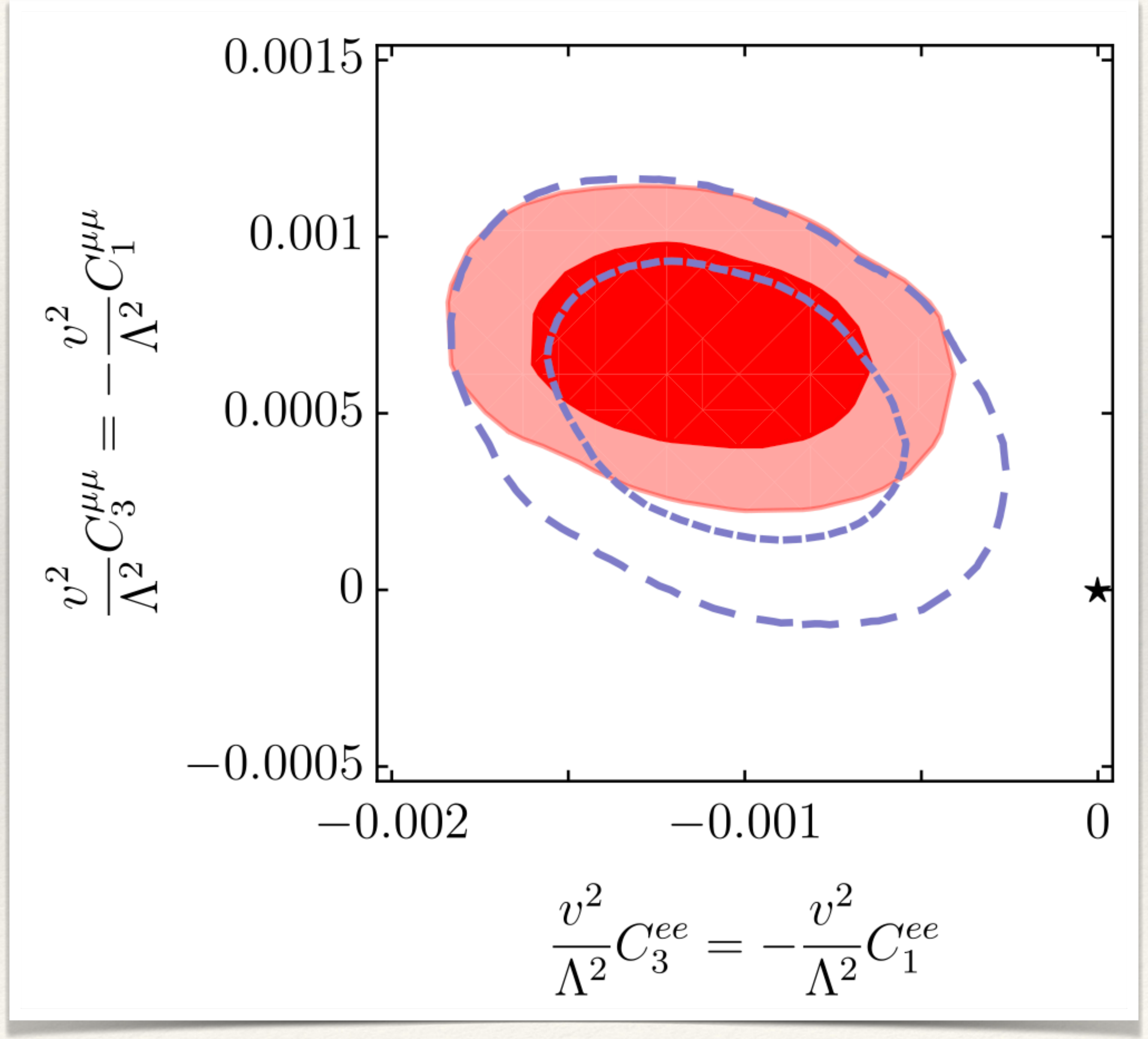
Needed for higher order corrections

The Cabibbo Angle Anomaly

$$\left|V_{ud}^{\beta}\right| \simeq \left|V_{ud}^{\mathscr{L}}\right| \frac{\left(1+\varepsilon_{ee}\right)}{\left(1+\varepsilon_{ee}+\varepsilon_{\mu\mu}\right)} \simeq \left|V_{ud}^{\mathscr{L}}\right| \left(1-\varepsilon_{\mu\mu}\right)$$

- Modified electron couplings do not affect the CAA!
- **LFUV needed**
- Necessary to fit several observables: EW, LFU, …
- The global fit prefers also non zero electron couplings, with opposite sign than for muons

2008.01113 *Crivellin, Kirk, Manzari, Montull*

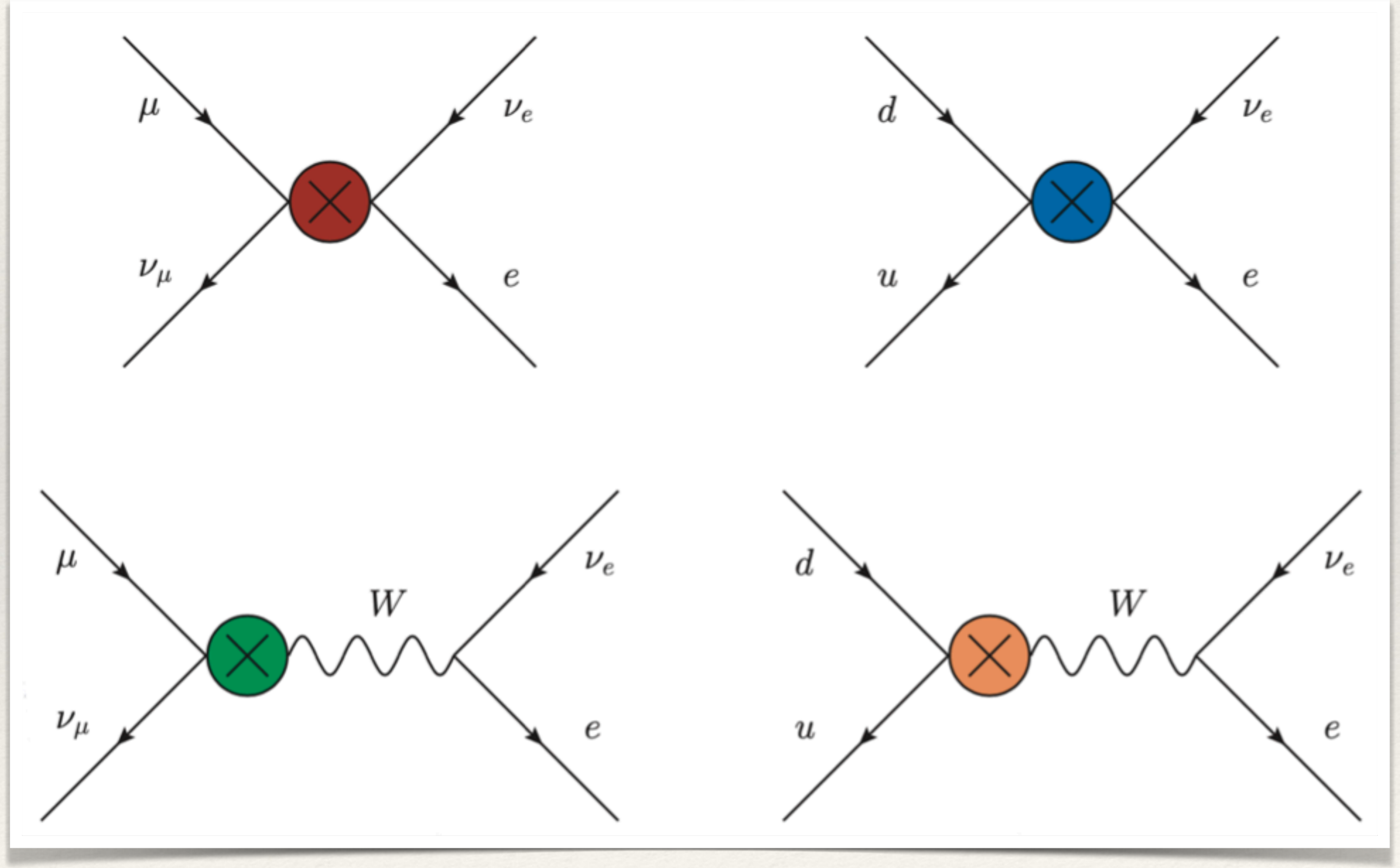


Solving the CAA

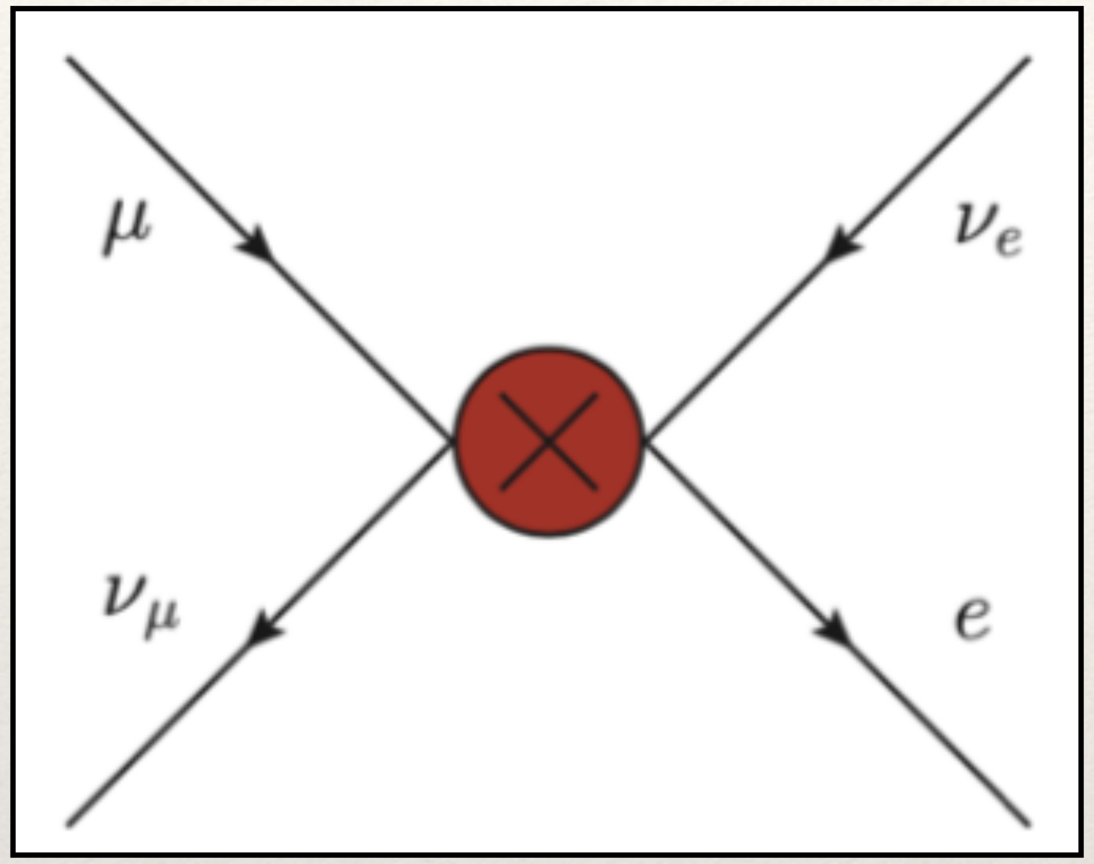
Solving the CAA: EFT Approach

BSM explanations can be grouped into 4 classes using an EFT approach with gauge-invariant dimension 6 operators (*2102.02825 Crivellin, Hoferichter, Manzari*)

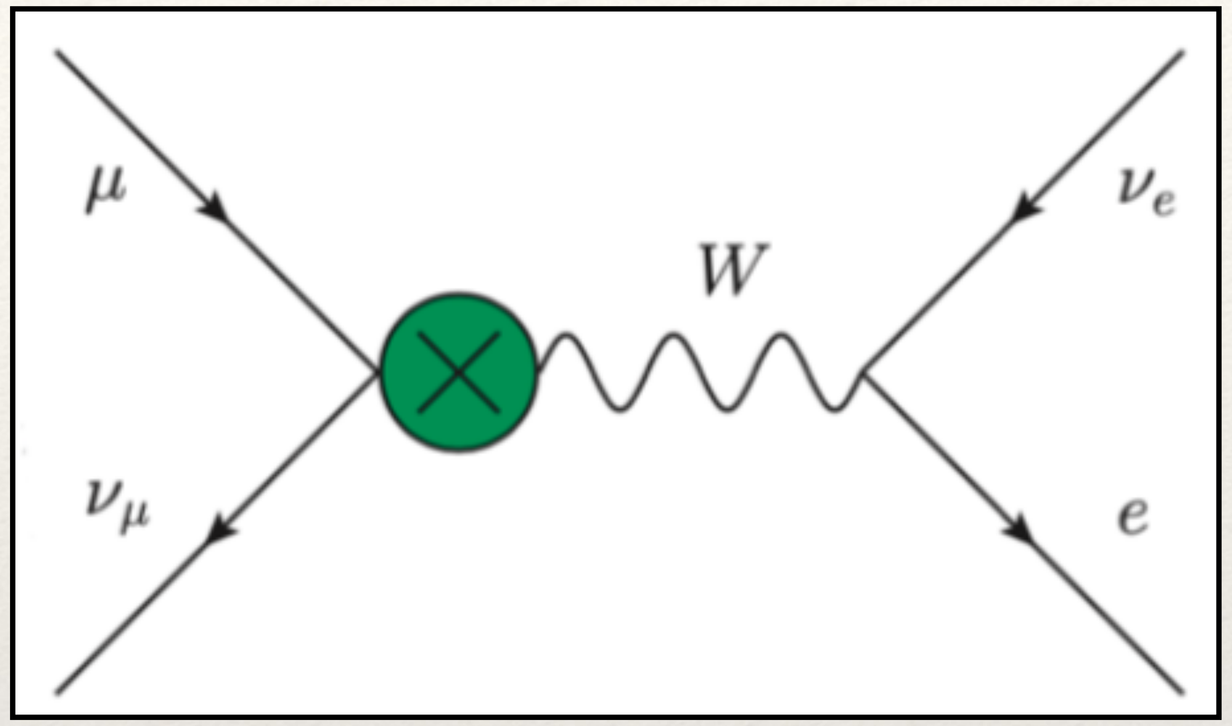
- Four-fermion operators in $\mu \to e\nu\nu$
- Four-fermion operators in $u \to de\nu$
- Modified $W - u - d$ couplings
- Modified $W - \ell - \nu$ couplings



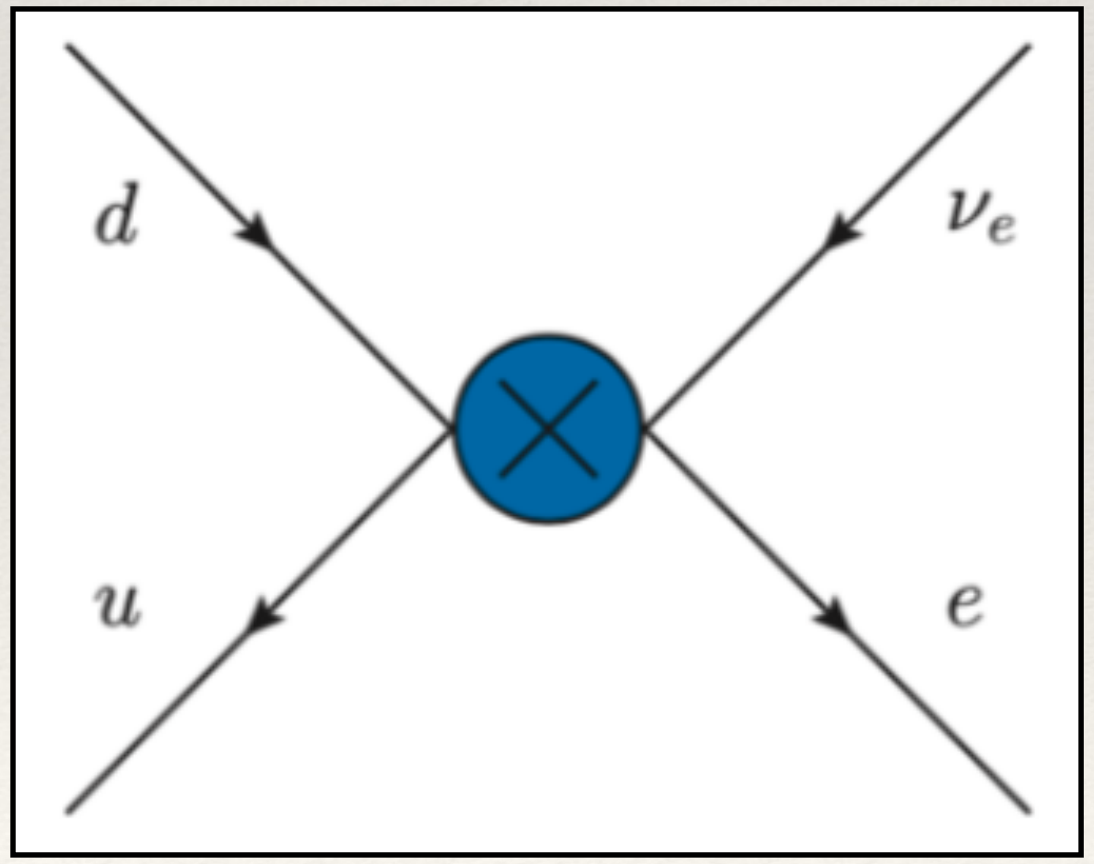
Solving the CAA: From EFT to Model Building



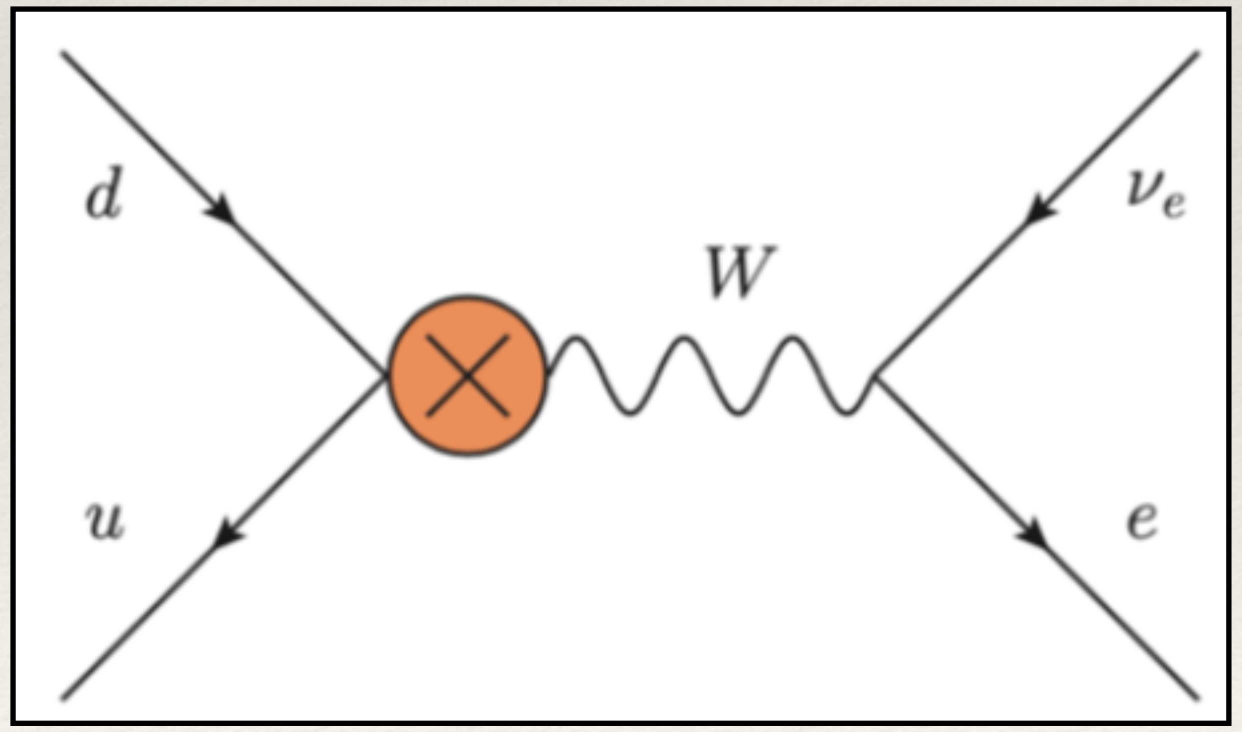
- Z'
- **Singly Charged Scalar**



- $W - W'$ **mixing**
- **Vector-like Leptons**



- W'
- **Leptoquarks**



- $W - W'$ **mixing**
- **Vector-like Quarks**

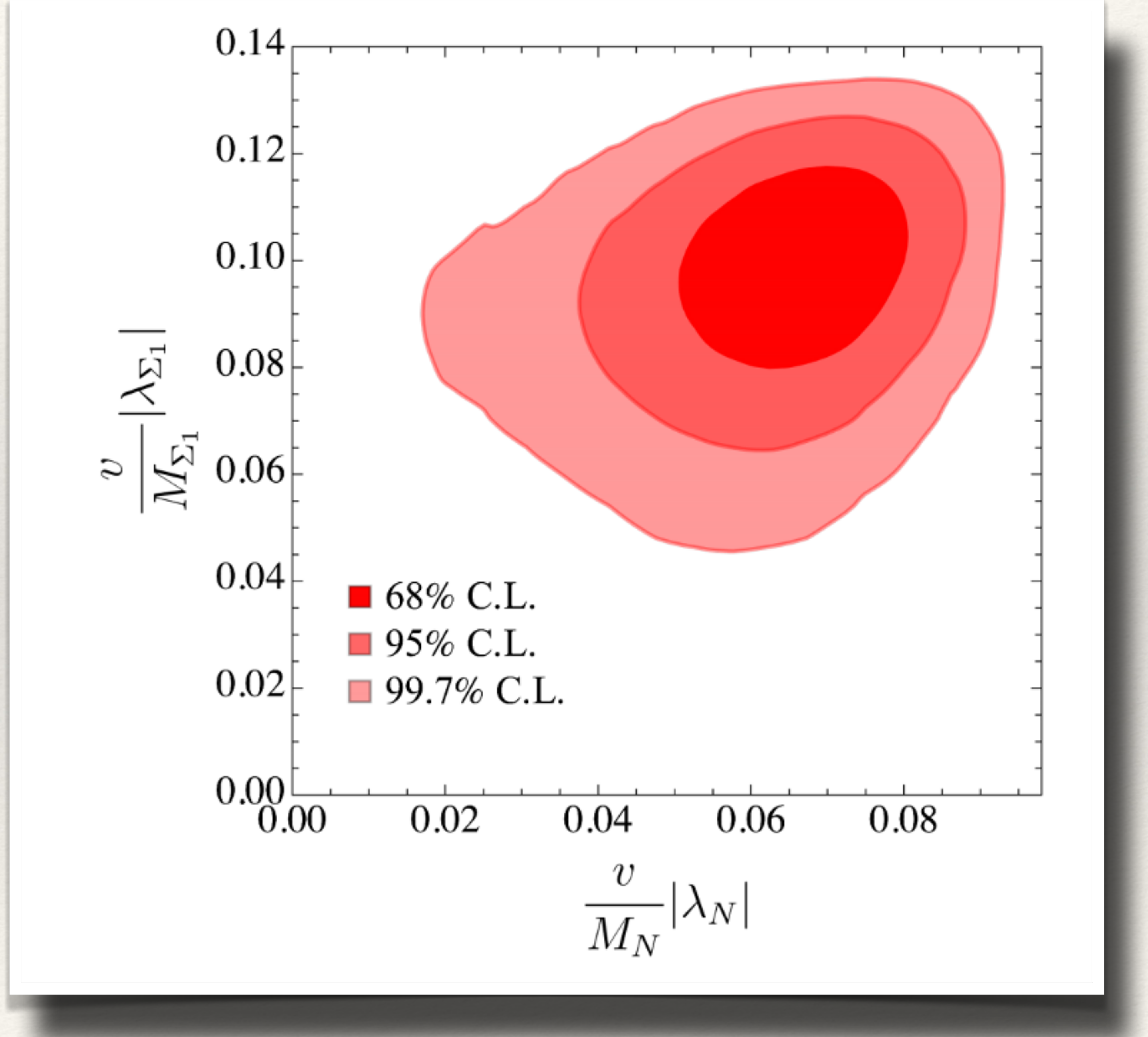
Solving the CAA: Vector-like Leptons

There are 6 possible representations under $U(1)_Y \times SU(2)_L$ generating different patterns of modified W and Z couplings.

- Each representation alone does not improve the fit w.r.t the SM
- **<u>Minimal model strongly improving the agreement with data</u>**: a singlet N coupling with electrons and a triplet Σ_1 coupling with muons!

	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$
ℓ	1	2	-1/2
e	1	1	-1
ϕ	1	2	1/2
N	1	1	0
E	1	1	-1
$\Delta_1 = (\Delta_1^0, \Delta_1^-)$	1	2	-1/2
$\Delta_3 = (\Delta_3^-, \Delta_3^{--})$	1	2	-3/2
$\Sigma_0 = (\Sigma_0^+, \Sigma_0^0, \Sigma_0^-)$	1	3	0
$\Sigma_1 = (\Sigma_1^0, \Sigma_1^-, \Sigma_1^{--})$	1	3	-1

<u>2008.01113</u> Crivellin, Kirk, Manzari, Montull

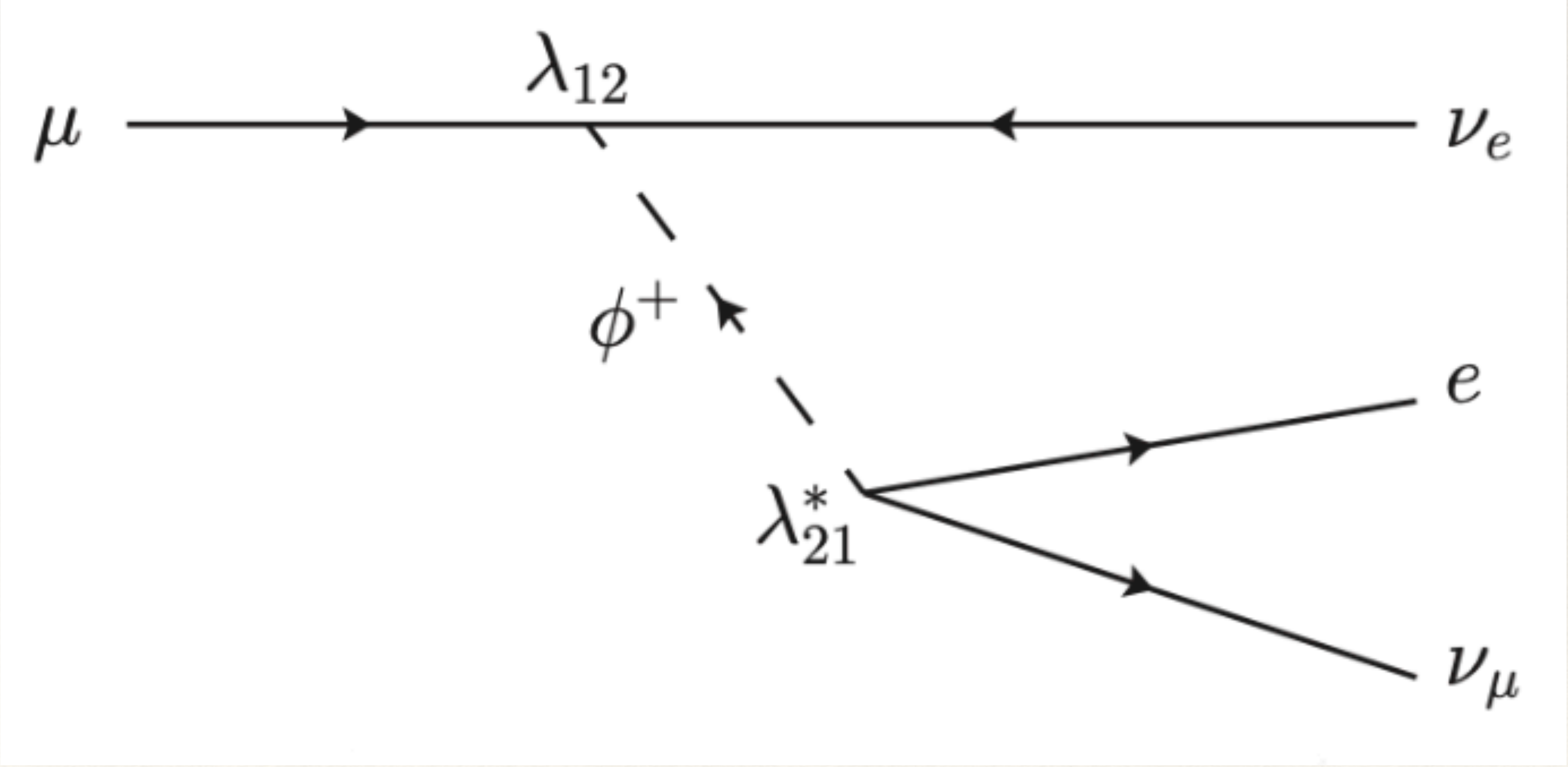


Solving the CAA: Singly Charged Scalar Singlet

2012.09845 *Crivellin, Kirk, Manzari, Panizzi*

- $SU(2)_L \times SU(2)_C$ scalar singlet with hyper charge $+1$
- Cannot couple to quarks because of quantum numbers
- Can only couple off diagonally to leptons $\Longrightarrow$ naturally introduce LFV

Very simple solutions for Model Building attempts to solve several anomalies



It affects the μ decay and the induced shift in G_F is in the direction needed by the CAA

EW fit + CAA

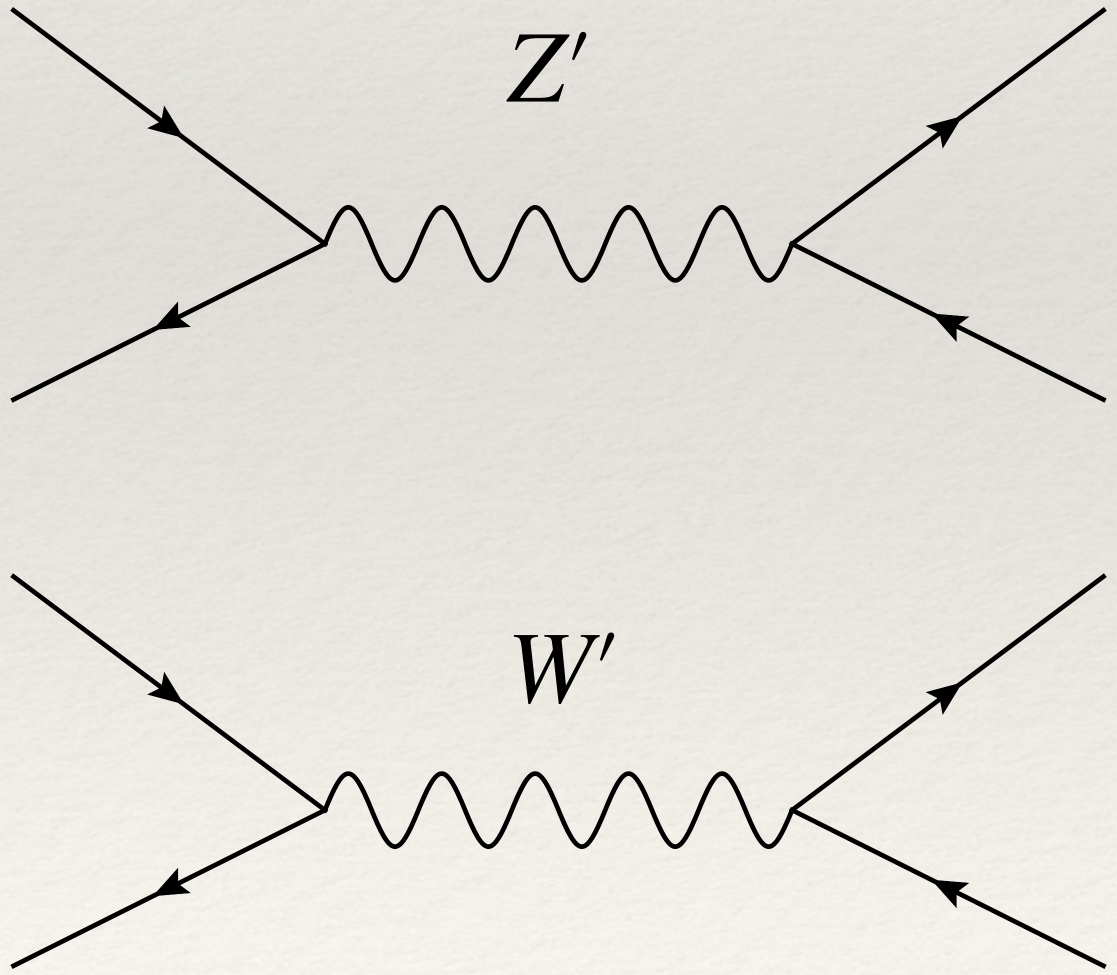
$$|\lambda_{12}|^2 = (0.043 \pm 0.010)\frac{m^2_{\phi^+}}{\text{TeV}^2}$$

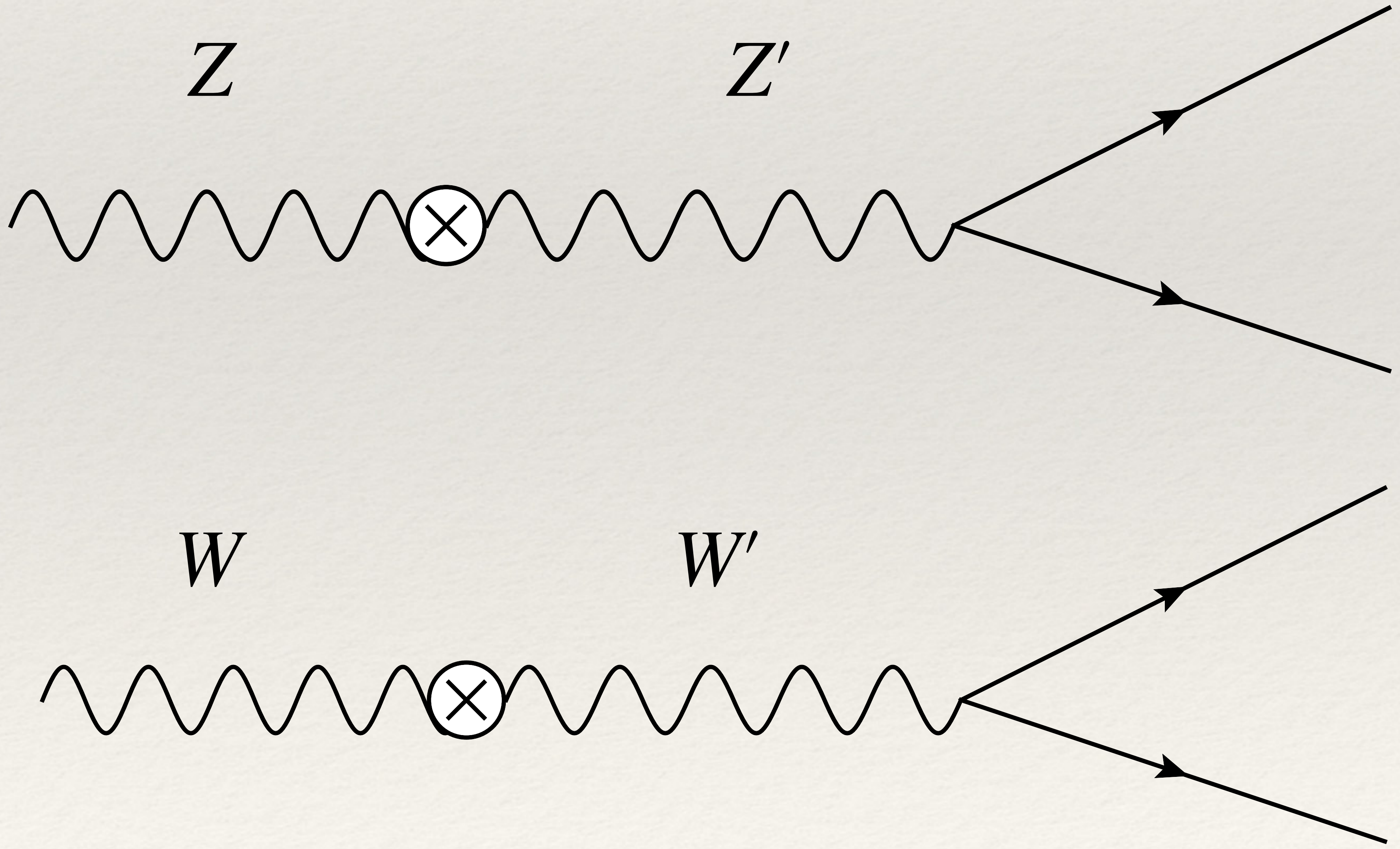
Simultaneous Explanations

A vector triplet for…CAA & $b \to s\ell\ell$

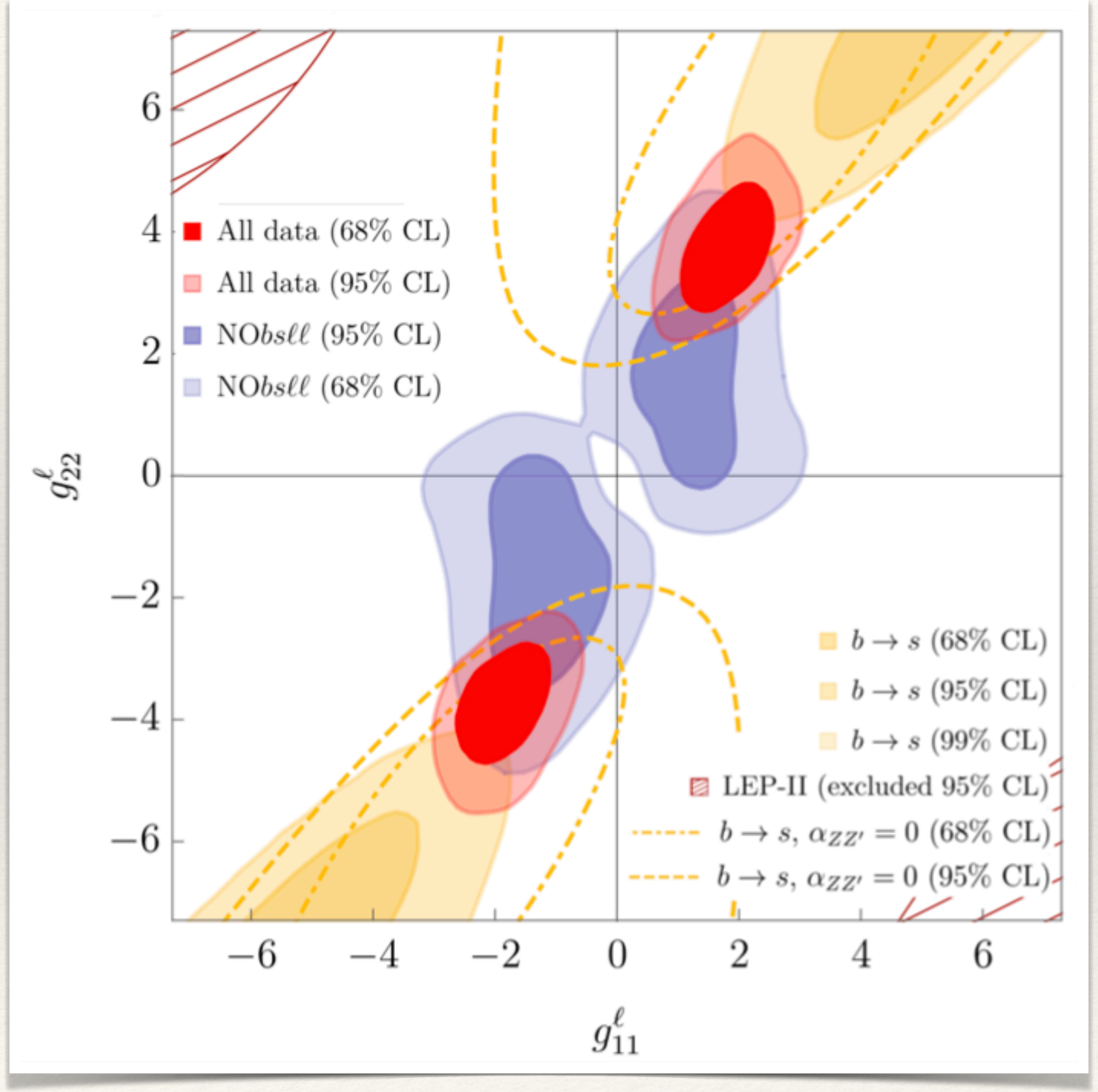
Let supplement the SM by a $SU(2)_L$ Triplet of Heavy Vector Bosons with 0 hypercharge: $W' + Z'$

- The W' generates 4-fermion operators and modified W couplings via $W - W'$ mixing
- **The Z' allows for interesting correlations with $b \to s\ell\ell$ data**





A vector triplet for…CAA & $b \to s\ell\ell$



2005.13542 *Capdevilla, Crivellin, Manzari, Montull*

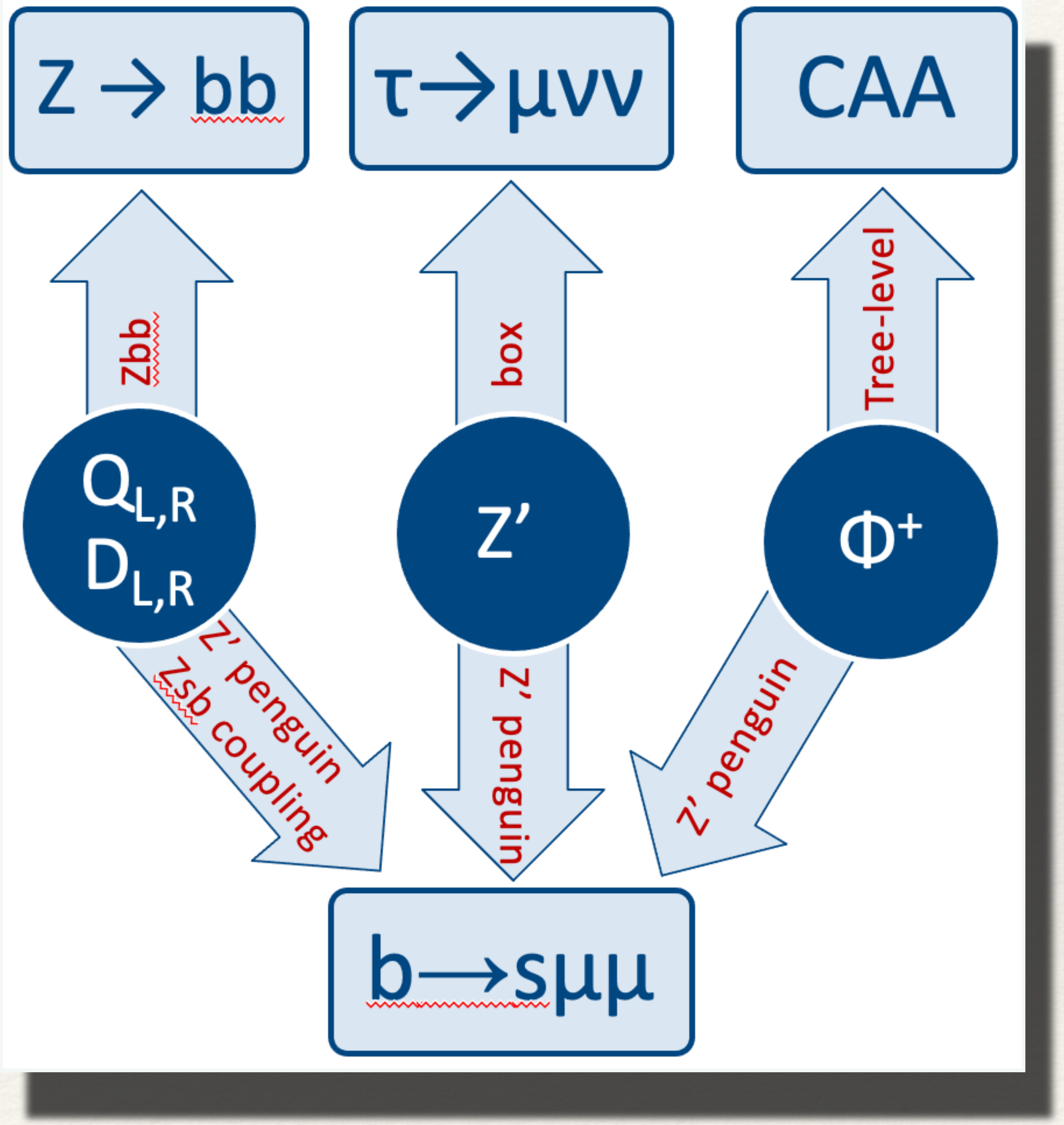
- Several observables need to be considered: CAA, EW data, LFU tests, LHC bounds, parity violation experiments, $b \to s\ell\ell$ data and $B_s - \bar{B}_s$ mixing

- The global fit improves the agreement with $b \to s\ell\ell$ data compared to the SM and solve the CAA

- Correlations between $R(K^*)$ and $\dfrac{\pi \to \mu\nu}{\pi \to e\nu}$ are predicted

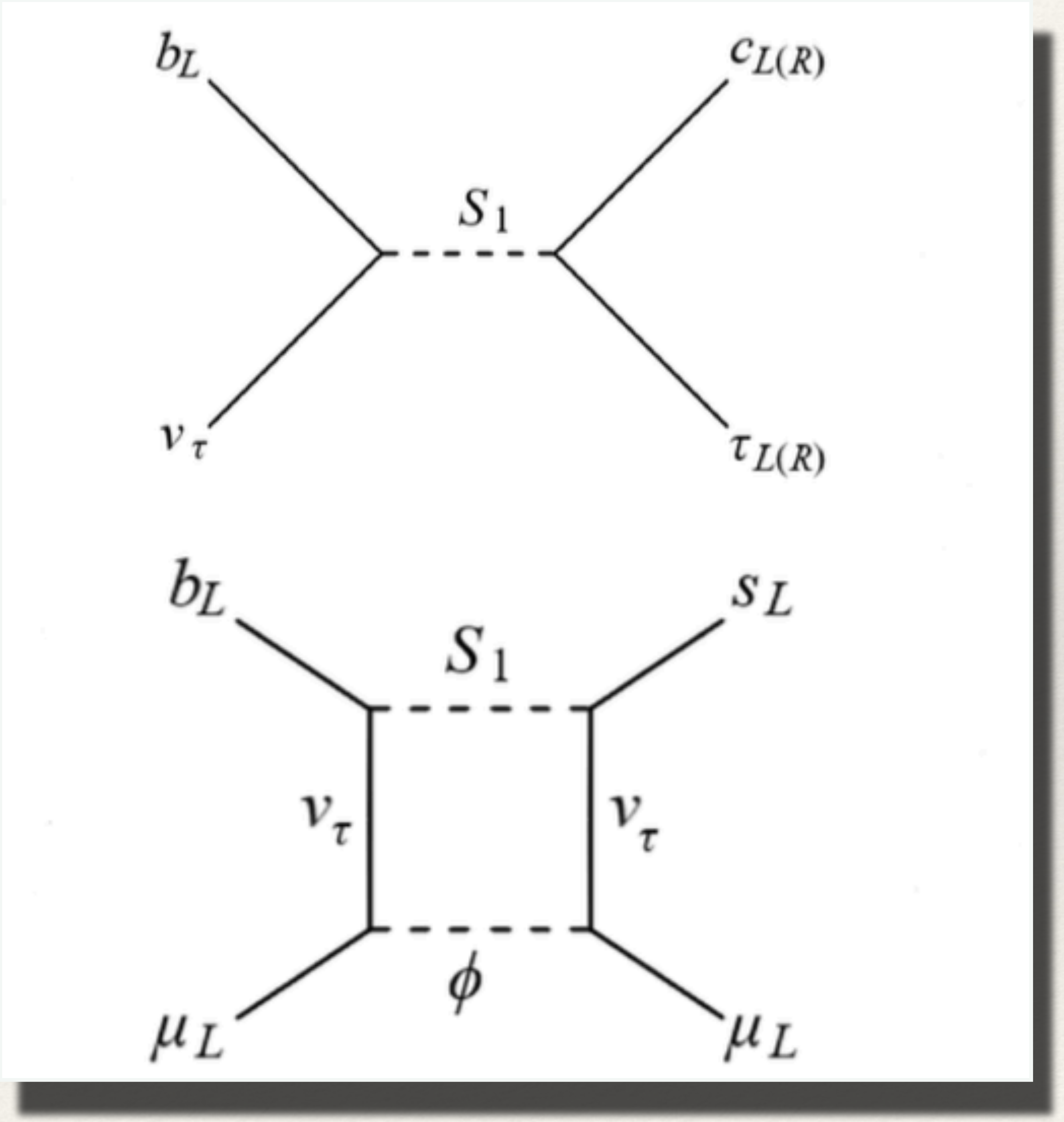
Solutions with ϕ^+

$\text{CAA} + b \to s\ell\ell + \; Z \to \bar{b}b + \; \tau \to \mu\nu\nu$



2010.14504 *Crivellin, Manzari, Algueró, Matias*

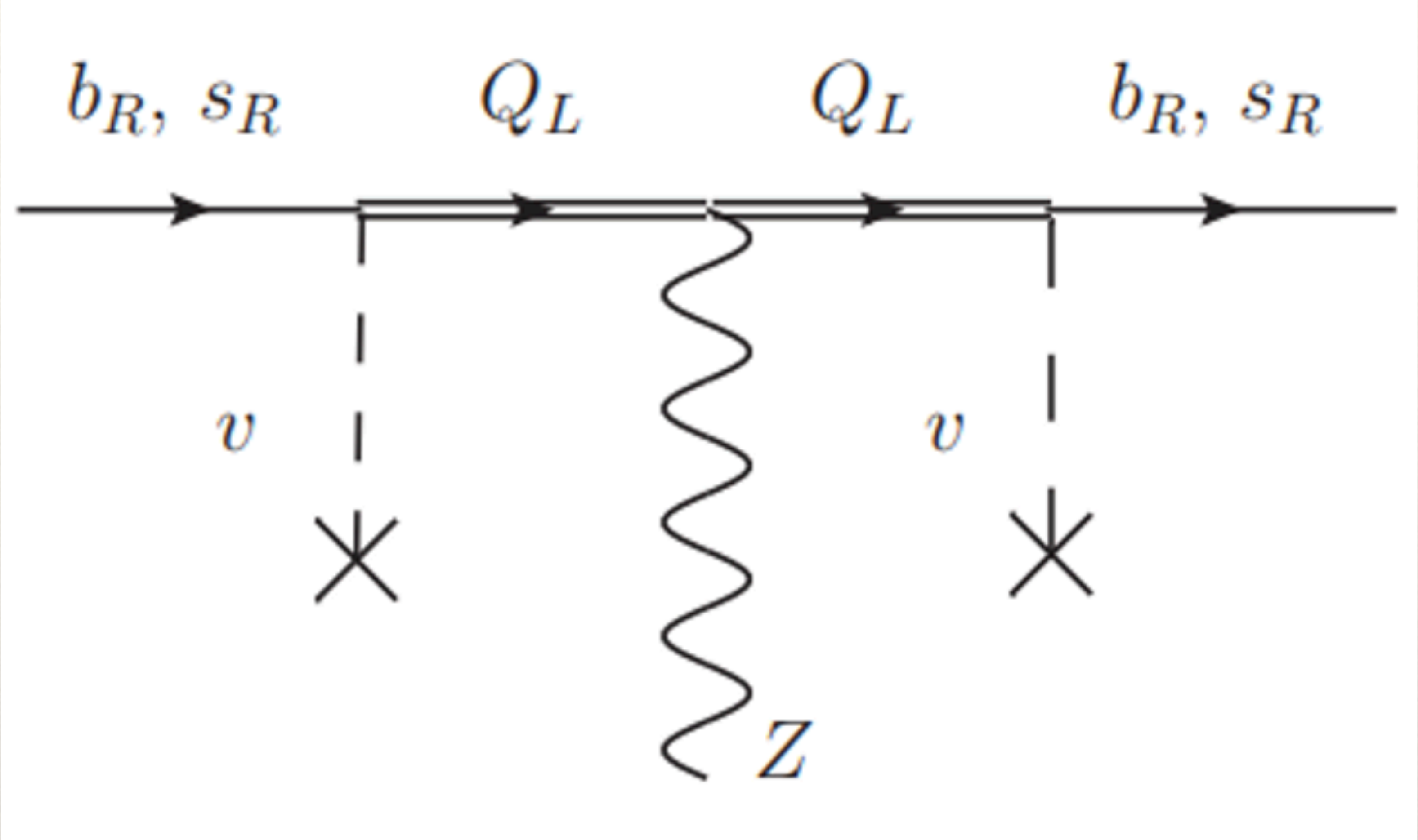
$\text{CAA} + b \to s\ell\ell + \; (g-2)_\mu$



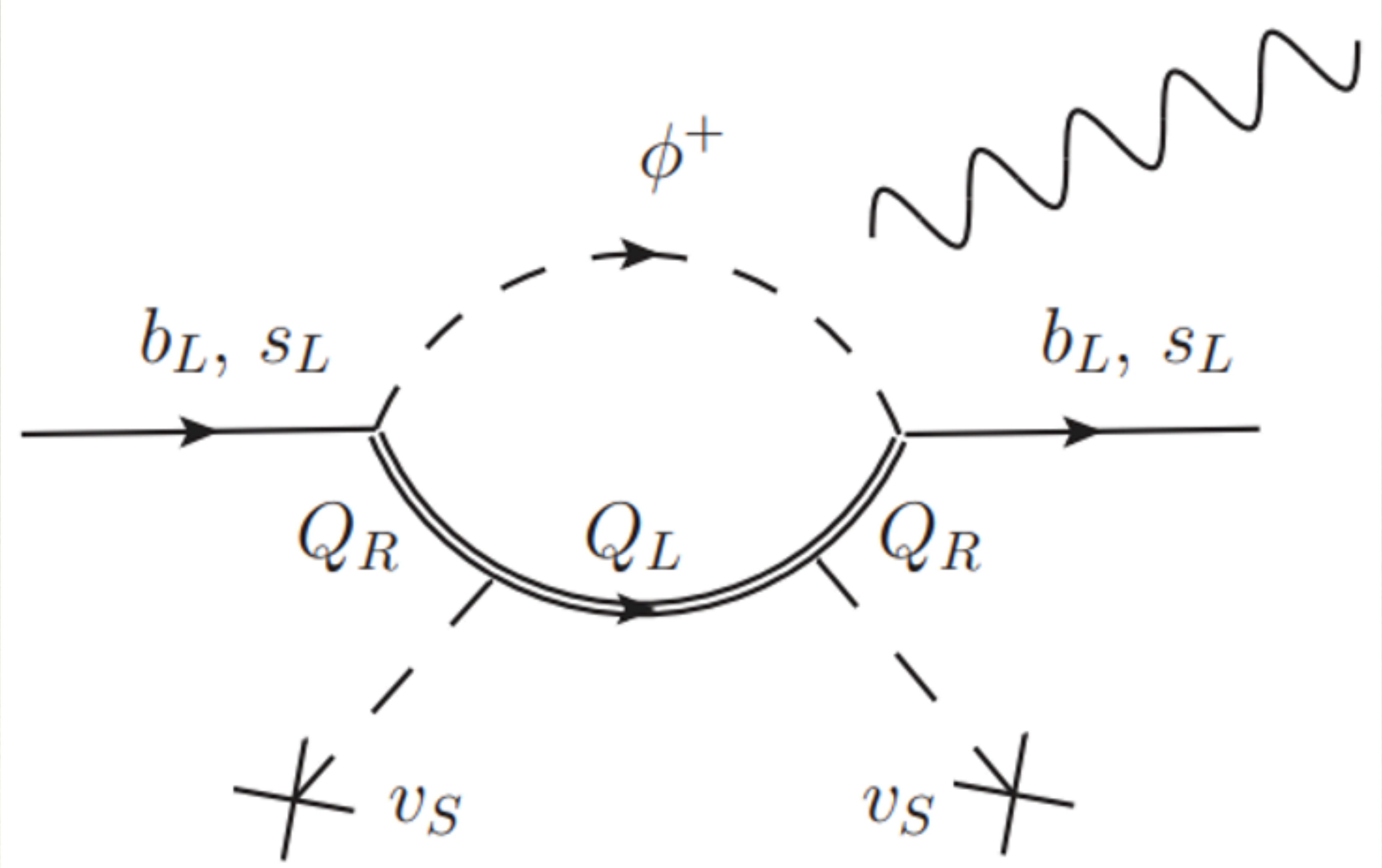
2104.05730 *Marzocca, Trifinopoulos*

Solutions with ϕ^+

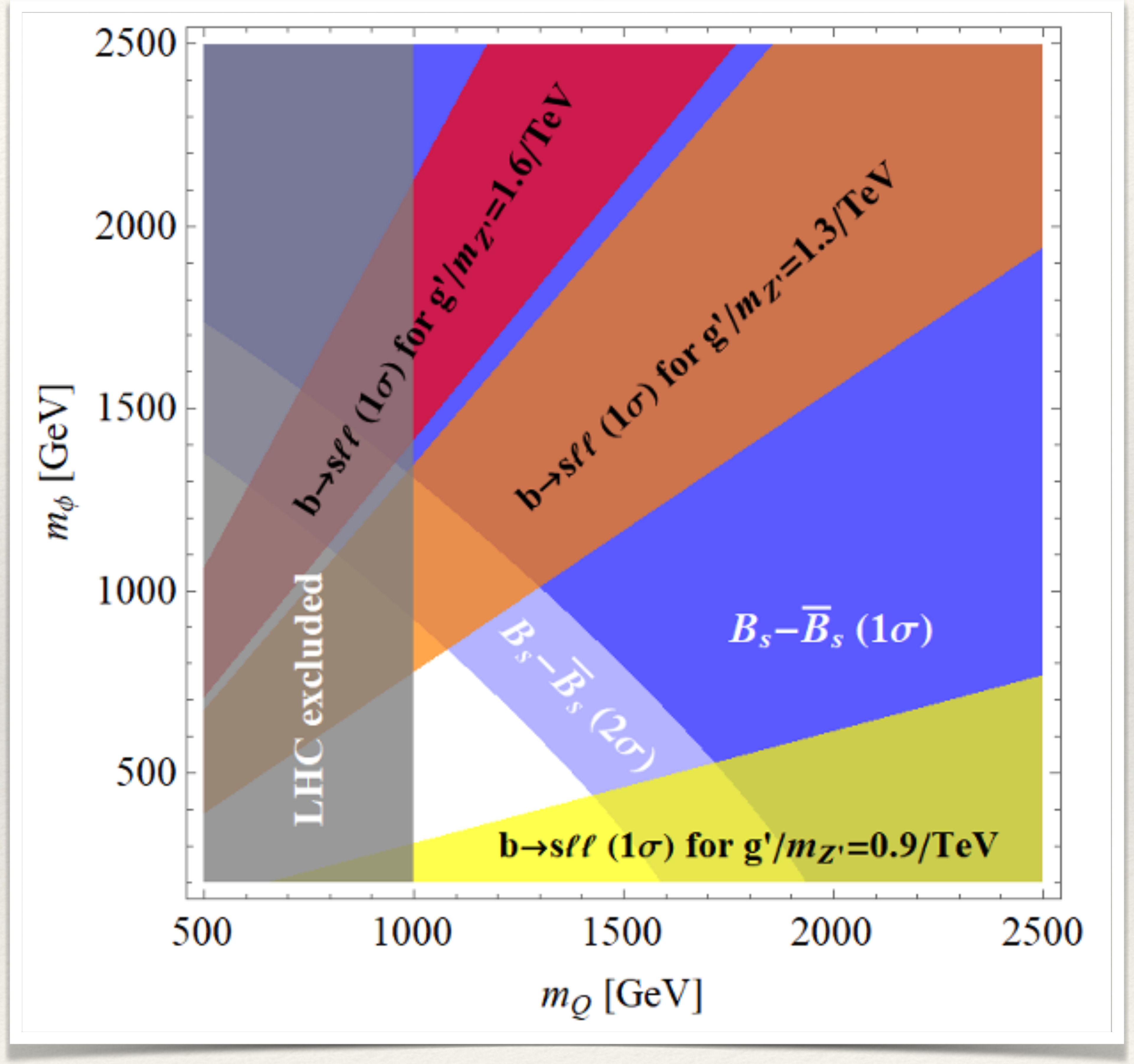
2010.14504 *Crivellin, Manzari, Algueró, Matias*



Tree-level effect in $Z \to \bar{b}b$



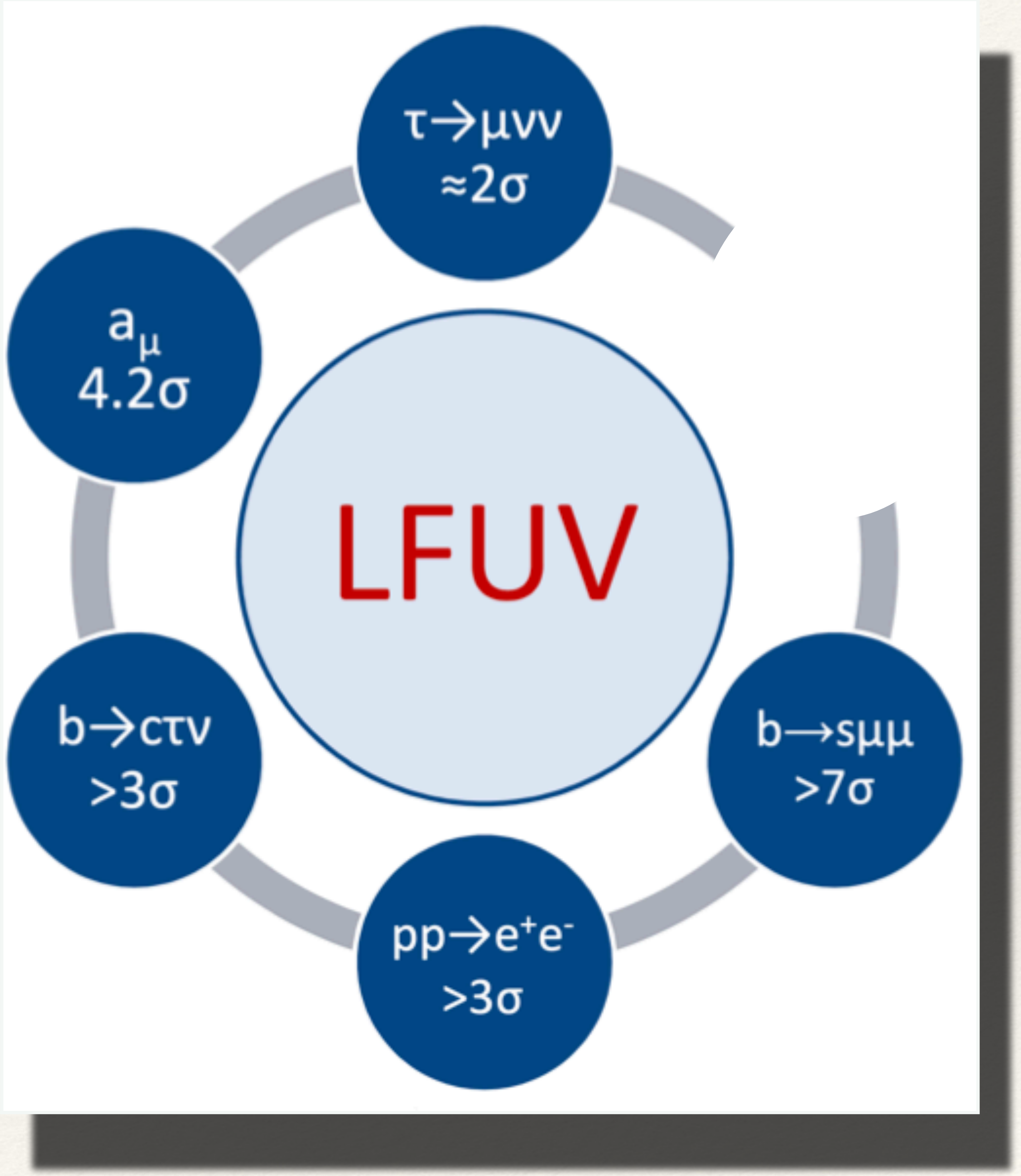
Loop induced $Z'\, b\, s$ couplings



Z' penguin + modified $Z\, b\, s$ couplings give a very good fit to $b \to s\ell\ell$ data

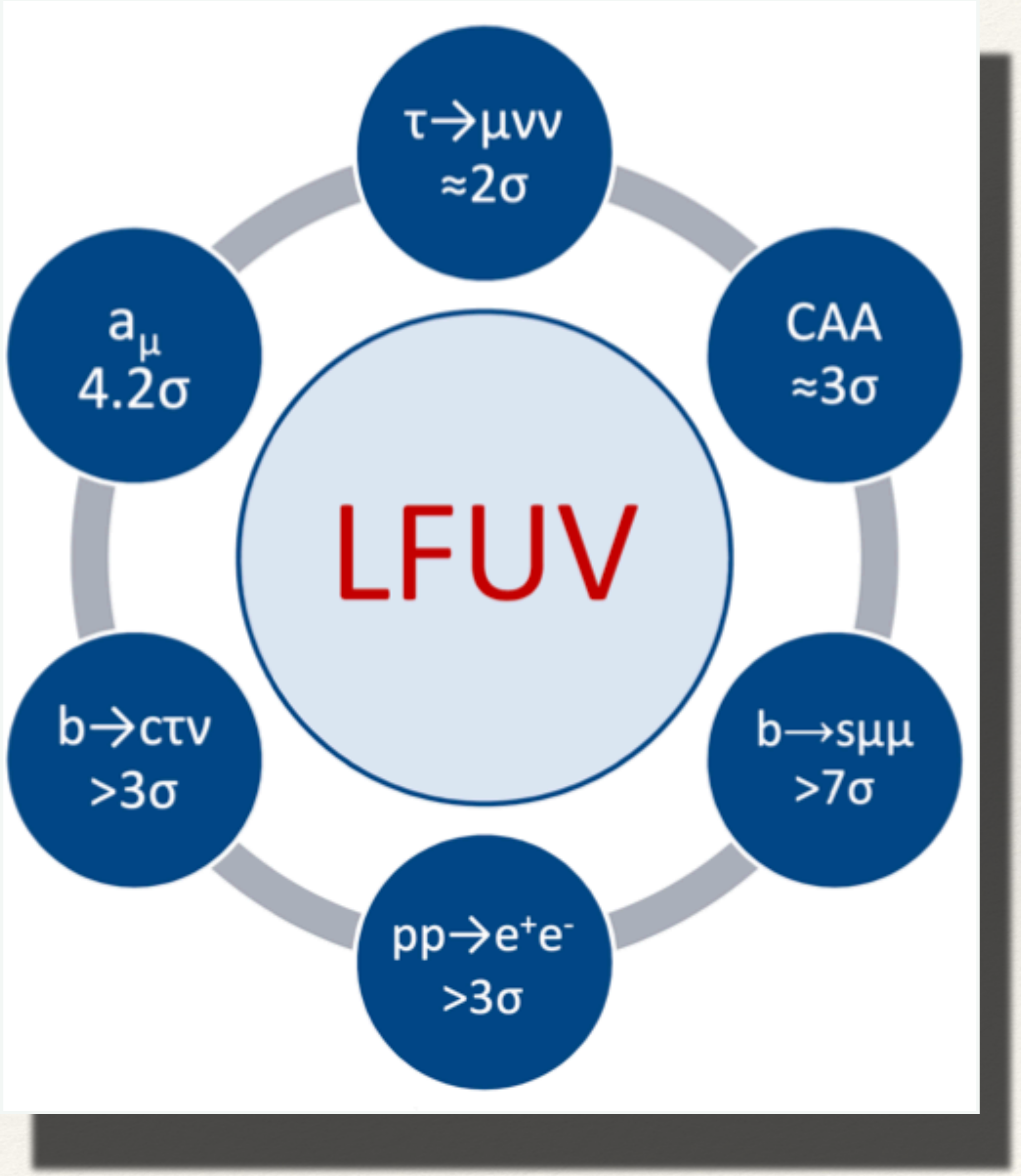
Conclusions

- So far, several evidences of LFUV have been collected at high and low energies
- Specific patterns of New Physics emerged and many directions are possible at the moment
- New observations and data will help to disentangle directions



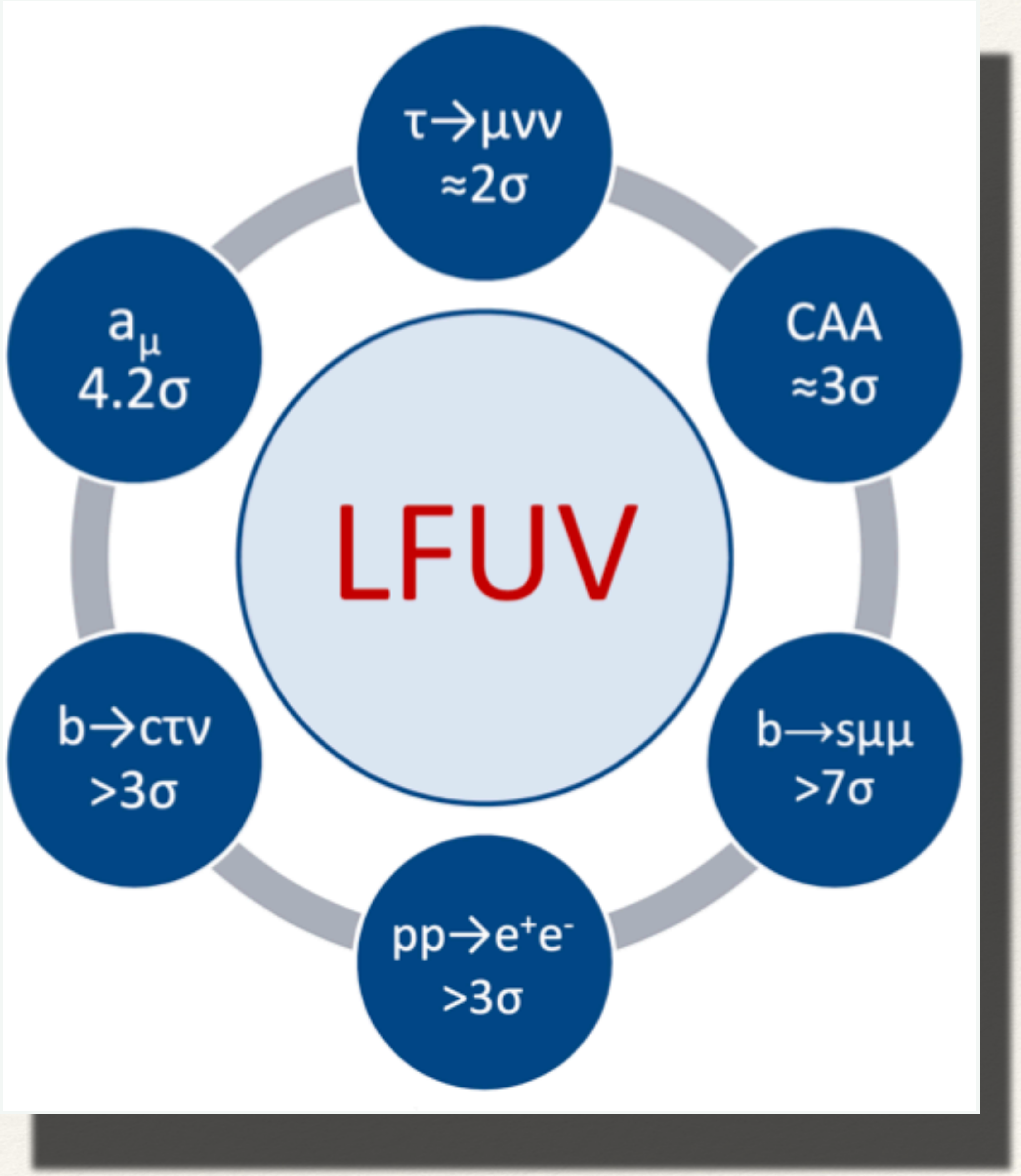
Conclusions

- So far, several evidences of LFUV have been collected at high and low energies
- Specific patterns of New Physics emerged and many directions are possible at the moment
- New observations and data will help to disentangle directions
- For this reason we proposed to interpret the Cabibbo Angle Anomaly as New Hint of LFUV



Conclusions

- The CAA is a deficit in the first row CKM unitarity
- Effects in β and/or μ decay can solve it
- In terms of modified W coupling with leptons, an effects in muons is needed (intriguing in connection with other anomalies)
- Simplified models introduce correlations with $b \to s\ell\ell$, $(g-2)_\mu$, etc., suggesting directions to follow for direct and indirect searches



Exciting Times are Ahead of Us…

…stay tuned!

Thank you for the Attention

Claudio Andrea Manzari

Backup

EW precision observables

Observable	Measurement	SM Posterior
M_W [GeV]	80.379(12)	80.363(4)
Γ_W [GeV]	2.085(42)	2.089(1)
BR($W \to$ had)	0.6741(27)	0.6749(1)
$\sin^2\theta_{\rm eff}^{\rm lept}(Q_{\rm FB}^{\rm had})$	0.2324(12)	0.2316(4)
$\sin^2\theta_{\rm eff(Tev)}^{\rm lept}$	0.23148(33)	0.2316(4)
$\sin^2\theta_{\rm eff(LHC)}^{\rm lept}$	0.23104(49)	0.2316(4)
$P_\tau^{\rm pol}$	0.1465(33)	0.1461(3)
A_ℓ	0.1513(21)	0.1461(3)
Γ_Z [GeV]	2.4952(23)	2.4947(6)
σ_h^0 [nb]	41.541(37)	41.485(6)
R_ℓ^0	20.767(35)	20.747(7)
$A_{\rm FB}^{0,\ell}$	0.0171(10)	0.0160(7)
R_b^0	0.21629(66)	0.21582(1)
R_c^0	0.1721(30)	0.17219(2)
$A_{\rm FB}^{0,b}$	0.0992(16)	0.1024(2)
$A_{\rm FB}^{0,c}$	0.0707(35)	0.0731(2)
A_b	0.923(20)	0.93456(2)
A_c	0.670(27)	0.6675(1)

- Good agreement between SM predictions and measurements
- Strong constraints on NP model modifying the SM :
  - Mixing
  - Modified couplings
  - Loop corrections
- A few tensions arise: M_W, A_ℓ, σ_h^0, $A_{\rm FB}^{0,b}$, but nothing critical

Anyway LFUV cannot be refused, IN PARTICULAR IN THE W COUPLINGS

Observable	Measurement	SM Posterior
Γ_W [GeV]	2.085(42)	2.089(1)
Γ_Z [GeV]	2.4952(23)	2.4947(6)

EW precision observables

Future Prospects

- Improvements in the determination of CKM unitarity:
  a. advances in nuclear-structure and EW radiative corrections treatment
  b. experimental developments in the determination from neutron decay, $K_{\ell 3}$ and complementary constraint on $|V_{ud}|/|V_{us}|$ via pion β decay
  c. improved measurements of $|V_{cd}|$ from D decays to bring the precision of the first column CKM unitarity competitive
- Improvement in a second G_F determination from the EW fit: Belle-II, FCC-ee, ILC, CEPC, or CLIC (m_t and m_W)

$pp \to ee$

4-fermion operators in $u \to de\nu$

We need constructive interference with the SM in β decays. The only possibility is

$$Q_{\ell q}^{(3)1111} = \left(\bar{\ell}_1 \gamma^\mu \tau^I \ell_1\right)\left(\bar{q}_1 \gamma^\mu \tau^I q_1\right)$$

The CAA at 1σ prefers

$$C_{\ell q}^{(3)1111} = \frac{1.22(4)}{(10\text{TeV})^2}$$

CMS $\equiv R_{\frac{e^+e^-}{\mu^+\mu^-}}$ di-lepton searches

$$R_\pi \equiv \frac{\pi \to \mu\nu}{\pi \to e\nu}$$