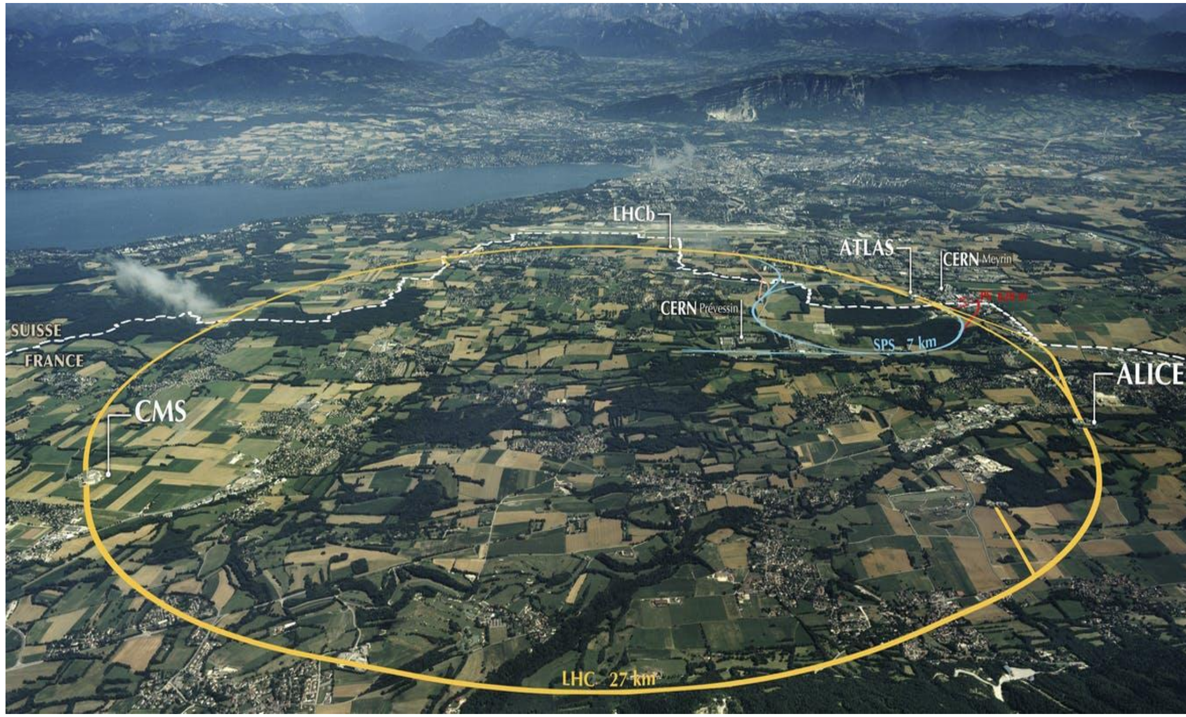


Andreas Crivellin

CERN Theory Division

Leave of absence from Paul Scherrer Institute & University of Zurich

Leptoquarks at Future e^+e^- Colliders

CEPC conference, 28.10.2020 (remote)

Work supported by FNSNF

Outline

- Introduction
- Leptoquarks and the Flavour Anomalies
  - $b \to s\mu\mu$
  - $b \to c\tau\nu$
  - a_μ
- Leptoquarks in EW Precision Observables
  - Oblique Corrections
  - $h \to \gamma\gamma$, $h \to gg$, $h \to \gamma Z$
  - $Z \to \mu\mu$, $Z \to \nu\nu$
  - a_μ, $h \to \mu\mu$
- Conclusions

Based on:

Scalar Leptoquarks in Leptonic Processes
arXiv:2010.06593 [hep-ph]

Correlating to the Anomalous Magnetic Moment of the Muon via Leptoquarks,
arXiv: 2008.02643

Leptoquarks in Oblique Corrections and Higgs Signal Strength: Status and Prospects
arXiv:1912.04224

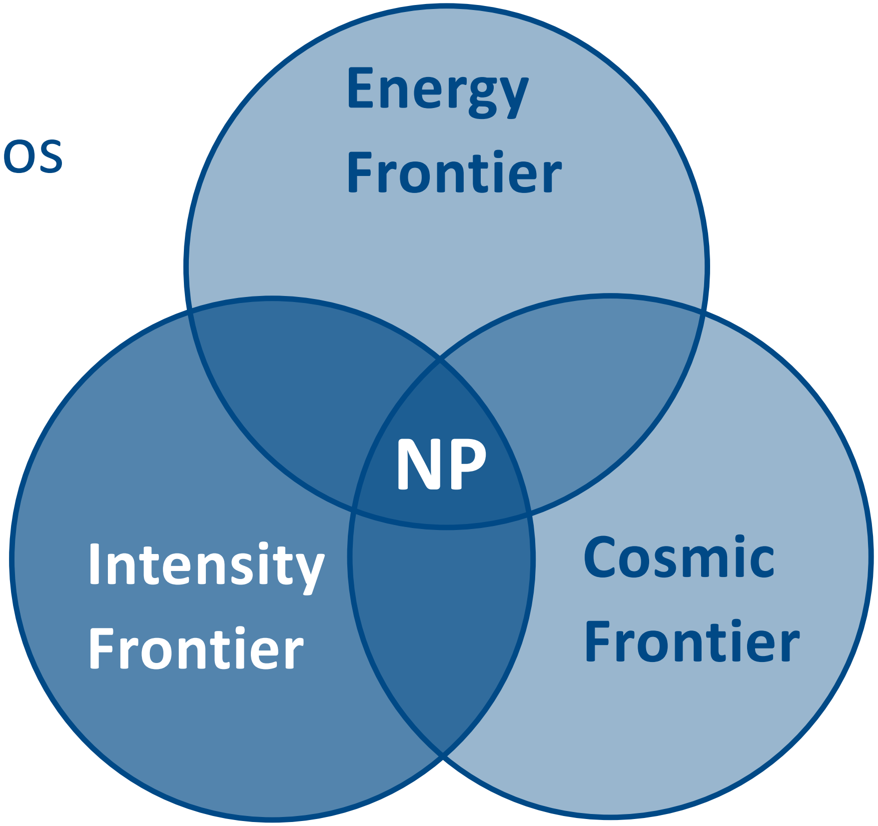
Flavor Phenomenology of the Leptoquark Singlet-Triplet Model
JHEP 06 (2020), 020

by AC, Dario Mueller, Francesco Saturnino

Introduction

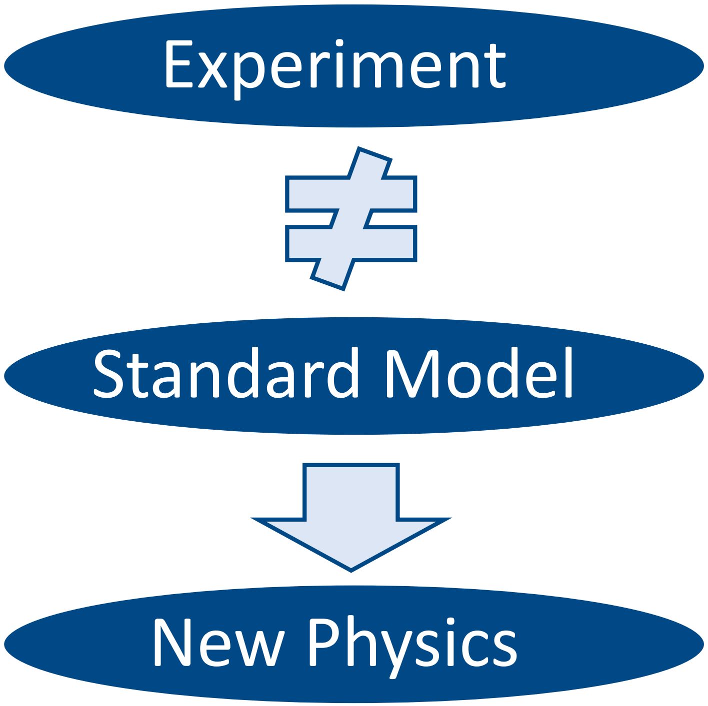
Discovering New Physics

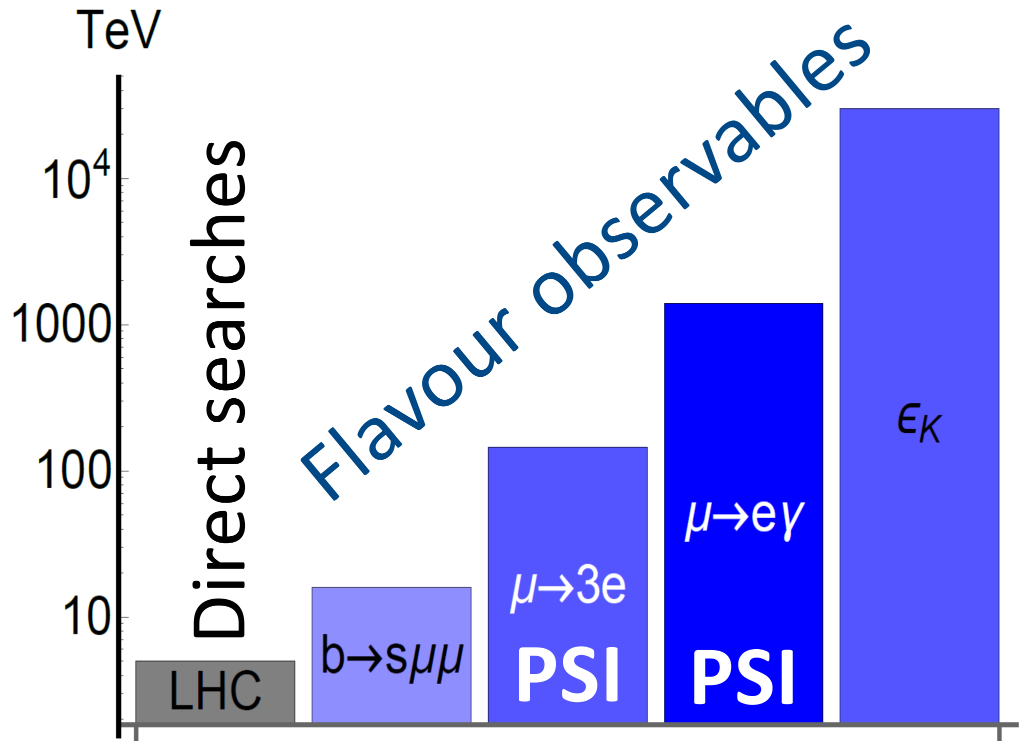
- Cosmic Frontier
  - Cosmic rays and neutrinos
  - Dark Matter
  - Dark Energy
- Energy Frontier
  - LHC
  - Future colliders
- Intensity Frontier
  - Flavour
  - Neutrino-less double-β decay
  - EW precision observables (ILC, CLIC, FCC-ee, CEPC)
  - Proton decay



Finding New Physics with Flavour

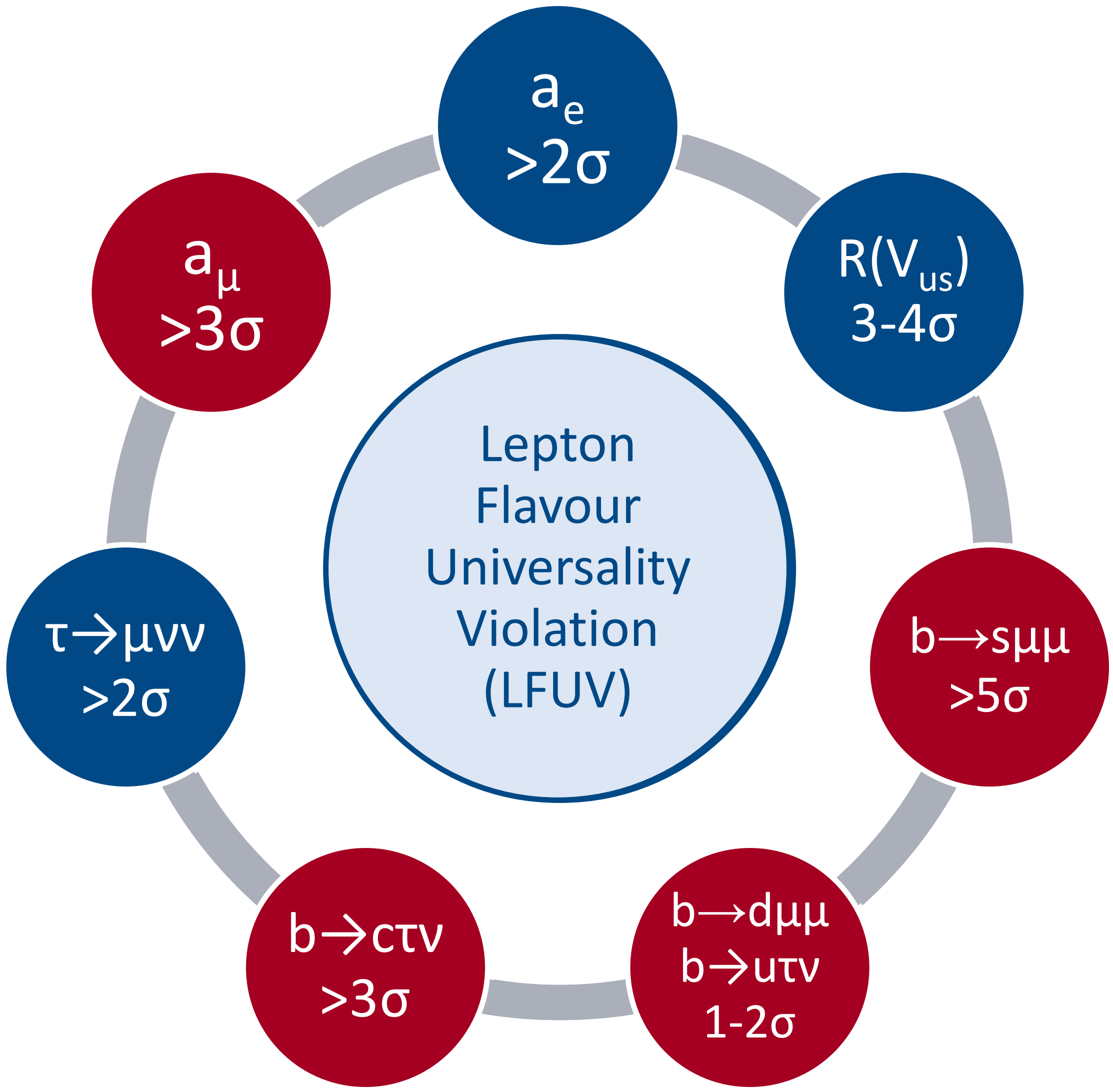
- At colliders one produces many (up to 10^{14}) heavy quarks or leptons and measures their decays into light flavours





Flavour observables can be sensitive to higher energy scales than collider searches

Hints for New Physics

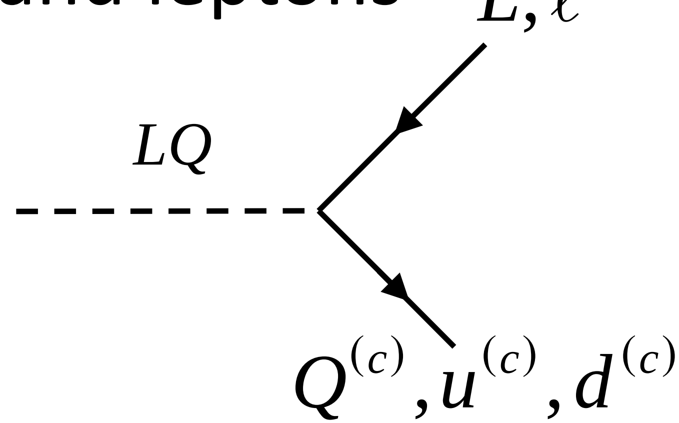


Scalar Leptoquark Representations

- 5 representations of Scalar Leptoquarks

	Φ_1	$\tilde{\Phi}_1$	Φ_2	$\tilde{\Phi}_2$	Φ_3
$\mathcal{G}_{\mathrm{SM}}$	$\left(3, 1, -\frac{2}{3}\right)$	$\left(3, 1, -\frac{8}{3}\right)$	$\left(3, 2, \frac{7}{3}\right)$	$\left(3, 2, \frac{1}{3}\right)$	$\left(3, 3, -\frac{2}{3}\right)$

- Couplings to quarks and leptons

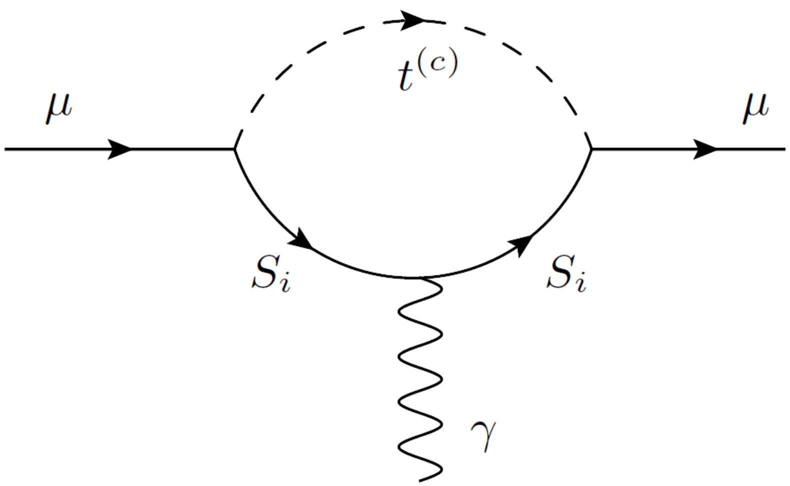


	L	e
$\bar{Q}$	$\kappa_L^1 \gamma_\mu V_1^{\mu\dagger} + \kappa^3 \gamma_\mu \left(\tau \cdot V_3^\mu\right)$	$\lambda_{LR}^2 \Phi_2$
$\bar{d}$	$\tilde{\lambda}^2 \tilde{\Phi}_2^T i\tau_2$	$\kappa_R^1 \gamma_\mu V_1^{\mu\dagger}$
$\bar{u}$	$\lambda_{RL}^2 \Phi_2^T i\tau_2$	$\tilde{\kappa}_i^1 \gamma_\mu \tilde{V}_2^{\mu\dagger}$
$\bar{Q}^c$	$\lambda^3 i\tau_2 (\tau \cdot \Phi_3)^\dagger + \lambda_{fi}^{1R} i\tau_2 \Phi_1^\dagger$	$\kappa_{LR}^2 \gamma_\mu \left(V_2^{\mu\dagger}\right)^T$
$\bar{d}^c$	$\kappa_{RL}^2 \gamma_\mu V_2^\dagger$	$\tilde{\lambda}^1 \tilde{\Phi}_1^\dagger$
$\bar{u}^c$	$\gamma_\mu \tilde{V}_2^{\mu\dagger}$	$\lambda_R^1 \Phi_1^\dagger$

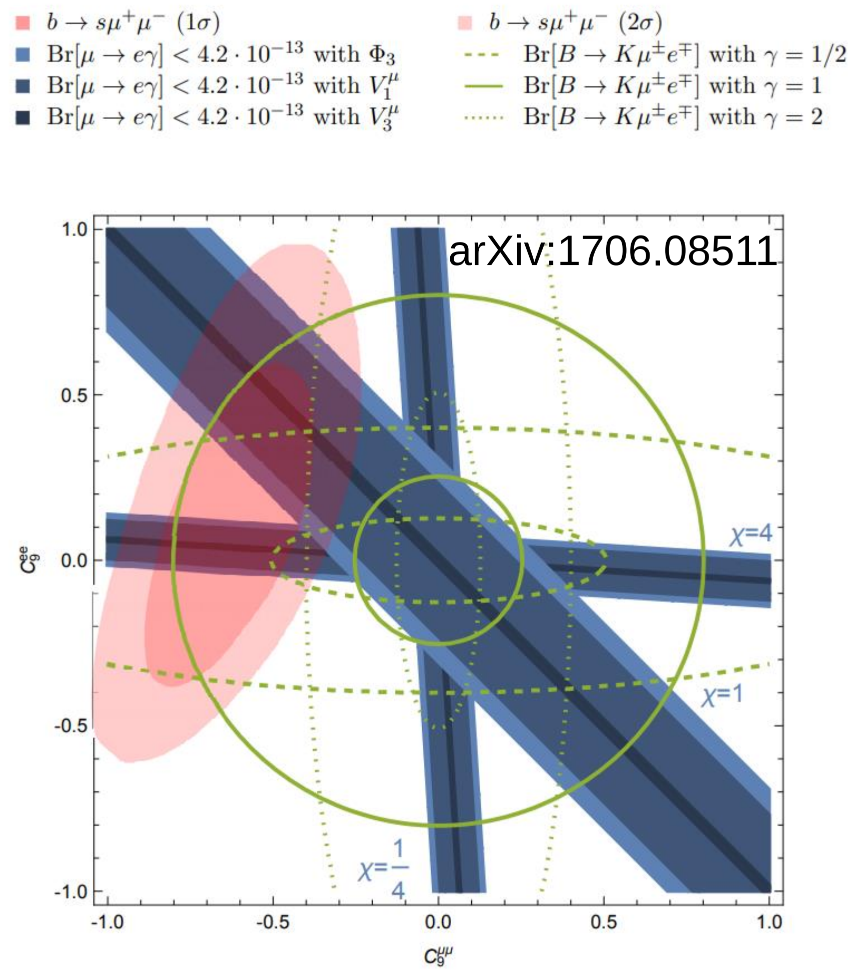
Possible couplings determined by the representation

LQ Explanations of the Anomalies

- a_μ with m_t enhanced effect



- b → s$\mu^+\mu^-$ & b →c$\tau\nu$ at tree-level



LQs can explain the three flavour anomalies

Combined Explanation with Φ_1 & Φ_3

- SU(2) singlet + SU(2) triplet Leptoquark

	κ_{22}	κ_{32}	κ_{23}	κ_{33}	λ_{22}	λ_{32}	λ_{23}	λ_{33}	$\hat{\lambda}_{32}$	$\hat{\lambda}_{23}$
p_1	-0.019	-0.059	0.58	-0.11	-0.0082	-0.016	-1.46	-0.064	-0.19	1.34
p_2	-0.017	-0.070	-1.23	0.066	0.0078	-0.055	1.36	0.052	-0.053	-1.47
p_3	0.0080	0.081	1.18	-0.073	-0.0017	0.16	-0.76	-0.068	0.023	1.23
p_4	-0.0032	-0.21	0.44	-0.20	0.014	-0.10	-1.38	-0.068	-0.032	0.57

	$C_9^{\mu\mu} = -C_{10}^{\mu\mu}$	$C_9^{\ell\ell}$	$\frac{R(D)}{R(D)_{\rm SM}}$	$\frac{R(D^*)}{R(D^*)_{\rm SM}}$	$\frac{B_s \to \tau\tau}{B_s \to \tau\tau\vert_{\rm SM}}$	$\tau \to \mu\gamma$ $\times 10^8$	δa_μ $\times 10^{11}$	$\tilde{V}_{cb}^e/\tilde{V}_{cb}^\mu - 1$ $\times 10^6$	$Z \to \tau\mu$ $\times 10^{10}$
p_1	-0.52	-0.21	1.15	1.10	59.88	4.35	207	291	0.117
p_2	-0.56	-0.28	1.14	1.10	99.76	0.766	199	448	2.38
p_3	-0.31	-0.31	1.14	1.09	112.5	3.62	255	17	0.129
p_4	-0.31	-0.31	1.13	1.11	112.5	0.734	230	934	45.6

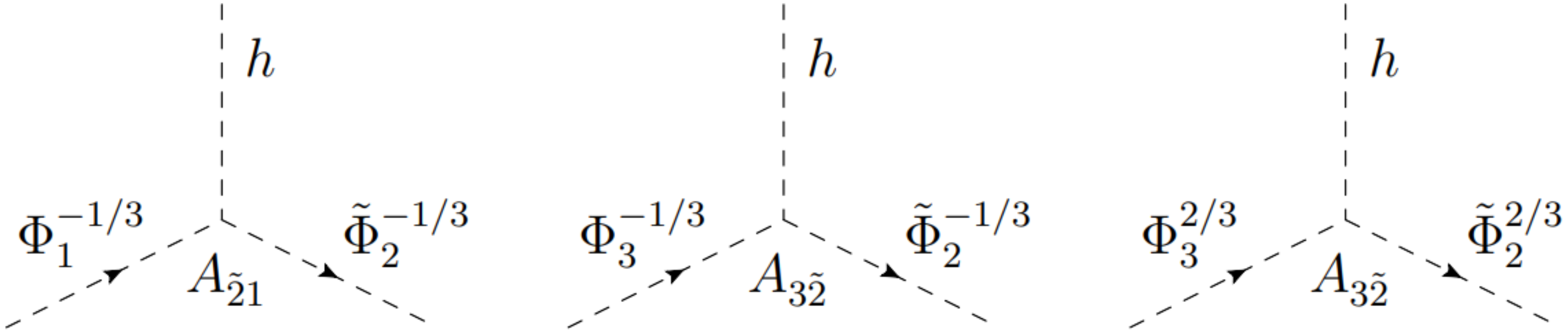
	$C_{SL}^{\tau\tau} = -4C_{TL}^{\tau\tau}$	$C_{VL}^{\tau\tau}$	$R_{\nu\bar{\nu}}^{K^{(*)}}$	$\frac{\Delta m_{B_s}^{\rm NP}}{\Delta m_{B_s}^{\rm SM}}$	$B \to K\tau\mu$ $\times 10^5$	$\tau \to \phi\mu$ $\times 10^8$	$\tau \to \mu ee$ $\times 10^{11}$	$\vert\Lambda_{33}^{\rm LQ}(0)\vert$ $\times 10^5$	$\frac{\Delta_{33}^L(m_Z^2)}{\Lambda_{\rm SM}^{L\ell} \times 10^{-5}}$
p_1	0.023	0.040	2.33	0.1	0.512	1.27	44.94	1.11	-3.64
p_2	0.020	0.040	0.87	0.16	3.32	4.73	7.783	0.90	-3.02
p_3	0.023	0.037	1.08	0.19	4.07	1.00	37.89	0.89	-3.51
p_4	0.010	0.047	2.43	0.18	3.69	0.0021	18.60	3.12	-10.04

Scalar LQs can explain the anomalies simultaneously

Leptoquark-Higgs Interactions

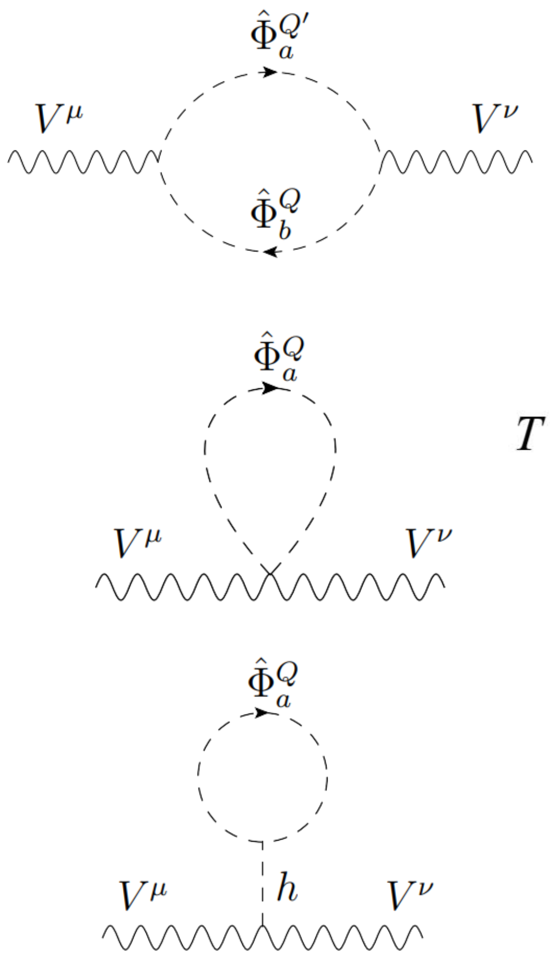
- LQs can (must) couple to the SM Higgs

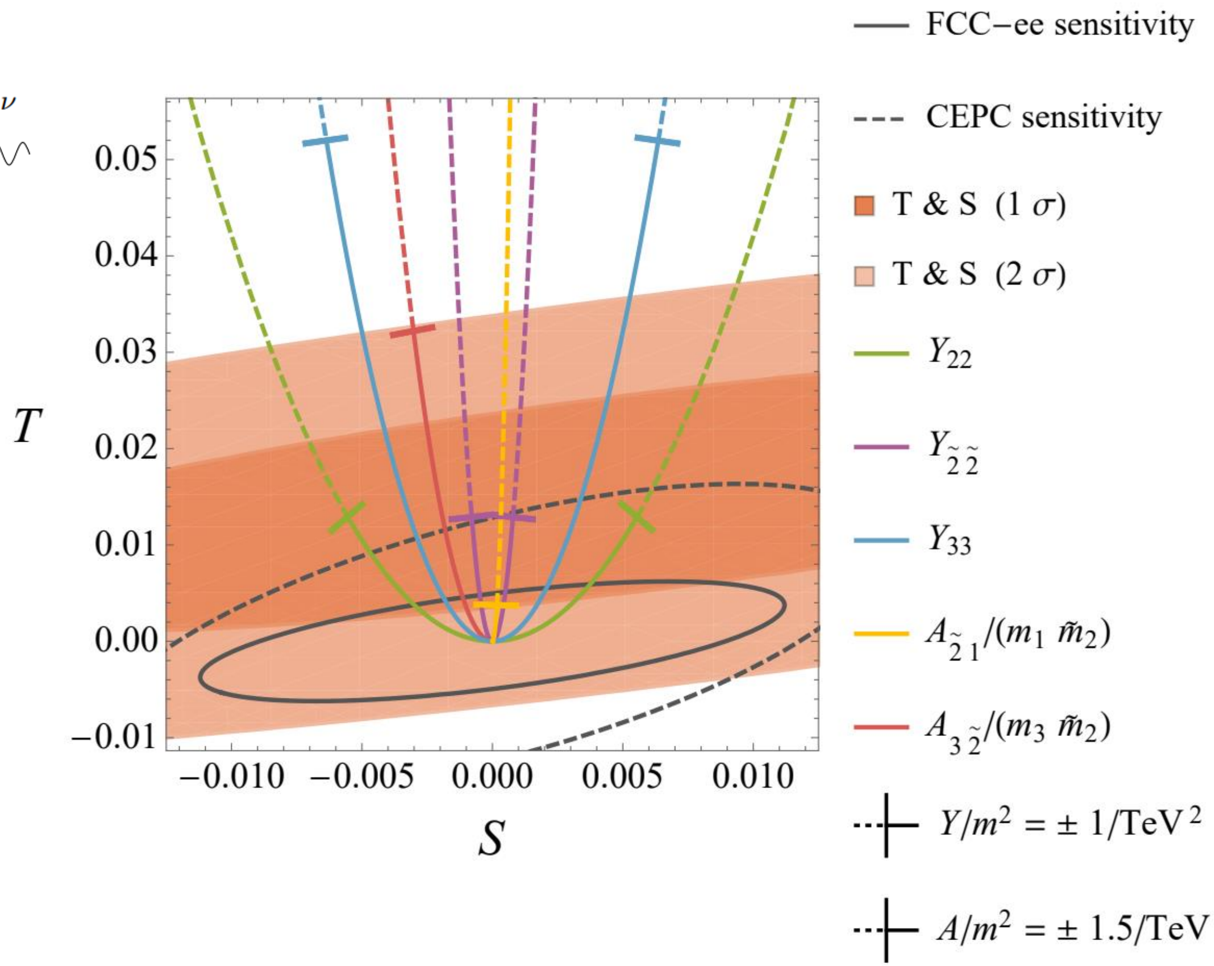
$$
\begin{aligned}
\mathcal{L}_{H\Phi} = & -A_{\tilde{2}1}\big(\tilde{\Phi}_2^\dagger H\big)\Phi_1 + A_{3\tilde{2}}\big(\tilde{\Phi}_2^\dagger\big(\tau\cdot\Phi_3\big)H\big) + Y_{\tilde{2}2}\big(\Phi_2^\dagger H\big)\big(Hi\tau_2\tilde{\Phi}_2\big) \\
& + Y_{3\tilde{1}}\big(Hi\tau_2\left(\tau\cdot\Phi_3\right)^\dagger H\big)\tilde{\Phi}_1 + Y_{31}\big(H^\dagger\left(\tau\cdot\Phi_3\right)H\big)\Phi_1^\dagger + \text{h.c.} \\
& - Y_{22}\big(Hi\tau_2\Phi_2\big)\big(Hi\tau_2\Phi_2\big)^\dagger - Y_{\tilde{2}\tilde{2}}\big(Hi\tau_2\tilde{\Phi}_2\big)\big(Hi\tau_2\tilde{\Phi}_2\big)^\dagger \\
& - iY_{33}\varepsilon_{IJK}H^\dagger\tau_I H\Phi_{3,K}^\dagger\Phi_{3,J} \\
& - \sum_{k=1}^{3}\big(m_k^2 + Y_k H^\dagger H\big)\Phi_k^\dagger\Phi_k - \sum_{k=1}^{2}\big(\tilde{m}_k^2 + Y_{\tilde{k}}H^\dagger H\big)\tilde{\Phi}_k^\dagger\tilde{\Phi}_k\,.
\end{aligned}
$$



Additional sources of EW Symmetry Breaking

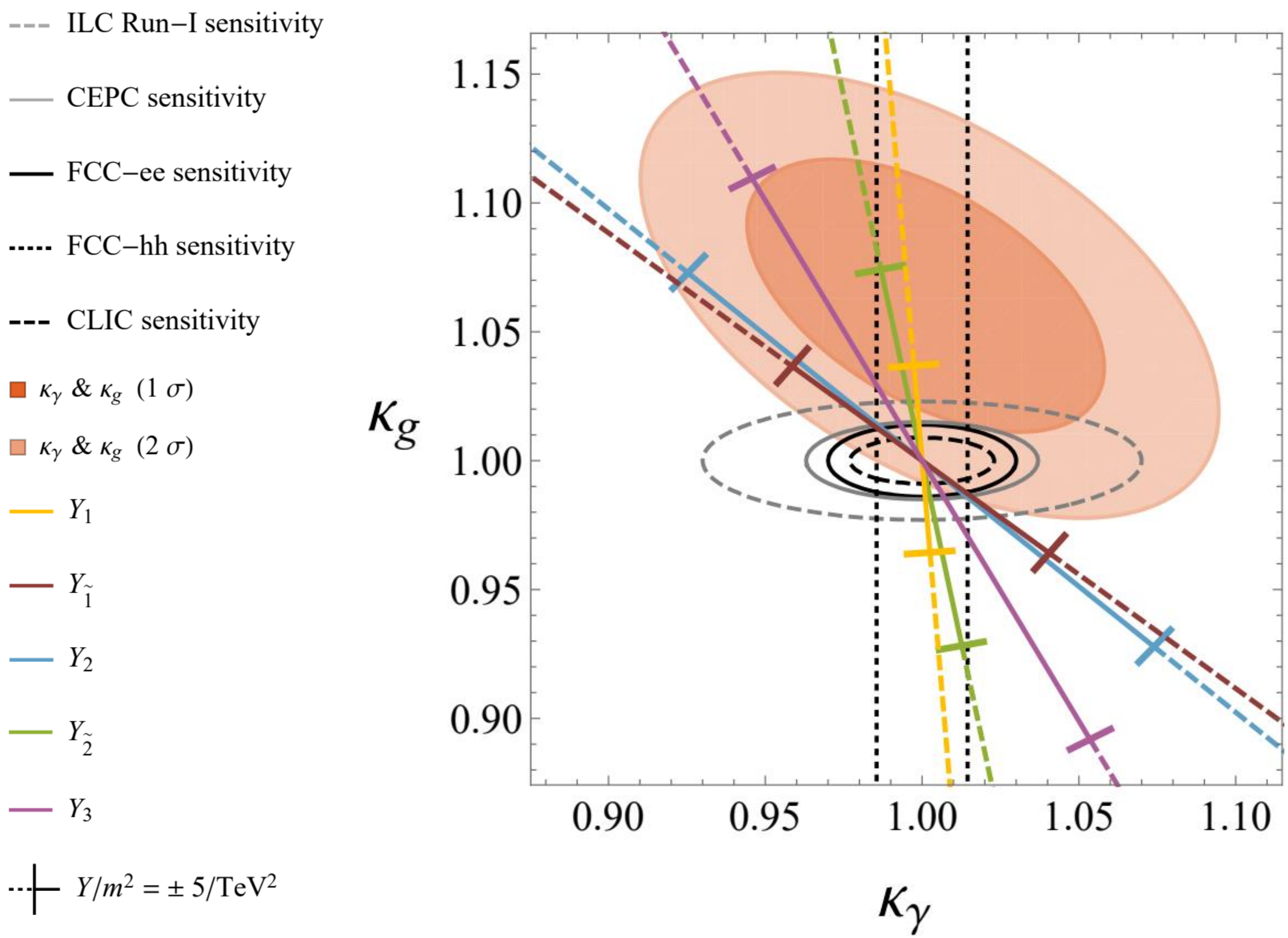
Oblique Corrections





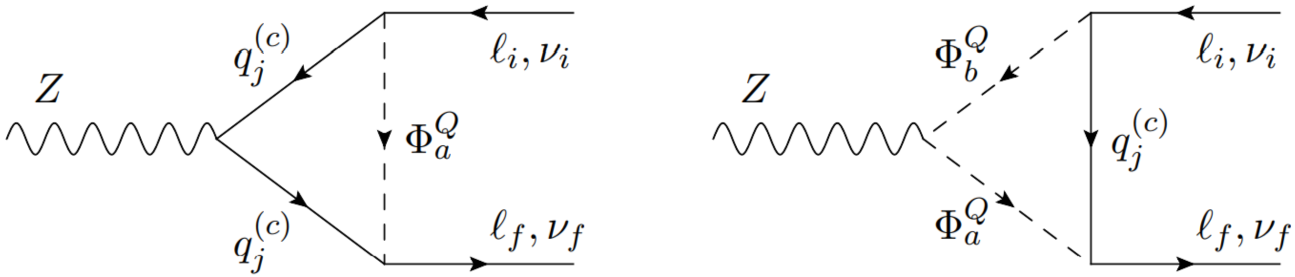
Positive effect in T parameter

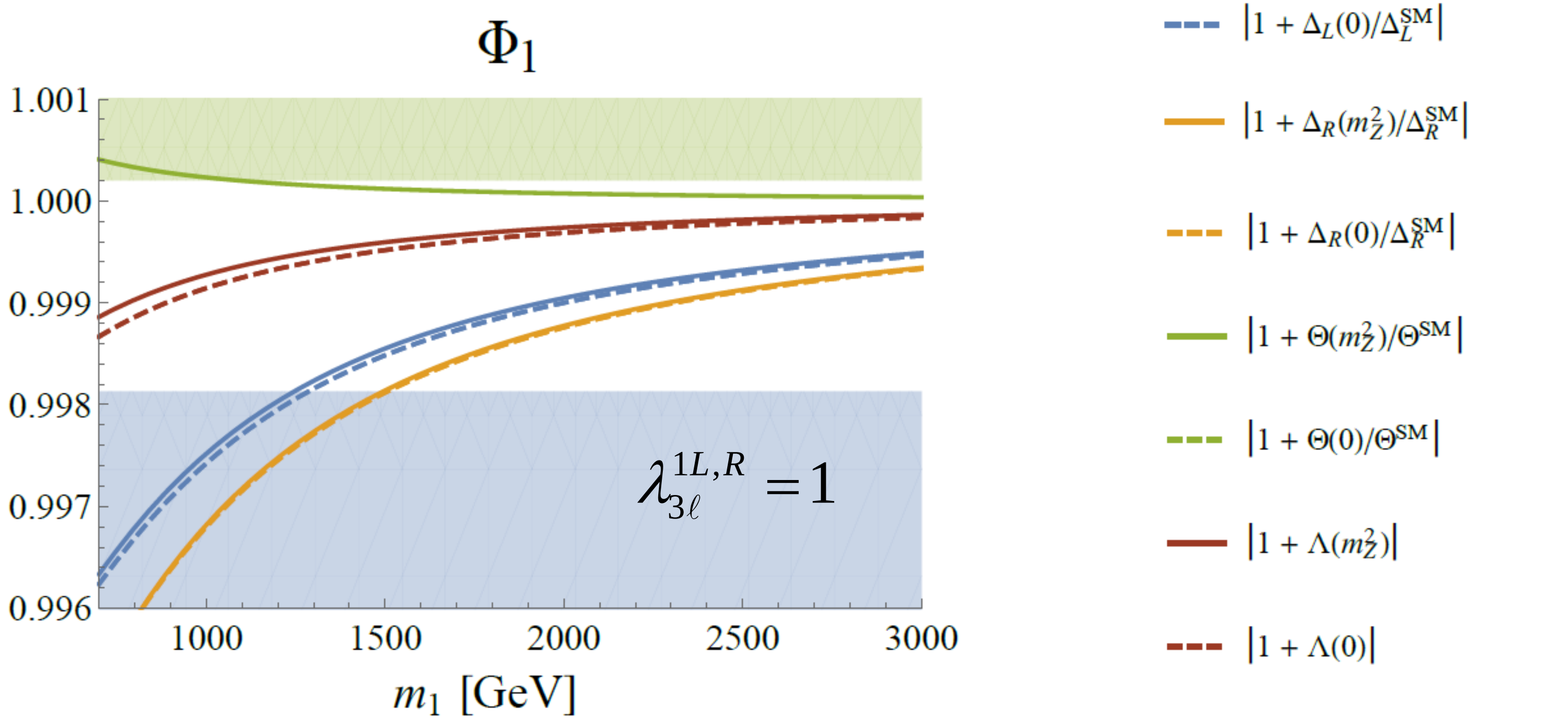
Higgs signal strength (γγ vs gg)



Representations experimentally distinguishable

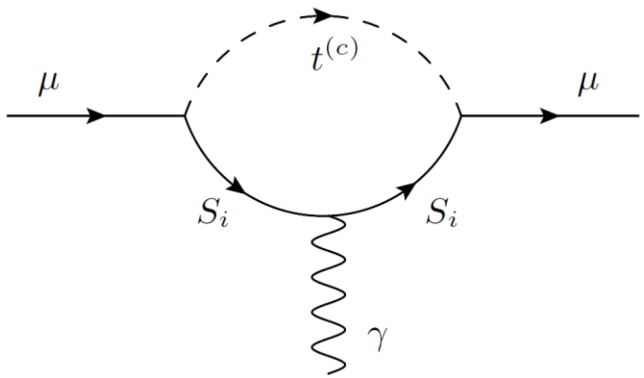
Z→ll, Z→νν and W→lν

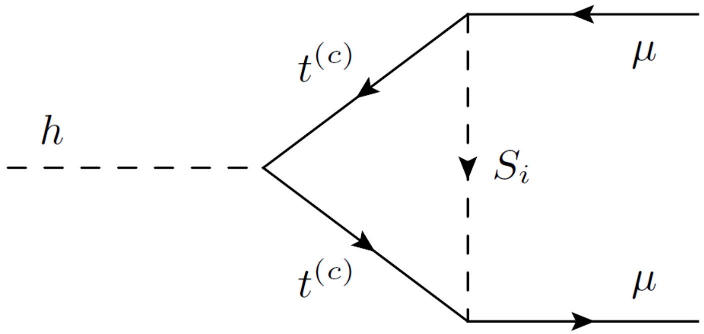


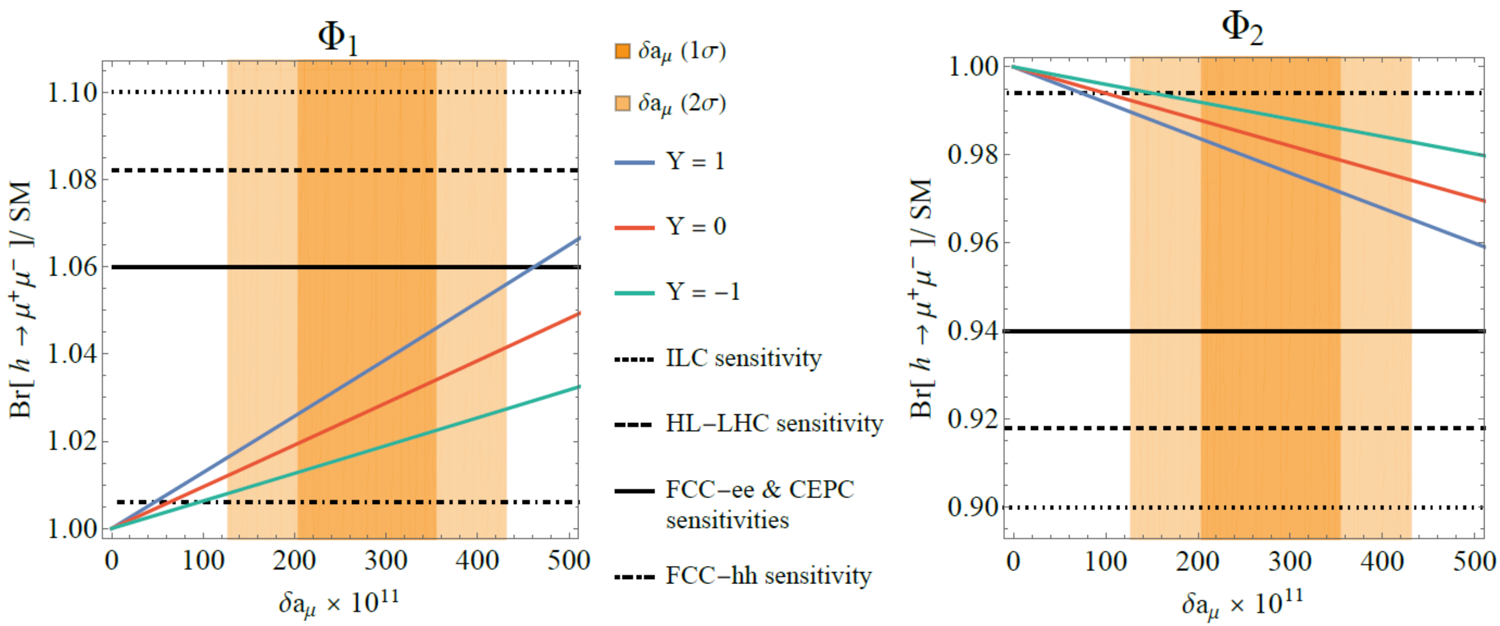


Per-mill effect for O(1) couplings and TeV masses

$(g-2)_\mu$ and $h \to \mu\mu$: Φ_1 and Φ_2

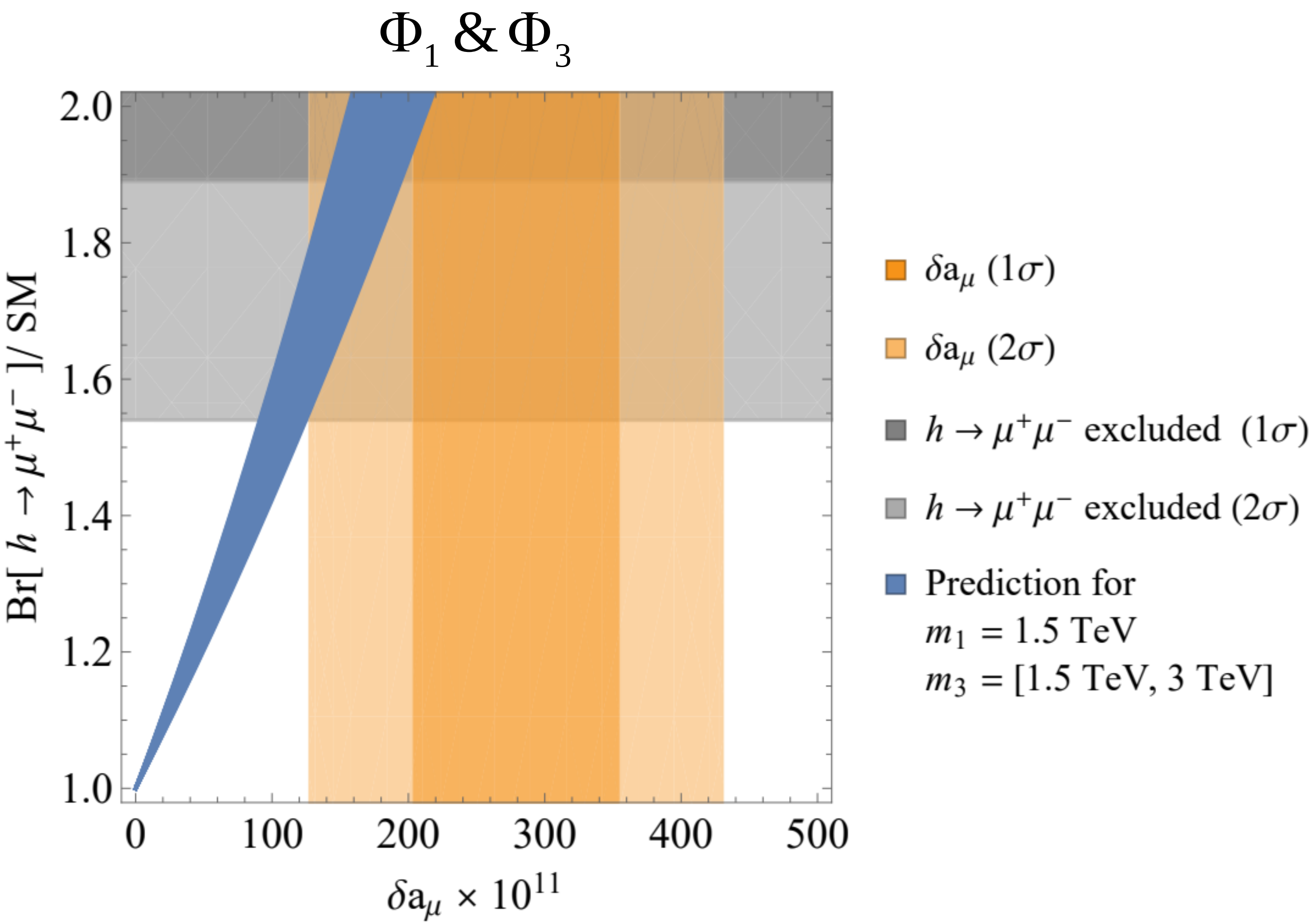






Chirally enhanced effects with direct correlation

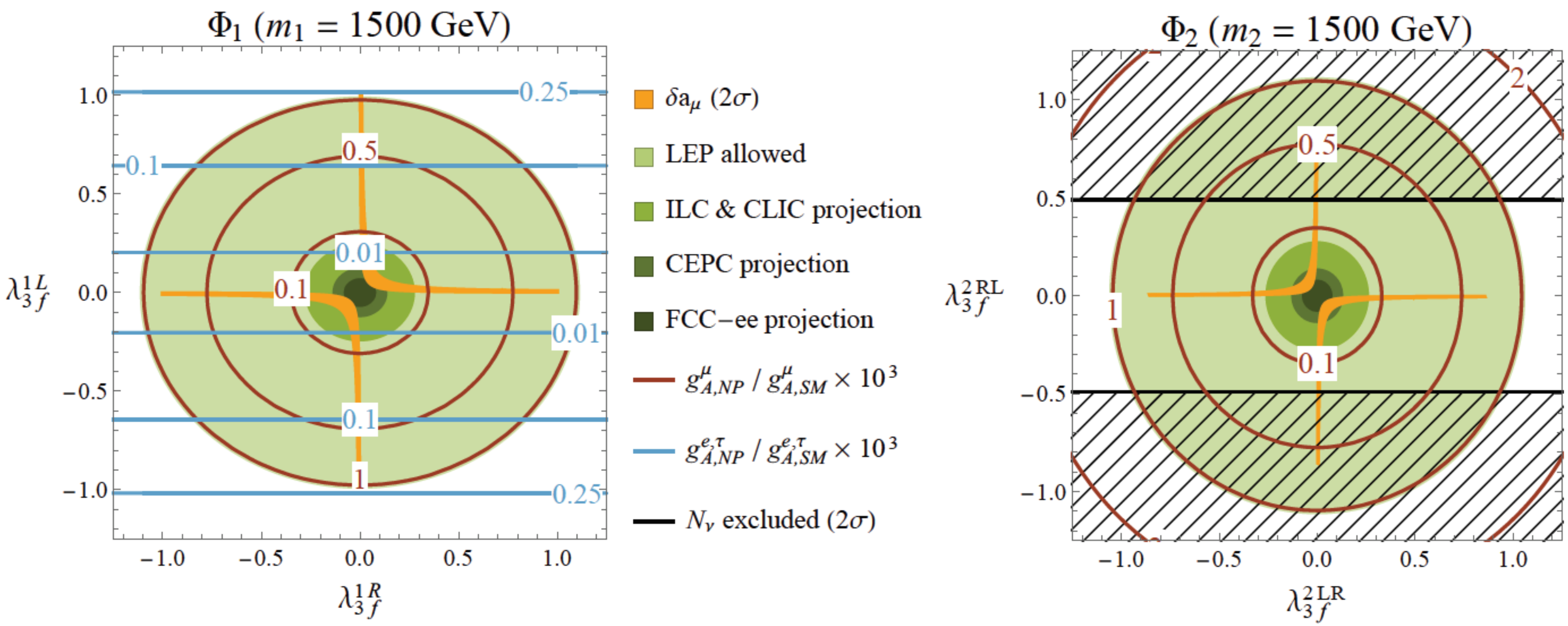
(g-2)$_\mu$ and h→μμ: Φ_1 & Φ_3 with mixing



Scenario already excluded by h→μμ

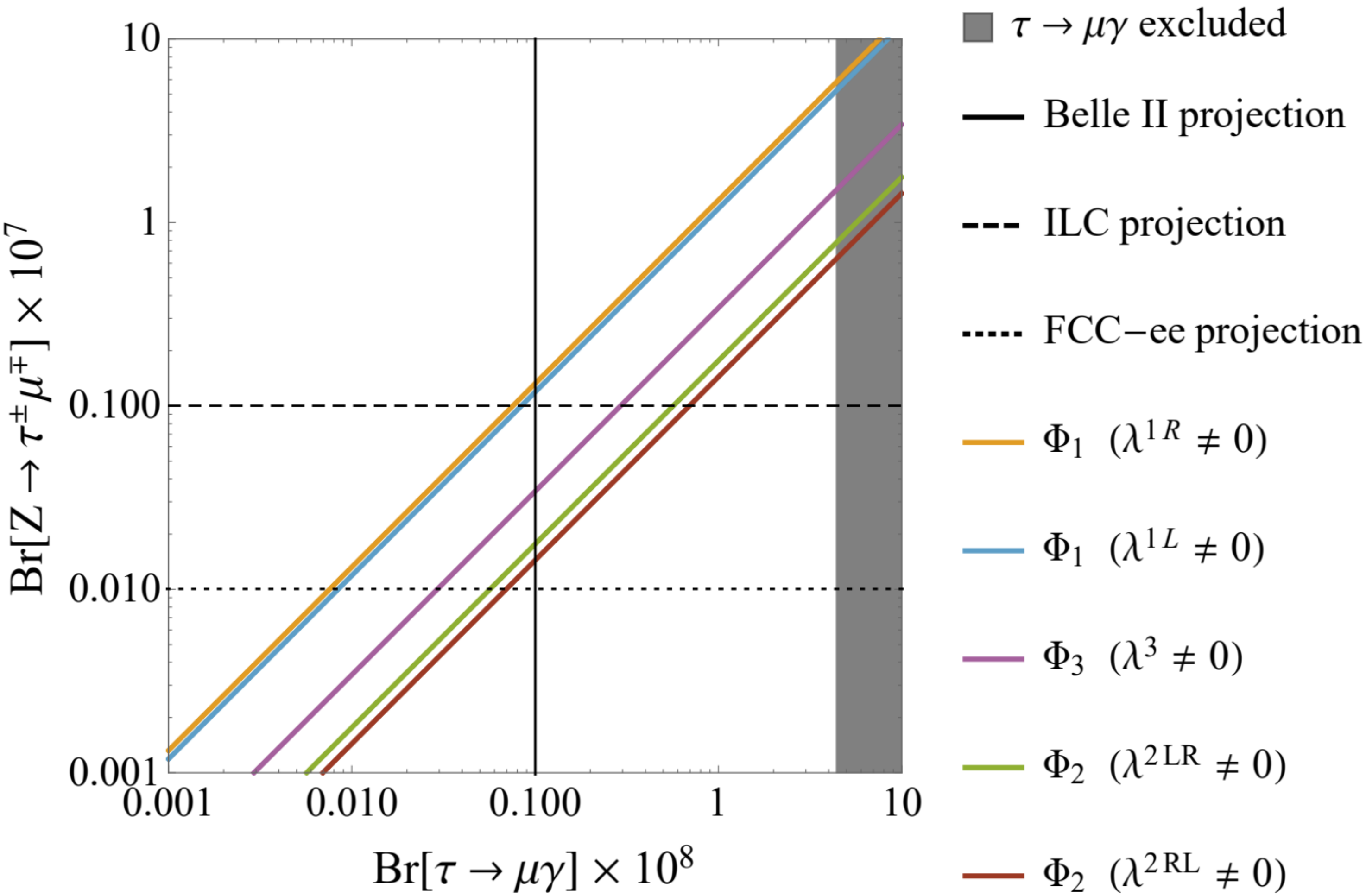
AMM of the muon and Z->ll

- $W\mu\nu$ modification also leads to an effect in $Z \to ee$
- $Z \to \nu\nu$ constraining for Φ_2



Observable effect in $Z \to \mu\mu$

Lepton Flavour Violating



Z→τμ promising channel

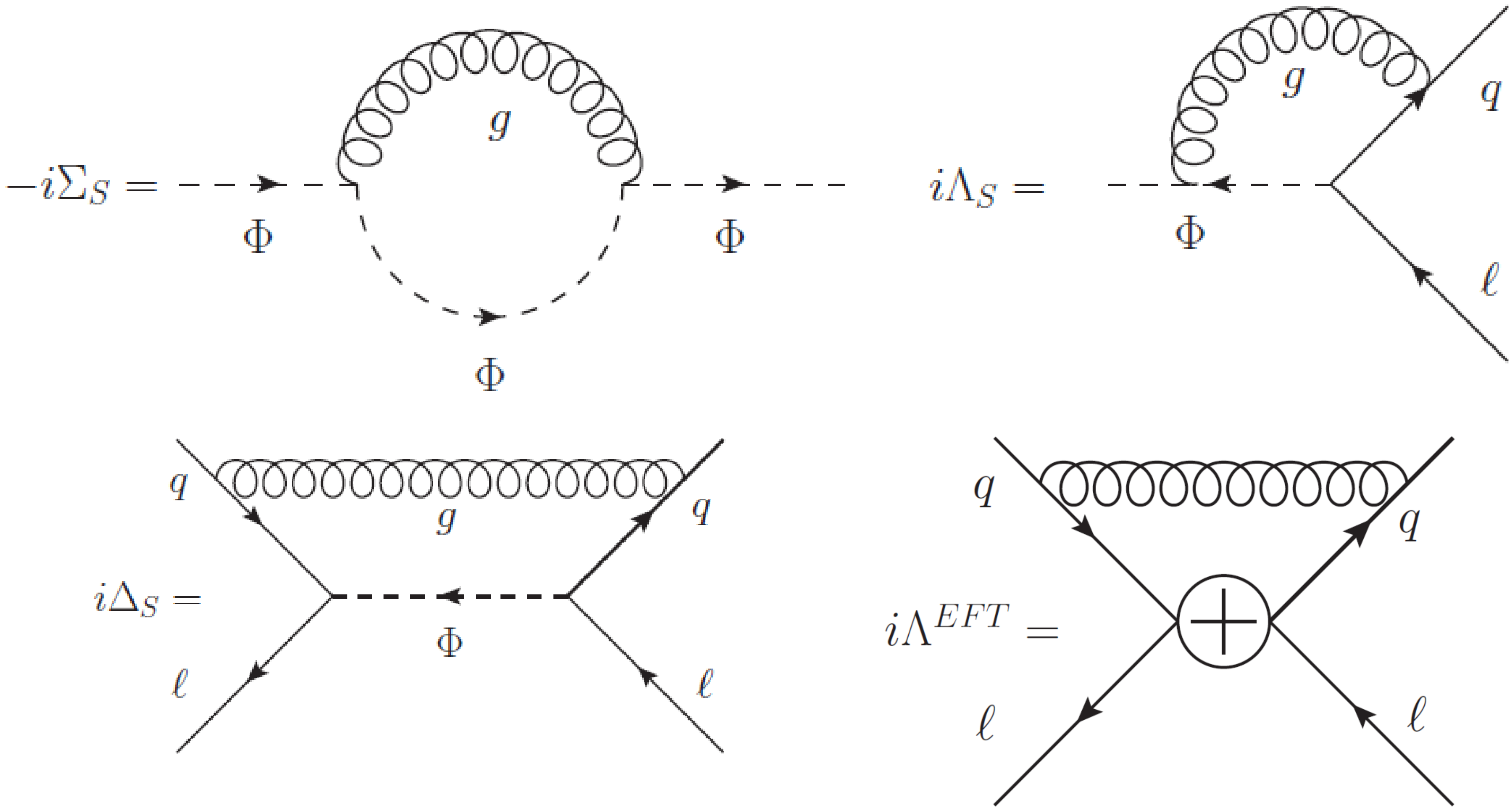
Conclusions

- Leptoquarks are well motivated by the flavour anomalies
- Even without couplings to fermions, they can affect oblique parameters and Higgs decays to gauge bosons
- $(g-2)_\mu$ motivates LQ couplings to muon and top quarks ➡ sizable effect in $Z \to \mu\mu$ and $h \to \mu\mu$
- Discovery potential at future e^+e^- colliders

Flavour Anomalies strengthen the physics case for future colliders like the CEPC

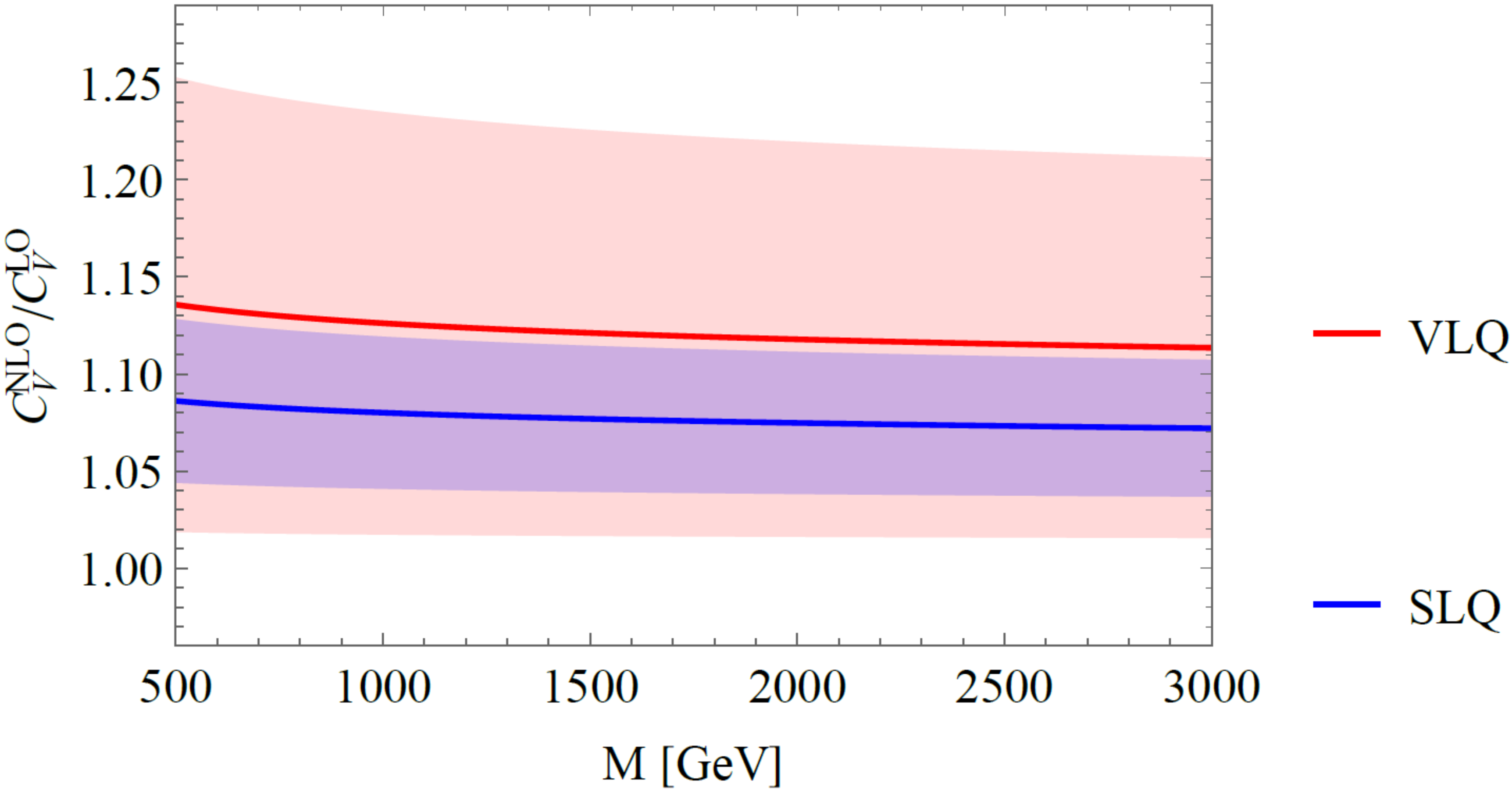
Backup

QCD corrections to the Matching



- Perform matching
- Correct for 4-dimensional Fierz identities

Results

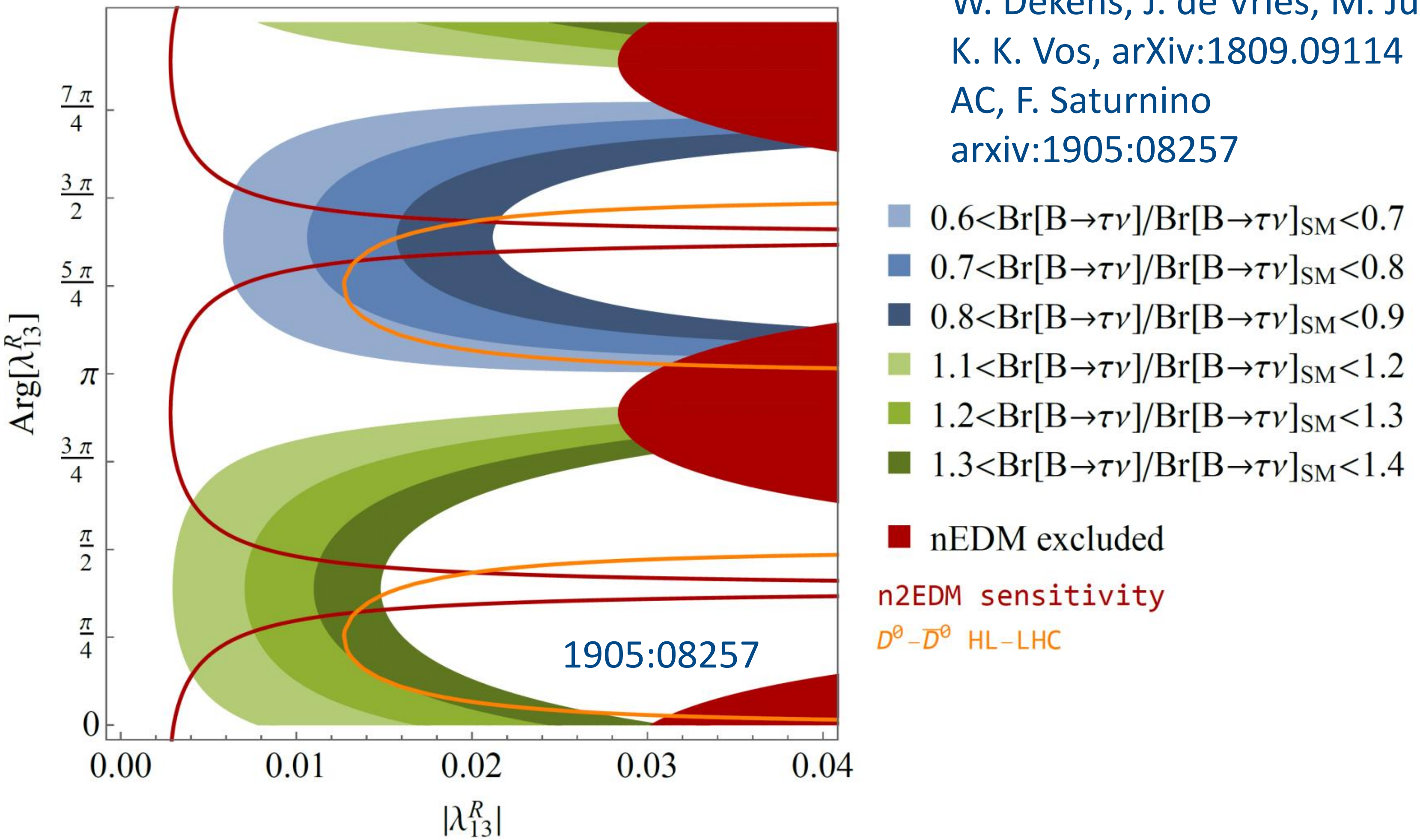


J. Aebischer, AC, C. Greub, 1811.08907

Slightly weaker LHC constraints

Correlations the neutron EDM with S1

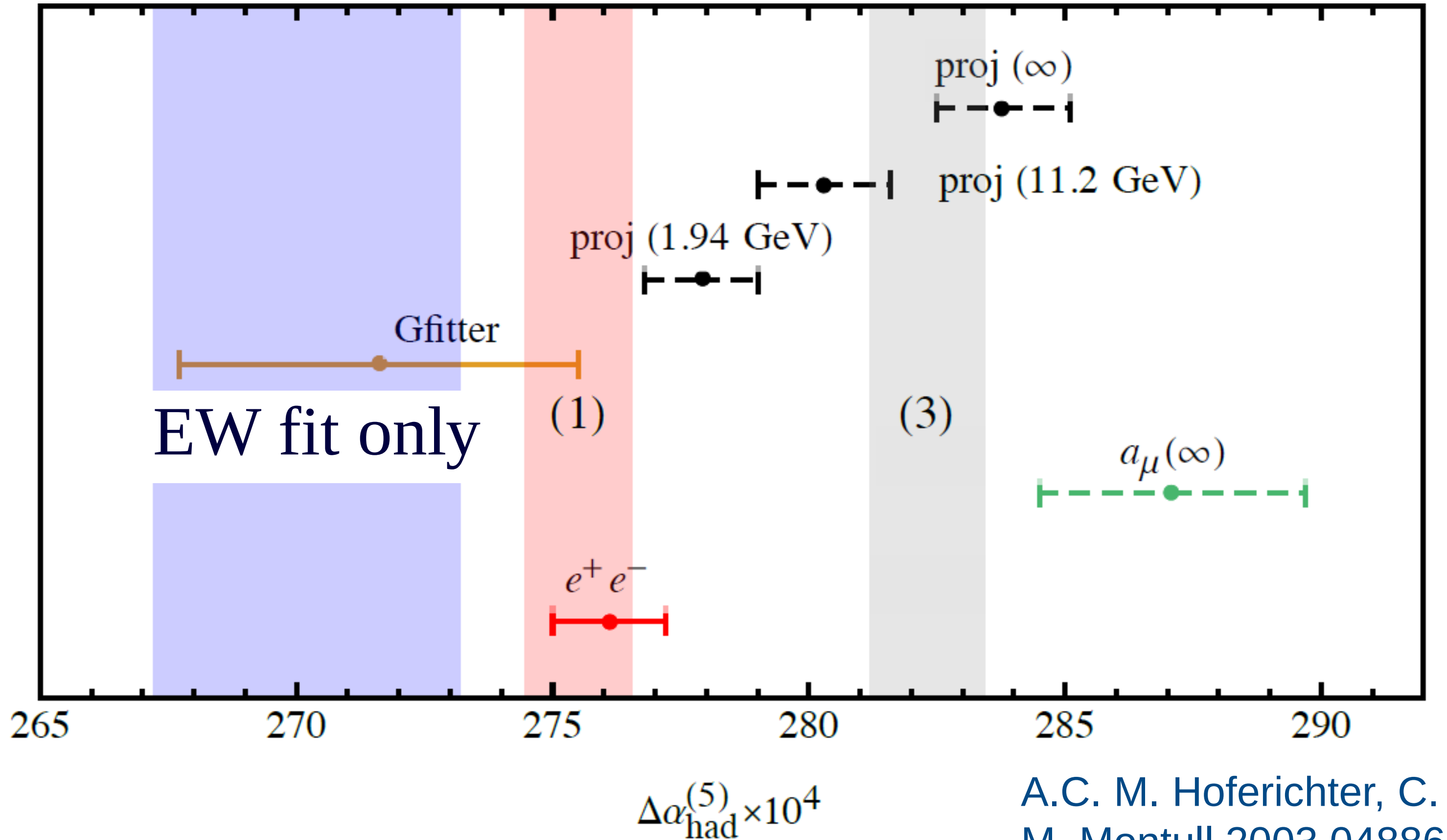
W. Dekens, J. de Vries, M. Jung, K. K. Vos, arXiv:1809.09114
AC, F. Saturnino arxiv:1905:08257



Effect in B predicts measurable nEDM effect

Hadronic Vacuum Polarization

- New BMWc lattice QCD result

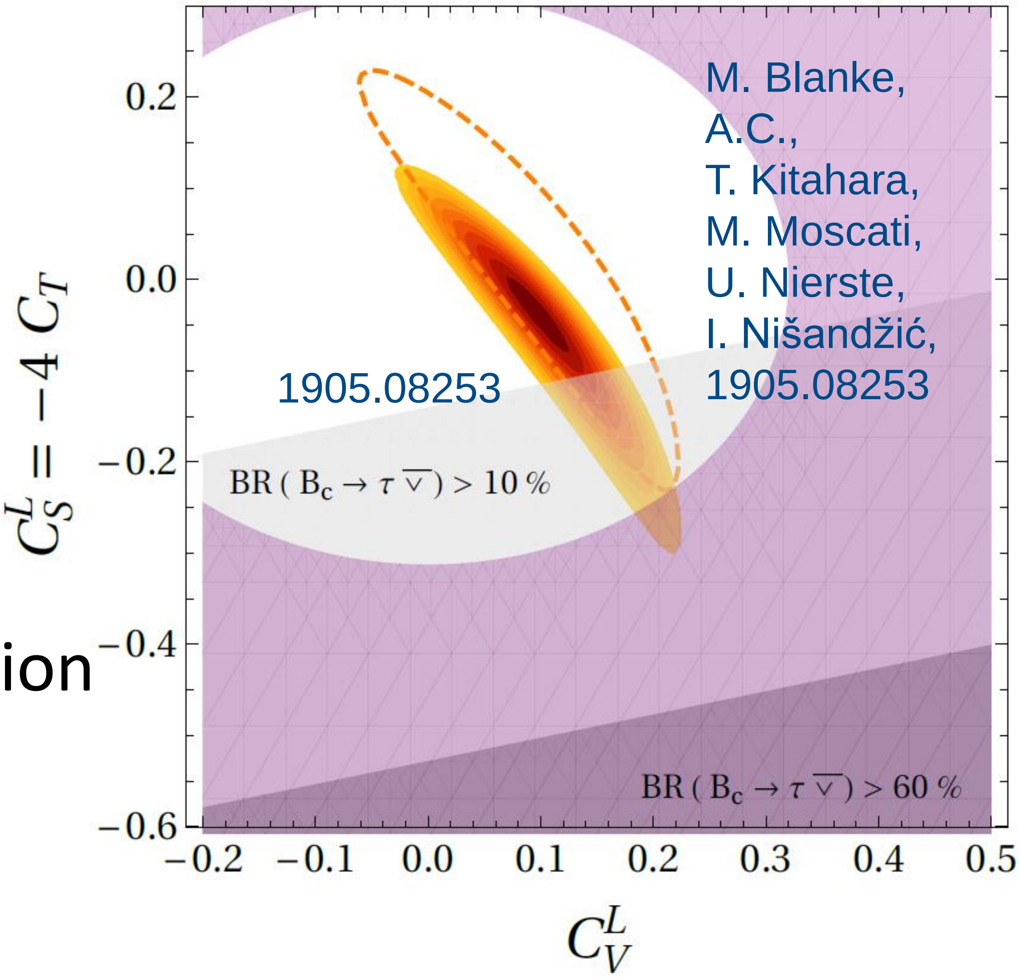


A.C. M. Hoferichter, C. Manzari, M. Montull 2003.04886

Up to 4σ tension in EW fit

$b \to c\tau\nu$ Global Fit

- Pure scalar-tensor explenations in tension
with the B_c lifetime
- Pure left-handed vector, i.e. contribution to the SM operator gives good fit

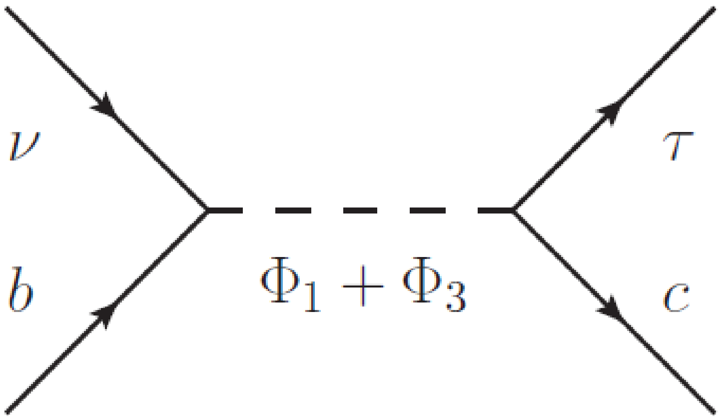


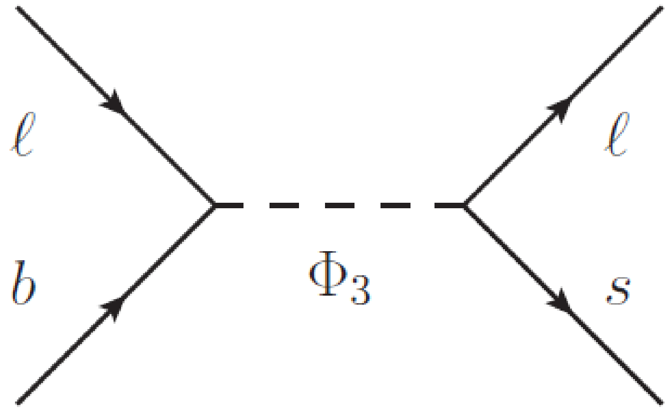
Global fit give up to 4σ preference for NP

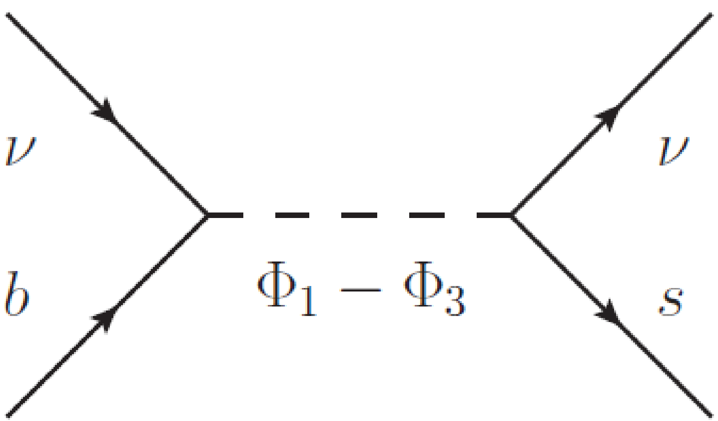
Two Scalar Leptoquarks

AC, D. Mueller, T. Ota
arxiv:1703.09226

- Φ_1 scalar leptoquark singlet with Y=-2/3
- Φ_3 scalar leptoquark triplet with Y=-2/3







Constructive in $R(D^{(*)})$

Destructive in $b \to s\mu\mu$

$R(D^{(*)})$, $b \to sll$ and a_μ

- 4 benchmark points

AC, D. Mueller, F. Saturnino
arxiv:1912.04224

	κ_{22}	κ_{32}	κ_{23}	κ_{33}	λ_{22}	λ_{32}	λ_{23}	λ_{33}	$\hat{\lambda}_{32}$	$\hat{\lambda}_{23}$
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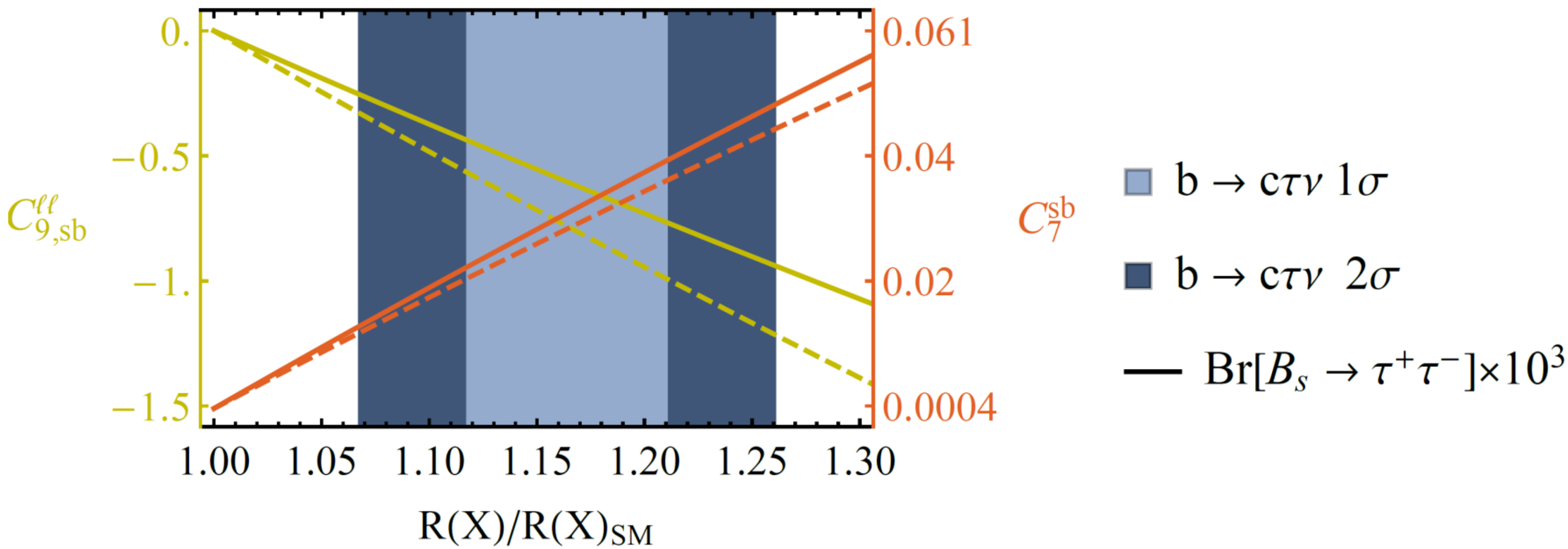
p_4	0.010	0.047	2.43	0.18	3.69	0.0021	18.60	3.12	-10.04

Common explanation possible

Important Loop-Effects

- Explanation of b→cτν requires large bτ and sτ couplings (follows from SU(2) invariance)

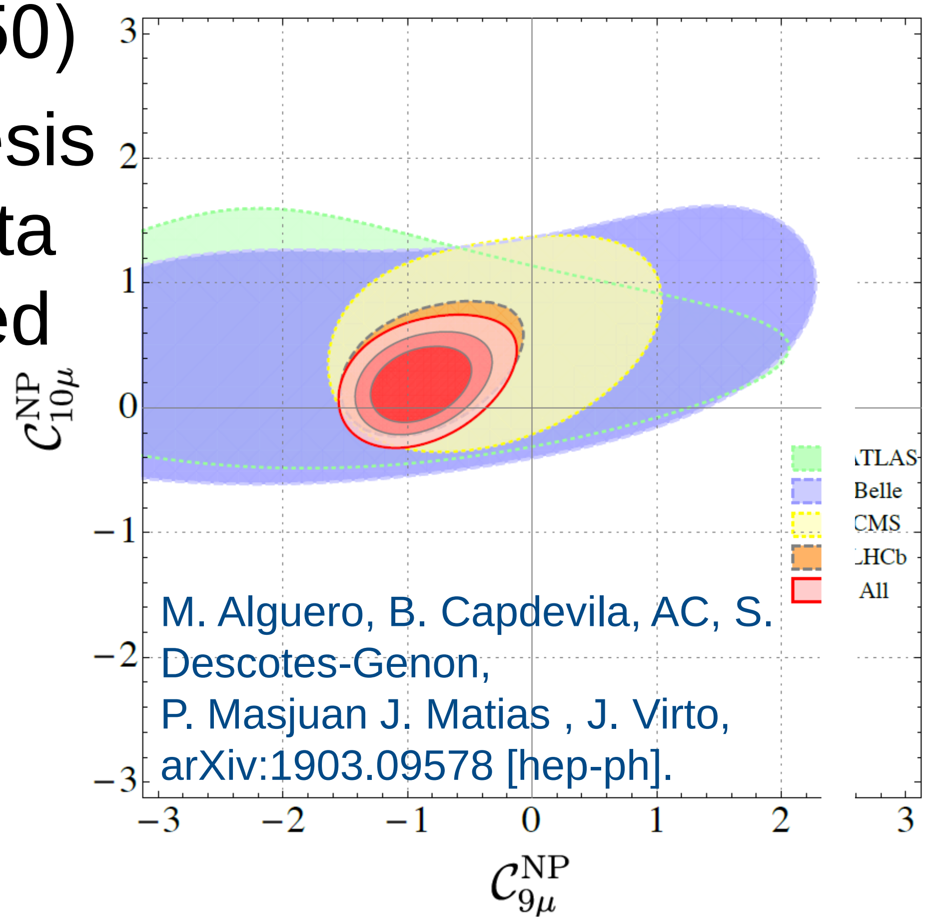


AC, C. Greub, D. Müller, F. Saturnino, PRL 2018

Large loop effects in b→sμμ

Global Fit to b→sμ⁺μ⁻ Data

- Perform global model independent fit to include all observables (≈150)
- Several NP hypothesis give a good fit to data significantly preferred over the SM hypothesis



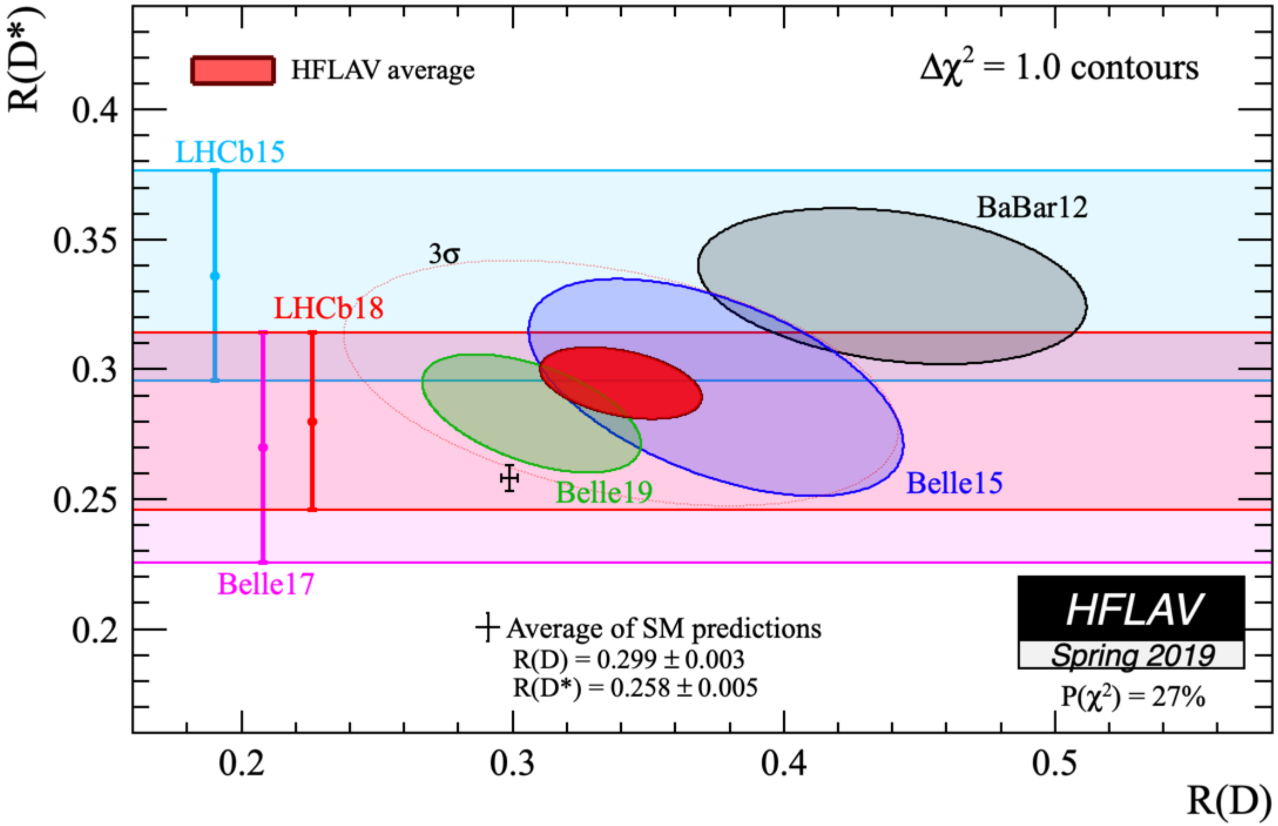
$$O_9 = \bar{s}\gamma^{\mu}P_L b\,\bar{\ell}\gamma_{\mu}\ell$$

$$O_{10} = \bar{s}\gamma^{\mu}P_L b\,\bar{\ell}\gamma_{\mu}\gamma^5\ell$$

Fit is 5-6 σ better than the SM

b→cτν Measurements

$$R\left(D^{(*)}\right) = B \to D^{(*)}\tau\nu / B \to D^{(*)}\ell\nu$$



All measurements above the SM prediction
O(10%) constructive effect at 3σ preferred

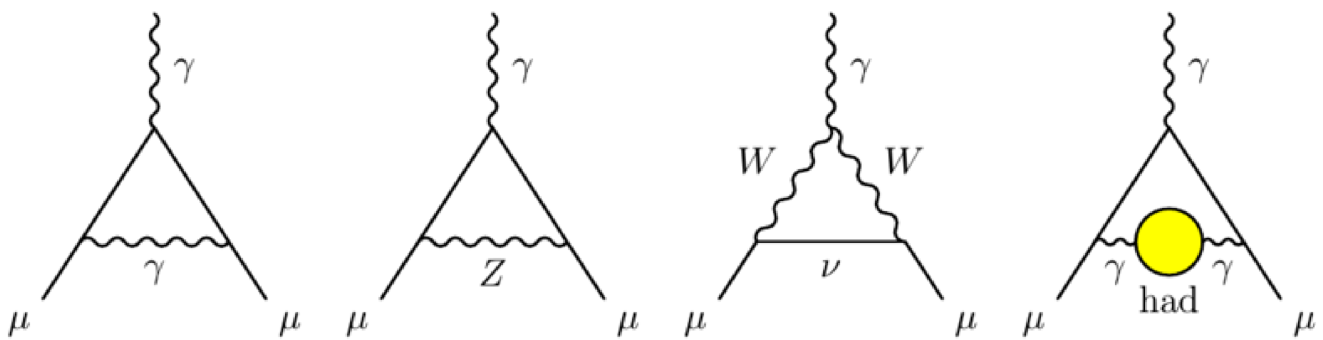
Muon Anomalous Magnetic Moment

- Single measurement from BNL
- Theory prediction sound but challenging because of hadronic effects.

$$\Delta a_\mu = \left(279 \pm 76\right) \times 10^{-11}$$

T. Aoyama et al., arXiv:2006.04822

- Soon new experimental results from Fermilab



- Small tension in Δa_e with opposite sign

3.7σ deviation (order of SM-EW contribution)

Possible UV completions

- $SU(4)\times SU(3)'\times SU(2)_L\times U(1)_Y$ + Vector-like fermions

  L. Di Luzio, A. Greljo, M. Nardecchia, arXiv:1708.08450
- $SU(4)\times U(2)_L\times SU(2)_R$ + Vector-like fermions

  L. Calibbi, AC, T. Li, arXiv:1709.00692
- $SU(4)\times SU(4)\times SU(4)$

  M. Bordone, C. Cornella, J. Fuentes-Martin, G. Isidori, arXiv:1712.01368
- $SU(4)\times U(2)_L\times SU(2)_R$ including scalar LQs and light right-handed neutrinos

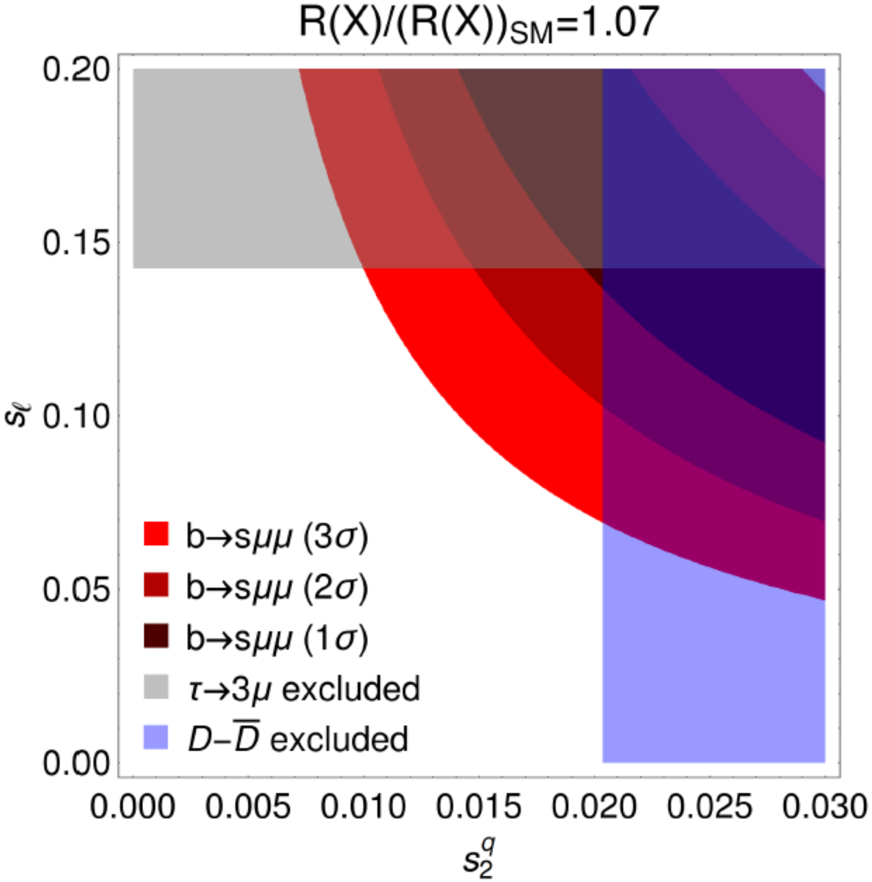
  J. Heeck, D. Teresi, arXiv:1808.07492
- $SU(8)$ might even explain ε'/ε

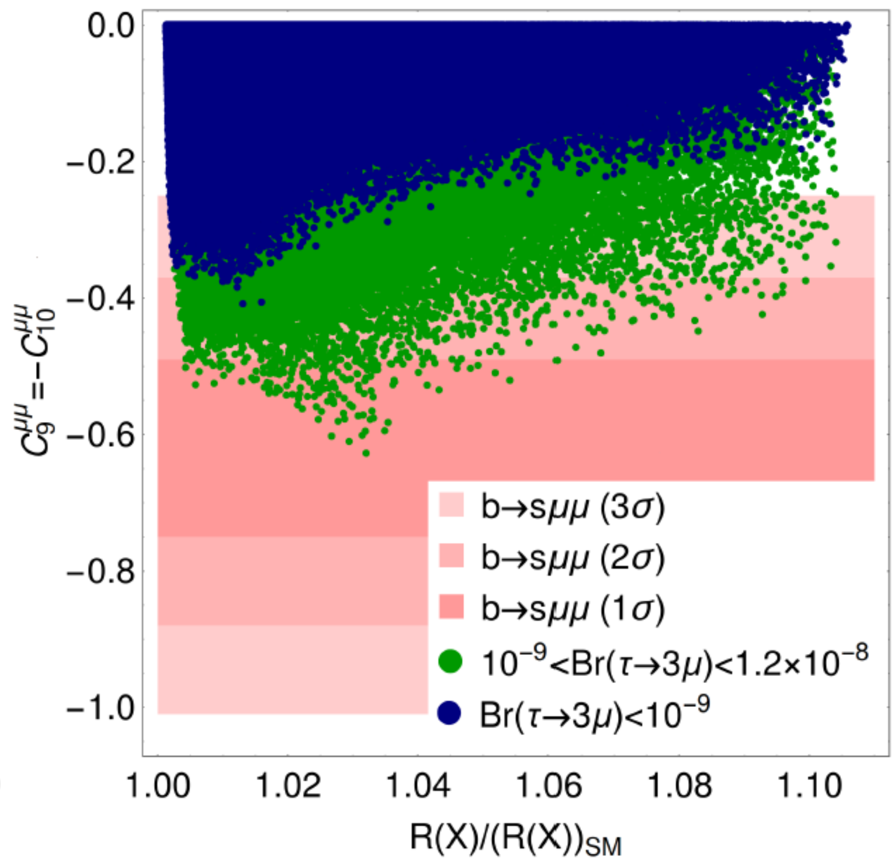
  S. Matsuzaki, K. Nishiwaki and K. Yamamoto, arXiv:1806.02312
- $SU(4)\times U(2)\times SU(2)_R$ in RS background

  M. Blanke, AC, arXiv:1801.07256

Good solution, but challenging UV completion

Pati-Salam RS Phenomenology



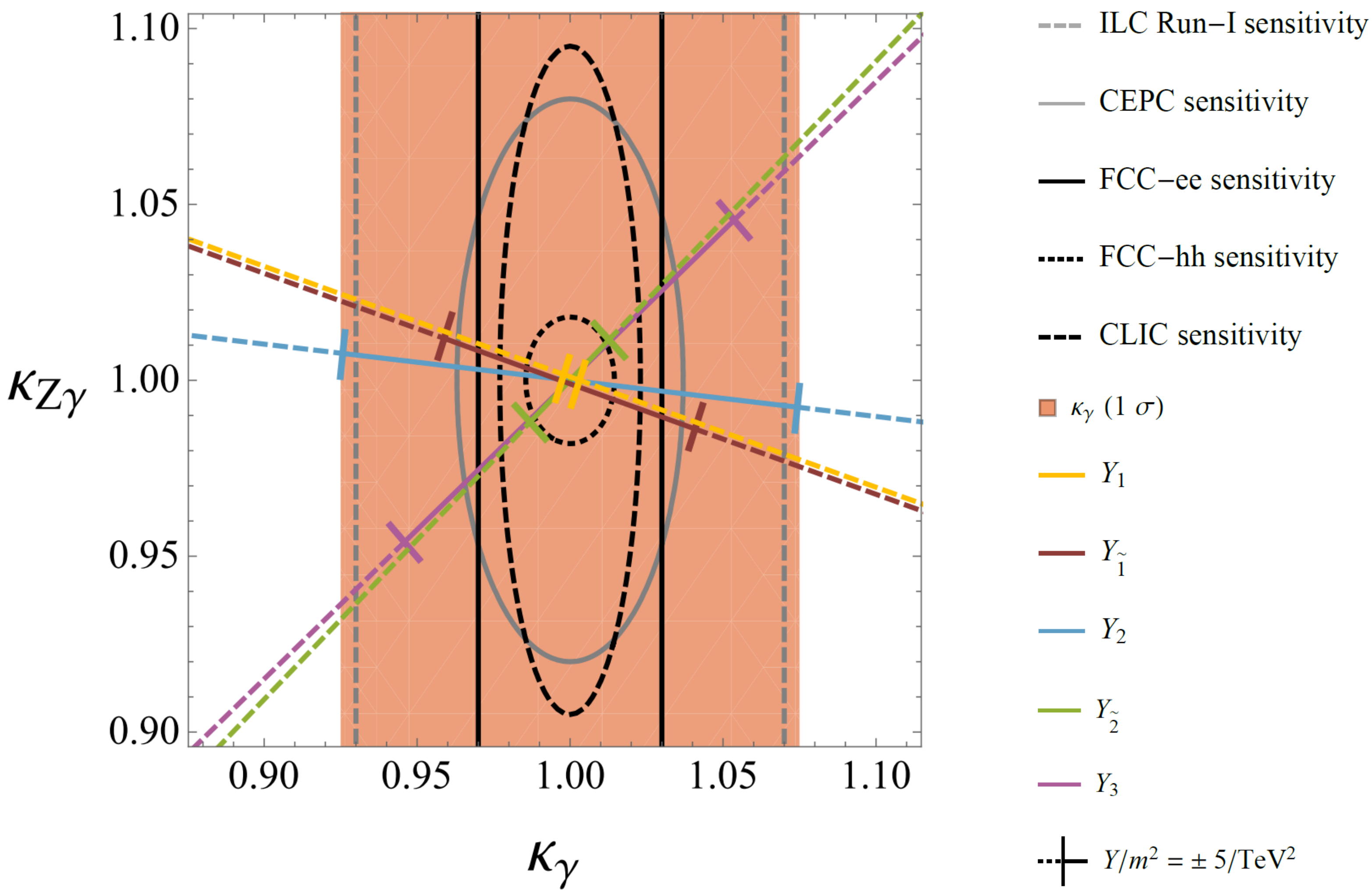


$M = 3\,\mathrm{TeV},\ s_2^\ell = 0.2,\ s_3^\ell = 1/\sqrt{2}$ and $s_3^q = \sqrt{3}/2$

M. Blanke, AC, PRL 2018

Model well motivated + limited but sizable effect

Higgs signal strength (γZ)



γZ provides complementary information