Implications of LHCb measurements and future prospects

21/10/2022

A bridge to new physics

Bridge solutions for a_μ and $b \to s\ell\ell$ anomalies

arXiv:2205.04480

G. Guedes, PO

Pablo Olgoso

FTAE High Energy Theory

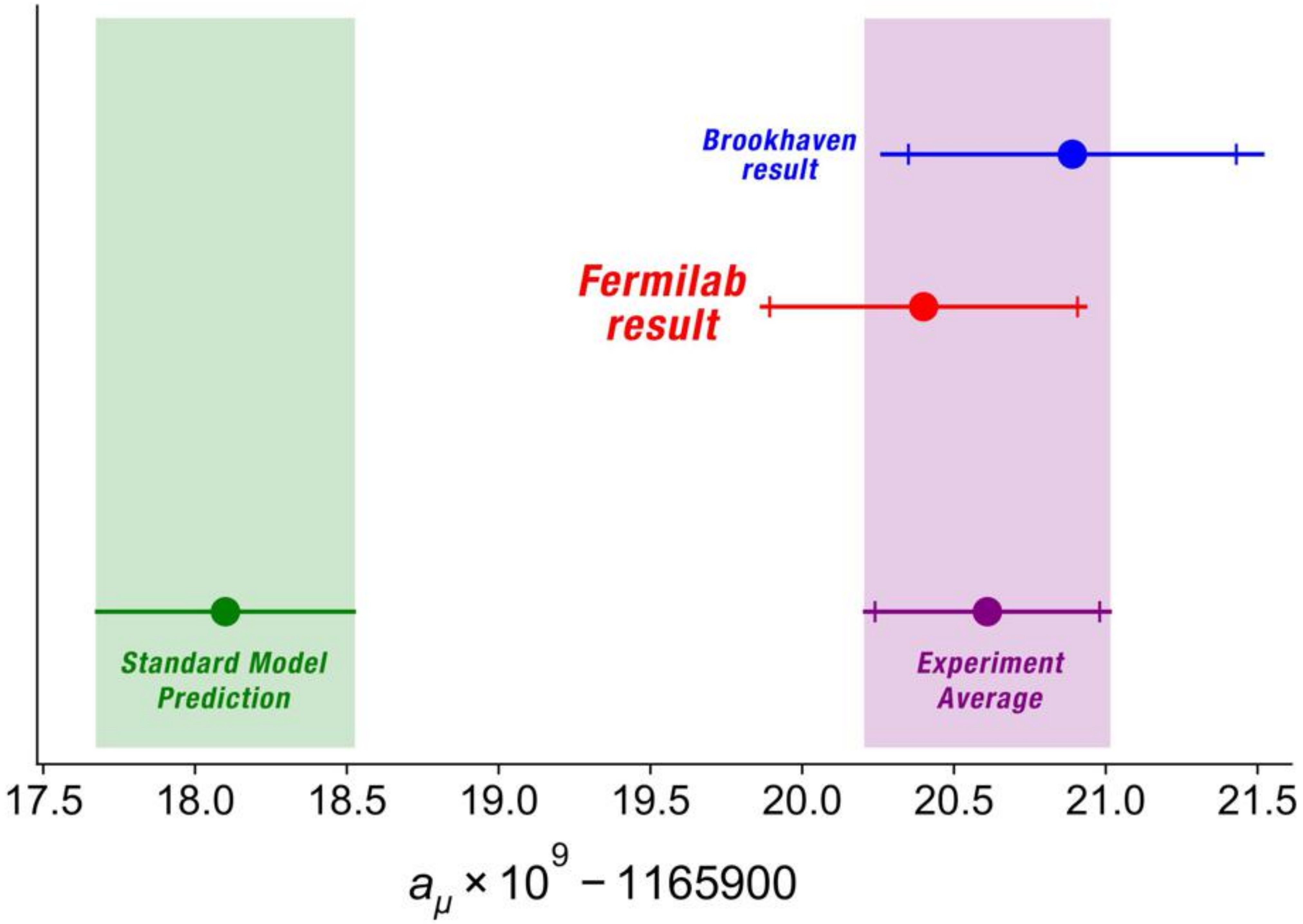
Universidad de Granada

The g-2 anomaly

- There has been a big effort to explain the discrepancy between the SM prediction and the observed value (4.2 σ).

- Disagreement in HVP contributions to SM prediction (tension would be reduced to 1.5 σ).

[S. Borsanyi et al., 2022.12347]
[M. Cè et al., 2206.06582]



The g-2 anomaly

- From the lens of the SMEFT, it is generated by the *dipole* operators:

$$\mathcal{O}_{eB} = (\bar{\ell}\sigma^{\mu\nu}e)HB_{\mu\nu} + \text{h.c.},$$
$$\mathcal{O}_{eW} = (\bar{\ell}\sigma^{\mu\nu}e)\sigma^I HW^I_{\mu\nu} + \text{h.c.}.$$

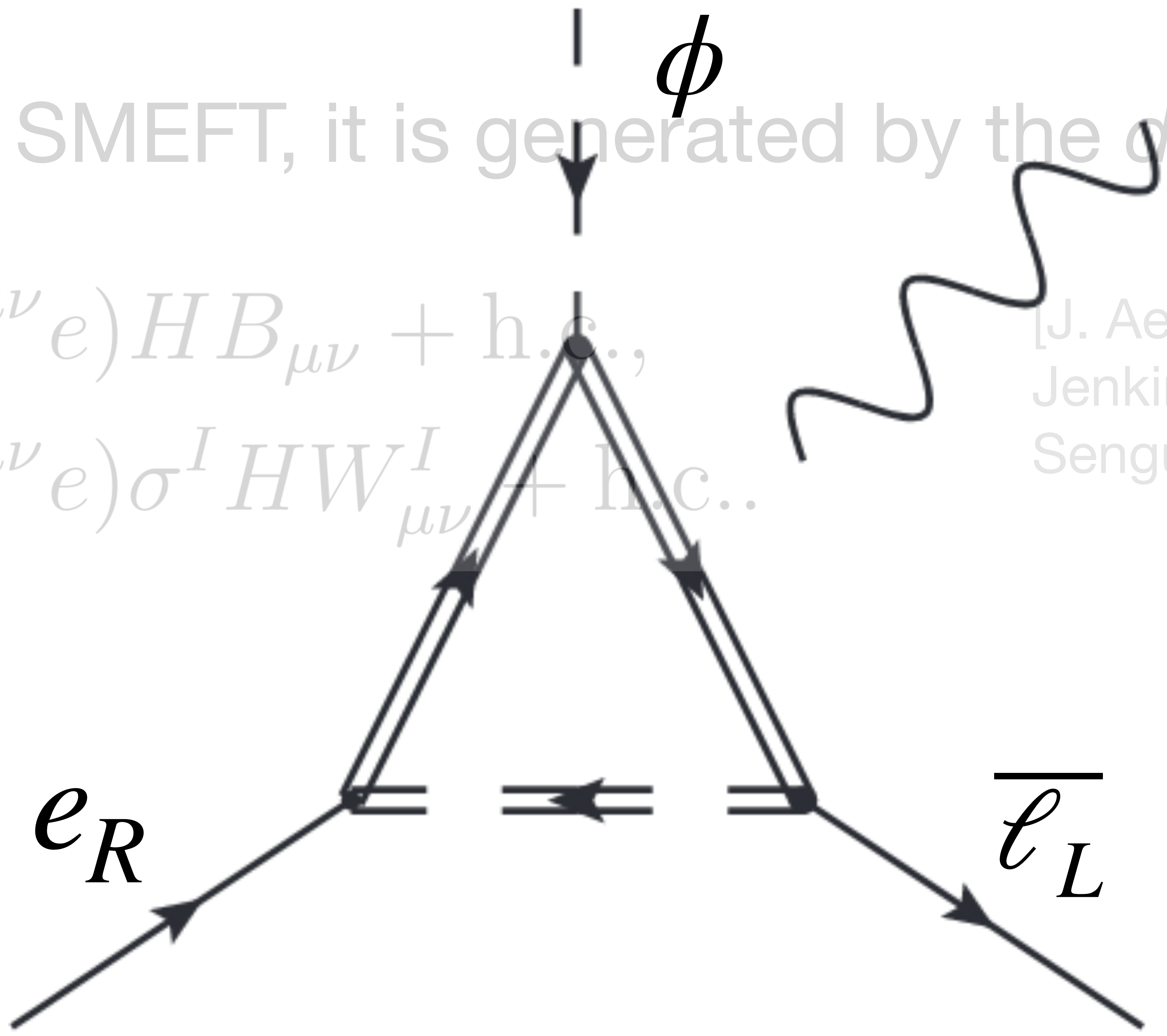
[J. Aebischer, W. Dekens, E. Jenkins, A. Manohar, D. Sengupta, P. Stoffer, 2102.08954]

The g-2 anomaly

- From the lens of the SMEFT, it is generated by the *dipole* operators:

$$\mathcal{O}_{eB} = (\bar{\ell}\sigma^{\mu\nu}e)HB_{\mu\nu} + \text{h.c.},$$
$$\mathcal{O}_{eW} = (\bar{\ell}\sigma^{\mu\nu}e)\sigma^I HW^I_{\mu\nu} + \text{h.c.}.$$

[J. Aebischer, W. Dekens, E. Jenkins, A. Manohar, D. Sengupta, P. Stoffer, 2102.08954]



The g-2 anomaly

- From the lens of the SMEFT, it is generated by the *dipole* operators:

$$\mathcal{O}_{eB} = (\bar{\ell}\sigma^{\mu\nu}e)HB_{\mu\nu} + \text{h.c.},$$
$$\mathcal{O}_{eW} = (\bar{\ell}\sigma^{\mu\nu}e)\sigma^I HW^I_{\mu\nu} + \text{h.c.}.$$

[J. Aebischer, W. Dekens, E. Jenkins, A. Manohar, D. Sengupta, P. Stoffer, 2102.08954]

- For a comprehensive review of the status of solutions, see:

[P. Athron, C. Balázs, D. Jacob, W. Kotlarski, D. Stöckinger, H. Stöckinger-Kim, 2104.03691]

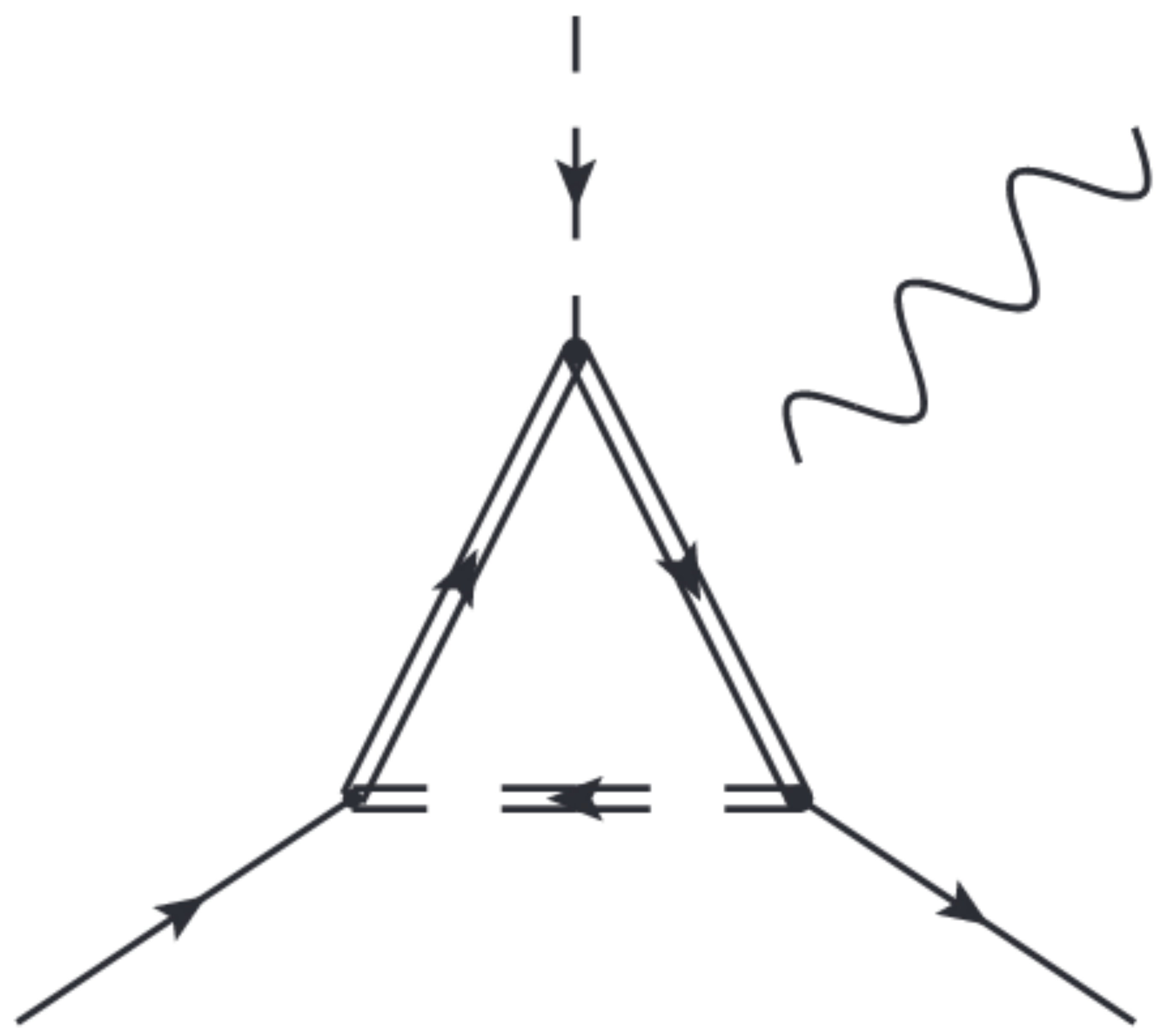
Chirally enhanced solutions

- $\mathcal{O}(TeV)$ solutions need chirally enhanced contributions, i.e., not proportional to the muon's Yukawa.

- Chirality flip comes from:

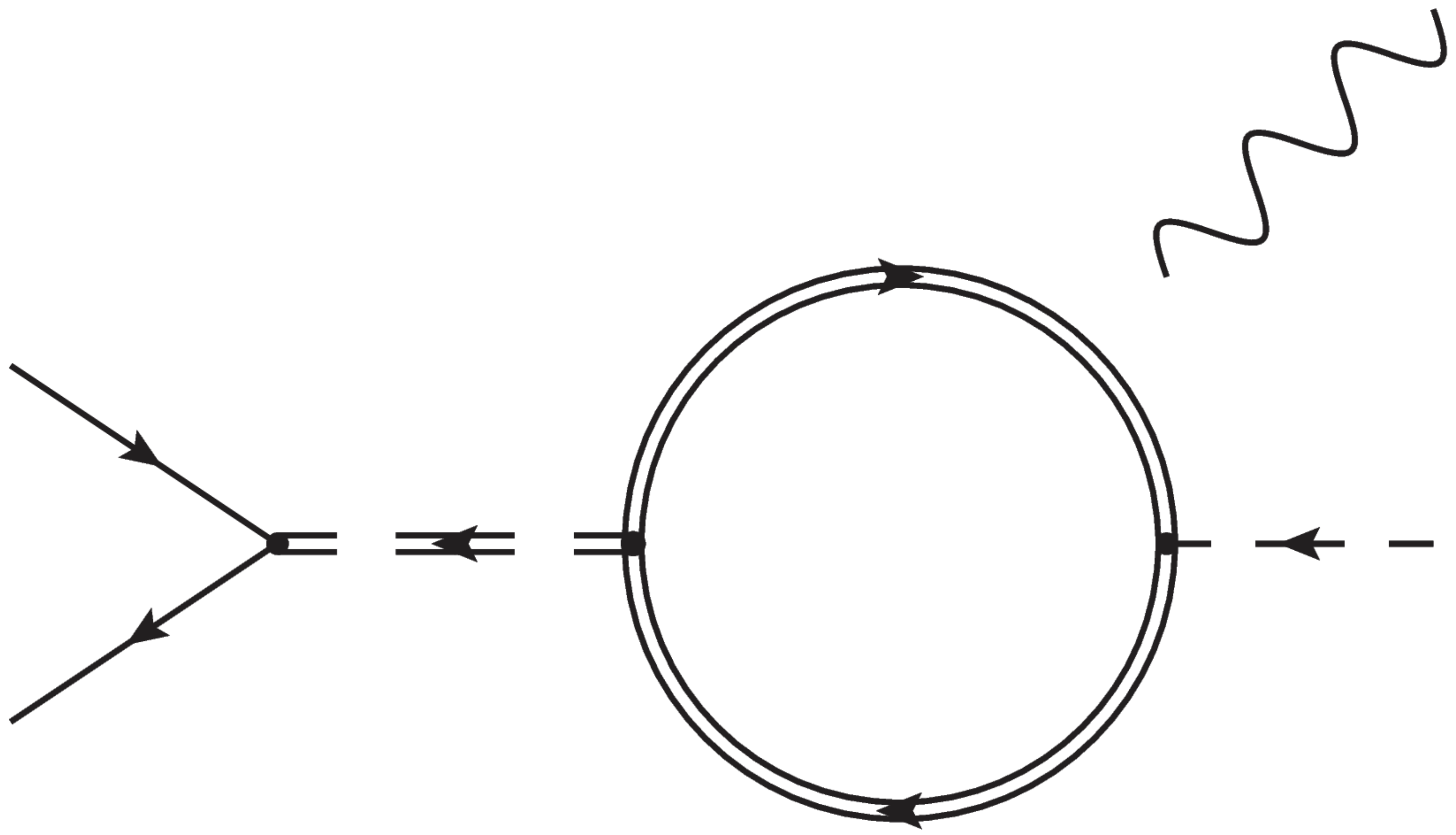
    - Top Yukawa (S1 leptoquark).

    - Heavy VL fermions.



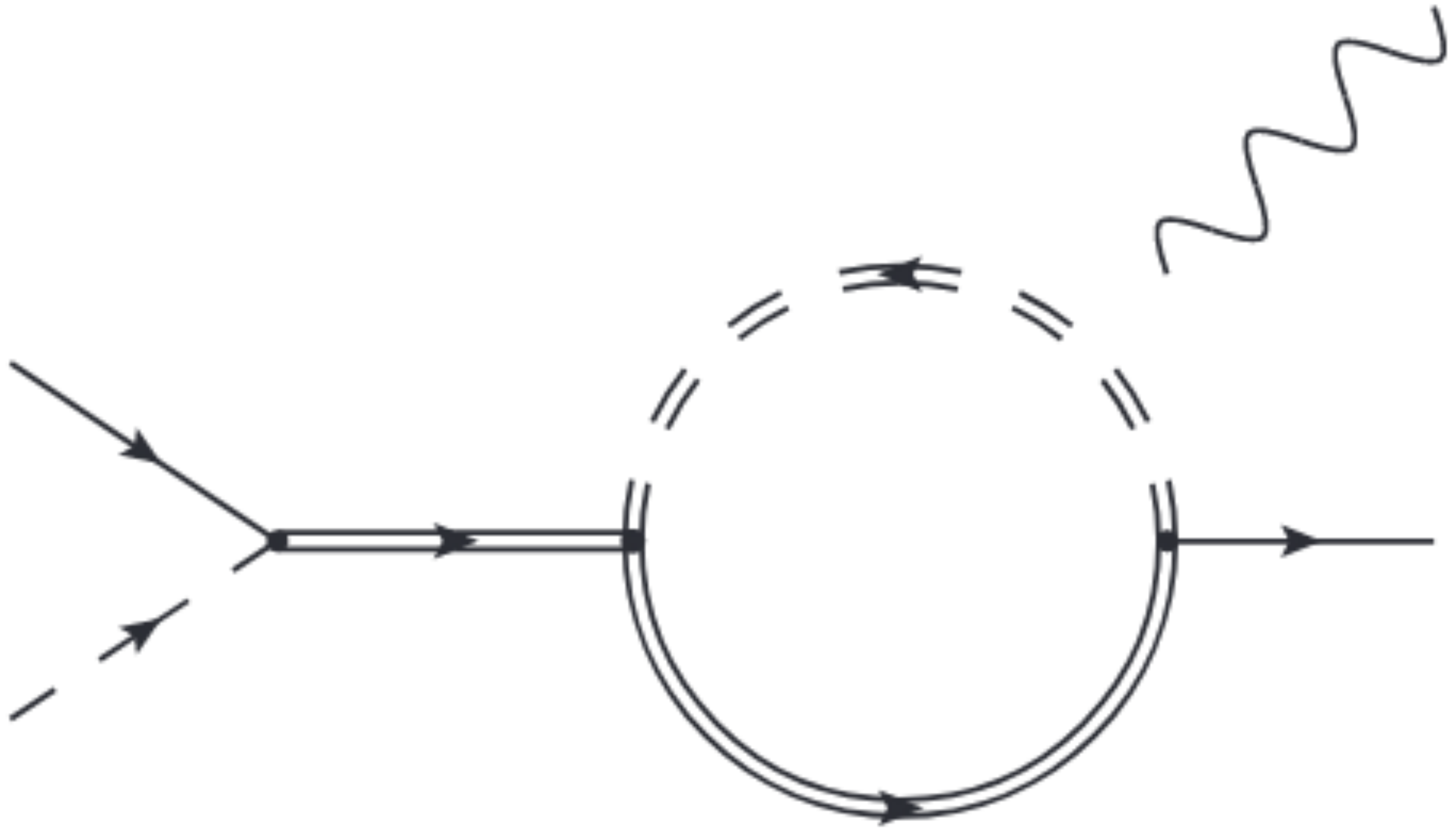
The bridge diagram

- In this work we focus on the *bridge* topology:



$\Phi \sim (1, 2, 1/2)$

(No contribution)



$E \sim (1, 1, -1)$

$\Delta \sim (1, 2, -1/2)$

$\Sigma \sim (1, 3, -1)$

The bridge diagram

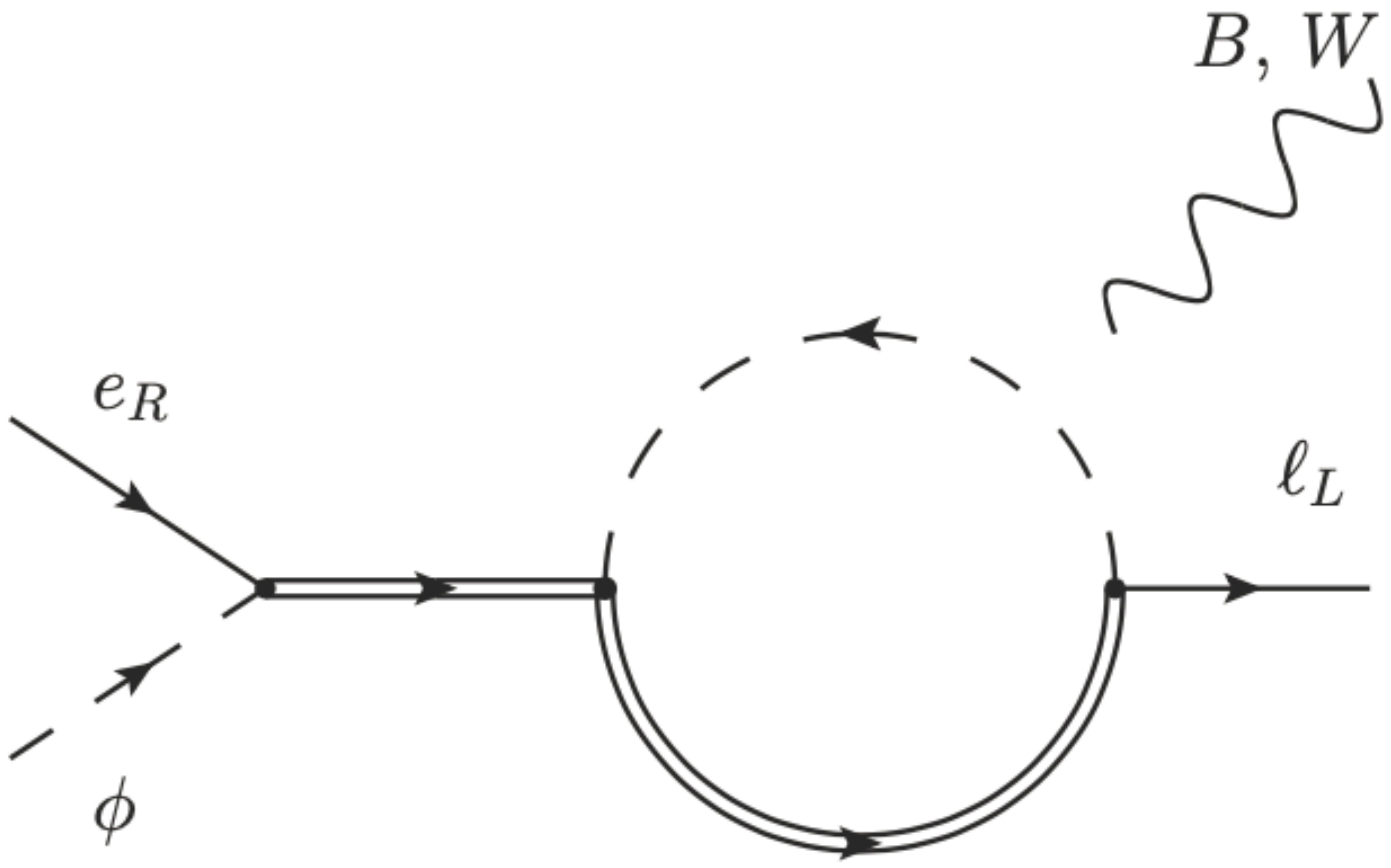
- General results:

$$\alpha_{e\gamma}^{2,2} = \frac{iN_c e}{4} y_M y_F y_b^R \sum_{IJ} T_{I2J} \left[\gamma_\Psi T_{I'I}^{\gamma,\Psi} T'_{2JI'} + \gamma_\Phi T_{JJ'}^{\gamma,\Phi} T'_{2IJ'} \right]$$

$$\gamma_\psi = \frac{-iM_\Psi}{(4\pi)^2 M_\Delta} \frac{M_\Psi^4 - 4M_\Psi^2 M_\Phi^2 + 3M_\Phi^4 + 2M_\Phi^4 \,\mathrm{Log}\left[M_\Psi^2/M_\Phi^2\right]}{(M_\Psi^2 - M_\Phi^2)^3} ,$$

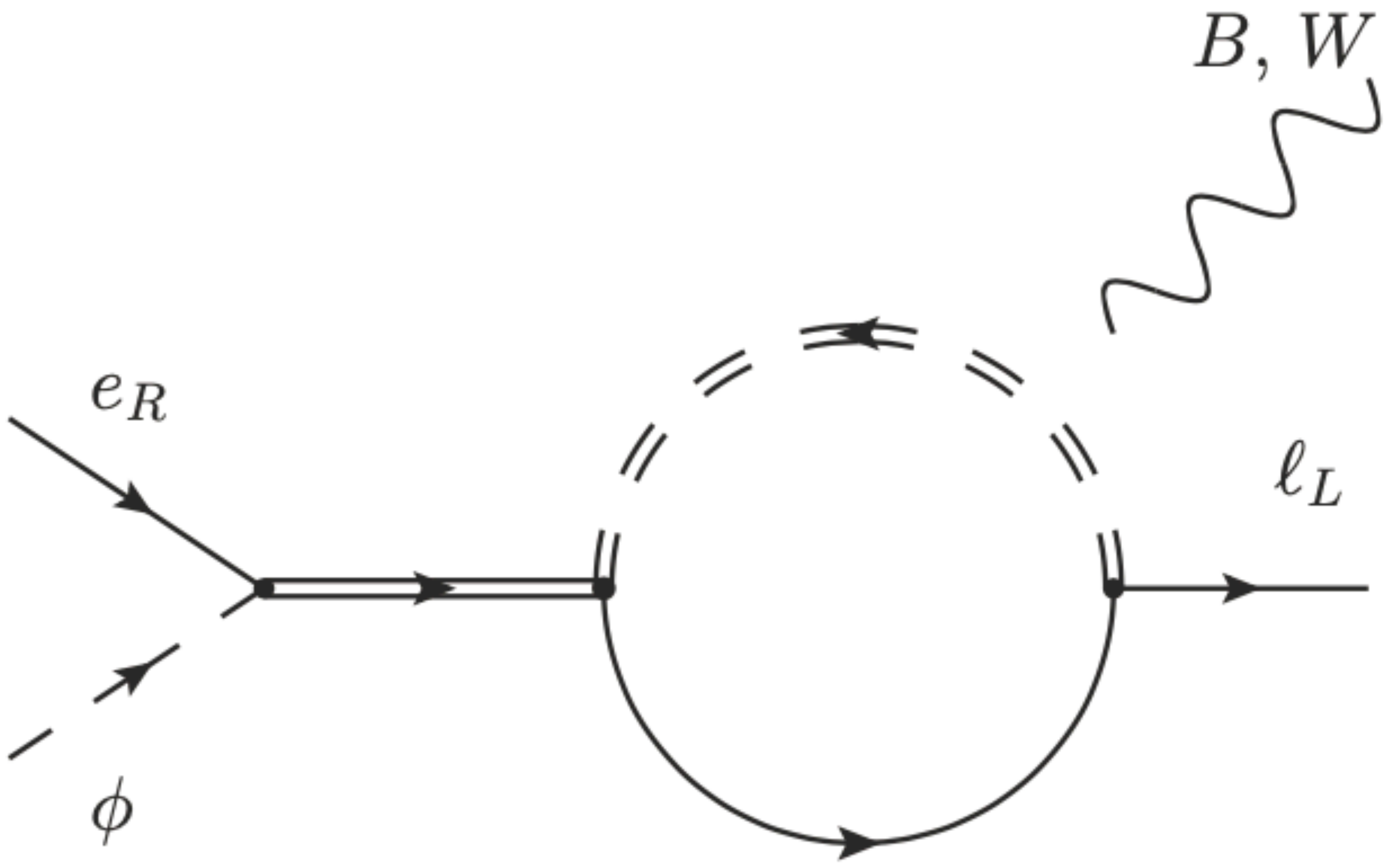
$$\gamma_\Phi = -\frac{iM_\Psi}{(4\pi)^2 M_\Delta} \frac{M_\Psi^4 - M_\Phi^4 - 2M_\Psi^2 M_\Phi^2 \,\mathrm{Log}\left[M_\Psi^2/M_\Phi^2\right]}{(M_\Psi^2 - M_\Phi^2)^3} .$$

2 field extensions



(a)

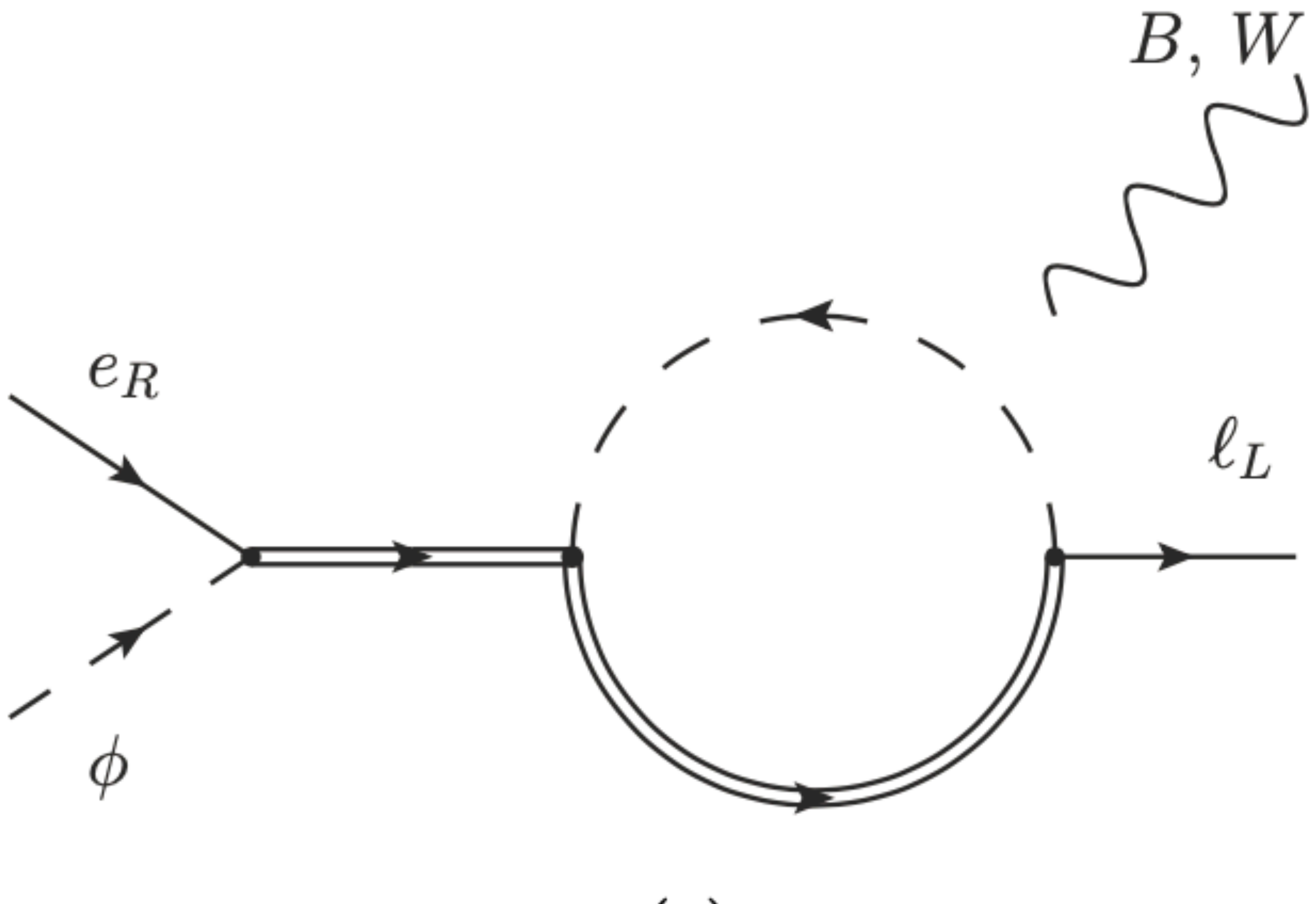
2 Fermion extension



(b)

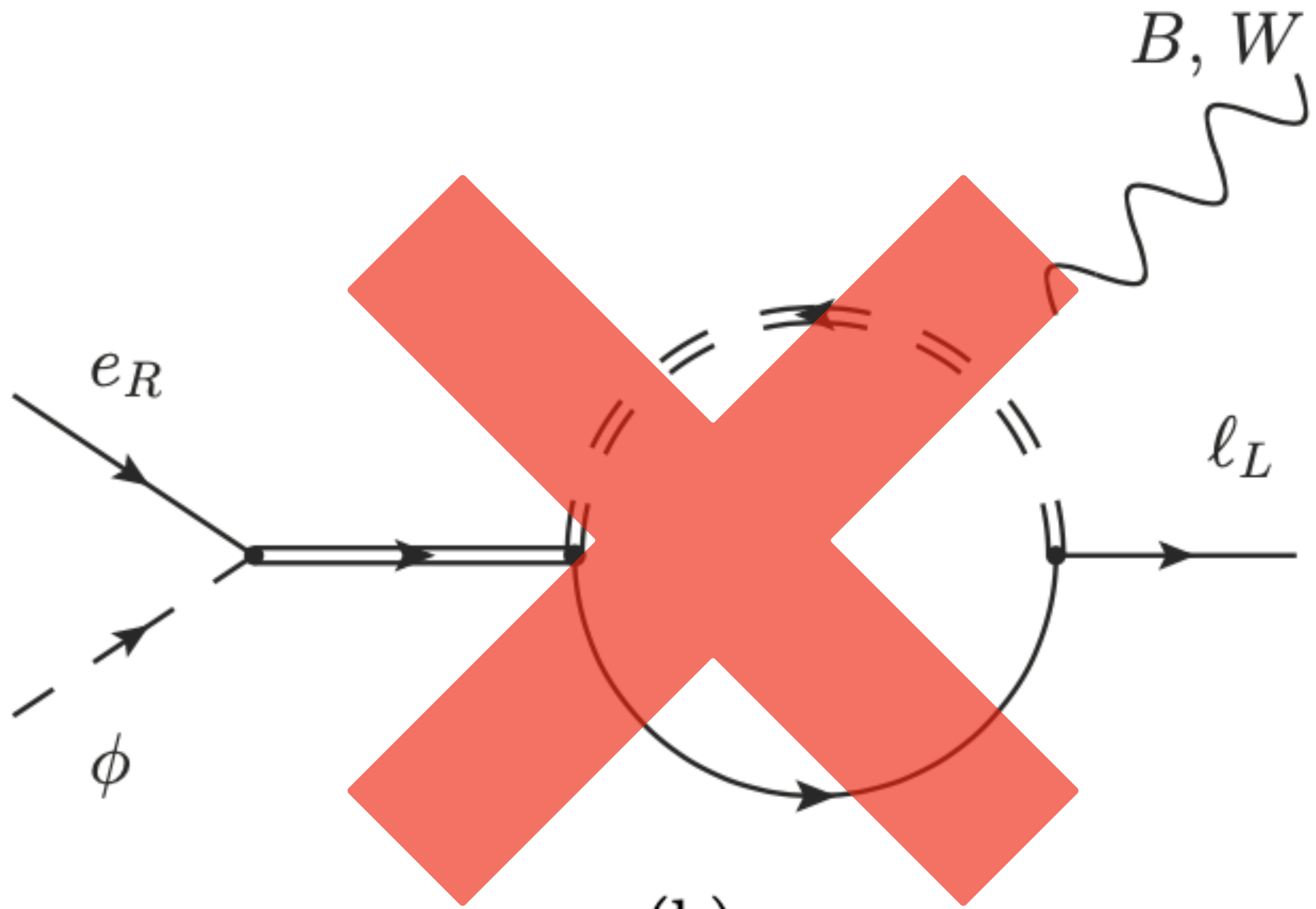
Fermion + Scalar extension

2 field extensions



(a)

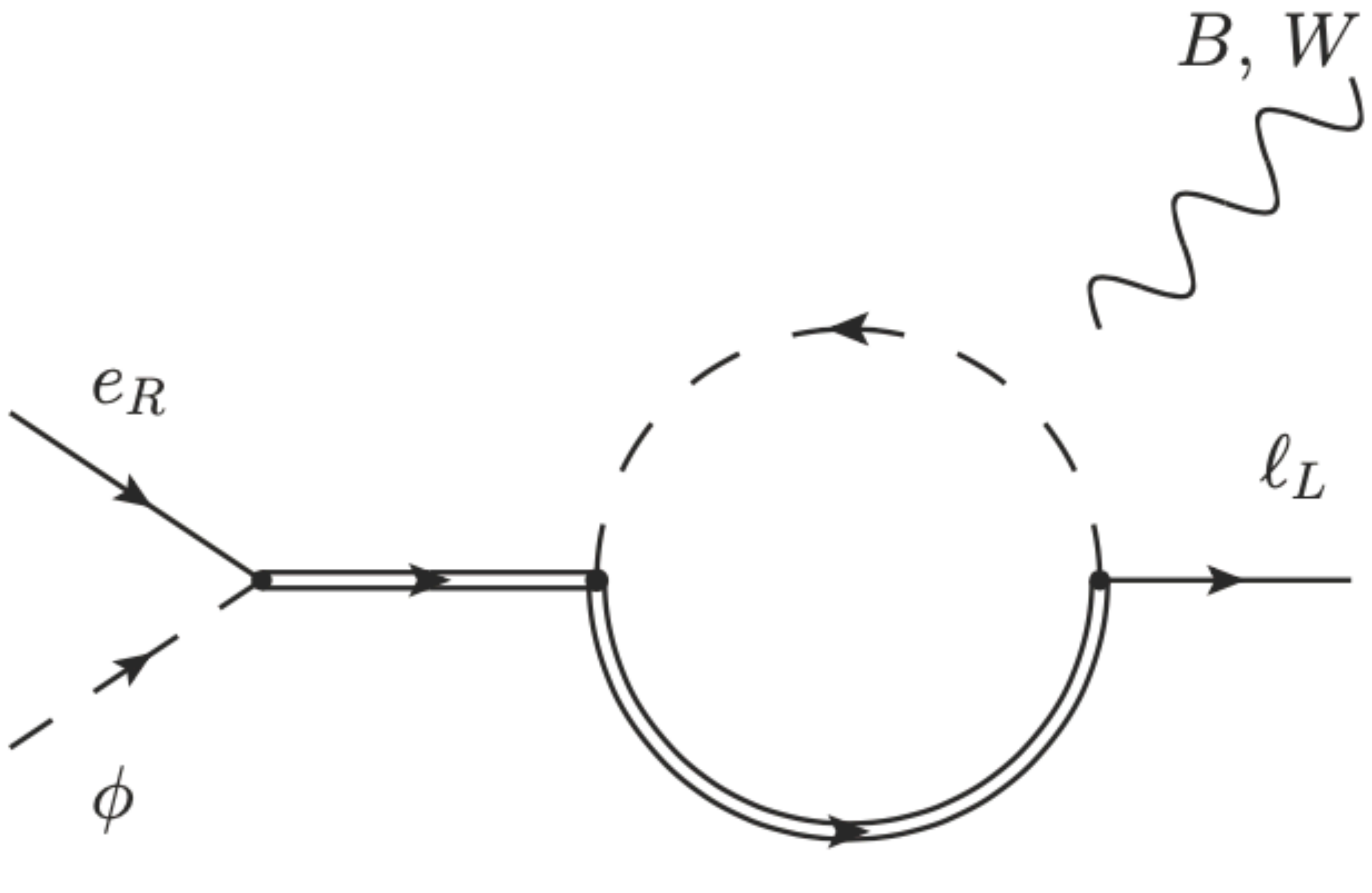
2 Fermion extension



(b)

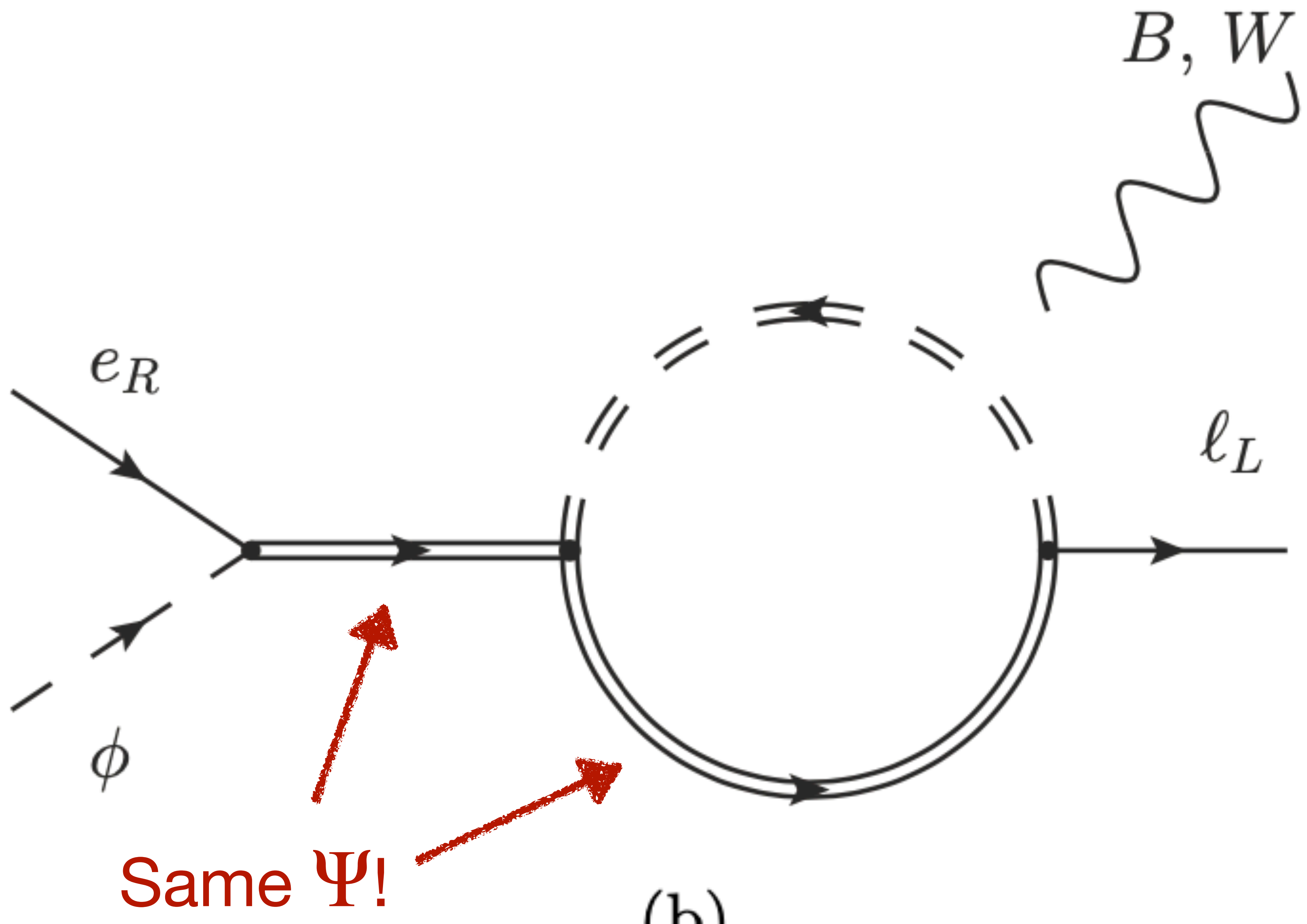
Fermion + Scalar extension

2 field extensions



(a)

2 Fermion extension



(b)

Fermion + Scalar extension

2 field extensions

Bridge	Other Fermion
$E \sim (1,1,-1)$	$\Delta \sim (1,2,-1/2)$
	$\Delta_3 \sim (1,2,-3/2)$
$\Delta \sim (1,2,-1/2)$	$E \sim (1,1,-1)$
	$\Sigma \sim (1,3,-1)$
	$N \sim (1,1,0)$
	$\Sigma_0 \sim (1,3,0)$
$\Sigma \sim (1,3,-1)$	$\Delta \sim (1,2,-1/2)$
	$\Delta_3 \sim (1,2,-3/2)$

[A. Freitas, J. Lykken, S. Kell, S. Westhoff, 1402.7065]

2 field extensions

Bridge	Other Fermion
$E \sim (1, 1, -1)$	$\Delta \sim (1, 2, -1/2)$
	$\Delta_3 \sim (1, 2, -3/2)$
$\Delta \sim (1, 2, -1/2)$	$E \sim (1, 1, -1)$
	$\Sigma \sim (1, 3, -1)$
	$N \sim (1, 1, 0)$
	$\Sigma_0 \sim (1, 3, 0)$
$\Sigma \sim (1, 3, -1)$	$\Delta \sim (1, 2, -1/2)$
	$\Delta_3 \sim (1, 2, -3/2)$

[A. Freitas, J. Lykken, S. Kell, S. Westhoff, 1402.7065]

[N. Arkani-Hamed and K. Harigaya, 2106.01373]

[N. Craig, I. Garcia, A. Vainshtein, Z. Zhang, 2112.05770]

[L. Rose, B. Harling and A. Pomarol, 2201.10572]

$$\Delta a_\mu = 0\,!$$

2 field extensions

Bridge	Other Fermion
$E \sim (1,1,-1)$	$\Delta \sim (1,2,-1/2)$
	$\Delta_3 \sim (1,2,-3/2)$
$\Delta \sim (1,2,-1/2)$	$E \sim (1,1,-1)$
	$\Sigma \sim (1,3,-1)$
	$N \sim (1,1,0)$
	$\Sigma_0 \sim (1,3,0)$
$\Sigma \sim (1,3,-1)$	$\Delta \sim (1,2,-1/2)$
	$\Delta_3 \sim (1,2,-3/2)$

Fermion	Scalar
$E \sim (1,1,-1)$	$\mathcal{S}_0 \sim (1,1,0)$
	$\mathcal{S}_2 \sim (1,1,-2)$
$\Delta \sim (1,2,-1/2)$	$\mathcal{S}_0 \sim (1,1,0)$
	$\mathcal{S}_1 \sim (1,1,-1)$
	$\Xi_0 \sim (1,3,0)$
	$\Xi_1 \sim (1,3,-1)$
$\Sigma \sim (1,3,-1)$	$\Xi_0 \sim (1,3,0)$
	$\Xi_2 \sim (1,3,-2)$

2 field extensions

Bridge	Other Fermion
$E \sim (1,1,-1)$	$\Delta \sim (1,2,-1/2)$
	$\Delta_3 \sim (1,2,-3/2)$
$\Delta \sim (1,2,-1/2)$	$E \sim (1,1,-1)$
	$\Sigma \sim (1,3,-1)$
	$N \sim (1,1,0)$
	$\Sigma_0 \sim (1,3,0)$
$\Sigma \sim (1,3,-1)$	$\Delta \sim (1,2,-1/2)$
	$\Delta_3 \sim (1,2,-3/2)$

Fermion	Scalar
$E \sim (1,1,-1)$	$\mathcal{S}_0 \sim (1,1,0)$
	$\mathcal{S}_2 \sim (1,1,-2)$
$\Delta \sim (1,2,-1/2)$	$\mathcal{S}_0 \sim (1,1,0)$
	$\mathcal{S}_1 \sim (1,1,-1)$
	$\Xi_0 \sim (1,3,0)$
	$\Xi_1 \sim (1,3,-1)$
$\Sigma \sim (1,3,-1)$	$\Xi_0 \sim (1,3,0)$
	$\Xi_2 \sim (1,3,-2)$

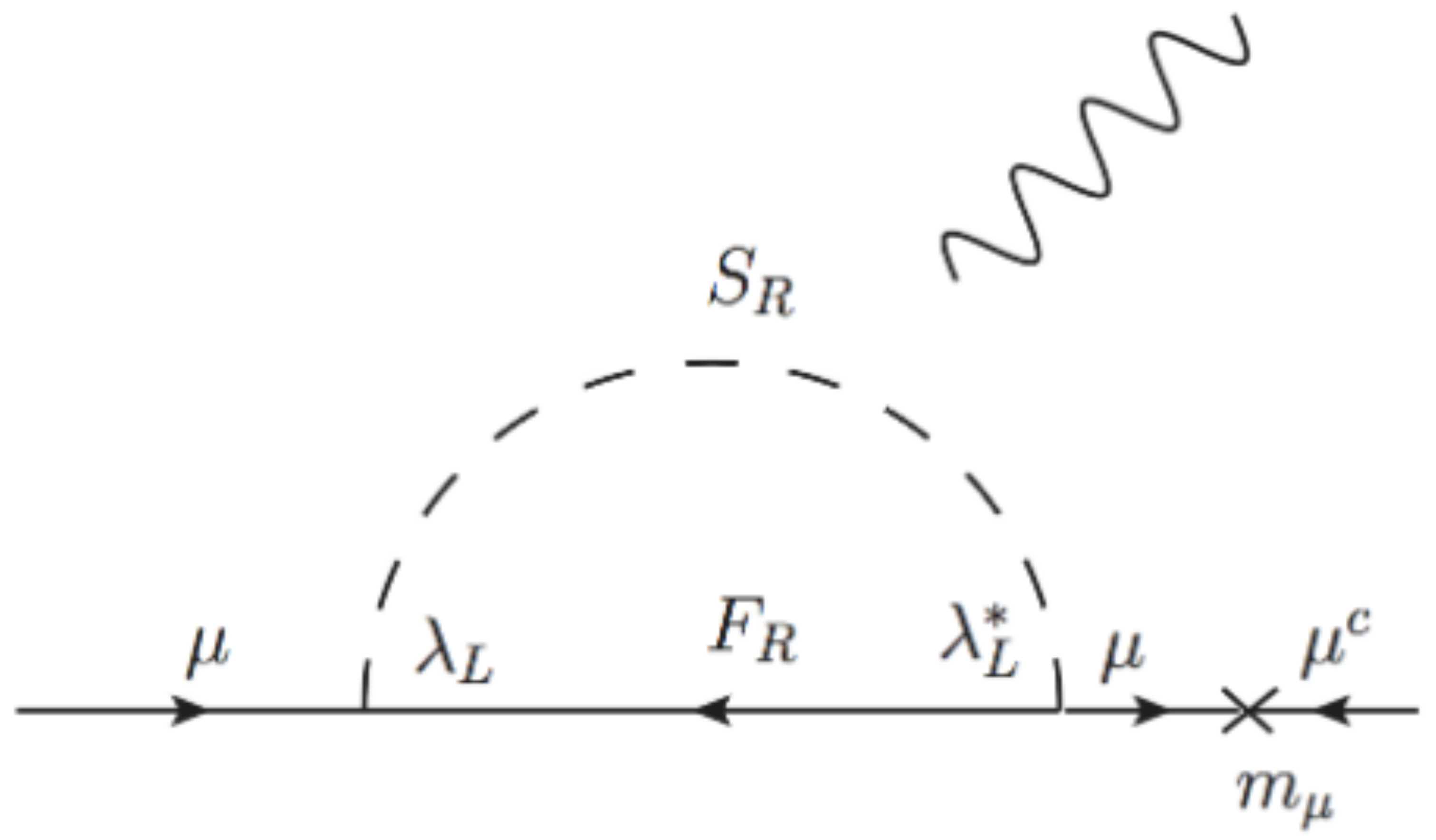
Excluded in the literature!

2 field extensions

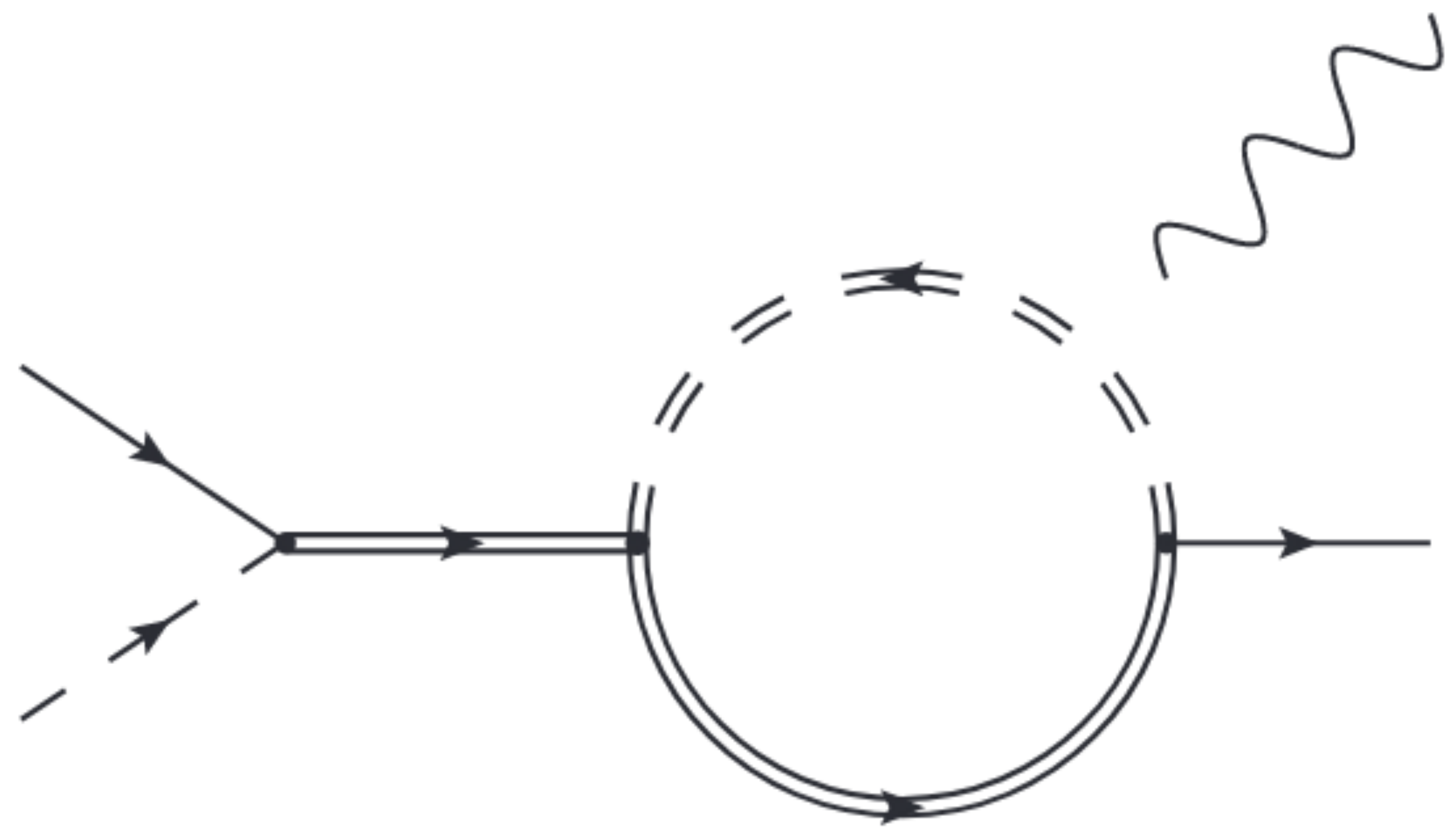
[P. Athron, C. Balázs, D. Jacob, W. Kotlarski, D. Stöckinger, H. Stöckinger-Kim, 2104.03691]

$$(\mathbf{1},\, \mathbf{3},\, 0)_0 \;\text{ and }\; (\mathbf{1},\, \mathbf{2},\, -1/2)_{1/2} \implies \Delta a_\mu < 0$$

(irrespective of $\mathbb{Z}_2$)



Yukawa-suppressed: <0



Bridge: no definite sign

$$\alpha_{e\gamma} = y_b y_M y_F f(M_\Delta, M_\Xi)$$

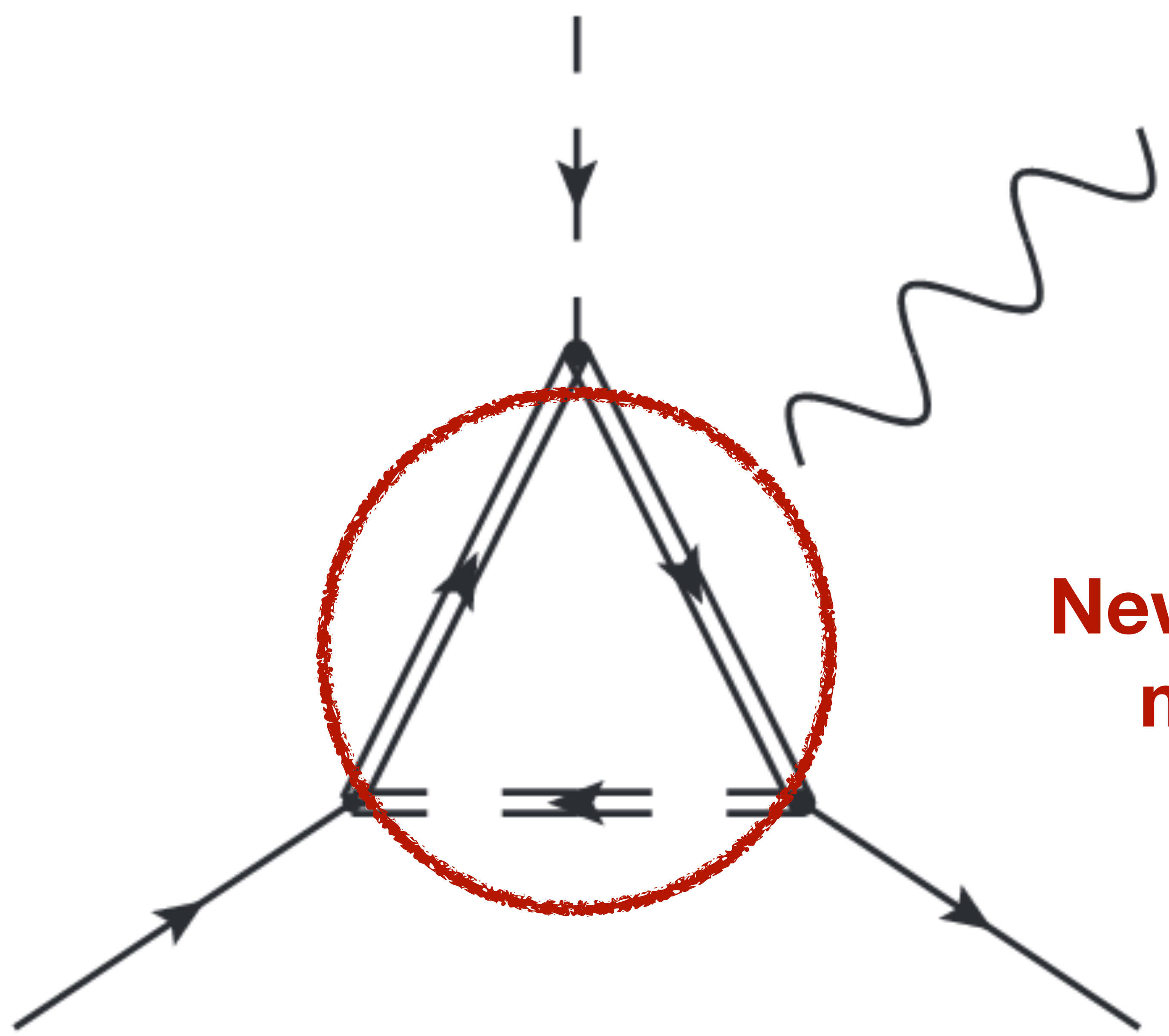
3 field extensions

Bridge	$(SU(2)_\Psi\,, SU(2)_\Phi)$
$E \sim (1,1,-1)$	(1,1)
	(2,2)
	(3,3)
$\Delta \sim (1,2,-1/2)$	(2,1)
	(2,3)
$\Sigma \sim (1,3,-1)$	(2,2)
	(3,3)

3 field extensions

Bridge	$(SU(2)_\Psi\,, SU(2)_\Phi)$
$E \sim (1,1,-1)$	(1,1)
	(2,2)
	(3,3)
$\Delta \sim (1,2,-1/2)$	(2,1)
	(2,3)
$\Sigma \sim (1,3,-1)$	(2,2)
	(3,3)

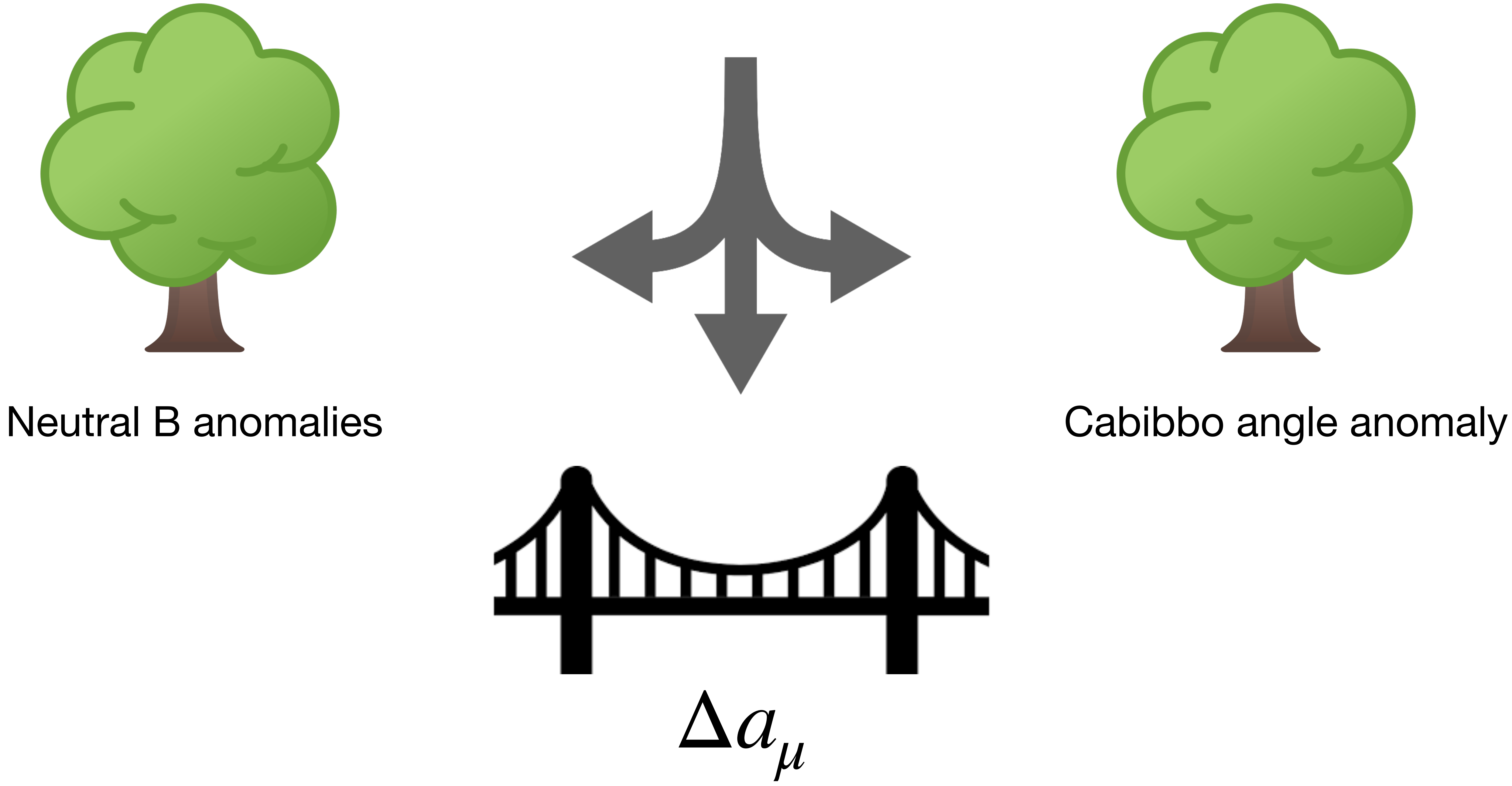
$\neq$



New class of models!

[A. Crivellin and M. Hoferichter, 2104.03202]
[L. Allwicher, L. Luzio, M. Fedele, F. Mescia, M. Nardecchia, 2105.13981]

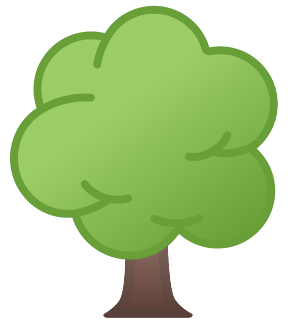
Connecting trees and bridges

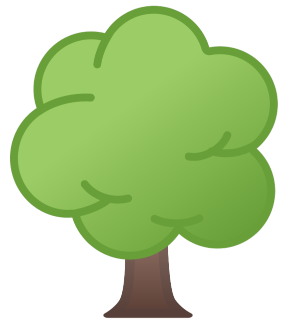


Connecting trees and bridges

- S_3 leptoquark $\sim (3,3,-1/3)$ to explain $R_K^{(*)}$. 🌳

Connecting trees and bridges

- S_3 leptoquark $\sim (3,3,-1/3)$ to explain $R_K^{(*)}$. 

- $\Sigma \sim (1,3,-1)$ to explain CAA. 

Tension between direct measurements of V_{us} and extraction from CKM unitarity (~3 σ depending on the parametrization of β decays).

$$R(V_{us}) = 1 - \left(\frac{V_{ud}}{V_{us}}\right)^2 v^2 \left[C_{H\ell}^{(3)}\right]_{22}$$

[M. Kirk, 2008.03261]
[A. Crivellin, F. Kirk, C. A. Manzari, M. Montull, 2008.01113]

Some tension with EWPD, worsened by CDF measurement.

Connecting trees and bridges

- S_3 leptoquark $\sim (3,3,-1/3)$ to explain $R_K^{(*)}$. 🌳

- $\Sigma \sim (1,3,-1)$ to explain CAA. 🌳

- $\Psi \sim (3,3,-4/3)$ to construct the bridge for Δa_μ 🌉

One loop phenomenology

Matchmakereft

A. Carmona, A. Lazopoulos, PO, J. Santiago
2112.10787

Automatic full one loop matching

One loop phenomenology

Matchma

A. Carmona, A. Lazopo
2112.1

Automatic full one

```
F[105] == {
  ClassName         -> FH,
  Indices           -> {Index[Colour],Index[SU2W]},
  SelfConjugate     -> False,
  QuantumNumbers -> {Y -> -4/3},
  FullName          -> "heavy",
  Mass              -> MF,
  Width             -> 0
},

F[107] == {
  ClassName         -> HTri,
  Indices           -> {Index[SU2W]},
  SelfConjugate     -> False,
  QuantumNumbers -> {Y -> -1},
  FullName          -> "heavy",
  Mass              -> MT,
  Width             -> 0
},

S[107] == {
  ClassName         -> SH,
  Indices           -> {Index[Colour],Index[SU2W]},
  SelfConjugate     -> False,
  QuantumNumbers -> {Y -> -1/3},
  FullName          -> "heavy",
  Mass              -> MS,
  Width             -> 0
}
```

One loop phenomenology

A. C

Au

```
  lag =
 yT[ff1] LLbar[sp1,ii,ff1].HTri[sp1,nn] Phi[jj] 2*Ta[nn,ii,jj]
 + yQ[ff1] FHbar[sp1,cc,ii].LR[sp1,ff1] SH[cc,ii]
 + YbridgeL HTribar[sp1,nn].left[FH[sp1,cc,ii]] SHbar[cc,jj]
I*fsu2[nn,ii,jj]
 + YbridgeR HTribar[sp1,nn].right[FH[sp1,cc,ii]] SHbar[cc,jj]
I*fsu2[nn,ii,jj]
 + lamS[ff1,ff2] CC[QLbar[sp1,ii,ff1,cc]].LL[sp1,kk,ff2]
Eps[ii,jj]2*Ta[nn,jj,kk] SHbar[cc,nn]
```

One loop phenomenology

Matchmakereft

$$\text{alphaOeW}[2,2] \to \frac{3\,\text{g2}\,\text{MF}\,\text{YbridgeR}\left(\text{MF}^2-\text{MS}^2-\text{MS}^2\,\text{Log}\left[\frac{\text{MF}^2}{\mu^2}\right]+\text{MS}^2\,\text{Log}\left[\frac{\text{MS}^2}{\mu^2}\right]\right)\text{yQ}[2]\times\text{yT}[2]}{16\left(\text{MF}^2-\text{MS}^2\right)^2\,\text{MT}\,\pi^2}$$

Automatic full one loop matching

One loop phenomenology

`Matchmakereft`

A. Carmona, A. Lazopoulos, PO, J. Santiago
2112.10787

Automatic full one loop matching

`smelli`

P. Stangl 2012.12211

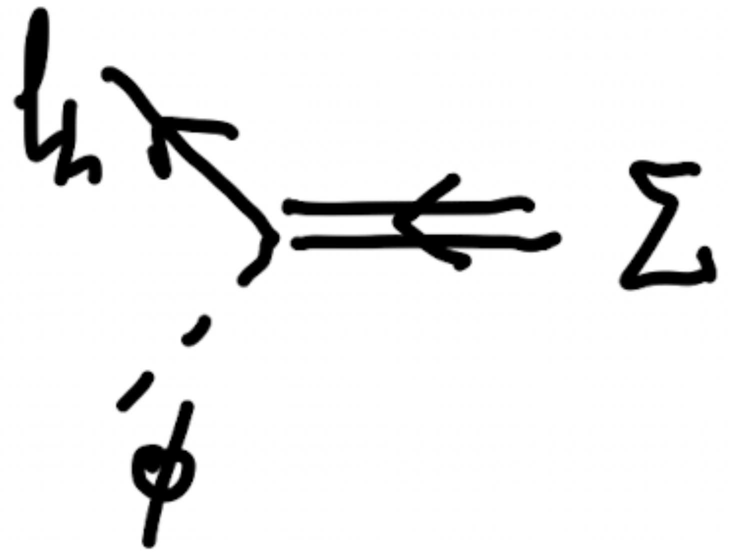
Fit to observables

One loop phenomenology

$$\mathcal{L} \supset y_T^i \bar{\ell}_{Li} \phi \sigma^I \Sigma_R^I + y_Q^i \overline{\Psi}_{QL}^I S_3^I \ell_{Ri} + y_b^L \epsilon^{IJK} \overline{\Sigma}_R^I \Psi_{Q,L}^J S_3^{K\dagger}$$
$$+ y_b^R \epsilon^{IJK} \overline{\Sigma}_L^I \Psi_{Q,R}^J S_3^{K\dagger} + \lambda_S^{ij} \overline{Q}_{Li}^c i\sigma^2 \sigma^I \ell_{Lj} S_3^{I\dagger} + \text{h.c.}$$

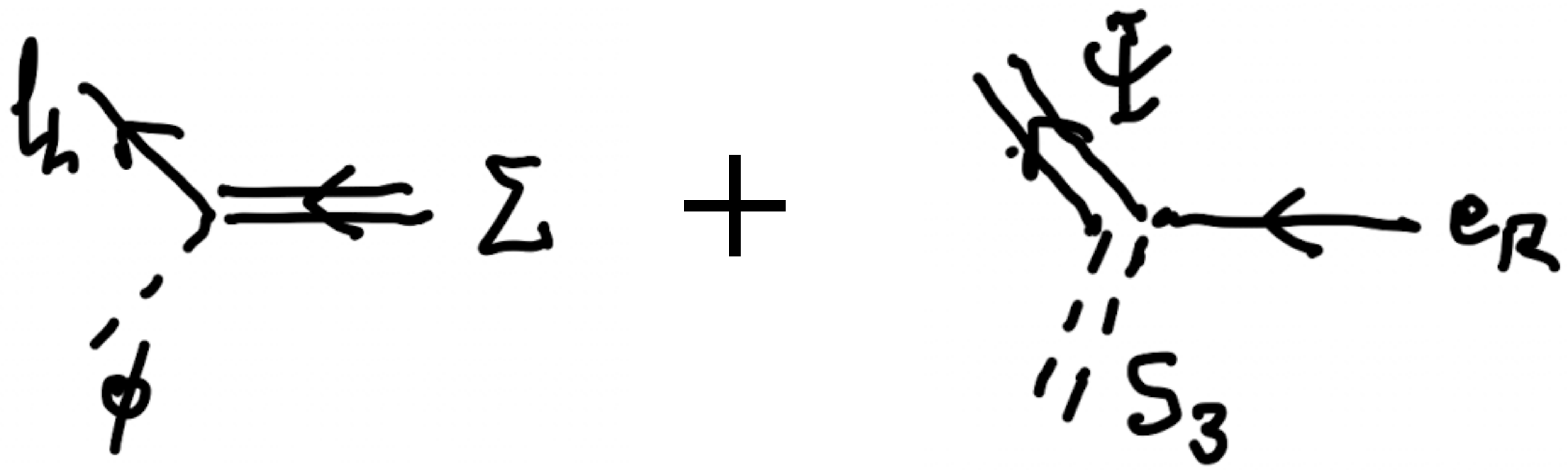
One loop phenomenology

$$\mathcal{L} \supset y_T^i \bar{\ell}_{Li} \phi \sigma^I \Sigma_R^I + y_Q^i \overline{\Psi}_{QL}^I S_3^I \ell_{Ri} + y_b^L \epsilon^{IJK} \overline{\Sigma}_R^I \Psi_{Q,L}^J S_3^{K\dagger}$$
$$+ y_b^R \epsilon^{IJK} \overline{\Sigma}_L^I \Psi_{Q,R}^J S_3^{K\dagger} + \lambda_S^{ij} \overline{Q}_{Li}^c i\sigma^2 \sigma^I \ell_{Lj} S_3^{I\dagger} + \text{h.c.}$$



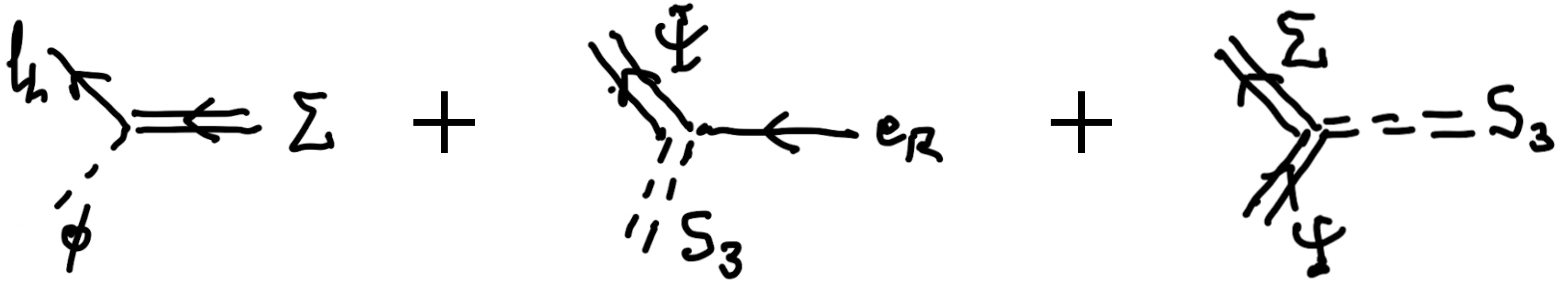
One loop phenomenology

$$\mathcal{L} \supset y_T^i \bar{\ell}_{Li} \phi \sigma^I \Sigma_R^I + y_Q^i \overline{\Psi}_{QL}^I S_3^I \ell_{Ri} + y_b^L \epsilon^{IJK} \overline{\Sigma}_R^I \Psi_{Q,L}^J S_3^{K\dagger}$$
$$+ y_b^R \epsilon^{IJK} \overline{\Sigma}_L^I \Psi_{Q,R}^J S_3^{K\dagger} + \lambda_S^{ij} \overline{Q}_{Li}^c i\sigma^2 \sigma^I \ell_{Lj} S_3^{I\dagger} + \text{h.c.}$$



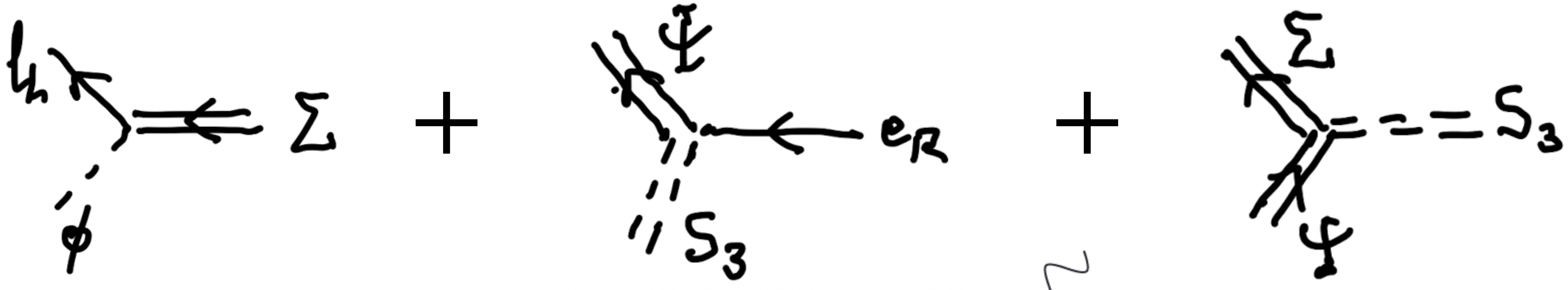
One loop phenomenology

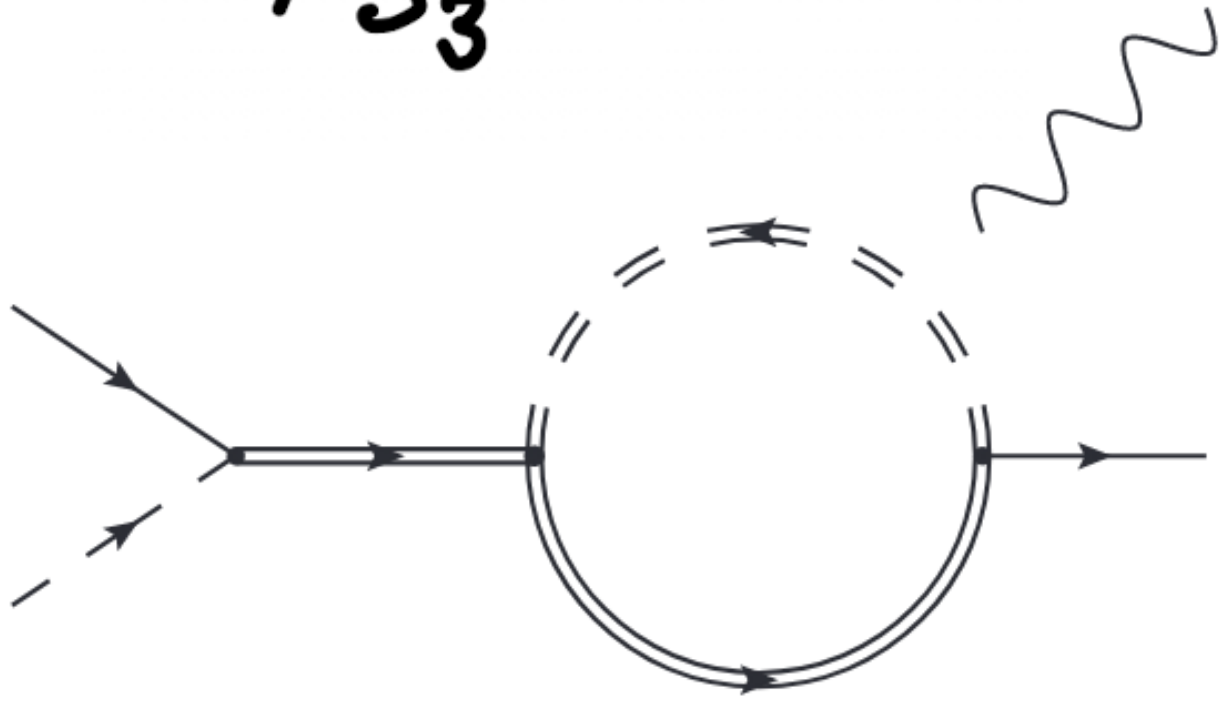
$$\mathcal{L} \supset y_T^i \bar{\ell}_{Li}\phi\sigma^I\Sigma_R^I + y_Q^i \overline{\Psi}_{QL}^I S_3^I \ell_{Ri} + y_b^L \epsilon^{IJK}\overline{\Sigma}_R^I \Psi_{Q,L}^J S_3^{K\dagger} + y_b^R \epsilon^{IJK}\overline{\Sigma}_L^I \Psi_{Q,R}^J S_3^{K\dagger} + \lambda_S^{ij}\overline{Q}_{Li}^c i\sigma^2\sigma^I \ell_{Lj} S_3^{I\dagger} + \text{h.c.}$$



One loop phenomenology

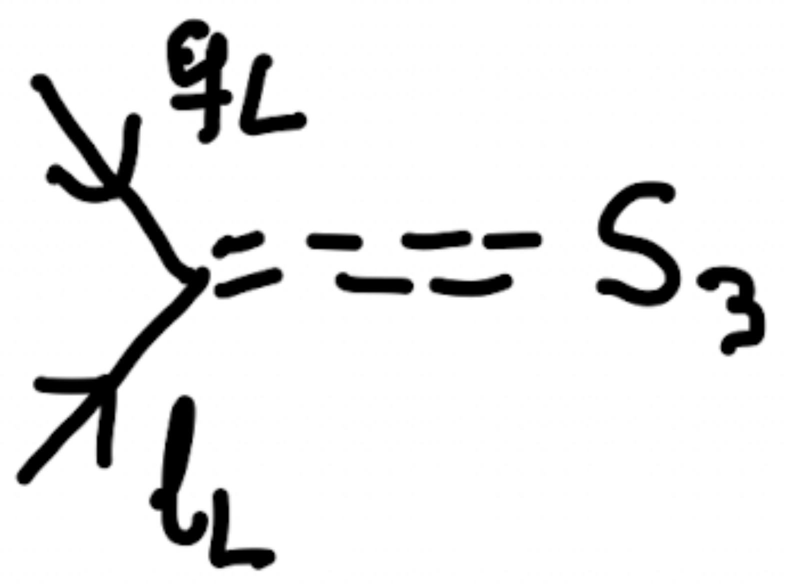
$$\mathcal{L} \supset y_T^i \bar{\ell}_{Li} \phi \sigma^I \Sigma_R^I + y_Q^i \overline{\Psi}_{QL}^I S_3^I \ell_{Ri} + y_b^L \epsilon^{IJK} \overline{\Sigma}_R^I \Psi_{Q,L}^J S_3^{K\dagger}$$
$$+ y_b^R \epsilon^{IJK} \overline{\Sigma}_L^I \Psi_{Q,R}^J S_3^{K\dagger} + \lambda_S^{ij} \overline{Q}_{Li}^c i\sigma^2 \sigma^I \ell_{Lj} S_3^{I\dagger} + \text{h.c.}$$





One loop phenomenology

$$\mathcal{L} \supset y_T^i \bar{\ell}_{Li} \phi \sigma^I \Sigma_R^I + y_Q^i \overline{\Psi}_{QL}^I S_3^I \ell_{Ri} + y_b^L \epsilon^{IJK} \overline{\Sigma}_R^I \Psi_{Q,L}^J S_3^{K\dagger}$$
$$+ y_b^R \epsilon^{IJK} \overline{\Sigma}_L^I \Psi_{Q,R}^J S_3^{K\dagger} + \lambda_S^{ij} \overline{Q}_{Li}^c i\sigma^2 \sigma^I \ell_{Lj} S_3^{I\dagger} + \text{h.c.}$$



One loop phenomenology

$$\mathcal{L} \supset y_T^i \bar{\ell}_{Li}\phi\sigma^I\Sigma_R^I + y_Q^i \overline{\Psi}_{QL}^I S_3^I \ell_{Ri} + y_b^L \epsilon^{IJK}\overline{\Sigma}_R^I \Psi_{Q,L}^J S_3^{K\dagger}$$
$$+ y_b^R \epsilon^{IJK}\overline{\Sigma}_L^I \Psi_{Q,R}^J S_3^{K\dagger} + \lambda_S^{ij}\overline{Q}_{Li}^c i\sigma^2\sigma^I \ell_{Lj} S_3^{I\dagger} + \text{h.c.}$$

Defining the ratios: $x_T \equiv y_T^\mu / M_T$ $\quad x_F \equiv y_Q^\mu / M_F$ $\quad x_S \equiv \lambda_S^{*s\mu}\lambda_S^{b\mu}/M_S^2$

Some considerations:

- x_T bounded from EWPO: $v\, x_T \leq 0.1(0.11)$
- No correction to the muon Yukawa!

One loop phenomenology

$$\mathcal{L} \supset y_T^i \overline{\ell}_{Li} \phi \sigma^I \Sigma_R^I + y_Q^i \overline{\Psi}_{QL}^I S_3^I \ell_{Ri} + y_b^L \epsilon^{IJK} \overline{\Sigma}_R^I \Psi_{Q,L}^J S_3^{K\dagger}$$
$$+ y_b^R \epsilon^{IJK} \overline{\Sigma}_L^I \Psi_{Q,R}^J S_3^{K\dagger} + \lambda_S^{ij} \overline{Q}_{Li}^c i\sigma^2 \sigma^I \ell_{Lj} S_3^{I\dagger} + \text{h.c.}$$

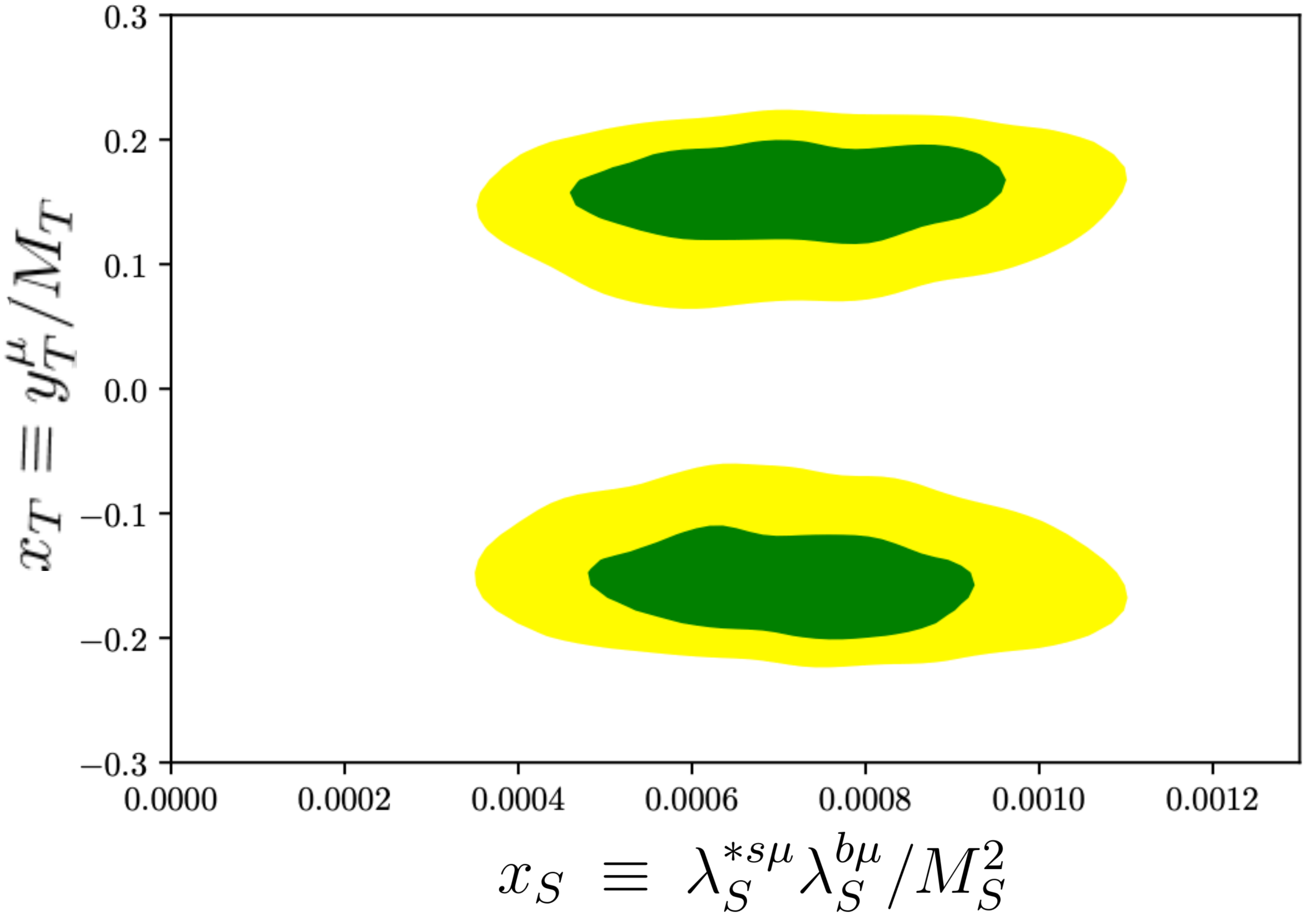
Defining the ratios: $x_T \equiv y_T^\mu / M_T$ $\quad x_F \equiv y_Q^\mu / M_F$ $\quad x_S \equiv \lambda_S^{*s\mu} \lambda_S^{b\mu} / M_S^2$

We find the best fit point:

$$M_{S_3} = 2 \text{ TeV}$$
$$M_\Sigma = 3.4 \text{ TeV}$$
$$M_{\Psi_Q} = 4.6 \text{ TeV}$$

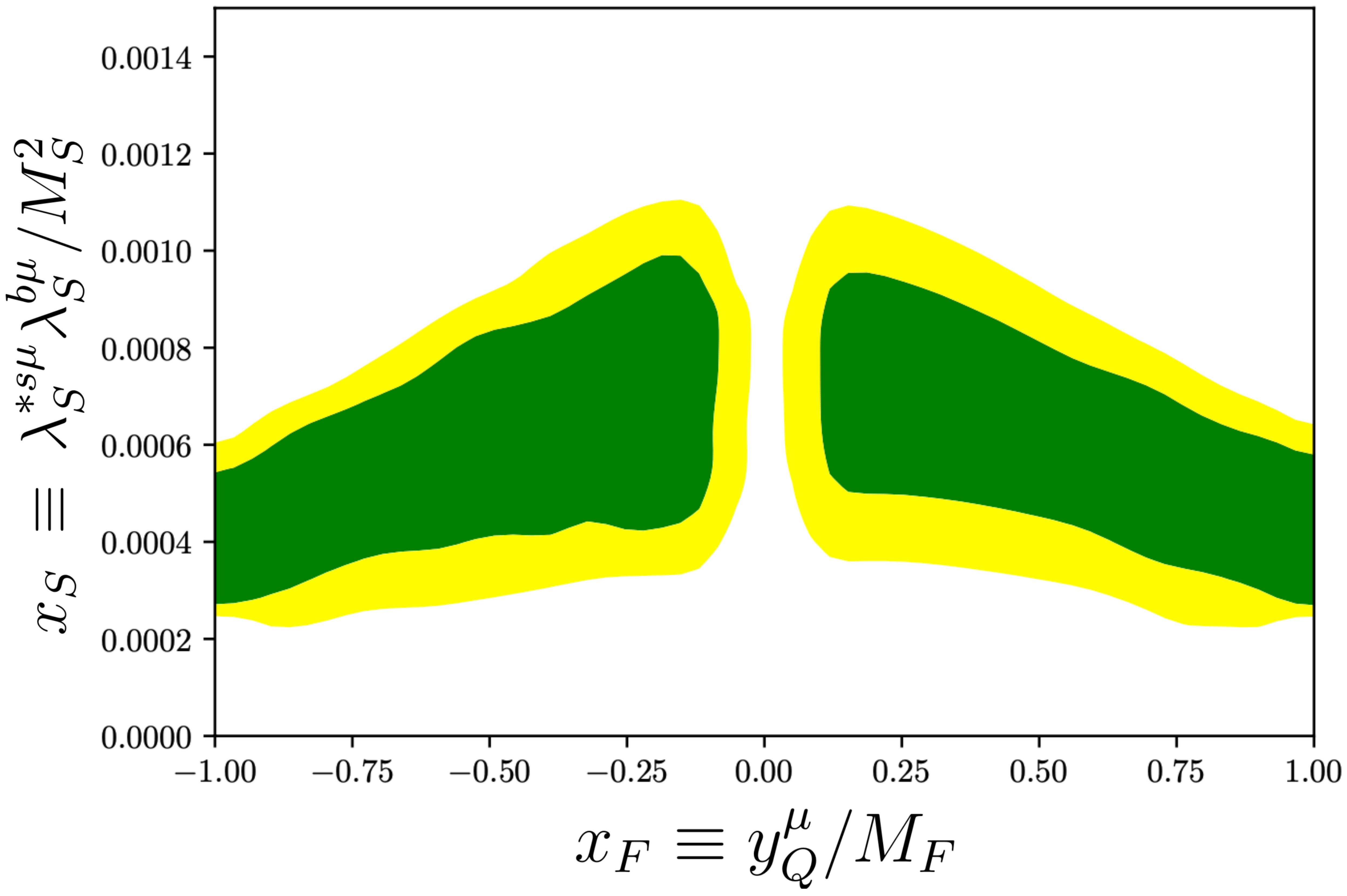
$x_F = 0.2 \ \text{TeV}^{-1}$	$x_S = 0.00078 \ \text{TeV}^{-2}$
$x_T = 0.17 \ \text{TeV}^{-1}$	$\lambda_S^{b\mu} = 0.07$
$y_b^L = 0.10$	$y_b^R = 0.13$

One loop phenomenology



- Results as expected from tree-level solutions.

One loop phenomenology



- Results as expected from tree-level solutions.
- Broad parameter space for couplings entering at one-loop.

Conclusions

- We have classified and computed all possible bridge contributions to g-2.
- This opens new possibilities for SM extensions explaining this anomaly.
- A thorough classification still needed at one-loop.
- A complete classification of one-loop solutions to anomalies can be helpful to connect tree-level ones.

Thanks for your attention!