2203.10111 (**Andreas Crivellin**, **Benjamin Fuks**, LS)

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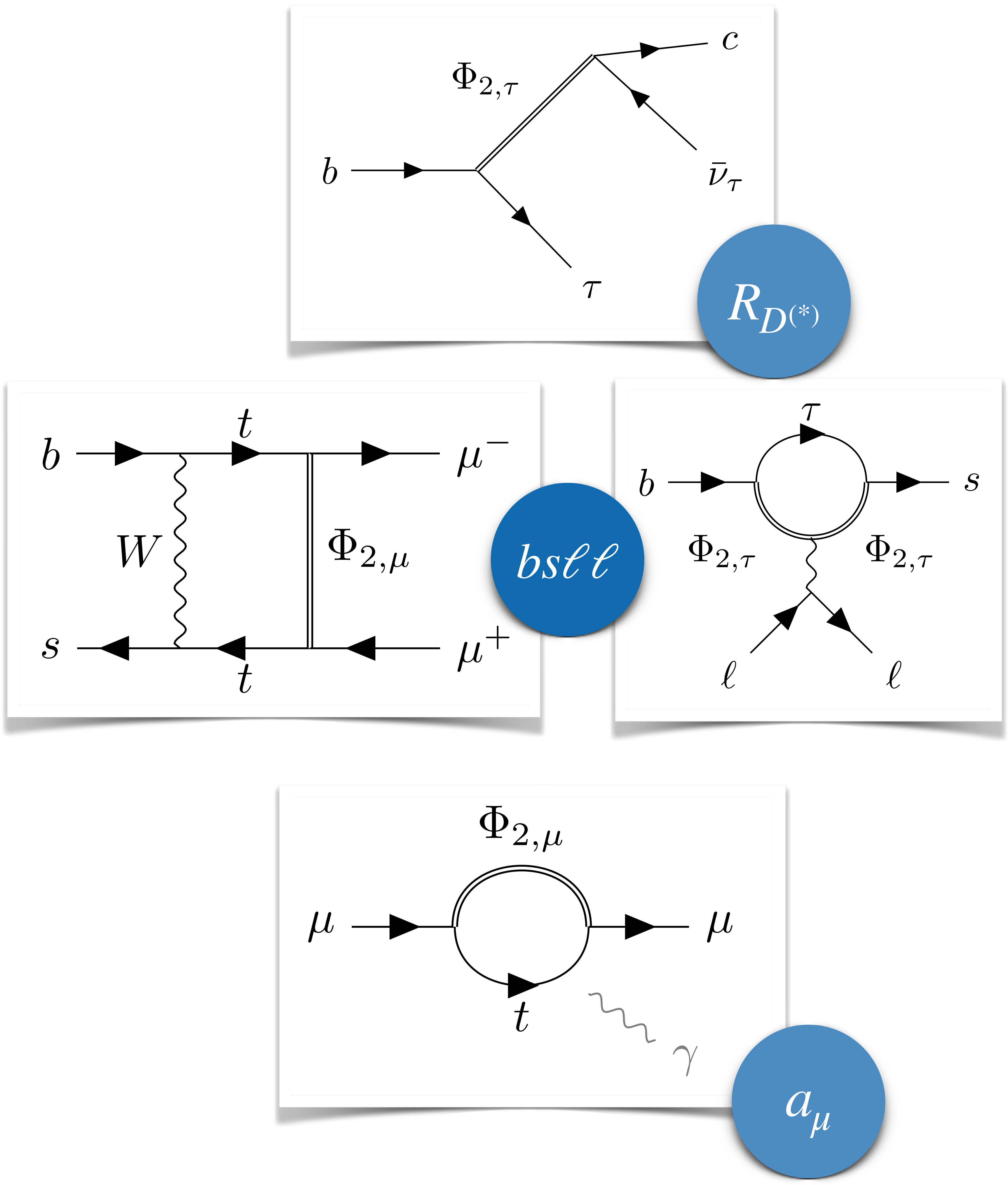
Explaining the Hints for Lepton Flavour Universality Violation with Three S_2 Leptoquark Generations

Luc Schnell

Flavor at the Crossroads
April 27, 2022



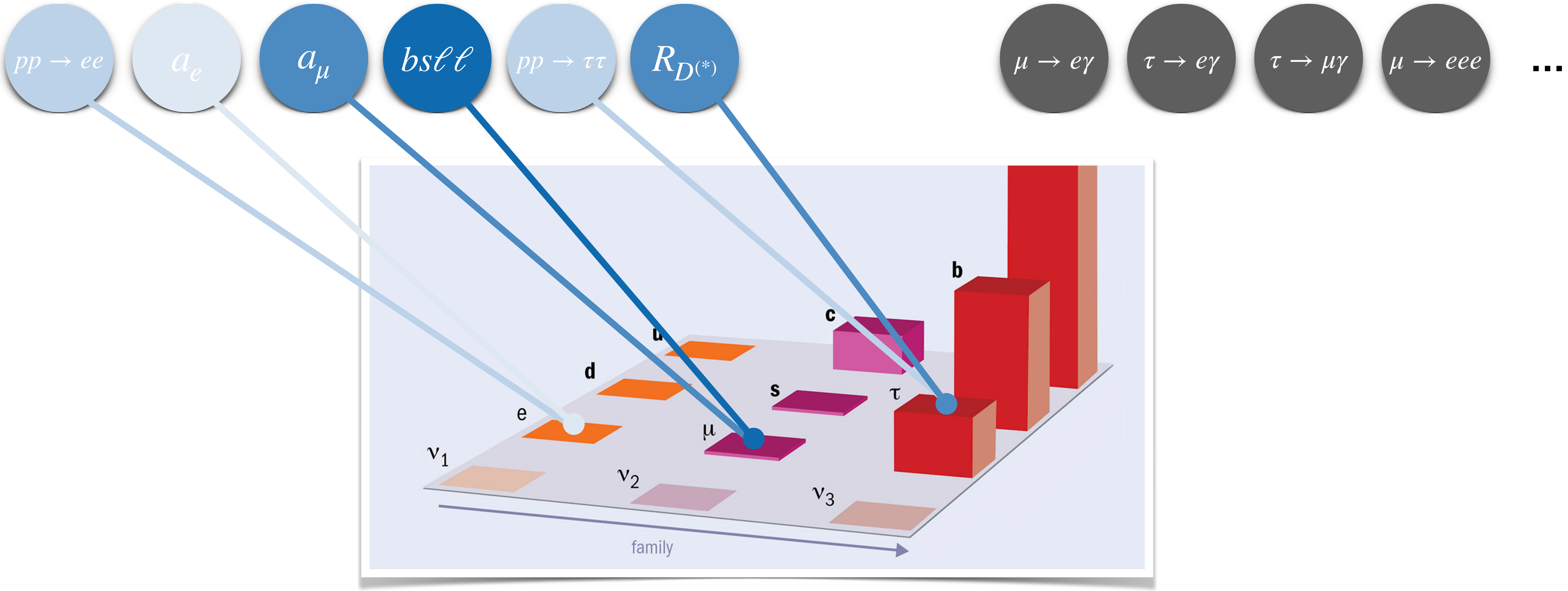
1. Motivation and Setup

1. Motivation and Setup

1.1 Flavour Anomalies

Hints for Lepton Flavour Universality Violation

No Hints for Charged Lepton Flavour Violation



Source: cerncourier.com

1. Motivation and Setup

1.2 Single Leptoquark Solutions

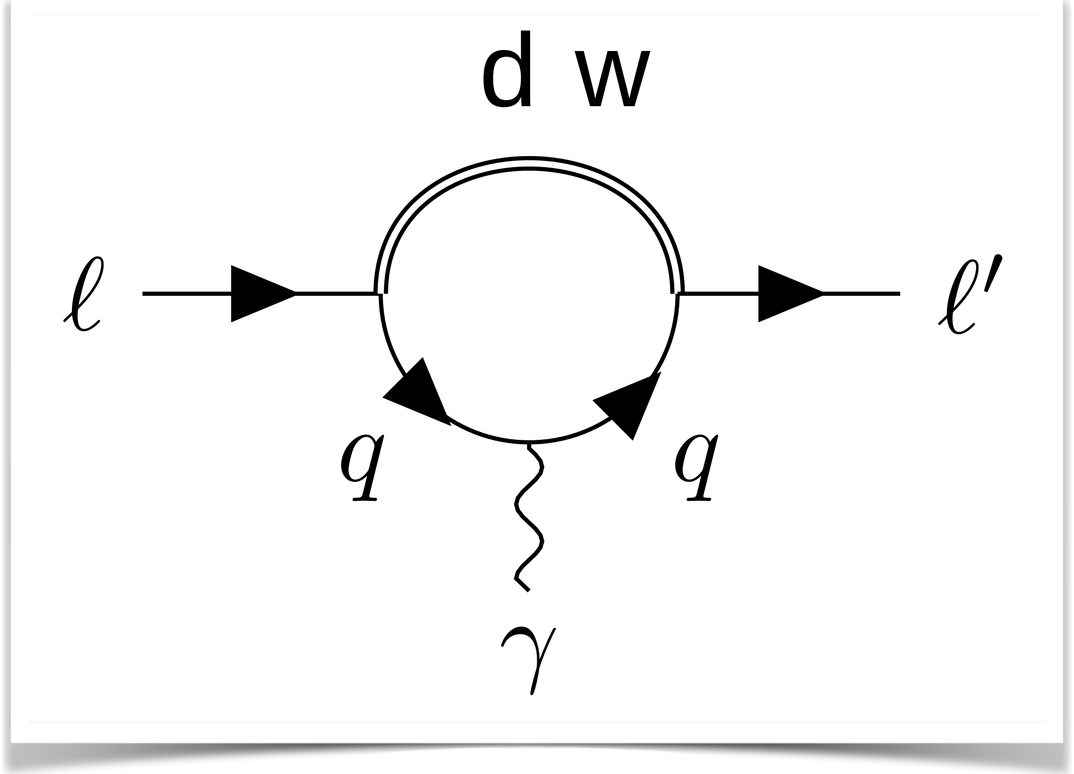
Also called R_2: $\left(\mathbf{3}, \mathbf{2}, \frac{7}{6}\right)$

Hints for Lepton Flavour Universality Violation

Leptoquark Representations	a_μ	$bs\ell\ell$	$R_{D^{(*)}}$	**Combined**
$\mathbf{S_1}$	✓	✗	✓	✗
$\mathbf{S_2}$	✓	—	✓	✗
$\mathbf{S_3}$	✗	✓	✗	✗
$\mathbf{U_1}$	✓	✓	✓	✗

Sources: 2103.12504 (Angelescu et al.), 2104.06656 (Ban et al.), 2002.12544 (Bigaran et al.), 1903.11517 (Cornella et al.), 2104.05685 (Du et al.)

$\mu \to e\gamma$ $\tau \to e\gamma$ $\tau \to \mu\gamma$ $\mu \to 3e$ ...



$$\mathcal{L}_{\rm eff} \supset -e\, v\, \bar{\ell}^i_{\rm L} \sigma^{\mu\nu} \ell^j_{\rm R} F_{\mu\nu}/(4\pi\Lambda_{ij})^2 + {\rm h.c.},$$

$$\Lambda_{22} \simeq 15\ {\rm TeV}$$

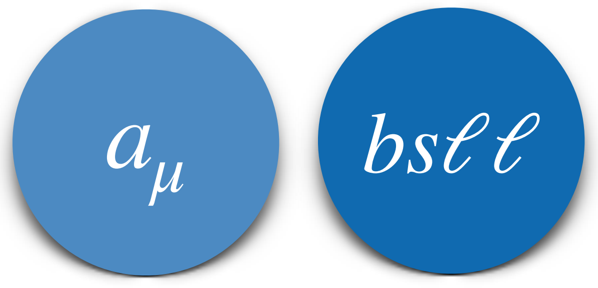
$$\Lambda_{12(21)} \gtrsim 3600\ {\rm TeV} \qquad \Lambda_{12(21)}\sqrt{m_e/m_\mu} \gtrsim 250\ {\rm TeV}$$

Source: 2107.07518 (Greljo, Soreq, Stangl, Thomsen, Zupan)

1. Motivation and Setup

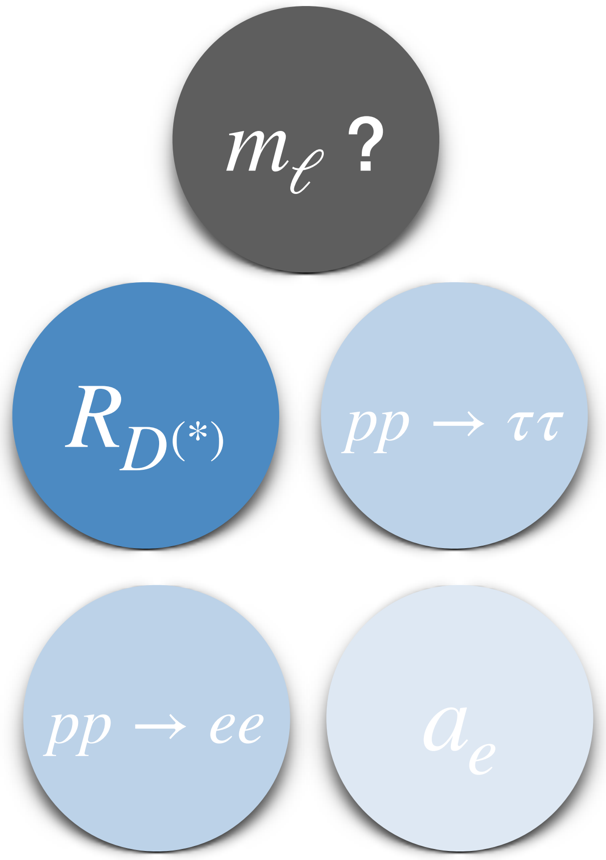
1.3 Leptoquarks with Lepton Flavour

- 2107.07518 (Greljo, Soreq, Stangl, Thomsen, Zupan) introduced a theoretical framework for **muoquarks**, LQs that only couple to muons.



- This can e.g. be achieved via appropriate $U(1)_X$ gauge extensions of the SM.
  - $X_H = 0, \qquad X_{Q_i} = X_{U_j} = X_{D_k} \equiv X_q$ for $i, j, k = 1,2,3$
  - $X_{\ell_2} \neq X_{\ell_{1,3}}$ for $\ell = L, E$ $\rightarrow$ if LQs have appropriate charges, they **couple exclusively to muons**.

- This is an economic framework for **joint explanations of the muon anomalies**. But it gives the muon a special treatment and leaves out the other anomalies.



$\rightarrow$ **Can this be extended to three generations?**

1. Motivation and Setup

1.4 Three Leptoquark Generations

- Three LQ generations that couple to one lepton flavour each (**tauquark**, **muoquark**, **electroquark**)
  - $X_H = 0, \qquad X_{Q_i} = X_{U_j} = X_{D_k} \equiv X_q$ for $i, j, k = 1,2,3$
  - $X_{\ell_1}, X_{\ell_2}, X_{\ell_3}$ pairwise different for $\ell = L, E$
- This is still satisfied by **234** charge assignments for $U(1)_X$ where $-10 \leq X_{F_i} \leq 10$ for all SM fermions (before it was **273**). A possible solution is $L_\mu - L_\tau$.

	a_μ	$bs\ell\ell$	$R_{D^{(*)}}$	**Combined**
$\mathbf{S_2}$	✔	—	✔	✘

Sources: 2103.12504 (Angelescu et al.), 2002.12544 (Bigaran et al.)

- Di-quark couplings not possible $\rightarrow$ no proton decay
- Radiative generation of charged lepton masses

m_ℓ ?

1. Motivation and Setup

1.5 Lagrangian

$$\mathcal{L}_{\rm LQ} = \left(Y^{RL}_{ij}\bar{u}_i\left[\Phi_2 \cdot L_j\right] + Y^{LR}_{ij}\left[\bar{Q}_i e_j \Phi_2\right] + \text{ H.c.}\right) - \left(M^2 + Y^{H(1)}\left[H^\dagger H\right]\right)\Phi_2^\dagger \Phi_2$$
$$- Y^{H(3)}\left[H \cdot \Phi_2\right]^\dagger \left[H \cdot \Phi_2\right] + \mathcal{L}_{4\Phi}\,,$$

Complete SLQ Lagrangian in 2105.04844 (Crivellin, LS)

Three LQ generations with lepton flavours.

$$\mathcal{L}_{\rm LQ} = \sum_\ell \left(Y^{RL}_{i\ell}\bar{u}_i\left[\Phi_{2,\ell} \cdot L_\ell\right] + Y^{LR}_{i\ell}\left[\bar{Q}_i e_\ell \Phi_{2,\ell}\right] + \text{ H.c.}\right)$$
$$- \left(M_\ell^2 + Y_\ell^{H(1)}\left[H^\dagger H\right]\right)\Phi_{2,\ell}^\dagger \Phi_{2,\ell} - Y_\ell^{H(3)}\left[H \cdot \Phi_{2,\ell}\right]^\dagger \left[H \cdot \Phi_{2,\ell}\right] + \mathcal{L}_{4\Phi}\,.$$

Source: 2203.10111 (Crivellin, Fuks, LS)

2. Phenomenology

2.1 Tauquark

2.2 Tauquark and Muoquark

2.3 Muoquark

2.4 Electroquark

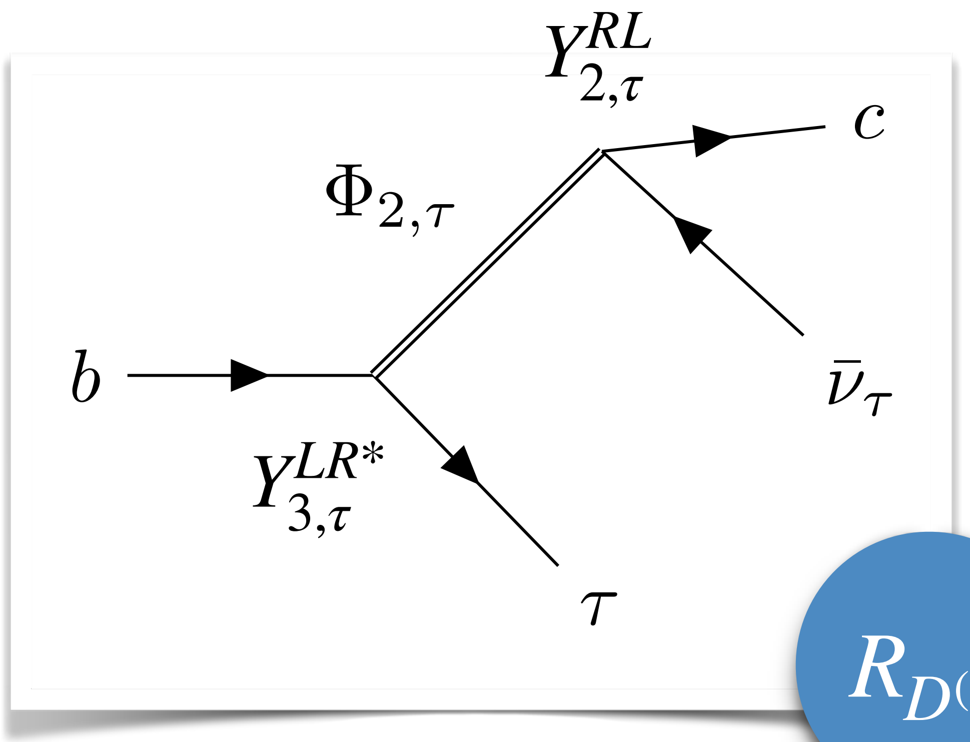
2.5 Higgs Couplings

2. Phenomenology

2.1 Tauquark

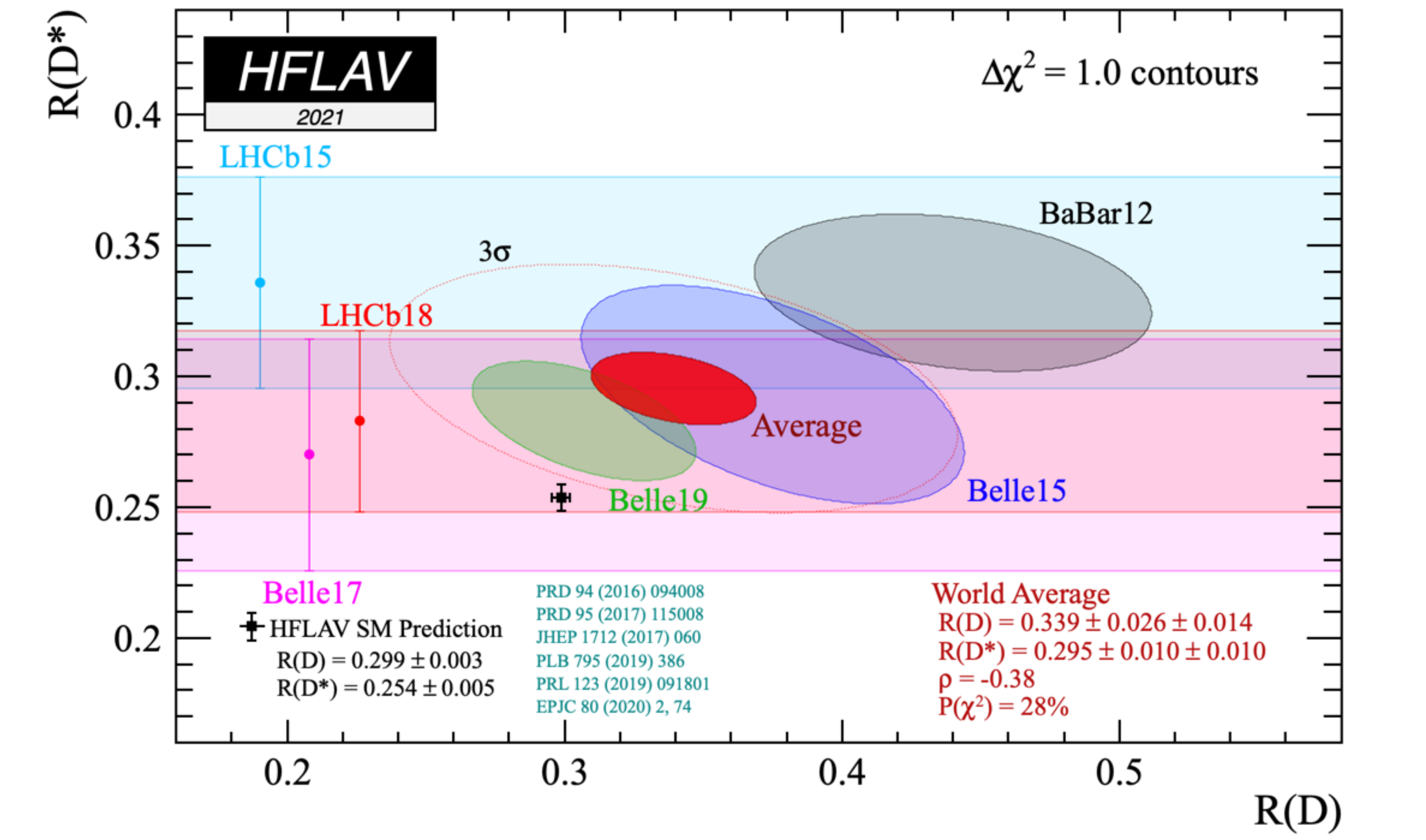
$R_{D^{(*)}}$ Anomaly

- $> 3\sigma$ deviation from SM predictions in $R_{D^{(*)}}$.
- In our model we get a **tree-level** contribution to $C_{S_L} = +4C_T$, giving an excellent fit to data provided that a complex phase is present.
- Running with **wilson**, fit with **flavio**.



$R_{D^{(*)}}$

$$R_{D^{(*)}} = \left.\frac{\text{Br}(B \to D^{(*)}\tau\bar{\nu})}{\text{Br}(B \to D^{(*)}\ell\bar{\nu})}\right|_{\ell\in\{e,\mu\}},$$



Source: HFLAV Semileptonic Results 2021

$$(\mathcal{O}_{S_L})_{bc\tau\nu_\tau} = -\frac{4G_F}{\sqrt{2}} V_{23}^{\text{CKM}} (\bar{c}P_L b)(\bar{\tau}P_L\nu_\tau),$$

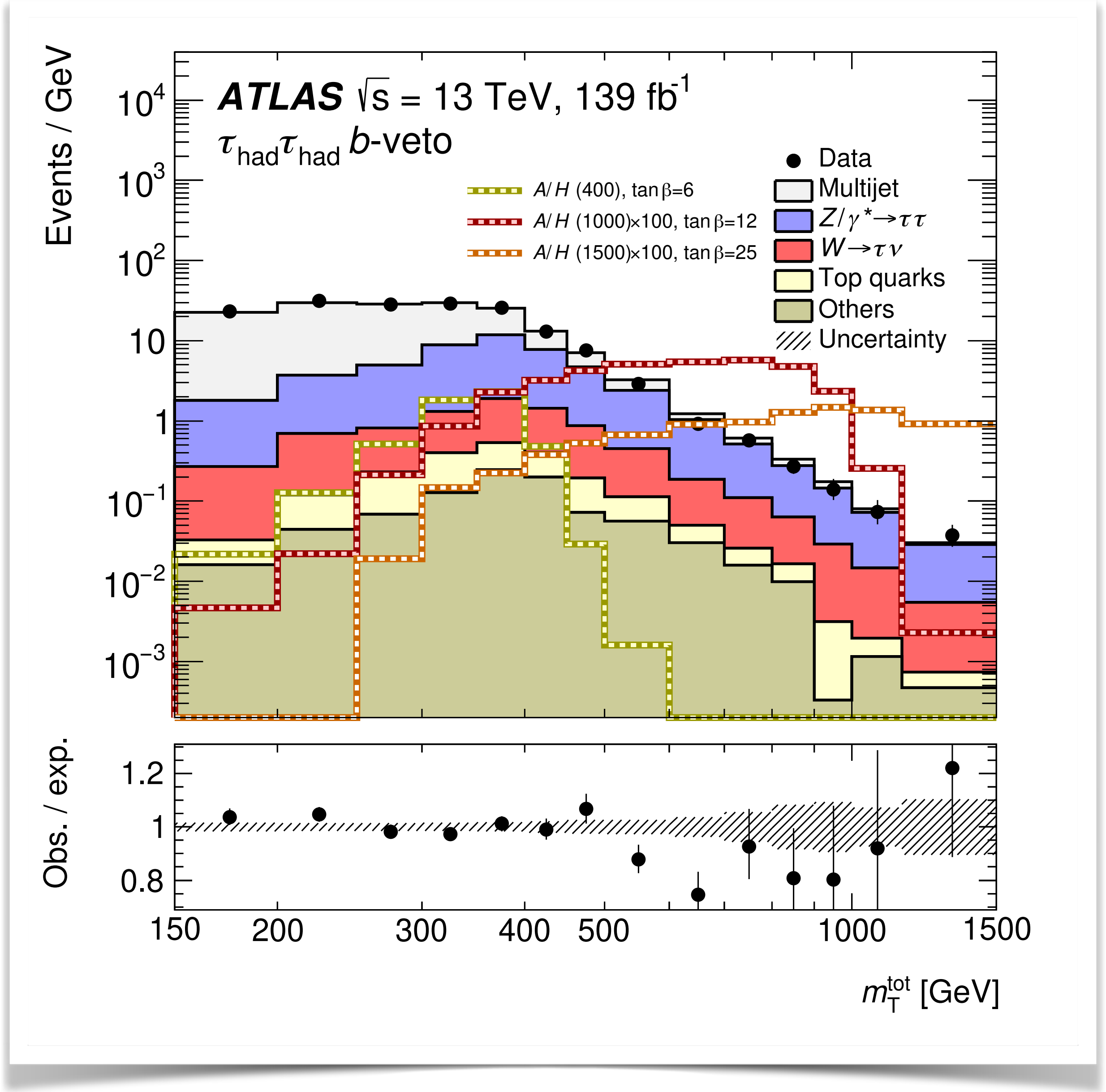
$$(\mathcal{O}_T)_{bc\tau\nu_\tau} = -\frac{4G_F}{\sqrt{2}} V_{23}^{\text{CKM}} (\bar{c}\sigma^{\mu\nu}P_L b)(\bar{\tau}\sigma_{\mu\nu}P_L\nu_\tau),$$

2. Phenomenology

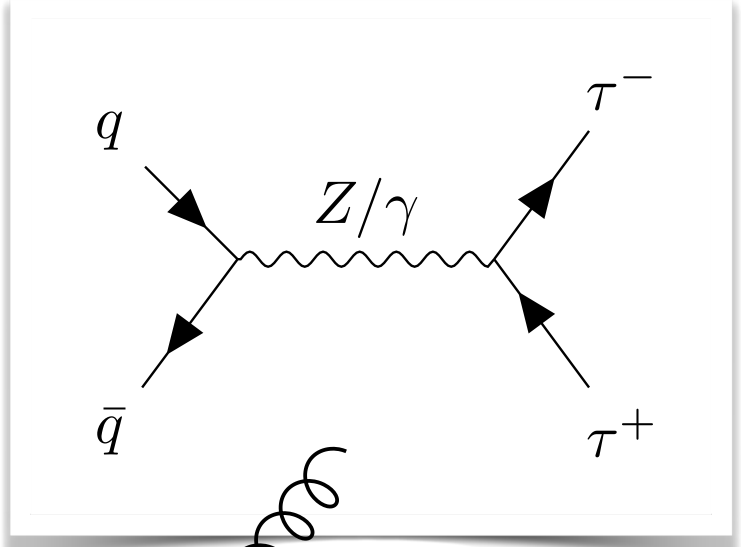
2.1 Tauquark

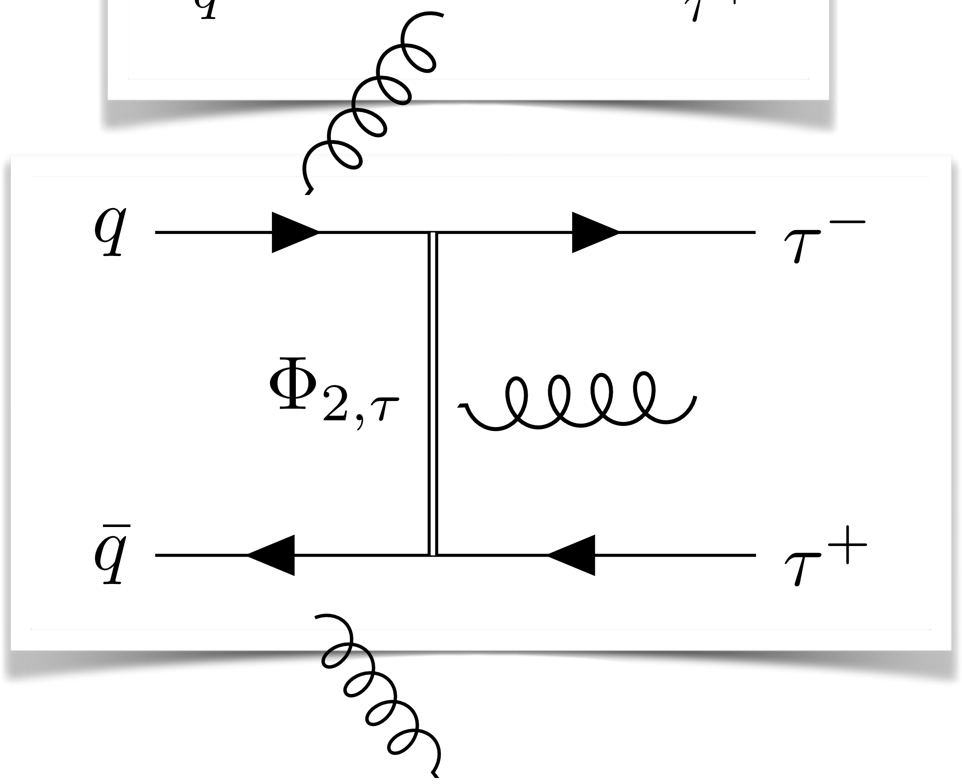
$pp \to \tau\tau$ Tail

- Tree-level t-channel contribution (→ **energy enhancement**).
- Simulation with **MadGraph_aMC@NLO+Pythia8**, reconstruction with **MadAnalysis5** (b-tag inclusive).

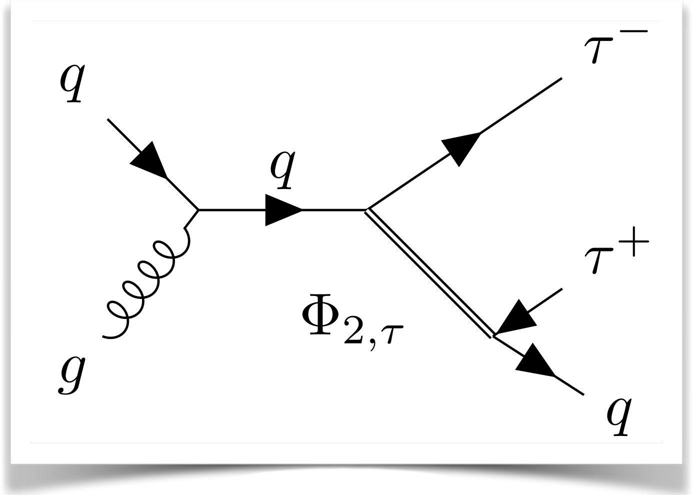


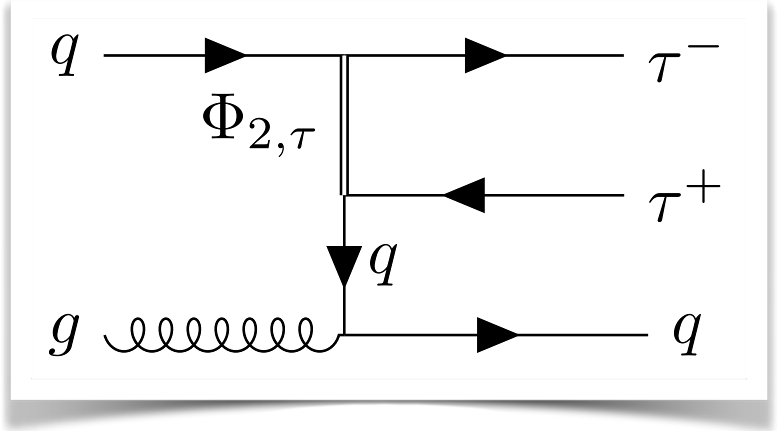
Source: 2002.12223 (ATLAS)

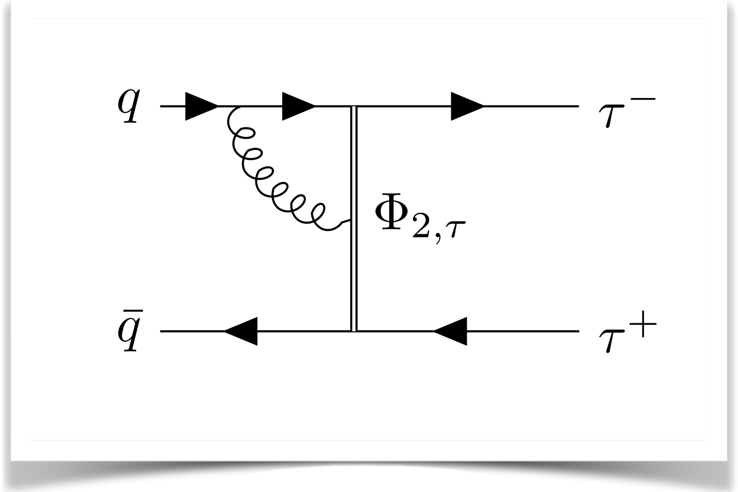


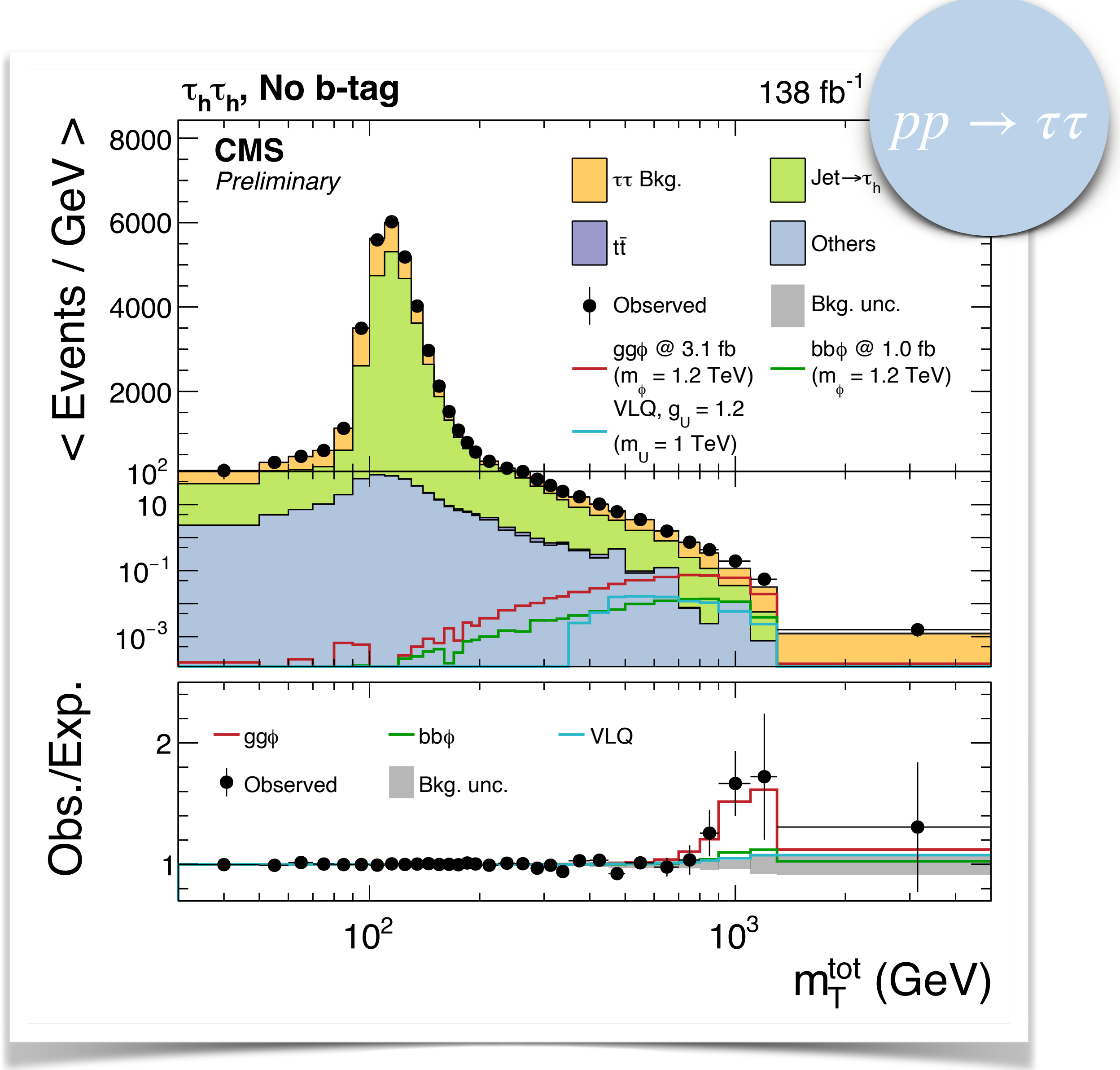


Go to **NLO** precision,
b-tag discrimination.





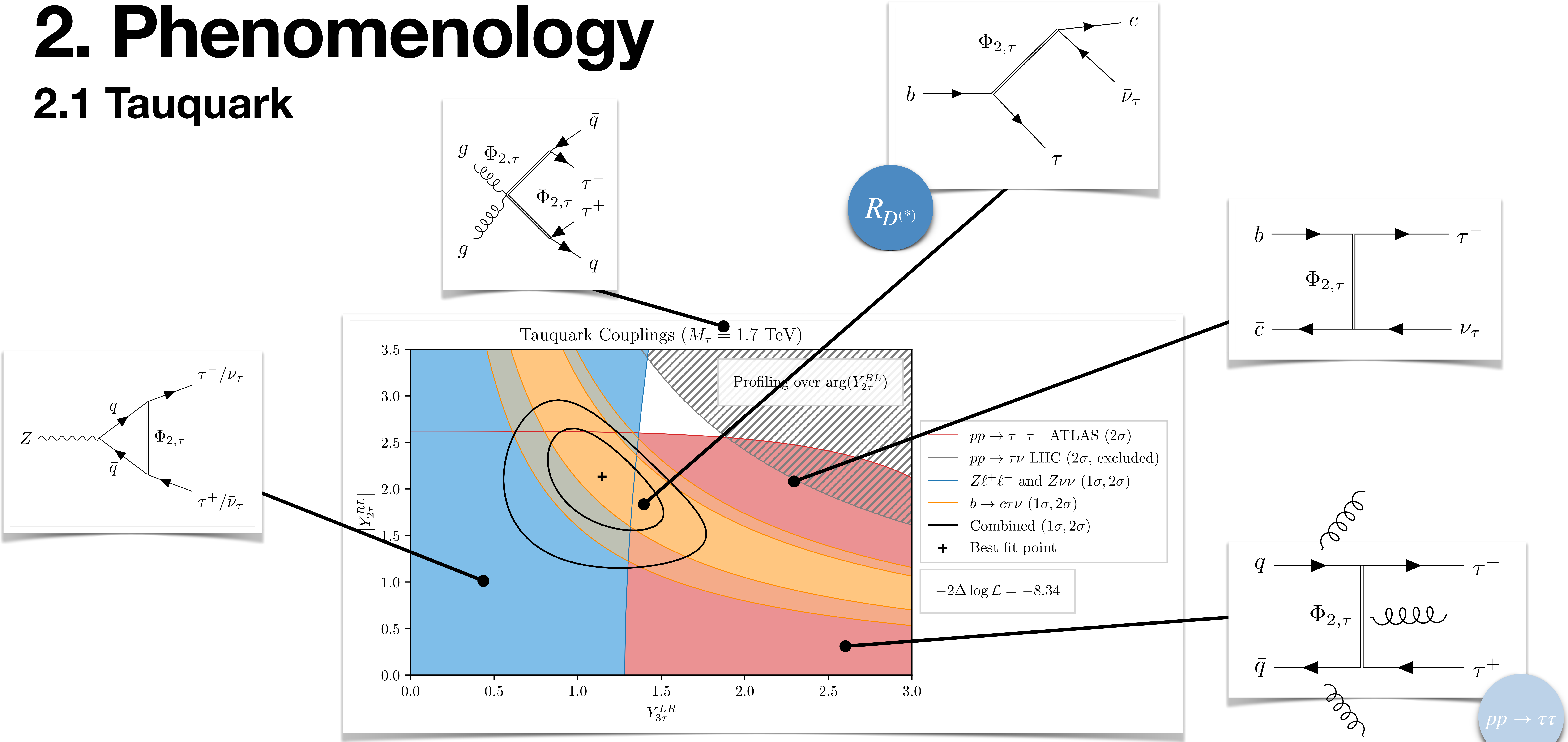




Source: CMS-PAS-HIG-21-001

2. Phenomenology

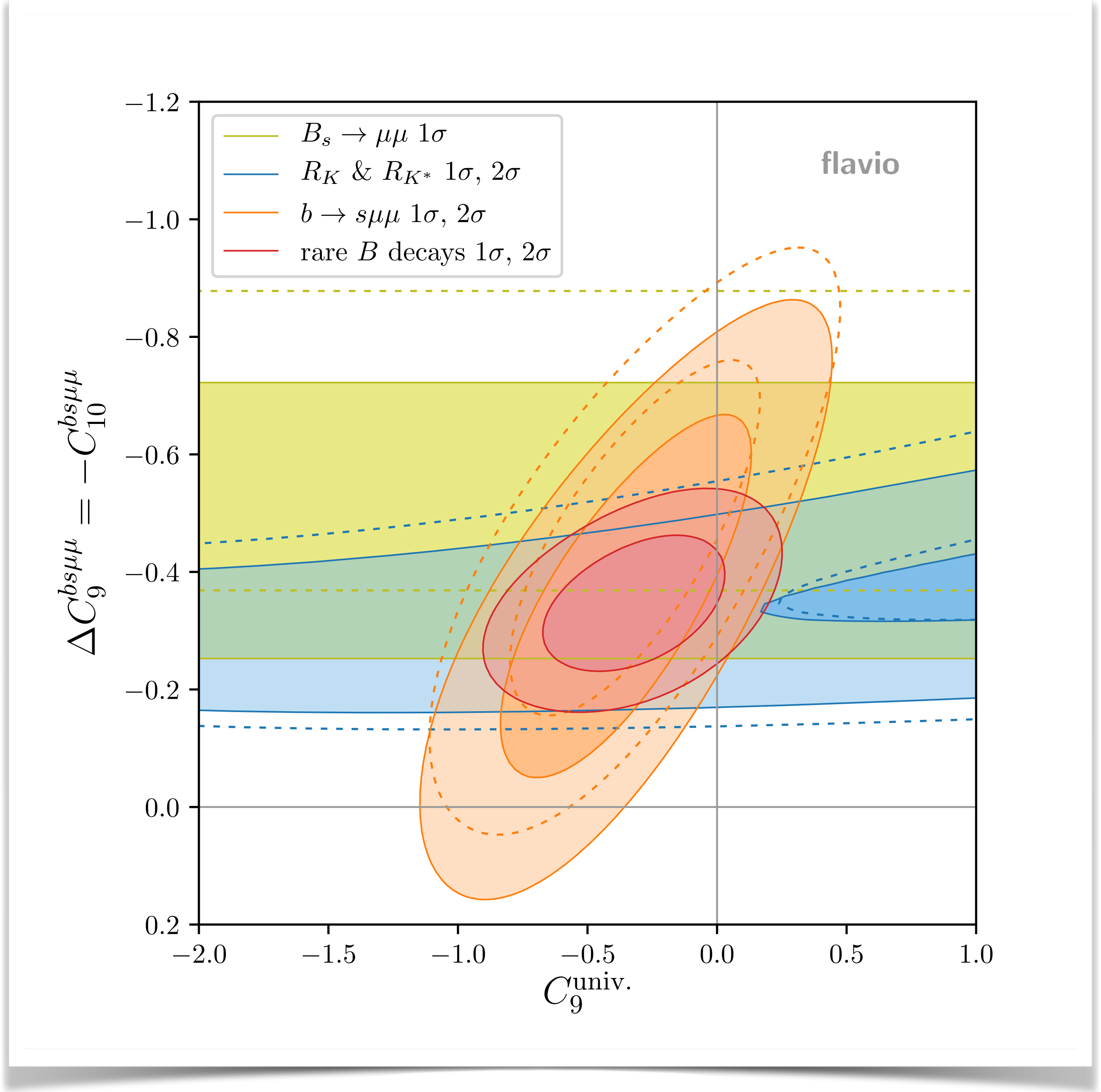
2.1 Tauquark



Source: 2203.10111 (Crivellin, Fuks, LS)

2. Phenomenology

2.2 Tauquark and Muoquark



Source: 2103.13370 (Altmannshofer, Stangl)

$b \to s\ell^+\ell^-$ **Anomalies**

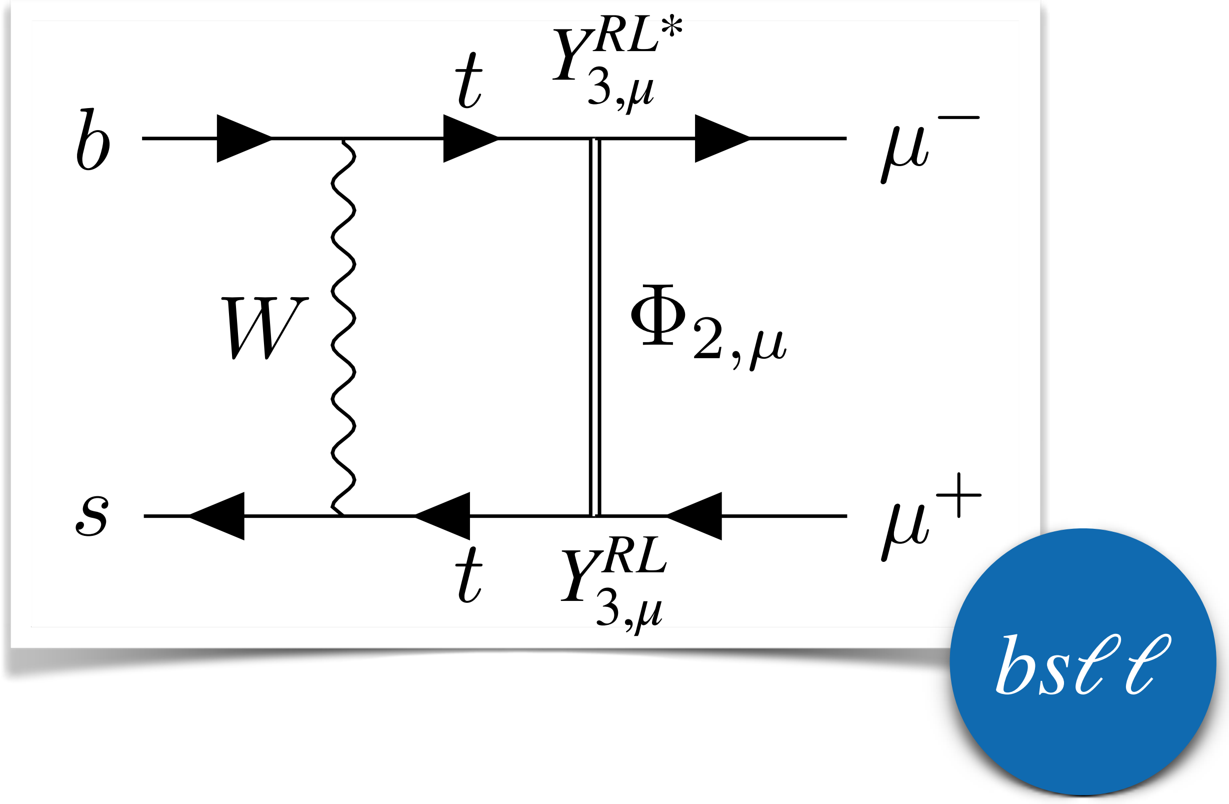
- Deviations $> 7\sigma$ ($> 4\sigma$) in global fits.
- The **muoquark** can yield a one-loop contribution to $C_9^\mu = -C_{10}^\mu$.
- This requires large couplings, in strong **tension with LEP data** $(Z \to \mu^+\mu^-)$.
- There is an additional contribution from the **tauquark** to C_9^U.
- Running with **wilson**, fit with **smelli**.

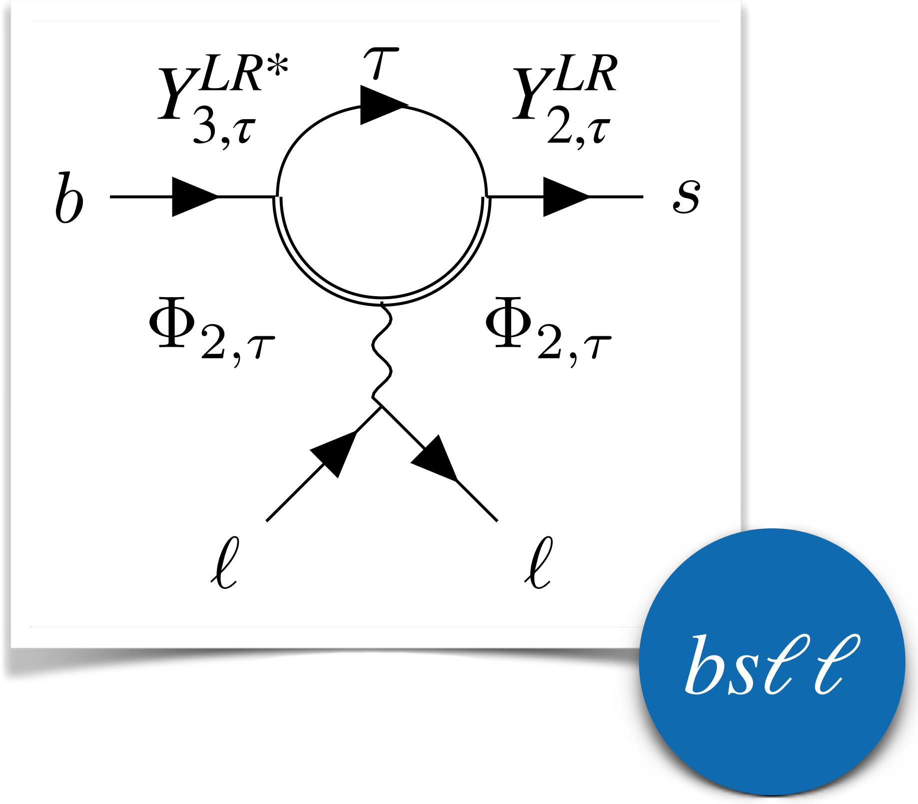
$$(\mathcal{O}_9)_{bs\ell\ell} = \frac{4G_F}{\sqrt{2}} V_{33}^{\text{CKM}} (V_{32}^{\text{CKM}})^* \frac{e^2}{16\pi^2} (\bar{s}\gamma^\mu P_L b)(\bar{\ell}\gamma_\mu \ell) ,$$

$$(\mathcal{O}_{10})_{bs\ell\ell} = \frac{4G_F}{\sqrt{2}} V_{33}^{\text{CKM}} (V_{32}^{\text{CKM}})^* \frac{e^2}{16\pi^2} (\bar{s}\gamma^\mu P_L b)(\bar{\ell}\gamma_\mu \gamma_5 \ell) ,$$

$$(\mathcal{O}_7)_{bs} = \frac{4G_F}{\sqrt{2}} V_{33}^{\text{CKM}} (V_{32}^{\text{CKM}})^* \frac{e}{16\pi^2} m_b (\bar{s}\sigma^{\mu\nu} P_R b) F_{\mu\nu} ,$$

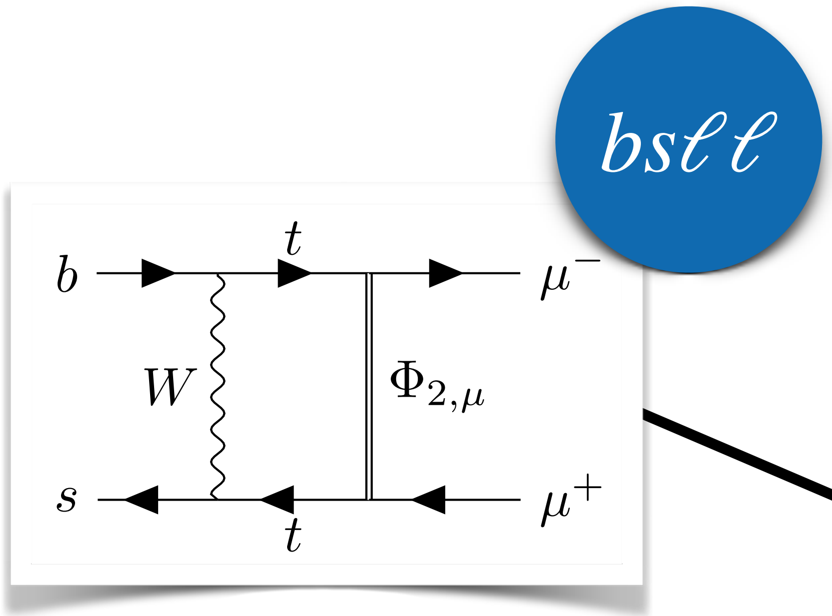
$$(\mathcal{O}_8)_{bs} = \frac{4G_F}{\sqrt{2}} V_{33}^{\text{CKM}} (V_{32}^{\text{CKM}})^* \frac{g_s}{16\pi^2} m_b (\bar{s}\sigma^{\mu\nu} T^a P_R b) G_{\mu\nu}^a ,$$

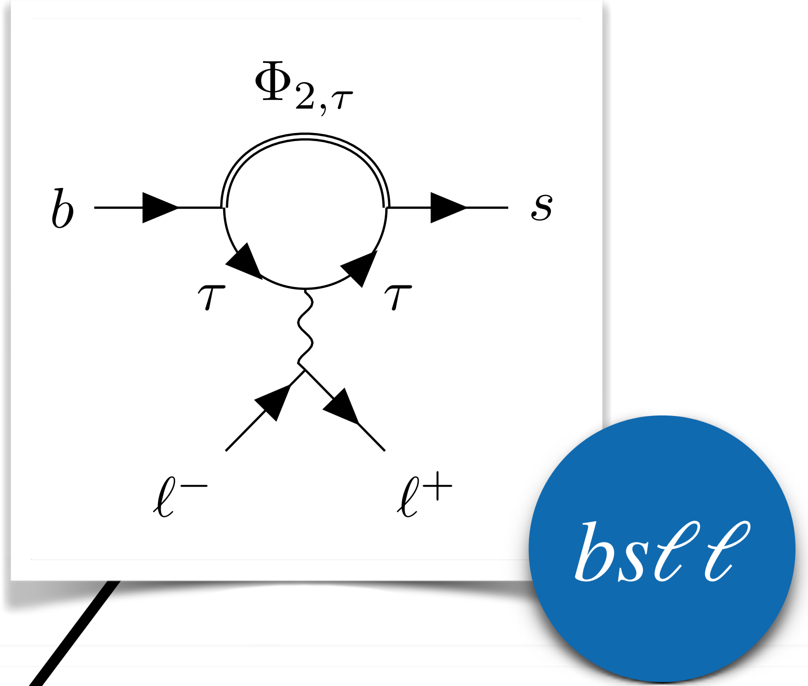


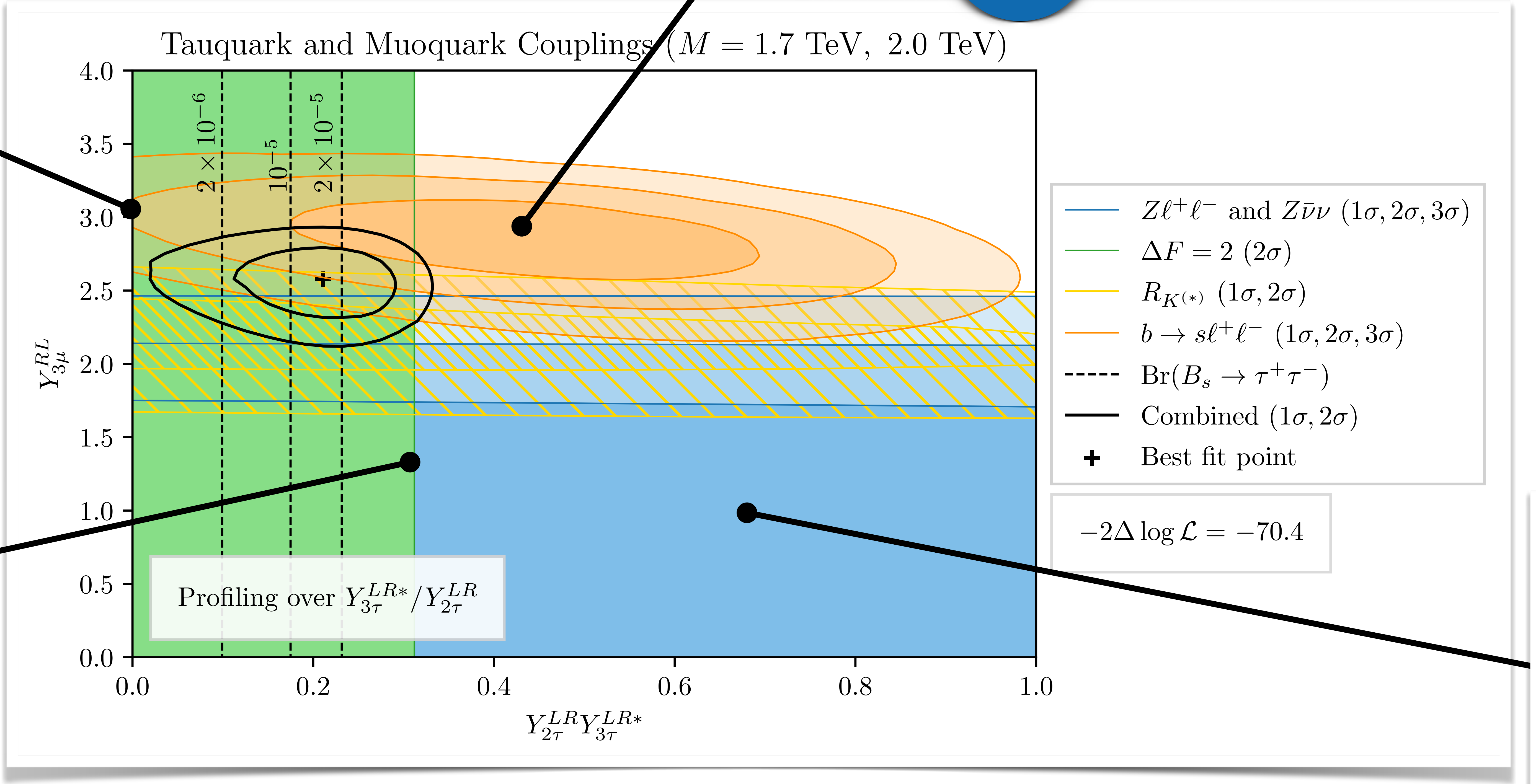


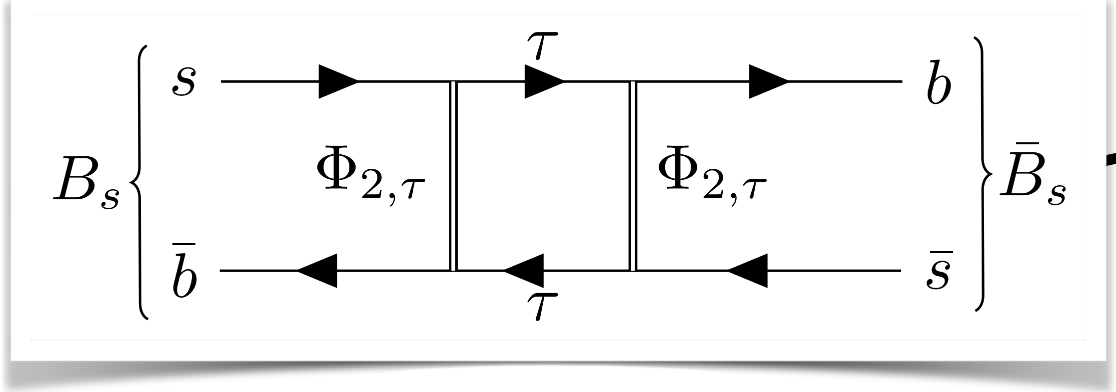
2. Phenomenology

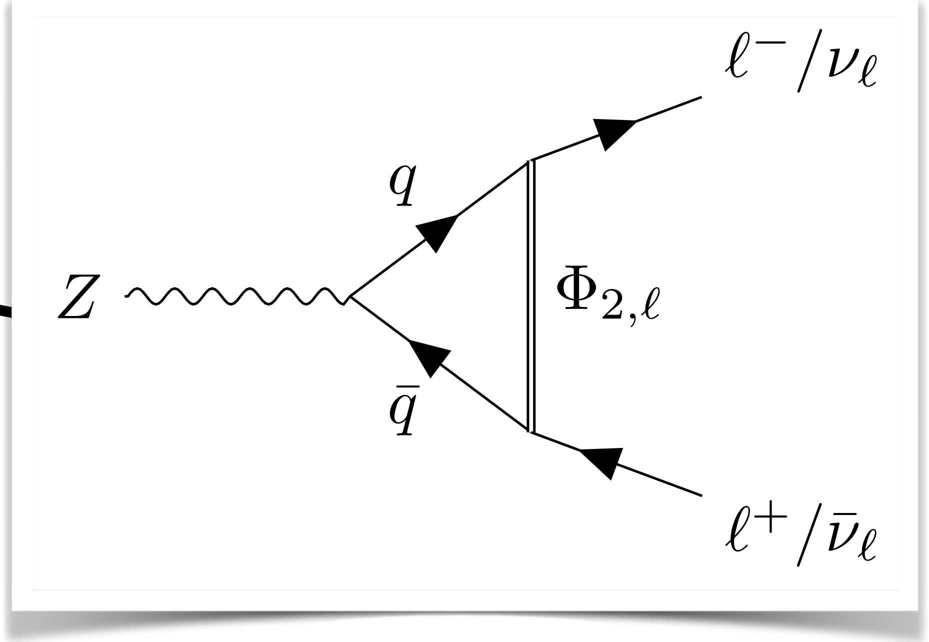
2.2 Tauquark and Muoquark







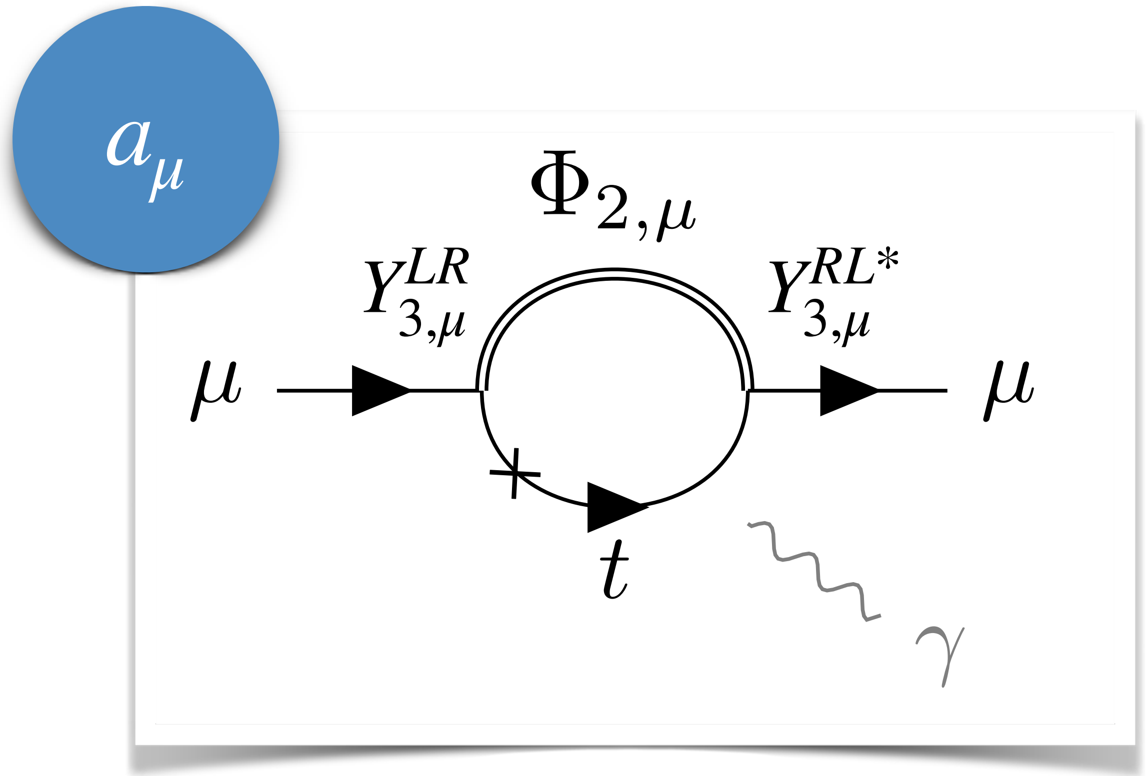




Source: 2203.10111 (Crivellin, Fuks, LS)

2. Phenomenology

2.3 Muoquark



Lepton Masses, AMMs and EDMs

- The contributions to these observables are **related**.
- There is a m_t-enhanced contribution to C_7 .

$$(\mathcal{O}_7)_{\ell\ell} = \frac{4G_F}{\sqrt{2}} \frac{e}{16\pi^2} m_\ell \left(\bar{\ell}\sigma^{\mu\nu} P_R \ell\right) F_{\mu\nu} \, .$$

$$a_\ell^{\rm LQ} = \frac{G_F m_\ell^2}{\sqrt{2}\pi^2} \,{\rm Re}\{ \,(\mathcal{C}_7)_{\ell\ell}\,\} \qquad \text{and} \qquad \left|d_\ell^{\rm LQ}\right| = \frac{eG_F m_\ell}{2\sqrt{2}\pi^2} \left|{\rm Im}\{\,(\mathcal{C}_7)_{\ell\ell}\,\}\right| ,$$

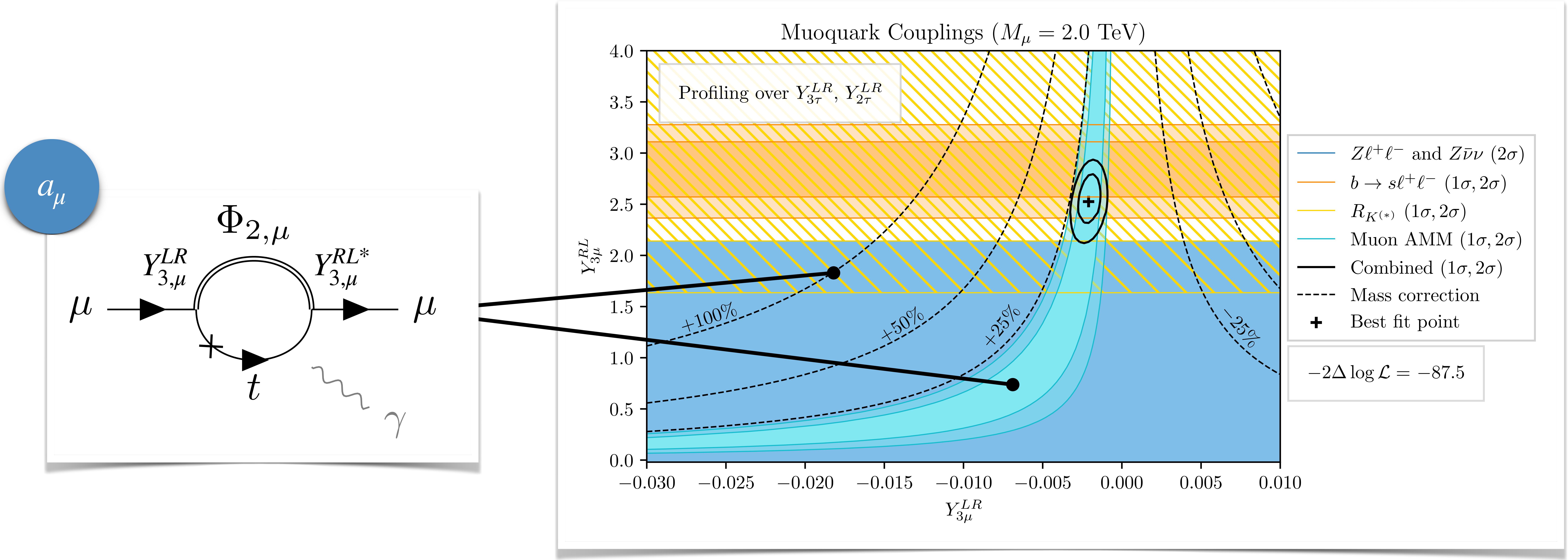
- The same diagram (without photon) also induces corrections to the **lepton masses**.

$$m_\ell^{\rm LQ} \approx -\frac{m_t N_c}{16\pi^2} \mathcal{E}_3 \left(\frac{\mu^2}{M_\ell^2}, \frac{m_t^2}{M_\ell^2}\right) \hat{Y}^{LR}_{3\ell} Y^{RL*}_{3\ell} \quad \text{with} \quad \mathcal{E}_3\left(x,y\right) = \frac{1}{\epsilon} + 1 + \log\left(x\right) + y\log\left(y\right) \, ,$$

→ **Could there be a common explanation to the lepton masses, $(g-2)_\ell$ and the absence of EDMs?**

2. Phenomenology

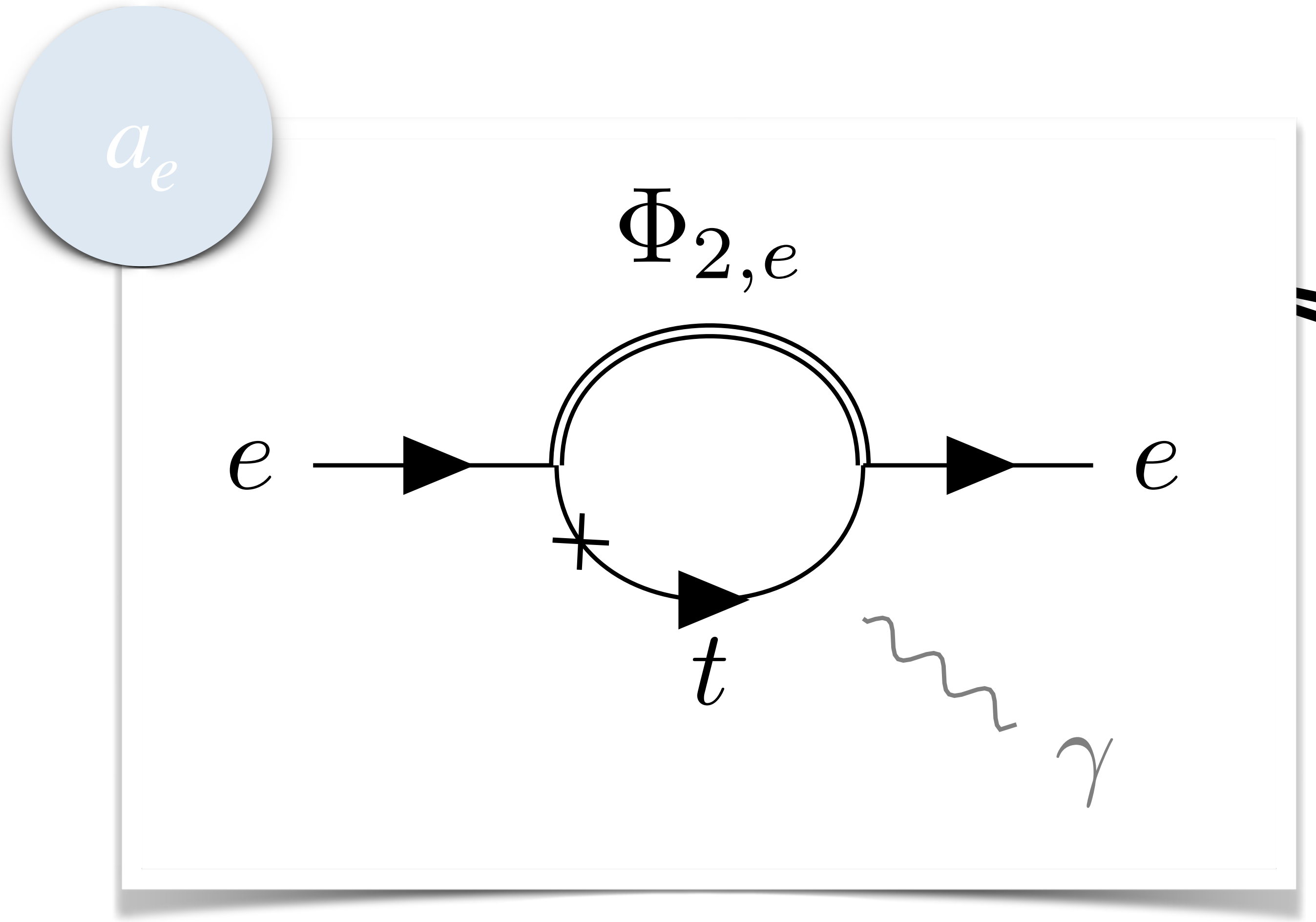
2.3 Muoquark

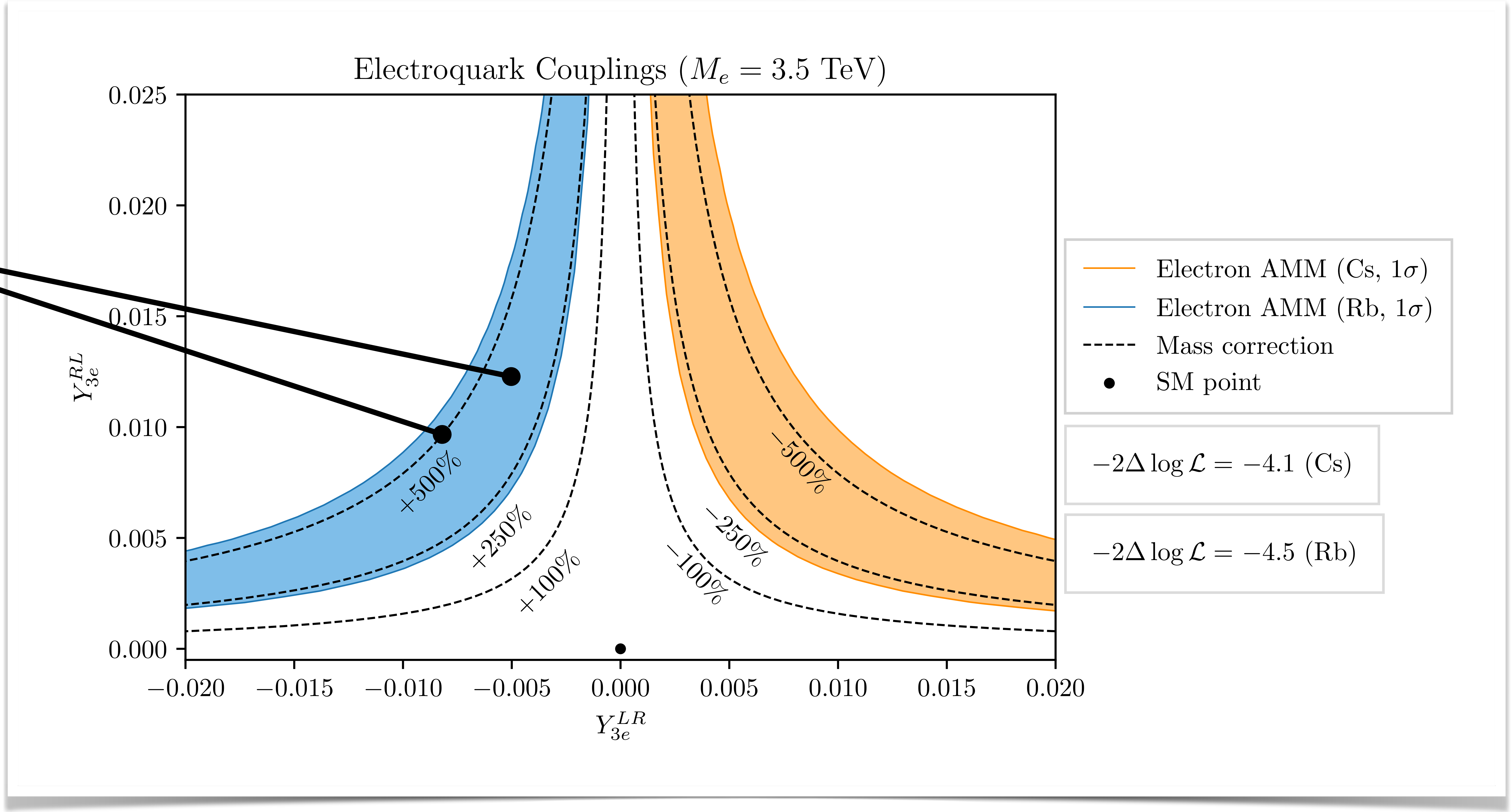


Source: 2203.10111 (Crivellin, Fuks, LS)

2. Phenomenology

2.4 Electroquark





Source: 2203.10111 (Crivellin, Fuks, LS)

2. Phenomenology

2.4 Electroquark

Radiative Mass Generation

- Model example discussed in 2107.07518 (Greljo, Soreq, Stangl, Thomsen, Zupan): **radiative mass generation** for charged leptons.

$$\mathcal{L} \supset \left(Y^{RL}_{i\ell}\, \bar{u}_i \left[\Phi^{RL}_{2,\ell} \cdot L_\ell\right] + Y^{LR}_{i\ell} \left[\bar{Q}_i e_\ell \Phi^{LR}_{2,\ell}\right] + \qquad \right)$$

✗ $\bar{L}_\ell \tilde{H} e_\ell$

$$-M^2_{\ell,LR} \Phi^{LR\,\dagger}_{2,\ell} \Phi^{LR}_{2,\ell} - M^2_{\ell,RL} \Phi^{RL\,\dagger}_{2,\ell} \Phi^{RL}_{2,\ell}$$

$$-\tilde{M}^2_\ell \left(\Phi^{LR\,\dagger}_{2,\ell} \Phi^{RL}_{2,\ell} + \qquad \right)t$$

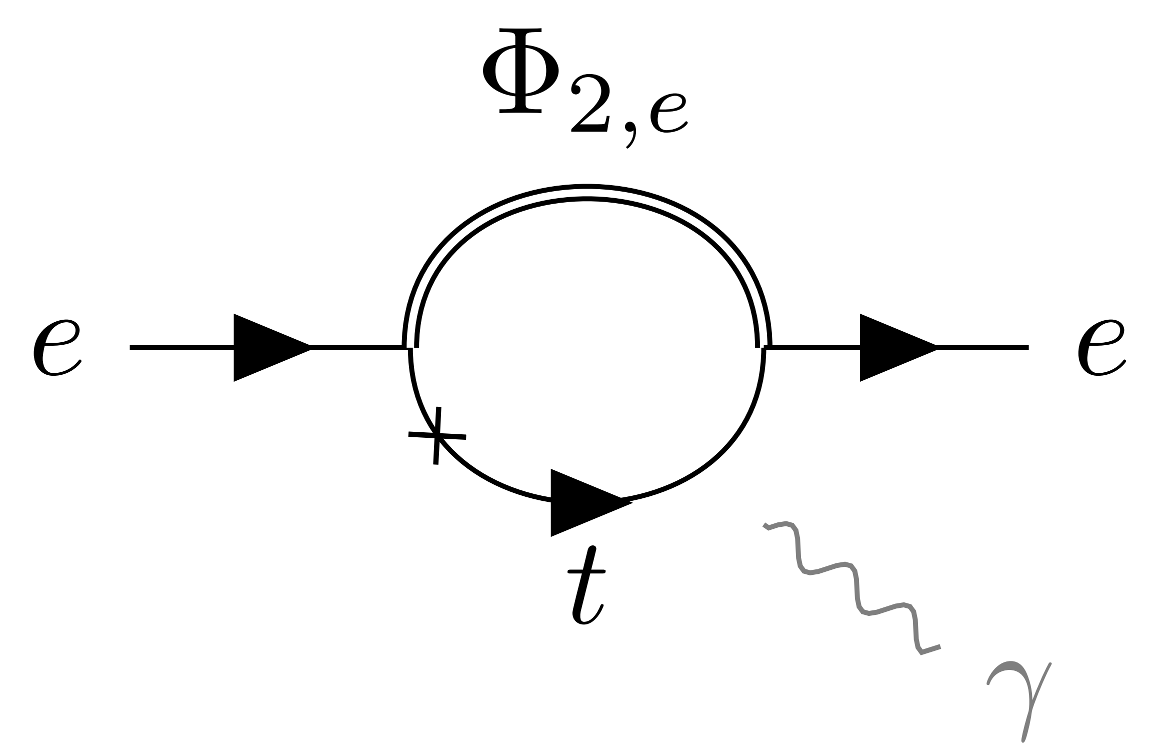
$$M_{\ell,LR} = M_{\ell,RL} \equiv M_\ell$$

$$\begin{pmatrix} M^2_\ell & \tilde{M}^2_\ell \\ \tilde{M}^2_\ell & M^2_\ell \end{pmatrix}$$

real → **no EDM**

$$m_e \approx \frac{3 m_t}{16\pi^2} Y^{LR}_{3e} Y^{RL}_{3e} \frac{\tilde{M}^2_e}{M^2_e}$$

$$a_e \approx \frac{3}{16\pi^2} Y^{LR}_{3e} Y^{RL}_{3e} \frac{m_\mu m_t \tilde{M}^2_e}{M^4_e} \left(-\frac{5}{3} + \frac{4}{3} \log \frac{M^2_e}{m^2_t}\right)$$



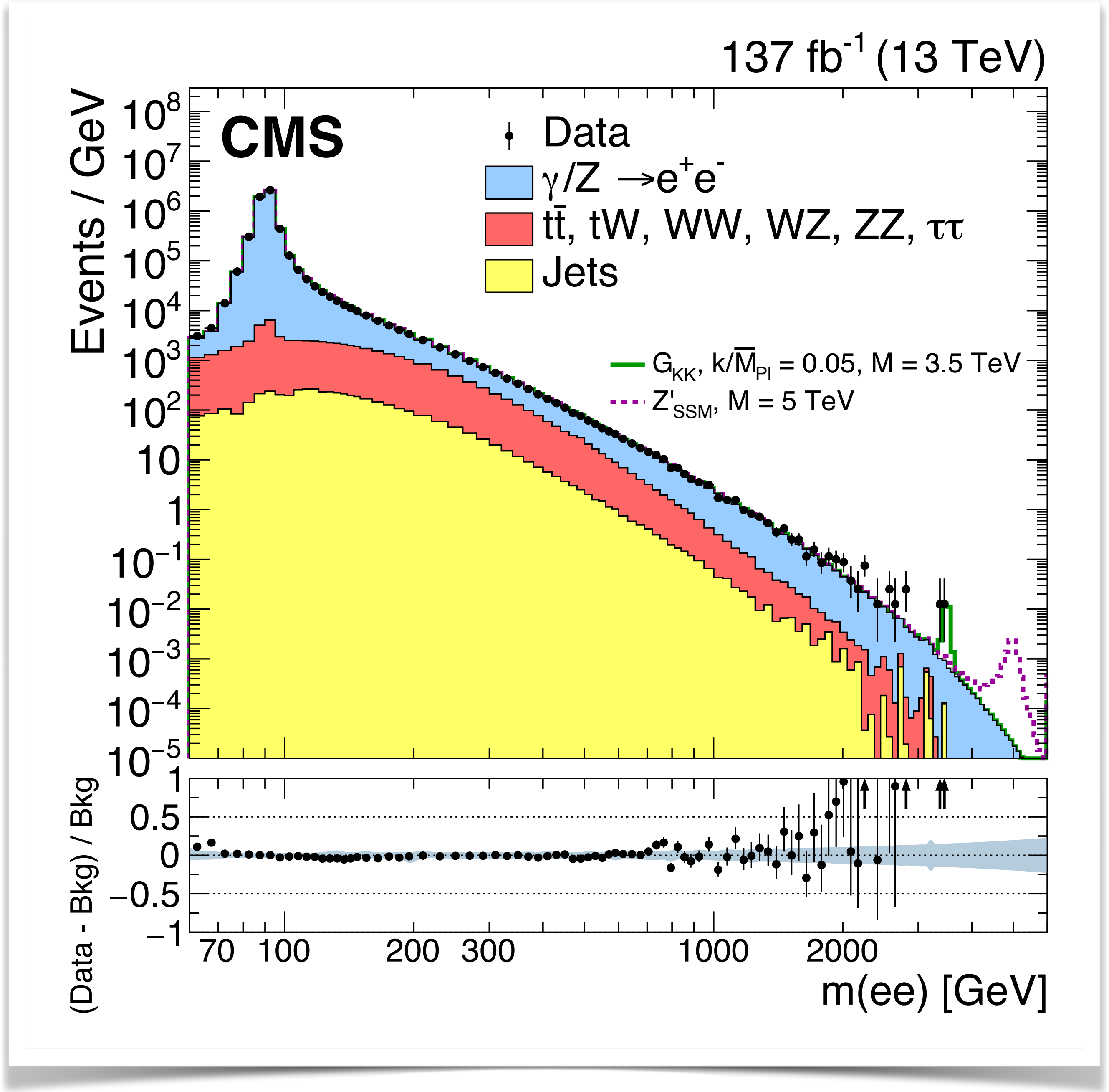
2. Phenomenology

2.4 Electroquark

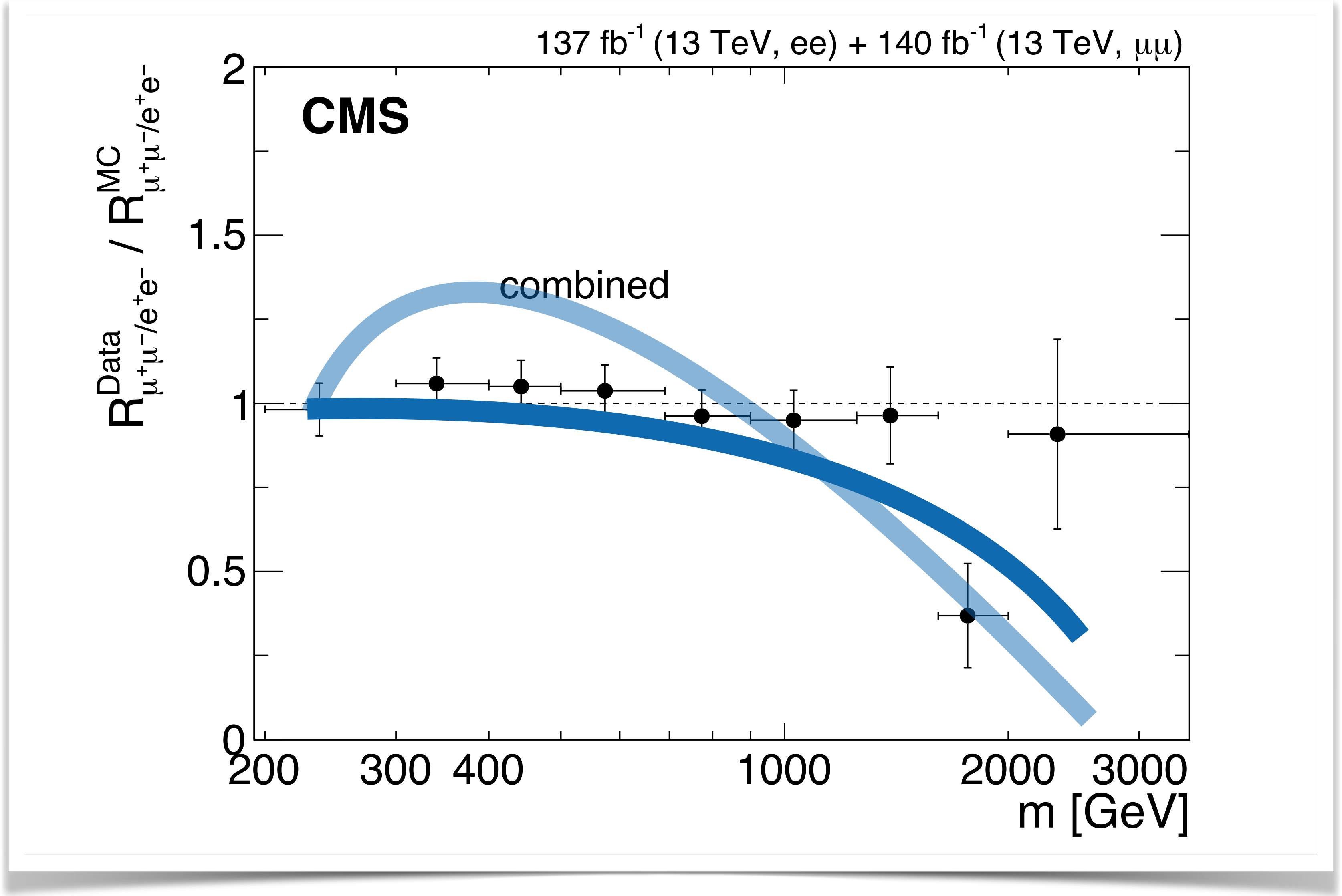
$pp \to ee$ Tail

- CMS found an **excess in di-electron** events.
- This was also found by ATLAS, but with less significance.
- The data prefers LQ representations interfering **constructively** with the SM contribution.
- $\sim 3\sigma$ improvement can be reached.

Source: 2104.06417 (Crivellin, Müller, LS)



Source: 2103.02708 (CMS)



Source: 2103.02708 (CMS)

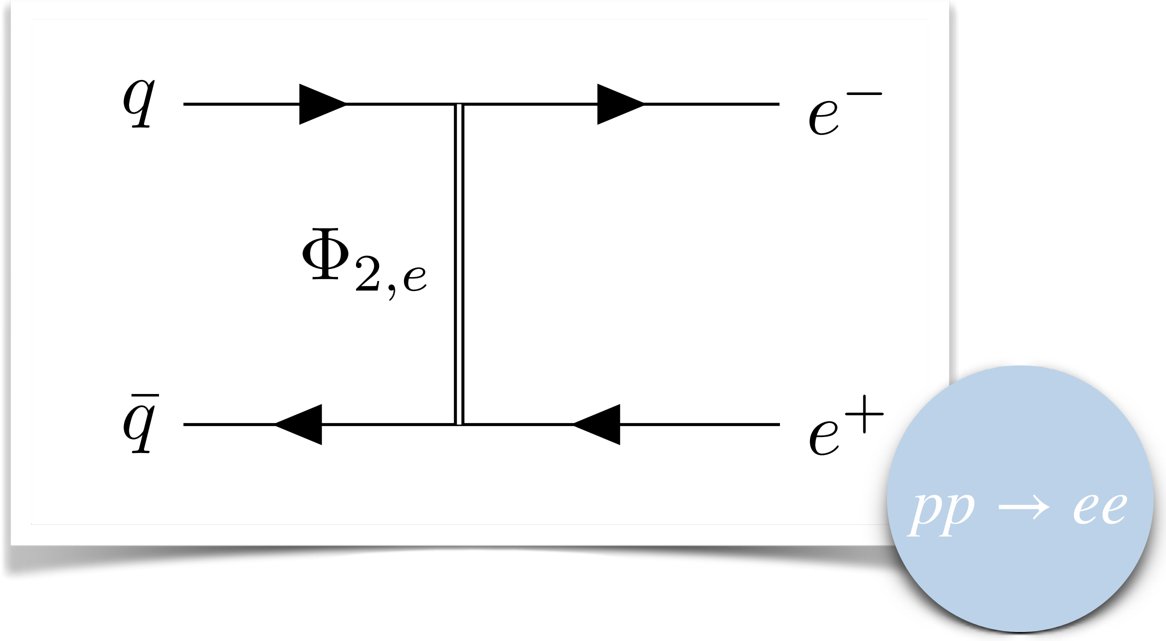


Table 4: The dielectron and dimuon event yields for the data, the expected background and the respective significance in the different SRs used in the analysis. The p-value of each observation is defined as the probability, given the background-only hypothesis, of an observation at least as large as that seen in the data. The significance is the Gaussian cumulative density function of the p-value, and negative significances correspond to deficits.

SR	Data	Background	Significance
e^+e^- Const.	19	12.4±1.9	1.28
e^+e^- Dest.	2	3.1±1.1	– 0.72
$\mu^+\mu^-$ Const.	6	9.6±2.1	– 0.99
$\mu^+\mu^-$ Dest.	1	1.4±0.9	– 0.58

Source: 2006.12946 (ATLAS)

2. Phenomenology

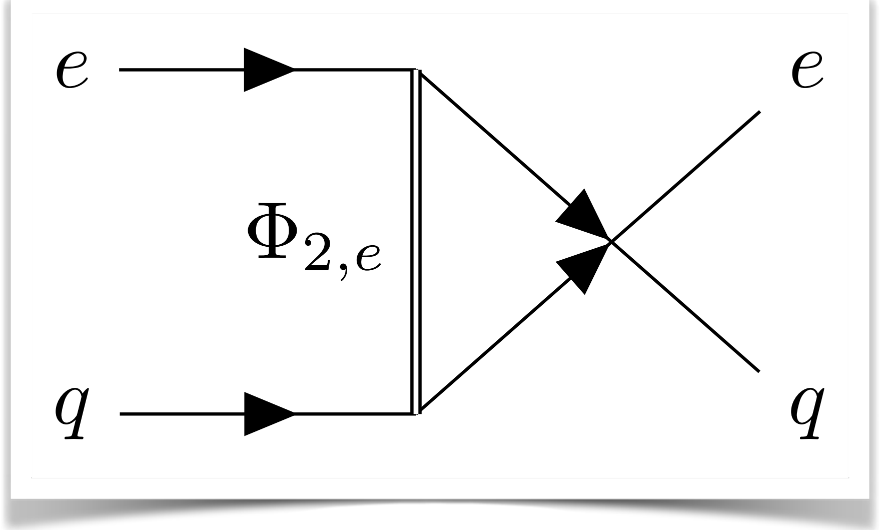
2.4 Electroquark

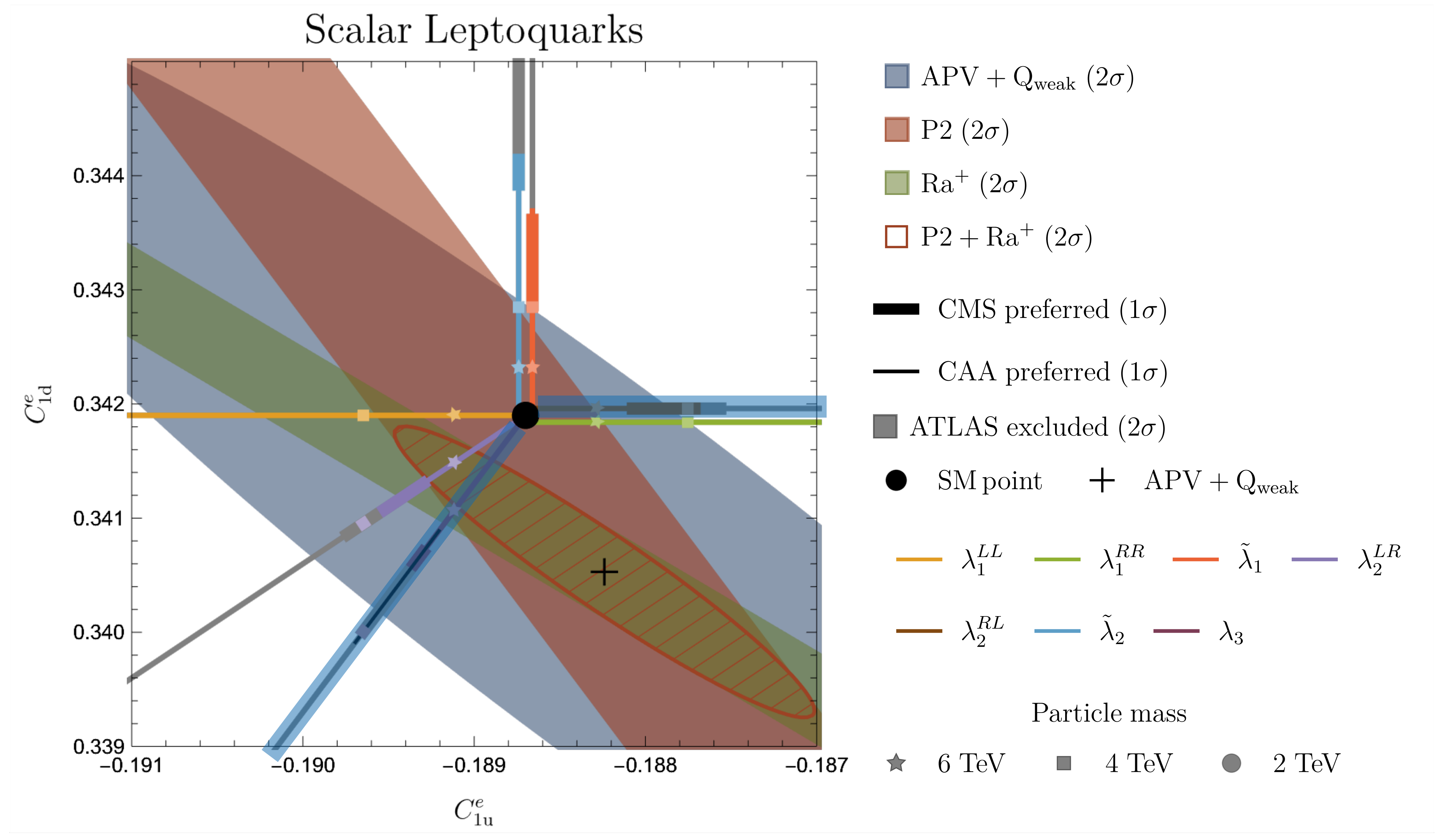
Parity Violation Data

$$\mathcal{L}_{\text{eff}}^{ee} = \frac{G_F}{\sqrt{2}} \sum_{q=u,d,s} \left(C_{1q}^e \left[\bar{q}\gamma^\mu q\right]\left[\bar{e}\gamma_\mu\gamma_5 e\right] + C_{2q}^e \left[\bar{q}\gamma^\mu\gamma_5 q\right]\left[\bar{e}\gamma_\mu e\right]\right),$$

$$Q_w = -2\left[Z\left(2C_{1u}^e + C_{1d}^e\right) + N\left(C_{1u}^e + 2C_{1d}^e\right)\right],$$

- LQs induce **parity-violating contributions** to electron-nucleon interactions.
- This modifies the **weak charge Q_w of nucleons**, as measured by Q_{weak} / APV.
  - Q_{weak} : low-energy electron-proton scattering
  - APV : parity-violating transitions in atoms (e.g. $7S - 6S$ in ^{133}Cs)

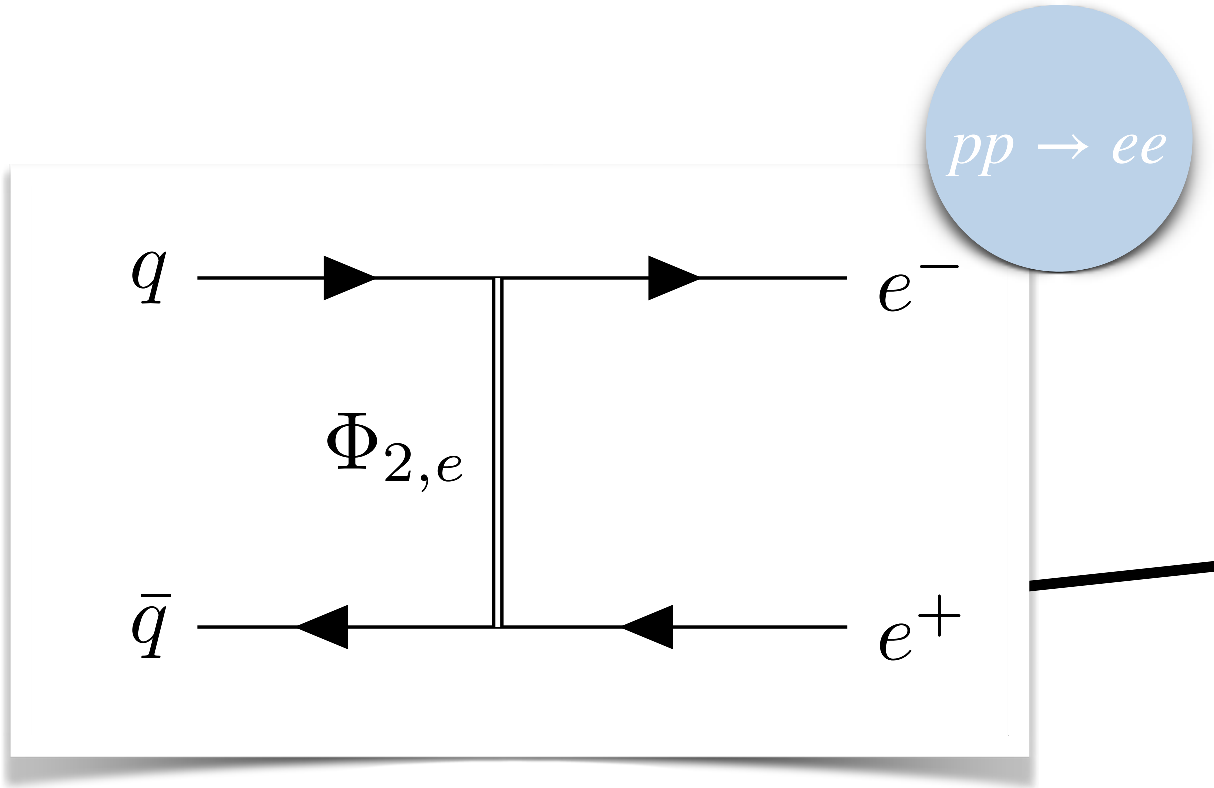


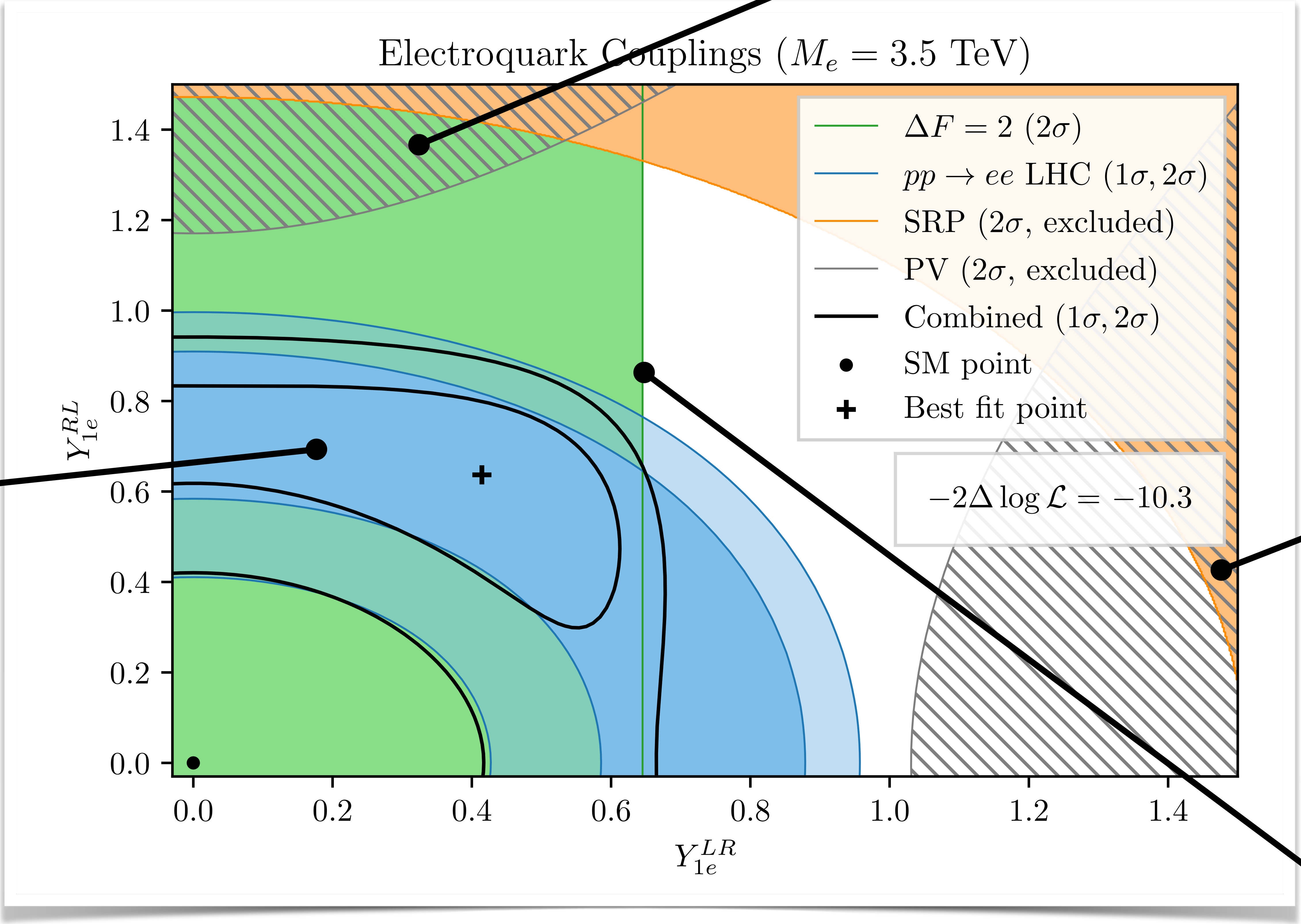


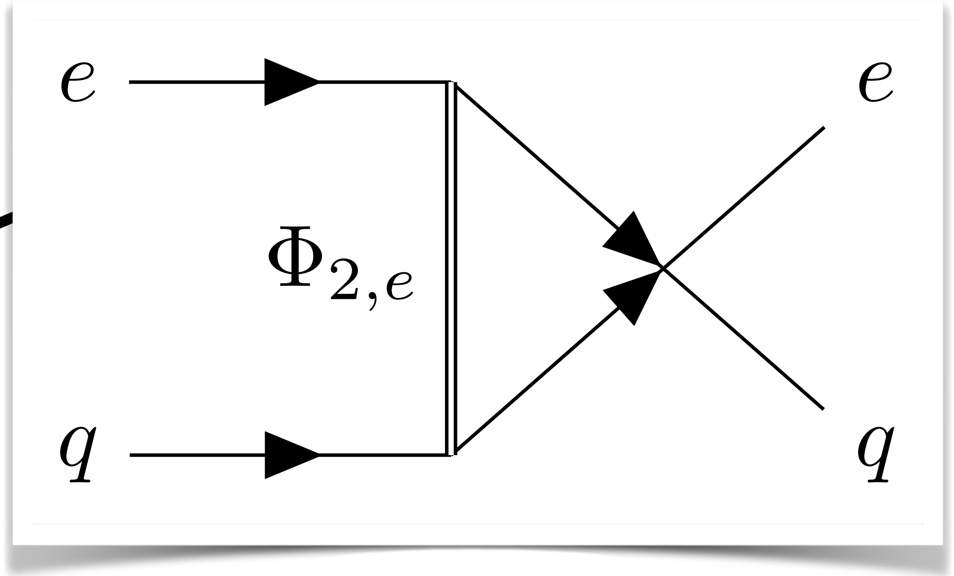
Source: 2107.13569 (Crivellin, Hoferichter, Kirk, Manzari, LS)

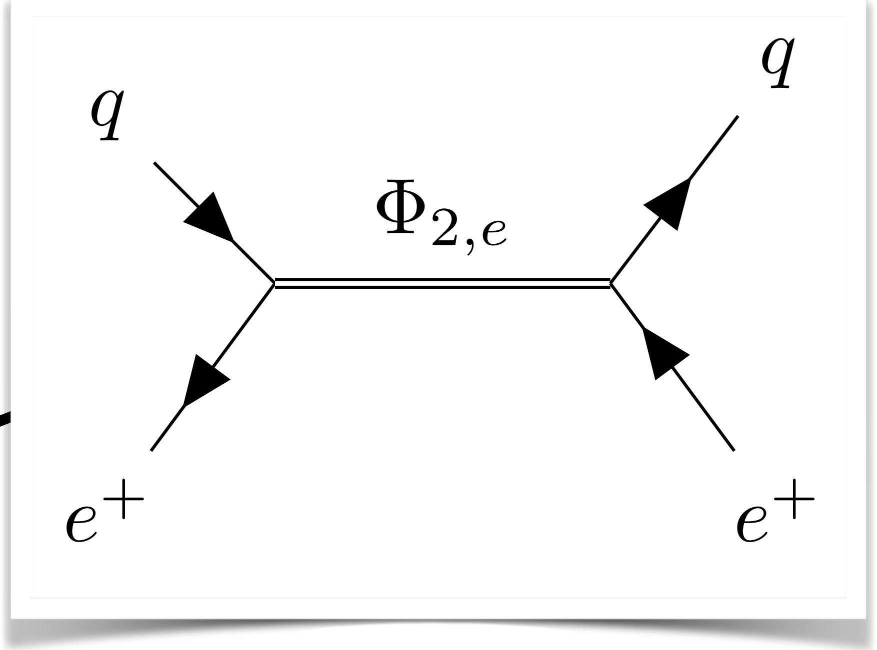
2. Phenomenology

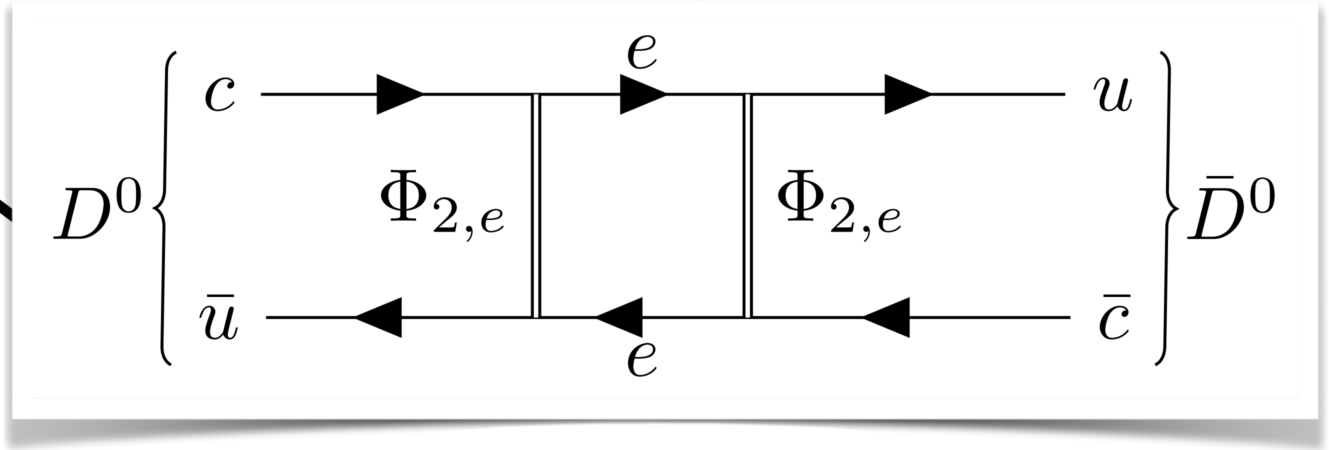
2.4 Electroquark











Source: 2203.10111 (Crivellin, Fuks, LS)

2. Phenomenology

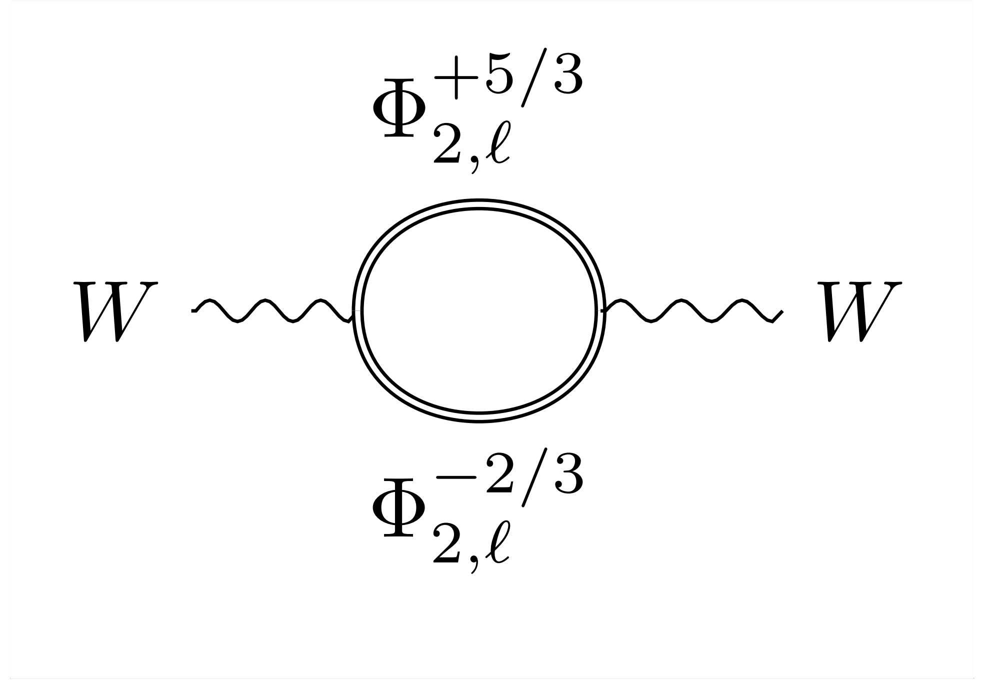
2.5 Higgs Couplings

Oblique Corrections

- We looked into this **before** the CDF II measurement.
- LQ-Higgs terms that **break** $SU(2)_L$ **spontaneously** lead to W**-mass corrections.**

$$S^{\rm LQ} \approx -\frac{7N_c v^2}{36\pi}\sum_\ell \frac{Y_\ell^{H(3)}}{M_\ell^2}$$

$$T^{\rm LQ} \approx +\frac{N_c v^2}{96\pi^2\alpha}\sum_\ell \left(\frac{Y_\ell^{H(3)}}{M_\ell}\right)^2$$

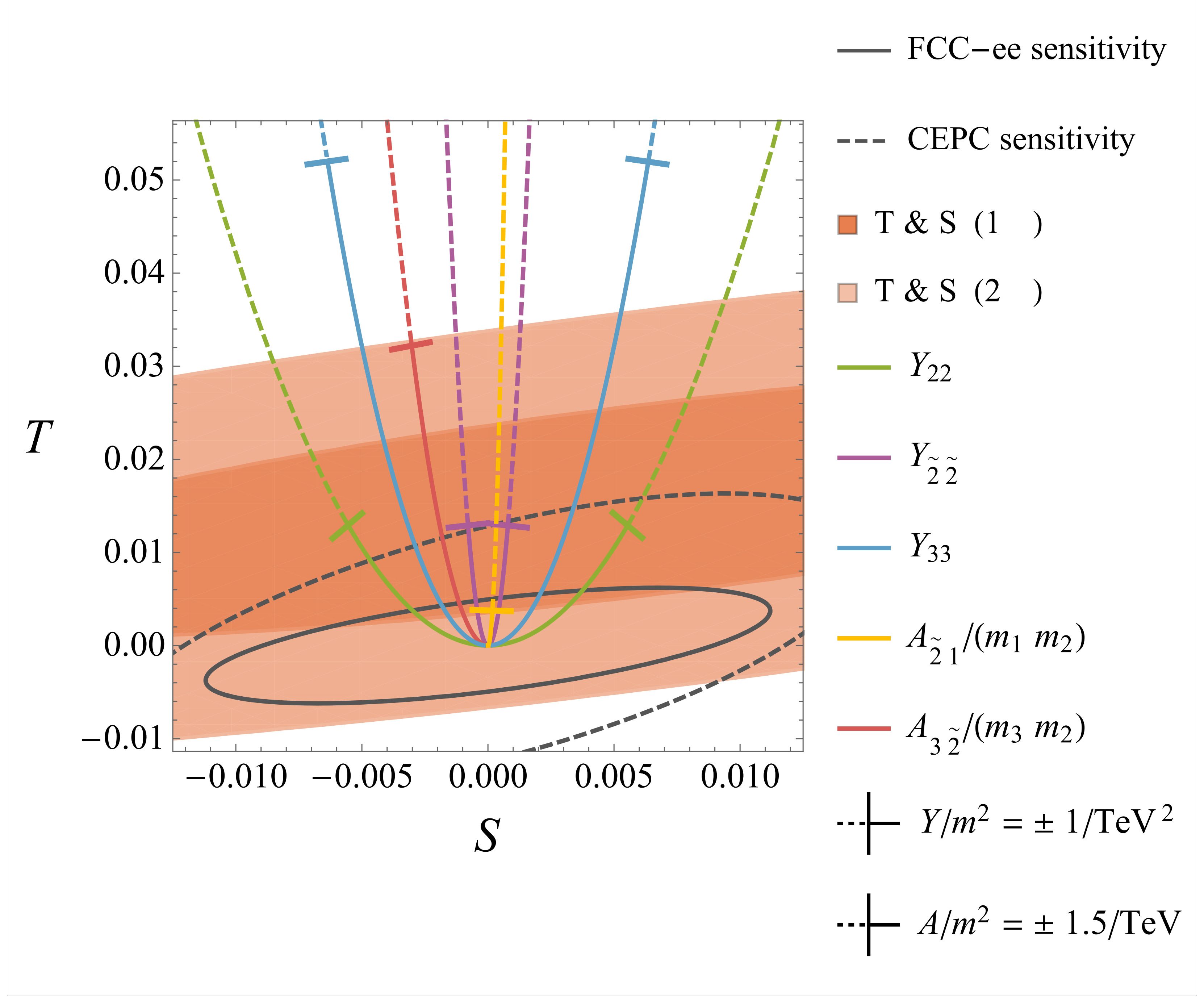


$$-\,Y_\ell^{H(3)}\left[H\cdot\Phi_{2,\ell}\right]^\dagger\left[H\cdot\Phi_{2,\ell}\right]$$

$$-Y_\ell^{H(3)}v^2\,\Phi_{2,\ell}^{-5/3}\Phi_{2,\ell}^{+5/3}$$

$$S = -\frac{4s_w^2c_w^2}{\alpha m_Z^2}\left(\Pi_{ZZ}(0)-\Pi_{ZZ}(m_Z^2)+\Pi_{\gamma\gamma}(m_Z^2)+\frac{c_w^2-s_w^2}{c_w s_w}\Pi_{Z\gamma}(m_Z^2)\right),$$
$$T = \frac{\Pi_{WW}(0)}{\alpha m_W^2}-\frac{\Pi_{ZZ}(0)}{\alpha m_Z^2},$$
$$U = -\frac{4s_w^2c_w^2}{\alpha}\left(\frac{\Pi_{WW}(0)-\Pi_{WW}(m_W^2)}{c_w^2 m_W^2}-\frac{\Pi_{ZZ}(0)-\Pi_{ZZ}(m_Z^2)}{m_Z^2}+\frac{s_w^2}{c_w^2}\frac{\Pi_{\gamma\gamma}(m_Z^2)}{m_Z^2}+2\frac{s_w}{c_w}\frac{\Pi_{Z\gamma}(m_Z^2)}{m_Z^2}\right),$$

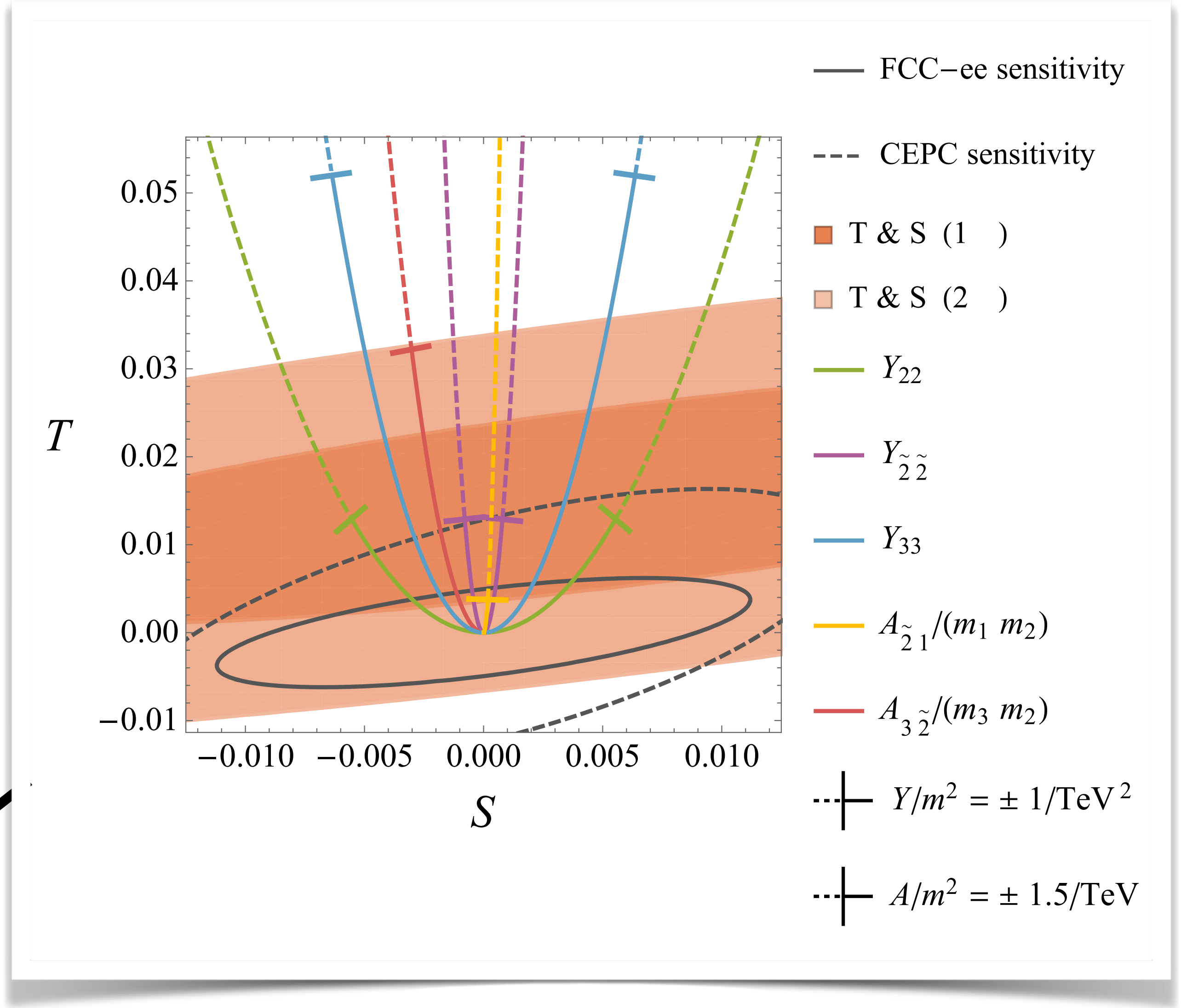
Source: 2006.10758 (Crivellin et al.)



Source: 2006.10758 (Crivellin et al.)

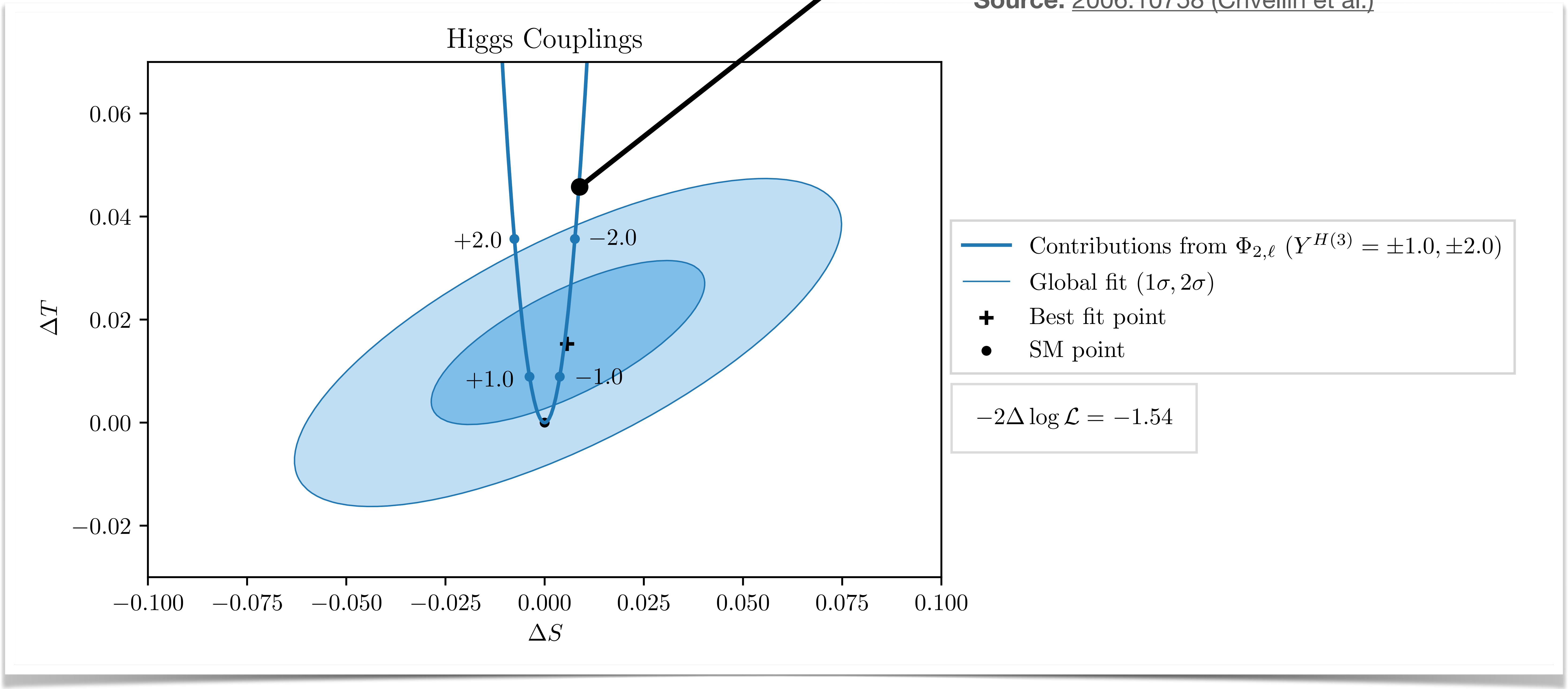
2. Phenomenology

2.5 Higgs Couplings



Source: 2006.10758 (Crivellin et al.)

- **Without** CDF II measurement:

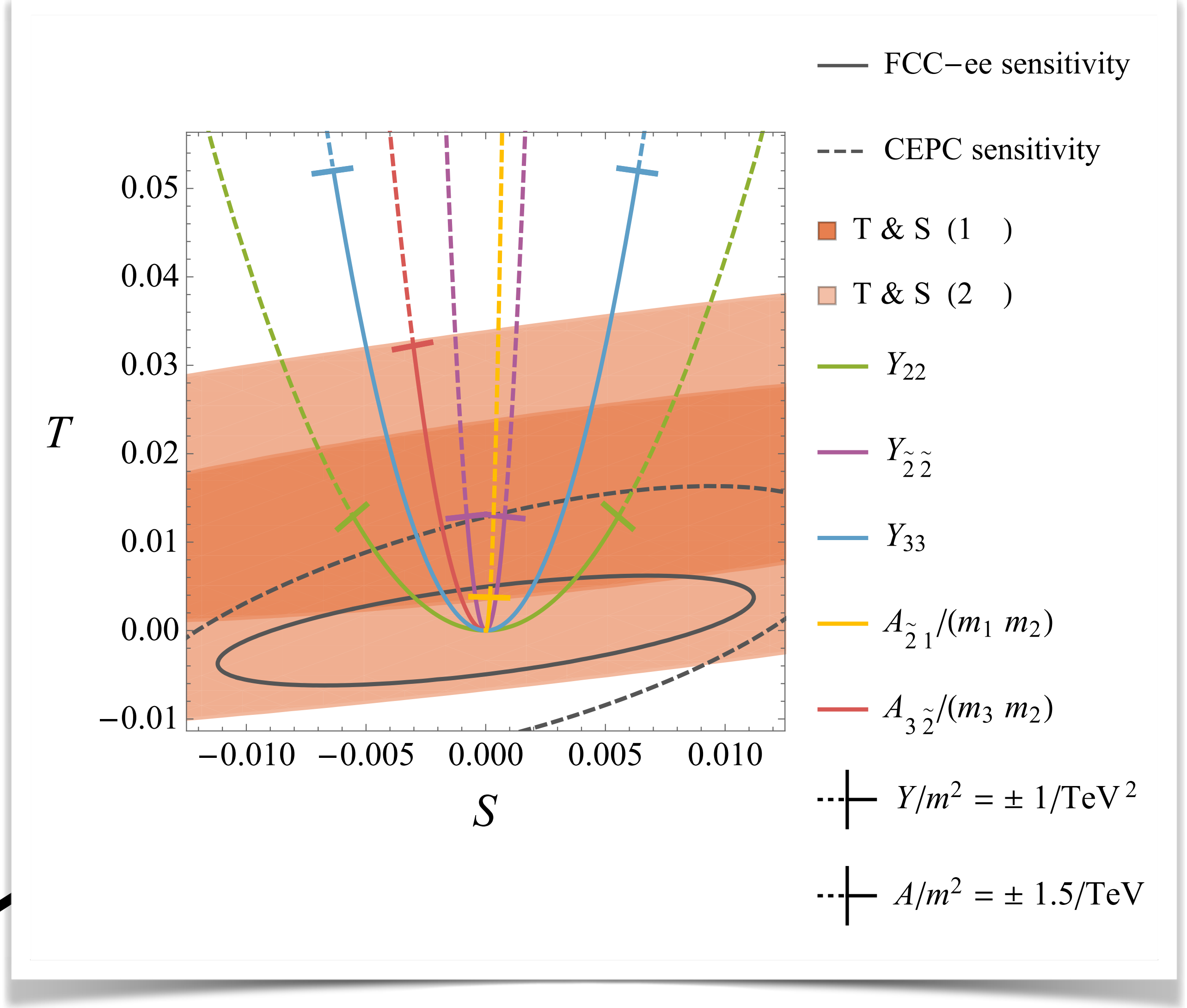


Source: 2203.10111 (Crivellin, Fuks, LS)

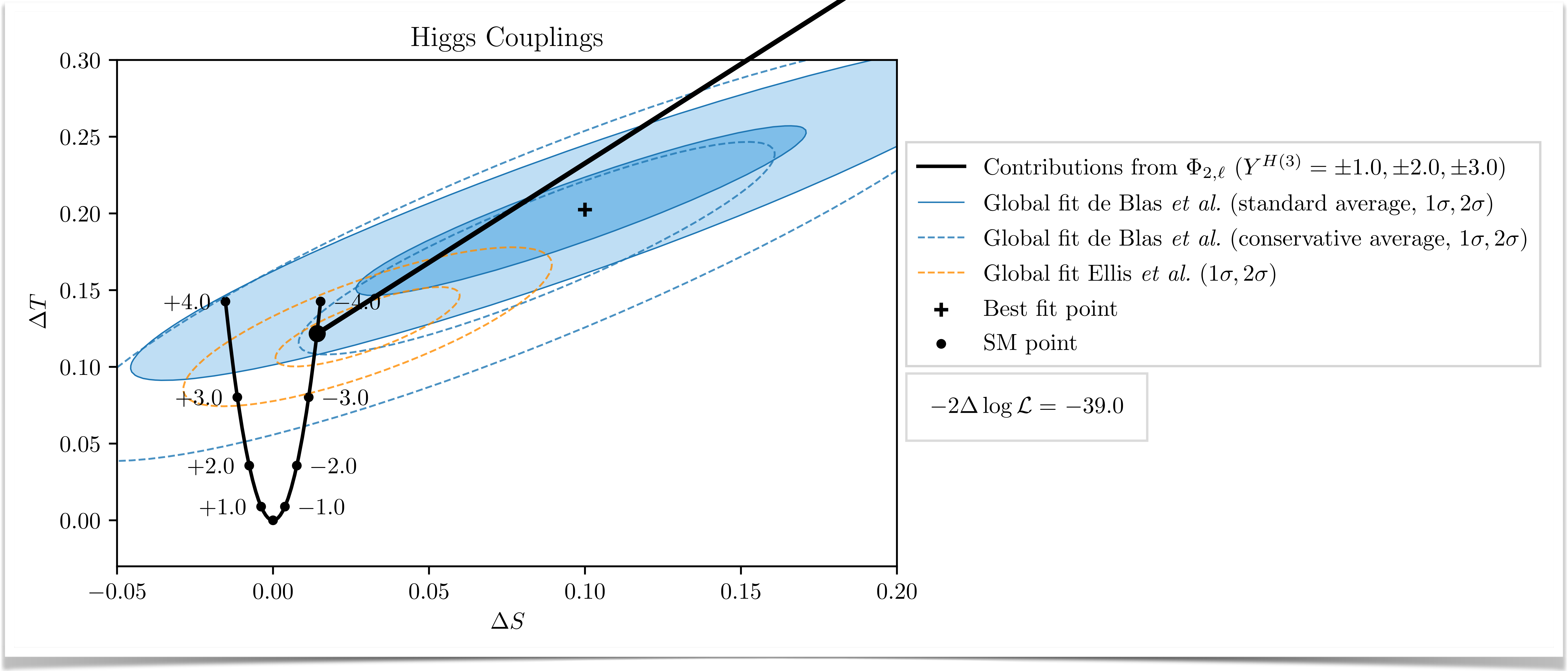
2. Phenomenology

2.5 Higgs Couplings

- **With** CDF II measurement:



Source: 2006.10758 (Crivellin et al.)



- S_2 still yields a good fit, but **very large couplings** are needed.
- $S_1 - S_3$ can accomplish **large contributions** to ΔT (→ lepton flavor violation?).

Source: 2204.03996 (Athron et al.), 2204.09031 (Bhaskar et al.)

3. Conclusions

3. Conclusions

- The hints for **LFUV** in multiple lepton generations and the absence of **LFV** motivate lepton flavoured LQs.
- We examined a corresponding model with **three** S_2 **generations**.
- It can provide explanations to deviations in
  - $R_{D^{(*)}}$,
  - $(b \to s\ell^+\ell^-)$,
  - a_μ ,
  - $pp \to ee$,
  - $(pp \to \tau\tau)$,
  - (S, T, U) ,
  - (a_e) .
- There is an interesting relation between the LQ contributions to the **charged lepton masses**, **AMMs** and **EDMs**.

Thank you for your attention!