Finanziato dall'Unione europea NextGenerationEU
Ministero dell'Università e della Ricerca
Italiadomani PIANO NAZIONALE DI RIPRESA E RESILIENZA
INFN

Closing in on new chiral leptons @ LHC

Some biased comments about NP physics + recent results based on

"Light vectors coupled to anomalous currents with harmless Wess-Zumino terms",
L. Di Luzio, MN, C. Toni,
JHEP, arXiv:2204.05945

"Closing in on new chiral leptons at the LHC",
D. Barducci, L. Di Luzio, MN, C. Toni
JHEP, arXiv: 2311.10130

15 April 2024, IRN Terascale @ LNF

New Physics

Experimental evidences:

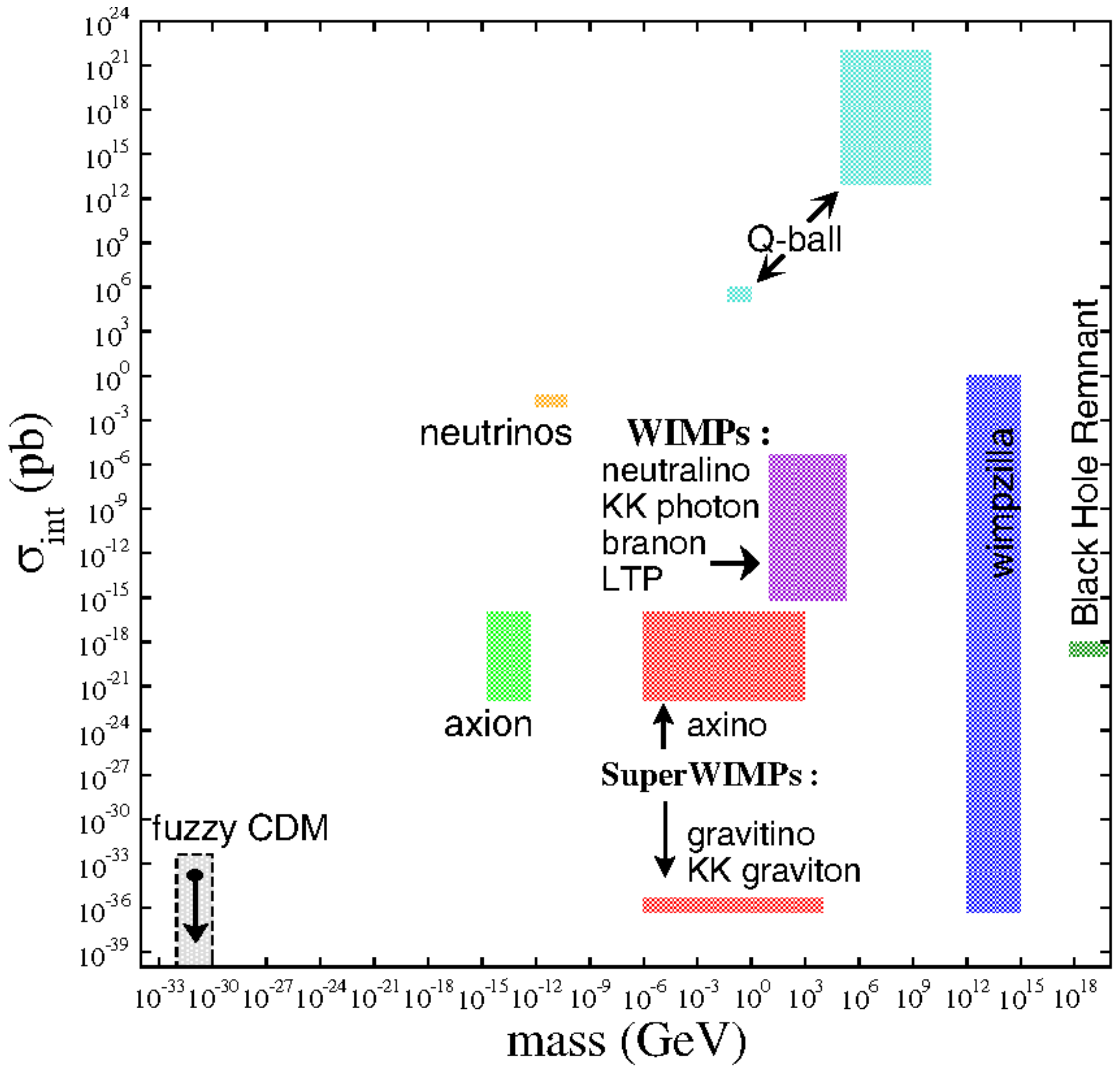
- Neutrino masses
- Dark Matter
- Baryon Asymmetry of the Universe
- (Gravity)

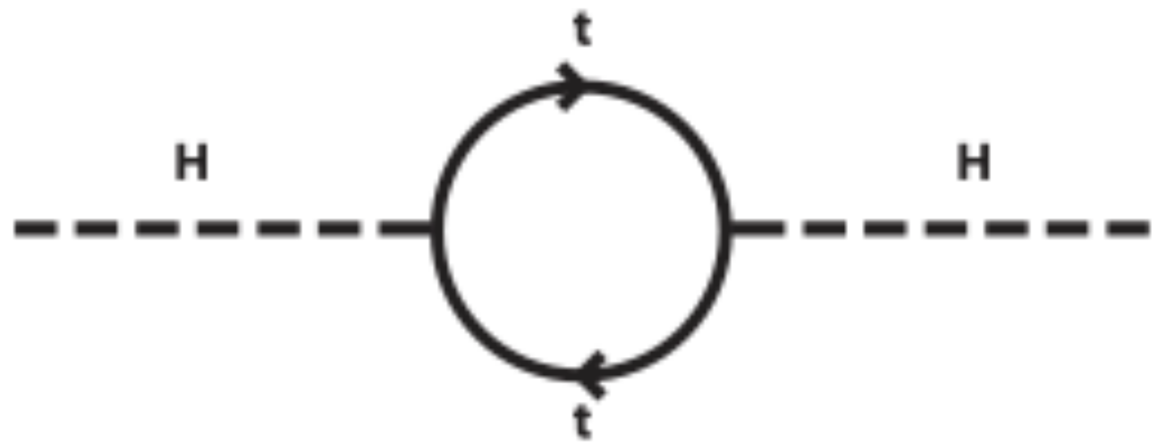
Theoretical problems/puzzles/hints:

- Hierarchy or Naturalness problem
- Flavour puzzle
- Strong CP problem
- Family replication
- GUT
- …..

What is the energy scale of New Physics at its coupling to the Standard Model?

Can we study it on shell?



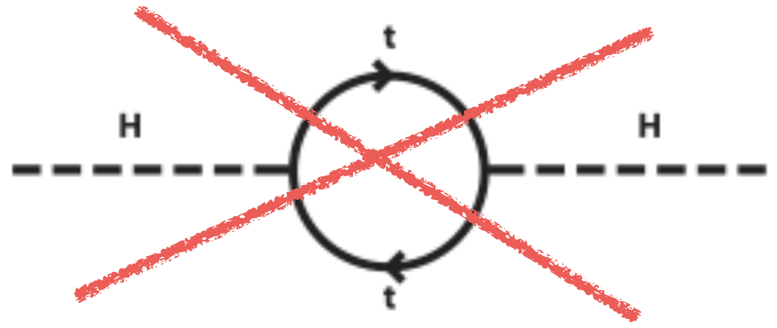


$$m_H^2 = m_{\text{tree}}^2 + \delta m_H^2$$

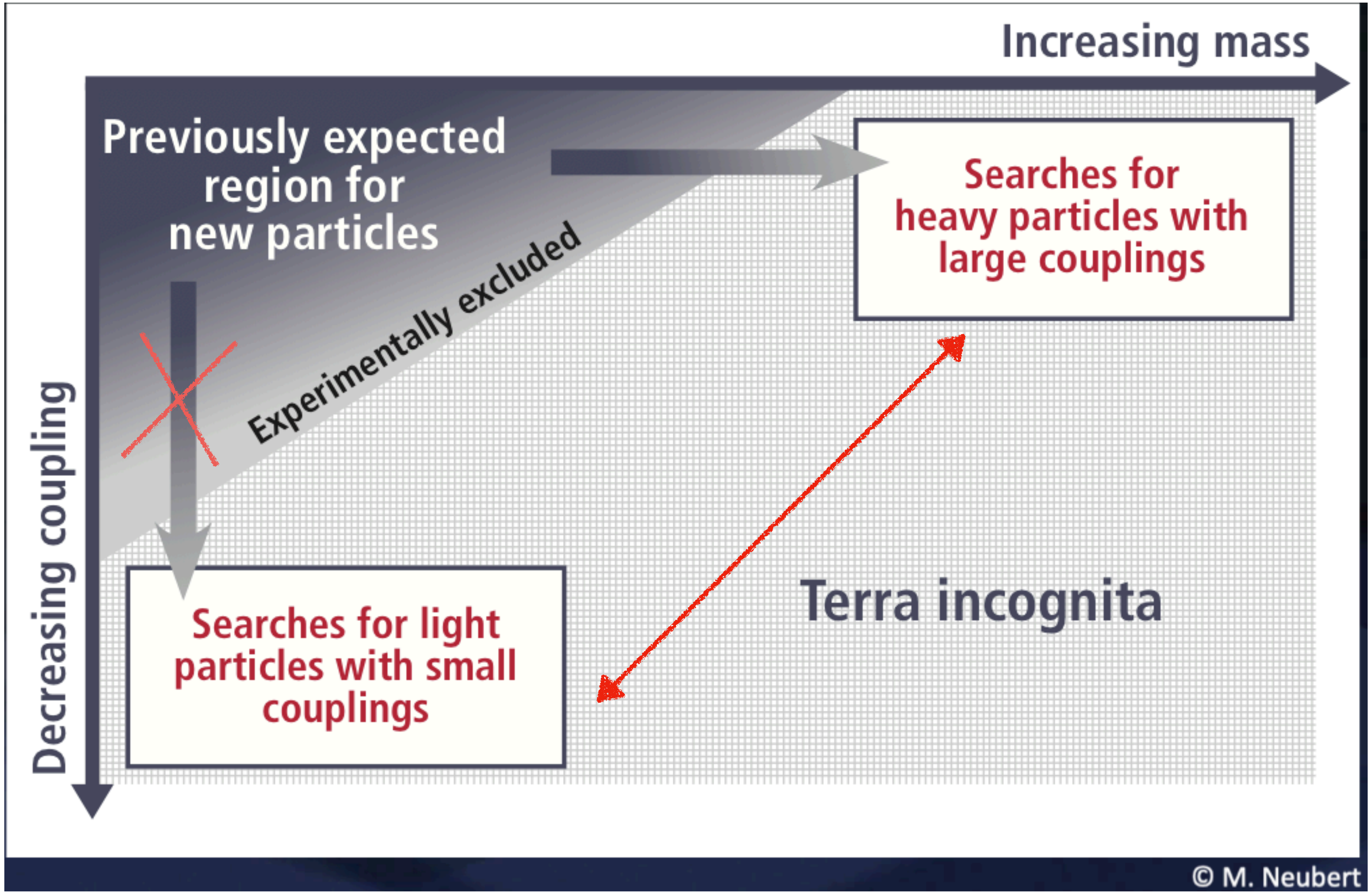
$$\delta m_H^2 = \frac{3}{\sqrt{2}\pi^2} G_F m_t^2 \Lambda^2 \approx (0.3\,\Lambda)^2$$

Coupling vs Mass Range

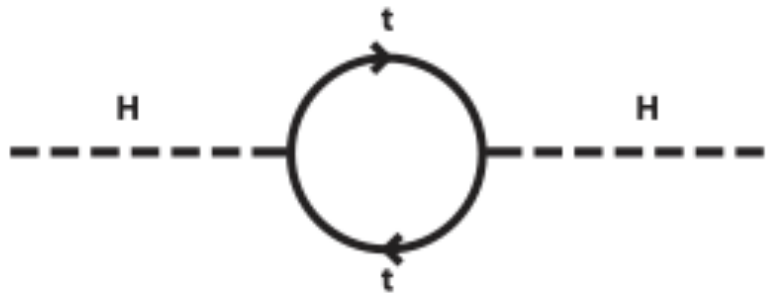
Why? Why not



- Didn't find NP at high energy
- Some problems can be addressed in this regime: axions, portal to DM sector, etc.
- Ideas for new experiments on smaller scale that LHC
- No "No-Lose Theorem"



Why?

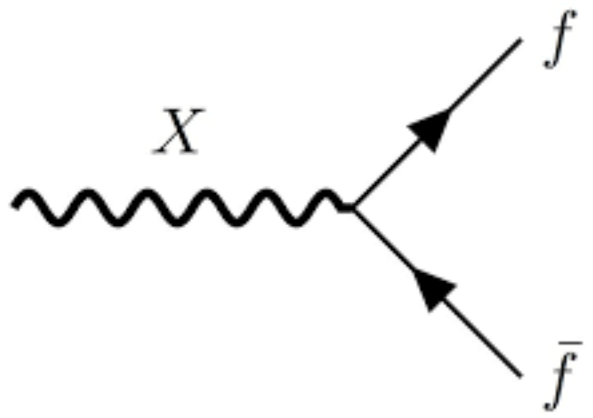


- SUSY
- Composite Higgs

UV completing the light NP physics could be phenomenologically important!

Light New Vector and (Anomalous) Currents

Consider, for example, a light vector coupled to the baryon number current:

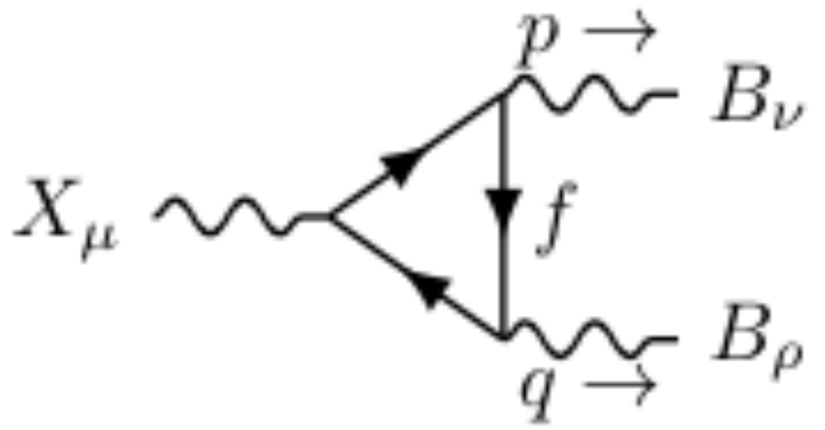


$$\mathcal{L} \supset g_X \frac{1}{3} Z'_{B\mu} \left(\bar{q}\gamma^\mu q\right)$$

(Notation: X=Z' interchangeably in what follows)

Naively, NP physics at low energy implies two parameters: the coupling and the mass

SM + X EFT is non-renormalizable and the current is anomalous at quantum level:



$$\partial^\mu J_\mu^{\text{baryon}} = \frac{\mathcal{A}}{16\pi^2}\left(g^2 W^a_{\mu\nu}(\tilde{W}^a)^{\mu\nu} - g'^2 B_{\mu\nu}\tilde{B}^{\mu\nu}\right)$$

A=3/2

EFT must be completed at a scale $\lesssim \frac{4\pi m_X}{g_X} / \left(\frac{3g^2}{16\pi^2}\right)$ [Preskill 1991]

UV physics implies the presence of Wezz-Zumino terms in the EFT:

$$\mathcal{L} \supset C_B g_X g'^2 \epsilon^{\mu\nu\rho\sigma} X_\mu B_\nu \partial_\rho B_\sigma$$
$$+ C_W g_X g^2 \epsilon^{\mu\nu\rho\sigma} X_\mu (W^a_\nu \partial_\rho W^a_\sigma + \frac{1}{3} g \epsilon^{abc} W^a_\nu W^b_\rho W^c_\sigma)$$

(Need also to specify regularisation of loop diagrams)

Background:
- D'Hoker, Farhi, 1984
- Preskill 1991
- Feruglio, Masiero, Maiani 1992

New constraints for light vectors:
- Dror, Lasenby, Pospelov 1707.01503
- Dror, Lasenby, Pospelov 1705.06726

Other pheno aspects, example DM:
- Ismail, Katz, Racco 1707.00709

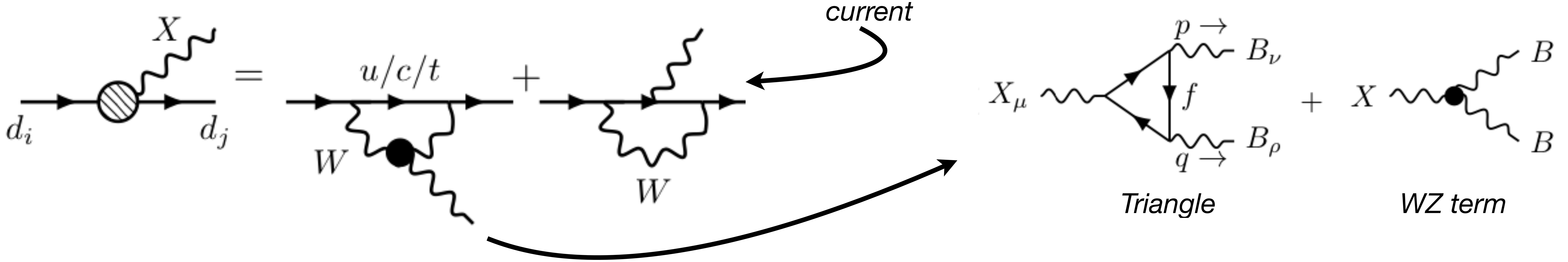
UV renormalizable models:
- Michaels, Yu 2020.00021

Energy / Mass Enhancement

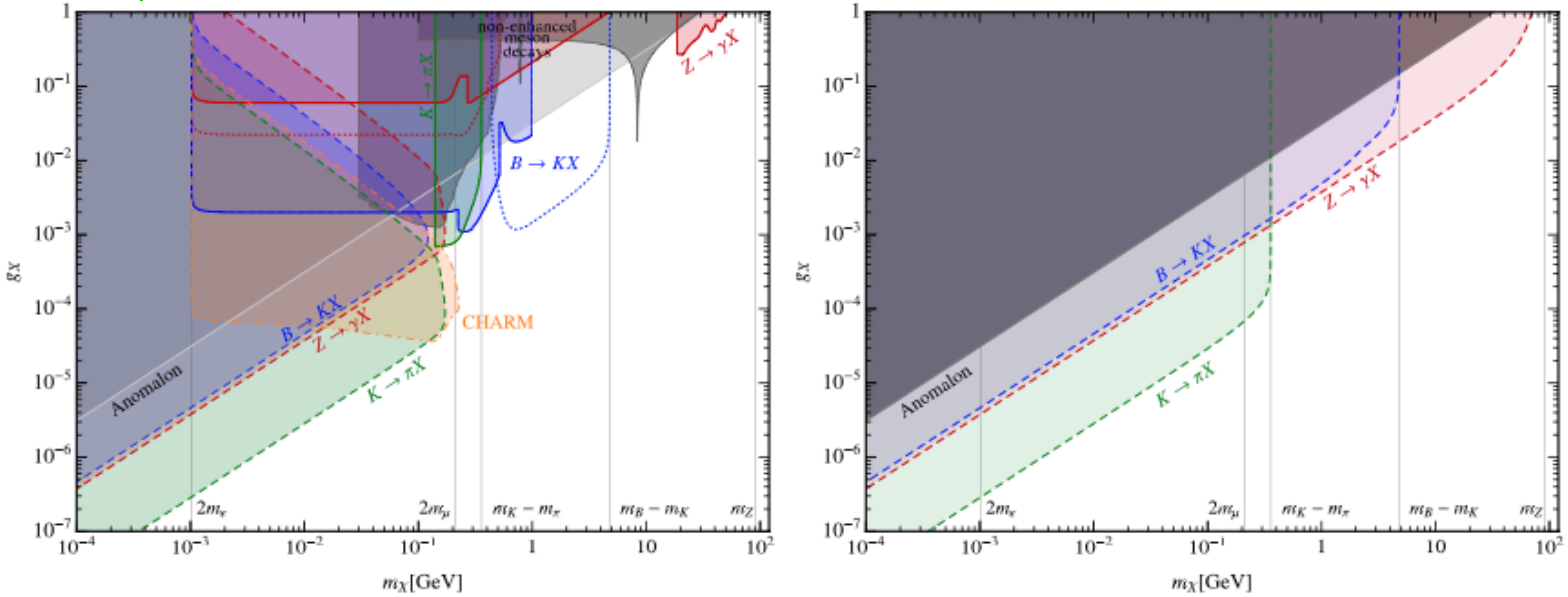
Generically, there are E/mx enhancements of the longitudinal polarisation of X leading to strong bounds.

$$\Gamma(A \to BX) \propto \frac{g_X^2}{m_X^2}$$

$$\mathcal{L} \supset g_{X d_i d_j} X_\mu \bar{d}_j \gamma^\mu \mathcal{P}_L d_i + \text{h.c.} + \ldots ,$$



example from 1707.01503



Constraints from:

$$B \to KX$$
$$K \to \pi X$$
$$Z \to \gamma X$$

Very strong constraints!

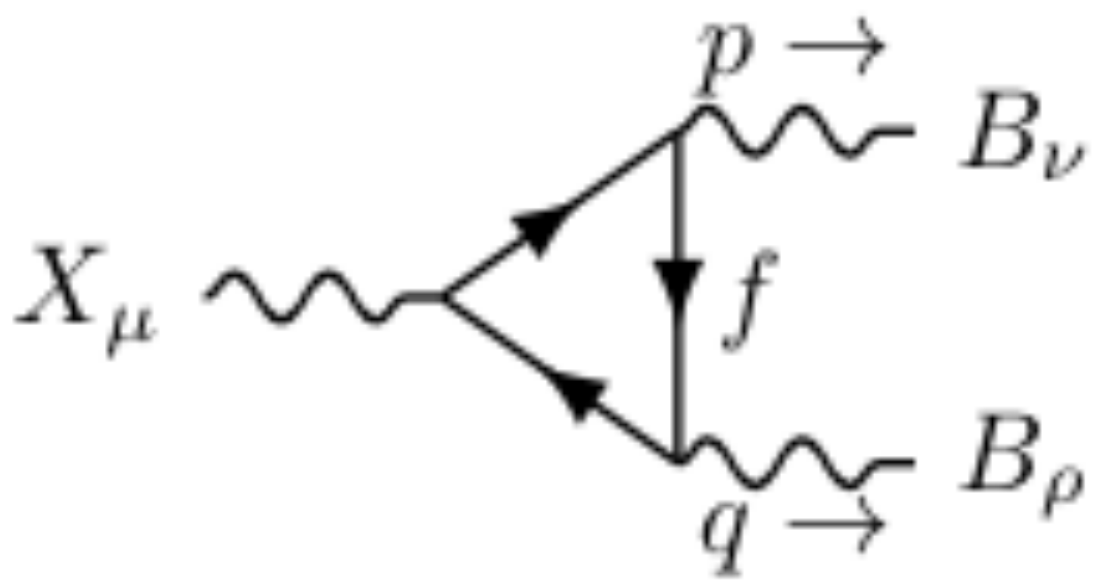
However there is a specific point in the EFT that do not exhibit this behaviour

What kind of UV physics is associated with that?

Anomalons

The light vector can be elementary or composite. If elementary, it is associated to a conserved symmetry and the current have to be non anomalous. In the UV we need new states to cancel the mass indipendent part of the triangular diagram:

$$\mathcal{M}^{\mu\nu\rho} \equiv \sum_{f, f_{\rm SM}}$$



,

Extra states are called anomalons in what follows. NP carries quantum number under both the SM gauge symmetry and the new symmetry

Anomalons are chiral with respect to the full group SM x U(1). The E/m enhancement is due to longitudinal d.o.f

Chiral fermions cannot get an explicit mass term.

SM and the light vector $\mathcal{X}$ (also keeping the Goldstone mode ξ, see App. A for details)

$$\begin{aligned}
\mathscr{L}_{\rm EFT}^{{\rm U}(1)_X} \supset\; & g_X g'^2 \frac{C_{BB}}{24\pi^2}\epsilon^{\alpha\mu\nu\beta}\mathcal{X}_\alpha B_\mu \partial_\beta B_\nu + g_X g^2 \frac{C_{ab}}{24\pi^2}\epsilon^{\alpha\mu\nu\beta}\mathcal{X}_\alpha W^a_\mu \partial_\beta W^b_\nu \\
& + g_X g g' \frac{C_{aB}}{24\pi^2}\epsilon^{\alpha\mu\nu\beta}\mathcal{X}_\alpha W^a_\mu \partial_\beta B_\nu + g_X g g' \frac{C_{Ba}}{24\pi^2}\epsilon^{\alpha\mu\nu\beta}\mathcal{X}_\alpha B_\mu \partial_\beta W^a_\nu \\
& + g_X g^2 \frac{D_{ab}}{48\pi^2}\frac{\xi}{m_\mathcal{X}}\epsilon^{\alpha\mu\beta\nu}(\partial_\alpha W^a_\mu)(\partial_\beta W^b_\nu) + g_X g'^2 \frac{D_{BB}}{48\pi^2}\frac{\xi}{m_\mathcal{X}}\epsilon^{\alpha\mu\beta\nu}(\partial_\alpha B_\mu)(\partial_\beta B_\nu) \\
& + g_X g g' \frac{D_{aB}}{24\pi^2}\frac{\xi}{m_\mathcal{X}}\epsilon^{\alpha\mu\beta\nu}(\partial_\alpha W^a_\mu)(\partial_\beta B_\nu)\,,
\end{aligned}$$

Anomalons have to pick up a mass from EW and/or U(1) symmetry breaking

$$H \overline{f}_L f_R \quad \text{and/or} \quad S \overline{f}_L f_R \qquad\qquad S \propto e^{i\xi}$$

Enhancement can be understood with the equivalence theorem

Goldstone term disappear if the Anomalons take mass from EW only

A Class of Renormalizable Models

Field	Lorentz	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$	$U(1)_X$
q_L^i	$(\frac{1}{2},0)$	3	2	1/6	$\alpha_B/3$
u_R^i	$(0,\frac{1}{2})$	3	1	2/3	$\alpha_B/3$
d_R^i	$(0,\frac{1}{2})$	3	1	$-1/3$	$\alpha_B/3$
ℓ_L^i	$(\frac{1}{2},0)$	1	2	$-1/2$	α_i
e_R^i	$(0,\frac{1}{2})$	1	1	-1	α_i
H	$(0,0)$	1	2	1/2	0
$\mathcal{L}_L$	$(\frac{1}{2},0)$	1	2	$\mathcal{Y}-1/2$	$X_{\mathcal{L}_L}$
$\mathcal{L}_R$	$(0,\frac{1}{2})$	1	2	$\mathcal{Y}-1/2$	$X_{\mathcal{L}_R}$
$\mathcal{E}_L$	$(\frac{1}{2},0)$	1	1	$\mathcal{Y}-1$	$X_{\mathcal{E}_L}$
$\mathcal{E}_R$	$(0,\frac{1}{2})$	1	1	$\mathcal{Y}-1$	$X_{\mathcal{E}_R}$
$\mathcal{N}_L$	$(\frac{1}{2},0)$	1	1	$\mathcal{Y}$	$X_{\mathcal{N}_L}$
$\mathcal{N}_R$	$(0,\frac{1}{2})$	1	1	$\mathcal{Y}$	$X_{\mathcal{N}_R}$
ν_R^α	$(0,\frac{1}{2})$	1	1	0	$X_{\nu_R}^\alpha$
$\mathcal{S}$	$(0,0)$	1	1	0	$X_{\mathcal{S}}$

$$-\mathscr{L}_Y = y_1\overline{\mathcal{L}}_L\mathcal{E}_R H + y_2\overline{\mathcal{L}}_R\mathcal{E}_L H + y_3\overline{\mathcal{L}}_L\mathcal{N}_R\tilde{H} + y_4\overline{\mathcal{L}}_R\mathcal{N}_L\tilde{H} + \text{h.c.}$$

- All gauge anomalies have to cancel
- SM quantum number set by a single parameter Y
- Charges are such that anomalons don't couple to S
- Mass purely from EW

Two important phenomenological implications:
1) non-decupling New Physics

$$M_{anom} = y\frac{v}{\sqrt{2}} \qquad M_{anom} \lesssim 600\ \text{GeV} \quad (y=\sqrt{4\pi})$$

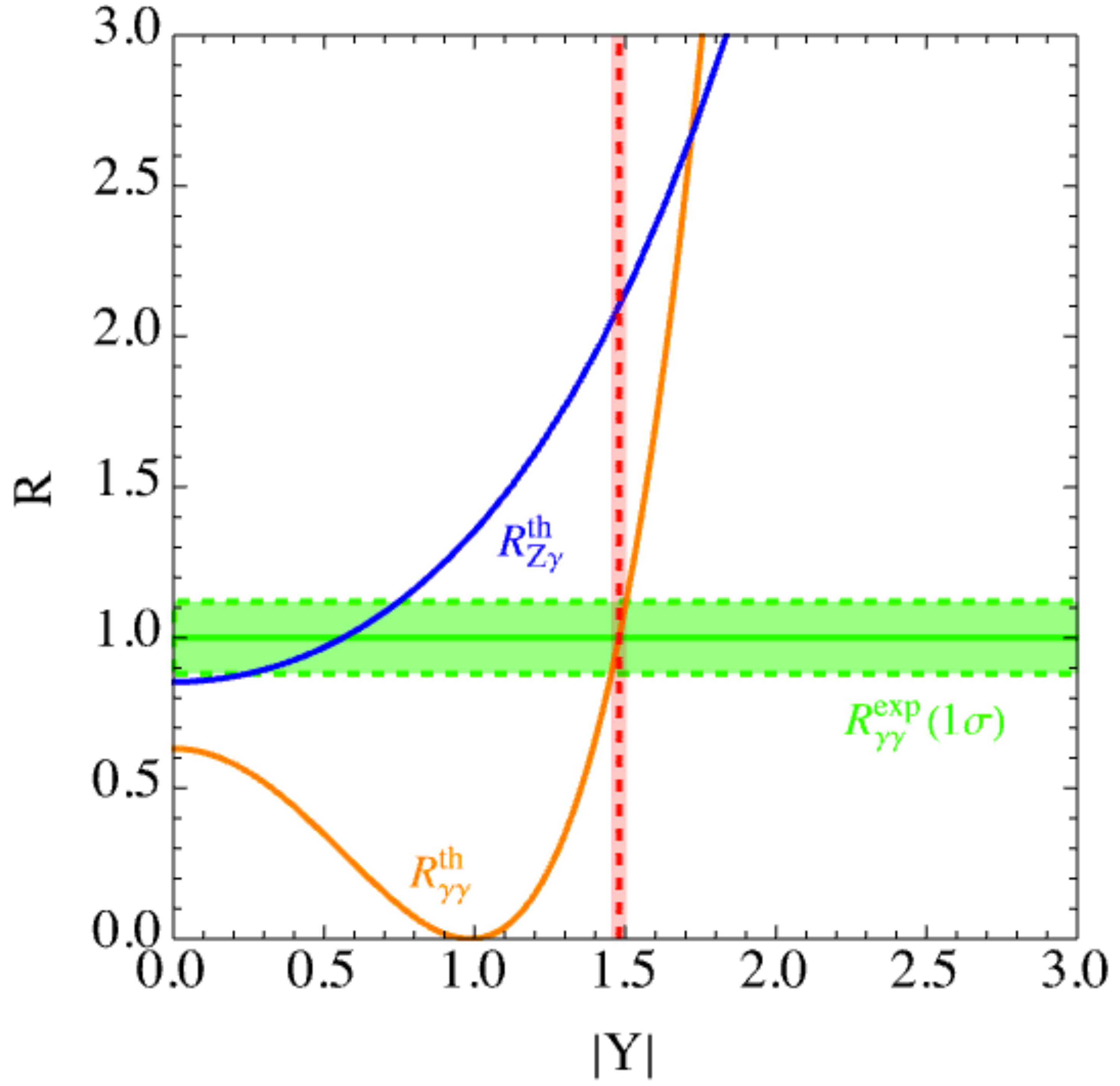
2) very large coupling to the Higgs

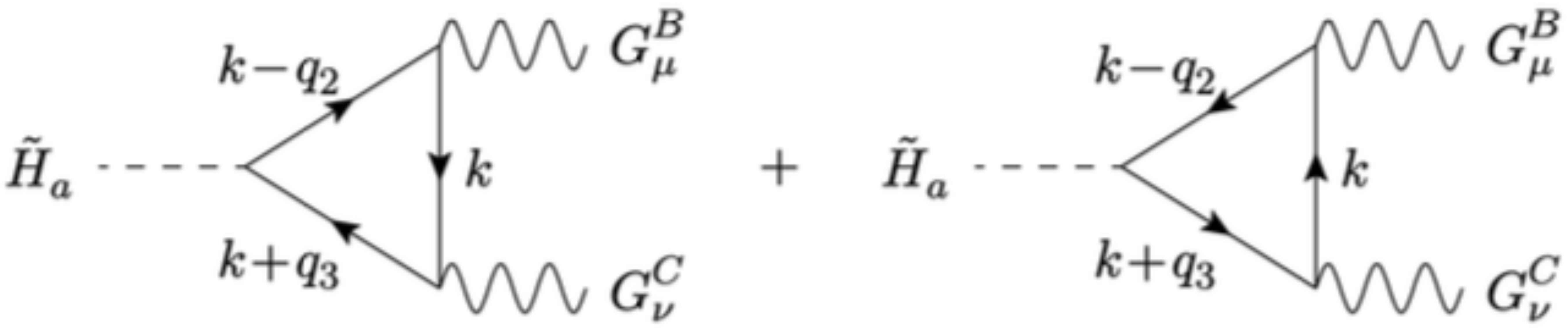
Anomalons are heavy leptons with exotic charges.
No QCD charge is allowed, because of Higgs overproduction at the LHC

Higgs Physics

Main effects are the radiative two-body decays of the Higgs into gauge bosons: $h \to Z\gamma$ and $h \to \gamma\gamma$

See also Bizot, Frigerio arXiv:1508.01645





$$R_{\gamma\gamma,Z\gamma} = \frac{|A^{SM}_{\gamma\gamma,Z\gamma} + A^{BSM}_{\gamma\gamma,Z\gamma}|^2}{|A^{SM}_{\gamma\gamma,Z\gamma}|^2}$$

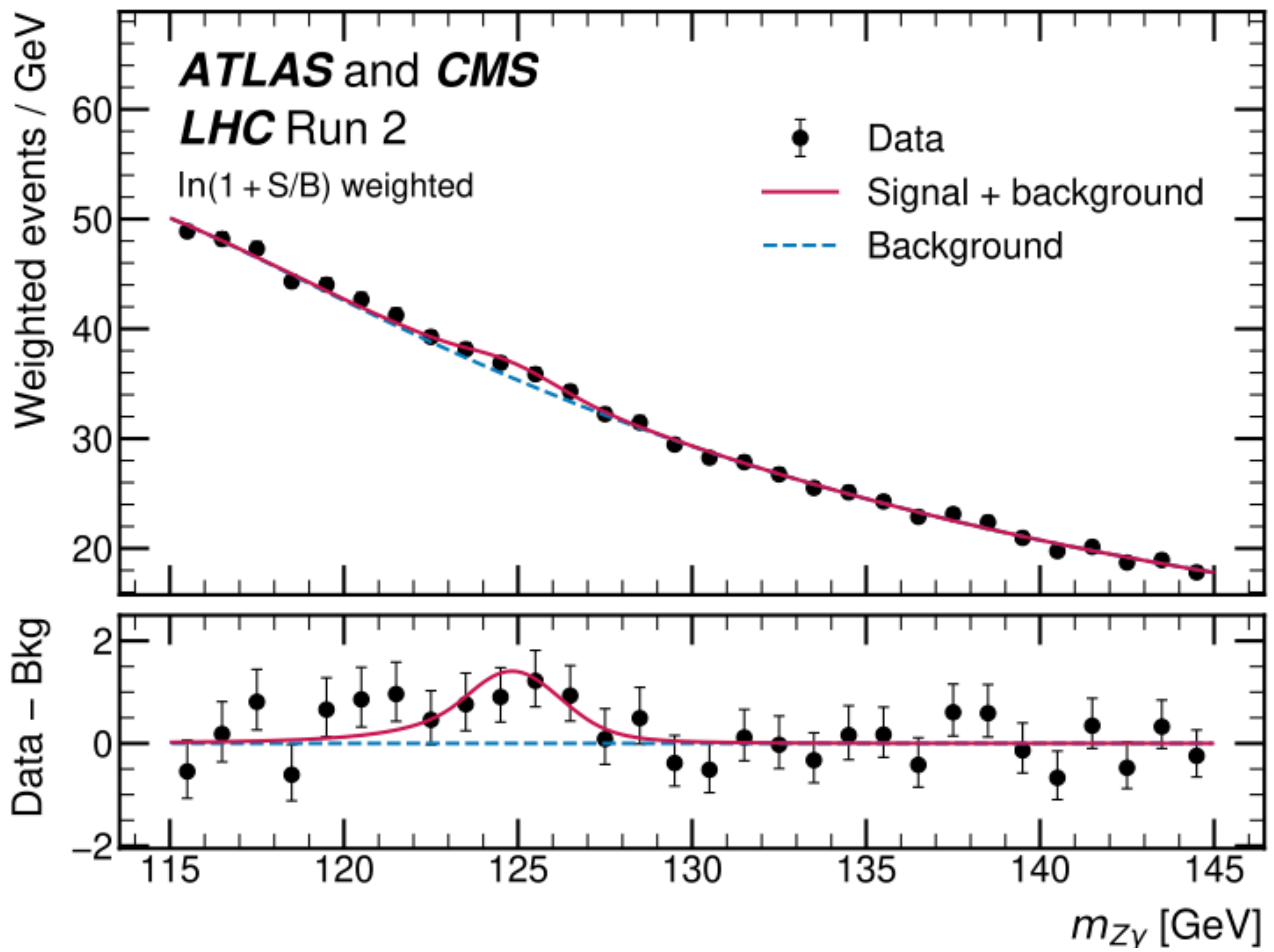
$$A^{BSM}_{\gamma\gamma} \simeq \frac{4}{3}\left(1+4Y^2\right) ,$$

$$A^{BSM}_{Z\gamma} \simeq \frac{2}{3}\left[1-(1+8Y^2)\mathrm{tg}^2_w\right]$$

- BSM contributions independent from the mass of new states when $m_h \ll M_{anom}$
- Diphoton contribution can be consistent only if $A^{BSM}_{\gamma\gamma} \simeq -2A^{SM}_{\gamma\gamma}$ $\qquad |Y| \approx \frac{3}{2}$
- In 2204.05945, clean prediction for the Z-photon channel $R_{Z\gamma} \approx 2.1$

Higgs to Z gamma

[ATLAS & CMS 2309.03501]



the signal strength is shown in Figure 3. The observed (expected) signal strength at the 68% confidence level is $\mu = 2.0^{+1.0}_{-0.9}$ (1.0 ± 0.9) for the ATLAS analysis, $\mu = 2.4^{+1.0}_{-0.9}$ $(1.0^{+1.0}_{-0.9})$ for the CMS analysis, and $\mu = 2.2 \pm 0.6\ (\text{stat.})^{+0.3}_{-0.2}\ (\text{syst.}) = 2.2 \pm 0.7$ $(1.0 \pm 0.6\ (\text{stat.}) \pm 0.2\ (\text{syst.}) = 1.0 \pm 0.6)$ for their combination.

This motivated us to study further the phenomenology of chiral leptons in 2311.10130 (JHEP)

Direct Searches of Anomalons

Recap: interesting case when new states have SM quantum number: $\mathcal{L}_{L,R} = \begin{pmatrix} \mathcal{N}_{\mathcal{L}} \\ \mathcal{E}_{\mathcal{L}} \end{pmatrix}_{L,R} \sim (\mathbf{1},\mathbf{2})_Y \,, \quad \mathcal{E}_{L,R} \sim (\mathbf{1},\mathbf{1})_{Y-\frac{1}{2}} \,, \quad \mathcal{N}_{L,R} \sim (\mathbf{1},\mathbf{1})_{Y+\frac{1}{2}}$

$|Y| \approx \frac{3}{2}$

After EWSB 4 Dirac fields with electric charges about 2 and 1. At the LHC, phenomenology depends if there are stable anomalons or not.

Stable anomalons give charged tracks at the LHC

$$M_{Q=2e} > 1030 \text{ GeV}$$

Adapting and rescaling the ATLAS analysis arXiv:2303.13613

$$M_{Q=e} > 600 \text{ GeV}$$

Adapting and rescaling the CMS analysis arXiv:1609.08382

Unstable anomalons are present for some specific U(1) charge assigments and $Y = -\frac{3}{2}$

There is a mixing with the SM charged leptons: $-\mathcal{L}_{\text{mix}} = \lambda_{i,R}\overline{L}^i_L H \mathcal{N}_R + \lambda_{i,L}\overline{\mathcal{L}}_L \tilde{H} e^i_R + h.c.$

Doubly charged states decays into same-sign lepton pair via: $\Psi^{\mathcal{E}_i} \to W^-\ell^- \to \ell^-\ell^- \not{E}_T$

$$M_{Q=2e} > 600 \text{ GeV}$$

Adapting and rescaling the ATLAS analysis arXiv:1710.09748

Model is perturbative excluded when considering a more refined bound using unitarity for Yukawa coupling $M_{anom} \lesssim 400 \text{ GeV}$

(Models that explains a possibile large effects in Z-photon can be constructed starting from this benchmark)

LHC and Non Decoupling New Physics

- In absence of New Physics, old fashioned solutions of the hierarchy problem cannot be ruled out

- This is because SUSY and Composite Higgs model can be continuously deformed to the SM

$$\lim_{m_{\rm soft}\to\infty} \text{MSSM} = SM \qquad \lim_{f\to\infty} \text{Composite Higgs} = SM$$

- What is getting worst is the little hierarchy problem. (The tuning of the heavy NP parameters to get the EW scale)

$$\Delta = \frac{v^2}{m_{\rm soft}^2} \qquad \Delta = \frac{v^2}{f^2}$$

- Non-decoupling New Physics does not have such smooth limit.

$$M_{anom} = y\frac{v}{\sqrt{2}}$$

$$M_{anom} \lesssim 400 \text{ GeV}$$ - Perturbativity

$$M_{anom} \gtrsim 600 \text{ GeV}$$ - Direct searches and Higgs Physics

- LHC is closing completely the window for new chiral fermions

Conclusions

- BSM physics exists, but experimental data does not favor any specific physics scenario.
- Traditional solutions to the hierarchy problem remain relevant despite requiring finer tuning.
- There is a growing interest in light and weakly coupled new physics, though its justification is arguable. However some models are very interesting and motivated.
- When considering light new physics, it is crucial to bear in mind an ultraviolet (UV) completion of the low-energy effective field theory (EFT).
- For instance, a light vector coupled to anomalous currents may exhibit E/mass enhancement but an explicit UV model can circumvent this feature by predicting that new fermions are chiral and acquire mass from the Higgs VEV.
- New chiral fermions are heavily constrained by LHC searches, if not entirely ruled out.

Backup

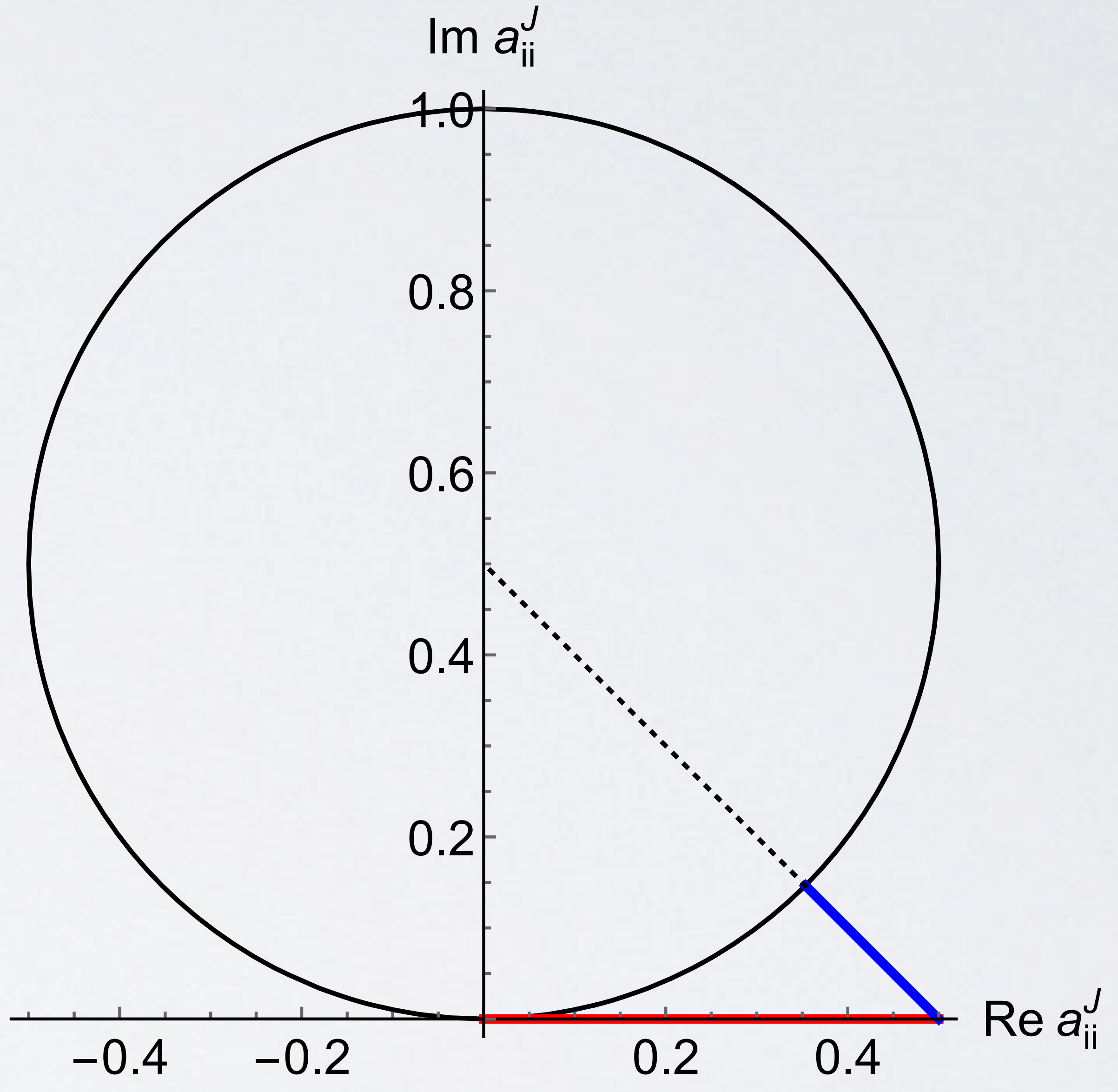
Perturbative Unitarity

- Unitarity (an axiom of QFT), focus 2 —> 2 scattering

$$SS^\dagger = 1 \qquad S = 1 + iT \quad \longrightarrow \quad \frac{1}{2i}\left(a^J_{fi} - a^{J*}_{if}\right) \geq \sum_{h \in \text{2-particle}} a^{J*}_{hf} a^J_{hi} \qquad a^J_{fi} \propto \langle f|T|i\rangle_J$$

- For f = i (optical theorem)

$$\mathrm{Im}\, a^J_{ii} \geq |a^J_{ii}|^2 \quad \longrightarrow \quad \left(\mathrm{Re}\, a^J_{ii}\right)^2 + \left(\mathrm{Im}\, a^J_{ii} - \frac{1}{2}\right)^2 \leq \frac{1}{4}$$



- In practical perturbative calculations S-matrix unitarity is always approximate

- signals breakdown of perturbative expansion

$$\left|\mathrm{Re}\,(a^J_{ii})^{\text{Born}}\right| \leq \frac{1}{2}$$

•Works both in the EFT and in explicit renormalizable models