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New Chiral Leptons at LHC

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26 March 2025, Moriond EW

Light-Heavy New Physics Connections

1) To evade direct searches, New Physics (NP) must be either light and very weakly coupled to the SM or heavy. In recent years, interest in light NP has been growing significantly.

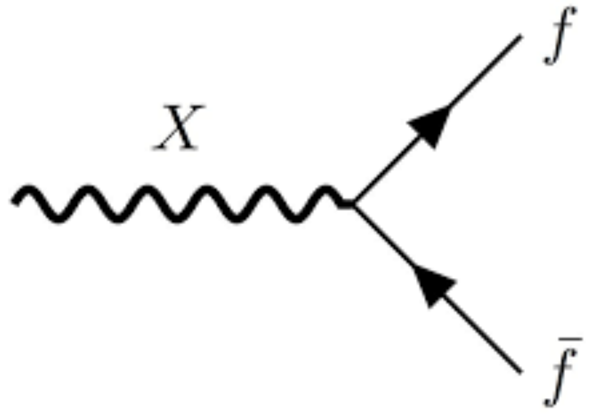
2) Light NP is described by an EFT. Providing UV explicit models that realise such an EFT is not merely a theoretical exercise but it can also reveal important phenomenological implications.

3) I will discuss an explicit example, that leads to the prediction of new chiral fermions and large effect in Higgs physics, $h \to Z\gamma$

based on
- L. Di Luzio, MN, C. Toni, JHEP, arXiv:2204.05945
- D. Barducci, L. Di Luzio, MN, C. Toni, JHEP, arXiv: 2311.10130

Light New Vector and (Anomalous) Currents

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



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

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

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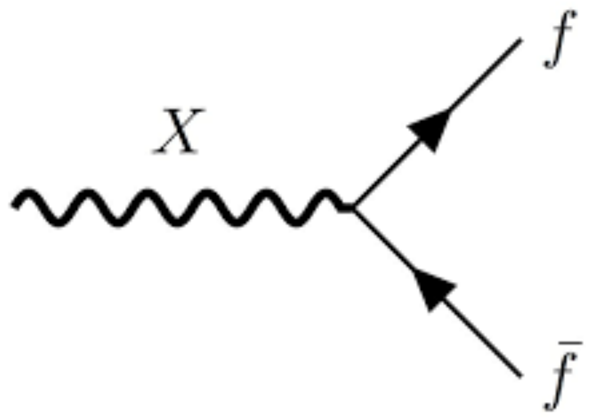

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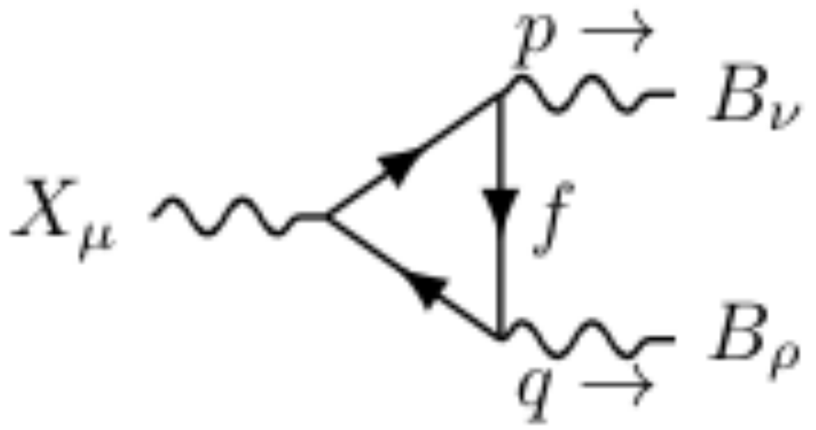
SM + X EFT is non-renormalizable and the current is anomalous at quantum level:



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

A=3/2

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

Need to include also
Wess-Zumino terms in the EFT:

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

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

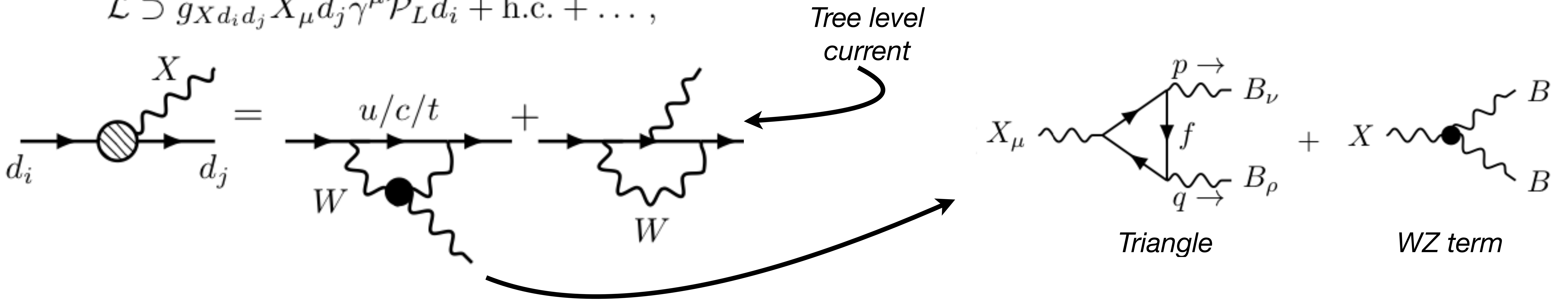
New constraints for light vectors:
- Dror, Lasenby, Pospelov 1707.01503
- Dror, Lasenby, Pospelov 1705.06726

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

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

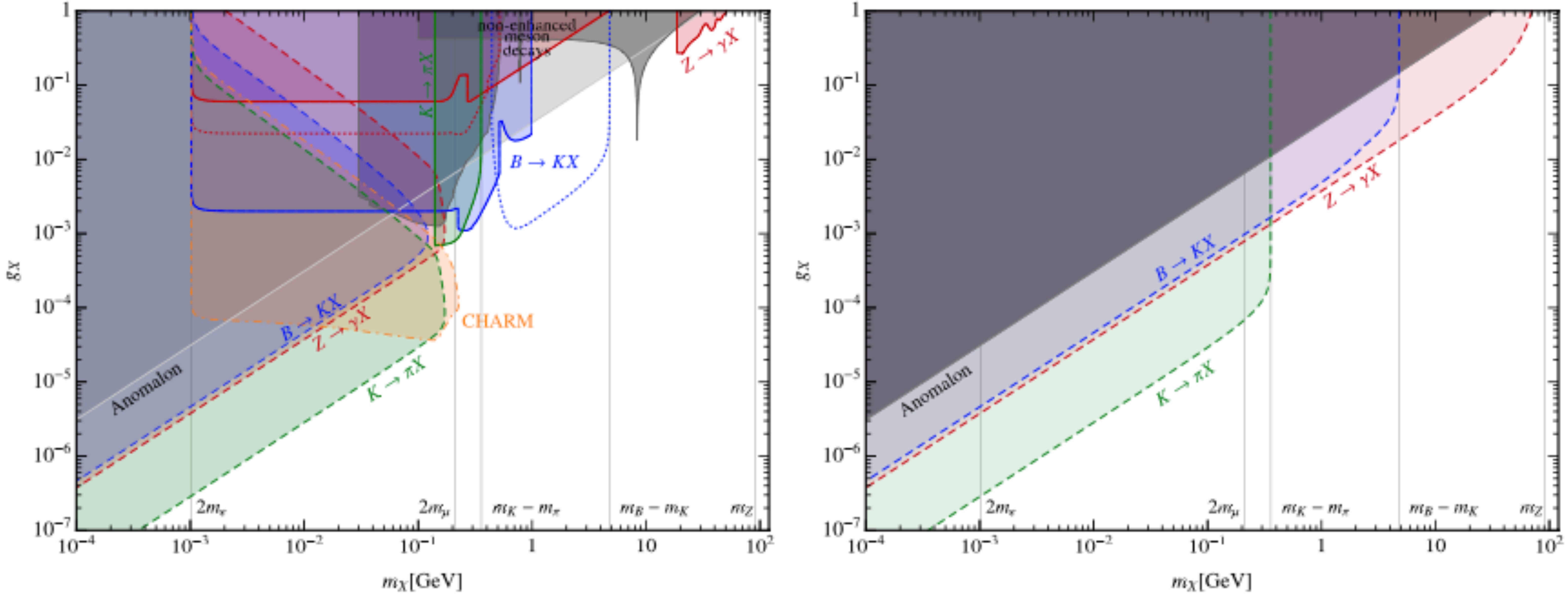


Tree level current

Triangle

WZ term

example from 1707.01503



Constraints from:

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

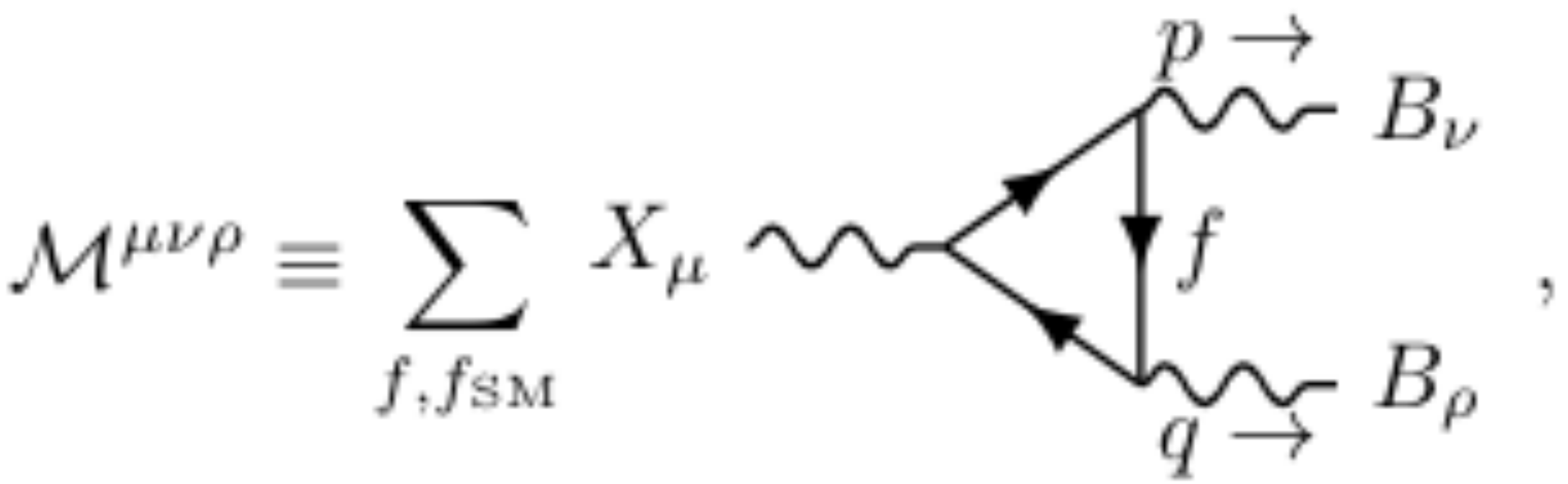
Very strong constraints!

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

What kind of UV physics is associated with that?

Anomalons

Let us assume X is a gauge boson. In the UV we need new states have to cancel the mass independent part of the triangular diagram:



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). Chiral fermions cannot get an explicit mass term.

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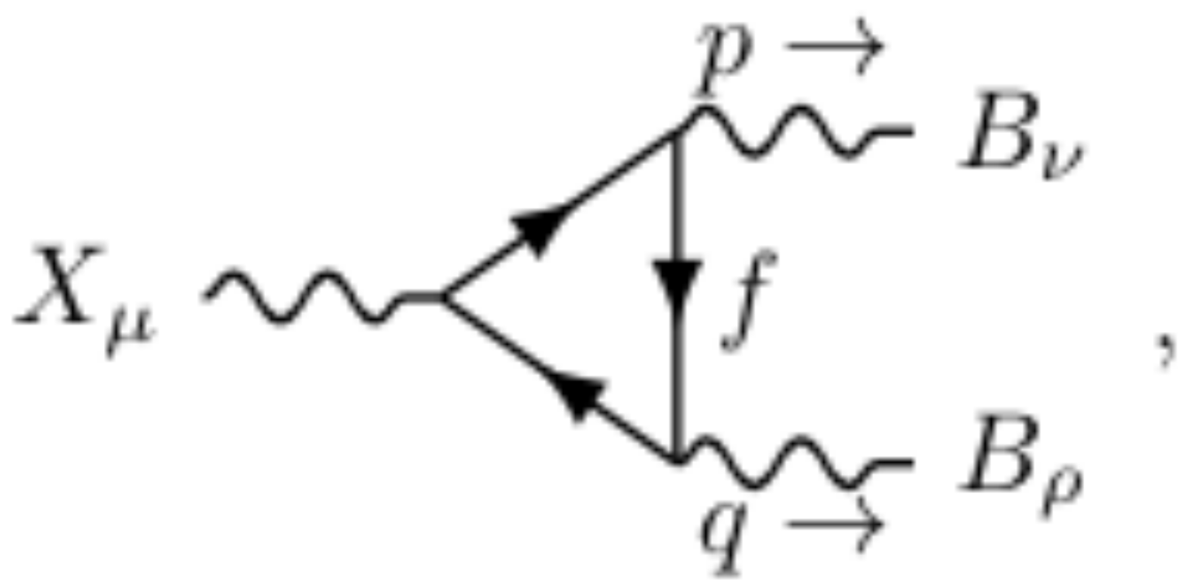
$$\mathcal{M}^{\mu\nu\rho} \equiv \sum_{f, f_{\rm SM}}$$



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The E/m enhancement is due to longitudinal d.o.f. The effect can be understood with the equivalence theorem: $X \to \xi$

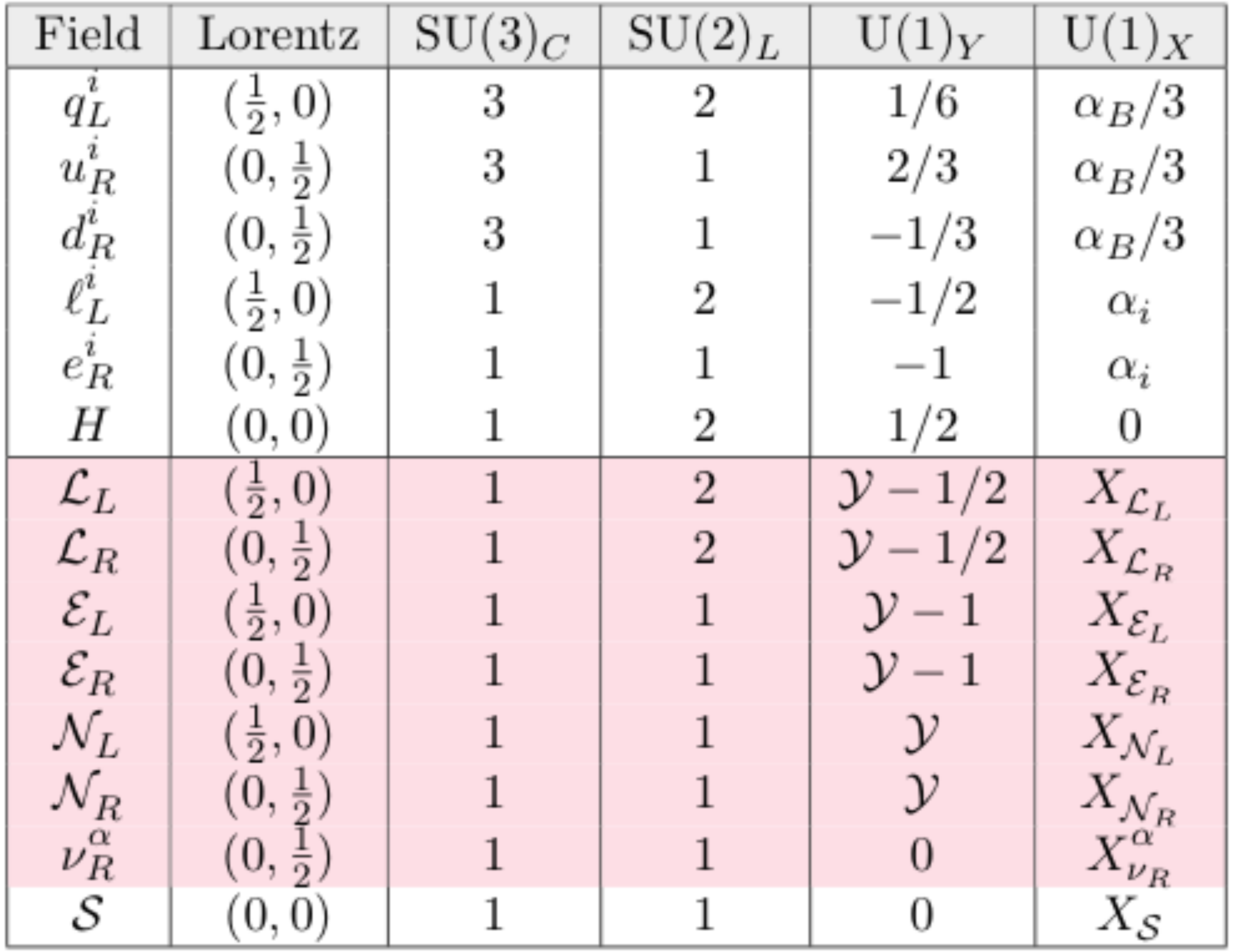
Do the Anomalons couple to the Goldstone boson of the new symmetry?

This depends on the physics that generate the mass term: $H\overline{f}_L f_R$ and/or $S\overline{f}_L f_R$ $\quad S \propto e^{i\xi}$

No couplings with the Goldstone boson if the Anomalons take mass from EW breaking only

E/m enhancement disappear in low energy observables

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

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

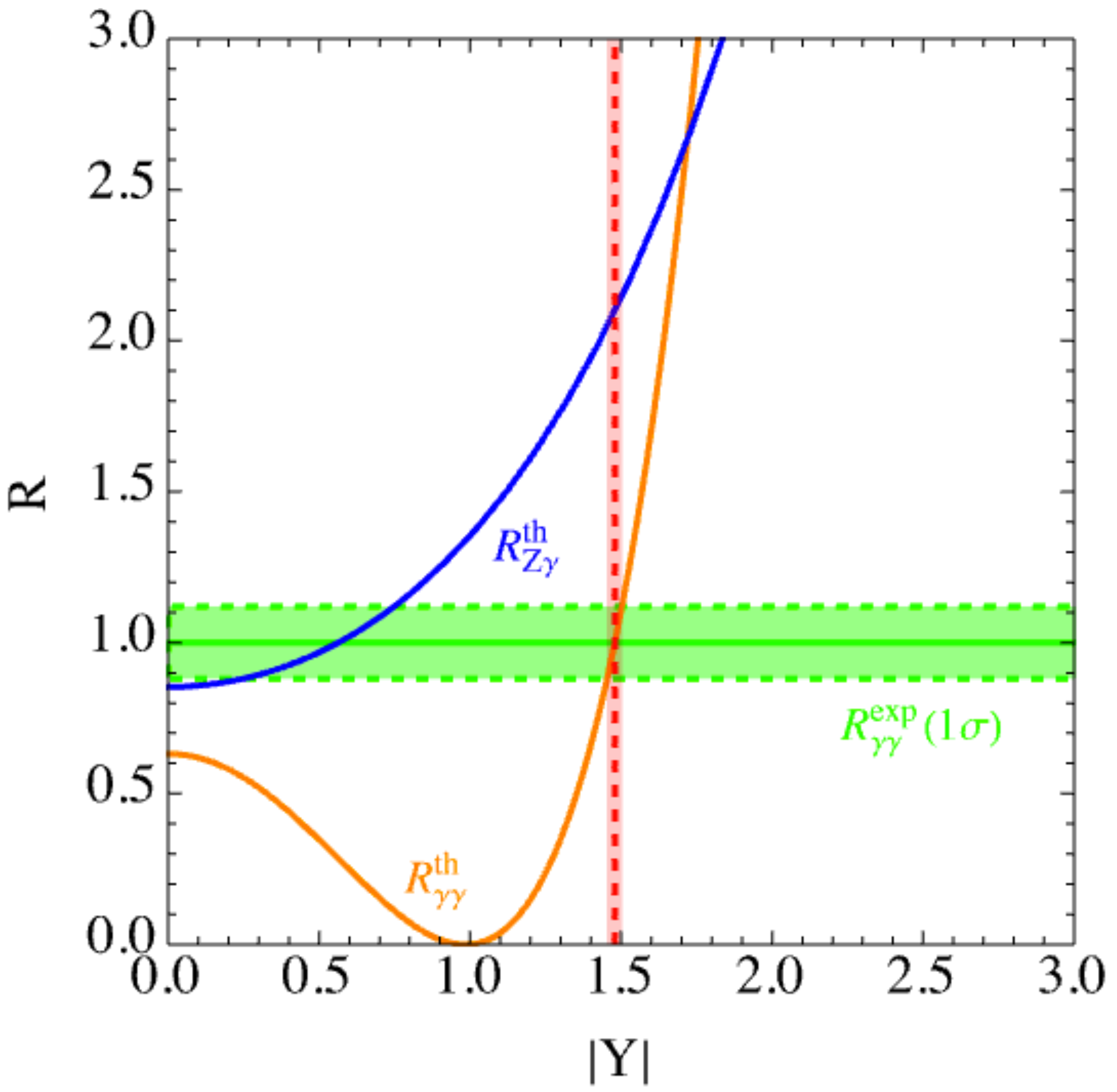
2) very large coupling to the Higgs

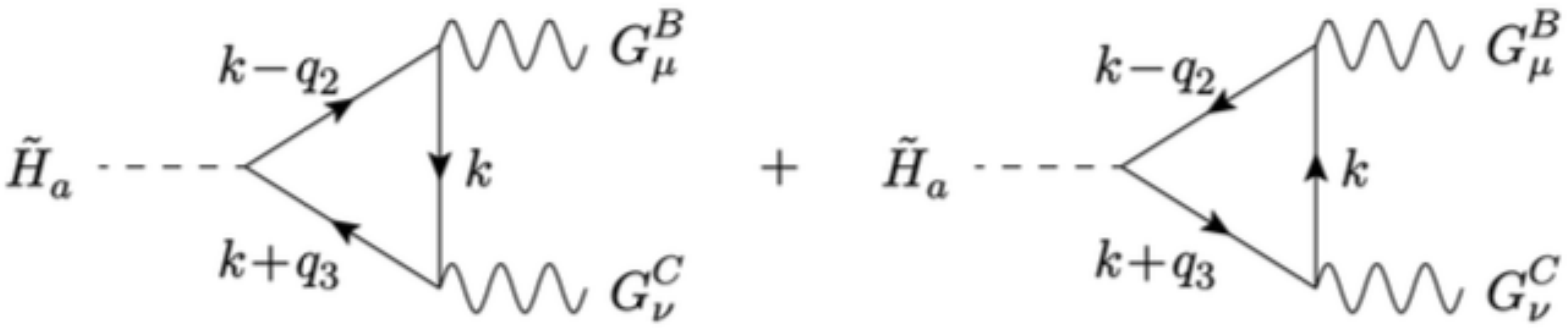
Anomalons are heavy leptons with exotic charges.
No QCD charge is allowed, because of Higgs overproduction at the LHC

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





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

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

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

- BSM contributions independent from the mass of new states when $m_h \ll M_{anom}$
- Diphoton contribution can be consistent only if $A^{\mathrm{BSM}}_{\gamma\gamma} \simeq -2A^{\mathrm{SM}}_{\gamma\gamma}$

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

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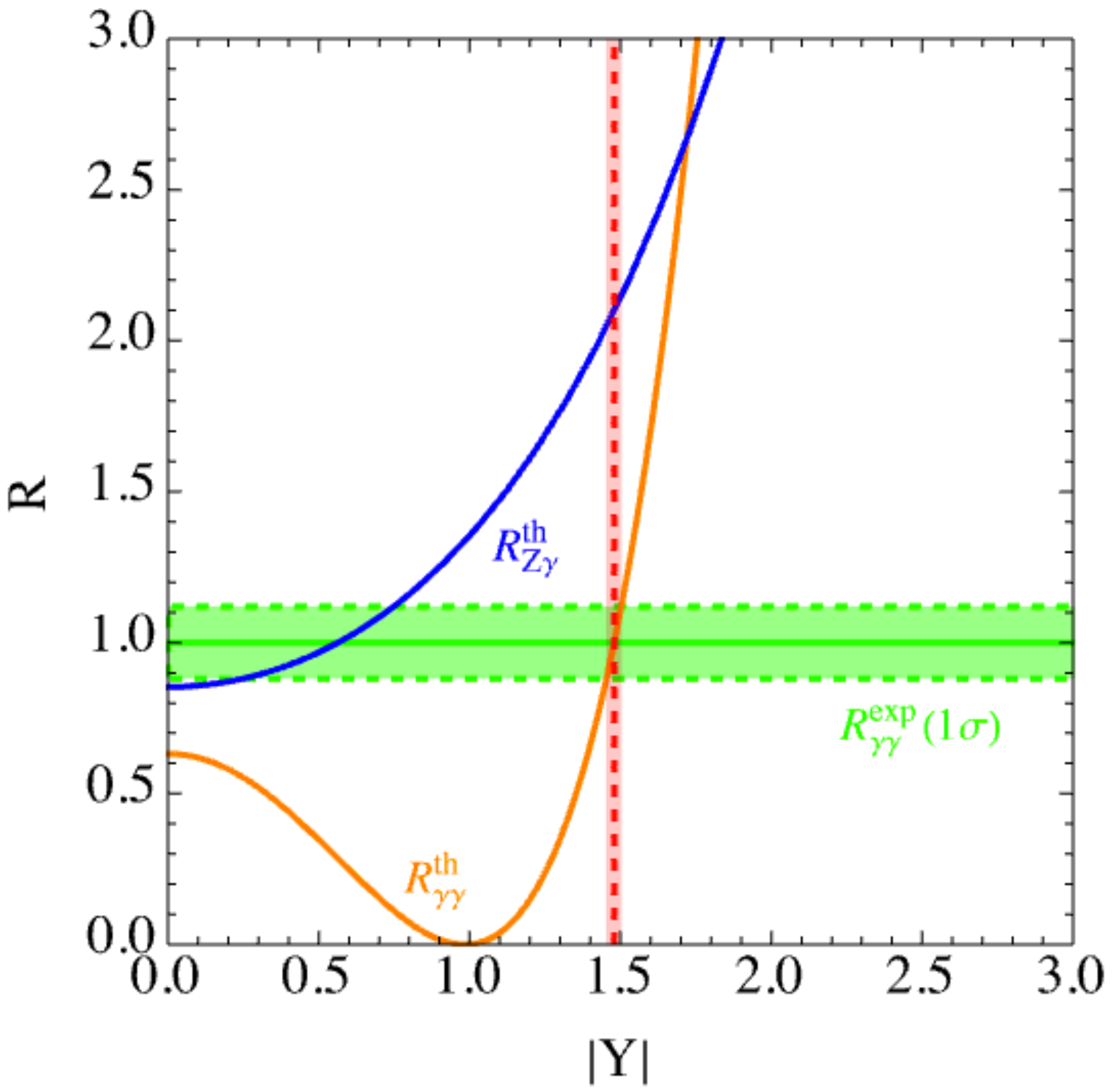

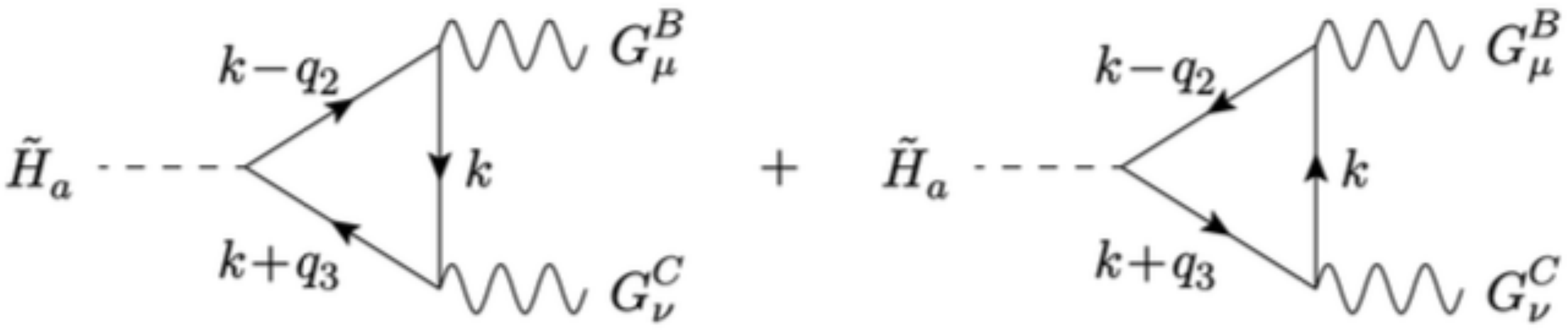

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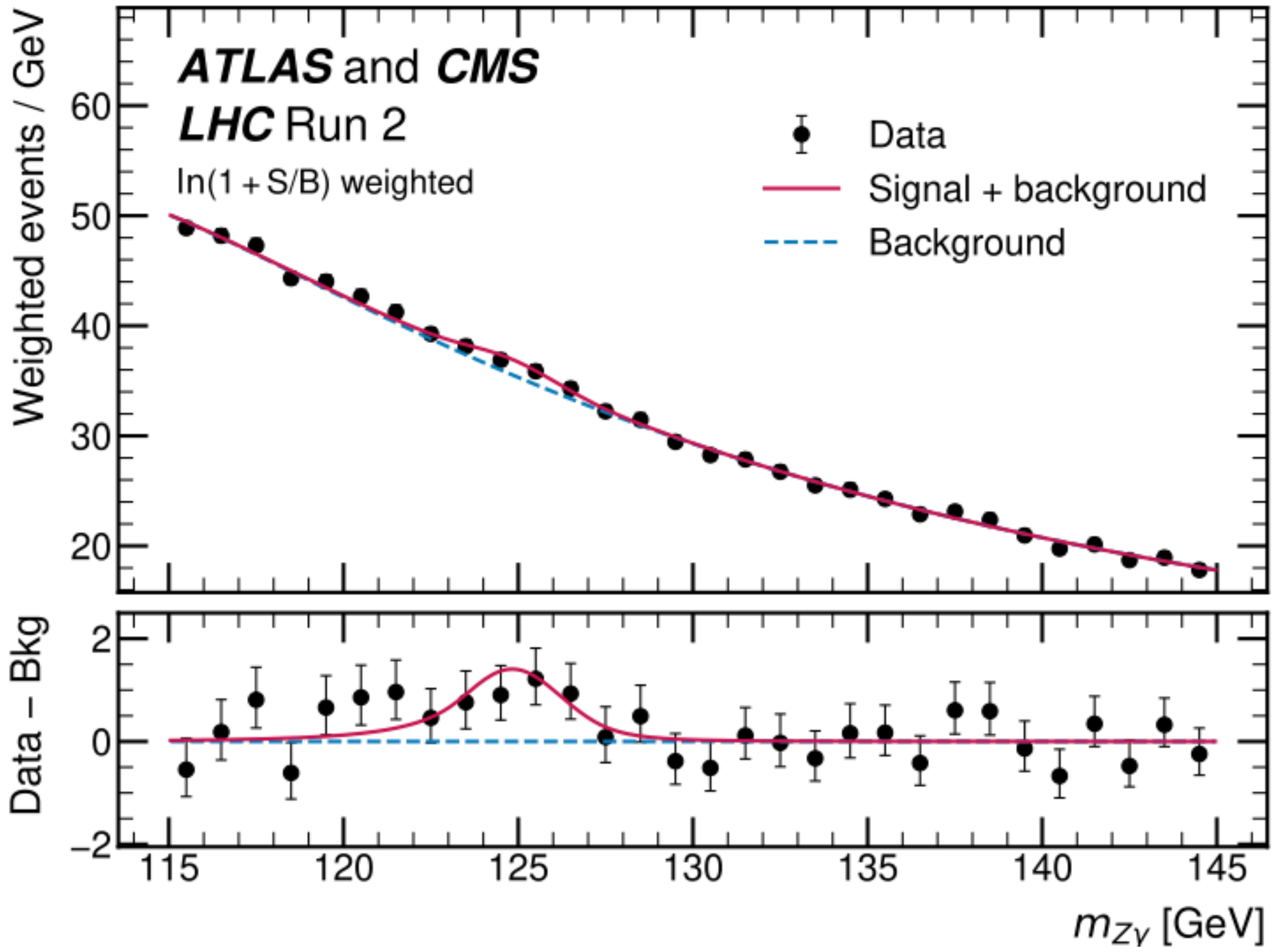
- In 2204.05945, clean prediction for the Z-photon channel $R_{Z\gamma} \approx 2.1$

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: $\mathcal{L}_{L,R} = \begin{pmatrix} \mathcal{N}_{\mathcal{L}} \\ \mathcal{E}_{\mathcal{L}} \end{pmatrix}_{L,R} \sim (\mathbf{1},\mathbf{2})_Y \,, \quad \mathcal{E}_{L,R} \sim (\mathbf{1},\mathbf{1})_{Y-\frac{1}{2}} \,, \quad \mathcal{N}_{L,R} \sim (\mathbf{1},\mathbf{1})_{Y+\frac{1}{2}} \quad |Y| \approx \frac{3}{2}$

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

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

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Unstable anomalons are present for some specific U(1) charge assignments 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: $\Psi^{\mathcal{E}_i} \to W^-\ell^- \to \ell^-\ell^-\not{E}_T$

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Adapting and rescaling the ATLAS analysis arXiv:1710.09748

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Model is perturbative excluded: using unitarity for Yukawa coupling $M_{anom} \lesssim 400 \text{ GeV}$

(Stability of the Higgs potential might be also an issue Hiller et al., 2207.07737)

Models that explain a possibile large effects in $h \to Z\gamma$ can be constructed starting from this benchmark (see our work 2311.10130)

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

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

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

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

- 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

- LHC is closing completely the window for new chiral fermions

Conclusions

- When considering light new physics, it is important to consider a possible ultraviolet (UV) completion of the low-energy effective field theory (EFT).

- For instance, a light vector coupled to anomalous currents generically might 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 and large effects in Higgs physics.

- New chiral leptons are heavily constrained by LHC searches, if not entirely ruled out.

Backup

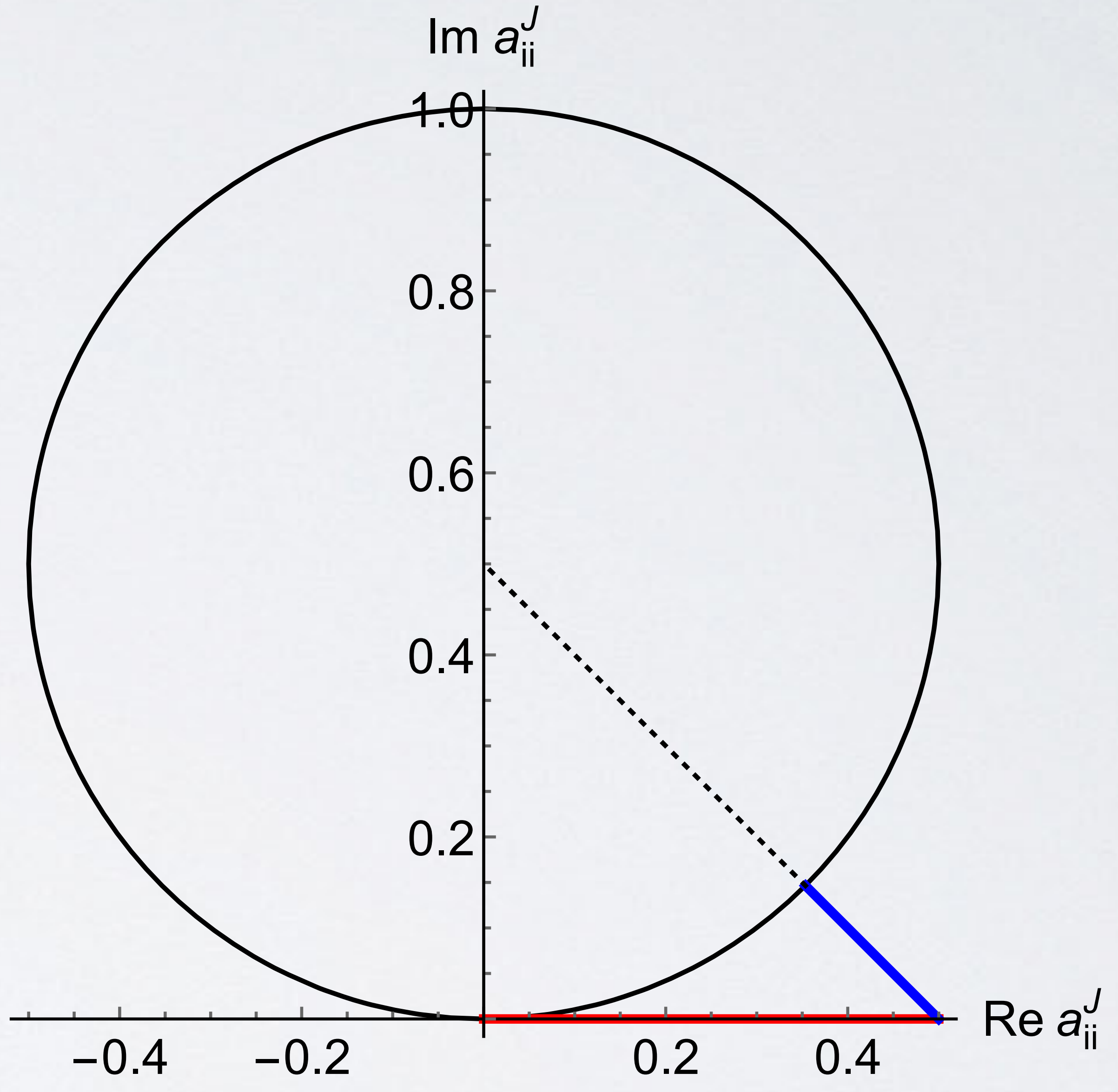
Perturbative Unitarity

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

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

- For f = i (optical theorem)

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



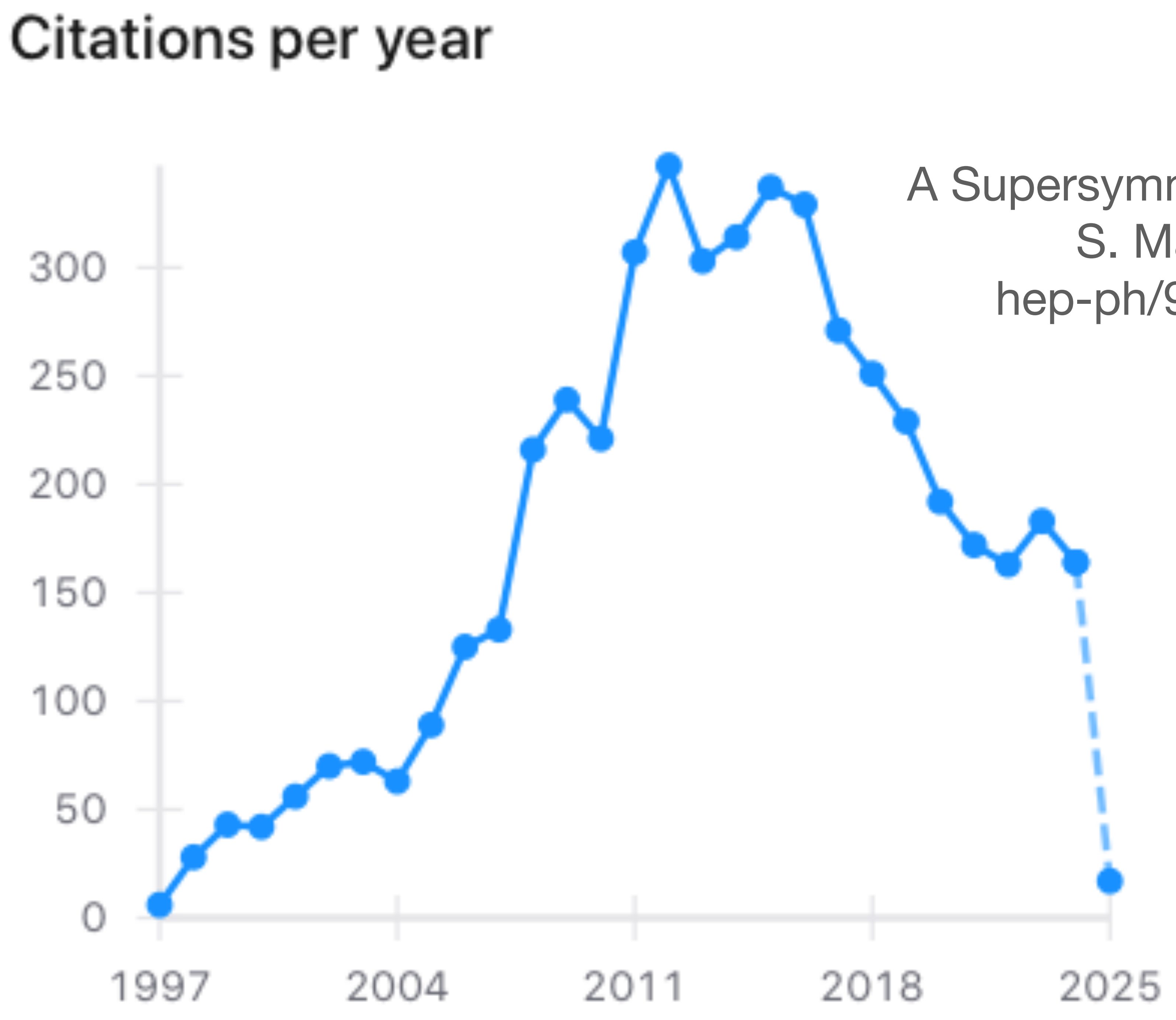
- In practical perturbative calculations S-matrix unitarity is always approximate

- signals breakdown of perturbative expansion

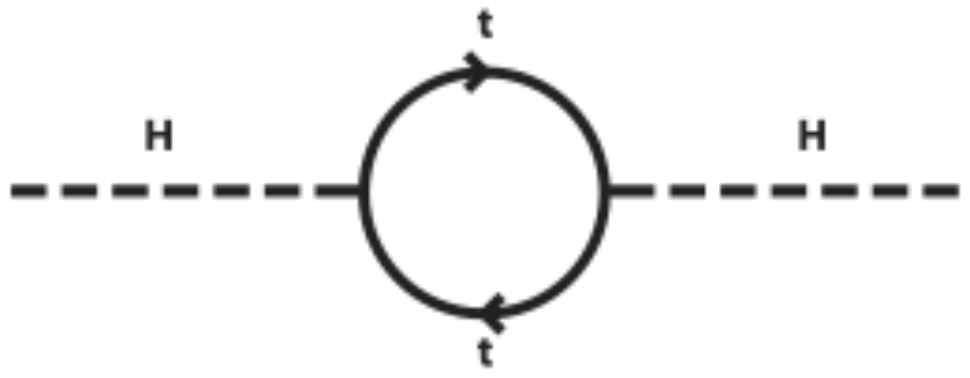
$$\boxed{\left|\mathrm{Re}\,(a^J_{ii})^{\text{Born}}\right| \leq \frac{1}{2}}$$

- Works both in the EFT and in explicit renormalizable models

New Physics trends



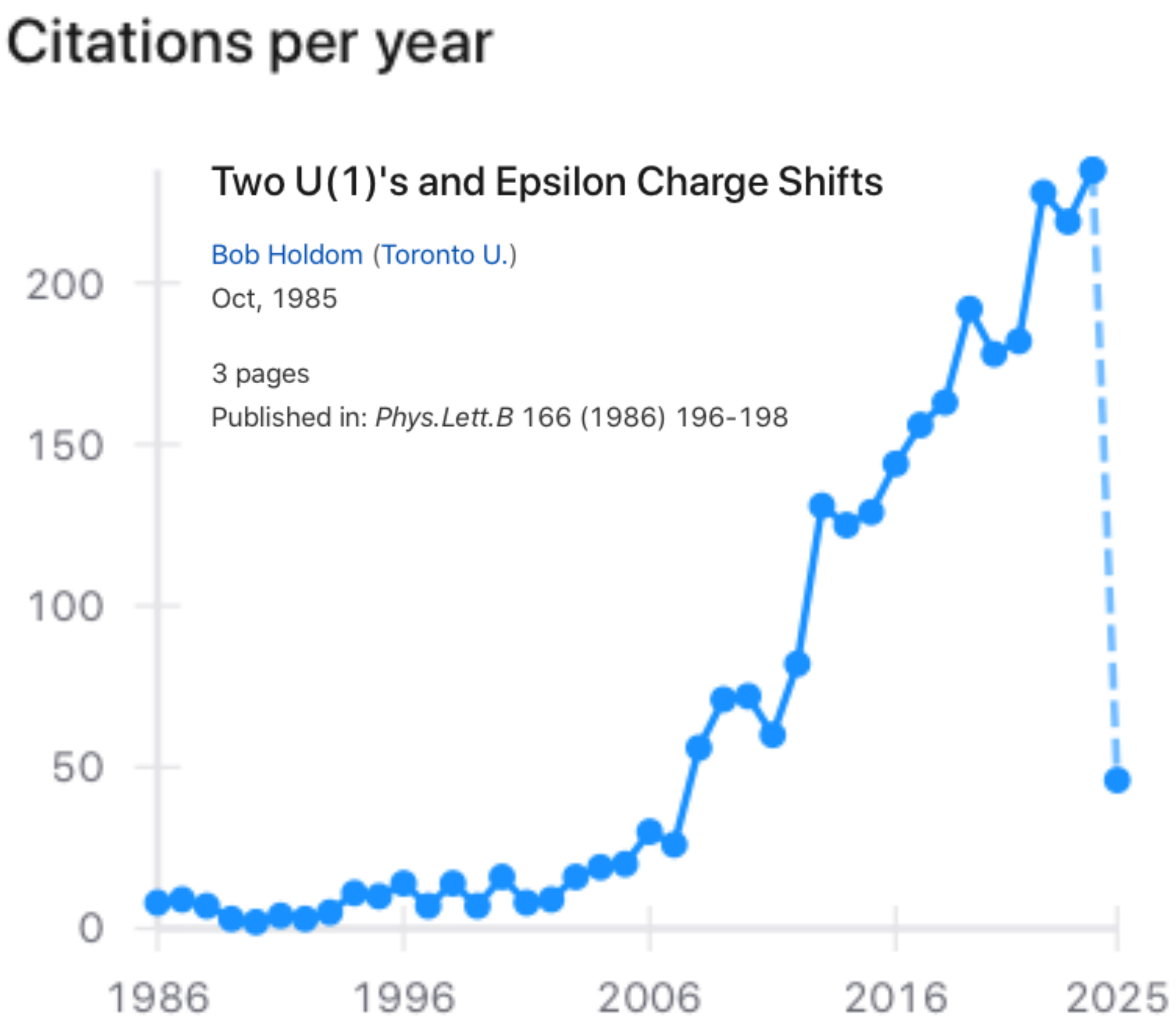
A Supersymmetry Primer
S. Martin
hep-ph/9709356



Why?

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

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



Two U(1)'s and Epsilon Charge Shifts

Bob Holdom (Toronto U.)

Oct, 1985

3 pages

Published in: *Phys.Lett.B* 166 (1986) 196-198

Why?

- Light states can be mediators to hidden sectors (DM,..)
- Some cases are well motivated (best example is the axion)
- Can fit experimental "anomalies" (X17, $B \to K\bar{\nu}\nu, \ldots$)
- Wide range of signatures and experiments can be done on smaller time and length scale
- Missing discovery of heavy NP at LHC
- A comment: no no-loose theorem