PROBING NEW U(1) GAUGE SYMMETRIES VIA EXOTIC Z →Z′γ DECAYS

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With Lisa Michaels, JHEP **03** (2021) 120, [2010.00021]
Including material from [2112.05392] with Bogdan Dobrescu (Fermilab)

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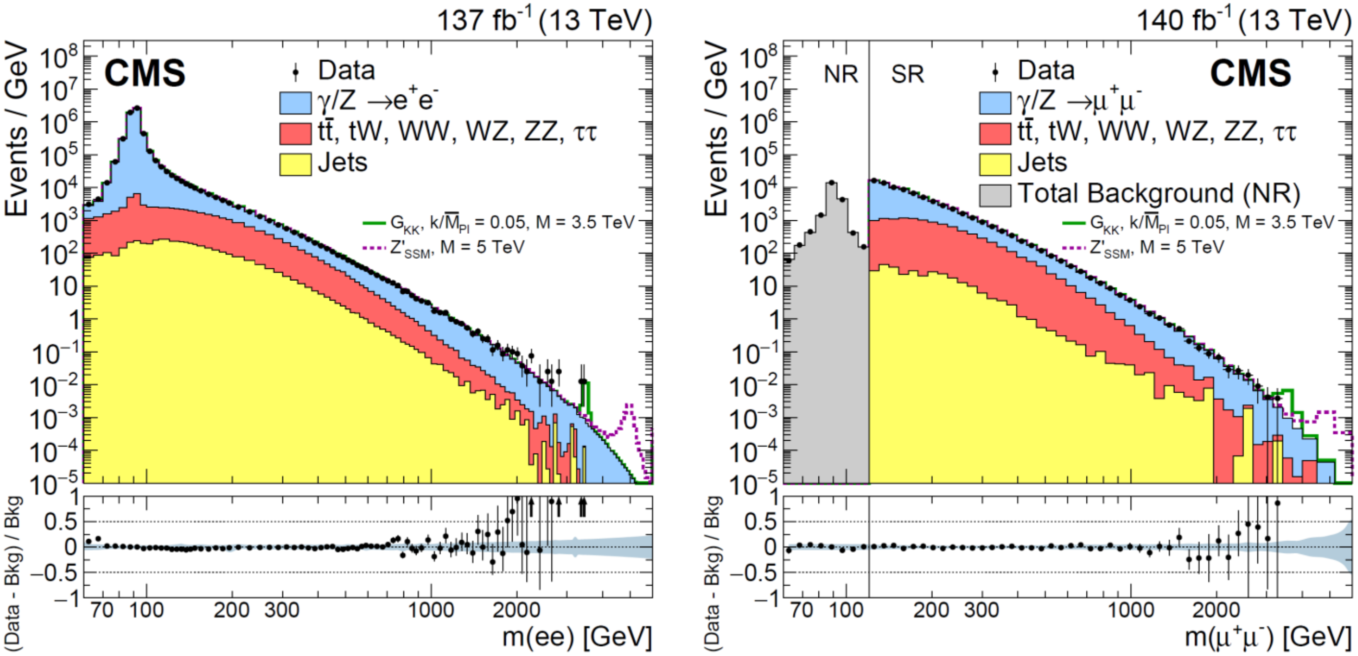
Introduction and Motivation

- Z′ bosons are a standard benchmark model for experimental searches
  - SM precision calculations also critical for long tails of distributions



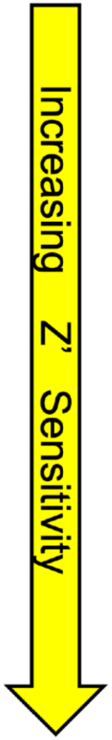
CMS [2103.02708]

Z′ bosons as a standard candle

- Offer one way to organize future collider BSM sensitivity
- New gauge coupling determines production rate, particle width, and lifetime

Robert Harris, FY, co-convenors of "New Bosons" subsection of Snowmass Energy Frontier BSM report [2209.13128]

Machine	Type	$\sqrt{s}$ (TeV)	$\int L\,dt$ (ab^{-1})	Source	Z′ Model	5σ (TeV)	**95% CL (TeV)**
HL-LHC	p p	14	3	R.H.	$Z'_{SSM} \to$ dijet	4.2	**5.2**
				ATLAS	$Z'_{SSM} \to l^+ l^-$	6.4	**6.5**
				CMS	$Z'_{SSM} \to l^+ l^-$	6.3	**6.8**
				EPPSU*	$Z'_{Univ}(g_Z'=0.2)$	--	**6**
ILC250/ CLIC380/ FCC-ee	$e^+ e^-$	0.25	2	ILC	$Z'_{SSM} \to f^+ f^-$	4.9	**7.7**
				EPPSU*	$Z'_{Univ}(g_Z'=0.2)$	--	**7**
HE-LHC/ FNAL-SF	p p	27	15	EPPSU*	$Z'_{Univ}(g_Z'=0.2)$	--	**11**
				ATLAS	$Z'_{SSM} \to e^+ e^-$	12.8	**12.8**
ILC	$e^+ e^-$	0.5	4	ILC	$Z'_{SSM} \to f^+ f^-$	8.3	**13**
				EPPSU*	$Z'_{Univ}(g_Z'=0.2)$	--	**13**
CLIC	$e^+ e^-$	1.5	2.5	EPPSU*	$Z'_{Univ}(g_Z'=0.2)$	--	**19**
Muon Collider	$\mu^+ \mu^-$	3	1	IMCC	$Z'_{Univ}(g_Z'=0.2)$	10	**20**
ILC	$e^+ e^-$	1	8	ILC	$Z'_{SSM} \to f^+ f^-$	14	**22**
				EPPSU*	$Z'_{Univ}(g_Z'=0.2)$	--	**21**
CLIC	$e^+ e^-$	3	5	EPPSU*	$Z'_{Univ}(g_Z'=0.2)$	--	**24**
FCC-hh	p p	100	30	R.H.	$Z'_{SSM} \to$ dijet	25	**32**
				EPPSU*	$Z'_{Univ}(g_Z'=0.2)$	--	**35**
				EPPSU	$Z'_{SSM} \to l^+ l^-$	43	**43**
Muon Collider	$\mu^+ \mu^-$	10	10	IMCC	$Z'_{Univ}(g_Z'=0.2)$	42	**70**
VLHC	p p	300	100	R.H.	$Z'_{SSM} \to$ dijet	67	**87**
Coll. In the Sea	p p	500	100	R.H.	$Z'_{SSM} \to$ dijet	96	**130**

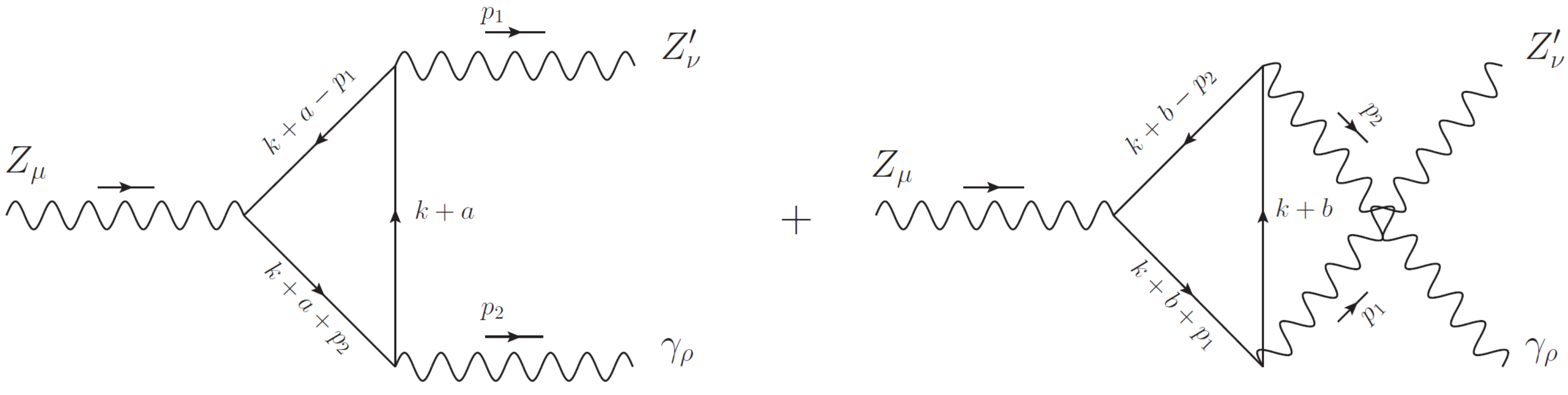


Z′ phenomenology basics

- Wide variety of BSM motivations (DM, LFnU, GUT, etc.) lead to large variability of search channels
  - To avoid generating tree-level FCNCs, sufficient to gauge subgroup of $U(1)_B \times U(1)_e \times U(1)_\mu \times U(1)_\tau$
- Tree-level gauge coupling to SM fermions dictate leading Z′ production and decay modes
  - Kinetic mixing (minimally generated at 1-loop) also relevant for $m_{Z'} \lesssim m_Z$
- Many $U(1)_B \times U(1)_e \times U(1)_\mu \times U(1)_\tau$ subgroups are anomalous – leads to unique Z-Z′-γ phenomenology

An anomaly-induced observable

- In a SM+U(1)′ theory, a novel decay arises from the non-trivial Z-Z′-γ vertex
  - Necessarily requires U(1)′ for non-vanishing on-shell
  - Vertex mediated by SM and new physics fermions
    - Famously related to ABJ chiral anomaly calculation



    - Set b = -a for vector current conservation

Michaels, FY [2010.00021]

Chiral anomaly vertex

- Triple gauge vertex has two undetermined parameters requiring physicality condition (conservation of charge/Ward identity)
  - [Massive Z, Z′ vectors also introduce Goldstone equivalence in Ward identity contribution]
  - General vertex structure characterized by 6 independent form factors

$$a^\mu = z\, p_1^\mu + w\, p_2^\mu$$

$$\begin{aligned}\Gamma^{\mu\nu\rho}(p_1, p_2; w, z) = &\\ &F_1(p_1,p_2)\epsilon^{\nu\rho|p_1||p_2|}p_1^\mu + F_2(p_1,p_2)\epsilon^{\nu\rho|p_1||p_2|}p_2^\mu + F_3(p_1,p_2)\epsilon^{\mu\rho|p_1||p_2|}p_1^\nu + F_4(p_1,p_2)\epsilon^{\mu\rho|p_1||p_2|}p_2^\nu \\ &+F_5(p_1,p_2)\epsilon^{\mu\nu|p_1||p_2|}p_1^\rho + F_6(p_1,p_2)\epsilon^{\mu\nu|p_1||p_2|}p_2^\rho + G_1(p_1,p_2;w)\epsilon^{\mu\nu\rho\sigma}p_{1\sigma} + G_2(p_1,p_2;z)\epsilon^{\mu\nu\rho\sigma}p_{2\sigma}\end{aligned}$$

Dedes, Suxho [1202.4940]

Chiral anomaly vertex

- Naïvely, can shift each loop integral independently, resulting in non-vanishing current divergence on each vertex

Weinberg, QFT Vol. II

  - No shift exists that allows all current divergences to vanish simultaneously for a given chiral fermion

$$
\begin{aligned}
(p_{1\mu} + p_{2\mu})\,\Gamma^{\mu\nu\rho} &= \frac{Q e_{\rm EM} g g_X}{4\pi^2 c_W} \epsilon^{\nu\rho|p_1||p_2|}\left((w - z)(g_v^{Z'} g_a^{Z} + g_v^{Z} g_a^{Z'}) + 4m^2 g_v^{Z'} g_a^{Z} C_0(m)\right), \\
-p_{1\nu}\Gamma^{\mu\nu\rho} &= \frac{Q e_{\rm EM} g g_X}{4\pi^2 c_W} \epsilon^{\mu\rho|p_1||p_2|}\left((w - 1)(g_v^{Z'} g_a^{Z} + g_v^{Z} g_a^{Z'}) - 4m^2 g_v^{Z} g_a^{Z'} C_0(m)\right), \\
-p_{2\rho}\Gamma^{\mu\nu\rho} &= \frac{Q e_{\rm EM} g g_X}{4\pi^2 c_W} \epsilon^{\mu\nu|p_1||p_2|}(z + 1)(g_v^{Z'} g_a^{Z} + g_v^{Z} g_a^{Z'}),
\end{aligned}
$$

Chiral anomaly vertex

- Adopting dim. reg., we reproduce the anomaly cancellation condition by **requiring** the overall vertex be independent of momentum shifts
  - Relative momentum shift is fixed by diagrams
  - Independence of overall momentum shift corresponds to anomaly cancellation
    - Relevant to EFT matching for Wess-Zumino terms

Exotic Z decay – complete result

- Adopt U(1)$_B$ gauged baryon symmetry specifically
- Anomalons do not decouple from partial width
  - If they only obtain mass from Z' symmetry breaking

$$
\begin{aligned}
\Gamma(Z \to Z'_B \gamma) = \frac{\alpha_{\rm EM}\alpha\alpha_X}{96\pi^2 c_W^2}\frac{m'^2_Z}{m_Z}\left(1 - \frac{m^4_{Z'}}{m^4_Z}\right) \\
\Bigg| - \sum_{f \in \text{ SM}} T_3(f) Q^e_f \left[\frac{m_Z^2}{m_Z^2 - m_{Z'}^2}\left(B_0(m_Z^2, m_f) - B_0(m_{Z'}^2, m_f)\right) + 2m_f^2 C_0(m_f)\right] \\
+ 3\left(\frac{m_Z^2}{m_Z^2 - m_{Z'}^2}\left(B_0(m_Z^2, M) - B_0(m_{Z'}^2, M)\right) + 2M^2 \frac{m_Z^2}{m_{Z'}^2} C_0(M)\right)\Bigg|^2 ,
\end{aligned}
$$

– C$_0$ and B$_0$ are usual three-pt., two-pt. scalar integrals

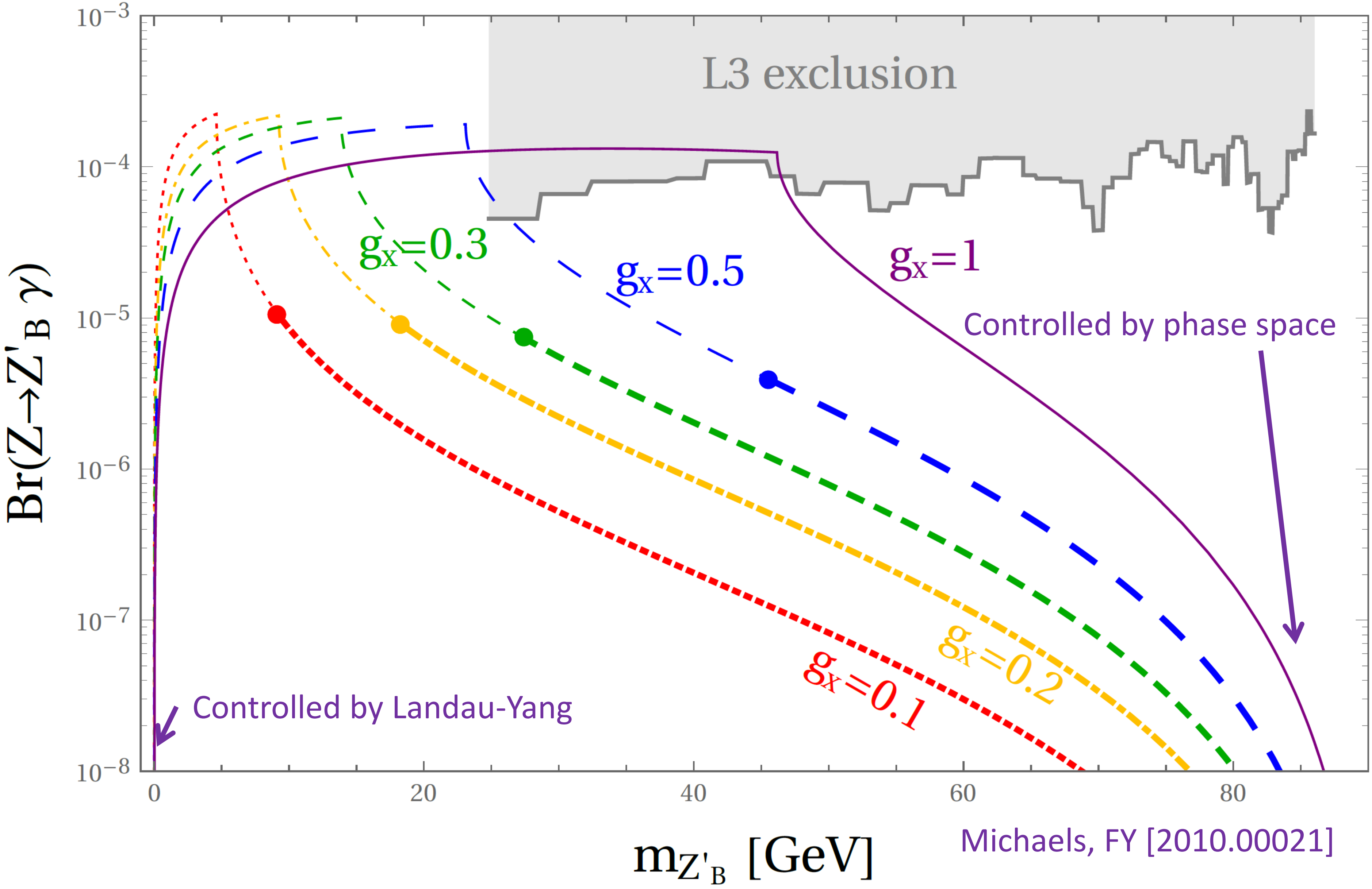
  - Top quark also effectively acts as an anomalon

Exotic Z decay to $(ff)_{\text{res}}\gamma$

- Rate was small for LEP
  - L3 probed Z → $(jj)_{\text{res}}\gamma$ for Br(O(10^{-4}))
  - Especially relevant GigaZ or TeraZ future e^+e^- collider
    - Also promising to consider Z → $(ll)\gamma$ to improve on LEP bounds

$$\begin{aligned}\Gamma(Z \to Z'_B \gamma) = {} & \frac{\alpha_{\text{EM}}\alpha\alpha_X}{96\pi^2 c_W^2}\frac{m'^2_Z}{m_Z}\left(1-\frac{m^4_{Z'}}{m^4_Z}\right) \\ & \Bigg| -\sum_{f\in\,\text{SM}} T_3(f)Q_f^e\left[\frac{m_Z^2}{m_Z^2-m_{Z'}^2}\left(B_0(m_Z^2,m_f)-B_0(m_{Z'}^2,m_f)\right)+2m_f^2C_0(m_f)\right] \\ & +3\left(\frac{m_Z^2}{m_Z^2-m_{Z'}^2}\left(B_0(m_Z^2,M)-B_0(m_{Z'}^2,M)\right)+2M^2\frac{m_Z^2}{m_{Z'}^2}C_0(M)\right)\Bigg|^2 ,\end{aligned}$$

Exotic Z decay $\mathrm{Br}(Z \to Z'_B\,\gamma)$ in $U(1)_B$

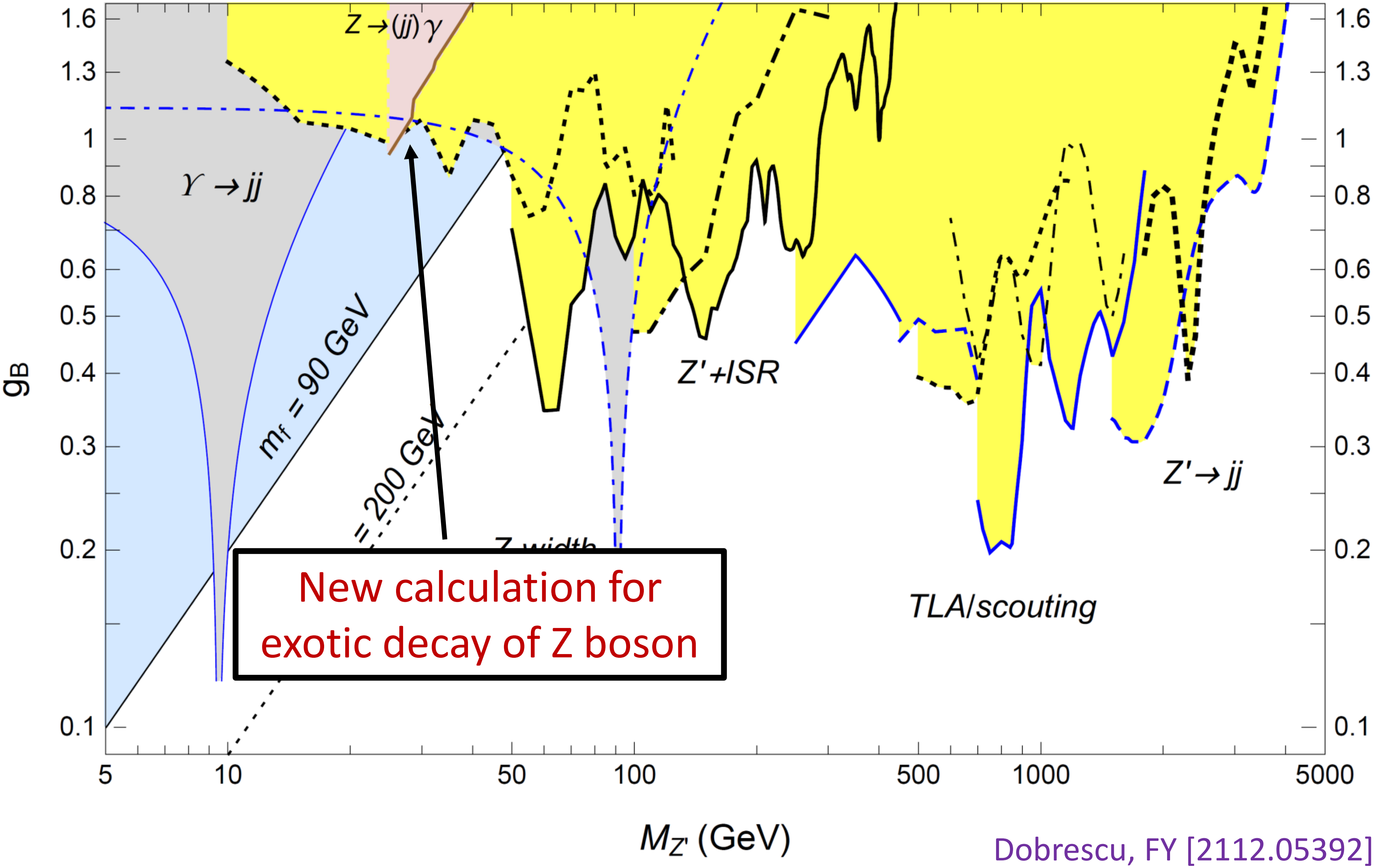


Controlled by phase space

Controlled by Landau-Yang

Michaels, FY [2010.00021]

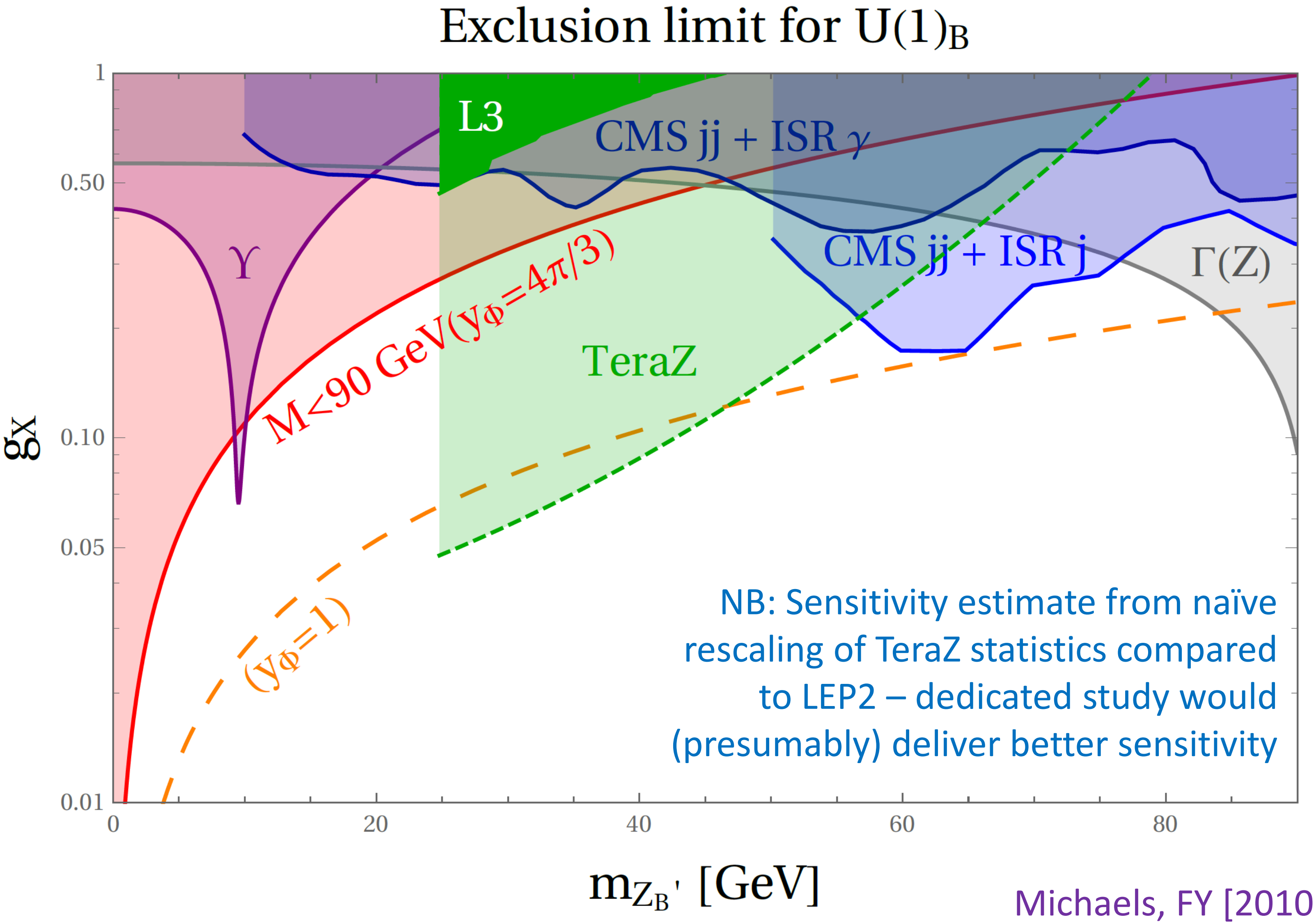
Current status of direct and indirect constraints on Z_B



New calculation for exotic decay of Z boson

Dobrescu, FY [2112.05392]

Future prospects with TeraZ collider



NB: Sensitivity estimate from naïve rescaling of TeraZ statistics compared to LEP2 – dedicated study would (presumably) deliver better sensitivity

Michaels, FY [2010.00021]

Conclusions

- Z′ bosons are a standard candle for experimental physics
- Calculated the exotic Z → Z′ γ decay uniquely sensitive to anomalous U(1)′ symmetries
  - Simplest non-trivial triple neutral current on-shell observable
  - Unique observable to probe at future Z pole runs

Gauged baryon model

- Minimal set of anomalons (SU(2), U(1)$_Y$, U(1)$_B$)
  - Collider pheno like SUSY EWinos

$$L_L(2,-\frac{1}{2},-1),\ L_R(2,-\frac{1}{2},2),\quad E_L(1,-1,2),\ E_R(1,-1,-1),$$
$$N_L(1,0,2),\ N_R(1,0,-1)$$

- Introduce ϕ as baryon-number Higgs (Q$_B$ = 3)

$$\mathcal{L} = -y_L \bar{L}_L \phi^* L_R - y_E \bar{E}_L \phi E_R - y_N \bar{N}_L \phi N_R + \text{ H.c.}$$

- In this construction, tree-level Z-Z′ mixing vanishes
  - Reintroduced logarithmically at anomalon mass scale but cannot be decoupled
  - Can also have tree or loop-generated Higgs-ϕ mixing

EW precision and Z pole constraints

- Kinetic mixing with Z boson constrained by hadronic Z decay width and change in hadronic Z-mediated cross section

PDG, PTEP 2020, 8 083C01 [2020]

$$-5.3 \times 10^{-4} < \frac{\Delta\Gamma_{\rm had}(Z)}{\Gamma^{\rm SM}_{\rm had}(Z)} < 4.3 \times 10^{-3}$$

$$-3.4 \times 10^{-4} < \frac{\Delta\sigma_{\rm had}}{\sigma^{\rm SM}_{\rm had}} < 3.2 \times 10^{-3}$$

  - Leads to direct constraints on g_B, baryon gauge coupling constant

$$g_B < \begin{cases} 0.90\left(1 - \frac{M_{Z'}^2}{M_Z^2}\right)^{1/2}, & \text{for } M_{Z'} \lesssim M_Z - \Gamma_Z \\ 2.6\left(\frac{M_{Z'}^2}{M_Z^2} - 1\right)^{1/2}, & \text{for } M_{Z'} \gtrsim M_Z + \Gamma_Z \end{cases}$$

From hadronic Z width

$$g_B^2 + \left[\left(\frac{1 - M_{Z'}/M_Z}{8.7 \times 10^{-3}\, g_B^2}\right)^2 + 0.40\right]^{-1} < \begin{cases} 1.0\left(1 - \frac{M_{Z'}}{M_Z}\right), & \text{for } \kappa_Z \lesssim 1 - \frac{M_{Z'}}{M_Z} \lesssim \frac{\Gamma_Z}{M_Z} \\ 9.8\left(\frac{M_{Z'}}{M_Z} - 1\right), & \text{for } \kappa_Z \lesssim \frac{M_{Z'}}{M_Z} - 1 \lesssim \frac{\Gamma_Z}{M_Z} \end{cases}$$

From hadronic Z cross section

Canonical resonance: Z′ bosons

- Z′ gauge bosons are ubiquitous
  - GUT extensions, *e.g.* B-L
  - Simplest Z′ dijet resonance (avoiding dilepton signals) arises in gauged baryon number
    - Revisited as *s*-channel simplified model of DM production
- Lagrangian and branching fraction

$$\mathcal{L}_q = \frac{g_B}{2} Z'_\mu \sum_q \left(\frac{1}{3} \bar{q}_L \gamma^\mu q_L + \frac{1}{3} \bar{q}_R \gamma^\mu q_R \right)$$

$$B(Z'_B \to jj) = \left[1 + \frac{1}{5} \left(1 + \frac{2m_t^2}{M_{Z'}^2} \right) \left(1 - \frac{4m_t^2}{M_{Z'}^2} \right)^{1/2} \right]^{-1}$$

Anomaly cancellation

- Renormalizability in UV requires new chiral fermions
  - VL representations ≡ allow tree-level Dirac mass term ≡ vanishing chiral anomaly contribution
  - Chiral representations ≡ forbidden tree-level Dirac mass term ≡ nonzero chiral anomaly contribution
- Mixed anomalies force introduction of new EW-charged states

Fileviez Perez, Wise [1002.1754]

  - Anomalons do not have to carry color
- Minimal set of anomalons (SU(2), U(1)$_Y$, U(1)$_B$)

$$L_L(2,-\frac{1}{2},-1),\ L_R(2,-\frac{1}{2},2),\quad E_L(1,-1,2),\ E_R(1,-1,-1),$$
$$N_L(1,0,2),\ N_R(1,0,-1)$$

Chiral anomalies

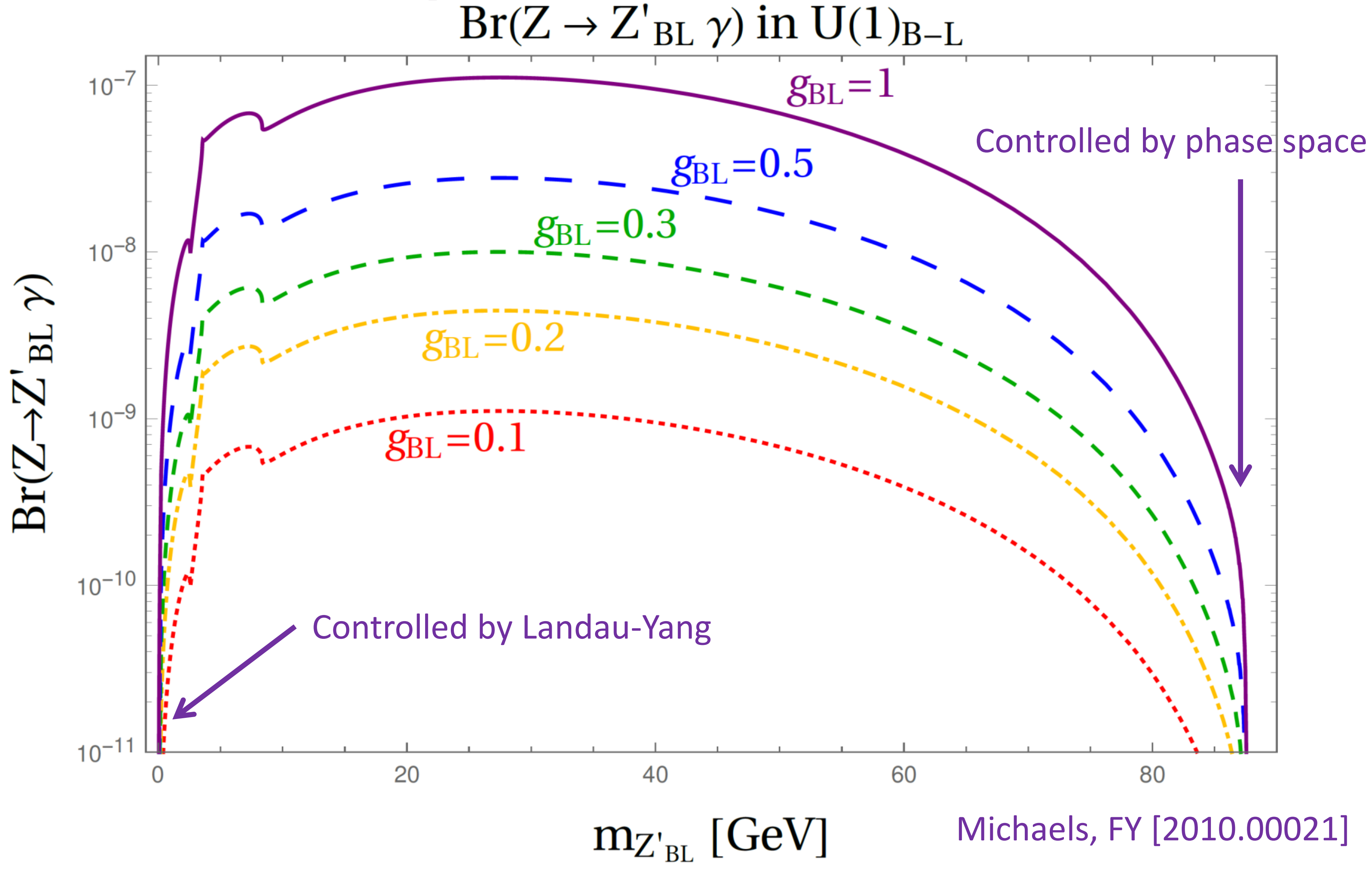
- Anomalons *are* basically SM leptons, except allow chiral mass under EW symmetry and chiral mass under $U(1)_B$

$$L_L(2,-\frac{1}{2},-1),\ L_R(2,-\frac{1}{2},2),\quad E_L(1,-1,2),\ E_R(1,-1,-1),$$
$$N_L(1,0,2),\ N_R(1,0,-1)$$

- Field content admits SM-like Yukawas as well as ϕ-coupled Yukawas
  - With both Yukawa terms, would have triangle diagrams with FCNC fermions

$$\mathcal{L} = -y_L\bar{L}_L\phi^* L_R - y_E\bar{E}_L\phi E_R - y_N\bar{N}_L\phi N_R + \text{ H.c.}$$
$$-y_1\bar{L}_L H E_R - y_2\bar{L}_R\tilde{H}E_L + \text{ H.c.}$$

Exotic Z decay for B-L



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Michaels, FY [2010.00021]

Gauged baryon model vs. EW SM

- Same structure in both cases
  - Chiral fermions, spontaneous breaking, Zs and Higgses
- One underlying scale for each chiral symmetry
- Yet, $U(1)_B$ (and any new chiral U(1)') can exhibit different mass hierarchy pattern than SM
- Consider all Yukawas larger than g_B, λ_B
  - Anomalons are non-decoupling a la top quark in $h \to \gamma\gamma$, $h \to gg$

Gauge anomalies and EFT

- Besides non-decoupling in Higgs physics, chiral fermions also exhibit non-decoupling in gauge interactions
  - Induce Wess-Zumino terms

$$\mathcal{L} \supset g_B g'^2 c_{BB} \epsilon^{\mu\nu\rho\sigma} Z_{B,\mu} B_\nu \partial_\rho B_\sigma$$
$$+ g_B g^2 c_{WW} \epsilon^{\mu\nu\rho\sigma} Z_{B,\mu} (W^a_\nu \partial_\rho W^a_\sigma + \frac{1}{3} g \epsilon^{abc} W^a_\nu W^b_\rho W^c_\sigma)$$

Harvey, Hill, Hill

Dror, Lasenby, Pospelov

Comparison to GBE

- Our result

$$\begin{aligned}\Gamma(Z \to Z'\gamma) = {} & \frac{g_B^2 g^2 e^2 m_{Z'}^2 (1-(m_{Z'}^4/m_Z^4))}{221184\pi^5 c_W^2 m_Z} \times \\ & \left(9 + 7\frac{m_Z^2}{m_Z^2 - m_{Z'}^2}\log(m_{Z'}^2/m_Z^2) + 4m_t^2 C_0(0, m_Z^2, m_{Z'}^2, m_t, m_t, m_t)\right. \\ & \left. +2\frac{m_Z^2}{m_Z^2 - m_{Z'}^2}(B_0(m_Z^2, m_t, m_t) - B_0(m_{Z'}^2, m_t, m_t))\right)^2\end{aligned}$$

- Dror, et. al.: Replace Z′ by Goldstone, only consider anomaly coupling
  - Ignores poles in finite form factors that cancel anomaly

$$\mathcal{L} = \frac{\mathcal{A}}{16\pi^2}\frac{g_X\varphi}{m_X}2gg'Z_{\mu\nu}\tilde{F}^{\mu\nu}$$

$$\Gamma(Z \to X\gamma) = 1.1 \times 10^{-5}\mathcal{A}^2 g_X^2 \left(\frac{100\ \mathrm{GeV}}{m_X}\right)^2$$

Dror, Lasenby, Pospelov
[1705.06726]

New gauge bosons and broken symmetries

- Consider augmenting SM by new U(1)′ symmetry
  - Directly charge SM fields under U(1)′
  - Flavor constraints imply U(1)′ should be subgroup of $U(1)_B \times U(1)_e \times U(1)_\mu \times U(1)_\tau$
    - Common examples: $U(1)_{B-L}$, L_μ-L_τ
- Since EW symmetry is chiral, most global symmetry choices are anomalous

Preskill (1991)

  - Renormalizability in UV requires new chiral fermions
  - Mixed anomalies force introduction of new EW-charged states

$$\mathcal{A}(SU(2)^2 \times U(1)_B) = \frac{3}{2} \qquad \mathcal{A}(U(1)_Y^2 \times U(1)_B) = \frac{-3}{2}$$