# PROBING NEW CHIRAL GAUGE SYMMETRIES WITH EXOTIC Z DECAYS AND ASSOCIATED Z′ PRODUCTION MODES

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Based on
*Michaels, FY: JHEP 03 (2021) 120, [2010.00021];*
*Dobrescu, FY, [2112.05392];*
*Armbruster, Dobrescu, FY [23xx.xxxxx]*

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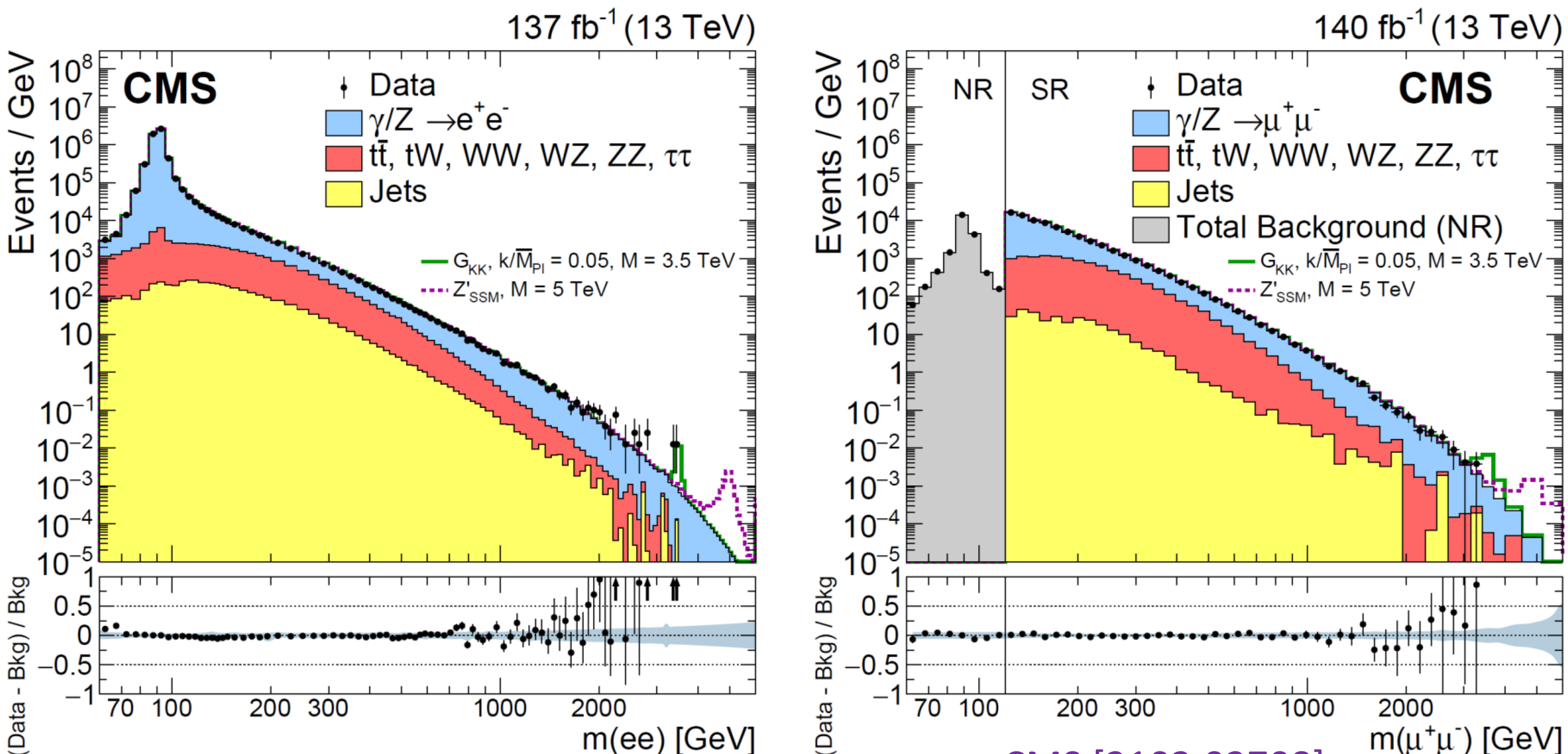
Topic of the Week seminar, LPC, Fermilab
June 20, 2023

PRiSMA+

# Introduction and Motivation

- Z′ bosons are a standard benchmark model for experimental searches




CMS [2103.02708]

# Z′ bosons

- Standard candle: offers one way to organize future collider BSM sensitivity

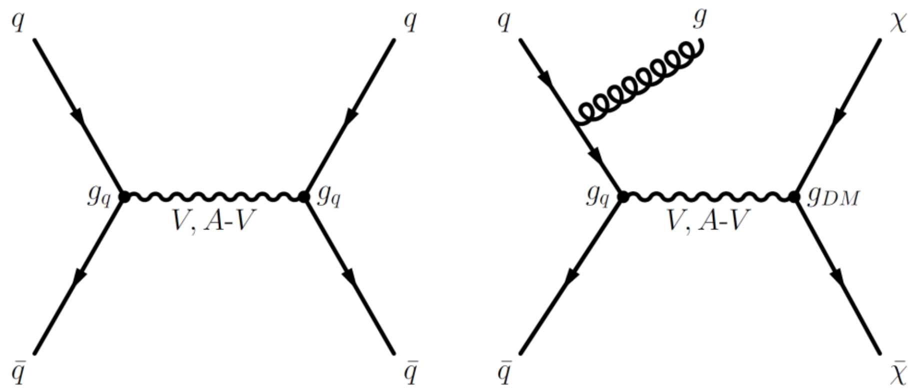
| Machine | Type | √s (TeV) | ∫L dt (ab$^{-1}$) | Source | Z′ Model | 5σ (TeV) | 95% CL (TeV) |
|---|---|---|---|---|---|---|---|
| HL-LHC | p p | 14 | 3 | R.H. | $Z'_{SSM} \to$ dijet | 4.2 | 5.2 |
| | | | | ATLAS | $Z'_{SSM} \to l^+ l^-$ | 6.4 | 6.5 |
| | | | | CMS | $Z'_{SSM} \to l^+ l^-$ | 6.3 | 6.8 |
| | | | | 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 |

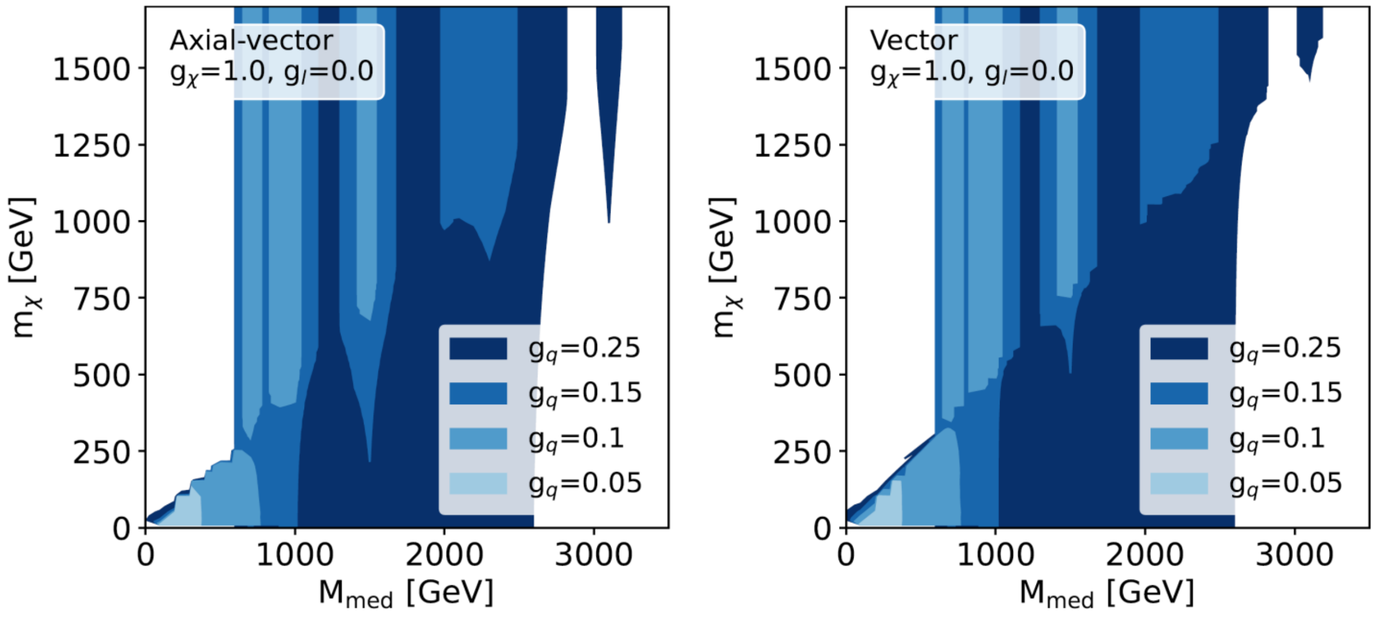
Increasing Z′ Sensitivity

Robert Harris, FY for the EF09 Snowmass report [2209.13128]

# Motivation: DM connection?

- s-channel simplified model
  - Z′ boson mediator to dark matter




Snowmass DM simplified model s-channel WG [2203.12035]

# Outline

- [Introduction and motivation]
- Building a Z′ model
- Anomaly-induced Z → Z′γ decay
  - First possibility to measure chiral gauge anomaly
- Scalar signals from chiral U(1)′ symmetry
  - "Irreducible" phenomenology from unmixed scalar φ
  - Mixing effects from 125 GeV Higgs
- Conclusions

# Old-fashioned portal: U(1)′ gauge

- A more old-fashioned "portal" coupling: add U(1)' gauge symmetry to SM
  - Directly charge SM fermions with new gauge interaction
- Adding new gauge interaction is "easy"!?
  - Only need the matter content for Z' current interaction?
    - $J_\mu$ sums over everything charged under U(1)' symmetry (i.e. SM fermions and NP scalars or fermions)

$$\mathcal{L} = \frac{-1}{4} Z'^{\mu\nu} Z'_{\mu\nu} + \frac{1}{2} M_{Z'}^2 Z'^2_\mu + g_X Z'^\mu J_\mu$$

# New gauge symmetries, chiral anomalies

- Complication: SM electroweak symmetry is chiral, Yukawa interactions respect chiral symmetry
  - SM fermion masses only vectorlike w.r.t. unbroken $SU(3)_c \times U(1)_{em}$ gauge symmetries
- If Yukawa matrices are U(1)′ symmetric, then U(1)′ is subgroup of $U(1)_B \times U(1)_L$ SM global symmetry
  - Otherwise, need BSM explanation for SM fermion masses and mixings
  - Must ensure gauge anomalies cancel

$$\mathcal{A}\left(SU(2)_L^2 \times U(1)_B\right) = \mathcal{A}\left(SU(2)_L^2 \times U(1)_L\right) = \frac{3}{2}$$

$$\mathcal{A}\left(U(1)_Y^2 \times U(1)_B\right) = \mathcal{A}\left(U(1)_Y^2 \times U(1)_L\right) = \frac{-3}{2}$$

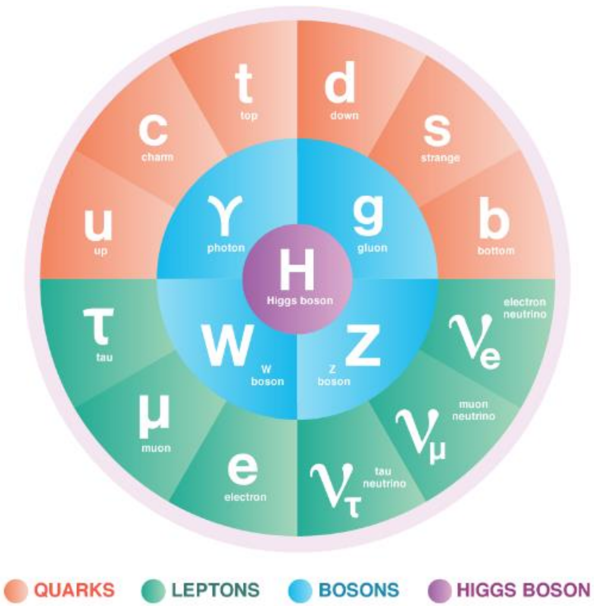
# Resolving "anomalous" gauge symmetries

- Only some specific choices are anomaly free
  - Popular choices: B-L; $L_\mu - L_\tau$
- Generally, $U(1)_B \times U(1)_L$ subgroups are *anomalous*
  - Renormalizability requires adding new EW charged particles = "anomalons"
  - Renormalizability also (minimally) satisfied by adding Higgs field for U(1)′ SSB

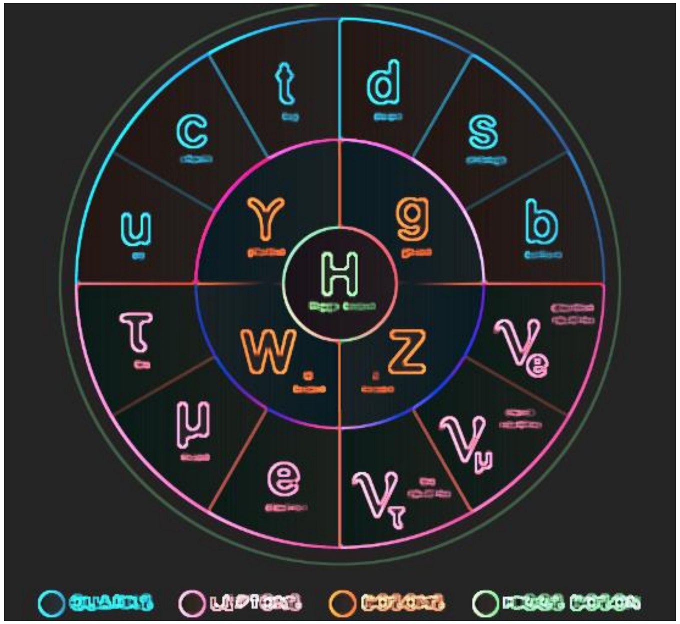
Preskill (1991); Kribs, Lee, Martin [2204.01755]

# Discovering new chiral symmetry

- Just like EW sector, U(1)′ symmetry can be chiral
  - “Minimally” contains its own Z′ gauge boson, exotic Higgs boson, and U(1)′ fermions
    - U(1)′ fermions necessarily EW charged!




Is NP also chiral?



# Discovering new chiral symmetry

- Just like EW sector, U(1)′ symmetry can be chiral
  - "Minimally" contains its own Z′ gauge boson, exotic Higgs boson, and U(1)′ fermions
- Just like EW sector, U(1)′ sector has one underlying scale = vev of exotic Higgs boson
  - Hierarchy of various masses follows couplings
  - Interesting to keep anomalons heavy compared to Z′, φ
    - Anomalons act "top-like" in loops to reflect Higgs low-energy theorem in NP sector – get non-decoupling effects in loops

$$M_{Z'} \sim g_X v' \qquad M_\varphi \sim \sqrt{\lambda_X} v' \qquad M_f \sim y v'$$

# Concrete gauged $U(1)_B$ model

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

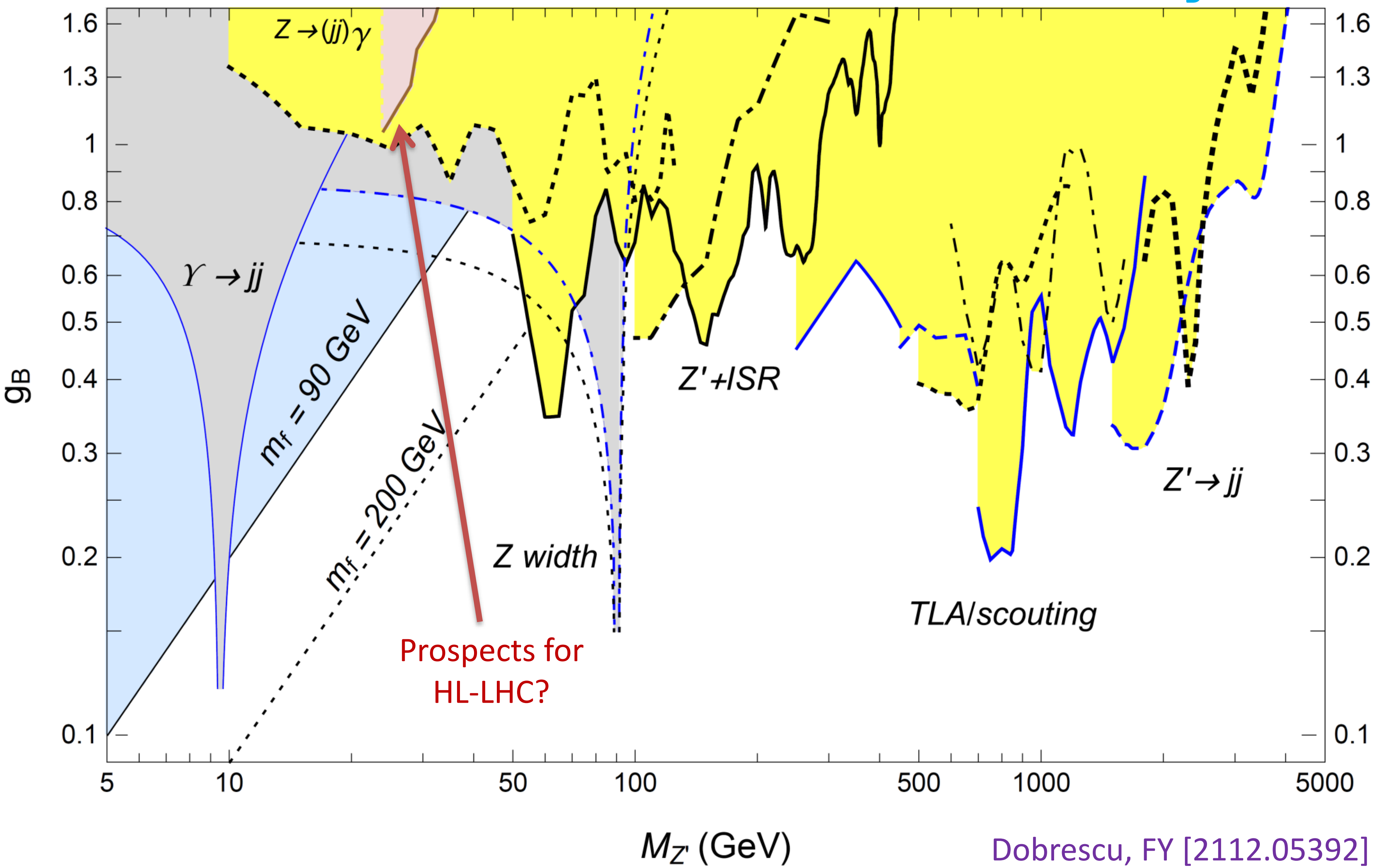
$$L_L(2,-\frac{1}{2},-1),\ L_R(2,-\frac{1}{2},2),\quad E_L(1,-1,2),\ E_R(1,-1,-1),$$
$$N_L(1,0,2),\ N_R(1,0,-1)$$

- Introduce $\phi$ as baryon-number Higgs ($Q_B = 3$)

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

- Tree-level kinetic mixing vanishes
  - Reintroduced logarithmically at anomalon mass scale
  - Can also have tree or loop-generated Higgs-$\phi$ mixing

# Current status of direct and indirect constraints on $Z_B$



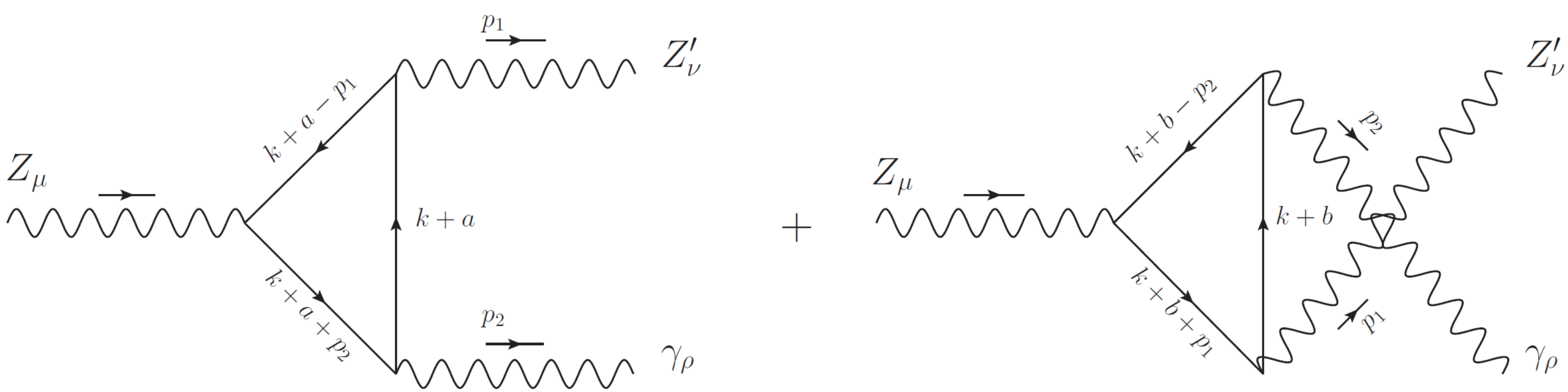

Dobrescu, FY [2112.05392]

# Probing new U(1) gauge symmetries via exotic $Z \to Z'\gamma$ decays

Michaels, FY, JHEP **03** (2021) 120 [2010.00021]

# 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, decompose $a_\mu = z\, p_{1\mu} + w\, p_{2\mu}$

# Calculating Z-Z′-γ

- Triple gauge vertex has two undetermined parameters (momentum shifts w, z) $a^\mu = z\, p_1^\mu + w\, p_2^\mu$
    - Massive Z, Z′ vectors also introduce GBE in non-decoupling
  - General vertex structure characterized by 6 independent form factors
  - Novel reformulation: requiring Z-Z′-γ vertex to be *independent* of (w, z) = anomaly cancellation

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

Dedes, Suxho [1202.4940]

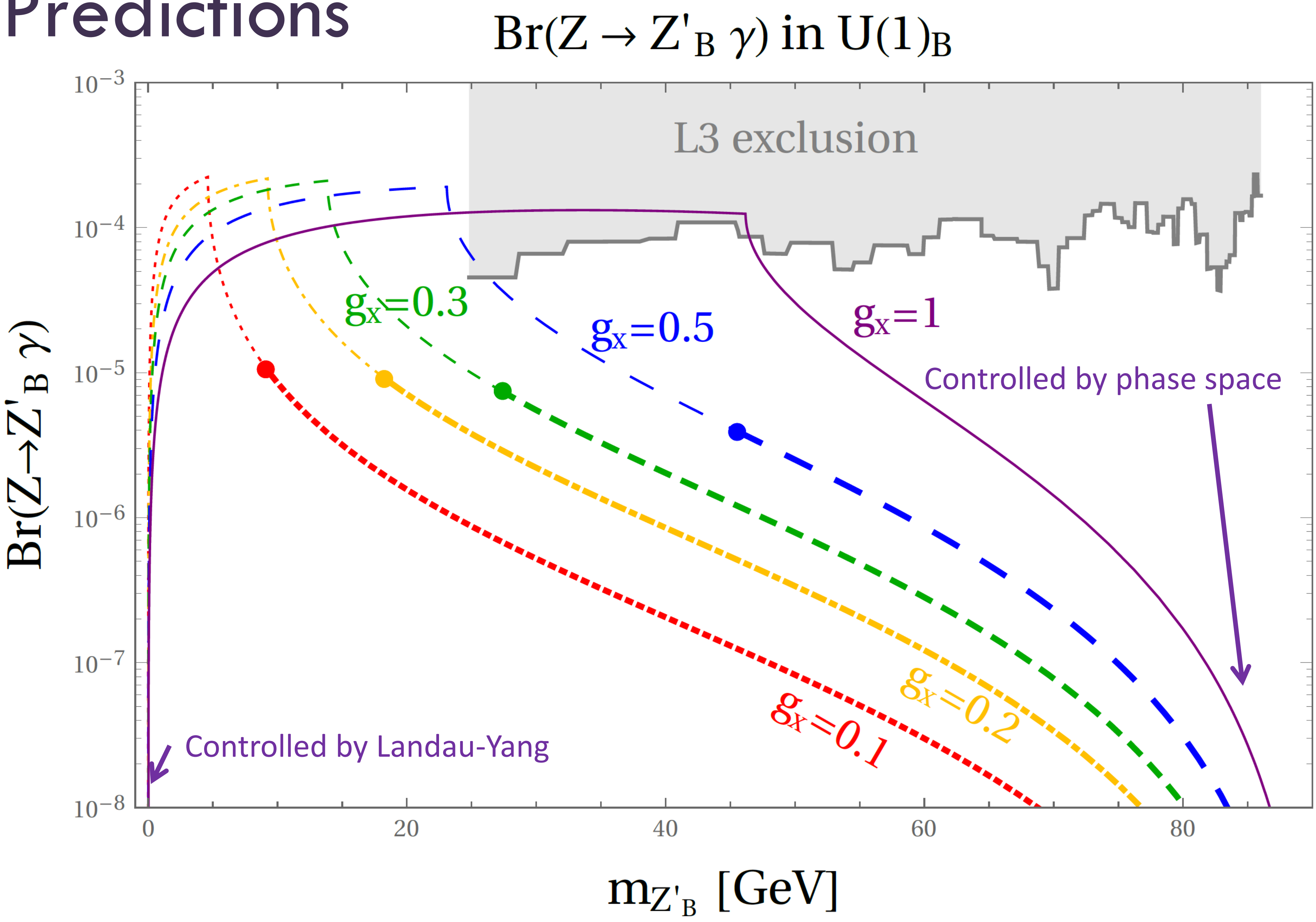
# Exotic Z decay – complete result

- Anomalons do not decouple from partial width
  - If they only obtain mass from Z' symmetry breaking

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

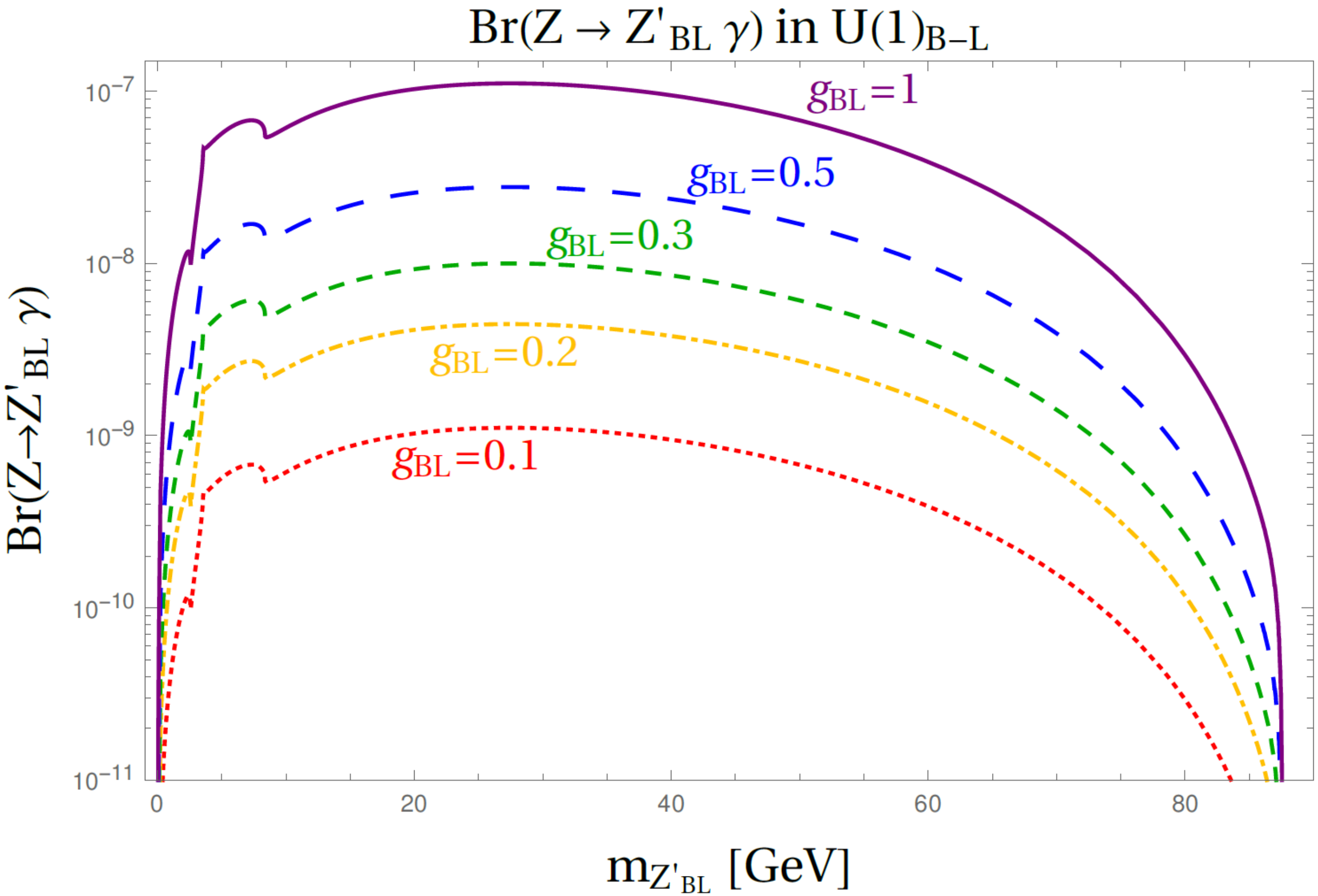
  - $C_0$ and $B_0$ are usual three-pt., two-pt. scalar integrals
    - Top quark effectively acts as an anomalon

# Predictions

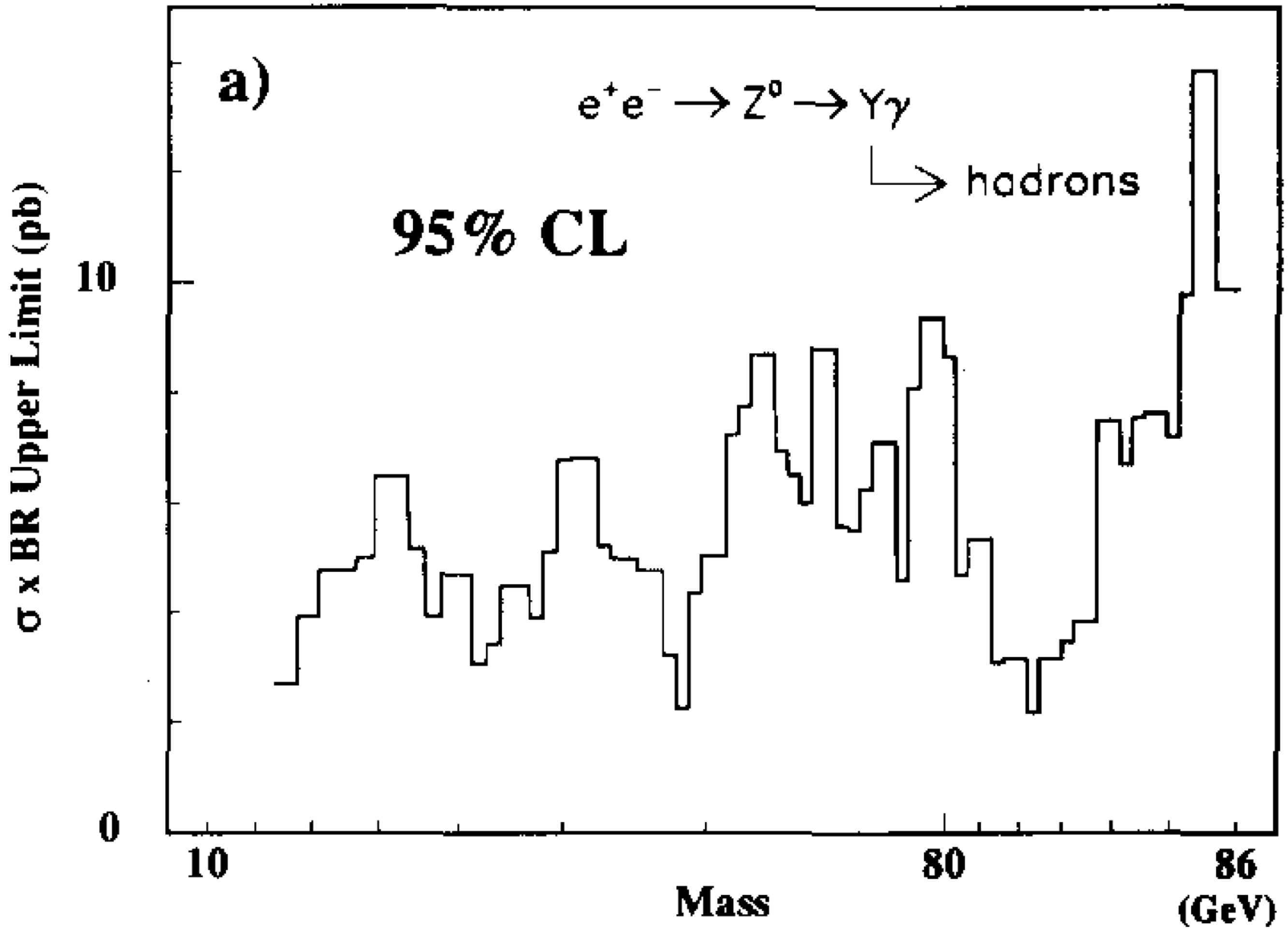


# Exotic Z decay for B-L gauge symmetry

- Only induced by mass splitting of SM fermions



# Current bound on Z → dijet + photon

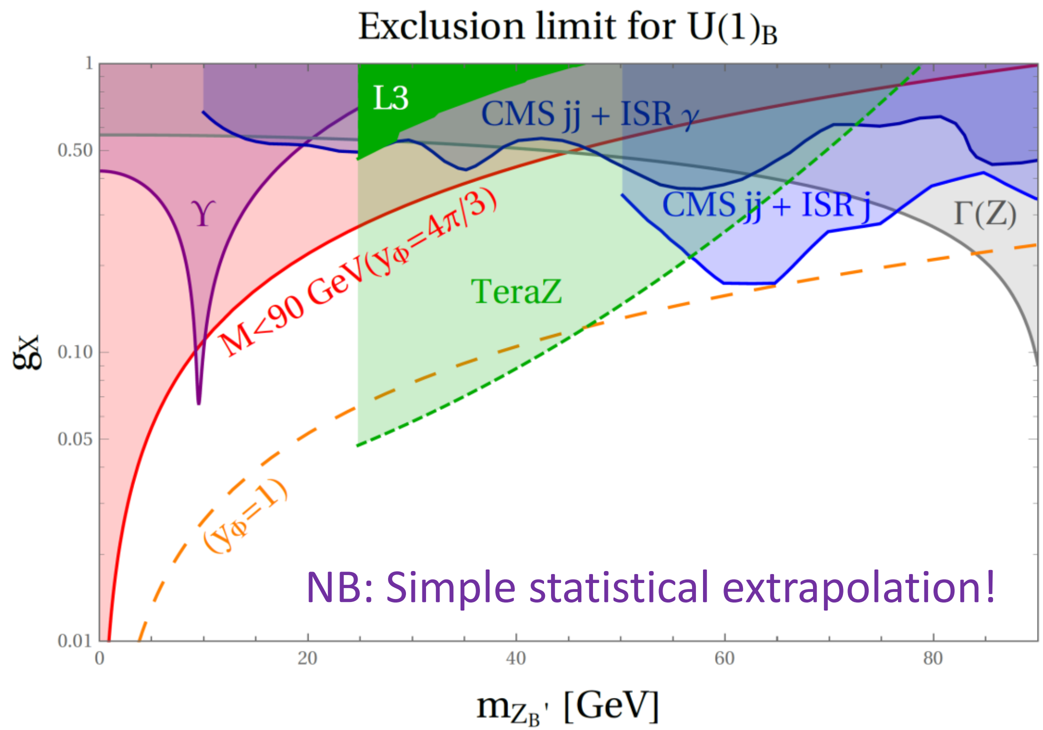



L3 Collaboration, PLB 292 (1992) 472

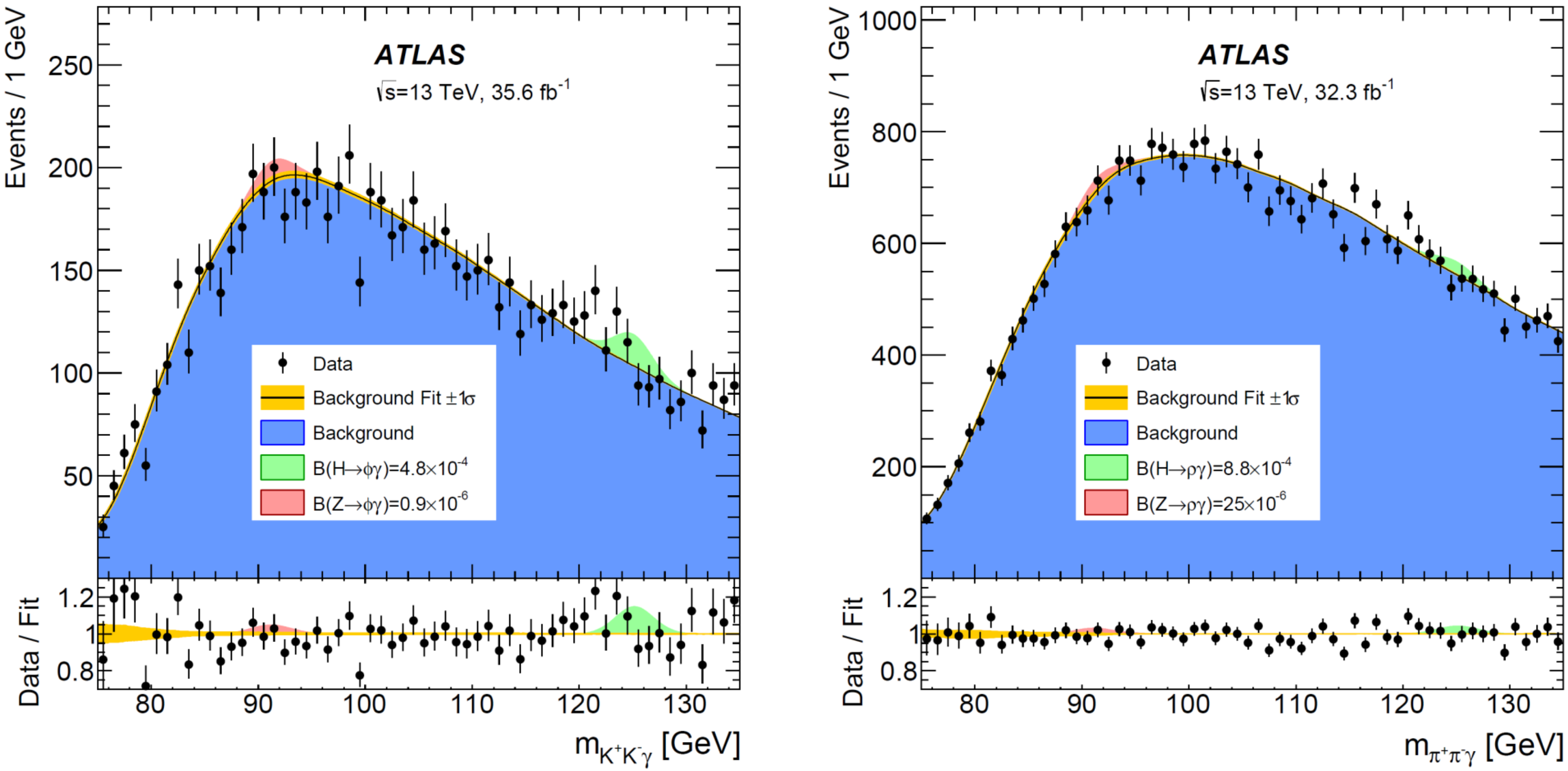
# Exotic Z decay

- Rate was small for LEP
  - L3 probed Z → (jj)γ for Br(O($10^{-4}$))
  - Possible for HL-LHC or even GigaZ/TeraZ future collider

Also critical to consider Z → (ll)γ to improve on LEP bounds – relevant for $L_\mu - L_\tau$ and B-L models



# Z rare decays in SM




Grossman, König, Neubert [1501.06569]

$B(Z \to \phi\gamma)_{SM} = 1.04 \times 10^{-8}$ $B(Z \to \rho\gamma)_{SM} = 4.19 \times$

ATLAS, JHEP **07** (2018) 127 [1712.02758]

Also see CMS, EPJC **79** (2019) 94 [1810.10056]

# Exotic Z decay

- Key prediction: exotic $Z \to Z' \gamma$ decay inescapable for *anomalous* U(1)′ gauge symmetries
  - Reflective of the chiral nature of the SM EW sector vs. chiral U(1)′ symmetry
  - Same vertex would be a critical post-discovery check when Z′ is heavier than Z boson, leading to $Z' \to Z \gamma$
- Difficult search but interesting double-resonance signal: coincidence in 2D plane of $M_{ff}$ vs. $M_{ff\gamma}$

# Quark-universal U(1) breaking scalar at the LHC

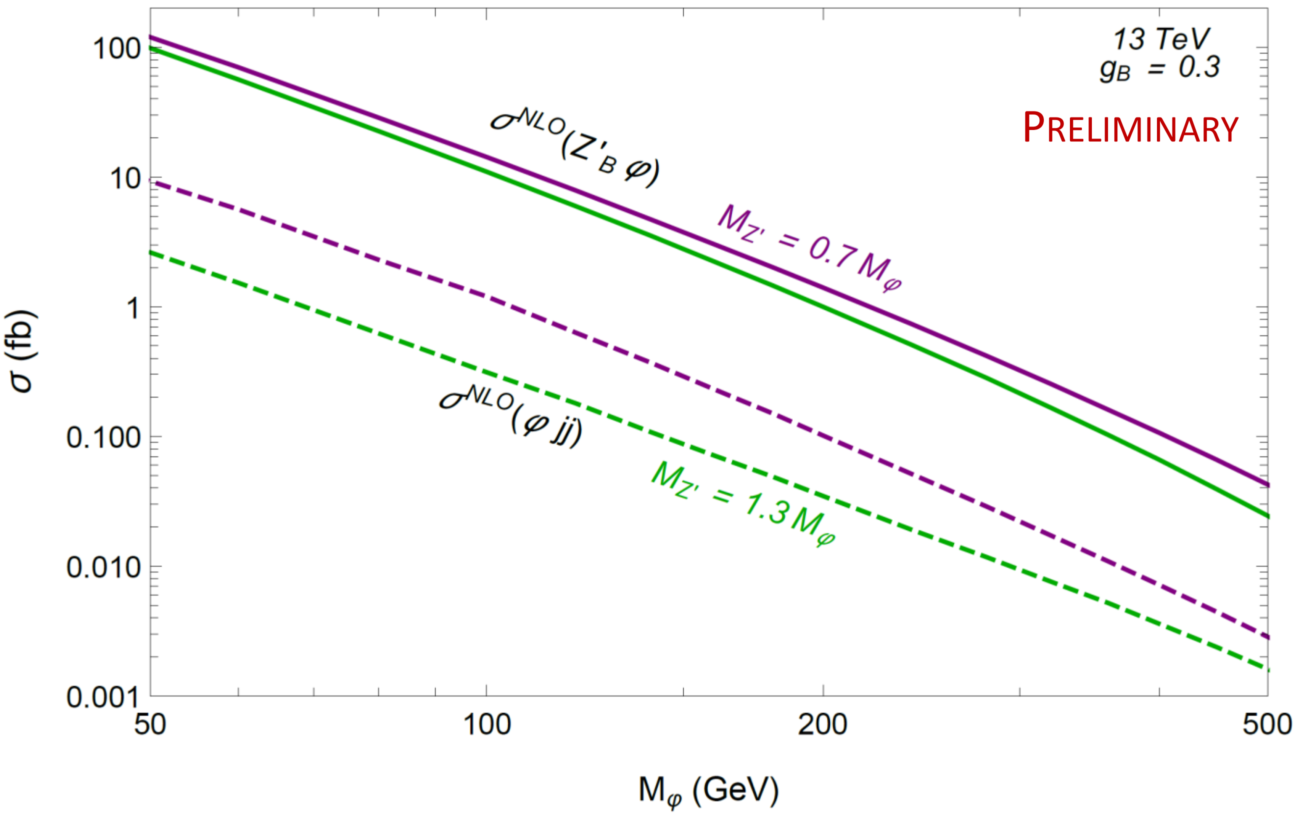
Armbruster, Dobrescu, FY [23xx.xxxxx]

# Discovering new chiral symmetry – the exotic Higgs boson

- New exotic Higgs boson has two “irreducible” production modes
  - Higgs-strahlung from Z′ Drell-Yan
  - Z′ vector boson fusion
- Scalar φ also has “irreducible” decay mode to $\gamma\gamma$
  - Low energy theorem in effect: Scalar φ decays to *any and all* kinematically accessible diboson states that anomalons are charged under
- Everything can be augmented by model-dependent mixing with 125 GeV Higgs boson

# Higgs-strahlung and Z′-fusion

- Given $U(1)_B$ gauge symmetry, get $(jj)_{res} + \varphi$ or VBF-tagged jj + φ signatures

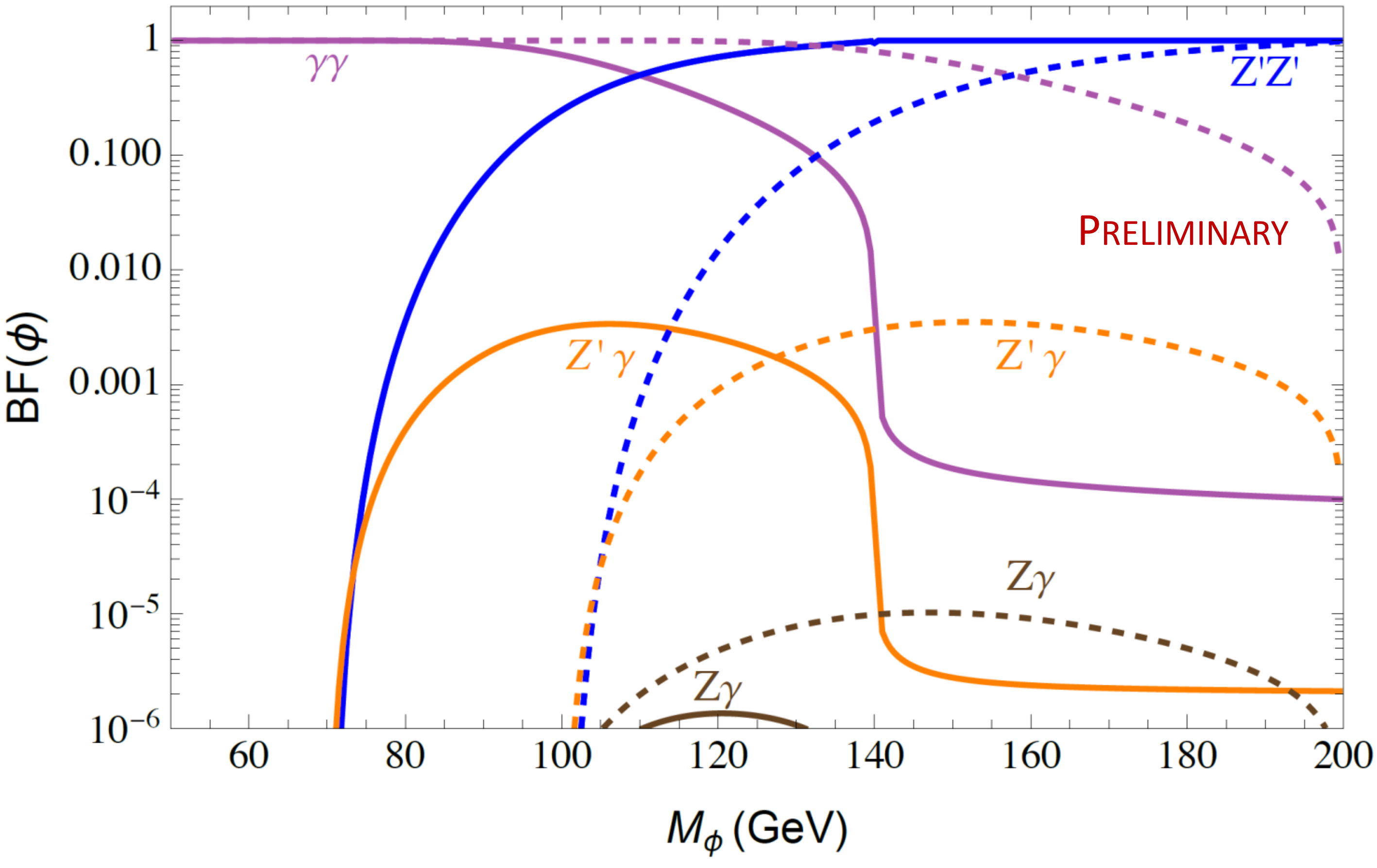


# Characteristic/diagnostic decays of chiral SSB

- Higgs LET and scalar-vector-vector couplings

Set Z' mass to 70 GeV (solid) or 100 GeV (dotted)

Set $g_B = 0.3$, anomalon masses = 200 GeV



# Discovering new chiral symmetry – the exotic Higgs boson

- Matching production and decay gives many interesting signatures

$Z' = (jj)_{res}$

VBF-tagged 2j

$\otimes$

$(\gamma\gamma)_{res}$

$Z'\,Z' = ([jj]_{res}[jj]_{res})_{res}$

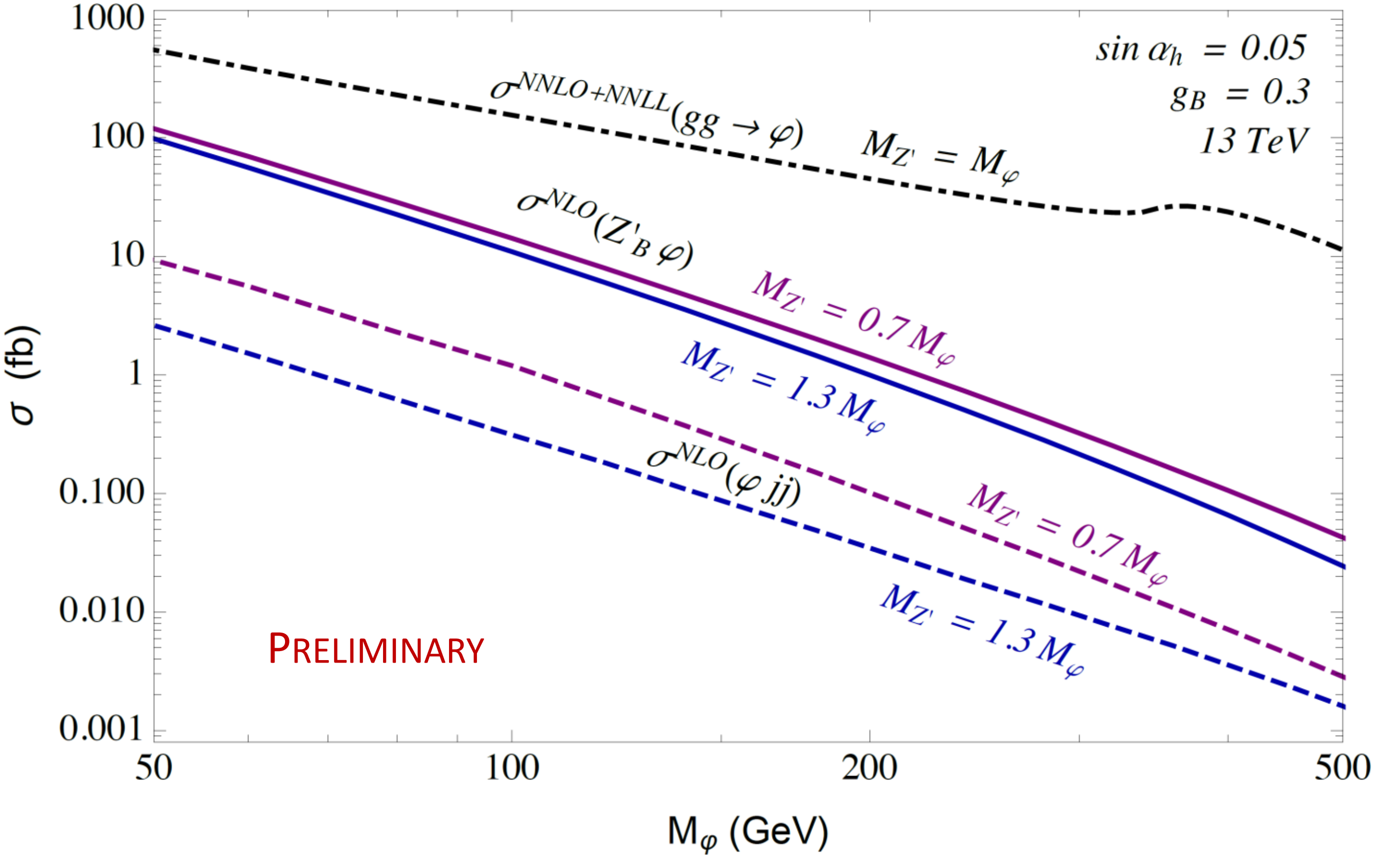
$Z'\,Z'^{*} = ([jj]_{res}[jj]_{non\text{-}res})_{res}$

$Z'\gamma = ([jj]_{res}\,\gamma)_{res}$

  – All jets can also be b-tagged (or even top-tagged for much heavier Z′ and φ states)

# Mixing scalars of chiral SSB

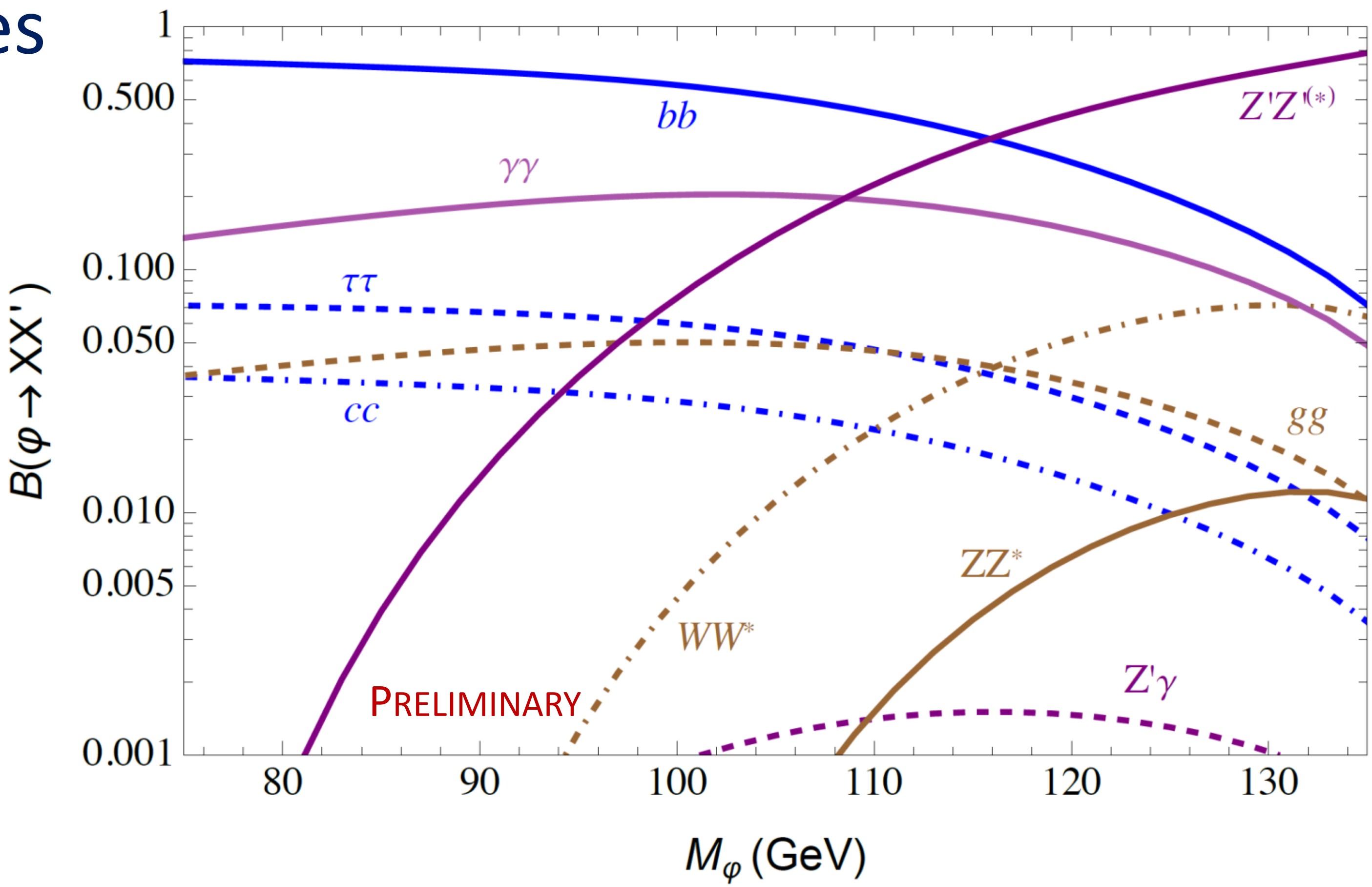
- Including small mixing angle with 125 GeV Higgs enriches collider possibilities



# Mixing scalars of chiral SSB

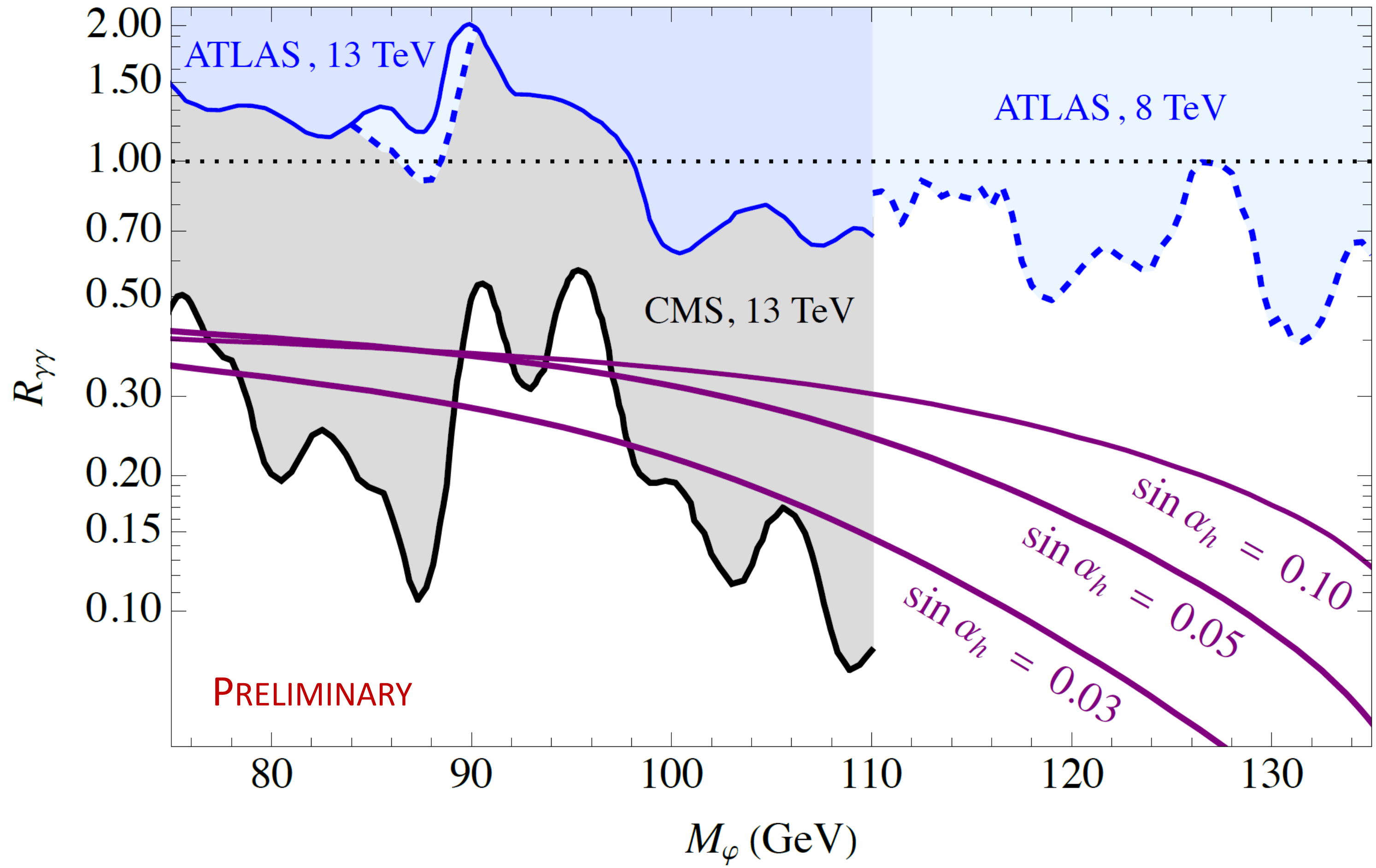
- New scalar mass eigenstate ϕ inherits many SM decay modes

Most non-trivial feature is diphoton decay mode, since intrinsic φ→γγ decay width was nonzero



# Mixing scalars of chiral SSB

- Predicted $R_{\gamma\gamma}$ rate is not linear with mixing angle



# Chiral U(1)′ SSB scalar takeaways

- Key message: general expectation (from perturbative unitarity) is the scalar boson is “close by” the Z′ boson
- Chiral structure imprints characteristic and diagnostic predictions on production and decay modes
- Extra bonus: Higgs-mixing (model-dependent) signals and cross-correlation with 125 GeV measurements

# Conclusions

- One of the biggest puzzles of QFT is understanding chiral gauge symmetries
- New U(1)′ chiral symmetry manifests as **rich set of signatures**
  - Exotic Z → Z′ + γ decay, Z′ → jj or $l^+l^-$
  - Exotic φ gives many resonant channels
  - Mixed ϕ further enriches possibilities

$Z' = (jj)_{res}$

VBF-tagged 2j

⊗

$(\gamma\gamma)_{res}$

$Z'\,Z' = ([jj]_{res}[jj]_{res})_{res}$

$Z'\,Z'^{*} = ([jj]_{res}[jj]_{non\text{-}res})_{res}$

$Z'\gamma = ([jj]_{res}\,\gamma)_{res}$

# Kinetic mixing and mass mixing

- Kinetic mixing operator induces non-unitary field transformations See, e.g. Liu, Wang, FY [1704.00730]
  - Operator generated by charged matter content under both U(1) currents
  - In EW broken phase, have separate Z and photon kinetic mixings and possible mass mixing with SM Z boson

$$\frac{1}{2} Z'^{\mu\nu}_B \left(\kappa_Z Z_{\mathrm{SM}\mu\nu} - \kappa_\gamma F_{\mu\nu}\right) + \Delta M^2_{Z'Z} Z'^{\mu}_B Z_{\mathrm{SM}\mu}$$

- Real part of 2-pt. amplitude generates kinetic and mass mixing

$$\mathrm{Re}\, \mathcal{A}^{\mu\nu}_{Z'Z} = \kappa_Z \left(g^{\mu\nu} p^2 - p^\mu p^\nu\right) + \Delta M^2_{Z'Z}\, g^{\mu\nu}$$

# Kinetic mixing and mass mixing

- When calculating 2-pt. amplitude, necessarily sum over products of charges of fermions

Dobrescu, FY [ 2112.05392]

$$\mathcal{A}^{\mu\nu} = i\,\frac{g_B g}{c_W} \int_0^1 dx \sum_f N_f \left\{ m_f^2 \left( g_L^f z_R^f + g_R^f z_L^f \right) g^{\mu\nu} I_0^f \right.$$

$$\left. + \left( g_L^f z_L^f + g_R^f z_R^f \right) \left[ g^{\mu\nu} I_1^f + x(1-x) \left( g^{\mu\nu} p^2 - 2 p^\mu p^\nu \right) I_0^f \right] \right\} \quad , \qquad \text{(A.2)}$$

$$I_0^f = \frac{-i}{(4\pi)^2} \ln \left( \frac{m_f^2}{\mu^2} - x(1-x)\frac{p^2}{\mu^2} - i\epsilon_0 \right)$$

$$I_1^f = -\left( m_f^2 - x(1-x) p^2 \right) I_0^f \quad ,$$

# Kinetic mixing and mass mixing

- When calculating 2-pt. amplitude, necessarily sum over products of charges of fermions

Dobrescu, FY [ 2112.05392]

$$\mathcal{A}^{\mu\nu} = i\frac{g_B g}{c_W}\int_0^1 dx \sum_f N_f \left\{ m_f^2 \left( g_L^f z_R^f + g_R^f z_L^f \right) g^{\mu\nu} I_0^f \right.$$
$$\left. + \left( g_L^f z_L^f + g_R^f z_R^f \right) \left[ g^{\mu\nu} I_1^f + x(1-x) \left( g^{\mu\nu} p^2 - 2p^\mu p^\nu \right) I_0^f \right] \right\} \quad , \qquad \text{(A.2)}$$

  - Can eliminate leading log divergence and universal finite remainder via *trace orthogonality* condition
    - Distinct from anomaly cancellation condition

$$\sum_f N_f \left( g_L^f z_L^f + g_R^f z_R^f \right) = 0$$

# Finite kinetic mixing

- In our canonical gauged baryon-number $U(1)_B$ model, resulting kinetic mixing is finite and log growth is fixed

$$\kappa_Z \simeq \frac{g_B g}{48\pi^2 c_W} \left[ \left( \frac{1}{2} - \frac{4}{3} s_W^2 \right) \mathcal{F}(m_t^2/M_Z^2) + \sum_{f=\text{anom.}} N_f \left( g_L^f B_L^f + g_R^f B_R^f \right) \mathcal{F}(m_f^2/M_Z^2) \right]$$

$$\mathcal{F}(m_f^2/M_Z^2) \simeq 2 \ln\left( \frac{m_f}{M_Z} \right) + \frac{5}{3} - \frac{M_Z^2}{5\, m_f^2}$$

  - Previous calculations decoupling anomalon sector and reintroduced log divergence   e.g. Carone, Murayama [hep-ph/9501220]
    - Not physically realistic given chiral $U(1)_B$ anomalon masses tie together Z′ mass scale with heavy anomalons

# 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]

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

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

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

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

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

From hadronic Z width

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

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

# 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

# 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: $U(1)_{B-L}$, $L_\mu$-$L_\tau$
- Since EW symmetry is chiral, most global symmetry choices are anomalous
  - Renormalizability in UV requires new chiral fermions
  - Mixed anomalies force introduction of new EW-charged states $\mathcal{A}(SU(2)^2 \times U(1)_B) = \frac{3}{2}$ $\quad \mathcal{A}(U(1)_Y^2 \times U(1)_B) = \frac{-3}{2}$

# 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]

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$$N_L(1, 0, 2),\ N_R(1, 0, -1)$$

# New building block: U(1)' gauge symmetries

- Eschew portal couplings, augment directly covariant derivative of subset of SM fields
  - New gauge coupling and symmetry-breaking scale are still free parameters
- Yet, possible chiral anomalies drive irreducible and characteristic phenomenology
  - Structure is reminiscent of EW Standard Model
  - Adopt UV motivation for dijet resonances for context: gauged baryon number

# Canonical resonance: Z′ bosons

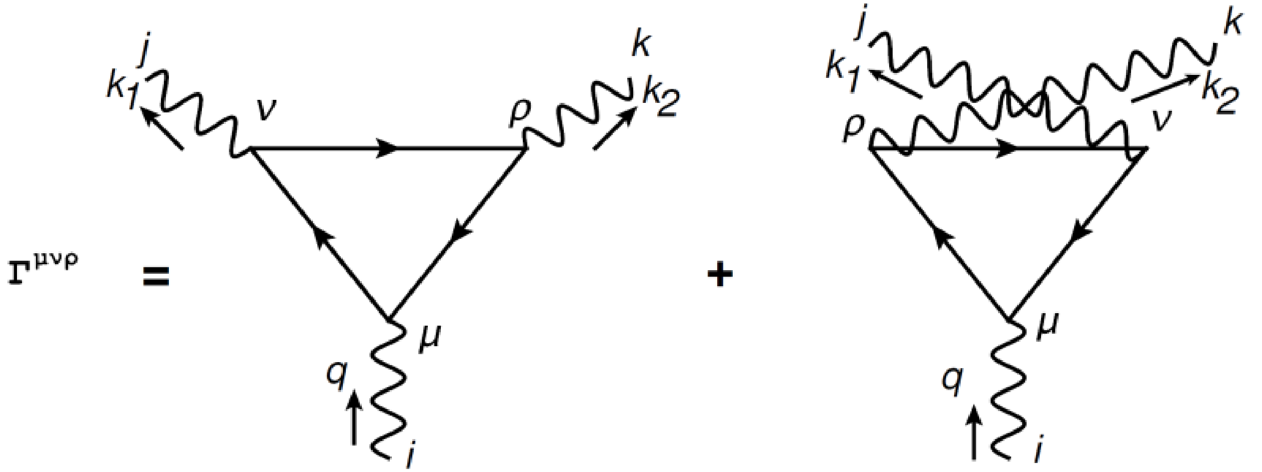
- Z′ gauge bosons are ubiquitous
  - GUT extensions, *e.g.* B-L
  - Simplest Z′ dijet resonance (avoiding dilepton signals) arises in gauged baryon number
    - Revisited as *s*-channel simplified model of DM production
- Lagrangian and branching fraction

$$\mathcal{L} = \tfrac{1}{3} g_B Z'_\mu \left(\bar{q}\gamma^\mu q\right)$$

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

# Gauge anomalies and EFT

- Calculating the triple gauge vertex
  - Using gauge eigenstates equivalent to mass eigenstates since coupling-mass degeneracy holds
  - Shifts which vertex has vector vs. axial-vector couplings




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

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

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

$$-p_{2\rho}\Gamma^{\mu\nu\rho} = \frac{Q e_{\mathrm{EM}} g g_X}{4\pi^2 c_W} \epsilon^{\mu\nu|p_1||p_2|}(z+1)(g_v^{Z'} g_a^{Z} + g_v^{Z} g_a^{Z'}),$$

# Gauge anomalies and EFT

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

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

Harvey, Hill, Hill
Dror, Lasenby, Pospelov

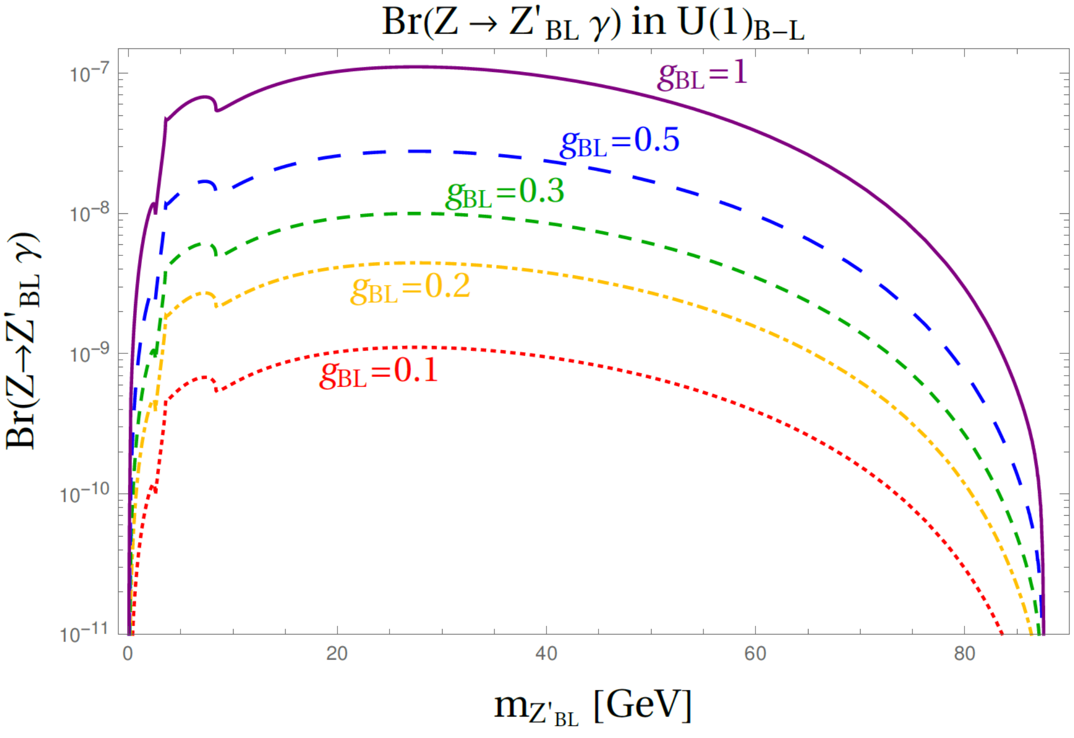
# Chiral anomaly vertex

- 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

Michaels, FY [2010.00021]

# Predictions – B-L gauge symmetry

$$\Gamma(Z \to Z'_{BL}\gamma) = \frac{\alpha_{EM}\alpha\alpha_{\text{BL}}}{96\pi^2 c_W^2}\frac{m_{Z'}^2}{m_Z}\left(1 - \frac{m_{Z'}^4}{m_Z^4}\right) \times$$
$$\left|\sum_f \left[T_3^f N_c^f Q_f^e Q_f^{BL}\left(2m_f^2 C_0(m_f) + \frac{m_Z^2}{m_Z^2 - m_{Z'}^2}\left(B_0(m_Z^2, m_f) - B_0(m_{Z'}^2, m_f)\right)\right)\right]\right|^2$$



# Side remark: diphoton excess fit

- Can find a consistent parameter space for 95.4 GeV diphoton excess from CMS
- Interesting pattern of SM-like vs. NP-like production modes