Effective Theories and Collider Physics of Gauged U(1)' Symmetries

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Based on
Lorin Armbruster, Bogdan A. Dobrescu, FY [2506.06068]
*Lisa Michaels, FY, JHEP **03** (2021) 120 [2010.00021]*

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PRISMA+

Effective Field Theory

- Several outstanding problems (dark matter, neutrino masses, baryon asymmetry of the universe, strong CP, inflation, hierarchy problem, new physics flavor problem, …) necessitate thinking of the Standard Model of particle physics as **incomplete**
- Effective Field Theory is perhaps our most powerful tool in modern particle physics phenomenology
  – Scale separation affords framework to capture wide classes of ultraviolet completions to the SM
- One particular focus of mine – chiral NP extensions
  – Effective descriptions generally exhibit **non-decoupling**
  – NP chirality can be orthogonal to SM chirality
    - Exhibit interplay of misaligned Higgsed/unbroken phases

Quick word on chiral symmetries

Minimal fermion reps. on 4D spacetime are either LH or RH Weyl spinors ⇔ Eigenvalues of γ^5 matrix

– Can assign distinct U(1) charges/gauge reps. to LH and RH fermions
  - Fermions are necessarily massless

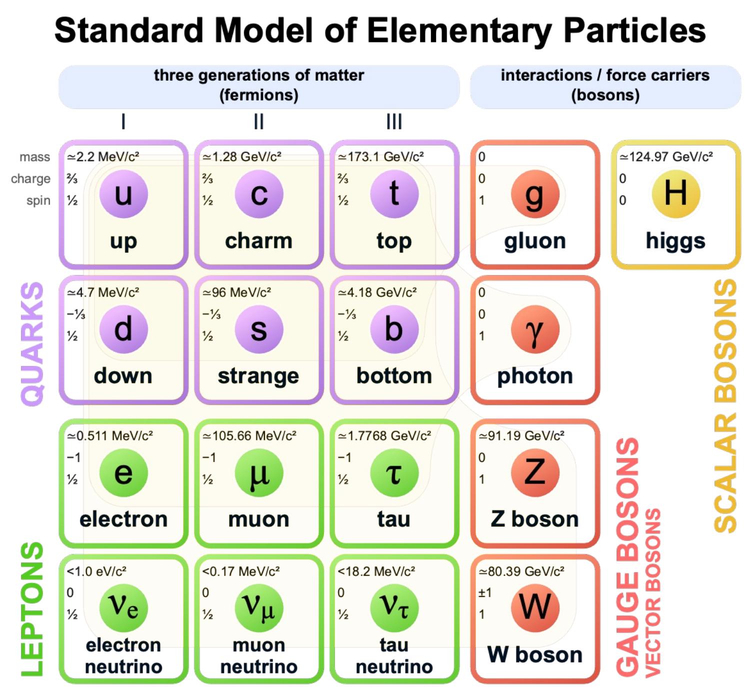
Can demonstrate (Fujikawa's method, 't Hooft-Veltman prescription, etc.) that each fermion contributes to current non-conservation at 1-loop – the **Adler-Bell-Jackiw anomaly**

Anomaly cancellation is a necessary, nontrivial consistency condition for gauged chiral symmetries

– 't Hooft anomaly matching ensures anomaly is cancelled at all scales, even across dual descriptions
  - SM fulfills this condition generation by generation

Lessons from SM

- Several open problems in BSM physics stem from (or rely crucially on) chiral nature of SM
  - Gauge hierarchy/Minimal Higgs content
  - New Physics Flavor Problem
  - Baryogenesis problem
  - Neutrino mass mechanism
  - Strong CP
  - *Aside: Lack of SUSY?*

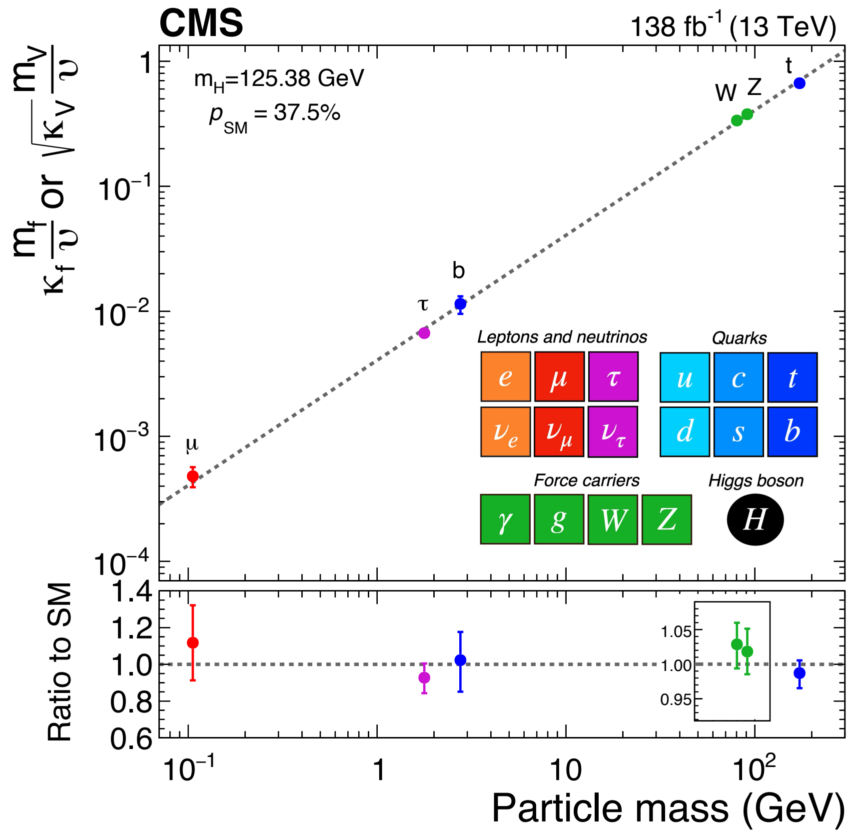


Effective theories of chiral physics

- Moreover, effective descriptions of chiral symmetry have widespread phenomenological use

Predictive nature of **SM Higgs physics** is controlled by chiral symmetry

Non-decoupling top quark dof gives Higgs low-energy theorems



Effective theories of chiral physics

- Another example: chiral Lagrangian for N_F = 3 QCD

Chiral effective Lagrangian models phenomenology of mesons via quark condensate ansatz

$$\langle \bar{q} q \rangle \equiv v^3$$

Meson spectroscopy leads to famous U(1) problem

$$\bar{u}_L u_R \approx |\langle \bar{u}_L u_R \rangle| \exp\big(i(\theta_{\pi^0} + \theta_{\eta'})\big) = \frac{v^3}{2} \exp\big(i(\theta_{\pi^0} + \theta_{\eta'})\big) \ ,$$

$$\bar{d}_L d_R \approx |\langle \bar{d}_L d_R \rangle| \exp\big(i(-\theta_{\pi^0} + \theta_{\eta'})\big) = \frac{v^3}{2} \exp\big(i(-\theta_{\pi^0} + \theta_{\eta'})\big) \ ,$$

$$\bar{s_L} s_R \approx |\langle \bar{s_L} s_R \rangle| \exp\big(i\theta_{\eta'}\big) = \frac{v^3}{2} \exp\big(i\theta_{\eta'}\big) \sim \frac{v^3}{2} \ ,$$

Phase counting leads to Strong CP problem

Kivel, Laux, FY, JHEP **11** (2022) 088 [2207.08740]

Global vs. gauged chiral symmetry

- Will focus on gauged chiral symmetries
  - Chiral anomalies (Adler-Bell-Jackiw) must cancel in UV
  - ‘t Hooft anomaly matching prescribes chiral transformations are inherited across phase boundaries
    - For example, pion decay to two photons via global $(U(1)_{EM})^2$ anomaly
  - One goal: construct an observable to “measure” gauge chiral anomaly

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

- *Aside: extending SM via a new global chiral symmetry is basis for axion physics*

Outline

- Introduction and motivation – why effective theory of chiral extensions?
- $U(1)_B$ model and field content
- Collider physics of new scalar ϕ
  - Z′-fusion and Higgsstrahlung production, decay patterns
  - Unmixed vs. mixed ϕ-h scenarios
- Z-Z′-γ vertex, measuring a chiral gauge anomaly
- Conclusions

Gauged U(1)$_B$ chiral symmetry

- SM has global U(1)$_B$ x U(1)$_L$ symmetry
- Can gauge any comb. of B or L without modifying SM Yukawas

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

- Choose gauged U(1)$_B$ symmetry (Z′ = di-jet res.)
  - Add new EW fields ("anomalons") to cancel anomalies

$$SU(2)_L \times U(1)_Y \times U(1)_B$$

New fermion fields, carry U(1)$_B$ charges

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

- Introduce Φ (B-charge = +3) to spont. break U(1)$_B$

$$\mathcal{L} = -\frac{1}{4} Z'_{\mu\nu} Z'^{\mu\nu} + |D_\mu \Phi|^2 - \mu_\Phi^2 |\Phi|^2 - \lambda_\Phi |\Phi|^4$$

$$\mathcal{L}_q = \frac{g_B}{6} Z'_\mu \sum_q \bar{q} \gamma^\mu q$$

$U(1)_B$ model and field content

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

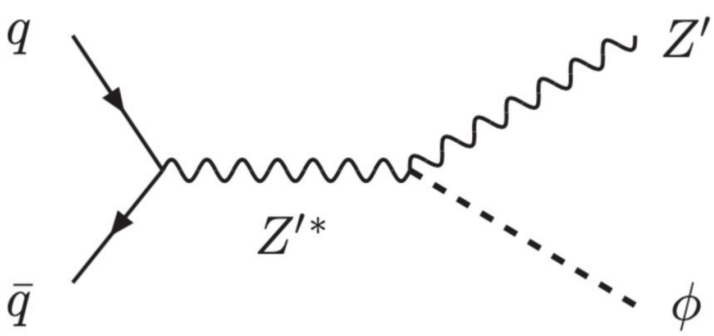
– Anomalons have two vevs for mass mechanism

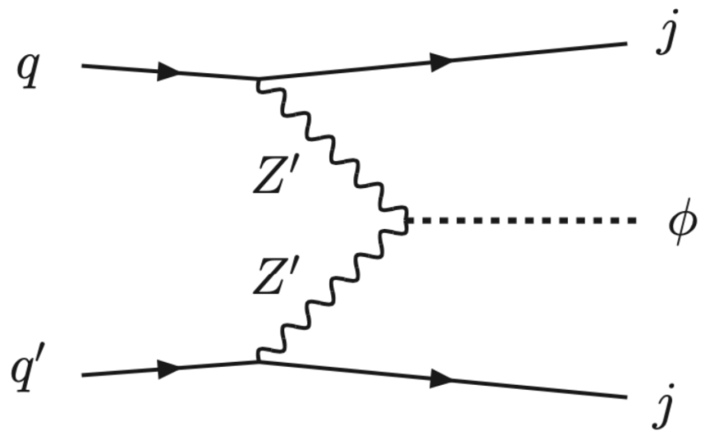
$$\begin{aligned}\mathcal{L}_{\text{Yuk}} = & -y_L \bar{L}_L \Phi^* L_R - y_E \bar{E}_L \Phi E_R - y_N \bar{N}_L \Phi N_R \\ & -y_1 \bar{L}_L H E_R - y_2 \bar{L}_R H E_L - y_3 \bar{L}_L \tilde{H} N_R - y_4 \bar{L}_R \tilde{H} N_L + \text{h.c.}\ ,\end{aligned}$$

- Set all Yukawas nonzero to avoid accidental Z_2 parity (stable charged particles)
  - Small y_1 and y_2 couplings give negligible effect on Br($h \to \gamma\gamma$)
- Will consider NP spectrum with heavy anomalons, lighter Z′ and ϕ dofs

Cross sections for ϕ

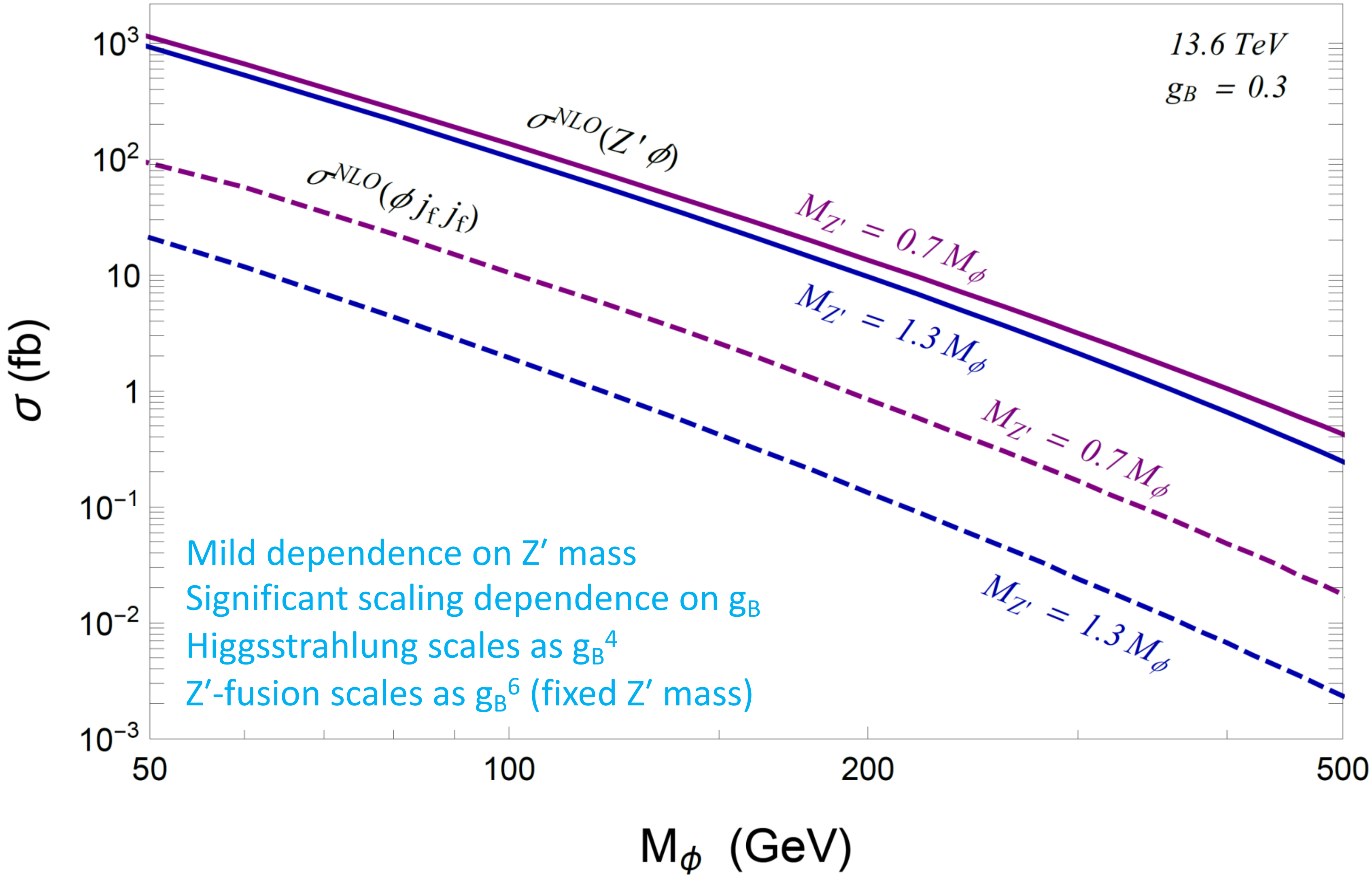
- First consider case with no ϕ-h mixing
- Leading production modes are "familiar" Higgsstrahlung and Z′-fusion
  - Reduce Higgs physics to the *diagnostic essentials*





Cross sections for ϕ

$M_{Z'} = 3\frac{g_B}{2}v'$



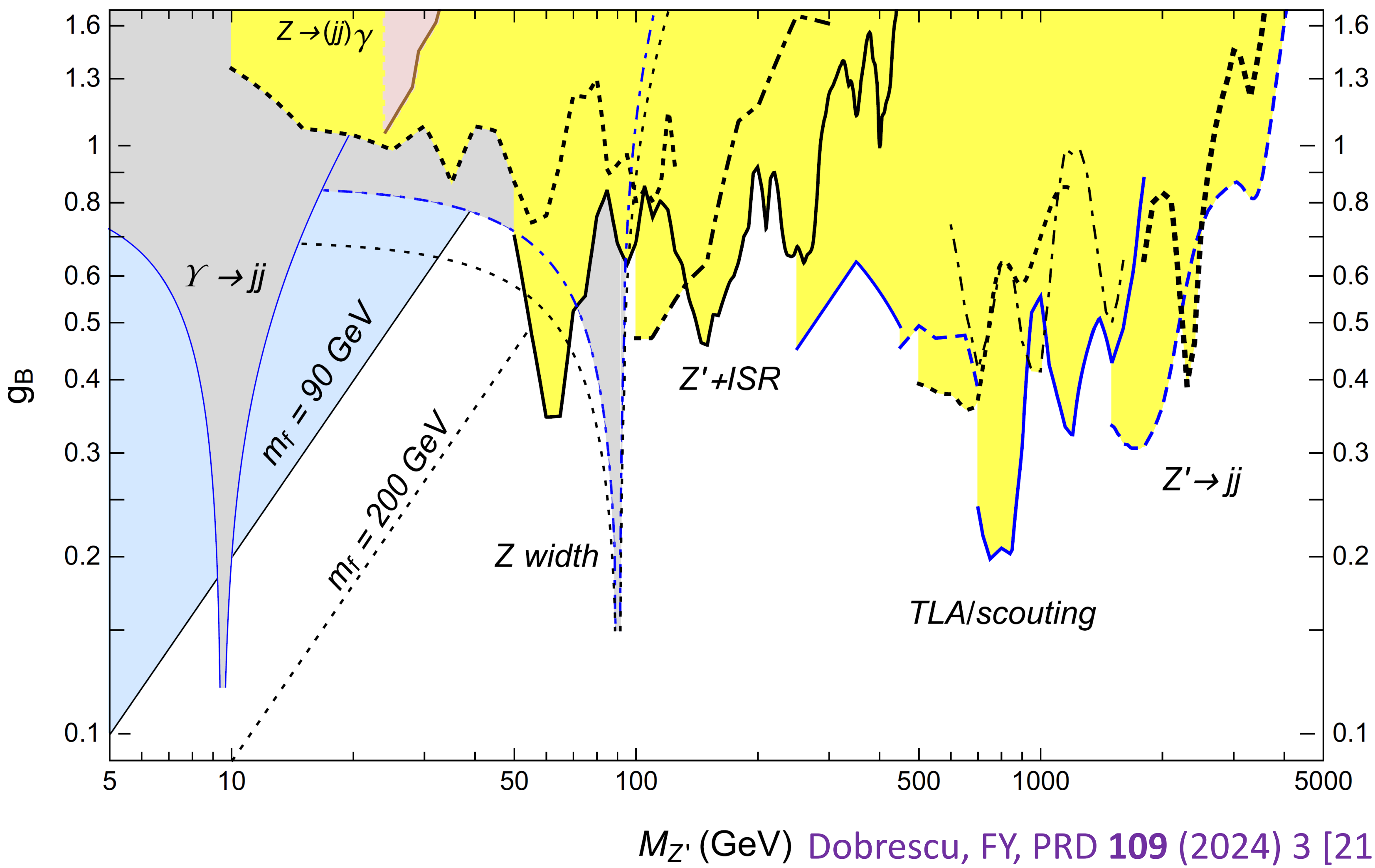
Mild dependence on Z′ mass

Significant scaling dependence on g_B

Higgsstrahlung scales as g_B^4

Z′-fusion scales as g_B^6 (fixed Z′ mass)

Current status: direct dijet resonance searches

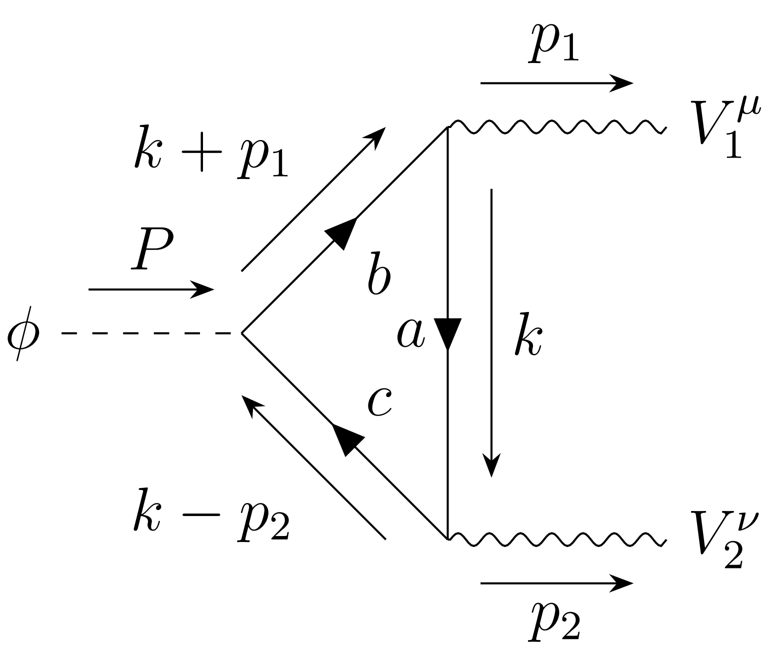


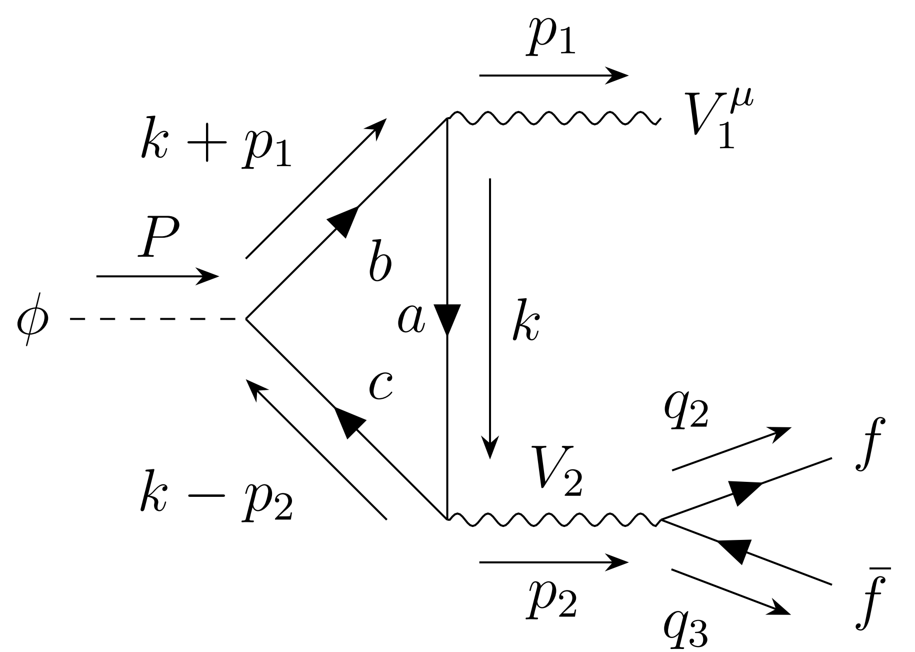
Dobrescu, FY, PRD **109** (2024) 3 [2112.05392]

Decays of ϕ

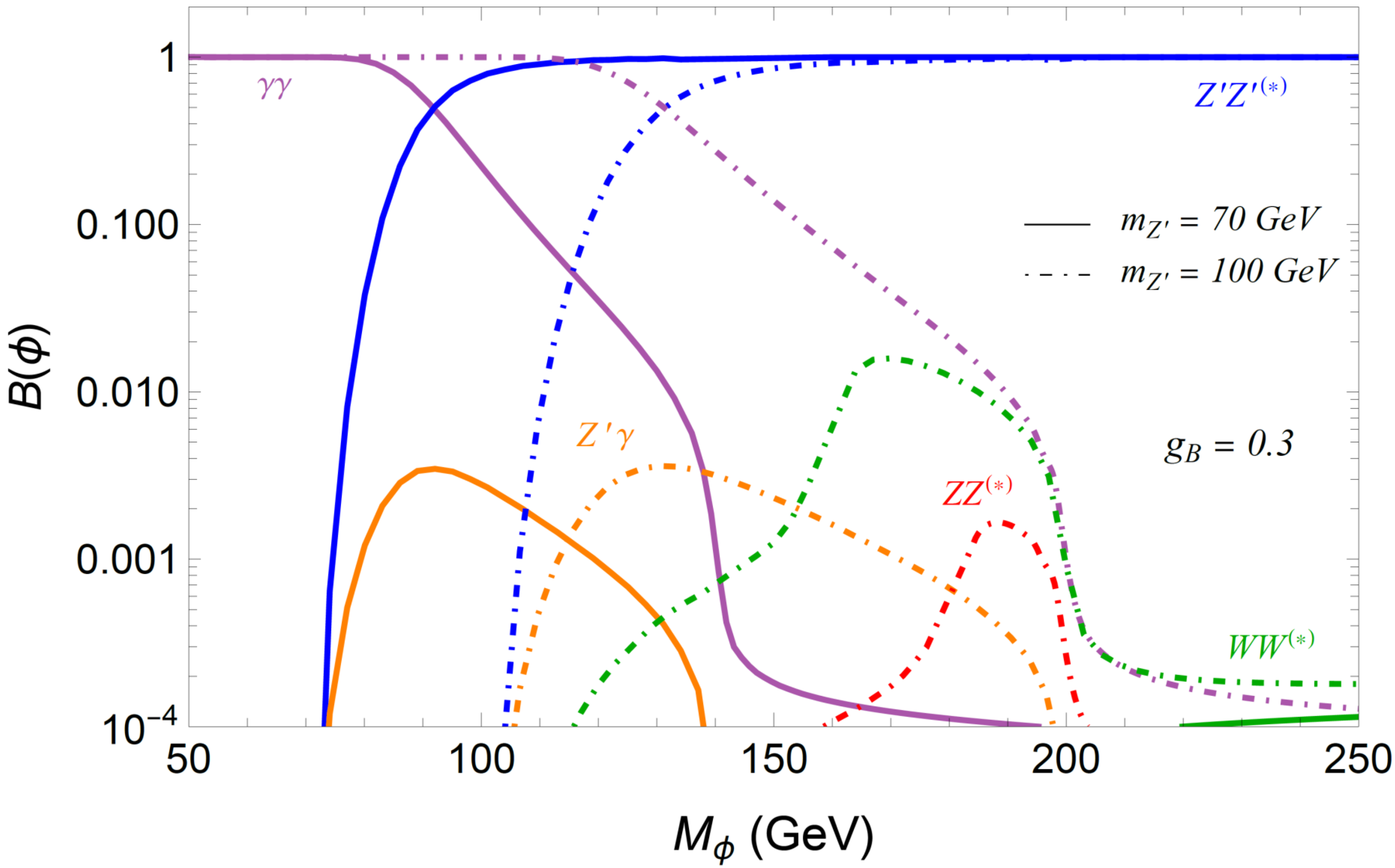
- For finite but heavy anomalon limit (M_1 = 200 GeV, M_2 = 250 GeV), only tree-level decay is $\phi \to Z'Z'$
  - When $M_\phi < 2 M_{Z'}$, one-loop decays of ϕ to $V_1 V_2$ or $V_1 f\bar{f}$ are most relevant

$V_1 V_2$ = γγ, Z′γ, WW, ZZ, Z′Z, Zγ



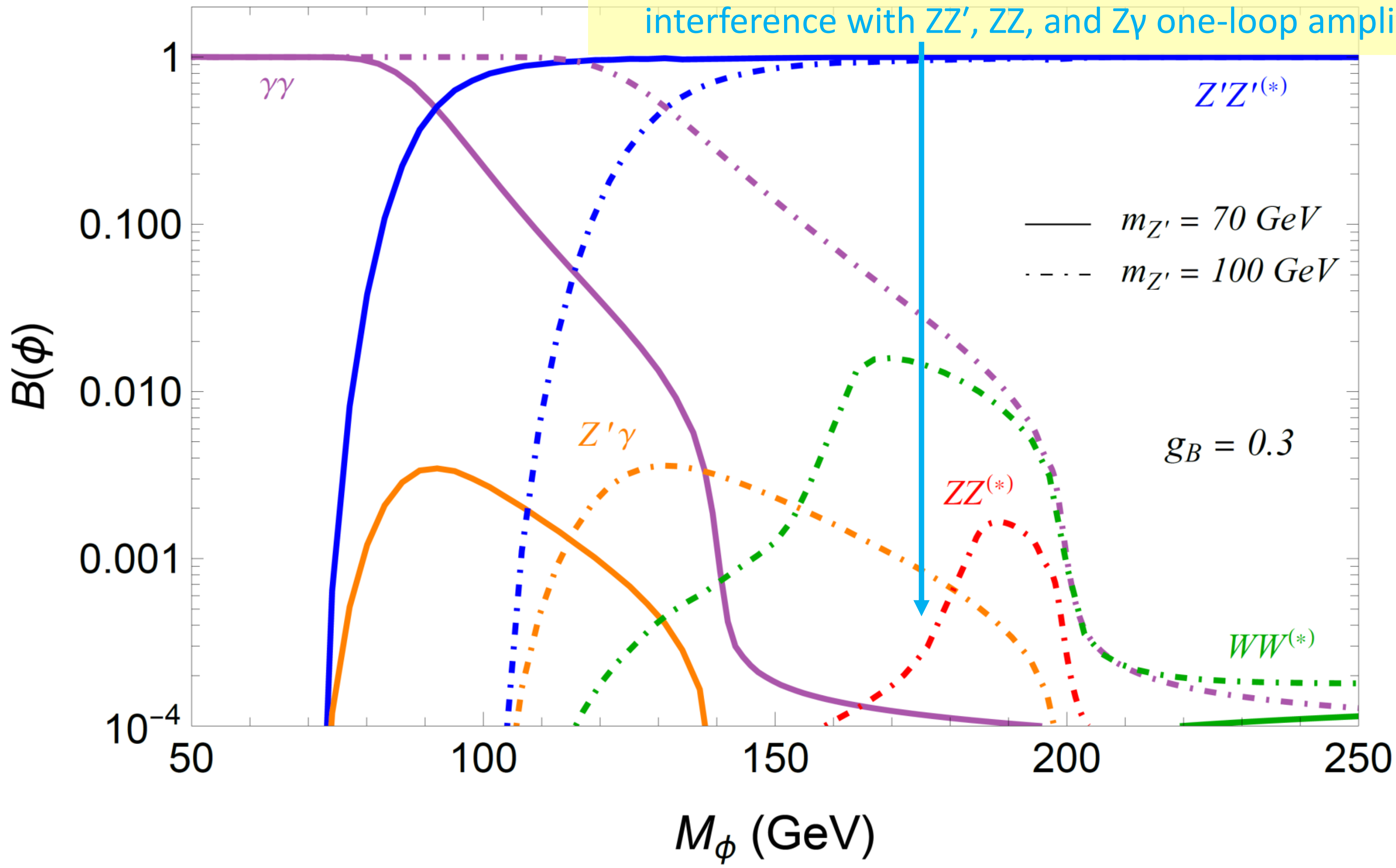


Decays of ϕ



Decays of ϕ

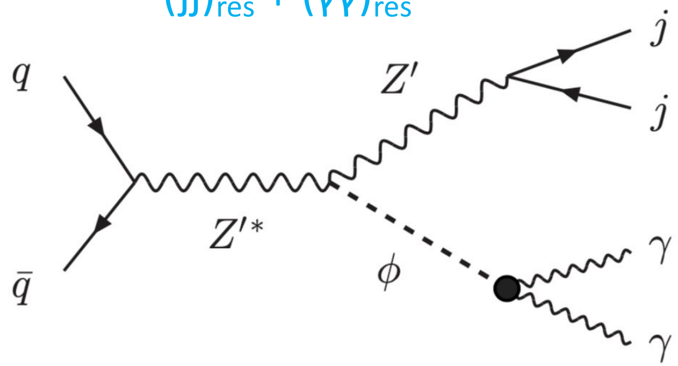
One curious feature: $Z + f\bar{f}$ decay includes interference with ZZ′, ZZ, and Zγ one-loop amplitudes



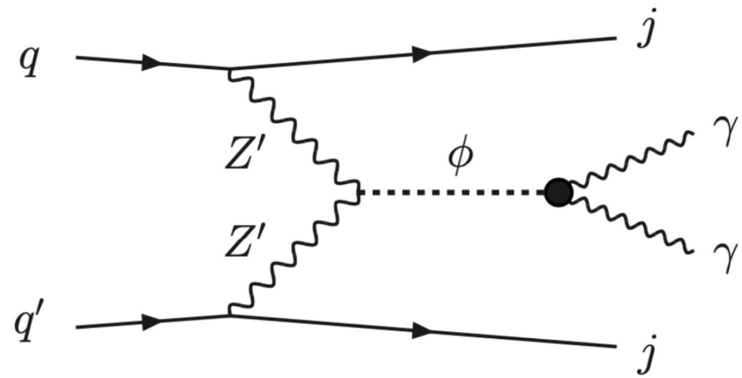
Suite of collider signatures

- Stitch together production and decay

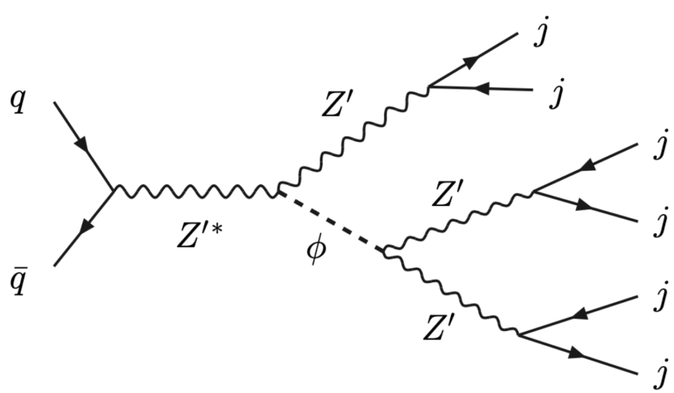
$(jj)_{res} + (\gamma\gamma)_{res}$



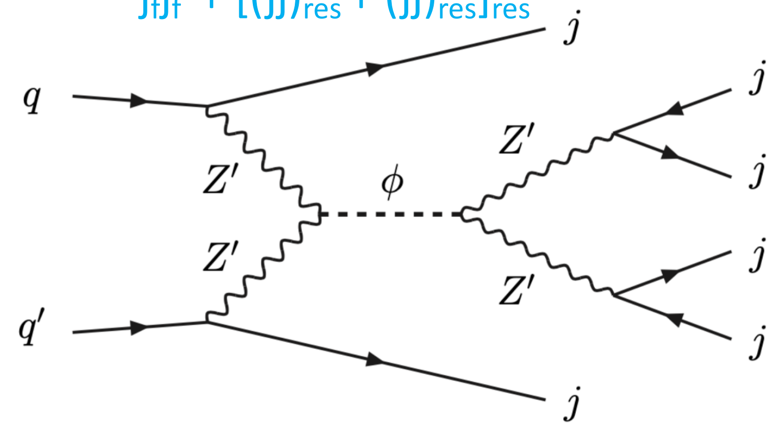
$j_f j_f\ (\gamma\gamma)_{res}$



$(jj)_{res} + [(jj)_{res} + (jj)_{res}]_{res}$



$j_f j_f + [(jj)_{res} + (jj)_{res}]_{res}$



Cross sections with Higgs mixing

- Now, incorporate scalar mixing angle

$$V(\Phi, H) = \lambda_\Phi \left(|\Phi|^2 - \frac{v_0'^2}{2} \right)^2 + \lambda_H \left(H^\dagger H - \frac{v_0^2}{2} \right)^2 + 2\lambda_p |\Phi|^2 H^\dagger H$$

$$v'^2 = \lambda_H \frac{\lambda_\Phi \, v_0'^2 - \lambda_p \, v_0^2}{\lambda_H \, \lambda_\Phi - \lambda_p^2}$$

$$v_h^2 = \lambda_\Phi \frac{\lambda_H \, v_0^2 - \lambda_p \, v_0'^2}{\lambda_H \, \lambda_\Phi - \lambda_p^2}$$

$$\sin \alpha_h \approx \frac{\lambda_p \, v_h v'}{\lambda_\Phi \, v'^2 - \lambda_H \, v_h^2}$$

- Current mixing angle constraints from overall signal strength

$$\left. \begin{aligned} \mu_{\rm ATLAS} &= 1.05 \pm 0.06 \\ \mu_{\rm CMS} &= 1.002 \pm 0.057 \end{aligned} \right\} \mu_{\rm LHC} = 1.026 \pm 0.041 \longrightarrow \sin \alpha_h \leq 0.24$$

CMS, Nature **607** (2022) [2207.00043]
ATLAS, Nature **607** (2022) [2207.00092]

Cross sections with Higgs mixing

- Now, incorporate scalar mixing angle

$$V(\Phi, H) = \lambda_\Phi \left(|\Phi|^2 - \frac{v_0'^2}{2}\right)^2 + \lambda_H \left(H^\dagger H - \frac{v_0^2}{2}\right)^2 + 2\lambda_p |\Phi|^2 H^\dagger H$$

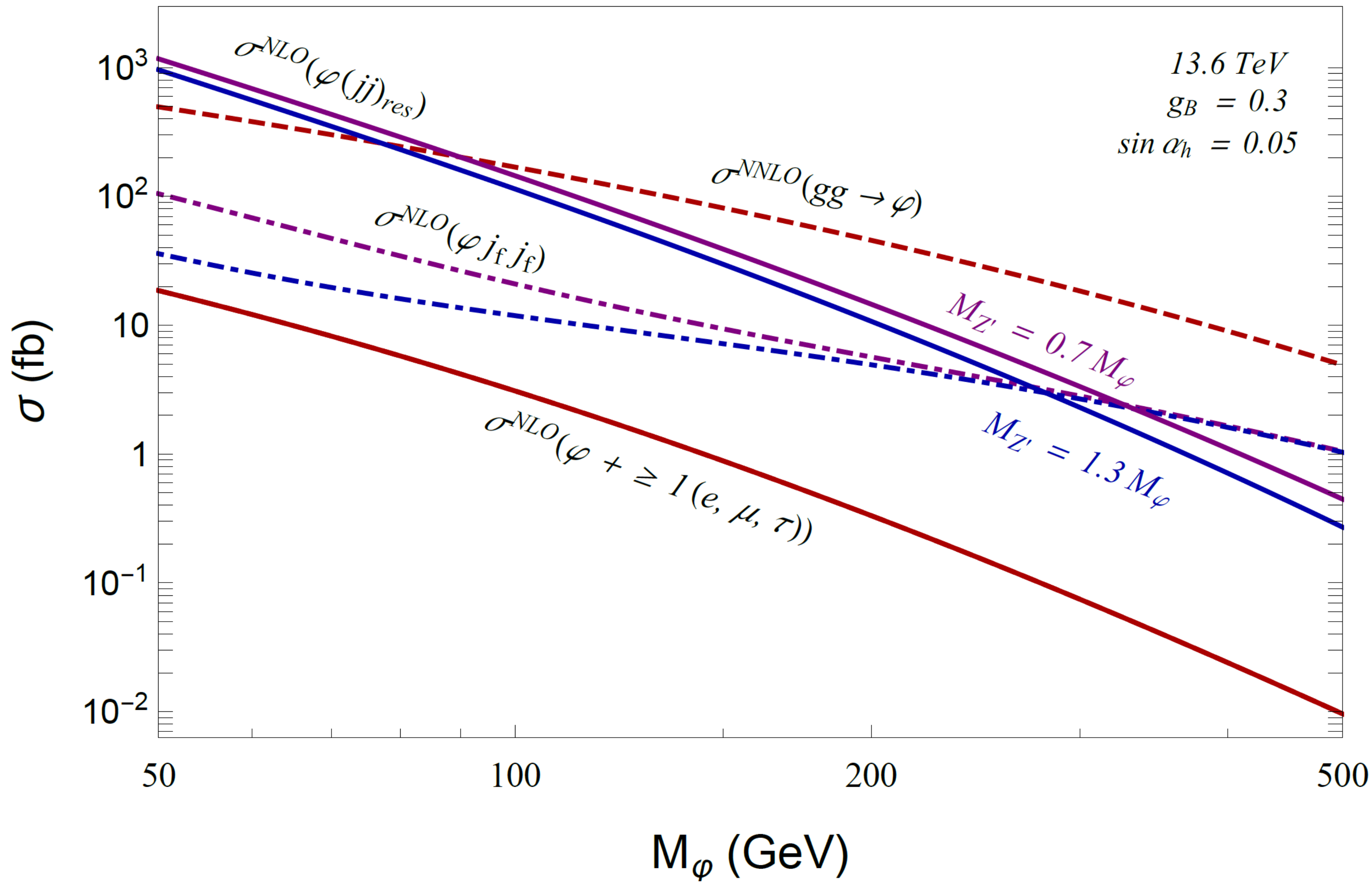
$$v'^2 = \lambda_H \frac{\lambda_\Phi\, v_0'^2 - \lambda_p\, v_0^2}{\lambda_H\, \lambda_\Phi - \lambda_p^2}$$

$$\sin\alpha_h \approx \frac{\lambda_p\, v_h v'}{\lambda_\Phi\, v'^2 - \lambda_H\, v_h^2}$$

$$v_h^2 = \lambda_\Phi \frac{\lambda_H\, v_0^2 - \lambda_p\, v_0'^2}{\lambda_H\, \lambda_\Phi - \lambda_p^2}$$

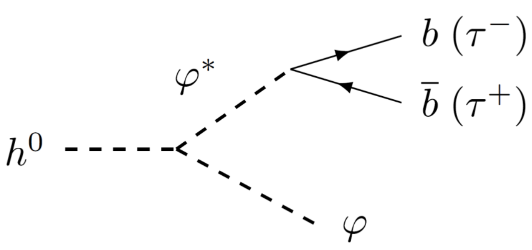
- Denote scalar mass eigenstates as φ and h^0
  - Production cross sections essentially factorize according to SM Higgs-like content vs. NP ϕ-like content
  - Most decay rates also factorize similarly
    - Important exception: $\varphi \to \gamma\gamma$

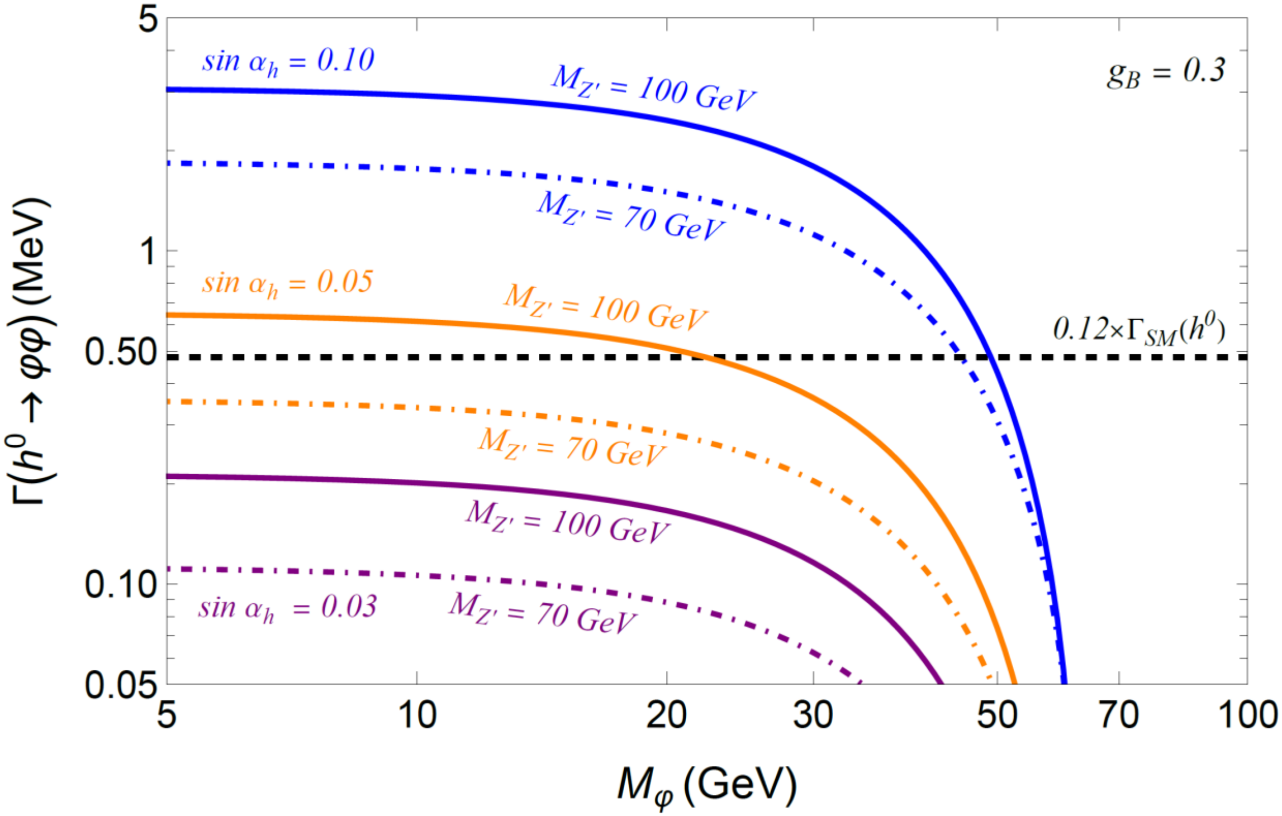
Cross sections with Higgs mixing



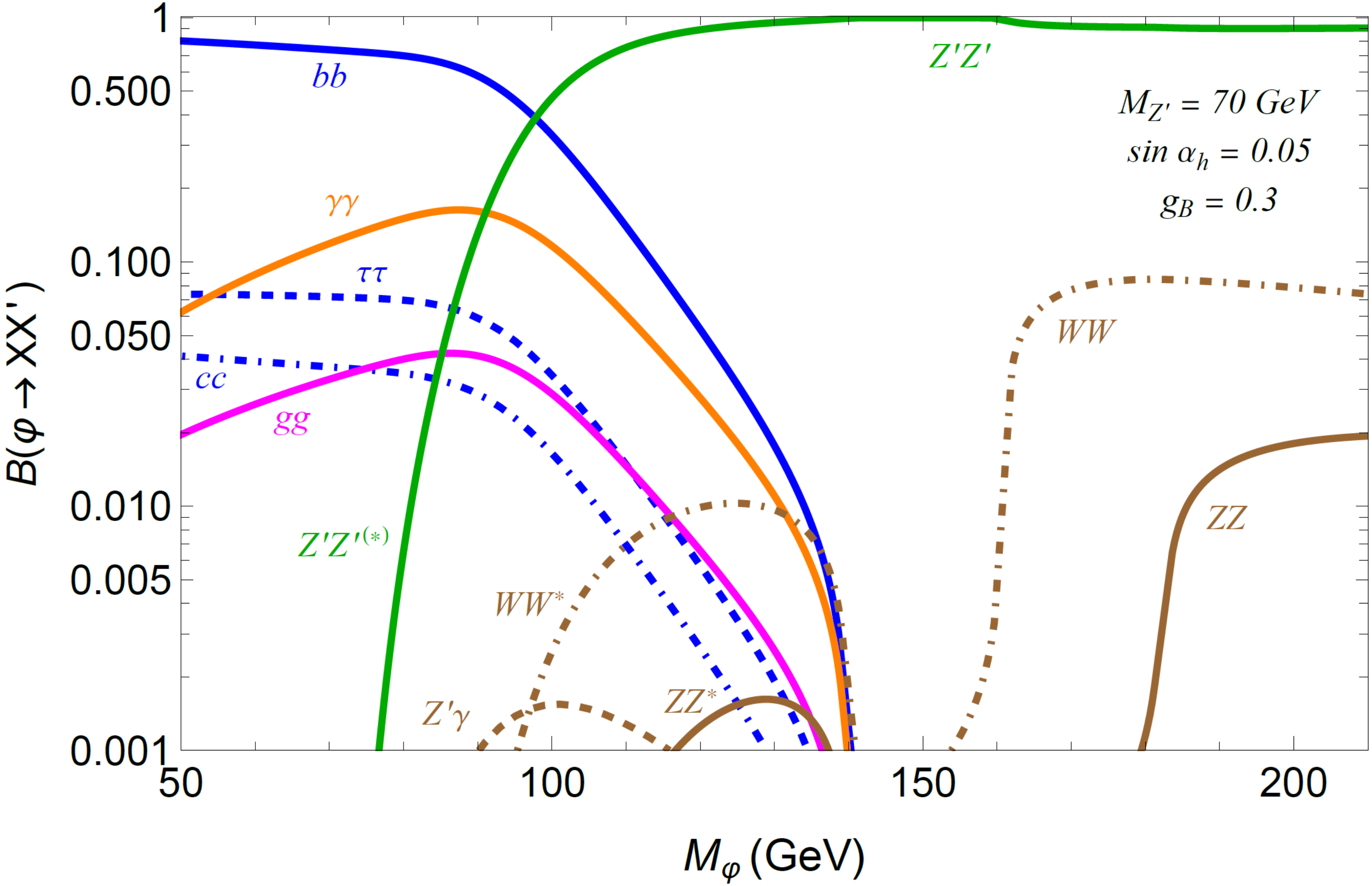
Effect on exotic Higgs decay

- For $M_\phi < m_h / 2$, must include induced exotic decay constraints

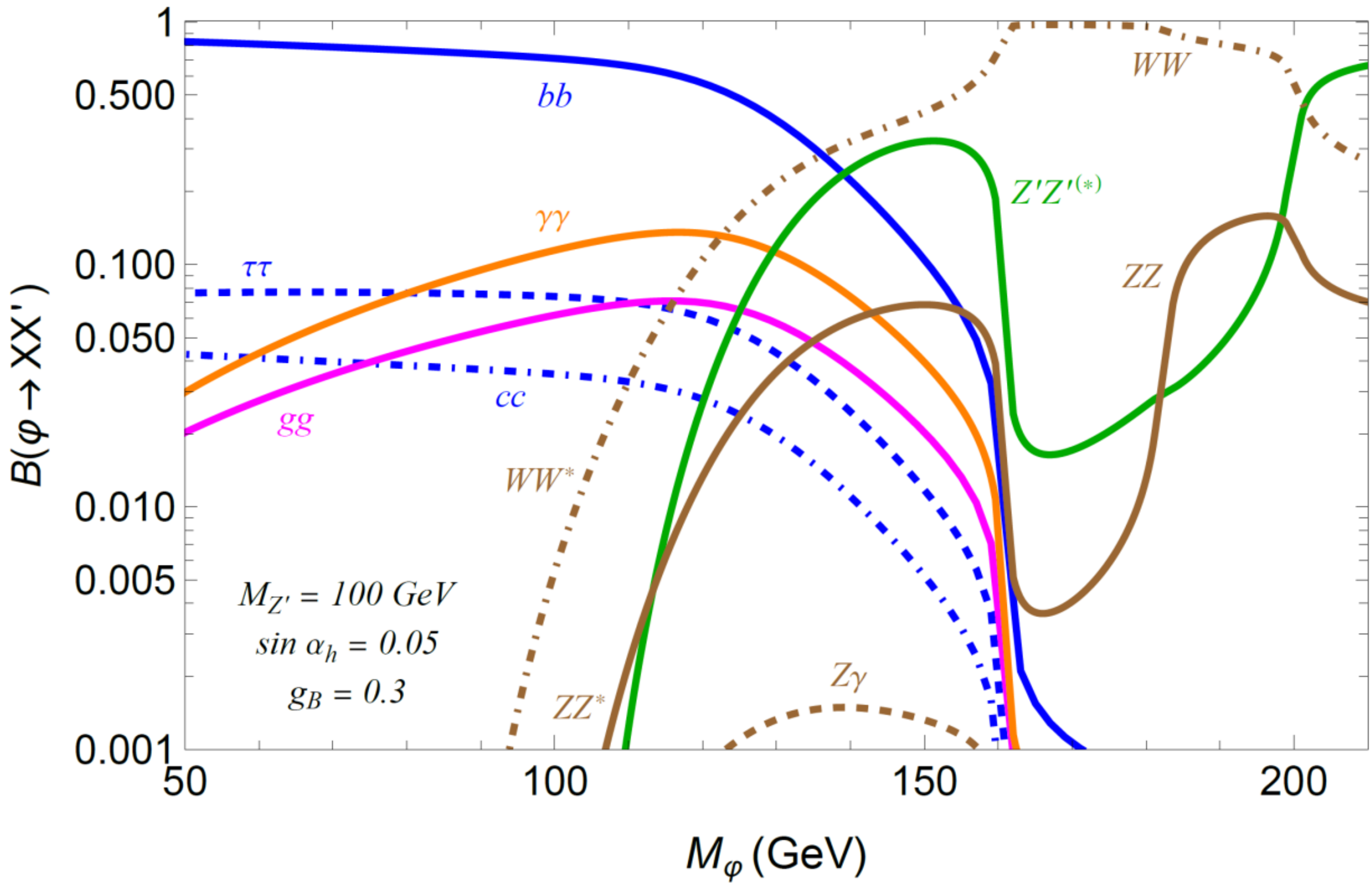




φ decays with h_{SM} mixing ($M_{Z'} = 70$ GeV)

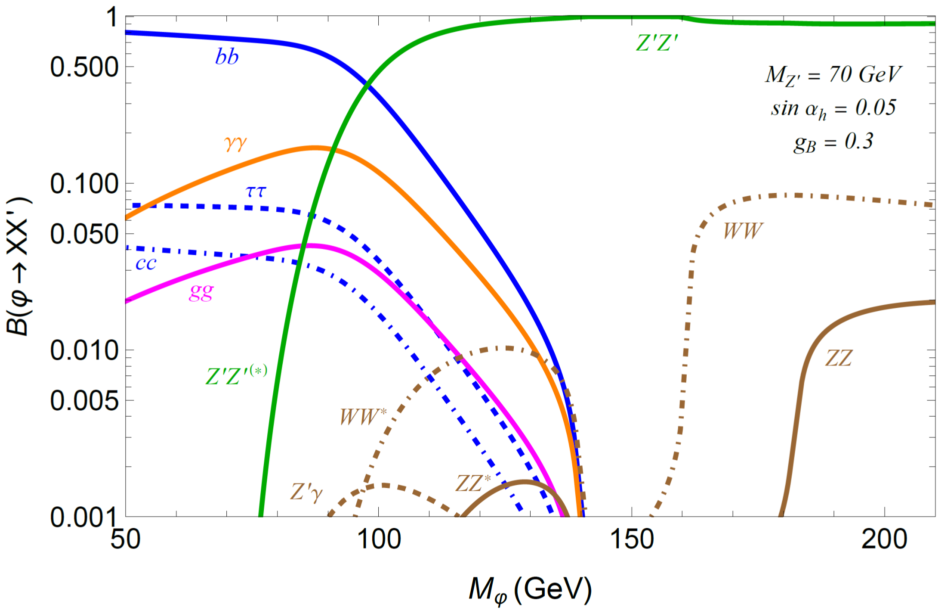


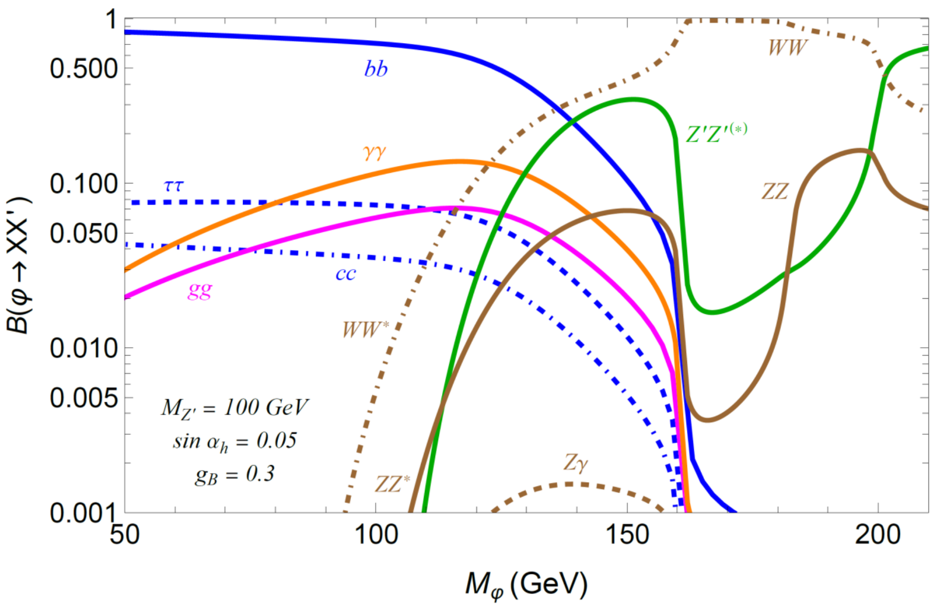
φ decays with h_{SM} mixing ($M_{Z'} = 100$ GeV)



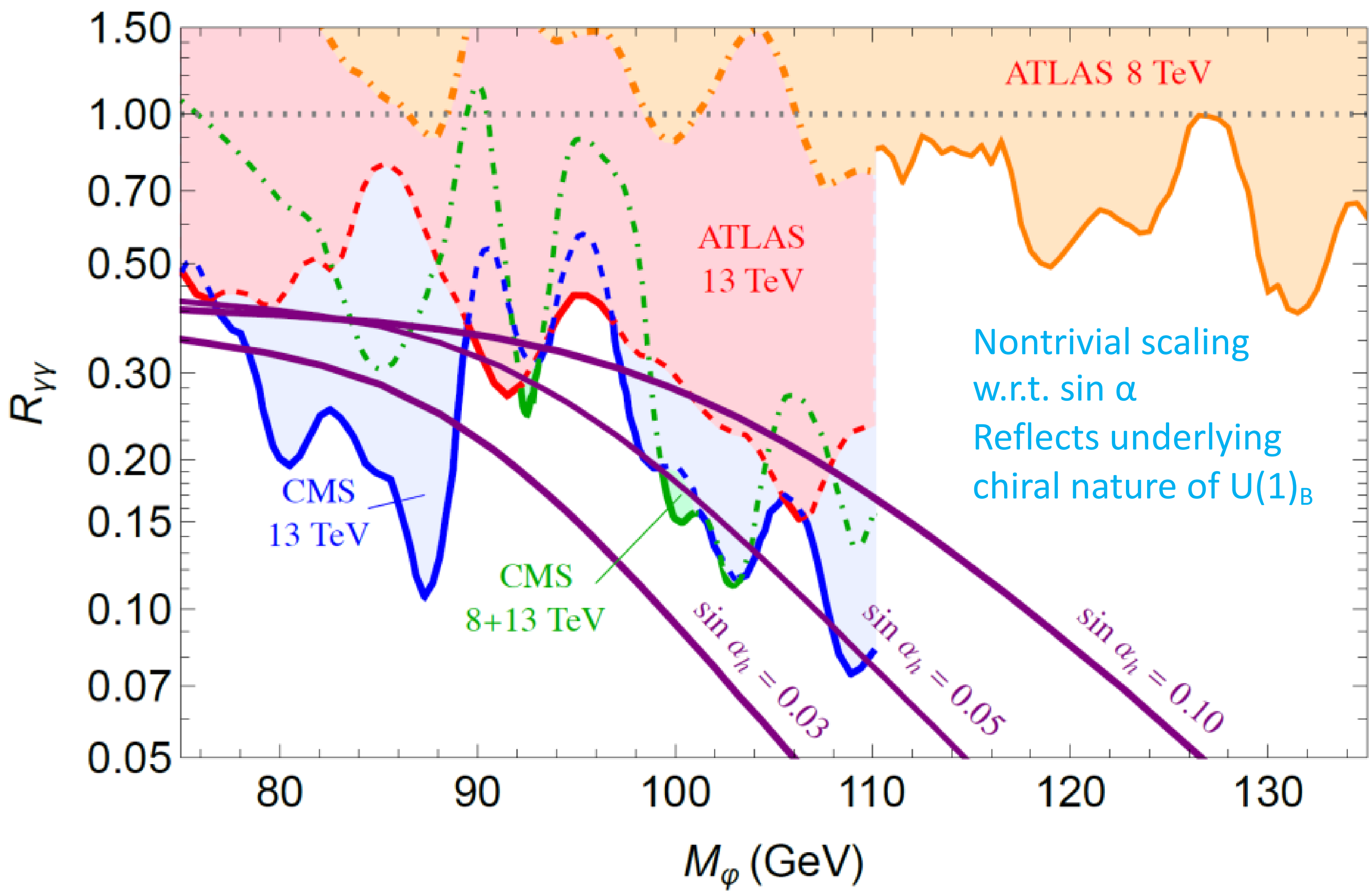
φ decays with h_{SM}: Comparison

- Intermediate mass behavior depends significantly on the $M_{Z'}$ vs. (M_W, M_Z) relative mass ordering





Leading constraints from $R_{\gamma\gamma}$

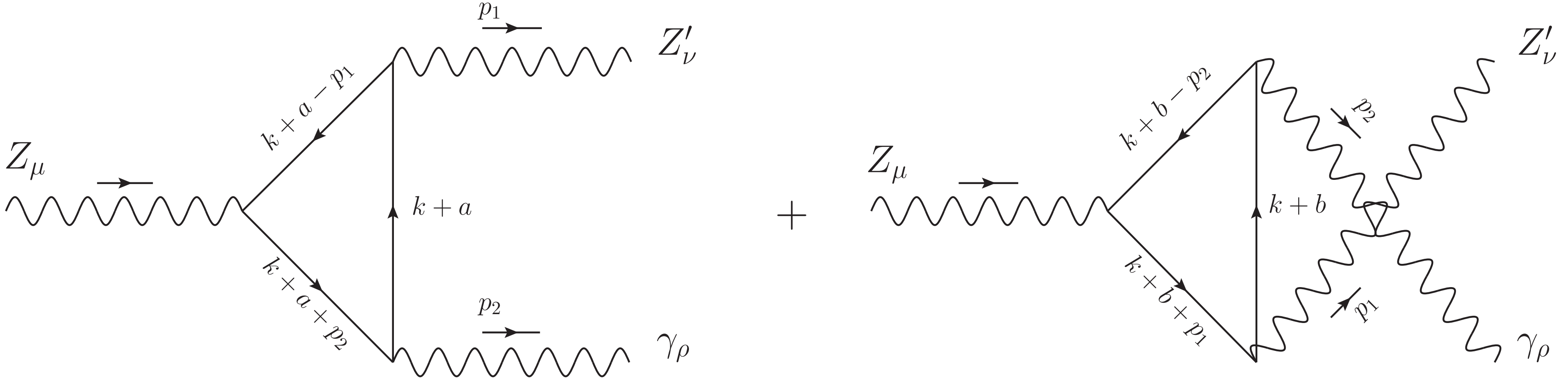


Nontrivial scaling w.r.t. sin α

Reflects underlying chiral nature of $U(1)_B$

Triple gauge boson vertex with chiral couplings

- Another important critical one-loop amplitude to calculate is the Z-Z′-γ vertex
  - Typically studied via 4-divergences for anomaly cancellation



  - Following Weinberg and Dedes, Suxho, allow each diagram to be shifted by $a^\mu = -b^\mu = z\, p_1^\mu + w\, p_2^\mu$, using dim. reg. and naïve γ^5

Dedes, Suxho, Phys. Rev. **D85** (2012) [1202.4940]

Triple gauge boson vertex with chiral couplings

- Vertex form factor decomposition (Lorentz-covariance)

$$\Gamma^{\mu\nu\rho}(p_1,p_2;w,z) =$$

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

  - The momentum-shift dependence in vertex is carried in G_1 and G_2 form factors

- Overcomplete basis: can eliminate F_1 and F_2 by redefining F_3, … F_6 and G_1 and G_2

$$\begin{aligned}
-p_1^{\mu}\epsilon^{\nu\rho|p_1||p_2|} &= -p_1^{\nu}\,\epsilon^{\mu\rho|p_1||p_2|} + p_1^{\rho}\,\epsilon^{\mu\nu|p_1||p_2|} \\
&\quad + \epsilon^{\mu\nu\rho\alpha}\left((p_1\cdot p_2)\,p_{1\alpha} - p_1^2\,p_{2\alpha}\right) \\
-p_2^{\mu}\epsilon^{\nu\rho|p_1||p_2|} &= -p_2^{\nu}\,\epsilon^{\mu\rho|p_1||p_2|} + p_2^{\rho}\,\epsilon^{\mu\nu|p_1||p_2|} \\
&\quad - \epsilon^{\mu\nu\rho\alpha}\left((p_1\cdot p_2)\,p_{2\alpha} - p_2^2\,p_{1\alpha}\right)
\end{aligned}$$

Dedes, Suxho, Phys. Rev. **D85** (2012) [1202.4940]

Triple gauge boson vertex with chiral couplings

- Vertex form factor decomposition (Lorentz-covariance)

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

  – The momentum-shift dependence in vertex is carried in G_1 and G_2 form factors

- Ward identities see 4-divergence dependence on form factors

$$(p_{1\mu} + p_{2\mu})\Gamma^{\mu\nu\rho} = (G_2' - G_1')\,\epsilon^{\nu\rho|p_1||p_2|}\,,$$
$$-\,p_{1\nu}\Gamma^{\mu\nu\rho} = (-F_3'\,p_1^2 - F_4'\,p_1\cdot p_2 + G_2')\epsilon^{\mu\rho|p_1||p_2|}$$
$$-\,p_{2\rho}\Gamma^{\mu\nu\rho} = (-F_5'\,p_1\cdot p_2 - F_6'\,p_2^2 + G_1')\epsilon^{\mu\nu|p_1||p_2|}$$

Triple gauge boson vertex with chiral couplings

- For our specific case, the vector and axial-vector Z and Z' couplings of the virtual fermions appear as

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

$$-p_{1\nu}\Gamma^{\mu\nu\rho} = \frac{Qe_{\mathrm{EM}}gg_X}{4\pi^2 c_W}\epsilon^{\mu\rho|p_1||p_2|}((w-1)(g_v^{Z'}g_a^Z+g_v^Z g_a^{Z'})-4m^2 g_v^Z g_a^{Z'} C_0(m))$$

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

  - Dictates "non-decoupling" behavior of virtual fermions via $m^2\, C_0(m) \rightarrow -1/2$ in heavy m limit

- Literature typically adopts a fixed choice of w, z to define "covariant" anomaly or "consistent" anomaly
  - Determines the corresponding Wess-Zumino effective operator

Preskill, Annals Phys. **210** (1991)

An observable: chiral gauge anomaly

- Point of departure: construct observable for exotic decay of $Z \to Z' \gamma$
  - New on-shell amplitude only possible in U(1) gauge extensions
  - Sum over all SM fermions and anomalons necessarily eliminates w, z dependence in total vertex function
    - Requiring a total vertex function to be w- and z-independent is **equivalent(!)** to anomaly cancellation condition

Should readily apply to NLO EW corrections

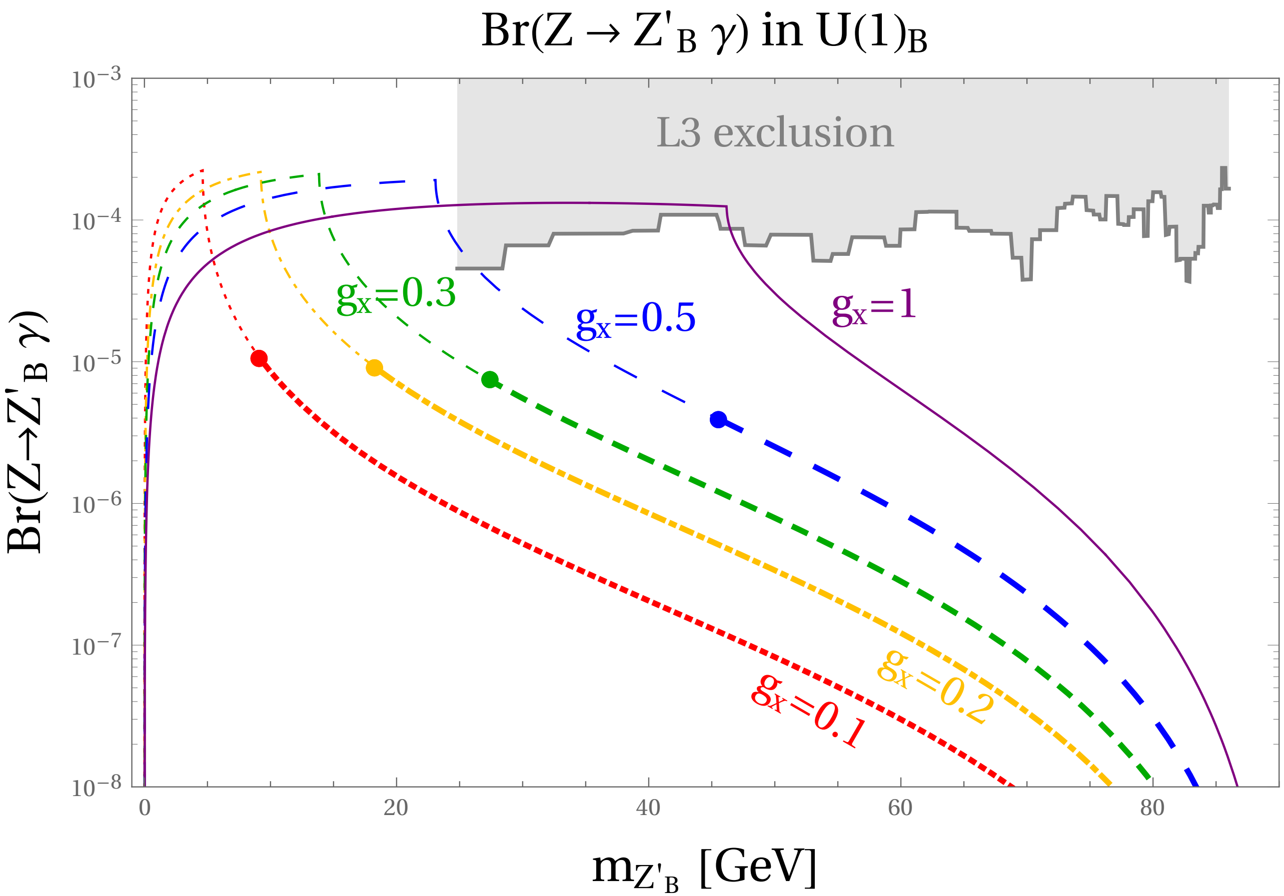
$$\Gamma(Z \to Z'_B \gamma) = \frac{\alpha_{\rm EM} \alpha \alpha_X}{96 \pi^2 c_W^2} \frac{m_Z'^2}{m_Z} \left(1 - \frac{m_{Z'}^4}{m_Z^4}\right)$$

$$\left| - \sum_{f \in \,\rm SM} T_3(f) Q_f^e \left[\frac{m_Z^2}{m_Z^2 - m_{Z'}^2} \left(B_0(m_Z^2, m_f) - B_0(m_{Z'}^2, m_f)\right) + 2 m_f^2 C_0(m_f) \right] \right.$$

$$\left. + 3 \left(\frac{m_Z^2}{m_Z^2 - m_{Z'}^2} \left(B_0(m_Z^2, M) - B_0(m_{Z'}^2, M)\right) + 2 M^2 \frac{m_Z^2}{m_{Z'}^2} C_0(M) \right) \right|^2 ,$$

An **observable:** chiral gauge anomaly

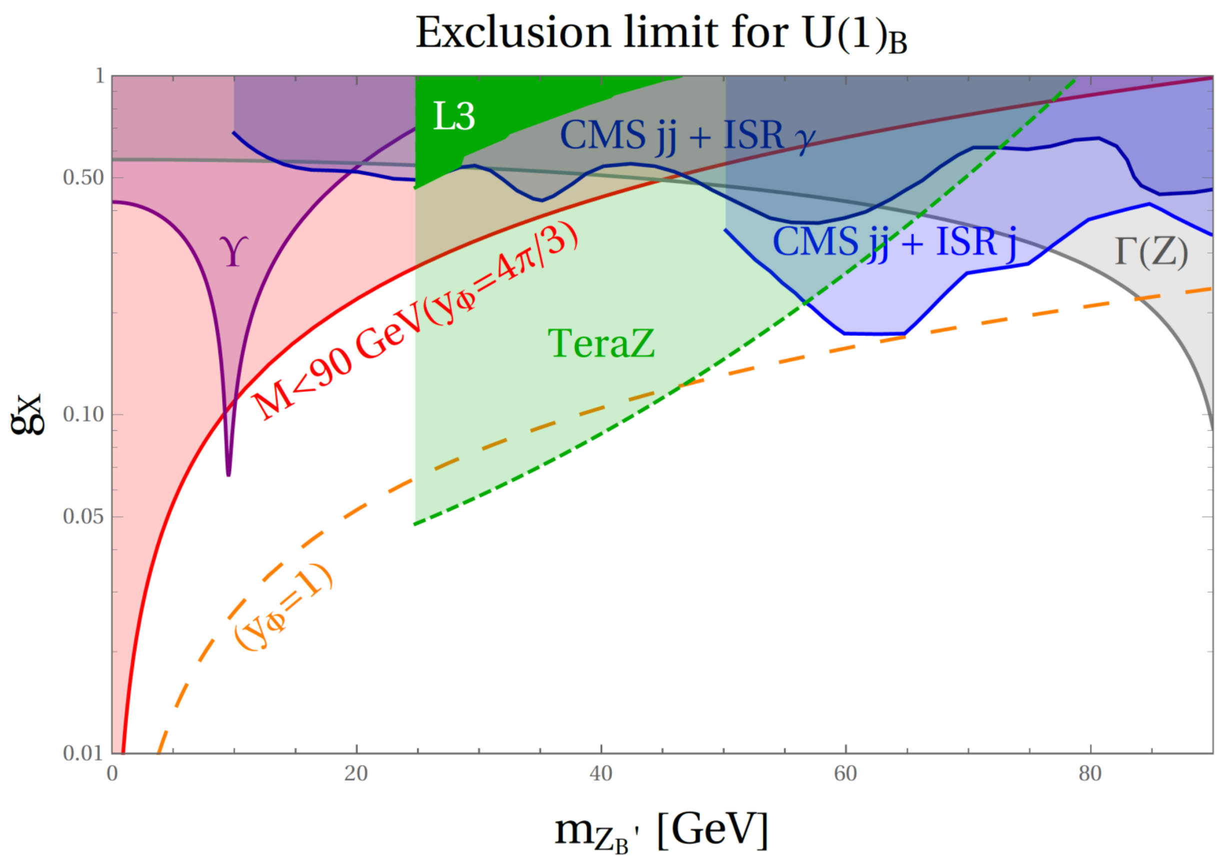
- Exotic Z decay is **emblematic** of gauge U(1)' extensions
  - Test paradigm of U(1)' gauge extensions by searching for suite of exotic Z decays



Importance of future colliders

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

- Future e^+e^- machines (CEPC, FCC-ee) will be crucial for testing new chiral gauge dynamics



Also, many CEPC/FCC-ee studies of kinetic mixing and DM production – see Liu, Wang, FY, JHEP **06** (2017) 077 [1704.00730]

An observable chiral gauge **anomaly**

- *Curious feature*: non-decoupling contribution for one generation of a mass-degenerate set of SM fermions and $U(1)_B$ anomalons

$$\Gamma(Z \to Z'_B \gamma)^{\text{non-anom.}} = \frac{3\,\alpha_{\text{EM}} \alpha \alpha_X}{32\,\pi^2 c_W^2} \frac{(m_Z^2 - m_{Z'}^2)^2}{m_Z m_{Z'}^2} \left(1 - \frac{m_{Z'}^4}{m_Z^4}\right)$$

  – Effectively counts the mixed gauge anomaly between chiral SM and $U(1)_B$ gauge symmetries

  In contrast to B-L or $L_\mu - L_\tau$ symmetries

  – Future work: obeys Adler-Bardeen non-renormalization theorem?

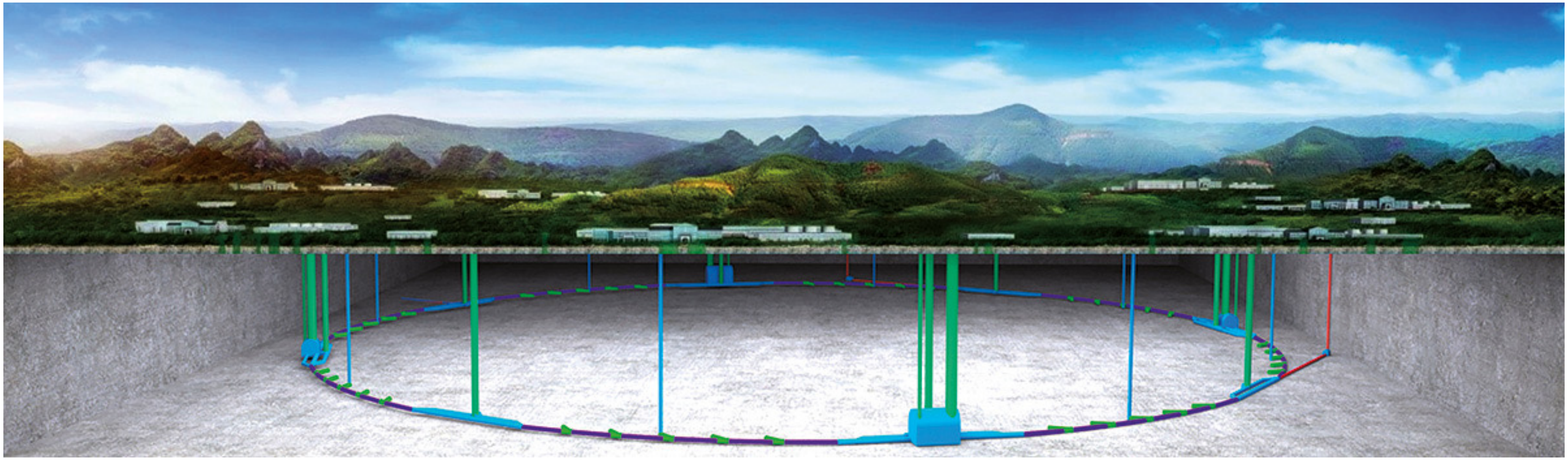
Conclusions

- Effective descriptions of chiral new physics carries rich phenomenology and field theory structure
  - Many features for ϕ collider phenomenology reminiscent of Higgs phenomenology, albeit with important interference effects
  - Effective operator construction for Z-Z′-γ vertex demonstrates a new formulation of chiral anomaly cancellation

Conclusions

- In era of many open questions and motivations for BSM physics, crucial to create and test **new paradigms**
- We are dealing with **big and fundamental questions**, which admittedly need experimental data to make progress
- Fortunately, the best data is yet to come!

Looking forward to CEPC as a new international flagship



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

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

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

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

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), $U(1)_Y$, $U(1)_B$)

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

Gauge anomalies and EFT

- After EWSB (and $U(1)_B$) breaking, generate an effective Z-Z′-γ vertex
- Naively proportional to $U(1)_B$ anomaly

Michaels, FY [2010.00021]

  – Calculate exotic Z decay width
  – Non-decoupling behavior is subtle
    - Anomalons must cancel their own anomaly contribution via mass-dependent non-decoupling limit
  – Inherent ambiguity in evaluation of triangle loop is entire motivation for ABJ chiral anomaly

Gauge anomalies and EFT

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

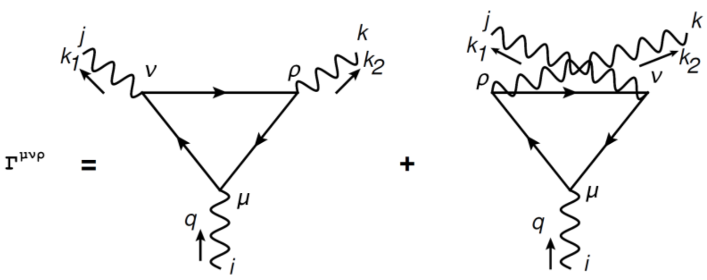
$$L_L(2,-\frac{1}{2},-1),\ L_R(2,-\frac{1}{2},2),\quad E_L(1,-1,2),\ E_R(1,-1,-1),$$
$$N_L(1,0,2),\ N_R(1,0,-1)$$

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

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

Gauge anomalies and EFT

- 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



$$\Gamma^{\mu\nu\rho}(k_1, k_2; w, z) = \Big[A_1(k_1, k_2; w)\, \varepsilon^{\mu\nu\rho\sigma}\, k_{2\sigma}$$

$$+ A_2(k_1, k_2; z)\, \varepsilon^{\mu\nu\rho\sigma}\, k_{1\sigma} + A_3(k_1, k_2)\, \varepsilon^{\mu\rho\beta\delta}\, k_2^\nu\, k_{1\beta}\, k_{2\delta}$$

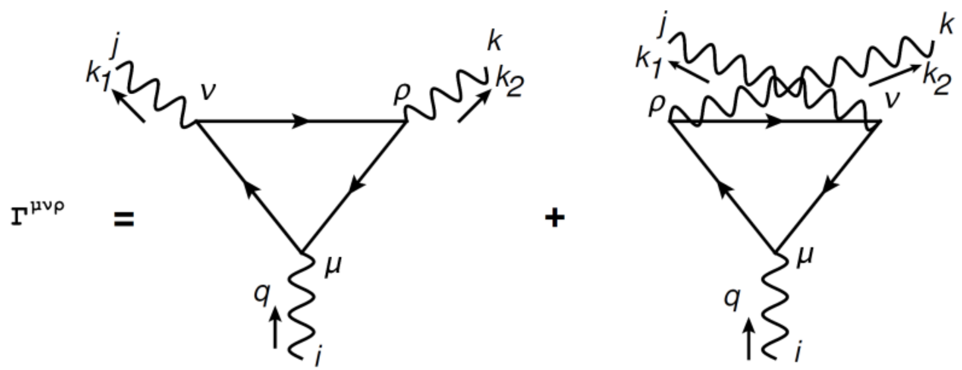
$$+ A_4(k_1, k_2)\, \varepsilon^{\mu\rho\beta\delta}\, k_1^\nu\, k_{1\beta}\, k_{2\delta} + A_5(k_1, k_2)\, \varepsilon^{\mu\nu\beta\delta}\, k_2^\rho\, k_{1\beta}\, k_{2\delta}$$

$$+ A_6(k_1, k_2)\, \varepsilon^{\mu\nu\beta\delta}\, k_1^\rho\, k_{1\beta}\, k_{2\delta} \Big] \, .$$

Dedes, Suxho [1202.4940]

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]

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

Harvey, Hill, Hill, PRD **77** (2008) 085017 [0712.1230]
Dror, Lasenby, Pospelov, PRL 119 (2017) 14 [1705.06726]

  – Induce Wess-Zumino terms

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

$$\mathcal{L} \supset -C_B \frac{e_{\rm EM} g g_X}{c_W} \epsilon^{\mu\nu\rho\sigma} Z'_\mu \left(Z_\nu \partial_\rho A_\sigma + A_\nu \partial_\rho Z_\sigma\right)$$

$$(p_{1\mu} + p_{2\mu}) \Gamma^{\mu\nu\rho} = C_B \frac{e_{\rm EM} g g_X}{c_W} \epsilon^{\nu\rho|p_1||p_2|} \,,$$
$$-p_{1\nu} \Gamma^{\mu\nu\rho} = 2 C_B \frac{e_{\rm EM} g g_X}{c_W} \epsilon^{\mu\rho|p_1||p_2|} \,,$$
$$-p_{2\rho} \Gamma^{\mu\nu\rho} = C_B \frac{e_{\rm EM} g g_X}{c_W} \epsilon^{\mu\nu|p_1||p_2|} \,.$$

Exotic Z decay – complete result

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

Michaels, FY [2010.00021]

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

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

Gauged $U(1)_B$ baryon model

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

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

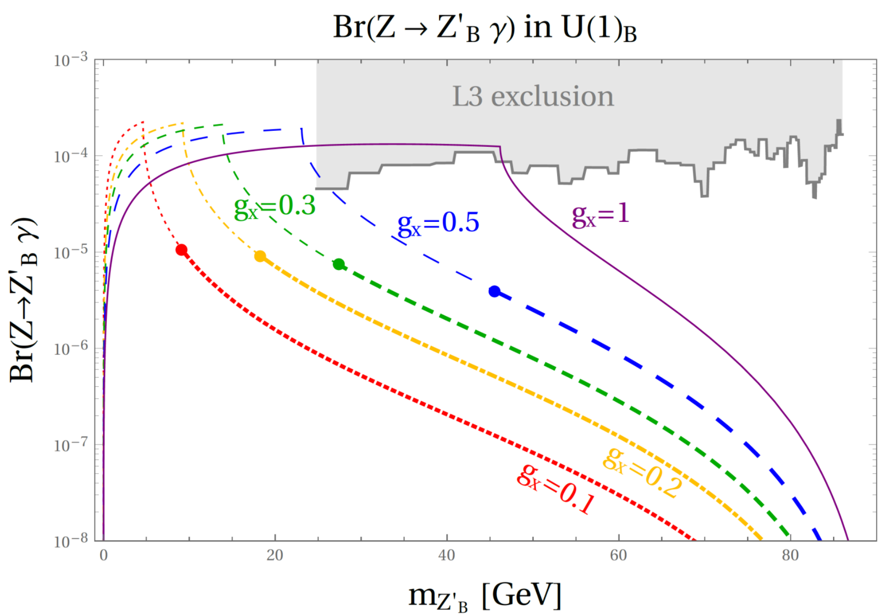
- Introduce ϕ as baryon-number Higgs ($Q_B = 3$)

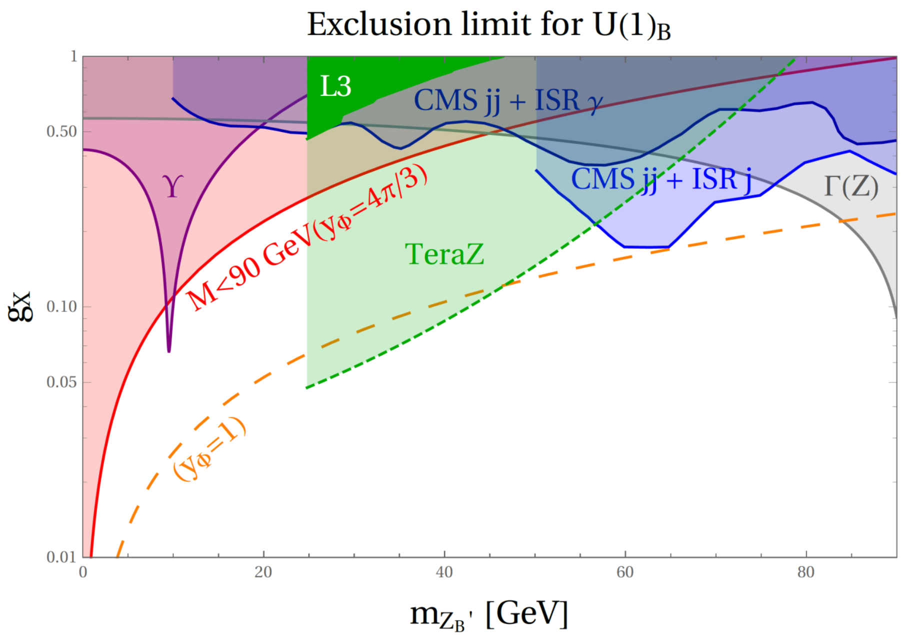
$$\mathcal{L} = -y_L \bar{L}_L \phi^* L_R - y_E \bar{E}_L \phi E_R - y_N \bar{N}_L \phi N_R + \text{ H.c.}$$

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

Aside: Chiral gauge theories

- Chiral U(1)′ gauge symmetries give novel signatures
  - After EWSB and $U(1)_B$ breaking, generate an effective Z-Z′-γ vertex





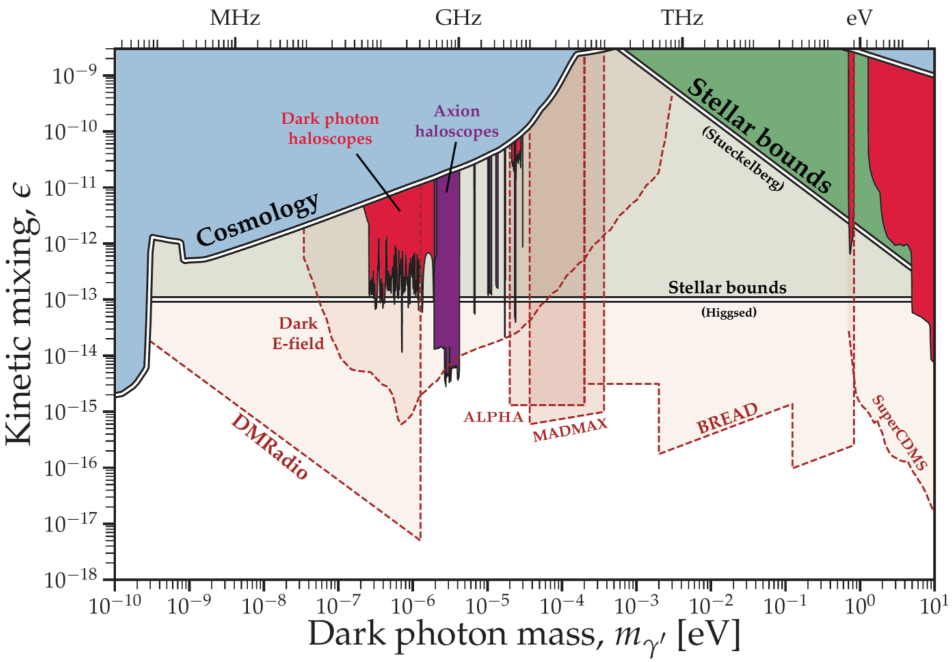
Michaels, FY, JHEP **03** (2021) 120 [2010.00021]

Introduction and Motivation

- Z′ bosons are ubiquitous feature of BSM physics
  - Arise in U(1)′ gauge extensions of SM
  - Vector or axial-vector mediator to dark sectors
  - Hidden photon DM candidate via kinetic mixing coupling

$$\mathcal{L} \supset \frac{\chi}{2\cos(\theta_W)} B_{\mu\nu} K^{\mu\nu}$$

Antypas, et. al., Snowmass whitepaper on scalar and vector ULDM [2203.14915]



Widely applicable phenomenology

- Z′ physics is a standard candle at colliders
  - Inform and establish discovery reach of possible future machines

Harris, FY, (sub-convenors), et. al. Snowmass subgroup on BSM at Energy Frontier [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.	$Z'_{SSM} \rightarrow$ dijet	4.2	5.2
				ATLAS	$Z'_{SSM} \rightarrow l^+ l^-$	6.4	6.5
				CMS	$Z'_{SSM} \rightarrow l^+ l^-$	6.3	6.8
				EPPSU*	$Z'_{Univ}(g_{Z'}=0.2)$	--	6
ILC250/ CLIC380/ FCC-ee	$e^+ e^-$	0.25	2	ILC	$Z'_{SSM} \rightarrow f^+ f^-$	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	$Z'_{SSM} \rightarrow e^+ e^-$	12.8	12.8
ILC	$e^+ e^-$	0.5	4	ILC	$Z'_{SSM} \rightarrow f^+ f^-$	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	$Z'_{SSM} \rightarrow f^+ f^-$	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.	$Z'_{SSM} \rightarrow$ dijet	25	32
				EPPSU*	$Z'_{Univ}(g_{Z'}=0.2)$	--	35
				EPPSU	$Z'_{SSM} \rightarrow l^+ l^-$	43	43
Muon Collider	$\mu^+ \mu^-$	10	10	IMCC	$Z'_{Univ}(g_{Z'}=0.2)$	42	70
VLHC	p p	300	100	R.H.	$Z'_{SSM} \rightarrow$ dijet	67	87
Coll. In the Sea	p p	500	100	R.H.	$Z'_{SSM} \rightarrow$ dijet	96	130

Increasing Z′ Sensitivity