JOHANNES GUTENBERG UNIVERSITÄT MAINZ

JG|U

Cluster of Excellence
PRISMA+
Precision Physics,
Fundamental Interactions
and Structure of Matter

Quark-Universal Breaking Scalar at the LHC

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based on **ArXiv:2506.06068**

with **Bogdan A. Dobrescu** and **Felix Yu**

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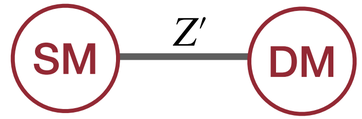
Outline

1. Motivation
2. Gauged $U(1)'$ extension to the Standard Model
3. Properties of anomalons
4. Non-mixing scalar signatures
5. Finite mixing scalar signatures

Motivation

searches for **low-energy dijet** resonances

s-channel mediated **dark matter** models



bottom-up (EFT): Z' with **quark-universal** couplings → Z' **production** at LHC

top-down (UV): Z' emerging from **gauged** $U(1)_B$ Dobrescu, Frugiuele ’12

Dobrescu, Yu ’21

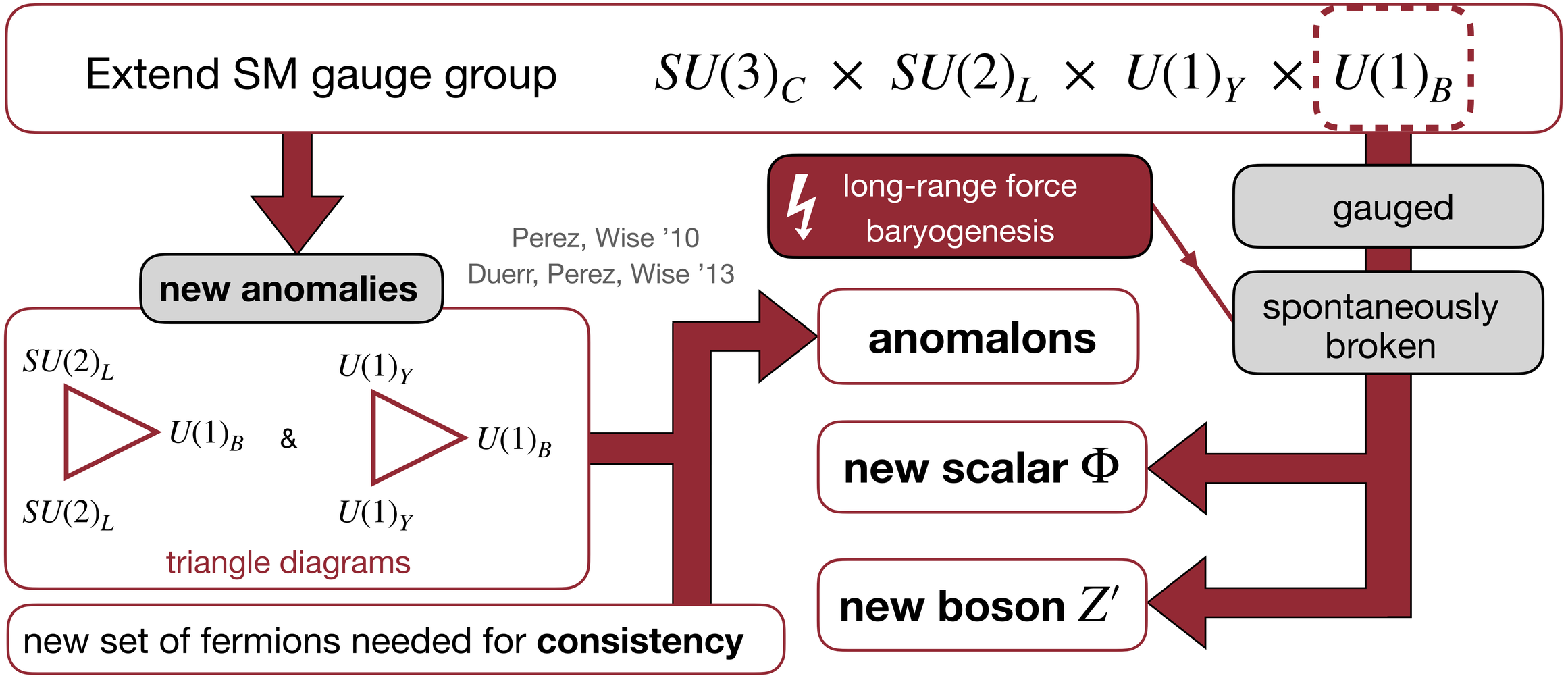
Dobrescu, Yu, LA ’25

limits on Z' boson

phenomenology of **scalar** sector

→ scalar sector as a generic feature

Gauged $U(1)_B$ Standard Model Extension



Anomalon and Scalar Charges

Duerr, Perez, Wise '13
Dobrescu, Frugiuele '14

anomalons

scalar

	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$	$U(1)_B$
L_L	0	2	$-1/2$	-1
E_L	0	1	-1	2
L_R	0	2	$-1/2$	2
E_R	0	1	-1	-1
N_L	0	1	0	2
N_R	0	1	0	-1
Φ	0	1	0	3

- **two SU(2) doublets**

$$L_{L,R} = \begin{pmatrix} \nu_{L,R} \\ e_{L,R} \end{pmatrix}$$

- **four SU(2) singlets**

$$E_L,\ E_R,\ N_L,\ N_R$$

→ anomalons assumed to have **no color** charge

Gauged $U(1)_B$ and Scalar Sector

$U(1)_B$ extension

$$\mathscr{L} \supset -\frac{1}{4} Z'_{\mu\nu} Z'^{\mu\nu} + \left| D_\mu \Phi \right|^2 - \mu_\Phi^2 |\Phi|^2 - \lambda_\Phi |\Phi|^4$$

Covariant Derivative

$$D_\mu = \partial_\mu - 3i \frac{g_B}{2} Z'_\mu$$

$$\Phi = (\phi + v')/\sqrt{2}$$

$$v'^2 = |\mu_\Phi|^2 / \lambda_\Phi$$

$$\mu_\Phi^2 < 0$$

spontaneous symmetry breaking

$$\mathscr{L} \supset -\frac{1}{4} Z'_{\mu\nu} Z'^{\mu\nu} + \frac{1}{2} \partial_\mu \phi \, \partial^\mu \phi + \frac{m_{Z'}^2}{2} Z'_\mu Z'^\mu + \dots$$

Goldstone mode eaten by Z' to acquire mass

Physical mode as new dynamical degree of freedom

→ new **real scalar** ϕ

Anomalon Yukawa Couplings

Yukawa Lagrangian

$$\mathscr{L} \supset -y_L\, \bar{L}_L\, \Phi^\star\, L_R - y_E\, \bar{E}_L\, \Phi\, E_R - y_N\, \bar{N}_L\, \Phi^\star\, N_R + \mathrm{h.c.}$$

$$\mathscr{L} \supset -y_1\, \bar{L}_L\, H\, E_R - y_2\, \bar{L}_R\, H\, E_L - y_3\, \bar{L}_L\, \tilde{H}\, N_R - y_4\, \bar{L}_R\, \tilde{H}\, N_L + \mathrm{h.c.}$$

$L_{L,R}, E_{L,R}, N_{L,R}$ are anomalons!

- **non-diagonal** Yukawa structure
  - Φ couples L to L (and E to E)
  - H couples lower-component of L to E
- **scalar** and **pseudo-scalar** Yukawa couplings
- two contributions to anomalon mass
- anomalons couple to **SM Higgs**

we assume $y_3, y_4 \ll y_1, y_2$ for simplicity

Anomalon Gauge Couplings

anomalon kinetic term

$$\mathscr{L}_{\text{kin}} \supset \bar{L}_L \not{D} L_L + \bar{E}_L \not{D} E_L + \text{h.c.}$$

scalar kinetic term

$$\mathscr{L}_{\text{kin}} \supset D_\mu \Phi \, D^\mu \Phi^*$$

covariant derivative

$$D_\mu = \partial_\mu + i z_f \frac{g_B}{2} Z'_\mu - i \frac{g}{\sqrt{2}} \left(\tau^+ W^+ + \tau^- W^- \right) + i e Q_f A_\mu - i \frac{g}{c_\theta} \left(\frac{\tau_3}{2} - Q s_\theta^2 \right) Z_\mu$$

vector- and axial-vector couplings

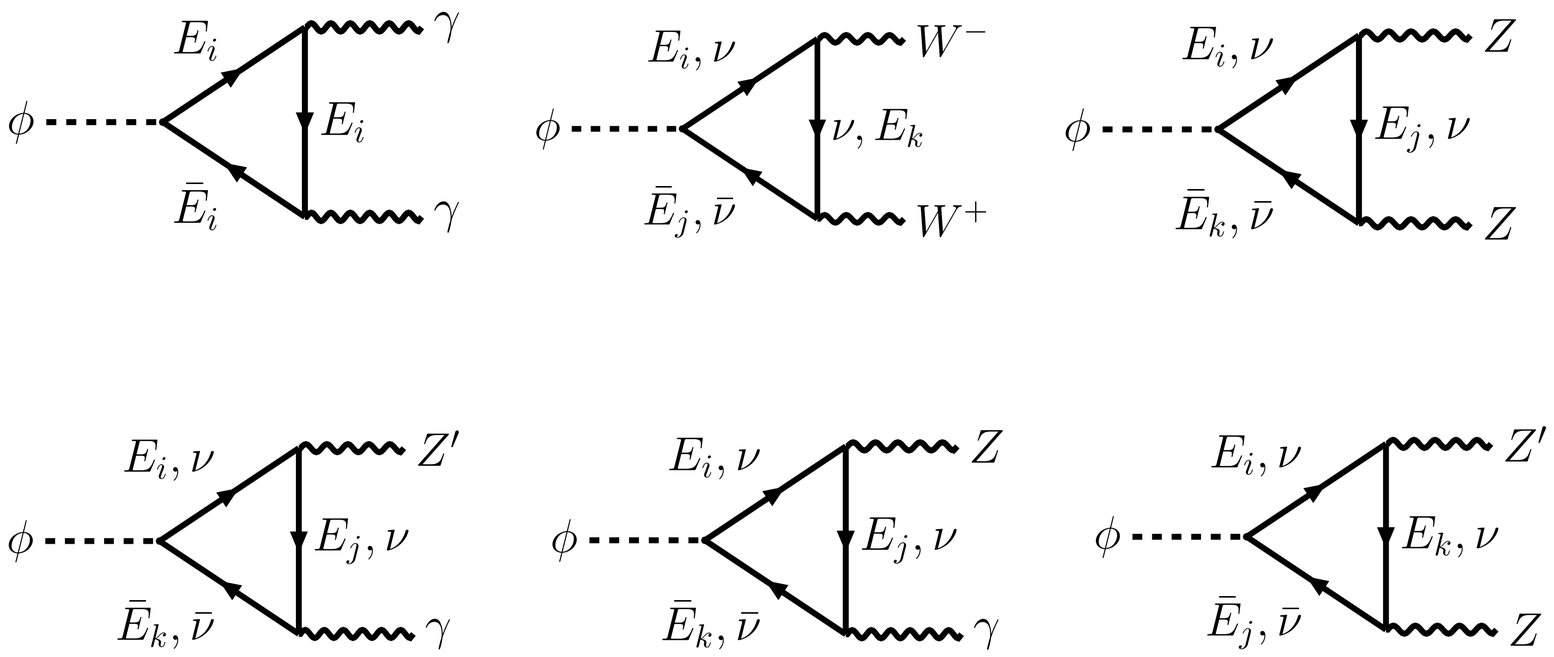
anomalon couplings to W^+, W^-, Z, γ and Z'

ϕ signatures in two-vector final states

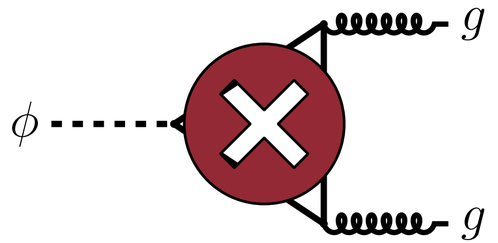
→ anomalon loops mediate ϕ couplings to EW gauge bosons

Anomalon-mediated Scalar Interactions

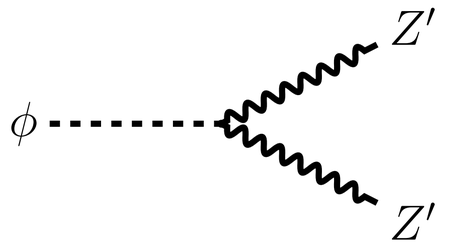
Decays to **electroweak** and $U(1)_B$ **gauge bosons**



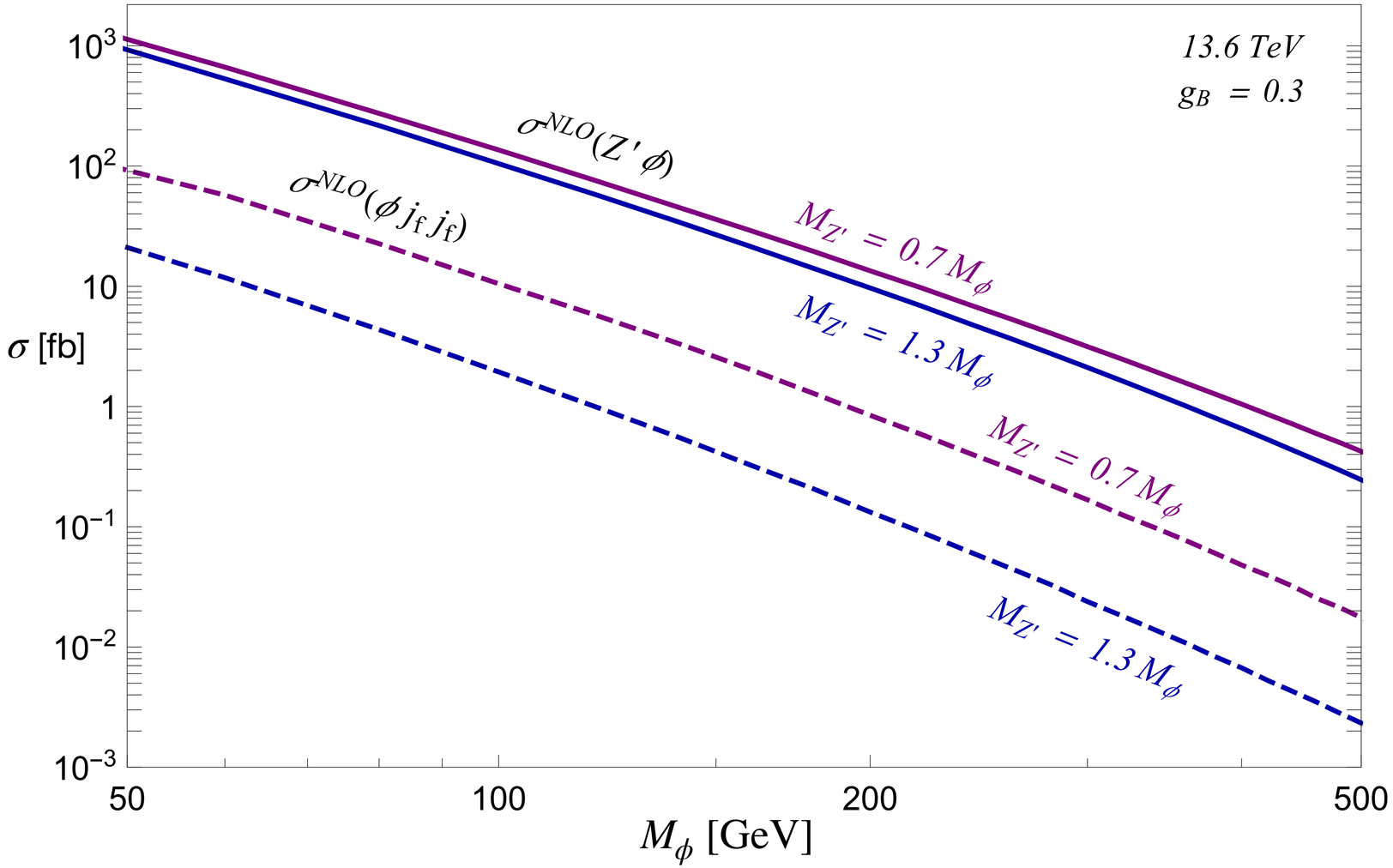
No **gluon** coupling



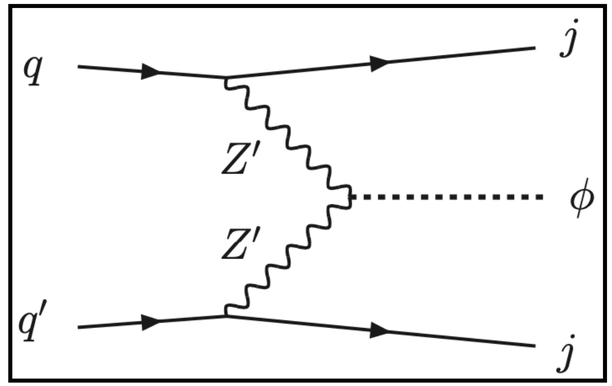
Z' tree level



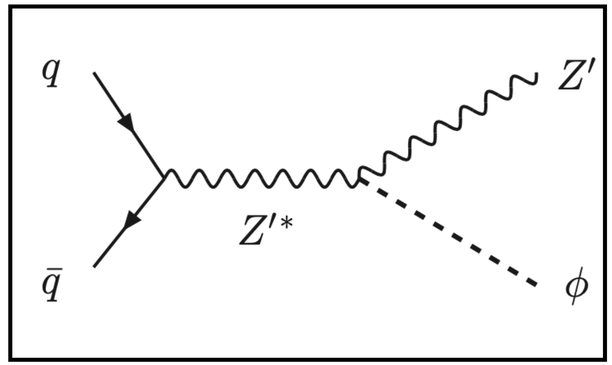
Scalar Production at the LHC



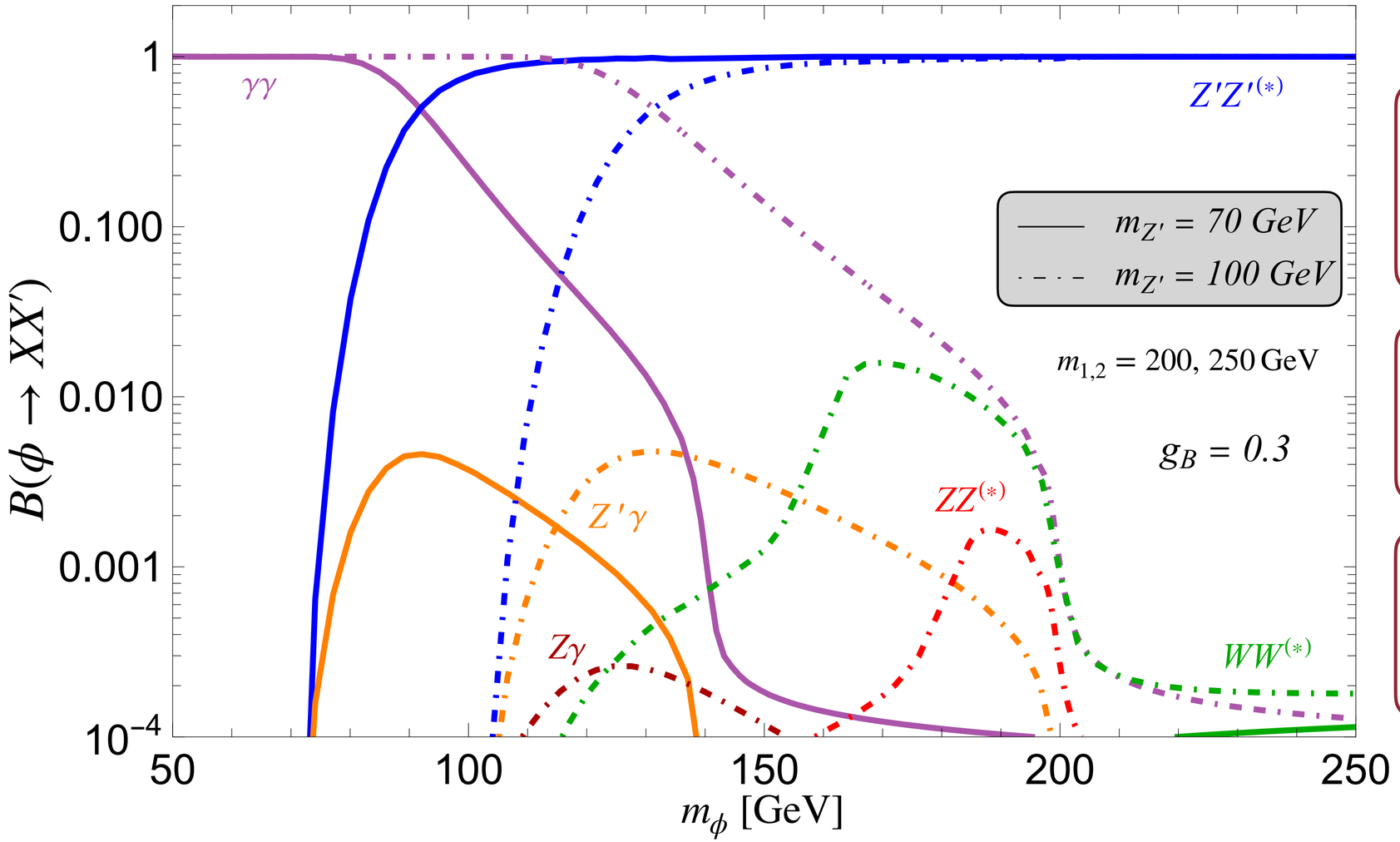
Z' fusion ($\phi j_f j_f$)



ϕ strahlung ($Z'\phi$)



Scalar Branching Fractions



Tree level **anomalon** decays kinematically forbidden

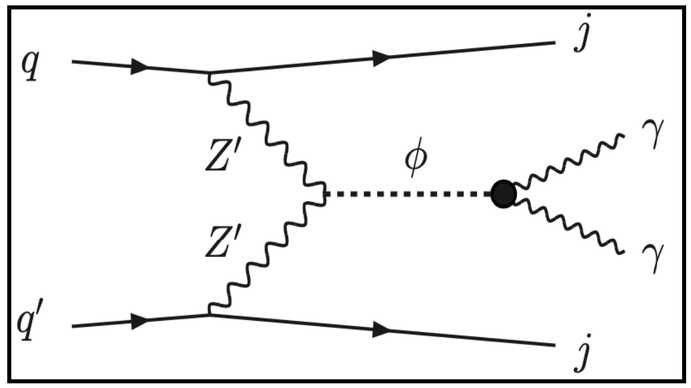
Loop induced decays to **SM gauge bosons**

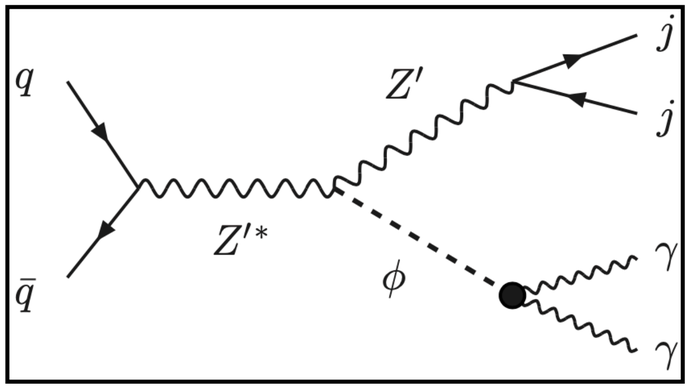
Leading **diphoton** and **tree-level** $Z'Z'$ decays

Scalar Sector Phenomenology

$\frac{m_\phi}{m_{Z'}} < 1$

$(\gamma\gamma)\, j_f\, j_f$

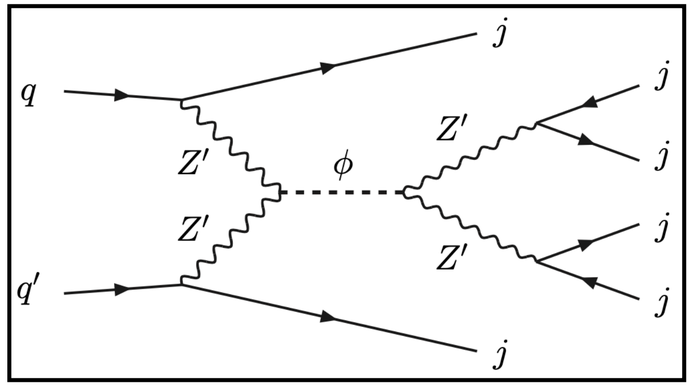


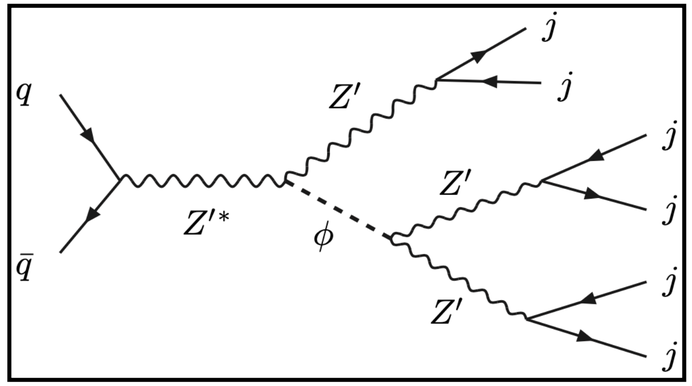


$(\gamma\gamma)\,(jj)$

$\frac{m_\phi}{m_{Z'}} > 1$

$(jj)\,(jj)\, j_f\, j_f$





$3\,(jj)$

Higgs-Scalar Mass Mixing

Scalar Lagrangian

$$\mathscr{L} \supset \left|D_\mu \Phi\right|^2 + \left|D_\mu H\right|^2 - V(\Phi, H)$$

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

portal coupling $\lambda_p \neq 0$ → mass mixing!

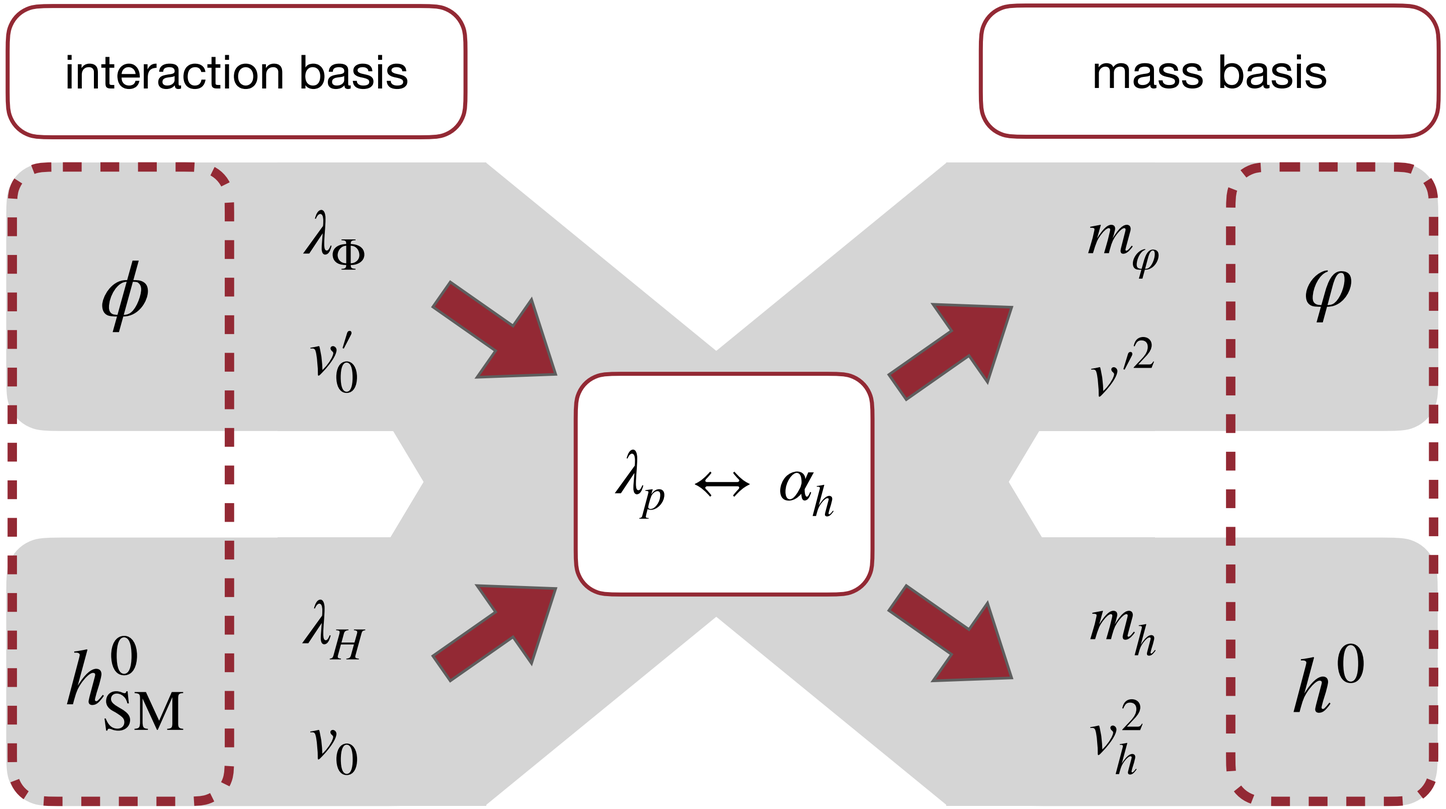
$$H = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v_h + h^0_{\mathrm{SM}} \end{pmatrix} \qquad \Phi = \frac{\phi + v'}{\sqrt{2}}$$

Mass matrix

$$\mathscr{L} \supset -\begin{pmatrix} \phi & h^0_{\mathrm{SM}} \end{pmatrix} \begin{pmatrix} \lambda_\Phi v'^2 & \lambda_p v_h v' \\ \lambda_p v_h v' & \lambda_H v_h^2 \end{pmatrix} \begin{pmatrix} \phi \\ h^0_{\mathrm{SM}} \end{pmatrix} = -\frac{1}{2} \begin{pmatrix} \varphi & h^0 \end{pmatrix} \begin{pmatrix} m_\varphi^2 & 0 \\ 0 & m_h^2 \end{pmatrix} \begin{pmatrix} \varphi \\ h^0 \end{pmatrix}$$

physical states

Higgs-Scalar Mass Mixing



free parameters

mass m_φ

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

mixing angle α_h

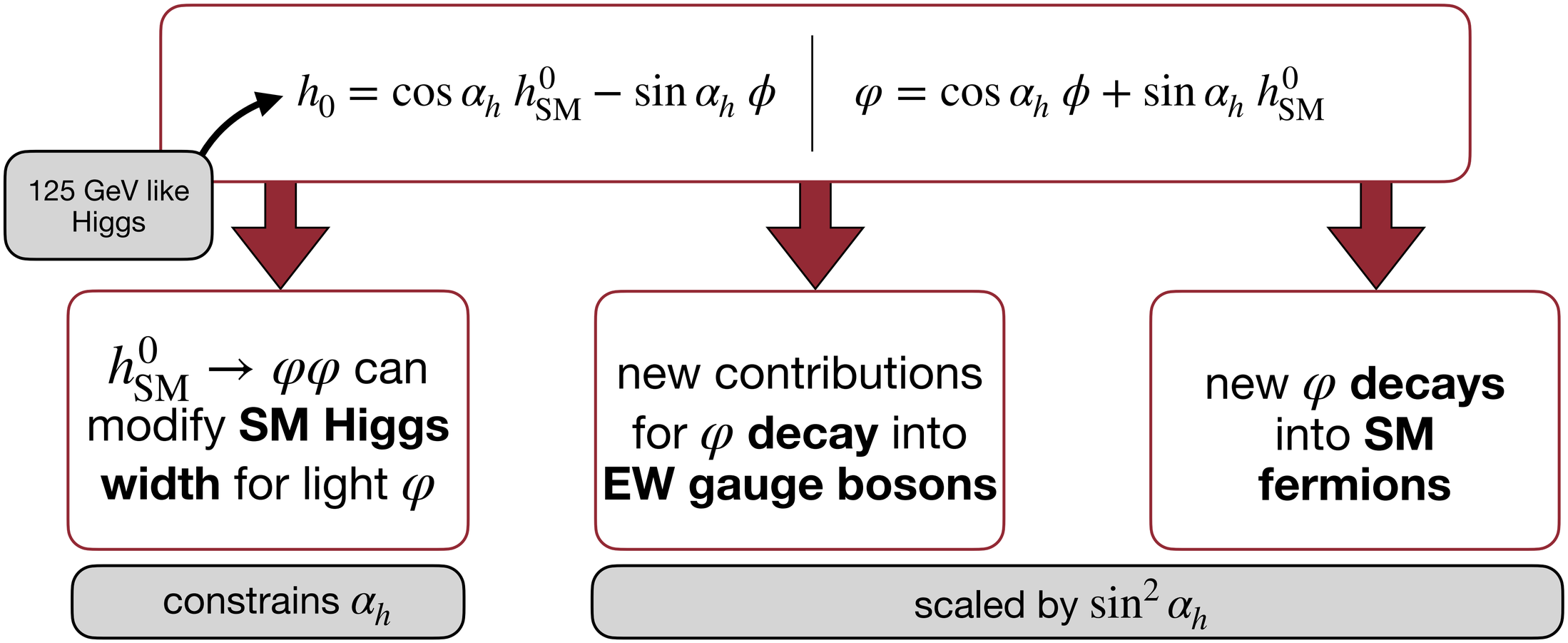
no mixing for $\alpha_h \to 0$

fixed parameters

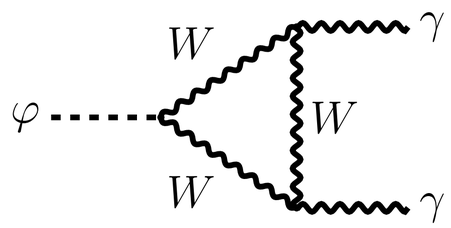
$v_h = 246\,\mathrm{GeV}$

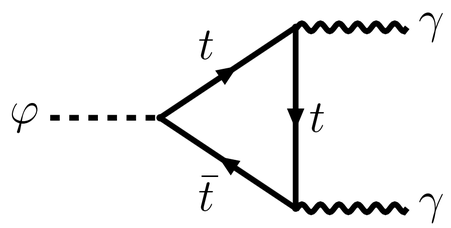
$m_h = 125\,\mathrm{GeV}$

Higgs-Scalar Mass Mixing

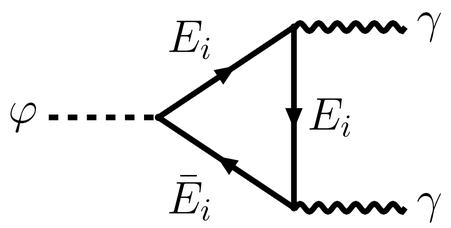


Mixed Scalar Interactions



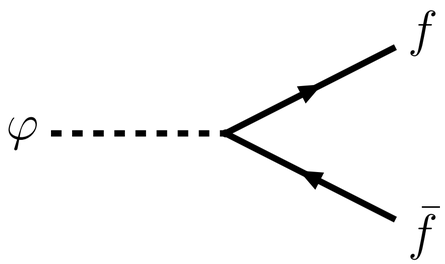


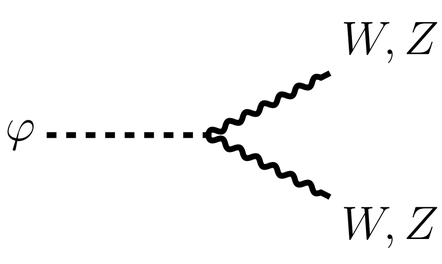
$\propto \sin \alpha_h$



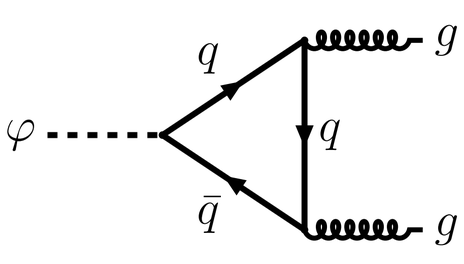
$\propto \cos \alpha_h$

modified **diphoton** decay





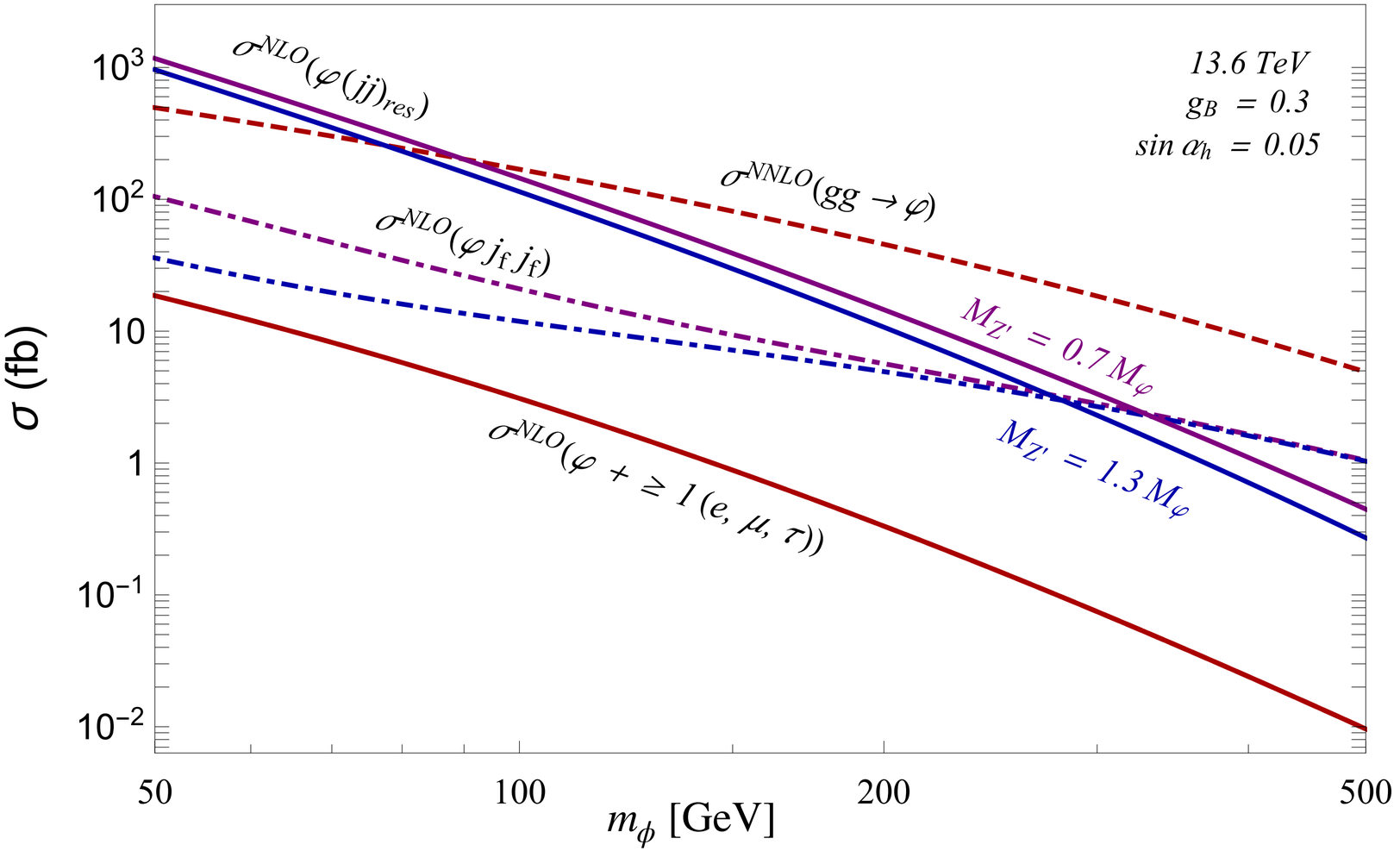
$\propto \sin \alpha_h$



tree level interactions

gluon decay / **gluon fusion**

Mixed Scalar Production at the LHC



Z' fusion $(\varphi\, j_f\, j_f)$

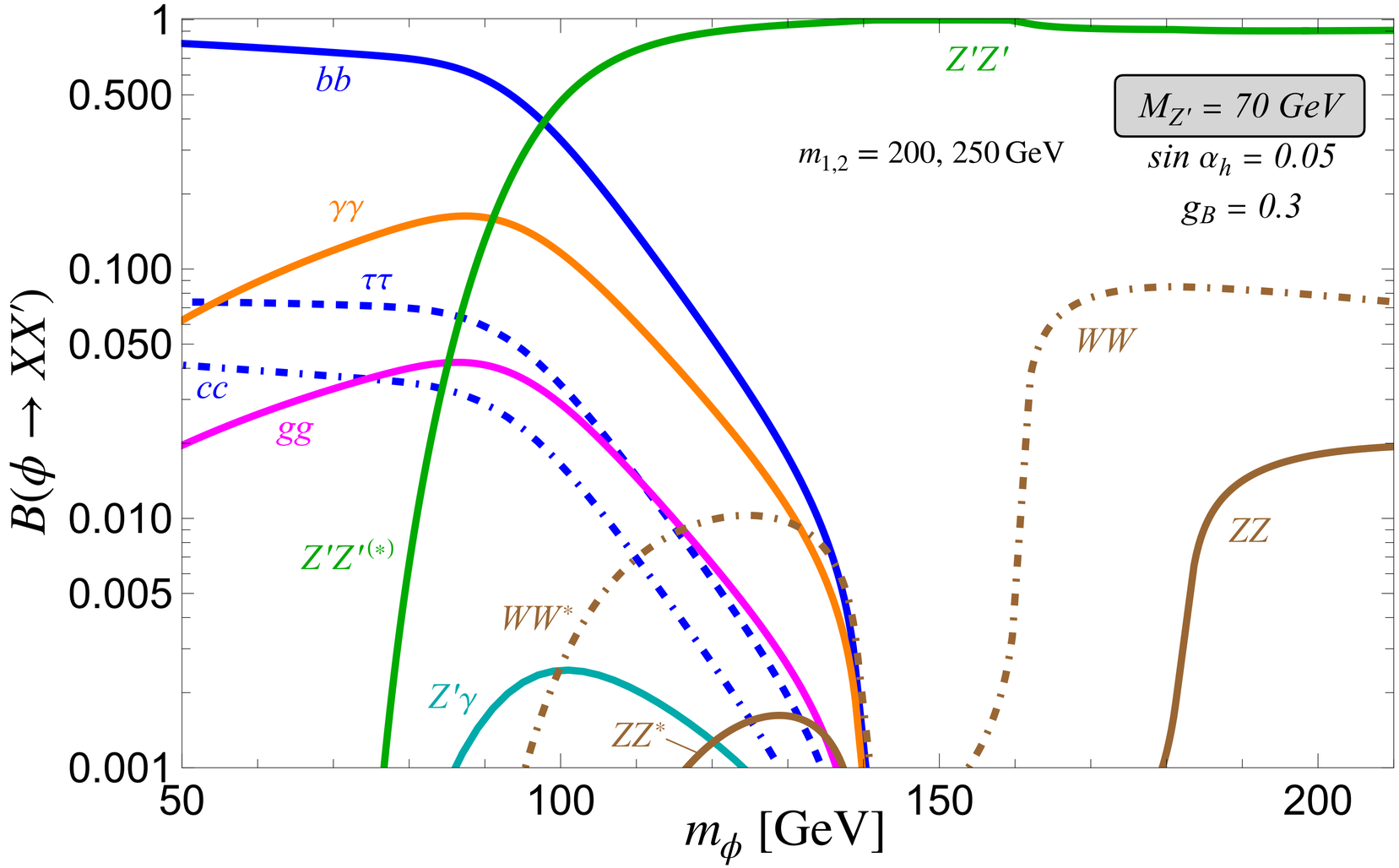
φ strahlung $(Z'\varphi)$

associated Higgs production $(\varphi + \cdots)$

gluon fusion $(gg \to \varphi)$

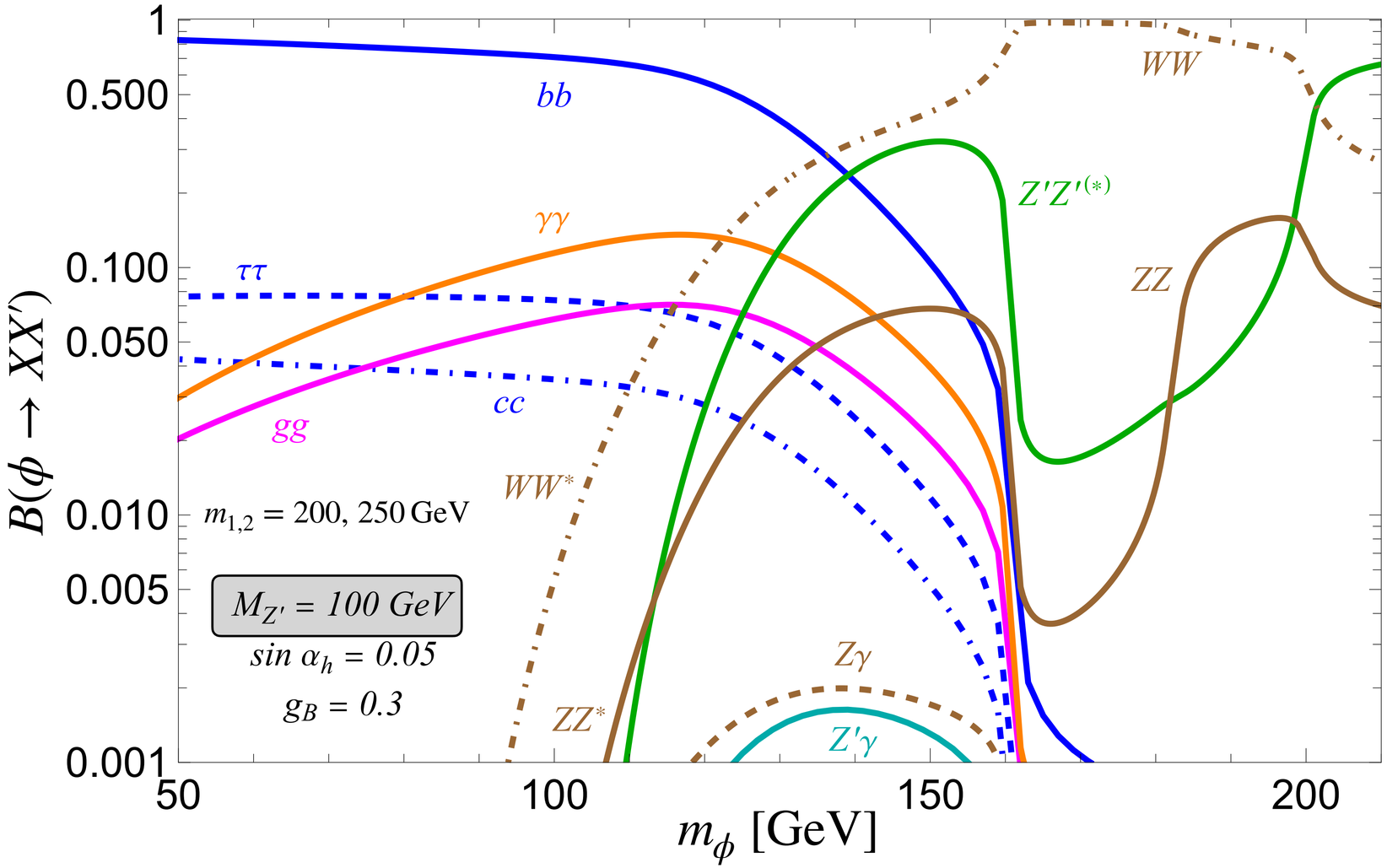
Dobrescu, Yu, LA '25

Mixed Scalar Branching Fractions



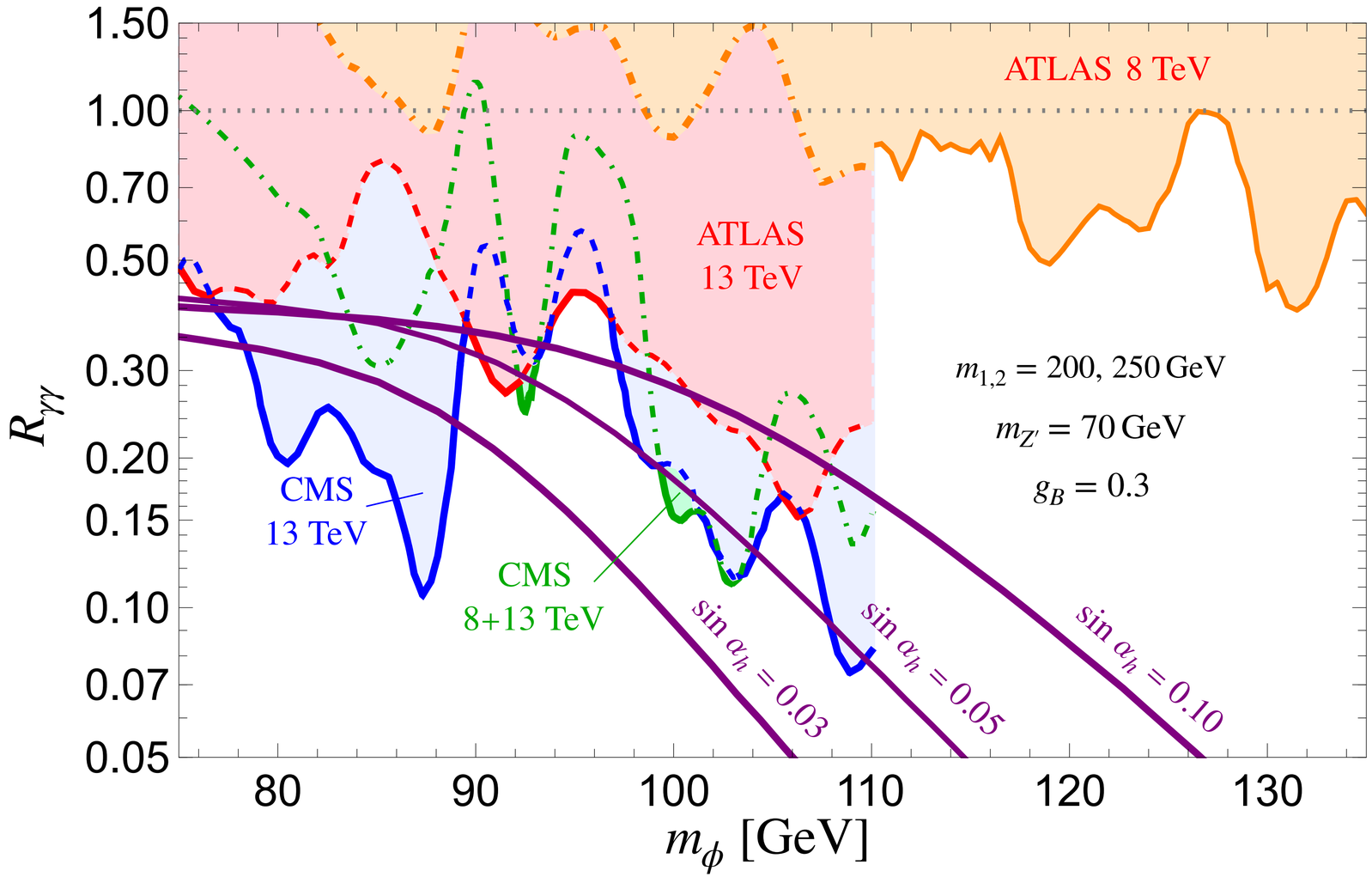
Dobrescu, Yu, LA '25

Mixed Scalar Branching Fractions



Dobrescu, Yu, LA '25

Diphoton Signature at the LHC



Dobrescu, Yu, LA '25

Summary and Outlook

Quark-universal Z' as gauge boson of **gauged** $U(1)_B$

Scalar sector spontaneously breaks $U(1)_B$

Rich **phenomenology** of scalar sector (also for $\sin\alpha_h = 0$)

Simulate collider signals of **diphoton** and **dijet** resonances?

Phenomenology of **anomalon** sector?

Appendix

Charged Anomalon Mass Mixing

$$H = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ h + v_{\mathrm{SM}} \end{pmatrix} \qquad \Phi = (\phi + v')/\sqrt{2}$$

parametrize

$$\mathscr{L} \supset \begin{pmatrix} \bar{e}_L & \bar{E}_L \end{pmatrix} \begin{pmatrix} y_L v' & y_1 v \\ y_2 v & y_E v' \end{pmatrix} \begin{pmatrix} e_R \\ E_R \end{pmatrix} + \mathrm{h.c.}$$

diagonalize

$$\mathscr{L} \supset \begin{pmatrix} \bar{E}_{2L} & \bar{E}_{1L} \end{pmatrix} \begin{pmatrix} m_2 & 0 \\ 0 & m_1 \end{pmatrix} \begin{pmatrix} E_{2R} \\ E_{1R} \end{pmatrix} + \mathrm{h.c.}$$

mass basis | interaction basis

$$\begin{pmatrix} E_{2L} \\ E_{1L} \end{pmatrix} = \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} e_L \\ E_L \end{pmatrix}$$

$$\begin{pmatrix} E_{2R} \\ E_{1R} \end{pmatrix} = \begin{pmatrix} \cos\chi & -\sin\chi \\ \sin\chi & \cos\chi \end{pmatrix} \begin{pmatrix} e_R \\ E_R \end{pmatrix}$$

trade free parameters

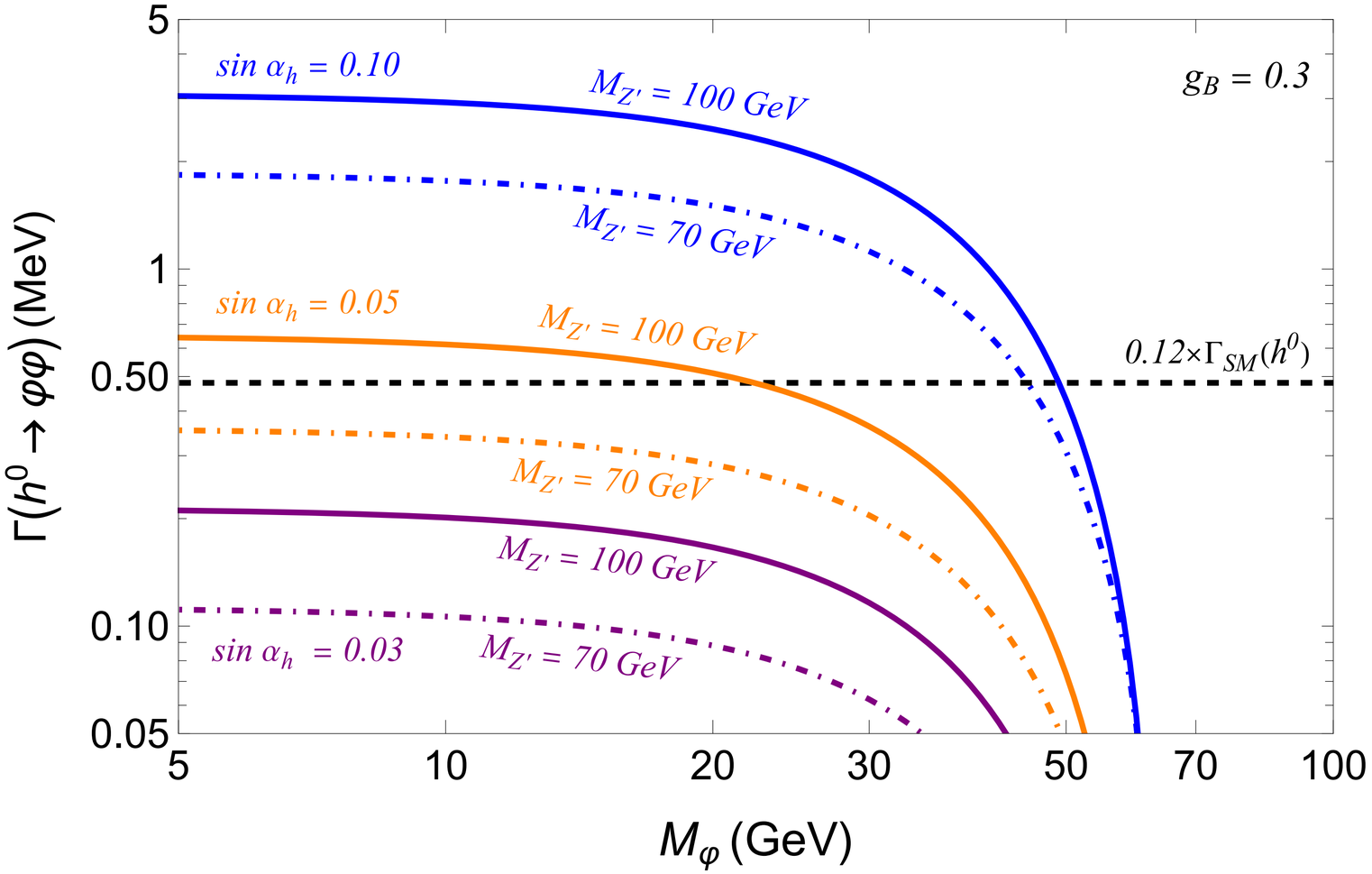
4 couplings

y_L, y_E, y_1, y_2

2 masses + 2 angles

$m_1, m_2 \qquad \theta, \chi$

125 GeV Higgs Decay Width



95 GeV excess