Dark Higgs shines through 750 GeV Dark Higgs Boson at the LHC

Pyungwon Ko (KIAS)

Based on arXiv:1601.02490 (PLB), arXiv:1607.06218 (review)

with Takaaki Nomura

Disclaimer

In this part, “Dark sector” means that it carries dark gauge charges.

Does not mean that it is made of SM singlets.

Properties of the diphoton excess

❖ Diphoton signal → interpret as a resonance: spin-0 or 2

✧ **We consider a scalar boson in this talk**

❖ Cross section

$$\sigma(pp \to S)BR(S \to \gamma\gamma) \approx 3-10 \text{ fb}$$

❖ Width

Best fit value by ATLAS : Γ~45 GeV

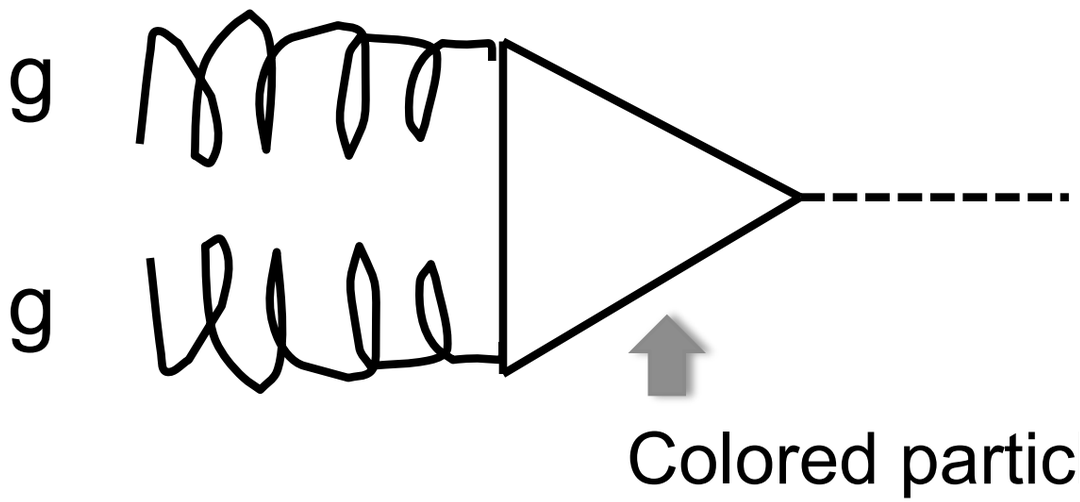
✓ Narrow width is also possible

❖ Absence of 750 GeV resonance with other decay modes

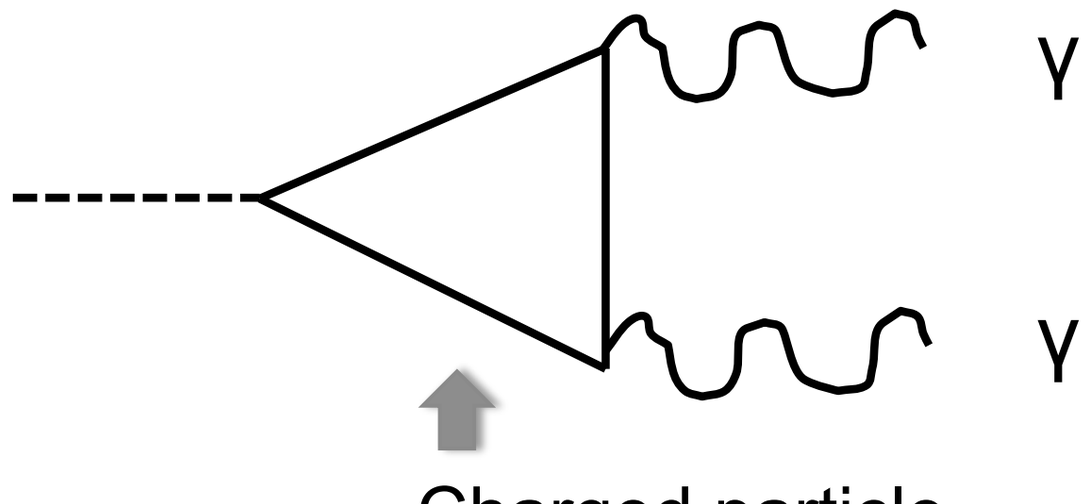
➡ BRs are constrained

One scenario: gluon fusion + diphoton decay via loop

Production: gluon fusion



Diphoton decay channel



It is not easy to get $\sigma(gg\rightarrow\Phi_{New})BR(\Phi_{New}\rightarrow\gamma\gamma)\sim 5$ fb

Ex) Two Higgs doublet Model (Type-II) (Angelescu, Djouadi, Moreau arxiv:1512.0492)

$\sigma(gg\rightarrow H)\sim 850\text{ fb}\times\cot^2\beta$ $\sigma(gg\rightarrow A)\sim 850\text{ fb}\times 2\cot^2\beta$

$BR(H\rightarrow\gamma\gamma)\sim O(10^{-5})$ $BR(A\rightarrow\gamma\gamma)\sim O(10^{-5})$

We need exotic colored and/or charged particles

Let us discuss simple case of (SM) singlet scalar boson + exotic particles

Basic Questions

- Raison d'être of (fundamental?) singlet scalar and vector-like fermions ? Completely singlet particles ???

- Uncomfortable to have a completely singlet

- Two Options : Another new Higgs boson related with

- New spontaneously broken gauge symmetry, or

- Composite (pseudo)scalar boson

- Why vector like fermions have EW scale mass ?

Answers

- New chiral U(1)' symmetry broken by new singlet scalar (Higgs)
- 750 GeV excess ~ U(1)' breaking scalar (could be even dark Higgs)
- Vectorlike fermions : chiral under new U(1)' , anomaly cancellation, and get massive by new Higgs mechanism ~ EW scale mass
- Can we generate phi(750) decay width ~ 45 GeV without any conflict with the known constraints ?
- Yes, if phi(750) mainly decays into new particles
- Many examples : (i) Leptophobic U(1)' with fermions in the fundamental representation of E6, (ii) anther similar 2HDM + singlet model (iii) Dark U(1)' plus dark sector, Dark Higgs decay into a pair of Z'

My own related works

- arXiv:1512.07853, “A Higgcision study on the 750 GeV Di-photon Resonance and 125 GeV SM Higgs boson with the Higgs-Singlet Mixing”, with Kingman Cheung, Jae Sik Lee, Po-Yan Tseng

- arXiv:1601.00586, “Diphoton Excess at 750 GeV in leptophobic U(1)’ model inspired by E6 GUT”, with Yuji Omura, Chaehyun Yu (JHEP, to appear)

- arXiv:1601.02490, “Dark sector shining through 750 GeV dark Higgs boson at the LHC”, with Takaaki Nomura

- arXiv:1602.07214, “Confronting a New Three-loop Seesaw Model with the 750 GeV Diphoton Excess”, with Takaaki Nomura, Hiroshi Okada, Yuta Orikasa

- arXiv:1602.08816, “ADMonium: Asymmetric Dark Matter Bound State”, with Xiao-Jun Bi, Zhaofeng Kang, Jinmian Li, Tianjun Li

- arXiv:1603.08802, “750 GeV diphoton excess as a composite (pseudo)scalar boson from new strong interaction” with Chaehyun Yu and T.C. Yuan, composite models

My own related works

- arXiv:1512.07853, “A Higgcision study on the 750 GeV Di-photon Resonance and 125 GeV SM Higgs boson with the Higgs-Singlet Mixing”, with Kingman Cheung, Jae Sik Lee, Po-Yan Tseng, (and work in progress)

- arXiv:1601.00586, “Diphoton Excess at 750 GeV in leptophobic U(1)’ model inspired by E6 GUT”, with Yuji Omura, Chaehyun Yu

- arXiv:1601.02490, “Dark sector shining through 750 GeV dark Higgs boson at the LHC”, with Takaaki Nomura

- arXiv:1602.07214, “Confronting a New Three-loop Seesaw Model with the 750 GeV Diphoton Excess”, with Takaaki Nomura, Hiroshi Okada, Yuta Orikasa

- arXiv:1602.08816, “ADMonium: Asymmetric Dark Matter Bound State”, with Xiao-Jun Bi, Zhaofeng Kang, Jinmian Li, Tianjun Li

- arXiv:1603.08802, “750 GeV diphoton excess as a composite (pseudo)scalar boson from new strong interaction” with Chaehyun Yu and T.C. Yuan, composite models

SM+$U(1)_X$ + New fermions and scalars with $U(1)_X$ charge

- ❖New fermions are VL under SM but chiral under $U(1)_X$
- ❖Relevant couplings are related to new gauge coupling g_X
- ❖750 GeV scalar can decay into new massive gauge boson (Z')
- ❖DM candidate is contained in a model

- Every f_R in the SM has its dark partner, F_L with the same SM quantum #'s and dark gauge charge

- $\overline{F_L}\, f_R\, X$: gauge invariant, due to a new complex scalar X which can make DM candidate, if $\langle X \rangle = 0$

- Similar to SUSY, but with different spin assignments

Model : Local $U(1)_X$ model with exotic particles

Contents in dark sector (anomaly free) (P.Ko, T.N. arXiv:1601.02490)

	Fermions								Scalar	
	E_L	E_R	N_L	N_R	U_L	U_R	D_L	D_R	Φ	X
SU(3)	**1**	**1**	**1**	**1**	**3**	**3**	**3**	**3**	**1**	**1**
SU(2)	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**
$U(1)_Y$	-1	-1	0	0	$\frac{2}{3}$	$\frac{2}{3}$	$\frac{-1}{3}$	$\frac{-1}{3}$	0	0
$U(1)_X$	a	$-b$	$-a$	b	$-a$	b	a	$-b$	$a+b$	a

(3 generations of fermions)

New Lagrangian **X,N : DM candidate**

$$L^Y = y^E \bar{E}_L E_R \Phi + y^N \bar{N}_L N_R \Phi^* + y^U \bar{U}_L U_R \Phi^* + y^D \bar{D}_L D_R \Phi$$

$$+ y^{Ee} \bar{E}_L e_R X + y^{Uu} \bar{U}_L u_R X^* + y^{Dd} \bar{D}_L d_R X + h.c.$$

$$V = \mu^2 |H|^2 + \lambda |H|^4 + \mu_\Phi^2 |\Phi|^2 + \mu_X^2 |X|^2$$

$$+ \lambda_\Phi |\Phi|^4 + \lambda_X |X|^4 + \lambda_{H\Phi} |H|^2 |\Phi|^2 + \lambda_{HX} |H|^2 |X|^2 + \lambda_{X\Phi} |X|^2 |\Phi|^2$$

Model : local $U(1)_X$ model with exotic particles

(P.Ko, T.N. arXiv:1601.02490)

Contents in dark sector (anomaly free)

	Fermions								Scalar	
	E_L	E_R	N_L	N_R	U_L	U_R	D_L	D_R	Φ	X
SU(3)	**1**	**1**	**1**	**1**	**3**	**3**	**3**	**3**	**1**	**1**
SU(2)	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**
$U(1)_Y$	-1	-1	0	0	$\frac{2}{3}$	$\frac{2}{3}$	$\frac{-1}{3}$	$\frac{-1}{3}$	0	0
$U(1)_X$	a	$-b$	$-a$	b	$-a$	b	a	$-b$	$a+b$	a

(3 generations of fermions)

New Lagrangian

X,N : DM candidate

$$L^Y = y^E \bar{E}_L E_R \Phi + y^N \bar{N}_L N_R \Phi^* + y^U \bar{U}_L U_R \Phi^* + y^D \bar{D}_L D_R \Phi$$

Giving mass for new fermions + gg fusion and γγ decay of Φ

$$+ y^{Ee} \bar{E}_L e_R X + y^{Uu} \bar{U}_L u_R X^* + y^{Dd} \bar{D}_L d_R X + h.c.$$

$$V = \mu^2 |H|^2 + \lambda |H|^4 + \mu_\Phi^2 |\Phi|^2 + \mu_X^2 |X|^2$$

$$+ \lambda_\Phi |\Phi|^4 + \lambda_X |X|^4 + \lambda_{H\Phi} |H|^2 |\Phi|^2 + \lambda_{HX} |H|^2 |X|^2 + \lambda_{X\Phi} |X|^2 |\Phi|^2$$

Model : local $U(1)_X$ model with exotic particles

Contents in dark sector（anomaly free） (P.Ko, T.N. arXiv:1601.02490)

	Fermions								Scalar	
	E_L	E_R	N_L	N_R	U_L	U_R	D_L	D_R	Φ	X
SU(3)	**1**	**1**	**1**	**1**	**3**	**3**	**3**	**3**	**1**	**1**
SU(2)	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**
$U(1)_Y$	-1	-1	0	0	$\frac{2}{3}$	$\frac{2}{3}$	$\frac{-1}{3}$	$\frac{-1}{3}$	0	0
$U(1)_X$	a	$-b$	$-a$	b	$-a$	b	a	$-b$	$a+b$	a

(3 generations of fermions)

New Lagrangian **X,N : DM candidate**

$$L^Y = y^E \bar{E}_L E_R \Phi + y^N \bar{N}_L N_R \Phi^* + y^U \bar{U}_L U_R \Phi^* + y^D \bar{D}_L D_R \Phi$$

Giving mass for new fermions + gg fusion and γγ decay of Φ

$$+ y^{Ee} \bar{E}_L e_R X + y^{Uu} \bar{U}_L u_R X^* + y^{Dd} \bar{D}_L d_R X + h.c.$$

Decay of new fermions F

$F \to X f_{SM}$

$$V = \mu^2 |H|^2 + \lambda |H|^4 + \mu_\Phi^2 |\Phi|^2 + \mu_X^2 |X|^2$$

$$+ \lambda_\Phi |\Phi|^4 + \lambda_X |X|^4 + \lambda_{H\Phi} |H|^2 |\Phi|^2 + \lambda_{HX} |H|^2 |X|^2 + \lambda_{X\Phi} |X|^2 |\Phi|^2$$

DM Stability/Longevity

- Accidental Z_2 symmetry after $U(1)_X$ symmetry breaking
- (F_L, F_R, X): Z_2-odd, whereas the rest fields are Z_2-even
- Have to be careful about operators that break this Z_2 symmetry, making X decay at (non)renormalizable level
- $X^\dagger \Phi^n$: gauge invariant operator that has to be forbidden
- a/(a+b)=n for gauge invariance : suitable choice of a, b can make a/(a+b) non-integer (absolutely stable), or make n very large (long-lived X). We choose a~b~1 for simplicity

Gauge Symmetry breaking and Z'

❖ VEVs of scalar fields

$$\langle H \rangle = \frac{1}{\sqrt{2}} v, \quad \langle \Phi \rangle = \frac{1}{\sqrt{2}} v_\phi$$

$$v \approx \sqrt{\frac{-\mu^2}{\lambda}}, \quad v_\phi \approx \sqrt{\frac{-\mu_\Phi^2}{\lambda_\Phi}} \qquad (\lambda_{H\Phi} << 1)$$

$$\Phi = (v_\phi + \phi + iG_X)/\sqrt{2}$$

$U(1)_X$ is broken by <Φ>

➡ Massive Z'

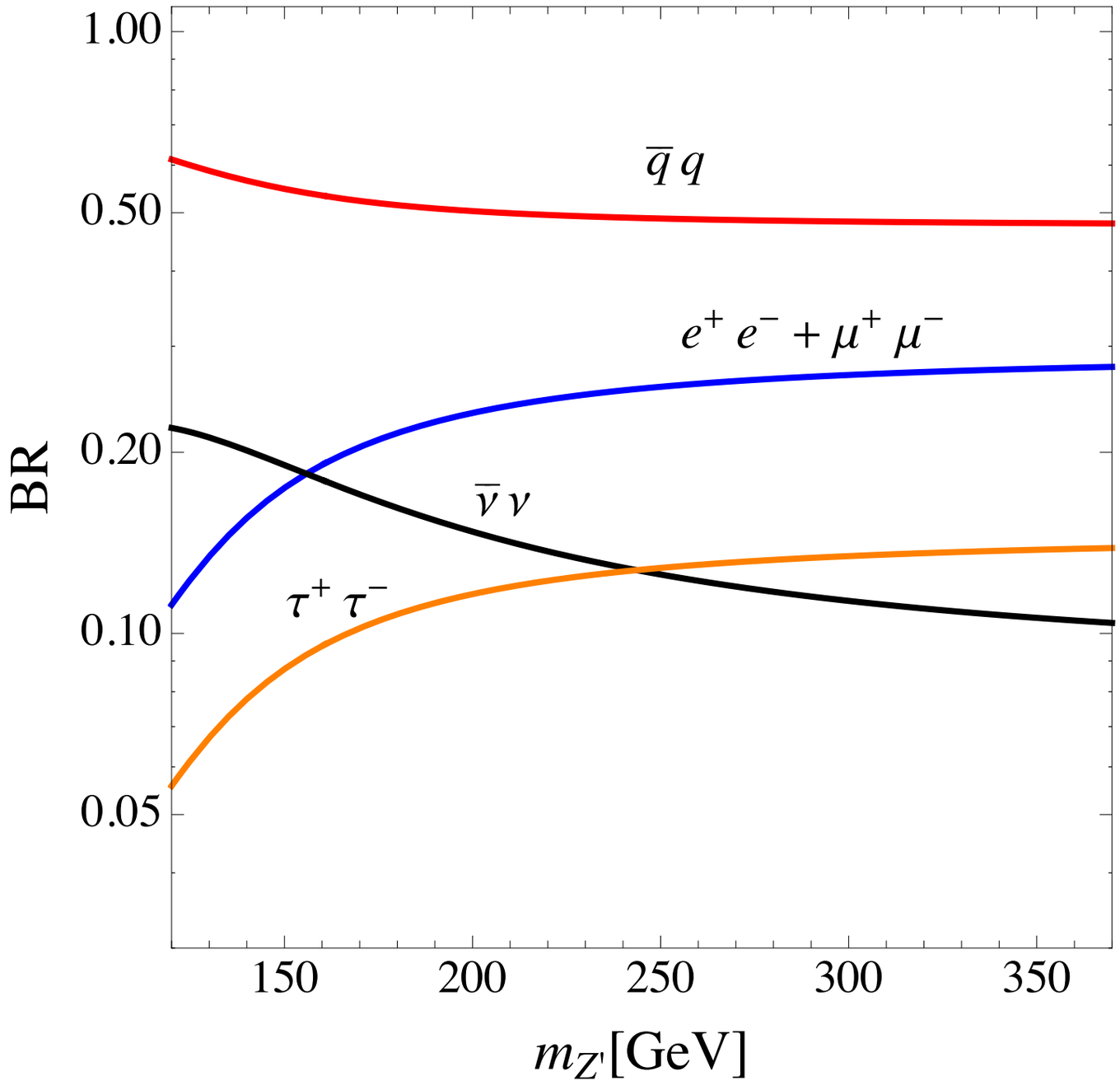
We assume H-Φ mixing is negligible

❖ Masses of Z' and new fermions

$$m_{Z'}^2 \approx (a+b)^2 g_X^2 v_\phi^2, \quad m_F = \frac{y^F}{\sqrt{2}} v_\phi \quad \Rightarrow \quad \begin{cases} y^F = \dfrac{\sqrt{2}(a+b) g_X m_F}{m_{Z'}} \\ \lambda_\Phi = \dfrac{2 m_\phi^2 g_X^2}{m_{Z'}^2} \end{cases}$$

❖ Z' decays through small Z-Z' mixing

BRs of Z'


1.00
0.50
0.20
0.10
0.05
BR
$\overline{q}\,q$
$e^+\,e^- + \mu^+\,\mu^-$
$\overline{\nu}\,\nu$
$\tau^+\,\tau^-$
150
200
250
300
350
$m_{Z'}$[GeV]

Gluon fusion and decay modes of φ

Gluon fusion and diphoton decay of φ via new fermion loop

$gg \rightarrow \varphi$ $$L_{\phi gg} = \frac{\alpha_s}{8\pi}\left(\sum_{F=U,D}\frac{(a+b)\sqrt{2}g_X}{m_{Z'}}A_{1/2}(\tau_F)\right)\phi G^{a\mu\nu}G^a_{\mu\nu}$$

Decay widths

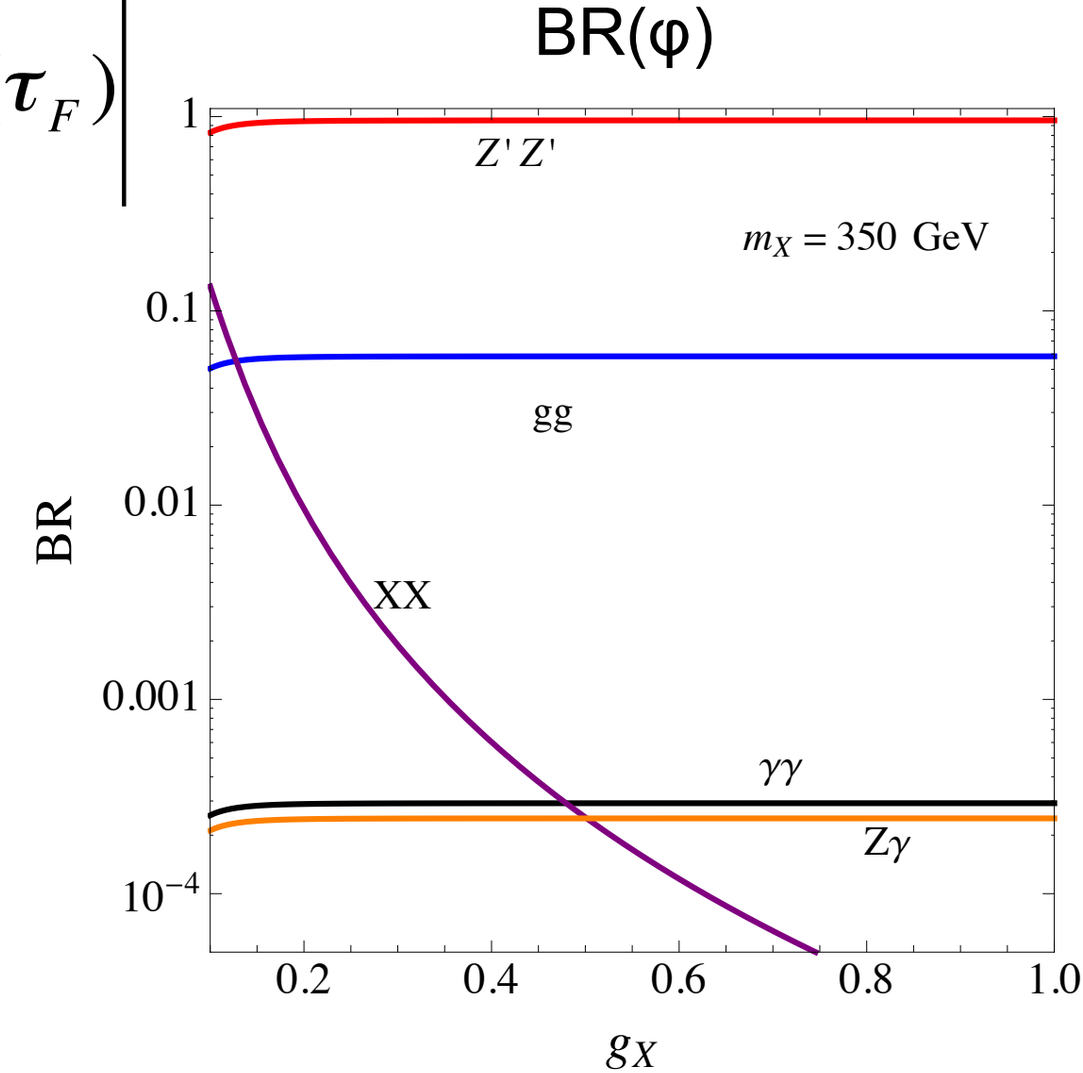
$$\Gamma(\phi\rightarrow\gamma\gamma)=\frac{\alpha^2 m_\phi^3}{256\pi^3}\left|\sum_F N_c^F\frac{(a+b)g_X Q_F^2}{m_{Z'}}A_{1/2}(\tau_F)\right|^2$$

$$\Gamma(\phi\rightarrow Z'Z')=\frac{(a+b)^2 g_X^2 m_\phi^3}{32\pi m_\phi}\sqrt{1-\frac{4m_{Z'}^2}{m_\phi^2}}\times\frac{m_\phi^4-4m_\phi^2 m_{Z'}^2+12m_{Z'}^4}{m_{Z'}^4}$$

▪

▪

▪



Gluon fusion and decay modes of φ

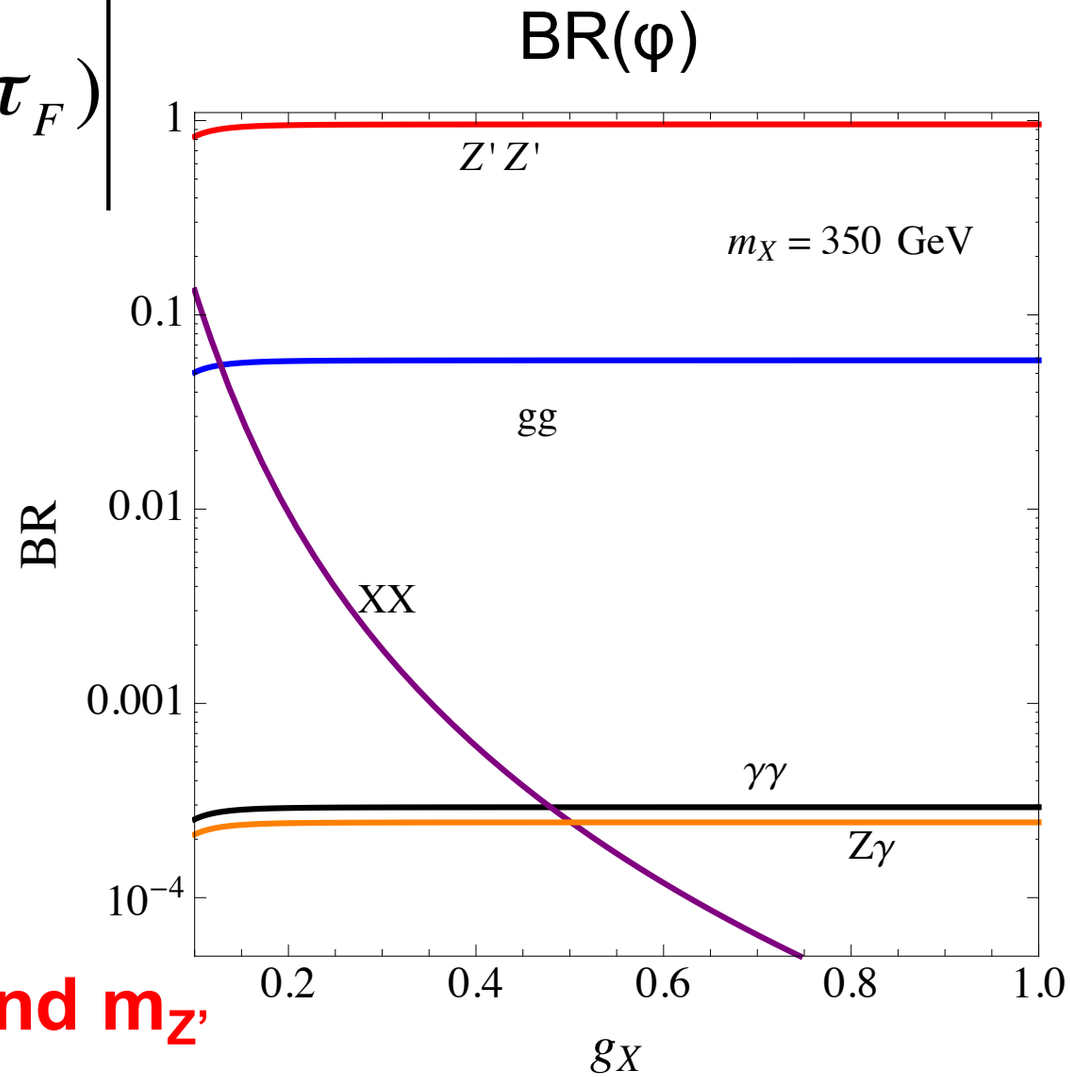
Gluon fusion and diphoton decay of φ via new fermion loop

$gg \rightarrow \varphi$ $$L_{\phi gg} = \frac{\alpha_s}{8\pi}\left(\sum_{F=U,D}\frac{(a+b)\sqrt{2}g_X}{m_{Z'}}A_{1/2}(\tau_F)\right)\phi G^{a\mu\nu}G^a_{\mu\nu}$$

Decay widths

$$\Gamma(\phi\rightarrow\gamma\gamma) = \frac{\alpha^2 m_\phi^3}{256\pi^3}\left|\sum_F N_c^F\frac{(a+b)g_X Q_F^2}{m_{Z'}}A_{1/2}(\tau_F)\right|^2$$

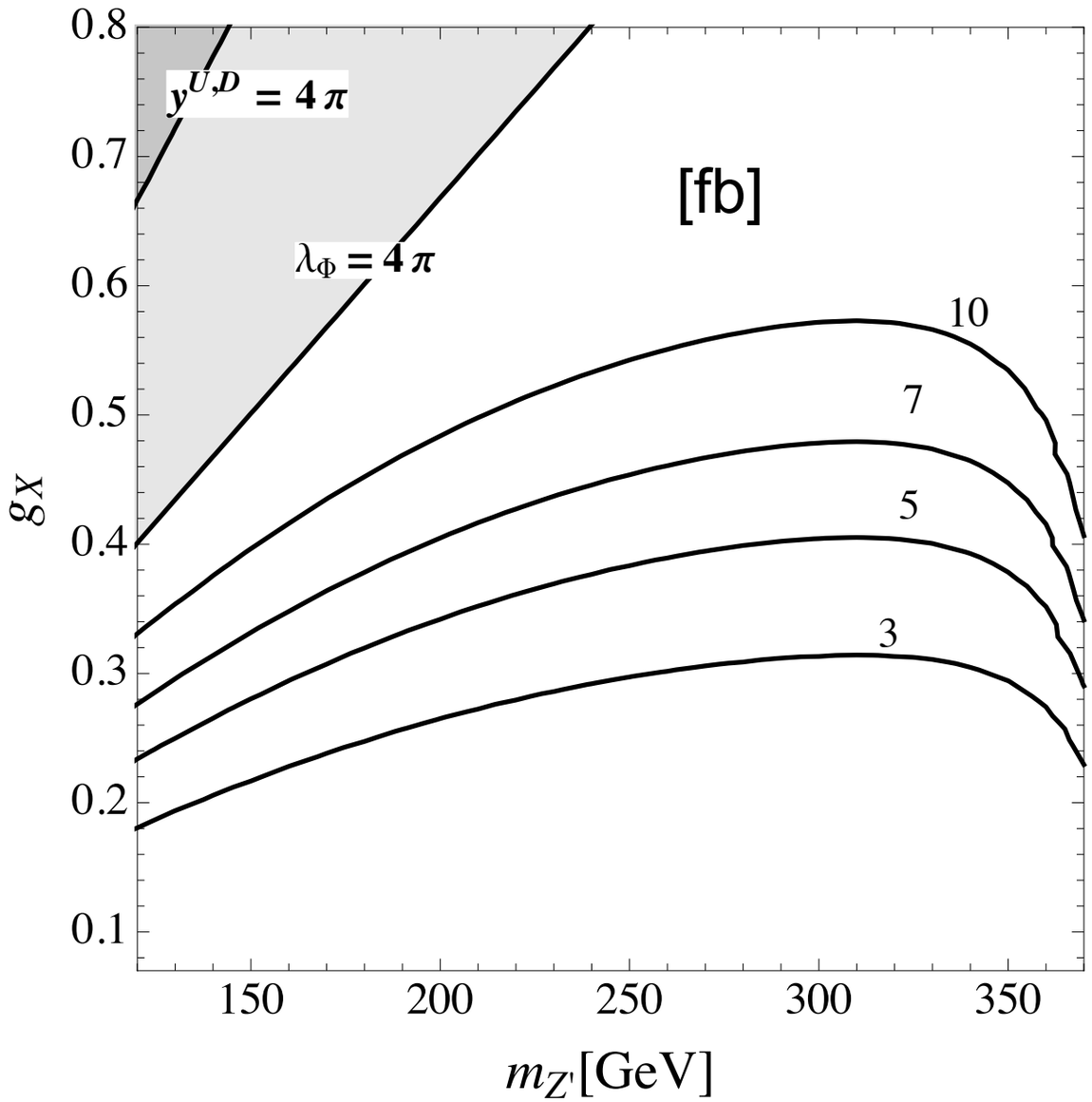
$$\Gamma(\phi\rightarrow Z'Z') = \frac{(a+b)^2 g_X^2 m_\phi^3}{32\pi m_\phi}\sqrt{1-\frac{4m_{Z'}^2}{m_\phi^2}} \times\frac{m_\phi^4-4m_\phi^2 m_{Z'}^2+12m_{Z'}^4}{m_{Z'}^4}$$



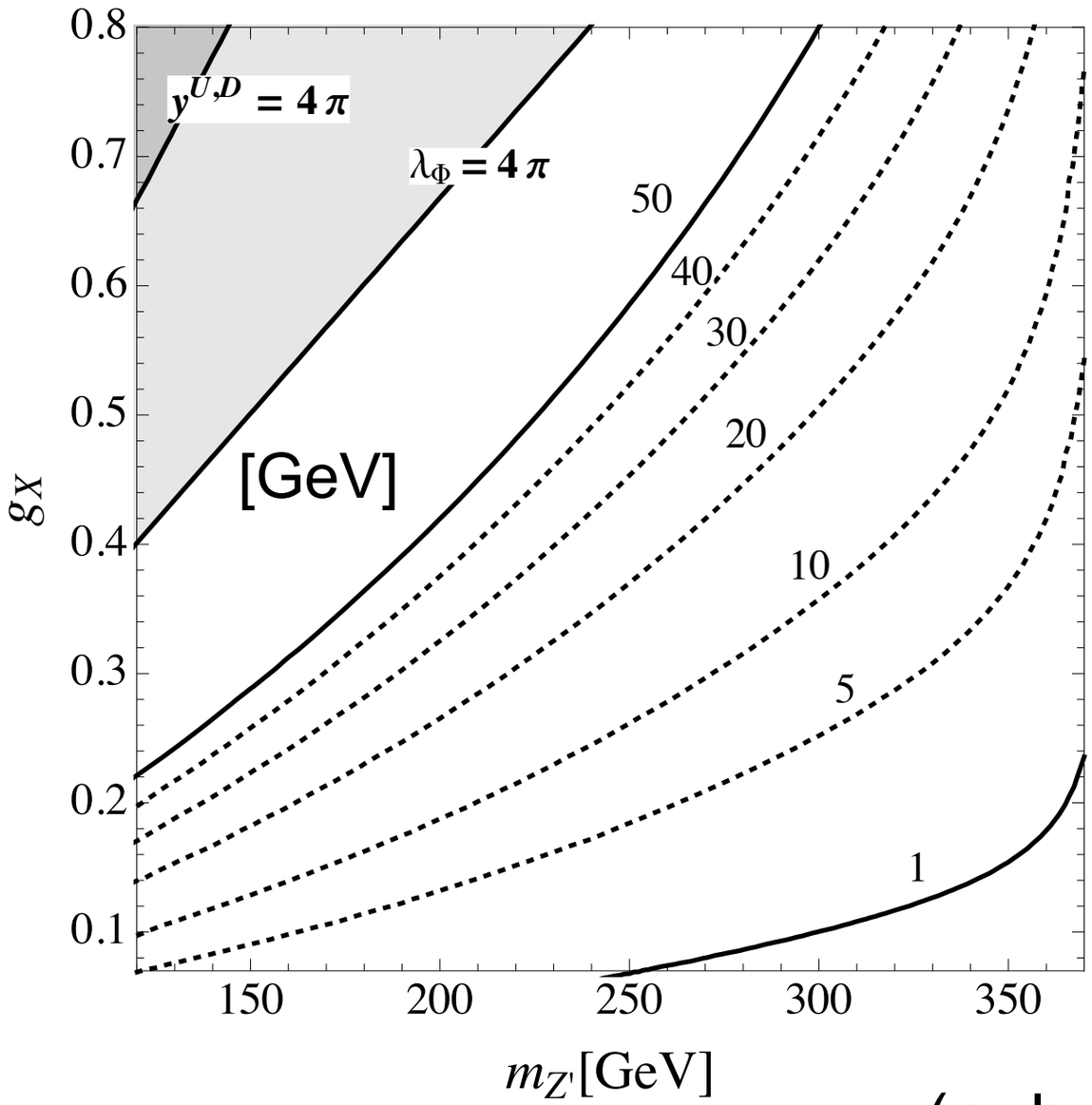
BRs and gluon fusion are function of g_X and $m_{Z'}$

Cross section and widht of φ

$\sigma(gg \to \phi)BR(\phi \to \gamma\gamma)$



Γ_ϕ

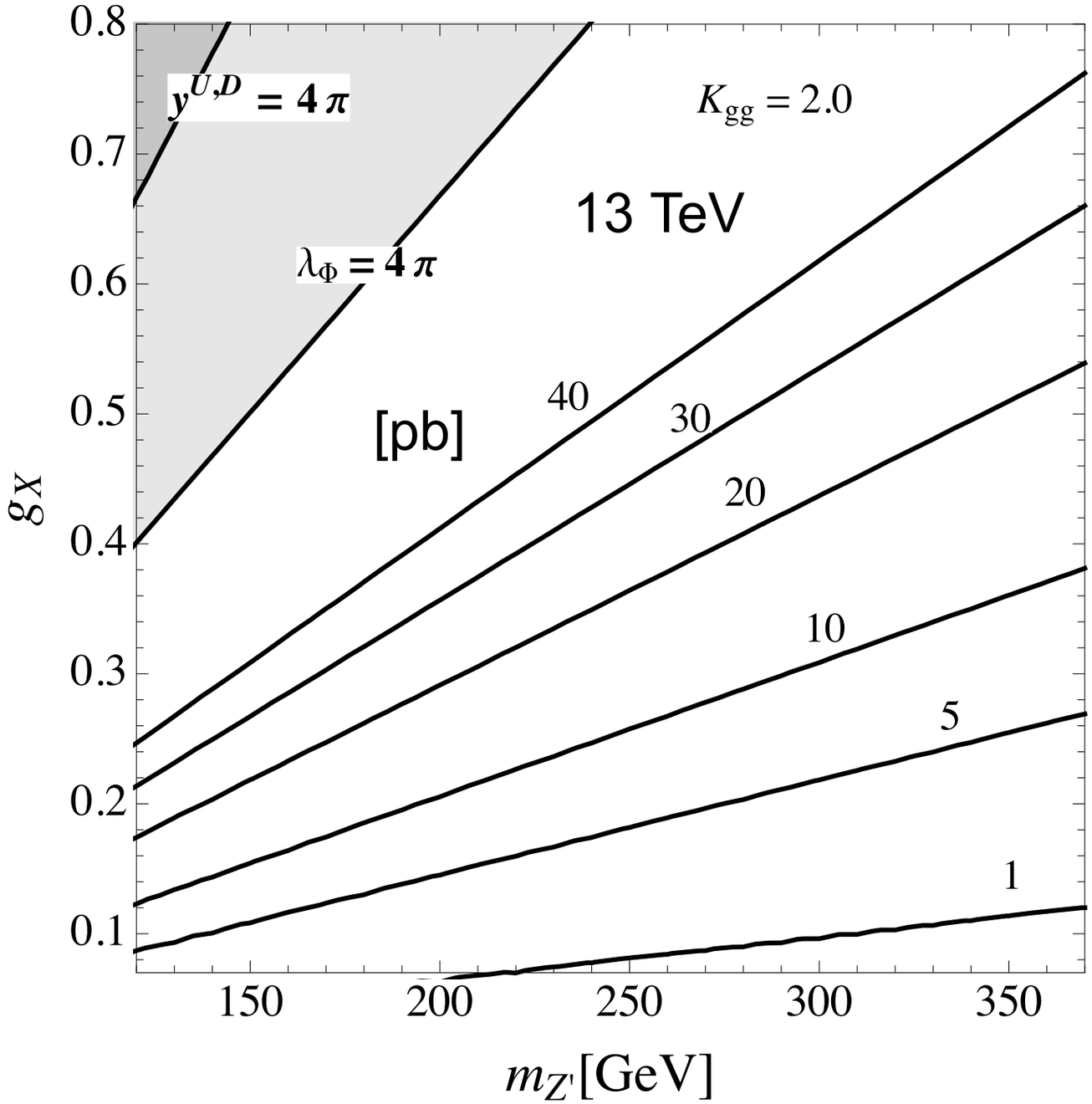


(a~b~1)

$\{M_{U,D}, M_{E,N}, M_X, \lambda_{X\Phi}\} = \{800\ \text{GeV}, 400\ \text{GeV}, 350\ \text{GeV}, 0.075\}$

- **~5 fb cross section with g_X=0.3~0.5 and $m_{Z'}$=120~360 GeV**
- **Decay width is relatively large: O(10~50) GeV**

Discussion: Cross section of φ production



- Large cross section of O(10) pb
- ~1/5 for 8 TeV case
- No direct constraints for

  $pp \to \varphi \to Z'Z' \to 4f_{SM}$
- Z' width is very narrow

  $\Gamma/M < 10^{-6}$ due to small Z-Z' mixing

$\{M_{U,D}, M_{E,N}, M_X, \lambda_{X\Phi}\} = \{800\ \text{GeV}, 400\ \text{GeV}, 350\ \text{GeV}, 0.075\}$

(a~b~1)

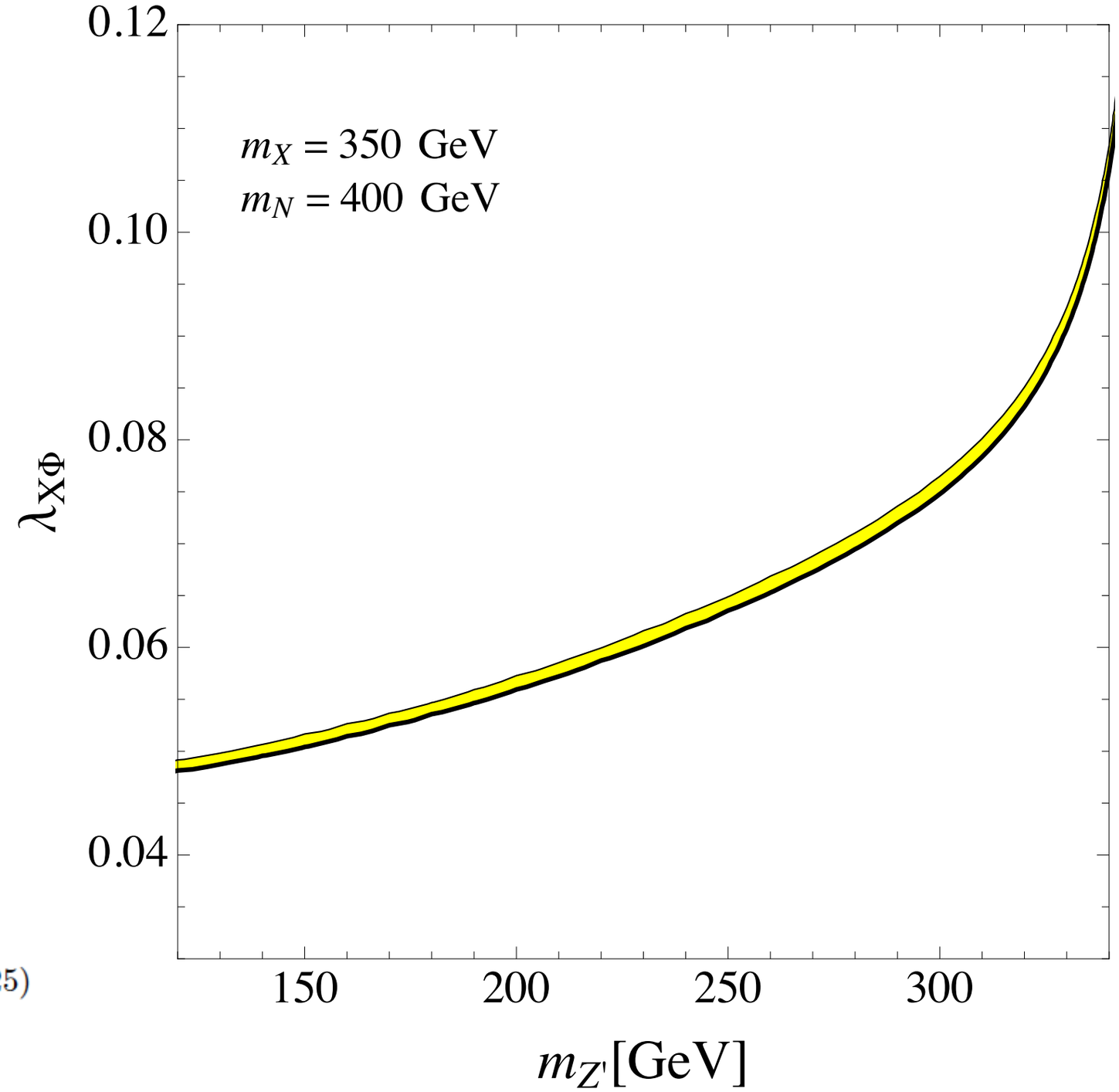
DM Relic Density

Annihilation process

$$XX \rightarrow Z'Z'$$
$$NN \rightarrow Z'Z'$$

$$\langle \sigma v \rangle_{XX^*} \simeq \frac{\lambda_{X\Phi}^2}{32\pi m_X^2} \frac{m_{Z'}^4}{(4m_X^2 - m_s^2)^2} \times \frac{4m_X^4 - 4m_X^2 m_{Z'}^2 + 3m_{Z'}^4}{m_{Z'}^4} \sqrt{1 - \frac{m_{Z'}^2}{m_X^2}} \quad (25)$$

$$\langle \sigma v \rangle_{N\bar{N}} \simeq \frac{g_X^4}{2\pi m_N^2} \frac{m_N^4}{(m_N^2 - m_s^2)^2} \frac{4m_N^4 - 4m_N^2 m_{Z'}^2 + 3m_{Z'}^4}{m_{Z'}^4} \sqrt{1 - \frac{m_{Z'}^2}{m_N^2}} \quad (26)$$



N is subdominant in our analysis

Digress on muon (g-2)

- For mX = 350 GeV and mEi = 400 GeV, we can account for the deficit in the $a_\mu = 8 \times 10^{-10}$, if $y^{Ei}_\mu \sim 2 - 3$

- However, in this case, the annihilation cross section for X is too large, and X cannot be the main component of the DM in the present universe

- So we don't pursue this possibility any further

Summary within this new DM model

- A new viable model for DM with rich dark sector & Interesting in its own, even if 750 GeV excess disappears

- 750 GeV excess = dark Higgs

- Can accommodate a large width with decay into Z'Z'

- Rich collider phenomenology, since dark fermions are charged under the SM gauge charges

- No strong constraints from DM (in)direct detection expt's, and rich Indirect signatures and $SU(2)_L$ charged case under study (arXiv:1607.06218)