Extensions of the SM with new chiral gauge sym's

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Multi-Higgs Workshop, Lisbon
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What if the 750 GeV diphoton excess is were confirmed ?

Also talk by A. Djouadi

Contents

- Prelude
- Why multi Higgs (scalar) models ?
- 750 GeV Diphoton excess at the LHC (talk by Djouadi)
- Model I : E_6 motivated leptophobic U(1)' model
- Model II : Dark Higgs interpretation of diphoton excess
- Model III : A Simple Composite Model
- Closing remarks

So Far, Only Higgs (~SM) and Nothing Else at the LHC & Local Gauge Principle Works !

Building Blocks of SM

- Lorentz/Poincare Symmetry
- Local Gauge Symmetry : Gauge Group + Matter Representations from Experiments
- Higgs mechanism for masses of weak gauge bosons and SM chiral fermions
- These principles lead to unsurpassed success of the SM in particle physics

Lessons from SM

- Specify local gauge sym, matter contents and their representations under local gauge group
- Write down all the operators upto dim-4 (Totalitarian principle)
- Check anomaly cancellation
- Consider accidental global symmetries
- Look for nonrenormalizable operators that break/conserve the accidental symmetries of the model

- If there are spin-1 particles, extra care should be paid : need an agency which provides mass to the spin-1 object
- Check if you can write Yukawa couplings to the observed fermion
- One may have to introduce additional Higgs doublets with new gauge interaction if you consider new chiral gauge symmetry (Ko, Omura, Yu on chiral U(1)' model for top FB asymmetry)
- Impose various constraints and study phenomenology

(3,2,1) or SU(3)cXU(1)em ?

- Well below the EW sym breaking scale, it may be fine to impose SU(3)c X U(1)em
- At EW scale, better to impose (3,2,1) which gives better description in general after all
- Majorana neutrino mass is a good example
- For example, in the Higgs + dilaton (radion) system, and you get different results
- Singlet mixing with SM Higgs

Why Multi Higgs (scalar) models ?

Phenomenological Reasons

- Why not ? (Against Occam's Razor Principle ?)
- We know there is one Higgs doublet, and should check if there are more (with different (T,Y) quantum #'s)
- New scalars appear in many models for Inflation, Radiative neutrino masses, EWBGEN, etc..
- Should be tested by experiments

Theoretical reasons

- Origin of mass

  - chiral symmetry for fermions

  - gauge symmetries for vector bosons

  - scale symmetry for scalars

- New Gauge symmetry (vectorlike or chiral for the SM fermions)

New Gauge Symmetries

- Vectorlike : At least one more singlet scalar to break it

  - B-L , U(1) B, U(1) L (extra fermions for anomaly cancel)

  - Dark gauge symmetry (Dark Higgs + Dark gauge boson)
  <u>Huge impacts on DM phenomenology and cosmology</u>

  talk by Jinsu Kim this afternoon about Higgs portal assisted Higgs inflation

- Chiral : At least one more SU(2) doublet Higgs with new gauge interactions (and extra fermions for animal cancel)

  - Chiral U(1) for up-type RH quarks (for top FBA)

  - 2HDM with local U(1) Higgs gauge symmetry

Origin of mass

- Higgs discovery : Origin of the SM particles come from Higgs VEV and strong interaction (confinement)
- Still the origin of Higgs VEV unknown….
- Neutrino mass : seesaw (tree level or radiative) ?
- Neutrino mass from strong dynamics ?
- DM mass from strong dynamics ?
- Let me present one model of such a kind

EWSB and CDM from Strongly Interacting Hidden Sector

All the masses (including ν's and CDM masses) from hidden sector strong dynamics, and CDM long lived by accidental sym

Hur, Jung, Ko, Lee : 0709.1218, PLB (2011)
Hur, Ko : arXiv:1103.2517,PRL (2011)
Proceedings for workshops/conferences during 2007-2011 (DSU,ICFP,ICHEP etc.)

Nicety of QCD

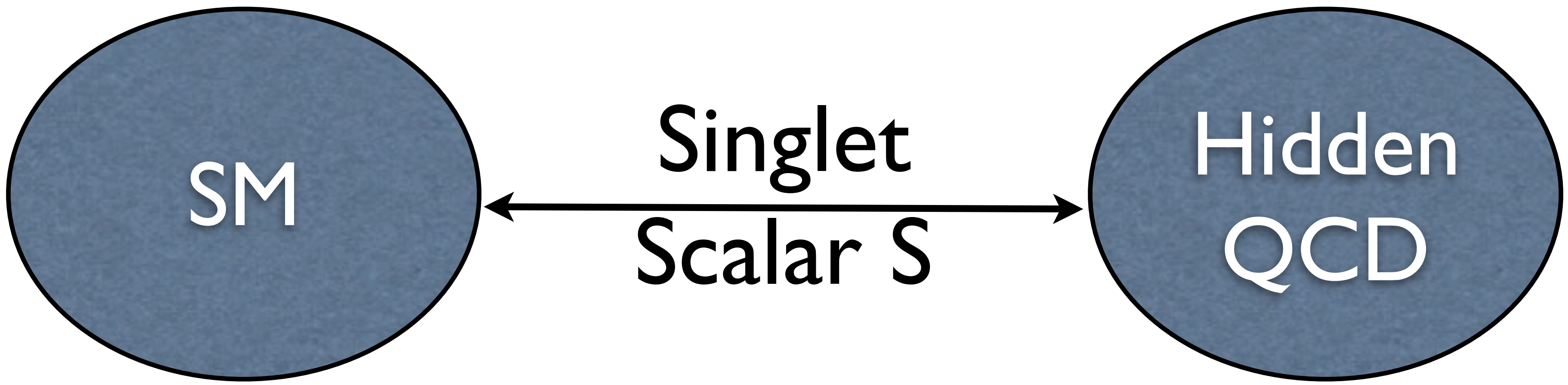
- Renormalizable
- Asymptotic freedom : no Landau pole
- QM dim transmutation :
- Light hadron masses from QM dynamics
- Flavor & Baryon # conservations : accidental symmetries of QCD (pion is stable if we switch off EW interaction; proton is stable or very long lived)

h-pion & h-baryon DMs

- In most WIMP DM models, DM is stable due to some ad hoc Z_2 symmetry
- If the hidden sector gauge symmetry is confining like ordinary QCD, the lightest mesons and the baryons could be stable or long-lived >> Good CDM candidates
- If chiral sym breaking in the hidden sector, light h-pions can be described by chiral Lagrangian in the low energy limit

Model I (Scalar Messenger)

Hur, Ko, PRL (2011)



- SM - Messenger - Hidden Sector QCD
- Assume classically scale invariant lagrangian --> No mass scale in the beginning
- Chiral Symmetry Breaking in the hQCD generates a mass scale, which is injected to the SM by “S”

Scale invariant extension of the SM with strongly interacting hidden sector

Modified SM with classical scale symmetry

$$
\begin{aligned}
\mathcal{L}_{\rm SM} &= \mathcal{L}_{\rm kin} - \frac{\lambda_H}{4}\,(H^\dagger H)^2 - \frac{\lambda_{SH}}{2}\,S^2\,H^\dagger H - \frac{\lambda_S}{4}\,S^4 \\
&+ \Big(\overline{Q}^i H Y_{ij}^D D^j + \overline{Q}^i \tilde{H} Y_{ij}^U U^j + \overline{L}^i H Y_{ij}^E E^j \\
&+ \overline{L}^i \tilde{H} Y_{ij}^N N^j + S N^{iT} C Y_{ij}^M N^j + h.c.\Big)
\end{aligned}
$$

Hidden sector lagrangian with new strong interaction

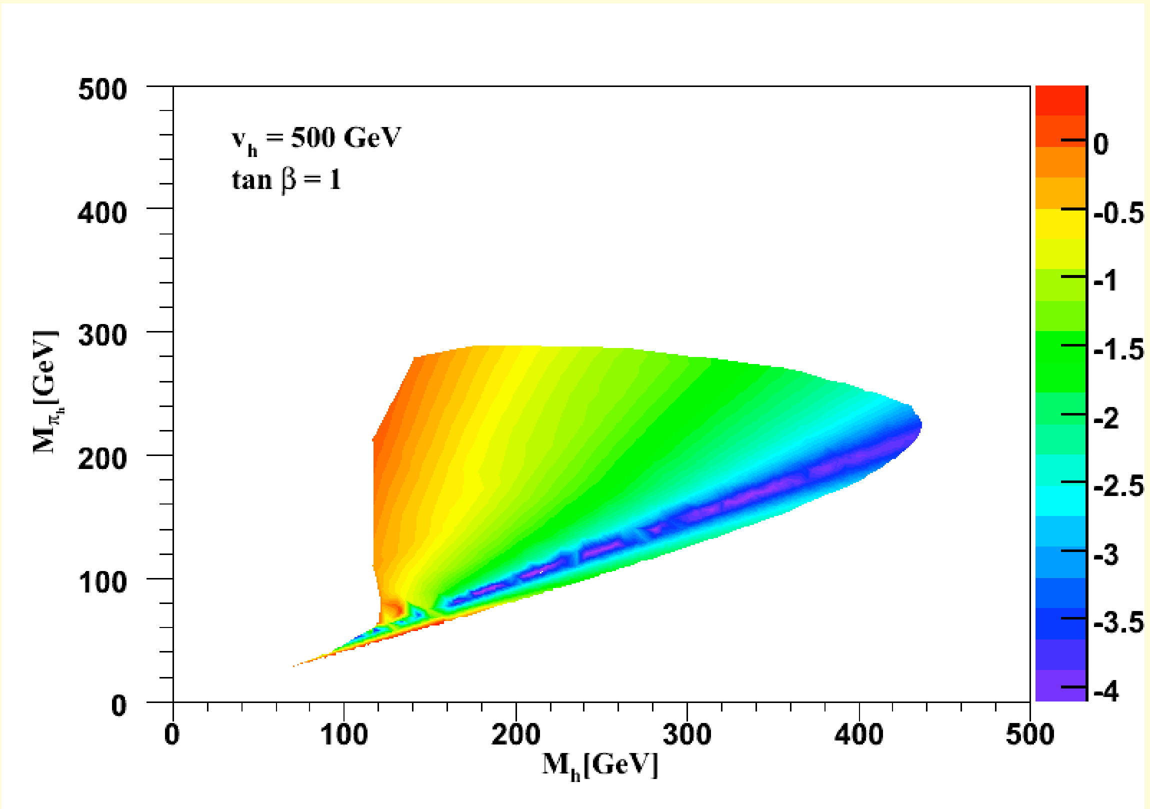
$$
\mathcal{L}_{\rm hidden} = -\frac{1}{4}\mathcal{G}_{\mu\nu}\mathcal{G}^{\mu\nu} + \sum_{k=1}^{N_{HF}} \overline{\mathcal{Q}}_k (i\mathcal{D}\cdot\gamma - \lambda_k S)\mathcal{Q}_k
$$

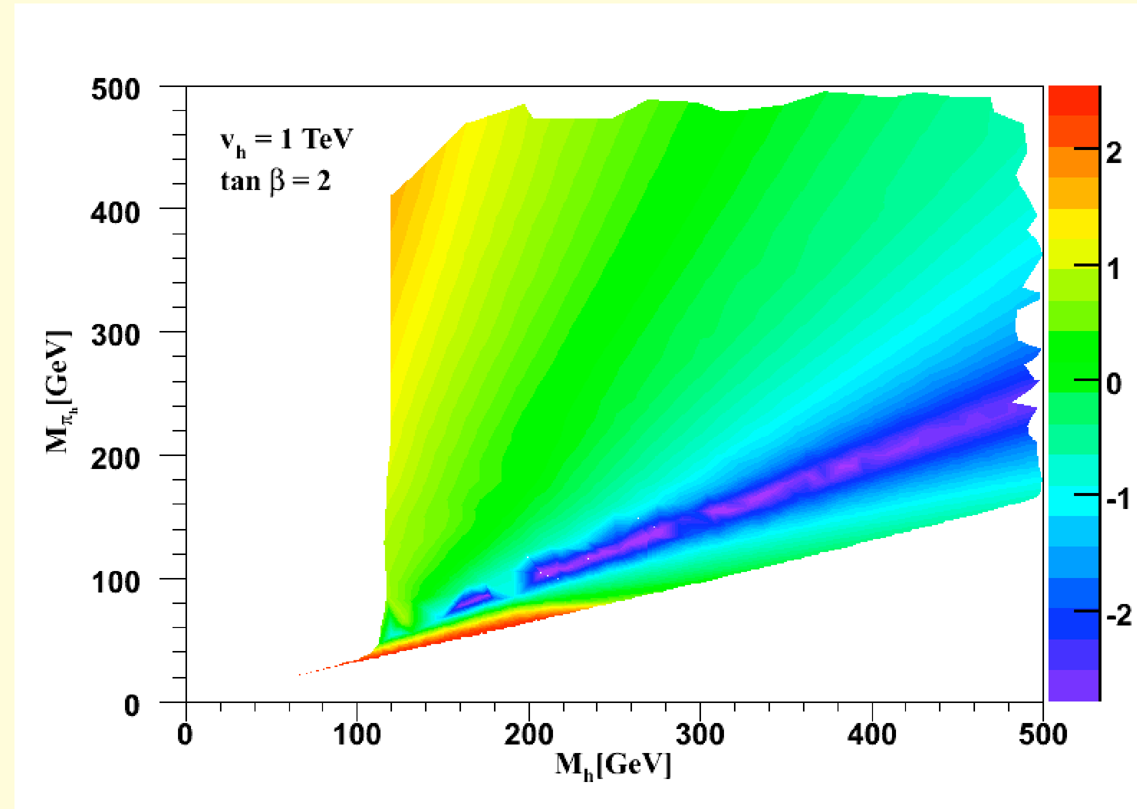
3 neutral scalars : h, S and hidden sigma meson
Assume h-sigma is heavy enough for simplicity

Effective lagrangian far below $\Lambda_{h,\chi} \approx 4\pi\Lambda_h$

$$
\begin{aligned}
\mathcal{L}_{\rm full} &= \mathcal{L}^{\rm eff}_{\rm hidden} + \mathcal{L}_{\rm SM} + \mathcal{L}_{\rm mixing} \\
\mathcal{L}^{\rm eff}_{\rm hidden} &= \frac{v_h^2}{4}{\rm Tr}[\partial_\mu \Sigma_h \partial^\mu \Sigma_h^\dagger] + \frac{v_h^2}{2}{\rm Tr}[\lambda S \mu_h (\Sigma_h + \Sigma_h^\dagger)] \\
\mathcal{L}_{\rm SM} &= -\frac{\lambda_1}{2}(H_1^\dagger H_1)^2 - \frac{\lambda_{1S}}{2} H_1^\dagger H_1 S^2 - \frac{\lambda_S}{8} S^4 \\
\mathcal{L}_{\rm mixing} &= -v_h^2 \Lambda_h^2 \left[\kappa_H \frac{H_1^\dagger H_1}{\Lambda_h^2} + \kappa_S \frac{S^2}{\Lambda_h^2} + \kappa_S' \frac{S}{\Lambda_h} \right. \\
&+ \left. O(\frac{S H_1^\dagger H_1}{\Lambda_h^3}, \frac{S^3}{\Lambda_h^3}) \right] \\
&\approx -v_h^2 \left[\kappa_H H_1^\dagger H_1 + \kappa_S S^2 + \Lambda_h \kappa_S' S \right]
\end{aligned}
$$

Relic density

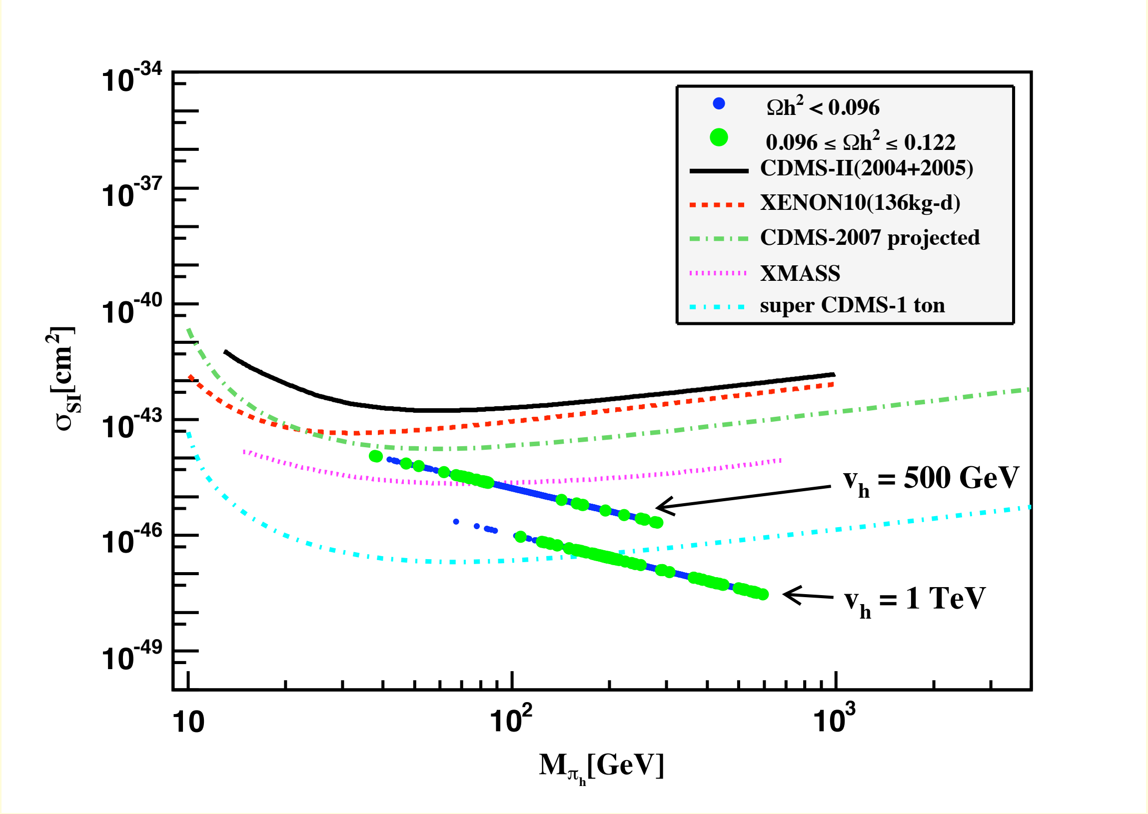




$\Omega_{\pi_h} h^2$ in the (m_{h_1}, m_{π_h}) plane for
(a) $v_h = 500$ GeV and $\tan\beta = 1$,

(b) $v_h = 1$ TeV and $\tan\beta = 2$.

Direct Detection Rate



$\sigma_{SI}(\pi_h p \to \pi_h p)$ as functions of m_{π_h}.

the upper one: $v_h = 500$ GeV and $\tan\beta = 1$,

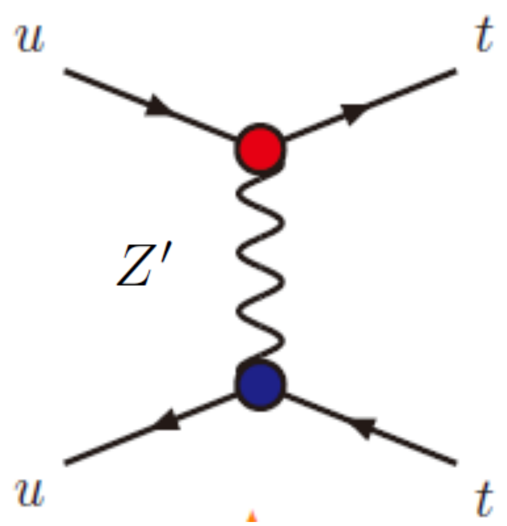
the lower one: $v_h = 1$ TeV and $\tan\beta = 2$.

Lesson & Further directions

- Understanding the origin of (scalar) masses seem require new scalar beyond the SM Higgs boson
- Some drawbacks: S is a gauge singlet (h-quarks are vector-like fermions)
- We can assume chiral U(1) in the hidden sector, which is spontaneously broken by U(1)-charged complex scalar
- h-Quarks becomes chiral, and no singlet scalar

Z′ model

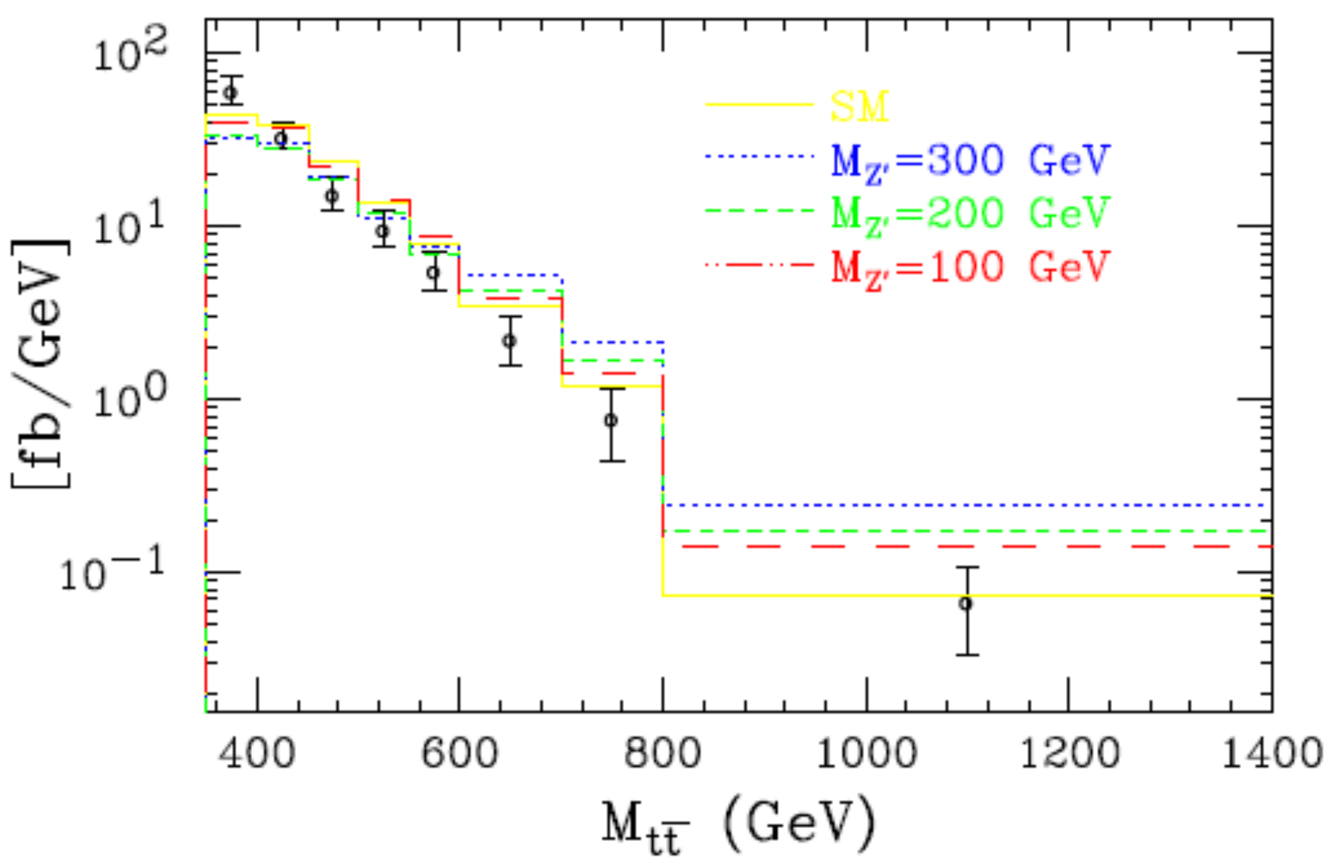
Jung, Murayama, Pierce, Wells, PRD81



- assume large flavor-offdiagonal coupling and small diagonal couplings.

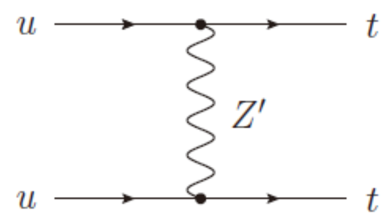
$$\mathcal{L} \ni g_X Z'_\mu \bar{u}\gamma^\mu P_R t + h.c.$$

- In general, could have different couplings to the top and antitop quarks.



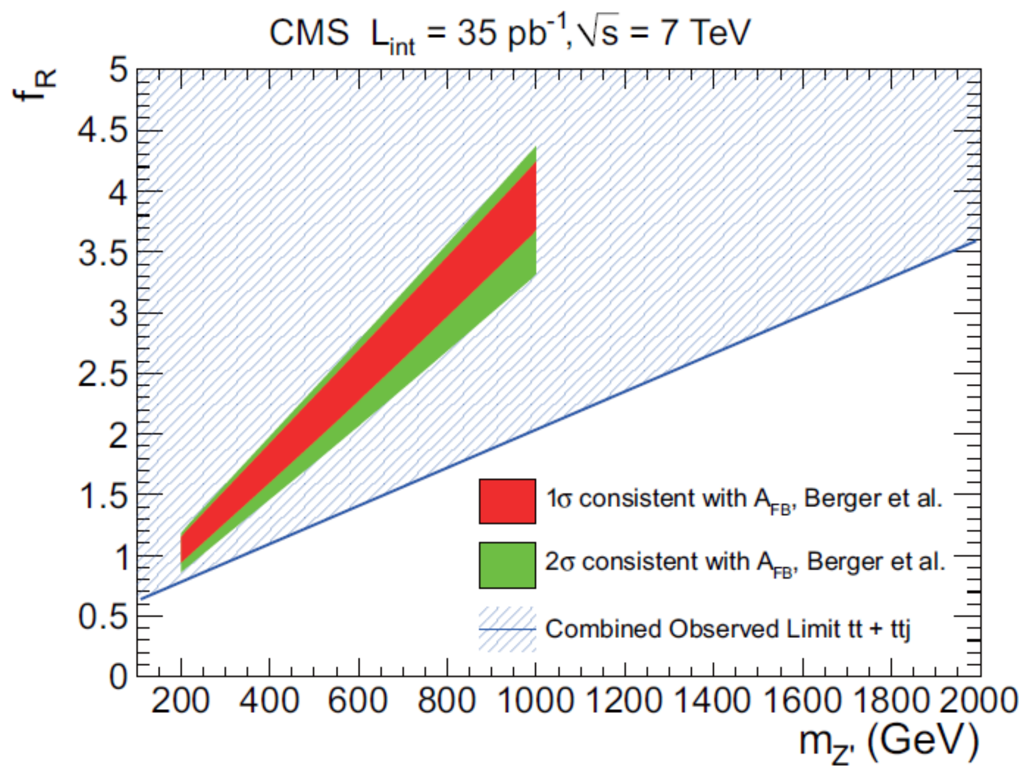
- light Z′ is favored from the M_{tt} distribution.
- severely constrained by the same sign top pair production.
  - the t-channel scalar exchange model has a similar constraint.

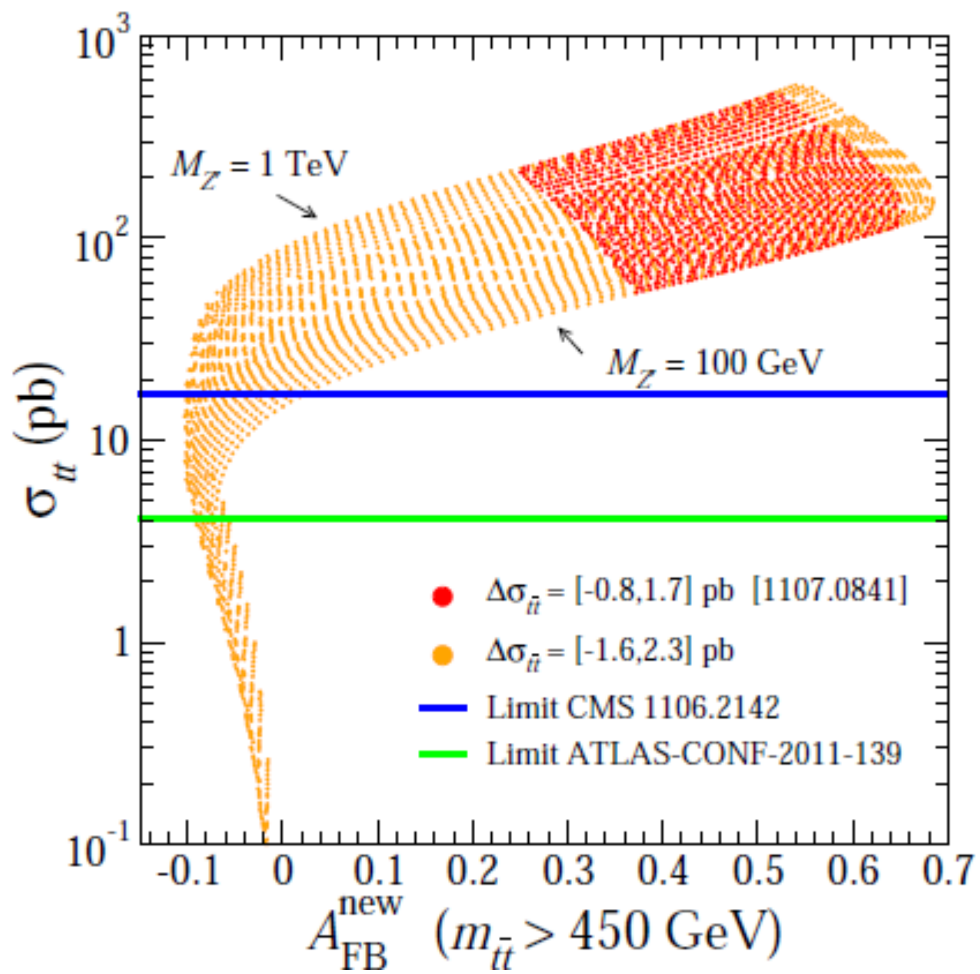
Same sign top pair production at LHC



$$\mathcal{L} = g_W \bar{u}\gamma^\mu (f_L P_L + f_R P_R) t Z'_\mu + \text{h.c.},$$

General exclusion plot





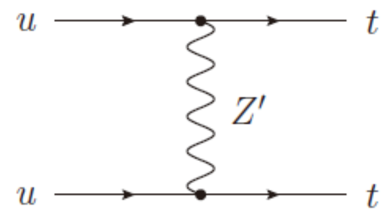
CMS: σ(pp→tt(j))<17 pb at 95C.L.
ATLAS: σ(pp→tt(j))<4 pb at 95C.L.

CMS, JHEP1108; ATLAS-CONF-2011-169♪

Aguilar-Saavedra, TOP2011♪

• the t-channel Z′ or scalar exchange models are excluded?

Same sign top pair production at LHC



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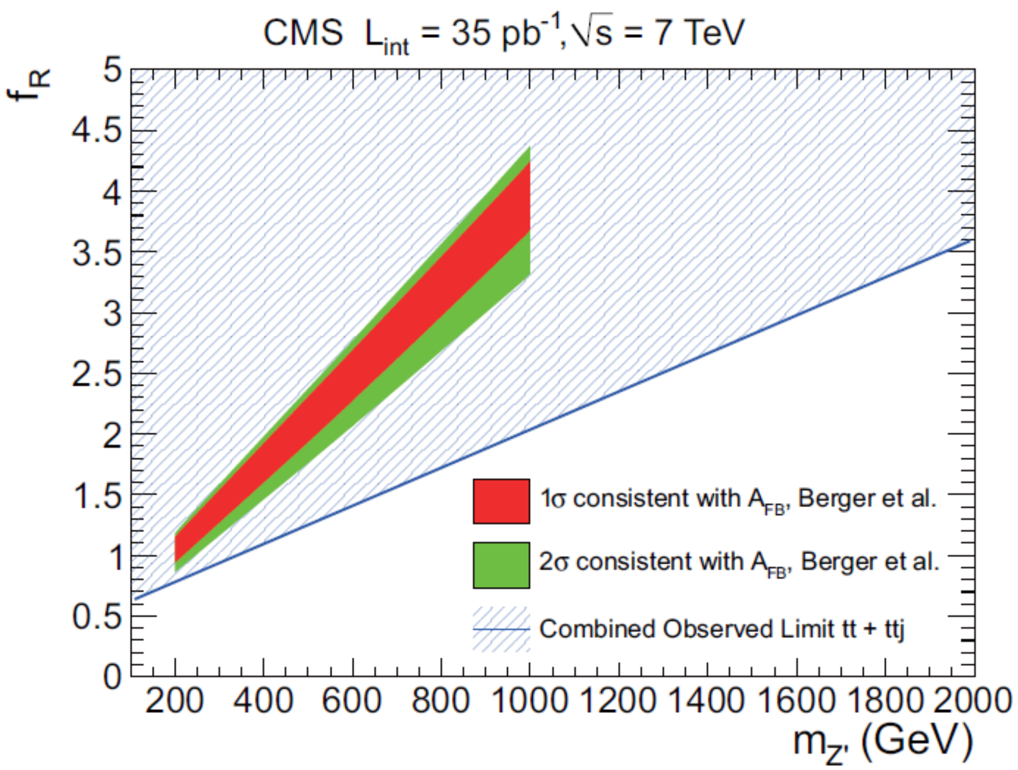

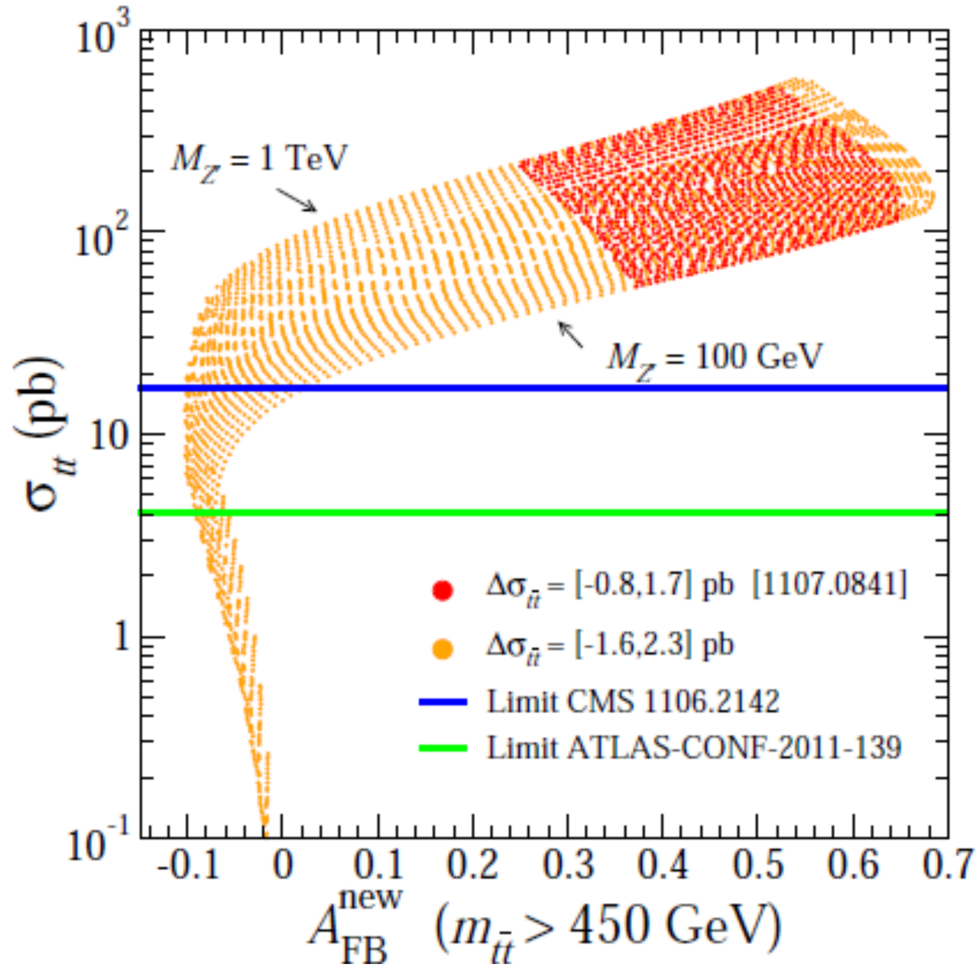

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CMS, JHEP1108; ATLAS-CONF-2011-169

Aguilar-Saavedra, TOP2011

- the t-channel Z′ or scalar exchange models are excluded?
- the answer is NO.

Is the Z’ model for top FB asym excluded by the same sign top pair production ?

Is the Z' model for top FB asym excluded by the same sign top pair production ?

NO !

NOT YET !

However, the story is not so simple for models with vector bosons that have chiral couplings with the SM fermions !

Chiral U(1)' model (Ko, Omura, Yu)

(1) arXiv:1108.0350, PRD (2012)
(2) arXiv:1108.4005, JHEP 1201 (2012) 147
(3) arXiv:1205.0407, EPJC 73 (2013) 2269
(4) arXiv:1212.4607, JHEP 1303 (2013) 151

What is the problem of the original Z' model ?

- Z' couples to the RH up type quarks : leptophobic and chiral : ANOMALY ?
- No Yukawa couplings for up-type quarks : MASSLESS TOP QUARK ? **Dead upon arrival**
- Origin of Z' mass
- Origin of flavor changing couplings of Z'

What is the problem of the original Z' model ?

$$\mathcal{L}_Y = -Y^U_{ij}\overline{Q_{Li}}\tilde{H}U_{Rj} - Y^D_{ij}\overline{Q_{Li}}HD_{Rj} + H.c.$$

Not gauge invariant

Gauge invariant : OK!

No Yukawa's for up-type quarks:
MASSLESS TOP QUARK !

How to cure this problem ?

This problem is independent of top FCNC

Answer : Extend Higgs sector

$$\mathcal{L}_Y = -Y^U_{ij}\overline{Q_{Li}}\tilde{H}U_{Rj} - Y^D_{ij}\overline{Q_{Li}}HD_{Rj} + H.c.$$

Not gauge invariant

Gauge invariant : OK!

$$\mathcal{L}_Y = -Y^U_{ijk}\overline{Q_{Li}}\tilde{H}_k U_{Rj} - Y^D_{ij}\overline{Q_{Li}}HD_{Rj} + H.c.$$

$H_k : U(1)$ charged

Mandatory to extend Higgs sector!
Z' only model does not exist!

# of U(1)'-charged new Higgs doublets depend on U(1)' charge assigments to the RH up quarks

Flavor-dependent U(1)′ model

- 2 Higgs doublet model : $(u_1, u_2, u_3) = (0, 0, 1)$

	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$	$U(1)'$
H	1	2	1/2	0
H_3	1	2	1/2	1
Φ	1	1	1	q_Φ

$$V_y = y^u_{i1}\overline{Q_i}\widetilde{H}U_{R1} + y^u_{i2}\overline{Q_i}\widetilde{H}U_{Rj} + y^u_{i3}\overline{Q_i}\widetilde{H_3}U_{Rj} + y^d_{ij}\overline{Q_i}HD_{Rj} + y^e_{ij}\overline{L_i}H\overline{E_j} + y^n_{ij}\overline{L_i}\widetilde{H}N_j.$$

$$V_h = Y^u_{ij}\overline{\hat{U}_{Li}}\hat{U}_{Rj}\hat{h}_0 + Y^d_{ij}\overline{\hat{D}_{Li}}\hat{D}_{Rj}\hat{h}_0,$$

$$Y^u_{ij} = \frac{m^u_i \cos\alpha}{v\cos\beta}\delta_{ij} + \frac{2m^u_i}{v\sin 2\beta}(g^u_R)_{ij}\sin(\alpha-\beta),$$

$$Y^d_{ij} = \frac{m^d_i \cos\alpha}{v\cos\beta}\delta_{ij},$$

$\propto$ the fermion mass

Flavor-dependent U(1)′ model

- Gauge coupling in the mass base

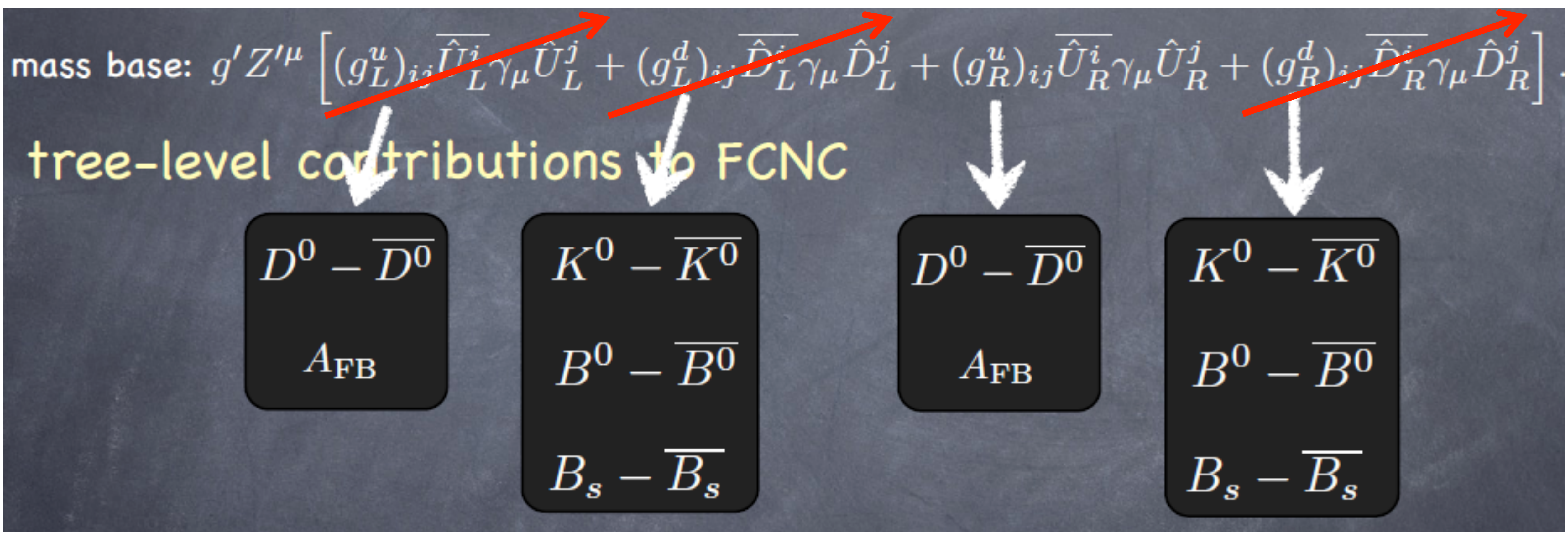
- Z′ interacts only with the right-handed up-type quarks

$$g' Z'^{\mu} \sum_{i,j=1,2,3} (g^u_R)_{ij} \overline{U_R}^{i} \gamma_\mu U^j_R \longleftarrow g' Z'^{\mu} \sum_{i=1,2,3} u_i \overline{U'_{Ri}} \gamma_\mu U'_{Ri}$$

- The 3 X 3 coupling matrix g^u_R is defined by

$$(g^u_R)_{ij} = (U^u_R)_{ik} u_k (U^u_R)^\dagger_{kj}$$

biunitary matrix diagonalizing the up-type quark mass matrix



Flavor-dependent U(1)′ model

- Yukawa coupling in the mass base (2HDM)

- lightest Higgs h: $V_h = Y^u_{ij}\overline{\hat{U}_{Li}}\hat{U}_{Rj}h + Y^d_{ij}\overline{\hat{D}_{Li}}\hat{D}_{Rj}h + Y^e_{ij}\overline{\hat{E}_{Li}}\hat{E}_{Rj}h + h.c.,$

$$Y^u_{ij} = \frac{m^u_i \cos\alpha}{v\cos\beta}\cos\alpha_\Phi\delta_{ij} + \frac{2m^u_i}{v\sin 2\beta}(g^u_R)_{ij}\sin(\alpha-\beta)\cos\alpha_\Phi,$$

$$Y^d_{ij} = \frac{m^d_i \cos\alpha}{v\cos\beta}\cos\alpha_\Phi\delta_{ij},$$

$$Y^e_{ij} = \frac{m^l_i \cos\alpha}{v\cos\beta}\cos\alpha_\Phi\delta_{ij},$$

- lightest charged Higgs h^+: $V_{h^\pm} = -Y^{u-}_{ij}\overline{\hat{D}_{Li}}\hat{U}_{Rj}h^- + Y^{d+}_{ij}\overline{\hat{U}_{Li}}\hat{D}_{Rj}h^+ + h.c.,$

$$Y^{u-}_{ij} = \sum_l (V_{\rm CKM})^*_{li}\left\{\frac{\sqrt{2}m^u_l\tan\beta}{v}\delta_{lj} - \frac{2\sqrt{2}m^u_l}{v\sin 2\beta}(g^u_R)_{lj}\right\},$$

$$Y^{d+}_{ij} = (V_{\rm CKM})_{ij}\frac{\sqrt{2}m^d_j\tan\beta}{v},$$

- lightest pseudoscalar Higgs a: $V_a = -iY^{au}_{ij}\overline{\hat{U}_{Li}}\hat{U}_{Rj}a + iY^{ad}_{ij}\overline{\hat{D}_{Li}}\hat{D}_{Rj}a + iY^{ae}_{ij}\overline{\hat{E}_{Li}}\hat{E}_{Rj}a + h.c.,$

$$Y^{au}_{ij} = \frac{m^u_i\tan\beta}{v}\delta_{ij} - \frac{2m^u_i}{v\sin 2\beta}(g^u_R)_{ij},$$

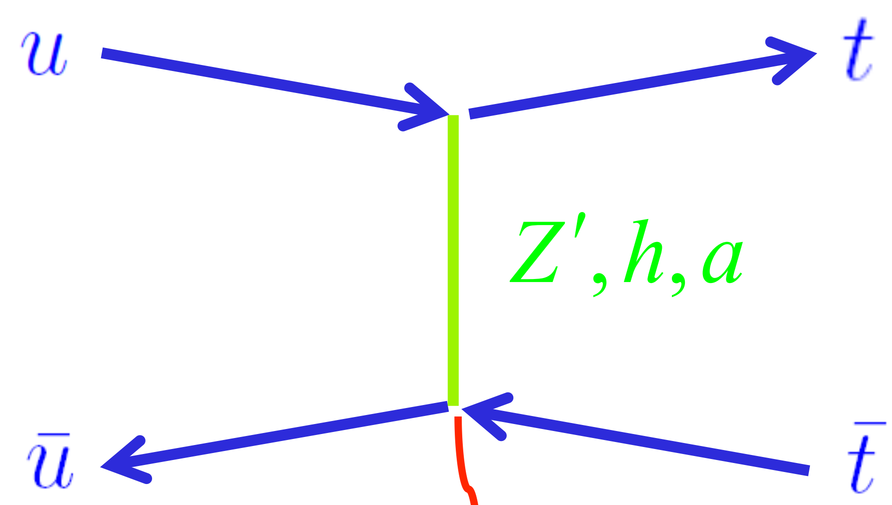
$$Y^{ad}_{ij} = \frac{m^d_i\tan\beta}{v}\delta_{ij},$$

$$Y^{ae}_{ij} = \frac{m^l_i\tan\beta}{v}\delta_{ij}.$$

Top-antitop pair production

1. Z′ dominant scenario

cf. Jung, Murayama, Pierce, Wells, PRD81(2010)♪



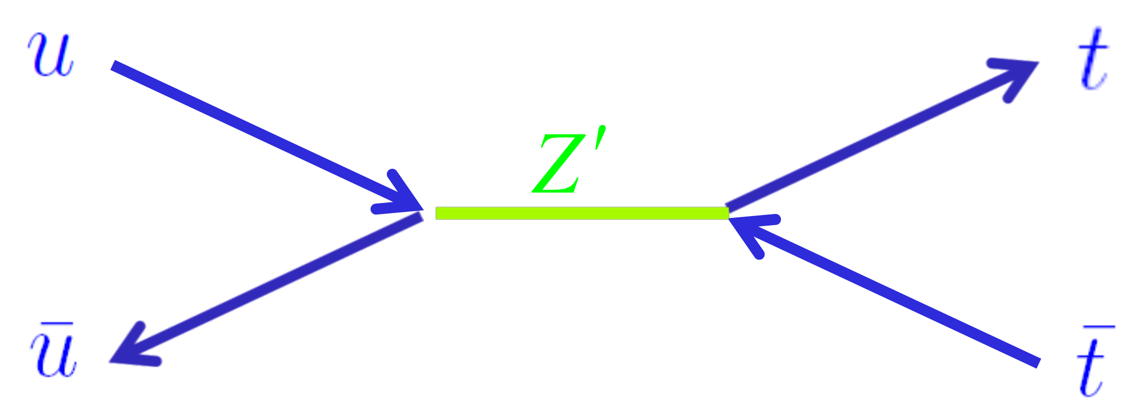
$$\alpha_X = \frac{(g' g^u_{Rut})^2}{4\pi}, Y_{tu}, Y^a_{tu}$$

2. Higgs dominant scenario

cf. Babu, Frank, Rai, PRL107(2011)♪

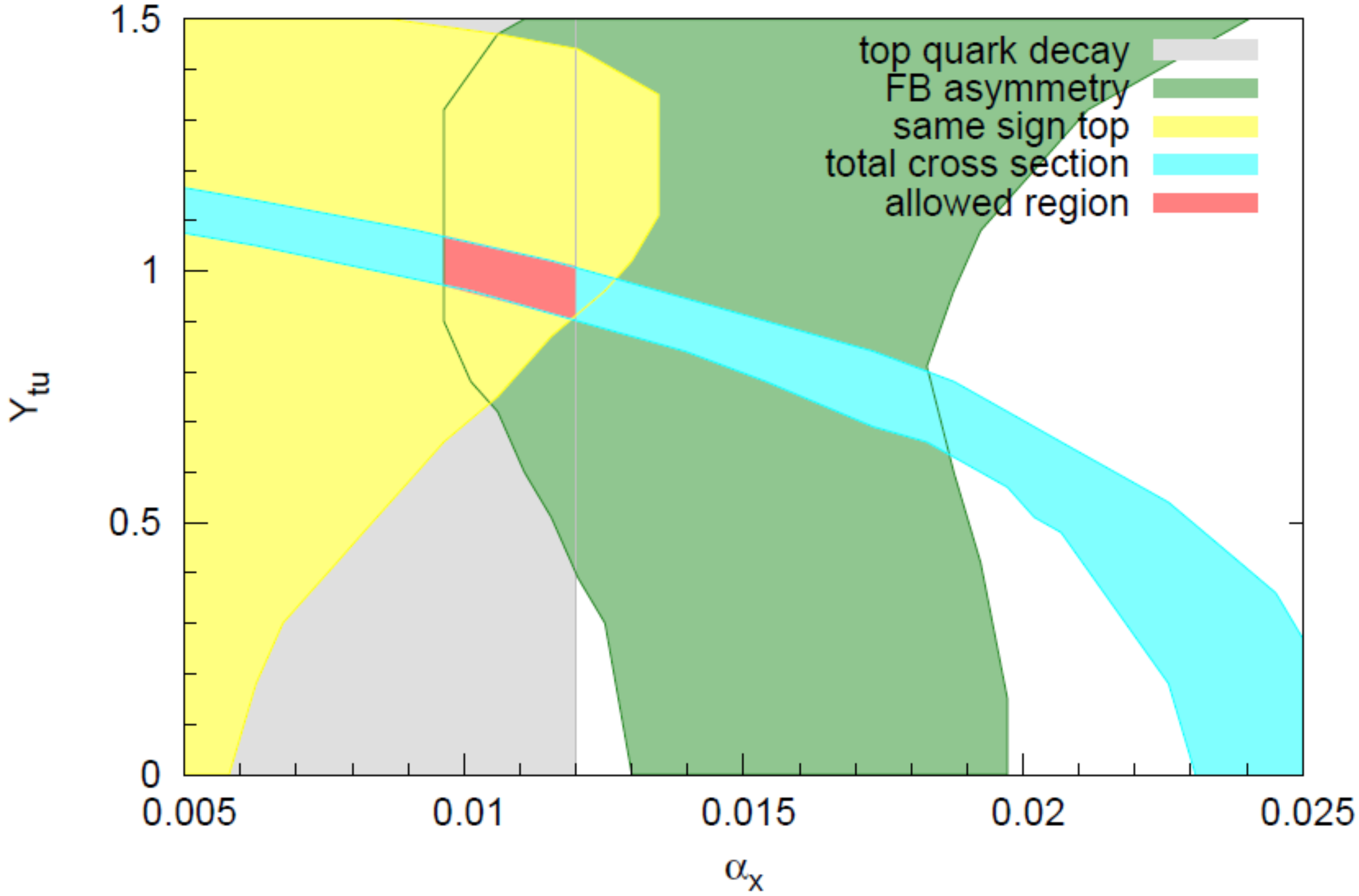
3. Mixed scenario

Destructive interference between Z’ and h,a for the same sign pair production (Ko, Omura, Yu)



Favored region

Z′+h+a case



$m_{Z'} = 145$ GeV

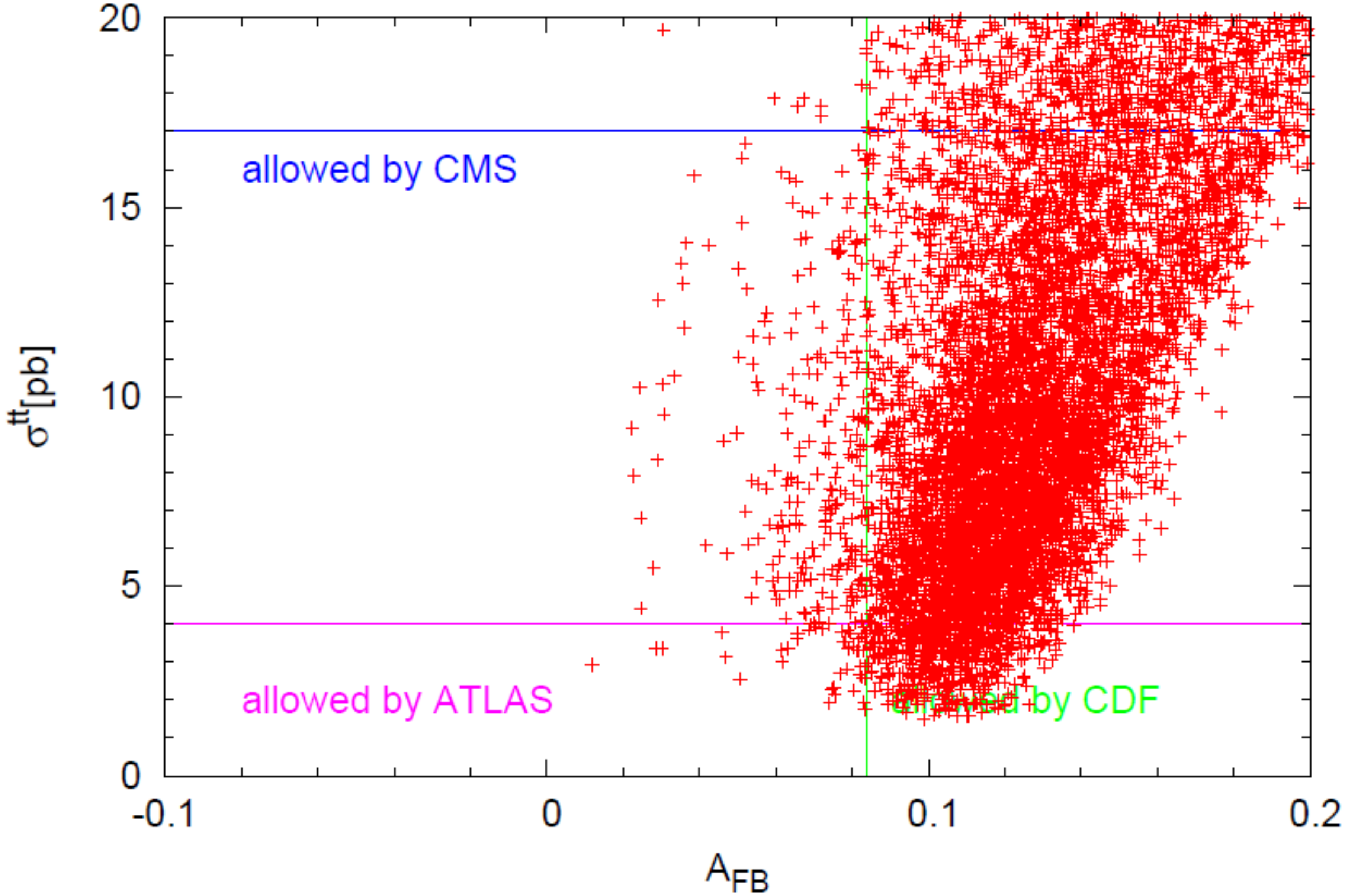
$m_h = 180$ GeV

$m_a = 300$ GeV

$Y_{tu}^a = 1.1$

- destructive interference between Z and Higgs bosons in the same signe top pair production.
- consistent with the CMS bound, but not with the ATLAS bound.

A_{FB} versus σ_{tt}



$m_{Z'} = 145$ GeV

$180\ \text{GeV} < m_h < 1$ TeV

$180\ \text{GeV} < m_a < 1$ TeV

$0.005 < \alpha_X < 0.025$

$0.5 < Y_{tu} < 1.5$

$0.5 < Y_{tu}^{a} < 1.5$

Have a trouble with new CMS data < 0.39 pb

$B \to D^{(*)}\tau\nu$ and $B \to \tau\nu$ in chiral $U(1)'$ models with flavored multi Higgs doublets

Ko, Omura, Yu, arXiv:1212.4607, JHEP(2013)

Conclusions

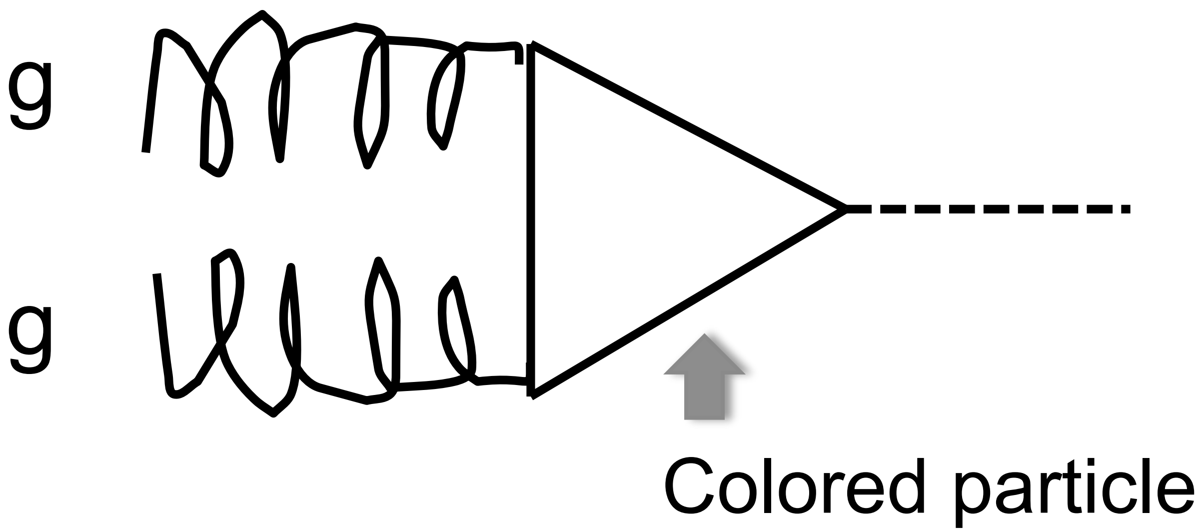
- We constructed realistic Z' models with additional Higgs doublets that are charged under U(1)' : Based on local gauge symmetry, renormalizable, anomaly free and realistic Yukawa
- New spin-one boson (Z') with chiral couplings to the SM fermion requires a new Higgs doublet that couples to the new Z'
- This is also true for axigluon, flavor SU(3)_R, W', etc.
- Our model can accommodate the top FB Asym @ Tevatron, the same sign top pair production, and the top CA@LHC

- Meaningless to say "The Z' model is excluded by the same sign top pair production."
- Important to consider a minimal consistent (renormalizable, realistic, anomaly free) in order to do phenomenology
- Flavor issues in B and charm systems were also studied (w/ Yuji Omura and C. Yu)
- Top longitudinal pol (which is zero in QCD because of Parity) could be another important tool for resolving the issue (Ko et al, Godbole et al, Degrande et al, etc)

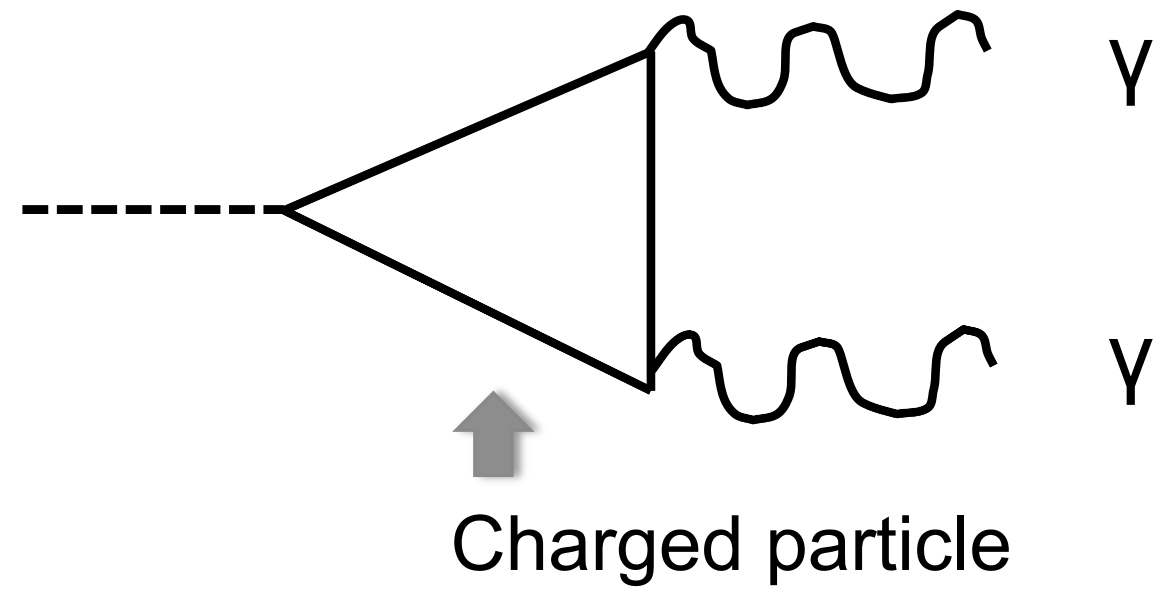
750 GeV diphoton excess at the LHC

One scenario: gluon fusion + diphoton decay via loop

Production: gluon fusion



Diphoton decay channel



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

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

$\sigma(gg\to H)$~850 fb × $\cot^2\beta$ $\sigma(gg\to A)$~850 fb × $2\cot^2\beta$

$BR(H\to\gamma\gamma)$~$O(10^{-5})$ $BR(A\to\gamma\gamma)$~$O(10^{-5})$

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 (and arXiv:1608.00382 with Jubin Park)
- 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

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- 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

For the 1st two models,

- Assume new chiral U(1)’ gauge symmetry under which the SM fermions could be charged or neutral
- New chiral fermions (vectorlike under the SM gauge group) needed to cancel gauge anomalies ~ their masses entirely from U(1)’ breaking
- 750 GeV diphoton excess ~ New Higgs that break U(1)’ spontaneously
- One or 2 HDM depending on the SM fermions chirally charged under U(1)’ or not

E6 motivated leptophobic U(1)' model

arXiv:1601.00586 (JHEP)

with Yuji Omura, Chaehyun Yu

2HDM with $U(1)_H$ gauge sym

- 2HDM: one of the popular extensions of the SM Higgs sector
- Yukawa's and mass matrices cannot be diagonalized simultaneously —> neutral Higgs mediated FCNC problem
- Natural Flavor Conservation : usually in terms of Z_2 (Glashow and Weinberg, 1977)

Natural Flavor Conservation
(Glashow and Weinberg, 1977)

- Fermions of the same electric charge get their masses from the same Higgs doublet [Glashow and Weinberg, PRD (1977)] NFC
- Impose a discrete Z2 sym, and assign different Z2 parity to H1 and H2
- This Z2 is softly broken to avoid the domain wall problem

However

- The discrete Z_2 seems to be rather ad hoc, and its origin and the reason for its soft breaking are not clear
- We implement the discrete Z_2 into a continuos local U(1) Higgs flavor sym under which H_1 and H_2 are charged differently [Ko, Omura, Yu PLB (2012)]
- This simple idea opens a new window for the multi-Higgs doublet models (2HDM could be due to new chiral U(1) gauge symmetry)

$$Z_2 : (H_1, H_2) \to (+H_1, -H_2).$$

TABLE I: Assignment of Z_2 parities to the SM fermions and Higgs doublets.

Type	H_1	H_2	U_R	D_R	E_R	N_R	Q_L, L
I	+	−	+	+	+	+	+
II	+	−	+	−	−	+	+
III	+	−	+	+	−	−	+
IV	+	−	+	−	+	−	+

$$V(H_1, H_2) = m_1^2 H_1^\dagger H_1 + m_2^2 H_2^\dagger H_2 + \frac{\lambda_1}{2}(H_1^\dagger H_1)^2 + \frac{\lambda_2}{2}(H_2^\dagger H_2)^2 + \lambda_3 H_1^\dagger H_1 H_2^\dagger H_2 + \lambda_4 H_1^\dagger H_2 H_2^\dagger H_1. \quad (4)$$

$$\Delta V = m_\Phi^2 \Phi^\dagger \Phi + \frac{\lambda_\Phi}{2}(\Phi^\dagger \Phi)^2 + (\mu H_1^\dagger H_2 \Phi + \text{h.c.}) + \mu_1 H_1^\dagger H_1 \Phi^\dagger \Phi + \mu_2 H_2^\dagger H_2 \Phi^\dagger \Phi, \quad (5)$$

Soft Z2 breaking is replaced by spontaneous U(1) Higgs gauge sym breaking

Ko, Omura, Yu: arXiv:1204.4588 [hep-ph]

Type-I Extensions

Models are anomaly free
without extra chiral fermions

TABLE II: Charge assignments of an anomaly-free $U(1)_H$ in the Type-I 2HDM.

Type	U_R	D_R	Q_L	L	E_R	N_R	H_1
$U(1)_H$ charge	u	d	$\frac{(u+d)}{2}$	$\frac{-3(u+d)}{2}$	$-(2u+d)$	$-(u+2d)$	$\frac{(u-d)}{2}$
$h_2 \neq 0$	0	0	0	0	0	0	0
$U(1)_{B-L}$	$1/3$	$1/3$	$1/3$	-1	-1	-1	0
$U(1)_R$	1	-1	0	0	-1	1	1
$U(1)_Y$	$2/3$	$-1/3$	$1/6$	$-1/2$	-1	0	$1/2$

See arXiv:1309.7256 for Higgs data analysis,
arXiv:1405.2138 for DM (Ko,Omura,Yu)

Type-II 2HDM with U(1)H gauge symmetry

Ko, Omura, Yu: arXiv:1204.4588 [hep-ph]

Table 1: Matter contents in U(1)′ model inspired by E_6 GUTs. Here, i denotes the generation index: $i = 1, 2, 3$.

Fields	SU(3)	SU(2)	$U(1)_Y$	$U(1)'$	Z_2^{ex}
Q^i	$\mathbf{3}$	$\mathbf{2}$	$1/6$	$-1/3$	
u_R^i	$\mathbf{3}$	$\mathbf{1}$	$2/3$	$2/3$	
d_R^i	$\mathbf{3}$	$\mathbf{1}$	$-1/3$	$-1/3$	
L_i	$\mathbf{1}$	$\mathbf{2}$	$-1/2$	0	$+$
e_R^i	$\mathbf{1}$	$\mathbf{1}$	-1	0	
n_R^i	$\mathbf{1}$	$\mathbf{1}$	0	1	
H_2	$\mathbf{1}$	$\mathbf{2}$	$-1/2$	0	
H_1	$\mathbf{1}$	$\mathbf{2}$	$-1/2$	-1	$+$
Φ	$\mathbf{1}$	$\mathbf{1}$	0	-1	
D_L^i	$\mathbf{3}$	$\mathbf{1}$	$-1/3$	$2/3$	
D_R^i	$\mathbf{3}$	$\mathbf{1}$	$-1/3$	$-1/3$	
$\widetilde{H}_L^i$	$\mathbf{1}$	$\mathbf{2}$	$-1/2$	0	$-$
$\widetilde{H}_R^i$	$\mathbf{1}$	$\mathbf{2}$	$-1/2$	-1	
N_L^i	$\mathbf{1}$	$\mathbf{1}$	0	-1	

A Type-II Extension has all the necessary ingredients

Table 1: Matter contents in U(1)′ model inspired by E_6 GUTs. Here, i denotes the generation index: $i = 1, 2, 3$.

Fields	SU(3)	SU(2)	$U(1)_Y$	U(1)′	Z_2^{ex}
Q^i	**3**	**2**	1/6	−1/3	
u_R^i	**3**	**1**	2/3	2/3	
d_R^i	**3**	**1**	−1/3	−1/3	
L_i	**1**	**2**	−1/2	0	+
e_R^i	**1**	**1**	−1	0	
n_R^i	**1**	**1**	0	1	
H_2	**1**	**2**	−1/2	0	
H_1	**1**	**2**	−1/2	−1	+
Φ	**1**	**1**	0	−1	
D_L^i	**3**	**1**	−1/3	2/3	
D_R^i	**3**	**1**	−1/3	−1/3	
$\widetilde{H}_L^i$	**1**	**2**	−1/2	0	−
$\widetilde{H}_R^i$	**1**	**2**	−1/2	−1	
N_L^i	**1**	**1**	0	−1	

Fermions : 27 of E6 (!!!)
Scalar Bosons : 2 Doublets + 1 Singlet

Basic Ingredients

- New vectorlike fermions which are chiral under new U(1)' : non-decoupling effects on X->gg, gam gam
- Diphoton at 750 GeV = Higgs boson from U(1)' sym breaking, mostly a SM singlet scalar
- All the masses from dynamical (Higgs) mechanism
- New decay modes to enhance the total decay rate

cf: SU(2)H by W.C.Huang, Y.L.S.Tsai, TCYuan (2015)
and applied for 750 GeV diphoton excess

Yukawa couplings

The U(1)′-symmetric Yukawa couplings in our model are given by

$$V_y = y^u_{ij}\overline{u^j_R}H_1^\dagger i\sigma_2 Q^i + y^d_{ij}\overline{d^j_R}H_2 Q^i + y^e_{ij}\overline{e^j_R}H_2 L^i + y^n_{ij}\overline{n^j_R}H_1^\dagger i\sigma_2 L^i + H.c., \tag{16}$$

where σ_2 is the Pauli matrix. The Yukawa couplings to generate the mass terms for the extra particles are

$$V^{\rm ex} = y^D_{ij}\overline{D^j_R}\Phi D^i_L + y^H_{ij}\overline{\widetilde{H}^j_R}\Phi\widetilde{H}^i_L + y^N_{IJ}\overline{N^c_L}H_1^\dagger i\sigma_2\widetilde{H}^i_L + y'^N_{IJ}\overline{\widetilde{H}^i_R}H_2 N^j_L + H.c.\ . \tag{17}$$

Complex Scalar DM

One can introduce new $Z_2^{\rm ex}$-odd scalar field X with the $SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_H$ quantum numbers equal to $(1,1,0;-1)$. Then the gauge-invariant Lagrangian involving X is given by

$$\begin{aligned}\mathcal{L}_X =\ & D_\mu X^\dagger D^\mu X - (m^2_{X0} + \lambda_{H_1X}H_1^\dagger H_1 + \lambda_{H_2X}H_2^\dagger H_2)X^\dagger X - \lambda_X (X^\dagger X)^2 \\ & - \left(\lambda''_{\Phi X}(\Phi^\dagger X)^2 + H.c.\right) - \lambda_{\Phi X}\Phi^\dagger\Phi X^\dagger X - \lambda'_{\Phi X}|\Phi^\dagger X|^2 \\ & - \left(y^D_{dX}\overline{d_R}D_L X + y^{\tilde{H}}_{LX}\overline{L}\widetilde{H}_R X^\dagger + H.c.\right)\end{aligned} \tag{18}$$

125 GeV Higgs Data

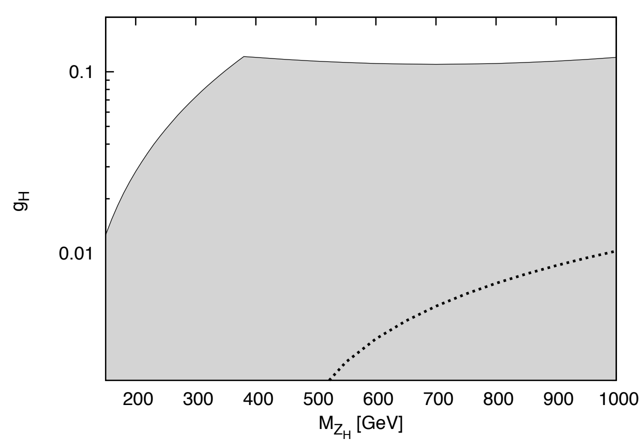
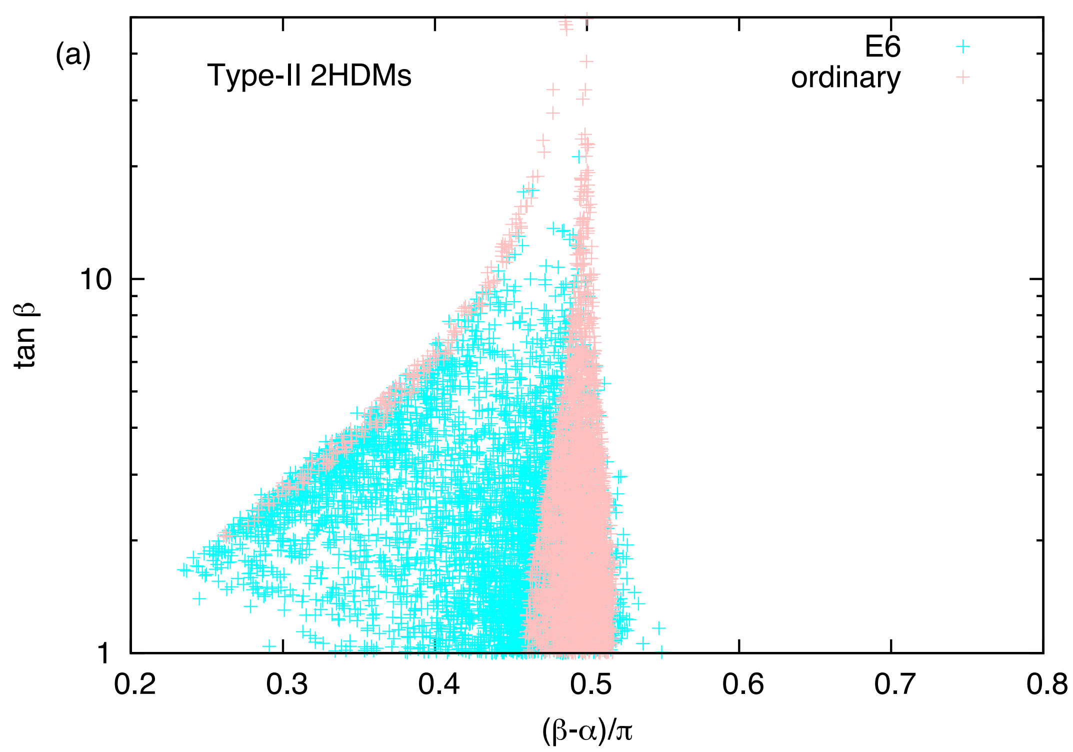


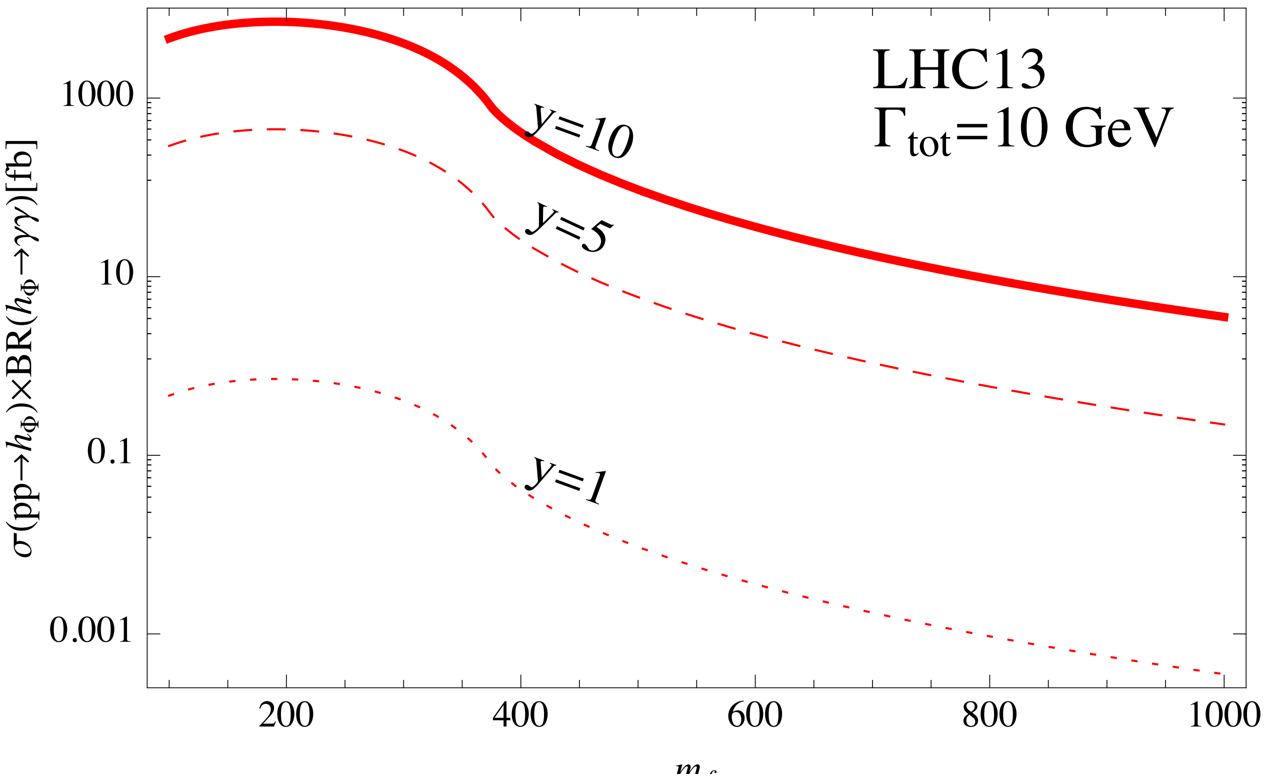
FIG. 1. M_{Z_H} and g_H in the type-II 2HDM$_{U(1)}$. The dot line is the upper bound on the $U(1)_\psi$ gauge boson, and the gray region is allowed for the $U(1)_H (\equiv U(1)_b)$ gauge boson.

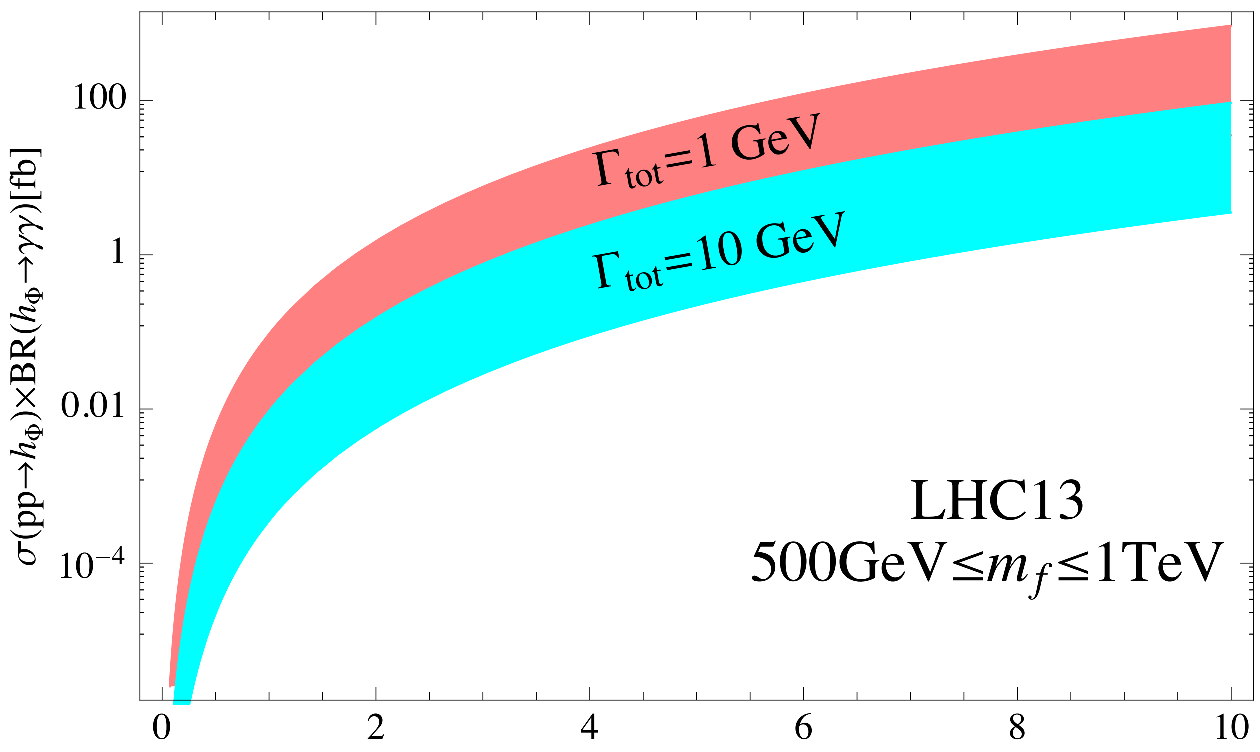


Qualitatively different from the ordinary Type-II 2HDM
arXiv:1502.00262 (Ko, Omura, Yu)

750 GeV Diphoton Excess

Ko, Omura, Yu, arXiv:1601.00586





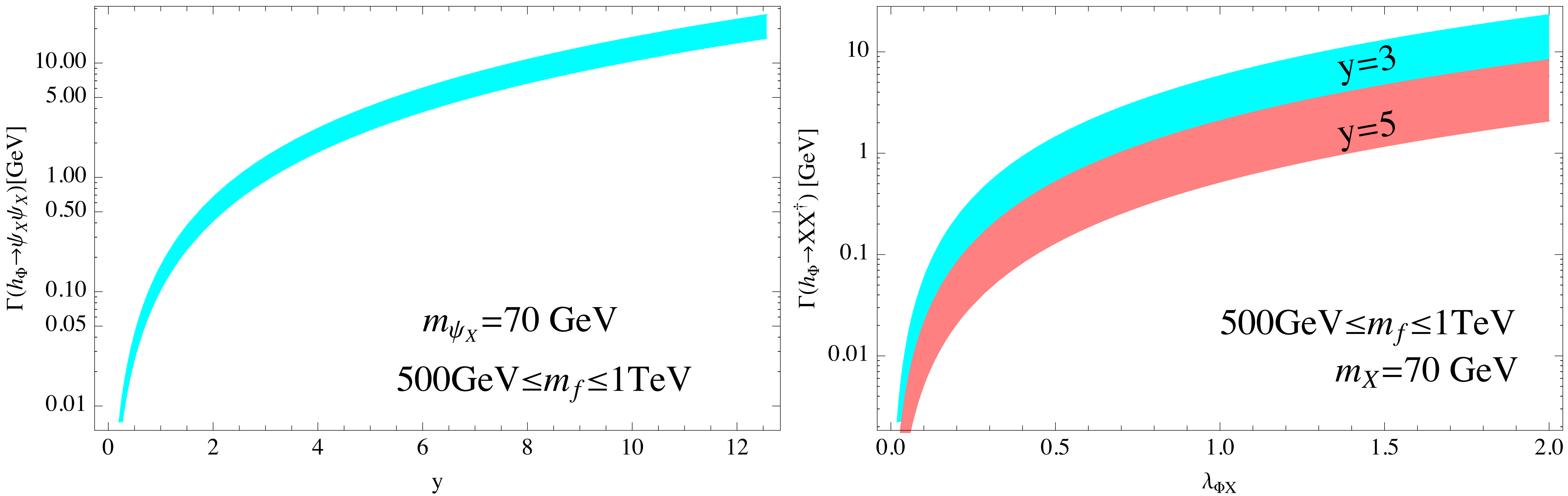


Figure 2: y vs. invisible decay width of h_Φ (GeV) in the fermionic DM scenario (left) and scalar DM scenario (right).The vector-like fermion mass is between 500 GeV and 1 TeV on the cyan and pink bands. The dark matter masses are 70 GeV in the both cases.

Constraints

final state f	σ at $\sqrt{s} = 8\,\text{TeV}$ observed	expected	ref.	implied bound on $\Gamma(S \to f)/\Gamma(S \to \gamma\gamma)_{\text{obs}}$
$\gamma\gamma$	< 1.5 fb	< 1.1 fb	[6,7]	$< 0.8\ (r/5)$
$e^+e^- + \mu^+\mu^-$	< 1.2 fb	< 1.2 fb	[8]	$< 0.6\ (r/5)$
$\tau^+\tau^-$	< 12 fb	15 fb	[9]	$< 6\ (r/5)$
$Z\gamma$	< 4.0 fb	< 3.4 fb	[10]	$< 2\ (r/5)$
ZZ	< 12 fb	< 20 fb	[11]	$< 6\ (r/5)$
Zh	< 19 fb	< 28 fb	[12]	$< 10\ (r/5)$
hh	< 39 fb	< 42 fb	[13]	$< 20\ (r/5)$
W^+W^-	< 40 fb	< 70 fb	[14, 15]	$< 20\ (r/5)$
$t\bar{t}$	< 550 fb	-	[16]	$< 300\ (r/5)$
invisible	< 0.8 pb	-	[17]	$< 400\ (r/5)$
$b\bar{b}$	$\lesssim 1$ pb	$\lesssim 1$ pb	[18]	$< 500\ (r/5)$
jj	$\lesssim 2.5$ pb	-	[5]	$< 1300\ (r/5)$

Rescaled Run I limits

[Franceschini et al, 1512.04933]

Key Aspects of the Model

- Extra fermions are chiral under U(1)', and vectorlike under the SM gauge group : this is the consequence of gauge anomaly cancellation (**27** rep. of E_6 group)

- Their masses from U(1)' breaking > nondecoupling

- U(1)'-breaking scalar produces a new singlet-like scalar h_phi ~ 750 GeV scalar boson

- Decay channels of 750 GeV are determined by gauge symmetry of the underlying Type-II 2HDM with U(1)' Higgs gauge symmetry (hh, Hh, HH, Z'Z',DM DM etc.)

Conclusion

- Type II 2HDM + U(1) Higgs gauge symmetry : leptophobic U(1)’ derived from E6
- Can accommodate the 750 GeV diphoton excess at qualitative level
- A few more different models within the same ingredients are being studied now
- A new playground for new gauge models (including DM)

Flavor dependent U(1)’

- One can consider flavor dependent U(1)’, assuming only the 3rd generation for example feels U(1)’

- Such model in fact was constructed by Yuji Omura, Chaehyun Yu and myself in the context of Top FBA at the Tevatron [Origin of nonMFV = flavor dep. U(1)’]

- Can accommodate B->D(*) tau nu anomaly too

- arXiv:1108.0350, 1108.4005, 1205.0407, 1212.4607 (and talk in 2014 meeting here at Lisbon)

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

Pyungwon Ko (KIAS)

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

with Takaaki Nomura @ KIAS

Disclaimer

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

Does not mean that it is made of SM singlets.

Dark Sector Shining through 750GeV Dark Higgs @ LHC

(arXiv:1601.02490 with Takaaki Nomura)

- Raison d'être of (fundamental?) singlet scalar and vector-like fermions ? Completely singlet particles ?
- 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
- Here we consider phi(750) decay into dark photons, assuming phi(750) is a dark Higgs boson

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

(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)

X,N : DM candidate

New Lagrangian

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

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

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

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

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)

X,N : DM candidate

New Lagrangian

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

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

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

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

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

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

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

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

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

Decay of new fermions F

$F \rightarrow X f_{SM}$

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

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

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

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

U(1)$_X$ is broken by <Φ>

➡ Massive Z'

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

We assume H-Φ mixing is negligible

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

❖ Masses of Z' and new fermions

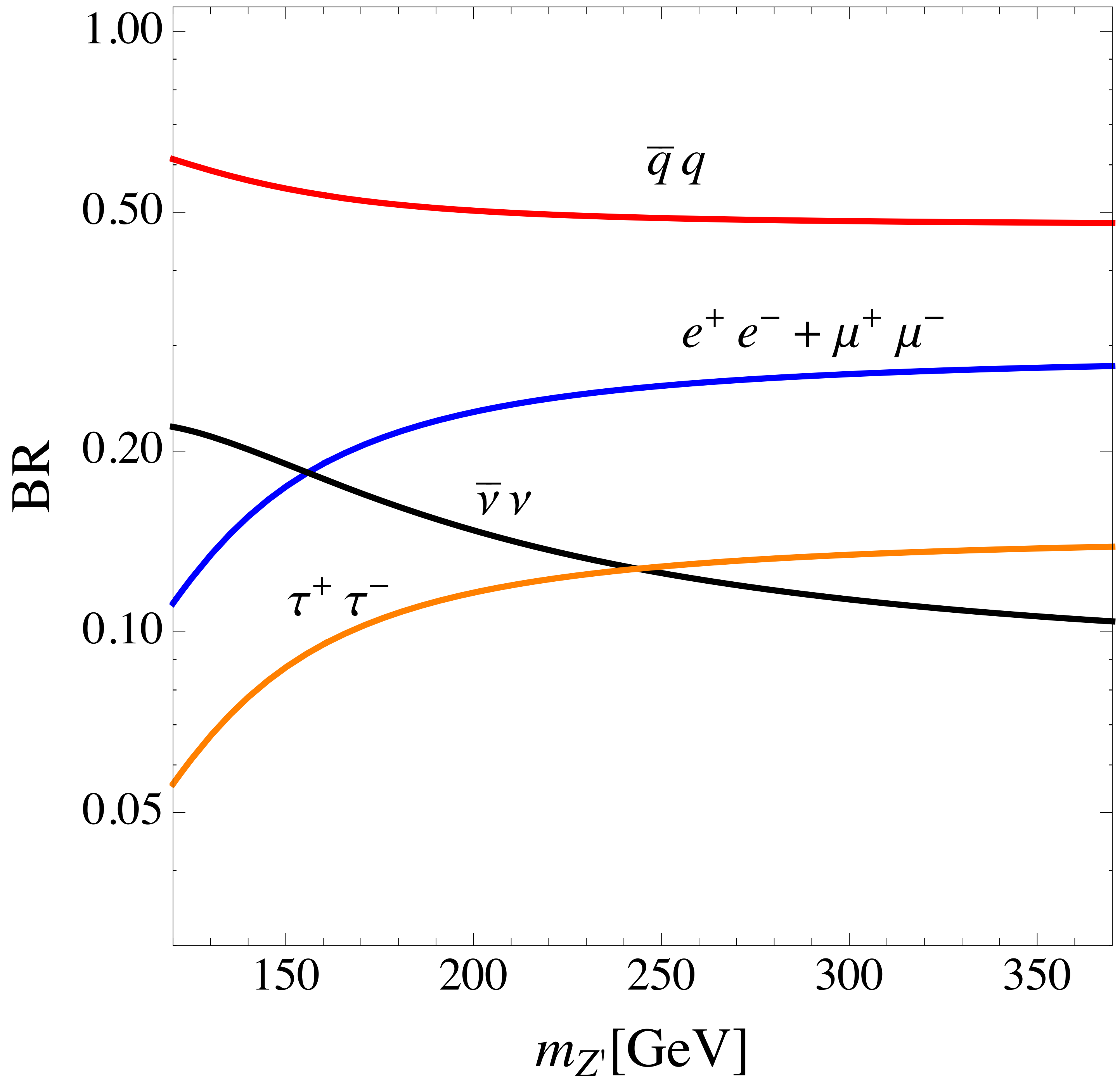
$$m_{Z'}^2 \approx (a+b)^2 g_X^2 v_\phi^2, \quad m_F = \frac{y^F}{\sqrt{2}} v_\phi$$

➡

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

❖ Z' decays through small Z-Z' mixing

BRs of Z’



1.00
0.50
0.20
0.10
0.05
BR
$\bar{q}\,q$
$e^+\,e^- + \mu^+\,\mu^-$
$\bar{\nu}\,\nu$
$\tau^+\,\tau^-$
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 ⟶ φ

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

Decay widths

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

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

.

.

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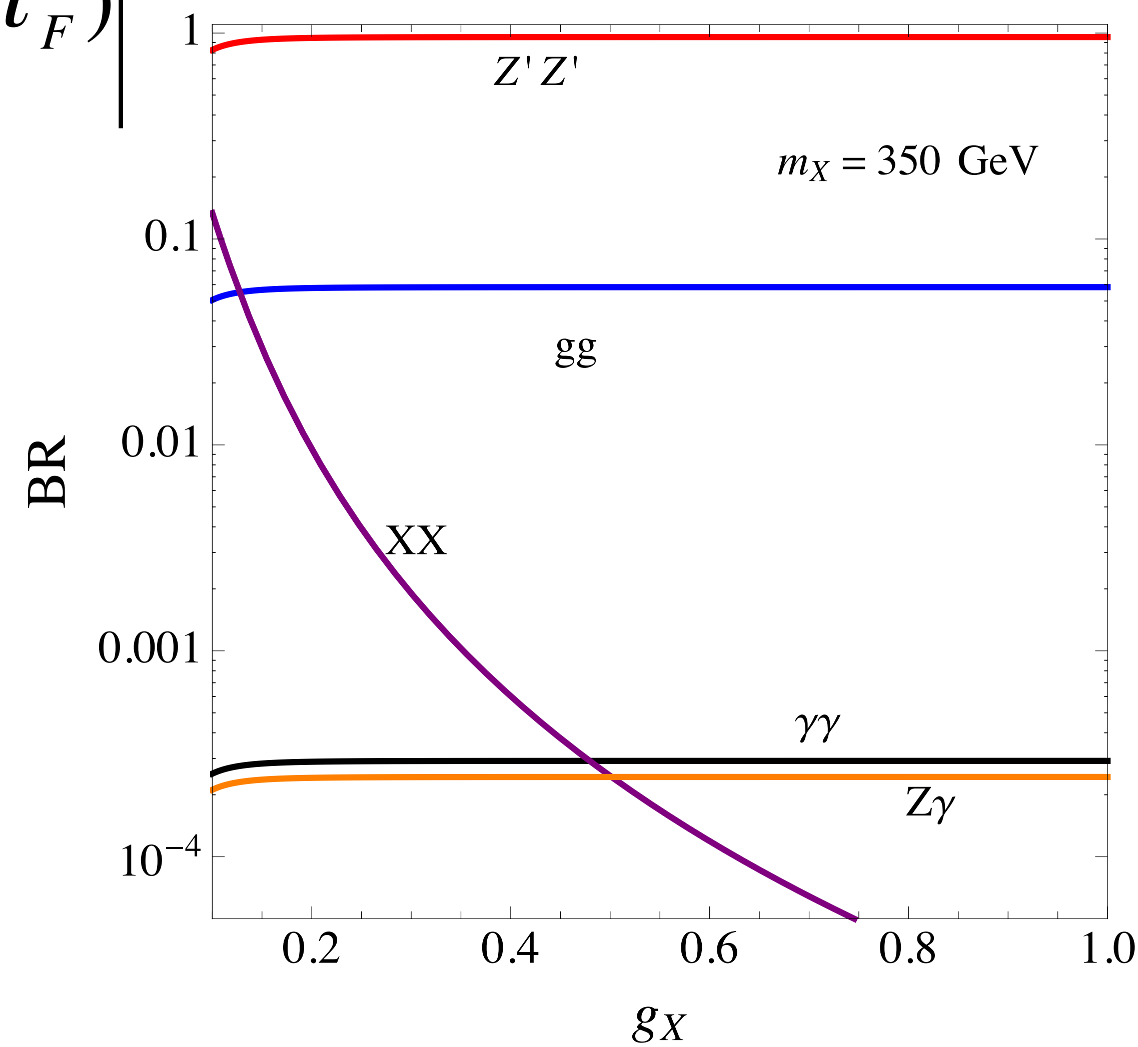
BR(φ)



Gluon fusion and decay modes of φ

Gluon fusion and diphoton decay of φ via new fermion loop

gg → φ

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

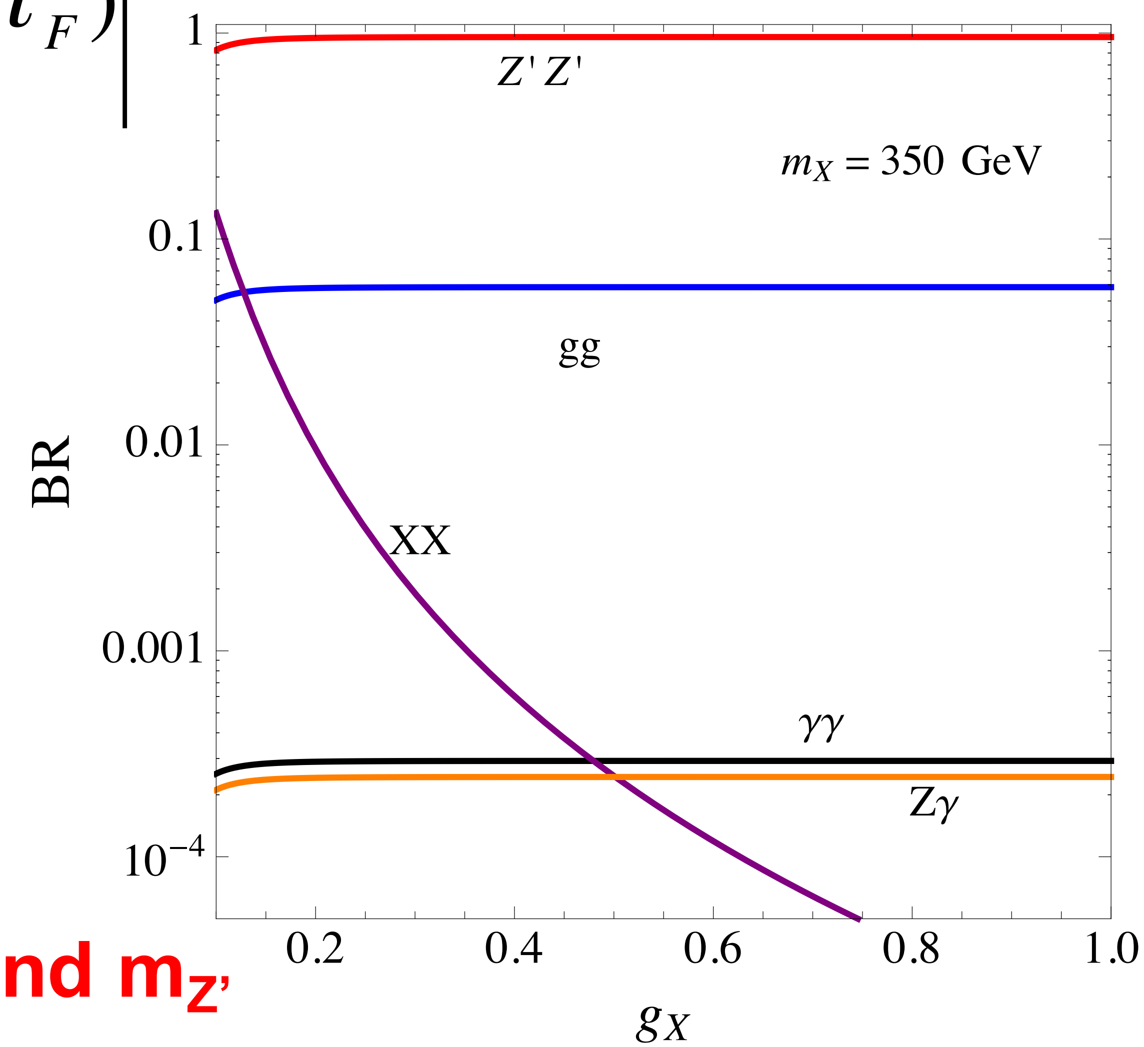
Decay widths

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

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

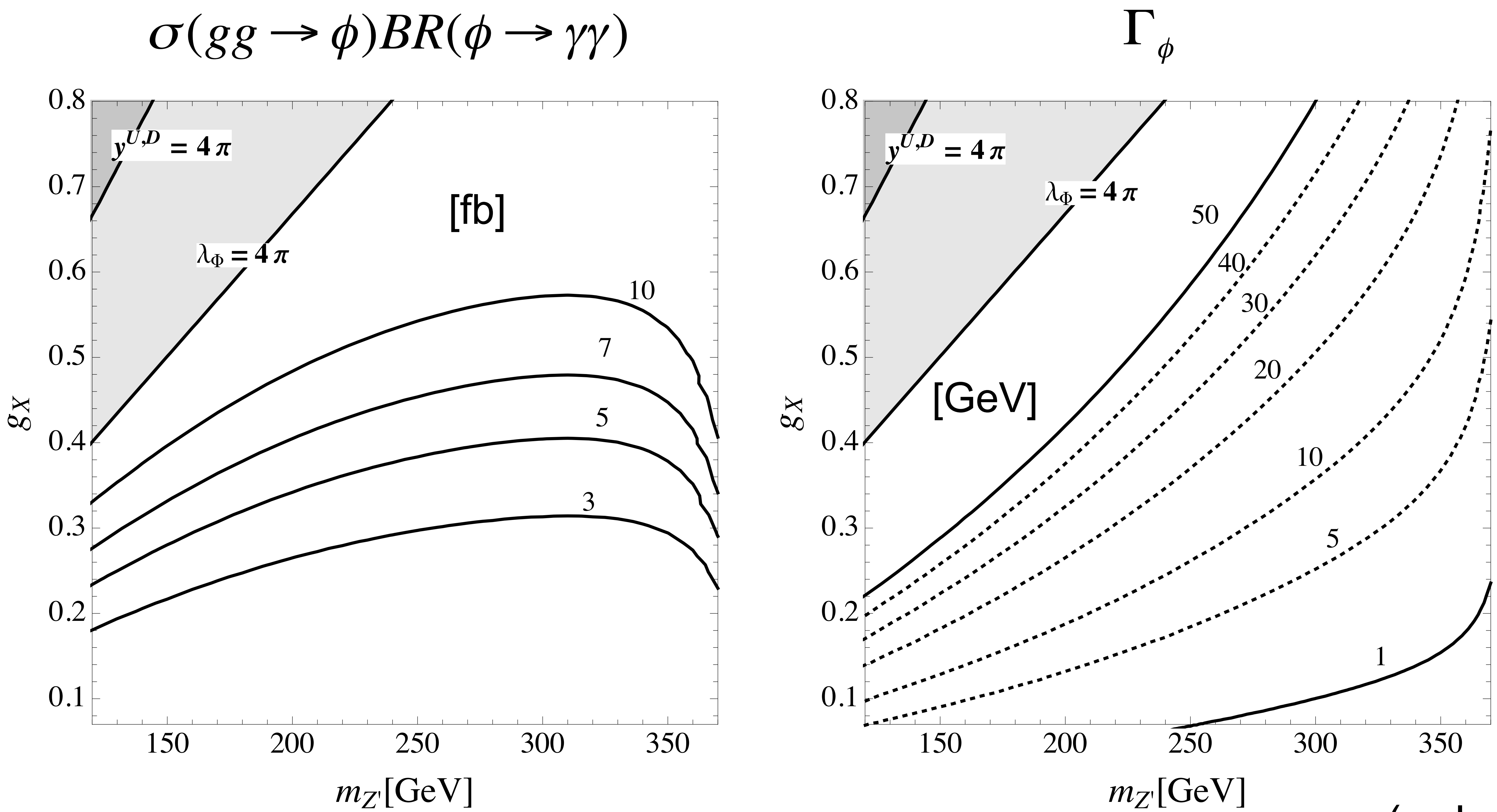
⋮

BR(φ)



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

Cross section and widht of φ

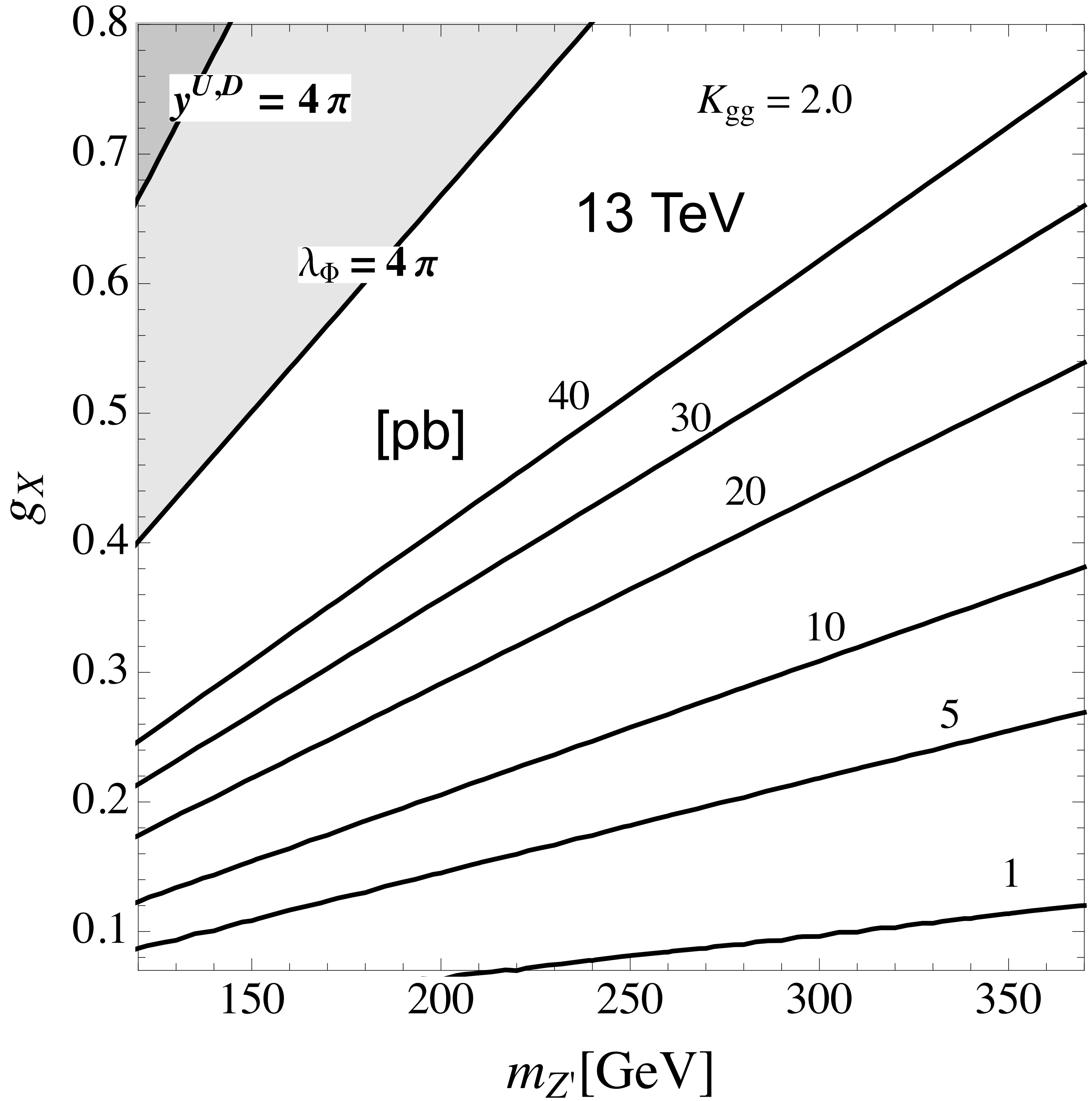


(a~b~1)

$\{M_{U,D}, M_{E,N}, M_X, \lambda_{X\Phi}\}$ = {800 GeV, 400 GeV, 350 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→φ→Z'Z'→$4f_{SM}$
- 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 GeV, 400 GeV, 350 GeV, 0.075}

(a~b~1)

DM Relic Density

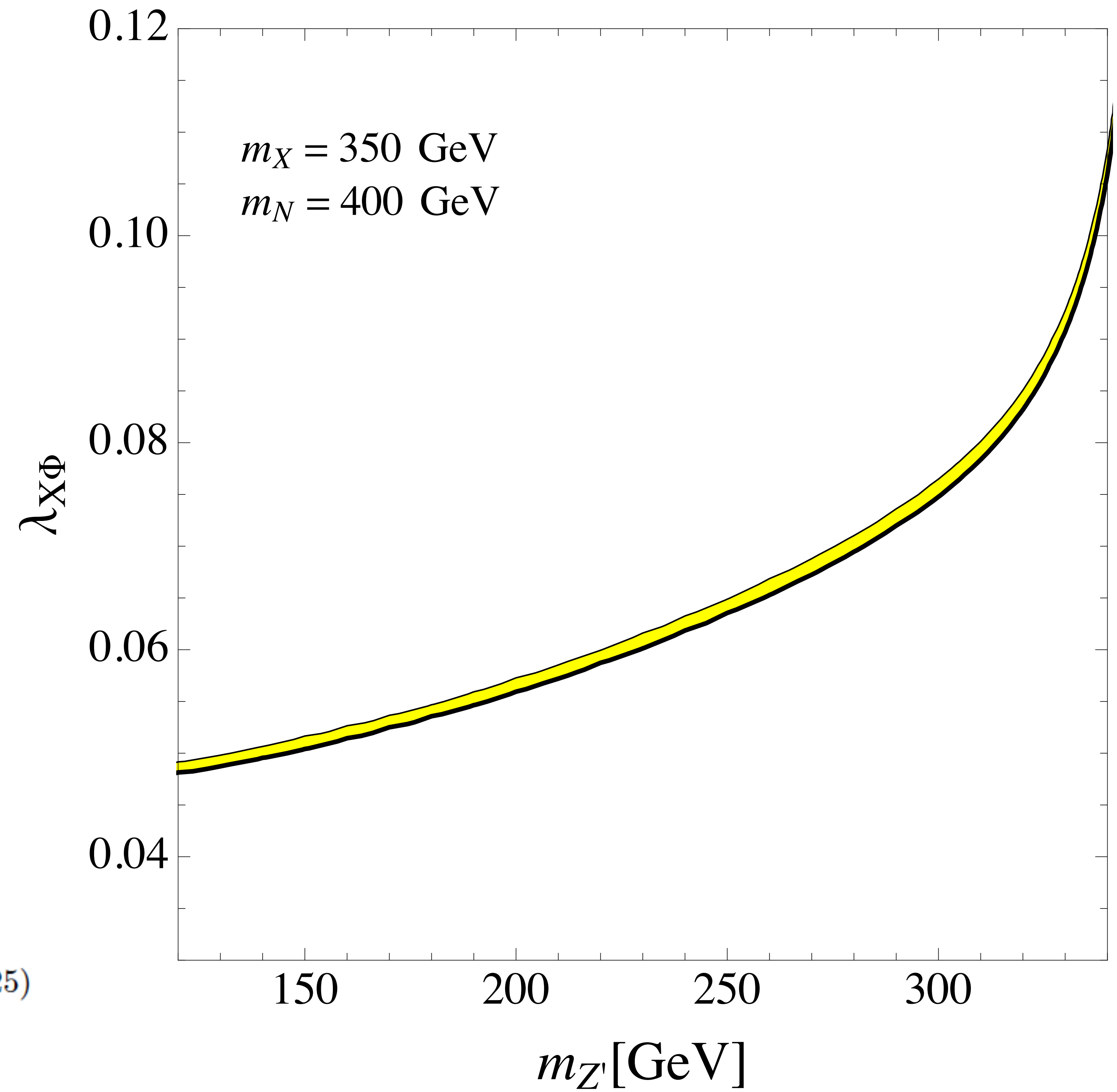
Annihilation process

XX → Z'Z'

NN → 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 m_X = 350 GeV and m_{E_i} = 400 GeV, we can account for the deficit in the $a_\mu = 8 \times 10^{-10}$, if $y^{E_i}_\mu \sim 2 - 3$
- 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 with this new DM model

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

New chiral gauge sym

- LH & RH fermions carry different gauge charges
- No Yukawa couplings for the SM Higgs doublet
- Has to extend the Higgs sector, by introducing a new Higgs doublet with nonzero charge under new gauge group
- May have to introduce new chiral fermions (vectorlike under the SM gauge group) for anomaly cancellation

Conclusions

- Multi Higgs (scalar) could be theoretically motived, if there are new gauge symmetries, or if we want to understand the origin of scalar masses

- Imposing new gauge symmetries in the DM, top physics, 750 GeV diphoton excess etc. open completely new windows for particle physics and cosmology (see arXiv: 1609.02307 today)

- In particular, new chiral gauge symmetries could be a rspossible motivation for 2HDM, 3HDM, etc.