What if the 750 GeV diphoton excess is confirmed ?

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Capri Workshop on Flavor Physics
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Does it have anything
to do with flavor physics ?

Does it have anything
to do with flavor physics ?

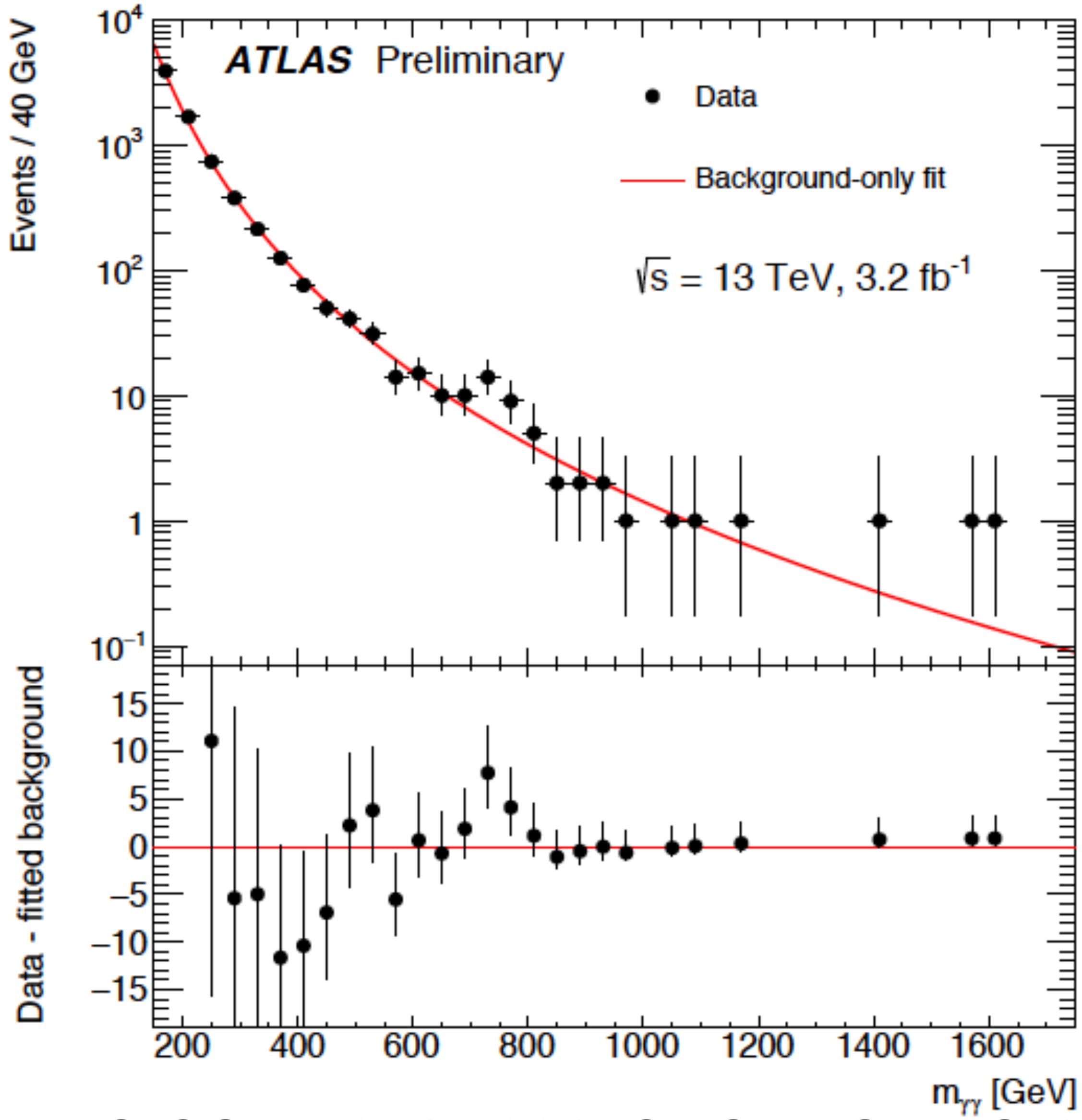
Yes, it can !

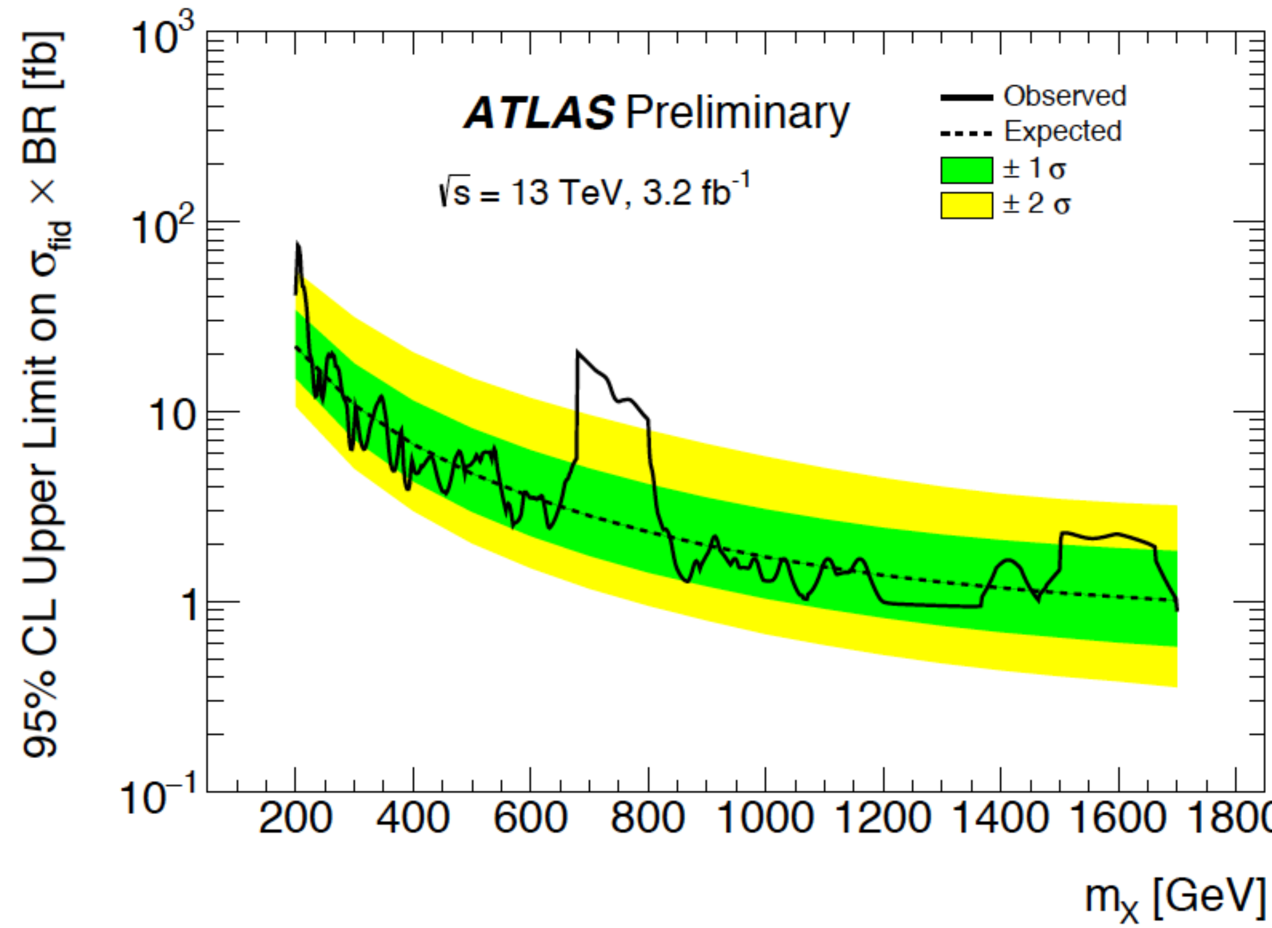
Contents

- 750 GeV Diphoton excess at the LHC
- Model I : E_6 motivated leptophobic U(1)' model + another example (related with flavor physics)
- Model II : Dark Higgs boson
- Closing remarks

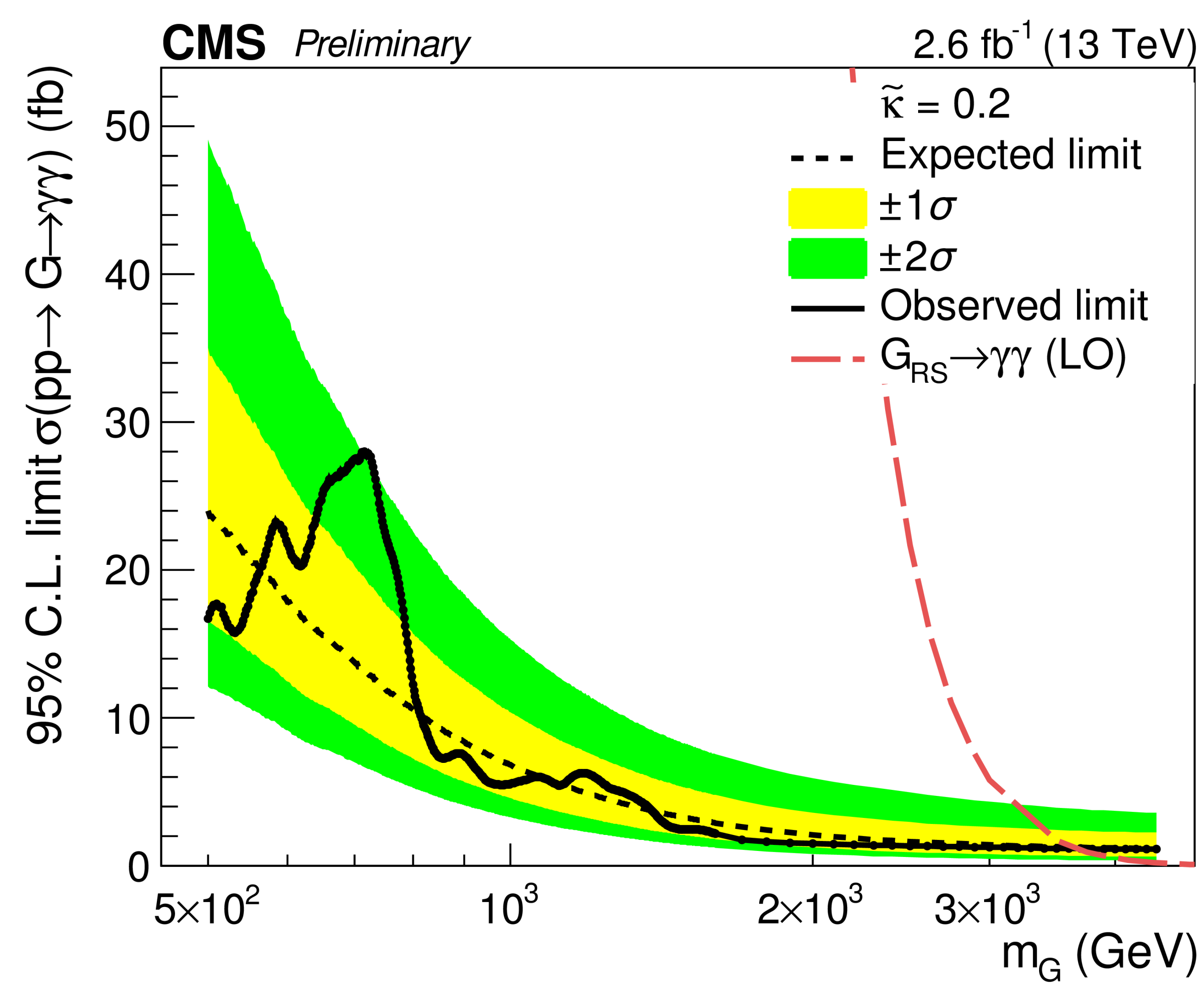
750 GeV diphoton excess at the LHC

Diphoton excess at 750 GeV





ATLAS-CONF-2015-081, CMS-PAS-EXO-15-004



Both ATLAS and CMS observed bump on diphton invariant mass distribution

3.6 σ : ATLAS

2.6 σ : CMS

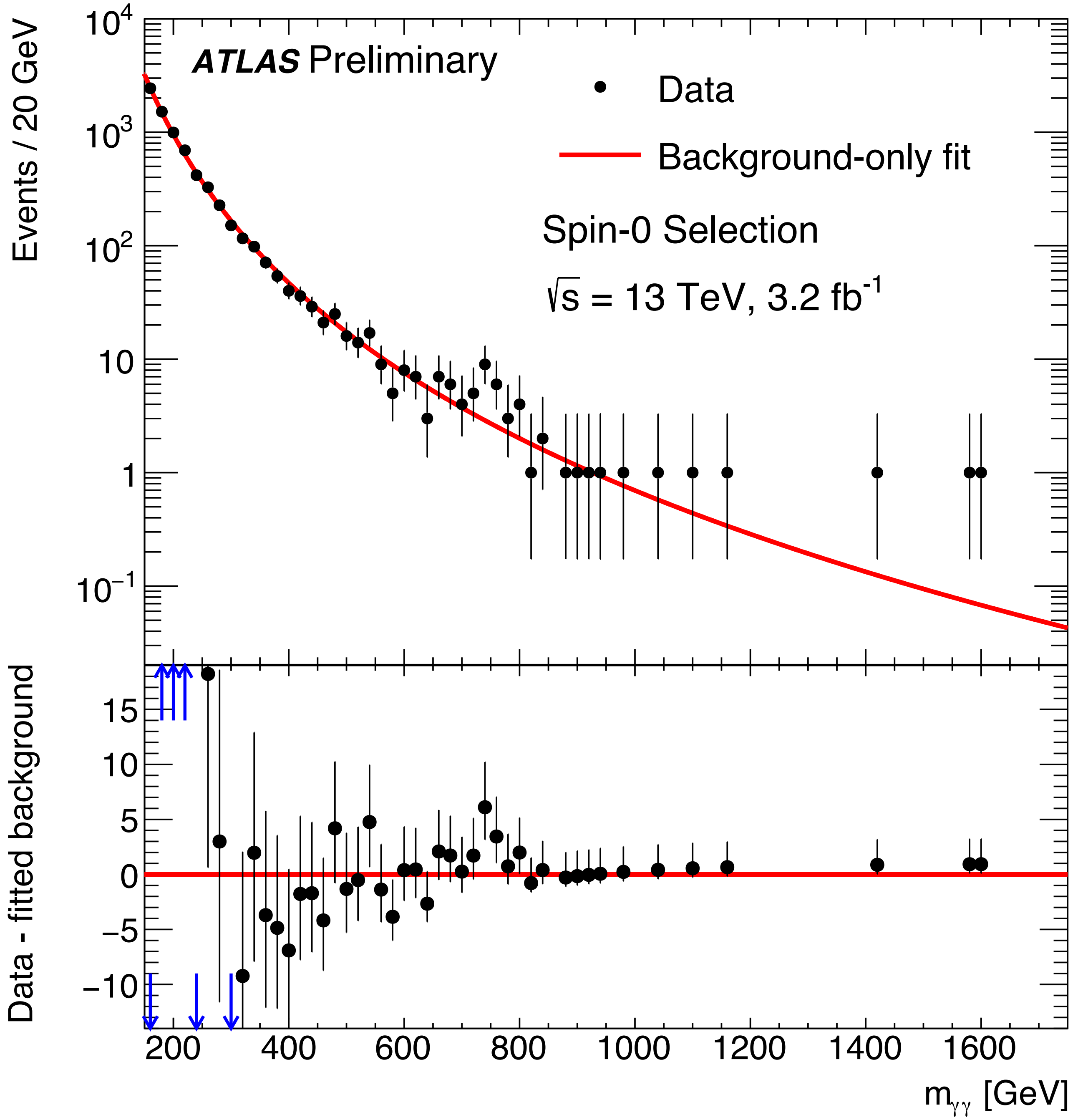
(Local significance)

After Moriond 2016

Results

SPIN-0 ANALYSIS

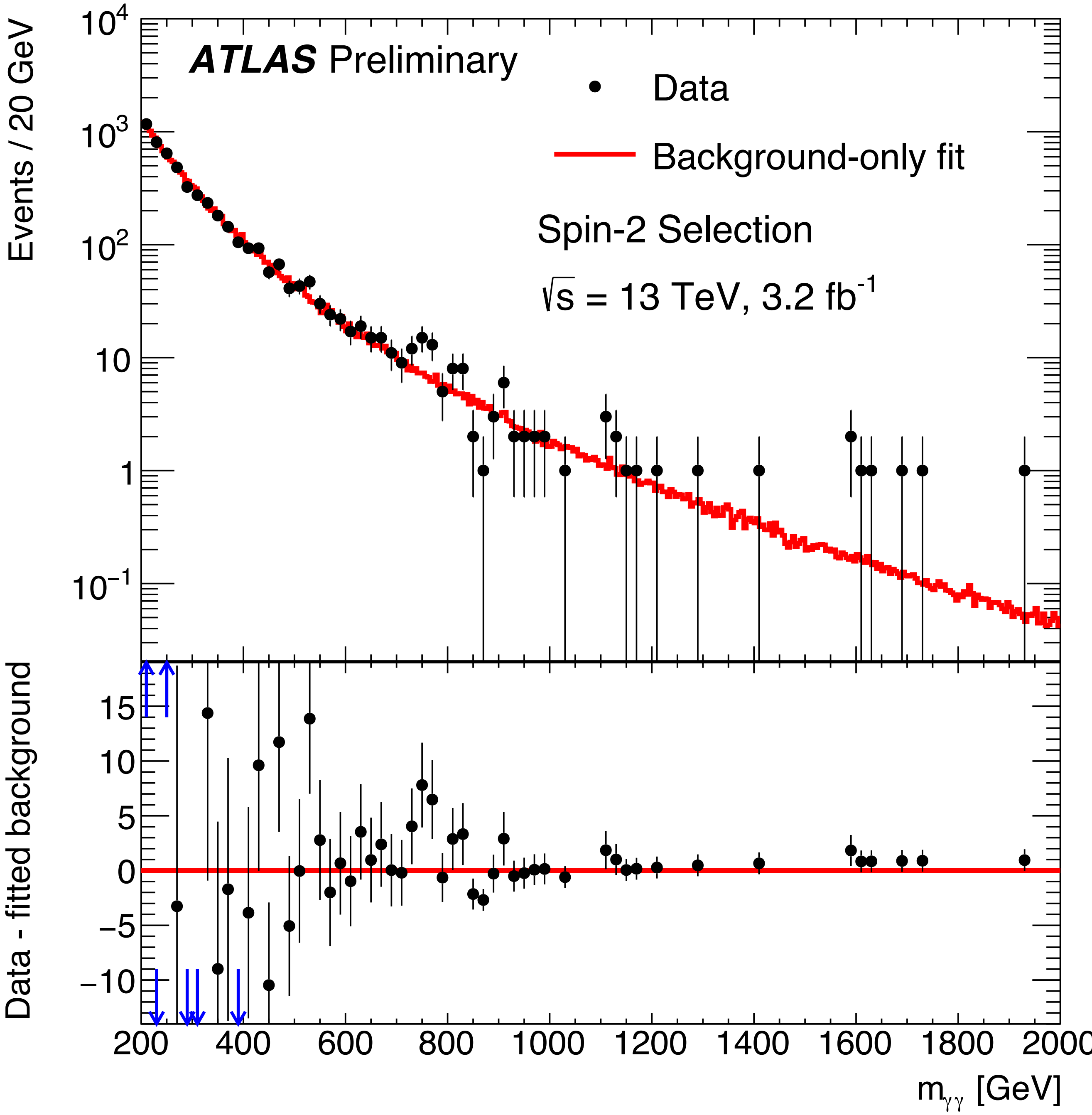
background-only fit



2878 events ($m_{\gamma\gamma}$ > 200 GeV)

SPIN-2 ANALYSIS

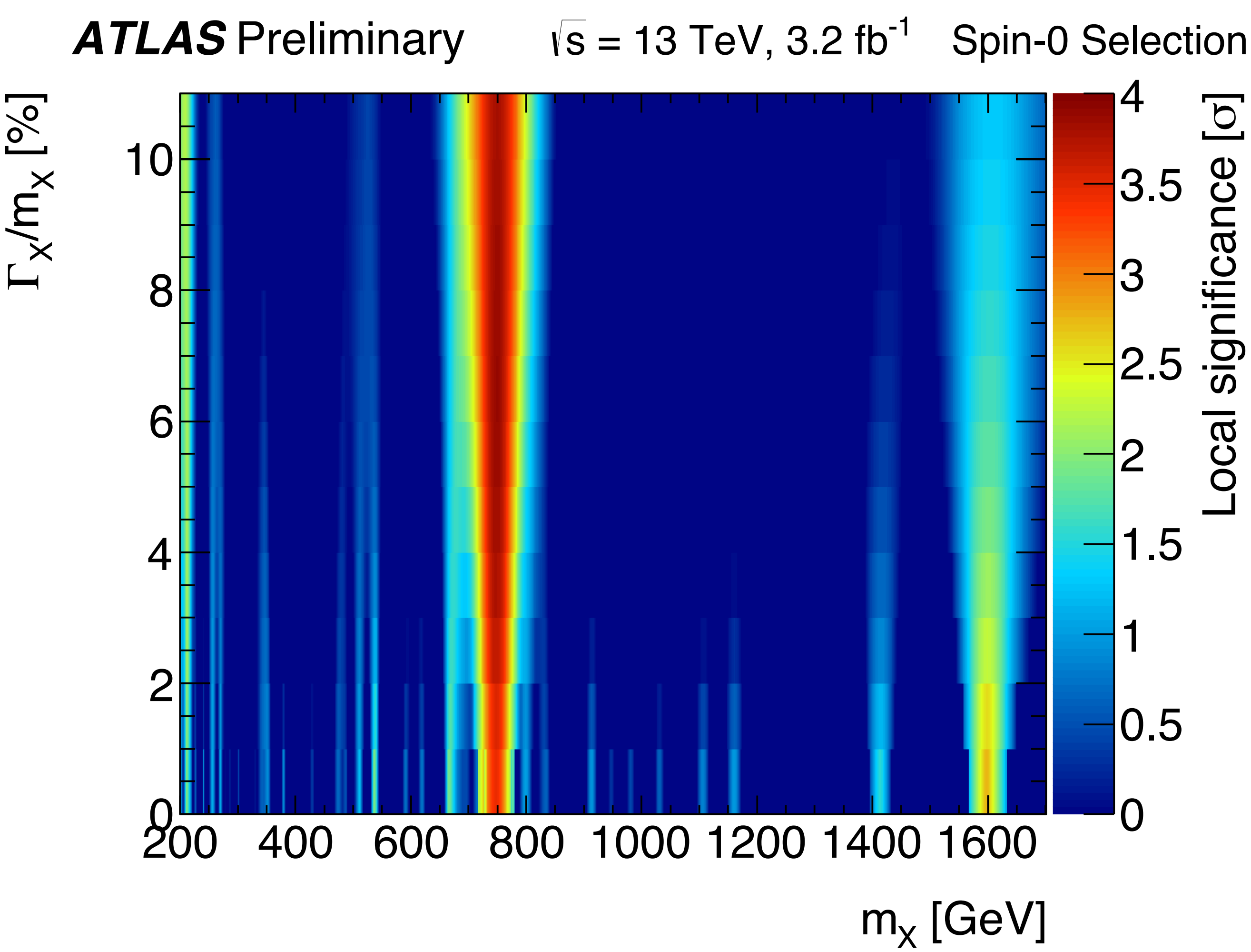
background-only fit



5066 events ($m_{\gamma\gamma}$ > 200 GeV)

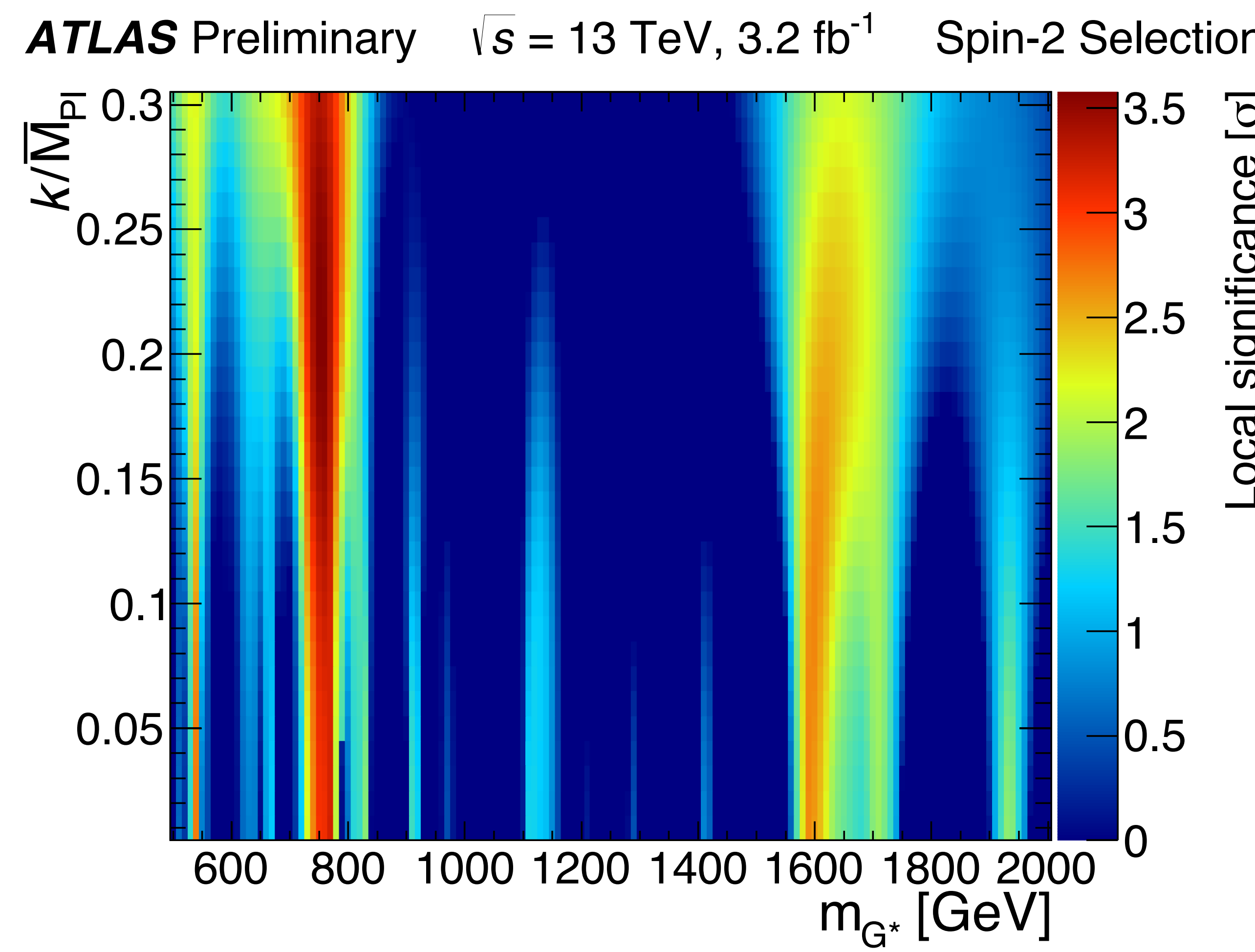
Results

SPIN-0 ANALYSIS



- Largest deviation from B-only hypothesis
  - ✓ $m_X \sim 750$ GeV, $\Gamma_X \sim 45$ GeV (6%)
  - ✓ Local Z = **3.9 σ**
  - ✓ Global Z = **2.0 σ**
    - m_X = [200 GeV - 2 TeV]
    - Γ_X/m_X = [1% - 10%]

SPIN-2 ANALYSIS



- Largest deviation from B-only hypothesis
  - ✓ $m_G \sim 750$ GeV, $\kappa/M_{Pl} \sim 0.2$ ($\Gamma_G \sim 6\%\ m_G$)
  - ✓ Local Z = **3.6 σ**
  - ✓ Global Z = **1.8 σ**
    - m_X = [500 GeV – 3.5 TeV]
    - κ/M_{Pl} = [0.01 – 0.3]

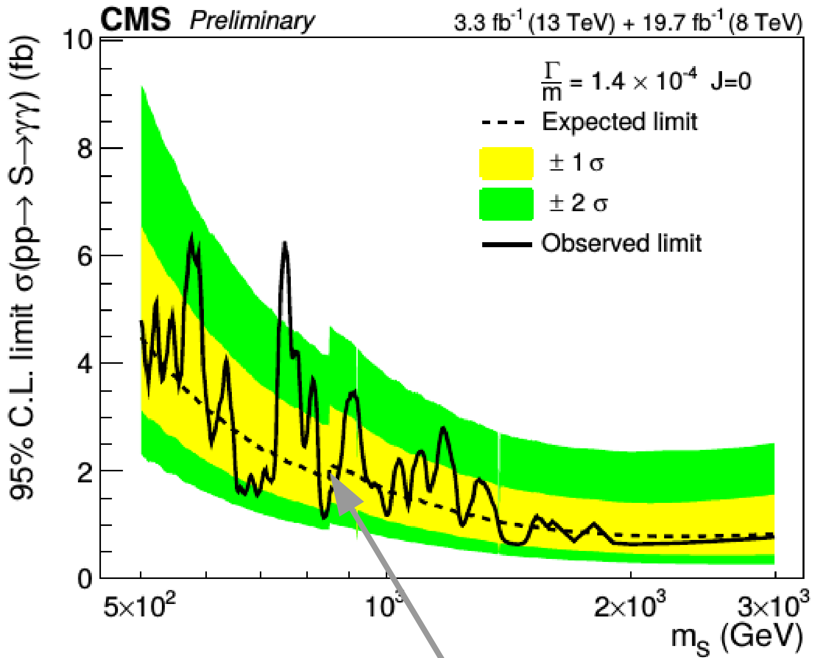
Summary

- Search for new resonances decaying to diphotons performed with 3.2 fb^{-1} 13 TeV data, with two analyses targeting "spin-0" and "spin-2" scenarios
- Most of the $\gamma\gamma$ spectrum consistent with B-only hypothesis
- Largest deviation from background-only hypothesis observed in broad region around 750 GeV, with global significance 2.0 (1.8) σ for the spin-0 (spin-2) analysis
- Numerous cross-checks of events with masses ~ 750 GeV performed
- 8 TeV data re-analyzed using latest Run1 calibration, compatibility with 13 TeV results assessed
  - ✓ Scalar 1.2 σ (gg) – 2.1 σ (qq)
  - ✓ Graviton 2.7 σ (gg) – 3.3 σ (qq)
- More data needed to verify excess origin: looking forward to 2016 LHC run!

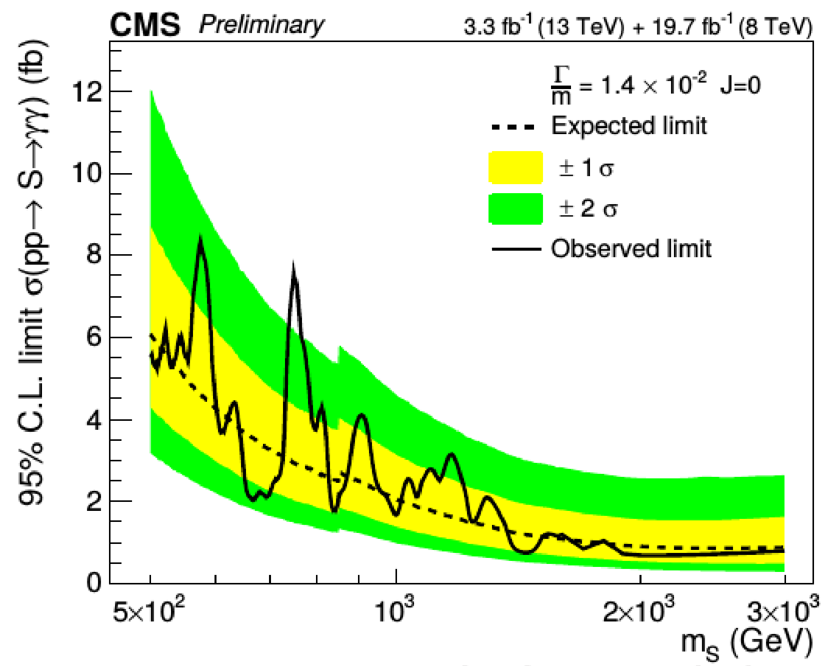
Upper limits (normalized to 13TeV x-sec)

- Compared to single analyses, sensitivity improved by 20-40%.

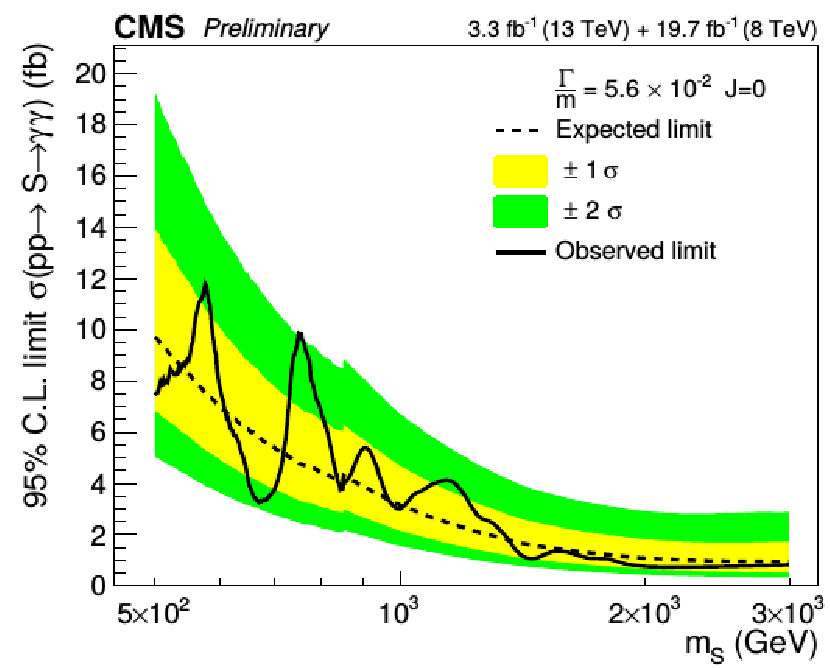
$\Gamma/m = 1.4\text{x}10^{-4}$



$\Gamma/m = 1.4\text{x}10^{-2}$



$\Gamma/m = 5.6\text{x}10^{-2}$

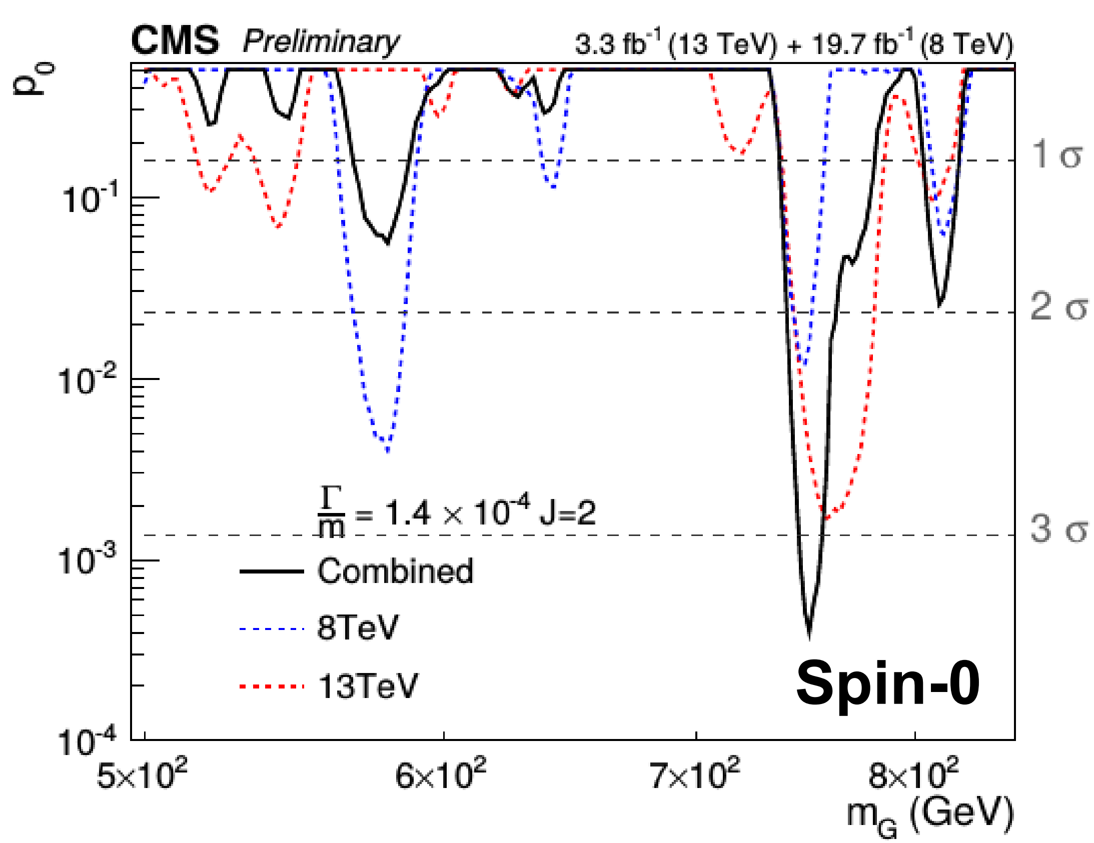


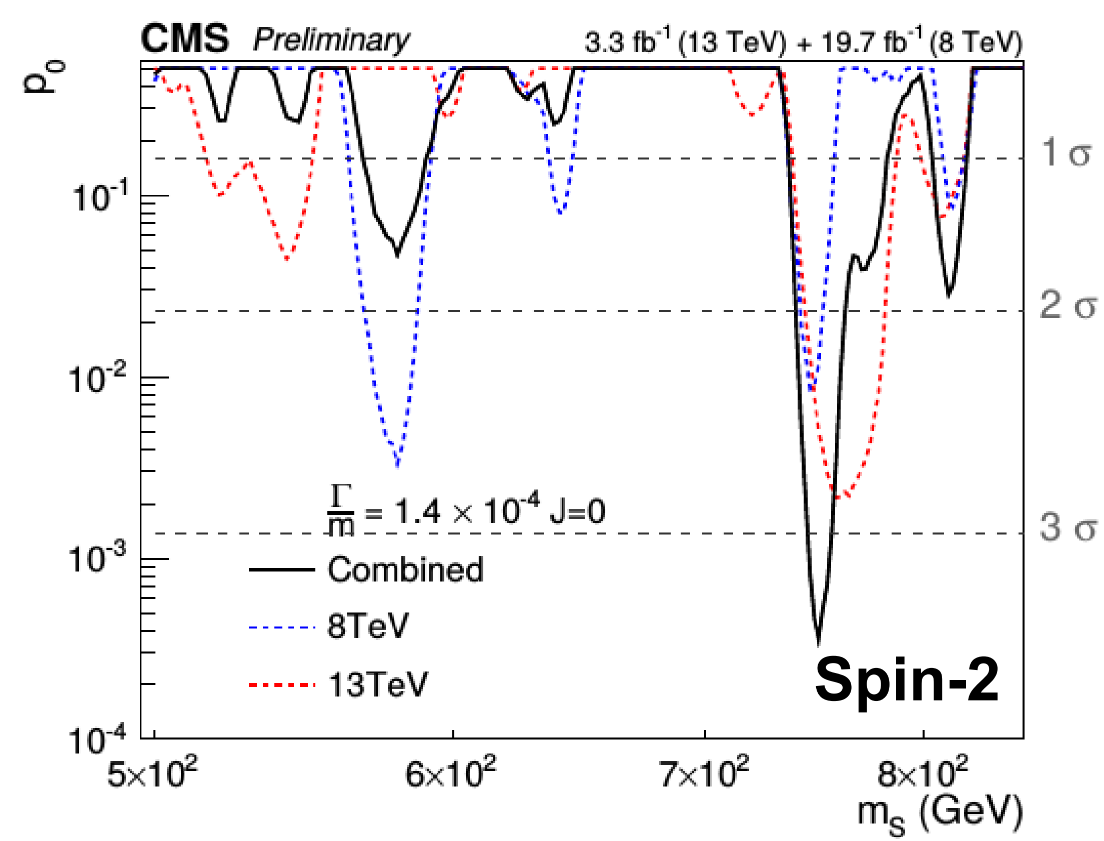
Spin 0

Switch between 8TeV analyses

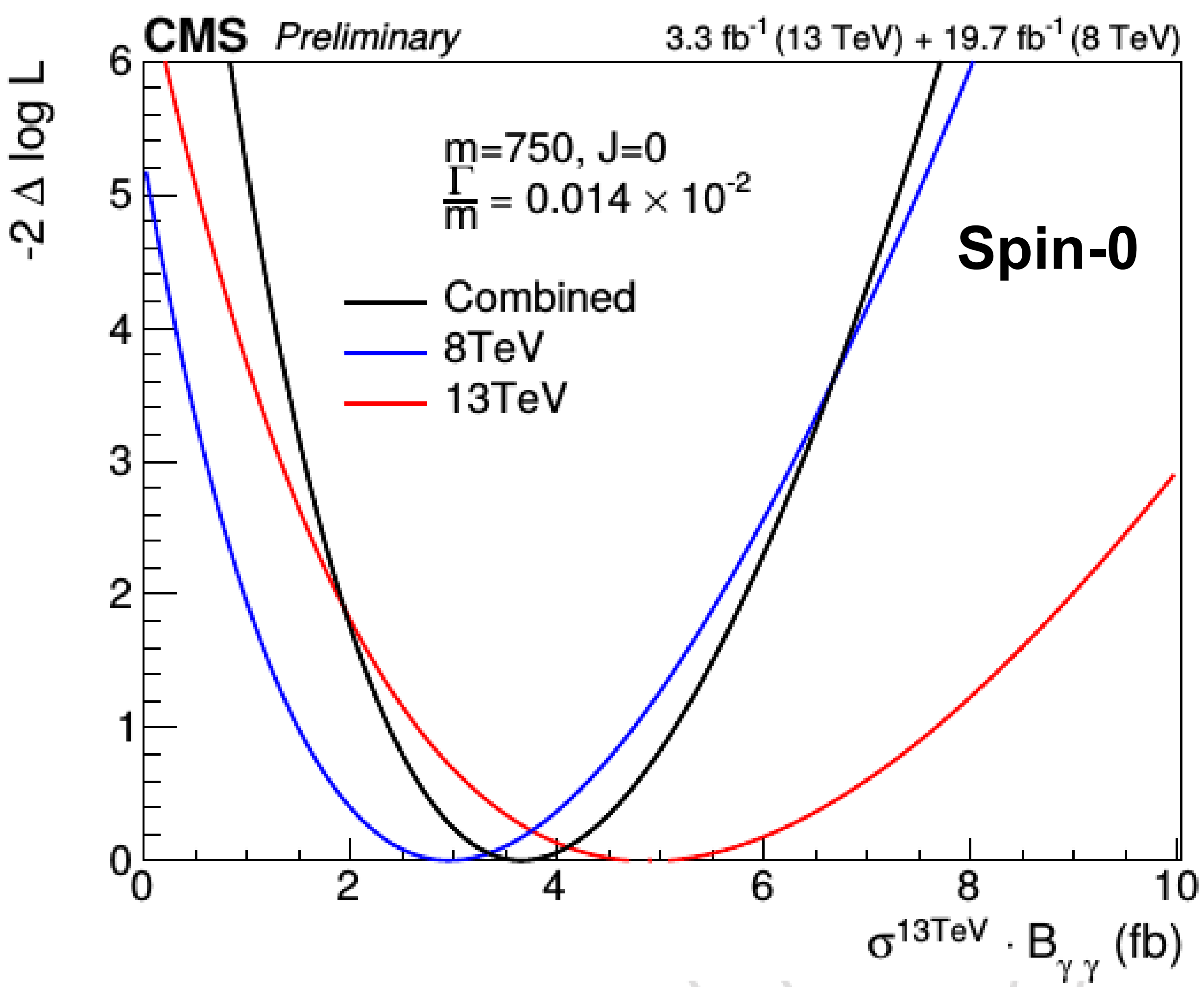
p-values

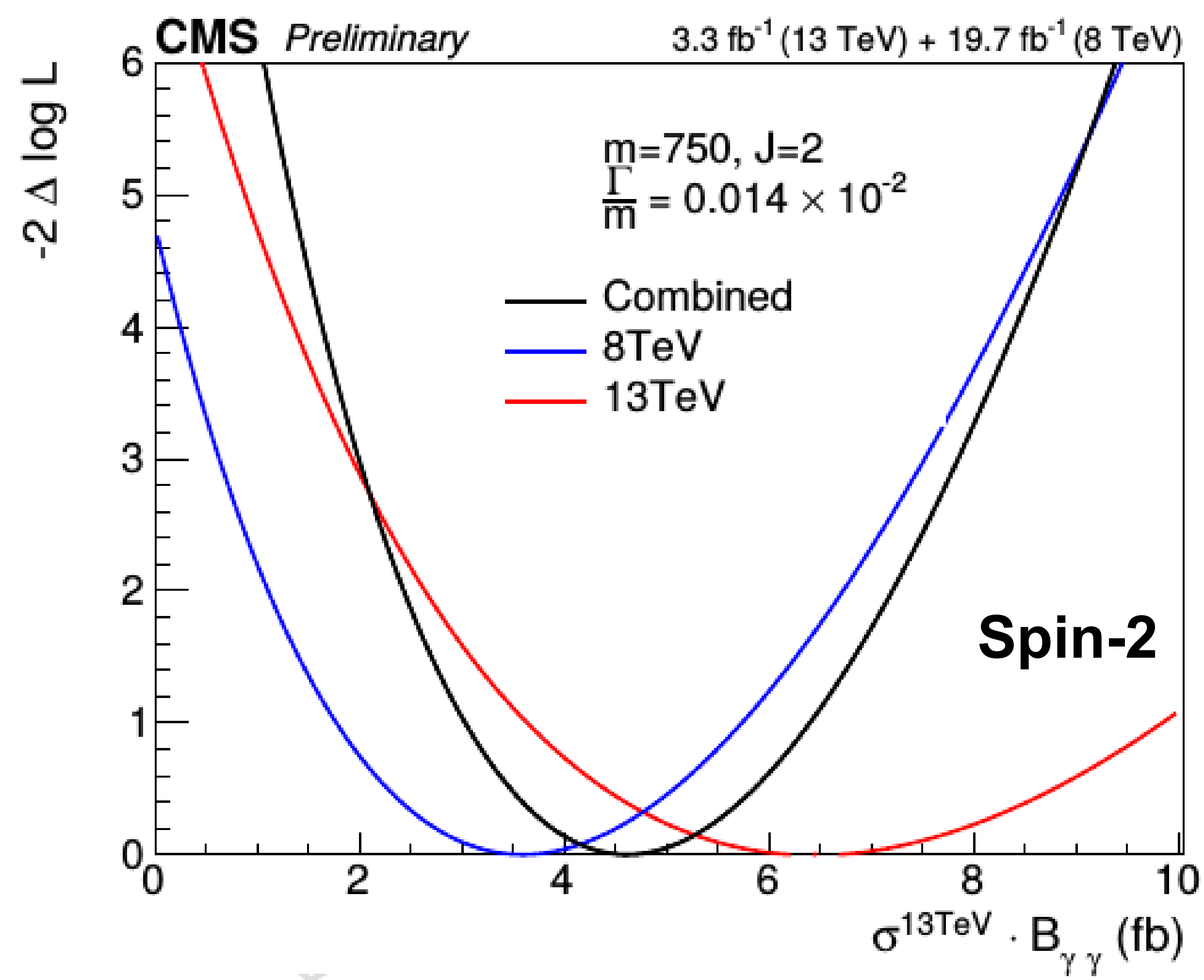
- Largest excess observed at $\mathbf{m_X = 750GeV}$ and for **narrow** width.
  - **Local** significance: **3.4σ**
  - Taking into account mass range 500-3500GeV (and all signal hypotheses), “**global**” significance becomes **1.6σ**





- Evaluated through likelihood scan vs equivalent 13TeV cross-section at m_X = 750GeV under both spin (narrow-width) hypotheses.
  - Compatible results observed in both datasets.





Summary

- Showed an **update on searches for diphoton resonances** in the mass range above 500GeV at 8 and 13TeV.
  - Used simple and robust analysis strategy.

- Used **improved** detector **calibration** and analyzed dataset recorded at **0T**.
  - Compared to previous results, 13TeV analysis improved **sensitivity** by **more than 20%**.
- Results interpreted in terms of scalar resonances and RS gravitons production of different widths.
  - Observation generally consistent with SM expectations.
  - **Modest excess** of events observed at $\mathbf{m_x = 750(760)GeV}$ for the 8+13TeV(13TeV) dataset.
  - **Local** significance is **3.4(2.9)σ**, **reduced to 1.6(<1)σ** after accounting for look-elsewhere-effect.

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

Properties of the diphoton excess

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]	$< 1300\ (r/5)$

$$r = \sigma_{13TeV} / \sigma_{8TeV}$$

$$\Gamma / M \approx 0.06$$

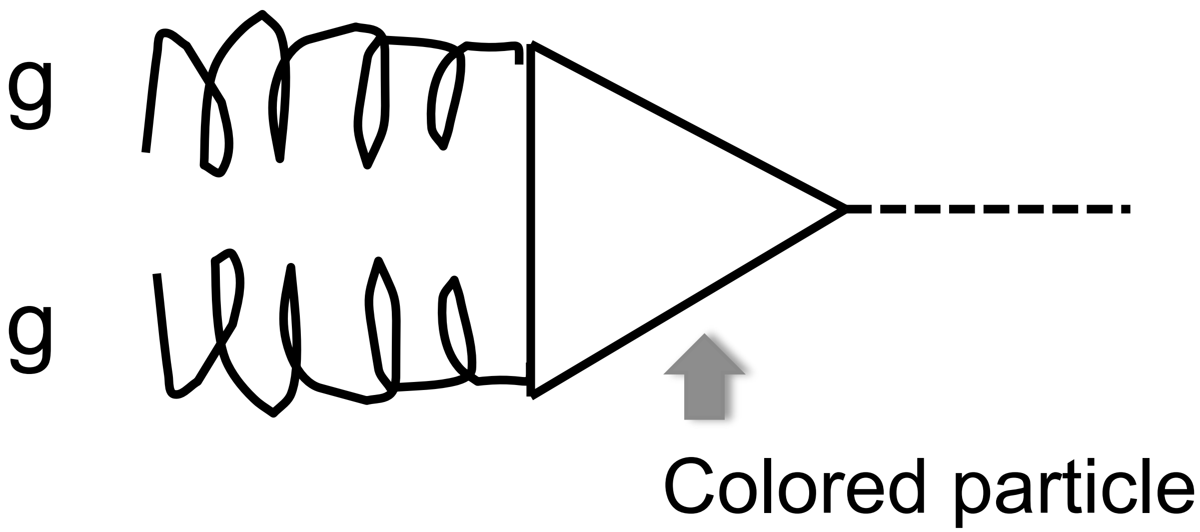
From Table 1 of arXiv:1512.04933 (Franceschini et. al.)

❖ Absence of 750 GeV resonance with other decay modes

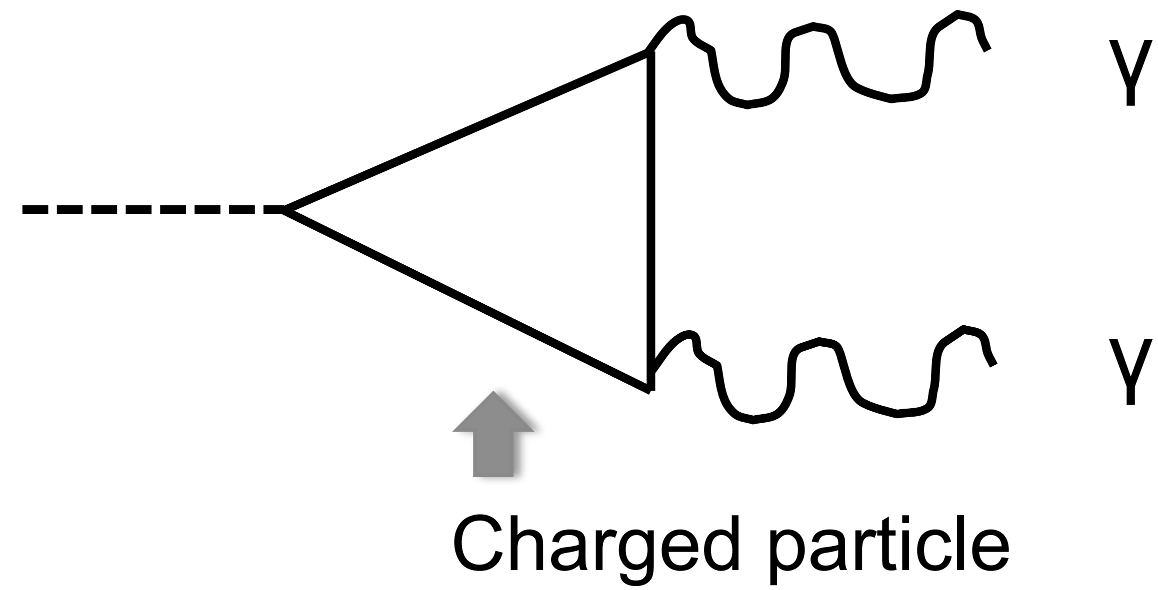
➡ BRs are constrained

One scenario: gluon fusion + diphoton decay via loop

Production: gluon fusion



Diphoton decay channel



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

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

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

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

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 (Not covered in this talk)

- 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' (see also Bhaskar Dutta et al based on SU(6) GUT)

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; And another in preparation
- 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

And a few more in preparation

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And a few more in preparation

Before 750 GeV diphoton,
Only Higgs (~SM) and Nothing
Else So Far 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
- 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 & B->D(*) tau nu puzzle)
- Impose various constraints and study phenomenology

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

In the models discussed here

- 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

E_6 motivated leptophobic U(1)’ model + another example

arXiv:1601.00586 (JHEP) & in preparation
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, which was not considered before

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

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	**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	

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: $i = 1, 2, 3$.

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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

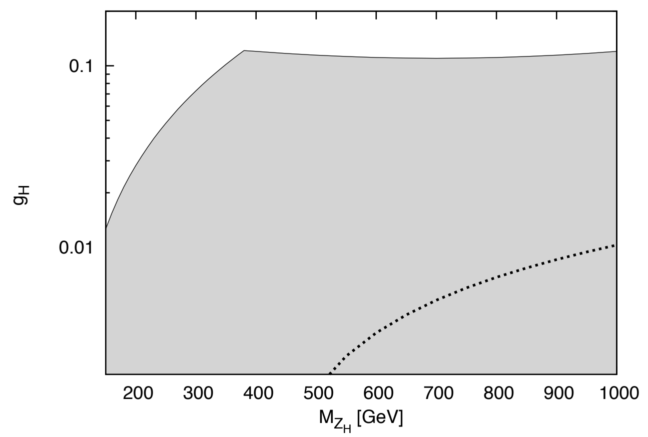
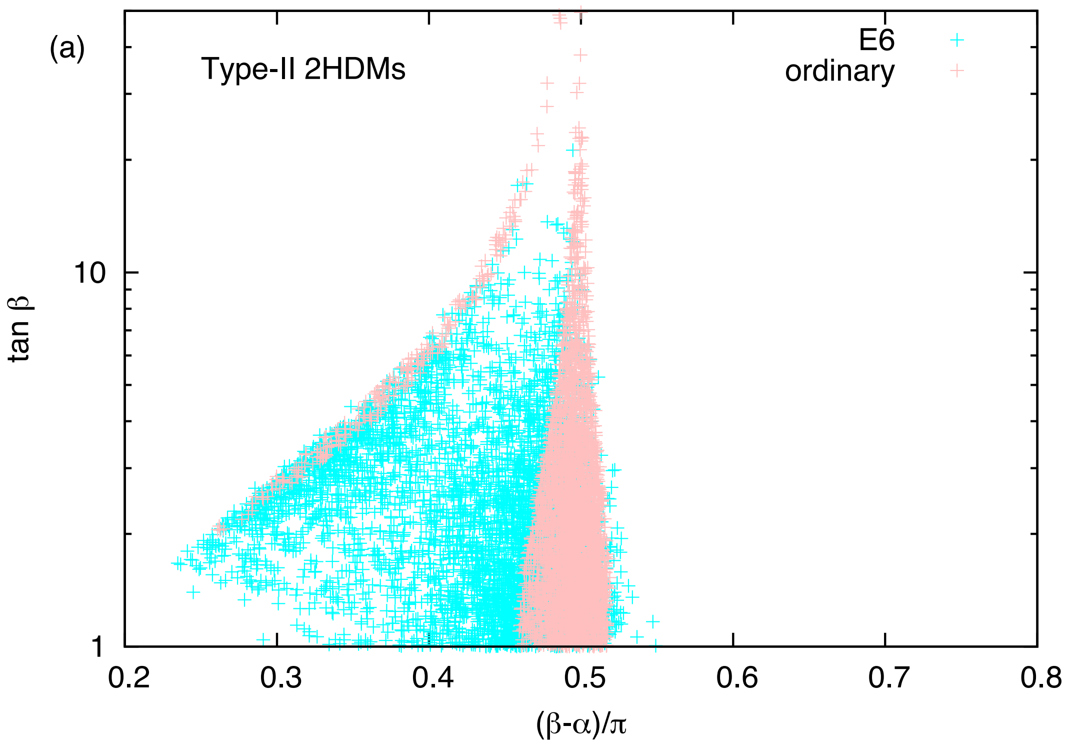


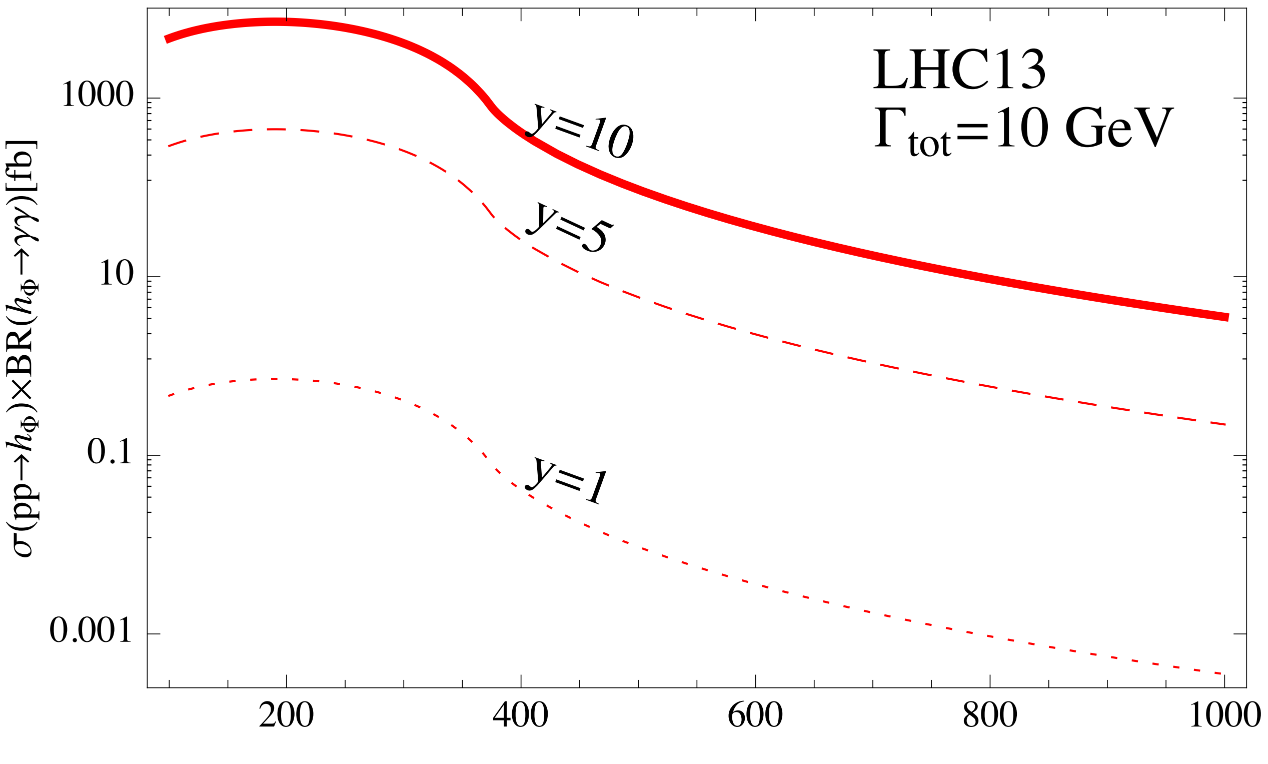
FIG. 1. M_{Z_H} and g_H in the type-II 2HDM$_{U(1)}$. The dot line is the upper bound on the $U(1)_\psi$ gauge boson, and the gray region is allowed for the $U(1)_H(\equiv U(1)_b)$ gauge boson.

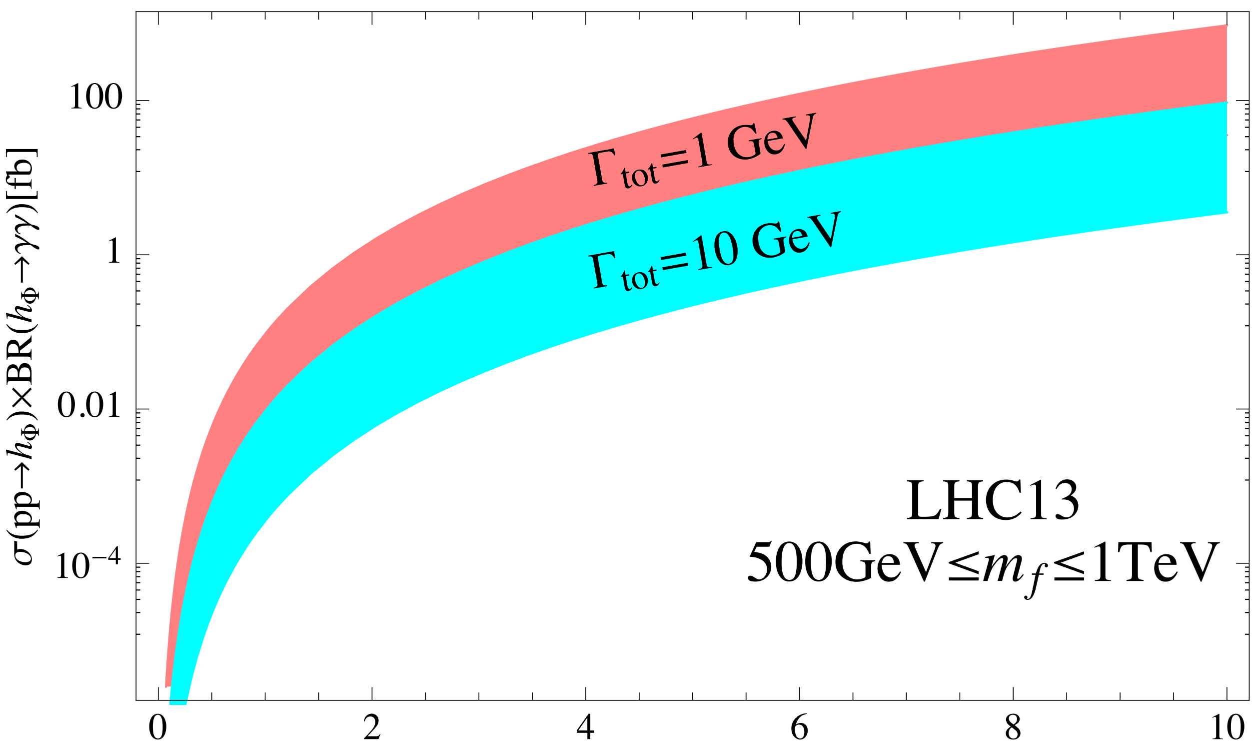


Qualitatively different from the ordinary Type-II 2HDM
arXiv:1502.00262 (Ko, Omura, Yu)

750 GeV Diphoton Excess

Ko, Omura, Yu, arXiv:1601.00586





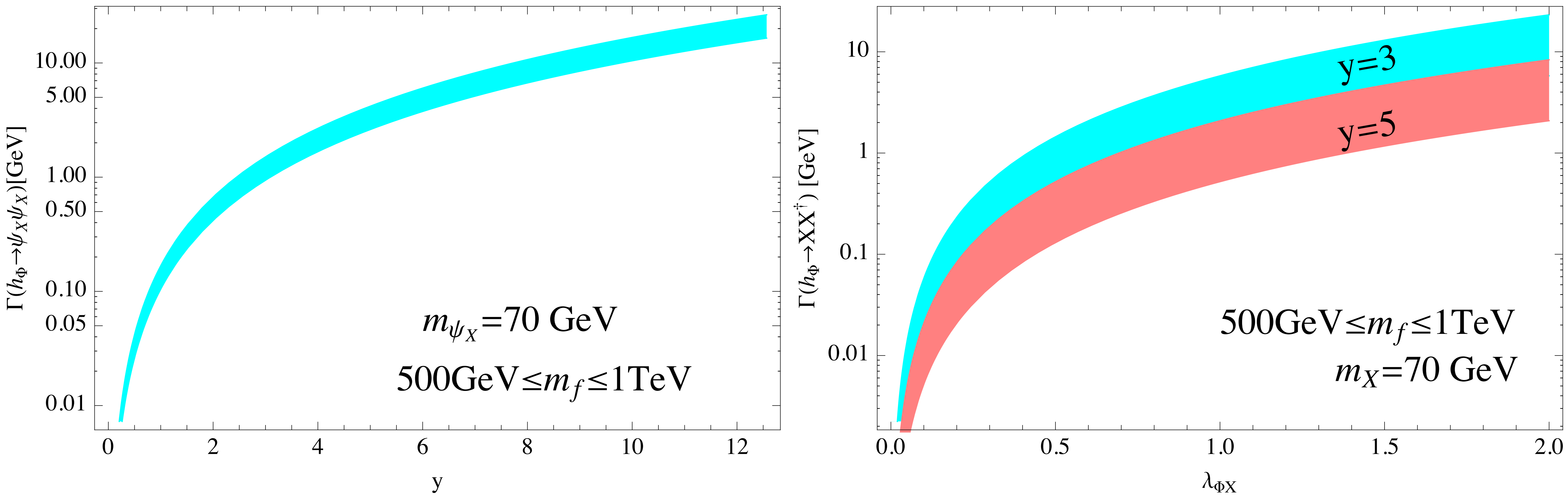


Figure 2: y vs. invisible decay width of h_Φ (GeV) in the fermionic DM scenario (left) and scalar DM scenario (right).The vector-like fermion mass is between 500 GeV and 1 TeV on the cyan and pink bands. The dark matter masses are 70 GeV in the both cases.

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.)

Many possibilities for anomaly cancellation

- Better to have VL fermions with larger electric charges in order to enhance the signal cross section

TABLE I: Charge assignments in the type-II 2HDM with $U(1)_H$. i denotes flavor.

chiral fermions	$SU(3)$	$SU(2)$	$U(1)_Y$	$U(1)_H$	Z_2
u_{Ri}	3	1	2/3	1	+
ν_{Ri}	1	1	0	1	+
U_{Li}	3	1	2/3	1	−
U_{Ri}	3	1	2/3	0	−
N_{Li}	1	1	0	1	−
N_{Ri}	1	1	0	0	−
H_1	1	2	1/2	1	+
Φ	1	1	0	1	+
X	1	1	0	1	−

$$V_m = y_{ij}\overline{U_{Li}}U_{Rj}\Phi + y^N_{ij}\overline{N_{Li}}N_{Rj}\Phi + h.c..$$

$$m^U_{ij}\overline{U_{Li}}u_{Rj} + h.c.,$$

Scalar DM : X

$$\lambda_{ij}X\overline{U_{Li}}u_{Rj}$$

Invisible Decay of 750 GeV resonance

$$\mathcal{L} \supset \lambda_{\Phi X}\Phi^\dagger\Phi X^\dagger X.$$

Then, write down all possible renormalizable terms

Preliminary Result

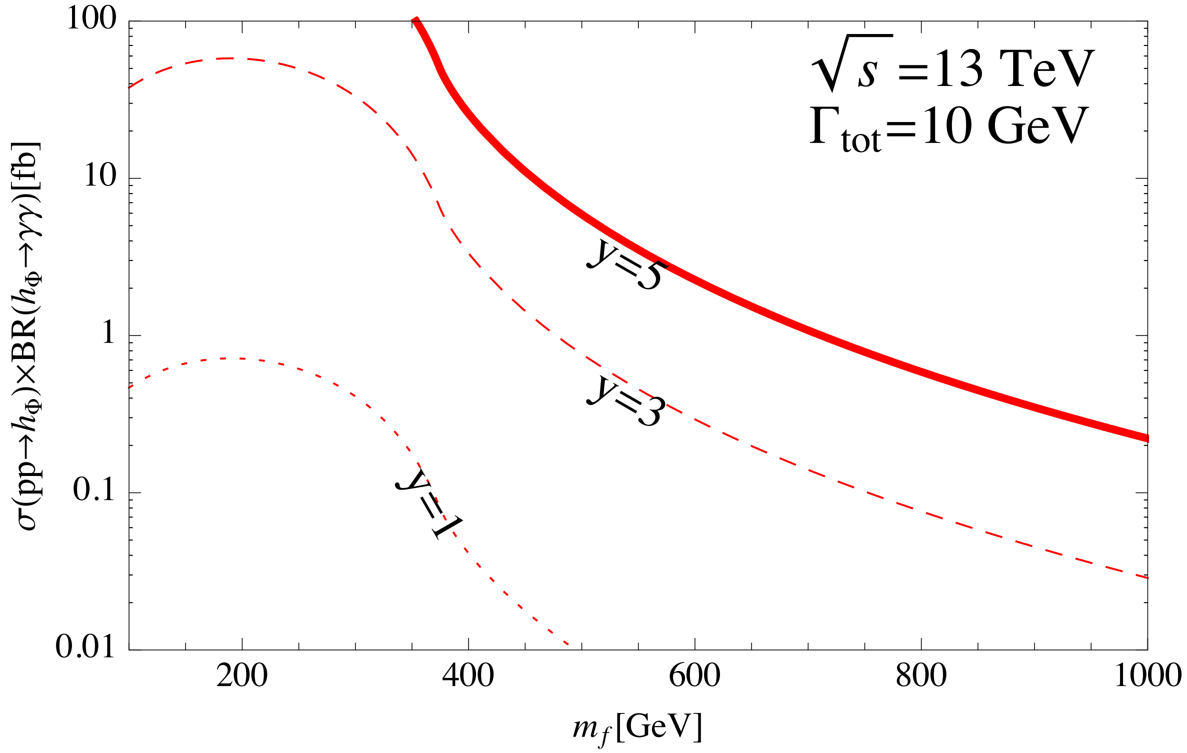


FIG. 1: (Left): m_f vs. the diphoton signal via the gluon-gluon fusion at $\sqrt{s}$ =13 TeV. The total decay widths is fixed at $\Gamma_{\rm tot} = 10$ GeV. The yukawa coupling y is $y = 1$ (dotted), 3 (dashed), and 5 (thick).

Conclusion

- Type II 2HDM + U(1) Higgs gauge symmetry : leptophobic U(1)' derived from E6, and many other possibilities
- Can accommodate the 750 GeV diphoton excess at qualitative level. Quantitatively in the future ?
- A new playground for new gauge models (including DM, see next part)

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

arXiv:1601.02490, with T. Nomura

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 $\langle X \rangle = 0$

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

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

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

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

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

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$U(1)_Y$	-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)

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

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

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

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

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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
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(3 generations of fermions)

X,N : DM candidate

New Lagrangian

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

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Decay of new fermions F

F → 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

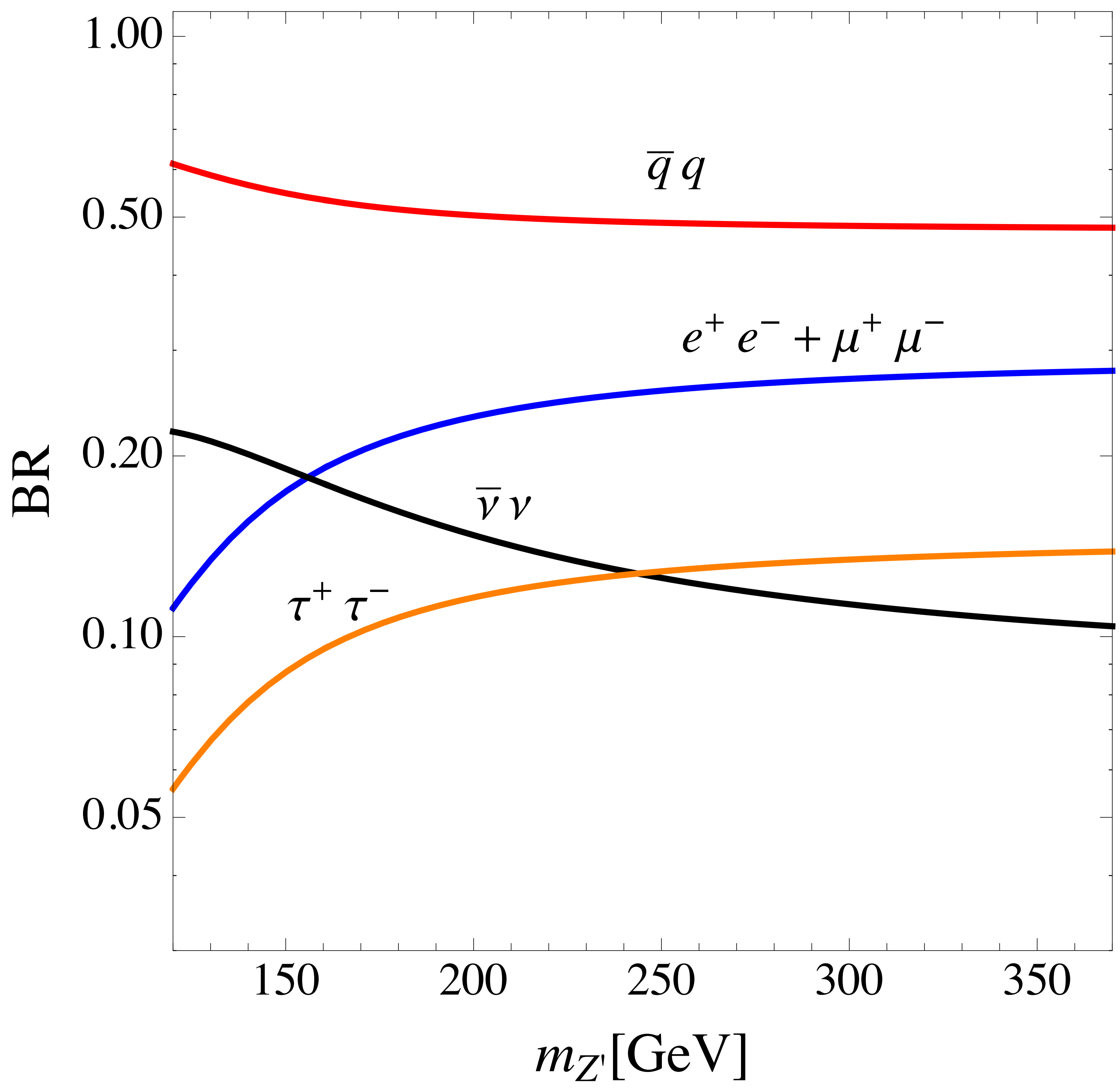
$$m_{Z'}^2 \approx (a+b)^2 g_X^2 v_\phi^2, \quad m_F = \frac{y^F}{\sqrt{2}} v_\phi$$

➡

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

❖ Z' decays through small Z-Z' mixing

BRs of Z'



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

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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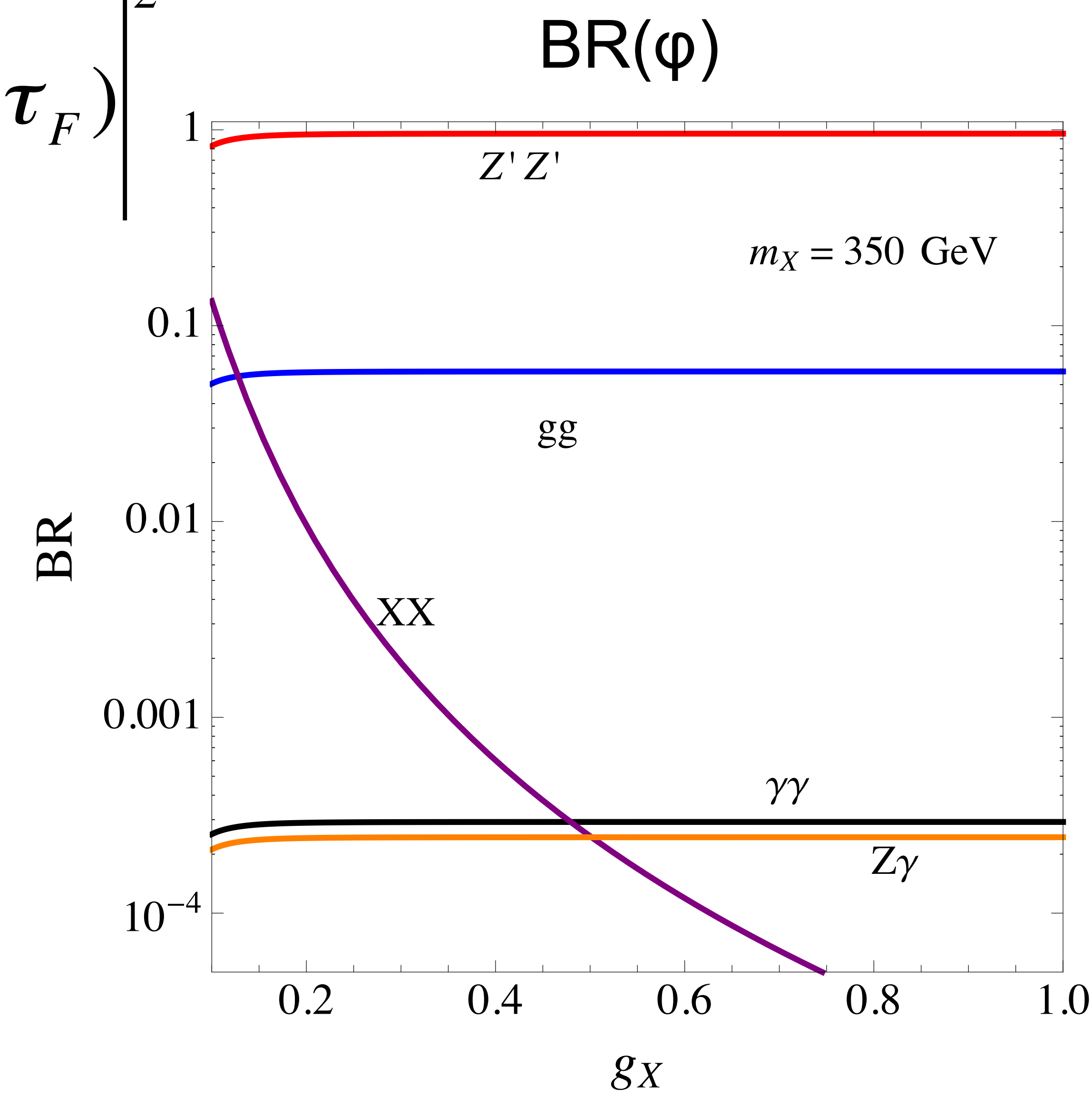

Gluon fusion and decay modes of φ

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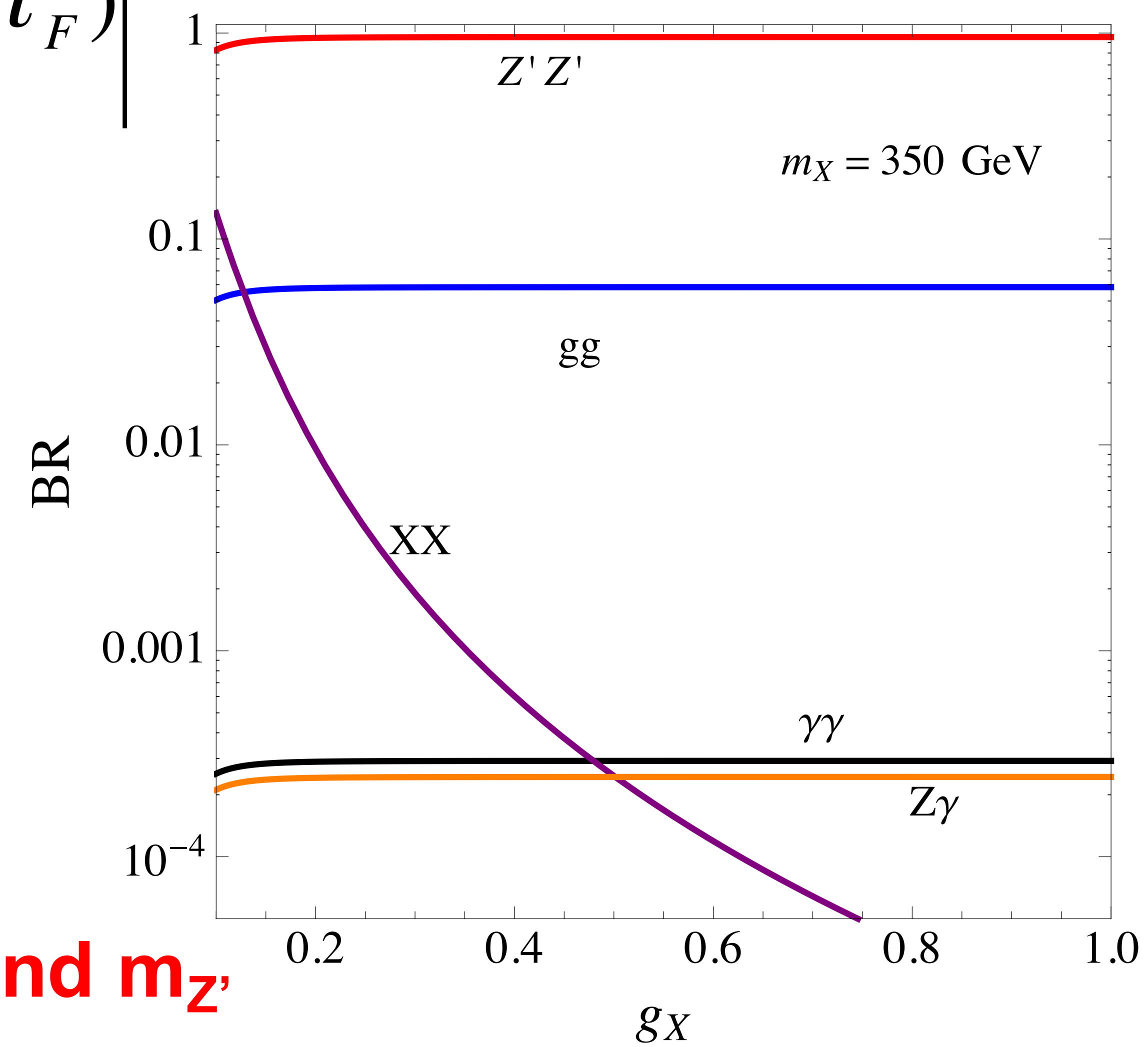
⋮

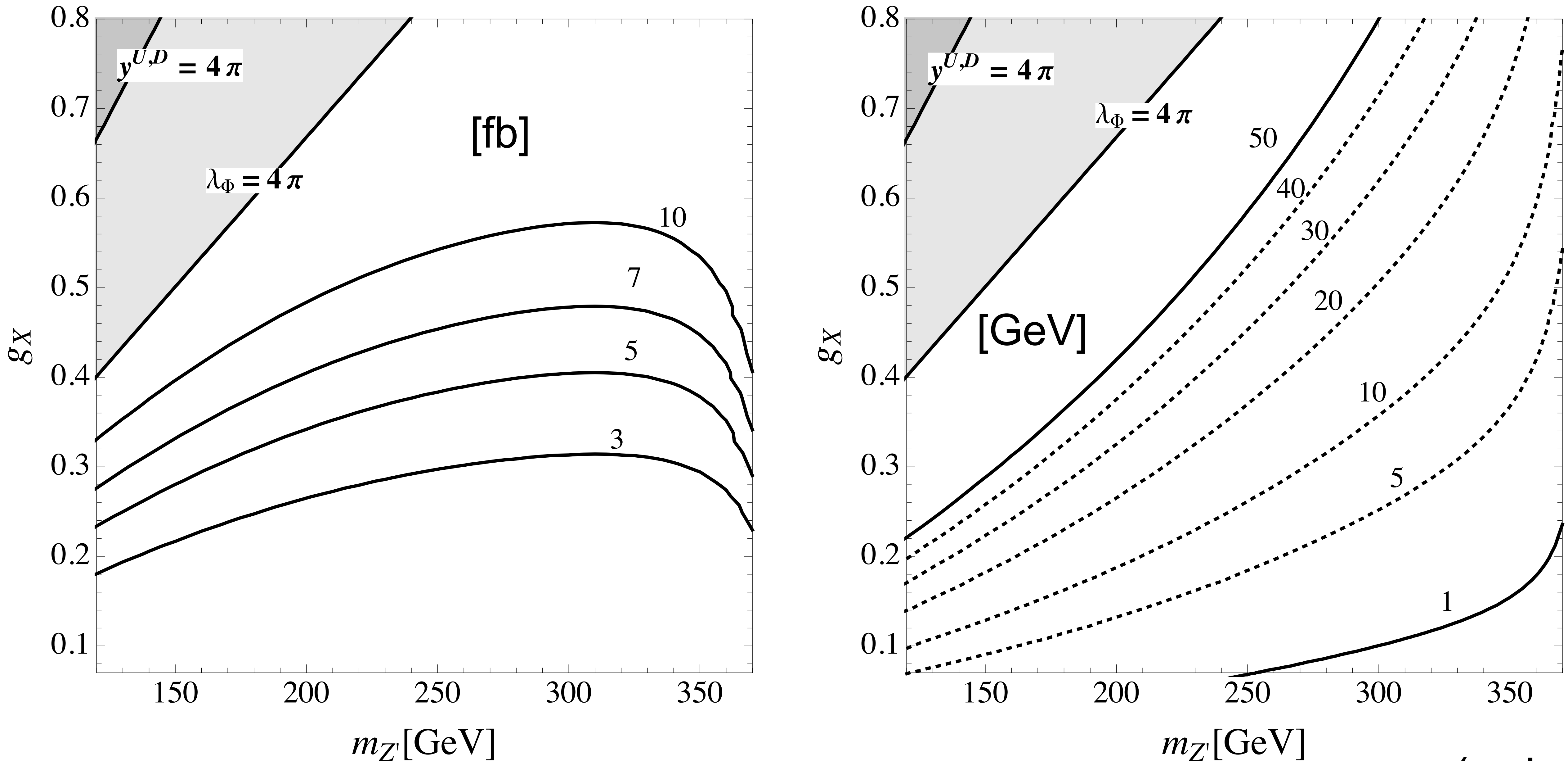
BR(φ)



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

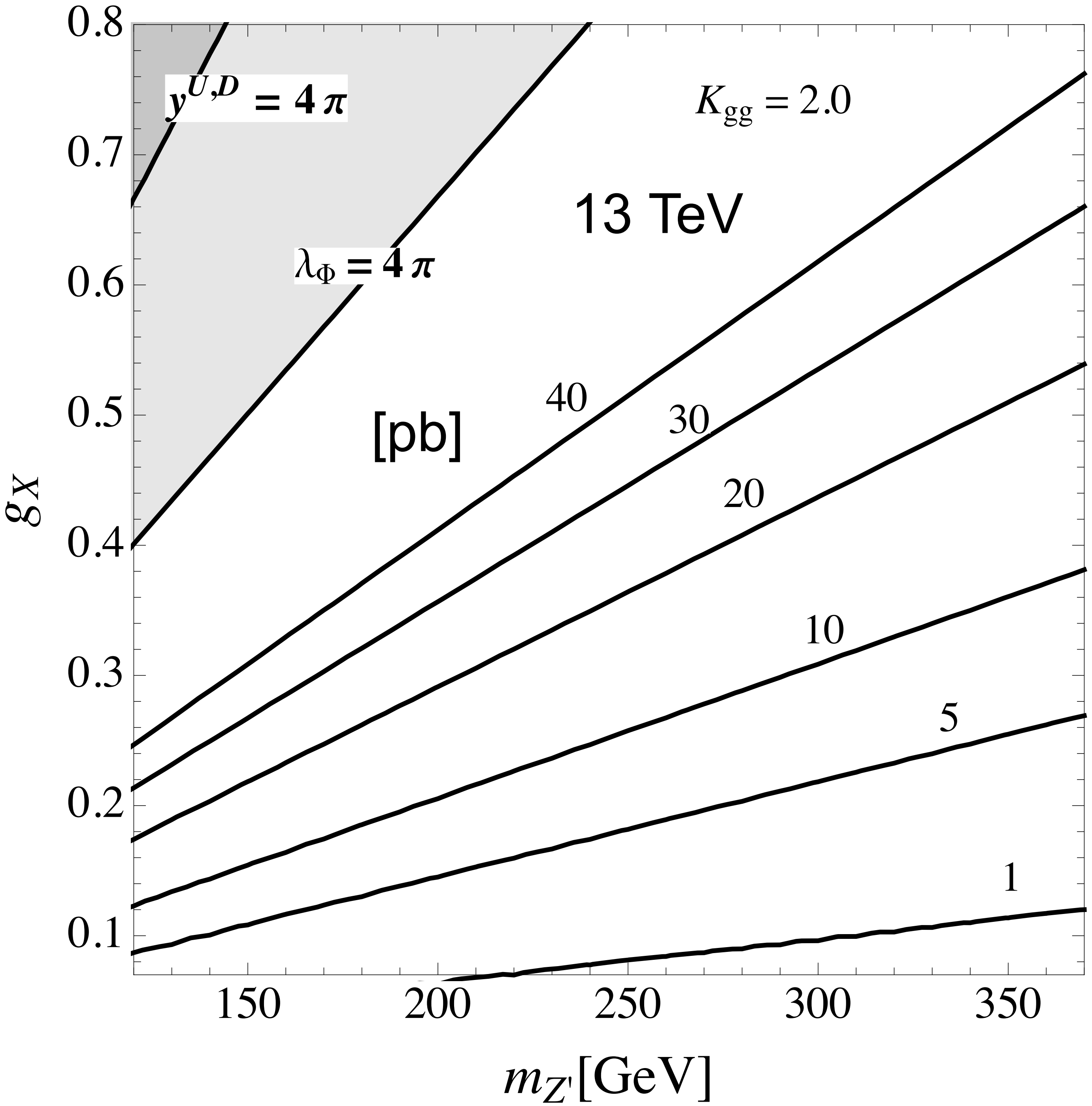


(a~b~1)

$\{M_{U,D}, M_{E,N}, M_X, \lambda_{X\Phi}\}$ = {800 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

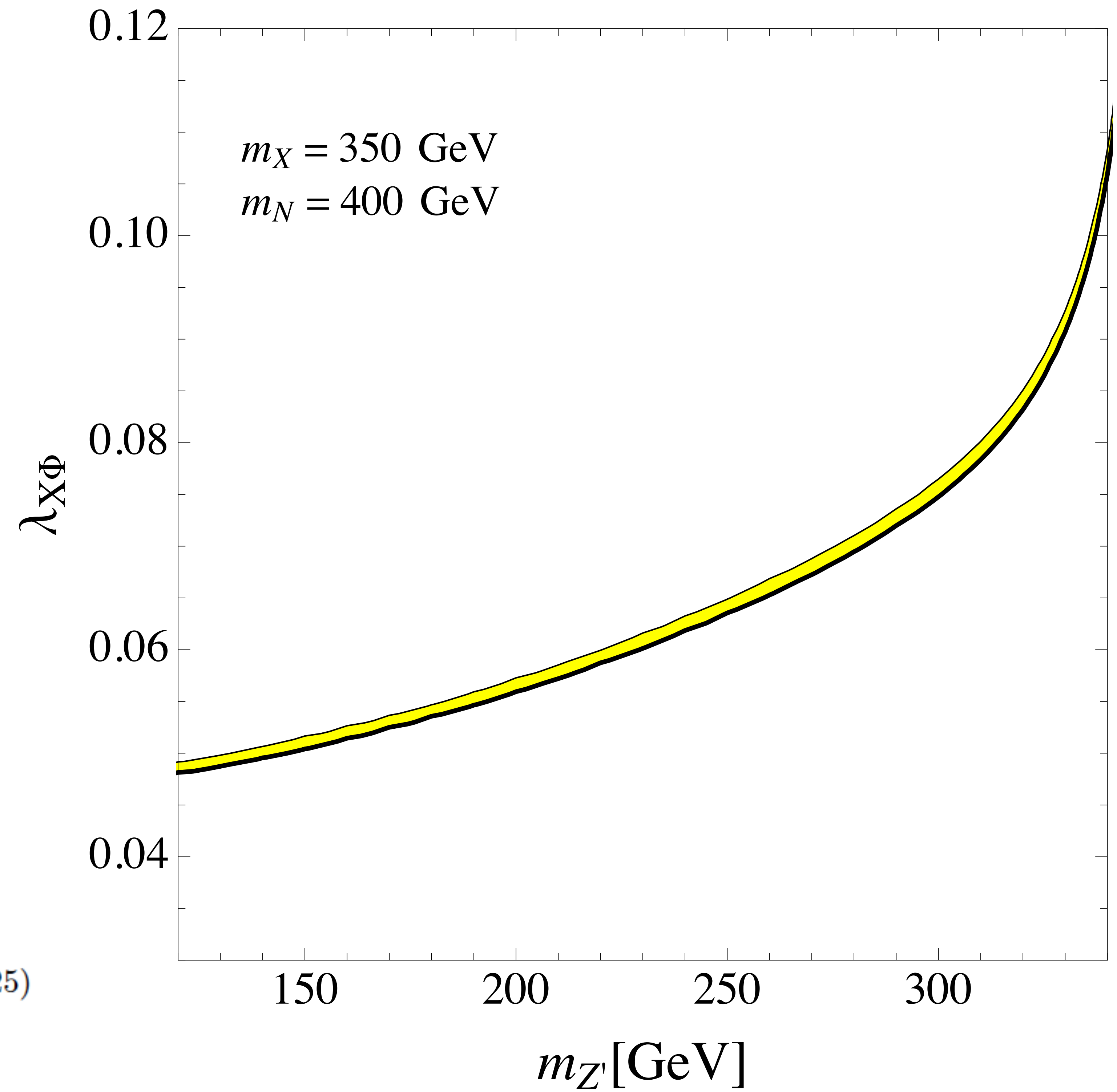
Annihilation process

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 mX = 350 GeV and mEi = 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
- Indirect signatures and $SU(2)_L$ charged case under study

Closing Remarks

- Diphoton excess needs to be confirmed this/next year
- If confirmed, this may be a signal of new gauge force and its Higgs boson, or new confining forces on new (s)quarks
- The width of the resonance is a crucial information for particle physics model buildings
- Could be a new Higgs boson related with new (chiral) gauge symmetry
- Generically large Yukawa > Low scale Landau Pole

Closing Remarks

- Also need very small mixing between the 125 GeV Higgs boson
- Not easy to have ~45 GeV width without conflict with the present constraints on other decay channels
- The easiest way is to allow new decay channels which are less constrained (dark photon pair, Hh, HA, etc..) : but will eventually be constrained by the near future LHC data
- These problems might be mitigated in composite model