Possible implications of 750 GeV diphoton excess @ LHC

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“Interplay between LHC and flavor physics”
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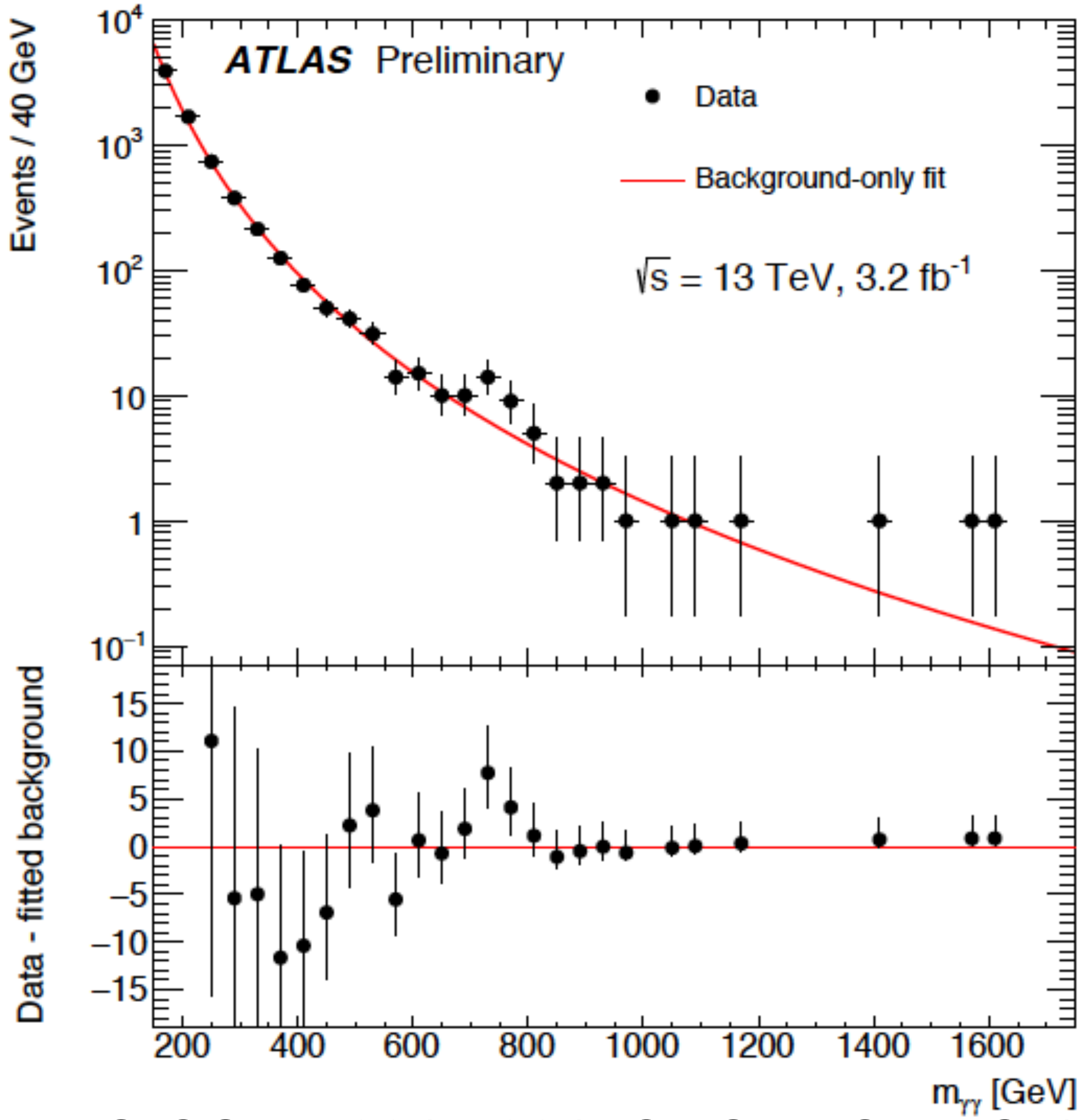
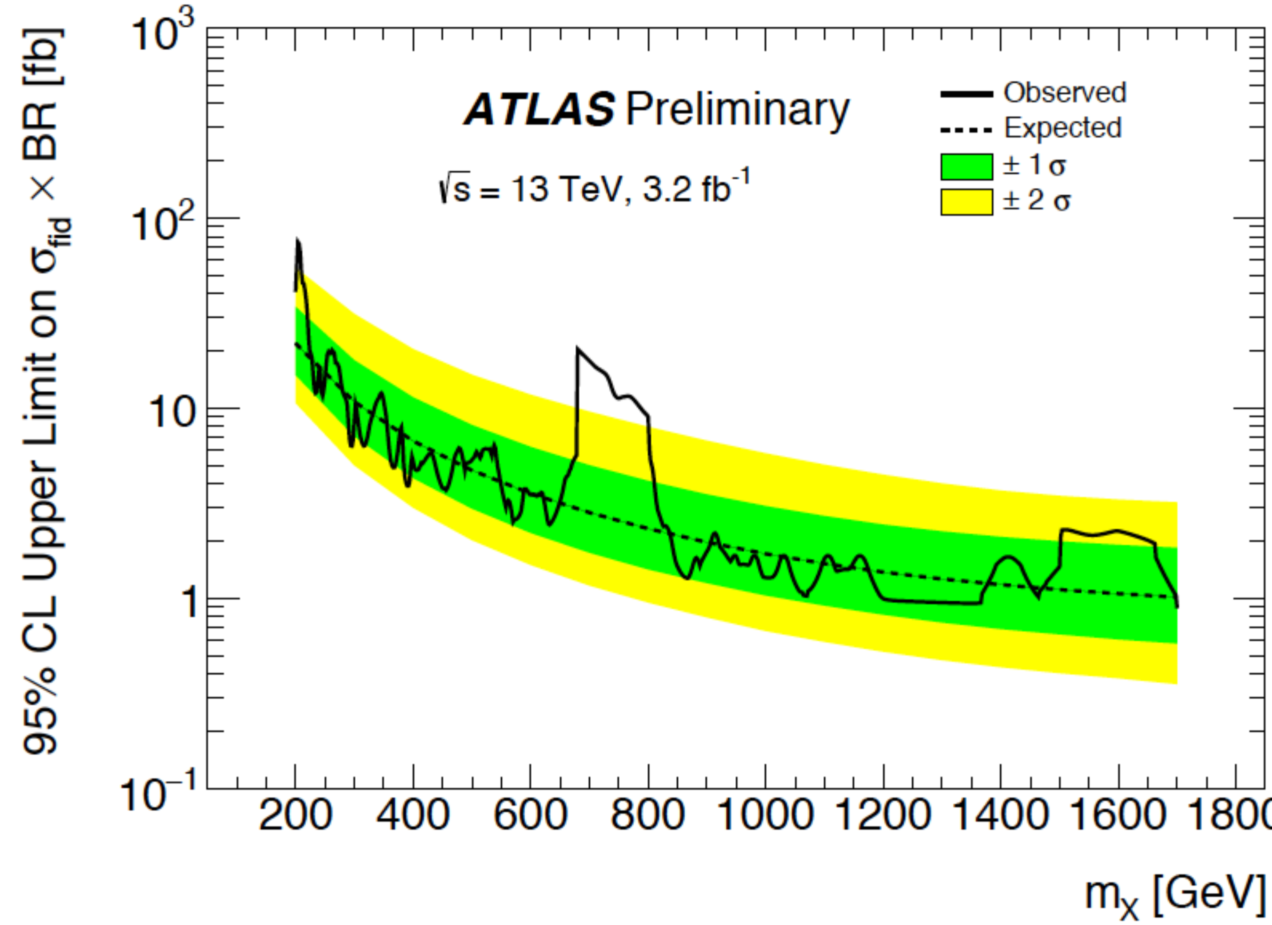
- Model I : E_6 motivated leptophobic U(1)' model
- Model II : Dark Higgs interpretation of diphoton excess
- Model III : Composite Models (??)
- Closing remarks

750 GeV diphoton excess at the LHC

Diphoton excess at 750 GeV



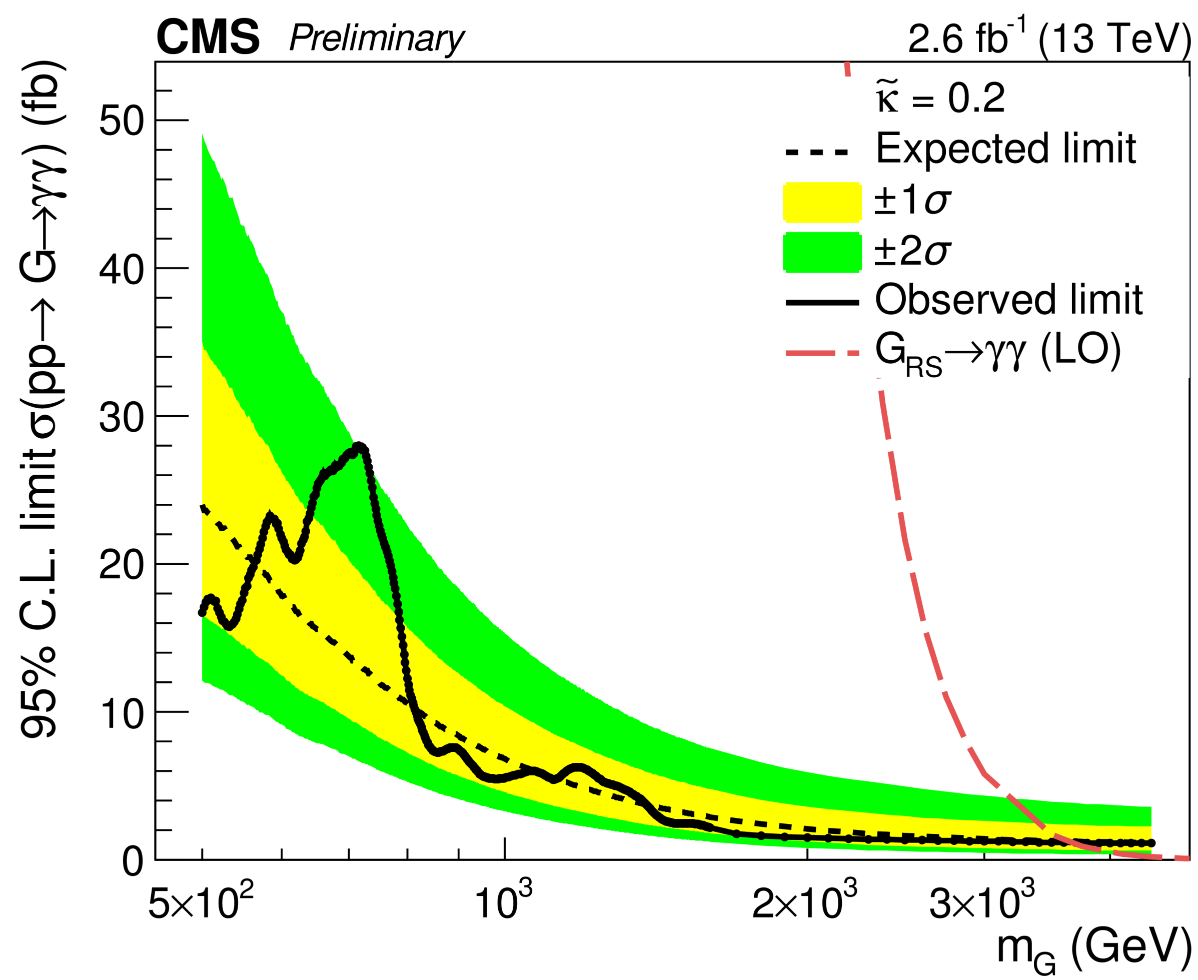


ATLAS-CONF-2015-081, CMS-PAS-EXO-15-004

Both ATLAS and CMS observed bump on diphton invariant mass distribution

3.6 σ : ATLAS
2.6 σ : CMS

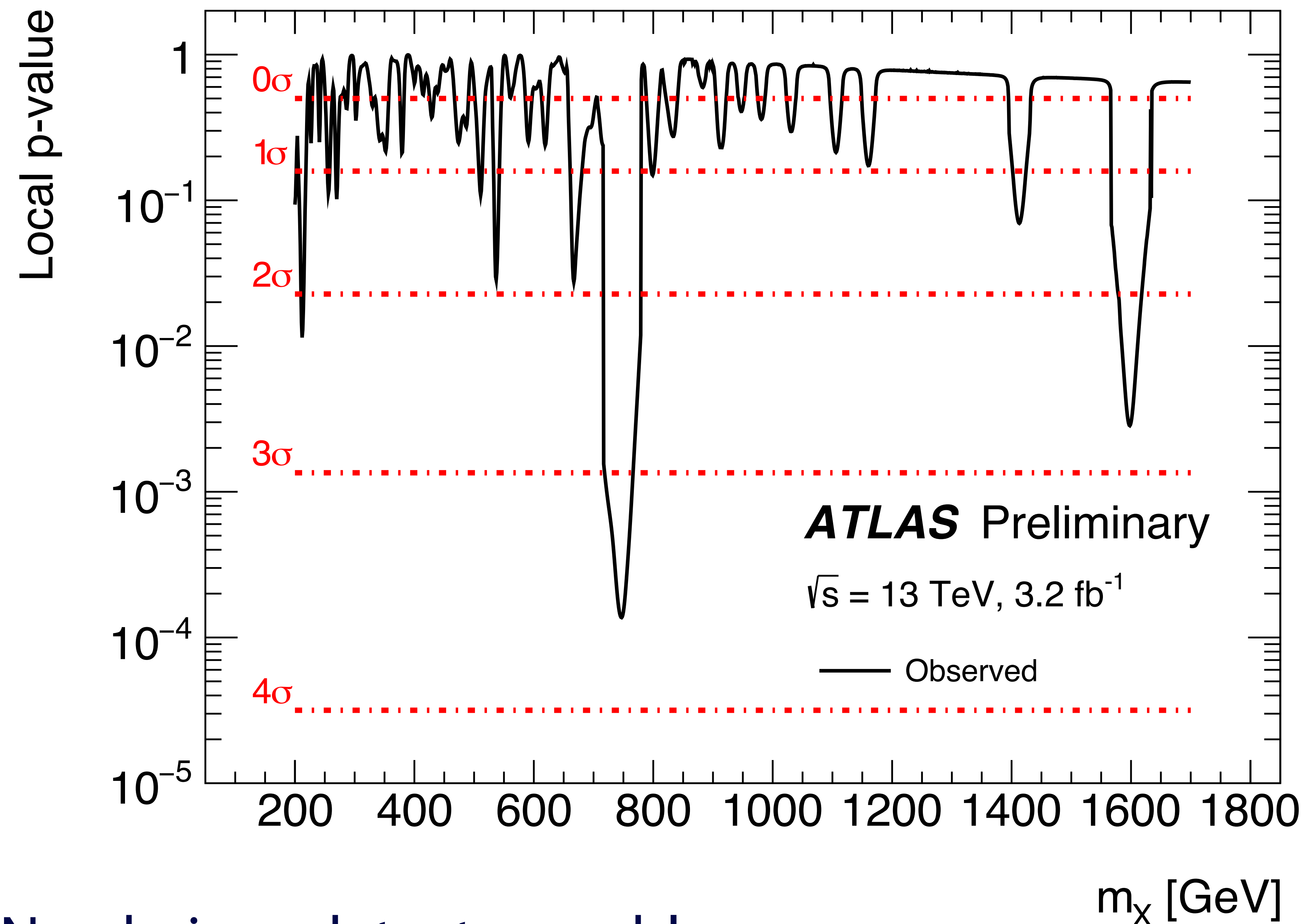
(Local significance)



Diphoton

Slides from Koji Terashi's talk

"Higgs-like" NWA scan → local(global) 3.6(2.0)σ excess around 750 GeV



- No obvious detector problems
- Event characteristics : consistent with mass sideband
- ~1.5σ pull of photon energy resolution systematics

Diphoton

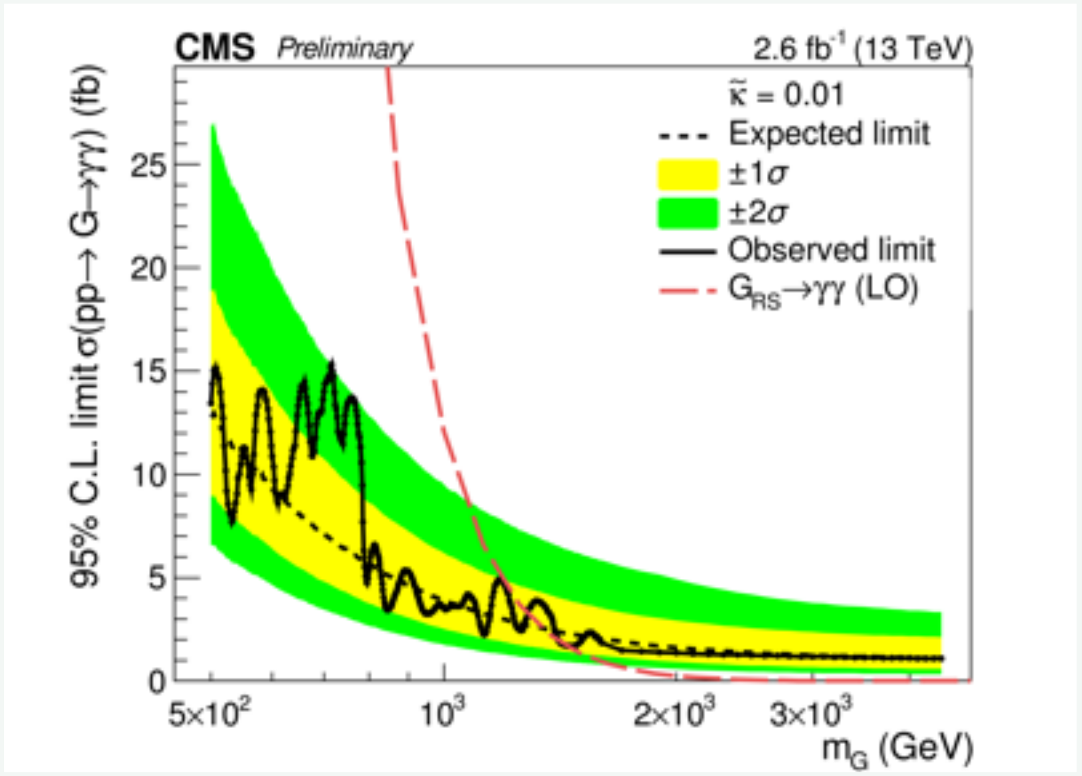
Slides from Koji Terashi's talk

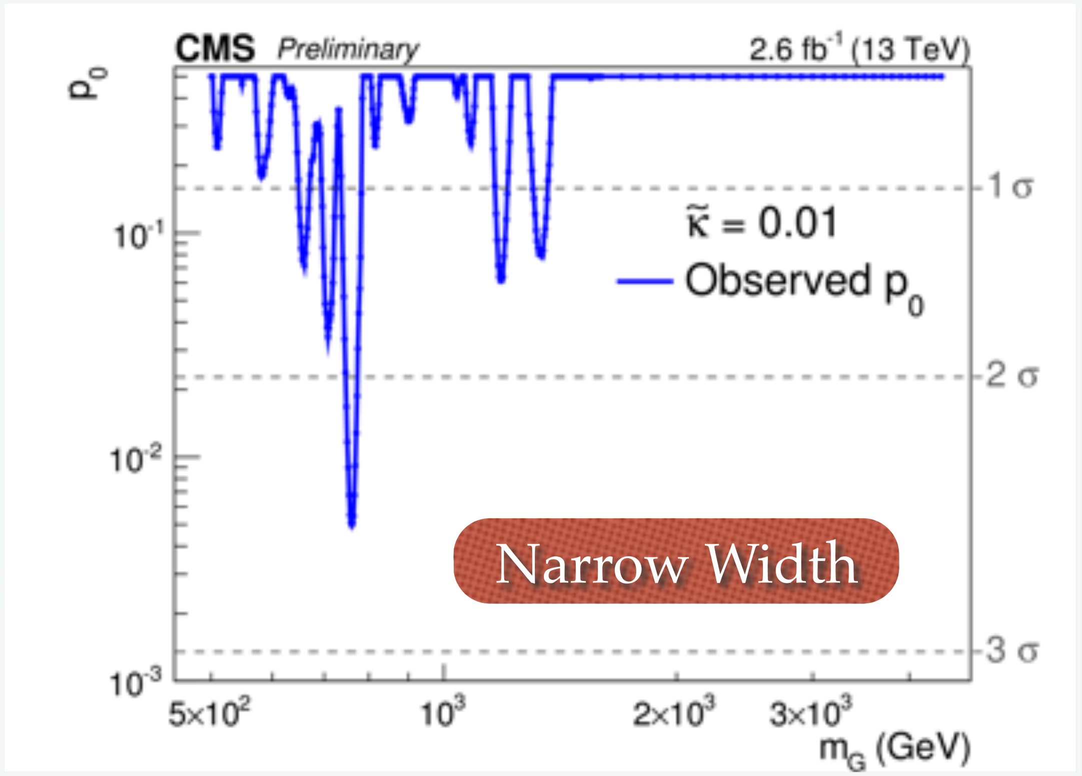
- 2D mass-width scan (mass = 200-2000 GeV, width =1-10%)
  - Local(global) 3.9(2.3)σ excess around 750 GeV
  - Best fit Γ/m ~ 6% (Γ ~ 45GeV)
- Compatible with Run 1 at 2.2(1.4)σ level for NWA (6% LWA) under gg hypothesis

Slides from Jack Kai-Feng Chen's talk

Diphoton Resonances (cont.)

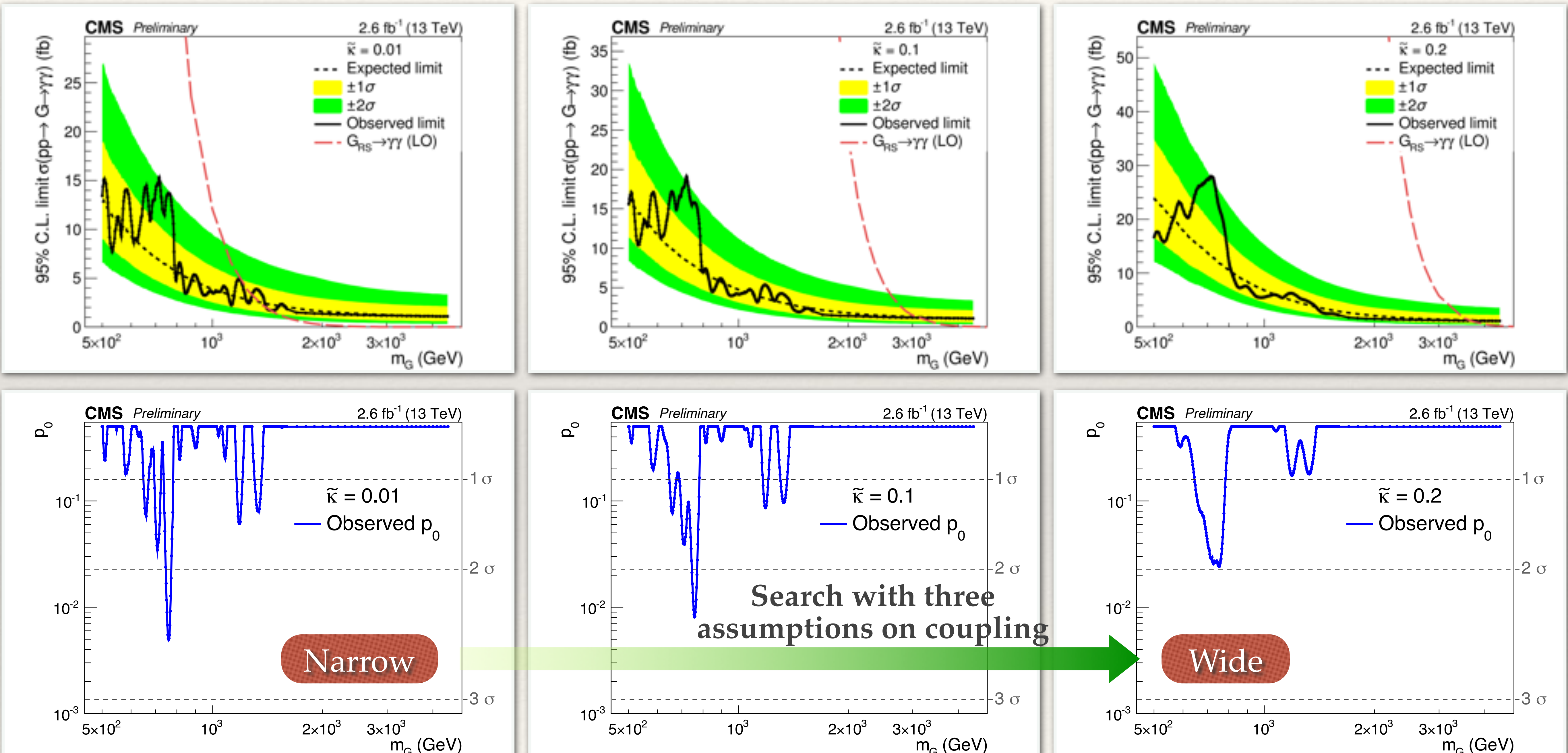
- **Statistical interpretation based on the m spectrum for the search of diphoton resonances.**
- Modeling in the interpretation:
  - Signal – interpolation of MC signal (spin-2 assumed)
  - Background – parametric fit to data.
- Excesses in two categories are not in the same mass window:
  - "wide excess": incompatible in terms of scale and resolutions.
  - Sensitivity is driven by the EB-EB category (90%).
- **Maximum local significance: 2.6σ at 760 GeV**





Slides from Jack Kai-Feng Chen's talk

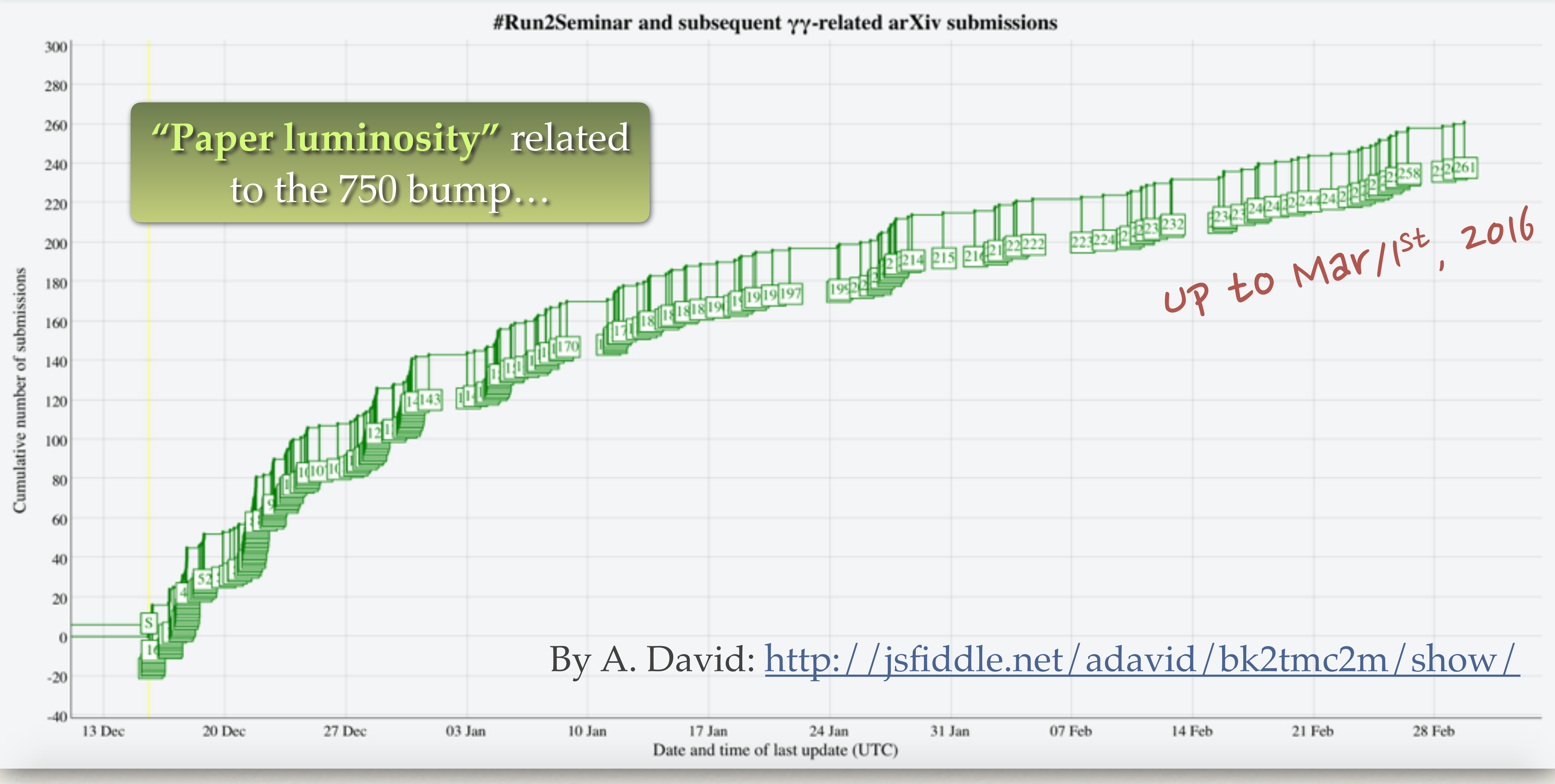
Diphoton Resonances (cont.)



Including LEE (0.5 - 4.5 TeV; narrow width), global p-value < 1.2σ

Slides from Jack Kai-Feng Chen's talk

Well, 261 Citations So Far…



By A. David: http://jsfiddle.net/adavid/bk2tmc2m/show/

We are living in
a very exciting era !

We are living in
a very exciting era !

Not only for particle physics,
But also for A.I.

(Sedol Lee) 1 : 3 (Alpha Go)

Watch AlphaGo take on Lee Sedol, the world's top Go player, in the fourth match of the Google DeepMind challenge.

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]	$< 1300\ (r/5)$

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

$$\Gamma / M \approx 0.06$$

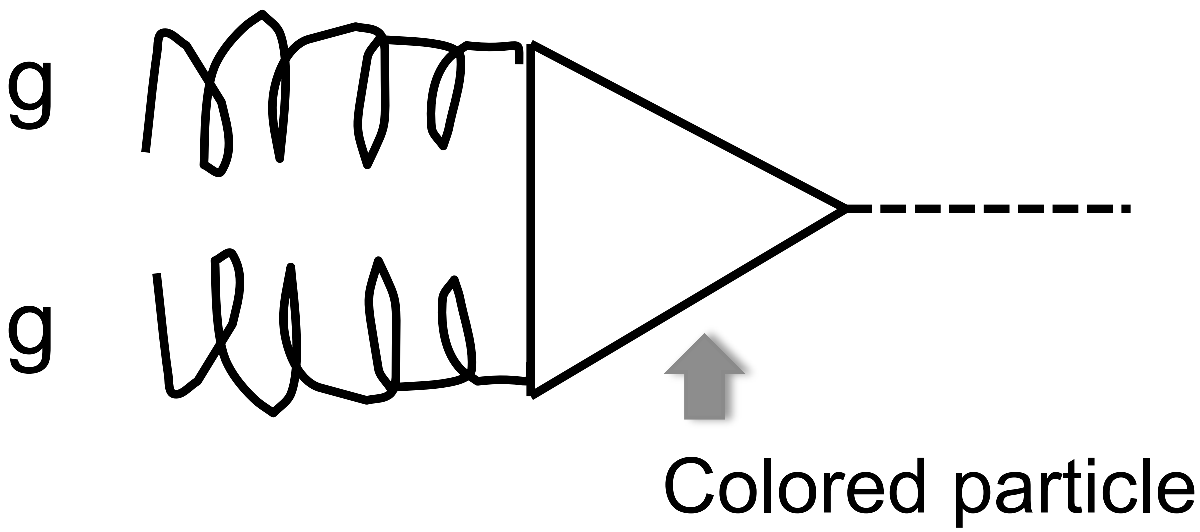
From Table 1 of arXiv:1512.04933 (Franceschini et. al.)

❖ Absence of 750 GeV resonance with other decay modes

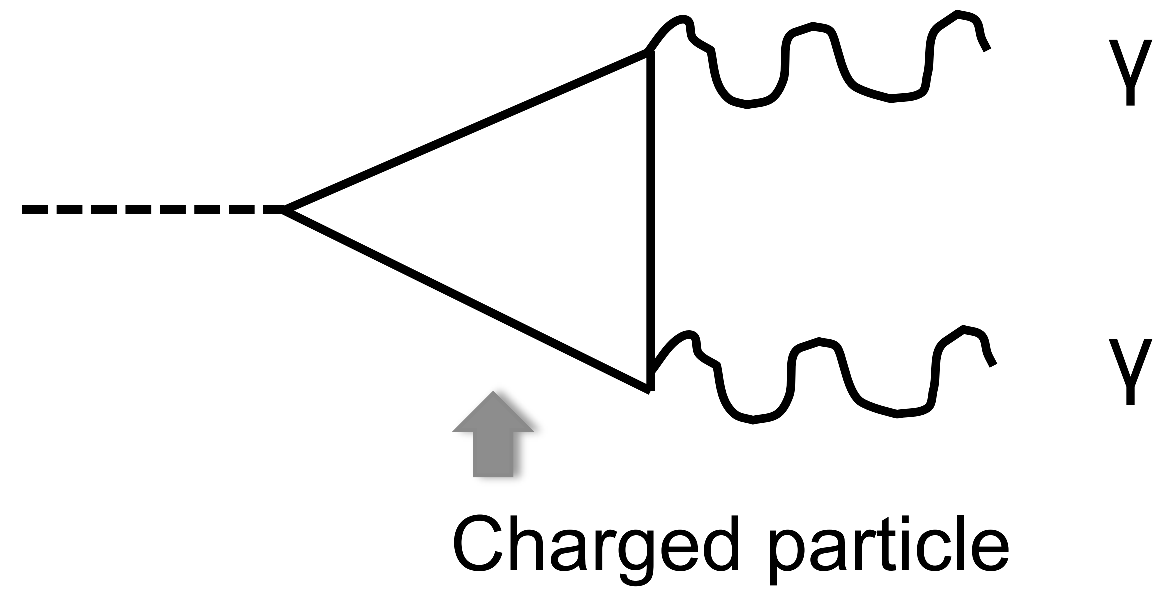
➡ BRs are constrained

One scenario: gluon fusion + diphoton decay via loop

Production: gluon fusion



Diphoton decay channel



It is not easy to get $\sigma(gg\to\Phi_{New})BR(\Phi_{New}\to\gamma\gamma)$~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 × $2\cot^2\beta$

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

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 ?

- 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) Dark U(1)' plus dark sector, Dark Higgs decay into a pair of Z'

- 750 GeV execss ~ U(1)' breaking scalar (Dark Higgs)

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 Tsung
- 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
- Work in preparation with Chaehyun Yu and T.C. Yuan, composite models

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- Work in preparation with Chaehyun Yu and T.C. Yuan, composite models (?)

E_6 motivated leptophobic U(1)' model

arXiv:1601.00586

with Yuji Omura, Chaehyun Yu

See also the poster presentation
by Yuji Omura today

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

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	

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

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

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

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)

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	+
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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

Yukawa couplings

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

$$V_y = y^u_{ij}\overline{u^j_R}H^\dagger_1 i\sigma_2 Q^i + y^d_{ij}\overline{d^j_R}H_2 Q^i + y^e_{ij}\overline{e^j_R}H_2 L^i + y^n_{ij}\overline{n^j_R}H^\dagger_1 i\sigma_2 L^i + H.c., \tag{16}$$

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

$$V^{\rm ex} = y^D_{ij}\overline{D^j_R}\Phi D^i_L + y^H_{ij}\overline{\widetilde{H}^j_R}\Phi \widetilde{H}^i_L + y^N_{IJ}\overline{N^c_L}H^\dagger_1 i\sigma_2 \widetilde{H}^i_L + y'^N_{IJ}\overline{\widetilde{H}^i_R}H_2 N^j_L + H.c.\ . \tag{17}$$

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

$$\begin{aligned}\mathcal{L}_X =\ & D_\mu X^\dagger D^\mu X - (m^2_{X0} + \lambda_{H_1 X} H^\dagger_1 H_1 + \lambda_{H_2 X} H^\dagger_2 H_2) X^\dagger X - \lambda_X (X^\dagger X)^2 \\ & - \left(\lambda''_{\Phi X}(\Phi^\dagger X)^2 + H.c.\right) - \lambda_{\Phi X}\Phi^\dagger \Phi X^\dagger X - \lambda'_{\Phi X}|\Phi^\dagger X|^2 \\ & - \left(y^D_{dX}\overline{d_R} D_L X + y^{\tilde{H}}_{LX}\overline{L}\widetilde{H}_R X^\dagger + H.c.\right) \end{aligned} \tag{18}$$

125 GeV Higgs Data

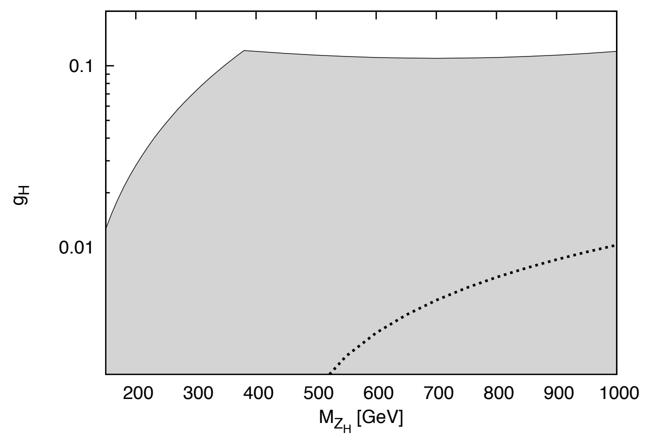
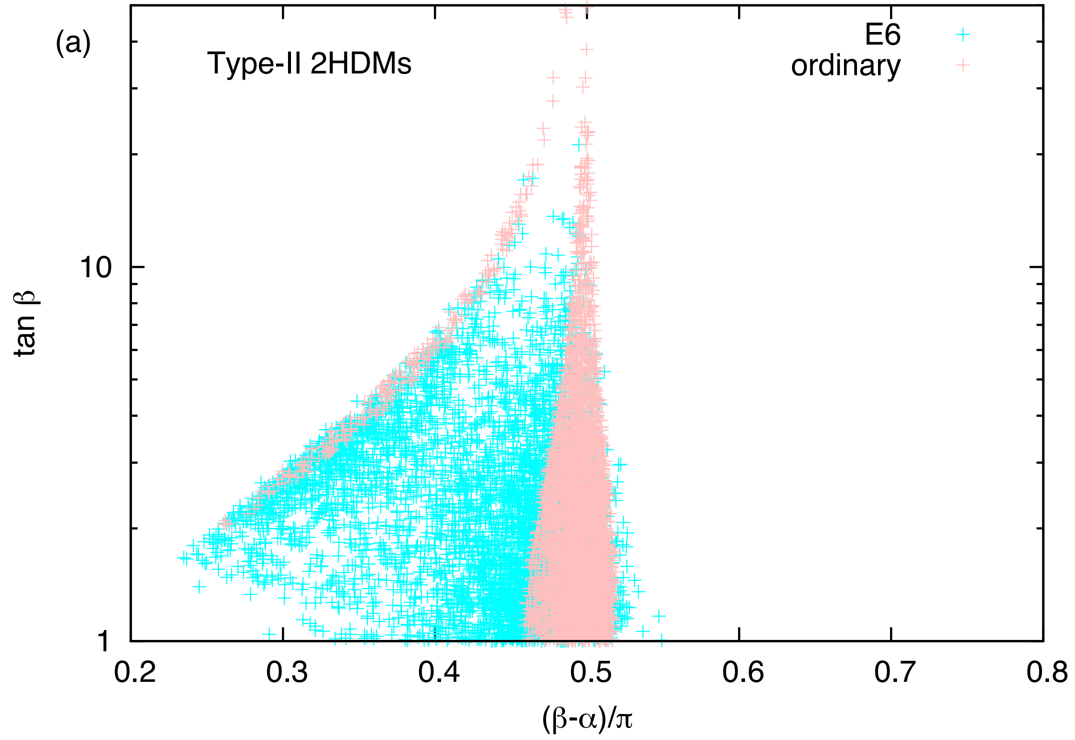


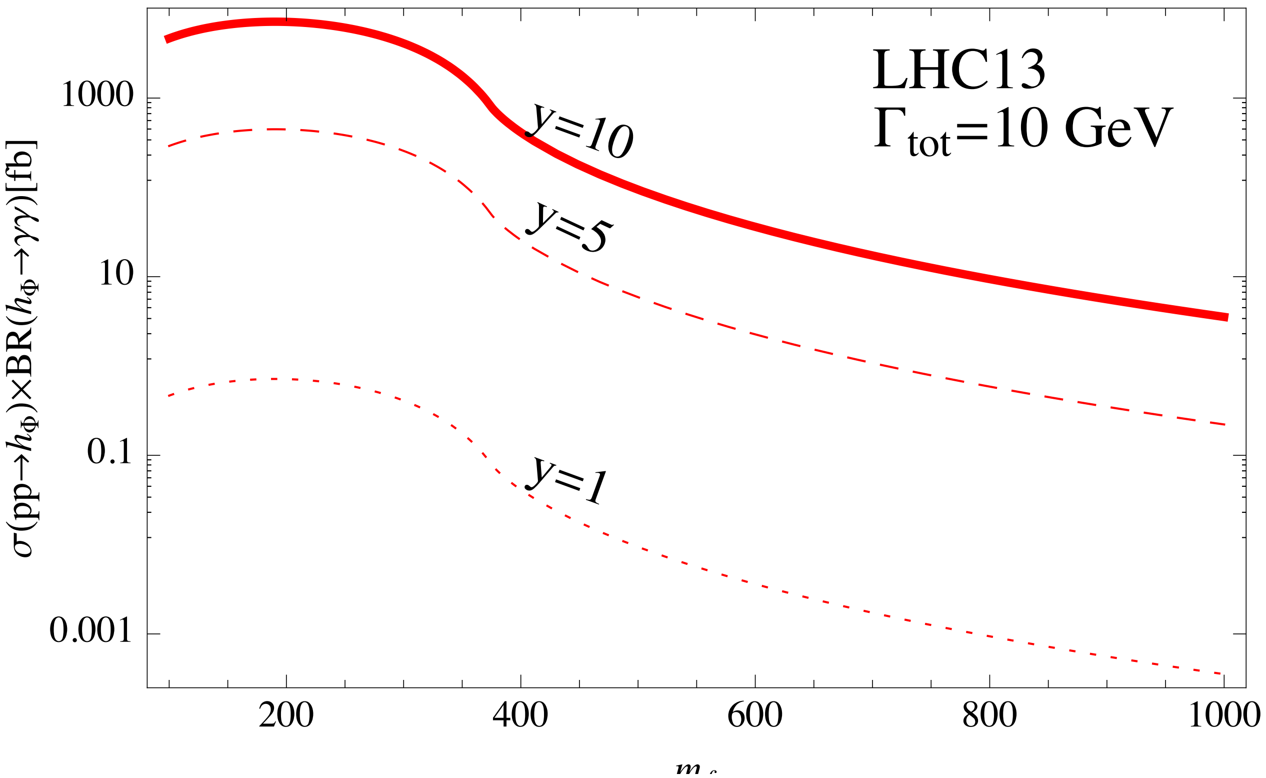
FIG. 1. M_{Z_H} and g_H in the type-II 2HDM$_{U(1)}$. The dot line is the upper bound on the $U(1)_\psi$ gauge boson, and the gray region is allowed for the $U(1)_H (\equiv U(1)_b)$ gauge boson.

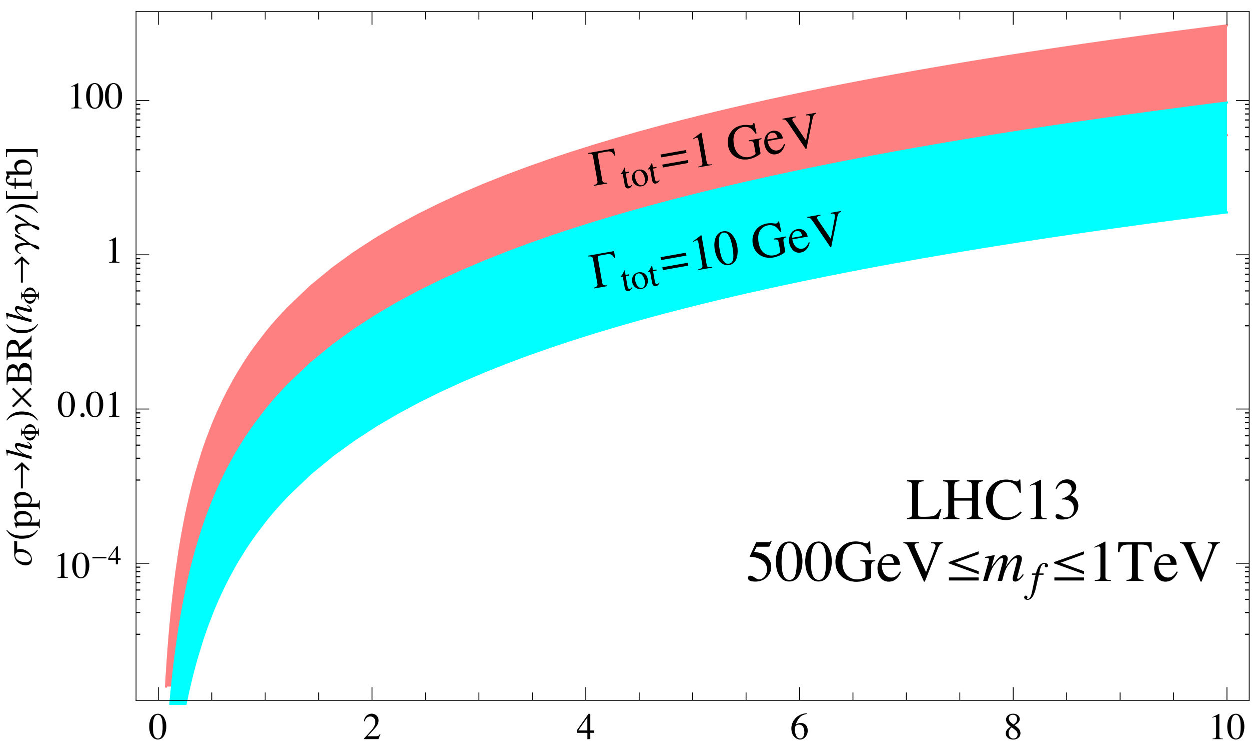


Qualitatively different from the ordinary Type-II 2HDM
arXiv:1502.00262 (Ko, Omura, Yu)

750 GeV Diphoton Excess

Ko, Omura, Yu, arXiv:1601.00586





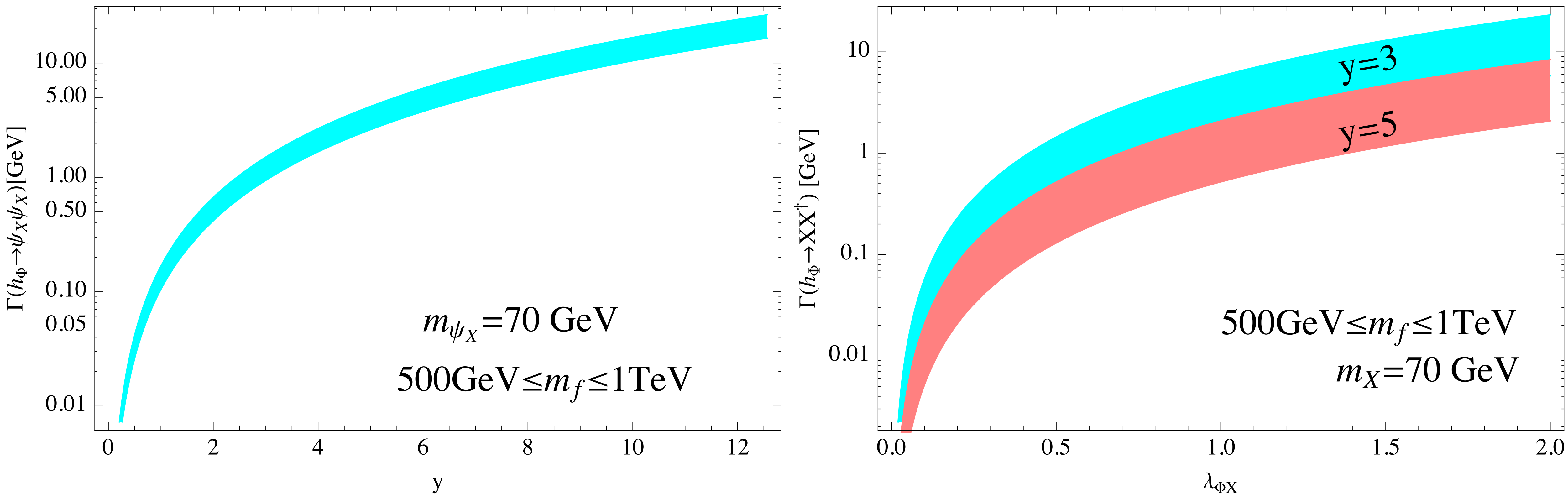


Figure 2: y vs. invisible decay width of h_Φ (GeV) in the fermionic DM scenario (left) and scalar DM scenario (right).The vector-like fermion mass is between 500 GeV and 1 TeV on the cyan and pink bands. The dark matter masses are 70 GeV in the both cases.

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]	$< 0.6\ (r/5)$
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jj	$\lesssim 2.5$ pb	-	[5]	$< 1300\ (r/5)$

Rescaled Run I limits

[Franceschini et al, 1512.04933]

- Most can be evaded
- Monojet + missing ET ??

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)
- 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. Quantitatively ?? (Work in progress)
- A few more different models within the same ingredients are being studied now : Stay tuned
- 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

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)

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)

New Lagrangian

X,N : DM candidate

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

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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$U(1)_Y$	-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

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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

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

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

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

$U(1)_X$ is broken by <Φ>

➡ Massive Z'

We assume H-Φ mixing is negligible

❖ Masses of Z' and new fermions

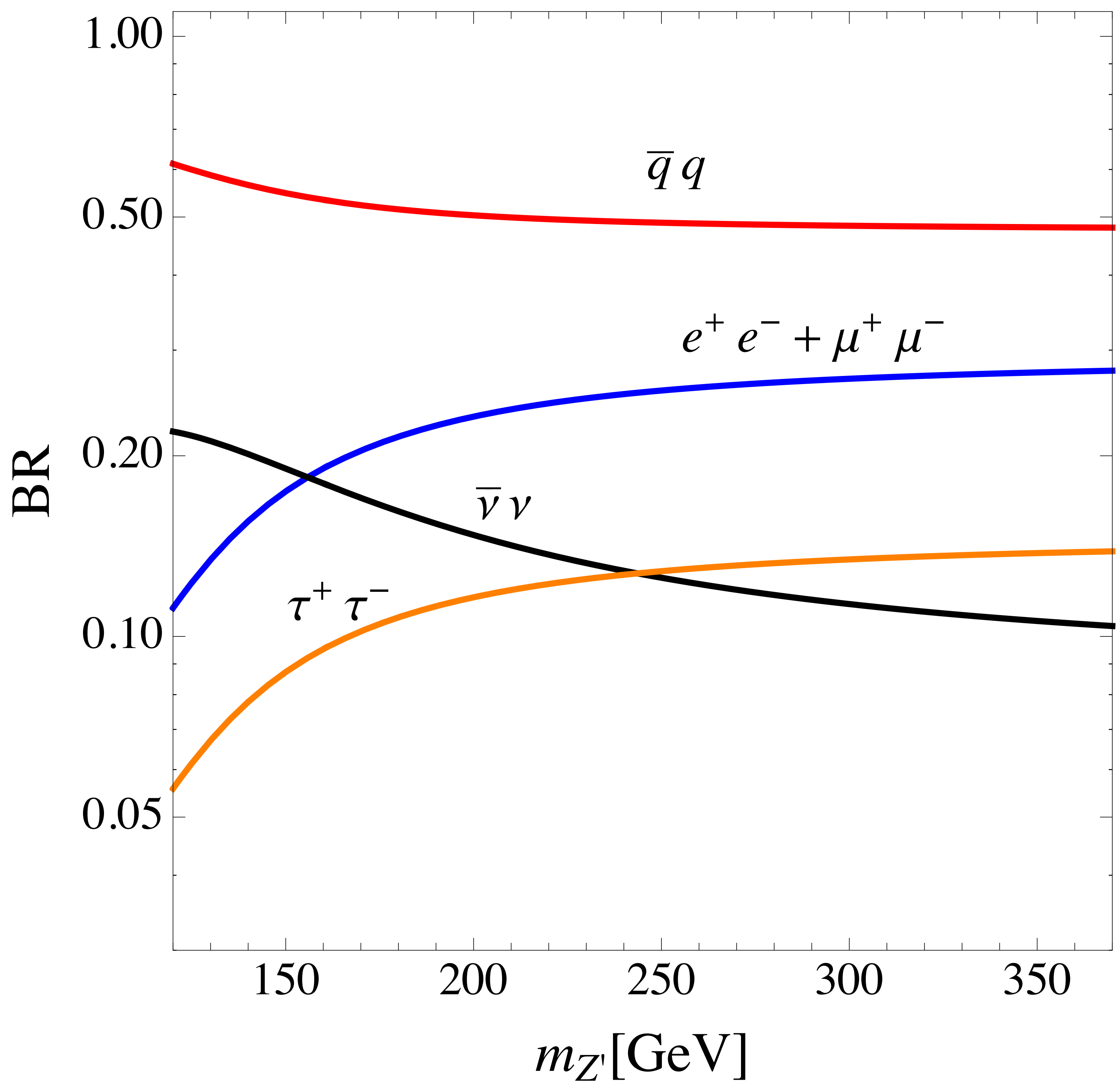
$$m_{Z'}^2 \approx (a+b)^2 g_X^2 v_\phi^2, \quad m_F = \frac{y^F}{\sqrt{2}} v_\phi$$

➡

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

❖ 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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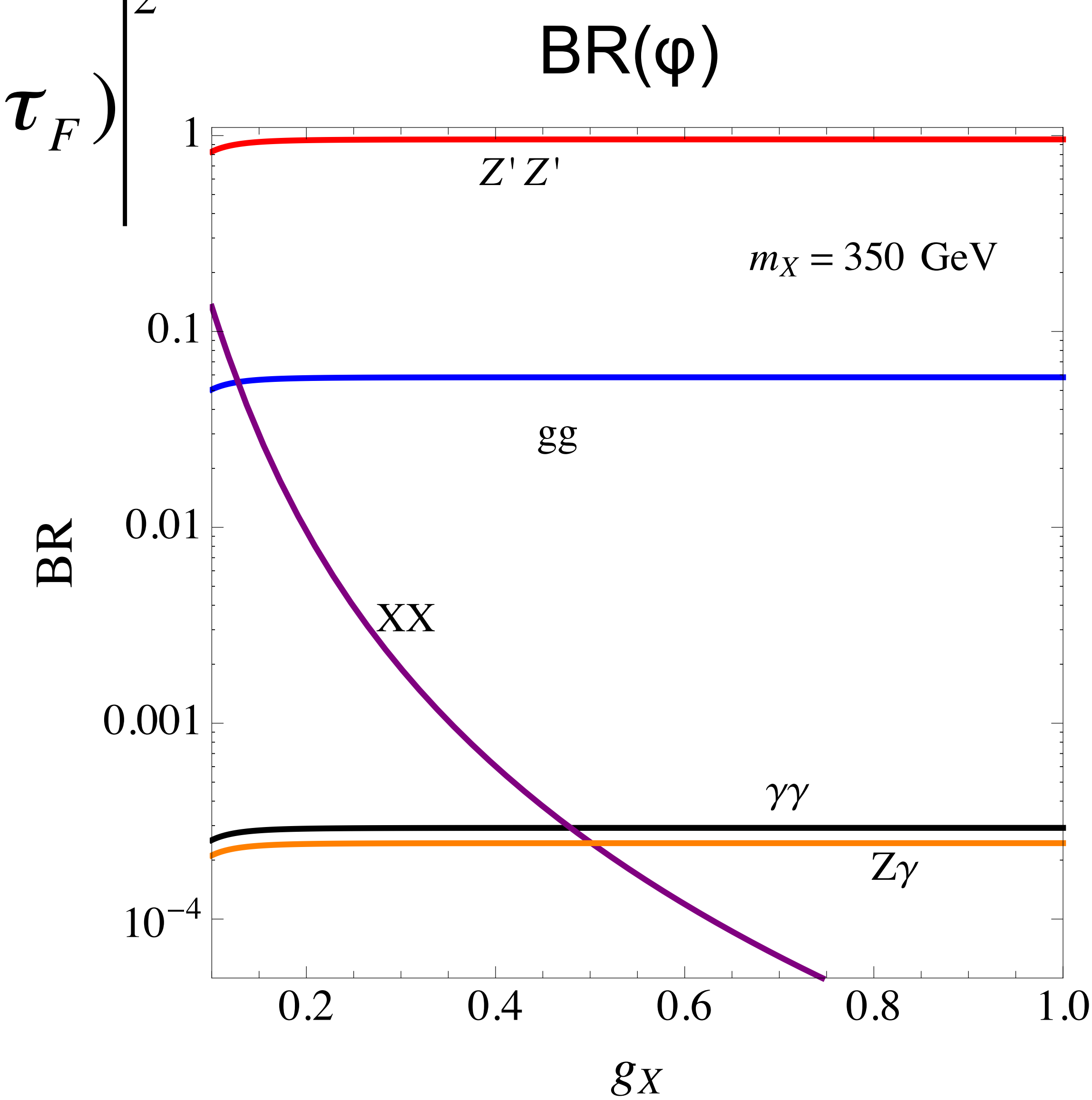

Gluon fusion and decay modes of φ

Gluon fusion and diphoton decay of φ via new fermion loop

gg → φ

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

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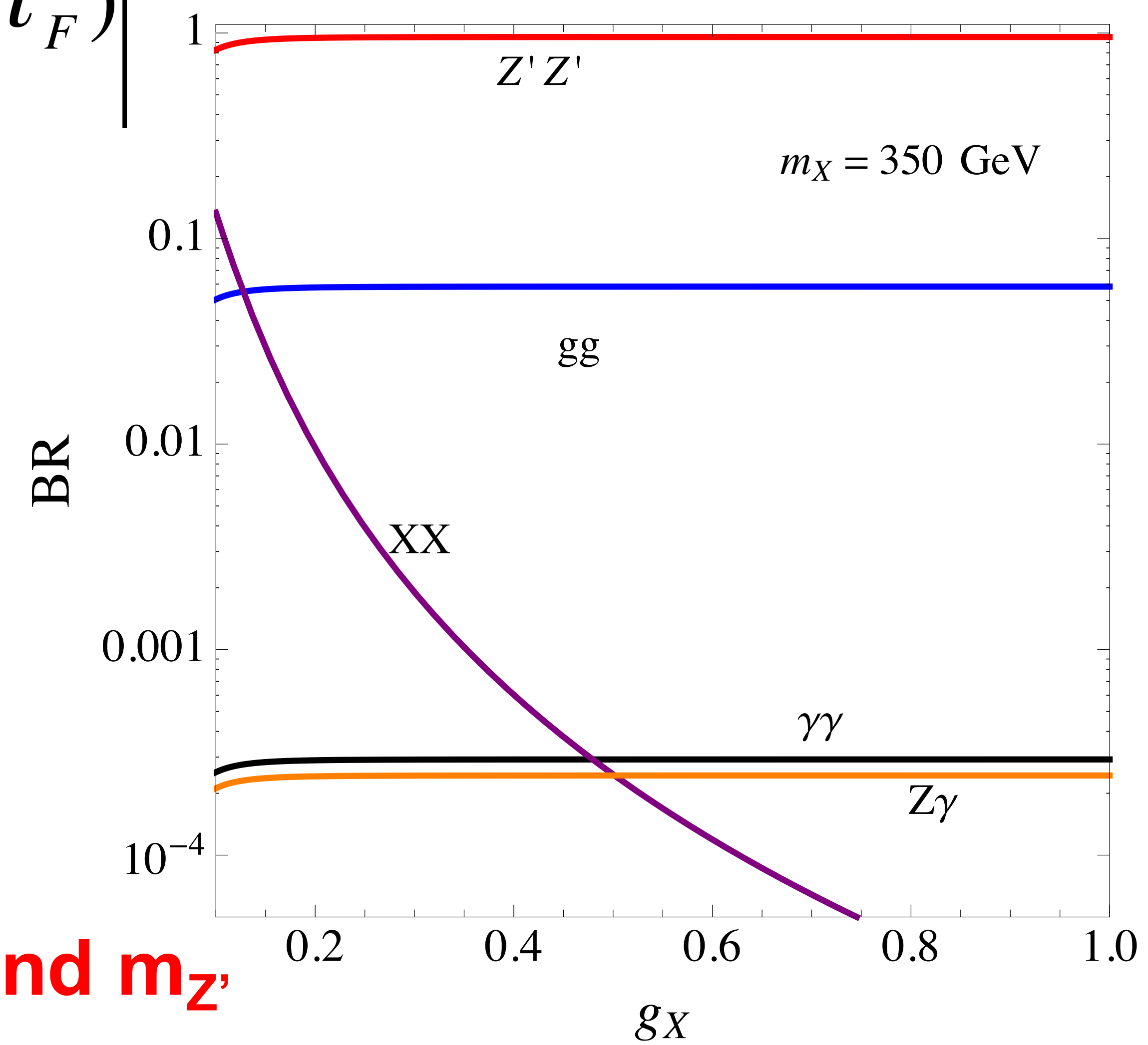
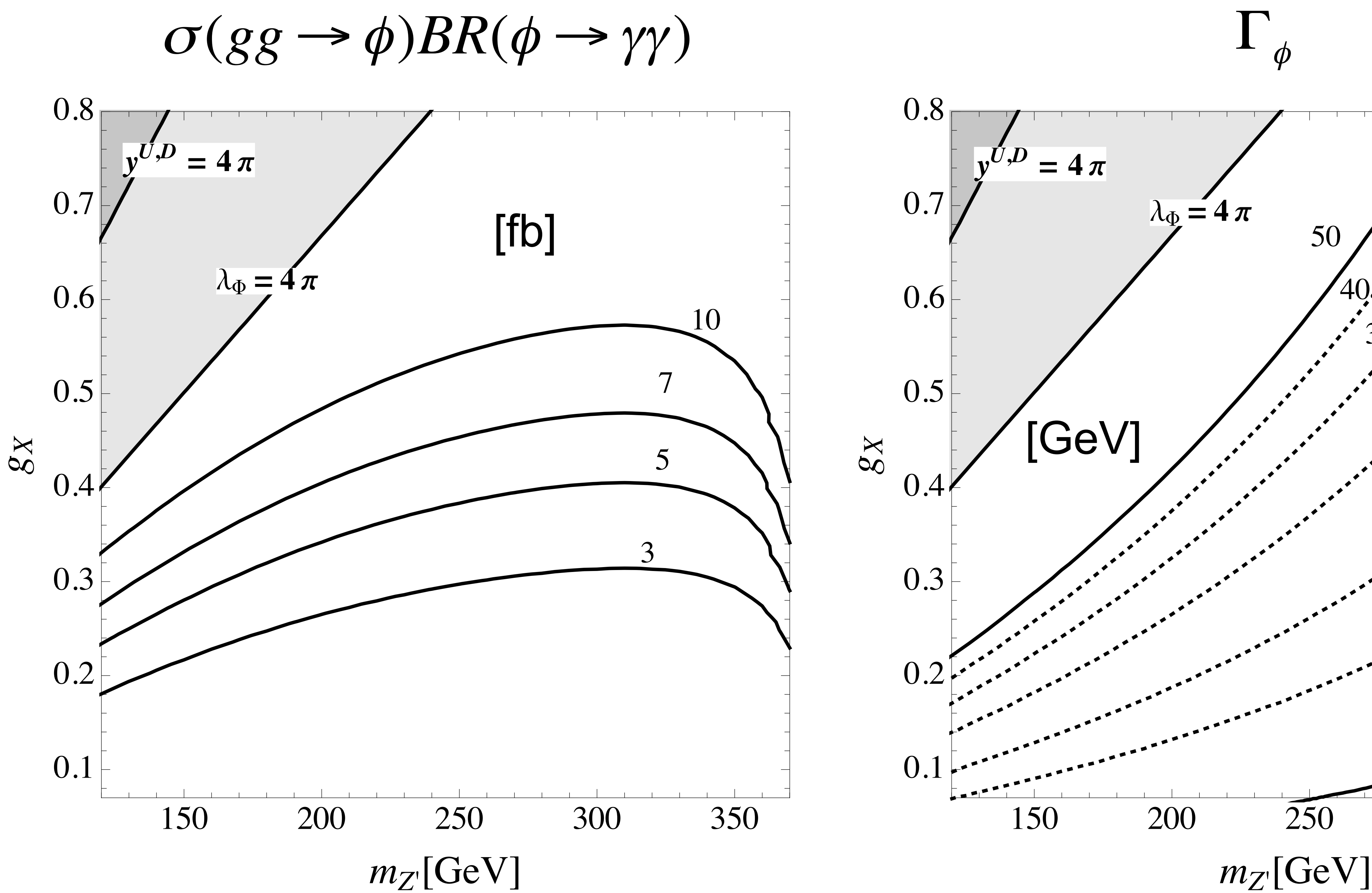
⋮

BR(φ)



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

Cross section and widht of φ

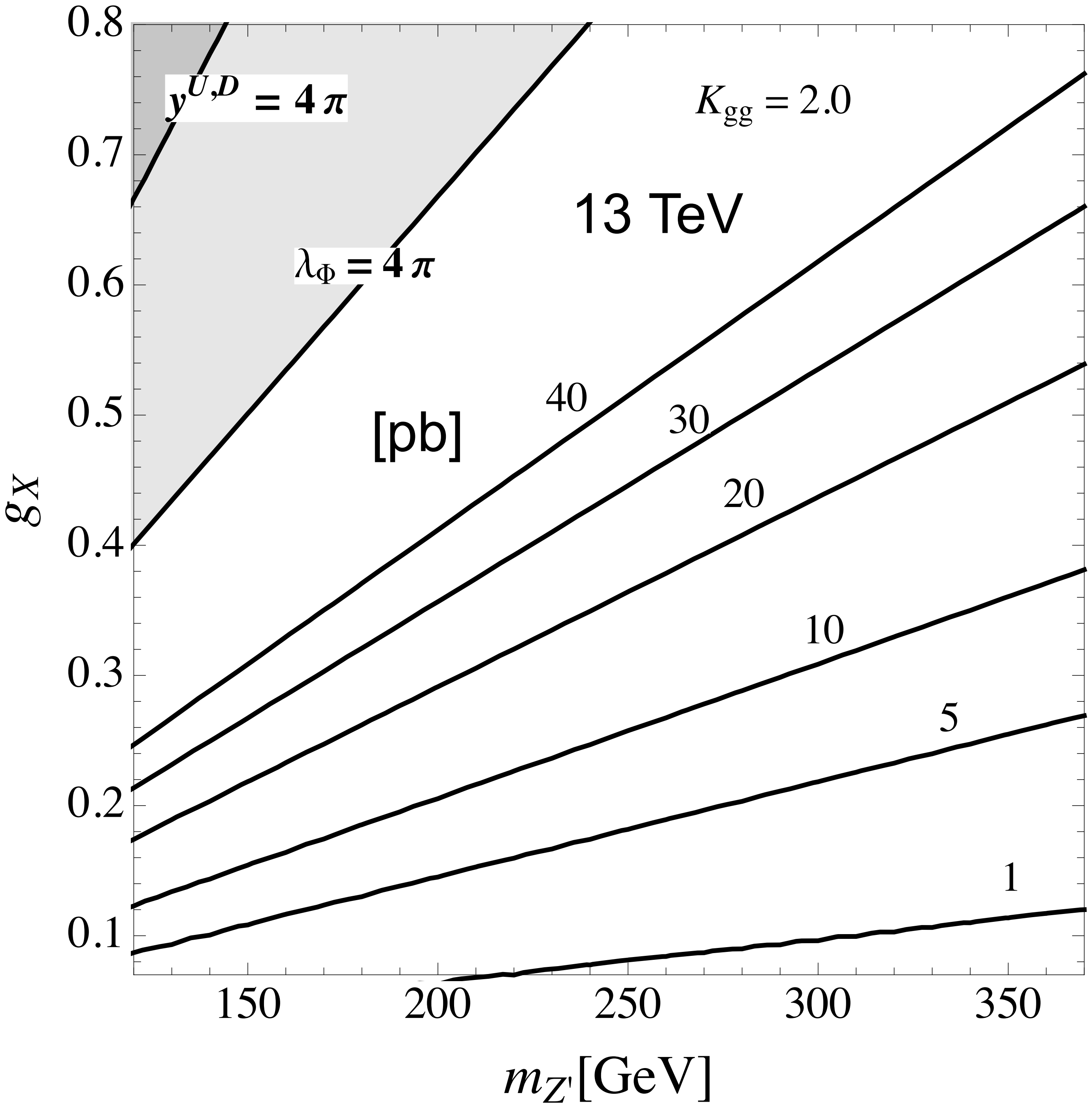


(a~b~1)

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

- **~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→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

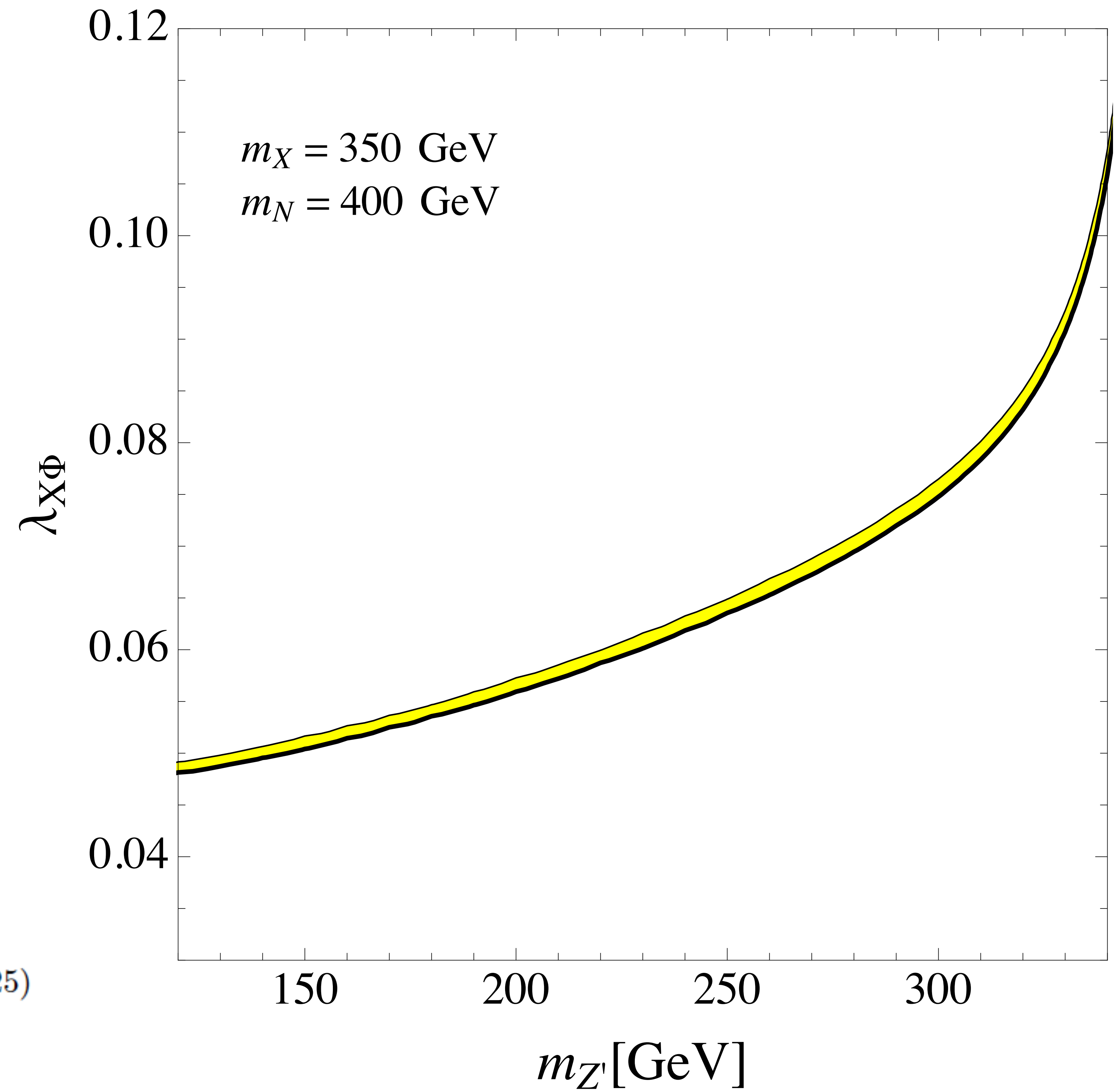
Annihilation process

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_μ = 8 × 10^{−10}, if y^Ei$_\mu$ ~ 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

Composite Models

Work in progress with
Chaehyun Yu, T.C. Yuan (Academia Sinica)

Basic assumptions

- New QCD-like confining gauge force described by $SU(N_h)$
- New Q's and L's charged under SU(Nh)
- $SU(2)_L$ doublets or singlets
- Q,L : Heavy fermions (>> new confining scale)
- Light h-glueball : decay into SM particles through loop
- 750 GeV excess ~ eta_Q

Ex : Doublet with Qe=2/3

$$\sigma(gg \to \eta_Q \to \gamma\gamma) = \frac{C_{gg}}{s m_{\eta_Q} \Gamma_{\text{tot}}} \Gamma[\eta_Q \to gg] \Gamma[\eta_Q \to \gamma\gamma],$$

$$\Gamma_{\gamma\gamma} = \frac{\alpha^2 N_c N_h e_Q^4}{m_Q^2} |R_{1S}(0)|^2 ,$$

$$\Gamma_{\gamma Z} = \frac{\alpha^2 N_c N_h e_Q^2 (1 + 4 e_Q x_w)^2 (4 - r_Z)}{32 m_Q^2 x_w (1 - x_w)} |R_{1S}(0)|^2 ,$$

$$\Gamma_{ZZ} = \frac{\alpha^2 N_c N_h (1 - r_Z)^{3/2}}{16 x_w^2 (1 - x_w)^2 m_Q^2 (2 - r_Z)^2} \left(1 + 4 e_Q x_w + 8 e_Q^2 x_W^2\right)^2 |R_{1S}(0)|^2 ,$$

$$\Gamma_{WW} = \frac{\alpha^2 N_c N_h (1 - r_W)^{3/2}}{8 x_w^2 m_Q^2 (2 - r_W)^2} |R_{1S}(0)|^2 ,$$

$$\Gamma_{gg} = \frac{C_F N_h \alpha_s^2}{2 m_Q^2} |R_{1S}(0)|^2 ,$$

$$\Gamma_{g_h g_h} = \frac{C_h N_c \alpha_h^2}{2 m_Q^2} |R_{1S}(0)|^2 ,$$

$$|R_{1S}(0)|^2 = m_Q \left\langle \frac{dV}{dr} \right\rangle = 4 \left(C_h \alpha_h \frac{m_Q}{2} \right)^3$$

g_h's will hadronize into a h-gleball, eventually decays into SM particles through loop diagrams (in progress)

In the numerical analysis, we use

$$|R_{1S}(0)|^2 = m_Q \left\langle \frac{dV}{dr} \right\rangle = 4\left(C_h \alpha_h \frac{m_Q}{2}\right)^3$$

$$\begin{aligned} N_c &= 3, \\ N_h &= 3, 4, 5, \\ m_{\eta_Q} &= 750\ \text{GeV}, \\ m_Q &= 375\ \text{GeV}, \\ \alpha &= \frac{1}{128}, \\ \alpha_s &= 0.12, \\ e_Q &= \frac{2}{3}. \end{aligned}$$

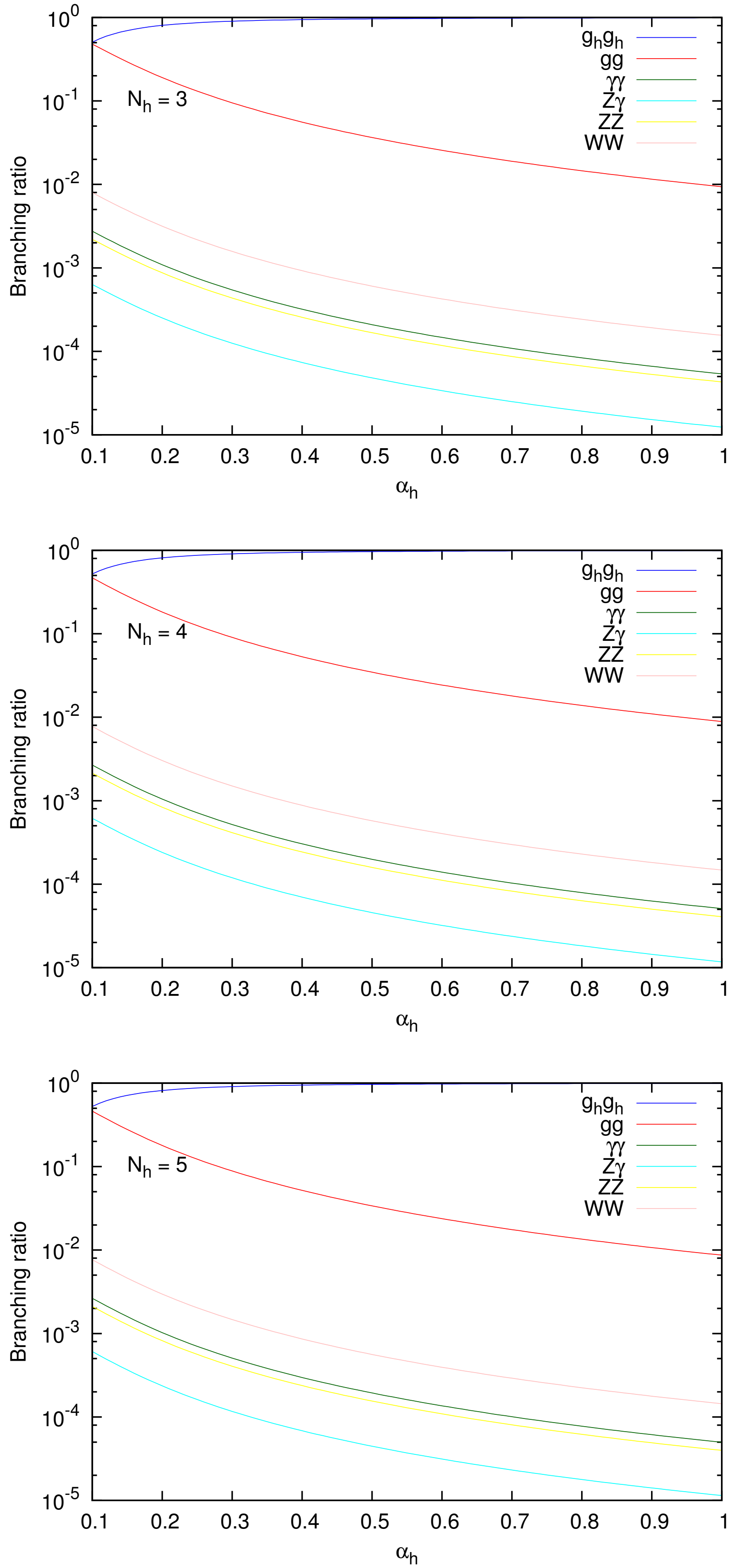


FIG. 1. Branching ratios of η_Q decays as a function of α_h for $N_h = 3$, 4, and 5, respectively.

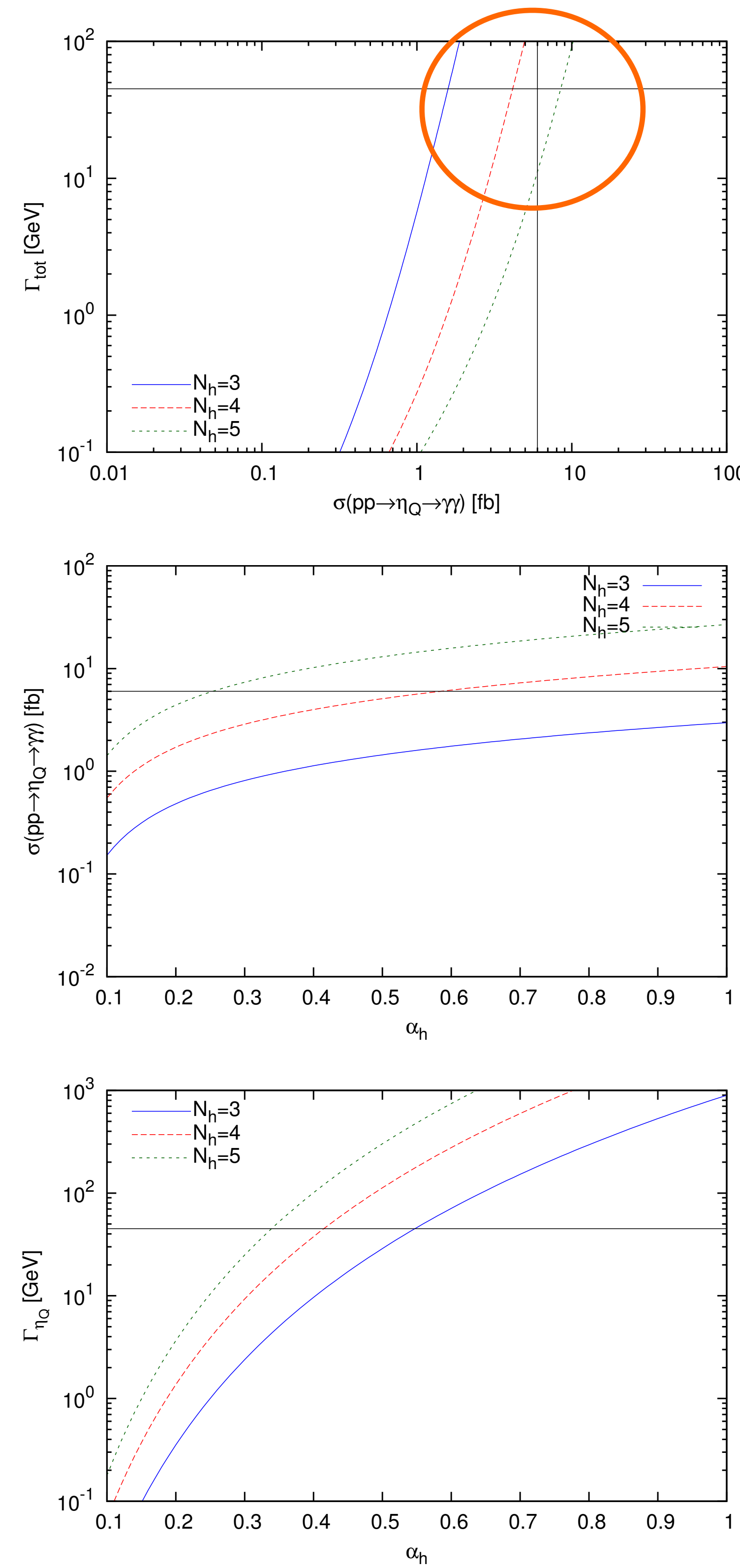


FIG. 2. (a) The cross section for $pp \to \eta_Q \to \gamma\gamma$ at $\sqrt{s} = 13$ TeV in unit of fb VS $\Gamma_{\rm tot}$ in unit of GeV. (b) The cross section in unit of fb as a function of α_h, and (c) $\Gamma_{\rm tot}$ in unit of GeV as a function of α_h.

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
- The width of the resonance is a crucial information for particle physics model buildings
- 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

Backup

Constraints on dark photon

Jaeckel and Spannowsky, arXiv:1212.3620 [hep-ph]

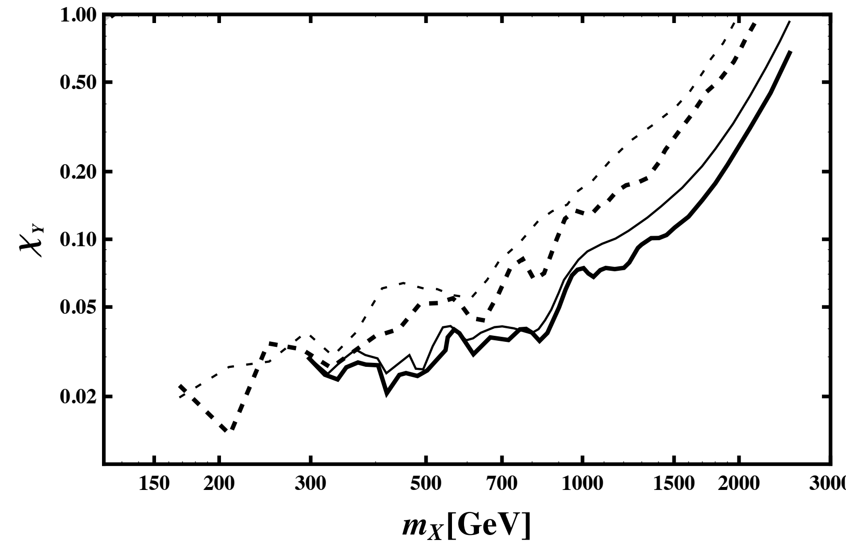


Figure 1: 95% exclusion limits on the kinetic mixing parameter χ_Y from the ATLAS (dashed) and CMS (solid) Z' searches. The thin lines correspond to the $\mu^+\mu^-$ channel only, while the thick lines result from a combination of the $\mu^+\mu^-$ and e^+e^- channels.

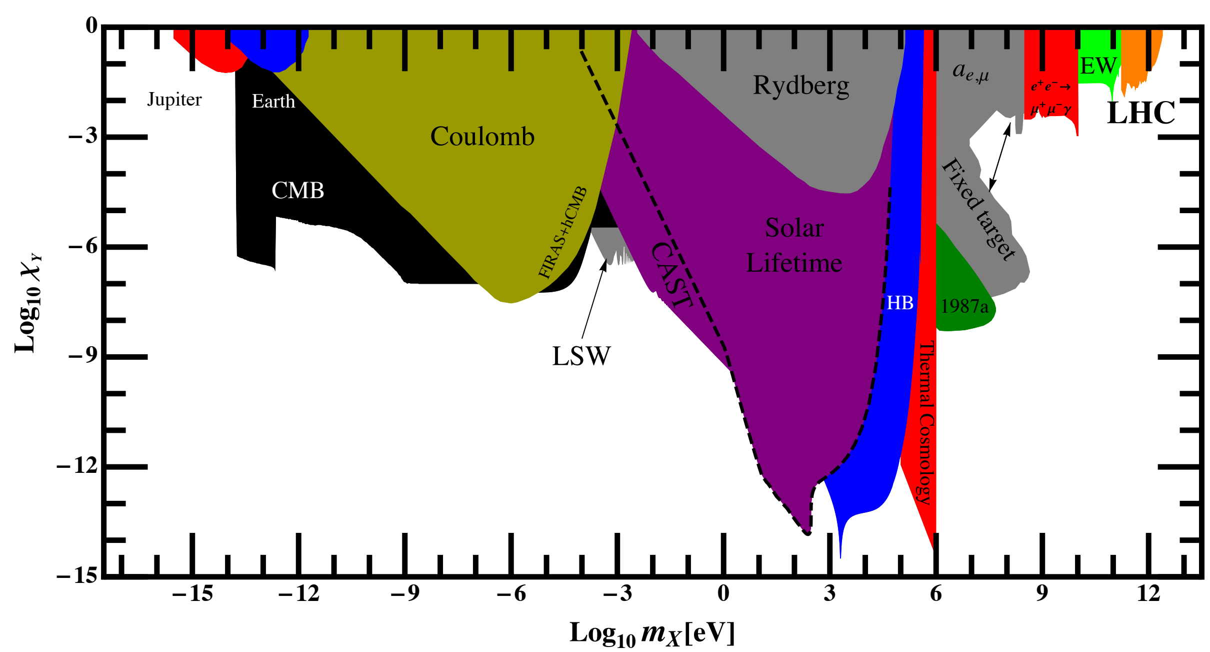


Figure 2: Combination of the new LHC limits with a range of other constraints on hidden photons (see refs. [19, 20] for details). The new "LHC" region is marked in orange and extends the existing bounds to a previously uncovered range of high masses. Note that the limits are with respect to the hypercharge mixing parameter χ_Y. For small hidden photon masses the kinetic mixing parameter with the ordinary photon is related to χ_Y through $\chi = \cos(\theta_W)\chi_Y$.