Multi-lepton Higgs Decays through the Dark Portal

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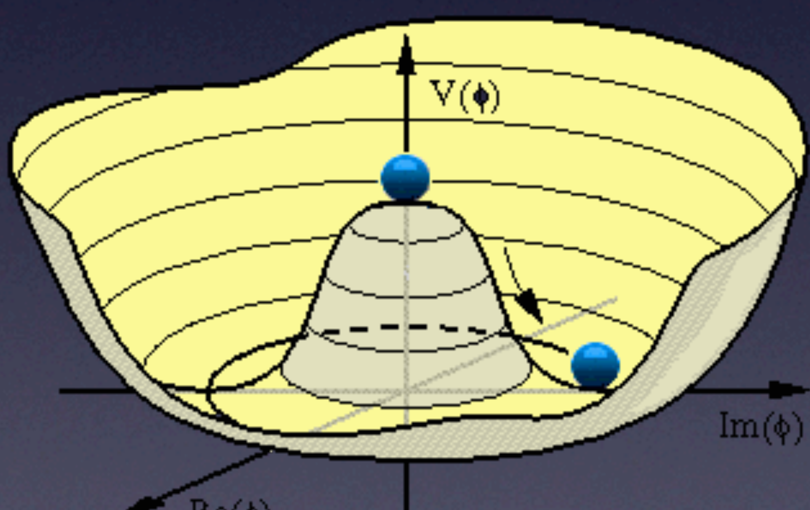
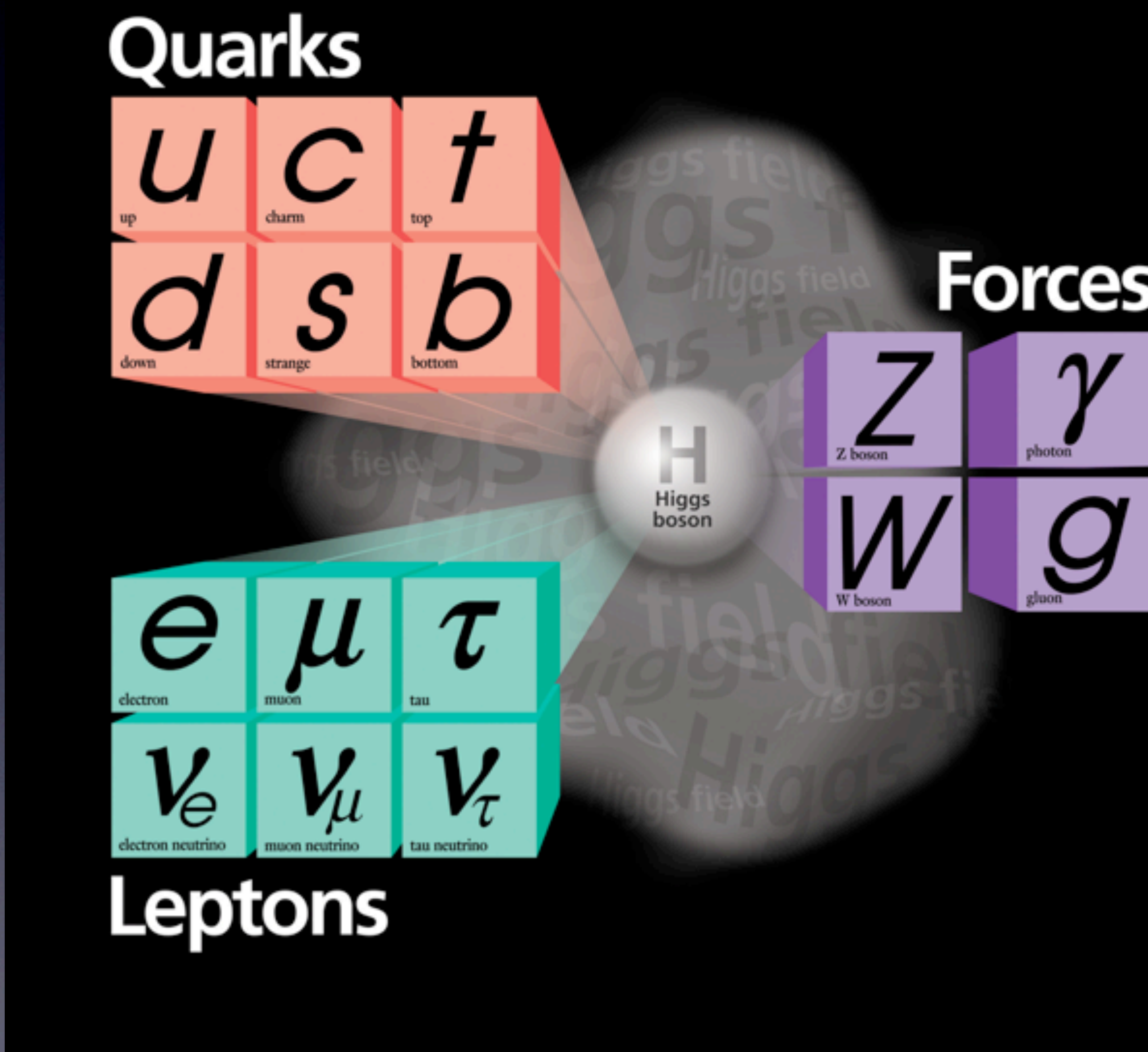
Standard Model/Theory

- SM is a gauge theory
- BEH particle - agent responsible to spontaneously electroweak symmetry breaking



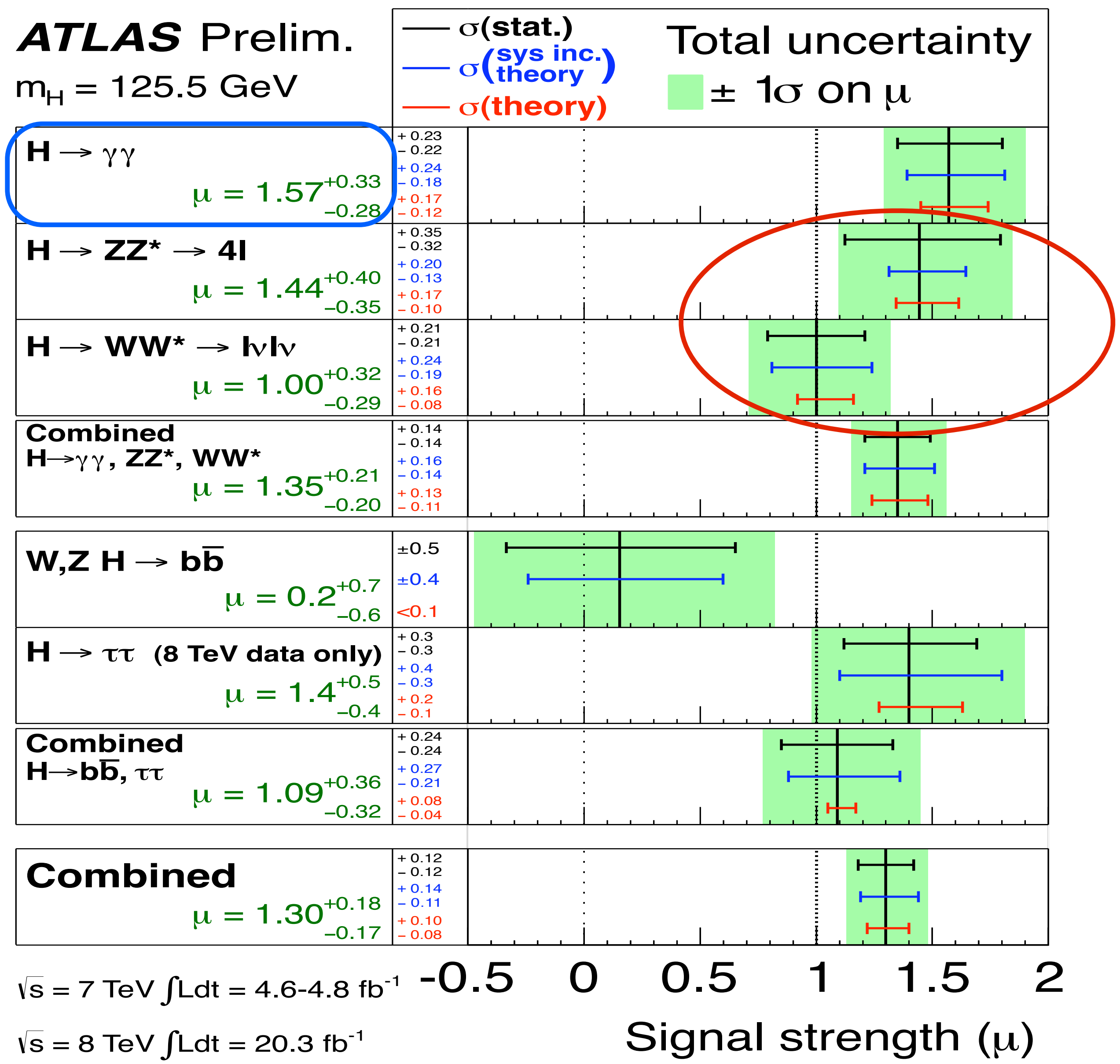
- Provide masses to quarks, charged leptons, and gauge bosons

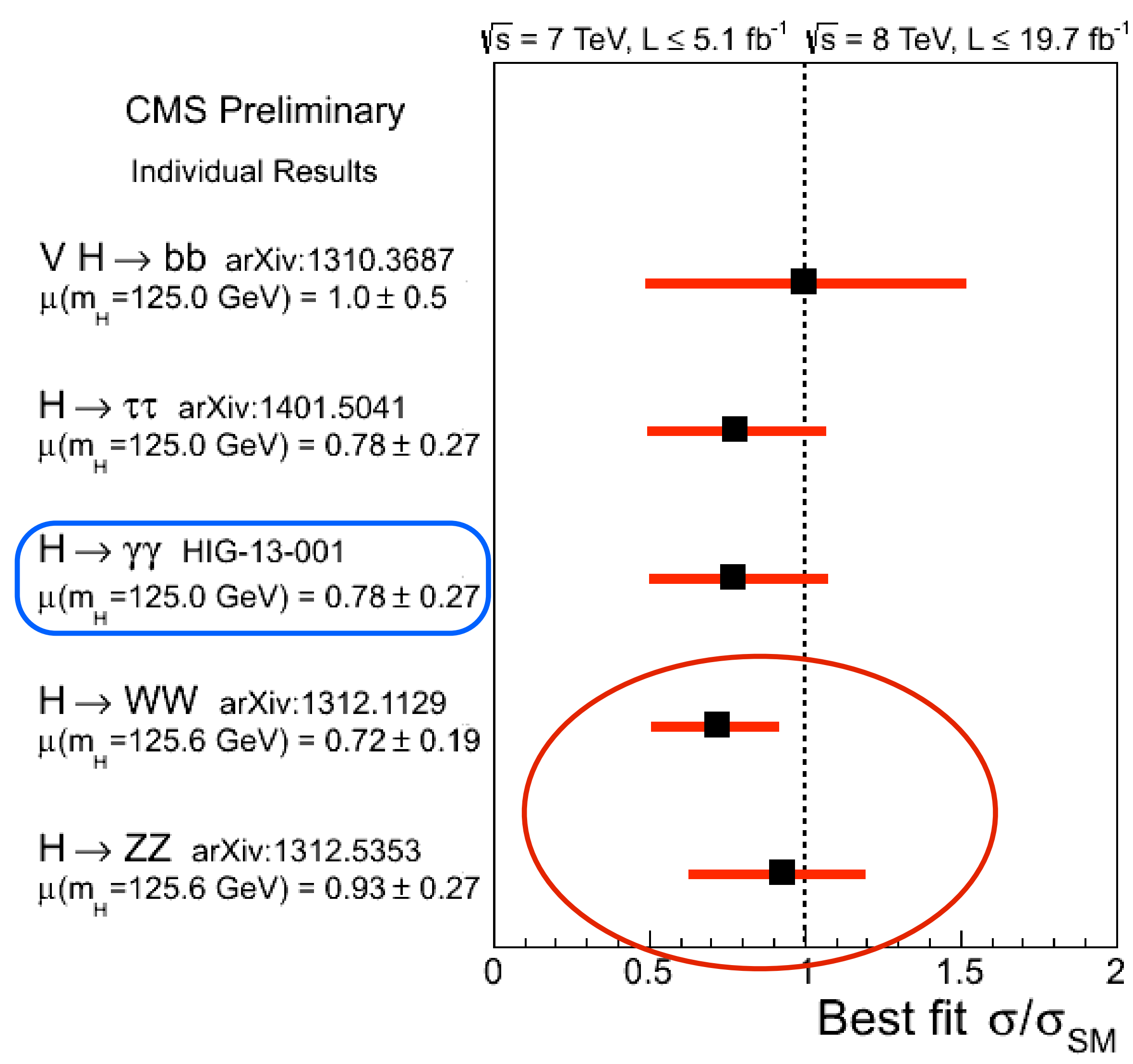


Higgs Production

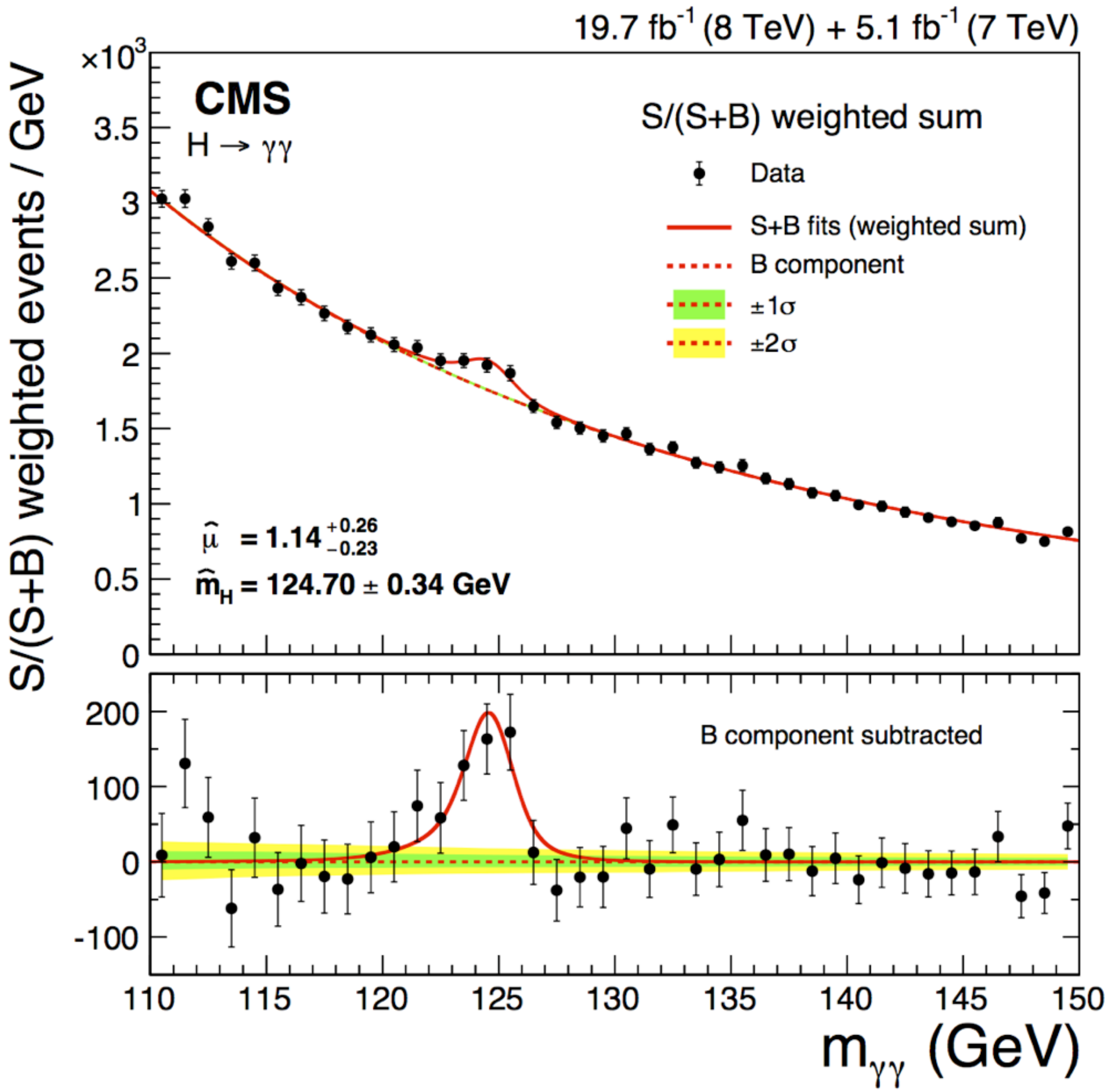
- Signal strengths for various Higgs decay modes at ATLAS and CMS
- To a large extent, LHC data consistent with SM predictions (with large uncertainties)

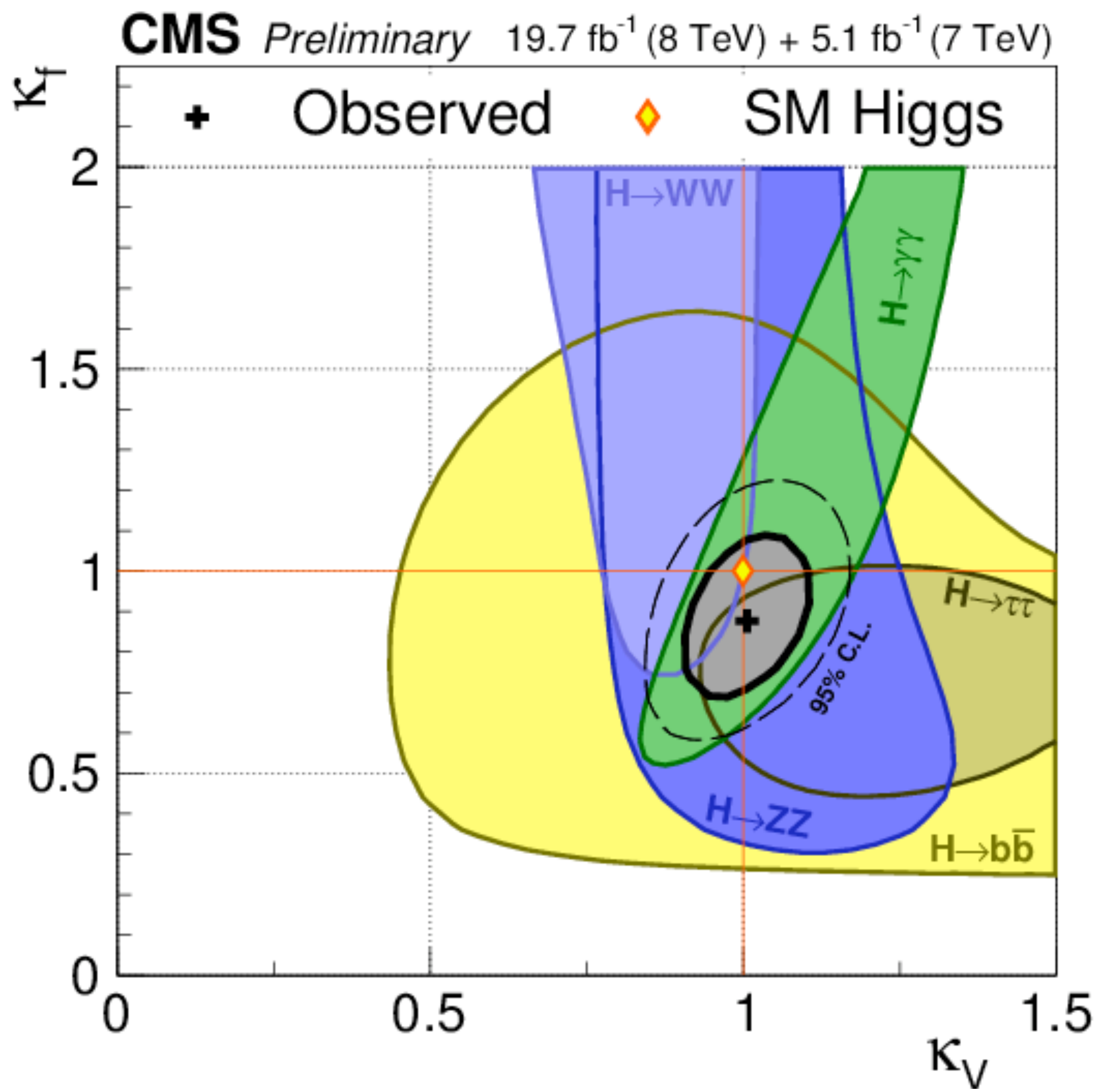
$$\text{Signal Strength } \mu_{ij} \equiv \frac{\sigma_{i\to h} \times \mathrm{BR}_{h\to j}}{\sigma_{i\to h_{SM}} \times \mathrm{BR}_{h_{SM}\to j}}$$





Latest CMS Results on Higgs Measurements (ICHEP 2014)





Is That All?

- Perhaps not!
- Exotic Higgs decay might be important but overlooked thus far.

Outline

- Original Abelian Higgs Model as Dark U(1)
- Studies of 2 and 4 lepton jets
- Summary

Based on Chia-Feng Chang, Ernest Ma, TCY, JHEP 1403 (2014) 054 [arXiv:1308.6071]

Original Higgs U(1) Model As Dark Sector

Chia-Feng Chang, Ernest Ma and TCY, [arXiv:1308.6071]

- The Model

Kinetic Mixing

$$\mathcal{L}_{\rm gauge} = -\frac{1}{4}\vec{W}_{\mu\nu}\cdot\vec{W}^{\mu\nu} - \frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{4}C_{\mu\nu}C^{\mu\nu} - \frac{\epsilon}{4}B_{\mu\nu}C^{\mu\nu} \ ,$$

$$\mathcal{L}_{\rm scalar} = |D_\mu \Phi|^2 + |D_\mu \chi|^2 - V_{\rm scalar}(\Phi, \chi) \ ,$$

$$V_{\rm scalar} = -\mu_\Phi^2 \Phi^\dagger\Phi + \lambda_\Phi \left(\Phi^\dagger\Phi\right)^2 - \mu_\chi^2 \chi^*\chi + \lambda_\chi \left(\chi^*\chi\right)^2 + \lambda_{\Phi\chi}\left(\Phi^\dagger\Phi\right)\left(\chi^*\chi\right) \ .$$

$$\Phi(x) = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v + h(x)\end{pmatrix} \ , \quad \chi(x) = \frac{1}{\sqrt{2}}\left(v_D + h_D(x)\right)$$

- SM Higgs and Dark Higgs Mixing

$$\begin{pmatrix} h_1 \\ h_2 \end{pmatrix} = \begin{pmatrix} \cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha \end{pmatrix}\begin{pmatrix} h \\ h_D \end{pmatrix} \ , \qquad \sin 2\alpha = \frac{2m_{12}^2}{m_1^2 - m_2^2} \ .$$

Heavier state identifies as SM 126 GeV Higgs

Partial List of References

[1] B. Holdom, PLB166 (1986) 196, PLB178 (1986)65
[2] Cheung and Yuan, hep-ph/0701107
[3] Feldman, Liu and Nath, hep-ph/0702123
[4] Gopalakrishna, Jung and Wells, 0801.3456
[5] Falkowski, Ruderman, Volansky and Zupan, 1007.3496, 1002.2952
[6] Davoudiasl, Lee and Marciano, 1203.2947
[7] Davoudiasl, Lee, Lewis and Marciano, 1304.4935
[8] ....

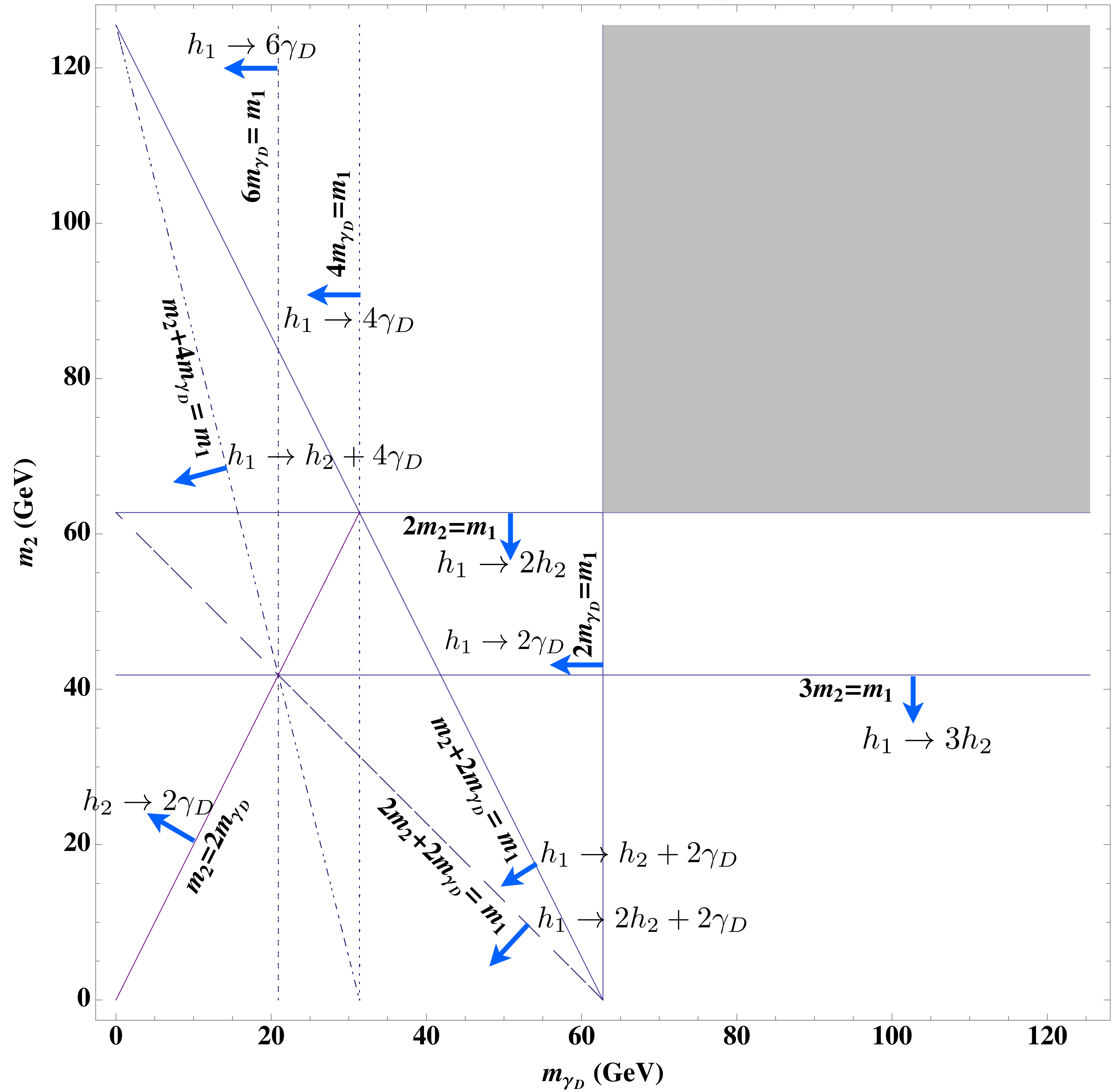
Rich and Distinctive Higgs Phenomenology

- Higgs mixings implies non-standard Higgs decay

$$h_1 \to \gamma_D \gamma_D$$
$$h_1 \to h_2 h_2$$
$$h_1 \to h_2 h_2^* \to h_2 \gamma_D \gamma_D$$
$$h_1 \to h_2 h_2 h_2$$

- h_2 decays predominantly into two dark photons $h_2 \to \gamma_D \gamma_D$
- Dark photon may decay to light SM fermions (e.g. leptons) through kinetic mixing with SM photon $\gamma_D \to \bar{l}l \quad (l = e, \mu)$
- This model predicts: non-standard modes of Higgs decay could be 4, 8, or even 12 leptons in the final states without missing energy (MET)!
- Similar signals (but with MET) can occur in hidden valley scenarios, SUSY, Weinberg's Higgs Portal model etc.

Kinematic Region $(m_1 = 126\ \text{GeV})$



Higgs Decay Width

- SM Higgs total width contains two pieces

$$\Gamma_{h_1} = \cos^2\alpha\,\hat{\Gamma}_h + \Gamma_{h_1}^{NS} \ ,$$

- Non-standard contributions from dark Higgs U(1) sector

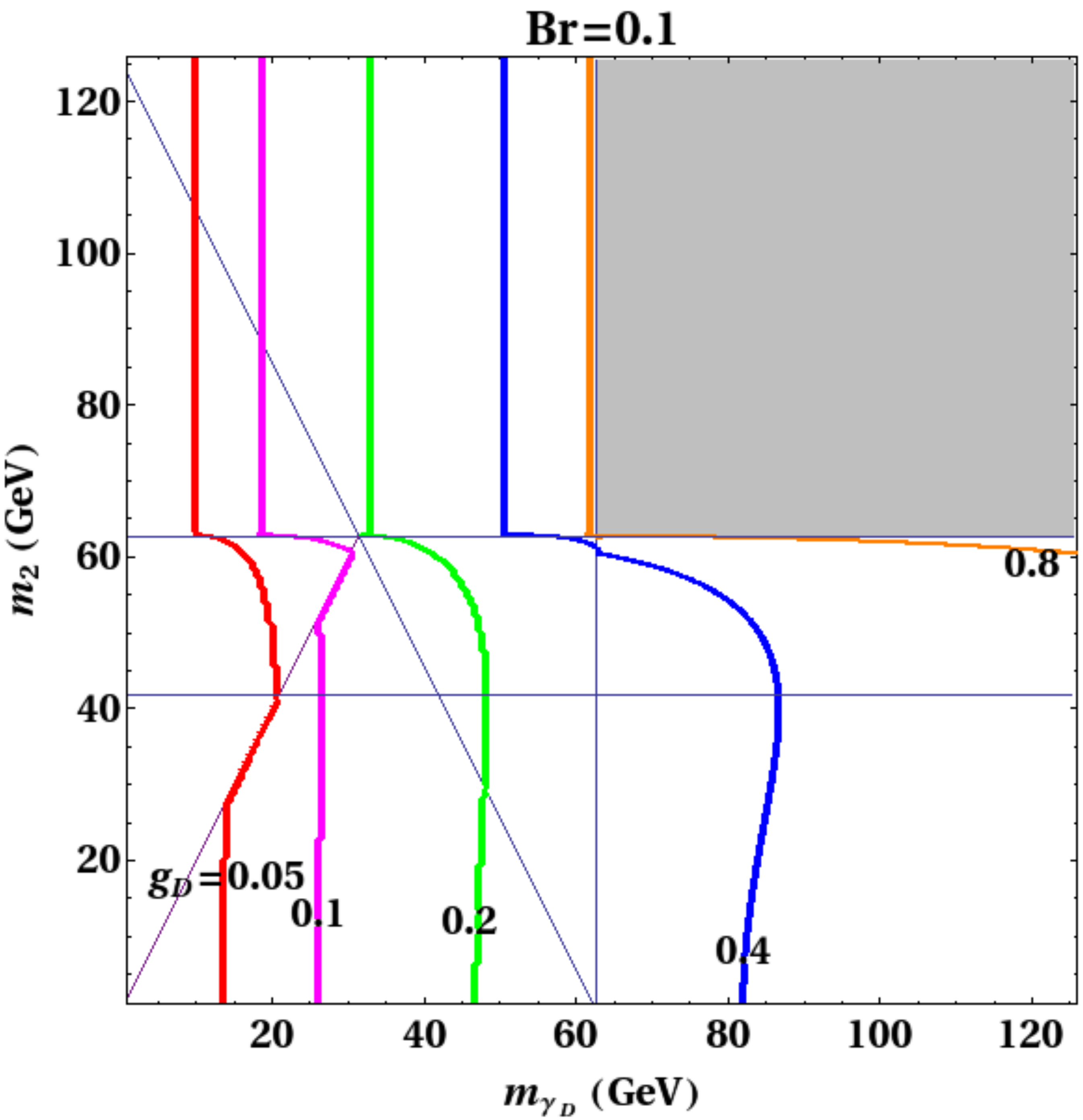
$$\Gamma_{h_1}^{NS} = \sin^2\alpha\,\hat{\Gamma}(h_1 \to \gamma_D\gamma_D) + \Gamma(h_1 \to h_2h_2) + \Gamma(h_1 \to h_2\gamma_D\gamma_D) + \Gamma(h_1 \to h_2h_2h_2) + \cdots$$

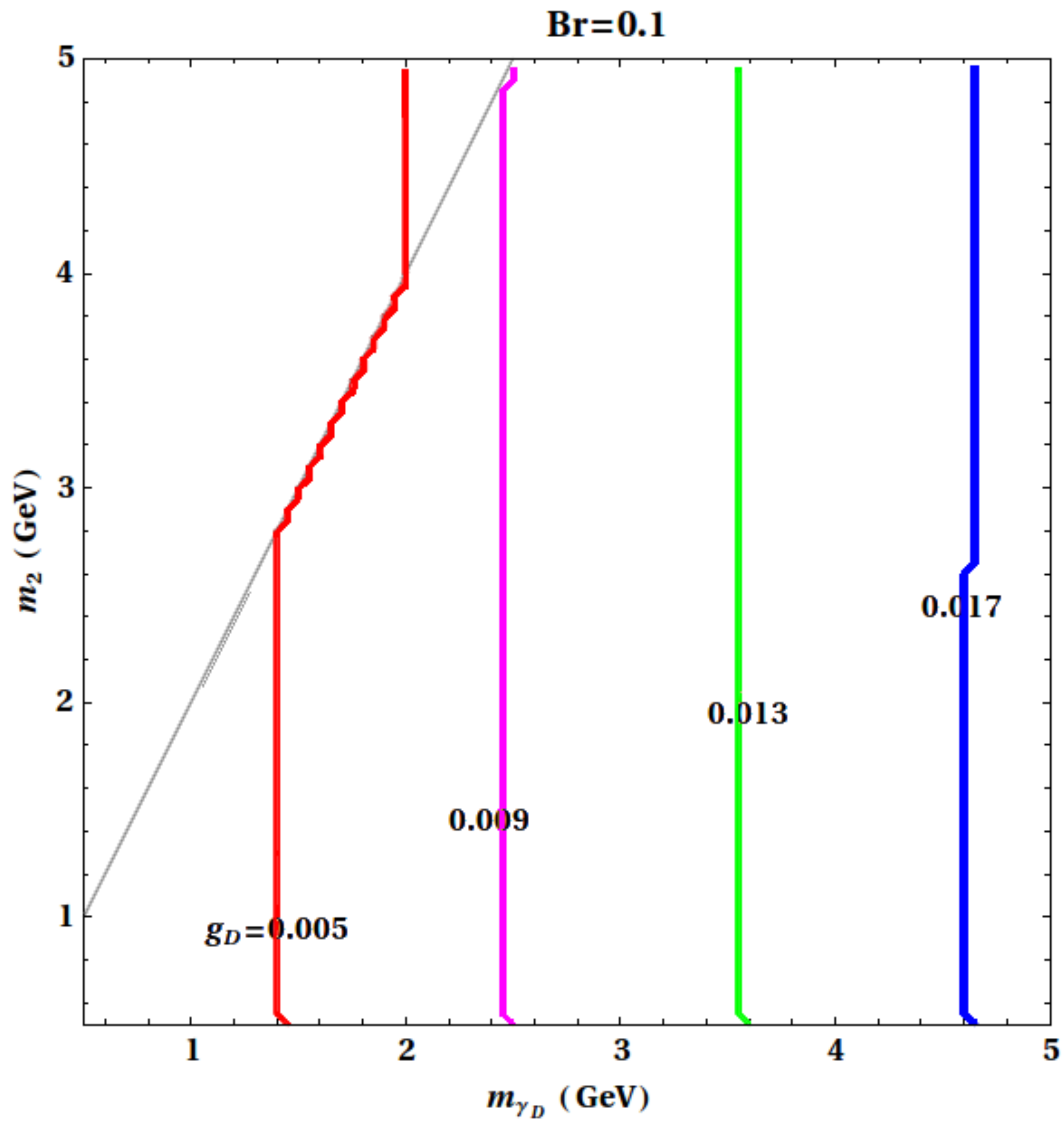
- The SM Higgs width is 4.03 MeV (Theory) while LHC constrains the non-standard Higgs width to be less than 3.3 MeV

Parameter Space: α, g_D, m_2, $m_{\gamma D}$ and ε

Contour Plots for non-standard branching ratio for standard model Higgs (($\sin^2\alpha$=0.0009;Br=0.1)

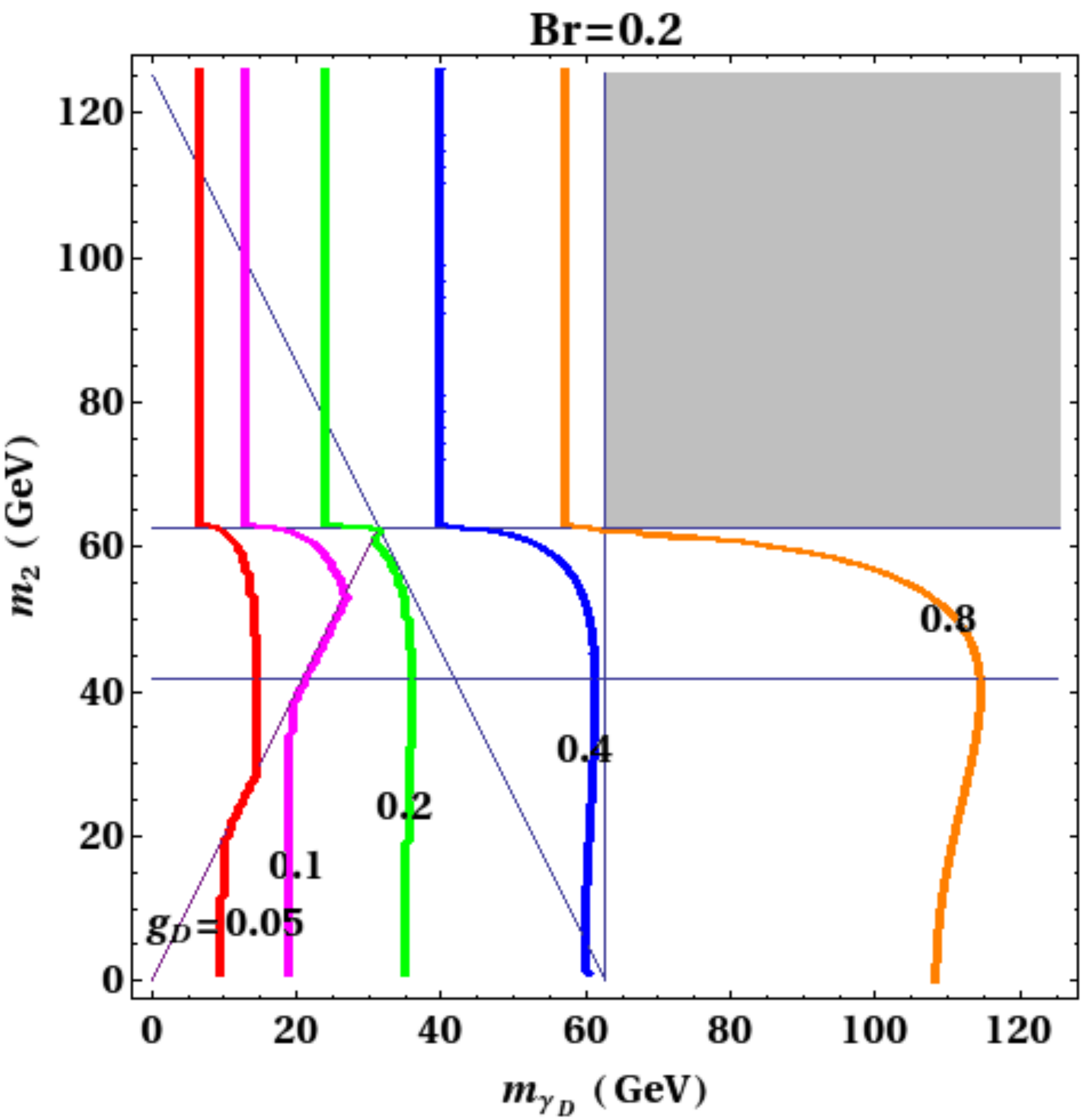
Chia-Feng Chang, Ernest Ma and TCY, [arXiv:1308.6071]

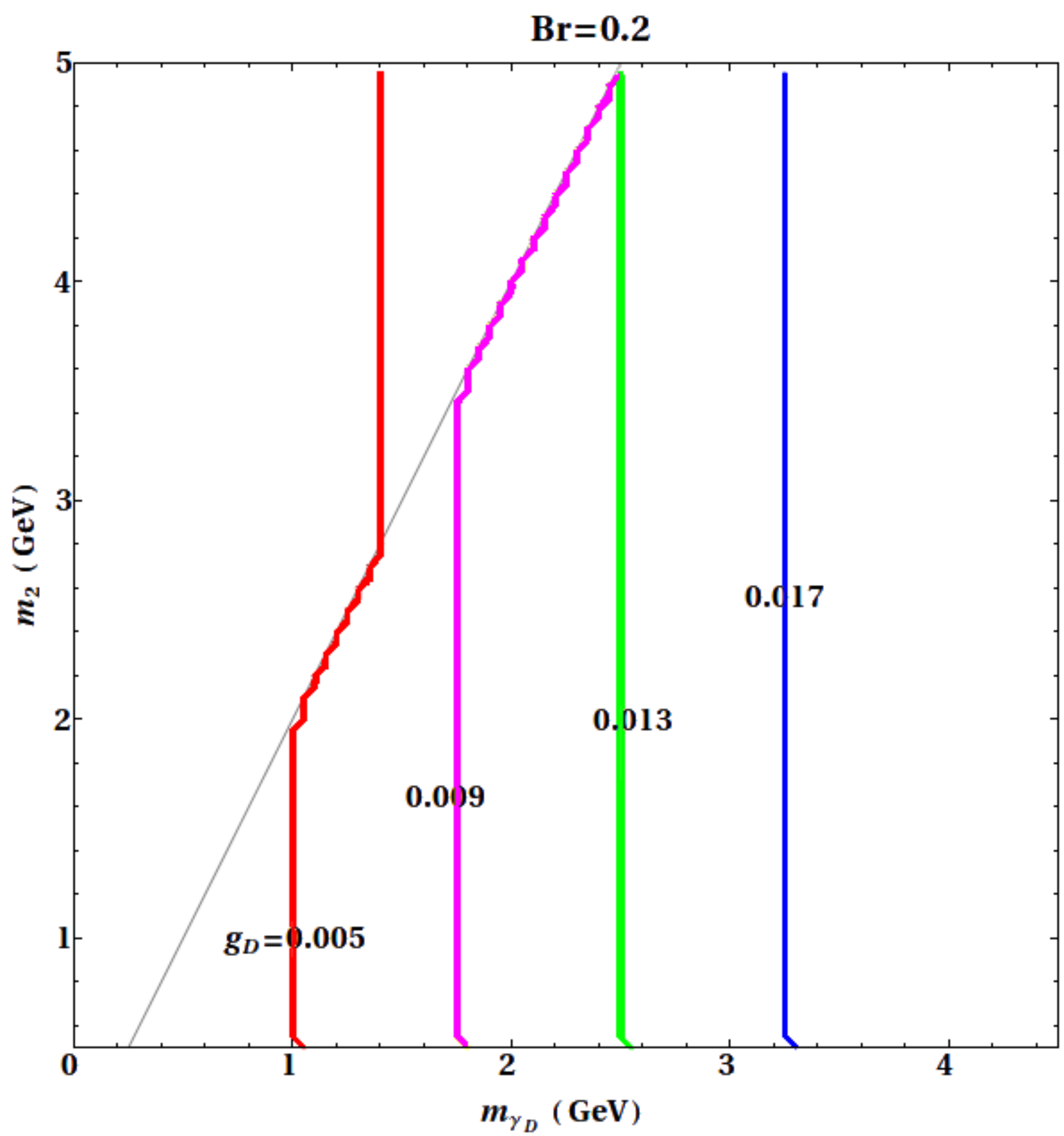




Light Mass Region

Contour Plots for non-standard branching ratio for standard model Higgs ($\sin^2\alpha$=0.0009;Br=0.2)





Light Mass Region

Multilepton Jets at the LHC

- Four processes which may lead to signals of multilepton jets at the LHC
- (I) and (II) are SM processes
- (III) and (IV) are dark processes
- (III) with X=Z is SM process with modified h_1 coupling

$$\text{(I)}\quad pp \to h \to ZZ \to l^+l^-l^+l^-$$

$$\text{(II)}\quad pp \to VV \to l^+l^-l^+l^- \qquad (VV \;=\; ZZ,\, \gamma\gamma,\, Z\gamma)$$

$$\text{(III)}\quad pp \to h_1 \to XX \to l^+l^-l^+l^- \qquad (XX \;=\; ZZ,\, \gamma_D\gamma_D,\, h_2h_2)$$

$$\text{(IV)}\quad pp \to h_1 \to h_2h_2 \to \gamma_D\gamma_D\gamma_D\gamma_D \to l^+l^-l^+l^-l^+l^-l^+l^-$$

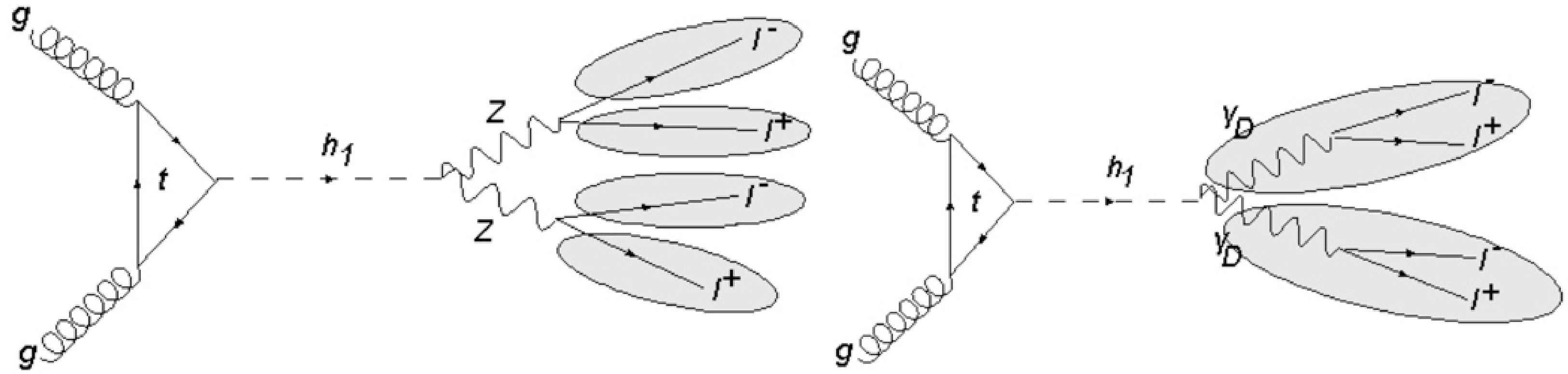


Figure 6. Some topologies of 4 (left) and 2 (right) lepton-jets for process III. The 4 lepton-jets can also be coming from the SM of process I with h_1 replaced by the SM h. The immediate state of h_2h_2 for the 2 lepton-jets is not shown since the branching ratio for $h_2 \to l^+l^-$ is very tiny.

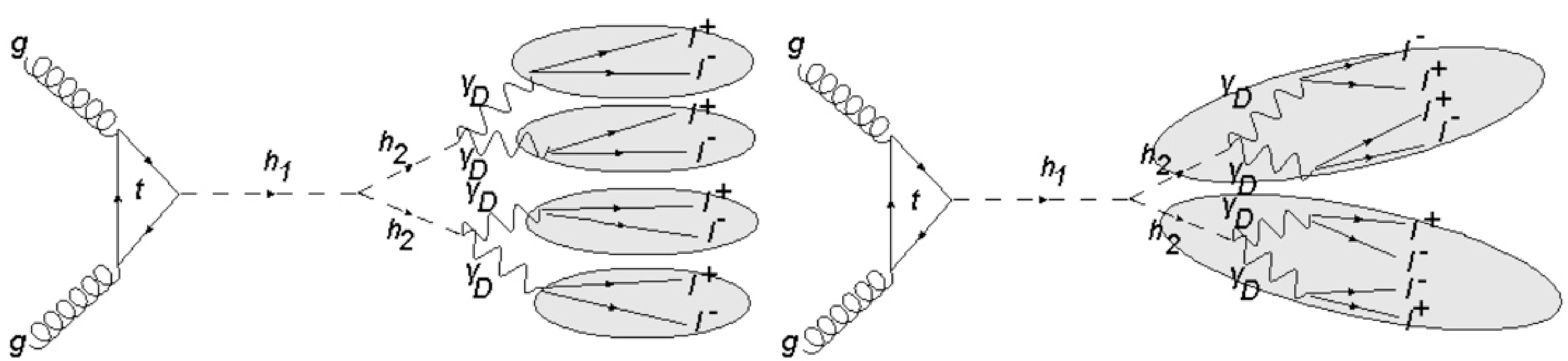


Figure 7. Some topologies of 4 (left) and 2 (right) lepton-jets for process IV.

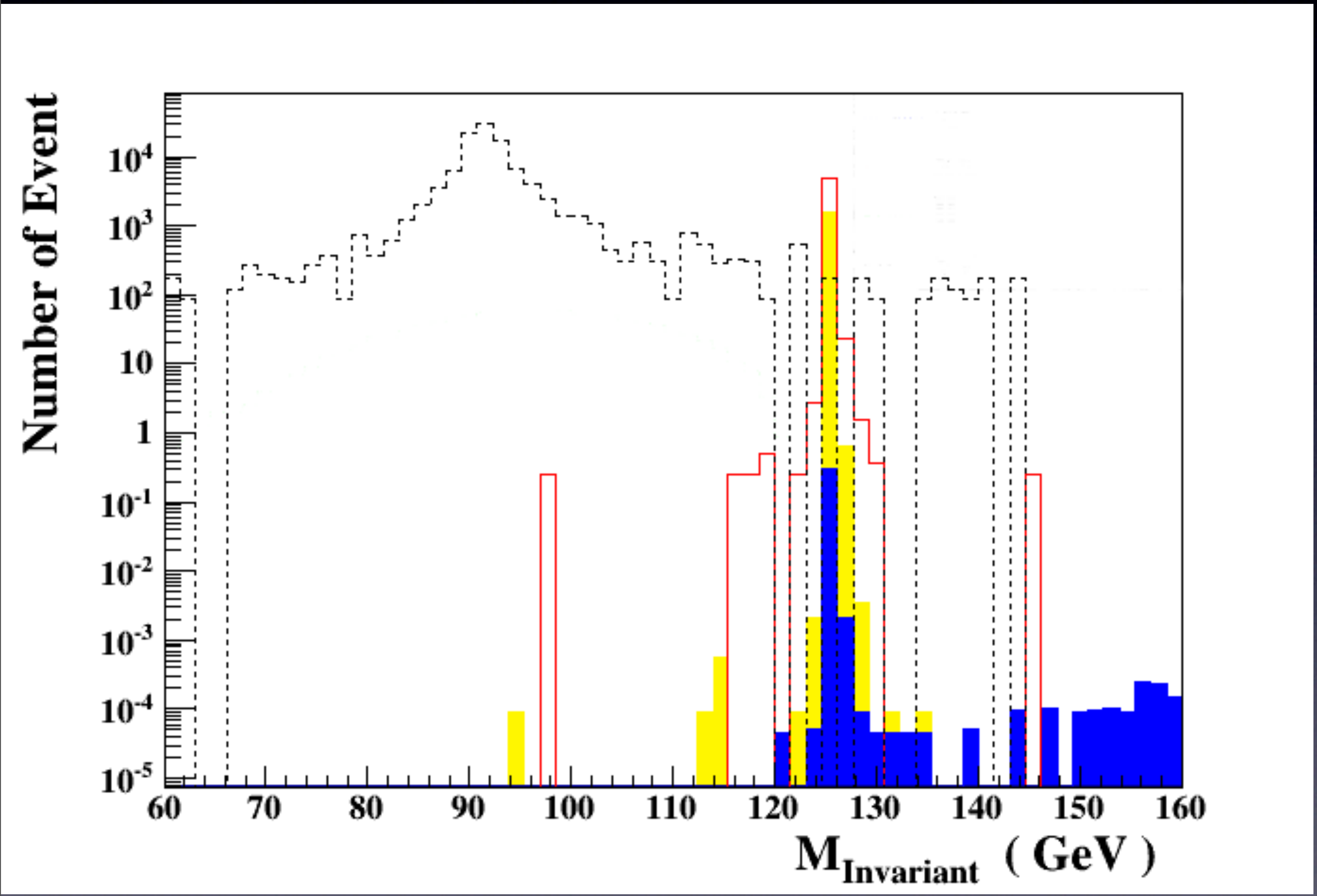
Benchmark Points

Benchmark Point	g_D	M_{γ_D}	m_2	$\mathrm{Br}_{h_1 \to \mathrm{DarkStuff}}$	$\mathrm{Br}_{h_2 \to \gamma_D \gamma_D}$	$\mathrm{Br}_{\gamma_D \to l^+ l^-}$
A	0.005	1.5	4	$\sim 16\%$	99%	50%
B	0.009	1.8	10	$\sim 20\%$	100%	50%
C	0.005	1.5	40	$\sim 15\%$	99%	50%
D	0.005	1.8	40	$\sim 11\%$	99%	50%

Table 1. Several benchmark points of the dark portal used to calculate the signals of multilepton jets ($\epsilon = 10^{-4}$ and $\sin^2 \alpha = 10^{-3}$). Mass in GeV.

(1) Nonstandard Higgs decay branching ratio is consistent with global fits
(2) Dark Higgs decays ~100% into 2 dark photons
(3) Dark photon decays into lepton pairs as large as 50%
(4) Mixing parameters α and ε are small so that cross section for h_1 production is close its SM value
(5) Dark photon mass is chosen less than 2 GeV such that small opening angle for the lepton pairs (as compared with Z)

Number of Events vs. M_{Inv}



- Benchmark point B
- No cuts
- Blue strip (I)
  Black dash (II)
  Red solid (III)
  Yellow strip (IV)

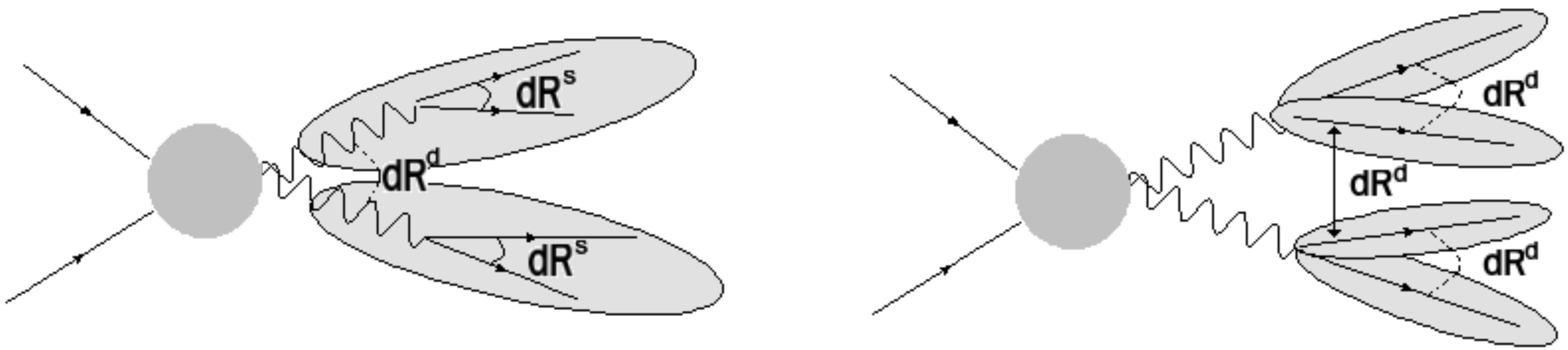
Kinematical Cuts

Basic cuts: (4 leptons case) $p_{T_l} \geq 20, 10, 10, 10\,\text{GeV}, \quad |\eta_l| < 2.3;$

(8 leptons case) $p_{T_l} \geq 20, 10, 10, 10, 0, 0, 0, 0\,\text{GeV}, \quad |\eta_l| < 2.3,$

4 lepton-jets cuts : $\Delta R^d_{j_i j_j} > 0.7, \quad \Delta R^s_{l_i l_j} < 0.2, \quad M_{\text{Invariant}} = M_{h_1} \pm 10\,\text{GeV};$

2 lepton-jets cuts : $\Delta R^d_{j_1 j_2} > 0.7, \quad \Delta R^s_{l_i l_j} < 0.2, \quad M_{\text{Invariant}} = M_{h_1} \pm 10\,\text{GeV}.$



References:
(1) Gopalakrishna, Jung and Wells, 0801.3456;
(2) Falkowski, Ruderman, Volansky and Zupan, 1007.3496;
(3) ATLAS collab. 1302.4403.

Cross Sections (fb) at Benchmark Points

- 2 and 4 lepton-jets cuts have great impact on SM processes, in particular for process (I) where gg → h_1 → ZZ → 4 leptons compared with process (II) where qq → ZZ → 4 leptons
- Process III where $h_1 \to \gamma_D \gamma_D \to$ 4 leptons favors by 2 lepton-cuts
- Lepton-jets cuts have non-trivial effects on process IV where $h_1 \to h_2 h_2 \to \gamma_D \gamma_D \gamma_D \gamma_D$ → 8 leptons; however in general it has smaller cross section than process III

(I) $pp \to h \to ZZ \to l^+l^-l^+l^-$

(II) $pp \to VV \to l^+l^-l^+l^- \quad (VV = ZZ, \gamma\gamma, Z\gamma)$

(III) $pp \to h_1 \to XX \to l^+l^-l^+l^- \quad (XX = ZZ, \gamma_D\gamma_D, h_2h_2)$

(IV) $pp \to h_1 \to h_2h_2 \to \gamma_D\gamma_D\gamma_D\gamma_D \to l^+l^-l^+l^-l^+l^-l^+l^-$

Cuts	Benchmark Point	I	II	III	IV
Basic	A	0.118	70.7	95.3	23.2
	B	0.118	70.7	204	45.8
	C	0.118	70.7	96.7	19.2
	D	0.118	70.7	68.3	13.1
Basic + 4 Lepton-Jets	A	9.63×10^{-3}	0.337	9.86×10^{-3}	$\leq 10^{-10}$
	B	9.63×10^{-3}	0.337	9.80×10^{-3}	$\leq 10^{-10}$
	C	9.63×10^{-3}	0.337	9.93×10^{-3}	3.05
	D	9.63×10^{-3}	0.337	9.84×10^{-3}	0.92
Basic + 2 Lepton-Jets	A	$\leq 10^{-10}$	0.08	95.3	1.75
	B	$\leq 10^{-10}$	0.08	201	$\leq 10^{-10}$
	C	$\leq 10^{-10}$	0.08	95.8	$\leq 10^{-10}$
	D	$\leq 10^{-10}$	0.08	68.2	$\leq 10^{-10}$

Table 2. Cross sections (in unit of fb) at the LHC-14 for the background processes (I and II) and dark sector processes (III and IV) with the basic, 4 and 2 lepton-jets cuts at the 4 benchmark points.

Summary

- Multi-lepton modes (No Missing Energy!) from SM Higgs decay are very interesting and should be studied in more details.
- Multi-pion jets may be interesting too. Need to differentiate between QCD jets and lepton jets.
- May be interesting to generalize to associated production of W/Z+Higgs.
- Exotic Higgs decay modes are important since it may lead to discovery of a hidden sector like a dark U(1) with light hidden particles.

Thank You