Two Higgs Doublet Models in light of LHC Data

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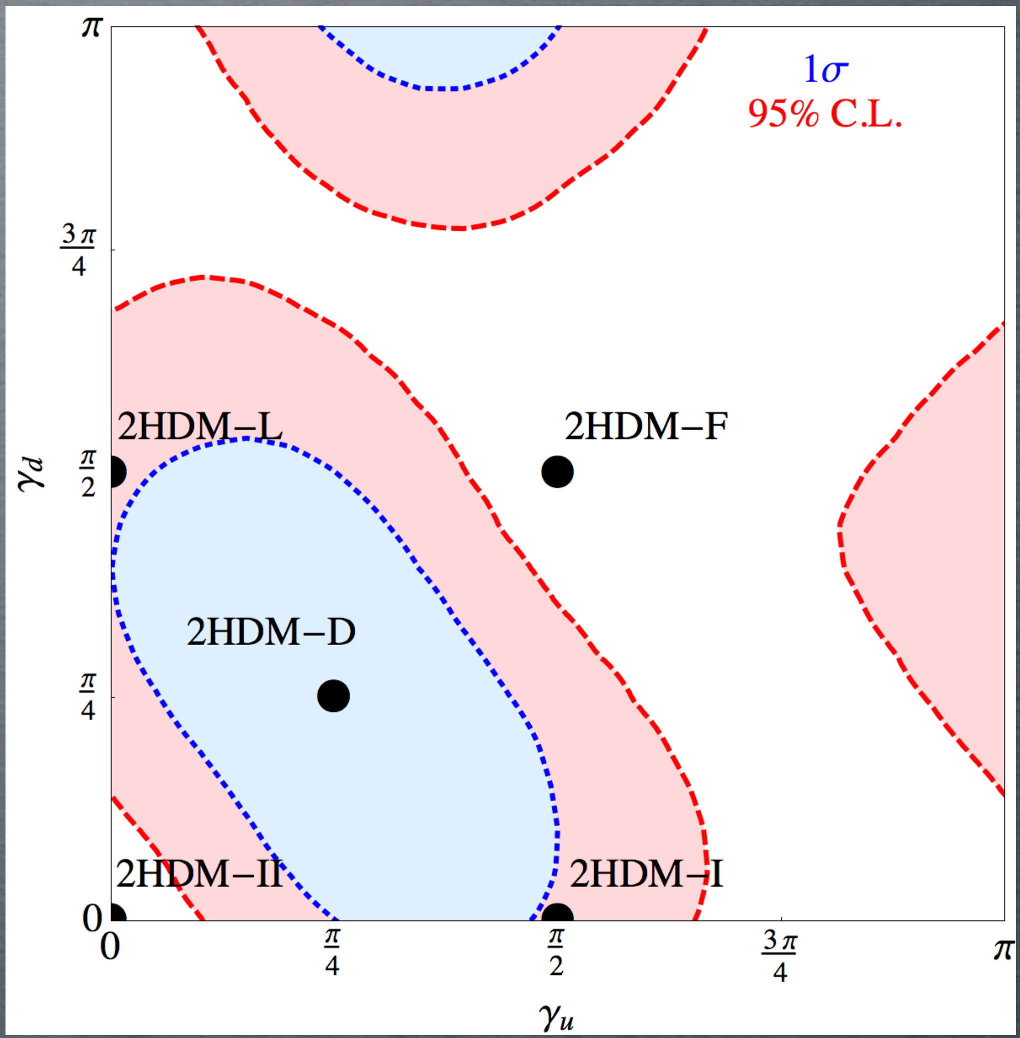


Overview of Two-Higgs Doublet Models

- Two complex SU(2) doublets with opposite hypercharge

$$\mathbf{\Phi}_1 = \begin{pmatrix} (v_1 + \phi_1^r + i\,\phi_1^i)/\sqrt{2} \\ \Phi_1^- \end{pmatrix} \quad \mathbf{\Phi}_2 = \begin{pmatrix} \Phi_2^+ \\ (v_2 + \phi_2^r + i\,\phi_2^i)/\sqrt{2} \end{pmatrix}$$

- Masses and couplings for W/Z occur via kinetic terms

$$\mathcal{L}_{Kin} = \sum_i \left| \left(\partial_\mu - igW_\mu^a T^a - ig' \frac{Y}{2} B_\mu \right) \Phi_i \right|^2$$

  - Gauge boson couplings obey usual relation

$$g_{hVV} = g_V\, m_V\ \sin(\beta - \alpha)$$

- Models vary depending on Yukawa coupling structure:
  - 2HDM-I $\quad \mathcal{L}_{Yuk} = -y_f \bar{f}_R \Phi_1^\dagger F_L + h.c.$
  - 2HDM-II (SUSY) $\quad \mathcal{L}_{Yuk} = -y_u \bar{u}_R \Phi_2^\dagger Q_L - y_d \bar{d}_R \Phi_1^\dagger Q_L - y_\ell \bar{\ell}_R \Phi_1^\dagger L_L + h.c.$
  - Lepton Specific $\quad \mathcal{L}_{Yuk} = -y_u \bar{u}_R \Phi_2^\dagger Q_L - y_d \bar{d}_R \tilde{\Phi}_2^\dagger Q_L - y_\ell \bar{\ell}_R \Phi_1^\dagger L_L + h.c.$
  - Flipped $\quad \mathcal{L}_{Yuk} = -y_u \bar{u}_R \tilde{\Phi}_1^\dagger Q_L - y_d \bar{d}_R \tilde{\Phi}_2^\dagger Q_L - y_\ell \bar{\ell}_R \Phi_1^\dagger L_L + h.c.$

The 2HDM-G

- Yukawa coupling structure generalized

$$\begin{aligned} -\mathcal{L}_{Yuk} \;\; = \;\; & y_u\,\overline{u}_R\,(\cos\gamma_u\,\mathbf{\Phi}_u \;-\; \sin\gamma_u\,\tilde{\mathbf{\Phi}}_d)\,Q_L \\ & + y_d\,\overline{d}_R\,(\cos\gamma_d\,\mathbf{\Phi}_d \;+\; \sin\gamma_d\,\tilde{\mathbf{\Phi}}_u)\,Q_L \\ & + y_\ell\,\overline{e}_R\,\mathbf{\Phi}_d\,L_L \;+\; \text{h.c.}\,, \end{aligned}$$

Bai, Barger, Everett, GS (1210.4922)

- FCNCs suppressed as flavor structure governed by same Yukawa matrix
- Yukawa couplings with respect to SM

$$ht\bar{t}: \quad \frac{\cos(\alpha+\gamma_u)}{\sin(\beta+\gamma_u)}\,, \qquad hb\bar{b}: \quad -\frac{\sin(\alpha-\gamma_d)}{\cos(\beta-\gamma_d)}\,, \qquad h\tau\bar{\tau}: \quad -\frac{\sin\alpha}{\cos\beta}\,,$$

- Traditional 2HDMs are a subset of the 2HDM-G model

Type	I	II	Lepton	Flipped	Democratic
γ_u	$\frac{\pi}{2}$	0	0	$\frac{\pi}{2}$	$\frac{\pi}{4}$
γ_d	0	0	$\frac{\pi}{2}$	$\frac{\pi}{2}$	$\frac{\pi}{4}$

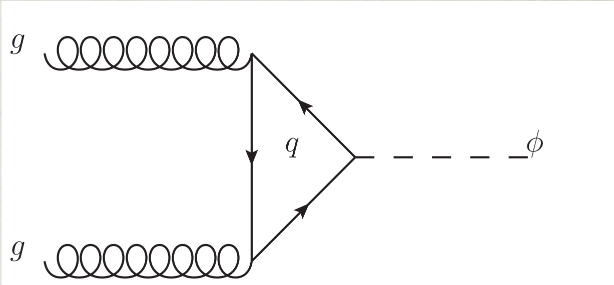
Pich and Tuzon PRD 80 91702

- SM recovered when $\gamma_u, \gamma_d \to 0, \quad \beta \to \alpha + \pi/2$

Altmannshofer, Gori, Kribs (1210.2465)

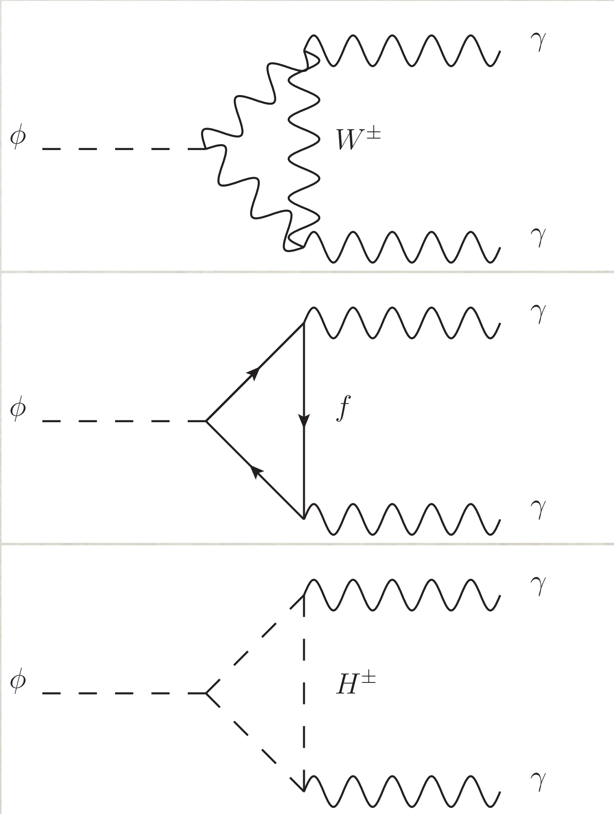
Loop induced couplings

- Gluon couplings induced via quark loops
  - Dominated by top-loop for most of the parameter ranges we see



- Photon couplings typically dominated by W-loop
  - Fermion loops with opposite sign reduces decay rate
  - Additional loop for charged scalars can be important for a light charged Higgs
- Trade couplings in scalar potential with masses and mixings:

$$g_{hH^+H^-} = 2\frac{\cos(\alpha+\beta)}{\sin 2\beta}\frac{M_h^2 - M_{12}^2}{v} + \sin(\beta-\alpha)\frac{2M_{H^\pm}^2 - M_h^2}{v},$$



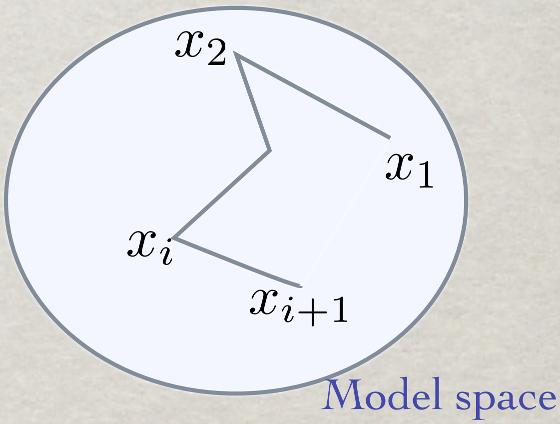
Aside: Bayesian fits

- Bayesian approach optimally scans parameter space
- More efficient with large number of parameters
- Chain based on collection of points chosen by relative likelihood
- Metropolis-Hastings Algorithm:
  - Probability of jump from current to next point in chain related to relative likelihood

$$P(x_i \to x_{i+1}) = \mathrm{Min}\left(1, \frac{\mathcal{L}_{i+1}}{\mathcal{L}_i}\right)$$

  - Likelihood constructed from chi-square

$$\mathcal{L}_i = e^{-\sum_j \chi_j^2/2}$$



- Collection of points in chain x_i approach posterior distribution of parameters of a model explaining the data
- Different than Frequentist χ^2 fits: probability of data explaining a model

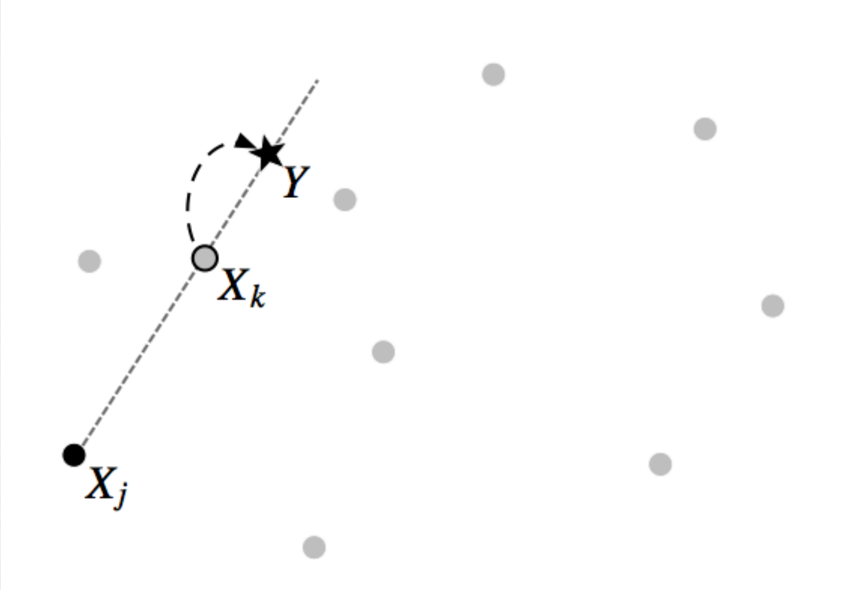
Goodman-Weare Algorithm

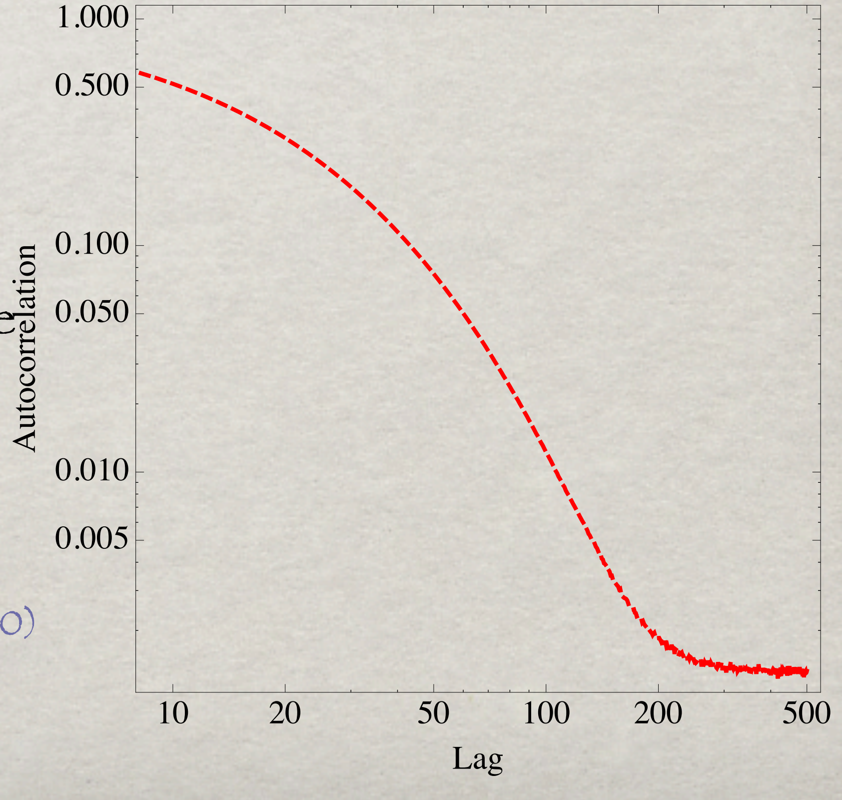
- Much more robust than Metropolis-Hastings
  - From Cosmology community
  - Set of random initial points in parameter space - each point a "Walker"
  - Trial point proposed along line linking two "Walkers"
  - Trial steps satisfy detailed balance*
  - Burn-in thrown away to decouple from initial set of points
- Convergence based on autocorrelation time of "Walkers"

$$C(T) = \frac{1}{n-T}\sum_{t=1}^{n-T}(X_t - \bar{X})(X_{t+T} - \bar{X})$$

- Very efficient (up to 10x faster than Metropolis-Hastings)

Goodman and Weare (2010) and 1202.3665



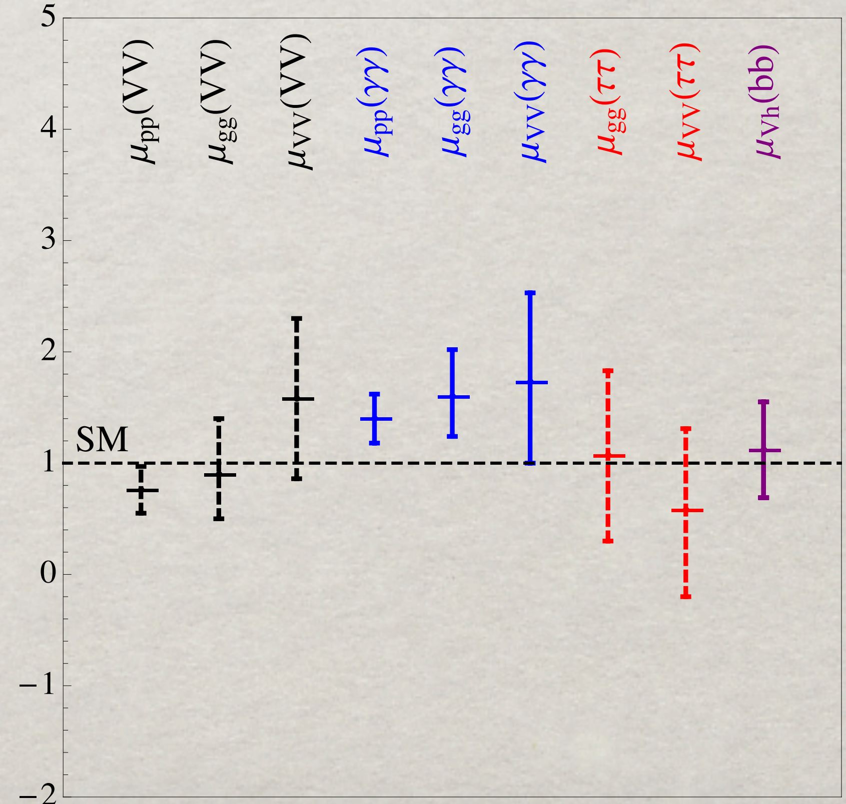


Bayesian Fit

- Flat prior for most parameters
  - Log prior for $\tan\beta$
- Scalar potential parameters traded for masses $(M_h, M_H, M_A, M_{H^\pm})$ and mixings $(\alpha, \tan\beta)$
- WW and ZZ couplings related by custodial symmetry
  - We consider measurement of decays to WW and ZZ to be equivalent probe of the model
- Perturbativity required of the scalar potential couplings and all Yukawa couplings $\lambda_i^2, y_f^2 < 4\pi$
- EWPT (S & T) and $BF(b \to s\gamma)$ included in likelihood

Distilled data from the LHC and Tevatron:

$$\begin{aligned}
\mu_{pp}(\gamma\gamma) &= 1.4^{+0.2}_{-0.2}\,, & \mu_{gg}(\gamma\gamma) = 1.6^{+0.4}_{-0.4}\,,\\
\mu_{VV}(\gamma\gamma) &= 1.7^{+0.8}_{-0.7}\,, & \mu_{pp}(VV) = 0.8^{+0.2}_{-0.2}\,,\\
\mu_{gg}(VV) &= 0.9^{+0.5}_{-0.4}\,, & \mu_{VV}(VV) = 1.6^{+0.7}_{-0.7}\,,\\
\mu_{gg}(\tau\tau) &= 1.1^{+0.8}_{-0.8}\,, & \mu_{VV}(\tau\tau) = 0.6^{+0.7}_{-0.8}\,,\\
\mu_{Vh}(b\bar{b}) &= 1.1^{+0.4}_{-0.4}\,,
\end{aligned}$$



B to X_s gamma

- HFAG combined measurement:

$$\mathrm{BF}\left(B^0 \to X_s + \gamma + X\right) = (3.43 \pm 0.22) \times 10^{-4}$$

- SM prediction (NNLO QCD): hep-ph/0609232

$$\mathrm{BF}\left(B^0 \to X_s + \gamma + X\right)_{SM} = (3.15 \pm 0.23) \times 10^{-4}$$

- Sensitive to charged Higgs

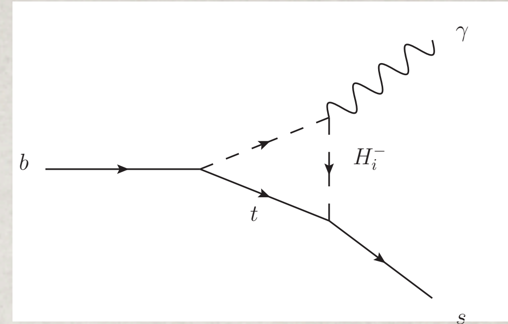
$$g_{H^- t\bar{b}} = \frac{\sqrt{2}}{v}(m_t A_u P_L + m_b A_d P_R)$$

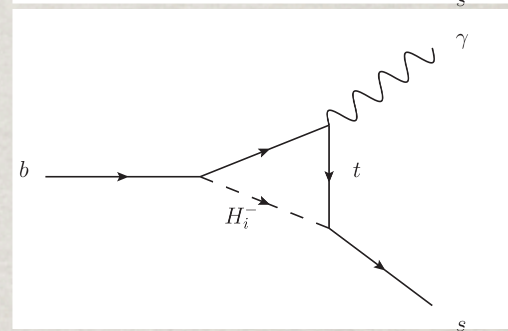
- Consistency with measurement requires simultaneous suppression of A_u and A_d

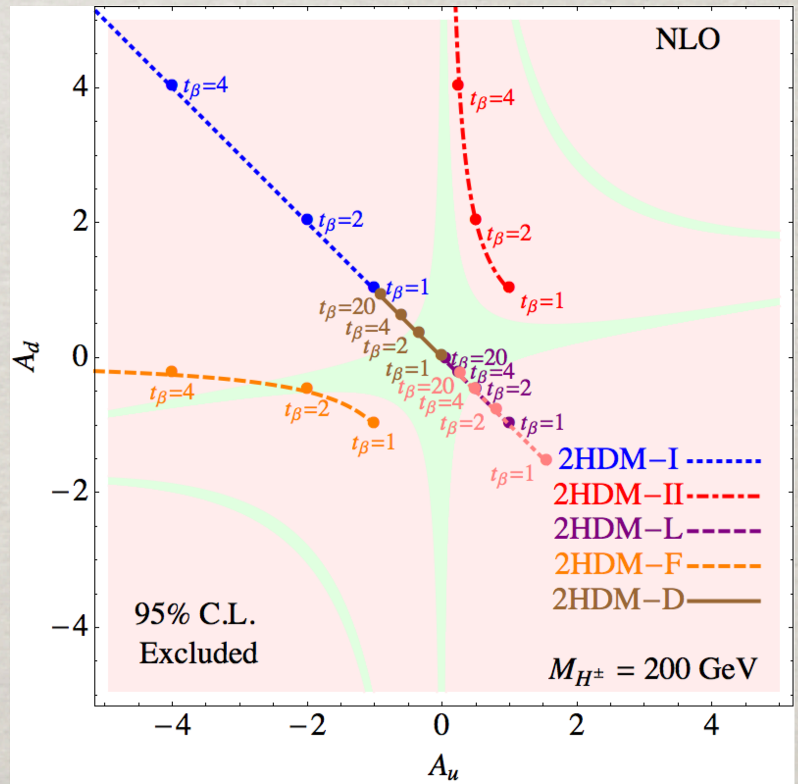
$$A_u = \cot(\beta + \gamma_u)$$

$$A_d = \tan(\beta - \gamma_d)$$

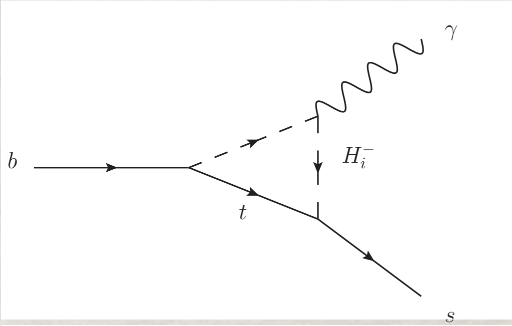
- 2HDM-II model requires heavy charged Higgs

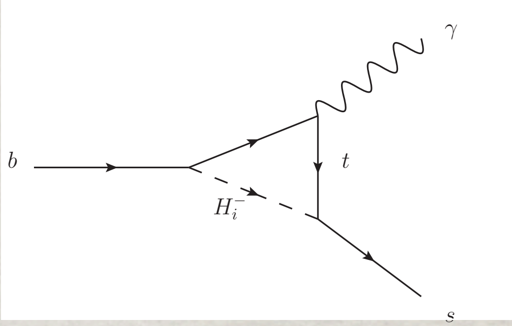






B to X_s gamma





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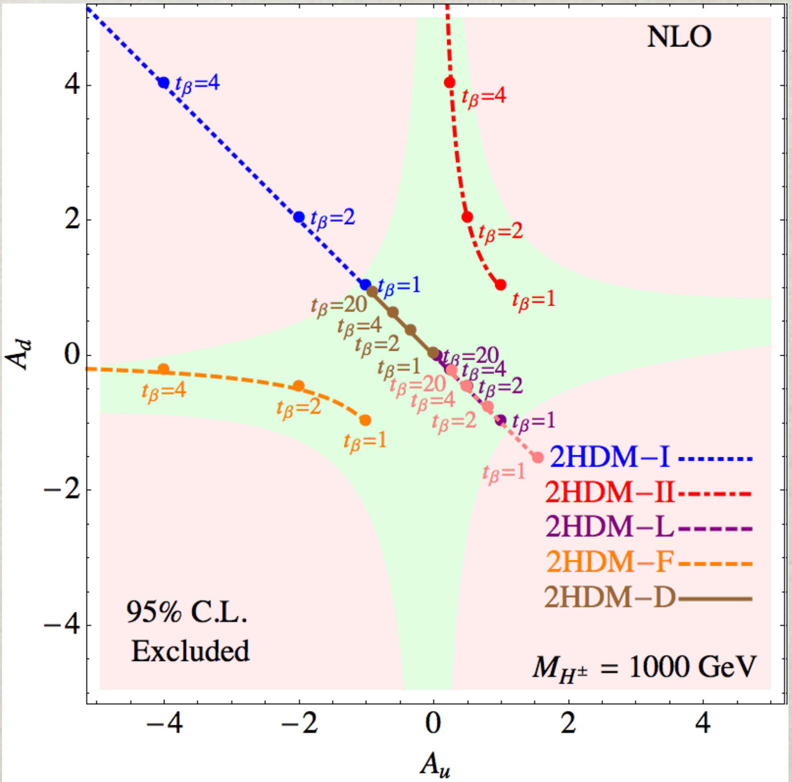
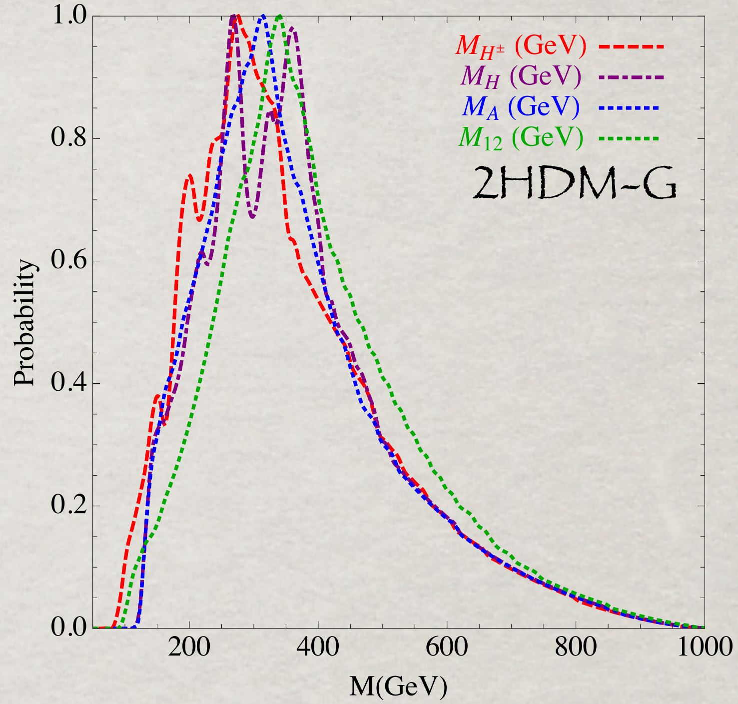
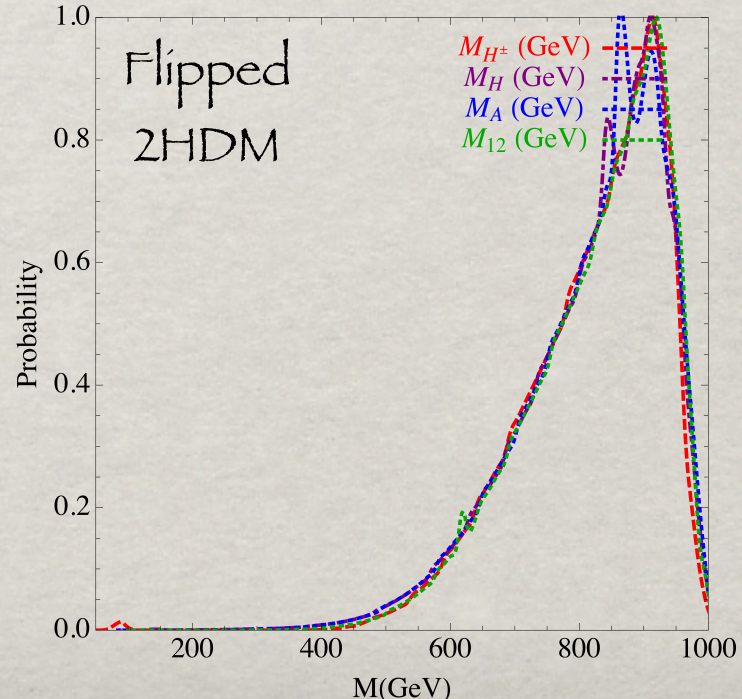


Heavy Higgs states

- To enhance the $\gamma\gamma$ rate, a light $H^{\pm}$ is needed
  - Electroweak precision has associated heavy state masses track $H^{\pm}$
  - Tension with $B^0 \to X_s + \gamma + X$ in Flipped and Type-II gives heavier Higgs sector
- Strong potential for future LHC searches of heavy states
  - Placed well for present charged Higgs search strategies: $pp \to t\bar{t} \to tH^{-}\bar{b}$ with $H^{-} \to \tau^{-}\nu$
  - Still, heavy charged Higgs searches need optimization

Everett, GS (in progress)





Bands by decay mode

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- W/Z couplings near decoupling limit
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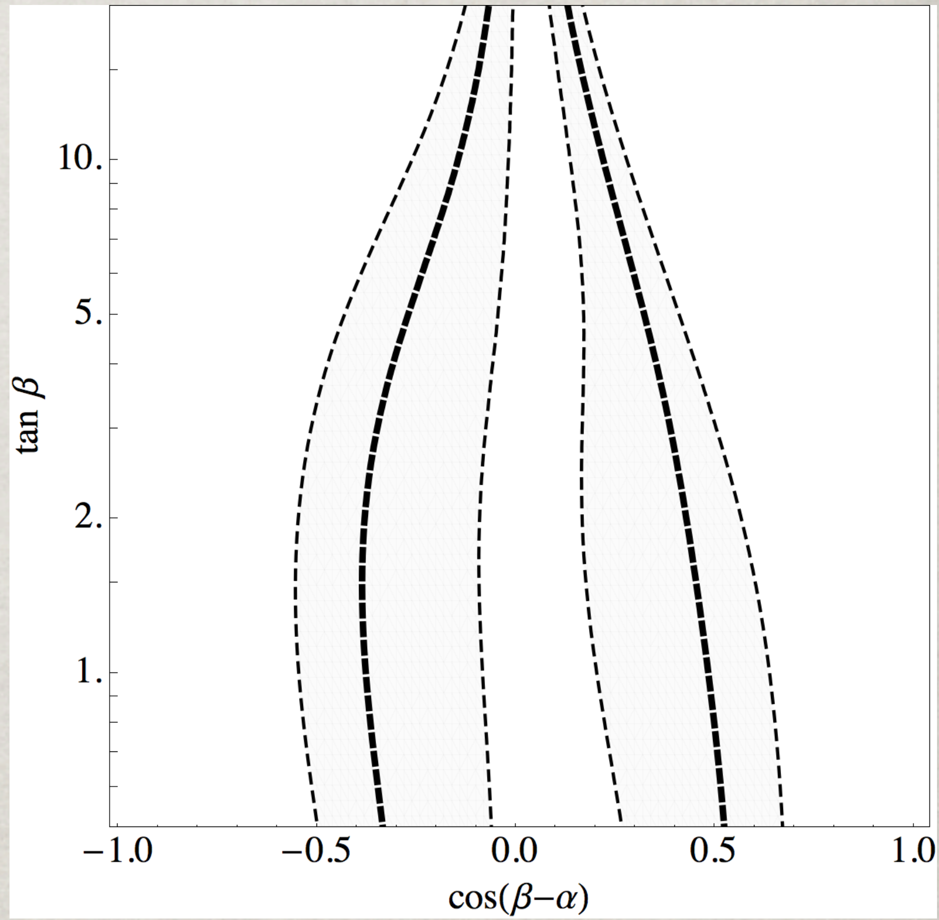

Bands taken from 2HDM-D model

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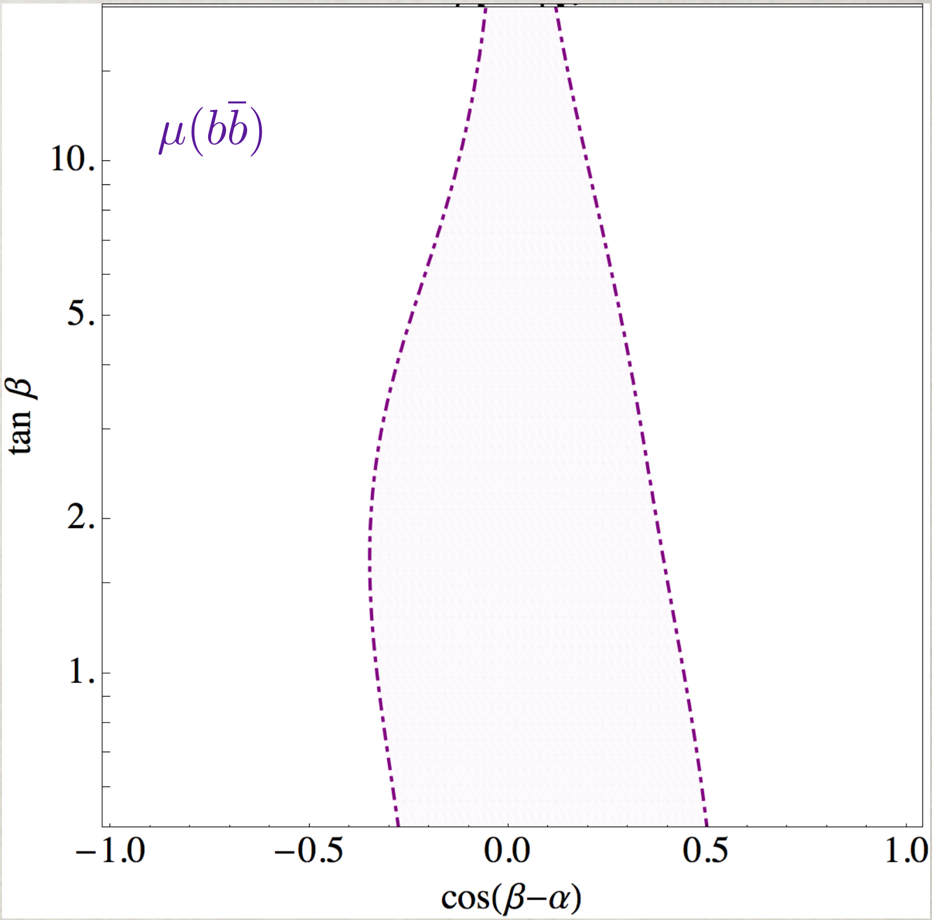
  - Difficult to obtain since bb dominates the SM Higgs BF



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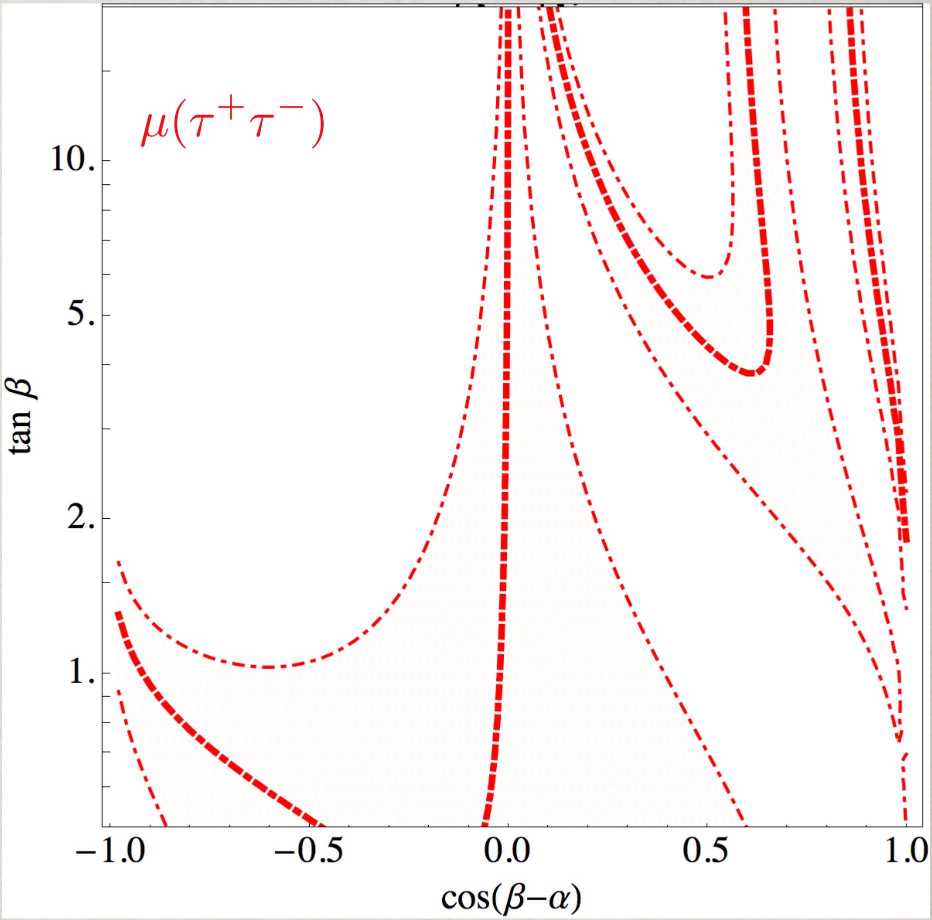

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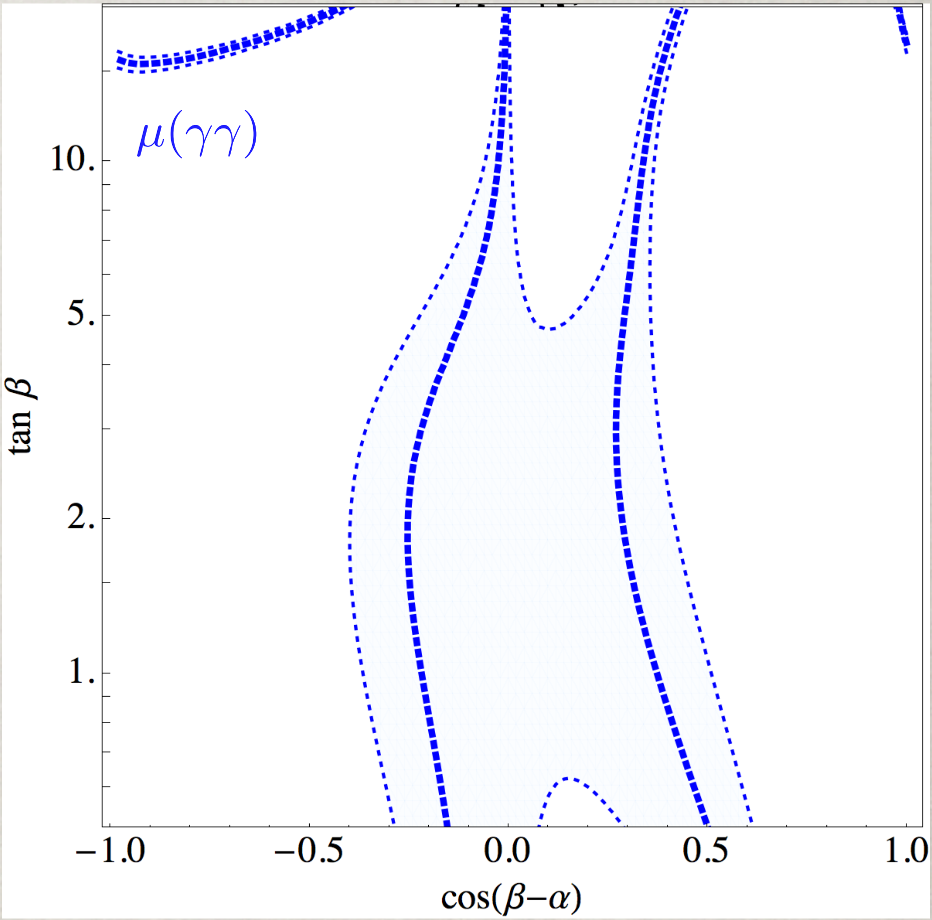

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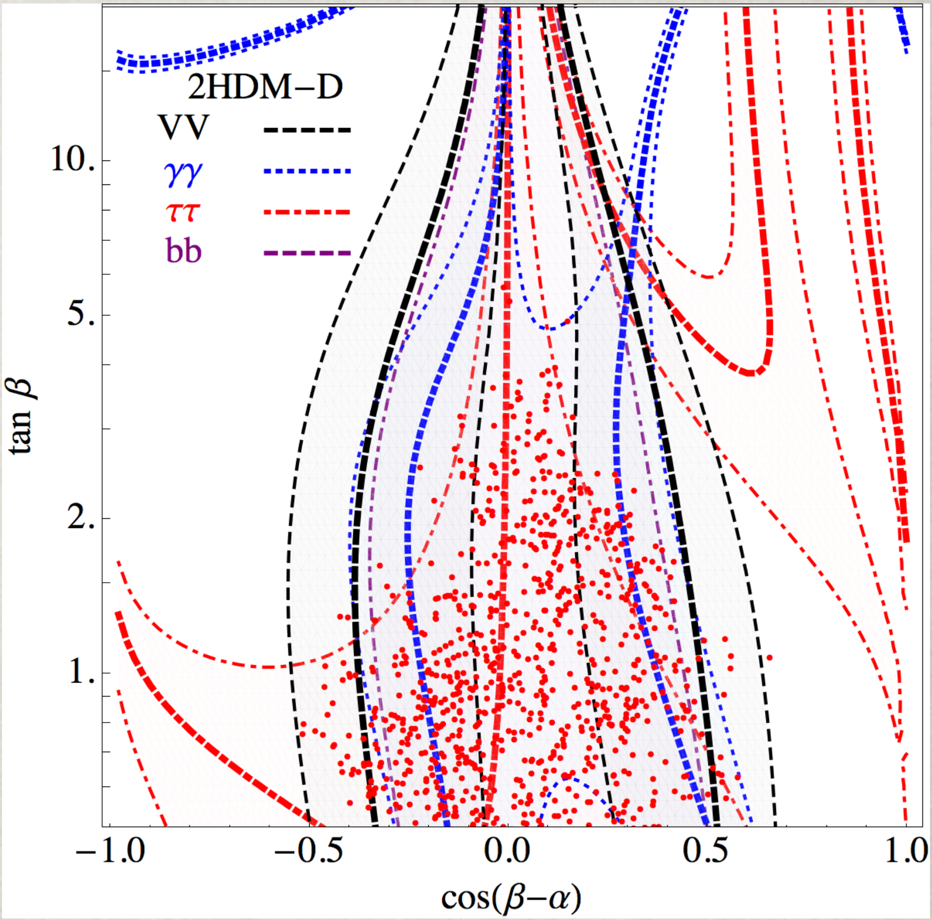
- Red points from Bayesian fit of 2HDM-G
- Points generally have low values of $\tan\beta$ due to $B^0 \to X_s + \gamma + X$



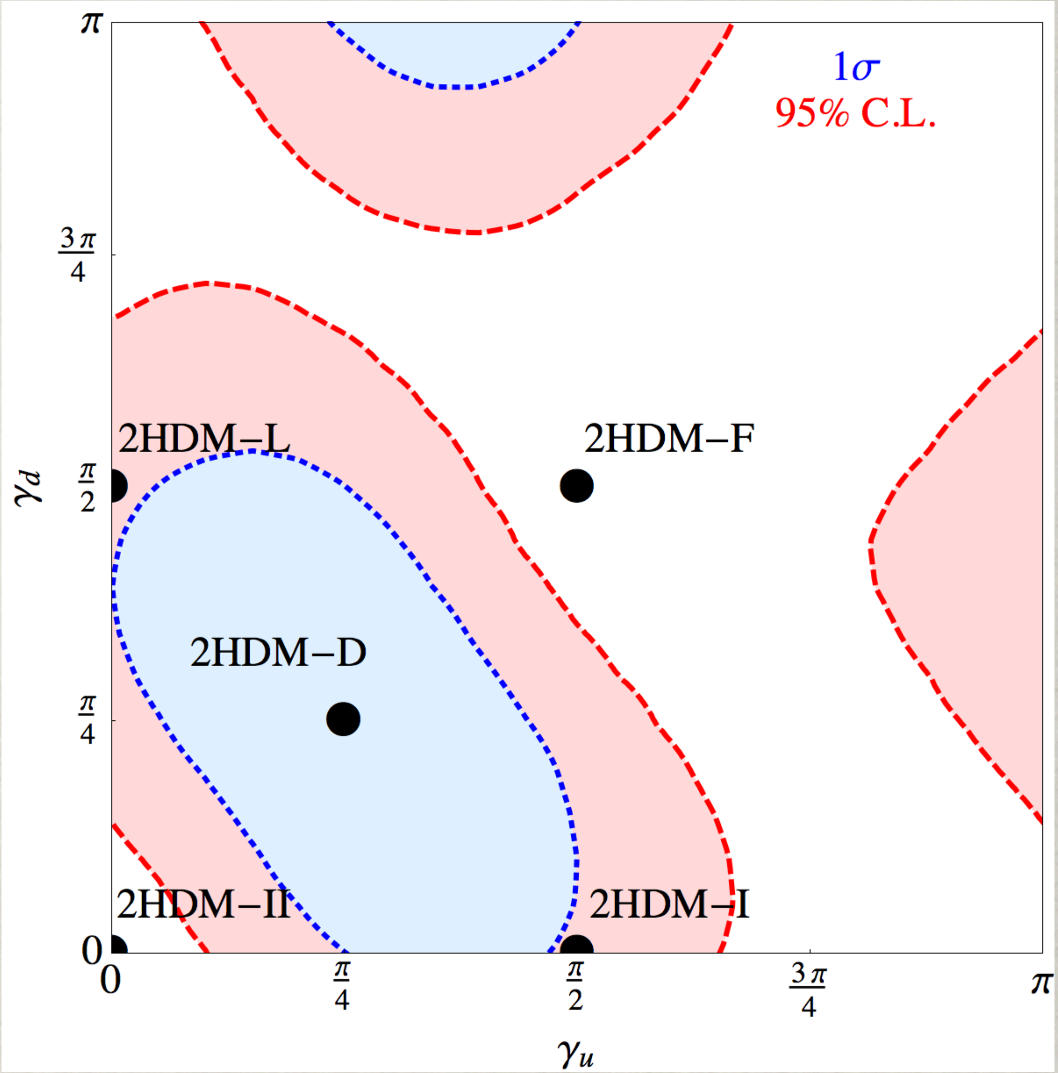
Bands taken from 2HDM-D model

Comparison with Traditional Models

- Type-II and F exhibit tension predominantly due to $BF(b \to s\gamma)$
- Lepton and Type-I models slight tension due to needing a slightly heavier $H^{\pm}$
- Democratic model provides great fit with equal quark and scalar doublet coupling

$$-\mathcal{L}_{Yuk} = y_u \, \overline{u}_R \, \frac{\mathbf{\Phi}_u - \tilde{\mathbf{\Phi}}_d}{\sqrt{2}} \, Q_L + y_d \, \overline{d}_R \, \frac{\mathbf{\Phi}_d + \tilde{\mathbf{\Phi}}_u}{\sqrt{2}} \, Q_L + y_\ell \, \overline{e}_R \, \mathbf{\Phi}_d \, L_L + \text{h.c.}\,,$$

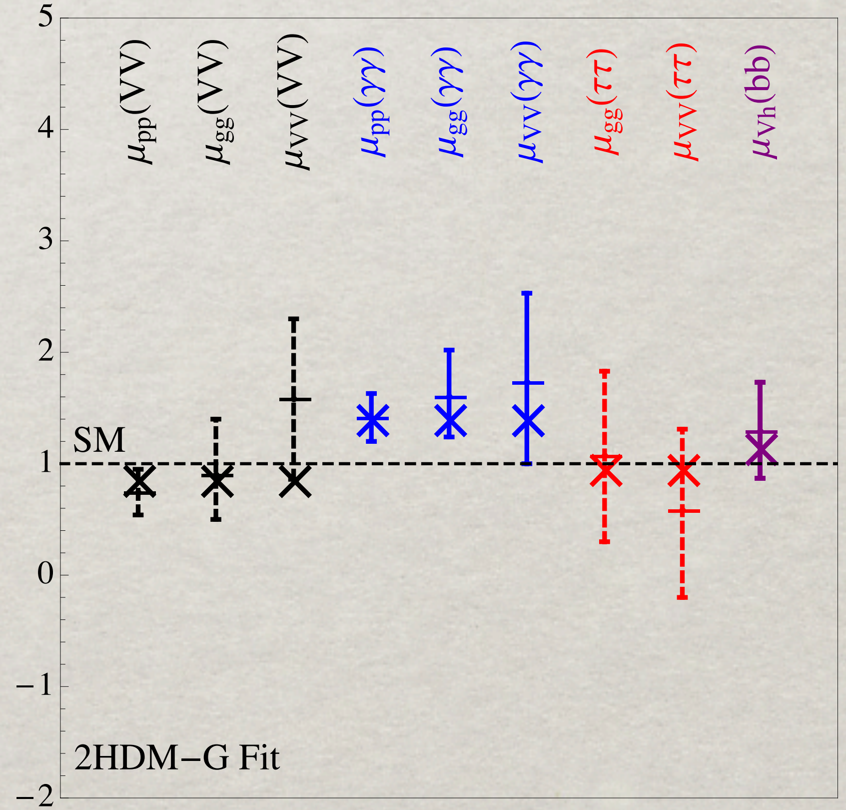
- Best fit sits at bottom of rather shallow χ^2 profile



Characteristics of model fits

- All models provide an excellent fit
- Type-II and Flipped model
  - Tension of light charged Higgs and $b \to s\gamma$ in 2HDM-II
  - Typically poor $\gamma\gamma$ rate fit associated with heavier charged Higgs
- Lepton specific and Type-I among best of the traditional models
  - Simultaneous suppression of charged Higgs coupling
- The General (2HDM-G) and Democratic models provide excellent fits

Model	χ^2_{VV}/ν	$\chi^2_{\gamma\gamma}/\nu$	$\chi^2_{b\bar{b}}/\nu$	$\chi^2_{\tau\tau}/\nu$	$\chi^2_{b\to s\gamma}/\nu$	$\chi^2_{\text{total}}/\nu$
SM	0.52	0.91	1.31	0.24	0.68	0.73
Type-I	0.31	0.49	1.45	0.22	0.03	0.48
Type-II	0.41	1.03	1.29	0.25	2.55	0.76
Lepton	0.33	0.51	1.44	0.21	0.02	0.49
Flipped	0.39	1.06	1.29	0.22	2.63	0.76
Democratic	0.27	0.41	1.49	0.40	0.05	0.49
General	0.24	0.49	1.23	0.21	0.01	0.42



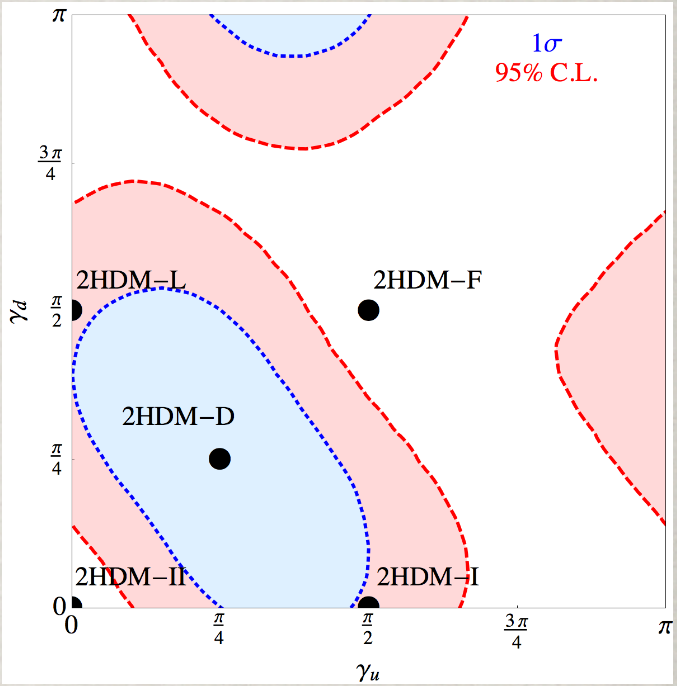
Summary and Outlook

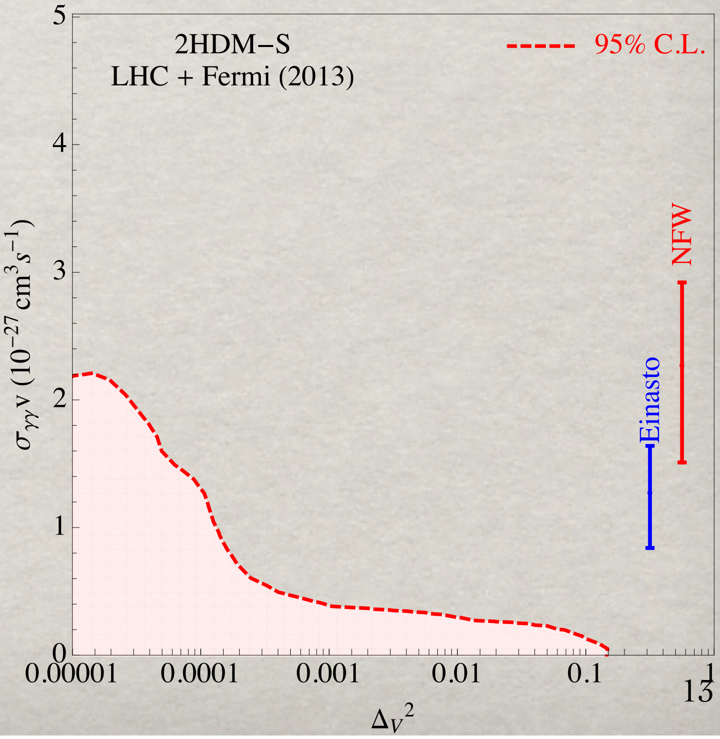
- Data from the LHC and Tevatron have provided a missing piece of the SM
- If the new boson is a scalar responsible for EWSB, much can be learned by probing its gauge and Yukawa couplings
- The 2HDM-G model offers an alternative to the traditional 2HDMs
  - The Democratic model is an interesting sub-model that can explain the data well
- Simple Dark Matter extension*: Explanation of Fermi line offers well defined predictions:
  - Very decoupled heavy scalar sector
  - Heavy CP-even Higgs with

$$265\ \text{GeV} < m_H < 280\text{GeV}$$

  - HESS-II well positioned to probe this region

Bai, Barger, Everett, GS (1212.5604)





Backup Slides

The general dark 2HDM

Simple Dark Extension

- Add a real scalar singlet to 2HDM-G model
- Now that a Higgs has been measured, it is worth looking into standard and new Higgs portals DM models for interesting directions
- Higgs doublet Potential:

$$\begin{aligned} V_\Phi &= m_1^2\Phi_1^\dagger\Phi_1 + m_2^2\Phi_2^\dagger\Phi_2 - \left(m_{12}^2\Phi_1^\dagger\tilde{\Phi}_2 + \text{h.c.}\right) \\ &+ \frac{\lambda_1}{2}|\Phi_1^\dagger\Phi_1|^2 + \frac{\lambda_2}{2}|\Phi_2^\dagger\Phi_2|^2 + \lambda_3|\Phi_1^\dagger\Phi_1\Phi_2^\dagger\Phi_2| \\ &+ \lambda_4|\Phi_1^\dagger\tilde{\Phi}_2\Phi_2^\dagger\tilde{\Phi}_1| + \frac{\lambda_5}{2}\left[(\Phi_1^\dagger\tilde{\Phi}_2)^2 + (\Phi_2^\dagger\tilde{\Phi}_1)^2\right], \end{aligned}$$

- Singlet potential

$$V_S = \frac{1}{2}m_S^2S^2 + \frac{\lambda_S}{4}S^4,$$

- Singlet - Higgs Mixing potential:

$$V_{\Phi S} = \frac{\delta_1}{2}S^2\Phi_1^\dagger\Phi_1 + \frac{\delta_2}{2}S^2\Phi_2^\dagger\Phi_2 + \frac{\delta_3}{2}S^2(\Phi_1^\dagger\tilde{\Phi}_2 + \text{h.c.}),$$

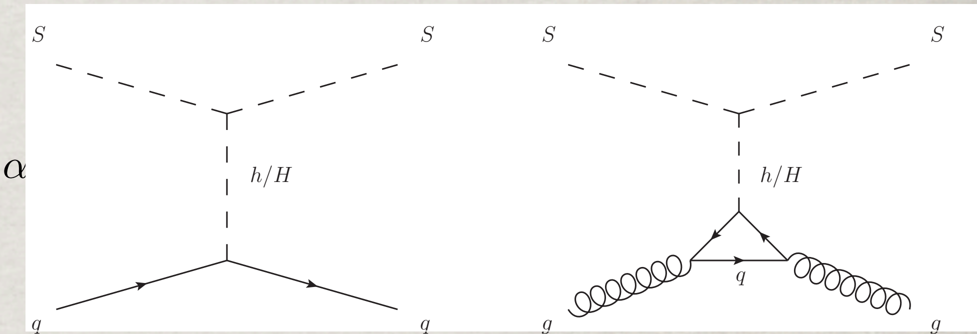
- New scalar acts as dark matter due to $\mathbb{Z}_2$ symmetry

Bai, Barger, Everett, GS (1212.5604)

Simple Dark Extension

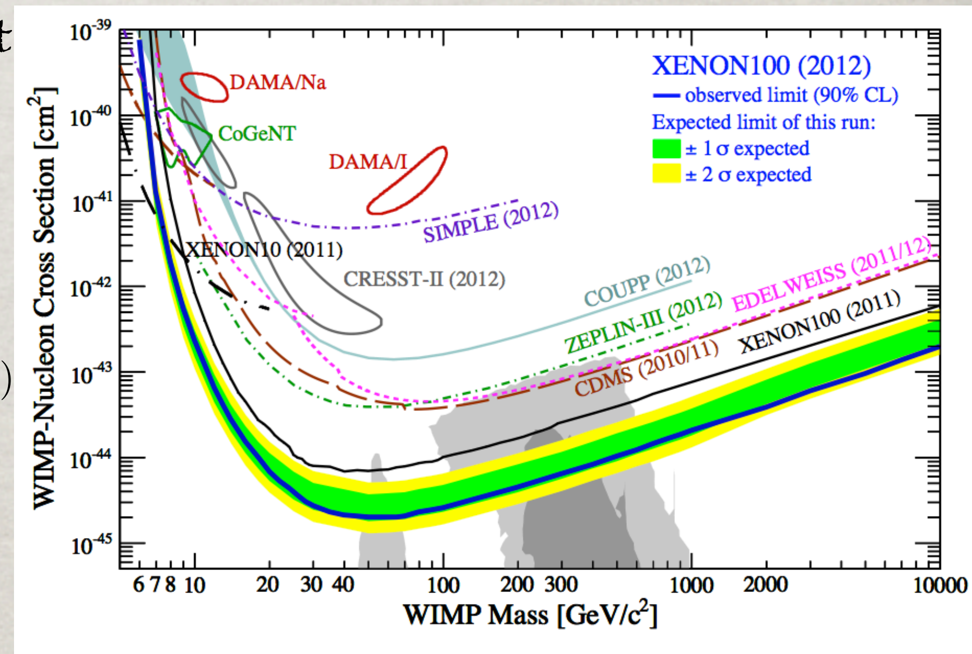
- Replace all mass terms and scalar couplings with masses of the model

$\lambda_{1,2,3,4,5}, m^2_{1,2,S} \rightarrow M_S, M_h, M_H, M_A, M_{H^\pm}, \tan\beta, \alpha$



- Scan over all masses and angles and perform MCMC fit
- Require scalar couplings perturbative at the weak scale: $\lambda_i^2 \leq 4\pi$
- Consistency with Xenon-100 scattering limits

$$\sigma^{SI}_{p-S} = \frac{m_p^4}{2\pi v^2_{\rm EW}(m_p + m_S)^2} \left\{ \sum_i \frac{g_{SSh_i}}{m^2_{h_i}} [f_{pu}\kappa_i(u) + f_{pd}\kappa_i(d) + f_{ps}\kappa_i(d) + \frac{2}{9} f_g \kappa_i(g)] \right\}^2 ,$$



- No limit from relic density applied

Fermi "line"

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- Very tentative Fermi line observation may pin down DM mass and properties

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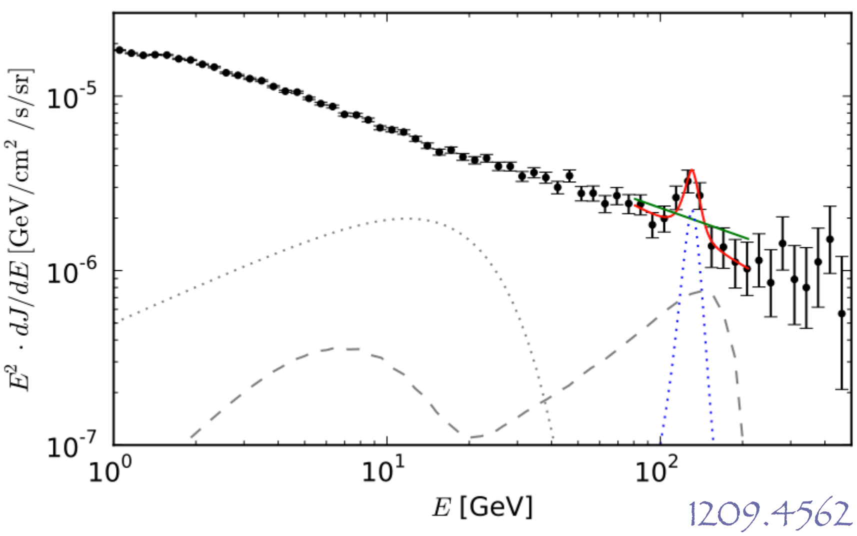
Weniger 1204.2792



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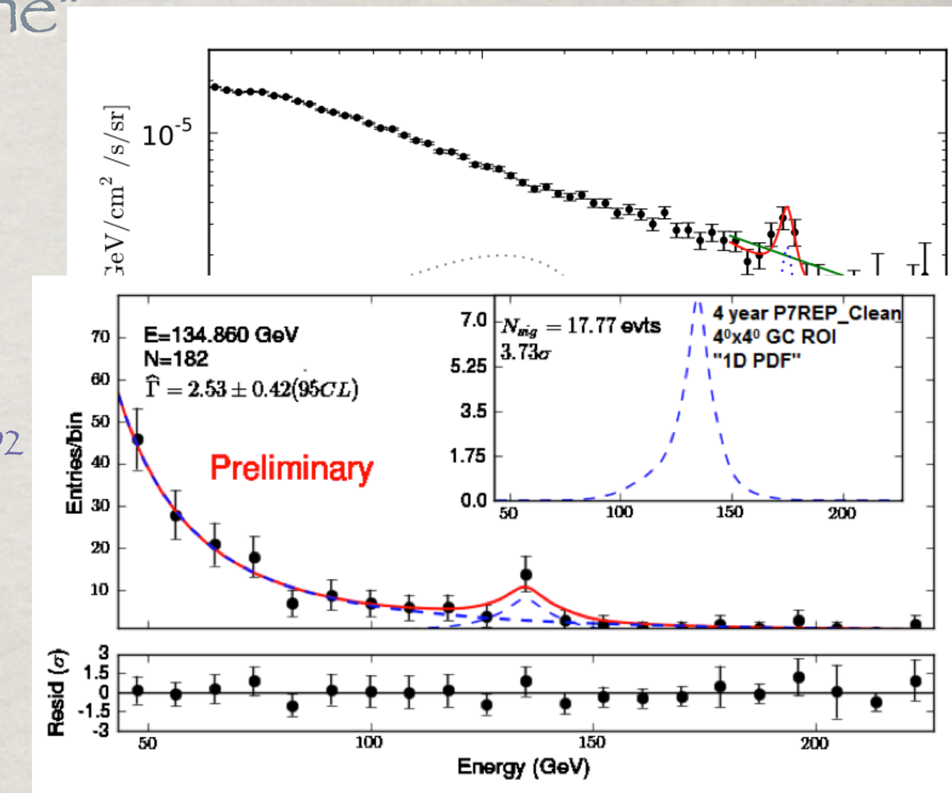

- Fermi Analysis shifts line to 135 GeV
  - Less significant than Weniger's claim: 3.7σ local 1-d fit, 3.4σ 2-d fit
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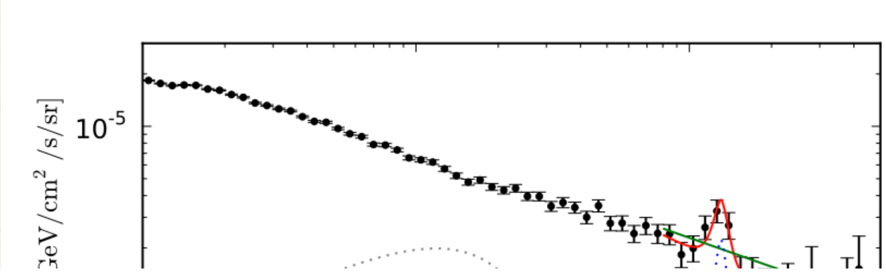

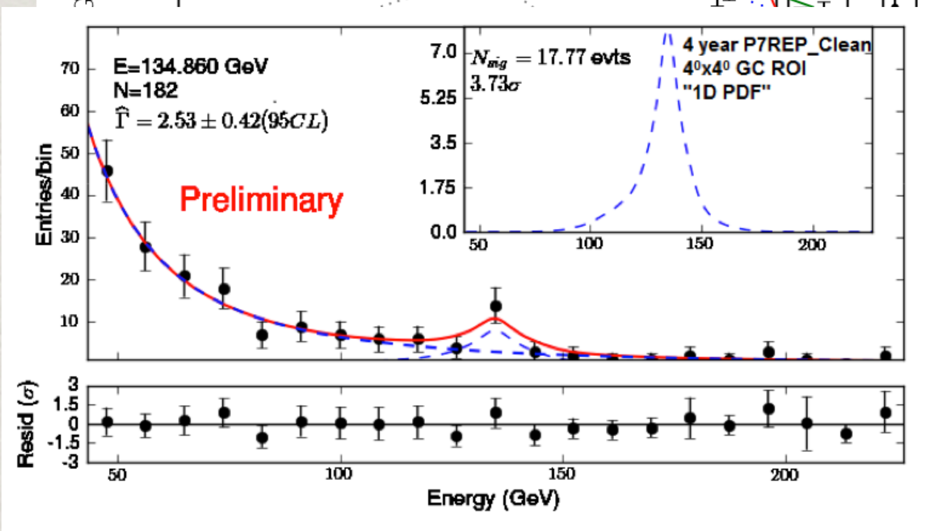

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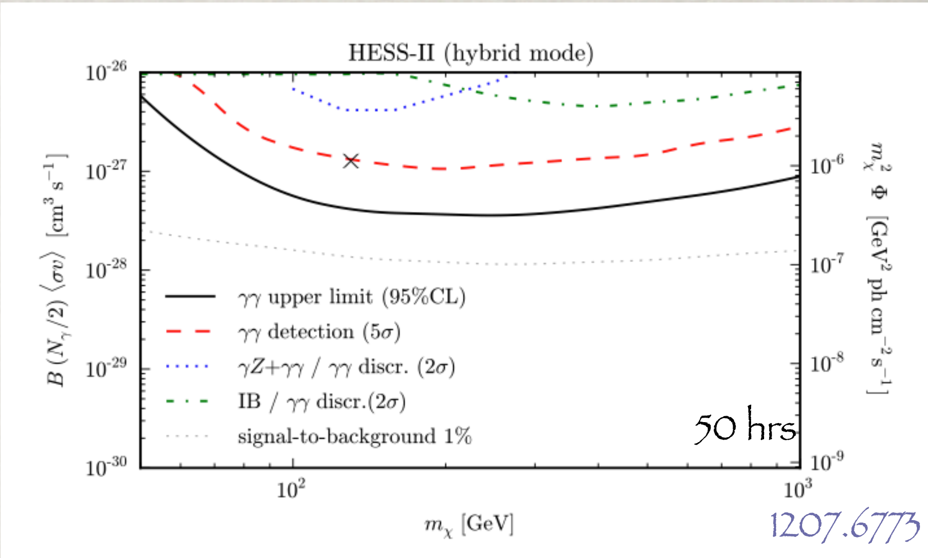
  - Less significant than Weniger's claim: 3.7σ local 1-d fit, 3.4σ 2-d fit
  - Line present in Earth limb, but not outside of region of interest**



1207.6773

- HESS-II to confirm or refute with less than 100hrs of observing time (expected late 2014)

2HDM Portal

- Now that a Higgs at 125 GeV is discovered, Higgs portals are more constrained
- Continuum γ limits from Fermi:

$$\sigma_{b\bar{b}} v \lesssim 4.2 \times 10^{-26}\,\mathrm{cm^3 s^{-1}},$$
$$\sigma_{W^+W^-} v \lesssim 3.8 \times 10^{-26}\,\mathrm{cm^3 s^{-1}},$$
$$\sigma_{\tau^+\tau^-} v \lesssim 1.4 \times 10^{-25}\,\mathrm{cm^3 s^{-1}}.$$

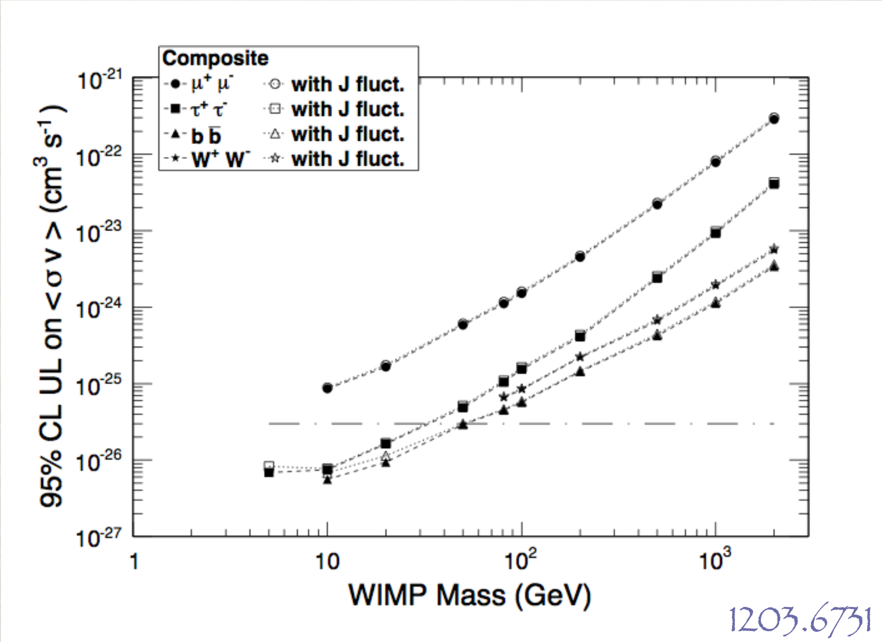
- Rate governed by "fake" Higgs width

$$\sigma_{SS\to X\overline{X}}\, v = \frac{\Gamma_{h^{SM}\to X\overline{X}}(m_{h^{SM}} = 2m_S)}{2m_S} \times \left| \frac{g_{SSh}\,\kappa_1(X\overline{X})}{4m_S^2 - m_h^2 + i m_h \Gamma_h} + \frac{g_{SSH}\,\kappa_2(X\overline{X})}{4m_S^2 - m_H^2 + i m_H \Gamma_H} \right|^2,$$

κ_i: amplitudes of $h_i \to X\bar{X}$

- Continuum limits on annihilation to Higgs boson estimated by

$$\sigma_{hh}(m_S)\cdot v = \sigma_{b\bar{b}}\left(\frac{m_S}{2}\right)\cdot v\,\frac{1}{2\,\mathrm{BF}(h\to b\bar{b})}.$$



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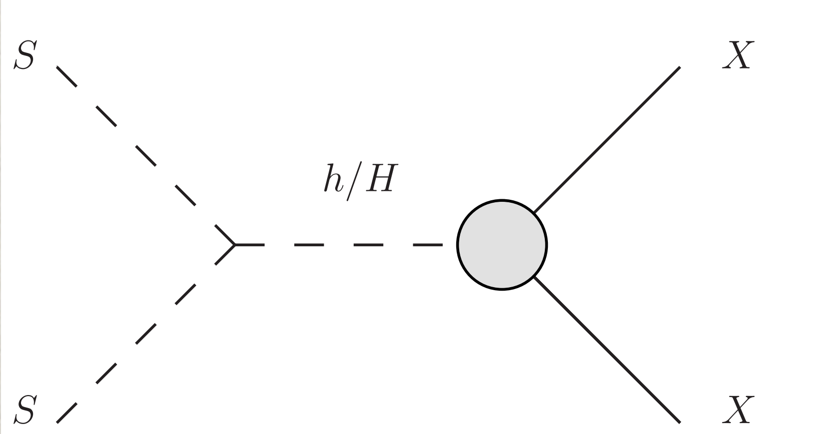
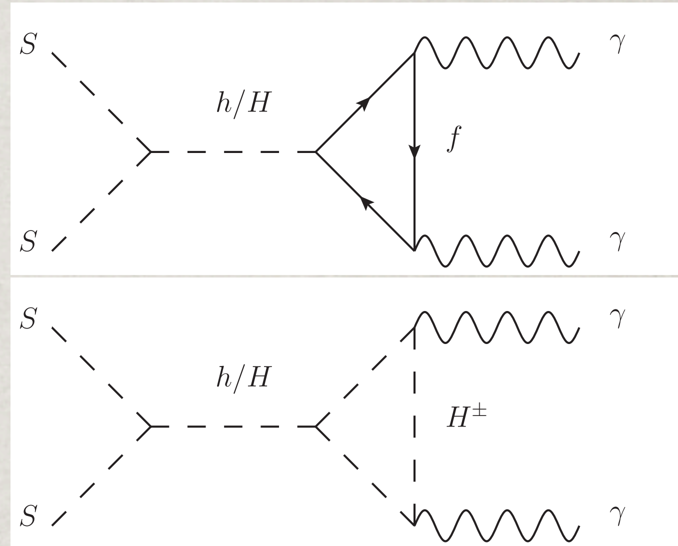


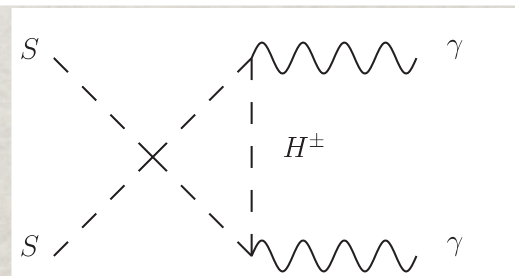
Annihilation to gamma rays

- SM Higgs portal dominated by annihilation to W^+W^- and ZZ
- Higgs portal: $$\frac{\mathrm{BF}(\phi \to \gamma\gamma)}{\mathrm{BF}(\phi \to W^+W^-)} \sim \mathcal{O}(10^{-5}),$$

$m_\phi = 2m_S = 270\ \mathrm{GeV}$

- Fermi line requires: $$\frac{\mathrm{BF}(\phi \to \gamma\gamma)}{\mathrm{BF}(\phi \to W^+W^-)} \gtrsim \mathcal{O}(10^{-2}),$$

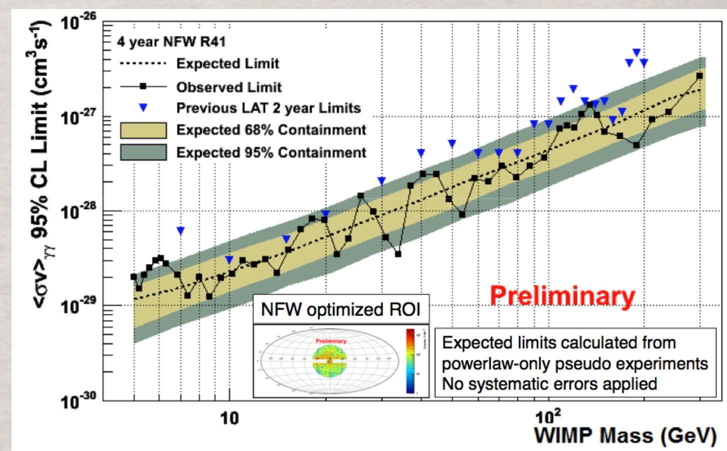




- Annihilation to photons dominated by fermion and charged scalar loop

$$\sigma_{SS\to\gamma\gamma}\, v = 7.7\times 10^{-8} \left| \frac{g_{SSh}\,\kappa_1(\gamma\gamma)}{4m_S^2 - m_h^2 + i m_h \Gamma_h} + \frac{g_{SSH}\,\kappa_2(\gamma\gamma)}{4m_S^2 - m_H^2 + i m_H \Gamma_H} + g_{SSH^+H^-} F_0\left(\frac{m_{H^\pm}^2}{m_S^2}\right) \right|^2,$$

- Charged Higgs can help enhance the annihilation rate to $\gamma\gamma$
- Line from $Z\gamma$ limited to be $\sigma_{Z\gamma} v \lesssim 1.4\times 10^{-27}\ \mathrm{cm^3 s^{-1}}$



Fit results

- Decoupling limit necessary to reproduce Fermi line
  - Generally required to have sizable $SS \to \gamma\gamma$ annihilation rate
- Since annihilation through heavy Higgs portal, well defined Heavy Higgs mass predicted

$$265 \text{ GeV} < m_H < 280\text{GeV}$$

- Cross-check at LHC
  - Likely discovered via $H^{\pm}$ as heavy neutral Higgs bosons are decoupled from vector bosons
  - Most promising channel: $pp \to t\bar{t} \to tH^{-}\bar{b}$