The Higgs - Dark Matter connection

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DOE site visit of ANL HEP - 2009

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Recent work in Higgs physics

Recent work in Higgs physics

- Determine effects of simple extension to Higgs sector:
  - Add one complex singlet that couples only to Higgs boson

$$
\begin{aligned}
V(H,\mathbb{S}) \;=\; & \frac{m^2}{2}H^\dagger H + \frac{\lambda}{4}(H^\dagger H)^2 + \left(\frac{|\delta_1|e^{i\phi_{\delta_1}}}{4}H^\dagger H\mathbb{S} + c.c.\right) + \frac{\delta_2}{2}H^\dagger H|\mathbb{S}|^2 \\
& + \left(\frac{|\delta_3|e^{i\phi_{\delta_3}}}{4}H^\dagger H\mathbb{S}^2 + h.c\right) + \left(|a_1|e^{i\phi_{a_1}}\mathbb{S} + c.c.\right) + \left(\frac{|b_1|e^{i\phi_{b_1}}}{4}\mathbb{S}^2 + c.c.\right) \\
& + \frac{b_2}{2}|\mathbb{S}|^2 + \left(\frac{|c_1|e^{i\phi_{c_1}}}{6}\mathbb{S}^3 + c.c.\right) + \left(\frac{|c_2|e^{i\phi_{c_2}}}{6}\mathbb{S}|\mathbb{S}|^2 + c.c.\right) \\
& + \left(\frac{|d_1|e^{i\phi_{d_1}}}{8}\mathbb{S}^4 + c.c.\right) + \left(\frac{|d_3|e^{i\phi_{d_3}}}{8}\mathbb{S}^2|\mathbb{S}|^2 + c.c.\right) + \frac{d_2}{4}|\mathbb{S}|^4
\end{aligned}
$$

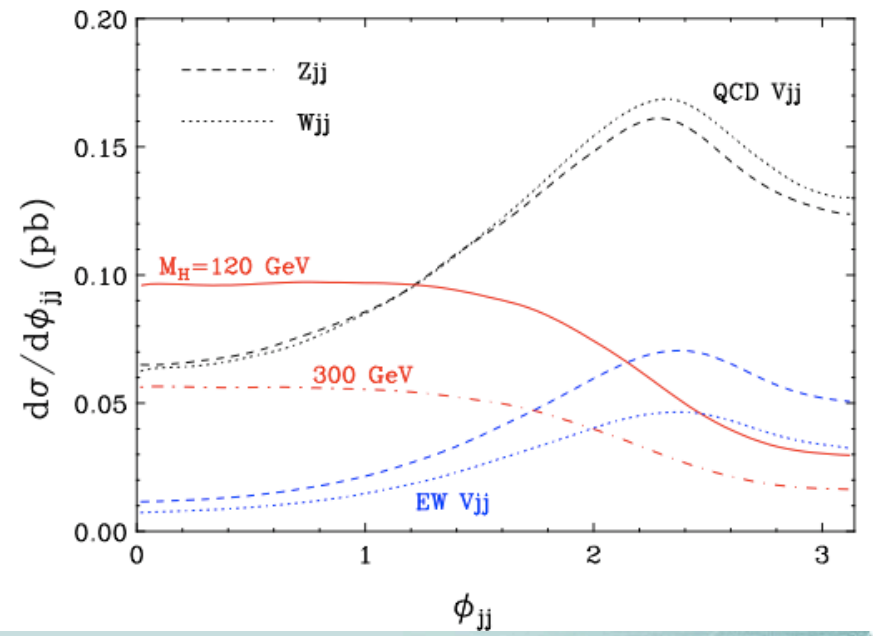
Barger, Langacker, McCaskey, Ramsey-Musolf, GS '08

- Depending on symmetries imposed two degrees of freedom correspond to:
  - One mixing scalar + one stable scalar*
  - Two mixing scalars
  - Two stable scalars*

* - Higgs may decay to these stable states

Higgs decays to DM pairs

- DM and Higgs talk to each other
  - Natural to expect Higgs decays to DM if kinematically allowed
  - May cause complications for Higgs discovery



Weak boson fusion:
Extract signal with cuts on azimuthal correlation of forward jets and large missing p_T

Eboli and Zeppenfeld

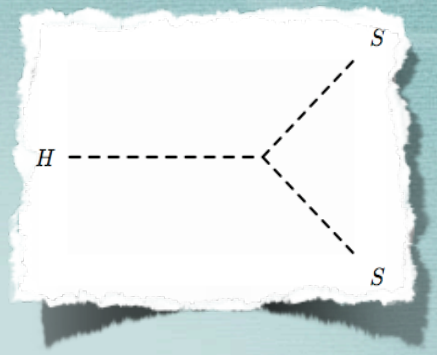
Z-Higgstrahlung:
Cuts on dilepton separation and invariant mass to extract signal

Davoudiasl, Han, Logan

Combined → model independent mass determination

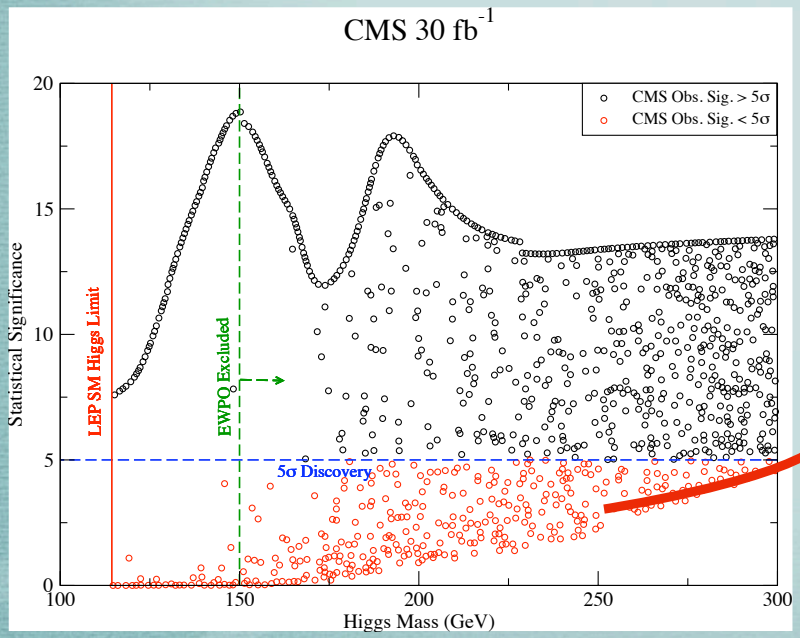
Effect on Higgs discovery in xSM

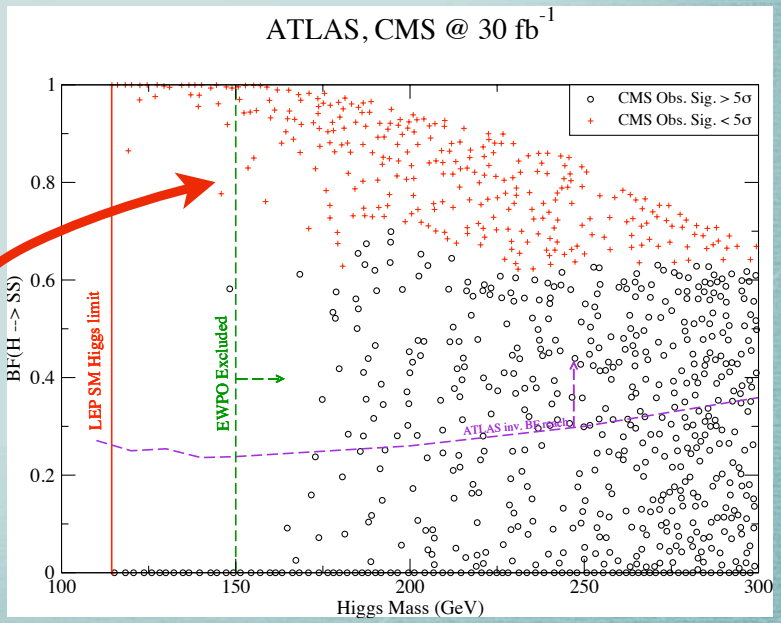
- May greatly affect Higgs discovery potential
  - Higgs decays to invisible states
  - Decrease rate of traditional Higgs modes
  - Discovery possible via dominant invisible decay



Red: not disc. with visible modes

Black: disc. with visible modes

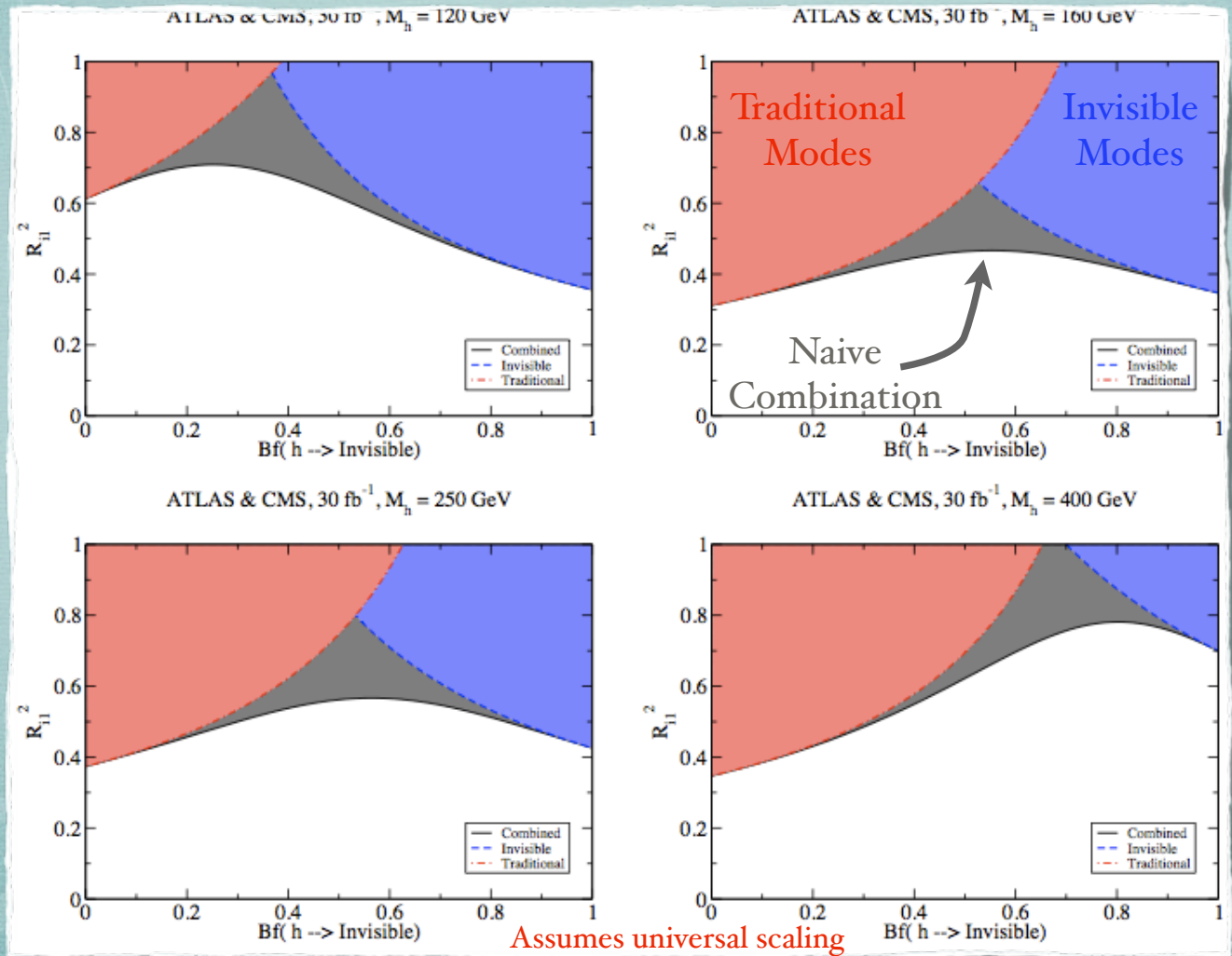




Higgs boson still discoverable even if decays to DM allowed!

Combination

- Simple (and naive) scaling for combination paints picture of how well LHC covers space of Higgs mixing and invisible decay



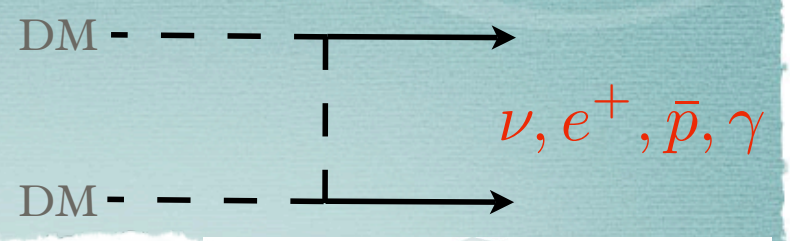
Assumes universal scaling

Barger, Langacker, McCaskey, Ramsey-Musolf, GS '08

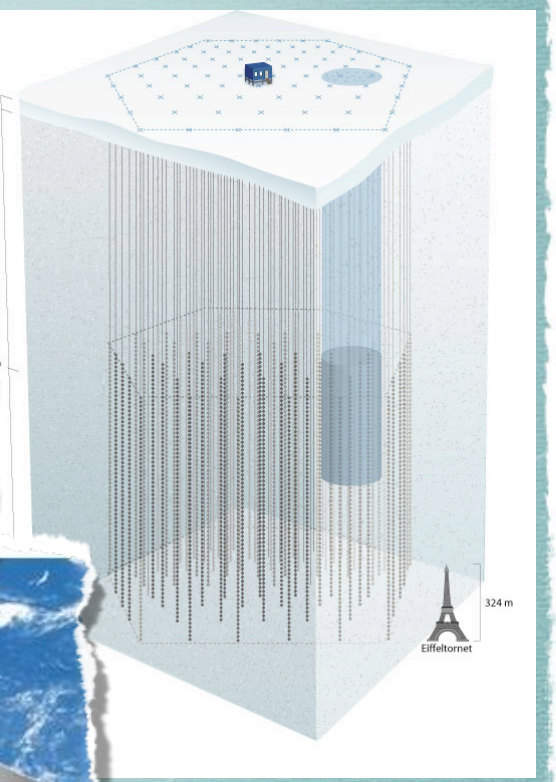
Recent work in Dark Matter

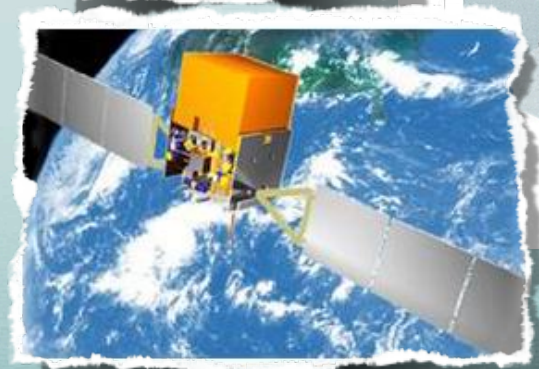
How do we find DM: Indirect Detection

- We can detect presence of DM by its annihilation products in the galactic halo



- Signatures include observation of cosmic rays
  - ν ◉ IceCube, Antares, Super-Kamiokande (neutrino detectors/ telescopes)
  - $e^+, \bar{p}$ ◉ PAMELA (satellite)
  - γ, e ◉ Fermi (satellite)

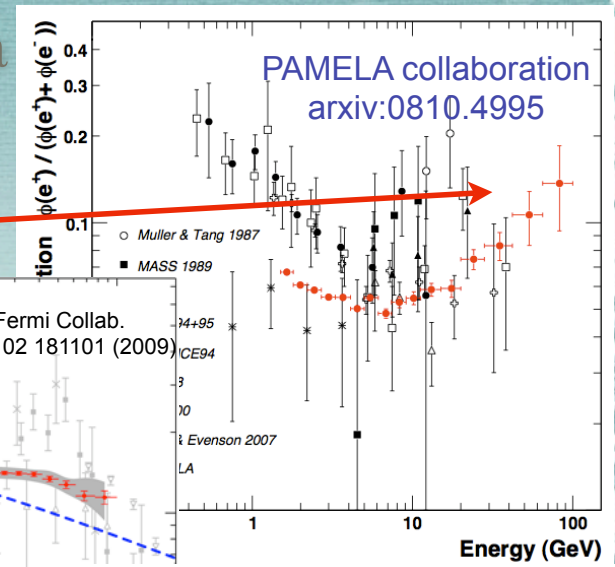


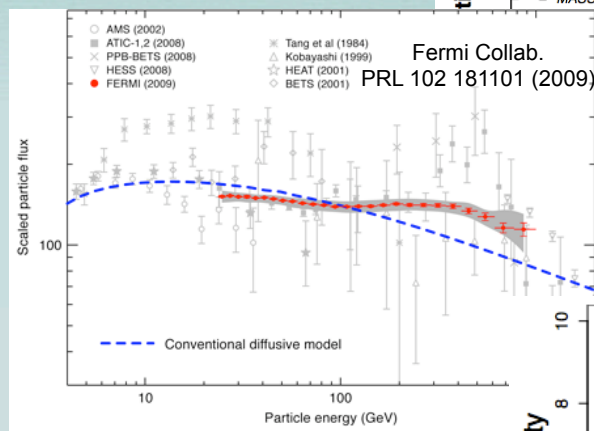


- How might these final states be connected with the Higgs?

Recent cosmic ray data

- PAMELA data point to anomalous excess of high energy positrons in galaxy
  - Injection thought to come from DM annihilations
  - Fermi sees slight excess in total electron data

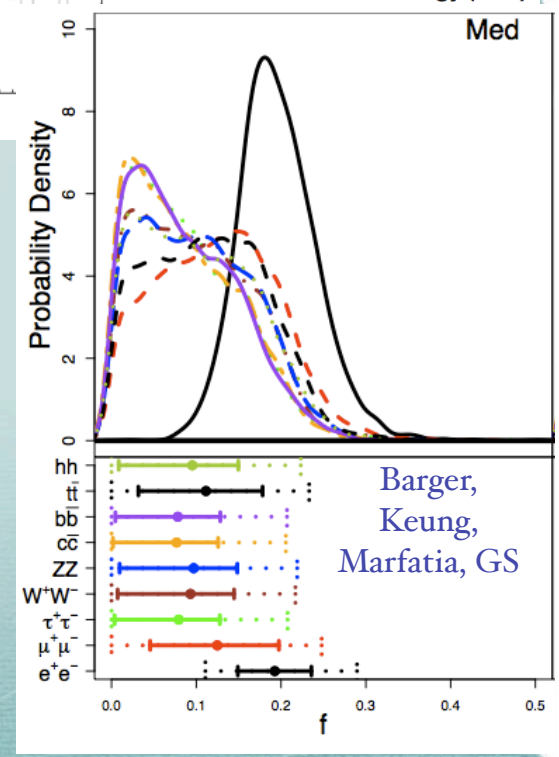




- Direct annihilation to charged lepton pairs most favorable to reproduce hard spectrum

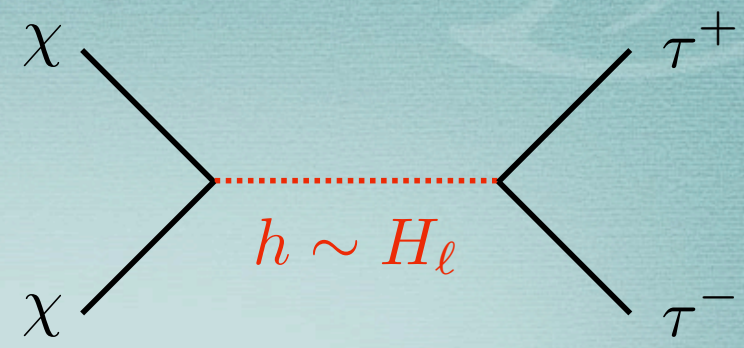
Cirelli, Kadastik, Raidal, Strumia '08
Barger, Keung, Marfatia, GS '08

- Annihilation to SM Higgs boson pairs unfavorable



Lepto-phillic Higgs mediated positron signals!

- However, leptophillic Higgs models can produce leptons prolifically

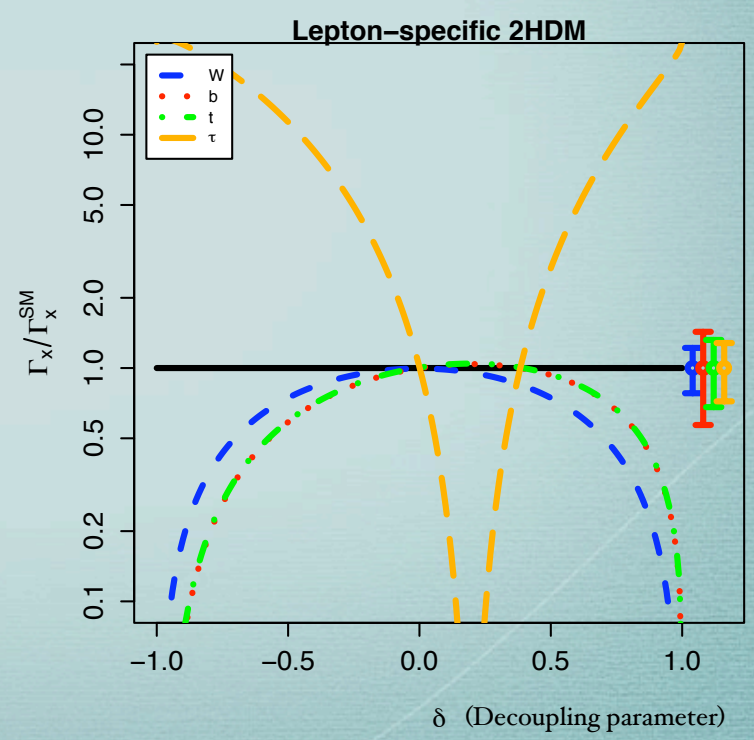


- Associated LHC signatures may be easy to distinguish from other Higgs sectors

Barger, Logan, GS '09

- Pattern relation among couplings within Lepton-specific model:

$$P_{u\ell} = \bar{g}_W(\bar{g}_q + \bar{g}_\ell) - \bar{g}_q\bar{g}_\ell = 1$$



Higgs in Space!

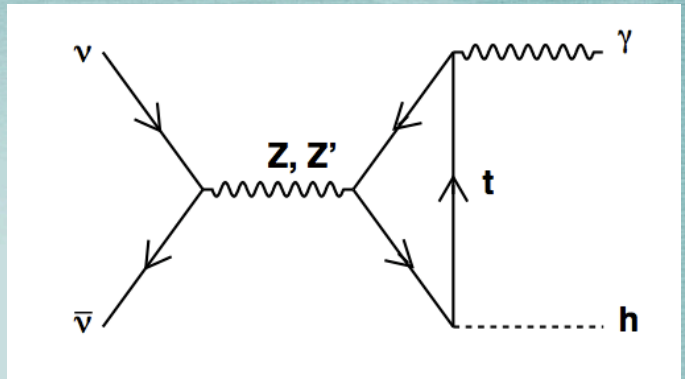
- Detection of DM via gamma rays can provide rich signatures

- Annihilation to $h\gamma$ can significantly displace photon line

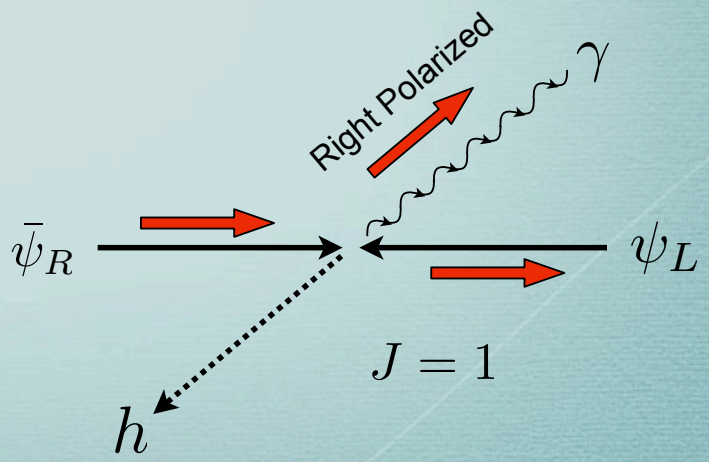
$$E_\gamma = M\left(1 - \frac{M_X^2}{4M^2}\right)$$

- Angular momentum conservation allows Dirac Fermion or Vector Boson in initial state

- Observation of Higgs line can help determine spin of DM state!



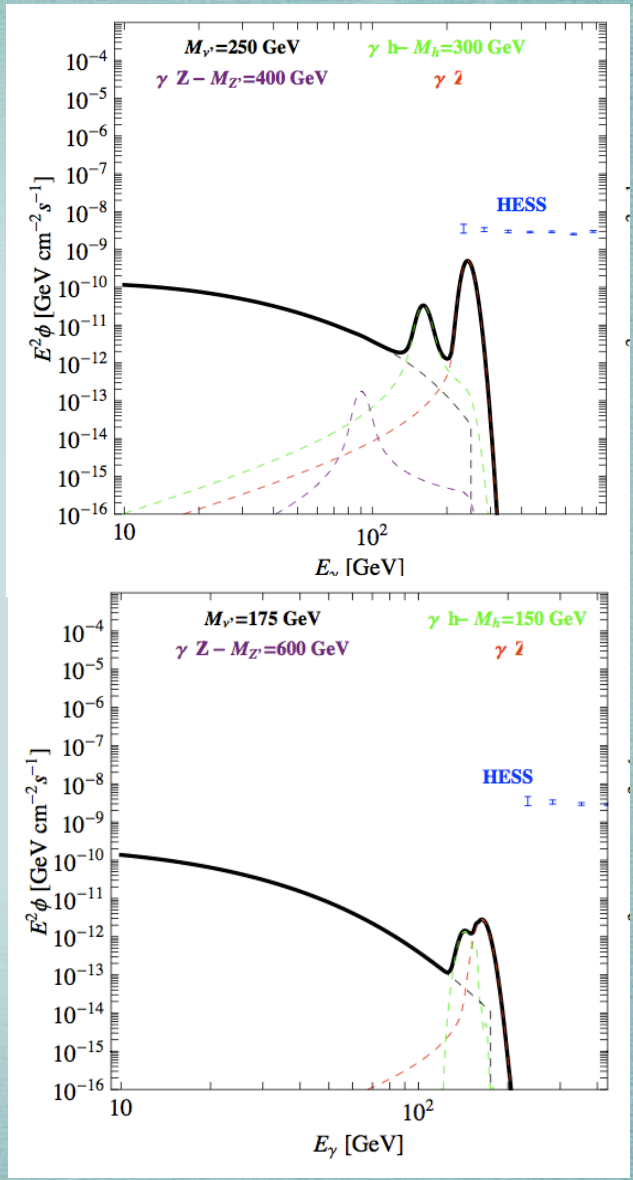
Randall-Sundrum example:
Jackson, Servant, GS, Tait, Taoso (in prep)



Higgs in Space!

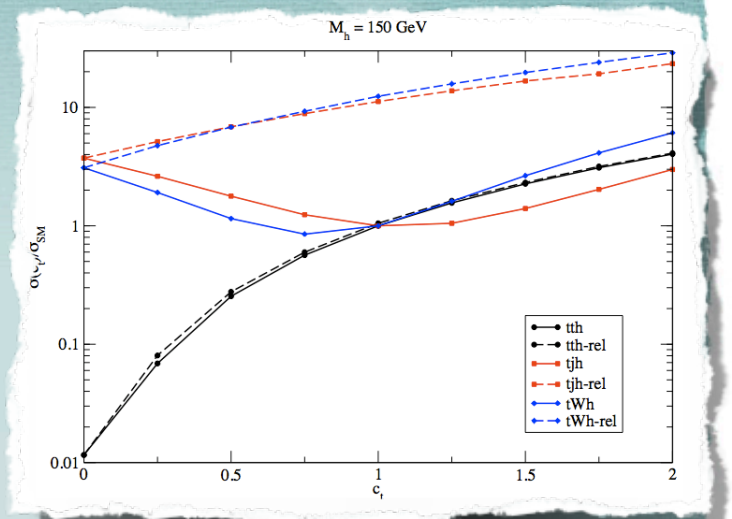
- Fermi energy resolution $\frac{\delta E}{E} \sim 10\%$ smears lines
- Observation of two lines can be checked for consistency with Higgs boson
- Additional lines may appear if associated states can be produced
  - Possible "WIMP Forest"
  - New physics spectroscopy

Bertone, Jackson, GS, Tait, Vallinoto '09

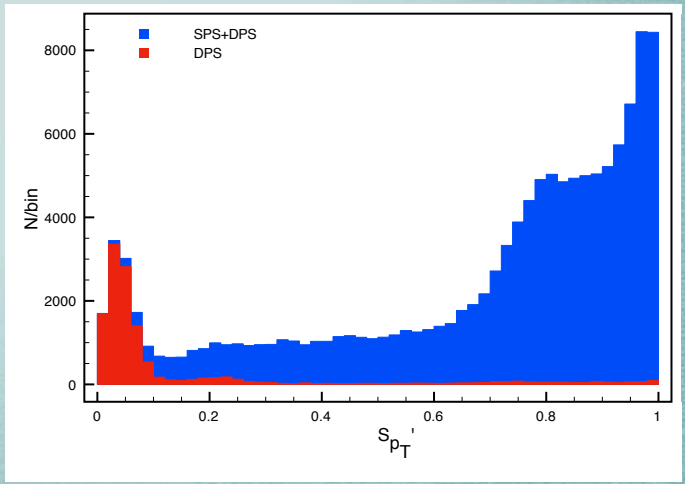


Future Directions: Higgs, Collider and DM physics

- Characterize sensitivity change for specific Higgs discovery channels with varying center of mass energies (with E. Berger, Q-H Cao, C. Jackson, T. Liu)



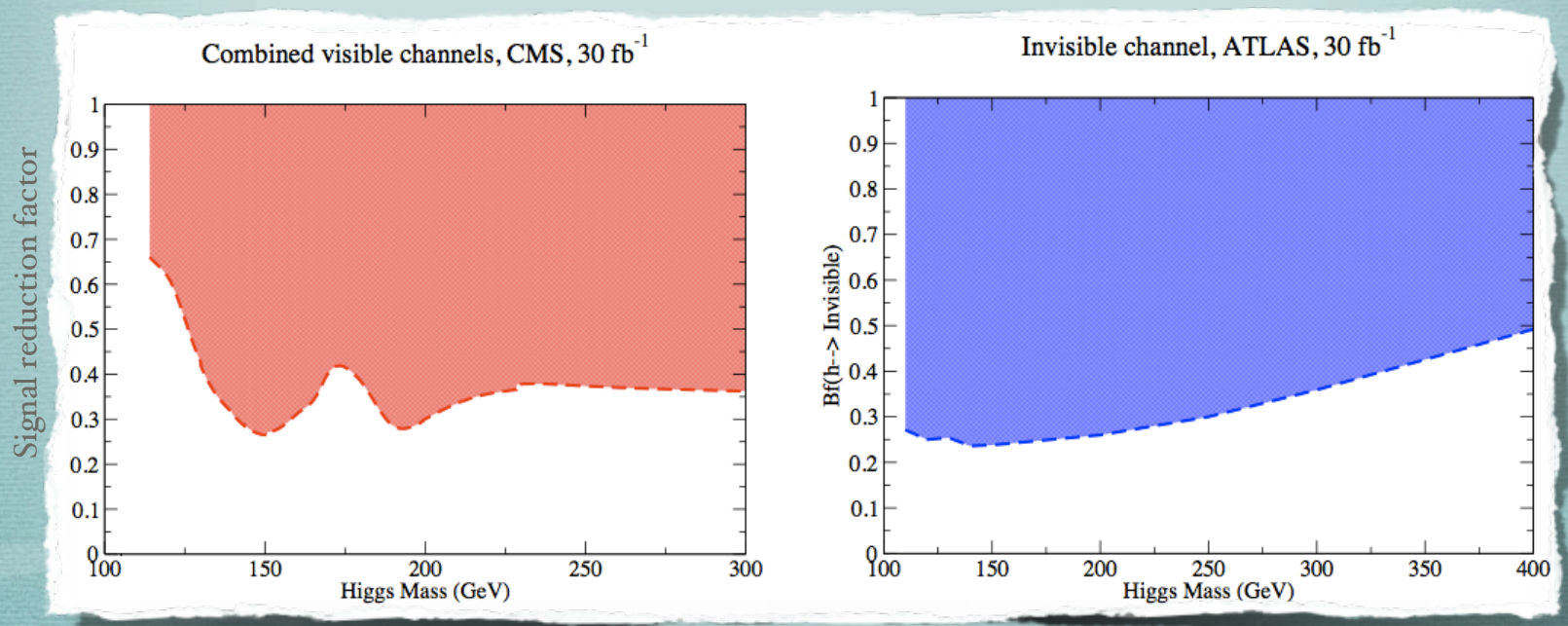
- Utilize method to constrain top quark Yukawa coupling via associated production with single top quark (with V. Barger, M. McCaskey)
  - With SM couplings, significant destructive interference suppresses these channels
- Characterize double parton scattering topologies and associated points in phase-space at the LHC (with E. Berger and C. Jackson)



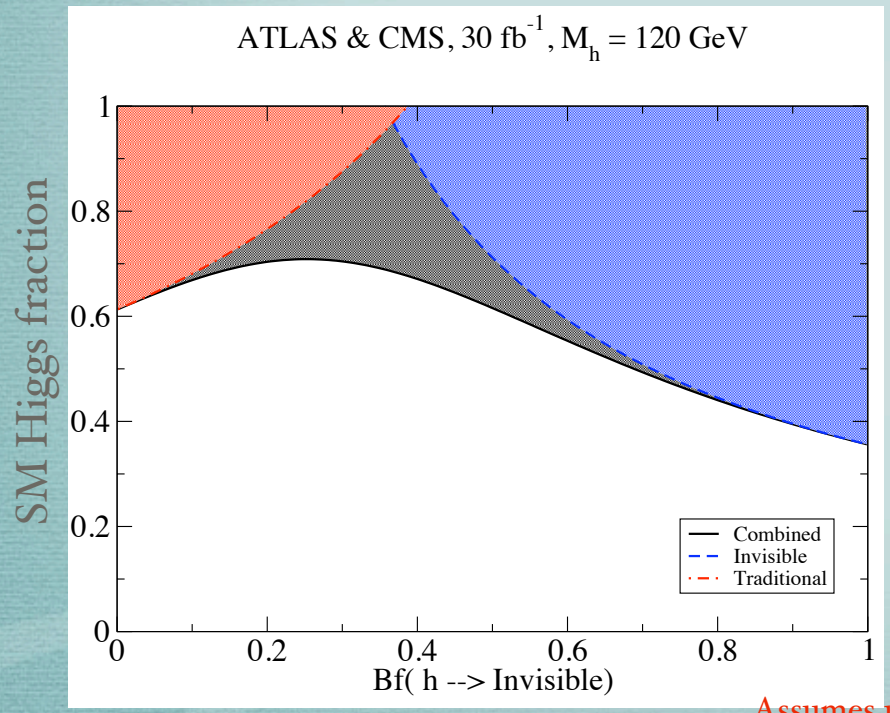
- Associated LHC signatures of leptonic-favored DM models (with Q-H Cao)
-
- Examine generic signatures of invisible state production at LHC and extract masses and coupling strengths (with A. de Gouvea, I. Low and J. Gainer)

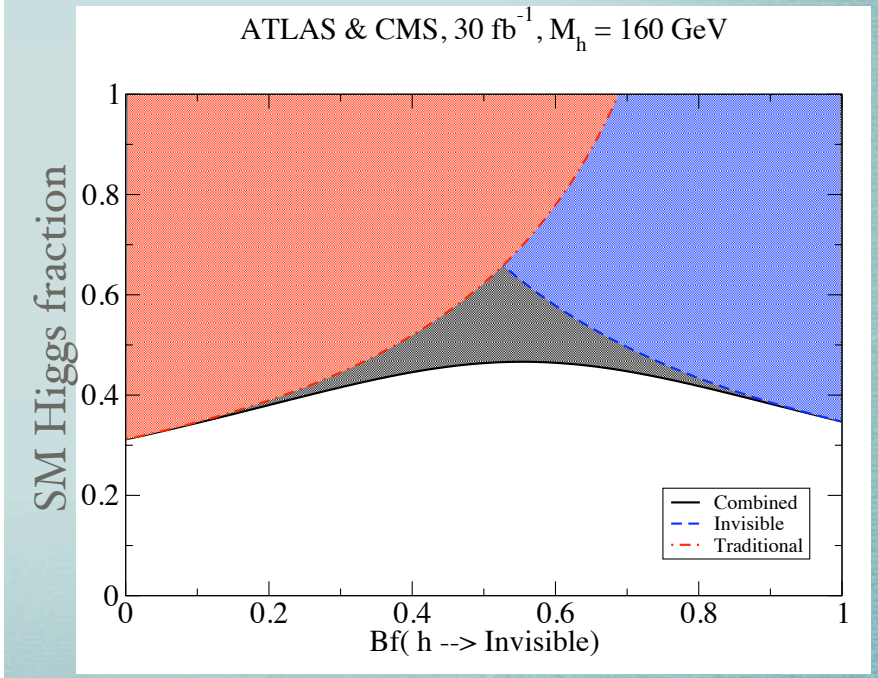
Backups

- Sensitivity can be inverted to determine level of Higgs mixing can be probed at LHC



- Most of mixing-invisible decay space can be covered at LHC with modest luminosity
- Difficult if more mixing-singlets are included





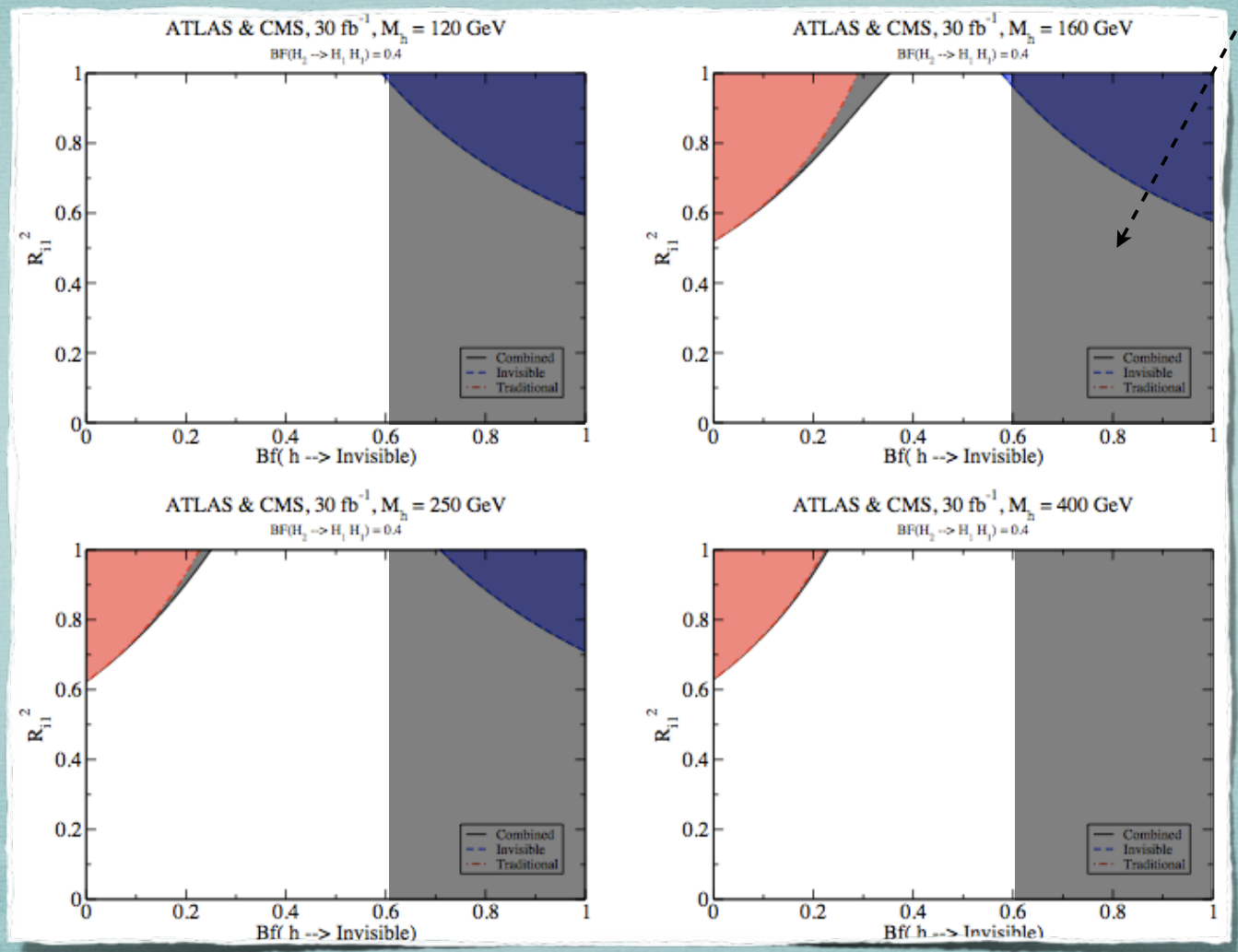
Assumes universal scaling

Barger, Langacker, McCaskey, Ramsey-Musolf, GS

Effect of other Higgs decays

- Complications if Higgs has additional non-SM decays
  - e.g. $BF(H_2 \to H_1 H_1) = 0.4$

Inaccessible



See work by Carena, Han, Huang, Wagner '07, for possible resolution

What we assume

- Natural flavor conservation
  - Due to symmetry of model Glashow & Weinberg, PRD15, 1958 (1977); Paschos, PRD15, 1966 (1977)
  - FCNCs can be mitigated by coupling of each fermion sector $(u, d, \ell^{\pm})$ to just one Higgs doublet

- Flavor conservation motivates three general classes of models based on the number of Higgs doublets
  - One doublet, Φ_f, $\Phi_{f'}$, couples to the three fermion sectors
  - Two doublets, $\Phi_u, \Phi_d, \Phi_\ell$, couples to the three fermion sectors in 3 combinations
  - Three distinct doublets, $ggh, \gamma\gamma h, Z\gamma h$, couple to each fermion sector separately

- Neglect loop induced couplings:

Notation

- Define the Higgs state as a sum of neutral, CP-even components of the doublets (and singlets, when present)

$$h = \sum_i a_i \phi_i$$

where $a_i \equiv \langle h|\phi_i\rangle$ are properly normalized: $\sum_i |a_i|^2 \equiv 1$

- Define the Higgs VEV that gives masses to W/Z bosons in a similar way:

$$\phi_v = \sum_i b_i \phi_i$$

with $g_W = g_W^{SM} \langle h|\phi_v\rangle$ so that $\sum_i |b_i|^2 \equiv 1$

- Barred couplings indicate rescaling with SM coupling

$$\bar{g}_W = g_W / g_W^{SM} = \langle h|\phi_v\rangle$$

  - Observables from rate measurements:

Couplings

- The W/Z coupling can be easily written as overlap of Higgs state with VEV that gives W/Z their mass $\bar{g}_W = g_W / g_W^{SM} = \langle h | \phi_v \rangle$

$$\bar{g}_W = \langle h | \phi_i \rangle \langle \phi_i | \phi_v \rangle = \sum_i a_i b_i \qquad (b_i = 0 \text{ for singlets})$$

- Fermion couplings induced via Yukawa int. $\mathcal{L} = y_f \bar{f}_R \Phi_f^\dagger F_L + \text{h.c.}$ $m_f = y_f b_f v_{SM} / \sqrt{2}$ so that

$$\rightarrow g_f = y_f / \sqrt{2} \langle h | \phi_f \rangle = \frac{m_f}{v_{SM}} a_f / b_f$$

$$\rightarrow \bar{g}_f = g_f / g_f^{SM} = a_f / b_f$$

$$\bar{g}_W = \bar{g}_f = 1$$

- Decoupling limit:

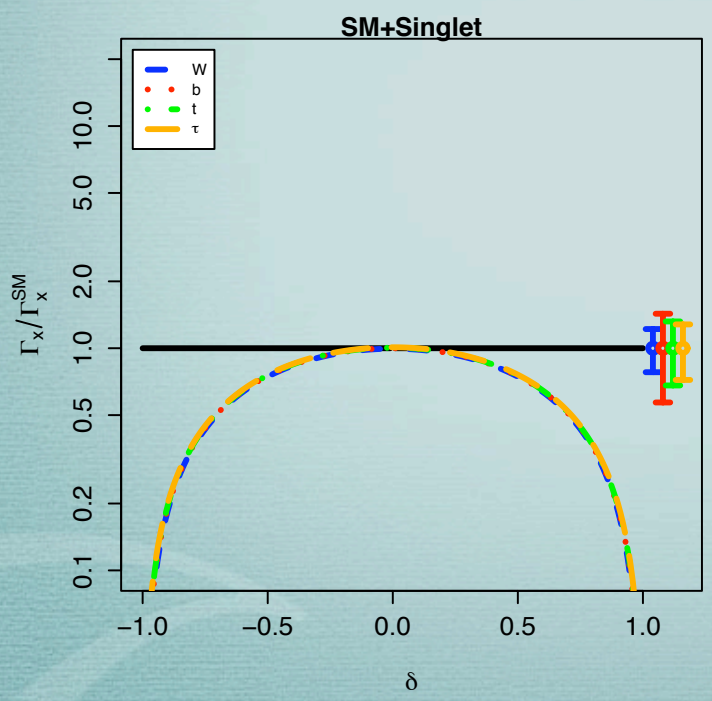
Higgs Model identification at the LHC

- One of the first goals of the LHC is to discover the Higgs boson
- Higgs coupling measurements are key to identifying a true Higgs boson (i.e. W/Z couplings)
- Many models contain Higgs sector that includes more Higgs states than in SM
- If we only see one Higgs state, can we expect to differentiate various Higgs sectors based on small deviations from SM couplings?

with V. Barger and H. Logan

SM + 1 gauge singlet

- Simplest extension of SM - all couplings universally reduced
  - Higgs state $h = a_f \phi_f + a_s S$
  - Normalization requires $a_f = \sqrt{1-\delta^2}$ where $\delta \equiv a_s$ is a decoupling parameter



- Scaled couplings set only by decoupling parameter:

$$\bar{g}_W = \bar{g}_f = \sqrt{1-\delta^2}$$

- No sensitivity to number of gauge singlets

Expected LHC sensitivities to W, b, t and τ for M_h=120 and 300 fb^{-1} x 2 detectors

Duhrssen, Heinemeyer, Logan, Rainwater, Weiglein, Zeppenfeld

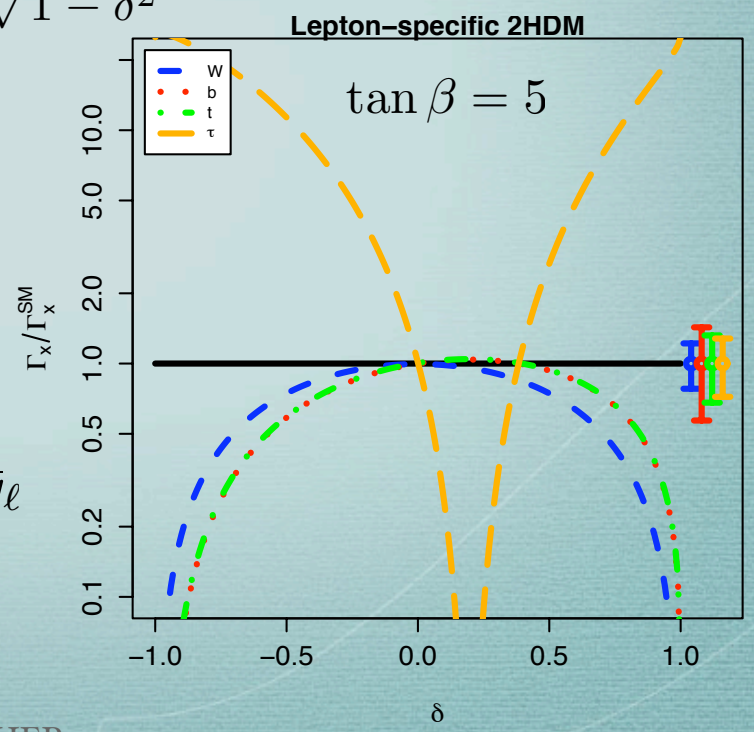
Lepton-specific 2HDM

- Masses for quarks given by ϕ_q and leptons by ϕ_ℓ both contribute to W/Z masses
  - Higgs state: $h = a_q \phi_q + a_\ell \phi_\ell$
- Two parameters: $\tan\beta \equiv b_q/b_\ell$, $\delta \equiv \cos(\beta - \alpha) = a_q b_\ell - a_\ell b_q$
- W/Z Couplings: $\bar{g}_W = a_q b_q + a_\ell b_\ell = \sqrt{1-\delta^2}$
- Fermion couplings:

$$\bar{g}_q = \sqrt{1-\delta^2} + \delta \cot\beta$$
$$\bar{g}_\ell = \sqrt{1-\delta^2} - \delta \tan\beta$$

- Generic features: $\bar{g}_W \neq \bar{g}_u = \bar{g}_d \neq \bar{g}_\ell$
- Pattern relation:

$$P_{u\ell} = \bar{g}_W(\bar{g}_q + \bar{g}_\ell) - \bar{g}_q \bar{g}_\ell = 1$$



How can we discriminate models?

- Pattern relation helps discriminate models
- Example: Lepton-specific 2HDM + additional singlets (with $\xi \leq 1$)

$$P_{u\ell} = \bar{g}_W(\bar{g}_q + \bar{g}_\ell) - \bar{g}_q\bar{g}_\ell = \xi$$

  - Fills 3-dim space of $\bar{g}_W, \bar{g}_q, \bar{g}_\ell$ with $0 \leq P_{u\ell} \leq 1$
  - Distinct relation from other models
  - Footprint of model inhabits different regions in $\bar{g}_W, \bar{g}_u, \bar{g}_d, \bar{g}_\ell$

- Invert relations to extract the Higgs components and VEV sharing of the model (step closer to understanding model):

$$\begin{aligned} b_q &= \left[\frac{\bar{g}_W - \bar{g}_\ell}{\bar{g}_q - \bar{g}_\ell}\right]^{1/2} = \left[\frac{\xi - \bar{g}_\ell^2}{\bar{g}_q^2 - \bar{g}_\ell^2}\right]^{1/2}, \\ b_\ell &= \left[\frac{\bar{g}_W - \bar{g}_q}{\bar{g}_\ell - \bar{g}_q}\right]^{1/2} = \left[\frac{\xi - \bar{g}_q^2}{\bar{g}_\ell^2 - \bar{g}_q^2}\right]^{1/2}, \\ a_q &= b_q\bar{g}_q, \qquad a_\ell = b_\ell\bar{g}_\ell, \qquad a_s = \sqrt{1-\xi}, \end{aligned}$$

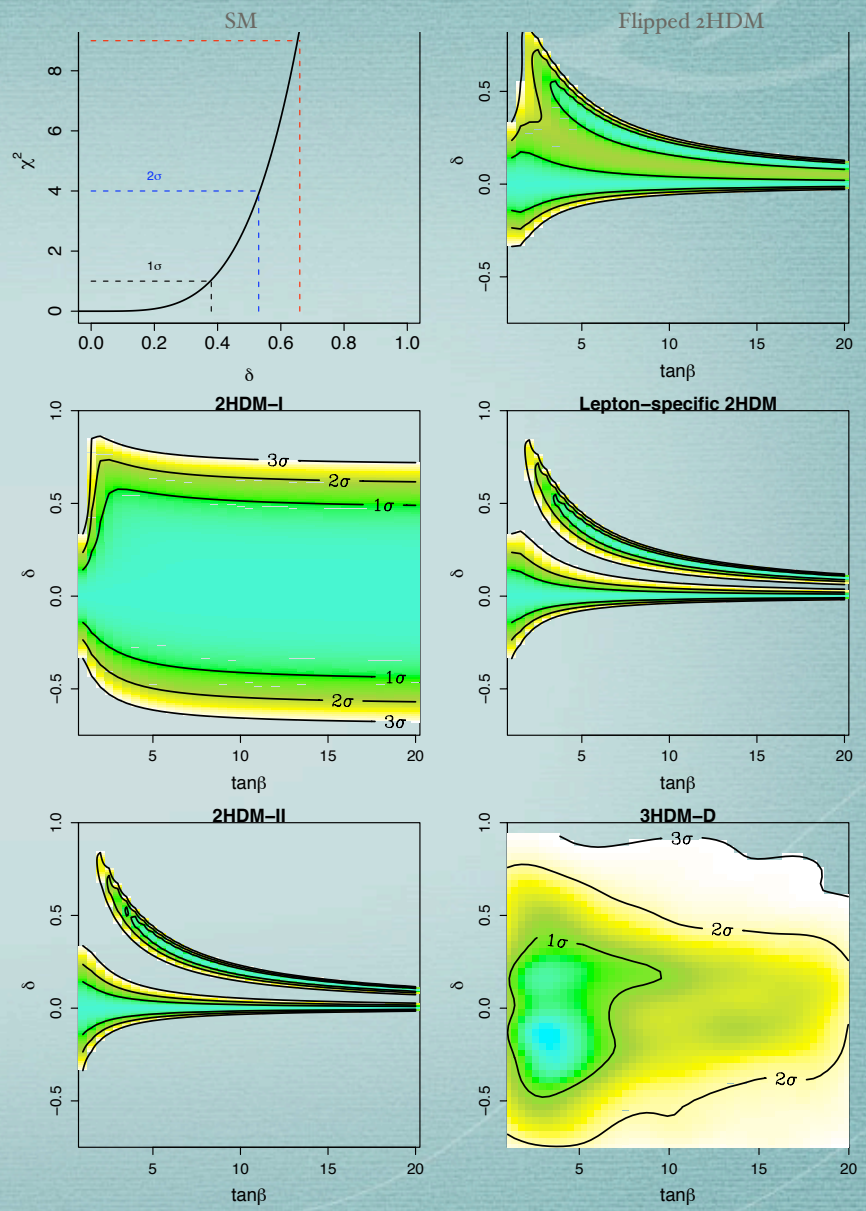
Decoupling limit at the LHC

- Method, of course, fails up to uncertainties in coupling measurements

- Decoupling region defined by uncertainties at the LHC/ ILC for 120 GeV Higgs mass:

	g_W^2	g_b^2	g_t^2	g_τ^2
LHC	22%	43%	32%	27%

Duhrssen, Heinemeyer, Logan, Rainwater, Weiglein, Zeppenfeld.
Look at Lafaye, Plehn, Rauch, Zerwas and Duhrssen for an updated analysis

- Regions defined by χ^2 :

$$\chi^2 = \sum_{i=W,b,t,\tau} \frac{(\Gamma_i - \Gamma_i^{SM})^2}{\left[\delta\Gamma_i^{SM}\right]^2}$$