Beyond-the-Standard Model Higgs Physics using the ATLAS Experiment

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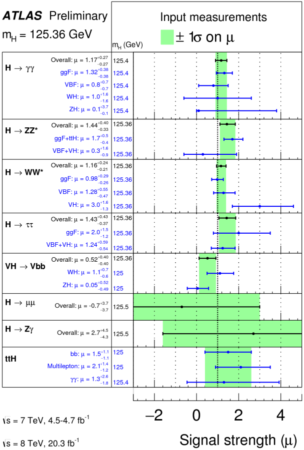
Outline

- Status of Higgs measurements (see Michaela Queitsch-Maitland's and Nan Lu's talks on Tuesday)
- The BSM Higgs Physics searches at ATLAS
- Highlighted results on
  - High mass searches in WW/ZZ final states
  - Lepton flavour violating (LFV) decay
  - Lightest neutral pseudoscalar Higgs (a) decay (NMSSM)
  - 3 photon search
  - BSM constraints from Higgs couplings
  - Invisible decays of the Higgs boson
- Summary

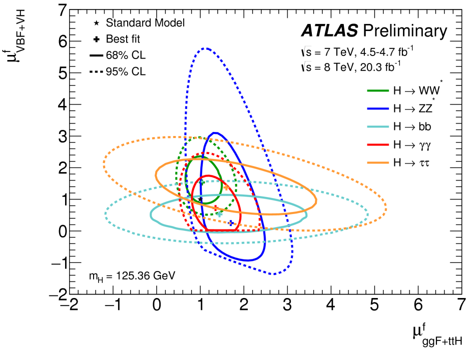
Combination of Higgs Measurements

- Summary of the signal strength measurements



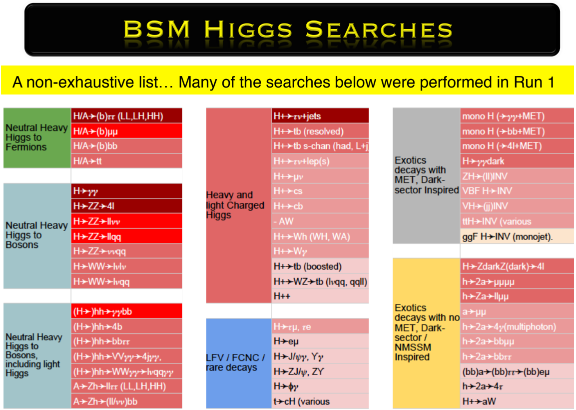
- $\mu = 1.18^{+0.15}_{-0.14}$

- Likelihood contours in the $(\mu^{f}_{\mathrm{ggF+tt̄H}}, \mu^{f}_{\mathrm{VBF+VH}})$ plane



- Higgs mass: $125.36 \pm 0.37(stat) \pm 0.18(syst)$ **GeV**
- Link: arXiv:1507.04548

From Pierre Savard - EPS2015



No significant excess yet

Strategies:

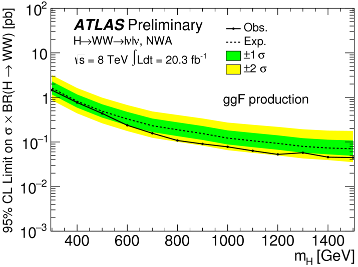
- Search for additional Higgs boson
- Search for exotic decays of the 125GeV-Higgs
- Use the 125GeV Higgs as a tool to find new physics
  - Tag a Higgs
  - Use SM Higgs measurements to constrain BSM parameter space
- More new results:
  - $H \to hh \to b\bar{b}b\bar{b}$
  - 3 photon search

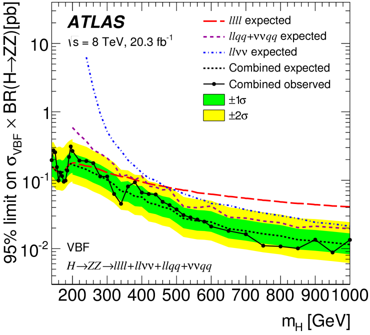
Additional-heavy Higgs decaying to WW/ZZ

- Search for a heavy neutral scalar
- Final states:
  - $WW \to \ell\nu\ell\nu, \ell\nu jj$ HIGG-2013-19
  - $ZZ \to \ell\ell\ell\ell, \ell\ell\nu\nu, \ell\ell qq, \nu\nu qq$ arXiv:1507.05930
- Results interpreted separately for VBF, ggF production modes. Upper limits for heavy Higgs boson which has a narrow width. At 95% CL:

Limits on	m_H	Upper Limit (fb) for H production mode	
		ggF	VBF
$\sigma_H \times BR(H \to WW)$	1500 GeV	21	6
$\sigma_H \times BR(H \to ZZ)$	195-950 GeV	530-8	310-9

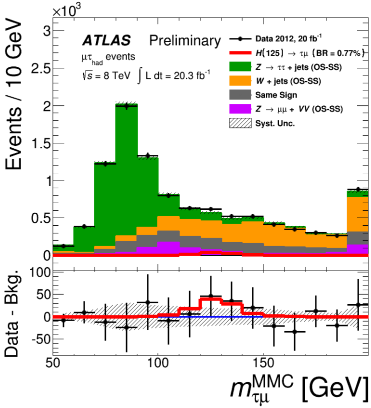
- No significant deviations observed





Lepton flavour violating decays

- The LFV Higgs decays ($H \to \tau\mu, \tau e, \mu e$) arise at tree level based on assumed flavor violating Yukawa interactions arXiv:1209.1397
- Search for LFV Higgs decays to τ and μ in hadronic τ decays arXiv:1508.03372
- Results: fit to the reconstructed mass distribution in data
  - Best fit of $BR(H \to \mu\tau)$: 0.77 ± 0.62 %
  - Upper limit on $BR(H \to \mu\tau)$ @ 95% CL: 1.85%(1.24%) obs(exp.)

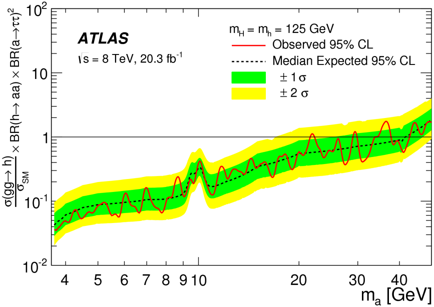


The reconstructed mass of the system of observed muon, τ (hadronic decay products) & E_T^{miss} objects by means of the Missing Mass Calculator (MMC) distribution

Next-To-Minimal Supersymmetric SM

NMSSM arXiv:1505.01609

- Search for the decay to a pair of the lightest neutral pseudoscalar Higgs (a) of either the 125 GeV Higgs (h) or a second CP-even Higgs (H)
- One a boson decays to 2 μ and the other decays to 2 τ
- Results:
  - The most stringent upper limit: 3.5% for $m_a = 3.75\ \mathrm{GeV}$



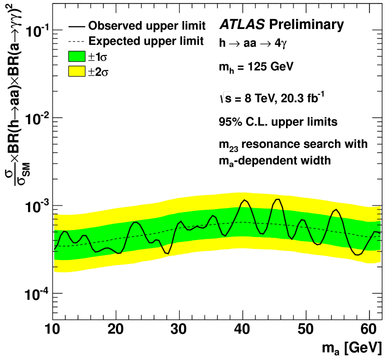
Limit for $\sigma_{ggH_{SM}} \times BR$ of h SM decays to aa $\times BR$ of a decays to $\tau\tau$ vs m_a

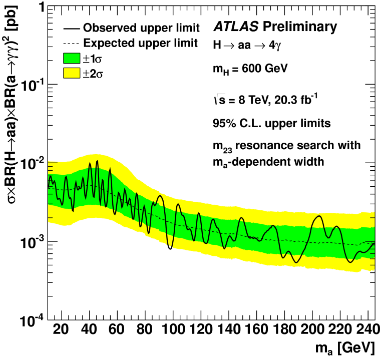
Search for 3 γ

- Search for events with at least 3 γ EXOT-2013-24
- Model-independent interpretations are the first of their kind:

- For SM Higgs $h \to aa \to \gamma\gamma\gamma\gamma$: $\sigma \times BR(h \to aa) \times BR(a \to \gamma\gamma)^2 < 10^{-3} \times \sigma_{SM}$ for $10\ \mathrm{GeV} < m_a < 62\ \mathrm{GeV}$

- For heavy Higgs boson-like scalar: $\sigma_H \times BR(H \to aa) \times BR(a \to \gamma\gamma)^2 <$ 0.02 to 0.001 pb (depending upon m_H, m_a)





BSM constraints from Higgs couplings

- HIGG-2015-03
- Use the measured production + decay rates of the Higgs boson ($\gamma\gamma$, ZZ, WW, $Z\gamma$, bb, $\tau\tau$, & $\mu\mu$; $t\bar{t}h$ with $h \to \gamma\gamma$, $b\bar{b}$ & multileptons)
  - Probe the scaling of the couplings with mass
  - Set limits on parameters in extensions of the SM
    - Composite Higgs boson
    - An additional electroweak singlet
    - Two-Higgs-doublet models
- Taking into account the measured m_H in the $\gamma\gamma$ & ZZ
  - Set lower limit on the pseudoscalar Higgs boson mass in the “hMSSM” arXiv: 1307.5205 [hep-ph]

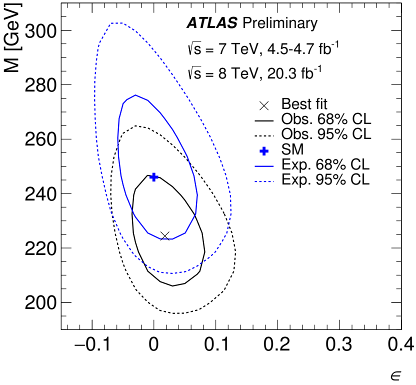
“Mass scaling” of couplings

- arXiv: 1303.3879 [hep-ph]
- Each coupling in terms of vev ($v \approx 246$ GeV) & ϵ (note that SM: $\epsilon \to 0$)

$$\kappa_{f,i} = v\frac{m_{f,i}^{\epsilon}}{M^{1+\epsilon}}, \kappa_{V,j} = v\frac{m_{V,j}^{2\epsilon}}{M^{1+2\epsilon}}$$

Parameter	Obs.	Exp.
ϵ	0.018 ± 0.039	0.000 ± 0.042
M	224^{+14}_{-12} **GeV**	246^{+19}_{-16} GeV

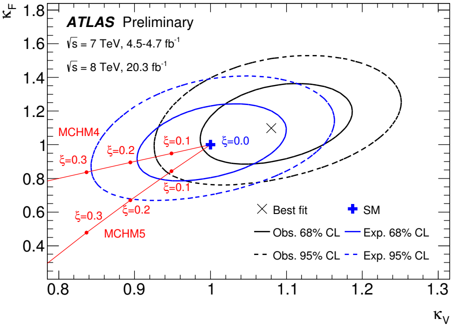
Observed & expected measurements of the mass scaling parameter ϵ & the vev parameter M



2-D confidence intervals as a function of the mass scaling factor ϵ & the vev parameter M

Minimal Composite Higgs Model

- Scalar Naturalness:
  Higgs $\rightarrow$ composite pseudo Nambu-Goldstone boson
- Higgs couplings modified as function of compositeness scale-f:
  $\xi = v^2/f^2$
  - MCHM4: $\sqrt{\kappa} = \kappa_V = \kappa_F = 1\xi$
  - MCHM5:
    $\kappa_V = 1-\xi, \kappa_F = \frac{1-2\xi}{\sqrt{1-\xi}}$
- SM recovered in the limit $\xi \rightarrow 0$, namely $f \rightarrow \infty$
- Results @95% CL obs(exp):
  MCHM4: f > 710(510) GeV;
  MCHM5: f > 780(600) GeV



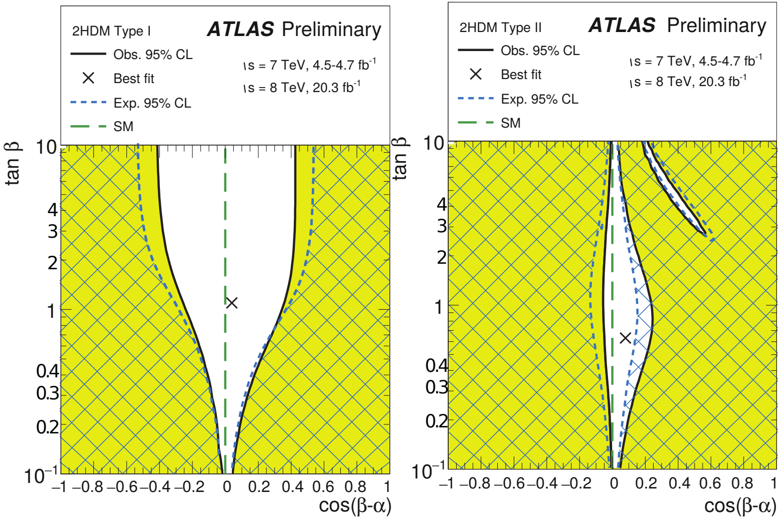
2-D likelihood contours in the (κ_V, κ_F) coupling scale factor plane

Two Higgs Doublet Model

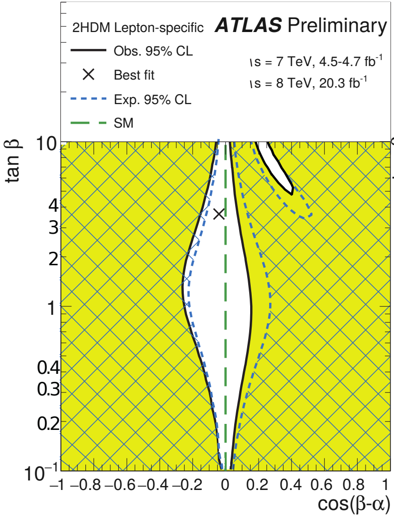
- Two complex SU(2) doublet scalar fields, 4 types of 2HDMs
- Consider the CP-conserving case with 6 sensitive parameters: 4 masses $m_h, m_H, m_{H^\pm}, m_A$ & 2 mixing angles α, β
- $\tan\beta = v_1/v_2$: ratio of vevs which satisfy $v_1^2 + v_2^2 = v^2 \approx (246\ \mathrm{GeV})^2$, α: mixing angle between h & H
- Assumptions (for interpretations): 125 GeV is the light higgs, no radiative corrections from BSM for the production of Higgs boson, only SM decays.
    - $g_{hVV}^{2HDM}/g_{hVV}^{SM} = \sin(\beta-\alpha)$, $g_{HVV}^{2HDM}/g_{HVV}^{SM} = \cos(\beta-\alpha)$
    - Convention: $\sin(\beta-\alpha) \geq 0$
- SM-like alignment limit retrieved at $\cos(\beta-\alpha) = 0$

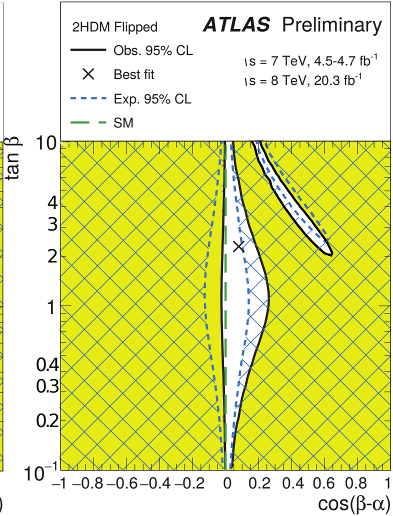
Two Higgs Doublet Model, Type I & II

- Excluded regions by fits to the measured rates of Higgs boson production & decays for type I- & II-2HDM



- Excluded regions by fits to the measured rates of Higgs boson production & decays for lepton specific- & flipped-2HDM





Searches for invisible decays of the Higgs boson

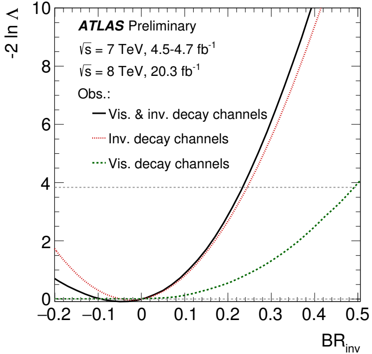
- Direct search strategies:
  - Select events with large missing energy, use particles produced associated with the Higgs
  - Assume productions (& acceptance) as in the SM $BR(h \to ZZ \to 4\nu) = 1.2 \times 10^{-3}$ ($\to$ result not sensitive to this)
- Analyses:
  - Z($\to$ ll) H $\to$ inv ($E_{\mathrm{T}}^{\mathrm{miss}}$) Phys. Rev. Lett. 112, 201802 (2014)
  - W/Z($\to$ jj) H $\to$ inv ($E_{\mathrm{T}}^{\mathrm{miss}}$) Submitted to EPJC (2015)
  - VBF ($\to$ jj) H $\to$ inv ($E_{\mathrm{T}}^{\mathrm{miss}}$)

Results	Observed	-2σ	-1σ	Expected	$+1\sigma$	$+2\sigma$
VBF h	**0.28**	0.16	0.21	0.31	0.41	0.56
$Z(\to \ell\ell)h$	**0.75**	0.33	0.45	0.62	0.86	1.19
$V(\to jj)h$	**0.78**	0.46	0.62	0.86	1.19	1.60
Combined Results	**0.25**	0.13	0.18	0.27	0.35	0.47

- Summary of 95% CL upper bounds on BR($h \to$ inv), the combination: 0.25(0.27) obs(exp)

Combine direct & indirect limit on BR($h \to inv$)

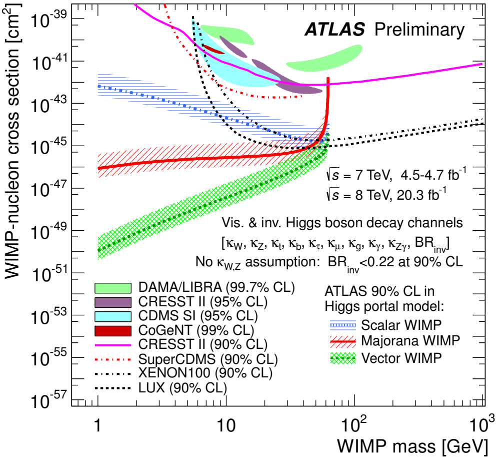
- HIGG-2015-03
- Using statistical method to combine direct + indirect search results (from the measured visible decay rates) $\to$ constrain a Higgs portal model of dark matter (next slide)
- Physical boundary $BR_{inv} > 0$
- The most general result with independent parameters: κ_W, κ_Z, κ_t, κ_b, κ_τ, κ_μ, κ_g, κ_γ, $\kappa_{Z\gamma}$, BR_{inv} (more parametrizations in backup)
- Result @95%CL upper limit of: 0.23(0.24) obs(exp.)



Likelihood scans of the Higgs' invisible branching ratio

Higgs Portal Interpretation

- Used 90%CL upper limit 0.22(0.23) obs.(exp.) of $BR(H \to inv)$ instead of 95%CL
- Sensitive for WIMP's mass $< m_h/2$
- Higgs as the only mediator...
- Higgs Portal $\to$ spin dependent!
- Form factor (Higgs-nucleon coupling) $f_N = 0.33^{+0.30}_{-0.07}$



Upper limit at 90% CL on the WIMP-nucleon scattering cross section, ATLAS's compared with the spin-independent direct searches

Summary

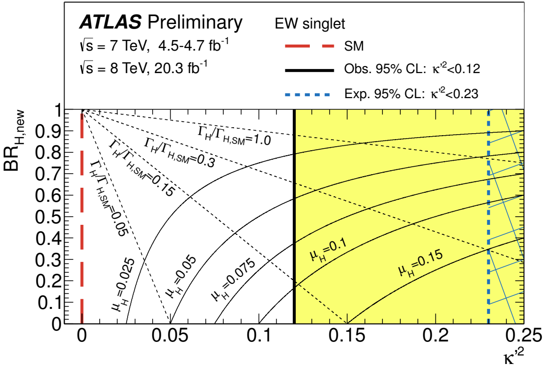
- No significant excess for BSM Higgs physics yet
- Precise measurements of the Higgs boson couplings allow to constrain new phenomena
- Understanding of the real nature of the Electroweak Symmetry Breaking $\rightarrow$ tool to explore new physics!
  - Mass scaling (ϵ : 0.018 ± 0.039, $M : 224 + 14 - 12$ GeV)
  - Minimal Composite Higgs models ($f > 710(780)$ GeV MCHM4(5))
  - Additional Electroweak Singlets ($\kappa^2 < 0.12$)
  - Two Higgs Doublet Models (Alignment limit within 1σ)
  - Simplified versions of MSSM ($m_A > 370$ GeV)
  - Higgs to invisible decays ($BR_{inv} < 0.23$)

THANKS!

BACK UP

Additional Real Electroweak Singlet

- Simplest extension: additional real EW singlet, $m_H > 125~\mathrm{GeV}$
- Couplings $\to$ mixing gives: $\kappa^2 + \kappa'^2 = 1$
- Coupling (and signal strength as predicted by heavier SM-like Higgs) modified by allowing new decays $\mathrm{BR_{H,new}}$, like $H \to hh$

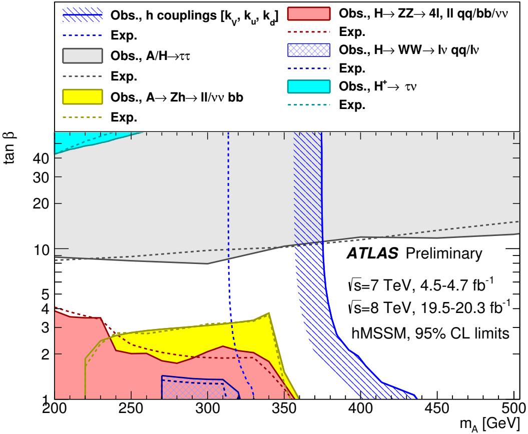


Result: @ 95%CL: $\kappa^2 < 0.12(0.23)$ **obs(exp)**

arXiv: 1307.5205 [hep-ph]

- Figure: Excluded region via direct searches for heavy Higgs and fits to the measured rates of observed Higgs production & decays.

- Assumptions
  - h production & decay modes as in the SM
  - stops in ggF and $\gamma\gamma$ not included
  - Same for light staus and charginos
  - Decays to SUSY or heavy-to-light Higgs decays not included
- **Result: for** $1 < \tan\beta < 60 : m_A > 370(310)$ GeV

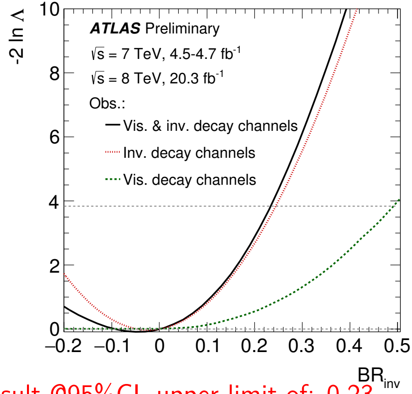


Combine direct & indirect limit on BR($h \to inv$)

- Combine direct searches, then adding the measured visible decay rates in a more general coupling fit $\to$ constrain a Higgs portal model of dark matter HIGG-2015-03

- Assuming $\Gamma(h \to \text{undetectable})$ (eg. gg) is negligible
- The visible channels alone (& $\kappa_V \leq 1$): ($BR_{inv} < 0.49(0.48)$ obs (exp)
- Combination visible channels & invisible searches one can remove restrictions of ($\kappa_V \leq 1$)
- Physical boundary $BR_{inv} > 0$
- The most general result with independent parameters: κ_W, κ_Z, κ_t, κ_b, κ_τ, κ_μ, κ_g, κ_γ, $\kappa_{Z\gamma}$, BR_{inv}

- Figure: likelihood scans of the Higgs invisible branching ratio



Result @95%CL upper limit of: 0.23 (0.24) obs (exp)

Higgs to invisible, different parametrizations

	Observed	Expected	Assumptions
Direct search	0.25	0.27	Productions as SM ($\kappa_i = 1$)
Indirect search	0.49	0.48	$\kappa_{Z,W} \leq 1$
Combination	0.23	0.24	None
Comb. 1	0.23	0.23	$\kappa_{Z,W} \leq 1$
Comb. 2	0.18	0.24	one κ_F and one κ_V
Comb. 3	0.16	0.23	one κ_F and one $\kappa_V \leq 1$

Missing Mass Calculator

The MMC method is an experimental technique for reconstructing the invariant mass of resonances decaying to a pair of τ leptons. MMC arxiv:1012.4686

- On top of the usual kinematics constraints, use additional information of the τ decay products such as the expected angular distance between the neutrino(s) and the visible decays products of the τ lepton $\rightarrow$ build a better likelihood estimator for $M_{\tau\tau}$
- Allow for a complete reconstruction of event kinematics in the $\tau\tau$ final states with significantly improved invariant mass and neutrino momentum resolutions.
- Can be applied to all $\tau\tau$ event topologies without sacrificing the reconstructed mass resolution.

Two Higgs Doublet Model

Coupling scale factor	Type I (fermiophobic)	Type II (MSSM-like)	Lepton-specific	Flipped
κ_V	$\sin(\beta-\alpha)$			
κ_u	$\cos(\alpha)/\sin(\beta)$			
κ_d	$\cos(\alpha)/\sin(\beta)$	$-\sin(\alpha)/\cos(\beta)$	$\cos(\alpha)/\sin(\beta)$	$-\sin(\alpha)/\cos(\beta)$
κ_ℓ	$\cos(\alpha)/\sin(\beta)$	$-\sin(\alpha)/\cos(\beta)$	$-\sin(\alpha)/\cos(\beta)$	$\cos(\alpha)/\sin(\beta)$

Table : Couplings of the light Higgs boson h to weak vector bosons (κ_V), up-type quarks (κ_u), down-type quarks (κ_d), and charged leptons (κ_ℓ), expressed as ratios to the corresponding SM predictions in 2HDMs of various types.

Higgs Portal Dark Matter

- The hashed bands indicate the uncertainty resulting from the systematic variation of the form factor f_N
- The ATLAS limits on the WIMP-nucleon scattering cross section are proportional to those on the invisible decay branching ratio. They are weaker (stronger) at low mass for scalar (Majorana and vector) WIMPs, and degrade as m_{WIMP} approaches $m_h/2$ as expected from kinematics. The limits are shown for $m_{WIMP} \geq 1$ GeV, but extend to WIMP masses smaller than this value.
- The Higgs portal model is a special case of the spin-independent limits where the Higgs boson is taken to be the only mediator.

2HDMs

- Type I: One Higgs doublet couples to vector bosons, while the other couples to fermions. The first doublet is "fermiophobic" in the limit that the two Higgs doublets do not mix
- Type II: This is an "MSSM-like" model, in which one Higgs doublet couples to up-type quarks and the other to down-type quarks and charged leptons. This model is realised in the MSSM
- Lepton-specific: The Higgs bosons have the same couplings to quarks as in the Type I model and to charged leptons as in Type II
- Flipped: The Higgs bosons have the same couplings to quarks as in the Type II model and to charged leptons as in Type I
- In each of the Type II, Lepton-specific, and Flipped models, at the upper right of the $(\cos(\beta-\alpha), \tan\beta)$ plane there is a narrow, curved region or "petal" of allowed parameter space with the surrounding region being excluded. These three allowed upper petals correspond respectively to an inverted sign of the coupling to down-type fermions, lepton, or the bottom quark. These couplings are measured with insufficient precision to be excluded. There is no upper petal at high $tan\beta$ in Type I as all the Yukawa couplings are identical.