Probing the nature of the extended scalar sectors with the CMS data

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Hamburg, 20.08.2020

Outline

The Standard Model ...

a renormalizable gauge quantum field theory of elementary particles ...

- **power counting:** only operators of mass dimension $[\mathcal{O}] \leq 4$
- **symmetries:** Poincaré $\otimes$ Internal, with Internal $= SU(3)_C \times SU(2)_L \times U(1)_Y$
- **field content:**

Name	Symbol	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$	Spin
Gauge fields	G^a_μ	$\mathbf{8}$	$\mathbf{1}$	0	1
	W^a_μ	$\mathbf{1}$	$\mathbf{3}$	0	1
	B_μ	$\mathbf{1}$	$\mathbf{1}$	0	1
Quarks	Q_L	$\mathbf{3}$	$\mathbf{2}$	$+\frac{1}{6}$	$\frac{1}{2}$
	u_R	$\mathbf{3}$	$\mathbf{1}$	$+\frac{2}{3}$	$\frac{1}{2}$
	d_R	$\mathbf{3}$	$\mathbf{1}$	$-\frac{1}{3}$	$\frac{1}{2}$
Leptons	L_L	$\mathbf{1}$	$\mathbf{2}$	$-\frac{1}{2}$	$\frac{1}{2}$
	e_R	$\mathbf{1}$	$\mathbf{1}$	-1	$\frac{1}{2}$
Higgs	H	$\mathbf{1}$	$\mathbf{2}$	$+\frac{1}{2}$	0

- remarkably successful in providing experimental predictions

- limitations: absence of gravity, dark matter and dark energy, unnaturalness ...

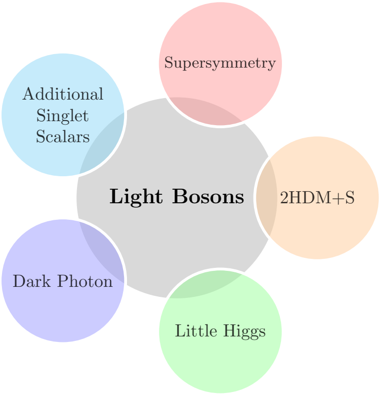
Extended Scalar Sectors

...

- modifications in the scalar sector are very common in new models
  - ∵ relevant operator $\sim \phi^2$
- several open questions addressed
  - ✓ hierarchy problem
  - ✓ dark matter
  - ✓ baryon asymmetry

possibility of light states in several well-motivated models

- light bosons (**a**) can couple to the 125-GeV Higgs boson ($\mathbf{h_{125}}$)



Probing Models with Light Bosons

× direct searches in production mode? ⇒ limited by small couplings of **a** to fermions

× indirect constraints from h_{125} cuplings? ⇒ $\mathcal{B}(h_{125} \to \mathrm{BSM})$ still relatively large

✓ alternative: *search for light bosons through exotic decays of* h_{125}

The 2HDM+S

Two Simple Assumptions ...

- 2HDM is near or in the decoupling limit (h_{125} becomes very SM-like): $\alpha \to \beta - \pi/2$
- Add one complex scalar singlet $S = \frac{1}{\sqrt{2}}(S_R + iS_I)$:

$$V_{2HDM+S}(H_1, H_2, S) = V_{2HDM}(H_1, H_2) + \lambda S H_1 H_2 + \frac{\kappa}{3} S^3 + \cdots$$

Light Boson Couplings

✓ a_1 (the mostly-singlet-like pseudoscalar)

$$a_1 = \cos\theta_{a_1} S_I + \sin\theta_{a_1} A \qquad (\theta_{a_1} \ll 1)$$

✓ could potentially be a light boson: $m_{a_1} < m_{h_{125}}/2$

✓ with couplings to fermions driven by: $\xi_{a_1} \sim \sin\theta_{a_1} \cdot \xi_A$

Eigenstate	**Coupling**	**Type-I**	**Type-II**	**Type-III**	**Type-IV**
	ξ_A^u	$\cot\beta$	$\cot\beta$	$\cot\beta$	$\cot\beta$
A	ξ_A^d	$-\cot\beta$	$\tan\beta$	$-\cot\beta$	$\tan\beta$
	ξ_A^l	$-\cot\beta$	$\tan\beta$	$\tan\beta$	$-\cot\beta$

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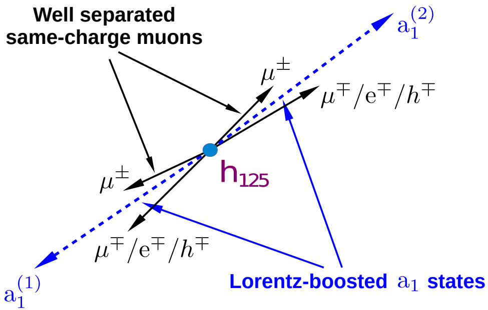
For Type-III ($\tan\beta > 1$), a_1 decays to $\tau^+\tau^-$ dominate even above the $b\bar{b}$-threshold

Analysis Strategy

- targeted mass range
  - ✓ very light a_1 (boosted)
- decay channels
  - ✓ $h_{125} \to a_1 a_1 \to 4\tau$ (main)
  - ✓ $h_{125} \to a_1 a_1 \to 2\mu 2\tau$
  - × $h_{125} \to a_1 a_1 \to 4\mu$ (neglected)
- h_{125} production mechanisms
  - ✓ ggF (main)
  - ✓ VBF, VH and ttH



Topology

- light pseudoscalar a_1 produced with a large Lorentz boost
- overlapped taus from $a_1 \to \tau\tau$ decays difficult to resolve by the CMS reconstruction algorithm
  - ⋆ solution: exploit the decay $a_1 \to \tau_\mu \tau_{\text{one-prong}}$
- requirement of two same-charge muons highly suppresses background events

Selection

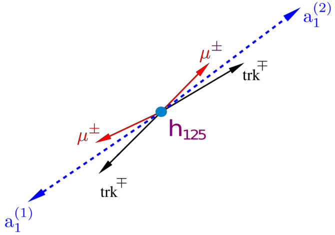
Cut-Based Approach

Physics Letters B 800 (2020) 135087

mass range covered in this first approach $4 \leq m_{a_1} \leq 15$ GeV

Online Selection: Trigger

- same-charge double-muon trigger without isolation requirements on muons



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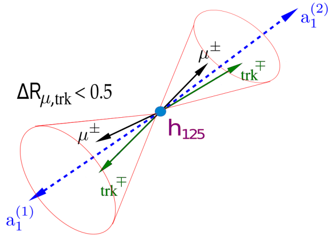
Offline Selection

- use of *muons* and *tracks* as physics objects



Background

- main contribution comes from QCD multi-jet events
- estimation is done using a data-driven procedure

Final Discriminant

Cut-Based Approach

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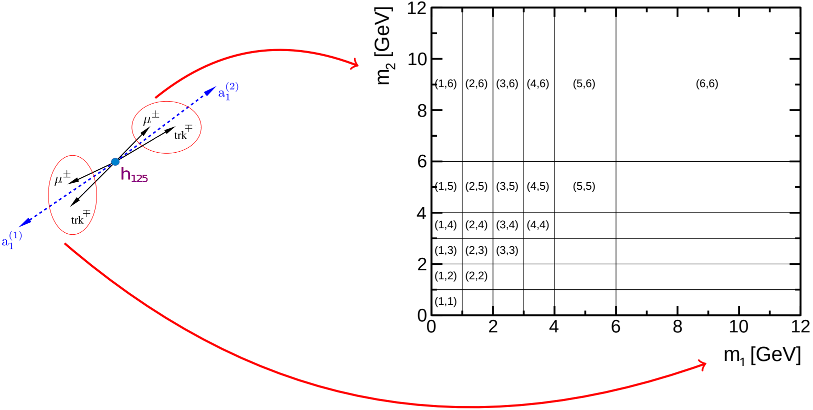
binned 2D distribution formed by the invariant masses of the muon-track systems



* *pairs of integers (i, j) label the bins*

- a_1 resonances poorly reconstructed due to presence of neutrinos in $a_1 \to \tau\tau$ legs

Results

Cut-Based Approach

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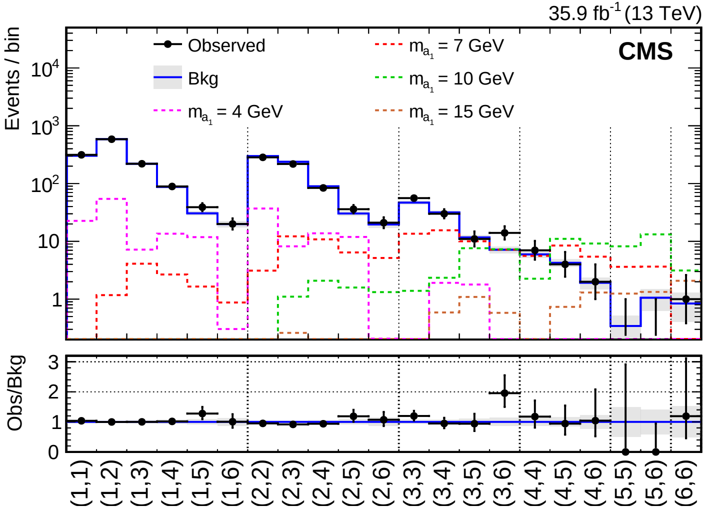

data was found consistent with the background-only hypothesis

Results

Cut-Based Approach

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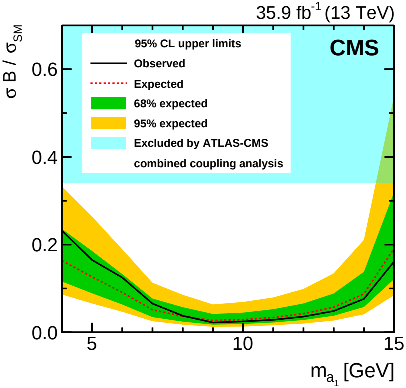
upper limits set on the signal strength modifier: $\mu = \frac{\sigma}{\sigma_{SM}} \mathcal{B}(h_{125} \to a_1 a_1) \mathcal{B}^2(a_1 \to \tau\tau)$



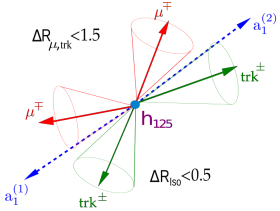
- Deterioration of the limits for low and high masses
  - ✓ low masses: poor discriminating power of the $2D(m_1, m_2)$ distribution
  - ✓ high masses: decrease in signal acceptance due to $\Delta R < 0.5$ cut

Analysis using Machine Learning

MVA-Based Approach

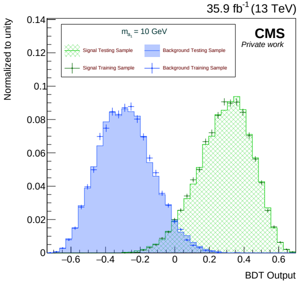
DESY-THESIS-2020-007

- ⋆ changes in preselection cuts and type of isolation
- ⋆ MVA classifier employed to increase discriminating power
  - BDT signal class
    - ✓ one category combining all production and decay modes
    - ✓ dedicated signal samples produced for $h_{125} \to a_1 a_1 \to 4\tau$
  - BDT background class
    - ✓ one category obtained from data-driven estimation



Variables

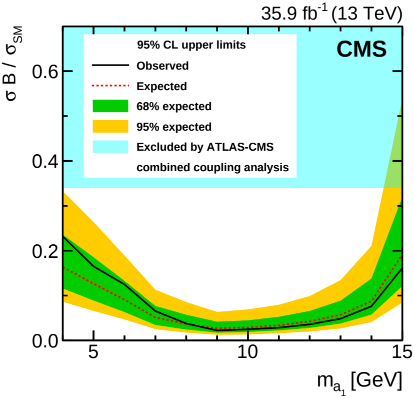
- $\Delta R_{\mu_L,\mu_S}$
- m_{μ_L,trk_L}
- m_{μ_S,trk_S}
- $p^{\mathrm{Reco}}_{T_{\mu_L,trk_L}}$
- $p^{\mathrm{Reco}}_{T_{\mu_S,trk_S}}$
- $\Delta R_{\mu_L,trk_L}$
- $\Delta R_{\mu_S,trk_S}$
- $\Delta\phi_{\vec{p}^{\,\mathrm{Reco}}_{T_{\mu_S,trk_S}},\vec{E}_T^{miss}}$
- $m_{\mu_L,trk_L,\mu_S,trk_S}$
- $m_{\mu_L,trk_L,\mu_S,trk_S,E_T^{miss}}$



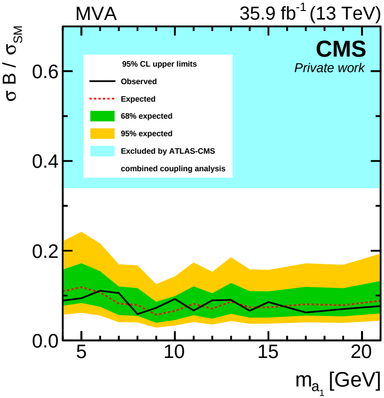
⋆ new approach allowed extending the mass range: $4 \leq m_{a_1} \leq 21$ GeV

Results

Cut-Based Approach



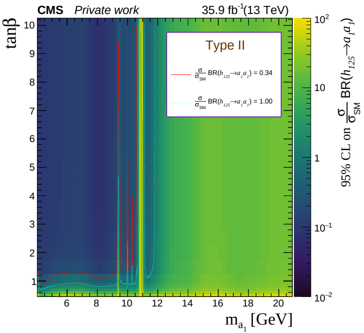
MVA-Based Approach

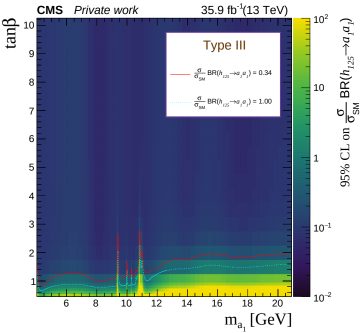


- MVA-Based
  - ✓ improvement in limits for very low and relative high masses
  - ✓ masses of up to $\sim$ 21 GeV can be probed (non-boosted regime)
- Cut-Based
  - ✓ better performance in the intermediate-mass range $\sim$ 9 GeV

Interpretation of the Results in the 2HDM+S Context

- phenomenology of $h_{125} \to a_1 a_1 \to x\bar{x}y\bar{y}$ decays determined by:
  - type of fermion coupling: **Type I**, **Type II**, **Type III**, and **Type IV**
  - three independent parameters: $\boldsymbol{\mathcal{B}(h_{125} \to a_1 a_1)}$, $\boldsymbol{\tan\beta}$, and $\boldsymbol{m_{a_1}}$





Type II

- sensitive for values of $\boldsymbol{\tan\beta > 1}$ and $\boldsymbol{m_{a_1}}$ below the b-quark pair threshold

Type III

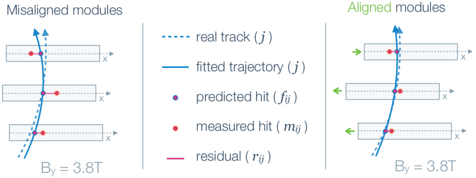
- highly sensitive to this model for $\boldsymbol{\tan\beta > 1}$

Tracker Alignment

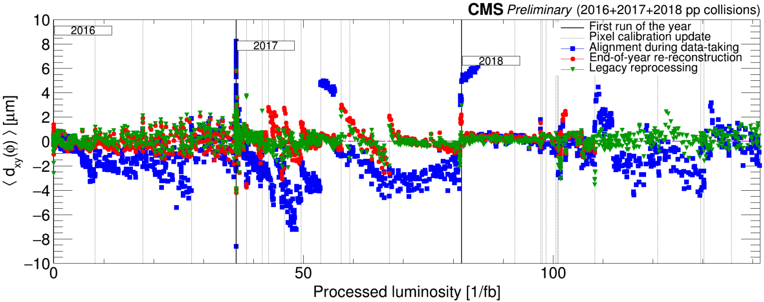
- optimal alignment of tracker detector is vital to have well-reconstructed tracks
- track-based alignment algorithm in CMS: use of *track-hit residuals*

Minimisation problem:

$$\chi^2(\vec{p},\vec{q}) = \sum_{j}^{tracks} \sum_{i}^{hits} \left(\frac{m_{ij} - f_{ij}(\vec{p},\vec{q}_j)}{\sigma_{ij}} \right)^2$$



Quantifiying the Traker Alignment Performance



Common Framework for 2HDM+S Interpretations

TWIKI

- developed in the context of the $h_{125} \to aa$ searches performed within CMS
- implementation covers the **4** main types of models (Type I, II, III, and IV) and **10** different decay channels:
  - ✓ $bbbb$
  - ✓ $bb\tau\tau$
  - ✓ $bb\mu\mu$
  - ✓ $bb\gamma\gamma$
  - ✓ $\tau\tau\tau\tau$
  - ✓ $\tau\tau\mu\mu$
  - ✓ $\tau\tau\gamma\gamma$
  - ✓ $\mu\mu\mu\mu$
  - ✓ $\mu\mu\gamma\gamma$
  - ✓ $\gamma\gamma\gamma\gamma$
- based on the assumption that upper limits are being set on signal strength modifier (otherwise easily adaptable):

$$\mu = (\sigma/\sigma_{SM})\mathcal{B}(h_{125} \to aa \to x\overline{x}y\overline{y})$$

- currently being employed for Run2 $h_{125} \to aa$ analyses

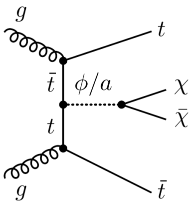
Direct Searches with Top-Quark Pairs

Simplified model with scalar (ϕ) or pseudoscalar (a) mediator

$$\mathcal{L}_\phi \supset g_\chi \phi \bar{\chi}\chi + \frac{g_q \phi}{\sqrt{2}} \sum_f y_f \bar{f} f$$

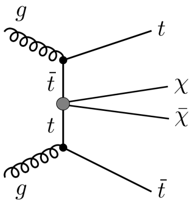
or

$$\mathcal{L}_a \supset i g_\chi a \bar{\chi}\gamma^5 \chi + \frac{i g_q a}{\sqrt{2}} \sum_f y_f \bar{f}\gamma^5 f$$



Dark Matter Effective Interaction with Quarks (Heavy Mediator)

$$\mathcal{O} = \sum_q \frac{m_q}{M_*^3} \bar{q} q \bar{\chi}\chi$$

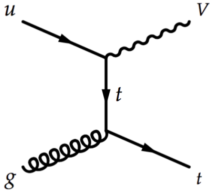


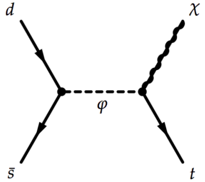
- exploit $\not{E}_T + t\bar{t}$ signatures with full Run 2 available data
- resort to multivariate techniques to enhance sensitivity
- perform interpretations in the context of relevant simplified/effective models

Direct Searches with Single-Top Signatures

FCN Interaction with V and Scalar Resonance with χ

$$\mathcal{L}_{Int} = V_\mu \bar{u}\gamma^\mu(a_{FC} + b_{FC}\gamma^5)u + \phi\bar{d}^c[a^q_{SR} + b^q_{SR}\gamma^5]d + \phi\bar{u}[a^{1/2}_{SR} + b^{1/2}_{SR}\gamma^5]\chi$$

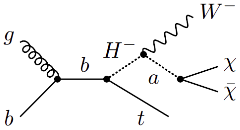


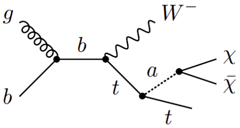


$t + \not{E}_T$
(boosted top)

2HDM plus Pseudoscalar (P) Model

$$\mathcal{L}_{Int} = V_{2HDM}(H_1, H_2) + V_{HP}(H_1, H_2, P) + V_P(P) \quad - \quad iy_\chi P\bar{\chi}\gamma^5\chi$$





$tW + \not{E}_T$
(boosted top)

Indirect Searches Through High-Precision Tests

A Model-Independent Parametrization of Heavy BSM Physics

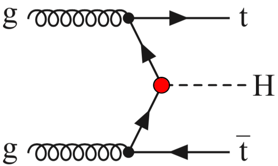
$$\mathcal{L}_{SMEFT} = \mathcal{L}_{SM} + \sum_i \frac{c_i^{(5)}}{\Lambda}\mathcal{O}_i^{(5)} + \sum_i \frac{c_i^{(6)}}{\Lambda^2}\mathcal{O}_i^{(6)} + \sum_i \frac{c_i^{(7)}}{\Lambda^3}\mathcal{O}_i^{(7)} + \sum_i \frac{c_i^{(8)}}{\Lambda^4}\mathcal{O}_i^{(8)} + \cdots$$

- many models contained within the same formalism
- connection to specific models via *matching*

Towards a Global Top & Higgs Fit

- Connection between Top and Higgs is clear:

$$O_{t\phi} = y_t^3(\phi^\dagger\phi)(\bar{Q}t)\tilde{\phi}$$



- contribute to the efforts on Top ($t\bar{t}/t\bar{t}Z$ diff.) & Higgs (STXS) combination
- translate limits on *Wilson coefficients* to constraints on specific models

Conclusions

- previous work mainly focused on searches for BSM Higgs sectors
  - light bosons via exotic decays of h_{125}
  - no sign of new light states
  - constraints set on relevant model (2HDM+S)
- interested in continuing the exploration of extended scalar sectors
  - exploit potential of direct searches (top-quark pair and single-top signatures)
  - contribute to global fits using combination of Top & Higgs observables
  - interpretation of results in the context of the various models

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Thanks for your attention!

Backup

Higgs Physics

▶ The Standard Model

▶ The Standard Model Higgs Boson

▶ Higgs Collider Phenomenology

▶ Models with Additional Singlet Scalars

▶ Adding a Vector Field

▶ Little Higgs Models

▶ Two Higgs Doublet Models

The Standard Model

$$\mathcal{L}_{SM} = -\frac{1}{4}G^a_{\mu\nu}G^{a\mu\nu} - \frac{1}{4}W^a_{\mu\nu}W^{a\mu\nu} - \frac{1}{4}B_{\mu\nu}B^{\mu\nu}$$

$$+ i\bar{Q}^n_L \not{D} Q^n_L + i\bar{d}^n_R \not{D} d^n_R + i\bar{u}^n_R \not{D} u^n_R + i\bar{L}^n_L \not{D} L^n_L + i\bar{e}^n_R \not{D} e^n_R$$

$$- [Y^{mn}_{(d)}\bar{Q}^m_L H d^n_R + Y^{mn}_{(u)}\bar{Q}^m_L H^c u^n_R + Y^{mn}_{(e)}\bar{L}^m_L H e^n_R + h.c.]$$

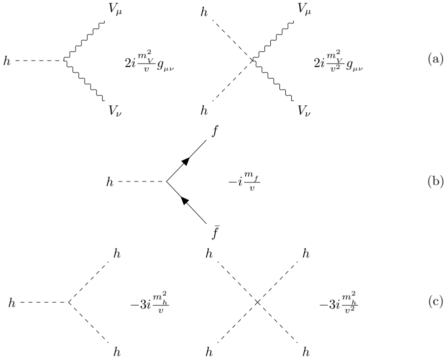
$$+ (D_\mu H)^\dagger (D^\mu H) - [-\mu^2 H^\dagger H + \lambda (H^\dagger H)^2]$$

...

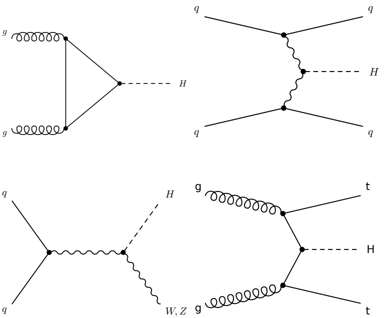
- the SM model contains in total 18 physical parameters: flavor sector 13 (9 lepton-quark masses and 4 in CKM matrix), gauge couplings 3, and Higgs sector 2
- flavor group: $U(3)^3_q \times U(3)^2_l \to U(1)_B \times U(1)^3_L$
- approximate symmetries: chiral symmetry protecting the fermion masses and the custodial symmetry in the Higgs sector

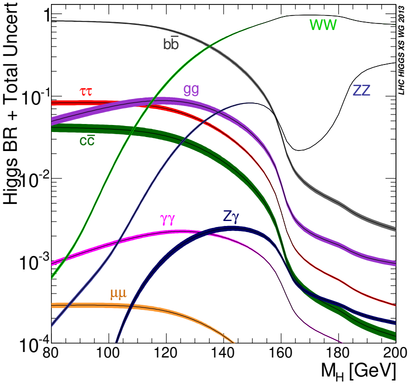
The Standard Model Higgs Boson

$$\begin{aligned}\mathcal{L}_{\cancel{SU(2)_L\times U(1)_Y}} = \; & \frac{1}{2}\partial_\mu h \partial^\mu h - \lambda v^2 h^2 - \lambda v h^3 - \frac{\lambda}{4}h^4 \\ & + \frac{1}{8}(v+h)^2[g_2^2(W^1_\mu - iW^2_\mu)(W^{1\mu}+iW^{2\mu}) + (g_1 B_\mu - g_2 W^3_\mu)^2] \\ & - \frac{1}{\sqrt{2}}(v+h)[Y^{mn}_{(d)}\bar{d}^m_L d^n_R + Y^{mn}_{(u)}\bar{u}^m_L u^n_R + Y^{mn}_{(e)}\bar{e}^m_L e^n_R + h.c.]\end{aligned}$$



Higgs Collider Phenomenology





Production cross-section (in pb) for $m_h = 125$ GeV in pp collisions at $\sqrt{s} = 13$ TeV				
ggF	VBF	WH	ZH	ttH
$48.6^{+5\%}_{-5\%}$	$3.78^{+2\%}_{-2\%}$	$1.37^{+2\%}_{-2\%}$	$0.88^{+5\%}_{-5\%}$	$0.50^{+9\%}_{-13\%}$

$$\Gamma(h \to f\bar{f}) = \frac{N_c}{8\pi} \frac{m_f^2}{v^2} m_h \left[1 - \frac{4m_f^2}{m_h^2}\right]^{\frac{3}{2}}$$

Models with Additional Singlet Scalars

...

- mainly motivated by dark matter considerations and EW baryogenesis
- N scalars transforming trivially under the SM internal symmetry group
- mixing between $\vec{\phi}$ and H if $\langle\vec{\phi}\rangle \neq 0$
- changes in the couplings of h_{125} due to mixing
- two simplest cases ($N = 1$ and $N = 2$) well studied
- decays of the form $h_{125} \to h_s h_s$ if h_s sufficiently light
- testing: precision studies and searches for additional bosons

$$V(H, \vec{\phi}) = -\mu_H^2 H^\dagger H + \lambda_H (H^\dagger H)^2 + \lambda_{ij}\phi_i\phi_j + \lambda_{ijkl}\phi_i\phi_j\phi_k\phi_l + \lambda_{ijHH}\phi_i\phi_j H^\dagger H$$

Adding a Vector Field

...

- motivation within the framework of dark matter
- dark photon model exploits kinematic mixing between B_μ and a new vector field X_μ
- model considers an extra $U(1)_D$ symmetry
- SM Higgs singlet under $U(1)_D$ and new dark Higgs transforms as $(\mathbf{1}, 0, q_D)$
- Z' gets a mass by "eating" the Goldstone boson of pseudoscalar component of H_D
- $H - H_D$ mixing enables the $h_{125} \to Z'Z'$ decay (when kinematically allowed)
- $h_{125} \to Z'Z'$ dominates over other decays if $\kappa \gg \chi$
- interaction of Z' with fermions driven by gauge couplings

$$\mathcal{L}_D = -\frac{1}{4} X_{\mu\nu} X^{\mu\nu} + \frac{\chi}{2} X_{\mu\nu} B^{\mu\nu} \\ + (D_\mu H_D)^\dagger (D^\mu H_D) + \mu_D^2 H_D^\dagger H_D - \lambda_D (H_D^\dagger H_D)^2 - \kappa H^\dagger H H_D^\dagger H_D$$

Little Higgs Models

...

- motivated by the unnaturalness problem
- light Higgs is a pseudo-Nambu-Goldstone boson (analog to QCD chiral theory)
- Higgs is composite at $\Lambda \simeq 4\pi v$ ($v \approx 246$ GeV)
- unbroken $\mathcal{H}$ (of global $\mathcal{G}$) contains $SU(2)_L \times U(1)_Y$
- $\mathcal{G}$ explicitly broken by gauging and Yukawa couplings
- EWSB driven by quantum effects (non-vanishing Higgs effective potential)

Littlest Higgs Model

- symmetry breaking via $SU(5)/SO(5)$: 14 Goldstone bosons
- explicitly breaking by gauging a $[SU(2) \times U(1)]^2$ subgroup
- condensate breaks $[SU(2) \times U(1)]^2$ to SM EW group
- EWSB through radiative-induced Higgs potential

Pseudo-Axion Model

- keep only one $U(1)$ ($U(1)_Y$) group gauged
- the other $U(1)$ global group explicitly broken
- massive (pseudo-)scalar (a) arises: $\sim \phi_a^2 H^\dagger H$
- decays of the form $h_{125} \to a\ a$

Two Higgs Doublet Models

$$V_{2HDM} = m_{11}^2 H_1^\dagger H_1 + m_{22}^2 H_2^\dagger H_2 - m_{12}^2 (H_1^\dagger H_2 + H_2^\dagger H_1) + \frac{\lambda_1}{2}(H_1^\dagger H_1)^2 + \frac{\lambda_2}{2}(H_2^\dagger H_2)^2$$
$$+ \lambda_3 H_1^\dagger H_1 H_2^\dagger H_2 + \lambda_4 H_1^\dagger H_2 H_2^\dagger H_1 + \frac{\lambda_5}{2}[(H_1^\dagger H_2)^2 + (H_2^\dagger H_1)^2]$$

Eigenstate	Coupling	Type-I	Type-II	Type-III	Type-IV
h_{125}	$\xi^u_{h_{125}}$	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$
	$\xi^d_{h_{125}}$	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$
	$\xi^l_{h_{125}}$	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$	$-\sin\alpha/\cos\beta$	$\cos\alpha/\sin\beta$
H^0	$\xi^u_{H^0}$	$\sin\alpha/\sin\beta$	$\sin\alpha/\sin\beta$	$\sin\alpha/\sin\beta$	$\sin\alpha/\sin\beta$
	$\xi^d_{H^0}$	$\sin\alpha/\sin\beta$	$\cos\alpha/\cos\beta$	$\sin\alpha/\sin\beta$	$\cos\alpha/\cos\beta$
	$\xi^l_{H^0}$	$\sin\alpha/\sin\beta$	$\cos\alpha/\cos\beta$	$\cos\alpha/\cos\beta$	$\sin\alpha/\sin\beta$
A	ξ^u_A	$\cot\beta$	$\cot\beta$	$\cot\beta$	$\cot\beta$
	ξ^d_A	$-\cot\beta$	$\tan\beta$	$-\cot\beta$	$\tan\beta$
	ξ^l_A	$-\cot\beta$	$\tan\beta$	$\tan\beta$	$-\cot\beta$

- α: diagonalizes the neutral scalar matrix
- $\tan\beta = v_2/v_1$: diagonalizes the charged scalar matrix

Analysis Using Cut-Based Approach

▶ Event Selection

▶ Background Modeling

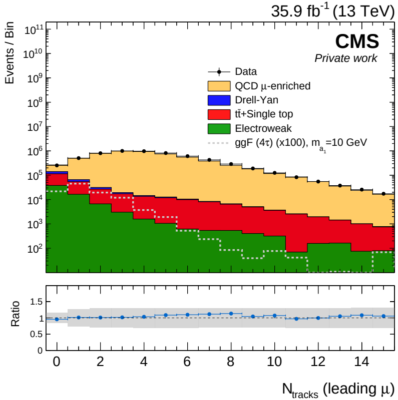
▶ Signal Modeling and Monte Carlo Corrections

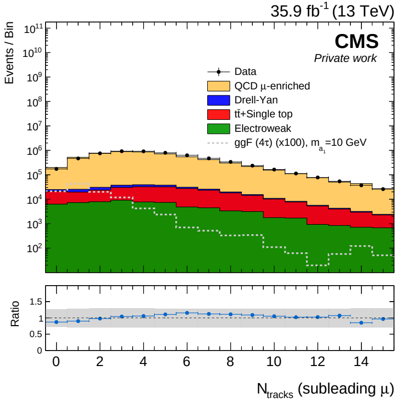
▶ Goodness-Of-Fit Tests

▶ Results

Event Selection

- “isolation” tracks: $p_T > 1$ GeV, $|\eta| < 2.4$, $|d_\perp| < 1$ cm, $|d_z| < 1$ cm
- “signal” tracks: $p_T > 2.5$ GeV, $|\eta| < 2.4$, $|d_\perp| < 0.02$ cm, $|d_z| < 0.04$ cm
- “soft” tracks: $1 < p_T < 2.5$ GeV, $|\eta| < 2.4$, $|d_\perp| < 1$ cm, $|d_z| < 1$ cm





Final Sample

Cut-Based Approach

Data

- 2035 observed events

Background

- prediction from simulation describes well the data
  - accuracy limited by size of simulated samples
  - simple composition study shows that QCD multi-jet events dominate
  - other background sources comprise $\sim 1\%$ of the total
- precise estimation requires a data-driven procedure

Signal

$\mathbf{m_{a_1}}$ [GeV]	Acceptance $\times 10^4$		Number of events	
	4τ	$2\mu 2\tau$	4τ	$2\mu 2\tau$
4	3.29 ± 0.16	89.3 ± 1.4	129.9 ± 6.2	54.7 ± 0.9
7	2.50 ± 0.14	69.0 ± 1.4	98.8 ± 5.5	22.5 ± 0.5
10	1.46 ± 0.11	47.1 ± 1.2	57.8 ± 4.2	14.2 ± 0.4
15	0.21 ± 0.04	3.5 ± 0.3	8.5 ± 1.1	1.0 ± 0.1

Pseudoscalar (2HDM+S)

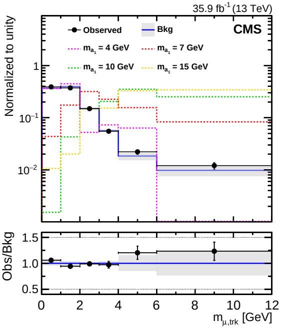
$$\frac{\Gamma(a_1 \to \mu\mu)}{\Gamma(a_1 \to \tau\tau)} = \frac{m_\mu^2 \sqrt{1 - (\frac{2m_\mu}{m_{a_1}})^2}}{m_\tau^2 \sqrt{1 - (\frac{2m_\tau}{m_{a_1}})^2}}$$

Background Modeling

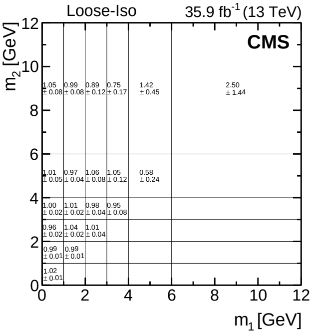
- estimation is done using a data-driven procedure
  - shape of 2D distribution derived in control regions
  - normalization parameter left unconstrained
  - validation and assessment of sys. unc. with hybrid method (MC & data-driven)
- model:

$$f_{2\mathrm{D}}(i,j) = \begin{cases} C(i,i) f_{1\mathrm{D}}(i) f_{1\mathrm{D}}(i) & i = j \\ C(i,j)(f_{1\mathrm{D}}(i) f_{1\mathrm{D}}(j) + f_{1\mathrm{D}}(j) f_{1\mathrm{D}}(i)) & j > i \end{cases}$$

$f_{1\mathrm{D}}(i)$



$C(i,j)$



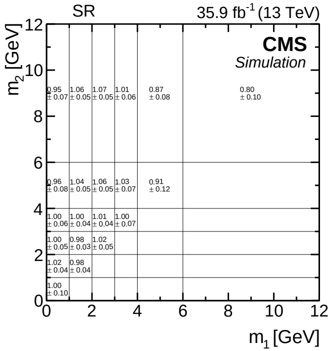
Background Modeling

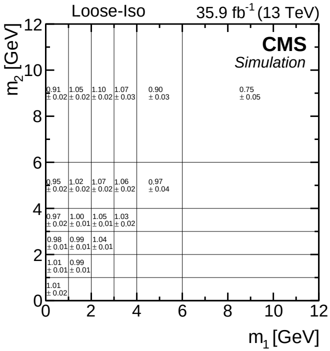
MC Study on QCD Sample

$$P(p_{\text{parton}}, p_{\mu}/p_{\text{parton}}, f_{\text{parton}}, q_{\mu} \cdot q_{\text{parton}}, m_{\mu,\text{trk}})$$

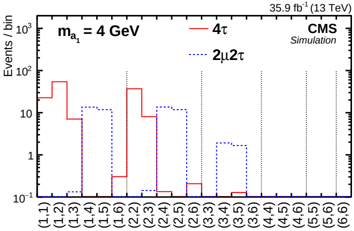
- probabilities derived in same-charge di-muon sample
- $f_{\text{2D}}(i,j)$ and f_{1D} distributions generated for each region

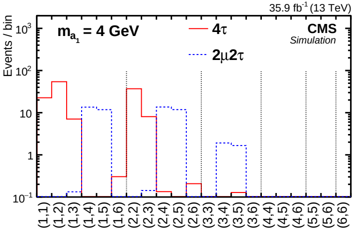
Validation of $C(i,j)$

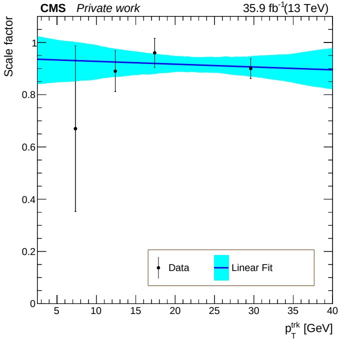




Signal Modeling and Monte Carlo Corrections







Systematic Uncertainties

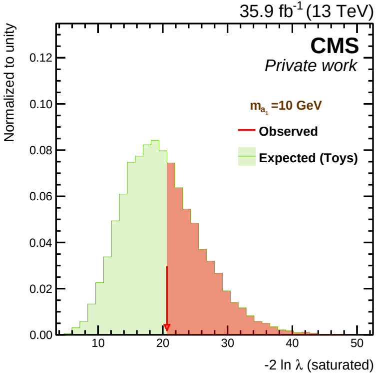
Cut-Based Approach

Affected Distribution	**Source**	**Value**	**Type**
Background	Stat. unc. in $C(i,j)$	$3-60\%$	bin-by-bin
	Syst. unc. in $C(i,j)$	-	shape
	Syst. unc. in $f_{1\text{D}}(i)$	-	shape
Signal	Integrated luminosity	2.5%	norm.
	Muon id. and trigger effic. (per μ)	2%	norm.
	Track id. effic. (per track)	$4-12\%$	shape & norm.
	MC stat. unc.	$8-100\%$	bin-by-bin
	$\mu_{\text{R,F}}$ variations (acceptance)	$0.8-2\%$	norm.
	PDF (acceptance)	$1-2\%$	norm.
	$\mu_{\text{R,F}}$ variations (ggF xsec.)	$5-7\%$	norm.
	$\mu_{\text{R,F}}$ variations (others xsec.)	$0.4-9\%$	norm.
	PDF (ggF xsec.)	3.1%	norm.
	PDF (others xsec.)	$2.1-3.6\%$	norm.

Goodness-Of-Fit Tests

GoF

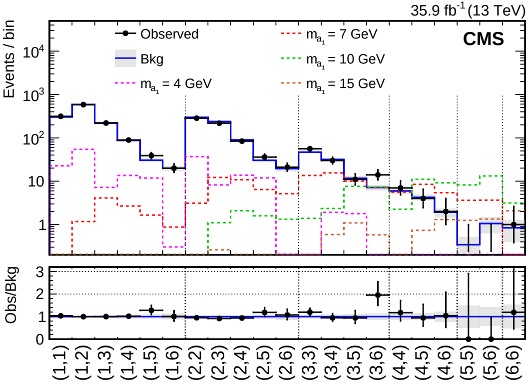
- Saturated: based on the likelihood ratio test and using as "alternative" hypothesis the saturated model ($f(x_i) = \text{data}_i$)
- Kolmogorov-Smirnov: distance between the empirical distribution function of the sample and the cumulative distribution function of the model ($D_n = \sup_x |F_n(x) - F(x)|$)
- Anderson-Darling: similar to the KS test but with $D_n = n \int_{-\infty}^{\infty} \frac{(F_n(x)-F(x))^2}{F(x)(1-F(x))} dF(x)$



Results

Cut-Based Approach

	p-value			
Hypothesis H_0	signal-plus-background			background-only
m_{a_1}	5 GeV	10 GeV	15 GeV	-
Sat.	0.427	0.441	0.436	0.409
KS	0.480	0.486	0.481	0.478
AD	0.423	0.468	0.444	0.413



Analysis Using MVA-Based Approach

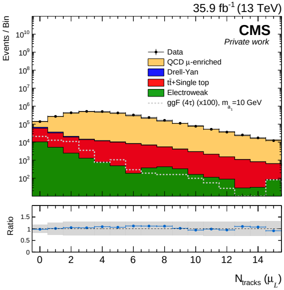
▶ Event Selection

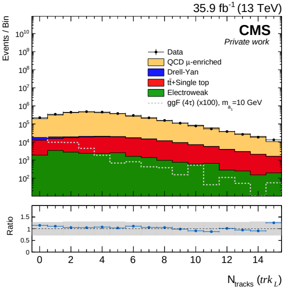
▶ Distributions of Input Variables

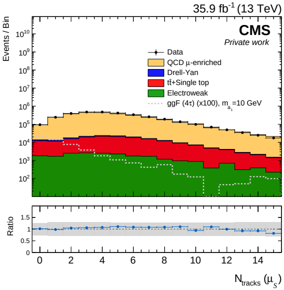
▶ Background Validation

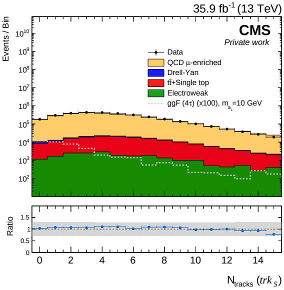
▶ Results

Event Selection

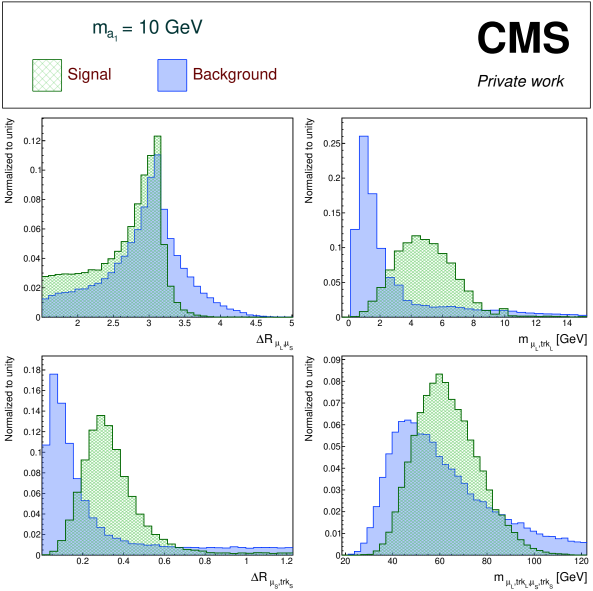








Distributions of Input Variables

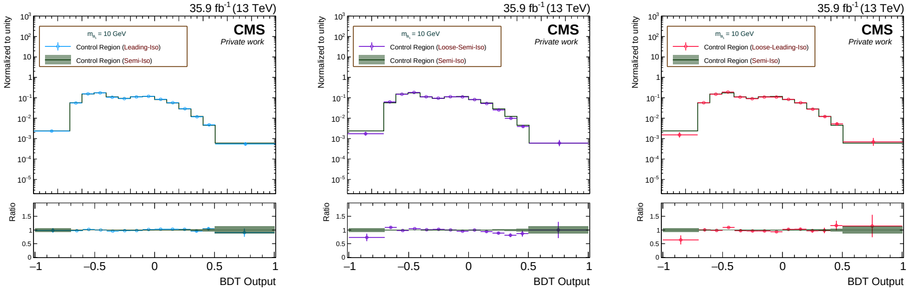


Background Modeling

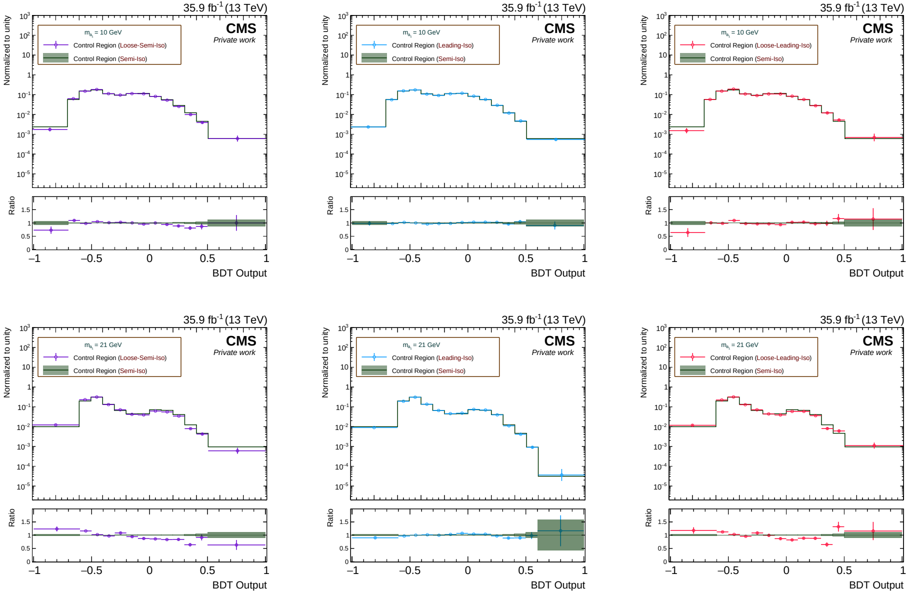
MVA-Based Approach

- estimation using a data-driven procedure
  - shape of multivariate distribution derived in control region “Semi-Iso”
  - validation and assessment of sys. unc. with additional control regions (closure test)

	Sideband region	μ_L and trk_L	μ_S and trk_S	Observed events
	Semi-Iso	$N_{\text{iso}} = 0$	$N_{\text{iso}} > 0,\ N_{\text{sig}} > 0$	106 592
		or		
		$N_{\text{iso}} > 0,\ N_{\text{sig}} > 0$	$N_{\text{iso}} = 0$	
↦	Leading-Iso	$N_{\text{iso}} = 0$	$N_{\text{iso}} > 0,\ N_{\text{sig}} > 0$	62 324
↦	Loose-Semi-Iso	$N_{\text{iso}} = 0$	$N_{\text{iso}} > 0,\ N_{\text{sig}} = 0$	13 998
		or		
		$N_{\text{iso}} > 0,\ N_{\text{sig}} = 0$	$N_{\text{iso}} = 0$	
↦	Loose-Leading-Iso	$N_{\text{iso}} = 0$	$N_{\text{iso}} > 0,\ N_{\text{sig}} = 0$	7 707



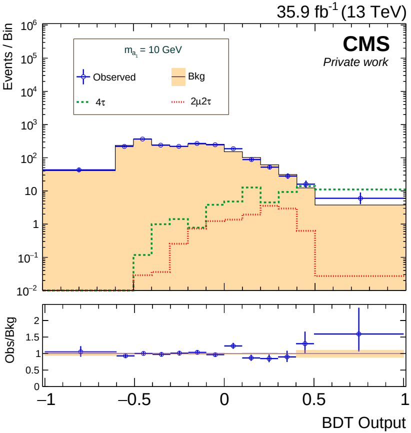
Background Validation

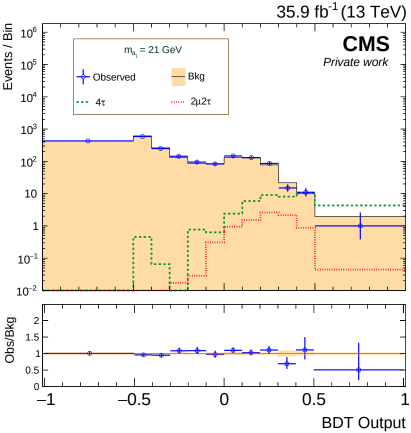


Results

MVA-Based Approach

	p-value			
Hypothesis H_0	background-only			
m_{a_1}	4 GeV	9 GeV	15 GeV	21 GeV
Sat.	0.137	0.240	0.571	0.707





The 2HDM+S

Types of 2HDMs

2HDM	up-type quarks	down-type quarks	charged leptons
Type-I	H_2	H_2	H_2
Type-II (MSSM-like)	H_2	H_1	H_1
Type-III (lepton-specific)	H_2	H_2	H_1
Type-IV (flipped)	H_2	H_1	H_2

Adding a Complex Scalar Singlet

- ✓ 2HDMs are assumed to be in the decoupling limit: h_{125} becomes very SM-like
- ✓ S couples to $H_{1,2}$ producing a small mixing
- ✓ 7 physical states: 2 charged, 3 CP-even and 2 CP-odd
- ✓ a_1 is the mostly-singlet-like pseudoscalar: $a_1 = \cos\theta_{a_1} S_I + \sin\theta_{a_1} A \qquad (\theta_{a_1} \ll 1)$

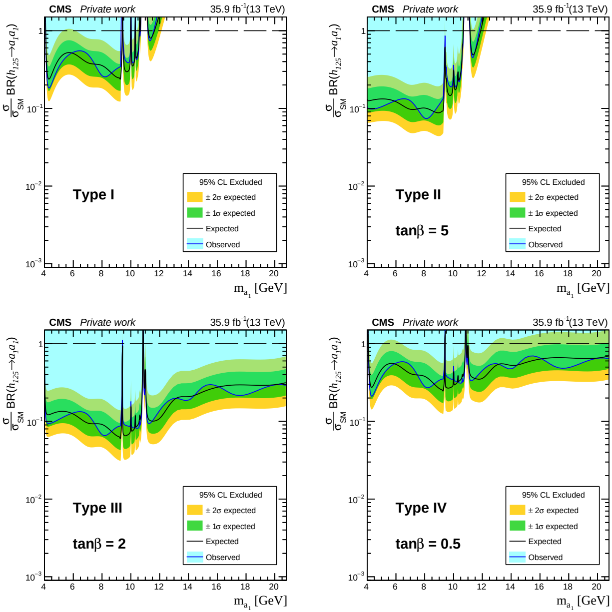
Couplings to Fermions ($\xi_{a_1} \sim \sin\theta_{a_1} \cdot \xi_A$)

A: 2HDM pseudoscalar

$$\tan\beta = \frac{v_2}{v_1}$$

Eigenstate	Coupling	Type-I	Type-II	Type-III	Type-IV
	ξ_A^u	$\cot\beta$	$\cot\beta$	$\cot\beta$	$\cot\beta$
A	ξ_A^d	$-\cot\beta$	$\tan\beta$	$-\cot\beta$	$\tan\beta$
	ξ_A^l	$-\cot\beta$	$\tan\beta$	$\tan\beta$	$-\cot\beta$

Projection of Limits on the Phase-Space $\sigma/\sigma_{SM}\,\mathcal{B}(h_{125} \rightarrow a_1 a_1)$ vs m_{a_1}



The SMEFT

▶ The Warsaw Basis

▶ Workflow for Generation of Effective Model

Warsaw Basis

$1: X^3$		$2: H^6$		$3: H^4 D^2$		$5: \psi^2 H^3 + \text{h.c.}$	
Q_G	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	Q_H	$(H^\dagger H)^3$	$Q_{H\Box}$	$(H^\dagger H)\Box(H^\dagger H)$	Q_{eH}	$(H^\dagger H)(\bar{l}_p e_r H)$
$Q_{\widetilde{G}}$	$f^{ABC} \widetilde{G}_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$			Q_{HD}	$\left(H^\dagger D_\mu H\right)^* \left(H^\dagger D_\mu H\right)$	Q_{uH}	$(H^\dagger H)(\bar{q}_p u_r \widetilde{H})$
Q_W	$\epsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$					Q_{dH}	$(H^\dagger H)(\bar{q}_p d_r H)$
$Q_{\widetilde{W}}$	$\epsilon^{IJK} \widetilde{W}_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$						

$4: X^2 H^2$		$6: \psi^2 X H + \text{h.c.}$		$7: \psi^2 H^2 D$	
Q_{HG}	$H^\dagger H\, G_{\mu\nu}^A G^{A\mu\nu}$	Q_{eW}	$(\bar{l}_p \sigma^{\mu\nu} e_r)\tau^I H W_{\mu\nu}^I$	$Q_{Hl}^{(1)}$	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{l}_p \gamma^\mu l_r)$
$Q_{H\widetilde{G}}$	$H^\dagger H\, \widetilde{G}_{\mu\nu}^A G^{A\mu\nu}$	Q_{eB}	$(\bar{l}_p \sigma^{\mu\nu} e_r) H B_{\mu\nu}$	$Q_{Hl}^{(3)}$	$(H^\dagger i \overleftrightarrow{D}_\mu^I H)(\bar{l}_p \tau^I \gamma^\mu l_r)$
Q_{HW}	$H^\dagger H\, W_{\mu\nu}^I W^{I\mu\nu}$	Q_{uG}	$(\bar{q}_p \sigma^{\mu\nu} T^A u_r)\widetilde{H}\, G_{\mu\nu}^A$	Q_{He}	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{e}_p \gamma^\mu e_r)$
$Q_{H\widetilde{W}}$	$H^\dagger H\, \widetilde{W}_{\mu\nu}^I W^{I\mu\nu}$	Q_{uW}	$(\bar{q}_p \sigma^{\mu\nu} u_r)\tau^I \widetilde{H}\, W_{\mu\nu}^I$	$Q_{Hq}^{(1)}$	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{q}_p \gamma^\mu q_r)$
Q_{HB}	$H^\dagger H\, B_{\mu\nu} B^{\mu\nu}$	Q_{uB}	$(\bar{q}_p \sigma^{\mu\nu} u_r)\widetilde{H}\, B_{\mu\nu}$	$Q_{Hq}^{(3)}$	$(H^\dagger i \overleftrightarrow{D}_\mu^I H)(\bar{q}_p \tau^I \gamma^\mu q_r)$
$Q_{H\widetilde{B}}$	$H^\dagger H\, \widetilde{B}_{\mu\nu} B^{\mu\nu}$	Q_{dG}	$(\bar{q}_p \sigma^{\mu\nu} T^A d_r) H\, G_{\mu\nu}^A$	Q_{Hu}	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{u}_p \gamma^\mu u_r)$
Q_{HWB}	$H^\dagger \tau^I H\, W_{\mu\nu}^I B^{\mu\nu}$	Q_{dW}	$(\bar{q}_p \sigma^{\mu\nu} d_r)\tau^I H\, W_{\mu\nu}^I$	Q_{Hd}	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{d}_p \gamma^\mu d_r)$
$Q_{H\widetilde{W}B}$	$H^\dagger \tau^I H\, \widetilde{W}_{\mu\nu}^I B^{\mu\nu}$	Q_{dB}	$(\bar{q}_p \sigma^{\mu\nu} d_r) H\, B_{\mu\nu}$	Q_{Hud} + h.c.	$i(\widetilde{H}^\dagger D_\mu H)(\bar{u}_p \gamma^\mu d_r)$

Warsaw Basis

$8:(\bar{L}L)(\bar{L}L)$	
Q_{ll}	$(\bar{l}_p\gamma_\mu l_r)(\bar{l}_s\gamma^\mu l_t)$
$Q_{qq}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{q}_s\gamma^\mu q_t)$
$Q_{qq}^{(3)}$	$(\bar{q}_p\gamma_\mu\tau^I q_r)(\bar{q}_s\gamma^\mu\tau^I q_t)$
$Q_{lq}^{(1)}$	$(\bar{l}_p\gamma_\mu l_r)(\bar{q}_s\gamma^\mu q_t)$
$Q_{lq}^{(3)}$	$(\bar{l}_p\gamma_\mu\tau^I l_r)(\bar{q}_s\gamma^\mu\tau^I q_t)$

$8:(\bar{R}R)(\bar{R}R)$	
Q_{ee}	$(\bar{e}_p\gamma_\mu e_r)(\bar{e}_s\gamma^\mu e_t)$
Q_{uu}	$(\bar{u}_p\gamma_\mu u_r)(\bar{u}_s\gamma^\mu u_t)$
Q_{dd}	$(\bar{d}_p\gamma_\mu d_r)(\bar{d}_s\gamma^\mu d_t)$
Q_{eu}	$(\bar{e}_p\gamma_\mu e_r)(\bar{u}_s\gamma^\mu u_t)$
Q_{ed}	$(\bar{e}_p\gamma_\mu e_r)(\bar{d}_s\gamma^\mu d_t)$
$Q_{ud}^{(1)}$	$(\bar{u}_p\gamma_\mu u_r)(\bar{d}_s\gamma^\mu d_t)$
$Q_{ud}^{(8)}$	$(\bar{u}_p\gamma_\mu T^A u_r)(\bar{d}_s\gamma^\mu T^A d_t)$

$8:(\bar{L}L)(\bar{R}R)$	
Q_{le}	$(\bar{l}_p\gamma_\mu l_r)(\bar{e}_s\gamma^\mu e_t)$
Q_{lu}	$(\bar{l}_p\gamma_\mu l_r)(\bar{u}_s\gamma^\mu u_t)$
Q_{ld}	$(\bar{l}_p\gamma_\mu l_r)(\bar{d}_s\gamma^\mu d_t)$
Q_{qe}	$(\bar{q}_p\gamma_\mu q_r)(\bar{e}_s\gamma^\mu e_t)$
$Q_{qu}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{u}_s\gamma^\mu u_t)$
$Q_{qu}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{u}_s\gamma^\mu T^A u_t)$
$Q_{qd}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{d}_s\gamma^\mu d_t)$
$Q_{qd}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{d}_s\gamma^\mu T^A d_t)$

$8:(\bar{L}R)(\bar{R}L)+\text{h.c.}$	
Q_{ledq}	$(\bar{l}_p^j e_r)(\bar{d}_s q_{tj})$

$8:(\bar{L}R)(\bar{L}R)+\text{h.c.}$	
$Q_{quqd}^{(1)}$	$(\bar{q}_p^j u_r)\epsilon_{jk}(\bar{q}_s^k d_t)$
$Q_{quqd}^{(8)}$	$(\bar{q}_p^j T^A u_r)\epsilon_{jk}(\bar{q}_s^k T^A d_t)$
$Q_{lequ}^{(1)}$	$(\bar{l}_p^j e_r)\epsilon_{jk}(\bar{q}_s^k u_t)$
$Q_{lequ}^{(3)}$	$(\bar{l}_p^j\sigma_{\mu\nu} e_r)\epsilon_{jk}(\bar{q}_s^k\sigma^{\mu\nu} u_t)$

Workflow for Generation of Effective Model