Status and prospects for Higgs exotic decays

Stefania Gori
Perimeter Institute for Theoretical Physics

on behalf of the conveners
Shikma Bressler (Weizmann institute, ATLAS)
Stefania Gori (Perimeter Institute, Theory)
Abdollah Mohammadi (Kansas State University, CMS)
Jessie Shelton (UIUC, Theory)

The 10th Workshop of the LHC Higgs Cross Section Working Group
CERN, July 16th 2015

Goals of the working group

Searches for new decay modes of the 125 GeV Higgs boson

Four main broad topics:

1. Flavor changing decays. Example: $h \to \tau\mu$
   Rare decays to mesons. Example: $h \to J/\Psi + \gamma$
(*) 2. Prompt decays without MET. Example: $h \to aa \to (b\bar{b})(\mu\bar{\mu})$
3. Prompt decays with MET. Example: $h \to \chi\chi \to 2\gamma + \mathrm{MET}$
4. Decays with displaced vertices. Example: $h \to g_B g_B \to 4f$

Previous meetings:

Kick-off Meeting, March 26-27, 2015
Workshop at Fermilab, May 21-22, 2015

(*) Discussed in great detail in the survey paper 1312.4992

Goals of the working group

Searches for new decay modes of the 125 GeV Higgs boson

Four main broad topics:

1. Flavor changing decays. Example: $h \to \tau\mu$
   Rare decays to mesons. Example: $h \to J/\Psi + \gamma$
2. Prompt decays without MET. Example: $h \to aa \to (b\bar{b})(\mu\bar{\mu})$
3. Prompt decays with MET. Example: $h \to \chi\chi \to 2\gamma + \mathrm{MET}$
4. Decays with displaced vertices. Example: $h \to g_B g_B \to 4f$

Constructive relations between theorists and experimentalists

Working mode:

- Motivations
- Benchmark scenarios for the interpretation of the results
- Feasibility studies

Theorists ⟷ Experimentalists

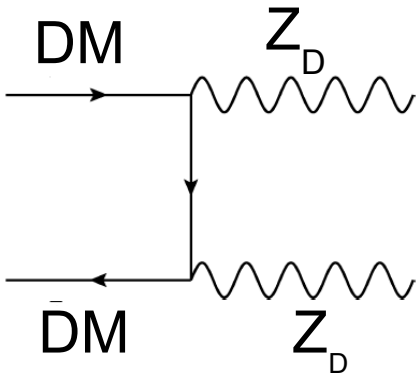
- Trigger capabilities
- Efficiency maps for low p_T objects
- Fiducial observables for displaced objects

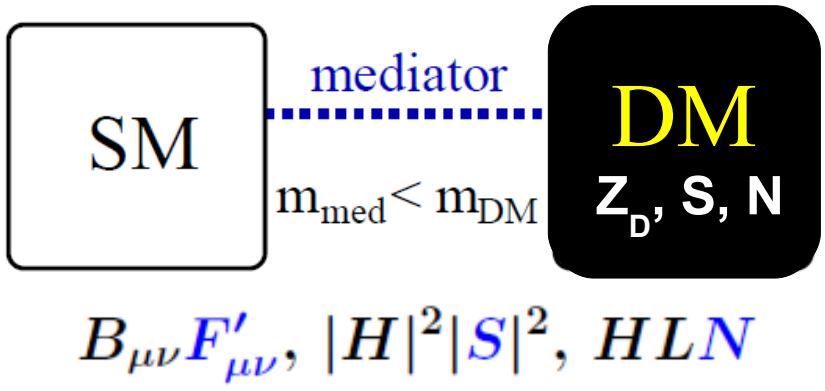
Review of motivations and models (1)

Theorists → Experimentalists

1. Dark Matter:

- WIMP miracle without an SU(2) WIMP
- DM lives in a dark sector, with additional singlet state particles



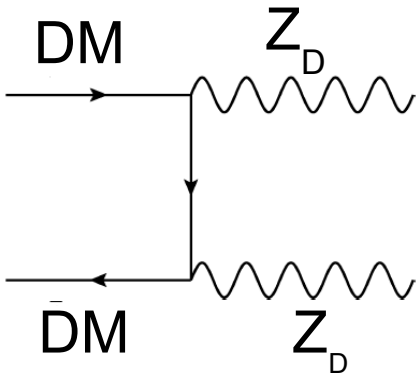


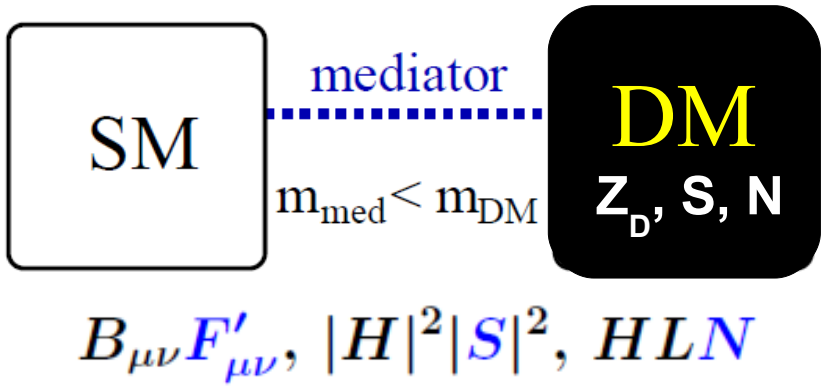
Review of motivations and models (1)

Theorists → Experimentalists

1. Dark Matter:

- WIMP miracle without an SU(2) WIMP
- DM lives in a dark sector, with additional singlet state particles





Decay topologies

h→ DM DM
h→ med med → 4f
h → NN→ 2f + MET or 2γ+MET

Review of motivations and models (2)

Theorists → Experimentalists

2. Hidden Naturalness:

The hierarchy (or little hierarchy) problem
addressed by particles not charged
under $SU(3)_c$, possibly completely neutral

3. Supersymmetry:

- MSSM:
low scale gauge mediation
with light Bino-like neutralino and gravitino

Benchmarks BP2, BP4, BP9
presented by Margarete yesterday

- NMSSM:
PQ-symmetric limit with a light singlino
R-symmetric limit with a light pseudoscalar

Review of motivations and models (2)

Theorists → Experimentalists

2. Hidden Naturalness:

The hierarchy (or little hierarchy) problem addressed by particles not charged under $SU(3)_c$, possibly completely neutral

Decay topologies

$h \rightarrow g_B\, g_B \rightarrow 4f$

typically displaced

3. Supersymmetry:

- MSSM:
low scale gauge mediation
with light Bino-like neutralino and gravitino

Benchmarks BP2, BP4, BP9
presented by Margarete yesterday

- NMSSM:
PQ-symmetric limit with a light singlino
R-symmetric limit with a light pseudoscalar

Decay topologies

$h \rightarrow \chi_2\chi_2 \rightarrow$ photons + MET

$h \rightarrow \chi_1\chi_1,\ \chi_2\chi_1,\ \chi_2\chi_2$
$\rightarrow$ MET + 2f, MET + 4f

$h \rightarrow aa \rightarrow 4f$

Tools

Our recommendations:

Theorists → Experimentalists

- Assume SM Higgs production cross sections and kinematics
- Higgs exotic branching ratios evaluated in simplified models

We aim to have Montecarlo tools for this (Madgraph NP models)

Nice factorization of the problem

Tools

Our recommendations:

Theorists → Experimentalists

- Assume SM Higgs production cross sections and kinematics
- Higgs exotic branching ratios evaluated in simplified models

We aim to have Montecarlo tools for this (Madgraph NP models)

Nice factorization of the problem

- We suggest a signature-based approach to searching for exotic decays

Example: A dark Z simplified model

MadGraph model:
http://insti.physics.sunysb.edu/~curtin/hahm_mg.html

Minimal model:

Free parameters: ε, m_{ZD} with the vector portal operator $\frac{\epsilon}{2\cos\theta}\hat{V}_{\mu\nu}\hat{B}^{\mu\nu}$

Exotic decays: $h \to ZZ_D \to 4f$

Next to minimal model:

Free parameters: ε, m_{ZD} (as in the minimal model), m_s, ζ
with Higgs portal operator $\zeta|S|^2|H|^2$

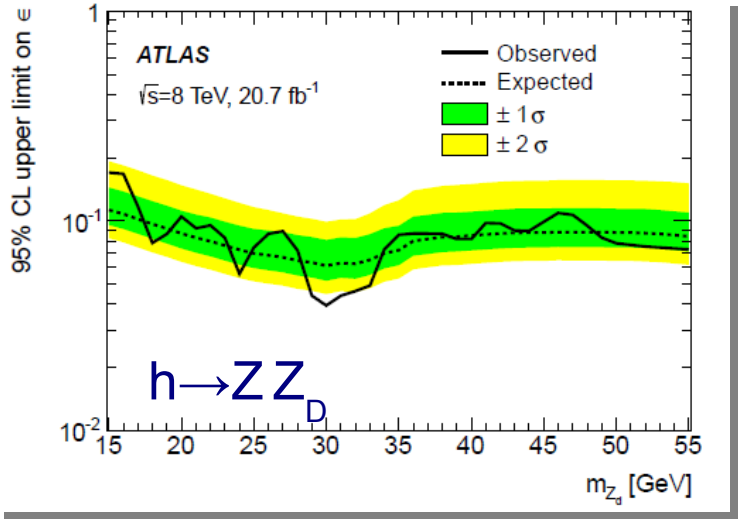
Exotic decays: $h \to Z_D Z_D \to 4f$

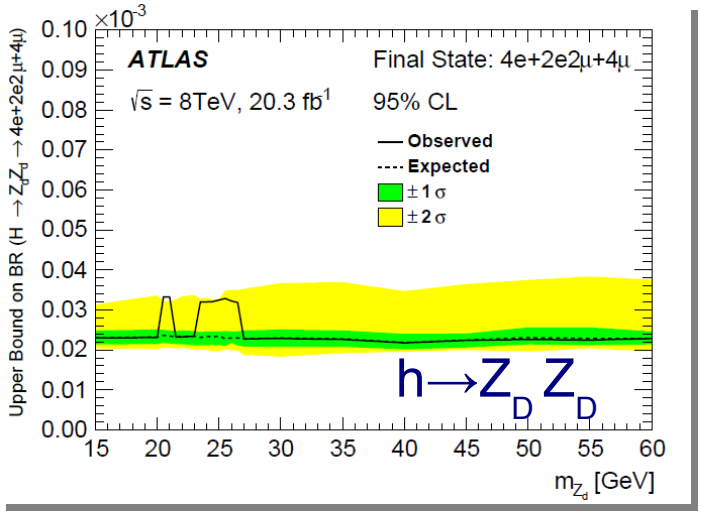
Curtin, Essig, SG, Shelton,1412.0018

Experimental searches since Jan. 2015

Increasing effort from the ATLAS and CMS collaborations

- ATLAS-CONF-2015-003
  - $h \rightarrow Z Z_D \rightarrow 4$ leptons
  - $h \rightarrow Z_D Z_D \rightarrow 4$ leptons

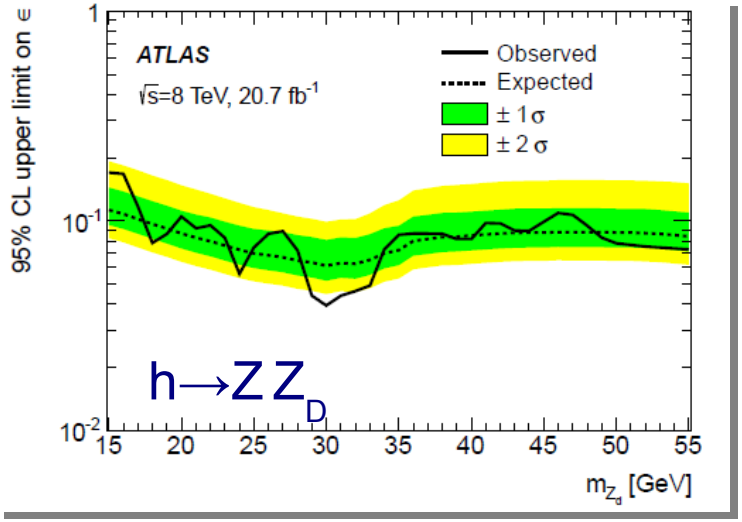


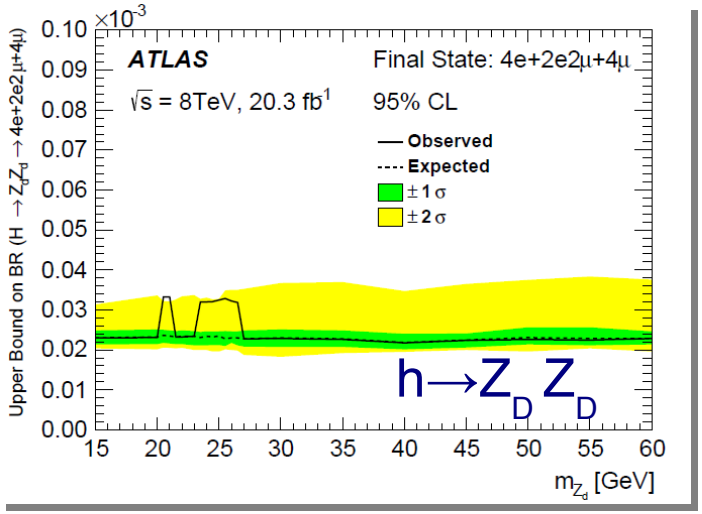


Experimental searches since Jan. 2015

Increasing effort from the ATLAS and CMS collaborations

- ATLAS-CONF-2015-003
  $h \to Z Z_D \to 4$ leptons
  $h \to Z_D Z_D \to 4$ leptons





- ATLAS-CONF-2015-004
  VBF Higgs, h → invisible

$$\mathrm{BR}(h \to \mathrm{inv}) < 0.29\,(0.35), \quad 95\%\ \mathrm{C.L.}$$

- CMS-PAS-HIG-14-038
  VBF Higgs, h → invisible

$$\mathrm{BR}(h \to \mathrm{inv}) < 0.57\,(0.40), \quad 95\%\ \mathrm{C.L.}$$

- ATLAS, 1504.04324
  Vh, V→ jets, h → invisible

$$\mathrm{BR}(h \to \mathrm{inv}) < 0.78\,(0.86), \quad 95\%\ \mathrm{C.L.}$$

Experimental searches since Jan. 2015

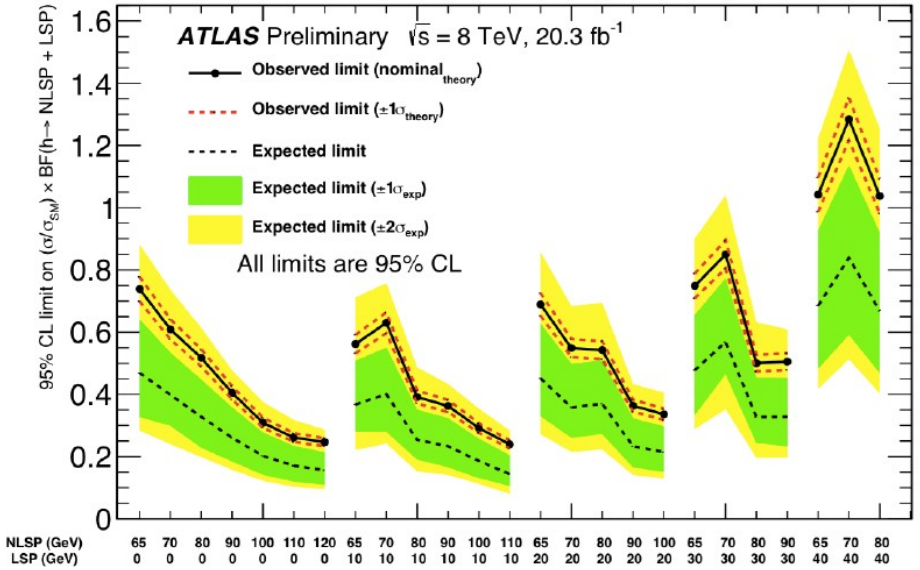
Increasing effort from the ATLAS and CMS collaborations

- ATLAS-CONF-2015-001

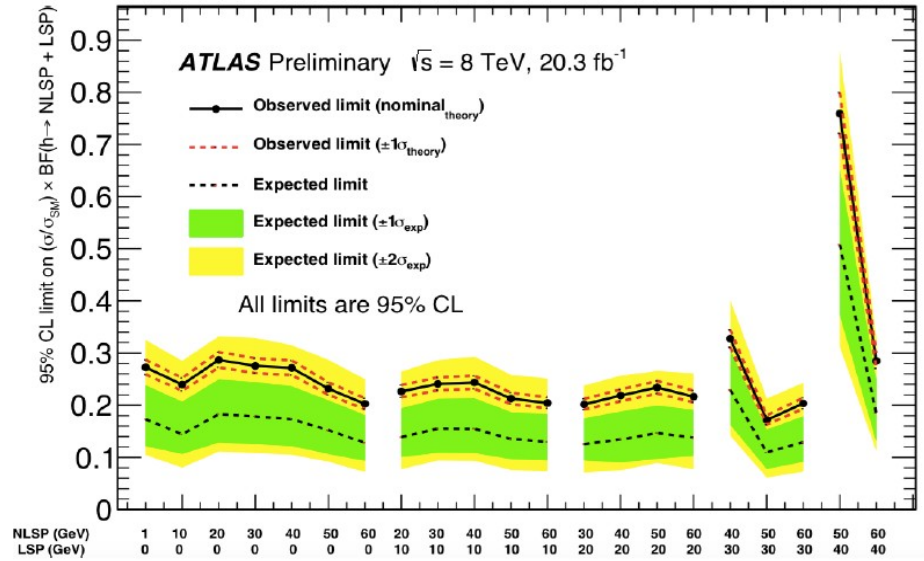
  VBF Higgs,

  $h \rightarrow N_2 N_1 \rightarrow$ 1 photon +MET

  $h \rightarrow N_2 N_2 \rightarrow$ 2 photons +MET



1-photon



2-photon

Experimental searches since Jan. 2015

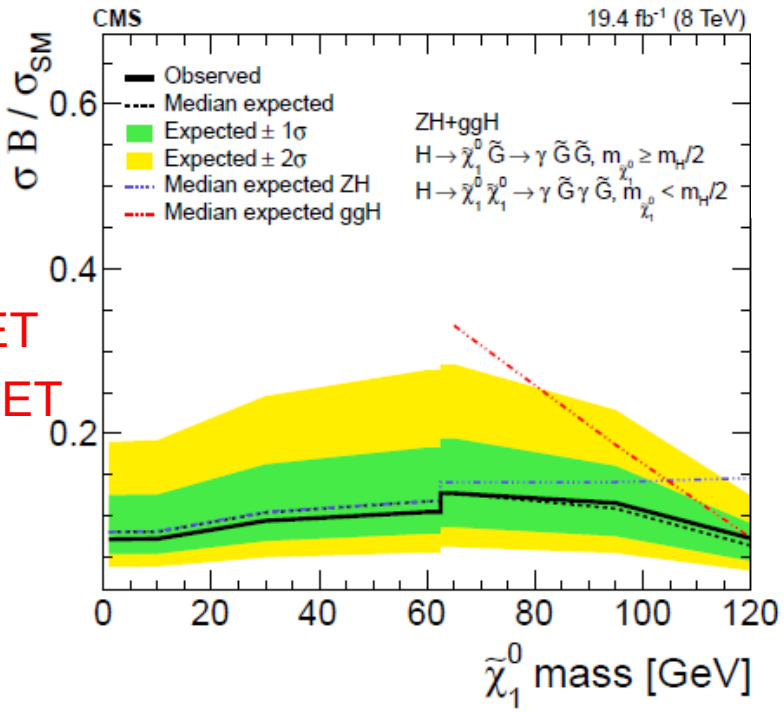
Increasing effort from the ATLAS and CMS collaborations

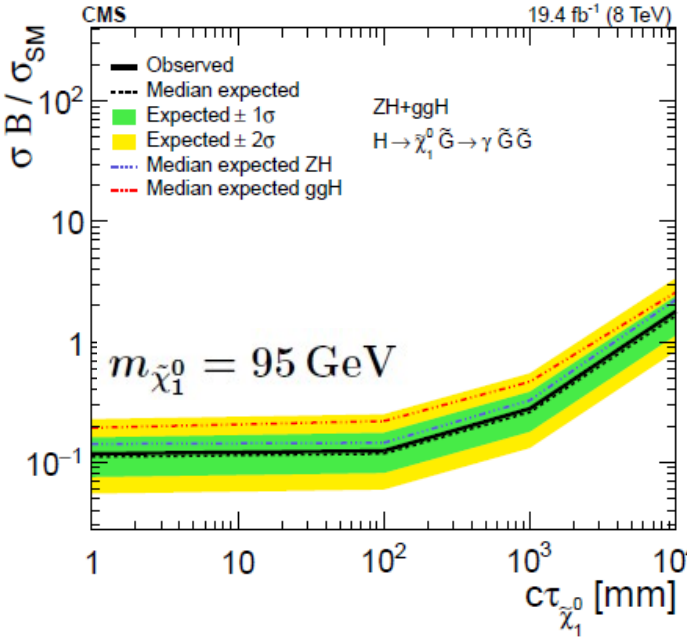
- ATLAS-CONF-2015-001

  VBF Higgs,
  $h \rightarrow N_2 N_1 \rightarrow$ 1 photon +MET
  $h \rightarrow N_2 N_2 \rightarrow$ 2 photons +MET

- CMS, 1507.00359

  gg Higgs and Zh,
  $h \rightarrow N_2 N_1 \rightarrow$ 1 photon +MET
  $h \rightarrow N_2 N_2 \rightarrow$ 2 photons +MET
  Eventually displaced





Experimental searches since Jan. 2015

Increasing effort from the ATLAS and CMS collaborations

- ATLAS-CONF-2015-001

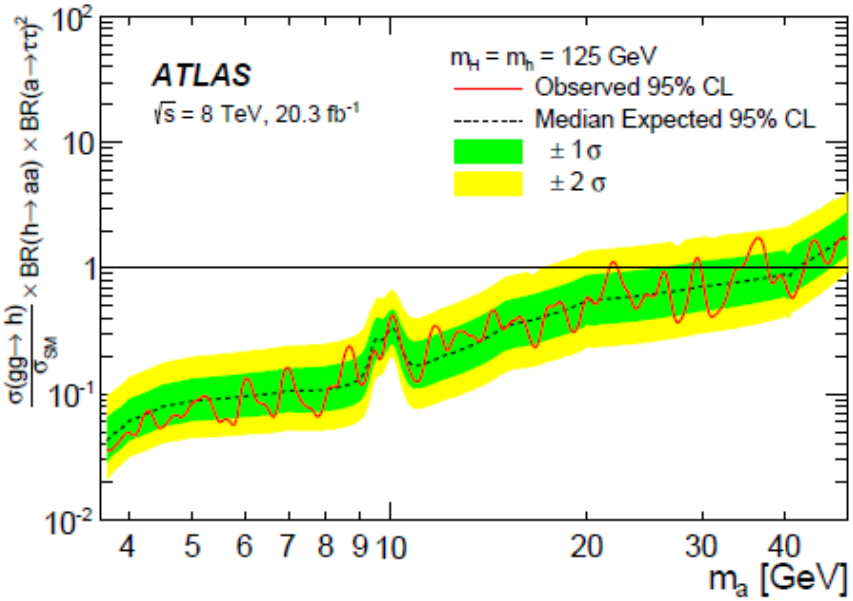
  VBF Higgs,
  $h \rightarrow N_2 N_1 \rightarrow$ 1 photon +MET
  $h \rightarrow N_2 N_2 \rightarrow$ 2 photons +MET

- CMS, 1507.00359

  gg Higgs and Zh,
  $h \rightarrow N_2 N_1 \rightarrow$ 1 photon +MET
  $h \rightarrow N_2 N_2 \rightarrow$ 2 photons +MET
  Eventually displaced

- ATLAS, 1505.01609

  $h \rightarrow aa \rightarrow \mu\mu\tau\tau$

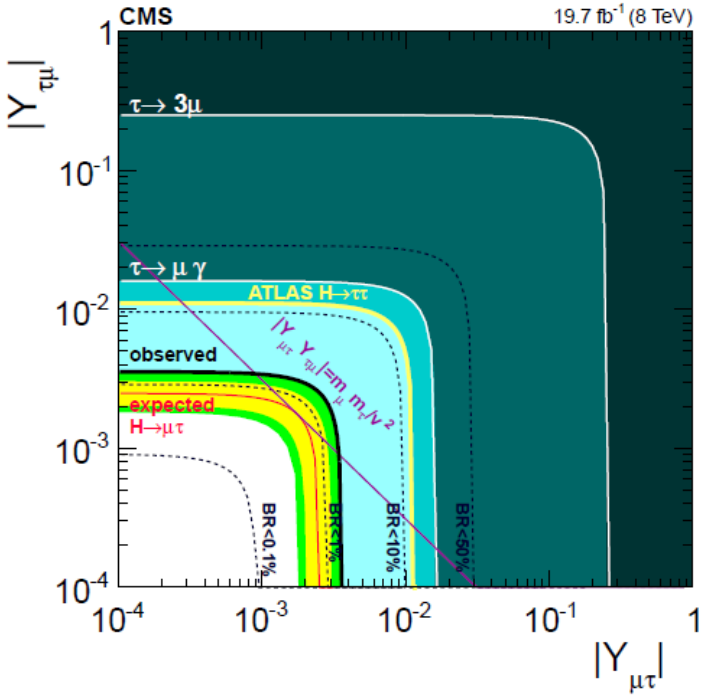


Experimental searches since Jan. 2015

Increasing effort from the ATLAS and CMS collaborations

- CMS, 1502.07400

  $h \to \mu\tau$



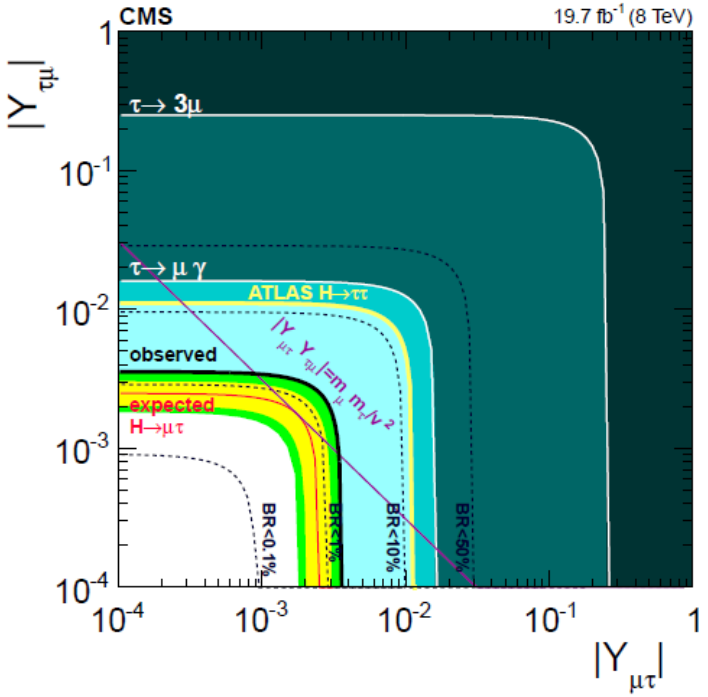
$$\mathrm{BR}(h \to \mu\tau) < 1.51\%,\ 95\%\ \mathrm{C.L.}$$
$$\mathrm{BR}(h \to \mu\tau) = (0.84^{+0.39}_{-0.37})\%$$

Experimental searches since Jan. 2015

Increasing effort from the ATLAS and CMS collaborations

- CMS, 1502.07400

  h → μτ



$$\mathrm{BR}(h \to \mu\tau) < 1.51\%, \ 95\%\ \mathrm{C.L.}$$
$$\mathrm{BR}(h \to \mu\tau) = (0.84^{+0.39}_{-0.37})\%$$

- ATLAS, 1501.03276

  h → J/ψ + photon

  h → ϒ (nS) + photon

$$\mathrm{BR}(h \to J/\Psi + \gamma) < 1.5\,(1.2) \times 10^{-3}, \ 95\%\ \mathrm{C.L.}$$
$$\mathrm{BR}(h \to \Upsilon(1S) + \gamma) < 1.3\,(1.8) \times 10^{-3}, \ 95\%\ \mathrm{C.L.}$$
$$\mathrm{BR}(h \to \Upsilon(2S) + \gamma) < 1.9\,(2.1) \times 10^{-3}, \ 95\%\ \mathrm{C.L.}$$
$$\mathrm{BR}(h \to \Upsilon(3S) + \gamma) < 1.3\,(1.8) \times 10^{-3}, \ 95\%\ \mathrm{C.L.}$$

SM (h → J/ψ + photon) is ~ 540 times larger than the bound

SM (h → ϒ (nS) + photon) is ~10^5 times larger than the bound

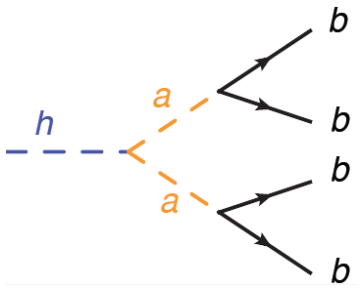
See also CMS 1507.03031

Bodwin et al. 1407.6695

Soft objects

The main question mark to keep in mind:

Soft objects coming from the decay of a (light) Higgs



$$p_T^b \lesssim 30\ \mathrm{GeV}$$

Experimentalists → Theorists

- How far down can we go in the reconstruction of soft objects?
Request for efficiency plots for several objects
- What about triggers? Public baseline trigger menu?
- For the most complicated modes, what is the most promising Higgs production mode to be used?

These questions are particularly relevant for the
- (some) decays into mesons
- decays to very well defined final states, eg. 4b
- semi-invisible decays, with MET

1. Rare decays to mesons

$$h \rightarrow \text{meson} + \gamma$$

- Action item: Facilitate interaction with Pythia authors to implement angular distributions in exclusive mesonic decays

- What about other rare meson decay modes like h → ϕ + γ (ϕ → K^+K^-)?
  Call for gamma + "tau-like jet" trigger, CMS

- Looking ahead to FTK (Track Trigger Upgrade) in ATLAS:
  track-based gamma+X options seem very promising

1. Rare decays to mesons

$$h \rightarrow \text{meson} + \gamma$$

- Action item: Facilitate interaction with Pythia authors to implement angular distributions in exclusive mesonic decays

- What about other rare meson decay modes like h → ϕ + γ (ϕ → K^+K^-)?
  Call for gamma + "tau-like jet" trigger, CMS

- Looking ahead to FTK (Track Trigger Upgrade) in ATLAS:
  track-based gamma+X options seem very promising

- Theory: model benchmarks for enhanced branching ratios, since in the SM:

$$\begin{aligned}
\mathrm{BR}(h \rightarrow J/\Psi + \gamma) &= 2.79 \times 10^{-6} \\
\mathrm{BR}(h \rightarrow \Upsilon(1S) + \gamma) &= 6.11 \times 10^{-10} \\
\mathrm{BR}(h \rightarrow \Upsilon(2S) + \gamma) &= 2.02 \times 10^{-9} \\
\mathrm{BR}(h \rightarrow \Upsilon(3S) + \gamma) &= 2.44 \times 10^{-9}
\end{aligned}$$

Bodwin et al. 1407.6695

- Multi-Higgs doublet models with Natural Flavor Conservation
- Giudice-Lebedev Model (+modifications),
- ... Bishara, et al. 1504.04022

See Bishara´s talk at the Fermilab Higgs exotic decay workshop

- What about the decays h → meson + Z (or W)? Isidori et al. 1305.0663

2. Decays without MET

Solid analysis in our survey on Higgs exotic decays
Curtin et al. 1312.4992

Example: $h \to ss \to 4f$

Presentation of the results:

Decay Mode $\mathcal{F}_i$	Projected/Current 2σ Limit on BR($\mathcal{F}_i$) 7/8 [14] TeV	Production Mode	quarks allowed: $\frac{\mathrm{BR}(\mathcal{F}_i)}{\mathrm{BR(non-SM)}}$	quarks allowed: Limit on $\frac{\sigma}{\sigma_{SM}} \cdot \mathrm{BR(non\text{-}SM)}$ 7/8 [14] TeV
$b\bar{b}b\bar{b}$	0.7^R [0.2^L]	W	0.8	0.9 [0.2]
$b\bar{b}\tau\tau$	> 1 [0.15^L]	V	0.1	> 1 [1]
$b\bar{b}\mu\mu$	$(2-7)\cdot 10^{-4\ T}$ [$(0.6-2)\cdot 10^{-4\ T}$]	G	3×10^{-4}	$0.6-1$ [$0.2-0.7$]
$\tau\tau\tau\tau$	$0.2-0.4^R$ [U]	G	0.005	$40-80$ [U]
$\tau\tau\mu\mu$	$(3-7)\cdot 10^{-4\ T}$ [U]	G	3×10^{-5}	$10-20$ [U]
$\mu\mu\mu\mu$	$1\cdot 10^{-4\ R}$ [U]	G	$1\cdot 10^{-7}$	1000 [U]

2. Decays without MET

Solid analysis in our survey on Higgs exotic decays
Curtin et al. 1312.4992

Example: $h \to ss \to 4f$

Presentation of the results:

Decay Mode $\mathcal{F}_i$	Projected/Current 2σ Limit on BR($\mathcal{F}_i$) 7/8 [14] TeV	Production Mode	quarks allowed: $\frac{\mathrm{BR}(\mathcal{F}_i)}{\mathrm{BR(non-SM)}}$	quarks allowed: Limit on $\frac{\sigma}{\sigma_{\mathrm{SM}}} \cdot \mathrm{BR(non\text{-}SM)}$ 7/8 [14] TeV
$bbbb$	$0.7^R\ [0.2^L]$	W	0.8	0.9 [0.2]
$b\bar{b}\tau\tau$	$> 1\ [0.15^L]$	V	0.1	> 1 [1]
$b\bar{b}\mu\mu$	$(2-7)\cdot 10^{-4\ T}$ $[(0.6-2)\cdot 10^{-4\ T}]$	G	3×10^{-4}	$0.6-1$ $[0.2-0.7]$
$\tau\tau\tau\tau$	$0.2-0.4^R$ [U]	G	0.005	$40-80$ [U]
$\tau\tau\mu\mu$	$(3-7)\cdot 10^{-4\ T}$ [U]	G	3×10^{-5}	$10-20$ [U]
$\mu\mu\mu\mu$	$1\cdot 10^{-4\ R}$ [U]	G	$1\cdot 10^{-7}$	1000 [U]

Run II triggers will be very important for assessing the feasibility/ goodness of these searches.
Under investigation

This can be read in terms of a bound on the operator $|H|^2|S|^2$ as a function of the mass m_s

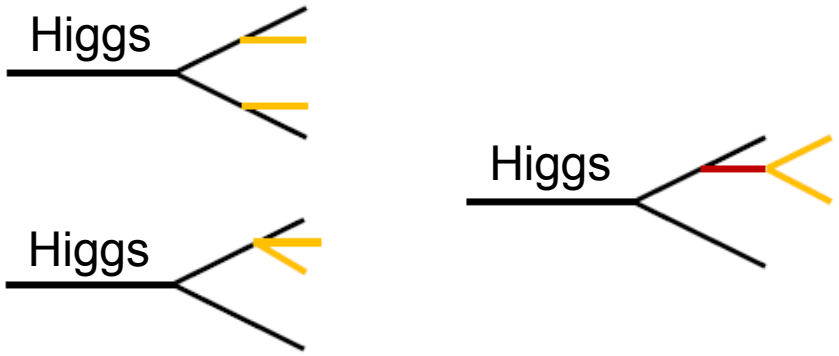
3. Semi-invisible decays

Theory: Need some more benchmark development

Probably the largest blind spot

Suggestion for a test case:

$$h \to 2\gamma + \text{MET}$$



Which production modes offer the best capabilities,
and how does this depend on the kinematics of the decay
and the trigger thresholds?

Working Point: Soft photons + Sizable MET

$gg \to h + \text{jets}$	h + VBF jets	Wh	$(Z \to \text{leptons})$ h
jet + MET $(+\gamma?)$	VBF jets + MET $(+1 \text{ or } 2\gamma?)$	$l\,(l + \gamma?)$	ll

Discussions with Matt Strassler

VBF + X trigger for 2016?

4. Decays with displaced vertices

Theorists → Experimentalists

- A generic set of signature arising from e.g.
  - theories with hidden naturalness
  - SUSY theories with long lived neutralinos

See
Craig et al. 1501.05310
Curtin et al. 1506.06141

4. Decays with displaced vertices

Theorists → Experimentalists

- A generic set of signature arising from e.g.
  - theories with hidden naturalness
  - SUSY theories with long lived neutralinos

See
Craig et al. 1501.05310
Curtin et al. 1506.06141

Experimentalists → Theorists

- Common issues shared with exotica searches.
Work needed in interpreting the displaced vertex analyses done in the context of the SUSY or exotic searches in terms of Higgs exotic decays.

Need of community standards for recasting displaced vertex searches.
Working out a set of fiducial observables that
can be used to present the results

Discussions with the ATLAS U-Washington group ongoing

- New analyses targeted to the Higgs are needed.

Conclusions and plans for YR4

- WG with signature based approach
  Use of simplified models/benchmark models

- Four sets of signatures:

1. Flavor changing decays & Rare decays to mesons
2. Prompt decays without MET.
3. Prompt decays with MET.
4. Decays with displaced vertices.

- The most difficult ones need a careful analysis of trigger capabilities.

Request for:
- Efficiency plots for several low p_T objects
- Public baseline trigger menu

- Most difficult decay modes:

What Higgs production modes offer the best capabilities?

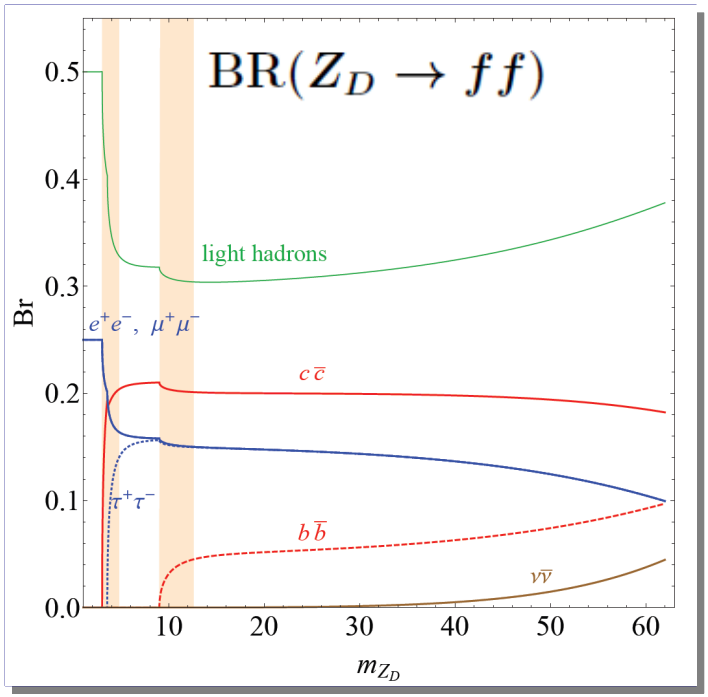
- Efficiency maps and fiducial observables of displaced decay modes

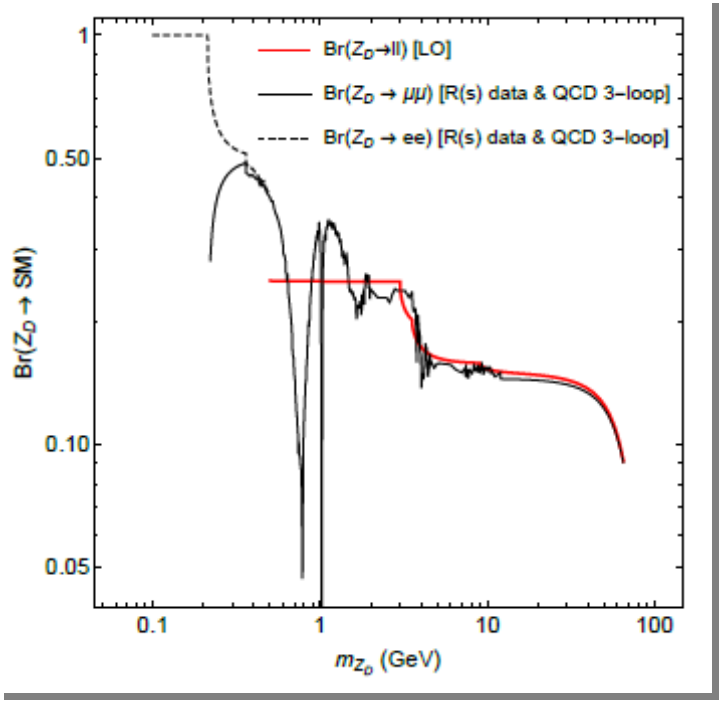
Probing dark Z gauge bosons

- Simplified model: $\mathcal{L} \supset \frac{\epsilon}{2\cos\theta}\hat{V}_{\mu\nu}\hat{B}^{\mu\nu} + \frac{1}{8}\langle S\rangle^2 g_D^2 (\hat{V}_\mu)^2 + \zeta |S|^2 |H|^2$

- Free parameters: m_{Z_D}, m_s, ϵ, $\kappa' \equiv \zeta \frac{m_h^2}{|m_h^2 - m_s^2|}$

- Z_D pheno: - Narrow resonance since $\Gamma_{Z_D} \propto \epsilon^2 m_{Z_D}$
  - Branching ratios well understood:





Dependence on m_{ZD}, only

Curtin, Essig, SG, Shelton, 1412.0018

UV-Complete models

- Beyond simplified models, we want to understand what more UV-complete models can tell us about Higgs exotic decays

- Examples:

  - NMSSM with an (approximate) R-symmetry (A_λ, $A_\kappa \longrightarrow 0$)

    Light pseudoscalar, mostly singlet like
    Possible sizable $h \longrightarrow aa$ branching ratios
    The pseudoscalar decays to fermions thanks to its (small) doublet component

  - NMSSM with an (approximate) PQ-symmetry (κ, $A_\kappa \longrightarrow 0$)

    Light pseudoscalar and neutralino (N_1), mostly singlet like
    The branching ratio for $h \longrightarrow aa$ is typically constrained to be rather small
    The second neutralino (mainly Bino) can also be light
    Large set of new signatures leading to MET: Eg. $h \longrightarrow N_1\ N_2$ with $N_2 \longrightarrow N_1\ s$
    or $N_2 \longrightarrow N_1\ \gamma$

  - MSSM with gauge mediation

    N_2 ~ Bino and N_1 ~ Gravitino, $h \longrightarrow N_2\ N_2$ with $N_2 \longrightarrow N_1\ \gamma$

Interplay with direct searches of the new states at the LHC

Our assumptions

1. The observed 125 GeV is SM-like

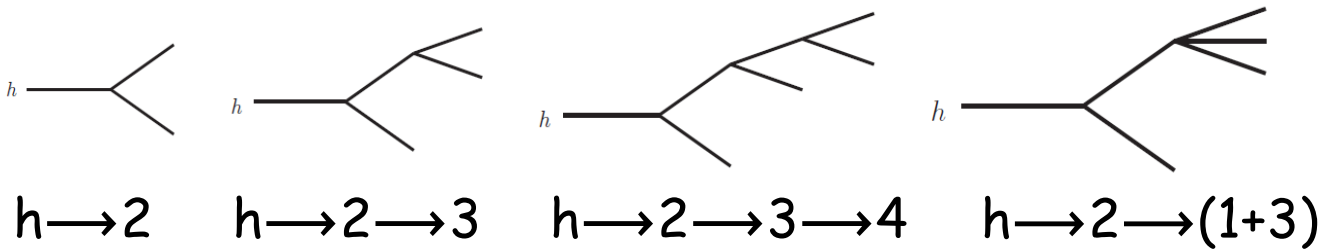
In particular its production cross section in the several channels is the one of the SM Higgs

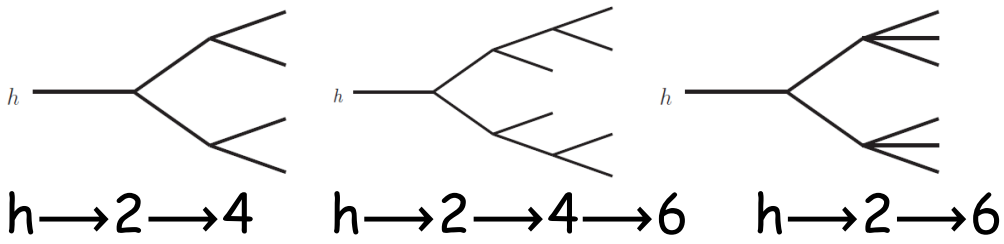
2. The Higgs decays promptly to new BSM particles that are either stable or promptly decaying

we do not consider rare or nonstandard decays to SM particles

3. The Higgs decay is a 2-body decay

3-body decays are possible, but require new light states with substantial coupling to h to overcome phase space suppression





$h \to MET$	$h \to Z_D Z_D \to 4l$
$h \to 4b$	$h \to \gamma + MET$
$h \to 2b2\tau$	$h \to 2\gamma + MET$
$h \to 2b2\mu$	$h \to 4l + MET$
$h \to 4\tau, 2\tau 2\mu$	$h \to 2l + MET$
$h \to 4j$	$h \to$ one lepton jet
$h \to 2\gamma 2j$	$h \to$ two lepton jets
$h \to 4\gamma$	$h \to bb + MET$
$h \to Z Z_D \to 4l$	$h \to \tau\tau + MET$