

Overview of Higgs exotic decays

Stefania Gori
University of Cincinnati

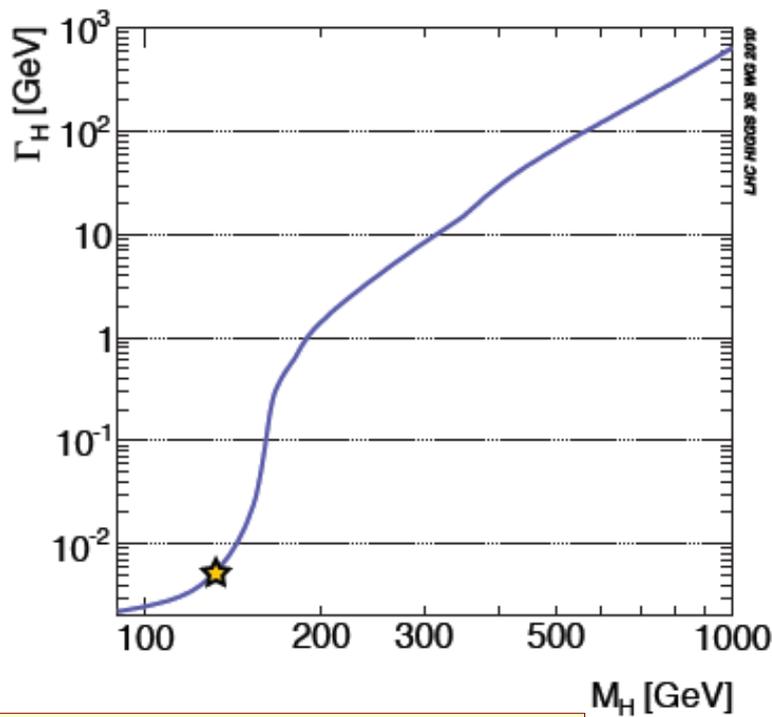
Higgs couplings 2016
SLAC, November 11th 2016

Why Higgs exotic decays?

1. We have discovered a light ($m_h < 2 m_W$) Higgs boson!

Very high sensitivity to New Physics

Even a small coupling to NP
produces a sizable BR for $h \rightarrow \text{NP NP}$



$$\Gamma_h^{\text{SM}}(125 \text{ GeV}) \sim 4.1 \text{ MeV}$$

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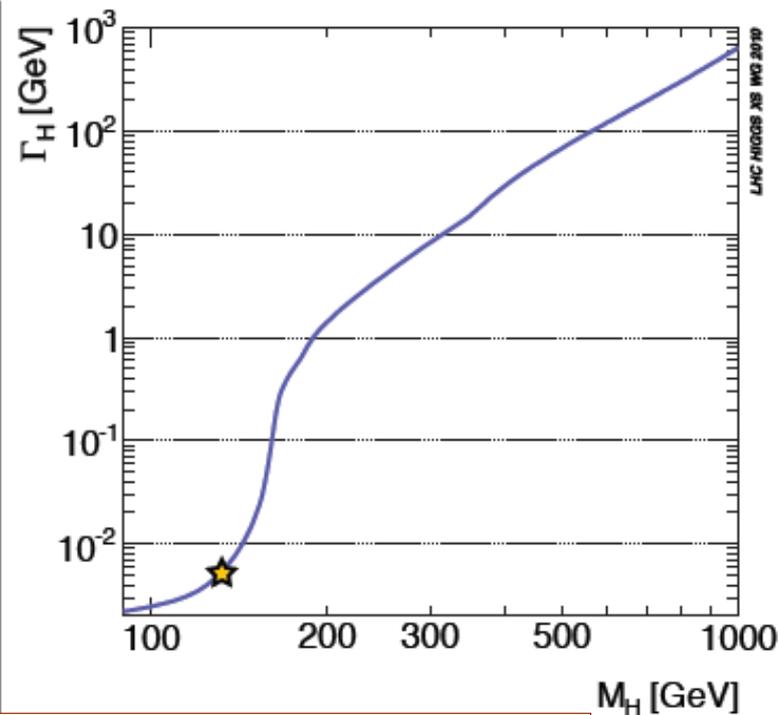
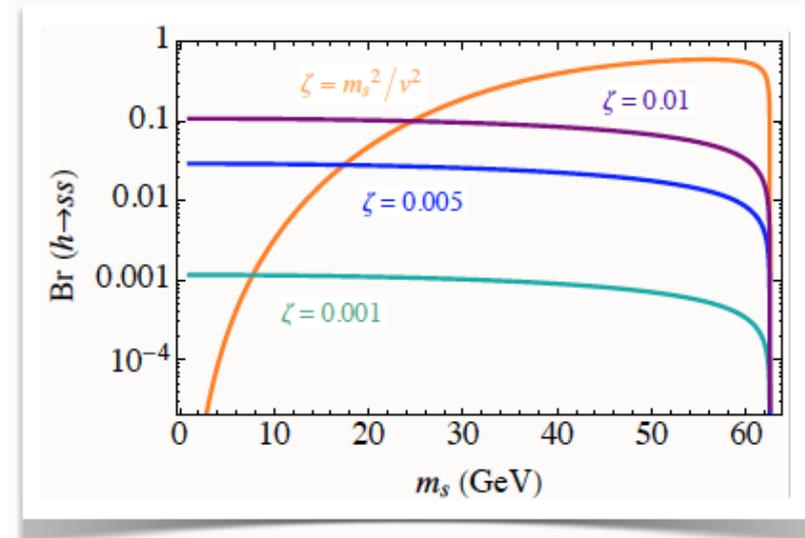
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Example: $V(H, s) \supset \zeta s^2 |H|^2$

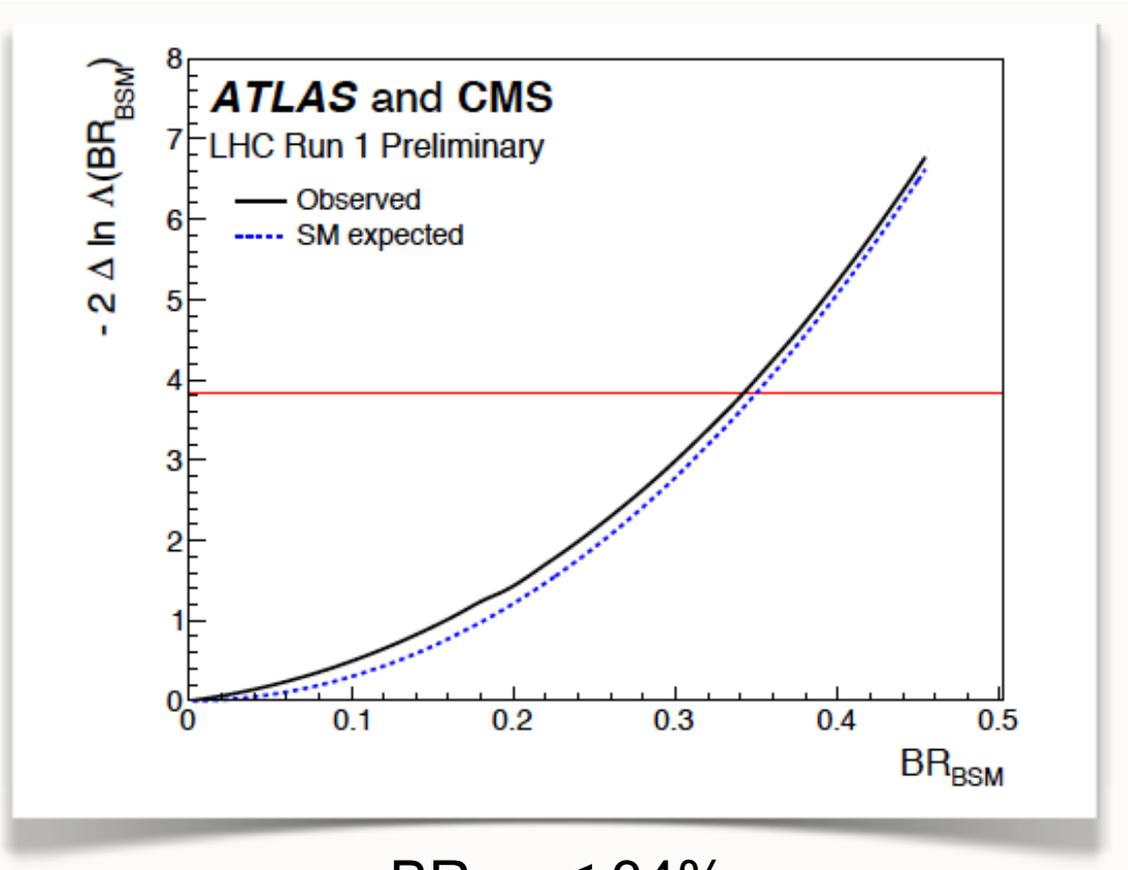
$\zeta = \mathcal{O}(0.01) \Rightarrow \text{Br}(h \rightarrow ss) = \mathcal{O}(10\%)$



$\Gamma_h^{\text{SM}}(125 \text{ GeV}) \sim 4.1 \text{ MeV}$

Why Higgs exotic decays?

2. Measurements of the Higgs width are NOT easy



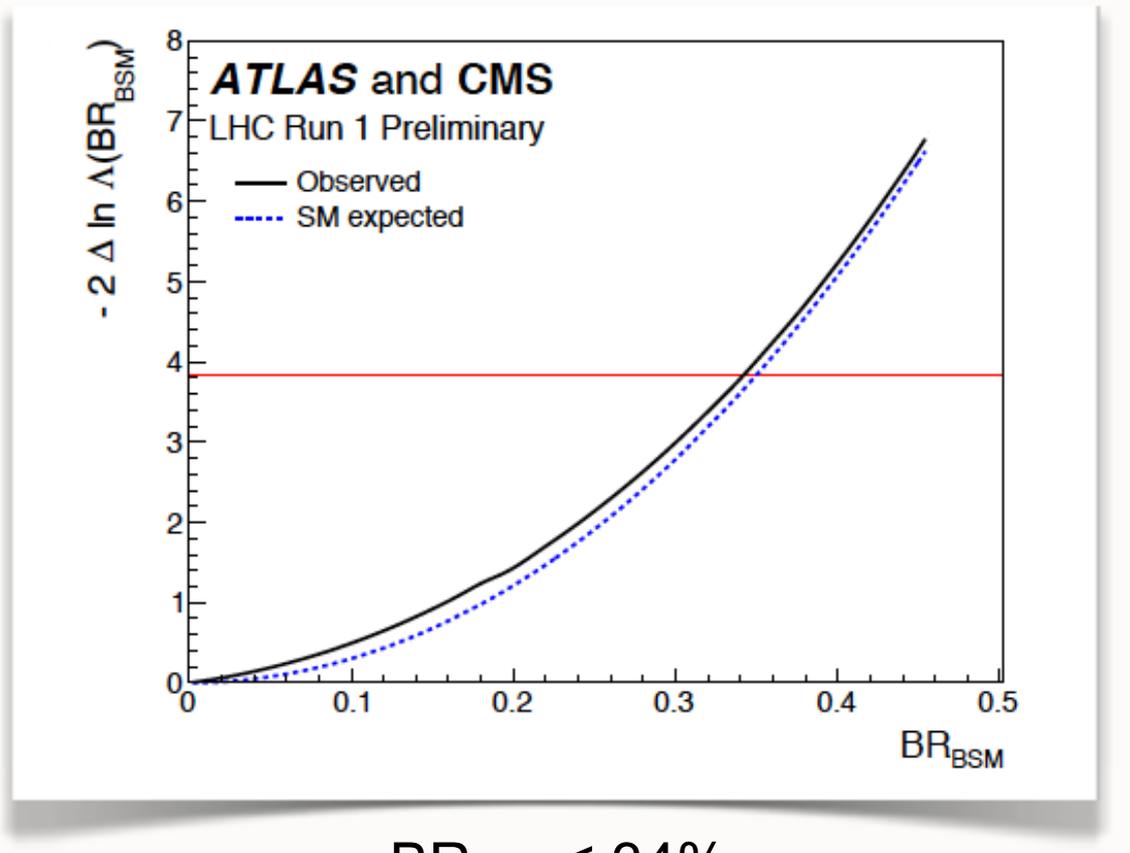
$$BR_{BSM} \leq 34\%$$

Future prospects:

~(5-10)% @ LHC with 3000 fb⁻¹

Why Higgs exotic decays?

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H off-shell measurements

$$\Gamma_h \leq 3.2 \Gamma_{H,SM} \quad (\text{CMS})$$

$$\leq 5.5 \Gamma_{H,SM} \quad (\text{ATLAS})$$

Talk by H. BRUN
yesterday

Line-shape

$$\Gamma_h \leq 1.7 \text{ GeV}$$

Interference in the di-photon spectrum

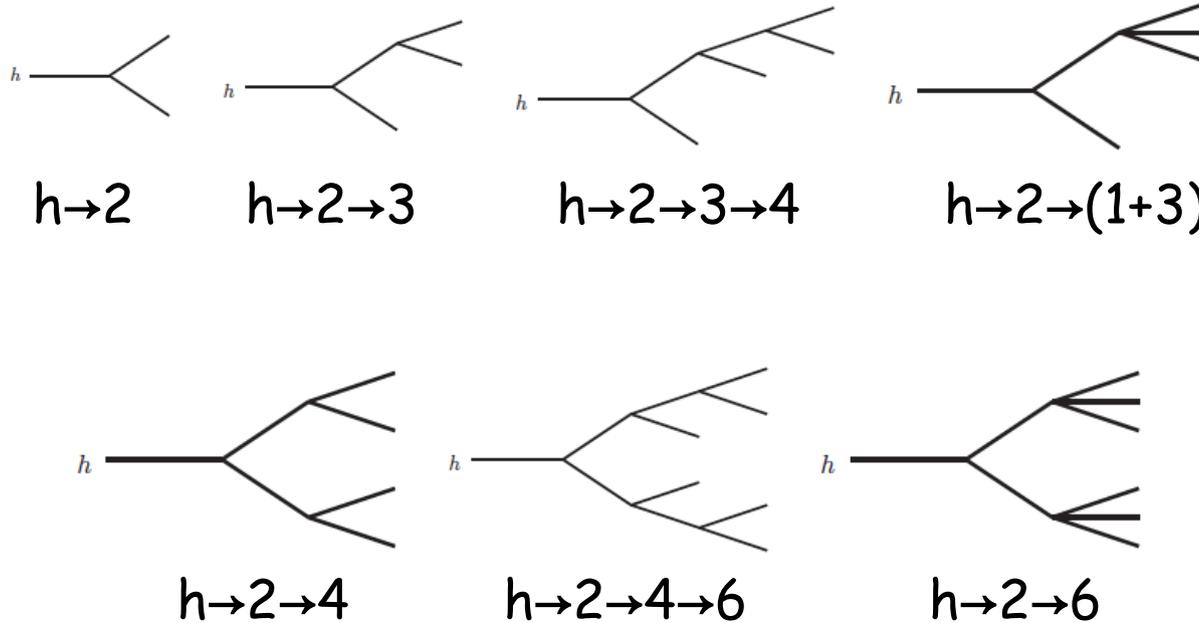
Dixon, Li,
1305.3854

$$\Gamma_h \leq 15 \Gamma_{SM} \quad (\text{@ HL-LHC})$$

Many possible decay modes

We need some organizing principle!

Signal topologies:



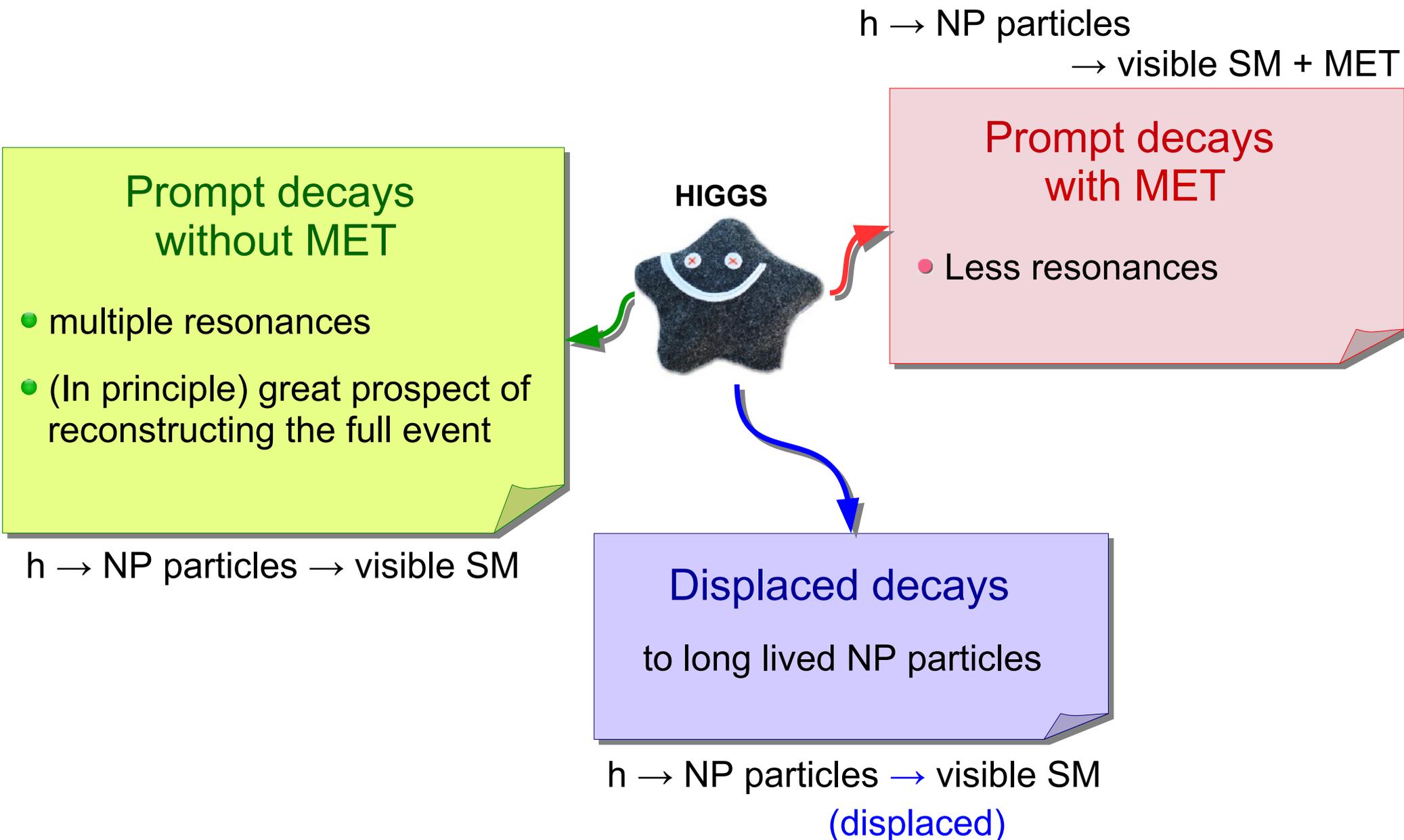
$h \rightarrow \text{NP} (\rightarrow \text{SM})$

Exotic decay
working group
of the LHCHSWG

Signature based approach, according to

- ✗ Multiplicity
- ✗ Feasibility of the experimental search
- ✗ Theory motivations/(a bit of) theory bias

(feasible) Signatures

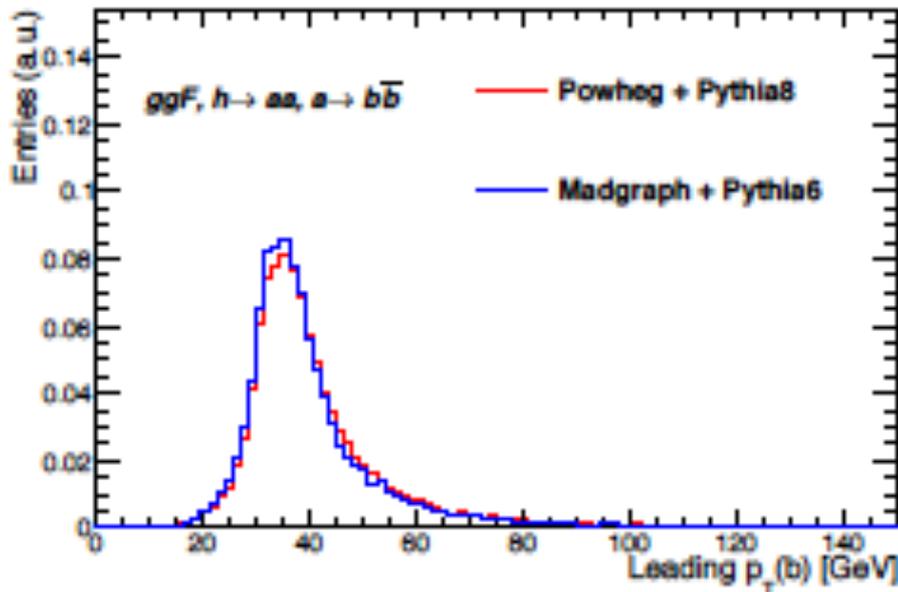


From an experimental perspective...

The program for Higgs exotic decays needs a particular effort in keeping low thresholds (starting from triggers)

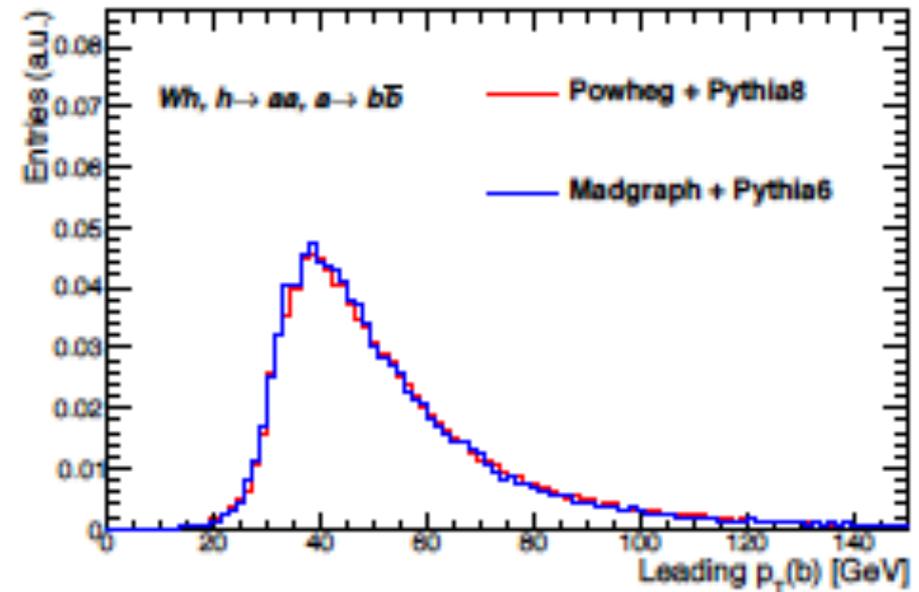
Case study: $h \rightarrow \color{red}{XX} \rightarrow \color{blue}{2Y2Y'}$
NP particles SM particles

Gluon fusion



$m_X = 60$ GeV

Wh associated production



$m_X = 60$ GeV

From the Yellow report 4

Target: probing neutral/dark particles

Theory Motivations:

many motivated BSM models predict the existence of **light dark**
(= neutral under the SM gauge symmetries) **particles**

- ✖ Theories of neutral naturalness
- ✖ Extensions of the MSSM (NMSSM, ...)
- ✖ Models of EW baryogenesis
- ✖ Hidden valley models
- ✖ Dark sector models for Dark Matter

Typically hidden to the LHC,
because not copiously produced

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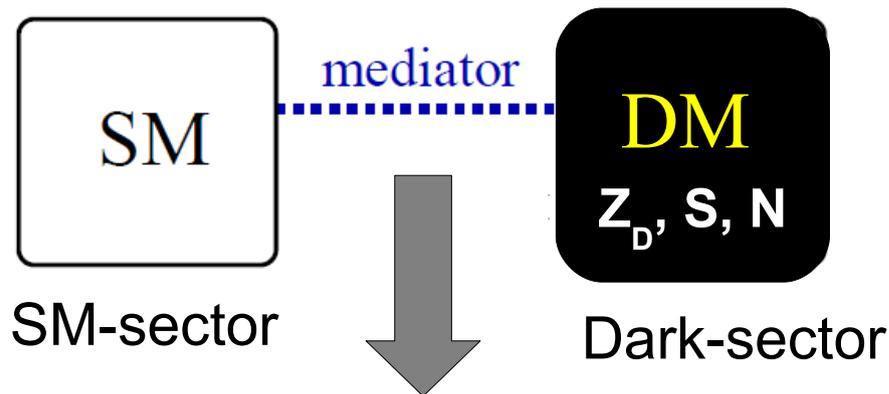
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From the bottom up:



Only a few operators can connect the two sectors:

$$B_{\mu\nu}F'_{\mu\nu}, |H|^2|S|^2, HLN$$

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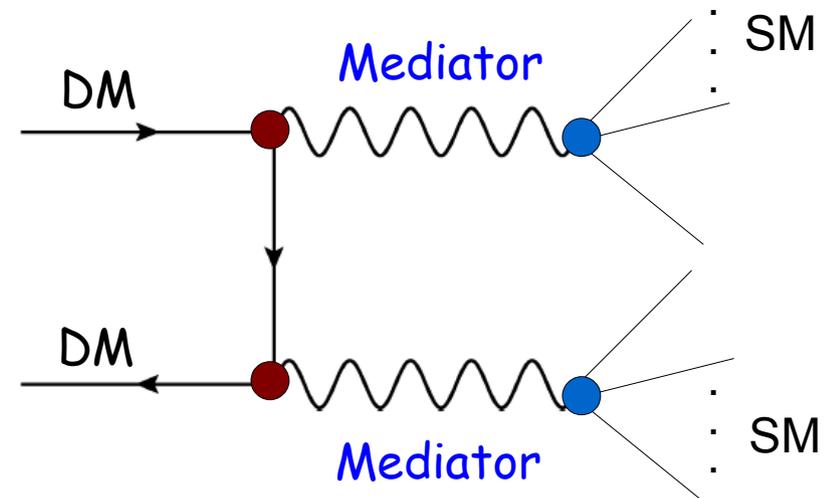
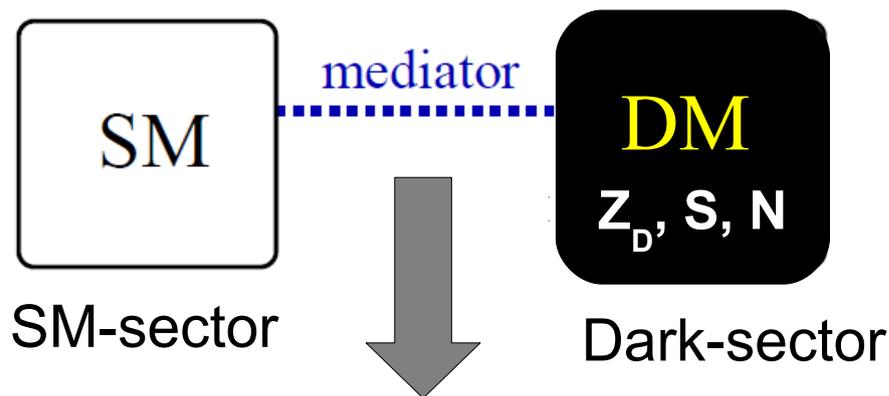
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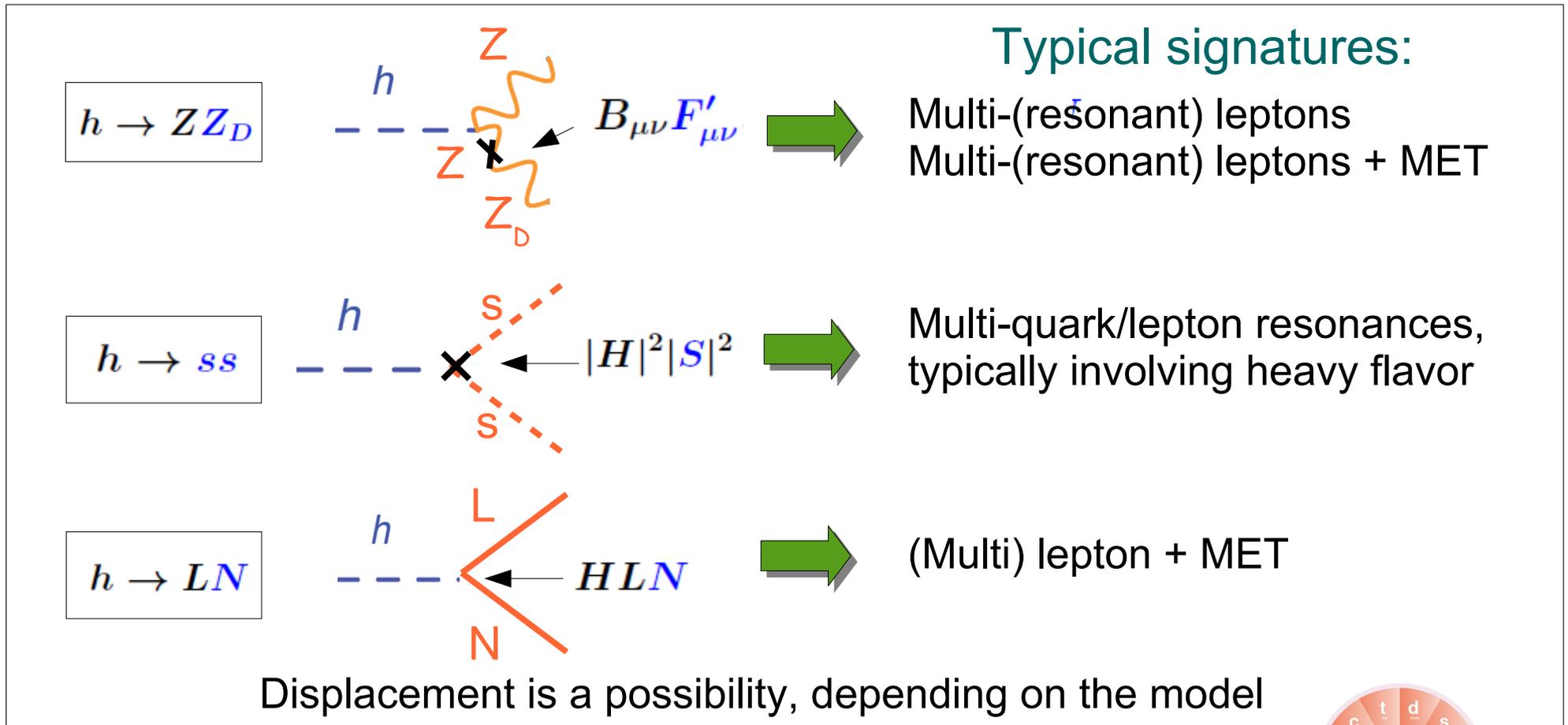
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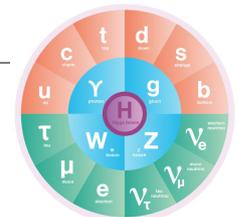
Simplified models for Higgs exotic decays

We can write down only a **limited set of renormalizable operators** connecting SM particles to new dark particles:

$$B_{\mu\nu}F'_{\mu\nu}, |H|^2|S|^2, HLN$$



In general, nature does not guarantee minimality
Crucial to cast a wide net of searches!



The Higgs portal

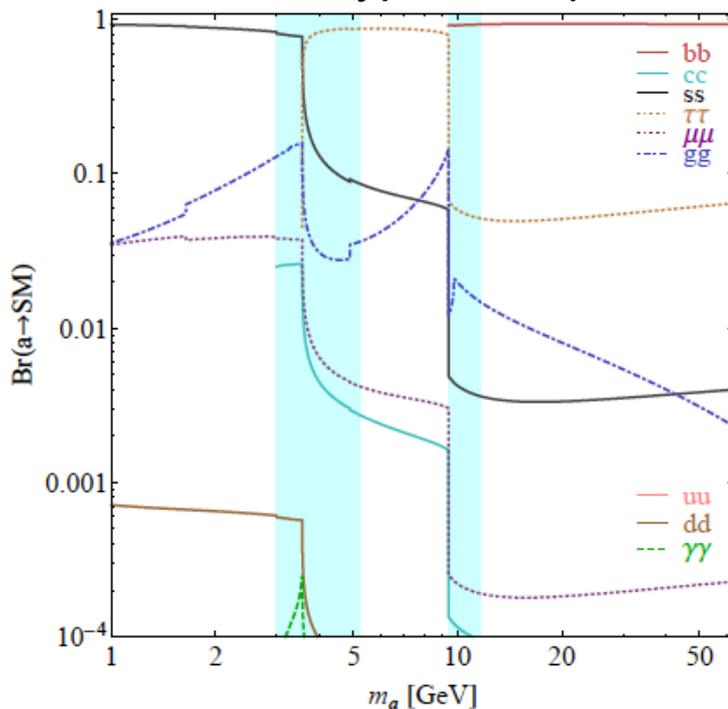
An (incomplete) set of models:

- ✗ Neutral naturalness models (twin Higgs),
- ✗ Relaxion models
- ✗ Models for EW baryogenesis
- ✗ NMSSM (R-symmetric or PQ symmetric limit)

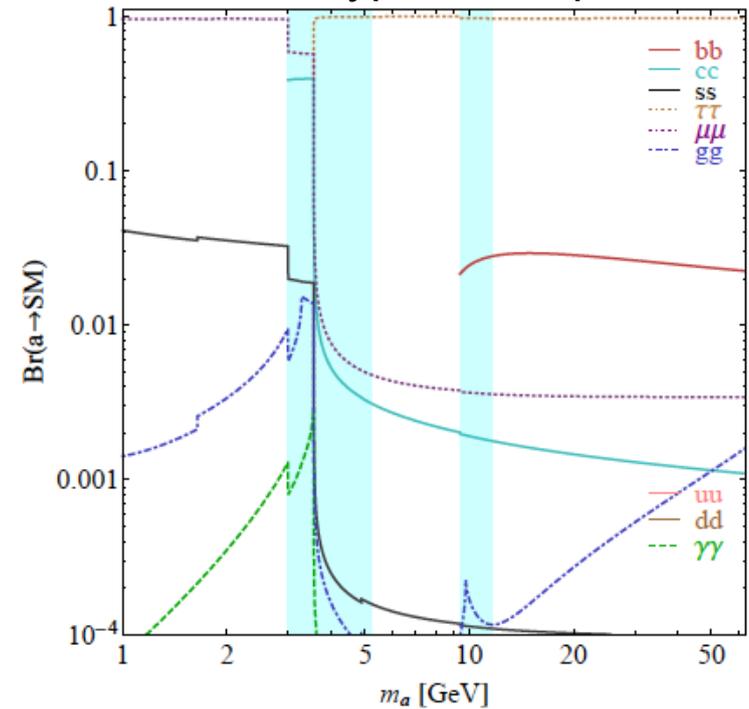
$$|H|^2 |S|^2$$

From the bottom up: $h \rightarrow ss$ determined by the Higgs portal coupling

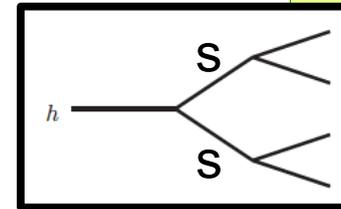
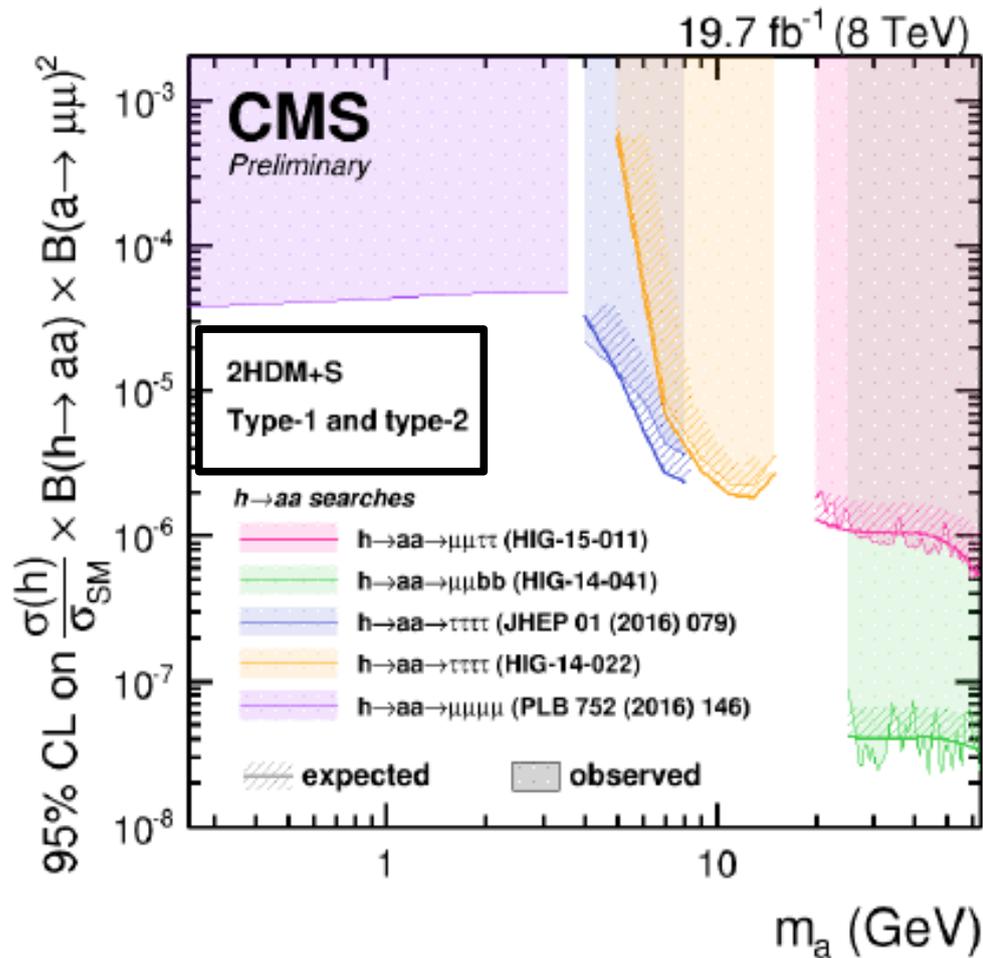
2HDM type II, $\tan\beta = 5$



2HDM type III, $\tan\beta = 5$



Several searches for this topology

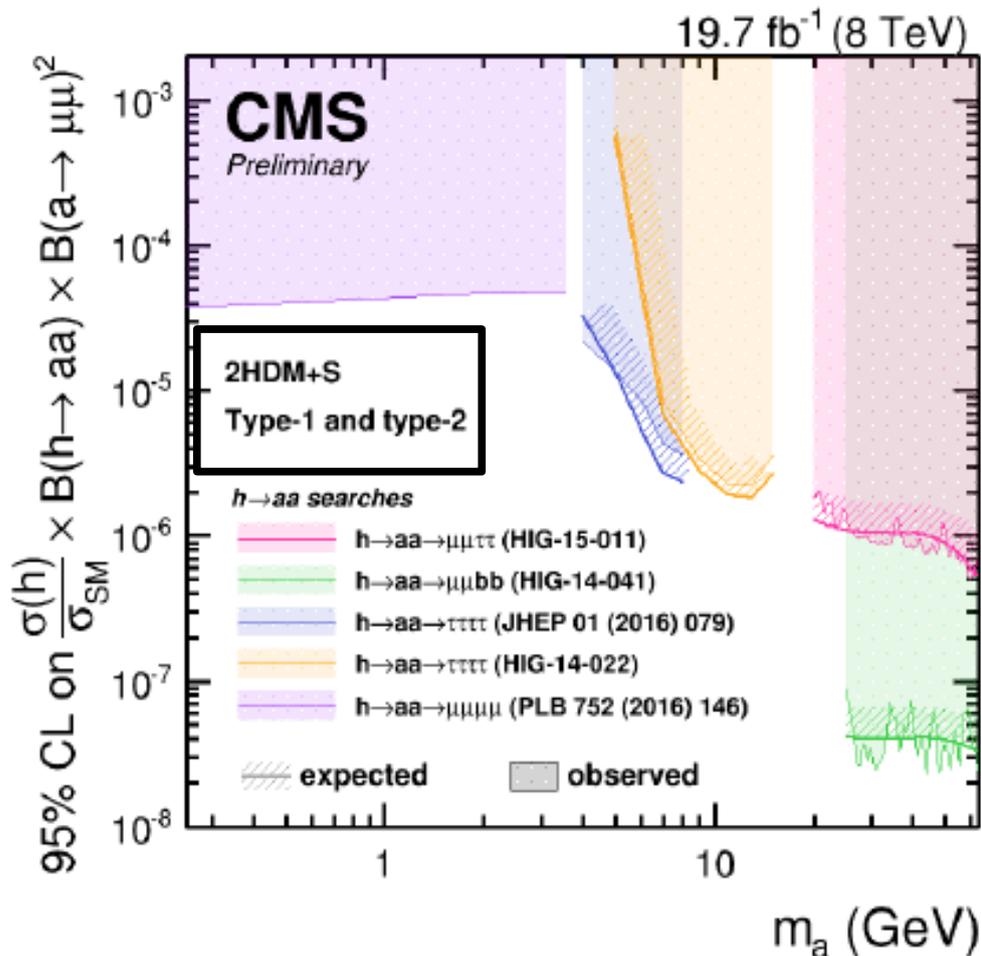


Prompt decays
without MET

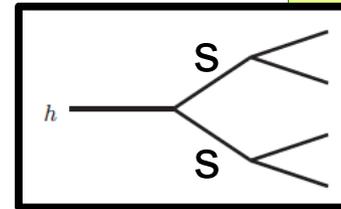
$b b b b$		
$b b \tau \tau$	$\tau \tau \tau \tau$	
$b b \mu \mu$	$\tau \tau \mu \mu$	$\mu \mu \mu \mu$

+ model independent presentation of results in terms of $BR(h \rightarrow ss \rightarrow 2f 2f')$

Several searches for this topology



+ model independent presentation of results in terms of $BR(h \rightarrow ss \rightarrow 2f 2f')$



Prompt decays without MET

bbbb		
bbtau tau	tau tau tau tau	
bb mu mu	tau tau mu mu	mu mu mu mu

What is left to be done for a full coverage?

- ✗ 2b2tau
- ✗ Comparative analysis of different Higgs production modes
- ✗ Coverage of the full mass range
- ✗ Diifferent masses: $h \rightarrow s_1 s_2$

The "generalized" neutrino portal

An (incomplete) set of models:

- ✗ Gauge mediated models with light Bino-LSP
- ✗ NMSSM (PQ symmetric limit)
- ✗ Models with light right-handed neutrinos
- ✗ DM models (inelastic DM, ...)



Not yet a good coverage of simplified models to be used for the experimental interpretation.

(future work for the exotic group of the LHCHSWG)

Signatures typically involve MET

● totally invisible decay mode:

Several searches for Higgs produced

- in association with jets
- VBF
- gauge boson

Talks by
Sridhara Dasu (today) &
Nick Smith (yesterday)

● semi-invisible decay modes

Semi-invisible decay modes

Much less is known...

$$h \rightarrow N_2 N_1 \rightarrow 1 \text{ photon} + \text{MET}$$

$$h \rightarrow N_2 N_2 \rightarrow 2 \text{ photons} + \text{MET}$$

ATLAS-CONF-2015-001,
CMS,1507.00359

Searches are more challenging

Prompt decays
with MET

In the case of a discovery,
it is more complicated to test
if the signature is
coming from the Higgs

Semi-invisible decay modes

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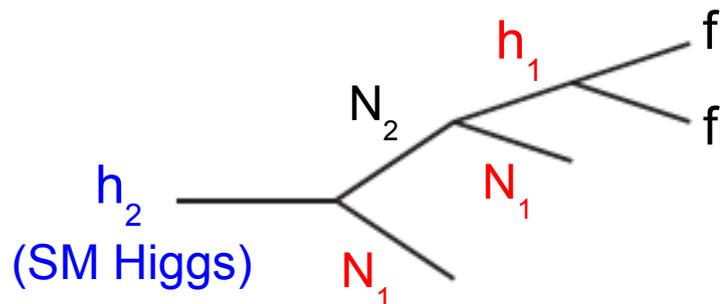
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A "theorist wish list"

One interesting model generating several semi-invisible signatures:
Approximately Peccei Quinn symmetric NMSSM (h_1, a_1, N_1 automatically light)



Scenario initially motivated
by DM anomalies
(CoGeNT and DAMA/LIBRA)

Draper et al, 1009.3963

Signatures: $2b + \text{MET}$, $2\mu + \text{MET}$, $2\tau + \text{MET}$, ...

Typically collimated

Huang, Liu, Wang,
Yu, 1407.0038

Theory motivations for displaced signatures

Meta-stable particles with proper lifetimes $c\tau \geq \mu\text{m}$ arise in a large variety of BSM scenarios:

1. Dark photon models with small kinetic mixing (signatures with multi-leptons)
2. Neutral naturalness (signatures with heavy flavors)
3. Gauge mediated SUSY models (signatures with photons)

Displaced decays

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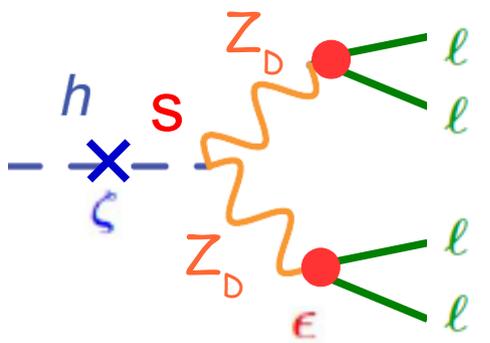
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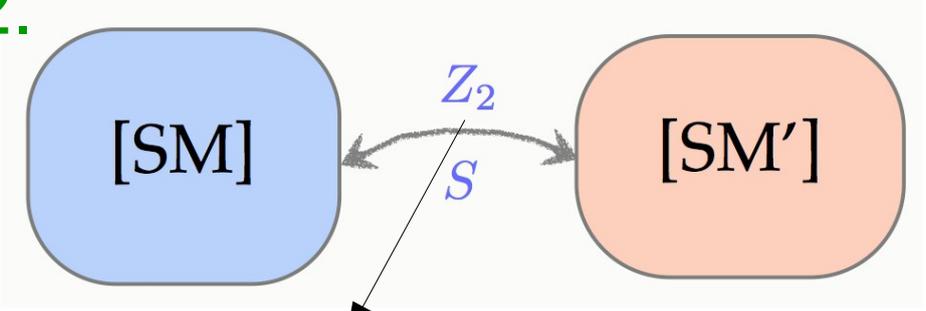
1. Dark photon models

$$\frac{\epsilon}{2 \cos \theta} \hat{V}_{\mu\nu} \hat{B}^{\mu\nu}, \quad \zeta |S|^2 |H|^2$$



If ϵ is small, Z_D decays with some displacement

2.



Not commuting with the SM color

Hidden QCD with hidden glueballs, bottomonium, ...

Examples:

Folded SUSY, Twin Higgs, Fraternal twin Higgs

Burdman et al, 0609152

Chacko et al, 0506256

Craig et al, 1501.05310

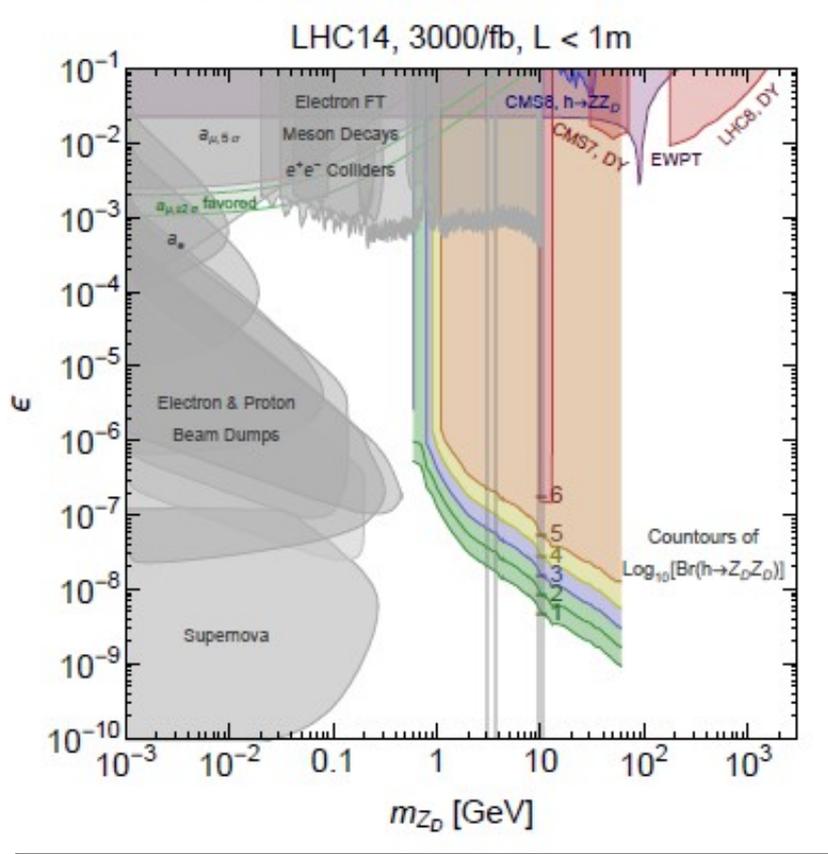
What are the available searches?

A few dedicated searches are available

So far, the main focus has been on leptons

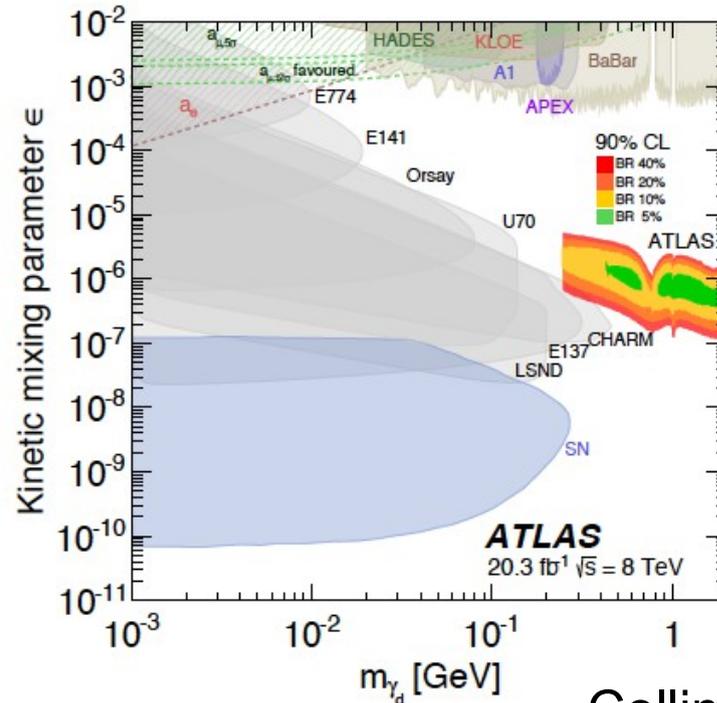
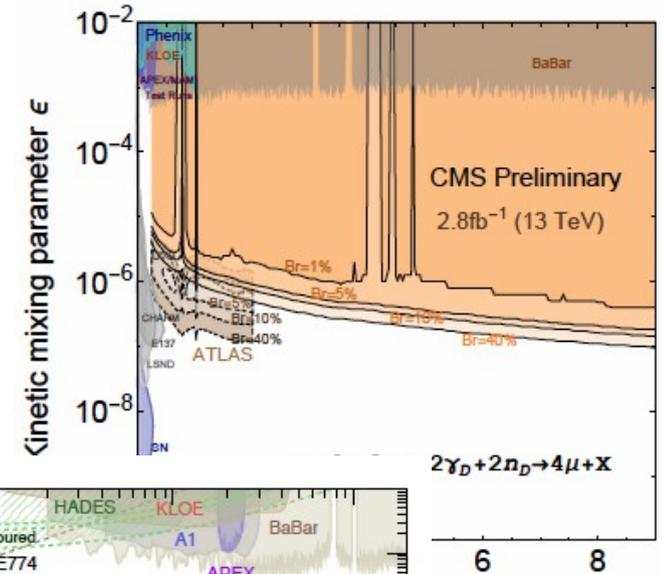
They set constraints on dark photon models

$h \rightarrow Z_D Z_D \rightarrow 4 \text{ leptons}$ (displaced)



Curtin, Essig, SG, Shelton, 1412.0018

Displaced decays



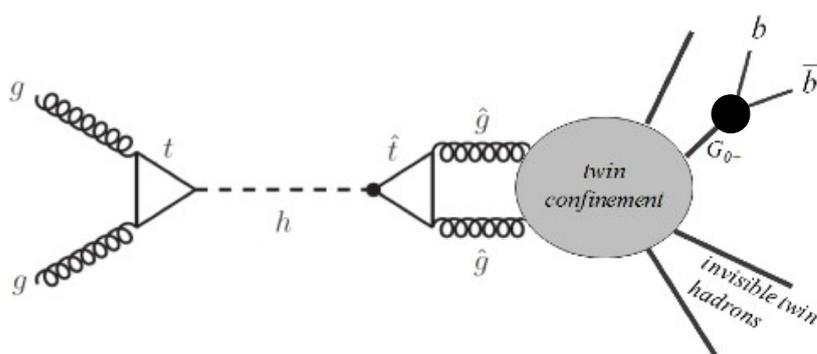
From yesterday talk of Sven Dildick

Collimated regime

Wish list for displaced decays

It will be crucial to have a broad program targeted on Higgs displaced decays

Particularly interesting are displaced jet signatures to test neutral naturalness models



Thanks to the mixing with the Higgs (that is small)

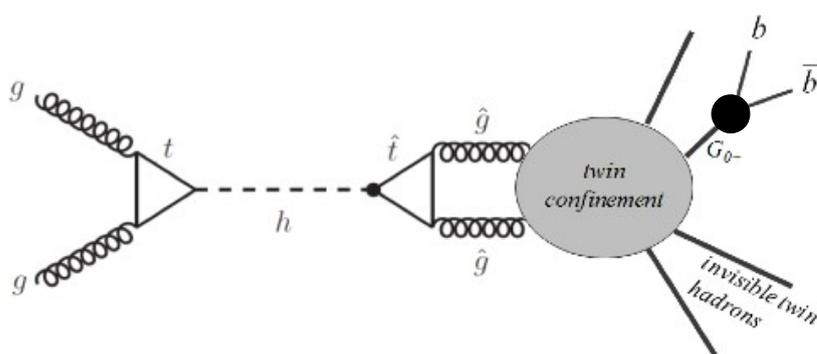
$h \rightarrow G_0 G_0 \rightarrow$ displaced jets
(glue-balls of the hidden sector of twin Higgs theories)

$$\text{BR}(h \rightarrow G_0 G_0) \approx 10^{-3} \kappa \left(\frac{400 \text{ GeV}}{m_T} \right)^4 \sqrt{1 - \frac{4m_0^2}{m_h^2}}$$

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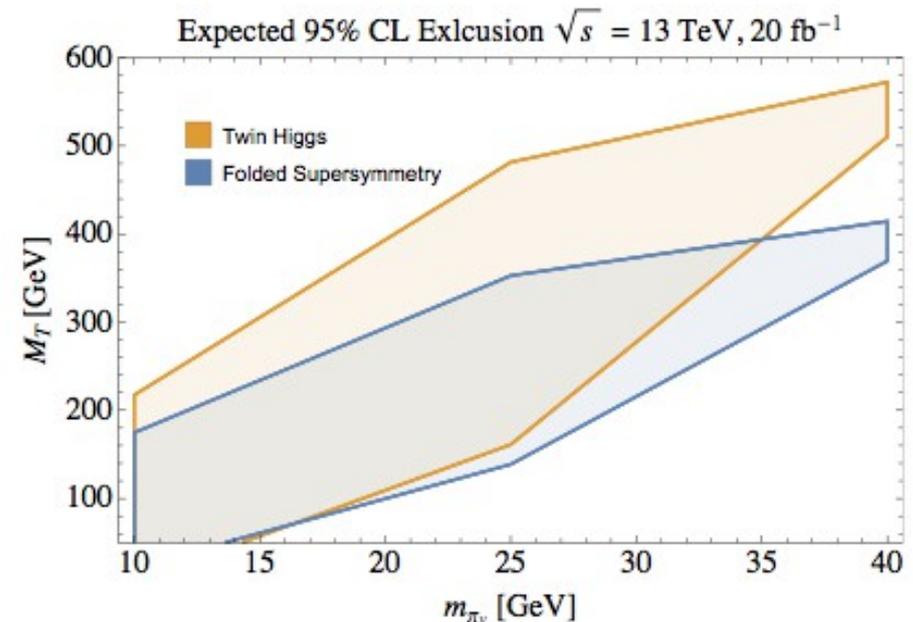
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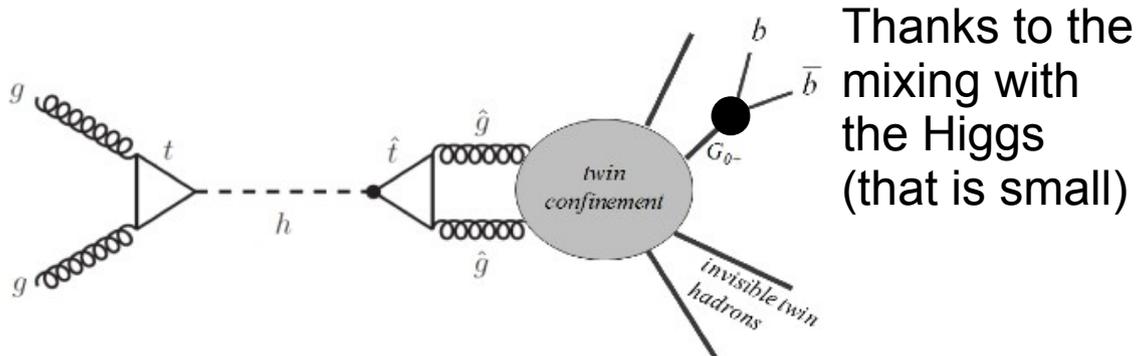


Csaki, Kuflik, Lombardo, Slone, 1508.01522

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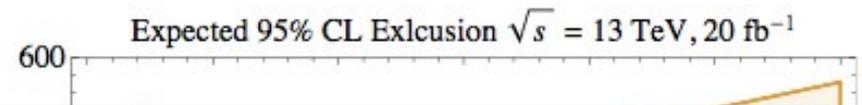
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Particularly interesting are displaced jet signatures to test neutral naturalness models



Thanks to the mixing with the Higgs (that is small)

$h \rightarrow G_0 G_0 \rightarrow$ displaced jets
(blue-balls)



Some question for future searches:

Existing searches focus on

- 2 displaced objects or 1 displaced object & high-threshold associated object

Is it possible to perform complementary searches with

- only 1 displaced object + thresholds suitable for the Higgs kinematics

- larger range of displacement

Conclusions/future work

The search for Higgs exotic decays has a crucial role in testing new light (dark) particles

A program that is complementary to the Higgs precision measurement program

Relatively good coverage

→ constraint on the Higgs portal

Prompt decays
without MET

Prompt decays
with MET

Displaced
decays

} Work
needed

Insights on otherwise
hidden theories:

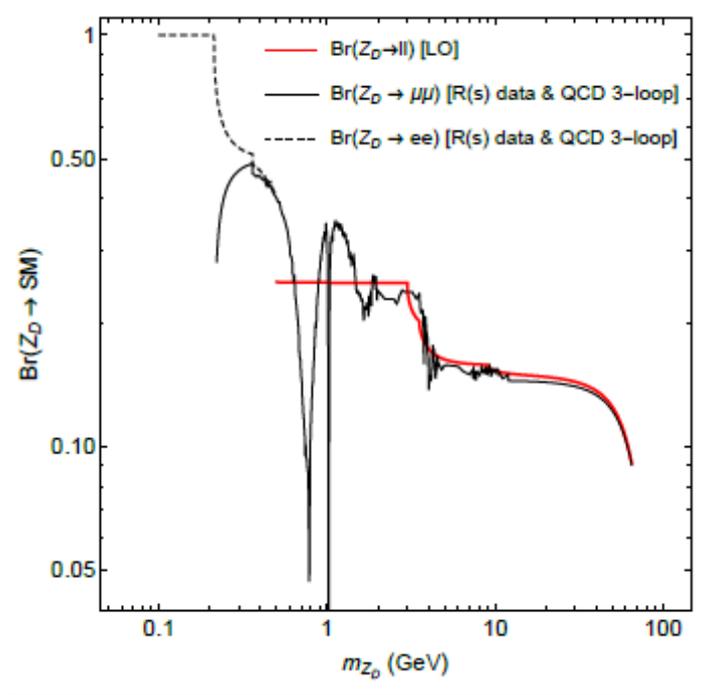
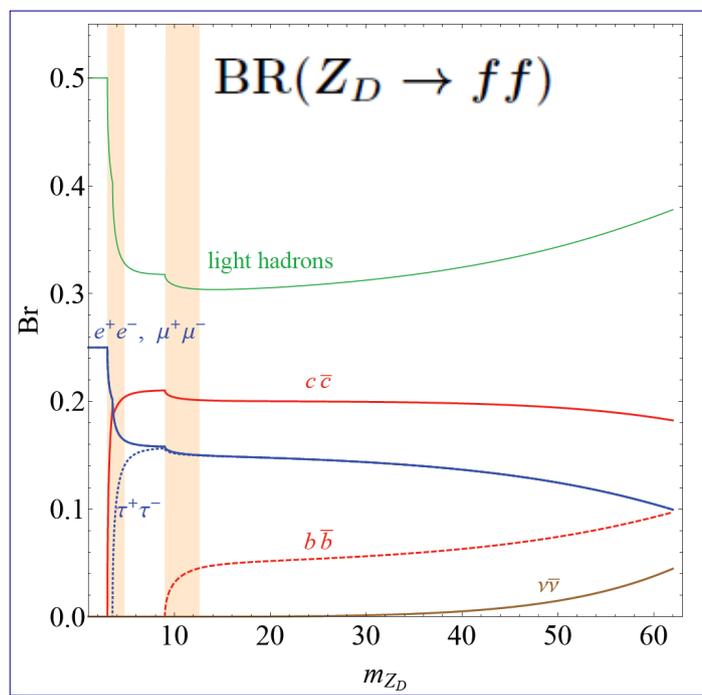
- ✗ Dark photon models
- ✗ Models with new light scalars (NMSSM)
- ✗ Models of neutral naturalness
- ...

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

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



Dependence on m_{Z_D} , only

Experimental searches

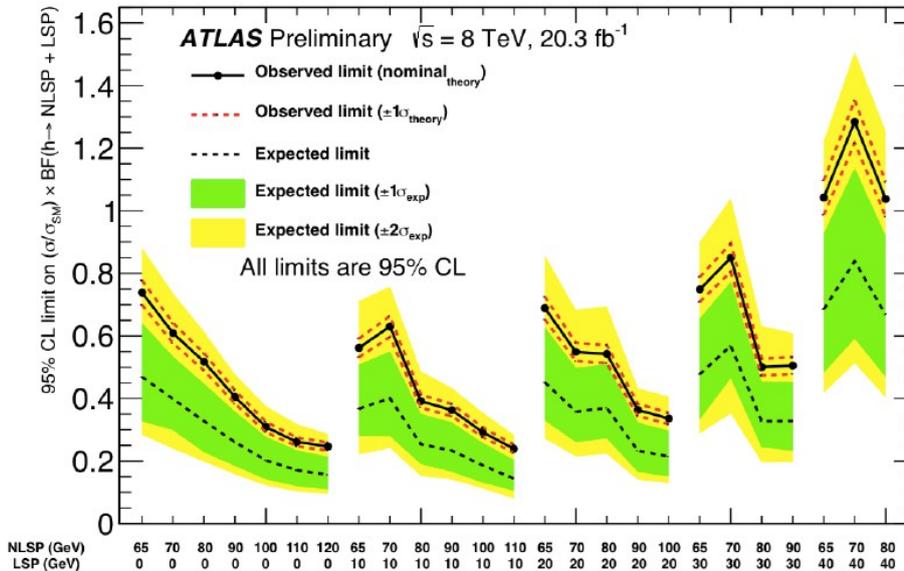
Increasing effort from the ATLAS and CMS collaborations

• ATLAS-CONF-2015-001

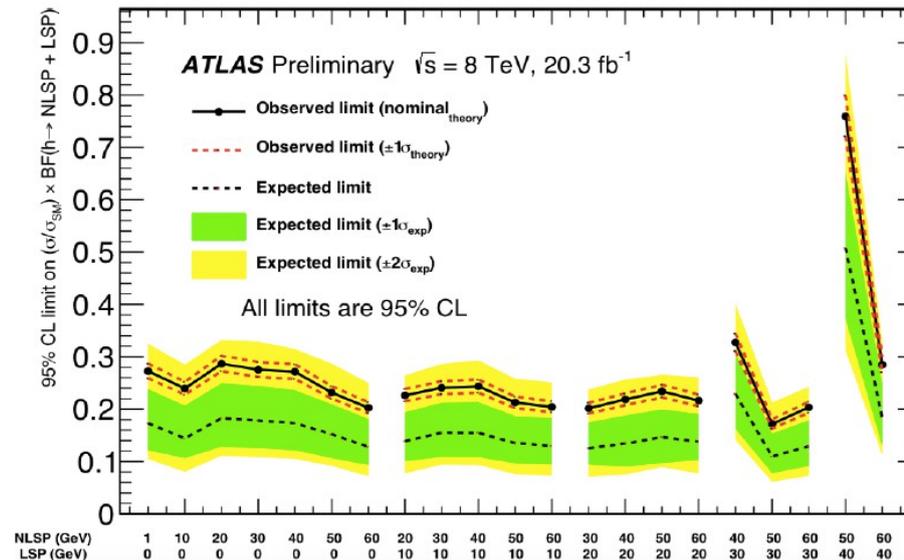
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1-photon



2-photon

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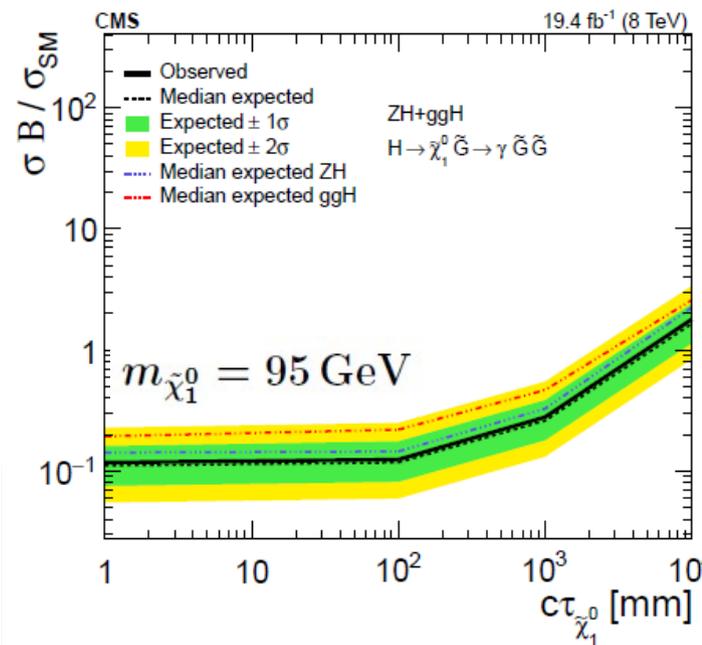
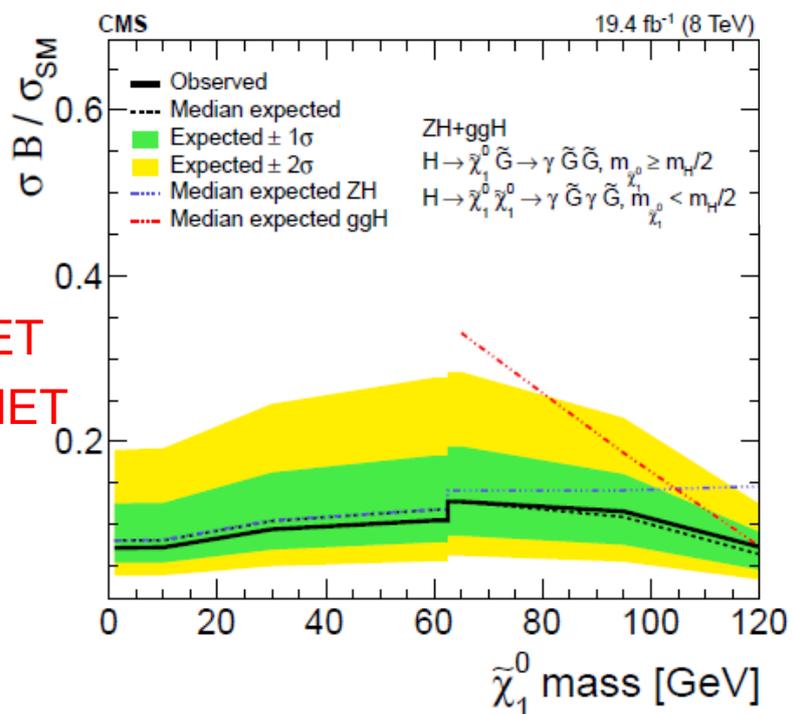
- CMS, 1507.00359

gg Higgs and Zh,

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Eventually displaced



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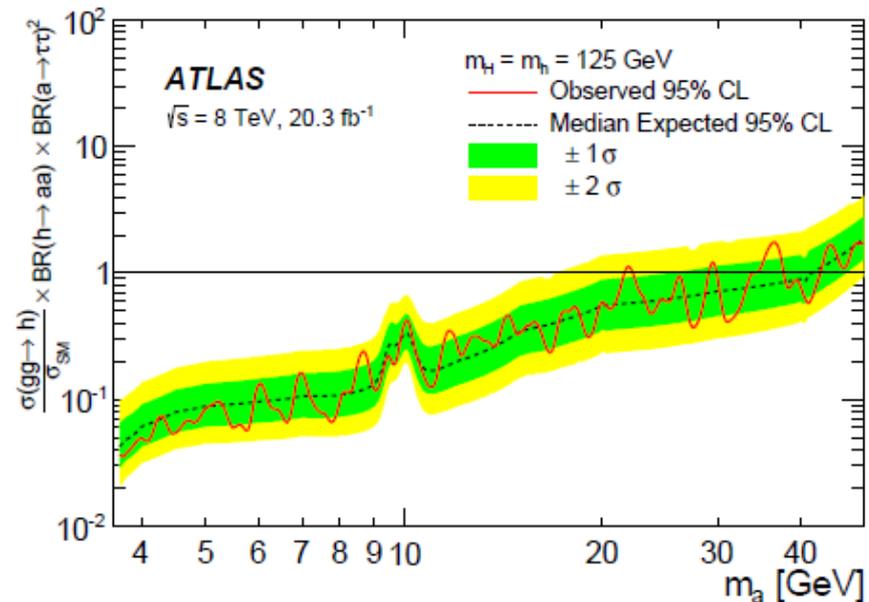
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Eventually displaced

- ATLAS, 1505.01609

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

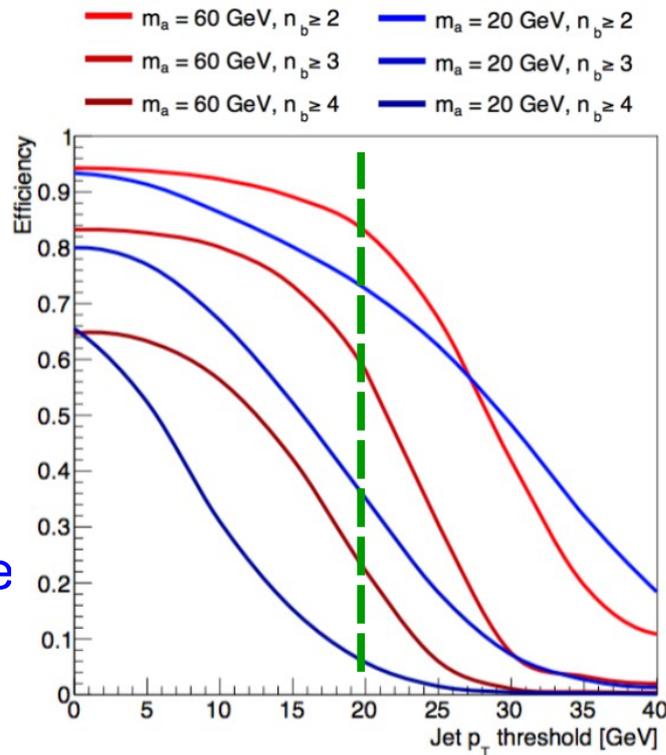


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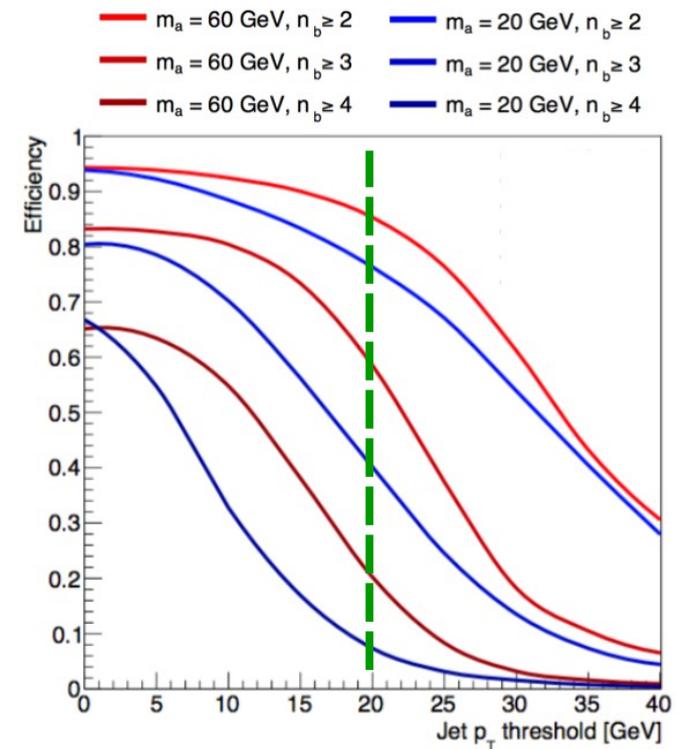
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