Exotic Higgs

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University of Cincinnati

Fermilab-CERN hadron collider physics summer school

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Outline

This is a special lecture on exotic decays of the 125 GeV Higgs boson

1. Introduction: why is this field interesting?

- Experimental motivation: the tiny Higgs width is difficult to measure at the LHC
- Theoretical motivation: theories with a dark/hidden sector

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2. Novel signatures

- Invisible decays of the Higgs boson
- Visible decays: searches already performed and open questions

3. Experimental challenges

- Low p_T objects ⇒ Triggers?

Aim: inspire young scientists to undertake new experimental searches/theory studies

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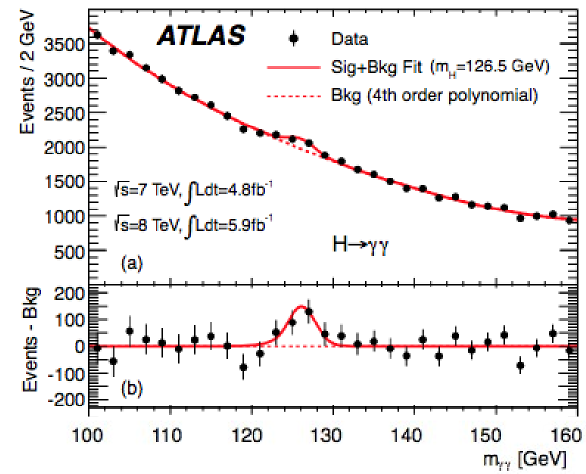
Some Review Article

- Exotic Decays of the 125 GeV Higgs Boson, 1312.4992, Phys. Rev. D90 (2014) no.7, 075004 D. Curtin, R. Essig, SG, P. Jaiswal, A. Katz, T. Liu, Z. Liu, D. McKeen, J.Shelton, M. Strassler, Z. Surujon, B. Tweedie, Y-M. Zhong
- LHC Higgs cross section working group Yellow report 4, appearing soon

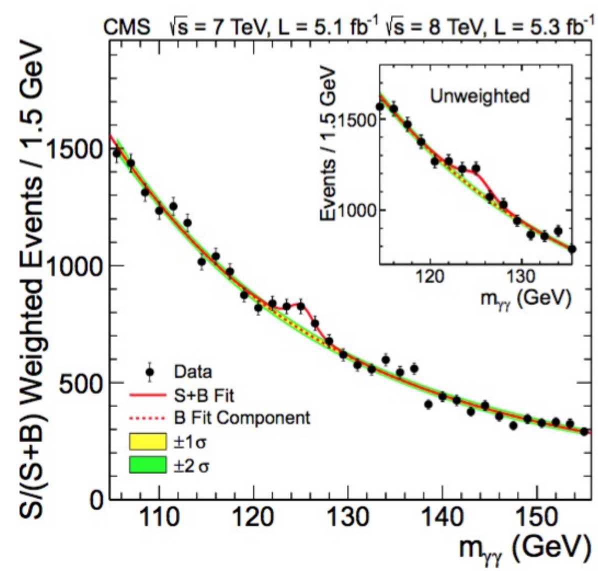
Discovery!

The first elementary particle discovery of 21st century



CERN, July 4th 2012, ~11am

After ~30 years of experimental searches (LEP, SLC, Tevatron, LHC)



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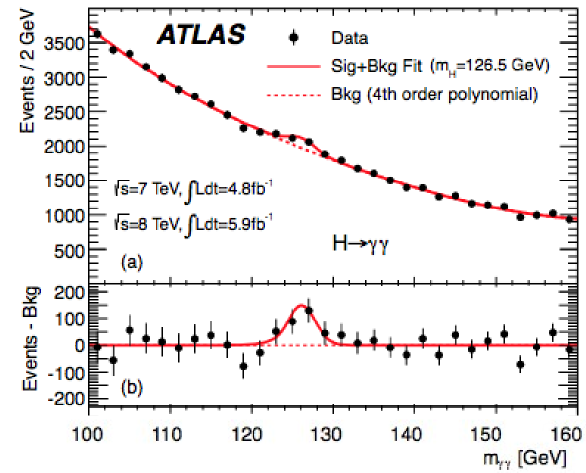

http://www.google.com/trends/

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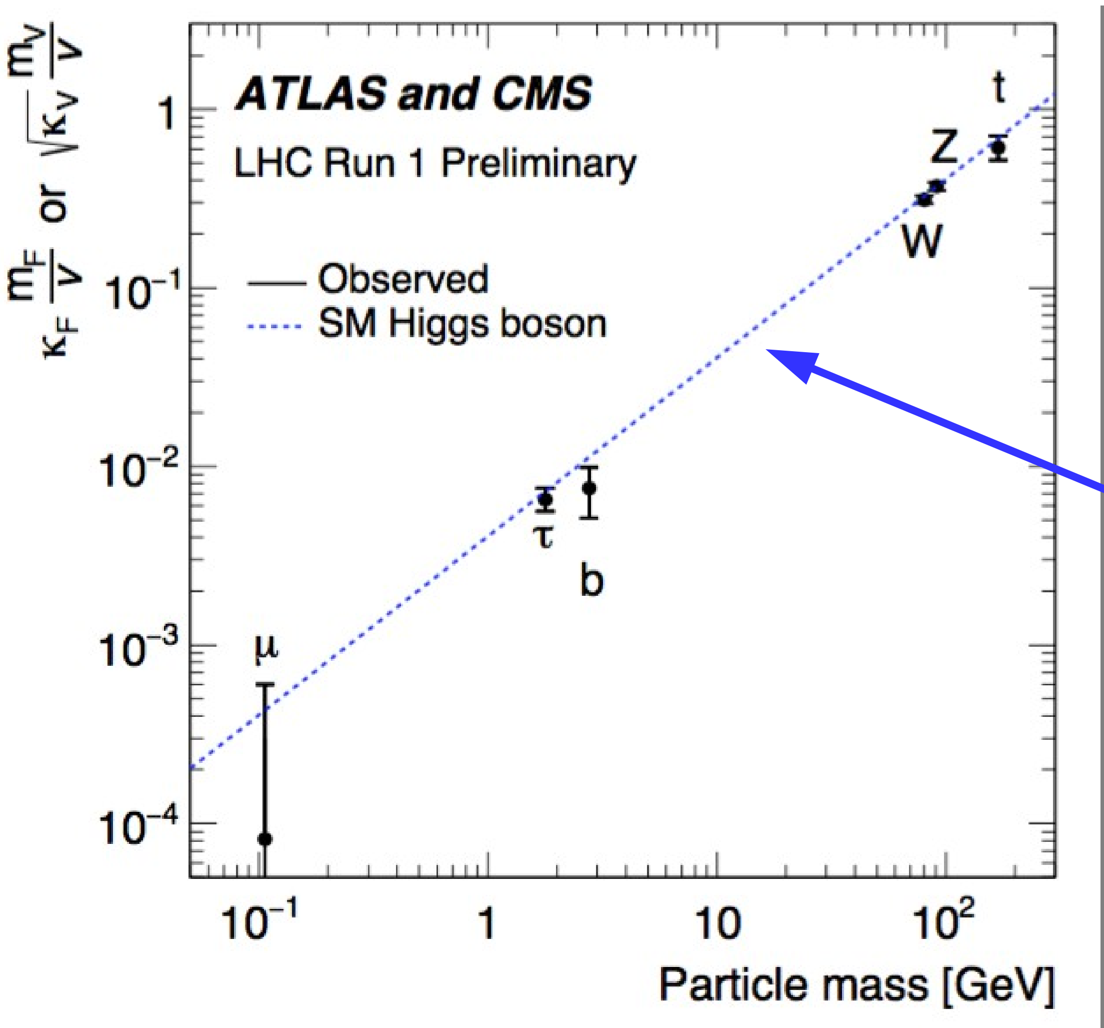
Giving mass to the massive SM particles



Flavor diagonal couplings to 3rd generation and to gauge bosons known with 20% - 30% uncertainty.

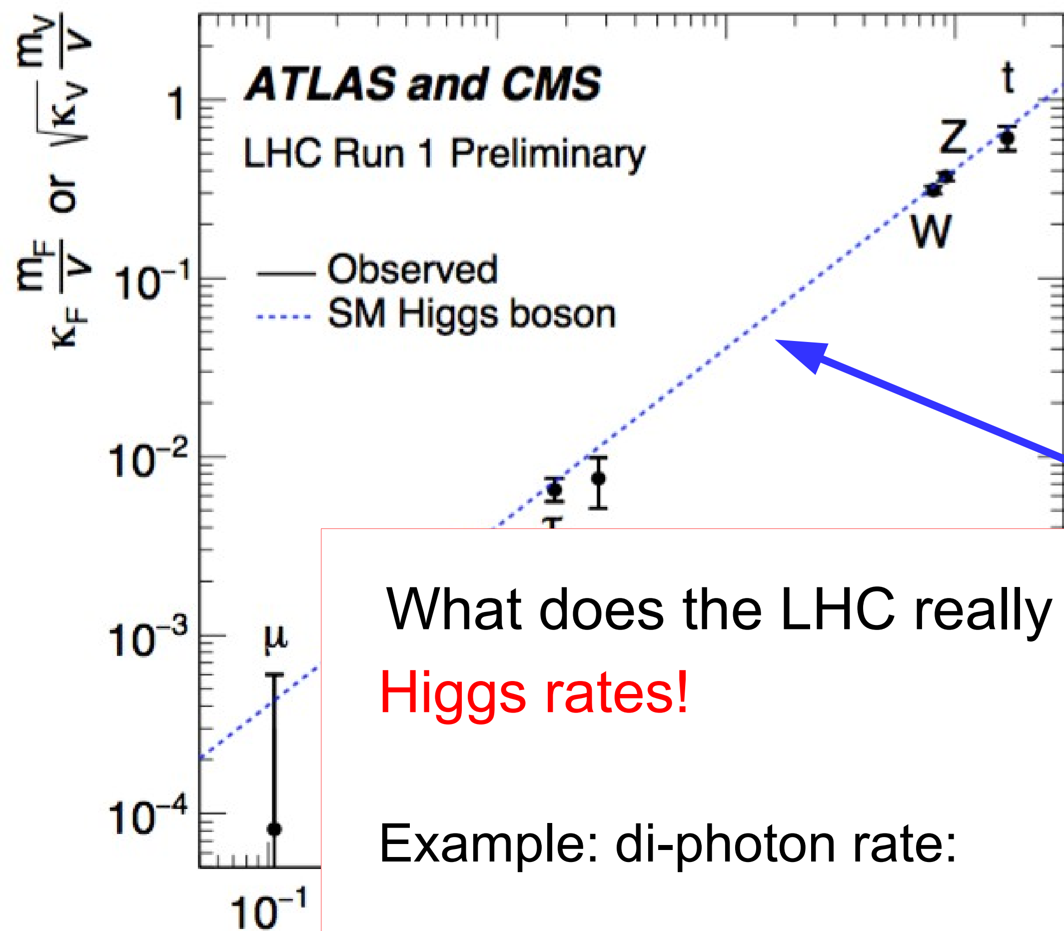
We are testing the SM prediction:

$$\kappa_F \propto m_F$$

$$\kappa_V \propto m_V^2$$

ATLAS-CONF-2015-044
CMS-PAS-HIG-15-002

Giving mass to the massive SM particles



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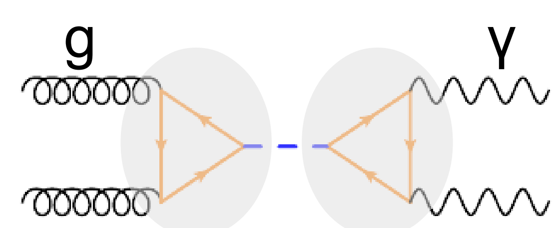
What does the LHC really measure?

Higgs rates!



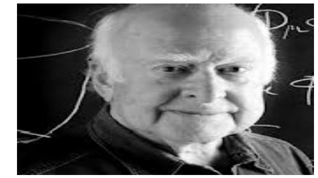
Example: di-photon rate:

$$\mu_\gamma \equiv \frac{\sigma(pp \to h \to \gamma\gamma)}{\sigma(pp \to h \to \gamma\gamma)_{\rm SM}} = \frac{\sigma(pp \to h)}{\sigma(pp \to h)_{\rm SM}} \times \frac{{\rm BR(h \to \gamma\gamma)}}{{\rm BR(h \to \gamma\gamma)_{SM}}} = \kappa_g^2 \kappa_\gamma^2 \frac{\Gamma^{\rm tot}_{\rm SM}}{\Gamma^{\rm tot}}$$

ATLAS-CONF-20
CMS-PAS-HIG-1

Higgs width (1)

What do we know about the Higgs width?



or

?

- The SM predicts a very small width: ~ 4MeV
- What about the measurement?

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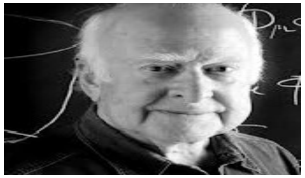

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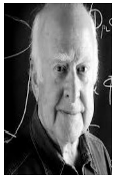
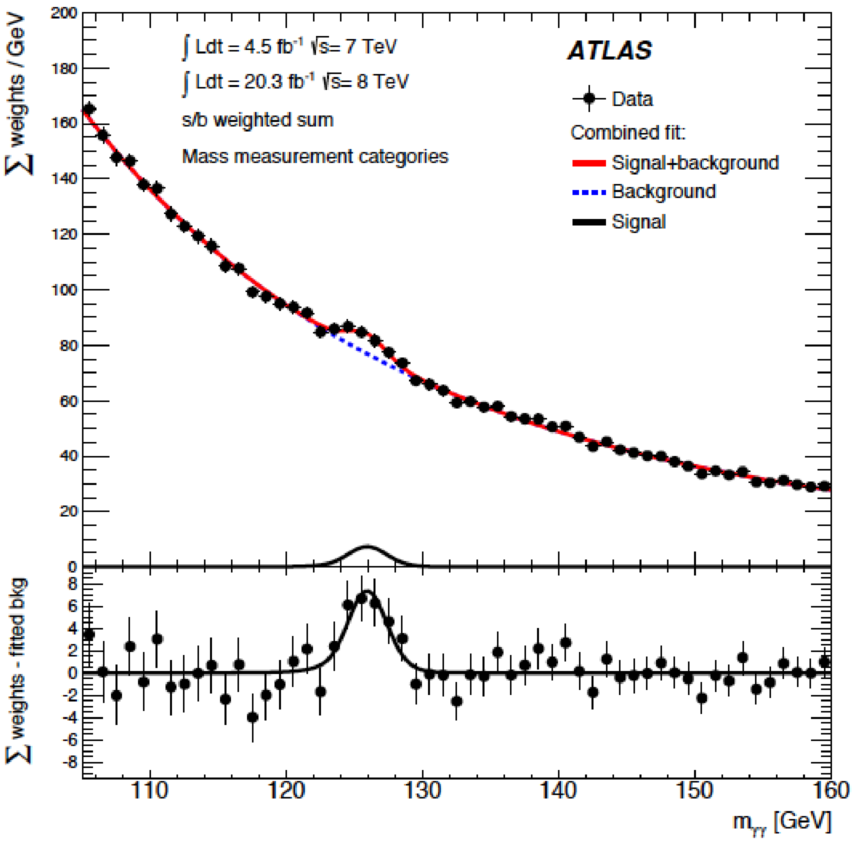


?

Model <u>independent</u> determination

Run I analyses:

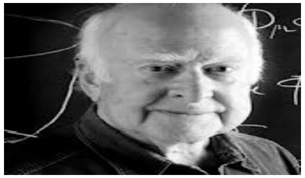
$$\Gamma_{\text{total}} < \begin{cases} 2.4,\ 5.0\,\text{GeV (CMS, ATLAS)} & h \to \gamma\gamma \\ 3.4,\ 2.6\,\text{GeV (CMS, ATLAS)} & h \to 4\ell \\ 1.7\,\text{GeV (CMS)} & \text{combined } h \to \gamma\gamma,\ 4\ell \end{cases}$$



Limited by the LHC resolution

Higgs width (2)

What do we know about the Higgs width?



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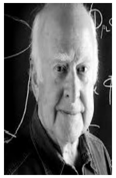

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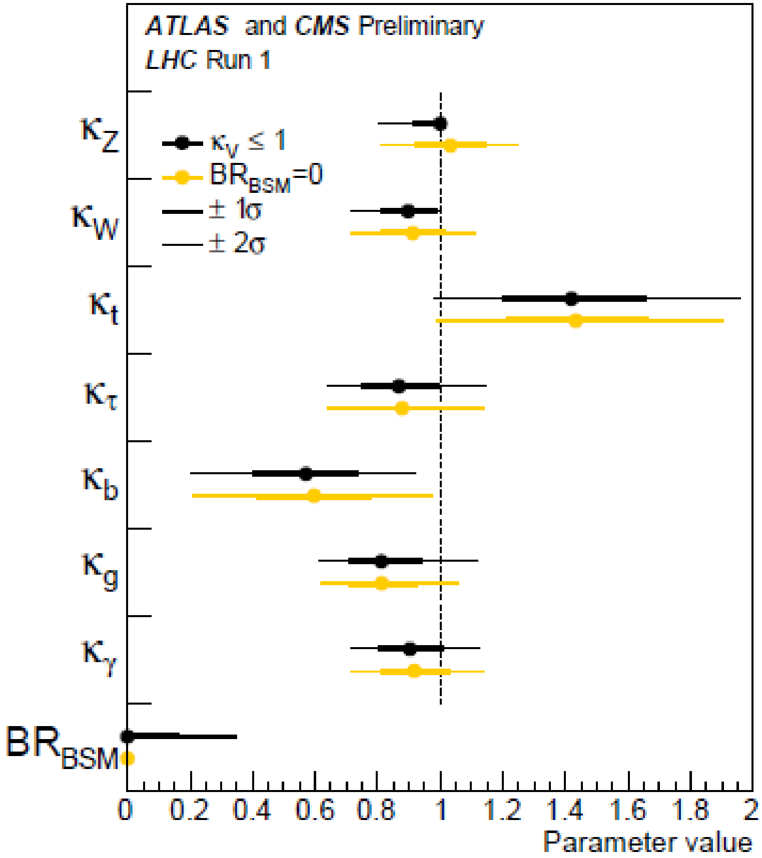
Model dependent determination(s)

Putting together the several measurements of the Higgs rates:



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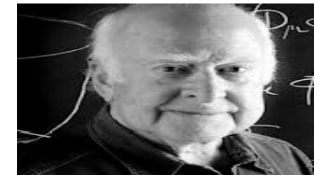 or  ?

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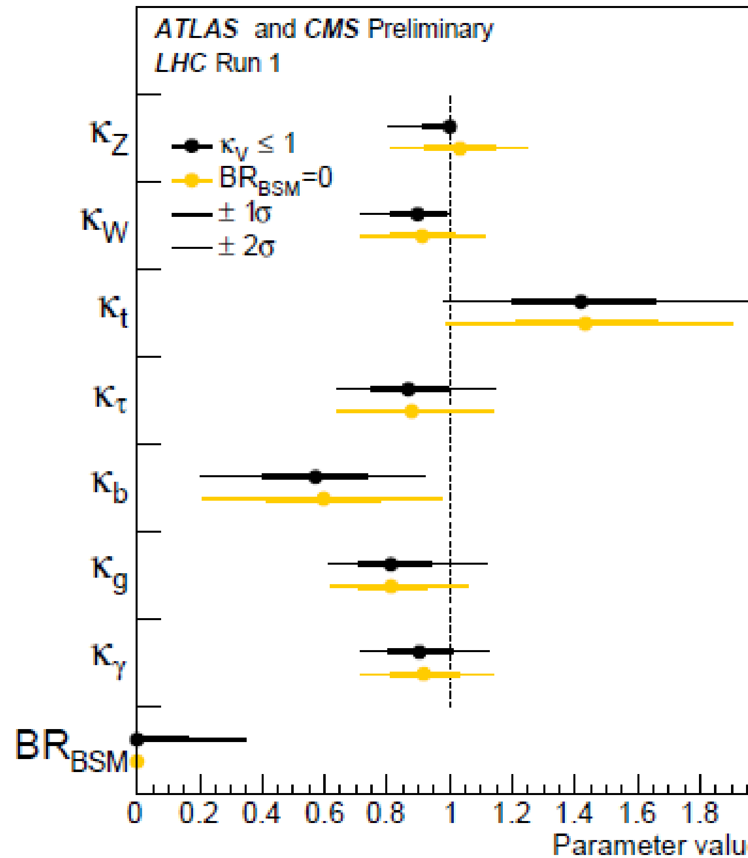

Some assumption has to go in!

— width of higgs determined by decays to SM particles (or equivalently, no BSM decays)

— The h couplings to massive gauge bosons is smaller or = 1 ($\kappa_V \leq 1$)

Present bound: $BR_{BSM} < 34\%$

Future projections: $BR_{BSM} < 10\%$

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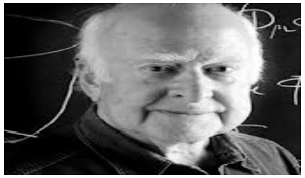
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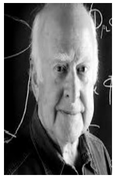
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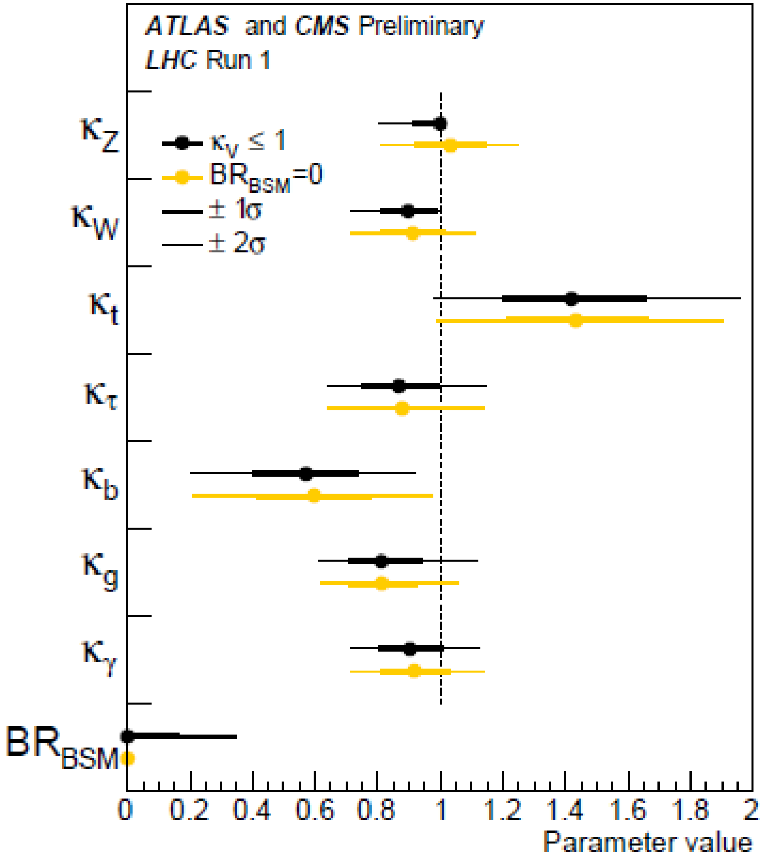


For additional model dependent bounds:
F. Caola, K. Melnikov (1307.4935),
J. Campbell et al. (1311.3589)
Dixon, Li, 1305.3854

A lot of events!

Even taking a 10% branching ratio:

Production	$N_{\rm ev}^{10\%}$, Run I
ggF	46.000
VBF	3.800
$hW^{\pm}$	1.700
hZ	1.000
$t\bar{t}h$	300

with (7+8)TeV LHC data set

Production	$N_{\rm ev}^{10\%}$, 14 TeV
ggF	1.3×10^7
VBF	1.1×10^6
$hW^{\pm}$	4.1×10^5
hZ	2.6×10^5
$t\bar{t}h$	1.5×10^5

with 3000 fb^{-1} 14 TeV LHC data

This is the rough number of Higgs bosons we could loose if we do not specifically look for exotic decays!

The Higgs and New Physics

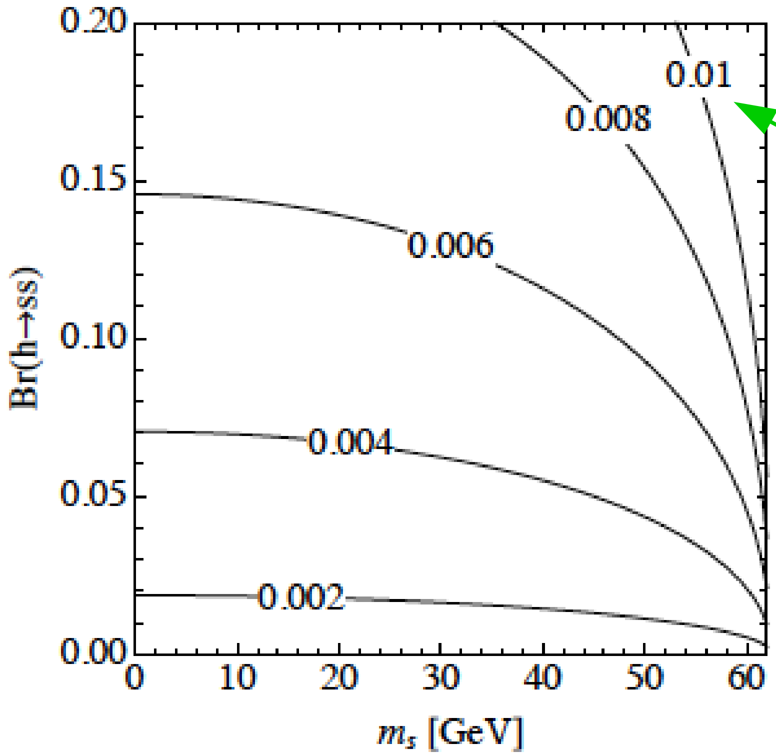
The Higgs likes to couple to New Physics (NP)!

For example,

many beyond the Standard Model (BSM) theories lead to the Higgs portal operator:

$$\frac{\xi}{2}|S|^2|H|^2$$

New SM singlet scalar



Value of ξ needed for the corresponding BR

$$\mathrm{BR}(h \to ss) = \frac{\Gamma(h \to ss)}{\Gamma(h \to ss) + \Gamma_{SM}^{tot}}$$

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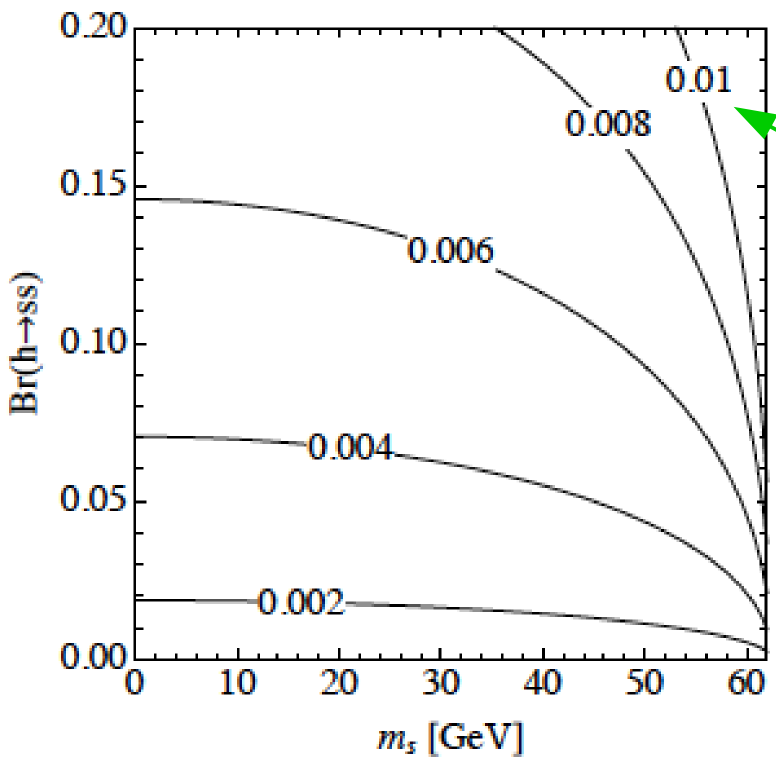

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$$\mathrm{BR}(\mathrm{h} \to \mathrm{ss}) = \frac{\Gamma(\mathrm{h} \to \mathrm{ss})}{\Gamma(\mathrm{h} \to \mathrm{ss}) + \Gamma_{\mathrm{SM}}^{\mathrm{tot}}}$$

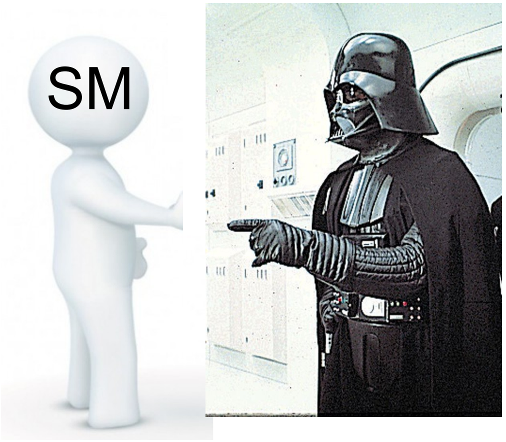
One needs only a very small coupling since

$$\Gamma_{\mathrm{SM}}^{\mathrm{tot}} \sim 2\Gamma_{\mathrm{SM}}^{\mathrm{bb}} \simeq \frac{3G_F}{4\sqrt{2}\pi} m_h y_b^2 \frac{v^2}{2}$$

is small as well (4 MeV)

Motivations for Higgs exotic decays (1)

In all generality, we are interested in testing **Dark (or hidden) sectors**, i.e. those particles not charged under the SM gauge symmetries



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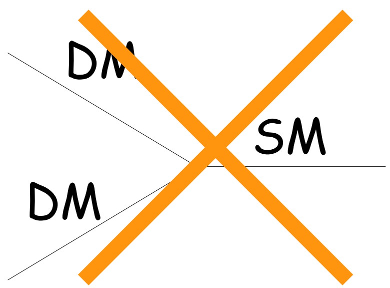
Dark matter (DM) does not interact "directly" with our SM world, but only "indirectly"



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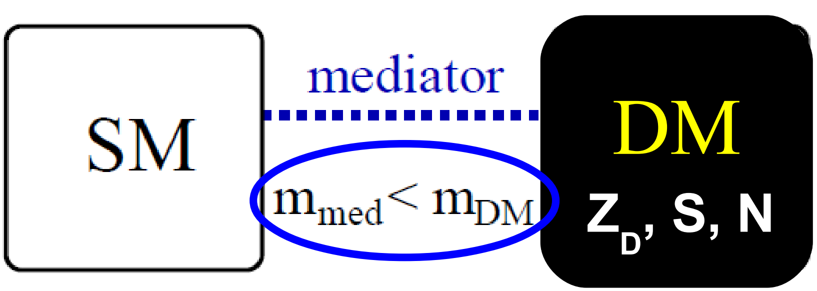
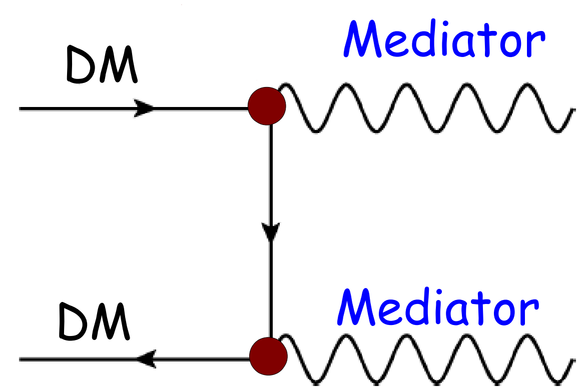


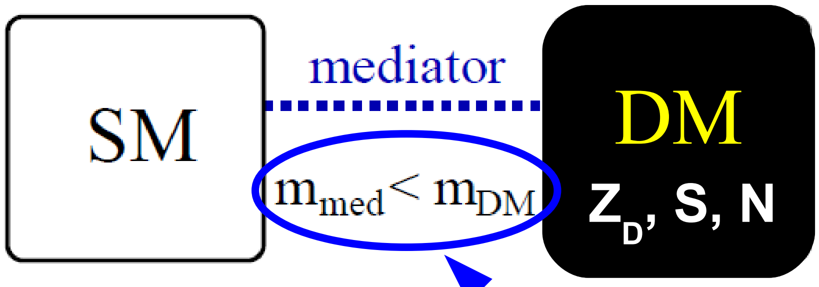
Pospelov et.al. 0711.4866
Feldman et al 0702123

DM annihilation:

Generically weak couplings



Looking for the mediators with the Higgs



How to write a Lagrangian connecting the two sectors?

Few renormalizable "portals"

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

New gauge boson

New scalar

New fermion (neutrino)

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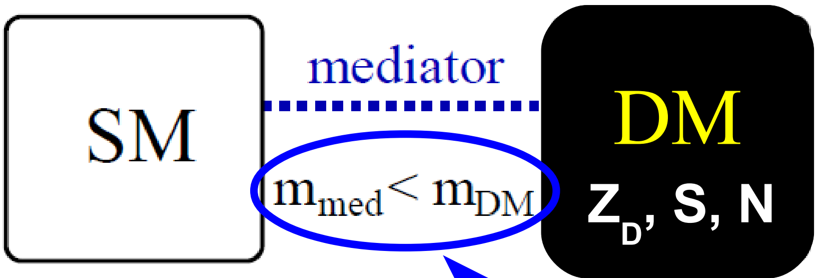

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Few renormalizable "portals"

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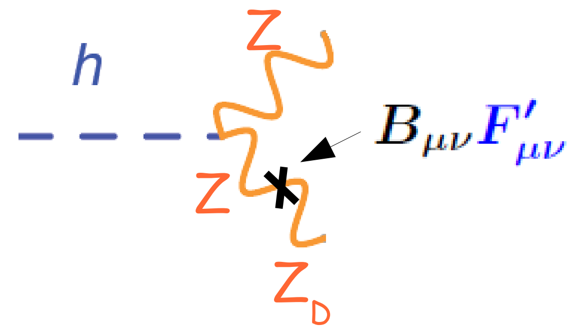
New gauge boson — New scalar — New fermion (neutrino)

If the mediators are relatively light, one expects exotic Higgs signatures

$h \to ZZ_D$



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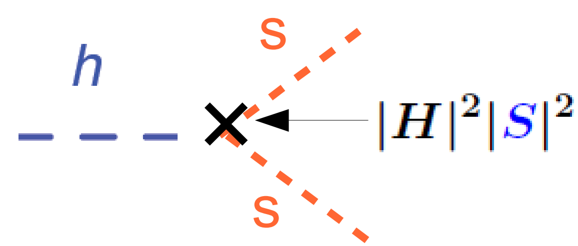
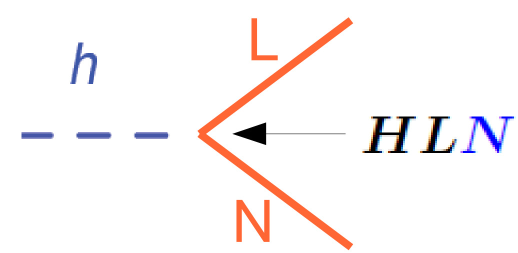


$h \to LN$



Motivations for Higgs exotic decays (2)

Beyond the Dark Matter motivation...

Models with extended Higgs sectors

Eg. Next to Minimal Supersymmetric Standard Model (NMSSM)

= MSSM + singlet chiral super-field

$$\hat{S} \rightarrow S, N_1$$

There are symmetries that protect the mass of these singlet states:

- Peccei-Quinn symmetry
- R-symmetry

⇒ S, N_1 can be naturally light

Natural frameworks to look for Higgs exotic decays!

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Theories of neutral naturalness

Eg. Twin Higgs models, Folded SUSY, ...

In these theories, the **(little) hierarchy problem** can be addressed by particles not charged under SU(3)

Typically, there is a hidden QCD + Higgs portal operator

Light bound states arise in the hidden QCD sector. These bound states (glue-balls, bottomonium states, ...) can be produced from the Higgs decay

Natural frameworks to look for Higgs exotic decays!

Weak limits and complementarity

We are speaking about very light ($m_{NP} < m_h/2$) new particles.

The LHC searches show already exclusions for particles with mass above the TeV. Why these new particles are not yet probed?

The singlet particles are not copiously produced at the LHC, since they do not couple to the SM gauge bosons → limits are weak!

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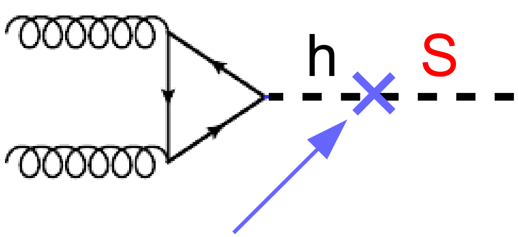
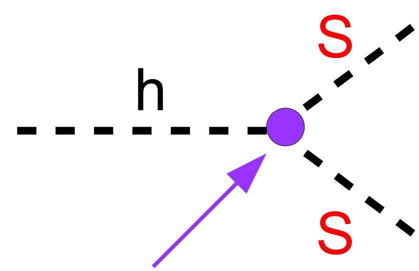
Direct production at the LHC



It happens only because S mixes with the Higgs

$$\sin\theta = \frac{\xi v v_s}{m_h^2 - m_s^2}$$

Production from the Higgs decay



$\sim \xi v$

Complementary probes of the singlet S

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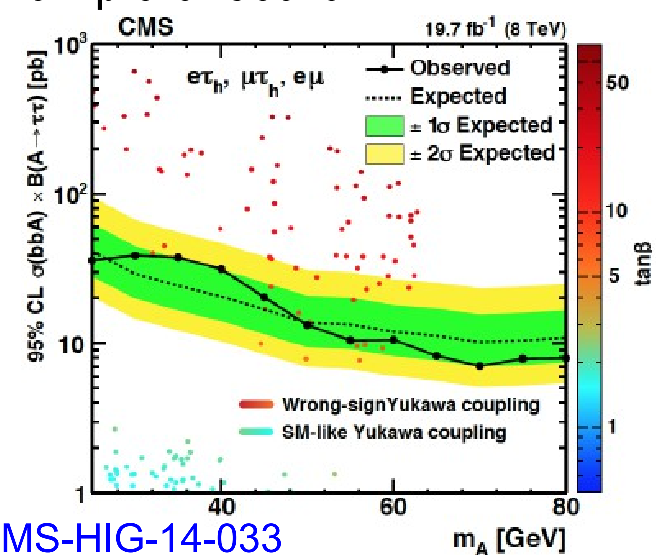
Direct production at the LHC

Example of search:



CMS-HIG-14-033

Production from the Higgs decay

What are the prospects?

Complementary probes of the singlet S

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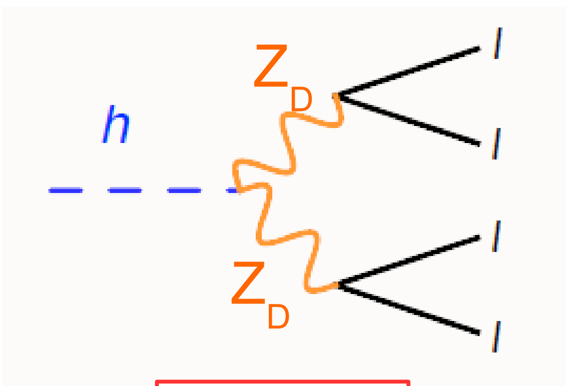
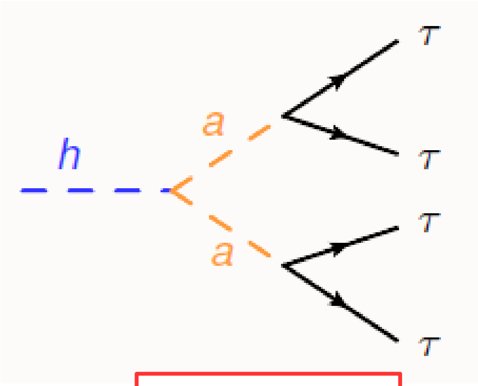
Novel signatures

Depending on the decay of the new singlet state, many new signatures arise

Examples:



$h \to 4l$



$h \to 4\tau$

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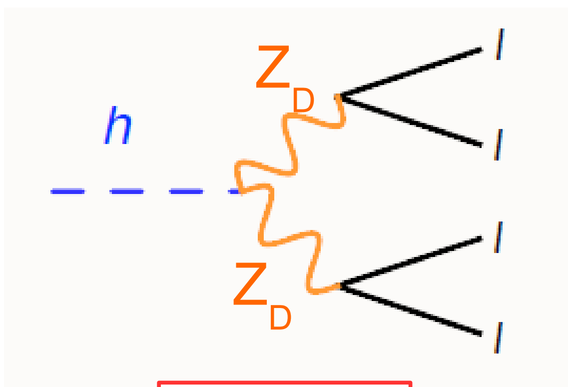

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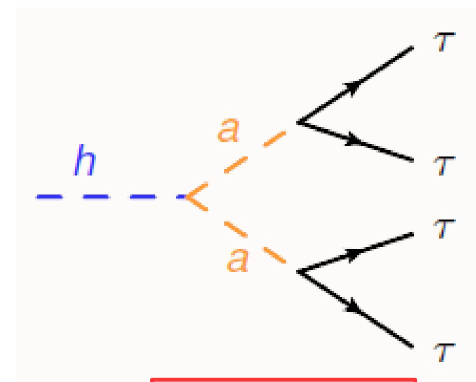

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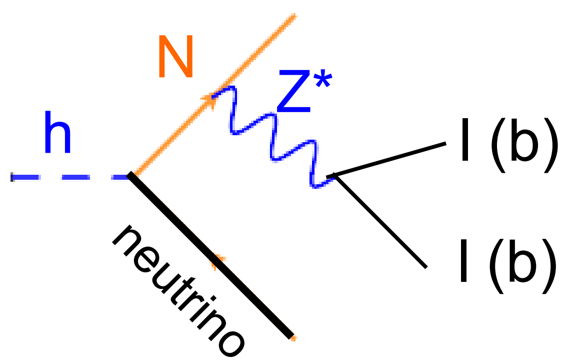


$h \to 2l(2b) + \mathrm{MET}$

Invisible signatures

Higgs decay to Dark Matter (any detector stable new particle).

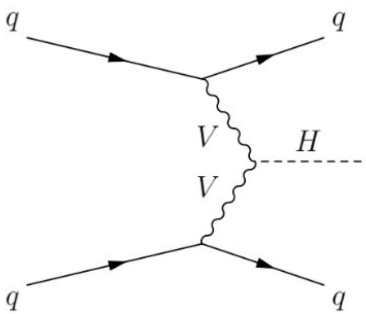
➡ Invisible signature

How to look for the invisible??

We need to produce the Higgs in association with something!

Some searches have been already performed:

$$\mathrm{BR}(h \to \mathrm{inv}) \lesssim$$



VBF: 0.32 (0.26)

CMS-PAS-HIG-16-016

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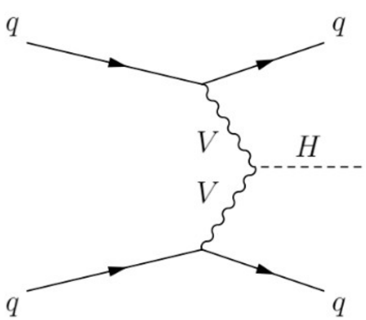

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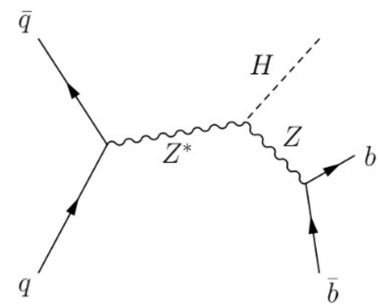
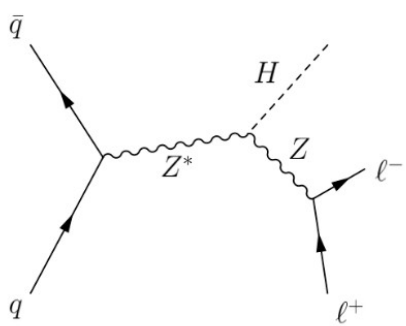


Zh, Z→bb: 1.82 (1.99)

CMS, 1404.1344

Z(W)h, Z(W)→jj: 0.78 (0.86)

ATLAS, 1504.04324



Zh, Z→ll: 0.75 (0.62)

ATLAS, 1402.3244

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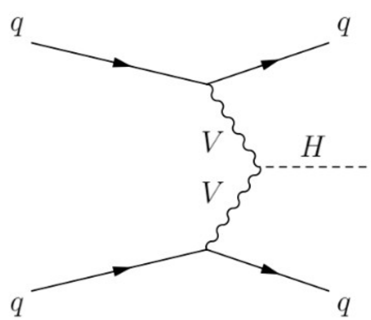

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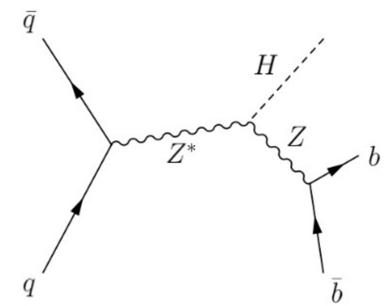
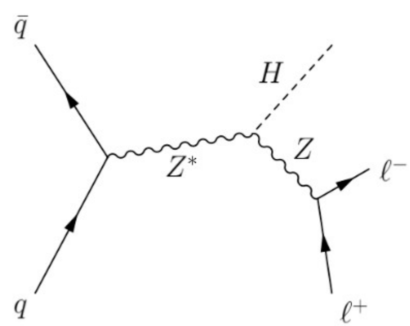
CMS-PAS-HIG-16-016

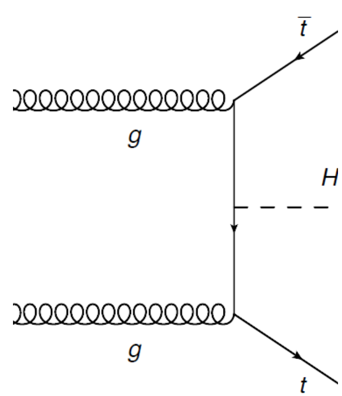


Zh, Z→bb: 1.82 (1.99)
CMS, 1404.1344

Z(W)h, Z(W)→jj: 0.78 (0.86)
ATLAS, 1504.04324



Zh, Z→ll: 0.75 (0.62)
ATLAS, 1402.3244

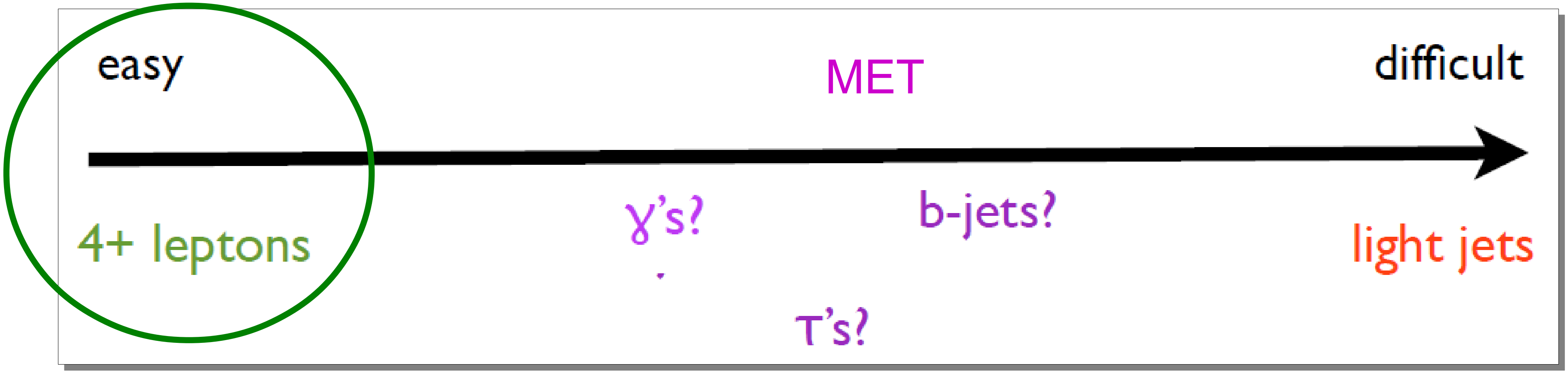


tth: 1.9 (3)
Zhou, et al., 1408.0011

?

No official search so far.
Somebody interested?

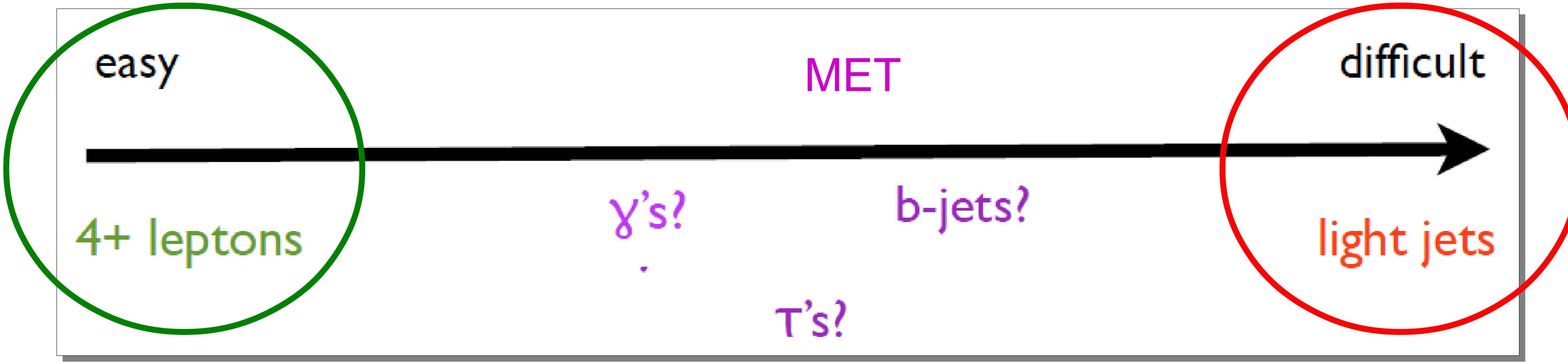
Beyond Higgs to invisible



Statistics limited

Great for the HL-LHC!

Beyond Higgs to invisible



Statistics limited

Great for the HL-LHC!

Background limited

It helps having extra handles:
New production modes
for the Higgs (tth, Zh, Wh, ...)

Some of these decays can also be displaced

Plenty of signatures have not beeing explored so far!

Don't forget to search!

Main experimental challenge for the searches of Higgs exotic decays:
The particles produced from the Higgs decay have a low p_T

➡ Dedicated studies of trigger strategies are needed

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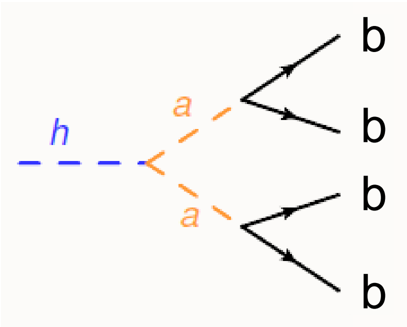
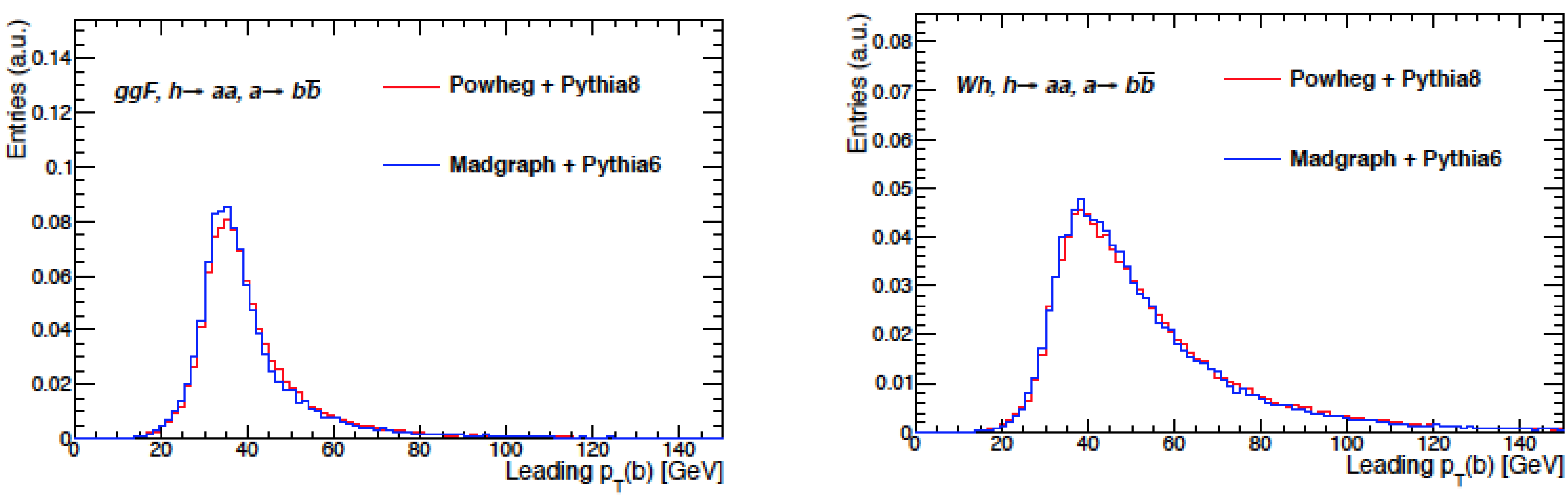
Let us take, for example, the challenging decay mode $h \rightarrow 4b$





From the LHC Higgs cross section working group, Yellow report 4

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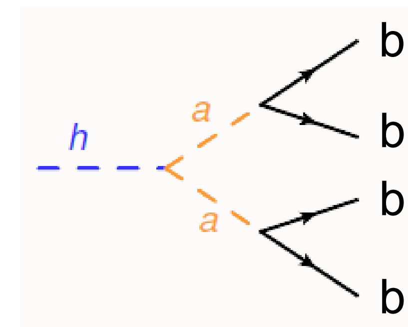

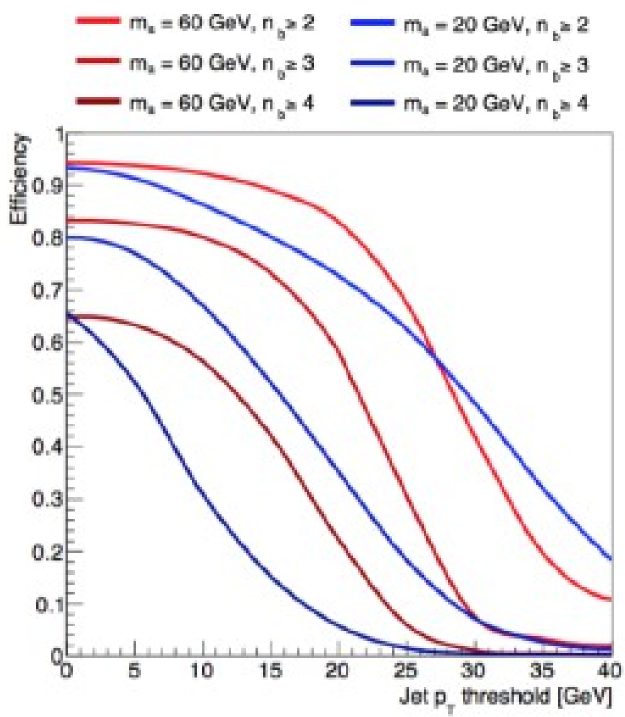

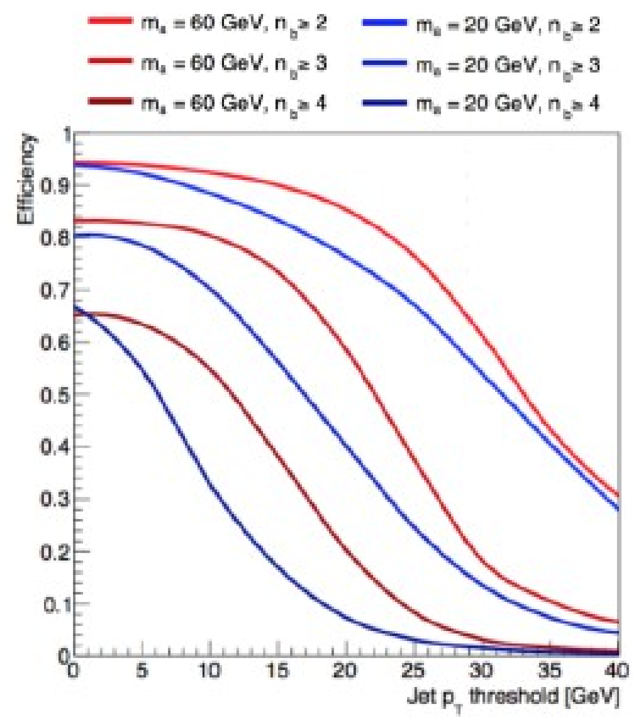

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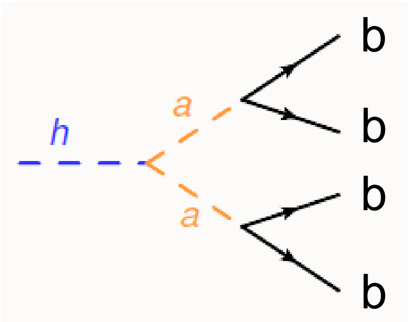

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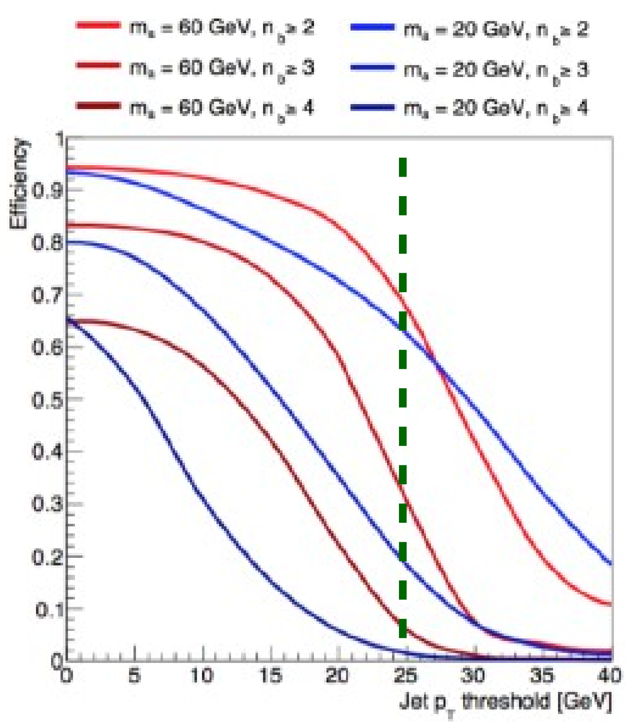
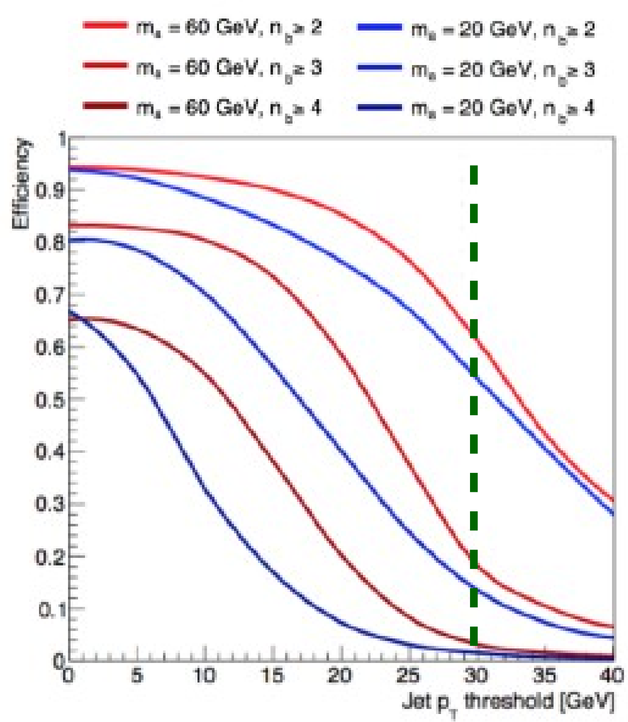




Risk of loosing the signal already at the trigger level

From the LHC Higgs cross section working group, Yellow report 4

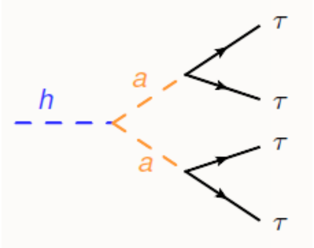
Characterizing Higgs exotic decays

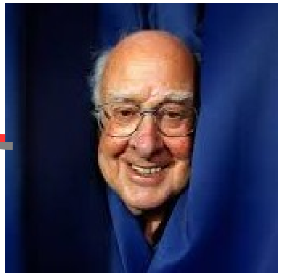
From a signature point of view:

So far, the most part of the experimental effort is in this direction

Higgs decays to multiple resonances without missing energy

e.g.





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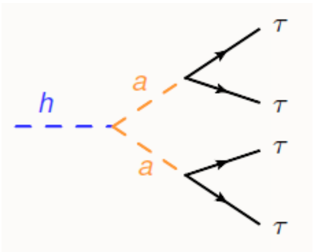
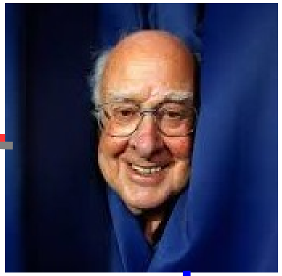
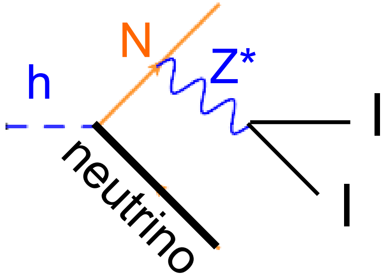




Higgs decays to missing energy + (soft) visible particles

e.g.



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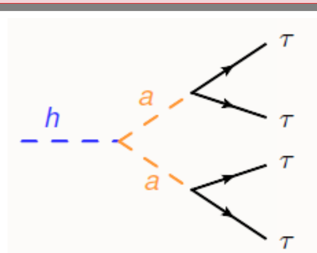
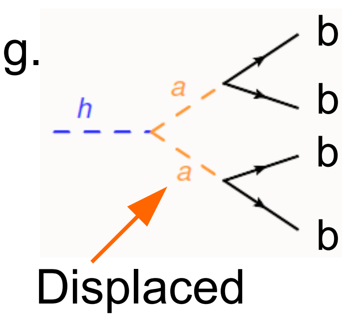
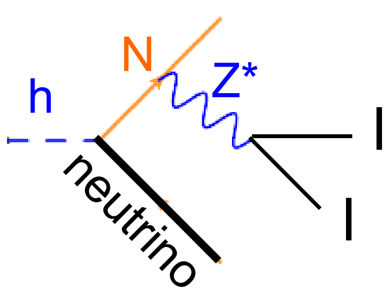


Higgs decays to displaced new physics particles (with or without missing energy)

e.g.



e.g.



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Characterizing Higgs exotic decays

From a signature point of view:

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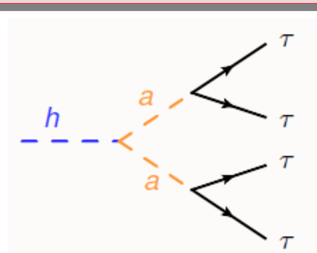
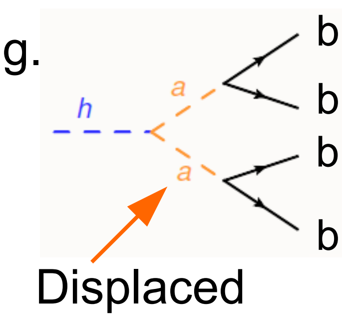
1. Higgs decays to multiple resonances without missing energy

e.g.

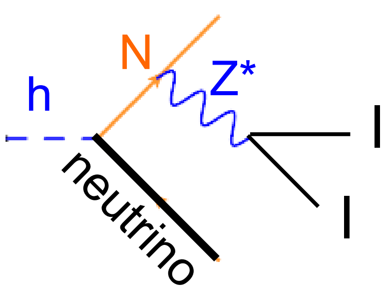


3. Higgs decays to displaced new physics particles (with or without missing energy)

e.g.



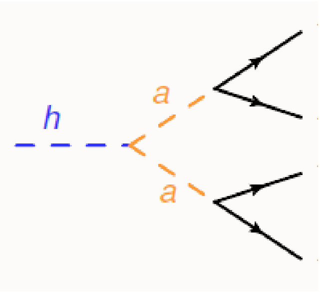
e.g.



2. Higgs decays to missing energy + (soft) visible particles

What has been done and what not (1)

Several searches are now publicly available



$h \to ss \to 4\mu$ — CMS, 1506.00424

$ss \to 4\tau$ — CMS, 1510.06534

$ss \to 2\mu\ 2\tau$ — CMS-PAS-HIG-15-011, ATLAS 1505.01609

$ss \to 2\mu\ 2b$ — CMS-PAS-GIH-14-41

$ss \to 4b$ — ATLAS, 1606.08391

$ss \to 4\gamma$ — ATLAS, 1509.05051

$h \to Z(Z_D)\ Z_D \to 4l$ — ATLAS, 1505.07645

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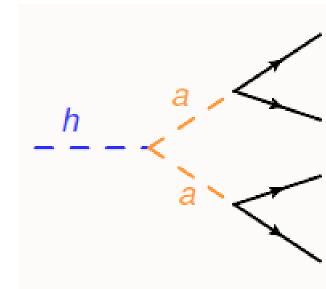

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- $h \to Z(Z_D)\, Z_D \to 4l$ — ATLAS, 1505.07645

These searches can be interpreted in our favorite model

$$\mathrm{BR}(\mathcal{F}_i) \equiv \mathrm{BR}(h \to ss \to (f\bar{f})(f'\bar{f}'))$$

BR(s)

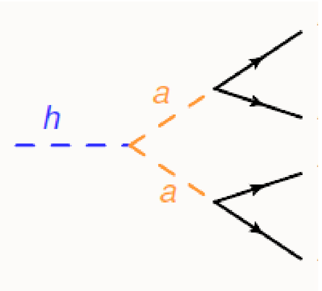
Decay Mode $\mathcal{F}_i$	Projected/Current 2σ Limit on $\mathrm{BR}(\mathcal{F}_\mathrm{i})$ 7/8 [14] TeV	Production Mode	quarks allowed: $\frac{\mathrm{BR}(\mathcal{F}_\mathrm{i})}{\mathrm{BR(non-SM)}}$	quarks allowed: Limit on $\frac{\sigma}{\sigma_{SM}} \cdot \mathrm{BR(non\text{-}SM)}$ 7/8 [14] 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]

Extracted bound on $\mathrm{BR}(h \to ss)$

From Curtin et al. 1312.4992

What has been done and what not (1)

Several searches are now publicly available



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$h \to Z(Z_D)\, Z_D \to 4l$ — ATLAS, 1505.07645

These searches can be interpreted in our favorite model

?

Comparative study for 4b

$$\mathrm{BR}(\mathcal{F}_i) \equiv \mathrm{BR}(h \to ss \to (f\bar{f})(f'\bar{f}'))$$

BR(s)

Decay Mode $\mathcal{F}_i$	Projected/Current 2σ Limit on $\mathrm{BR}(\mathcal{F}_i)$ 7/8 [14] TeV	Production Mode	quarks allowed: $\frac{\mathrm{BR}(\mathcal{F}_i)}{\mathrm{BR(non-SM)}}$	quarks allowed: Limit on $\frac{\sigma}{\sigma_{SM}} \cdot \mathrm{BR(non-SM)}$ 7/8 [14] TeV
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$b\bar{b}\mu\mu$	$(2-7)\cdot 10^{-4\,T}$ $3 \cdot 10^{-4}$	G	3×10^{-4}	$0.6 - 1$ [$0.2 - 0.7$]
$\tau\tau\tau\tau$	0.2 0.25	G	0.005	$40 - 80$ [U]
$\tau\tau\mu\mu$	$(3-7)\cdot 10^{-4}$ $4 \cdot 10^{-4}$	G	3×10^{-5}	$10 - 20$ [U]
$\mu\mu\mu\mu$	$1 \cdot 10^{-4}$ $4 \cdot 10^{-5}$	G	$1 \cdot 10^{-7}$	1000 [U]

?

Extracted bound on BR($h \to ss$)

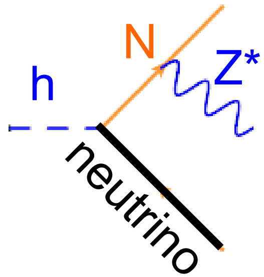
From Curtin et al. 1312.4992

?

Wider mass ranges

What has been done and what not (2)

Much less is known...



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

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

ATLAS-CONF-2015-001,
CMS,1507.00359

Bounds on the BRs are up to ~5% (7+8 TeV data)

It is more complicated to test if the signature is coming from the Higgs

What has been done and what not (2)

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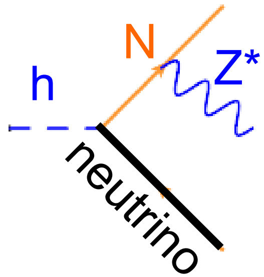

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ATLAS-CONF-2015-001,
CMS,1507.00359

Bounds on the BRs are up to ~5% (7+8 TeV data)

It is more complicated to test if the signature is coming from the Higgs

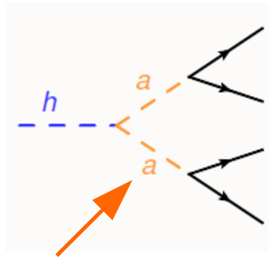
Experiment: additional possible channels to search for: ?

$h \rightarrow 2l$ + MET, $h \rightarrow 2\tau$ + MET, $h \rightarrow 2b$ + MET

Theory: need more studies of the theories producing these signatures ?

What has been done and what not (3)

Completely un-explored territory



Displaced

Only available search: h → X X→ 4l CMS, 1411.6977

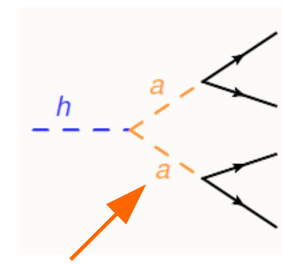
Experiment: many additional searches to be performed! ?

Theory: Need more accurate predictions for the Higgs branching ratios in theory of neutral naturalness ?

What has been done and what not (3)

Completely un-explored territory

Only available search: h → X X→ 4l CMS, 1411.6977



Displaced

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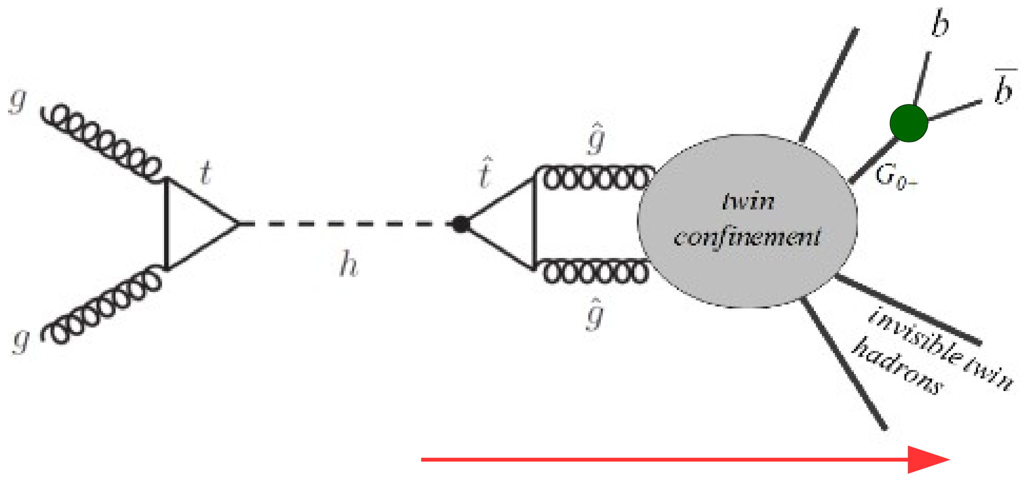
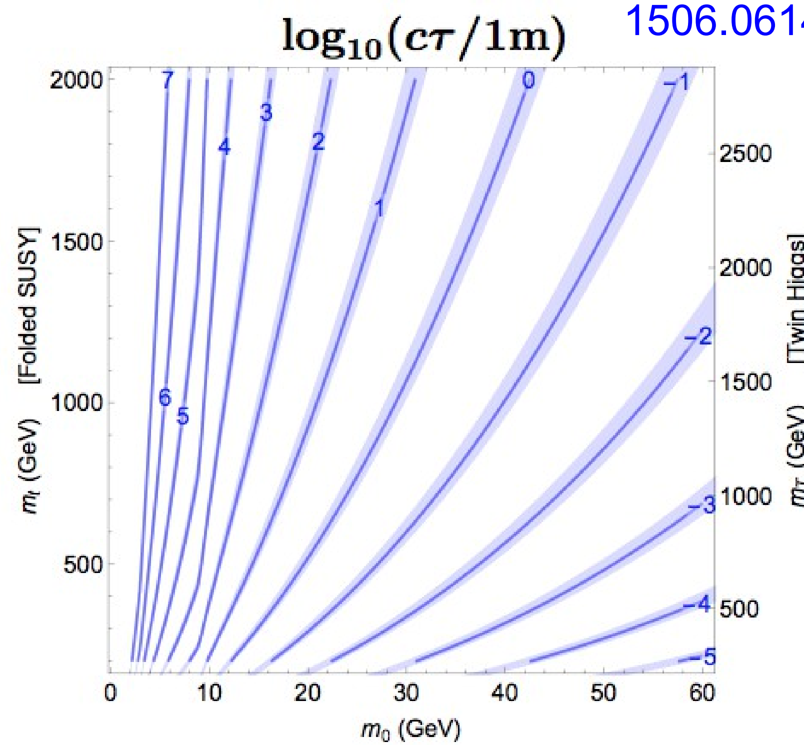
Hidden QCD



How to compute this branching ratio?

Curtin, Verhaaren, 1506.06141



Conclusions and outlook

✖ In spite of the first SM-like measurements, the Higgs boson can hide a "New Physics nature" and decay exotically (no direct access to the Higgs width at the LHC).

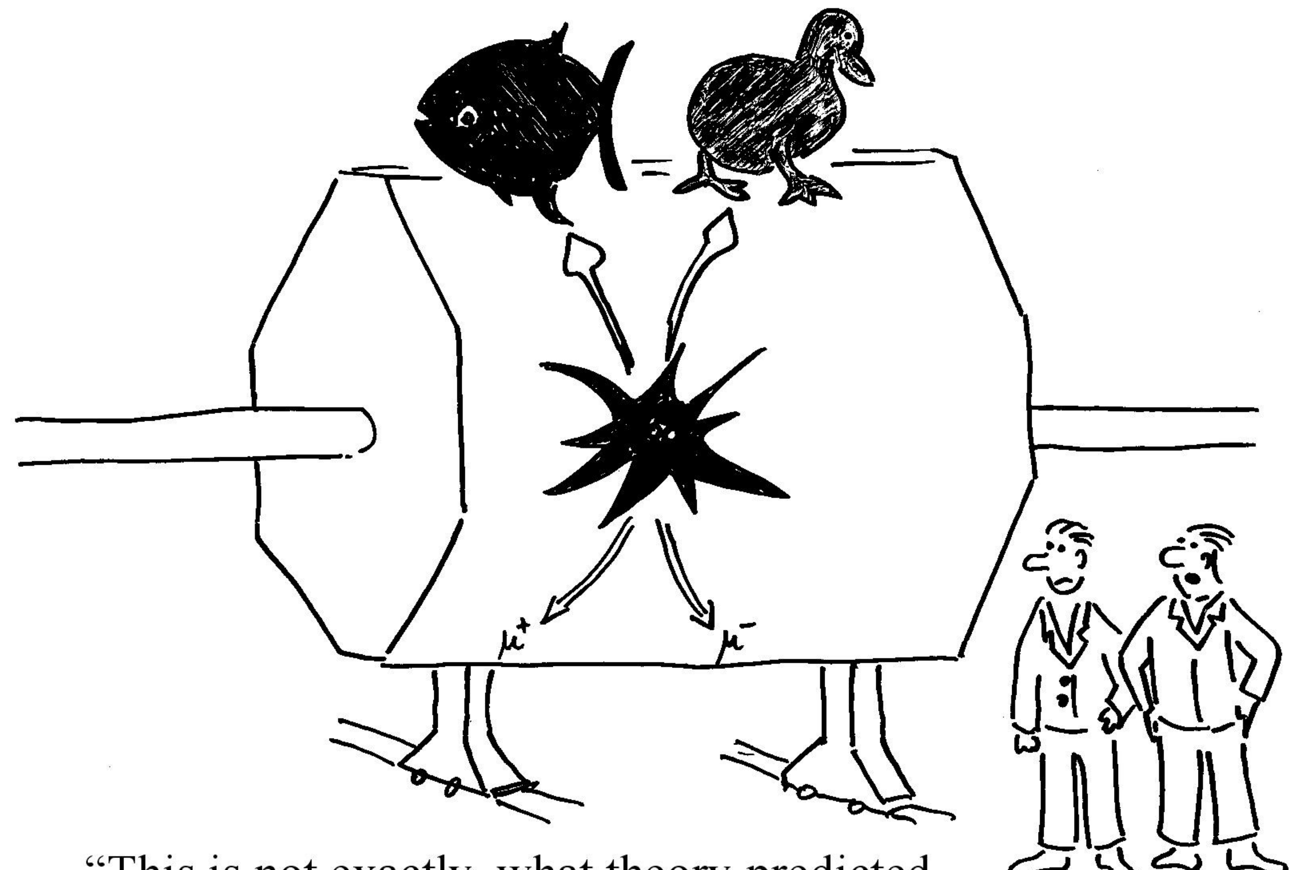
✖ Higgs exotic decays can offer one of the best routes to access light dark/hidden new physics particles.

The field recently started.
Many open questions both for experimentalists and theorists!

Warning: urgency of searching for Higgs exotic decays in order not too loose the capability of searching for them (trigger thresholds!).

Conclusions and outlook

It is crucial to think broadly about the Higgs boson!



"This is not exactly, what theory predicted for the Higgs decay!"

Our assumptions and decay topologies

1. The observed 125 GeV is SM-like

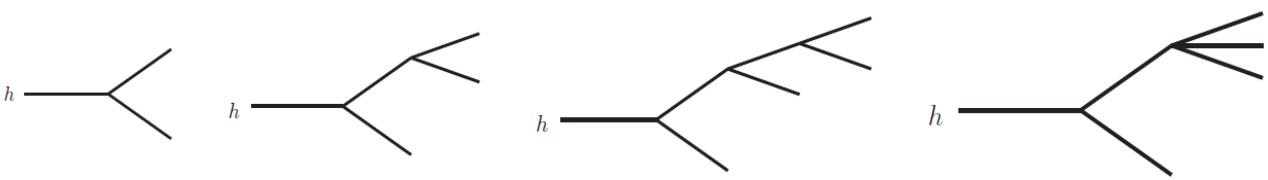
- In particular its production cross section in the several channels is the one of the SM Higgs

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

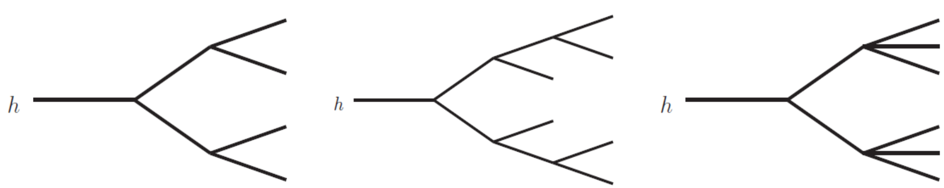
- we do not consider rare or nonstandard decays to SM particles

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



$h \to 2$ $h \to 2 \to 3$ $h \to 2 \to 3 \to 4$ $h \to 2 \to (1+3)$



$h \to 2 \to 4$ $h \to 2 \to 4 \to 6$ $h \to 2 \to 6$

h→MET	h→$Z_D Z_D$→4l
h→4b	h→γ+MET
h→2b2τ	h→2γ+MET
h→2b2μ	h→4l+MET
h→4τ, 2τ2μ	h→2l+MET
h→4j	h→one lepton jet
h→2γ2j	h→two lepton jets
h→4γ	h→bb+MET
h→ZZ_D→4l	h→ττ+MET