Review on Higgs exotic decays

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Perimeter Institute for Theoretical Physics

LHCP conference
Columbia University, New York

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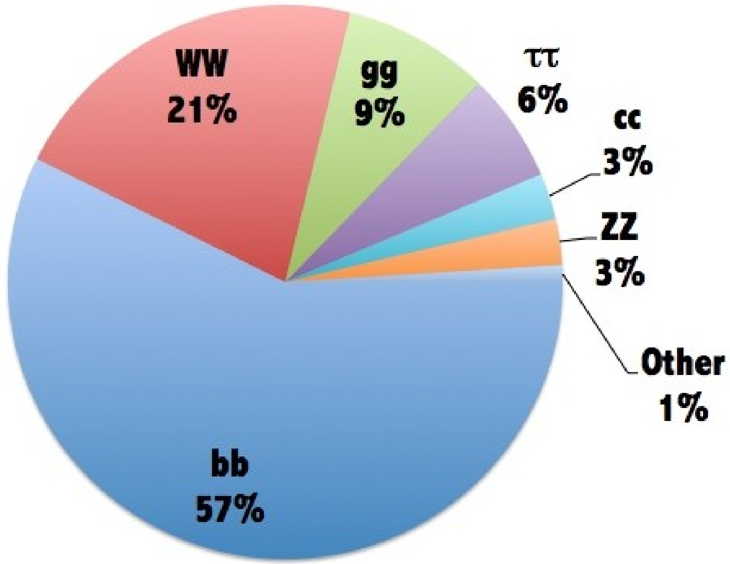
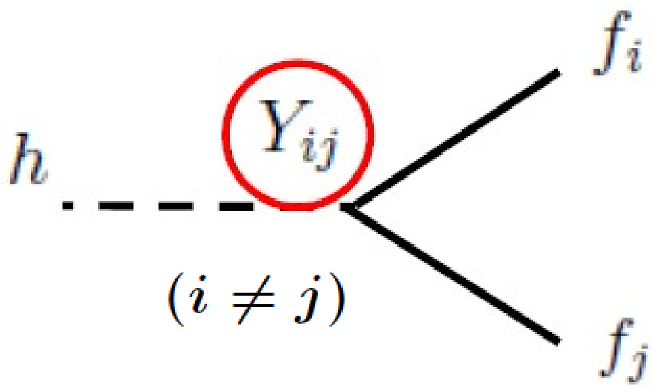
What´s exotic?



Standard model decay channels

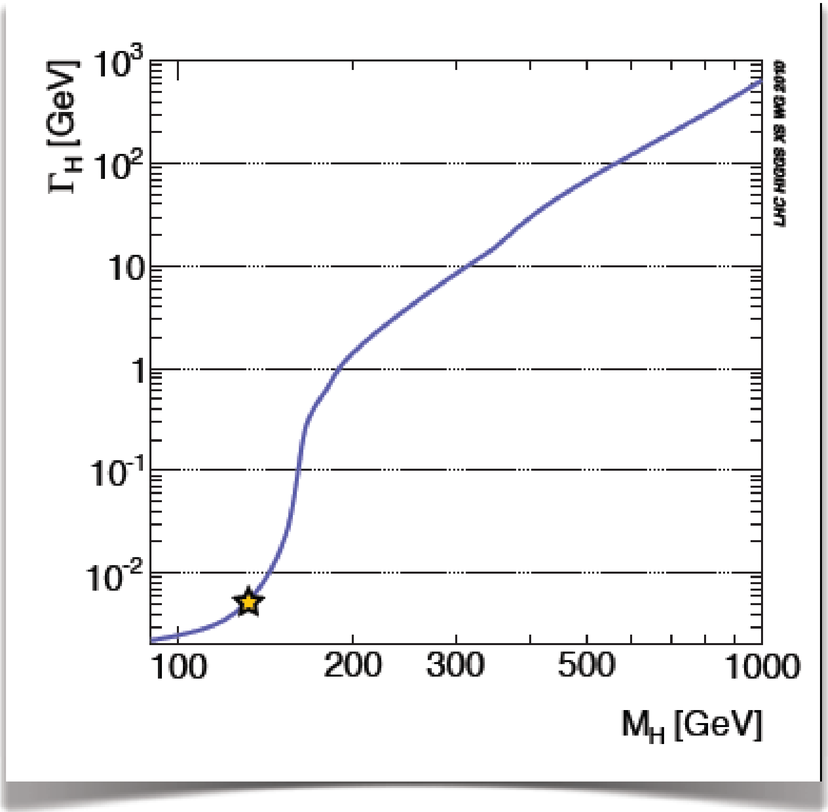


Flavor violating channels

What about $h \to \mathrm{NP}$?

Why is it interesting?

We discovered a quite light Higgs boson



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

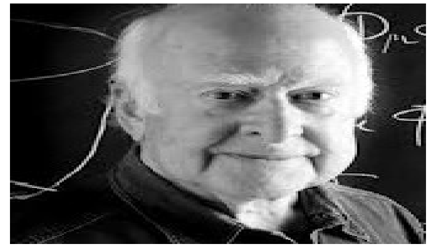
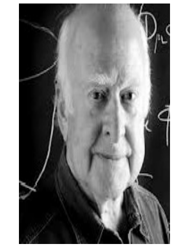
Even a small coupling to a light NP particle can lead to a sizable Higgs branching ratio for h $\longrightarrow$ NP NP

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

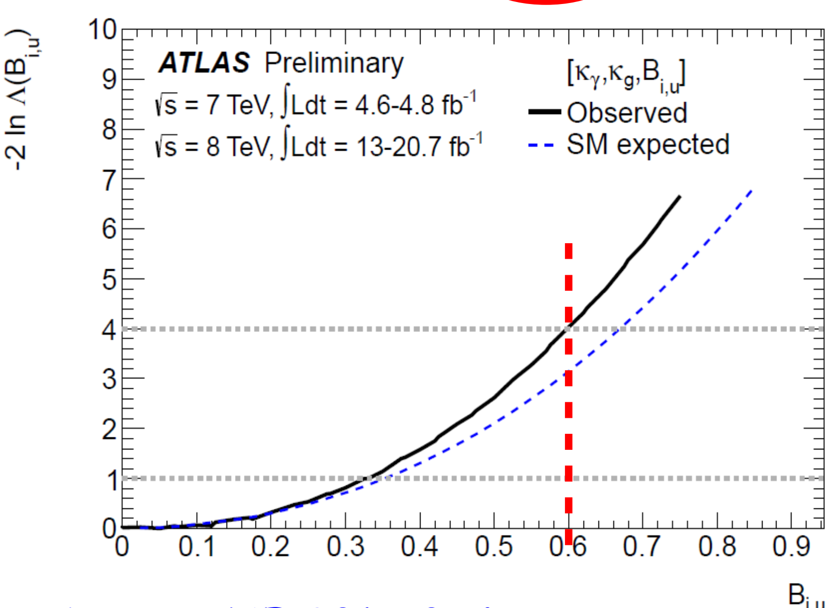
$$\zeta = \mathcal{O}(0.01) \Rightarrow {\rm Br}(h \to ss) = \mathcal{O}(10\%)$$

How to see it?

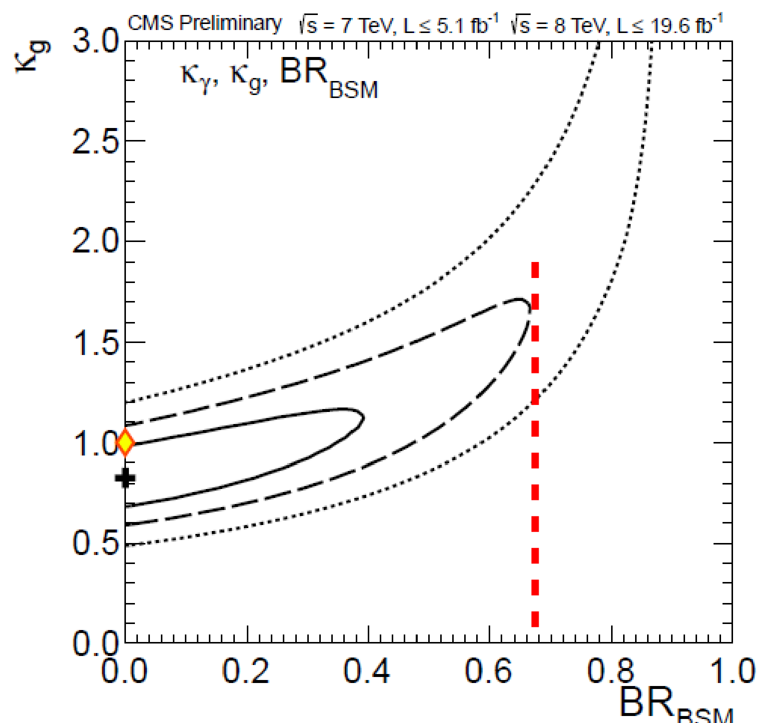
We have to determine if the Higgs has a

large width  or small width 

$$\text{rate} = \sigma(pp \to h)\frac{\Gamma(h \to X_{\rm SM})}{\Gamma_{\rm tot}}$$



ATLAS-CONF-2013-034



CMS-PAS-HIG-13-005

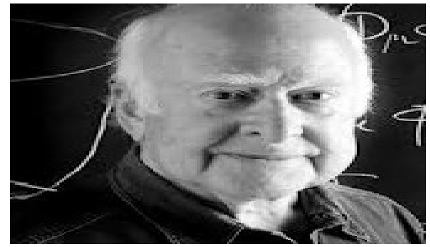
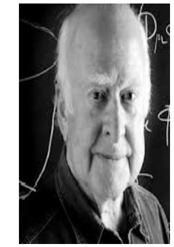
More direct measurement of the Higgs width

$\Gamma_H < 4.2(8.5)\ \Gamma_{H,SM}$

CMS PAS HIG-14-002

How to see it?

We have to determine if the Higgs has a

large width  or small width 

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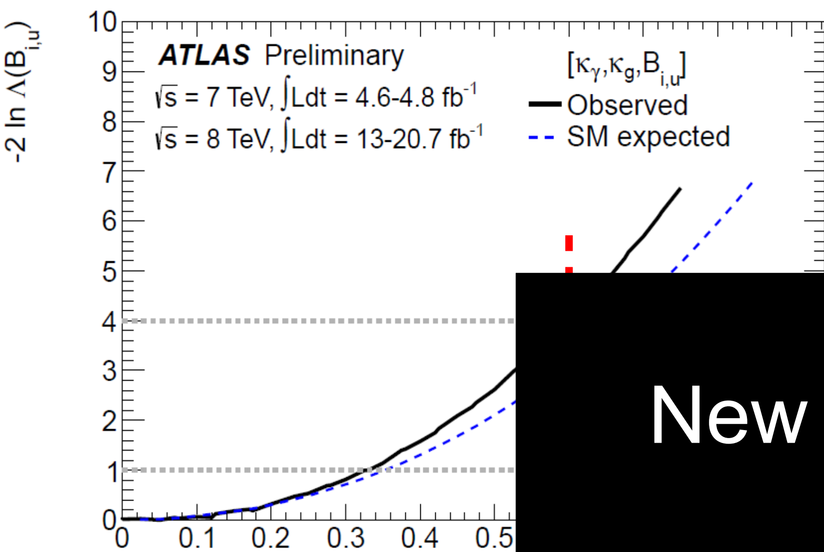
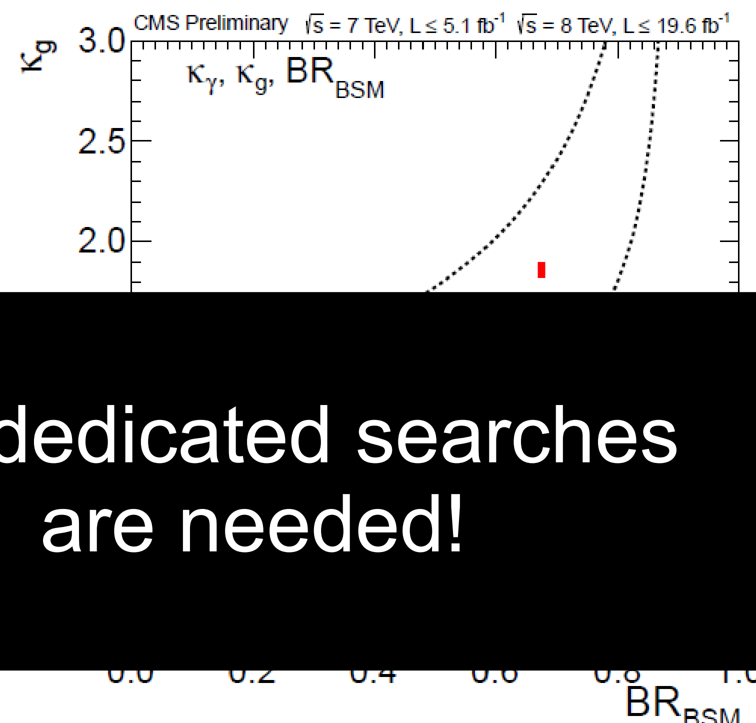


ATLAS-CONF-2013-034



CMS-PAS-HIG-13-005

New dedicated searches are needed!

More direct measurement of the Higgs width

$\Gamma_H < 4.2(8.5)\ \Gamma_{H,SM}$

CMS PAS HIG-14-002

Also in the future (300fb^{-1} 14TeV), we do not expect a (indirect) measurement better than ~10%

Shouldn´t it be already discovered?

Higgs ⟶ NP

Light NP Particles ($m_{NP} < m_h$)

- EW precision measurements
- Direct searches
- Flavor measurements

Not necessarily!

Shouldn´t it be already discovered?

Higgs ⟶ NP

Light NP Particles ($m_{NP}<m_h$)

- EW precision measurements
- Direct searches
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Not necessarily!

The Higgs can give us access to „dark sectors“ that communicate with the SM only very weakly

g,W,Z,γ

Known forces

?

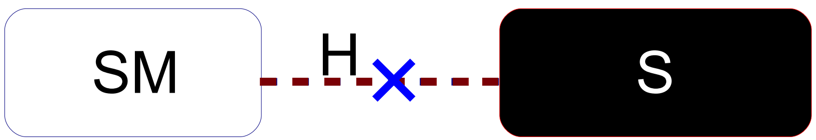
„Dark sectors“
Forces, particles, dark matter

only a few important possibilities exist that are allowed by Standard Model symmetries

Scalar & vector portals

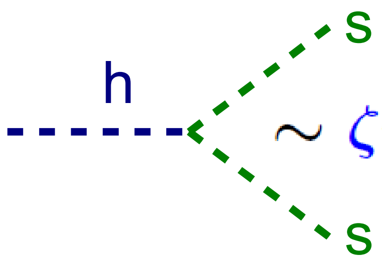
- Scalar portal

$$V(H,S) \supset \zeta |S|^2 |H|^2$$



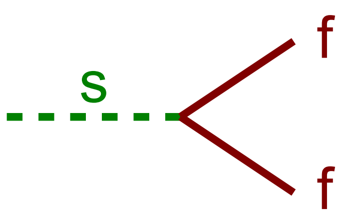
Arising in extended Higgs sector models: NMSSM, ...

After EWSB:



$\sim \zeta v$

If also S aquires a VEV, S and H mix and S is unstable ($\Theta \gtrsim 10^{-6}$ to have a prompt decay):



Scalar & vector portals

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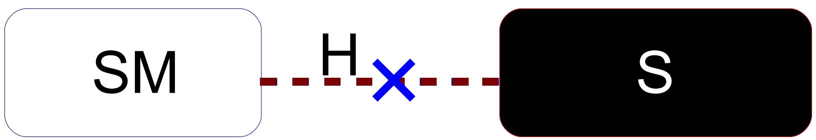

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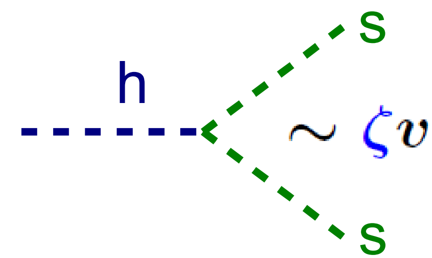

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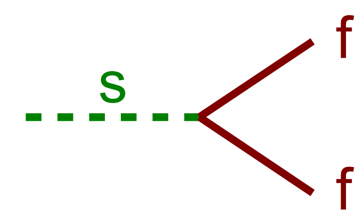
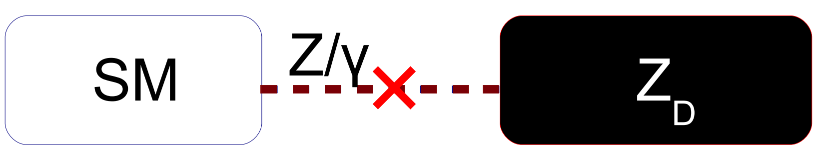
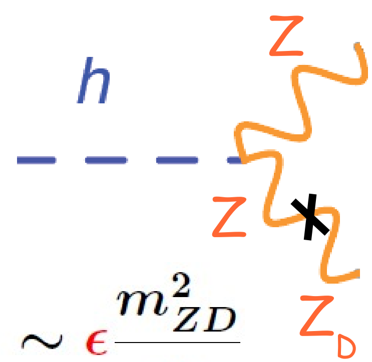


- Vector portal

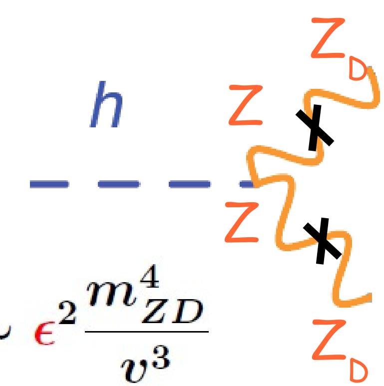
$$\mathcal{L} \supset \frac{\epsilon}{2\cos\theta} \hat{B}_{\mu\nu} \hat{Z}_D^{\mu\nu}$$



Realized e.g. in Hidden valley models, ...



$\sim \epsilon \frac{m^2_{ZD}}{v}$

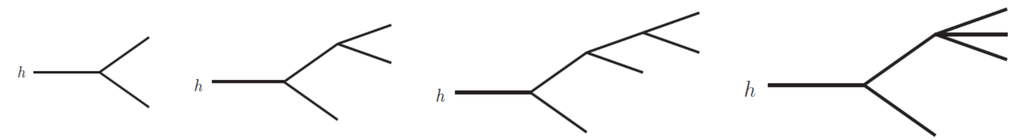


$\sim \epsilon^2 \frac{m^4_{ZD}}{v^3}$

Z_D decays proptly as long as $\varepsilon \gtrsim O(10^{-4})$

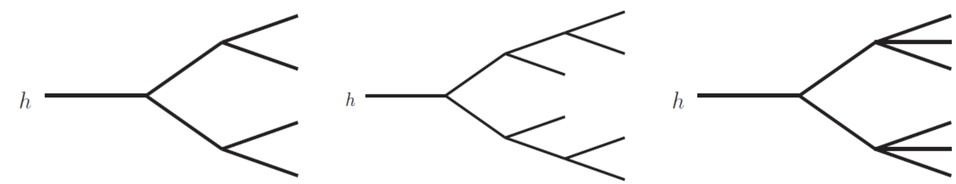
Huge landscape of possibilities

Signatures depend on how
NP states decay back to the SM



h⟶2; h⟶2⟶3; h⟶2⟶3⟶4; h⟶2⟶(1+3)

NMSSM-like, semi-invisible,
high multiplicity, displaced, ...



h⟶2⟶4; h⟶2⟶4⟶6; h⟶2⟶6

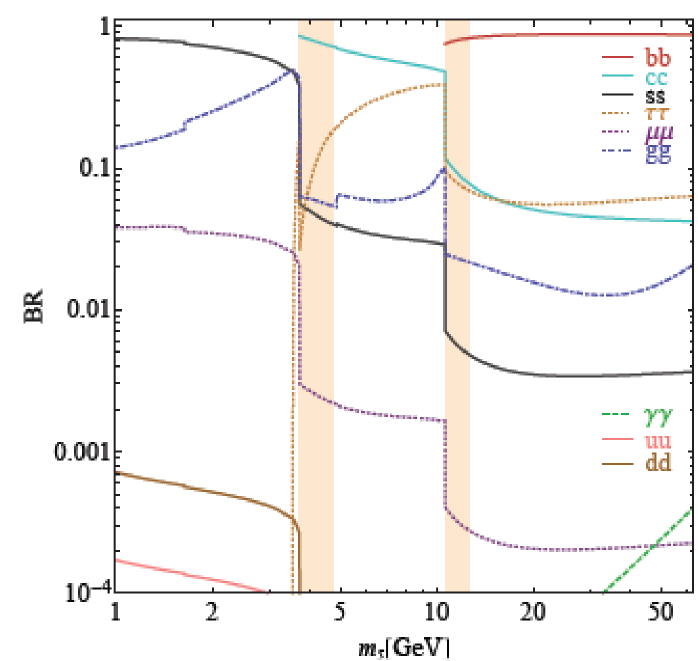
Example:
the „minimal scalar portal“ model

$$h \to ss$$

Exotic scorecard

	jj	bb	$\tau\tau$	ll	$\gamma\gamma$
jj					
bb					
$\tau\tau$					
ll					
$\gamma\gamma$					

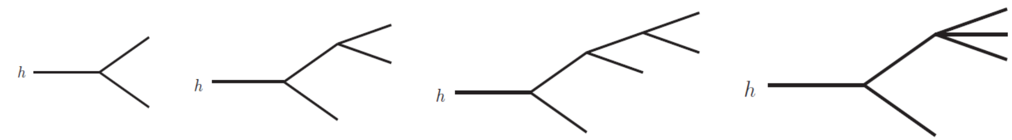
Prospects?



S branching ratios

Huge landscape of possibilities

Signatures depend on how NP states decay back to the SM



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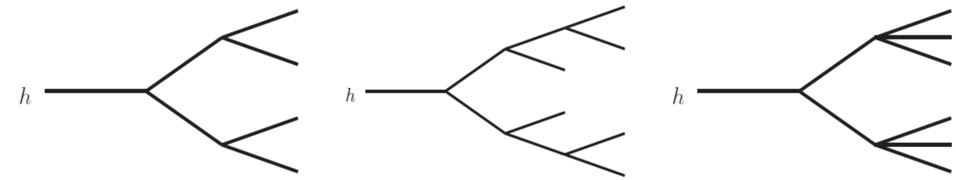


h⟶2⟶4; h⟶2⟶4⟶6; h⟶2⟶6

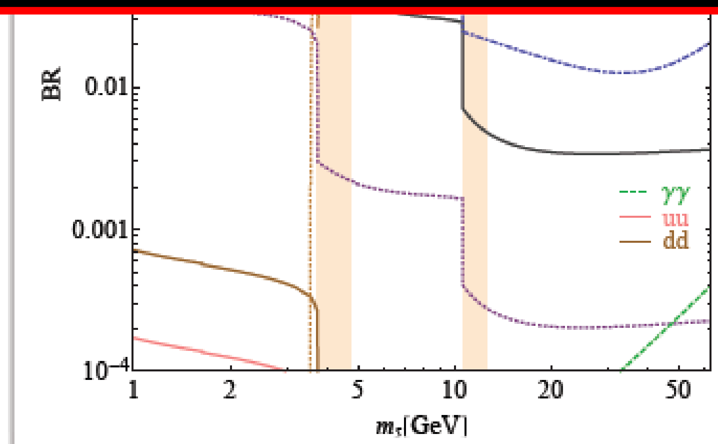
Exotic Decays of the 125 GeV Higgs Boson, 1312.4992

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

Exotic scorecard

	jj	bb	ττ	ll	γγ
jj					
bb					
ττ					
ll					
γγ					

Prospects?

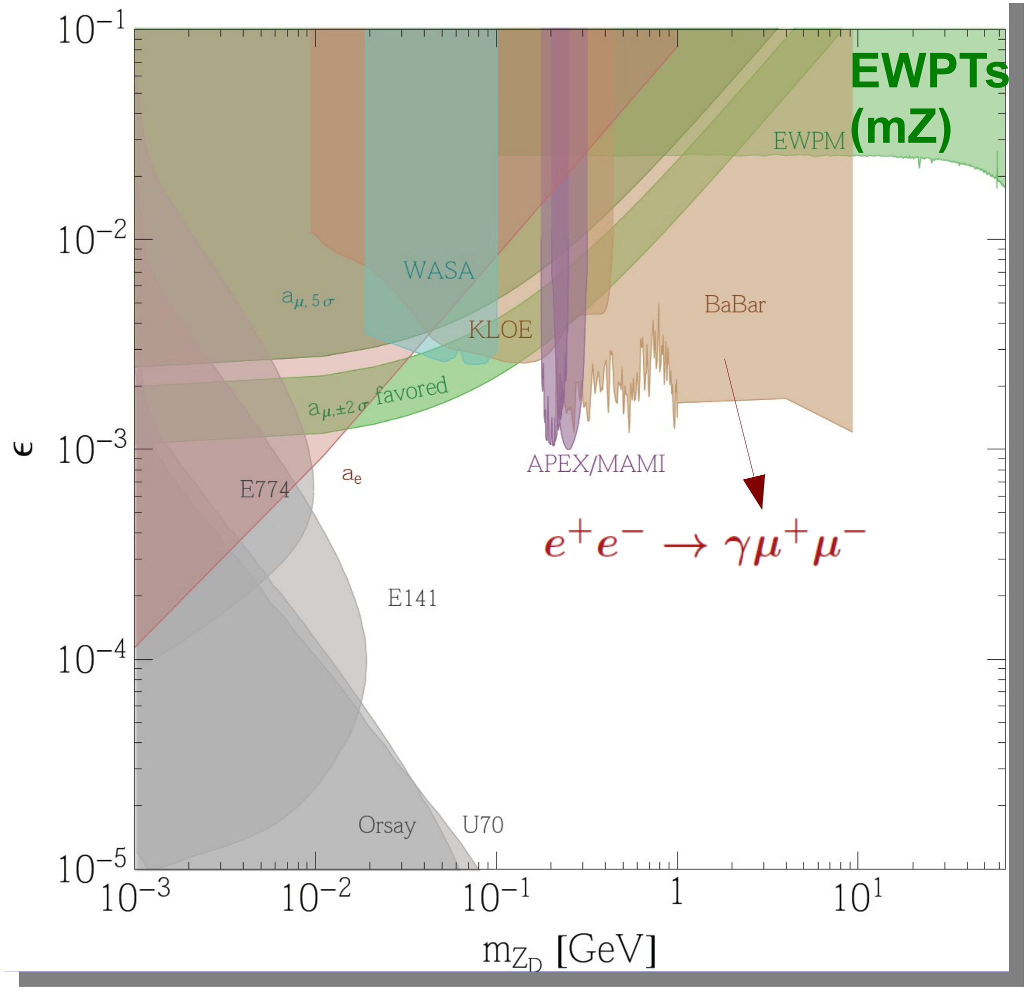


S branching ratios

Multileptons from a dark boson

Let´s work out a very interesting possibility:
new kinetically mixed gauge bosons

Present bounds from „non-Higgs searches“



$$\mathcal{L} \supset \frac{\epsilon}{2\cos\theta} \hat{B}_{\mu\nu} \hat{Z}_D^{\mu\nu}$$

+ mass term for Z_D
coming from Stueckelberg mechanism / dark Higgs that breaks the U(1)' symmetry

Multileptons from a dark boson

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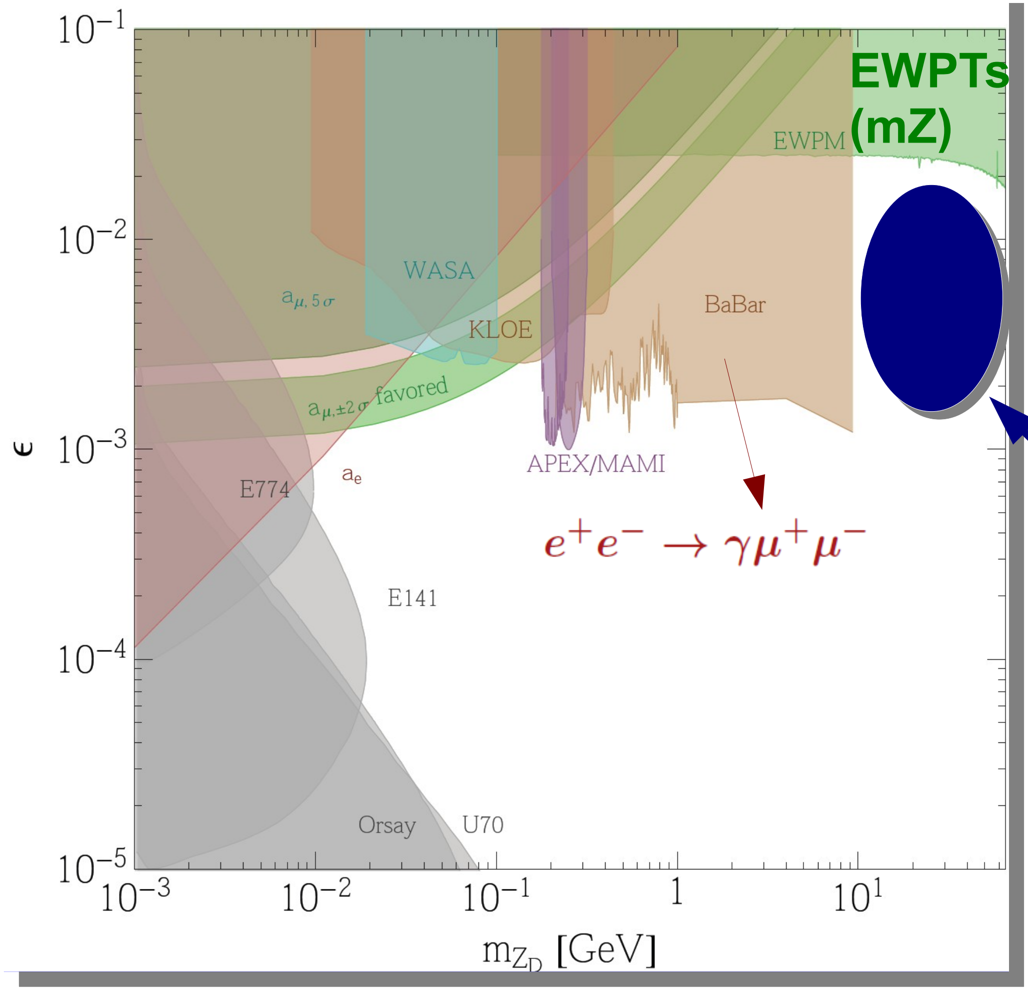
Present bounds from „non-Higgs searches"



$$\mathcal{L} \supset \frac{\epsilon}{2\cos\theta}\hat{B}_{\mu\nu}\hat{Z}_D^{\mu\nu}$$

$$h \to ZZ_D,\ h \to Z_D Z_D$$

Natural value for ε if generated at the loop level

Multileptons from a dark boson

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new kinetically mixed gauge bosons

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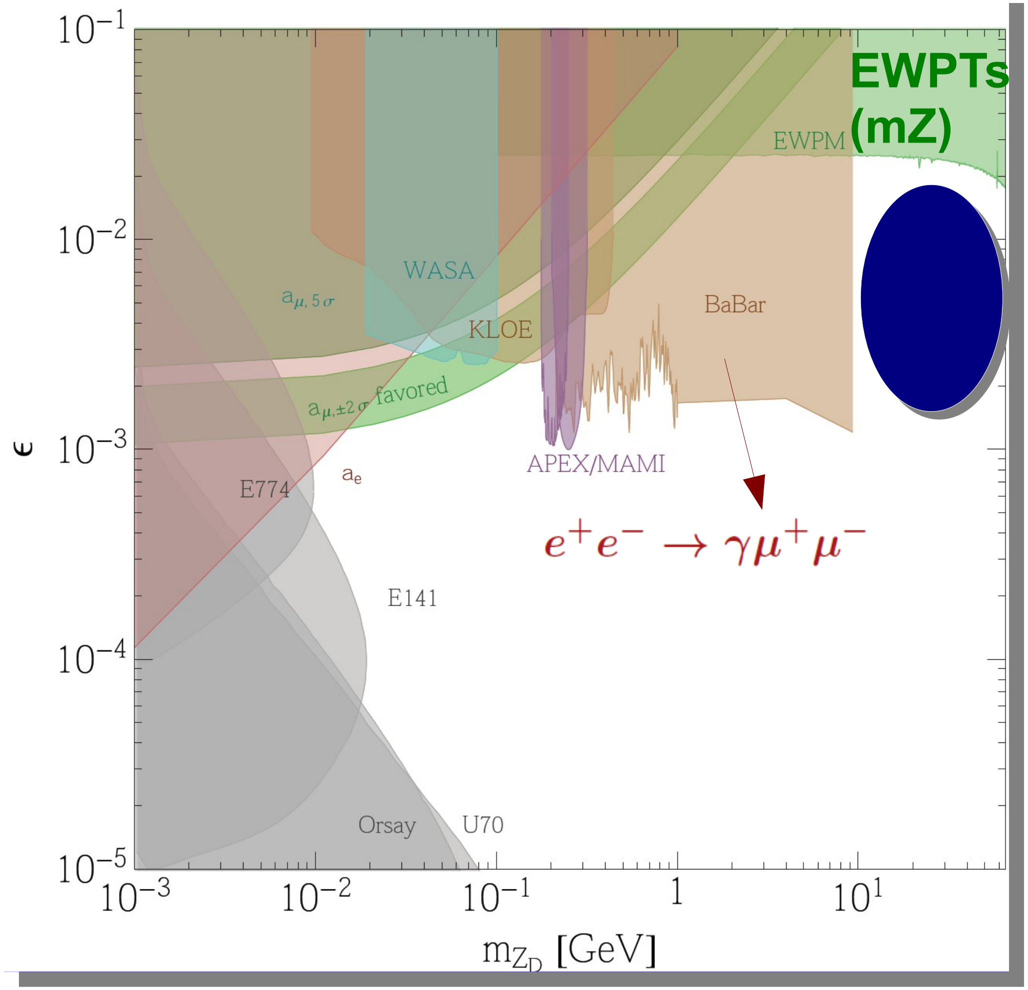

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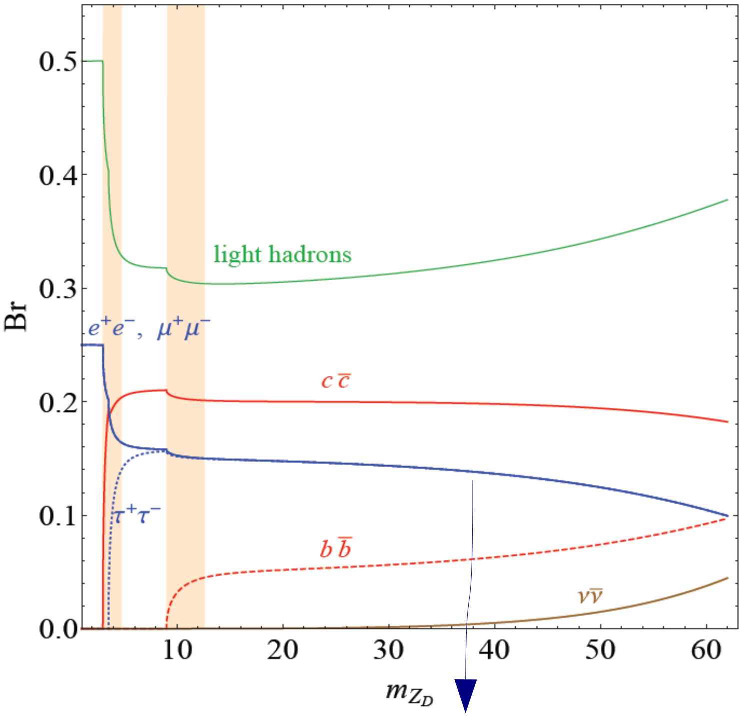
$$h \to ZZ_D,\ h \to Z_DZ_D$$



Higgs four lepton signature!

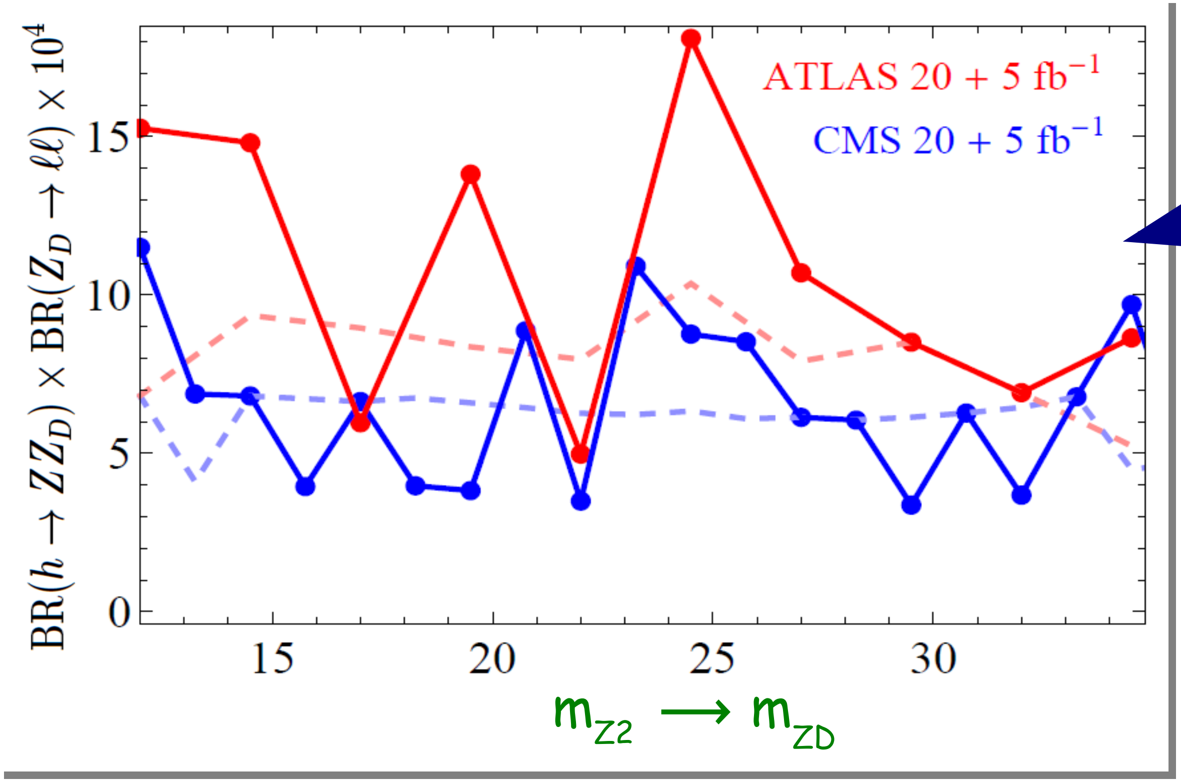
Setting bounds ZZ_D: present

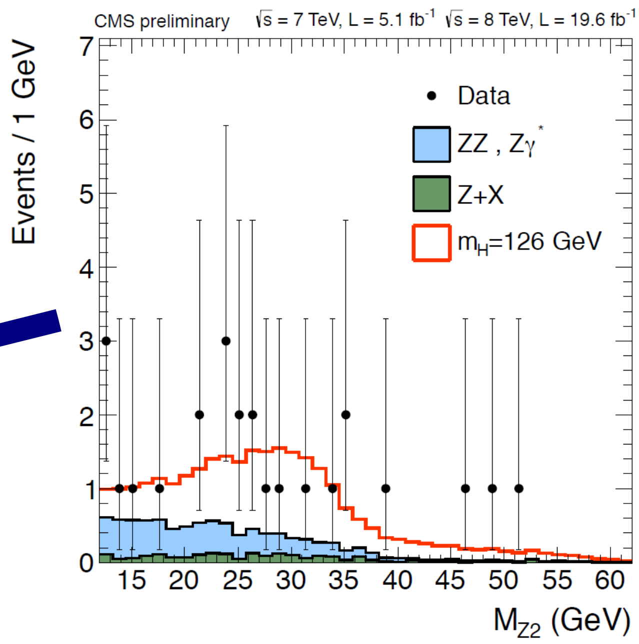
Bounds coming from SM h → ZZ*→ 4l searches at the LHC
CMS PAS HIG-13-002, ATLAS-CONF-2013-013

The four leptons are divided in two same flavor opposite sign (SFOS) pairs: the pair closest to Z „Z1“ and the other pair „Z2“

$$hZZ_D \sim \epsilon \frac{m_{ZD}^2}{v}$$

Counting experiment:





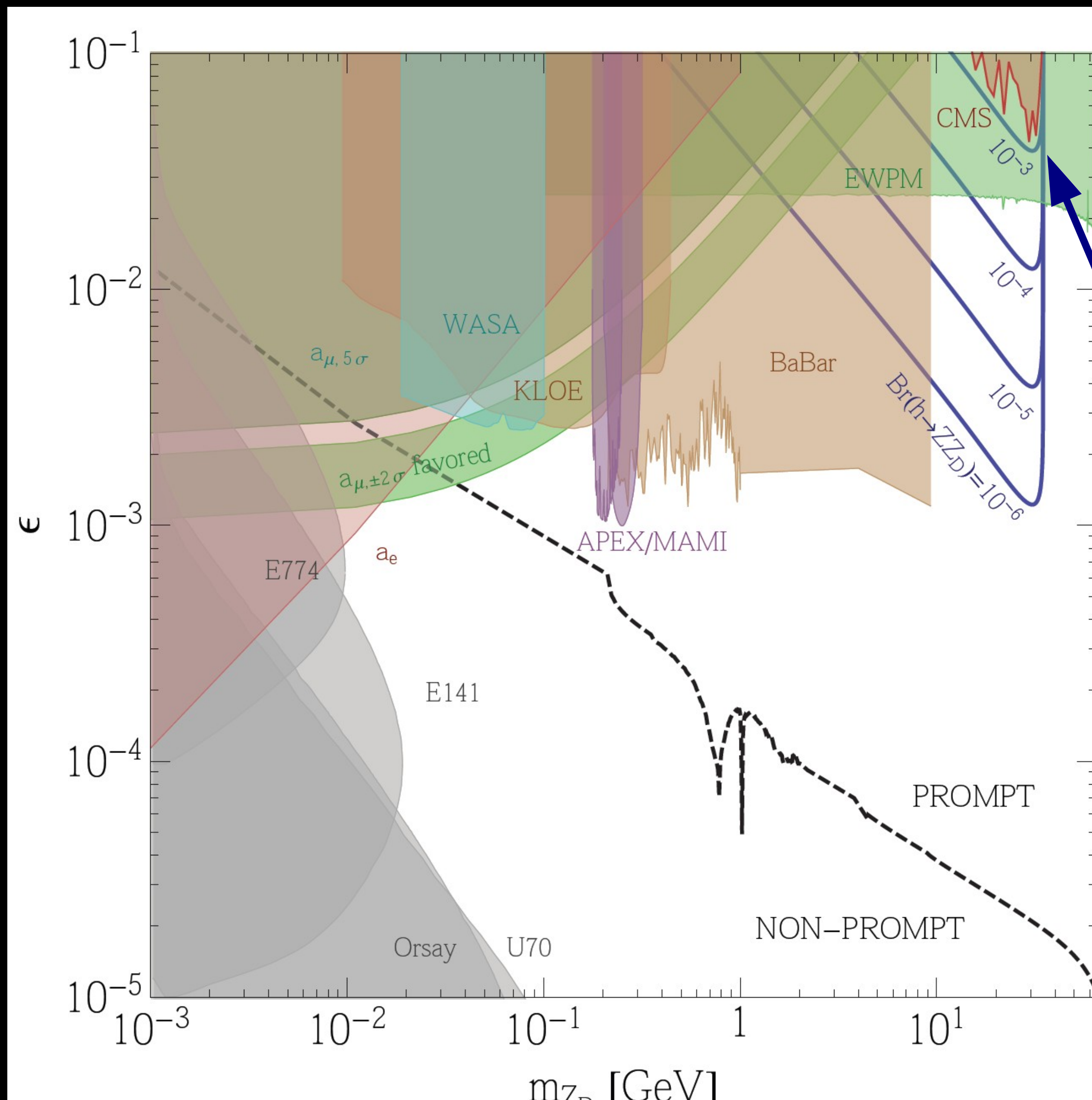
BR($h \longrightarrow ZZ_D$)~10^{-3} are already probed with the present (un-dedicated) 7+8 TeV LHC searches

Setting bounds ZZ_D : present

Bounds coming from SM $h \to ZZ^* \to 4l$ searches at the LHC

The f
two s
pairs

Coun



The Higgs bound is already approaching the bound coming from ~20 years of EWPTs!

eady
nt
V
LHC searches

Setting bounds $Z_D Z_D$: present

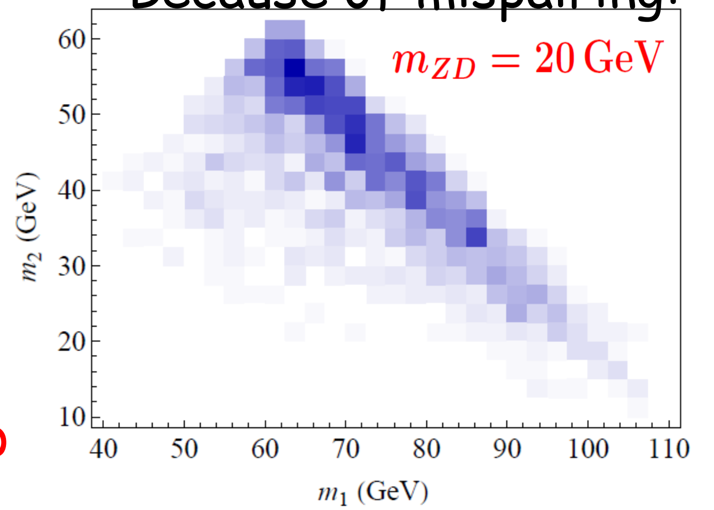
Bounds coming from SM h → ZZ*→ 4l searches at the LHC

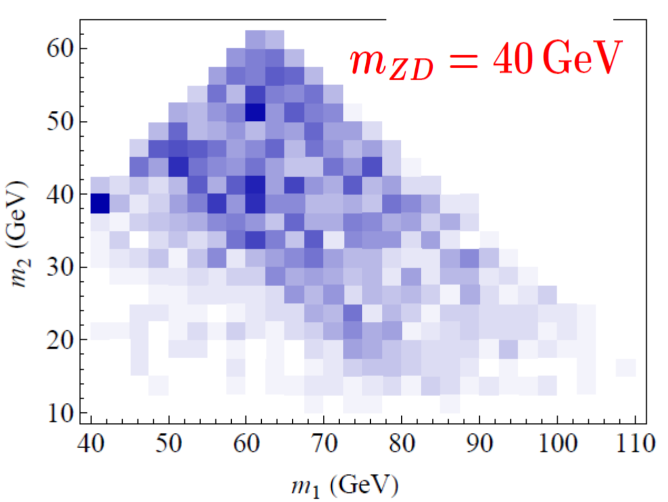
CMS PAS HIG-13-002, ATLAS-CONF-2013-013

$$hZ_DZ_D \sim \epsilon^2 \frac{m_{ZD}^4}{v^3}$$

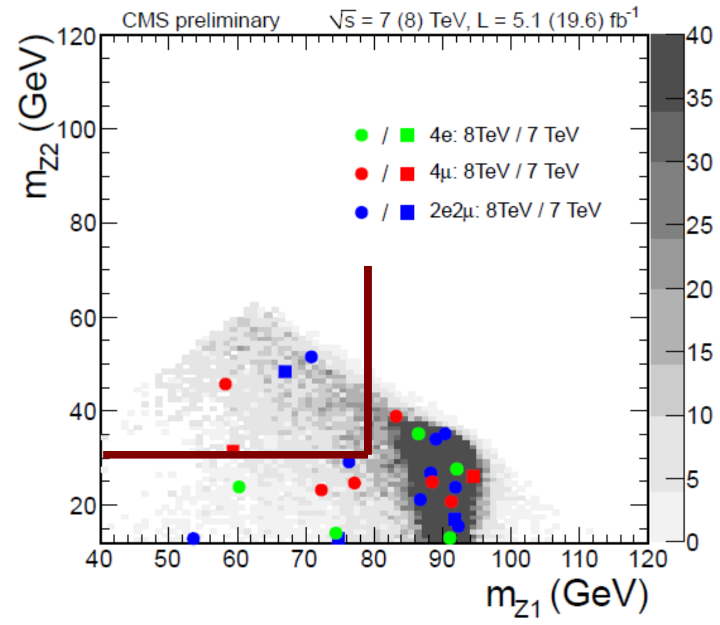
Our signal

Because of mispairing:





To compare to the experimental data:

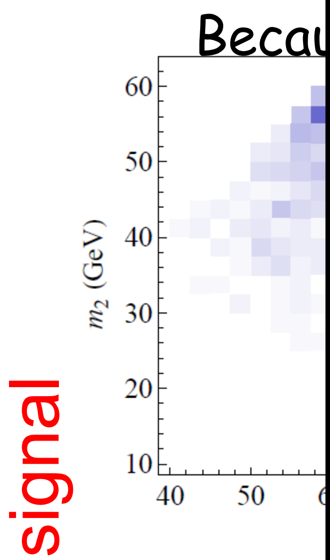


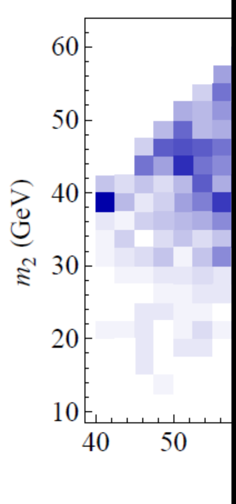
CMS PAS HIG-13-002

Setting bounds $Z_D Z_D$: present

Bounds com… -2013-013

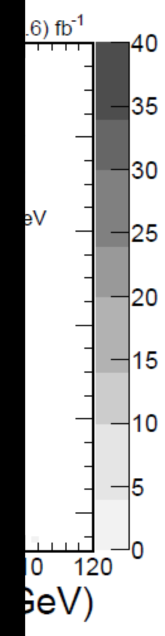
Becau…



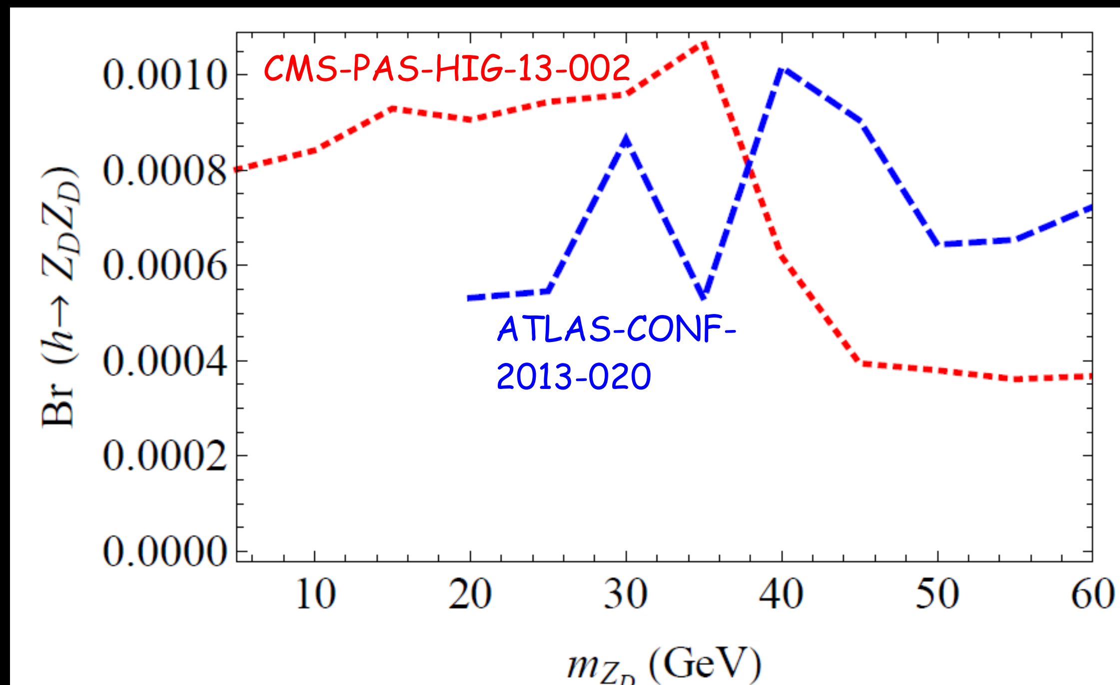


$\ldots Z_D \sim \epsilon^2 \frac{m_{ZD}^4}{v^3}$

…mental data:

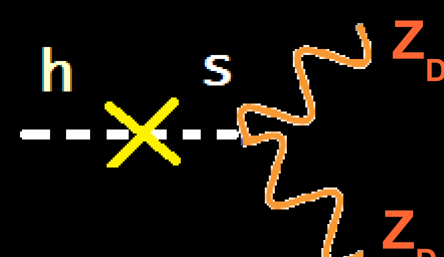


CMS-PAS-HIG-13-002



No relevant bounds in the ε-m_{ZD} plane

Still important bounds for different theories



Setting bounds: future

D.Curtin, R.Essig, S.G., J.Shelton, in preparation

- What about the projection for the 14 TeV LHC?
- What about heavier (>35GeV) Z_D bosons?

And in particular what about the shape of the two invariant mass distributions in the case of off-shell Z_D? (some interference effects with $h \longrightarrow ZZ^*$?)

Good prospects using the matrix element method
Falkowski, Vega Morales, 1405.1095

Dedicated searches at LHC14 can give a bound $BR(ZZ_D) \sim 10^{-4}$ for $m_{ZD} \leq 10$ GeV
Davoudiasl et al.1304.4935

- Interplay with EW precision measurements:

LHC will give us a much more precise measurement of the W mass:

	Present	Tevatron full dataset	LHC14, 300 fb^{-1}	LHC14, 3000 fb^{-1}
ΔM_W (MeV)	15	9	8	5

NP effects in the T parameter

The Z_D scorecard

$h \to ZZ_D$

Decay Mode $\mathcal{F}_i$	Projected/Current 2σ Limit on $\mathrm{Br}(\mathcal{F}_i)$ 7+8 [14] TeV	Production Mode	$\frac{\mathrm{Br}(\mathcal{F}_i)}{\mathrm{Br}(non-SM)}$	Limit on $\frac{\sigma}{\sigma_{SM}} \cdot \mathrm{BR(non\text{-}SM)}$ 7+8 [14] TeV
$ZZ_D \to \ell\ell\ell\ell$	$2 \cdot 10^{-5\ R}$ [U]	G	0.02	0.001 [U]

(experiment) $h \longrightarrow 4l$

(theory) $ZZ_D \longrightarrow 4l$

$h \longrightarrow ZZ_D$

$h \to Z_D Z_D$

Decay Mode $\mathcal{F}_i$	Projected/Current 2σ Limit on $\mathrm{Br}(\mathcal{F}_i)$ 7+8 [14] TeV	Production Mode	$\frac{\mathrm{Br}(\mathcal{F}_i)}{\mathrm{BR(non-SM)}}$	Limit on $\frac{\sigma}{\sigma_{SM}} \cdot \mathrm{BR(non\text{-}SM)}$ 7+8 [14] TeV
$jjjj$	> 1 $[0.1^{L*}]$	W	0.25	> 1 [0.4*]
$\ell\ell\ell\ell$	$4 \cdot 10^{-5\ R}$ [U]	G	0.09	$4 \cdot 10^{-4}$ [U]
$jj\mu\mu$	$0.002 - 0.008\ ^T$ $[(5-20) \times 10^{-4\ T}]$	G	0.15	$0.01 - 0.06$ $[0.003 - 0.01]$
$b\bar{b}\mu\mu$	$(2-7) \cdot 10^{-4\ T}$ $[(6-20) \cdot 10^{-5\ T}]$	G	0.015	$0.01 - 0.05$ $[0.003 - 0.01]$

Chen, Nojiri, Sreethawong 1006.1151 ($jjjj$, $\ell\ell\ell\ell$)

Our theory study ($jj\mu\mu$, $b\bar{b}\mu\mu$)

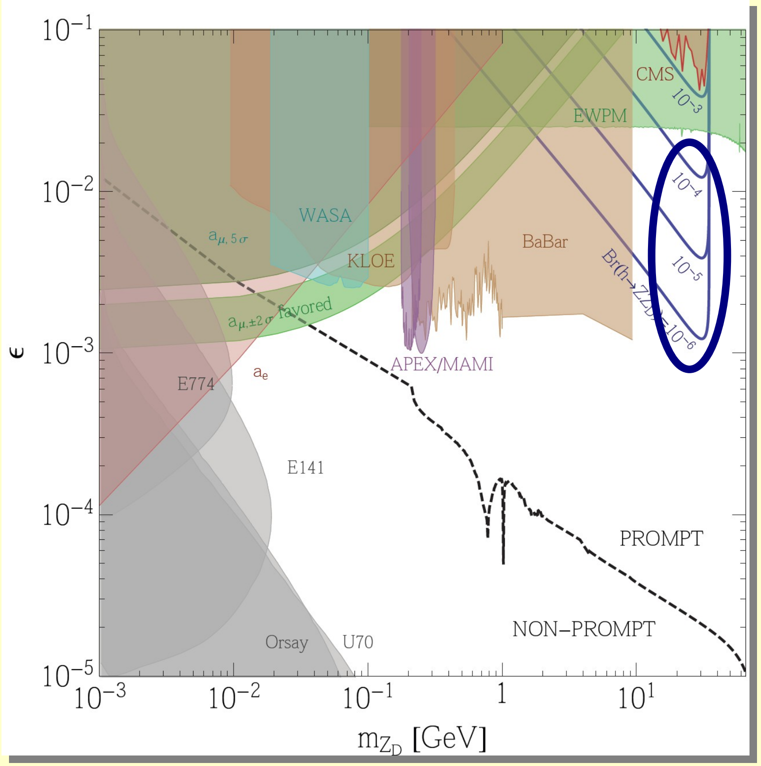
Conclusions

- The observed 125 GeV Higgs boson is highly sensitive to the potential existence of new light degrees of freedom
- Exotic Higgs decays are a robustly-motivated class of signatures that must be searched for explicitly

- Exciting prospects to probe dark Z models in a „natural“ region of the parameter space

$\varepsilon \sim 10^{-2}$, $10\,\mathrm{GeV} \lesssim m_{Z_D} \lesssim m_Z$

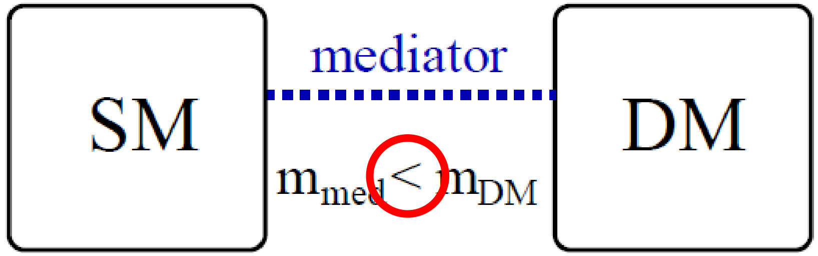
through the golden channel: $h \to Z\, Z_D \to 4l$

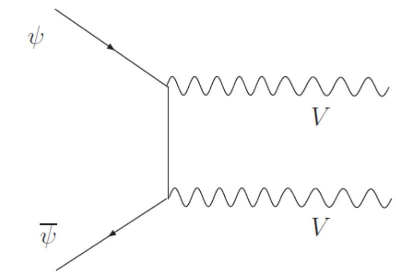


Secluded models for dark matter

Arkani-Hamed et al 0810.0713
Pospelov et.al. 0711.4866

Mechanism:





Suppression of DM direct detection signals, but still possible to have a thermal DM candidate

The only link between the SM and the dark sector: $\mathcal{L} \supset \frac{\epsilon}{2\cos\theta} \hat{B}_{\mu\nu} \hat{Z}_D^{\mu\nu}$

+ mass term for Z_D coming from Stueckelberg mechanism / dark Higgs that breaks the U(1)' symmetry

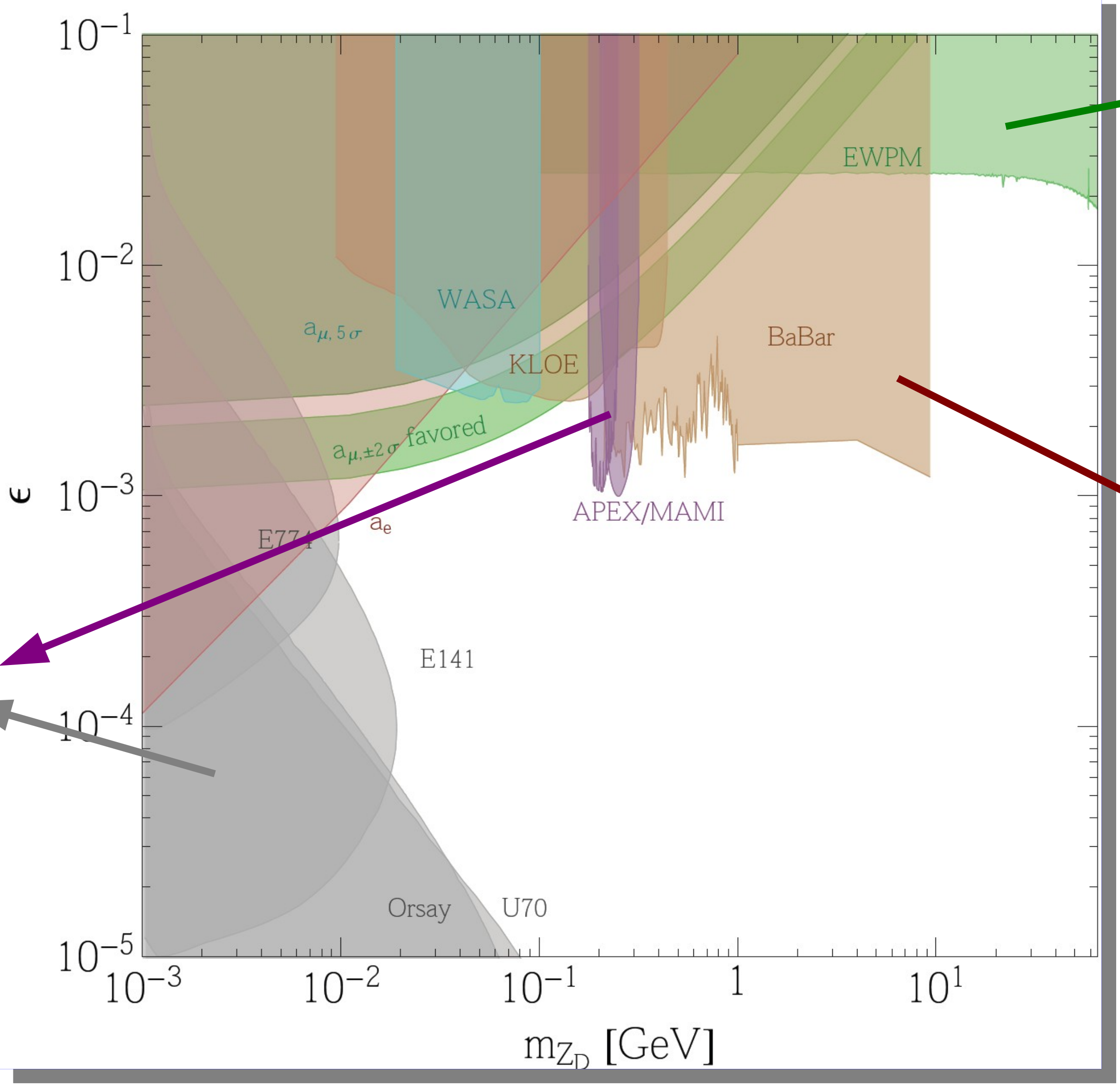
Minimal extension:
the sector that breaks U(1)' does not talk to the SM Higgs

NP effects for the Z boson:

- Tree level shift in the Z mass: $m_Z^2 \sim m_{Z0}^2 (1 + \epsilon^2 \tan^2\theta)$
- Modification of the Z couplings $\sim (Zf\bar{f})_{\rm SM} \left(1 + \epsilon^2 \frac{\tan^2\theta}{2} \cdot \frac{T_3 - Q(1+\cos^2\theta)}{T_3 - Q\sin^2\theta}\right)$

How to probe the model

A plethora of probes of the model



Mainly driven by the tree level shift in the Z boson mass

Hook, Izaguirre, Wacker, 1006.0973

$e^+e^- \to \gamma\mu^+\mu^-$

0902.2176

Fixed targed experiments

Bjorken, Essig, Schuster, Toro 0906.0580

Curtin, Essig, S.G., Jaiswal, Katz, Liu, Liu, McKeen, Shelton, Strassler, Surujon, Tweedie, Zhong, 1312.4992

Our assumptions

1. The observed 125 GeV is SM-like

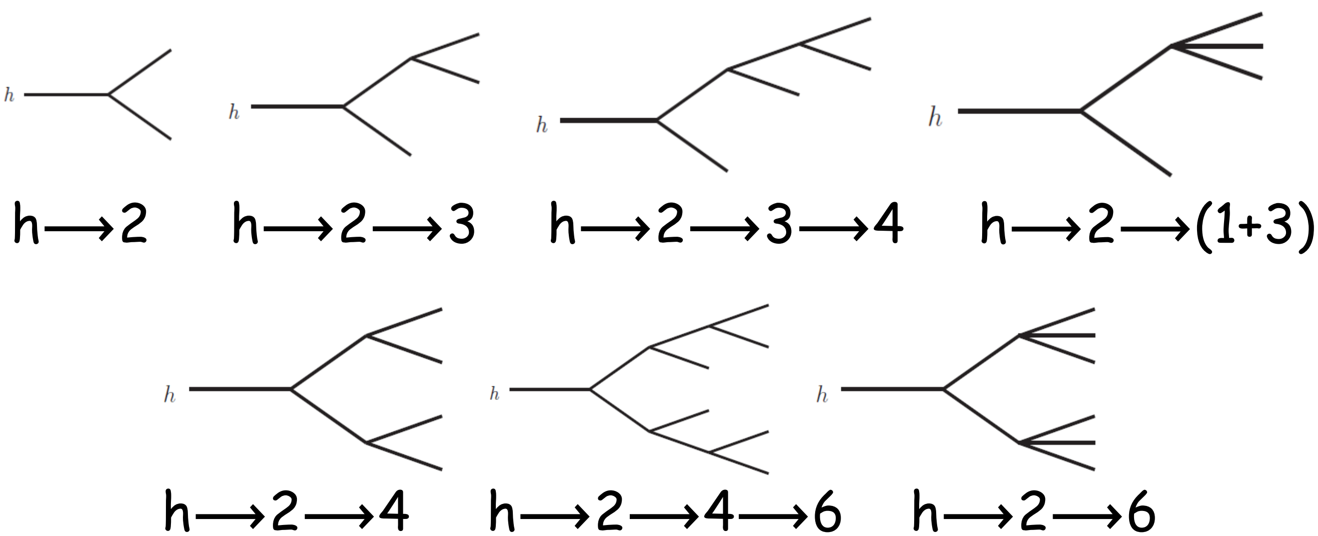
• In particular its production cross section in the several channels is the one of the SM Higgs

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→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

Higgs width: direct measurement

CMS PAS HIG-14-002

F. Caola, K. Melnikov (1307.4935)
J. Campbell et al. (1311.3589)

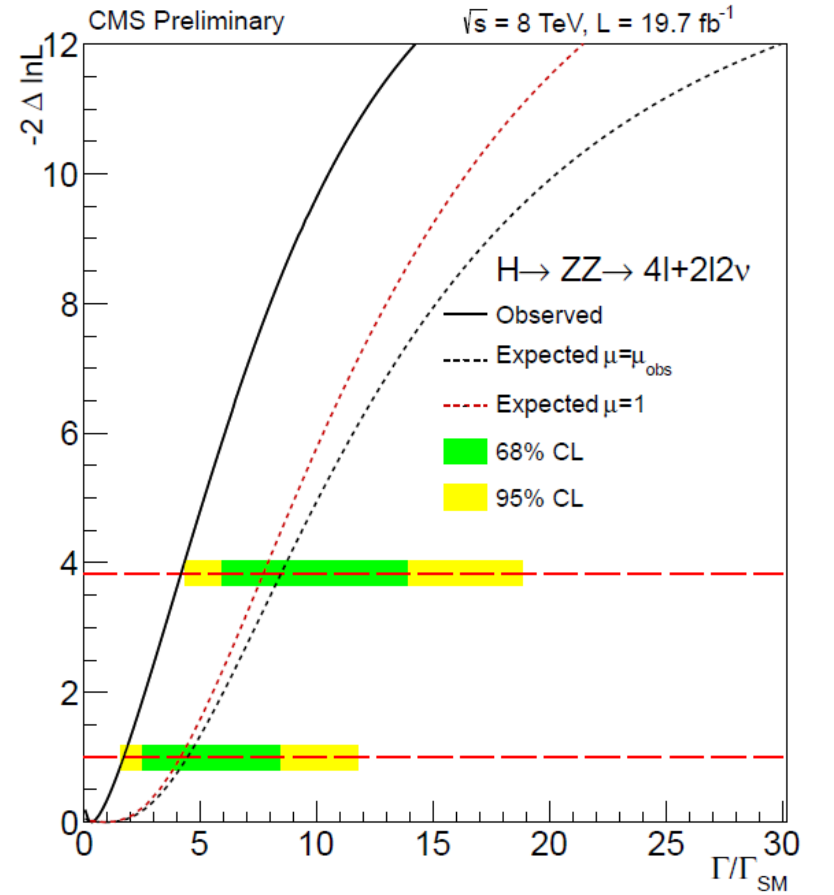
Very interesting new CMS measurement

In a nutshell:

$$\begin{cases} \sigma_{gg\to H\to ZZ}^{\rm on-peak} = \dfrac{\kappa_g^2\kappa_Z^2}{r}(\sigma\cdot {\rm BR})_{\rm SM} \equiv \mu(\sigma\cdot{\rm BR})_{\rm SM} \\ \dfrac{\sigma_{gg\to H\to ZZ}^{\rm off-peak}}{dm_{ZZ}} = \kappa_g^2\kappa_Z^2\dfrac{\sigma_{gg\to H\to ZZ}^{\rm off-peak,\,SM}}{dm_{ZZ}} = \mu r\dfrac{\sigma_{gg\to H\to ZZ}^{\rm off-peak,\,SM}}{dm_{ZZ}} \end{cases}$$

$$\kappa_g = g_{ggH}/g_{ggH}^{\rm SM}$$
$$\kappa_Z = g_{HZZ}/g_{HZZ}^{\rm SM}$$
$$r = \Gamma_H/\Gamma_H^{\rm SM}$$

$\Gamma_H < 4.2(8.5)\,\Gamma_{H,SM}$



Combining the 4l and the 2l2ν channels