# Dark forces and Higgs exotic decays

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BSM Higgs Workshop @ LPC
Fermilab

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# Dark Matter and the Higgs

- The nature of dark matter is still a mystery
- The WIMP miracle and EWSB point towards the same scale: the electroweak scale
- Maybe the Higgs is (one of) the best way to have access to DM?
- The Higgs can easily couple to DM: $\frac{1}{\Lambda} H H^\dagger \bar{\chi}\chi, \; H H^\dagger S^2$

Very much motivated to look for the Higgs decaying to invisible!

In good shape:

ATLAS 1402.3244, Zh, Z→ll,
CMS PAS HIG-13-018, Zh, Z→ll,
CMS PAS HIG-13-028, Zh, Z→bb,
CMS-PAS-HIG-13-013 VBF Higgs

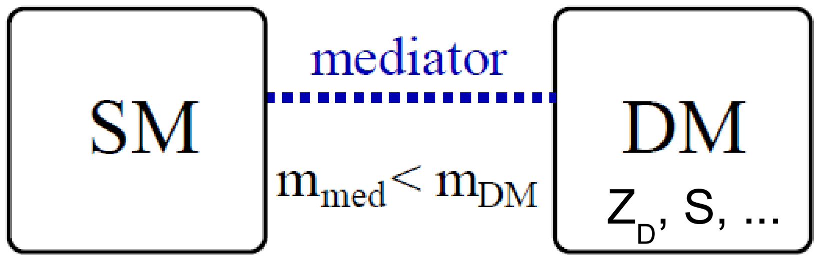
Zhou, et al. tth, 1408.0011

# Secluded Dark Matter

## Something beyond this simple framework?

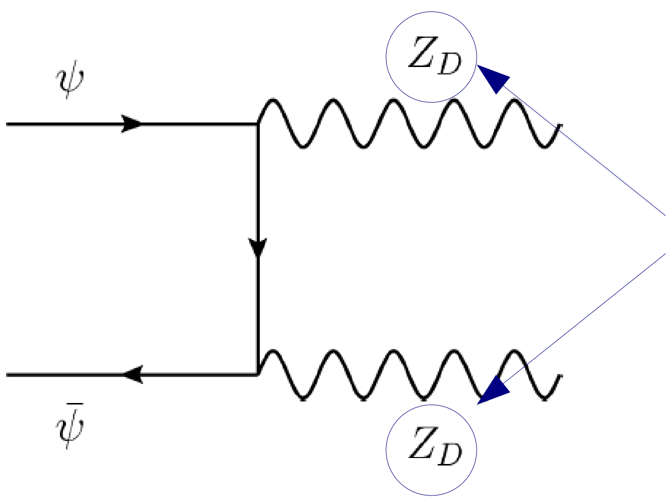
Pospelov et.al. 0711.4866
Feldman et al 0702123

DM does not interact „directly“ with our SM world, but only „indirectly“




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

Example:




They ultimately decay to SM states thanks to the „**portal**“

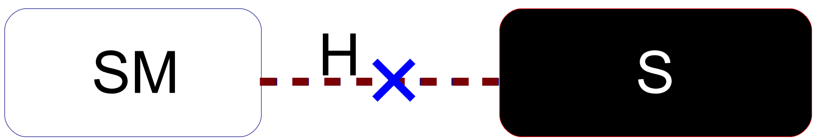
$$\frac{\epsilon}{2\cos\theta}\hat{B}_{\mu\nu}\hat{Z}_D^{\mu\nu}$$

How to probe this setup in non-DM experiments? New Higgs measurements?

# Secluded DM & Visible Matter

- Scalar portal

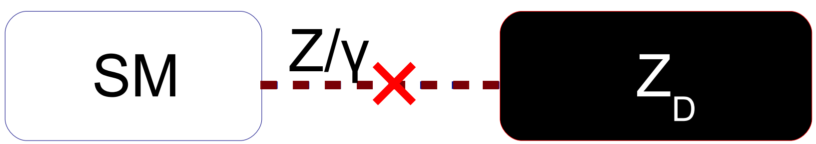
$$V(H,S) \supset \zeta |S|^2 |H|^2$$




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

- 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, ...

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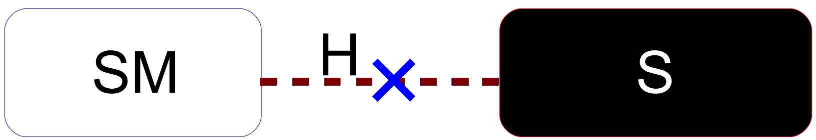
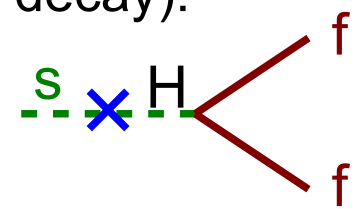



Arising in extended Higgs sector models: NMSSM, ...

**After EWSB:**

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

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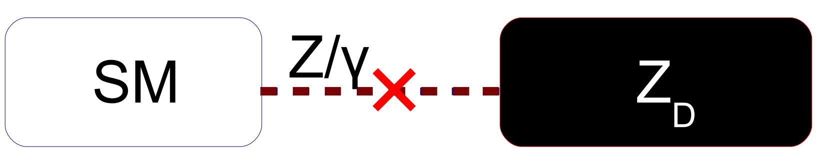


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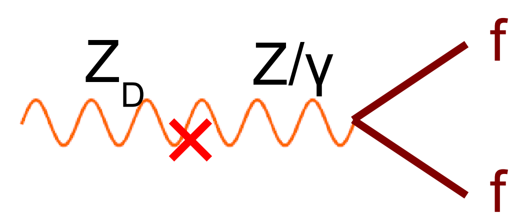


$Z_D$ decays **proptly** as long as $\boldsymbol{\varepsilon \gtrsim O(10^{-4})}$

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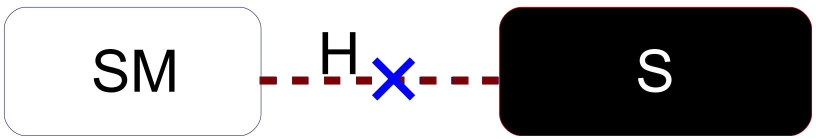


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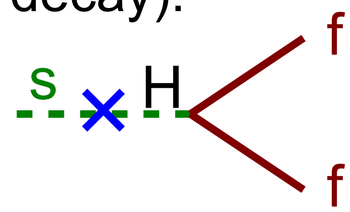


Jessie´s talk

- Vector portal

**This talk**

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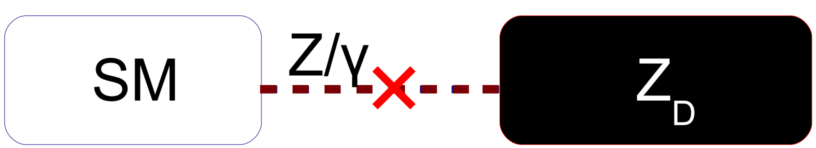


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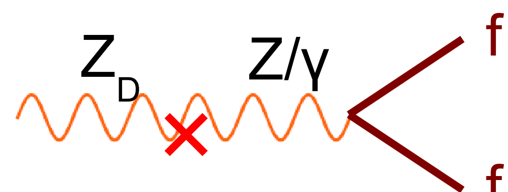


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# The Higgs connection

<u>Minimal model:</u>

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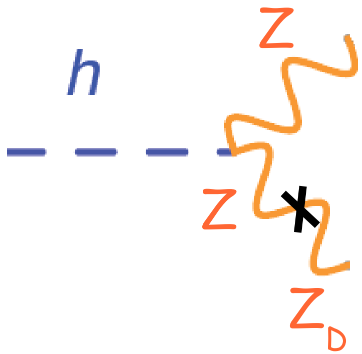


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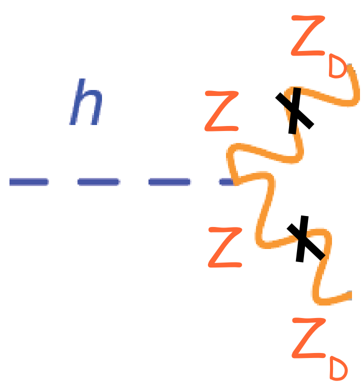
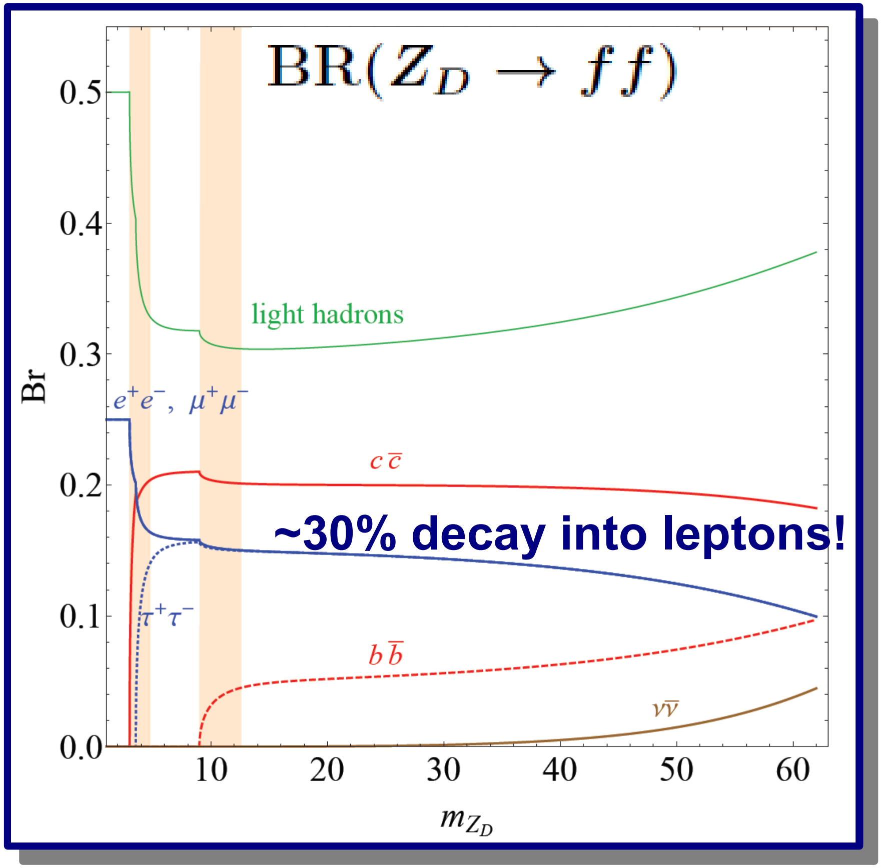



$$hZ_DZ_D \sim \epsilon^2 \tan^2\theta \frac{m_{ZD}^4}{m_Z^2 v}$$



# The final aim

$h \longrightarrow ZZ_D,\ h \longrightarrow Z_D Z_D$

Exotic scorecard

| | jj | bb | $\tau\tau$ | ll | $\nu\nu$ |
|---|---|---|---|---|---|
| jj | | | | | |
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Prospects?

## Initial attempt for $h \longrightarrow Z_D Z_D$ (by theorists)

| Decay Mode $\mathcal{F}_i$ | Projected/Current $2\sigma$ Limit on BR($\mathcal{F}_i$) 7+8 [14] TeV | Production Mode | $\frac{BR(\mathcal{F}_i)}{BR(non-SM)}$ | Limit on $\frac{\sigma}{\sigma_{SM}} \cdot$ BR(non-SM) 7+8 [14] TeV |
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| $\ell\ell\ell\ell$ | $4 \cdot 10^{-5}$ | $G$ | 0.09 | $4 \cdot 10^{-4}$ |
| $jj\mu\mu$ | $0.002 - 0.008$ $[(5-20) \cdot 10^{-4}]$ | $G$ | 0.15 | $0.01 - 0.06$ $[0.003 - 0.01]$ |
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Curtin, Essig, SG, Jaiswal, Katz, Liu, Liu, Mckeen, Shelton, Strassler, Surujon, Tweedie, Zhong, 1312.4992

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# Overview of the existing bounds for $Z_D$

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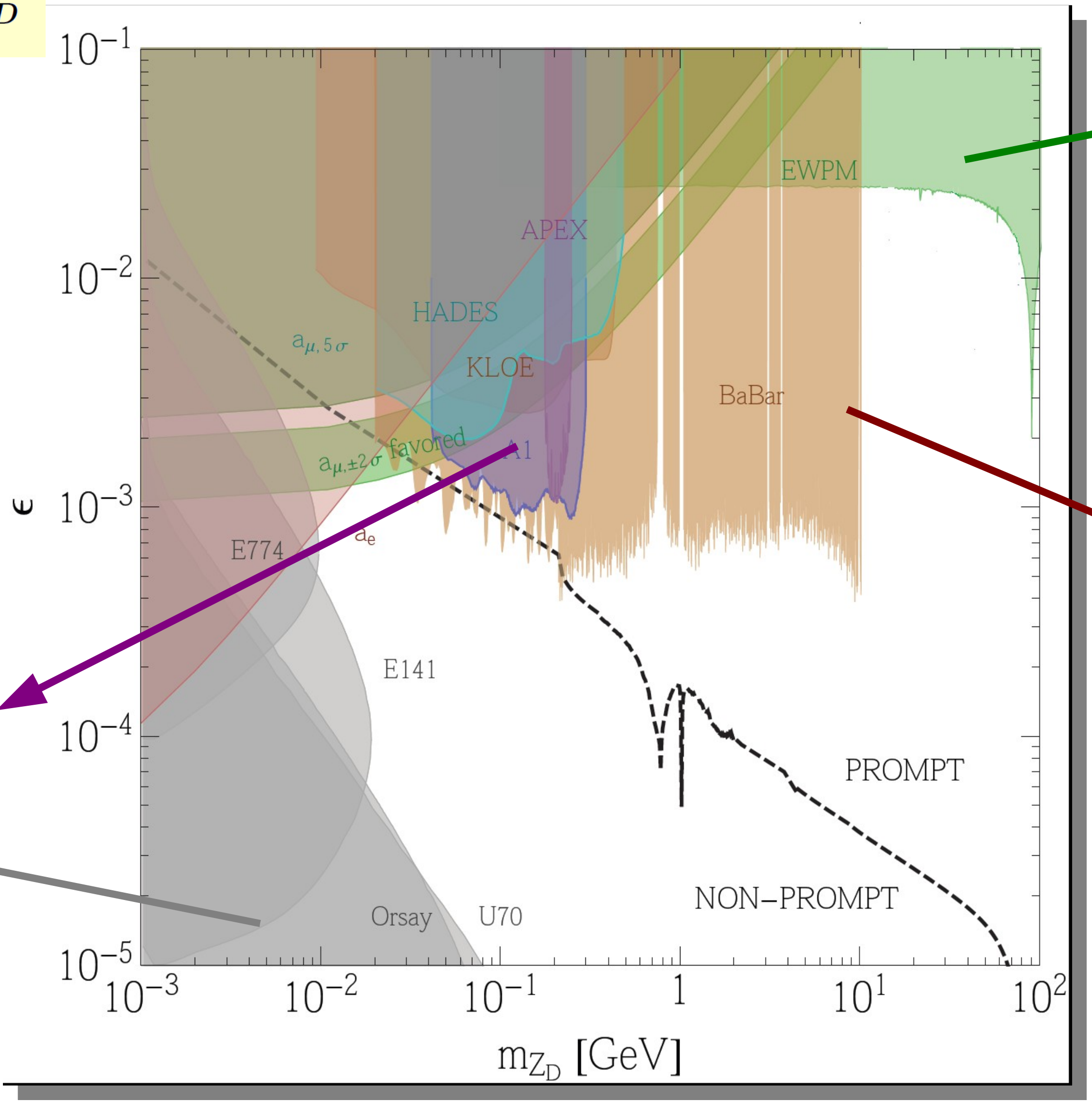
**Minimal model**




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

Hook, Izaguirre, Wacker, 1006.0973
Gopalakrishna et al., 0801.3456

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

Babar, 1406.2980

Fixed target/ beam dump experiments

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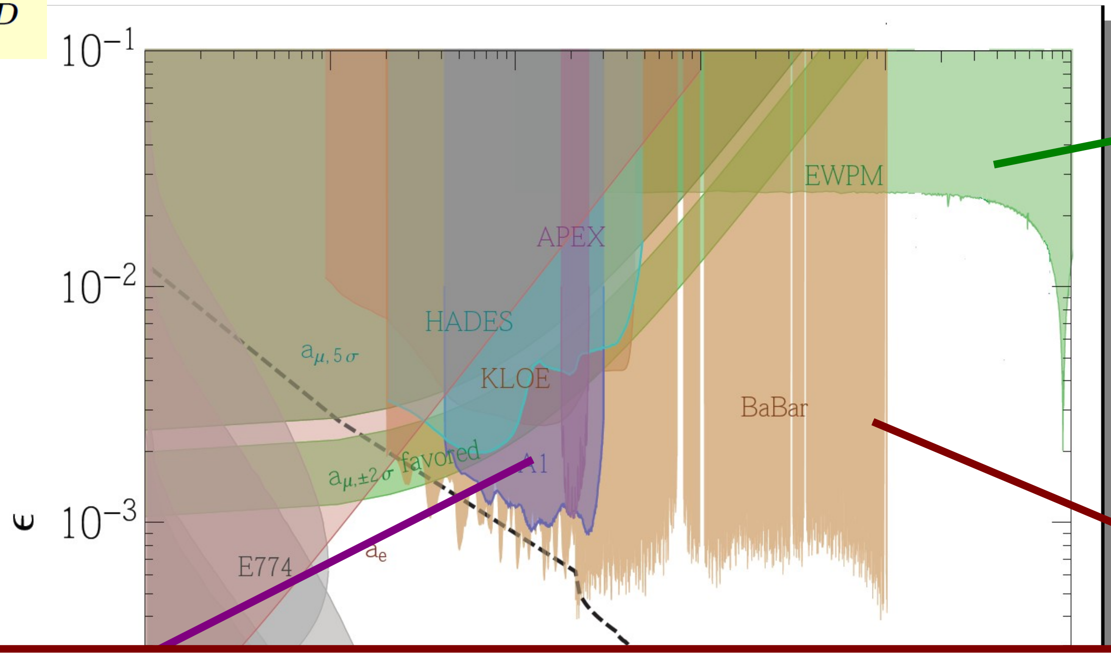


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<u>The ultimate goal</u>: probing as much parameter space as possible

<u>A little theory bias</u>: in GUT theories, the kinetic mixing operator is generated at one loop

$$\epsilon \sim \frac{g_1 g'}{16\pi^2} \log\left(\frac{M_1}{M_2}\right) \sim (10^{-3} - 10^{-4}) \log\left(\frac{M_1}{M_2}\right)$$

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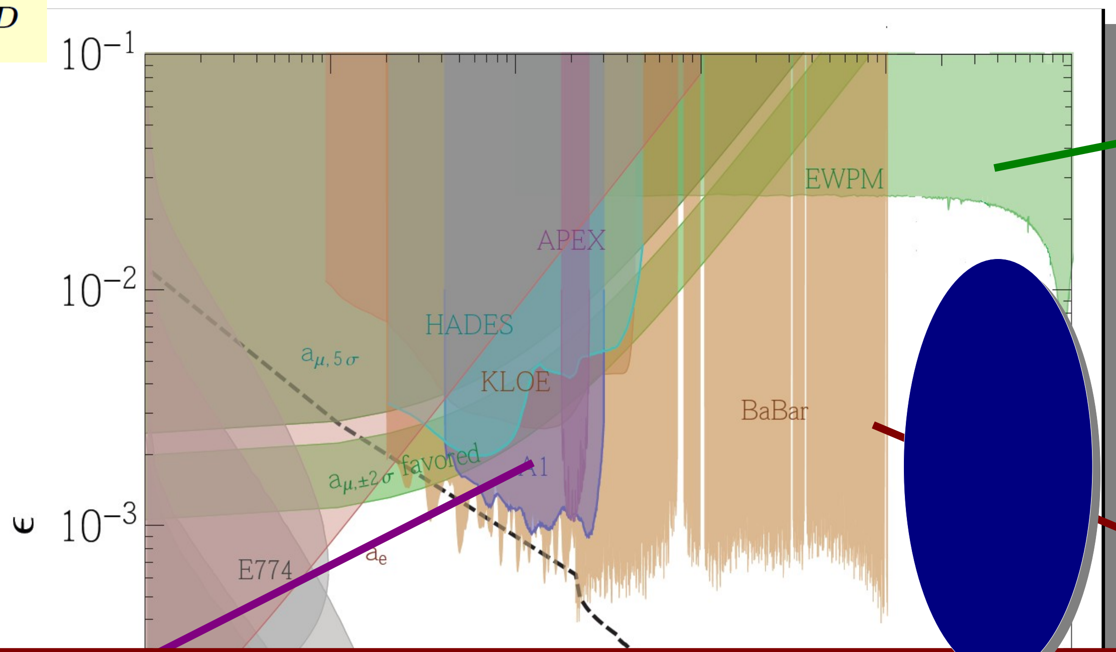


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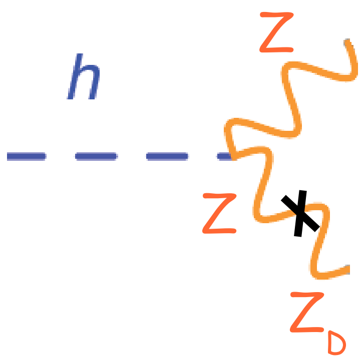
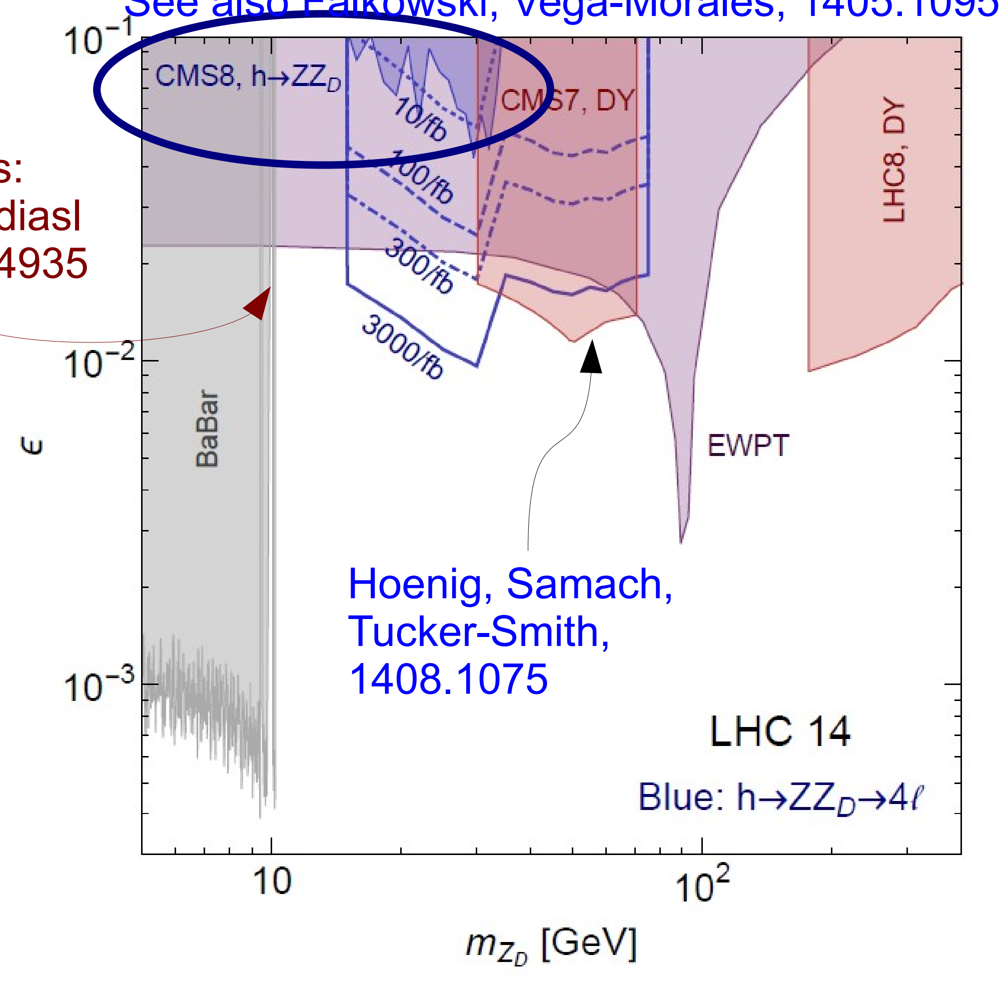



$$hZZ_D \sim 2\epsilon \tan\theta \frac{m_{ZD}^2}{v}$$

Lower mass:
See Davoudiasl et al. 1304.4935

See also Falkowski, Vega-Morales, 1405.1095




Hoenig, Samach, Tucker-Smith, 1408.1075

Curtin, Essig, SG, Shelton, appearing soon

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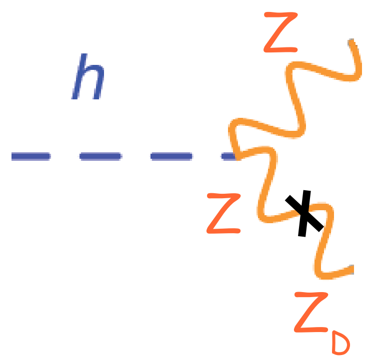


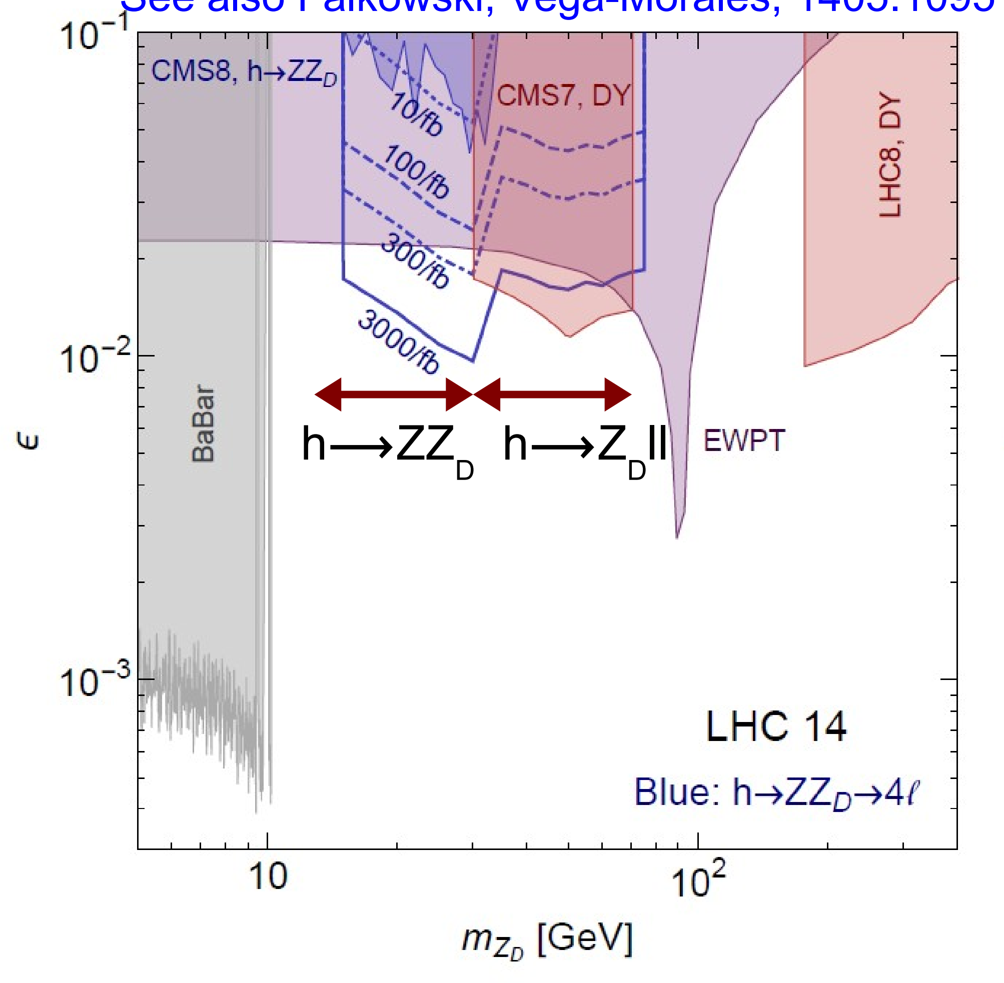

$$hZZ_D \sim 2\epsilon \tan\theta \frac{m_{ZD}^2}{v}$$

$$120\,\mathrm{GeV} < \mathrm{m}_{4\ell} < 130\,\mathrm{GeV}$$

Bump hunt in the SFOS dilepton invariant mass most away from $m_Z$: $M_2$

$$|M_2 - m_{Z_D}| < \begin{cases} 0.02 M_2 & \text{(electrons)} \\ 2.5(0.026\ \mathrm{GeV} + 0.013 M_2) & \text{(muons)} \end{cases}$$

See also Falkowski, Vega-Morales, 1405.1095

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# Complementarity with EWPMs

**Minimal model:**

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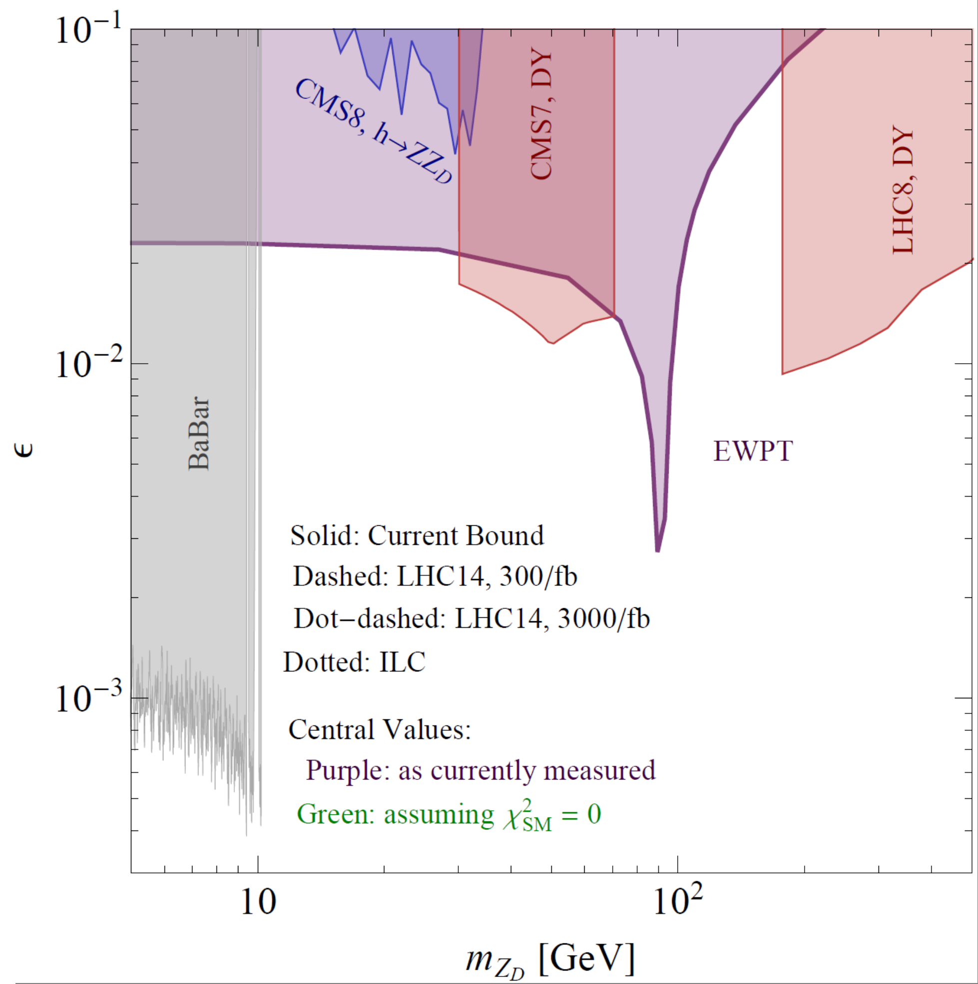
Effects on the Z phenomenology!

- Tree level shift in the Z mass;
- Modification of the Z couplings

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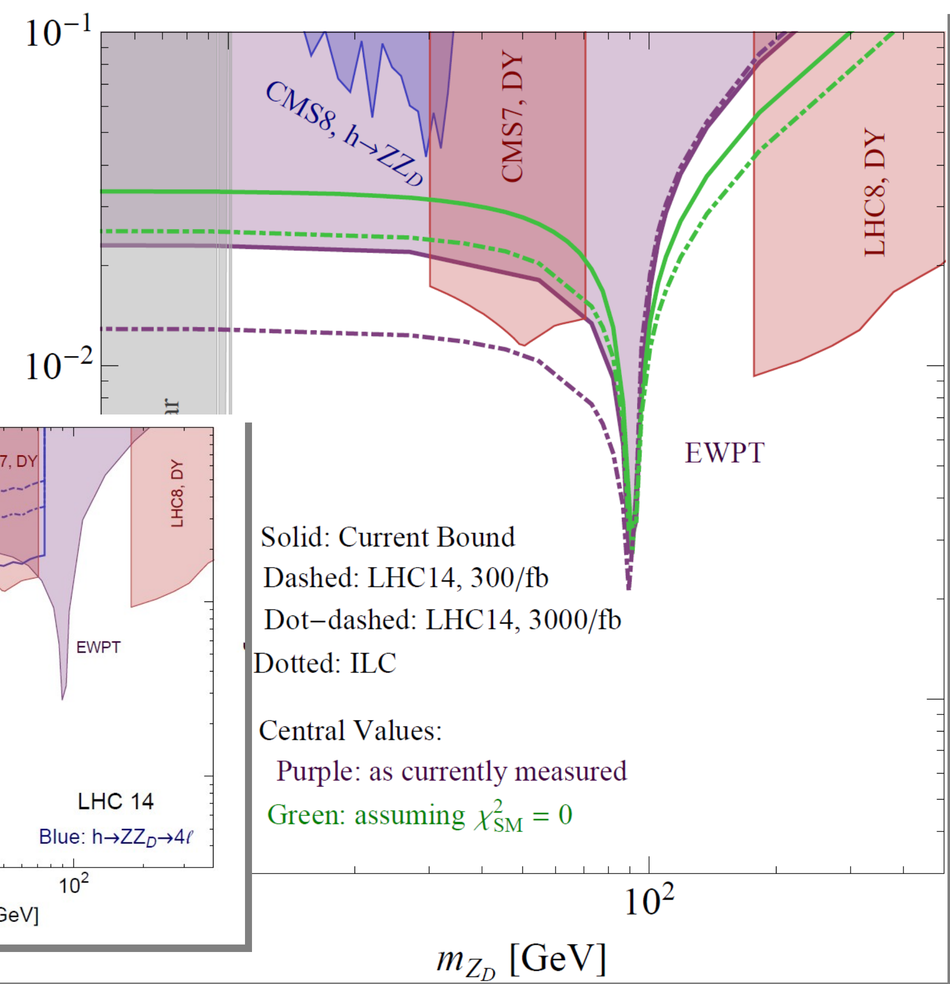
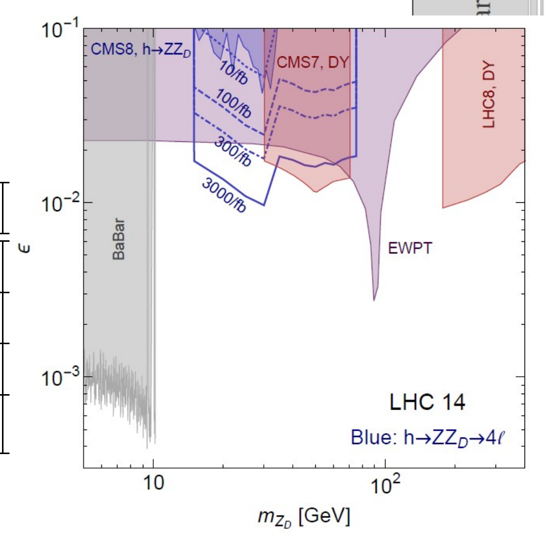
In the future, a global fit will give stronger constraints

| | Now | Future HL-LHC |
|---|---|---|
| $\delta m_W$ | 15 MeV | 5 MeV |
| $\delta m_h$ | 0.24 GeV | 0.05 GeV |
| $\delta m_t$ | 0.76 GeV | 0.2 GeV |
| $\delta \Delta\alpha^{(5)}_{\rm had}$ | $10 \cdot 10^{-5}$ | $4.7 \cdot 10^{-5}$ |

Babar expectation

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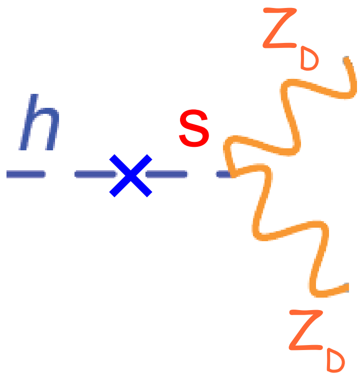
# The Higgs and the $Z_D$ (2)

**Next to Minimal model:**

Kinetic mixing and scalar portal are the link between the dark and the SM sectors

The scalar S is responsible of breaking U(1)'




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

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

Responsible for the decay of $Z_D$ back to the SM

Free parameters:

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

A very clean 4l signal with two equal mass resonances!

Bound from recasting CMS-ATLAS h→ZZ*→4l:

BR($h \to Z_D Z_D \to 4l$) ≤ few*$10^{-5}$, at best

Curtin, et al. 1312.4992

**We can for sure do much better!**

# The Higgs and the $Z_D$ (3)

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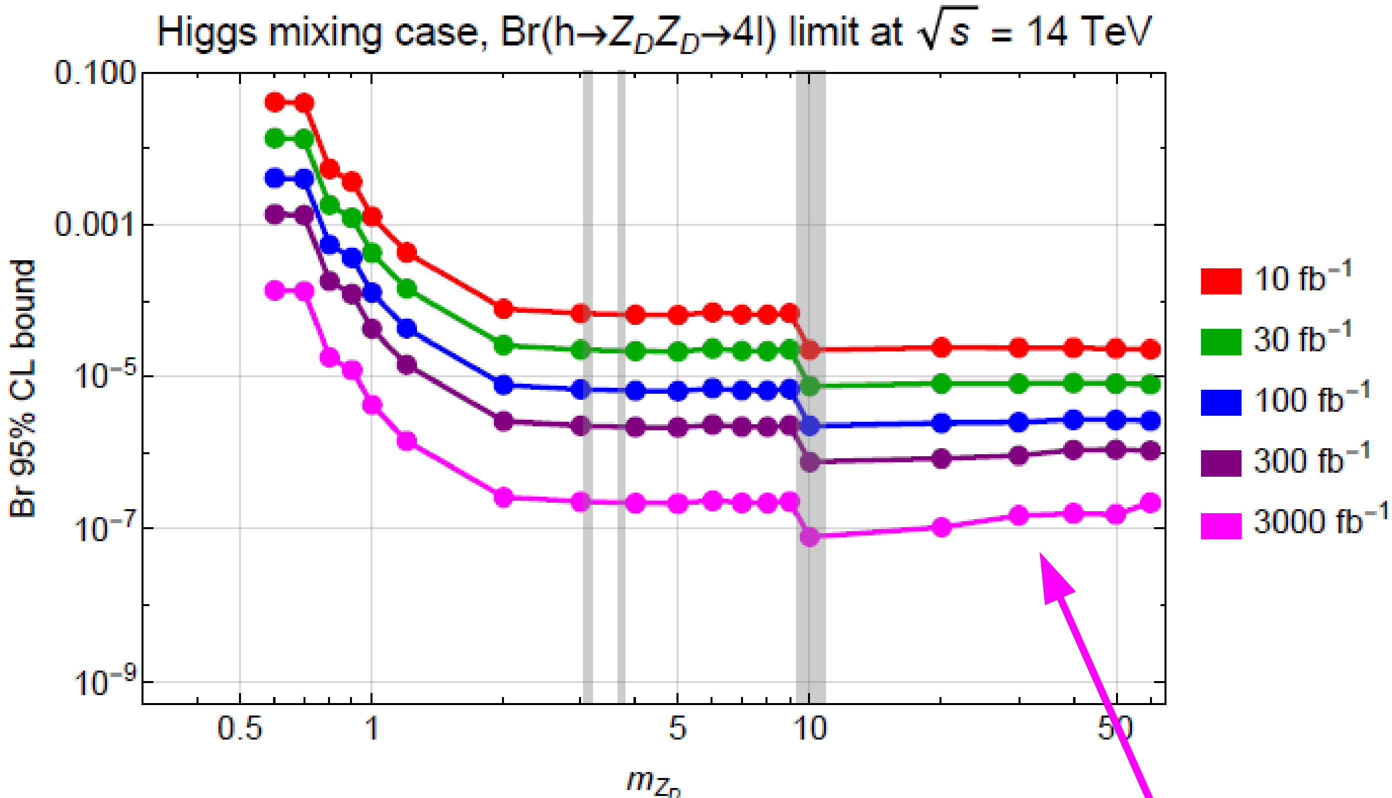


This corresponds to set a bound on the Higgs mixing with another scalar at the level of

$$\kappa' \sim \text{few} \cdot 10^{-5}$$

**HL** is crucial since the search is almost background free/ statistically limited

# A non-promptly decaying $Z_D$

<u>Next to Minimal model:</u>

Kinetic mixing and scalar portal are the link between the dark and the SM sectors

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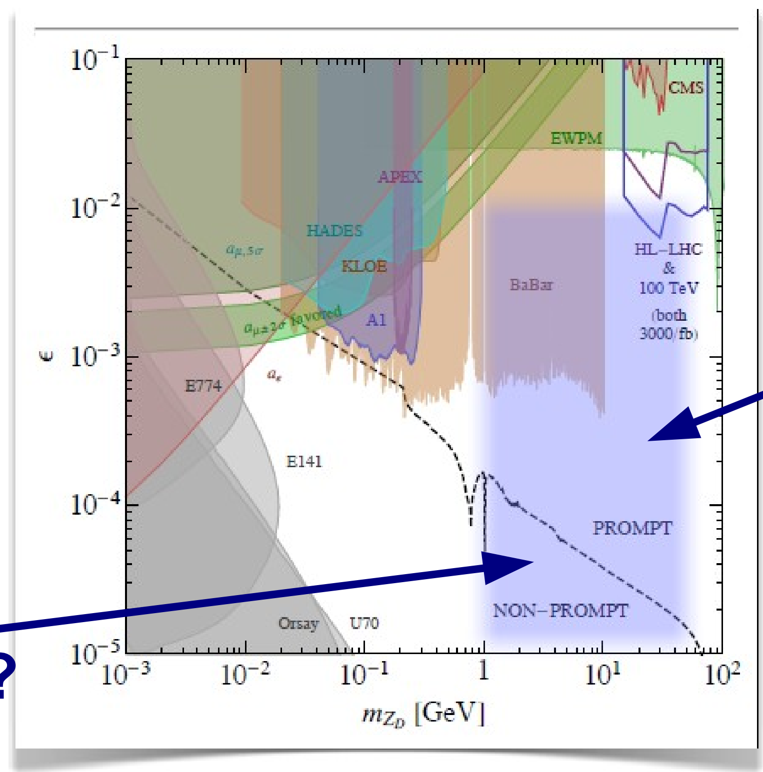
What if the kinetic mixing is very small $\epsilon \lesssim 10^{-4} - 10^{-5}$
and $Z_D$ does not decay promptly?




Probed by $h \to Z_D Z_D$

**Accessible?**

 S.Gori

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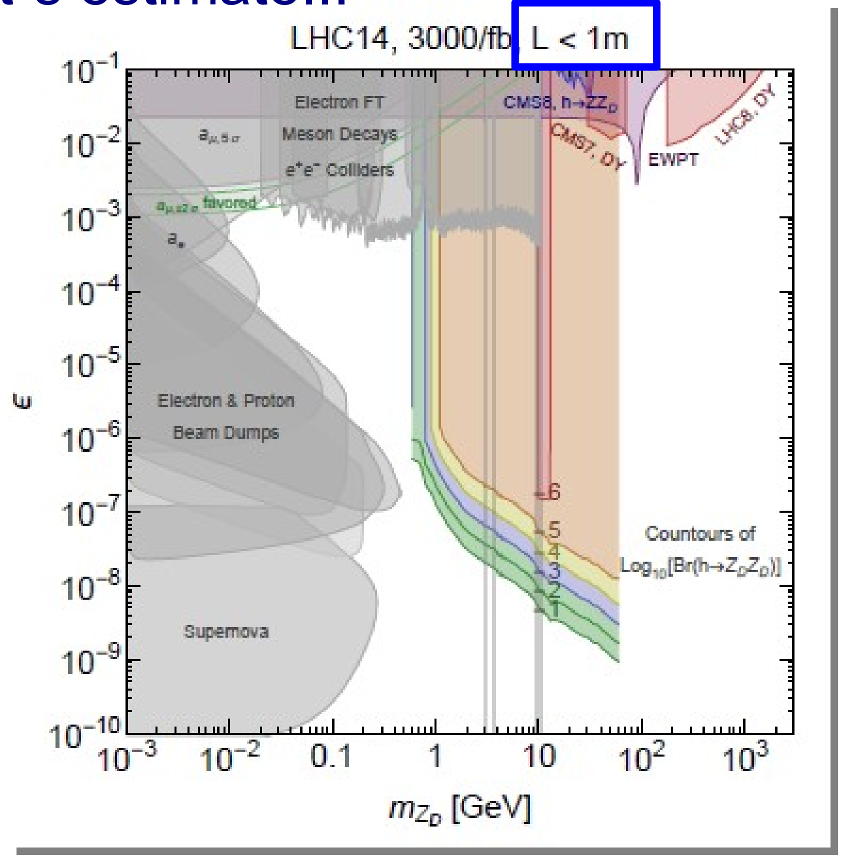
Let´s estimate...




A similar signal efficiency should be achievable for macroscopic decay lenghts contained in the inner detector

$$\mathrm{BR}_{\mathrm{eff}} = \mathrm{BR}(h \to Z_D Z_D)\ P(L, \sqrt{s}, m_{Z_D}, \epsilon)$$

The BR we measure

Probabilty for $Z_D$ to decay inside the detector

# Going to higher energy?

What we will gain on the Higgs exo. decays going to higher energy?

Huge productions!

| | √S=14 TeV | √S=33 TeV | √S=100 TeV |
|---|---|---|---|
| ggF | 50.4 pb | 178 pb | 740 pb |
| VBF | 4.4 pb | 17 pb | 82 pb |
| WH | 1.6 pb | 4.7 pb | 16 pb |
| ttH | .62 pb | 4.6 pb | 38 pb |
| HH | .034 pb | .2 pb | 1 pb |

Higgs cross section working group

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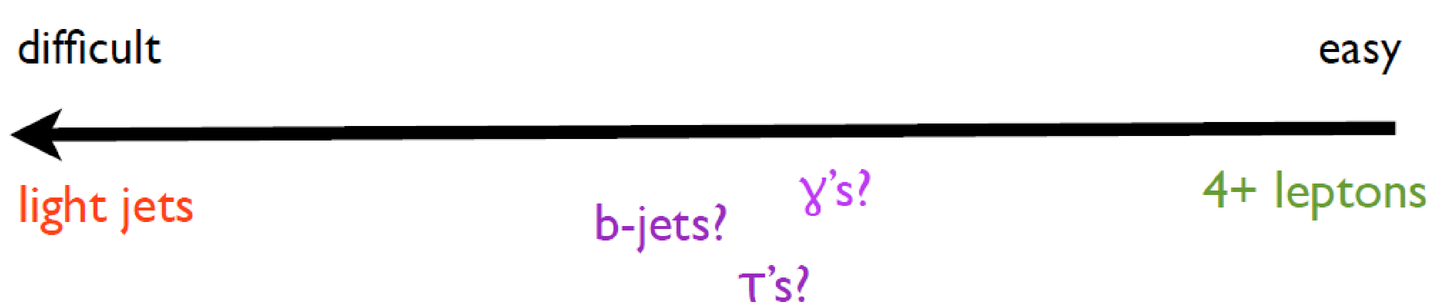
Higgs cross section working group

**1. Difficult decay modes**
Benefit from having „accessible“ Higgs production in association with tops, Z bosons, ...

**2. Clean decay modes**
At the high-lumi LHC, we cannot expect to be able to put bounds on $BR_{exo} \leq 10^{-6}-10^{-7}$ because of the lack of statistics



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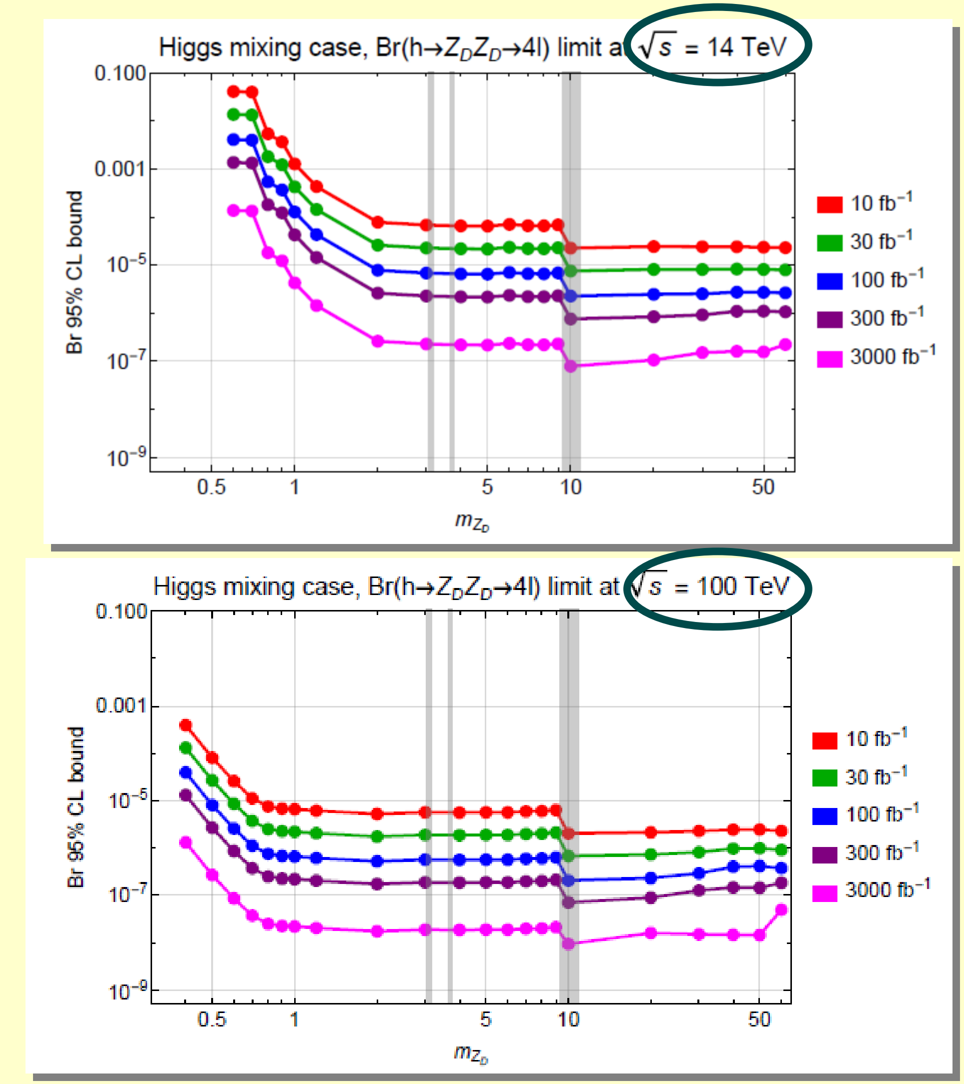
difficult

←

light jets

b-jets?

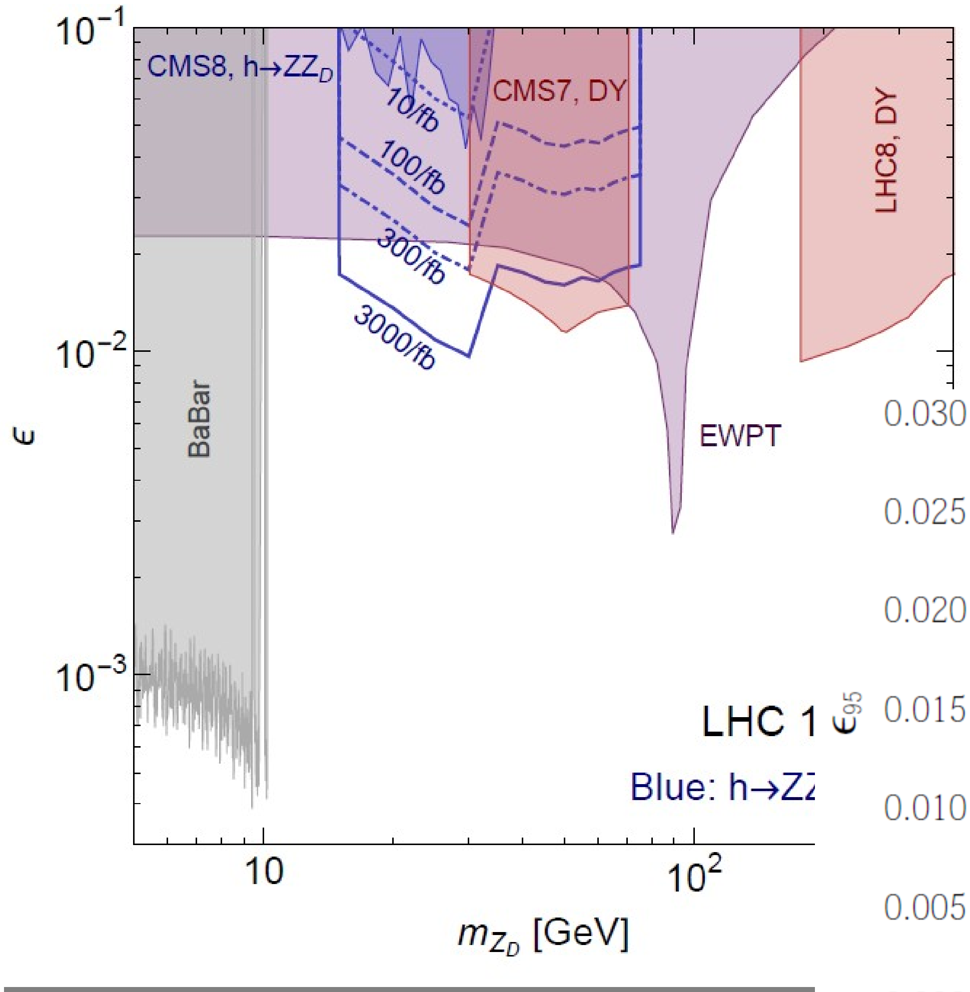


# Conclusions & lessons

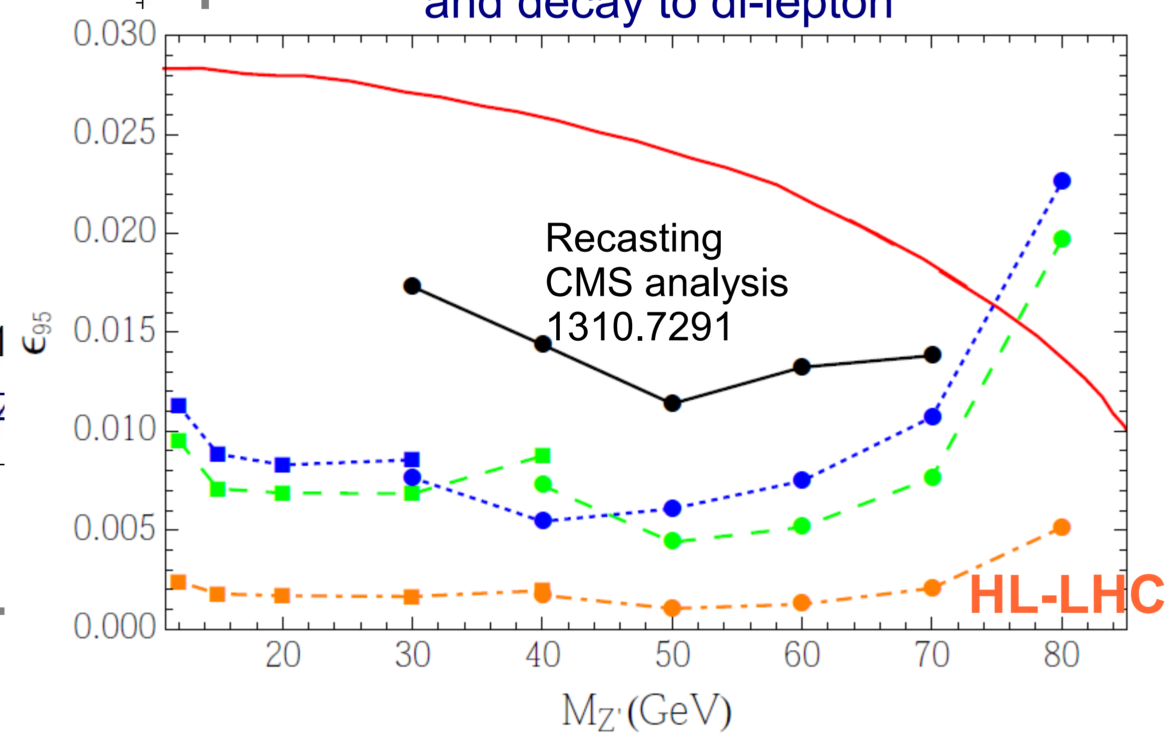
**Great opportunity to test new forces using Higgs decays!**

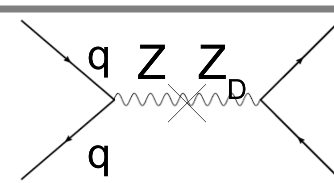
- Interesting possibility of testing $Z_D$ gauge bosons from dark sectors using new Higgs boson decays
- Access to regions of parameter space very well theoretically motivated
- We will incredibly benefit from the High-Luminosity LHC, since the signature is very clean
- Going to higher energy, we will gain in rate: 100TeV collider can set bounds $BR(h \to Z_D Z_D \to 4l) \sim \text{few}*10^{-8}$ !

# Drell-Yan production of $Z_D$




Drell-Yan production
and decay to di-lepton

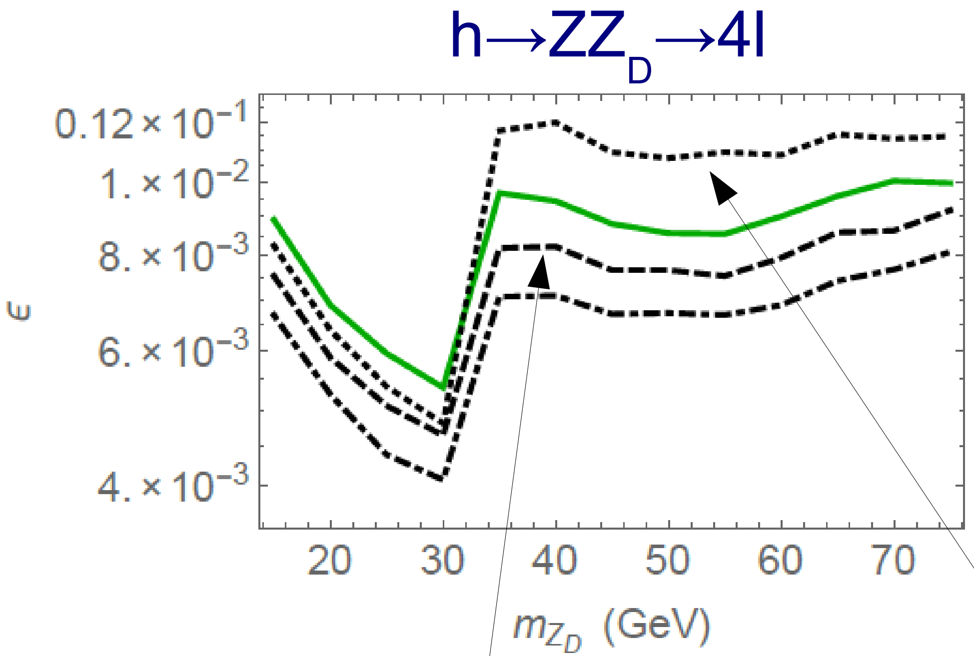


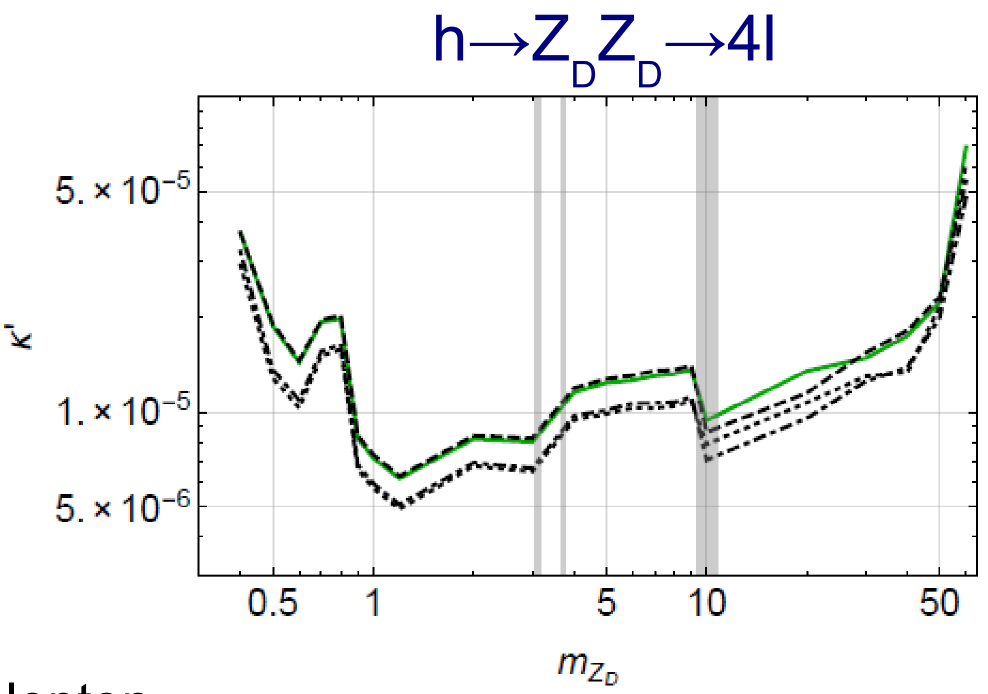




Hoenig, Samach, Tucker-Smith, 1408.1075

# Importance of detector design

Reach at 100 TeV, with 3000 $fb^{-1}$




Increased lepton acceptance |η|<4

Improved mass resolution

$$|M_{\ell\ell} - m_{Z_D}| < 0.015\, M_{\ell\ell}$$

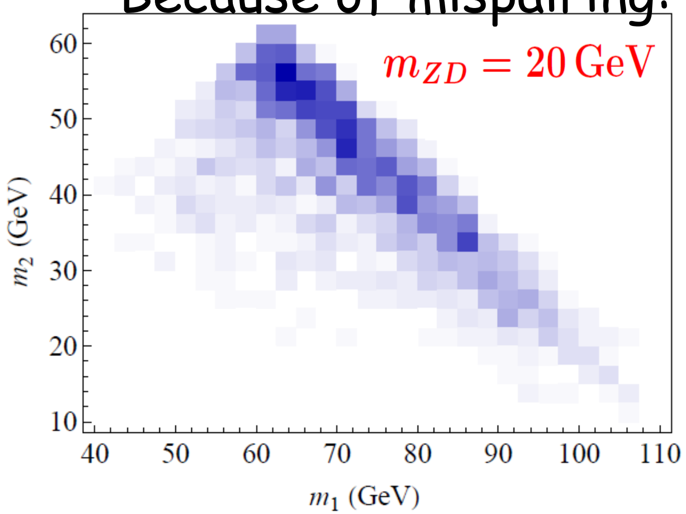
# Setting bounds on $Z_D Z_D$: present

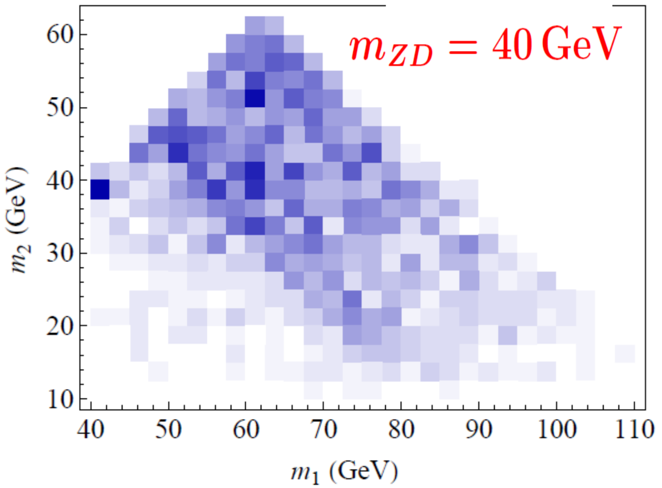
Bounds coming from SM h → ZZ*→ 4l searches at the LHC

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

Our signal

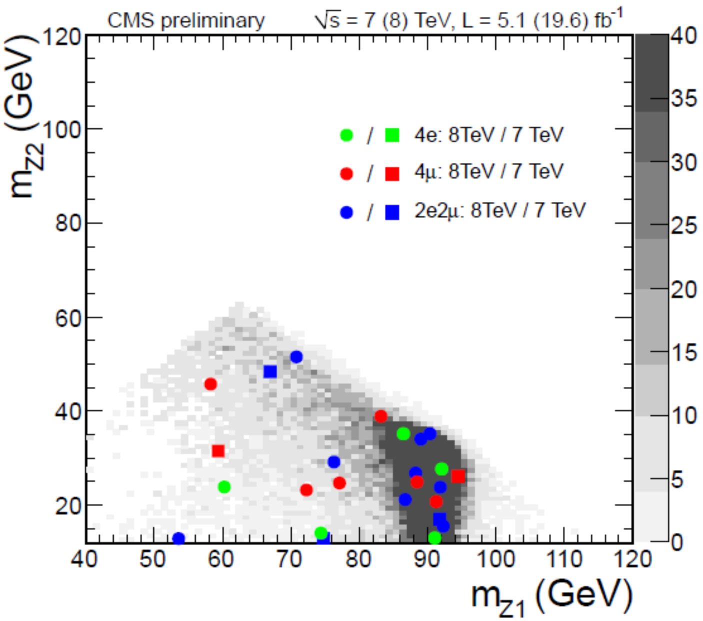
Because of mispairing:




40 GeV < $m_1$ < 120 GeV,
12 GeV < $m_2$ < 120 GeV

To compare to the experimental data:



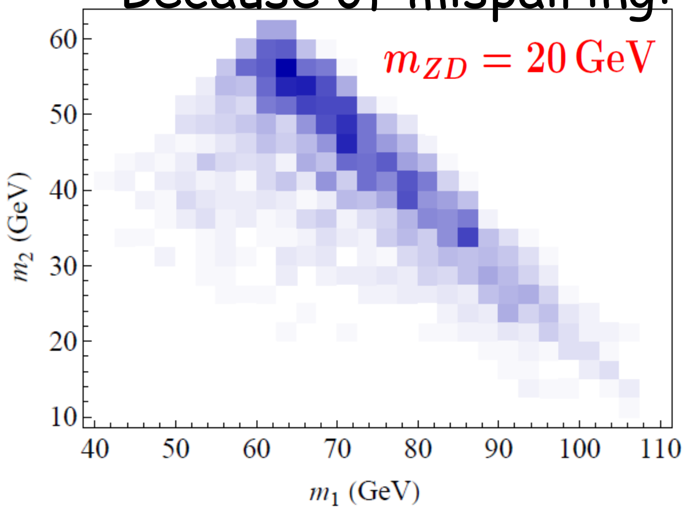

CMS PAS HIG-13-002

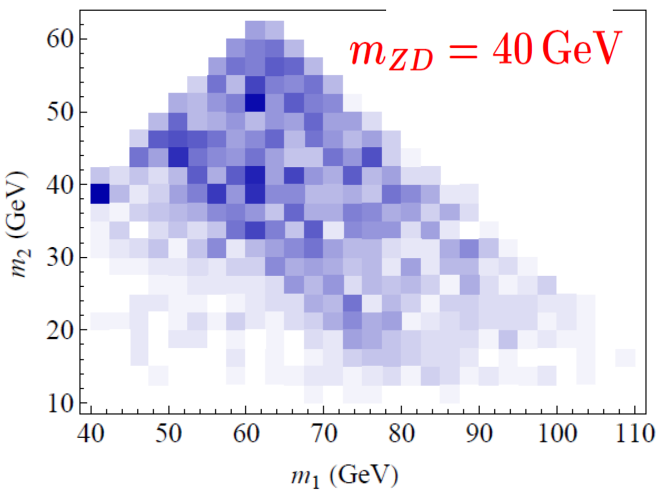
# Setting bounds on $Z_D Z_D$: present

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

Our signal

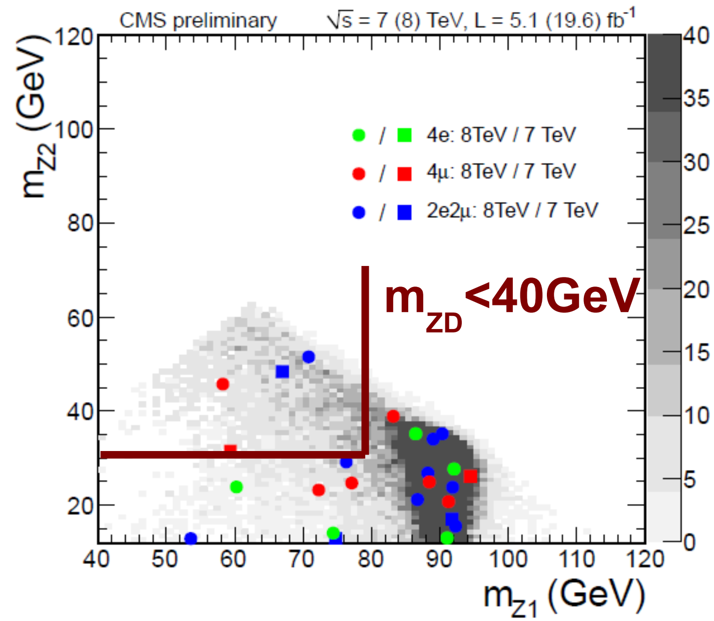
Because of mispairing:




40 GeV < $m_1$ < 120 GeV,
12 GeV < $m_2$ < 120 GeV

To compare to the experimental data:




CMS PAS HIG-13-002

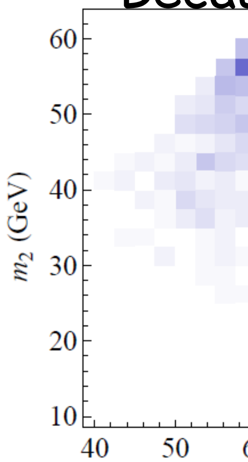
**For $m_{ZD}$>40GeV:**
**$m_{ZD} \pm 5$ GeV**

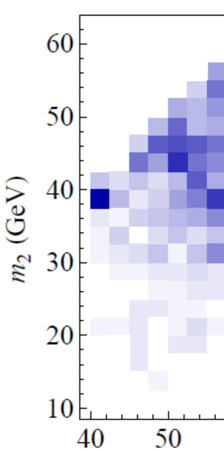
# Setting bounds on $Z_D Z_D$: present

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

Because of mispairing:

Our signal

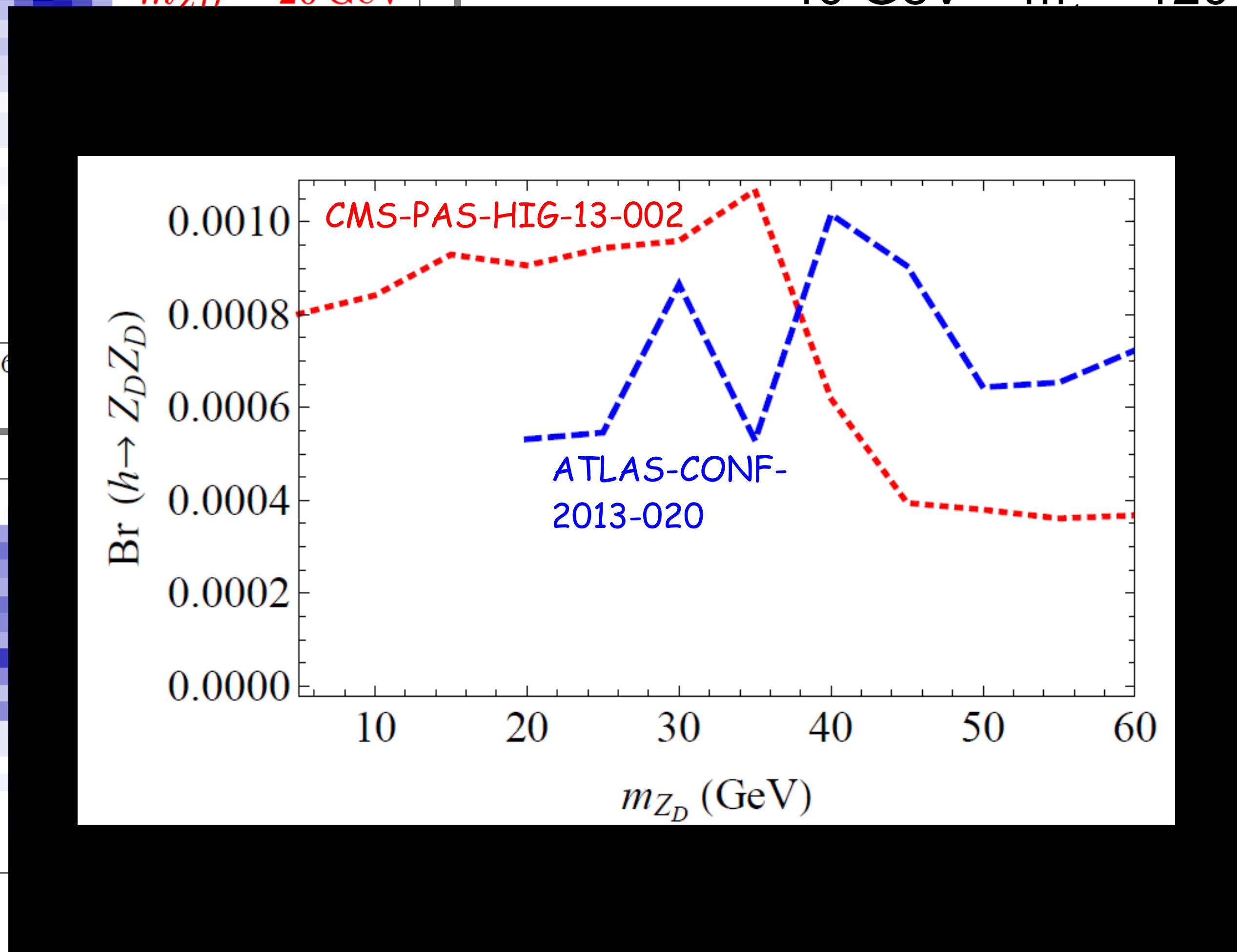


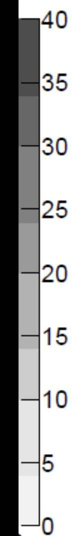




40 GeV < m < 120 GeV,

GeV

ntal data:




**For $m_{ZD}$>40GeV:**
**$m_{ZD}$ ± 5 GeV**