Higgs exotic decays at high energy colliders

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Perimeter Institute for Theoretical Physics

Aspen 2015 Winter conference:
Exploring the Physics Frontier with Circular Colliders

Aspen,
January 29th 2015

Program for Higgs characterization

BSM ⟶ Higgs

Exotic <u>production modes</u>

Higgs SM coupling measurement

(including those couplings that are very suppressed in the SM e.g. Zγ)

Higgs ⟶ BSM

Exotic <u>decay modes</u>

Program for Higgs characterization

BSM ⟶ Higgs

Exotic production modes

Higgs SM coupling measurement

(including those couplings that are very suppressed in the SM e.g. Zγ)

More effort needed!

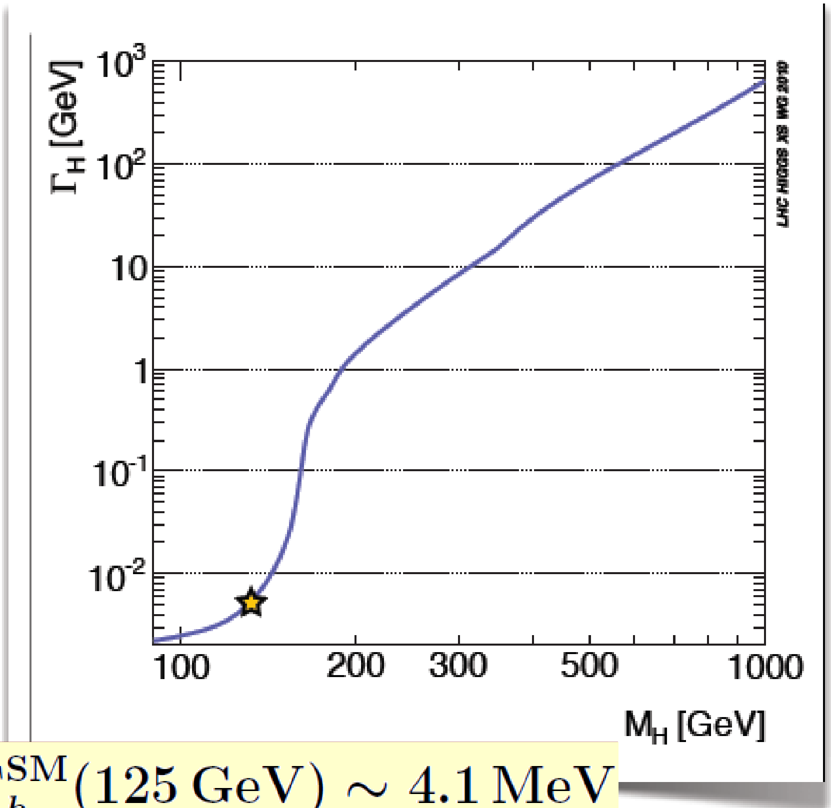
Higgs ⟶ BSM

Exotic decay modes

For this talk

Why (now)

The physics-case for Higgs exotic decays in one slide:



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

Even a small coupling to NP
will give a sizable BR for h → NP NP

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

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

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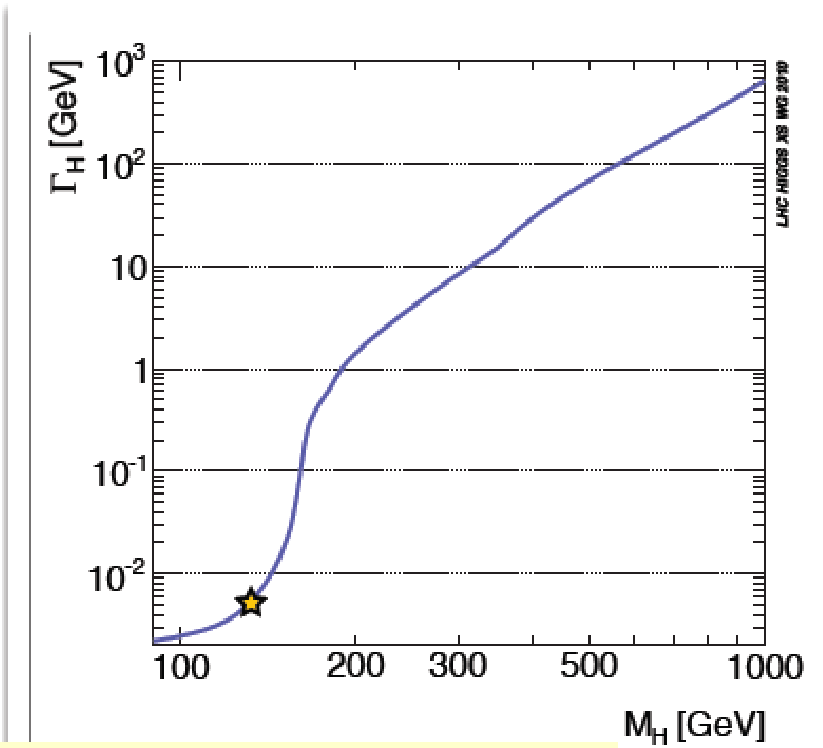

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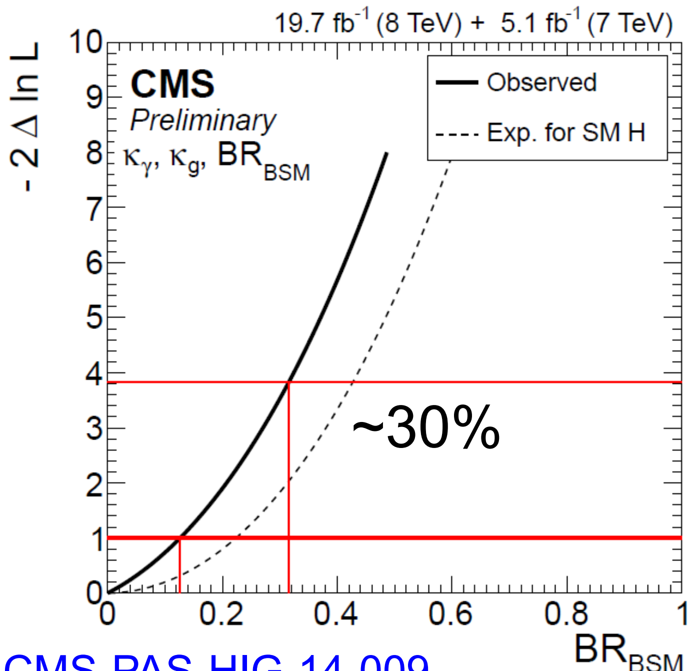
Higgs width: from global fits



CMS-PAS-HIG-14-009

Higgs width: from H off-shell measurements

$\Gamma_H < 4.2\ \Gamma_{H,SM}$

$< (4.8 – 7.7)\ \Gamma_{H,SM}$

CMS-PAS-HIG-14-002
ATLAS-CONF-2014-042

Based on
Caola, Melnikov, 1307.4935
Campbell, Ellis, Williams, 1311.3589

Why (future)

Future measurements of the total Higgs width

Prospects for LHC RunII

From global fits:
Expected bound on the BSM width:
(14-18)% with 300 fb^{-1};
(7-11)% with 3000 fb^{-1};

Prospects at linear e^+e^- colliders:

The BSM width can be bounded in a model-independent way thanks to the measurement of

$$e^+e^- \to Zh$$

ILC: Bound at the level of 5%

From snowmass Higgs report 1310.8361

A lot of events!

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

with the present (7+8)TeV LHC data set

Production	$N_{ev}^{10\%}$, 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

Production	$N_{ev}^{10\%}$, 100 TeV
ggF	2.2×10^8
VBF	2.5×10^7
$hW^{\pm}$	4.8×10^6
hZ	3.4×10^6
$t\bar{t}h$	1.1×10^7

with 3000 fb^{-1} data

100 TeV pp collider as a high-intensity Higgs machine

A look at models

Higgs ⟶ NP

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

Shouldn´t it be already discovered?

- EW precision measurements
- Direct searches
- Flavor measurements

Not necessarily!

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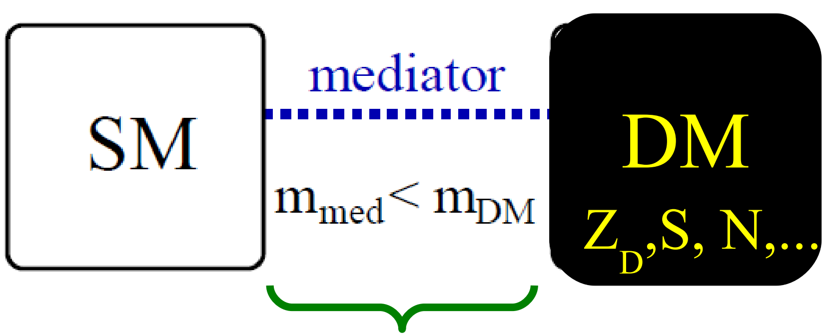
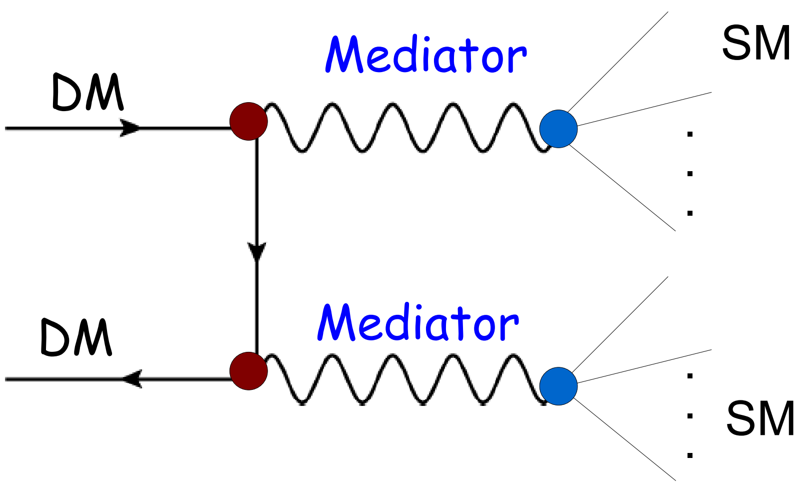


Thanks to (a few) renormalizable "portals"

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



Higgs couples to New Physics easily: $|H|^2$

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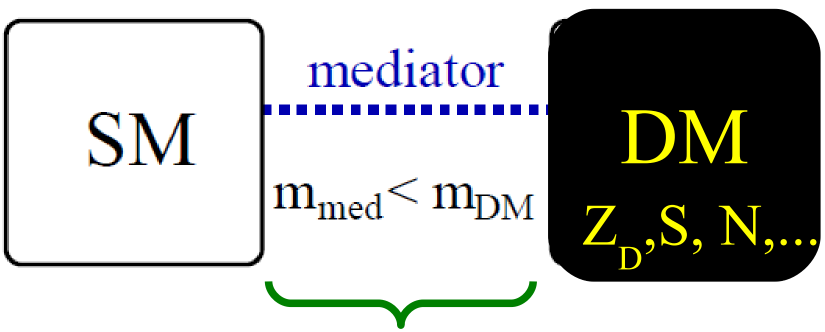


Thanks to (a few) renormalizable "portals"

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

Not only dark matter motivated models:

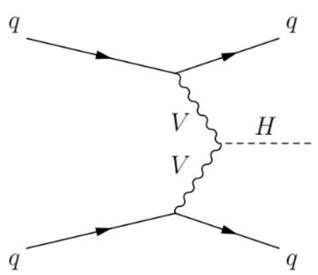
- Models stabilizing the electroweak scale: Twin Higgs models
- Models with extended Higgs sectors: NMSSM

Higgs couples to New Physics easily: $|H|^2$

A first connection to the dark sector

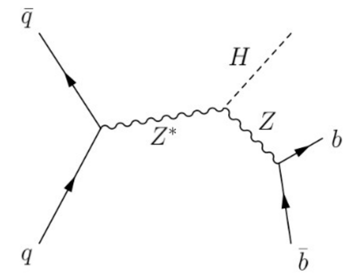
Higgs decay to Dark Matter. Invisible

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



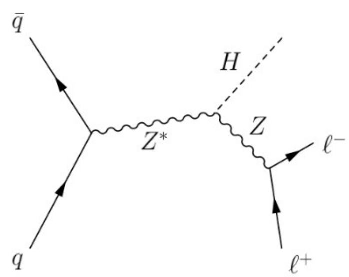
VBF: 0.65 (0.49)

CMS, 1404.1344



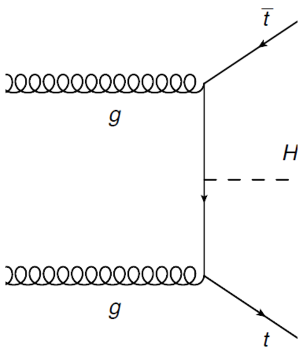
Zh,Z⟶bb: 1.82 (1.99)

CMS, 1404.1344



Zh,Z⟶ll: 0.75 (0.62)

ATLAS, 1402.3244



tth: 0.40 (0.65)

Zhou, et al. tth, 1408.0011

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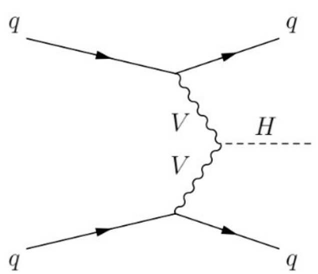

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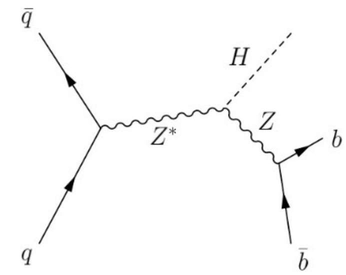

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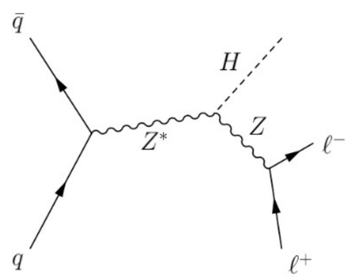

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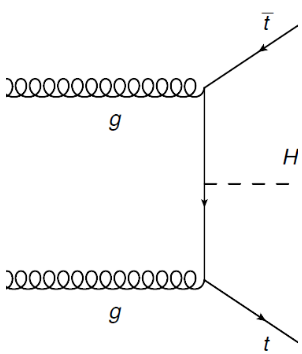

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Great prospects for the future:

LHC300: ~20%
LHC3000: ~10%
} Snowmass Higgs report 1310.8361

ILC250, 250fb^{-1}: ~ 0.69% Ishikawa @ ILC Tokusui Workshop 2014

CepC 5ab^{-1}: ~0.28% preliminary, Qian et al.

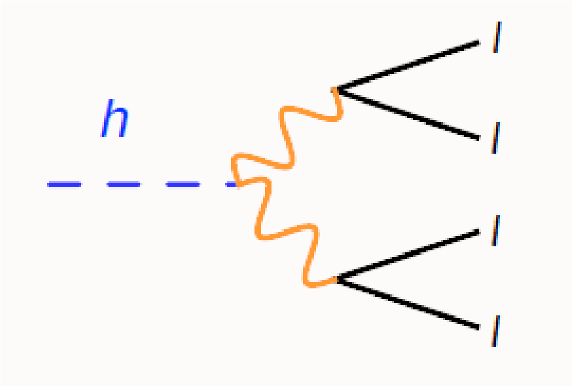
Lessons from LHC8 recasts

What else can we measure to test hidden singlets?

Higgs exotic decay review, 1312.4992
Curtin, Essig, SG, Jaiswal, Katz, Liu, Liu, McKeen, Shelton, Strassler, Surujon, Tweedie, Zhong

Prospects depend in detail on the particles in the final state, and range from spectacular to very hard

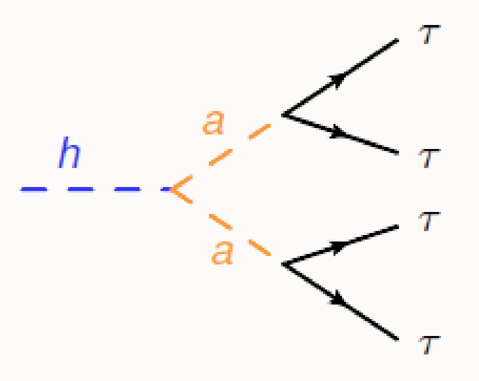
Easy



multiple resonant leptons

$$\mathrm{BR} \lesssim 4 \times 10^{-5}$$

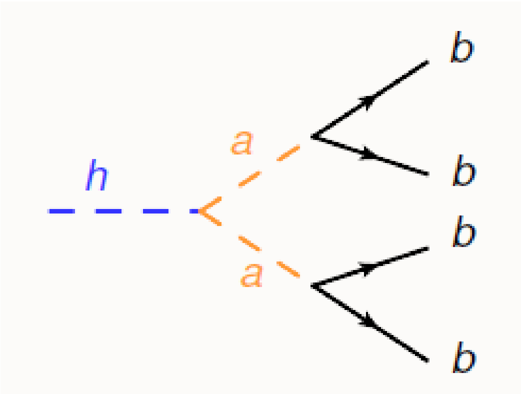
Moderate



multiple EW object
but
poor mass resolution

$$\mathrm{BR} \lesssim 0.2 - 0.4$$

Hard



all hadronic

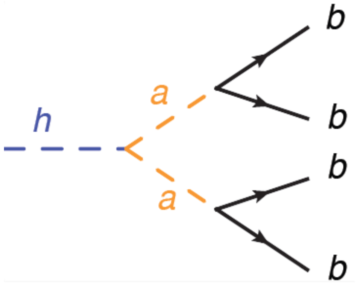
$$\mathrm{BR} \lesssim 0.7$$

Looking forward: LHC RunII & 100 TeV

What will we gain going to higher energies?

The <u>main question mark</u> to keep in mind:

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



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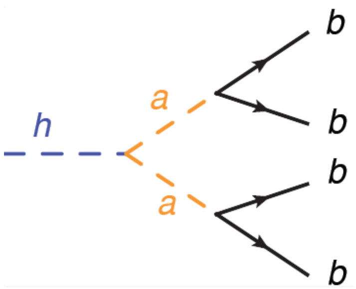

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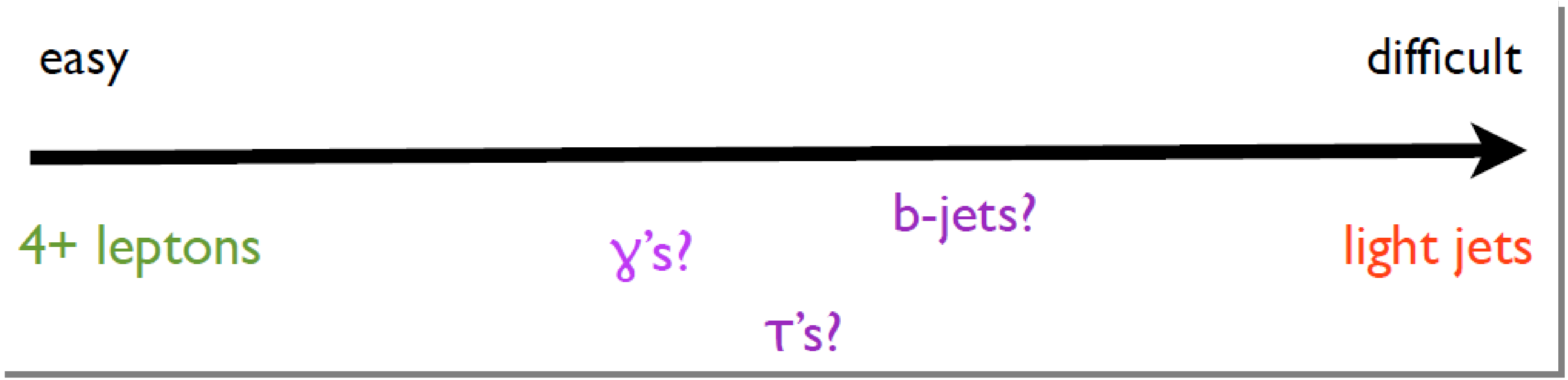

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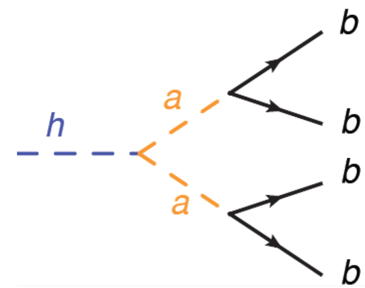

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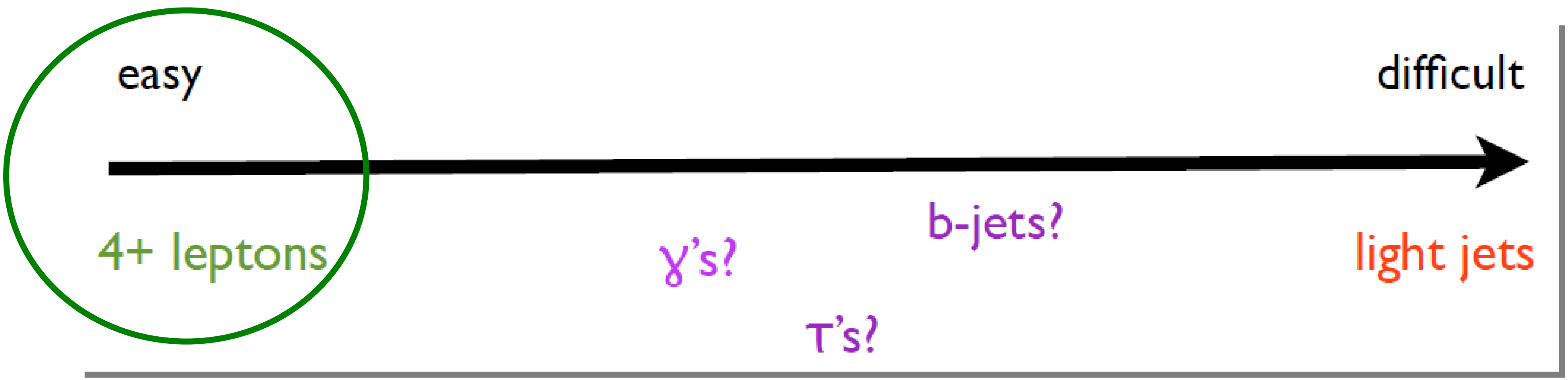

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It helps having
- large rates
- new detectors
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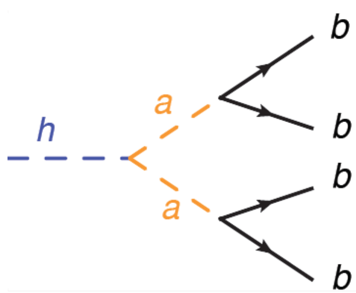

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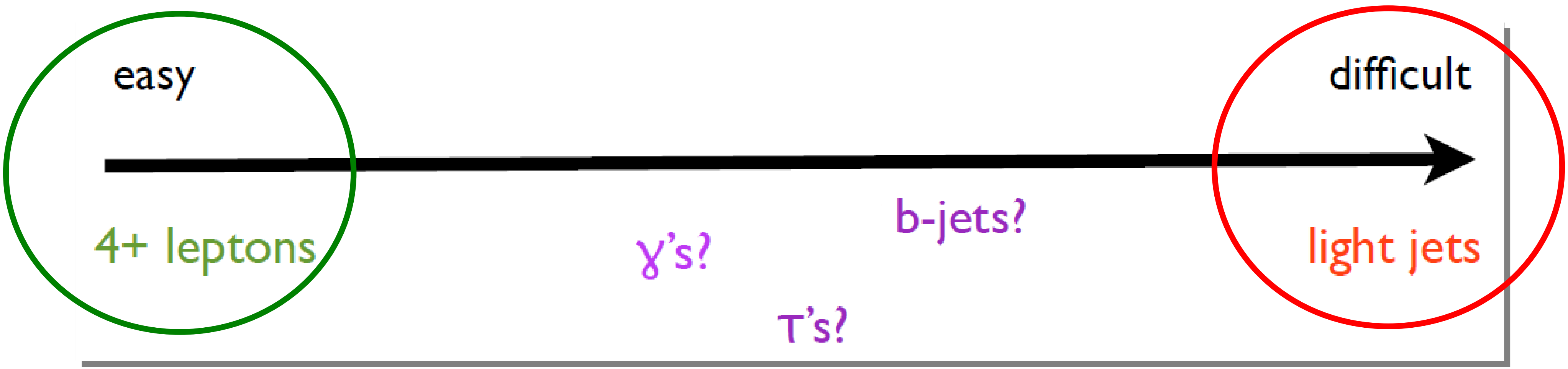

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It helps having extra handles:
New production modes
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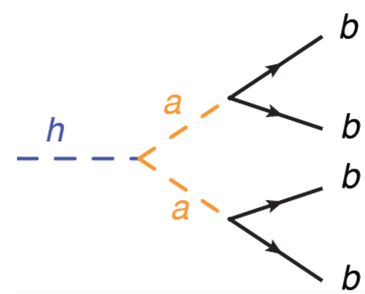

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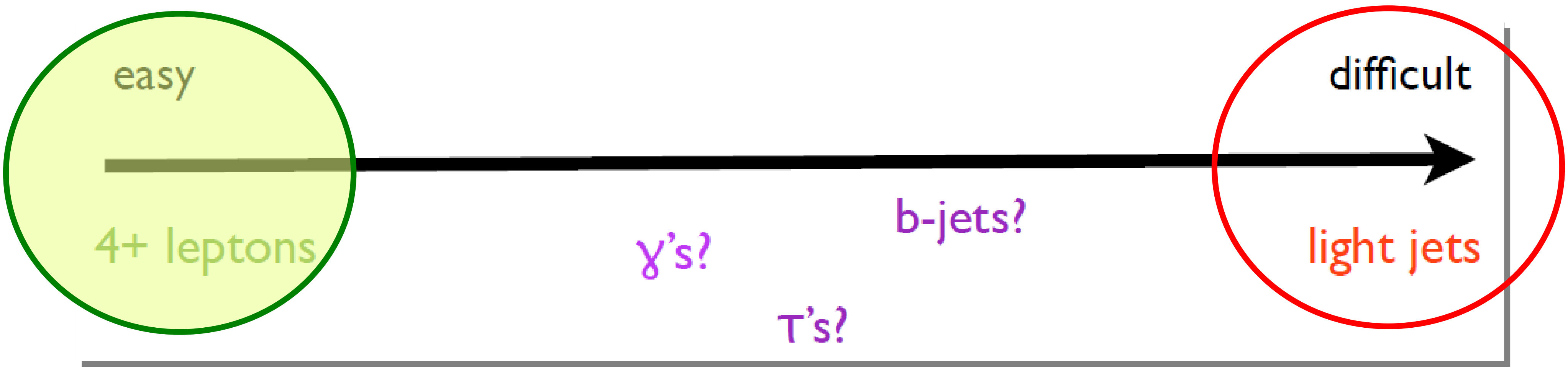

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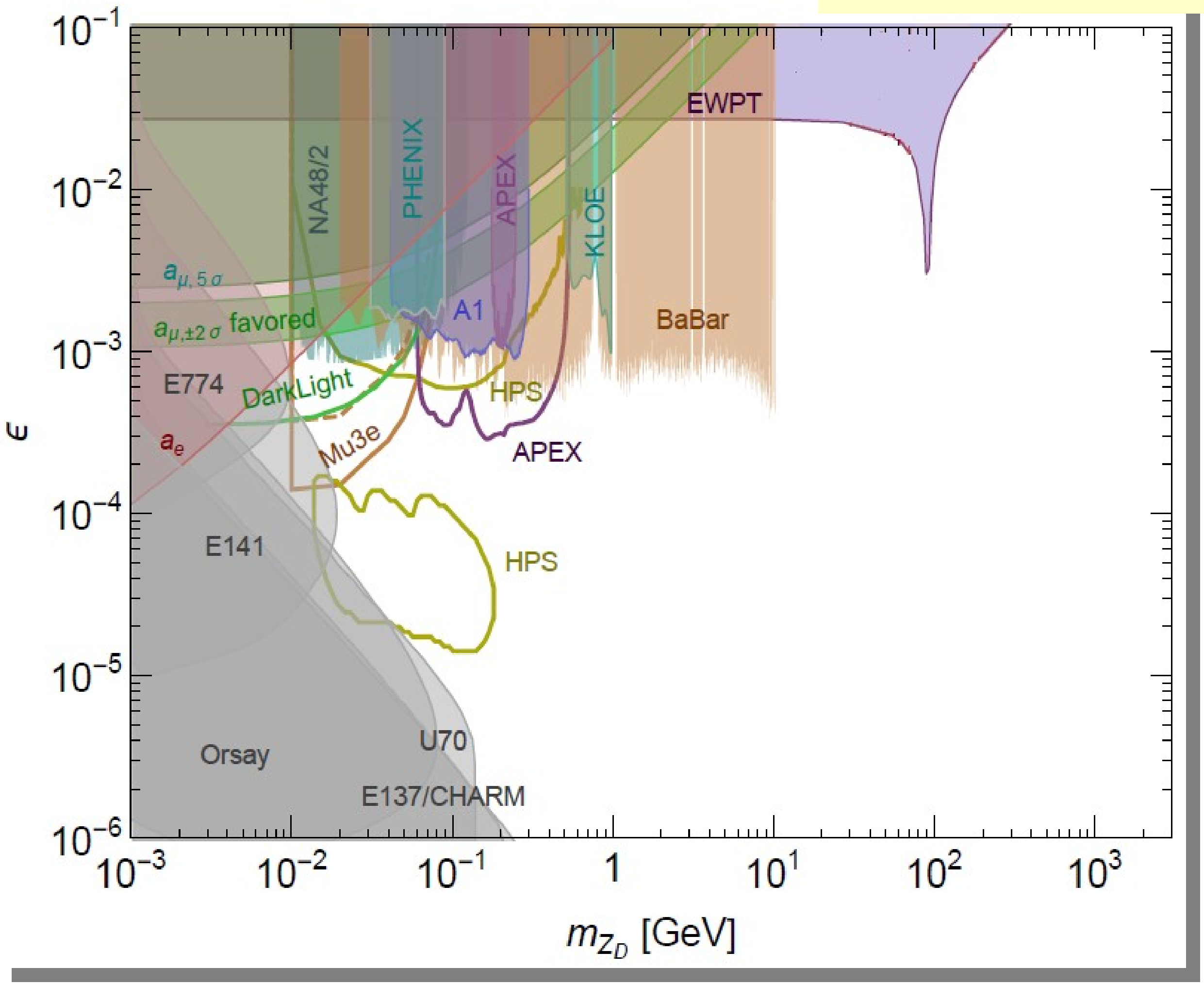
Looking for a new force (past studies)

Example: a dark photon

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



In Grand Unified theories, the kinetic mixing is generated at one loop → $\epsilon \sim 10^{-3} - 10^{-4}$

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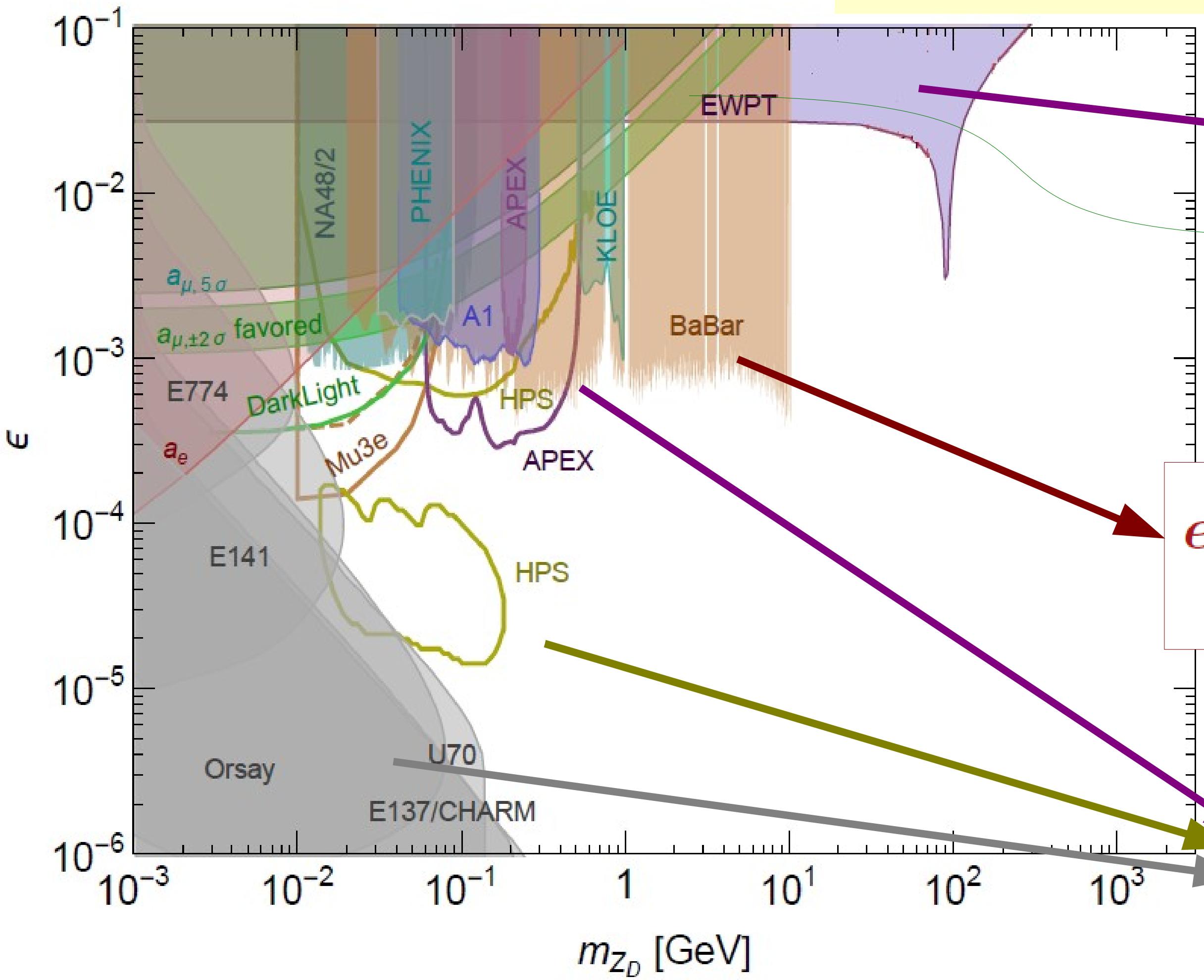

(g-2)$_\mu$

EW precision measurements at the Z peak

Gopalakrishna, Jung, Wells, 0801.3456

Hook, Izaguirre, Wacker, 1006.0973

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

1406.2980

Fixed target/beam dump experiments

Bjorken, Essig, Schuster, Toro, 0906.0580

In Grand Unified theories, the kinetic mixing is generated at one loop

$$\epsilon \sim 10^{-3} - 10^{-4}$$

 S.Gori

What else can we do?

Dark-Z bosons (Z_D) can be very well probed by the search for Higgs to multi-leptons

Curtin, Essig, SG, Shelton, 1412.0018

- In the framework of simplified models:

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

<u>After EWSB</u>: Z,γ,Z_D neutral gauge bosons

- Z_D pheno in a nutshell:

1. Z_D couplings = Photon-like, for $m_{ZD} \ll m_Z$; Z-like, for $m_{ZD} \sim m_Z$
2. $\Gamma_{Z_D} \propto \epsilon^2 m_{Z_D}$

Always sizable BR into leptons

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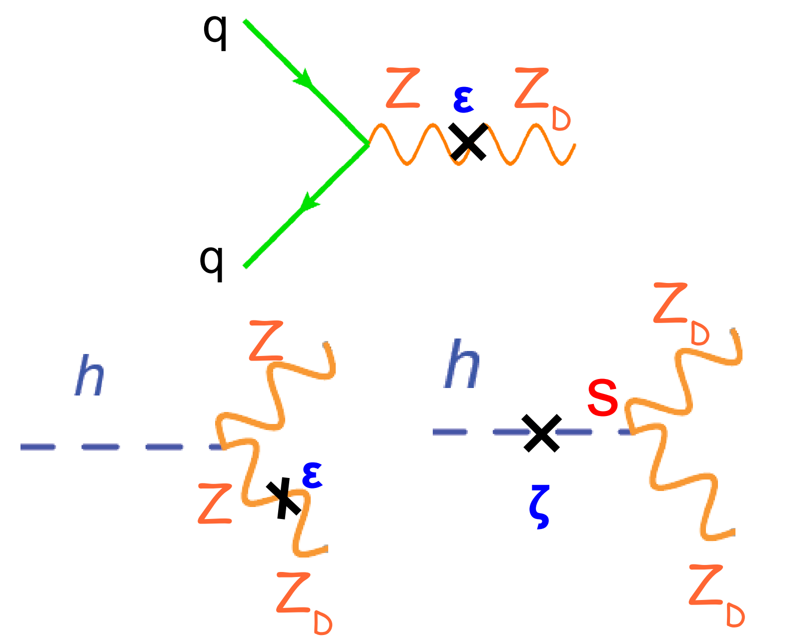
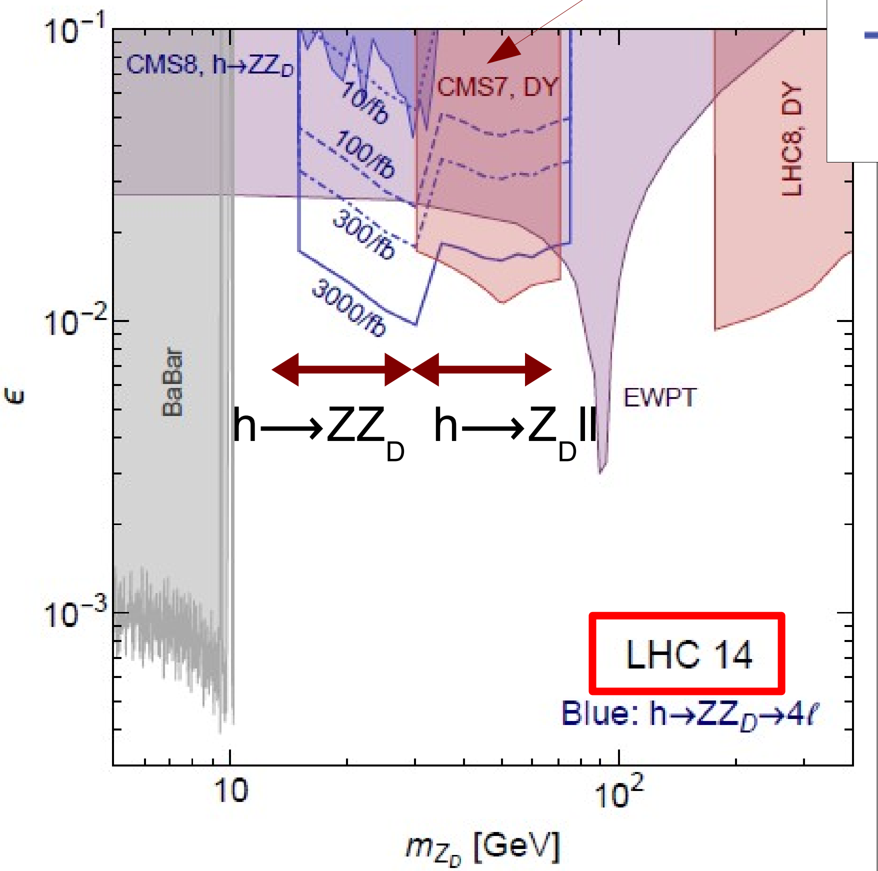
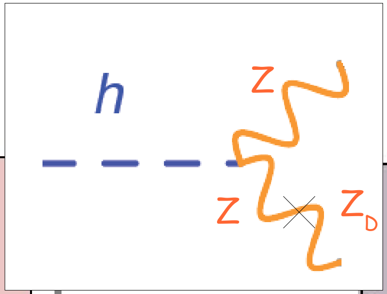
Production of Z_D at colliders

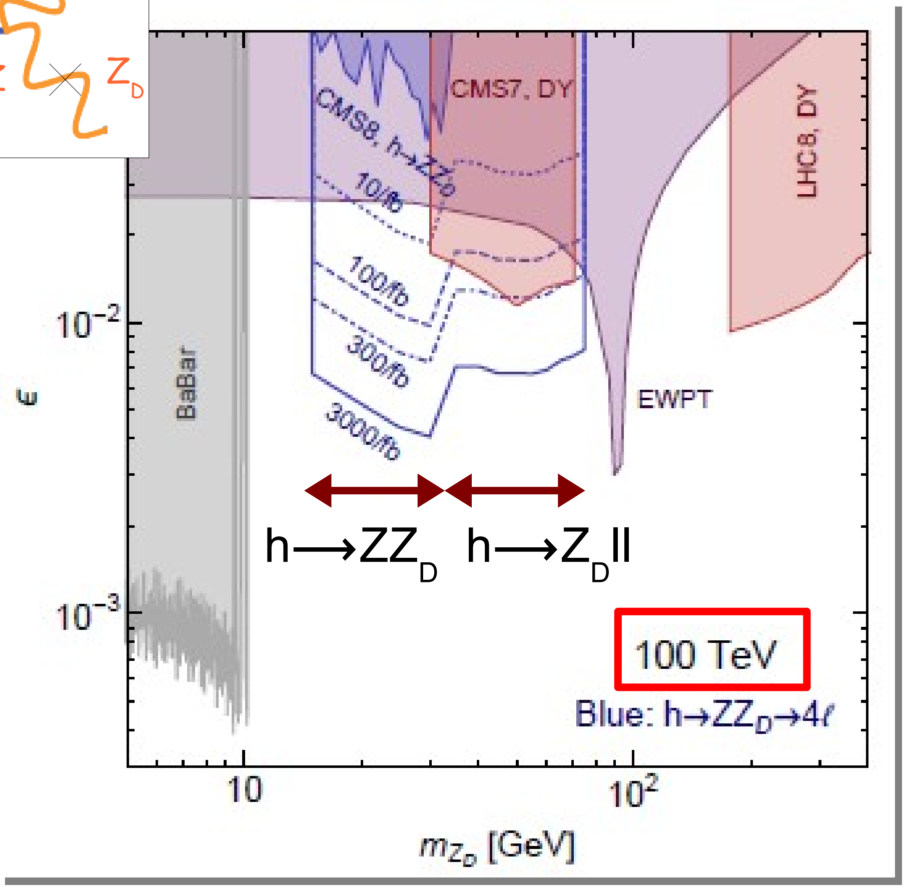


A dedicated search for ZZ_D

Hoenig, Samach,
Tucker-Smith, 1408.1075







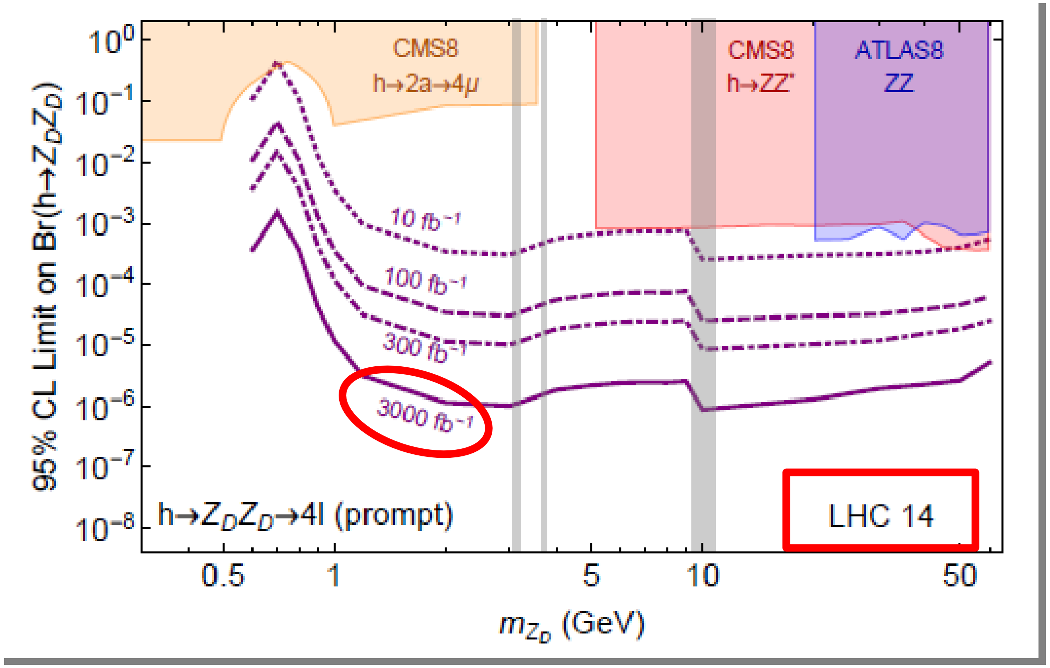
$BR(h \longrightarrow ZZ_D \longrightarrow 4l) \geq 10^{-6}$
can be tested

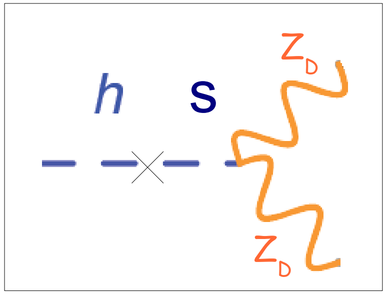
$BR(h \longrightarrow ZZ_D \longrightarrow 4l) \geq 2\times10^{-7}$
can be tested

Curtin, Essig, SG, Shelton, 1412.0018

A dedicated search for $Z_D Z_D$

A almost background
free search





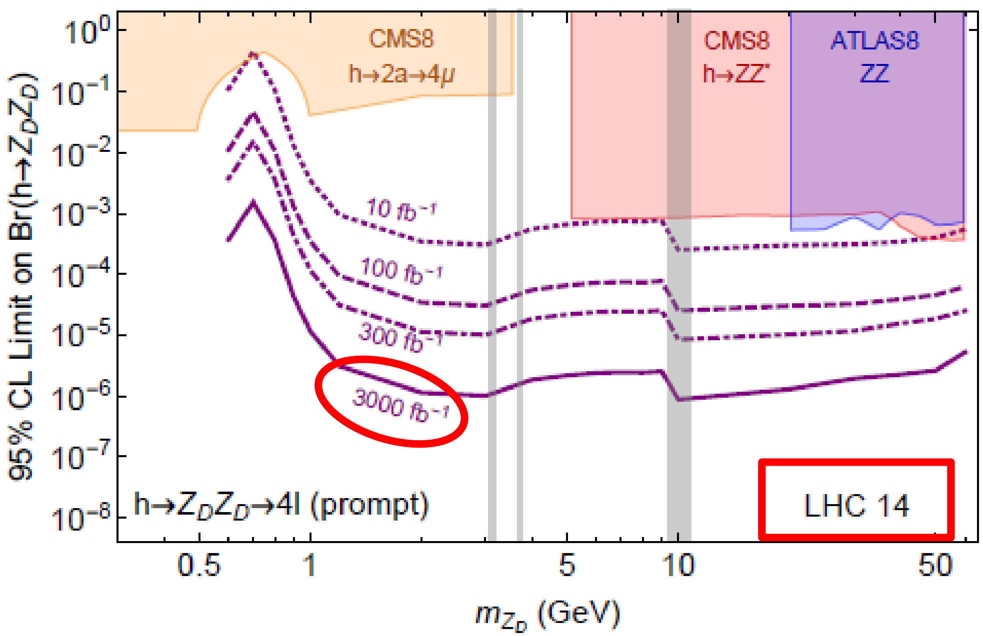
$\mathrm{BR}(h \longrightarrow Z_D Z_D \longrightarrow 4l) \geq 10^{-7}$

can be tested

This corresponds to setting a bound on the Higgs mixing with another scalar at the level of few $\times 10^{-5}$

A dedicated search for $Z_D Z_D$

A almost background free search



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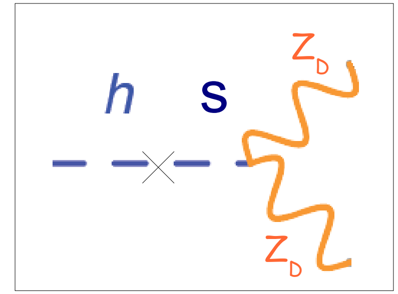
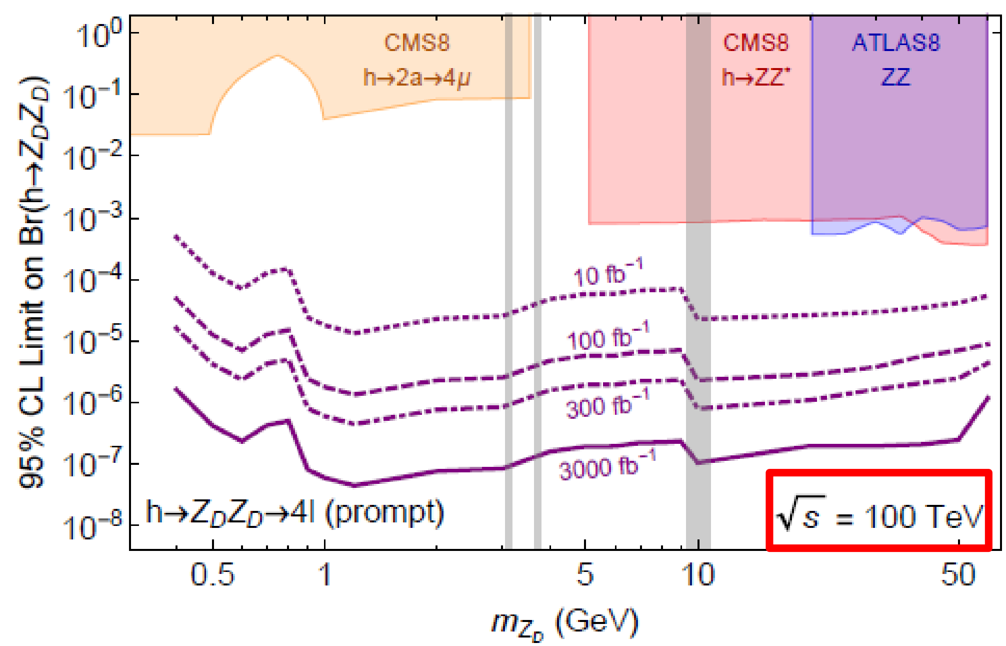
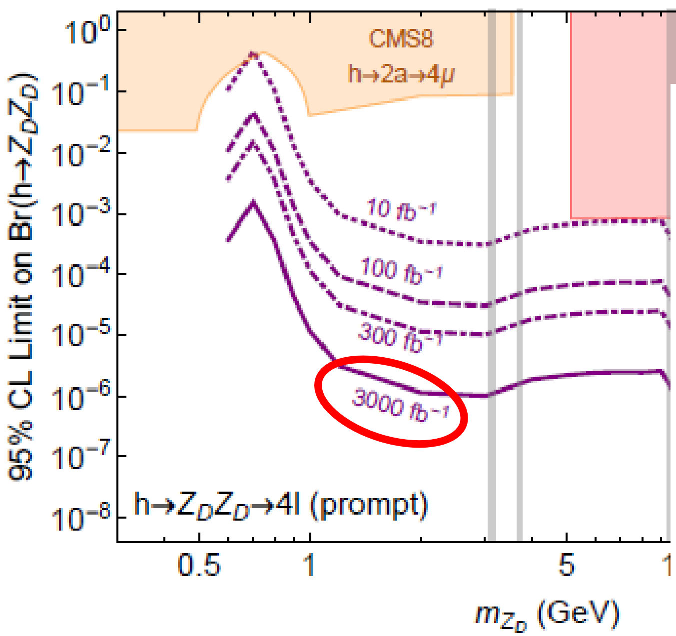


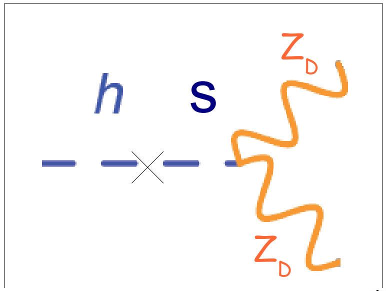


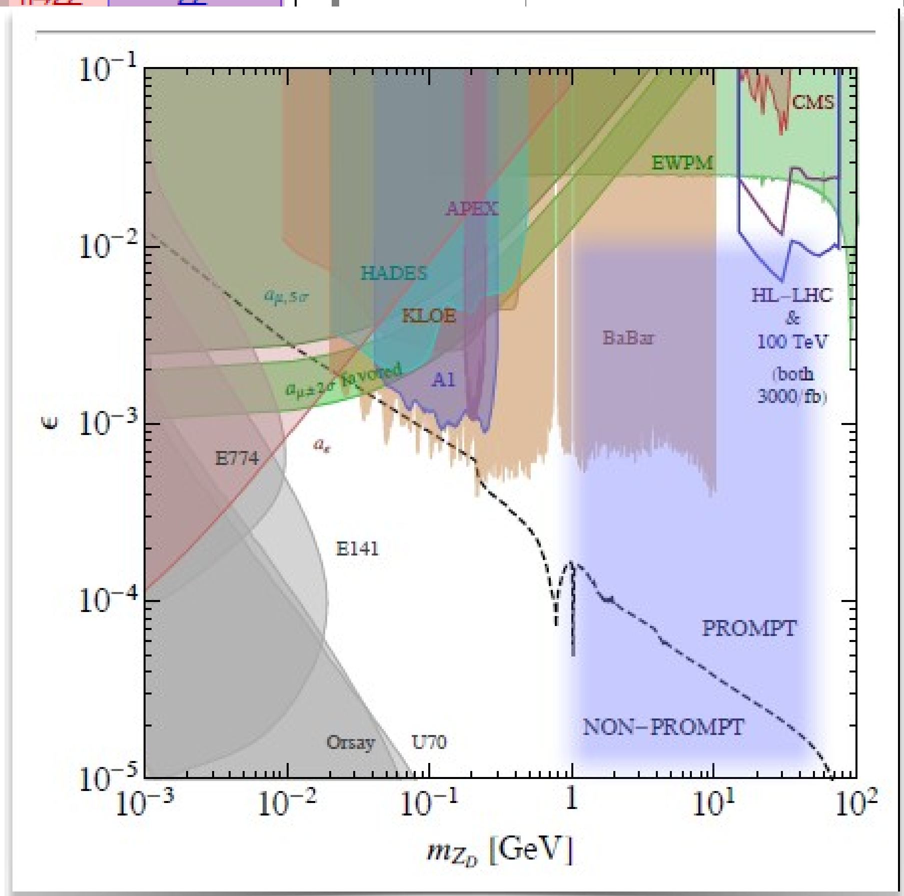
$BR(h \longrightarrow Z_D Z_D \longrightarrow 4l) \geq$ few $\times 10^{-9}$ can be tested

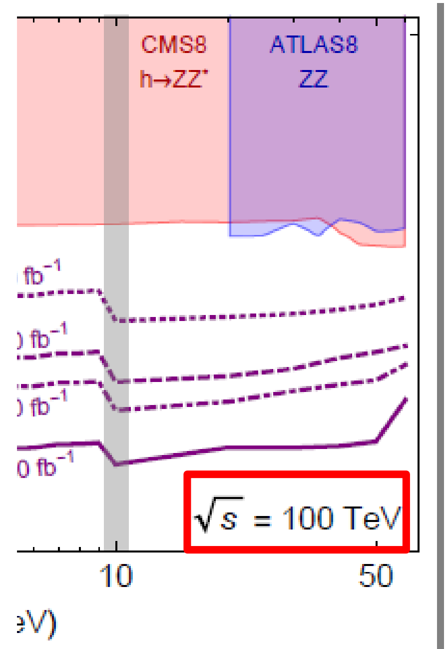
A dedicated search for $Z_D Z_D$

A almost background free search









$BR(h \to Z_D Z_D \to 4l$
can be teste

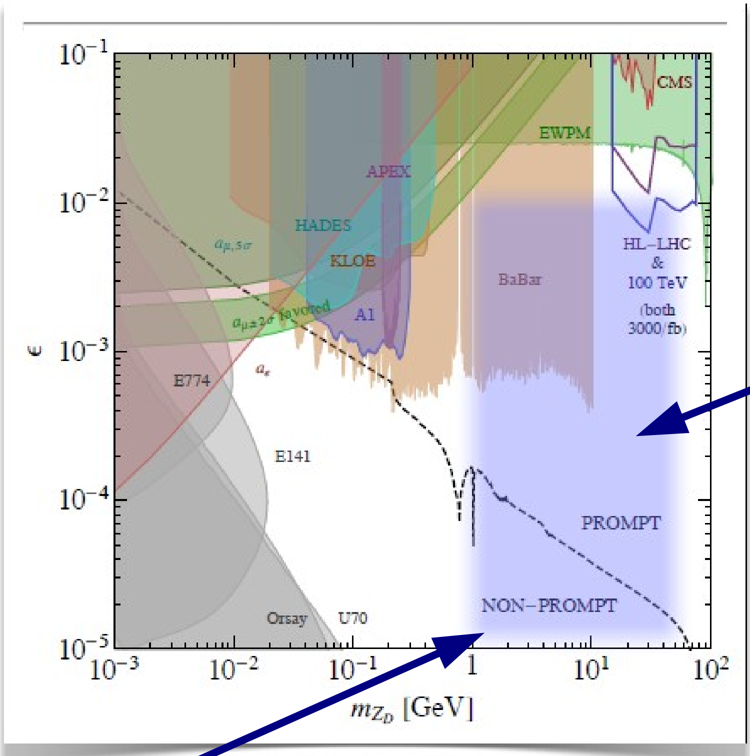
This corresponds to set
bound on the Higgs mix
with another scalar at
the level of few $\times 10^{-5}$

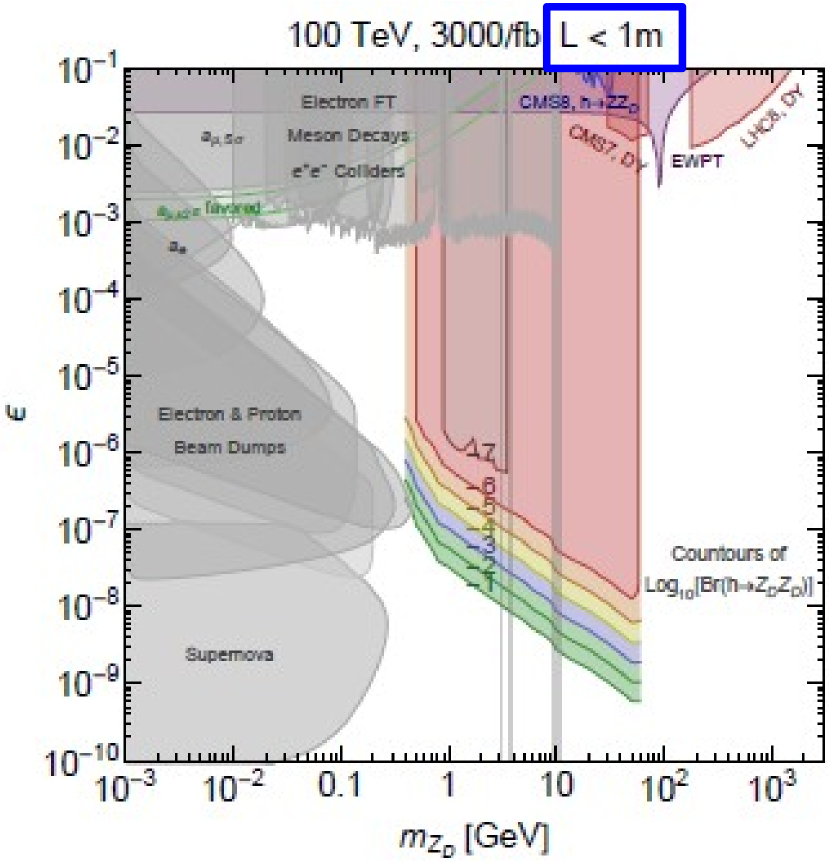
$) \geq$ few $\times 10^{-9}$
can be tested

A non-promptly decaying Z_D

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

Let´s estimate...





Probed by $h \to Z_D Z_D$

Accessible?

Probabilty for Z_D to decay inside the detector

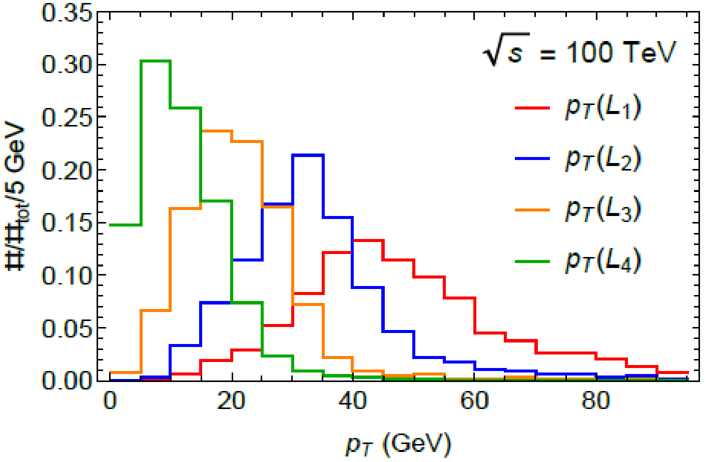
The BR we measure

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

A completely new detector!

Some thoughts...

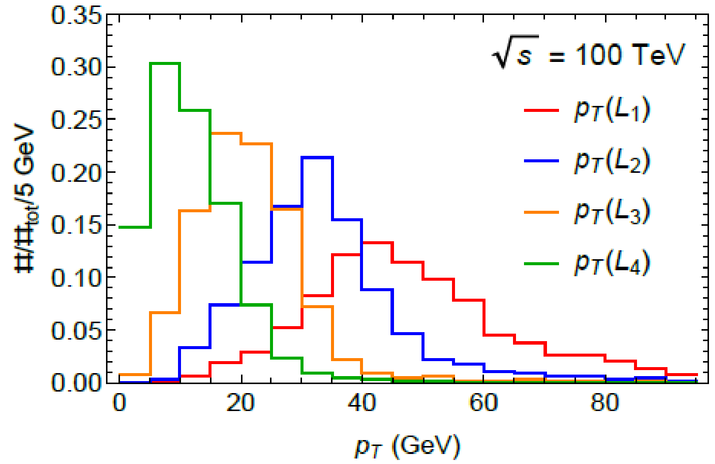
- In general, it is crucial to keep low (lepton) reconstruction p_T thresholds



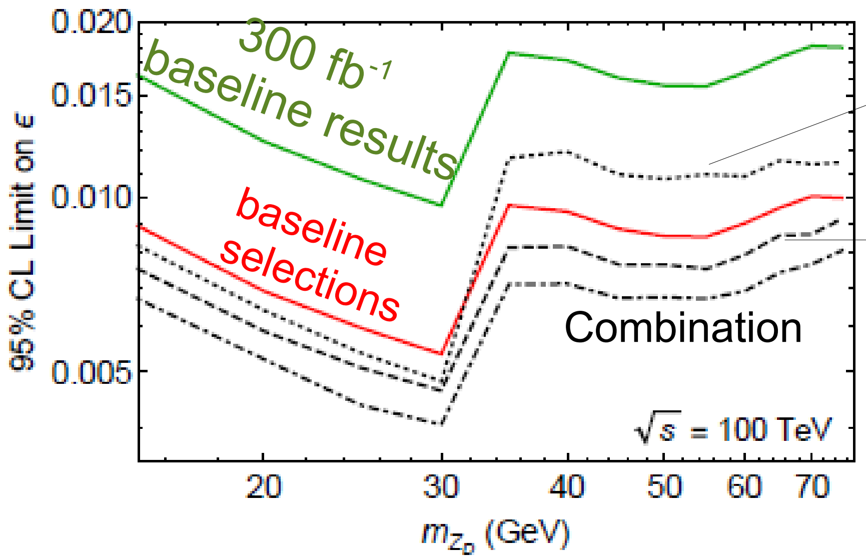
A completely new detector!

Some thoughts...

- In general, it is crucial to keep low (lepton) reconstruction p_T thresholds



- We might gain having a better eta coverage and mass resolution



Bound from $h \longrightarrow ZZ_D$, 3000 fb^{-1}

1. Larger η coverage ($|\eta|<4$)

2. Better mass resolution

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

instead of

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

Conclusions

A high energy, high luminosity proton proton machine offers a unique opportunity to test exotic decays of the 125GeV Higgs bosons

Branching ratios as low as ~few $\times 10^{-9}$ could be tested with $3000 fb^{-1}$ 100TeV data for particularly clean modes

Our assumptions

1. The observed 125 GeV is SM-like

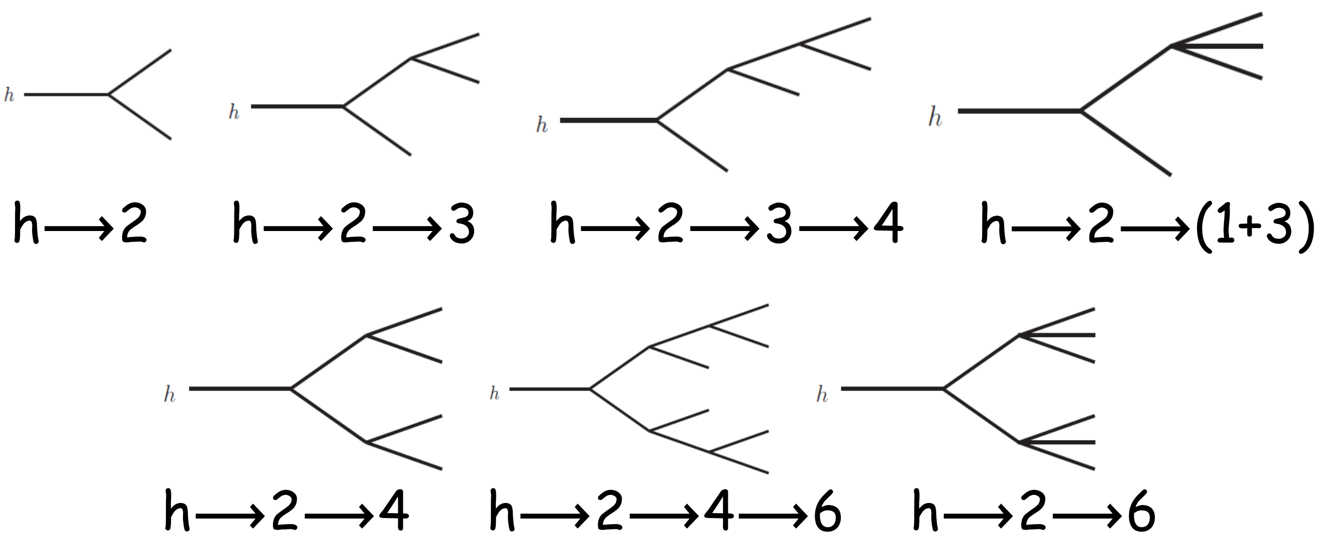
- In particular its production cross section in the several channels is the one of the SM Higgs

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



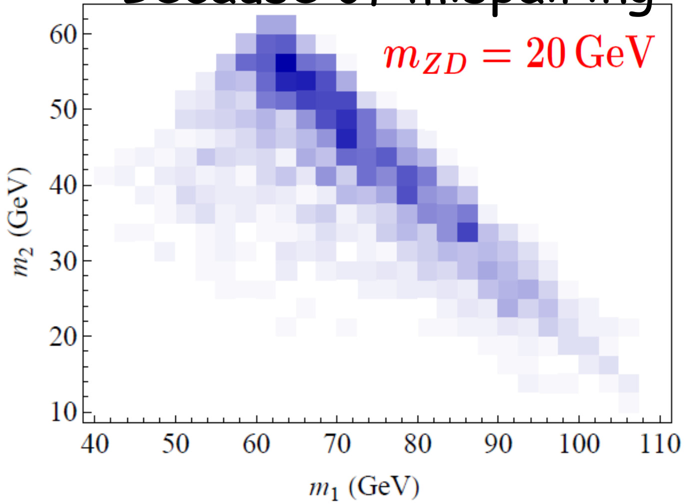
$h \to MET$
$h \to 4b$
$h \to 2b2\tau$
$h \to 2b2\mu$
$h \to 4\tau, 2\tau 2\mu$
$h \to 4j$
$h \to 2\gamma 2j$
$h \to 4\gamma$
$h \to ZZ_D \to 4l$
$h \to Z_D Z_D \to 4l$
$h \to \gamma + MET$
$h \to 2\gamma + MET$
$h \to 4l + MET$
$h \to 2l + MET$
$h \to$ one lepton jet
$h \to$ two lepton jets
$h \to bb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

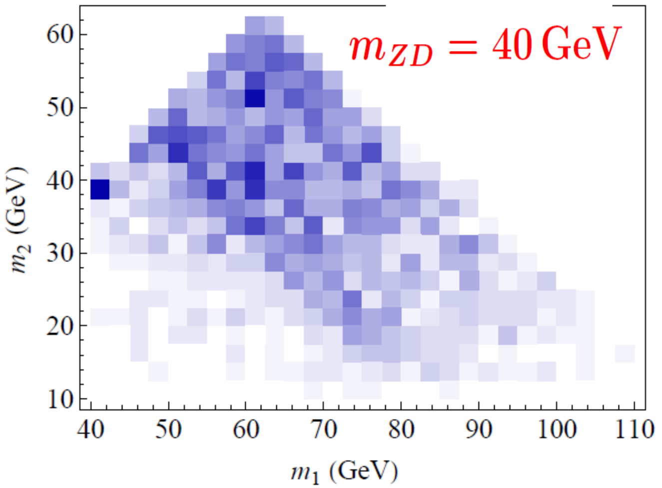
Setting bounds on $Z_D Z_D$: present

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

Our signal

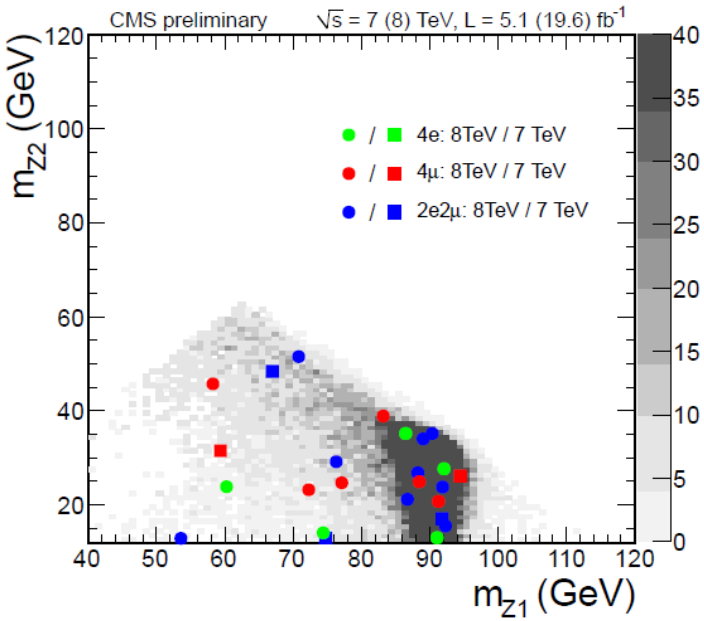
Because of mispairing:





$$40 \text{ GeV} < m_1 < 120 \text{ GeV},$$
$$12 \text{ GeV} < m_2 < 120 \text{ GeV}$$

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

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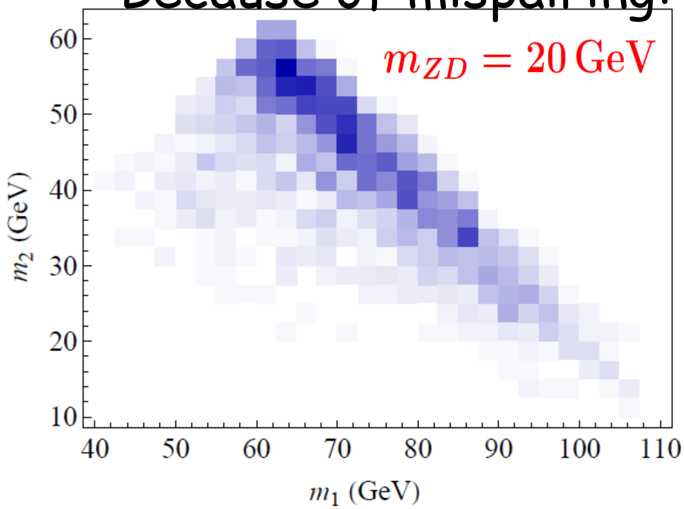
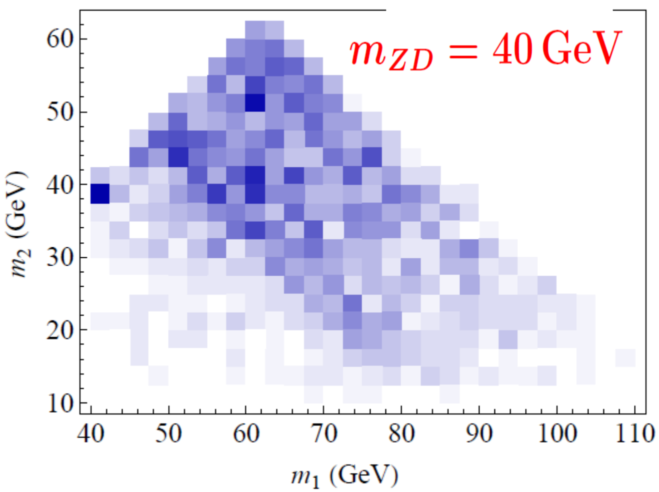
Because of mispairing:





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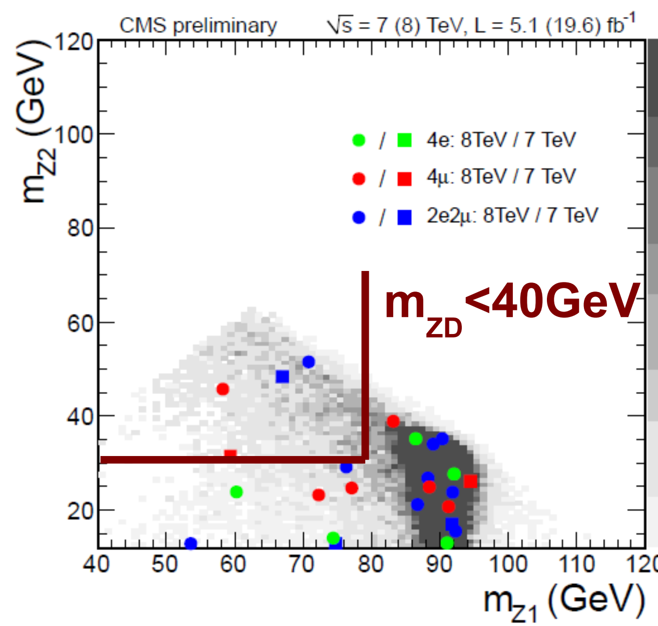


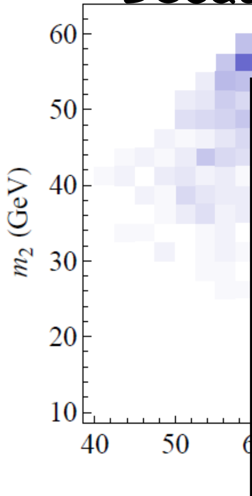
CMS PAS HIG-13-002

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

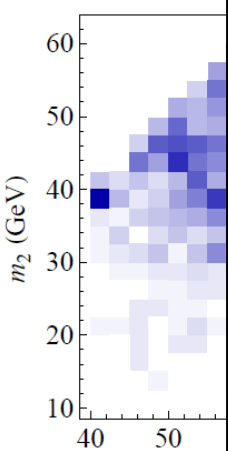
Setting bounds on $Z_D Z_D$: present

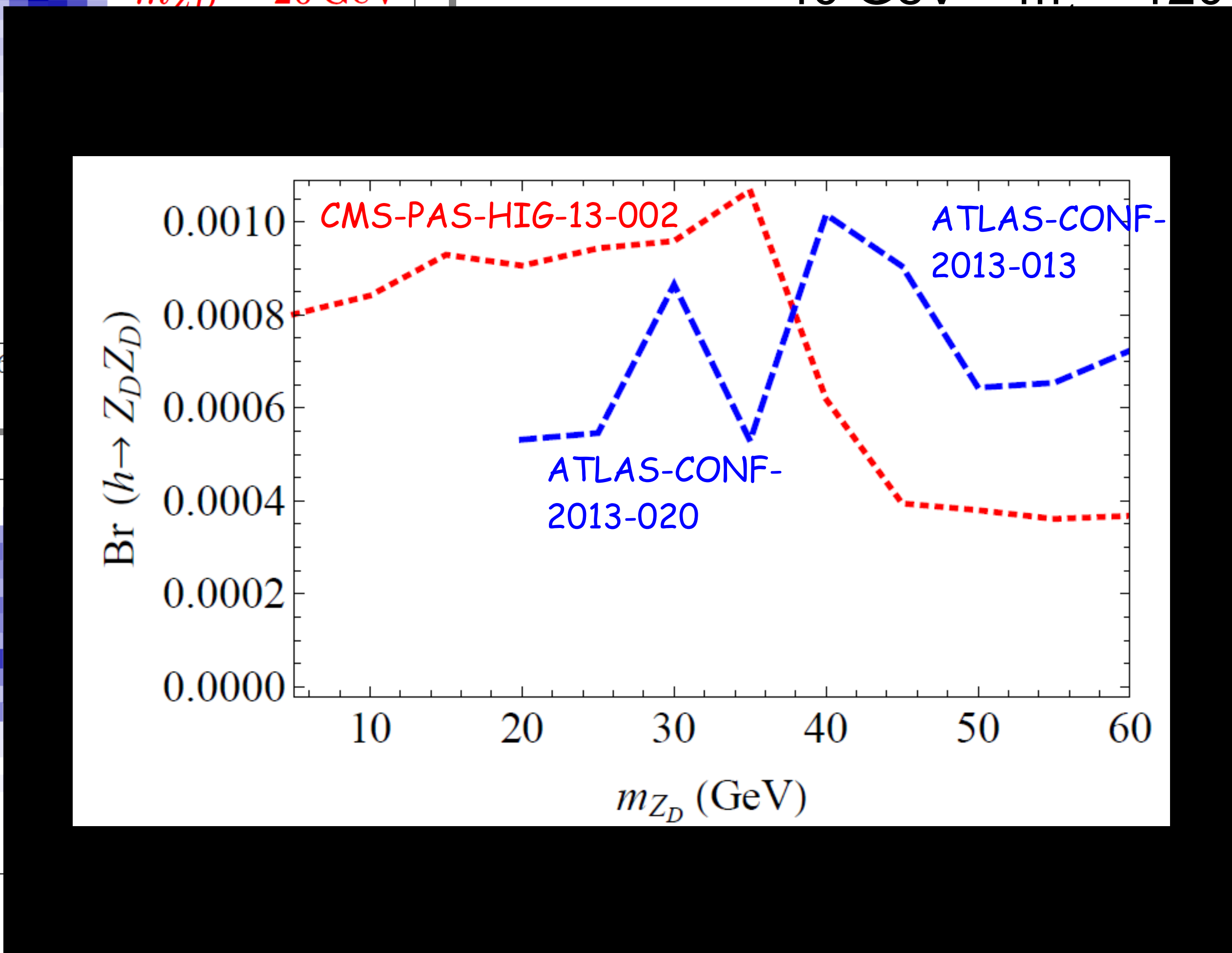
Bounds coming from SM h → ZZ*→ 4l searches at the LHC
CMS PAS HIG-13-002, ATLAS-CONF-2013-013

Because of mispairing:



Our signal





40 GeV < m_ < 120 GeV,

GeV

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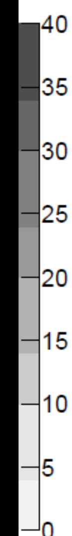

For m_{ZD}>40GeV:
$m_{ZD} \pm 5$ GeV

The final aim

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

Exotic scorecard

	jj	bb	$\tau\tau$	ll	$\nu\nu$
jj					
bb					
$\tau\tau$					
ll					
$\nu\nu$					

Prospects?

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

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 $\frac{\sigma}{\sigma_{\mathrm{SM}}} \cdot \mathrm{BR}(\text{non-SM})$ 7+8 [14] TeV
$jjjj$	> 1 [0.1*]	W	0.25	> 1 [0.4*]
$\ell\ell\ell\ell$	$4 \cdot 10^{-5}$	G	0.09	$4 \cdot 10^{-4}$
$jj\mu\mu$	$0.002 - 0.008$ $[(5-20) \cdot 10^{-4}]$	G	0.15	$0.01 - 0.06$ $[0.003 - 0.01]$
$b\bar{b}\mu\mu$	$(2-7) \cdot 10^{-4}$ $[(0.6-2) \cdot 10^{-4}]$	G	0.015	$0.01 - 0.05$ $[0.003 - 0.01]$

Curtin, Essig, SG, Jaiswal, Katz, Liu, Liu, Mckeen, Shelton, Strassler, Surujon, Tweedie, Zhong, 1312.4992