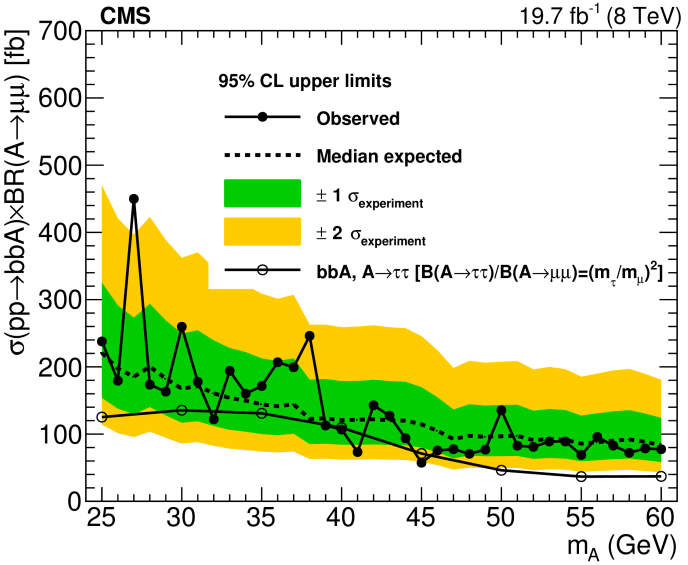
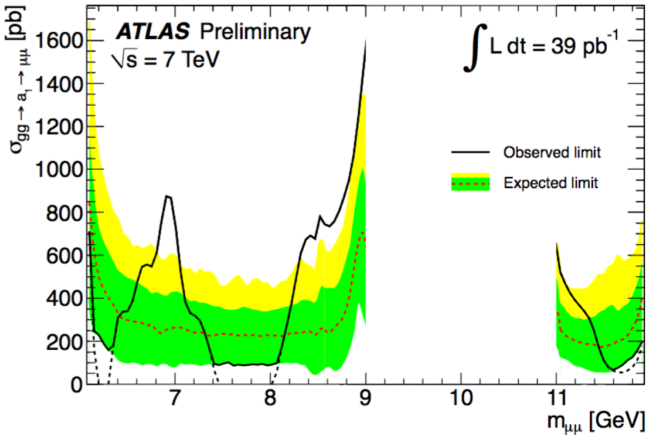
1.

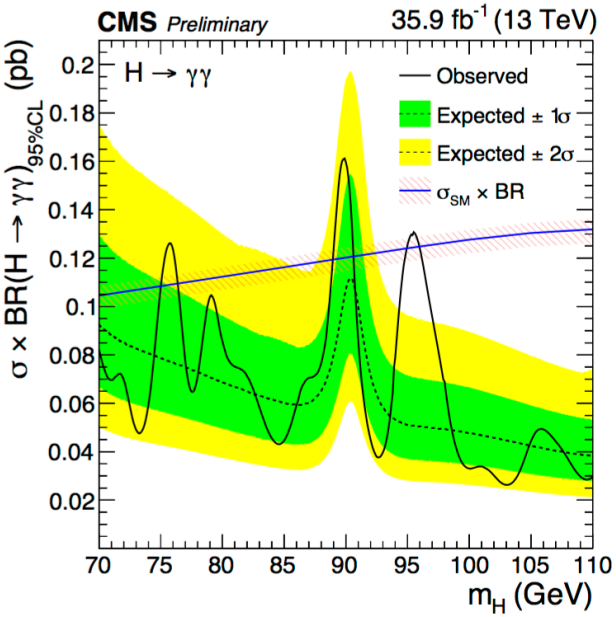
Direct production of a new scalar

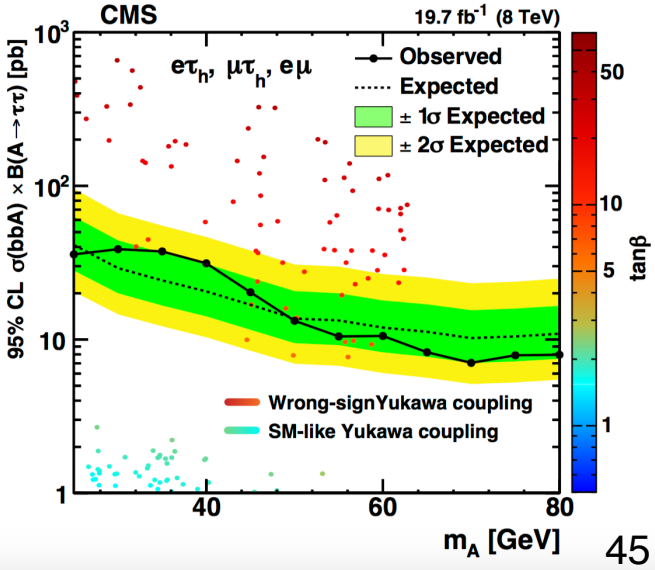
The production cross section_s = production_SM Higgs*$\sin^2(\theta_S)$
Same production modes as for the SM Higgs

Only a few LHC searches have been performed.
Examples are bbA, A →μμ
ggA, A →μμ, (also searched for by LHCb)
ggA, A →γγ
bbA, A →tautau









The Higgs width & Higgs exotic decays

The extraction of info on the Higgs width is hard and has typically some model dependence at the LHC (hadron colliders)

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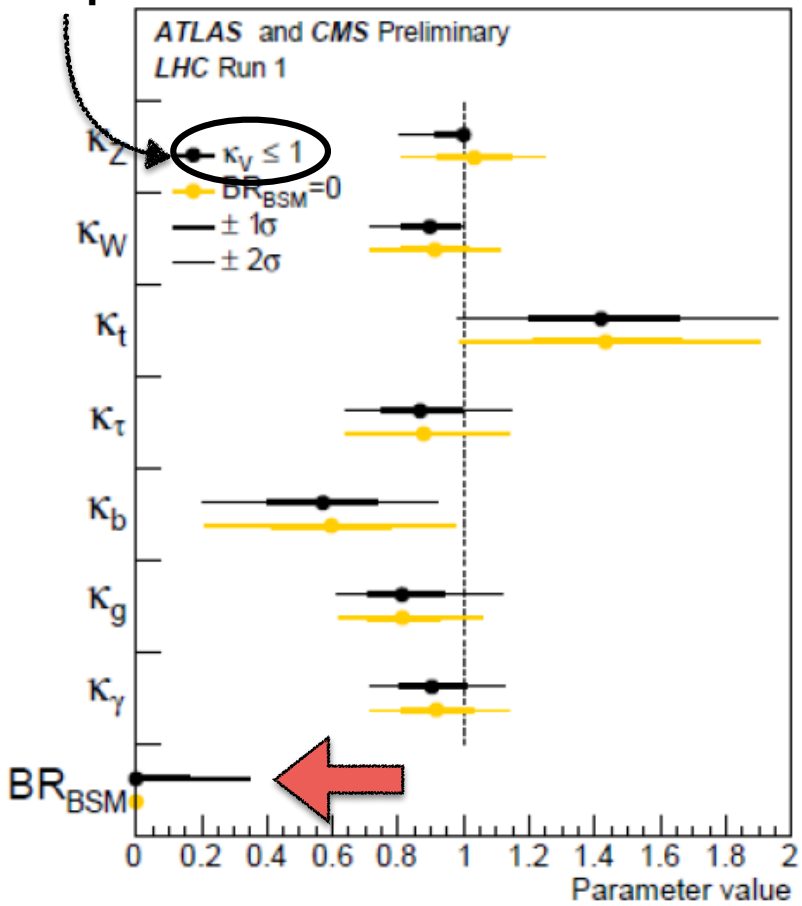

BR_{BSM} < 34% (BR_{BSM} < 26% (ATLAS-CONF-2018-031))

Prospects for the HL-LHC: ~5-10%

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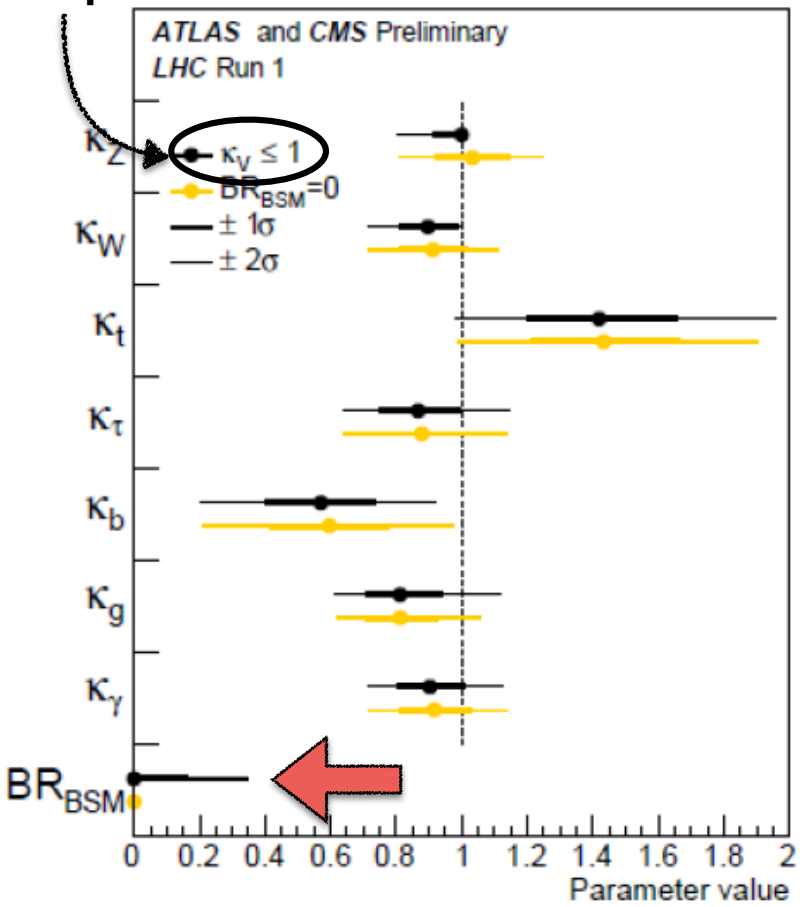

Beyond Higgs coupling measurements, there are other complementary ways to access the Higgs width:

- Off-shell measurements in $gg \to h^* \to ZZ$ — Caola, Melnikov, 1307.4935
- interference between $gg \to \gamma\gamma$ and $gg \to h \to \gamma\gamma$ — Dixon, Li, 1305.3854

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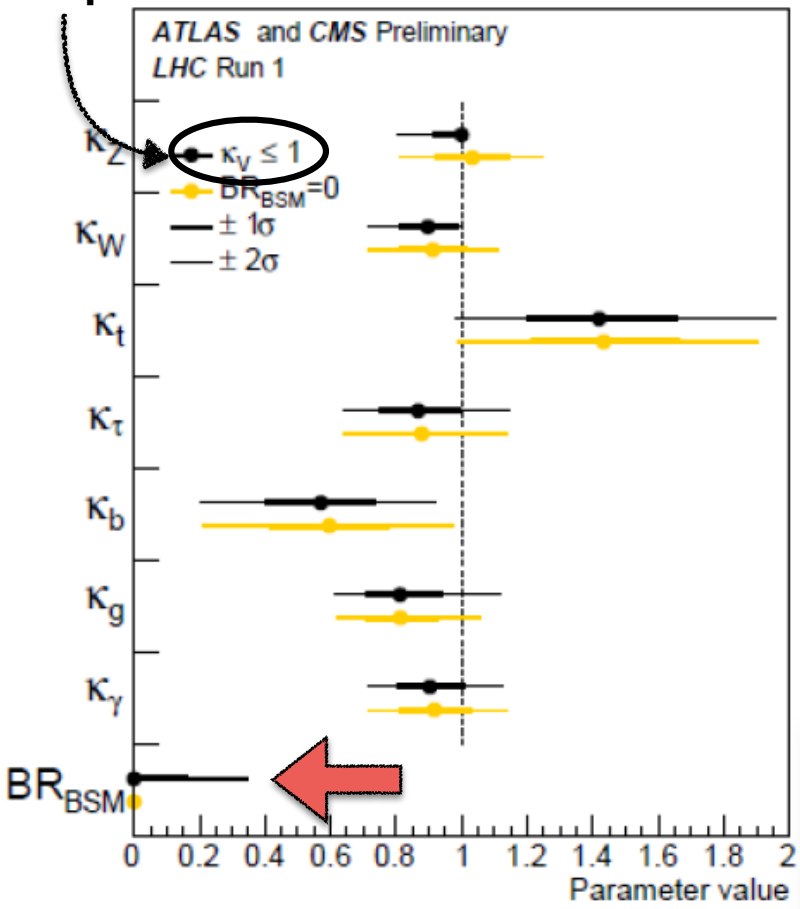

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The Higgs can have some "extra width". Said in other words: the Higgs can have some exotic decays to New Physics particles

Higgs invisible decays… and beyond

One classic example is the Higgs decaying invisibly

This is realized in e.g. DM theories where the DM particle couples to the Higgs and is light

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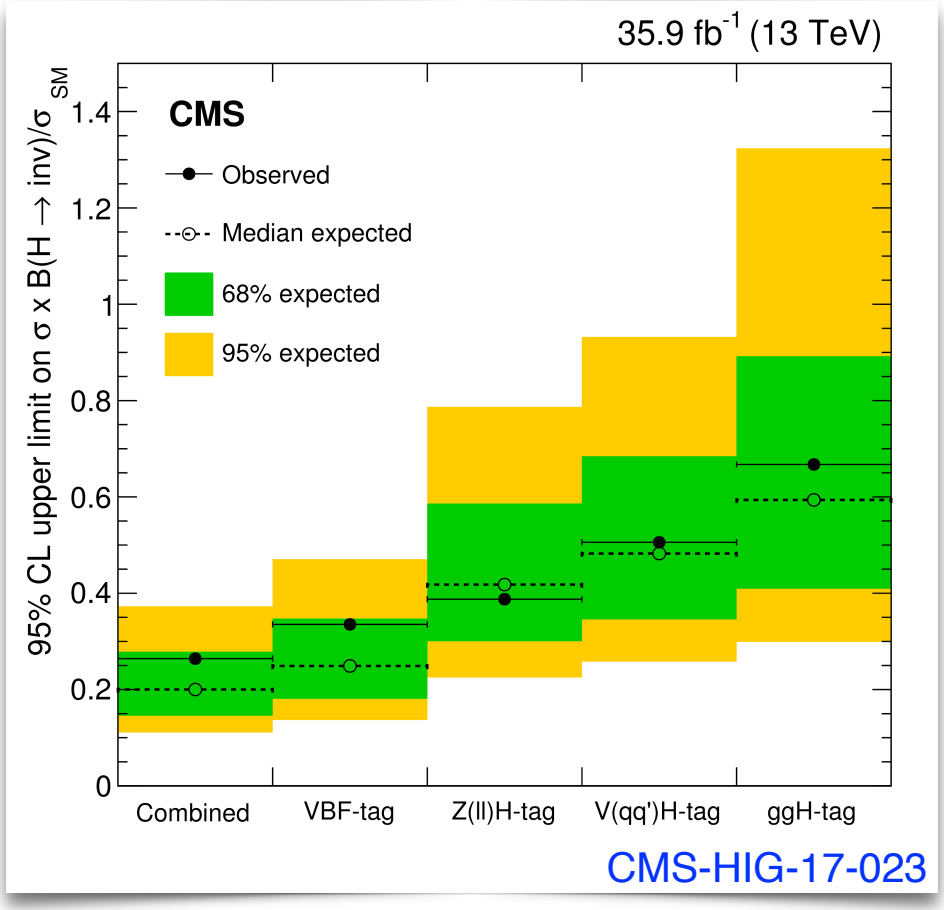

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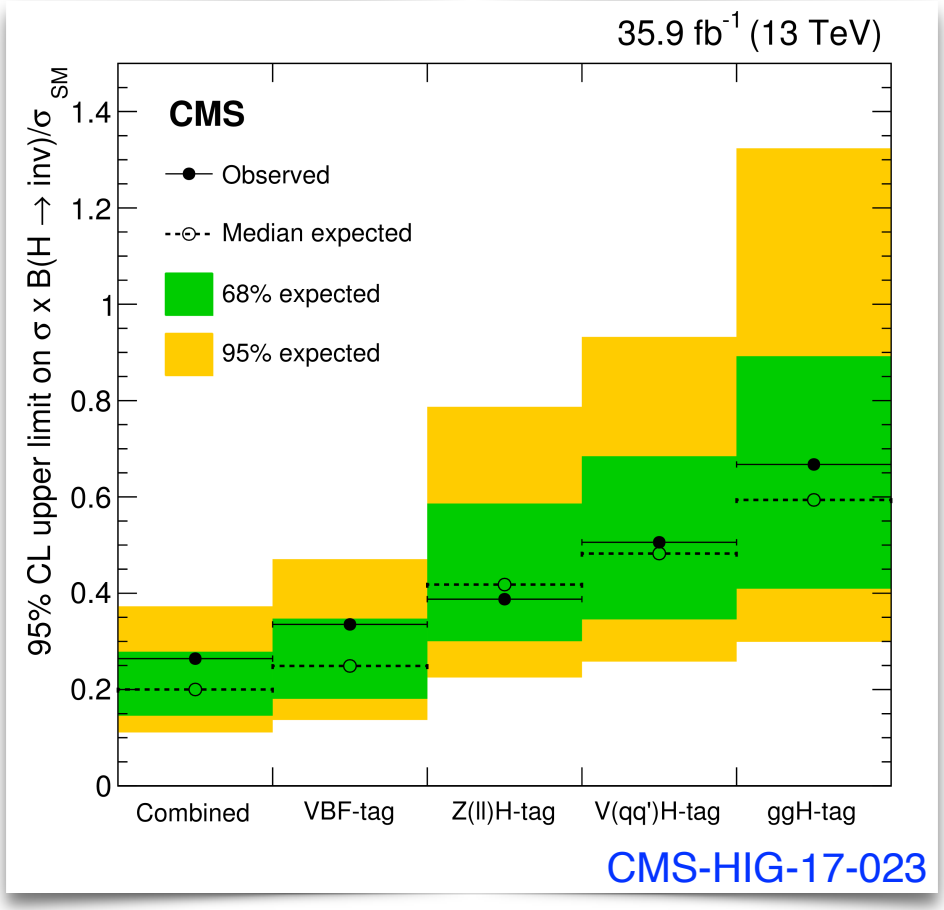
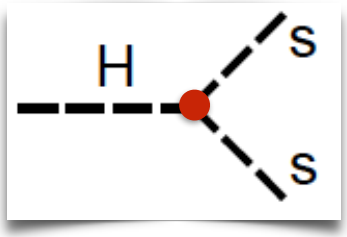


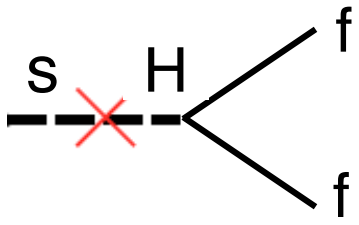
But what about the “extra width” arising from different decay modes that are (at least partially) visible? We have to look for them directly!

3.

A program for searches for h → ss



The scalar can decay thanks to its mixing with the Higgs



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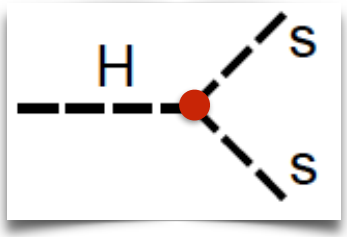

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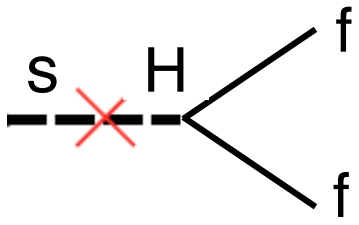

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  - ⇒ Higgs invisible decay
- If $\theta_s \neq 0$, s will decay to SM particles

$$\Gamma(s \to f\bar{f}) = \sin^2\theta_S \frac{N_c}{8\pi} \frac{m_s m_f^2}{v^2} \beta_f^3$$

Main BRs: bb, ττ, cc, ...

$\mathrm{Sin}(\theta_s) \geq O(10^{-5})$
S decays promptly

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S has displaced decays

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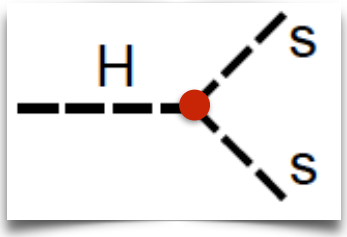

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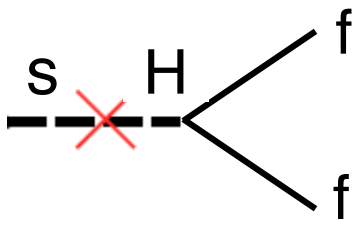

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In this minimal model:

Many possible signatures to look for

gg → h → ss → 4b
gg → h → ss → 2b 2tau
gg → h → ss → 2b 2μ
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both prompt & displaced

+ sub-leading production modes of the Higgs boson

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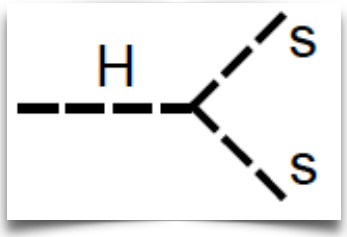

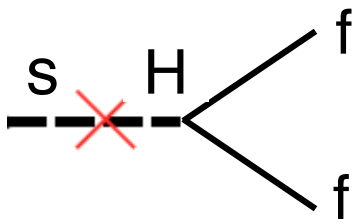

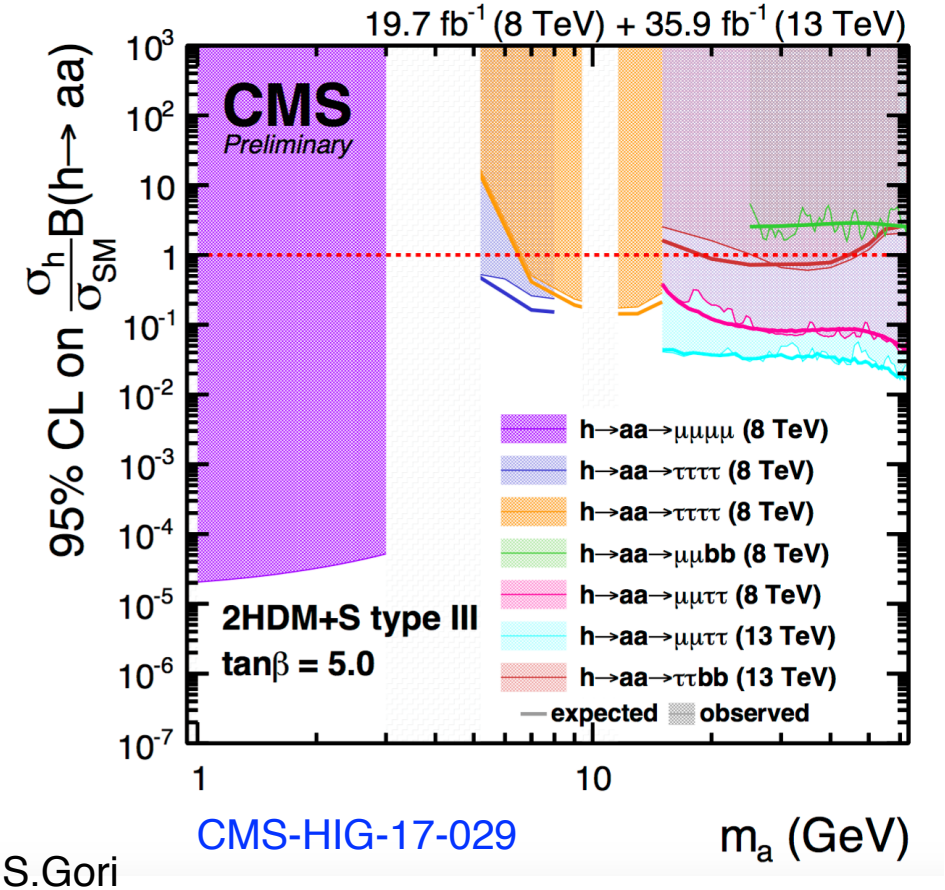

CMS-HIG-17-029

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The challenge: soft objects

To be sensitive to Higgs exotic decays, dedicated studies of trigger strategies are needed

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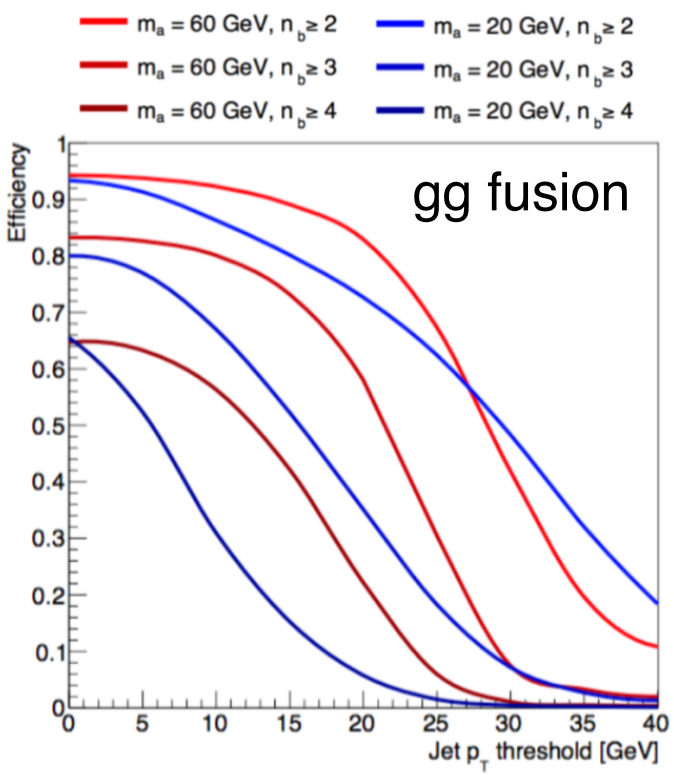
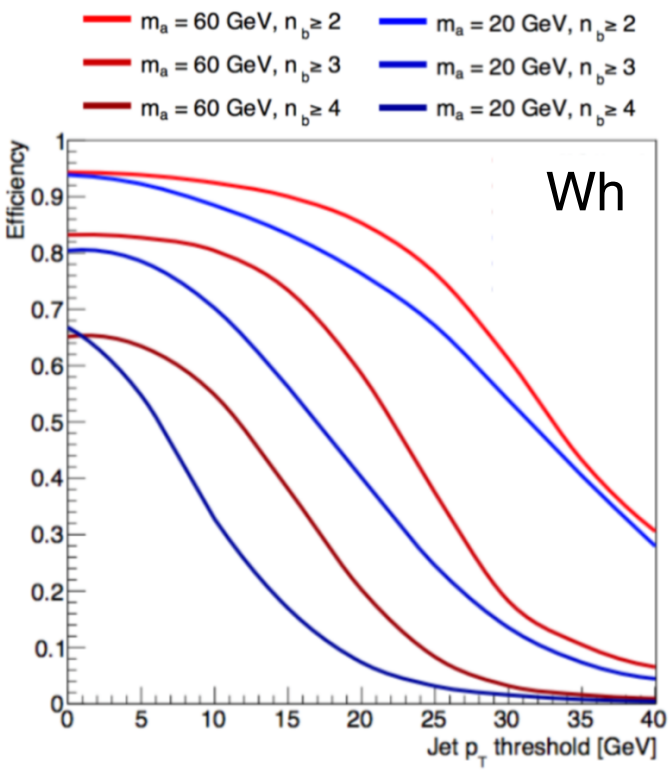
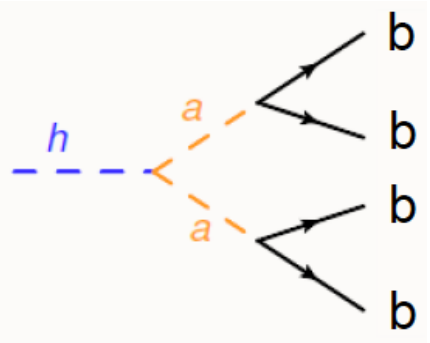
Let us take, for example, the challenging decay mode h → 4b





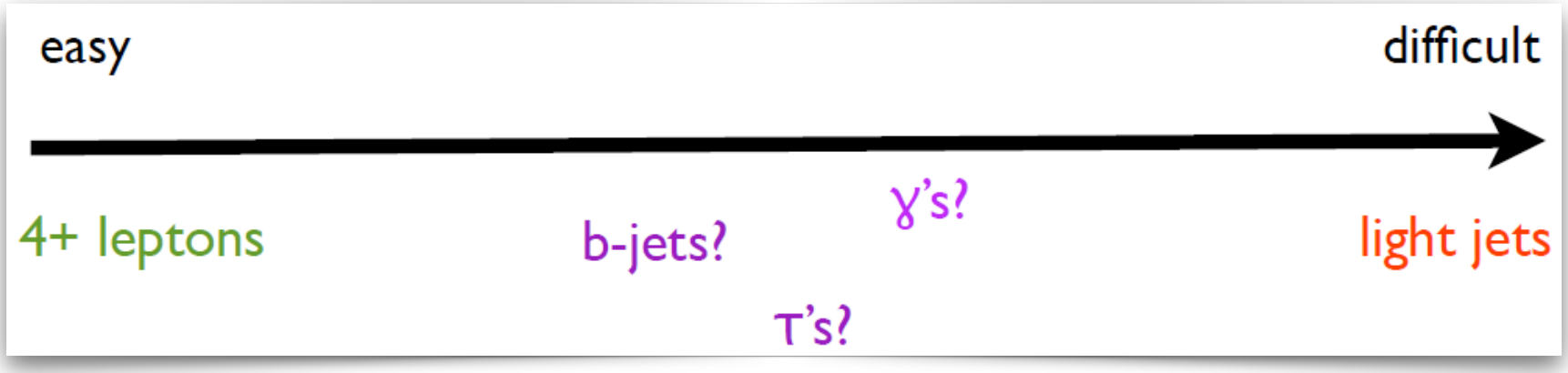


Risk of loosing the signal already at the trigger level

From the LHC Higgs cross section working group, Yellow report 4, 1610.07922

Toward a broader program for H exotic decays

From the signature point of view:



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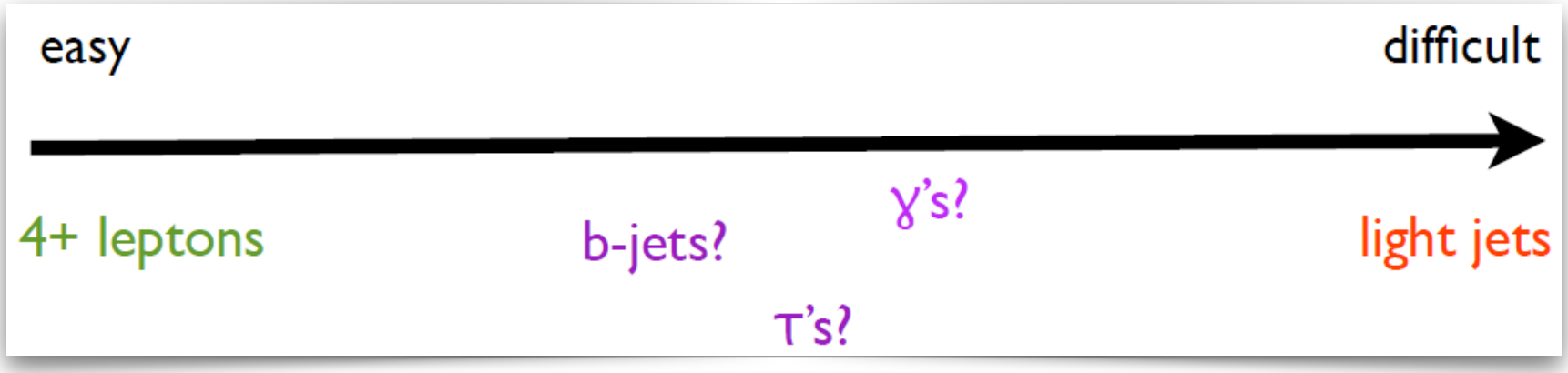

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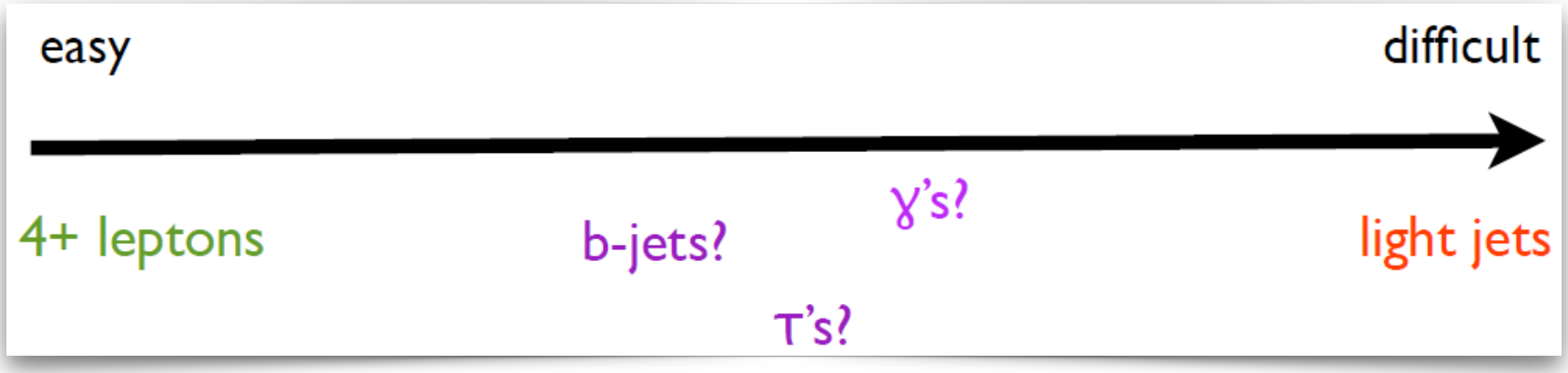

Statistics limited
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Background limited
It helps having extra handles:
New production modes
for the Higgs (tth, Zh, Wh, …).

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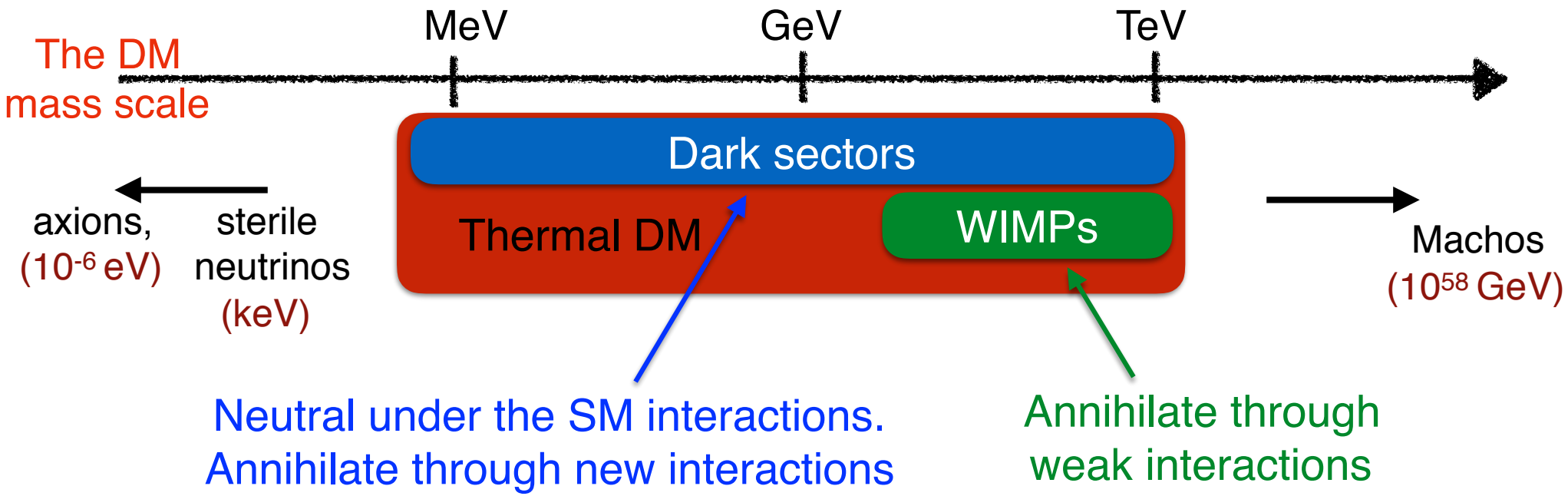
Chapter 4

From Higgs exotic decays
to dark sector models

- dark scalars
- dark photons
- dark neutrinos

from symmetry magazine

Thermal dark matter



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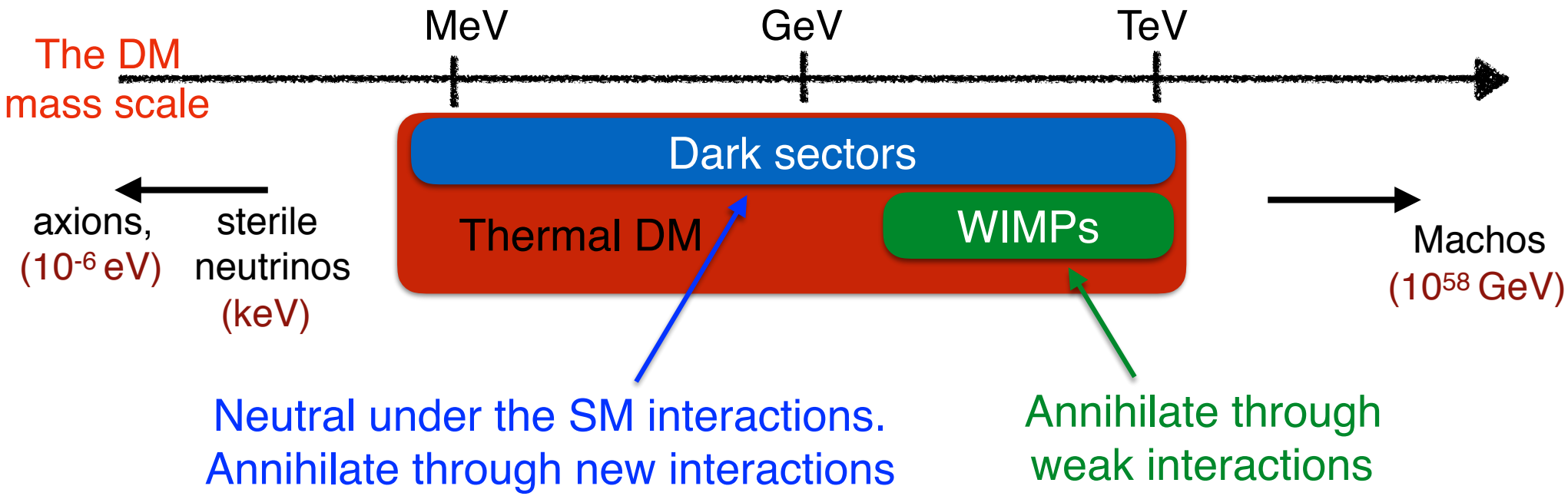

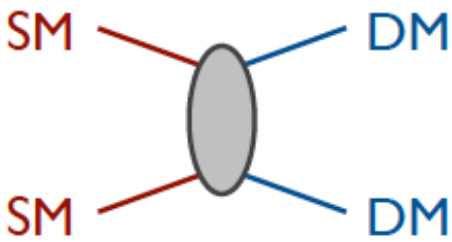

This coupling cannot be too small
for DM to be in thermal equilibrium
with the SM in the early universe

Detectability?

Dark sectors

Further motivations beyond DM?

- Several anomalies in data can be addressed by dark sectors
(eg. $(g\text{-}2)_\mu$, B-physics anomalies, Dark Matter anomalies (galactic center excess), …);

- Neutrino mass model building

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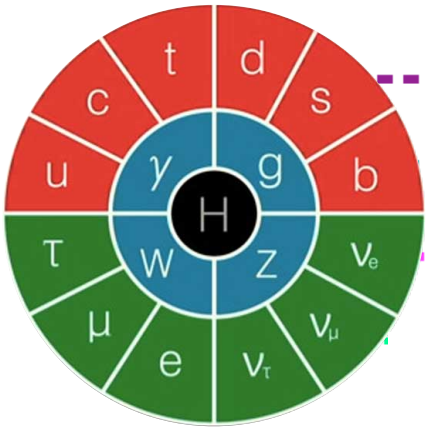

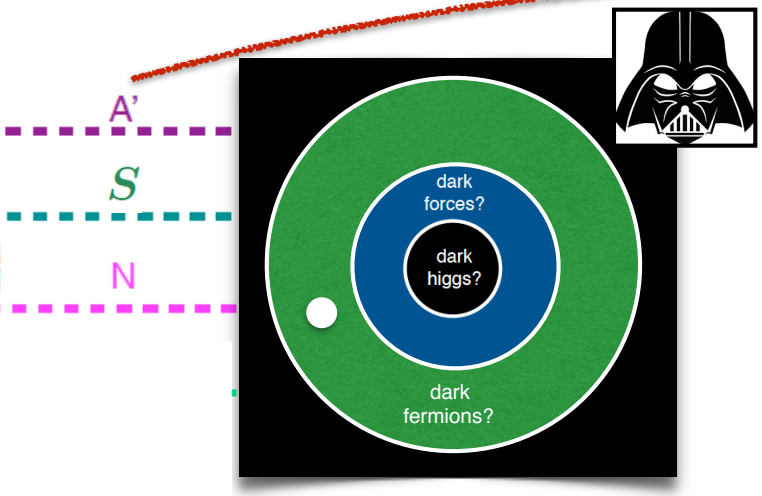

Not charged under the SM gauge symmetries

"Portals":

Dark photon $\epsilon Z^{\mu\nu} A'_{\mu\nu}$

Higgs $\kappa |H|^2 |S|^2$ ✓

Neutrino $yHLN$

generically small parameters

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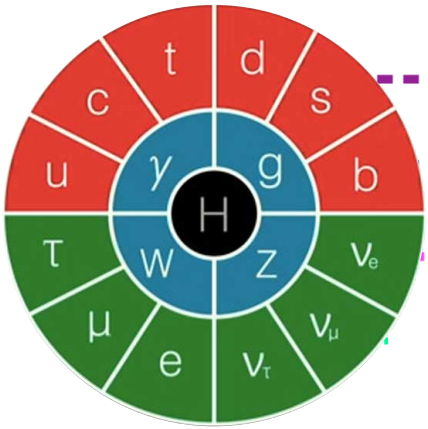
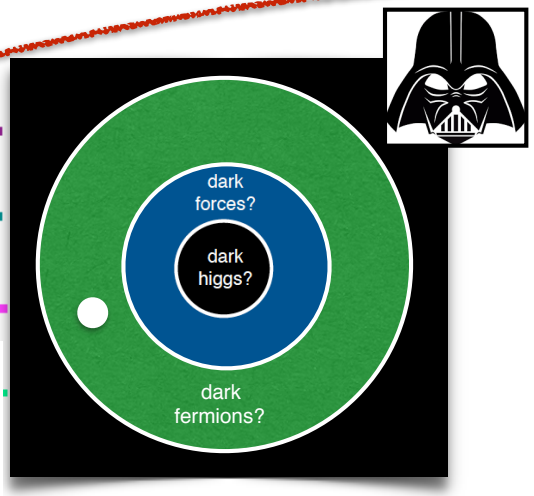


A'

S

N



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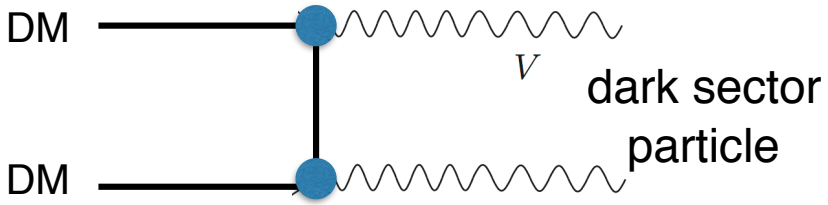
Dark matter cosmology:



The dark photon

Nature seems well described by a SU(3) x $SU(2)_L$ x $U(1)_{em}$ gauge theory. We need to check this assumption!

Additional gauge symmetries in nature? **U(1)'?**

Holdom, '86

$$\mathcal{L} \subset \epsilon Z^{\mu\nu} A'_{\mu\nu} + m^2_{A'} A'_\mu A'^\mu$$ + couplings within the dark sector

Mixing with the SM hyper-charge gauge boson

arising from
* dark Higgs mechanism or
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The SM Z boson is affected

Mass of the Z boson:

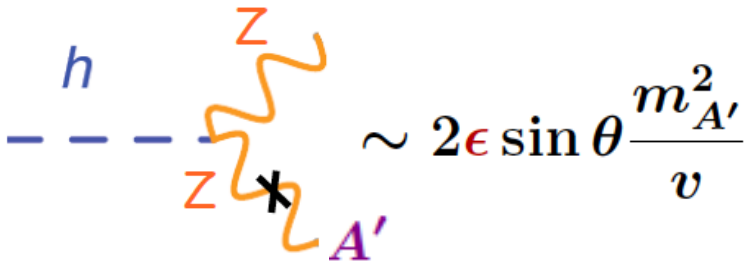
$$m_Z^2 \sim m_{Z0}^2 (1 + \epsilon^2 \sin^2\theta)$$

Couplings of the Z boson with fermions:

$$(Z f \bar{f}) \left(1 + \epsilon^2 \sin^2\theta F(T_3, Q)\right)$$

⇒ LEP bounds

The SM Higgs boson is affected



$$\sim 2\epsilon \sin\theta \frac{m^2_{A'}}{v}$$

Novel Higgs decays

⇒ New opportunities for the LHC

Minimal dark photon signatures

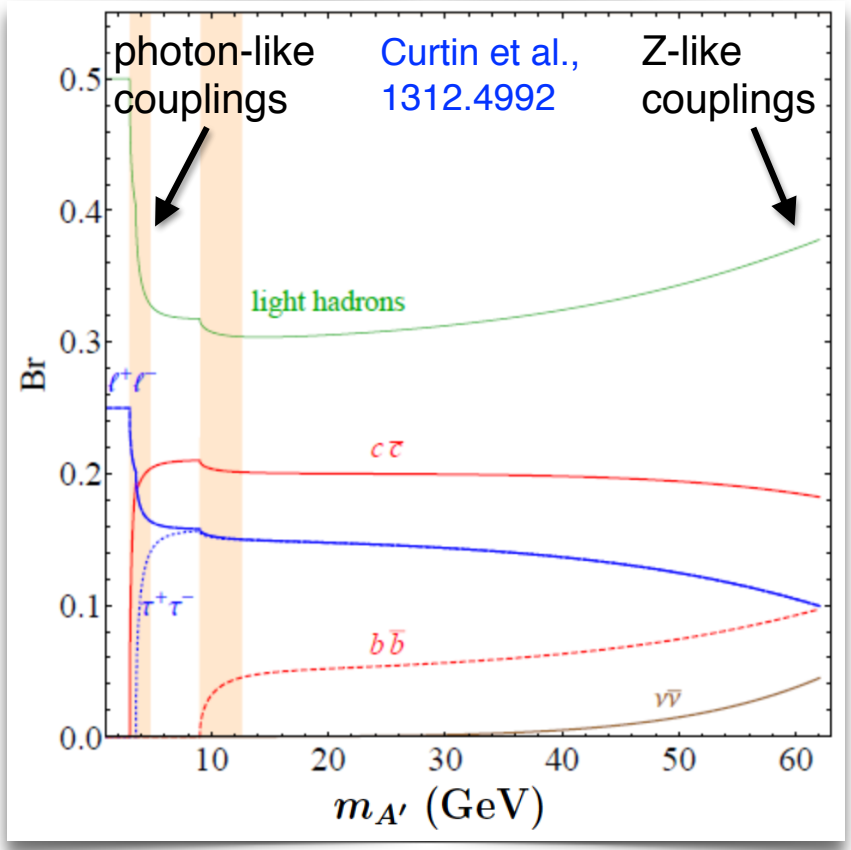
(secluded*)

*DM is heavier

Lifetime and decay mode dictates search strategy

Only relevant free parameters of the minimal model: ϵ, $m_{A'}$

The dark photon can only decay to SM particles (visible decays)



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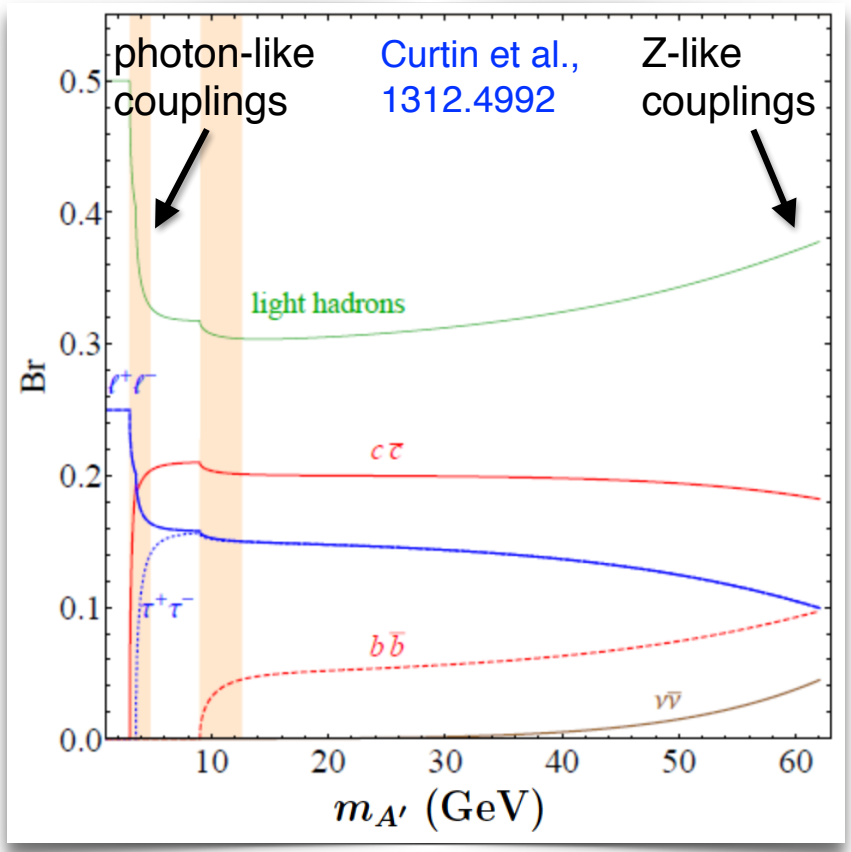

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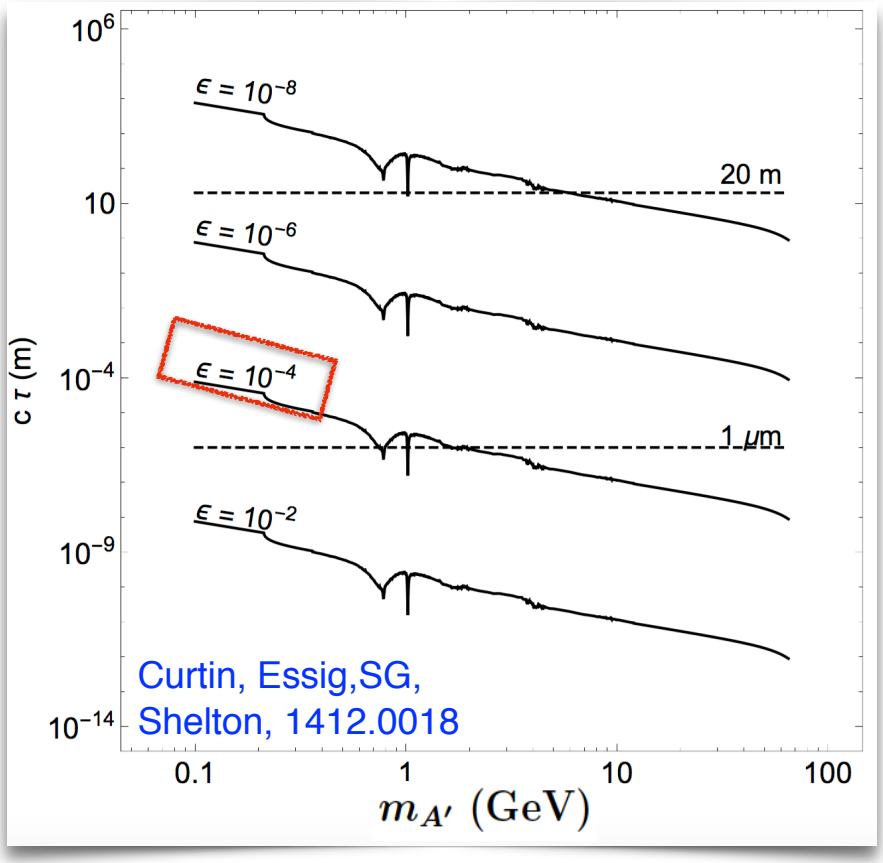

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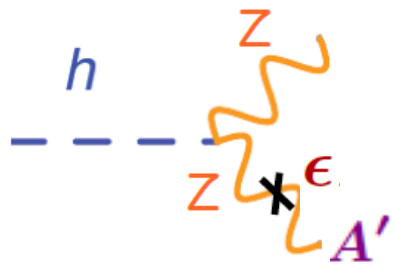

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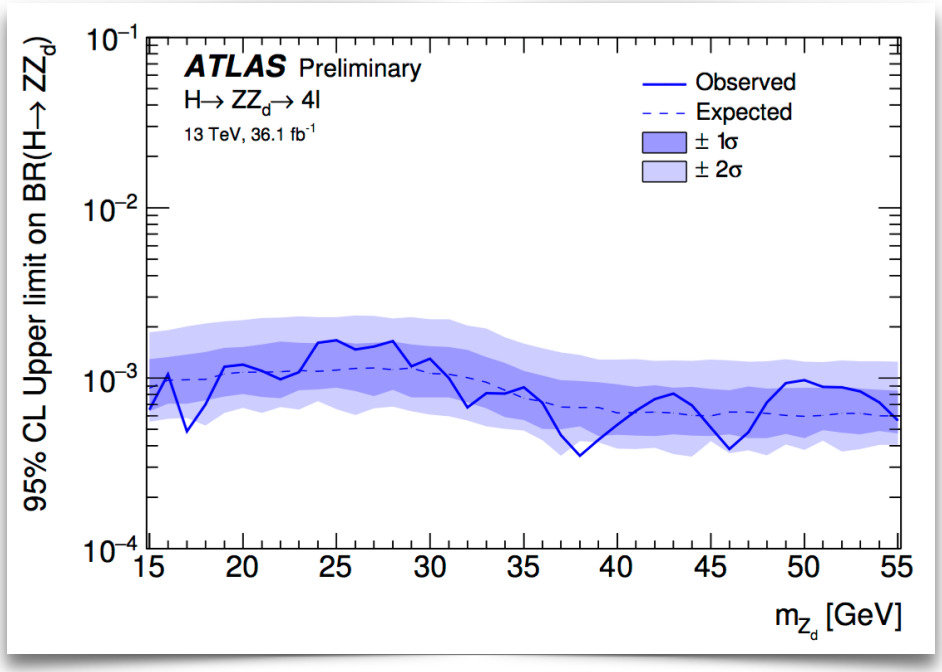
$$h \to ZA' \to 2\ell\, 2\ell'$$



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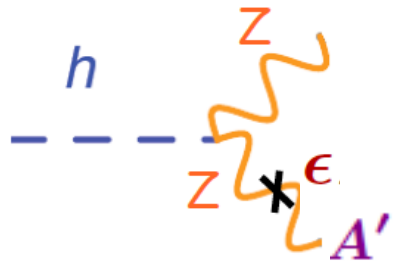
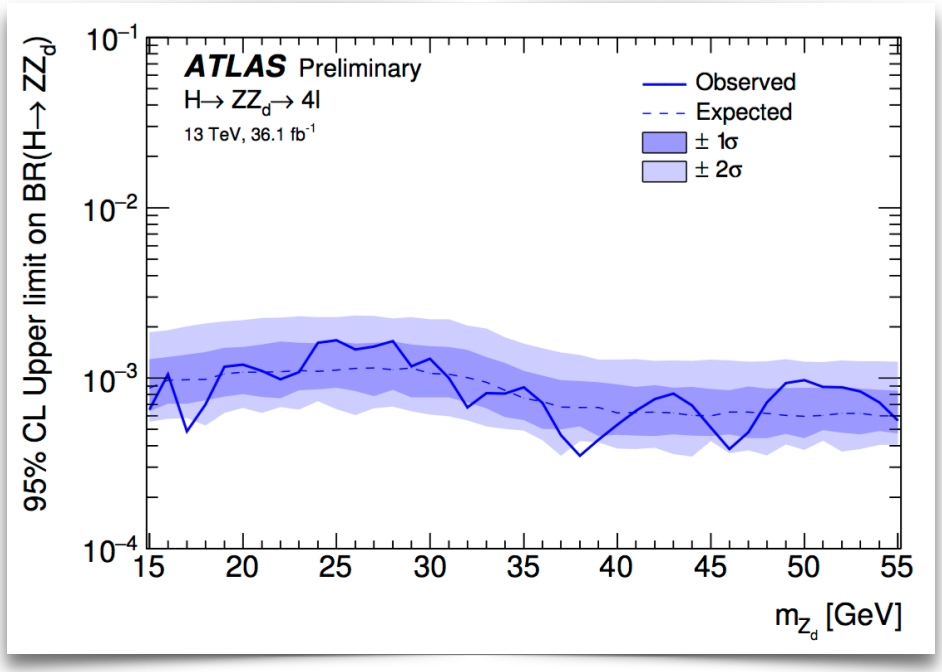
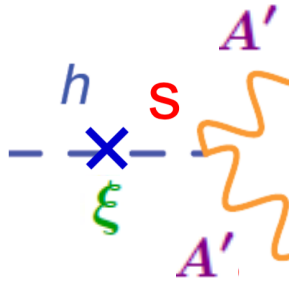


$$\epsilon Z^{\mu\nu} A'_{\mu\nu}$$

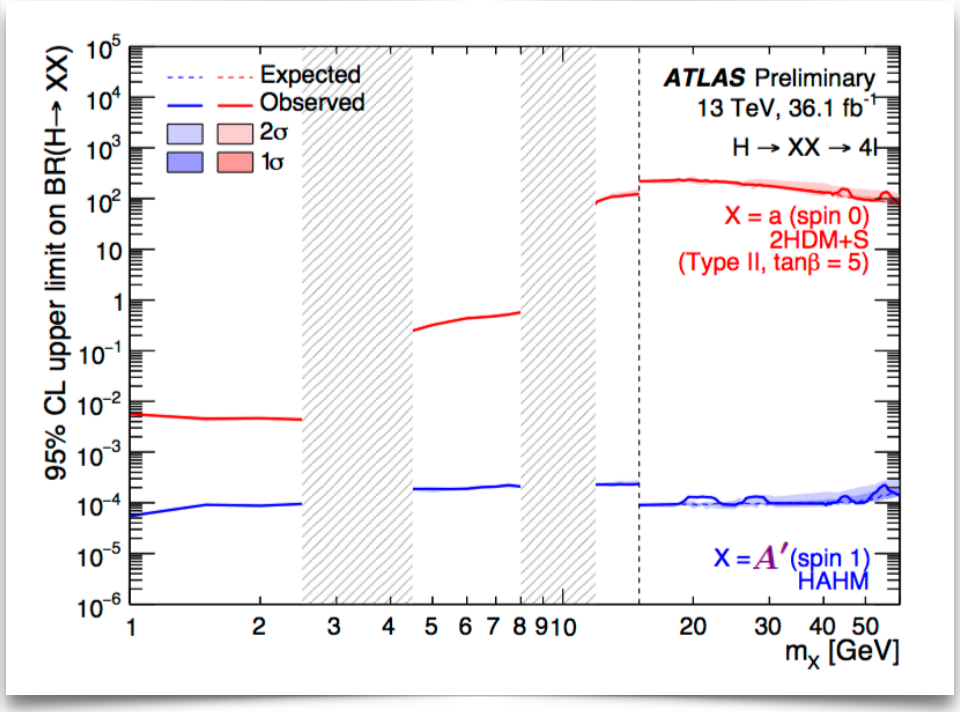
$$h \to ZA' \to 2\ell\, 2\ell'$$





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

$$h \to A'A' \to 2\ell\, 2\ell'$$



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Complementarity with lower energy experiments

Dark photons can be produced at a plethora of lower energy collider experiments.

Examples are:

- e^+e^- machines like Babar and Belle (II)
- electron fixed target experiments (HPS, …)
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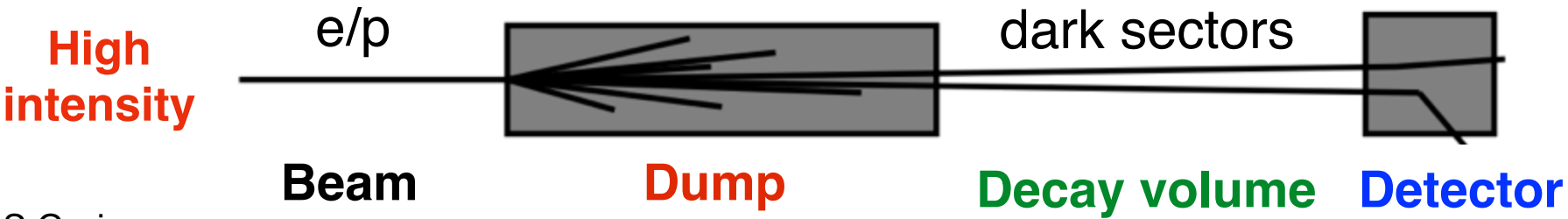

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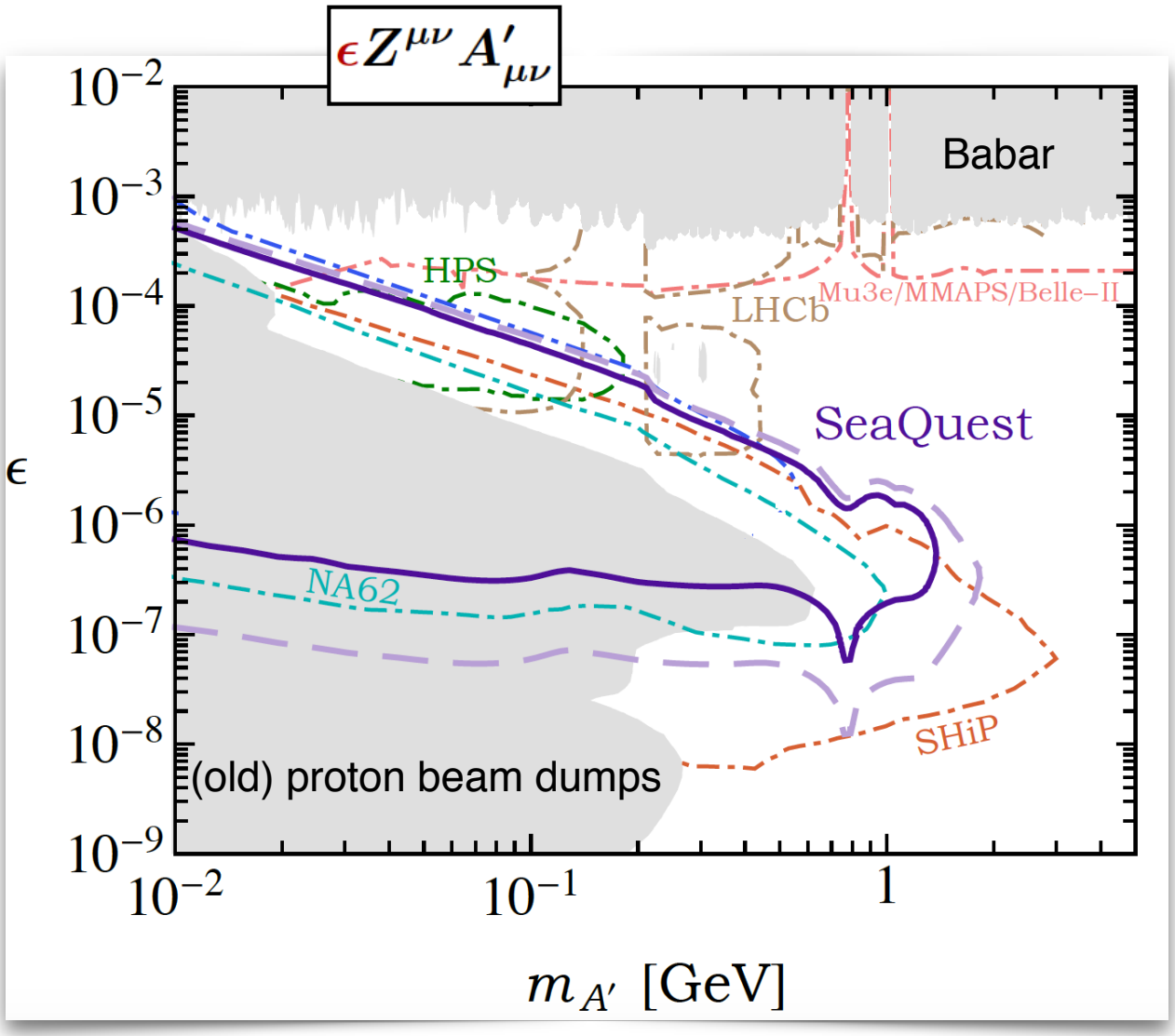

Berlin, SG, Schuster, Toro, 1804.00661

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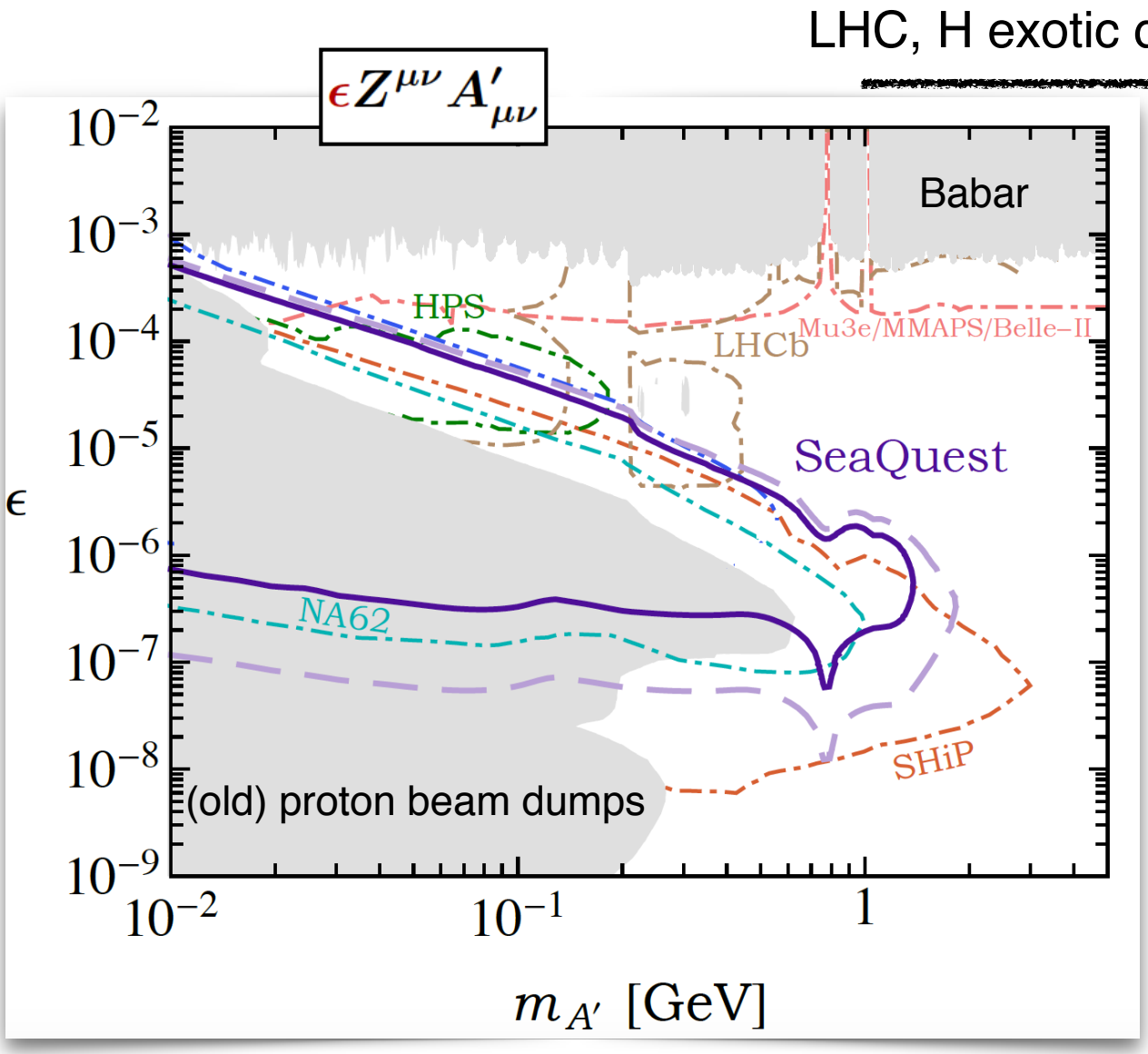

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