Lectures on BSM and Dark Matter theory (2nd class)

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UC Santa Cruz

15th annual Fermilab - CERN

Hadron Collider Physics Summer School

August 10-21, 2020

Twin Higgs models & the hierarchy problem

$\boxed{SM_A \times SM_B \times Z_2}$

Global symmetry of the scalar potential (e.g. SU(4))

→ The SM Higgs is a (massless) Nambu-Goldstone boson

$$H = \begin{pmatrix} H_A \\ H_B \end{pmatrix}$$

~SM Higgs doublet

Twin Higgs doublet

$$V(H) = -m^2 H^\dagger H + \lambda (H^\dagger H)^2$$

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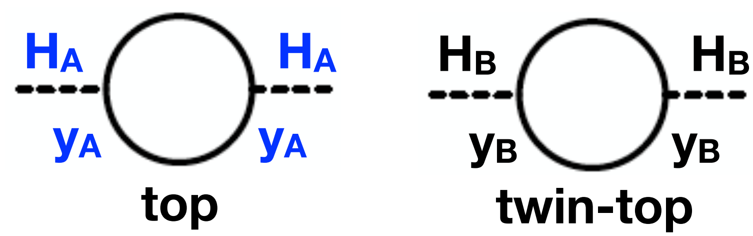
Loop corrections to the Higgs mass: $\frac{3}{8\pi^2}\Lambda^2 (y_A^2 H_A^\dagger H_A + y_B^2 H_B^\dagger H_B)$



$$\boxed{Z_2 \Rightarrow y_A = y_B}$$

Loop corrections to mass are SU(4) symmetric

⇒ no quadratically divergent corrections!

Twin Higgs models & the hierarchy problem

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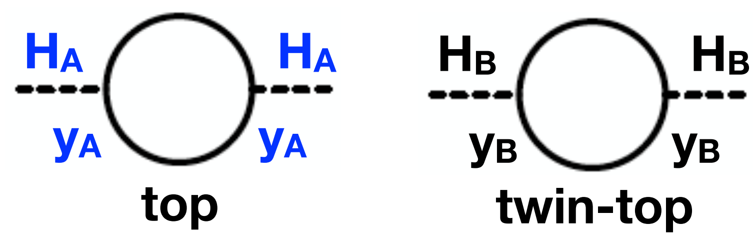

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Loop corrections to mass are SU(4) symmetric

→ no quadratically divergent corrections!

SU(4) and Z_2 are (softly) broken:

$v_A \neq v_B$

$(f^2 \equiv v_A^2 + v_B^2 \gg 246 \text{ GeV})$

Phenomenology of the twin Higgs

A typical spectrum:

H_{twin}

Twin tops

Twin W, Z

SM Higgs

Twin bottoms

Twin taus

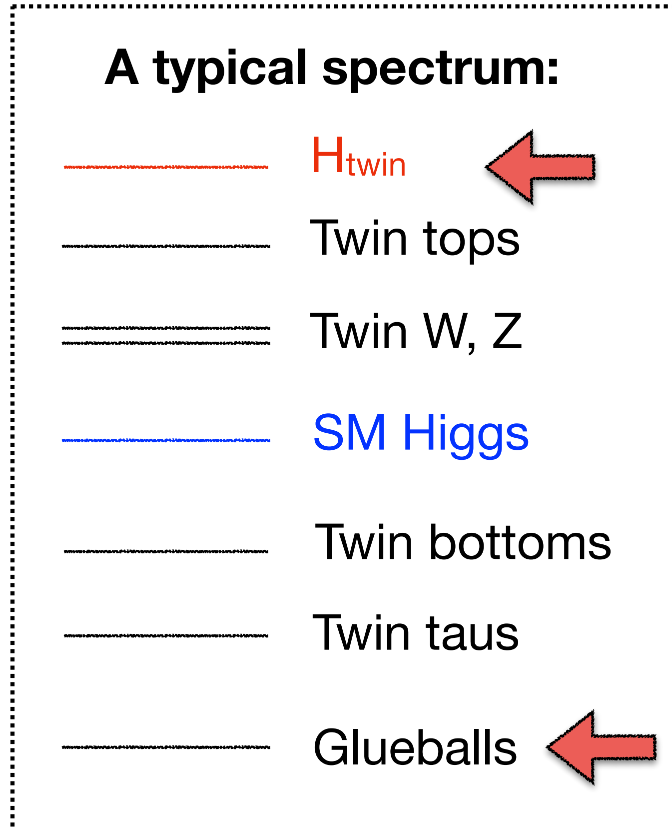
Glueballs

Phenomenology of the twin Higgs

1. **Production of the twin Higgs**

The twin Higgs will mix with the 125 GeV Higgs with a mixing angle ~ v^2 / f^2

Because of this mixing, it can be produced as a SM Higgs boson (reduced rates!)



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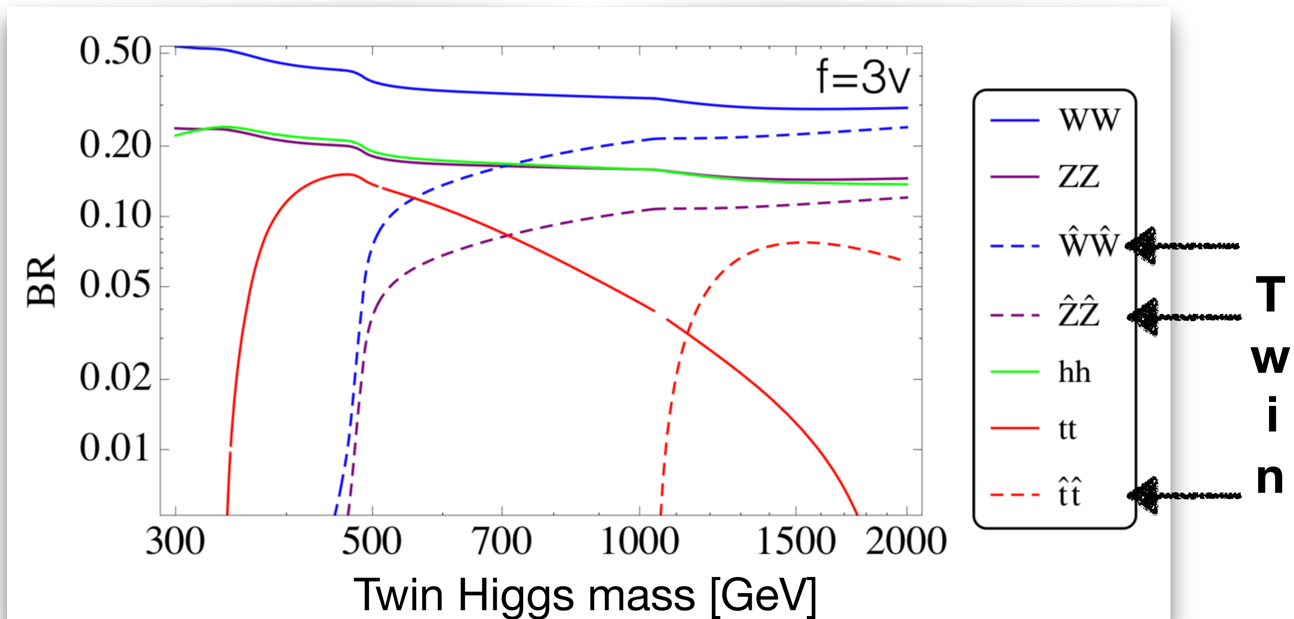
2. **Decay of the twin Higgs**

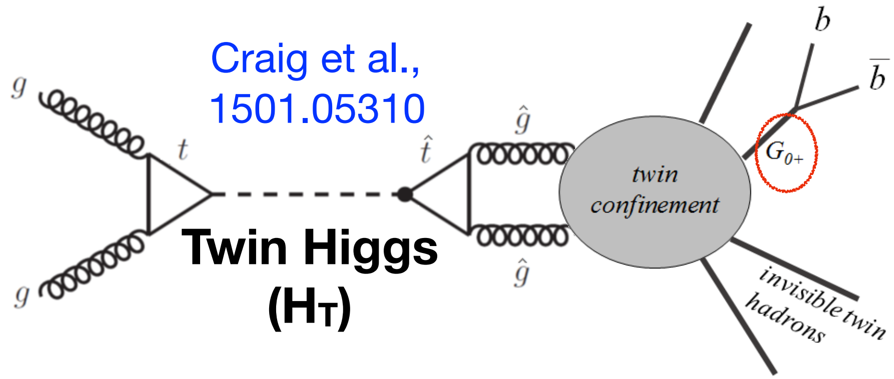


N.Craig

A typical spectrum:

Twin particles undertake cascade decays to (typically) long lived glue-balls

Long-lived signatures from twin Higgs decays



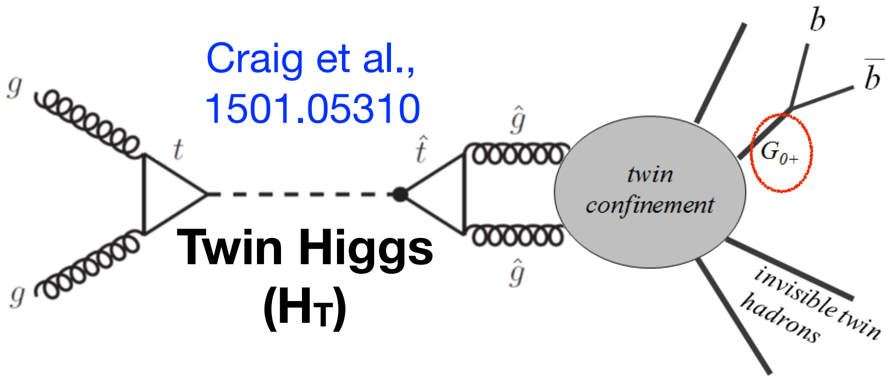
Craig et al., 1501.05310

Twin Higgs (H_T)

Glue-ball.
O^{++} mixes with the 125 GeV Higgs and decays typically displaced.

Signature: $H_T \to$ >= 2 displaced

Long-lived signatures from twin Higgs decays



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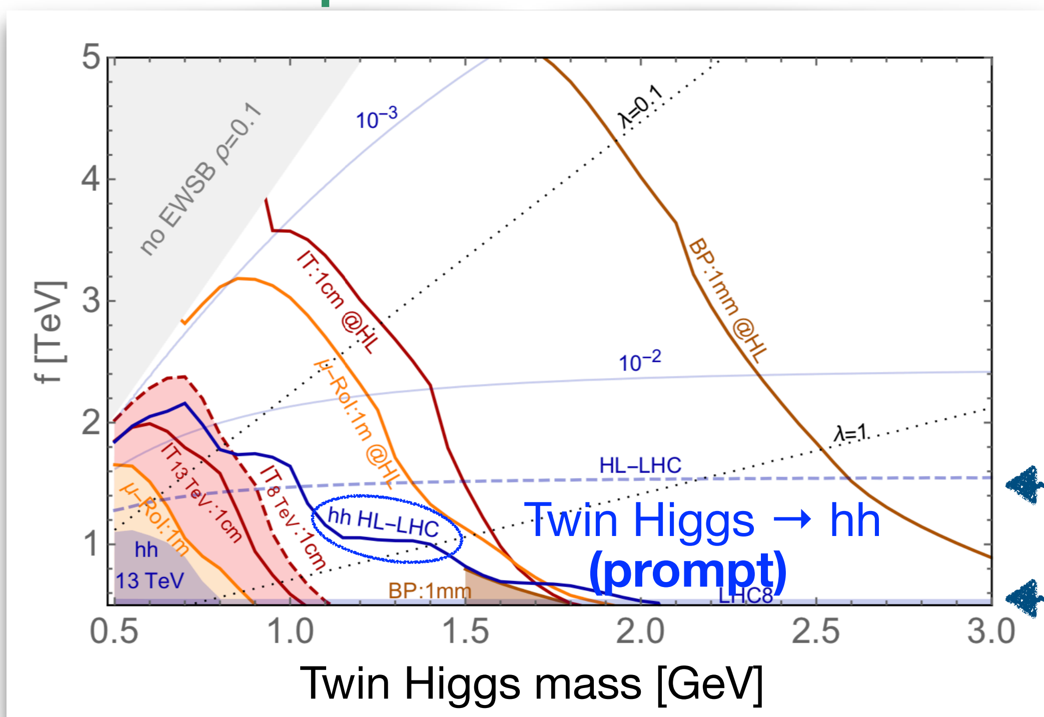
Prospects for the HL-LHC



125 GeV Higgs coupling measurements

Alipour-Fard, Craig, SG, Koren, Redigolo, 1812.09315

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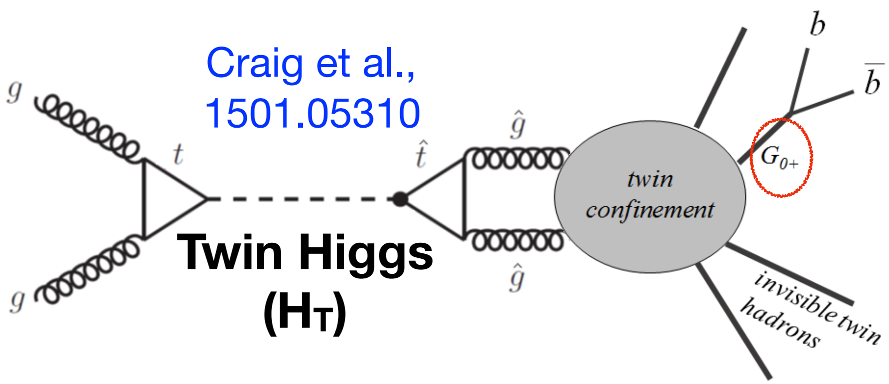

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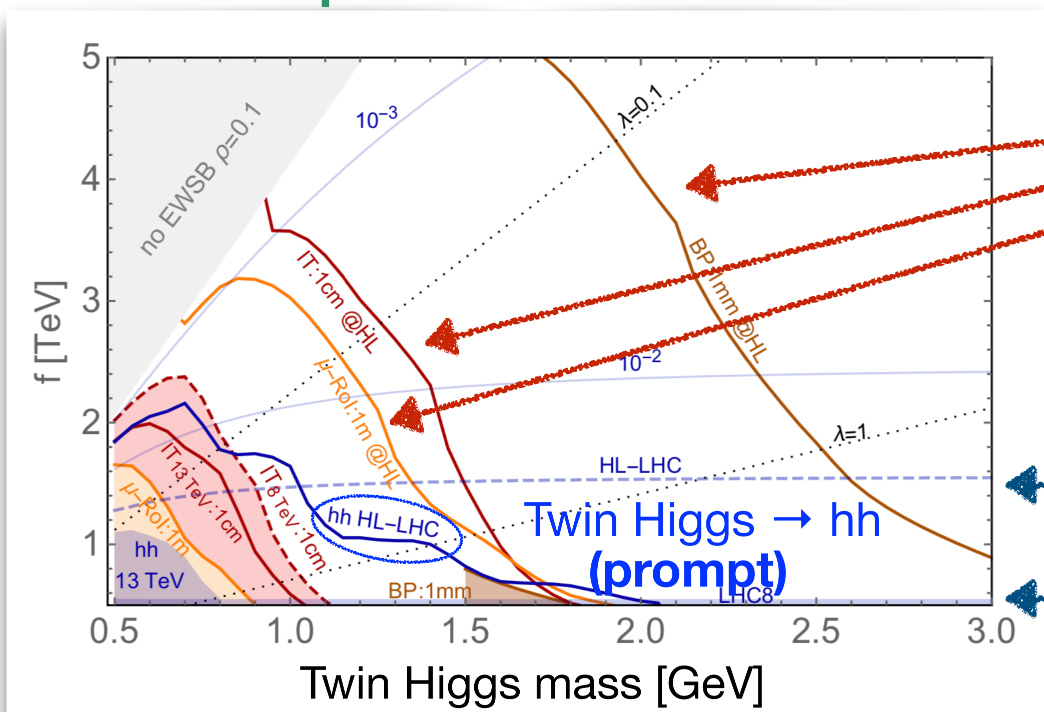

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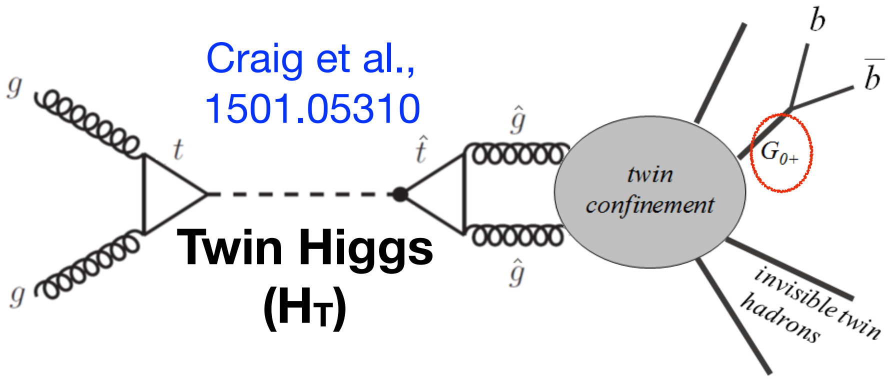
Twin Higgs → glue-balls:
(long lived)

CMS beam pipe analysis;
CMS inner tracker analysis;
ATLAS muon spectrometer analysis

The relative strength depends on other parameters of the theory

125 GeV Higgs coupling measurements

Long-lived signatures from twin Higgs decays



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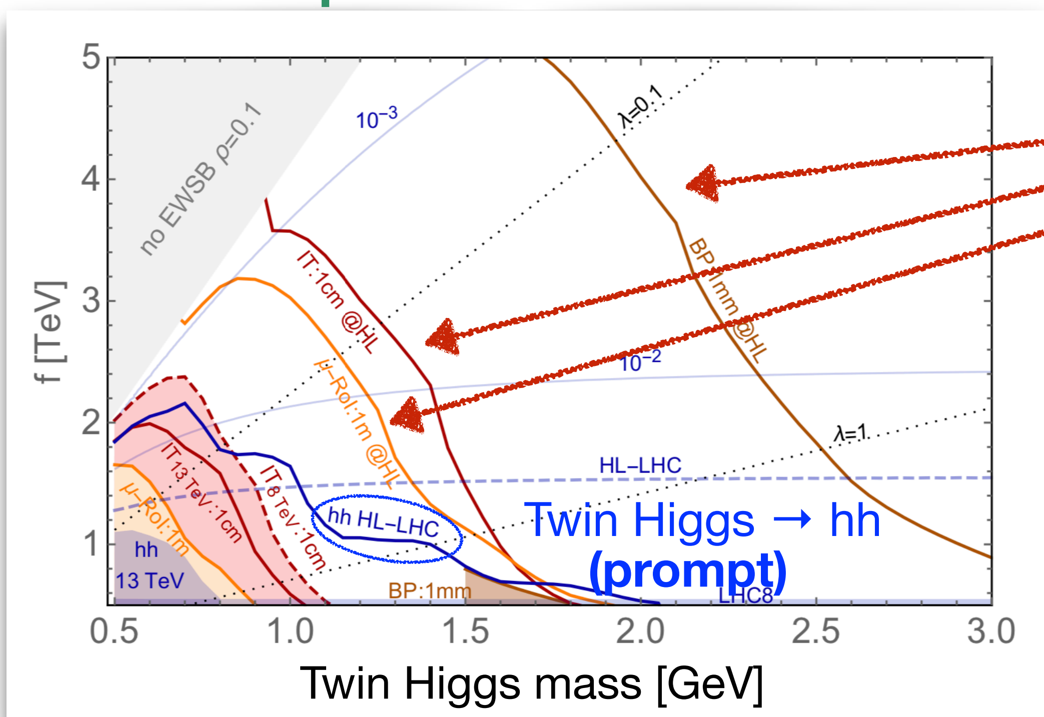

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Twin Higgs → glue-balls:
(long lived)

CMS beam pipe analysis;
CMS inner tracker analysis;
ATLAS muon spectrometer analysis

The relative strength depends

Note:

also the SM Higgs will decay to glue-balls.
Displaced signatures coming from Higgs exotic decays.

Overview

Chapter 1: Introduction:
The Standard Model and its open problems

Chapter 2:
* SUSY theories.
Direct & indirect searches of SUSY particles
* Twin Higgs theories.
Direct & indirect searches of the "twin Higgs"

TODAY

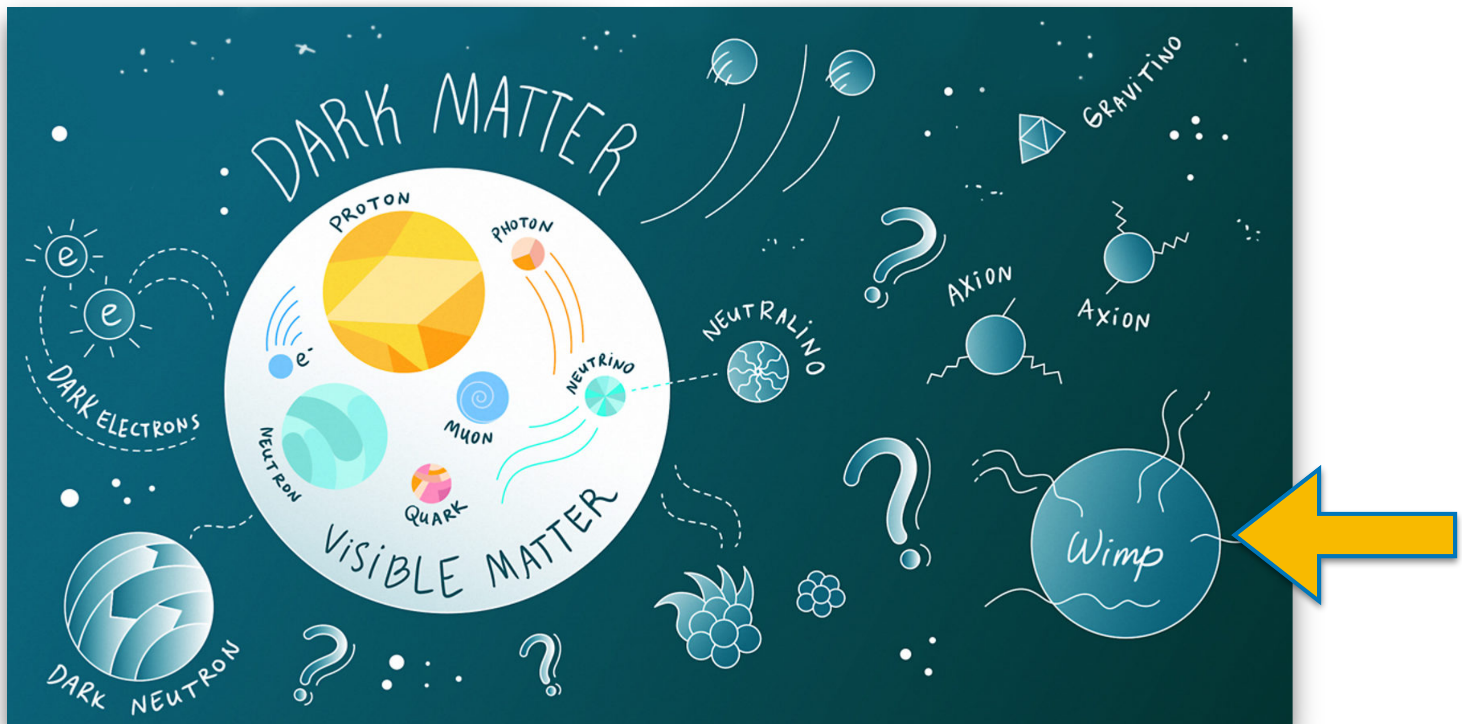
Chapter 3:
* Introduction to Dark Matter
* WIMP Dark Matter; Complementarity of searches

Chapter 4:
* (Light) Dark Matter living in a dark sectors
* Complementarity of accelerator experiments
(high energy vs. high intensity)

TOMORROW

Goal: Some basics + overview of what I find exciting about BSM theories + pheno
Disclaimer: not comprehensive!
Please interrupt **to ask questions! We do not have to go through all slides! :)**

Chapter 3:
- Introduction to Dark Matter
- WIMP Dark Matter; Complementarity of searches



S.Gori

Dark Matter (DM) is there!

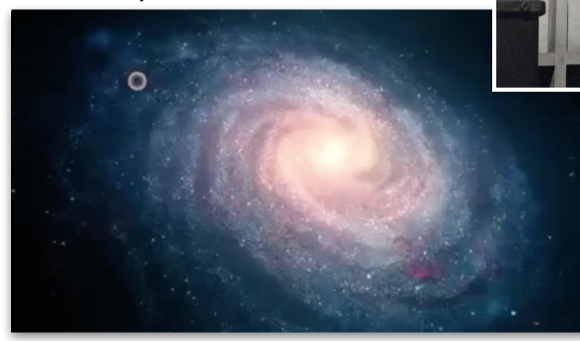
What do we know about it? Not much

1. It gravitates

1933 Fritz Zwicky

Coma cluster (of galaxies)

1970, Vera Rubin

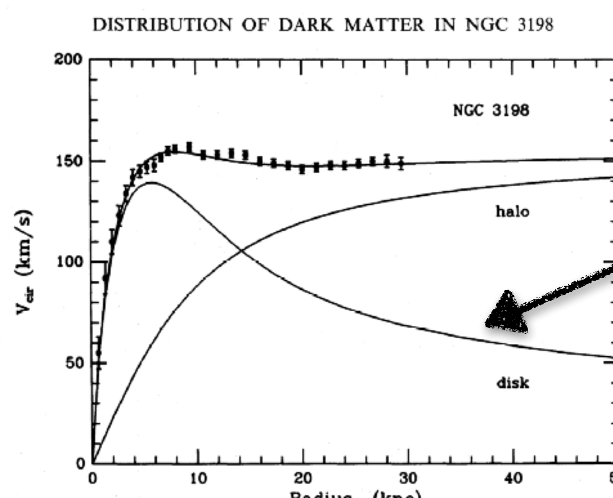


Andromeda Galaxy

Virial theorem

$$2\langle K \rangle = -\langle V \rangle$$

$$M = \frac{v^2 R}{G_N}$$



$$\frac{v^2}{r} = \frac{G_N M}{r^2}$$

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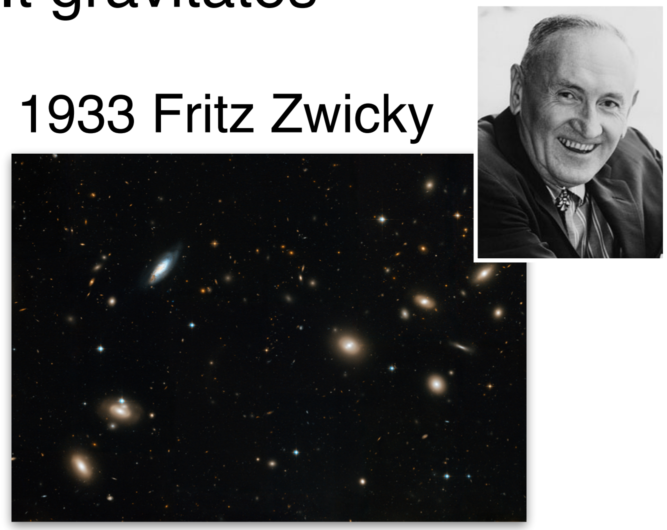

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Andromeda Galaxy

2. It is dark (i.e. it does not interact with photons)
3. It is stable on cosmological scales

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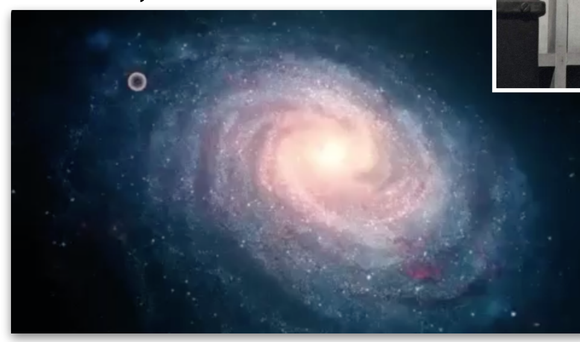


Andromeda Galaxy

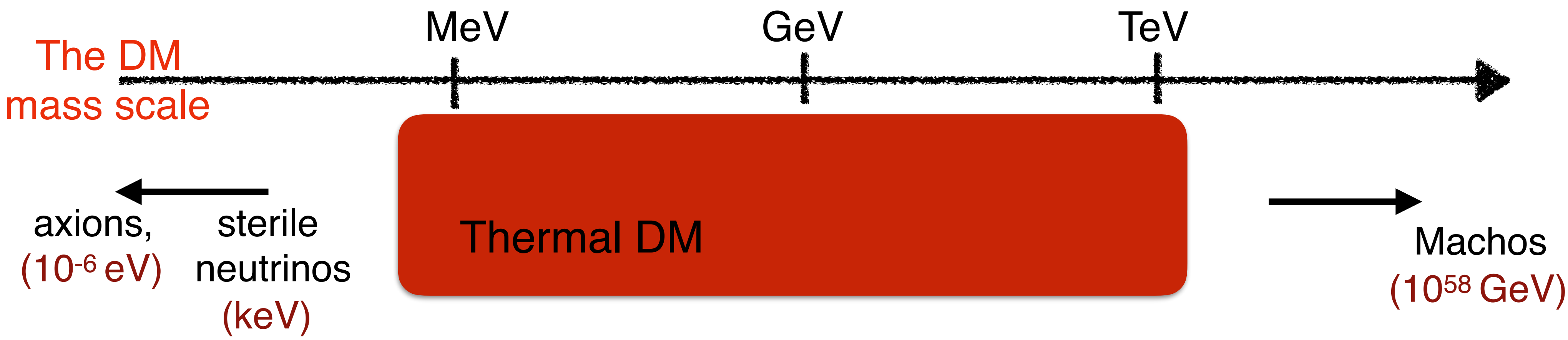
2. It is dark (i.e. it does not interact with photons)

3. It is stable on cosmological scales

Fun fact: There is lots of DM in the Universe, but
for DM particles weighing several hundred times the mass of the proton,
there should be about one DM particle per coffee-cup-sized volume of space.

“Weakly” interacting DM

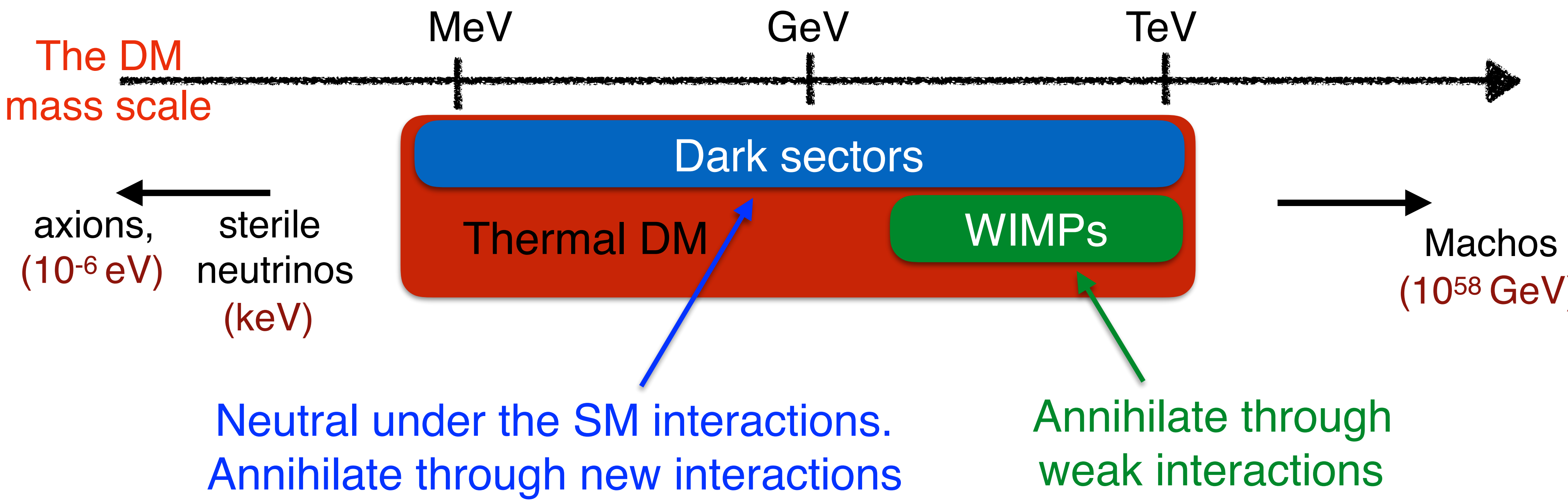
The Dark Matter scale



The dark matter scale is **unknown**.
Completely different search strategies depending on the mass of dark matter

In these lectures, we will focus on dark matter with a mass in **~(MeV, TeV)**

The Dark Matter scale



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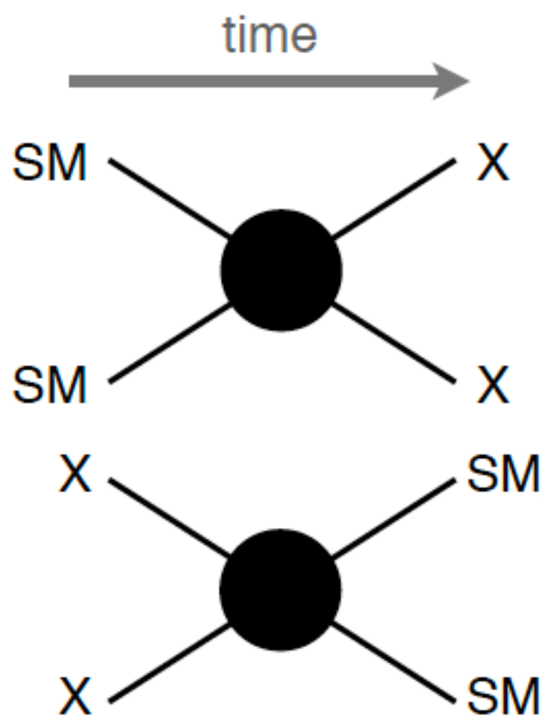
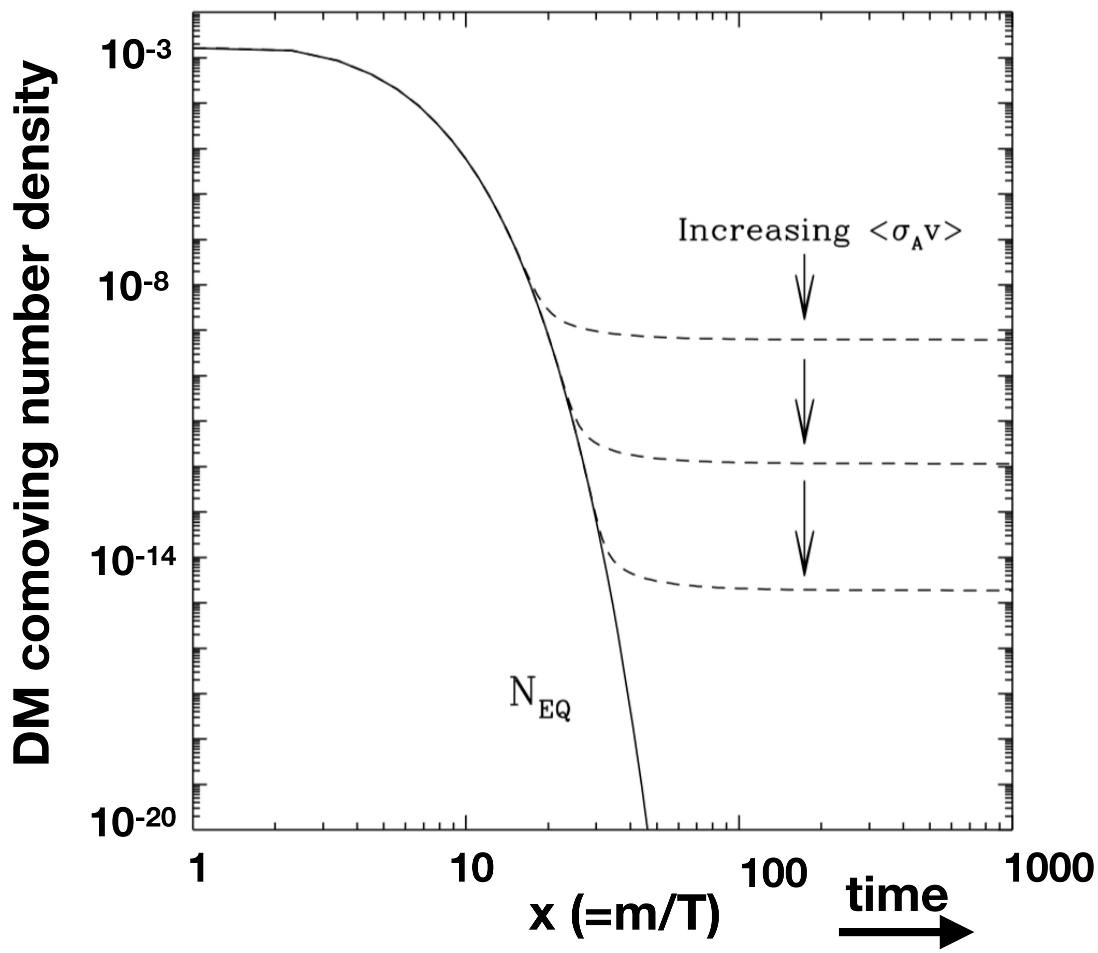
The WIMP miracle

(Weakly Interacting Massive Particles)

Thermal in the early universe





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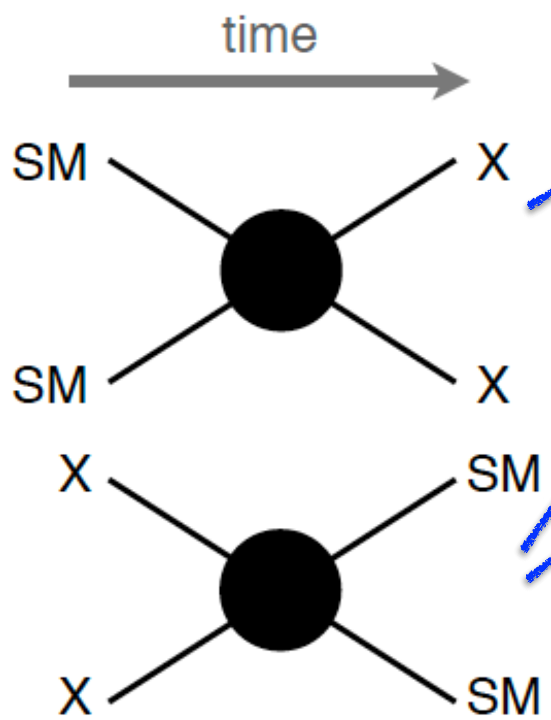

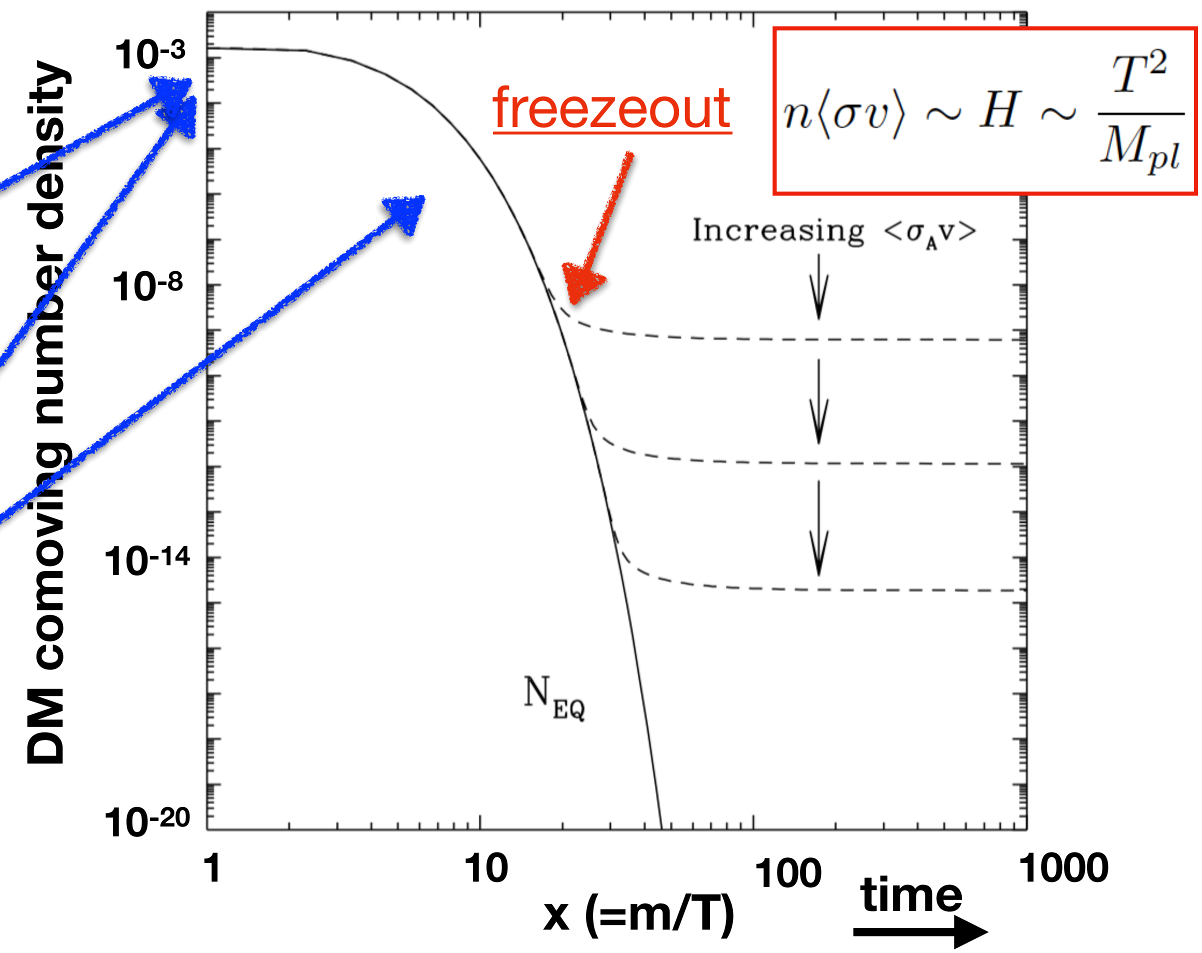

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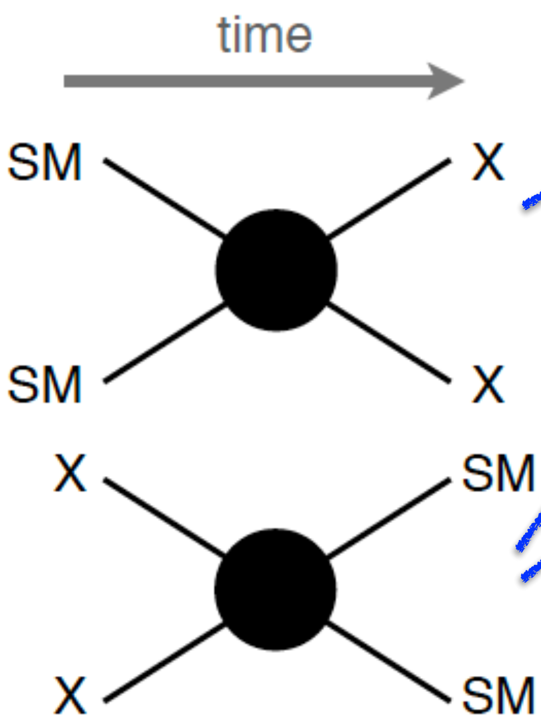
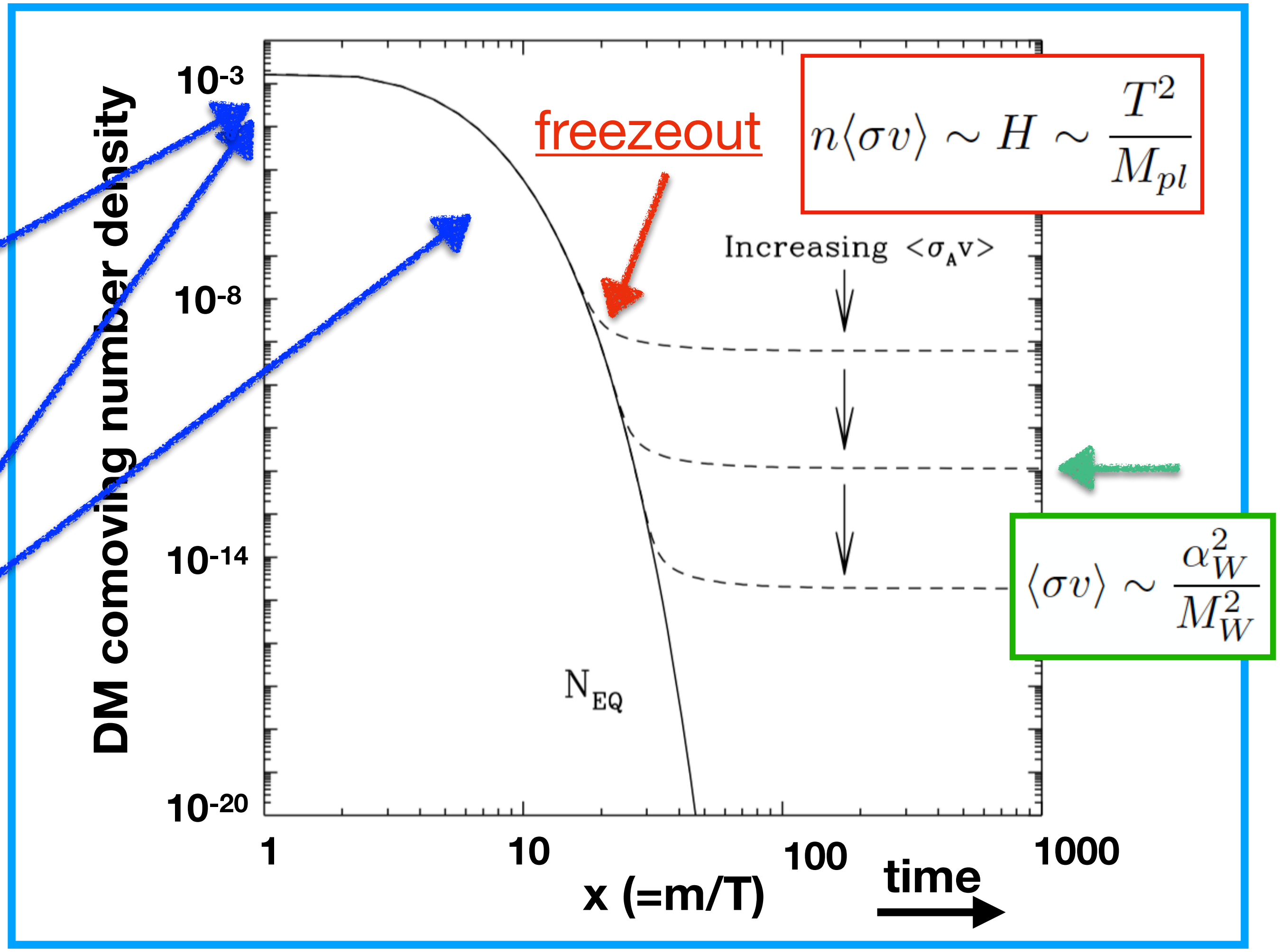


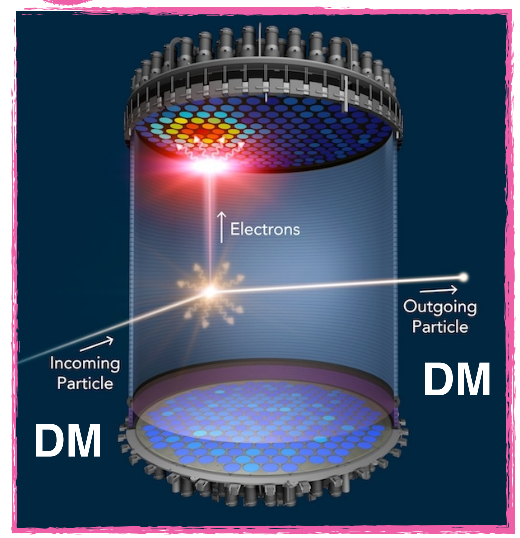


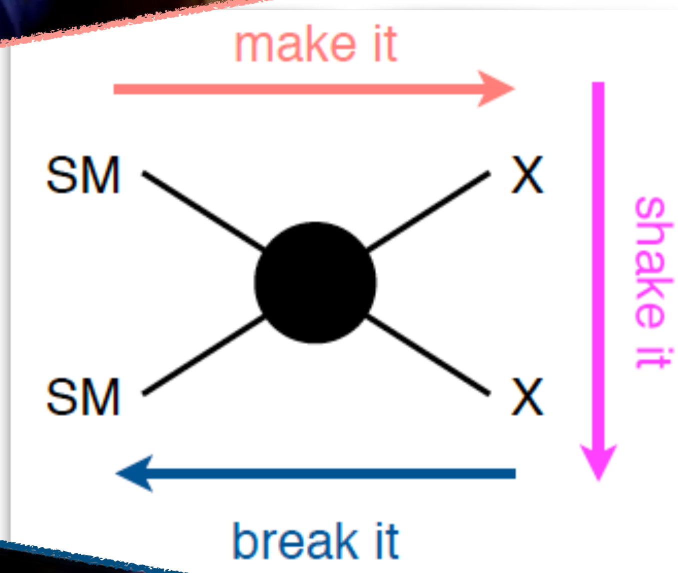
If dark matter is entirely made up of a single particle X with a mass at the electroweak scale that interacts via the W and Z bosons, **the predicted relic density agrees with what we observe in the universe today**.

Complementary probes of WIMPs

3. Collider searches

2. Direct detection





1. Astrophysical probes

Famous example of WIMPs:

lightest neutralino in SUSY models with R-Parity conservation

1.

Astrophysical probes

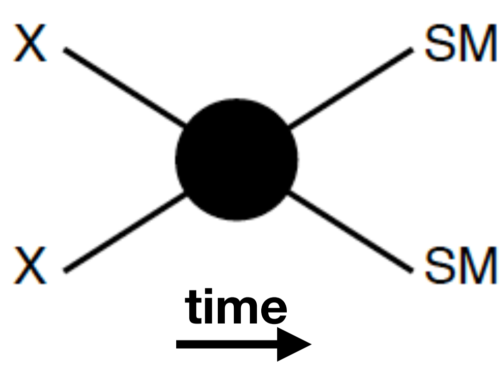
The best places to look for WIMP annihilation are in dark-matter-dense objects (galaxy clusters, Milky Way dwarf galaxies, the Milky Way halo, …)

Searches for the products of WIMP annihilation from the sky:

- charged particles
- photons
- neutrinos

Some experiments:

AMS-02 experiment (positrons)
Fermi-LAT, DES, Veritas (photons)
Icecube (neutrinos)



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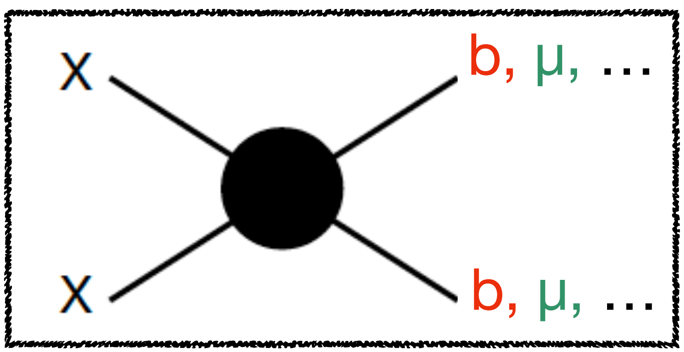
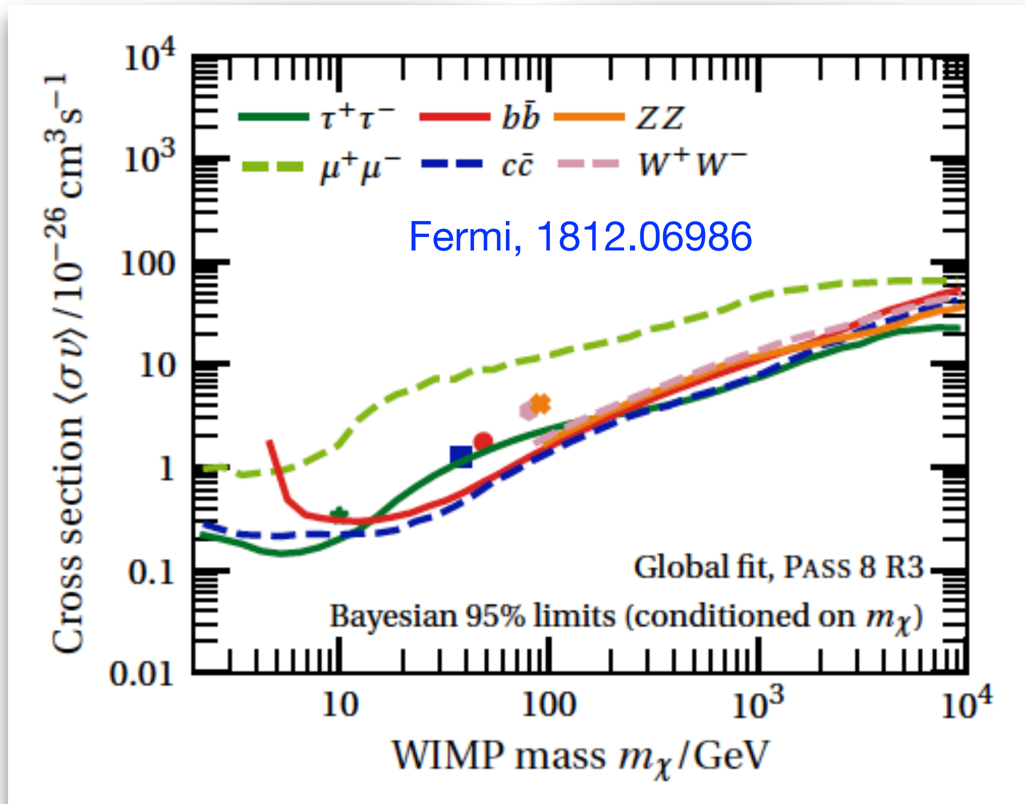


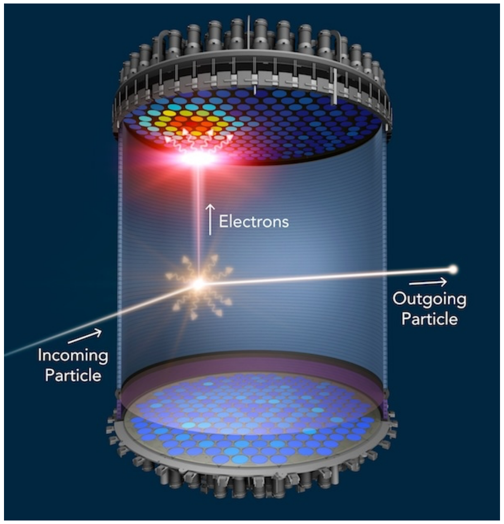
Milky Way Dwarf Spheroidal Galaxies

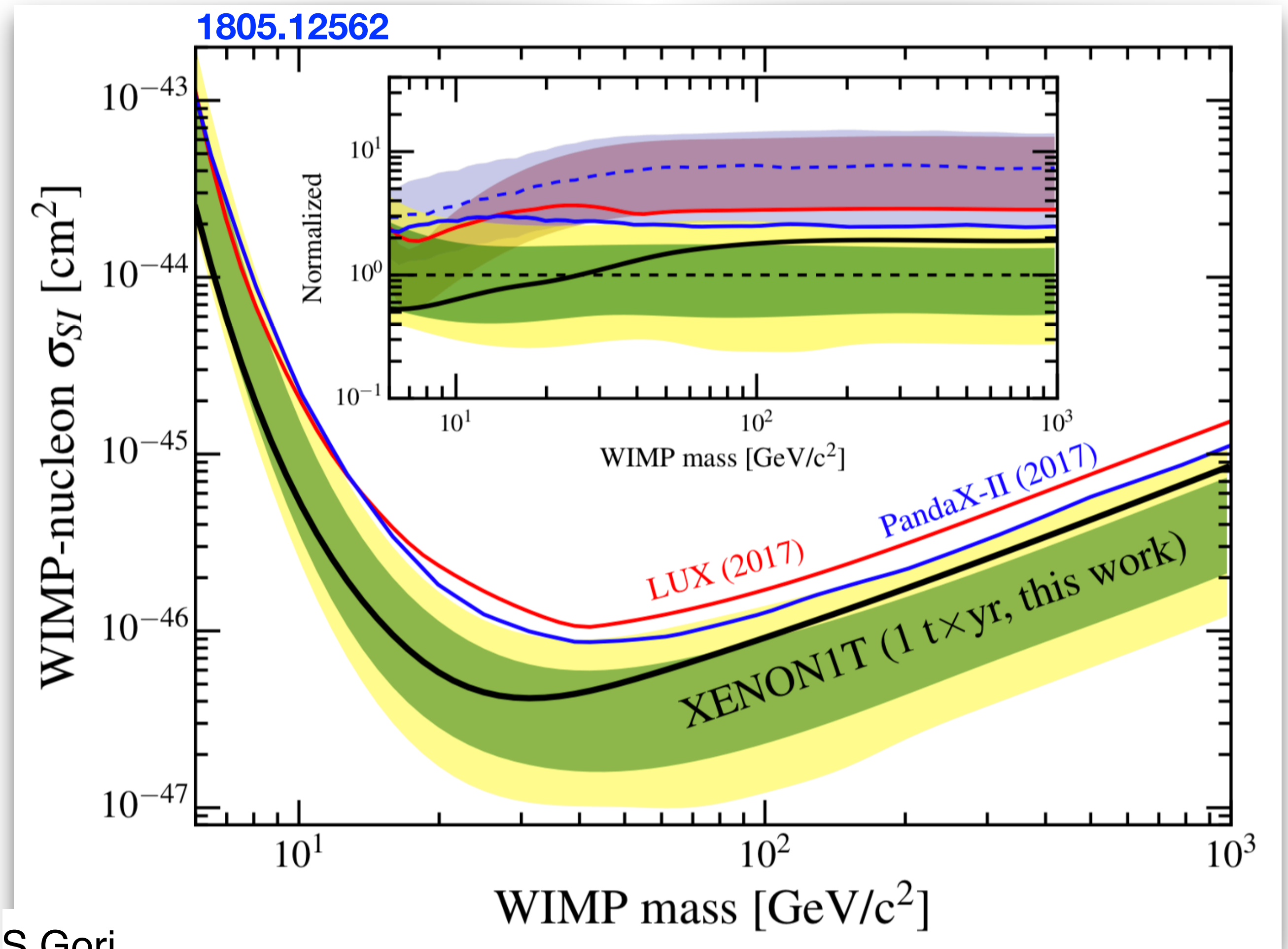


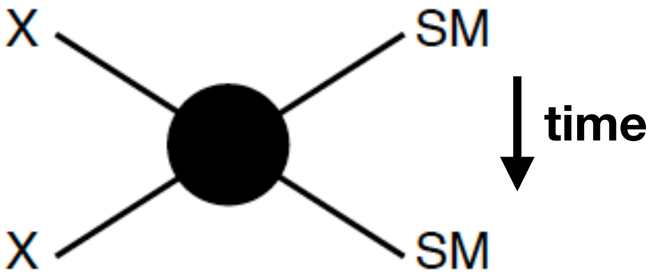
2.

Direct detection

Large detectors that search for DM scattering







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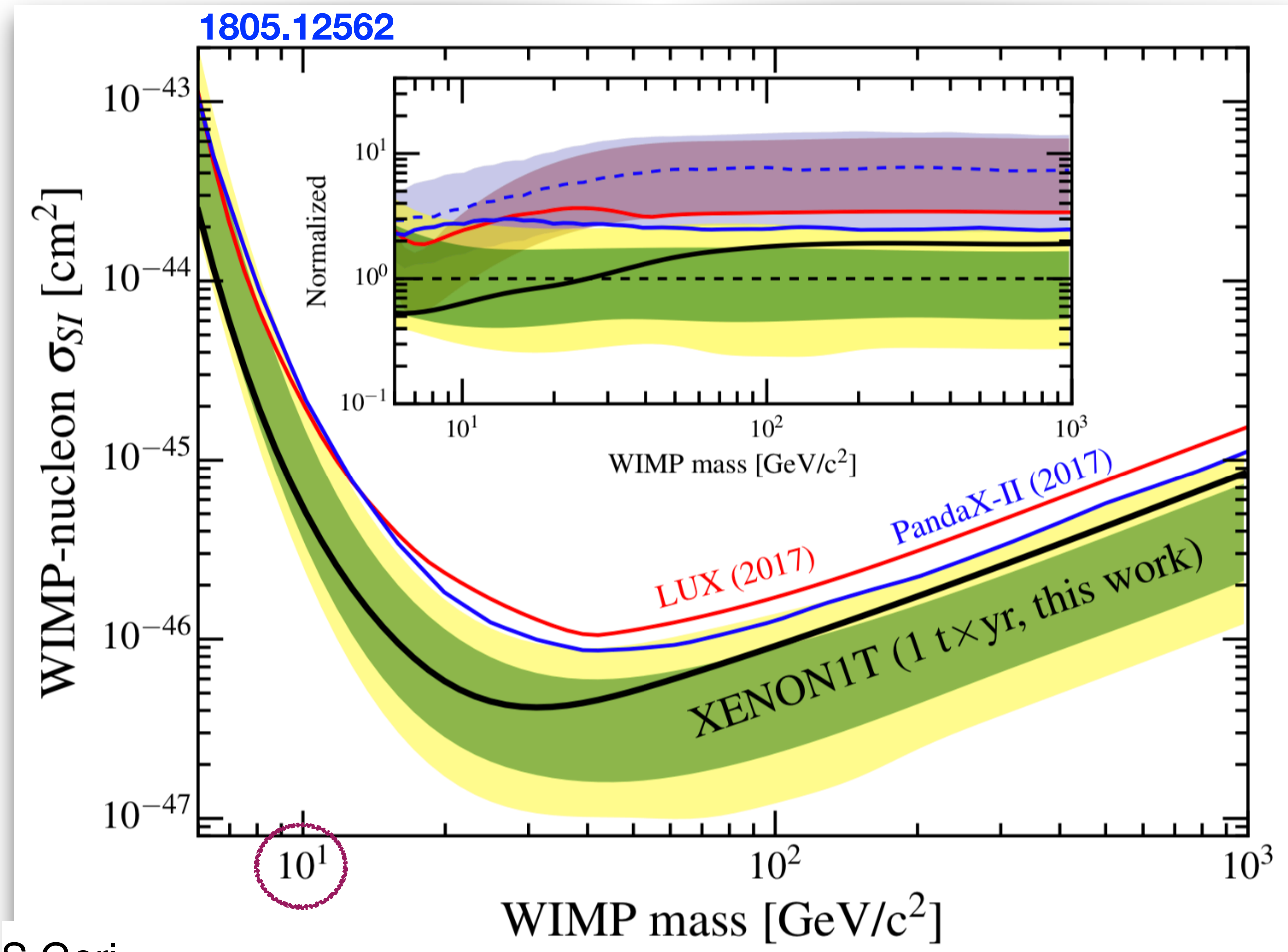
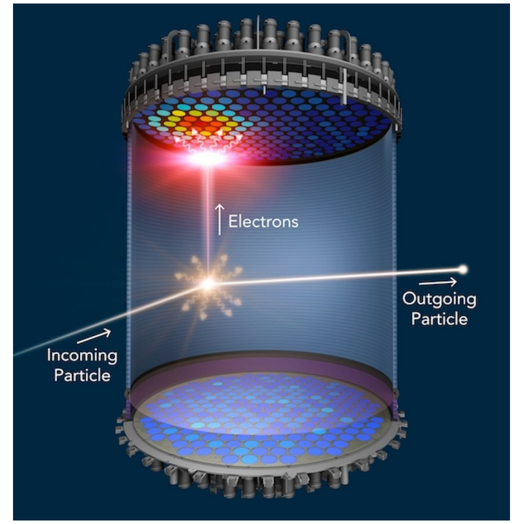
Direct detection

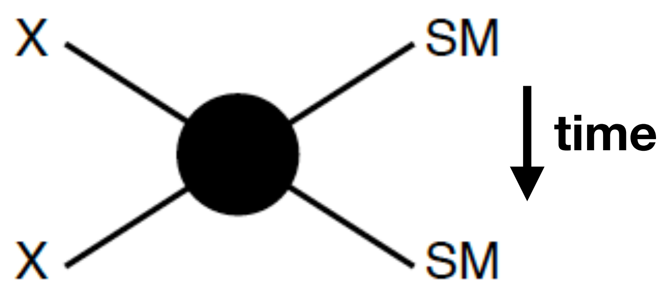
Large detectors that search for DM scattering

Lower energy thresholds for the scattering recoil

→ access to masses above ~few GeV







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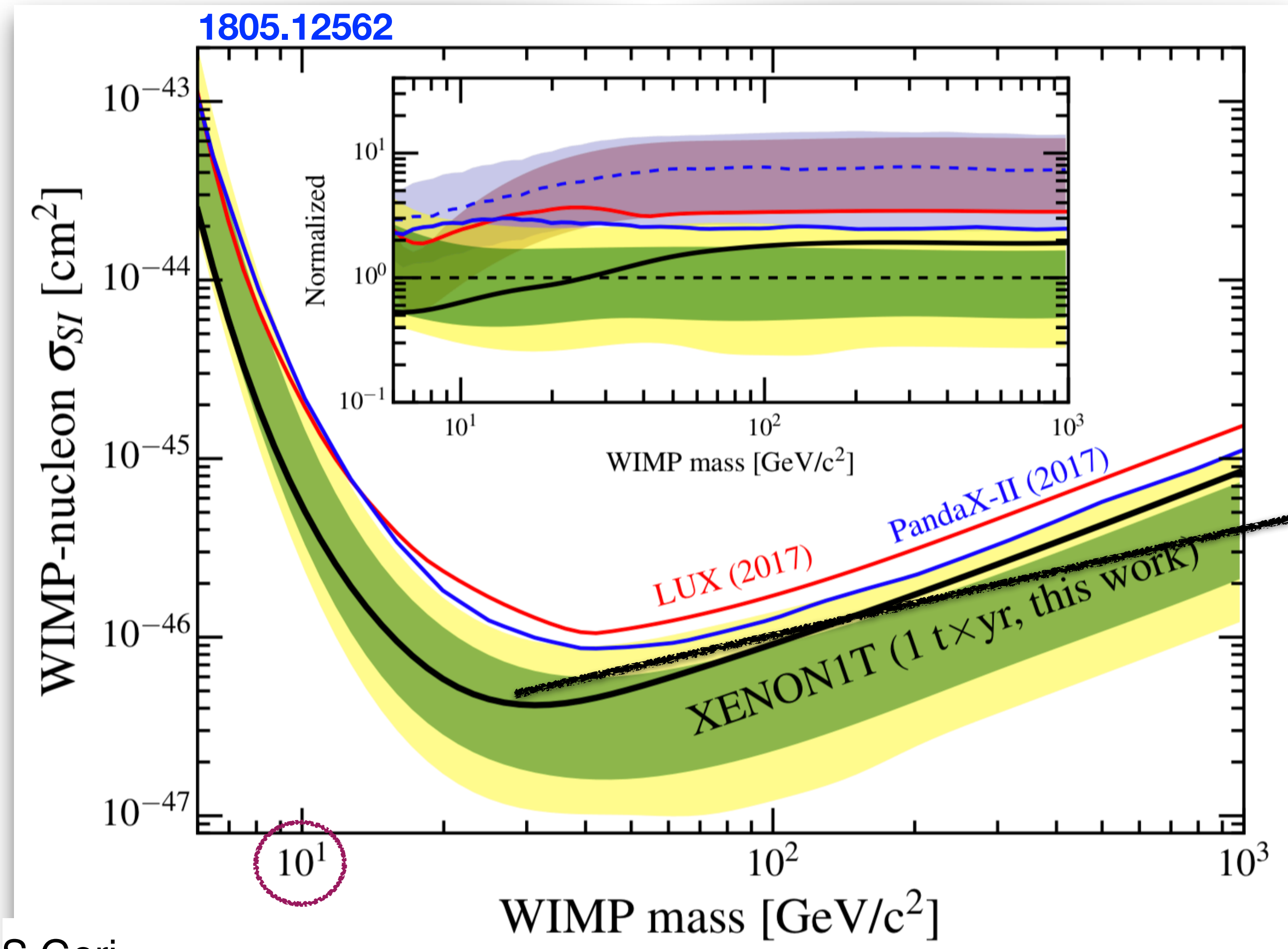

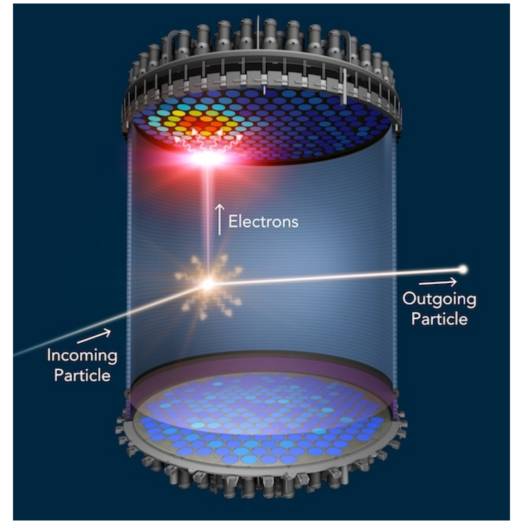

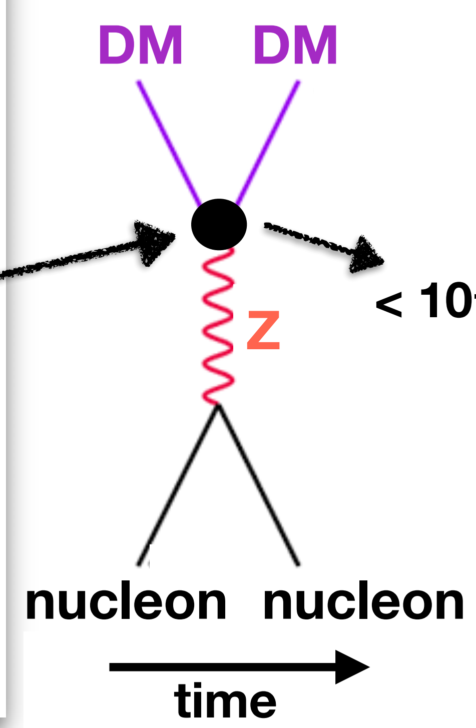

< 10^{-3} * weak coupling

3.

LHC production

WIMP Dark Matter can be produced at high energy colliders like the LHC, thanks to its interactions with the Z and Higgs boson:

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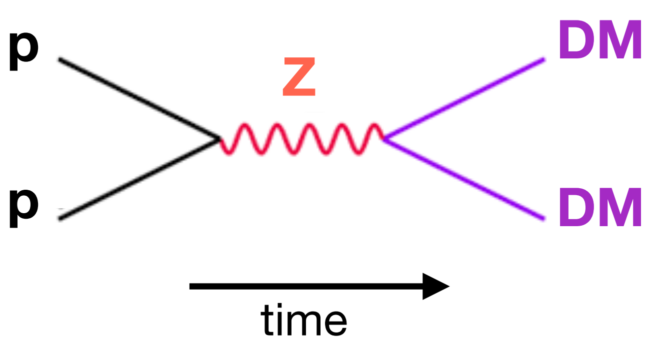
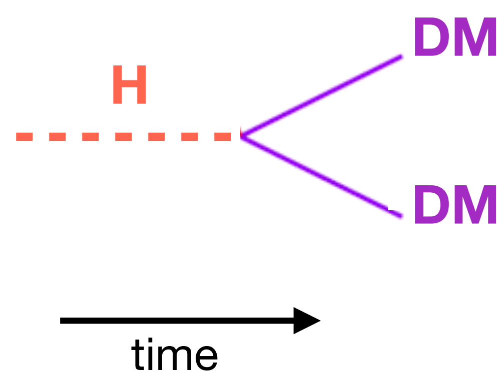
WIMP Dark Matter can be produced at high energy colliders like the LHC, thanks to its interactions with the Z and Higgs boson:

a. **Drell-Yan production**



Higgs decays **b.**

If DM is lighter than half of the Higgs:

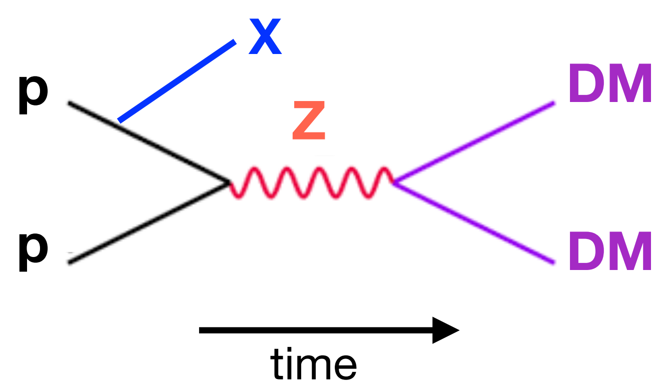


But this would be “invisible” at the LHC!

3. LHC production

WIMP Dark Matter can be produced at high energy colliders like the LHC, thanks to its interactions with the Z and Higgs boson:

a. Drell-Yan production



Mono-X searches
(mono-photon, mono-Z, mono-jet, …)

Higgs decays **b.**

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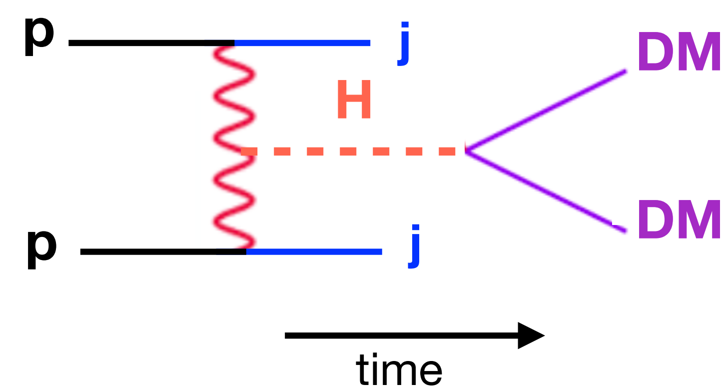
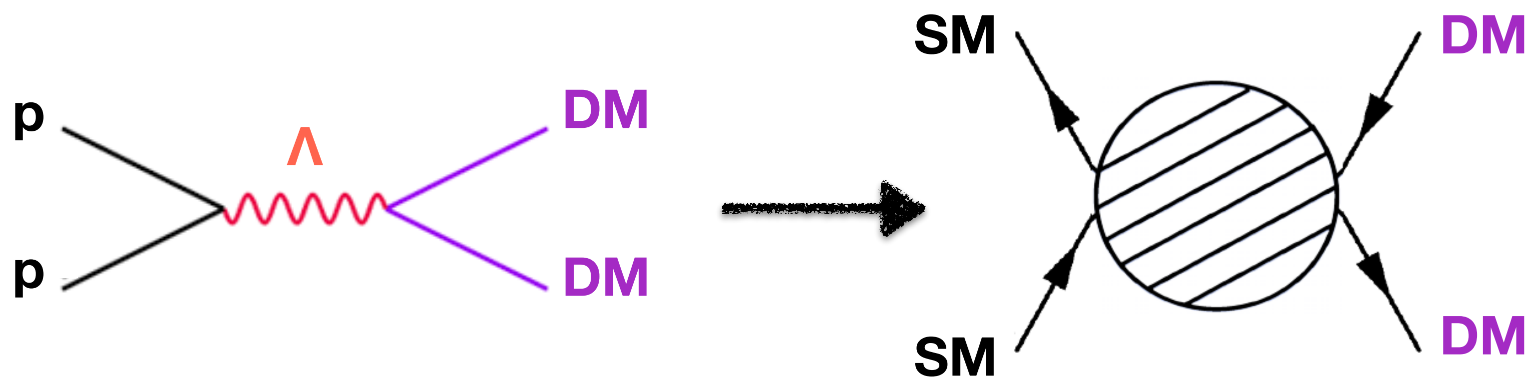


Searches for Higgs invisible decays, with the Higgs produced in association with something
(vector boson fusion, Zh, …)

a.

EFTs for the mono-X searches

- From an effective theory(*) point of view:



(*) Assumption of a **heavy** "mediator"
at the scale Λ that can be integrated out

a.

EFTs for the mono-X searches

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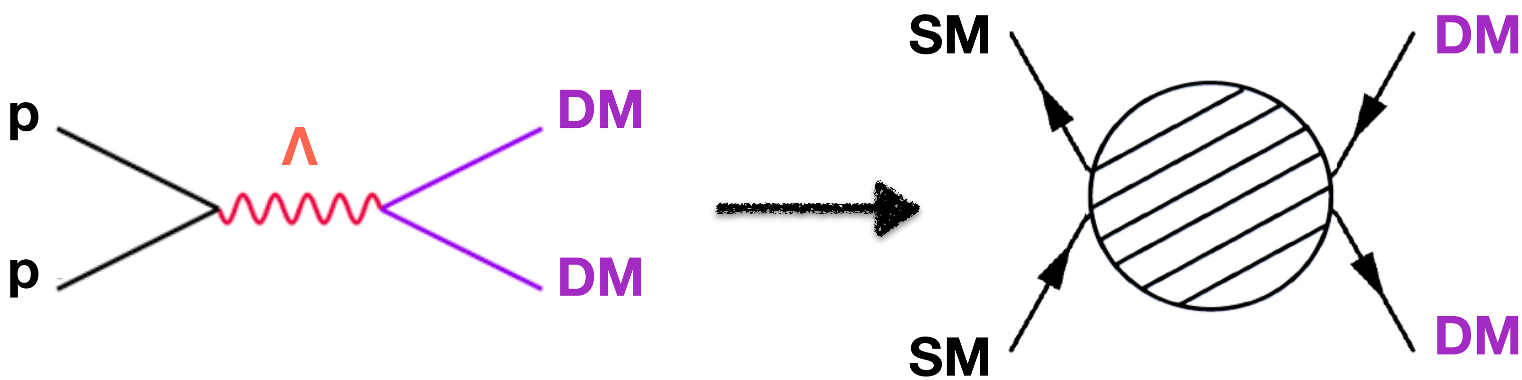


(*) Assumption of a **heavy** "mediator" at the scale Λ that can be integrated out

- Several operators can generate this interaction:

$$\mathcal{O}_V = \frac{(\bar{\chi}\gamma_\mu\chi)(\bar{q}\gamma^\mu q)}{\Lambda^2},$$

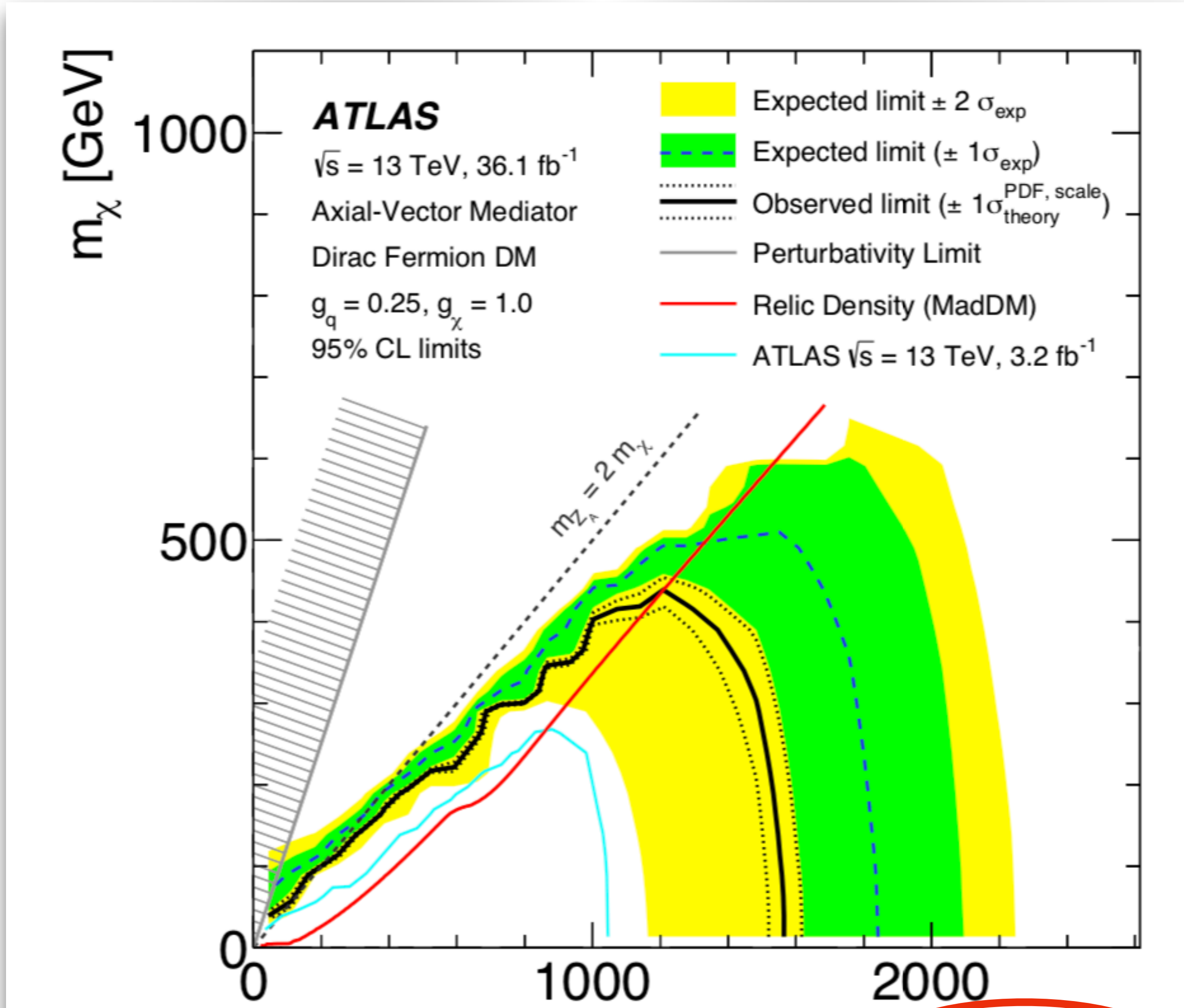
$$\mathcal{O}_A = \frac{(\bar{\chi}\gamma_\mu\gamma_5\chi)(\bar{q}\gamma^\mu\gamma_5 q)}{\Lambda^2},$$

$$\mathcal{O}_t = \frac{(\bar{\chi}P_R q)(\bar{q}P_L\chi)}{\Lambda^2} + (L \leftrightarrow R)$$

The bound on the cross section for mono-X can be interpreted as a bound on the scale Λ as a function of the DM mass. The bound will depend on the particular operator chosen.

a.

Example of a LHC bound



1711.03301

Mono-jet + MET search

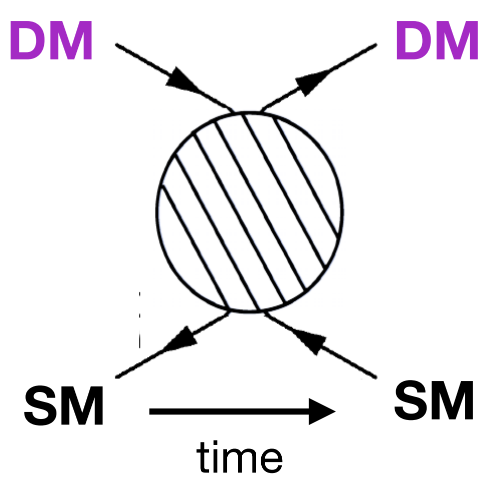
axial-vector mediator

$$\mathcal{O}_A = \frac{(\bar{\chi}\gamma_\mu\gamma_5\chi)(\bar{q}\gamma^\mu\gamma_5 q)}{\Lambda^2}$$

a.

Theory interpretations of the mono-X searches

Once we fix the operator, the mono-X LHC bound can be placed together with the bound from dark matter direct detection:



Eg. $\mathcal{O}_V = \frac{(\bar{\chi}\gamma_\mu\chi)(\bar{q}\gamma^\mu q)}{\Lambda^2}$

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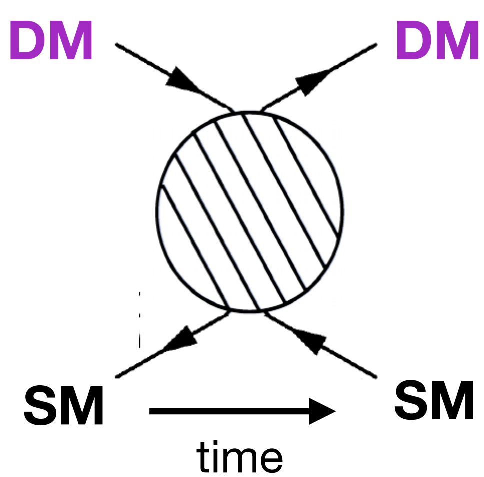
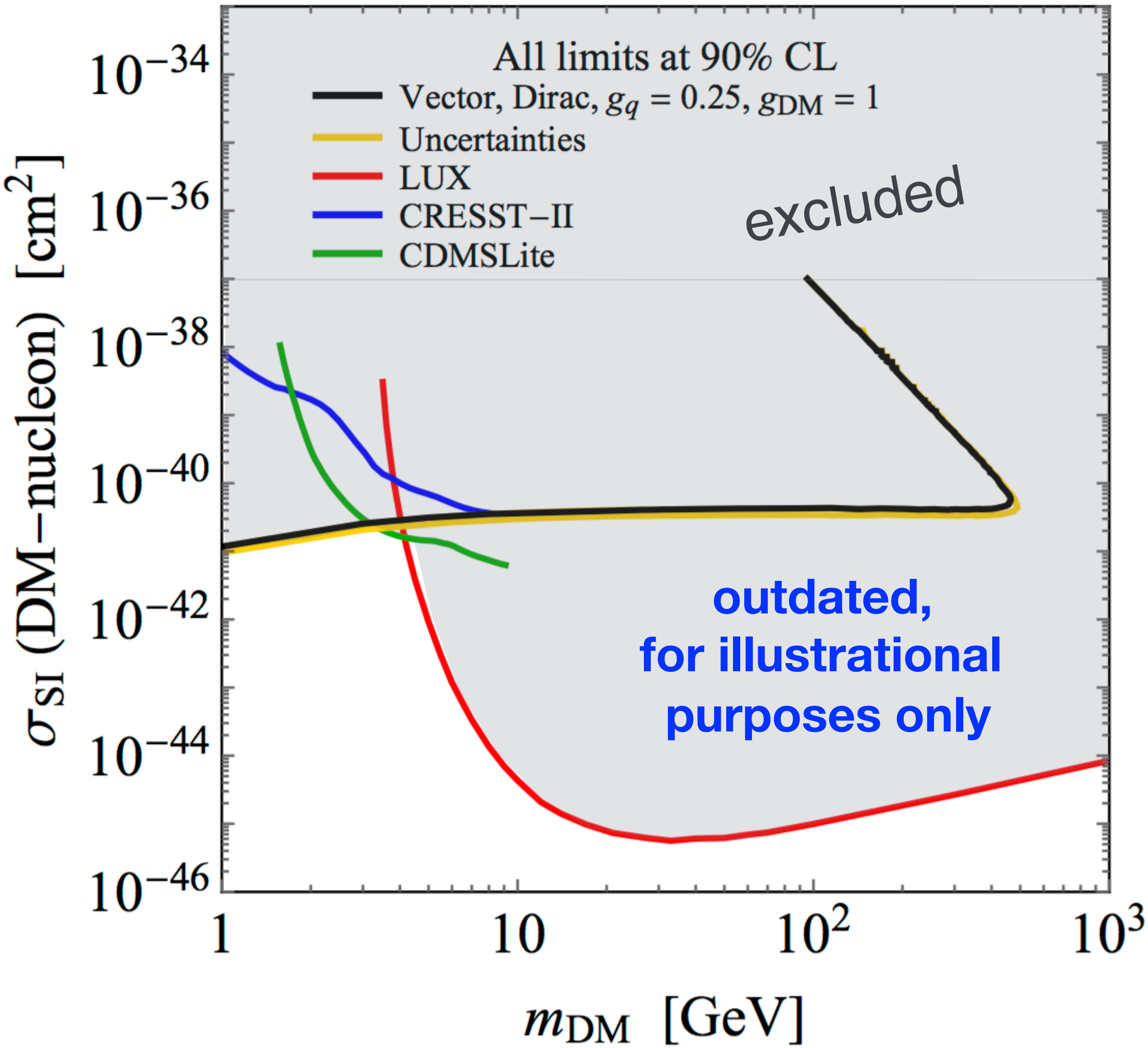


Eg. $\mathcal{O}_V = \frac{(\bar{\chi}\gamma_\mu\chi)(\bar{q}\gamma^\mu q)}{\Lambda^2}$



Theory interpretations of the mono-X searches

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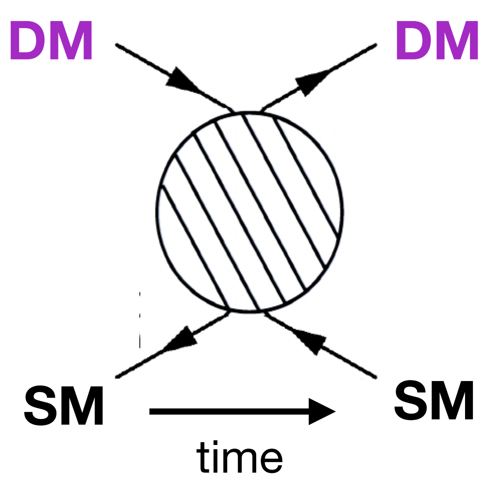

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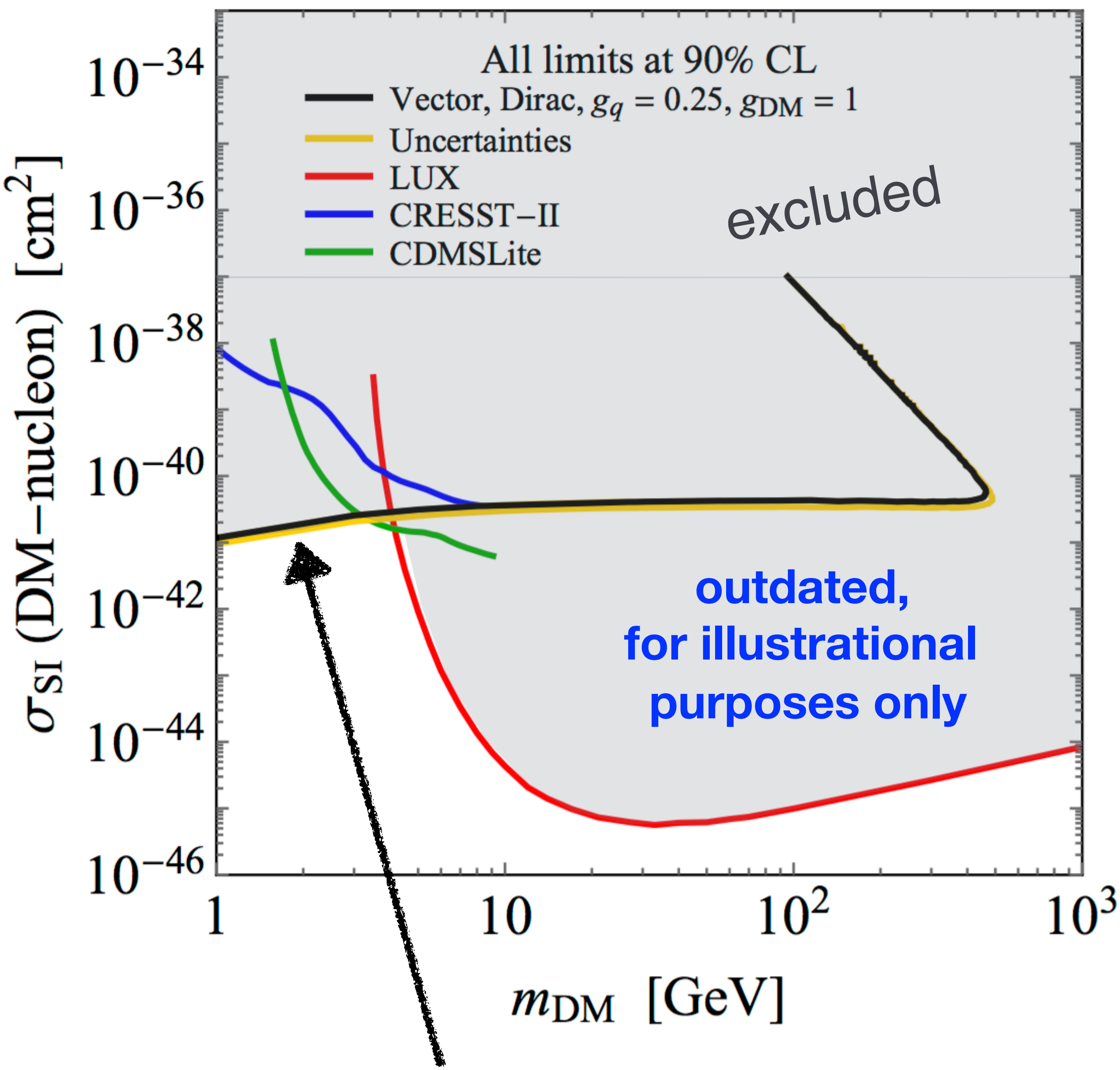
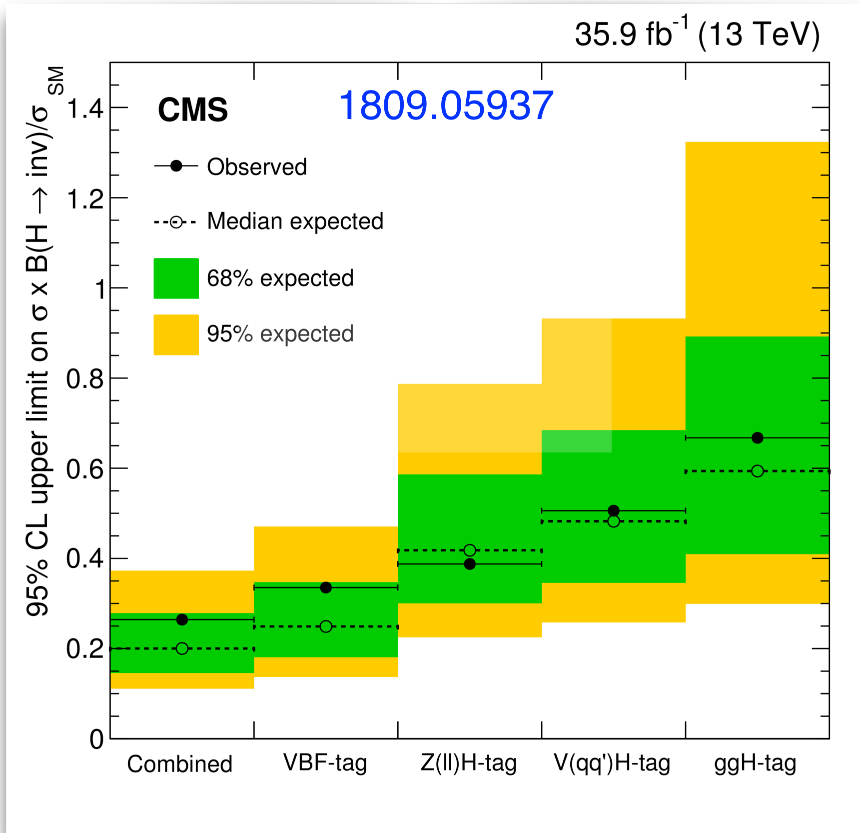


Notice that the LHC bounds have access to lighter DM masses

b.

Higgs invisible decays

The Higgs can decay to Dark Matter.
We can search for Higgs invisible decays directly!



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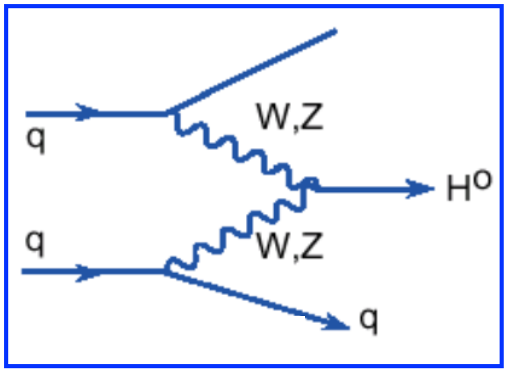
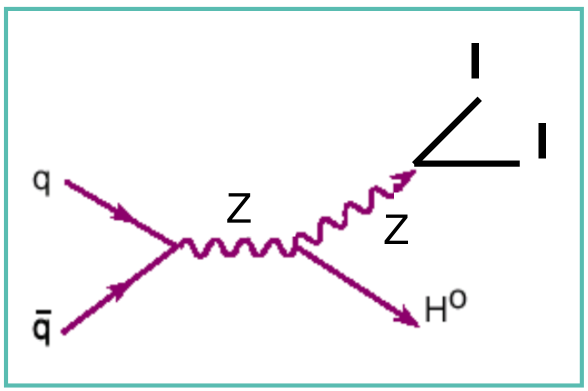
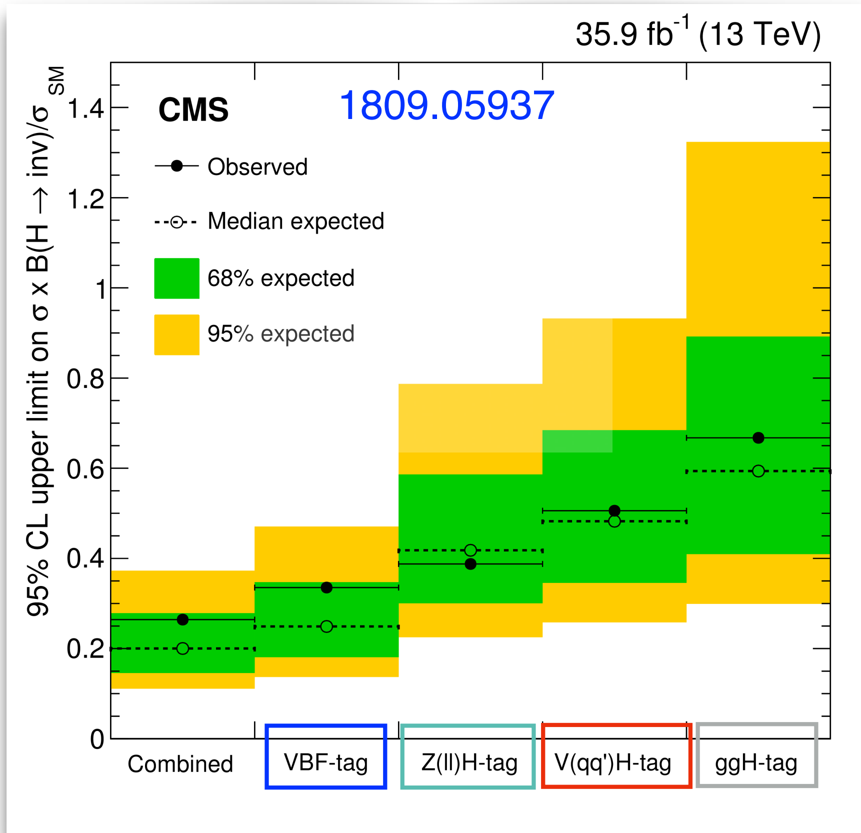
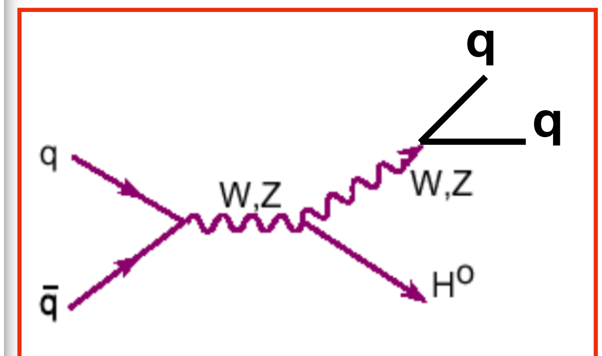
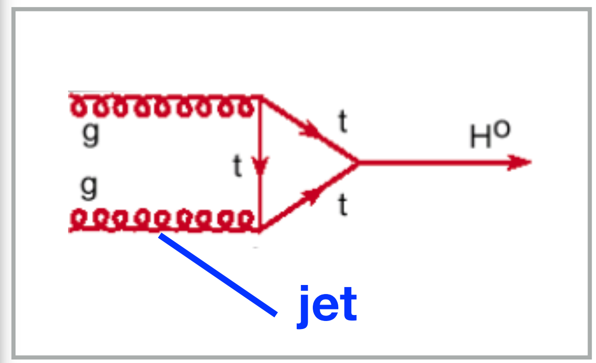






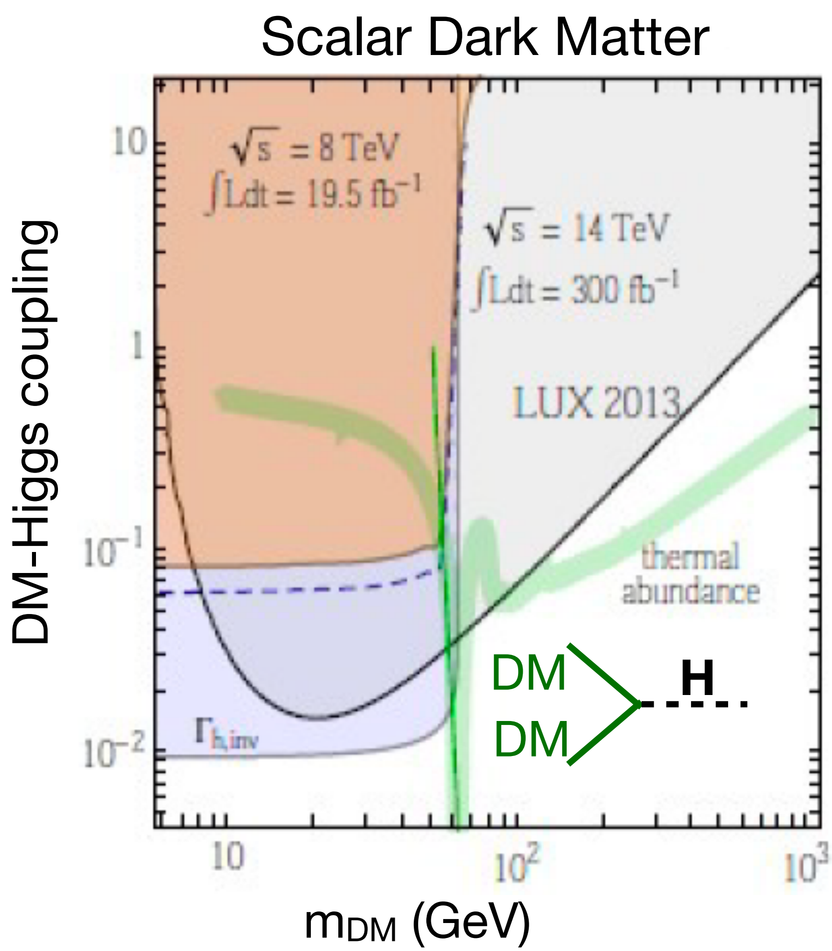




+ htt production: BR<0.46 (CMS PAS HIG-18-008)

The bounds are more stringent than the indirect bound from Higgs coupling measurements (~ 35%)

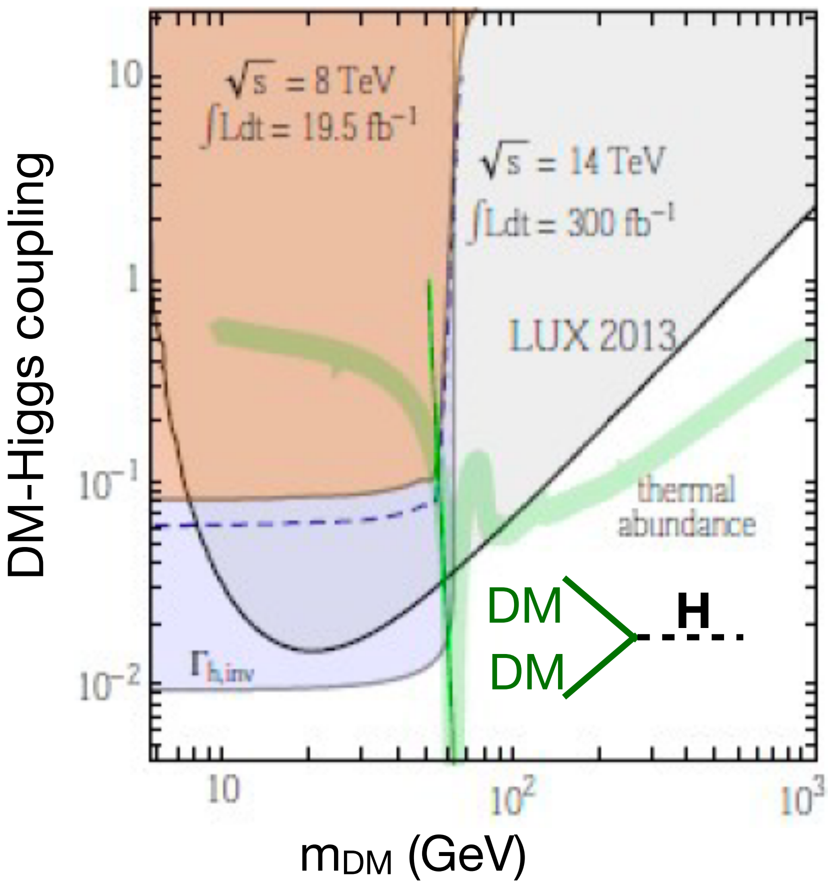
A full picture for Higgs-mediated DM?



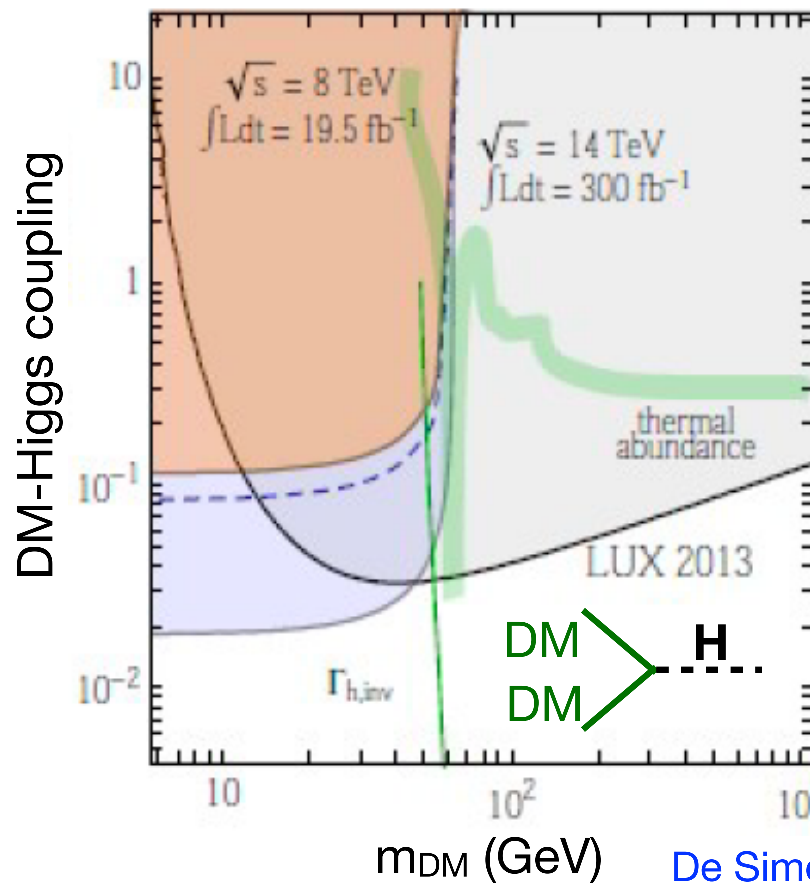
De Simone et al, 1402.6287

A full picture for Higgs-mediated DM?

Scalar Dark Matter



Fermion Dark Matter



De Simone et al, 1402.6287

Conclusion: **in minimal models**, if the Higgs is the particle responsible of DM annihilation, then DM cannot be too light

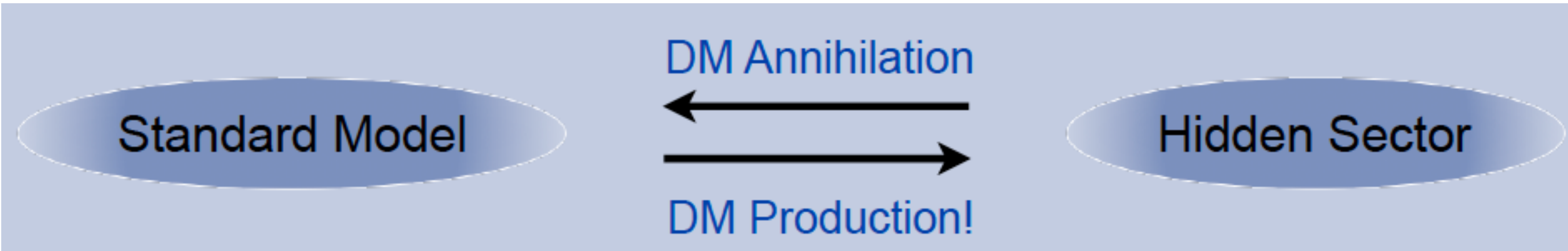
Chapter 4:

- (Light) Dark Matter living in a **dark sectors**
- Complementarity of accelerator experiments (high energy vs. high intensity)

What if DM is lighter than a few GeV?

The framework described so far does not work anymore!

M.Pospelov



The mediator responsible of DM annihilation and thermalization with the SM cannot be heavy (>= EW scale) anymore

One can still write models with heavy mediators, BUT these models need to have a non-standard thermal history

→ **The hidden sector needs to have light degrees of freedom (the mediators), in addition to DM**

Thermal DM is still possible!

Effective field theories can break down!

Dark sectors

Further motivations beyond DM?

- Several anomalies in data can be addressed by dark sectors (eg. $(g\text{-}2)_\mu$, B-physics anomalies @ LHCb, Dark Matter anomalies, …);
- Neutrino mass model building

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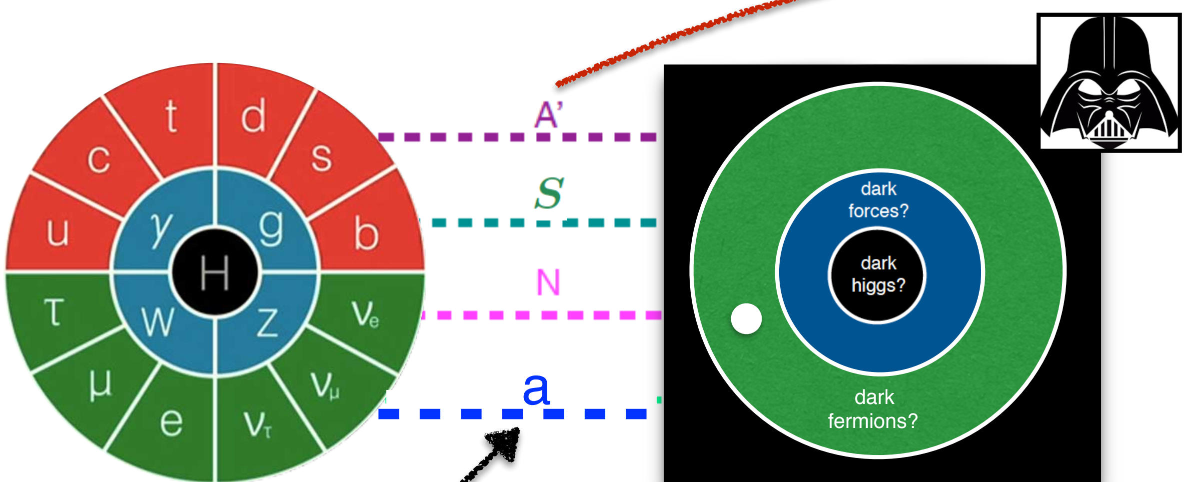
How to test this emerging paradigm?



mediators

Not charged under the SM gauge symmetries

"Portals":

Dark photon	$\epsilon B^{\mu\nu} \tilde{Z}'_{\mu\nu}$
Higgs	$\kappa \lvert H \rvert^2 \lvert S \rvert^2$
Neutrino	$y H L N$
Axion	$g_{a\gamma}\, a \tilde{F}_{\mu\nu} F^{\mu\nu}$

The dark photon / Z boson

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)'?**

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$$\mathcal{L} \supset \epsilon B^{\mu\nu} \tilde{Z}'_{\mu\nu} + \frac{1}{2} m^2_{Z'} \tilde{Z}'_{\mu} \tilde{Z}'^{\mu}$$ + couplings within the dark sector

Mixing with the SM hyper-charge gauge boson

arising from
* dark Higgs mechanism or
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~SM photon ~dark photon/Z

mixing

Electro-weak precision tests (EWPTs) and the dark photon / Z

Because of kinetic mixing,
the Z' mixes with the SM Z boson

Effects on the Z phenomenology:

1. Tree level shift in the Z mass

(more specifically the Z and W mass get a relative shift)

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

2. Modification of the Z couplings

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

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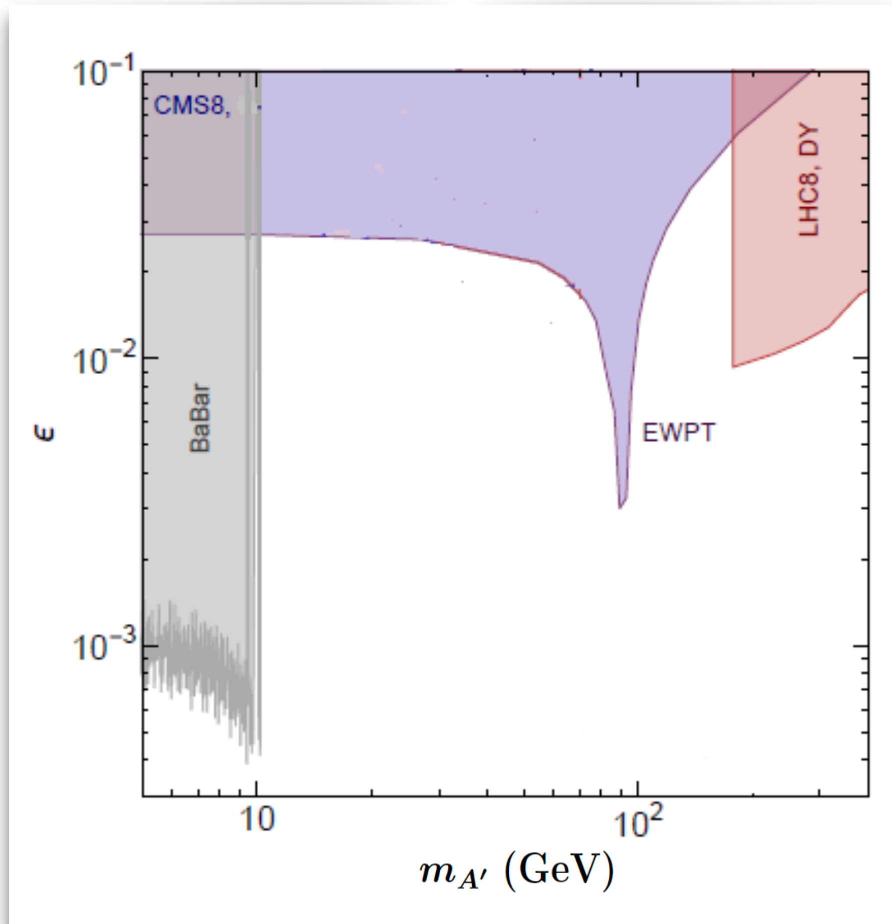
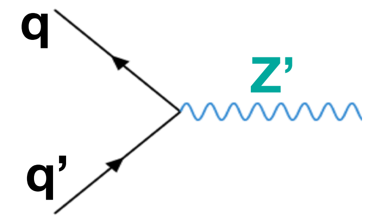


Curtin, Essig, SG, Shelton, 1412.0018
See also Hook, Izaguirre, Wacker, 1006.0973

What about the LHC phenomenology?

* The dark photon / Z can be produced in the same way we produce the SM Z and photons
* Lifetime and decay mode dictates search strategy



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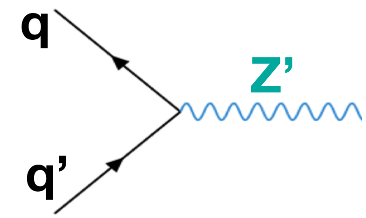

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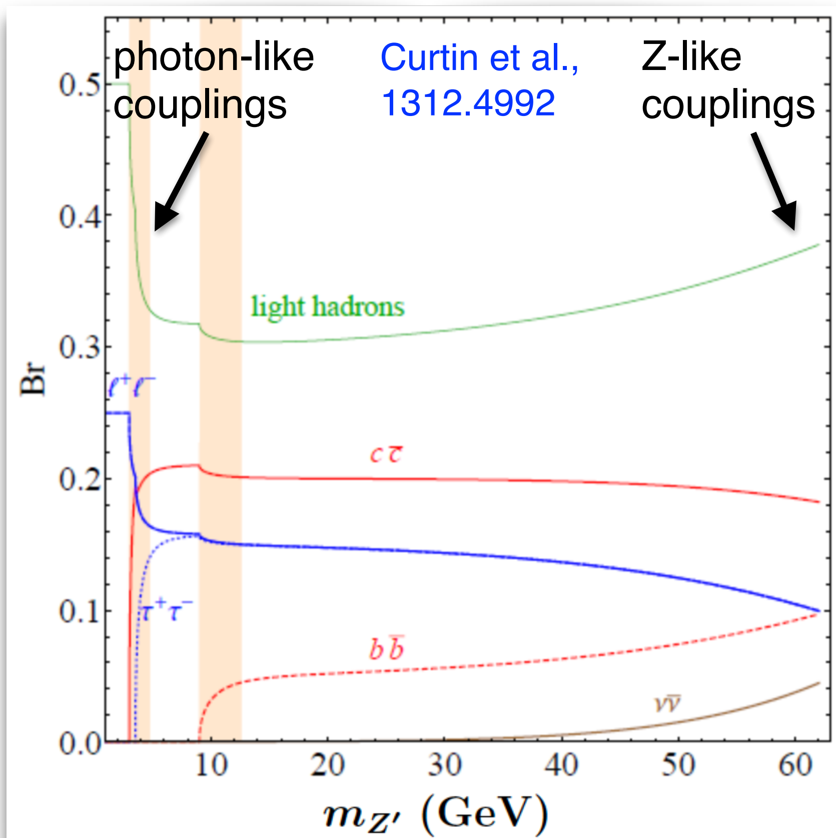

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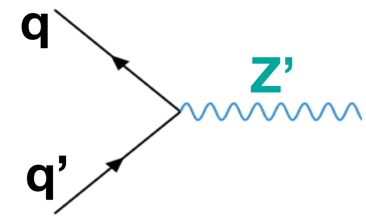

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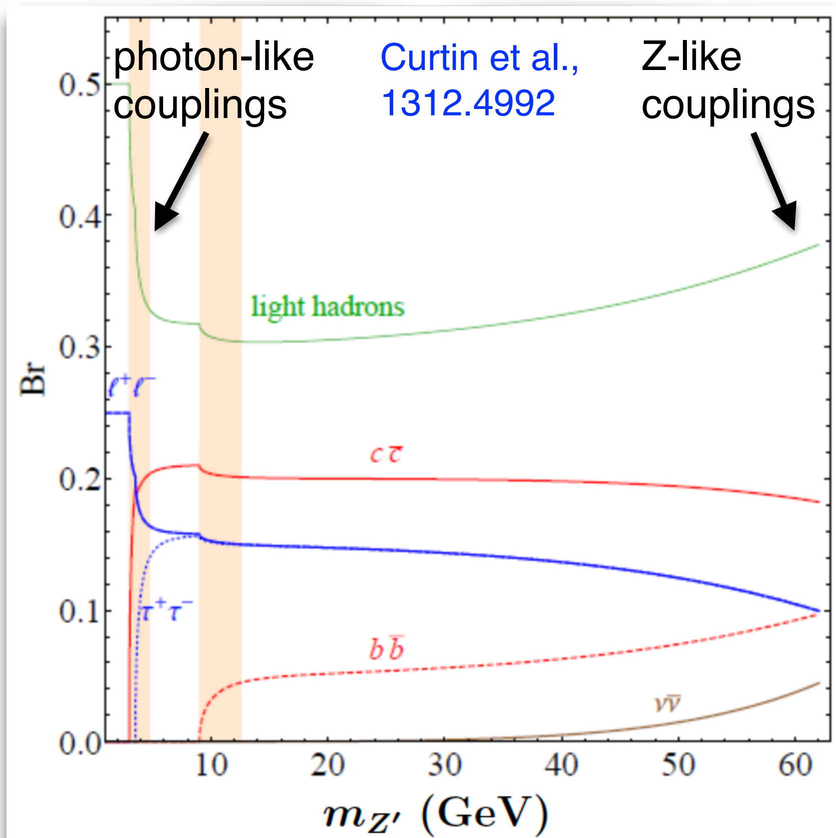

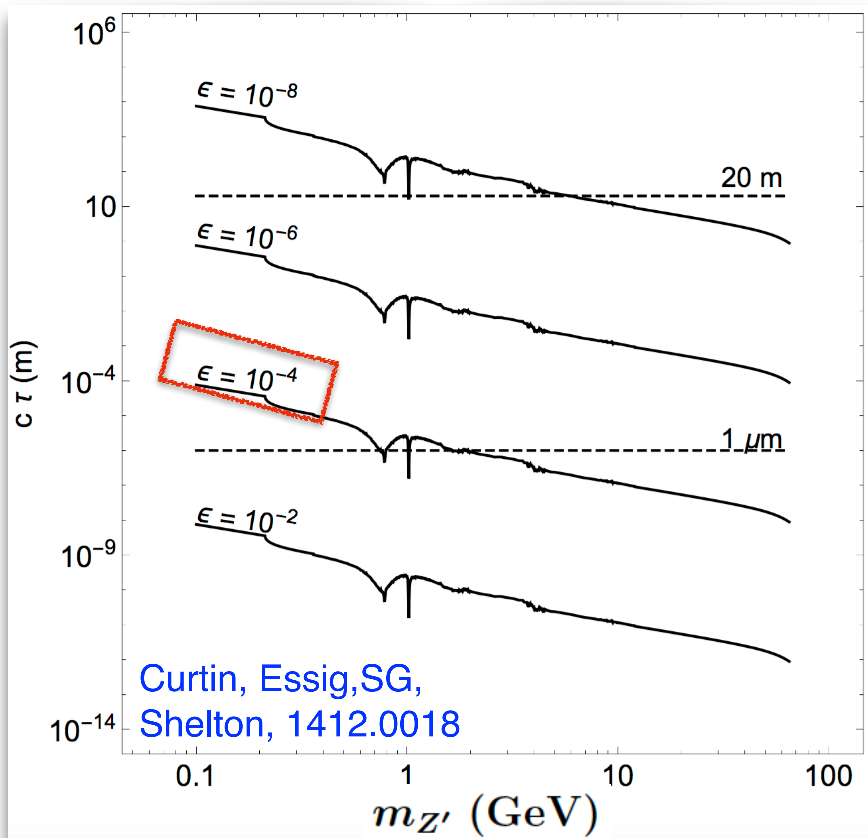

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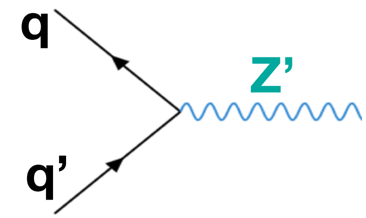

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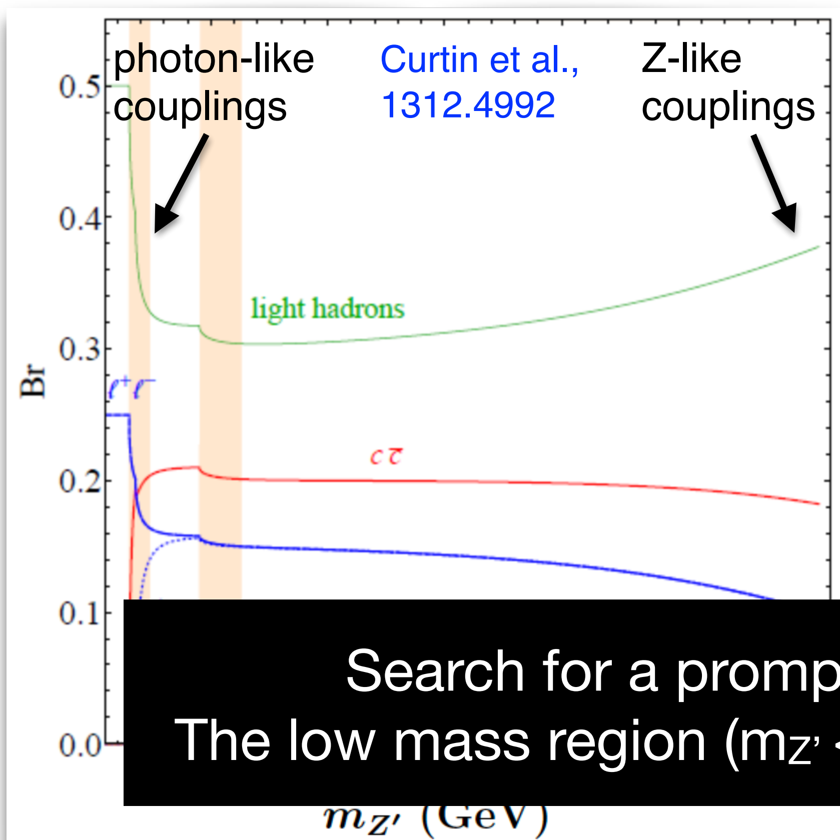
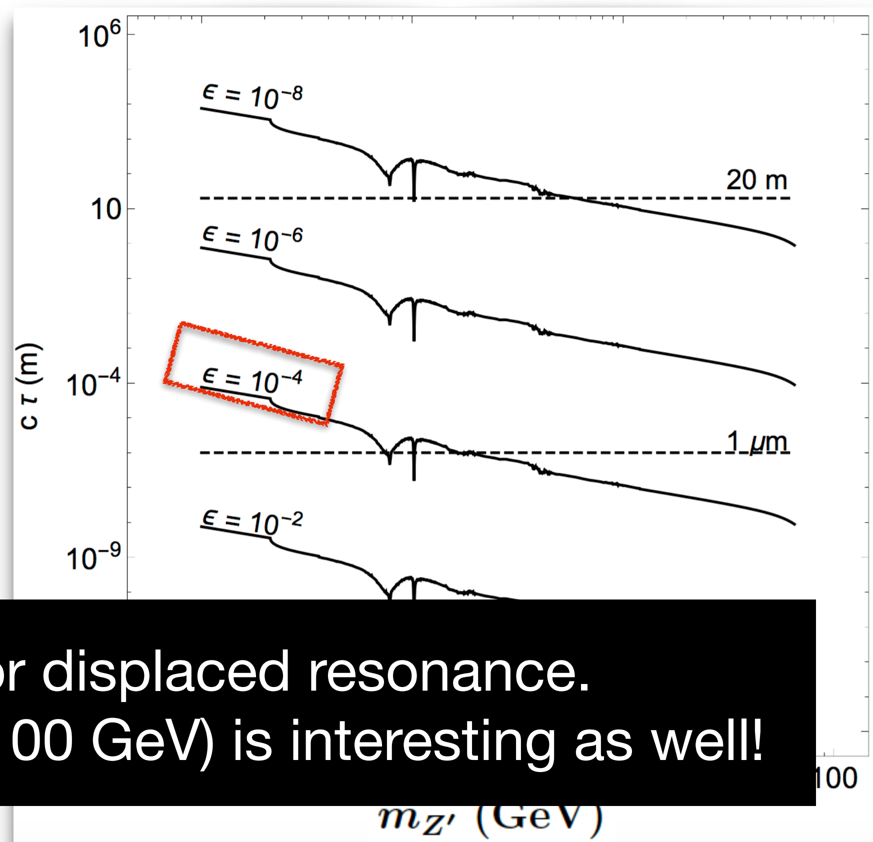
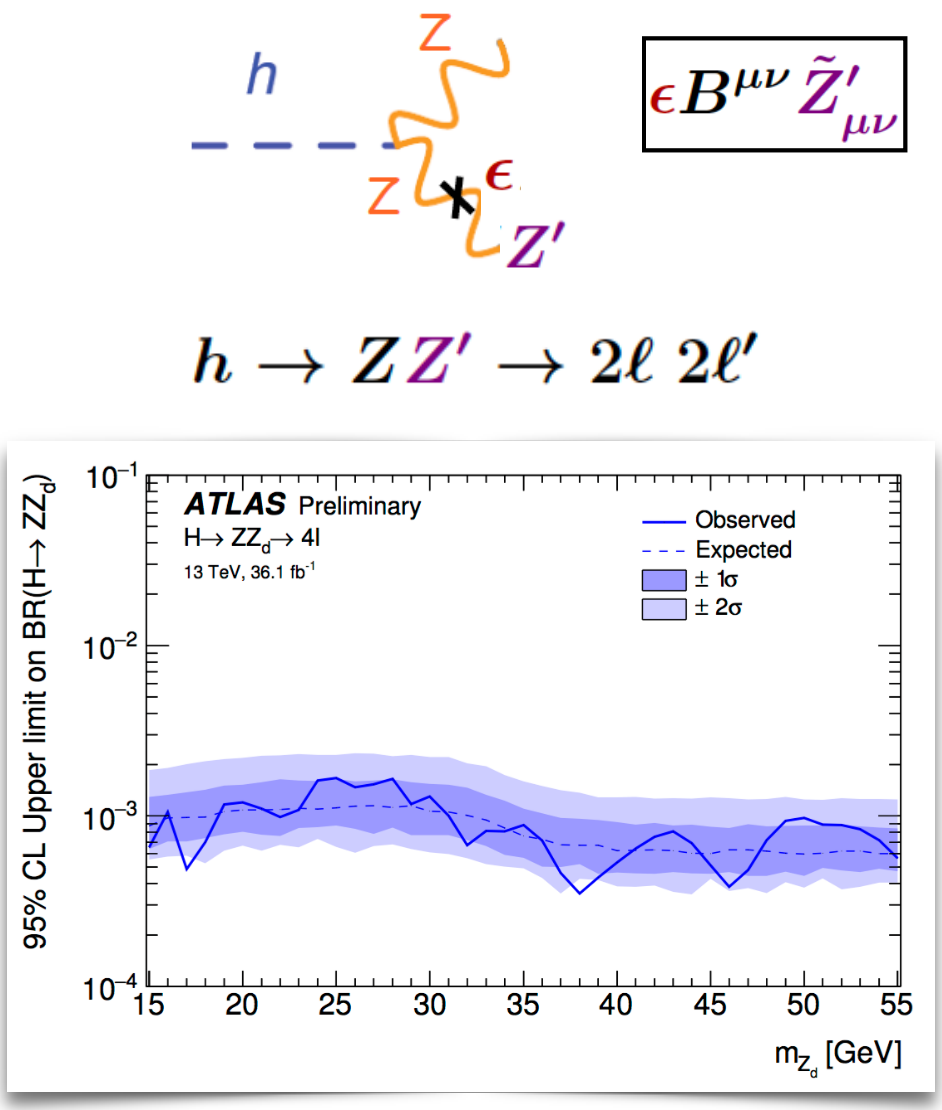




Search for a prompt or displaced resonance.
The low mass region ($m_{Z'} < 100$ GeV) is interesting as well!

No ϵ dependence

Higgs exotic decays to dark photons



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ATLAS-CONF-2017-042

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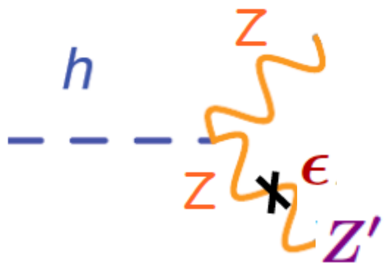

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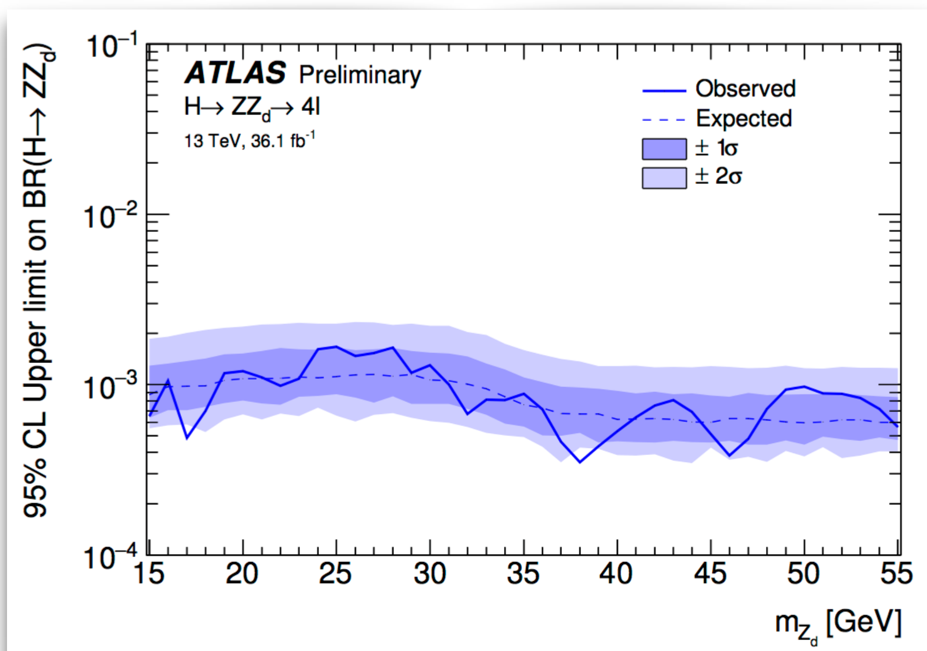

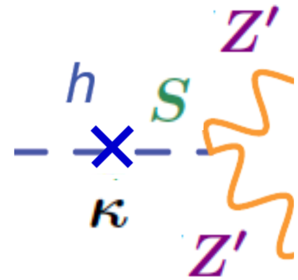

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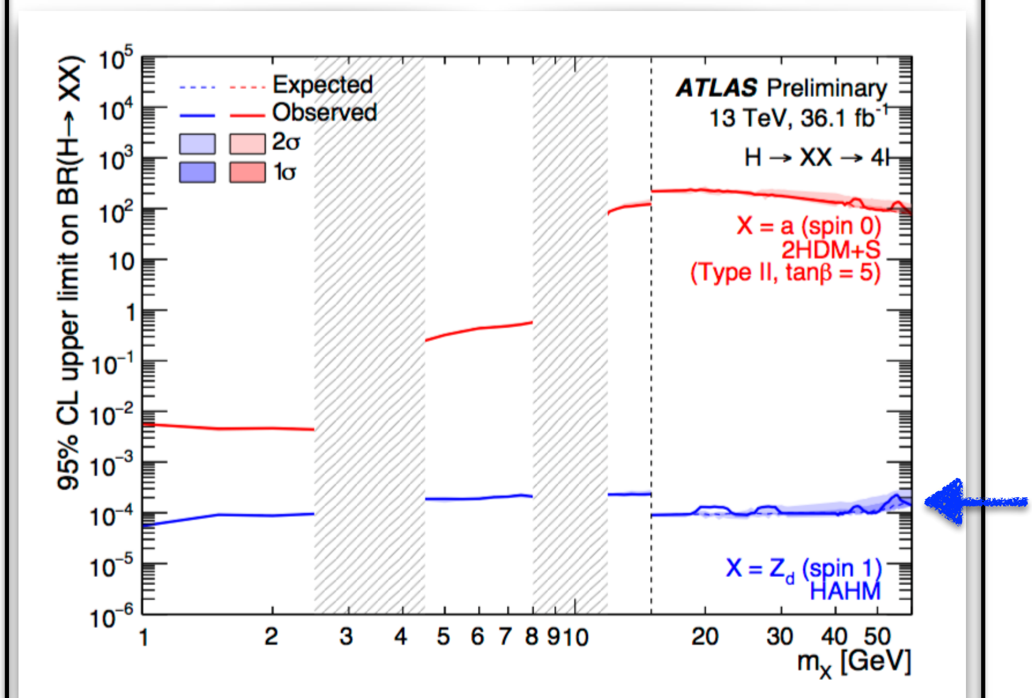

Complementarity with lower energy experiments

Dark photons/Z can be produced at a plethora of high intensity (low energy) experiments.

Examples are:

* e^+e^- machines like Babar and Belle (II)
* electron fixed target experiments (HPS, NA64, …)
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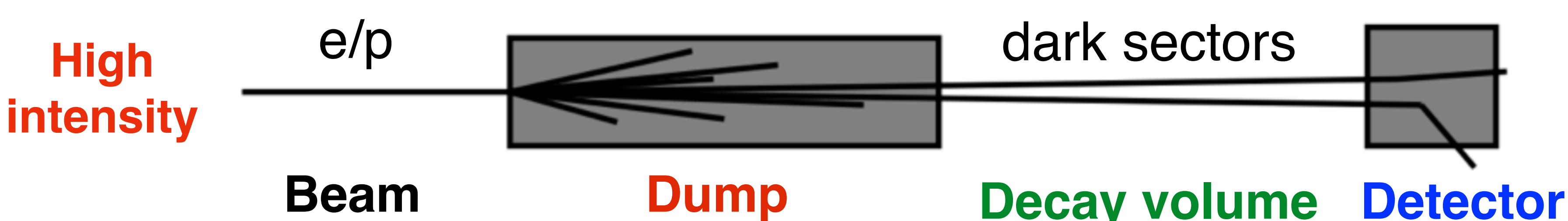

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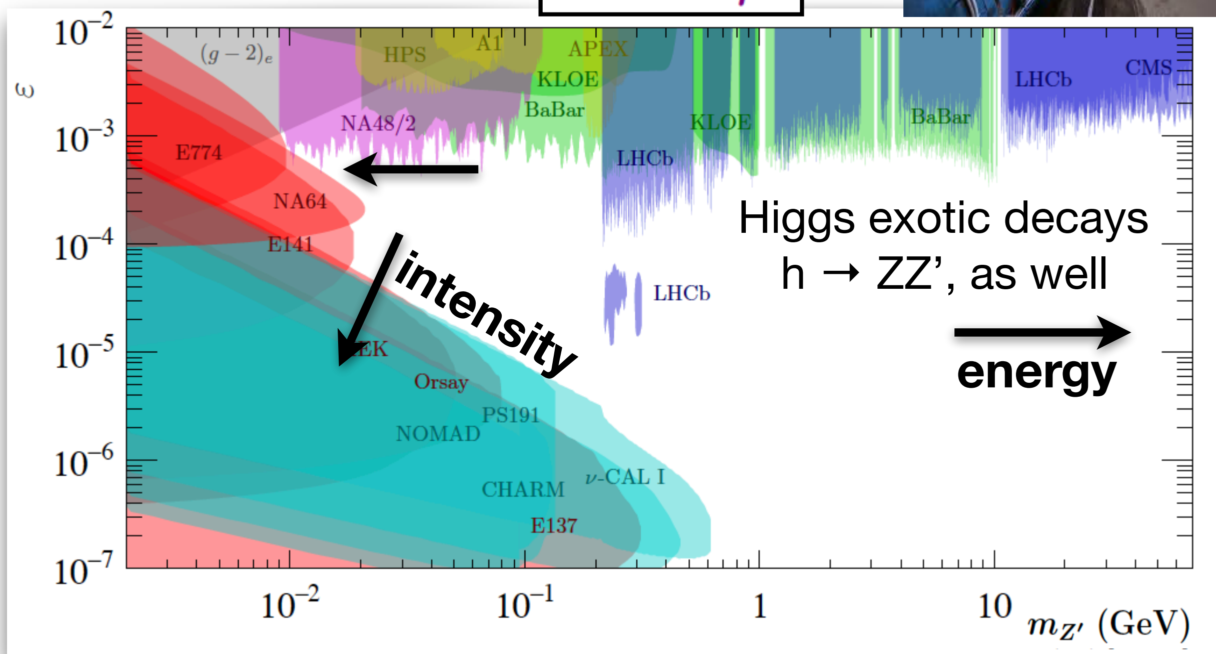
$$\epsilon B^{\mu\nu} \tilde{Z}'_{\mu\nu}$$



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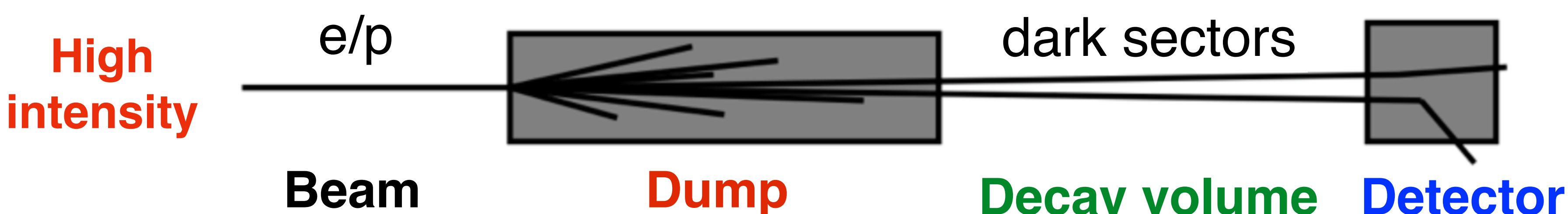

A Higgs exotic decay program to probe dark sectors

We have seen that Dark Matter can be produced from Higgs decays (Higgs invisible decays).

More in general, any light ($m < m_h$) dark sector particle can be produced from Higgs decays.

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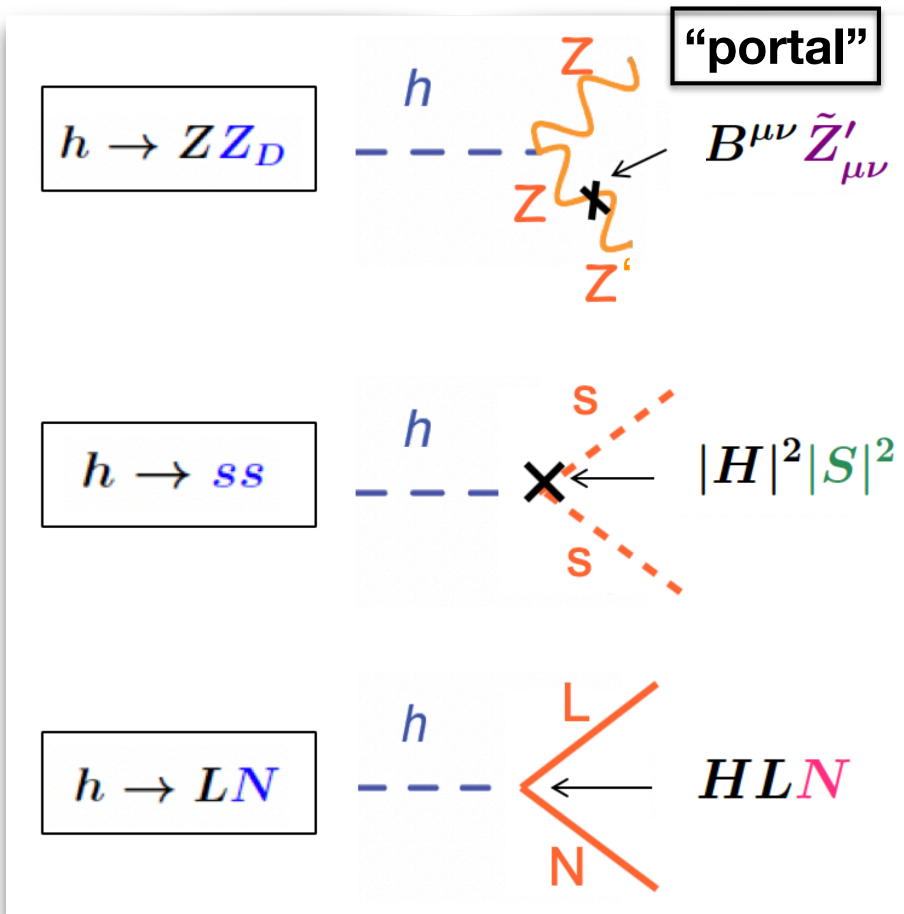

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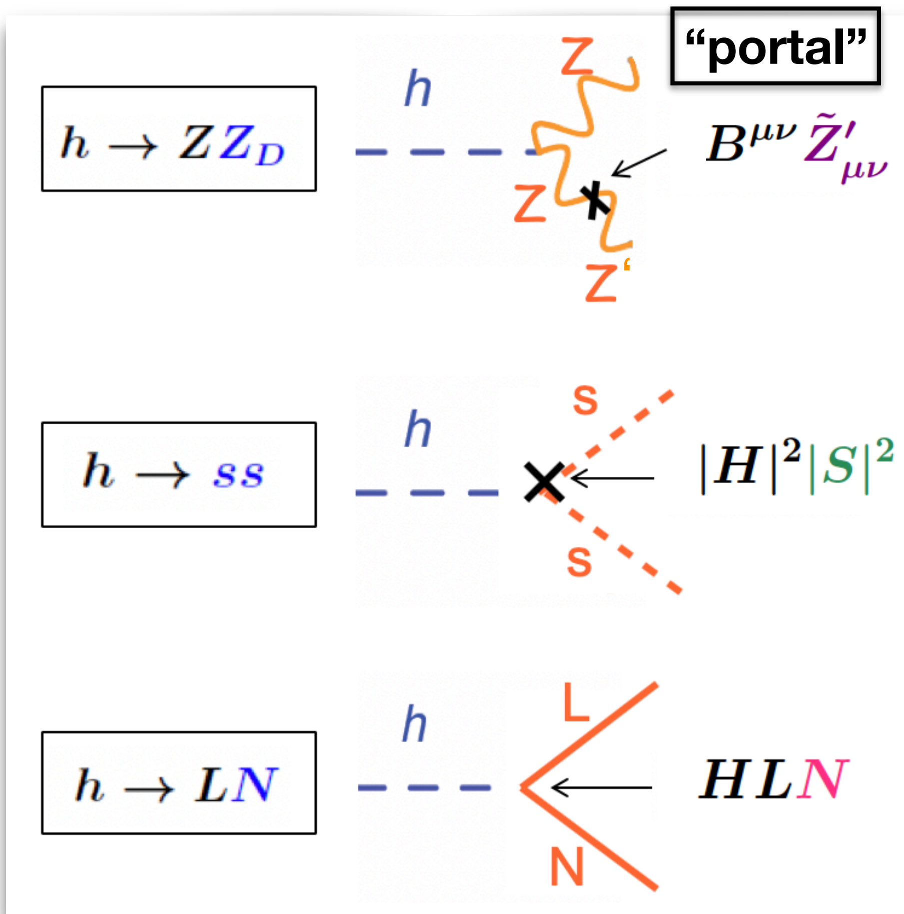

The SM Higgs width is small (~ 4 MeV), so it is easy to get sizable branching ratios into dark sector particles

Plenty of signatures to look for, depending on the decay mode of the dark sector particle:

- some decay promptly to visible particles;
- some decay promptly to visible particles + MET;
- some are displaced.

The challenge: soft objects

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

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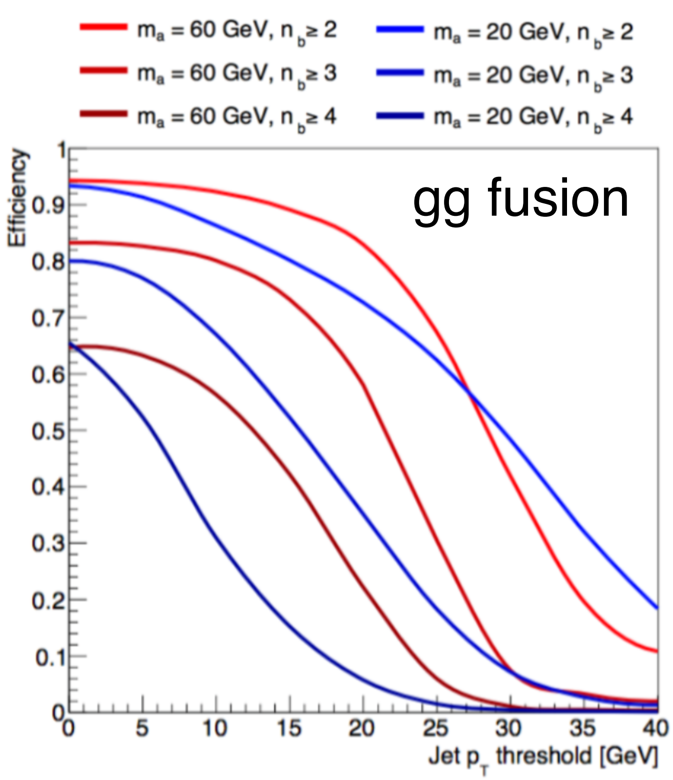
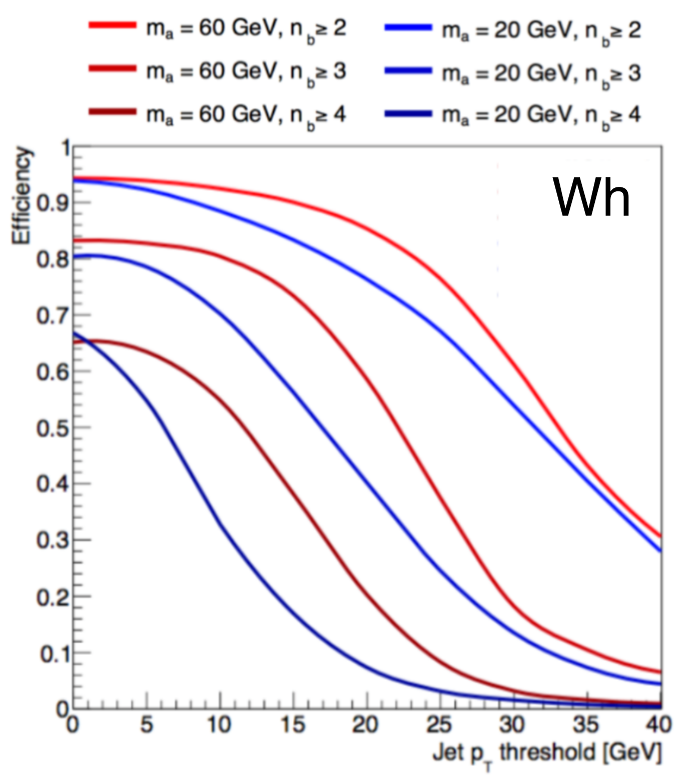
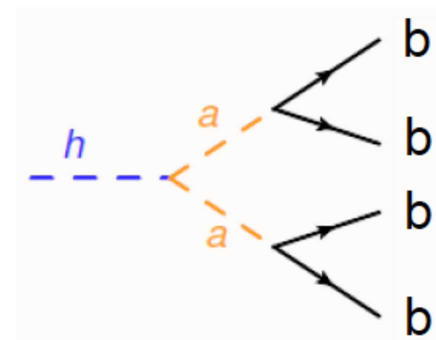
Let us take, for example, the challenging decay mode h → 4b







Risk of loosing the signal already at the trigger level

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

Outlook: What have we learned?

Introduction to Dark Matter

What do we know?

WIMP Dark Matter

Interplay between
- indirect searches
- direct searches
- LHC

LHC has fully probed minimal DM models where DM annihilate through the Higgs (and $m_{DM} < m_h / 2$)

(Light) Dark Matter from a dark sector

Portals between the dark sector and the SM

The dark photon / Z phenomenology at the LHC

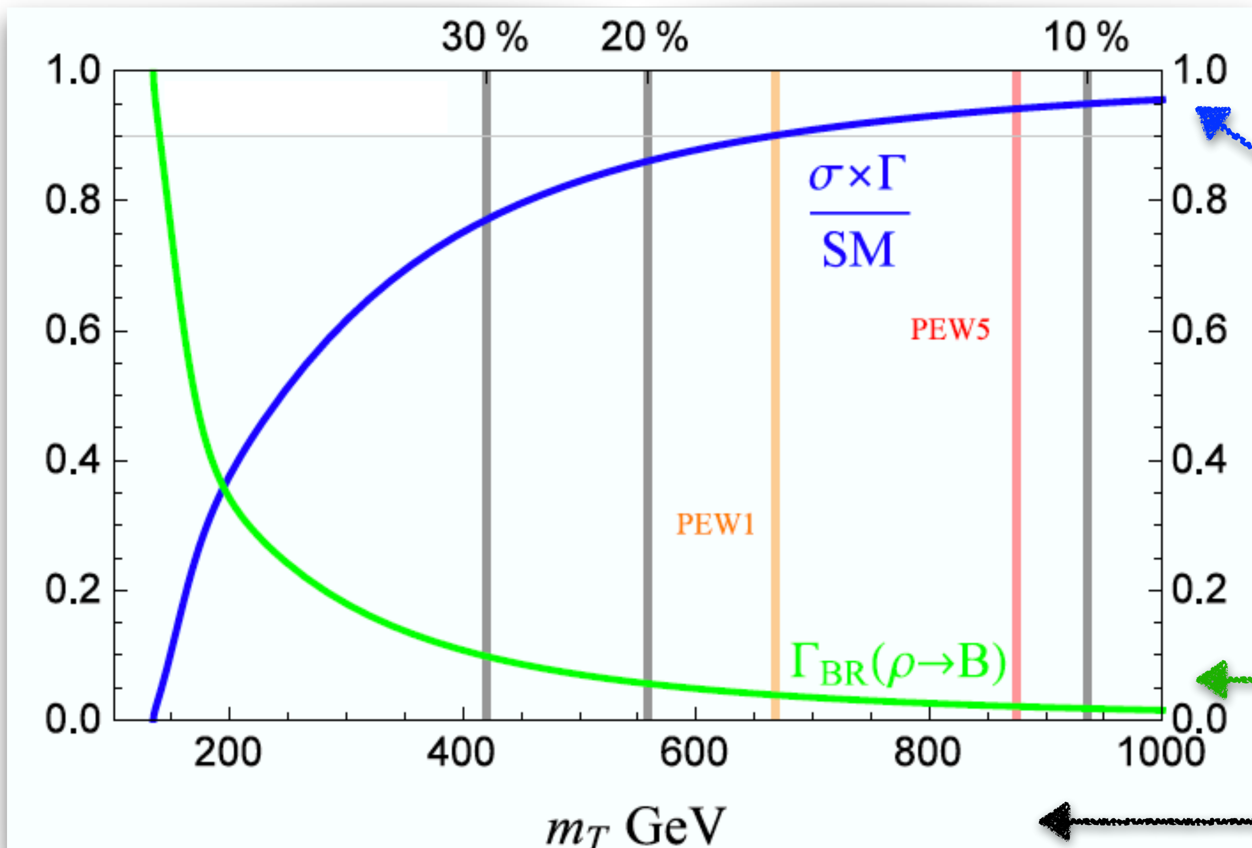
Complementarity with high intensity experiments

The LHC program for Higgs exotic decays

Effects on the 125 GeV Higgs pheno

The 125 GeV Higgs will mix with the twin Higgs with a mixing angle ~ v^2/f^2

- The Higgs couplings to the SM particles will be reduced
- The Higgs will decay to light twin states (invisible Higgs width)



Higgs rates into SM particles

Width into the twin-sector

Mass of the top-partner

Burdman et al, 1411.3310

Xenon1T excess

2006.09721