

# Searches for Dark matter at the LHC

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## Two measure ways:

### 1. Direct Detection(DD): DM-nucleus elastic scattering

The WIMPs through weak interaction interact with the target nucleus of the ground detector , which will elastic scattering occurs, and the recoil nucleus is ejected. The detector records the recoil nuclear energy and obtains a signal that the dark matter interacts with the detector.

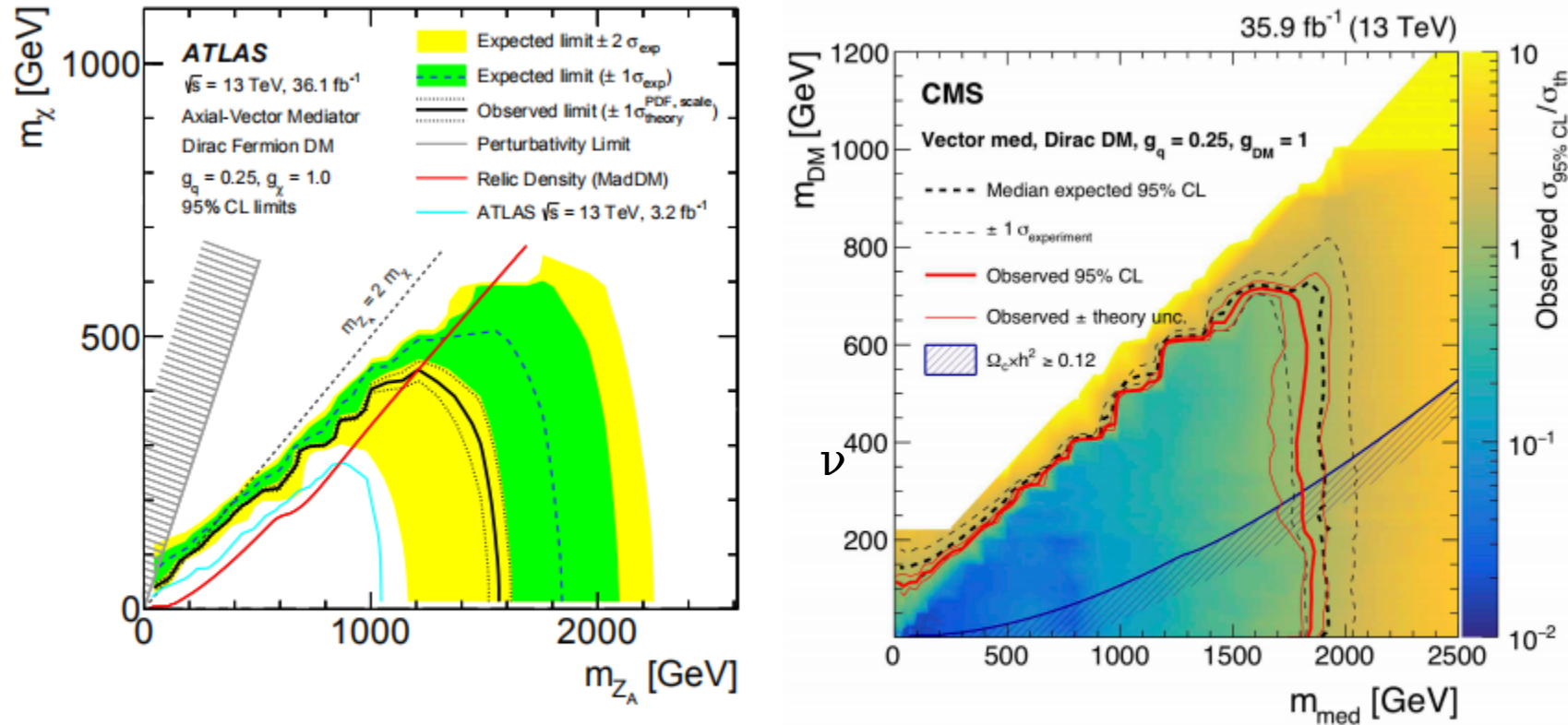
### 2. Indirect Detection(ID): DM annihilation or decay to SM

- Measure missing transverse momentum.
- Probe the interaction between dark matter and SM particles.

# Searches for DM with ( $E_T^{\text{miss}}$ +X) Signatures

1.  $E_T^{\text{miss}}$ : When DM is produced at colliders, it escapes without detection which results in an imbalance in transverse momentum  $p_T$ . The magnitude of the missing  $p_T$  is denoted  $E_T^{\text{miss}}$ .
- 2.X: a jet, a photon, a vector boson (W or Z), heavy flavor quark (t or b quark) and a Higgs boson h.
- 3.Snigle mediator, Dirac fermion DM ,The parameters of the model are the mass of the mediator  $m_{\text{med}}$ , the DM mass  $m_\chi$ , the coupling of the mediator to quarks and DM,  $g_q$  and  $g_\chi$ .

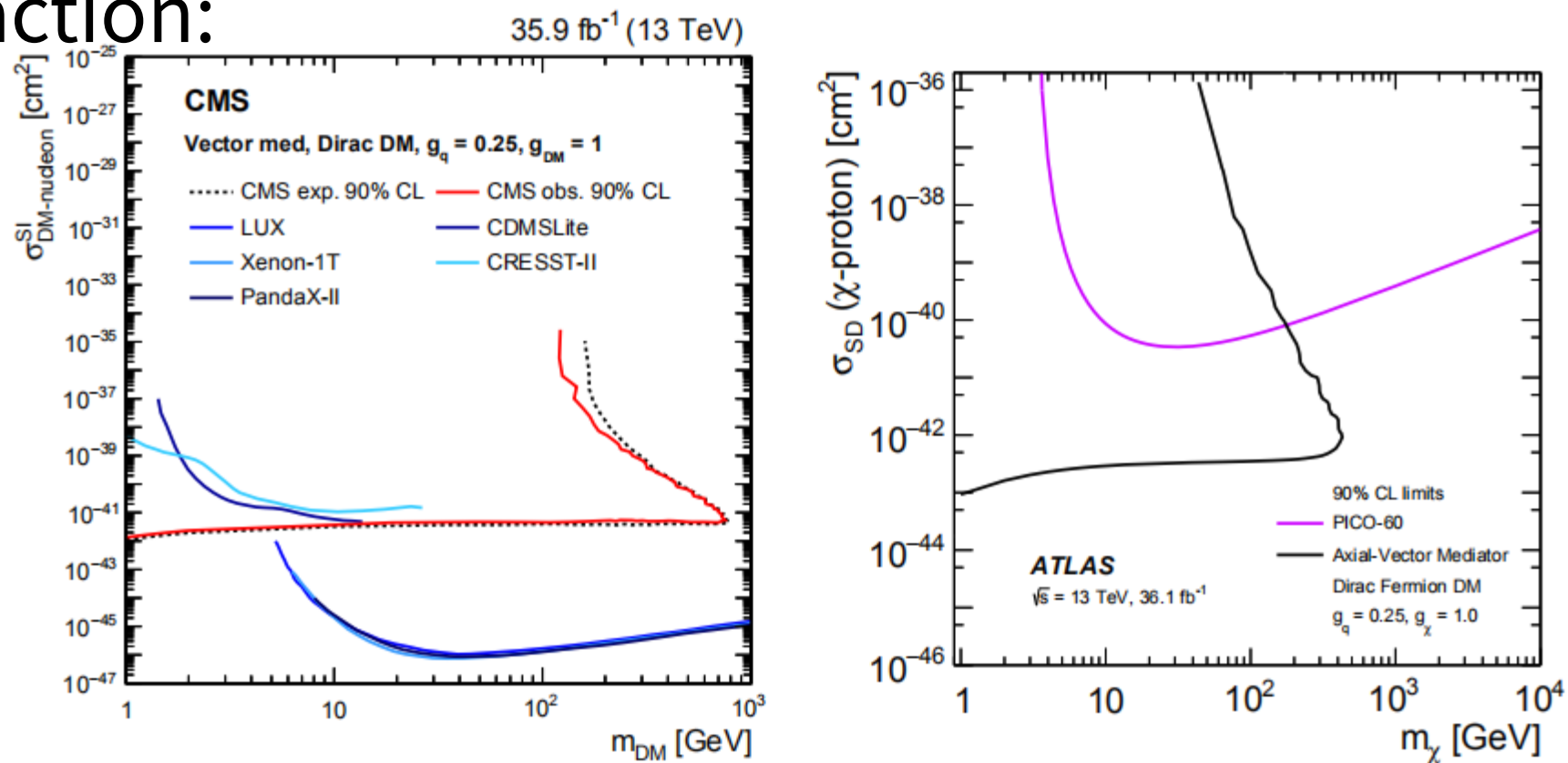
$E_T^{\text{miss}}$  +jet channel:



**Figure 1:** Exclusion regions in the DM mass-mediator mass plane from searches in the  $(E_T^{\text{miss}} + \text{jet})$  channel: (left) from ATLAS for an axial-vector mediator [8] and (right) from CMS for a vector mediator [7].

Backgrounds:  $Z(\nu\nu) + \text{jets}$  and  $W(l\nu) + \text{jets}$

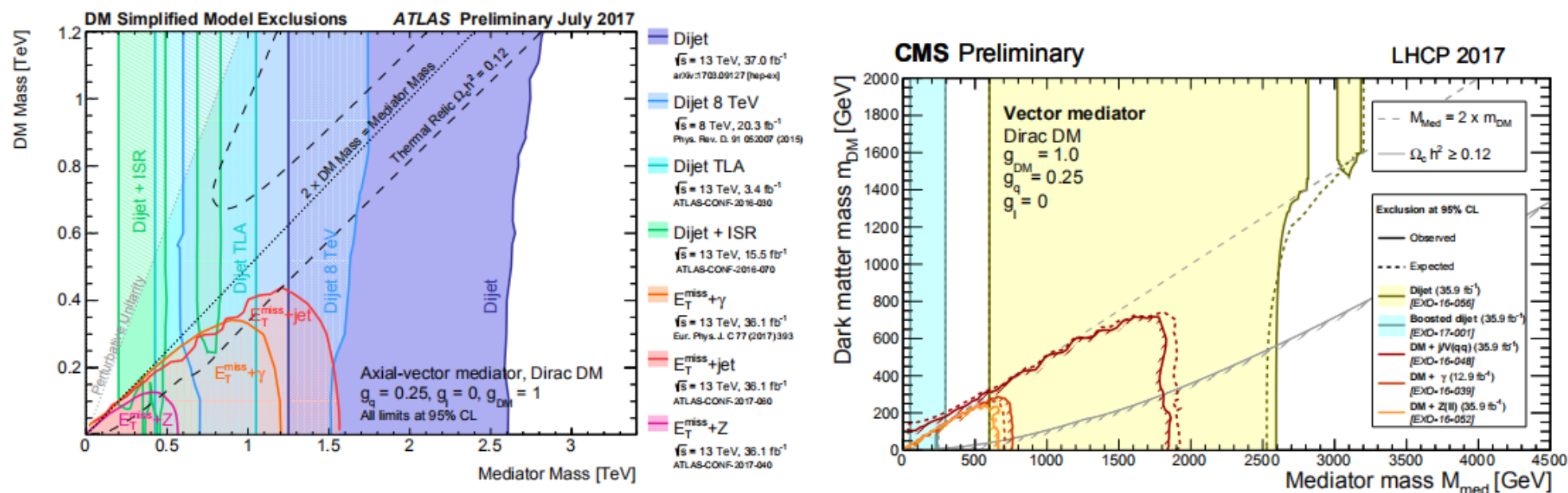
# Limits on DM-nucleon cross-section and DM-proton interaction:



**Figure 2:** Comparison of LHC results from searches in the  $(E_T^{\text{miss}} + \text{jet})$  channel with results from DD experiments: (left) the limit on the spin-independent DM-nucleon cross-section vs. DM mass from CMS [7] and (right) the limit on the spin-dependent  $\chi$ -proton cross-section vs. DM mass from ATLAS [8].

# Seaches for mediators:

LHC is a mediator machine, mediators rather than DM are directly produced by the interaction.



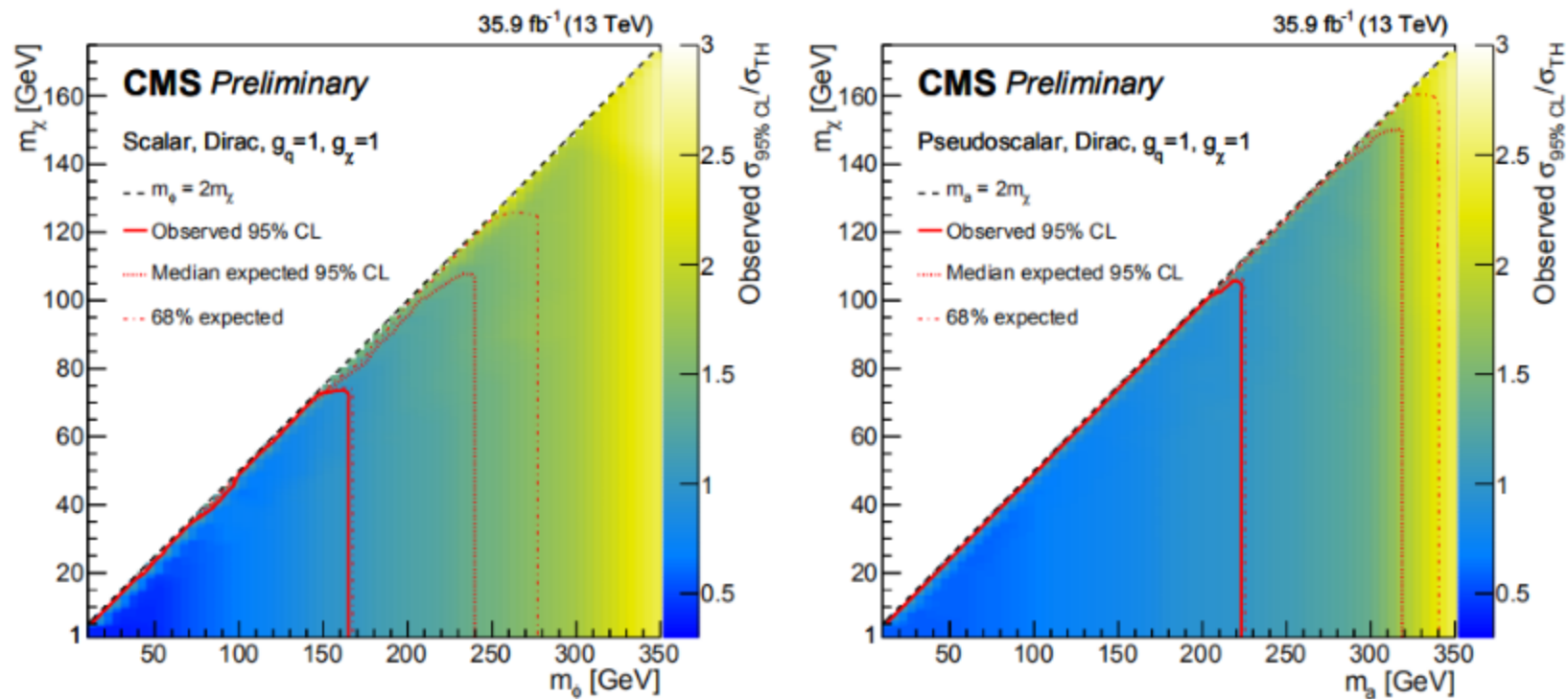
**Figure 4:** Compilation of exclusion regions in the DM mass-mediator mass plane: (left) from ATLAS for an axial-vector mediator [10] and (right) from CMS for a vector mediator [11].

## Search for Dark Matter Plus Heavy Flavor:

Spin-0 mediators (the scalar  $\phi$  and the pseudoscalar  $a$ ) couple strongly to  $t$  or  $b$  quarks.

Higgs-like Yukawa couplings which means that they couple most strongly to  $t$  and  $b$  quarks. This motivates looking for  $\phi/a \rightarrow \chi\bar{\chi}$  in final states with heavy flavor quarks and large  $E_T^{\text{miss}}$ . CMS has searched for  $pp \rightarrow t\bar{t} + \chi\bar{\chi}$  [14] using multiple signal regions based on the  $t\bar{t}$  decays (all-hadronic,  $\ell + \text{jets}$  and dileptonic) which provide complementary sensitivity. The  $t\bar{t}$ ,  $W + \text{jets}$  and  $Z + \text{jets}$  backgrounds are constrained by control regions. Results are shown in Figure 6 where, for

# Limit on scalar mediator and pseudoscalar mediator:



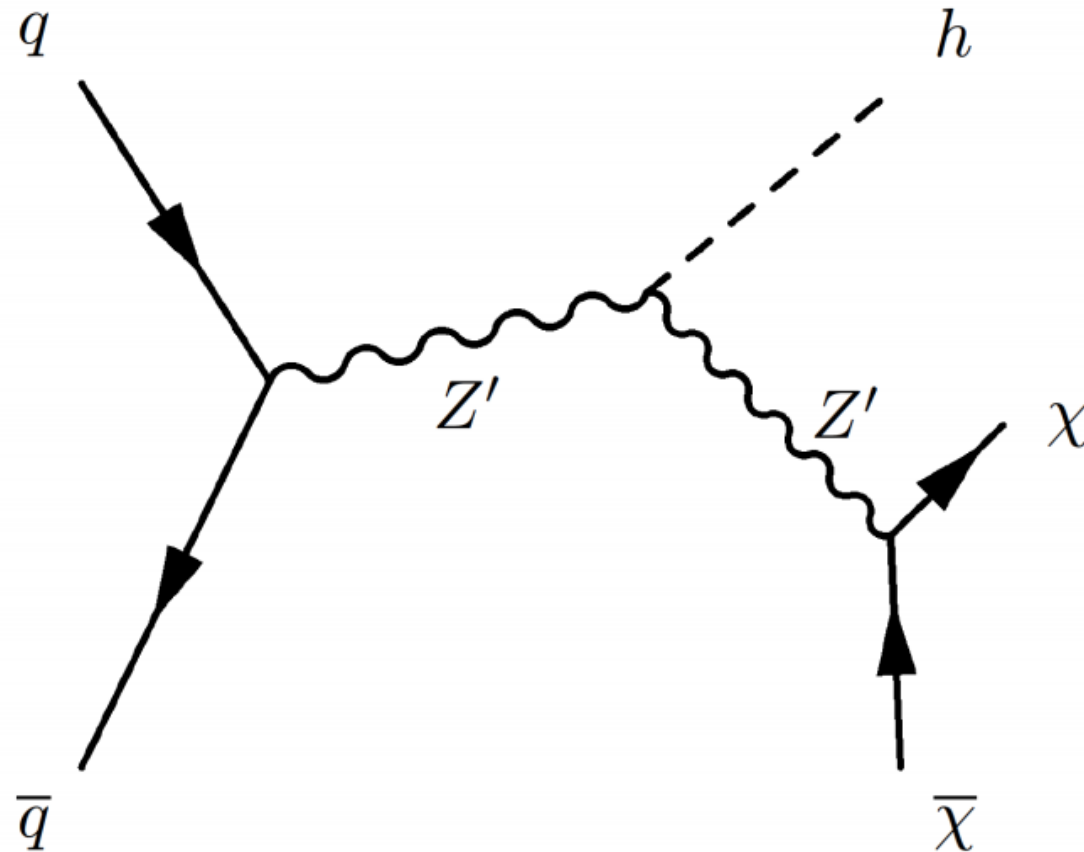
**Figure 6:** Exclusion regions in the DM mass-mediator mass plane from the CMS search in the  $t\bar{t} + \chi\bar{\chi}$  channel [14]: (left) for a scalar mediator and (right) for a pseudoscalar mediator.



# Searches in the ( $E_T^{\text{miss}} + \text{Higgs}$ ) Channel:

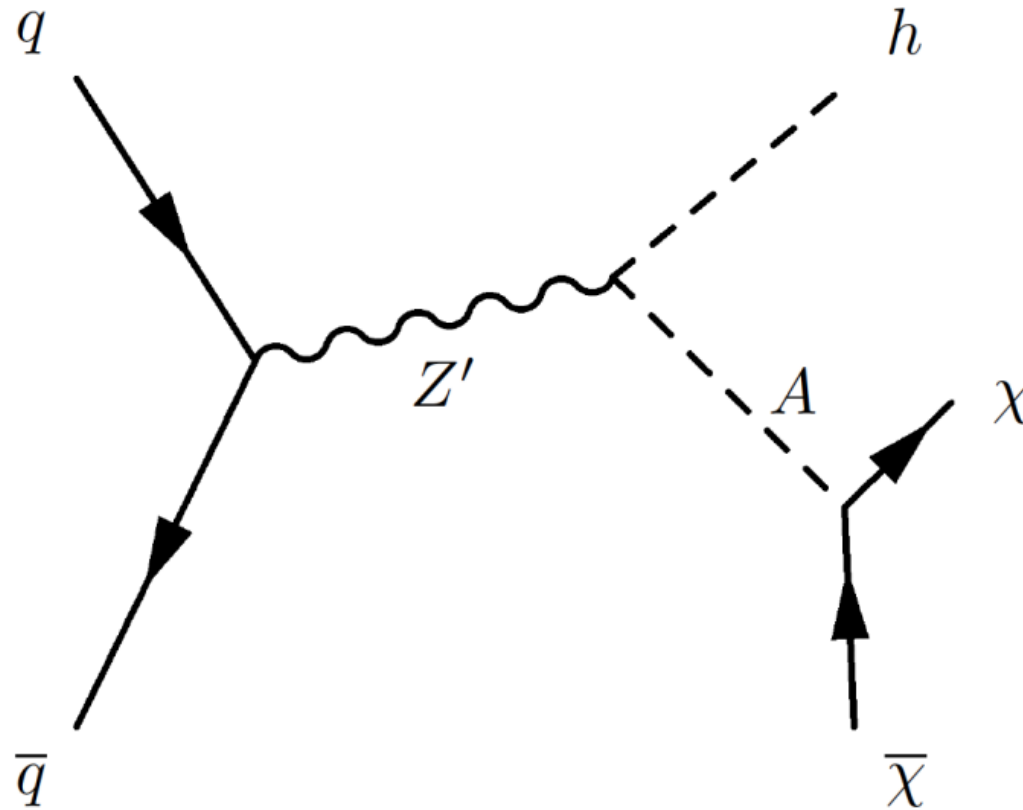
Two models:

presented here. In the “Baryonic  $Z'$ ” model, the mediator  $Z'$  is produced in the  $s$ -channel, it radiates the  $h$  and then decays  $Z' \rightarrow \chi\bar{\chi}$ . CMS has searched for this process where the  $h$  decays to either  $\gamma\gamma$  or  $\tau^+\tau^-$  [15]. Results are shown in Figure 7 (left) where the  $Z'$  is excluded up to 815 GeV for low

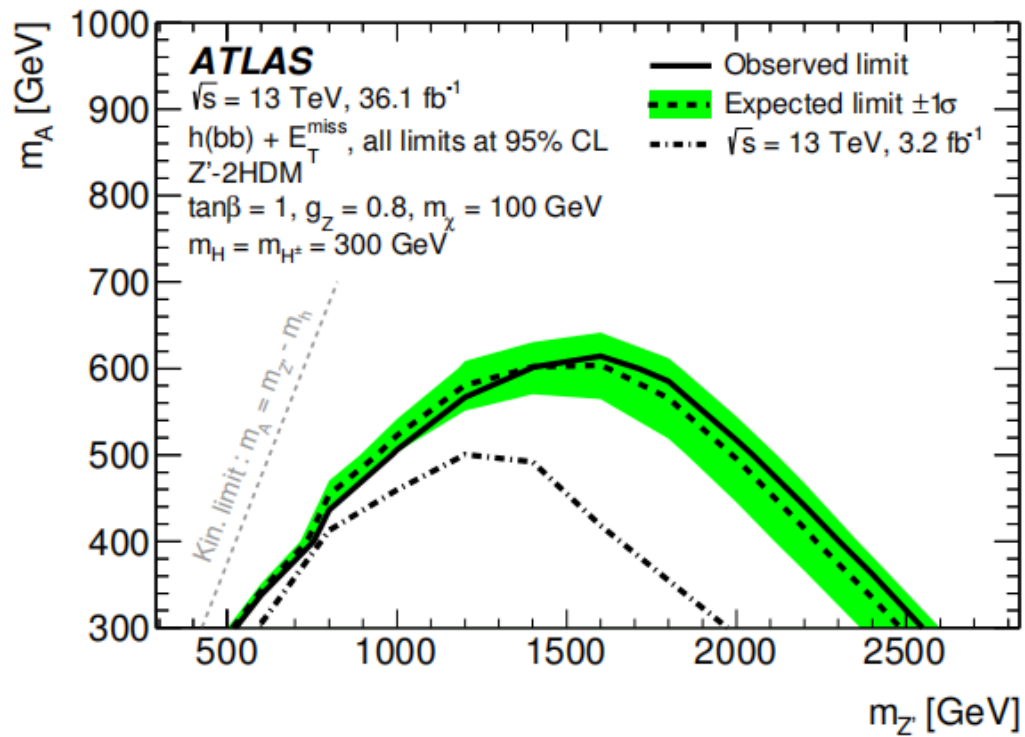
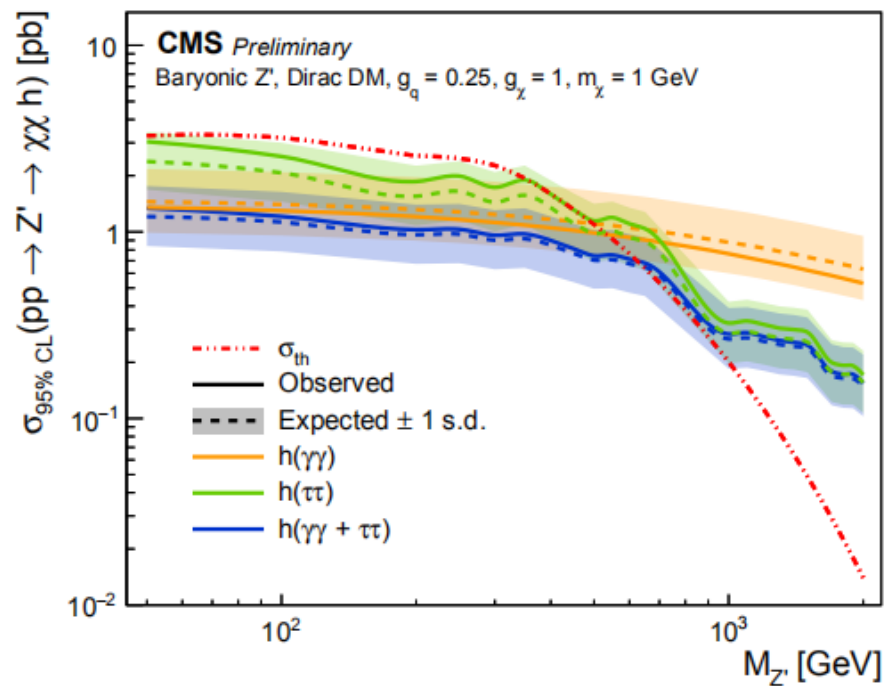


## Two models:

$m_\chi$ . ATLAS has searched for DM in the context of a  $Z'$ -2HDM model where  $Z' \rightarrow hA$  followed by the pseudoscalar Higgs  $A$  decaying to  $\chi\bar{\chi}$ . The Higgs boson decays to  $b\bar{b}$  and is reconstructed using resolved or merged jets [16]. Results are presented in the  $m_A$ - $m_{Z'}$  plane in Figure 7 (right)



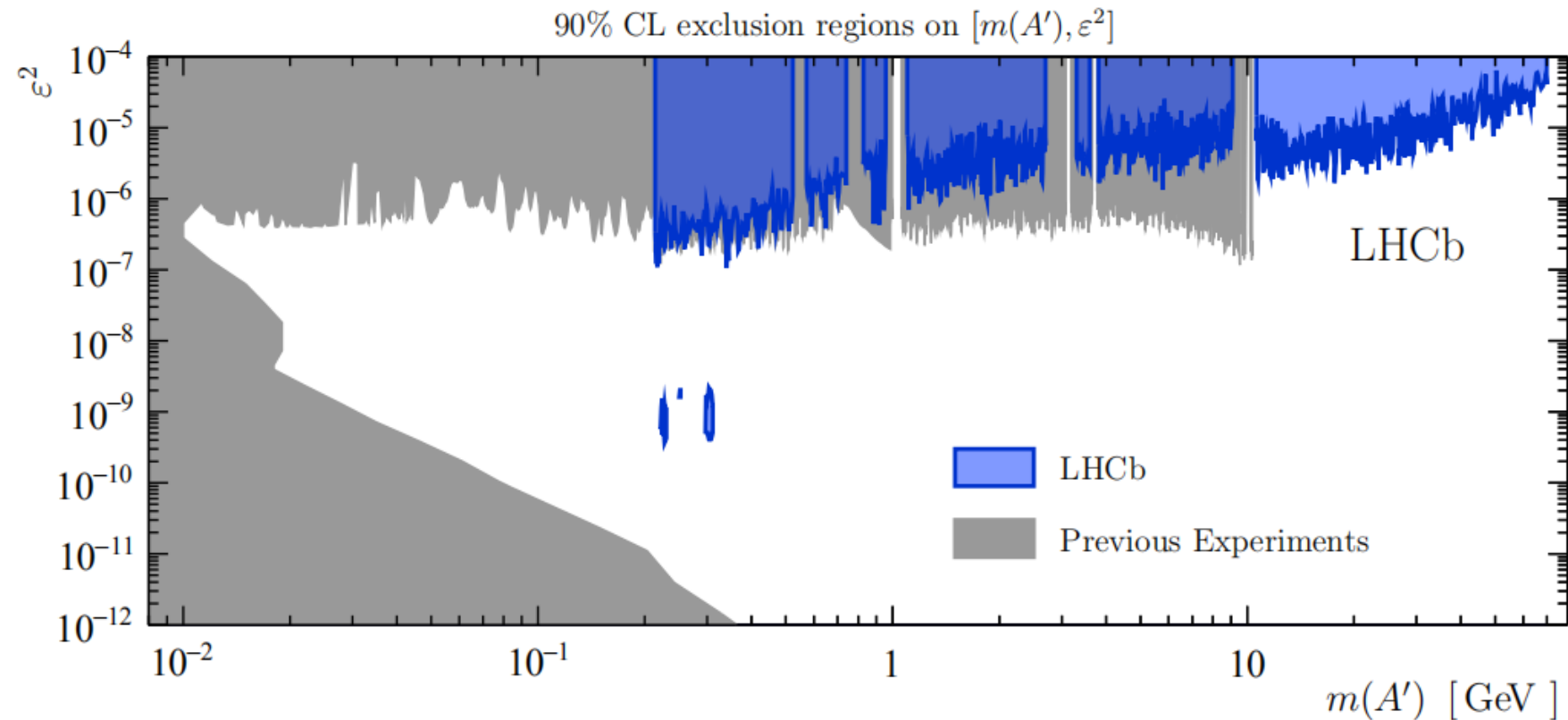
# Different models different measure ways:



**Figure 7:** (Left) Limit on cross-section vs. mediator mass for the Baryonic  $Z'$  models from CMS [15]. (Right) Exclusion region in the  $m_A$ - $m_{Z'}$  plane in the context of the  $Z'$ -2HDM model from ATLAS [16].

# Search for Dark Photons:

Massive dark photon  $A'$  couples to the SM via “kinetic mixing”  $\varepsilon$ . A signature at colliders is  $A' \rightarrow \mu^+ \mu^-$ .



**Figure 8:** Exclusion in the mixing-dark photon mass plane from LHCb [17].

## Search in the Mono- $Z'$ Channel:

can either be resolved or merged. Two (DM +  $Z'$ ) signal models are studied: (1) a “dark-fermion” model where the  $Z'$  couples to a heavier dark-sector fermion  $\chi_2$  and a lighter fermion  $\chi_1$  which is the DM candidate and (2) a “dark-Higgs” model where the dark-sector Higgs boson  $h_D$  is radiated from the  $Z'$  and  $h_D$  decays to  $\chi\bar{\chi}$ . Examples of limits on the coupling of the  $Z'$  to quarks  $g_{\text{SM}}$  for

# Summary

- Introduced some models about searching for dark matter.
- No evidence for DM has been observed, but there is much more phase space to be explored.
- Compared different interactions and mediators' effect on phase space.