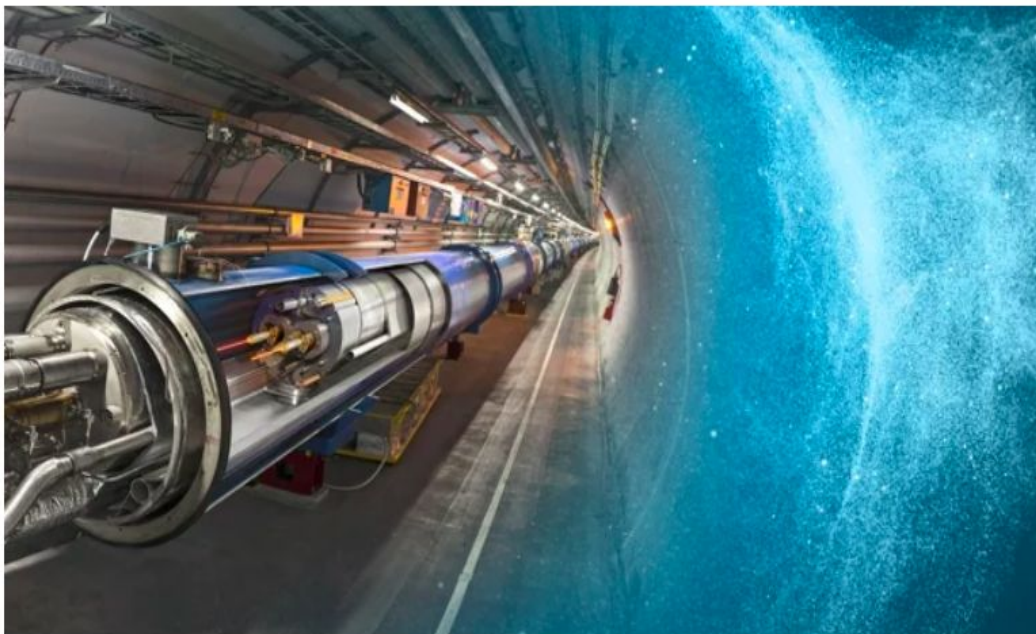
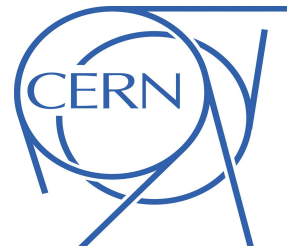


# Prompt signature searches for Dark Matter in the ATLAS collaboration



*Alvaro Lopez Solis*  
on behalf of the ATLAS collaboration

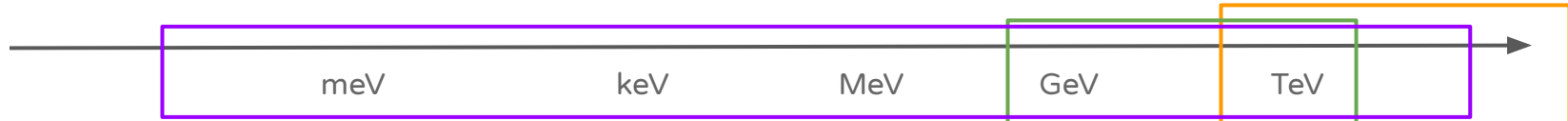
*LHCP 2023*  
*Belgrade, 22<sup>nd</sup> - 26<sup>th</sup> May 2023*



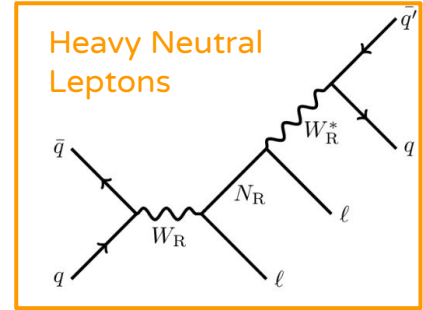
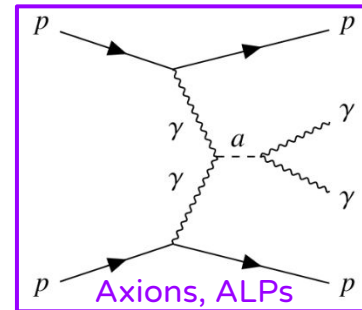
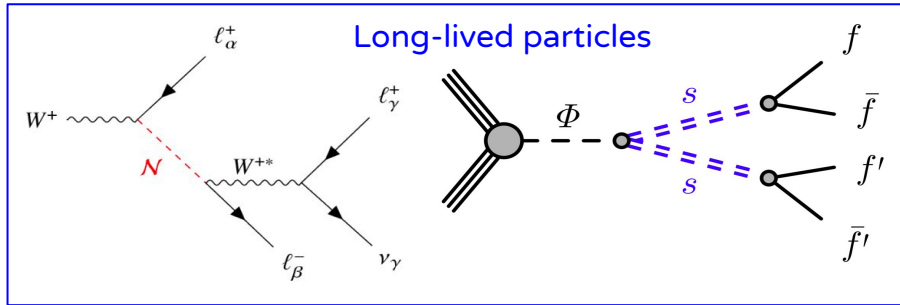
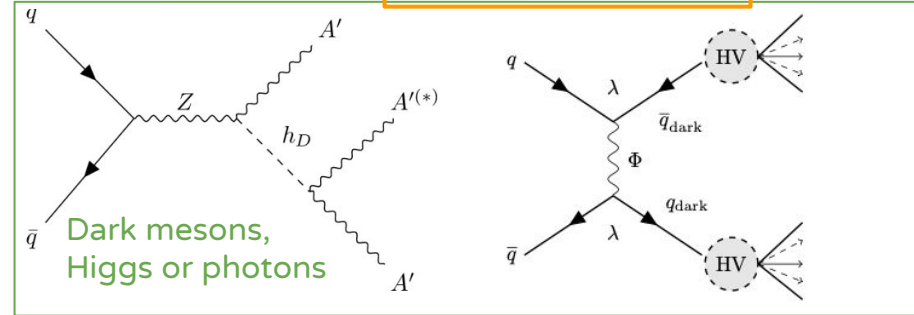
**HELMHOLTZ**  
RESEARCH FOR GRAND CHALLENGE



# Searches for feebly interacting particles



Powerful evidence of existence of non-baryonic matter from measurements  $\rightarrow$  Dark Matter  
 85% of all matter in the Universe  $\rightarrow$  However, nature and couplings are still unknown!  
 Some candidates interacting weakly with SM  $\rightarrow$  FIP  
 Signatures: resonances in wide mass range, semi visible jets,  $E_T^{\text{miss}}$ , multi-particle final states, long-lived particles



# Dark mesons: $\pi^\pm \pi^{\pm,0} \rightarrow t\bar{t}b/\bar{t}tbb$

New  
for  
LHCP

Dark sector might be strongly-coupled  $\rightarrow$  Dark hadrons

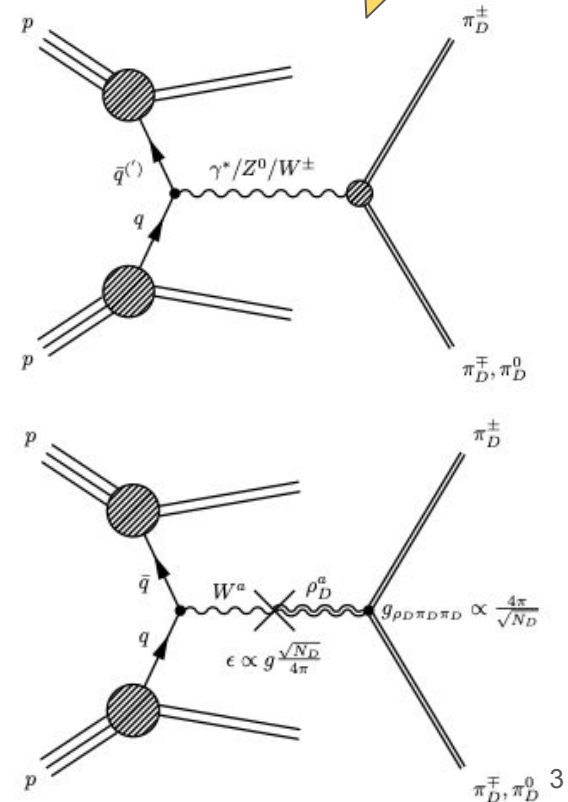
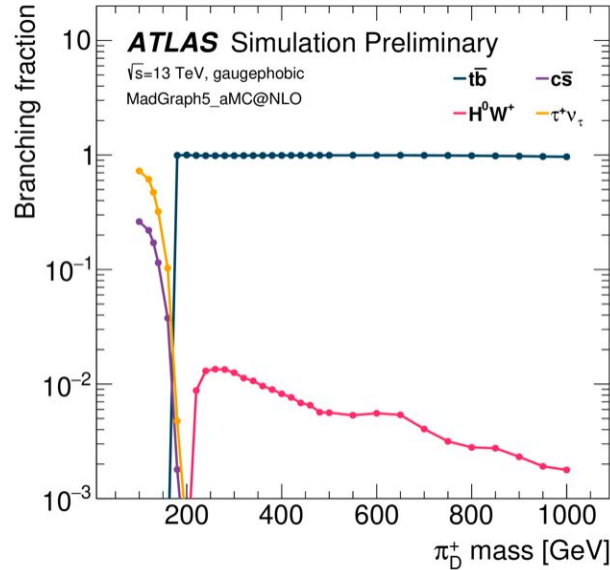
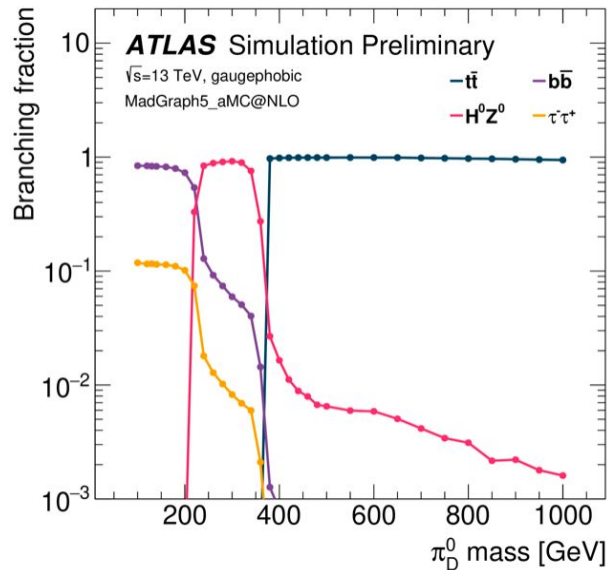
Stealth Dark Matter ([theory](#))  $\rightarrow$  vector-like fermions coupling to EWK SM sector

- Coupling with quarks, bosons and Higgs

Search for dark pions produced by SM bosons or dark rho ( $\eta = m_\pi/m_\rho < 0.5$ )

- Focusing on  $m_\pi$  between [300,600] GeV

First dedicated search for dark pions. Previous constraints from [reinterpretation](#)





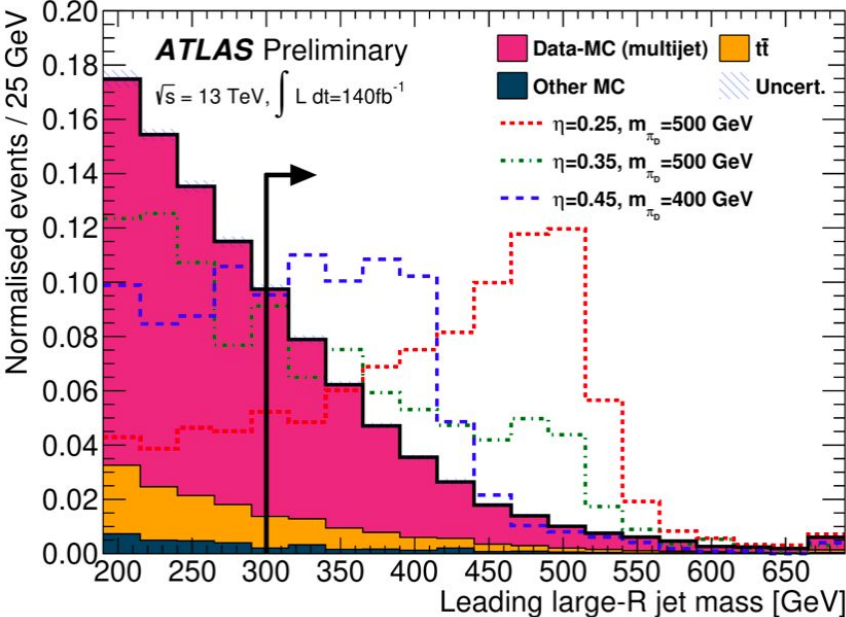
# Dark mesons: $\pi^\pm \pi^{\pm,0} \rightarrow t\bar{t}b/t\bar{t}bb$

Zero-lepton search: two  $R=1.2$  jets (reclustered from  $R=0.4$  jets), each with 2 overlapping  $R=0.4$  b-jets

Signal region divided in 9 bins in large-R jet mass.

Main background: multijet (data-driven)

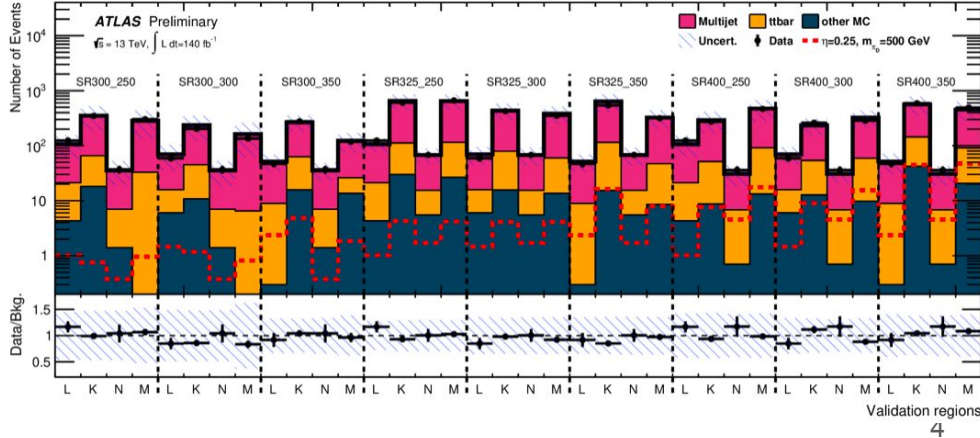
- Extended ABCD method: inversion of 4 variables.
- Validated in validation regions (VRs)



Leading large-R jet

	$\pi_{D,1} b b_1$	$\pi_{D,1} b \bar{b}_1$	$\pi_{D,1} b b_1$	$\pi_{D,1} b \bar{b}_1$
$\pi_{D,2} b b_2$	J	K	L	S
$\pi_{D,2} b \bar{b}_2$	B	D	H	N
$\pi_{D,2} b b_2$	E	F	G	M
$\pi_{D,2} b \bar{b}_2$	A	C	I	O

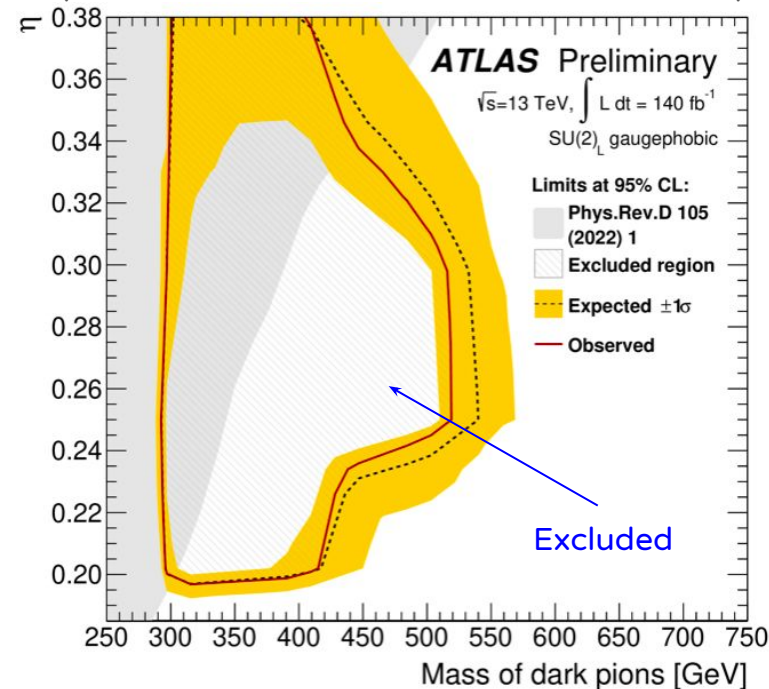
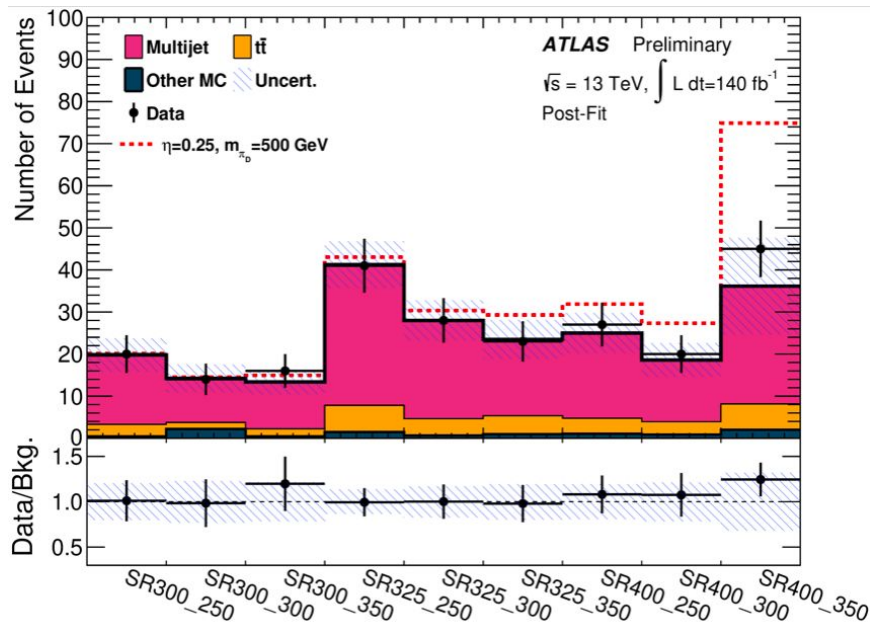
Sub-leading large-R jet



# Dark mesons: $\pi^\pm \pi^{\pm,0} \rightarrow t\bar{t}b/t\bar{t}b\bar{b}$

New  
for  
LHCP

Main uncertainties from QCD estimation (non-closure uncertainty evaluated on VRs and statistical uncertainty)  
Fit on 9 bins of signal region



No sign of dark mesons observed in this channel  $\rightarrow$  Extending sensitivity to low  $\eta$  values.

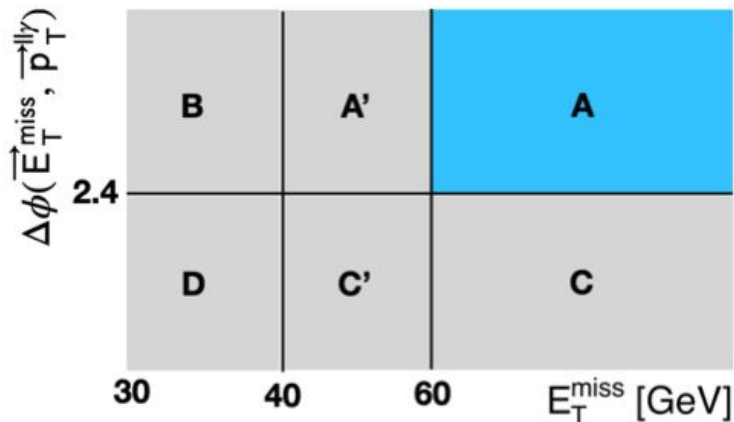
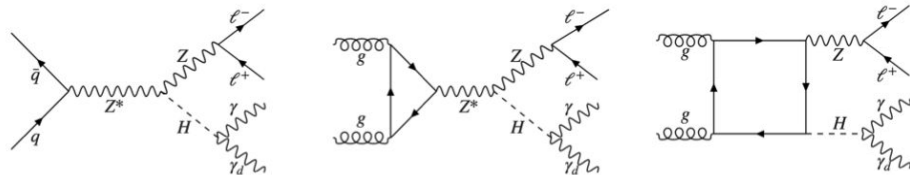


# Dark photon searches: $ZH \rightarrow \Upsilon\Upsilon_d$

Testing dark matter models with mixing of  $U(1)_D$  boson with SM photon  $\rightarrow$  dark photon.

Stable dark photon  $\rightarrow$  Signature  $E_T^{\text{miss}}$ .

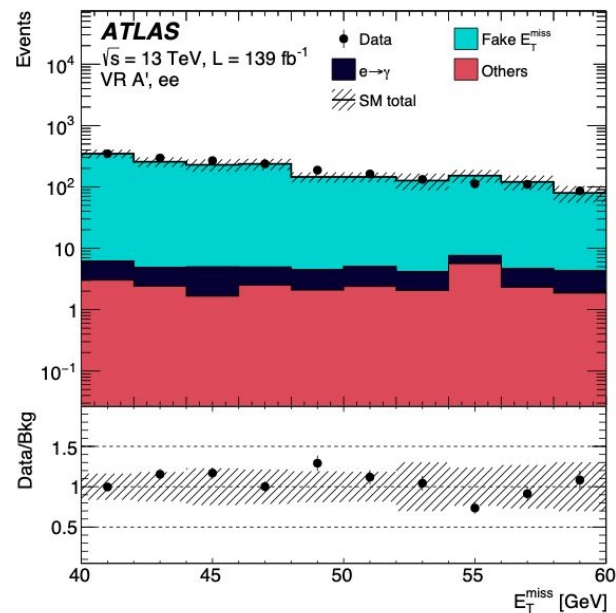
$ZH (\rightarrow \Upsilon\Upsilon_D)$  production  $\rightarrow Z(\rightarrow ll) + \Upsilon + E_T^{\text{miss}}$ .



Main backgrounds correspond to:

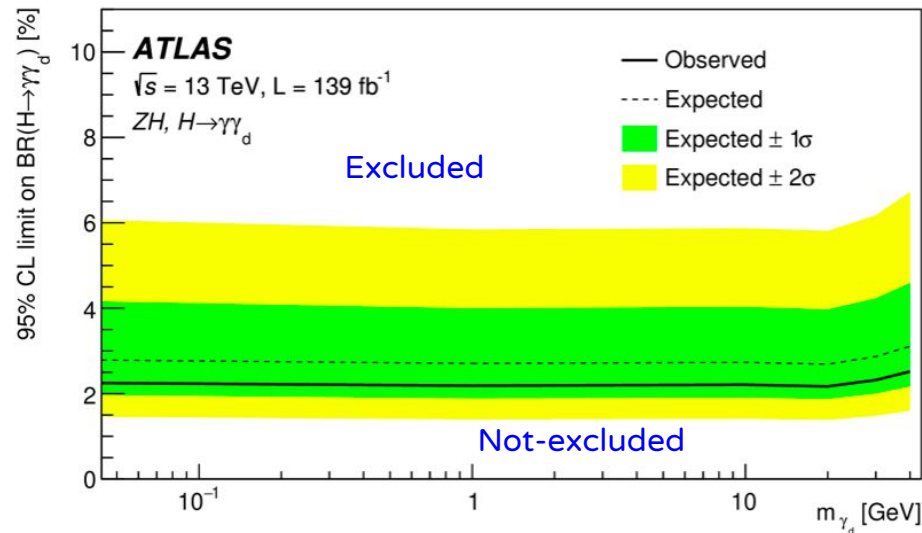
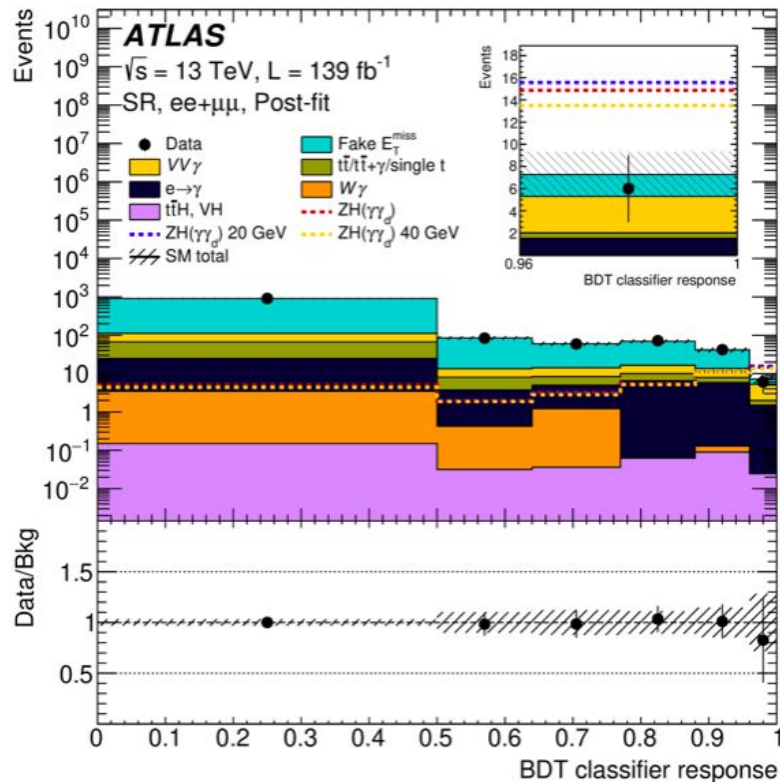
- Irreducible  $VV\Upsilon$  and top-background (control regions)
- $E_T^{\text{miss}}$  fake (data-driven, ABCD method)
- $e \rightarrow \Upsilon$  fakes (data-driven)

Dedicated validation regions separated in di-lepton flavours.



# Dark photon searches: $ZH \rightarrow \gamma\gamma_d$

Dominated by statistics, fake  $E_T^{\text{miss}}$  shape and jet uncertainties. Final fit to BDT distribution



$BR(H \rightarrow \gamma\gamma_d) < 2.28$  (2.82 expected) @95%CL for  $m(\gamma_d) = 0$

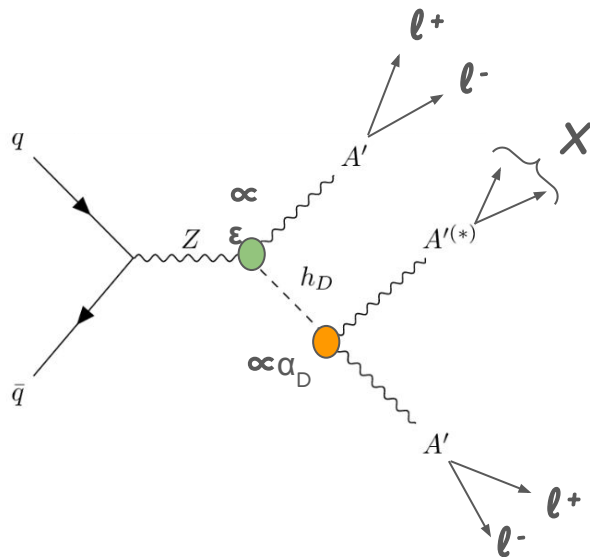
# Dark photons and Dark Higgs: rare Z decays

Models with dark photon connecting SM-DM sectors and dark Higgs mechanism ( $h_D$ )

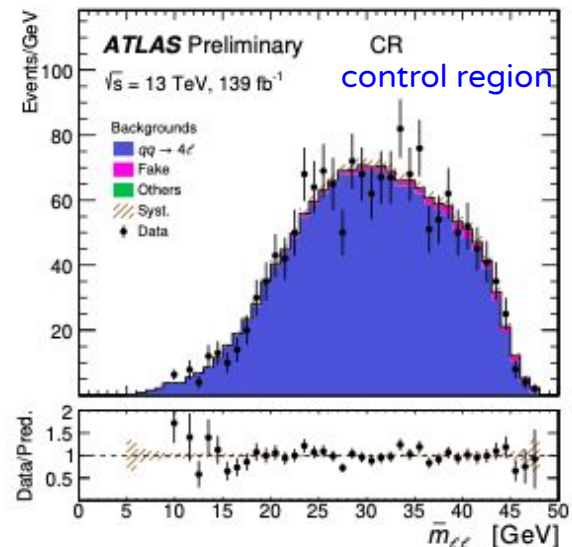
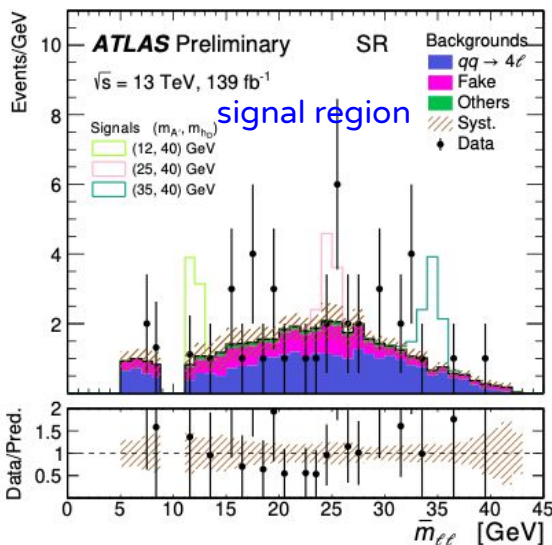
Search for Higgs-strahlung  $Z \rightarrow A' h_D$  decays  $\rightarrow$  sensitive to the dark photon ( $A'$ ) coupling to SM particles ( $\epsilon$ ) and the hidden sector ( $\alpha_D$ ).

- Focusing in  $m_Z > m_{A'} + m_{h_D}$

At least two on-shell  $A'$   
Focusing on  $A' \rightarrow \ell\ell$  decays ( $e\bar{e}, \mu\bar{\mu}$ ).



$$\bar{m}_{\ell\ell} = (m_{\ell_1\ell_2} + m_{\ell_3\ell_4})/2$$



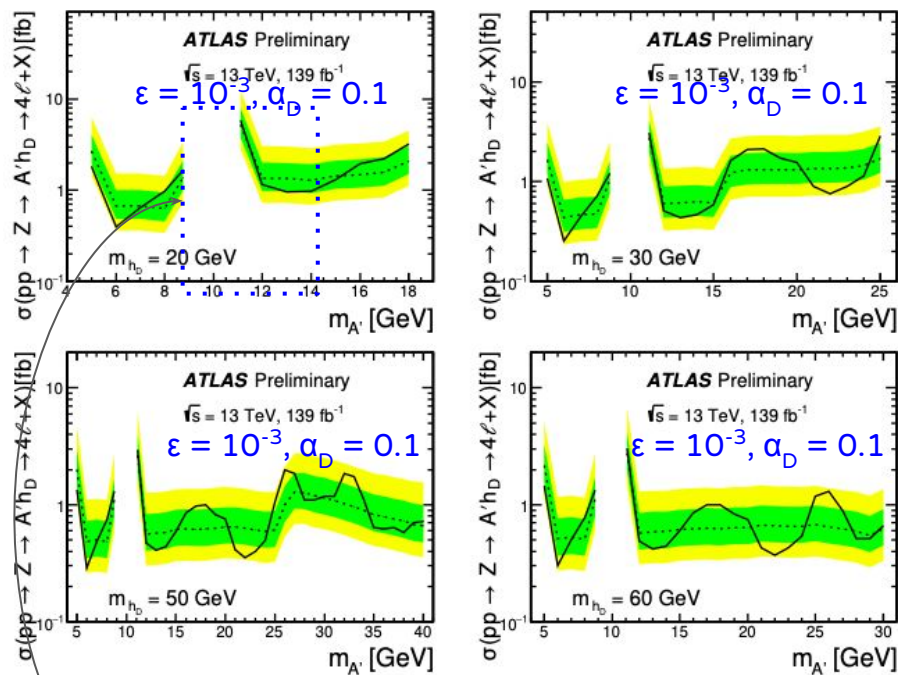
Main backgrounds:  $qq \rightarrow 4\ell$  (dedicated CR) and fakes from hadron decays:  $Z$ +jets, top-quark,  $WZ$ +jets (data-driven factors)



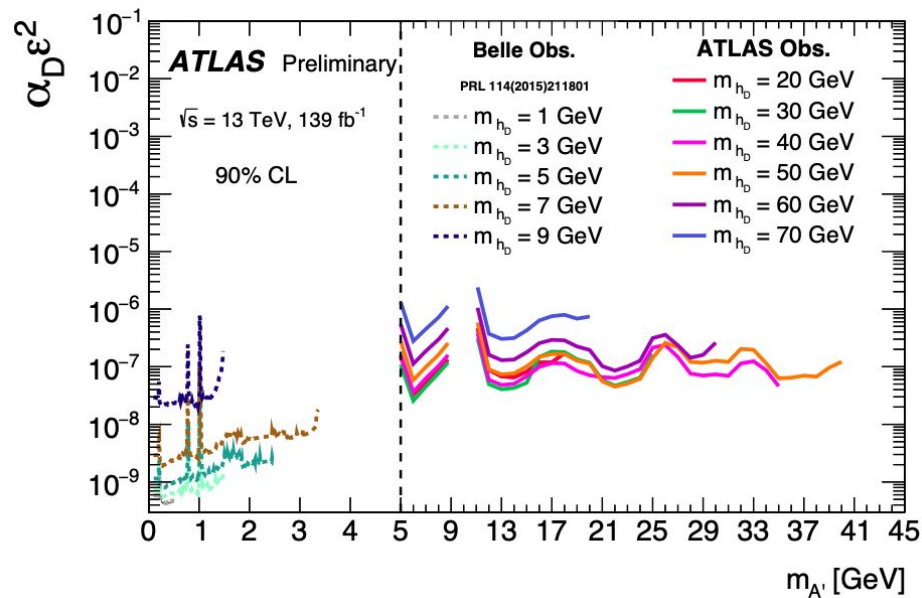
# Dark photons and Dark Higgs: rare Z decays

Limited by statistical uncertainties. Fit performed on average dilepton mass  $m(\ell\ell)$ .  
Focusing on  $m_{h_D} < 70$  GeV but  $m_{h_D} > m_{A'}$ .

$$\bar{m}_{\ell\ell} = (m_{\ell_1\ell_2} + m_{\ell_3\ell_4})/2$$



Veto on events with  $m(\ell\ell) - m(Y) < 0.75$



Complementarity between ATLAS and Belle-II

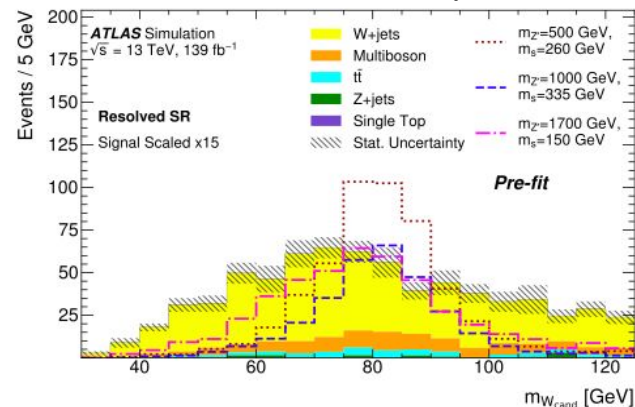
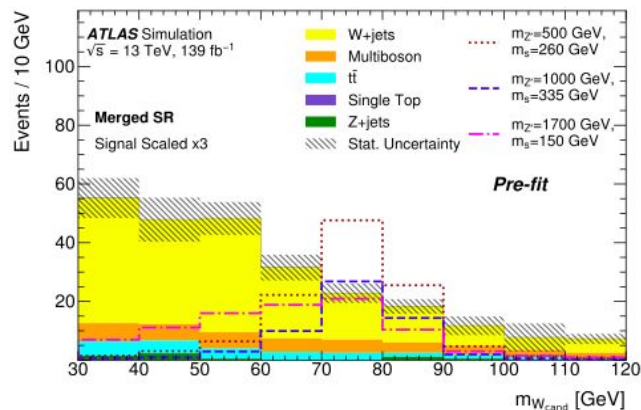
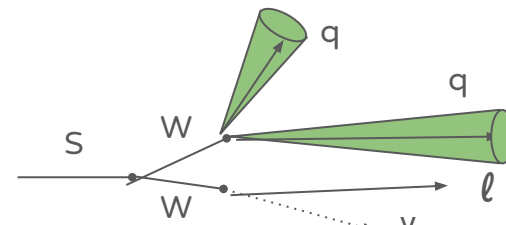
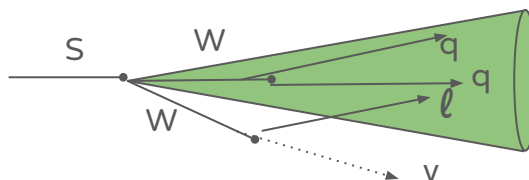
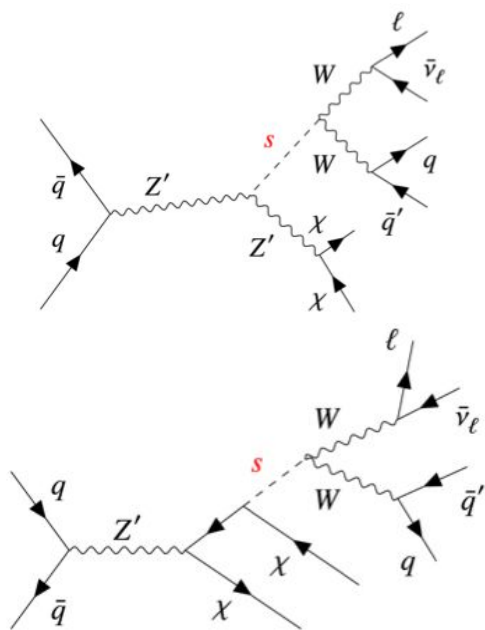
# Heavy Dark Higgs searches: $s \rightarrow WW$

Complementarily, other models predict dark Higgs bosons coupling to heavy mediators  $Z'$ .

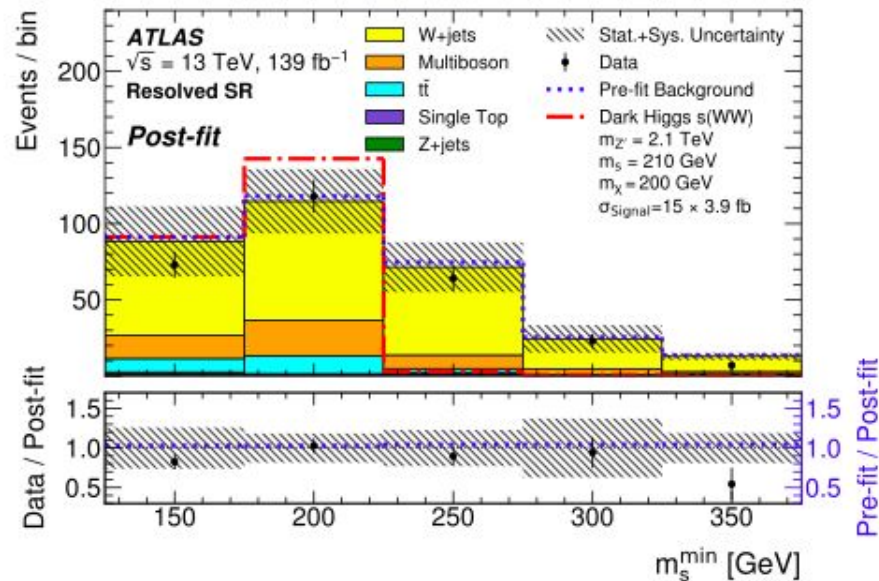
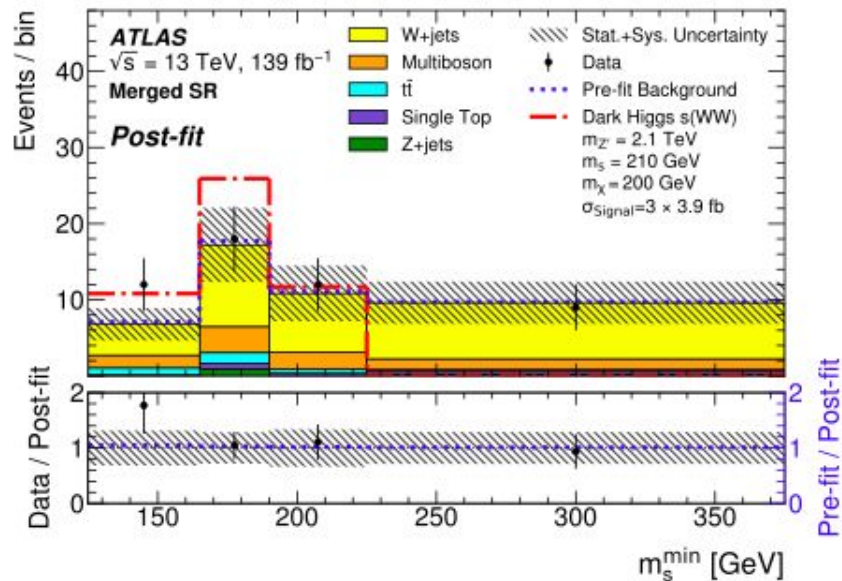
Dedicated searches in ATLAS in  $s \rightarrow W (\rightarrow \ell \nu) W (\rightarrow qq)$ . For large  $m_S$ , hadronic  $W$ -boson decays might be boosted

Merged cat. TAR R1.0 jet as  $W$ -cand  
Dedicated  $W$ -tagging for lepton overlap

Resolved cat.: two  $R=0.4$  jets



# Heavy Dark Higgs searches: $s \rightarrow WW$



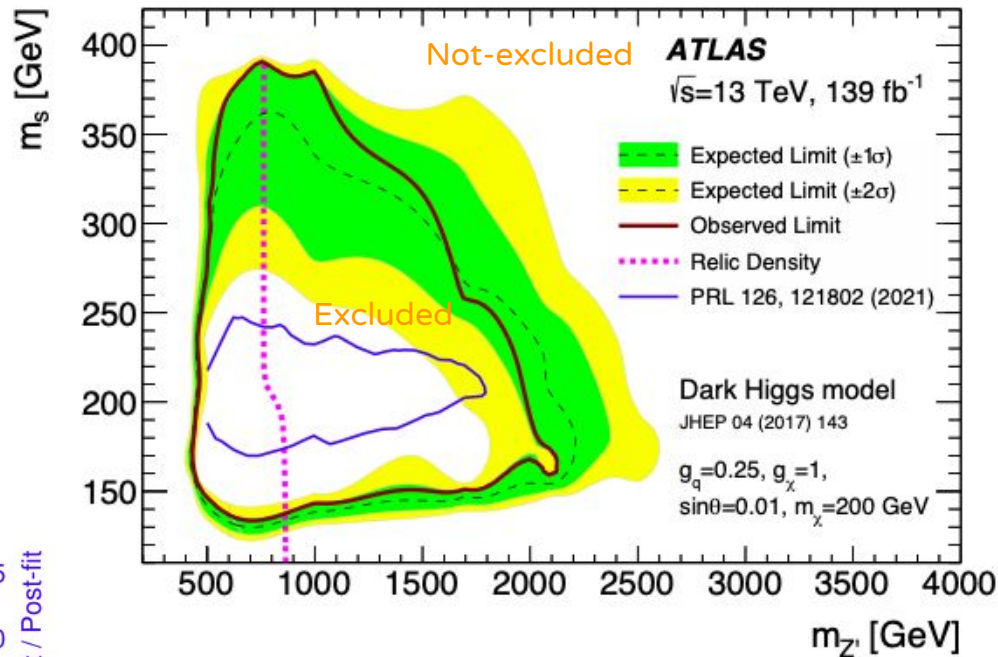
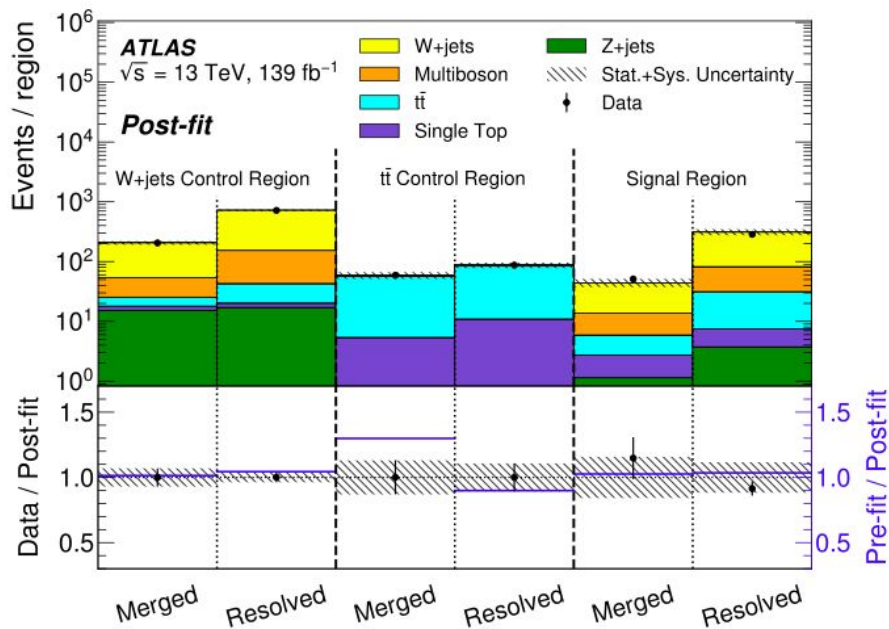
$$m_s^2 = \left( E_\ell + \frac{m_W^2}{2E_\ell(1 - \cos\theta_{\ell\nu})} + E_{W_{\text{cand}}} \right)^2 - \left( \left| \vec{p}_{W_{\text{cand}}} \right| \sin\theta_{W_{\text{cand}}\ell} + \frac{m_W^2 \sqrt{1 - \cos^2\theta_{\ell\nu}}}{2E_\ell(1 - \cos\theta_{\ell\nu})} \right)^2 - \left( E_\ell + \left| \vec{p}_{W_{\text{cand}}} \right| \cos\theta_{W_{\text{cand}}\ell} + \frac{m_W^2 \cos\theta_{\ell\nu}}{2E_\ell(1 - \cos\theta_{\ell\nu})} \right)^2,$$

Reconstruction of the invariant mass of the Dark Higgs.  
 Due to missing neutrino, final fit discriminant:  $m_s^{\text{min}}$ .

$$m_s^{\text{min}} \equiv \min(m_s).$$

# Heavy Dark Higgs searches: $s \rightarrow WW$

Dominant backgrounds  $W$ +jets and  $t\bar{t} \rightarrow CR$   
 Dominated by statistical uncertainties and jet energy uncertainties



Excluded  $m_s > 130 \text{ GeV}$  and  $m_Z < 2000 \text{ GeV}$   
 Great sensitivity improvement w.r.t  $s \rightarrow VV \rightarrow qqqq$   
 Constraints from  $bb + E_T^{\text{miss}}$  ( $m_s \sim 125 \text{ GeV}$ )

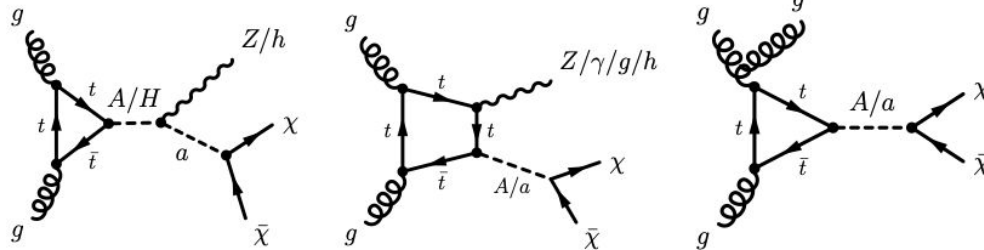


# WIMP DM searches: 2HDM+a model

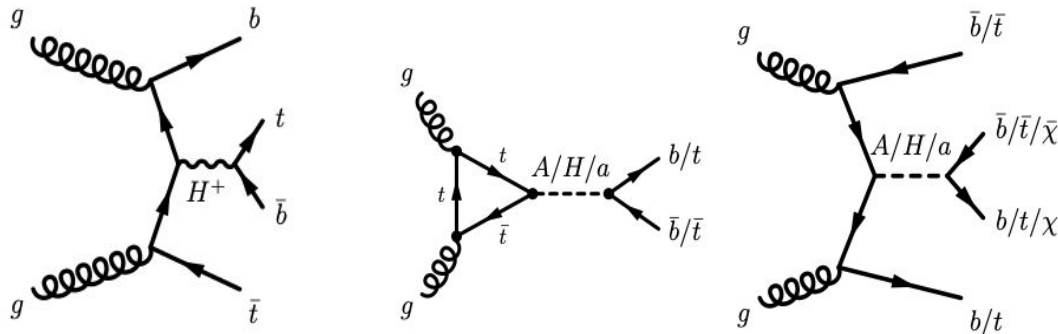
New  
for  
LHCP

Extended Higgs section connecting SM to DM sector: 2HDM+a  
Rich phenomenology in several final states at colliders.

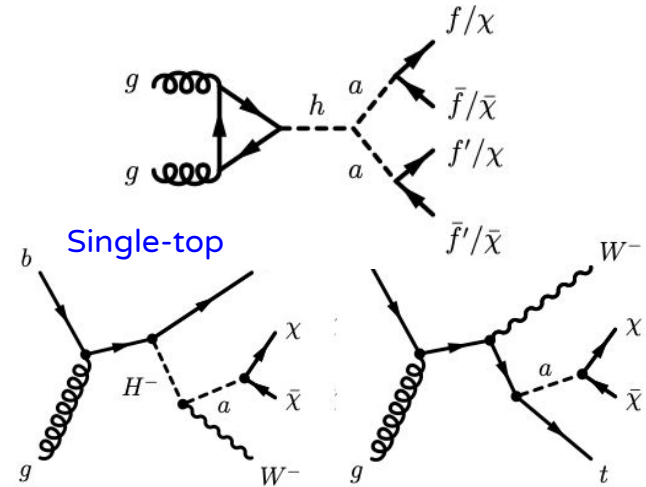
mono-H, mono-Z, mono-jet, mono- $\gamma$



tt, bb, multi-top, multi-b, charged Higgs



Low mass resonances



Important parameters

- $m_a, m_{A/H/H^\pm}, m_\chi$
- $\sin\theta$  (mixing  $a$ - $A$ )
- $\tan\beta = v_u/v_d$

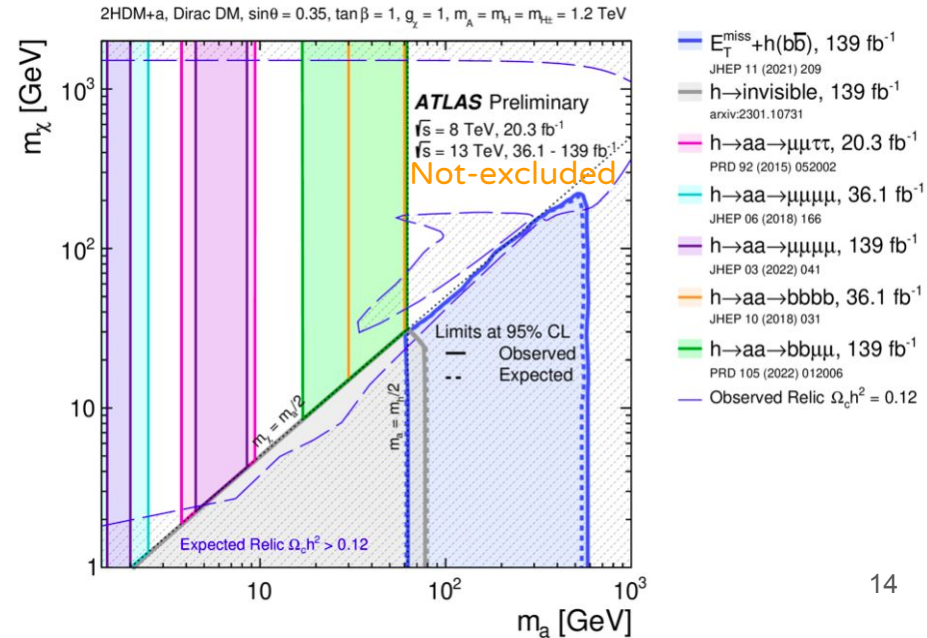
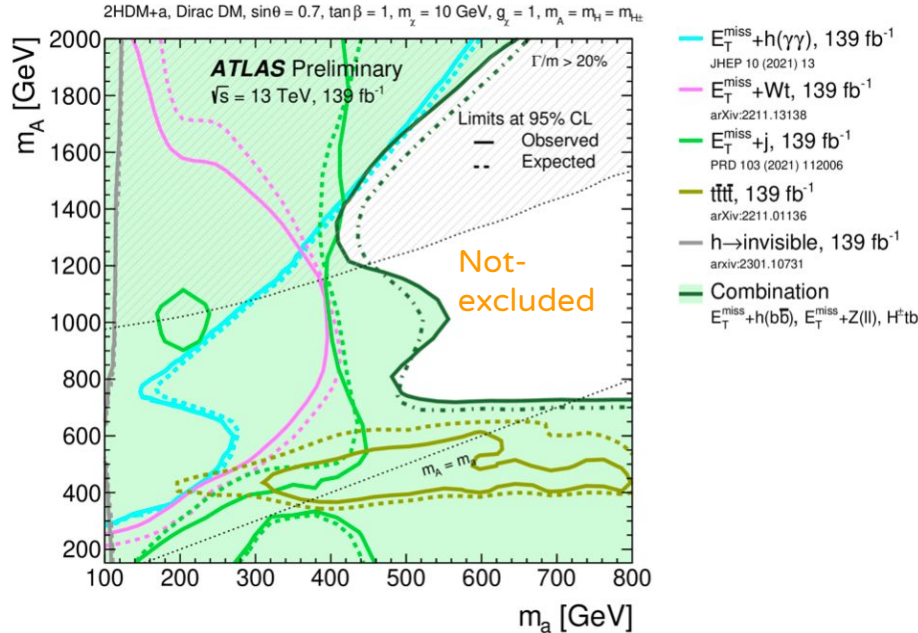


# WIMP DM searches: 2HDM+a model

New  
for  
LHCP

First statistical combination of mono-H ( $\rightarrow b\bar{b}$ ) + Mono-Z ( $\rightarrow \ell\bar{\ell}$ ) +  $tb \rightarrow H^\pm (\rightarrow t\bar{b})$  searches.  
Interpretation in planes defined by all relevant parameters

- Heavy Higgs bosons in 100 GeV - 2 TeV rejected for different combinations of parameters
- Including for the first time limits from  $h \rightarrow a\bar{a}$  searches. Rejecting various hypothesis with  $ma < 62.5$  GeV.



# Higgs portal: invisible Higgs combination

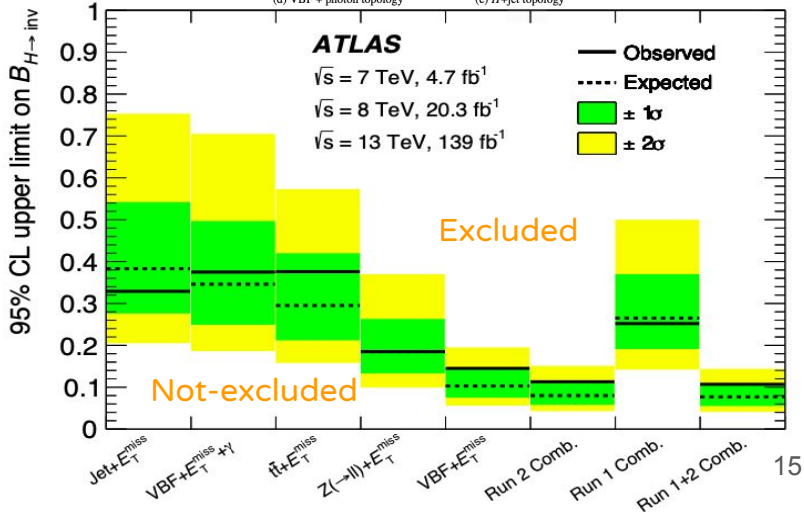
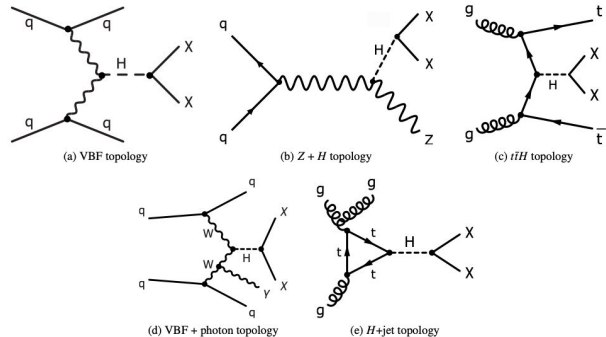
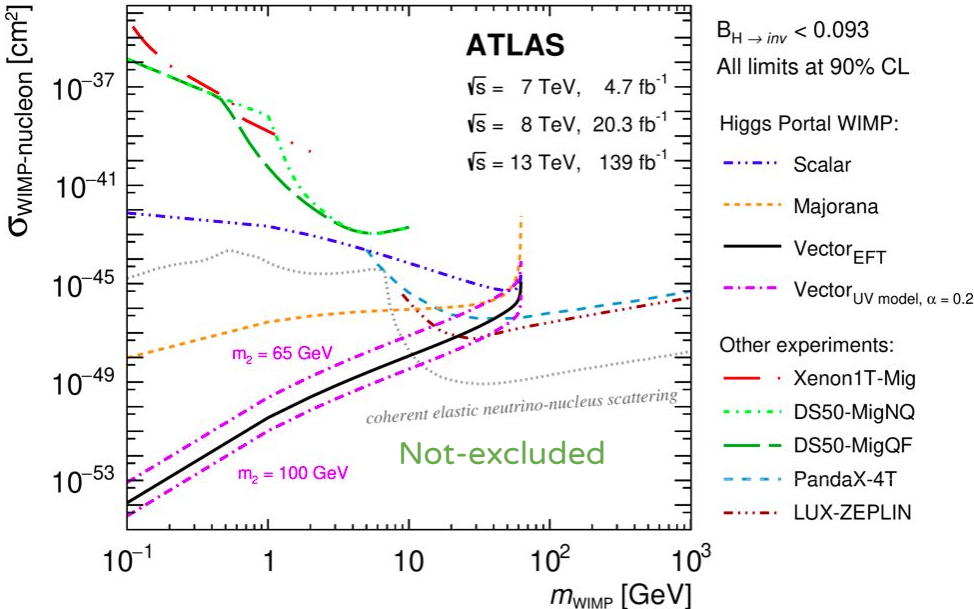
SM Higgs boson as the main connection with the dark sector →

**Higgs portal theories**

Statistical combination of Run-2 and Run-1+Run-2 analyses:

**observed BR( H → inv ) < 0.107 @ 95%CL !**

Limits also derived for WIMP-nucleon cross-section



# Conclusion

Run-2 has provided us with more and improved DM searches and seen the expansion of ATLAS research to more exotic topologies

Several searches presented today looking for feebly interacting particles composing dark sectors and/or connecting them to SM

No sign of new physics observed so far but a lot of phase space still available to search for.

LHC Run-3 started. New and exciting results await us. Stay tuned !



# Backup

# Dark photon searches: $ZH \rightarrow \gamma\gamma_d$

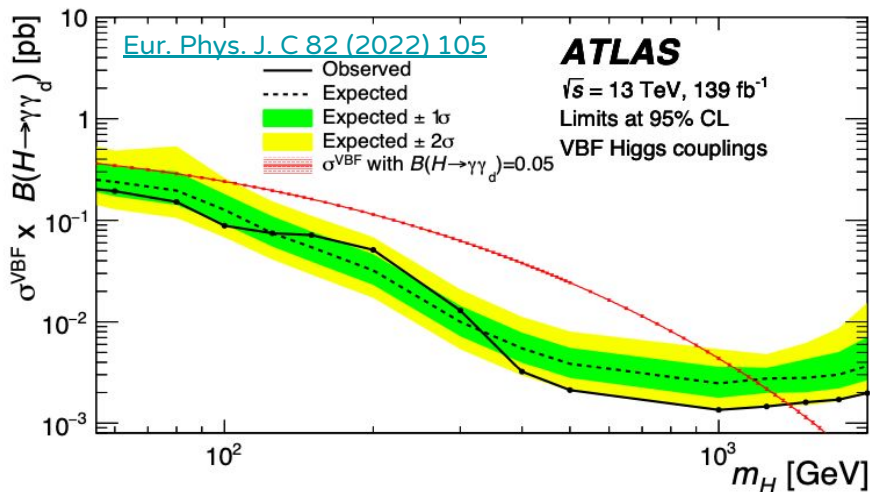
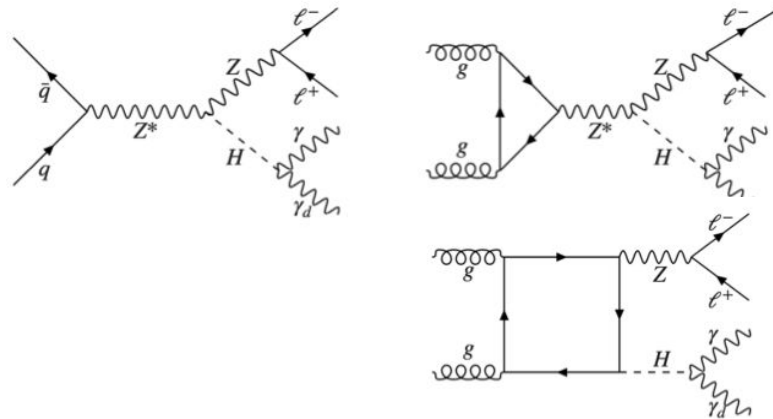
Testing dark matter models with mixing of U(1)<sub>D</sub> boson with SM photon  $\rightarrow$  dark photon.

Previous search in ATLAS looking at VBF production ( $\text{BR}(H \rightarrow \gamma\gamma_d) < 1.8\%$ ).

$\rightarrow$  Here, ZH production where  $Z \rightarrow \ell\ell$ .

Selection based on  $Z(\rightarrow \ell\ell) + \gamma + E_T^{\text{miss}}$ .

Signature of dark photon,  $E_T^{\text{miss}}$ . Assuming stable.



Two same flavour, opposite sign, medium ID and loose isolated leptons, with leading  $p_T > 27 \text{ GeV}$ , sub-leading  $p_T > 20 \text{ GeV}$

Veto events with additional lepton(s) with loose ID and  $p_T > 10 \text{ GeV}$

$76 \text{ GeV} < m_{\ell\ell} < 116 \text{ GeV}$

Only one tight ID, tight isolation photon with  $E_T^\gamma > 25 \text{ GeV}$

$E_T^{\text{miss}} > 60 \text{ GeV}$  with  $\Delta\phi(\vec{E}_T^{\text{miss}}, \vec{p}_T^{\ell\ell\gamma}) > 2.4 \text{ rad}$

$m_{\ell\ell\gamma} > 100 \text{ GeV}$

$N_{\text{jet}} \leq 2$ , with  $p_T^{\text{jet}} > 30 \text{ GeV}$ ,  $|\eta| < 4.5$

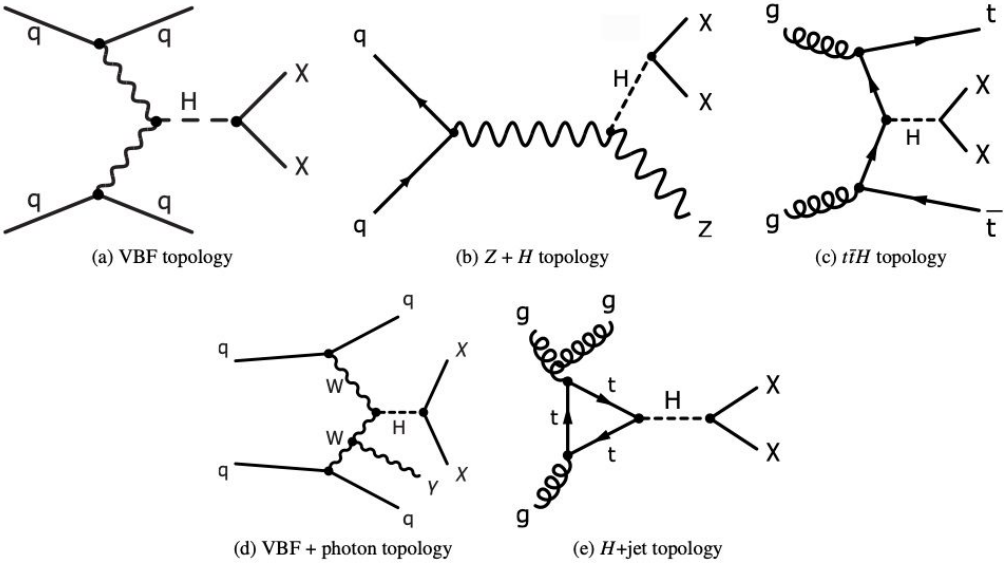
Veto events with  $b$ -jet(s)



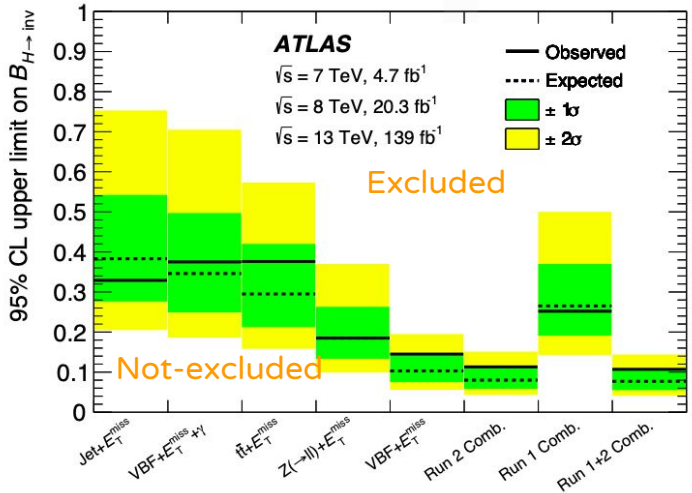
# Higgs portal: invisible Higgs combination

SM Higgs boson as the main connection with the dark sector → **Higgs portal theories**

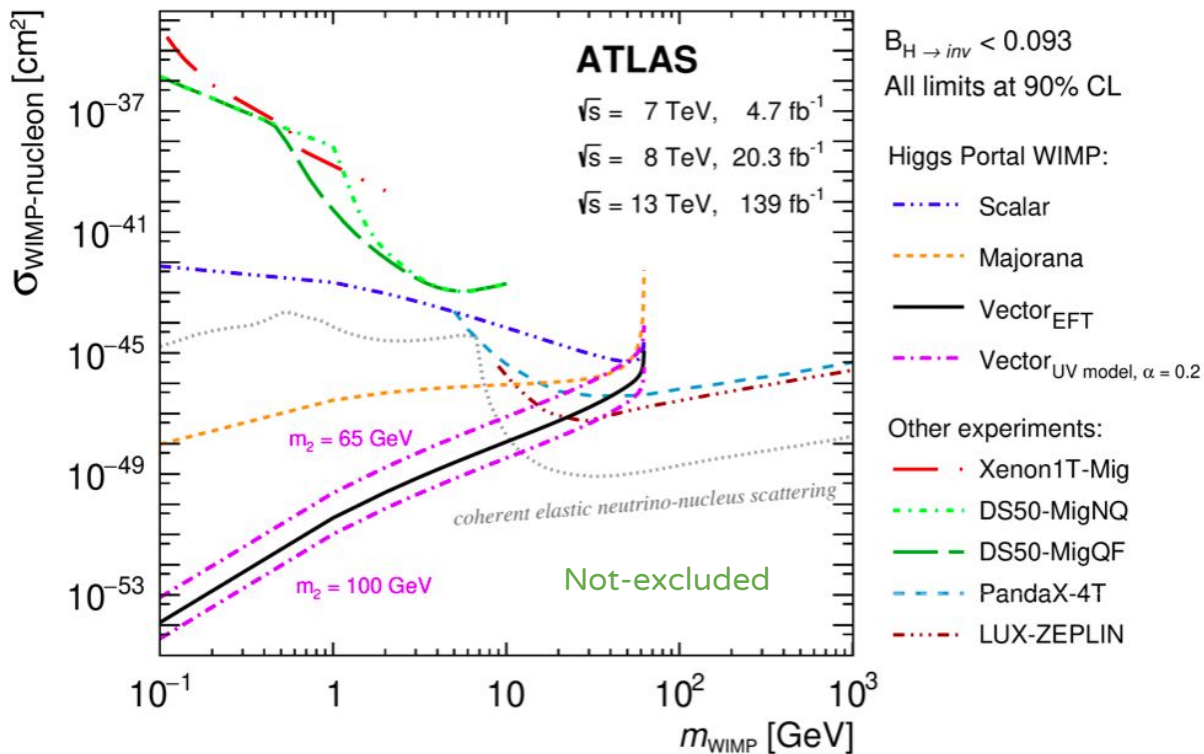
Statistical combination of Run-2 and Run-1+Run-2 analyses: **observed BR( H → inv) < 0.107 @ 95%CL !**



Analysis	Best fit $\mathcal{B}_{H \rightarrow \text{inv}}$	Observed 95% U.L.	Expected 95% U.L.
Jet + $E_T^{\text{miss}}$	$-0.09^{+0.19}_{-0.20}$	0.329	$0.383^{+0.157}_{-0.107}$
VBF + $E_T^{\text{miss}} + \gamma$	$0.04^{+0.17}_{-0.15}$	0.375	$0.346^{+0.151}_{-0.097}$
$t\bar{t} + E_T^{\text{miss}}$	$0.08 \pm 0.15$	0.376	$0.295^{+0.125}_{-0.083}$
$Z(\rightarrow \ell\ell) + E_T^{\text{miss}}$	$0.00 \pm 0.09$	0.185	$0.185^{+0.078}_{-0.052}$
VBF + $E_T^{\text{miss}}$	$0.05 \pm 0.05$	0.145	$0.103^{+0.041}_{-0.028}$
Run 2 Comb.	$0.04 \pm 0.04$	0.113	$0.080^{+0.031}_{-0.022}$
Run 1 Comb.	$-0.02^{+0.14}_{-0.13}$	0.252	$0.265^{+0.105}_{-0.074}$
Run 1+2 Comb.	$0.04 \pm 0.04$	0.107	$0.077^{+0.030}_{-0.022}$



# Higgs portal: invisible Higgs combination



Translation of limits into WIMP-nucleon cross-section and different DM particle hypotheses.