Dark Matter in ATLAS and CMS

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On behalf of the ATLAS and CMS Collaboration

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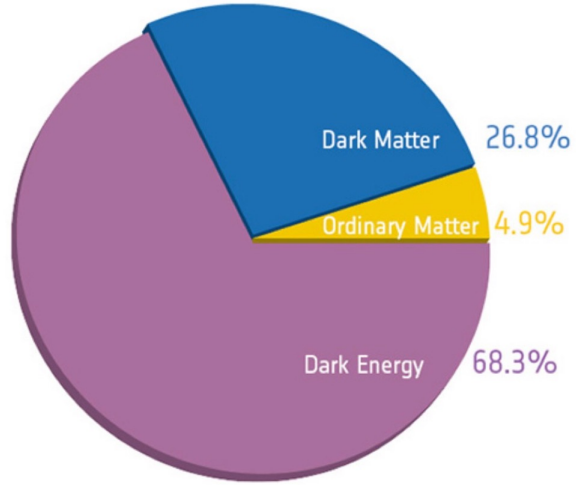
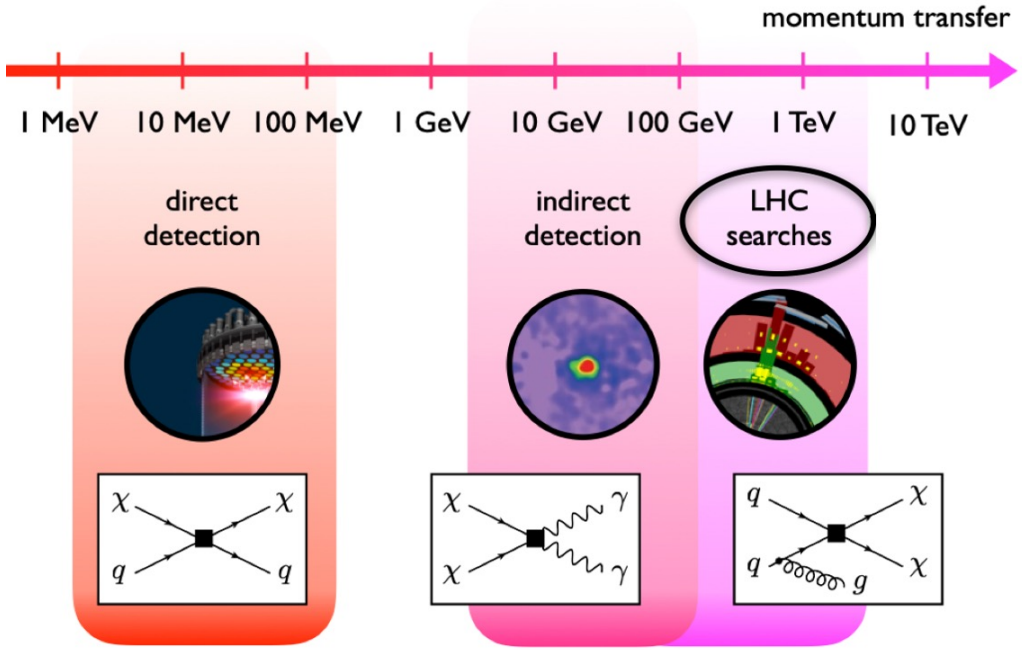
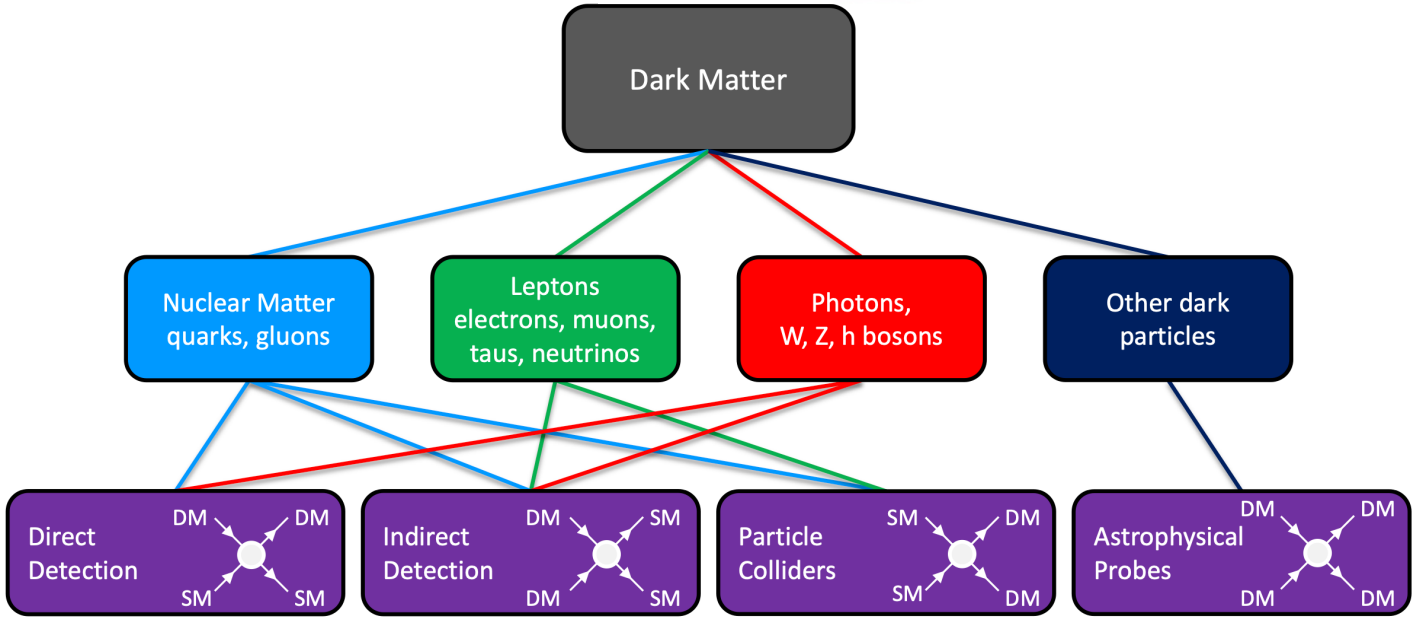
Introduction to Dark Matter

- Standard Model is the most accurate theory of particle physics, but some questions are still to be answered.
  - Gravity
  - Dark matter(DM)
  - Dark energy
  - Matter anti-matter asymmetry…
- Dark Matter is supported by many astrophysical measurements;
- Dark Matter is ~**5 times more** than ordinary matter.



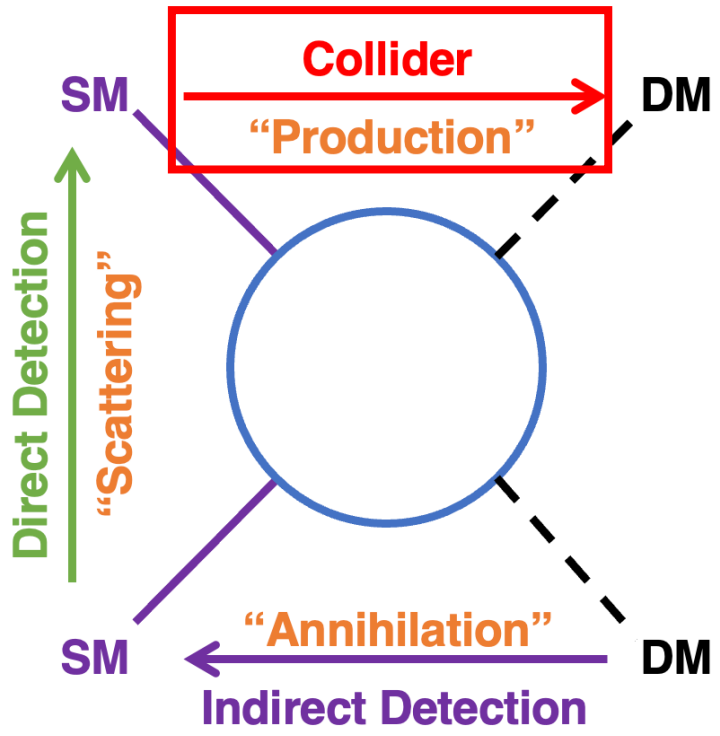




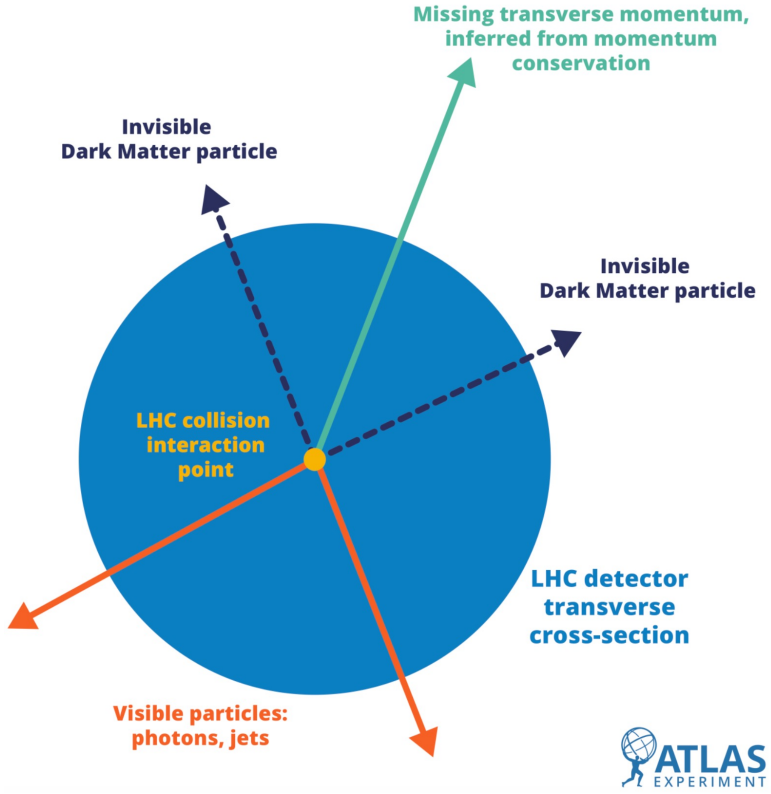
Dark Matter searches at the Large Hadron Collider

- With proton-proton collision at LHC and two largest detector ATLAS and CMS, dark matter could be produced from **interaction of SM particles** and be detected indirectly by its special **experimental signature** – **Missing transverse momentum (E_T^{miss})**.

DM production in collider experiments



Missing transverse momentum from LHC searches



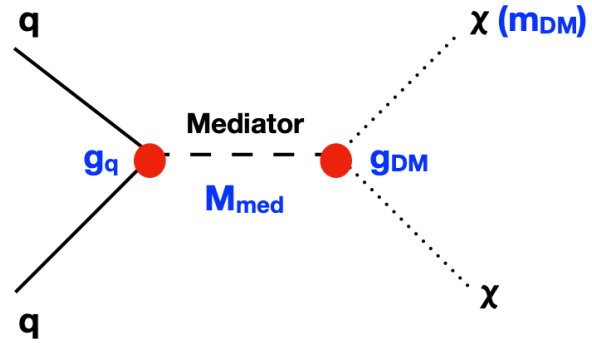
From Theodota Lagouri

Dark Matter models

- As there is no suitable DM candidate available in SM, two popular interpretations are considered for ATLAS and CMS DM searches

Simplified dark matter model

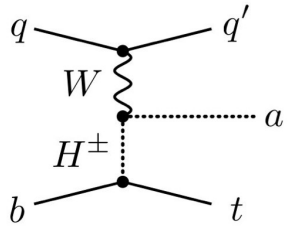
- Capture the essential features of DM signals through a minimal set of parameters.

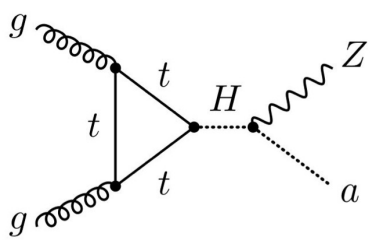


- Model parameters:
  - Spin/parity of the mediator
  - M_{med}-Mediator mass
  - m_{DM}-DM mass
  - g_{DM}-Mediator coupling to quarks
  - g_q-Mediator coupling to DM

2HDM+a

- Less simplified model.
- Exist more rich dynamics and interactions.





- Fully defined by 14 parameters:

$$v, m_h, m_A, m_H, m_{H^\pm}, m_a, m_\chi$$
$$\cos(\beta-\alpha), \tan\beta, \sin\theta$$
$$y_\chi, \lambda_3, \lambda_{P1}, \lambda_{P2}$$

- **5 remain unconstrained** with EWK and flavour constraints
  - $m_A = m_H = m_{H^\pm}$ - masses of heavy Higgs
  - m_a - mass of pseudo-scalar mediator
  - m_χ - DM mass
  - $\sin\theta$ – Mixing angle between CP-odd stats a and A
  - $\tan\beta$ – Ratio of 2 Higgs doublet VEVs

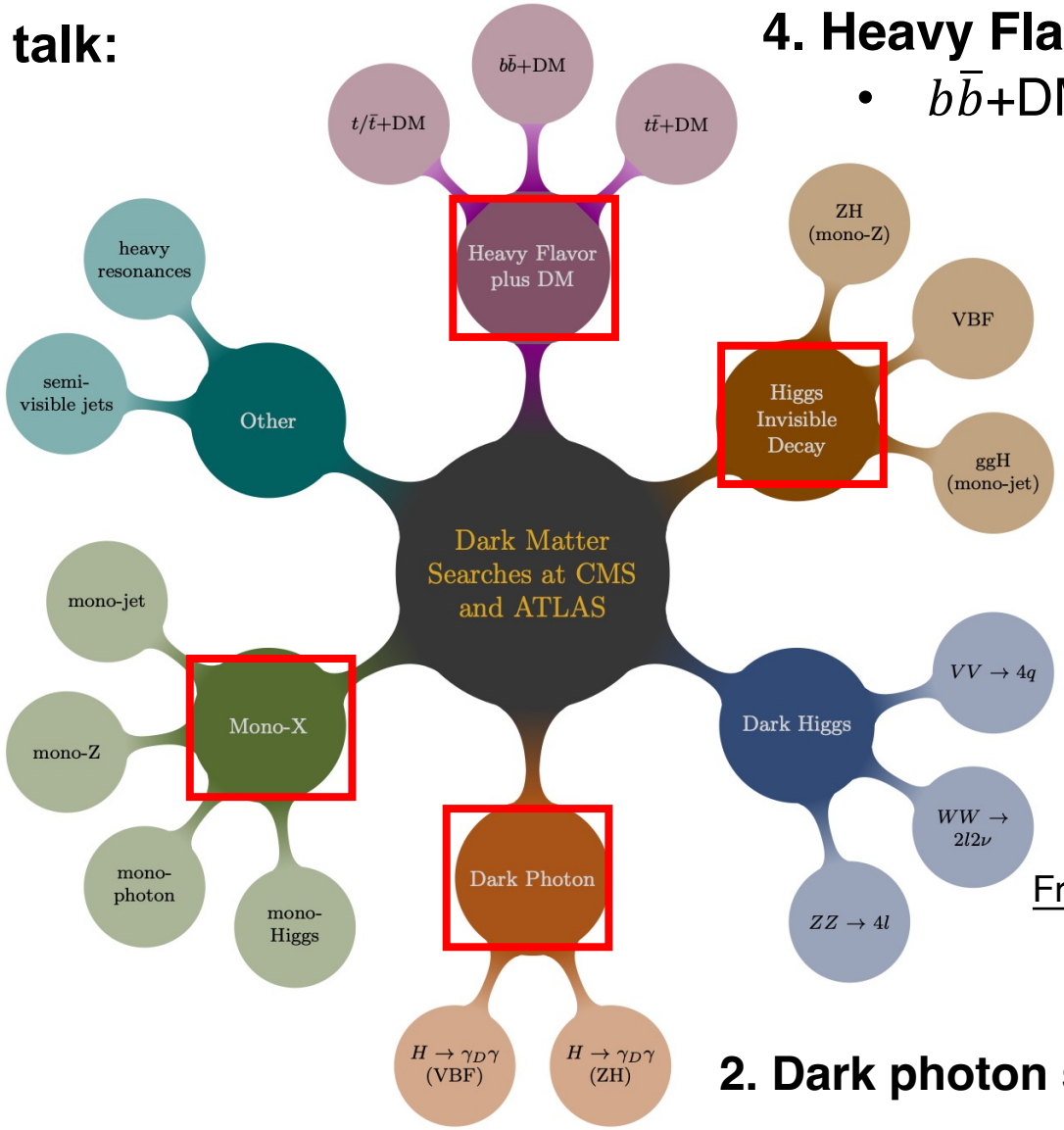
Dark matter searches at ATLAS and CMS

From Danyer Perez Adan

Dark matter searches at ATLAS and CMS

Topics introduced in this talk:

1. Mono-X searches
- Mono-top
- Mono-V
- Mono-Jet



4. Heavy Flavour + DM
- $b\bar{b}$+DM

3. Higgs invisible decay

From Danyer Perez Adan

2. Dark photon searches

Dark matter searches at ATLAS and CMS

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1. Mono-X searches
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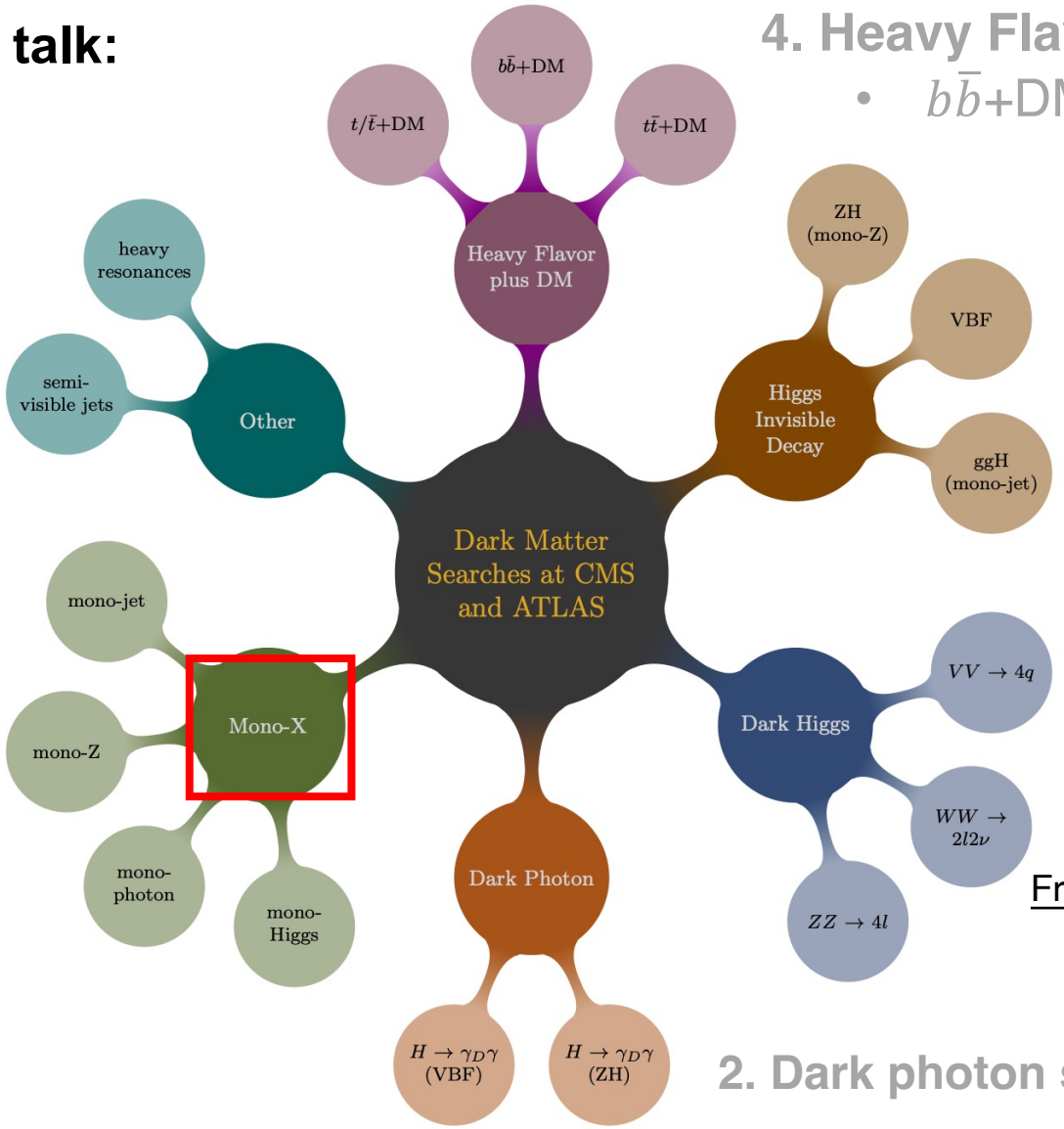

4. Heavy Flavour + DM
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From Danyer Perez Adan

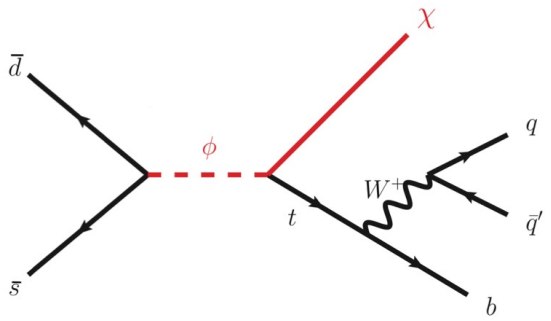
2. Dark photon searches

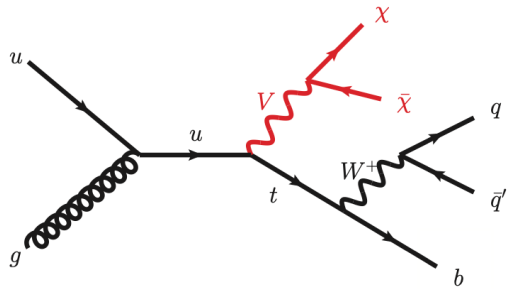
Mono-X searches: Mono-Top

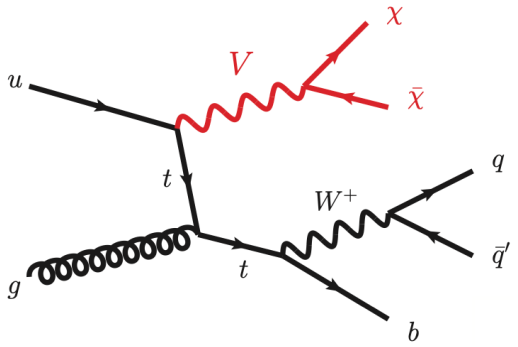
ATLAS:[arXiv:2402.16561]
CMS-PAS-SUS-23-004

- Experimental signature: MET + top-tagged jet
- Only consider hadronic top quark decay
- At tree level, the mono-top could be produced via flavour-changing neutral current (FCNC)

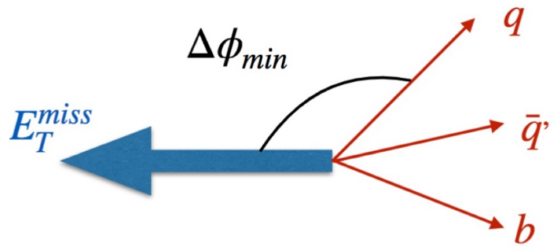
ATLAS Scalar-mediator | Vector-mediator **CMS**







- Large $\Delta\phi_{min}(\mathrm{MET}, \mathrm{jet}\ p_T)$ to reduce QCD backgrounds.
- Main backgrounds: V(W/Z)+jets and $t\bar{t}$

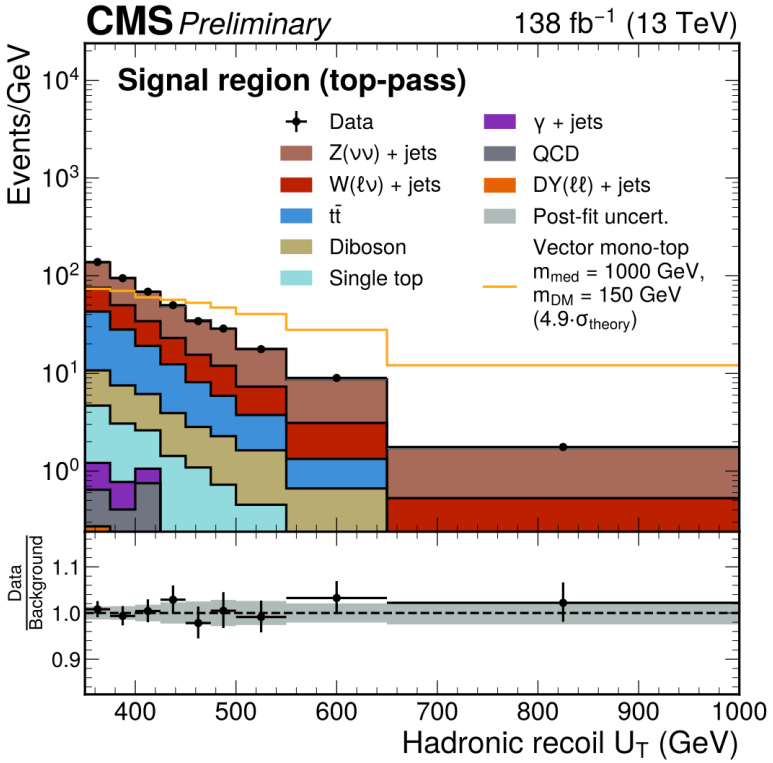


Mono-X searches: Mono-Top

ATLAS:[arXiv:2402.16561]
CMS-PAS-SUS-23-004

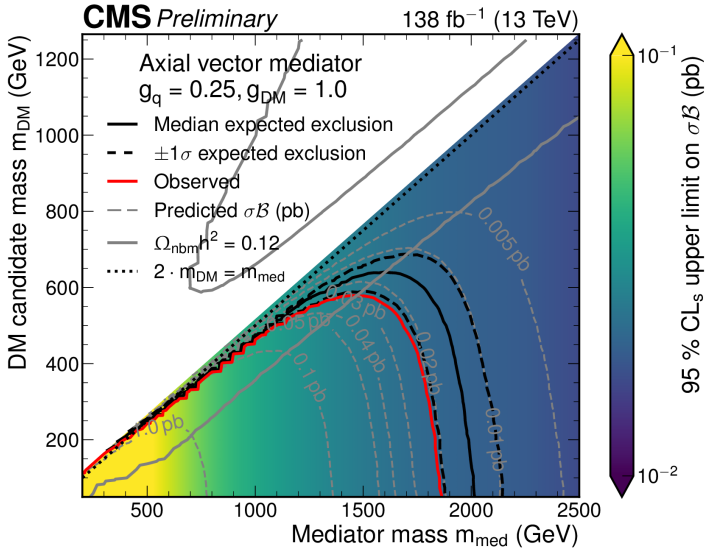
- The observable - hadronic recoil U_T is defined as $\overrightarrow{U_T} = \vec{p}_T^{miss} + \sum_i \vec{p}_{T,i}$
- The major backgrounds in the SRs are estimated using orthogonal data in the CRs.
- The minor backgrounds are all determined from simulation.
  - Single top quark, diboson and QCD multijet production

Post-fit plots with vector-mediator

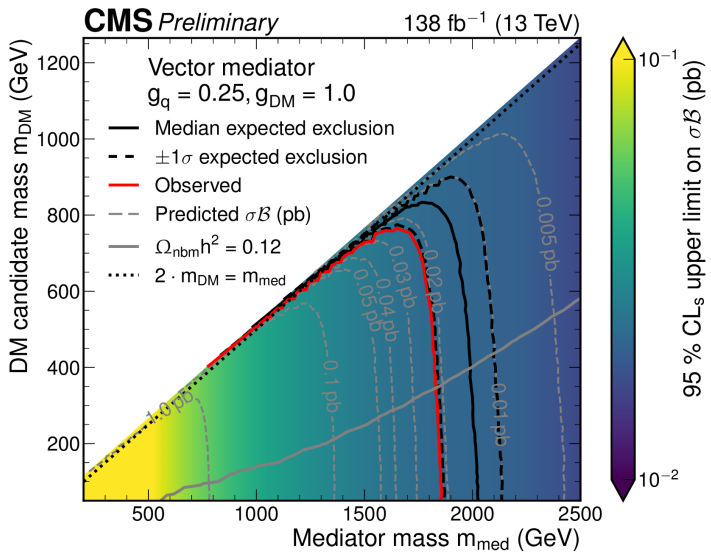


Regions exclude in $(m_{DM}, m_{\phi/V})$ space

Axial vector mediator



Vector mediator



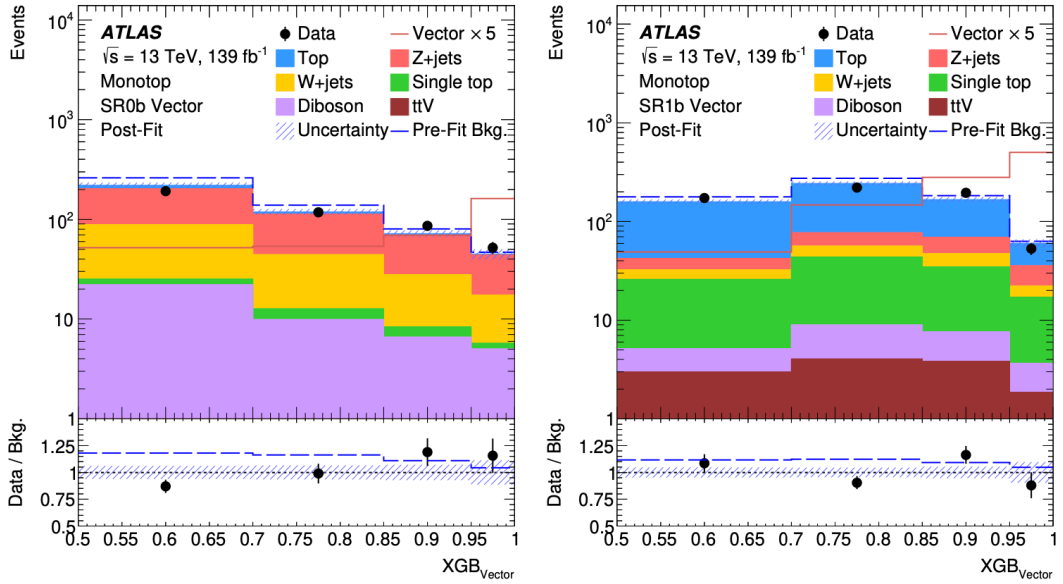
- Most stringent exclusion limits for (axial) vector coupled dark matter production via an up-top FCNC to date.

Mono-X searches: Mono-Top

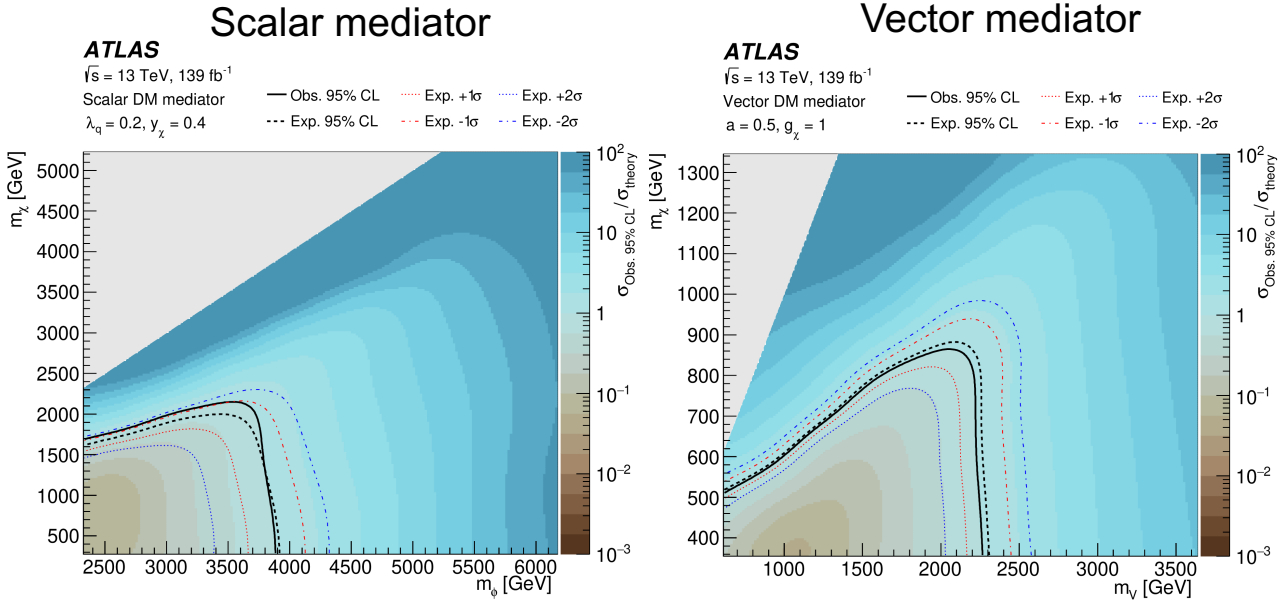
ATLAS:[arXiv:2402.16561]
CMS-PAS-SUS-23-004

- Signal regions are defined to maximize the discovery potential.
- Extreme gradient-boosted (XGBoost) decision tree (BDT) to enhance the signal discrimination against the SM background.
- No significant excess above the SM expectation is found in any of the SRs.

Post-fit plots with vector-mediator



Regions exclude in $(m_{DM}, m_{\phi/V})$ space

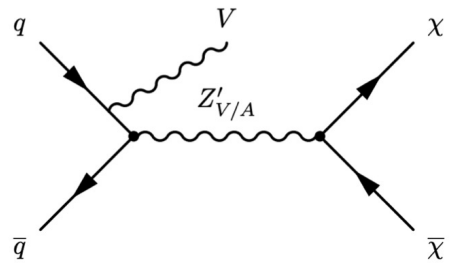


- With couplings $\lambda_q = 0.6$ and $y_\chi = 0.4$, excluding scalar DM mediator masses up to 4.3 TeV,
- With couplings $\mathrm{a} = 0.5$ and $g_\chi = 1$, excluding vector DM mediator masses up to 2.3 TeV

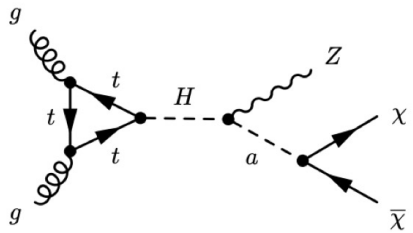
Mono-X searches: Mono-V(W/Z)jets

ATLAS: [arXiv: 2406.01272]

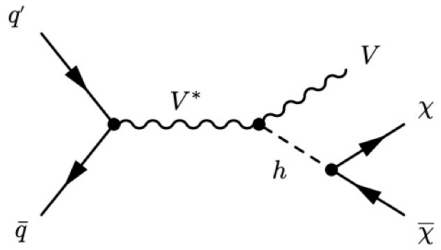
- Experimental signature: V(W/Z, had) + MET



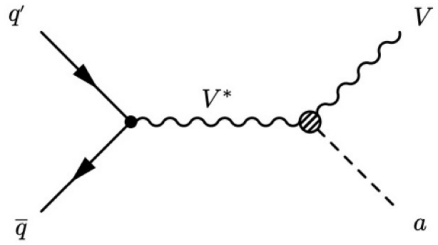
Simplified Dark Matter model with a vector or axial-vector mediator



Two-Higgs-doublet model with a pseudoscalar



Invisible decaying Higgs boson



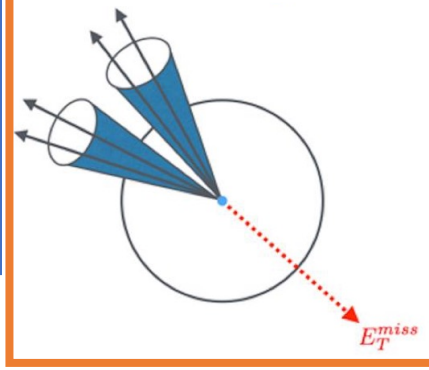
ALP (Axion-Like Particles)

- Two different topologies are considered depending on Lorentz boost of the vector boson
  - The jets move closer together with increasing *V* momentum

Pre-selection

$$p_{\mathrm{T},\ell}^{\mathrm{miss}} > 30\,\mathrm{GeV}$$
$$\min_i(\Delta\phi(\boldsymbol{E}_{\mathrm{T},\ell}^{\mathrm{miss}}, j_i)) > 20°$$
$$\Delta\phi(\boldsymbol{E}_{\mathrm{T},\ell}^{\mathrm{miss}}, \boldsymbol{p}_{\mathrm{T},\ell}^{\mathrm{miss}}) < 90°$$

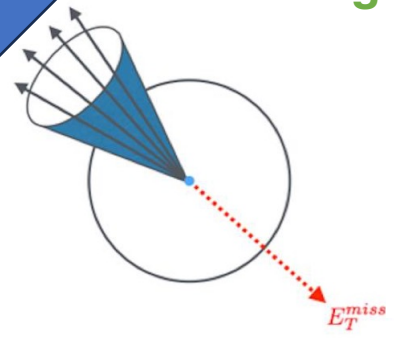
Resolved regime



$$\Delta\phi(\boldsymbol{E}_{\mathrm{T},\ell}^{\mathrm{miss}}, j_1 j_2) > 120°$$
$$> 200\,\mathrm{GeV}$$
$$\geq 2j;\ \leq 4j$$
$$p_{\mathrm{T}}^{j_1} > 45\,\mathrm{GeV}$$
$$\textstyle\sum_i p_{\mathrm{T}}^{j_i} \geq 120\,(150)\,\mathrm{GeV}\ \text{for}\ 2j\ (\geq 3j)$$
$$\Delta\phi(j_1, j_2) < 140°;\ \ \Delta R(j_1, j_2) < 1.4$$
$$m_{j_1 j_2} \in [65, 105]\,\mathrm{GeV}$$

P_T increasing

Merged regime



$$\Delta\phi(\boldsymbol{E}_{\mathrm{T},\ell}^{\mathrm{miss}}, J_1) > 120°$$
$$> 250\,\mathrm{GeV}$$
$$\geq 1J;\ \leq 4j$$
$$p_{\mathrm{T}}^{J_1} > 200\,\mathrm{GeV}$$
b-tagged track jet veto outside J_1

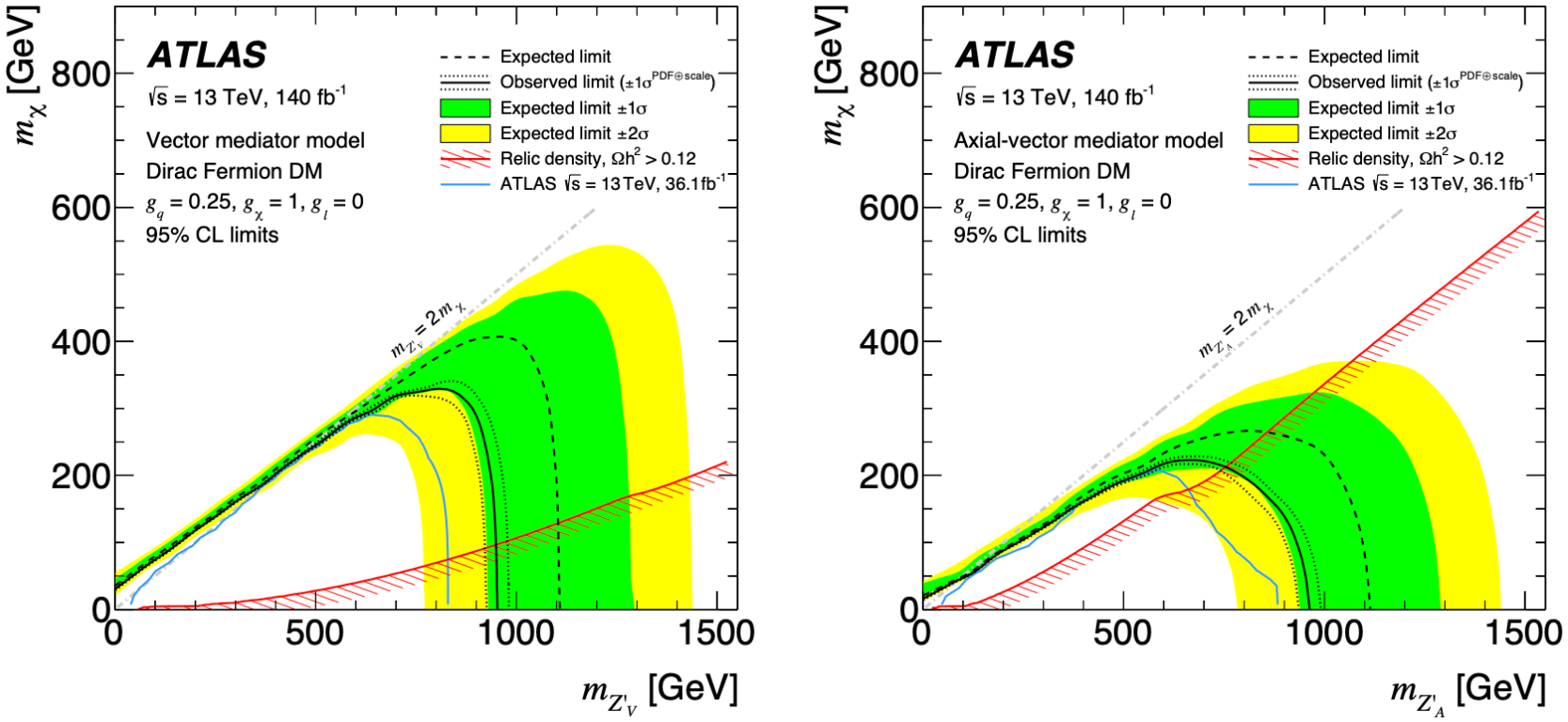
- Main backgrounds: W($l\nu$)/Z ($\nu\nu$)+jets, di-boson and $t\bar{t}$

Mono-X searches: Mono-V(W/Z)jets

ATLAS: [arXiv: 2406.01272]

Simplified DM model

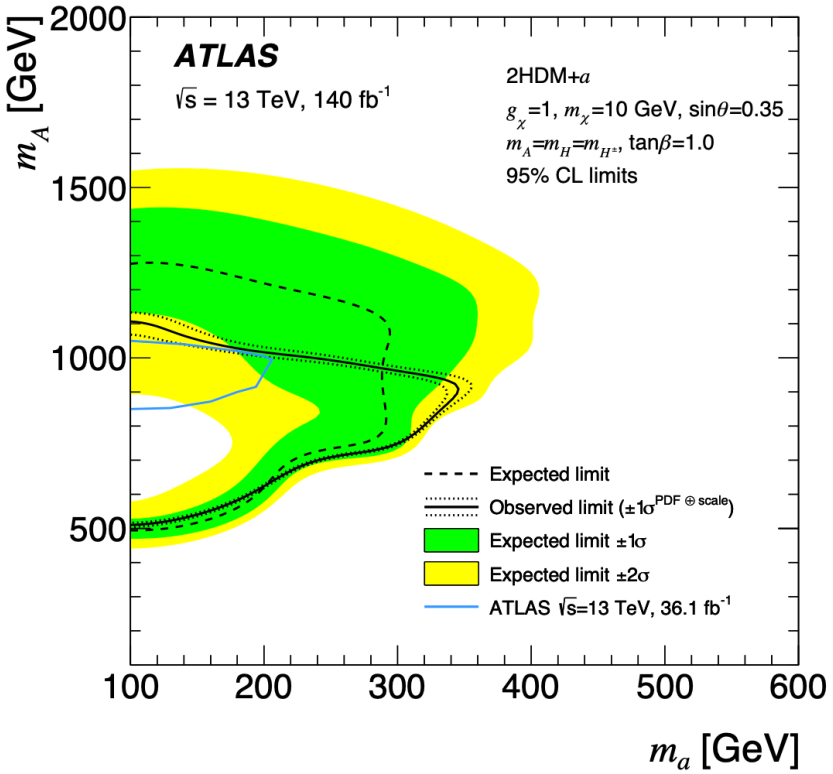
- Exclusion contours at 95% CL on the DM and mediator masses in the simplified DM model

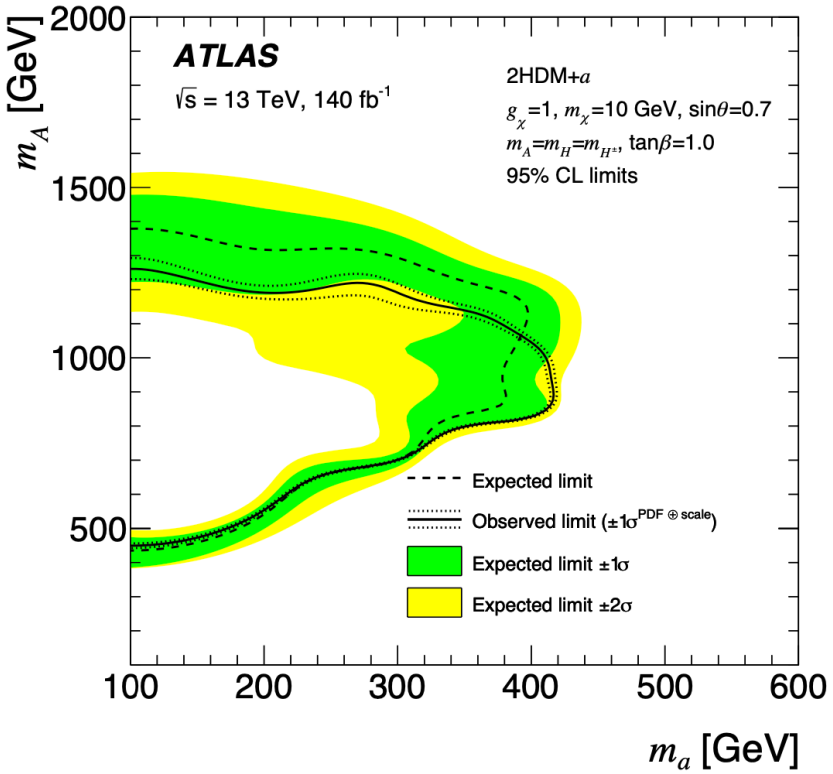


- For the **vector mediator model**, masses up to 955 GeV are excluded for m_χ = 1 GeV.
- For the **axial-vector mediator model**, masses up to 965 GeV are excluded for m_χ = 1 GeV.

2HDM + a model

- The exclusion contours in the m_A–m_a scans with **sinθ = 0.35** and **sinθ = 0.7**



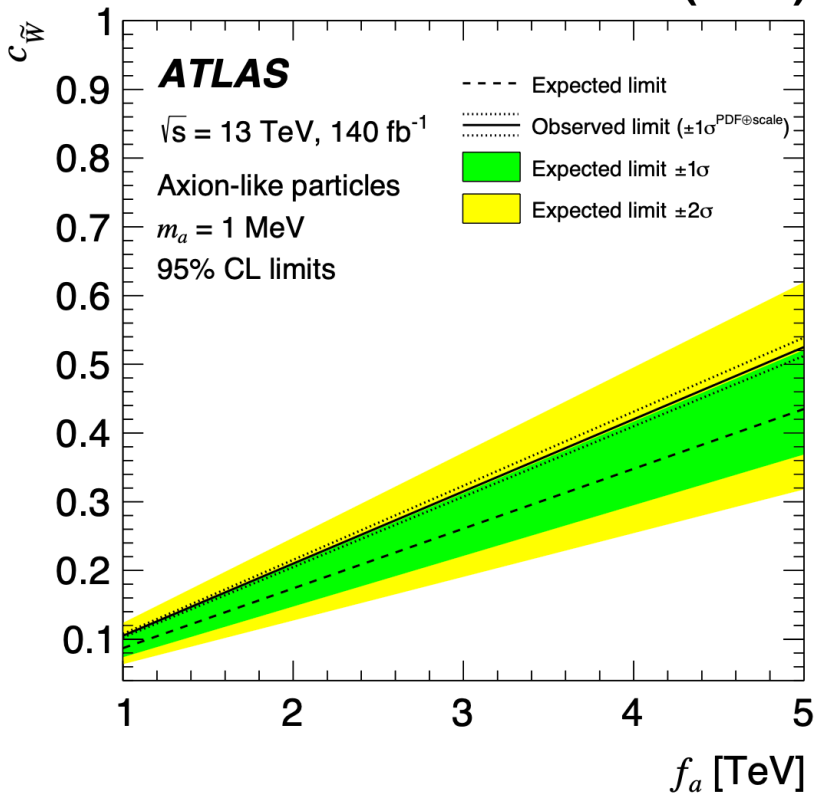


- Maximum reach is m_a = 340 (420) GeV at m_A = 900GeV,
  while values between m_a = 520 (480) GeV and m_A = 1100 (1220) GeV are excluded for m_a = 100 GeV.

Mono-X searches: Mono-V(W/Z)jets

ATLAS: [arXiv: 2406.01272]

Axion-Like Particles (ALP)

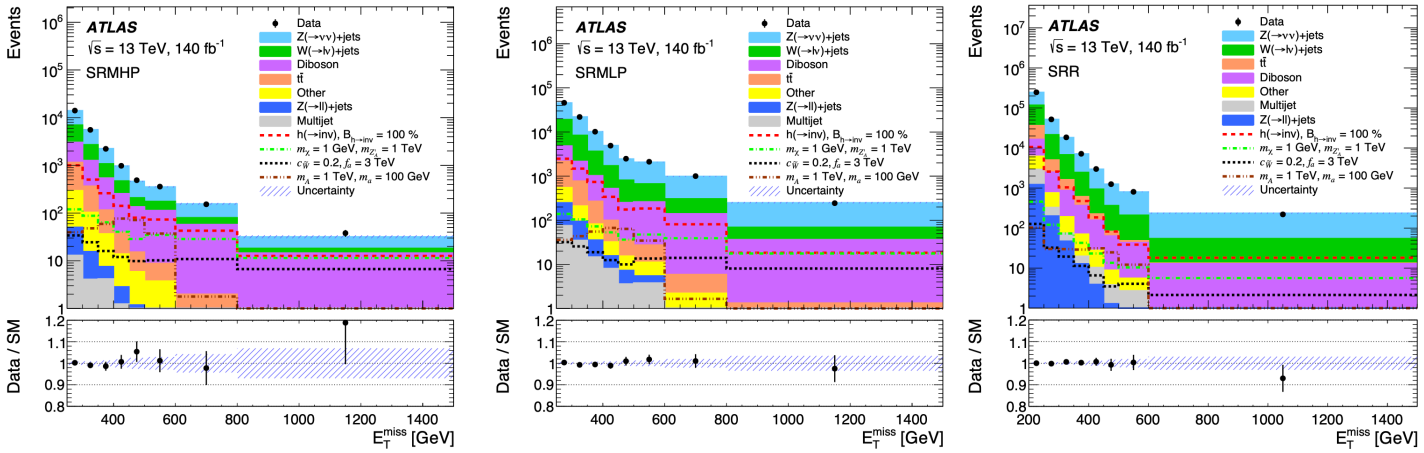


- Exclusion contour in the $c_{\widetilde{W}} - f_a$ plane for a fixed axion mass of 1 MeV

Higgs invisible decay

- Likelihood fit with data on MET to obtain limits for B(H->inv)

Distribution of MET after bkg-only fit

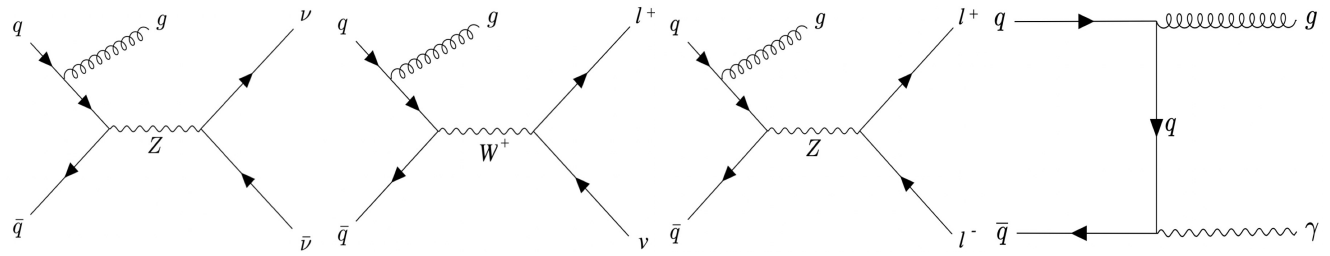


Limits on $B_{h\to inv.}$	Expected limit	Observed limit
Merged topology	$0.34^{+0.14}_{-0.09}$	0.38
Resolved topology	$0.54^{+0.23}_{-0.15}$	0.71
Combined	$0.31^{+0.13}_{-0.09}$	0.34

Mono-X searches: Mono-Jet

ATLAS: [arXiv: 2403.02793]

- Interpretation of jets + MET differential xs measurement in **axial-vector mediator DM model** and **2HDM+a**
- Combine different regions in a fit after unfolding.
- Experimental signature: jet(s) + p_T^{miss} /MET
- Main backgrounds:
  - jets are mis-reconstructed or mis-calibrated, giving rise to fake p_T^{miss}
  - Z/W+jet, top, diboson, multi-jet
- Jet topologies:



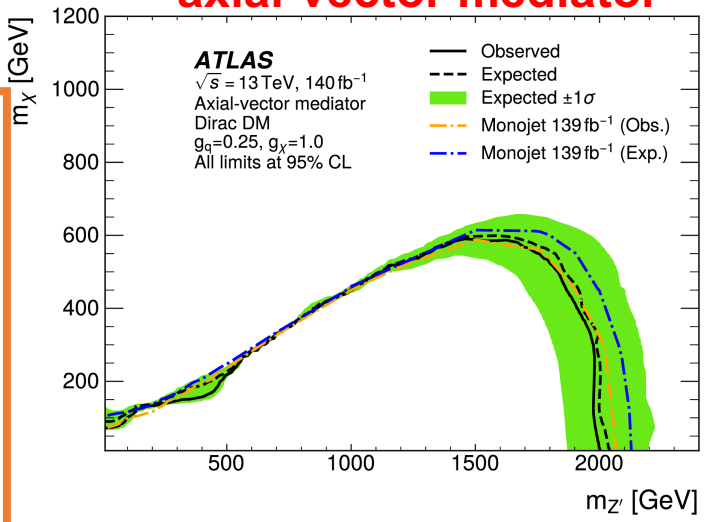
Mono-Jet

- ≥ 1 jet
- leading jet:
  - $p_T > 120$ GeV
  - $|\eta| < 2.4$

VBF process

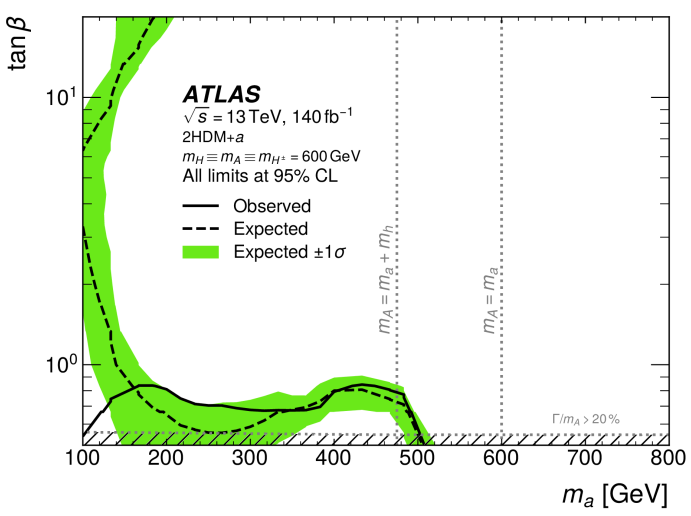
- ≥ 2 jets
- leading jet:
  - $p_T > 80$ GeV
- subleading jet:
  - $p_T > 50$ GeV
- $|\Delta y_{jj}| > 1$, in-gap jet veto
- $m_{jj} > 200$ GeV

Dark matter with axial-vector mediator



Exclusion limits at 95% in the plane of ($m_{Z'}$, m_χ) for a simplified DM model

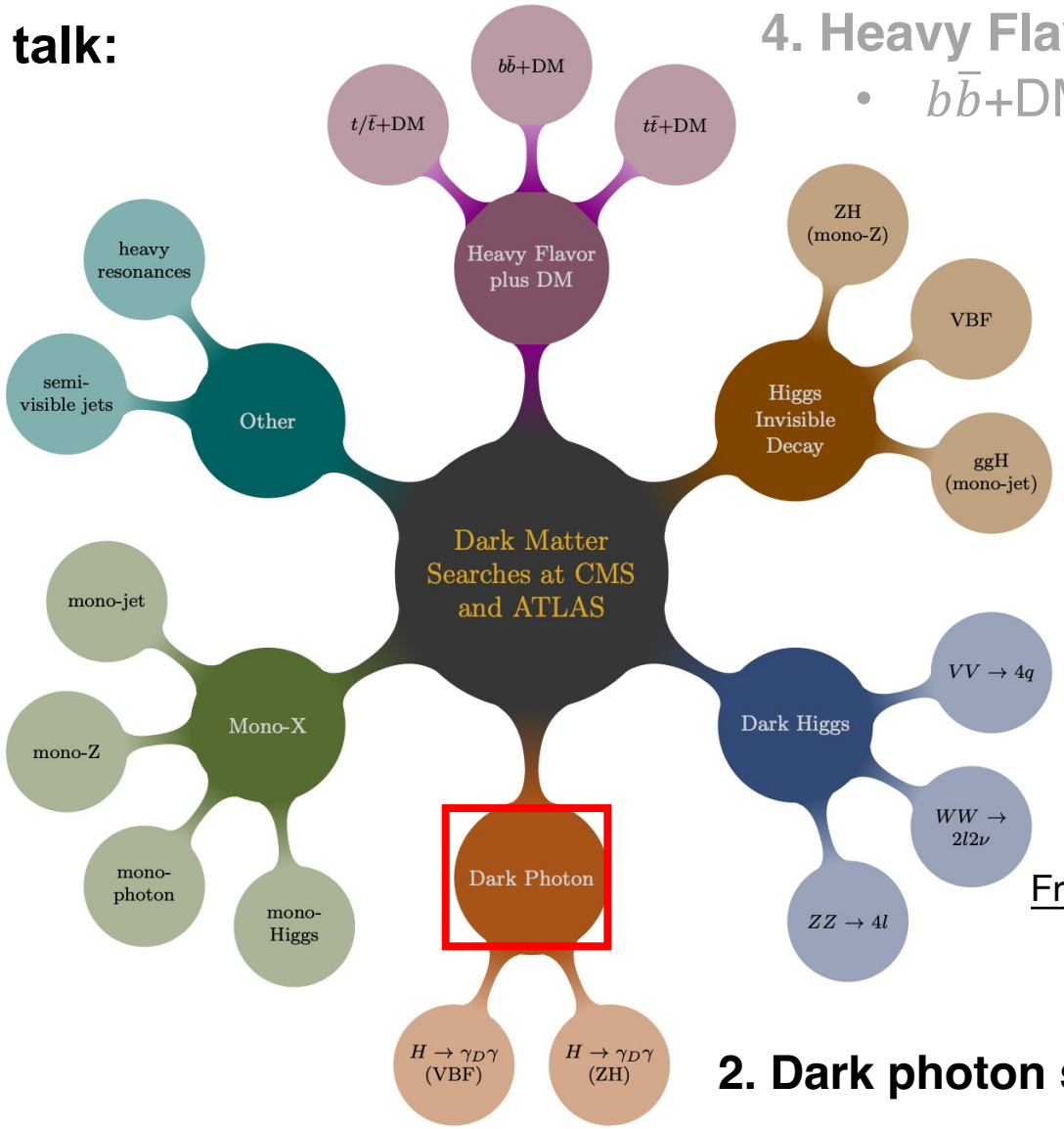
2HDM + a



Exclusion limits at 95% in the (m_a, tanβ) plane for the 2HDM+a mode

Dark matter searches at ATLAS and CMS

Topics introduced in this talk:



4. Heavy Flavour + DM
   - $b\bar{b}$+DM

3. Higgs invisible decay

1. Mono-X searches
   - Mono-top
   - Mono-V
   - Mono-Jet

From Danyer Perez Adan

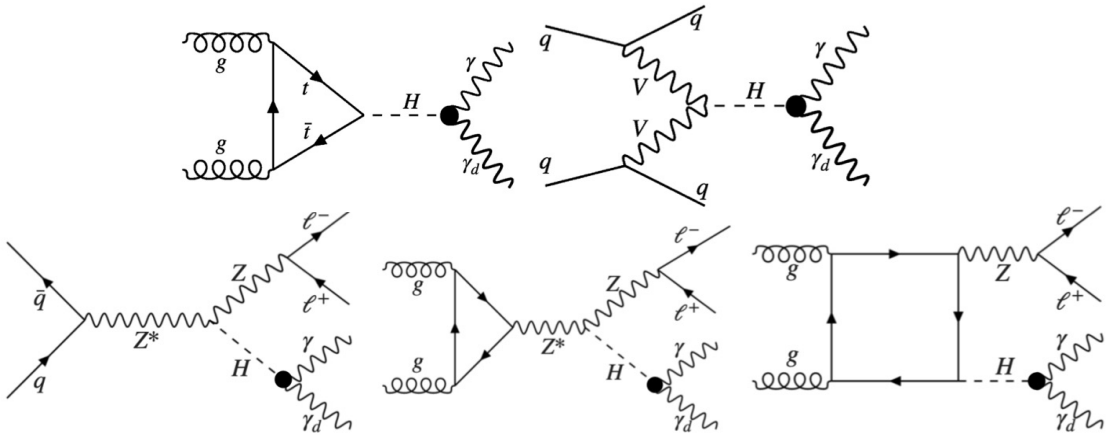
2. Dark photon searches

Dark photon searches

CMS: [arXiv:1908.02699], [arXiv:2009.14009]
ATLAS: [arXiv:2406.01656]

- Experimental signatures:

$\gamma + \mathrm{MET} +$
- Forward jets (VBF channel)
- Z (ZH channel)
- no extra high p_T signature (ggF channel)

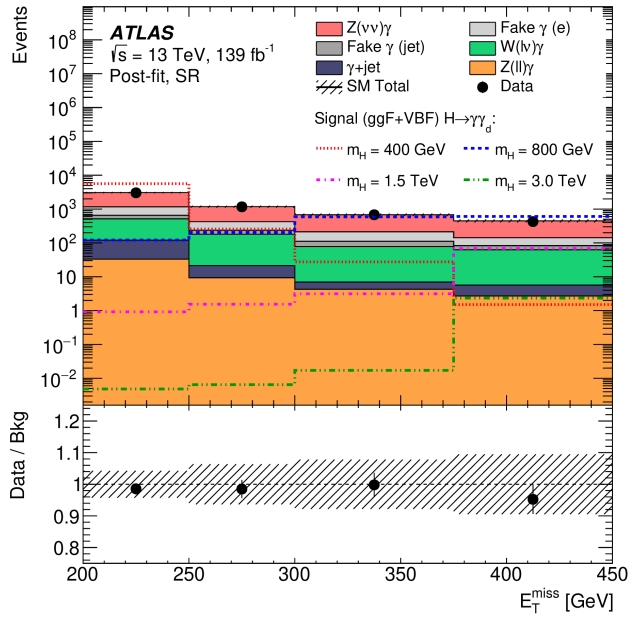


- Main backgrounds in different channel:

	VBF	ZH	ggF
ATLAS	$Z\gamma, W\gamma + jets$	fake MET from $Z/Z\gamma + jets$	$Z(\rightarrow \nu\nu)\gamma, W(\rightarrow l\nu)\gamma,$ $\gamma + jets$ and $Z(\rightarrow ll)\gamma$
CMS		WZ and ZZ	-

- Likelihood fit on MET distribution to obtain limits of BR($\mathrm{H} \rightarrow \gamma\gamma_d$)

Post-fit plots in ggF channel

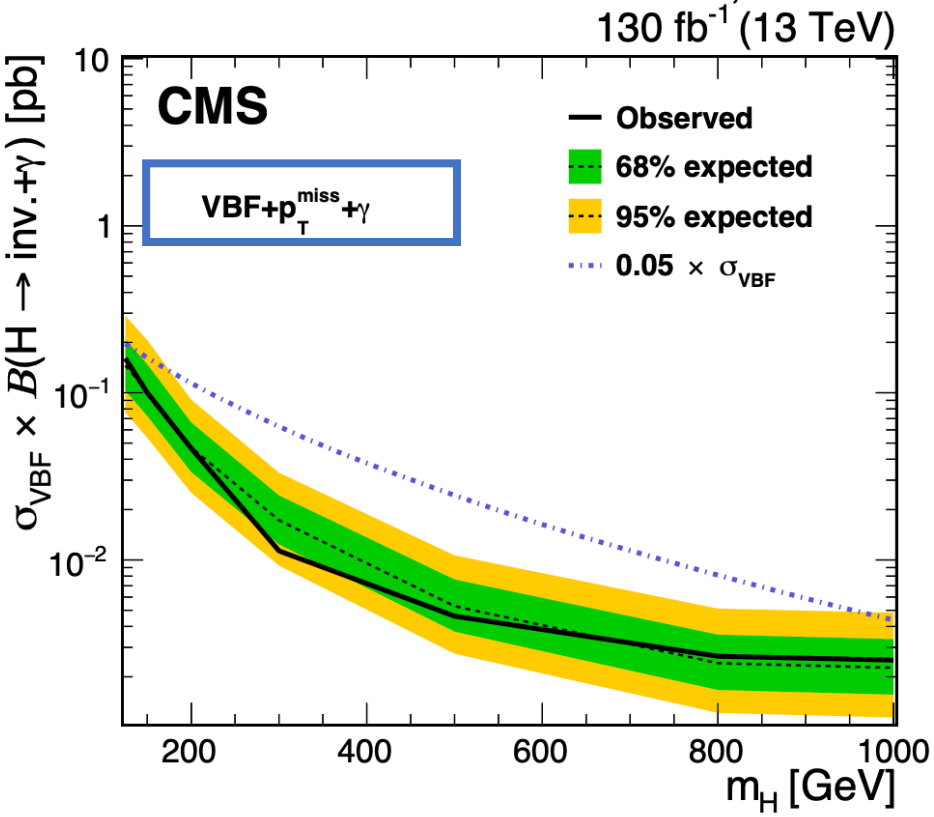


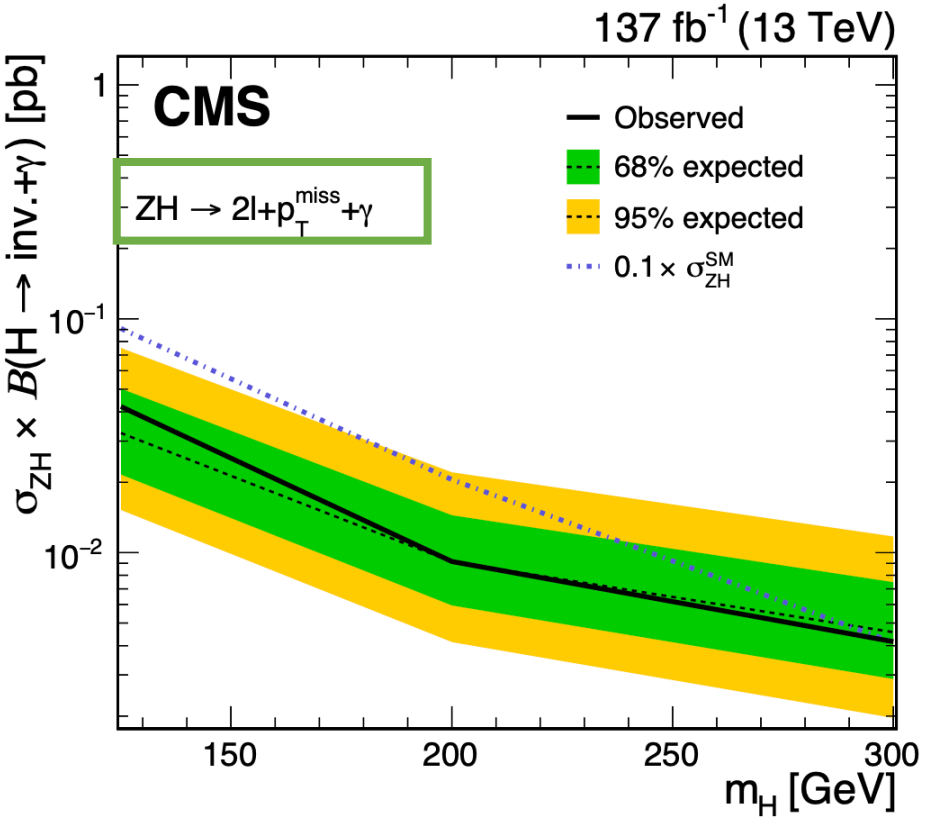
Dark photon searches

CMS: [arXiv:1908.02699]
CMS: [arXiv:2009.14009]

- Limits obtained by CMS
- For **SM** Higgs, the upper limits of BR($H \to \gamma\gamma_d$) is 2.9%
- For **BSM** Higgs, limits scans from
  - 125 GeV to 1000 GeV in **VBF** channel;
  - 125 GeV to 300 GeV in **ZH** channel;

VBF		ZH		VBF+ZH	
Obs. (%)	Exp. (%)	Obs. (%)	Exp. (%)	Obs. (%)	Exp. (%)
3.5	$2.8^{+1.3}_{-0.8}$	4.6	$3.6^{+2.0}_{-1.2}$	2.9	$2.1^{+1.0}_{-0.7}$





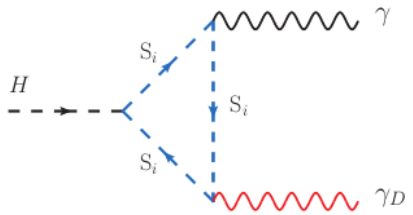
Dark photon searches

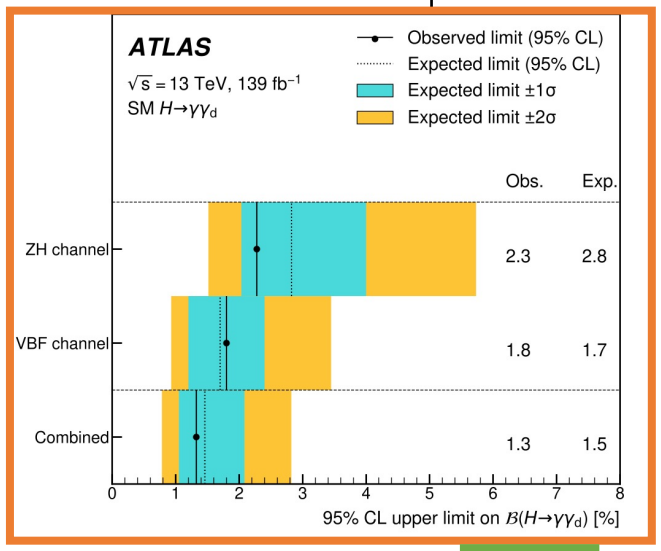
ATLAS: [arXiv:2406.01656]

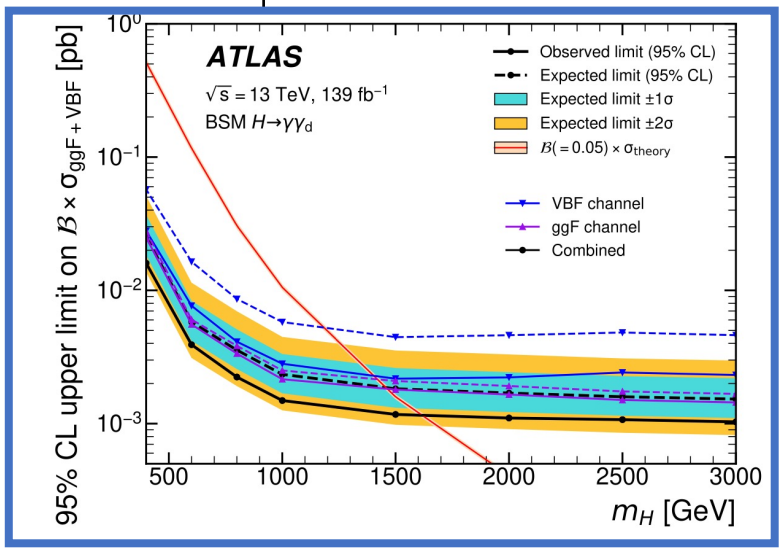
- Limits obtained by ATLAS Run 2 combination
- For **SM Higgs**,
  BR($\mathrm{H} \to \gamma\gamma_d$) is 1.3%
  - Improvement of 29% in sensitivity compared to VBF limit
  - Most stringent results for BR($\mathrm{H125} \to \gamma\gamma_d$)
- For **BSM Higgs**,
  limit scans from 500 GeV to 3TeV
  - Improvement of 33% at m_H=1500GeV compared to ggF results

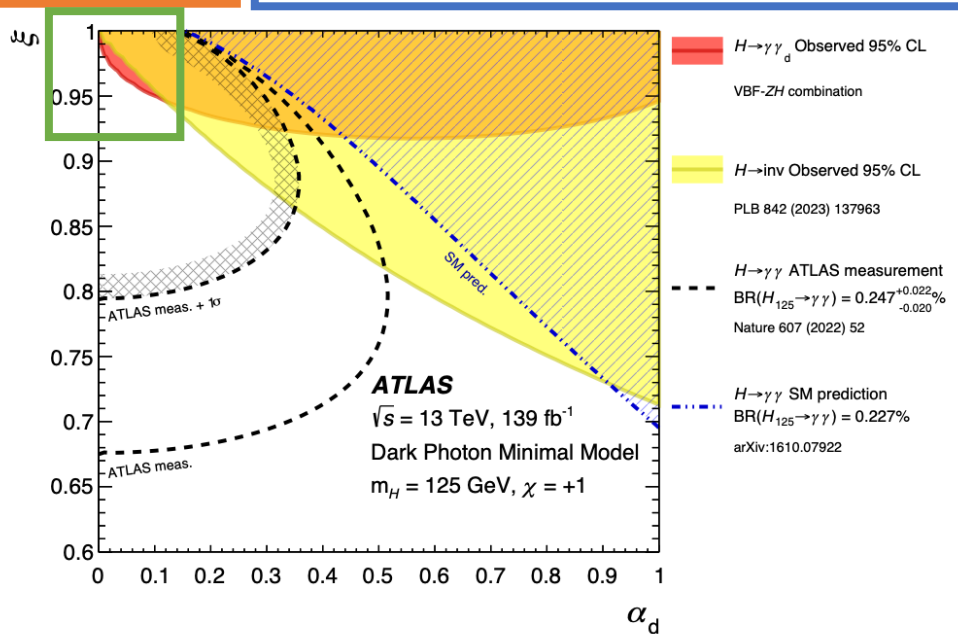
Interpreted with minimal simplified model:

$$L^0 = \partial_\mu \hat{S}^\dagger \partial^\mu \hat{S} - \hat{S}^\dagger M_S^2 \hat{S}$$





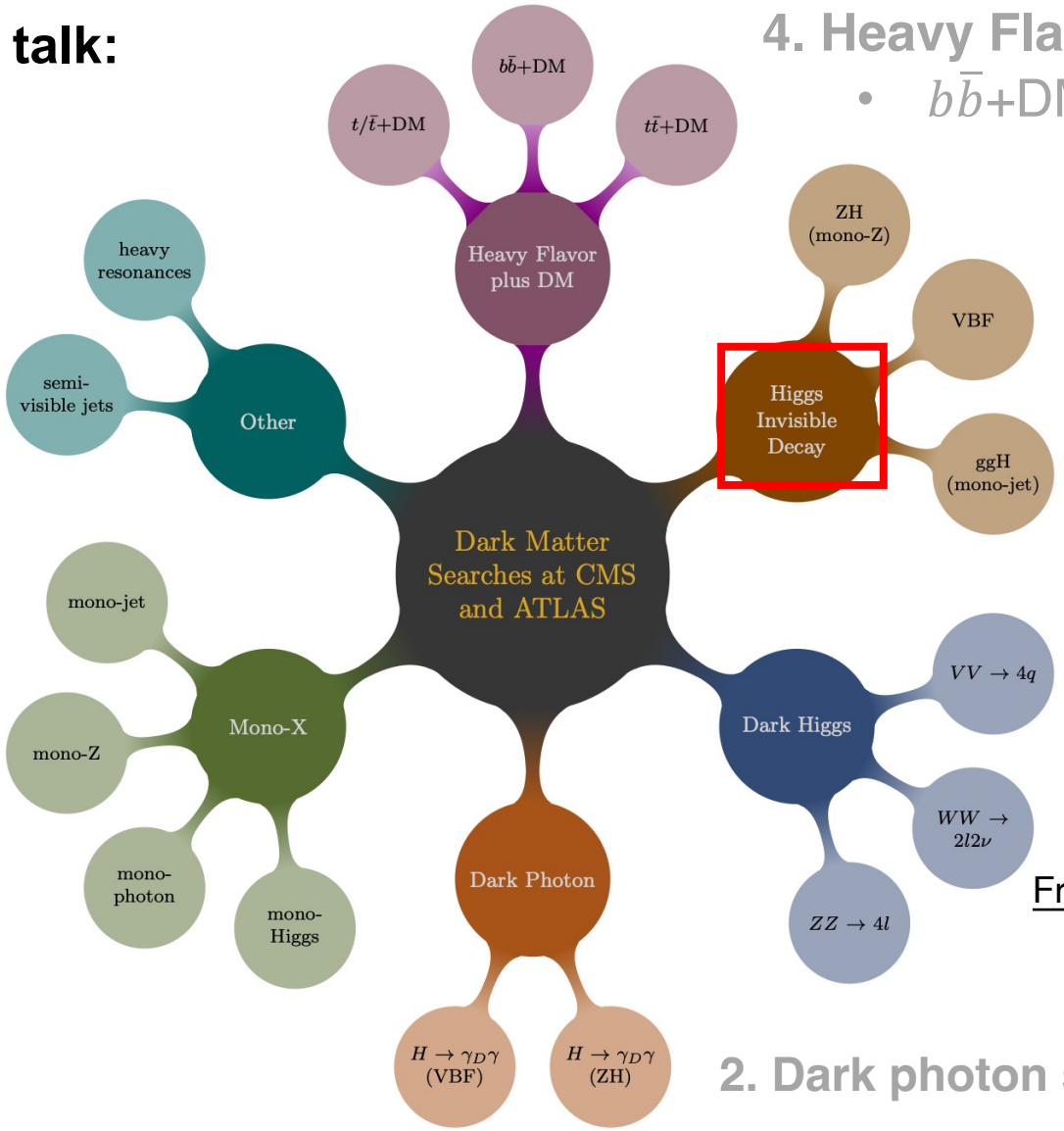




- 2 scalar messengers $S_i (i = +, -)$ allow for $H125 \to \gamma\gamma_d$ at 1-loop.
  - Messenger sector couples to both U(1) and U(1)$_\mathrm{d}$ gauge fields, allowing three Higgs boson decay modes: $\gamma\gamma_\mathrm{d}$, $\gamma_\mathrm{d}\gamma_\mathrm{d}$ and $\gamma\gamma$
- Combination provides **additional sensitivity** in the low α_d region

Dark matter searches at ATLAS and CMS

Topics introduced in this talk:



1. Mono-X searches
   - Mono-top
   - Mono-V
   - Mono-Jet

4. Heavy Flavour + DM
   - $b\bar{b}$+DM

3. Higgs invisible decay

From Danyer Perez Adan

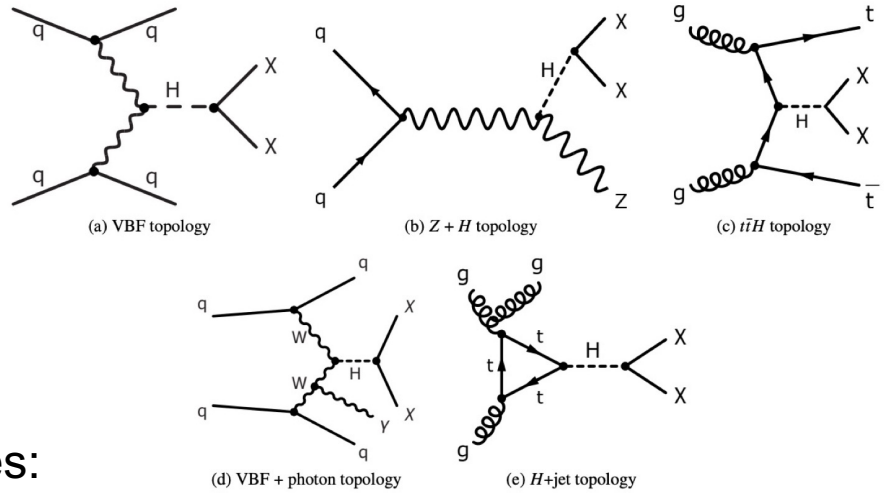
2. Dark photon searches

Higgs invisible decay

CMS: [arXiv: 2303.01214]
ATLAS: [arXiv: 2301.10731]

- Search for Higgs invisible decay via multiple Higgs production modes.
- Experimental signatures: Jet + H(→inv), Z(ll) + H(→inv)
- Strategy:
  - SM BR($\mathrm{H} \to inv$) = 0.1% ($\mathrm{H} \to ZZ^* \to 4\nu$)
  - Higgs invisible decay would increase the BR w.r.t SM prediction.
- The sensitivity is driven by **VBF** and **Z+H** channel.

Higgs production modes



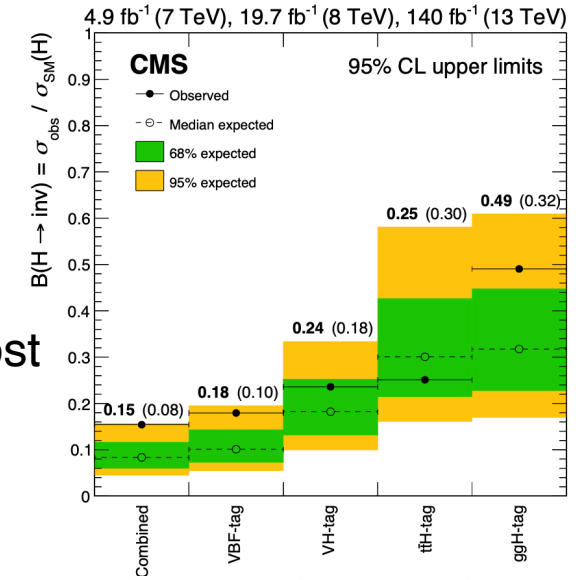
- Main backgrounds and signature from different Higgs production modes:

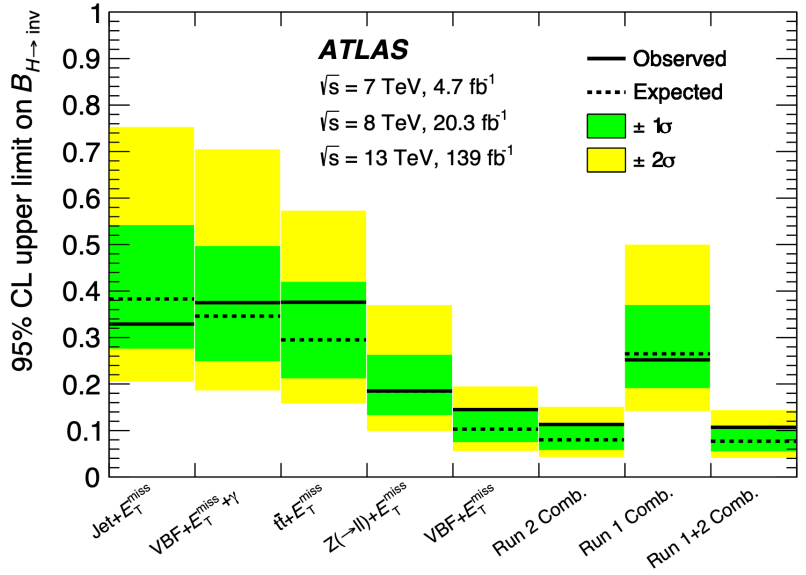
Higgs production mode	Experimental signature	Leading Backgrounds
VBF	VBF+H(→inv)	$Z(\to \nu\nu)$+jets and $W(\to l\nu)$+jets
Z+H	Z(ll)+H(→inv)	$Z\ (\to ll)\ Z\ (\to \nu\bar{\nu})$ and WZ
$\mathrm{t\bar{t}H}$	$\mathrm{t\bar{t}}$+H(→inv)	$\mathrm{t\bar{t}}$ and $Z\ (\to \nu\bar{\nu})$ +jets in 0-lepton channel, $\mathrm{t\bar{t}}$ in 1-lepton channel, ttZ in 2-lepton channel
VBF+photon	VBF+H(→inv)+γ	$V\gamma$+jets
H+jet	jet+H(→inv)	$Z\ (\to \nu\nu)$ + jets and $W\ (\to \mathrm{l}\nu)$ + jets

Higgs invisible decay

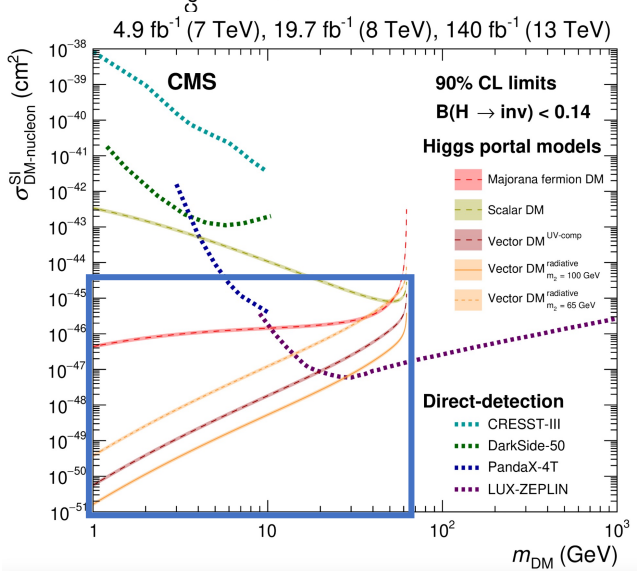
CMS: [arXiv: 2303.01214]
ATLAS: [arXiv: 2301.10731]

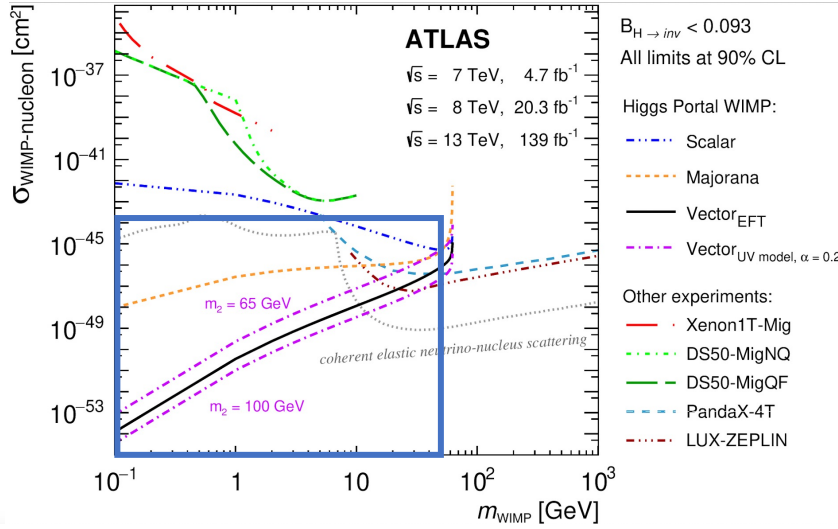
- The upper limits of BR($H \to inv$) is obtained with Run 1 and Run 2 data.
- Combined **95% CL** upper limits on B($H \to inv$);
  - CMS: B($H \to inv$) < 0.15(0.08);
  - ATLAS: B($H \to inv$) < 0.107(0.077);
- Sensitivity improved by 20% compared to the most sensitive single channel.





- Model-dependent **exclusion limits** at **90% CL** are found to complement direct-detection experiments in low mass region.





Dark matter searches at ATLAS and CMS

Topics introduced in this talk:

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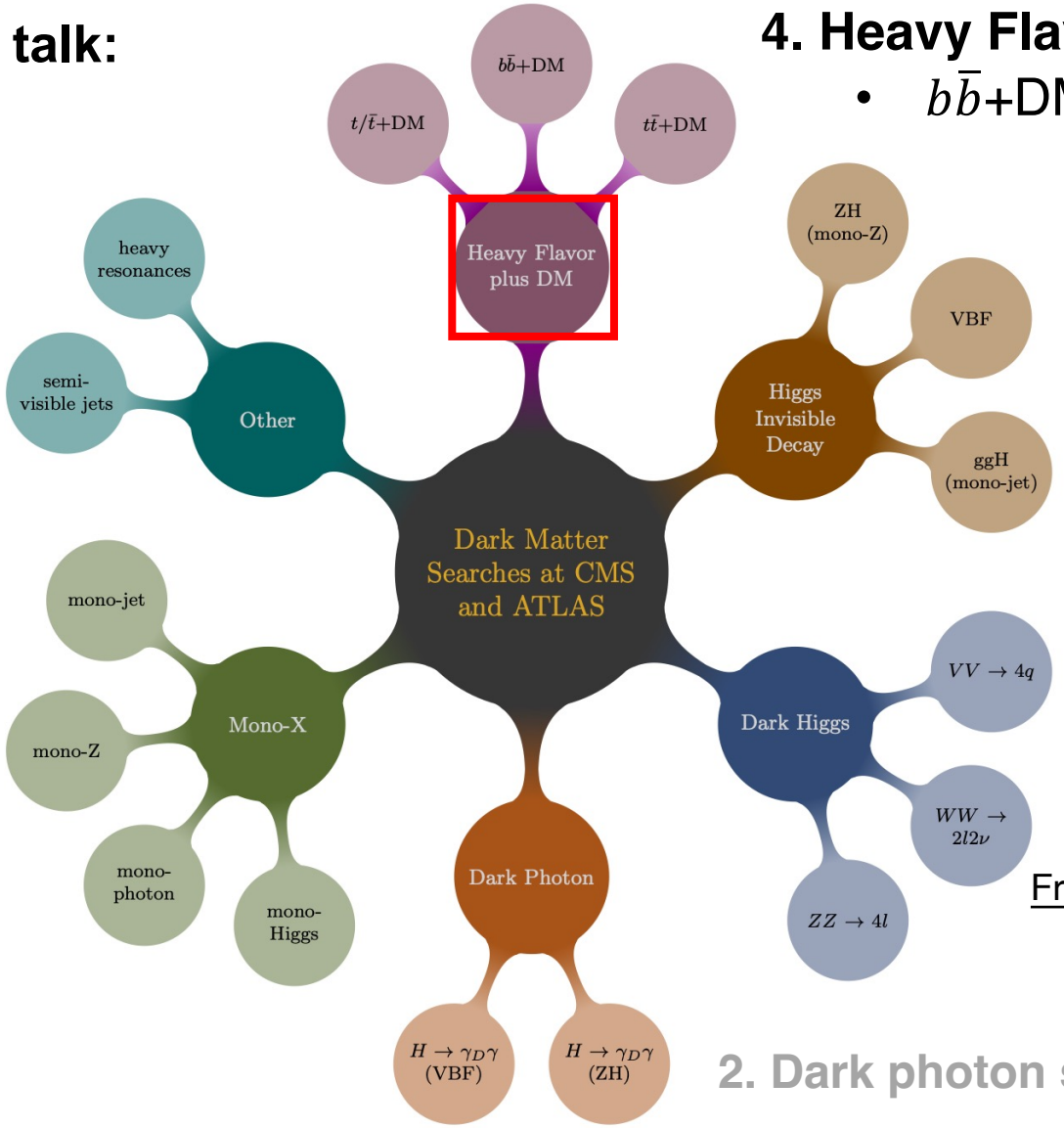
- Mono-Jet



2. Dark photon searches

3. Higgs invisible decay

4. Heavy Flavour + DM
- $b\bar{b}$+DM

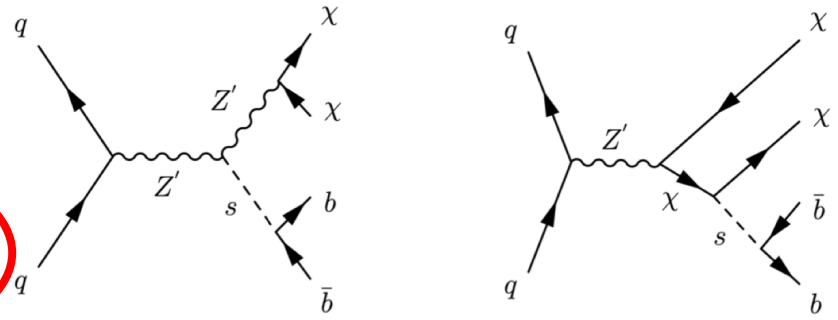
From Danyer Perez Adan

Heavy Flavour + DM

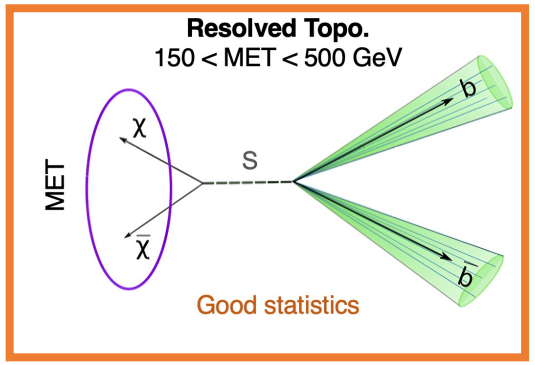
ATLAS: [arXiv:2407.10549]

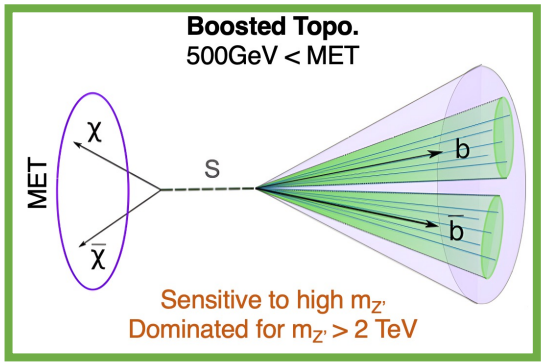
- Experimental signature: X(decays into b pair) + MET
- Dark Higgs Model:
  - Majorana DM candidate's mass m_χ,
  - Z' mass $m_{Z'}$
  - Dark Higgs boson mass m_s
  - Coupling of the Z' boson to quarks g_q
  - Coupling to DM g_χ
  - Mixing angle between the SM and dark Higgs bosons θ

Free parameters to describe interaction with SM and DM



- **Resolved** and **Merged** topologies are considered to cover all the interested phase space.





- Novel tagging algorithm is employed to improved sensitivity

- Main backgrounds: V+jets, and $t\bar{t}$
  At large MET regions, di-boson also contributed as non-negligible backgrounds.

Heavy Flavour + DM

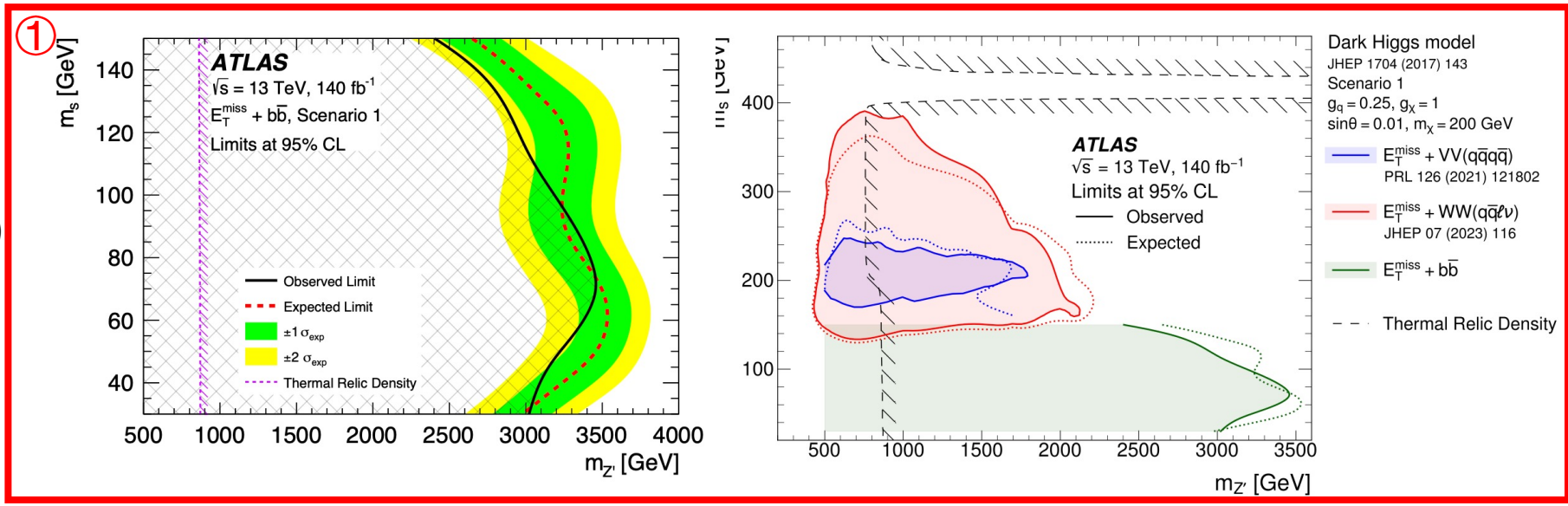
ATLAS: [arXiv:2407.10549]

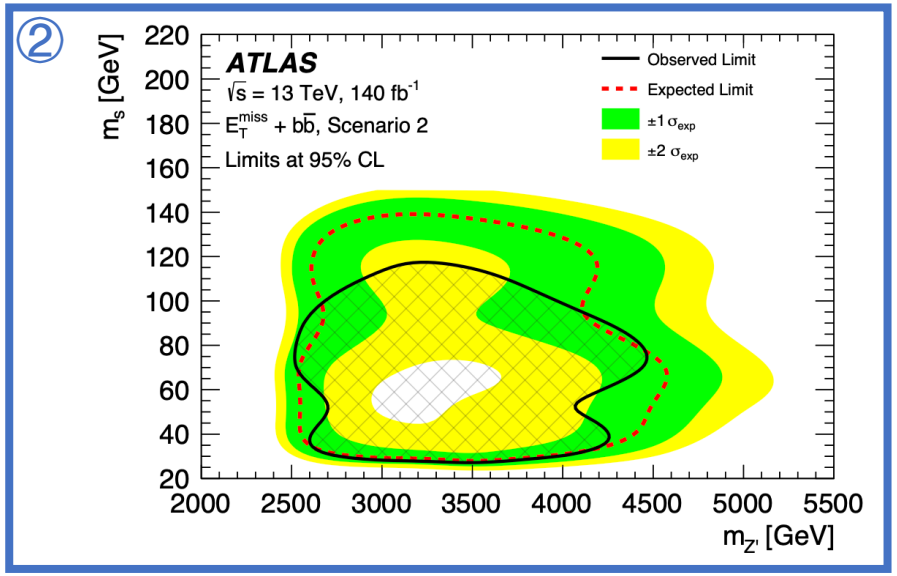
- Three scenarios are set:

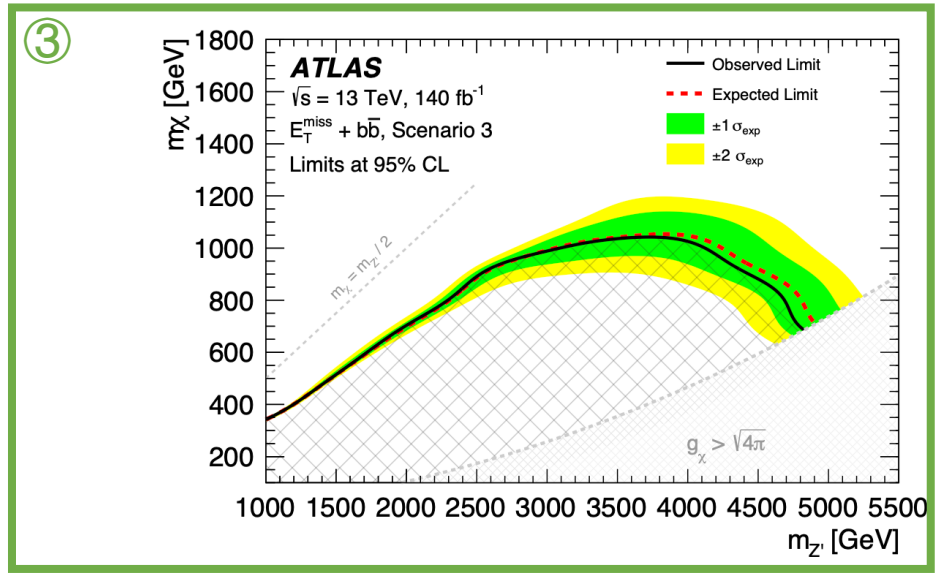
① **$(m_{Z'}, m_s)$ plane**,
m_s: 30–150 GeV,
$m_{Z'}$ up to 4 TeV,
m_χ = 200 GeV(avoid $s \to \chi\chi$)
g_q = 0.25,g_χ = 1.0,
sinθ = 0.01

② **$(m_{Z'}, m_s)$ plane**,
same from S1,
but: m_χ =900GeV

③ **$(m_{Z'}, : m_\chi)$ plane**,
same from S1,
but: m_s= 70 GeV



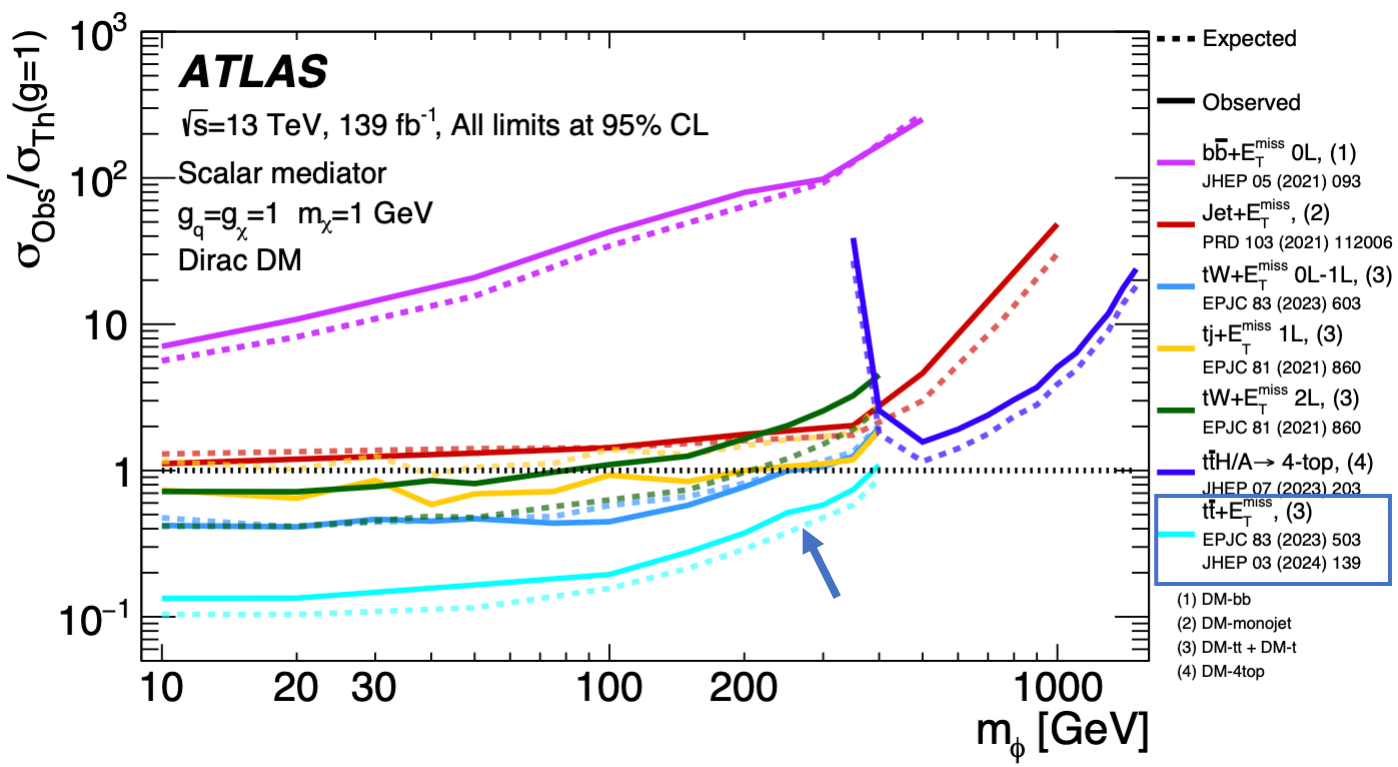


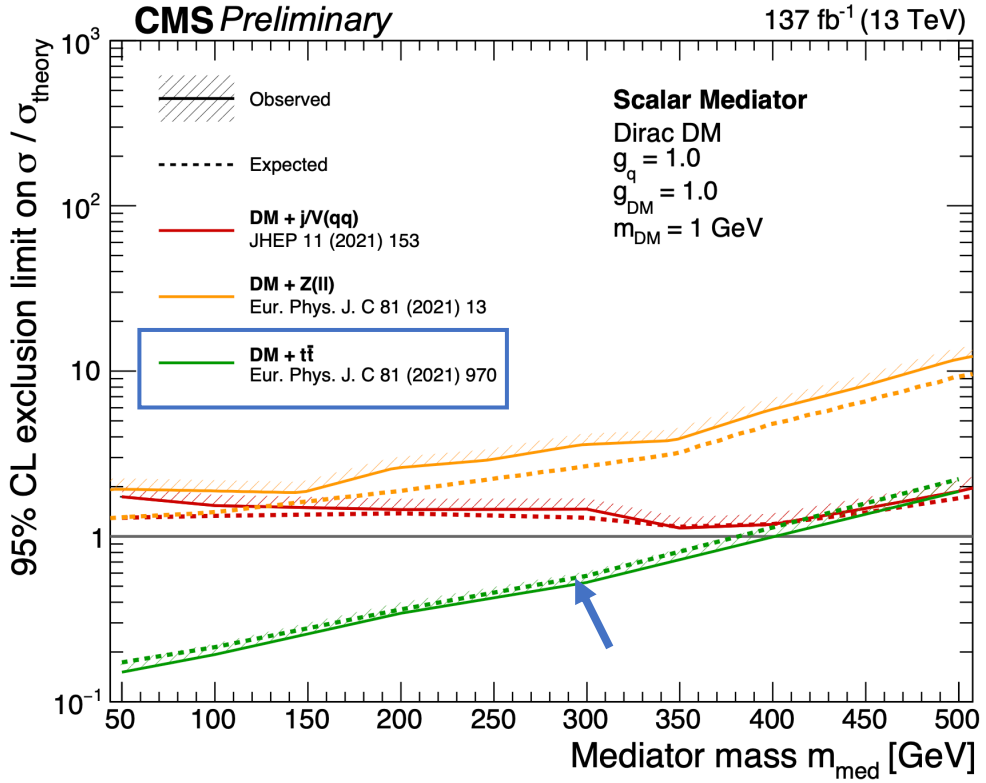


Summary plots of DM searches in ATLAS and CMS

Summary of Simplified model searches

- ATLAS & CMS summary plots with simplified DM model of scalar mediator searches
  - MET+ $t\bar{t}$



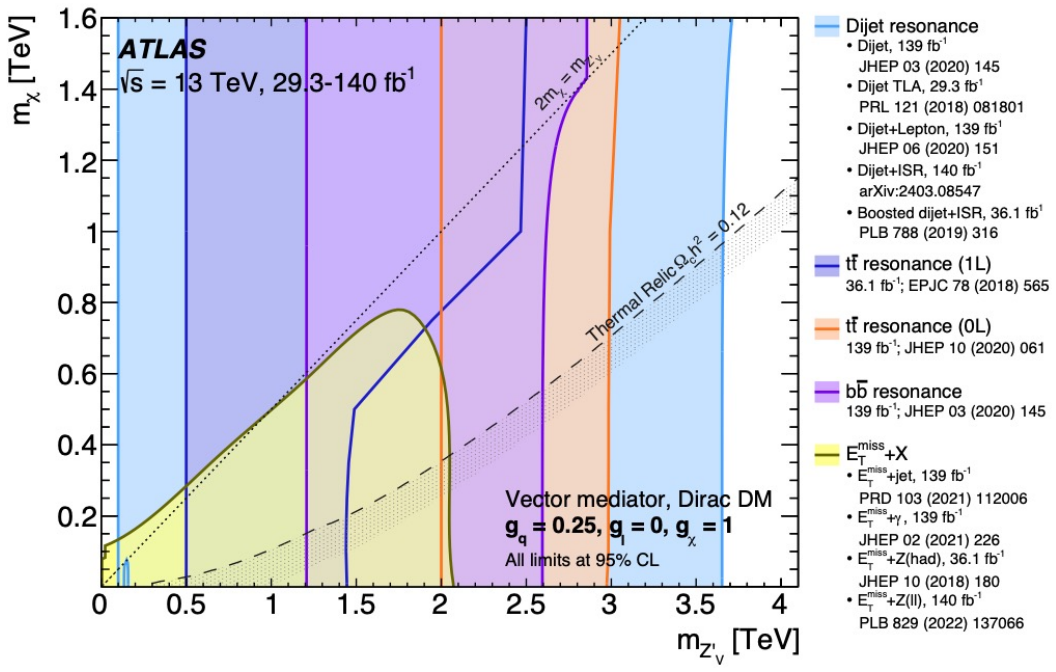


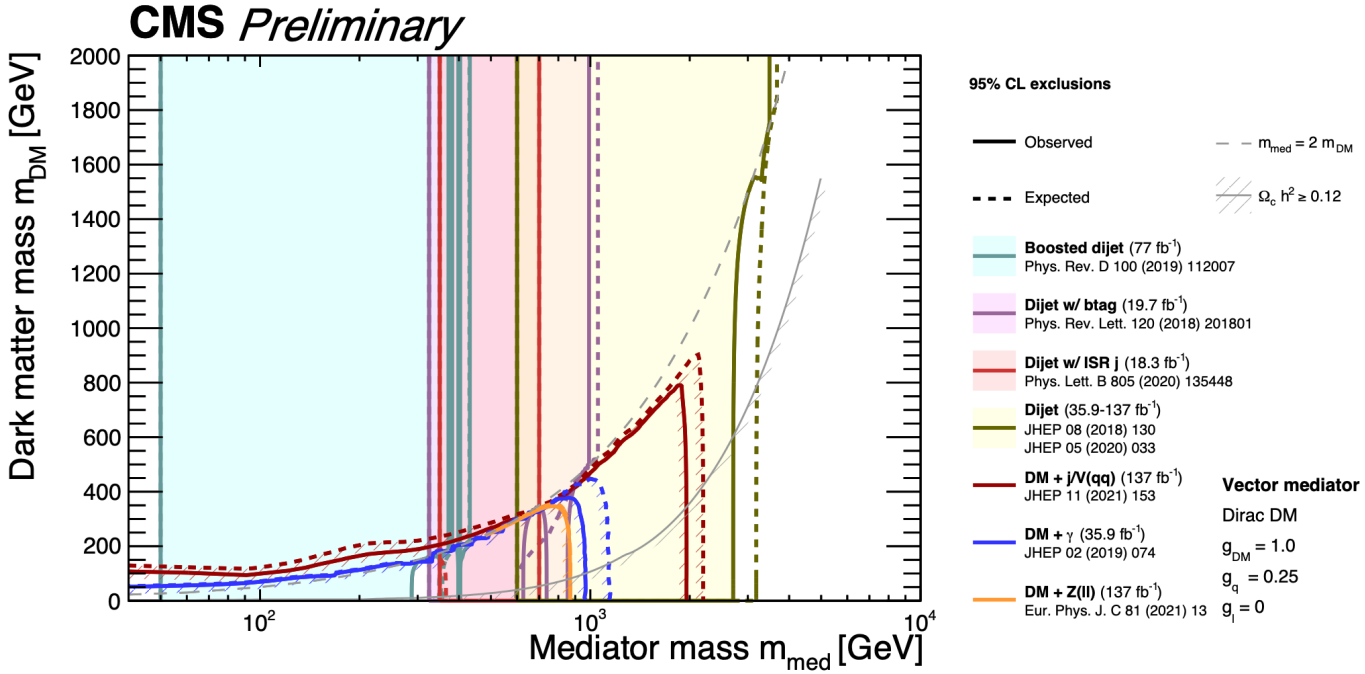
Plots for pseudo-scalar mediator searches in backup.

Summary of Simplified model searches

ATLAS Summary Plots
CMS Summary Plots

- ATLAS & CMS summary plots with simplified DM model of vector mediator searches



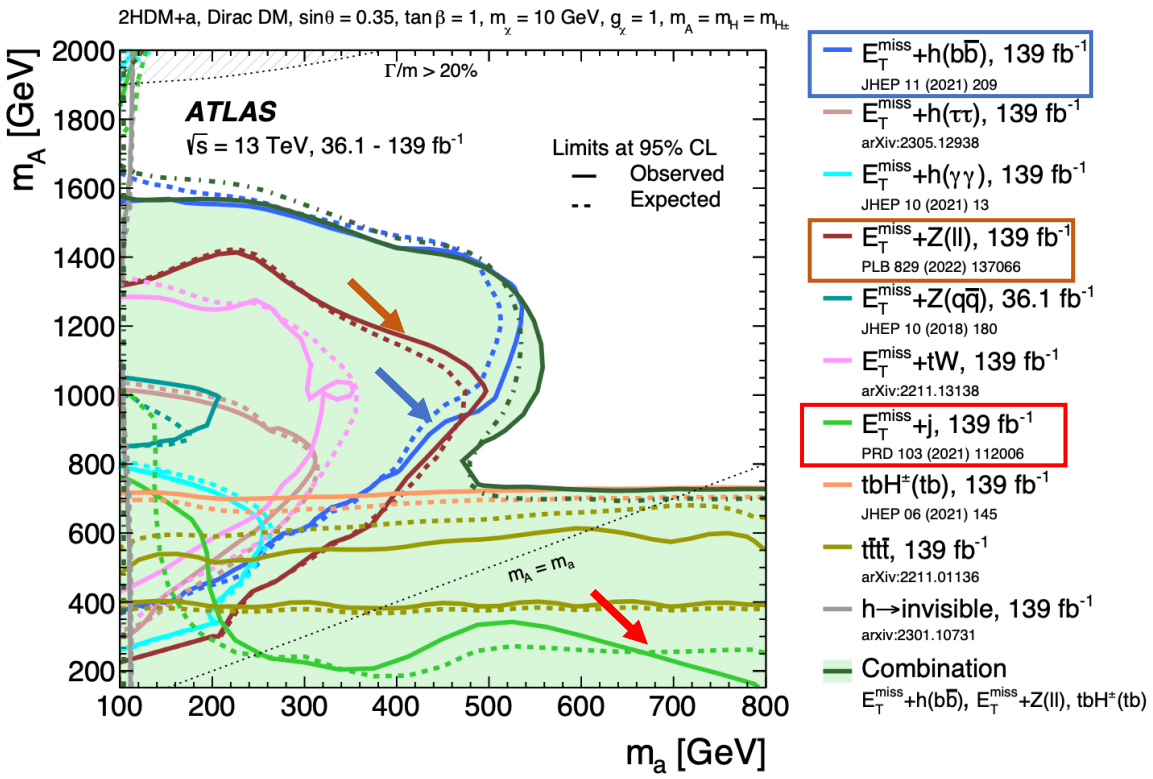


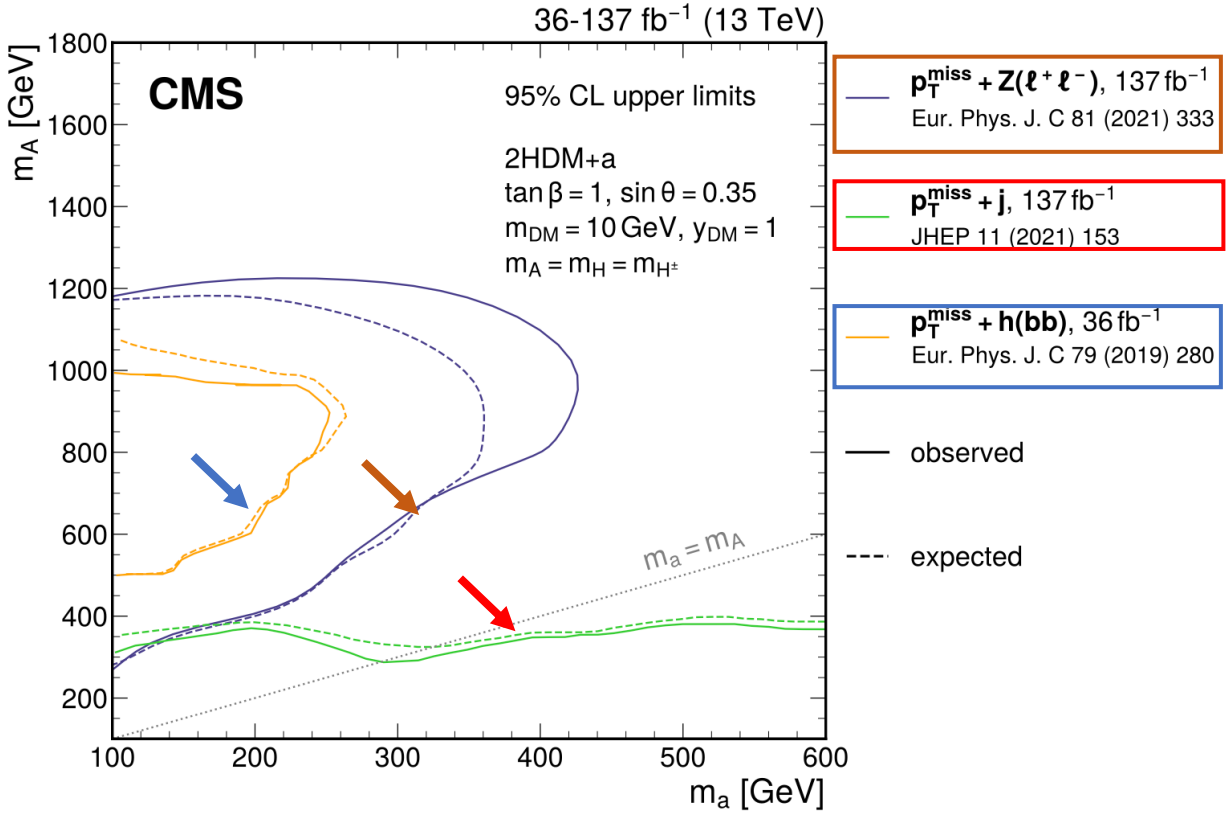
Plots for axial-vector mediator searches in backup.

Summary of 2HDM+a searches

ATLAS Summary Plots
CMS Summary Plots

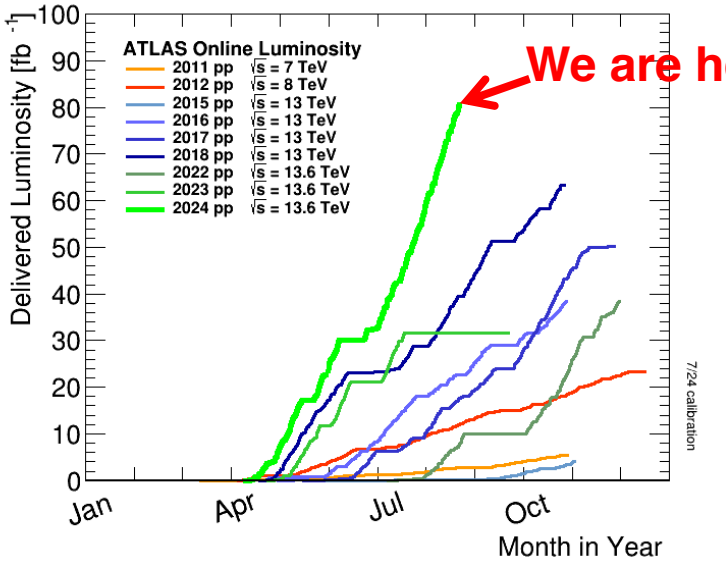
- ATLAS & CMS summary plots with 2HDM + a model
  - h(bb)+MET, $Z(\rightarrow ll)$+MET, jet+MET…





Summary

- Wide range dark matter model searches at ALTAS and CMS:
  - Most on Simplified models .
  - Extended dark matter models also included like 2HDM+a.
- Sensitivity improved from latest searches and combinations.
- So far **no significant** dark matter signal found .
- ATLAS and CMS provides nice **summary plots** for Run 2 DM searches.



- Run 3 and HL-LHC datasets will provide a good opportunity for discoveries.
  - With larger datasets and technique improvement, the exclusion would be more stringent.

- More DM search results, please visit ATLAS/CMS public website.

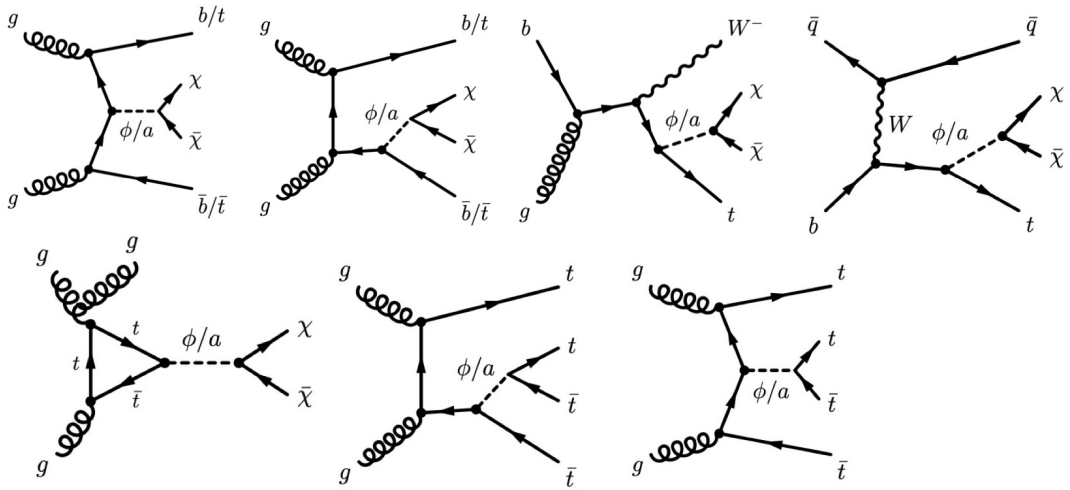
Thanks for you attention!

Backup

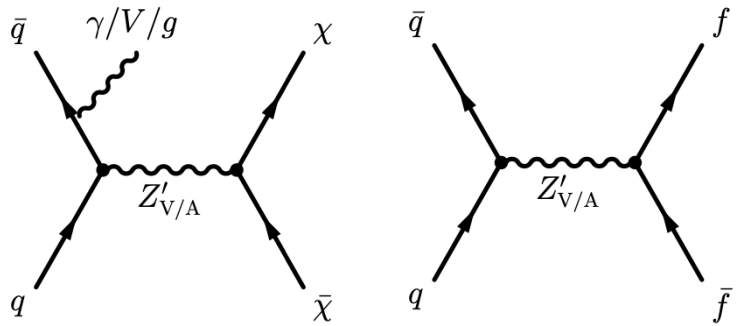
Summary of DM searches

- Experimental signatures:
  - **Spin-0**: tt/bb + MET, jet + MET, t(W/j) + MET, tt resonance
  - **Spin-1**: X+MET, Resonances
- Analyses with MET
  - Invisible decays:
    - tt/bb + MET, t(W/j) + MET, jet + MET…
  - Visible decays:
    - Dijet TLA, Dijet + lepton, Dilepton…
- Main backgrounds:
  - tt/bb + MET: top pair production, W+jets, Z+jets
  - t(W/j) + MET: top pair production, W+jets, Z+jets
  - jet + MET:$Z(\nu\nu)$+jets and $W(l\nu)$+jets
  - γ + MET: $W\gamma$, $Z\gamma$, and γ+jets
  - Z(ll) + MET: ZZ and WZ
  - V + MET:$t\bar{t}$ and W/Z+jets

Spin 0

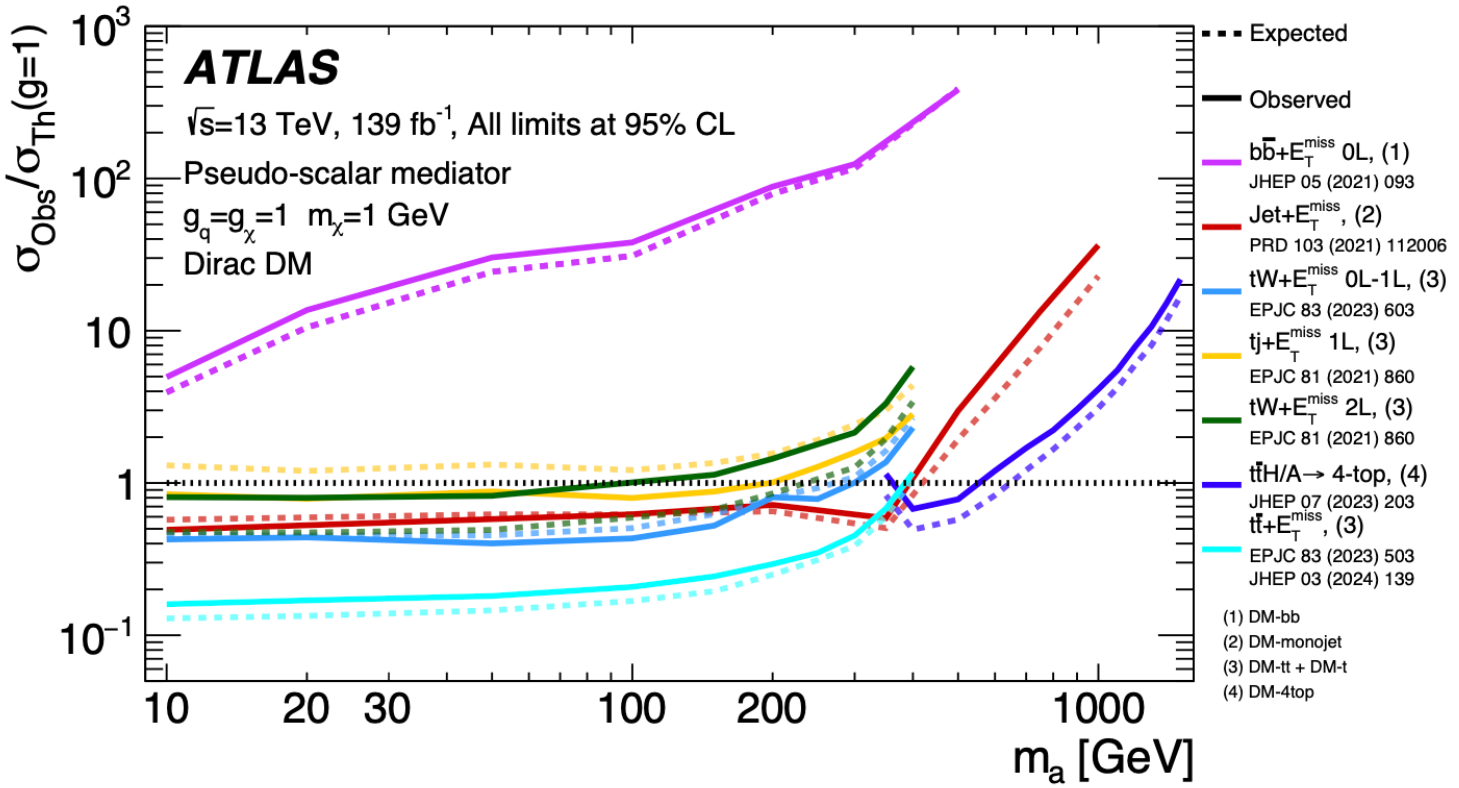


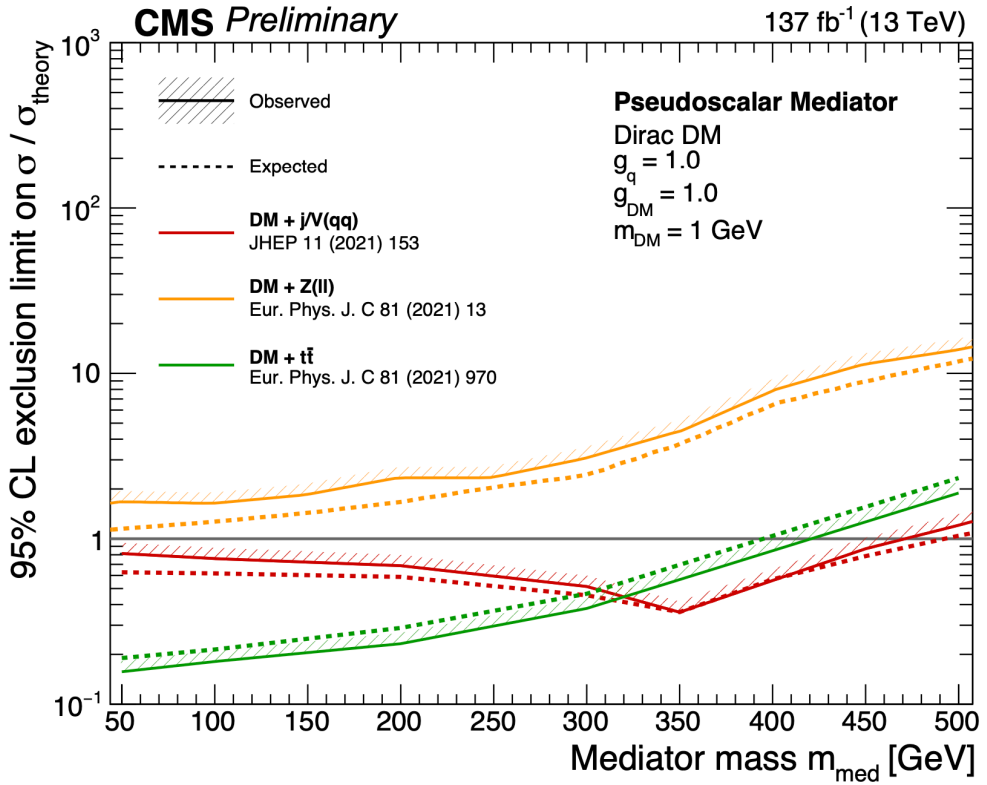
Spin 1



Summary of Simplified model searches

- ATLAS & CMS summary plots with simplified DM model of pseudo-scalar mediator searches





Summary of Simplified model searches

ATLAS Summary Plots
CMS Summary Plots

- ATLAS & CMS summary plots with simplified DM model of axial-vector mediator searches