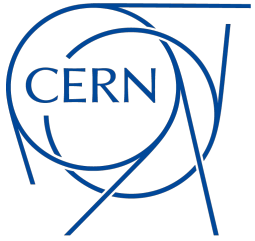
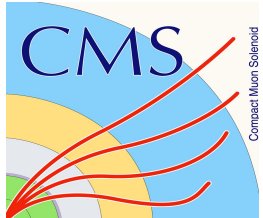
Dark Matter in ATLAS and CMS

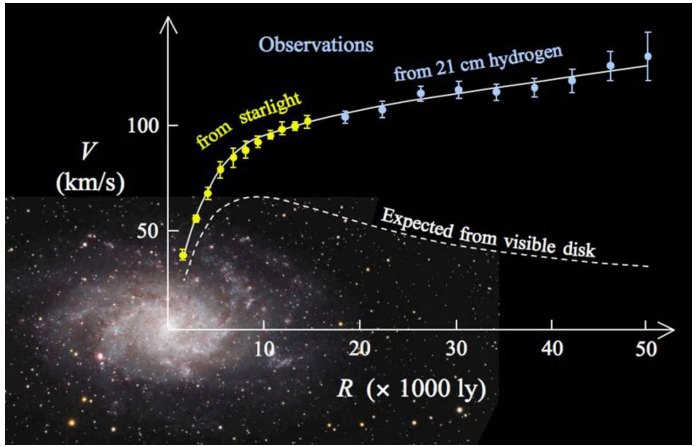
BISNUPRIYA SAHU
University of Hyderabad, India
On behalf of the CMS and ATLAS collaborations

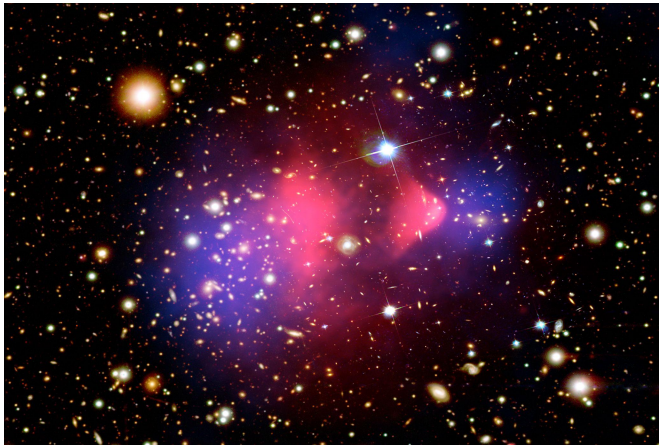
23rd Hellenic School and Workshops on Elementary Particle Physics and Gravity, Corfu, Greece 2023
Workshop on the Standard Model and Beyond
August 30th 2023

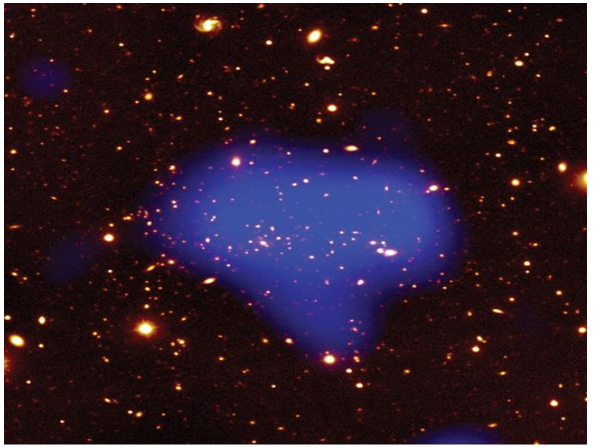




Introduction







1. Rotation Curve Galaxy

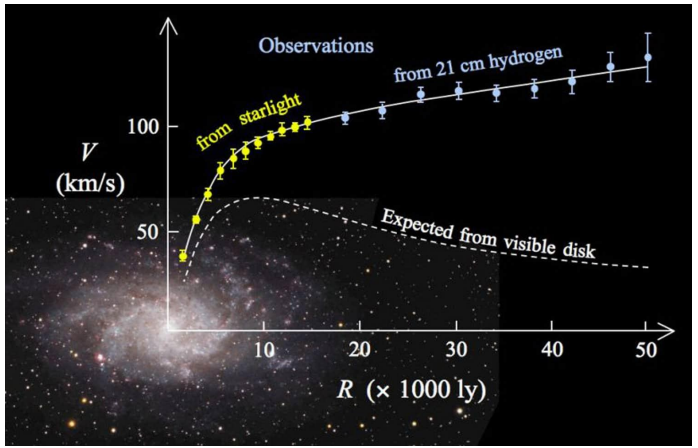
2. Bullet Cluster

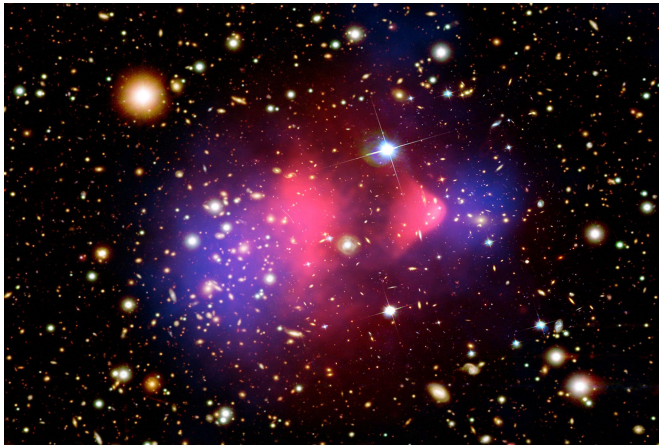
3. Hot gas in clusters of galaxies

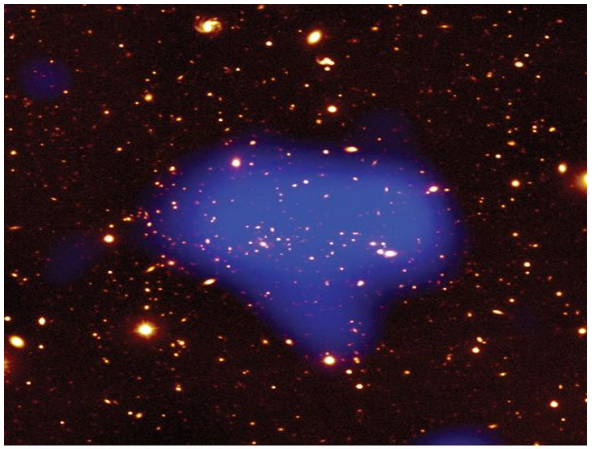
Dark Matter:

- Electrically Neutral
- Interact only through gravity
- Weakly Interacting Massive Particles (WIMPs)

Introduction







1. Rotation Curve Galaxy

2. Bullet Cluster

3. Hot gas in clusters of galaxies

Dark Matter:

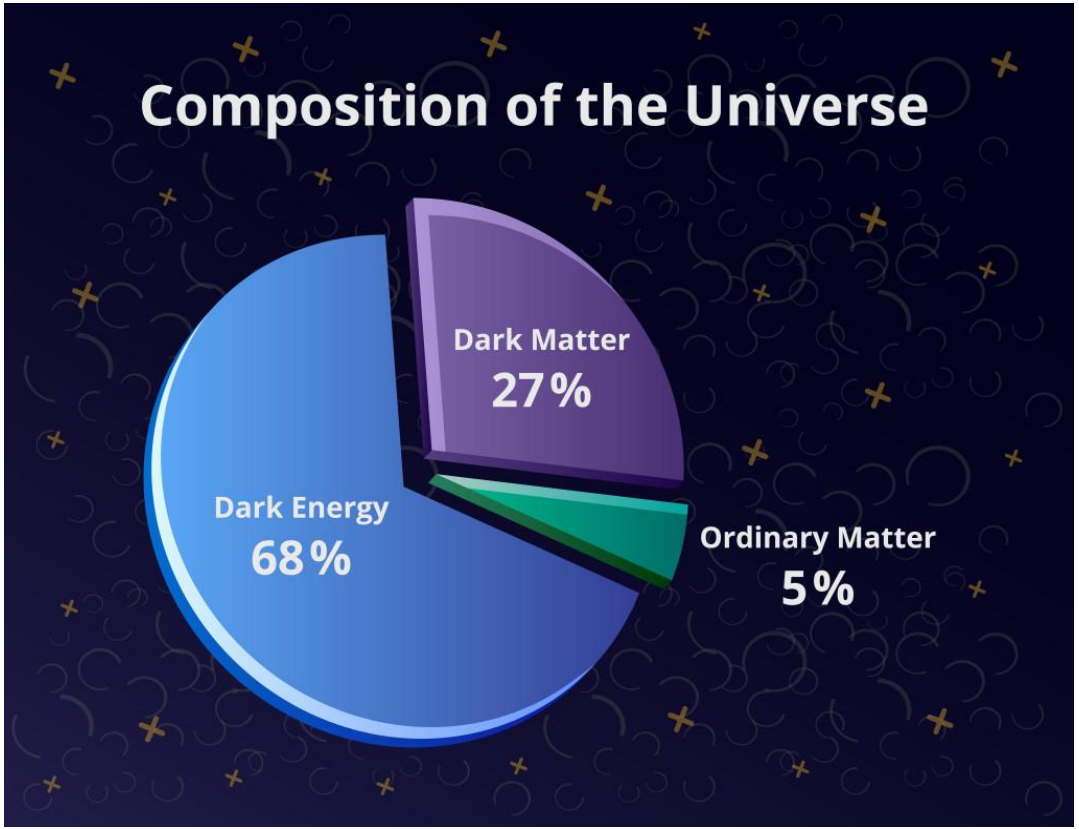
Electrically Neutral

Interact only through gravity

Weakly Interacting Massive P[illegible]cl[illegible] (WIMPs)

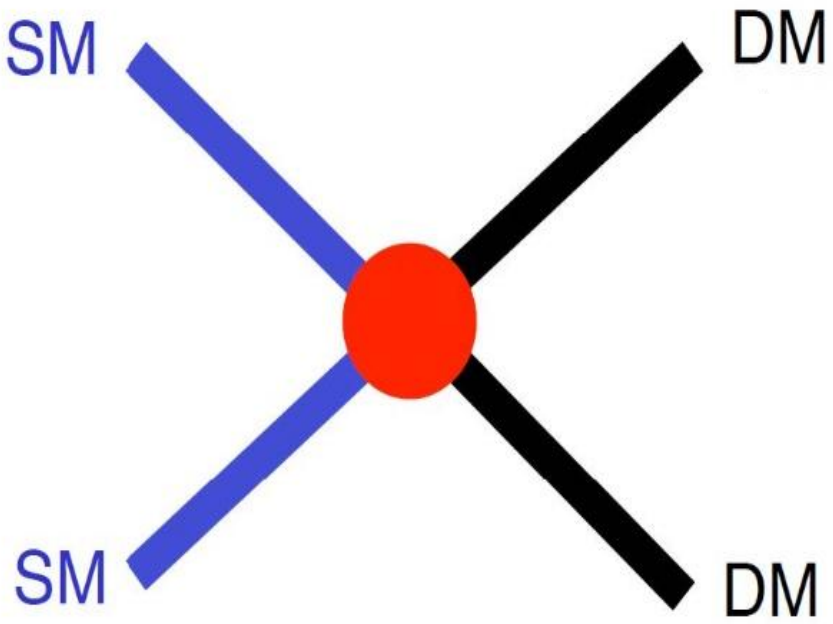
NO DIRECT OBSERVATION

Composition of Universe



DM is six times more abundant than baryons

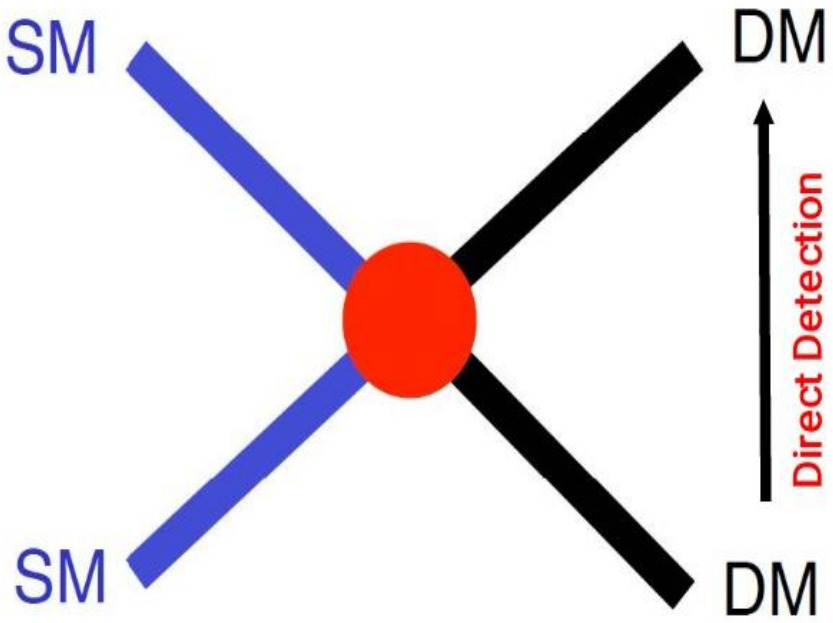
How to Detect Dark matter?



Three ways to detect DM

Goal is to maintain the theoretical connection between these approaches

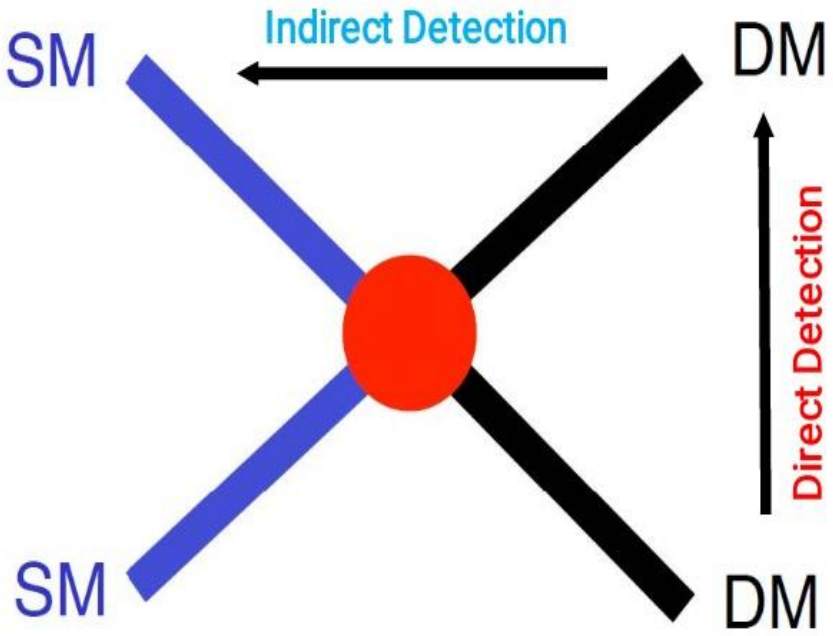
How to Detect Dark matter?



Scattering of DM particles on nuclei of detector material

How to Detect Dark matter?

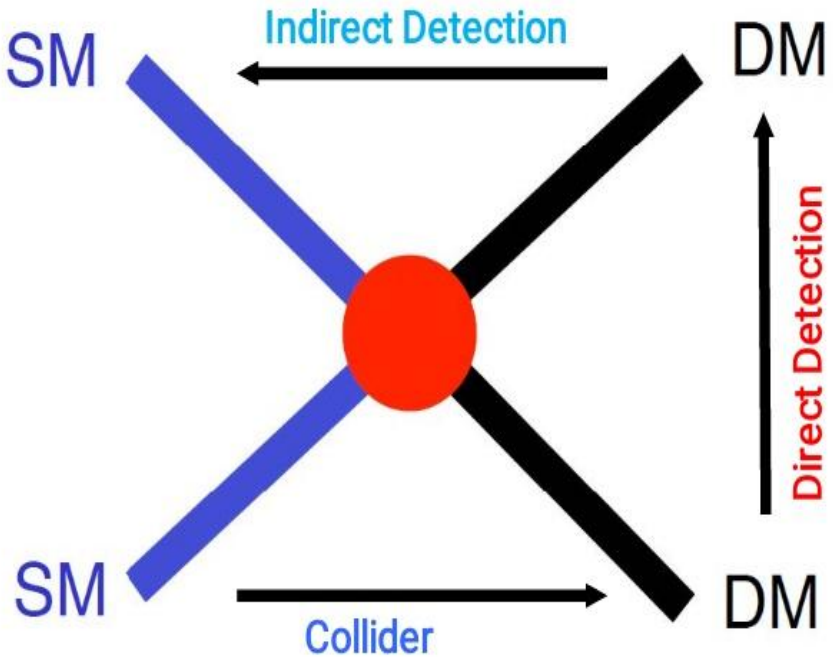
Assume annihilation of DM particles



Scattering of DM particles on nuclei of detector material

How to Detect Dark matter?

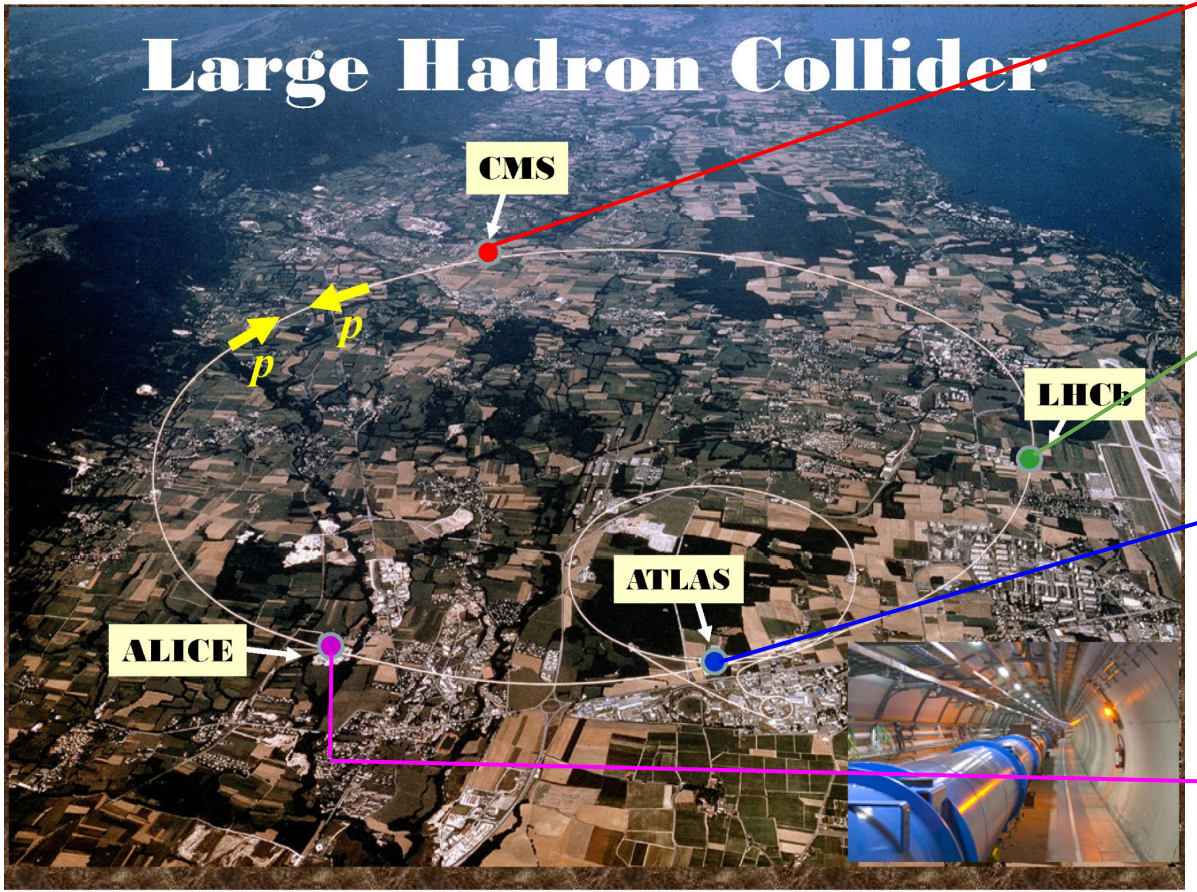
Assume annihilation of DM particles

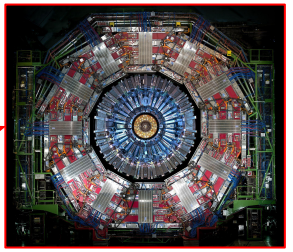


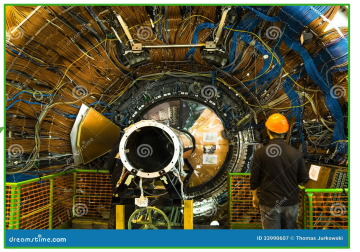
Scattering of DM particles on nuclei of detector material

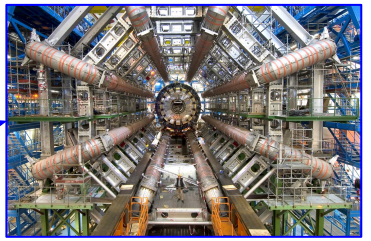
Collision of SM particles (p-p at LHC) DM may produced, appear as **Missing Transverse Momentum**

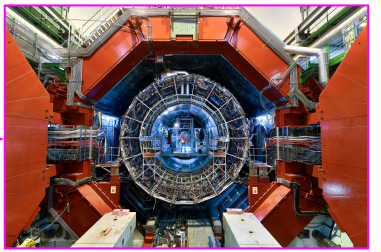
Collider searches at LHC





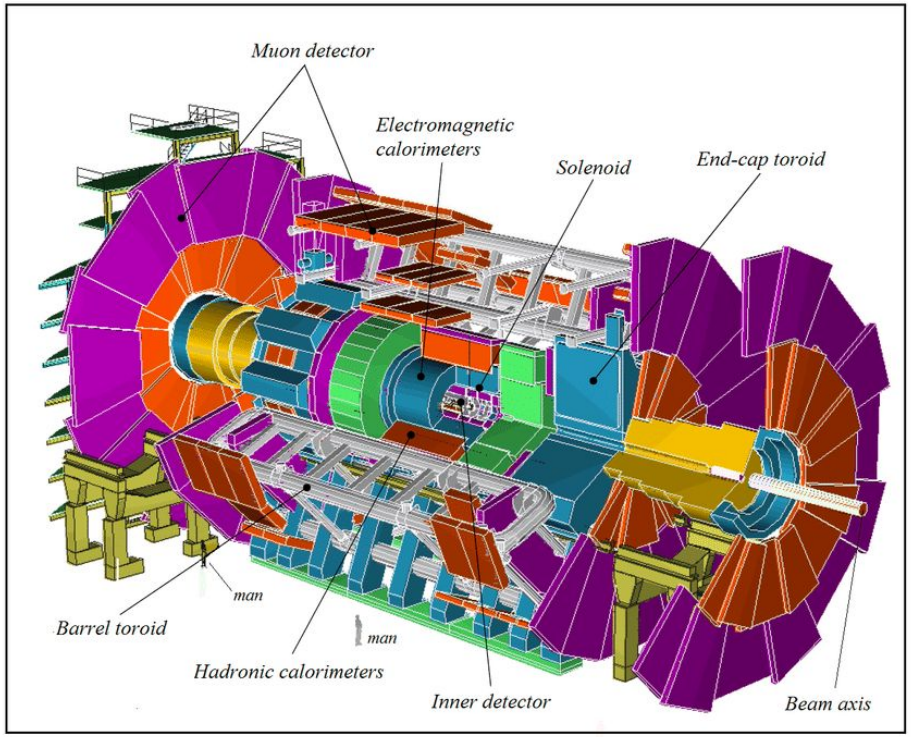






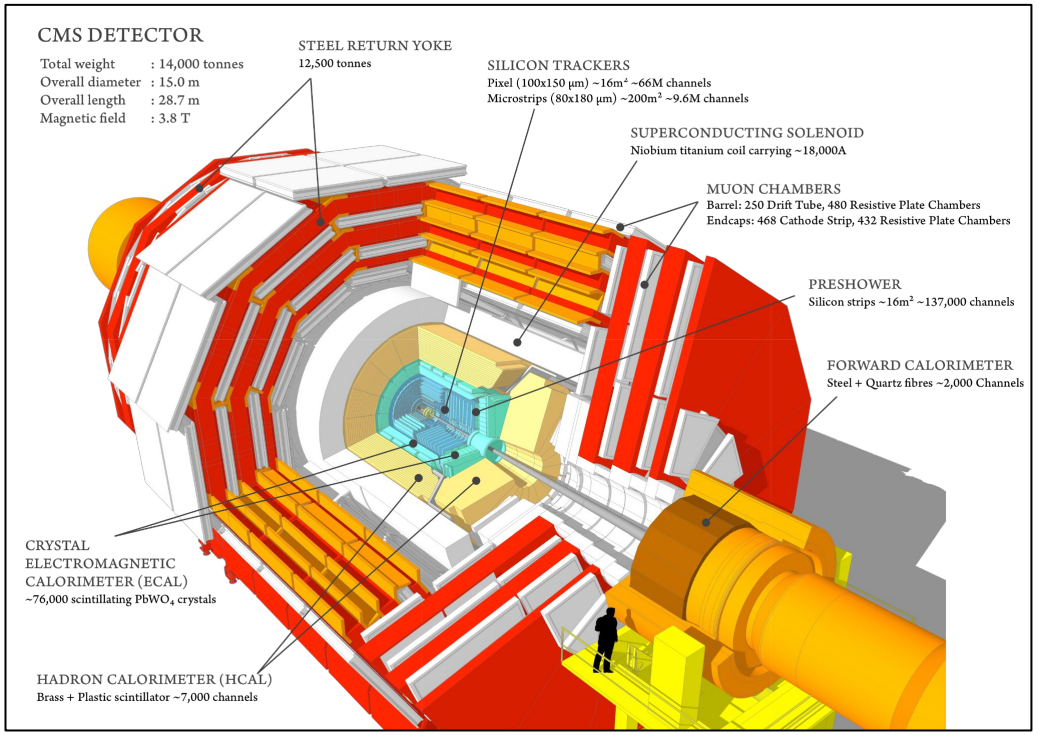
Detectors

ATLAS



46m long, 25m high,
weighs 7000 tons

Compact Muon Solenoid (CMS)



21m long, 15m high,
weighs 14000 tons

Dark matter searches

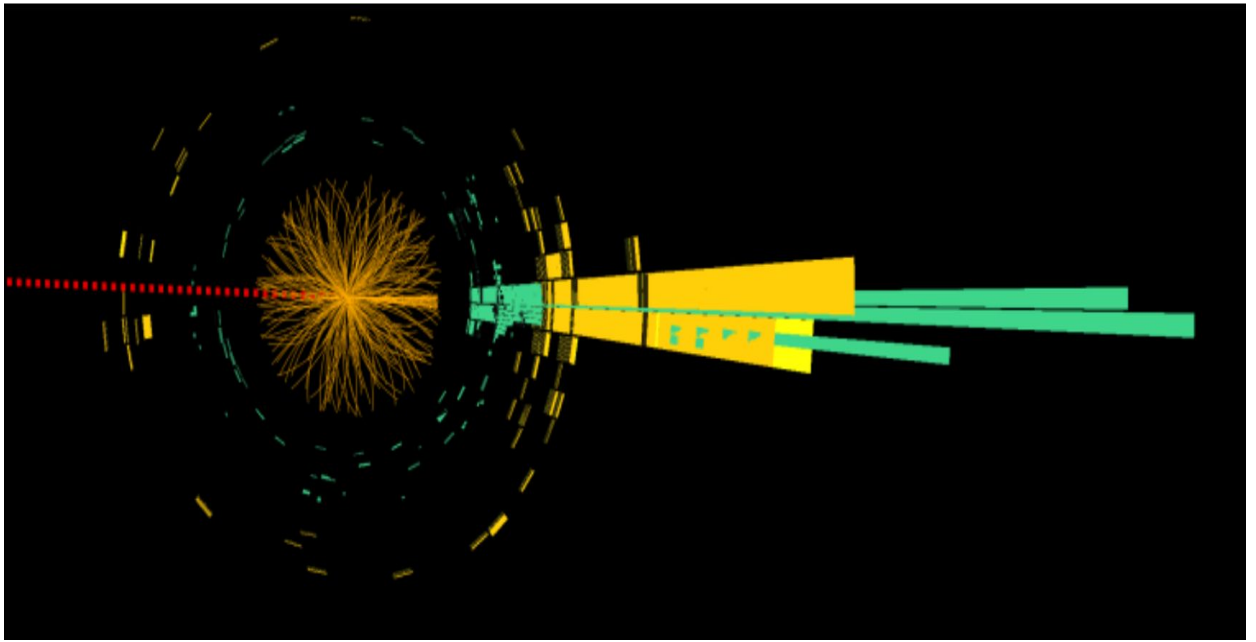
Slide taken from Danyer Pérez Adán

Subset of dark matter topics covered in this talk

Mono-X searches
- Mono-Jets
- Mono-Z
- Mono-Higgs

Higgs to invisible searches

Dark Higgs



Mono-X searches: Mono-Jets

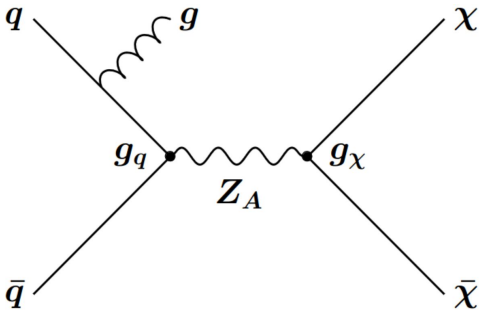
Experimental signature: Jet + Missing Transverse Momentum(MET)

Triggering: Depends on MET
- High MET
- Removes multi-jets backgrounds

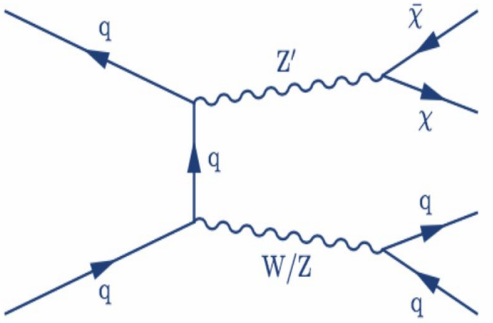
Backgrounds:
- Z/W+jet, top, dibosons, multijet

Event selections:
- Two types of jets are selected
  - MonoV: fat jets produced in V→ qq decays
    - collimated hadrons from energetic quarks
  - MonoJet: standard size jets
- Events with e, μ, τ or γ are vetoed
- large Δφ(jet p_T, MET) to reduce QCD jets

Simplified Model: MonoJet



Simplified Model: MonoV

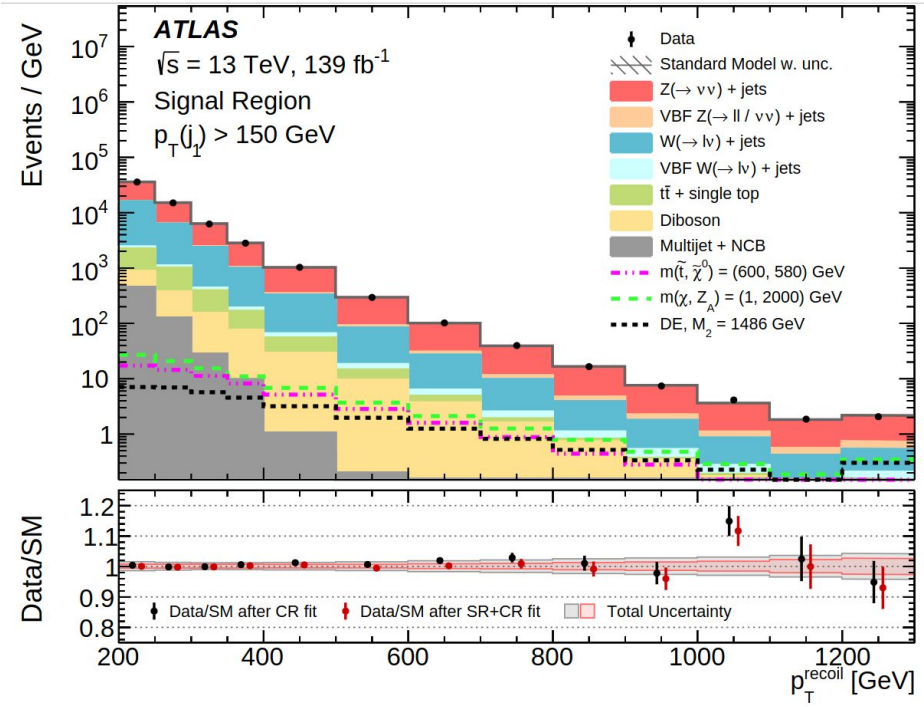


2107.13021 2102.10874

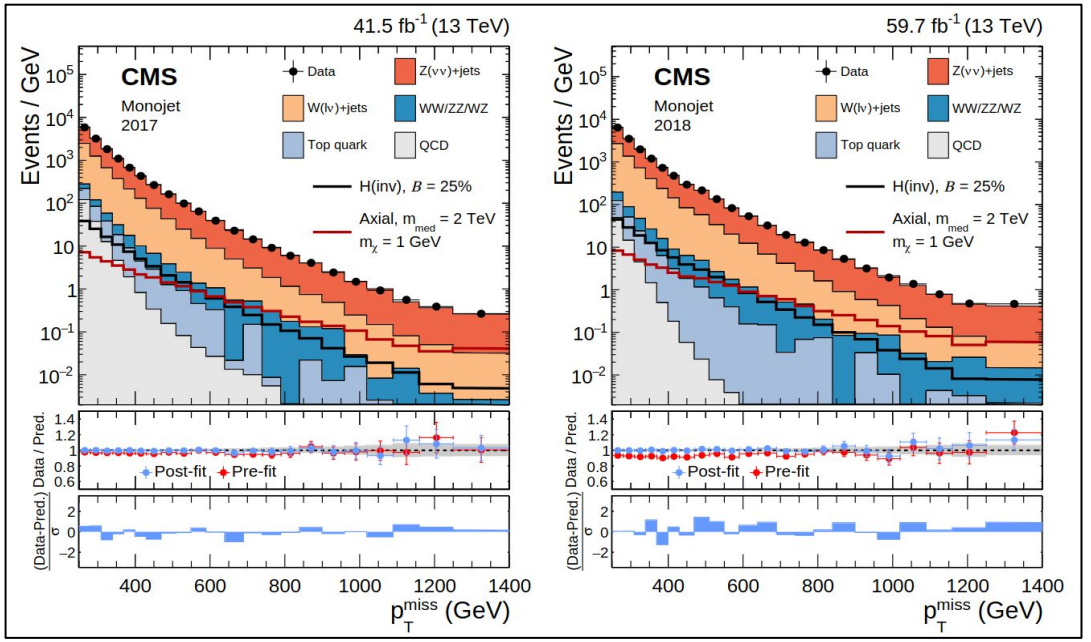
Mono-X searches: Mono-Jets

MET Distribution:

ATLAS: MET includes all CR



CMS: MET includes CR 2017



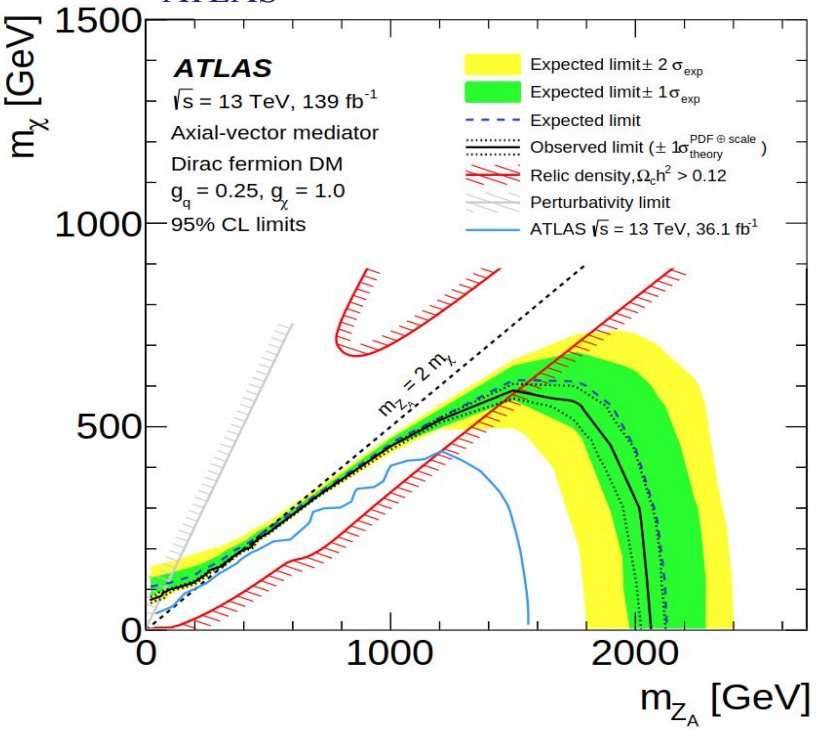
CMS: MET includes CR 2018

2107.13021 2102.10874

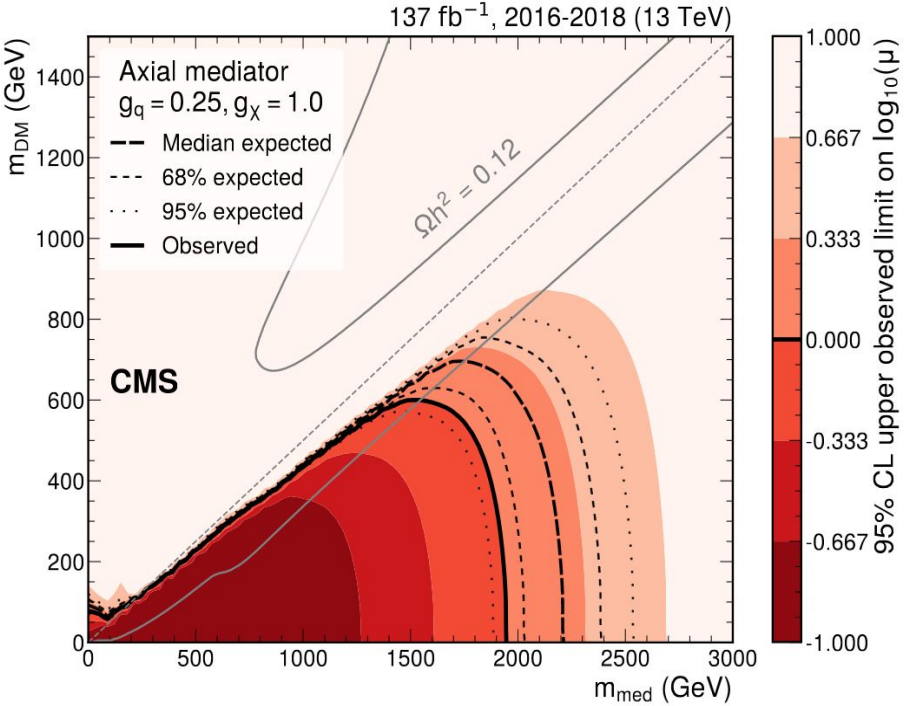
Mono-X searches: Mono-Jets

Results: 2d scan of mediator mass vs dark matter mass

ATLAS



CMS



CMS & ATLAS: Excluding upto mediator mass 2000 GeV

2107.13021 2102.10874

Mono-X searches: Mono-Z(ll)

Experimental signature: Z(→ Two leptons) + Missing Transverse Momentum(MET)

Triggering:

- Depends on 1 or 2 leptons

Backgrounds:

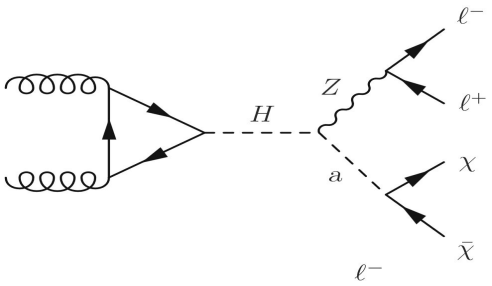
- major backgrounds: ZZ, WZ
- other backgrounds: tt, WW
- To reduce background
  - 3ℓ, 4ℓ CRs to constrain WZ/ZZ
  - eμ CR to constrain tt, WW

Event selections:

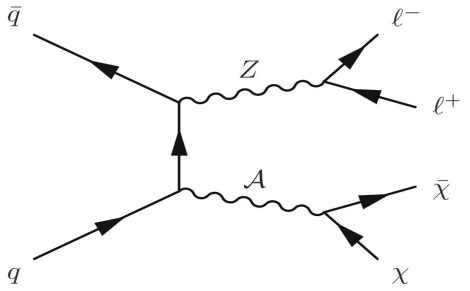
Similar selections in both ATLAS and CMS

- Two lepton with invariant mass (76,106) GeV
- small ΔR(two lepton) to reduce multi-leptons background

2HDM+a



Simplified model

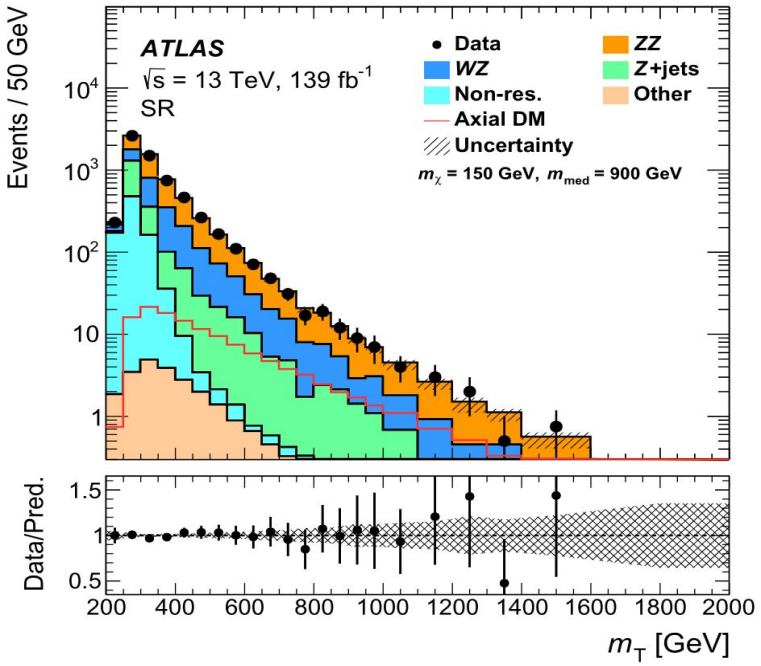


Physics Letters B 829 (2022) 137066 Eur. Phys. J. C (2021)

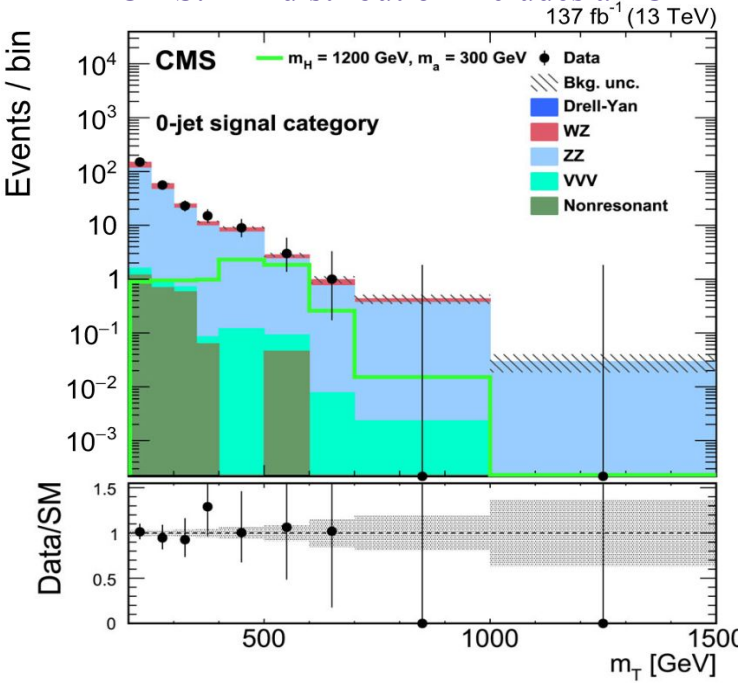
Mono-X searches: Mono-Z(ll)

Transverse Mass Distribution:

ATLAS: MT distribution includes all CR



CMS: MT distribution includes all CR



Non-res: includes WW, ttbar, single top-quark and Z→τ τ
Other: tri-boson, ttbar + V and Z Z → 4l production

Non-resonant: W→ ttbar, tW, and WW

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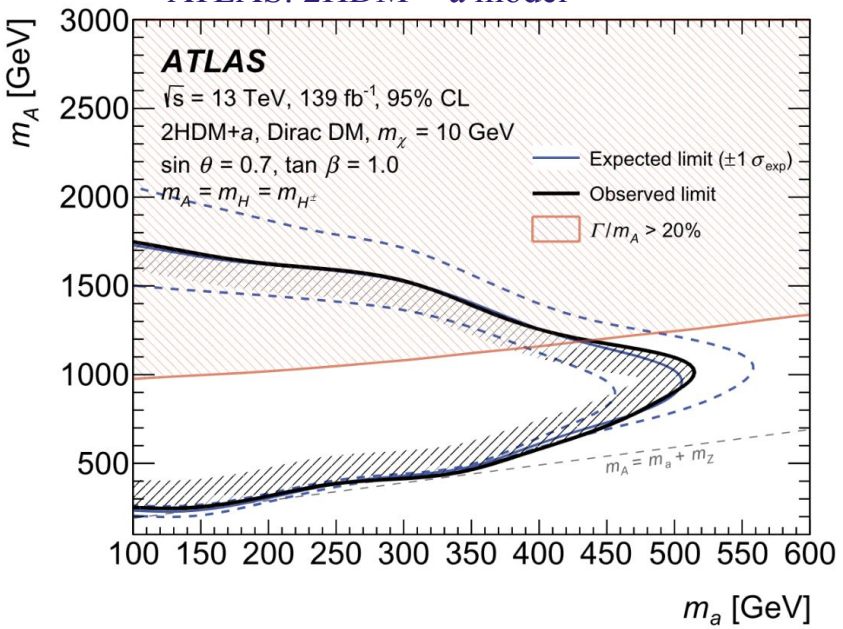
Mono-X searches: Mono-Z(ll)

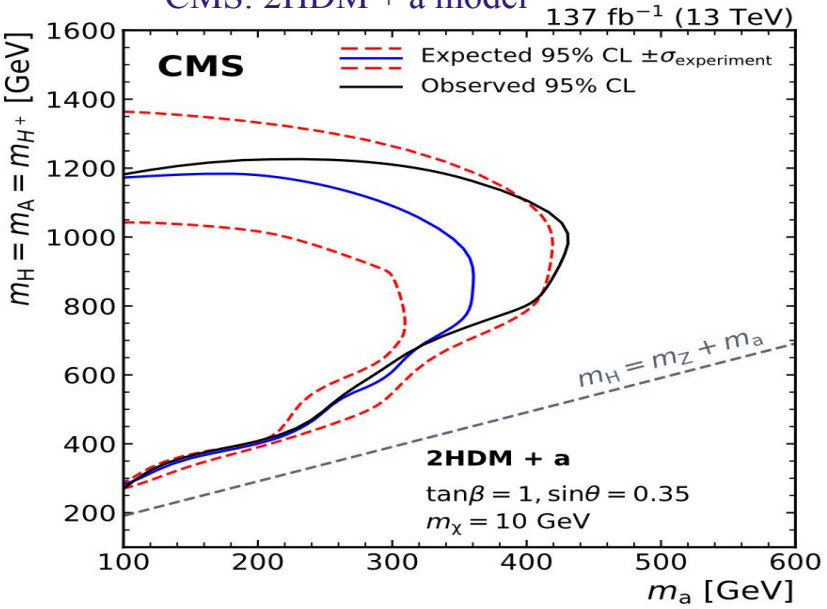
Results: 2d scan of two pseudo-scalar mass

ATLAS: 2HDM + a model



ATLAS Excluding upto mediator mass ~ 250-1700 GeV

CMS: 2HDM + a model



CMS Excluding upto mediator mass ~ 250-1200 GeV

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Mono-X searches: Mono-Higgs($h \rightarrow \tau_h \tau_h$)

Experimental signature: h (→ Two taus) + Missing Transverse Momentum(MET)

Triggering:

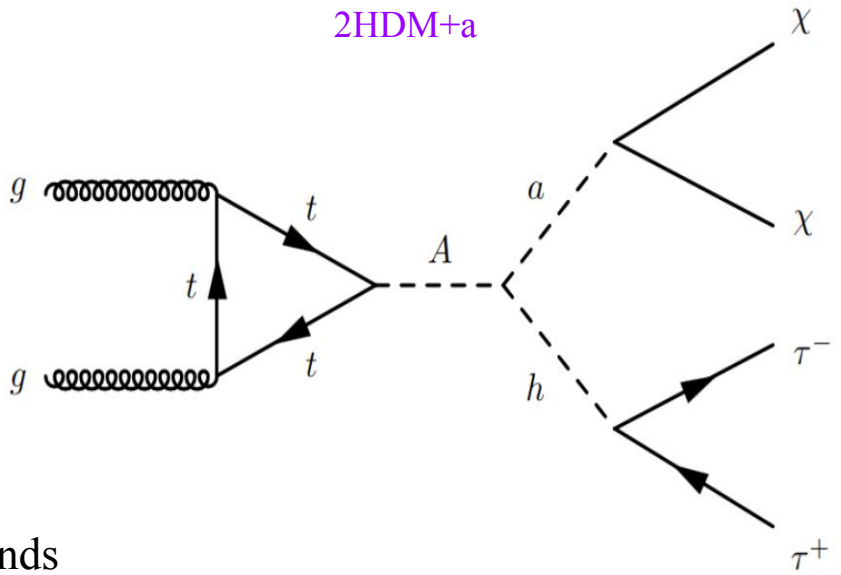
- Di-tau triggers

Backgrounds:

- Dominant background: VV, VH, tt, V+jets

Event selections:

- Two taus with opposite charge
- Third lepton veto: reject multi-lepton backgrounds
- b-jet veto: reject multi jet backgrounds



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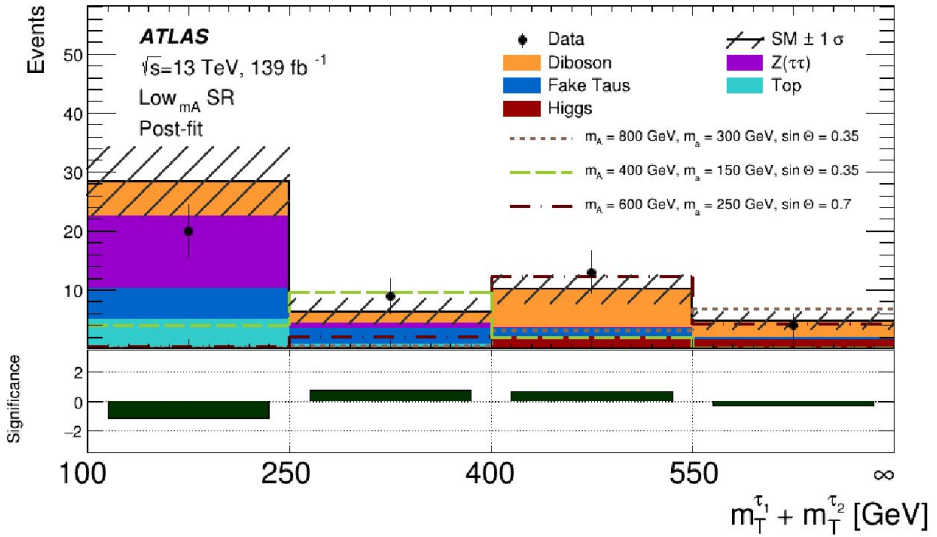
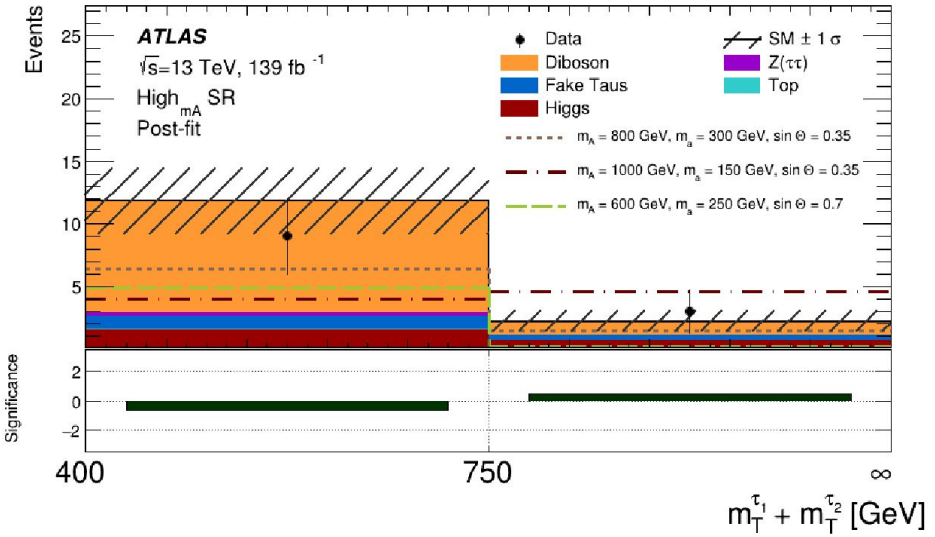
Mono-X searches: Mono-Higgs($h \to \tau_h \tau_h$)

Transverse Mass Distribution: $MT(\tau_1) + MT(\tau_2)$





Low SR: $MT(\tau_1) > 50$, $MT(\tau_2) > 25$, visible mass > 75 GeV

High SR: Total MT > 400 GeV

$MT(\tau_1)$: transverse mass of leading tau
$MT(\tau_2)$: transverse mass of sub-leading tau

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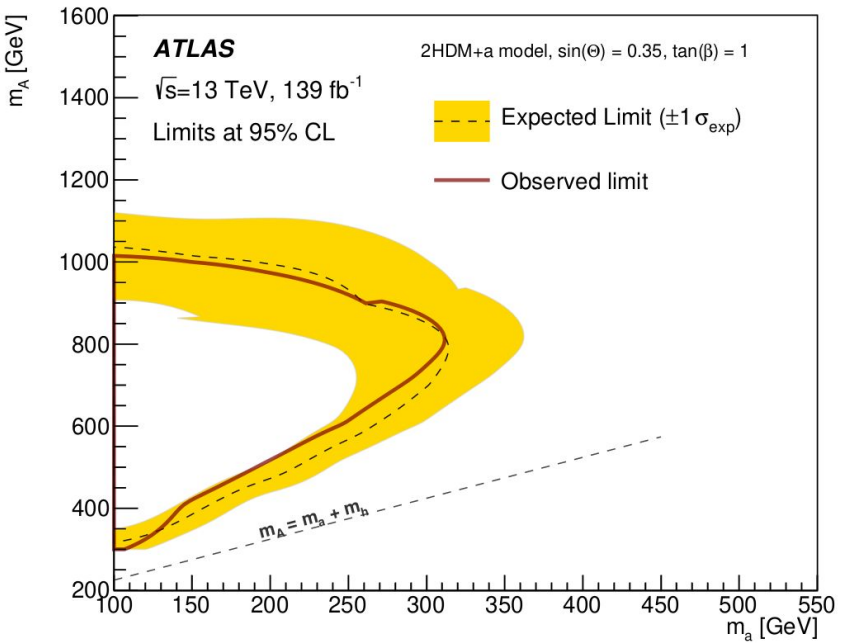
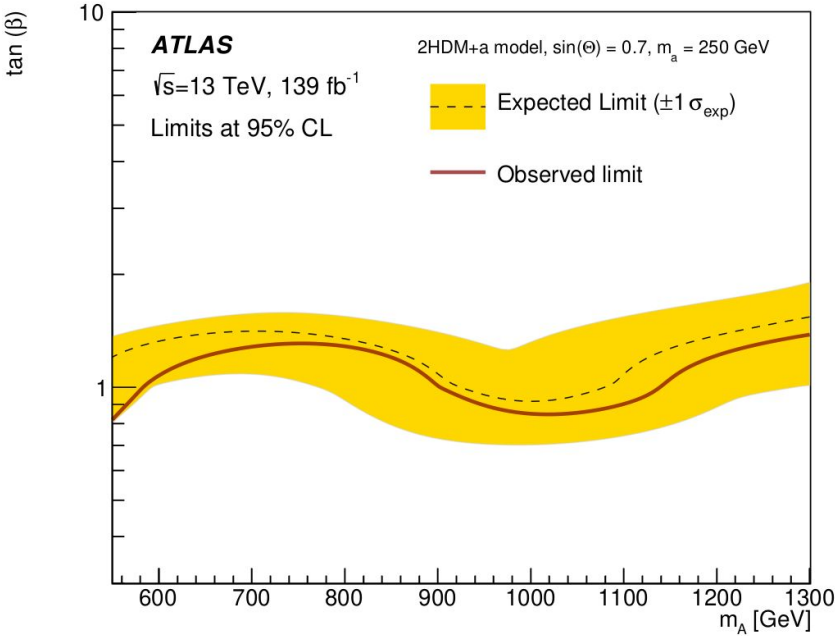
Mono-X searches: Mono-Higgs($h \rightarrow \tau_h \tau_h$)

Results:



For low ma, mA is excluded from ~ 300-1000 GeV,
for sinθ 0.35, tanβ 1



for low tanβ excluding mA from 600 GeV
At sinθ 0.7, ma: 250

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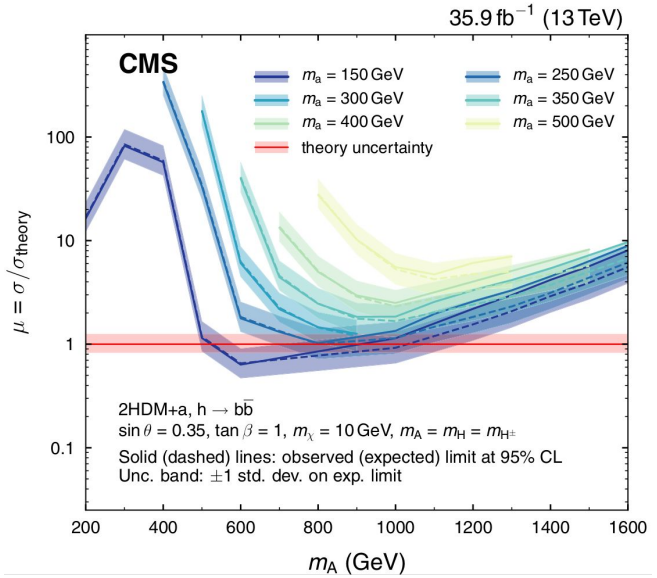
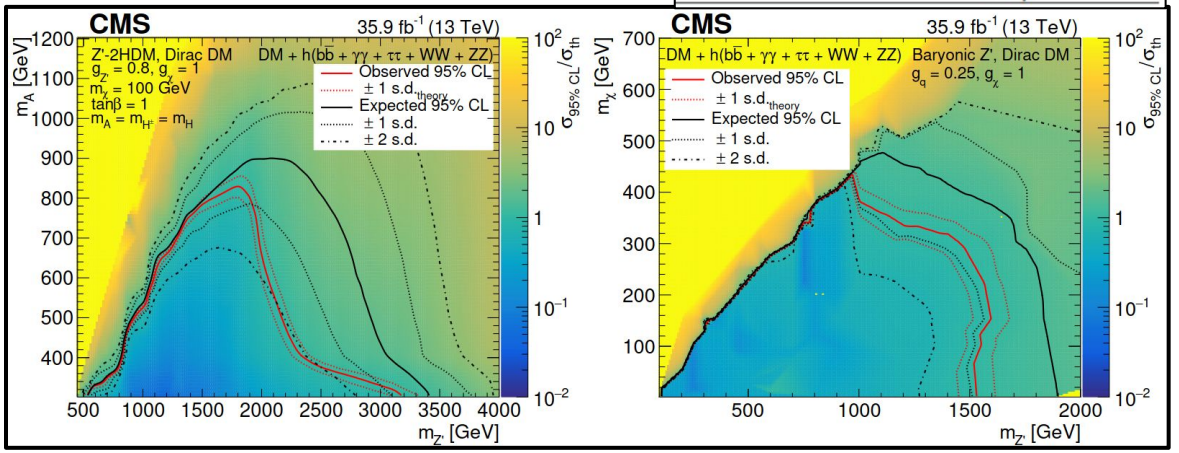
Mono-X searches: Mono-Higgs

Results:

H→bb	most sensitive
2HDM+a	CA15 jets
Baryonic-Z'	CA15 jets
Z'-2HDM	AK8 jets

Decay channel	Final state or category
$h \to bb$	AK8 jet (Z′-2HDM) CA15 jet (Baryonic Z′)
$h \to \gamma\gamma$	$p_T^{miss} \in 50$–130 GeV $p_T^{miss} > 130$ GeV
$h \to \tau\tau$	$\tau_h\tau_h$ $\mu\tau_h$ $e\tau_h$
$h \to WW$	$e\nu\mu\nu$
$h \to ZZ$	$4e$ 4μ $2e2\mu$





h → bbar, mA is excluded from ~400-800 GeV, for sinθ 0.35, tanβ 1, mDM 10 GeV

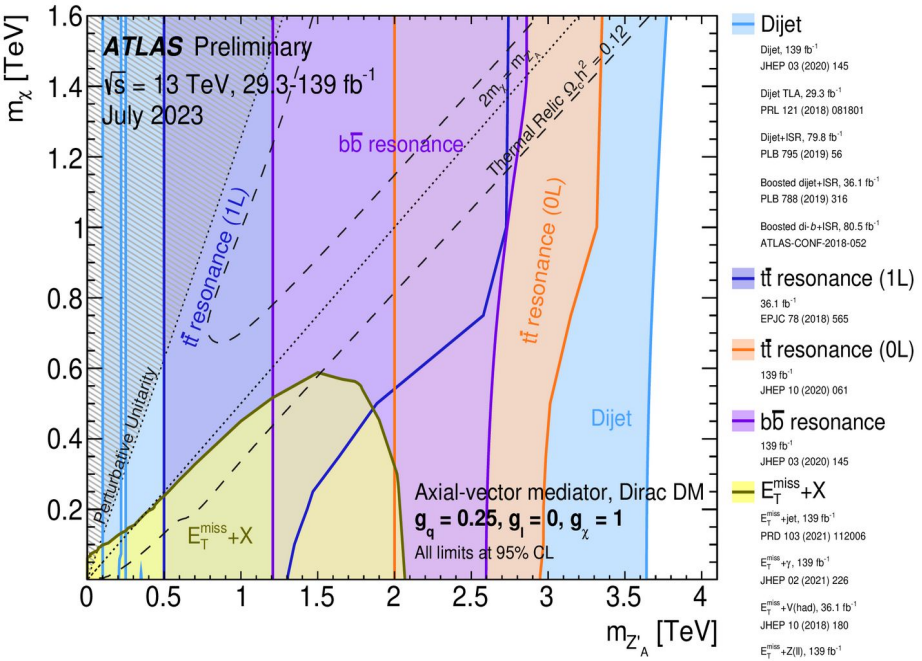
[s10052-019-6730-7]

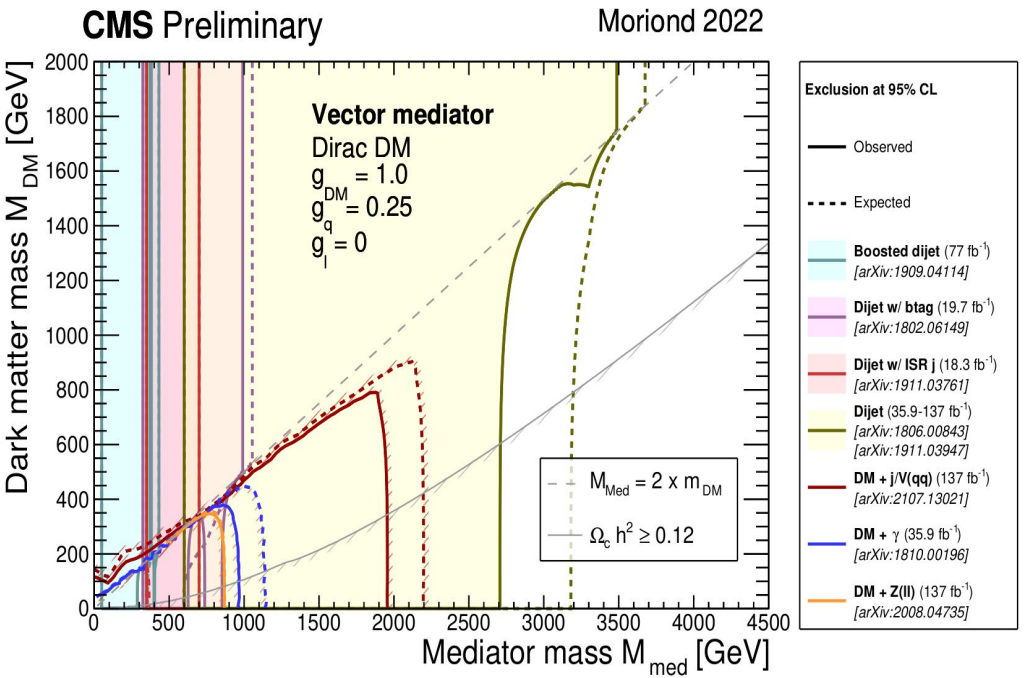
Exclusion region:
Z'-2HMD: mZ' ~ 500-3500 GeV, mass of DM: 850 GeV
Baryonic Z': ~ 2000 GeV, mass of DM: ~ 400 GeV

[JHEP03(2020)025]

Dark matter summary plots

Summary plots of **vector** mediator in simplified model





Exclusions depend on coupling parameters in mediator searches

coupling constant $g_q = 0.25$, $g_\chi = 1$

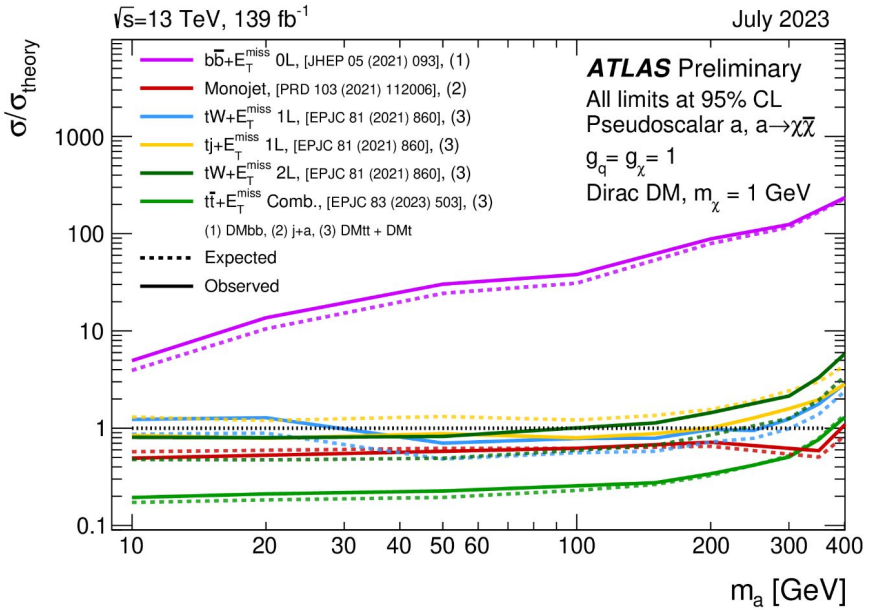
[ATL-PHYS-PUB-2023-018]

[CMS-EXOTICA-Summary]

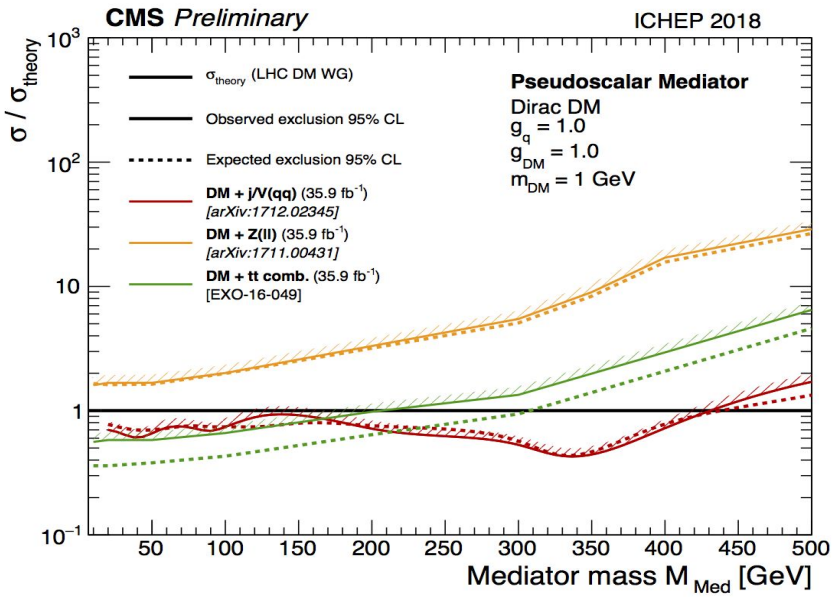
Dark matter summary plots

Summary plots of **pseudoscalar** mediator in simplified model

ATLAS:



CMS:



Exclusions depend on coupling parameters in mediator searches

coupling constant $g_q = g_\chi = 1$

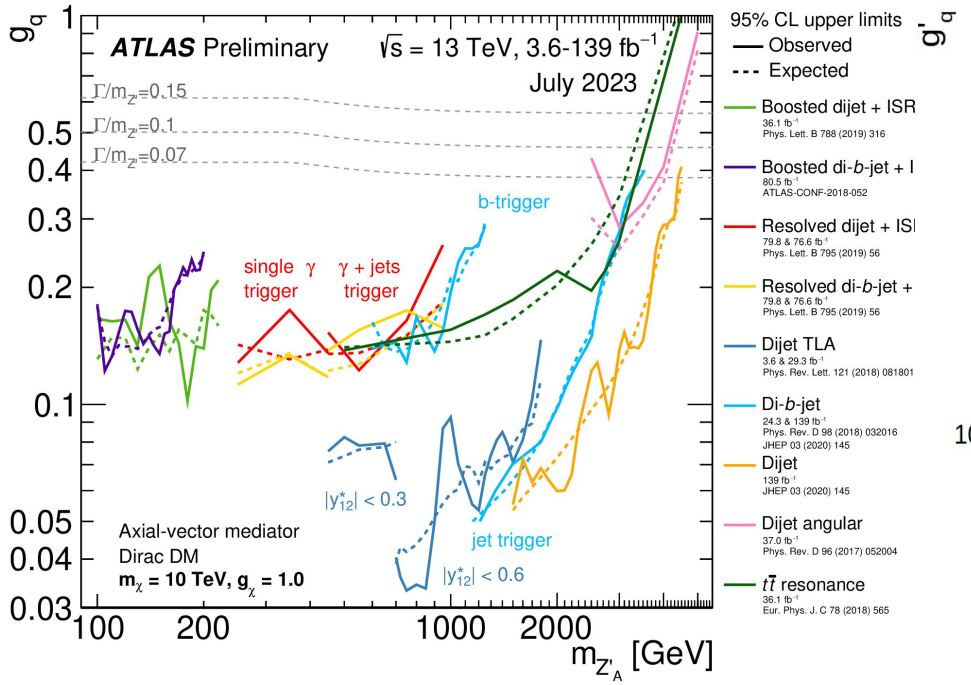
[ATL-PHYS-PUB-2023-018]

[CMS-EXOTICA-Summary]

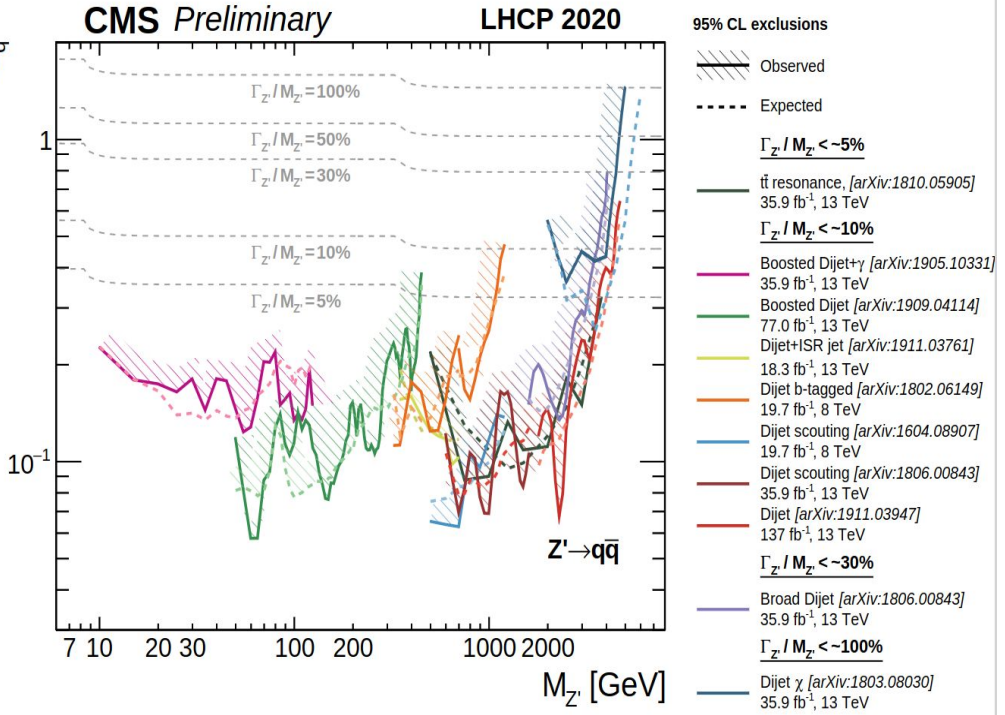
Dark matter summary plots

Summary plots of **coupling constant** in simplified model

ATLAS:



CMS:



Exclusions on the coupling constant depend on decay width of Z' to the Z' mass

[ATL-PHYS-PUB-2023-018]

[CMS-EXOTICA-Summary]

Higgs to invisible searches

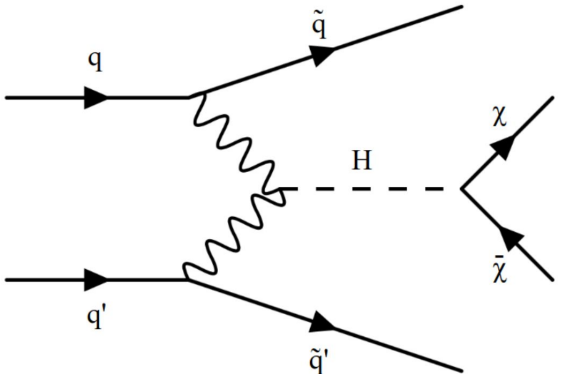
Experimental signature: Jets+ Higgs → Missing Transverse Momentum (MET)

SM BR(h→inv) = 0.1% (h → ZZ*→4ν)

Invisible Higgs decay would increase BR (h->inv) wrt SM predictions

VBF is the most sensitive production mode

VBF Higgs production



Backgrounds:

- Dominant background: Z(→ ν ν) + Jets, W (→ lν) + Jets

Event selections:

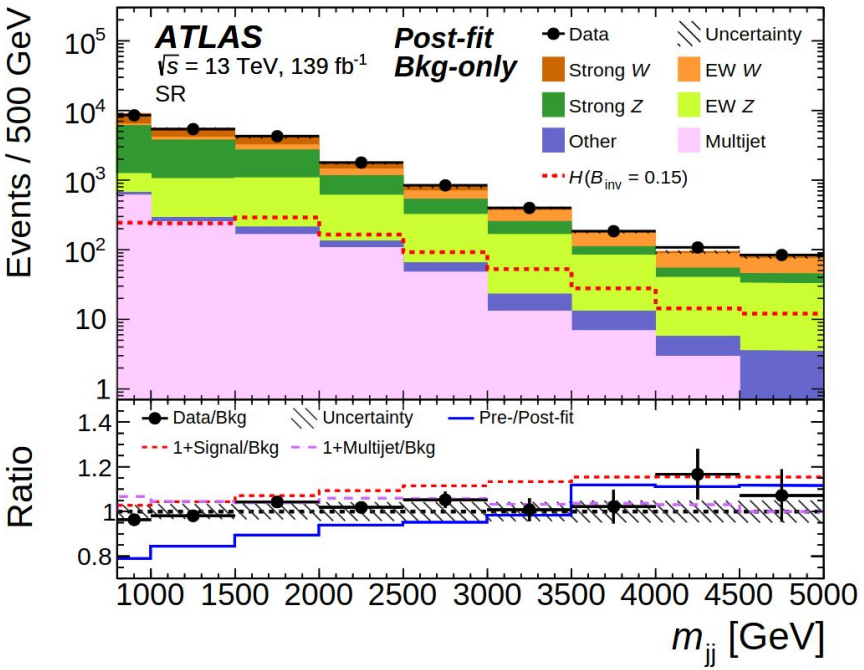
- Triggers: Combination of MET and VBF-like triggers
- Two different category:
  - Moderate MET (VTR), MET p_T (160,250 GeV)
  - High MET (MTR), MET p_T (> 250 GeV)
- Two jets of opposite charge, $|\eta_{jj}| > 1$,
- $\Delta\varphi$(two jets) < 2.0, to avoid double counting of leading jets
- events with charged leptons and photons are vetoed

1903.03616 2202.07953 2201.11585

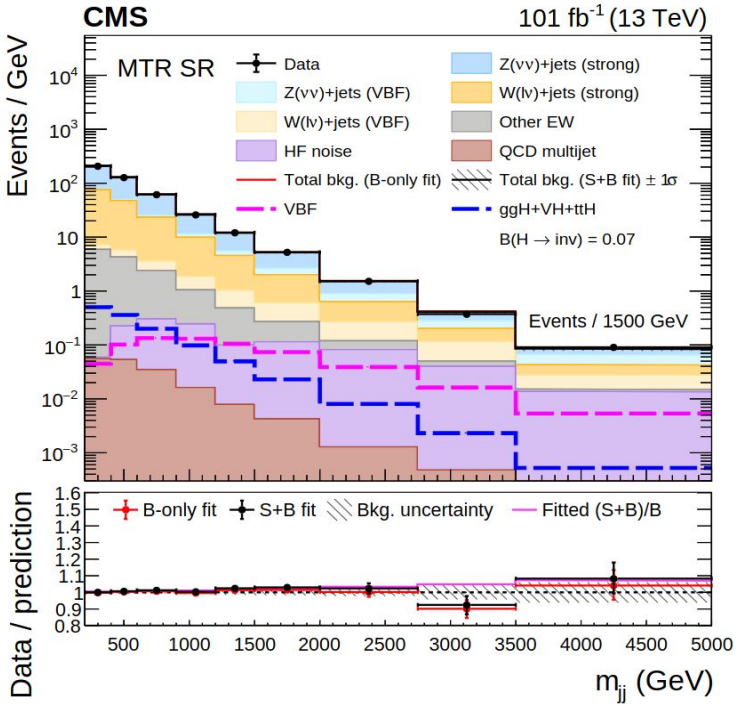
Higgs to invisible searches

Dijet Mass Distribution:

ATLAS:



CMS:

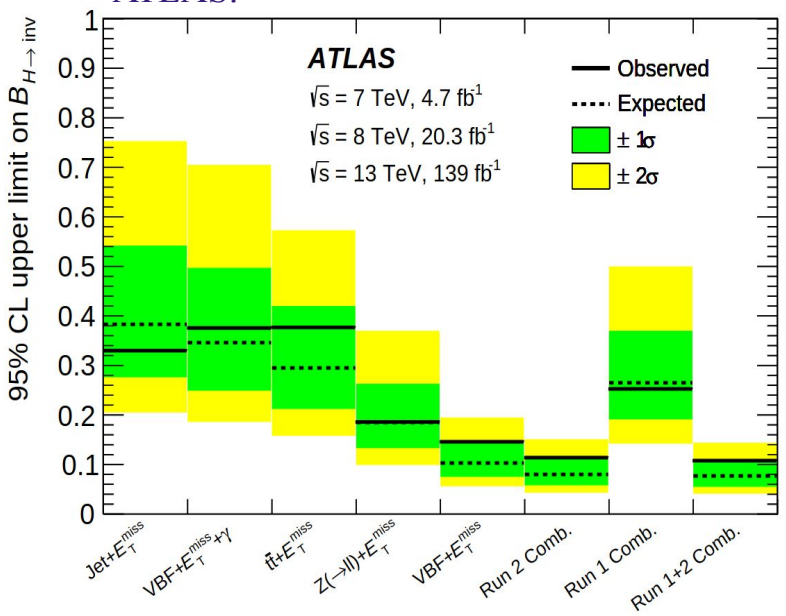


[1903.03616](#) [2202.07953](#) [2201.11585](#)

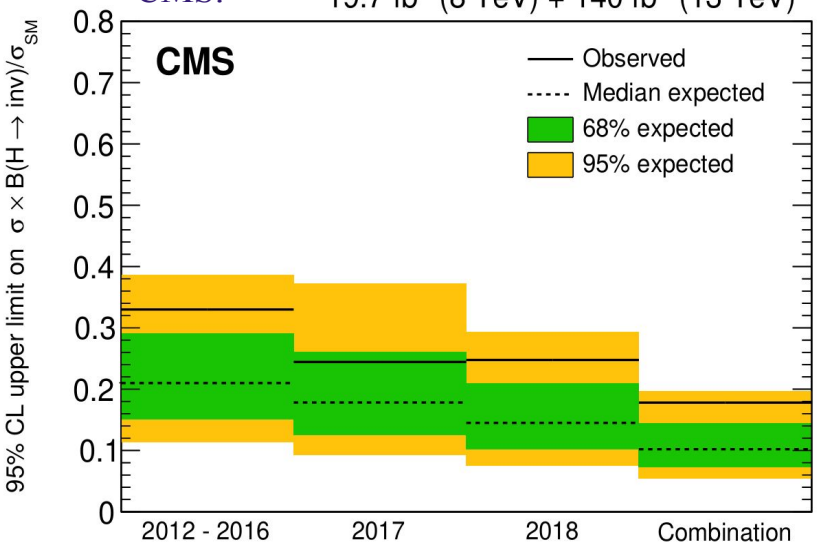
Higgs to invisible searches

results: Upper limits on the BR of h → invisible decay

ATLAS:



CMS:



ATLAS: B(H → Inv) ~ 0.107 2301.10731
CMS: B(H → Inv) ~ 0.18 2201.11585

1903.03616 2301.10731 2201.11585

Dark Higgs

Experimental signature: s → WW → (ℓν+qq)+Missing Transverse Momentum (MET)

Triggering:

- MET
- Single object trigger

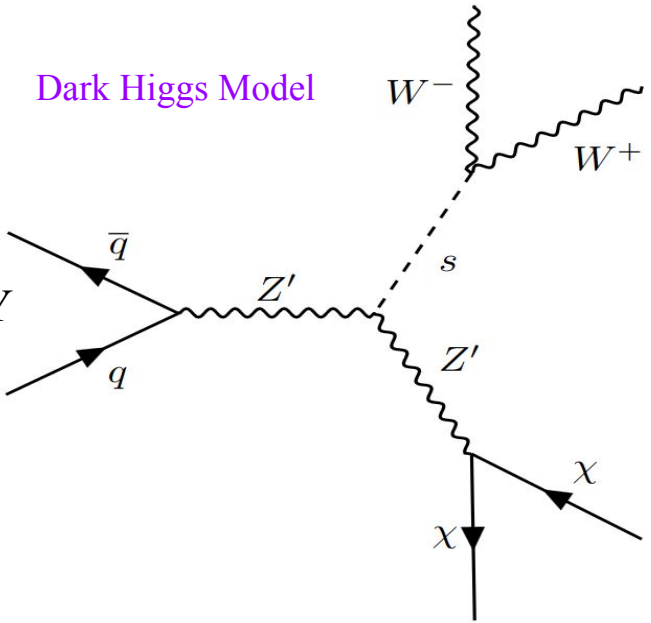
Backgrounds:

- Dominant background: W (→ lν) + Jets, ttbar, WW, DY

Event selections:

- Final state: Hadrons (leptons) at ATLAS (CMS)
- MET: > 200 GeV (> 20 GeV) at ATLAS (CMS)

Dark Higgs Model



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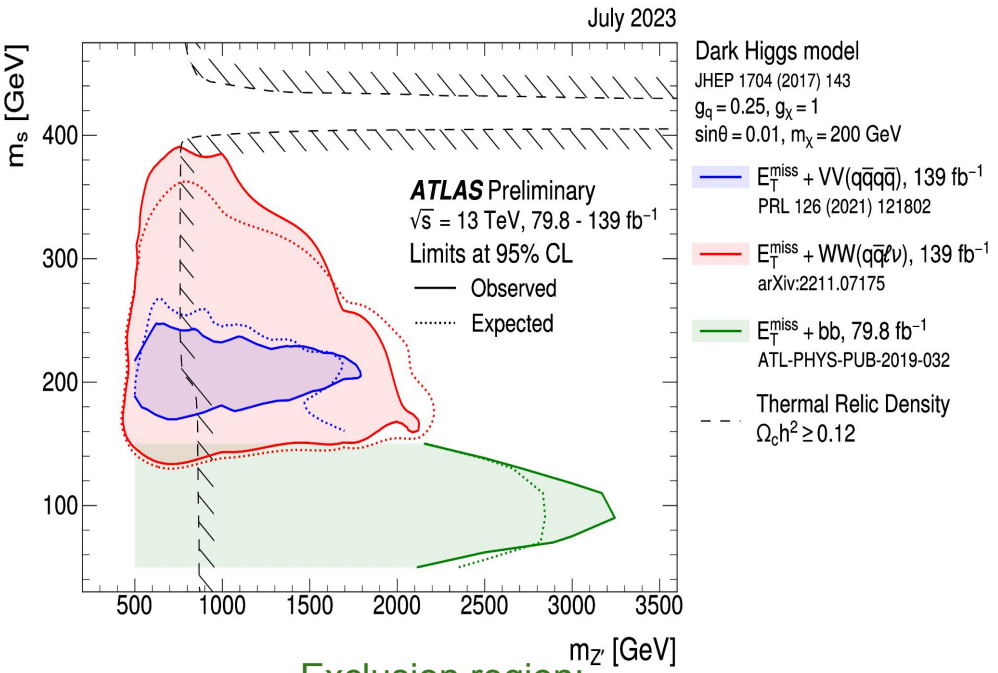
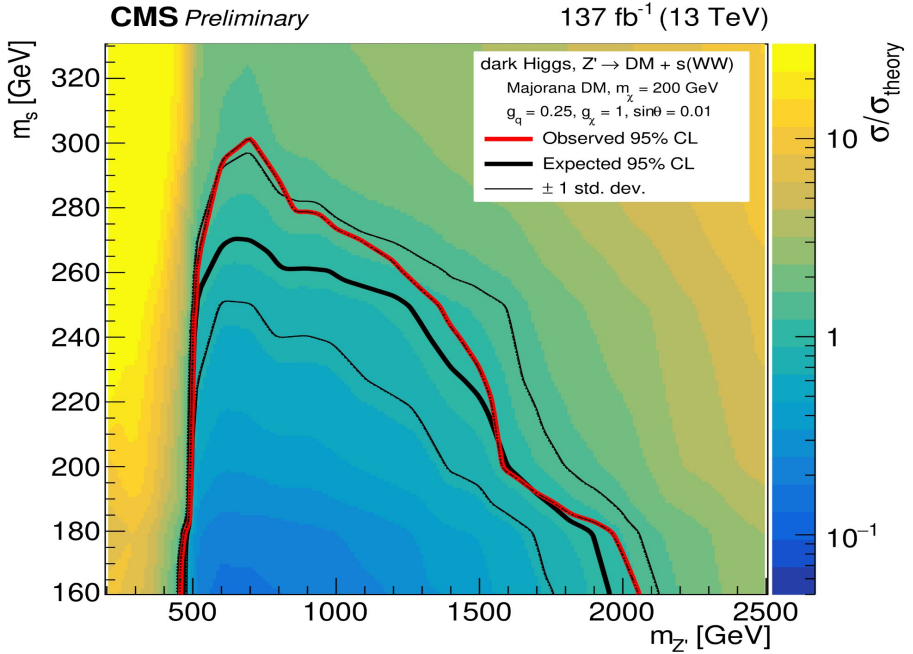
Dark Higgs

Results: 2d scan varying Z' mass vs s mass

coupling constant $g_q = 0.25$, $g_\chi = 1$, mDM = 200





Exclusion region:

- ATLAS (ms ~ 250 GeV, mZ' ~ 2000 GeV)
- CMS (ms ~ 300 GeV, mZ' ~ 500-2000 GeV)

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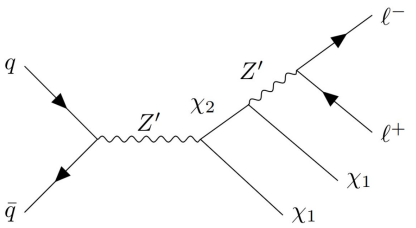
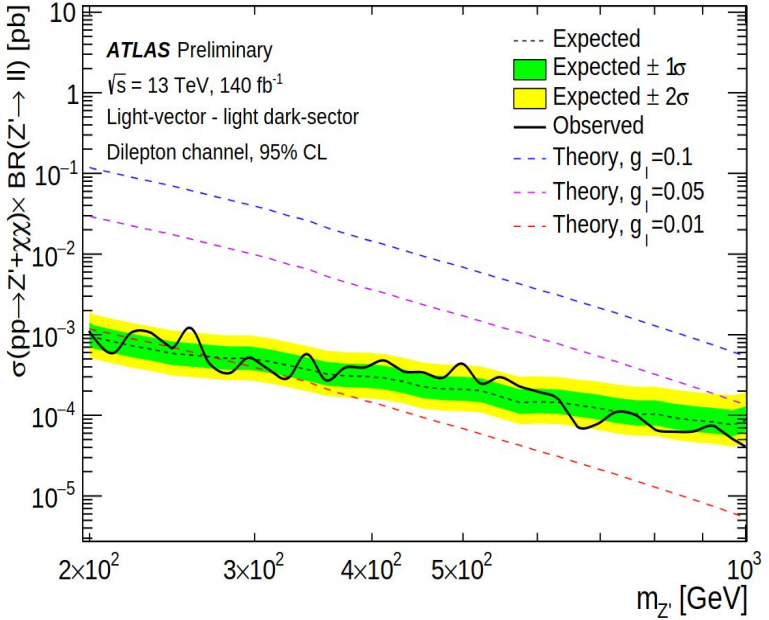
Dark Higgs

Light-vector Model

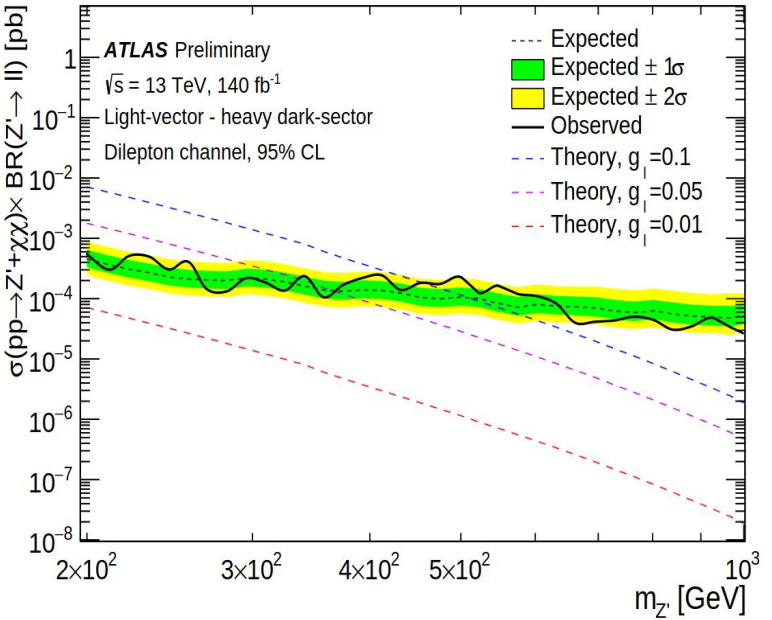


Results: Light Vector model, $g_{DM} = 1$, $g_q = 0.1$, and $g_l = 0.01$

Light Dark sector: combined dilepton channel



Heavy Dark sector: combined dilepton channel



Exclusion region: Z ′ masses ~200-1000 GeV

- Light dark sector: $1 \cdot 10^{-3}$ to $3 \cdot 10^{-5}$ pb
- Heavy dark sector: $4 \cdot 10^{-4}$ to $2 \cdot 10^{-5}$ pb

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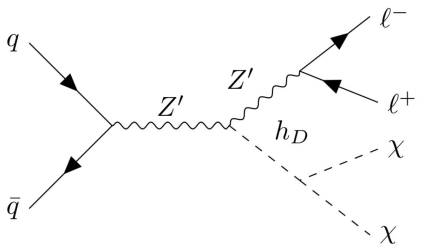
ATLAS-CONF-2023-045.

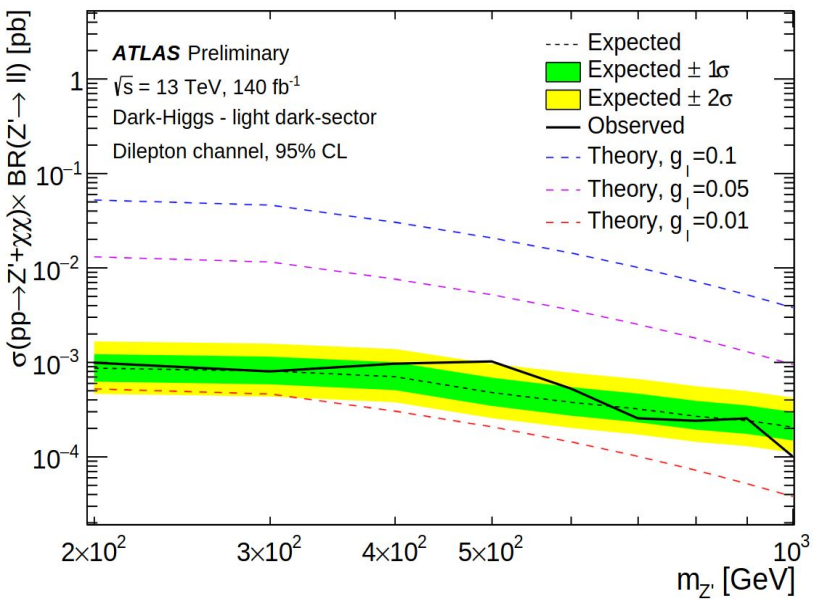
Dark Higgs

Dark-Higgs Model

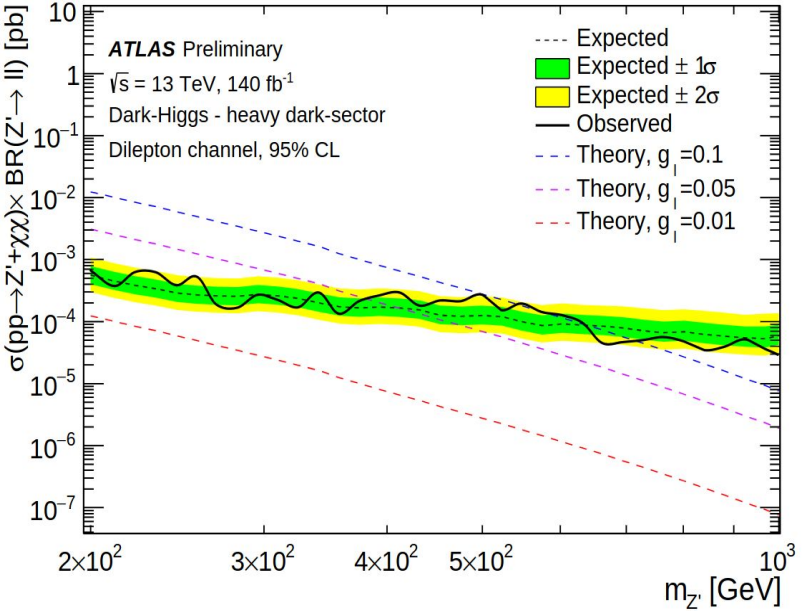


Results: Light Vector model, $g_{DM} = 1$, $g_q = 0.1$, and $g_l = 0.01$

Light Dark sector: combined dilepton channel



Heavy Dark sector: combined dilepton channel



Exclusion region: Z ′ masses ~200-1000 GeV

- Light dark sector: $1.5 \cdot 10^{-3}$ to $3 \cdot 10^{-4}$ pb
- Heavy dark sector: $5 \cdot 10^{-4}$ to $2 \cdot 10^{-5}$ pb

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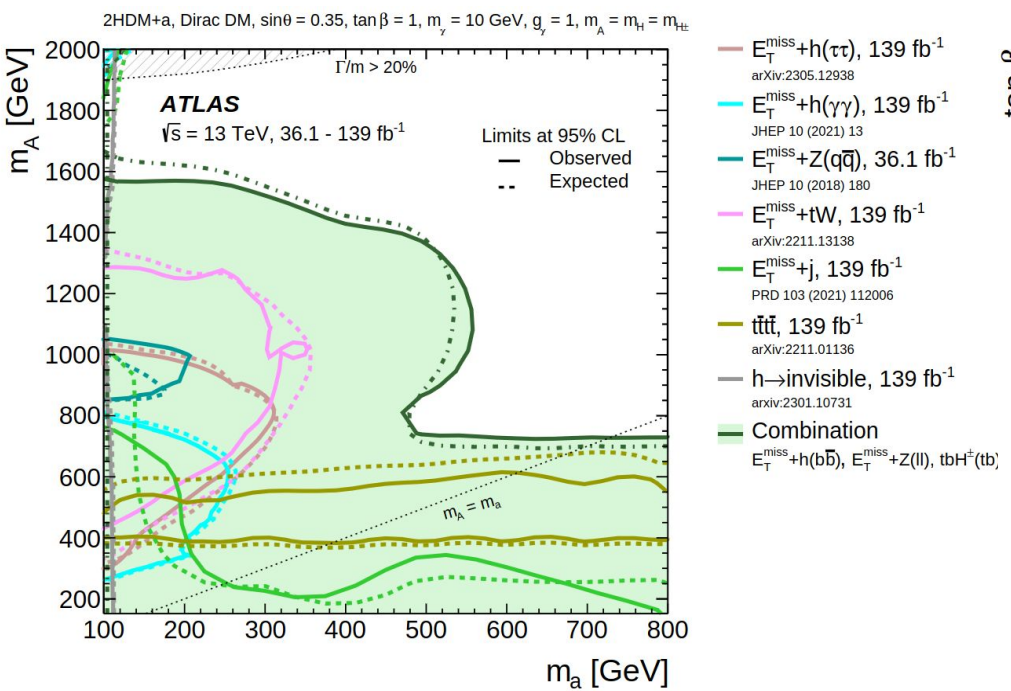
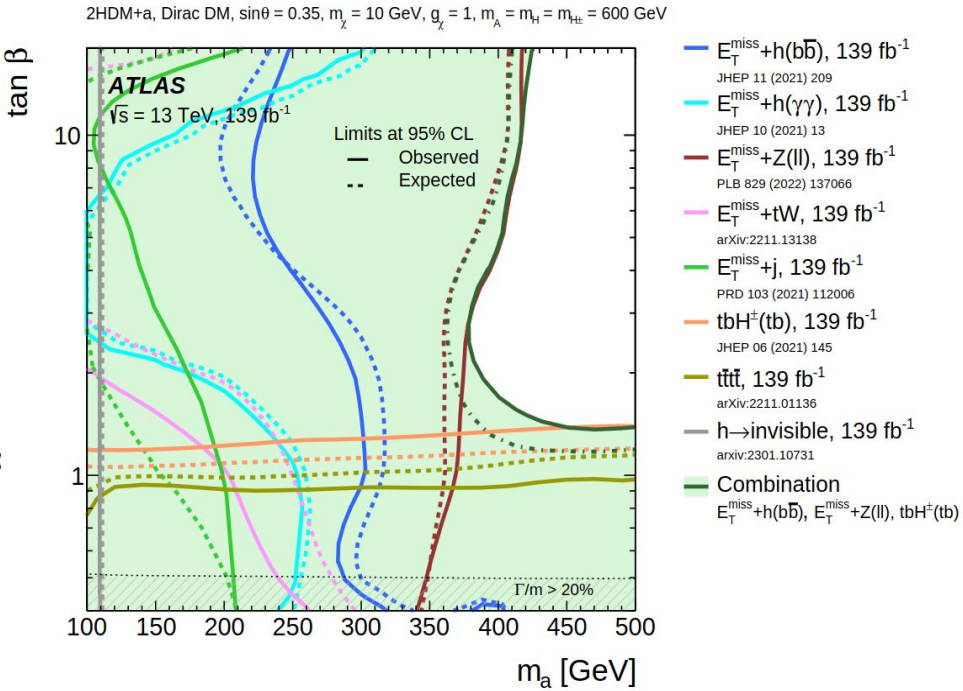
ATLAS-CONF-2023-045.

ATLAS Dark matter summary with 2HDM+a model

2d scan varying two Pseudoscalar masses



2d scan varying light pseudoscalar mass vs tanβ



2306.00641

Summary

- Interesting results for the search of dark matter performed with ATLAS and CMS detector are discussed
- Both ATLAS and CMS experiments probed a wide range of final states and models
- No signal is observed yet
- With large RunII dataset and good improvement on analysis techniques, the background modeling and estimation led to more stringent exclusions
- **Stay tuned for the new results with Run3…**

For more results on DM searches visit ATLAS/CMS

Thank you for your attention…

Backup

Mono-X searches: Mono-Jets

- At least one high pT central jet
- Veto events with leptons (e, μ,τ) and photons γ
- MET (Hadronic Recoil) > 250 GeV

- Events are broadly categorized in mono-jet and mono-V based on leading jet pT
  - **Mono-V:** Jet pT (AK8) > 250 GeV
  - **Mono-jet:** Jet pT (AK4) > 100 (150) GeV

Mono-X searches: Mono-Z(ll)

Table 1 Summary of the kinematic selections for the signal region

Quantity	Requirement	Target backgrounds
N_ℓ	$= 2$ with additional lepton veto	WZ, VVV
p_T^ℓ	$> 25/20$ GeV for leading/subleading	Multijet
Dilepton mass	$\lvert m_{\ell\ell} - m_Z \rvert < 15$ GeV	WW, top quark
Number of jets	≤ 1 jet with $p_T^j > 30$ GeV	DY, top quark, VVV
$p_T^{\ell\ell}$	> 60 GeV	DY
b tagging veto	0 b-tagged jet with $p_T > 30$ GeV	Top quark, VVV
τ lepton veto	0 τ_h cand. with $p_T^\tau > 18$ GeV	WZ
$\Delta\phi(\vec{p}_T^{\,j}, \vec{p}_T^{\,miss})$	> 0.5 radians	DY, WZ
$\Delta\phi(\vec{p}_T^{\,\ell\ell}, \vec{p}_T^{\,miss})$	> 2.6 radians	DY
$\lvert p_T^{miss} - p_T^{\ell\ell} \rvert / p_T^{\ell\ell}$	< 0.4	DY
$\Delta R_{\ell\ell}$	< 1.8	WW, top quark
p_T^{miss} (all but 2HDM+a)	> 100 GeV	DY, WW, top quark
p_T^{miss} (2HDM+a only)	> 80 GeV	DY, WW, top quark
m_T (2HDM+a only)	> 200 GeV	DY, WW, ZZ, top quark

CMS selection

Events in the SR are required to have exactly two oppositely charged electrons or muons with an invariant mass consistent with the mass of the Z boson. The leptons must have $p_T^\ell > 20, 30$ GeV when ordered in increasing p_T. The lepton pair is required to have an invariant mass $m_{\ell\ell}$ in the range $76 < m_{\ell\ell} < 106$ GeV. In order to select events in the SR consistent with invisible particles recoiling against the Z boson, events are required to have $E_T^{miss} > 90$ GeV, $S_{E_T^{miss}} > 9$ and a separation of $\Delta R_{\ell\ell} < 1.8$ between the leptons.

ATLAS selection

Dark Higgs

Signal selection by ATLAS

Table 1: The mass parameters assumed in the light dark-sector and heavy dark-sector benchmark scenarios

	Dark Higgs	Light Vector
Light dark-sector	$m_{\chi} = 5$ GeV	$m_{\chi_1} = 5$ GeV
	$m_{h_D} = 125$ GeV	$m_{\chi_2} = m_{\chi_1} + m_{Z'} + 25$ GeV
Heavy dark-sector	$m_{\chi} = 5$ GeV	$m_{\chi_1} = m_{Z'}/2$
	$m_{h_D} = m_{Z'}$	$m_{\chi_2} = 2m_{Z'}$

In light vector boson mediator: $g_{DM} = 1$, $g_q = 0.1$, and $g_l = 0.01$

Benchmark model	**Limit**	**Cross Section [pb]** *ee*	**Cross Section [pb]** $\mu\mu$	**Lepton Coupling** *ee*	**Lepton Coupling** $\mu\mu$
Light Vector – light dark-sector	Expected	2.5×10^{-4}	4.6×10^{-4}	0.019	0.026
	Observed	3.6×10^{-4}	9.4×10^{-4}	0.023	0.037
Light Vector – heavy dark-sector	Expected	1.3×10^{-4}	2.1×10^{-4}	0.11	0.14
	Observed	1.9×10^{-4}	4.7×10^{-4}	0.13	0.20
Dark Higgs – light dark-sector	Expected	5.8×10^{-4}	1.0×10^{-3}	0.017	0.022
	Observed	8.9×10^{-4}	2.0×10^{-3}	0.021	0.031
Dark Higgs – heavy dark-sector	Expected	1.6×10^{-4}	2.4×10^{-4}	0.076	0.094
	Observed	2.3×10^{-4}	5.3×10^{-4}	0.091	0.14

Event selection by CMS

Quantity	Selection
Number of leptons	2
Lepton flavors	$e\mu$, μe
Lepton charges	Opposite
Additional leptons	0
$p_T^{\ell\,\max}$	> 25
$p_T^{\ell\,\min}$	> 20
$m_{\ell\ell}$	> 12
$p_T^{\ell\ell}$	> 30
p_T^{miss}	> 20
$p_{T,\text{proj}}^{\text{miss}}$	> 20
$m_T^{ll,p_T^{\text{miss}}}$	> 50
$\Delta R_{\ell\ell}$	< 2.5
Number of b-tagged jets	0