qibin.liu@cern.ch

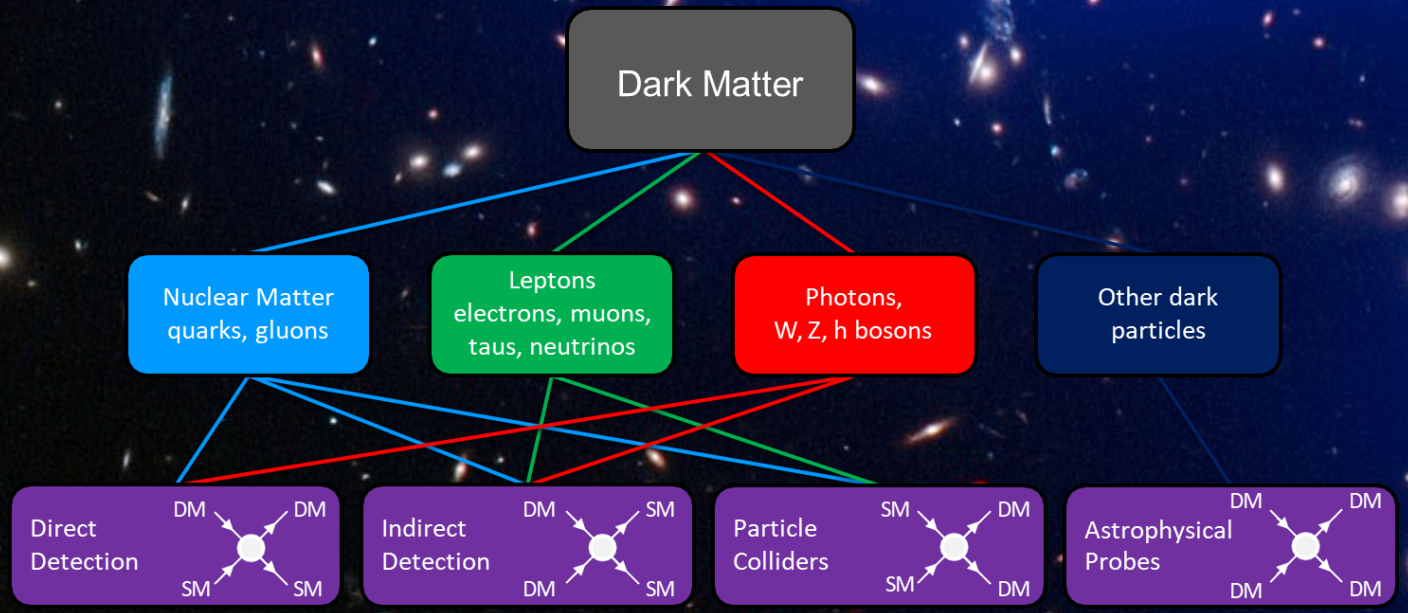
SEARCHES FOR DARK MATTER AT ATLAS

Qibin LIU on behalf on the ATLAS Collaboration

The 29th International Symposium on Particles, Strings and Cosmology (PASCOS2024)

The Dark Matter

- Existence of dark matter (DM) supported by many pieces of evidence and contradictions in DM-free theories
  - Galaxy rotation , gravity lensing, bullet cluster, cosmic microwave background, so on
- DM makes up most of our universe – its nature remains largely unknown
  - Known only from its gravitational effect
- In quest to search for any possible interaction beyond gravity

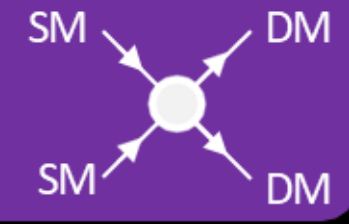


1305.1605

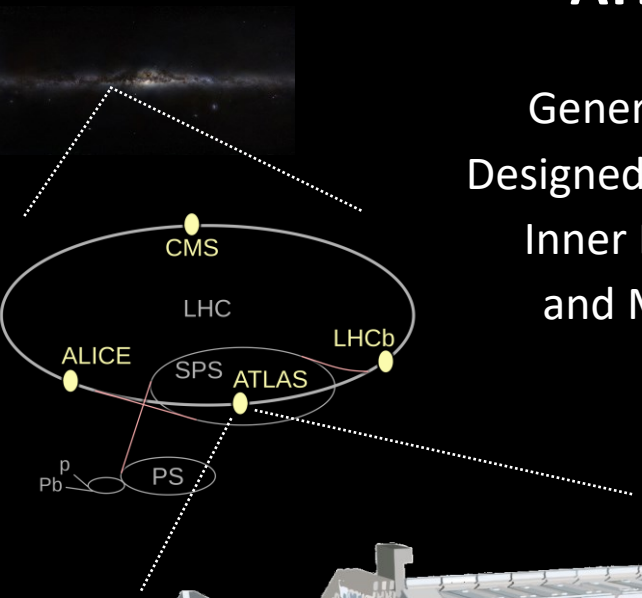
MACS J0152.5-2852

Dark Matter Search at ATLAS

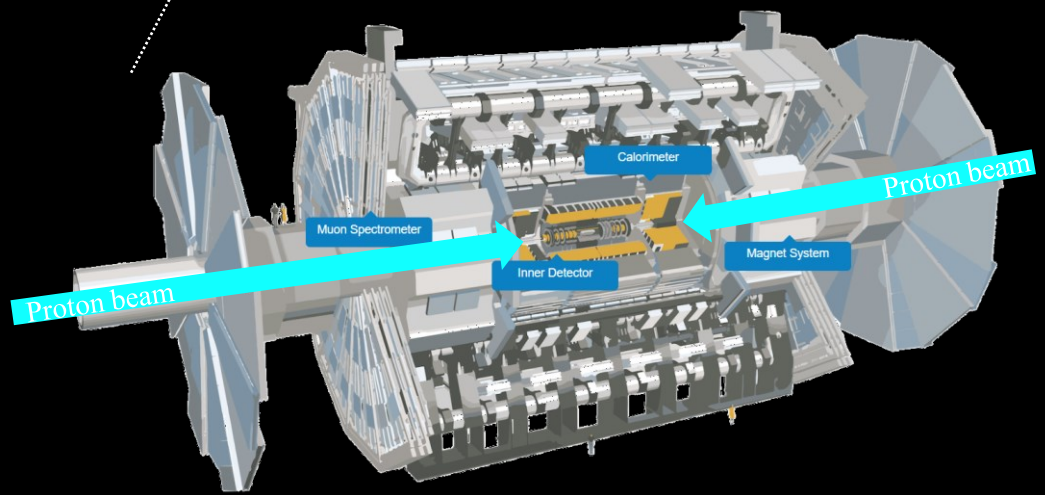
Particle Colliders

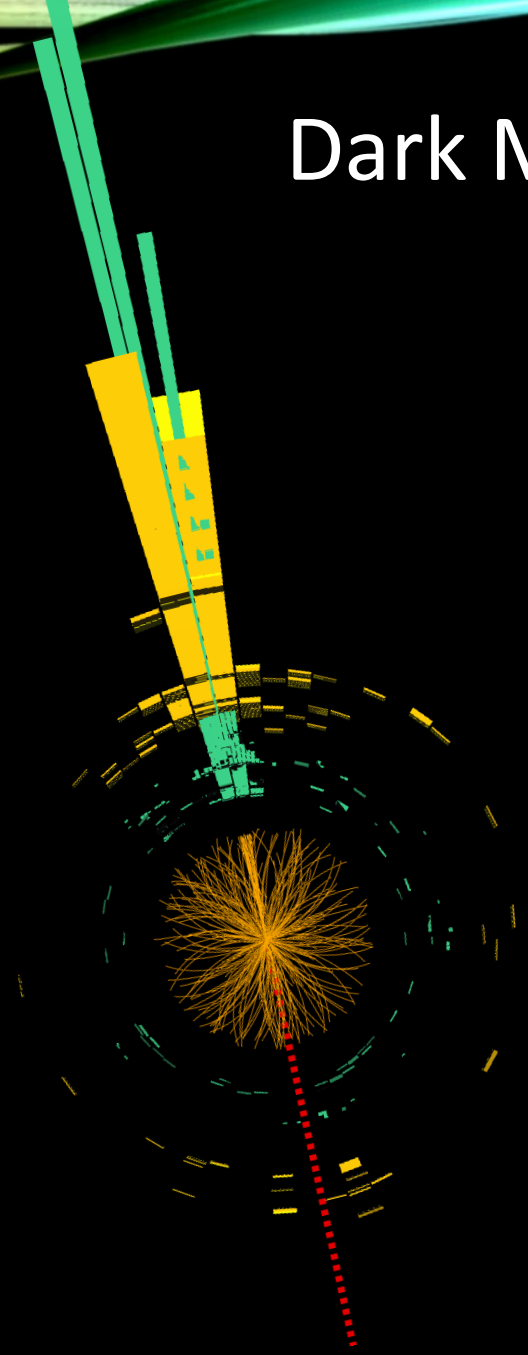


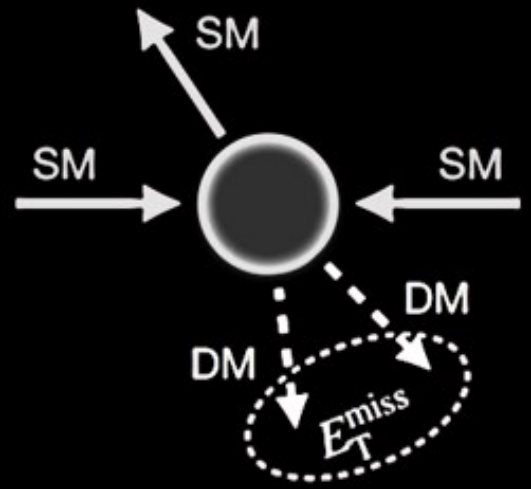
ATLAS Detector



General-purpose detector
Designed for p-p collision at LHC
Inner Detector, calorimeters
and Muon spectrometer





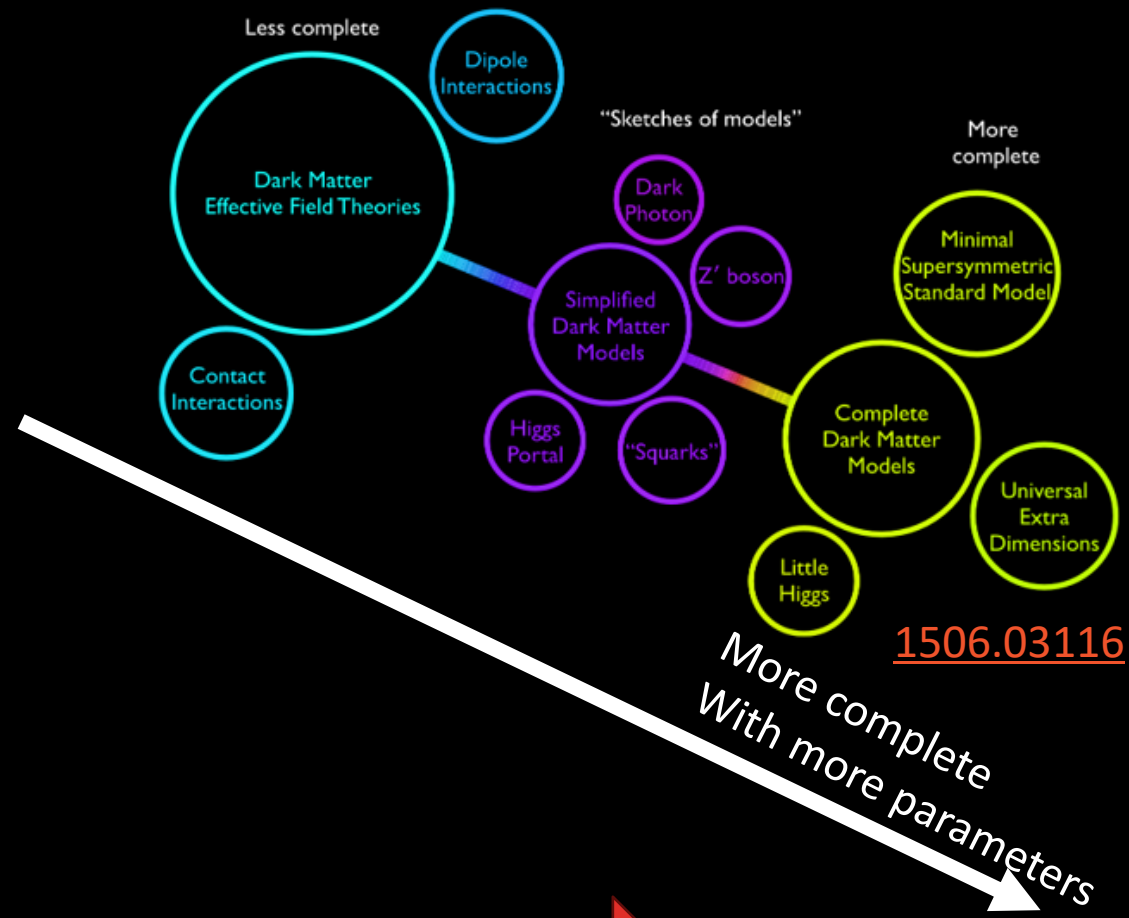


Detection of Dark Matter

DM invisible from detector: E_T^{miss}
→ Detect from recoil of visible particles
→ Detect from resonance or unusual signature
If nothing detected: exclusion limit is set

Outline of Contents

- Recent ATLAS results on DM searches covered:
  - Signature-oriented analyses with model interpretation: mono-X (X=t, Z/W), dark Higgs, dark meson and so on
  - Model-driven summary or combination: s-channel simplified model, extended two-Higgs-doublet (2HDM) model
- Topics not covered: more results which are interesting!
  - $E_T^{miss} + t\bar{t}$, ISR Dijet, Invisible Higgs, Semi-visible jets, Rare Z decay, ...
  - Search for supersymmetry (SUSY) particles
  - Model-agnostic DM search
  - Check on ATLAS latest public results
- Let's dive in the dark!



Dark Higgs
Dark Meson
Dark Jet
Dark Photon

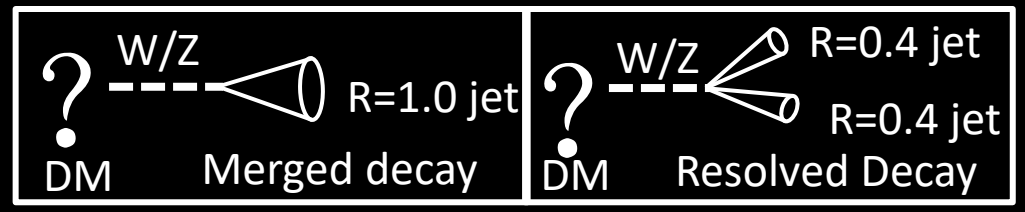
Model-agnostic — **Signature-oriented** — **Model-driven**

(See Antonio's talk)

Mono-Top
Mono-V

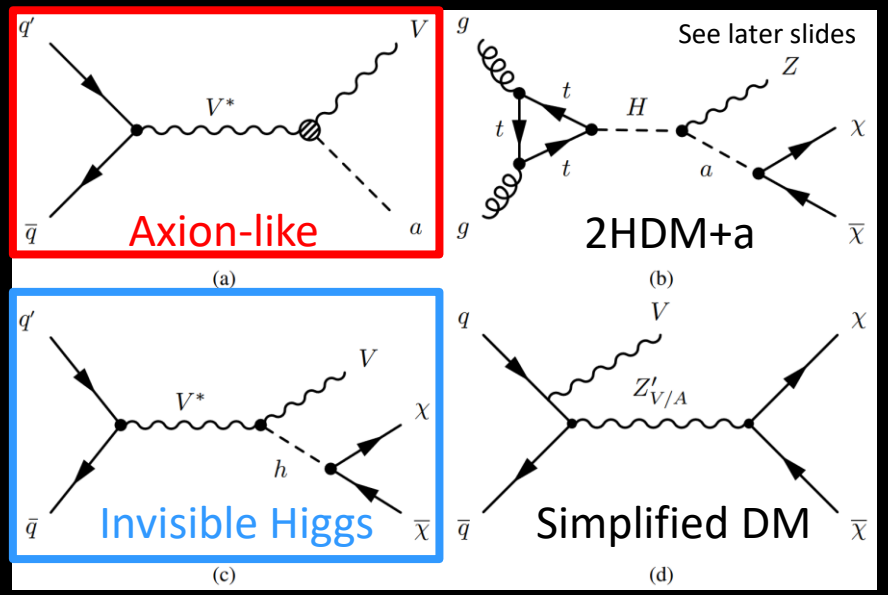
S-channel Simplified Model
Extended Higgs (2HDM+S,2HDM+a)

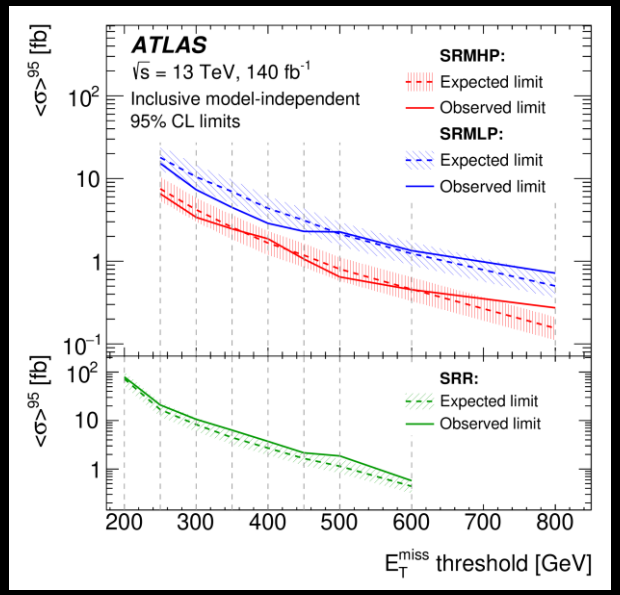
$E_T^{miss} + W/Z(qq)$



- Search for DM with hadronic decay vector boson + E_T^{miss}
- **Merged (SRM)** and resolved (SRR) regions
  - High purity (HP) region: pass **W/Z tagger**
  - Low purity (LP) region: fail tag but in W/Z mass window
- Background:
  - $Z(\nu\nu) + jets, W(l\nu) + jets, t\bar{t}$: MC and control using data
  - QCD: estimated from data sideband and <1% in total

3-var W/Z tagger
jet mass
number of track
jet substructure(D2)

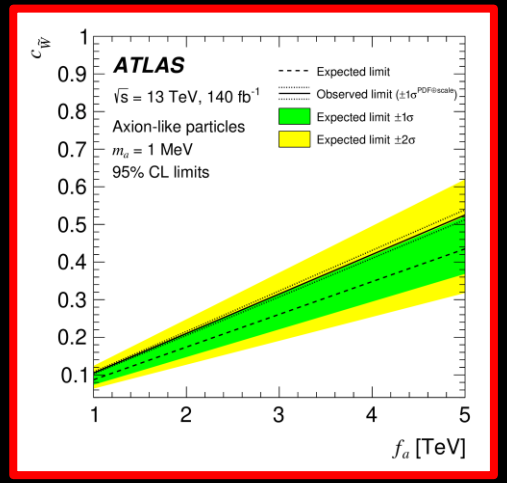




Model Independent Limit

→ **No significant excess observed above SM**

→ **Upper exclusion limits 79.5 fb - 0.3 fb at 95% CL**

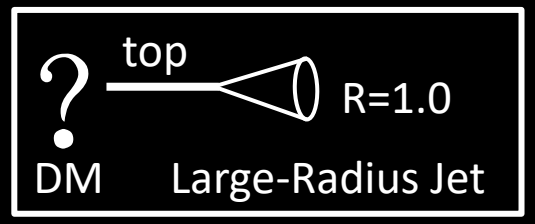


Limits on $B_{h\to inv.}$	Expected limit
Merged topology	$0.34^{+0.14}_{-0.09}$
Resolved topology	$0.54^{+0.23}_{-0.15}$
Combined	$0.31^{+0.13}_{-0.09}$

Limits on $B_{h\to inv.}$	Observed limit
Merged topology	0.38
Resolved topology	0.71
Combined	0.34

Model Dependent Limit

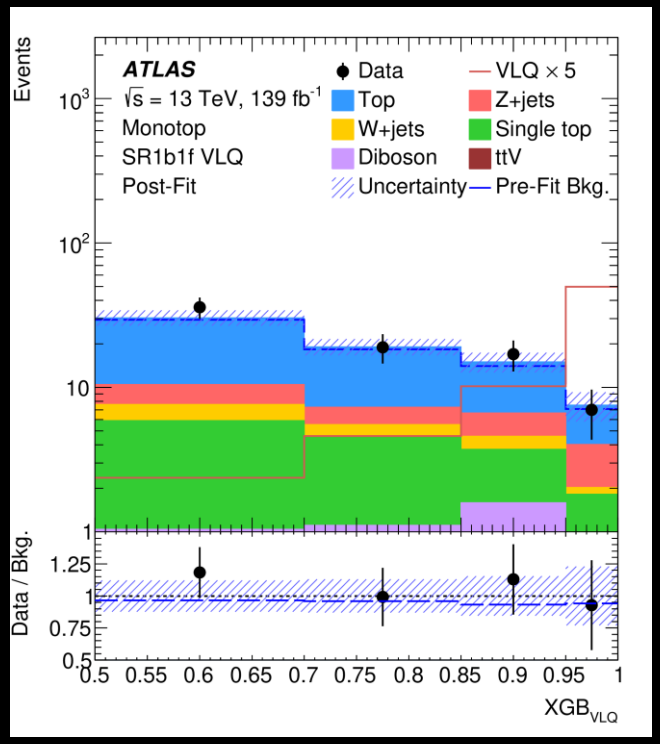
E_T^{miss} + top



Top-tagger [EPJC 79 (2019) 375]
Kinematic + substructure of large-R jet
Reject multijet($\gamma + jet$) up to 70x(90x) when 50% top accepting

- Search for DM with hadronically decaying top + E_T^{miss}
- **Boosted top reconstructed with R=1.0 jet and top-tagged**
- Major bkg. from $t\bar{t}$ and $V + jets$. Negligible multijet
  - Est. from MC. Controlled with control regions
- **XGB algorithm maximize S/B for specific signal**

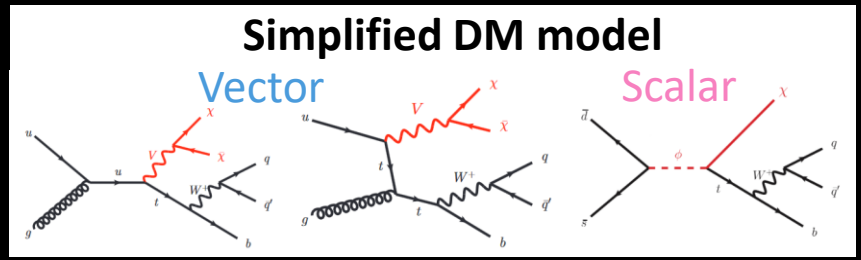
Pre-Selection
$E_T^{miss} > 250$ GeV, 0 $lepton$
$p_T^J \in [350,2500]$ GeV
$m_J \in [40,600]$ GeV
$\Delta\phi(j, E_T^{miss}) > 0.2$

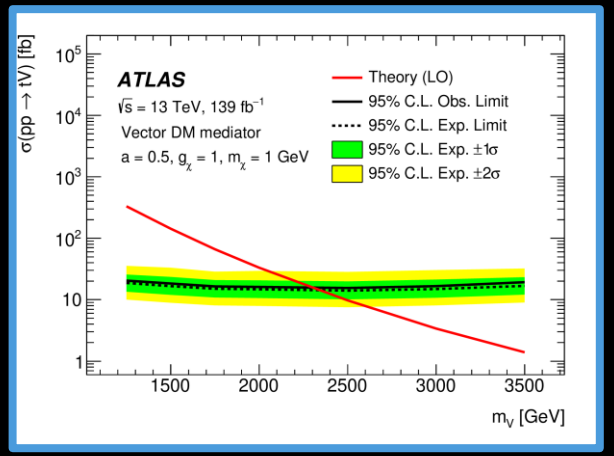


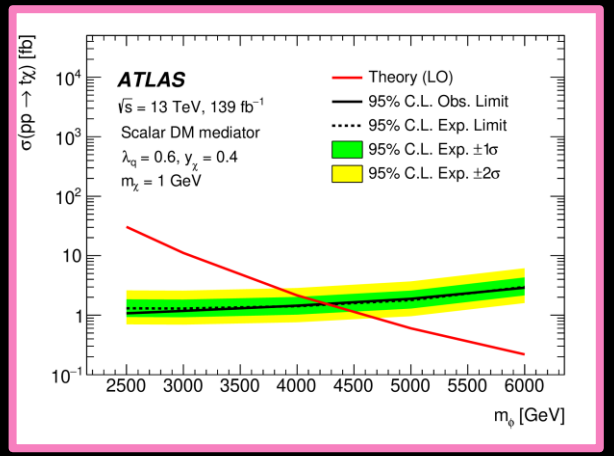
XGBoost Decision Tree
Based on E_T^{miss}, p_T balance, N_j, ΔR, so on
Trained to maximize the Sig/Bkg difference

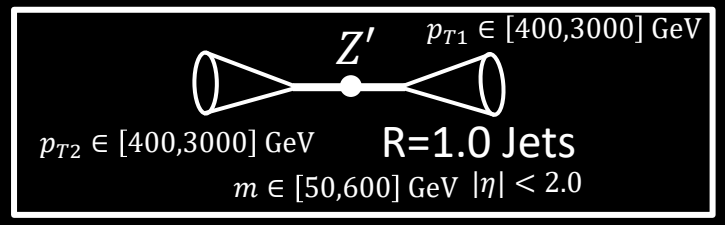
No significant excess above SM

Simplified DM model





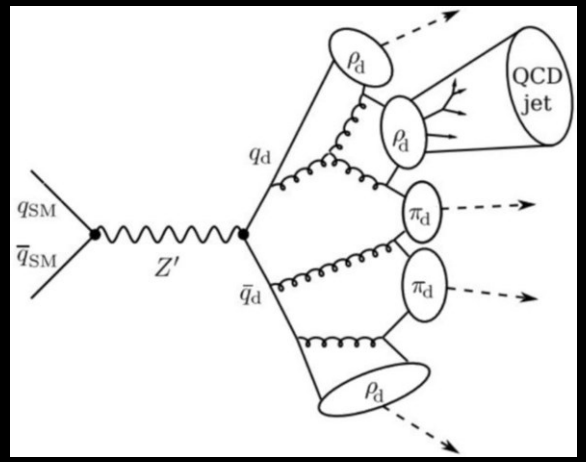


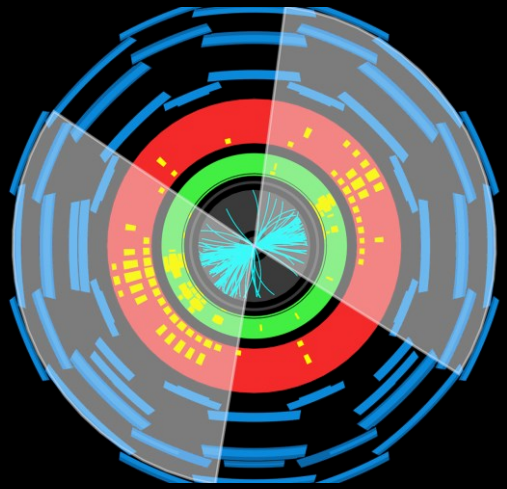


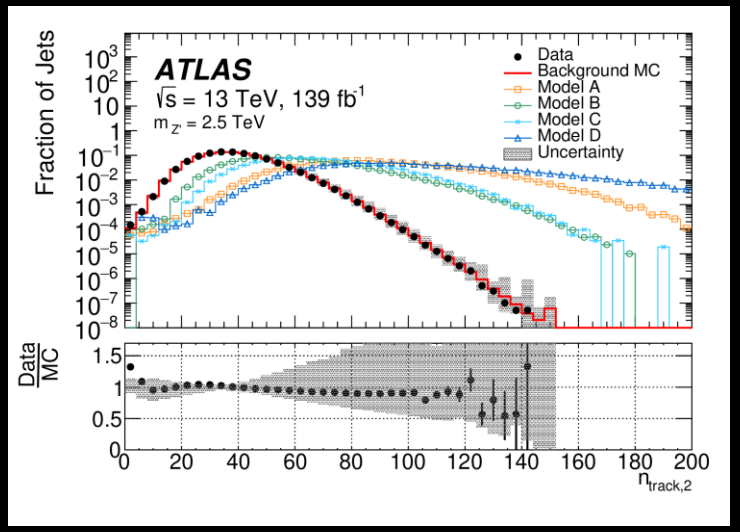
Dark Jet

Search for resonant production of dark quarks in the dijet final state

- Search for QCD-like dark sector with "unusual" jets
  - Decay promptly to SM and QCD-like jet (visible and no displaced vertex)
  - Double hadronization, first in dark sector then in SM: **larger jets**
  - Higher running coupling: **more charged-particle multiplicity**
- Data-driven multijet estimation
  - **Mass-decorrelated n_{trk}^{ϵ}**: after cut the falling m_{jj} spectrum of multijet is kept
  - Shape (bin difference) extracted from control region (low track multiplicity)
  - Normalization (total yield) fit in signal region (high track multiplicity)

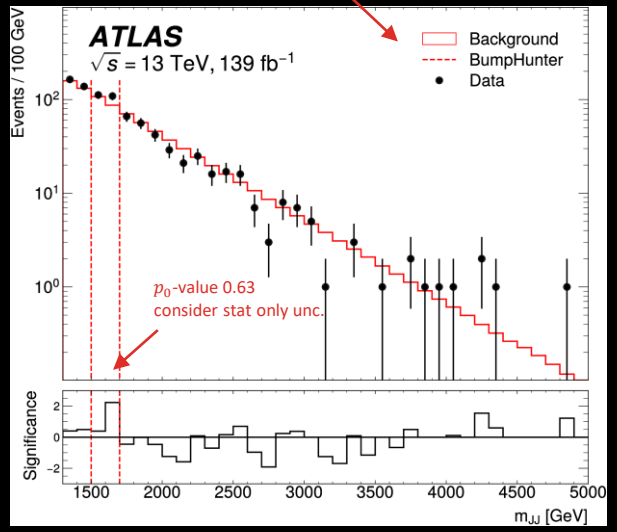






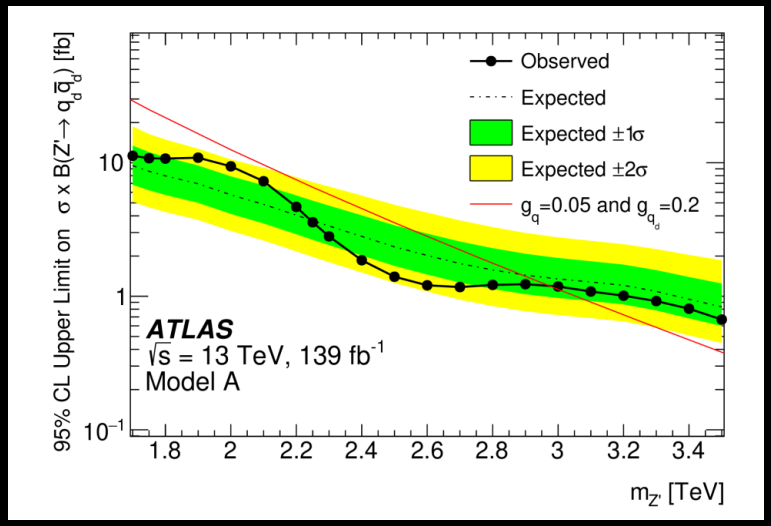
Charged tracks in sub-leading Large-R jet

More in dark jet than in SM jet!



Model independent "bump hunt"

No significant excess over SM background

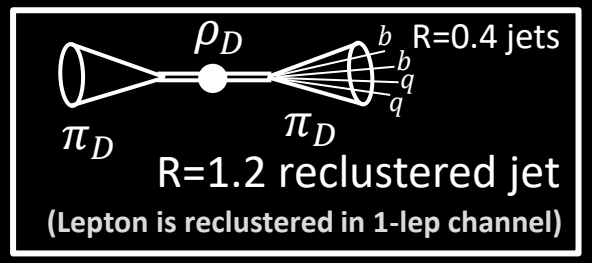


Model dependent limit

Exclude $m_{Z'}$ up to 3 TeV with g_q=0.05, g_D=0.2

Dark Meson

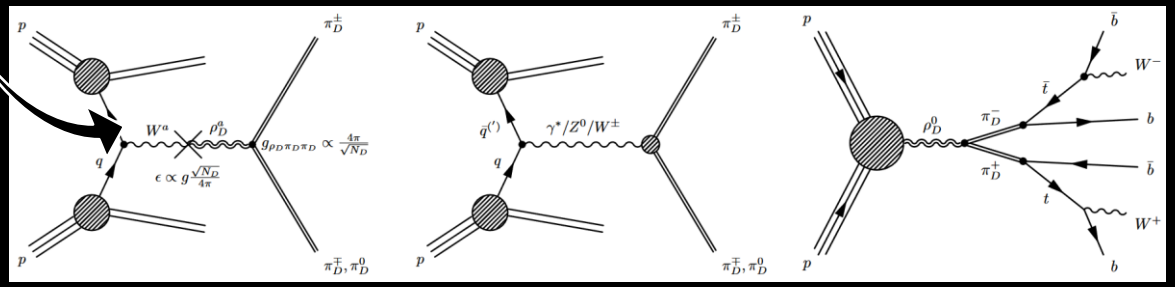
Search for dark mesons decaying to top and bottom quarks



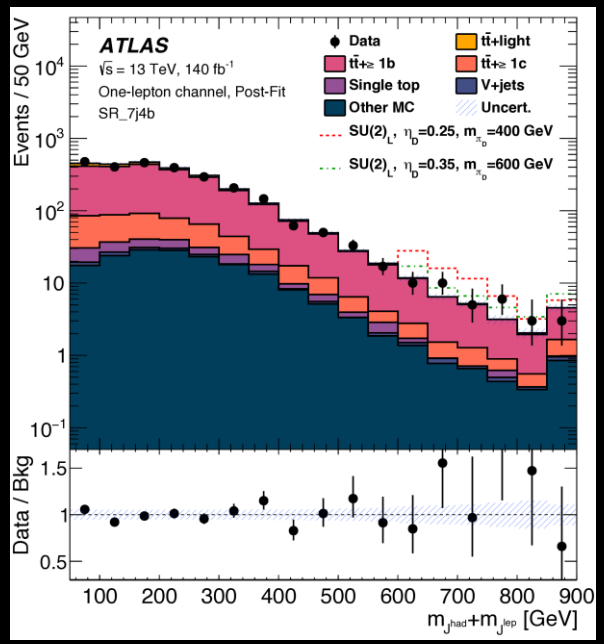
Mixing with W-field: $SU(2)_L$ model

$SU(2)_R$ model also possible which mixing with B-filed but much smaller XS!

- Search for dark mesons decaying into SM $t\bar{t}b\bar{b}/t\bar{t}t\bar{b}$
  - Strongly-coupled dark sector conserving SU(2) dark flavor symmetry
  - Composite of vector-like fermions and two sates dark ρ_D and π_D
  - Parameters: m_{π_D} , m_{ρ_D} and fixed $N_D = 4$ (*dark colors*)
  - Focus on $m_{\pi_D}/m_{\rho_D} < 0.5$ where nearly 100% $\rho_D \to \pi_D\pi_D$



95% CL limits on $SU(2)_L$ model: First Direct Collider Constraint!



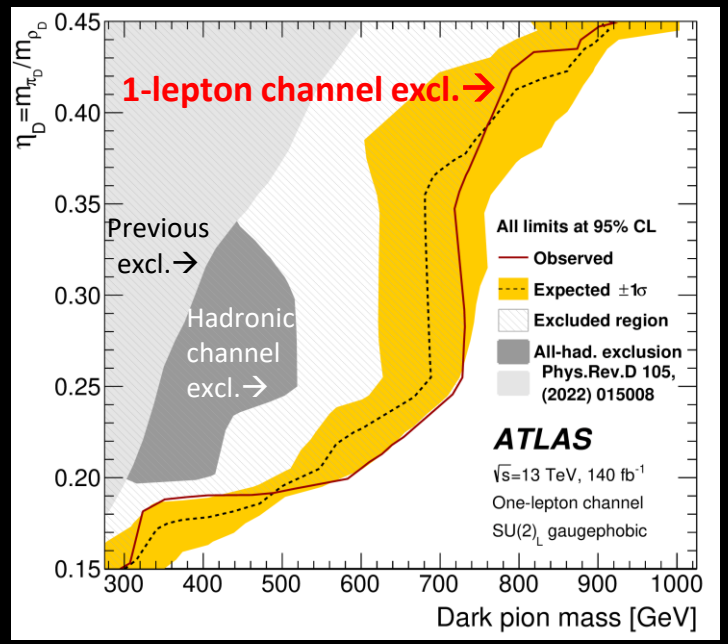
All hadronic channel

- $H_T > 1.15$ TeV
- ≥ 6 small-R jets (≥ 3 b-tag)
- ≥ 2 large-R jets
- Multijet estimated from data

One-lepton channel

- $H_T > 300$ GeV
- ≥ 5 small-R jets (≥ 3 b-tag)
- ≥ 2 large-R jets (lepton cluster in jet)
- Major background $t\bar{t}$ from MC

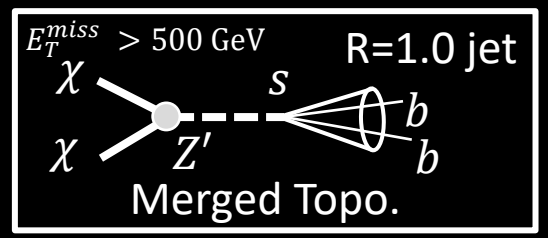
No excess above SM observed

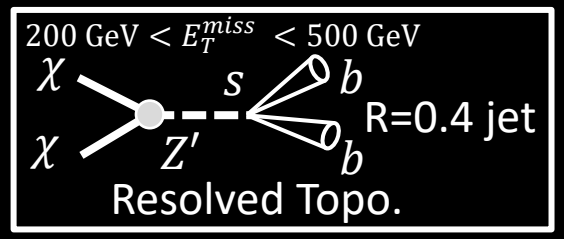


Strongest exclusion from **1-lepton channel**

Excluded m_{π_D} to 940 GeV ($m_{\pi_D}/m_{\rho_D} = 0.45$)

Excluded m_{π_D} to 740 GeV ($m_{\pi_D}/m_{\rho_D} = 0.25$)

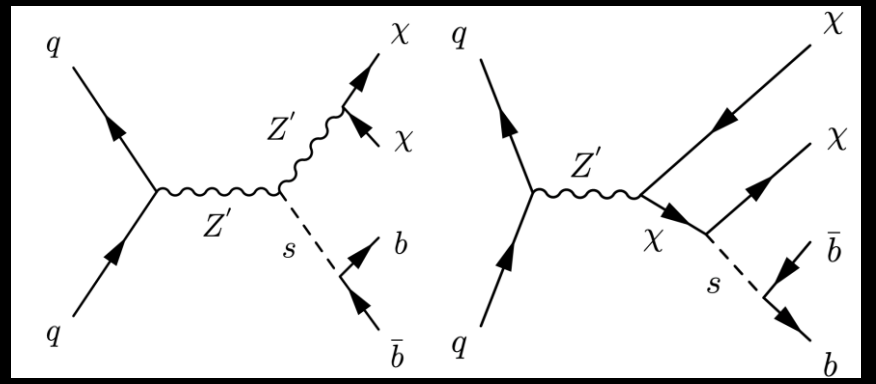




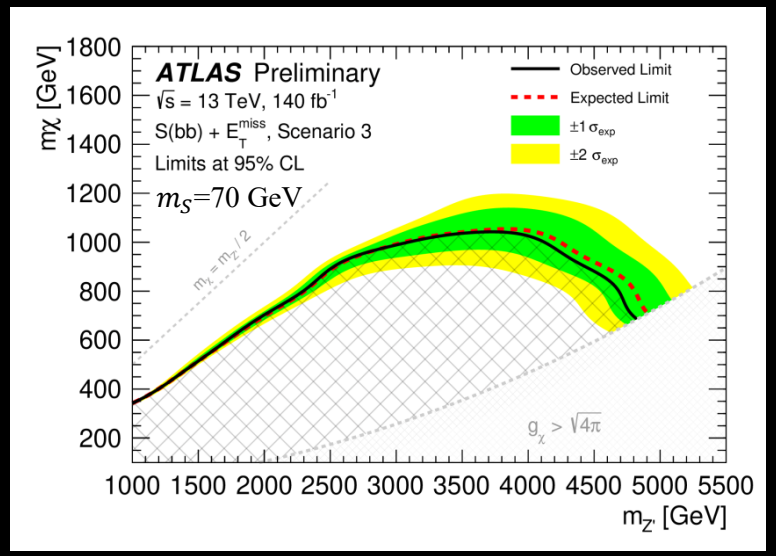
Dark Higgs

Search for dark matter produced in association with a dark Higgs boson in the bb final state

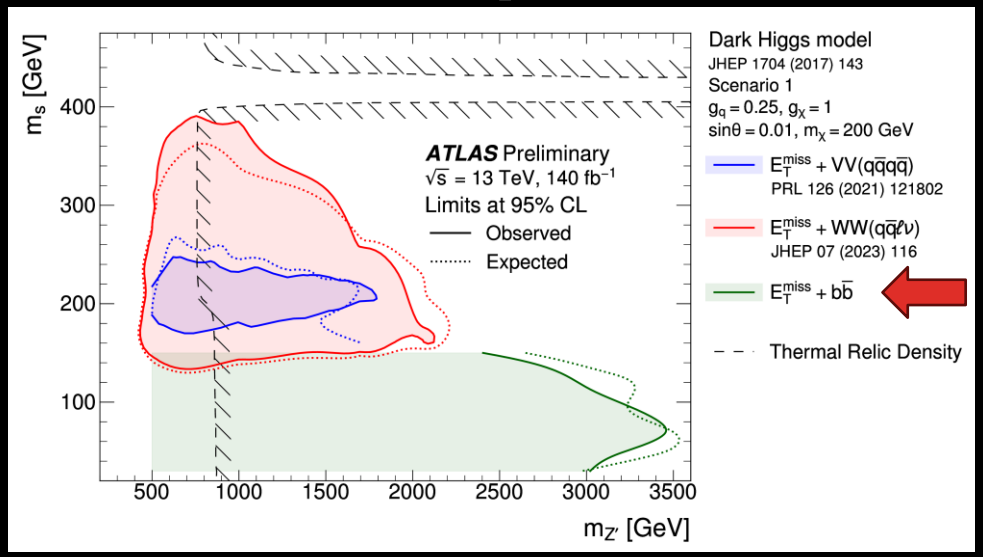
- Search for dark Higgs boson with $b\bar{b} + E_T^{miss}$ signature
  - Explain the mass origin in dark sector with Higgs mechanism
  - **Majorana** DM χ interacts with SM via spin-1 mediator Z' and a singlet s under $U(1)'$
- Probe E_T^{miss} down to 200 GeV and m_{bb} down to 30 GeV
  - Trigger efficiency correction; Reclustering technique and calibration propagation
- **Deep learning based mass-agnostic boosted Xbb tagging**

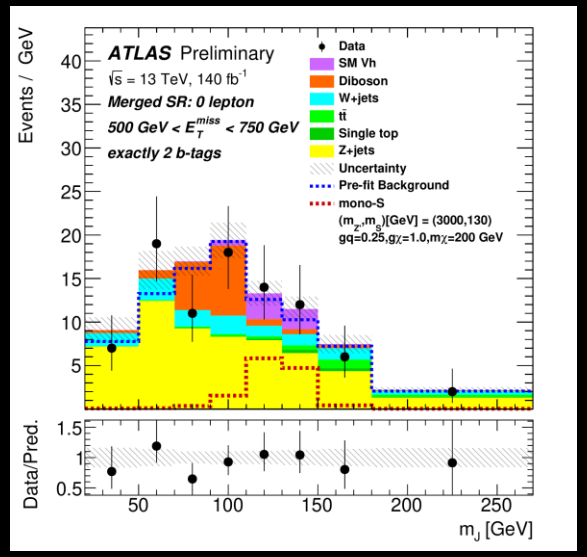


Relic density coherent parameters



Benchmark parameters





No significant derivation from SM

Excluded $m_{Z'}$ up to perturbative limit

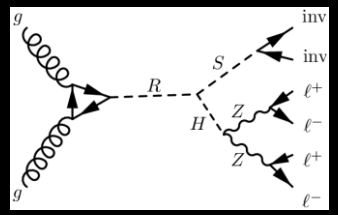
Excluded dark Higgs with m_S < 150 GeV, $m_{Z'}$ up to 3.5 TeV

2401.04742

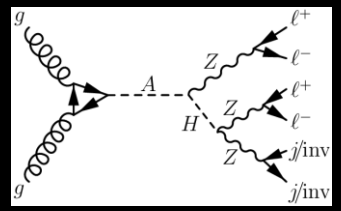
2HDM/2HDM+S

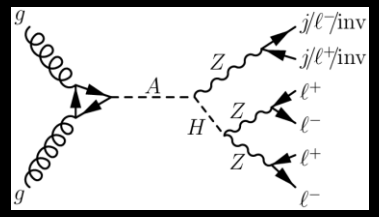
Search for heavy resonances in final states with four leptons and missing transverse momentum or jets

R→SH model



A→ZH model

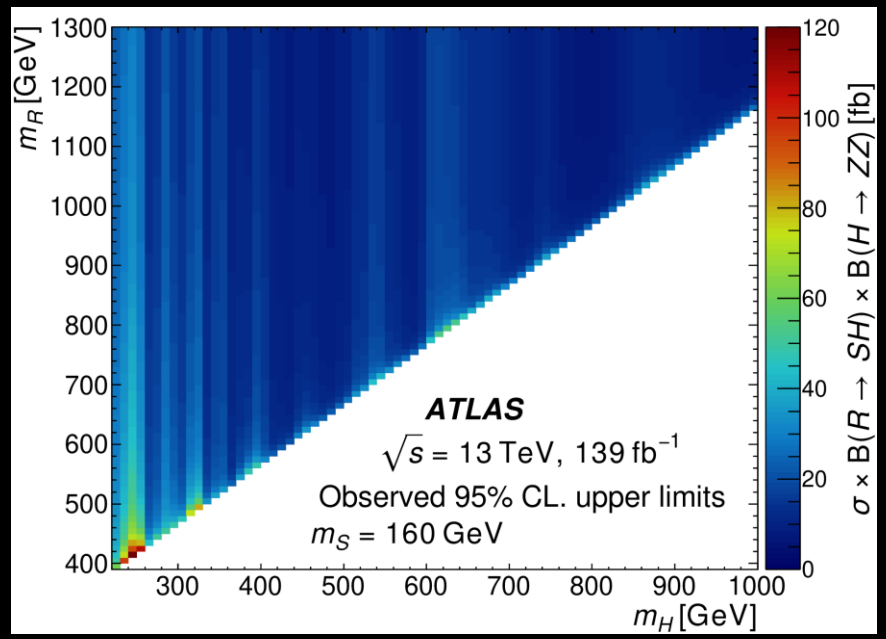




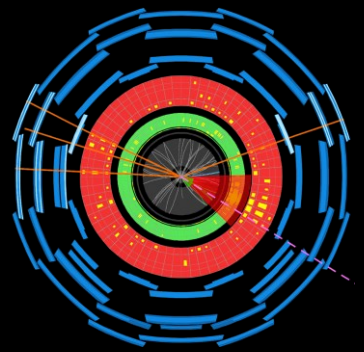
- Search for DM from extended 2HDM model with 4 lepton + E_T^{miss} final states
- Optimized for **narrow width** 2HDM+S(R→SH) and 2HDM(A→ZH) model
- Bkg. mainly from di-boson and tri-boson, modelled with **analytical function**
- **No significant deviation from SM observed**

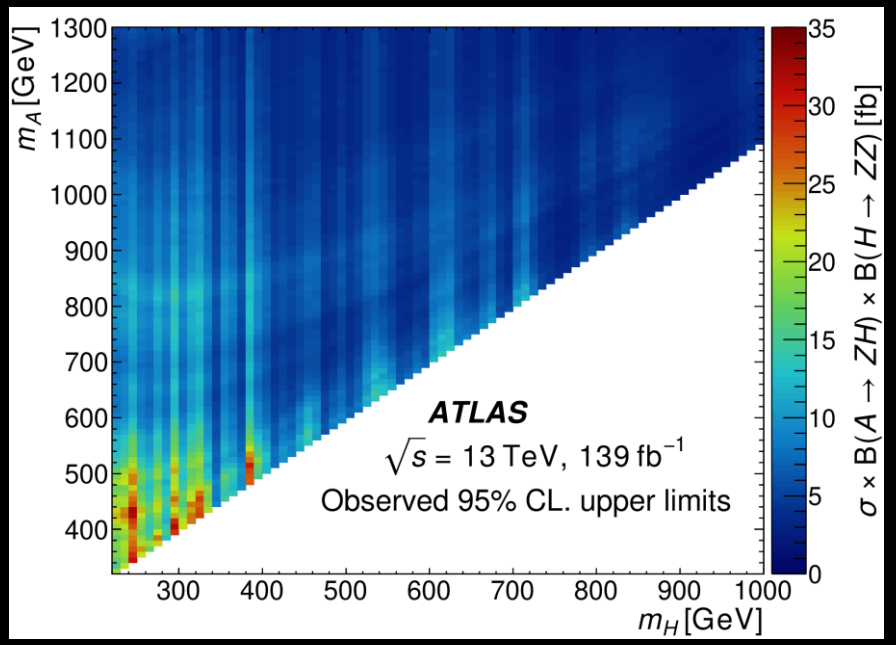
$$f(m_{4l}) = H(m_0 - m_{4l})f_1C_1 + H(m_{4l} - m_0)f_2C_2$$

H: Heaviside func.
f_1: ZZ threshold shape
f_2: high mass tail



Observed upper limit for R→SH: 6.8 - 119.2 fb





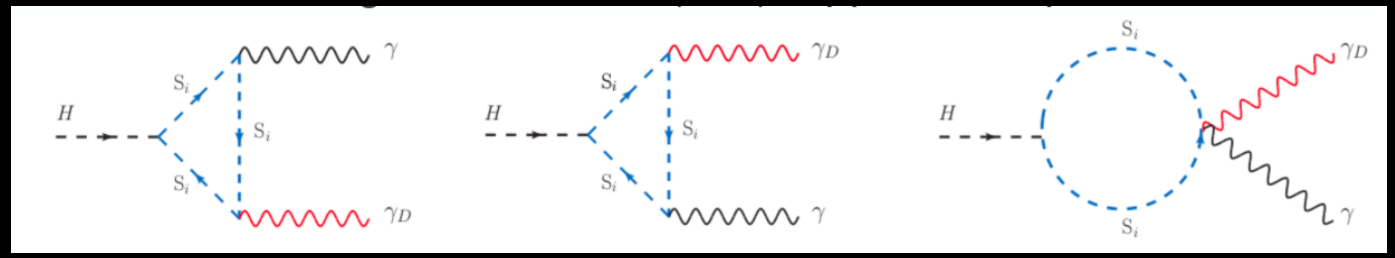
Observed upper limit for A→ZH: 2.1 - 32.3 fb

Width assumptions	Mass points [GeV]	Upper limits in the $\sigma(gg \to A)$ [fb]		Ratio w.r.t Narrow width
		Observed	Expected	
Narrow width	$(m_A, m_H) = (320, 220)$	19.6	25.1	1.0
	$(m_A, m_H) = (1190, 600)$	4.8	3.5	1.0
$(\Gamma_A/m_A, \Gamma_H/m_H) = (15\%, 5\%)$	$(m_A, m_H) = (320, 220)$	31.5	36.2	1.4
	$(m_A, m_H) = (1190, 600)$	8.3	6.0	1.7
$(\Gamma_A/m_A, \Gamma_H/m_H) = (30\%, 10\%)$	$(m_A, m_H) = (320, 220)$	38.9	42.5	1.7
	$(m_A, m_H) = (1190, 600)$	8.9	6.6	1.9

Limit for large width A→ZH: 1.9x worse

Dark Photon

Combination of ATLAS $H \to \gamma\gamma_D$ searches



μ: mass parameter
S_L: SU(2)L doublet
S_R: SU(2)R singlet

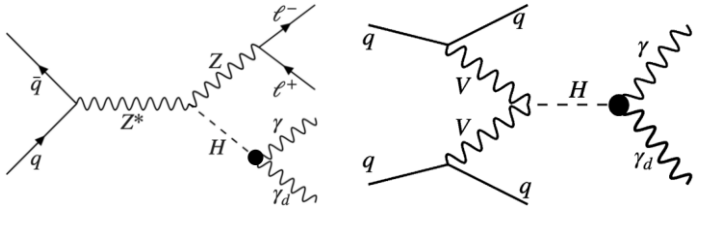
$$\mathcal{L} \sim \mu \cdot H^\dagger S_L S_R + h.c.$$

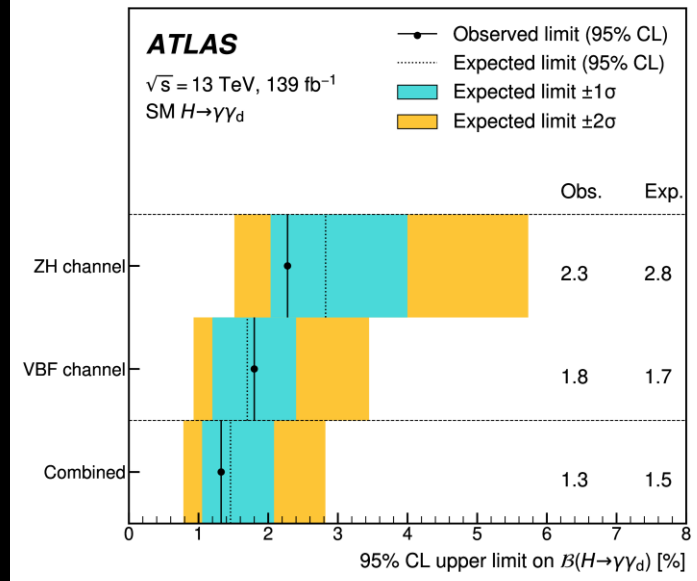
$$\xrightarrow{\text{EWSB}} \mathcal{L}_S^0 = \partial_\mu \hat{S}^\dagger \partial^\mu \hat{S} - \hat{S}^\dagger M_S^2 \hat{S}$$

Minimal Dark Photon Model

PRD 90, 055032 (2014)

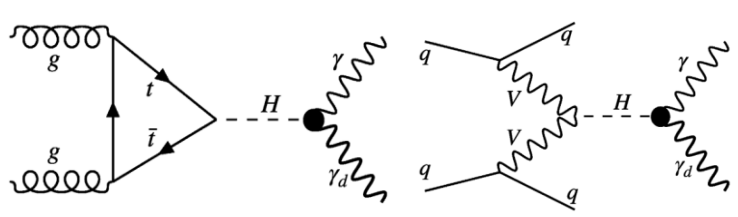
Dark photon couple to SM Higgs

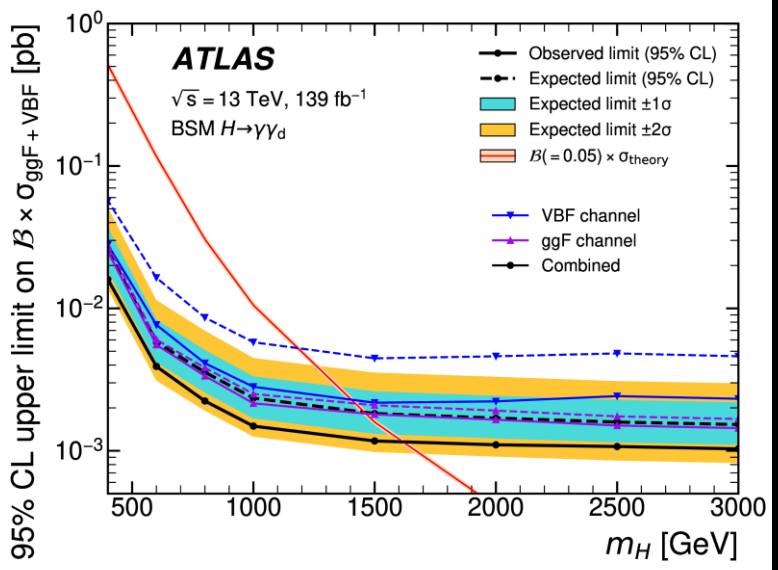




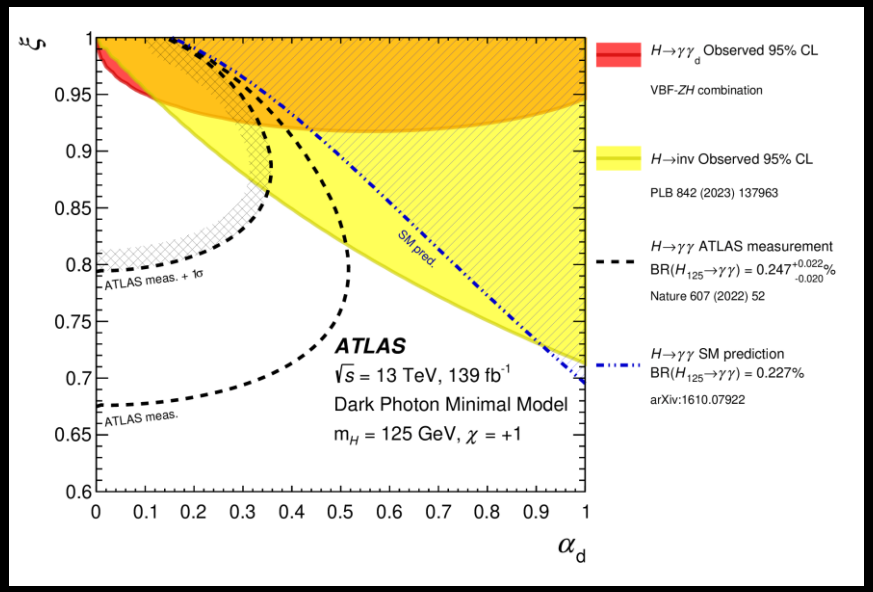
Observed $\mathcal{B}(H_{125} \to \gamma\gamma_D) < 1.3\%$

Dark photon couple to heavy Higgs





Observed 95% CL Limit σ < 16 fb - 1.0 fb



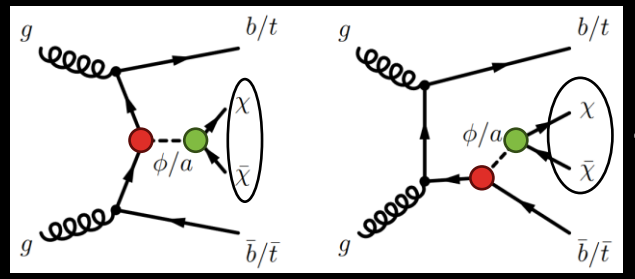
Exclusion of Parameter Space

(with Dirac DM)

Summary of Simplified Model: Spin-0

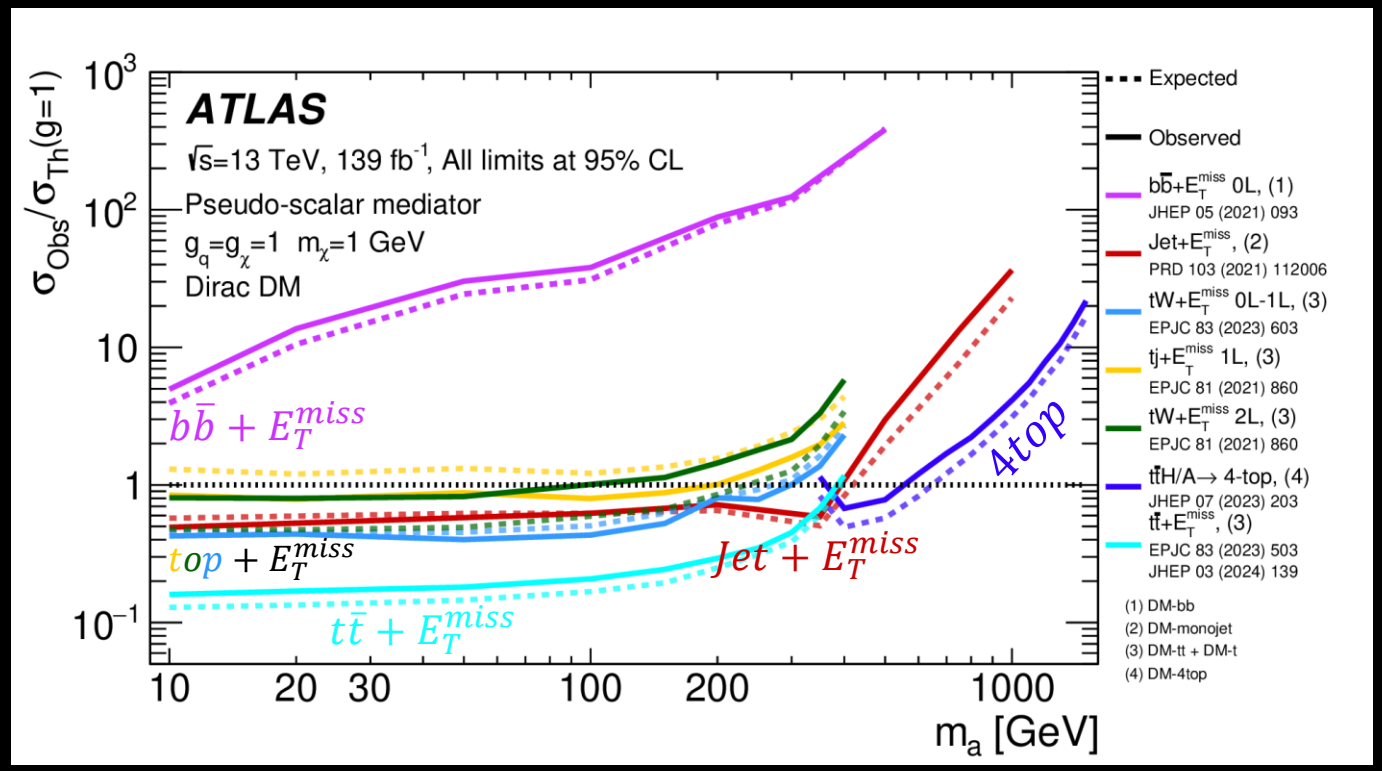
(In backups)

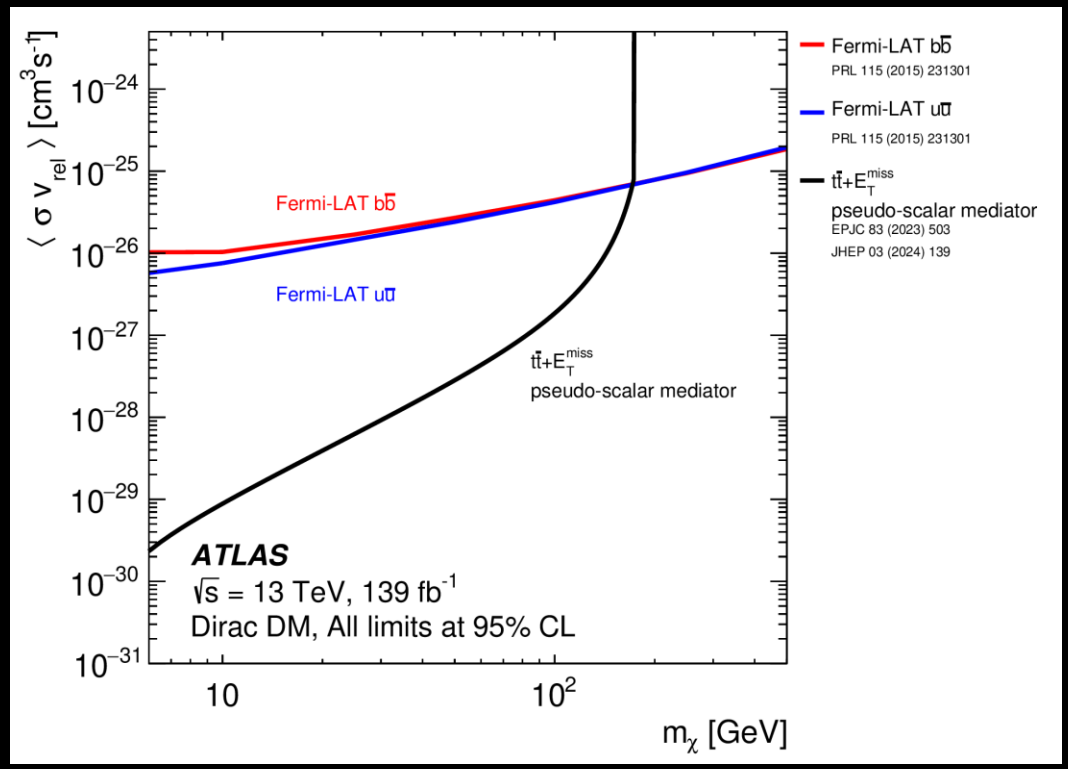
Spin-0 Mediator	J^P	Coupling	Signature
Scalar	0^+	$g_q = g_\chi = 1$	SM + E_T^{miss} 4-top
Pseudo-Scalar	$\mathbf{0^-}$		



More diagrams in backup

→ **decay to $t\bar{t}$ opens up when $m_{med} > 2m_t$ *(4-top signature)***





Excluded mediator mass up to 400 GeV (1 GeV DM)

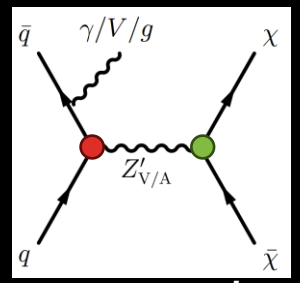
Limit on WIMP annihilation rate

(with Dirac DM)

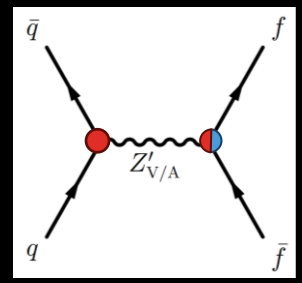
Summary of Simplified Model: Spin-1

(In backups)

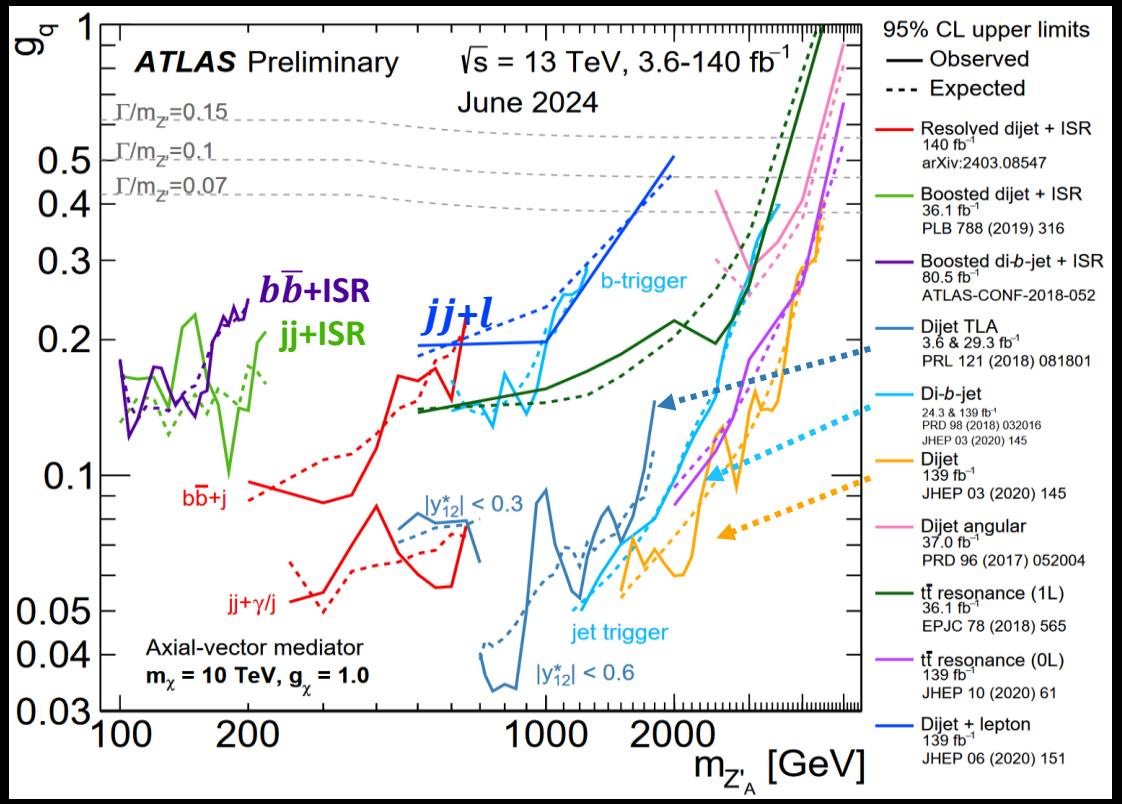
Spin-1 Mediator	J^P	Couplings	Signatures
Vector	1^+	Various (g_q, g_l)	SM + E_T^{miss}
Axial-Vector	$\mathbf{1^-}$	$g_\chi = 1$	Resonance (dilep, dijet)



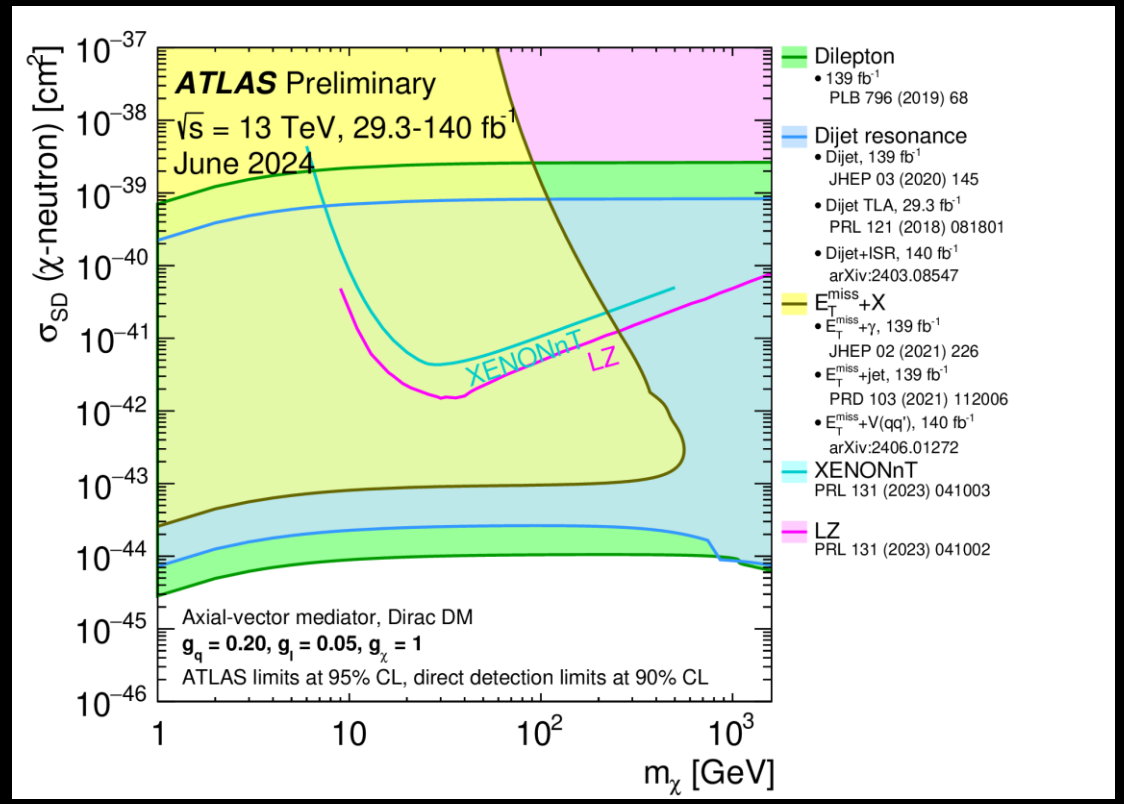
SM+ E_T^{miss}



Resonance



g_q Limit with 10 TeV DM and $g_l = 0$ (no lepton coupling)



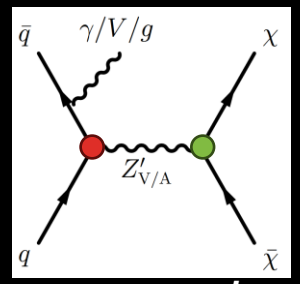
Limit on Spin-Dependent Cross-section

(with Dirac DM)

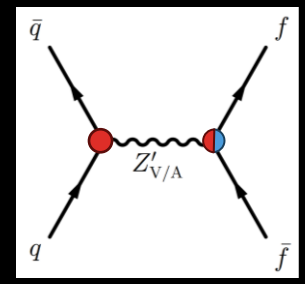
Summary of Simplified Model: Spin-1

(In backups)

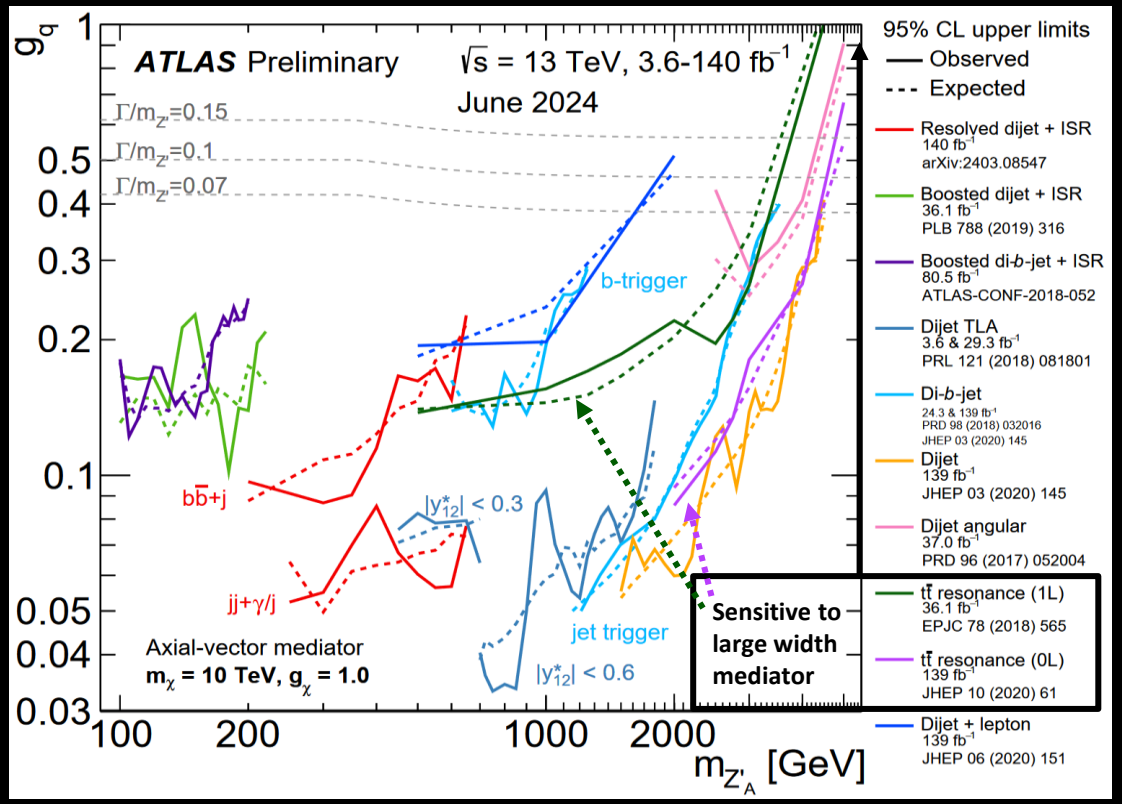
Spin-1 Mediator	J^P	Couplings	Signatures
Vector	1^+	Various (g_q, g_l)	SM + E_T^{miss}
Axial-Vector	$\mathbf{1^-}$	$g_\chi = 1$	Resonance (dilep, dijet)



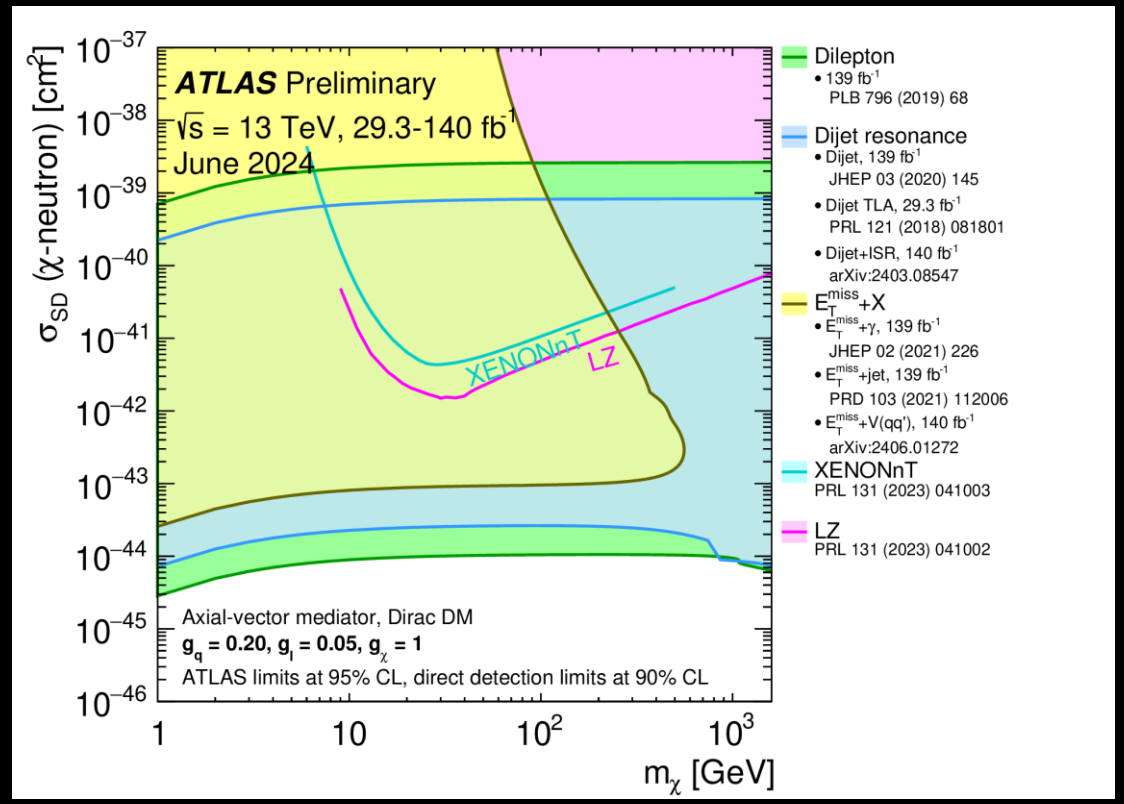
SM+ E_T^{miss}



Resonance



g_q Limit with 10 TeV DM and $g_l = 0$ (no lepton coupling)



Limit on Spin-Dependent Cross-section

LHC Dark Matter Benchmark Model

Combination of 2HDM+a Searches

Higgs Bosons

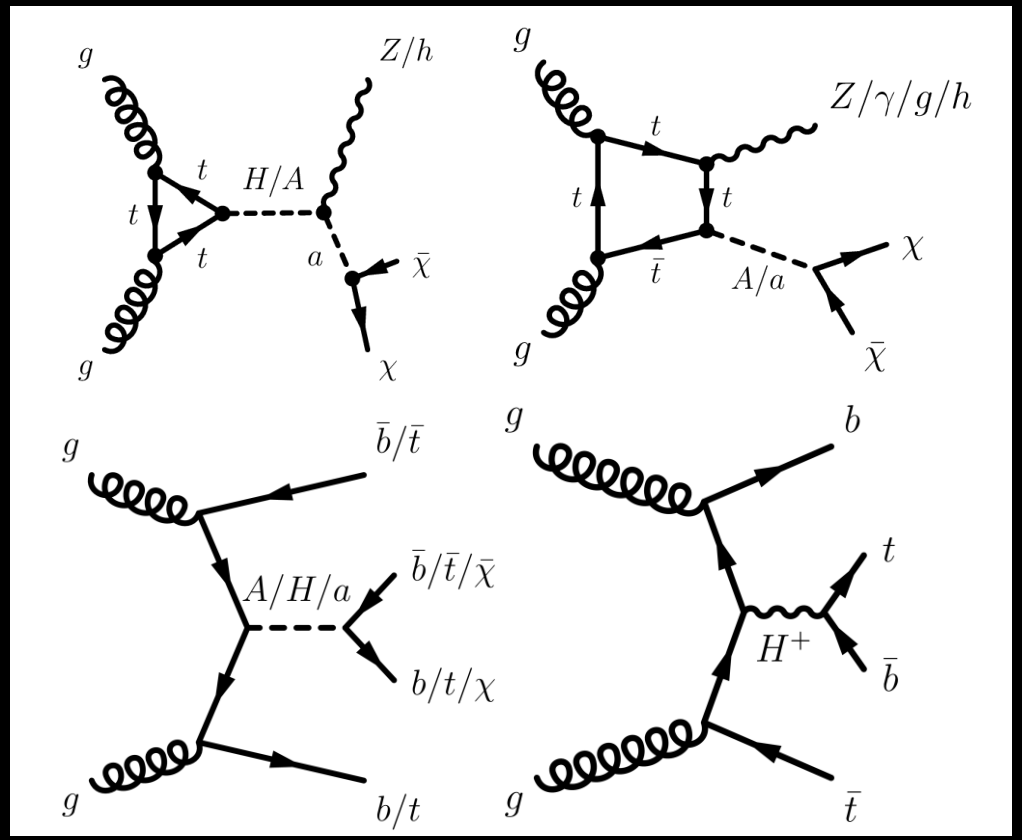
- H: heavy scalar
- h: SM Higgs
- A: pseudo-scalar
- $H^{\pm}$: charged scalar

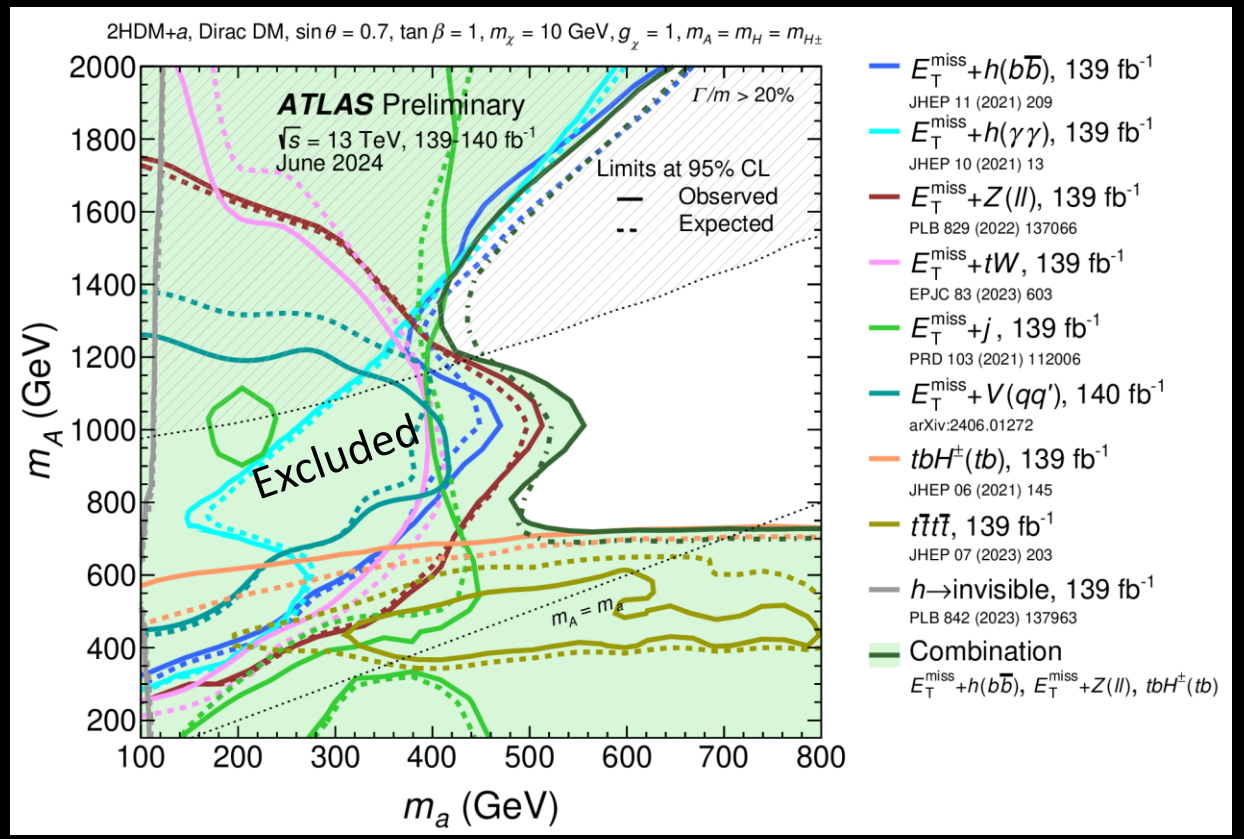
Parameters

- $sin\theta$: mixing angle of A and a
- g_χ: dark-sector Yukawa coupling
- $tan\beta$: ratio of VEV of Higgs doublet
- $m_A = m_H = m_{H^{\pm}}$: degenerated H mass
- m_a: mediator mass; m_χ: DM mass

2HDM+a: Two-Higgs-Doublet-Model with an additional pseudo-scalar mediator a (coupled to fermionic DM χ)

Diverse signatures: combination of multiple ATLAS analyses to set the best exclusion limit



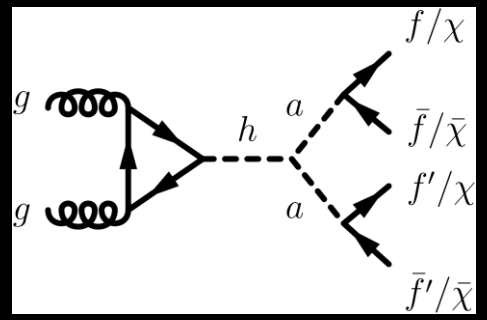


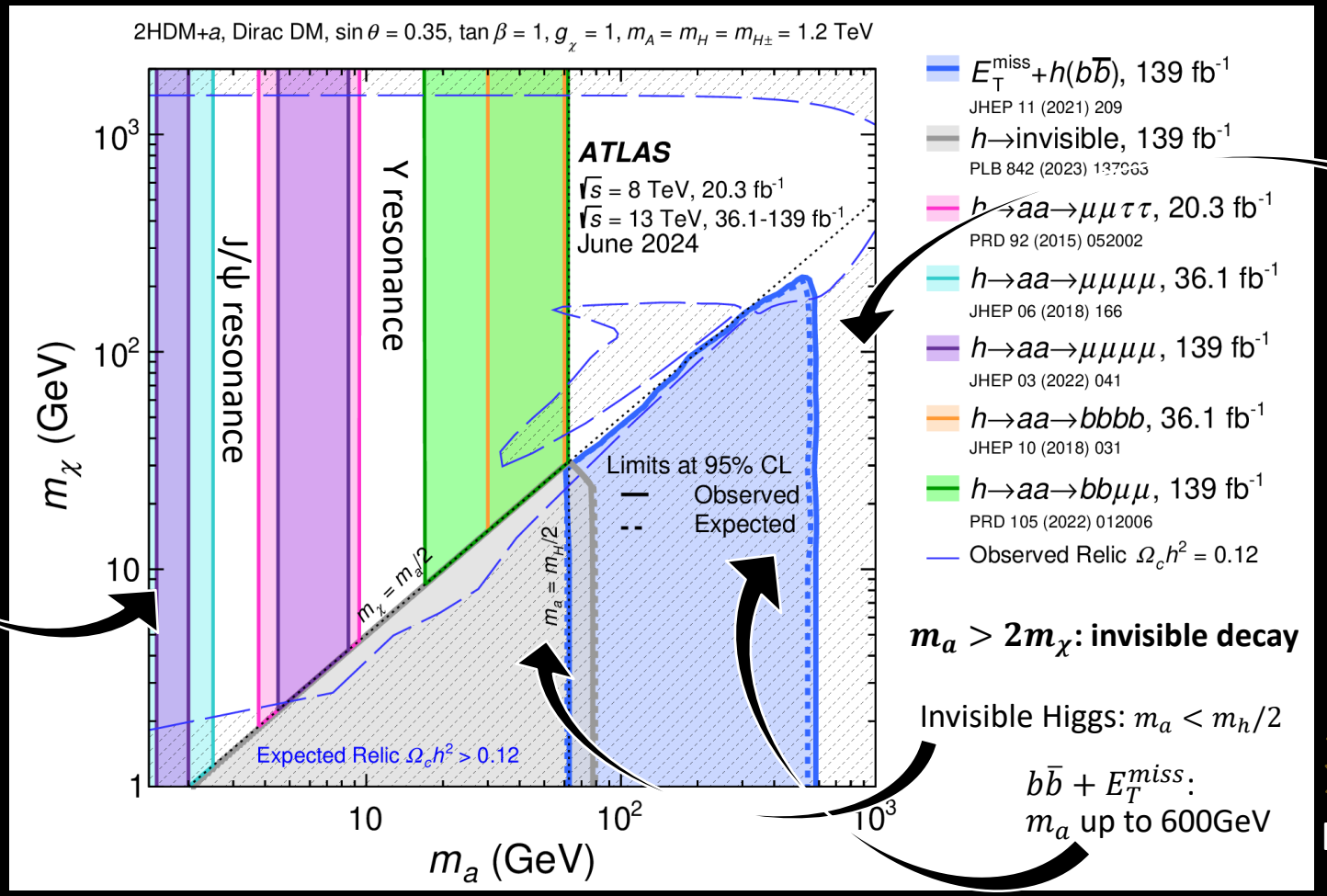
10+ different analyses involved and 3 most sensitive channels $E_T^{miss} + h(bb)$, $E_T^{miss} + Z(ll)$ and $tbH^{\pm}(t)$ combined

Combination of 2HDM+a Searches

Series of h→aa→4f searches included first time: good sensitivity for low mass pseudo-scalar a

Broad variety of searches in ATLAS combined in the context of 2HDM+a: rule out large area of parameter space





$m_a < 2m_\chi$: visible decay

h→aa→4f when $m_a < m_h/2$

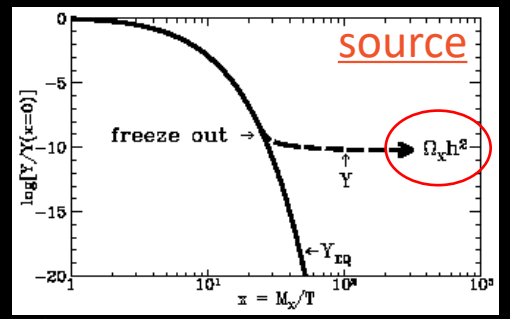
$m_a > 2m_\chi$: invisible decay

Invisible Higgs: $m_a < m_h/2$

$b\bar{b} + E_T^{miss}$:
m_a up to 600GeV

Cosmology Constraint

DM Relic Density Ω_h^2 = 0.1200 [PLANCK2018]
Excluded over-abundant region where all possible DM χ annihilation is forbidden due to kinematics

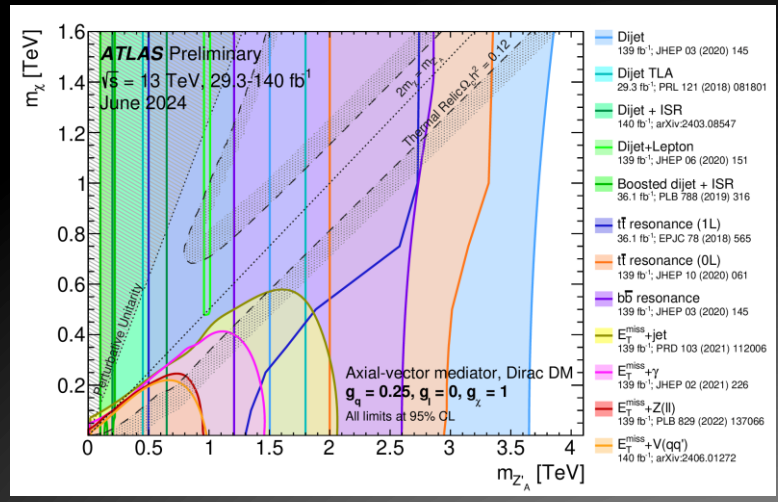


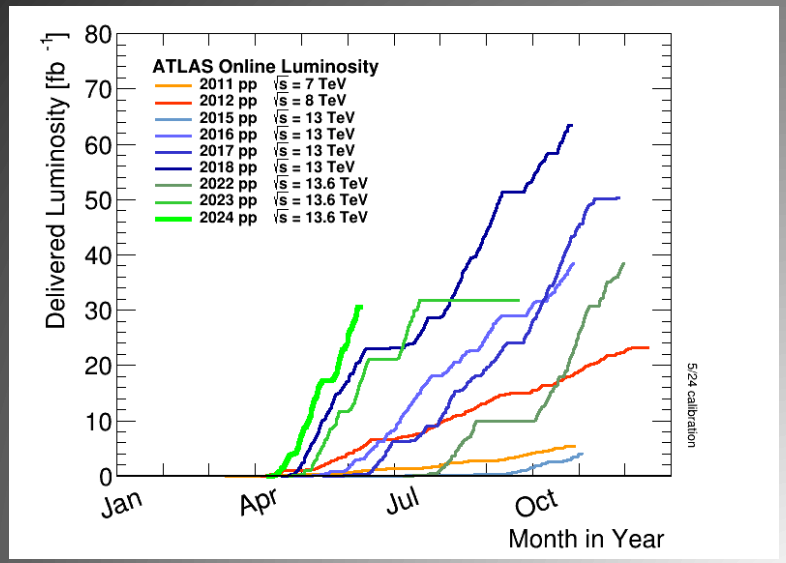
Big Bang → Freeze out

Summary

- Large variety of searches for Dark Matter performed at ATLAS
  - Covered wide range of final state of SM+E_T^{miss} and other unusual signatures
- Excluded large area on the parameter space of DM models
  - S-channel simplified model, 2HDM+a and different models focusing on dark sector
- Complete the picture together with non-collider search and cosmology observation
  - Compatibility of Relic Density; Comparison to the Direct Search
- **Still a lot to fully understand the DM but progressing!**
  - Analyses based on ATLAS Run 2 data still coming
  - Accumulating ATLAS Run 3 data...

Stay Tuned!

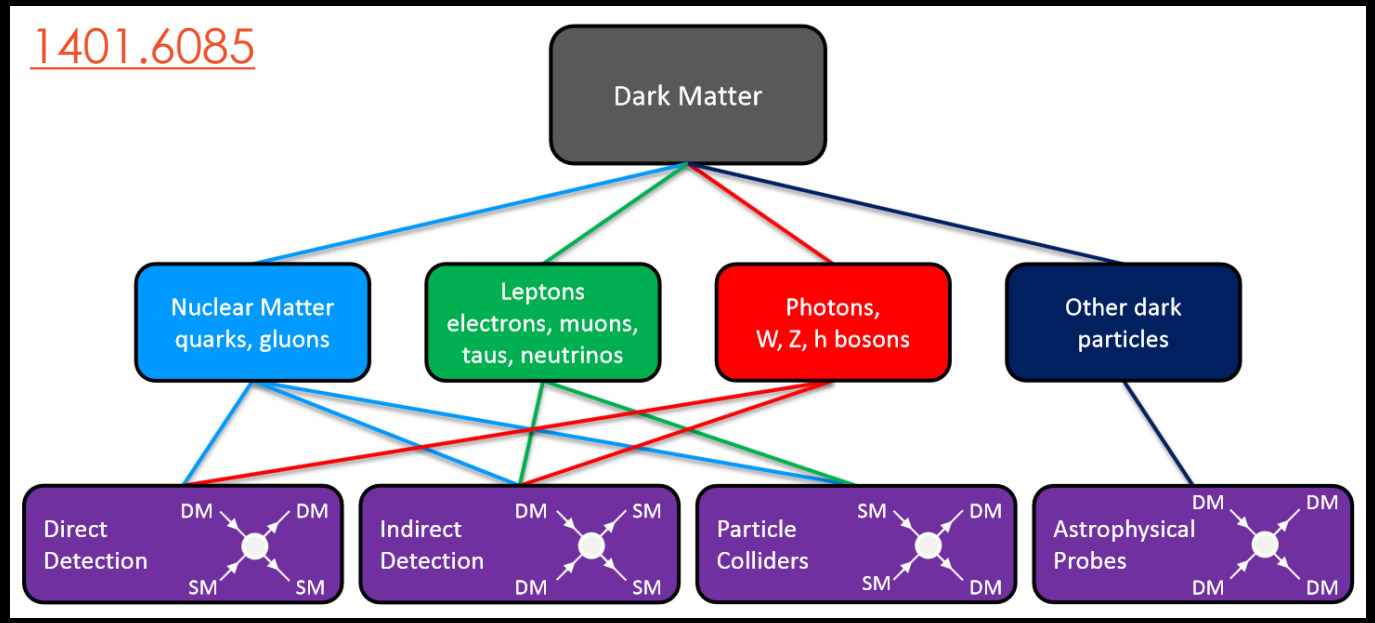




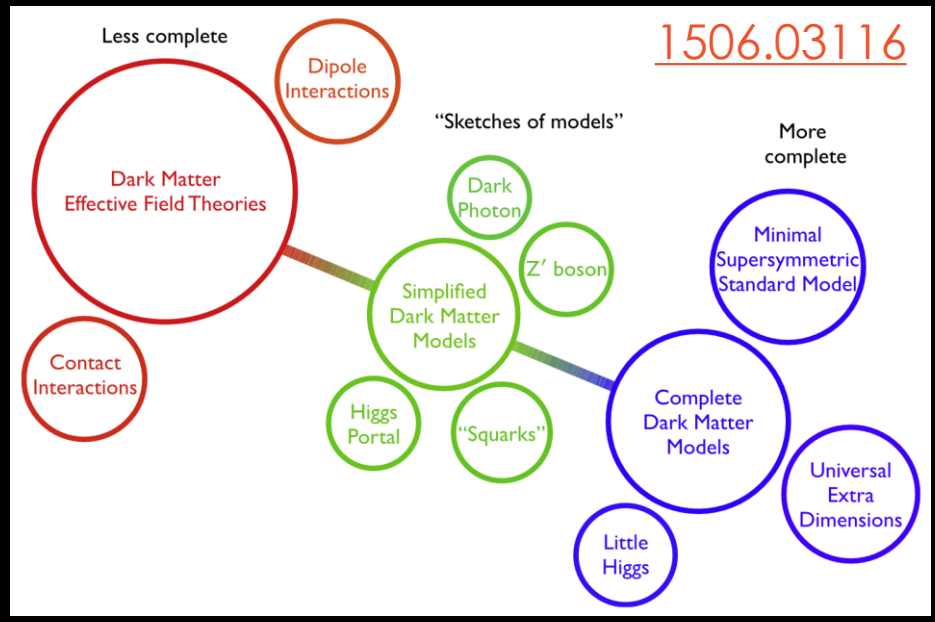
More the luminosity Less the dark!

BACKUP

DM Interaction

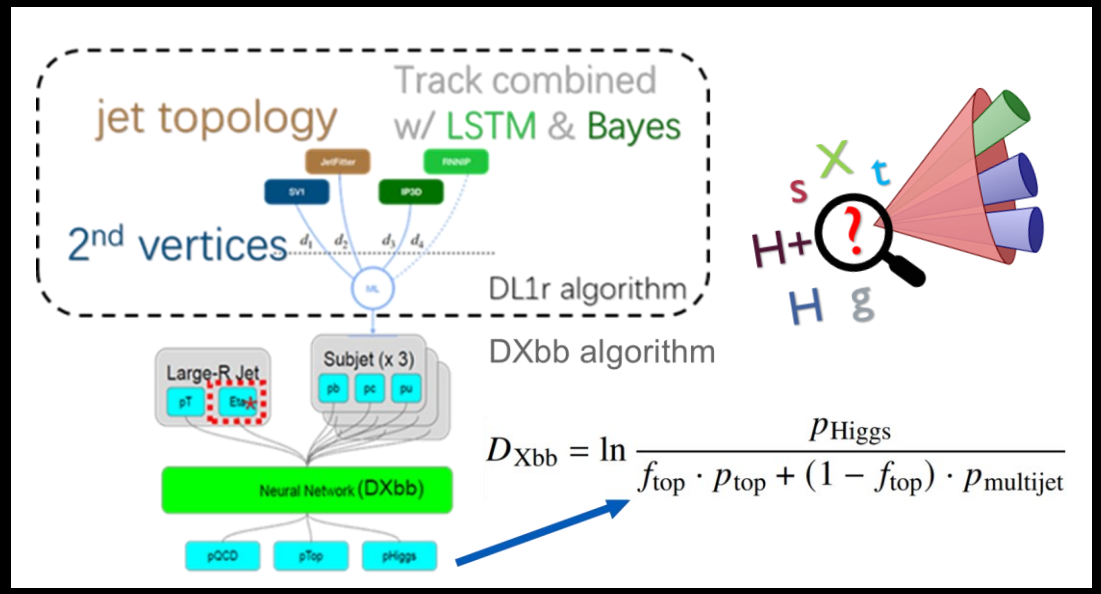


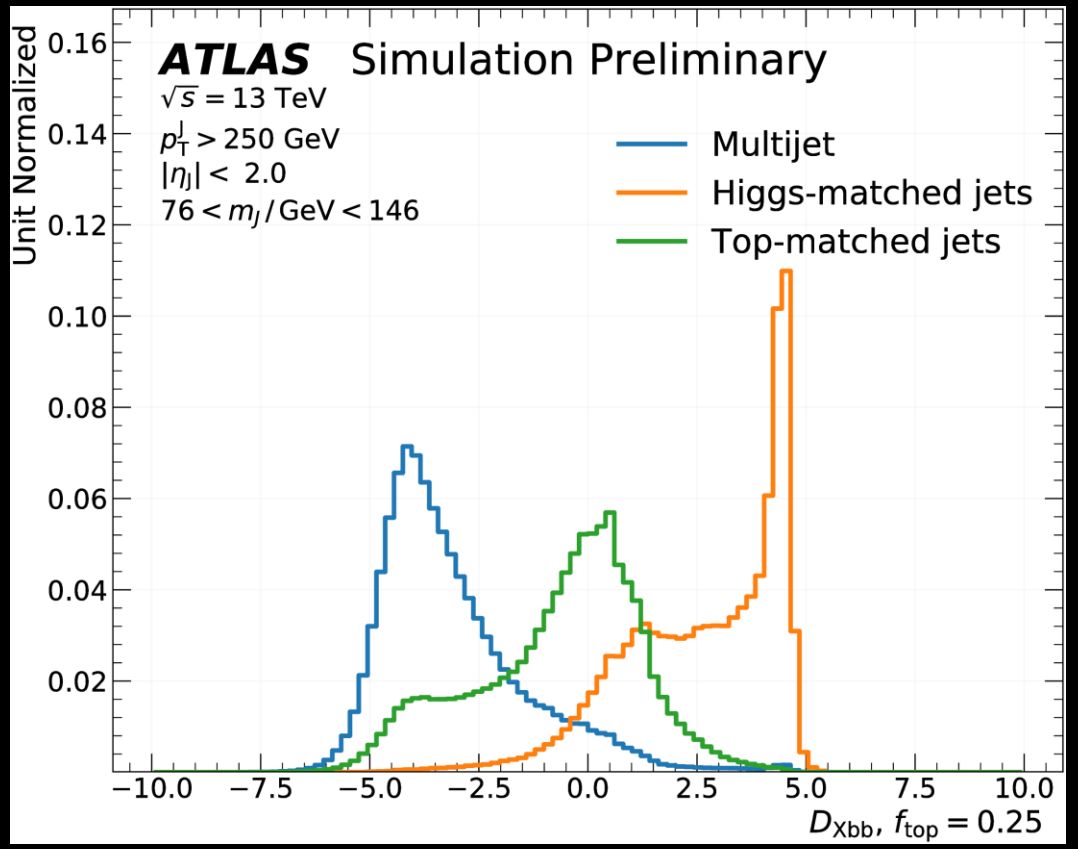
DM Theory



Boosted Xbb tagger in ATLAS

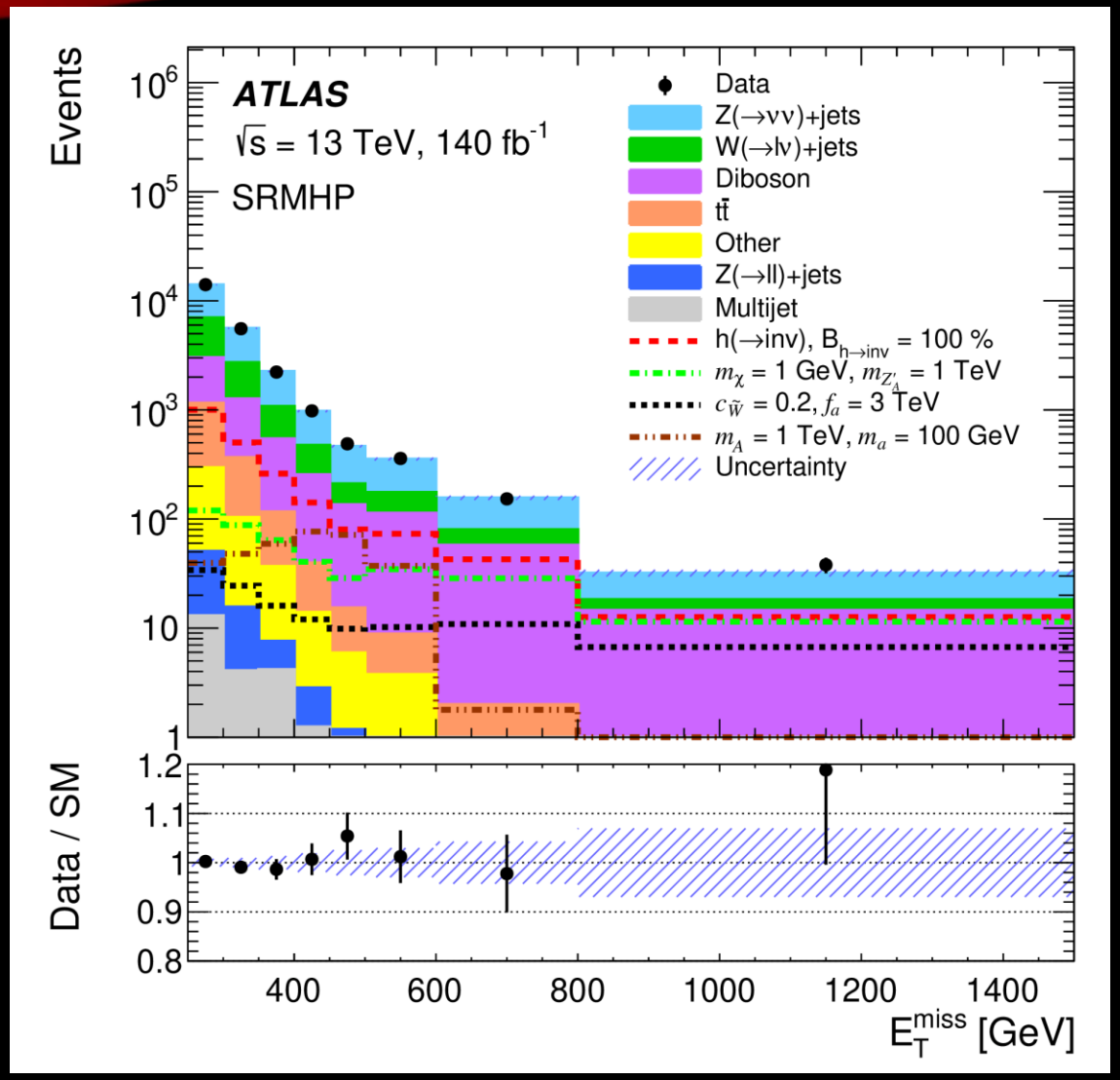
DXbb tagger [ATL-PHYS-PUB-2020-019]
Deep Neural Network based Xbb tagging
Hbb(mass-agnostic) v.s. QCD v.s. Top

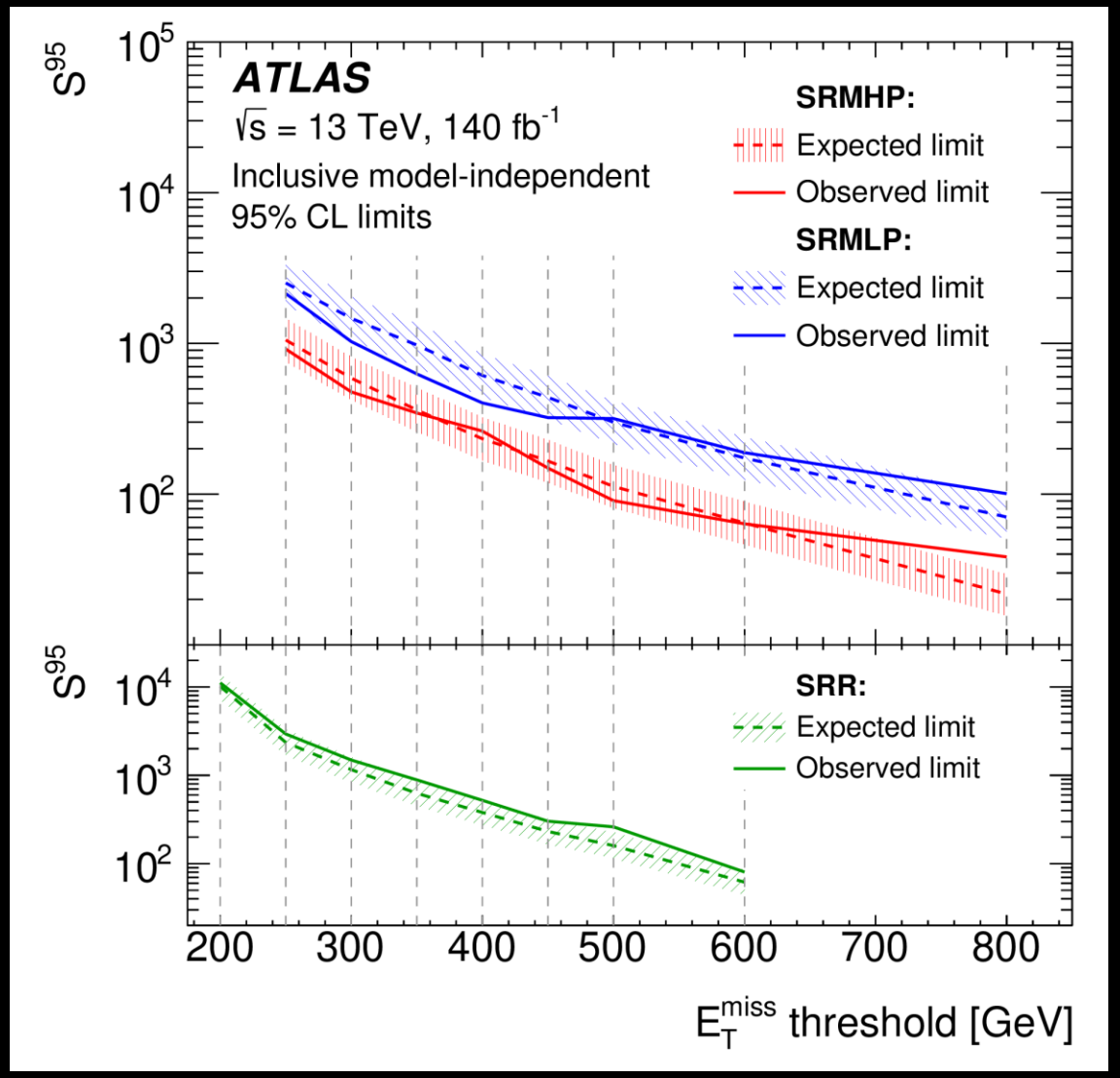




Updated! GN2X tagger [ATL-PHYS-PUB-2023-021]
Transformer based Xbb tagging
(New analyses coming soon!)

$E_T^{miss} + W/Z(qq)$

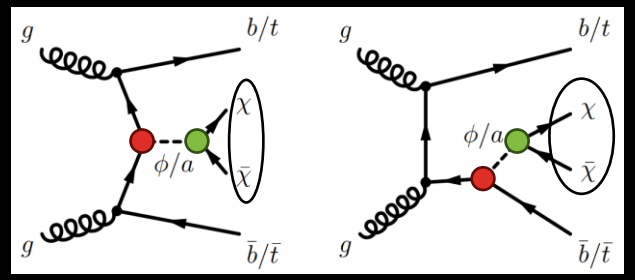

ATLAS
√s = 13 TeV, 140 fb-1
SRMHP
Data
Z(→νν)+jets
W(→lν)+jets
Diboson
tt̄
Other
Z(→ll)+jets
Multijet
h(→inv), B h→inv = 100 %
mχ = 1 GeV, mZA = 1 TeV
cW̃ = 0.2, fa = 3 TeV
mA = 1 TeV, ma = 100 GeV
Uncertainty
Events
Data / SM
E T miss [GeV]


ATLAS
√s = 13 TeV, 140 fb-1
Inclusive model-independent
95% CL limits
SRMHP:
Expected limit
Observed limit
SRMLP:
Expected limit
Observed limit
SRR:
Expected limit
Observed limit
S95
E T miss threshold [GeV]

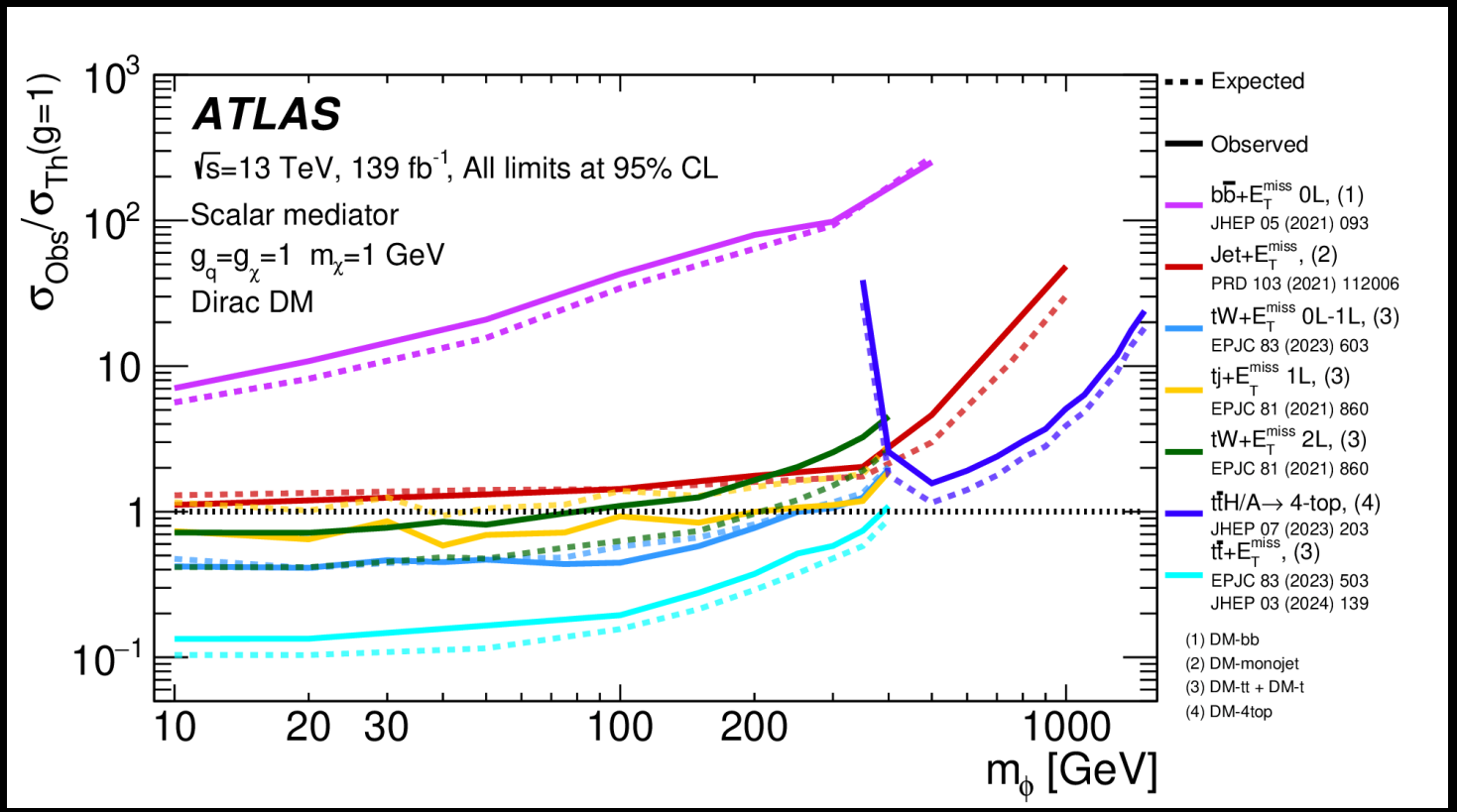
2404.15930

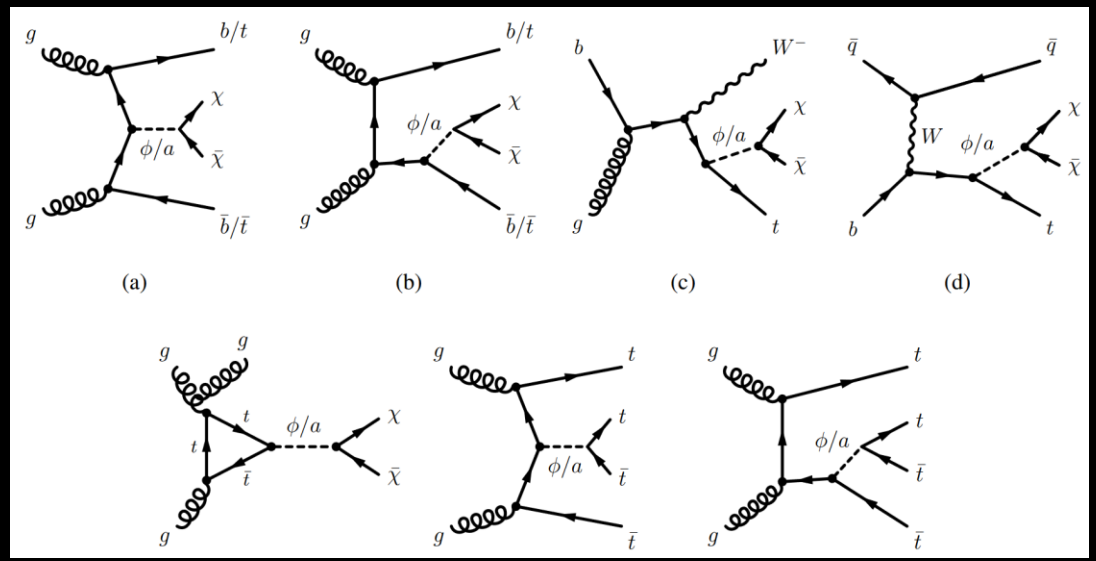
SUMMARY OF SIMPLIFIED MODEL: SPIN-0

Spin-0 Mediator	J^P	Coupling	Signature
Scalar	$\mathbf{0^+}$	$g_q = g_\chi = 1$	SM + E_T^{miss} 4-top
Pseudo-Scalar	0^-		



Excluded mediator mass up to 400GeV assuming 1GeV DM



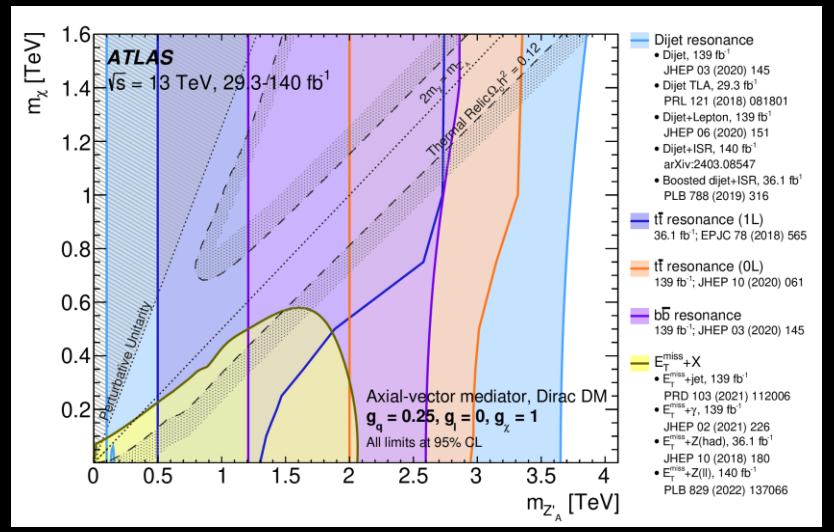


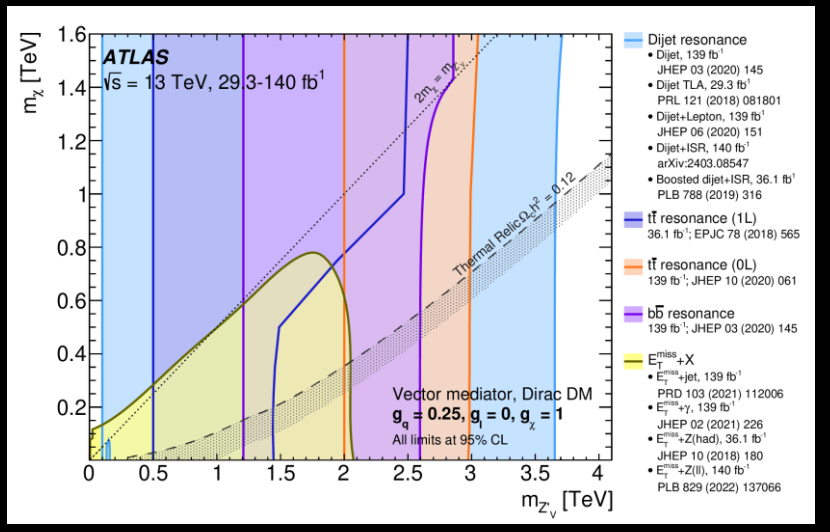
Model and Final State	UFO	Generator and Parton Shower	Cross-section
DM-monojet	DMS_tloop	POWHEG BOX v2 + PYTHIA 8.205	NLO
DM-$t\bar{t}$, DM-tW, DM-tj, DM-4top	DMScalarMed_loop	MADGRAPH5_aMC@NLO 2.3.3 (LO) + PYTHIA 8.186	NLO
DM-$b\bar{b}$	DMScalarMed_loop	MADGRAPH5_aMC@NLO 2.3.3 (LO) + PYTHIA 8.186	NLO

2404.15930

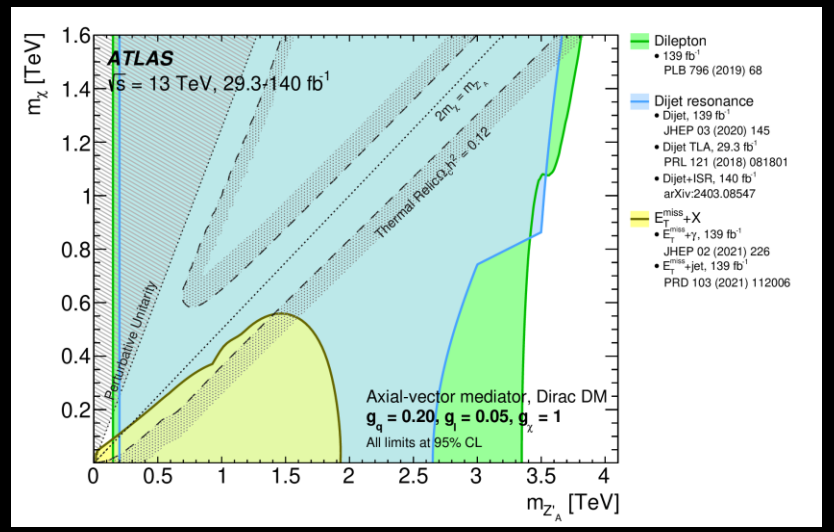
SUMMARY OF SIMPLIFIED MODEL: SPIN-1

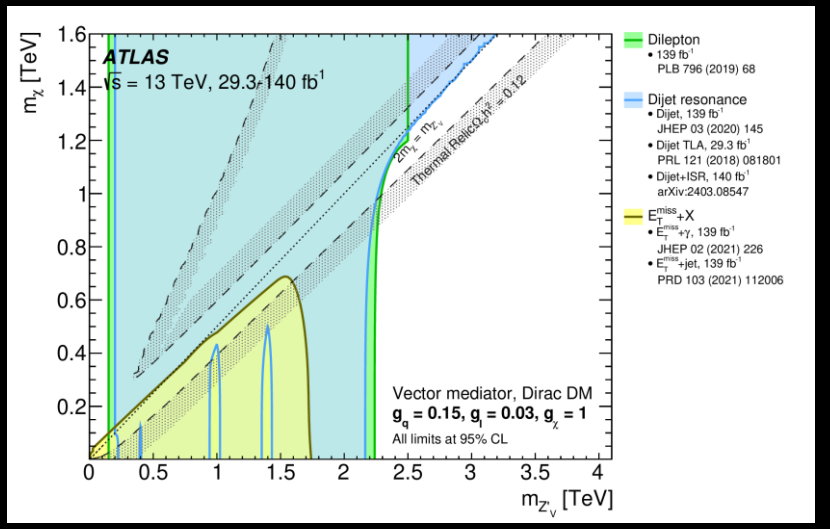
Spin-1				g_q	g_l	g_χ
Vector	V1	Z'_V	1^-	0.25	0.0	1.0
	V2			0.1	0.01	1.0
	V3			0.07	0.0	1.0
	V4			0.15	0.03	1.0
Axial-Vector	A1	Z'_A	1^+	0.25	0.0	1.0
	A2			0.1	0.1	1.0
	A3			0.07	0.0	1.0
	A4			0.2	0.05	1.0





Model and Final State	UFO	Generator and Parton Shower	Cross-section
$Z'(\chi\bar{\chi}) + j$	DMV	Powheg Box v2 + Pythia 8.205	NLO
$Z'(\chi\bar{\chi}) + \gamma$	DMSimp	MadGraph5_aMC@NLO 2.4.3 (NLO) + Pythia 8.212	NLO
$Z'(qq)$ or $Z'(qq)$+ISR	DMSimp	MadGraph5_aMC@NLO 2.2.3 (NLO) + Pythia 8.210	NLO
$Z'(b\bar{b})$	DMSimp	MadGraph5_aMC@NLO 2.2.3 (NLO) + Pythia 8.210	NLO
$Z'(\ell\ell)$	DMSimp	MadGraph5_aMC@NLO 2.2.2 (NLO) + Pythia 8.212	NLO
$Z'(t\bar{t})$	DMSimp	MadGraph5_aMC@NLO 2.4.3 (LO) + Pythia 8.186	LO





EXOT-2018-62: s-channel simplified DM Summary

Semi-visible Final States

Analysis	Models targeted	Final state signature	Key Characteristics
$b\bar{b} + E_{\mathrm{T}}^{\mathrm{miss}}$ [53]	S/PS	2 b-jets, $E_{\mathrm{T}}^{\mathrm{miss}}$, 0 ℓ	Boosted decision tree and binned likelihood fit of $\cos\theta^{*}_{bb}$
$t\bar{t} + E_{\mathrm{T}}^{\mathrm{miss}}$ [54–57]	S/PS	0-1-2ℓ, $E_{\mathrm{T}}^{\mathrm{miss}}$, ≥ 1 b-jets	Statistical combination of $t\bar{t} + E_{\mathrm{T}}^{\mathrm{miss}}$ final state analysis
tW + $E_{\mathrm{T}}^{\mathrm{miss}}$ 0-1ℓ [58]	S/PS	0-1ℓ, $E_{\mathrm{T}}^{\mathrm{miss}}$, ≥ 1 b-jets, W tagged jets	Binned likelihood fit of $E_{\mathrm{T}}^{\mathrm{miss}}$
tW + $E_{\mathrm{T}}^{\mathrm{miss}}$ 2ℓ [59]	S/PS	2ℓ, ≥ 1 b-jet, $E_{\mathrm{T}}^{\mathrm{miss}}$	Single bin likelihood fit
tj + $E_{\mathrm{T}}^{\mathrm{miss}}$ [59]	S/PS	1ℓ, 1-4 jet, 1-2 b-jet, $E_{\mathrm{T}}^{\mathrm{miss}}$	Binned likelihood fit of BDTs
Jet + $E_{\mathrm{T}}^{\mathrm{miss}}$ [60]	S/PS,V/AV	1 high-p_{T} jet, $E_{\mathrm{T}}^{\mathrm{miss}}$, 0 ℓ	Binned likelihood fit of $E_{\mathrm{T}}^{\mathrm{miss}}$
$\gamma + E_{\mathrm{T}}^{\mathrm{miss}}$ [61]	V/AV	1 high-p_{T} γ, $E_{\mathrm{T}}^{\mathrm{miss}}$, 0 ℓ	Binned likelihood fit of $E_{\mathrm{T}}^{\mathrm{miss}}$
$Z(\ell\ell) + E_{\mathrm{T}}^{\mathrm{miss}}$ [62]	V/AV	$2\ell^{+}\ell^{-}$, $E_{\mathrm{T}}^{\mathrm{miss}}$, 0 jets	Binned likelihood fit of $E_{\mathrm{T}}^{\mathrm{miss}}$
$W(qq')/Z(q\bar{q}) + E_{\mathrm{T}}^{\mathrm{miss}}$ [63]	V/AV	$E_{\mathrm{T}}^{\mathrm{miss}}$, W/Z candidate (resolved and boosted topologies)	Binned likelihood fit fo $E_{\mathrm{T}}^{\mathrm{miss}}$

EXOT-2018-62: s-channel simplified DM Summary

Visible Final States

Analysis	Models targeted	Final state signature	Key Characteristics
Dijet [64]	V/AV	2 jets, m_{jj}, y^*	Sliding-window fit of m_{jj}
Dijet angular [65]	V/AV	2 jets, m_{jj}, y^*	Binned likelihood fit of χ_{jj}
Dijet ISR resolved [66]	V/AV	2 jets, γ, m_{jj}, y^*	Sliding-window fit of m_{jj}
Dijet ISR boosted [67]	V/AV	1 small-R jet, 1 large-R jet, m_{jj}, y^*	Data-driven extrapolation from control region via transfer factor
Dijet TLA [68]	V/AV	2 trigger-level jets, m_{jj}, y^*	Sliding-window fit of m_{jj}
Dijet + lepton [69]	V/AV	2 jets, ℓ, m_{jj}	Fit of m_{jj}
Dilepton [70]	V/AV	2 e or 2 μ	$Z/\gamma^* \to \ell\ell$ from fit of $m_{\ell\ell}$
$t\bar{t}$ [71, 72]	V/AV, S/PS	ℓ+jets; 2 large-R jets	Binned likelihood fit of $m_{t\bar{t}}$
$t\bar{t}t\bar{t}$ [73]	S/PS	Same-sign $\ell^{\pm}\ell^{\pm}$ and $\ell^{\pm}\ell^{\pm}\ell^{\mp}$	Binned likelihood fit of BDT

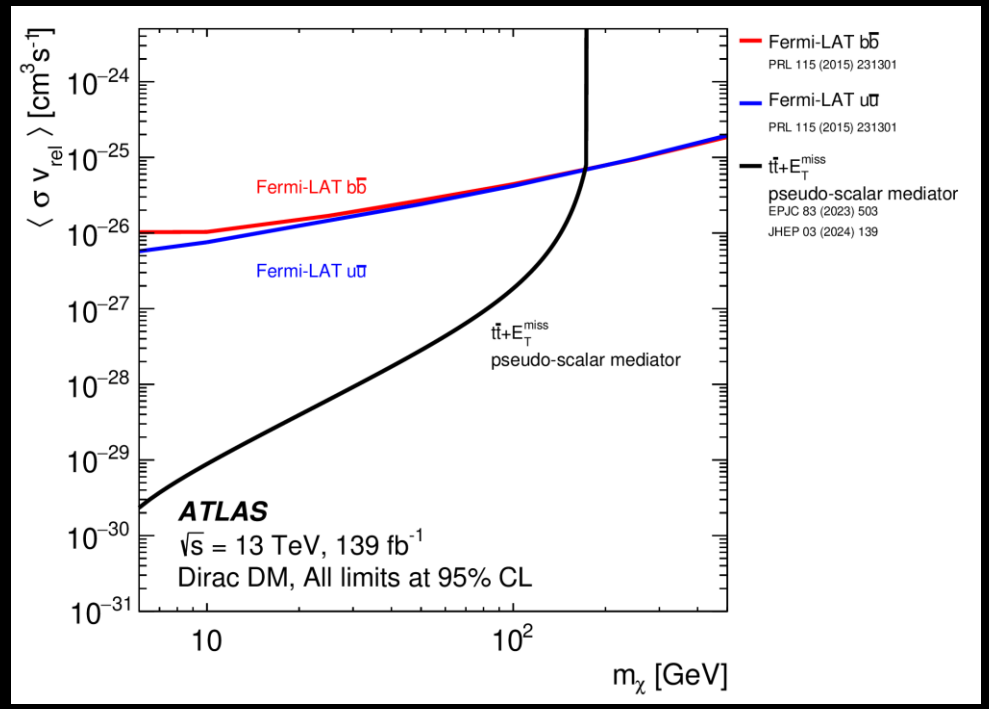
Phys. Dark Univ. 27 (2020) 100365

s-channel Simplified Model: Compare to direct search

Annihilation rate (for pseudo-scalar)

$$\langle \sigma v_{\mathrm{rel}} \rangle_q = \frac{3m_q^2}{2\pi v^2} \frac{g_q^2 g_\chi^2 m_\chi^2}{\left(m_{\mathrm{Med}}^2 - 4m_\chi^2\right)^2 + m_{\mathrm{Med}}^2 \Gamma_{\mathrm{Med}}^2} \sqrt{1 - \frac{m_q^2}{m_{\mathrm{Med}}^2}}$$

$$\langle \sigma v_{\mathrm{rel}} \rangle_g = \frac{\alpha_s^2}{2\pi^3 v^2} \frac{g_q^2 g_\chi^2}{\left(m_{\mathrm{Med}}^2 - 4m_\chi^2\right)^2 + m_{\mathrm{Med}}^2 \Gamma_{\mathrm{Med}}^2} \cdot \left| \sum_q m_q^2 f_{PS}\left(\frac{m_q^2}{m_\chi^2}\right) \right|^2$$



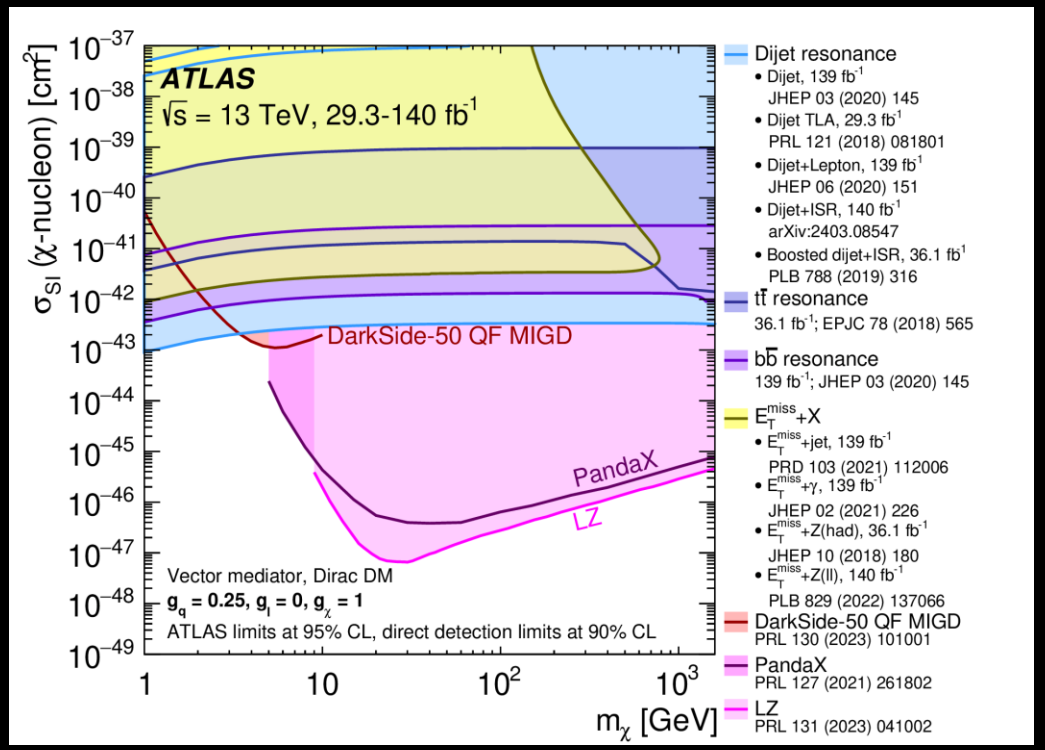
Phys. Dark Univ. 27 (2020) 100365

Spin-independent

$$\sigma_{SI} = \frac{f^2(g_q) g_\chi^2 \mu_{n\chi}^2}{\pi m_{\text{Med}}^4}$$

μ: DM-nucleon reduced mass

$f(g_q)$: mediator-nucleon coupling

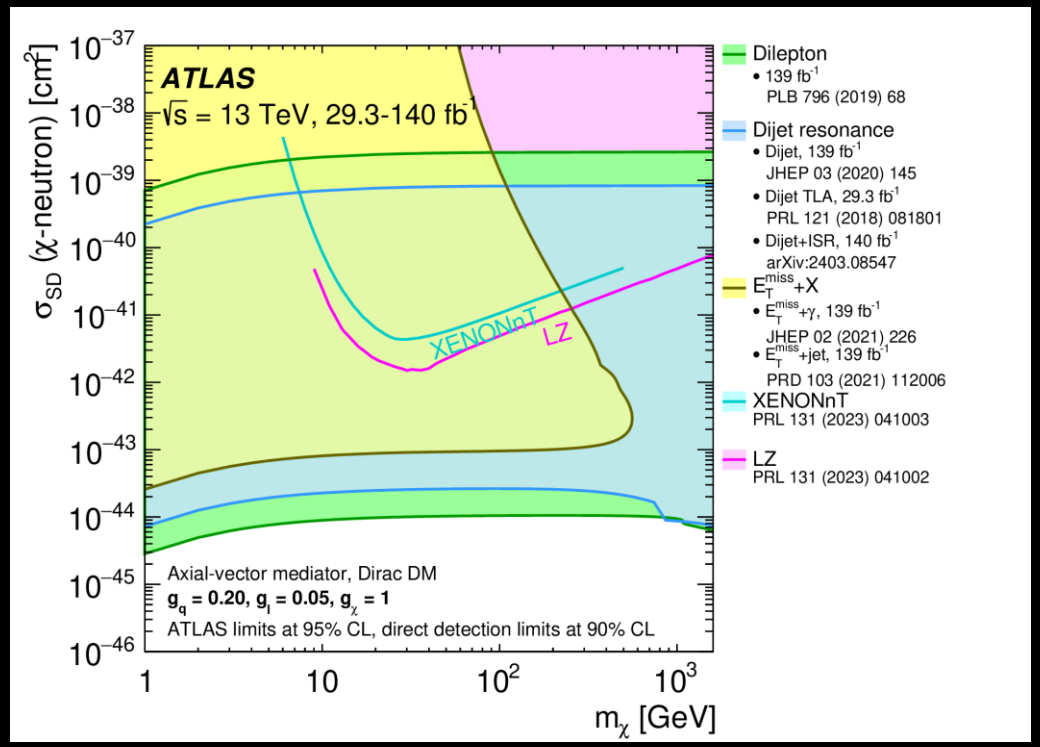


s-channel Simplified Model: Compare to direct search

Spin-dependent

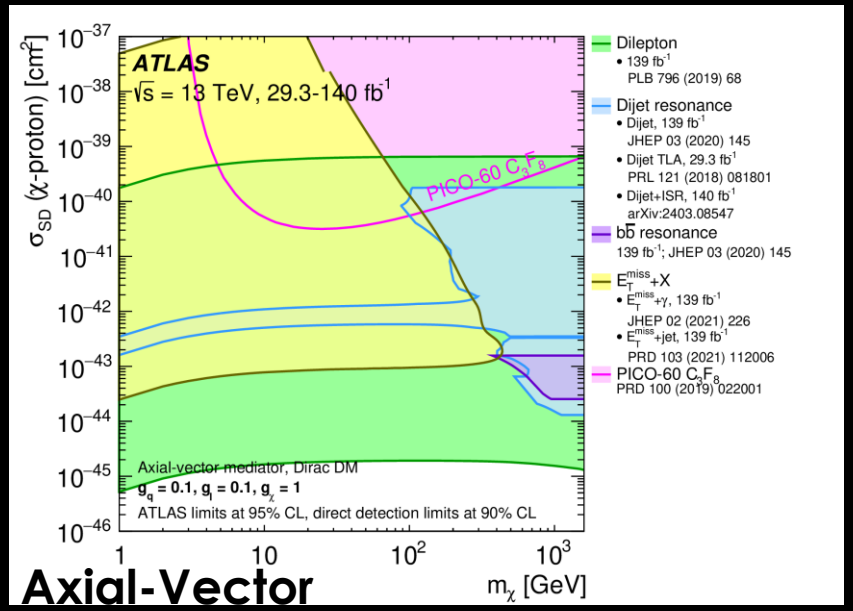
$$\sigma_{SD} = \frac{3 f^2(g_q) g_\chi^2 \mu_{n\chi}^2}{\pi m_{\text{Med}}^4}$$

$f_{p/n}(g_q)$: mediator-proton/neutron coupling

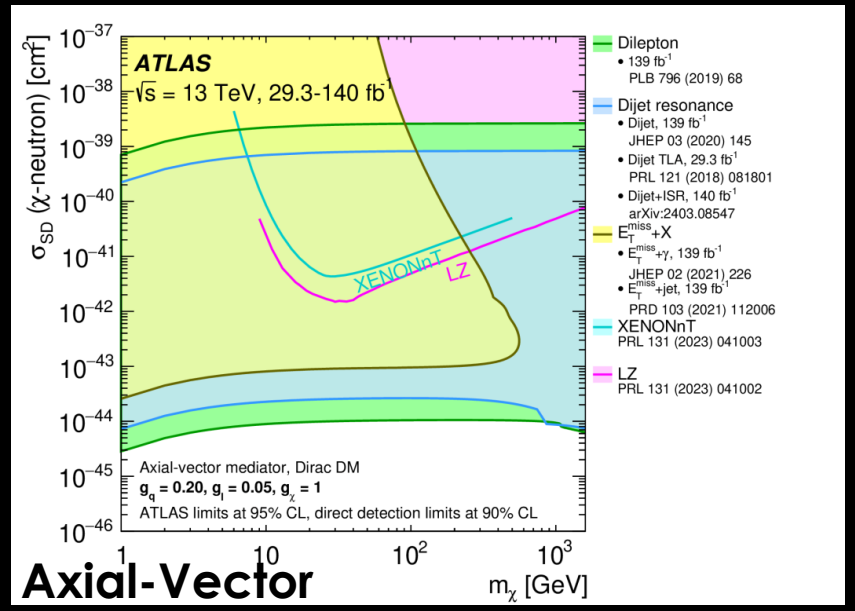


2404.15930

Spin-dependent

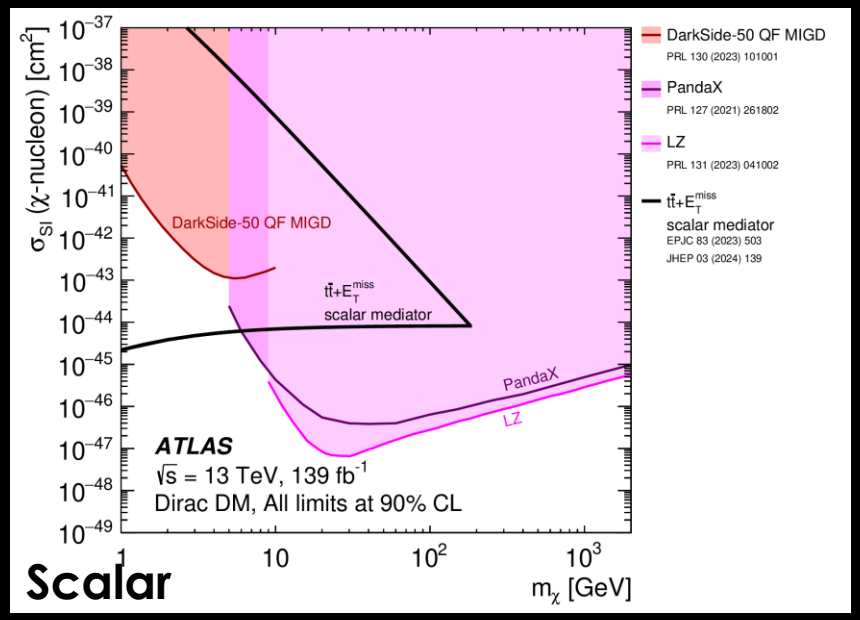


Axial-Vector

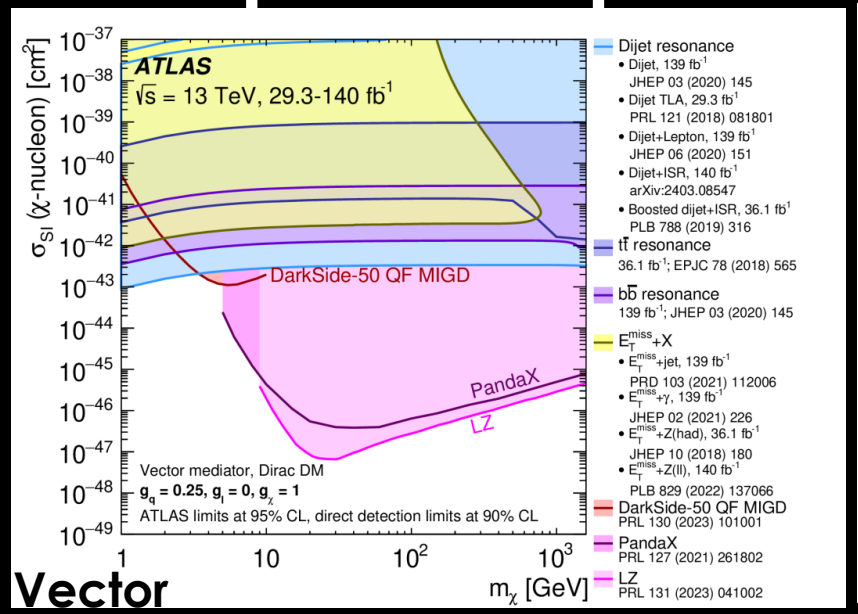


Axial-Vector

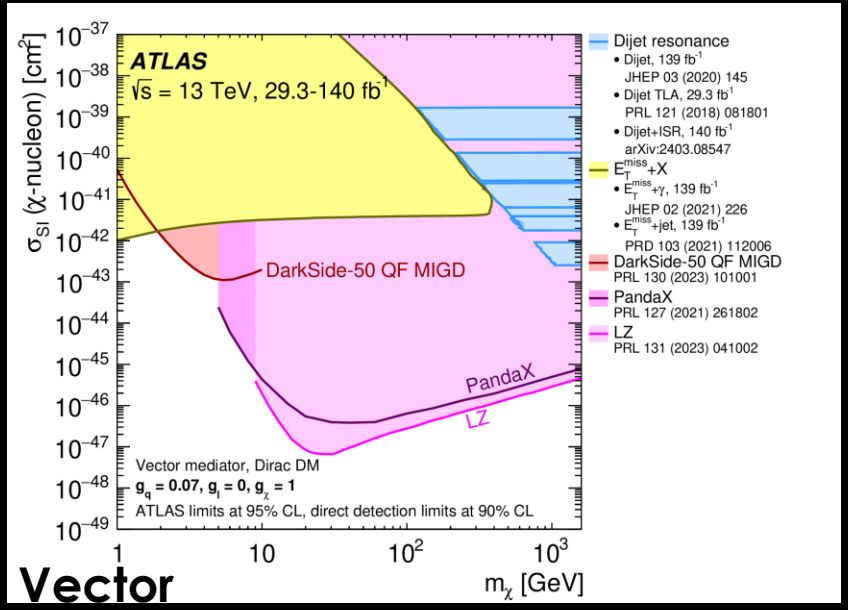
Spin-independent



Scalar



Vector



Vector

Higgs Bosons

H/h: scalar

A: pseudo-scalar

$H^{\pm}$: charged scalar

The model is fully defined by 14 parameters:

(5 free parameters)

$$\left\{\begin{array}{c} \nu,\ M_h, \\ y_\chi = 1, \\ cos(\beta-\alpha) = 0, \\ \lambda_3 = \lambda_{P_1} = \lambda_{P_2} = 3 \\ m_A = m_{H^\pm} = m_H \\ m_\chi,\ m_a,\ sin\theta,\ tan\beta \end{array}\right\}$$

Free Parameters

$sin\theta$: mixing angle of A and a

g_χ: dark-sector Yukawa coupling

$tan\beta$: ratio of VEV of Higgs doublet

$m_A = m_H = m_{H^\pm}$: degenerated mass

m_a: DM mediator mass

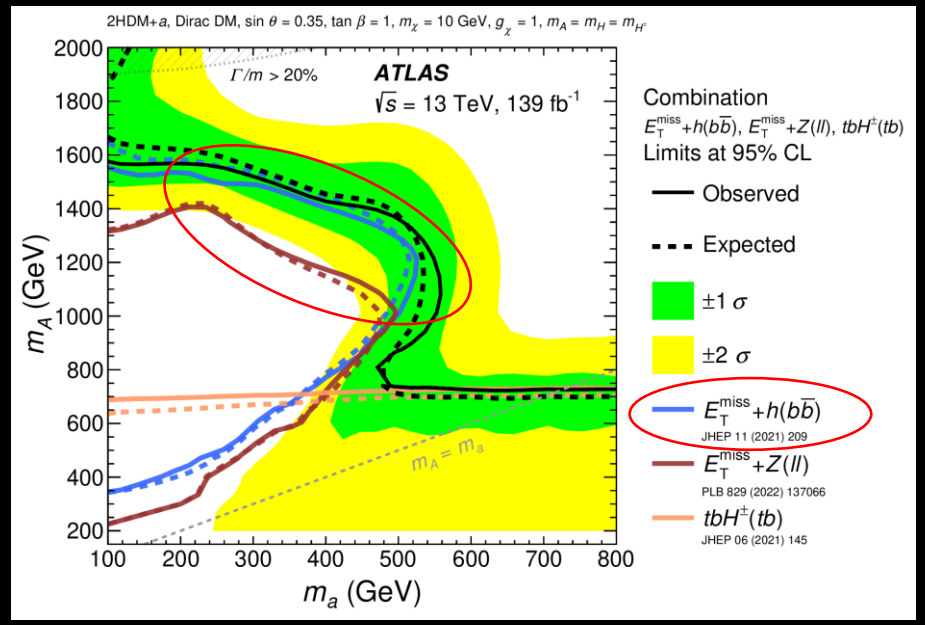
LHC Dark Matter Benchmark Model

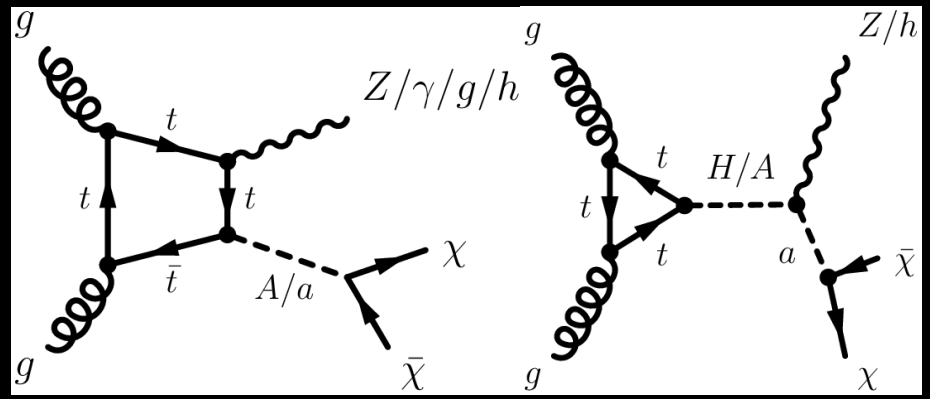
2HDM+a

Theory Model: JHEP 05 (2017) 138

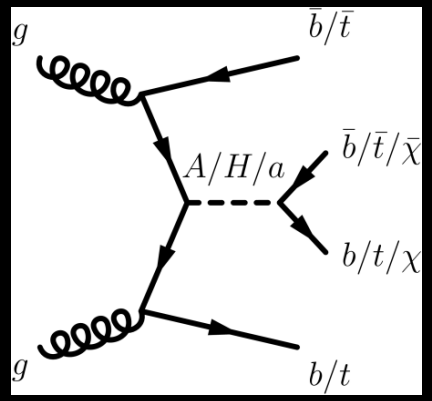
Latest results: EXOT-2018-64

- Extension of pseudo-scalar mediator simplified model
  - UV-complete, gauge-invariant and renormalizable
- Two Higgs Doublet Model (2HDM) plus pseudo-scalar mediator a
  - Scalar sector of SM extended by an additional complex doublet
    Well-motivated by theory e.g. hierarchy, baryogenesis, strong CP
    Type-II 2HDM with 5 Higgs bosons $\boldsymbol{H}$, $\boldsymbol{h}$, $\boldsymbol{A}$, $\boldsymbol{H^{\pm}}$ and $\boldsymbol{h}$ as SM Higgs
  - 1 pseudo-scalar mediator $\boldsymbol{a}$ coupled to Dirac DM $\boldsymbol{\chi}$
    Enable the interplay with SM and dark sector
  - Full set of 14 parameters: 5 free parameters for benchmark

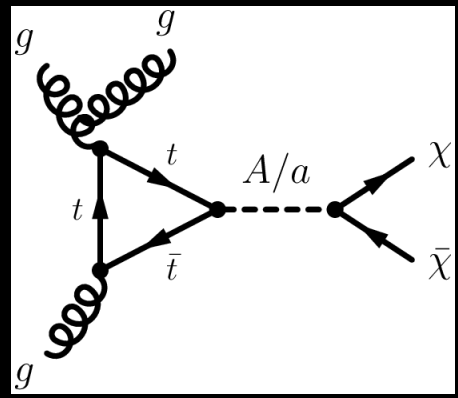




Mono-h, Mono-V

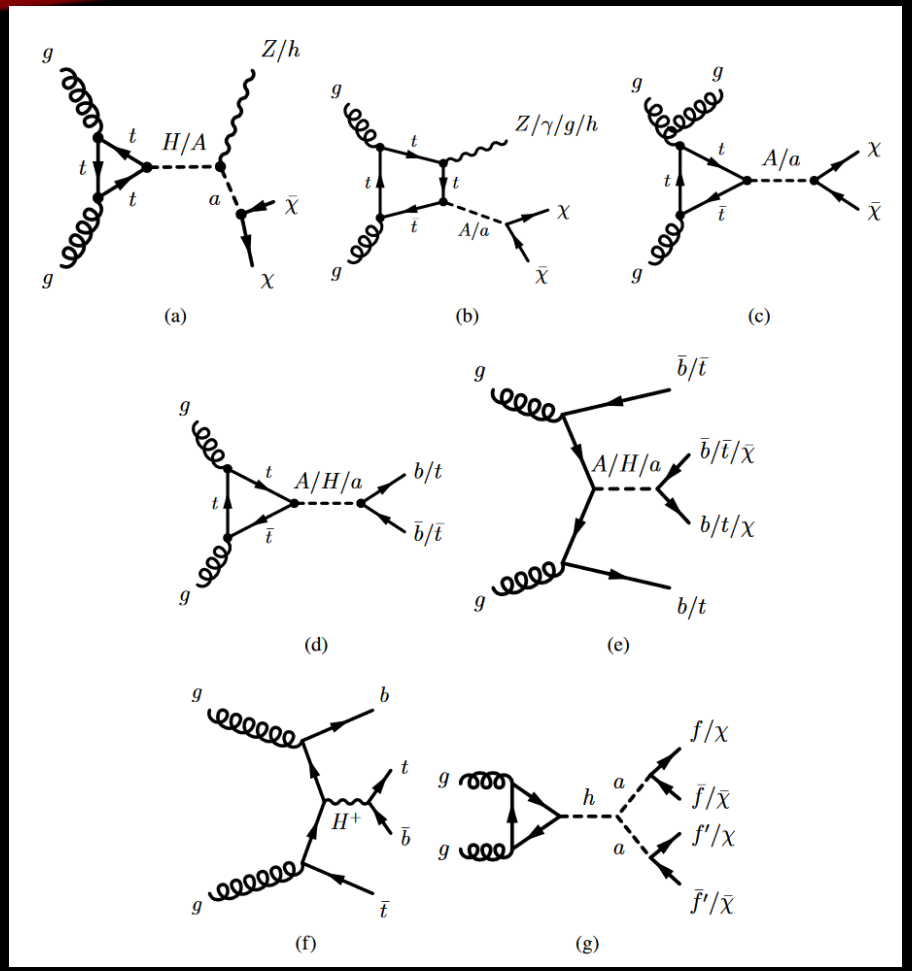


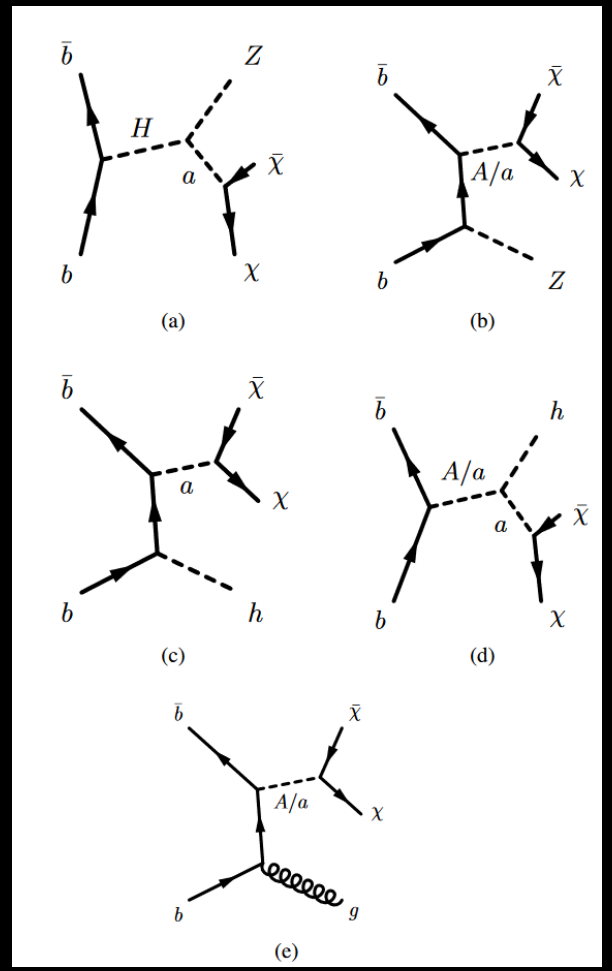
bb+MET

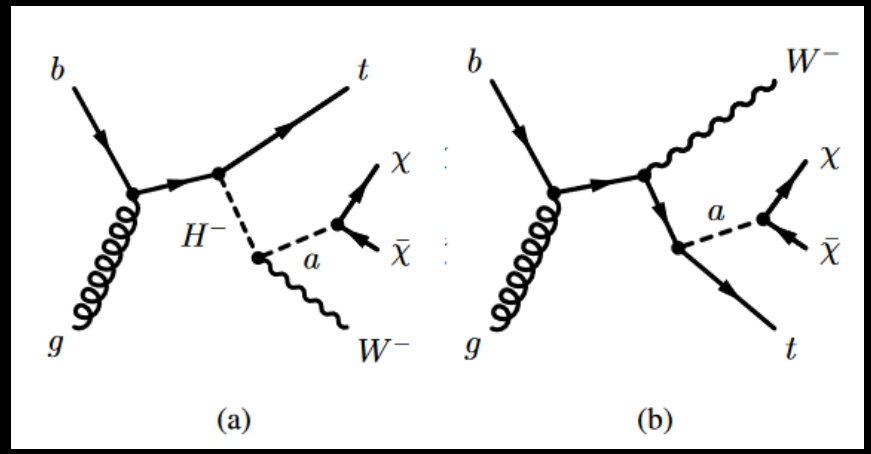


Mono-j

2HDM+a


g
Z/h
t
H/A
t
t
a
χ̄
g
χ
(a)
g
Z/γ/g/h
t
t
t
A/a
g
χ
χ̄
(b)
g
g
t
A/a
χ
t
t̄
χ̄
g
(c)
g
b/t
t
A/H/a
t
b̄/t̄
g
(d)
g
b̄/t̄
A/H/a
b̄/t̄/χ̄
b/t/χ
g
b/t
(e)
g
b
t
H+
b̄
g
t̄
(f)
g
h
a
f/χ
f̄/χ̄
g
a
f′/χ
f̄′/χ̄
(g)

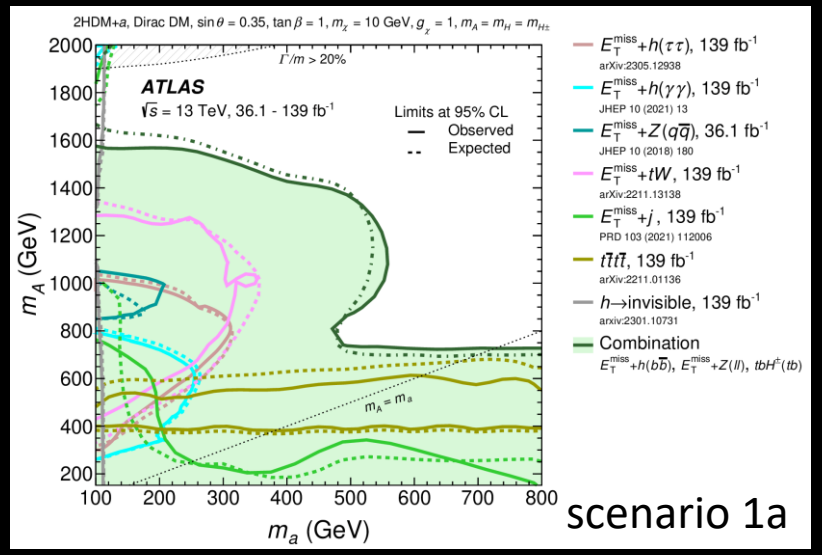

b̄
Z
H
a
χ̄
b
χ
(a)
b̄
χ̄
A/a
χ
b
Z
(b)
b̄
χ̄
a
χ
b
h
(c)
b̄
h
A/a
a
χ̄
b
χ
(d)
b̄
χ̄
A/a
χ
b
g
(e)


b
t
H−
χ
a
χ̄
g
W−
(a)
b
W−
χ
a
χ̄
g
t
(b)

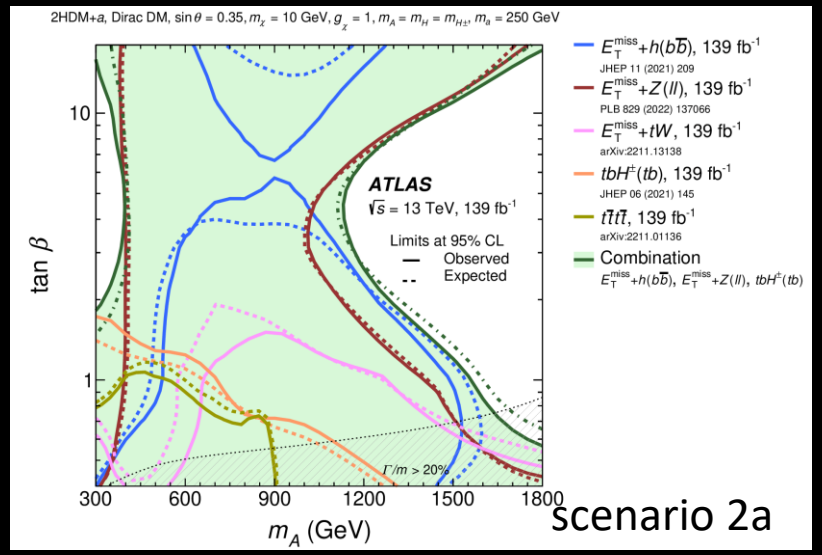
2HDM+a

Scenario		Fixed parameter values					Varied parameters
		$\sin\theta$	m_A [GeV]	m_a [GeV]	m_χ [GeV]	$\tan\beta$	
1	a	0.35	–	–	10	1.0	(m_a, m_A)
	b	0.70	–	–	10	1.0	
2	a	0.35	–	250	10	–	$(m_A, \tan\beta)$
	b	0.70	–	250	10	–	
3	a	0.35	600	–	10	–	$(m_a, \tan\beta)$
	b	0.70	600	–	10	–	
4	a	–	600	200	10	1.0	$\sin\theta$
	b	–	1000	350	10	1.0	
5		0.35	1000	400	–	1.0	m_χ
6		0.35	1200	–	–	1.0	(m_a, m_χ)

Analysis/Scenario	1a	1b	2a	2b	3a	3b	4a	4b	5	6
$E_{\mathrm{T}}^{\mathrm{miss}} + Z(\ell\ell)$ [74]	x	x	x	x	x	x	x	x	x	
$E_{\mathrm{T}}^{\mathrm{miss}} + h(b\bar{b})$ [75]	x	x	x	x	x	x	x	x	x	x
$E_{\mathrm{T}}^{\mathrm{miss}} + h(\gamma\gamma)$ [84]	x	x			x	x	x	x		
$E_{\mathrm{T}}^{\mathrm{miss}} + h(\tau\tau)$ [78]	x			x						
$E_{\mathrm{T}}^{\mathrm{miss}} + tW$ [77]	x	x	x	x	x	x	x	x		
$E_{\mathrm{T}}^{\mathrm{miss}} + j$ [45]	x	x			x	x	x	x		
$h \rightarrow$ invisible [86]	x	x			x					x
$E_{\mathrm{T}}^{\mathrm{miss}} + Z(q\bar{q})$ [126]	x						x	x		
$E_{\mathrm{T}}^{\mathrm{miss}} + b\bar{b}$ [127]							x	x		
$E_{\mathrm{T}}^{\mathrm{miss}} + t\bar{t}$ [127, 128]							x	x		
$t\bar{t}t\bar{t}$ [85]	x	x	x	x	x	x	x	x	x	
$tbH^{\pm}(tb)$ [76]	x	x	x	x	x	x	x	x	x	
$h \rightarrow aa \rightarrow f\bar{f}f'\bar{f}'$ [79–83]										x



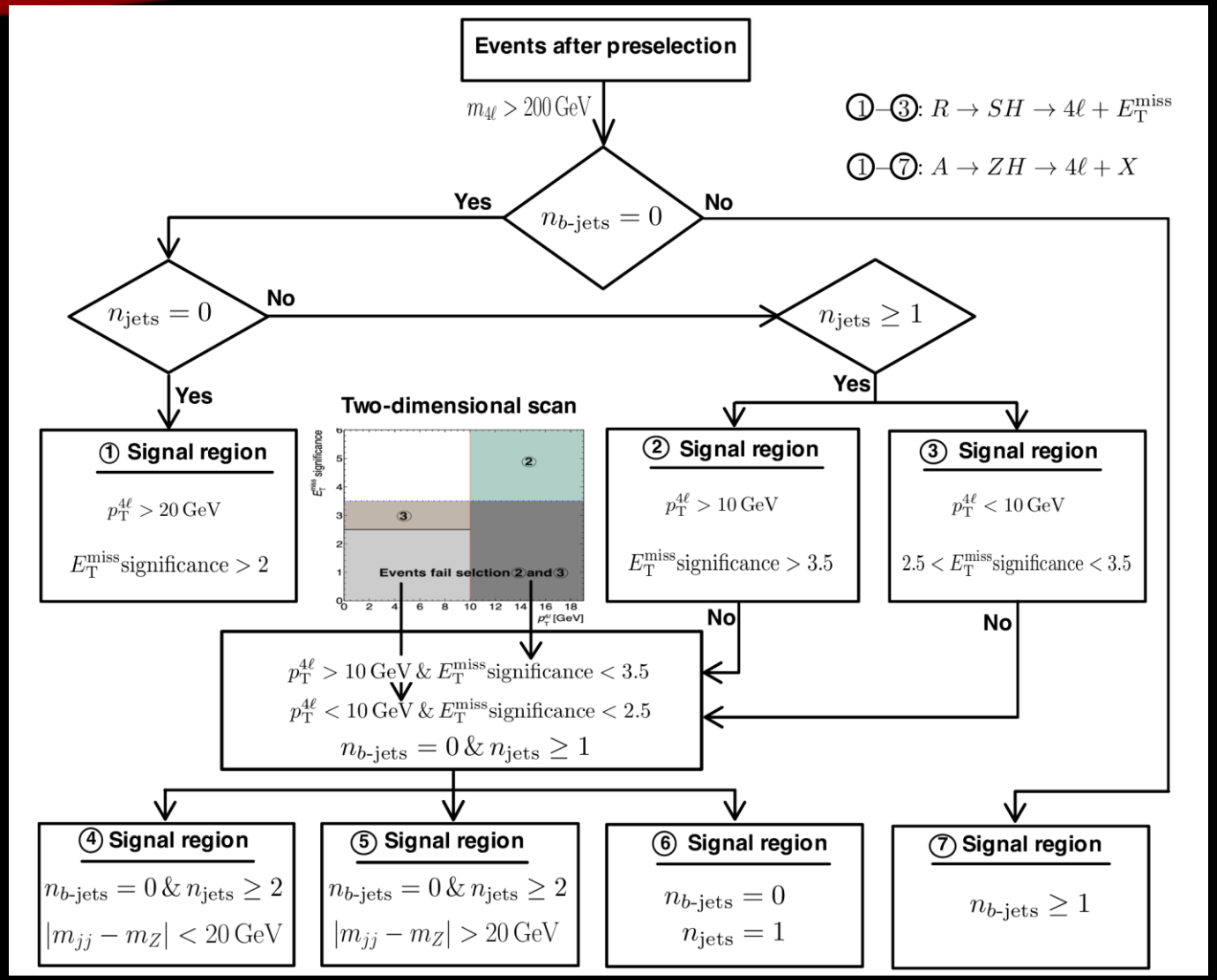
scenario 1a



scenario 2a

2HDM

Search for heavy resonances in final states with four leptons and missing transverse momentum or jets



$$f(m_{4\ell}) = H(m_0 - m_{4\ell}) f_1(m_{4\ell}) C_1 + H(m_{4\ell} - m_0) f_2(m_{4\ell}) C_2,$$

$$f_1(m_{4\ell}) = \frac{a_1 \cdot m_{4\ell} + a_2 \cdot m_{4\ell}^2}{1 + \exp\left(\frac{m_{4\ell} - a_1}{a_3}\right)},$$

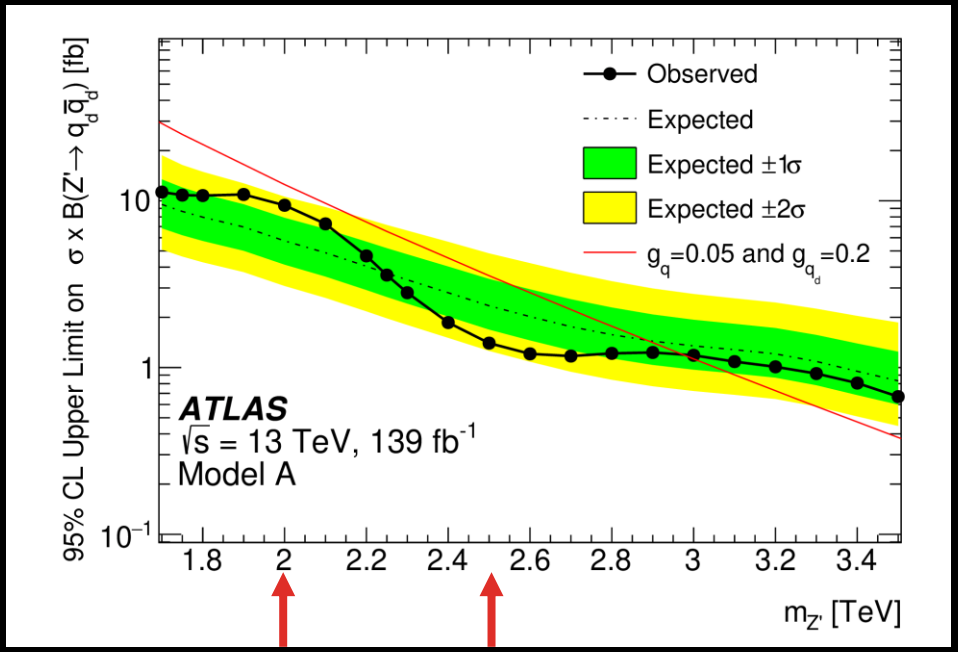
$$f_2(m_{4\ell}) = \left(1 - \frac{m_{4\ell}}{n_C}\right)^{b_1} \cdot \left(\frac{m_{4\ell}}{n_C}\right)^{\left(b_2 + b_3 \cdot \ln\left(\frac{m_{4\ell}}{n_C}\right)\right)},$$

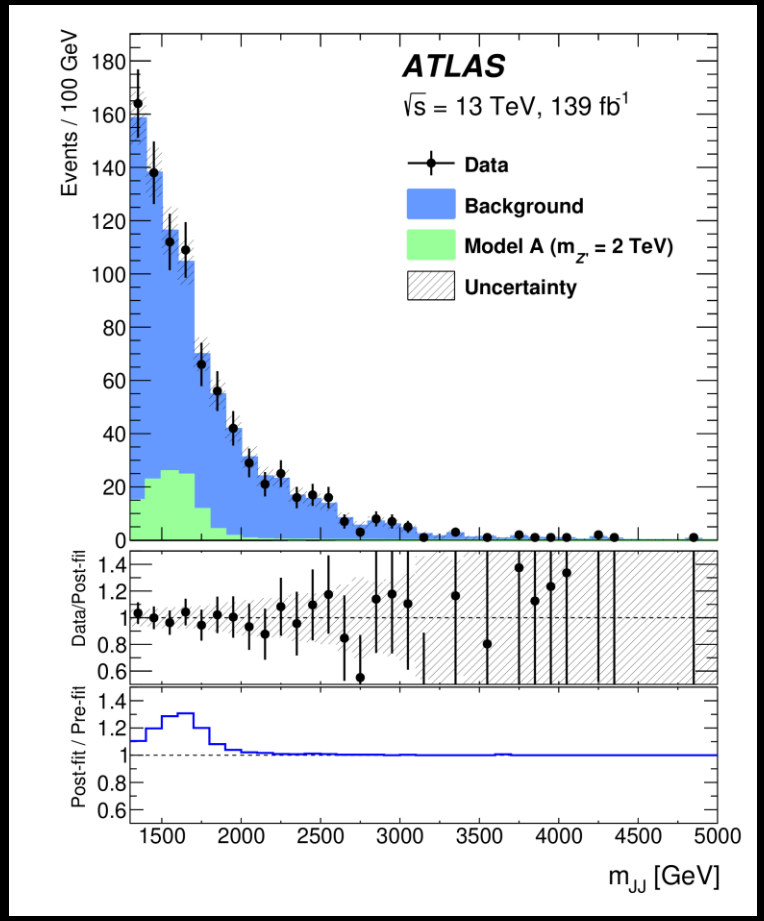
$$C_1 = \frac{1}{f_1(m_0)}, \qquad C_2 = \frac{1}{f_2(m_0)}.$$

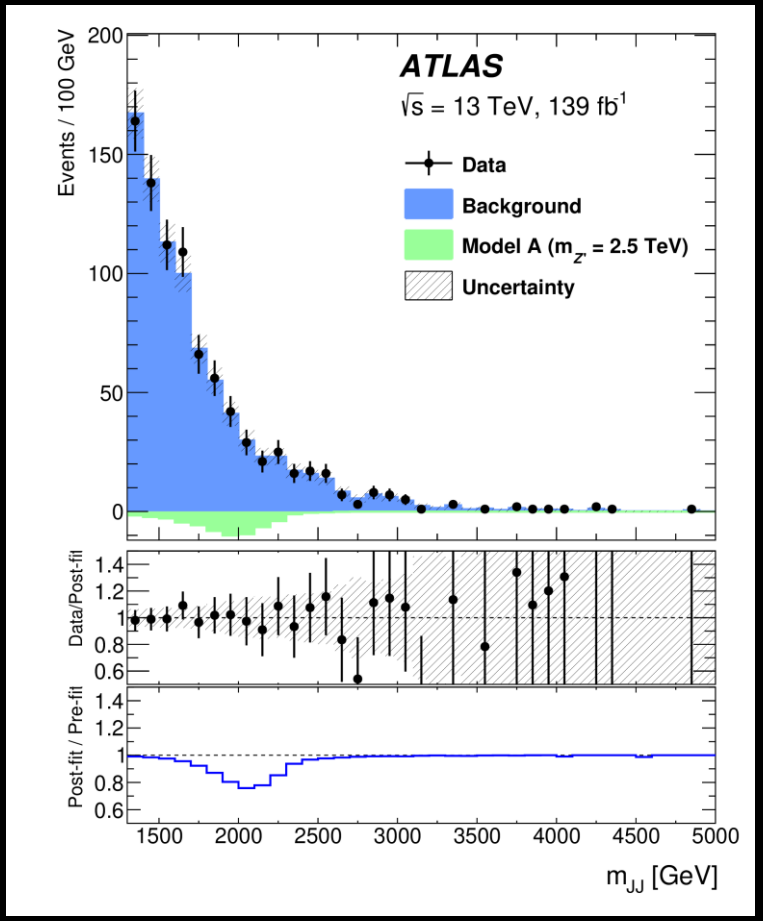
Signal region	$R \to SH \to 4\ell + E_{\mathrm{T}}^{\mathrm{miss}}$ and $A \to ZH \to 4\ell + X$			
SR1	$n_{b\text{-jets}} = 0$	$n_{\mathrm{jets}} = 0$	$p_{\mathrm{T}}^{4\ell} > 20$ GeV	$E_{\mathrm{T}}^{\mathrm{miss}}$ significance >2.0
SR2		$n_{\mathrm{jets}} \geq 1$	$p_{\mathrm{T}}^{4\ell} > 10$ GeV	$E_{\mathrm{T}}^{\mathrm{miss}}$ significance > 3.5
SR3			$p_{\mathrm{T}}^{4\ell} < 10$ GeV	$2.5 < E_{\mathrm{T}}^{\mathrm{miss}}$ significance < 3.5
	$A \to ZH \to 4\ell + X$			
SR4	$n_{b\text{-jets}} = 0$	$n_{\mathrm{jets}} \geq 2$	$\lvert m_{jj} - m_Z \rvert < 20$ GeV	
SR5			$\lvert m_{jj} - m_Z \rvert > 20$ GeV	
SR6		$n_{\mathrm{jets}} = 1$		
SR7	$n_{b\text{-jets}} \geq 1$			

$R \to SH \to 4\ell + E_{\mathrm{T}}^{\mathrm{miss}}$			$A \to ZH \to 4\ell + X$		
(m_R, m_H) [GeV]	Uncertainty source	$\Delta\sigma/\sigma$ [%]	(m_A, m_H) [GeV]	Uncertainty source	$\Delta\sigma/\sigma$ [%]
(390, 220)	Jet flavour composition	6.2	(320, 220)	Other backgrounds parameterisation SR7	5.0
	Jet flavour response	4.8		$q\bar{q} \to ZZ$ parameterisation SR7	3.9
	Jet energy scale	4.2		Jet flavour composition	3.9
	Pile-up reweighting	4.0		Luminosity	3.7
	CKKW parton showering ($gg \to ZZ$) SR2	3.8		$gg \to ZZ$ parameterisation SR6	3.6
(500, 300)	CKKW parton showering ($gg \to ZZ$) SR2	3.1	(510, 380)	Luminosity	2.4
	QSF parton showering ($gg \to ZZ$) SR2	3.0		Jet flavour composition	2.4
	$q\bar{q} \to ZZ$ parameterisation SR2	2.0		Jet energy scale	1.7
	Pile-up reweighting	1.9		Jet energy resolution	1.5
	VVV parameterisation SR2	1.9		Signal PDF	1.4
(1300, 1000)	$q\bar{q} \to ZZ$ parameterisation SR2	9.3	(1300, 1000)	CKKW parton showering ($gg \to ZZ$) SR2	3.3
	Jet flavour composition	7.3		QSF parton showering ($gg \to ZZ$) SR2	3.3
	Jet flavour response	3.5		Other backgrounds parameterisation SR2	2.6
	Pile-up reweighting	2.9		$q\bar{q} \to ZZ$ parameterisation SR5	2.1
	CKKW parton showering ($gg \to ZZ$) SR2	2.9		VVV parameterisation SR2	2.1

Dark Jet


95% CL Upper Limit on σ x B(Z'→ q_d q̄_d) [fb]
Observed
Expected
Expected ±1σ
Expected ±2σ
g_q=0.05 and g_q_d=0.2
ATLAS
√s = 13 TeV, 139 fb-1
Model A
m_Z' [TeV]


ATLAS
√s = 13 TeV, 139 fb-1
Data
Background
Model A (m_Z' = 2 TeV)
Uncertainty
Events / 100 GeV
Data/Post-fit
Post-fit / Pre-fit
m_JJ [GeV]


ATLAS
√s = 13 TeV, 139 fb-1
Data
Background
Model A (m_Z' = 2.5 TeV)
Uncertainty
Events / 100 GeV
Data/Post-fit
Post-fit / Pre-fit
m_JJ [GeV]

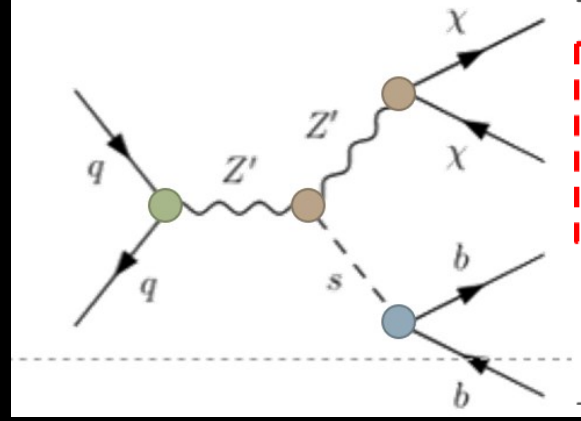
[1]: 1701.08780
[2]: 1606.07609

Dark Higgs

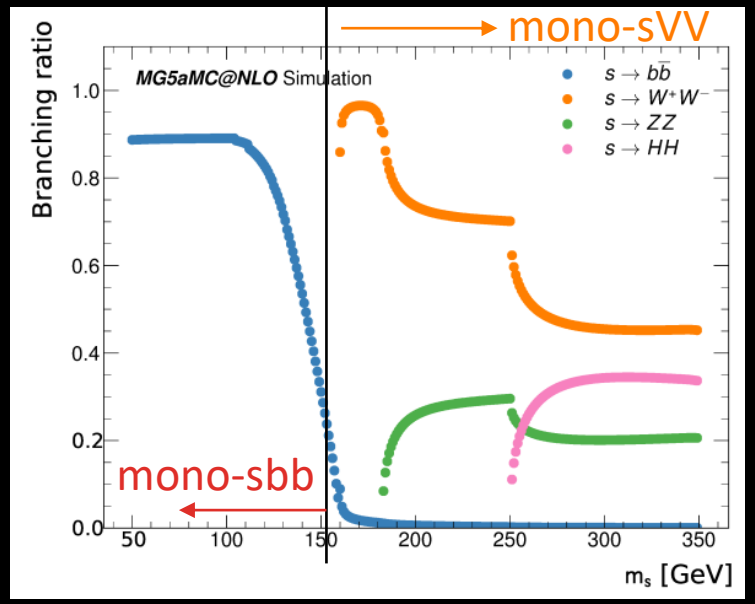
- Spontaneously broken U(1)' gauge symmetry introduced in the WIMP model **account the mass origin in dark sector**
- Scalar particle ***S*** called Dark Higgs[1], vector boson ***Z'*** and Majorana DM χ : two-mediator model (2MDM) [2]
- Detectable final states from mixing with SM Higgs: $s \to bb$, $s \to VV$, ... depending on mass; as well as large MET
- $\chi\chi \to ss$ annihilation relax the relic density constraint from cosmology: prevent DM over-production issue
  - Effectively reduce one parameter → search in 3-D parameter space

$$\mathcal{L}_\chi = -g_q Z'^\mu \bar{q}\gamma_\mu q$$

$$\mathcal{L}_\chi = -\frac{1}{2} g_\chi Z'^\mu \bar{\chi}\gamma^5\gamma_\mu\chi - g_\chi \frac{m_\chi}{m_{Z'}} s\bar{\chi}\chi + 2\, g_\chi\, Z'^\mu Z'_\mu \left(g_\chi\, s^2 + m_{Z'} s\right)$$

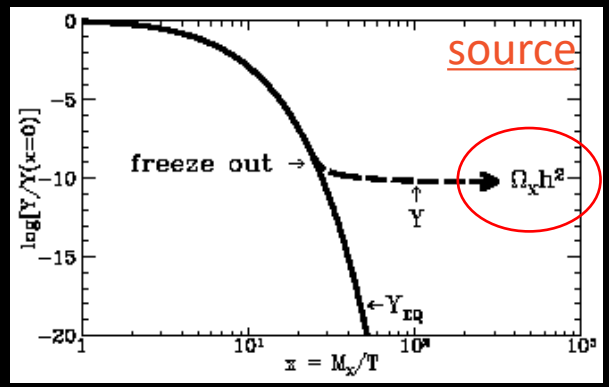


Parameter	Explain
m_s	mass of Dark Higgs
m_χ	mass of DM
$m_{z'}$	mass of heavy mediator
g_χ	coupling in dark sector between s, X, Z'
g_q	coupling with SM: q<->Z' fixed 0.25 as benchmark
θ	mixing angle of SM Higgs<->dark Higgs fixed according to [1]



ATL-PHYS-PUB-2019-032

Relic Density
Over-abundant model disfavored



Big Bang Freeze out

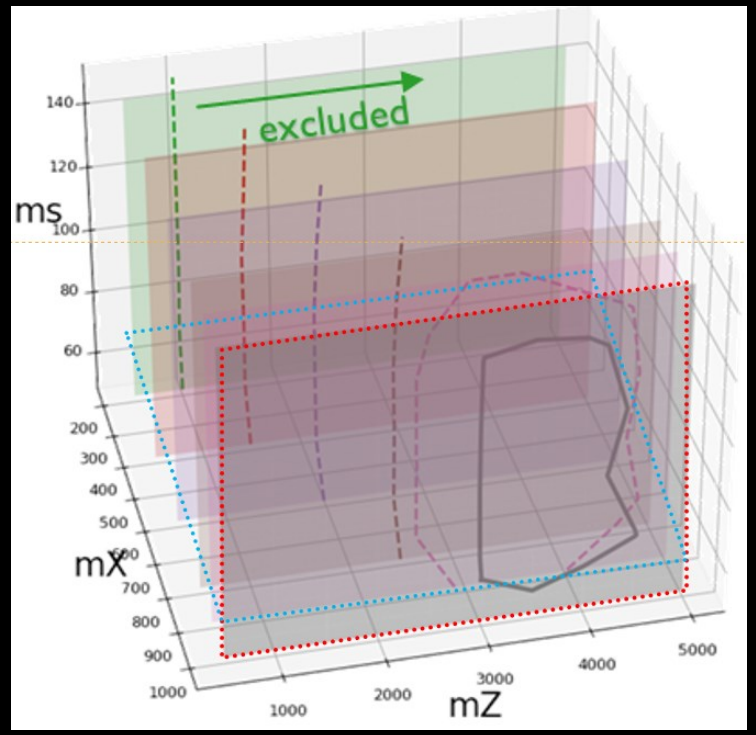
Dark Higgs

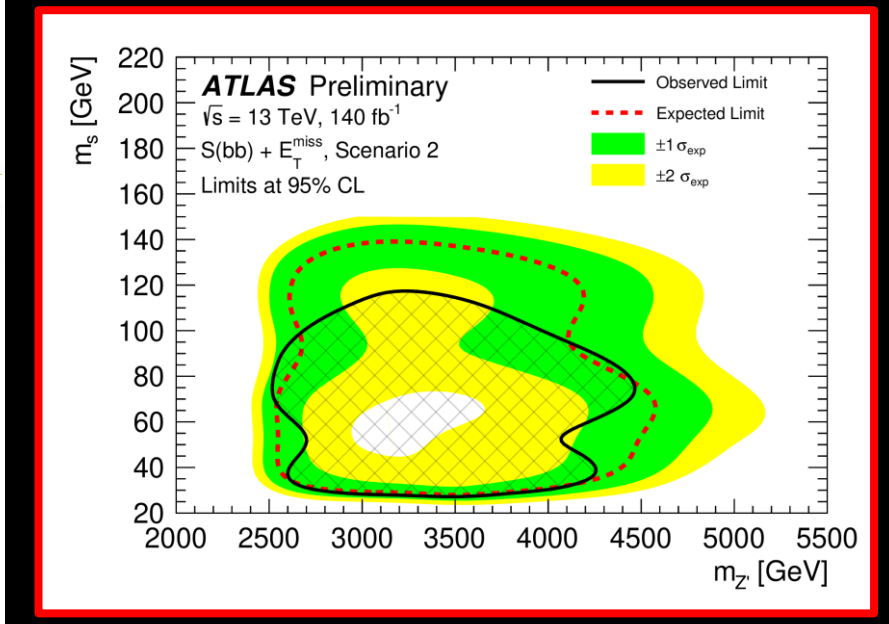
Relic-coherent 3-D Parameter Space

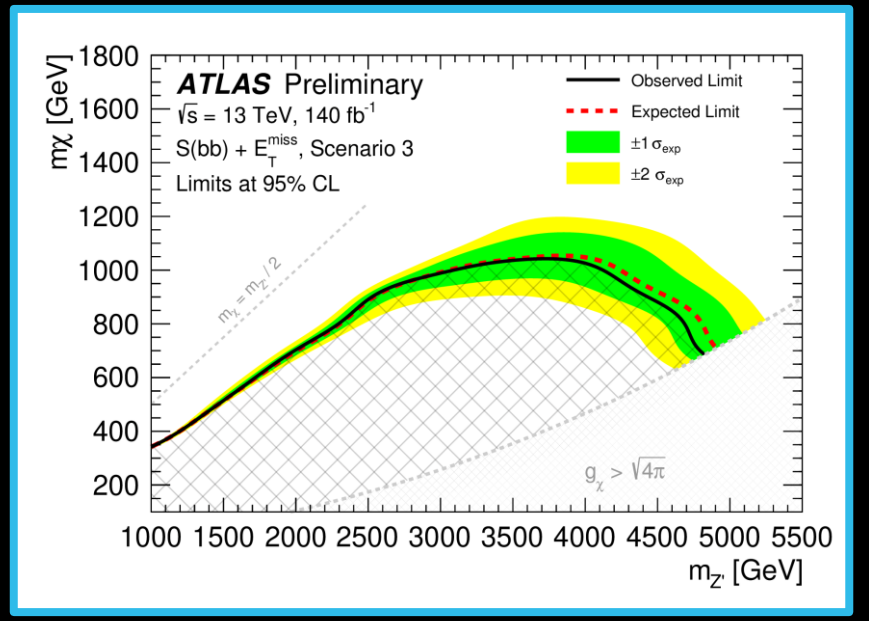
How relic density used to reduce parameter space of DM model

Reco Analysis Result

Set the final exclusion limit







Phys. Rev. Lett. 38 (1977) 1440.
Eur. Phys. J. C 77 (2017) 572

Axion Like Particle (ALP)

- Global U(1) symmetry added to solve the CP symmetry problem in QCD interaction
- Weakly interacting pseudo-scalar particle $\boldsymbol{a}$
- Heavy ALP in the GeV-TeV range usually searched similarly as WIMP
- Light ALP probed with coupling to gluon, photon, fermion and vector boson
- Effective scale f_a: regulates the dimension-5 operators built from the SM fields and the ALPs
  - E.g. in MonoV(had) probed f_a up to 5TeV with 1MeV ALP
- Linear EWSB realizations with general linear bosonic Lagrangian, including only the NLO corrections involving $\boldsymbol{a}$

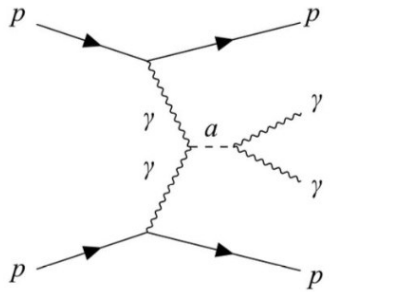
$$\mathscr{L}_{\text{eff}}^{\text{linear}} = \mathscr{L}^{\text{LO}} + \delta\mathscr{L}_a^{\text{bosonic}}$$

$$\mathscr{L}^{\text{LO}} = \mathscr{L}_{\text{SM}} + \frac{1}{2}(\partial_\mu a)(\partial^\mu a)$$

kinetic term

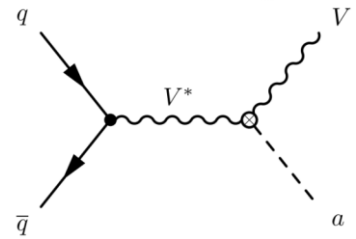
for photon

$$\delta\mathscr{L}_a^{\text{bosonic}} \supset -\frac{1}{4} g_{a\gamma\gamma}\, a\, F_{\mu\nu}\tilde{F}^{\mu\nu} \qquad g_{a\gamma\gamma} = \frac{4}{f_a}(c_{\tilde{B}} c_\theta^2 + c_{\tilde{W}} s_\theta^2)$$



for W

$$\delta\mathscr{L}_a^{\text{bosonic}} \supset -\frac{1}{4} g_{aWW}\, a\, W_{\mu\nu}\tilde{W}^{\mu\nu} \qquad g_{aWW} = 4c_{\tilde{W}}/f_a$$

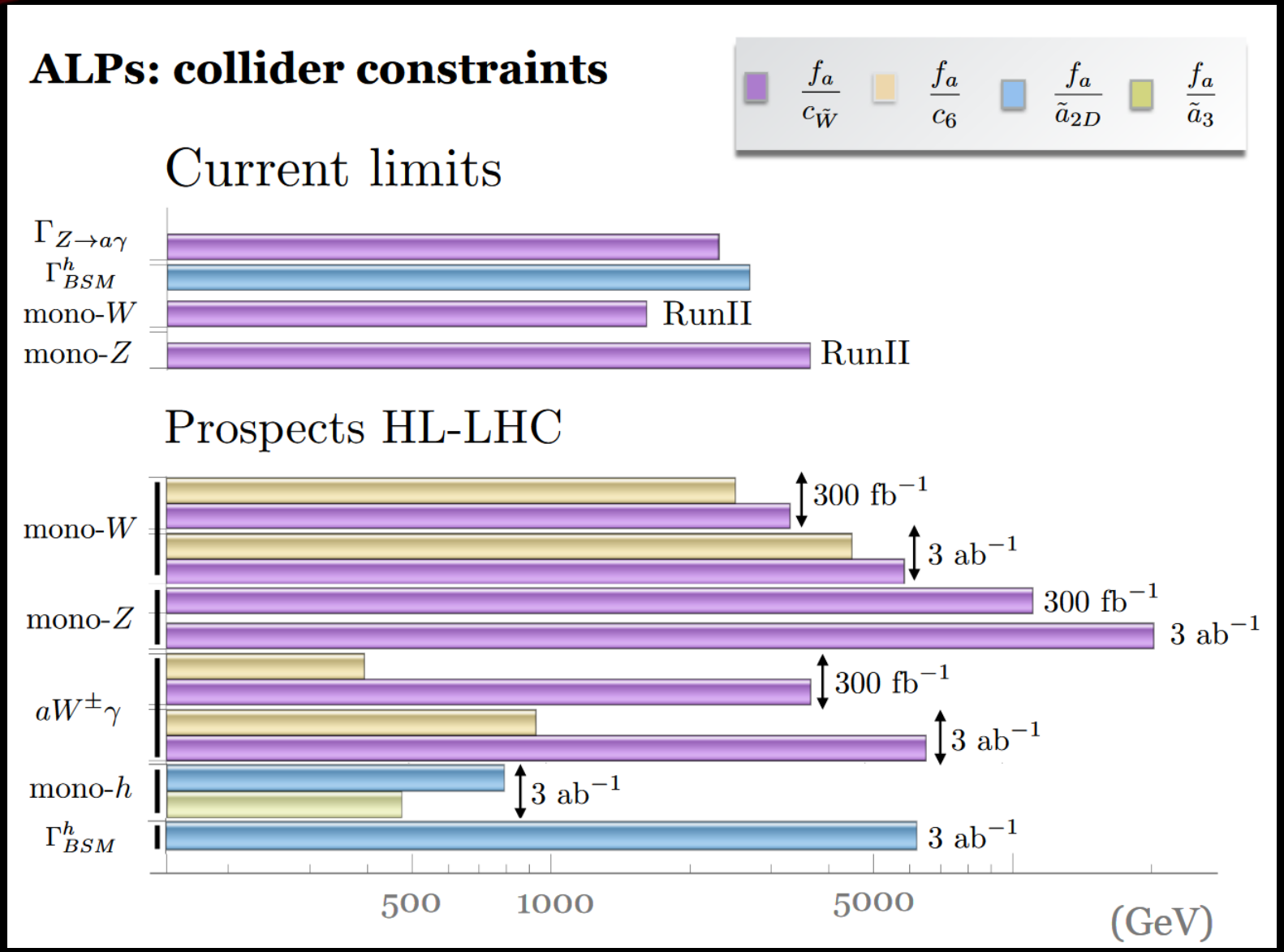


1701.05379

LHC 13TeV

Orthogonal to photon coupling ($g_{a\gamma\gamma} = 0$)

Axion Like Particle (ALP)



Axion Like Particle (ALP)

$$\delta\mathscr{L}_a^{\text{bosonic}} = c_{\tilde{W}}\mathcal{A}_{\tilde{W}} + c_{\tilde{B}}\mathcal{A}_{\tilde{B}} + c_{\tilde{G}}\mathcal{A}_{\tilde{G}} + c_{a\Phi}\mathbf{O}_{a\Phi}\,, \tag{4}$$

with

$$\mathcal{A}_{\tilde{B}} = -B_{\mu\nu}\tilde{B}^{\mu\nu}\frac{a}{f_a}\,, \tag{5}$$

$$\mathcal{A}_{\tilde{W}} = -W^a_{\mu\nu}\tilde{W}^{a\mu\nu}\frac{a}{f_a}\,, \tag{6}$$

$$\mathcal{A}_{\tilde{G}} = -G^a_{\mu\nu}\tilde{G}^{a\mu\nu}\frac{a}{f_a}\,, \tag{7}$$

$$\mathbf{O}_{a\Phi} = i(\Phi^\dagger \overleftrightarrow{D}_\mu \Phi)\frac{\partial^\mu a}{f_a}\,, \tag{8}$$

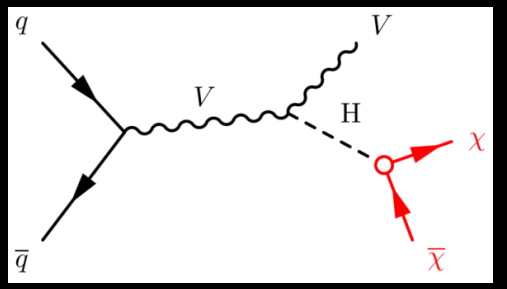
Axion Like Particle (ALP)

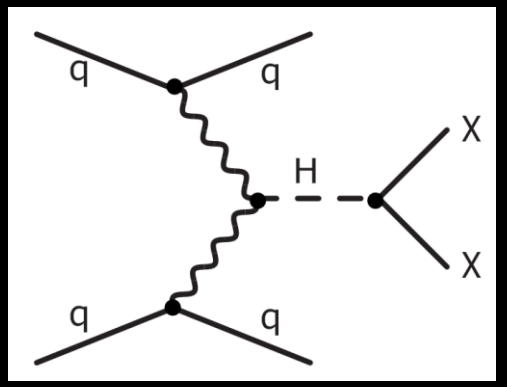
	Observables/Processes		Parameters contributing	
			Linear	**Non-Linear**
	Astrophysical obs.	$g_{a\gamma\gamma}$	$\mathbf{c_{\tilde{W}}}$ $\mathbf{c_{\tilde{B}}}$	$\mathbf{c_{\tilde{W}}}$ $\mathbf{c_{\tilde{B}}}$
	Rare meson decays		$\mathbf{c_{\tilde{W}}}$ $\mathbf{c_{a\Phi}}$	$\mathbf{c_{\tilde{W}}}$ $\mathbf{c_{2D}}$ c_2 c_6 c_8 c_{17}
New constraints	**LEP data**			
	BSM Z width	$\Gamma(Z \to a\gamma)$	$\mathbf{c_{\tilde{W}}}$ $\mathbf{c_{\tilde{B}}}$	$\mathbf{c_{\tilde{W}}}$ $\mathbf{c_{\tilde{B}}}$ c_1 c_2 c_7
	LHC processes			
	Non-standard h decays	$\Gamma(h \to aZ)$		$\mathbf{\tilde{a}_{2D}}$ $\tilde{a}_3$ $\tilde{a}_{10}$ $\tilde{a}_{11-14}$ $\tilde{a}_{17}$
	Mono-Z prod.	$pp \to a\,Z$	$\mathbf{c_{\tilde{W}}}$ $\mathbf{c_{\tilde{B}}}$ $c_{a\Phi}$	$\mathbf{c_{\tilde{W}}}$ $\mathbf{c_{\tilde{B}}}$ c_{2D} c_1 c_2 c_3 c_7 c_{10} c_{11-14} c_{17}
	Mono-W prod.	$pp \to a\,W^{\pm}$	$\mathbf{c_{\tilde{W}}}$ $c_{\tilde{B}}$ $c_{a\Phi}$	$\mathbf{c_{\tilde{W}}}$ $c_{\tilde{B}}$ c_{2D} c_2 $\mathbf{c_6}$ c_8 c_{10}
Prospects	Associated prod.	$pp \to aW^{\pm}\gamma$	$\mathbf{c_{\tilde{W}}}$ $c_{\tilde{B}}$ $c_{a\Phi}$	$\mathbf{c_{\tilde{W}}}$ $c_{\tilde{B}}$ c_{2D} c_1 c_2 $\mathbf{c_6}$ c_7 c_8
	VBF prod.	$pp \to ajj(\gamma)$	$c_{\tilde{W}}$ $c_{\tilde{B}}$ $c_{a\Phi}$	$c_{\tilde{W}}$ $c_{\tilde{B}}$ c_{2D} c_1 c_2 c_6 c_7 c_8
	Mono-h prod.	$pp \to h\,a$		$\mathbf{\tilde{a}_{2D}}$ $\mathbf{\tilde{a}_3}$ $\mathbf{\tilde{a}_{10}}$ $\tilde{a}_{11-14}$ $\tilde{a}_{17}$
	$at\bar{t}$ prod.	$pp \to at\bar{t}$	$\mathbf{c_{a\Phi}}$	$\mathbf{c_{2D}}$

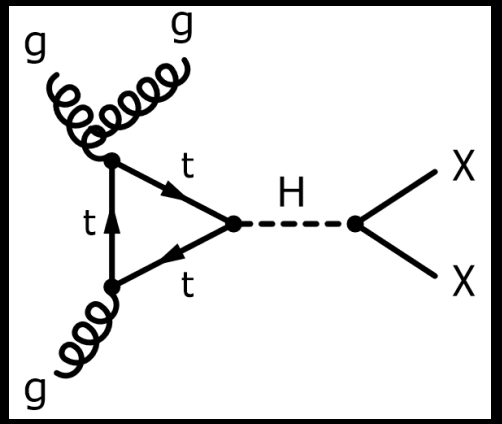
[1] V. Silveira, A. Zee, Phys. Lett. B161, 136 (1985)
[2] Eur.Phys.J.C 73 (2013) 6, 2455
[3] Phys. Rev. D 90, 055014 (2014)

Invisible Higgs

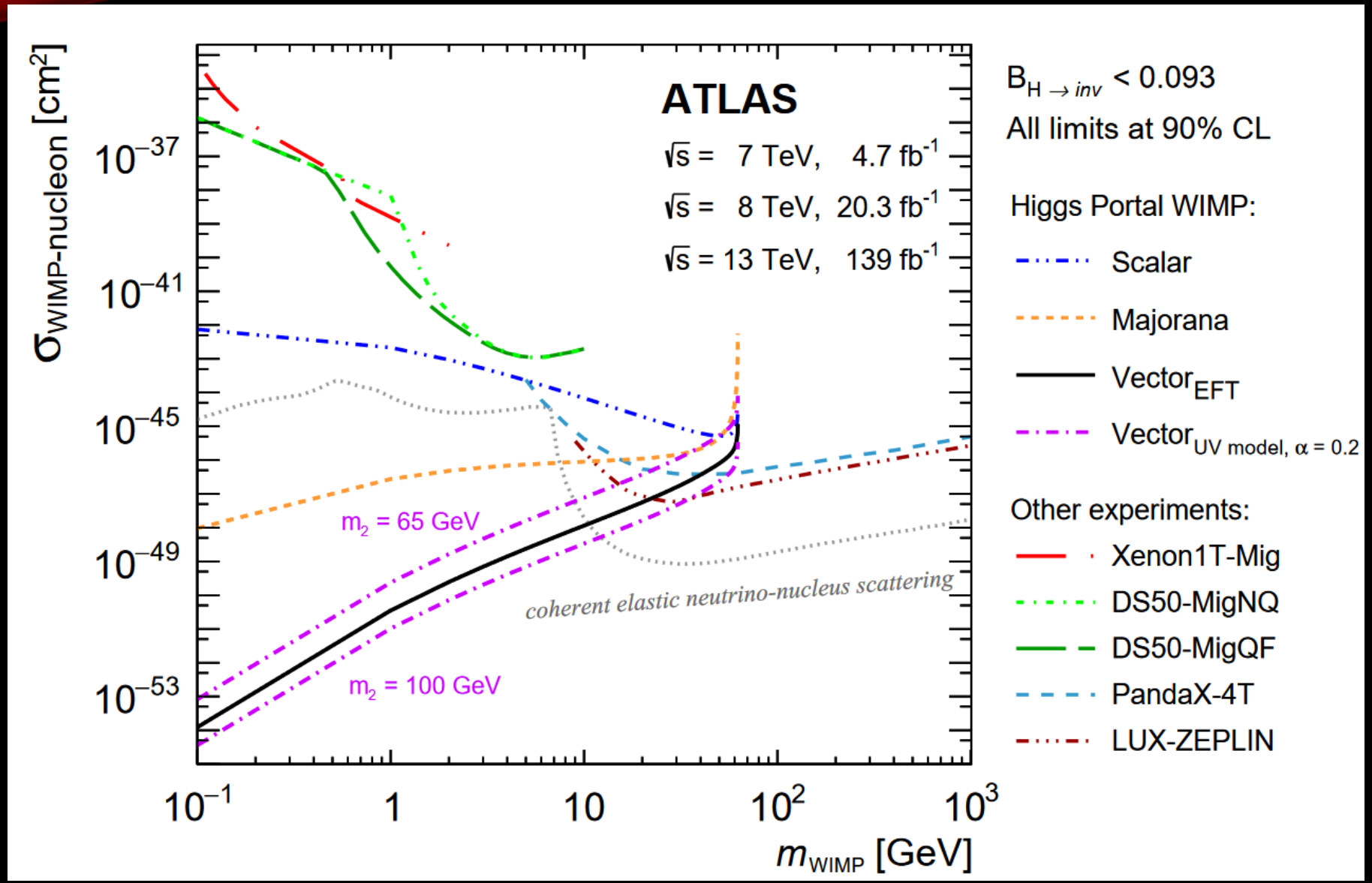
- SM Invisible Higgs decay via ZZ*→4nu and Br~0.1%
- Many DM theory models contribute to BSM invisible Higgs decay
  - Higgs portal[1][2][...] with m_WIMP<mh/2
    - Scalar, Majorana fermion, vector like DM
  - UV-complete model (vector DM)[3,...]: U(1)' gauge field
    - Adding singlet-like scalar and mixing to SM H to be UV-complete
    - Similar to dark Higgs while no heavy mediator Z' involved (more like typical WIMP)
- Limit converted to spin-independent WIMP-nucleon XS
  - Comparable to direct search







Invisible Higgs



Dark jet/Semi-visible jet

- Dark sector with gauge group $SU\ (N_d)$ leading to confinement at a scale Λ_d
- Dark hadron decay QCD-like, fraction decay back to SM
- Unusual jet signature:
  - Double hadronization→ larger and wider
  - Different running coupling → number of tracks
  - Invisible fraction (R_inv)→MET in jet
  - Displaced vertex (not covered this time)
- s-channel/t-channel: different topology