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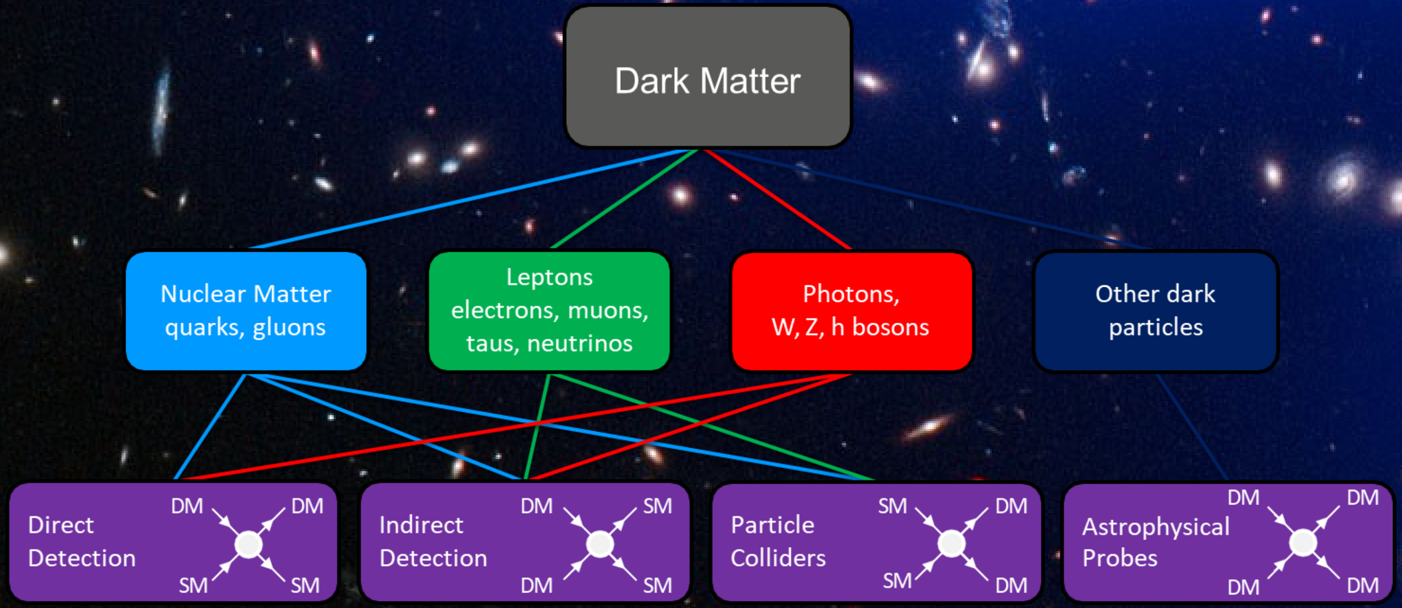
Recent ATLAS results of Dark Matter combination and Dark Higgs search

Qibin LIU on behalf on the ATLAS Collaboration

The 10th China LHC Physics Conference (CLHCP2024)

The Dark Matter

- Existence of dark matter (DM) supported by many pieces of evidence
  - Galaxy rotation , gravity lensing, bullet cluster, cosmic microwave background, contradictions in MOND, so on
- DM makes up most of our universe – its nature remains largely unknown
- In quest to search for any possible interaction of DM beyond gravity
  - Major effort in nowadays study for new physics



1305.1605

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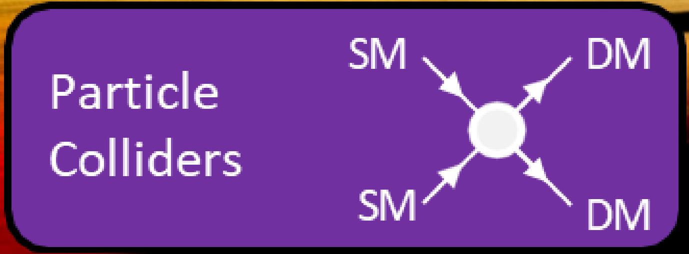
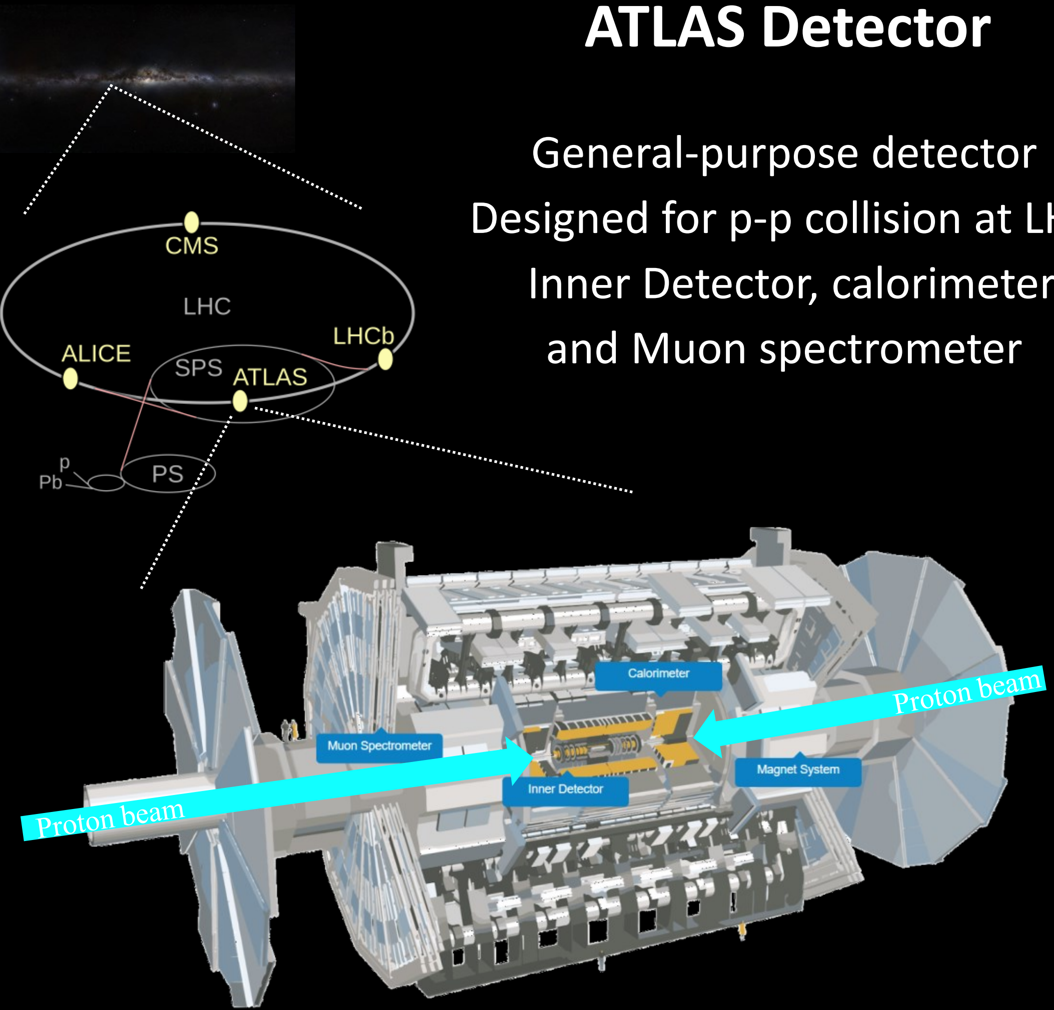
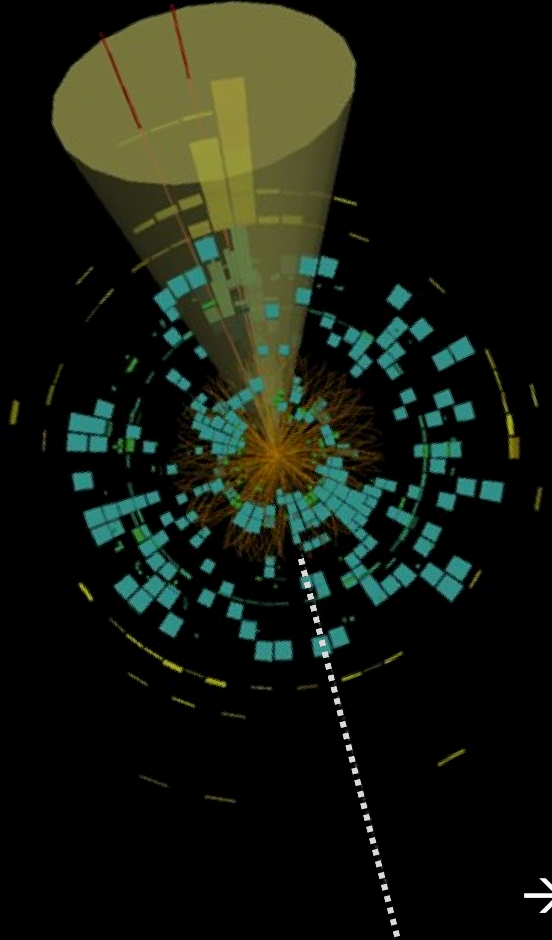


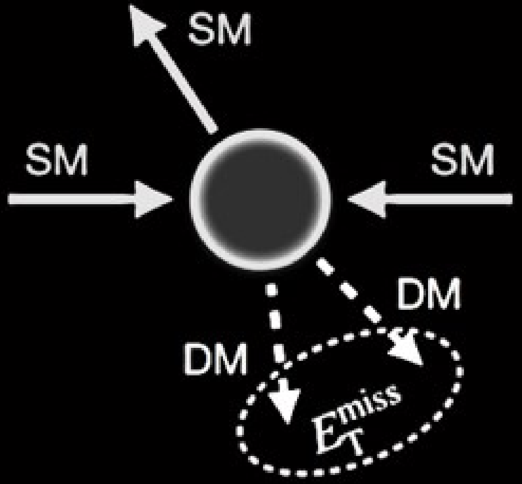
Dark Matter Searches at ATLAS



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

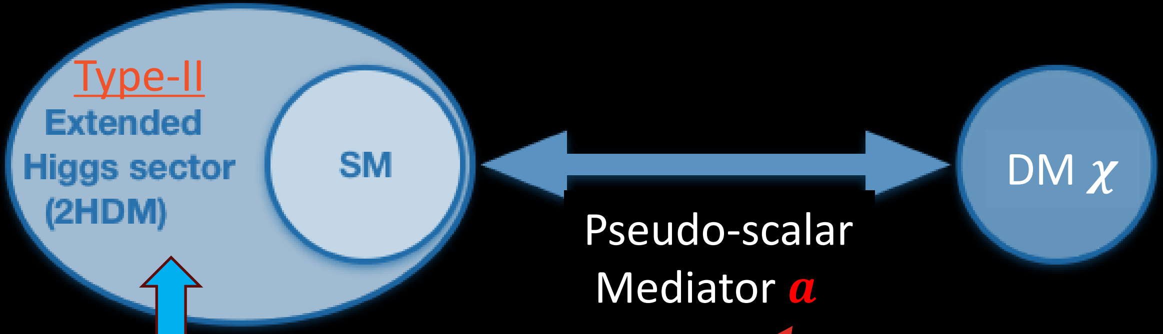
Combination and summary of ATLAS dark matter searches interpreted in a 2HDM with a pseudo-scalar mediator using 139 fb^{-1} of $\sqrt{s}$ = 13 TeV pp collision data

Science Bulletin 69 (2024) 3005

Phys. Rev. D 91 (2015) 015017
Phys. Dark Univ. 27 (2020) 100351

2HDM+a Model

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



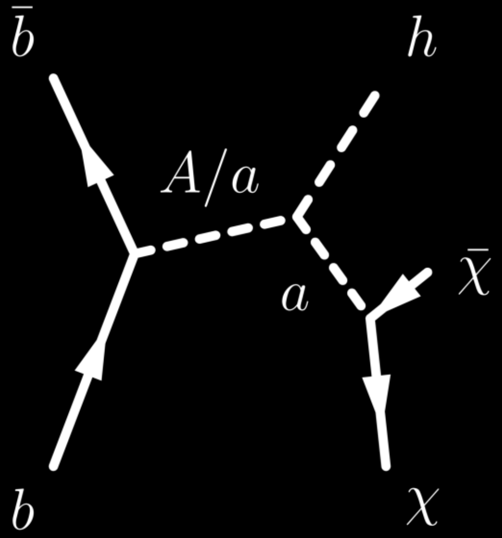
- Extended scalar (Higgs) sector of SM: addressing EWK hierarchy, baryogenesis, strong CP problems
- Coupled to dark sector with extended pseudo-scalar mediator simplified model
- UV-complete, gauge-invariant and renormalizable

In full configuration 14 parameters and simplified with 5 free parameters

Scalar Sector

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

mixing



Free Parameters

$sin\theta$: mixing angle of A and a
$tan\beta$: ratio of VEV of Higgs doublet
$m_A = m_H = m_{H^{\pm}}$: Heavy H mass
m_a: mediator mass
m_χ: DM mass

Fix Parameters

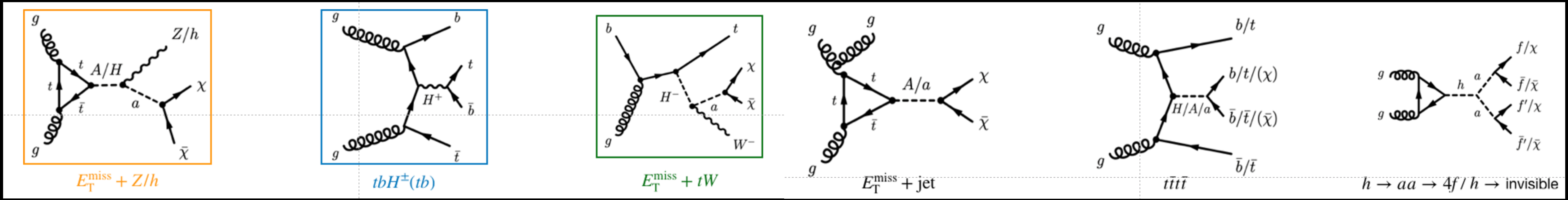
g_χ=1: dark-sector Yukawa coupling
$m_h, v, \cos(\beta - \alpha)$: Align with SM Higgs
$\lambda_3 = \lambda_{P1} = \lambda_{P2} = 3$: quartic couplings

Widely studied as *LHC Dark Matter Benchmark Model*

*: possible $b\bar{b}$-initiated production also included, see backups

Signatures and Combination Strategy

Diverse signatures and rich phenomenology: MET+X and 4 fermions (including 4top)



Multiple ATLAS analyses interpreted in different scenarios for benchmark
And combination of most sensitive channels to set the best exclusion limit

Analysis/Scenario	1a	1b	2a	2b	3a	3b	4a	4b	5	6
$E_T^{miss} + Z(\ell\ell)$	x	x	x	x	x	x	x	x	x	
$E_T^{miss} + h(b\bar{b})$	x	x	x	x	x	x	x	x	x	x
$E_T^{miss} + h(\gamma\gamma)$	x	x			x	x	x	x		
$E_T^{miss} + h(\tau\tau)$	x			x						
$E_T^{miss} + tW$	x	x	x	x	x	x	x	x		
$E_T^{miss} + j$	x	x			x	x	x	x		
$h \to$ invisible	x	x			x					x
$E_T^{miss} + Z(q\bar{q})$	x						x	x		
$E_T^{miss} + b\bar{b}$							x	x		
$E_T^{miss} + t\bar{t}$							x	x		
$t\bar{t}t\bar{t}$	x	x	x	x	x	x	x	x	x	
$tbH^{\pm}(tb)$	x	x	x	x	x	x	x	x	x	
$h \to aa \to f\bar{f}f'\bar{f}'$										x

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)

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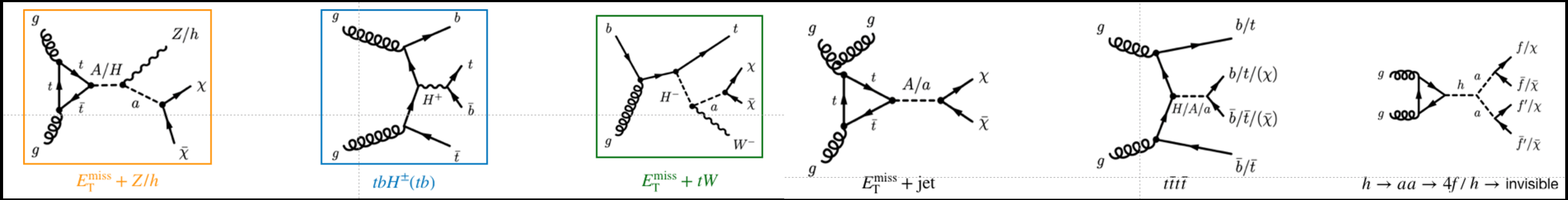
Diverse signatures and rich phenomenology: MET+X and 4 fermions (including 4top)



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$E_T^{miss} + h(\gamma\gamma)$	x	x			x	x	x	x		
$E_T^{miss} + h(\tau\tau)$	x			x						
$E_T^{miss} + tW$	x	x	x	x	x	x	x	x		
$E_T^{miss} + j$	x	x			x	x	x	x		
$h \to$ invisible	x	x			x					x
$E_T^{miss} + Z(q\bar{q})$	x						x	x		
$E_T^{miss} + b\bar{b}$							x	x		
$E_T^{miss} + t\bar{t}$							x	x		
$t\bar{t}t\bar{t}$	x	x	x	x	x	x	x	x	x	
$tbH^{\pm}(tb)$	x	x	x	x	x	x	x	x	x	
$h \to aa \to f\bar{f}f'\bar{f}'$										x

Scenario		Fixed parameter values					Varied parameters
		$\sin\theta$	m_A [GeV]	m_a [GeV]	m_χ [GeV]	$\tan\beta$	
1	a	0.35	Rich phenomenology		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	–	
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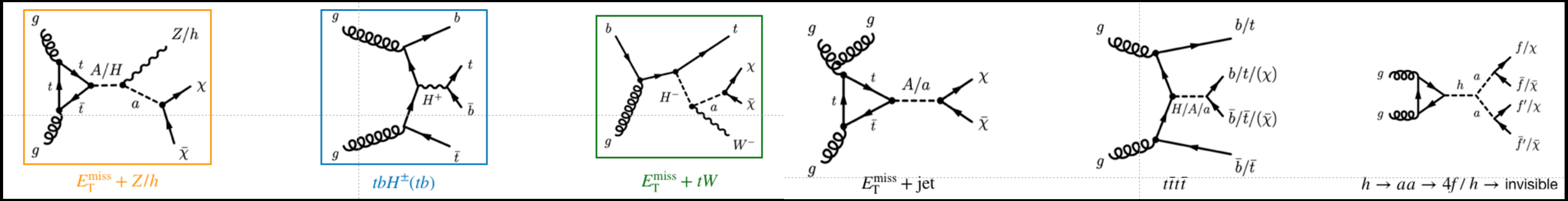
Diverse signatures and rich phenomenology: MET+X and 4 fermions (including 4top)



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$E_T^{miss} + h(\gamma\gamma)$	x	x			x	x	x	x		
$E_T^{miss} + h(\tau\tau)$	x			x						
$E_T^{miss} + tW$	x	x	x	x	x	x	x	x		
$E_T^{miss} + j$	x	x			x	x	x	x		
$h \to$ invisible	x	x			x					x
$E_T^{miss} + Z(q\bar{q})$	x						x	x		
$E_T^{miss} + b\bar{b}$							x	x		
$E_T^{miss} + t\bar{t}$							x	x		
$t\bar{t}t\bar{t}$	x	x	x	x	x	x	x	x	x	
$tbH^{\pm}(tb)$	x	x	x	x	x	x	x	x	x	
$h \to aa \to f\bar{f}f'\bar{f}'$										x

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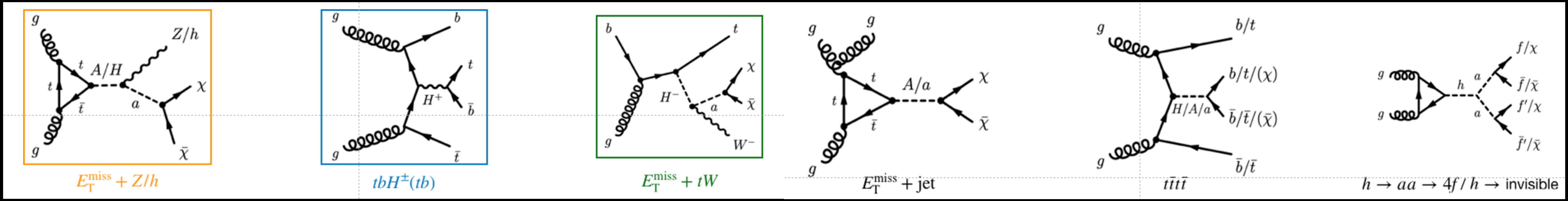
	b	0.70	–			–	
3	a	0.35	600			–	$(m_a, \tan\beta)$
	b	0.70	600	–	10	–	
4	a	–	600	200	10	1.0	$\sin\theta$
	b	–	1000	350	10	1.0	
5		0.35	1000	400	–	1.0	m_χ
6		0.35	1200	–	–	1.0	(m_a, m_χ)

General 2HDM Scan

*: possible $b\bar{b}$-initiated production also included, see backups

Signatures and Combination Strategy

Diverse signatures and rich phenomenology: MET+X and 4 fermions (including 4top)



Multiple ATLAS analyses interpreted in different scenarios for benchmark

And combination of most sensitive channels to set the best exclusion limit

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$E_T^{miss} + h(b\bar{b})$	x	x	x	x	x	x	x	x	x	x
$E_T^{miss} + h(\gamma\gamma)$	x	x			x	x	x	x		
$E_T^{miss} + h(\tau\tau)$	x			x						
$E_T^{miss} + tW$	x	x	x	x	x	x	x	x		
$E_T^{miss} + j$	x	x			x	x	x	x		
$h \to$ invisible	x	x			x					x
$E_T^{miss} + Z(q\bar{q})$	x						x	x		
$E_T^{miss} + b\bar{b}$							x	x		
$E_T^{miss} + t\bar{t}$							x	x		
$t\bar{t}t\bar{t}$	x	x	x	x	x	x	x	x	x	
$tbH^{\pm}(tb)$	x	x	x	x	x	x	x	x	x	
$h \to aa \to f\bar{f}f'\bar{f}'$										x

Scenario		Fixed parameter values					Varied parameters
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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	–	Visible v.s. Invisible mediator decay				$\sin\theta$
	b	–					
5		0.35	1000	400	–	1.0	m_χ
6		0.35	1200	–	–	1.0	(m_a, m_χ)

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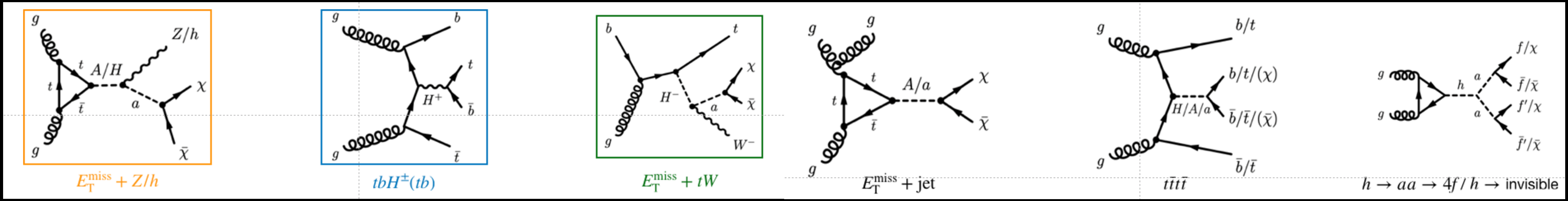
Signatures and Combination Strategy

Diverse signatures and rich phenomenology: MET+X and 4 fermions (including 4top)



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$E_T^{miss} + h(\gamma\gamma)$	x	x			x	x	x	x		
$E_T^{miss} + h(\tau\tau)$	x			x						
$E_T^{miss} + tW$	x	x	x	x	x	x	x	x		
$E_T^{miss} + j$	x	x			x	x	x	x		
$h \to$ invisible	x	x			x					x
$E_T^{miss} + Z(q\bar{q})$	x						x	x		
$E_T^{miss} + b\bar{b}$							x	x		
$E_T^{miss} + t\bar{t}$							x	x		
$t\bar{t}t\bar{t}$	x	x	x	x	x	x	x	x	x	
$tbH^{\pm}(tb)$	x	x	x	x	x	x	x	x	x	
$h \to aa \to f\bar{f}f'\bar{f}'$										x

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	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		Compare to cosmological and non-collider limit					m_χ
6		0.35	1200	–	–	1.0	(m_a, m_χ)

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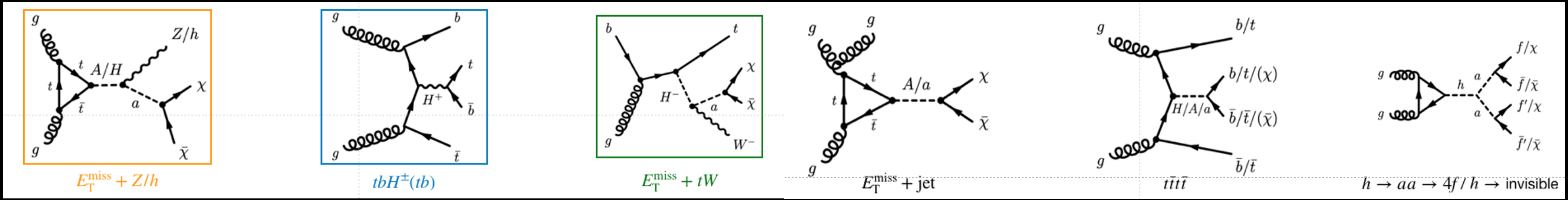
Signatures and Combination Strategy

Diverse signatures and rich phenomenology: MET+X and 4 fermions (including 4top)



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$E_T^{miss} + j$	x	x			x	x	x	x		
$h \to$ invisible	x	x			x					x
$E_T^{miss} + Z(q\bar{q})$	x						x	x		
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$tbH^{\pm}(tb)$	x	x	x	x	x	x	x	x	x	
$h \to aa \to f\bar{f}f'\bar{f}'$										x

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	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		Invisible and exotic SM Higgs decay					(m_a, m_χ)

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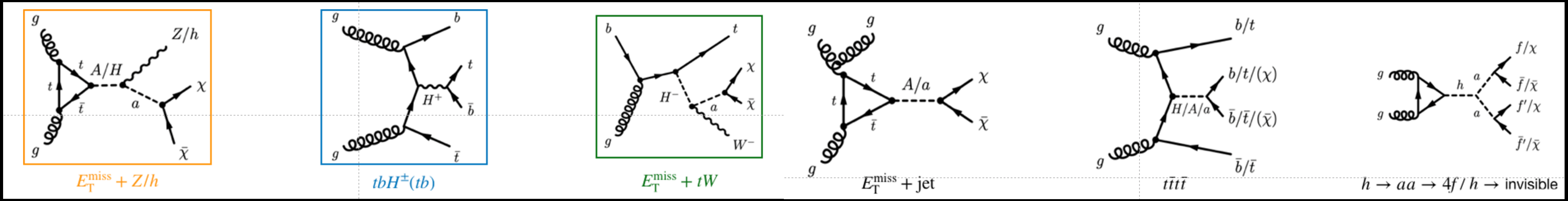

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$E_T^{miss} + h(\gamma\gamma)$	x	x			x	x	x	x		
$E_T^{miss} + h(\tau\tau)$	x			x						
$E_T^{miss} + tW$	x	x	x	x	x	x	x	x		
$E_T^{miss} + j$	x	x			x	x	x	x		
$h \to$ invisible	x	x			x					x
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$E_T^{miss} + t\bar{t}$							x	x		
$t\bar{t}t\bar{t}$	x	x	x	x	x	x	x	x	x	
$tbH^{\pm}(tb)$	x	x	x	x	x	x	x	x	x	
$h \to aa \to f\bar{f}f'\bar{f}'$										x

More in backups

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)
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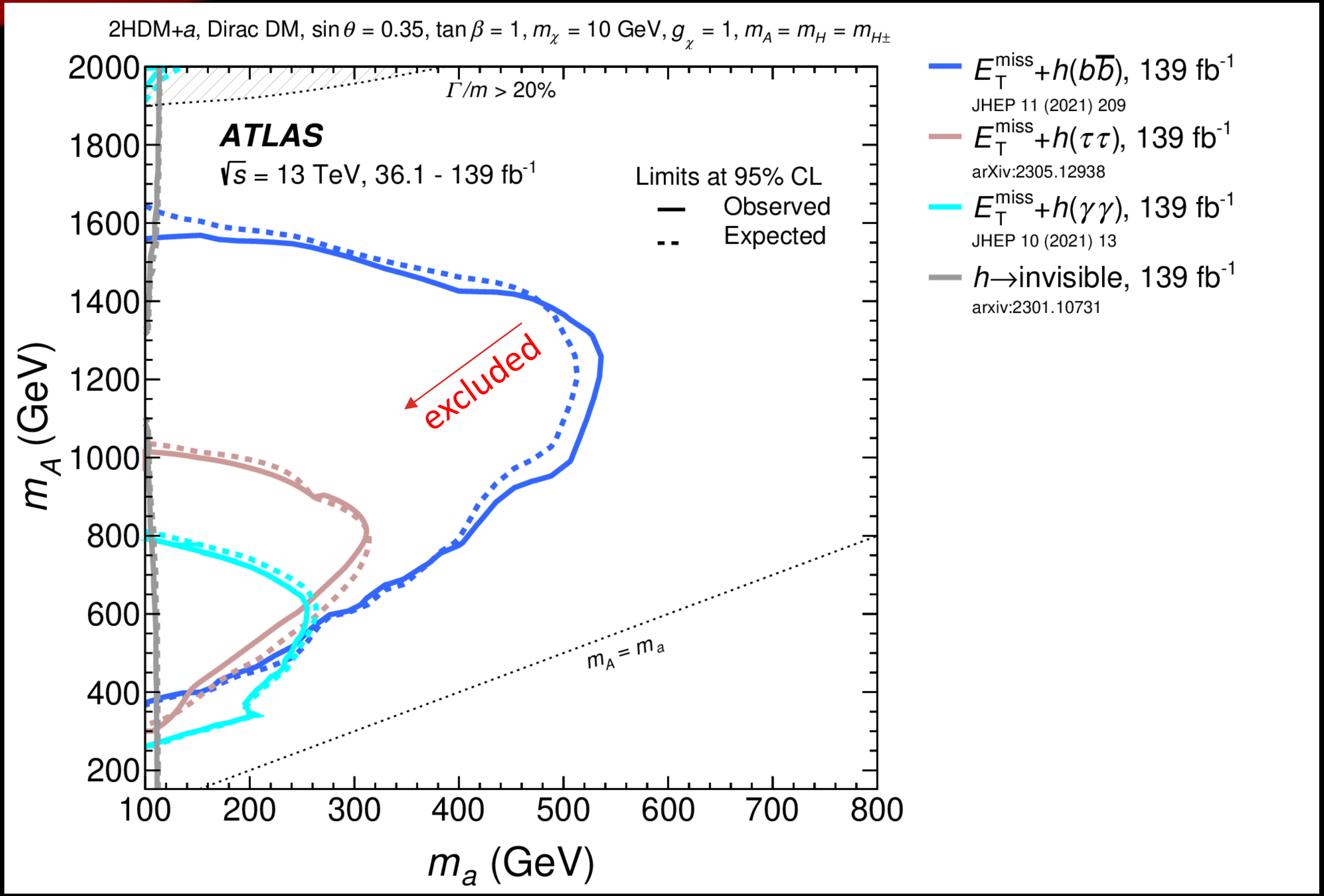
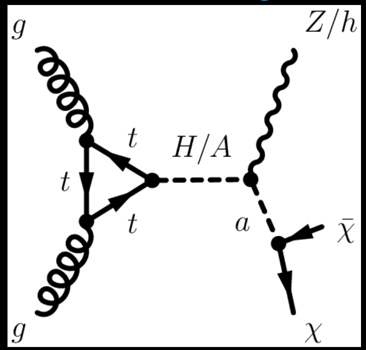
	b	0.70	–	250	10	–	
3	a	0.35	600	–	10	–	$(m_a, \tan\beta)$
	b	0.70	600	–	10	–	
4	a	–	600	200	10	1.0	$\sin\theta$
	b	–	1000	350	10	1.0	
5		0.35	1000	400	–	1.0	m_χ
6		0.35	1200	–	–	1.0	(m_a, m_χ)

Scan in $m_a - m_A$ Parameter Space

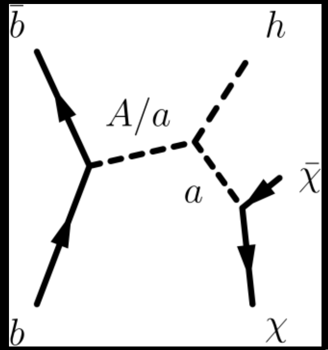


- Invisible Higgs decay shows sensitivity for light a
- Mono-h (MET+h) searches show similar exclusion shape in $m_a - m_A$ plane, with h(bb) most sensitive due to large branching ratio and special $a \to ah$ diagram
- h(γγ) outperforms in low MET region (low m_A) using photon trigger

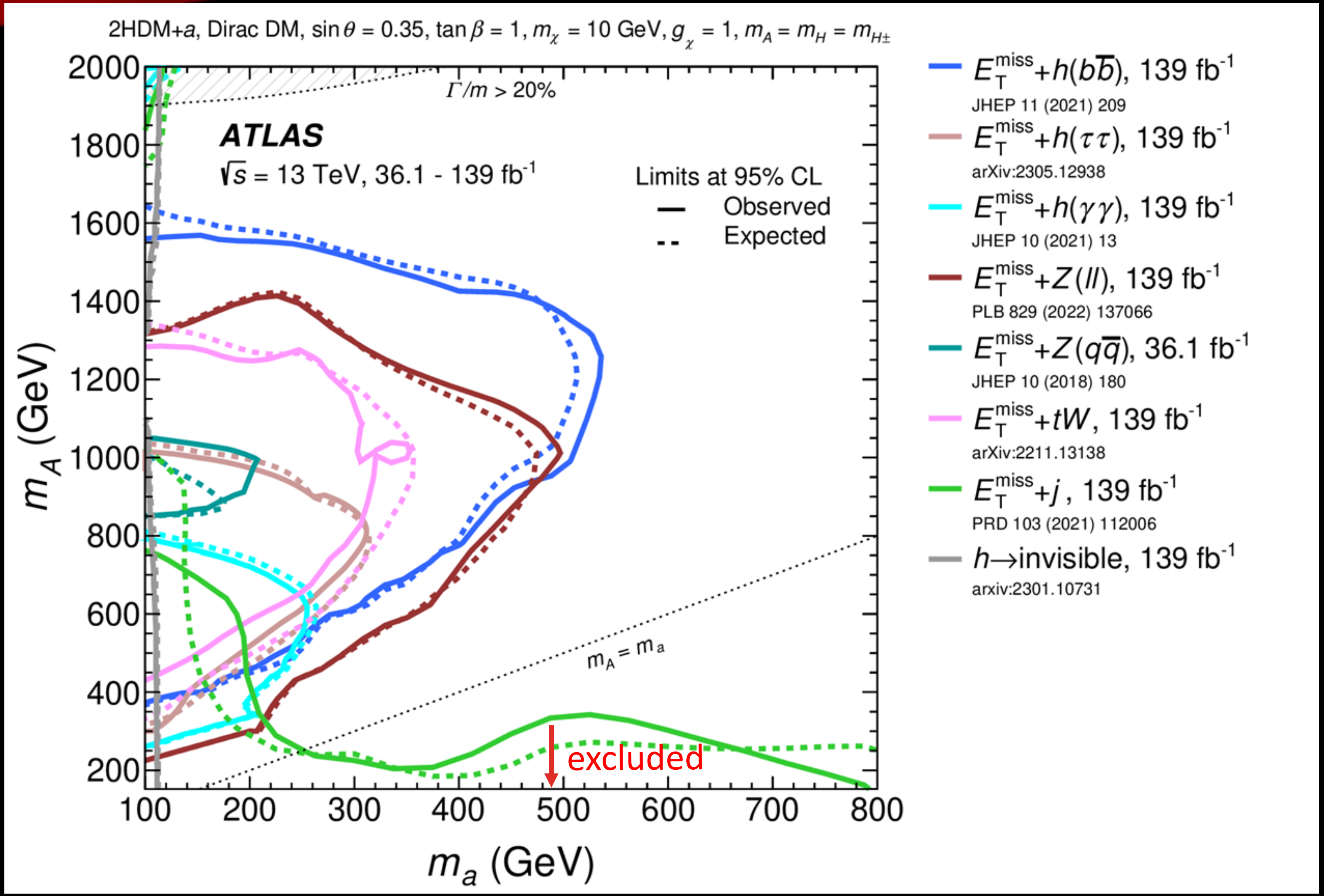
Mono-Z/h



$a \to ah$

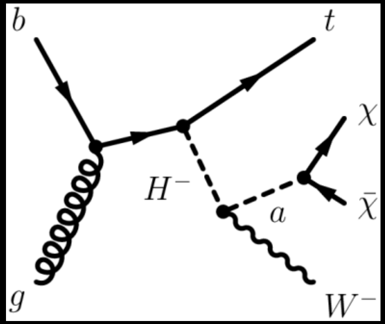


Scan in $m_a - m_A$ Parameter Space

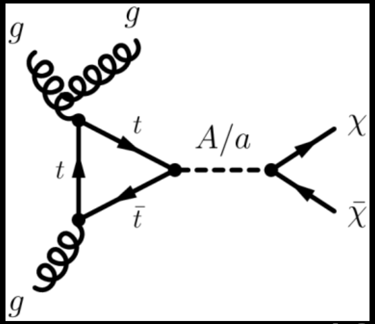


- Mono-Z (MET+Z) searches especially lepton final states extend the limit on low MET region (low m_A) due to the lepton trigger and smaller mass of Z
- MET+tW search shows weaker observed limit due to excees in 2-lepton channel
- Mono-j (MET+j) search shows different exclusion shape due to lack of resonant diagram

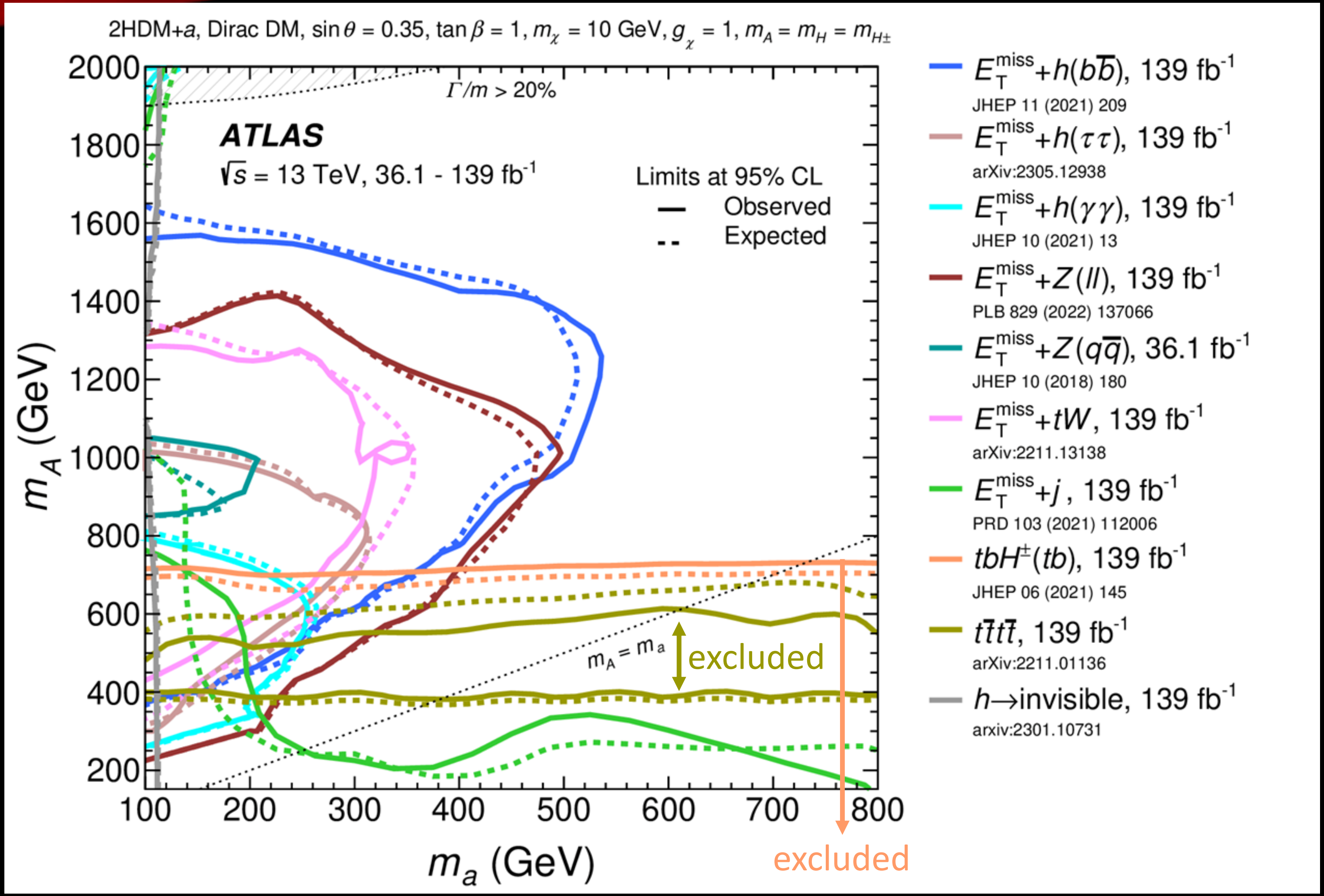
MET+tW



Mono-jet

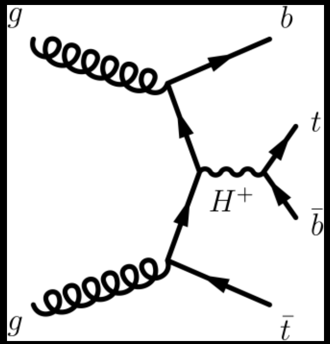


Scan in $m_a - m_A$ Parameter Space

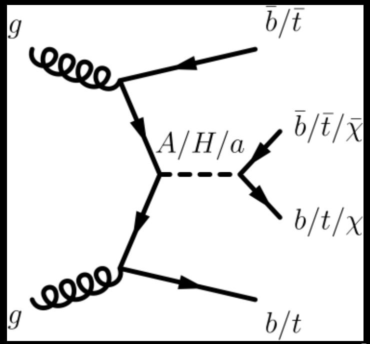


- Charged Higgs search ($tbH^{\pm}$) extends the limit on low m_A and little dependence on m_a since not directly probe a production
- 4top analysis excludes 2HDM+a model only above ttbar threshold ($m_A > 2m_t$)

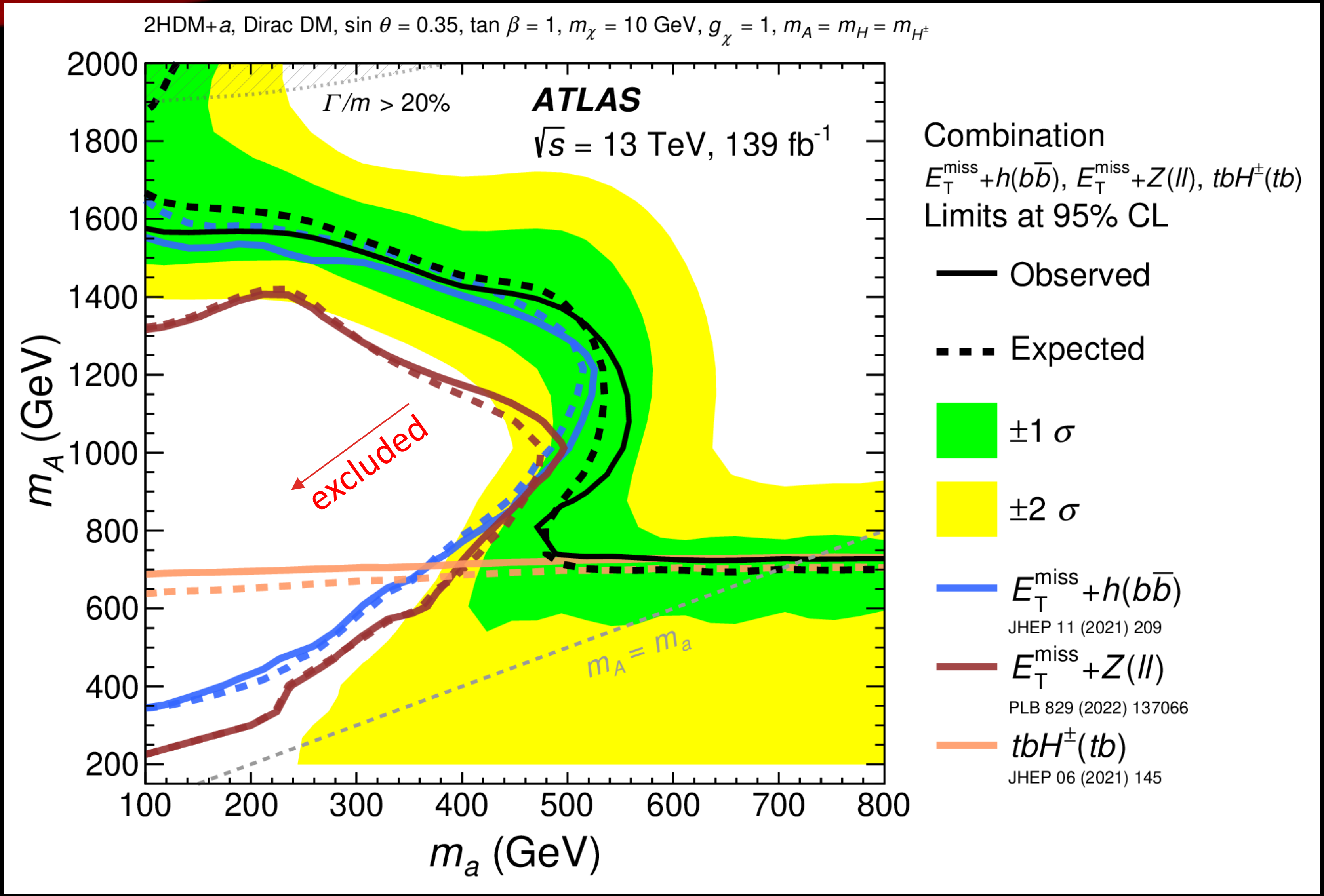
$tbH^{\pm}$



4top



Combined Limit in $m_a - m_A$ Plane

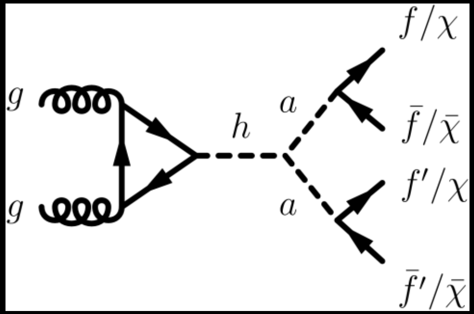


- 3 most sensitive channels got statistical combination: profiled likelihood fitting combines all the parameters, regions and statistics
- Decorrelate NP for pulled/over-constrained uncertainty across different channel to avoid bias
- Latest collider constraint on 2HDM+a model (more backups)

Scan in $m_a - m_\chi$ Parameter Space

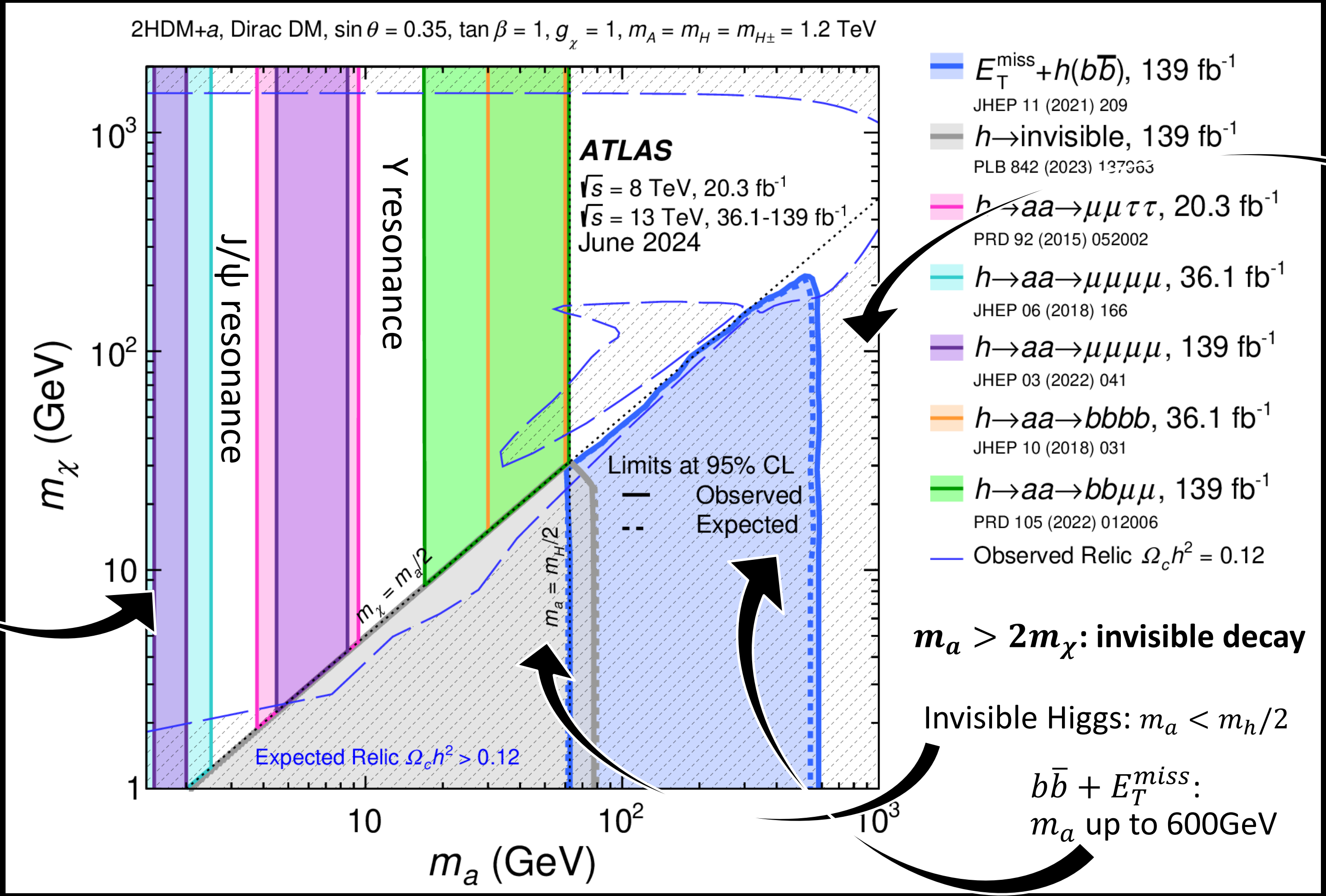
Series of h→aa→4f searches included first time: good sensitivity for low mass pseudo-scalar a

Broad variety of searches in ATLAS combined and rule out large area of parameter space



$m_a < 2m_\chi$: visible decay

h→aa→4f when $m_a < m_h/2$



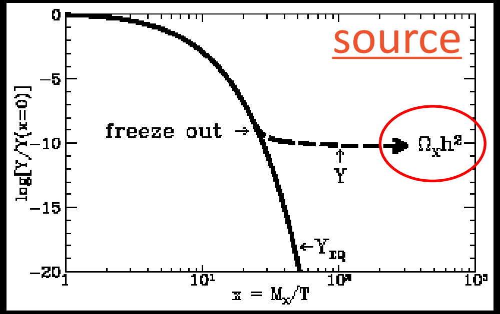
$m_a > 2m_\chi$: invisible decay

Invisible Higgs: $m_a < m_h/2$

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

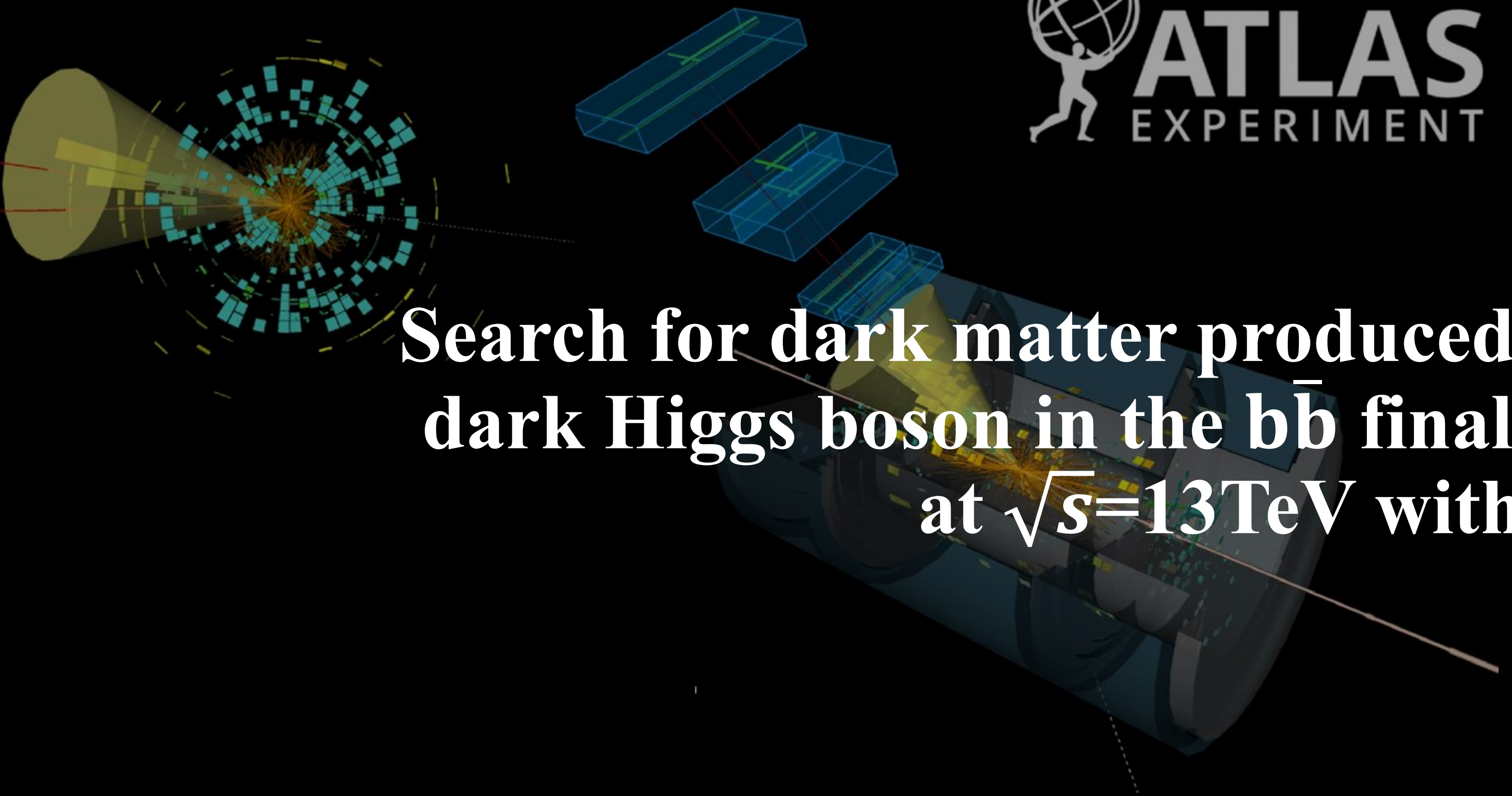
Cosmology Constraint

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



Search for dark matter produced in association with a dark Higgs boson in the $b\bar{b}$ final state using collisions at $\sqrt{s}$=13TeV with the ATLAS detector

ATLAS-CONF-2024-004

2407.10549

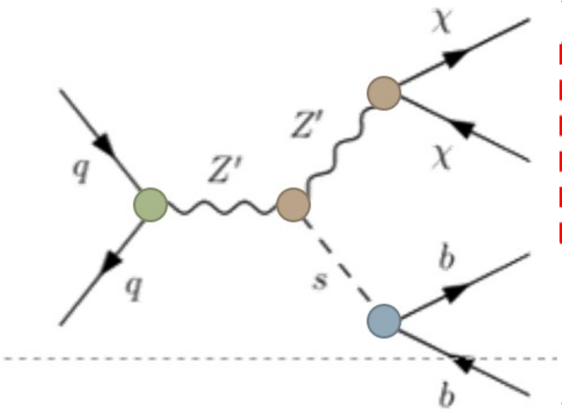
[1] JHEP 04 (2017) 143
[2] PLANCK2018

Higgs Mechanism in Dark Sector

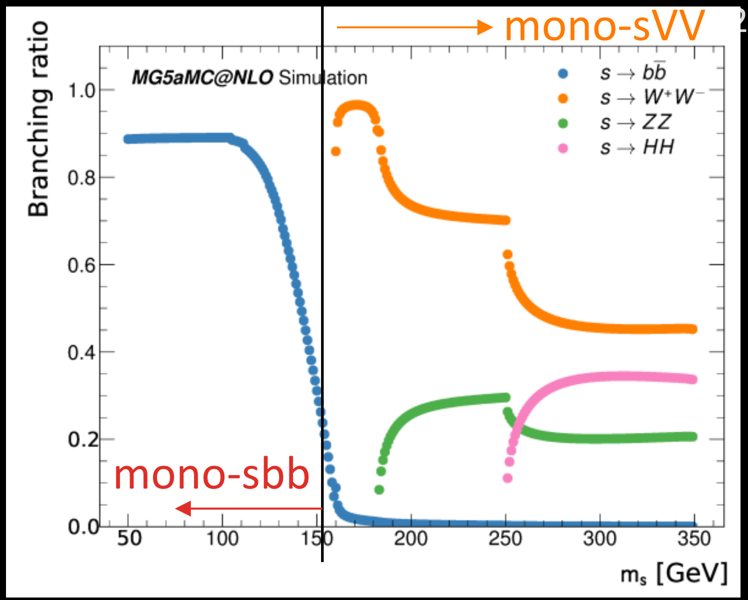
- Explain the mass of DM with Higgs mechanism in dark sector: spontaneously broken U(1)' gauge symmetry
- **Majorana** DM χ interacts with SM via spin-1 mediator $\boldsymbol{Z'}$ and a singlet $\boldsymbol{s}$ under $U(1)'$
- Mixing of dark Higgs $\boldsymbol{s}$ and SM Higgs $\boldsymbol{h}$: detectable decay as $s \to b\bar{b}$, $s \to VV$ depending on mass
- New annihilation channel to SM open up ($\chi\chi \to \boldsymbol{ss} \to SM$): prevent DM Relic Density (Ωh^2) over-production
- 4 parameters of interest and 2 scan scenarios with Ωh^2 fix at 0.12 (assuming all DM from this mechanism) [2]
  - First time directly require Ωh^2 condition in collider DM search

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

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



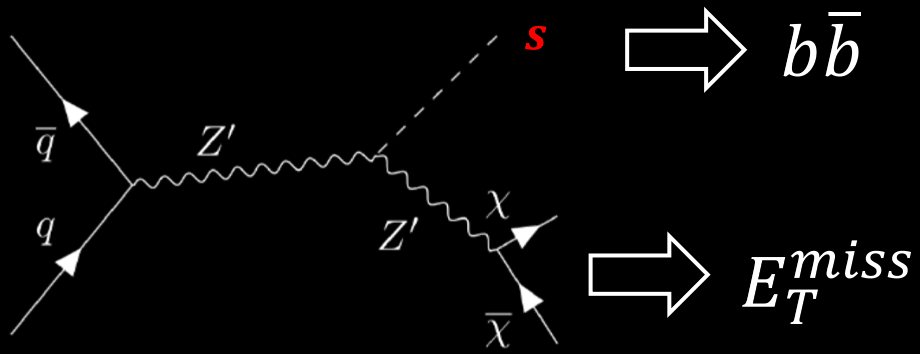
Parameter	Explain
m_s	mass of Dark Higgs
m_χ	mass of DM
$m_{Z'}$	mass of heavy mediator
g_χ	coupling in dark sector between s, X, Z'
g_q	coupling with SM: q<->Z' fixed 0.25 as benchmark
θ	mixing angle of SM Higgs<->dark Higgs fixed according to [1]

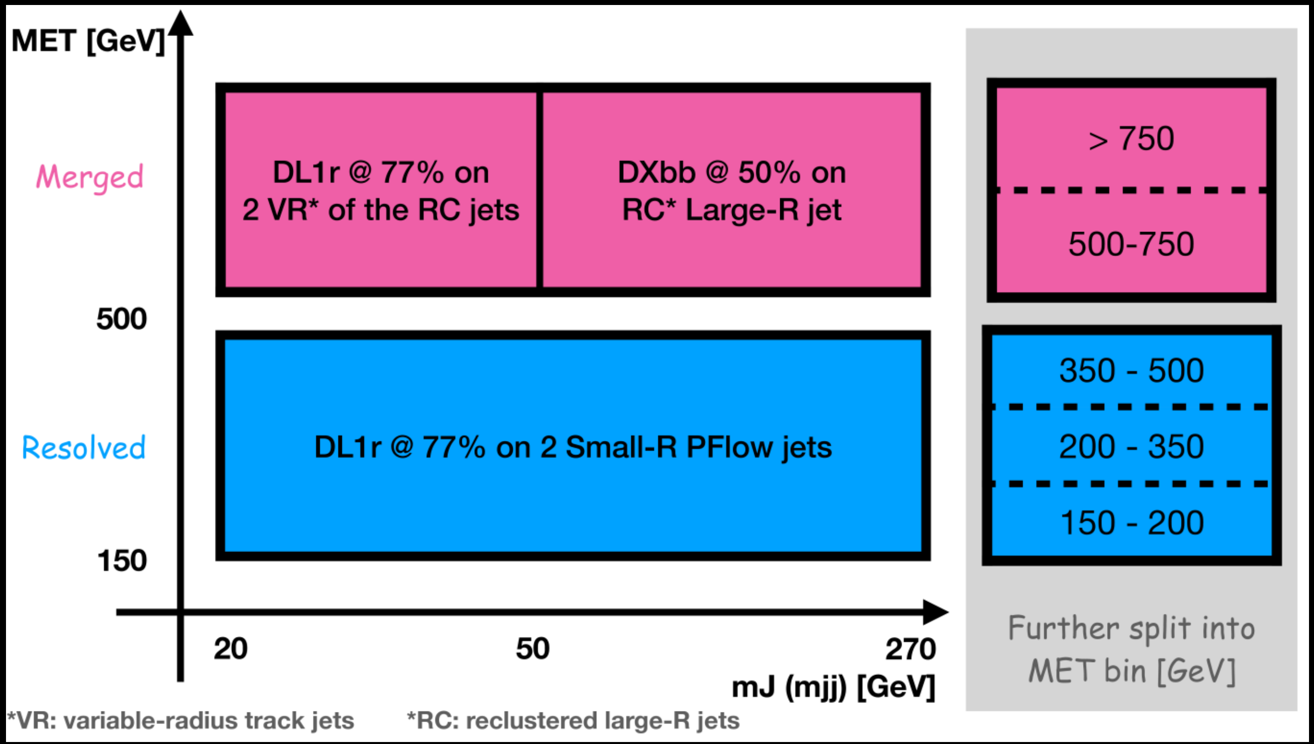


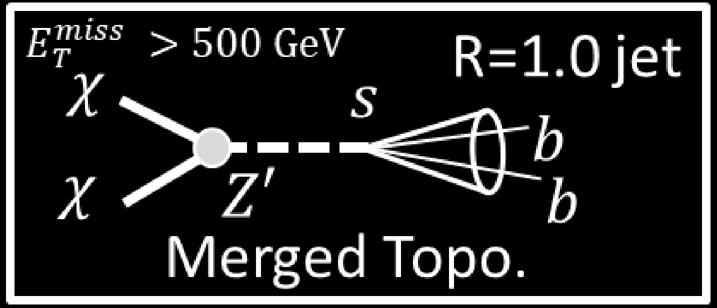
ATL-PHYS-PUB-2019-032

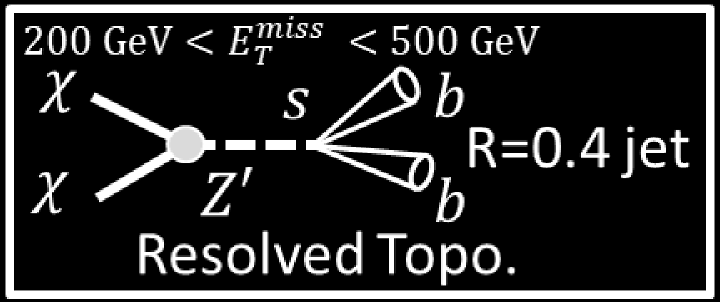
Overview of Mono-S(bb) Analysis

- Search for dark Higgs boson with $b\bar{b} + E_T^{miss}$ signature
- Probe E_T^{miss} down to 200 GeV and m_{bb} down to 30 GeV
- Resolved/boosted topology reconstructed depending on MET



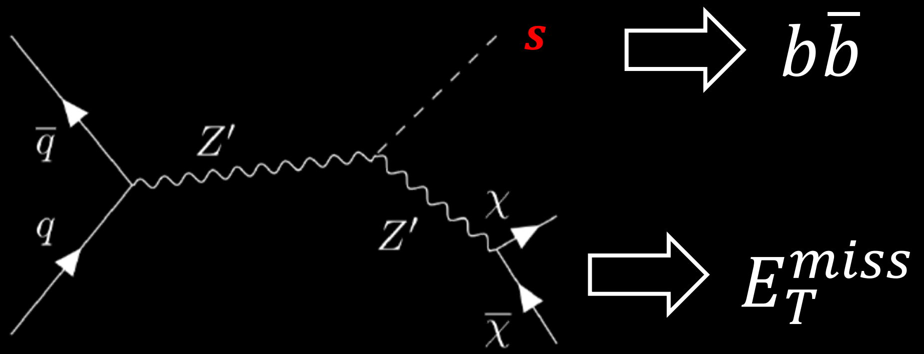


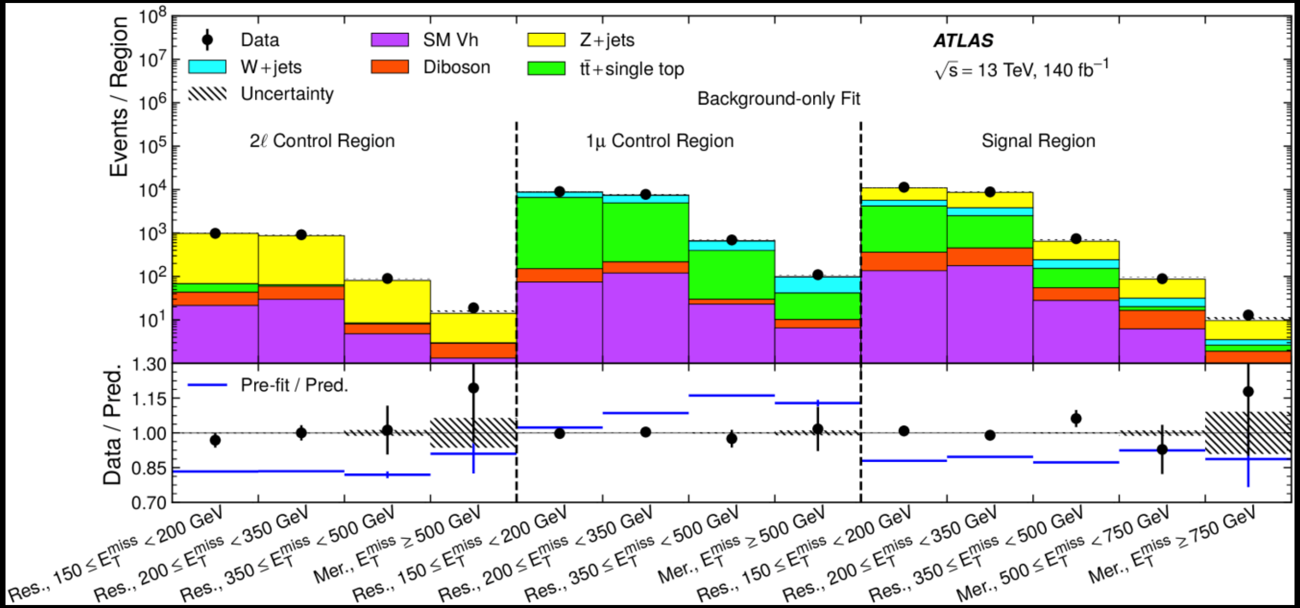




Overview of Mono-S(bb) Analysis

- Search for dark Higgs boson with $b\bar{b} + E_T^{miss}$ signature
- Probe E_T^{miss} down to 200 GeV and m_{bb} down to 30 GeV
- Resolved/boosted topology reconstructed depending on MET
- Background from W+jets, ttbar (τ not vetoed) and Z+jets ($Z\nu\nu + b\bar{b}$)
  - Estimated from MC and normalization fitted to data in 1-muon and 2-lepton control region
- Dominant uncertainties from Z+jets fitting, Z+jets modelling, jet flavor tagging and data statistics

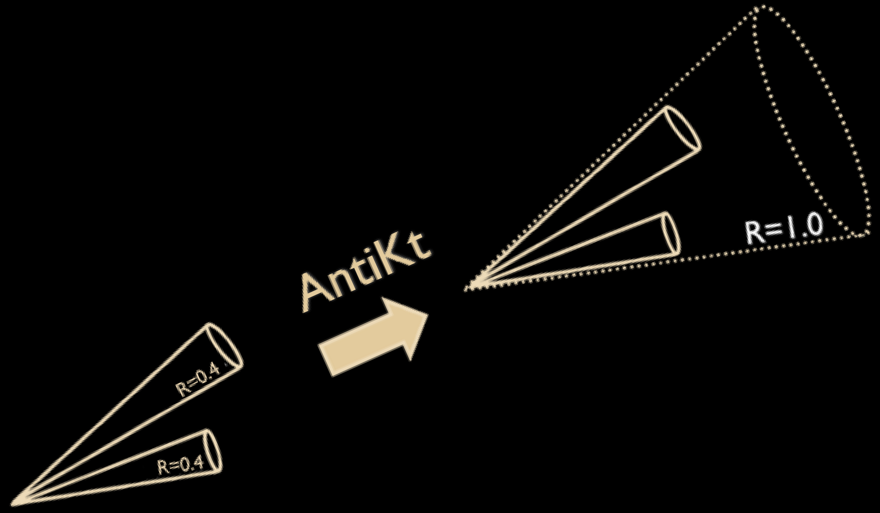


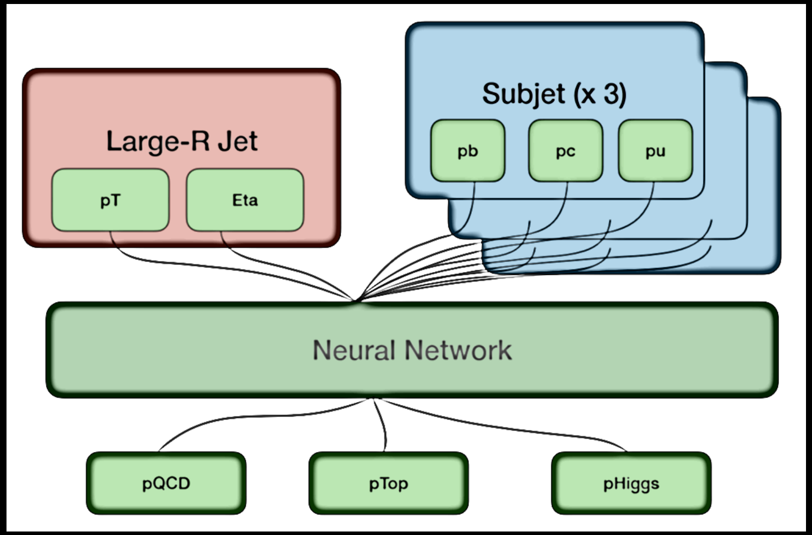


Source of uncertainty	Fraction of total uncertainty [%] (a)	(b)	(c)
Signal modeling	0	1	0
Z+jets normalization	41	11	11
W+jets normalization	8	13	13
$t\bar{t}$ normalization	1	7	8
Z+jets theory	16	24	25
W+jets theory	8	12	9
$t\bar{t}$ theory	3	8	11
Other background theory	10	16	22
MC statistics	15	17	18
Flavor tagging	18	47	37
Jet energy	3	7	11
Other experimental	2	4	3
Total systematic uncertainty	57	66	63
Data statistical uncertainty	82	75	77
Total uncertainty	100	100	100

Novel Analysis Techniques in Merged Region

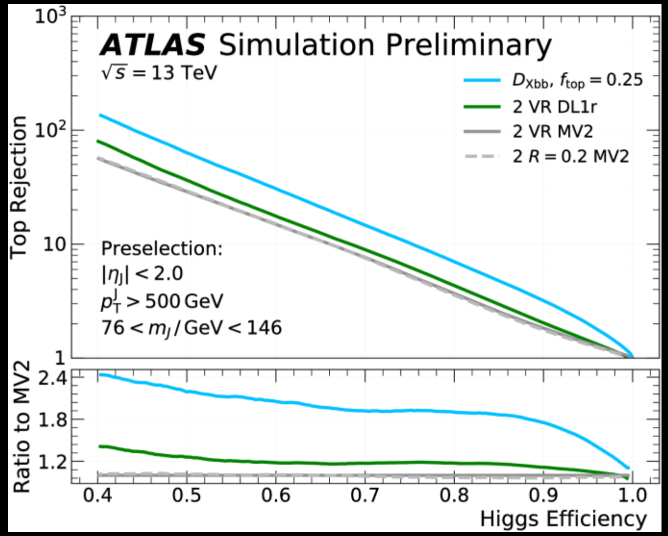
- **Reclustering(RC) jet extends the search range for scalar mass down to 20GeV**
  - Jet reconstruction at low mass is challenging standard large-R jet is NOT supported for mJ below 50GeV
  - Jet mass well-defined: calculated from calibrated input jets and systematic uncertainty propagated
- **Combining Large-R jet kinematics and sub-jet information for boosted Xbb tagging: *DXbb tagger***
  - High efficiency discriminating Hbb v.s. Top/QCD and mass-agnostic design applicable in a wide mass range
  - Calibrated using Zbb (signal jet efficiency) and semi-leptonic ttbar (background jet efficiency)





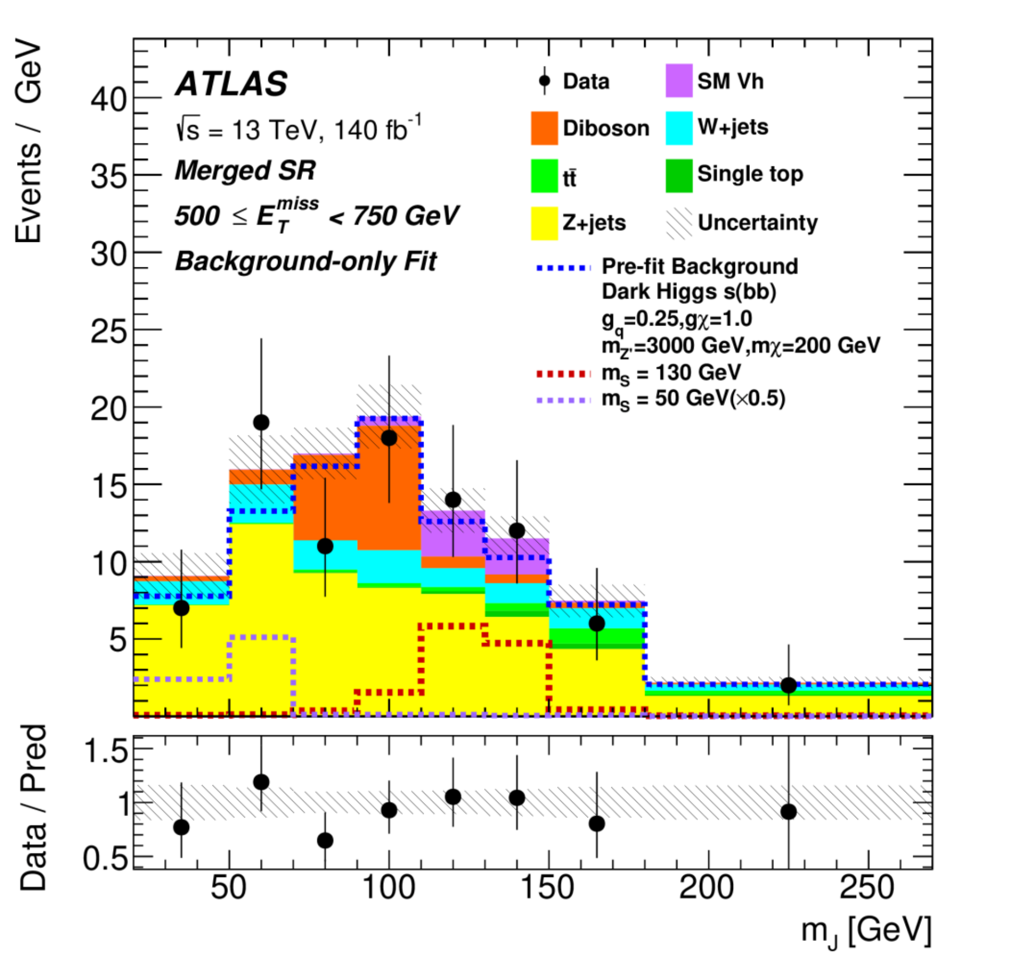
ATLAS Boosted Xbb jet tagging (*DXbb*)

ATL-PHYS-PUB-2020-019



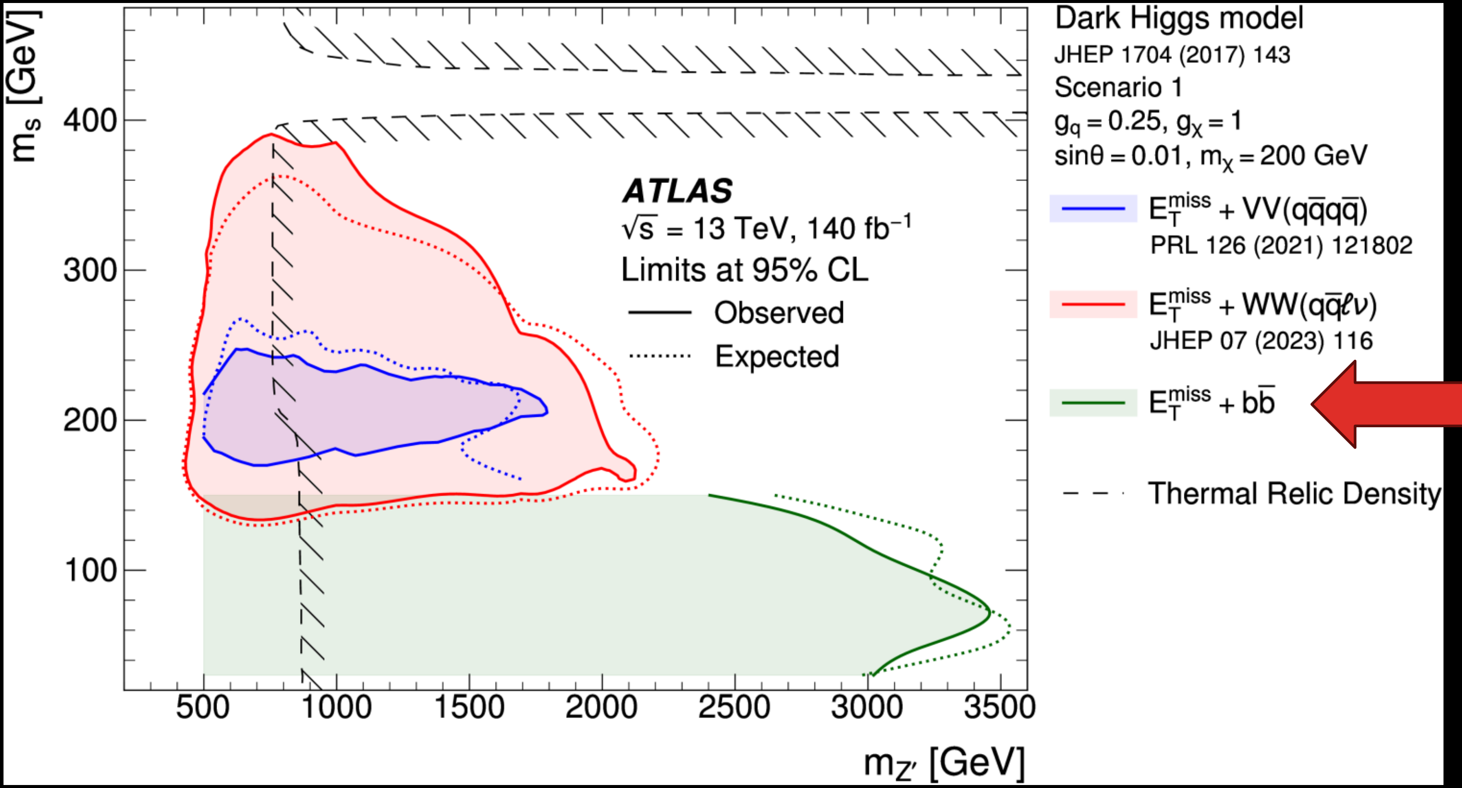
***DXbb* v.s. 2 single-b jets tagging**

Results & Latest Collider Constrain on Dark Higgs



No significant derivation from SM

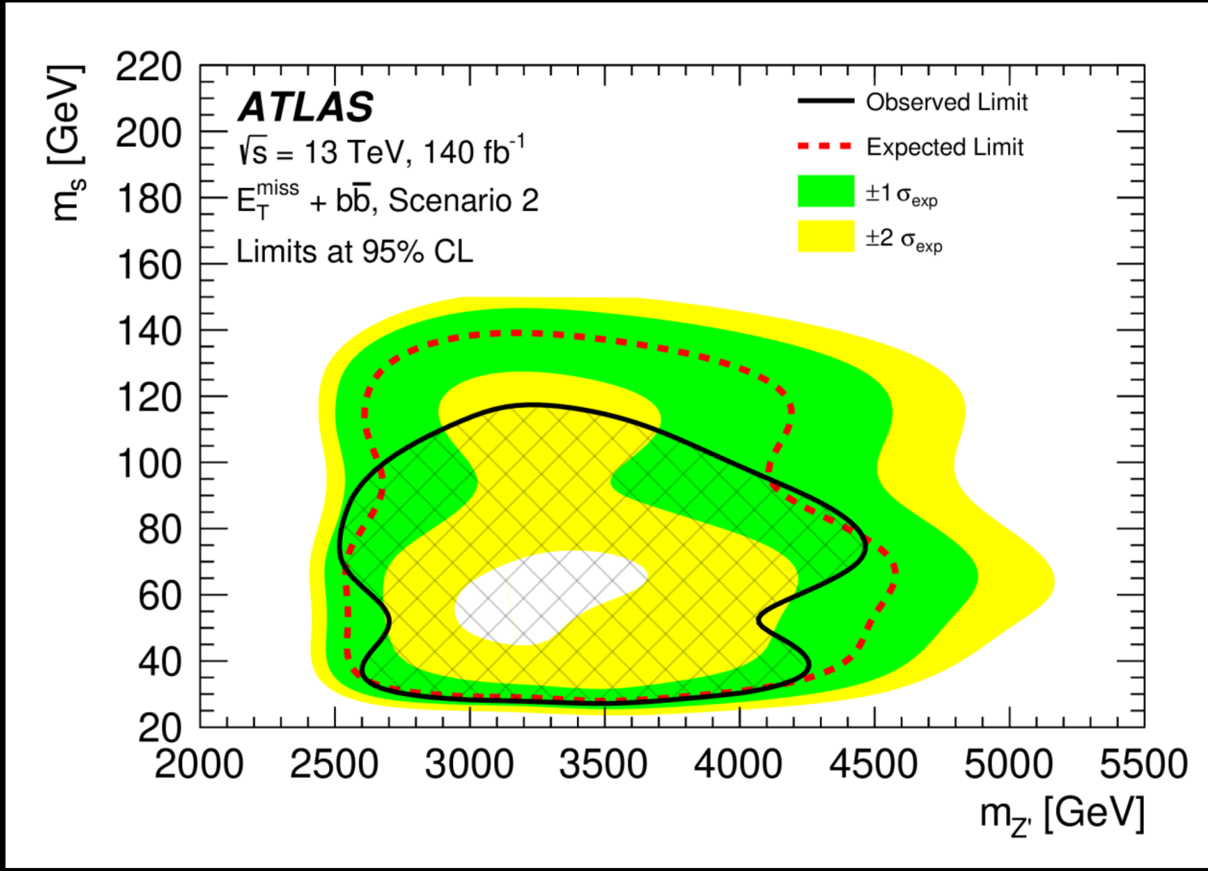
Benchmark setup of dark Higgs model (g_χ=1, m_χ=200GeV)

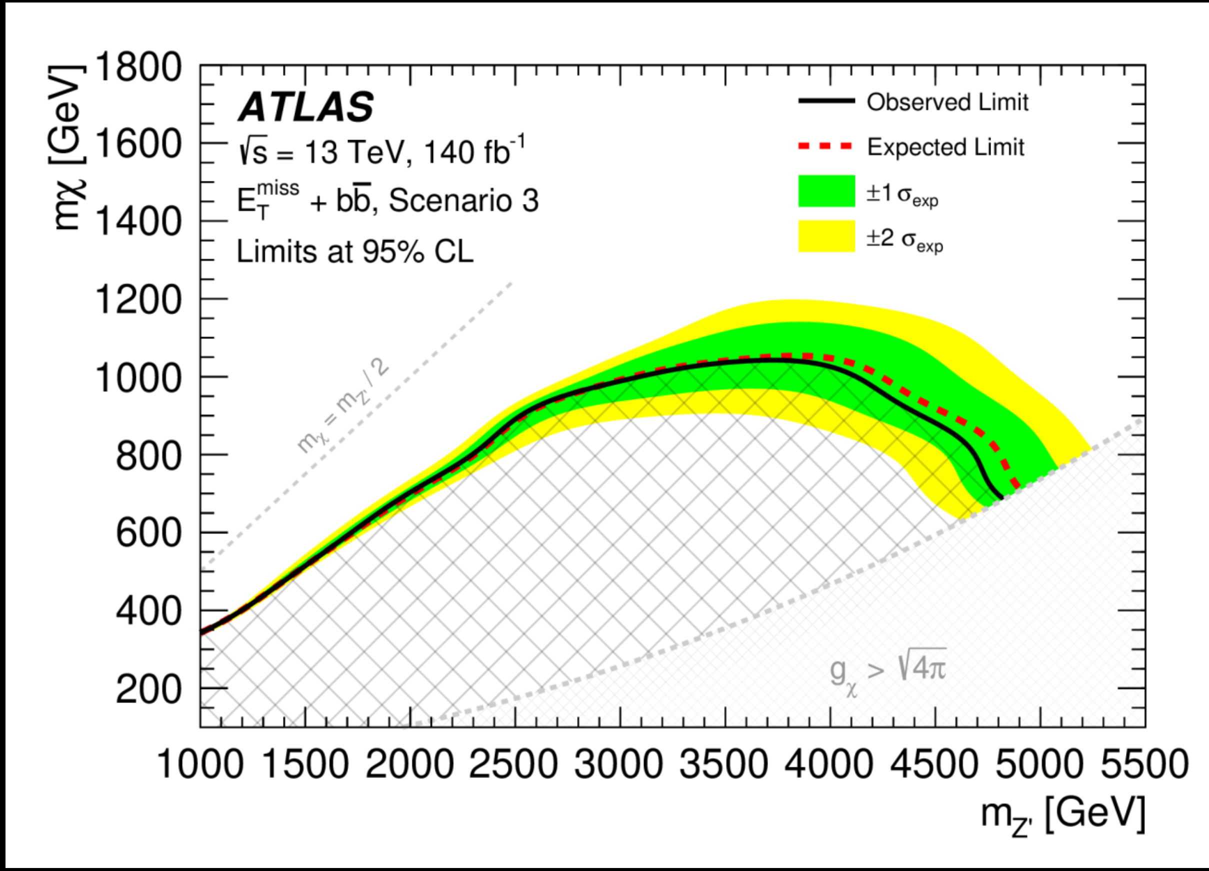


Excluded dark Higgs m_S < 150 GeV and $m_{Z'}$ up to 3.5 TeV
Complete mass scan from 400GeV to 30GeV

Latest Collider Constrain on Dark Higgs

Relic density compatible setup ($\Omega h^2 = 0.12$)





Scenario2 (m_χ = 900GeV)
Excluded $m_{Z'}$ up to 4.1 TeV

Scenario3 (m_S = 70GeV)
Excluded $m_{Z'}$ up to perturbative limit

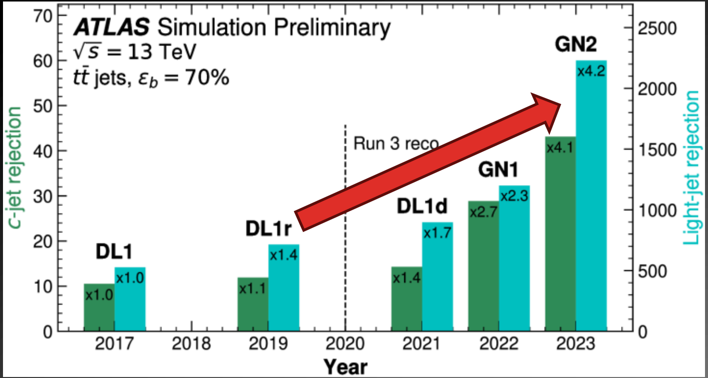
Science Bulletin 69 (2024) 3005
2407.10549

Summary

- **Recent searches for Dark Matter in 2HDM+a and dark Higgs at ATLAS reported**
- **Searches targeting different signatures combined in the context of 2HDM+a model**
  - Benchmark of latest DM searches in ATLAS and new collider constraints derived
- **Search for Dark Higgs in bb+MET final states using full Run2 data**
  - Coherent relic density with cosmology and complete the scan of scalar mass in 30-400GeV
  - Enabled by novel ML-based mass-agnostic Xbb tagging and low mass boosted jet
- **Still a lot to fully understand the DM but progressing + promising!**
  - New jet flavor tagging based on advanced ML development (GN2, GN2X)
  - Trigger-level analysis utilizing more data statistics
  - Model independent DM searches using Anomaly Detection
  - Well accumulating ATLAS Run 3 data and hardworking CP efforts!

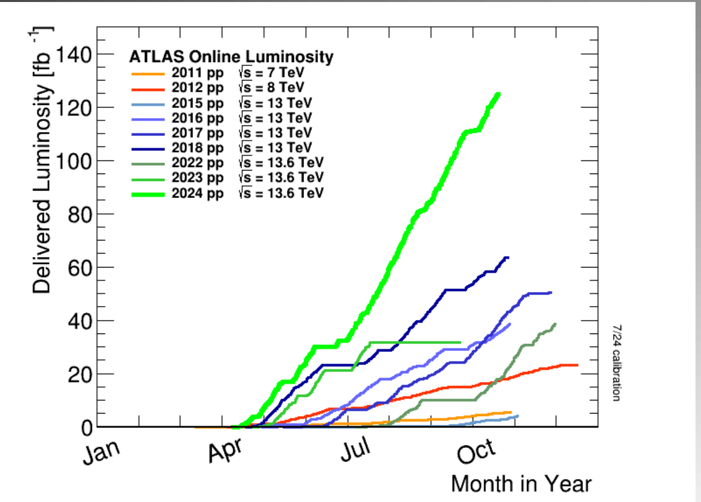
Stay Tuned!

FTAG-2023-01



More we tag, Less the unknown!

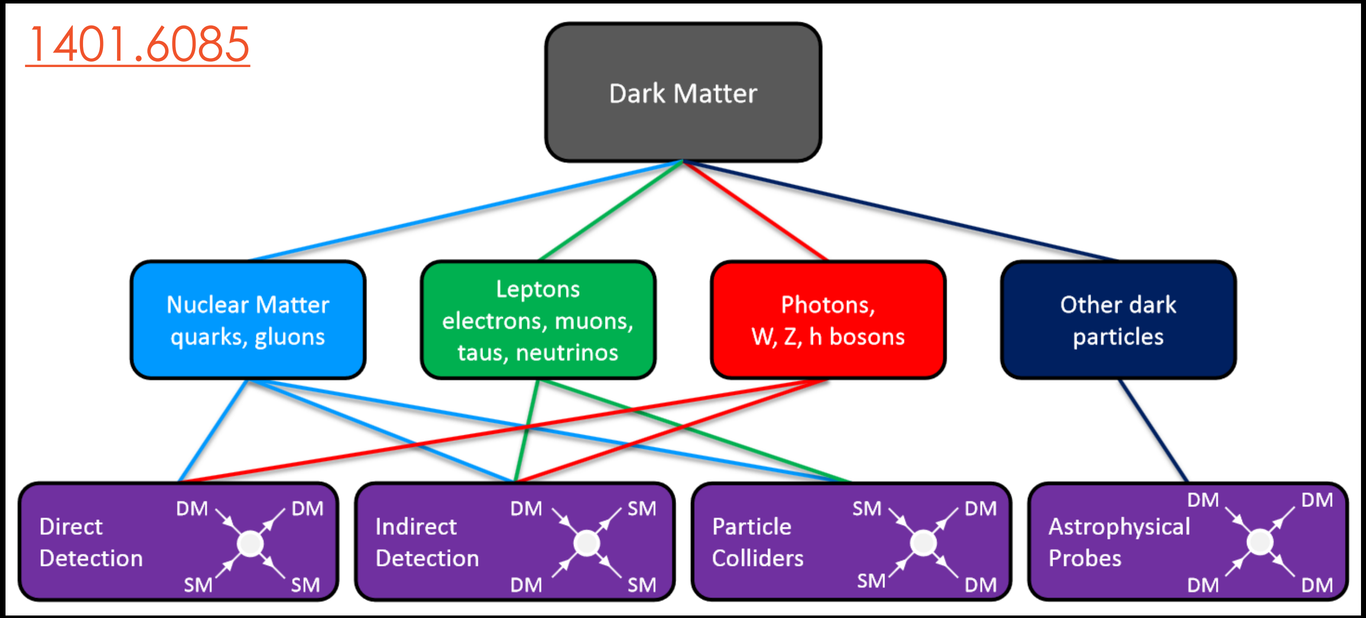
ATLAS Luminosity



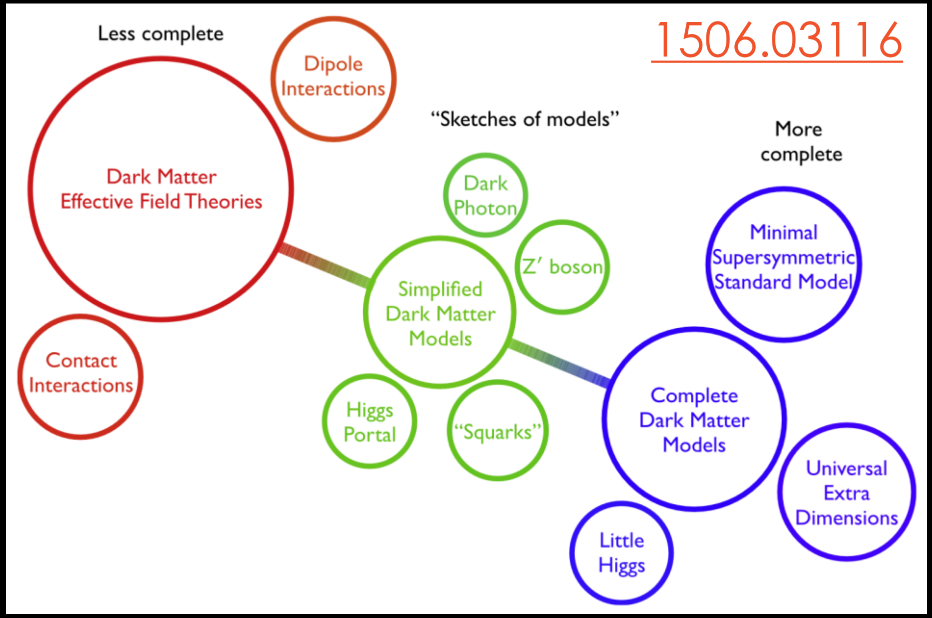
More the luminosity, Less the dark!

BACKUP

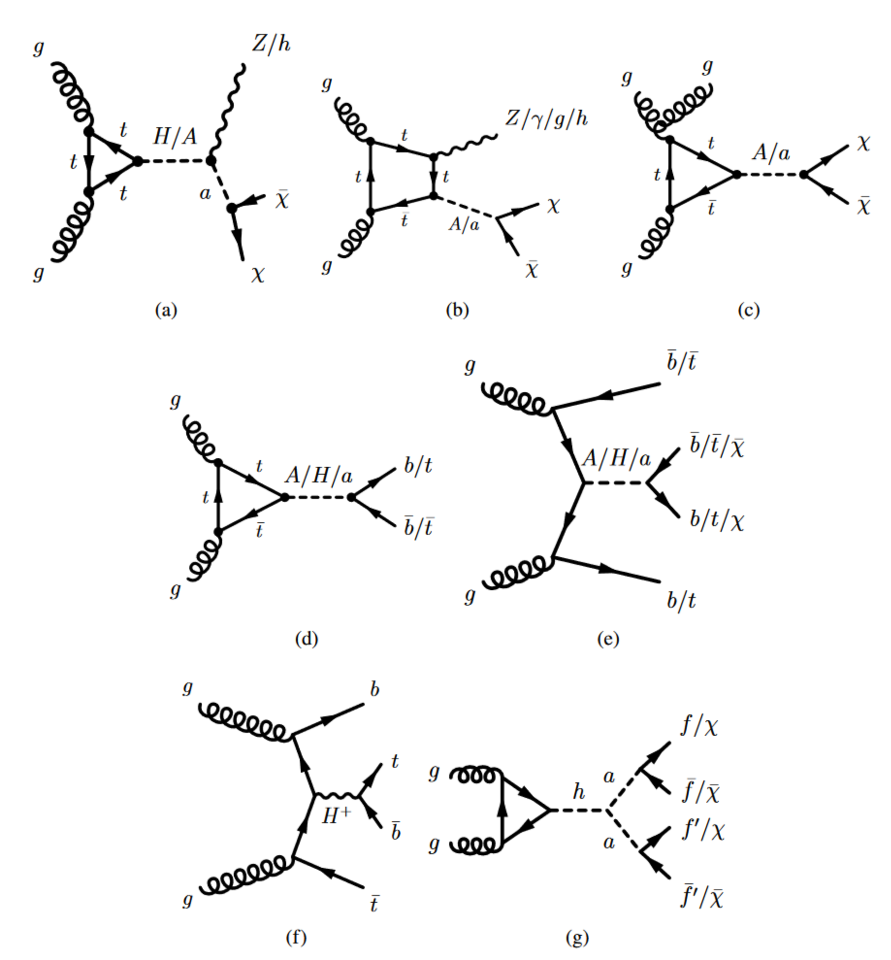
DM Interaction

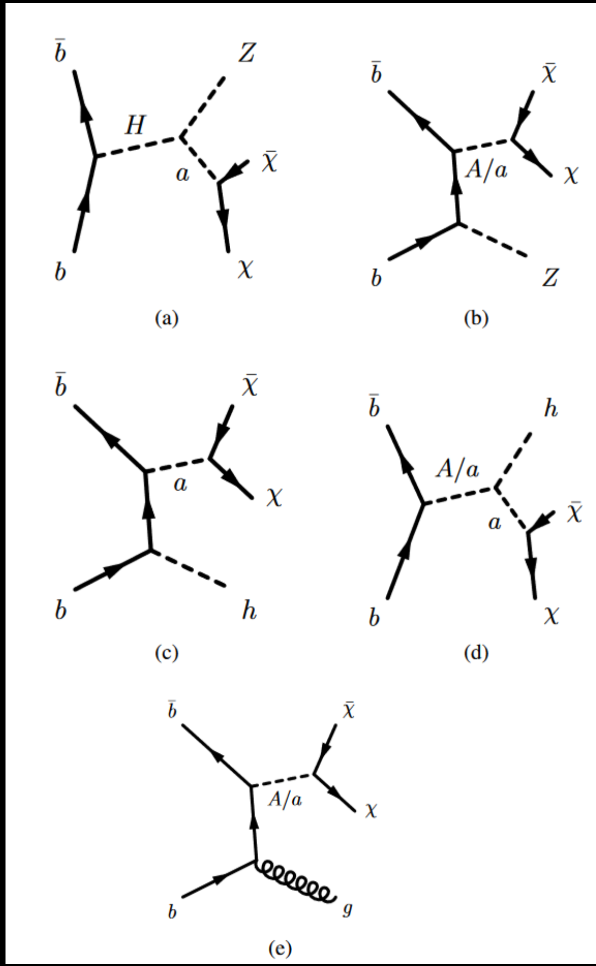


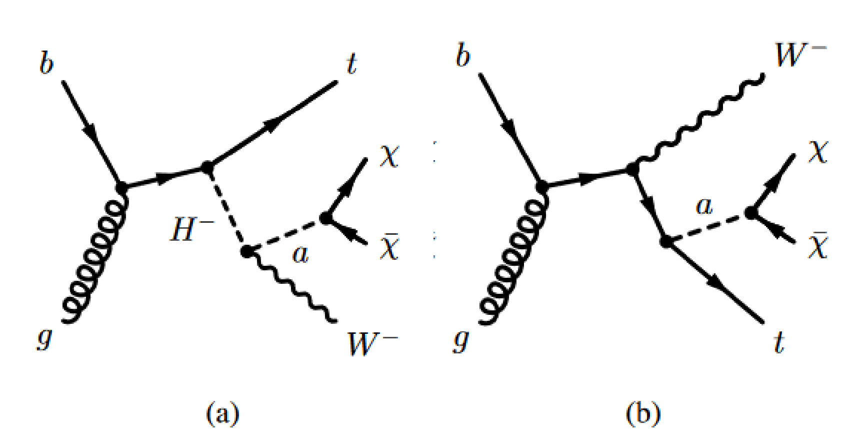
DM Theory



2HDM+a

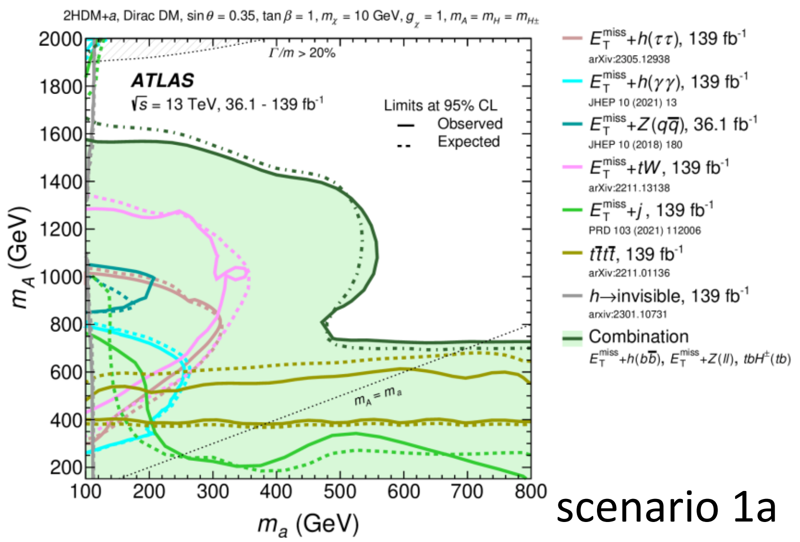

g
Z/h
t
H/A
t
t
a
$\bar{\chi}$
g
χ
(a)
$Z/\gamma/g/h$
t
t
t
A/a
χ
$\bar{\chi}$
(b)
A/a
χ
$\bar{\chi}$
$\bar{t}$
(c)
A/H/a
b/t
$\bar{b}/\bar{t}$
(d)
$\bar{b}/\bar{t}$
A/H/a
$\bar{b}/\bar{t}/\bar{\chi}$
$b/t/\chi$
b/t
(e)
b
t
H^+
$\bar{b}$
$\bar{t}$
(f)
h
a
f/χ
$\bar{f}/\bar{\chi}$
f'/χ
$\bar{f}'/\bar{\chi}$
(g)


$\bar{b}$
Z
H
a
$\bar{\chi}$
b
χ
(a)
A/a
χ
Z
(b)
h
(c)
(d)
(e)

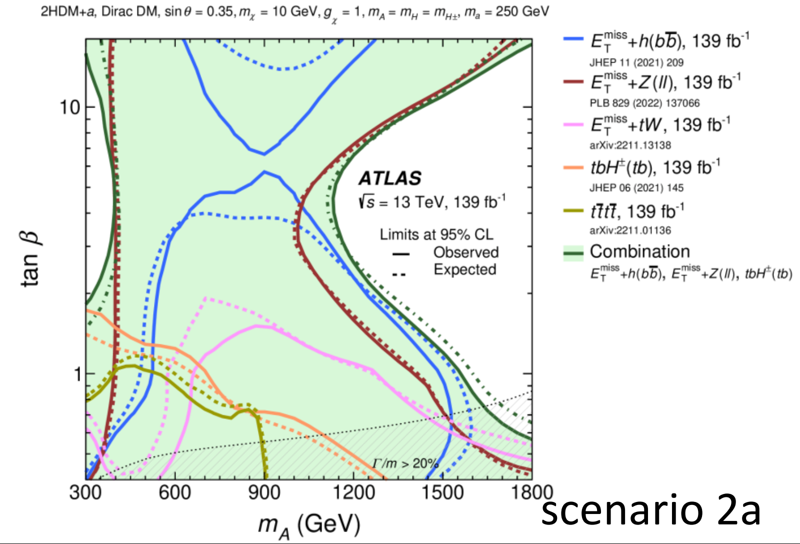

b
t
χ
H^-
a
$\bar{\chi}$
g
W^-
(a)
(b)

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)



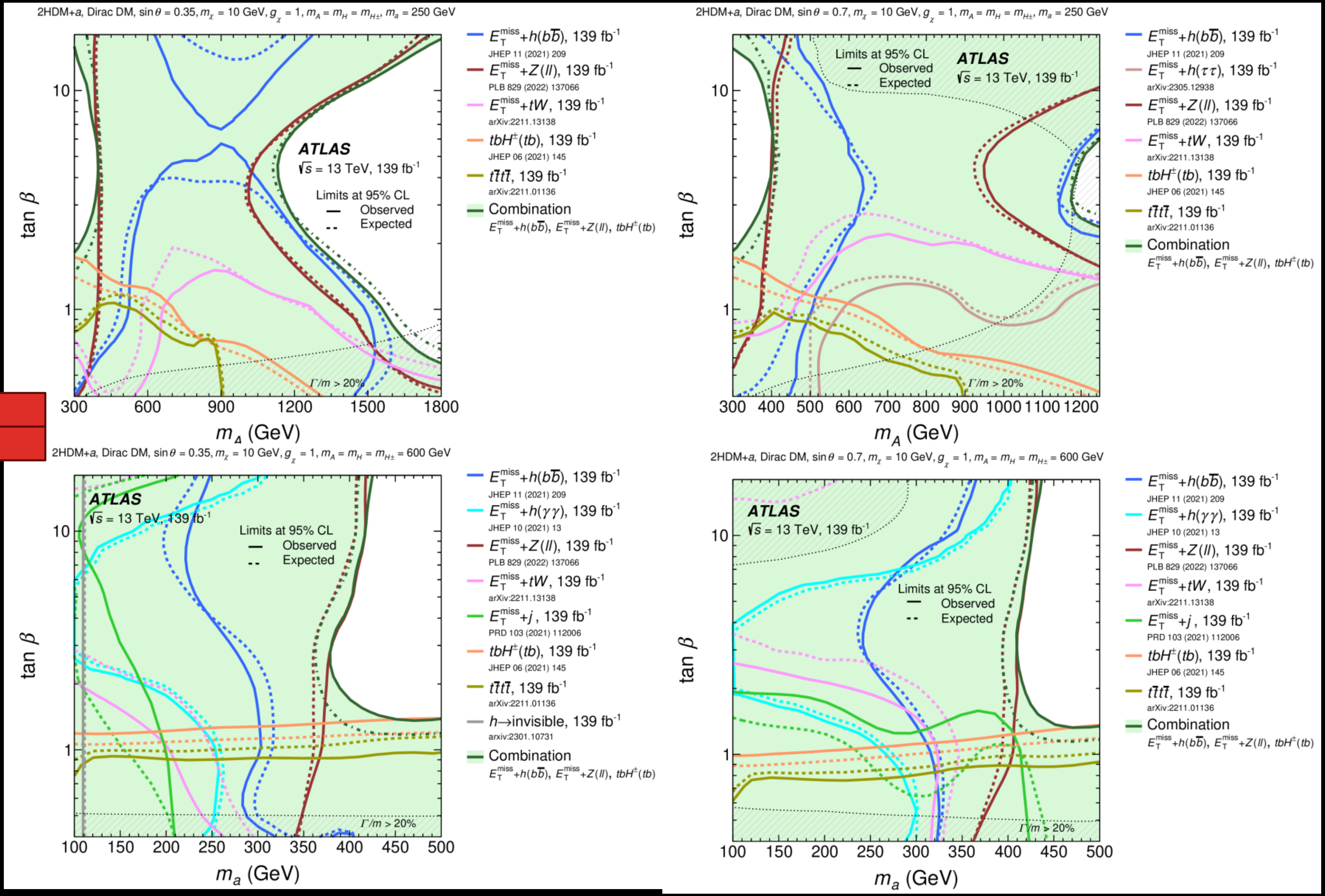
scenario 1a



scenario 2a

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)



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	$\sin\theta$
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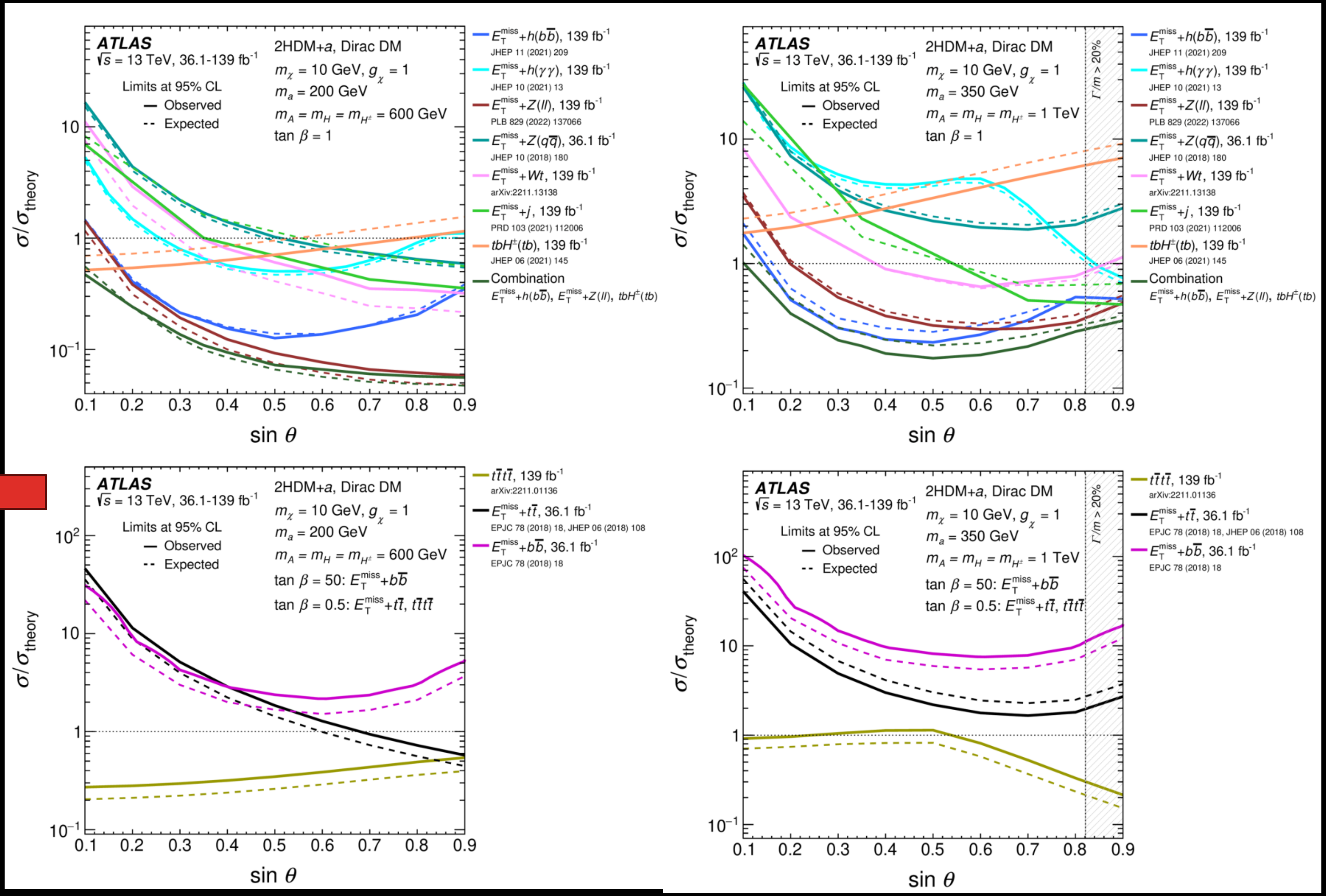
5		0.35	1000	400	–	1.0	m_χ
6		0.35	1200	–	–	1.0	(m_a, m_χ)



2HDM+a

Scenario		Fixed parameter values					Varied parameters
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	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	
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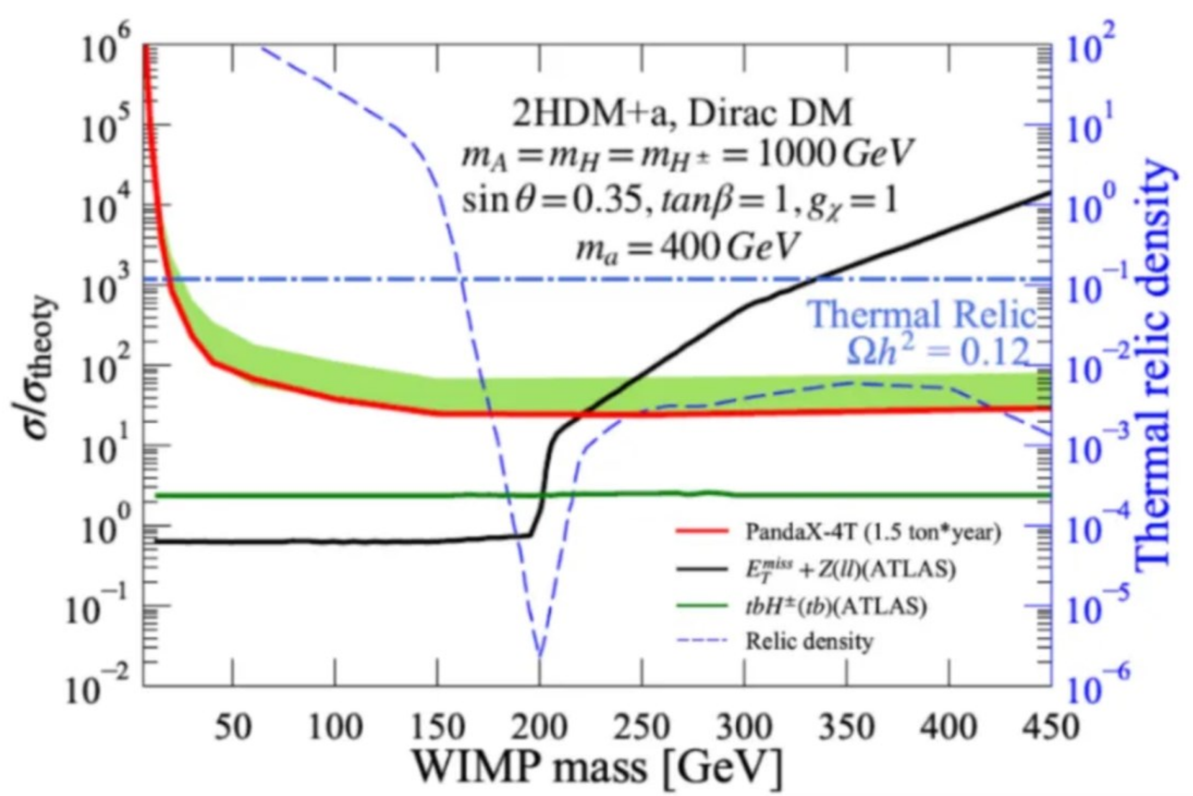
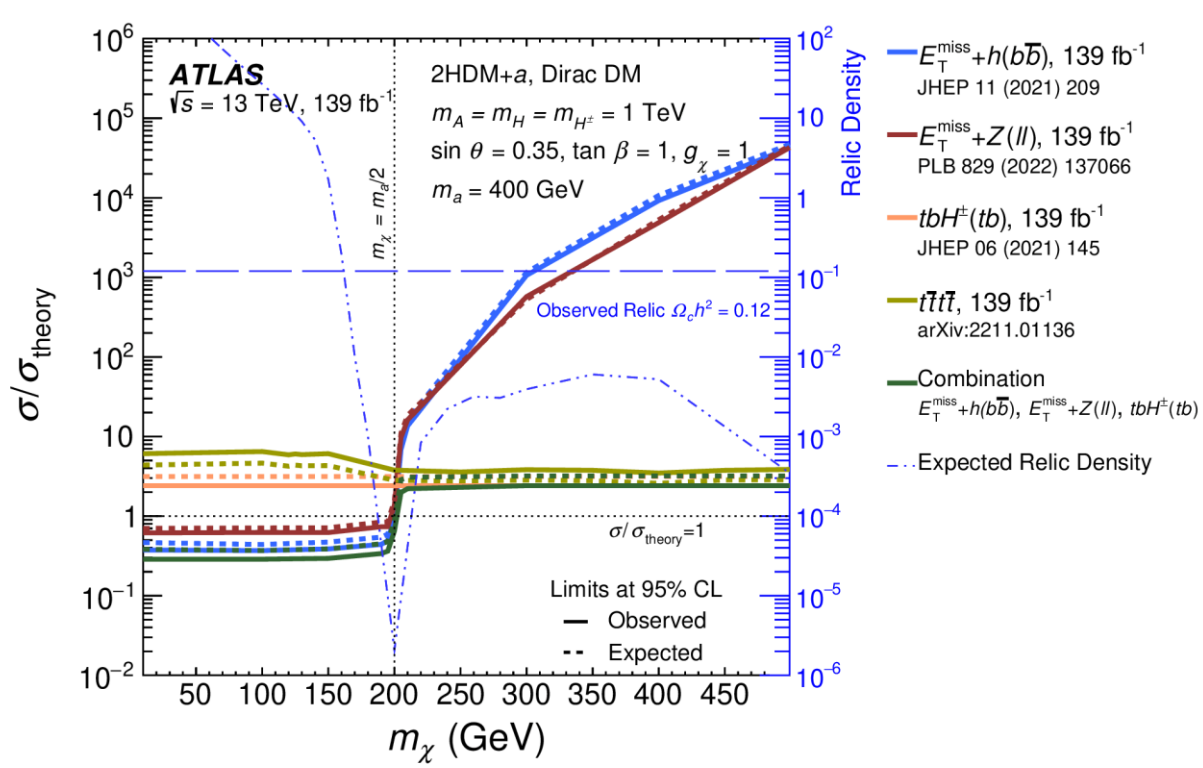
6		0.35	1200	–	–	1.0	(m_a, m_χ)

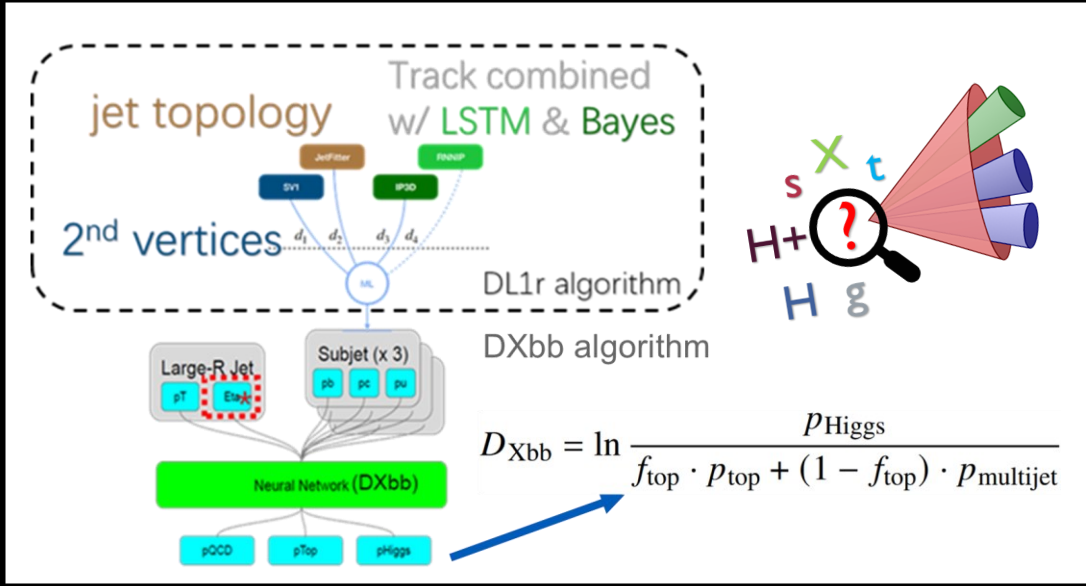
https://mp.weixin.qq.com/s/l1Mgrwyh15KMKnf9r9yjsQ



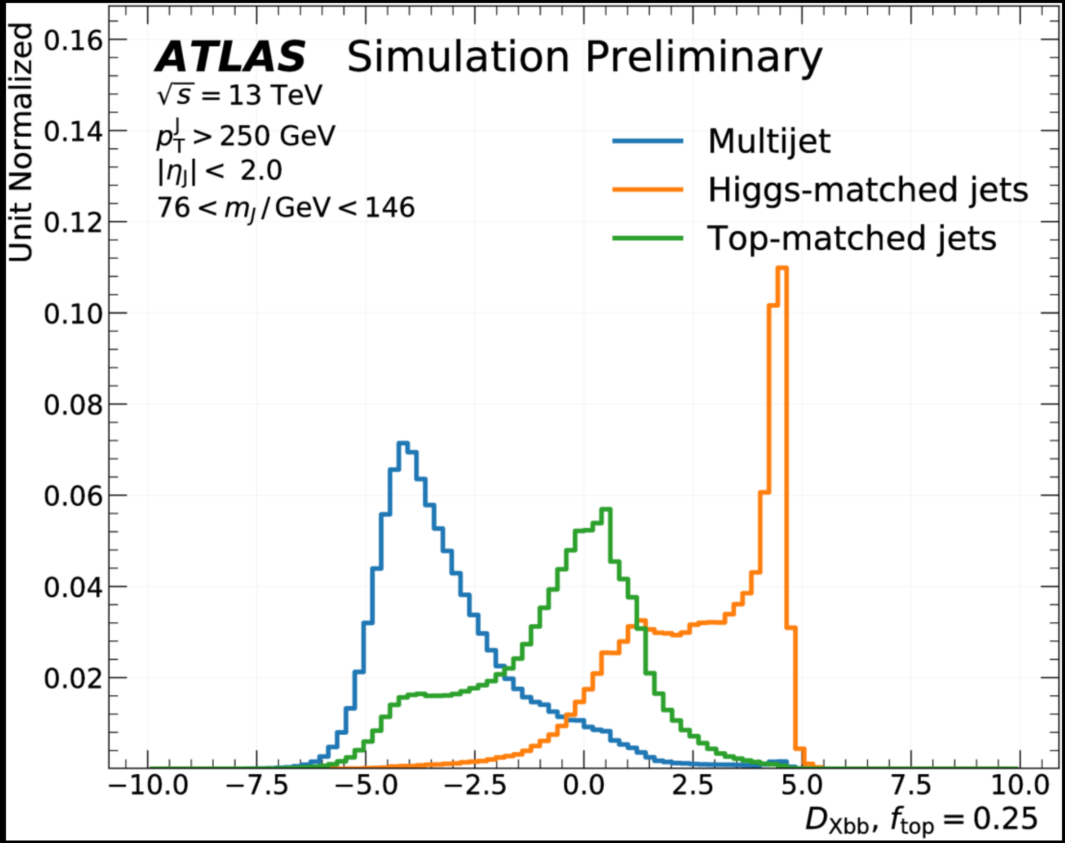


Boosted Xbb tagger in ATLAS

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



$$D_{\mathrm{Xbb}} = \ln \frac{p_{\mathrm{Higgs}}}{f_{\mathrm{top}} \cdot p_{\mathrm{top}} + (1 - f_{\mathrm{top}}) \cdot p_{\mathrm{multijet}}}$$



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

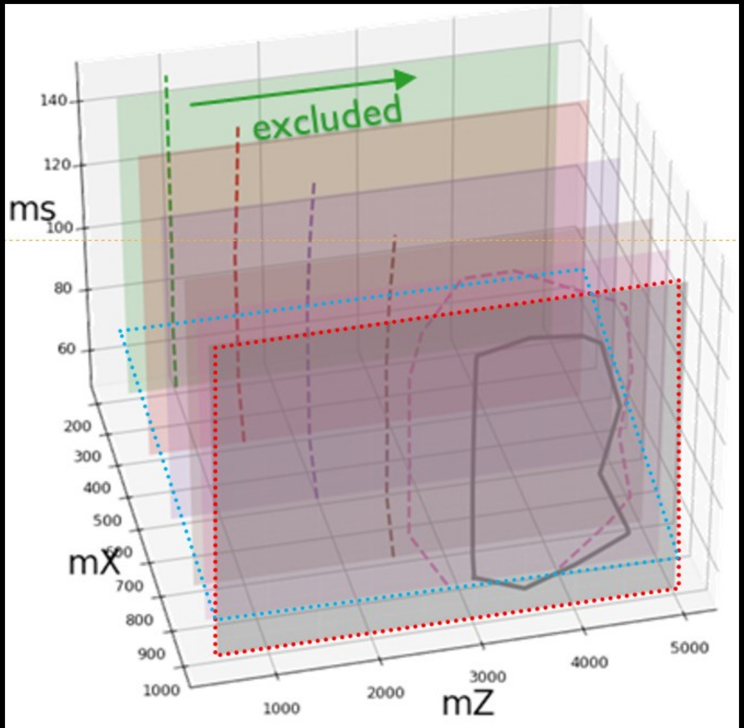
Dark Higgs

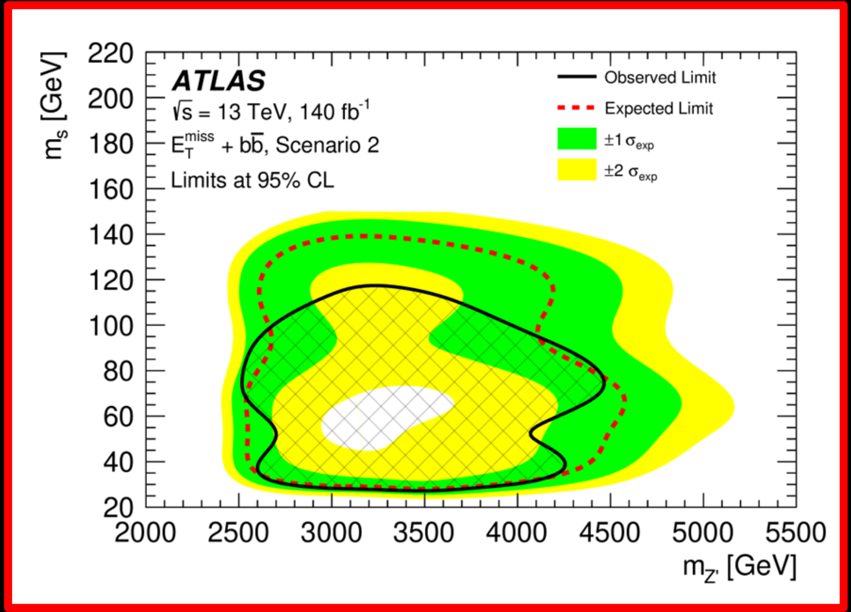
Relic-coherent 3-D Parameter Space

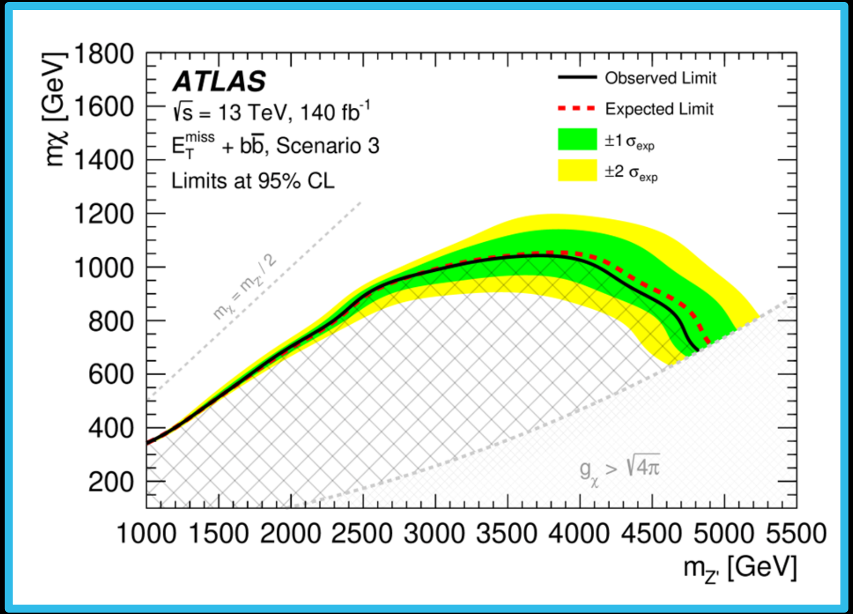
How <u>relic density</u> used to reduce parameter space of DM model

Reco Analysis Result

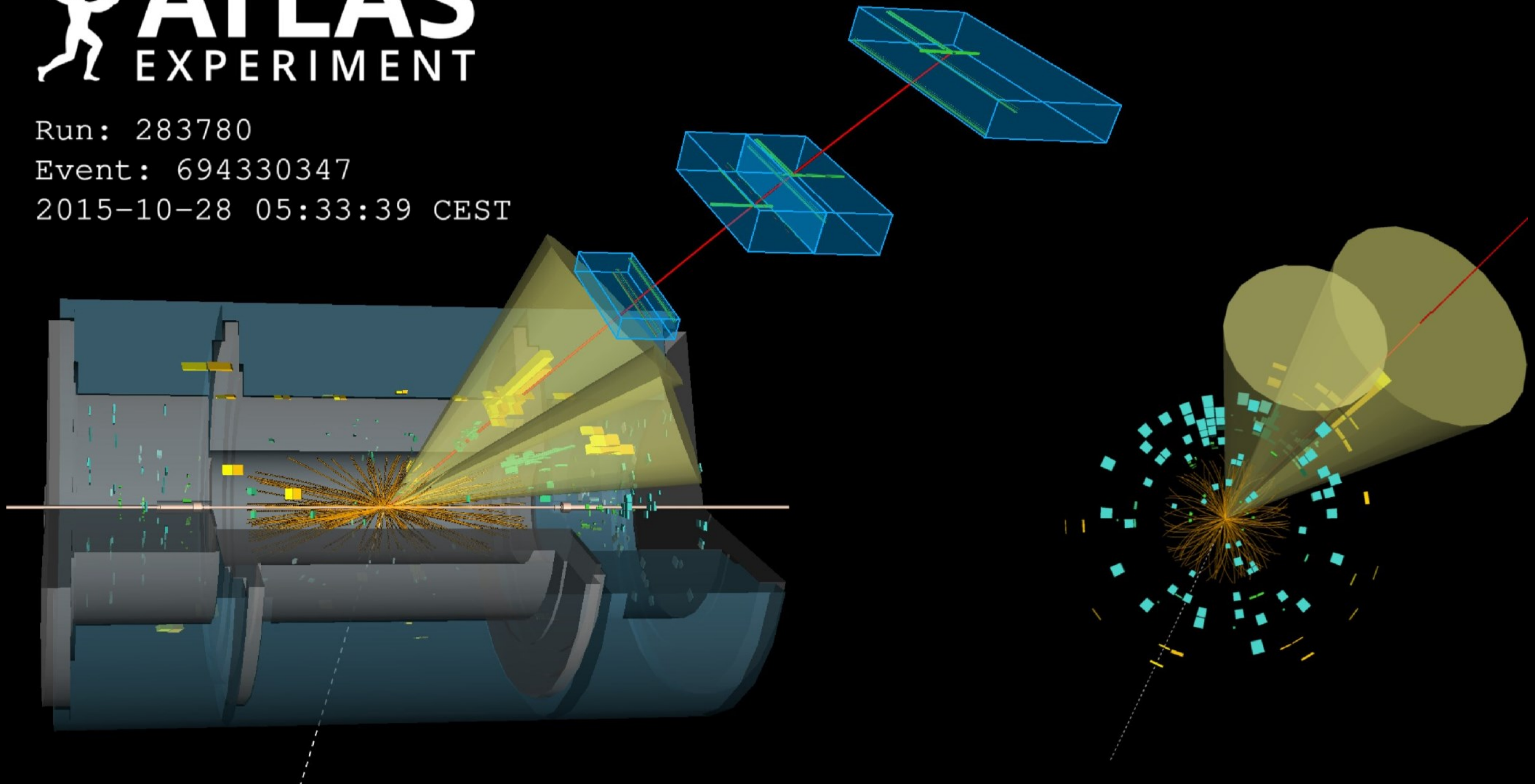
Set the final exclusion limit



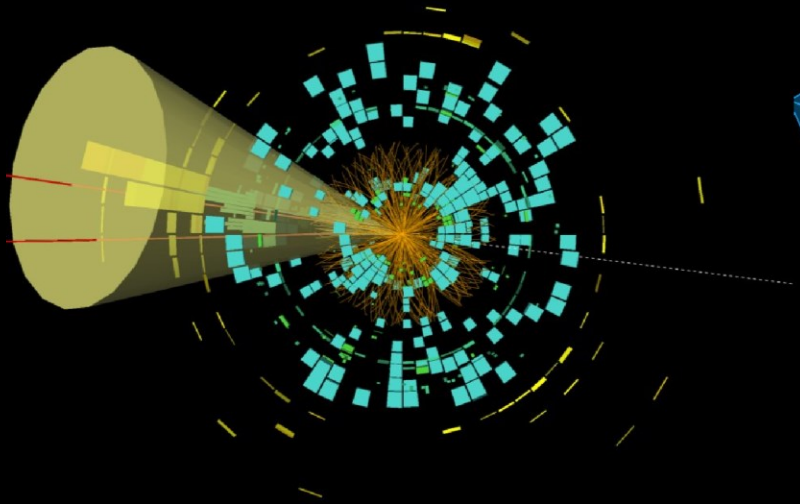


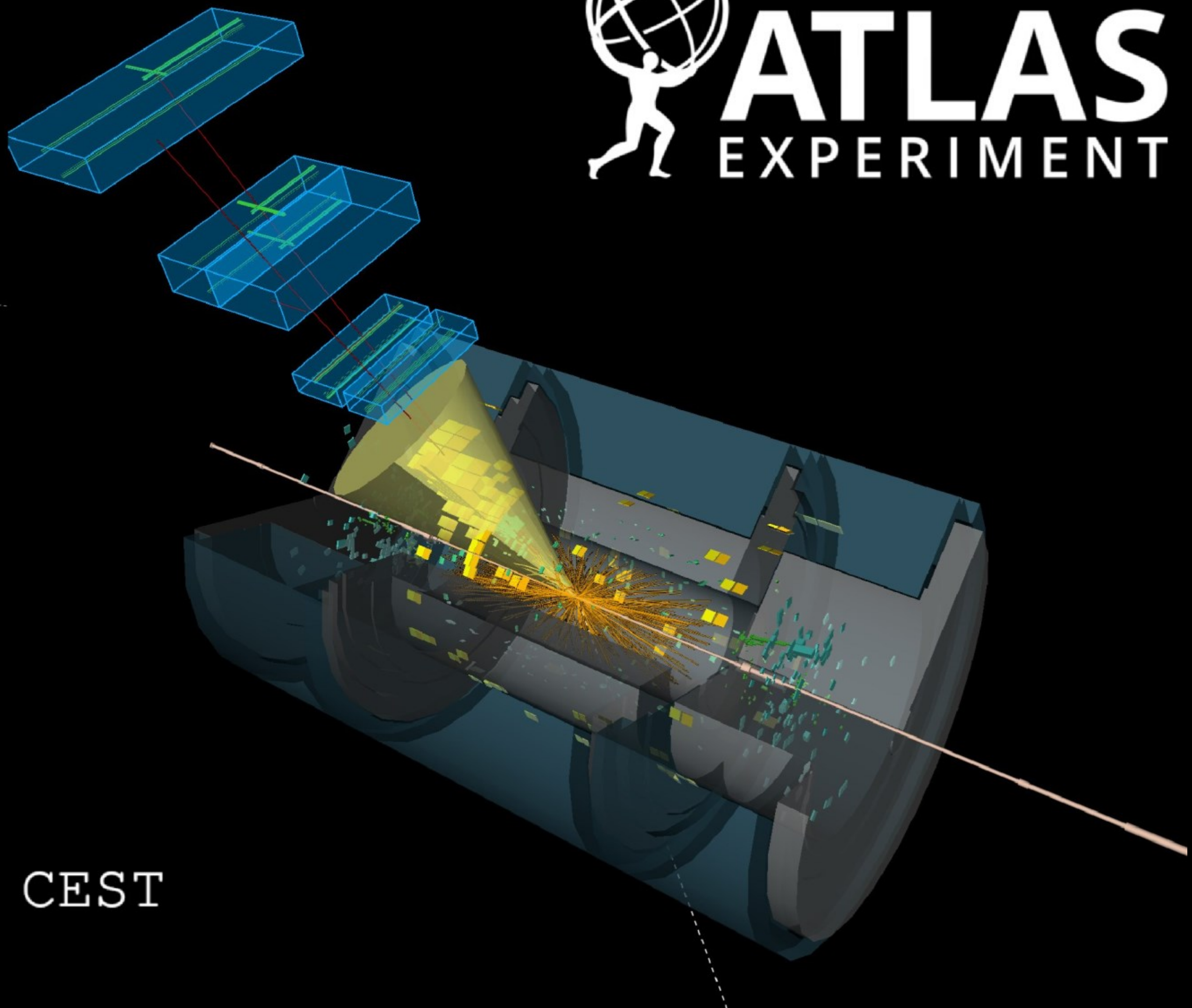


ATLAS
EXPERIMENT



ATLAS
EXPERIMENT





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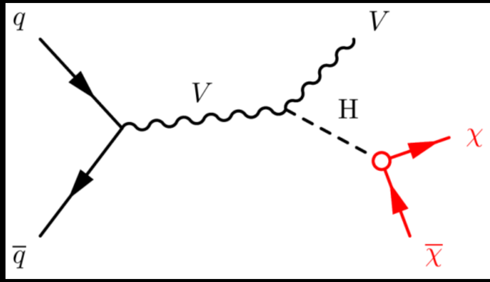
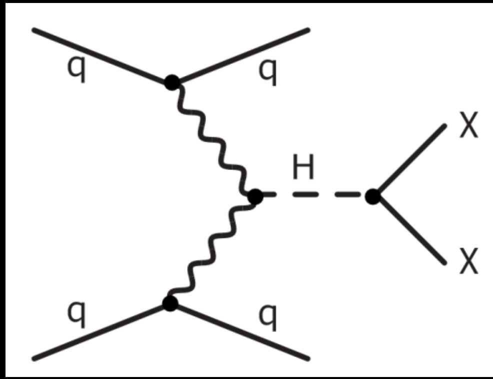
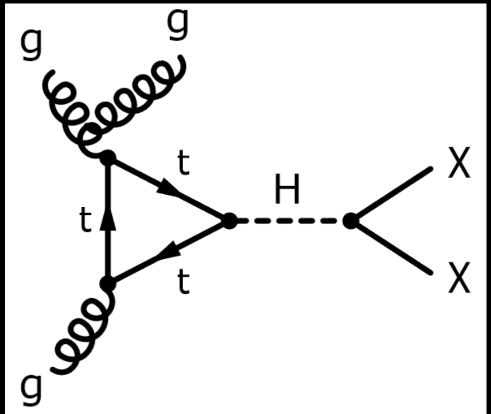
[1] V. Silveira, A. Zee, Phys. Lett. B161, 136 (1985)
[2] Eur.Phys.J.C 73 (2013) 6, 2455
[3] Phys. Rev. D 90, 055014 (2014)

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