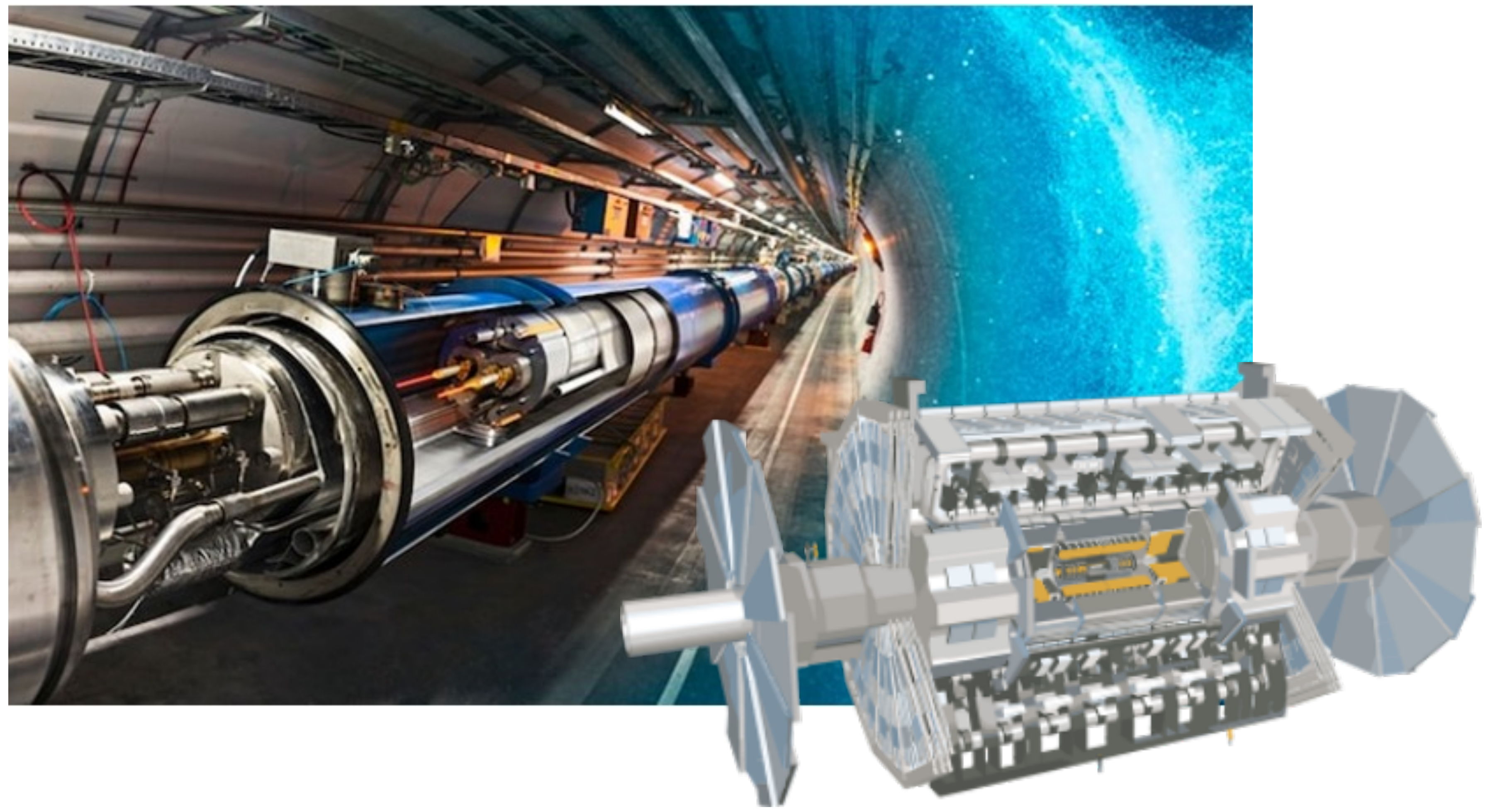
Tsung-Dao Lee Institute

ATLAS EXPERIMENT

Recent Dark “Matter/Photon/Higgs” search results from ATLAS

2024年紫金山暗物质研讨会

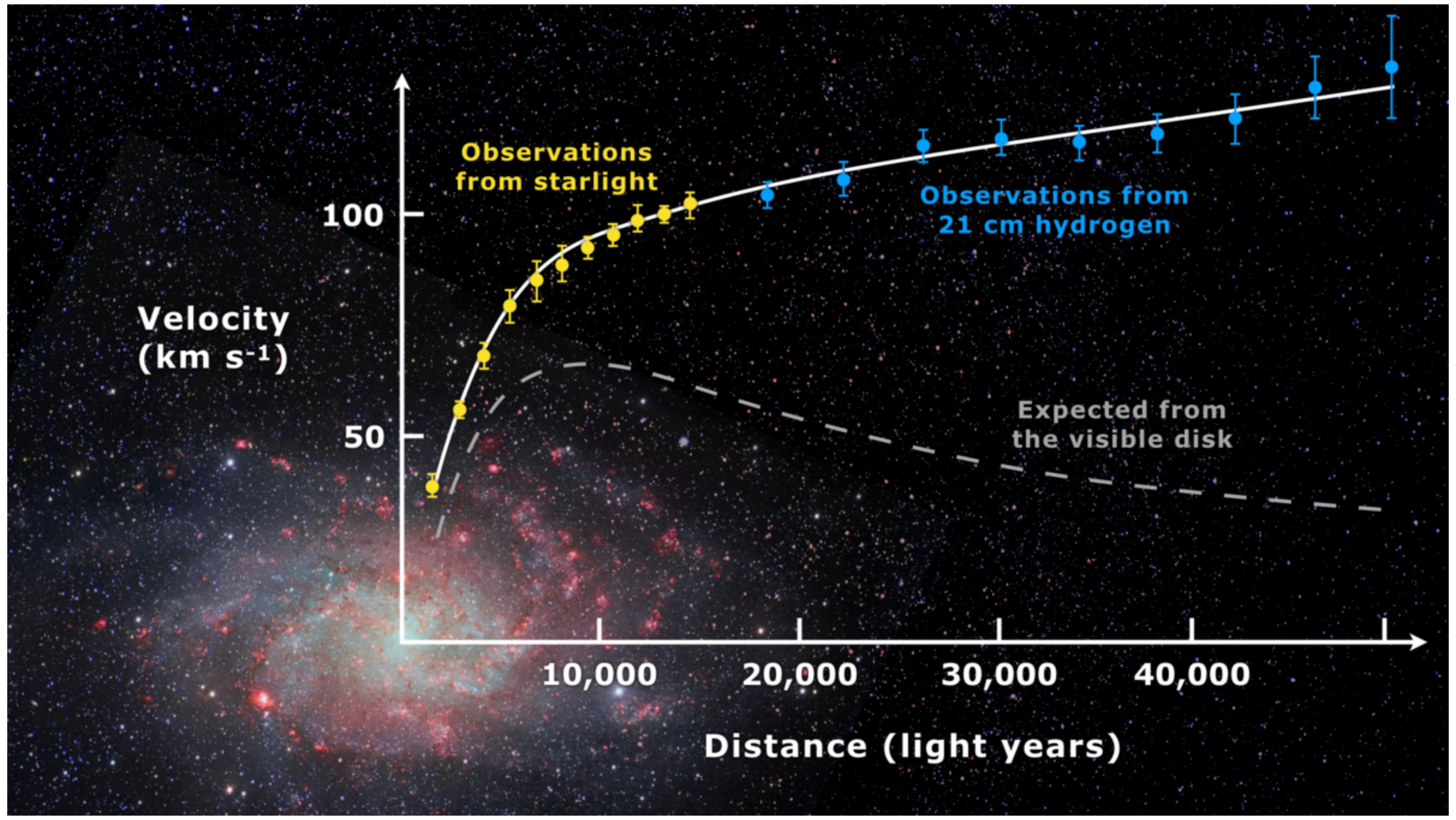


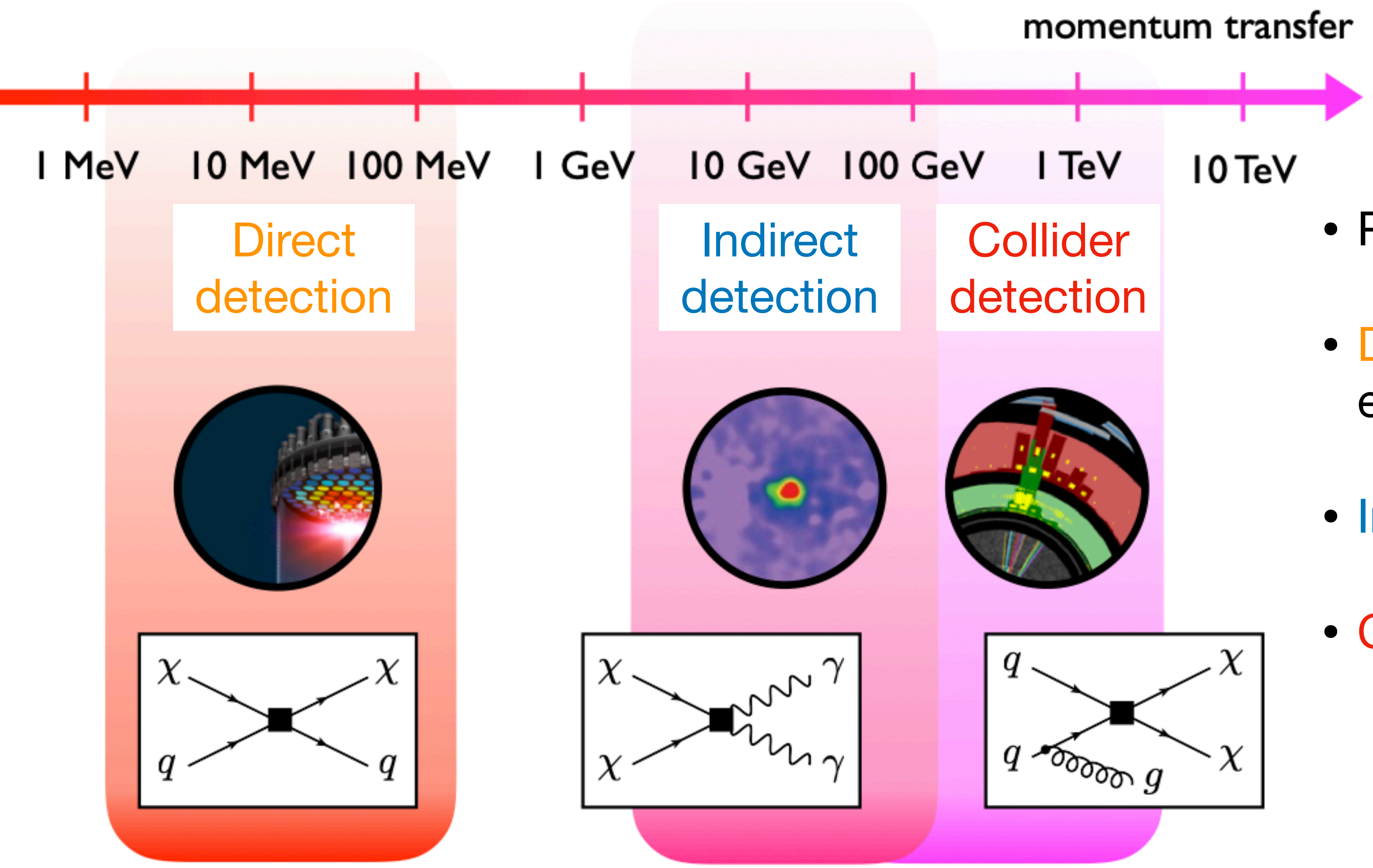
Khanh N. Vu

Suzhou, 14/10/2024

Dark Matter

- Dark Matter existence supported by plethora of astrophysical measurements.
  - NOT sufficiently explained by Standard Model, making DM nature a central question in particle physics.
  - ***DM candidate***: a strong consideration in many beyond-the-SM models.



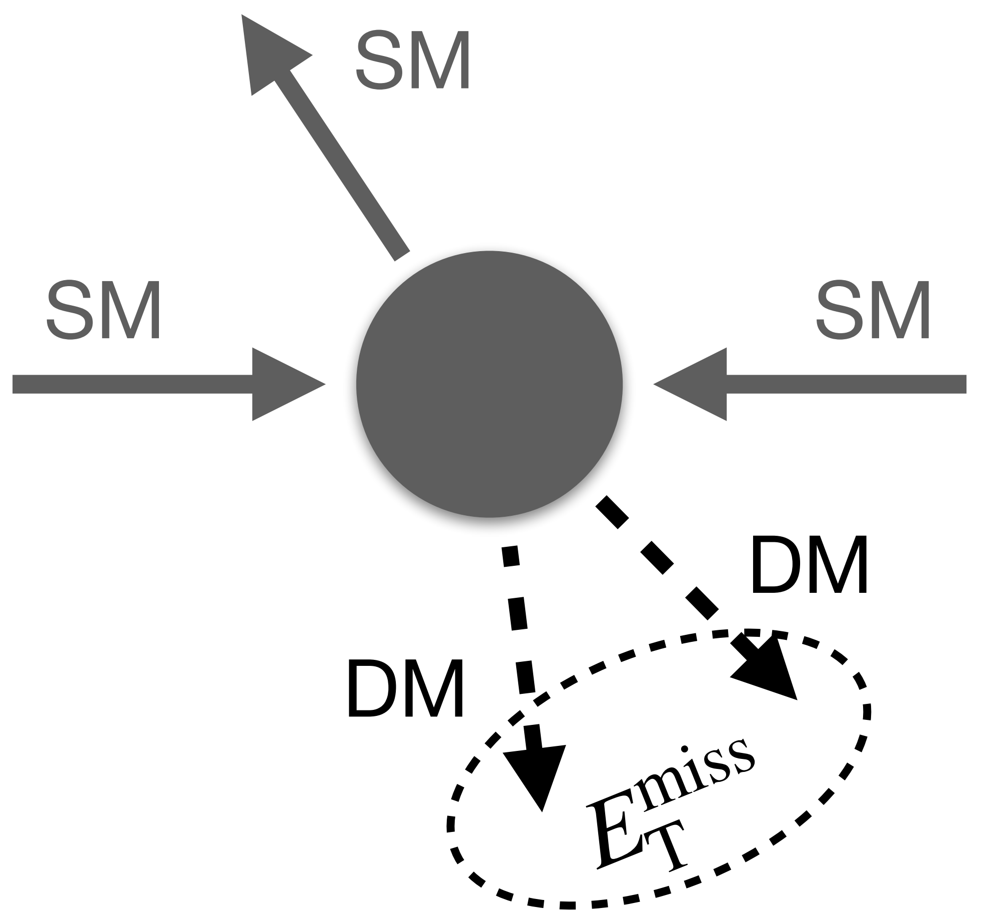


1810.09420

- Probes of DM underway in several areas.
- Direct searches for elastic scattering between DM and nuclei or electrons.
- Indirect searches for products of DM annihilation or decay.
- Collider searches for production of DM from collisions of SM particles
  - complementarity to other detections at GeV-TeV scale.
  - provide access to particles mediating interactions between DM and SM sector.

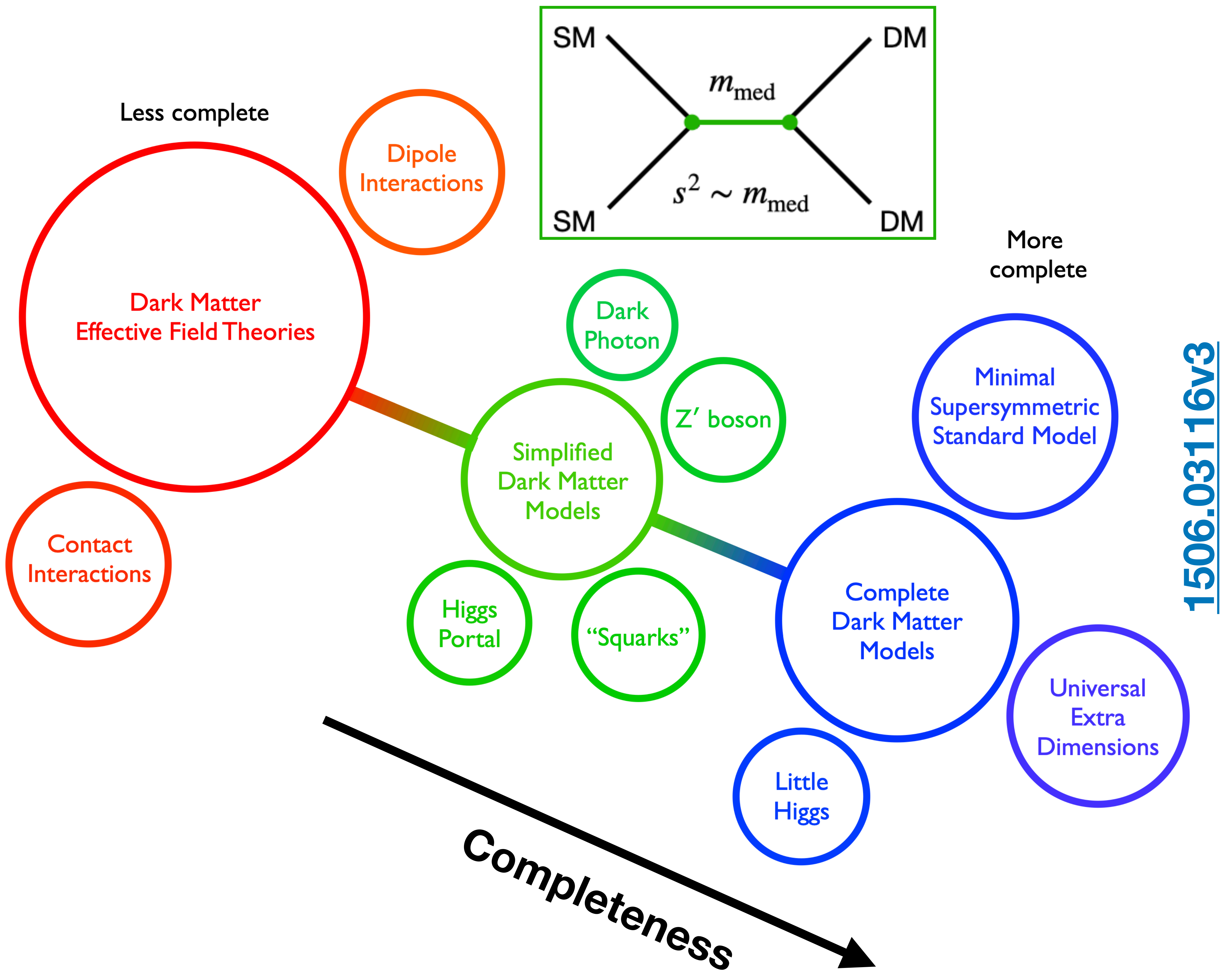
Dark Matter probes at ATLAS

- ATLAS sensitive to wide variety of potential DM candidates.
- Most of DM searches at the LHC focus on ***Weakly Interacting Massive Particles*** (***WIMPs)***.
  - usually in ***simplified models*** where DM couples to SM via mediator.
  - more complete (hence more complicated) models e.g *2HDM(+a)* also considered.
  - detected in signatures with large **Missing Transverse Momentum** recoiling against SM particles ($E_{\mathrm{T}}^{\mathrm{miss}} + X$, so called ***mono-X***).



- Also search for ***(Hidden) Dark Sector*** such as Dark Photon, Dark Higgs, Dark QCD, and so on.

DM benchmark models at LHC



1506.03116v3

Today's talk

- Thanks and credits to the Chinese ATLAS collaborators:
  - **Michigan**: Zirui Wang; **Wisconsin**: Rui Zhang
  - **USTC**: Chuanshun Wei, Lailin Xu
  - **IHEP**: Xinhui Huang, Zhijun Liang
  - **TDLI/SJTU**: Changqiao Li, Shu Li, Qibin Liu, Xuliang Zhu, Ngoc Khanh Vu

EUROPEAN ORGANISATION FOR NUCLEAR RESEARCH (CERN)

ATLAS EXPERIMENT

j.scib.2024.06.003

Sci. Bull. (in press)

Submitted to: Science Bulletin

CERN-EP-2023-088
2nd June 2023

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

The ATLAS Collaboration

ION FOR NUCLEAR RESEARCH (CERN)

JHEP 08 (2024) 153

Published in JHEP

CERN-EP-2024-152
5th June 2024

Combination of searches for Higgs boson decays into a photon and a massless dark photon using pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector

The ATLAS Collaboration

TION FOR NUCLEAR RESEARCH (CERN)

arXiv: 2407.10549

Submitted to PRL

CERN-EP-2024-170
July 16, 2024

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

The ATLAS Collaboration

PART 01

Combination and summary of ATLAS Dark Matter searches interpreted in 2HDM+a

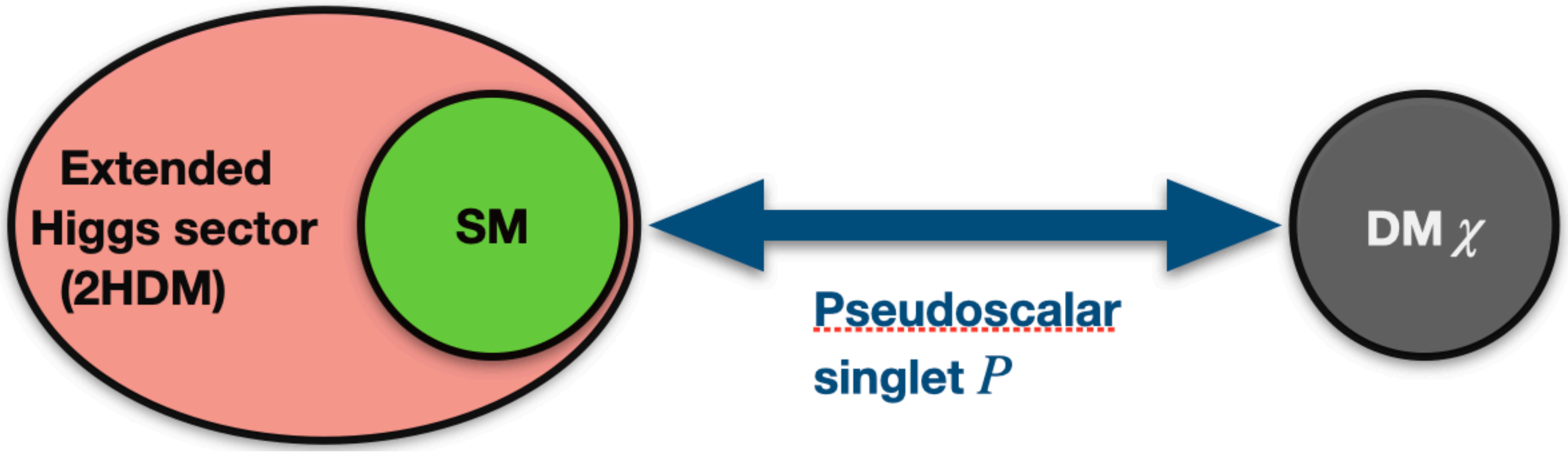
Two-Higgs-Doublet-Model + pseudo-scalar mediator (2HDM+a)

[LHC Dark Matter Working Group](#)
[JHEP 05 (2017) 138](#)

- Minimal, UV-complete extension of pseudo-scalar DM simplified models.
- Fully defined by 14 parameters but reduced to **5 unconstrained parameters.**

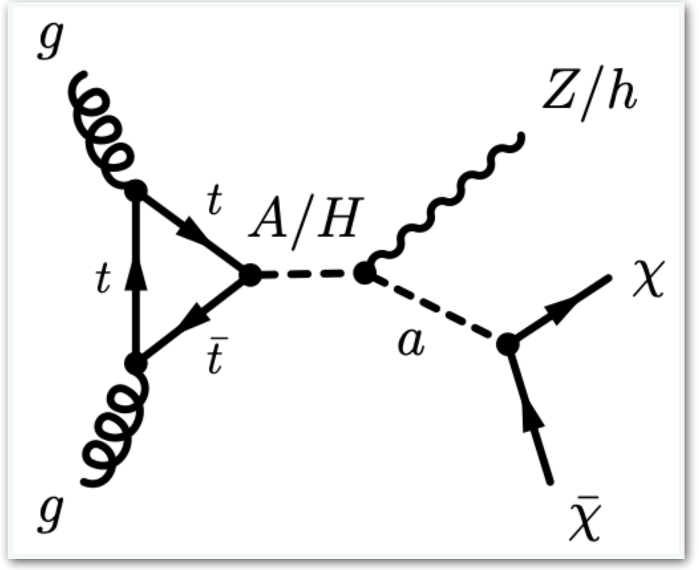
$m_A = m_H = m_{H^\pm}$	**masses of additional heavy Higgs**
m_a	**mass of pseudo-scalar mediator**
m_χ	**DM mass**
$\sin\theta$	**mixing angle between the pseudo-scalars**
$\tan\beta$	**ratio of 2 Higgs doublet VEVs**

- 2HDM+a is complicated **BUT more theoretically complete,** predicting broader range of collider signatures wrt common simplified models.

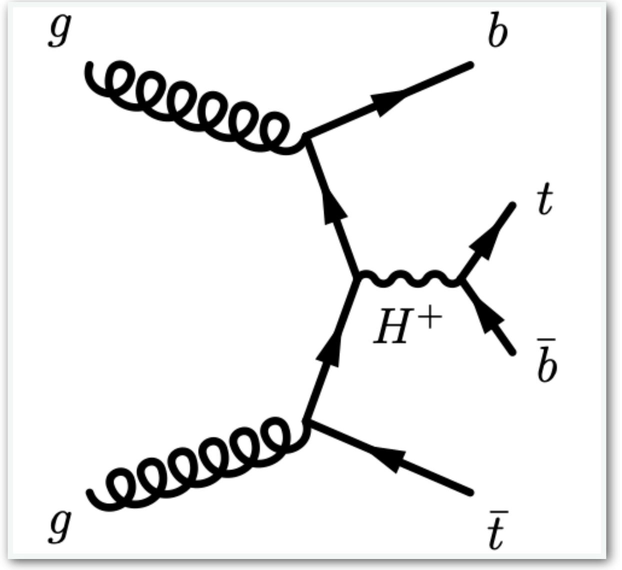


- Scalars: h, H,
- Pseudoscalar: A,
- Charged Higgs: H$^\pm$

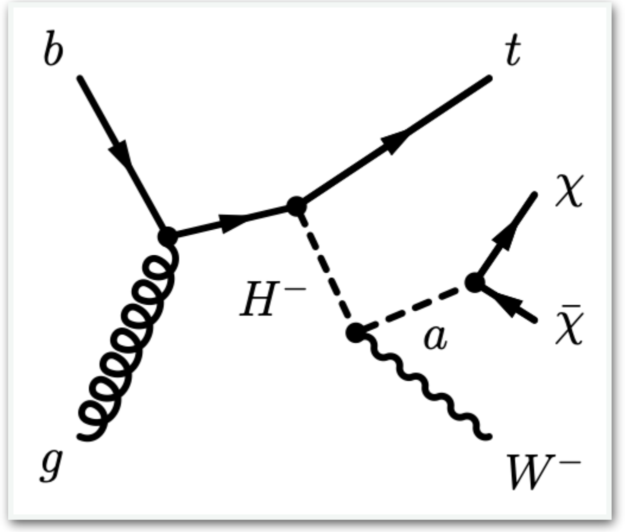
\+ Pseudoscalar: a + Dirac DM χ



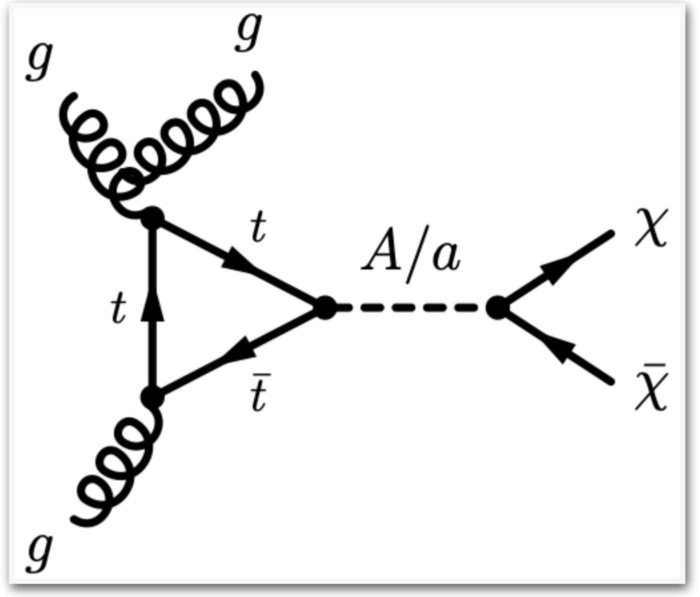
$E_T^{\rm miss} + Z/h$



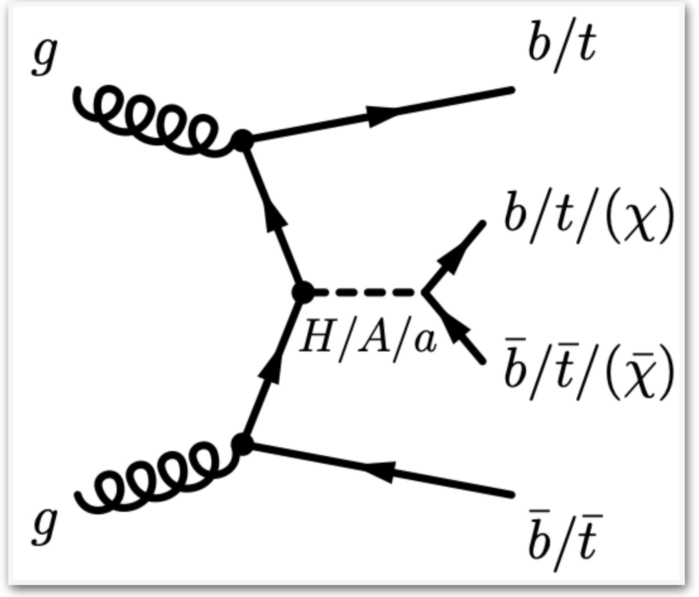
$tbH^\pm(tb)$



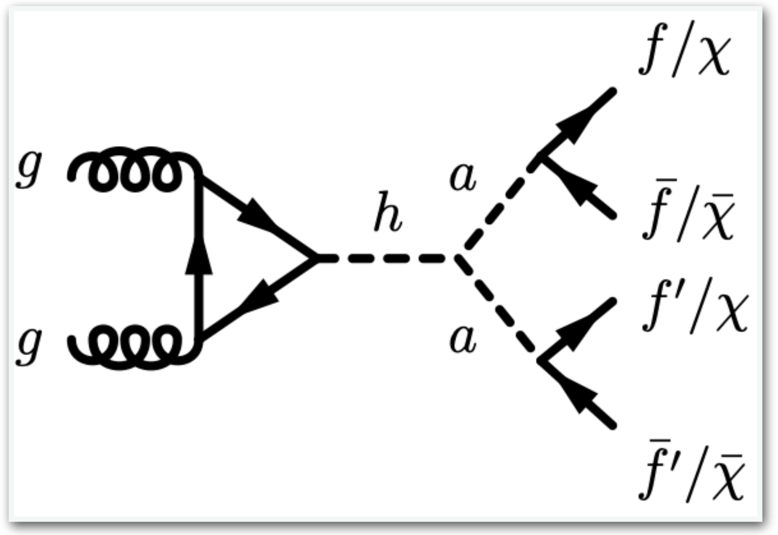
$E_T^{\rm miss} + tW$



$E_T^{\rm miss} + {\rm jet}$

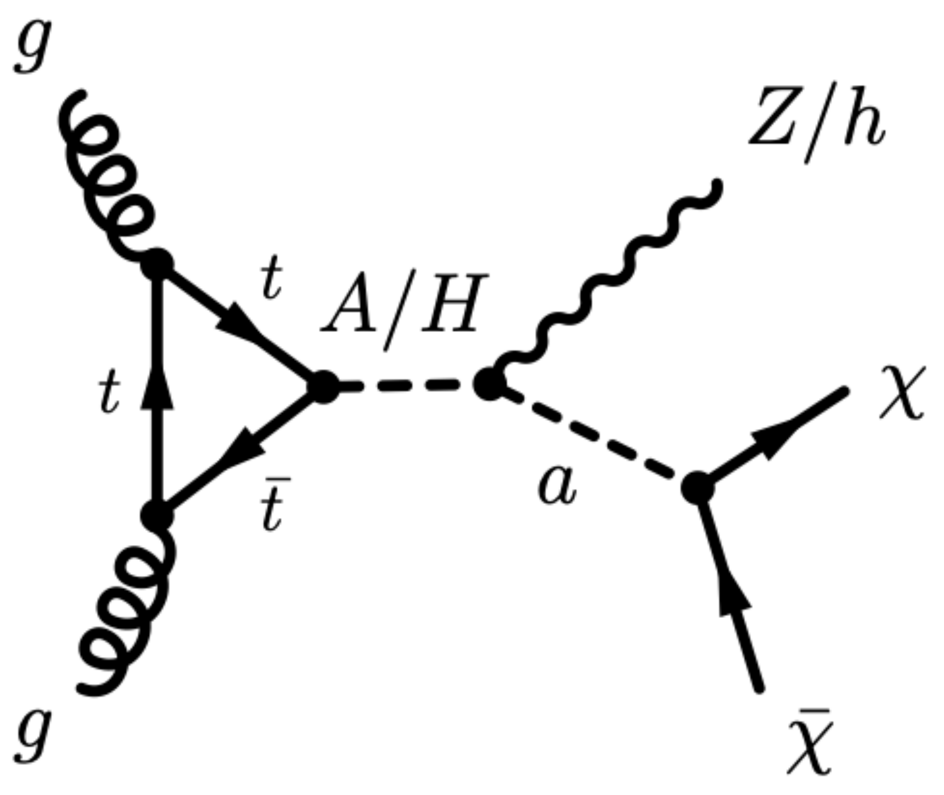


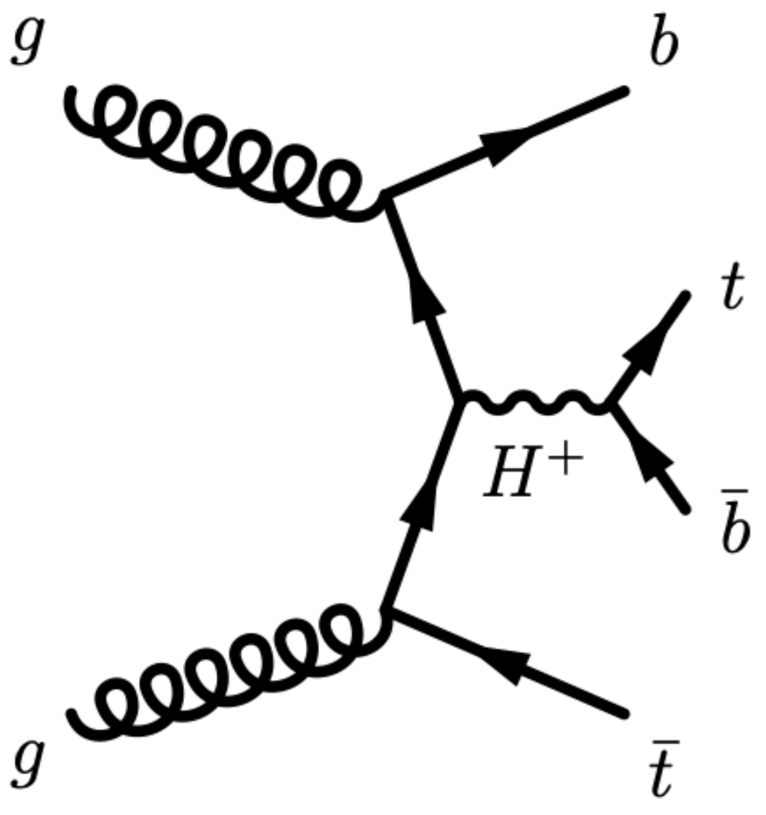
$t\bar{t}t\bar{t}$



$h \to aa \to 4f$ or $h \to$ inv

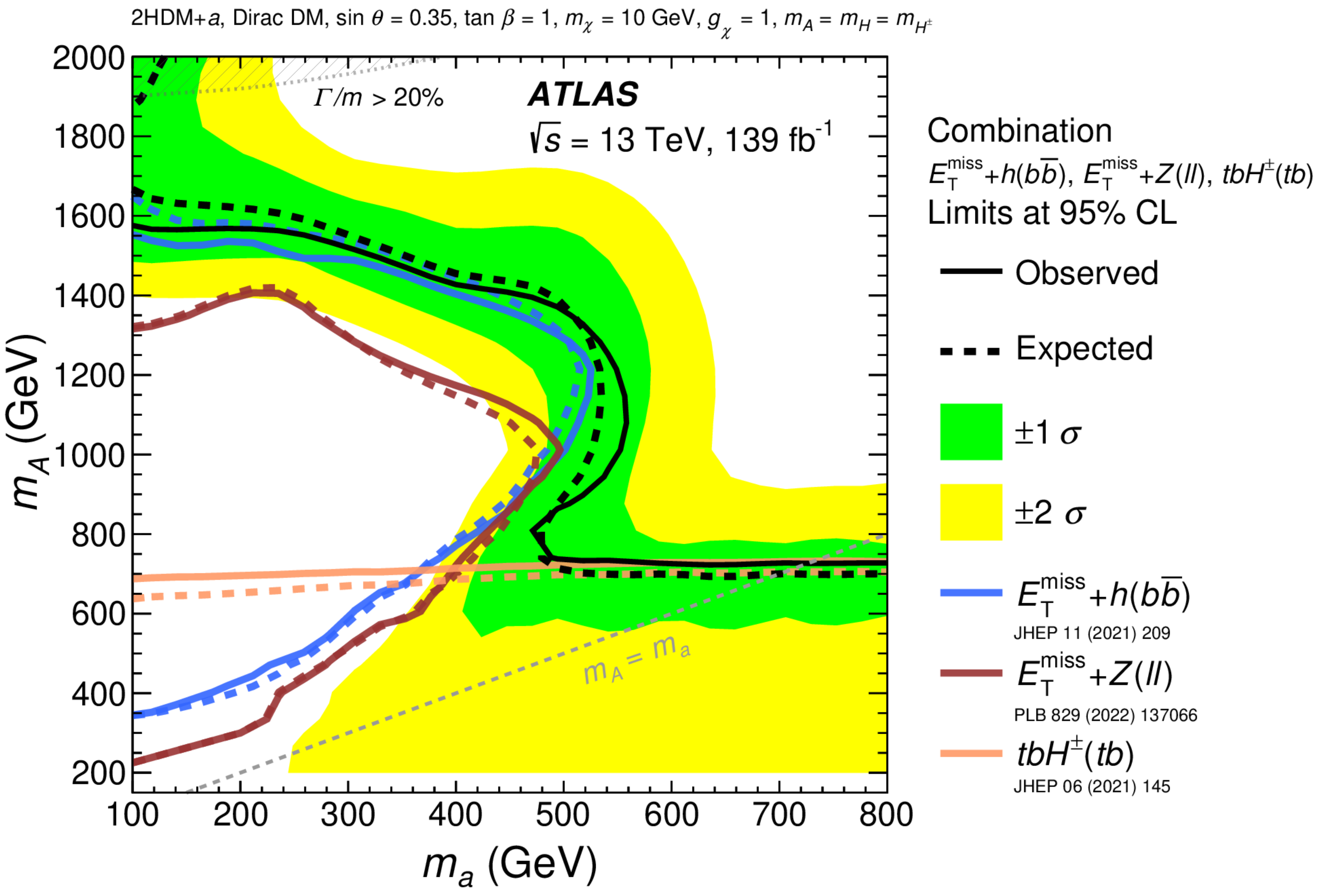
Experimental signatures





- Most constraining signatures of 2HDM+a
  - $E_T^{miss} + h(\to bb)$ **[JHEP 11 (2021) 209]**
  - $E_T^{miss} + Z(\to \ell\ell)$ **[PLB 829 (2022) 137066]**
  - $tbH^{\pm}(tb)$ **[JHEP 06 (2021) 145]**

- $tbH^{\pm}(tb)$ gives significant complementarity to sensitivities of $E_T^{miss} + X$

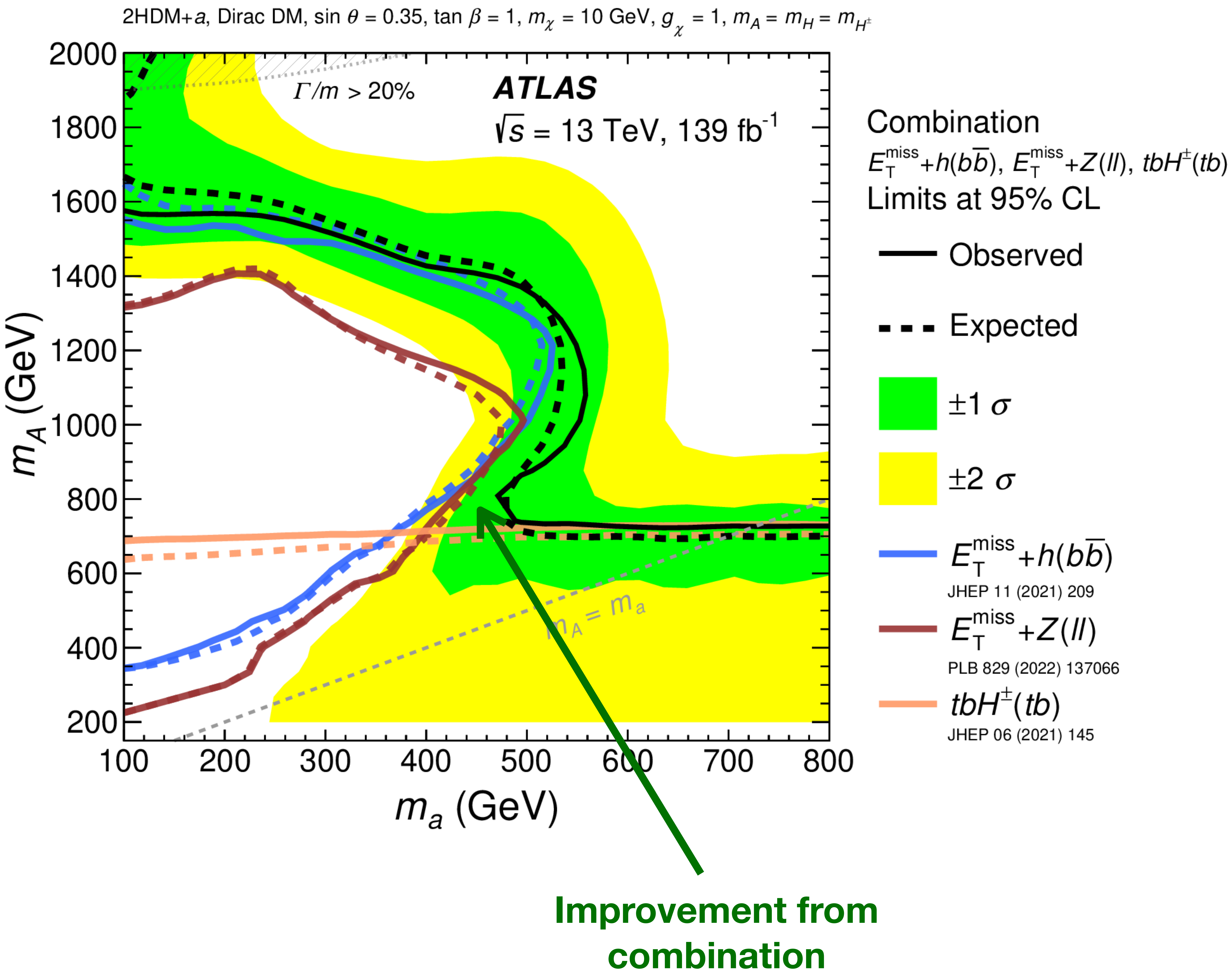


Statistical combination

- Stat. combination of 3 channels to maximize 2HDM+a constraints in parameter space.

- Combined upper limits obtained from **likelihood function** - product of **likelihoods from 3 input channels**, using profile-likelihood-ratio test with ***CLs method*** following ***asymptotic formulae***.

- Syst. uncertainties correlated where appropriate except those from modelling and those over-constrained / pulled in individual channels.



Summary of constraints on 2HDM+a

- Constraints on 2HDM+a interpreted in **6 benchmark scenarios**.
  - Highlight diverse phenomenology of 2HDM+a.
  - Study the interplay and complementarities between different signatures.

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

(m_a, m_A) → shows interplay due to mass hierarchies

$(m_A, \tan\beta)$, $(m_a, \tan\beta)$ → motivated by similar scans done for general 2HDMs

$\sin\theta$ → illustration a-A mixing parameter effect

m_χ → connection with cosmological constraints and direct/indirect searches

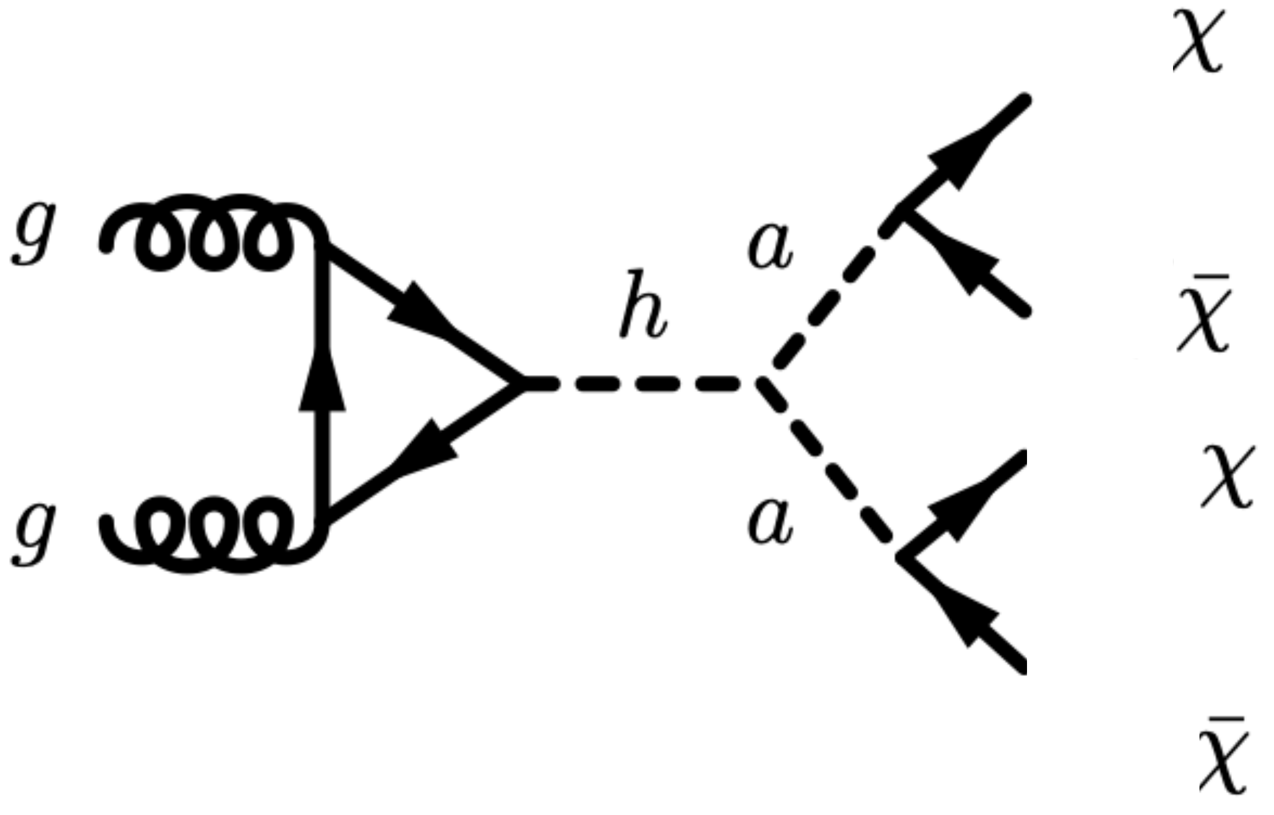
(m_a, m_χ) → showed for the 1st time

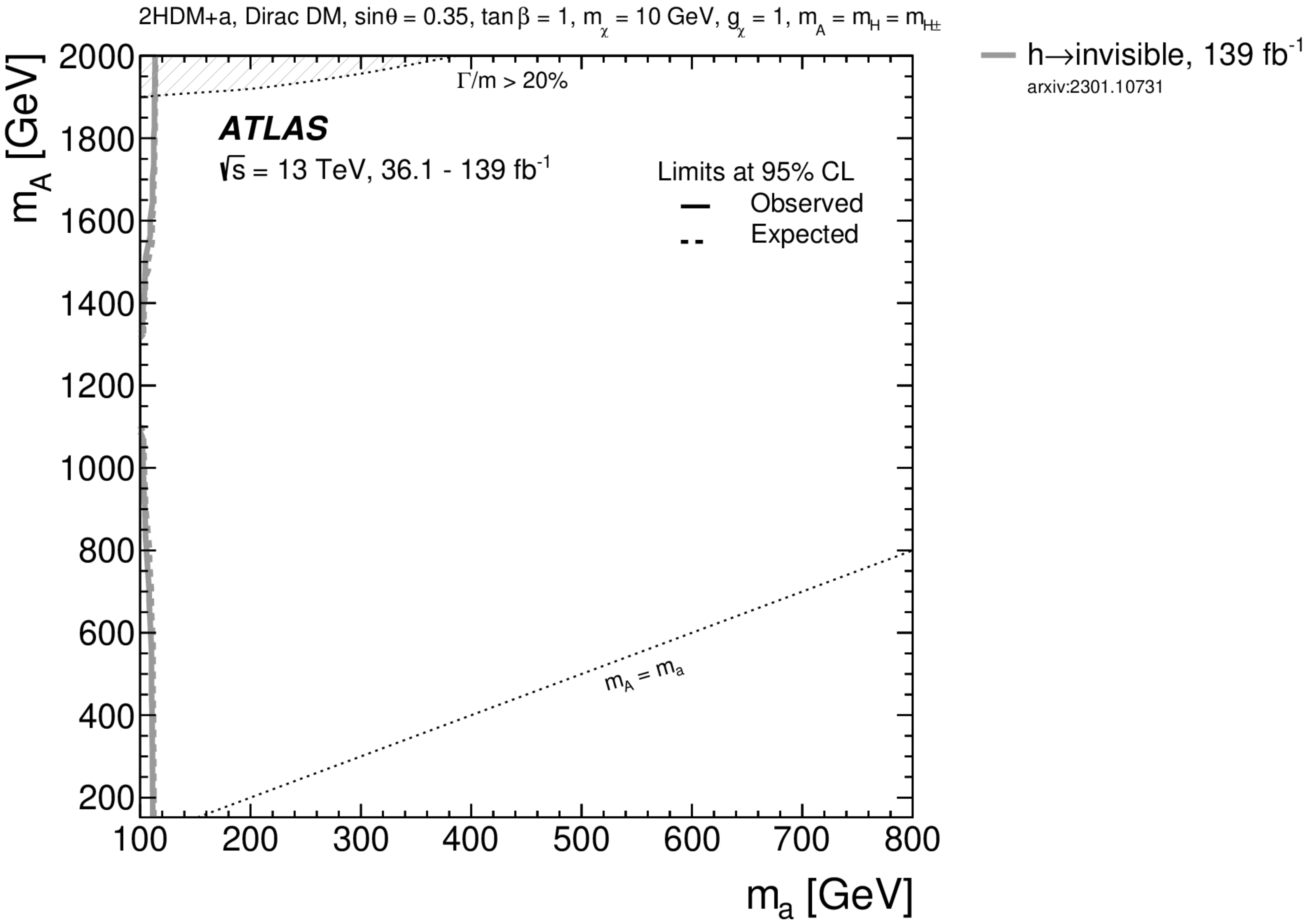
m_χ set to 10 GeV in all scenarios, except 5 and 6

Summary of constraints on 2HDM+a

Scenario 1a: $\sin\theta = 0.35$, $\tan\beta = 1$, m_a-m_A scan

- $h \to$ invisible constrains very low m_a.

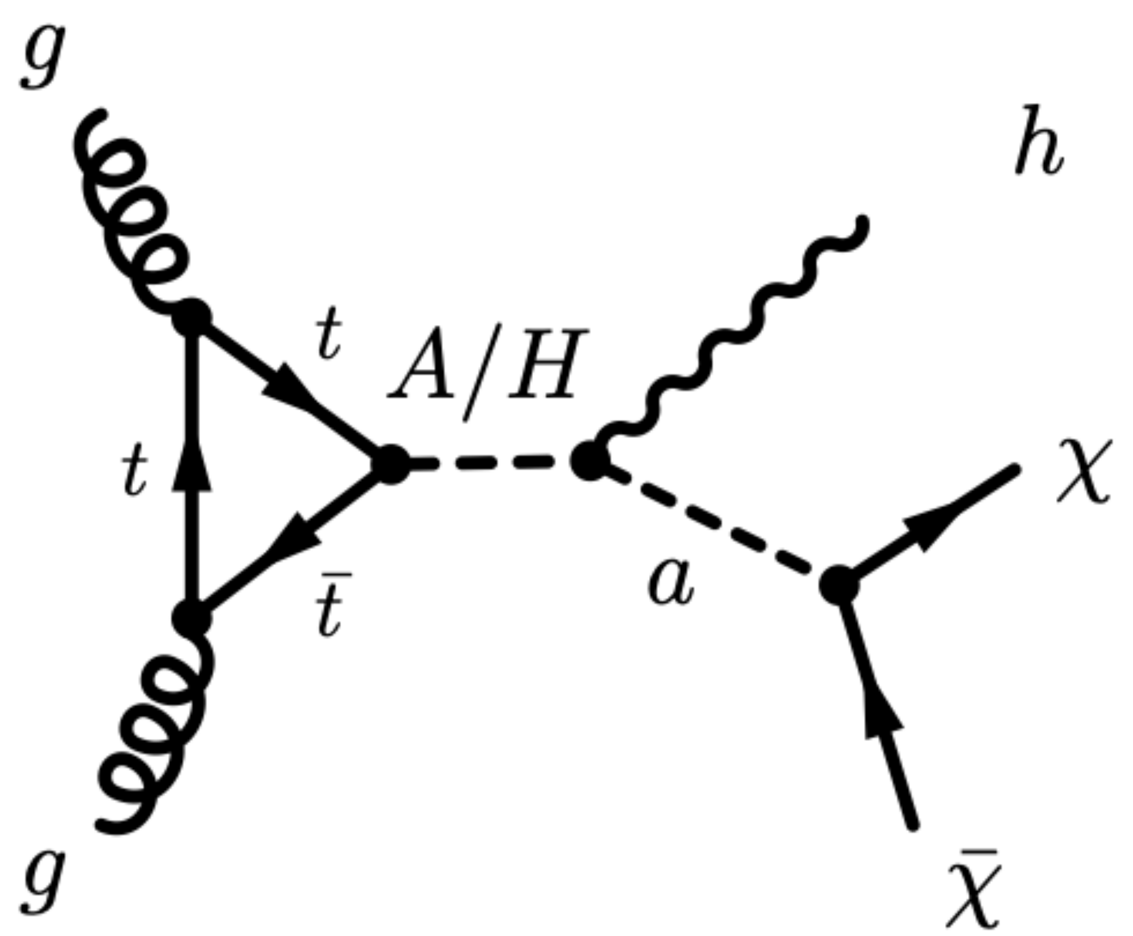


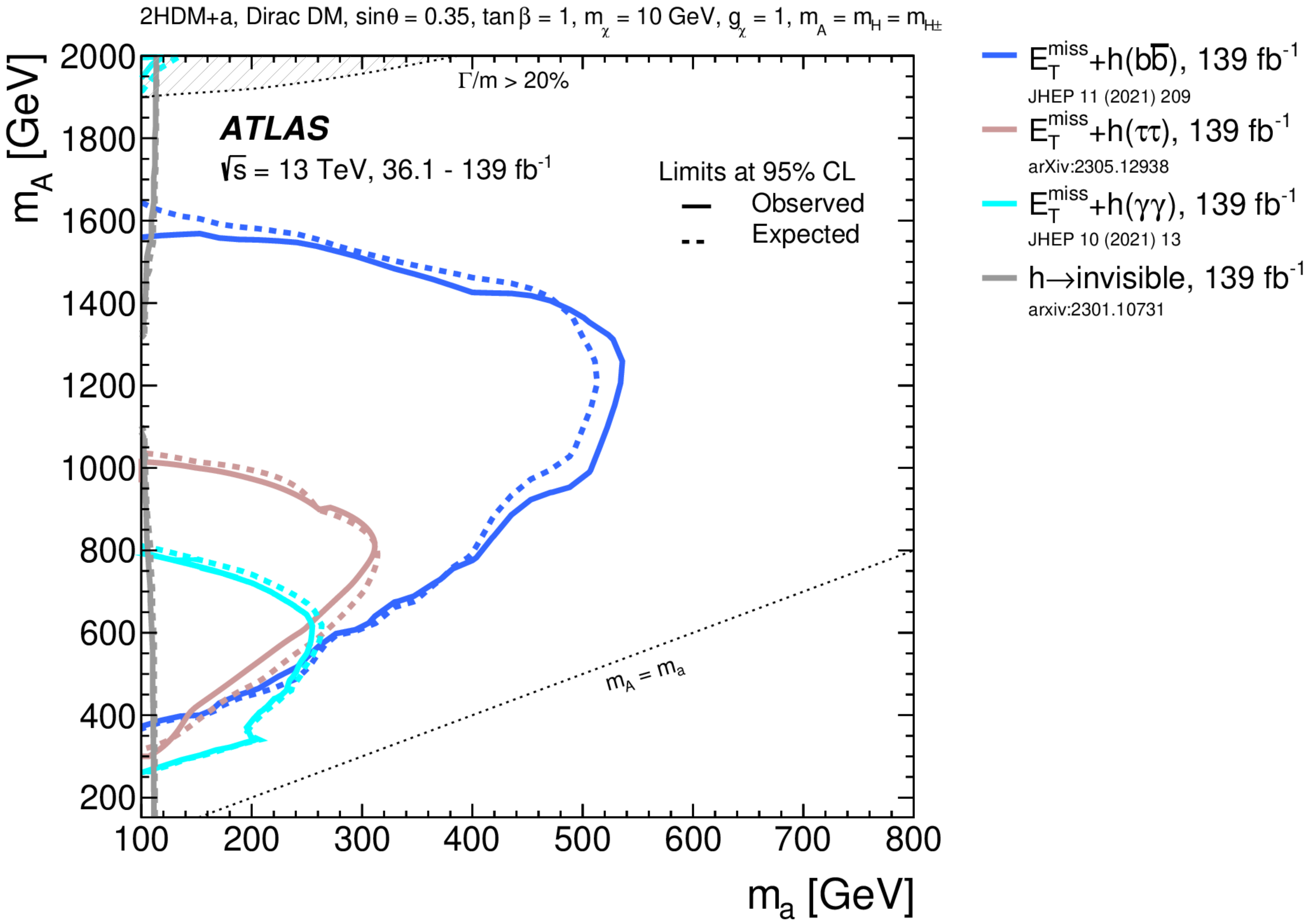


Summary of constraints on 2HDM+a

Scenario 1a: $\sin\theta = 0.35$, $\tan\beta = 1$, m_a-m_A scan

- Constraints from $E_{\mathrm{T}}^{\mathrm{miss}} + h$ signatures: similar m_A-m_a dependence, with $h \to bb$ most sensitive.

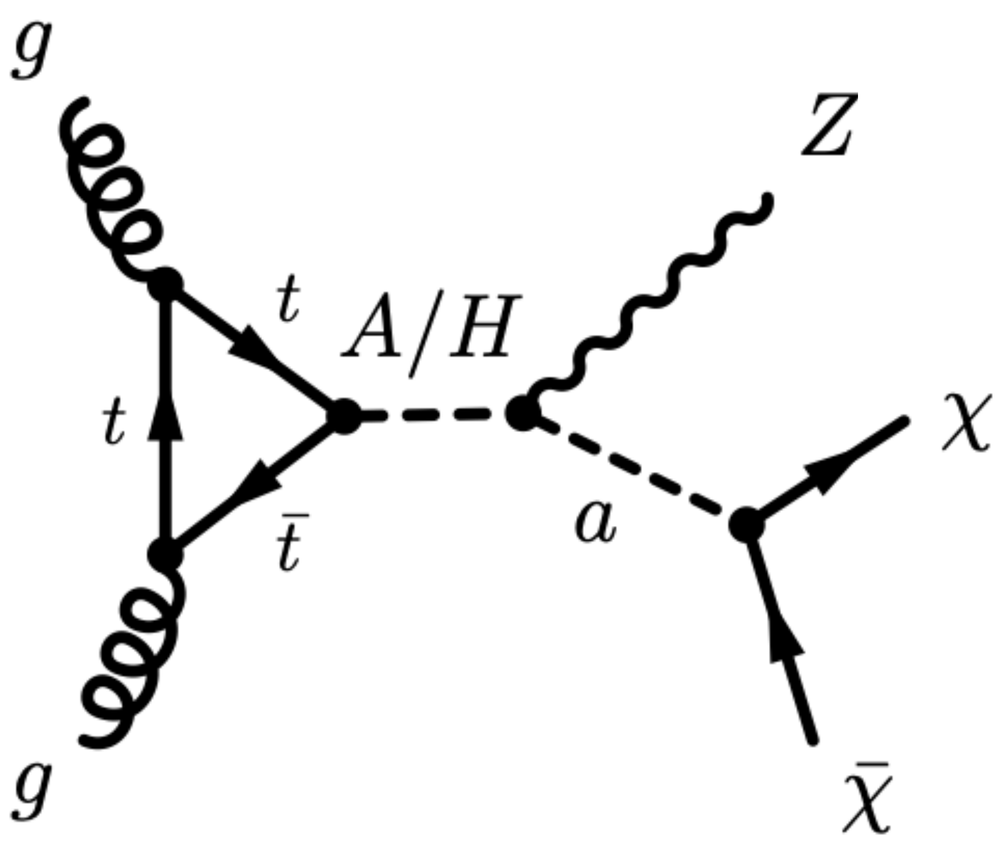


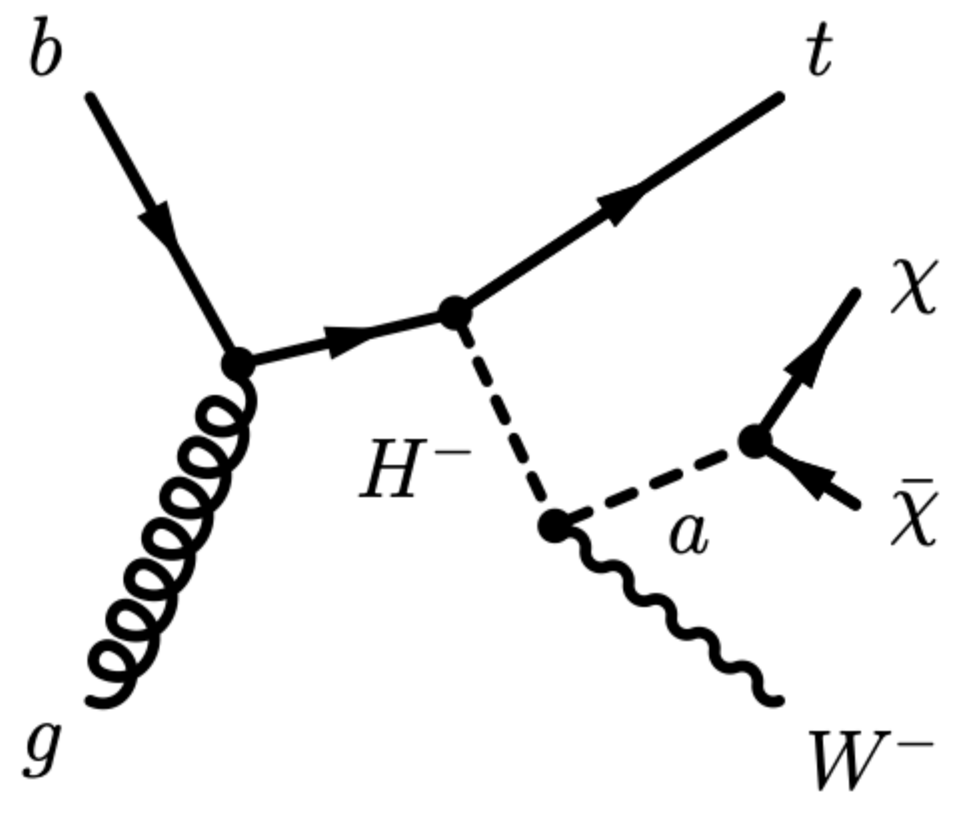


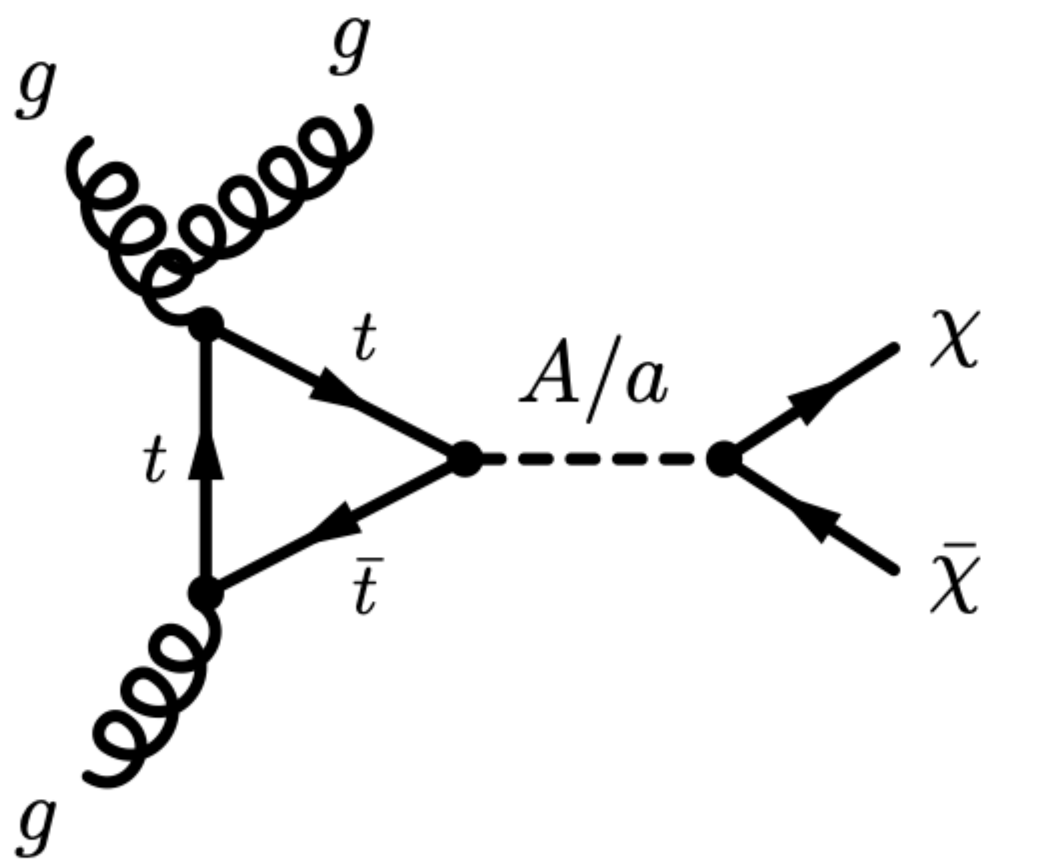
Summary of constraints on 2HDM+a

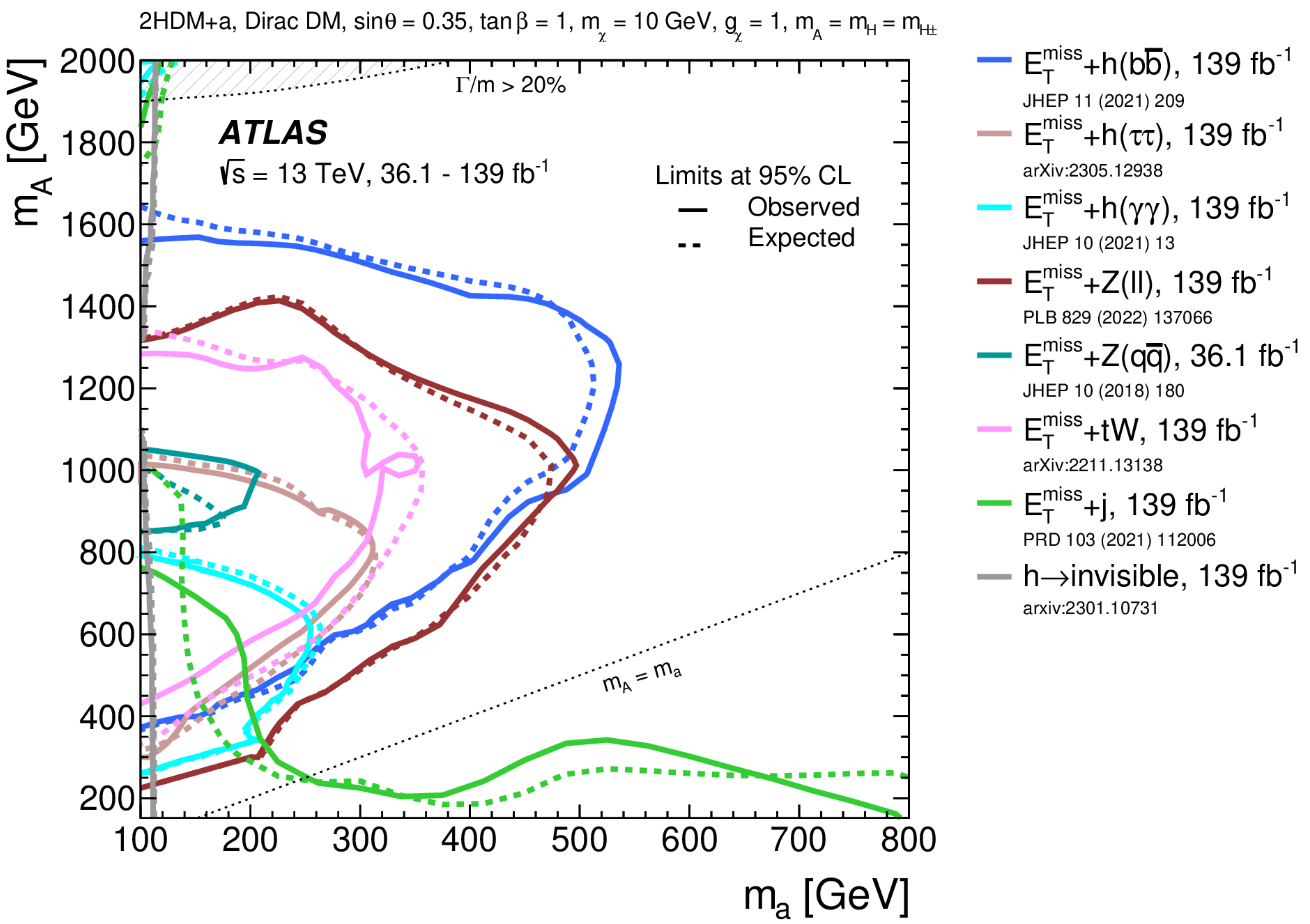
Scenario 1a: $\sin\theta = 0.35$, $\tan\beta = 1$, m_a-m_A scan

- $E_T^{\rm miss} + Z$ and $E_T^{\rm miss} + tW$ are similar while $E_T^{\rm miss} + \rm jet$ notably different.





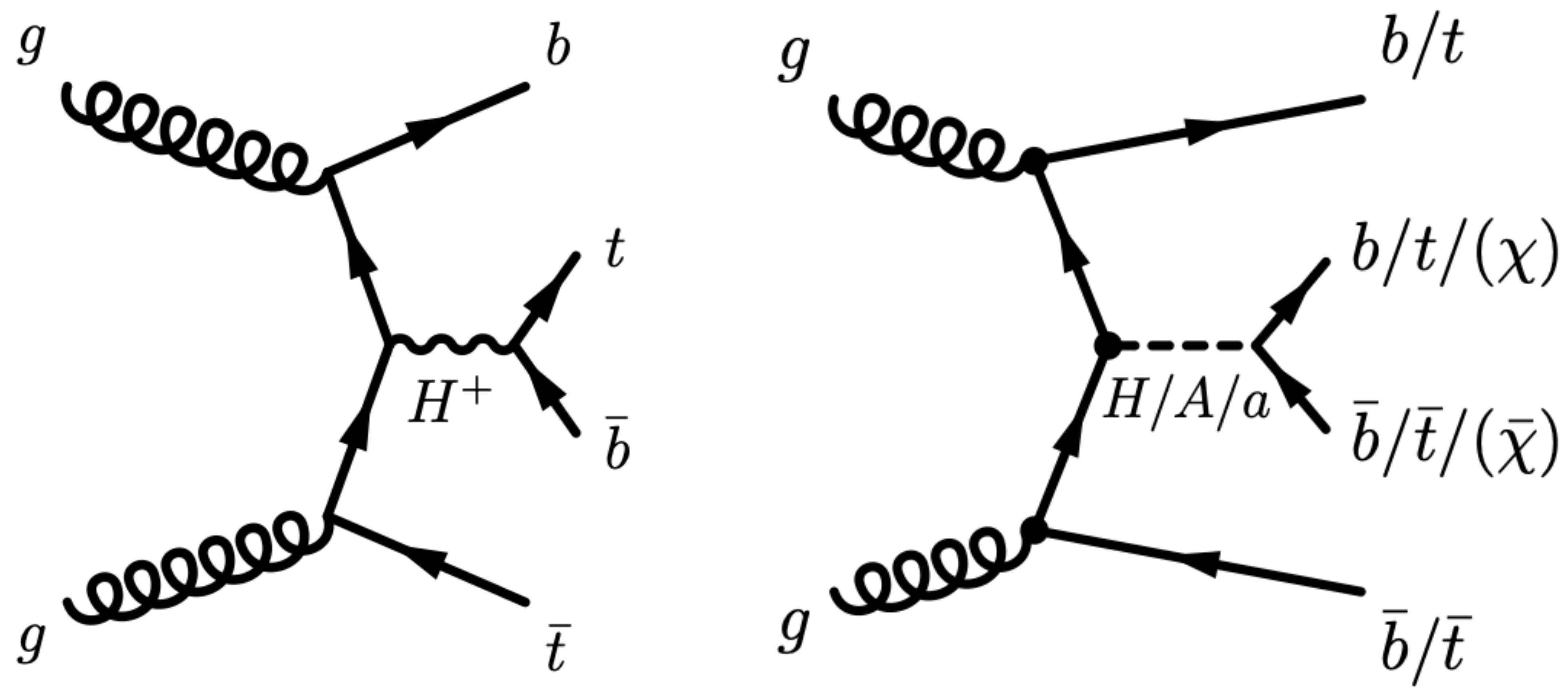


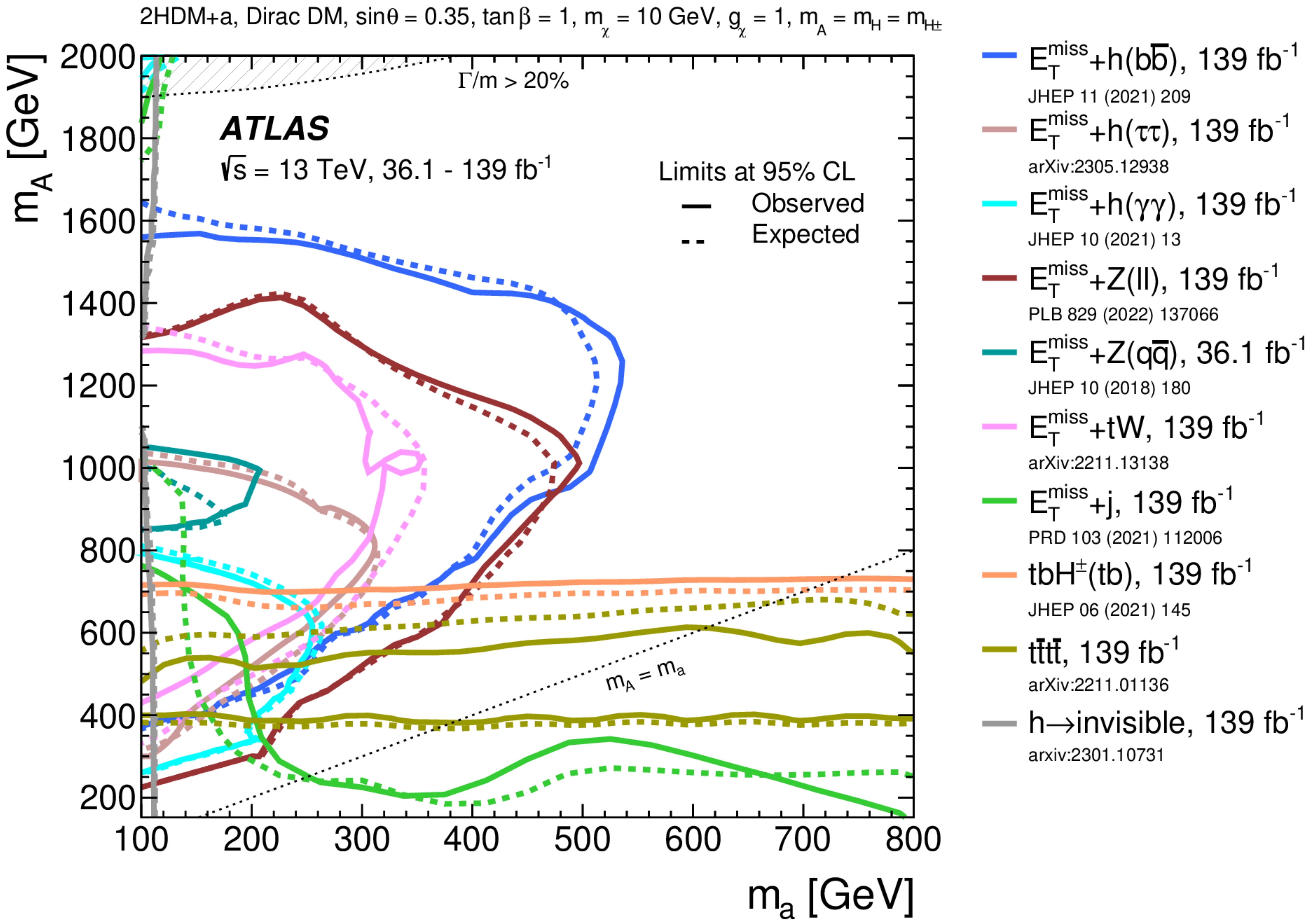


Summary of constraints on 2HDM+a

Scenario 1a: $\sin\theta = 0.35$, $\tan\beta = 1$, m_a-m_A scan

- Complementary constraints from searches not targeting DM.

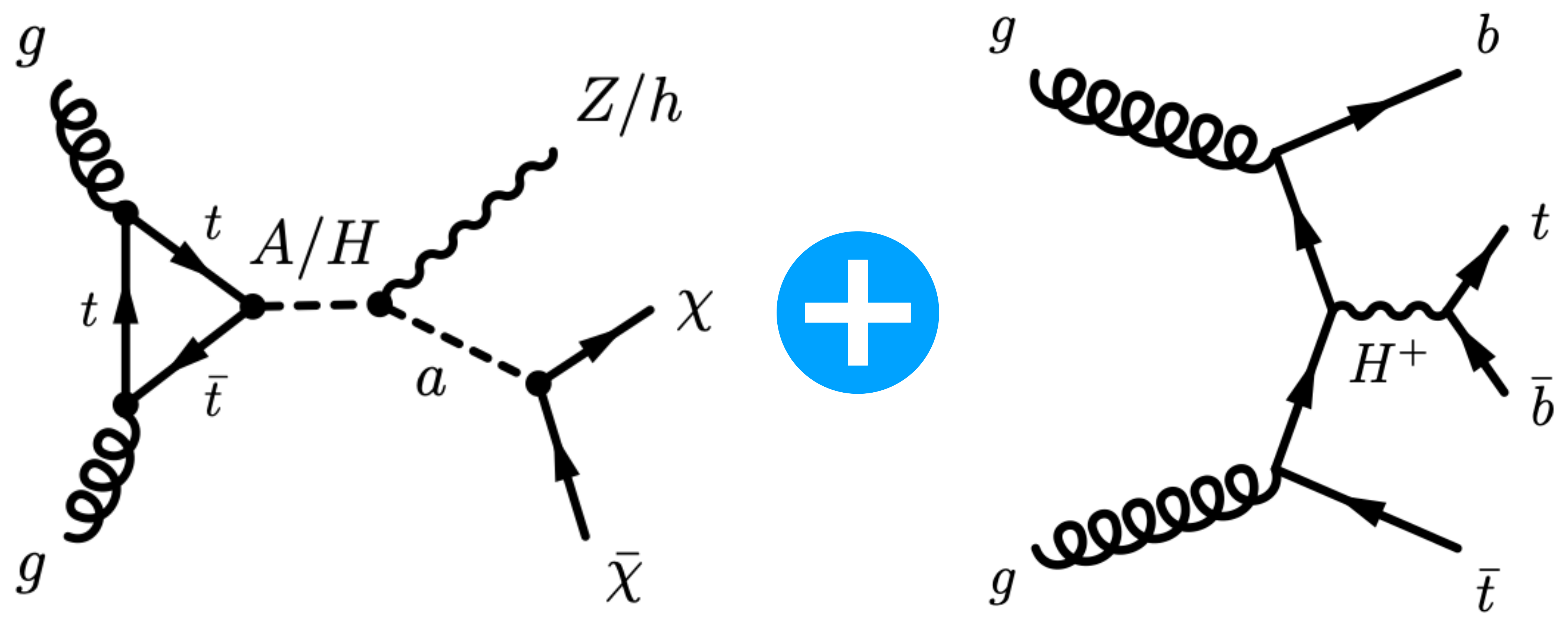




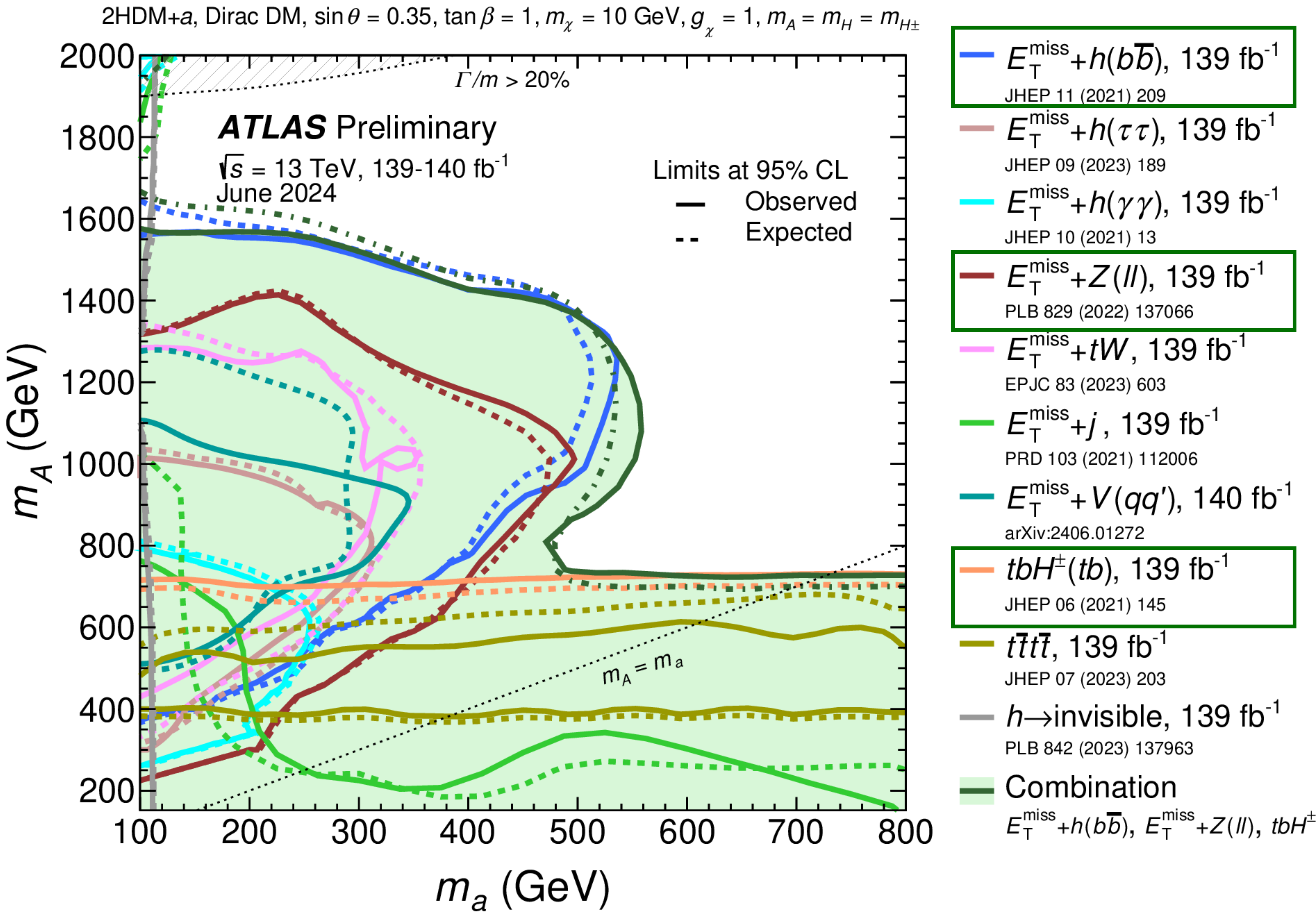
Summary of constraints on 2HDM+a

Scenario 1a: $\sin\theta = 0.35$, $\tan\beta = 1$, m_a-m_A scan

- Sensitivity of 2HDM+a driven by the combination.

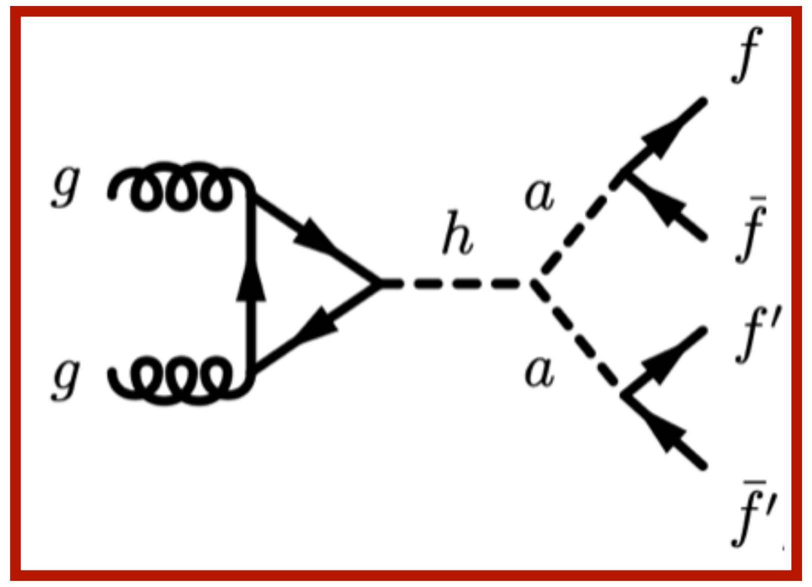


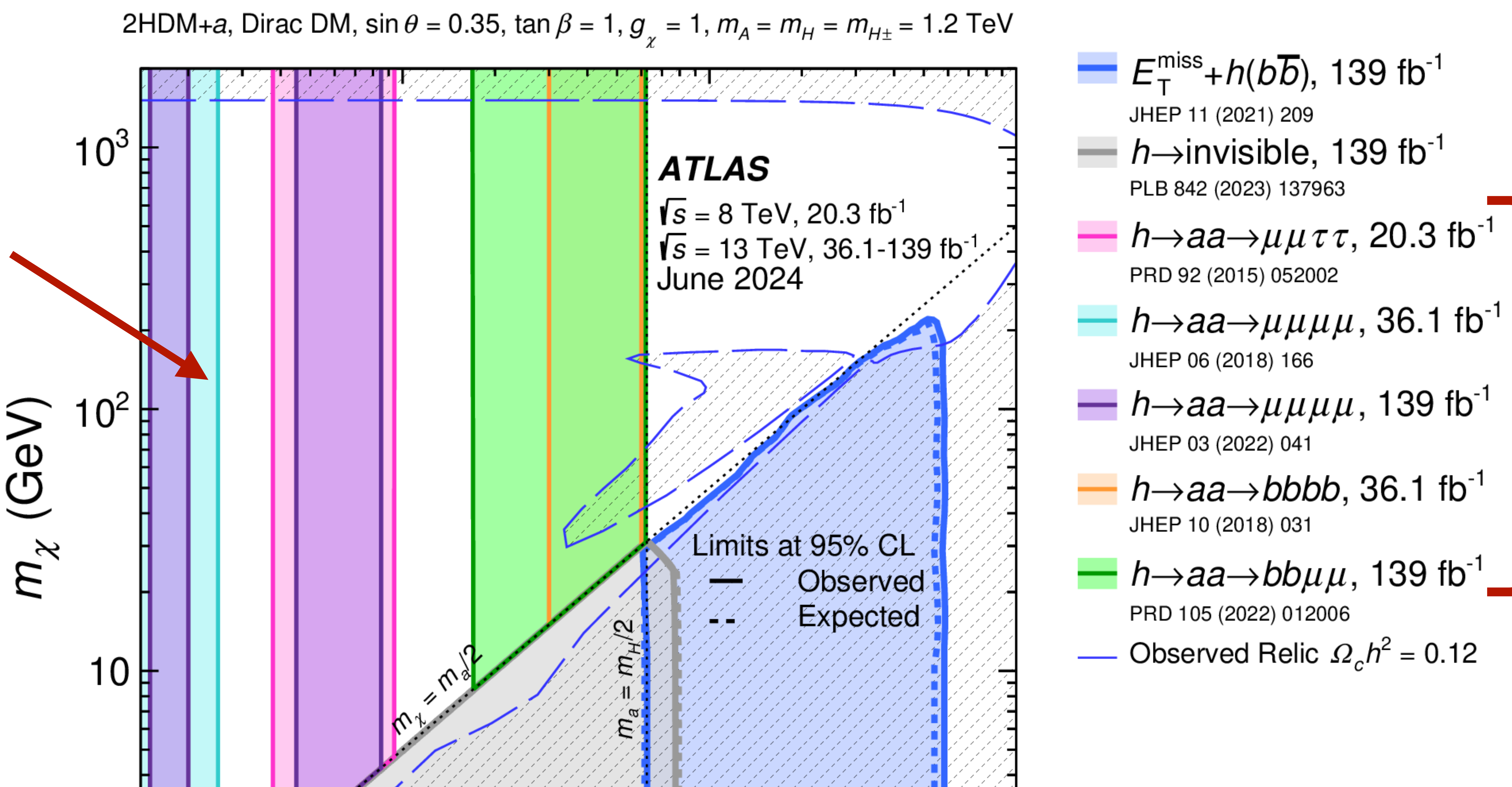
Most comprehensive set of constraints on 2HDM+a to date



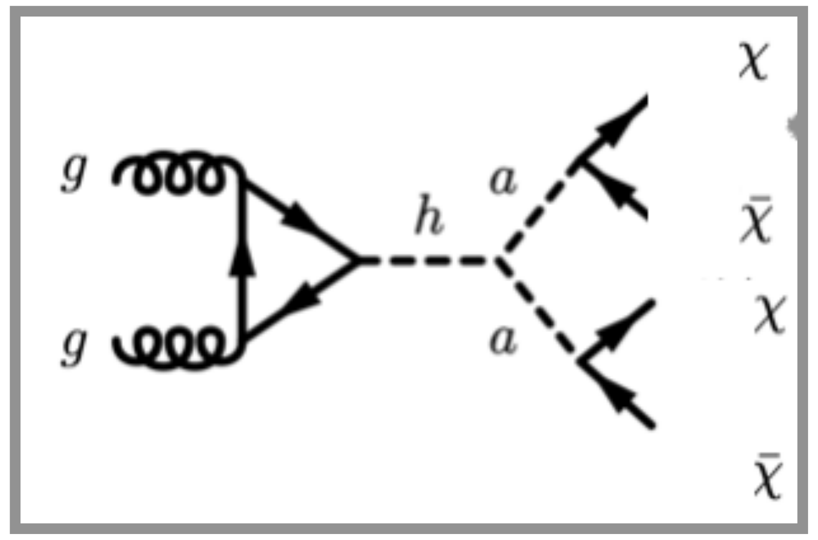
Summary of constraints on 2HDM+a

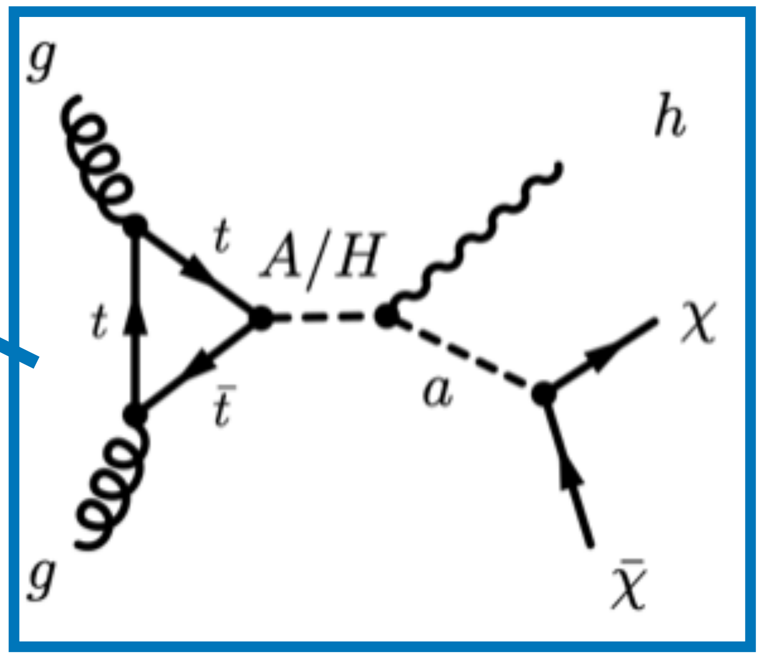
Scenario 6: $\sin\theta = 0.35$, $\tan\beta = 1$, $m_A = 1.2$ TeV, m_a-m_χ scan





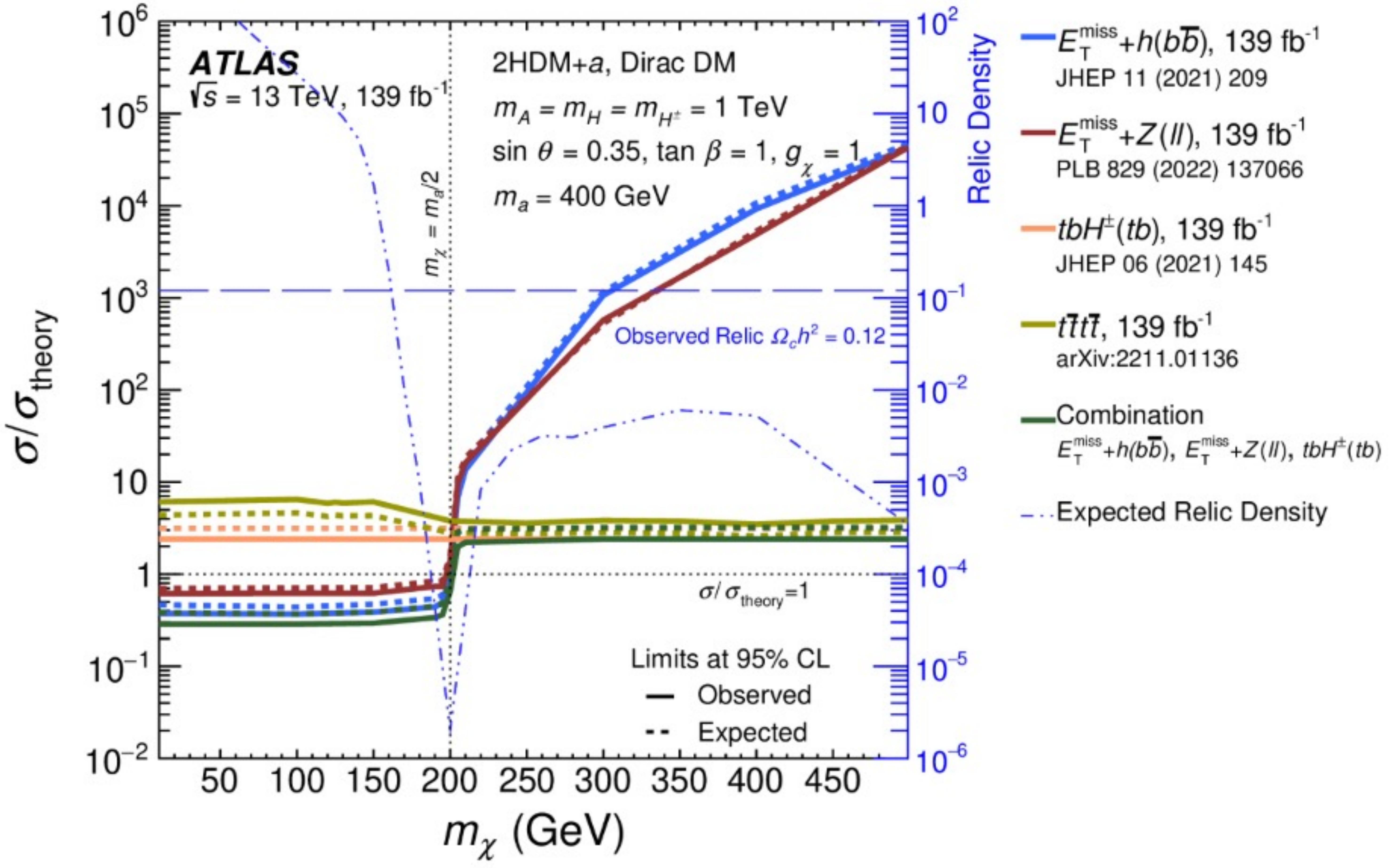
results used to constrain part of previously unprobed region where $a \nrightarrow \chi\chi$ for the 1st time



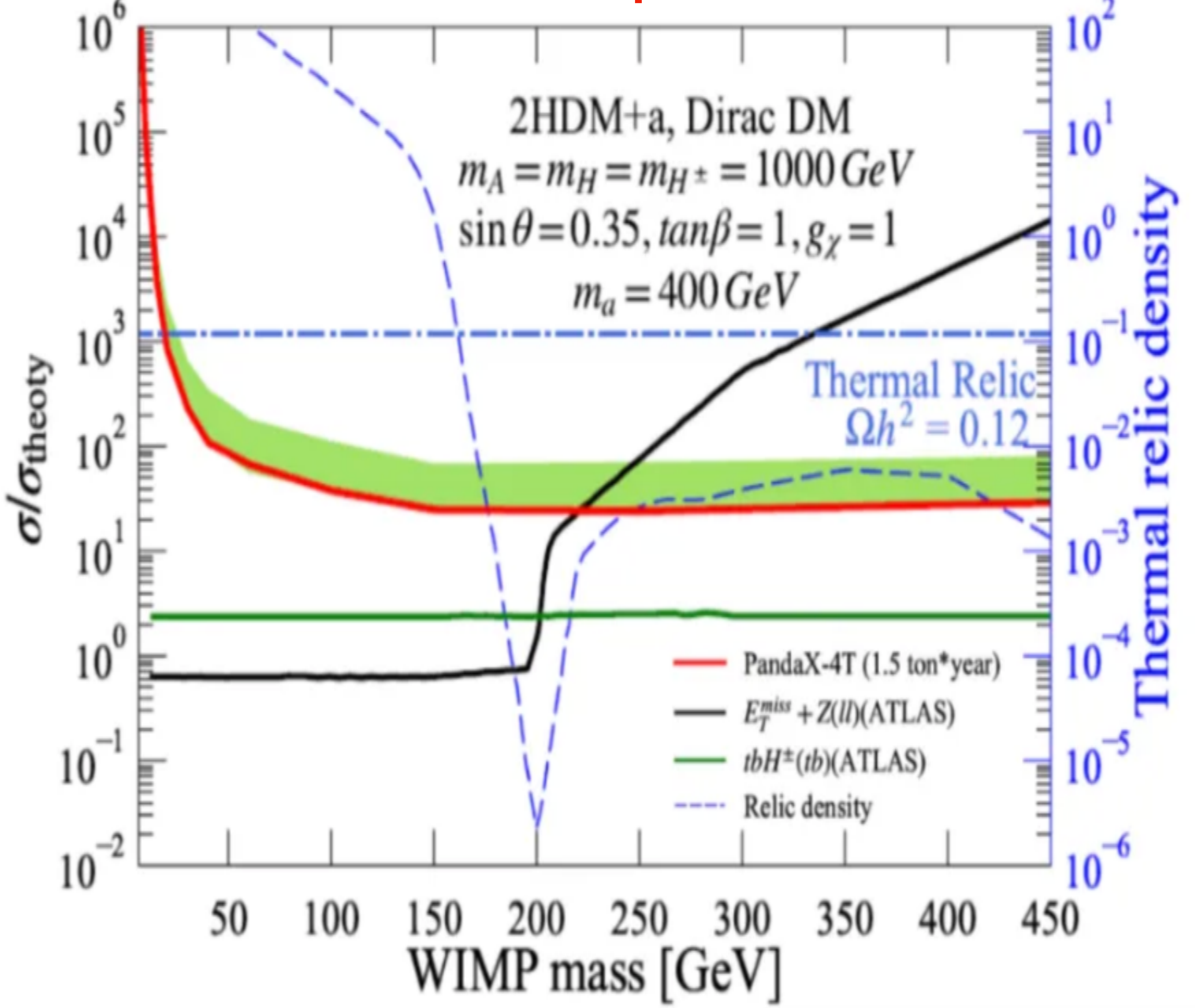


Summary of constraints on 2HDM+a

Scenario 5: $\sin\theta = 0.35$, $\tan\beta = 1$, $m_a = 400$ GeV, m_χ scan



Comparison with Direct Detection Experiment



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

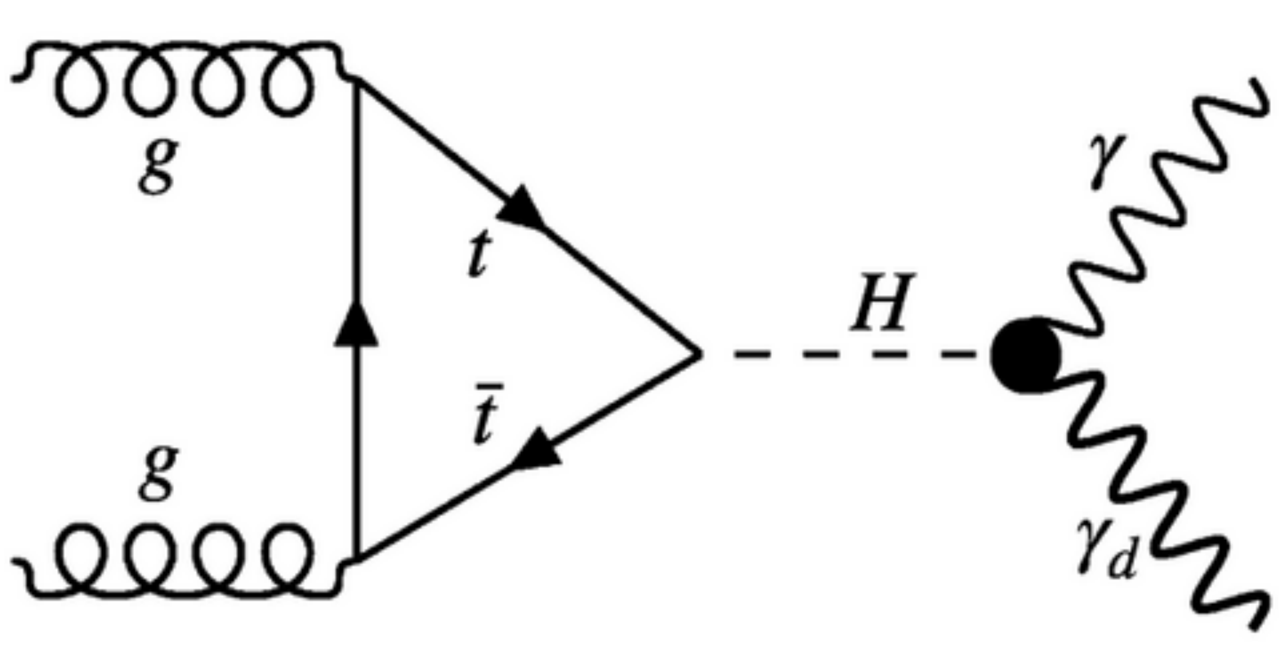
PART 02

NEW Combination of ATLAS searches for Higgs boson decays into a photon and a massless dark photon

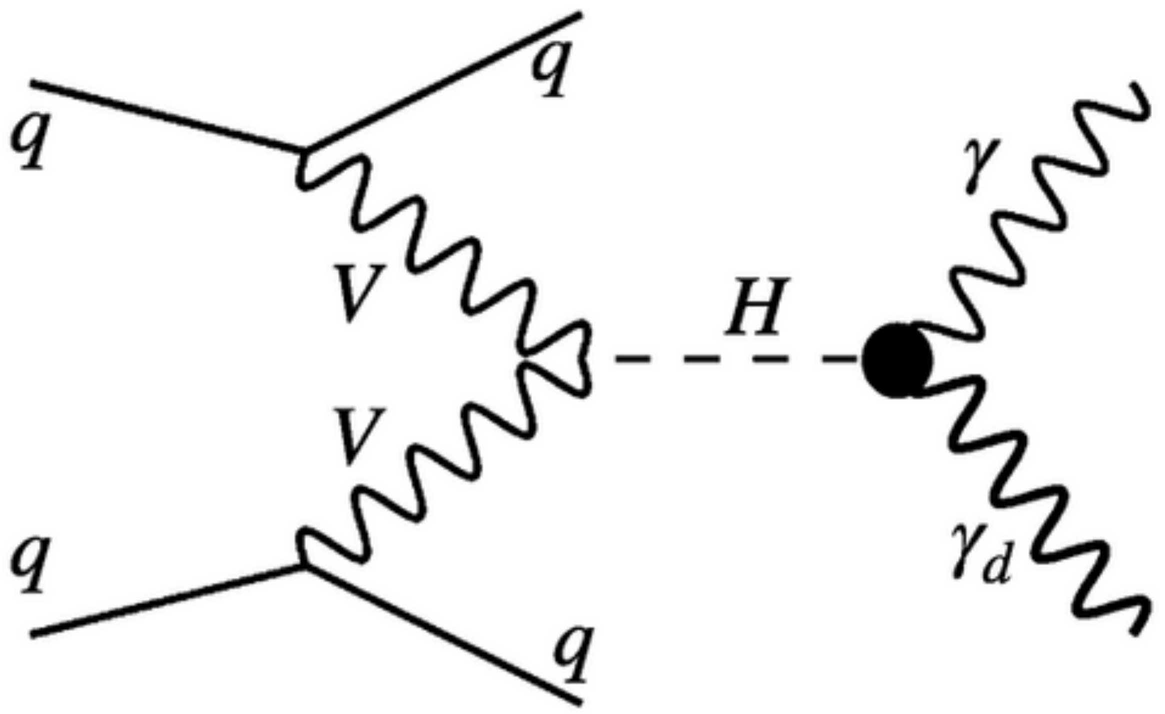
Massless dark photon

- Undetected Higgs decay $\mathscr{B}_{\mathrm{u.}} < \mathcal{O}(10\%)$ from *ATLAS* and *CMS* motivates searches for elusive BSM dark sector particles coupled to Higgs. One attractive candidate is undetectable, massless dark photon (γ_{d}).
  - Force carrier of extra $U(1)_{\mathrm{d}}$ gauge symmetry of dark sector.
  - Introducing dark matter self-interactions for solving *small-scale structure formation problem* and *PAMELA-Fermi-AMS2 anomaly*.
  - Enhancing light DM annihilation rate, making *asymmetric DM scenarios* phenomenologically viable.

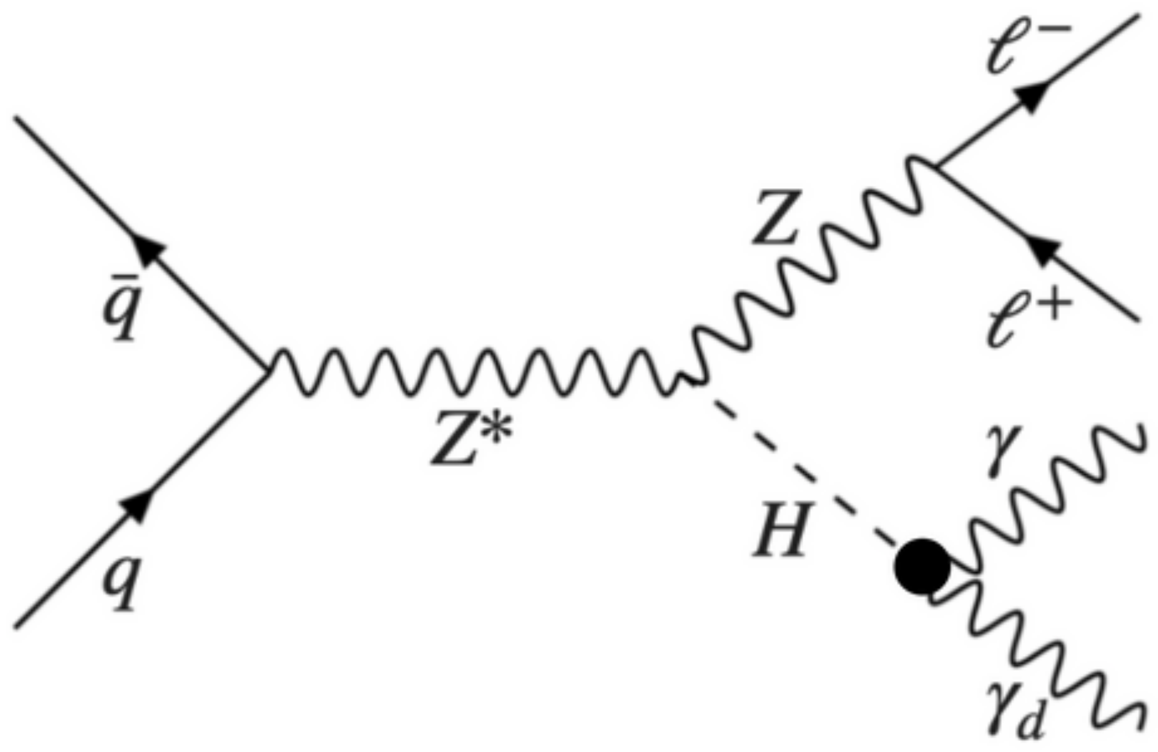
- Potential approach is search for $H \to \gamma\gamma_{\mathrm{d}}$ in resonant $\gamma + E_{\mathrm{T}}^{\mathrm{miss}}$ signatures via three Higgs production modes



ggF process



VBF process



ZH process

Recent $H \to \gamma\gamma_d$ searches

⭐ "Process" refers to production mode
⭐ "Channel" refers to selection topology

❖ Both ATLAS and CMS published various results for $H \to \gamma\gamma_d$ searches in distinct final states using LHC full Run 2 data:

	$\gamma + E_T^{miss}$ (ggF channel)	$\gamma + E_T^{miss}$ + VBF jets (VBF channel)	$\gamma + E_T^{miss} + Z(\to \ell\ell)$ (*ZH* channel)
ATLAS	reinterpretation of mono-γ	EPJC 82 (2022) 105	JHEP 07 (2023) 133
CMS	--	JHEP 03 (2021) 011	JHEP 10 (2019) 139; JHEP 03 (2021) 011

$H_{125} \to \gamma\gamma_d$

	ZH channel	VBF channel	Combined
ATLAS	2.3 (2.8) %	1.8 (1.7) %	This analysis
CMS	4.6 (3.6) %	3.5 (2.8) %	2.9 (2.1) %

95% CL limit on BR

$H_{BSM} \to \gamma\gamma_d$

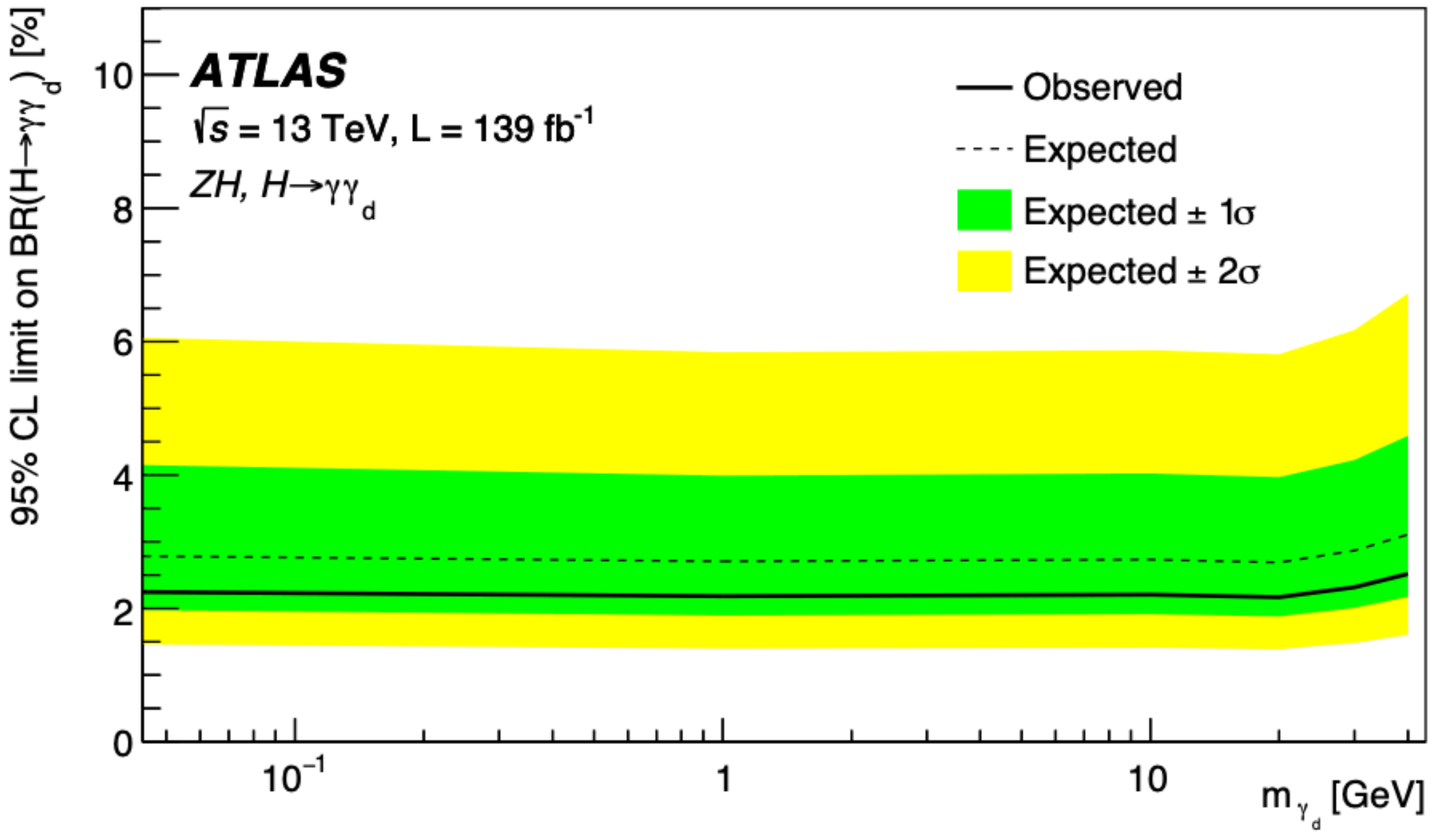
	VBF channel	ggF channel	Combined
ATLAS	Up to 2 TeV	Up to 3 TeV	This analysis
CMS	Up to 1 TeV	--	--

Mass range probed for *H*

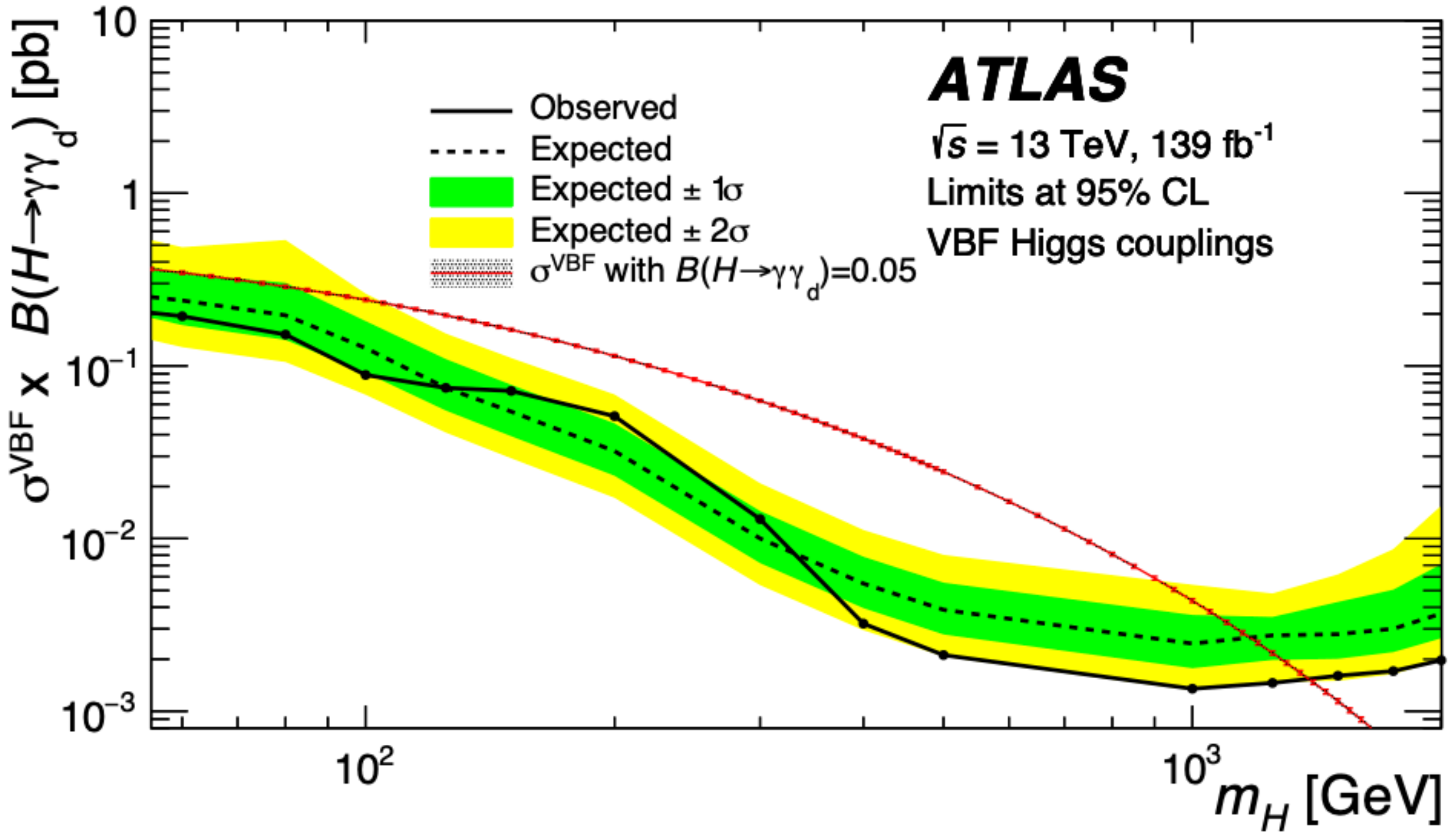
❖ ATLAS provided competitive and complementary results, strong motivation for stat. combination to bring the best LHC constraint on $H_{125} \to \gamma\gamma_d$ and broadest search in terms of BSM *H* mass (400 - 3000 GeV).

Scenarios of combination

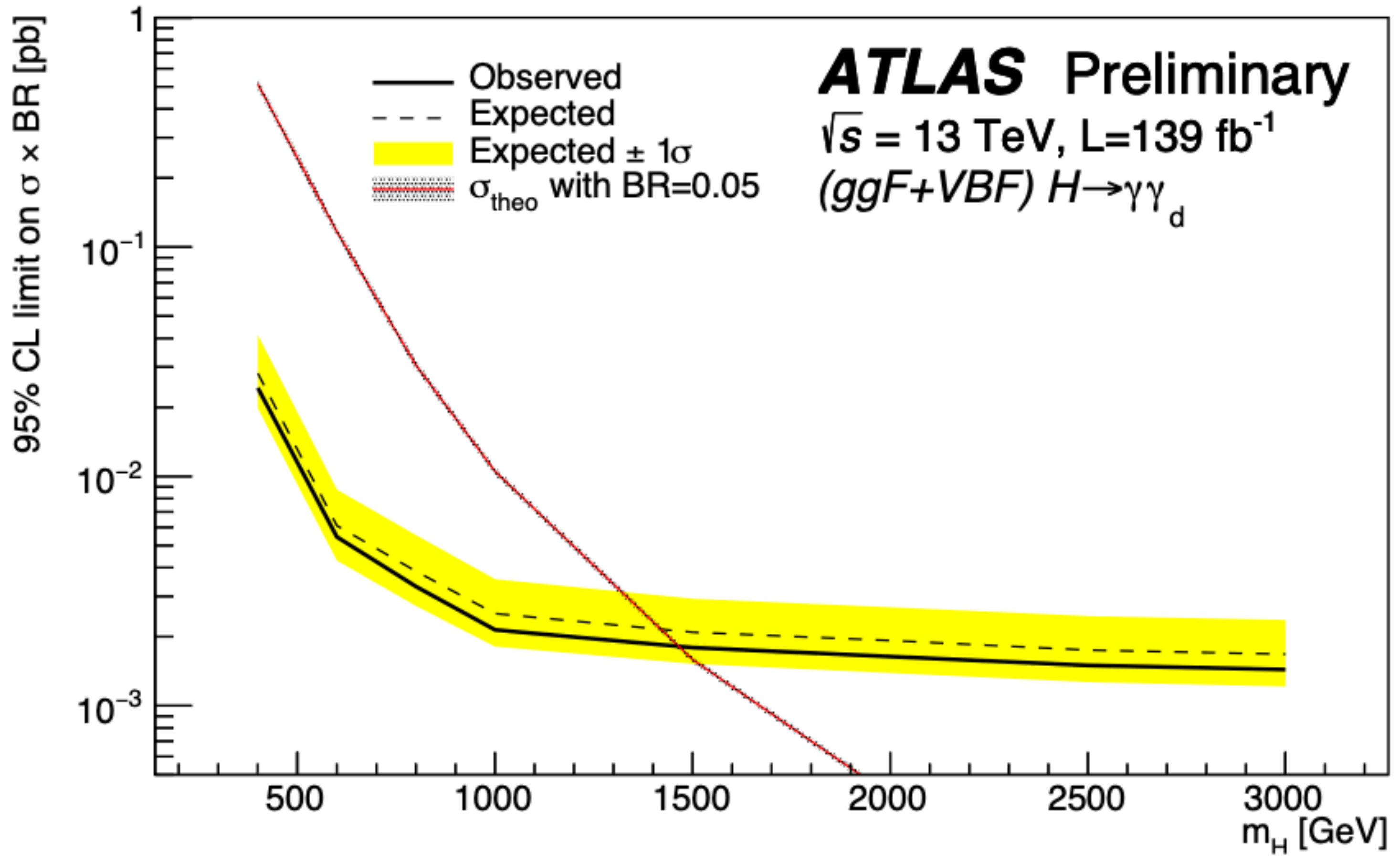
***ZH* channel**



VBF channel



ggF channel

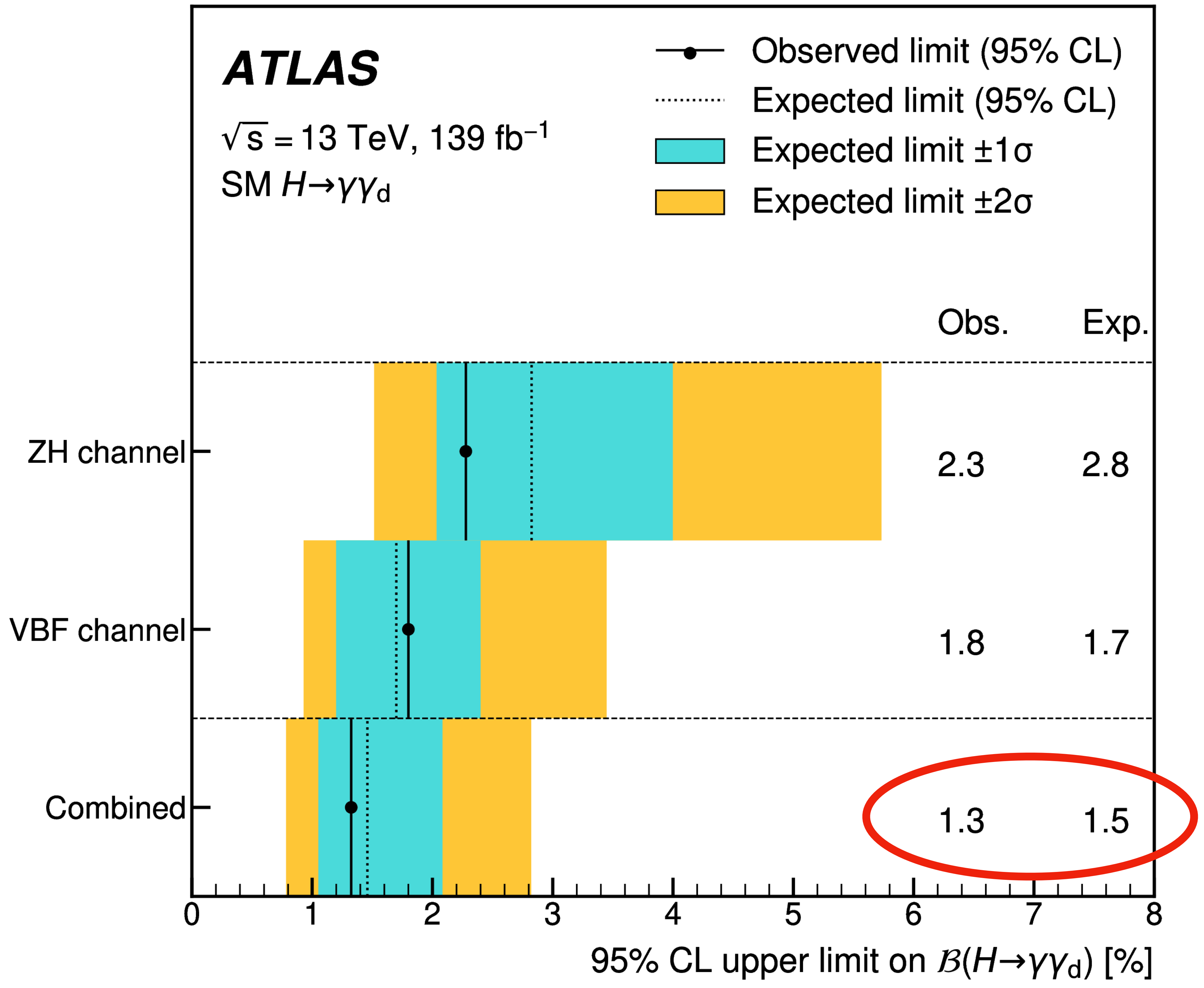


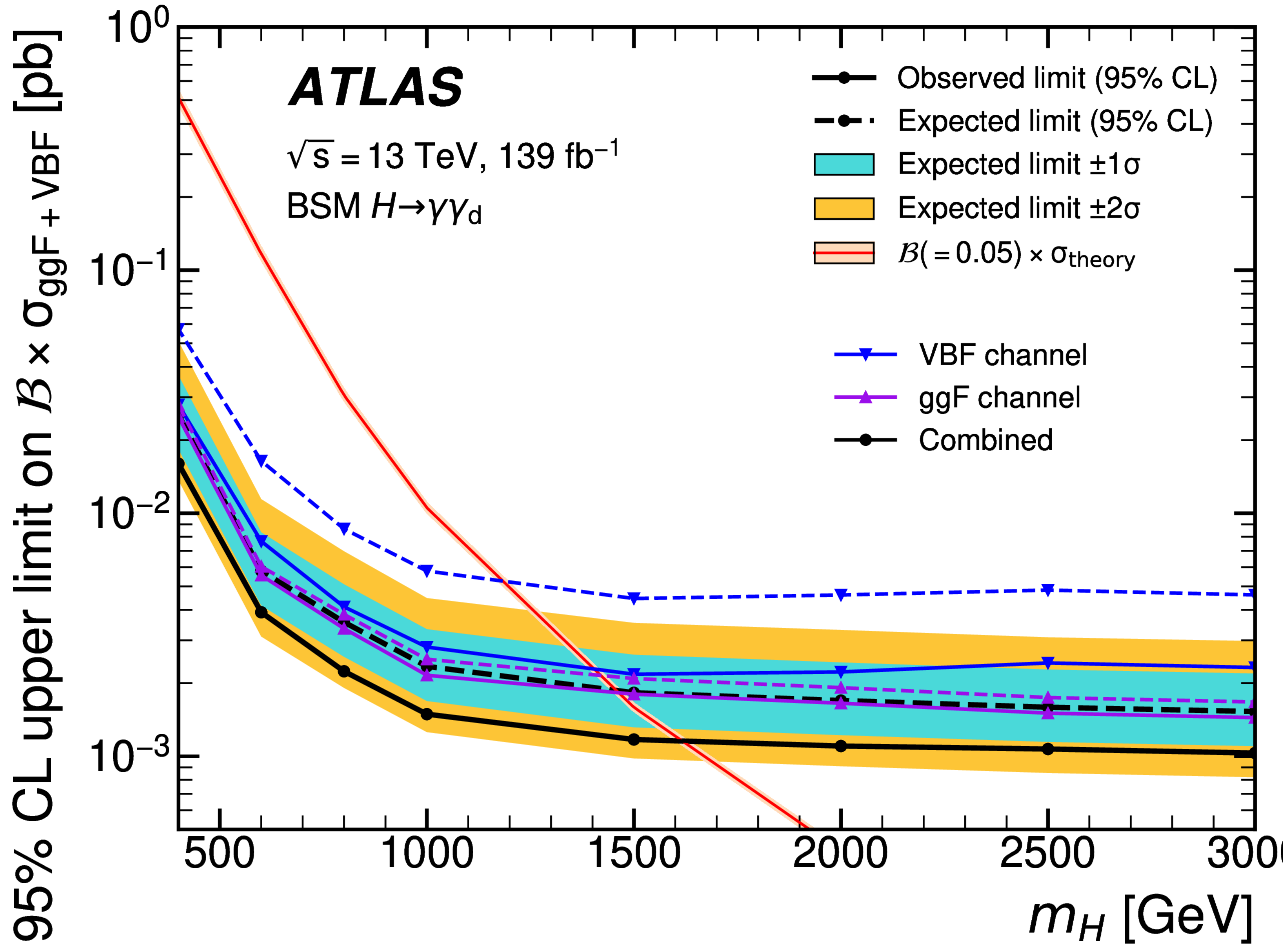
- Most straightforward and worthy scenarios for the statistical combination, based on 3 input analyses.

Input channel	Signals	m_H	m_{γ_d}	Combination scenarios
ZH	SM $(ZH)H \to \gamma\gamma_d$	125 GeV	[0, 40] GeV	**ZH + VBF** for **SM Higgs**, massless γ_d, targeting $\mathbf{BR(H125 \to \gamma\, \gamma_d)}$
VBF	SM $(ggF + VBF)H \to \gamma\gamma_d$	125 GeV	Massless γ_d	
	BSM $(VBF)H \to \gamma\gamma_d$	[60, 2000] GeV	Massless γ_d	**ggF + VBF** for **Heavy Higgs**, massless γ_d, targeting $\boldsymbol{\sigma(ggF + VBF)\times BR(H \to \gamma\gamma_d)}$
ggF	BSM $(ggF + VBF)H \to \gamma\gamma_d$	[400, 3000] GeV	Massless γ_d	

❖ For this combination, adjustments wrt original VBF channel
- ggF process contribution included for BSM Higgs decay search.
- Extend H mass to 3 TeV.

Stat. combination -- Results





- ❖ VBF-*ZH* combination set strongest limit on $\mathscr{B}(H_{125} \to \gamma\gamma_d)$ at LHC to date.
  - ◉ improved by 29% wrt VBF channel.

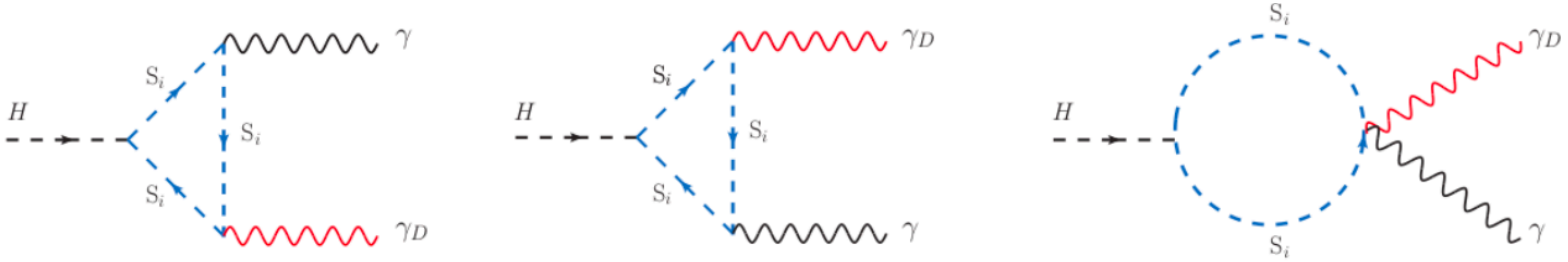
- ❖ VBF-ggF combination set most comprehensive constraints on $\sigma_{ggF+VBF} \times \mathscr{B}(H_{BSM} \to \gamma\gamma_d)$ for *H* mass up to 3 TeV.
  - ◉ improved by 33% wrt ggF channel at $m_H = 1.5$ TeV.

Physics interpretation

- VBF-*ZH* combined limit on $\mathscr{B}(H_{125} \to \gamma\gamma_\mathrm{d})$ interpreted in a ***Minimal Simplified Model*** [1405.5196]
  - Generic Lagrangian: $\mathcal{L} \sim \mu \cdot H^\dagger S_L S_R + h.c. \xrightarrow{\text{EWSB}} \mathcal{L}_S^0 = \partial_\mu \hat{S}^\dagger \partial^\mu \hat{S} - \hat{S}^\dagger M_S^2 \hat{S}$
  - μ - mass parameter; S_L - $SU(2)_\mathrm{L}$ doublet; S_R - $SU(2)_\mathrm{L}$ singlet
  - Allowing $H_{125} \to \gamma\gamma_\mathrm{d}$ at 1-loop

$$\hat{S} = (S_L, S_R)$$

$$M_S^2 = \begin{pmatrix} m_L^2 & \Delta \\ \Delta & m_R^2 \end{pmatrix}$$



- BR of $H \to \gamma\gamma_\mathrm{d}$ / $\gamma_\mathrm{d}\gamma_\mathrm{d}$ / $\gamma\gamma$ can be expressed as functions of $U(1)_\mathrm{d}$ fine-structure-constant α_d and mixing parameter ξ

$$\mathrm{BR}_{\gamma\gamma_\mathrm{D}} = \mathrm{BR}_{\gamma\gamma}^{\mathrm{SM}} \frac{r_{\gamma\gamma_\mathrm{D}}}{1 + r_{\gamma_\mathrm{D}\gamma_\mathrm{D}} \mathrm{BR}_{\gamma\gamma}^{\mathrm{SM}}}$$

$$\mathrm{BR}_{\gamma_\mathrm{D}\gamma_\mathrm{D}} = \mathrm{BR}_{\gamma\gamma}^{\mathrm{SM}} \frac{r_{\gamma_\mathrm{D}\gamma_\mathrm{D}}}{1 + r_{\gamma_\mathrm{D}\gamma_\mathrm{D}} \mathrm{BR}_{\gamma\gamma}^{\mathrm{SM}}}$$

$$\mathrm{BR}_{\gamma\gamma} = \mathrm{BR}_{\gamma\gamma}^{\mathrm{SM}} \frac{(1 + \chi\sqrt{r_{\gamma\gamma}})^2}{1 + r_{\gamma_\mathrm{D}\gamma_\mathrm{D}} \mathrm{BR}_{\gamma\gamma}^{\mathrm{SM}}}$$

$$r_{\gamma\gamma_\mathrm{D}} = 2X^2 \left(\frac{\alpha_D}{\alpha}\right)$$

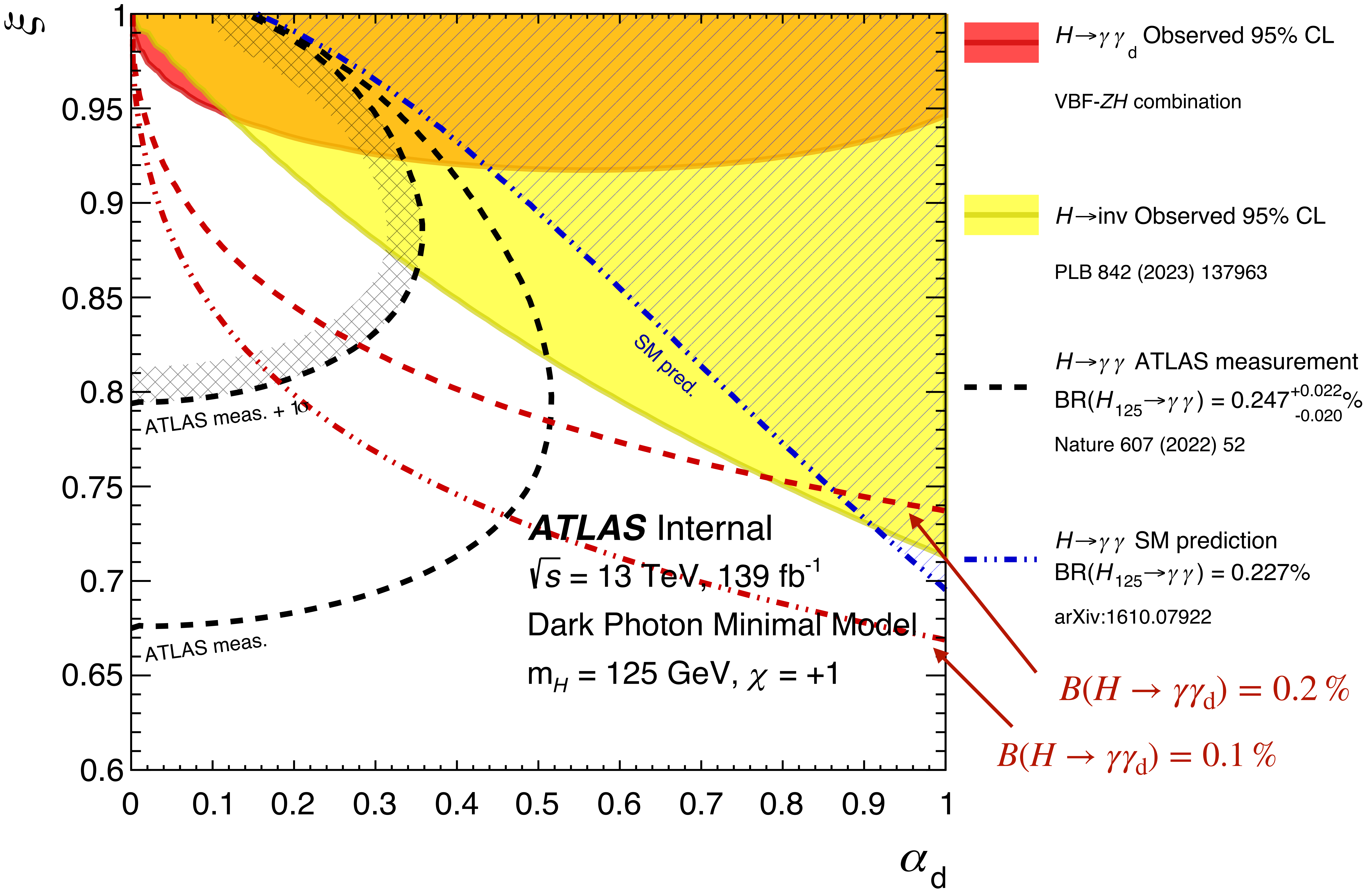
$$r_{\gamma_\mathrm{D}\gamma_\mathrm{D}} = X^2 \left(\frac{\alpha_D}{\alpha}\right)^2$$

$$r_{\gamma\gamma} = X^2$$

$$X \equiv \frac{\xi^2}{3F(1-\xi^2)}$$

$$\xi = \frac{\Delta}{\bar{m}^2}$$

Physics interpretation



$\chi = +1$: scenario with constructive interference from messenger sector in $H_{125} \to \gamma\gamma$

BR limits and measurements from this combination, $H \to \text{inv}$ or $H \to \gamma\gamma$ can be translated into constraints in (α_d, ξ).

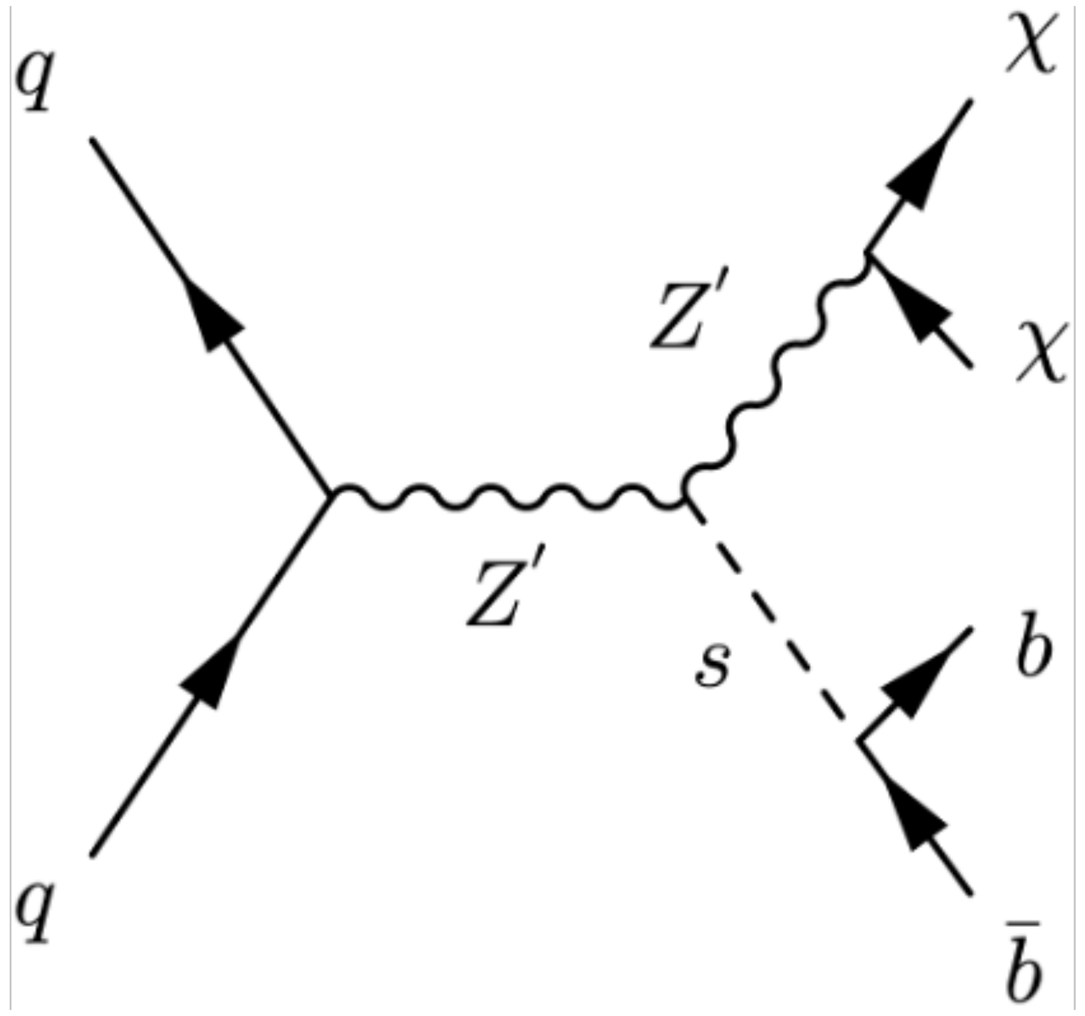
- ❖ $\xi \simeq 0.7$ at $\alpha_\text{d} = 1$ excluded by $\mathcal{B}(H_{125} \to \text{inv})$ limit interpreted in terms of $H_{125} \to \gamma_\text{d}\gamma_\text{d}$ signal.
- ❖ $H_{125} \to \gamma\gamma_\text{d}$ combination provides additional sensitivity in low-α_d region, which is disfavoured by ATLAS $\mathcal{B}(H_{125} \to \gamma\gamma)$ measurement.
- ❖ Still need ~$\mathcal{O}(1)$ better in sensitivity for $H_{125} \to \gamma\gamma_\text{d}$ search.

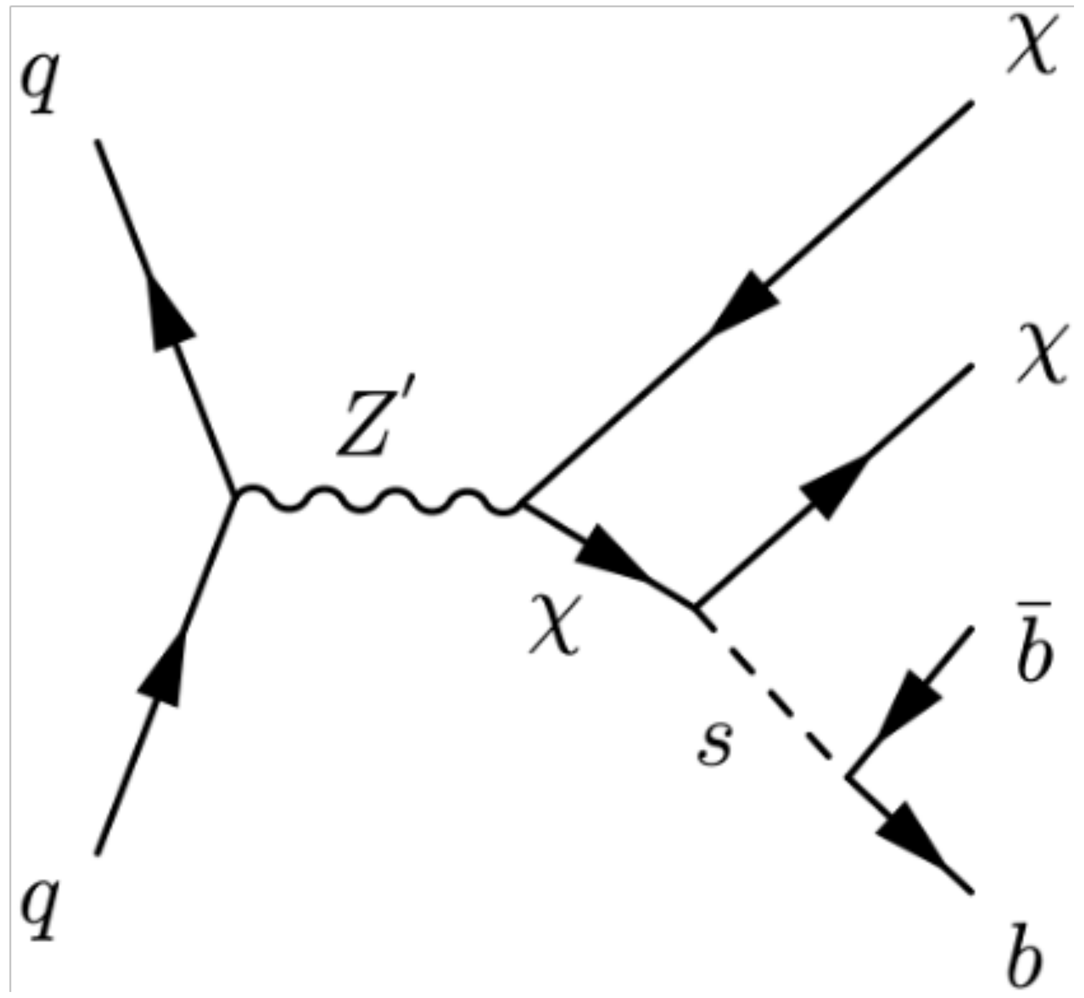
PART 03

NEW ATLAS Dark Higgs search in *bb* final state

Dark Higgs + *Z'* search

Mono-S(→bb)





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

- Dark Higgs boson (scalar *s*) introduced together with *Z'* and Majorana DM [JHEP 04 (2017) 143]
- New DM annihilation channel to SM opened up ($\chi\chi \to s \to \ldots$).
  - Relax the constraint from cosmology → Prevent DM relic density (Ωh^2) over-production issue of common WIMP model.
- Scalar particle mixing with SM Higgs.
  - Detectable decay products depending on mass: $s \to VV$, $s \to bb$.
- ATLAS reported results for high mass dark Higgs searches through $s \to VV$ channel.

First search aiming for a low-mass dark Higgs boson + new benchmark scenarios

30 < m_s < 150 GeV

Benchmark scenarios

- 6 parameters controlling the interaction with SM and DM.

- Fixed-g_χ search as benchmark (**scenario 1**)
  - Scan m_s v.s $m_{Z'}$ with $m_\chi = 200$ GeV, $g_\chi = 1.0$

- Cosmological constraint: freeze-out relic density Ωh^2
  - Observation from PLANCK2018: $\Omega h^2 = 0.1200 \pm 0.0012$

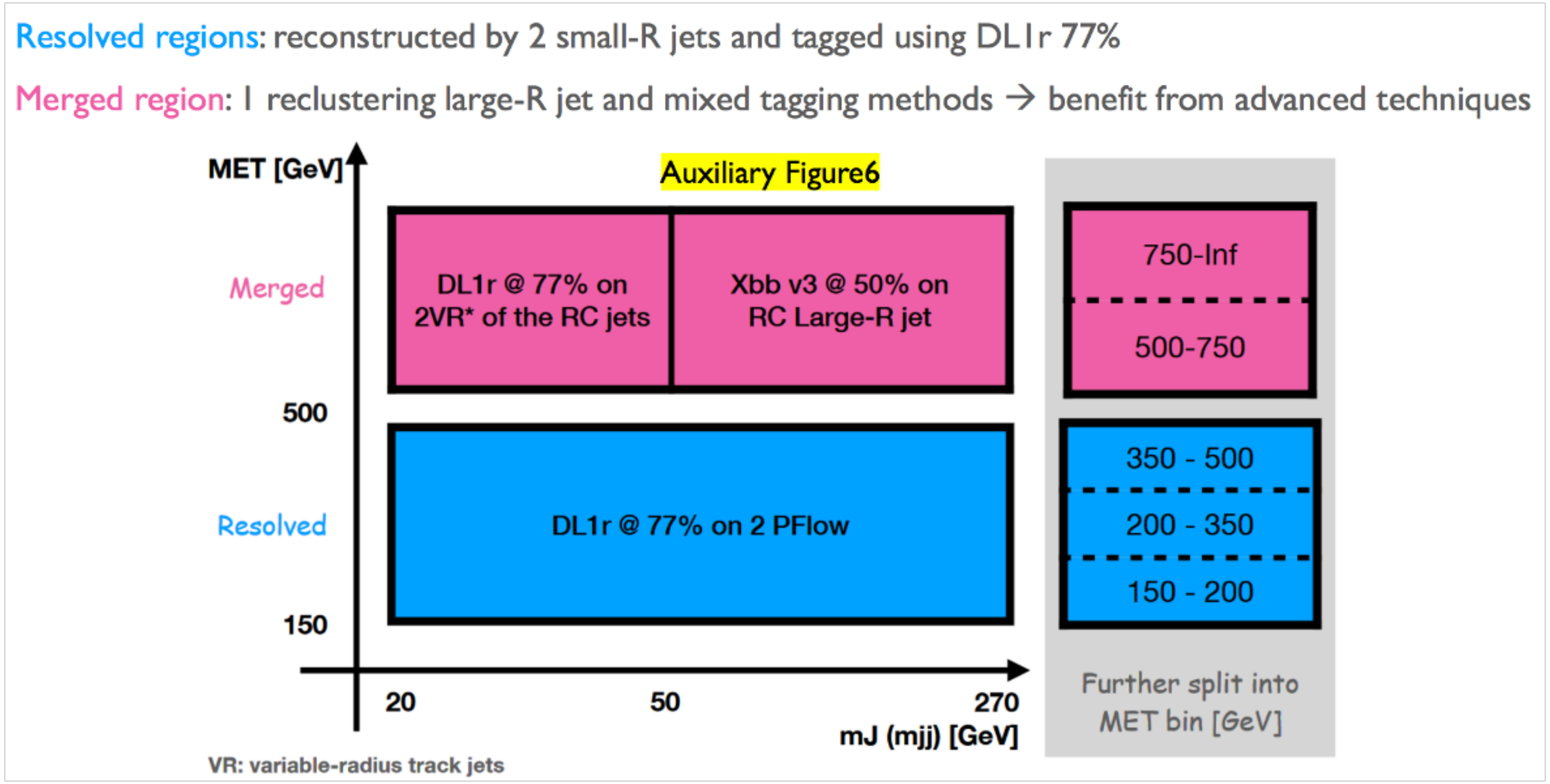
- Introduce 2 new benchmark scenarios [**First time!**] with g_χ varied to satisfy the observed relic density (**scenario 2, 3**)
  - Scan m_s v.s $m_{Z'}$ with $m_\chi = 900$ GeV.
  - Scan m_χ v.s $m_{Z'}$ with $m_s = 70$ GeV.

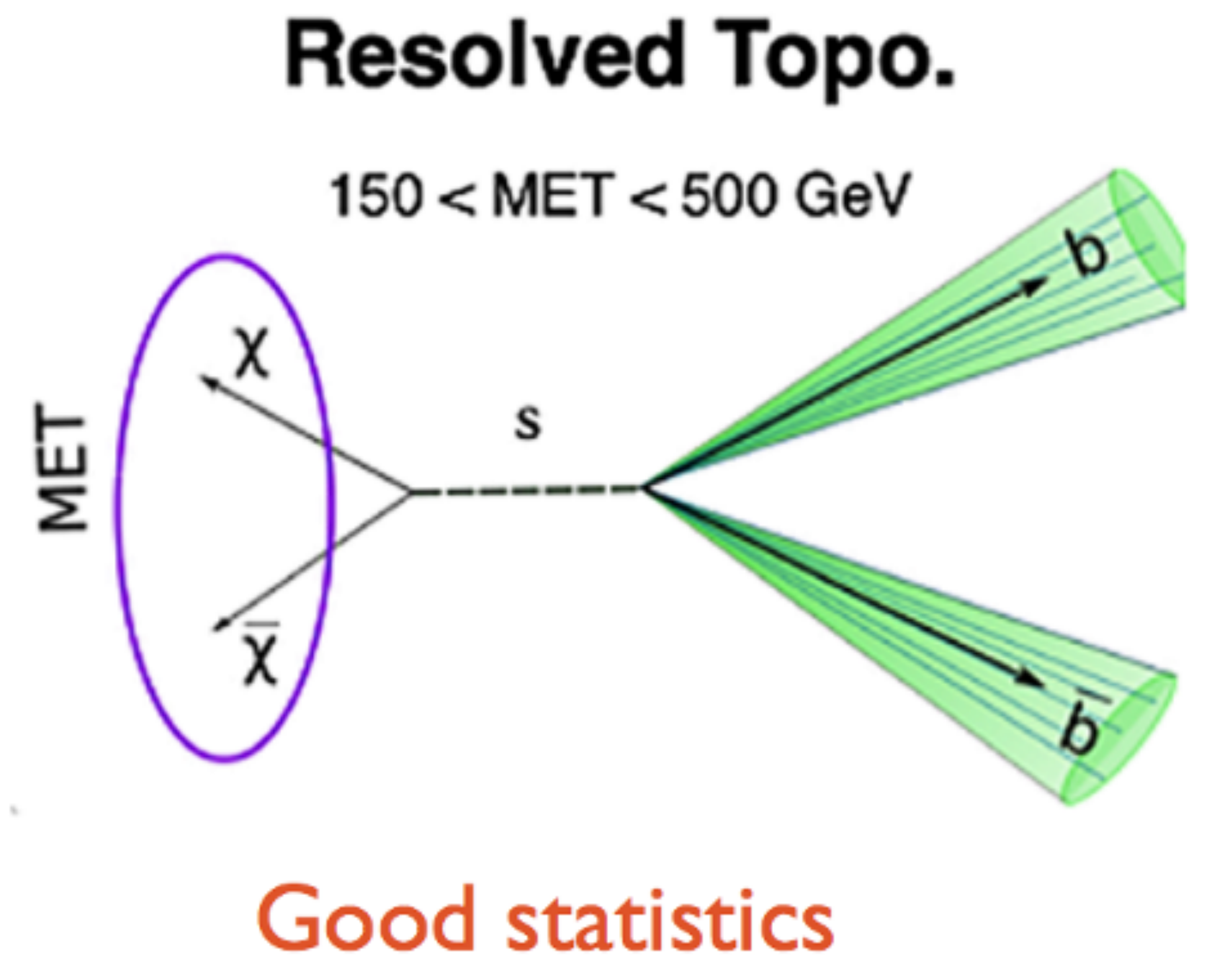
Parameter	Explain
m_s	mass of dark higgs
m_χ	mass of DM
	to search
$m_{Z'}$	mass of heavy mediator
g_χ	coupling in dark sector between s, X, Z'
g_q	coupling with SM: q<->Z' fixed 0.25 as benchmark
θ	mixing angle of SM Higgs<->dark Higgs fixed according to [1]

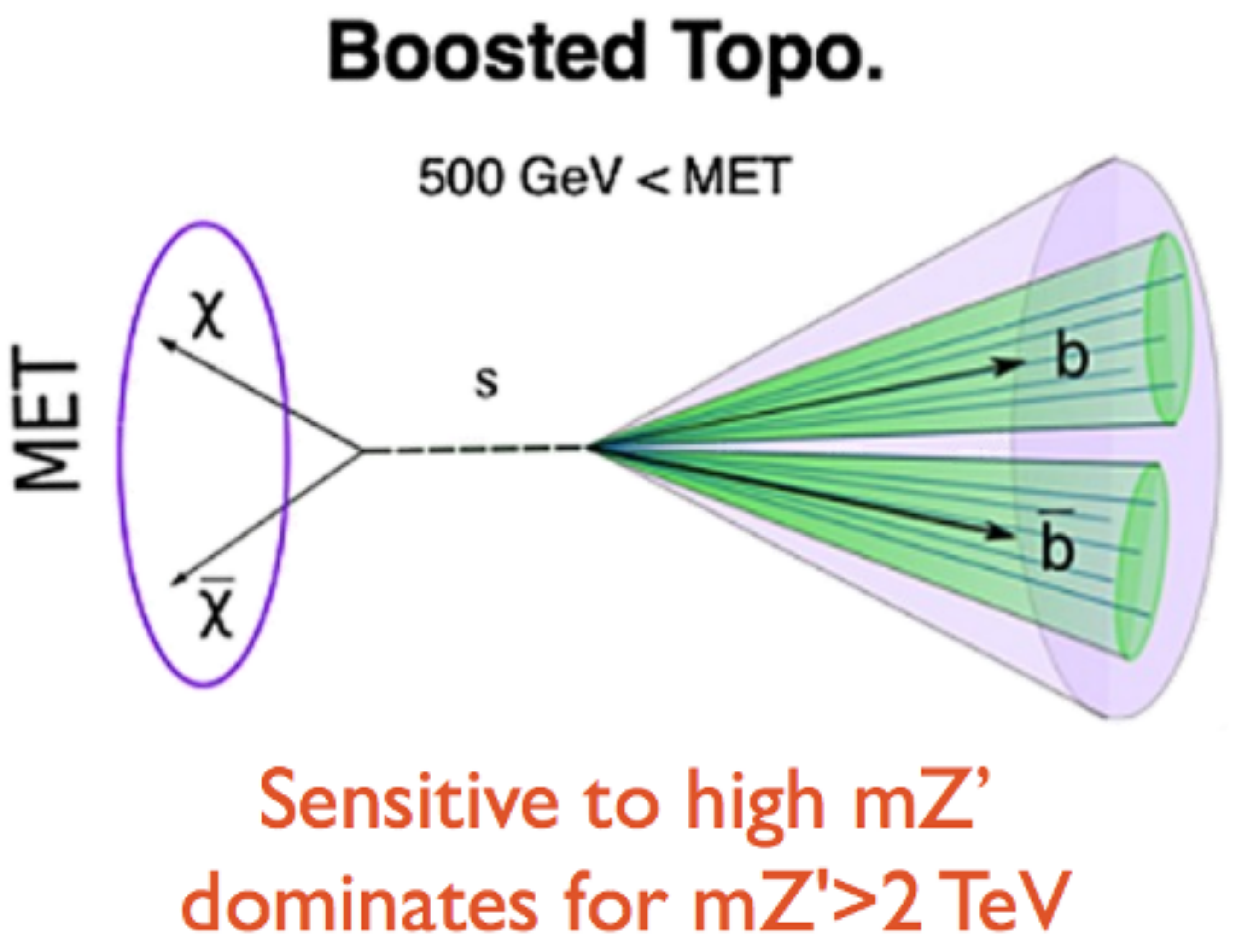
[1] JHEP 04 (2017) 143

Analysis strategy

- Search for low mass dark Higgs with $bb + E_{\mathrm{T}}^{\mathrm{miss}}$ signature
- Data triggered with $E_{\mathrm{T}}^{\mathrm{miss}}$ and search starts from 150 GeV
- Regions divided by $E_{\mathrm{T}}^{\mathrm{miss}}$: from resolved to merged topology to cover all the interesting phase space.





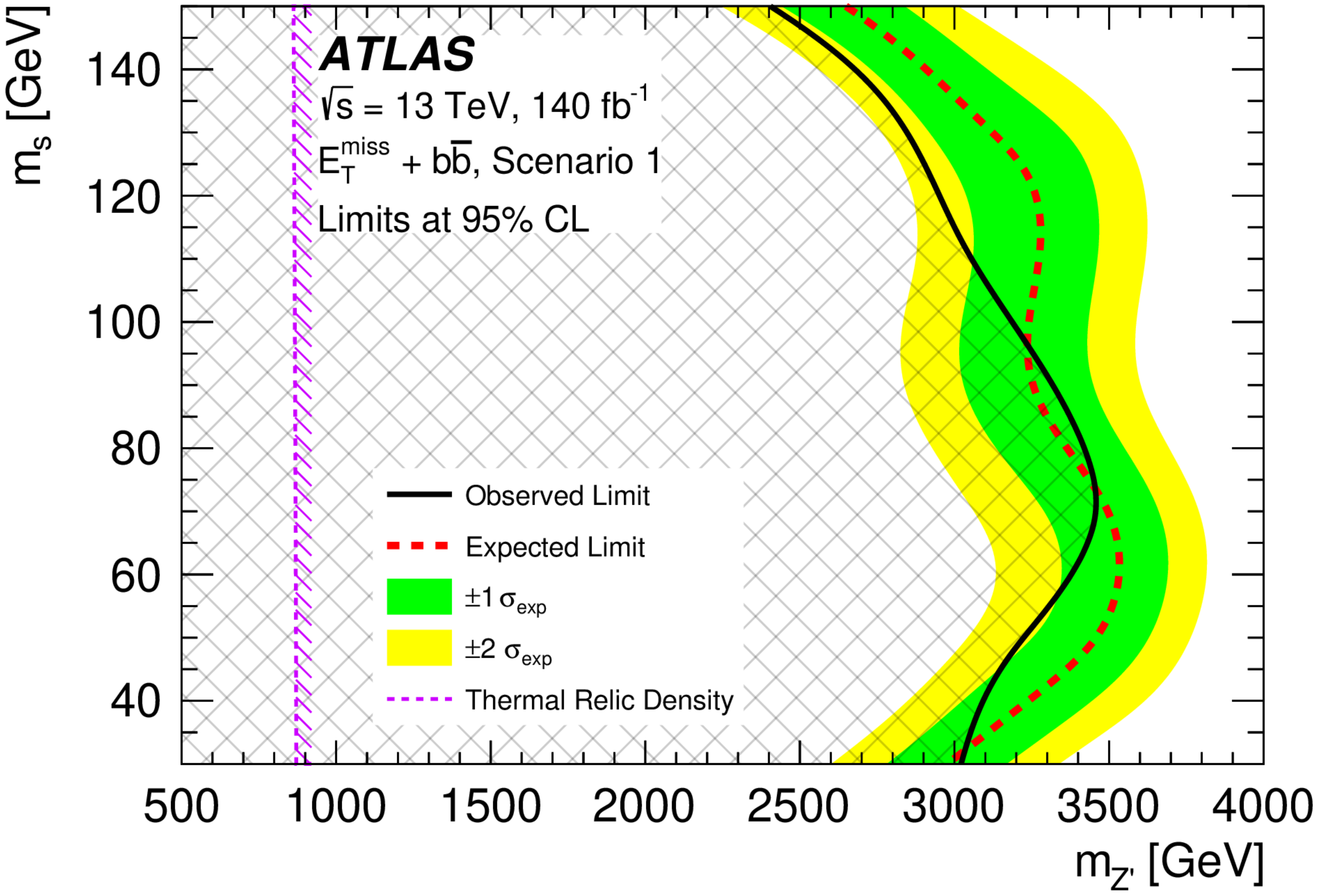


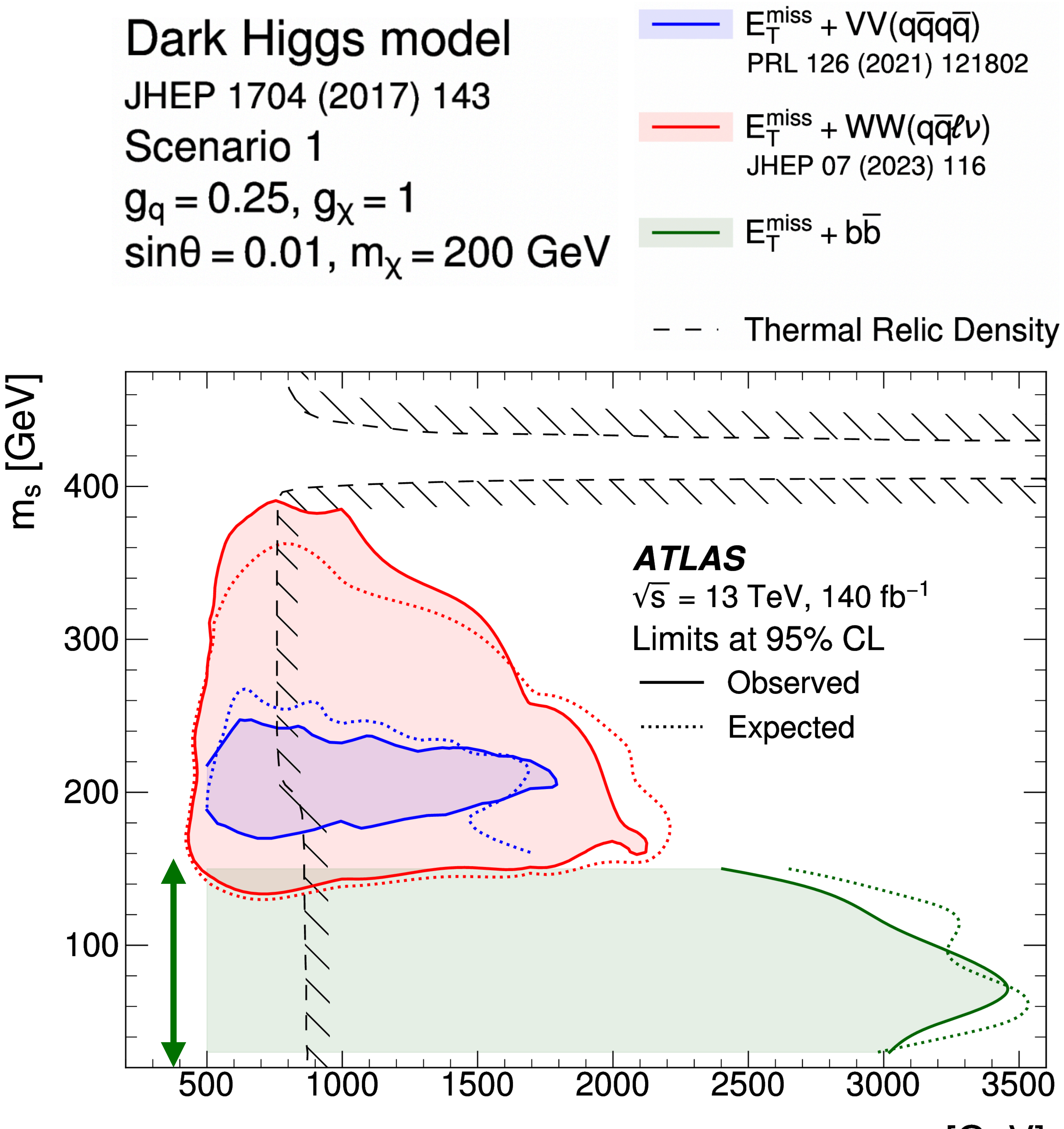
Reclustering(RC) jet extend searched scalar mass down to 20GeV
Large-R jet kin. and sub-jet info. combined for boosted Xbb tagging: DXbb

Results

Scenario 1

- $m_{Z'}$ values are excluded up to 3.4 TeV at m_S = 70 GeV.
- Highest mass exclusions for this conventional benchmark model.



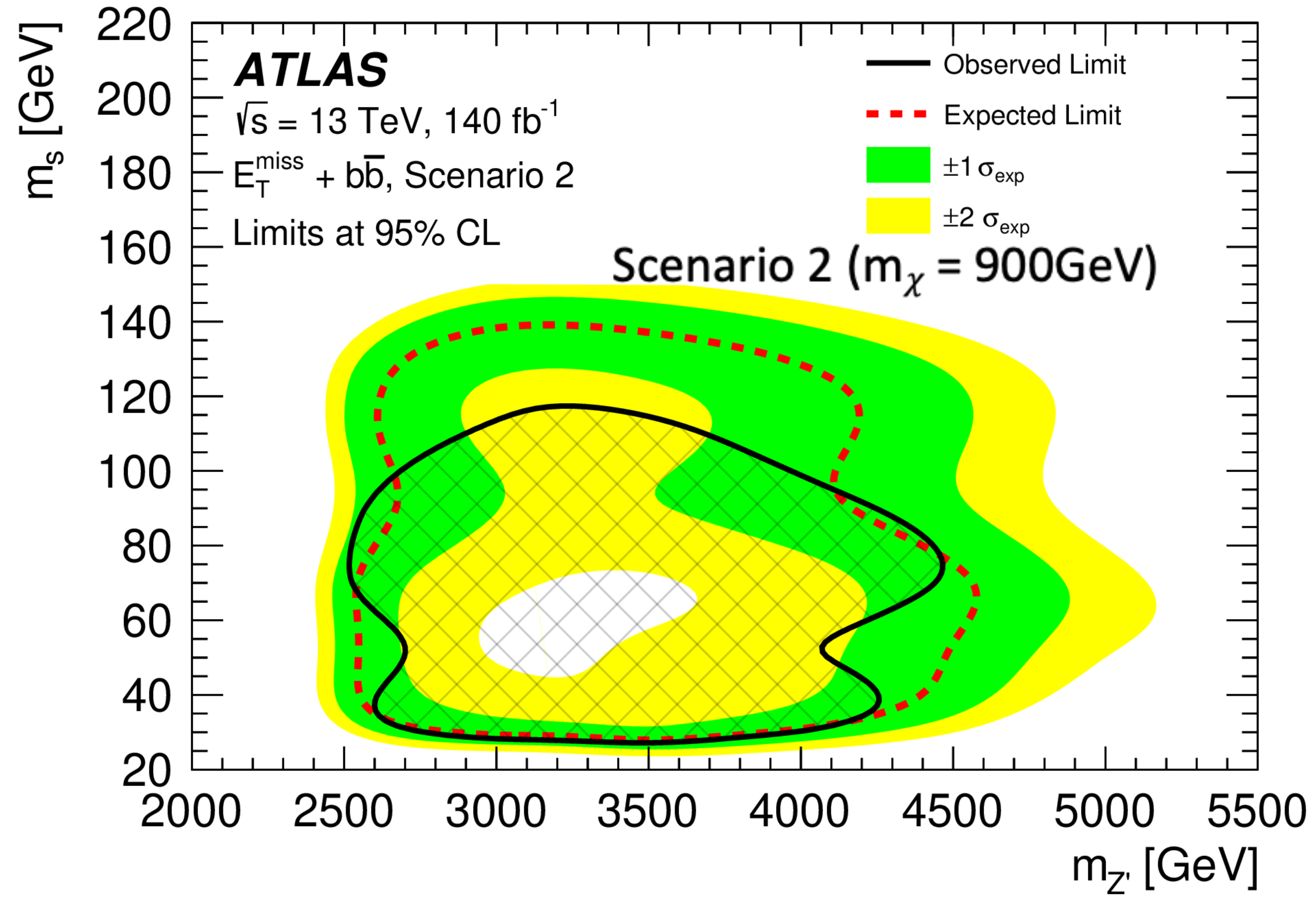


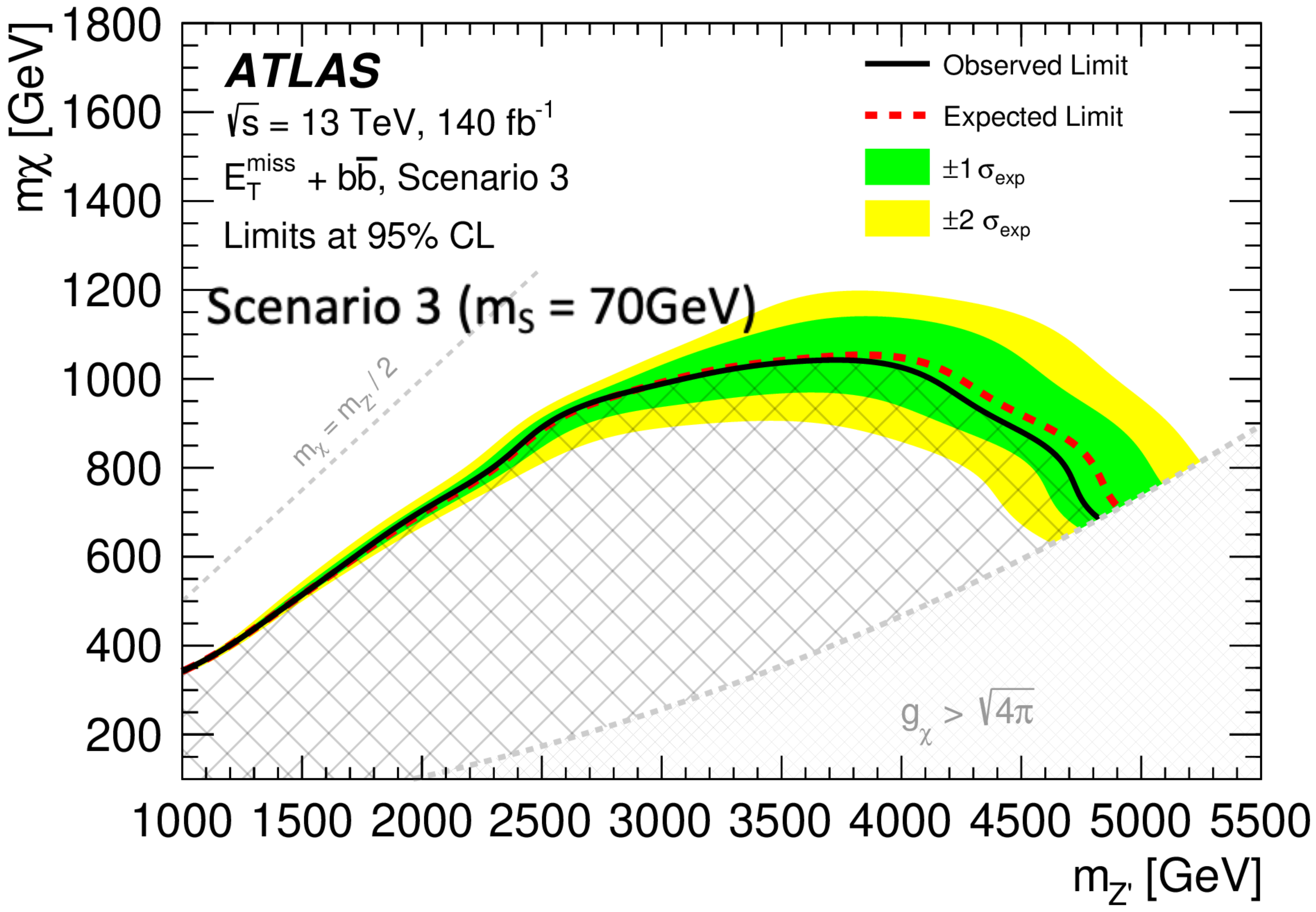
Complementary sensitivity to other Dark Higgs searches at low-m_s

Results

Scenarios 2 & 3

- DM coupling varies to satisfy the observed relic density throughout
  - $m_{Z'}$ excluded up to 4.1 TeV with fixed m_χ at 900 GeV (scenario 2)
  - $m_{Z'}$ excluded up to the perturbative limit and m_χ excl. to 1TeV at m_S = 70 GeV (scenario 3)





First LHC dark Higgs search in cosmology coherent context

Conclusions

- Unfortunately, Dark Matter particles have NOT YET been discovered at the colliders. DM nature is still one of central questions to our understandings about the Universe.

- Wide range of DM benchmark models and experimental signatures has been probed at both ATLAS and CMS using full Run-2 data:
  - Constraints set on extended Higgs models and Dark Sector (Dark Photon, Dark Higgs).
  - Many combination efforts to improve sensitivity reach.
  - Results are complementary to Direct and Indirect experiments.

- LHC Run-2 results are still coming.

- Much more to come with Run-3 dataset including upgraded detectors and innovative methods.

STAY TUNED!

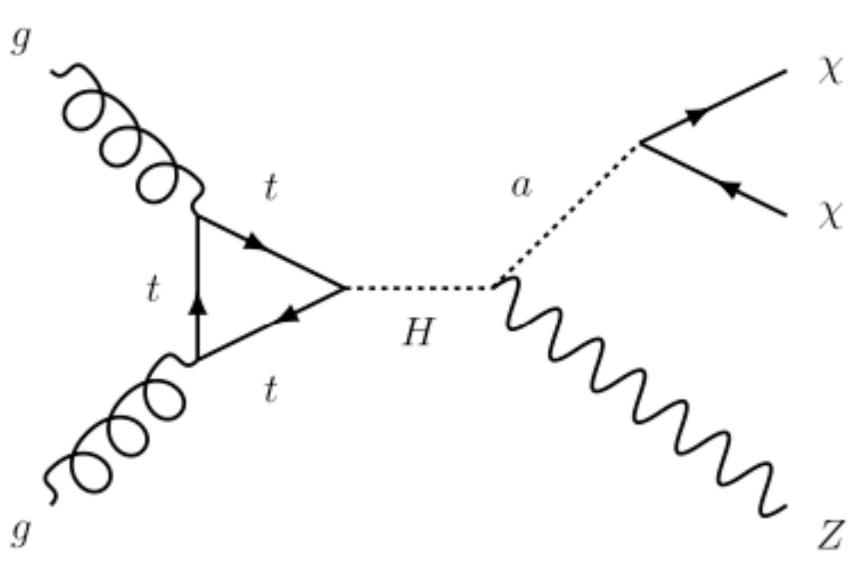
Thank you for attention

Backup

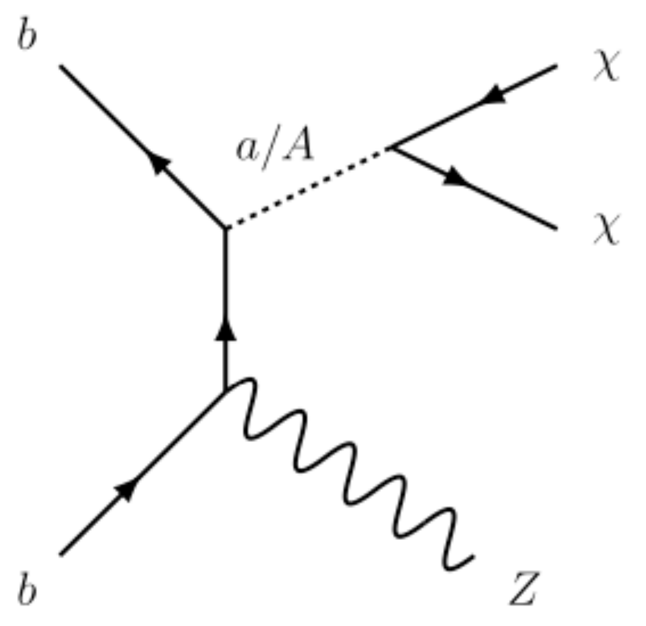
$E_{\mathrm{T}}^{\mathrm{miss}} + Z(ll)$

[Phys. Lett. B 829 (2022) 137066]

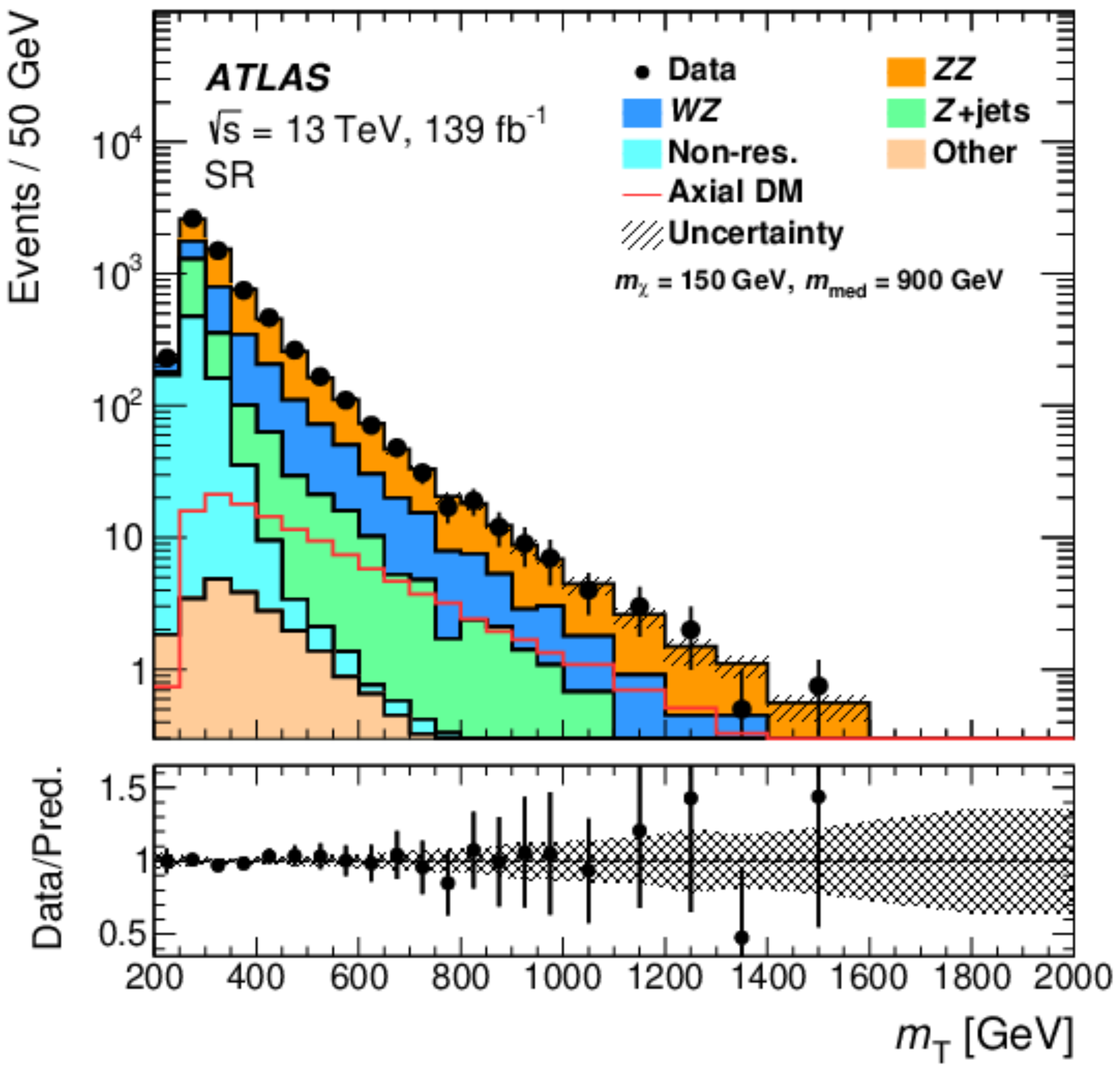
- **Event topology**:
  - Z boson recoiling against large $E_{\mathrm{T}}^{\mathrm{miss}}$
  - Presence of a pair of high-p_{T}, same flavour, oppositely charged leptons.
- SM backgrounds estimated using **dedicated Control Regions.**
- Fit to data is performed on $m_{\mathrm{T}}^{\mathrm{lep}}$ and $E_{\mathrm{T}}^{\mathrm{miss}}$

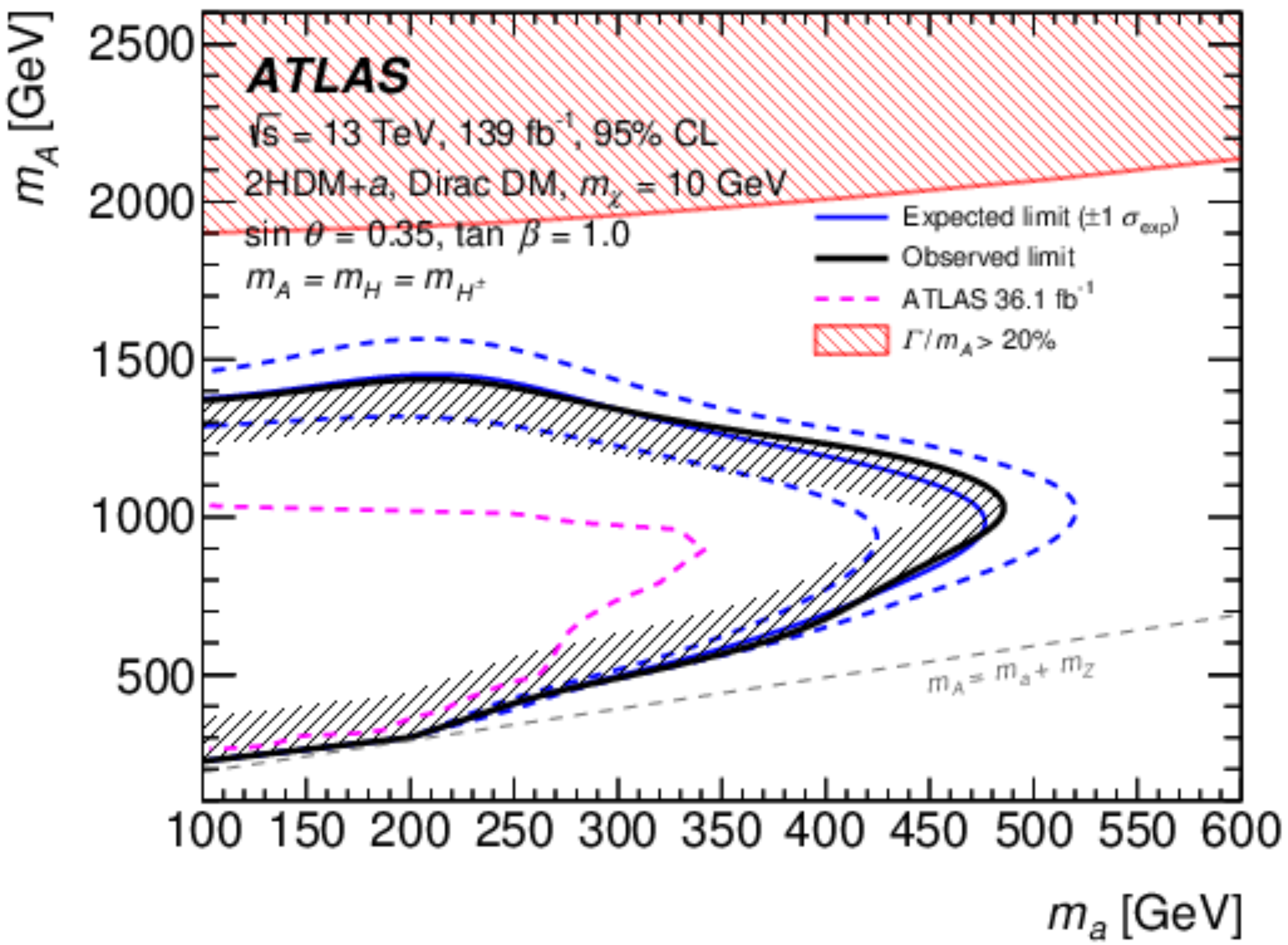


gg-initiated



bb-initiated



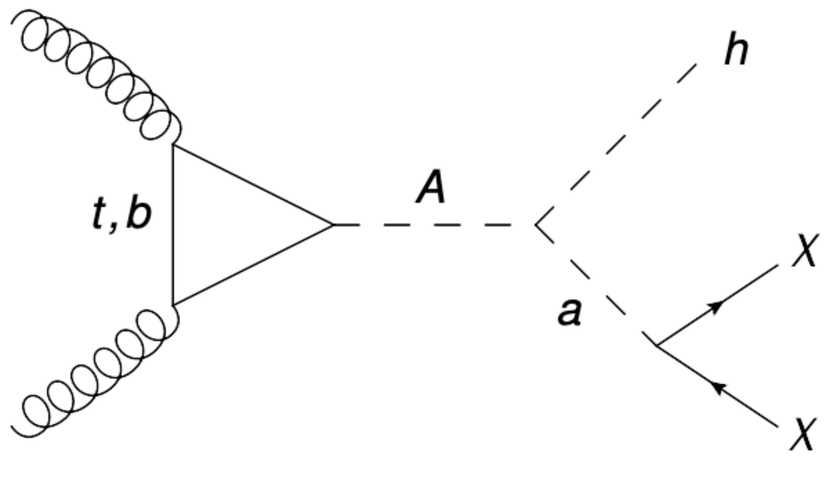


$$m_{\mathrm{T}}^{\mathrm{lep}} = \sqrt{\left[\sqrt{m_Z^2 + (p_{\mathrm{T}}^{\ell\ell})^2} + \sqrt{m_Z^2 + (E_{\mathrm{T}}^{\mathrm{miss}})^2}\right]^2 - \left[\vec{p}_{\mathrm{T}}^{\,\ell\ell} + \vec{p}_{\mathrm{T}}^{\,\mathrm{miss}}\right]^2}$$

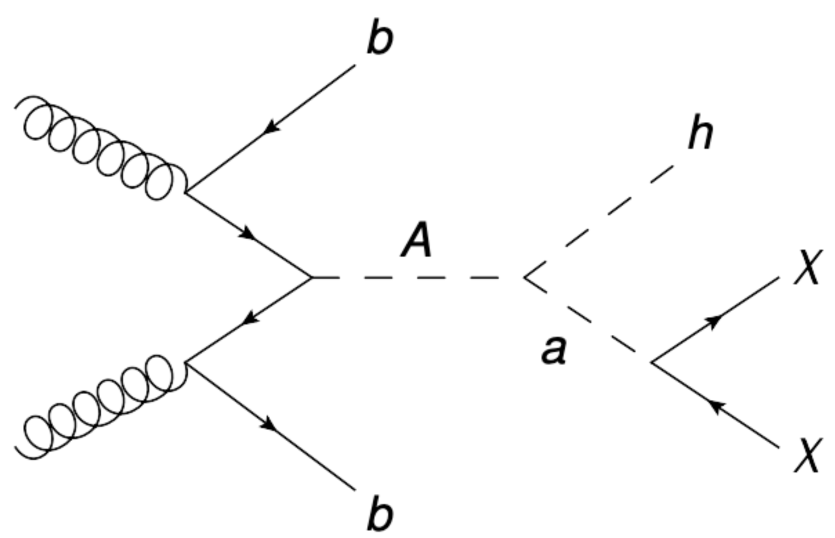
$E_{\mathrm{T}}^{\mathrm{miss}} + h(bb)$

[JHEP 11 (2021) 209](https://doi.org/)

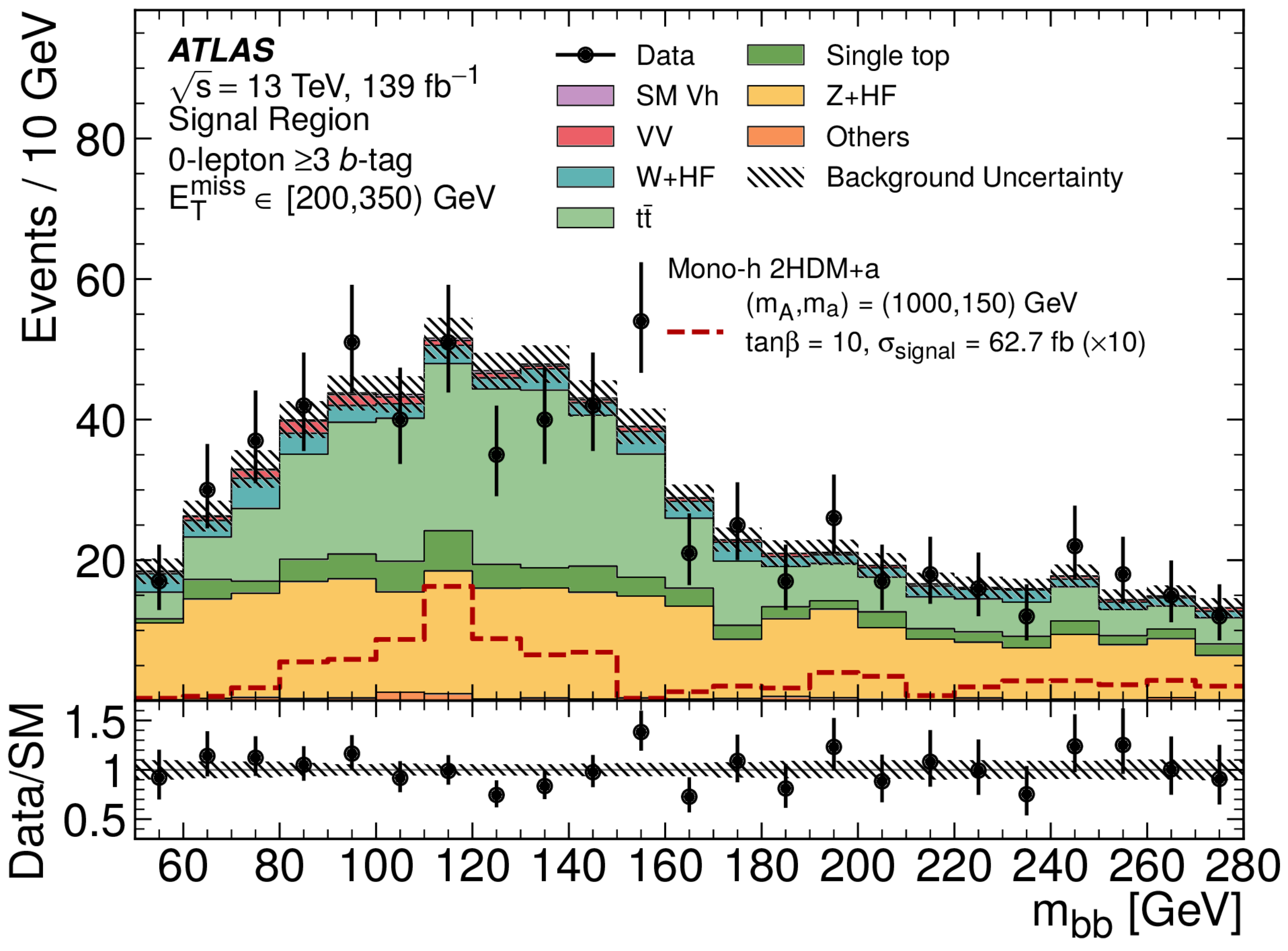
- Event topology:
  - Higgs boson recoiling against large $E_{\mathrm{T}}^{\mathrm{miss}}$
  - at least 2 b-jets.
  - Higgs decay reconstructed as single large Radius jet for events with high $E_{\mathrm{T}}^{\mathrm{miss}}$.
- SM backgrounds estimated from Control Regions.
- Fit to data on m_{bb} and event counting in CRs.

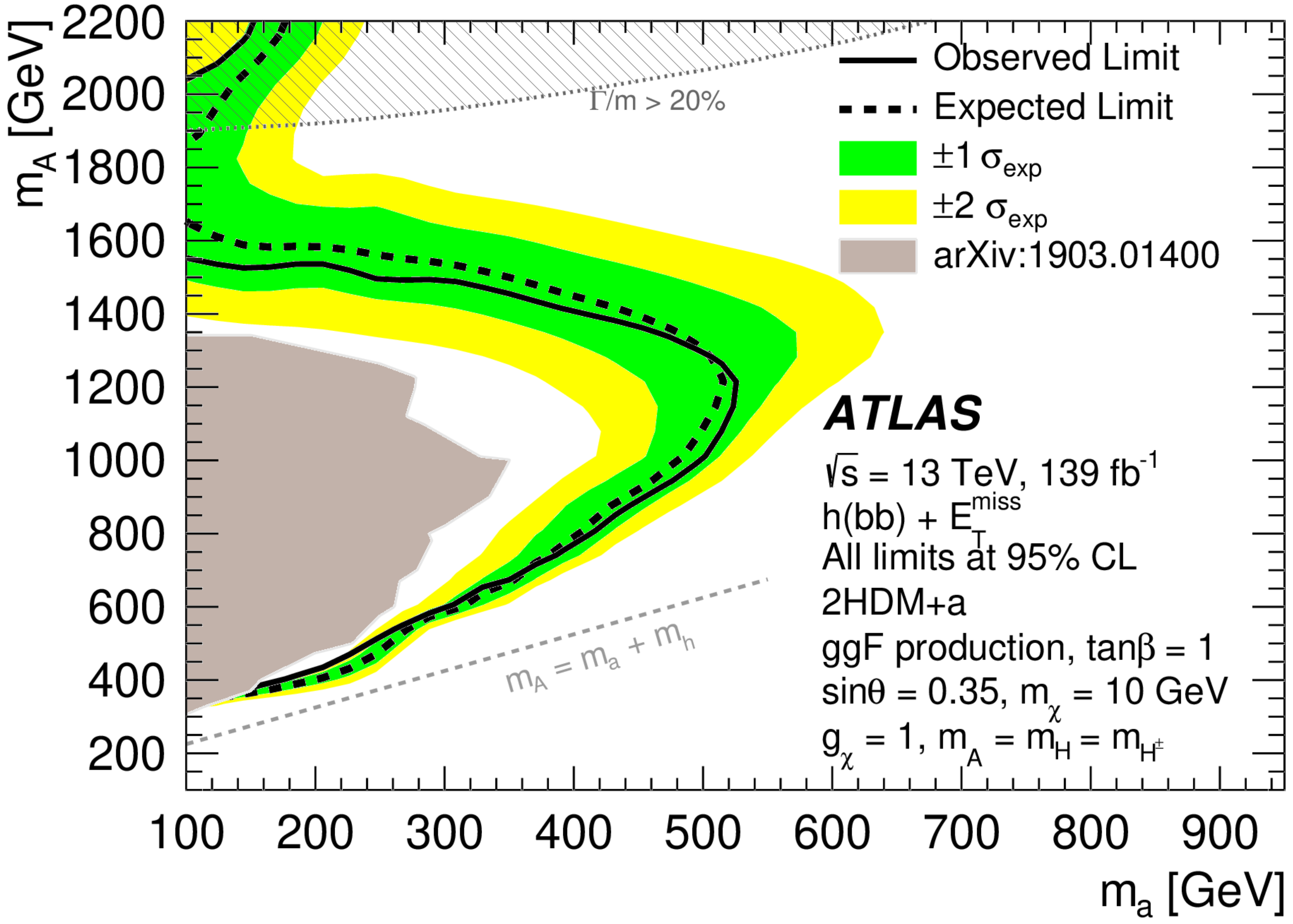


gg-induced



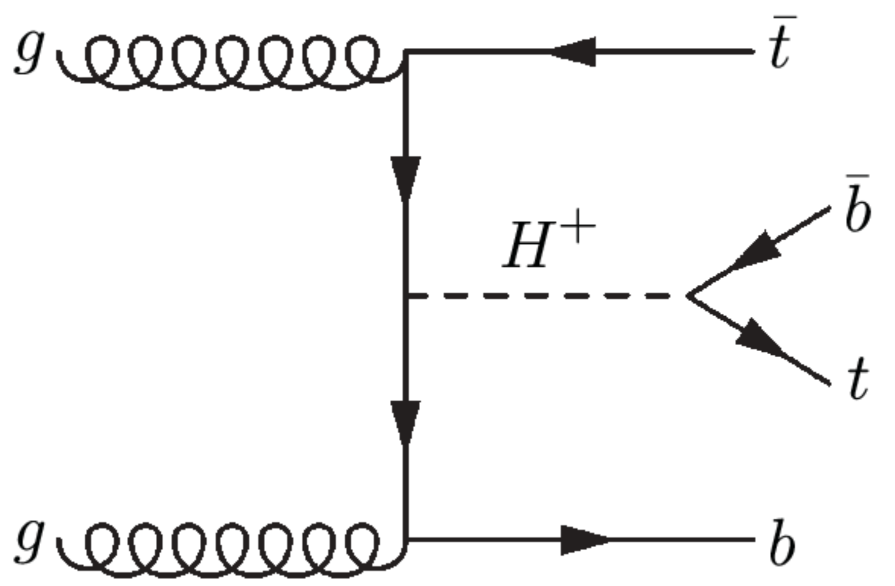
bb-induced



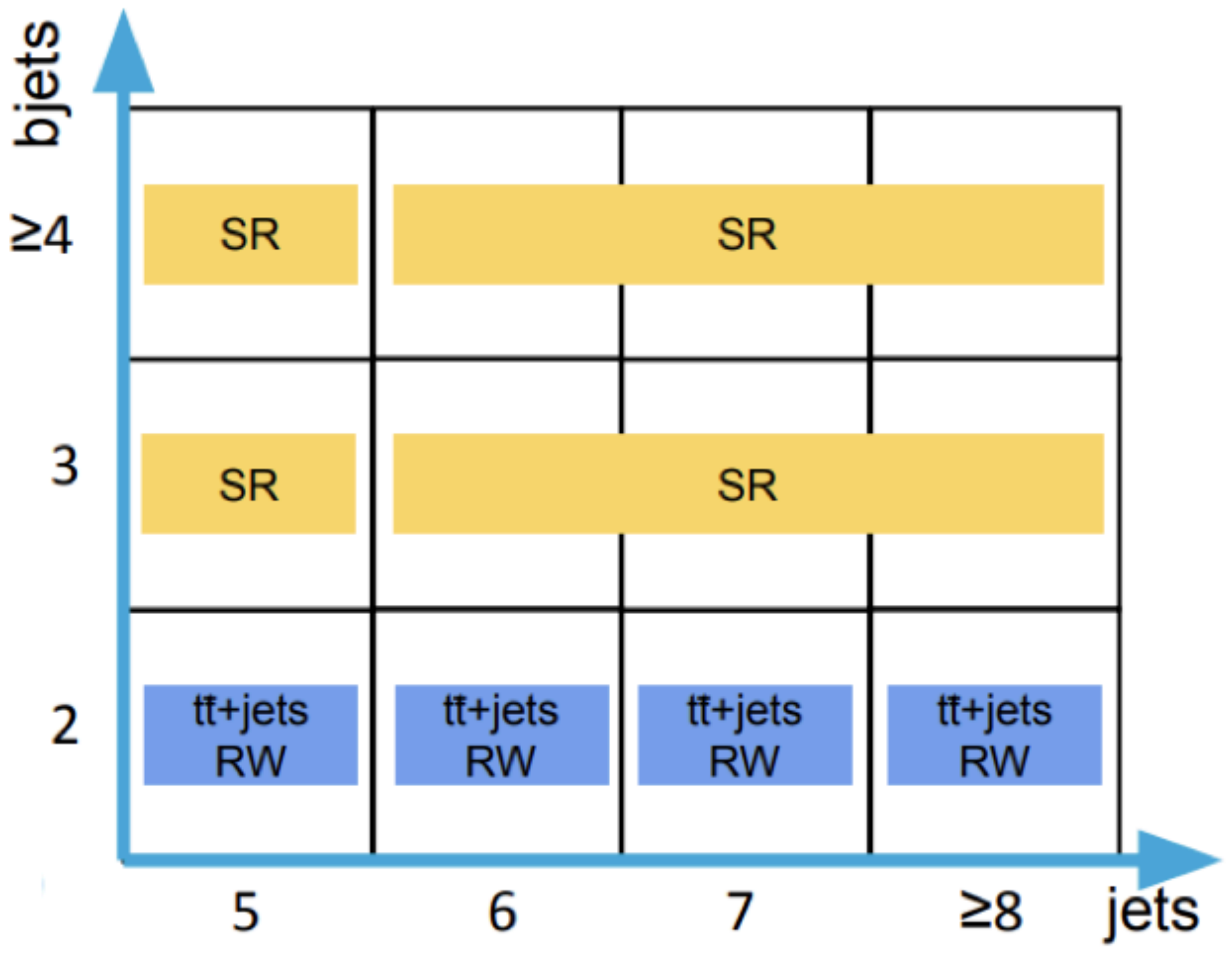


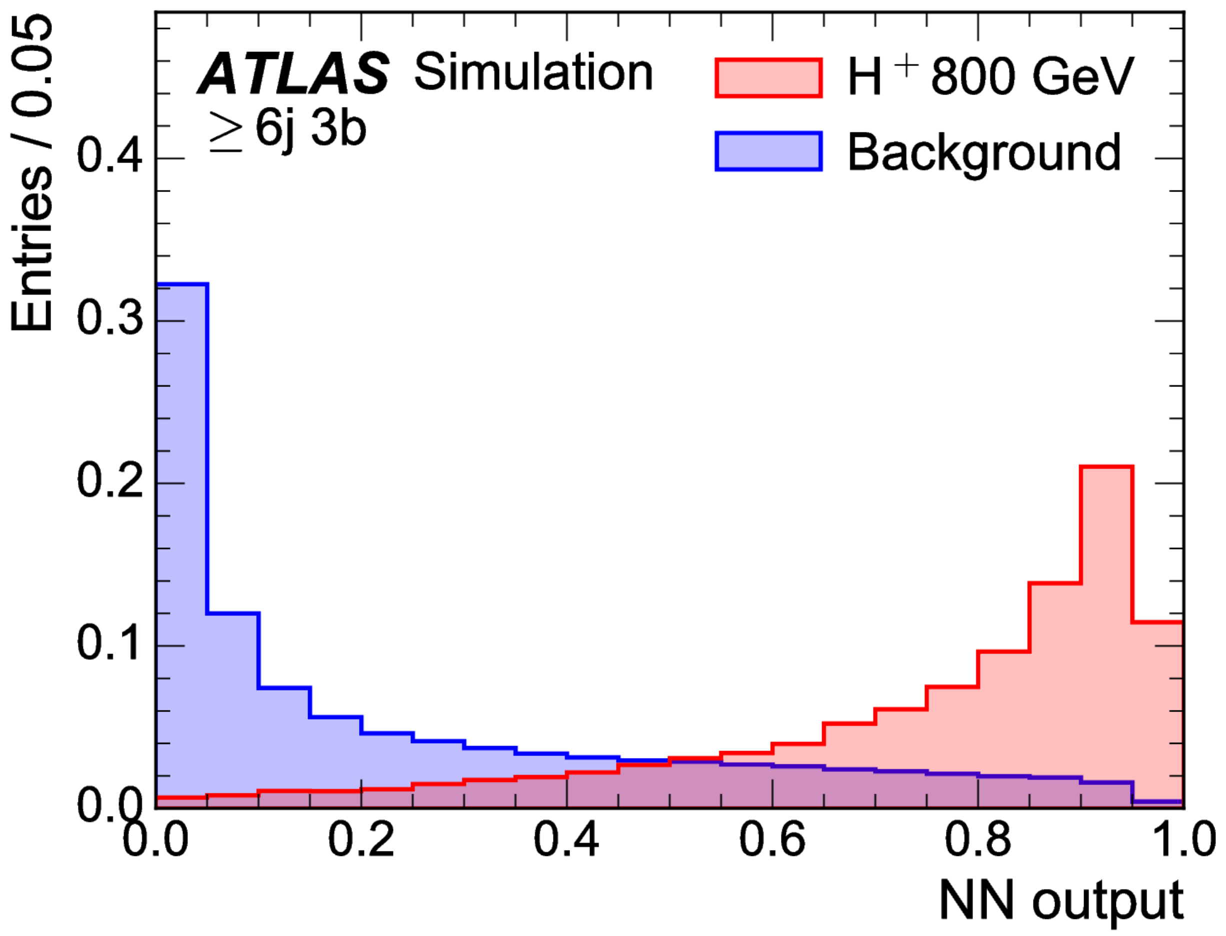
$tbH^{\pm}(tb)$

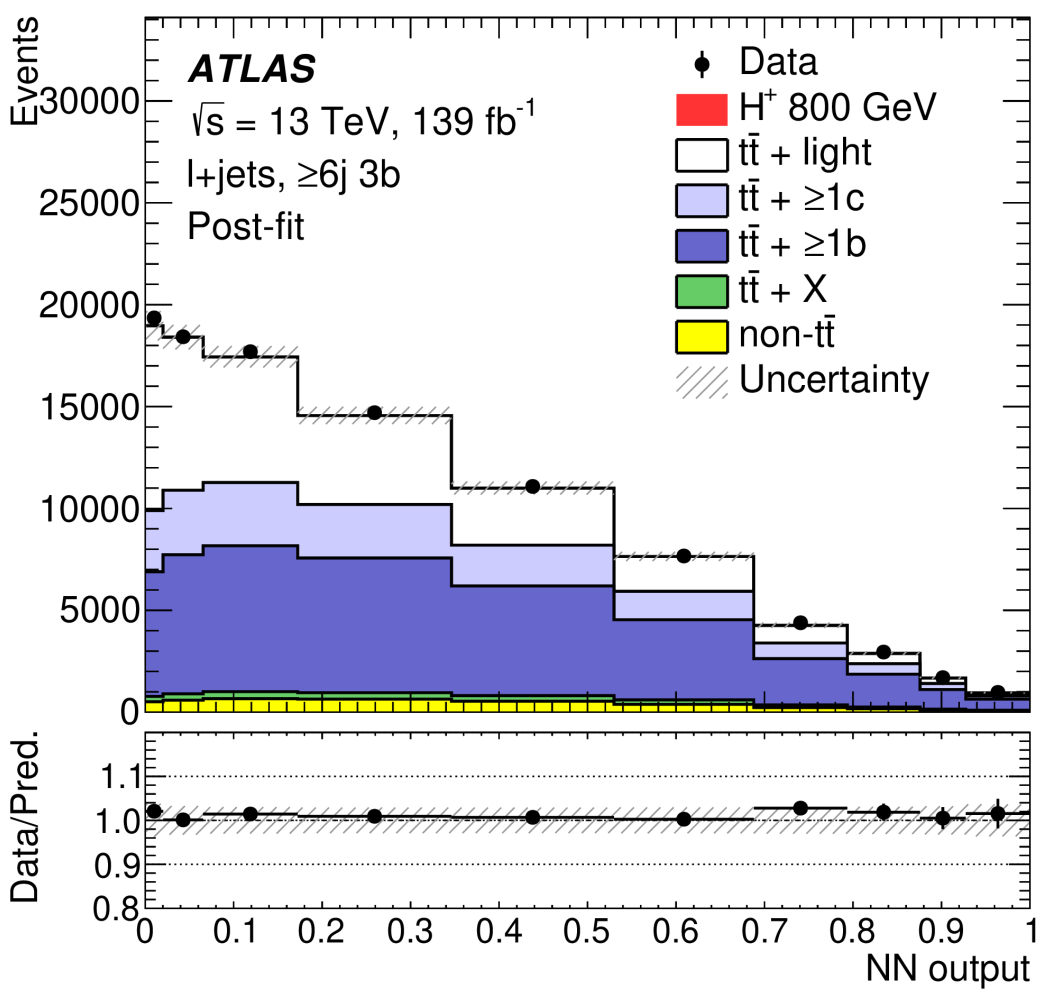
[JHEP 06 (2021) 145]

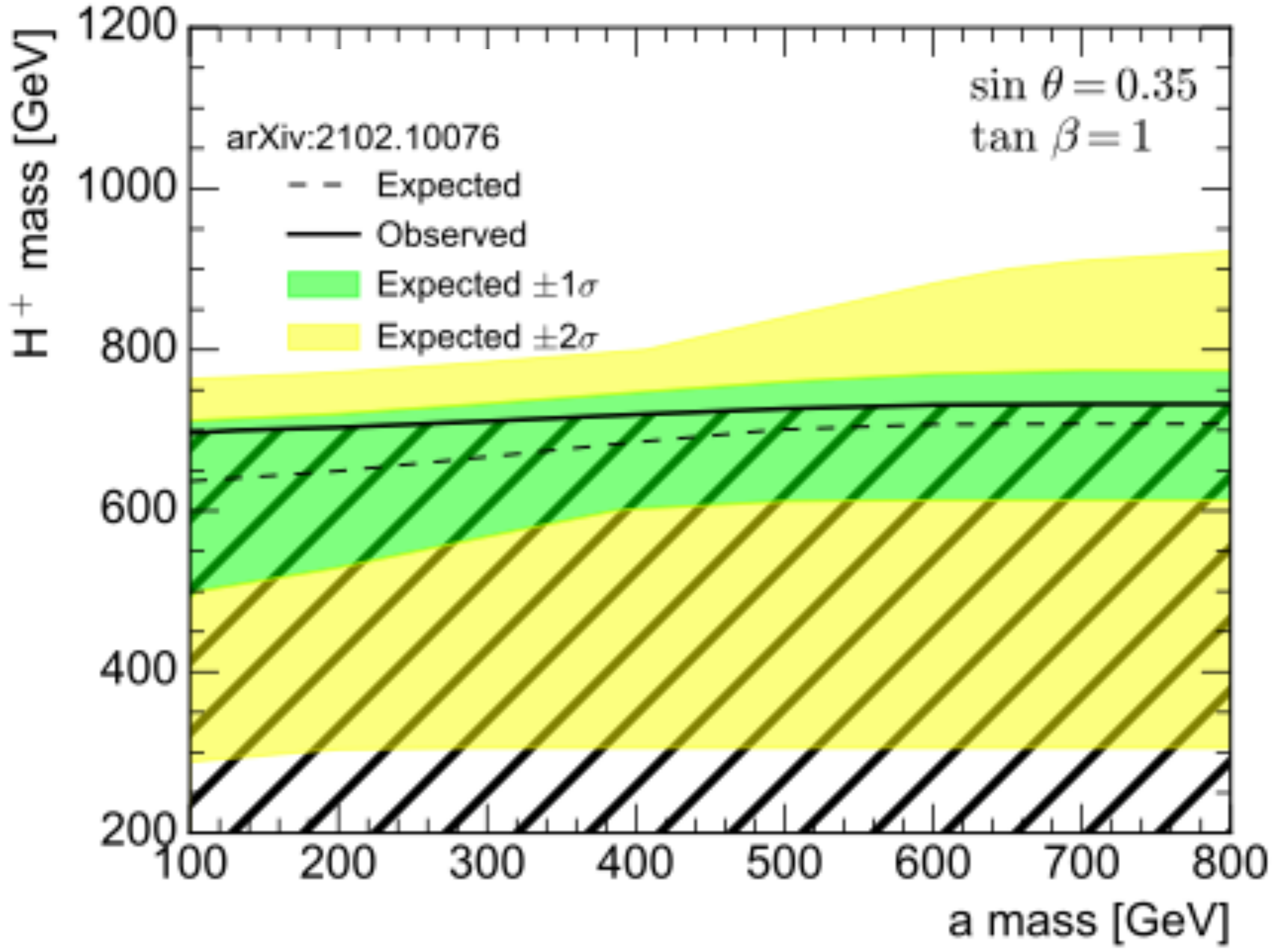


- re-interpretation of general 2HDM search by rescaling exclusion upper limits.
- **Event topology**:
  - **1lepton + $\geq$ 5j + $\geq$ 3b** to target semi-leptonic decay of one of top quarks
- **A Neural Network** used to enhance discrimination between signals and bkgs.
- Dominant background estimated using data-driven technique.
- Fit to data performed on NN distributions.



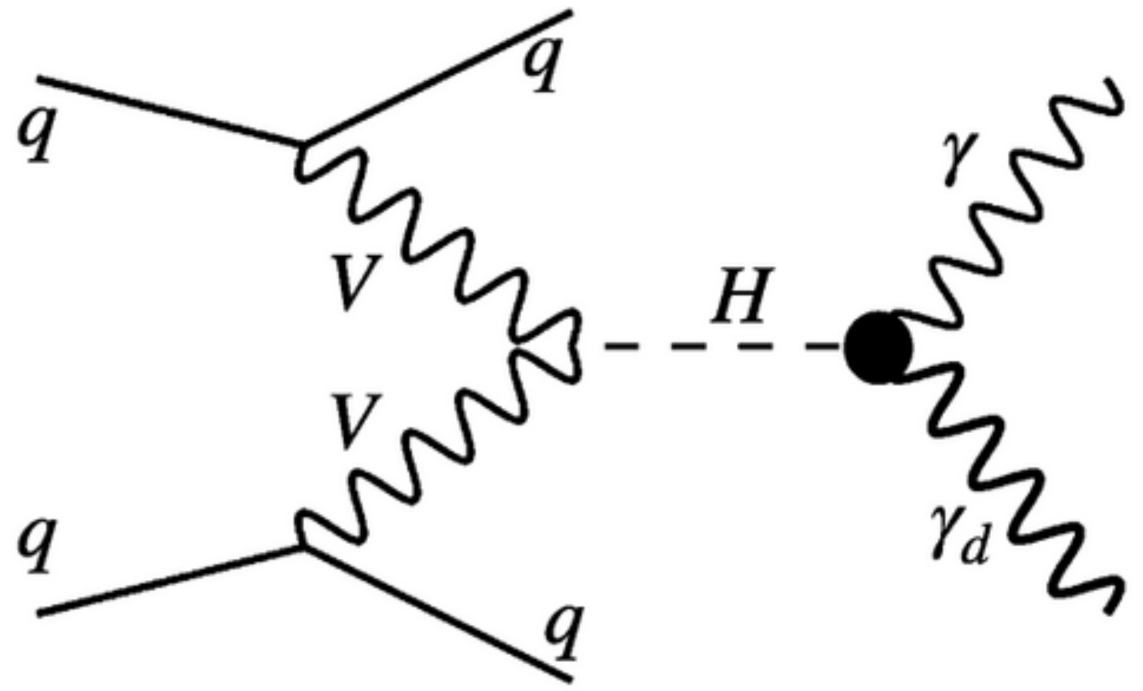






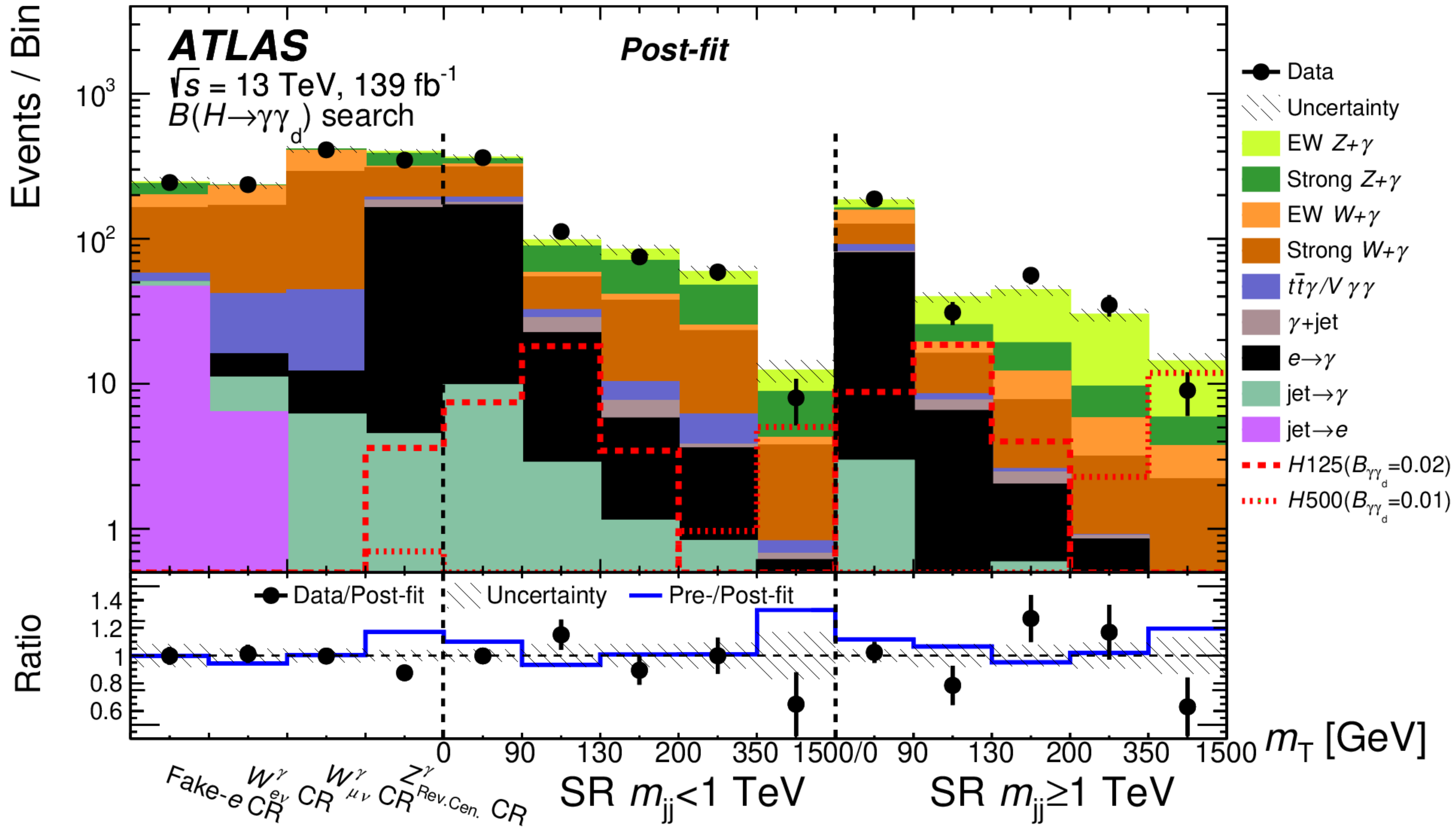
Input overview

VBF channel EPJC 82 (2022) 105



- Topology:
  - 1 photon, 2 or 3 VBF jets, E_T^{miss}
  - Lepton $(e,\ \mu)$ veto
- Background estimation
  - $W(\to \ell\nu)\gamma + \text{jets}$, $Z(\to \nu\nu)\gamma + \text{jets}$, and e-fake γ from control regions (CR).
  - jet-fake γ from data-driven.
- Fit to data on $m_{j_1j_2}$, $m_T(\gamma, E_T^{\text{miss}})$ bins in SR and 4 CRs.

Channels	VBF	ZH	ggF
Trigger	E_T^{miss}	Lepton(s)	Photon
Photons	$= 1,\ C_\gamma > 0.4$	$= 1$	≥ 1
E_T^γ [GeV]	$\in (15, \max(110, 0.733 \times m_T))$	> 25	> 150
E_T^{miss} [GeV]	> 150	> 60	> 200
Jets	2 or 3, $m_{j_1j_2} > 250\,\text{GeV}$, $\lvert\Delta\eta_{j_1j_2}\rvert > 3$ $\eta_{j_1} \cdot \eta_{j_2} < 0$, $\Delta\phi_{j_1j_2} < 2$, $C_{j_3} < 0.7$	≤ 2	≤ 1
Leptons	$= 0\ (e, \mu)$	$= 2$, SFOC $m_{\ell\ell} \in (76, 116)$ GeV	$= 0\ (e, \mu, \tau)$



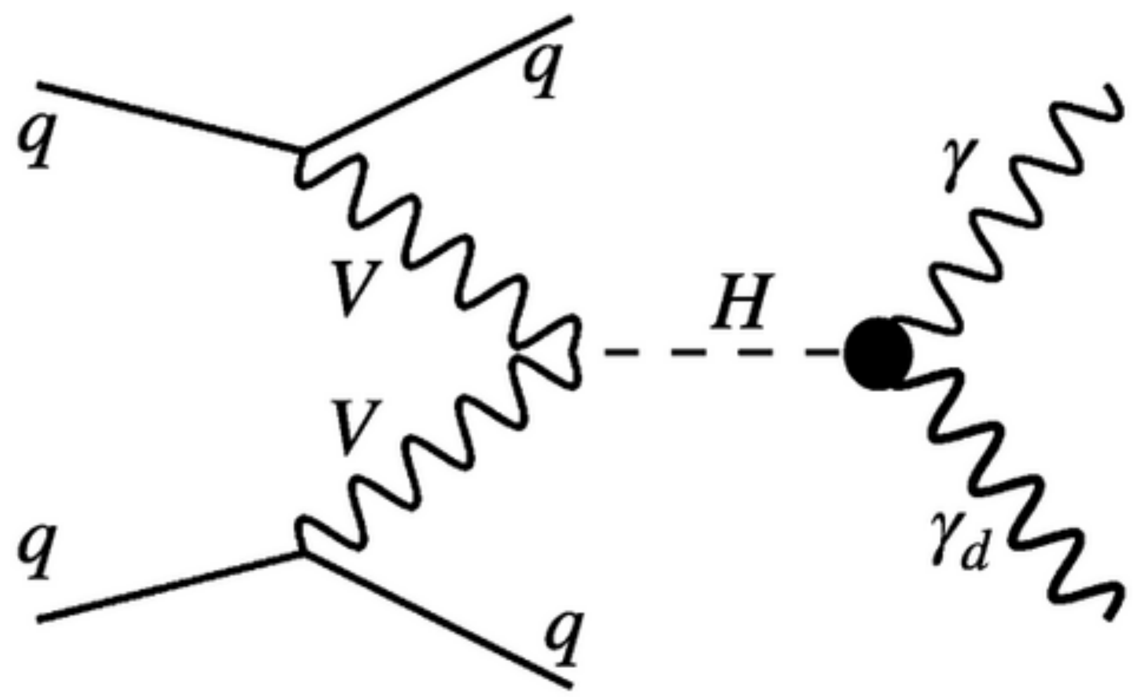
No significant deviation from SM prediction.

$$m_T(\gamma, E_T^{\text{miss}}) = \sqrt{2E_T^\gamma E_T^{\text{miss}}\left[1 - \cos(\phi_\gamma - \phi_{E_T^{\text{miss}}})\right]}$$

$$C_i = \exp\left[-\frac{4}{(\eta_{j_1} - \eta_{j_2})^2}\left(\eta_i - \frac{\eta_{j_1}+\eta_{j_2}}{2}\right)^2\right]$$

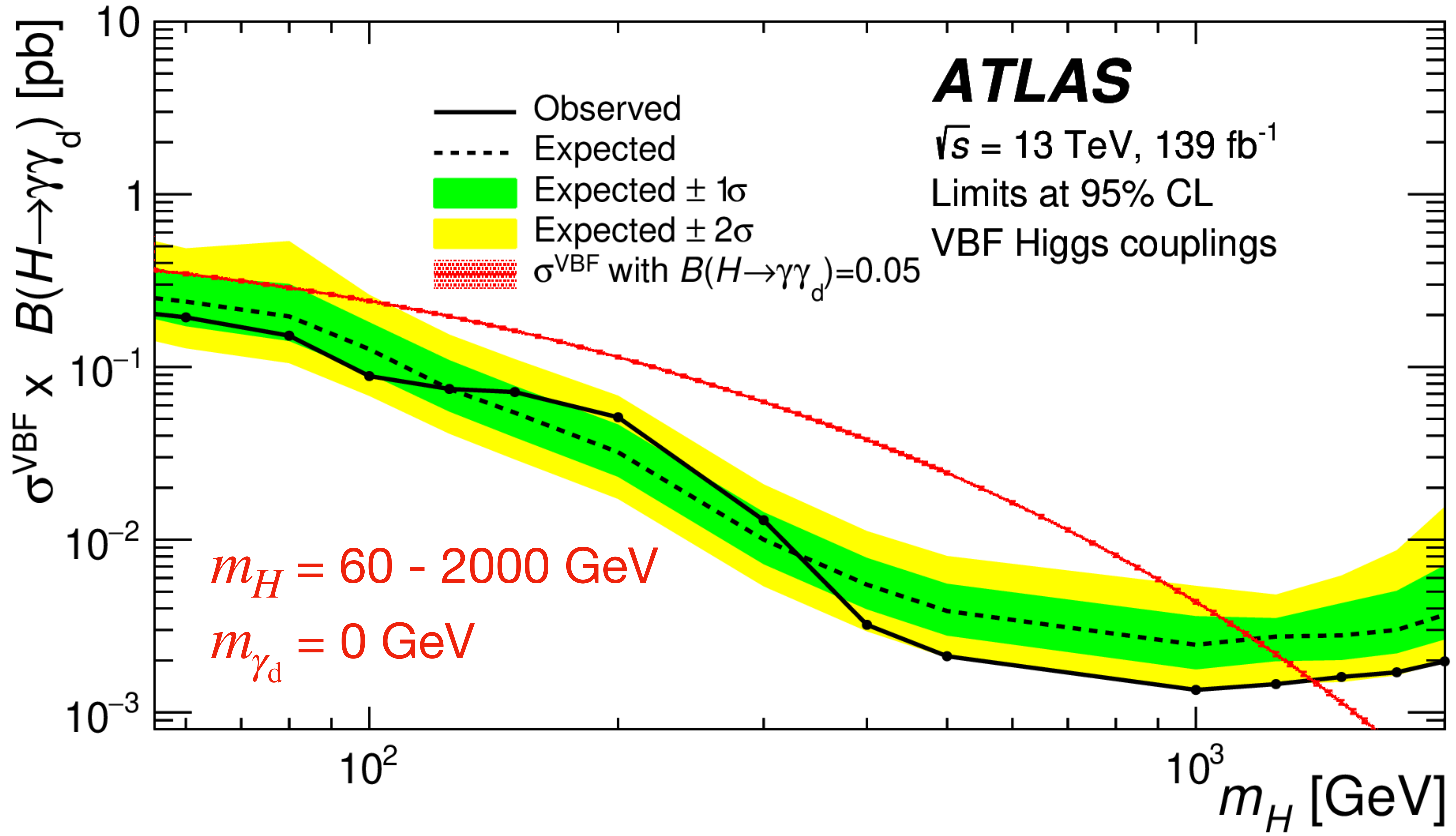
Input overview

VBF channel EPJC 82 (2022) 105



- Topology:
  - 1 photon, 2 or 3 VBF jets, E_T^{miss}
  - Lepton (e, μ) veto
- Background estimation
  - $W(\to \ell\nu)\gamma + \text{jets}$, $Z(\to \nu\nu)\gamma + \text{jets}$, and e-fake γ from control regions (CR).
  - jet-fake γ from data-driven.
- Fit to data on $m_{j_1j_2}$, $m_T(\gamma, E_T^{\text{miss}})$ bins in SR and 4 CRs.

Channels	VBF	ZH	ggF
Trigger	E_T^{miss}	Lepton(s)	Photon
Photons	$= 1, C_\gamma > 0.4$	$= 1$	≥ 1
E_T^γ [GeV]	$\in (15, \max(110, 0.733 \times m_T))$	> 25	> 150
E_T^{miss} [GeV]	> 150	> 60	> 200
Jets	2 or 3, $m_{j_1j_2} > 250$ GeV, $\lvert\Delta\eta_{j_1j_2}\rvert > 3$ $\eta_{j_1} \cdot \eta_{j_2} < 0$, $\Delta\phi_{j_1j_2} < 2$, $C_{j_3} < 0.7$	≤ 2	≤ 1
Leptons	$= 0\ (e, \mu)$	$= 2$, SFOC $m_{\ell\ell} \in (76, 116)$ GeV	$= 0\ (e, \mu, \tau)$

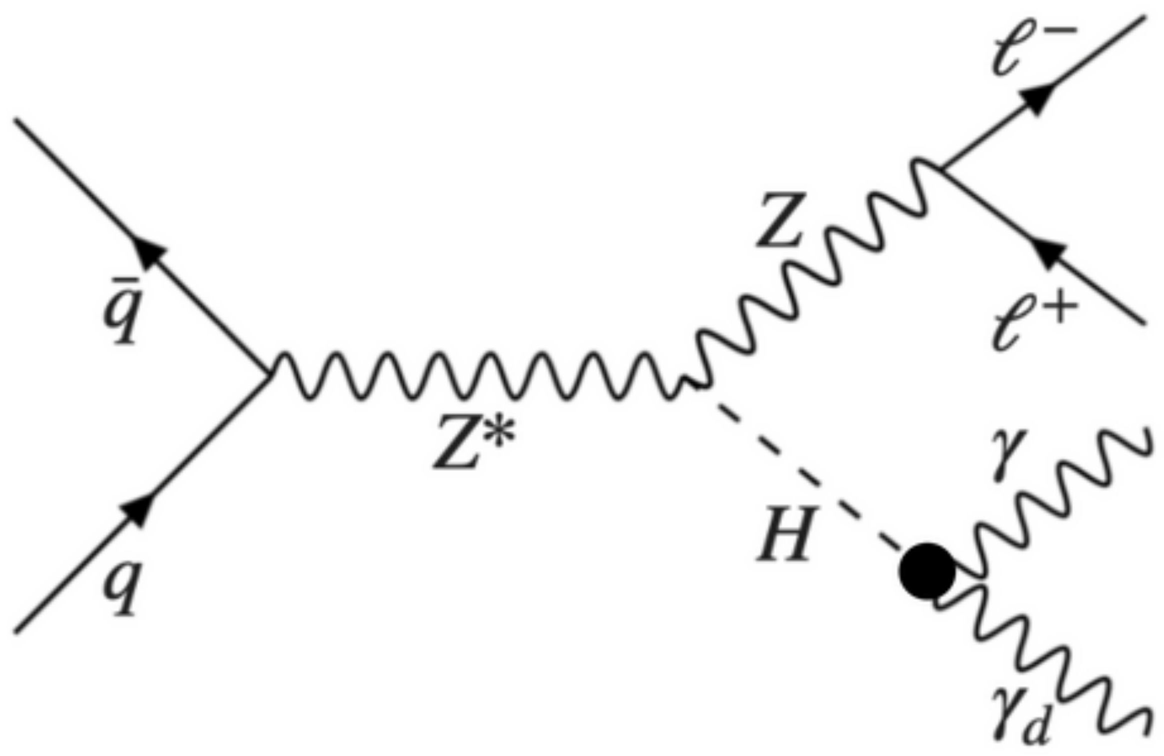


- For this combination,
  - ggF process contribution included for BSM Higgs decay search.
  - Extend H mass to 3 TeV.

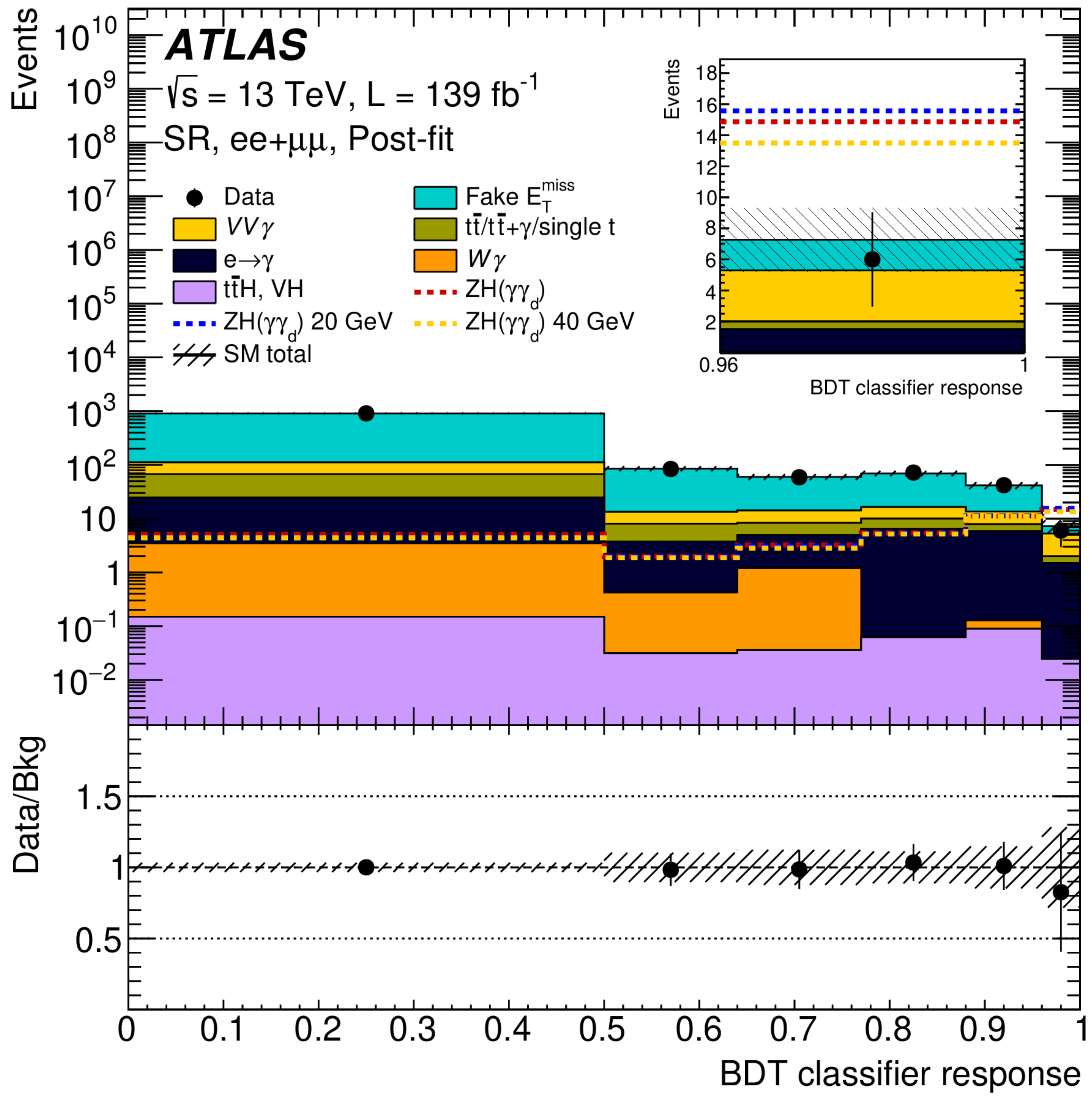
Input overview

ZH channel JHEP 07 (2023) 133

Channels	VBF	ZH	ggF
Trigger	$E_{\mathrm{T}}^{\mathrm{miss}}$	Lepton(s)	Photon
Photons	$= 1, C_{\gamma} > 0.4$	$= 1$	≥ 1
E_{T}^{γ} [GeV]	$\in (15, \max(110, 0.733 \times m_{\mathrm{T}}))$	> 25	> 150
$E_{\mathrm{T}}^{\mathrm{miss}}$ [GeV]	> 150	> 60	> 200
Jets	2 or 3, $m_{j_1 j_2} > 250$ GeV, $\lvert\Delta\eta_{j_1 j_2}\rvert > 3$ $\eta_{j_1} \cdot \eta_{j_2} < 0$, $\Delta\phi_{j_1 j_2} < 2$, $C_{j_3} < 0.7$	≤ 2	≤ 1
Leptons	$= 0\ (e, \mu)$	$= 2$, SFOC $m_{\ell\ell} \in (76, 116)$ GeV	$= 0\ (e, \mu, \tau)$



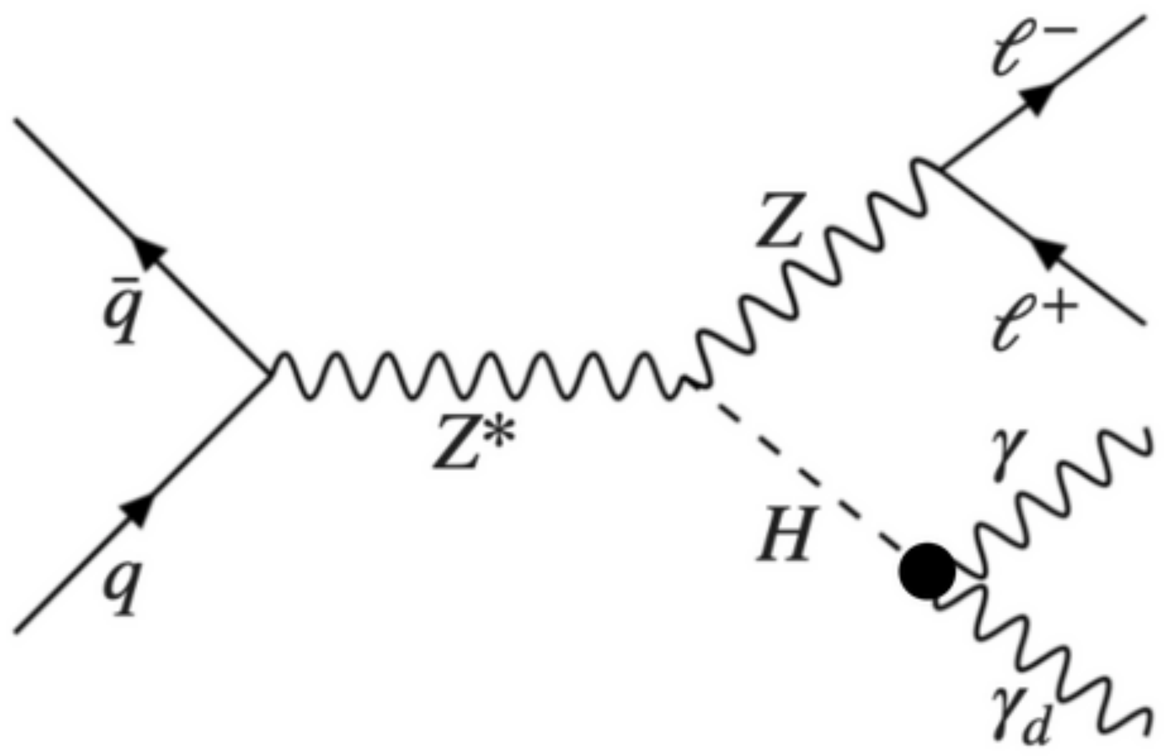
- Topology
  - 1 photon, no more than 2 jets, E_{T}^{miss}
  - 2 same-flavour, oppositely charged (SFOC) leptons within Z mass window
- BDT applied to enhance signal-bkg separation.
- Bkg estimation
  - Irreducible $VV\gamma$ from a dedicated CR.
  - Major $Z\gamma + \text{jets}$, $Z + \text{jets}$ and e-fake γ from data-driven
- Fit to data performed including SR (binned by BDT) and $VV\gamma$ CR.



No significant deviation from SM prediction.

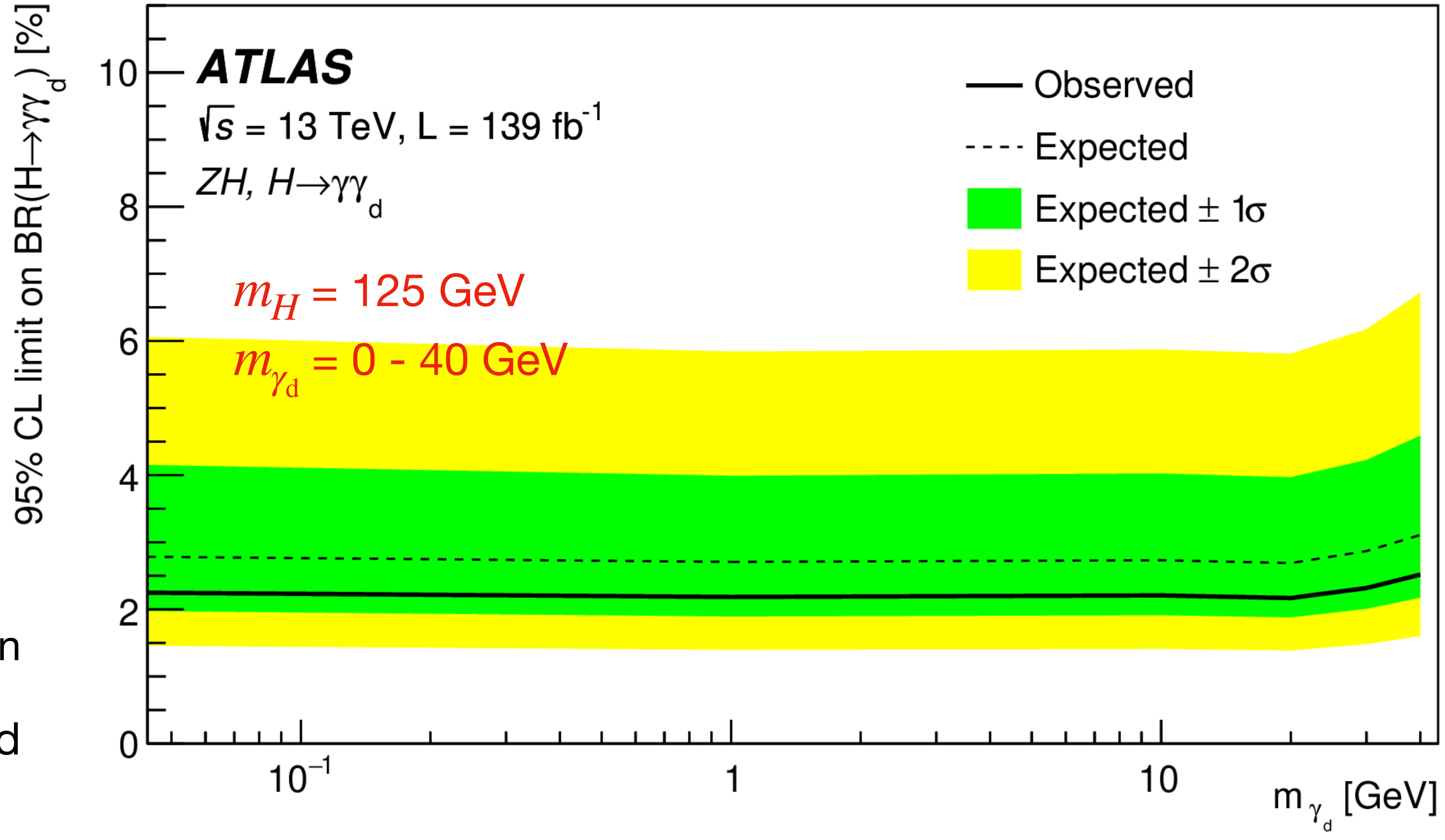
Input overview

ZH channel JHEP 07 (2023) 133



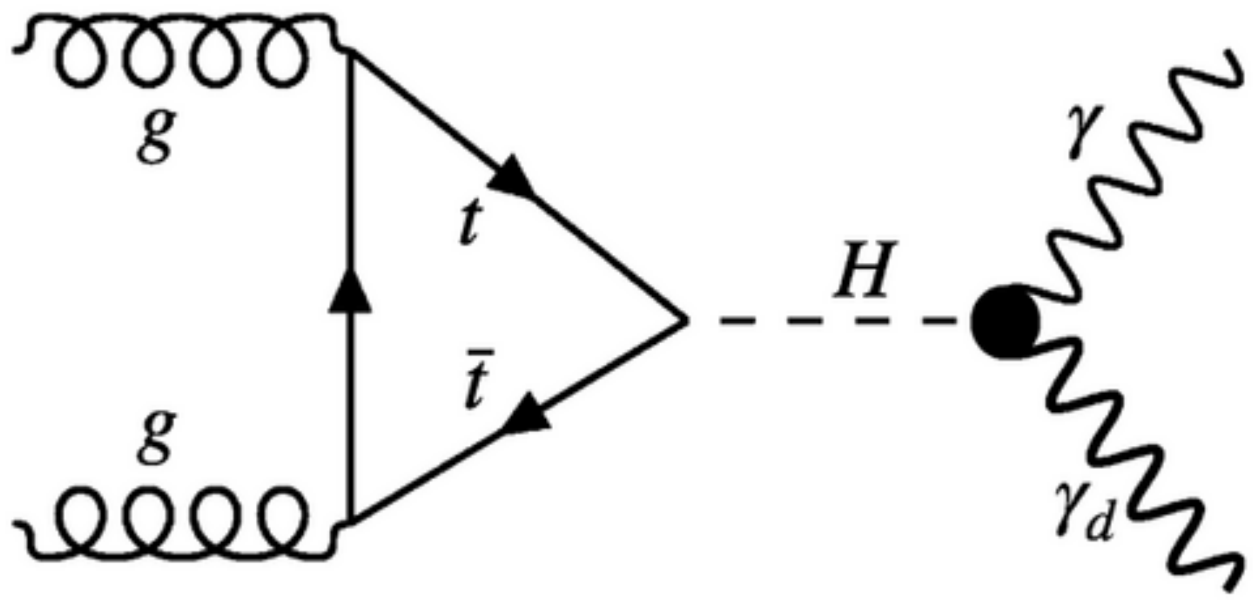
Channels	VBF	ZH	ggF
Trigger	E_T^{miss}	Lepton(s)	Photon
Photons	$= 1, C_\gamma > 0.4$	$= 1$	≥ 1
E_T^γ [GeV]	$\in (15, \max(110, 0.733 \times m_T))$	> 25	> 150
E_T^{miss} [GeV]	> 150	> 60	> 200
Jets	2 or 3, $m_{j_1j_2} > 250$ GeV, $\lvert\Delta\eta_{j_1j_2}\rvert > 3$ $\eta_{j_1} \cdot \eta_{j_2} < 0$, $\Delta\phi_{j_1j_2} < 2$, $C_{j_3} < 0.7$	≤ 2	≤ 1
Leptons	$= 0$ (e, μ)	$= 2$, SFOC $m_{\ell\ell} \in (76, 116)$ GeV	$= 0$ (e, μ, τ)

- ❖ Topology
  - ◉ 1 photon, no more than 2 jets, E_T^{miss}
  - ◉ 2 same-flavour, oppositely charged (SFOC) leptons within *Z* mass window
- ❖ BDT applied to enhance signal-bkg separation.
- ❖ Bkg estimation
  - ◉ Irreducible $VV\gamma$ from a dedicated CR.
  - ◉ Major $Z\gamma + \text{jets}$, $Z + \text{jets}$ and e-fake γ from data-driven
- ❖ Fit to data performed including SR (binned by BDT) and $VV\gamma$ CR.



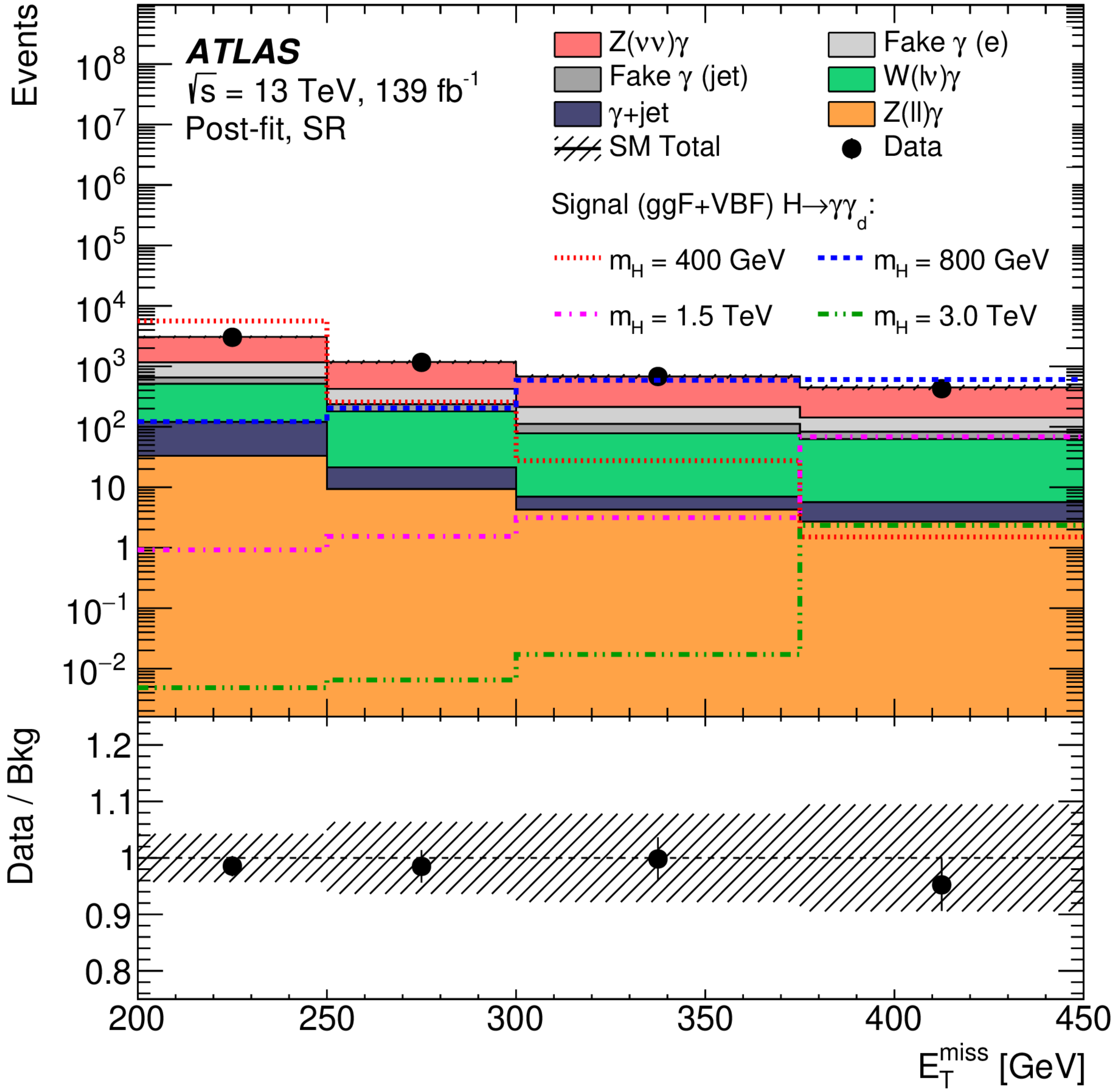
Input overview

ggF channel



Channels	VBF	ZH	ggF
Trigger	E_T^{miss}	Lepton(s)	Photon
Photons	$= 1, C_\gamma > 0.4$	$= 1$	≥ 1
E_T^γ [GeV]	$\in (15, \max(110, 0.733 \times m_T))$	> 25	> 150
E_T^{miss} [GeV]	> 150	> 60	> 200
Jets	2 or 3, $m_{j_1 j_2} > 250$ GeV, $\lvert\Delta\eta_{j_1 j_2}\rvert > 3$	≤ 2	≤ 1
	$\eta_{j_1} \cdot \eta_{j_2} < 0$, $\Delta\phi_{j_1 j_2} < 2$, $C_{j_3} < 0.7$		
Leptons	$= 0$ (e, μ)	$= 2$, SFOC	$= 0$ (e, μ, τ)
		$m_{\ell\ell} \in (76, 116)$ GeV	

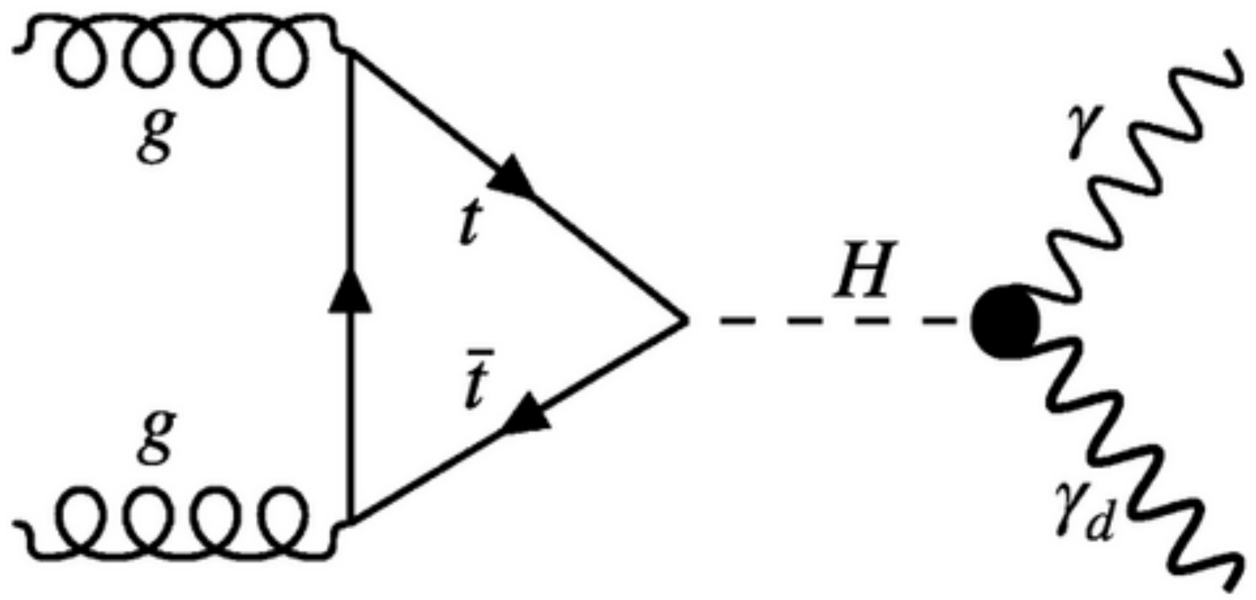
- Topology
  - At least 1 photon, max 1 jet, large E_T^{miss}
  - Lepton (e, μ, τ_{had}) veto
- Background estimation
  - True photon bkgs: $Z(\to \nu\nu)\gamma$, $W(\to \ell\nu)\gamma$ and $Z(\to \ell\ell)\gamma$ from dedicated CRs.
  - e-fake γ and jet-fake γ from data-driven.
- Fit to data performed including all SR (binned by E_T^{miss}) and CRs.
  - Including both VBF and ggF processes.



No significant deviation from SM prediction.

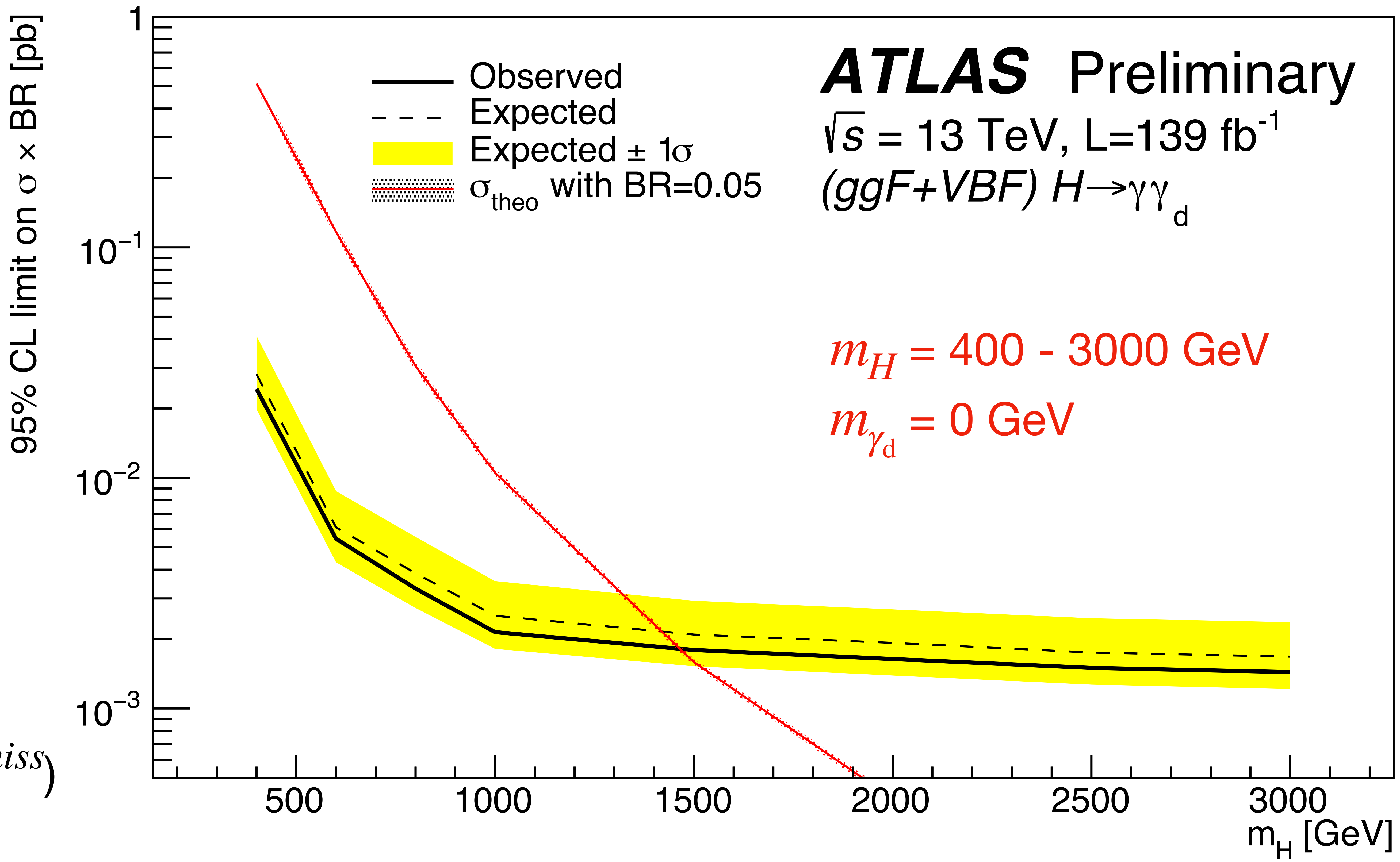
Input overview

ggF channel



- Topology
  - At least 1 photon, max 1 jet , large E_T^{miss}
  - Lepton $(e,\ \mu,\ \tau_{had})$ veto
- Background estimation
  - True photon bkgs: $Z(\to \nu\nu)\gamma$, $W(\to \ell\nu)\gamma$ and $Z(\to \ell\ell)\gamma$ from dedicated CRs.
  - e-fake γ and jet-fake γ from data-driven.
- Fit to data performed including all SR (binned by E_T^{miss}) and CRs.
  - Including both VBF and ggF processes.

Channels	VBF	ZH	ggF
Trigger	E_T^{miss}	Lepton(s)	Photon
Photons	$= 1, C_\gamma > 0.4$	$= 1$	≥ 1
E_T^γ [GeV]	$\in (15, \max(110, 0.733 \times m_T))$	> 25	> 150
E_T^{miss} [GeV]	> 150	> 60	> 200
Jets	2 or 3, $m_{j_1 j_2} > 250$ GeV, $\lvert\Delta\eta_{j_1 j_2}\rvert > 3$ $\eta_{j_1} \cdot \eta_{j_2} < 0$, $\Delta\phi_{j_1 j_2} < 2$, $C_{j_3} < 0.7$	≤ 2	≤ 1
Leptons	$= 0\ (e, \mu)$	$= 2$, SFOC $m_{\ell\ell} \in (76, 116)$ GeV	$= 0\ (e, \mu, \tau)$



Stat. combination

Systematic uncertainty correlation

- Uncertainties from **luminosity**, **pile-up modelling** are correlated.

- **Experimental uncertainties**: correlated where appropriate, exceptions are:
  - Uncertainties related to same objects but **implemented with different schemes** among input channels (e.g Jet-Energy-Resolution).
  - Uncertainties **heavily constrained or pulled** in original input analyses.

- **Background modelling uncertainties**
  - Uncorrelated since bkg composition and phase space are different.

- **Signal modelling uncertainties**
  - Stemming from choice of parton distribution functions and QCD calculations; minor impact on final results; uncorrelated.

Stat. combination -- SM Higgs

Uncertainty source	$\Delta\mathcal{B}_{group}/\Delta\mathcal{B}_{total}[\%]$
Theory uncertainties	49
Signal modelling	2.2
Background modelling	47
Experimental uncertainties	63
Luminosity, pile-up	< 0.1
Jets, E_T^{miss}	40
Electrons, muons	11
Fake background	35
MC statistical uncertainty	36
Systematic uncertainties	75
Statistical uncertainty	66
Total uncertainty	100

- Comparable impacts from Syst. and Stat. uncertainties.
- Leading syst. uncertainties from bkg modelling, Jets, E_T^{miss}, Fake bkg and MC stat.

Stat. combination -- BSM Higgs

Uncertainty source	$\Delta\mathcal{B}_{\text{group}}/\Delta\mathcal{B}_{\text{total}}$ [%]				
m_H [GeV]	400	800	1000	2000	3000
Theory uncertainties	30	27	28	40	35
Signal modelling	2.2	4.6	5.2	6.9	2.0
Background modelling	30	27	27	38	34
Experimental uncertainties	64	51	45	37	41
Luminosity, pile-up	4.6	2.6	2.9	2.8	2.3
Jets, $E_{\mathrm{T}}^{\mathrm{miss}}$	22	12	11	13	14
Electrons, muons	20	23	18	13	14
Fake background	52	41	35	25	29
MC statistical uncertainty	20	17	19	19	23
Statistical uncertainty	75	84	87	85	86
Systematic uncertainties	67	55	49	53	52
Total uncertainty	100	100	100	100	100

- Stat. uncertainty dominant at higher *H* masses.
- Leading syst. uncertainties from fake-bkg estimate and bkg modelling. Others share ~20% impact each.