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ATLAS EXPERIMENT

Search for dark matter in events with missing transverse momentum and a Higgs boson decaying to two photons

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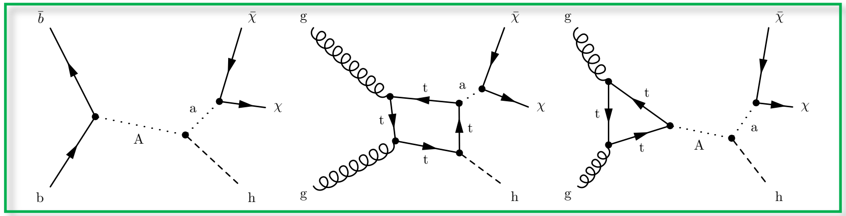
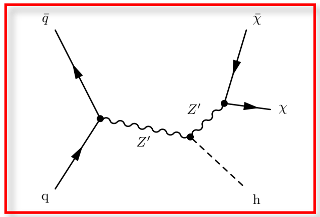
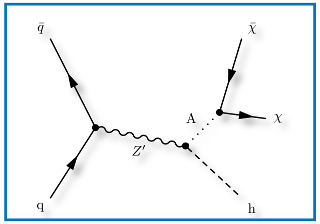
Introduction

- Search for possible DM candidates in three simplified model **Z'B**, **Z'-2HDM** and **2HDM+a** model.

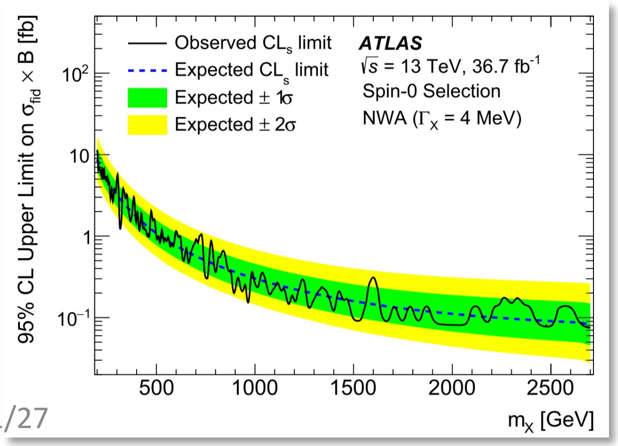


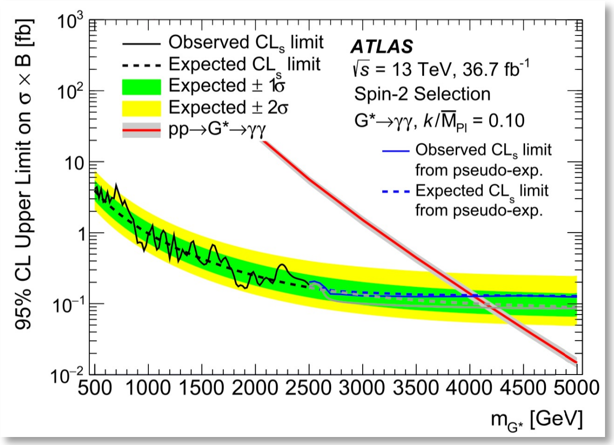




- The diphoton channel is triggered by photon pair, allows much **lower** and **better resolved** E_T^{miss} and has **good resolution** and **small background**.

- In the previous study, no significant deviation from the SM is observed. [Physics Letters B 775 (2017) 105–125]





Samples

- ATLAS full Run-II data, 139 fb^{-1}, ~4 times than previous study.

- Signal MC sample, more details in backup

- **Z'B :** $m_{Z'}$ in [10, 2000] GeV, m_χ in [1, 1000] GeV
- **Z'-2HDM :** $m_{Z'}$ in [400, 1600] GeV, m_A in [200, 600] GeV, m_χ =100GeV
- **2HDM+a :** $sin\theta$ scan, 2D scan on $m_A - m_a$ and $tan\beta - m_a$ plane

- Background samples
  - SM $H \to \gamma\gamma$: ggF, VBF, WH, ZH, $t\bar{t}$H, tHqb and tWH
  - non-resonant $\gamma\gamma$, $\gamma + \mathrm{jet}$, $V\gamma$ and $V\gamma\gamma$(V=W,Z)

Object and event selection

Photon

- Tight identification criteria
- $P_T > 25$GeV
- |η| < 2.37, excluding 1.37 < |η| < 1.52
- Isolation requirement:
  - Topoetcone$\gamma 1$/pT$\gamma 1$ < 0.065
  - ptcone$\gamma 1$/ pT$\gamma 1$ < 0.05
- Remove electrons, muons and jets within ΔR=0.4 of photon.

Leptons

- $P_T > 10\text{GeV}$
- |η| < 2.47, excluding 1.37 < |η| < 1.52 for electron
- FCLoose(electron),PflowLoose_FixedRad(muon)
- $|Z_0|\sin\theta < 0.5\text{mm}$, $|d_0|/\sigma_{d_0}$< 5.0(3.0) for electron (muon)
- Remove jets within ΔR=0.2 of electron

MET

- Both di-photon(NN) and hardest vertex are used.

Event selection

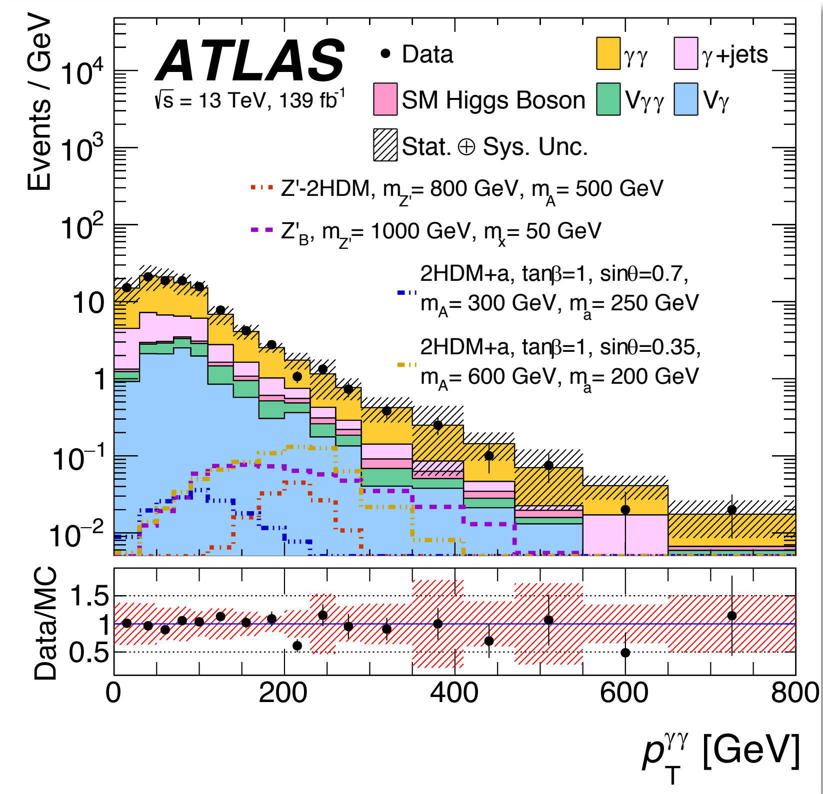
- Trigger selection: diphoton trigger, $P_{T,\gamma 1} >$ 35GeV, $P_{T,\gamma 2} >$ 25GeV
- pT $/m_{\gamma\gamma}$ > 0.35(0.25) for $\gamma_1(\gamma_2)$
- No leptons
- MET > 90 GeV
- $105 < m_{\gamma\gamma} < 160$ GeV
- Δ MET < 30 GeV, MET(diphoton) – MET(hardestvertex)

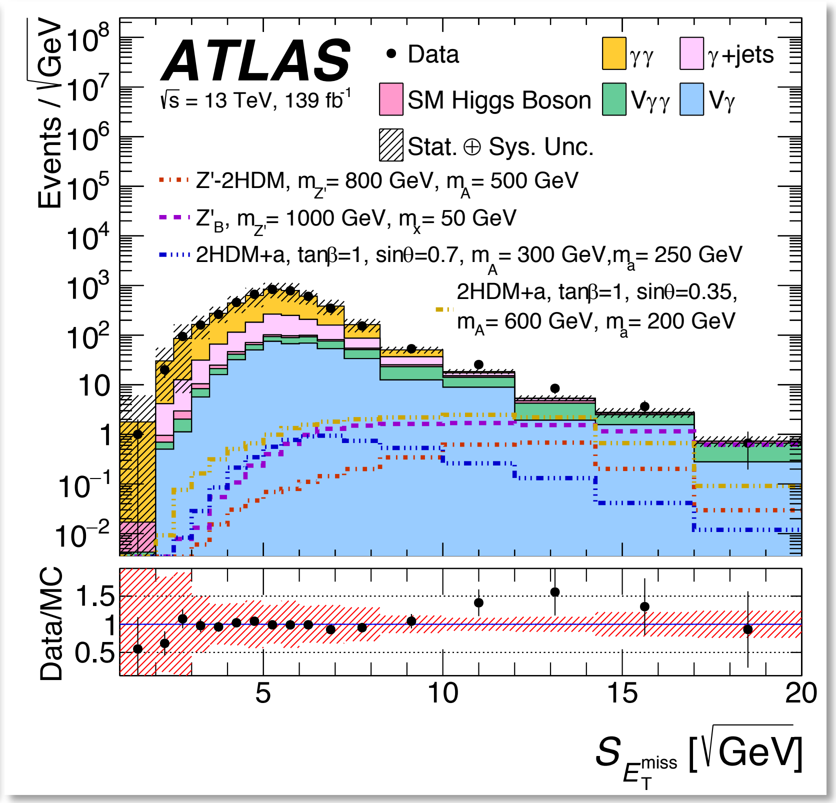
Jets

- $P_T > 25$GeV
- PFlow Jets, |η| < 4.4
- JVT < 0.5 for jets with pT < 60 GeV and |η| < 2.4
- Remove electrons and muons within $\Delta R = 0.4$ of jet

Control plots

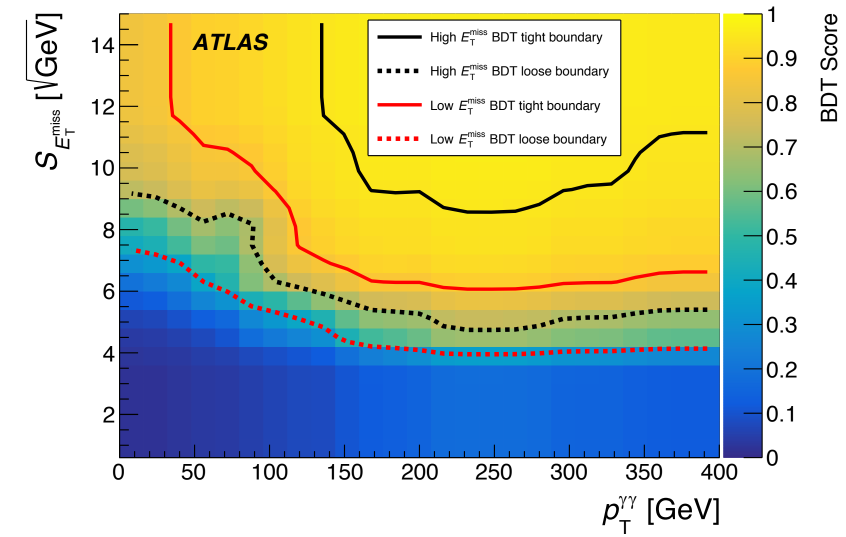
Data and MC distributions of pT$\gamma\gamma$ and significance of MET, both photon requirements and event selection cuts applied .

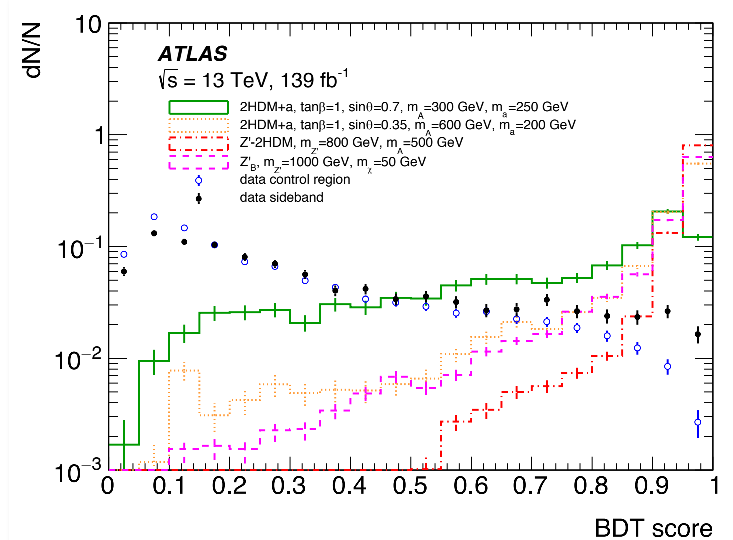




Main backgrounds: non-resonant $\gamma\gamma$, γj.

- Perform BDT categorization to the event passing **pre-selection**.
- Input variables : **pTγγ, significance of MET**





Category	E_T^{miss} requirement	BDT score range
High E_T^{miss} BDT tight	$E_T^{miss} > 150$ GeV	$0.950 <$ BDT score < 1
High E_T^{miss} BDT loose	$E_T^{miss} > 150$ GeV	$0.694 <$ BDT score < 0.950
Low E_T^{miss} BDT tight	$E_T^{miss} < 150$ GeV	$0.864 <$ BDT score < 1
Low E_T^{miss} BDT loose	$E_T^{miss} < 150$ GeV	$0.386 <$ BDT score < 0.864

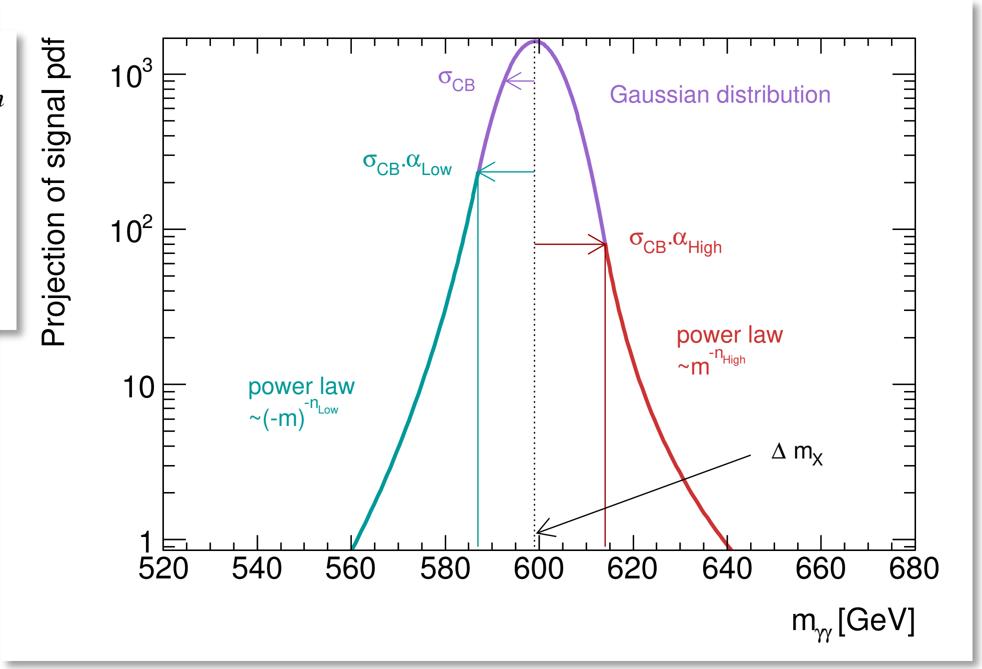
Gain wrt cut-based selection up to **140 %**,depending on specific model.

Signal and resonant background modelling

- Double side crystal ball (DSCB) function for the BSM Higgs signal and SM Higgs background.

$$N \cdot \begin{cases} e^{-t^2/2} & \text{if } -\alpha_{Low} \leq t \leq \alpha_{High} \\ \dfrac{e^{-0.5\alpha_{Low}^2}}{\left[\frac{\alpha_{Low}}{n_{Low}}\left(\frac{n_{Low}}{\alpha_{Low}}-\alpha_{Low}-t\right)\right]^{n_{Low}}} & \text{if } t < -\alpha_{Low} \\ \dfrac{e^{-0.5\alpha_{High}^2}}{\left[\frac{\alpha_{High}}{n_{High}}\left(\frac{n_{High}}{\alpha_{High}}-\alpha_{High}+t\right)\right]^{n_{High}}} & \text{if } t > \alpha_{High}, \end{cases}$$

$$t = \Delta m_X/\sigma_{CB},\ \Delta m_X = m_X - \mu_{CB}$$



- Different BSM signal parameterizations for different models.

Non-resonant background modelling

- The 2x2D sideband method is used to estimate the di-photon purities.

Purity	γ–jet	jet–jet	$\gamma\gamma$
Preselection	0.18 ± 0.03	0.01 ± 0.01	0.80 ± 0.03

- Use the purities to build the background template, scaled to the sideband of data, [105,120] ∪ [130,160] GeV

- Background fit function : perform S+B fit to the background-only MC template, measure the spurious signal .

Exponential function

Category	$\Delta N_{\text{sig}}^{\text{bkg model}}$	$\Delta N_{\text{sig}}^{\text{bkg model}}/N_{\text{bkg}}^{\text{non-res.}}$ [%]
High $E_{\text{T}}^{\text{miss}}$ BDT tight	0.54	6.8
High $E_{\text{T}}^{\text{miss}}$ BDT loose	1.07	4.2
Low $E_{\text{T}}^{\text{miss}}$ BDT tight	0.62	6.3
Low $E_{\text{T}}^{\text{miss}}$ BDT loose	2.64	2.0

Systematic uncertainties

Source	Signals [%]	Backgrounds [%]	
		SM Higgs boson	Non-resonant background
Experimental			
Luminosity	1.7	1.7	– – –
Trigger efficiency	1.0	1.0	– – –
Vertex selection (inclusive cat.)	0.01	0.01	– – –
Photon energy scale	1.0	1.2	– – –
Photon energy resolution	0.3	0.4	– – –
Photon identification efficiency	1.3	1.3	– – –
Photon isolation efficiency	1.3	1.4	– – –
ATLFASTII simulation	2.0	– – –	– – –
$E_{\mathrm{T}}^{\mathrm{miss}}$ reconstruction and jet uncertainty	2.8	1.7	– – –
Pile-up reweighting	2.3	2.0	– – –
Signal efficiency interpolation	< 13	– – –	– – –
Non-resonant background modelling	– – –	– – –	6.8
Theoretical			
Factorization and renormalization scale in migration	1.3	3.5	– – –
PDF+α_s in migration	1.2	1.0	– – –
Factorization and renormalization scale in cross section	– – –	2.8	– – –
PDF+α_s in cross section	– – –	2.8	– – –
Multi-parton interactions, ISR/FSR, hadronization	3.0	3.0	– – –
$B(H \to \gamma\gamma)$	1.7	1.7	– – –

Experimental

Theoretical

- Uncertainties on the most sensitive category are shown.
- The dominate uncertainty is from the **signal efficiency interpolation**.
- An interpolation method is used to efficiently create new samples from existing fully simulated ones.

A summary of the experimental and theoretical uncertainties in terms of the relative impact on the number of events.

Statistic procedures

- A likelihood fit of the $m_{\gamma\gamma}$ distribution is used to derive the results.

$$\mathcal{L} = \prod_{c=1}^{4} \left(\mathrm{Pois}(n_c | N_c(\theta)) \cdot \prod_{i=1}^{n_c} f_c(m^i_{\gamma\gamma}, \theta) \cdot G(\theta) \right)$$

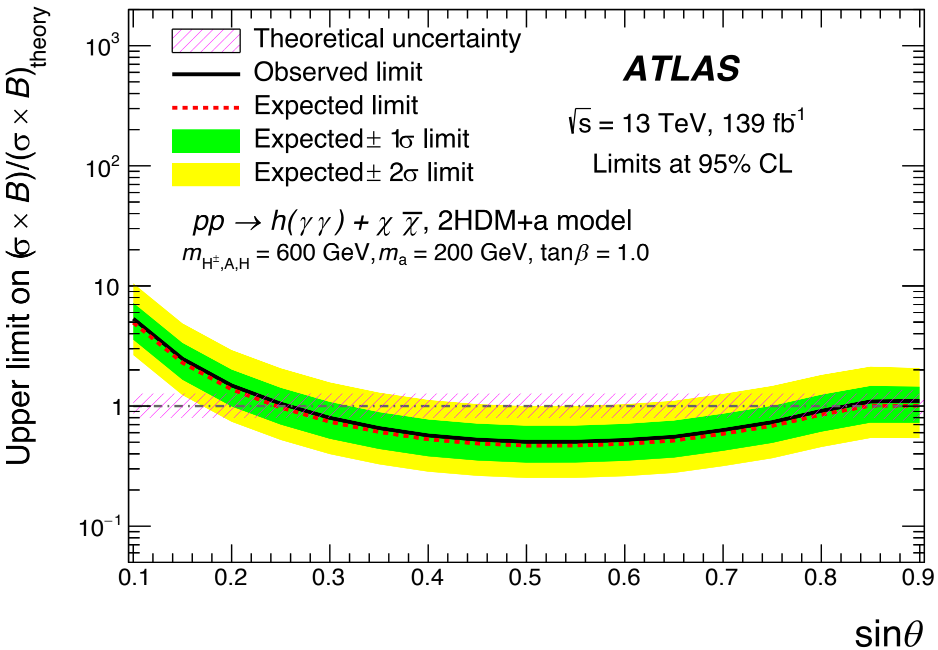
Poisson item PDF of $m_{\gamma\gamma}$ Gaussian constraint of NPs

$$N_c(\theta) = \mu \cdot N_{\mathrm{BSM},c}(\theta_{\mathrm{yield}}) + N_{\mathrm{Higgs},c}(\theta_{\mathrm{yield}}) + \Delta N^{\text{bkg model}}_{\mathrm{sig},c} \cdot \theta^{\text{bkg model}}_{\mathrm{sig},c} + N^{\text{non-res.}}_{\mathrm{bkg},c}$$

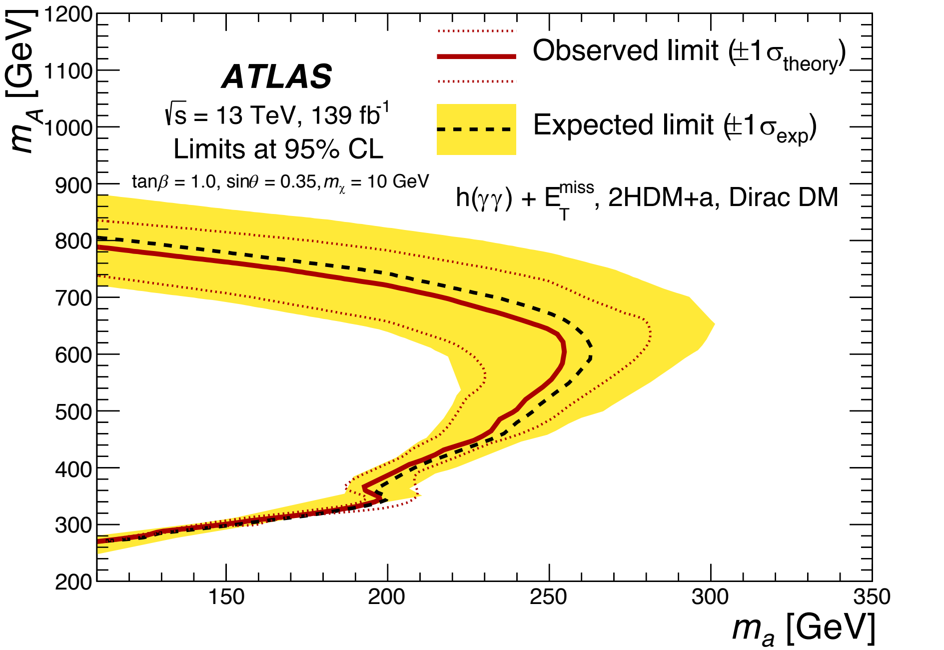
- Test statistic of upper limits(95%C.L.), based on the likelihood ratio approach.

$$\tilde{q}_\mu = \begin{cases} -2\ln\tilde{\lambda}(\mu) & \hat{\mu} \le \mu \\ 0 & \hat{\mu} > \mu \end{cases} = \begin{cases} -2\ln\frac{L(\mu,\hat{\hat{\boldsymbol{\theta}}}(\mu))}{L(0,\hat{\hat{\boldsymbol{\theta}}}(0))} & \hat{\mu} < 0\ , \\ -2\ln\frac{L(\mu,\hat{\hat{\boldsymbol{\theta}}}(\mu))}{L(\hat{\mu},\hat{\boldsymbol{\theta}})} & 0 \le \hat{\mu} \le \mu\ , \\ 0 & \hat{\mu} > \mu\ . \end{cases}$$

Results of 2HDM+a model



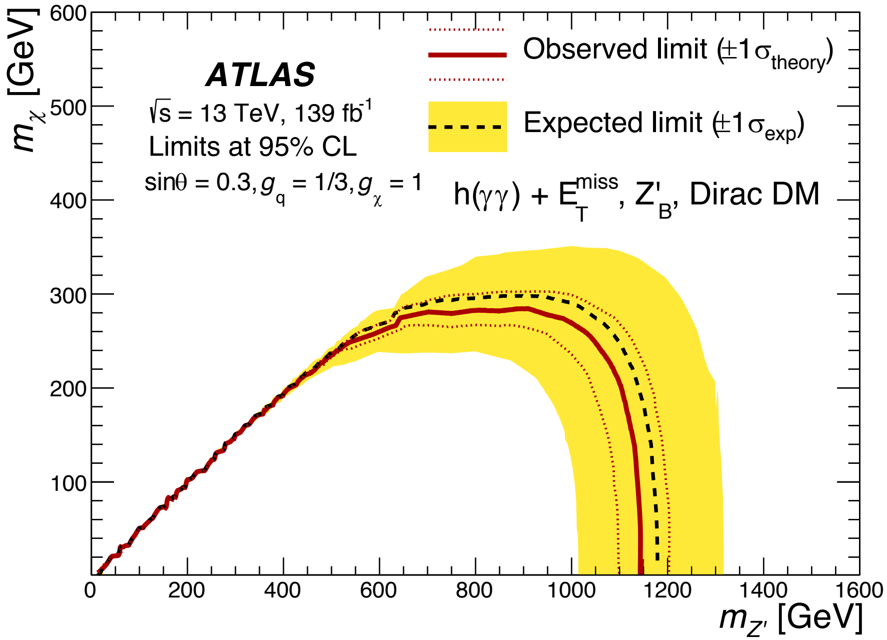
Limit scan of $sin\theta$ in 2HDM+a model

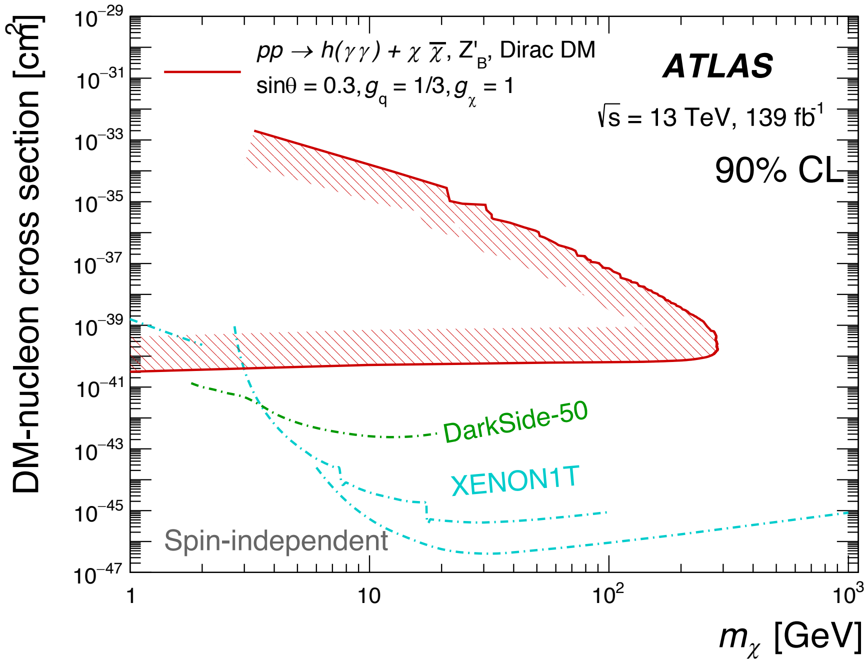


Exclusion limit contours at 95% CL in the m_A–m_a plane

- The data excludes a vast domain of possible mixing angle θ values.
- The highest excluded m_A is 800 GeV for m_a = 110 GeV
- The maximum excluded m_a reaches about 260 GeV for mA = 600 GeV.

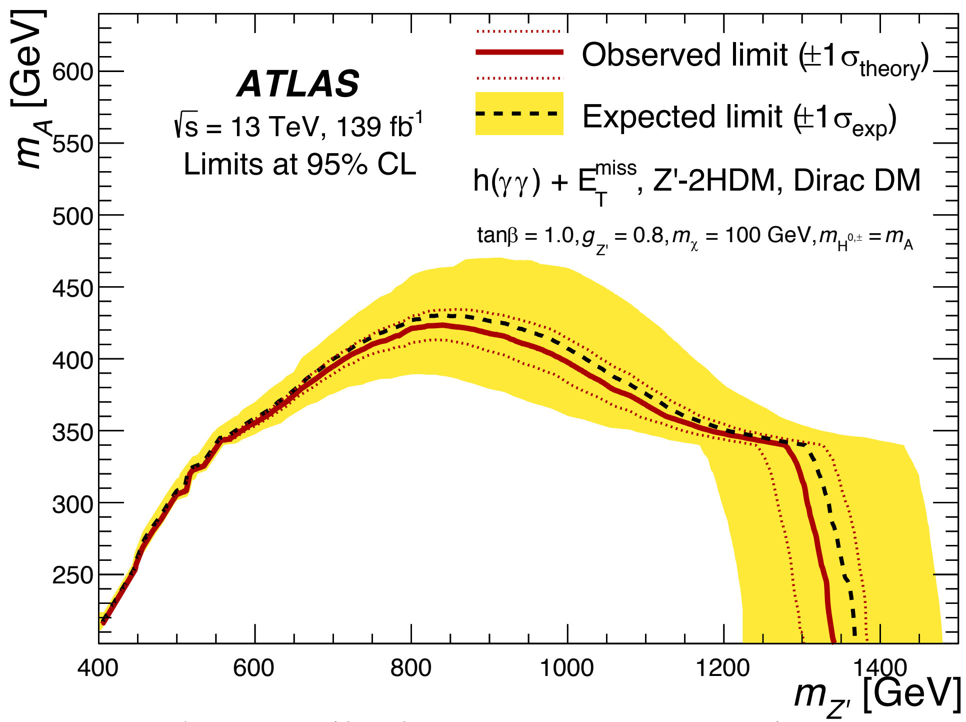
Results of Z'B model





- The limit extends up to 1150 GeV in mZ′ .
- The maximum limit on m_χ reaches 280 GeV, increases by more than 100 GeV.
- Extract the spin-independent DM-nucleon XS(90%C.L.), show the complementary result with direct search result.

Results of Z’-2HDM model



95% CL limit on $m_{Z'} - m_A$ plane

The maximum limit on m_A reaches 420 GeV for a Z′ mass of $m_{Z'}$ = 825 GeV.

Summary

- A search for dark matter on **Z'B**, **Z'-2HDM** and **2HDM+a** model in the events with $\boldsymbol{H(\gamma\gamma)} + \boldsymbol{MET}$ with the 139 fb^{-1} data is presented in JHEP10(2021)013
- Z'B
  - Limit of $m_{Z'}$ extends up to 1150 GeV, **150 GeV larger** than previous.
  - Limit of m_χ increases **more than 100 GeV** than before.
- Z'-2HDM : Limit of m_A reaches to 420 GeV.
- 2HDM+a
  - Excludes a vast domain of possible mixing angle θ values.
  - Highest excluded m_A is 800 GeV for m_a = 110 GeV.

Backup