Search for dark matter in events with missing transverse momentum and a Higgs boson decaying into a photon pair in pp collisions at $\sqrt{s}$ = 13 TeV with the ATLAS detector

Yan Qian

University of Wisconsin

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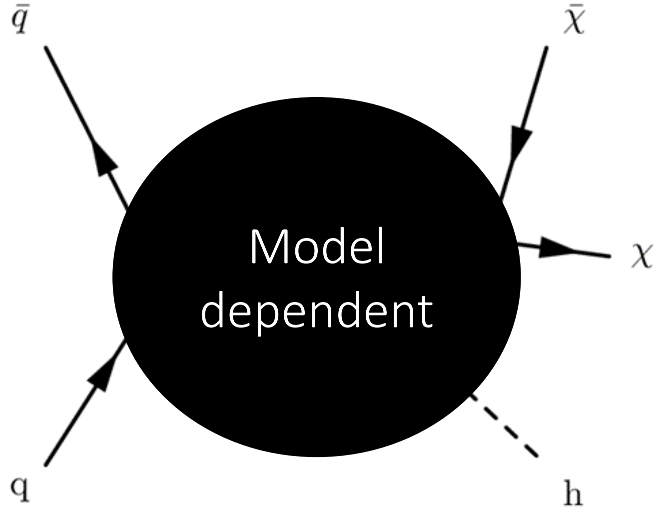
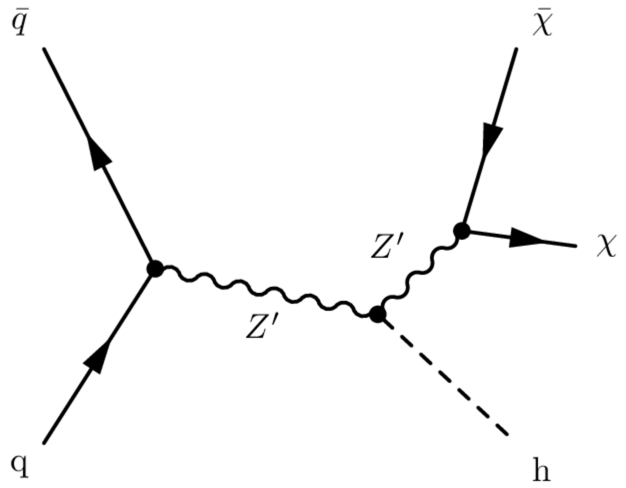
(arXiv:2104.13240)

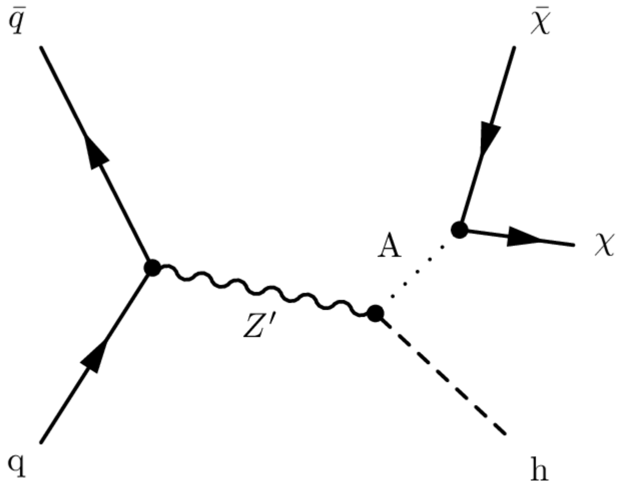
Introduction

- Dark matter (DM) search at the Large Hadron Collider (LHC)
- Key assumption: dark matter has a particle nature

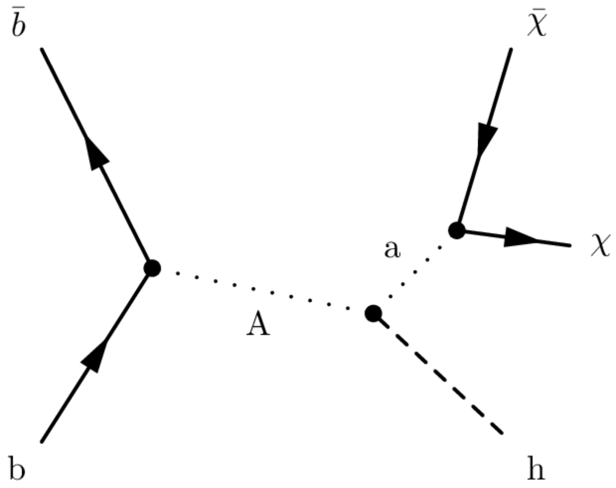




Z'_B model



Z'-2HDM model



2HDM+a model
(one of the diagrams)

Introduction

- DM particles are expected to escape detection at collider: search for final states with missing transverse momentum (E_T^{miss})

- This analysis: search for DM particles (χ) in association with the SM Higgs boson (h) (arXiv:2104.13240)

- Aim for (large) $E_T^{miss} + h \rightarrow \gamma\gamma$ decays

Data and Simulation

- Use 139 fb^{-1} of pp collision data at $\sqrt{s}$ = 13 TeV, collected by the ATLAS detector between 2015 and 2018

- But further for the analysis to:

i. design the event selection

ii. categorize events,

iii. estimate systematic uncertainties of statistical inference (for the presence of a possible DM signal in the dataset)

➢ Use Monte Carlo (MC) generated samples

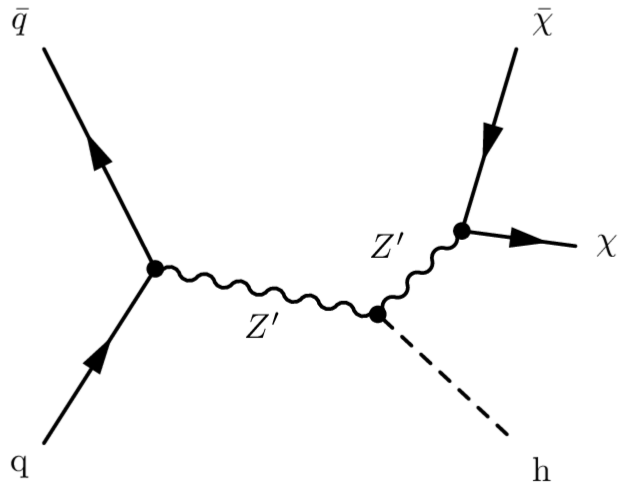
Simulation samples

- DM signals: MadGraph5 + Pythia, with the following simulated variable spaces

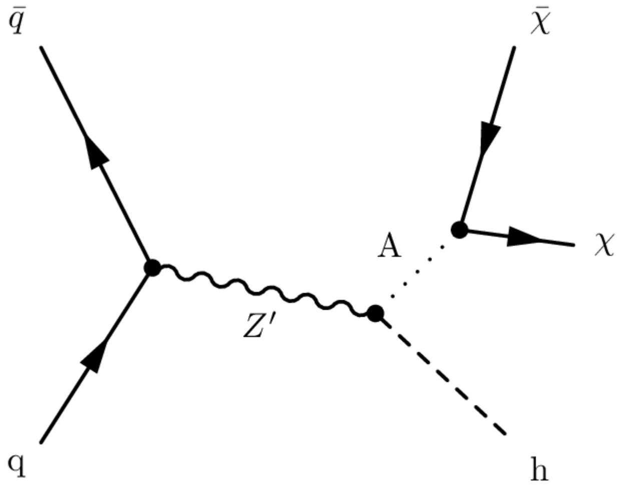
i. For Z'_B model: $m_{Z'}$, m_χ

ii. For Z'-2HDM model: $m_{Z'}$, m_A (and fix m_χ = 100 GeV)

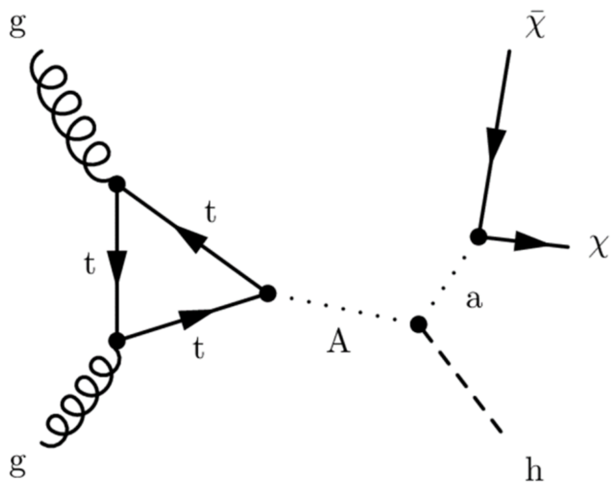
iii. For 2HDM+a model: m_A, m_a, tanβ, sinθ (and fix m_χ = 10 GeV)



Z'_B model



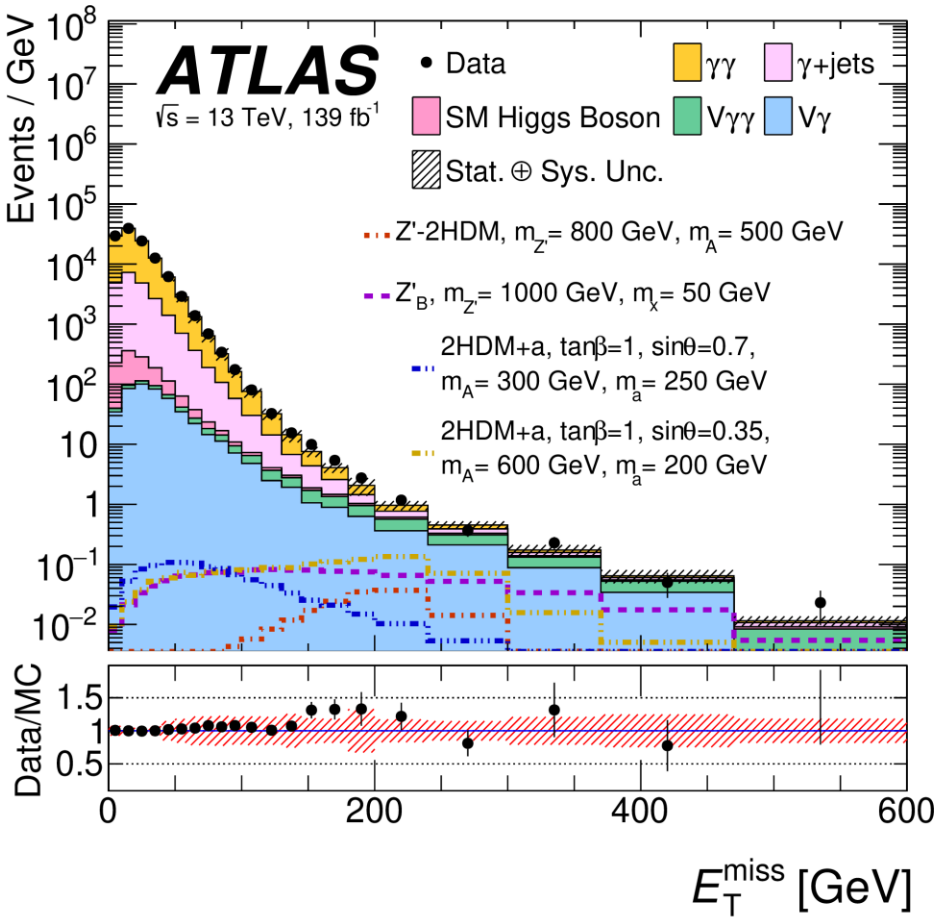
Z'-2HDM model



2HDM+a model
(another one of the diagrams)

Event selection

Need to know: diphoton mass for this



- Standard di-photon trigger:

i. At least 2 photons

ii. and $p_T > 0.35\ (0.25) \times\ m_{\gamma\gamma}$ for leading (sub-leading) photon

iii. and $m_{\gamma\gamma}$ in [105, 160] GeV

- Electrons/muons veto

- Missing transverse momentum:

i. After di-photon trigger, $E_T^{miss} > 90$ GeV

ii. and $\Delta E_T^{miss} < 30$ GeV

(Here ΔE_T^{miss} = E_T^{miss} of (neural-network-selected) diphoton vertex minus E_T^{miss} of the hardest vertex)

Machine Learning: BDT

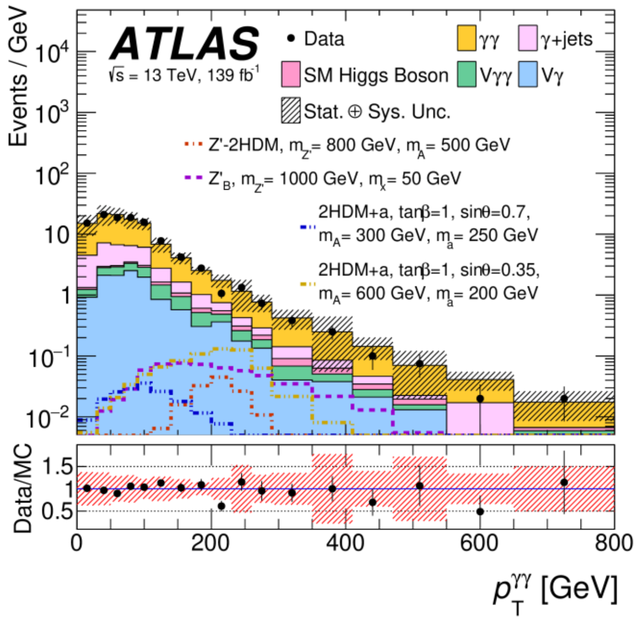
- Boosted Decision Tree (XGBoost BDT)
- BDT model is trained based on

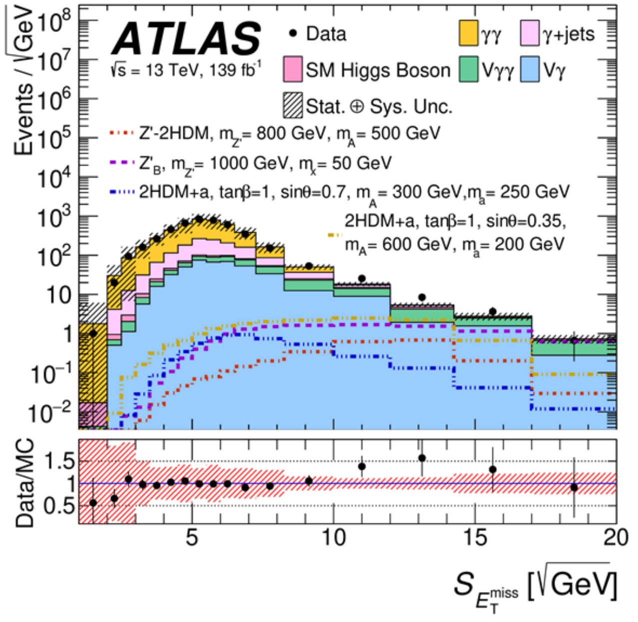
i. the observed diphoton transverse momentum $p_T^{\gamma\gamma}$, and

ii. Missing ET significance

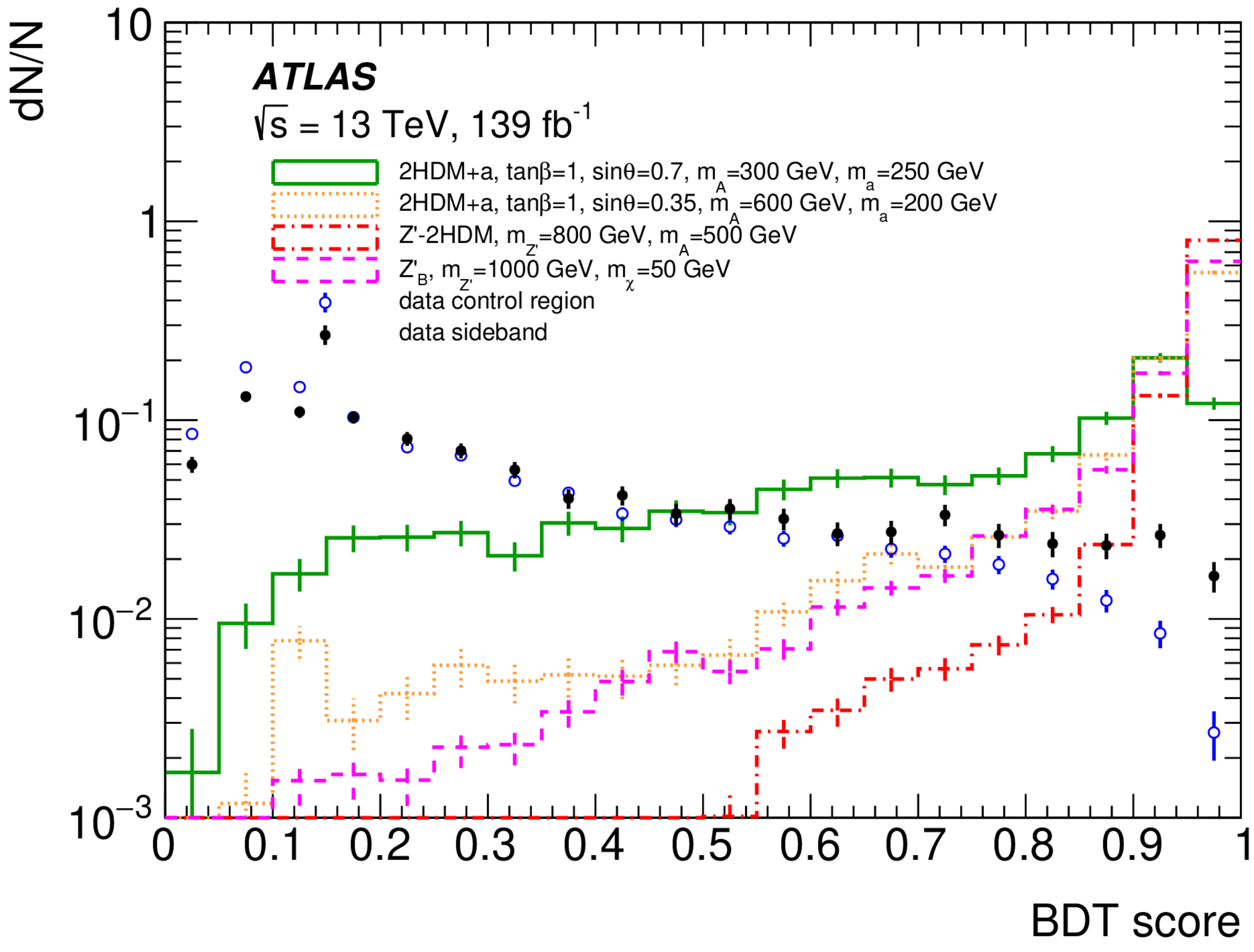
$$S_{E_T^{miss}} = E_T^{miss}/\sqrt{\sum E_T}$$

(From a single 2HDM+a point:
m_A = 300 GeV, m_a = 250 GeV, tanβ = 1, sinθ = 0.7)





Machine Learning: BDT

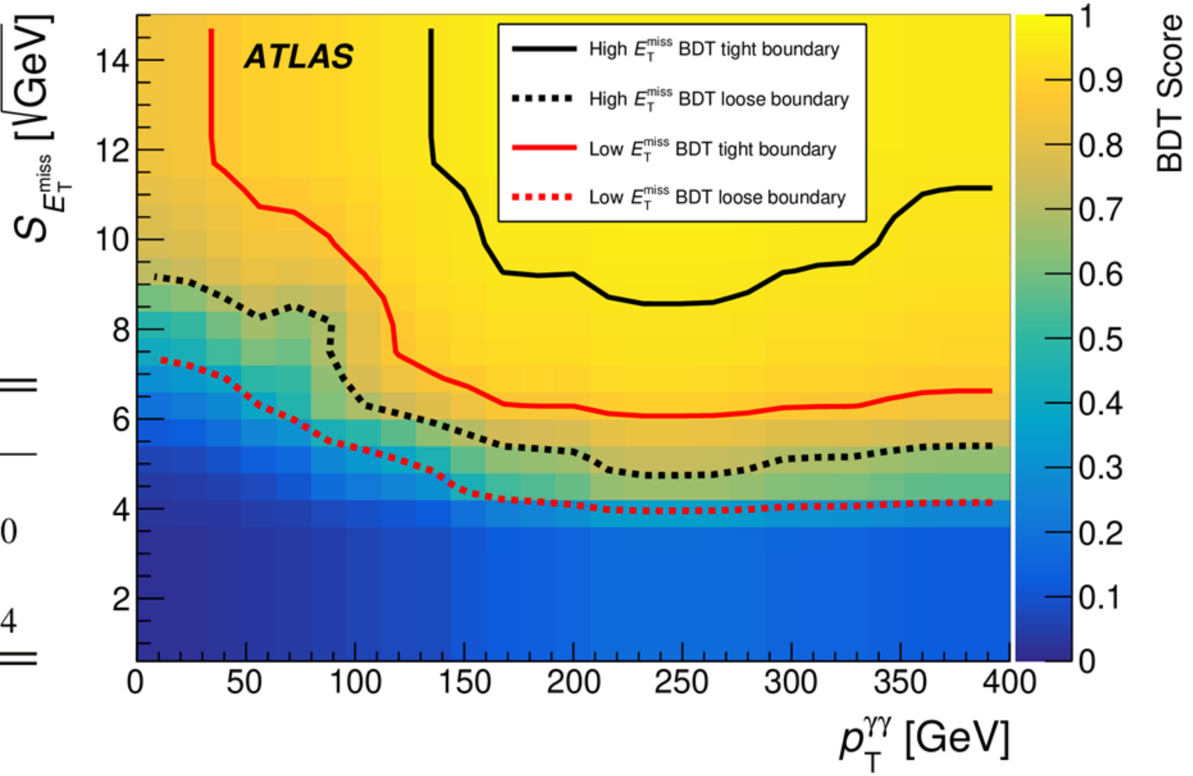


- Output: BDT score between 0 and 1, with 1 being more signal-like and 0 being more background-like

Categorization based on BDT scores

- BDT scores are used to separate events together with E_T^{miss}
- Events are divided into 4 signal regions:

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



Results: event yields

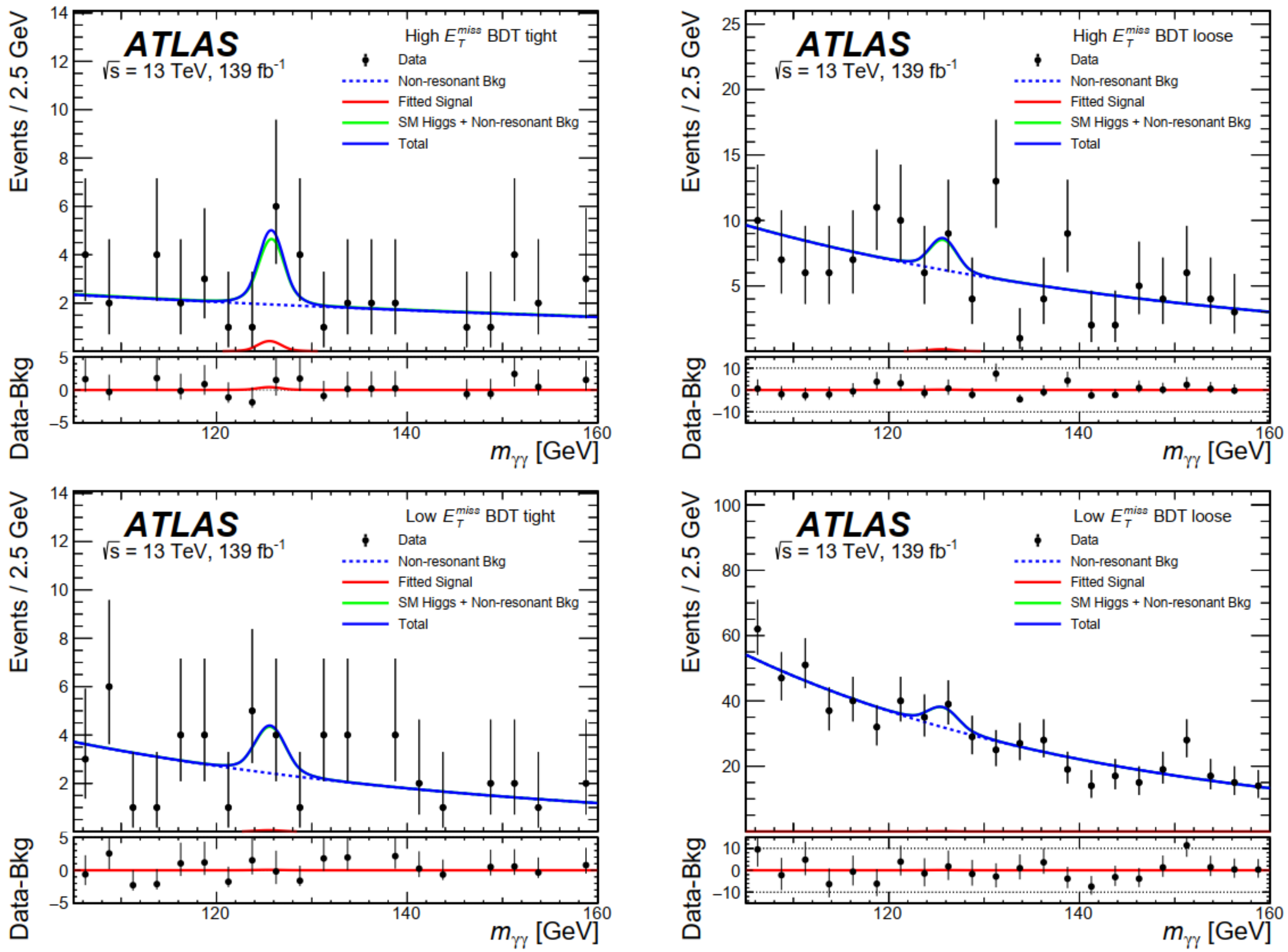
- Event yields and uncertainties after a fit to data in the range of $120 < m_{\gamma\gamma} < 130$ GeV

Category	High E_T^{miss} BDT tight	High E_T^{miss} BDT loose	Low E_T^{miss} BDT tight	Low E_T^{miss} BDT loose
Data	12	29	11	143
Backgrounds				
SM Higgs boson	3.74 ± 0.25	3.40 ± 0.28	3.12 ± 0.23	9.9 ± 1.5
Non-resonant	7.8 ± 1.3	25.3 ± 2.3	9.8 ± 1.5	130 ± 5
Total	11.6 ± 1.3	28.7 ± 2.3	12.9 ± 1.5	140 ± 5
Z'_B model, $m_{Z'} = 1000$ GeV, $m_\chi = 50$ GeV				
Signal yields	0.7 ± 3.1	0.1 ± 0.6	0.1 ± 0.6	0.1 ± 0.6
Z'-2HDM model, $m_A = 800$ GeV and $m_\chi = 500$ GeV				
Signal yields	0.6 ± 3.1	0.1 ± 0.4	0.05 ± 0.26	0.03 ± 0.17
2HDM+a model, $m_A = 600$ GeV, $m_a = 200$ GeV, $\tan\beta = 1.0$, $\sin\theta = 0.35$				
Signal yields	0.6 ± 3.1	0.2 ± 1.2	0.1 ± 0.5	0.1 ± 0.7

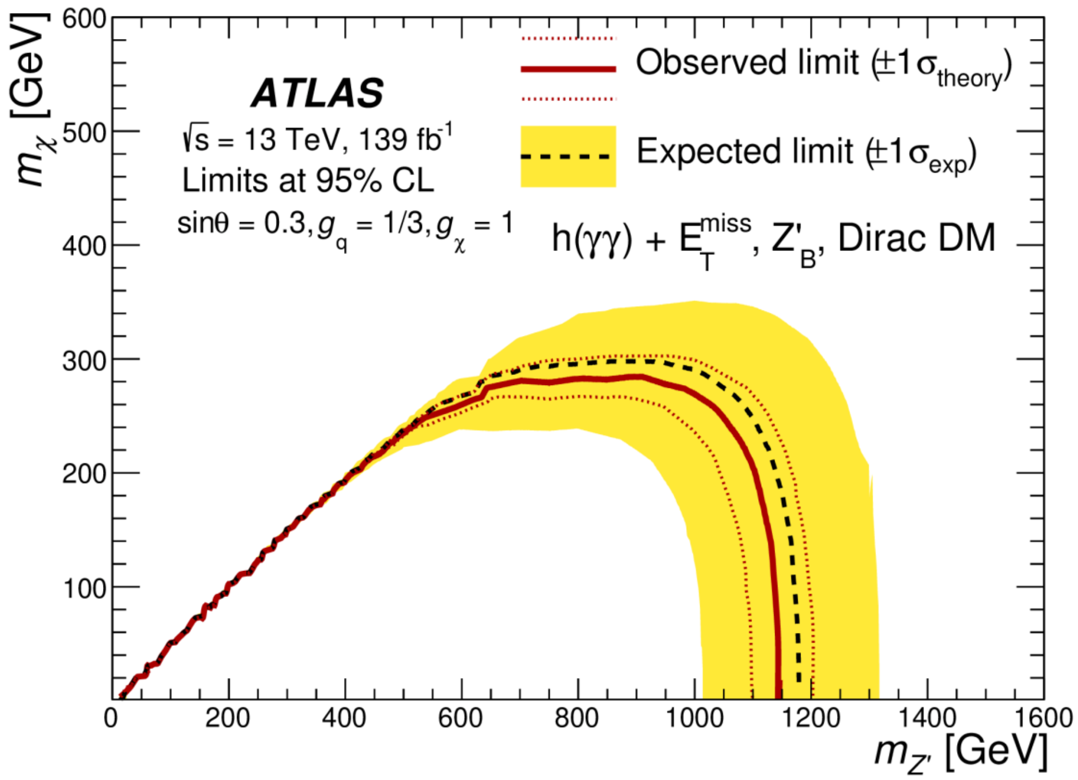
Results: diphoton invariant mass spectra

- No significant excess (over the Standard Model prediction) w.r.t. total background

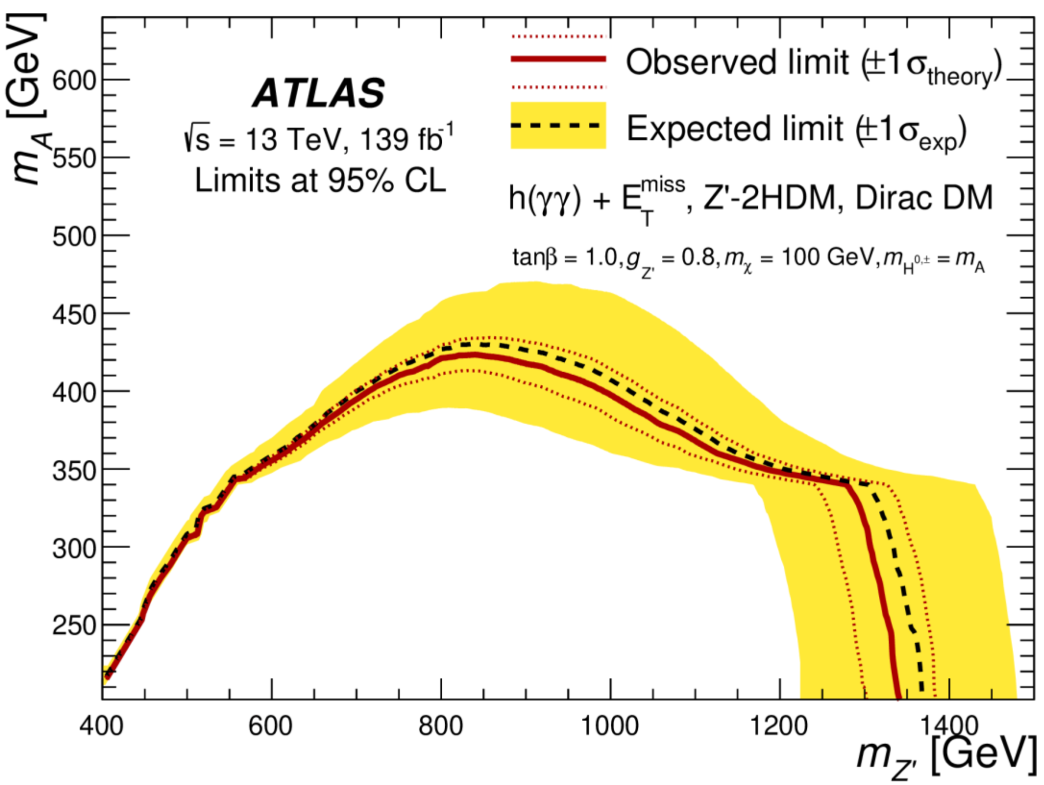
(The signal in the pictures is the 2HDM+a model with: $\tan\beta$ = 1.0, $\sin\theta$ = 0.35, m_A = 600 GeV, and m_a= 200 GeV)



Results: limits on Z'_B and Z'-2HDM models

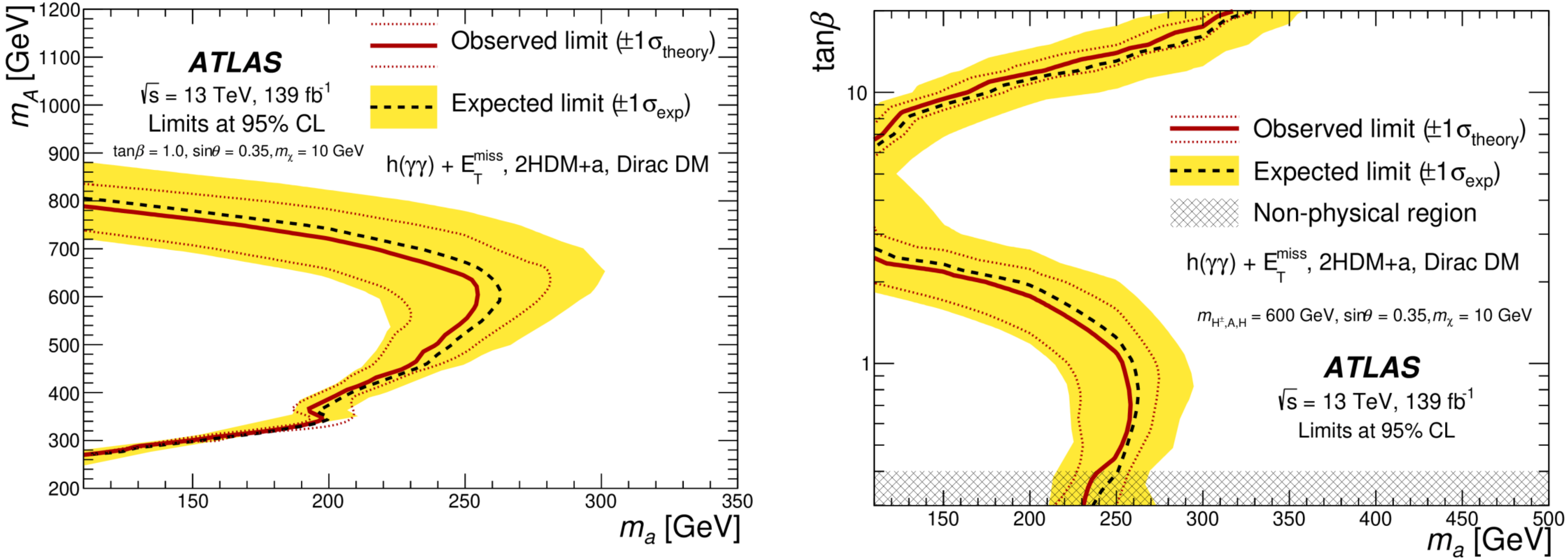


Limits on mediator $m_{Z'}$ extends to 1150 GeV (vs. less than 1000 in previous publication) for Z'_B model



Limit on m_A reaches 420 GeV for $m_{Z'}$ = 825 GeV for Z'-2HDM model

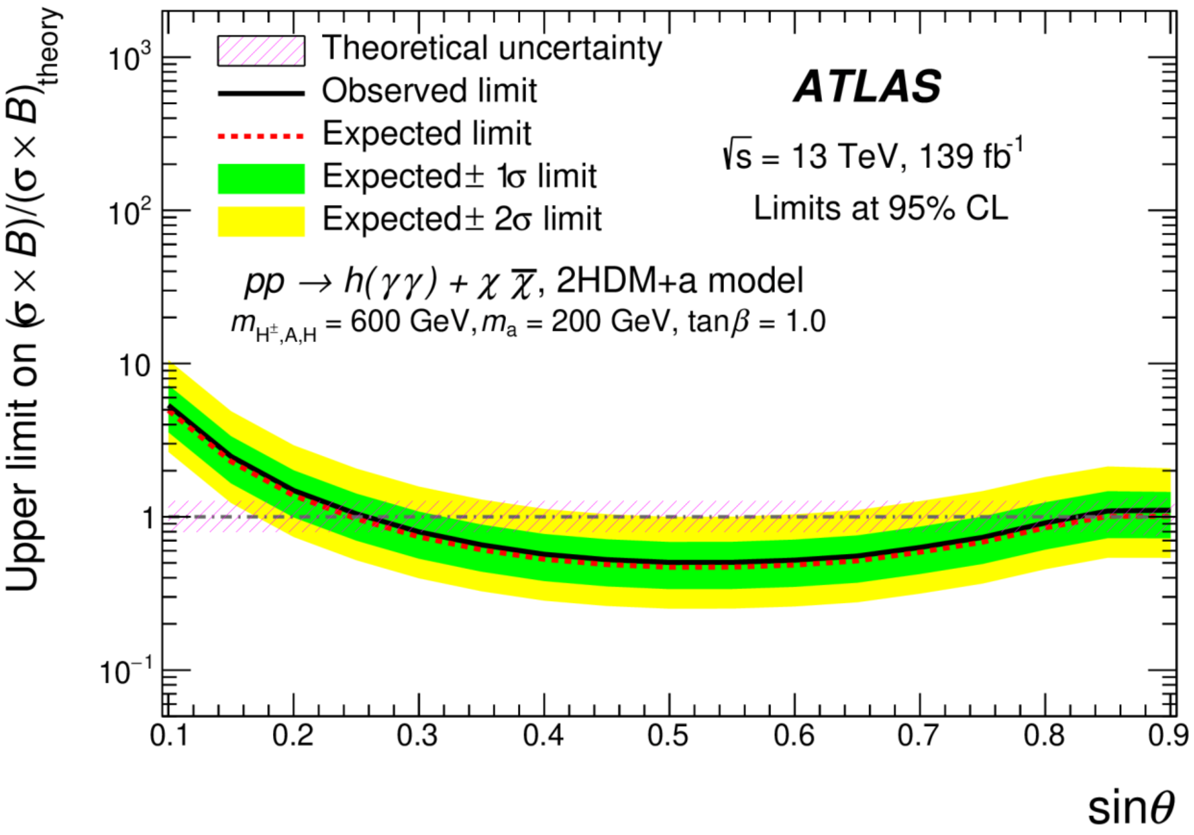
Results: 2HDM+a model



- For the 2HDM+a model: m_A-m_a and tanβ-m_a planes
- The upper limit on m_A is 800 GeV for m_a = 110 GeV,
  while the maximum excluded m_a reaches about 260 GeV for m_A = 600 GeV

Results: 2HDM+a model

- The observed (solid line) and expected (dashed lines) exclusion limits at 95% CL for the 2HDM+a model as a function of sinθ.
- For this benchmark point the ATLAS data excludes a vast domain of possible mixing angle θ values.



Summary

- A search for dark matter in association with a Higgs boson decaying to two photons is presented
- No significant excess over the expected background is observed
- Limits at 95% CL on different parameters (i.e., mass of mediators) based on the $Z'B$, Z'-2HDM and 2HDM+a models are set
- Paper (arXiv: 2104.13240) submitted to JHEP

- Prospective: (based on the improved limits) continue to explore microscopic nature of dark matter in the coming Run 3 Stage at LHC

Backup

- Packages for simulation samples
- Event reconstruction
- Signal and background parametrization
- Systematic uncertainty
- Results: inferred limits for $Z'B$

Simulation samples

- DM signals: MadGraph5 + Pythia, with the following simulated variable spaces

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iii. For 2HDM+a model: m_A, m_a, tanβ, sinθ (and fix m_χ = 10 GeV)

- Backgrounds:
- ggF, VBF, Wh, Zh, $t\bar{t}h$: Powheg Boxv2 + Pythia8.2
- thqb, tWh: MadGraph5_aMC@NLO + Pythia8.2
- $\gamma\gamma$, $V\gamma\gamma$, and $V\gamma$: Sherpa v2.2.4

Event reconstruction

- Photons: p_T > 25 GeV , $|\eta|$ < 2.47 (veto 1.37 < $|\eta|$ < 1.52)
- Electrons: p_T > 10 GeV , $|\eta|$ < 2.47 (veto 1.37 < $|\eta|$ < 1.52)
- Muons: p_T > 10GeV , $|\eta|$ < 2.7
- Jets: p_T > 25 GeV, $|\eta|$ < 4.4
- E_T^{miss}: the magnitude of the negative vectorial sum of the transverse momenta of all selected and calibrated physics objects of an event that can be matched to the primary vertex.

Signal and background parametrization

- DM signal and SM Higgs background: normalization and shape (double sided crystal ball) extracted from MC
- Non-resonant background: normalization and shape extracted by fitting the $m_{\gamma\gamma}$ distribution in data for each category
- The non-resonant background modelling uncertainty $\Delta N_{\mathbf{sig}}^{\mathbf{bkg\ model}}$ is estimated for each category:

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 uncertainty

- Systematics by 2HDM+a model with low E_T^{miss}:

➢ Gives a conservative estimate of systematics to include more possibilities

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	–

Results: inferred limits for Z'_B

- Compare the inferred limits (in the context of Z'_B) on the spin-independent DM−nucleon cross section to the constraints from direct detection experiments

- Improves limits for m_χ < 2 GeV:

➢ Factor of 2 better w.r.t. previous publication