Search for Dark Matter Produced in Association with a Higgs Boson Decaying to Two Photons at CMS

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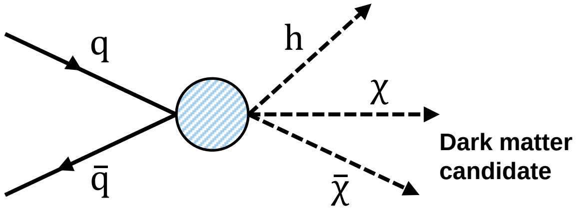
Outline

- Introduction
  - Primary Background
  - Physics Objects
- Analysis Workflow
  - Preselection
  - Deep Neural Network (DNN) based Selection
  - Event Categorization
- Expected Limits
- Summary and Conclusion

Introduction

- General model signature: **MET + h** ; **h** $\rightarrow \gamma\gamma$
- Final state: **MET +** $\gamma\gamma$
- Run 2 Data: **2017 (41.5 fb^{-1})** and **2018 (59.69 fb^{-1})**



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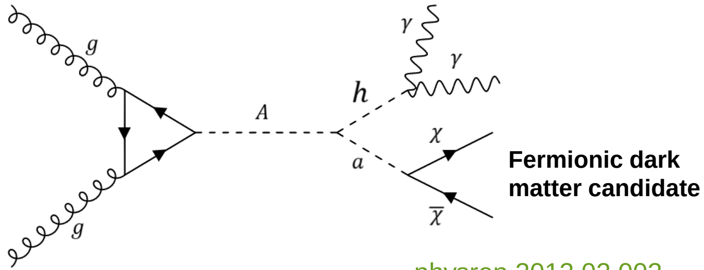
- Signal & Resonant background shapes: from Monte Carlo (MC) samples
- Non-resonant background shape: from Data
- Results interpreted in the framework of 2-Higgs Doublet + a Model (2HDM+a)

$$\left(\begin{array}{l} m_A = 200 - 900\ \text{GeV} \quad ; \quad m_a = 150\ \text{GeV} \\ m_H = m_{H^\pm} = m_A \ ;\ \sin\theta = 0.35 \ ;\ \tan\beta = 1.0 \end{array} \right)$$



physrep.2012.02.002

$m_{A,a} \to$ mass of pseudoscalars A, a

$m_H \to$ mass of the heavy neutral Higgs H

$m_{H^\pm} \to$ mass of the charged Higgs

$\theta \to$ mixing angle between the pseudoscalars

$\tan\beta \to$ ratio of the VEVs of the Higgs doublets

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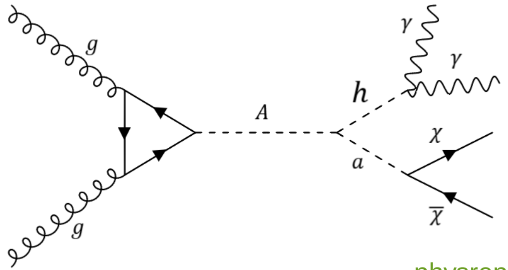
- Other channels explored in MonoHiggs analysis at CMS: **bb** $\tau^+\tau^-$ W^+W^- & ZZ
  - Run 2 data of **2016 (35.9 fb^{-1})** was analyzed
  - Results interpreted under **Z'-2HDM and Z'-Baryonic** models



Fermionic dark matter candidate

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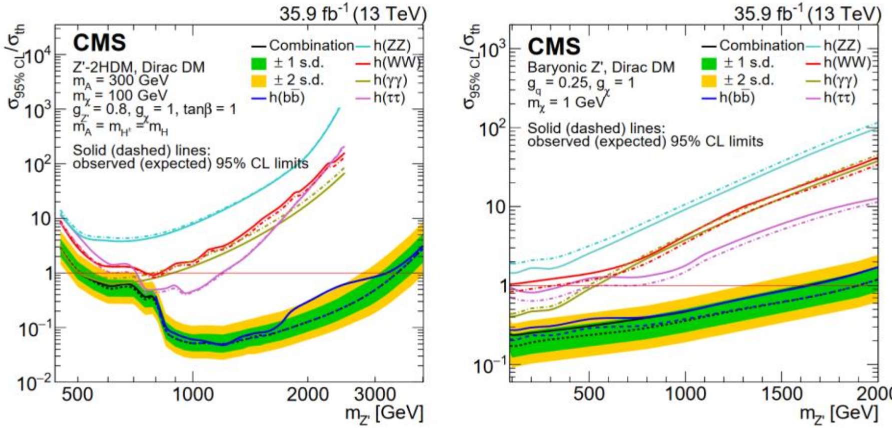

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Primary Background

Resonant

- SM h $\longrightarrow \gamma\gamma$ with mis-measured MET
- Associated production of W with SM h
  W $\longrightarrow l\nu$
  (missed lepton giving mis-measured MET)

Non-resonant

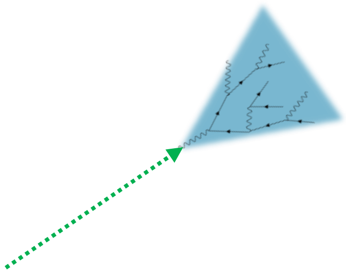
- Several processes with two reconstructed γ and mis-measured MET
  QCD, Z+jets, Single top, $t\bar{t}$ +jets or Wγ or W$\gamma\gamma$, ZZ, $\gamma\gamma$, γ+jet and Drell-Yan production of two e's

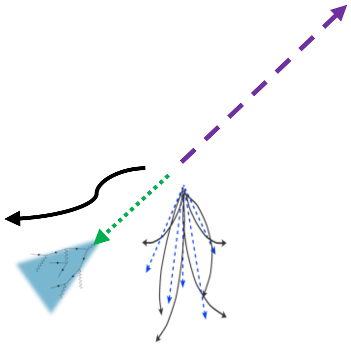
Reducible background

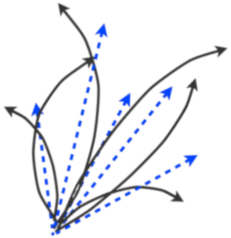
- Associated production of Z (decaying to $\nu\nu$ (MET)) with SM h

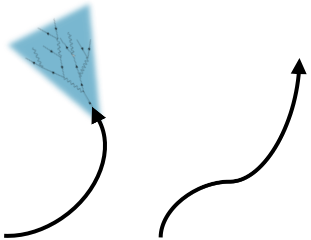
Irreducible background

Physics Objets







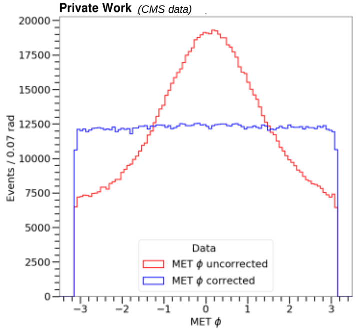


Photons

- Selection details in subsequent slides

MET

- $p_T^{miss} = -\sum_{\text{All particles}} p_T$
- MET filters applied to remove anomalous MET
- MET Φ corrections applied



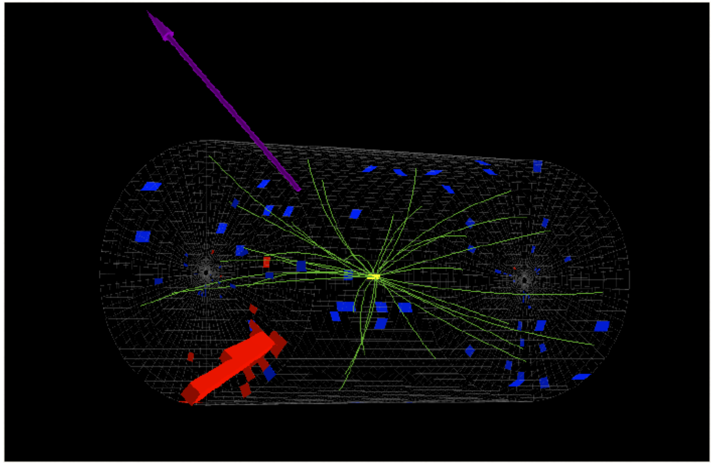
Jets

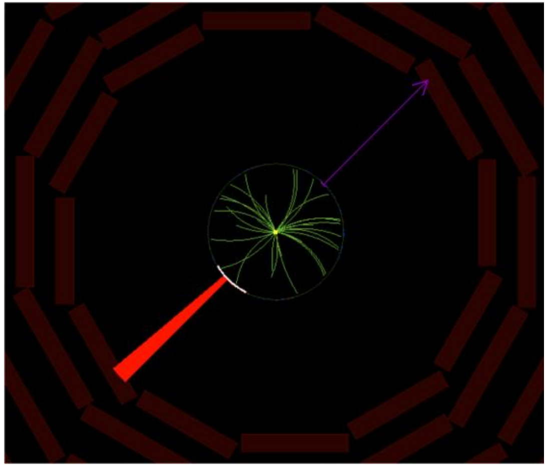
- Anti-kT with radius 0.4
- $p_T \geq 20$ GeV
- $|\eta| < 4.7$
- Passes Tight JetID
- ΔR(photon, jet) > 0.4

Leptons (e,μ)

- $p_T \geq 20$ GeV
- $|\eta| < 2.5$ (2.4)
- Passes Loose ID
- ΔR(photon, lepton) > 0.4

MET Filters





Run no.: 304062 Lumi: 815
Event: 1217738994

Leading photon p_T: 2967.29
η: -1.70261 Φ: -2.36444

Sub-leading photon p_T: 1397.09
η: -1.82336 Φ: -2.36945

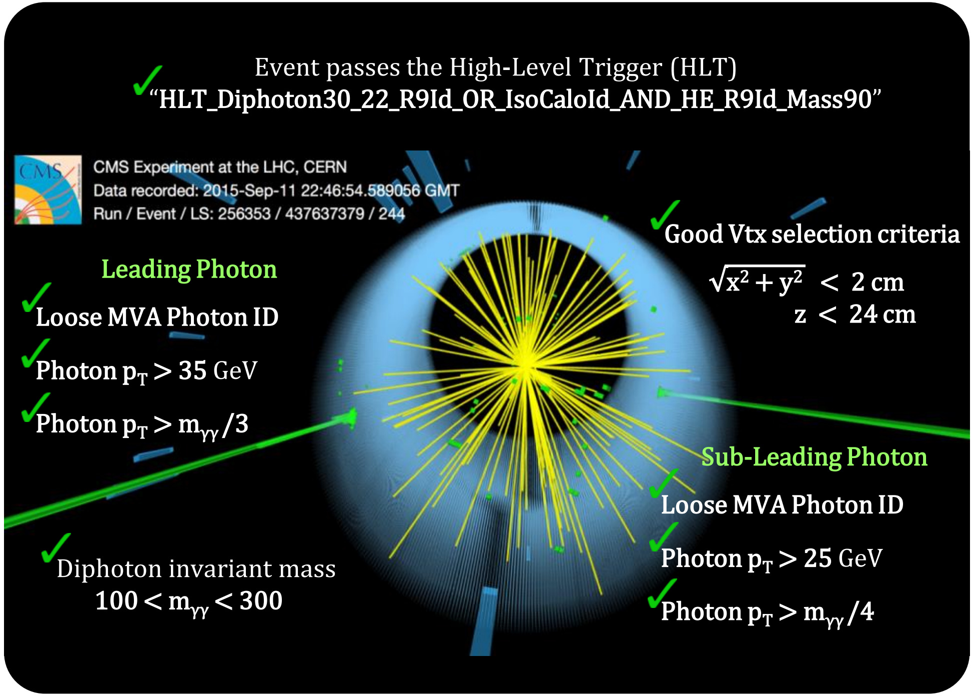
- **Event looks like a perfect candidate for MET+$\gamma\gamma$**
- However, this particular **event was removed by the EEbadSC noise filter**
- Shows the importance of understanding the behavior of the detector and how even the minute things can affect the event selection

1. Primary Vertex Filter
2. Beam halo filter
3. HCal Barrel, HCal Endcap (HBHE) noise filter
4. HBHE Isolation noise filter
5. ECal Trigger Primitive filter
6. Bad PF Muon Filter
7. ECal Endcap bad Supercluster (EEbadSC) noise filter
8. ECal bad calibration filter

Analysis Workflow

Preselection

- Events pass through a set of loose preselection
  1. Event passes the HLT "hltDiphoton30Mass90"
  2. Both leading and sub-leading photon passes R9 (η and H/E dependent) cut
  3. Both leading and sub-leading photon passes loose MVA photon ID --> Multi-variate based photon ID; 90% (loose) photon ID efficiency
  4. Both leading and sub-leading photon passes electron veto
  5. Leading photon $p_T > 35$ GeV and sub-leading photon $p_T > 25$ GeV
  6. Leading photon $p_T > m_{\gamma\gamma}/3$ and sub-leading photon $p_T > m_{\gamma\gamma}/4$
  7. Event must fulfil good vtx selection criteria
  8. DiPhoton invariant mass window 100 to 300 GeV

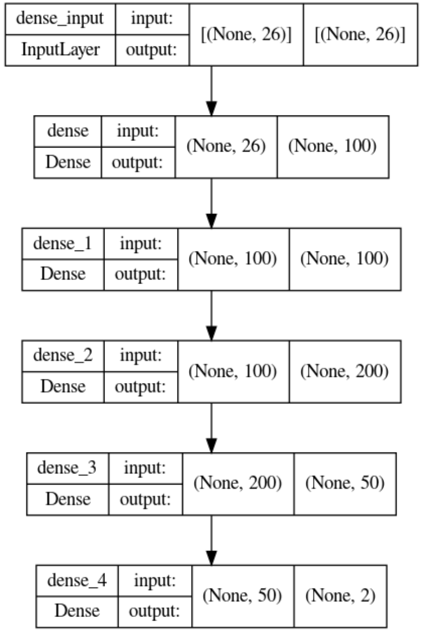


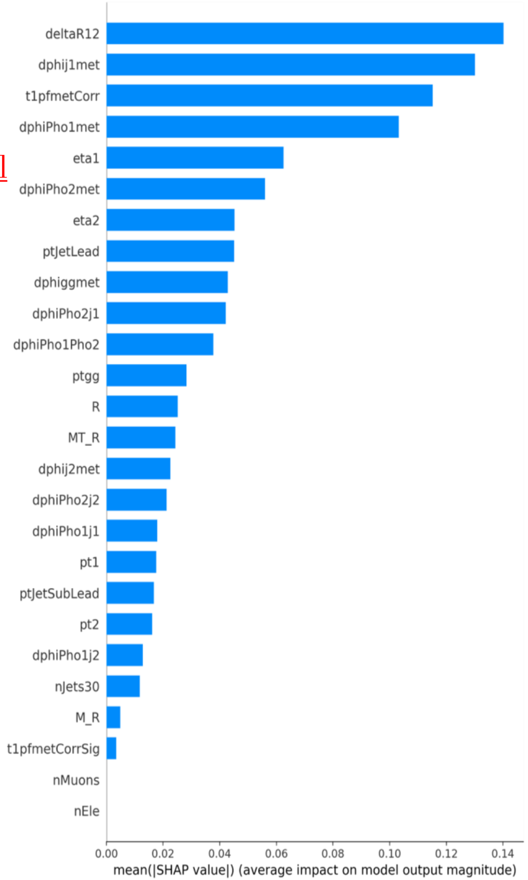
Analysis Workflow

DNN based Selection

- Events pass through a set of loose preselection
- The preselected events are passed through a pre-trained DNN
  - DNN utilized to increase the signal efficiency and thus improve sensitivity
  - Simple DNN (sDNN): No mediator mass as input feature (trained at m_A=300 GeV)
  - Parametric DNN (pDNN): Mediator mass (m_A) present as one of the input features to facilitate learning of the mass dependent correlations among the input features

Choice of the input features (total 26) motivated from the phenomenology paper: The mono-Higgs + MET signal at the Large Hadron Collider





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  - Parametric DNN (pDNN): Mediator mass (m_A) present as one of the input features to facilitate learning of the mass dependent correlations among the input features
  - Background in both the trainings come from data itself, by inverting the photon ID criteria i.e. events with one of the photon candidates failing the loose photon ID; rich in QCD and γ+Jet type background

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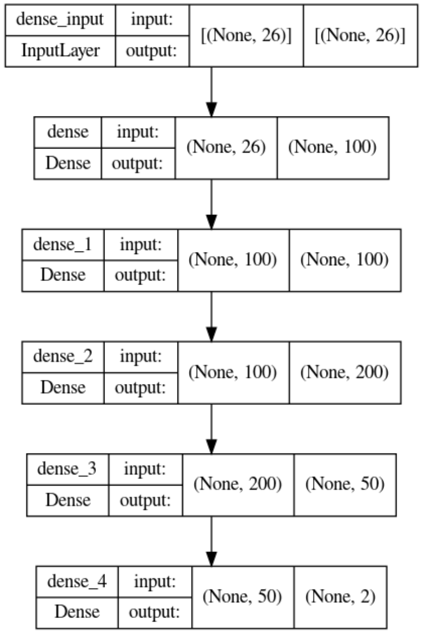
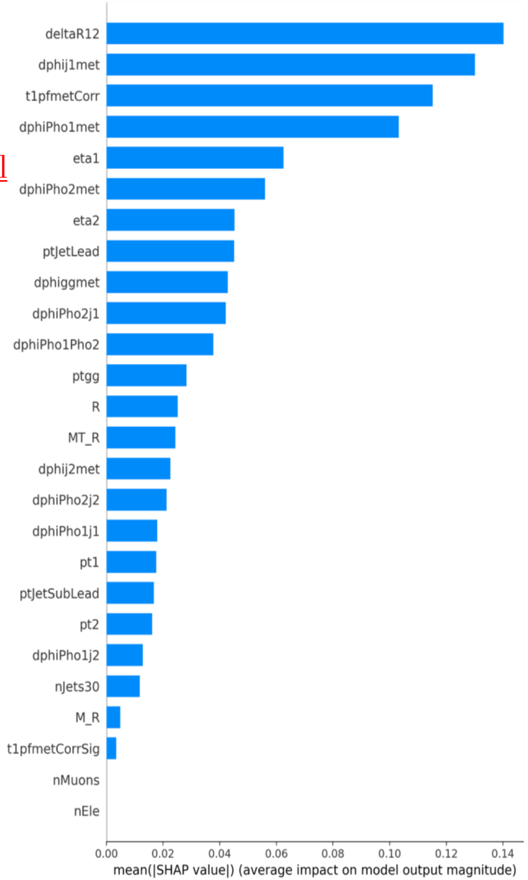




Analysis Workflow

Additional Cuts

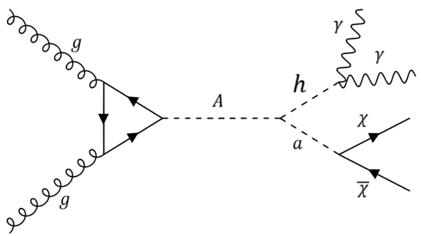
- Events pass through a set of loose preselection
- The preselected events are passed through a pre-trained DNN
- Additional cuts applied to further reduce the background

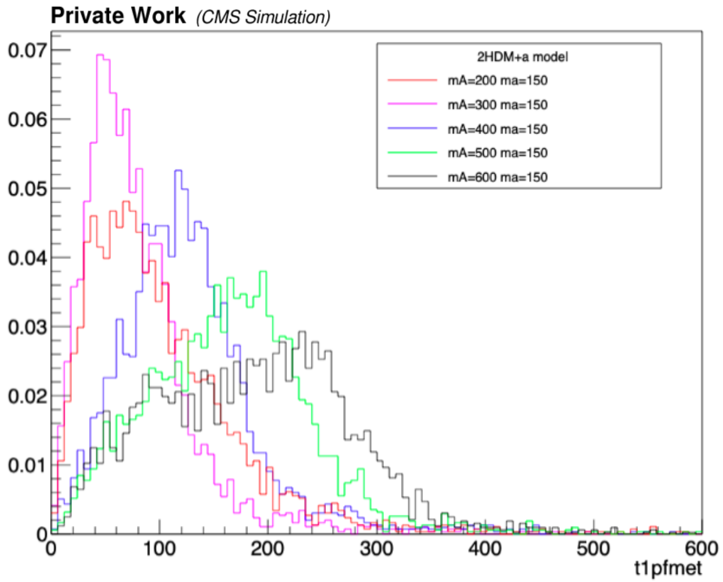
  MET > 80

  number of b-jets = 0

  number of electrons = 0

  numbe of muons = 0



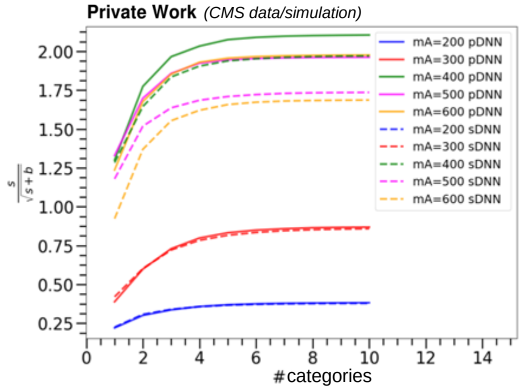


Analysis Workflow

Event Categorization

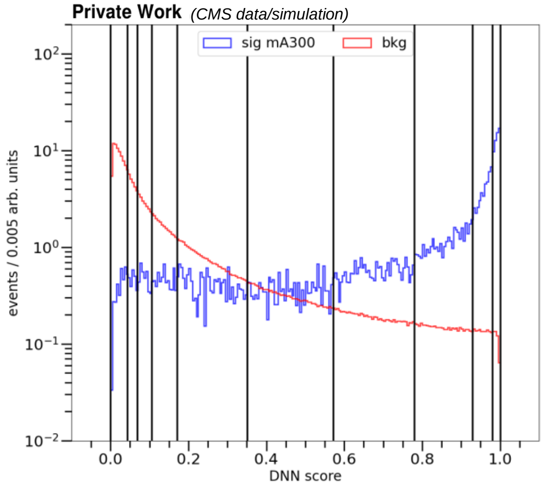
- ❖ Events pass through a set of loose preselection
- ❖ The preselected events are passed through a pre-trained DNN
- ❖ Additional cuts applied to further reduce the background
- ❖ Events are categorized in DNN scores to optimize combined significance (s ÷ √(s+b))

  Each new category is formed by placing the boundary such that the sum of significance (from each category) is maximized



pDNN → parametric DNN

sDNN → simple DNN



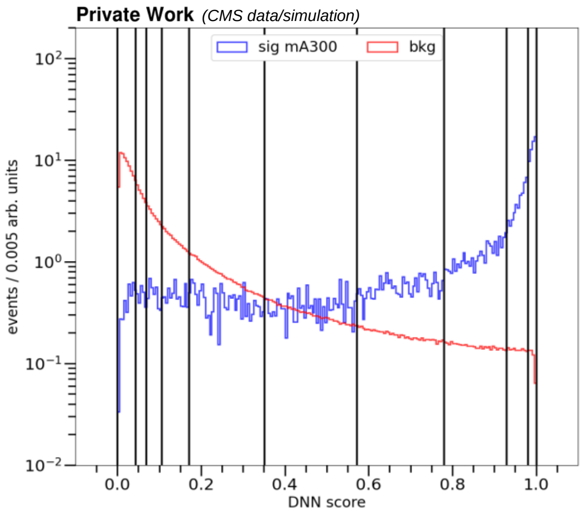
Vertical lines indicate boundaries of each category

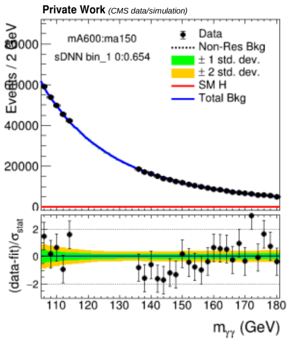
Analysis Workflow

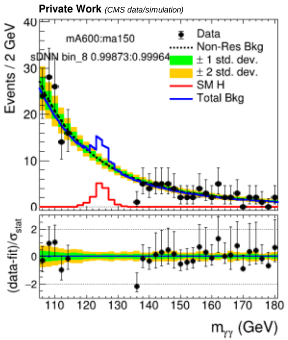
Signal & Background Estimation

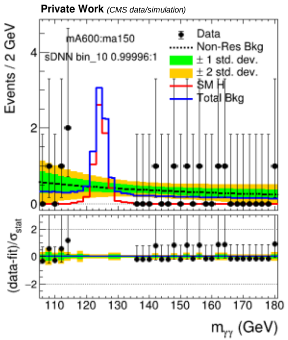
- ❖ Events pass through a set of loose preselection
- ❖ The preselected events are passed through a pre-trained DNN
- ❖ Additional cuts applied to further reduce the background
- ❖ Events are categorized in DNN scores to optimize combined significance (s ÷ √(s+b))
- ❖ In each category the falling background is estimated from data, and resonant background and signal from MC

Vertical lines indicate boundaries of each category







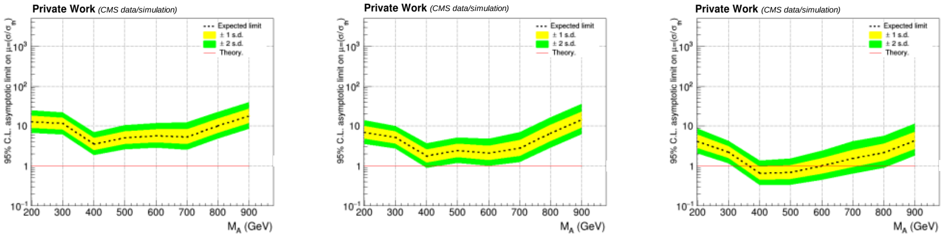


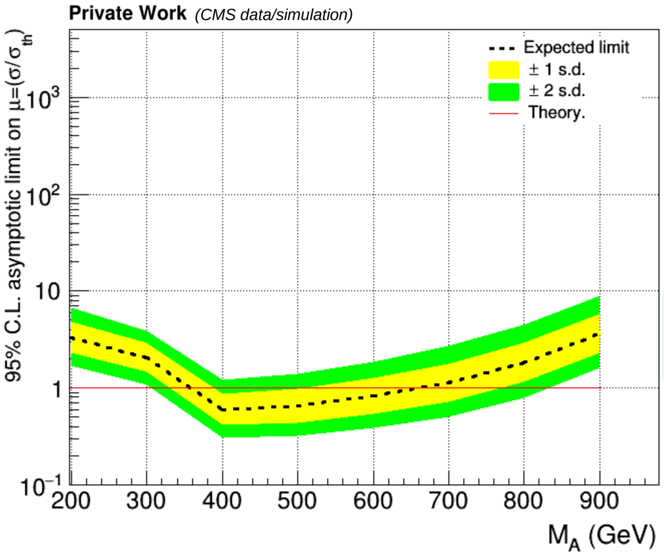
Analysis Workflow

Expected limit Calculation

- Events pass through a set of loose preselection
- The preselected events are passed through a pre-trained DNN
- Additional cuts applied to further reduce the background
- Events are categorized in DNN scores to optimize combined significance (s ÷ √(s+b))
- In each category the falling background is estimated from data and resonant background and signal from MC
- A combined limit of all these categories is then obtained

DNN Category-wise limit plots

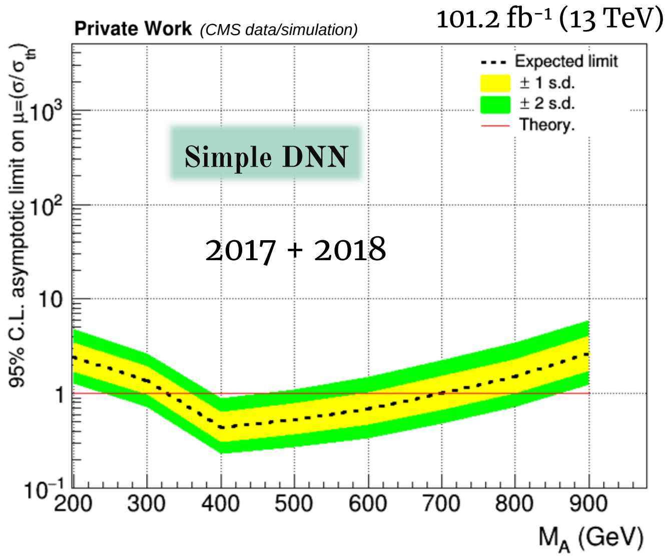




m_a= 150 GeV

Combined limit for 2018

Expected Limits



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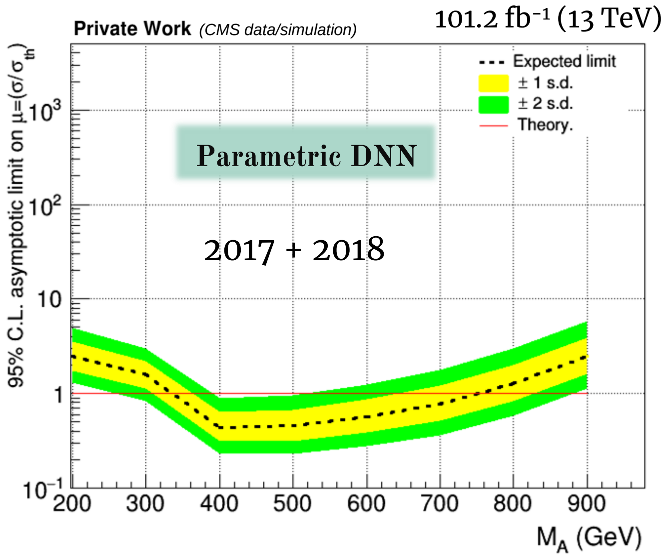

- The expected limits are encouraging since the analysis is **sensitive enough to exclude a portion of the phase-space**
- Data is currently blinded, since the networks have not been optimized for the re-calibrated Run 2 data.

	Lower end	Upper end
sDNN	330	700
pDNN	340	750

Summary and Conclusion

- Dark matter search with Run 2 data, total 101.2 fb^{-1} luminosity
- Results interpreted in the context of the 2HDM+a model
  - Analysis strategy optimized with the following parameter values:

    m_A = 200 – 900 GeV ; m_a = 150 GeV

    $m_H = m_{H^\pm} = m_A$; $\sin\theta = 0.35$; $\tan\beta = 1.0$

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- Events selected with two photons passing MVA photon ID and having large MET (> 80 GeV)
- Number of leptons and jets used to constrain events (nJets = 0 ; nLeptons = 0)
- DNN based final selection of events:
  - Simple DNN optimized specifically for m_A = 300 GeV, and applied at all mass points
  - Parametric DNN, m_A also included as a training parameter -> learns correlation for all mass points

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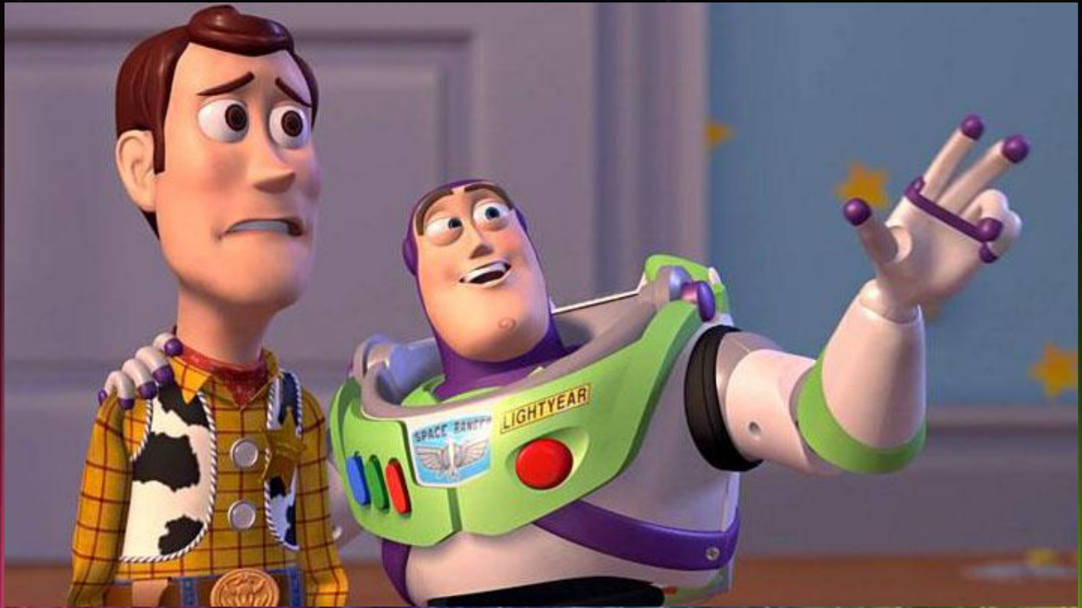
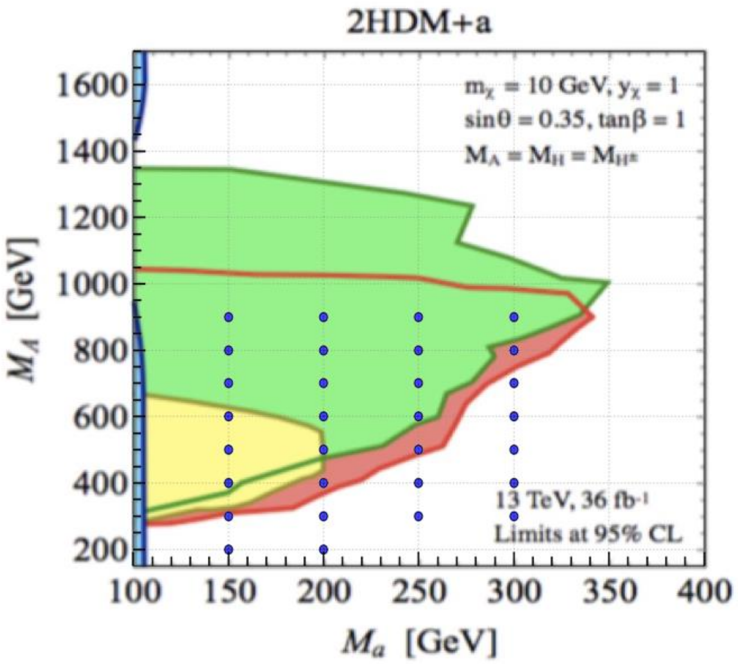
  - Simple DNN optimized specifically for m_A = 300 GeV, and applied at all mass points
  - Parametric DNN, m_A also included as a training parameter -> learns correlation for all mass points
- Expected limits calculated at 95% CL after categorizing events based on their DNN score
  - Simple DNN gives exclusion in the range mA = 330 – 700 GeV
  - Parametric DNN gives, mA = 340 – 750 GeV; overall performs better than simple DNN
- **Data blinded**, as DNNs yet to be optimized for the **re-calibrated Run 2 data**



Dark matter, dark matter everywhere,
But none in the detector, anywhere

BACKUP

Analysis Sensitivity



- Aiming to optimize the analysis for 2HDM+a model
- The yellow patch is the target exclusion for MonoHiggs to gamma-gamma channel
- This motivates our choice of signal phase-space

Analysis Workflow

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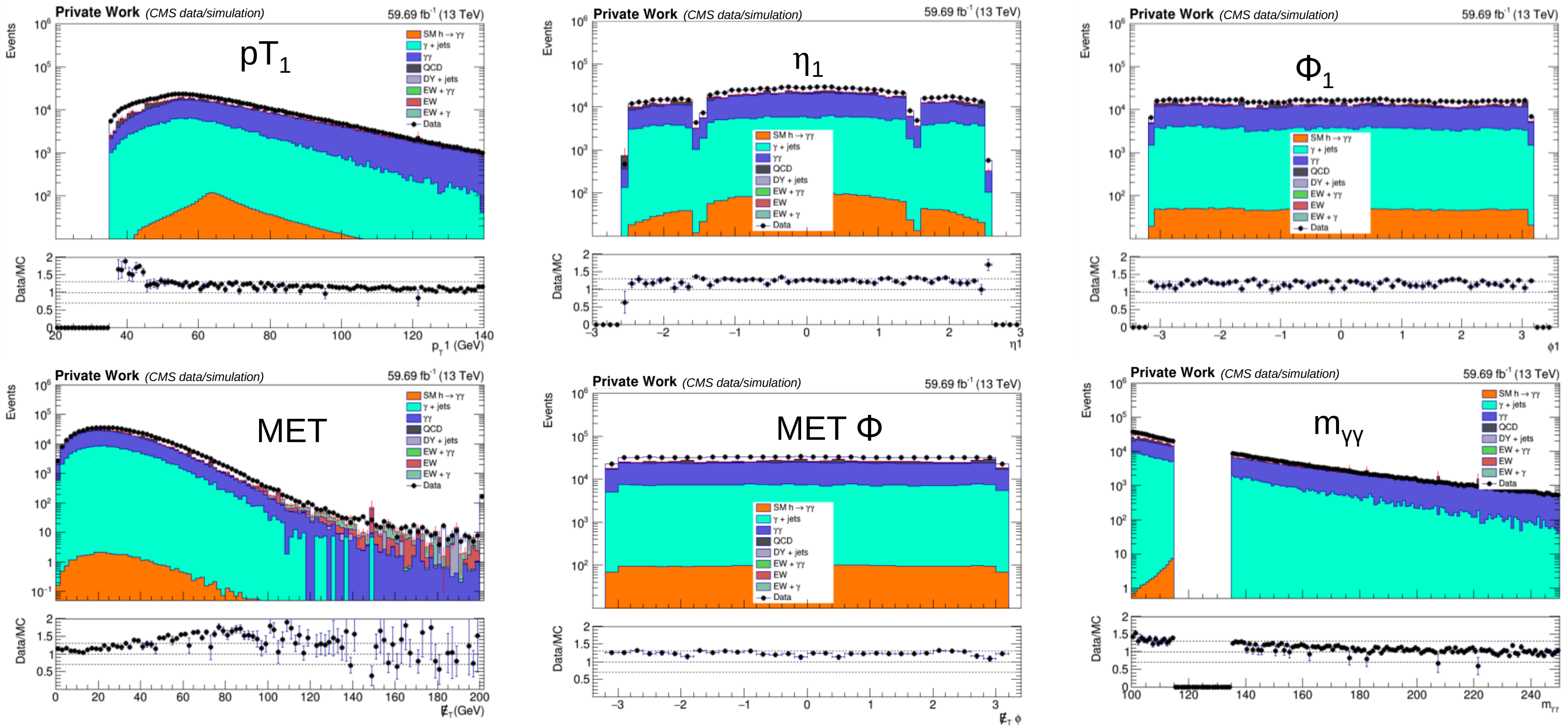
Data-MC Comparison

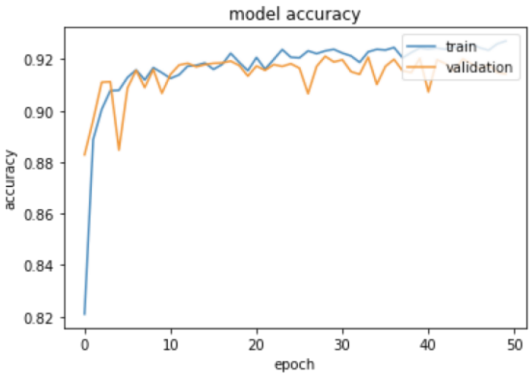
Run 2 2018 (59.69 fb^{-1})

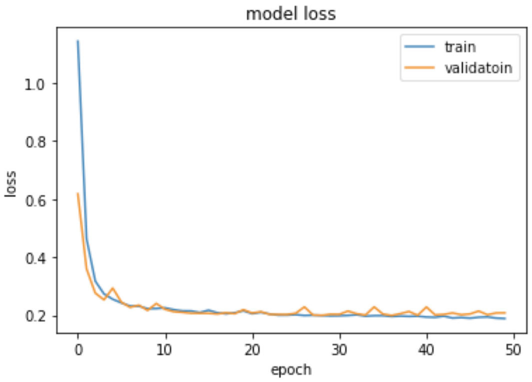


DNN

Choice of the input features (total 26) motivated from from our phenomenology paper: The mono-Higgs + MET signal at the Large Hadron Collider

variable	description
p_T^{miss}	*Missing transverse momentum*
$p_T^{\gamma_1}$	*Leading Photon* p_T
$p_T^{\gamma_2}$	*Sub – leading Photon* p_T
$p_T^{\gamma\gamma}$	p_T *of* $\gamma\gamma$ *system*
$metSig$	*Met significance*
$\Delta R_{\gamma_1\gamma_2}$	ΔR *between leading and – leading photon*
$N_{j(30)}$	*Number of jets above* 30 *GeV*
N_e	*Number of electrons*
N_μ	*Number of muons*
$\Delta\phi(\gamma\gamma, P_T^{miss})$	$\Delta\phi$ *between* $\gamma\gamma$ *system and* p_T^{miss}
$\Delta\phi(\gamma_1, P_T^{miss})$	$\Delta\phi$ *between leading photon and* p_T^{miss}
$\Delta\phi(\gamma_2, P_T^{miss})$	$\Delta\phi$ *between sub – leading photon and* p_T^{miss}
$\Delta\phi(j_1, P_T^{miss})$	$\Delta\phi$ *between leading jet and* p_T^{miss}
$\Delta\phi(j_2, P_T^{miss})$	$\Delta\phi$ *between sub – leading jet and* p_T^{miss}
$\Delta\phi(\gamma_1, j_1)$	$\Delta\phi$ *between leading photon and leading jet*
$\Delta\phi(\gamma_1, j_2)$	$\Delta\phi$ *between leading photon and sub – leading jet*
$\Delta\phi(\gamma_2, j_1)$	$\Delta\phi$ *between sub – leading photon and leading jet*
$\Delta\phi(\gamma_2, j_2)$	$\Delta\phi$ *between sub – leading photon and sub – leading jet*
$\eta^{\gamma 1}$	η *of leading photon*
$\eta^{\gamma 2}$	η *of sub – leading photon*
$\Delta\phi(\gamma_1, \gamma_2)$	$\Delta\phi$ *between leading and sub – leading photon*
$p_T^{j_1}$	*Leading jet* p_T
$p_T^{j_2}$	*Sub – leading jet* p_T
M_R	$\sqrt{(E_{\gamma 1} + E_{\gamma 2})^2 + (p_{z_{\gamma 1}} + p_{z_{\gamma 2}})^2}$
M_R^T	$p_T^{miss}(p_{\gamma_1}^T + p_{\gamma_2}^T) - p_T^{miss} p_{\gamma_1}^T cos(\Delta\phi_{\gamma_1, p_T^{miss}})$
R	$\frac{M_R^T}{M_R}$

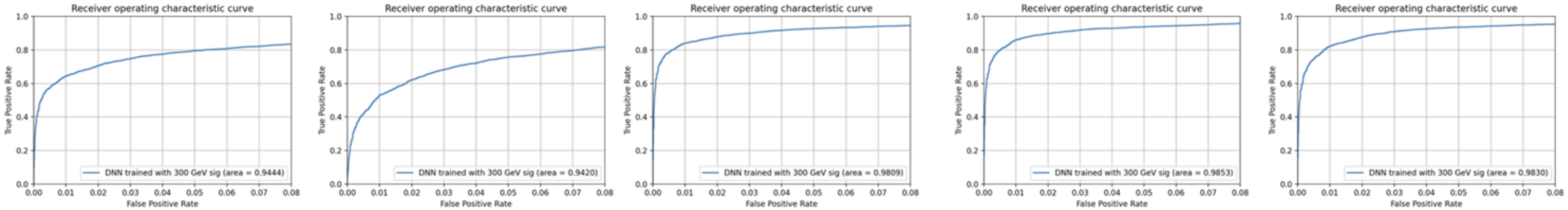




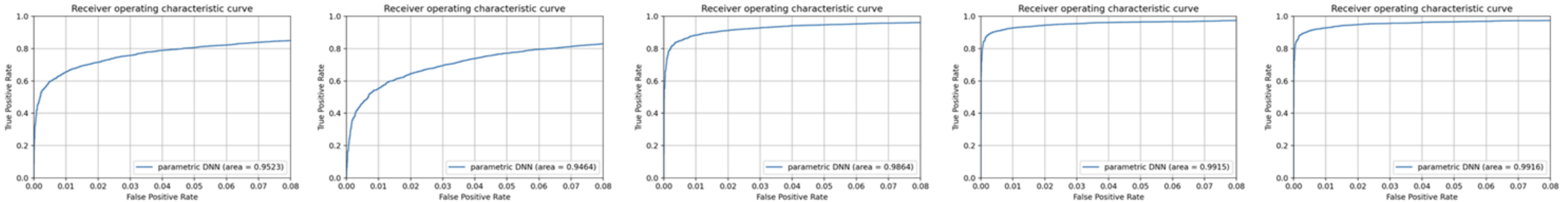
Comparison between Simple DNN (at 300 GeV) and Parametric DNN

mA = 200 GeV | mA = 300 GeV | mA = 400 GeV | mA = 500 GeV | mA = 600 GeV

Performance of dedicated DNN tarined with 300 GeV



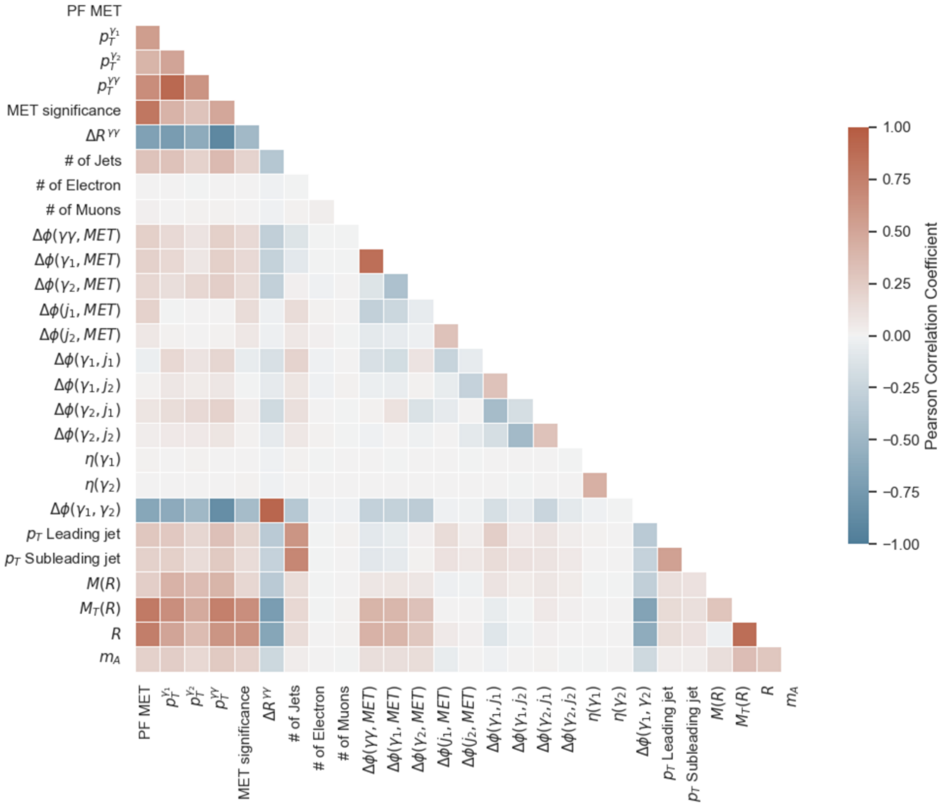
Performance of parametrized DNN

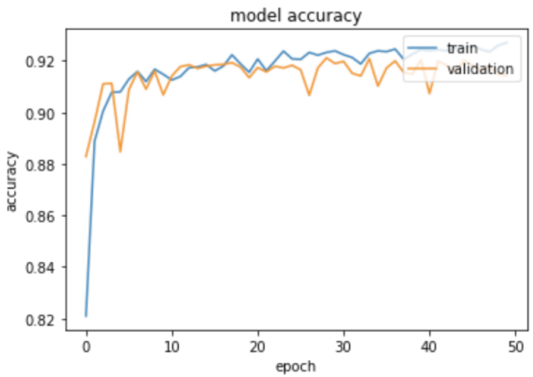


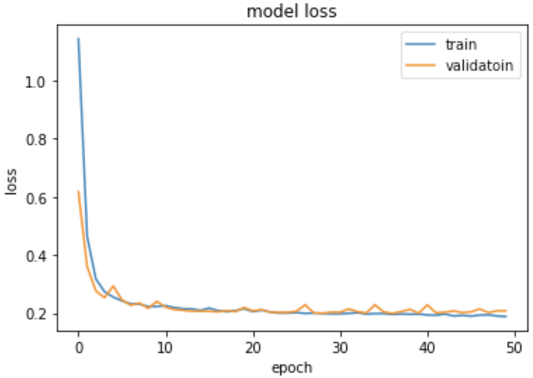
$m_A(GeV)$	AUC from DNN tarined with 300 GeV	AUC from parametric DNN
200	0.9444	0.9523
300	0.9420	0.9464
400	0.9809	0.9864
500	0.9853	0.9915
600	0.9830	0.9916

- m_A has been fed to the parametrized network as parameter (m_a=150 GeV is fixed)
- **Parameterized DNN tends to show improved performance** for the higher mass points without losing the performance at 300 GeV

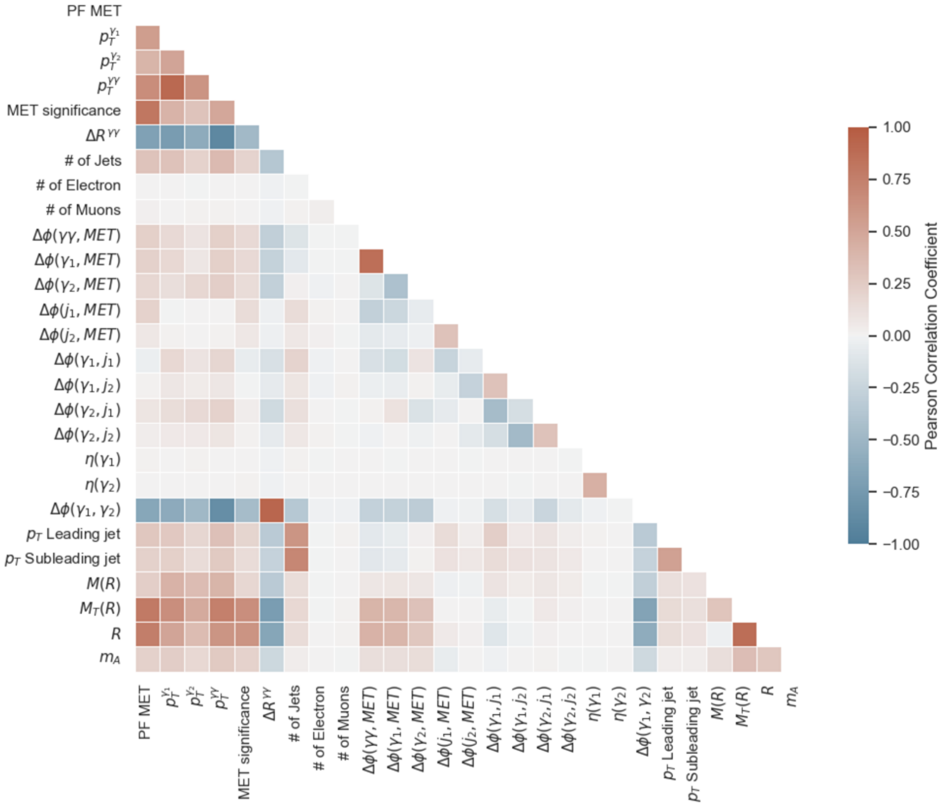
DNN

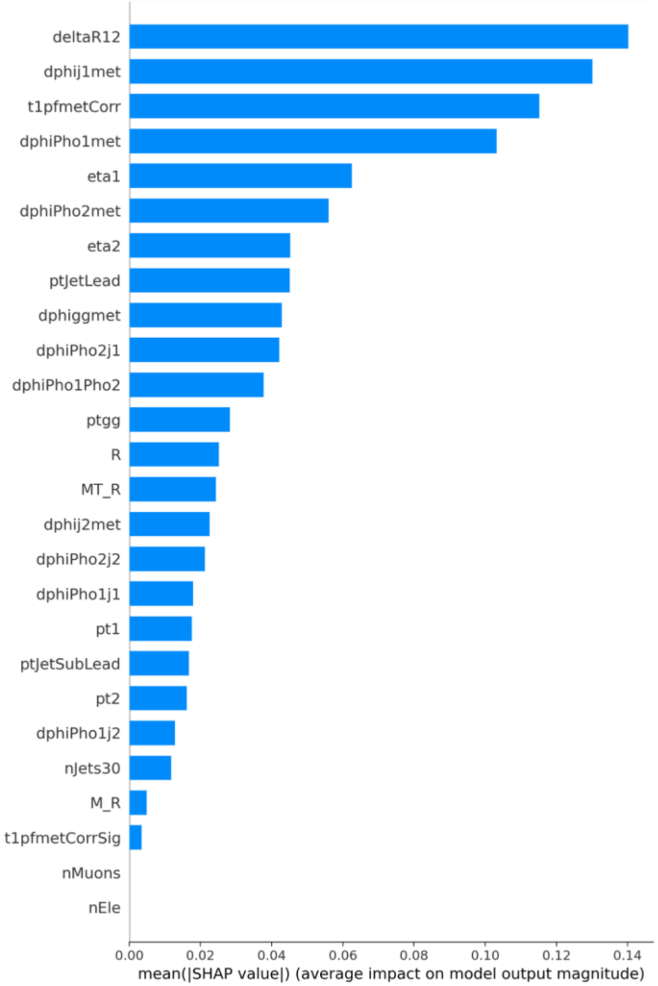

Pearson Correlation Coefficient
PF MET
# of Jets
# of Electron
# of Muons
MET significance
pT Leading jet
pT Subleading jet


model accuracy
accuracy
epoch
train
validation

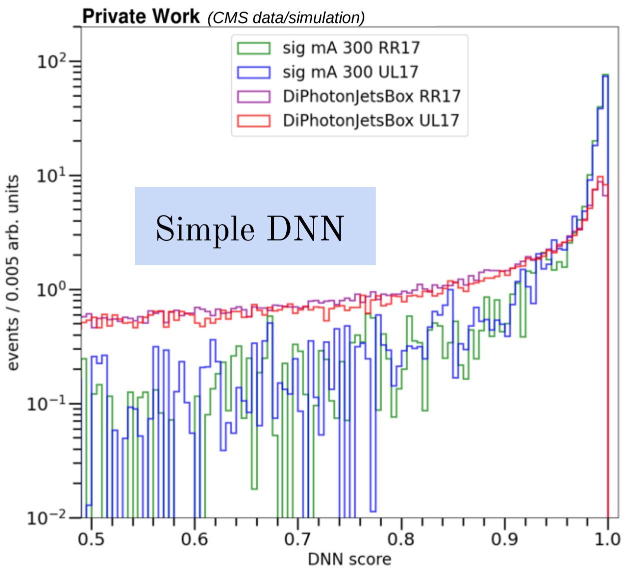

model loss
loss
epoch
train
validatoin

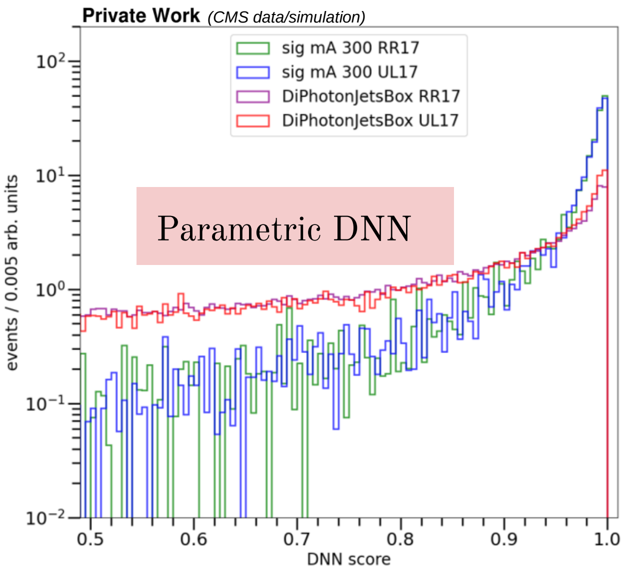
DNN


PF MET
$p_T^{\gamma_1}$
$p_T^{\gamma_2}$
$p_T^{\gamma\gamma}$
MET significance
$\Delta R^{\gamma\gamma}$
# of Jets
# of Electron
# of Muons
$\Delta\phi(\gamma\gamma, MET)$
$\Delta\phi(\gamma_1, MET)$
$\Delta\phi(\gamma_2, MET)$
$\Delta\phi(j_1, MET)$
$\Delta\phi(j_2, MET)$
$\Delta\phi(\gamma_1, j_1)$
$\Delta\phi(\gamma_1, j_2)$
$\Delta\phi(\gamma_2, j_1)$
$\Delta\phi(\gamma_2, j_2)$
$\eta(\gamma_1)$
$\eta(\gamma_2)$
$\Delta\phi(\gamma_1, \gamma_2)$
p_T Leading jet
p_T Subleading jet
$M(R)$
$M_T(R)$
R
m_A
1.00
0.75
0.50
0.25
0.00
−0.25
−0.50
−0.75
−1.00
Pearson Correlation Coefficient


deltaR12
dphij1met
t1pfmetCorr
dphiPho1met
eta1
dphiPho2met
eta2
ptJetLead
dphiggmet
dphiPho2j1
dphiPho1Pho2
ptgg
R
MT_R
dphij2met
dphiPho2j2
dphiPho1j1
pt1
ptJetSubLead
pt2
dphiPho1j2
nJets30
M_R
t1pfmetCorrSig
nMuons
nEle
0.00
0.02
0.04
0.06
0.08
0.10
0.12
0.14
mean(|SHAP value|) (average impact on model output magnitude)

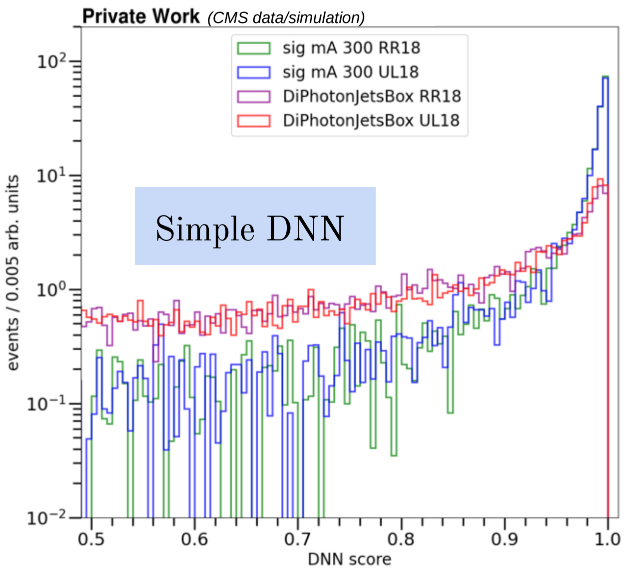
DNN Score Distribution

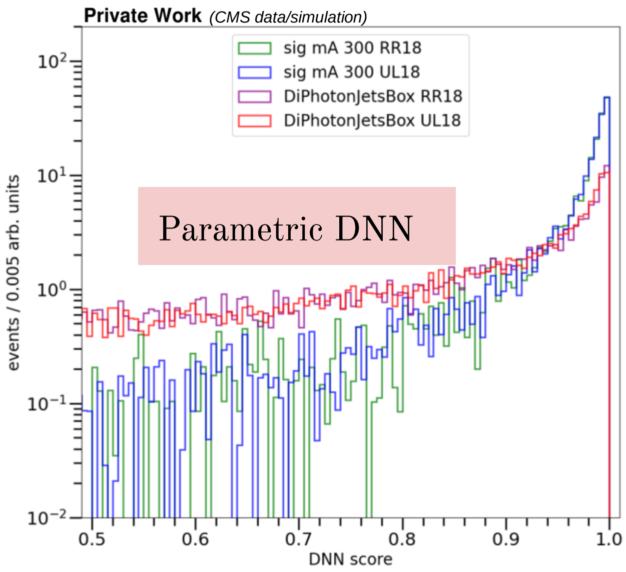




DNN score dist. shown for m_A= 300 GeV for 2017 data

DNN Score Distribution



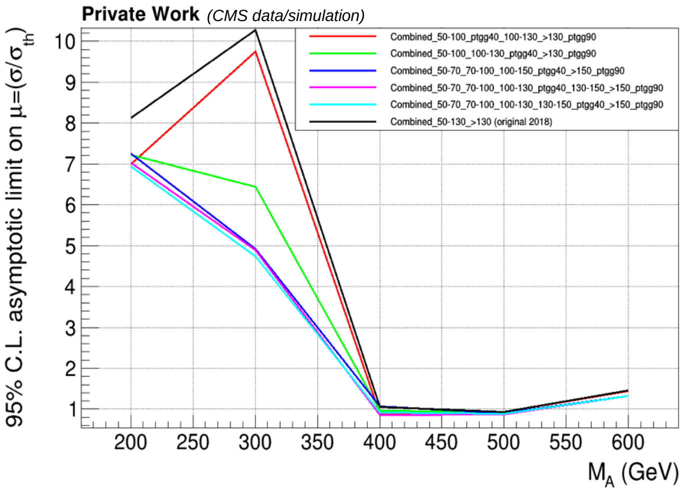


DNN score dist. shown for m_A= 300 GeV for 2018 data

Analysis Strategy

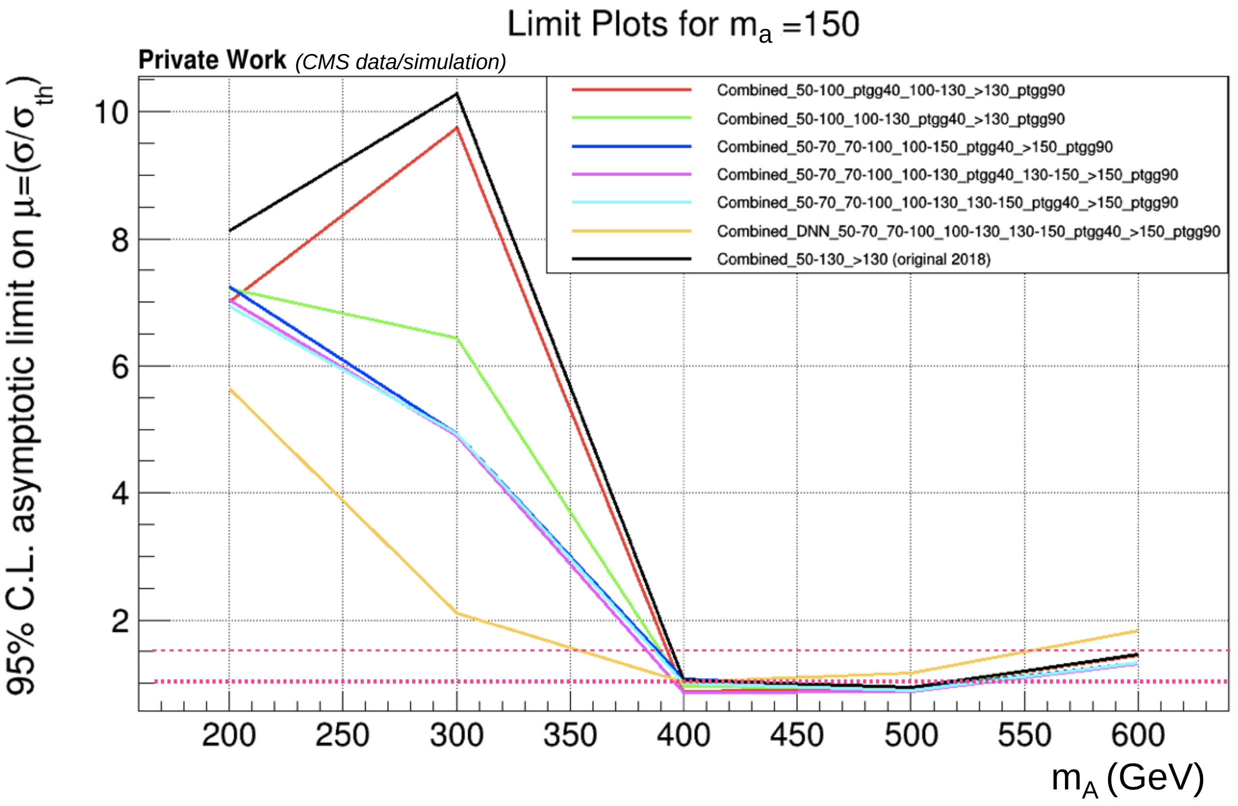
- **Vertex selection**
  - BDT vertex → DiPhoton vertex chosen by a BDT discriminator as used by the Hgg group.
- Weights applied to address L1Prefiring issue of 2017
- Hadronic Endcap Minus **(HEM)** issue of 2018 addressed → Removing events that have jets in region: **$-2.5 < \eta < -1.3$** and **$-1.57 < \phi < -0.87$**

Analysis Strategy



- ❑ Before moving to DNN, after a series of iteration with cut-based optimizations we knew mA=300 GeV is particularly challenging for ma=150 GeV
  (For purely kinematic reason, a 300 GeV resonance decaying to a 150 GeV ma and 125 GeV Higgs, resulting very soft MET)
- ❑ Thus, two choices of DNN were explored
- ❑ 1 trained particularly with 300GeV mediator mass signal
- ❑ 1 parametric DNN (parametrization in mediator mass)
- ❑ Background in both the training come from data itself (NOT from MC)
  (altering the photon ID criteria)

Cut-Based Iterations and Comparison with DNN



Systematics

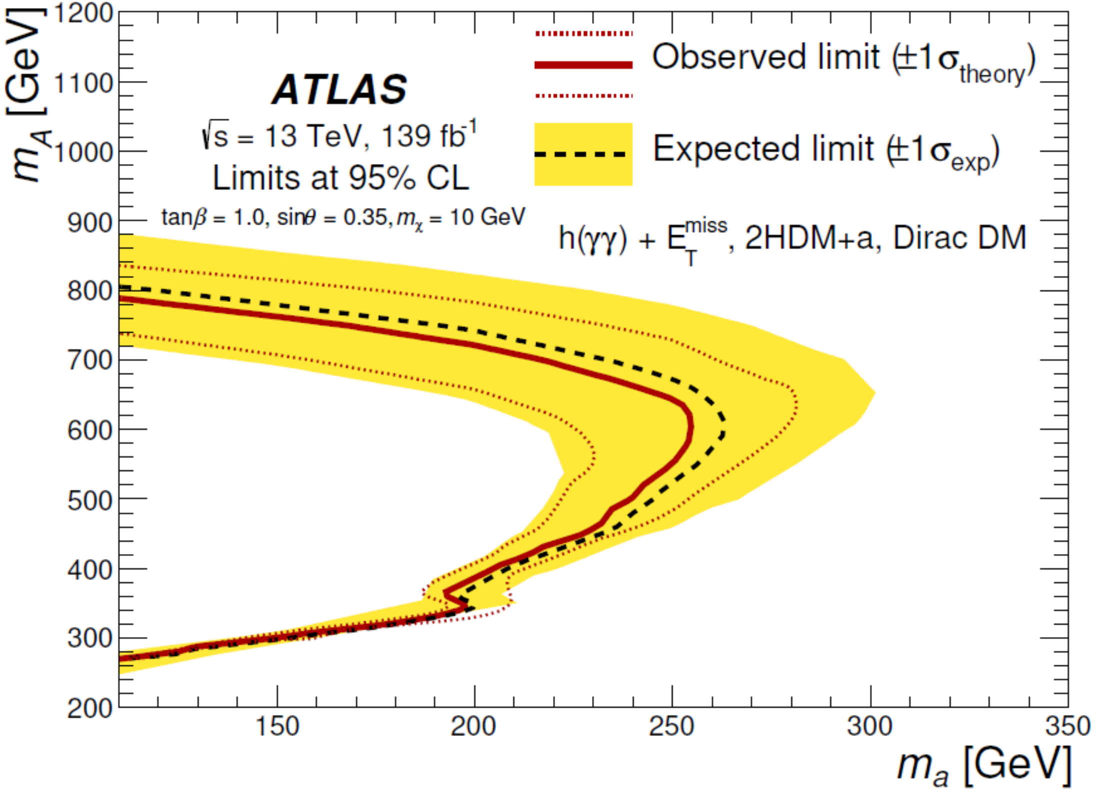
	Signal	SM h
Theoretical sources:		
PDF	—	
SM(ggh) cross section	—	
Branching fraction	~ 1.7 %	~ 1.7 %
Experimental sources:		
Luminosity	~ 2.5 %	~ 2.5 %
Trigger efficiency	~ 1%	~ 1%
Photon ID efficiency	~ 2%	~2%
Photon energy scale	~ 0.5%	~ 0.5%
MET mis-measurements(ggh & VBF) :	—	~ 50%
$\Delta\phi$ election efficiency (ggh and VBF)	—	~1-4%

Production	Scale [%]	PDF + α_s [%]
$gg \rightarrow H$	+4.6,-6.7	±3.9
VBF	+0.4,-0.3	±2.1
WH+ZH	+3.8,-3.1	±2.5
tt+H	+5.8,-9.2	±3.6

Numbers are not very accurate yet

- no systematic uncertainties for non-resonant background, extracted from a fit to data analysis is statistically driven

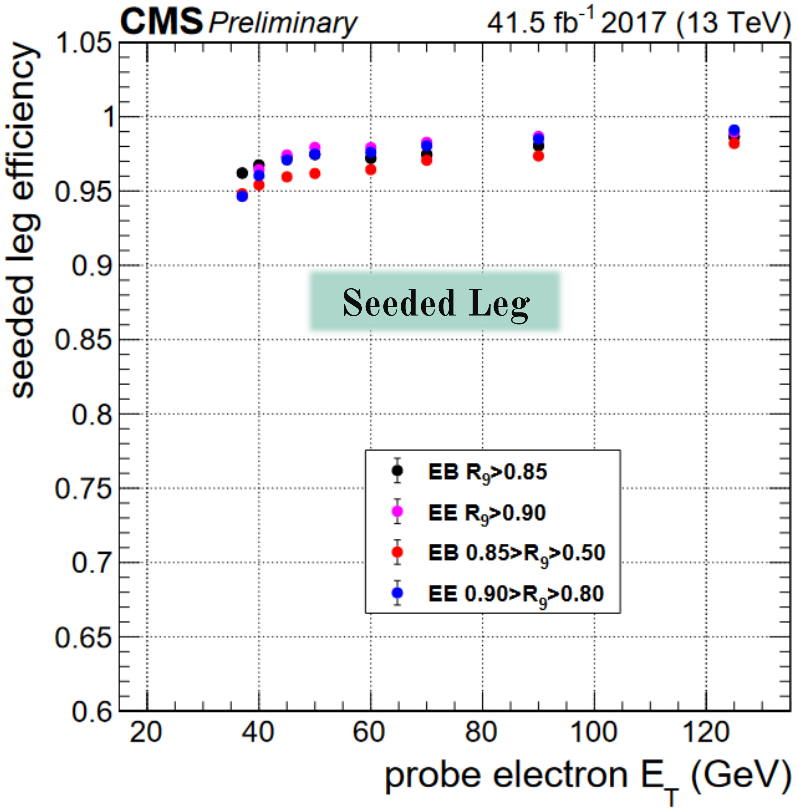
ATLAS Result for MonoH to γγ

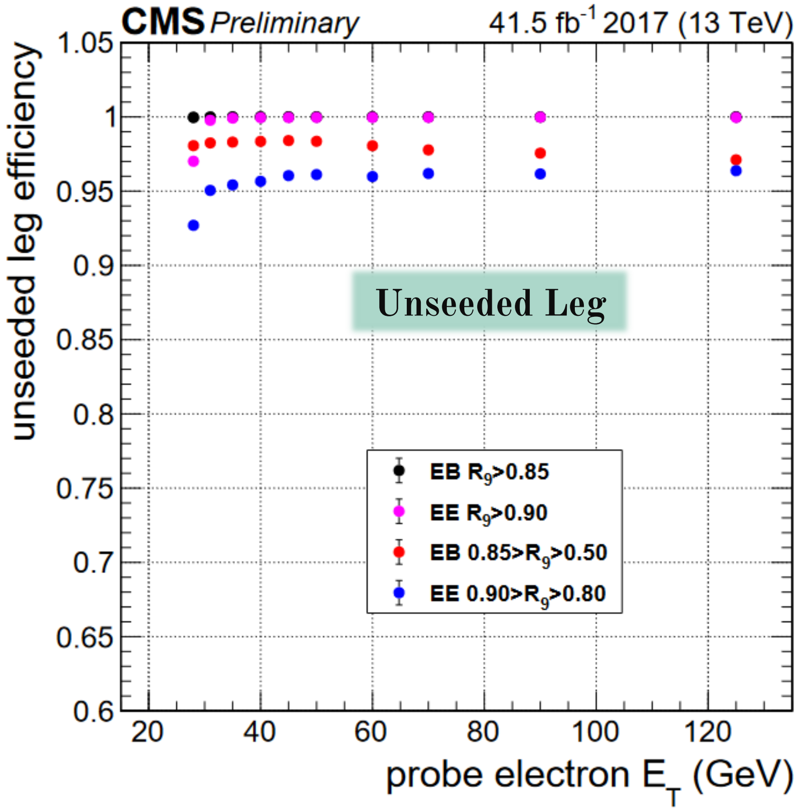


Trigger Criteria

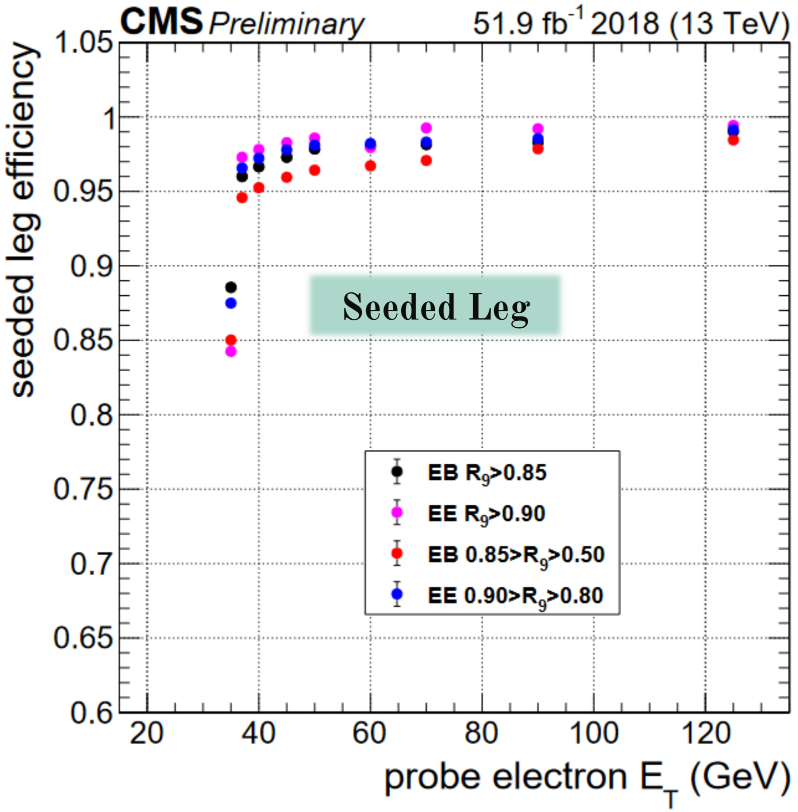
	H/E	$\sigma_{i\eta i\eta}$ (5x5)	R_9 (5x5)	ECAL PF cluster iso.	Track iso.
EB; $R_9 > 0.85$	< 0.12	–	> 0.5	–	–
EB; $R_9 \leq 0.85$	< 0.12	< 0.015	> 0.5	$< (6.0 + 0.012E_T)$	$< (6.0 + 0.002E_T)$
EE; $R_9 > 0.90$	< 0.1	–	> 0.8	–	–
EE; $R_9 \leq 0.90$	< 0.1	< 0.035	> 0.8	$< (6.0 + 0.012E_T)$	$< (6.0 + 0.002E_T)$
Other trigger requirements					
HLT seeded $E_T > 30$ GeV		HLT unseeded $E_T > 18$ GeV		$m_{\gamma\gamma} > 90$ GeV	

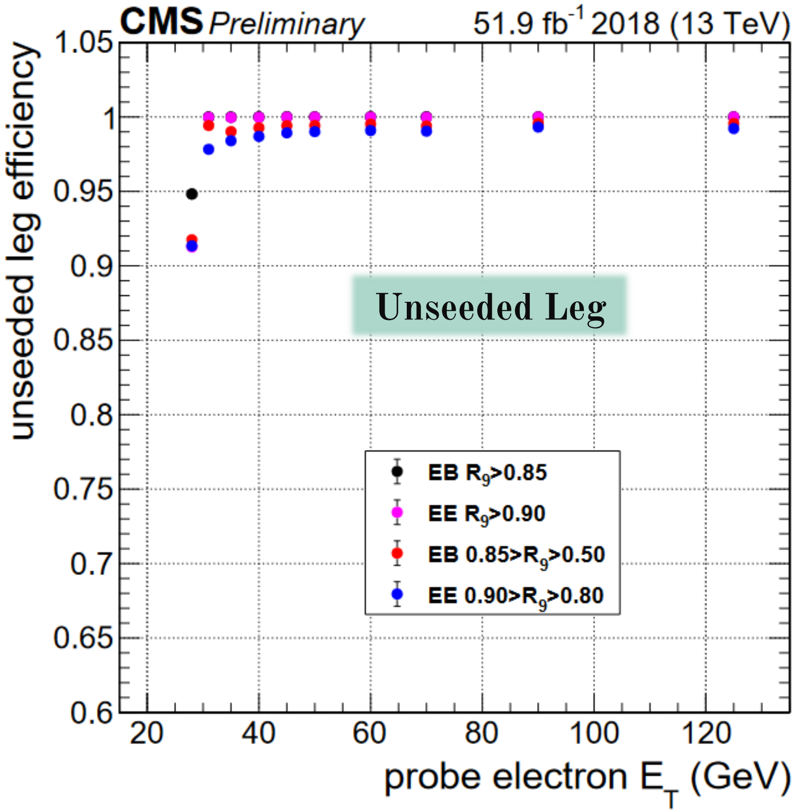
Trigger Efficiency - 2017





Trigger Efficiency - 2018





Background Composition - 2018