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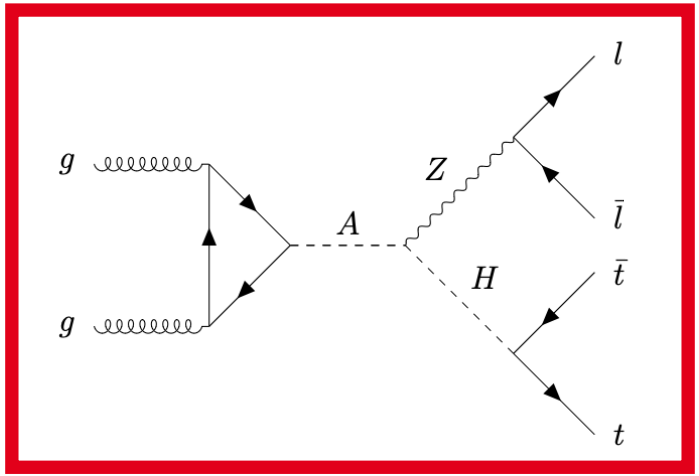


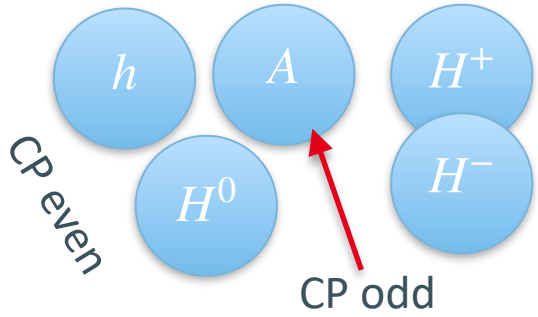
Matteo Bonanomi, Lukas Ebeling, **Yannick Fischer**, Johannes Haller, Daniel Hundhausen, Matthias Schröder, Bianca Weidner

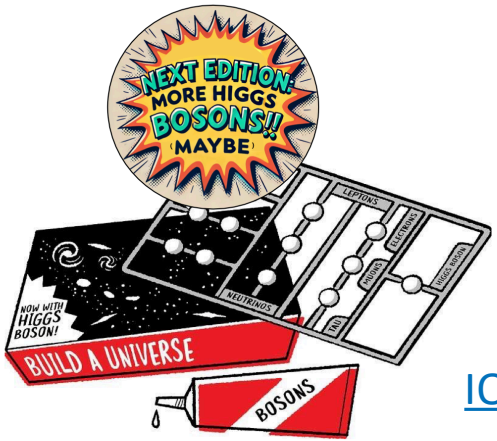
Search for 2HDM Heavy Higgs Bosons in the $t\bar{t}Z$ (2l+jets) Final State in Run 3

FSP meeting, 18.09.25

Two Higgs Doublet Model (2HDM)

- Additional Higgs doublet → **5 Higgs bosons**
- Important free parameters:
  - $\tan(\beta) = \frac{v_1}{v_2}$
  - $\cos(\beta - \alpha) \to 0$ (alignment-limit, ensures SM-like behavior of h)





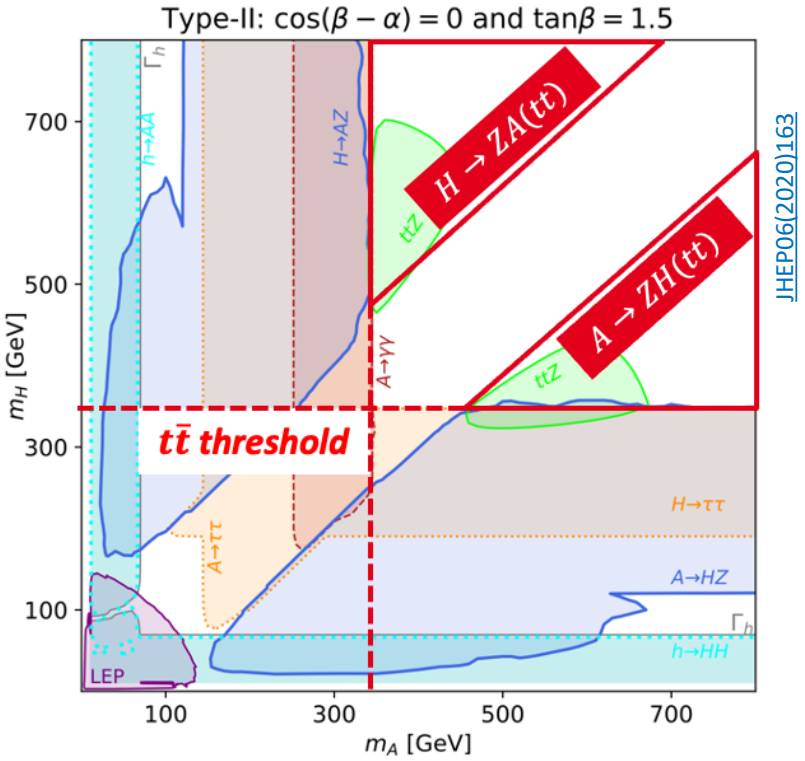
IOP

2HDM explored parameter space

- At low $m_{A/H}$: $A \rightarrow HZ$ with

  $H \rightarrow bb/\tau\tau$ sensitive

- At high $m_{A/H}$: region largely unexplored
- This analysis: $\boldsymbol{A \rightarrow ZH}$ with $\boldsymbol{H \rightarrow t\bar{t}}$



$A \rightarrow ZH \rightarrow llt\bar{t}$

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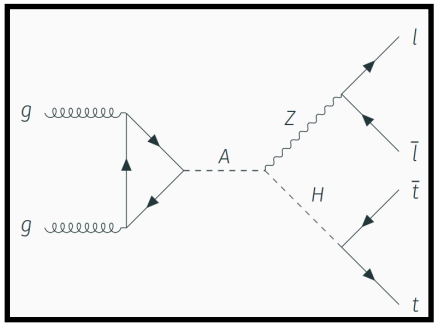
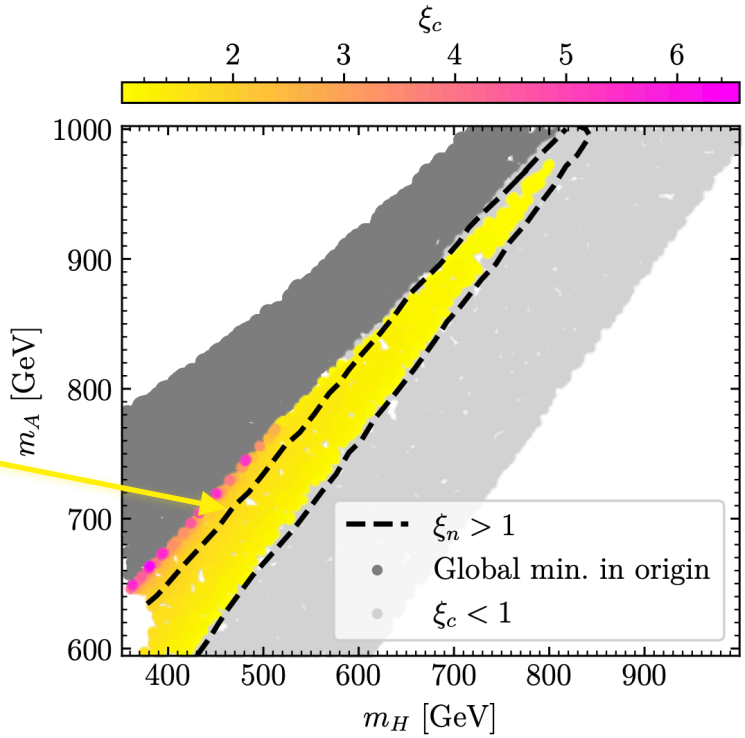
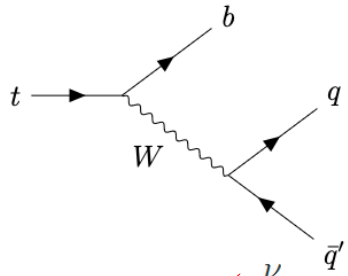
- Probing 2HDM parameter region at high masses with large gap $m_A - m_H$ and small $\tan(\beta)$
  - Interesting parameter region for models of EW baryogengesis



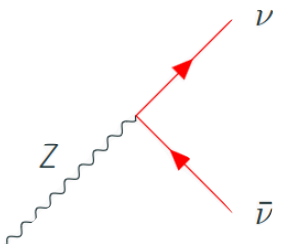


arXiv:2208.14466

Search for A→ZH→Ztt̄



Z→ll̄, tt̄→all jets with Run 2 data published (B2G-23-006)
Phys. Lett. B Vol.866 139568 (2025)



Z→νν̄, tt̄→all jets
MSc thesis at UHH
by Lukas Ebeling

ATLAS: search for llbb̄ (and νν̄bb̄)
JHEP 02 (2024) 197
(Observed $2.85\ \sigma$ excess at $m_{A/H} = 650/450$ GeV, not confirmed by CMS)

- Now: Run 3 analysis in Z→ll̄, tt̄→all channel:
  - Targeting early Result with 2022+2023 data
- Close collaboration with $t\bar{t} \rightarrow$ leptons + jets channel B2G-24-002 at UIC

Analysis of Run 3 data

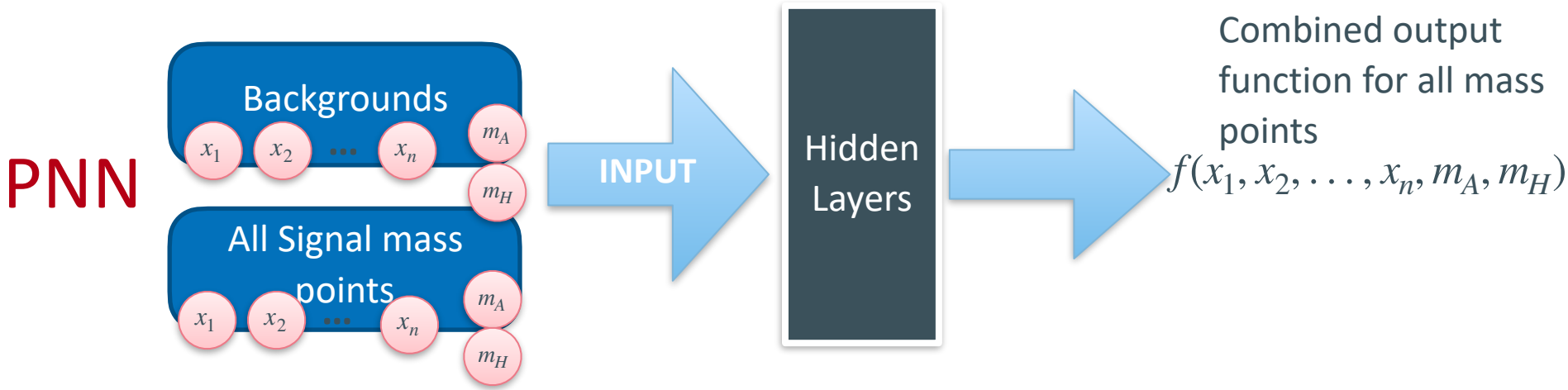
Improvements in Run 3 analysis

- Improvements compared to Run 2 analysis:
  - Parametrized neural network (PNN) as sensitive observables instead of 2D($\Delta m, p_T^Z$)
  - Finished porting analysis to new framework Columnflow[1]
  - Addition of =4 jets region (targeting Z+b background and additional signal efficiency)

columnflow

[1] Columnflow on Github

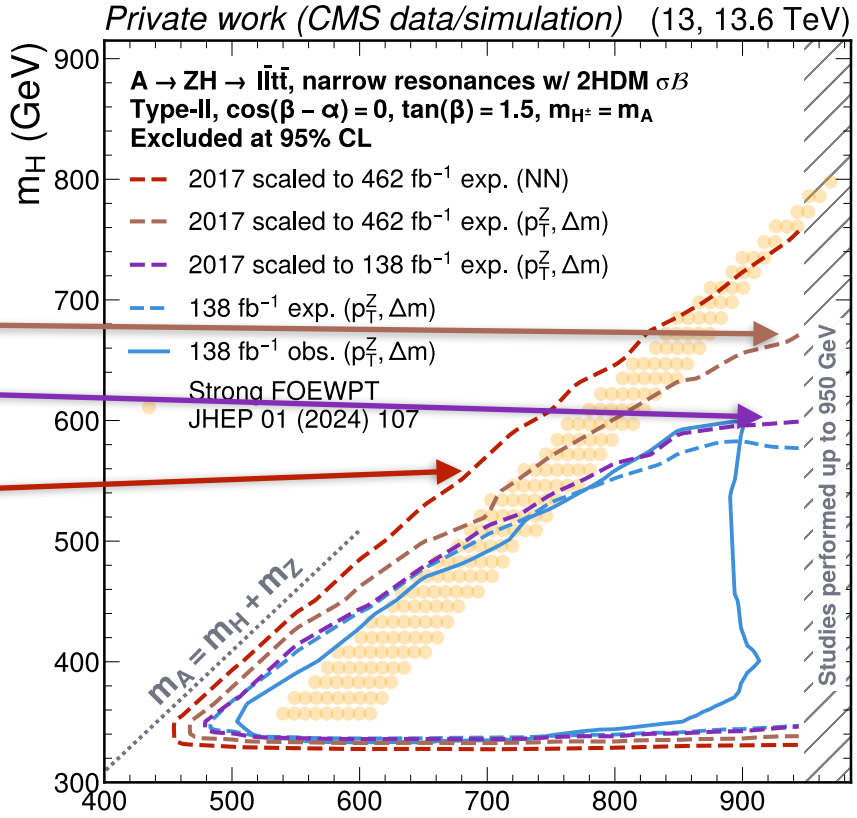
New analysis strategy: The PNN



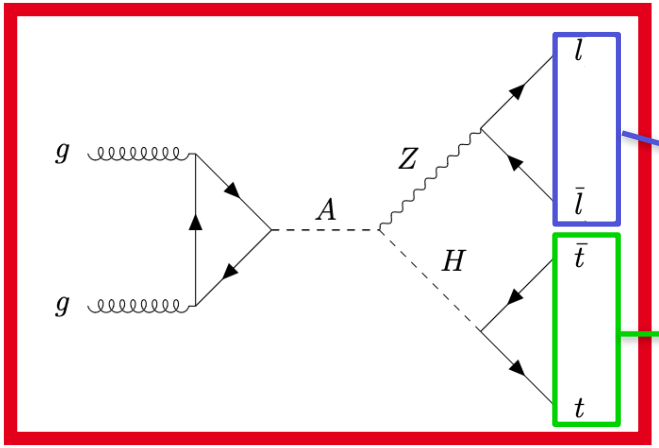
- Parametrized DNN: One network for all mass points
- Idea: Network learns signal topologies depending on m_A and m_H
- PNN only trained in the signal region

New analysis strategy: The PNN

- Study by Daniel Hundhausen on Run 2 MC with NN approach promise significantly better limits:
  - Violet vs brown: Improvement from Run 2 to Run 2+3
  - Red vs brown: improvement from $(p_T^Z, \Delta m)$ to NN-classifier



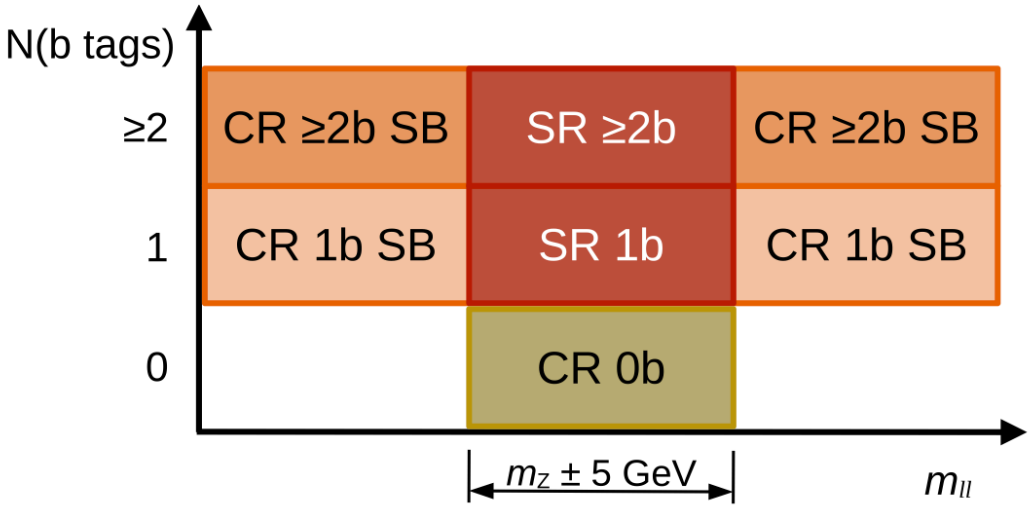
Event selection



- Event selection:
  - Exactly 2 opposite-sign, same-flavour leptons (e/μ)
  - ≥ 4 jets, ≥ 1 of which b-tagged

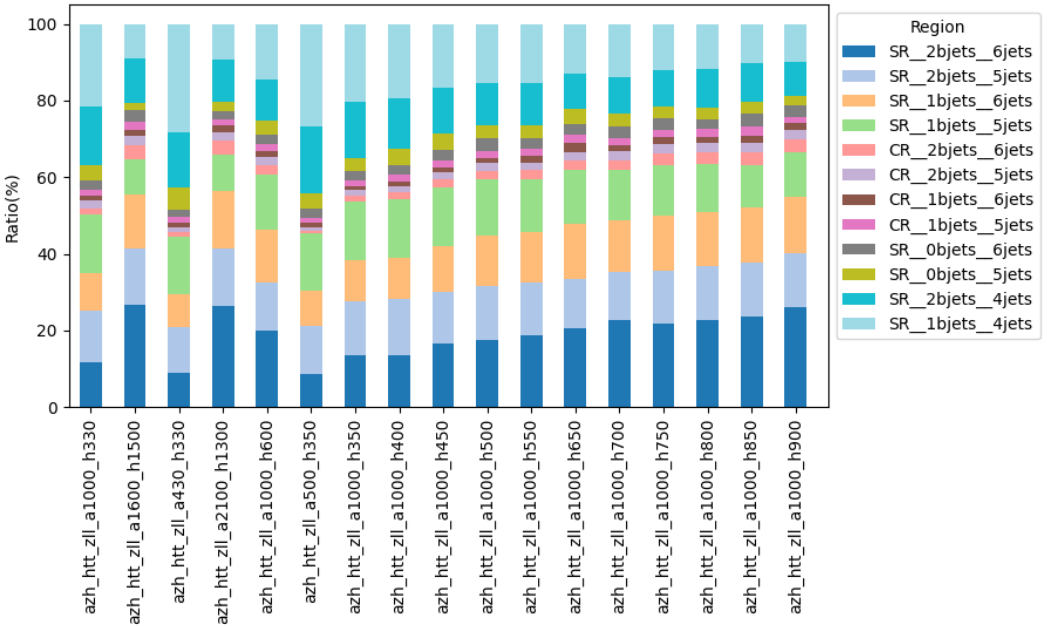
Event categorization

- Signal categories defined with respect to number of jets and number of b-tagged jets
- Background control regions:
  - m_{ll} outside Z mass window (SB) for $t\bar{t}$
  - 0 b-tagged jets and for DY
- Recent improvement: Addition of 4 jet region



4 Jet region

- 4 jet region increase signal efficiency and add further handle on Z+b background
- Contains a sizable fraction of signal especially in low mass region
- Next: assessing impact of analysis sensitivity and background modeling



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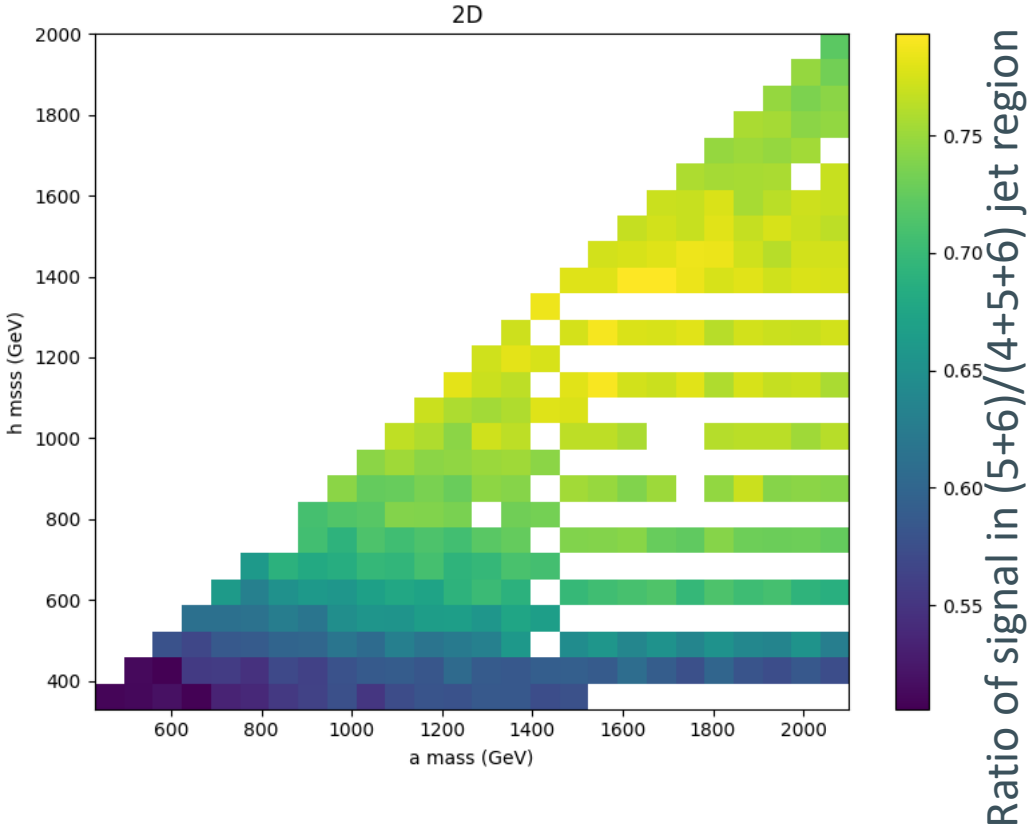
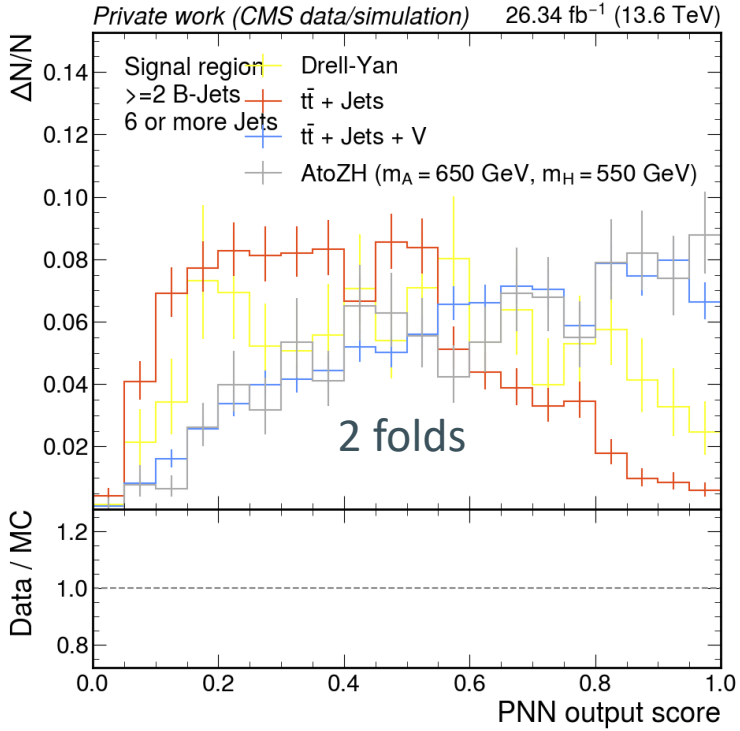


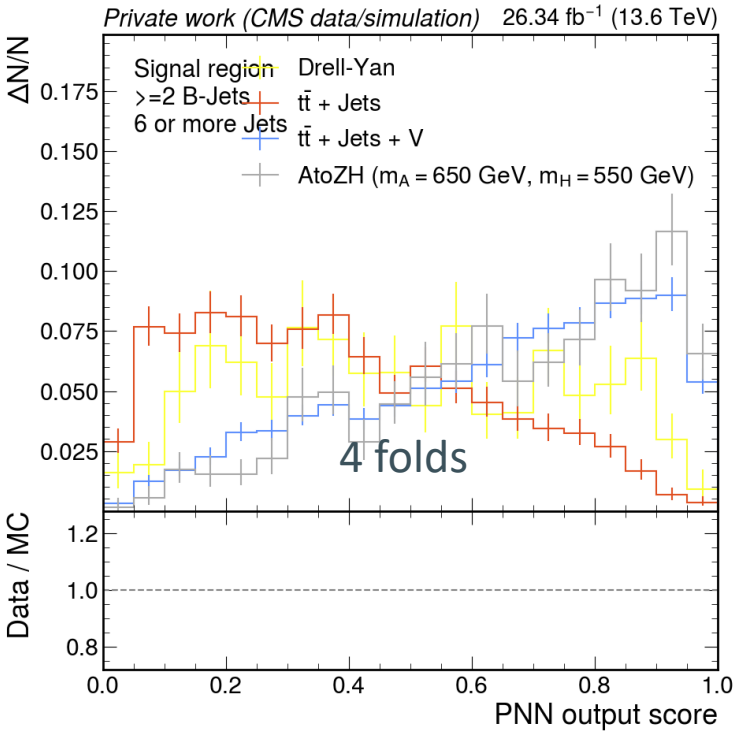
Background modeling

- Limits shown use only SR PNN output
- Target: Add CR and freely floating background norms
- Three background norms:
  - $t\bar{t}$
  - DY + heavy flavor
  - DY + light flavor

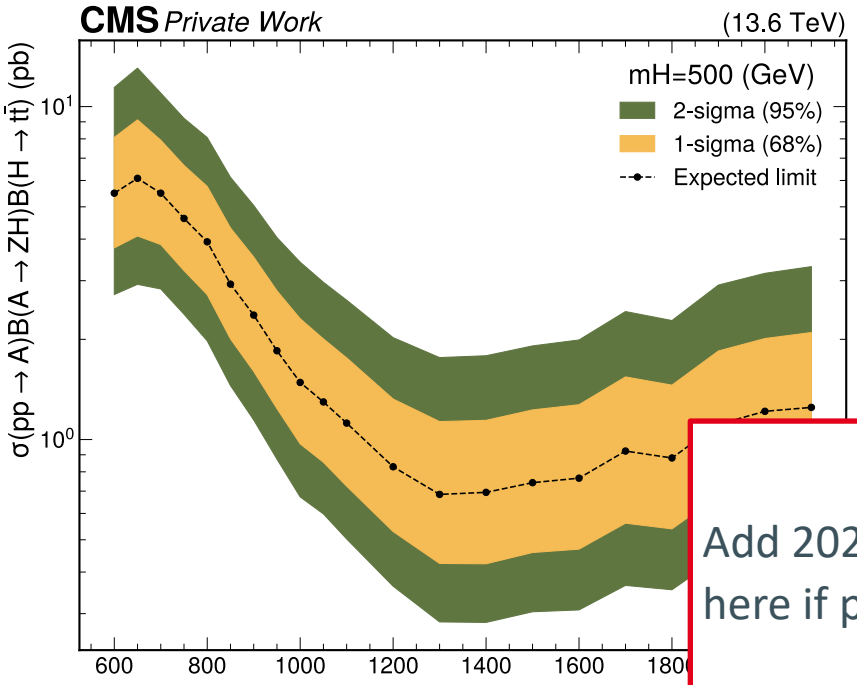
Add newest PNN output with dy_hf,dy_lf separation

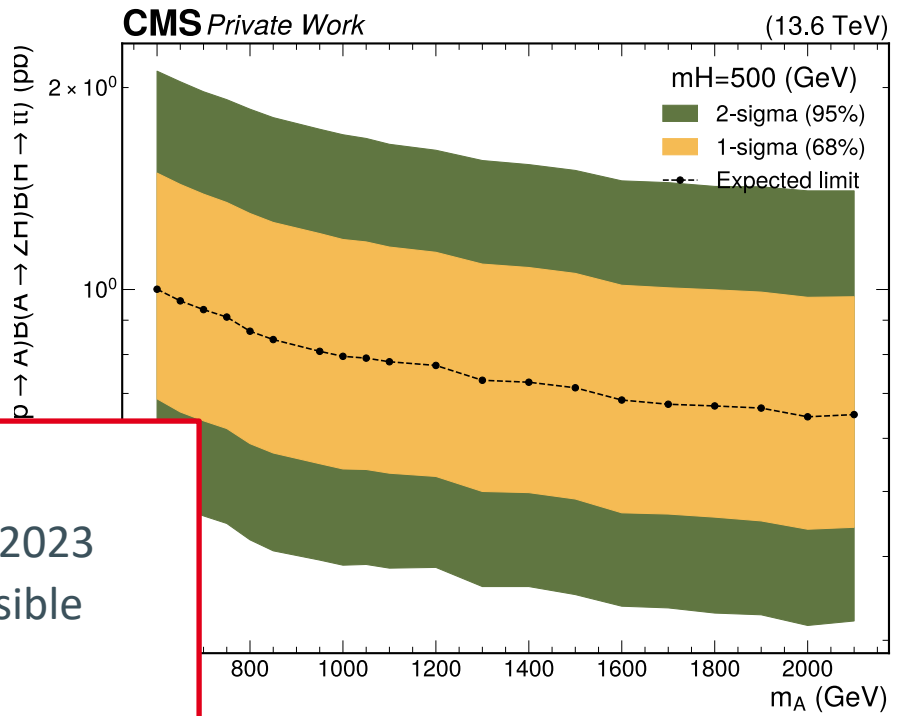
2 folds vs 4 folds





Limits with Run 3 data





Add 2022+2023 here if possible

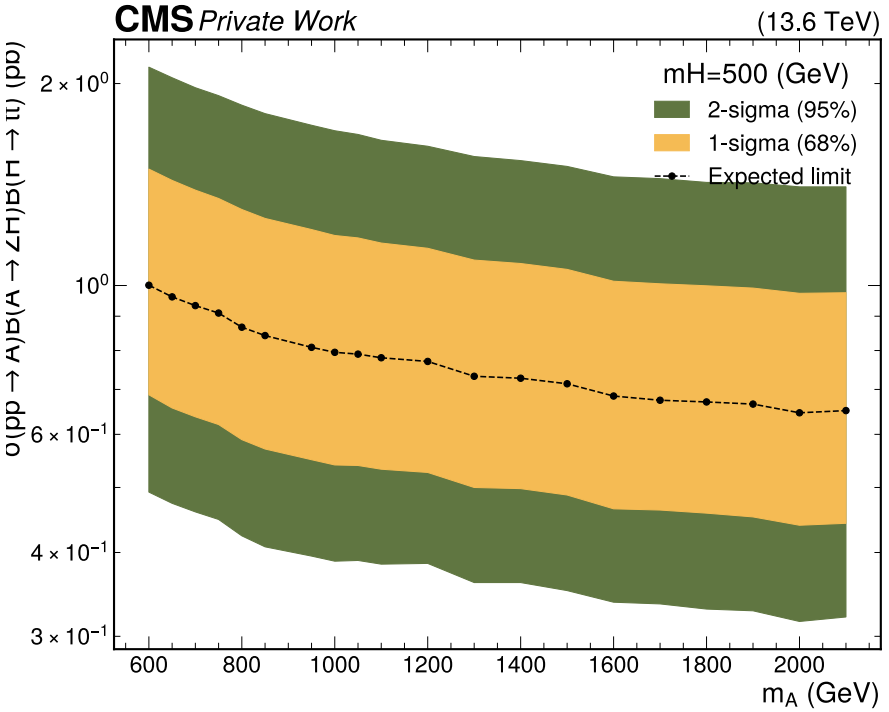
2022 pre EE (8 fb^{-1})

2022 post EE (26 fb^{-1})

Fits including only SR PNN output!

Summary

- AZH analysis on the way to produce Run 3 results
- Improved analysis strategy based on parametrized NN classifier
- Addition of 4 jet region
- Outlook:
  - Including and combining full 22+23 datasets
  - Optimization of PNN architecture



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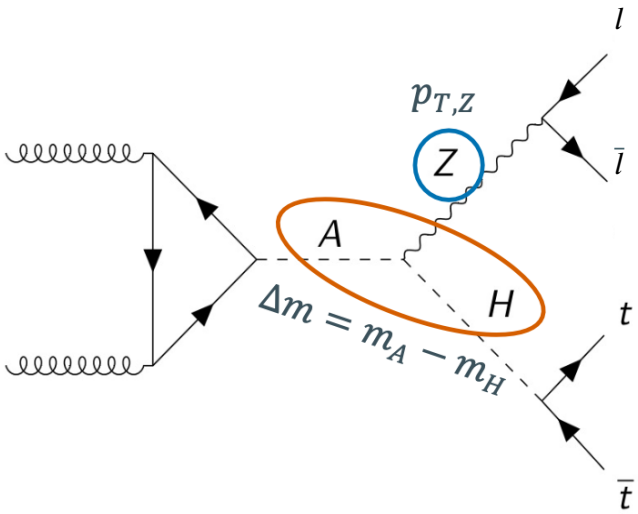
Backup

18.10.25

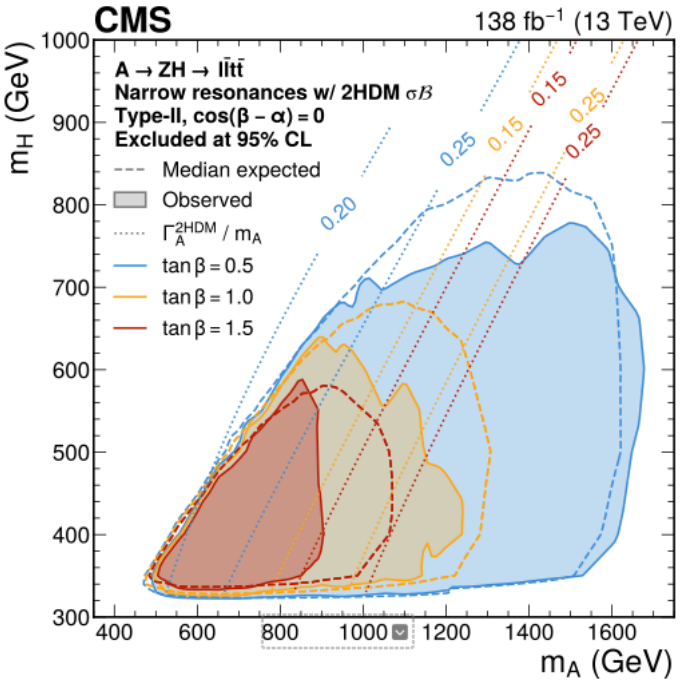
Reminder of Run 2 analysis

- Targeting resonant $A \rightarrow ZH$ production
  - Modeled as narrow resonance
- Sensitive variables $\mathrm{p_T}(Z)$ and $\Delta m = m_A - m_H$ JHEP 151 (2018)



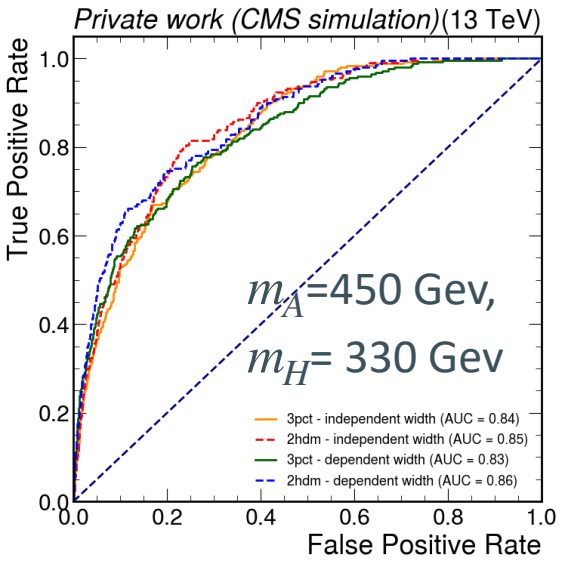
- Event selection
  - ≥ 5 jets, ≥ 1 of which b-tagged
  - Exactly 2 opposite-sign, same-flavour leptons leptons (e/μ)

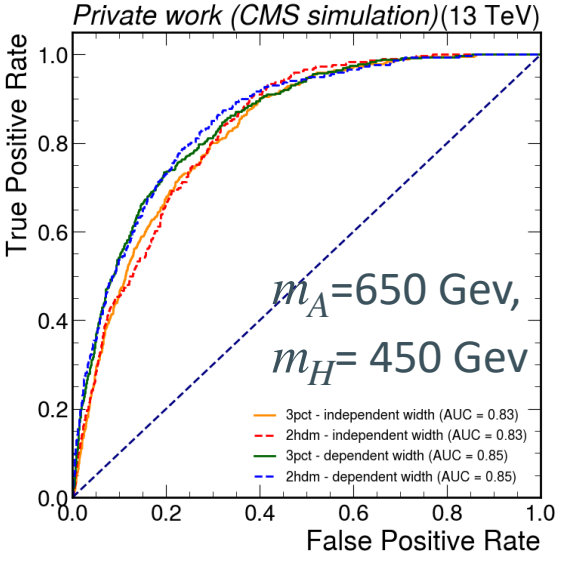
2HDM interpretation of obtained exclusion limits



Impact of A boson width in 2HDM interpretation

- Reminder: in 2HDM, A boson natural width can become sizable at large m_A, which can affect analysis sensitivity.
  - Test (performed with Run 2 samples) by Bianca Weidner: NN trained on samples with narrow A and evaluated on:
    - Samples with narrow A
    - Samples with wide A
  - NN classifier performance robust against effects of A boson width





Object Definition

- Electrons :
  - $p_T > 35$ GeV (for first electron)
  - $p_T > 20$ GeV (for second electron)
  - $|\eta| < 2.4$
  - mvaIso_WP80 (for tight selection)
  - mvaIso_WP90 (for loose selection)

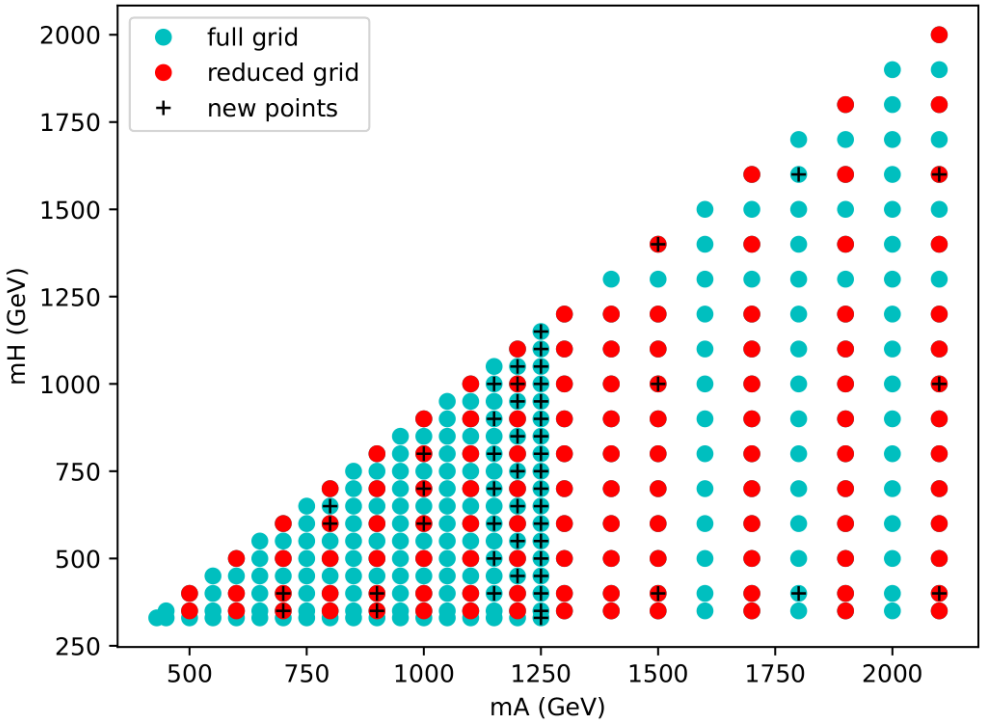
- Muons :
  - $p_T > 35$ GeV (for first muon)
  - $p_T > 20$ GeV (for second muon)
  - $|\eta| < 2.4$
  - highPtId + tkIsoID tight (for tight selection)
  - looseId + tkIsoId loose (for loose selection)

- Jets :
  - $p_T > 30$ GeV
  - $|\eta| < 2.4$
  - Tight Lepton Veto ID

- B Jets:
  - Deep Flavor Medium WP

Run 3 A→ZH→Ztt̄ signal samples

- MC samples for Run 3 produced.
- Points aligned with Run 2 UL samples
  - Crosses on points: not in UL samples will be additionally produced
- Plan to submit some points with A bosons with larger width (for validation of 2HDM interpretation)



First Look into Run 3 Data

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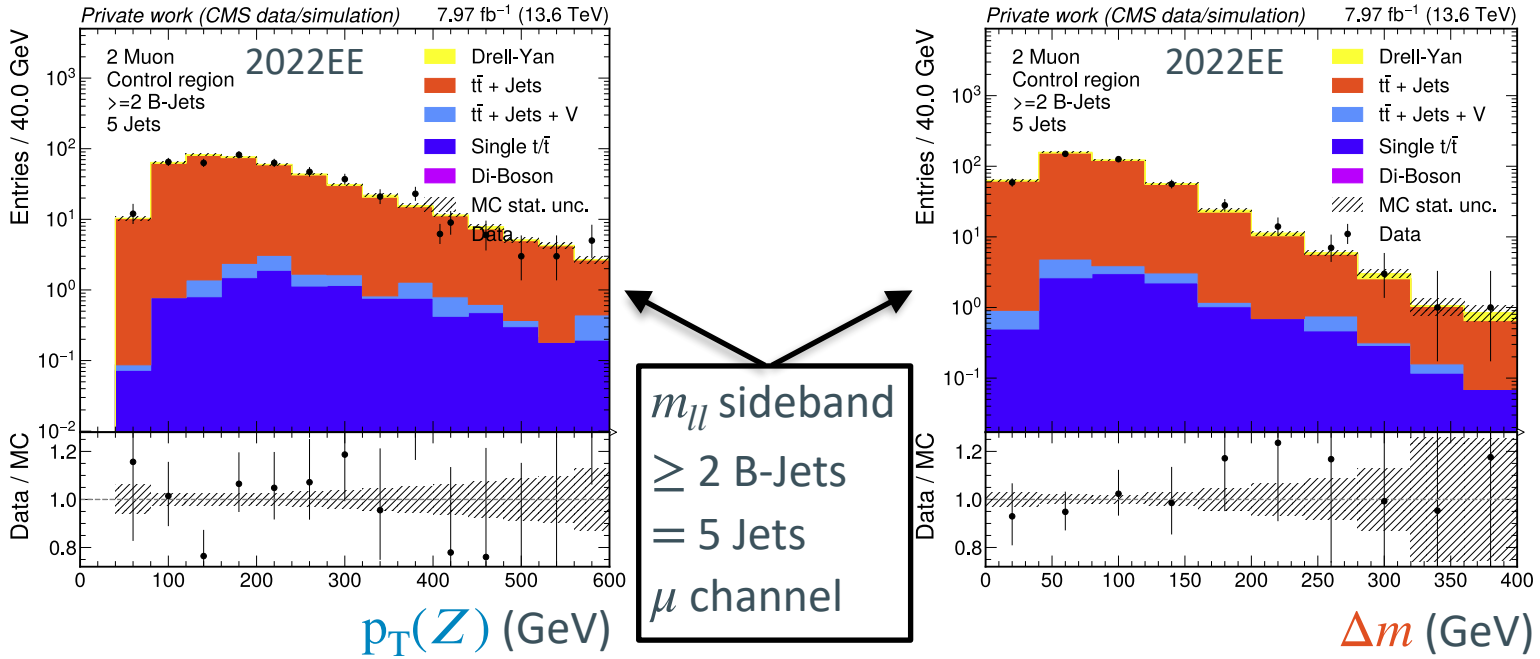
First data to MC comparison looks promising in the control regions

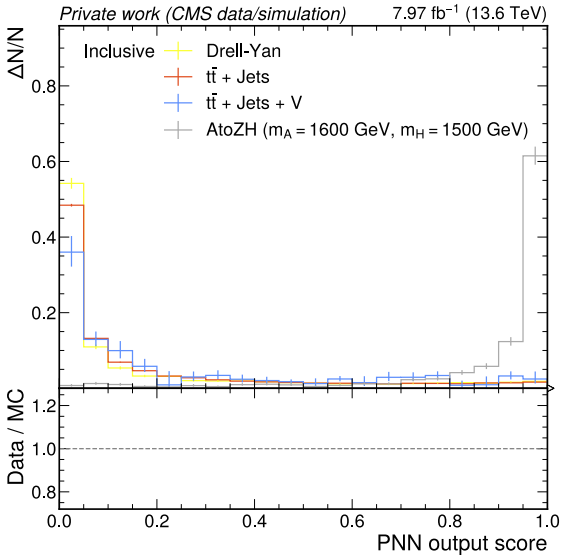


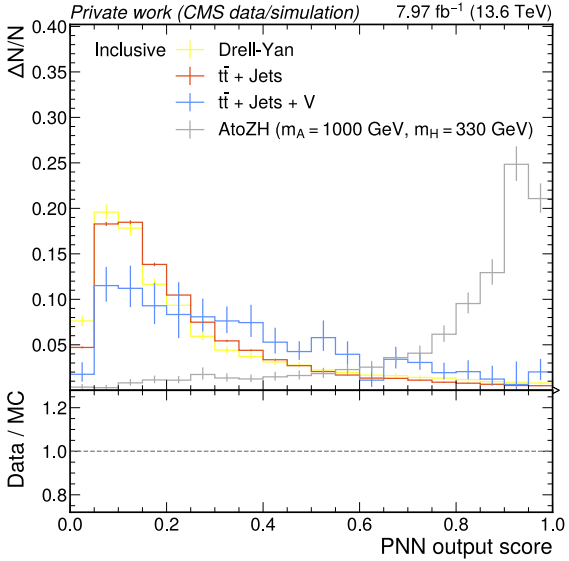
PNN classifier

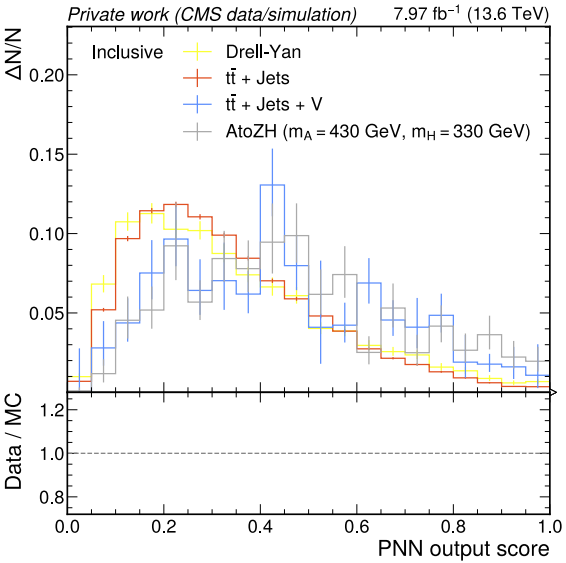
- General architecture studied and optimized for Run 2 by Bianca Weidner in her bachelors thesis
- Projection studies from Run 2 promise large improvements in sensitivity from NN
- NN still work in progress, expecting more improvements from optimization of input variables, more statistics, and improvement of binning strategy

- General Architecture:
  - Folds: 4
  - Dropout: 0.5
  - Layers: [512,512]
  - Learning rate: 0.0005
  - Epochs: 500
  - Validation fraction: 0.25
- Input features:
  - $p_T, \eta, \Delta\phi$, mass and b-tagging score of jets1-4,
  - $p_T, \eta, \Delta\phi$, of the two Leptons
  - reconstructed A and H mass
  - reconstructed p_T^Z, m_Z, ΔR(leading b-jet and Z)
  - $\Delta\phi$(MET,Jet1-3), MET/H_T
  - A and H mass parameter

Parametrized Neural network with Run 3 samples

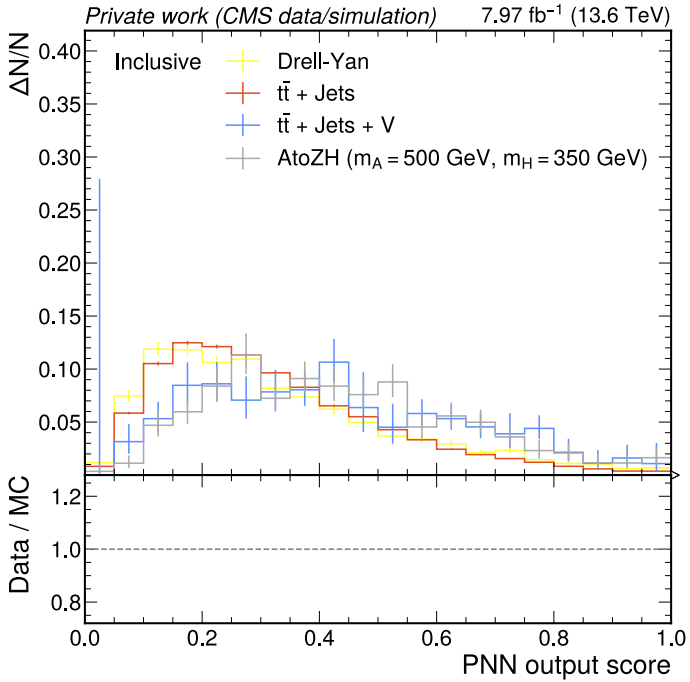


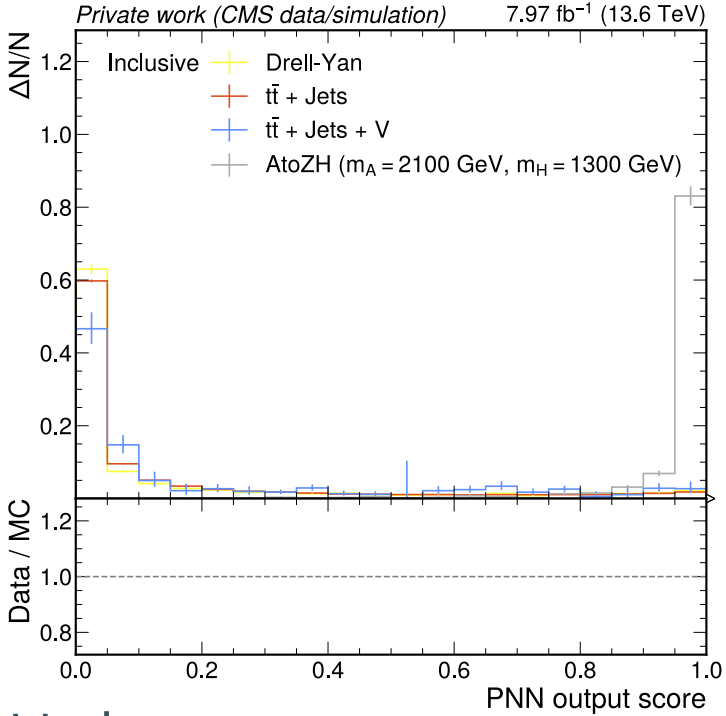




- NN Trained and evaluated on the same three mass points (Very first test to commission implementation)

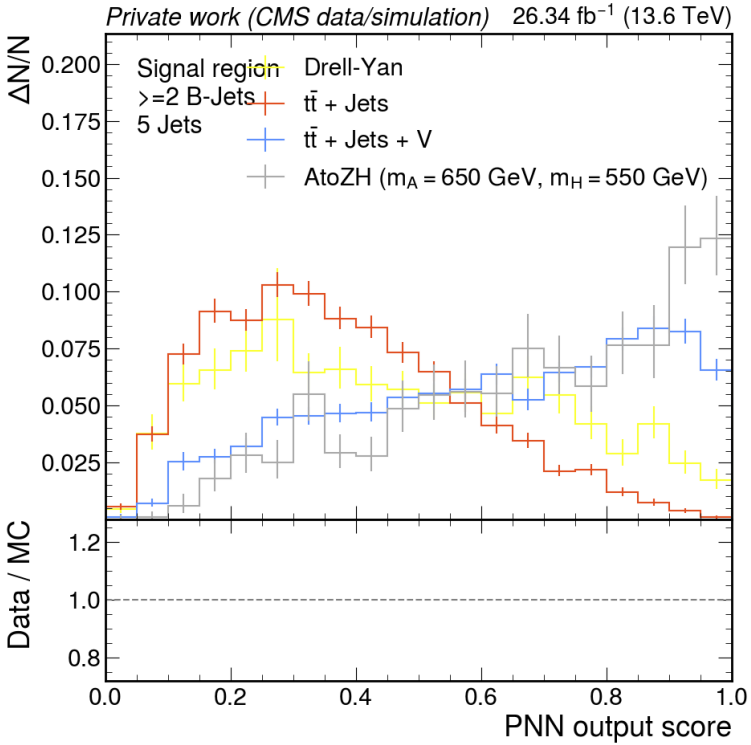
Parametrized Neural network with Run 3 samples

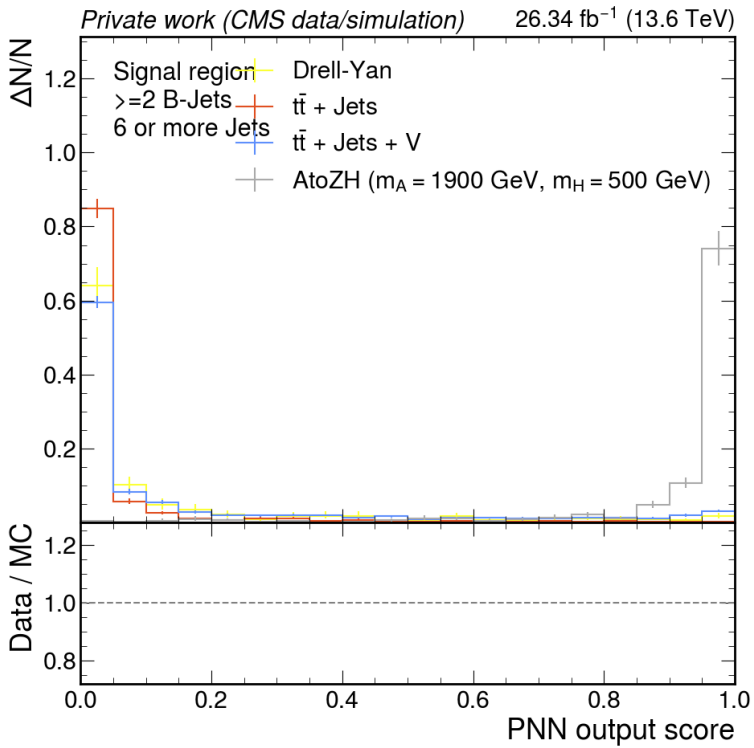




- NN evaluated on mass points it did not train on

NN output for 22 postEE





Datasets and triggers for 2022

- Datasets:
  - /Muon/Run2022X-22Sep2023-v1/NANOAOD (C-G)
  - /EGamma/Run2022X-22Sep2023-v1/NANOAOD (C-G)
  - /MuonEG/Run2022X-22Sep2023-v1/NANOAOD (C-G)
  - /DoubleMuon/Run2022C-22Sep2023-v1/NANOAOD
- c+d: preEE
- f-g: postEE

- Trigger paths :
  - HLT_Mu17_TrkIsoVVL_Mu8_TrkIsoVVL_DZ_Mass3p8
  - HLT_Ele23_Ele12_CaloIdL_TrackIdL_IsoVL

TODO: check trigger efficiencies and see if additional trigger paths are necessary