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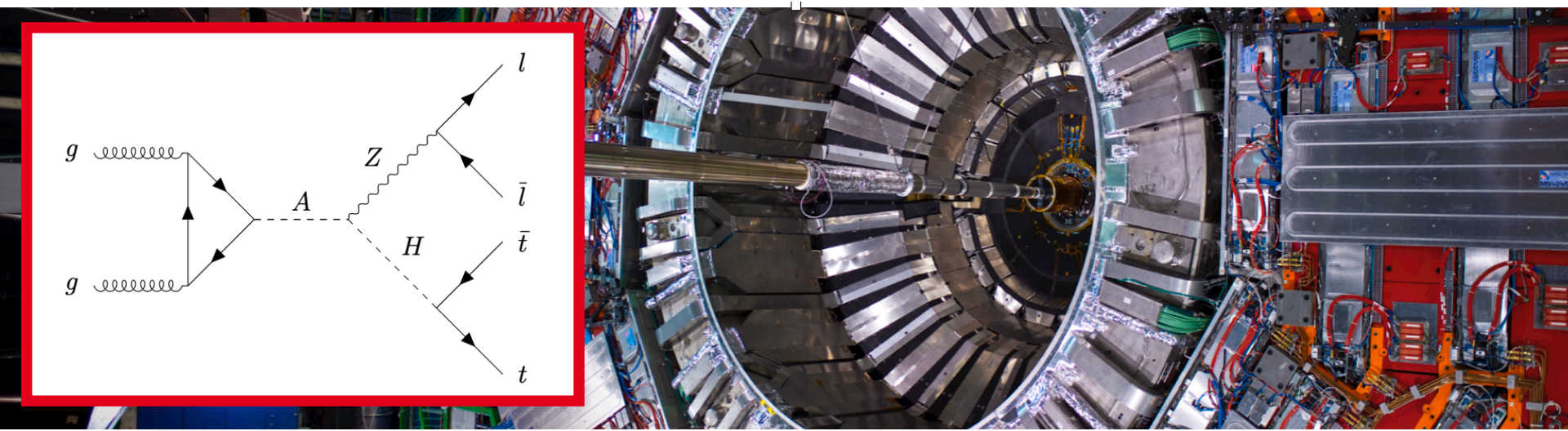


Matteo Bonanomi, Lukas Ebeling, **Yannick Fischer**, Johannes Haller, Daniel Hundhausen, Matthias Schröder, Bianca Weidner

Search for 2HDM Heavy Higgs Bosons in the $t\bar{t}Z$ Final State at CMS

DPG spring conference 2025, Göttingen

2HDM motivation and parameter space

- Two Higgs Doublet Model (2HDM) introduces an additional Higgs doublet to the SM → 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)

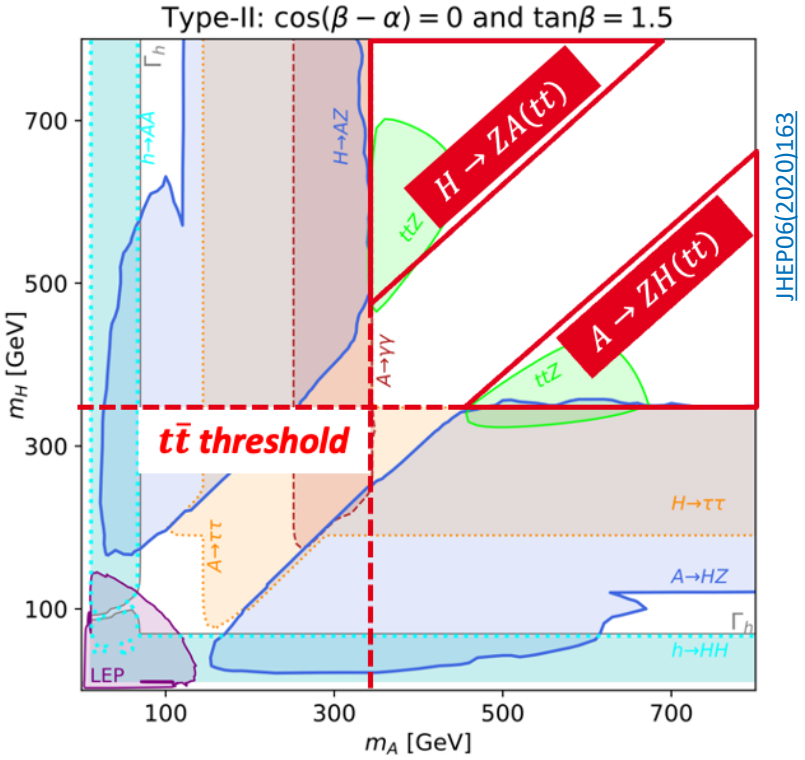
The Higgs bosons of the 2HDM

Boson	Charge	Properties
h	0	CP even
H^0	0	CP even
A	0	CP odd
$H^\pm$	± 1	charged

- For this analysis: assume $m_A \neq m_H$ (non-degenerate case)

2HDM motivation and 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 $\boldsymbol{H \rightarrow t\bar{t}}$
- Smoking gun channel for first order electroweak phase transition, possible explanation for baryon asymmetry



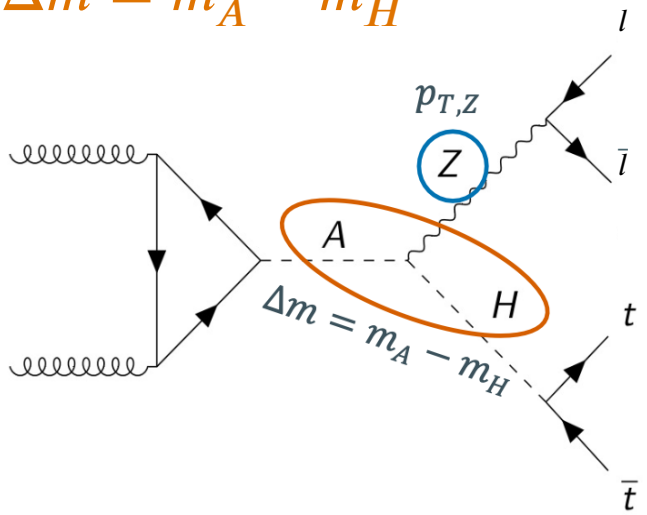
Search for 2HDM Higgs bosons in $t\bar{t}Z$ final state

- CMS Run 2 analysis targeting resonant $A \rightarrow ZH$ production
  - Modeled as narrow resonance

arXiv:2412.00570 (subm. to PLB)

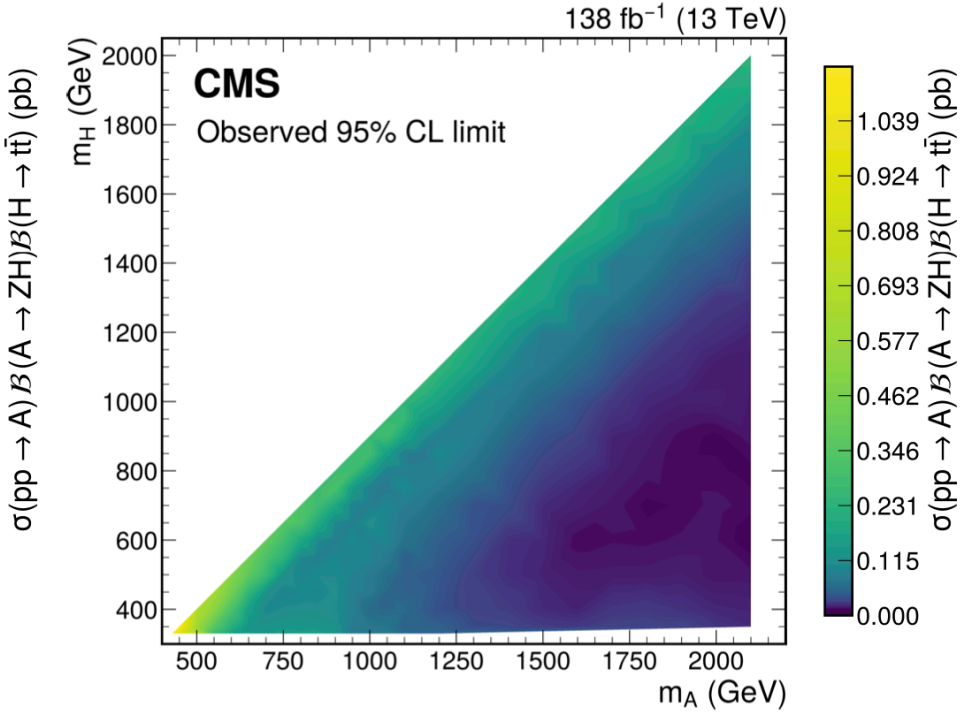
- Final sensitive observable: 2D distribution of $p_T(Z)$ and $\Delta m = m_A - m_H$

JHEP 151 (2018)

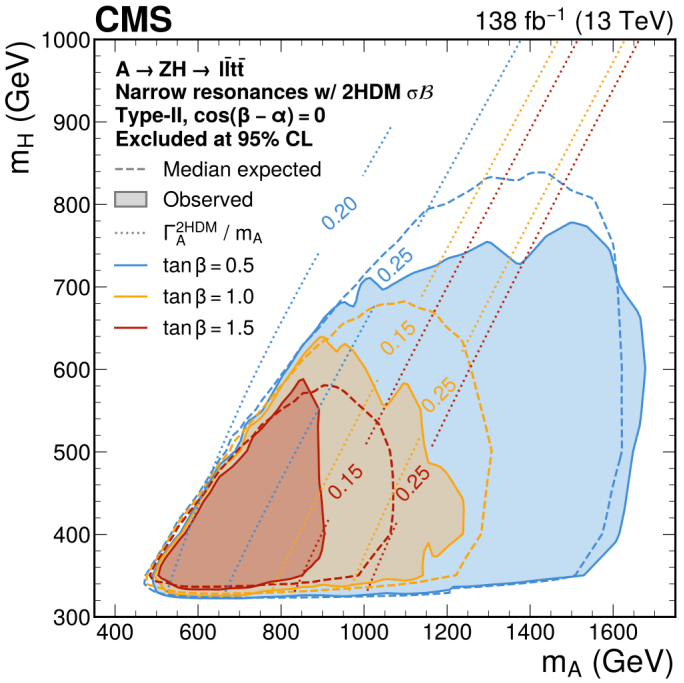


- Event selection
  - ≥ 5 jets, ≥ 1 of which b-tagged
  - Exactly 2 opposite-sign, same-flavour leptons (e/μ)

Upper limits and model interpretation



Observed upper production limits on cross section times branching ratio



2HDM interpretation of exclusion limits

arXiv:2412.00570

Run 3 Analysis

Used data

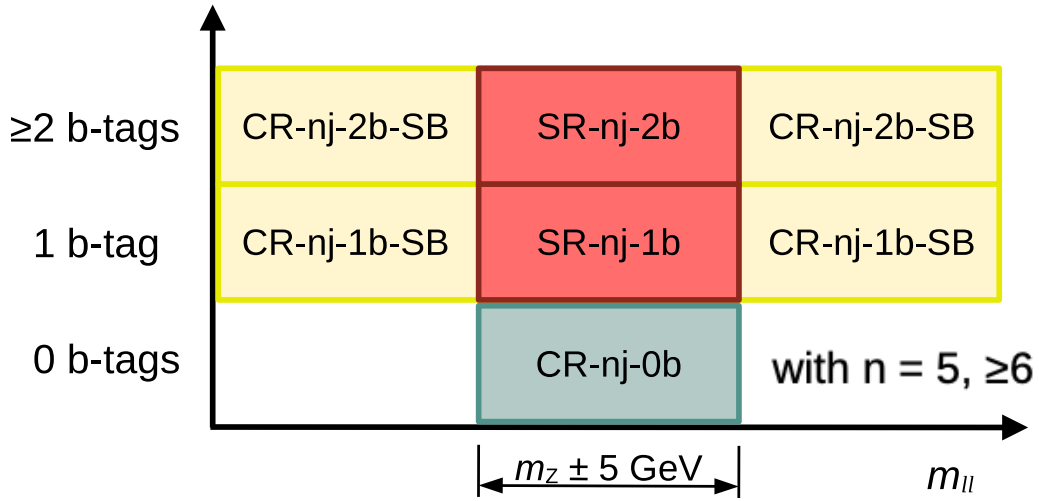
- Luminosity used so far: 7.96 fb^{-1} (first half of 2022 data taking period)
- Event selection:
  - Exactly two opposite-sign same-flavor leptons (e/μ)
  - $m_Z - 5$ GeV $< m_{ll} < m_Z + 5$ GeV
  - $p_T^{ll} > 15$ GeV
  - At least five jets
  - At least one b-jet
- Triggers:
  - Di-Muon Trigger
    (HLT_Mu17_TrkIsoVVL_Mu8_TrkIsoVVL_DZ_Mass3p8)
  - Di-Electron Trigger
    (HLT_Ele23_Ele12_CaloIdL_TrackIdL_IsoVL)

Object definition

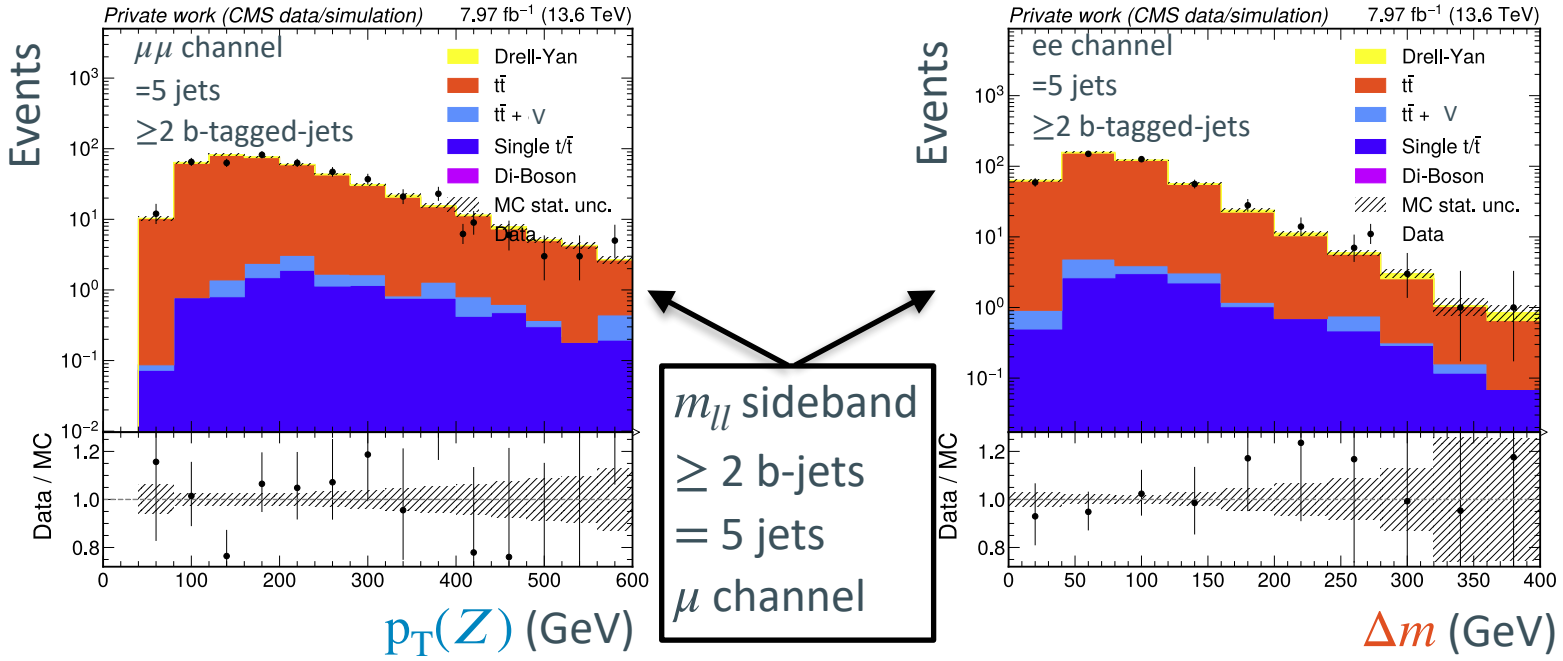
	Electron	Muons	Jets
p_T	**>35 GeV** (leading) **>20 GeV** (subleading)	**>35 GeV** (leading) **>20 GeV** (subleading)	**>30 GeV**
$\|\eta\|$	**<2.4**	**<2.4**	**<2.4**
Quality isolation criteria	Tight isolation ID	High pt-ID, tracker & isolation ID	Tight lepton veto

Categorization

- Signal categories defined with respect to number of jets and number of b-jets
- Background freely floating in fit, using control regions:
  - m_{ll} outside Z mass window (SB) for $t\bar{t}$
  - 0 b-jets for DY

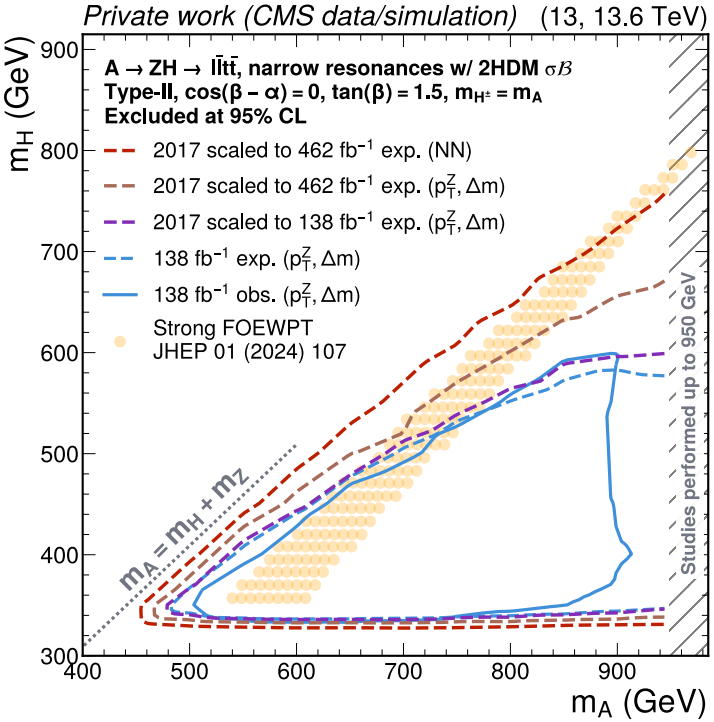


Data in the CR modelled well



New analysis strategy

- Biggest development: replace 2D distribution (p_T, $\Delta m = m_A - m_H$) with neural network (NN) output score, since projection of Run 2 data with NN approach promise significantly better limits



D. Hundhausen, PhD Thesis, Universität Hamburg

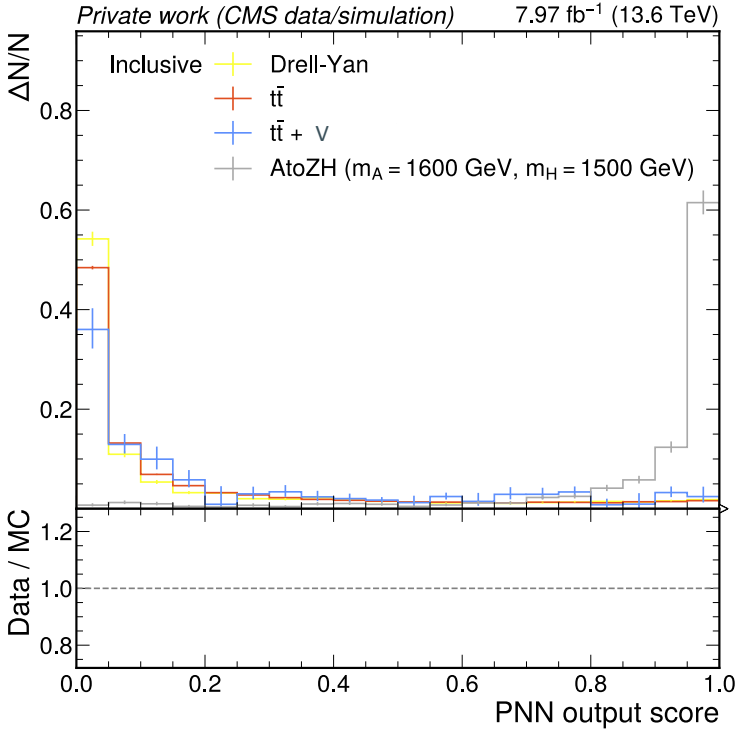
New analysis strategy

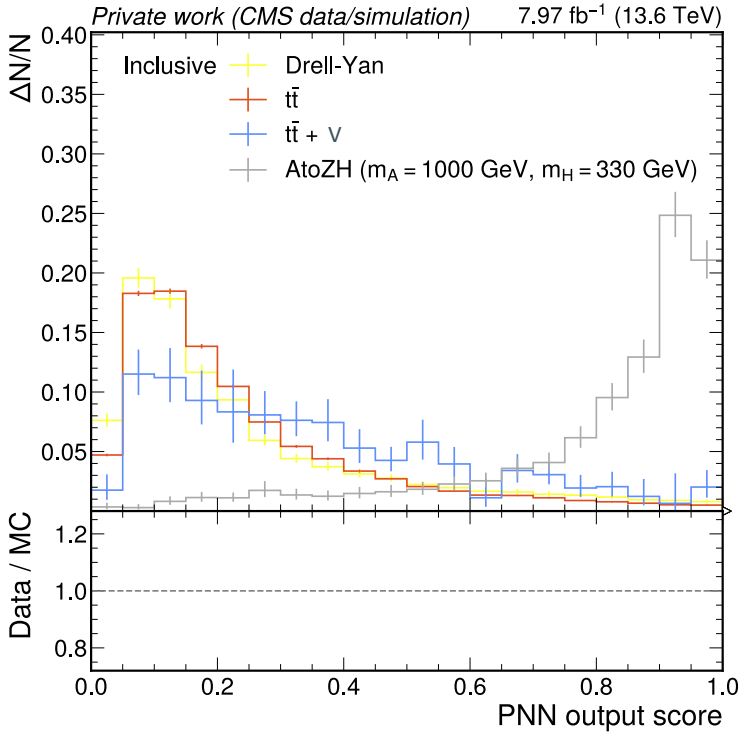
- Biggest development: replace 2D distribution (p_T, $\Delta m = m_A - m_H$) with neural network (NN) output score, since projection of Run 2 data with NN approach promise significantly better limits
- Instead of training individual NN for each mass hypothesis, choose a parametrized NN:
  - Train NN with all signal hypothesis simultaneously, adding the masses m_A and m_H as input features
  - For background, add a random m_A and m_H pair from the list of used mass points for each event
  - Evaluation of each mass point individually, setting m_A and m_H to desired values
- Idea: Network learns what signal topology looks like, since it depends on m_A and m_H in a parametric way

The parametrized NN: details

- NN trained only in signal region (within Z mass window, ≥1 b-jet, ≥5 jets)
- Output score as binary classifier (signal/background)
- NN trained on all $\mathcal{O}(300)$ signal mass points, $t\bar{t}$, Drell-Yan and $t\bar{t} + Z$
- Optimization and validation of NN shown in the next talk by Bianca
- Large number of individual evaluations of the network: Porting analysis to new columnar-based framework columnflow, allowing much faster turnaround time

PNN output score with Run 3 samples



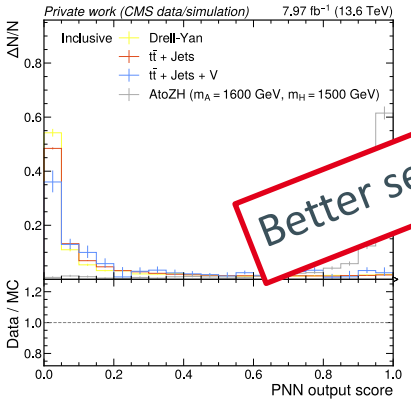


Limits with Run 3 data

Something meaningful about limit plot

Summary

- $A \rightarrow ZH \rightarrow t\bar{t}Z$ probes interesting 2HDM parameter space
- Search with Run 2 data published
- Improvements foreseen for Run 3 analysis: NN



Limit Plot

Better sensitivity

Backup

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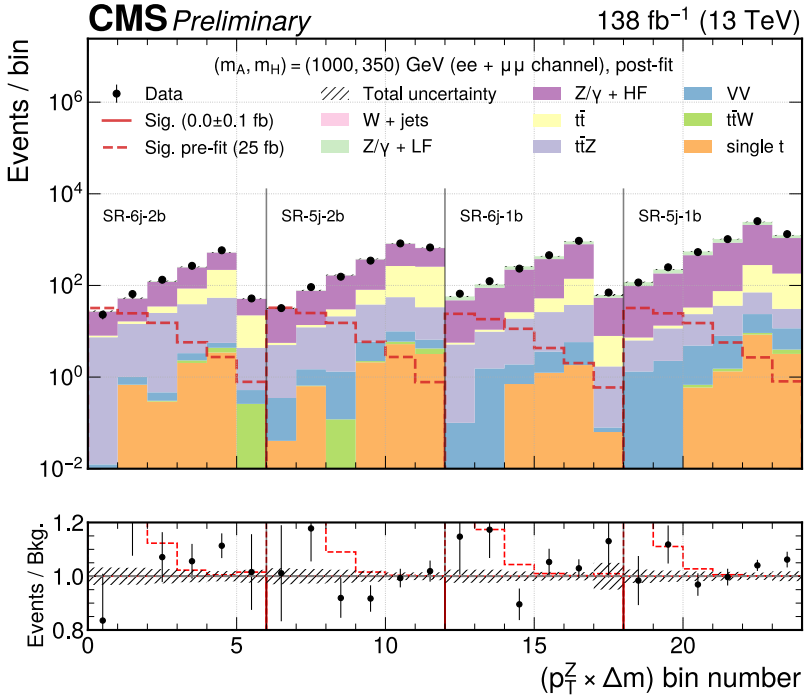
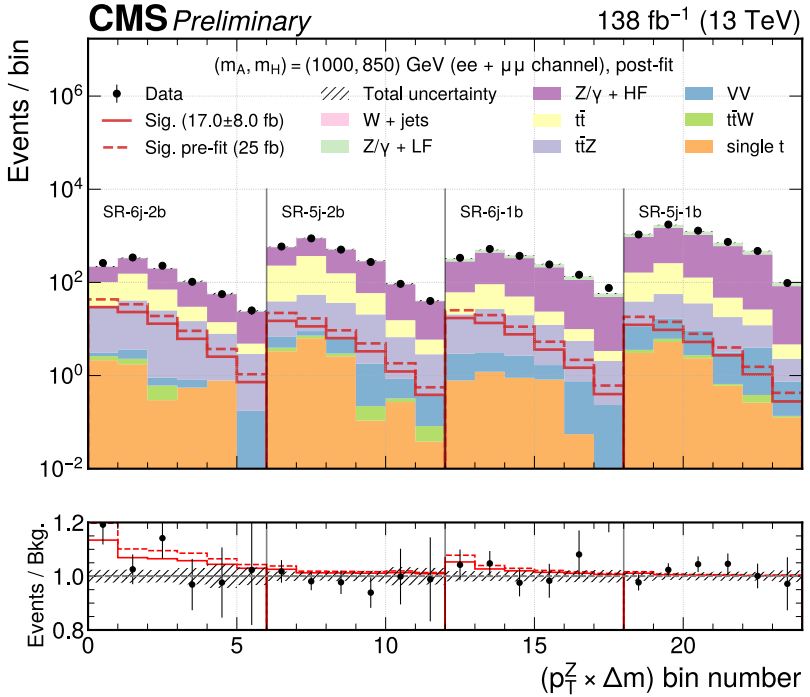
Run 2 Backup

01.04.25

Results





- No significant excess observed
- $m_{A/H} = 650/450$ GeV local significance of the deviation from the background at this point of 0.4 SD

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