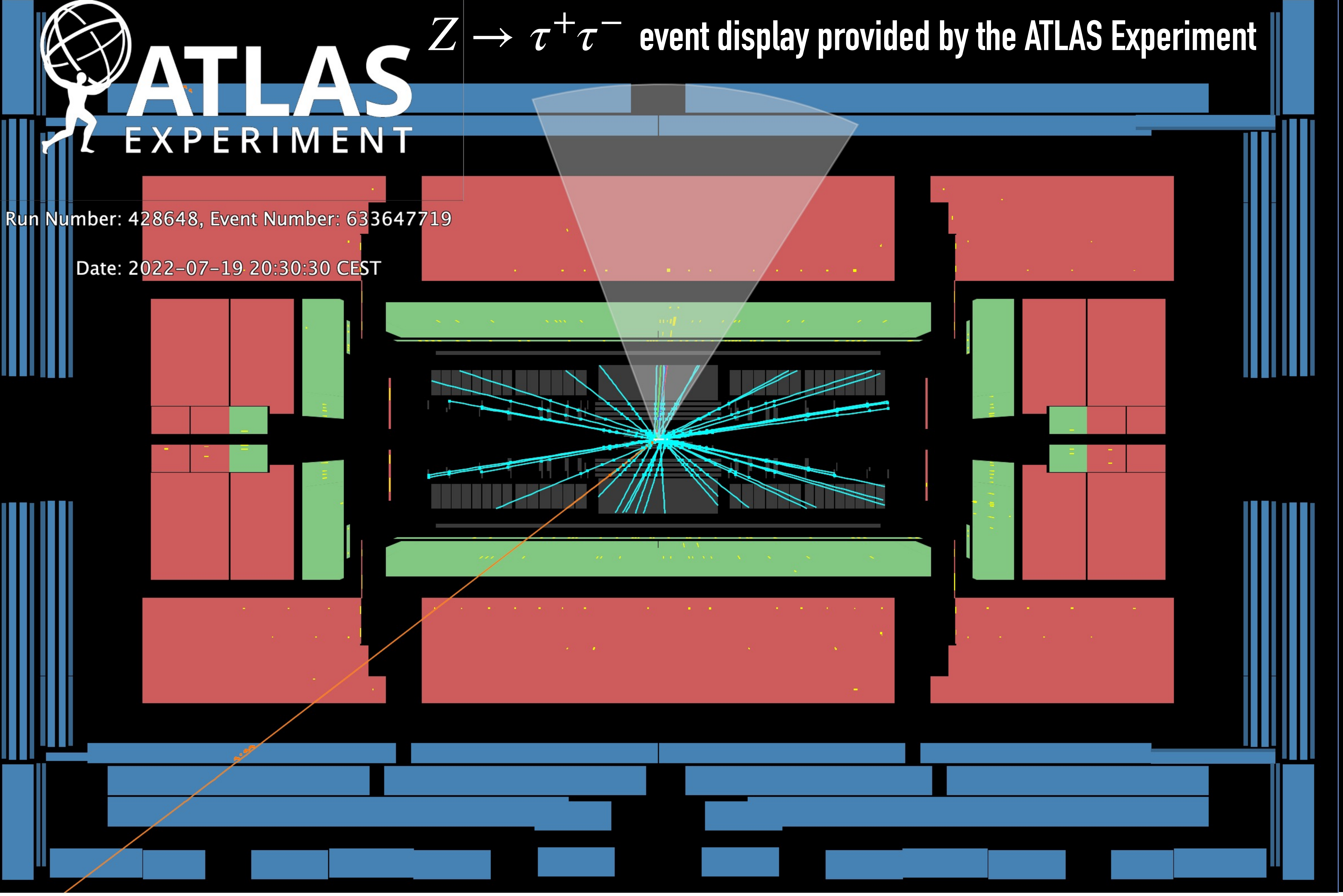
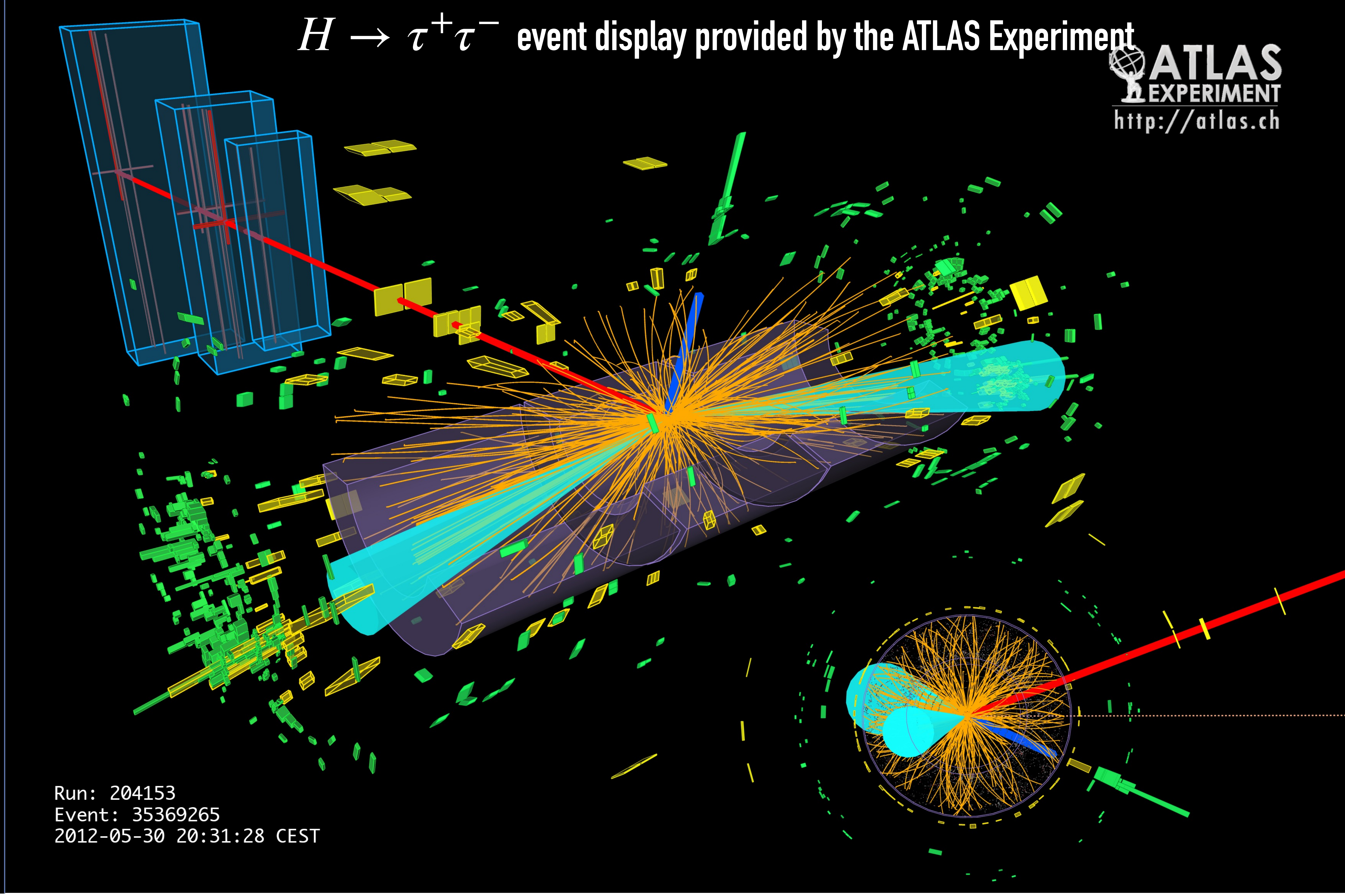


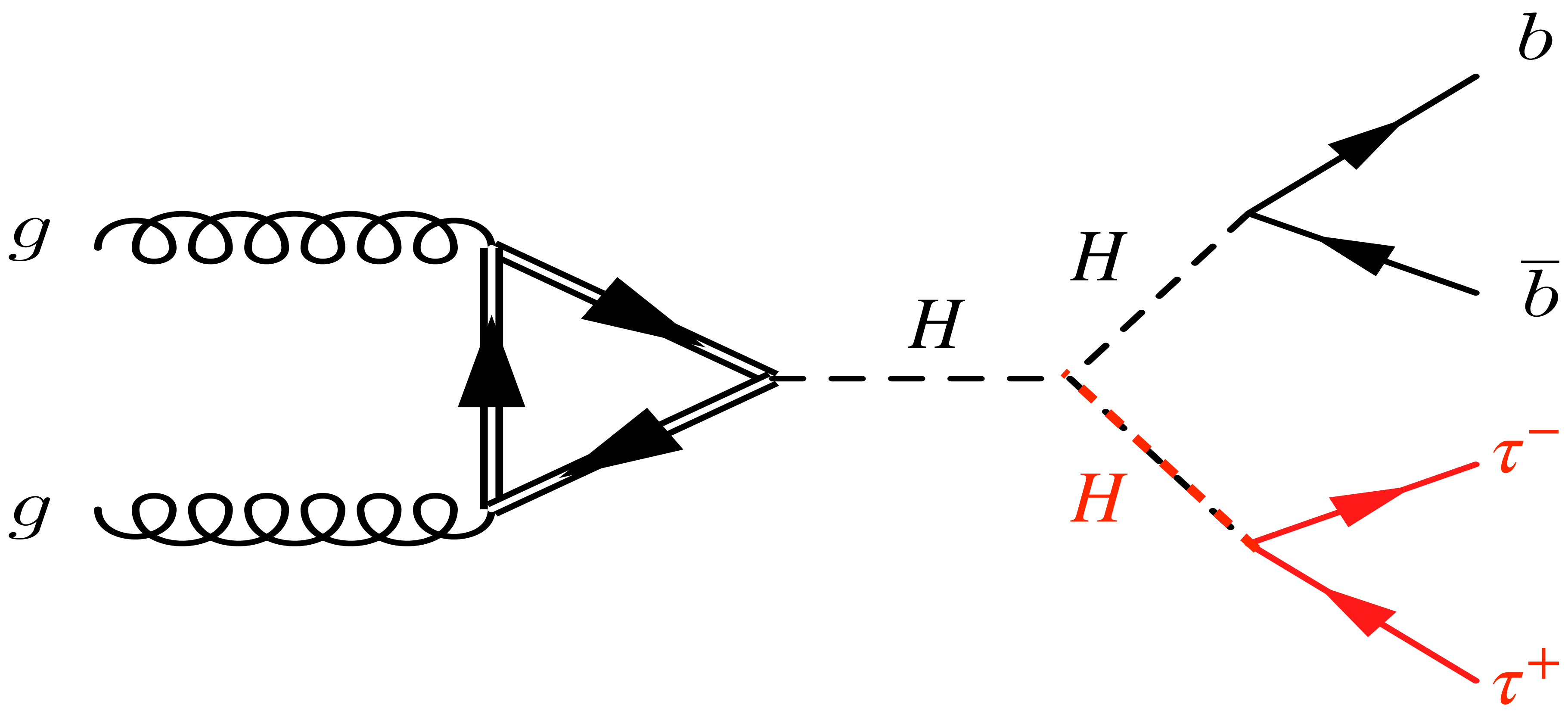


Studies into di-τ mass reconstruction for high mass resonances at the ATLAS experiment

Kyle Granados, Kathryn Grimm, Jason Veatch, Joshua Moss

Motivation

- Since the discovery of the Higgs boson in 2012 by the ATLAS and CMS collaborations:
  - Dedicated analyses for the Higgs self-interaction have been underway to reveal details of the shape of the Higgs potential.
  - The Higgs self-coupling measurement is a major focus of the LHC/HL-LHC



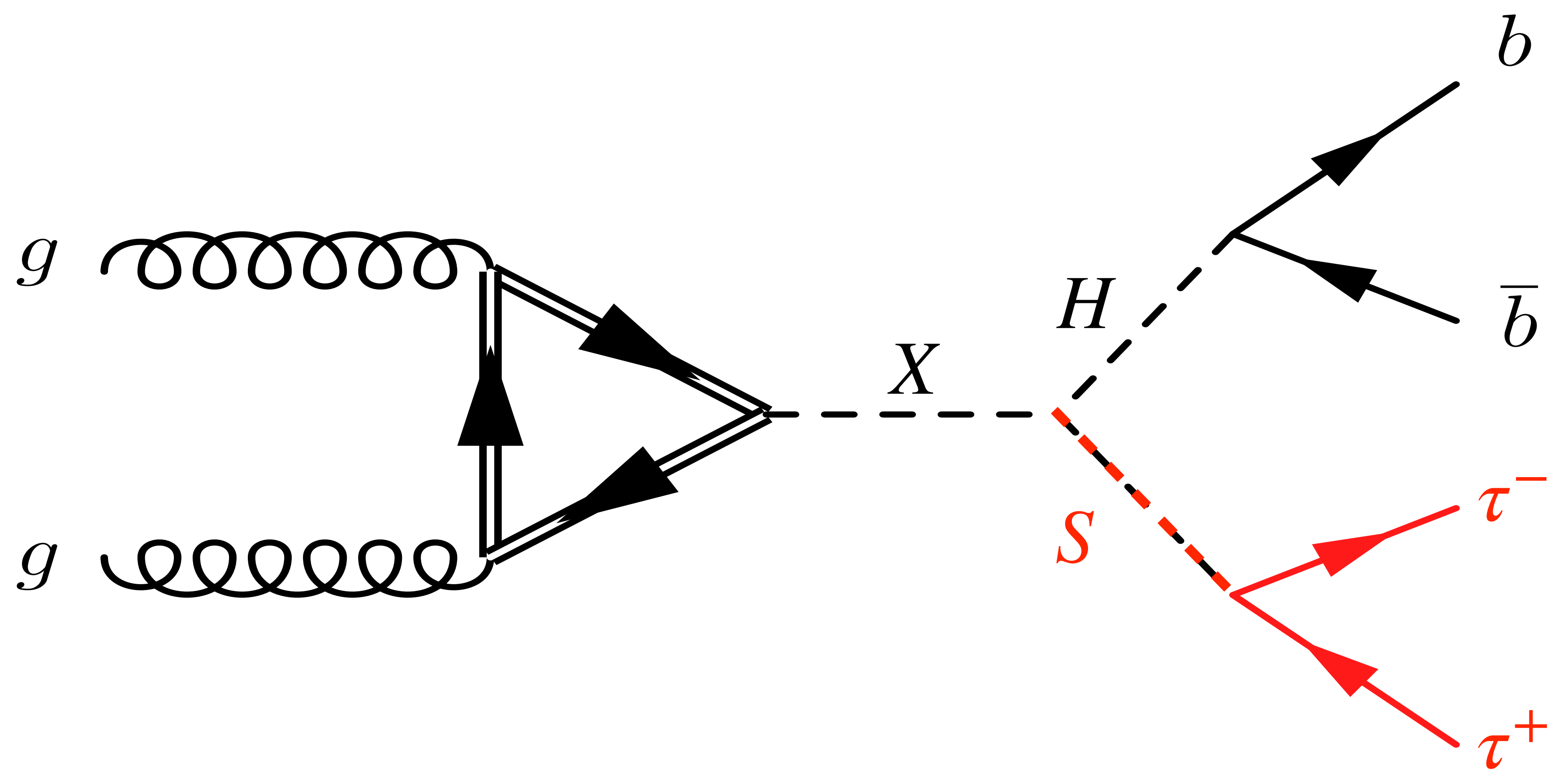
	bb	WW	ττ	ZZ	γγ
bb	34%				
WW	25%	4.6%			
ττ	7.3%	2.7%	0.39%		
ZZ	3.1%	1.1%	0.33%	0.069%	
γγ	0.26%	0.10%	0.028%	0.012%	0.0005%

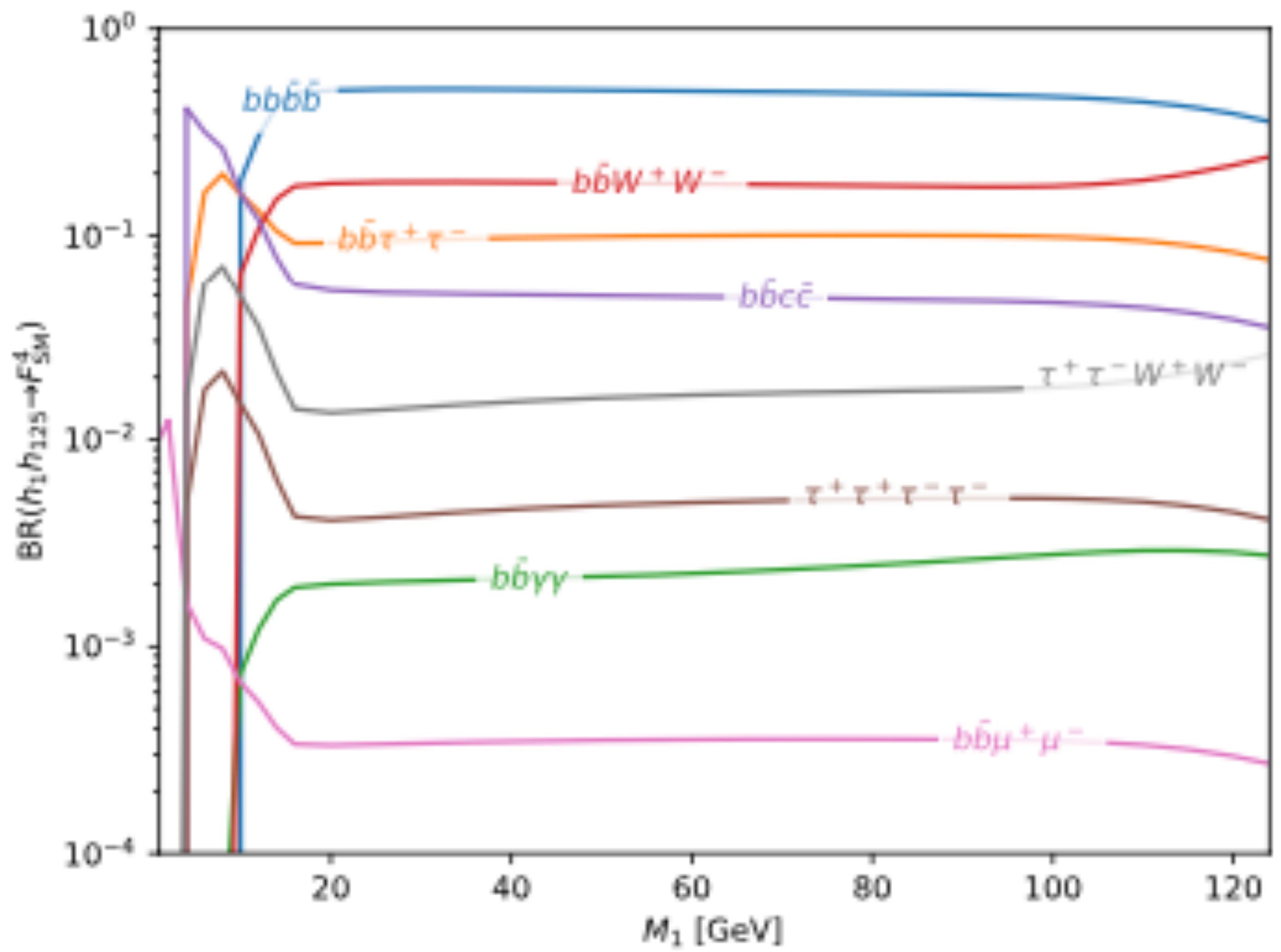
- The HH → bb$\tau\tau$ channel has the third highest branching ratio in these studies.
  - The branching ratio of one of these Higgs decaying into two tau leptons is significant with BR = 6.32%

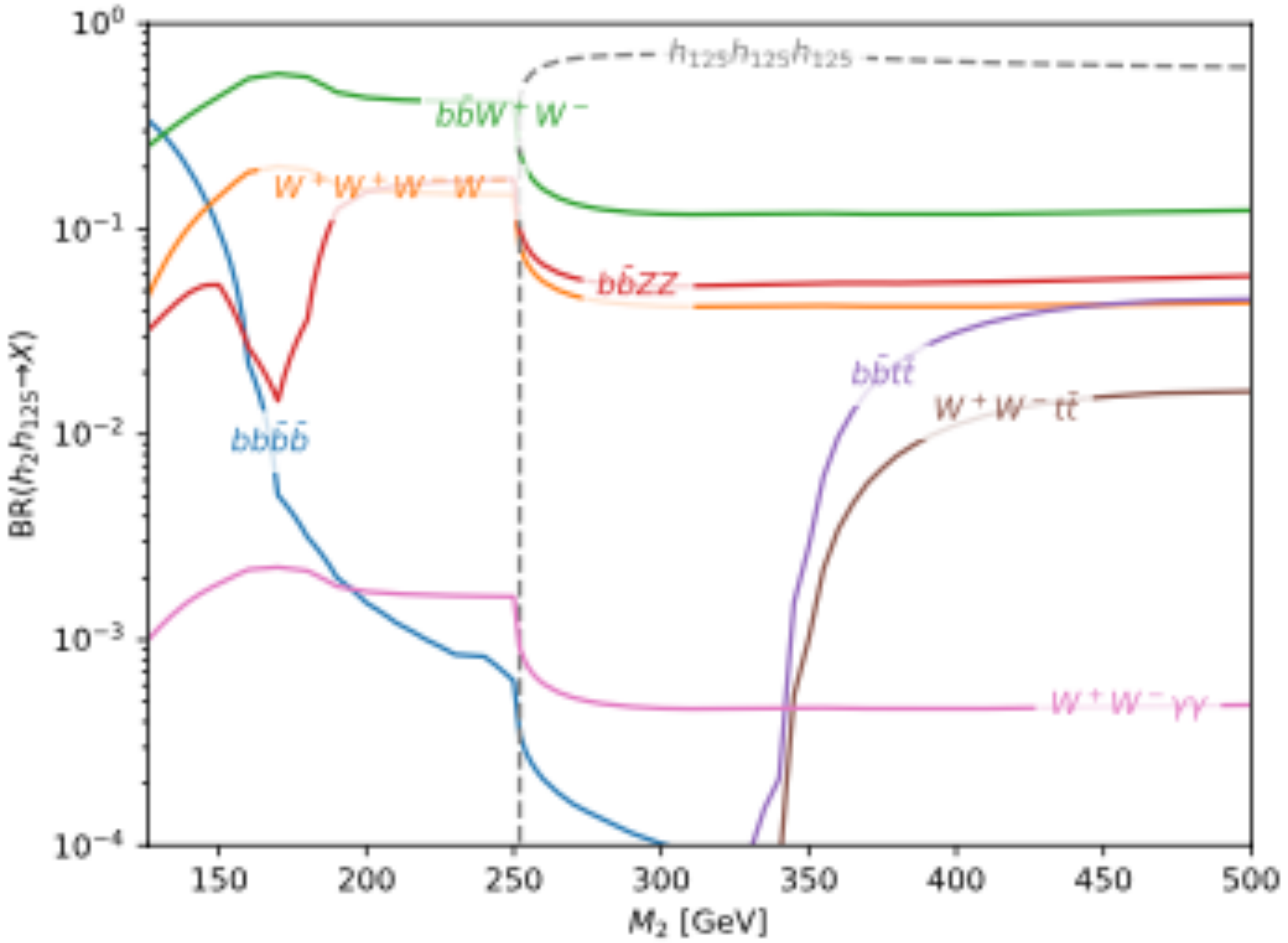
Decay channel	Branching ratio	Rel. uncertainty
$H \to \gamma\gamma$	2.28×10^{-3}	$^{+5.0\%}_{-4.9\%}$
$H \to ZZ$	2.64×10^{-2}	$^{+4.3\%}_{-4.1\%}$
$H \to W^+W^-$	2.15×10^{-1}	$^{+4.3\%}_{-4.2\%}$
$H \to \tau^+\tau^-$	6.32×10^{-2}	$^{+5.7\%}_{-5.7\%}$
$H \to b\bar{b}$	5.77×10^{-1}	$^{+3.2\%}_{-3.3\%}$
$H \to Z\gamma$	1.54×10^{-3}	$^{+9.0\%}_{-8.9\%}$
$H \to \mu^+\mu^-$	2.19×10^{-4}	$^{+6.0\%}_{-5.9\%}$

Motivation

- Beyond-the-Standard-Model (BSM) analyses dedicated to extending the Higgs sector of the SM have been underway at ATLAS
  - This stems from the theoretical motivations for releasing the mass constraint of the Higgs (i.e. candidates for heavy dark matter)
- BSM model considered: Two Real Scalar Singlet Extension to the Standard Model [arXiv:2209.10996]
  - Extends the Higgs sector by two neutral scalar singlets: X and S
  - X is set to decay to S and the SM Higgs, S is set to S → $\tau\tau$ and the SM Higgs is set to H → bb



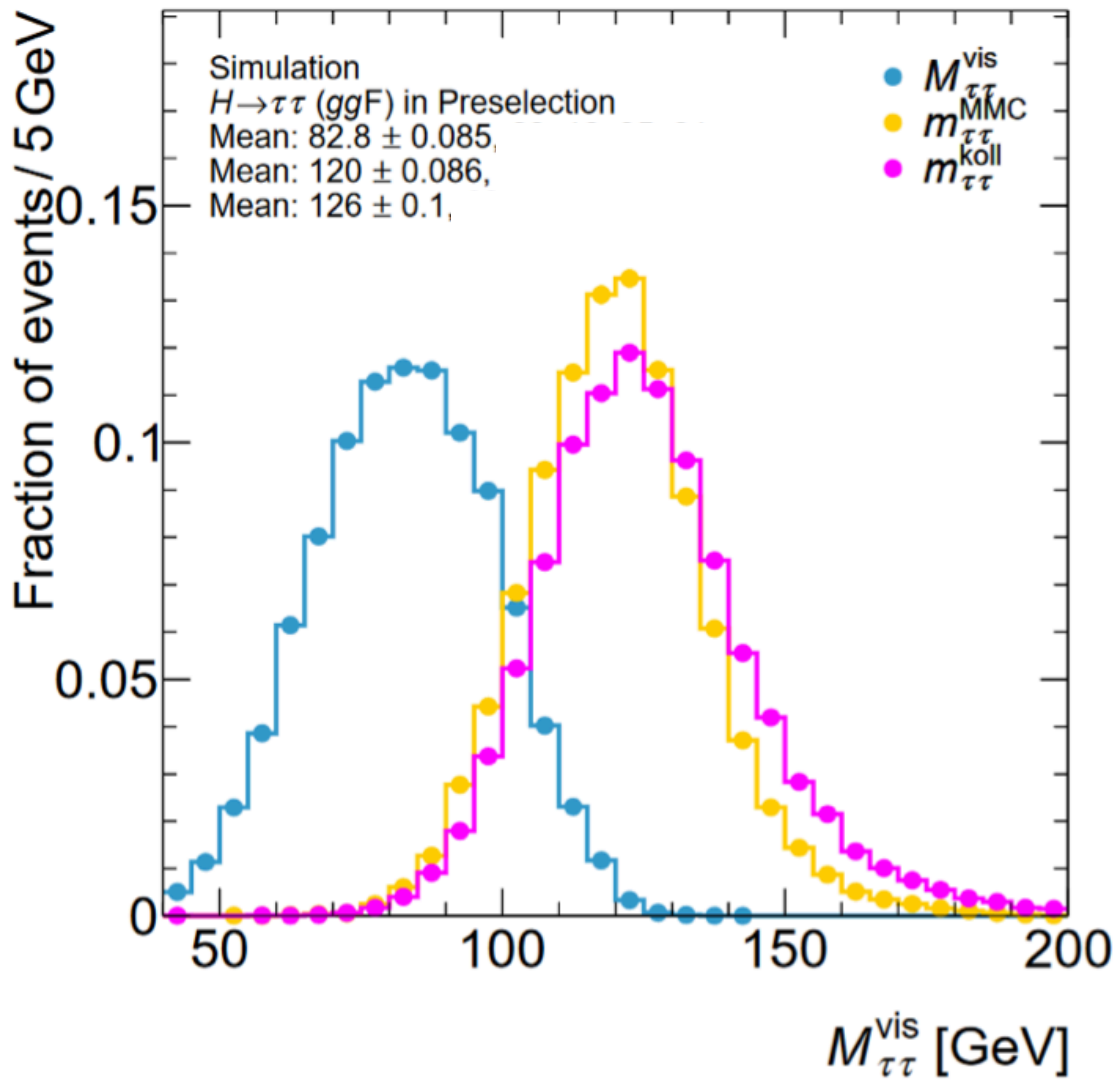


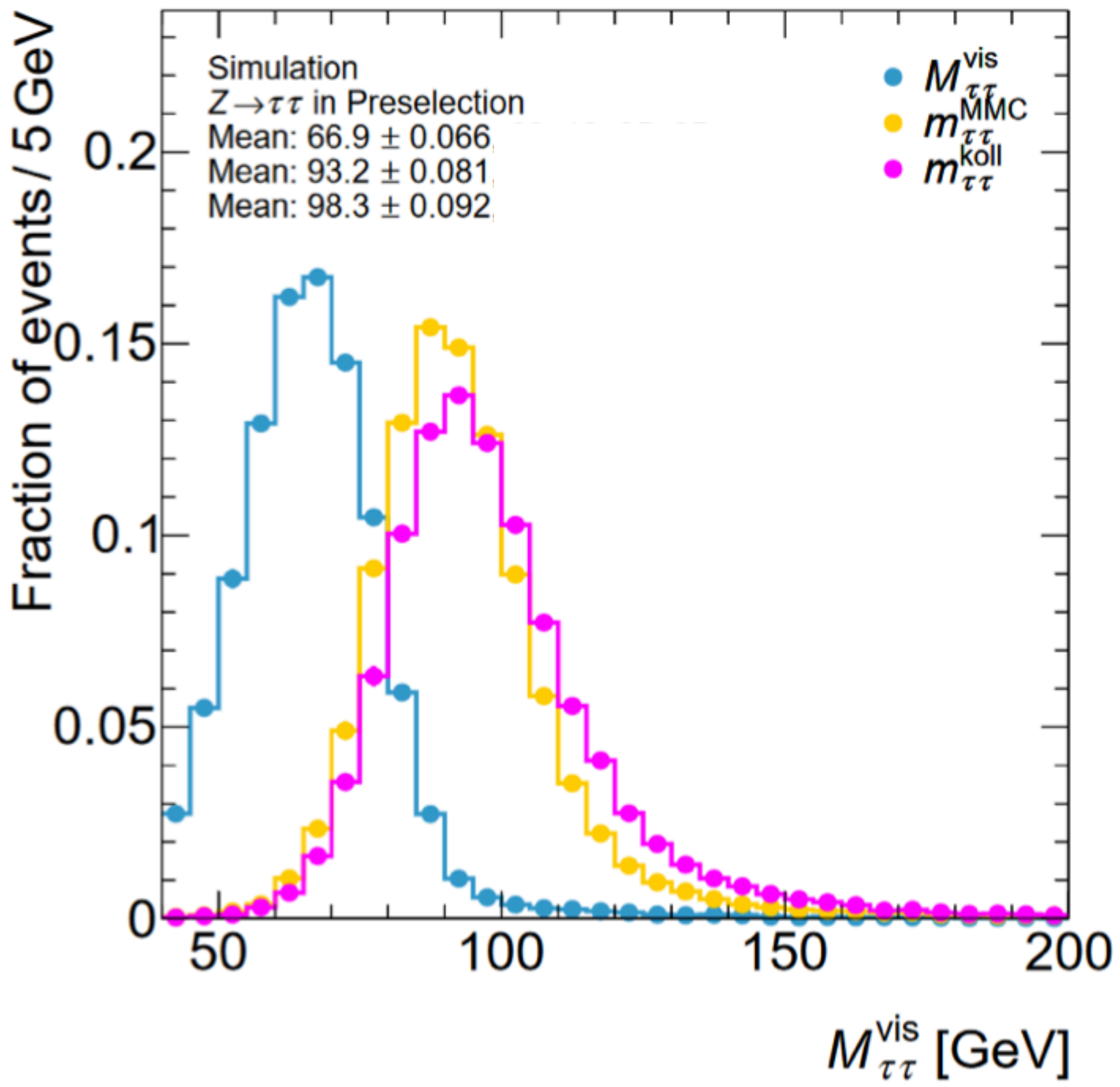


- Benchmark scenarios for this model have already been published and are the basis of this analysis.

Di - τ events in the ATLAS detector

- τ leptons have two decay paths:
  - A light lepton (e / μ) + two neutrinos
  - A jet + one neutrino
- Full reconstruction of di - τ invariant mass is impossible
  - Due to neutrinos involved in the events, which escape detection in ATLAS

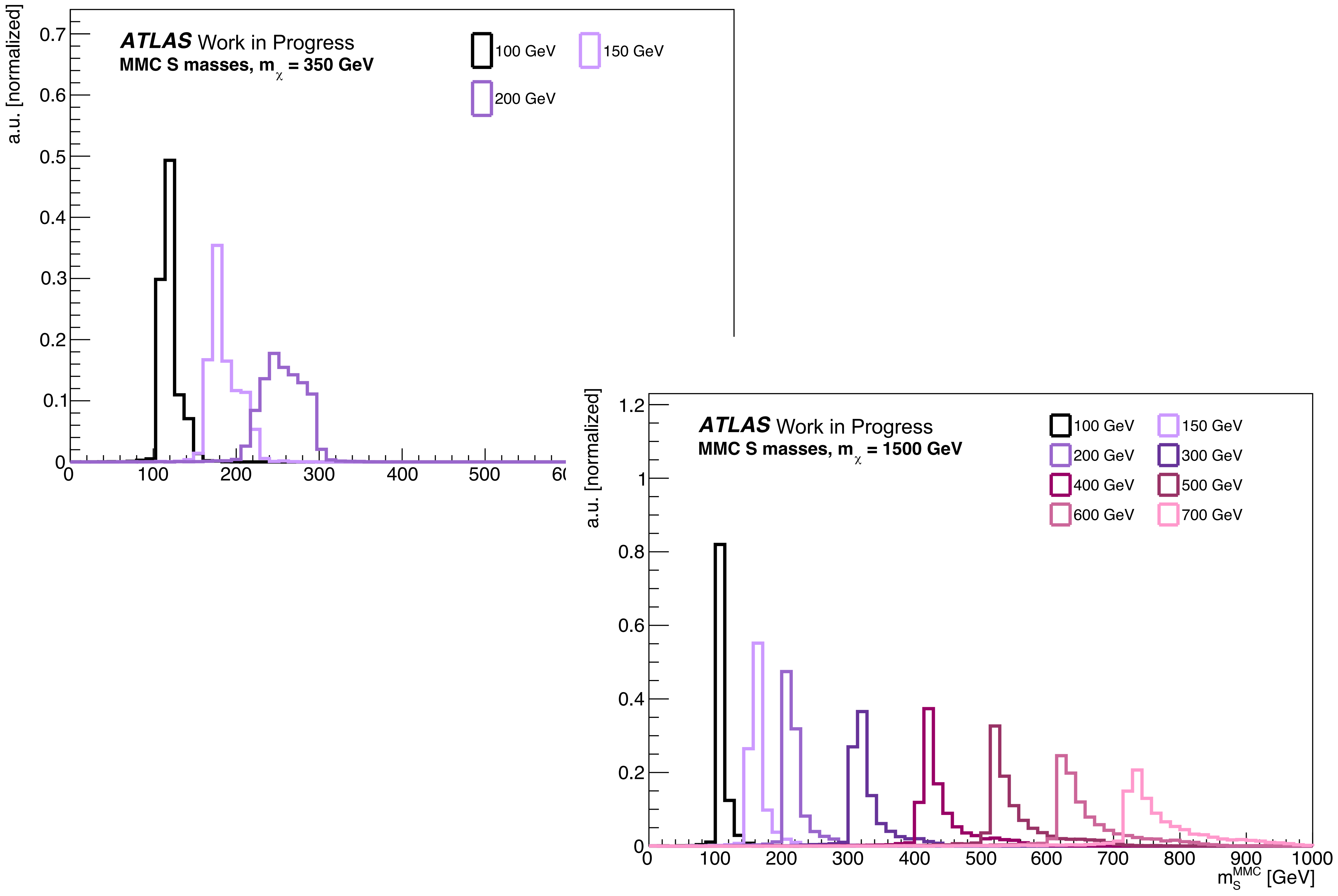


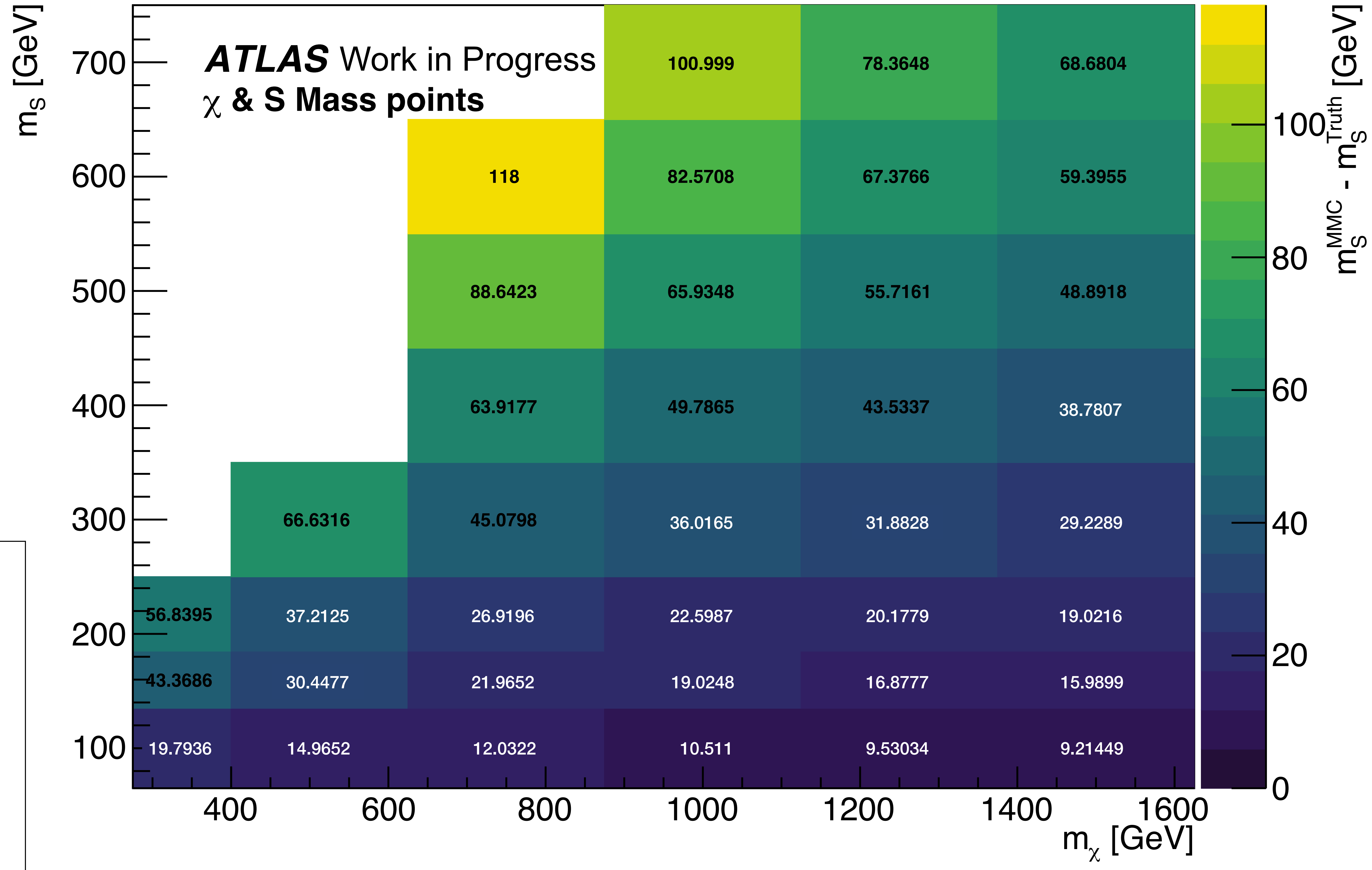


- Mass reconstruction with visible tau mass leads to a significant deviation from the true mass.
  - The invisible contribution is non-trivial.
- ATLAS utilizes a probabilistic mass reconstruction technique:
  - **Missing Mass Calculator** (MMC)
    - Current method of di - τ mass reconstruction used in ATLAS
    - Finds the most probable solutions to a system of equations based on event kinematics.
    - Calibrated for $Z \to \tau\tau$ events, underestimates Higgs mass

MMC performance at higher mass resonances

- Tests on the MMC performance at higher masses were conducted:
  - X and S masses in consideration: X (350 - 1500 GeV) and S (100 - 700 GeV)
  - At heavier X and S masses, the performance of the MMC deteriorates.

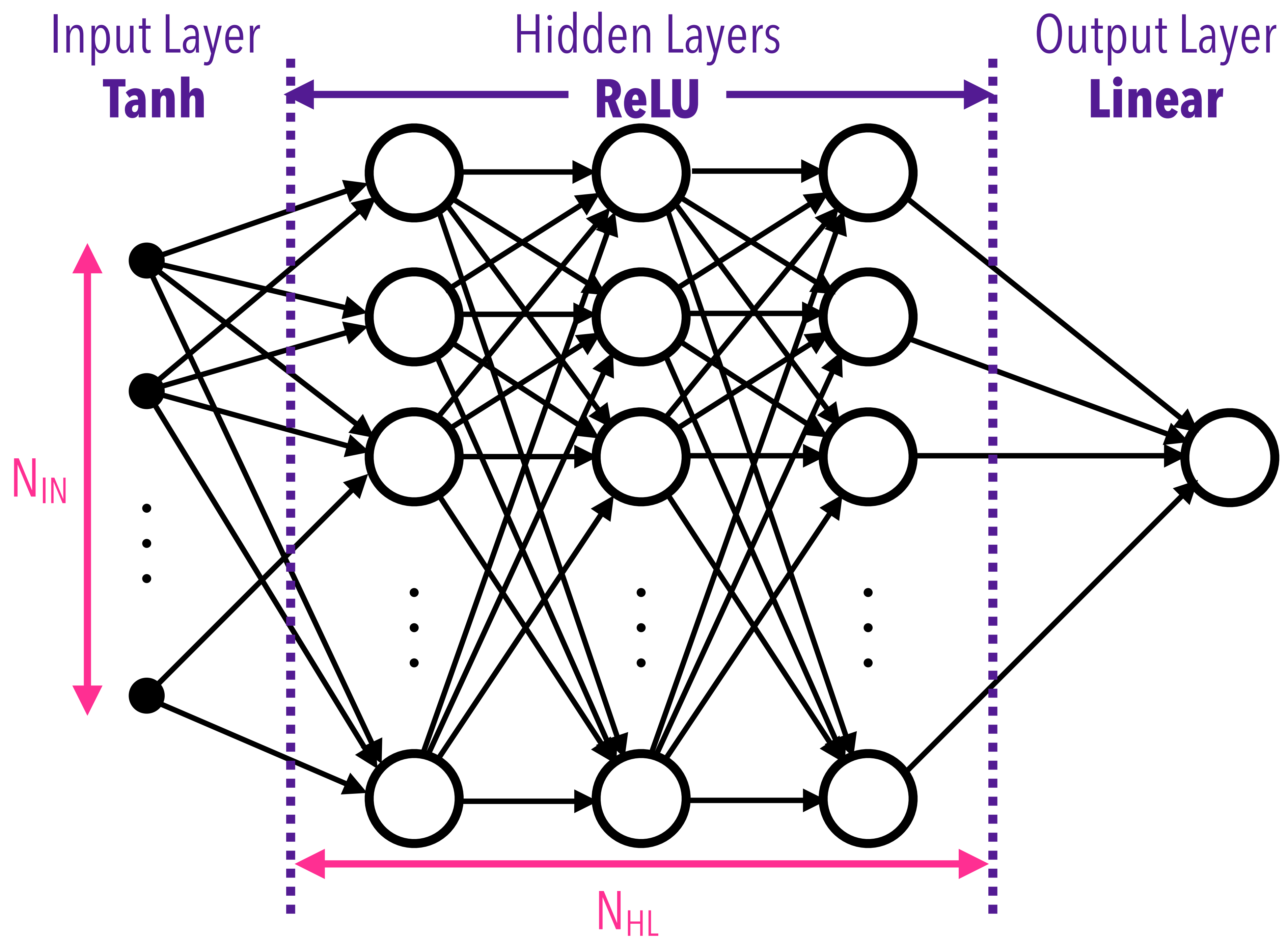




Deep learning solution

- Goal: to utilize a technique that is agnostic to the mass that it is trained on
- A deep neural network can provide a solution to the problems faced with the MMC
  - MMC is calibrated on the mass of the Z boson (~ 91 GeV), thus it is more accurate at resonances closer to the Z mass
    - NN is able to calculate masses higher than 91 GeV with higher accuracy
- Deep Neural Network (DNN) tests have been conducted and compared to the MMC

Chosen DNN Architecture



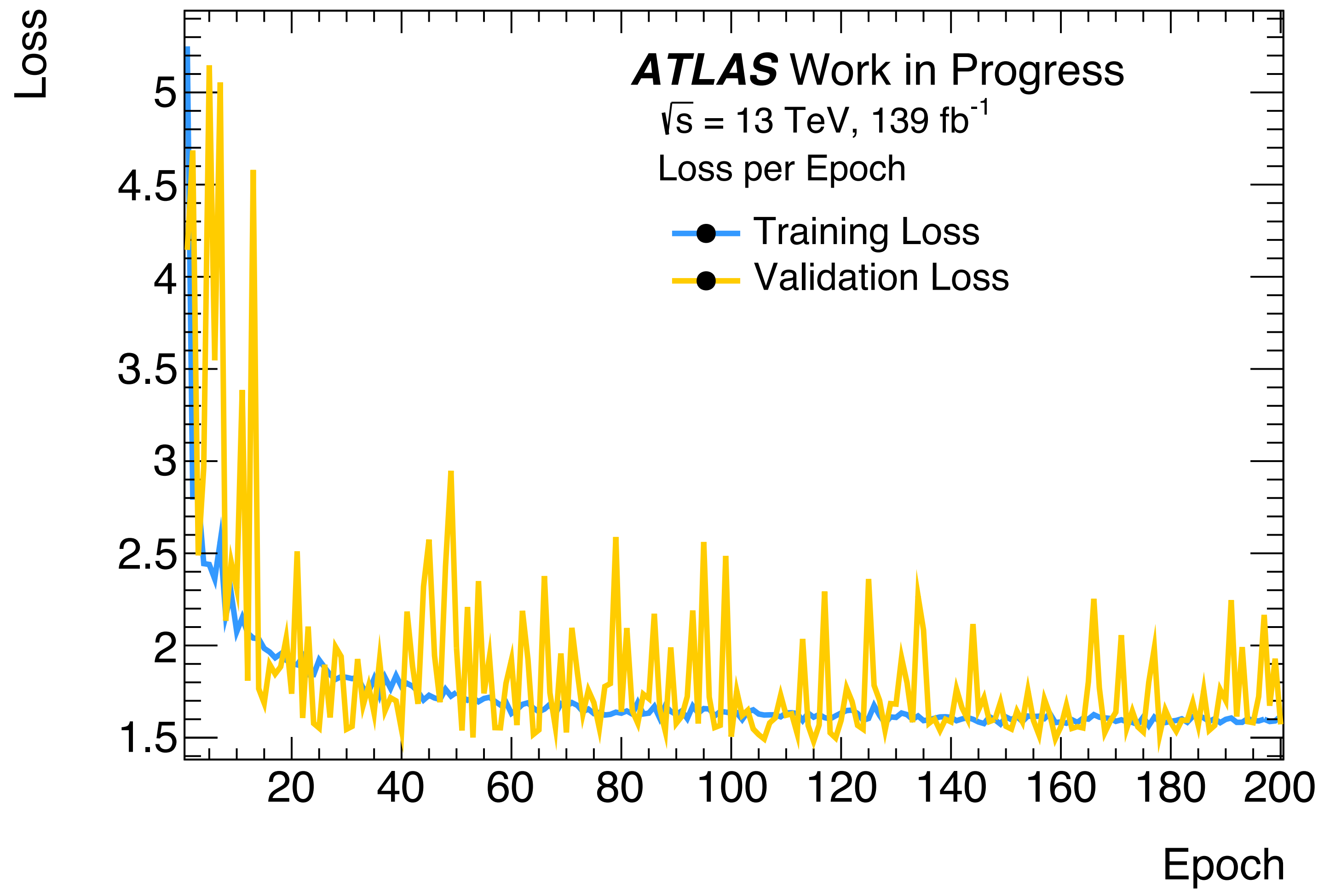
- N_{IN} = 31 nodes
- N_{HL} = 3 Hidden Layers → 100 Nodes per Hidden Layer
- Chosen hyperparameters:
  - **Adam** optimizer
  - **MAPE (Mean Absolute Percentage Error)** loss function
  - **200** Epochs
  - Batch size of **32**
  - Learning Rate of **0.01**

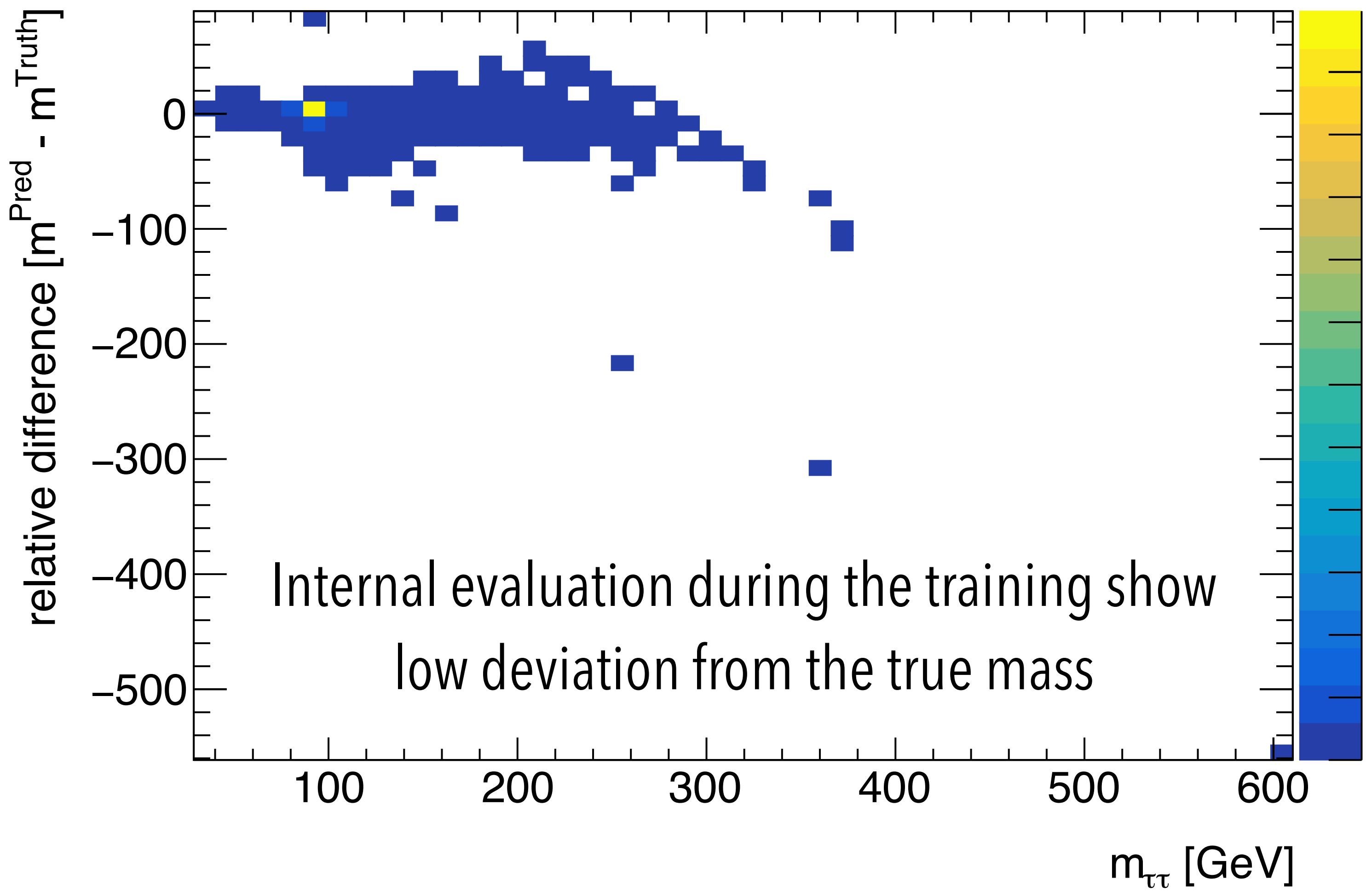
Chosen via Bayesian optimization

- Chosen input variables, based on MMC input parameters:
  - τ_1-vis and τ_2-vis: p_T, **η**, **ϕ**, m
  - MET: MET, **ϕ**, p_x, p_y, $\mathbf{\Sigma} E_T$
  - Jet 1 and Jet 2: E, p_T, **η**, **ϕ**
  - Number of jets per event
  - $\Delta\phi(\tau_1$-vis, τ_2-vis), $\Delta\phi(\tau_1$-vis, MET), $\Delta\phi(\tau_2$-vis, MET), $\Delta\eta(\tau_1$-vis, τ_2-vis), $\Delta R(\tau_1$-vis, τ_2-vis)

Neural Network performance

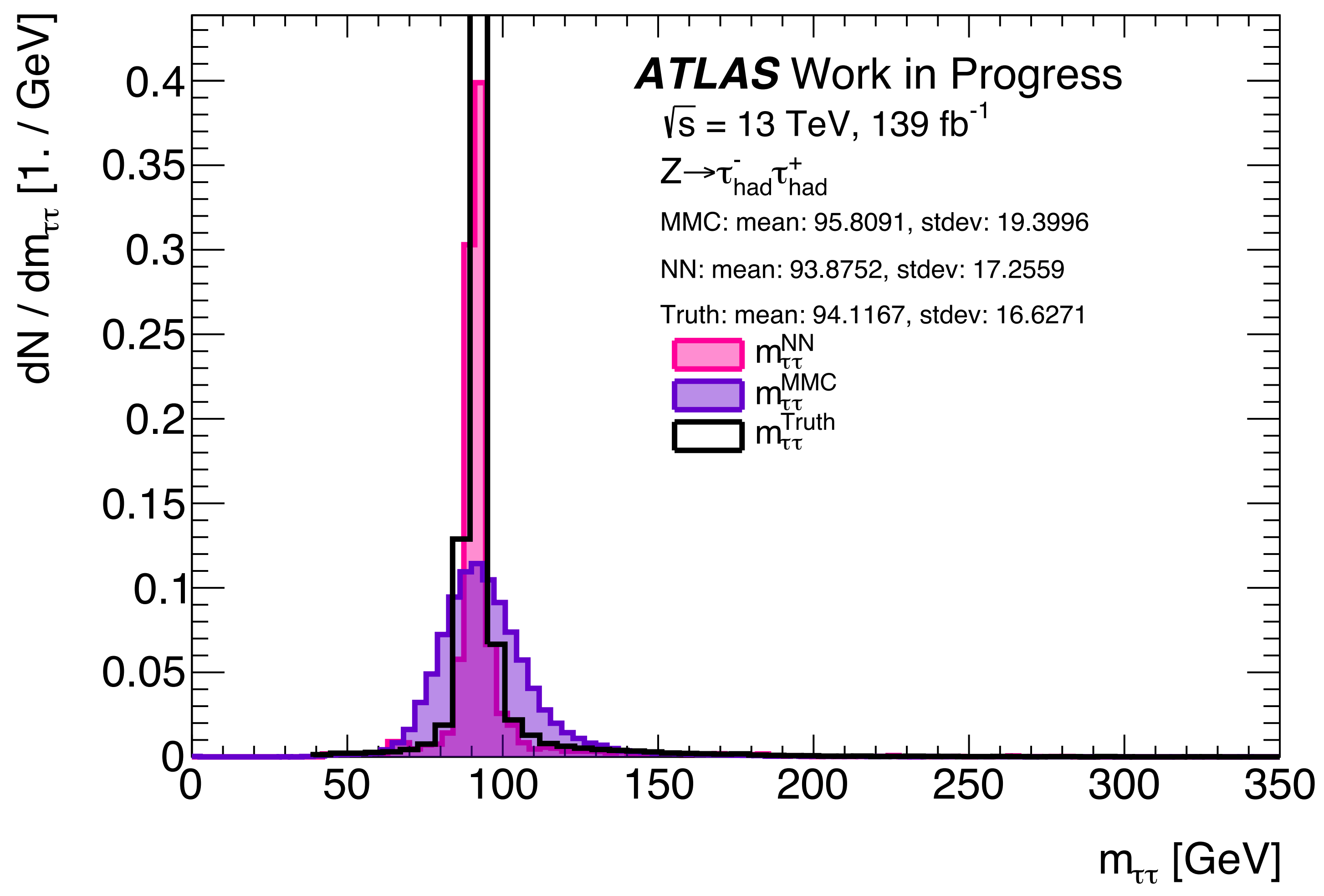
- First tests of the deep neural network is trained on hadronic Z → $\tau\tau$ events

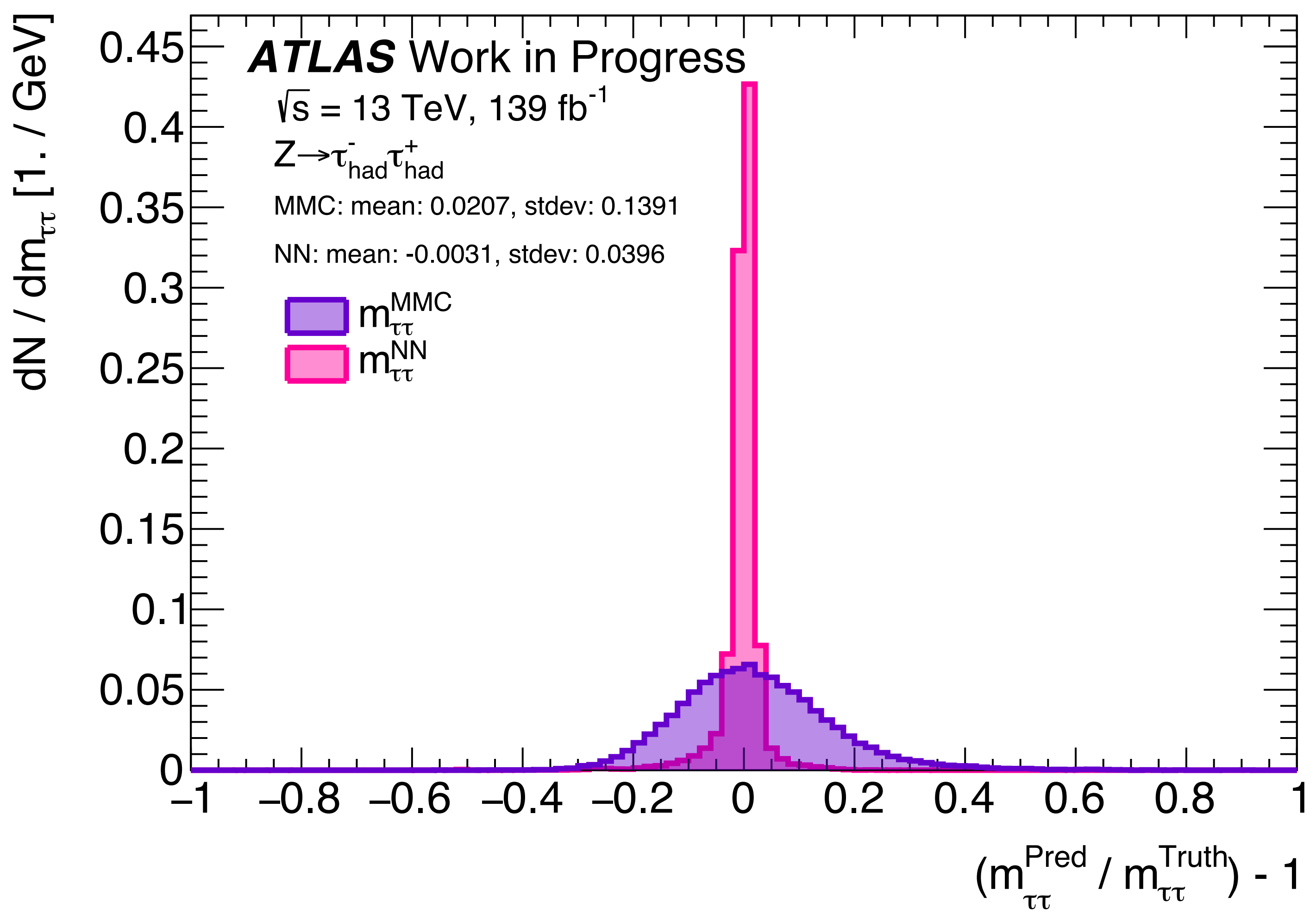




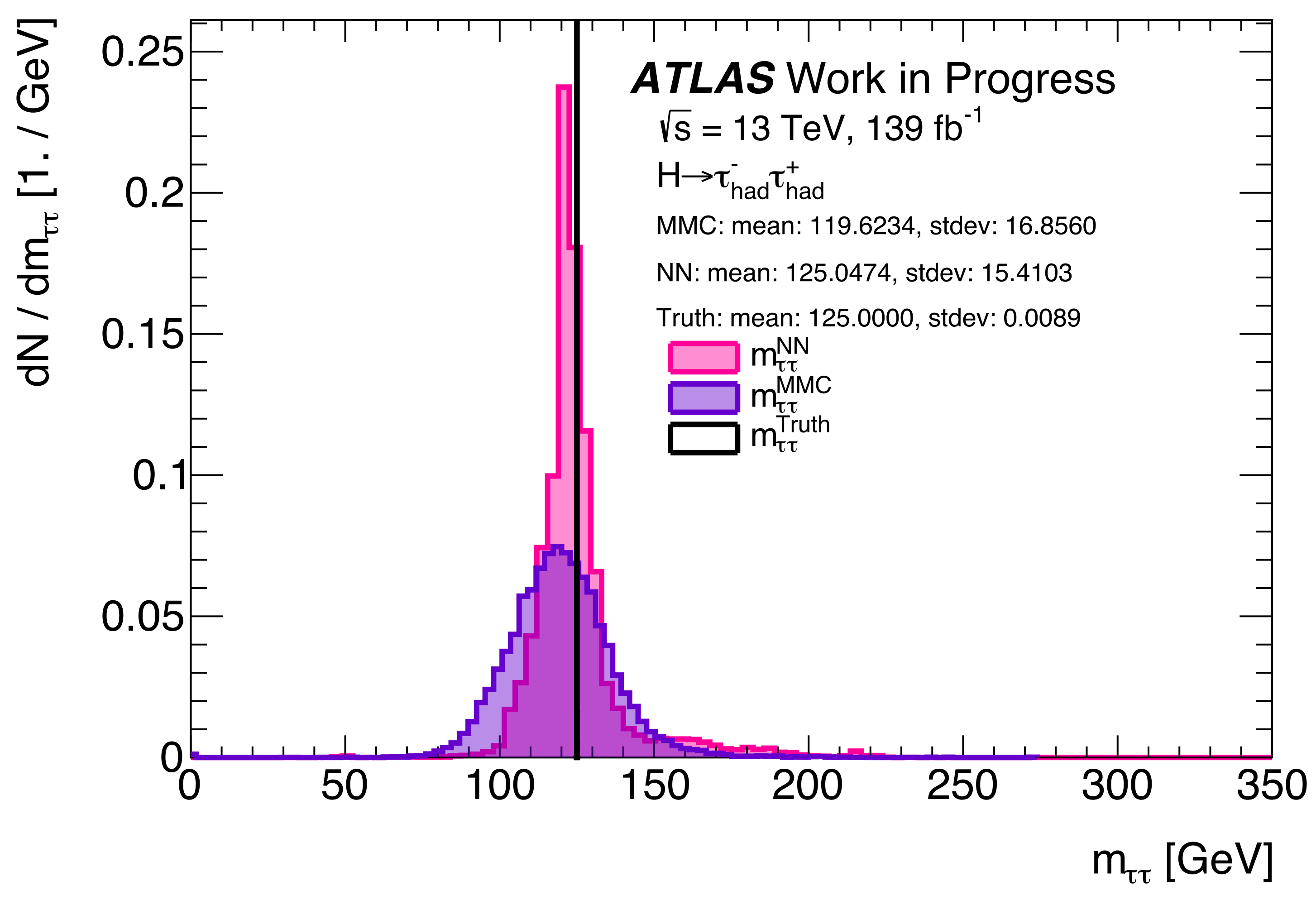
Internal evaluation during the training show low deviation from the true mass

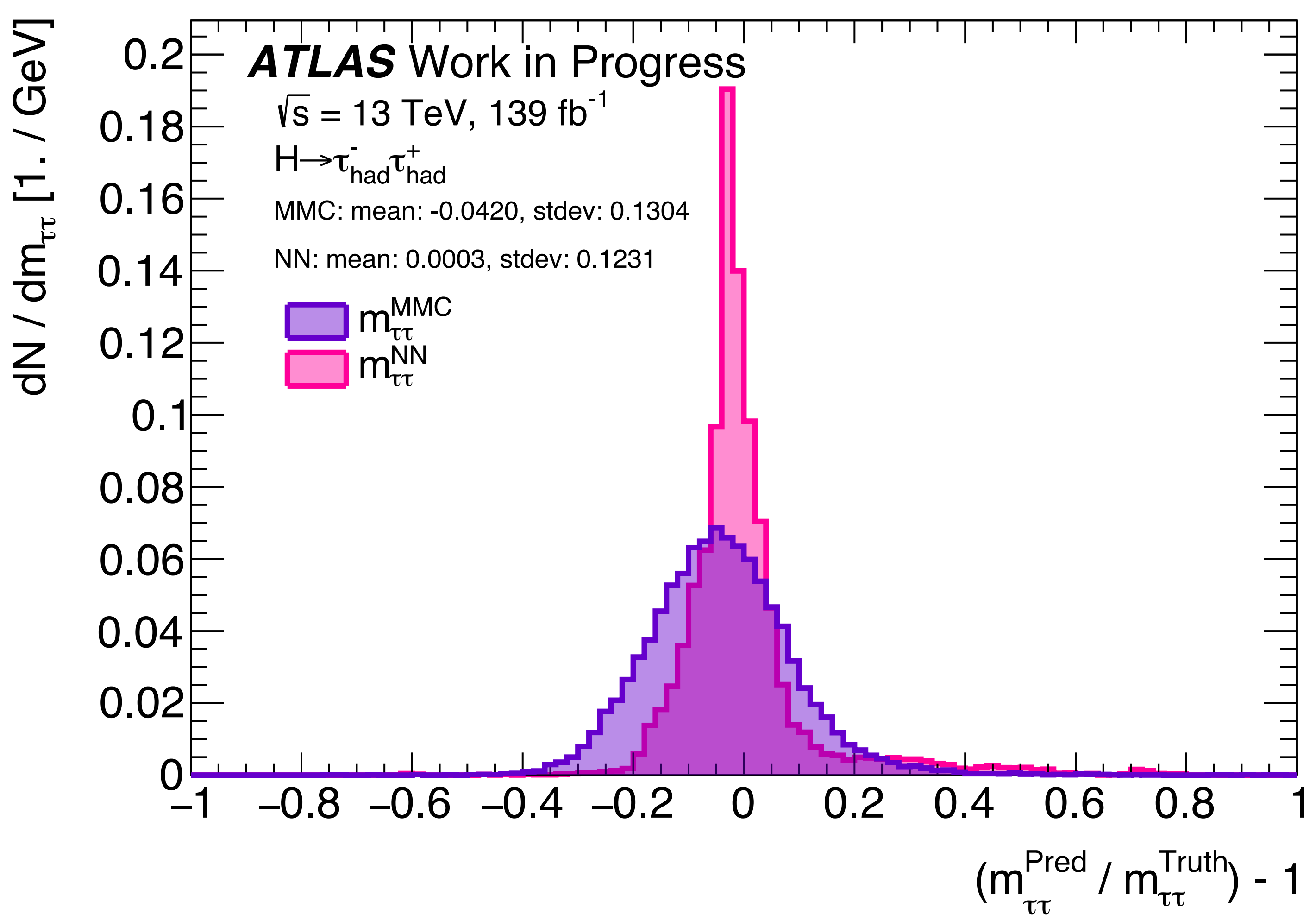
- Evaluated on **hadronic Z → $\tau\tau$ events**





- Evaluated on **hadronic H → $\tau\tau$ events**





Summary + Next Steps

- We are looking at an alternate di-τ mass reconstruction method in the context of X → SH, where S → $\tau\tau$
- DNN performance on Z/H masses show promising results
  - Tests show improved resolution and mean compared to the MMC
- Next steps:
  - Test the performance of this DNN on a wider range of masses beyond the Z/Higgs mass
  - We will check NN performance on relevant di-τ backgrounds
  - Sequentially training the DNN on different masses

Back-up

More info on MMC

$$\mathscr{L} = -\log(\mathscr{P}(\Delta R_{vis,miss1,p_T1}) \times \mathscr{P}(\Delta R_{vis,miss2,p_T2}) \times \mathscr{P}(\not{E}_{Tx,y}) \times \mathscr{P}(E_{vis,\tau1}) \times \mathscr{P}(E_{vis,\tau2})) \times \mathscr{P}(m_{miss1}) \times \mathscr{P}(m_{miss2})$$

- First proposed here: arXiv:1012.4686
- The Missing Mass Calculator (MMC) utilizes a system of equations that use the missing values that are carried away by neutrinos, and the observable properties of the visible decay products.
- MMC assumes the only source of $\not{E}_T$ are the neutrinos.
- For each event, the MMC scans over the possible configurations of the visible and invisible decay products.
  - For each configuration, the final solution with the highest log-likelihood is set as the final estimator for m_H.

$$\not{E}_{T_x} = p_{\text{mis}_1} \sin\theta_{\text{mis}_1} \cos\phi_{\text{mis}_1} + p_{\text{mis}_2} \sin\theta_{\text{mis}_2} \cos\phi_{\text{mis}_2}$$

$$\not{E}_{T_y} = p_{\text{mis}_1} \sin\theta_{\text{mis}_1} \sin\phi_{\text{mis}_1} + p_{\text{mis}_2} \sin\theta_{\text{mis}_2} \sin\phi_{\text{mis}_2}$$

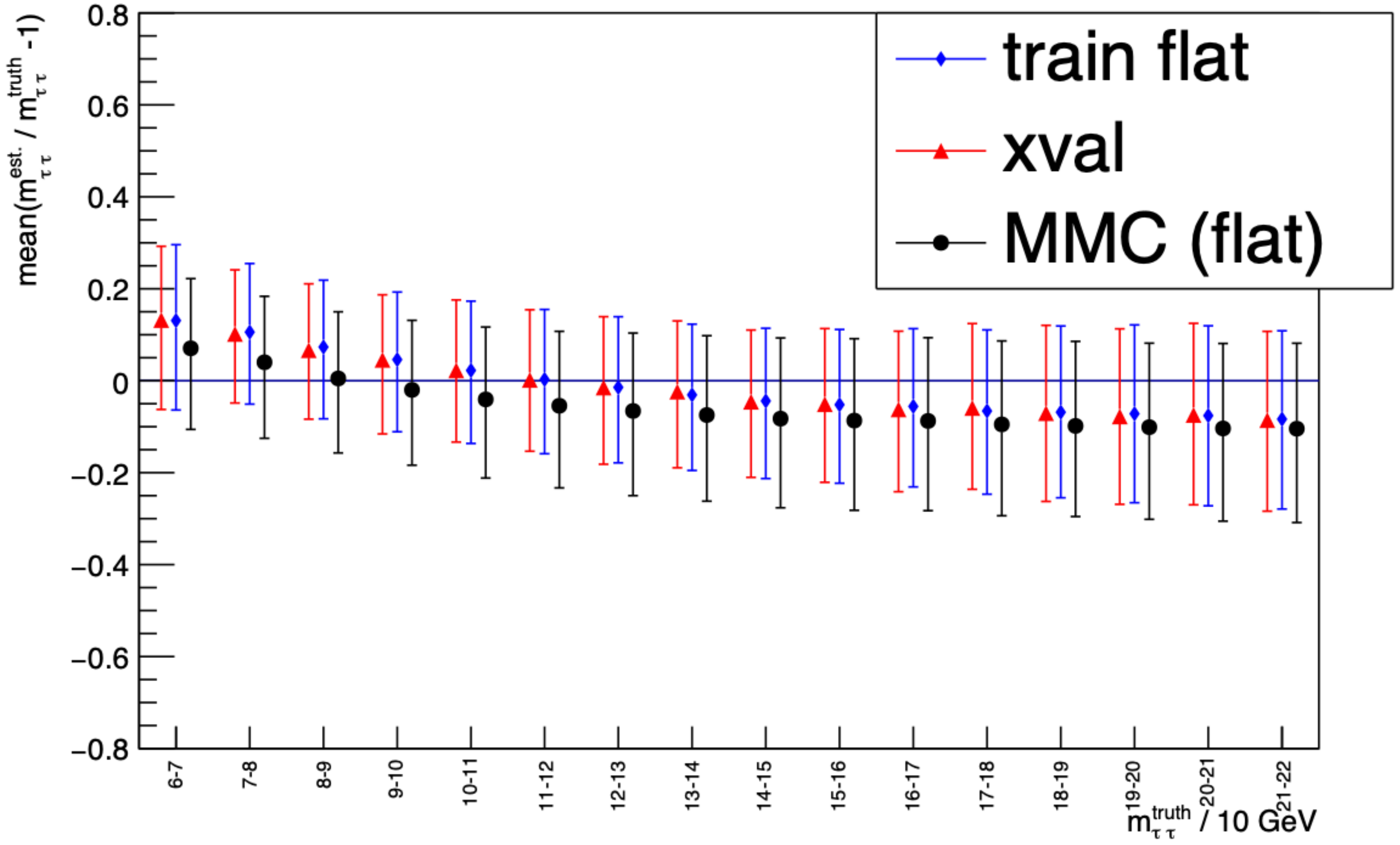
$$M_{\tau_1}^2 = m_{\text{mis}_1}^2 + m_{\text{vis}_1}^2 + 2\sqrt{p_{\text{vis}_1}^2 + m_{\text{vis}_1}^2}\sqrt{p_{\text{mis}_1}^2 + m_{\text{mis}_1}^2} - 2p_{\text{vis}_1} p_{\text{mis}_1} \cos\Delta\theta_{vm_1}$$

$$M_{\tau_2}^2 = m_{\text{mis}_2}^2 + m_{\text{vis}_2}^2 + 2\sqrt{p_{\text{vis}_2}^2 + m_{\text{vis}_2}^2}\sqrt{p_{\text{mis}_2}^2 + m_{\text{mis}_2}^2} - 2p_{\text{vis}_2} p_{\text{mis}_2} \cos\Delta\theta_{vm_2}$$

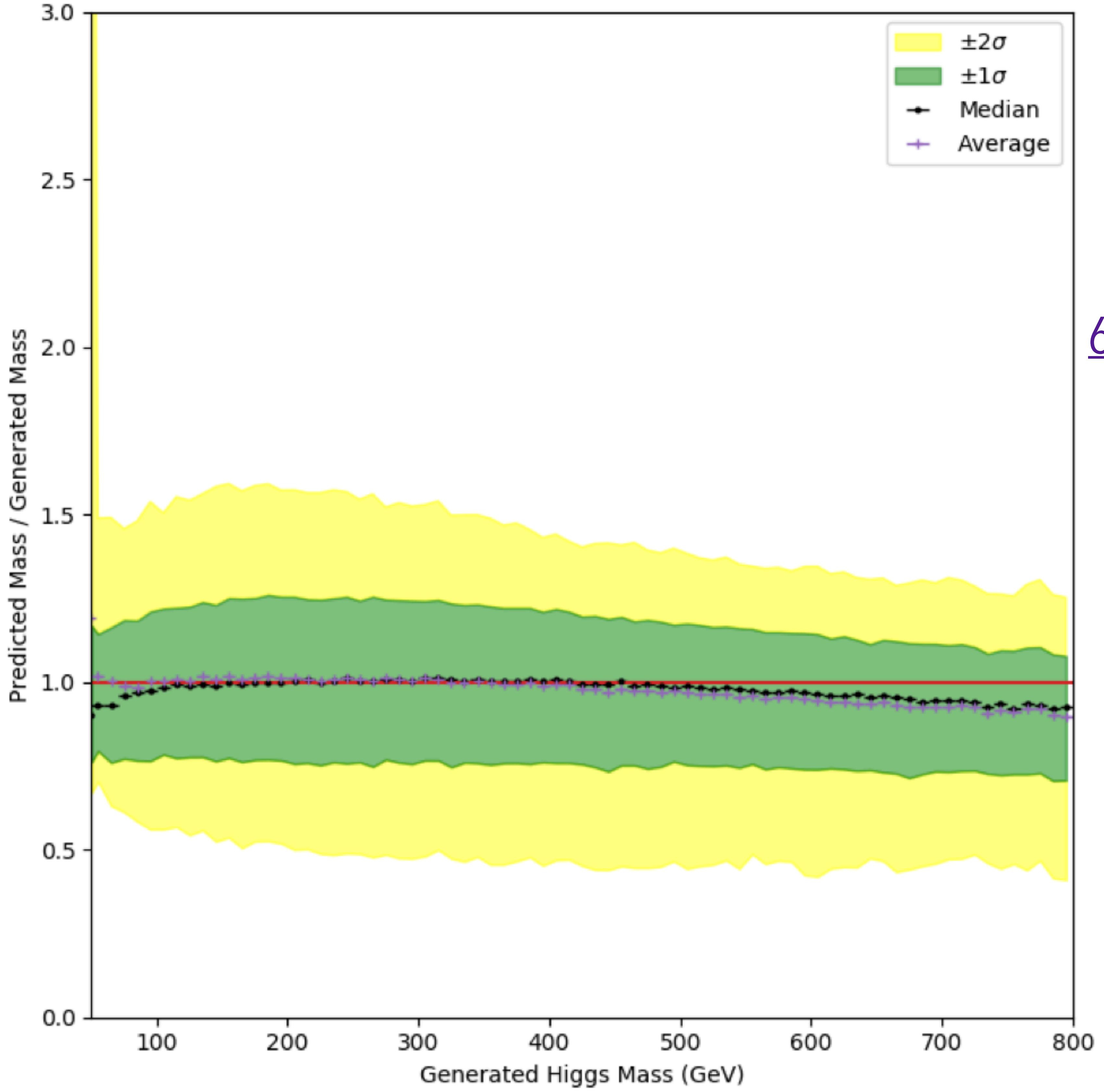
System of equations the MMC solves, these four equations connect the visible and invisible properties of each event

Previous NN work

- Groups in both ATLAS and CMS have done work into potential NN solutions to di - τ mass reconstruction.
  - The ATLAS group at the University of Bonn employed a Neural Network with a mass grid of 60 - 220 GeV
  - CMS has explored custom loss functions to improve accuracy at higher masses



https://www.pi.uni-bonn.de/desch/de/ergebnisse/dateien/t00000102.pdf



https://indico.in2p3.fr/event/22938/contributions/93153/attachments/63067/86639/2021-03-16-TORTEROTOT-IN2P3-IRFU_ML_workshop.pdf