

Search for an exotic Higgs boson decay to two pseudoscalar bosons with a four photon final state

Oral Candidacy Proposal

December 13, 2023

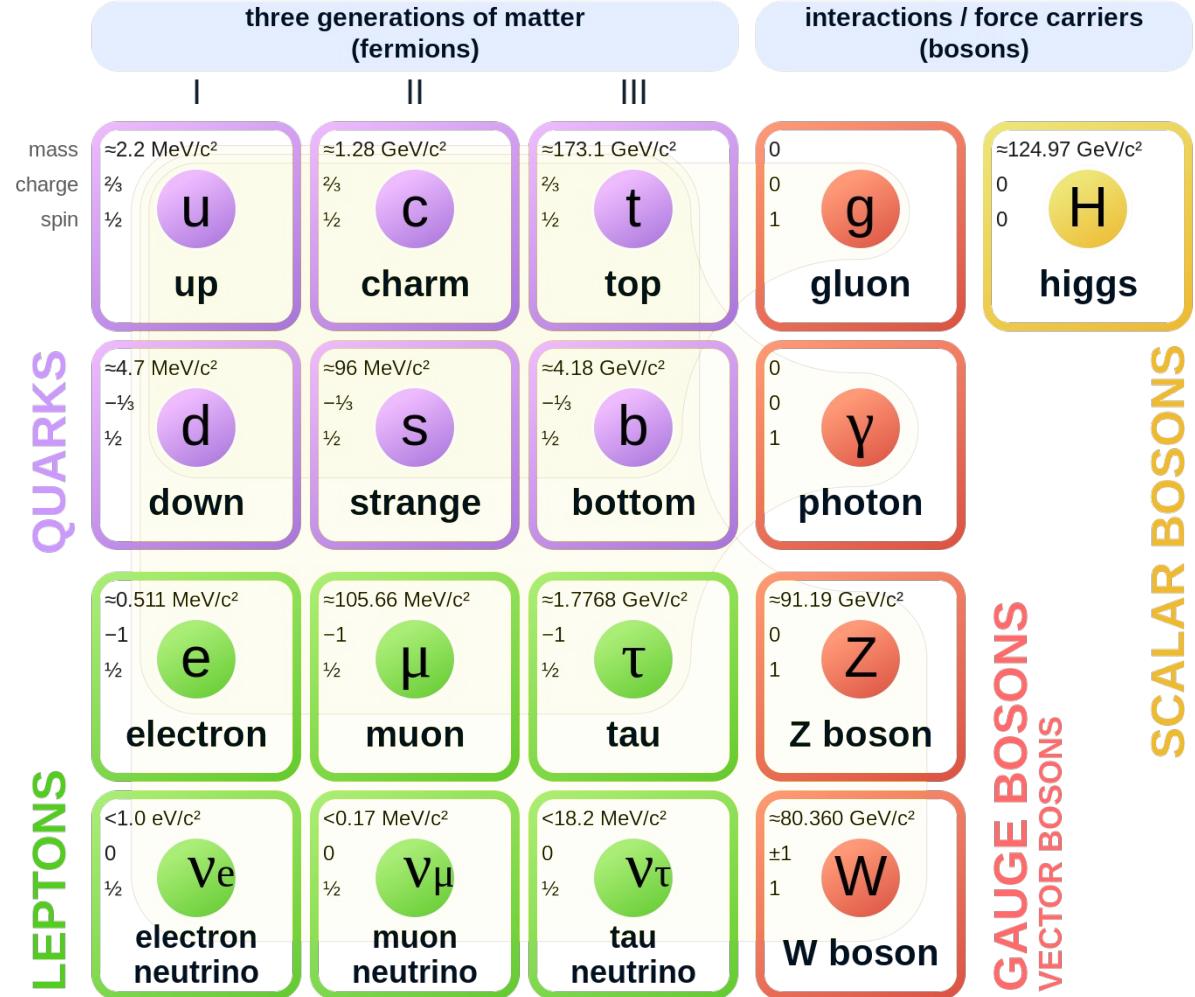
Sergi Castells

Advisors: Colin Jessop and Nancy Marinelli

- I. The Standard Model and Beyond
- II. LHC, CMS, Technical Contribution
- III. Introduction to Analysis
- IV. Sample Generation
- V. Event Selection
- VI. Signal Modelling
- VII. Advancements on Previous Studies
- VIII. Summary

The Standard Model

- Most complete model of particle physics that describes all known elementary particles.
- Describes three fundamental interactions:
 - Weak
 - Strong
 - Electromagnetic
- Rich Higgs sector phenomenology:
 - Higgs mechanism yields gauge boson masses
 - Higgs vacuum expectation value & Yukawa couplings yield other particle masses excluding neutrinos

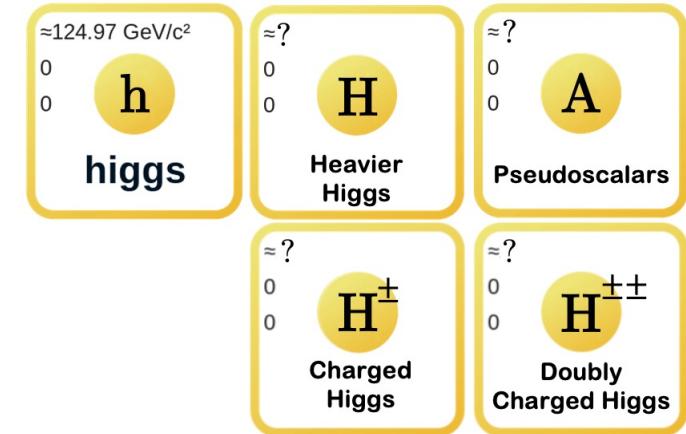


Beyond the Standard Model

- Beyond the Standard Model physics can remedy its shortcomings and predict interesting, new physics.

New phenomenologies are introduced that can be checked experimentally!

- Many models introduce an *extended Higgs sector*.
- Can answer hierarchy problem, dark matter, and more.



New matter content of common models:

| | SM | BSM |
|------------------------|-------|-------------------------------|
| Singlet Models | h^0 | s |
| 2 Higgs Doublet Models | h^0 | H^0, H^\pm, A^0 |
| Higgs Triplet Models | h^0 | $H^0, H^\pm, H^{\pm\pm}, A^0$ |

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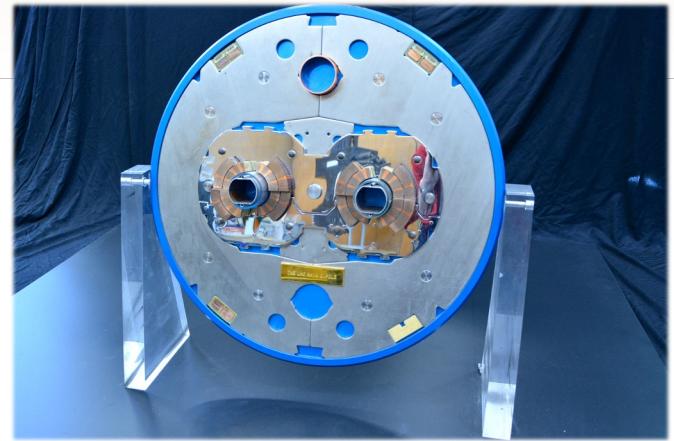
VI. Signal Modelling

VII. Advancements on Previous Studies

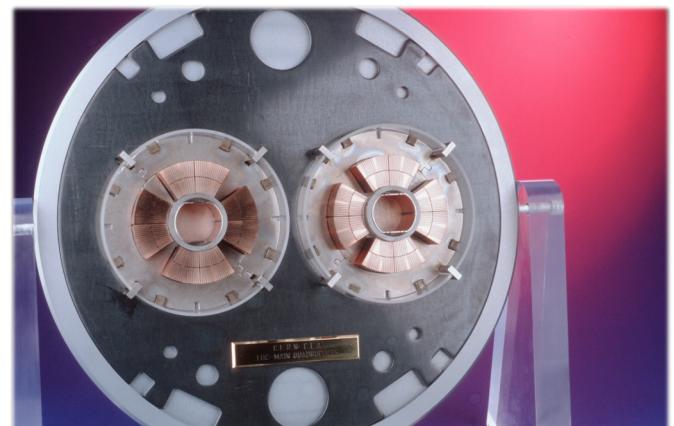
VIII. Summary

The Large Hadron Collider (LHC)

- The LHC is the world's largest particle accelerator, located on the border of France and Switzerland.
- It is 27 km in circumference and operates at a center-of-mass energy of 13.6 TeV.
- The LHC can achieve a nominal instantaneous luminosity of $10^{33} \text{ cm}^{-2} \text{ s}^{-1}$, colliding proton beams at a frequency of 40 MHz.
- Superconducting dipole and quadrupole magnets bend and squeeze the proton beams, respectively.
- Four detectors along beamline:
 - General purpose: CMS and ATLAS
 - Specialized: ALICE and LHCb



Above: Slice of LHC dipole magnets.
Below: Slice of LHC quadrupole magnets



Compact Muon Solenoid (CMS)

- **Silicon tracker**

- Solid-state pixel and strip detectors
- Detects charged particle tracks

- **Electromagnetic calorimeter (ECAL)**

- Homogenous detector
- Consists of 75,000 PbWO₄ crystals
- Detects electromagnetically interacting particle showers

- **Hadronic calorimeter (HCAL)**

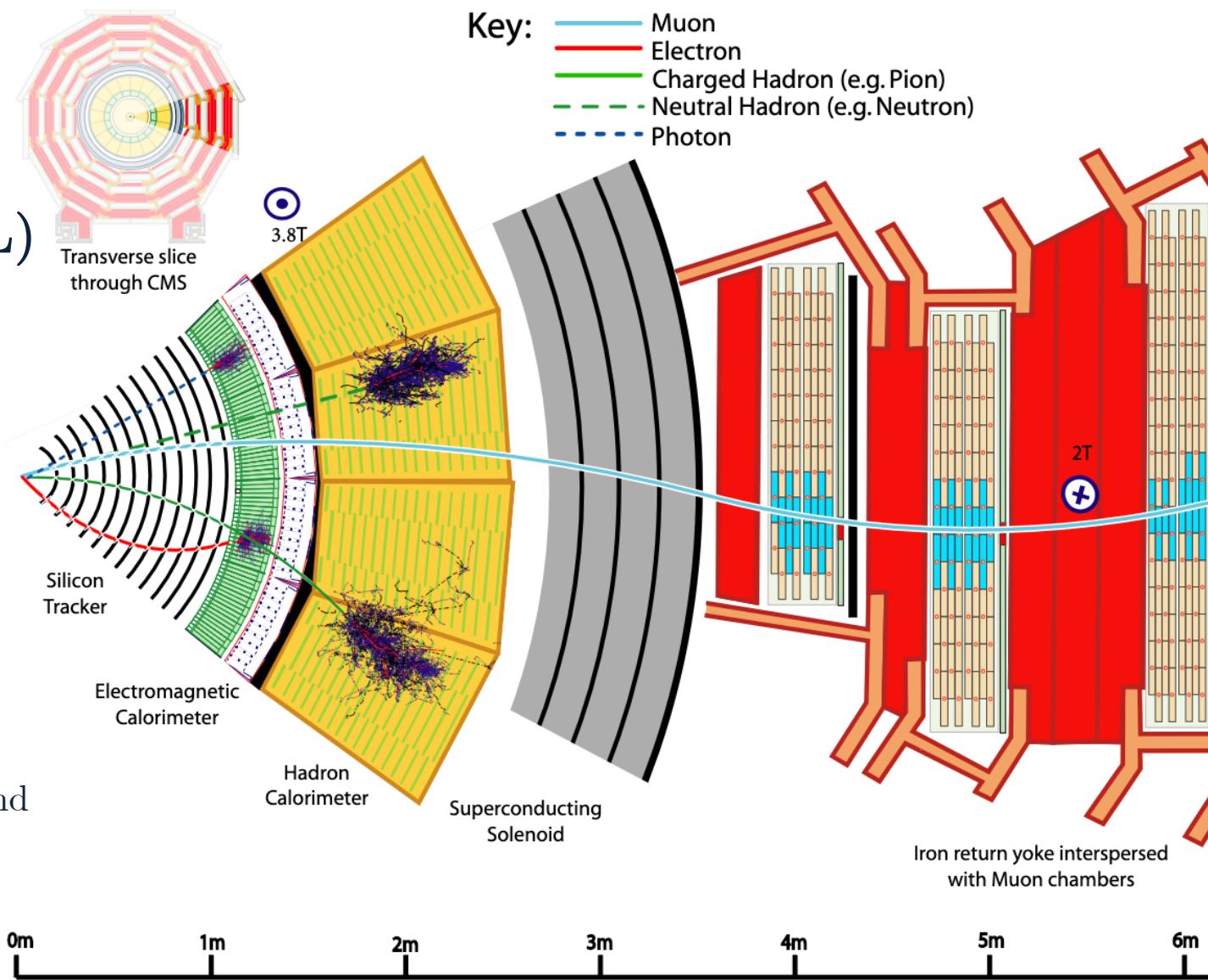
- Sampling calorimeter
- Layers of plastic scintillator and brass absorbers
- Detects neutral and charged hadrons

- **Solenoid Magnet**

- Bends charged particles to measure momentum and sign of charge

- **Muon chambers**

- Detects muons

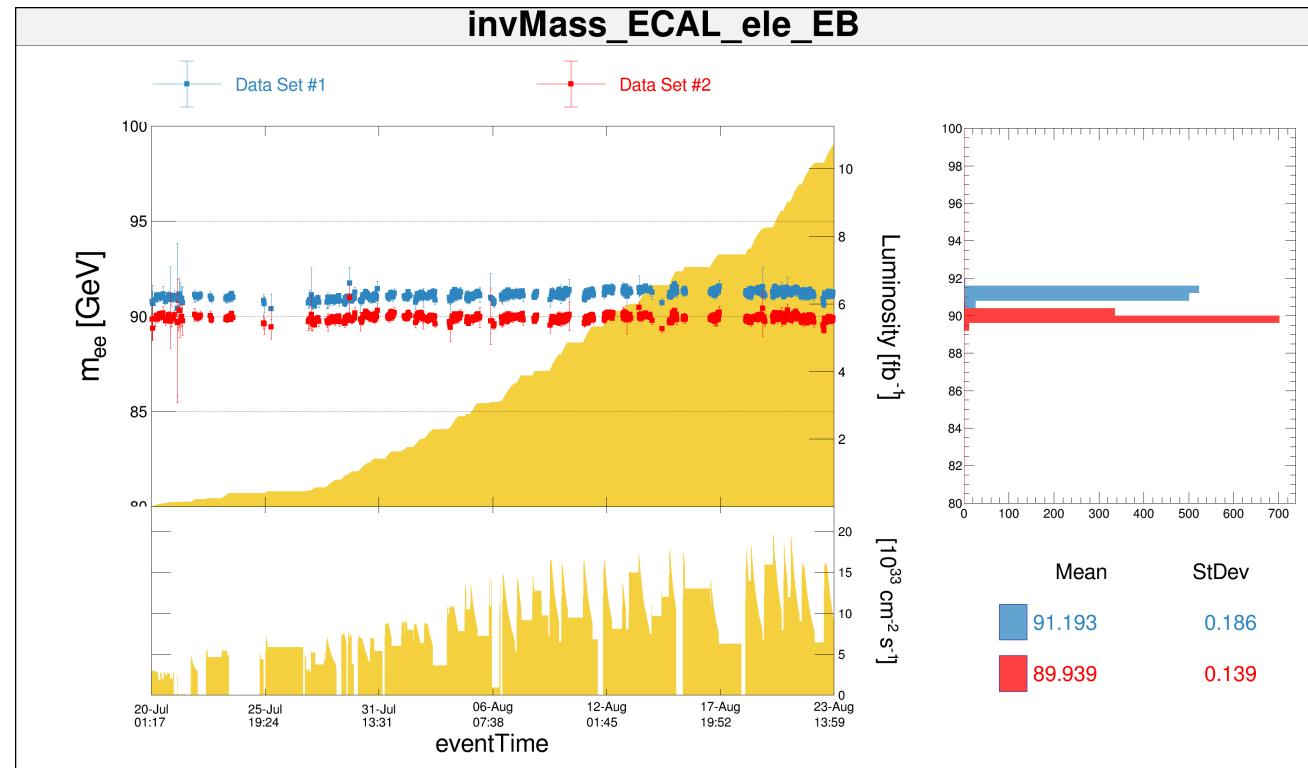


Phase II ECAL Upgrade

Working on Phase II upgrade for ECAL Barrel

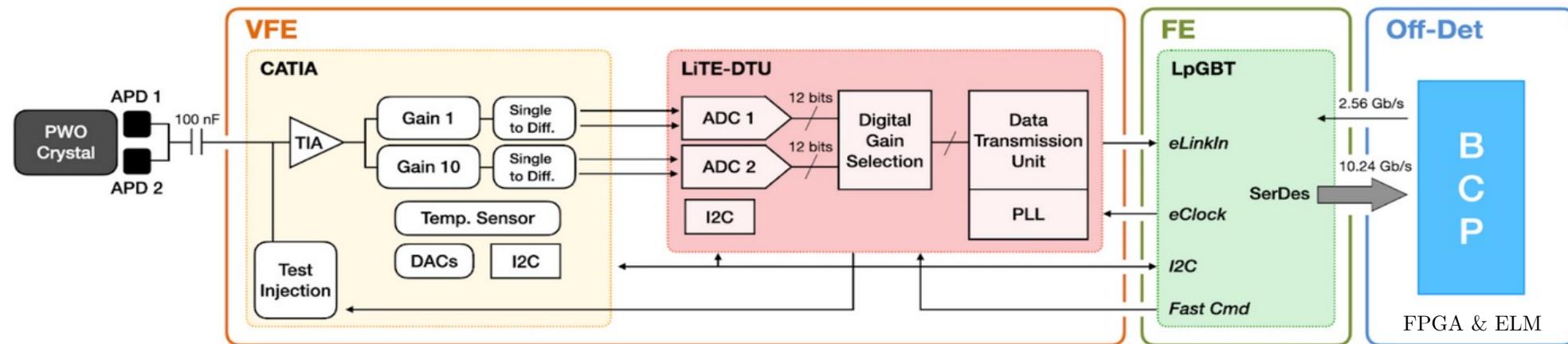
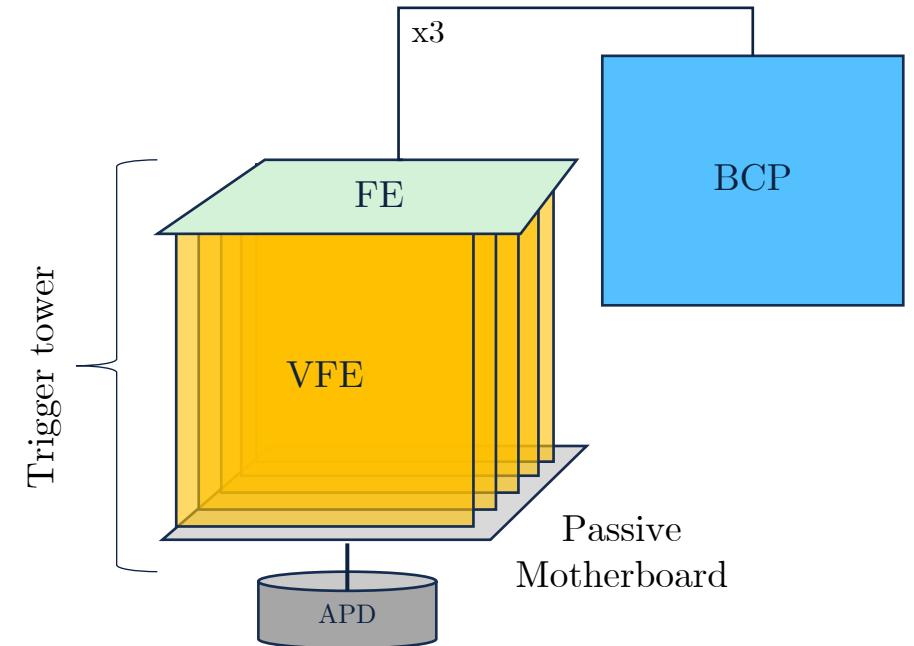
- The Phase II upgrade will entail a refurbishment of readout electronics of ECAL Barrel to accommodate the higher rate and latency requirements of the HL-LHC.

- Part of this upgrade is streamlining calibration of ECAL. 
- Developed an automatic monitoring tool alongside the new automatic ECAL calibration software. $Z \rightarrow ee$ events are one way to calibrate the detector.

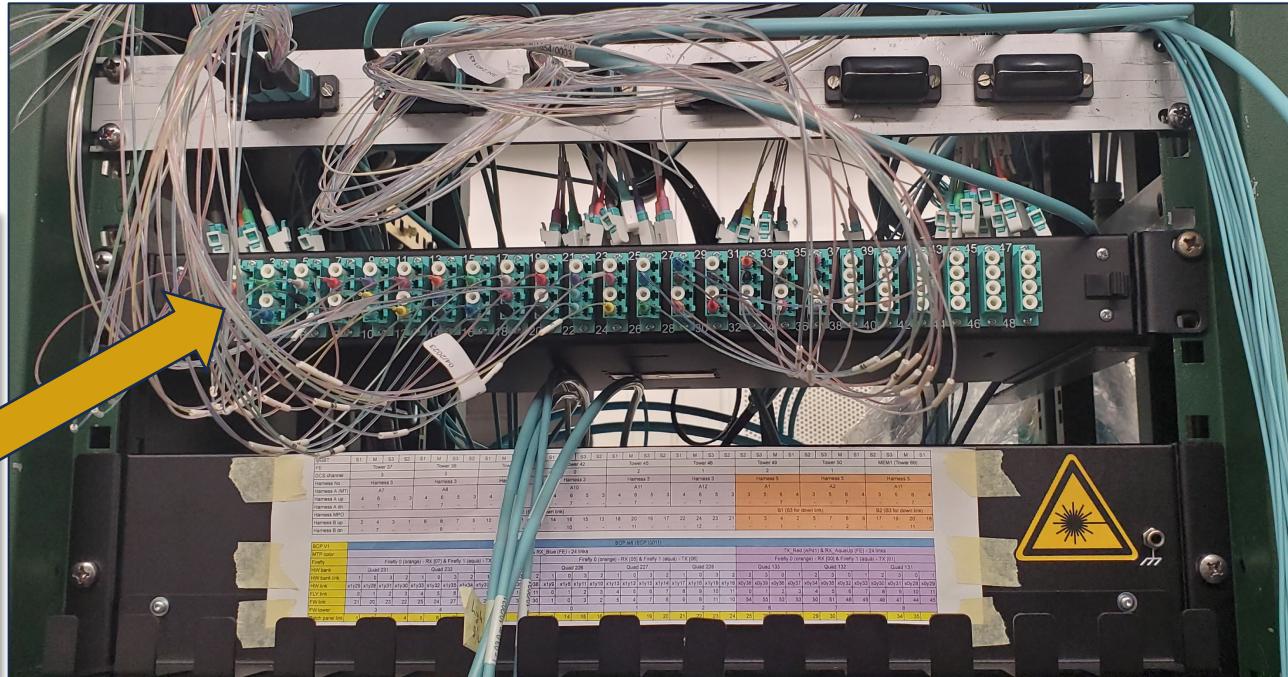
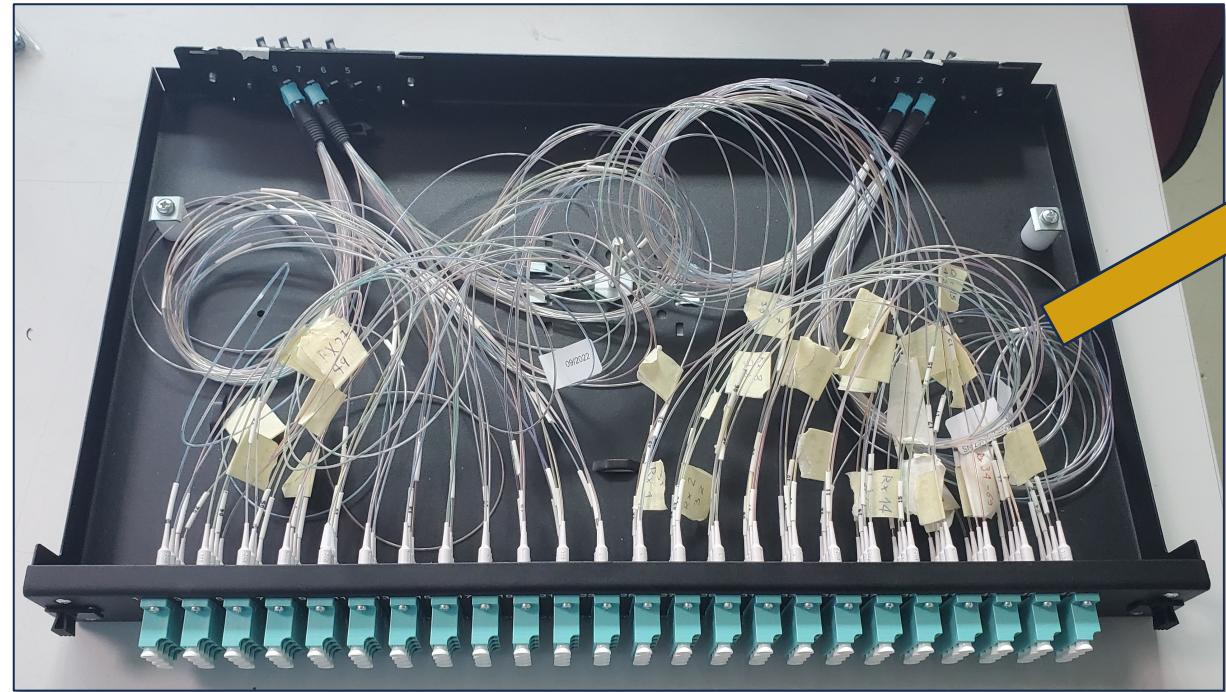


Technical Work

- Hardware is also replaced to improve timing and spatial precision of ECAL.
- I've been working on running systems tests for new suite of on/off-detector readout hardware.
- Developing high-level software for executing commands on hardware
- Involved in test beams and analysis



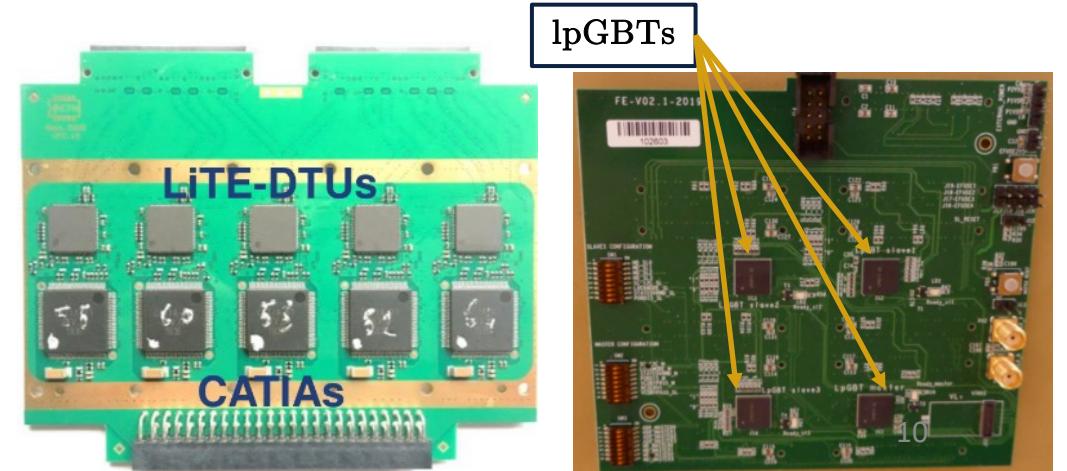
Technical Work (cont.)



Above: Patch panel reconfiguration for a new BCP firmware version.

Hardware

- Set up patch panels for additional hardware
- Write tests to check patch panel configuration
- Prepare hardware for test beams

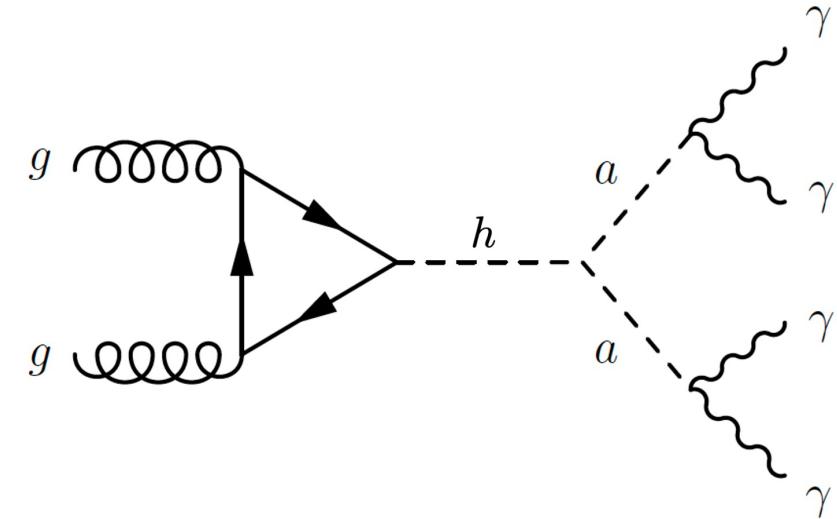


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Introduction to Analysis

Signal: $h \rightarrow aa \rightarrow \gamma\gamma\gamma\gamma$

- Clean final state with low SM background
- Model agnostic search allows for greater impact of any limits or discovery
- Improved sensitivity could allow for a discovery
- Currently working on a proof-of-concept study with the $h \rightarrow \gamma\gamma$ group's new framework.
- This proof-of-concept study consists of recreating a previous Run 2 analysis for 2018 data. The goal is to apply this work to Run 3 data and increase analysis sensitivity in hopes of producing a discovery.

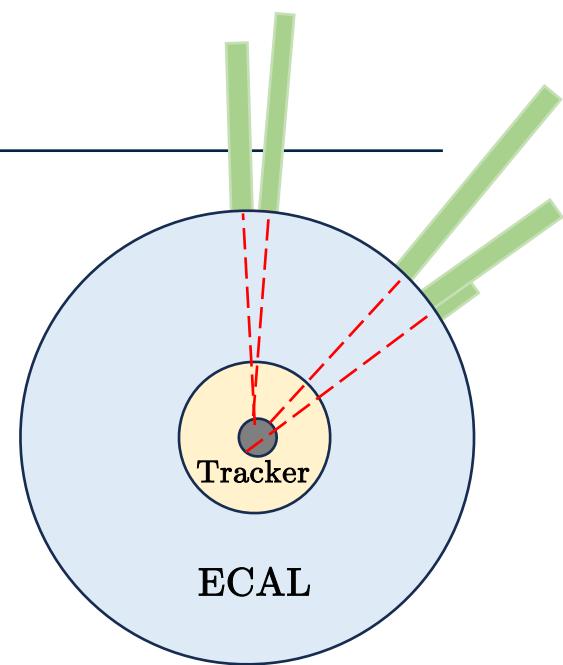


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Sample Generation

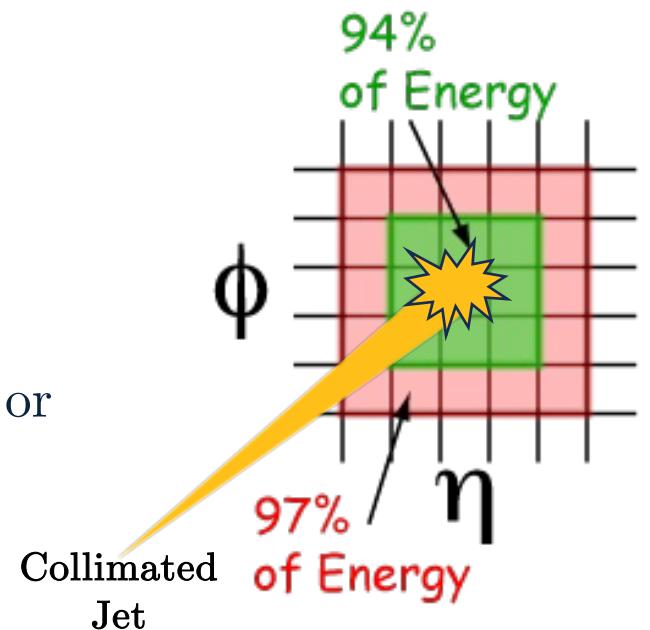
- Signal Monte Carlo (MC):

- Simulated $h \rightarrow aa \rightarrow \gamma\gamma\gamma\gamma$ samples
- Pseudoscalar mass range of $15 < m_a < 60$ GeV in steps of 5 GeV
- Decays from a SM Higgs boson with $m_h = 125$ GeV
- Only gluon fusion production mode of the Higgs boson considered



- Background:

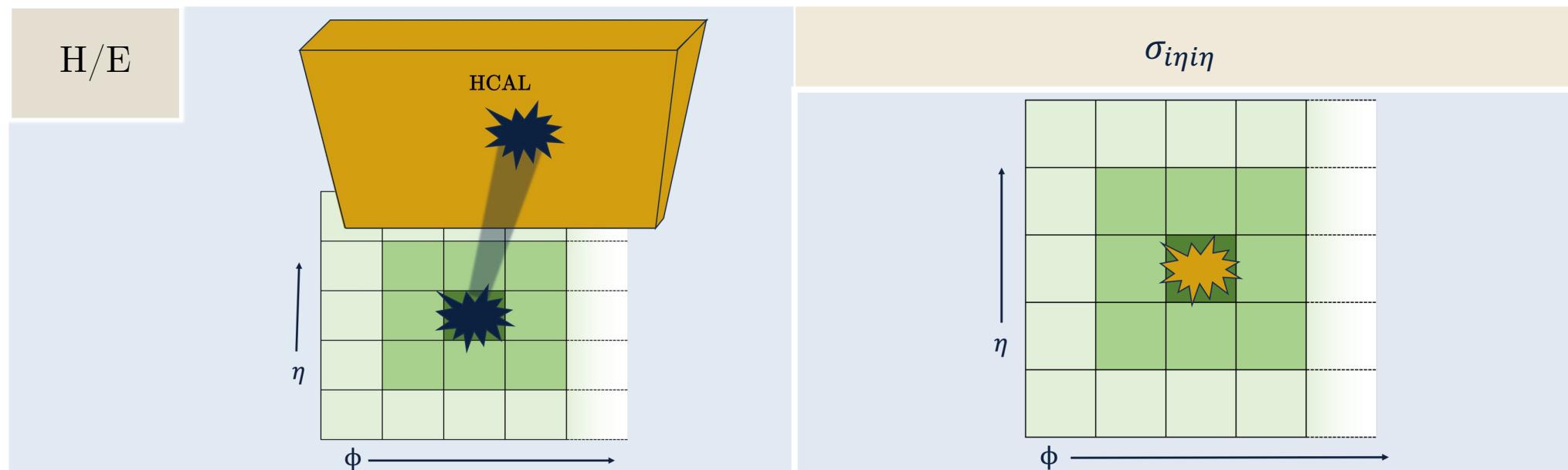
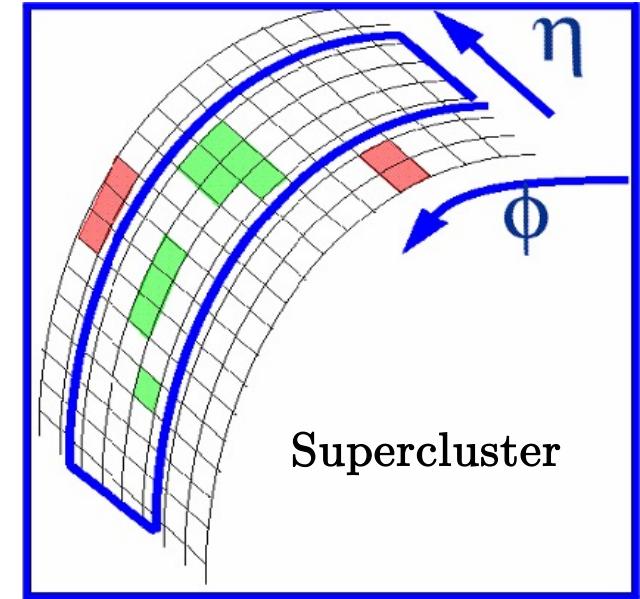
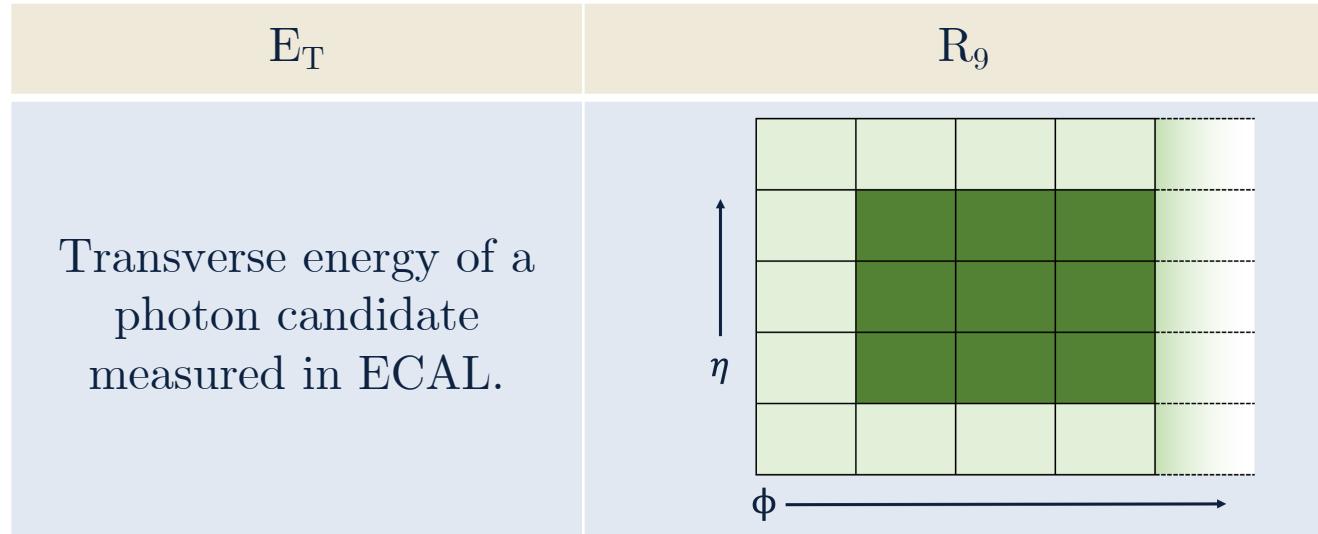
- A data-driven background is used
- Use event mixing technique:
 - Shuffle photons in an event with photons from consecutive events
 - Removes presence of any signal while retaining background shape
- Main backgrounds: either prompt photons from collision event or isolated photons reconstructed due to highly collimated decays fragmented from jets (fake photons)



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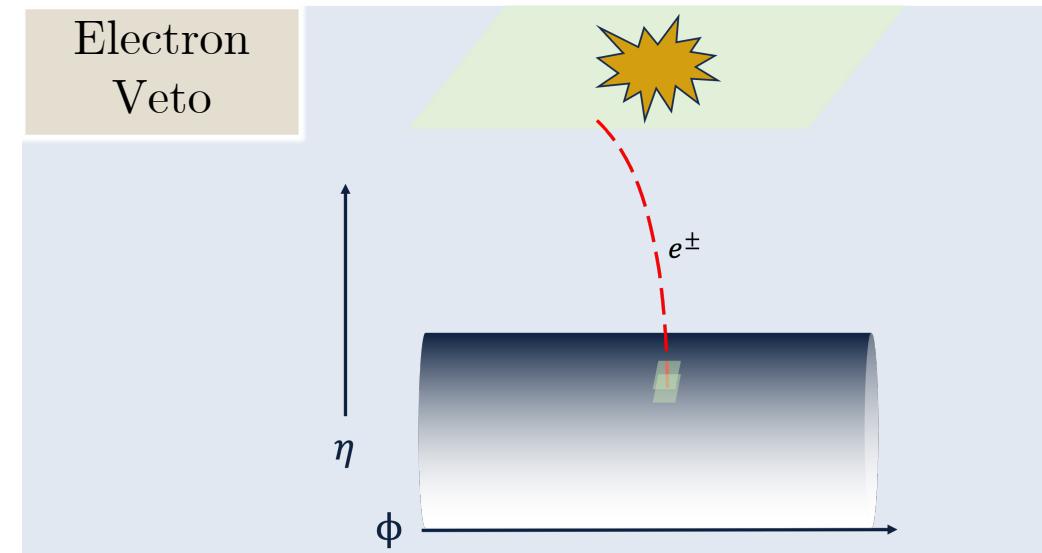
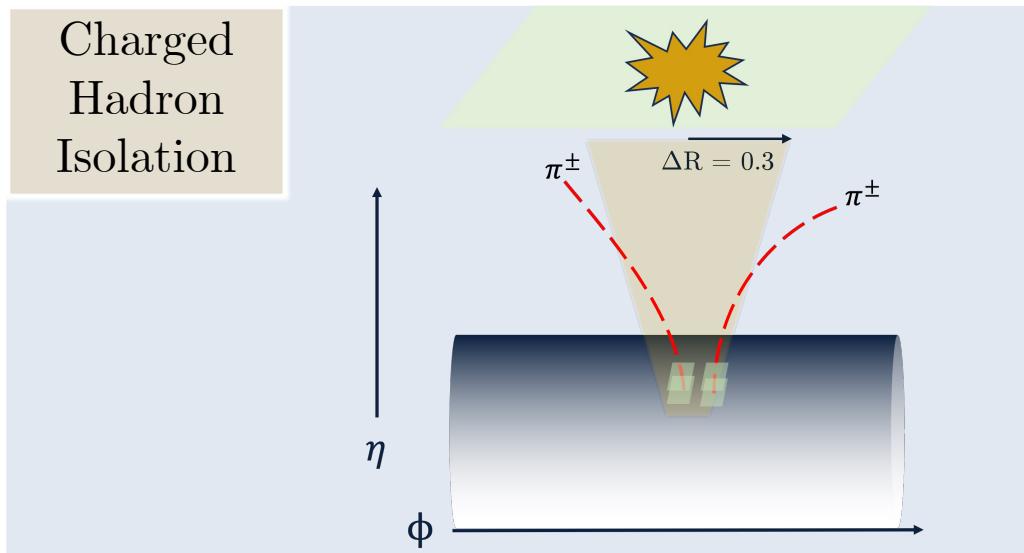
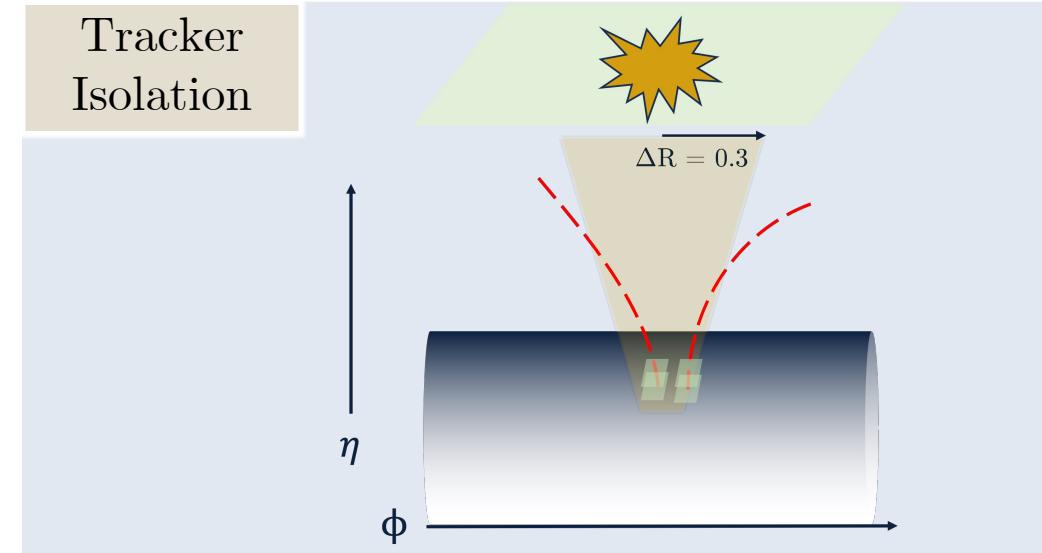
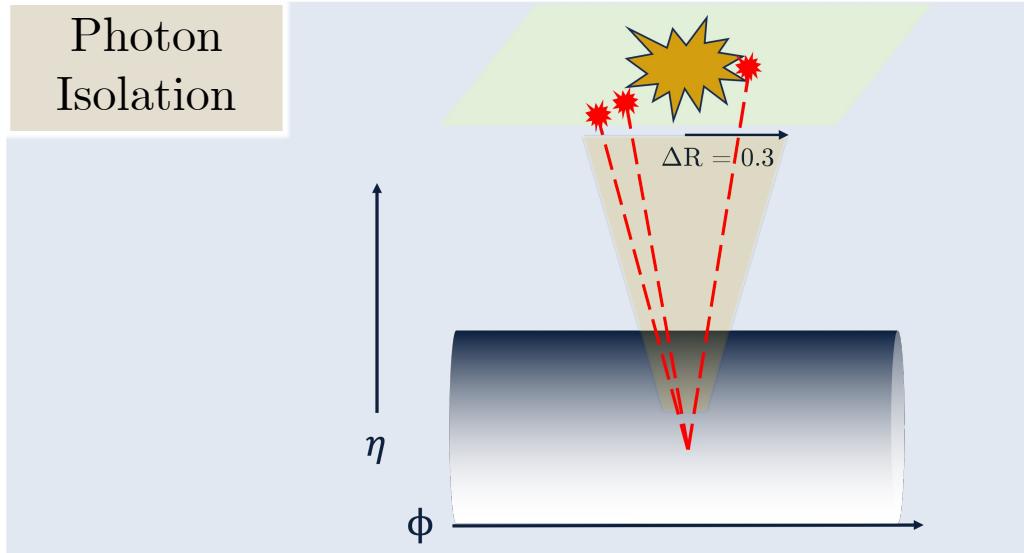
Choosing Candidate Photons

Energy deposition and shape of photon candidates:



Choosing Candidate Photons

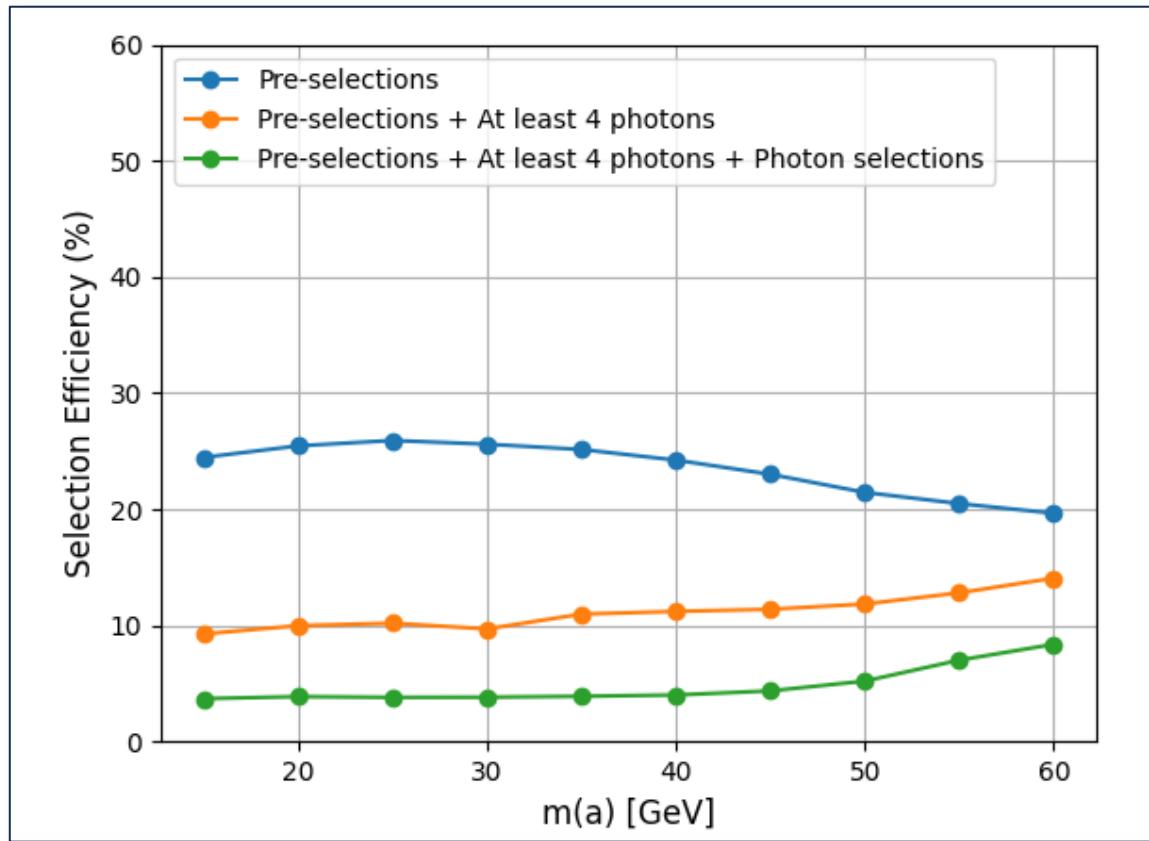
Isolation of photon candidates:



Selections

- Selections not shown are applied to photon candidates.
- Events must contain at least one diphoton and at least 4 photons.
- Additional cuts (below) are required to ensure optimal pseudoscalar reconstruction.
- $\Delta M = |m_{\gamma_a \gamma_b} - m_{\gamma_c \gamma_d}|$ is minimized to choose optimal pseudoscalar candidates

| | p_T | η | $m_{\gamma\gamma\gamma\gamma}$ |
|------------|----------|--------------------------|--|
| γ_1 | > 30.0 | | |
| γ_2 | > 18.0 | $ \eta < 2.5$ | |
| γ_3 | > 15.0 | $1.442 < \eta < 1.556$ | $110 < m_{\gamma\gamma\gamma\gamma} < 180 \text{ GeV}$ |
| γ_4 | > 15.0 | | |



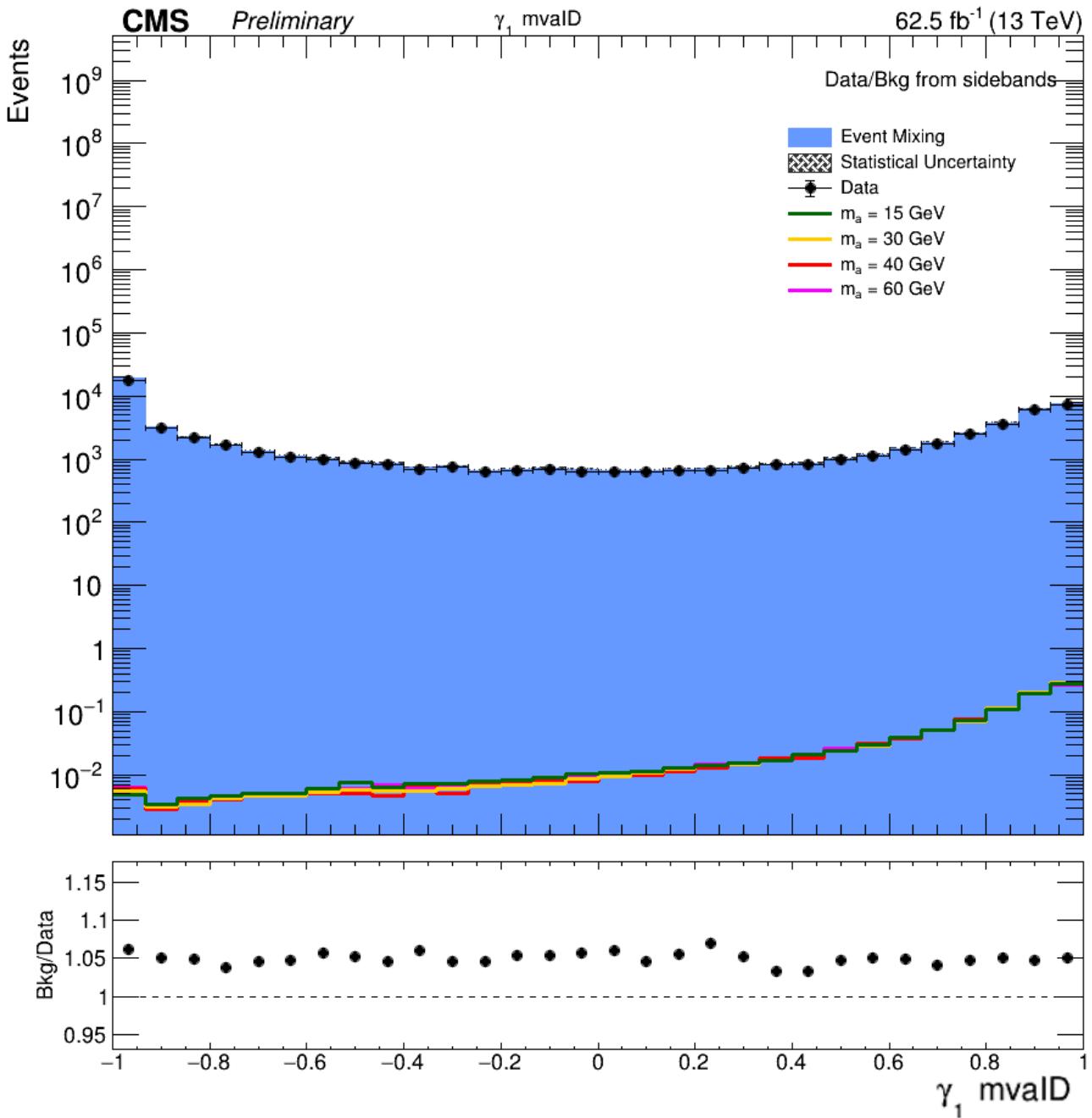
Above: Efficiencies of selections at various stages of selections for all nominal pseudoscalar mass points. This should improve at higher mass points.

Left: Additional selections applied to photons passing pre-selections.

Results of Selections

Photon Multivariate Analysis ID

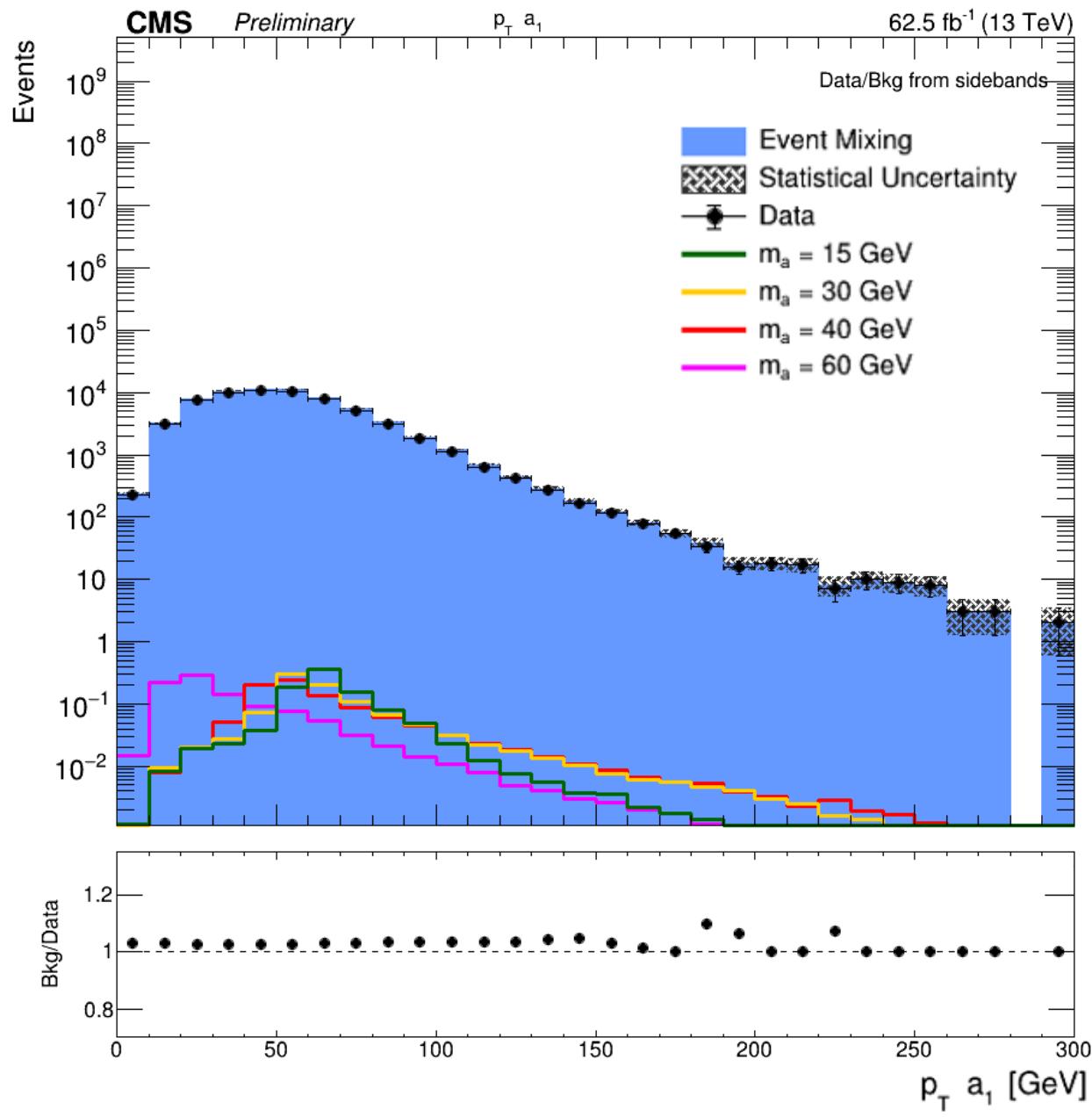
- Discriminates real photons from fake photons (collimated jets)
- Likelihood score: High score (~ 1) corresponds to real photon-like and low score (~ -1) corresponds to fake photon-like



Results of Selections

Looking at pseudoscalar kinematics:

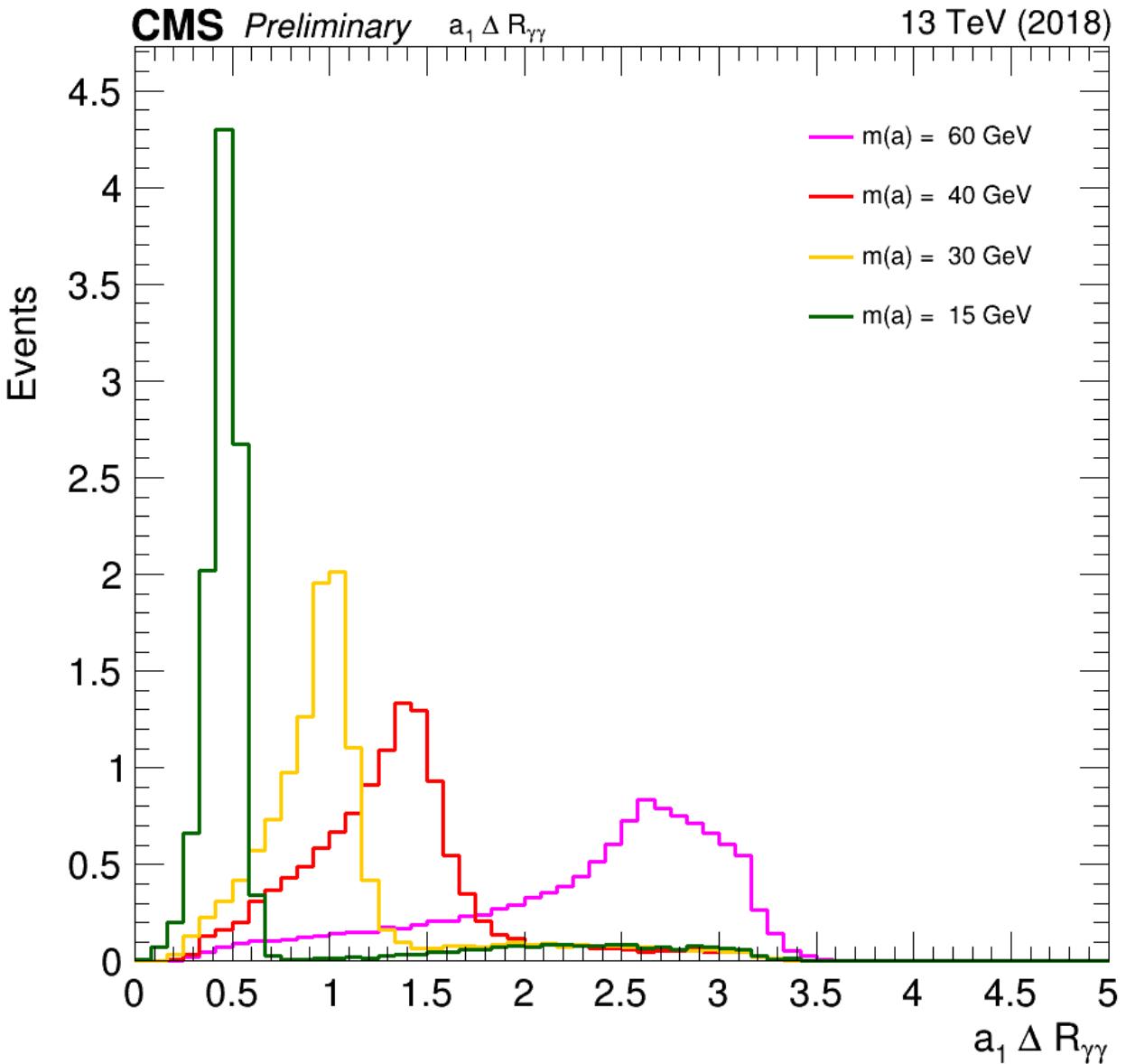
- p_T peak moves left with increasing mass
- ΔR peaks move right with increasing mass means less boosting as pseudoscalar mass increases



Results of Selections

Looking at pseudoscalar kinematics:

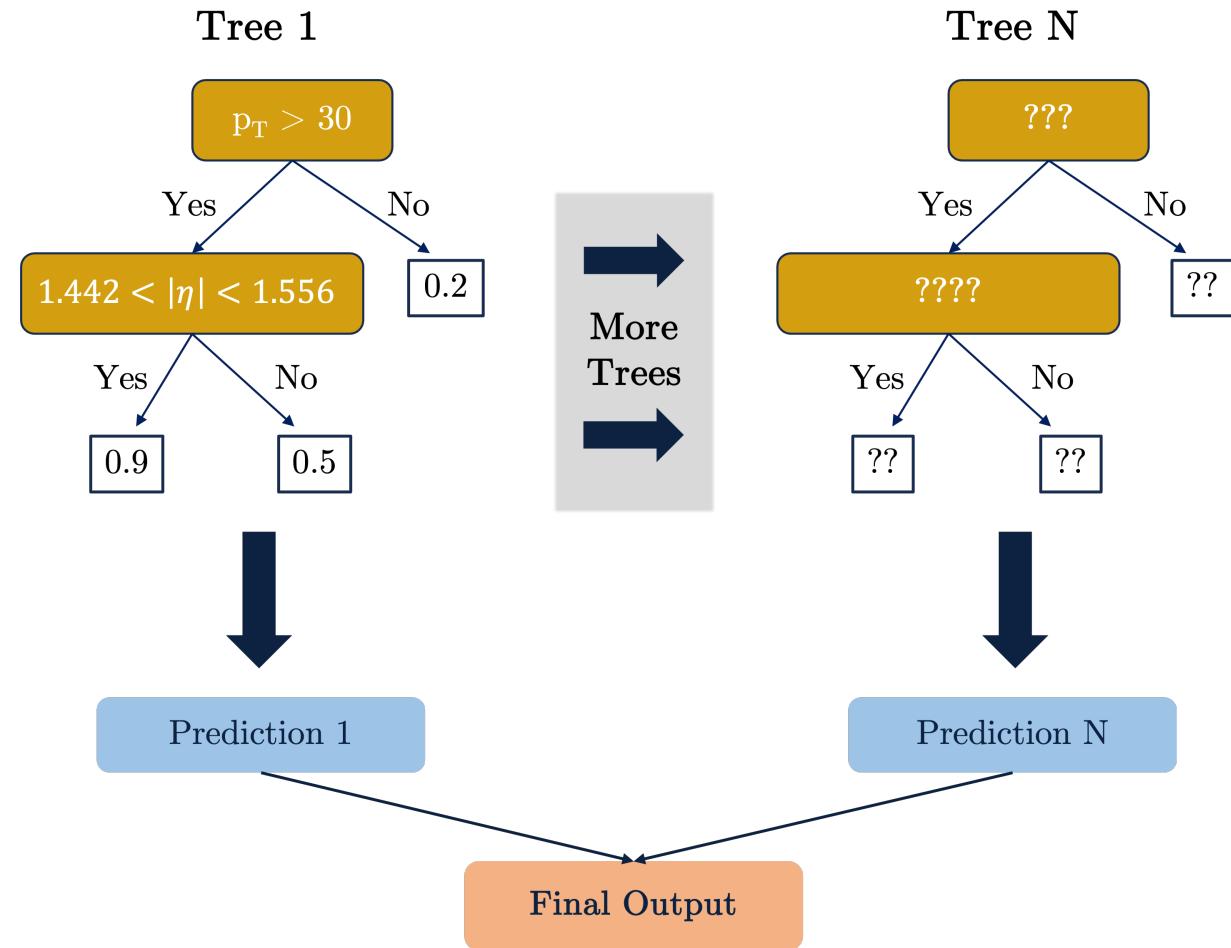
- p_T peak moves left with increasing mass
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Event Selection BDT

What is a BDT?

- Boosted Decision Tree
- Combination of many weak learners (trees) into a strong classifier
- Need a BDT to better distinguish signal-like events from background-like events
- A BDT can significantly improve analysis sensitivity compared to a purely cut-based analysis.
- Only one BDT model is required for the entire event selection.

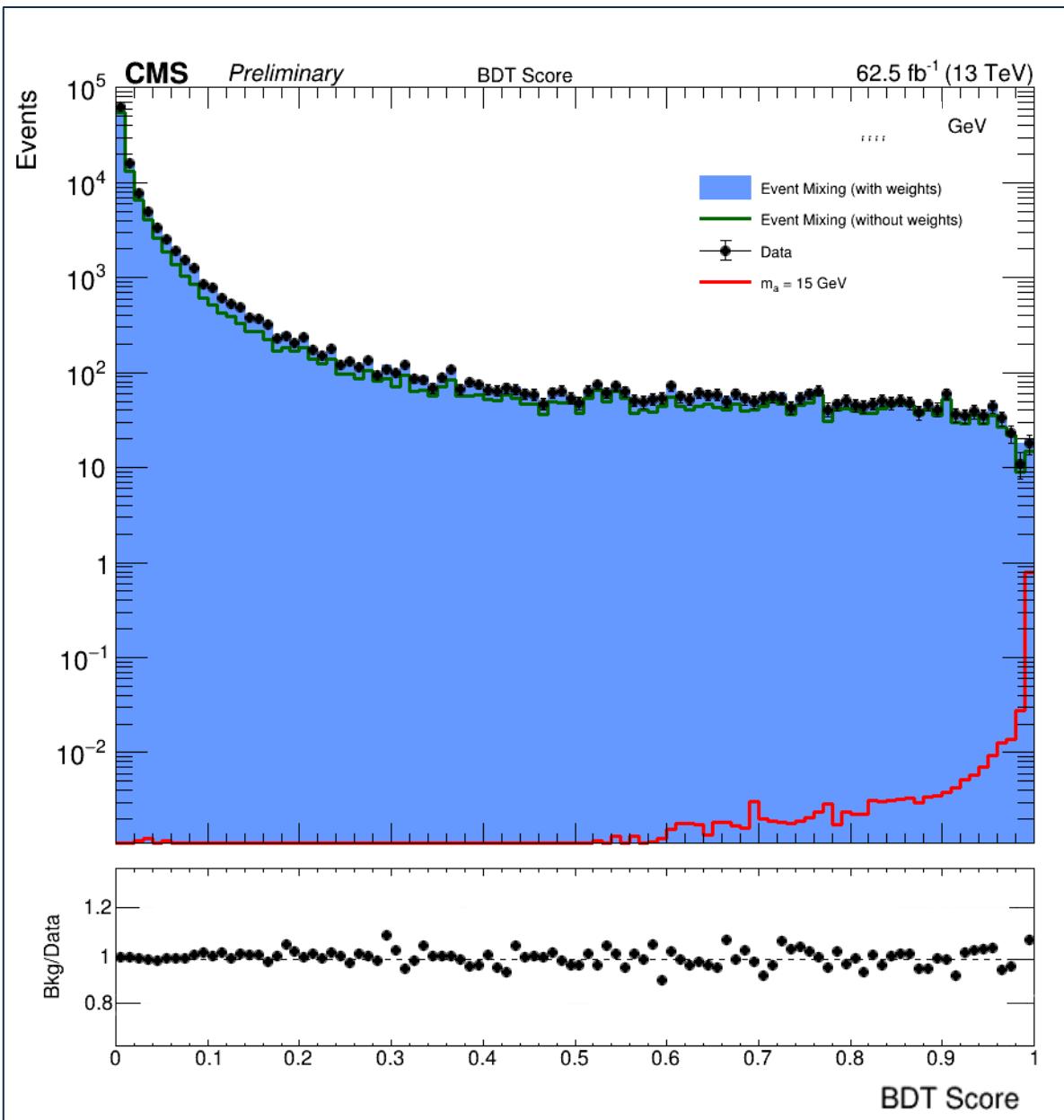


Applying the Event Selection BDT

- The event selection BDT model is applied to all samples for each nominal mass point.

For each nominal mass point:

- Signal MC, event mixed background, and data are all processed with the BDT, configured for the given mass point.
- A prediction distribution of event selection BDT score is generated for signal MC, event mixed background, and data. Shown for $m_a = 15 \text{ GeV}$.



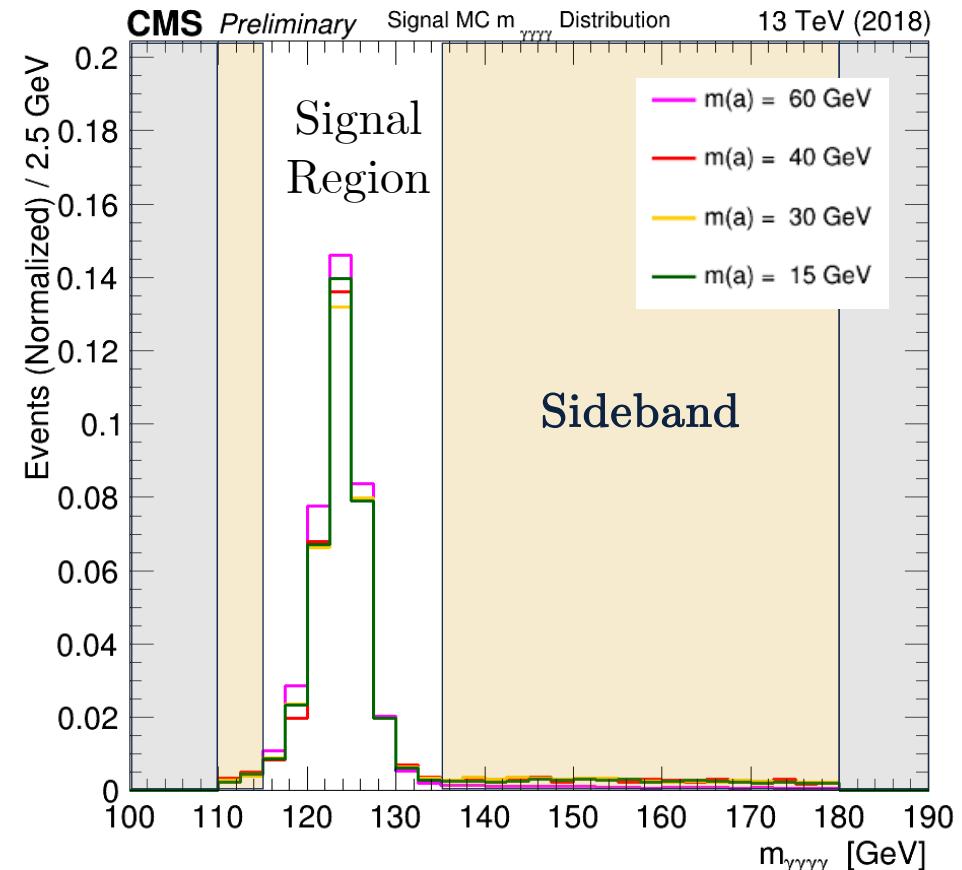
BDT Score Categorization

The goal of the event selection procedure is to maximize significance of the analysis. Approximate Mean Significance (AMS) is defined as:

$$\text{AMS} = \sqrt{2 \left[(S + B) \ln \left(1 + \frac{S}{B} \right) - S \right]}$$

where S and B reference to the number of signal and background events.

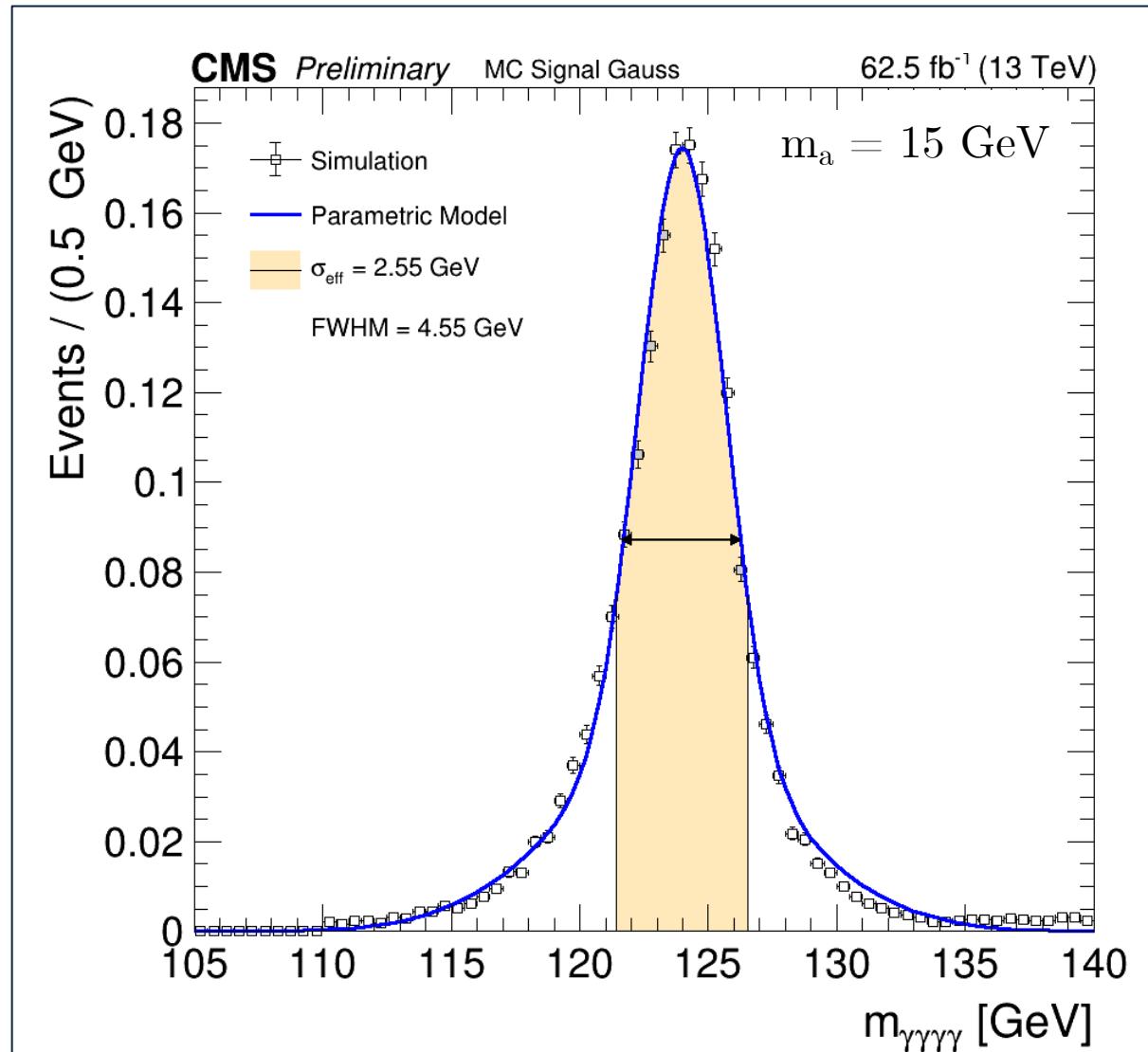
- Categories are constructed to maximize significance in the signal region.
- Cuts on category boundaries are applied on top of all analysis selections for all samples. A minimum of 8 data events in sideband region are required.



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Signal Modelling

- Signal models of $m_{\gamma\gamma\gamma\gamma}$ are constructed for all nominal pseudoscalar mass points.
- The parametric model is constructed from the sum of 2 Gaussians.
- Intermediate masses are modelled by the nearest nominal mass model with normalization interpolated from detector efficiency \times analysis acceptance.
- σ_{eff} refers to the region in which 68% of signal events are contained and FWHM to the Full Width Half Maximum of the parametric model.



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Advancements on Previous Studies

How to increase analysis sensitivity:

- Statistics
- Better estimation of background
- Improved event selection procedure

Ways to improve on Run 2 analysis:

- Expect Run 3 statistics to match Run 2 statistics by end-2024. Current Run 3 statistics are at $\sim 60 \text{ fb}^{-1}$.
- Even more statistics if doing combined Run 2 + partial Run 3
- Improvement of $\sqrt{2}$ in precision from Run 2 to Run 3
- New background MC samples
- Deep learning model instead of a BDT for event selection

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Summary

A search for the SM Higgs boson decaying to two pseudoscalars with a fully resolved, four photon final state was proposed.

Many of the tools needed to perform the full analysis are constructed:

- Event selections processor
- Event selection BDT
- BDT score category optimization tools
- Signal modelling tools for nominal mass points

Future Work:

- Fix any problems with current suite of analysis tools
- Background modelling
- $m_{\gamma\gamma\gamma\gamma}$ fitting for limit setting in Run 2 proof-of-concept study
- Applying work to Run 3 data

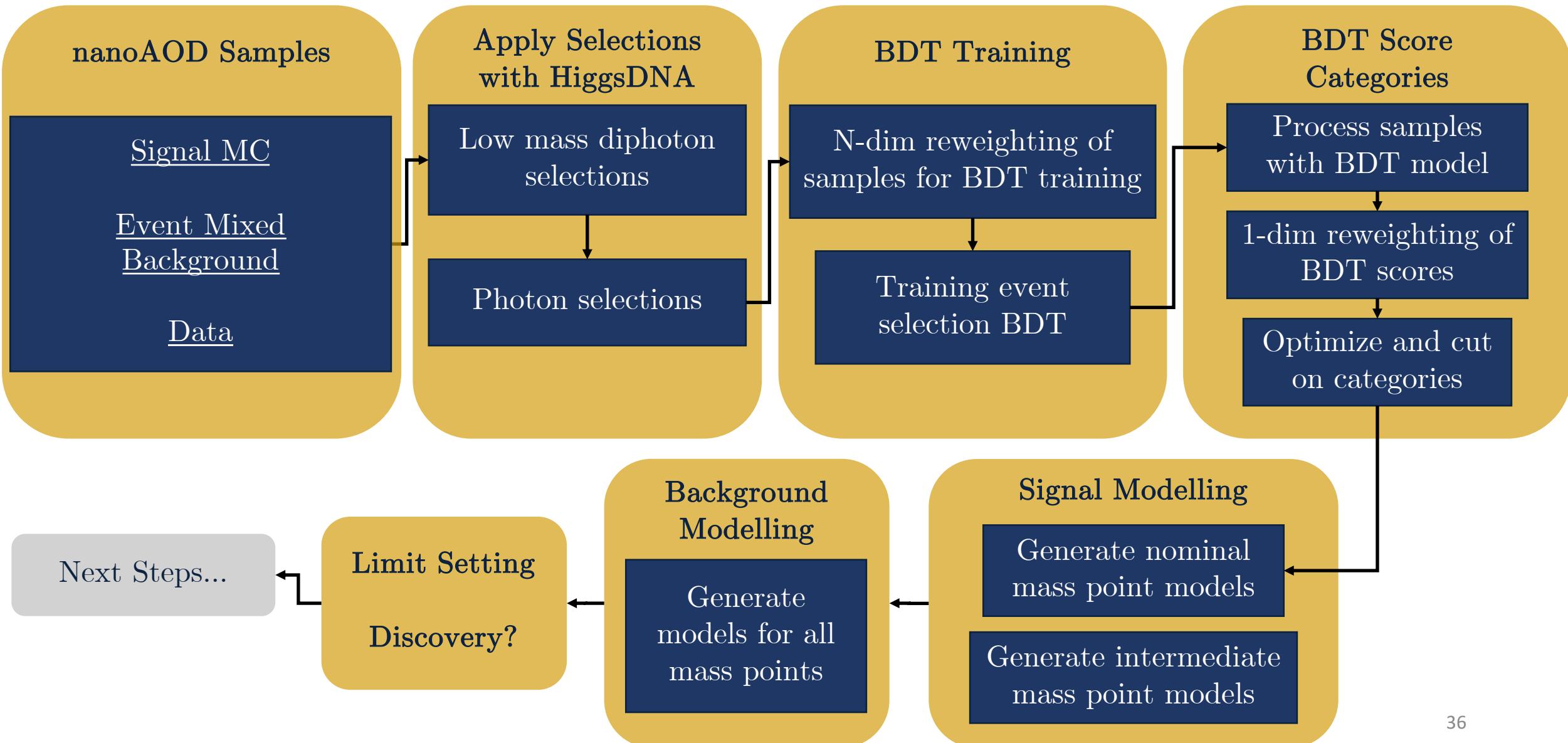
Goals:

- Complete reproduction of Run 2 analysis for 2018 subset with new analysis framework
- Increase analysis sensitivity for Run 3 data and produce a discovery

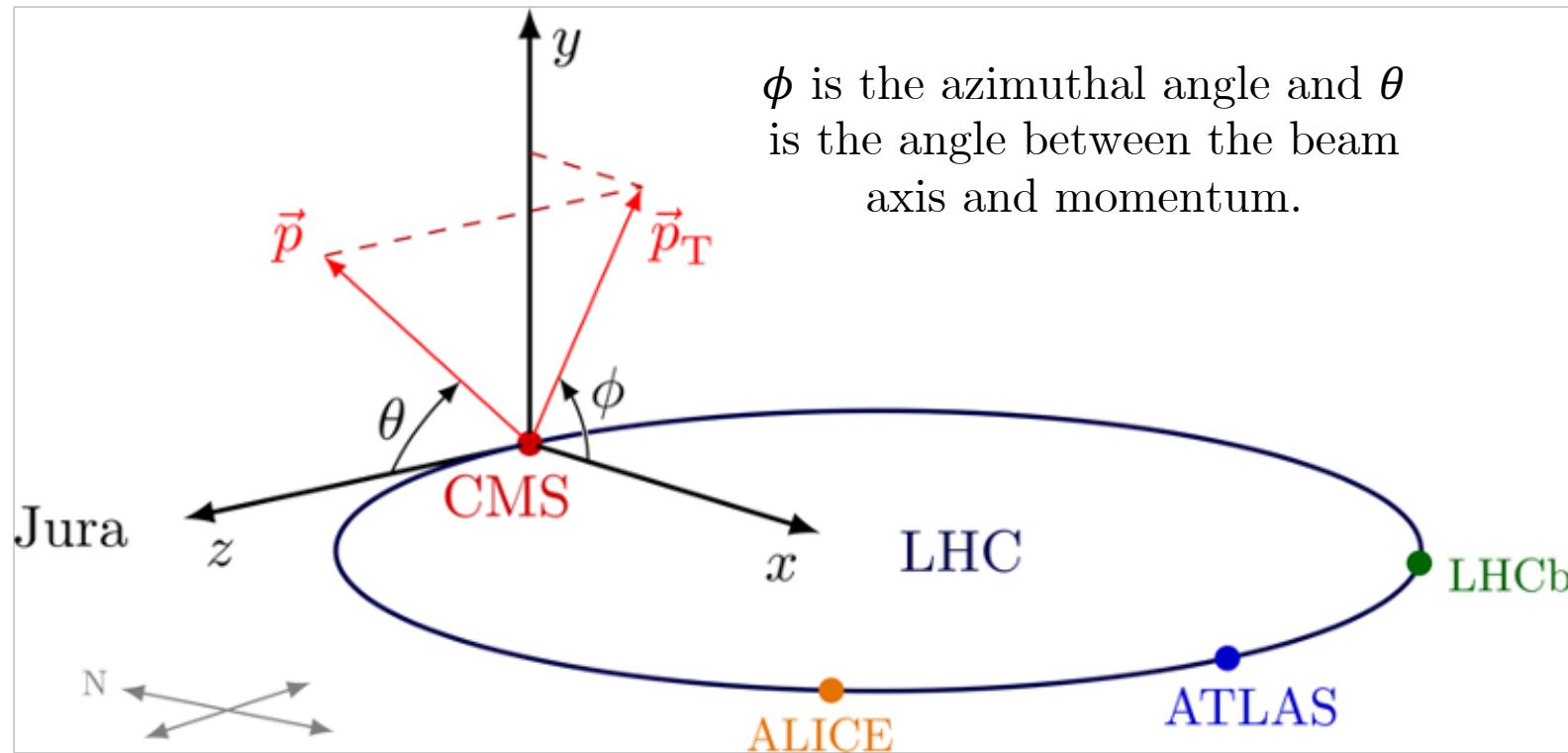
Thank You!

Backup

Analysis Overview



Quick Geometry of CMS

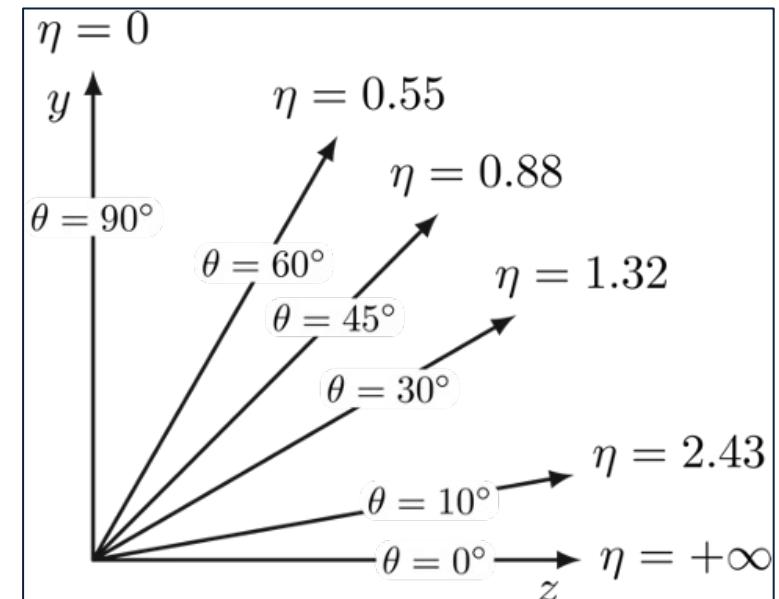


ϕ is the azimuthal angle and θ is the angle between the beam axis and momentum.

Angular Displacement:

$$\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$$

where $\eta \equiv -\ln \left[\tan \left(\frac{\theta}{2} \right) \right]$



Electroweak Symmetry Breaking

The Higgs get a non-zero vacuum expectation value (VEV), by convention $\langle \Phi \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix}$. This VEV breaks the $SU(2)_L \times U(1)_Y \rightarrow U(1)_{EM}$.

We can now expand around the VEV and parameterize Φ as follows:

$$\Phi = \begin{pmatrix} G^+ \\ v + \frac{1}{\sqrt{2}}(H^0 + iG^0) \end{pmatrix} = e^{i\vec{\chi} \cdot \vec{\tau}} \begin{pmatrix} 0 \\ v + \frac{1}{\sqrt{2}}h \end{pmatrix} \xrightarrow{\text{Unitary Gauge}} \begin{pmatrix} 0 \\ v + \frac{1}{\sqrt{2}}h \end{pmatrix} \quad (8)$$

where $\vec{\chi}$ are the eaten Goldstone bosons (GSBs) corresponding to G^+ and G^0 , and $\vec{\tau}$ are the associated broken generators.

From here it is relatively straightforward to generate a mass term for every elementary particle and interactions with the SM Higgs:

$$\mathcal{L} \supset |D_\mu \Phi|^2 - y_d \bar{Q}_L \Phi d_R - y_d \bar{Q}_L \tilde{\Phi} u_R - y_e \bar{L}_L \tilde{\Phi} e_R + h.c. \quad (9)$$

Higgs Mechanism

Expanding $|D_\mu \Phi|^2 = \left| \frac{1}{\sqrt{2}} (\partial_\mu g T^i W_\mu^i + g' B_\mu) \begin{pmatrix} 0 \\ v \end{pmatrix} \right|^2$, we get

$$= \frac{v^2}{8} \left[g^2 \left((W_\mu^1)^2 + (W_\mu^2)^2 \right) + (g W_\mu^3 - g' B_\mu)^2 \right].$$

This yields masses for W/Z and the photon:

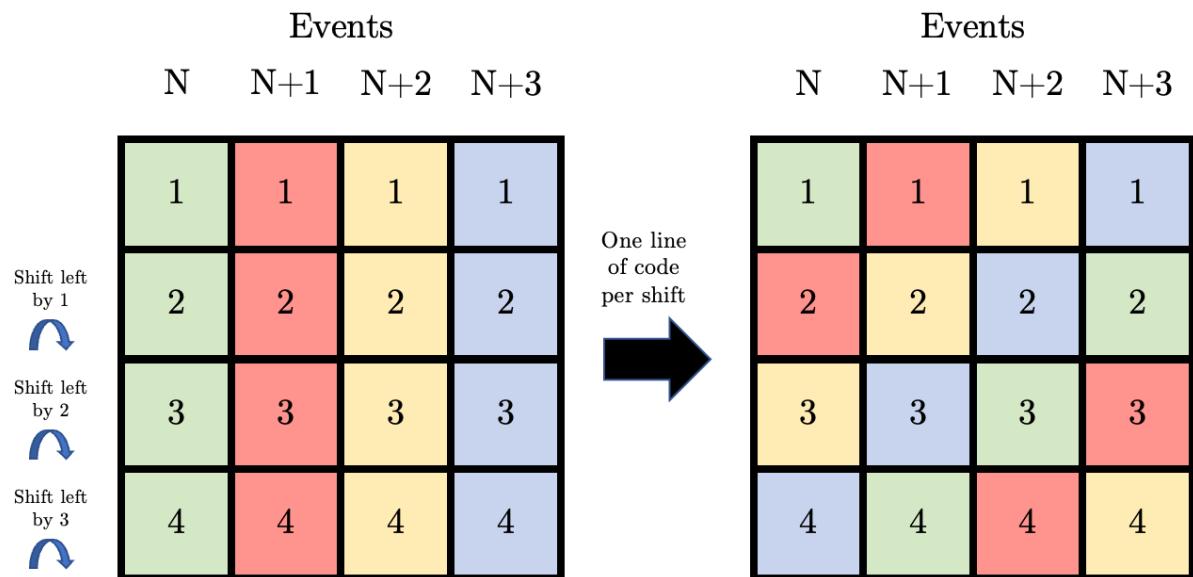
$$W_\mu^\pm \equiv \frac{1}{\sqrt{2}} (W_\mu^1 \mp i W_\mu^2) \quad \text{with mass} \quad m_W = \frac{g v}{2}$$

$$Z_\mu \equiv \frac{1}{\sqrt{g^2 + g'^2}} (g W_\mu^3 - g' B_\mu) \quad \text{with mass} \quad m_Z = \frac{v}{2} \sqrt{g^2 + g'^2},$$

$$A_\mu \equiv \frac{1}{\sqrt{g^2 + g'^2}} (g' W_\mu^3 + g B_\mu) \quad \text{with mass} \quad m_A = 0.$$

Event Mixing

- Expected shuffling:



- Events are color coded and then shuffled.
- How to read: Event N has photon N → event N, photon 2 → event N+1, etc.

- Observed shuffling:

- Photon 1 (Evt 1) → Photon 1 (Evt 1)
- Photon 2 (Evt 1) → Photon 2 (Evt 2)
- Photon 3 (Evt 1) → Photon 3 (Evt 3)
- Photon 4 (Evt 1) → Photon 4 (Evt 4)

And so on for the other events...

Pre-selections

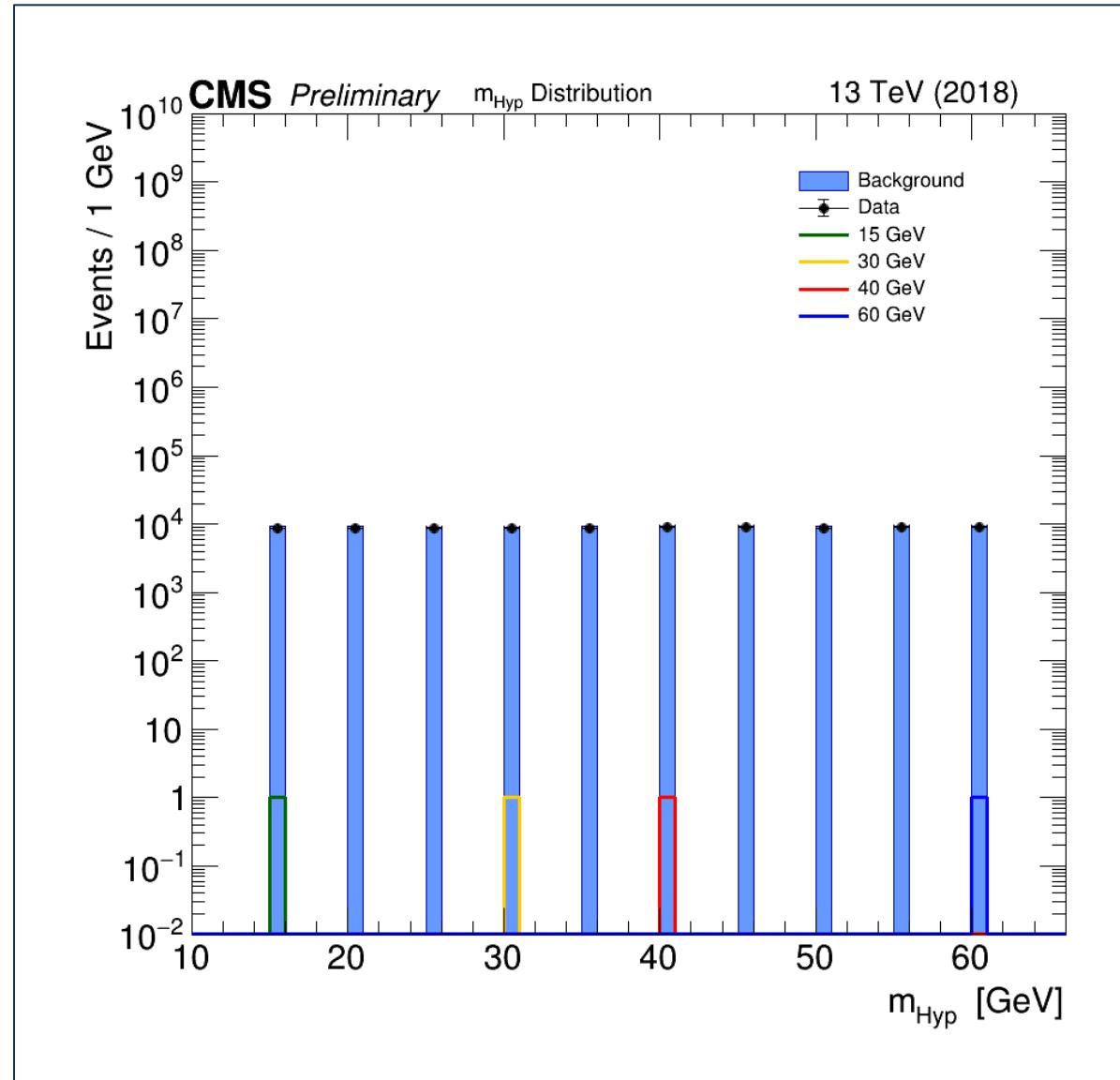
| γ_1 must be: | E_T | R_9 | H/E | $\sigma_{i\eta i\eta}$ | PF Pho Iso | Tracker Iso |
|---------------------|-------|---------|----------|------------------------|------------|-------------|
| EB; $R_9 > 0.85$ | | | | < 0.015 | | |
| EB; $R_9 \leq 0.85$ | 15.0 | > 0.5 | < 0.08 | | < 4.0 | < 6.0 |
| EE; $R_9 > 0.9$ | | | | < 0.035 | | |

- Selections slightly more strict than High Level Trigger (HLT) are applied
- Events must pass at least one of Options 1-3 (motivated by miniAOD cuts)
- Photons must also pass an electron veto
- Events must have at least two photon candidates
- Diphoton candidates require $p_T > 30$ GeV and $p_T > 18$ GeV for leading and subleading daughter photons

| Option 1 | Option 2 | Option 3 |
|-------------|--------------------------------|---------------------------------|
| $R_9 > 0.8$ | Charged Hadron Iso < 20.0 | Charged Hadron Iso/ $p_T < 0.3$ |
| | | IF $p_T > 14.0$ |
| | | AND $H/E < 0.15$ |

Event Selection BDT

- One event selection BDT model is produced for all mass points, made possible by using a constructed variable: hypothesis mass or m_{Hyp}
- m_{Hyp} has the associated value for a given pseudoscalar mass point for signal MC but a flat distribution for event mixed background and data, by construction.

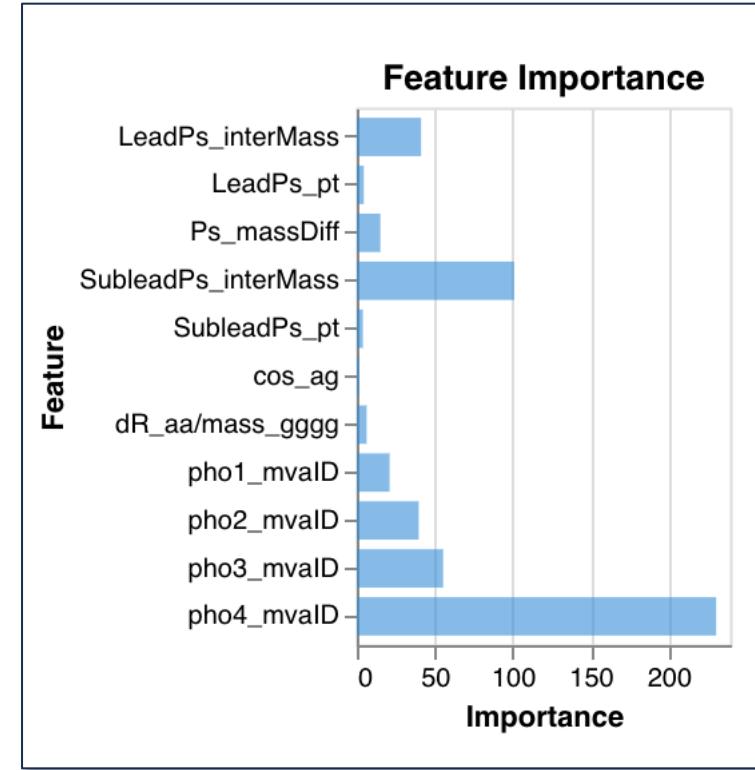


Event Selection BDT Inputs

- Processed signal MC samples are combined into one signal-like sample. Processed event mixed background is used as the background-like sample.
- An N-dim reweighting is performed to correct discrepancies between event mixed background and data before training.

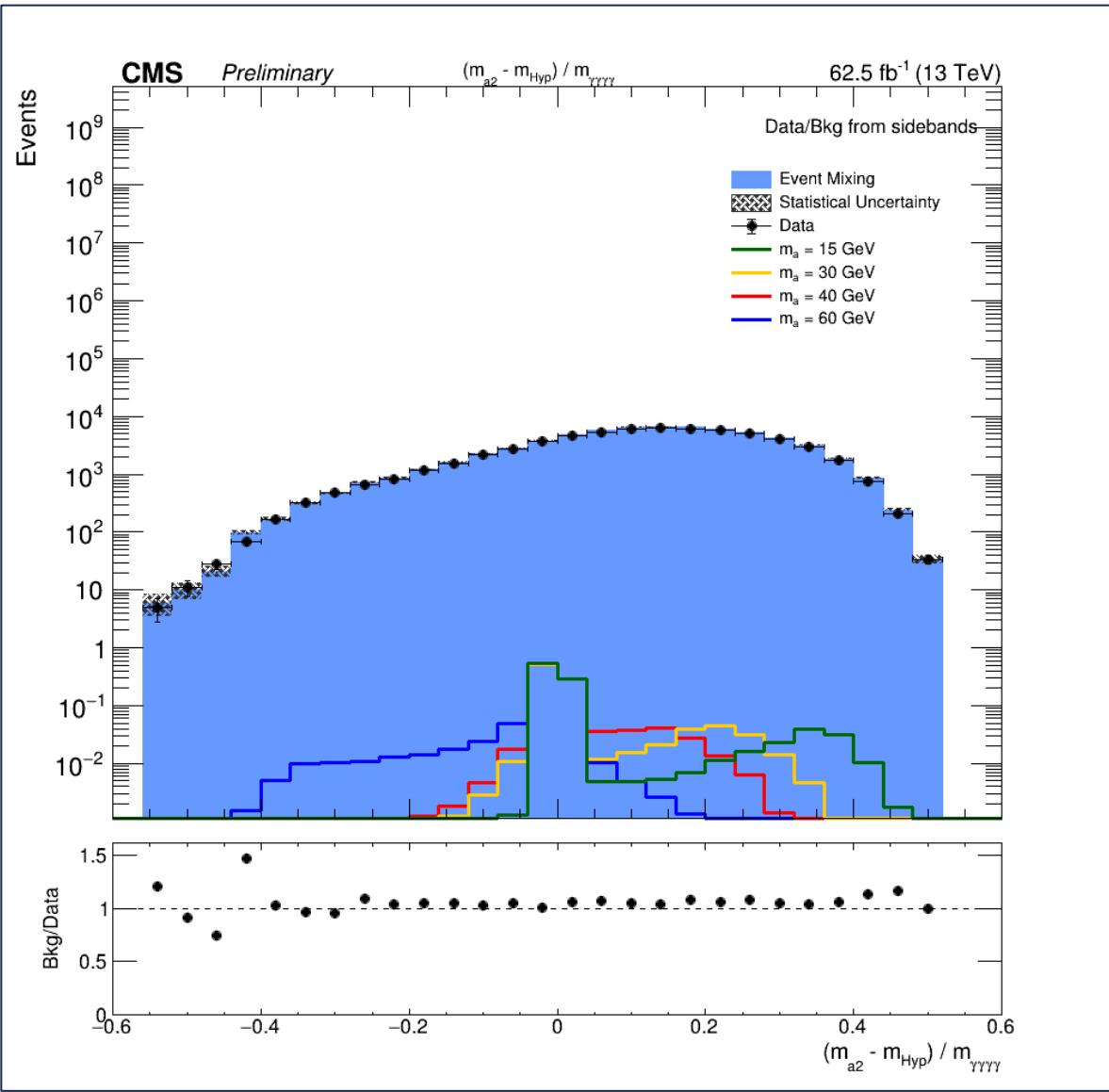
Input variables:

- $\gamma_{1,2,3,4}$ MVA ID
- a_1 pT a_2 pT
- $\Delta R(a_1, a_2) / m_{\gamma\gamma\gamma\gamma}$
- $m_{a1} - m_{a2}$
- $\cos(\theta_{a\gamma})$, where $\theta_{a\gamma}$ is the angle between the leading photon coming from the leading pseudoscalar and the direction of $a \rightarrow \gamma\gamma$
- $\frac{m_{a1\ RECO} - m_{a\ Hyp}}{m_{\gamma\gamma\gamma\gamma}}$ $\frac{m_{a2\ RECO} - m_{a\ Hyp}}{m_{\gamma\gamma\gamma\gamma}}$

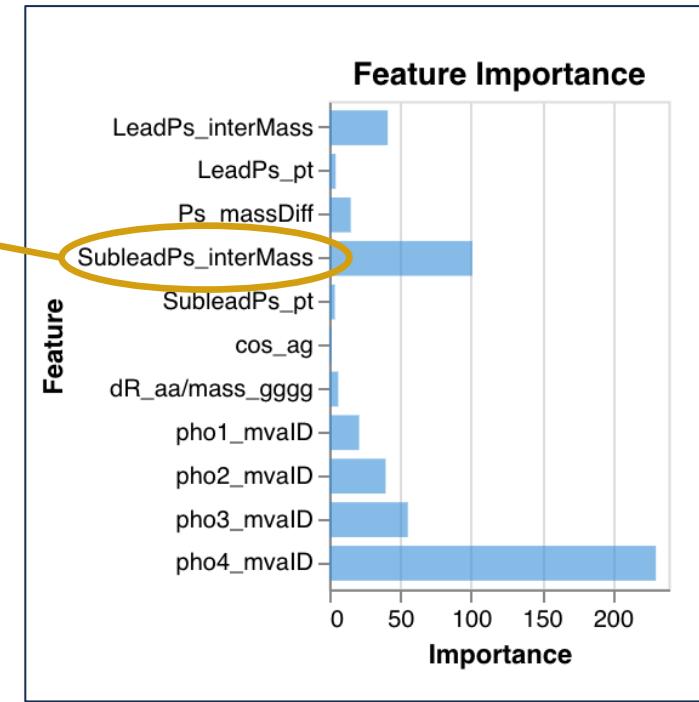


Above: Chart of feature importance for the event selection BDT input variables from one of the best performing models.

Important BDT Input Variables



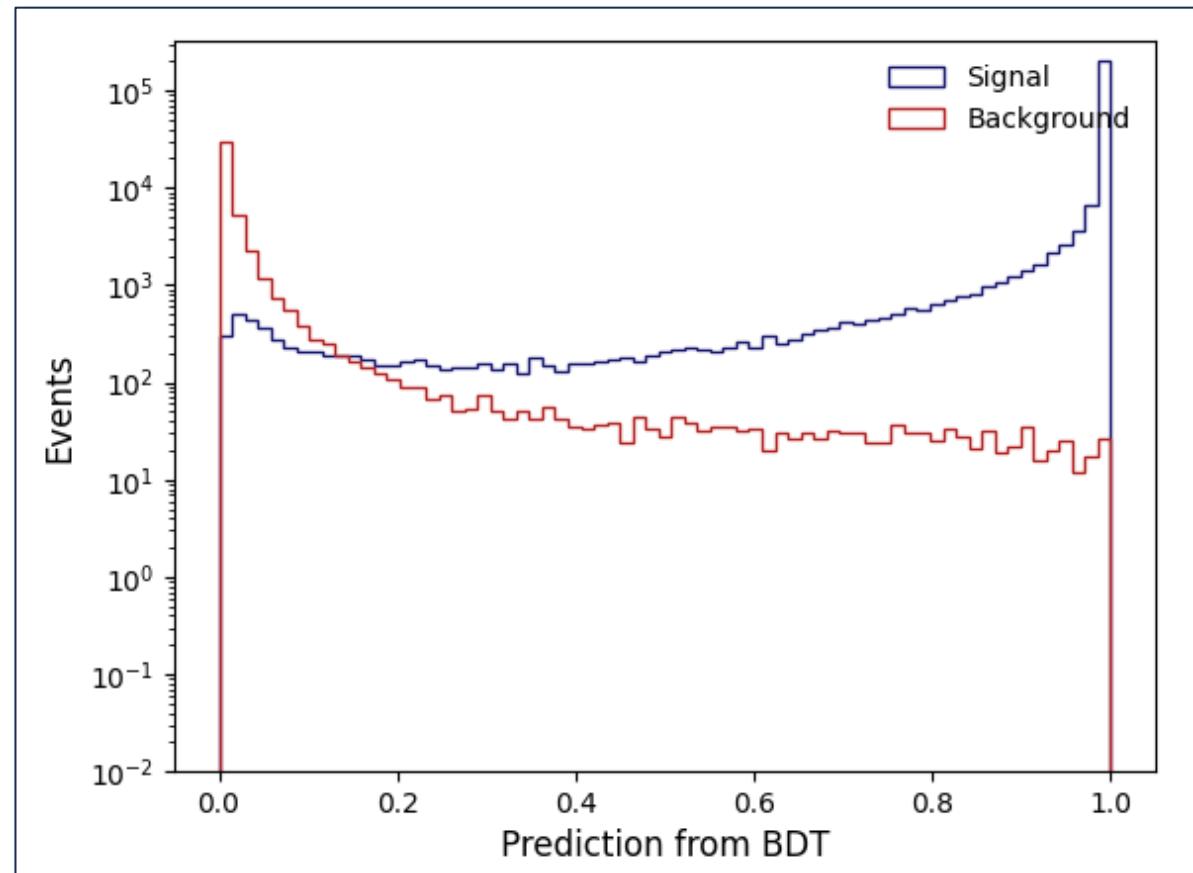
Left: Distribution of $(m_{a2} \text{ RECO} - m_a \text{ Hyp}) / m_{\gamma\gamma\gamma\gamma}$ for subleading pseudoscalar candidate. Shown for signal MC at 15, 30, 40, 60 GeV pseudoscalar mass points, event mixed background, and data. All selections have been applied.



Above: Chart of feature importance for the event selection BDT input variables from one of the best performing models.

Training the Event Selection BDT

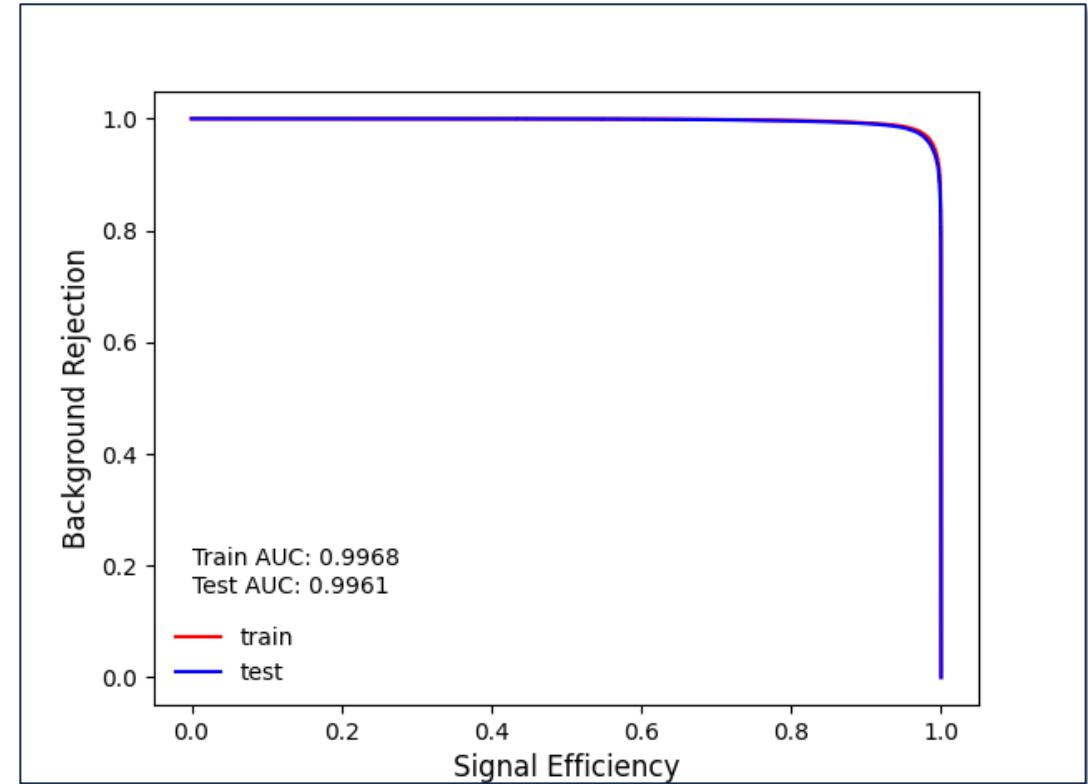
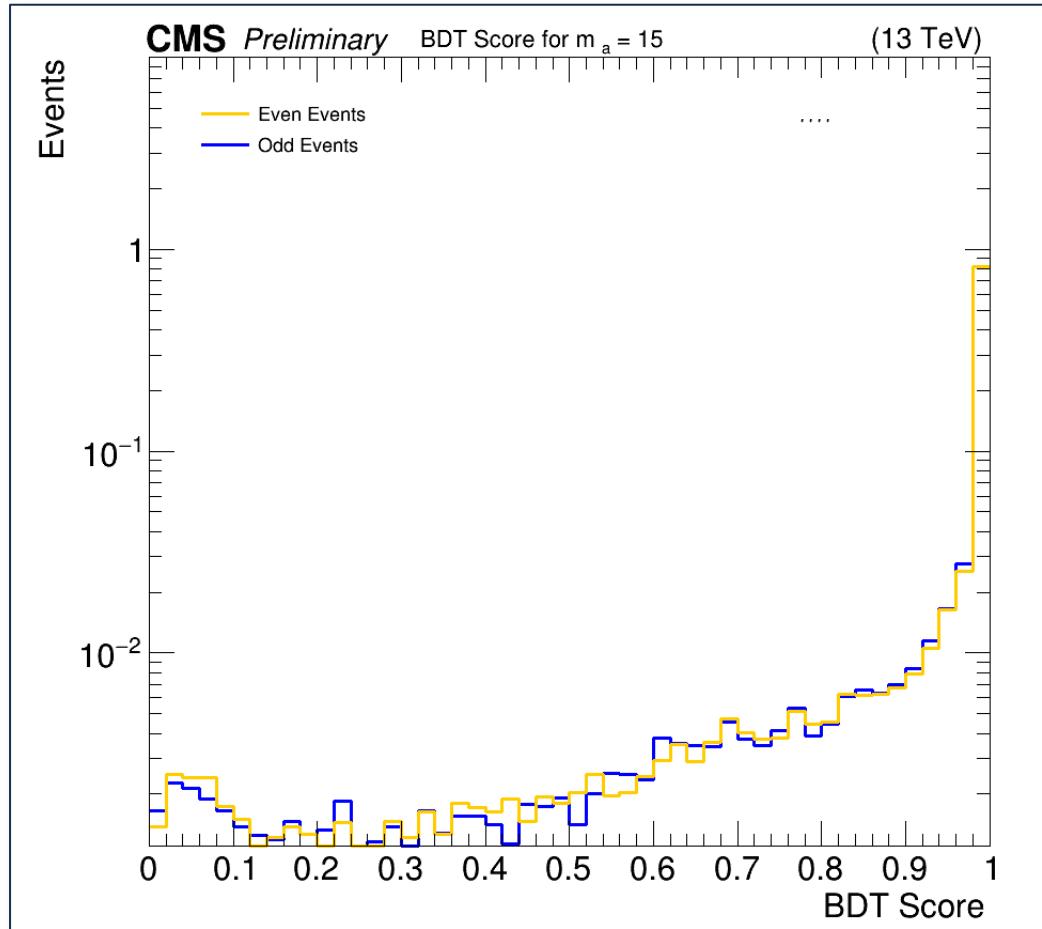
- A 1-dim reweighting of BDT score is required for each pseudoscalar mass point after training the event selection model.
- Training/testing is split amongst odd/even events and is performed over the full $m_{\gamma\gamma\gamma\gamma}$ mass range.
- Samples are weighted by the appropriate luminosity and the per-event N-dim reweights before training.
- Metrics for evaluating BDT performance:
 - AUC
 - Log loss minimization
 - Error rate
 - Average truth deviation
 - F1 score
 - ROC curve



Above: Event selection BDT predictions for training set using processed signal MC and event mixed background.

Checking the Event Selection BDT

- Checks for overtraining are done to ensure an optimal event selection model is produced.
- ROC checks can be done for the entire model at once and even/odd checks must be done by nominal mass point.



Above: ROC curve for one of the best event selection BDT models. A match between train/test curves and their associated area under curve (AUC) indicates a lack of overtraining.

Left: Overtraining check by comparing prediction distribution of trained event selection BDT model for $m_a = 15$ GeV. Odd/even (train/test) samples should have a similar distribution which would indicate a lack of overtraining.

BDT Score Categorization Details

- Reminder: Approximate Mean Significance (AMS)

$$\text{AMS} = \sqrt{2 \left[(S + B) \ln \left(1 + \frac{S}{B} \right) - S \right]}$$

where S and B reference to the number of signal and background events, respectively.

- The BDT score distributions for signal MC, event mixed background, and data are smoothed for each nominal mass point to account for statistical fluctuations when using very fine binning.
- Category boundaries are optimized to maximize total AMS in the signal region while requiring at least 8 data events in the sideband region.
- In the case of multiple categories, AMS is added in quadrature.
- Cuts at category boundaries will be applied to all samples.

BDT Score Category Optimization

