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

Oral Candidacy Proposal

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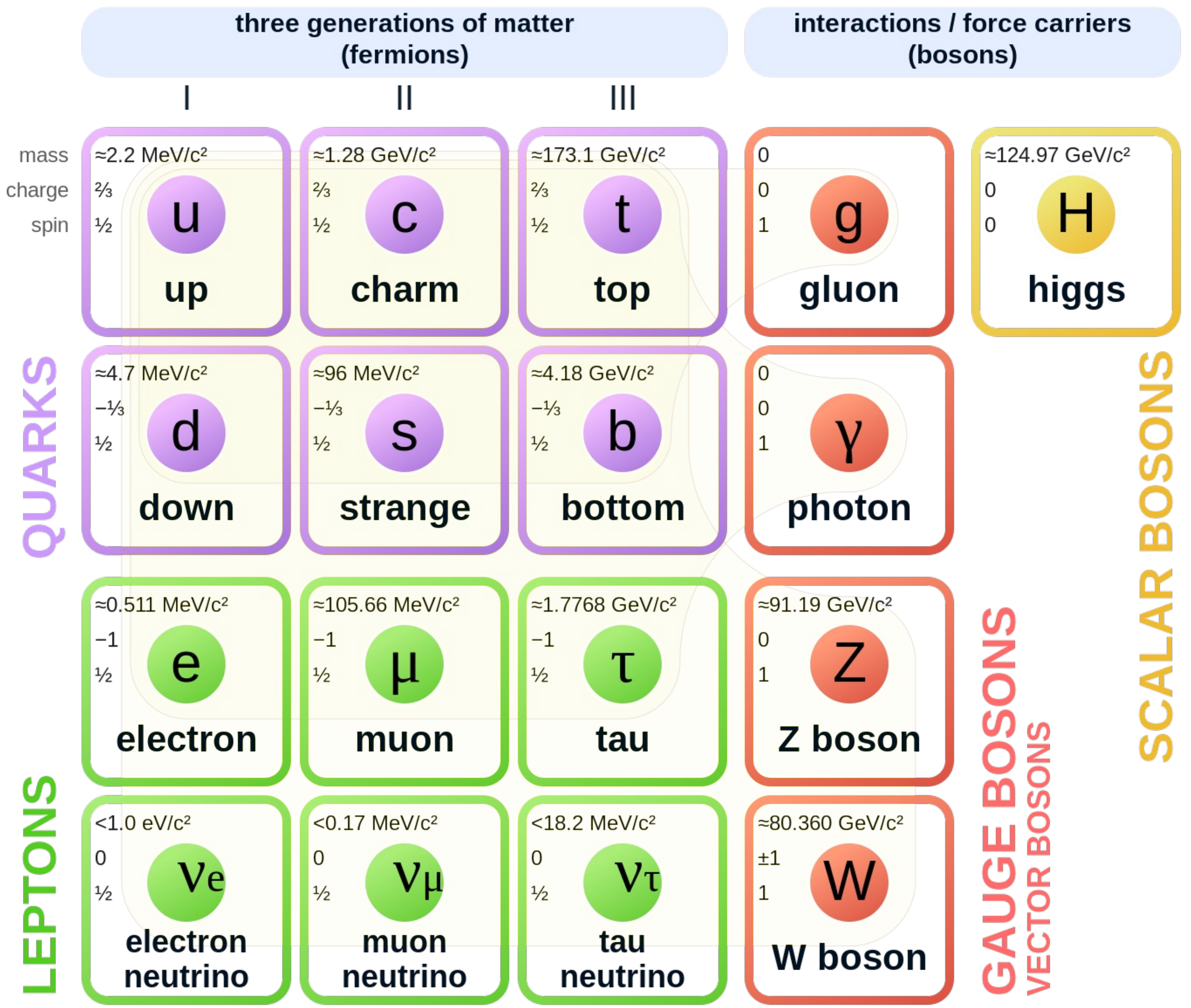
VIII. Summary

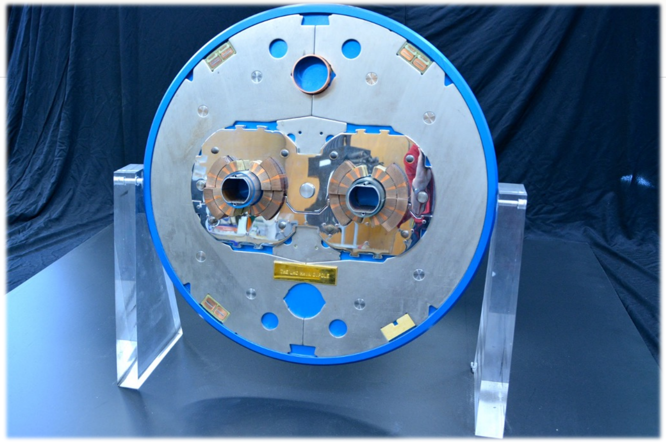
The Standard Model and Beyond

- 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 VEV & Yukawa couplings yield other particle masses excluding neutrinos
- Beyond the Standard Model physics can remedy its shortcomings and predict interesting, new physics.

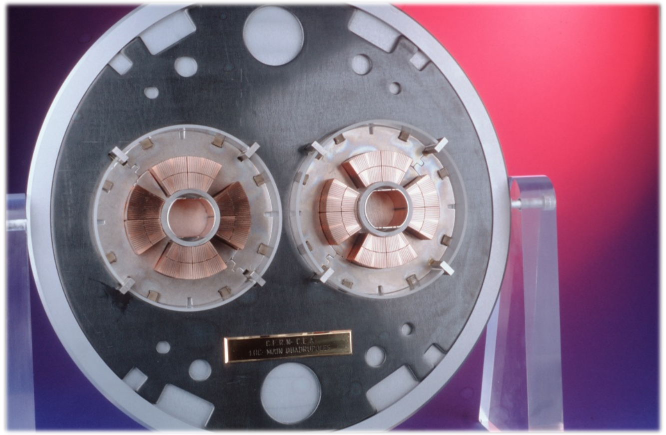


The Large Hadron Collider (LHC)

- 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} cm^{-2} 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



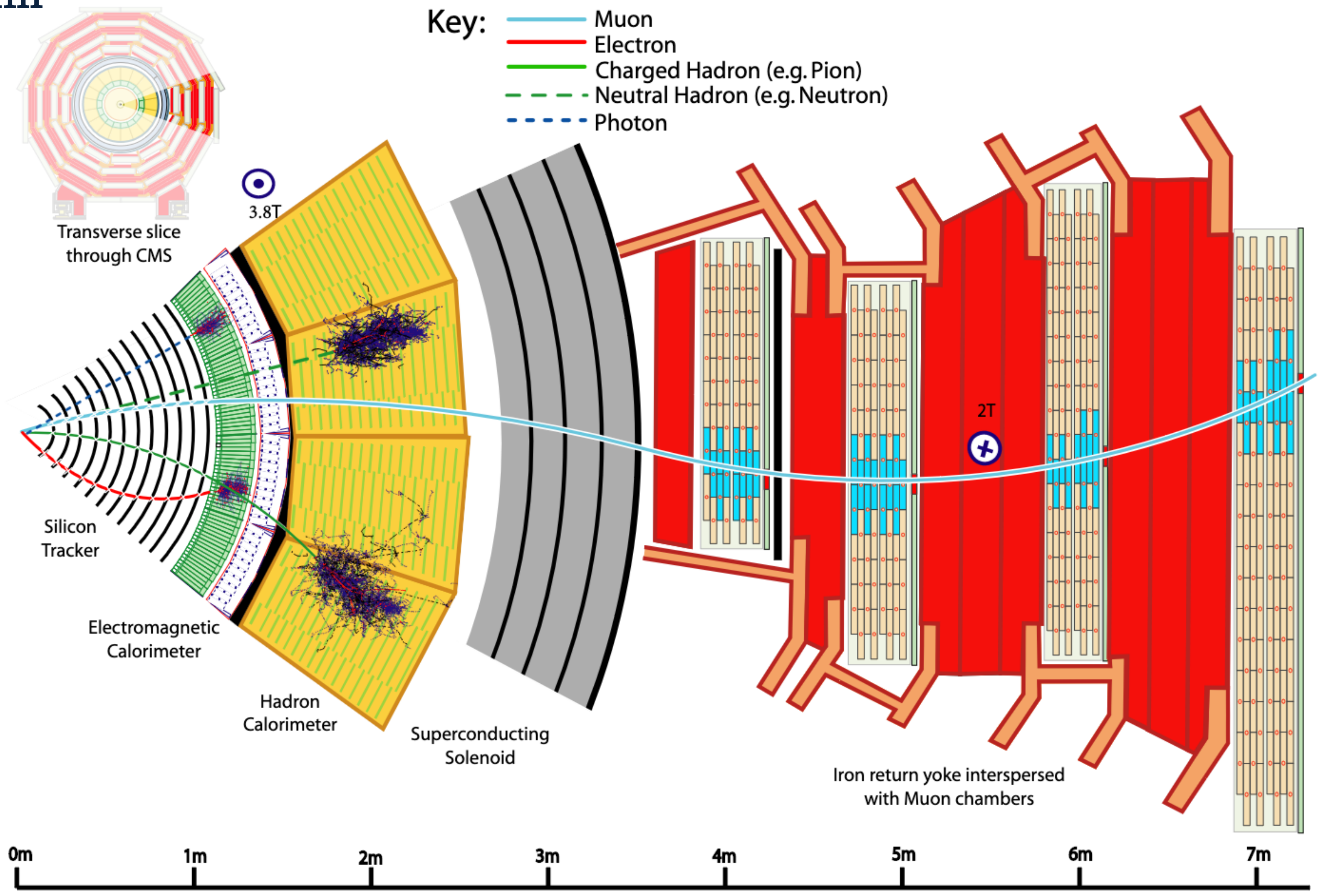
Compact Muon Solenoid (CMS)

- **Silicon tracker**
  - Solid-state pixel and strip detectors
  - Detects charged particle tracks
- **Electromagnetic calorimeter (ECAL)**
  - Homogenous detector
  - Consists of 75,000 $PbWO_4$ 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
- **Muon chambers**
  - Detects muons

Object Reconstruction

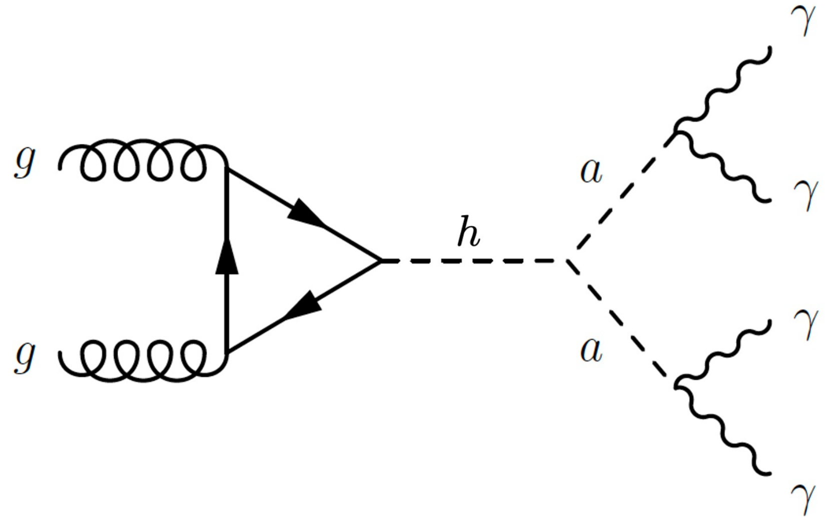
Particle Flow (PF) Algorithm

- Takes raw hits in the detector and creates PF elements
- Links PF elements between sub-detectors to create particle candidates
  - Reconstruct muons
  - Electrons and isolated photons
  - Charged/neutral hadrons and non-isolated photons
- Combines particle candidates to build a picture of a collision event



Introduction to Analysis

Signal: $h \to aa \to \gamma\gamma\gamma\gamma$



Why do this analysis?

- 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 $\mathbf{h} \to \gamma\gamma$ group's new framework: Higgs to Diphoton NanoAOD Framework (HiggsDNA).

- 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.

Sample Generation

- **Signal Monte Carlo (MC):**
  - Simulated $h \rightarrow aa \rightarrow \gamma\gamma\gamma\gamma$ samples
  - Pseudoscalar mass range of $15 < \mathrm{m_a} < 60$ GeV in steps of 5 GeV
  - Decays from a SM Higgs boson with $\mathrm{m_h} = 125$ GeV
  - Only gluon fusion production mode of the Higgs boson considered

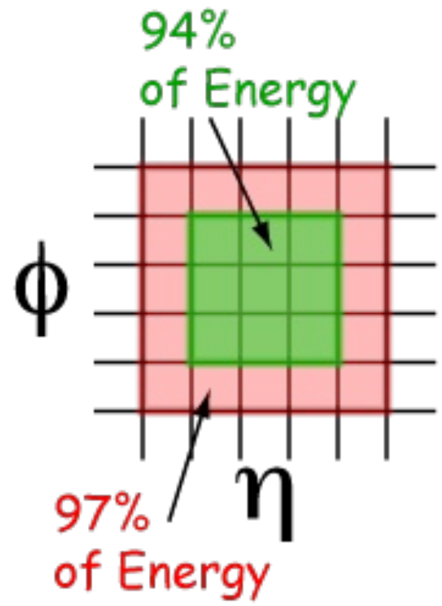
- **Background:**
  - A data-driven background is used
  - Use event mixing technique:
    - Shuffle photons in an event with photons from consecutive events
    - Removes presence of any signal while retaining background shape
  - Main backgrounds: either prompt photons from collision event or isolated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

Choosing Candidate Photons

Energy deposition and shape of photon candidates:

E_T	R_9
Transverse energy of a photon candidate measured in ECAL.	Ratio of energy deposited in ECAL inside 3x3 crystals centered on the most energetic crystal in the supercluster and the supercluster energy.

Supercluster:
5×5 ECAL Crystals



H/E	$\sigma_{i\eta i\eta}$
Ratio of energy deposited in nearest HCAL tower within a cone of radius $\Delta R = 0.15$ centered on photon candidate direction and energy deposited in its supercluster.	Energy weighted standard deviation of a single crystal's η within 5x5 crystals centered at the crystal with maximum energy.

Choosing Candidate Photons

Isolation of photon candidates:

Particle Flow Photon Isolation	Tracker Isolation
Sum of E_T of all Particle Flow photon candidates within a cone of radius $\Delta R = 0.3$ excluding candidate photon.	Sum of track p_T within a cone of $\Delta R = 0.3$.

Charged Hadron Isolation	Electron Veto
Sum of p_T of all Particle Flow charged hadron candidates within a cone of radius $\Delta R = 0.3$.	Checks that no electron candidate track matches photon candidate supercluster.

Pre-selections

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

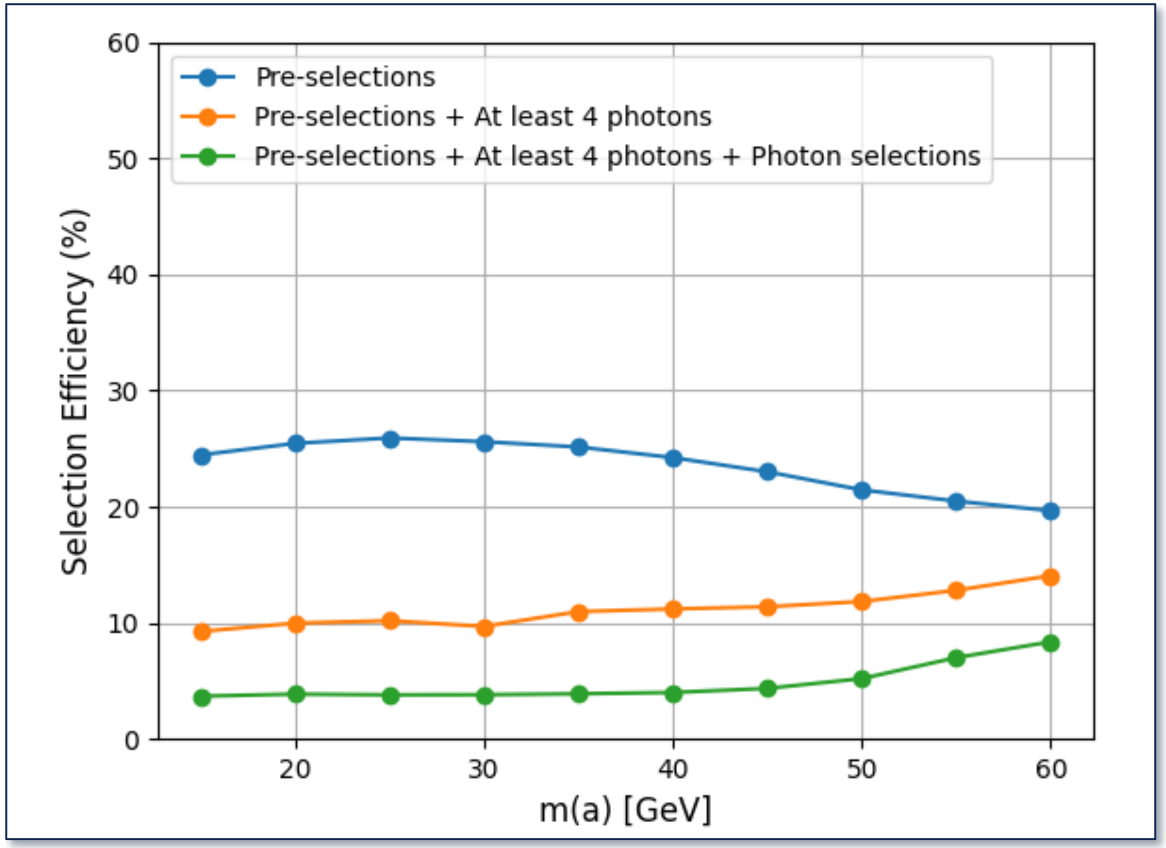
- Selections slightly more strict than High Level Trigger (HLT) are applied
- Events must pass at least one of Options 1-3 (motivated by miniAOD cuts)
- Photons must also pass an electron veto
- Events must have at least two photon candidates
- Diphoton candidates require $p_T > 30$ GeV and $p_T > 18$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

Photon Selections

- Require events have at least one diphoton candidate before applying photon selections
- Selections are applied to events passing pre-selections with at least 4 photon candidates
- $\Delta\mathrm{M} = |m_{\gamma_a\gamma_b} - m_{\gamma_c\gamma_d}|$ is minimized to choose optimal pseudoscalar candidates

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



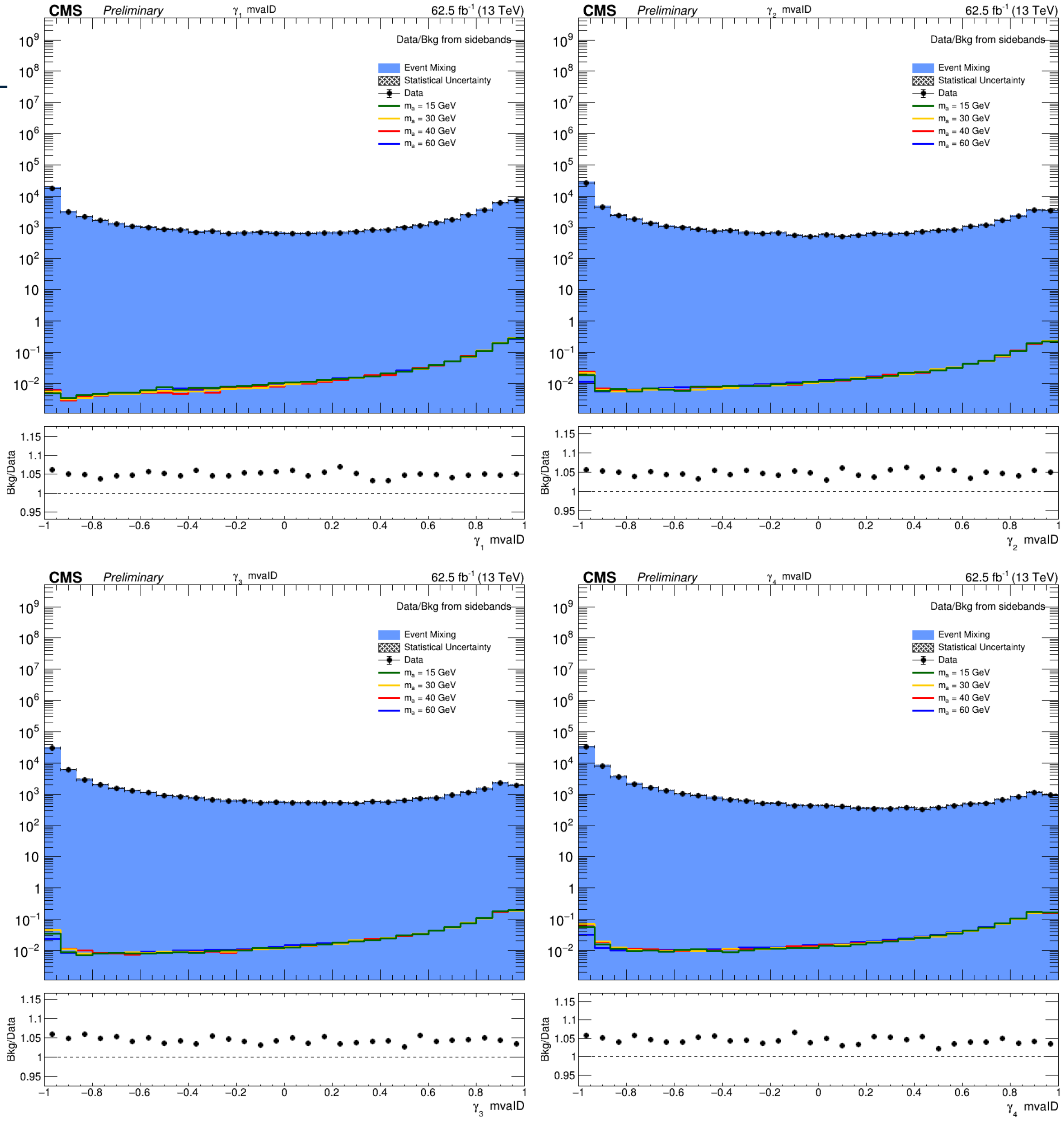
Above: Efficiencies of selections at various stages of selections for all nominal pseudoscalar mass points. This should improve at higher mass points.

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

Results of Selections

Photon MVA ID

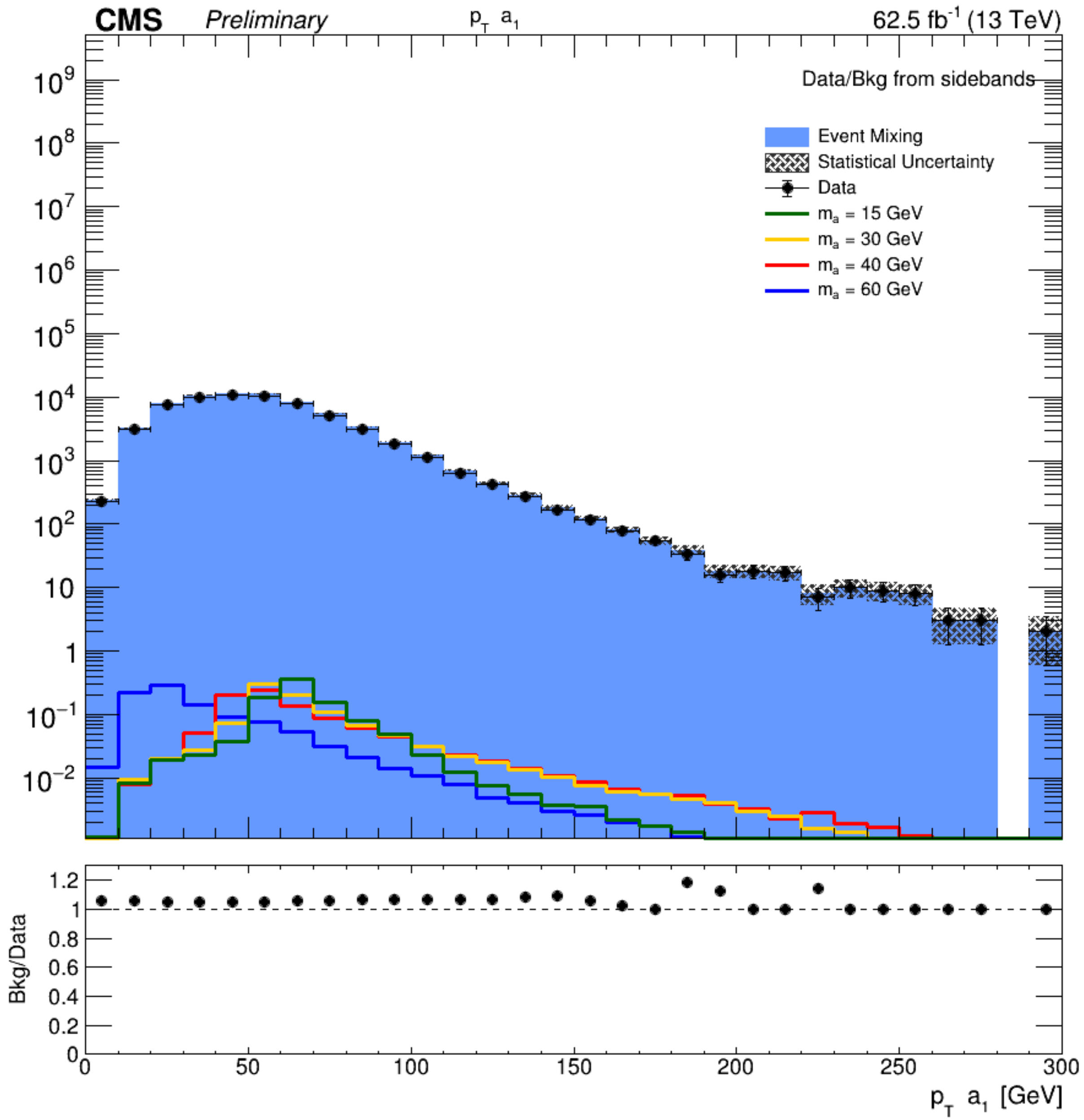
- Multivariate Analysis technique employing a boosted decision tree
- Discriminates real photons from fake photons (collimated jets, prompt photons)
- Likelihood score: High score (~1) corresponds to signal-like (real photon) and low score (~ -1) corresponds to background-like (fake photon)
- No cuts are applied to this variable to maximize training data for event selection BDT



Results of Selections

Are pseudoscalar kinematics sensible?

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



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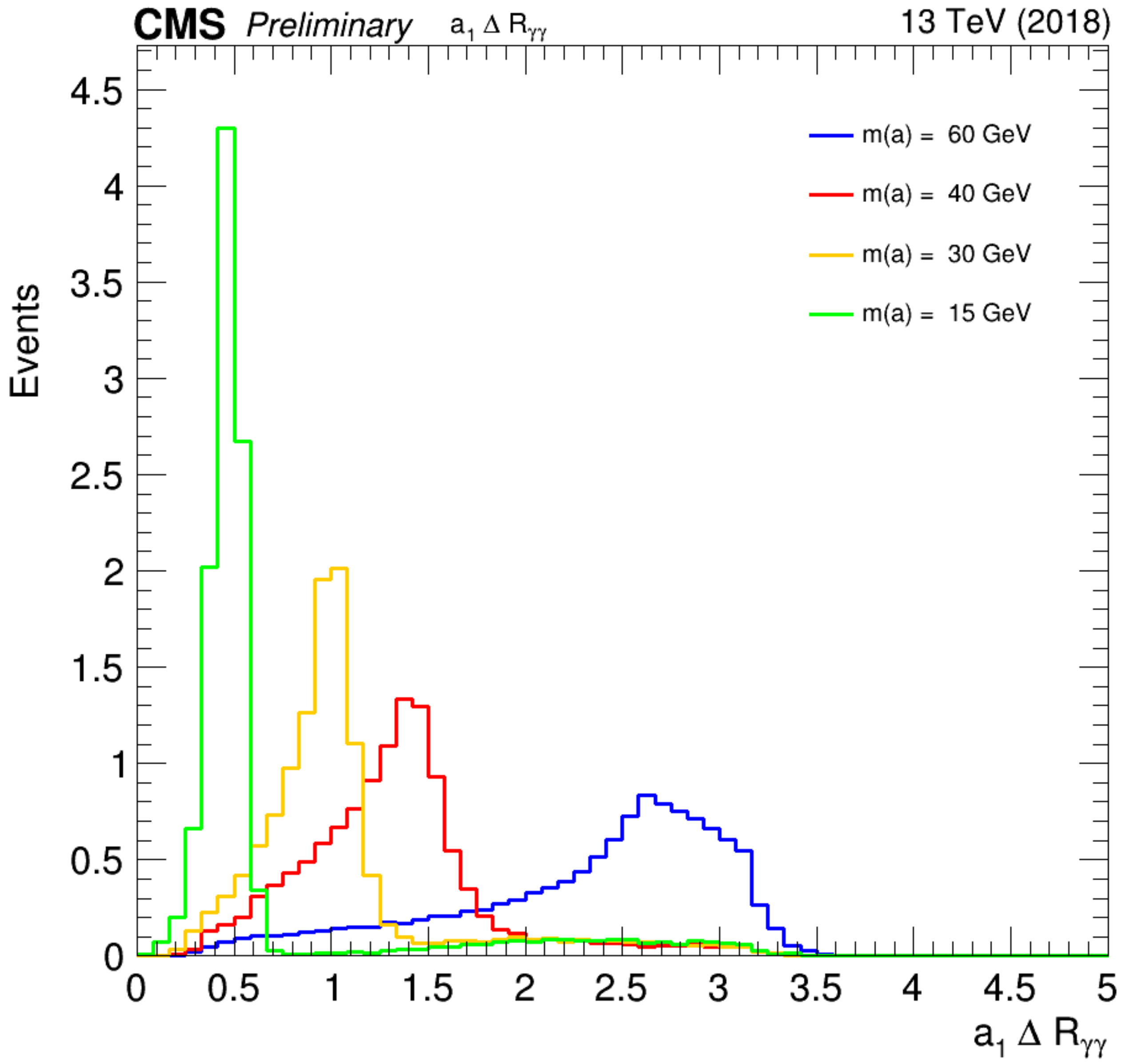
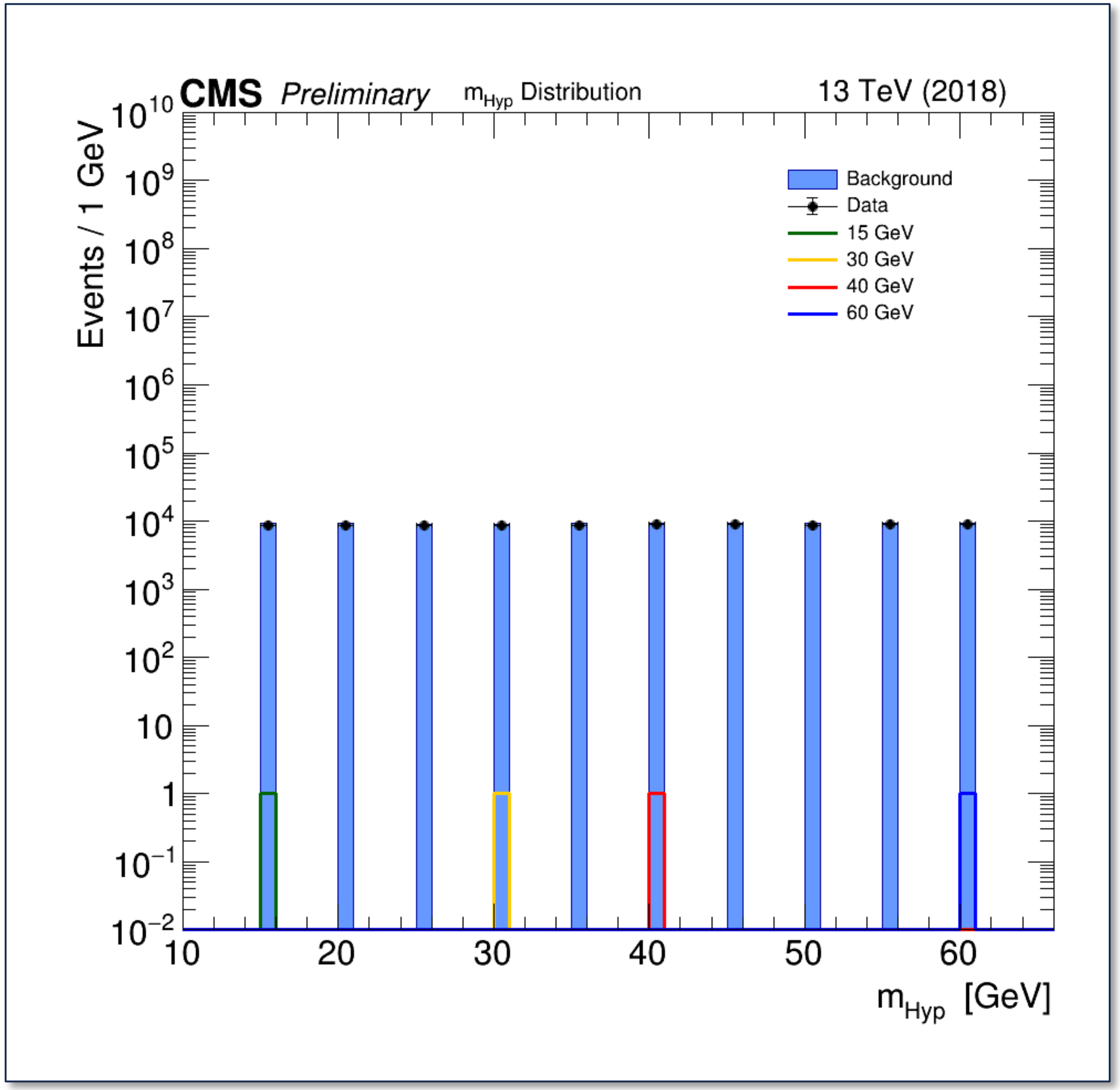


Event Selection BDT

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.
- 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.

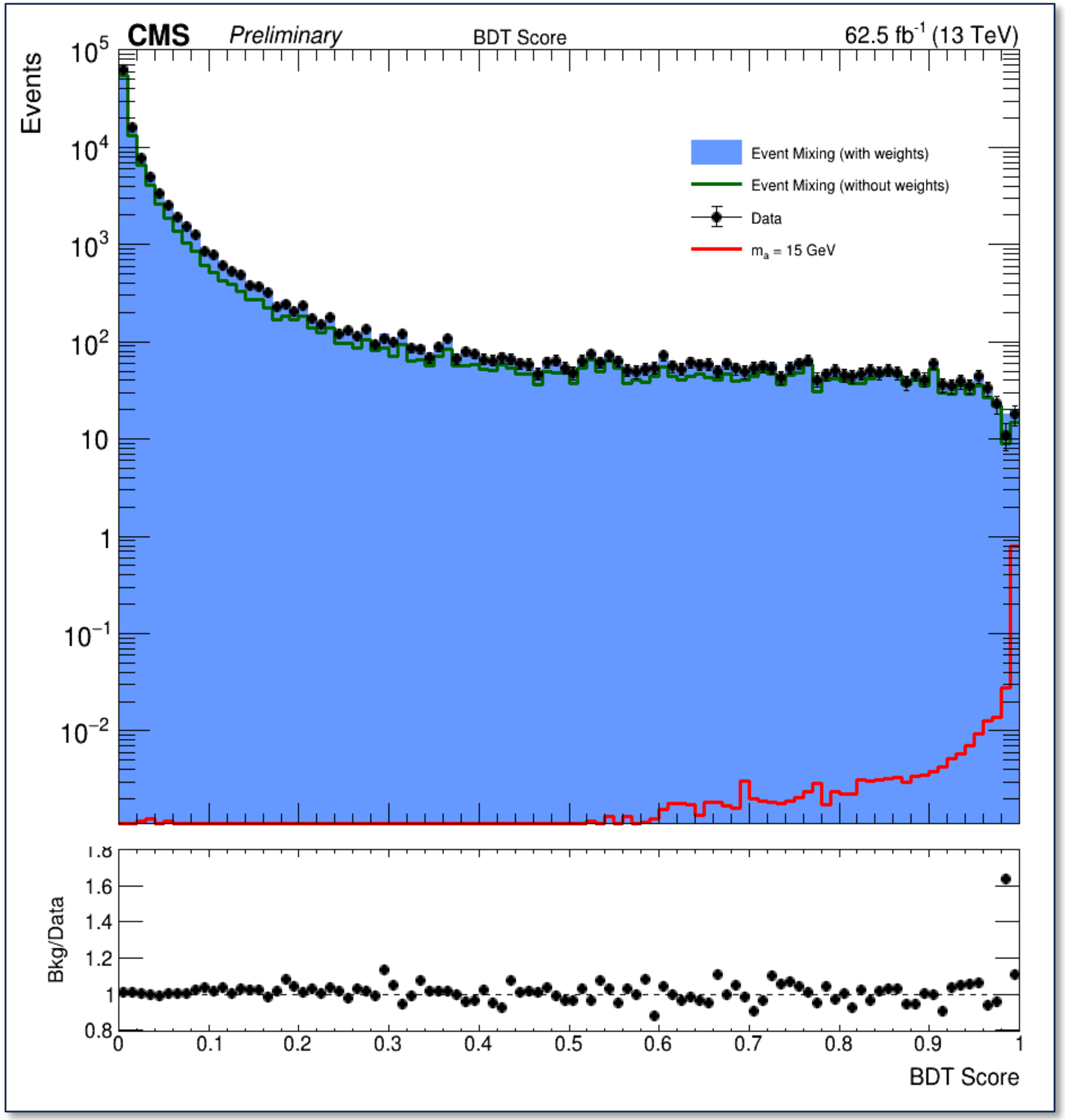


Applying the Event Selection BDT

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

For each nominal mass point:

- m_{Hyp} is set to the nominal mass point of interest for appropriate signal MC sample, event mixed background, and data.
- Input variables dependent on m_{Hyp} are recalculated.
- A prediction distribution of event selection BDT score is generated for signal MC, event mixed background, and data. Shown for $m_a = 15$ 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:

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

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

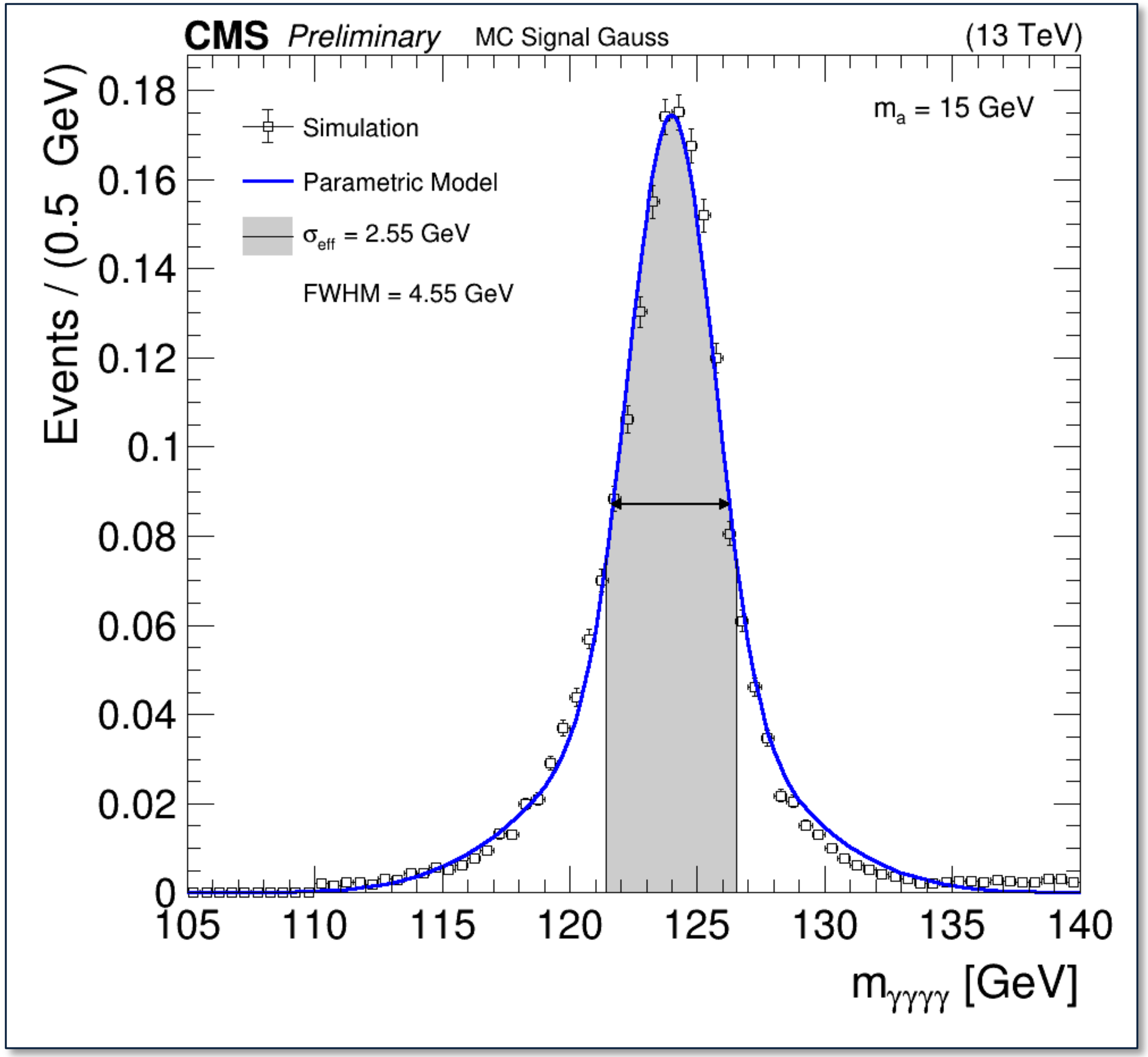
Signal Region: $115 < m_{\gamma\gamma\gamma\gamma} < 135$ GeV

Sideband Region: $(110 < m_{\gamma\gamma\gamma\gamma} < 115) \cup (135 < m_{\gamma\gamma\gamma\gamma} < 180)$ **GeV**

- Categories are constructed to maximize significance in quadrature 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.

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 × 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.



Advancements on Previous Studies

Facts about previous analysis:

- Run 2 analysis looked at 2016–2018 data
- 132 fb^{-1} of raw statistics
- Set limits on $\sigma(pp \rightarrow h) \times Br(h \rightarrow aa \rightarrow \gamma\gamma\gamma\gamma)$ of 0.80 fb for $m_a = 15$ GeV and 0.26 fb for $m_a = 62$ GeV

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 ~60 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

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

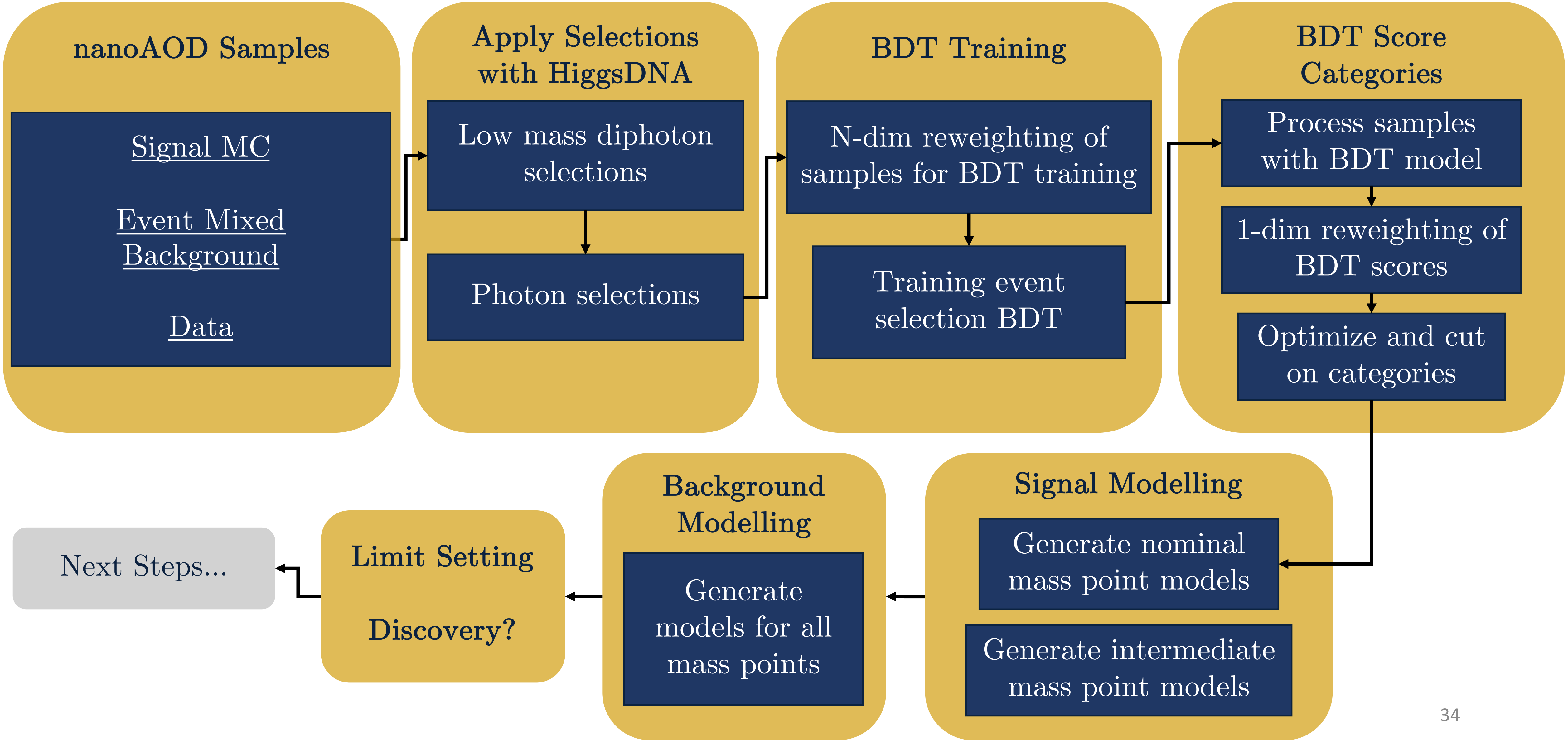
Goals:

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

Thank You!

Backup

Analysis Overview

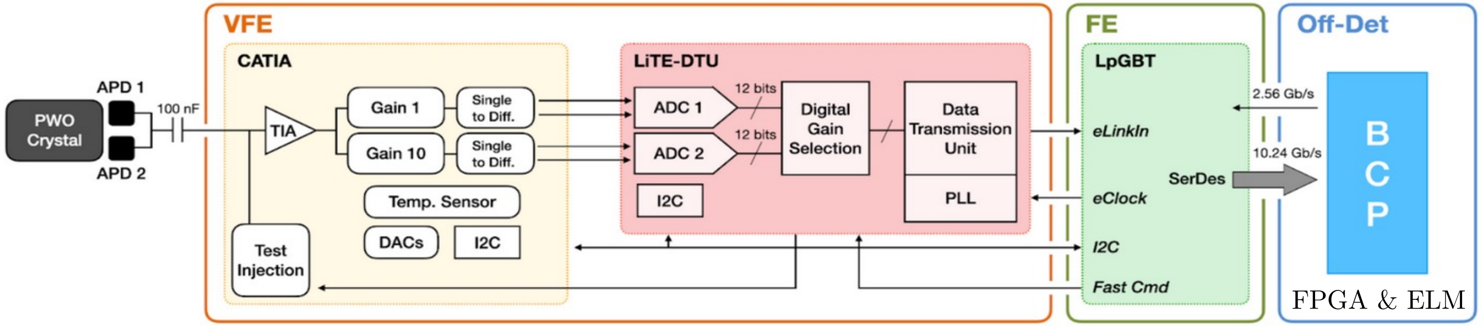


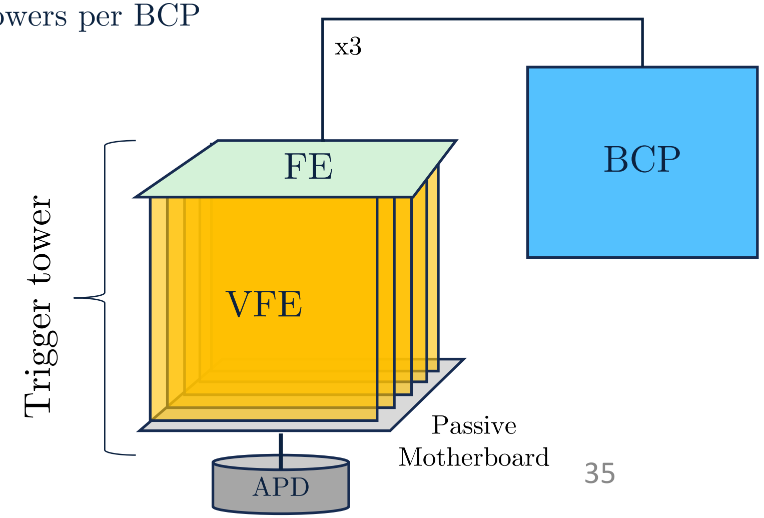
Technical Work

- Working on Phase II upgrade for ECAL Barrel
  - Phase II upgrade will entail a refurbishment of the readout electronics of the ECAL barrel to accommodate the higher rate and latency requirements of the HL-LHC
  - Running systems tests for new suite of on/off-detector readout hardware

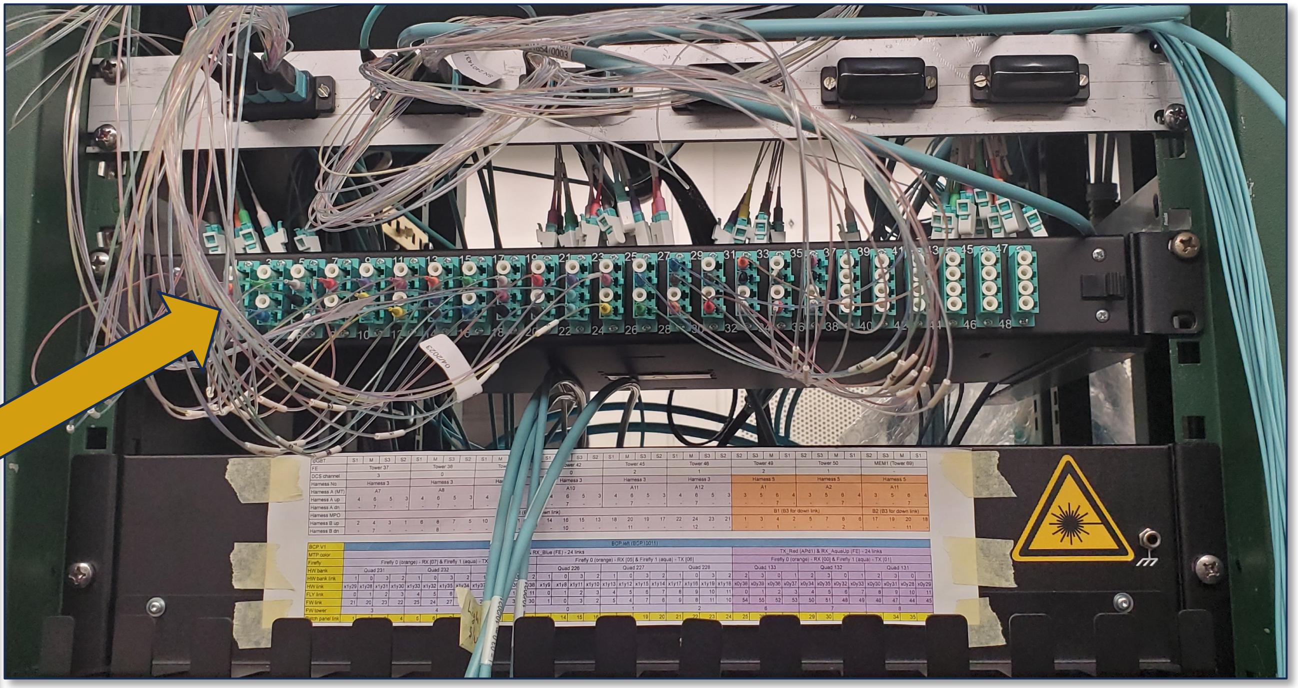
Software

- Verify firmware mapping of registers on BCP
- Each ECAL corresponds to a readout channel. Wrote tests to verify long-term channel stability (errors, alignment of messages)
- Develop high-level software for writing/reading BCP registers and executing commands on hardware (configure, align BCP, optimize pedestal ADCs from APD voltage)
  - Originally run on lpGBT (on FE) vs now running on ELM (on BCP) for increased speed
  - Updated high-level software to accommodate firmware change allowing for multiple trigger towers per BCP
- Write tests to check patch panel configuration
- Convert test software procedures for test beams





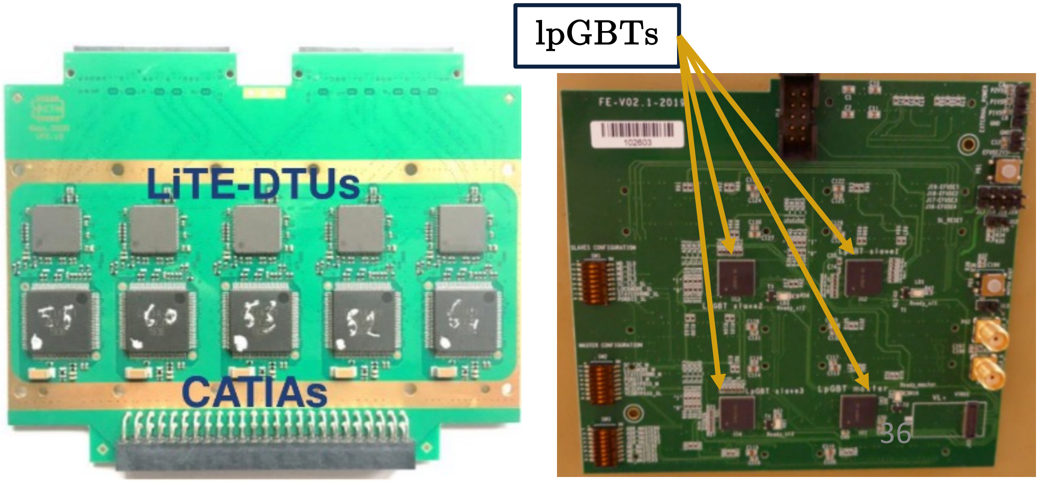
Technical Work (cont.)



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

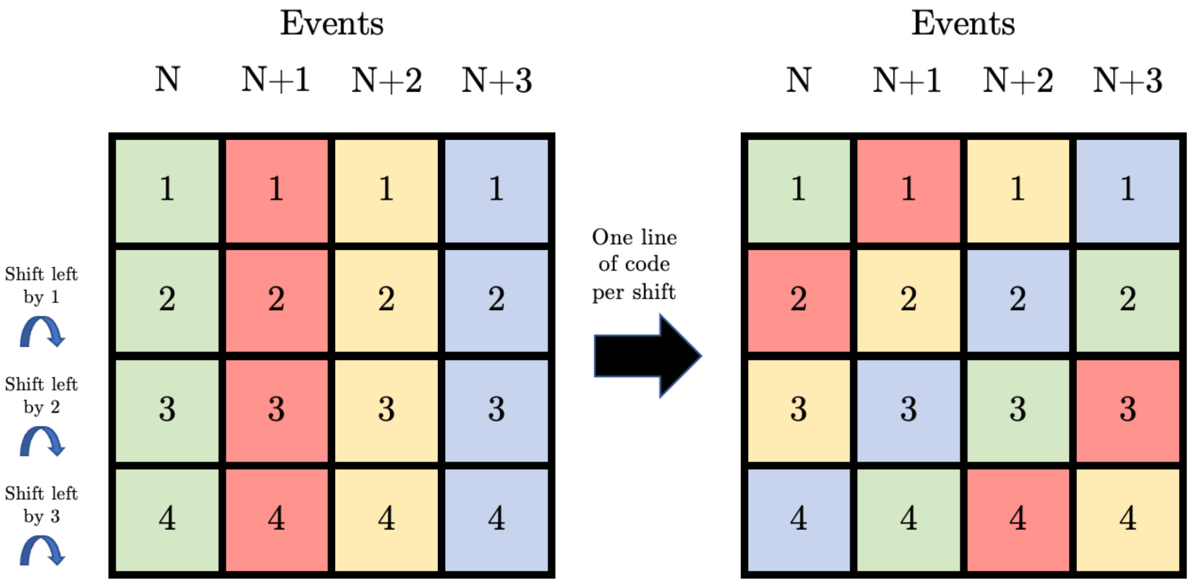
Hardware

- Set up patch panels for additional hardware (BCPs)
- Prepare hardware for test beams



Event Mixing

- Expected shuffling:



- Events are color coded and then shuffled.
- <u>How to read</u>: 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)

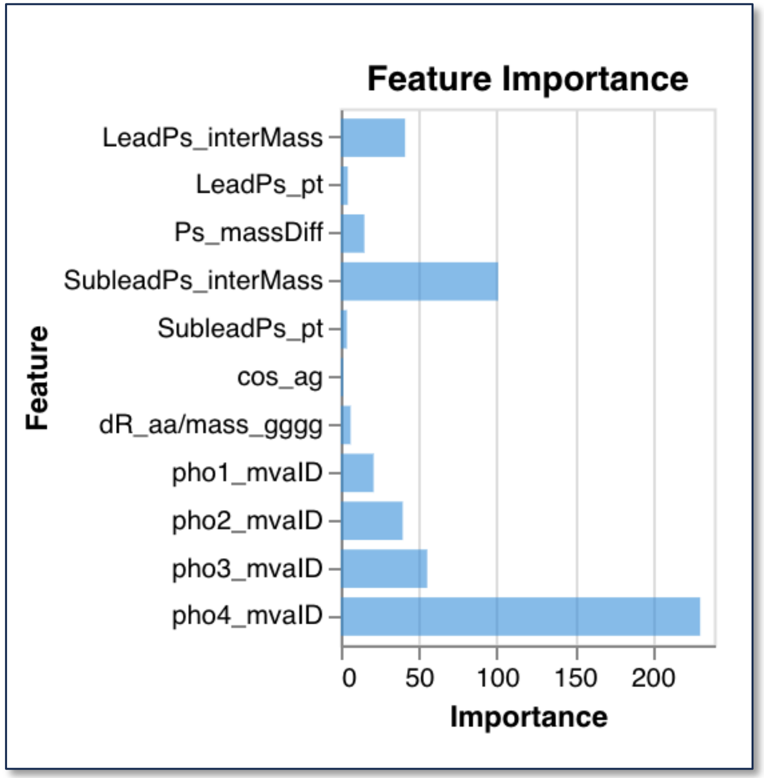
And so on for the other events...

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.

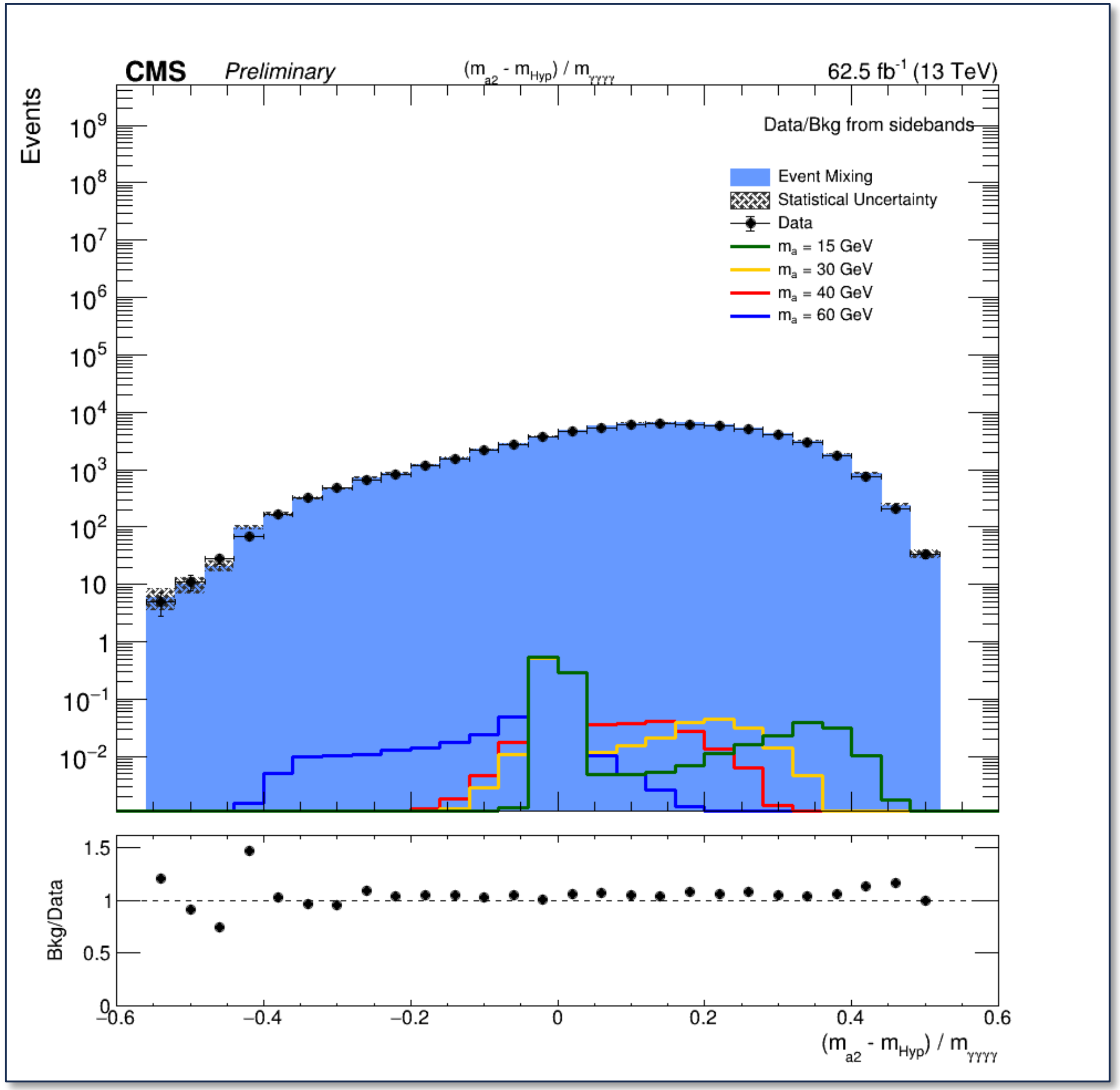
Input variables:

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

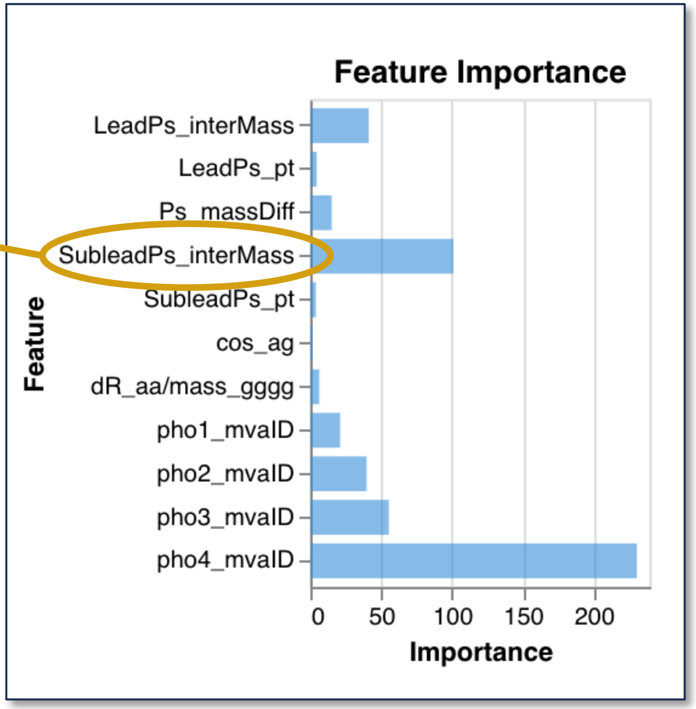


Above: Chart of feature importance for the event selection BDT input variables from one of the best performing models.

Important BDT Input Variables



Left: Distribution of $(m_{a2\ RECO} - m_{a\ Hyp})/m_{\gamma\gamma\gamma\gamma}$ 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.

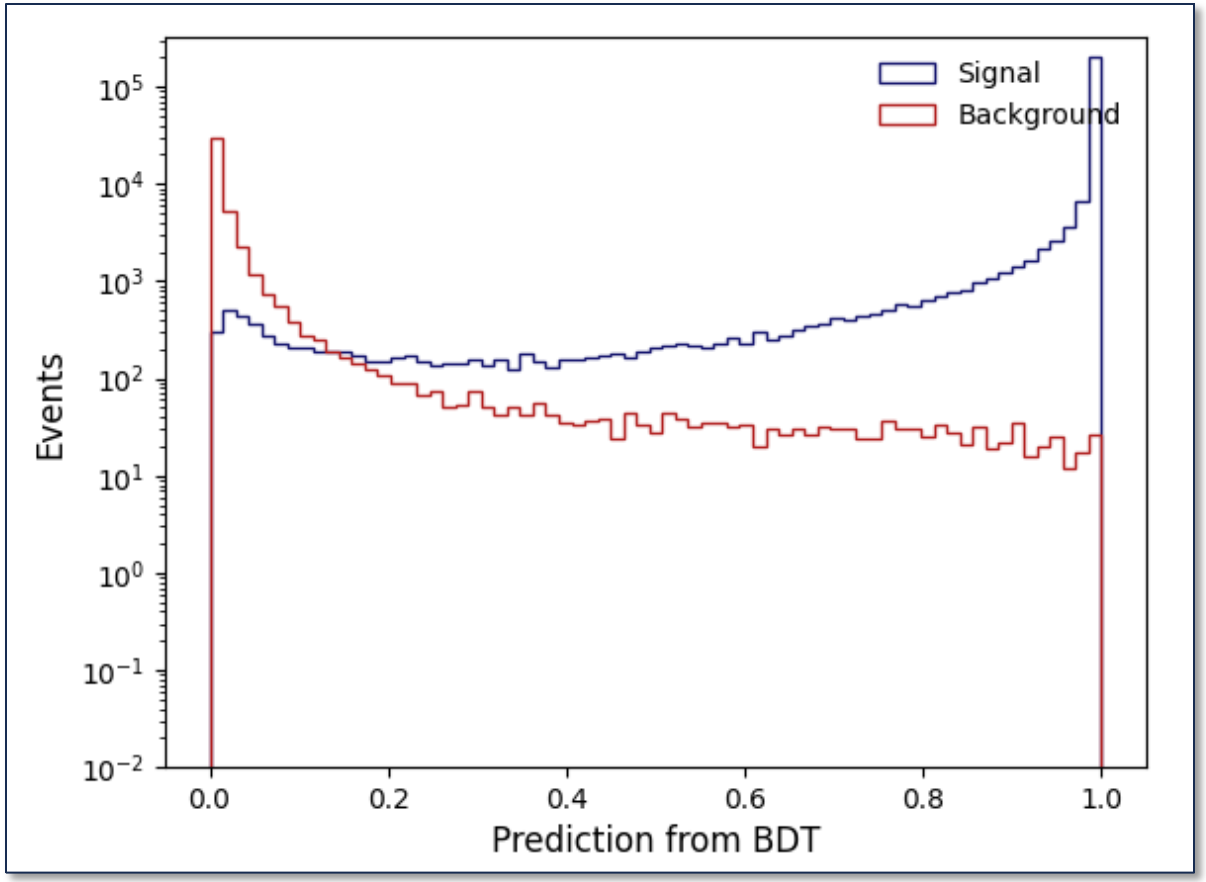


Above: Chart of feature importance for the event selection BDT input variables from one of the best performing models.

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.

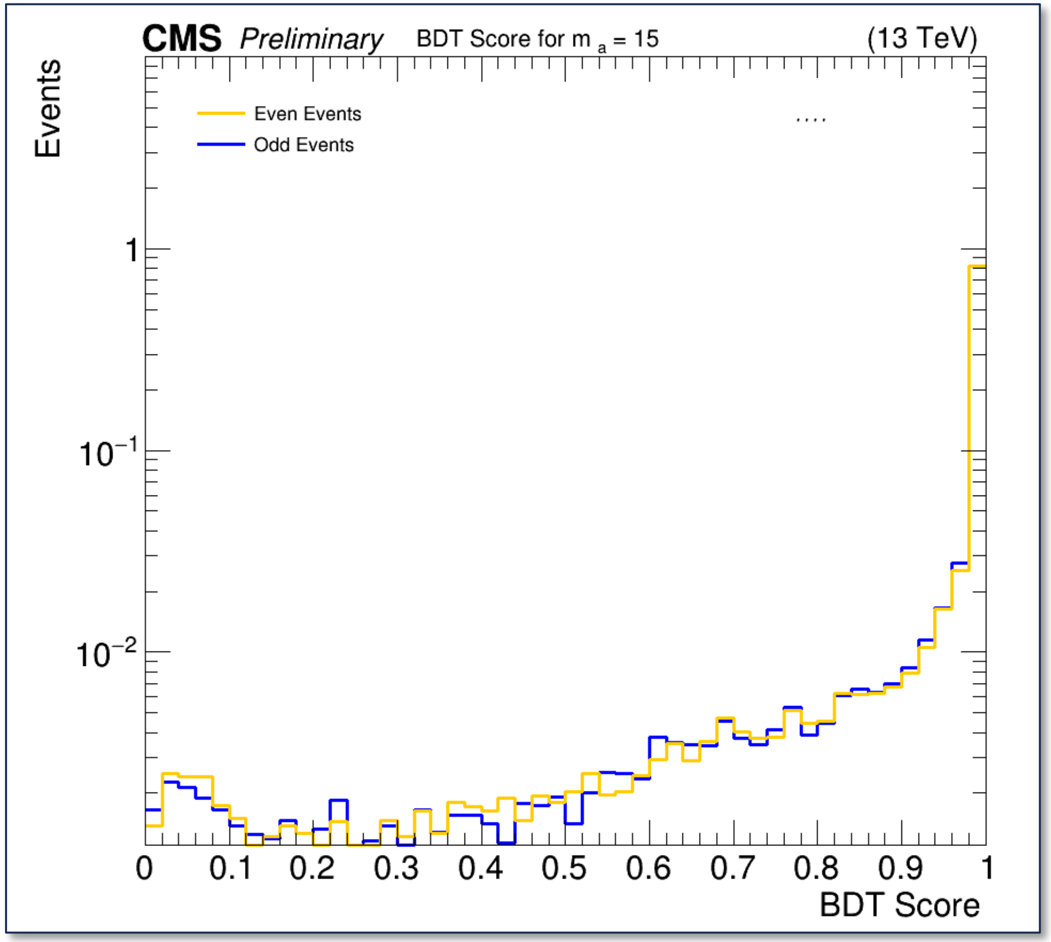
- Metrics for evaluating BDT performance:
  - AUC
  - Log loss minimization
  - Error rate
  - Average truth deviation
  - F1 score
  - ROC curve

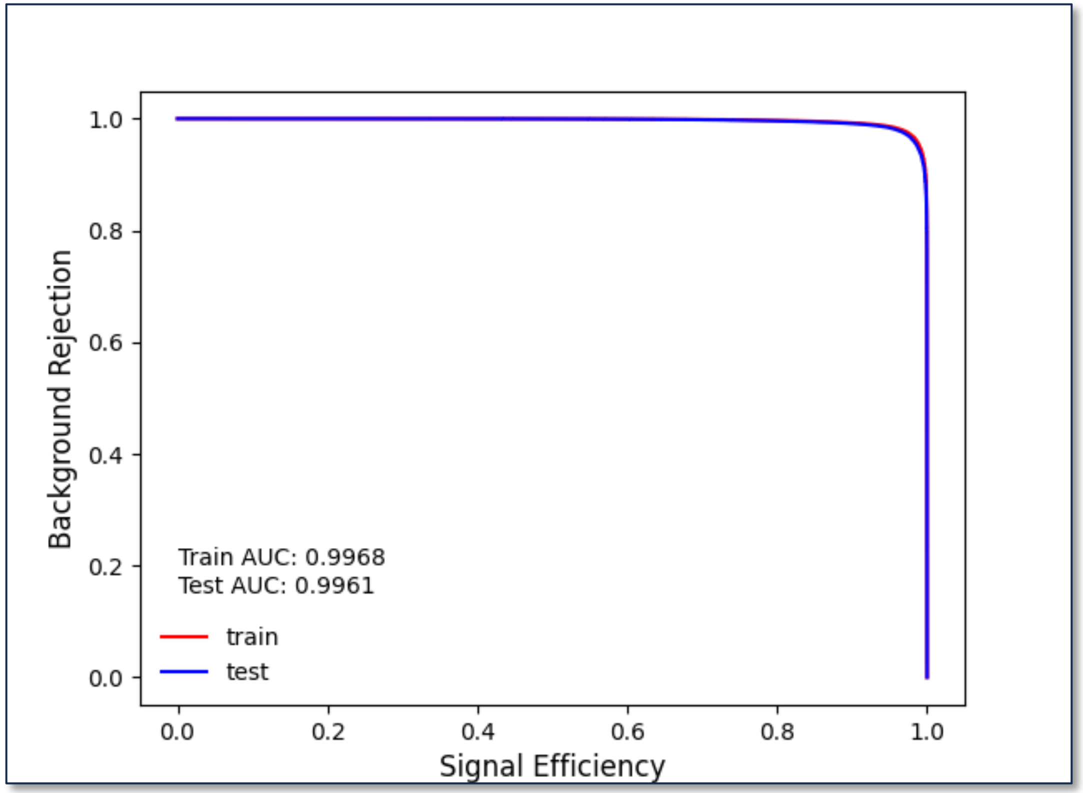


Above: Event selection BDT predictions for training set using processed signal MC and event mixed background.

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

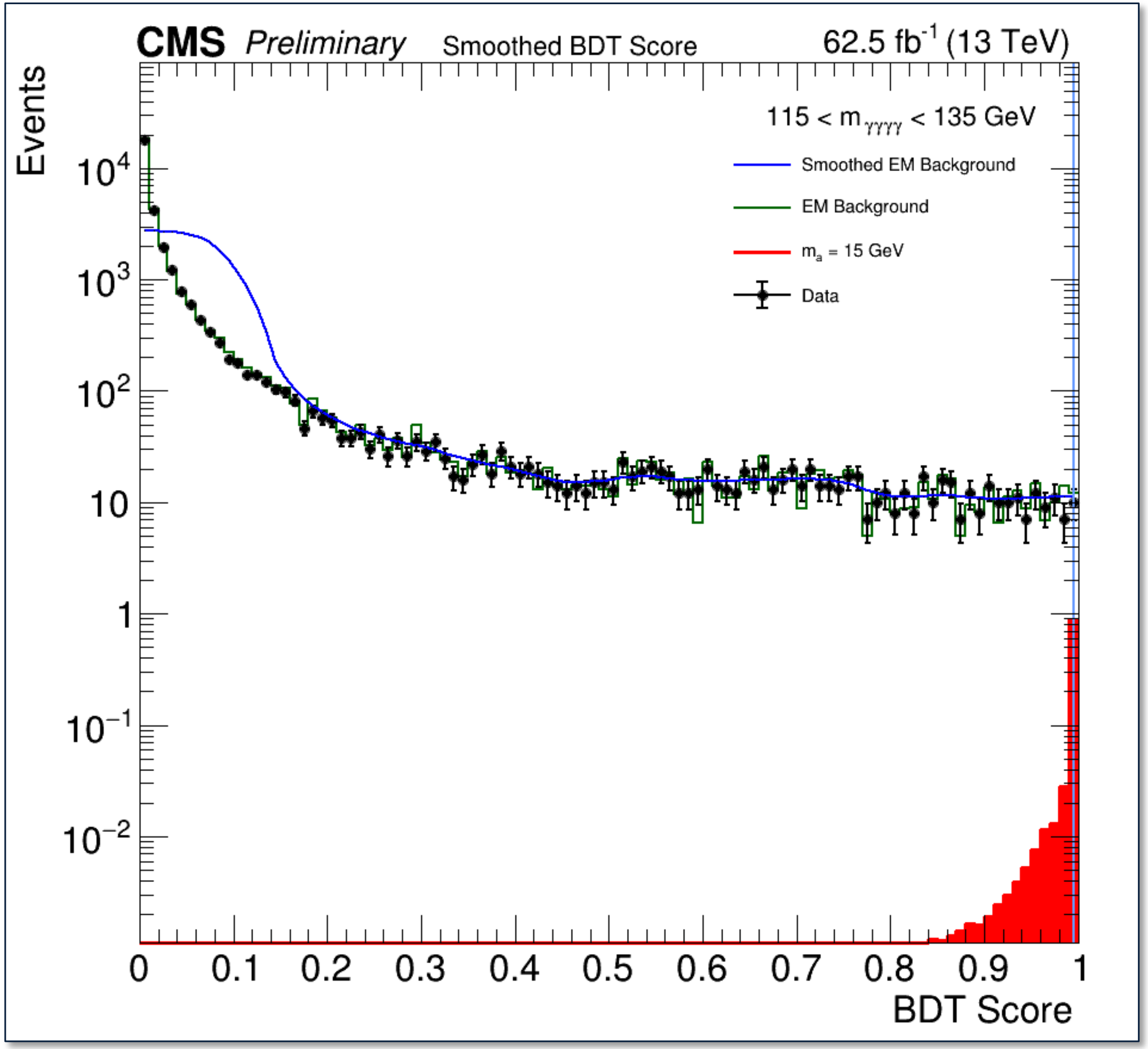
- Reminder: Approximate Mean Significance (AMS)

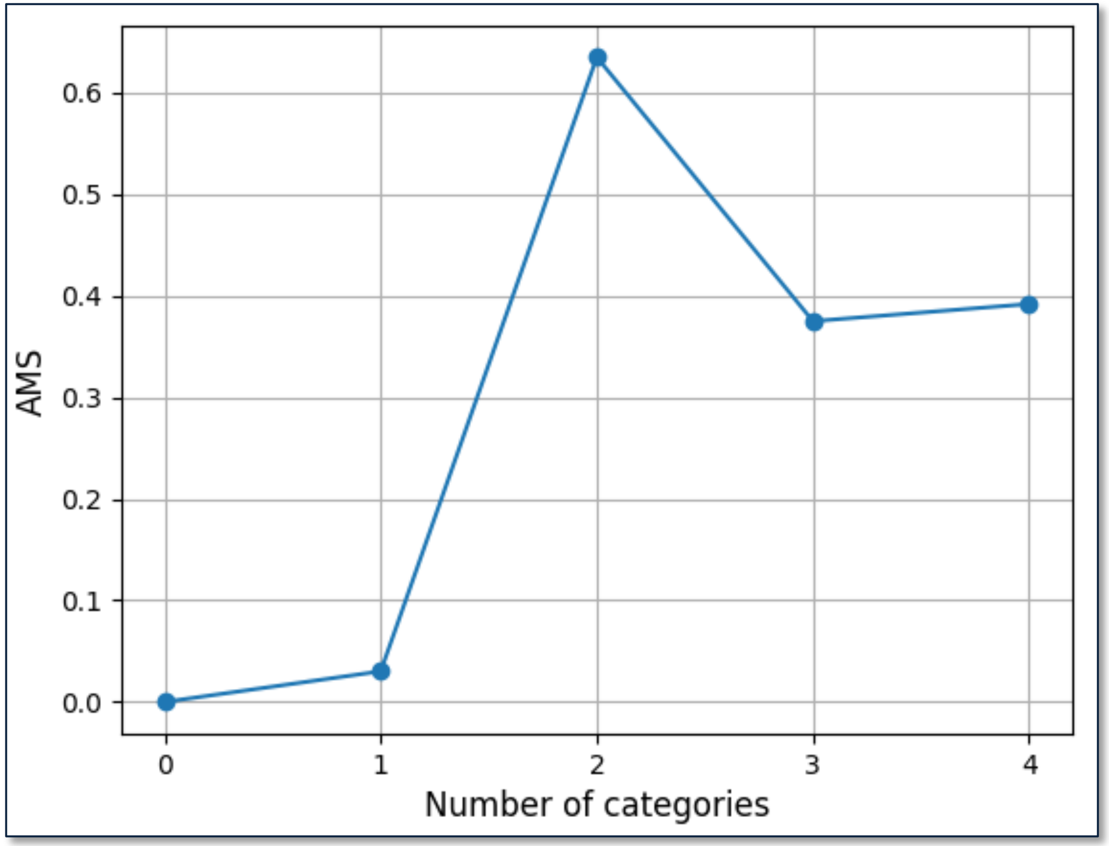
$$\mathrm{AMS} = \sqrt{2\left[(S+B)\ln\left(1+\frac{S}{B}\right)-S\right]}$$

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





Top: Total AMS for up to 4 categories. Ideally, total AMS would always increase and then plateau.

Left: Event selection BDT predictions for signal MC, event mixed background, and data for $m_a = 15$ GeV in the signal region. Smoothed background is shown. To properly smooth the background distribution, a cut at ~0.1 is needed. A category boundary line is shown in light blue near 1.