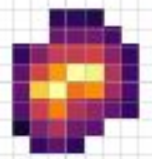

DPF-PHENO 2024

Search for new resonances decaying to pairs of merged diphotons in proton-proton collisions at 13 TeV

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On behalf of the CMS Collaboration

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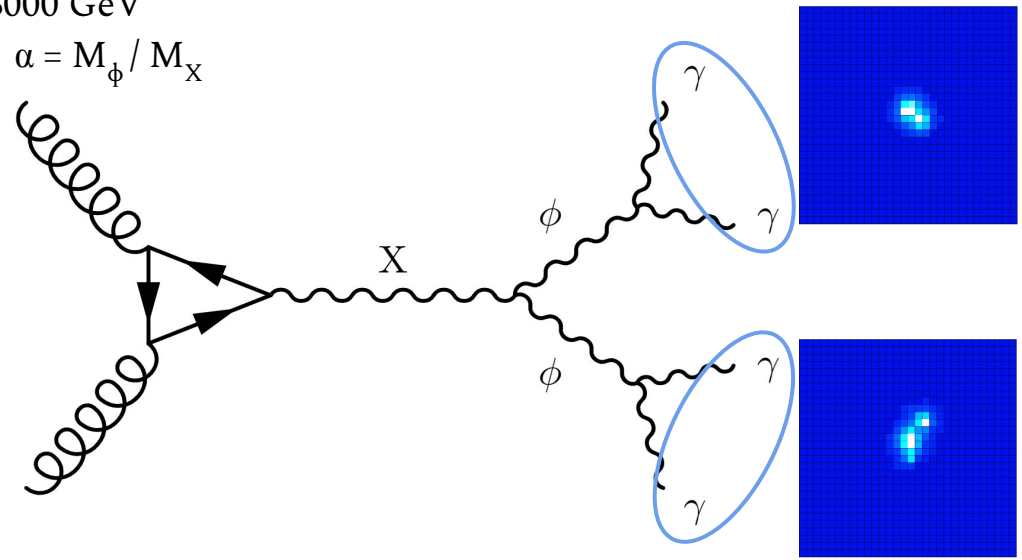
Motivation: $X \rightarrow \phi\ \phi \rightarrow (\gamma\gamma)\ (\gamma\gamma)$

- X is higgs-like and ϕ is pseudo-goldstone boson or axion-like particle:
  - Loop production of X with cross-section depending on what's in the loop
- Search for resonant production of pairs of merging photons
- Analysis Regime:
  - $300\ \text{GeV} < M_X < 3000\ \text{GeV}$
  - $0.005 < \alpha < 0.025,\ \alpha = M_\phi / M_X$
  - *Barrel Only*

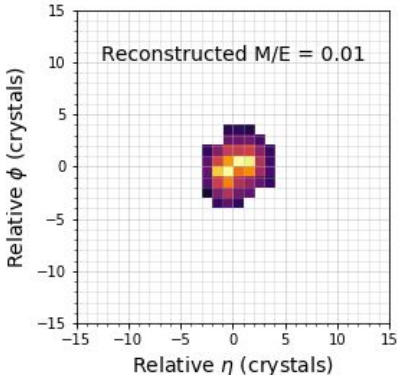
- Submitted to PRL (arXiv:2405.00834)
- Extends search to mass regions inaccessible by the boosted (bb)(bb) search (PLB / arXiv:2203.00480)
- Similar final state and techniques to $H \rightarrow AA \rightarrow$ *Merged Diphotons* (PRL / arXiv:2209.06197)



Merged Diphoton Reconstruction *requires new analysis tools (ML)*

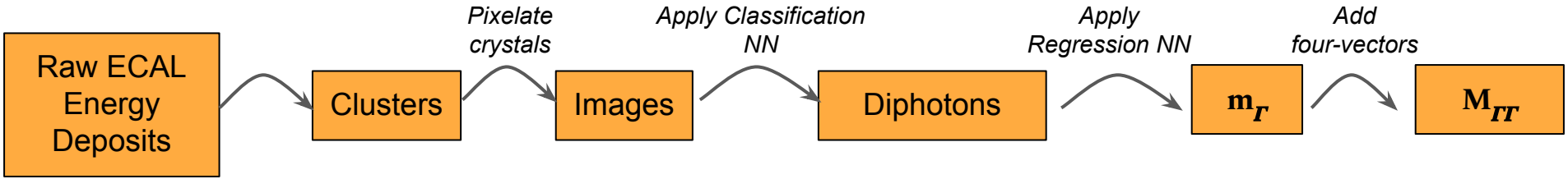
Diphoton Object

- Analysis utilizes custom '*diphoton clusters*'
  - Images made from ECal detector information
- Cluster images are then fed into two Convolutional Neural Networks:
  - **Classification NN** *selects* diphotons from monophoton and hadronic background
  - **Regression NN** *predicts* mass of the diphoton
  - $\mathbf{m_{\gamma}}$≡ diphoton cluster mass



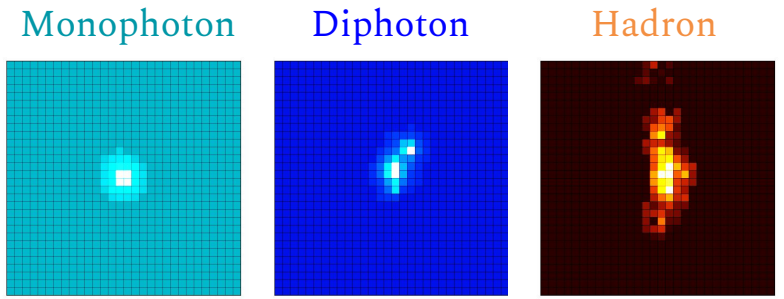
One $\boldsymbol{\gamma}$ contains *both* merged photons

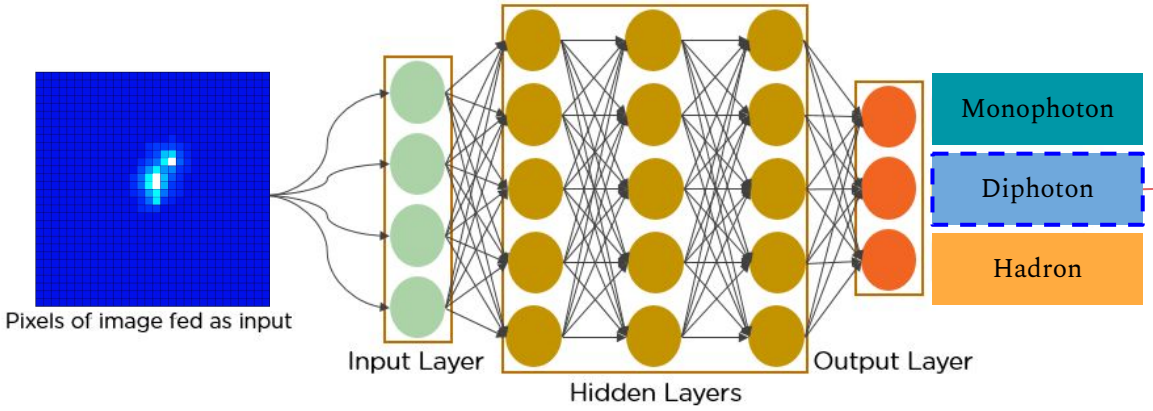
- Combine clusters to get the **Di-Cluster mass, $\mathbf{M_{\gamma\gamma}}$**, i.e. reconstructed X or four-photon mass
- Final search is a bump hunt in $\mathbf{M_{\gamma\gamma}}$



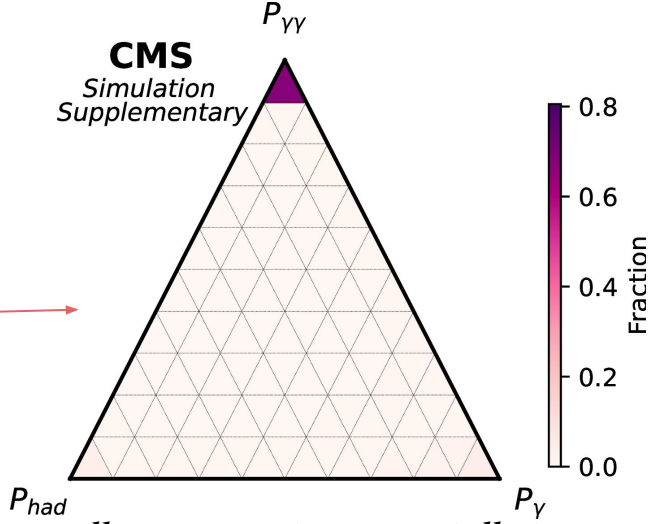
Classification CNN

- Convolutional Neural Net for diphoton (Γ) classification, background rejection
- Classifies images of clusters as Monophoton, Diphoton, or Hadron
- CNN assigns a probability of belonging to each class: $\mathbf{P_{\gamma}+P_{\gamma\gamma}+P_{had}=1}$





Classifier score of true diphotons

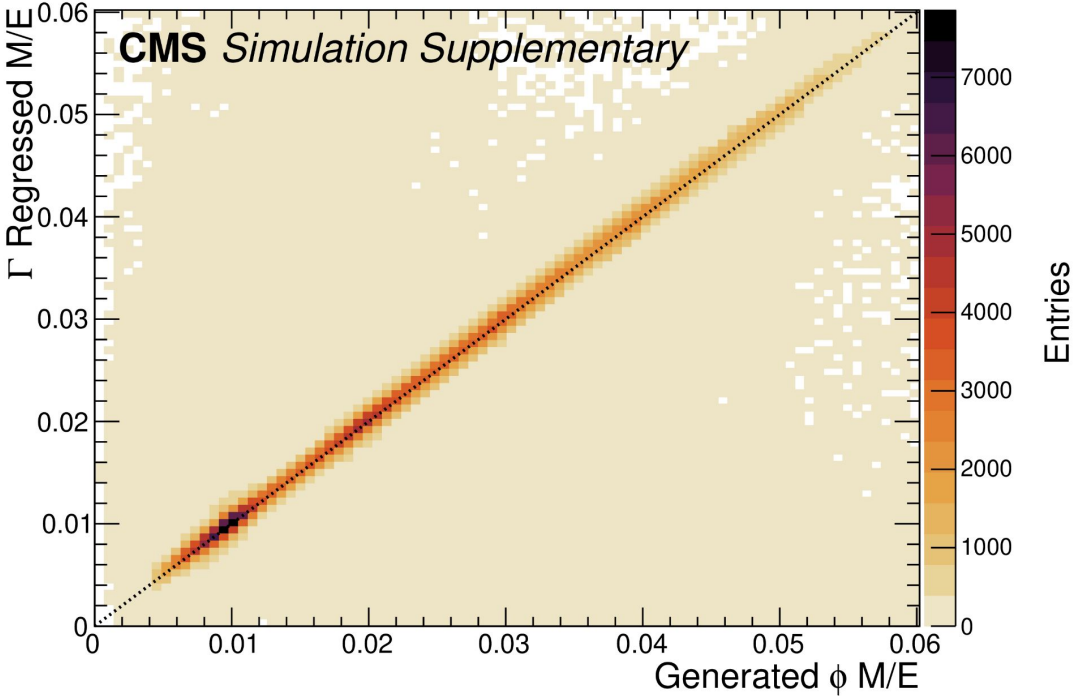


Excellent separation, especially in diphoton class!

Mass Regression CNN

- Now we need the mass of the particle which produced the cluster
- Separate CNN estimates the mass-to-energy ratio of the object based on the image
  - M = (Regressed M/E) x (Measured Energy)
- Trained over a flat sample of M/E to avoid bias; endpoints beyond the scope of our analysis to avoid edge-effects

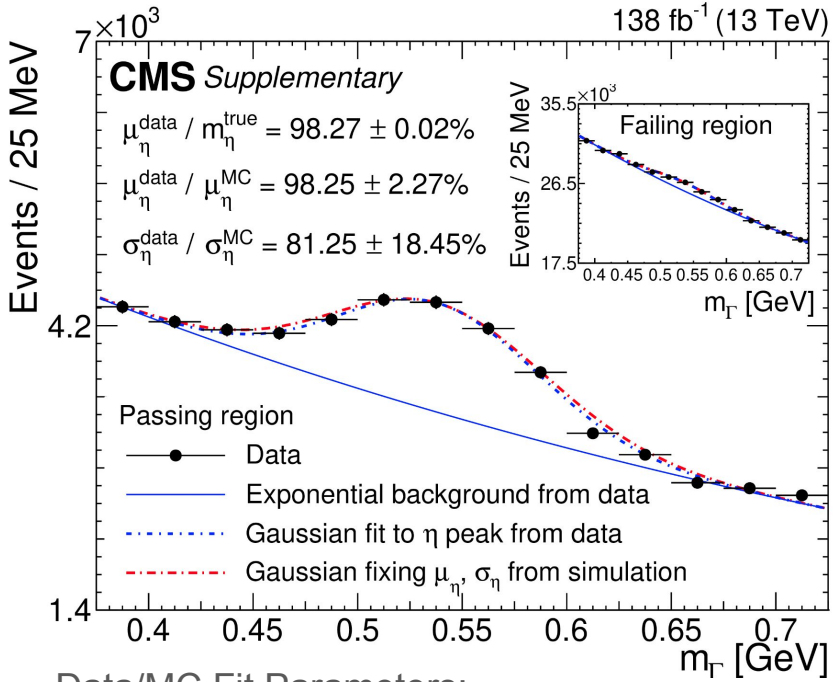
Predicted vs. True M/E in Signal MC



Strong agreement in validation, but how do we know it'll work in data?

Eta meson reconstruction in data & MC

- Reconstruct η → γγ decays (inside jets) to validate analysis tools
- Event Selection:
  - $30 < E_{\Gamma} < 60$ GeV
  - $|\eta_{\Gamma}| < 1.4$
  - $0.5 <$ Isolation< 1
  - $P_{\gamma\gamma} > 0.9$ for pass, otherwise fail
- Simultaneous fits of pass/fail η peaks allows for Data/MC comparison
- η peak fit with Gaussian, bkg fit with exponential
- Derive systematics:
  - Classification efficiency: 10% per Γ
  - α^{reco} shape: 23% (dominant uncertainty)



Data/MC Fit Parameters:

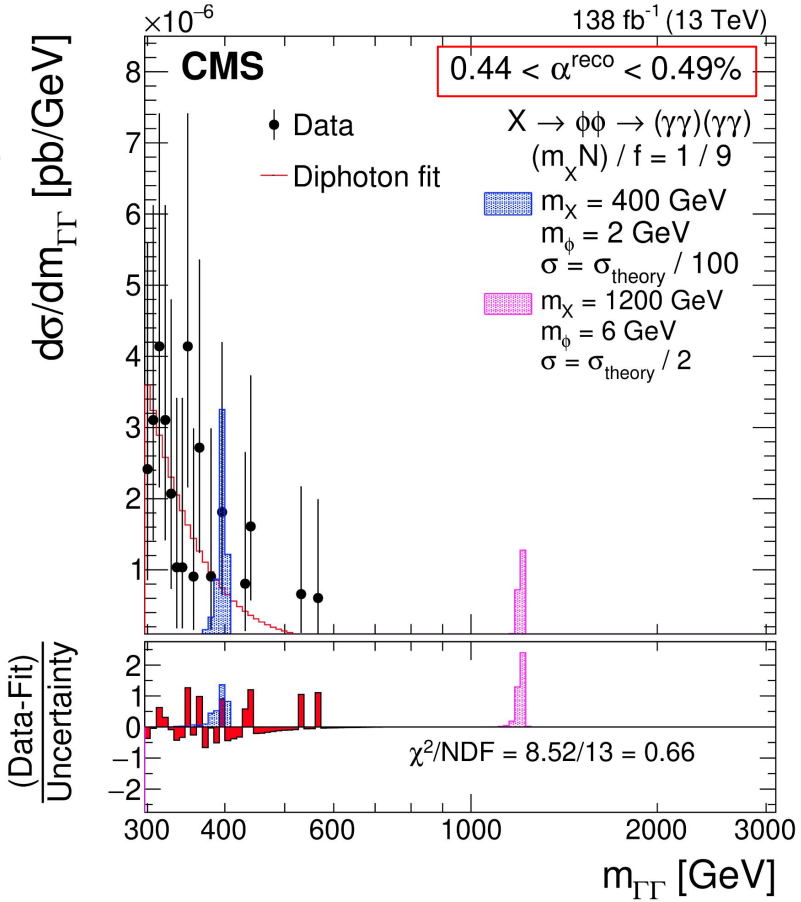
Parameter	Data	GJets MC
μ	0.5384 ± 0.0001	0.5480 ± 0.0127
σ	0.0403 ± 0.0001	0.0496 ± 0.0113

$m_{\eta}^{true} = 0.5479$ GeV

Analysis Strategy

- Final search is a bump hunt in data Di-Cluster mass distribution ($\mathbf{M_{\Gamma\Gamma}}$)
- Data is binned in <u>fixed slices</u> of α^{reco}
  - $\boldsymbol{\alpha^{reco}} = \hat{\mathbf{m}}_{\boldsymbol{\Gamma}} / \mathbf{M_{\Gamma\Gamma}}$
- Fit falling data spectrum **<u>in each α^{reco} slice</u>**
- Optimized final event selection:

Variable	Requirement
p_T	> 90 GeV
|Mass Asymmetry|	< 0.25
$\lvert \Delta\eta \rvert$	< 1.5
$P_{\gamma\gamma}$	> 0.9
Isolation	> 0.8

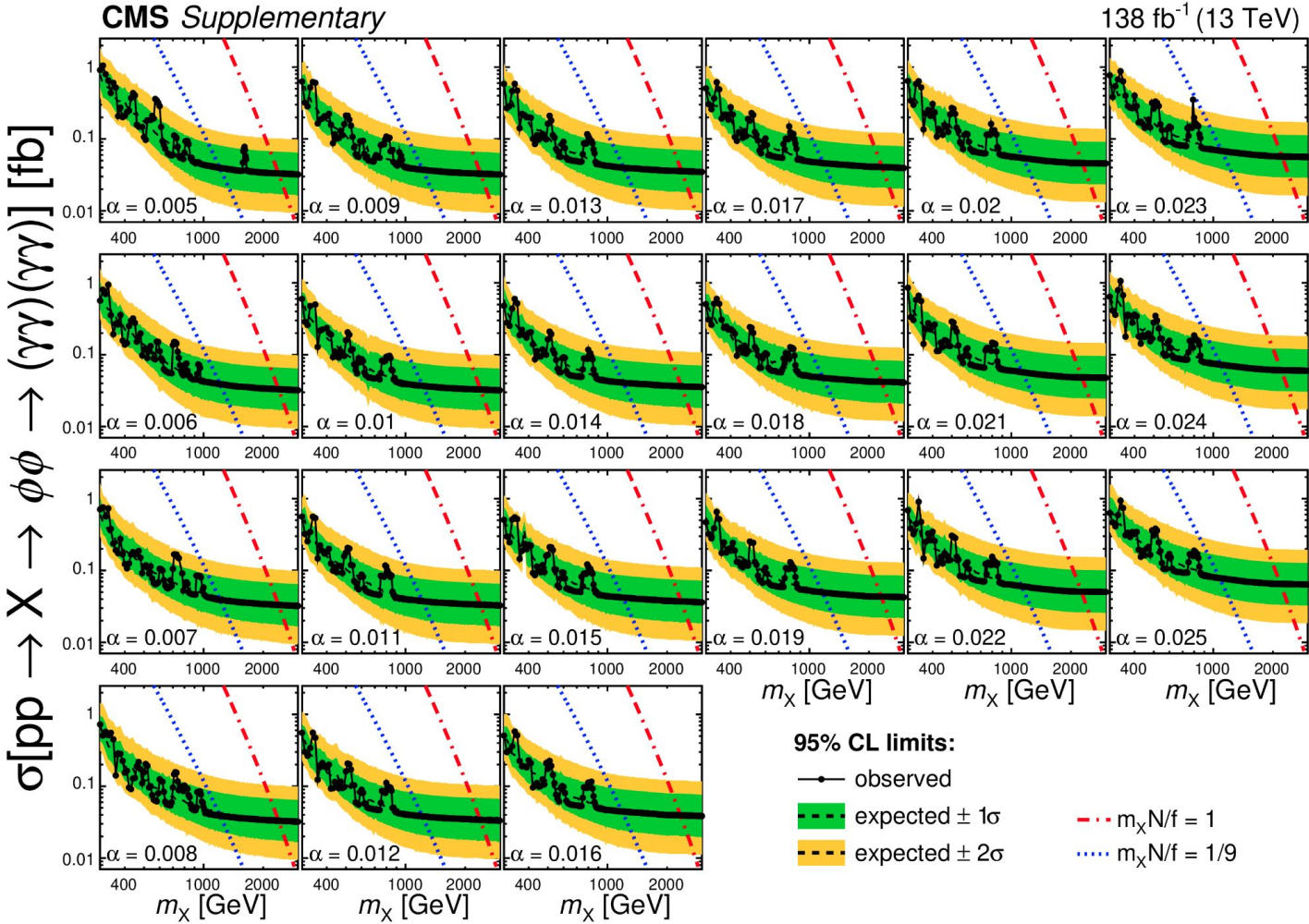


Mass Asym. = $|M_{\Gamma 1}-M_{\Gamma 2}| / (M_{\Gamma 1}+M_{\Gamma 2})$
$|\Delta\eta| = |\eta_{\Gamma 1} - \eta_{\Gamma 2}|$
$P_{\gamma\gamma}$ = Classifier Diphoton Score

Isolation = $E_{\Gamma}/E_{(\text{Nearest AK4 Jet})}$
Iso = 1 when no other activity present

Results

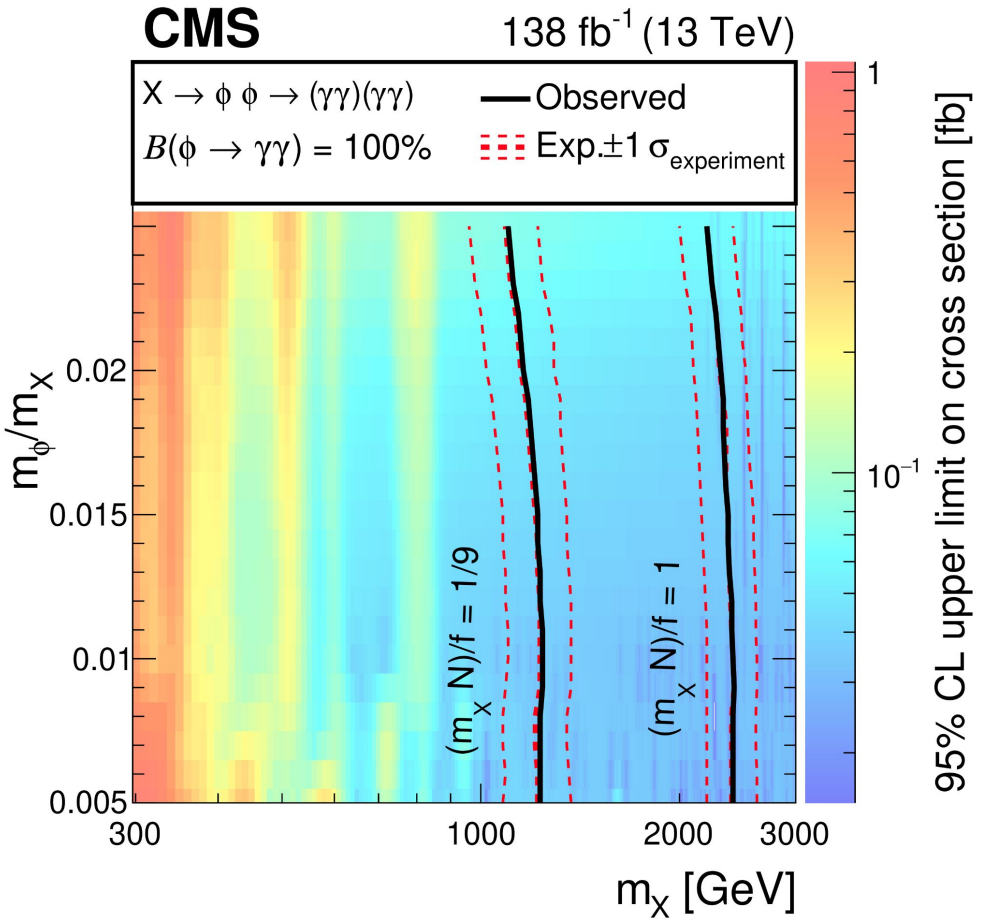
- 95% CL limits on production cross section
- Calculated in slices of α, as a function of m_X
- Limits range between 0.03-1.6 fb
- Cross section depends on model parameters $m_X N/f$



Results

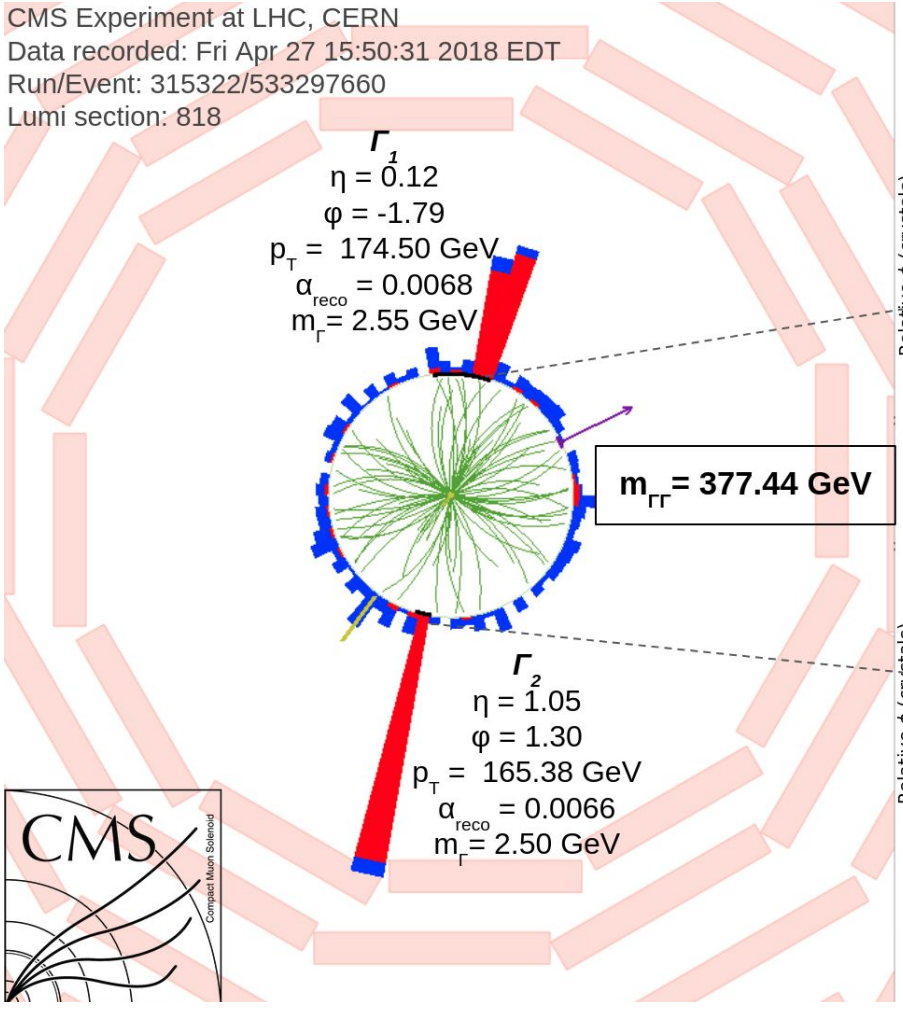
- Strongest limits on this process at the LHC!
  - Limits range between 0.03-1.6 fb for X masses between 0.3-3 TeV and α between 0.5%-2.5%

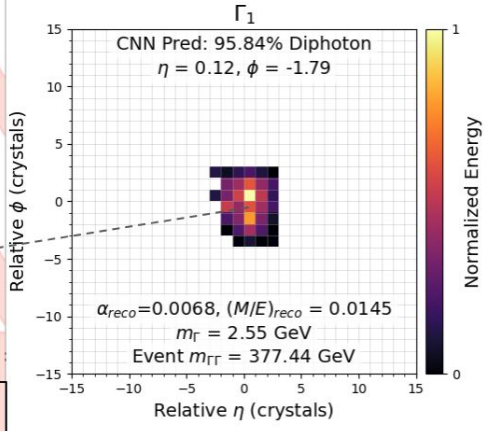
- Results: https://cms-results.web.cern.ch/cms-results/public-results/publications/EXO-22-022/

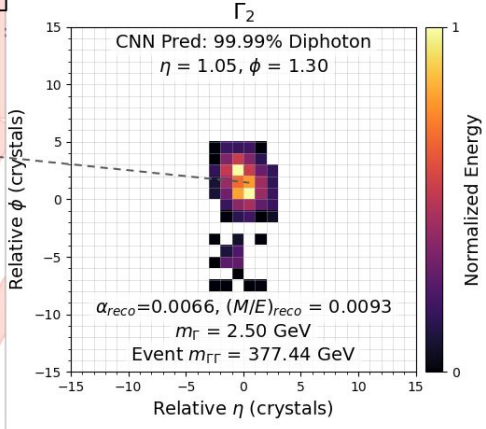


Event Display

Event display from data diphoton event!





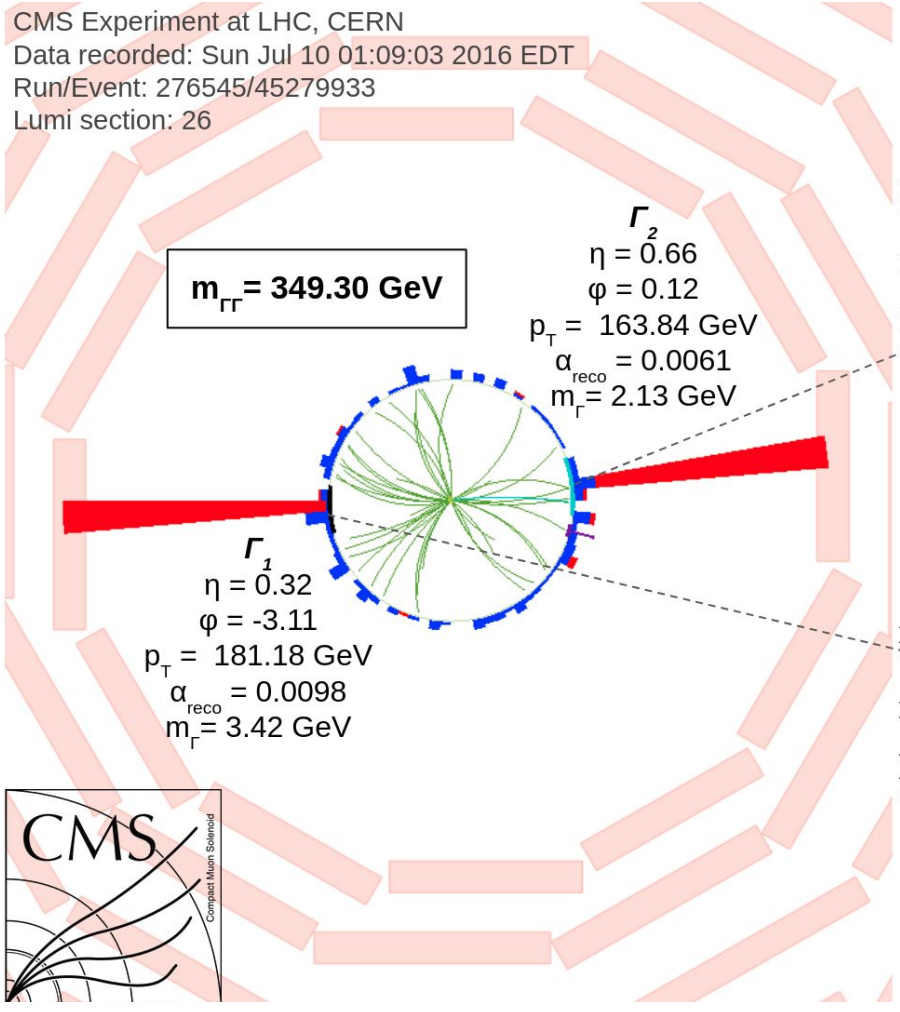


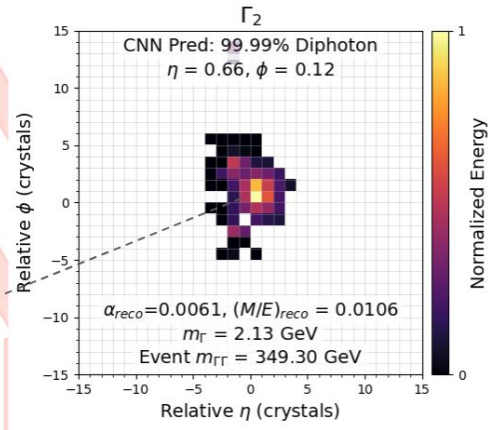
Conclusion

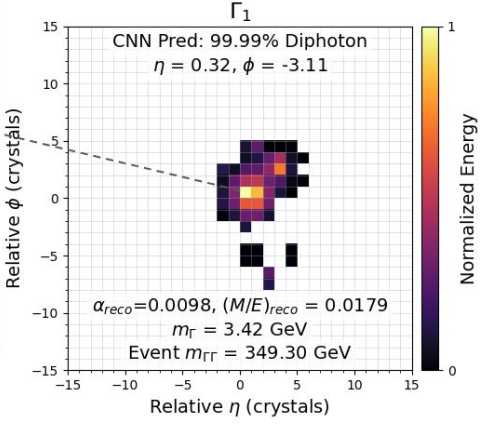
- **Search for X → $\phi\phi$ → (γγ) (γγ) with boosted diphotons**
  - Diphoton Clusters containing two merged photons are formed from ECAL energy deposits
  - Classification Neural Network is used to identify diphoton clusters from background events
  - Regression NN predicts the mass of the diphoton clusters, M_{Γ}
  - The final search is conducted as a bump hunt in Di-Cluster Mass, $M_{\Gamma\Gamma}$
- Extended Higgs sector limits at 95% CL set on cross section times BR vs. mass of **X** and ratio $\boldsymbol{\alpha = M_{\varphi}/M_X}$
  - Limits range between 0.03-1.6 fb for X masses between 0.3-3 TeV and α between 0.5%-2.5%
- Results: https://cms-results.web.cern.ch/cms-results/public-results/publications/EXO-22-022/

Backup

Event Display

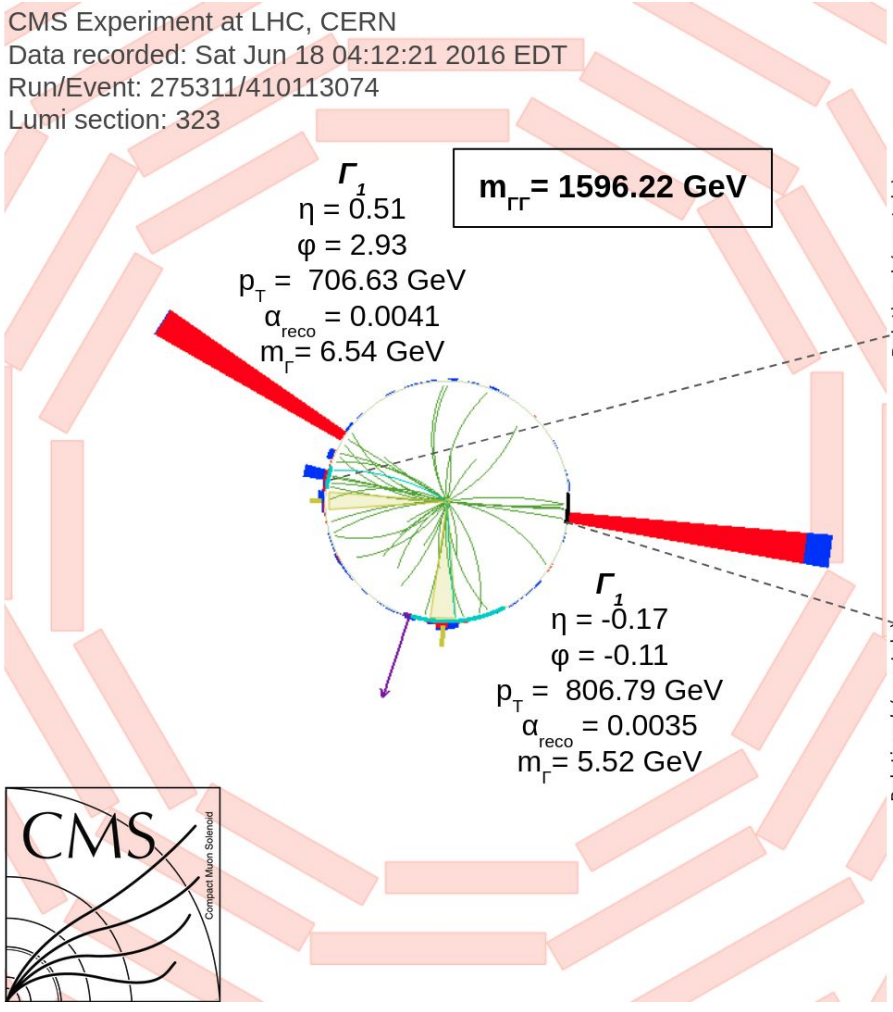


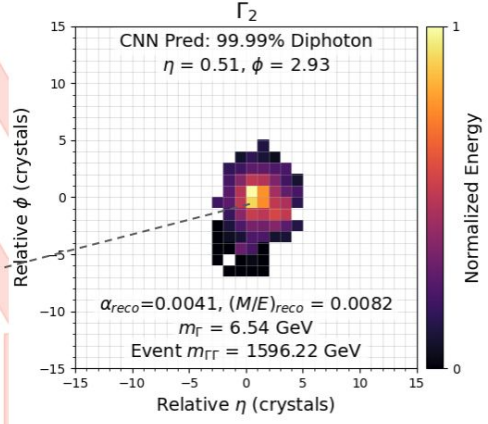


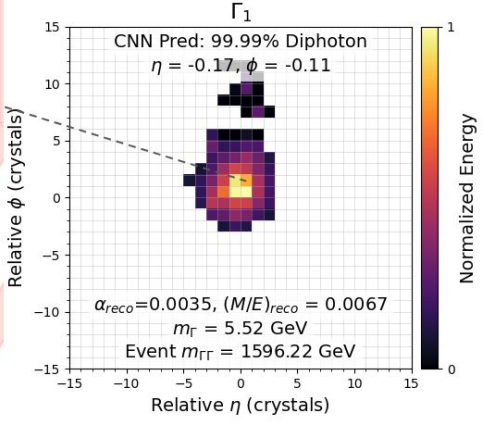


Event Display

Highest $M_{\gamma\gamma}$ event

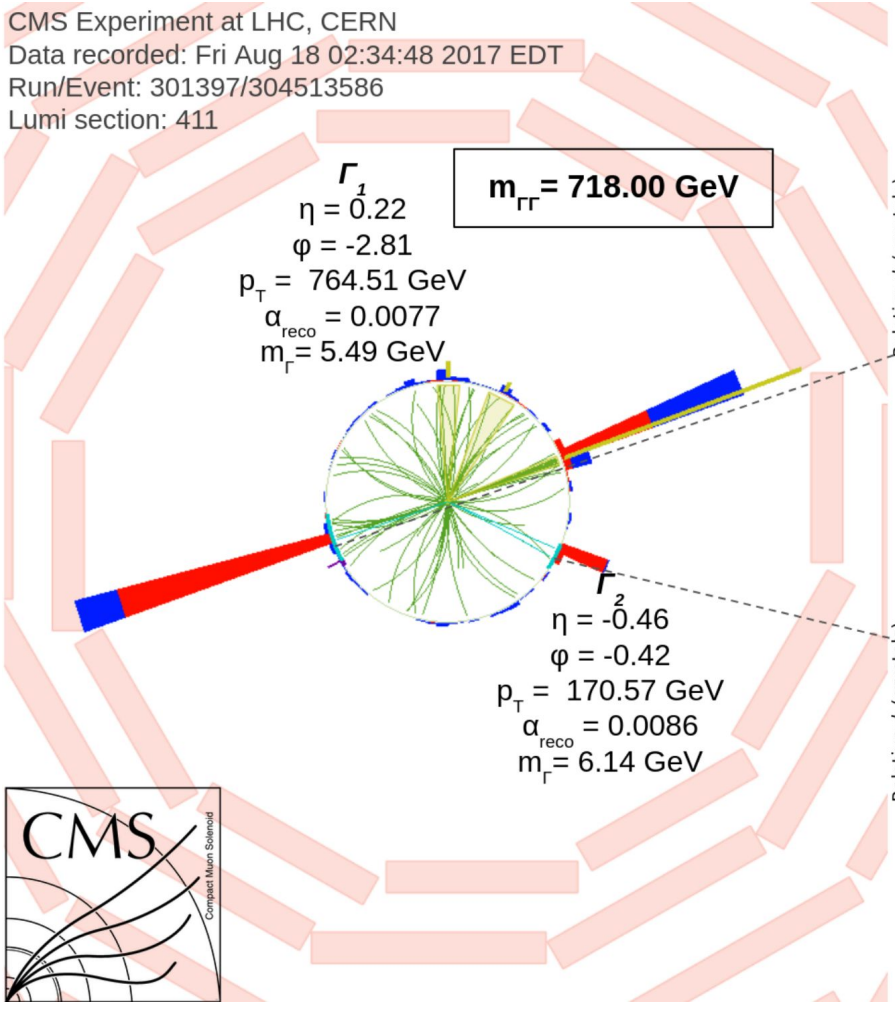


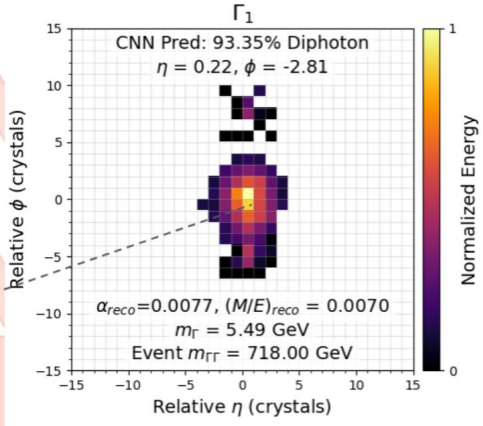


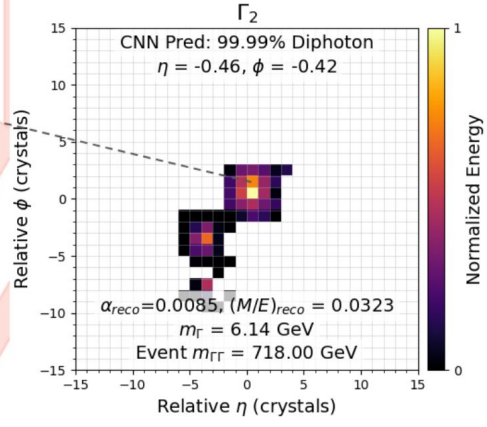


Event Display

Event near largest significance







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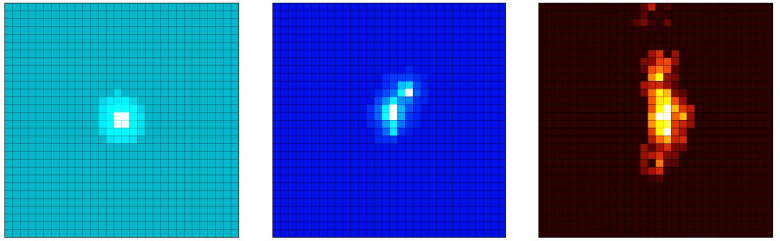
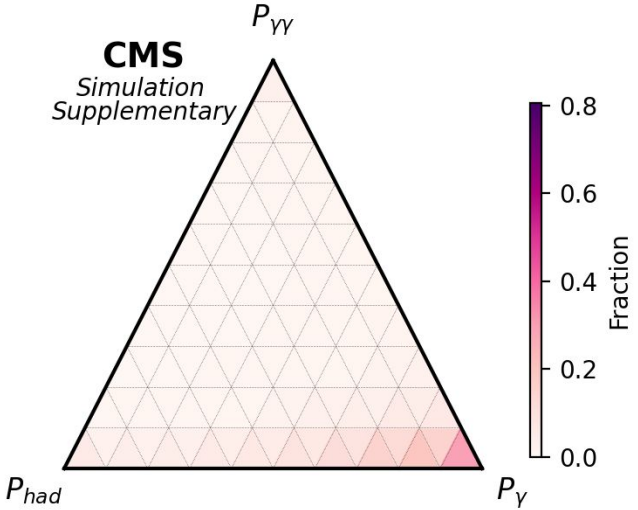
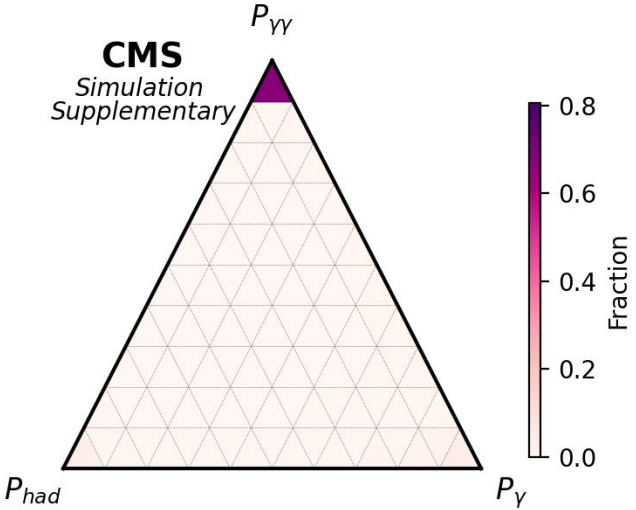


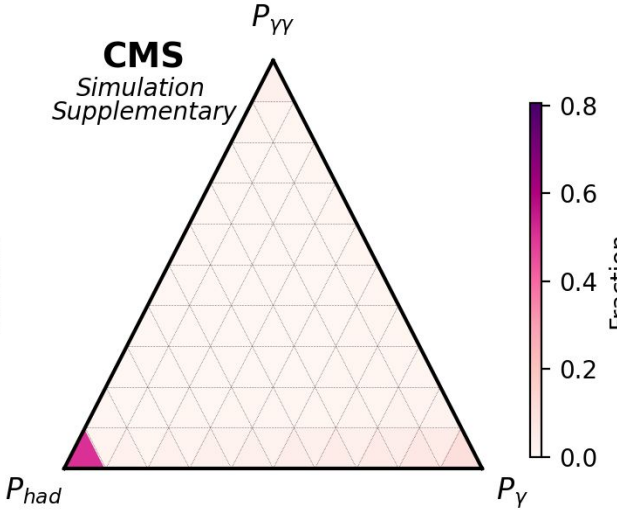
Classifier score of true monophotons



Classifier score of true diphotons



Classifier score of true hadrons



Signal Systematic Uncertainties

Nuisances (Normalization):

- Luminosity
  - Run 2 combined, 1.6%
- Trigger
  - 5%
- Classification efficiency
  - From η reconstruction: 10%
  - Applied to each cluster, total = 21%
- α^{reco} Shape
  - 23%

↓

All sampled from Log-normal priors

Nuisances (Shape):

- Energy Scale per Cluster
  - From Z-peak measurement- 0.5% per cluster
- Pileup Reweighting
  - < 21%, bin by bin

↓

All sampled from Gaussian priors

Background Uncertainties: Only background systematic comes from the fit itself

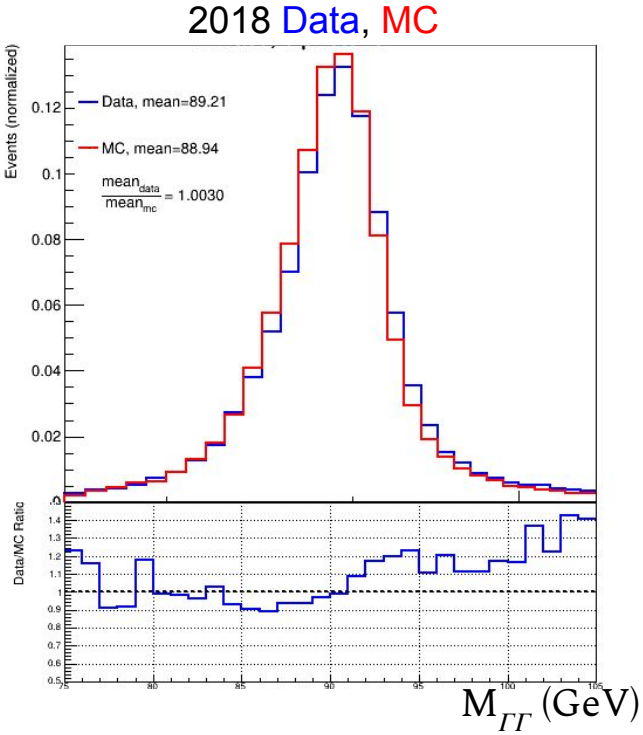
$Z \to e^+e^-$ Reconstruction

Process:

- Reconstruct $Z \to e^+e^-$ peaks after applying Classification NN
- Note: each e forms a Γ candidate
  - $M_{Z,reco} = M_{\Gamma\Gamma}$
- Selection:
  - $P_{\gamma\gamma} > 0.75$, Energy isolation > 0.8

Motivation:

- e/γ leave similar signatures in ECAL
  - No electron veto is used
- Useful to further validate ML
- Extract Data/MC systematic



0.5% Energy scale (per Γ) systematic is adopted to account for difference

Significance Test

- Local Significance plot shown on right
- Largest Excesses:
  - **M_X=720 GeV, α_{true}= 0.007**
    - **3.57σ local/ 1.07σ global**
  - M_X=590 GeV, α_{true}= 0.005
    - 2.99σ local/ 0.62σ global
- Global significance accounts for Look Elsewhere Effect