Nevis Laboratories Summer REU Program
Columbia University

Search for Displaced Diphoton Resonances

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NEVIS LABORATORIES
COLUMBIA UNIVERSITY

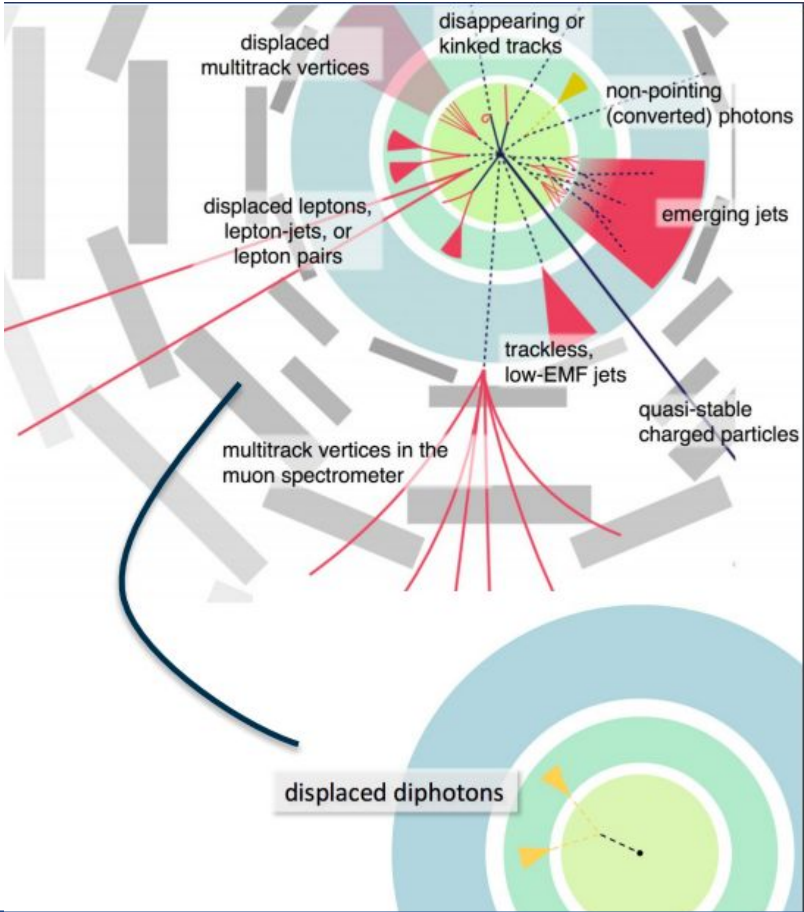
NSF

ATLAS EXPERIMENT

CERN

Outline

- ➢ Introduction
  - ○ The Standard Model, the Higgs Boson, and Supersymmetry
  - ○ The Large Hadron Collider and the ATLAS experiment
- ➢ Search for Displaced Diphoton Resonances
  - ○ Displaced diphoton resonances
  - ○ Trackless calo-vertexing method
- ➢ Data and Monte Carlo Simulations
- ➢ Preselections and Cuts
- ➢ Search strategy and analysis
  - ○ Timing and Vertexing by Photon Identification
  - ○ Validation Region Signal Contamination Study
- ➢ Conclusions



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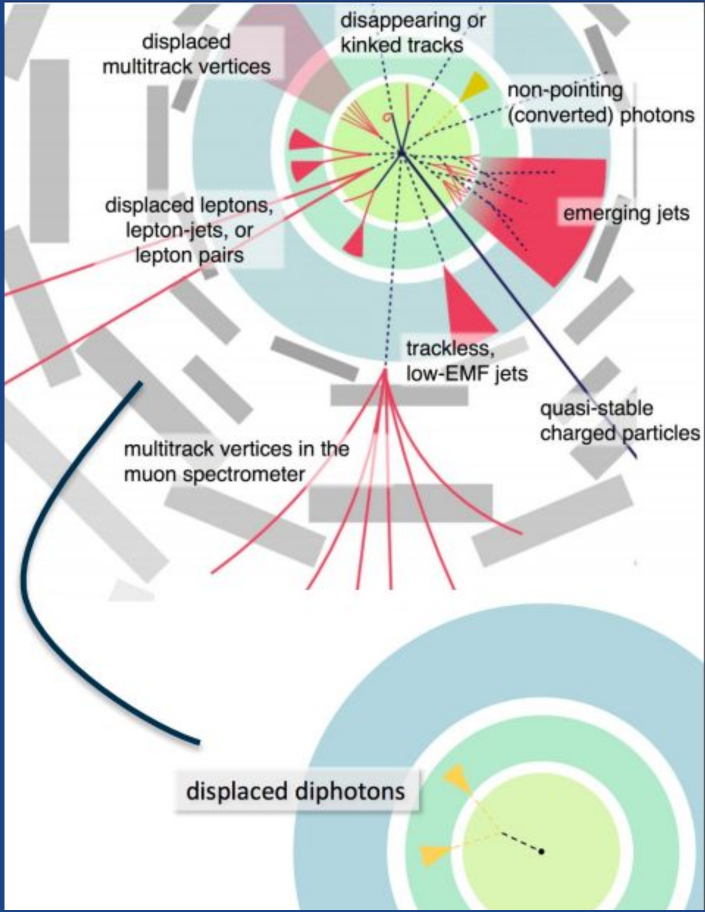


The Standard Model of Particle Physics

- Quantum Field Theory (QFT) that describes three of the four known fundamental forces in the universe and classifies all known elementary particles.
- Elementary particles are broken down into three basic groups: fermions, gauge bosons, and the Higgs.
- Fermions: Half integral spin particles that bind together to form matter.
- Gauge Bosons: Force carriers that mediate the interactions between the fermions.

Gauge boson		Spin	Charge	Mass	Force
photon	γ	1	0	0	electromagnetic
W-boson	$W^{\pm}$	1	± 1	80.4 GeV	weak
Z-boson	Z^0	1	0	91.2 GeV	weak
gluons	g	1	0	0	strong
graviton	G	2	0	0	gravitation

Figure 2: Nathal Severijns, KU Leuven

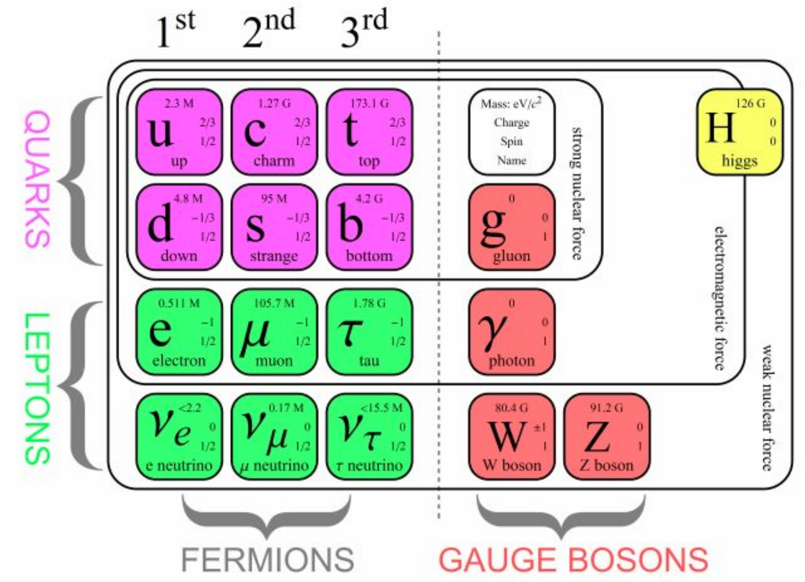


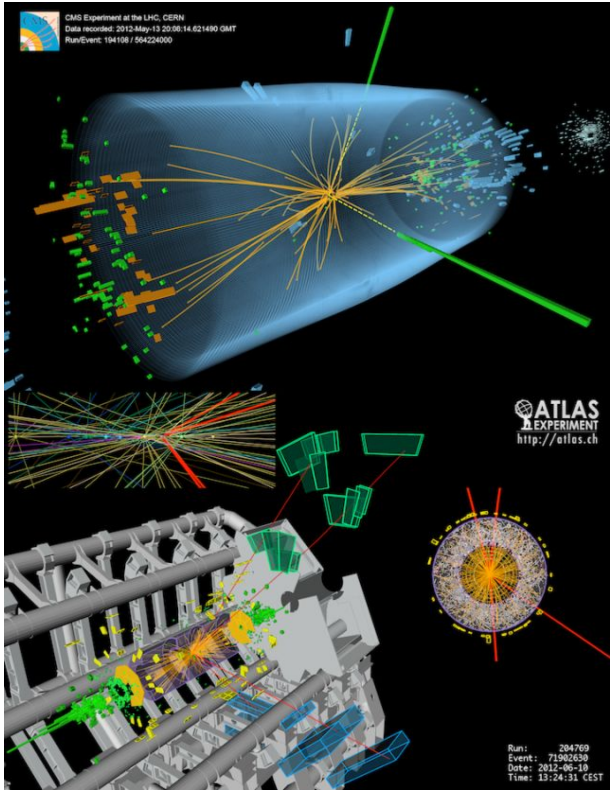
Figure 1: Matic Lubej, University of Ljubljana

The Higgs Boson

➢ The Higgs boson is not a gauge boson but instead mediates particles' interaction with the Higgs Field, which is responsible for giving other particles the ability to gain mass.

➢ Brout-Englert-Higgs mechanism, predicted in 1964. Discovered in 2012 by CERN in the mass region around 125 GeV. Nobel Prize awarded in 2013 to Englert and Higgs.

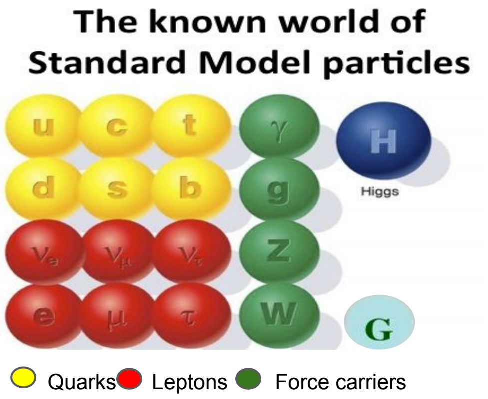
➢ Other types of Higgs bosons are predicted by other theories that go beyond the Standard Model.

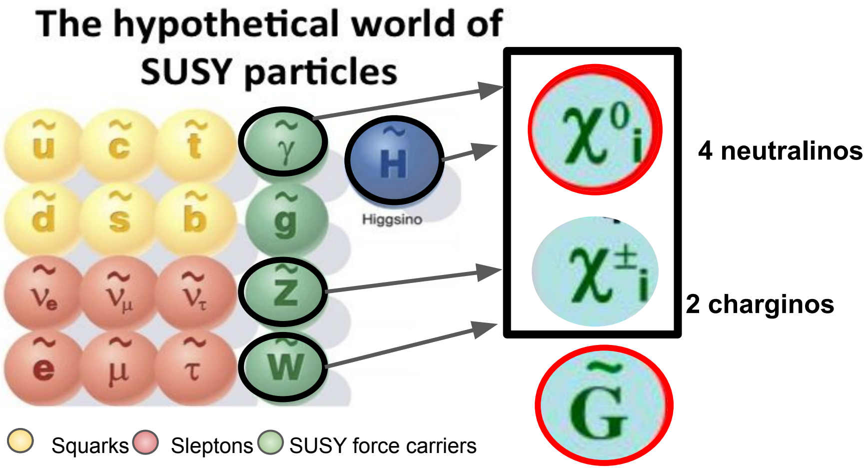


Candidate Higgs boson events from collisions between protons in the LHC. The top event in the CMS experiment shows a decay into two photons (dashed yellow lines and green towers). The lower event in the ATLAS experiment shows a decay into four muons (red tracks) (Image: CMS/ATLAS/CERN)

Supersymmetry (SUSY)

- SM does not explain gravity, dark matter, the observed physical Higgs mass, and many other key phenomena -> need for Beyond Standard Model physics.
- SUSY introduces the existence of partner sparticles for every particle in the SM that differs by spin ½.
- "Higgsino" is the superpartner of the Higgs boson.
- These sparticle partners should exist at the TeV scale and thus can be accessible at the LHC.





The Large Hadron Collider (LHC)

- World's largest and most powerful particle accelerator.
- Ring of superconducting magnets with accelerating structures that boost particles energies.
- Particles travel to nearly the speed of light.
- Collision rates of 40 MHz and energy scales of 13 TeV.
- Proton-proton and heavy-ion collisions recreate the conditions immediately following the Big Bang.

Figure: LHC at CERN, Geneva

The ATLAS (A Toroidal LHC ApparatuS) Experiment

- The ATLAS detector consists of an inner tracking detector surrounded by a thin superconducting solenoid providing a 2 tesla axial magnetic field, electromagnetic and hadronic calorimeters, and a muon spectrometer.

- Lead/Liquid-Argon (LAr) sampling calorimeters provide electromagnetic (EM) energy measurements with high granularity.

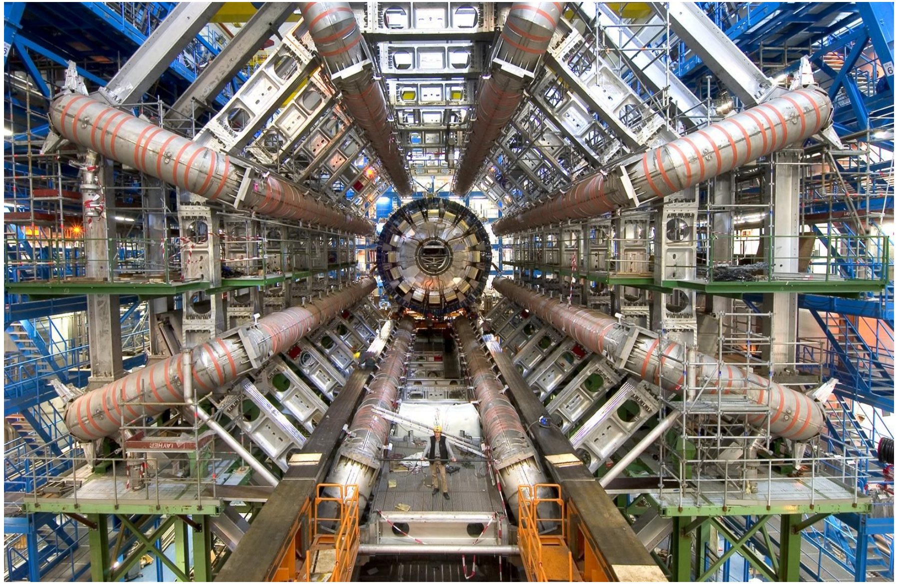


Figure: ATLAS detector, Credit: CERN

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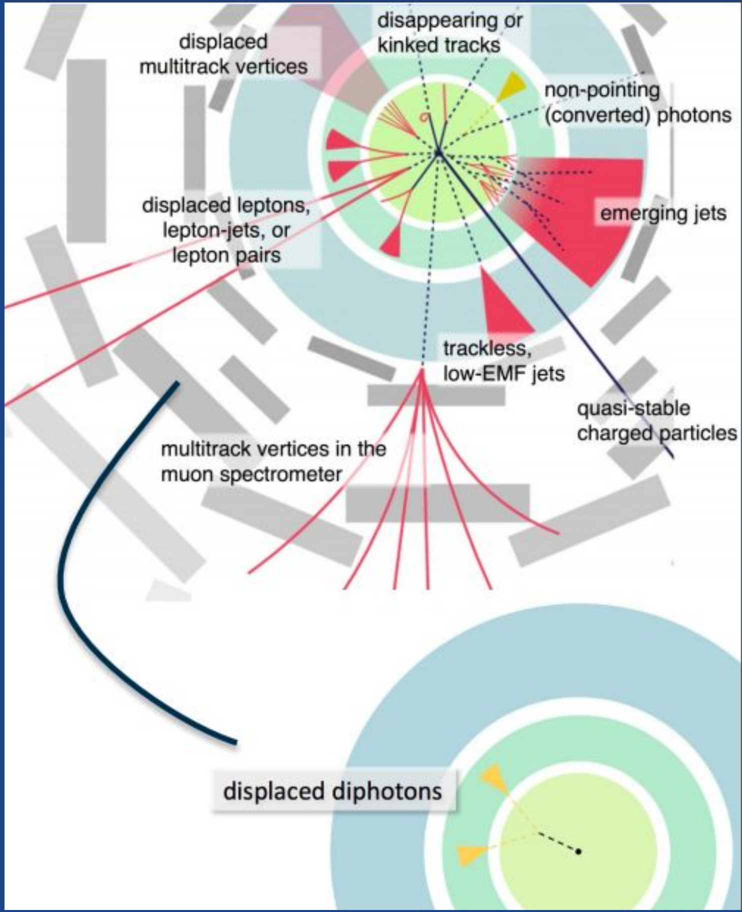


Displaced Diphoton Resonances

- Search for displaced diphoton resonances originating from the decay of a Long-Lived Particle (LLP).
- The signal is produced through pair production of long-lived higgsinos -> decay into a SM Higgs boson -> decays into two photons.
- Highly displaced electrons are reconstructed as photons -> can include di-electron vertex signal from a Z boson.
- Combined detector information of the two photons (or electrons) can determine their production vertex, revealing the lifetime of the parent higgsino.

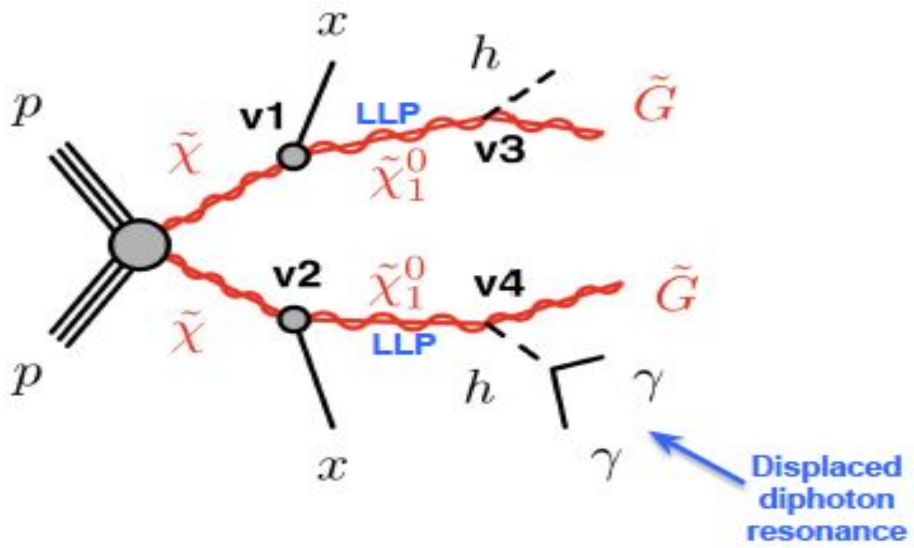
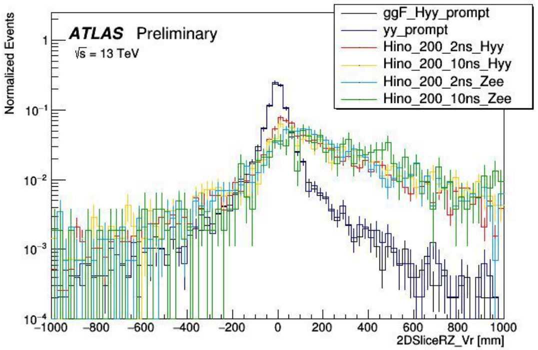


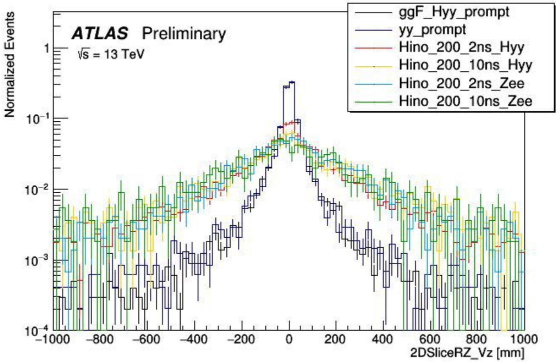
Figure: A Feynman diagram of the signal studied in this analysis, direct pair production of neutralinos decaying to a final state of two SM Higgs bosons and two gravitinos.

- Requiring a track creates a loss in efficiency as a function of displacement.
- Calo-vertexing finds the displaced vertices using only LAr calorimeter pointing and timing information to determine the vertex displacement.
- Project all photon measurements onto the R-Z plane (slice phi=0). Draw a line through the photon shower barycenters in the front and middle layers of the LAr calorimeter. Find the point of intersection: the vertex position.

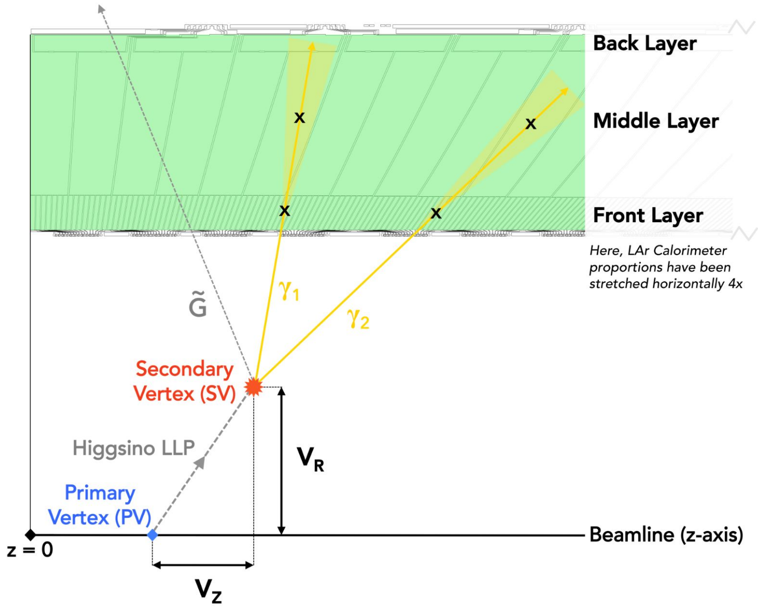
Vertex in R Direction



Vertex in Z Direction



LAr Vertexing



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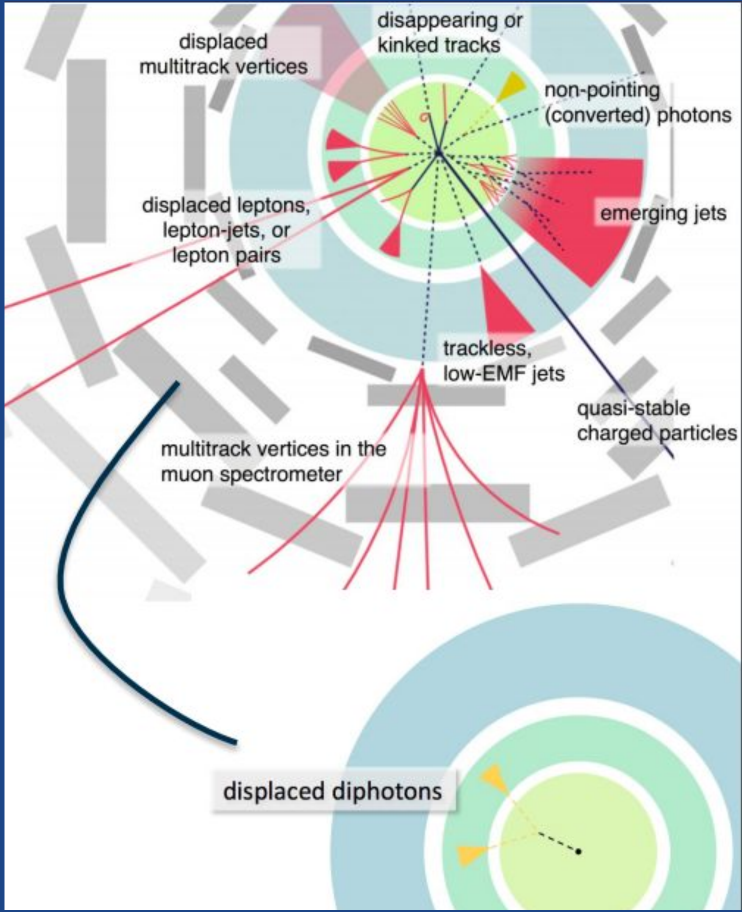

➢ In this study we used background data in conjunction with Higgs decay signals.

➢ In order to focus on the decays that can be detected by trackless calo-vertexing, generated events are filtered such that only Hyy and Zee final states are included.

➢ Signal files are MC Simulations of final states HyyHSM and ZeeZSM with 2ns and 10ns lifetime and 100 GeV to 800 GeV mass.

Final State / Higgsino Mass [GeV]	100	150	200	300	400	500	600	800	1000
HyyHSM		✓	✓	✓	✓	✓	✓		
HyyZSM		✓	✓	✓	✓	✓	✓		
ZeeHSM		✓	✓	✓	✓	✓	✓	✓	✓
ZeeZSM	✓	✓	✓	✓	✓	✓	✓	✓	✓

Generate each point with higgsino lifetimes of:
2 ns
10 ns

Figure: Analysis signal grid, broken down by higgsino mass and lifetime, and final state. 2ns and 10ns are the benchmark lifetimes for the ongoing NPP analysis (glance). We can use a lifetime reweighting procedure to extrapolate intermediate lifetimes.

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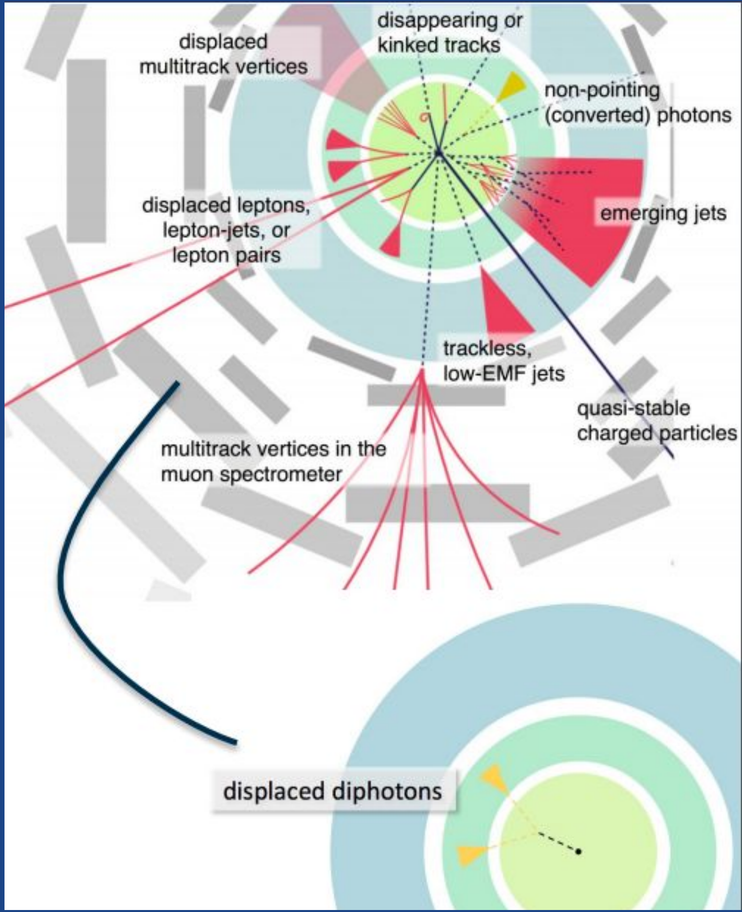
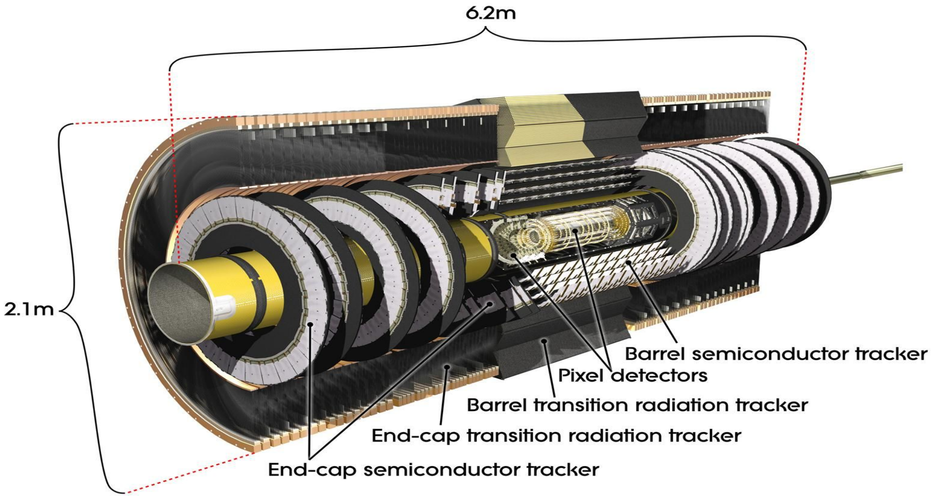


Preselections and Cuts

- Photon objects in the analysis are subject to a basic preselection. At least two photons are required in the event.

- Basic Cuts
  - abs(ph1_t) < 12 && abs(ph2_t) < 12
  - abs(dEta_ph) > 0.1
  - Hcand_M > 60 && Hcand_M < 160
  - abs(2DSliceRZ_Vr) < 1050 && abs(2DSliceRZ_Vz) < 3000
- Trigger
  - Given that the final state of the long-lived higgsino decay contains both two photons and missing energy from the gravitino, both diphoton and MET triggers were studied for maximal signal efficiency.
- Detector Region
  - Events that pass BB detector region selection have both photons in the barrel.
  - Events that pass BE selection can be either: leading photon in barrel and subleading photon in endcap or vice versa.

Atlas Inner Detector



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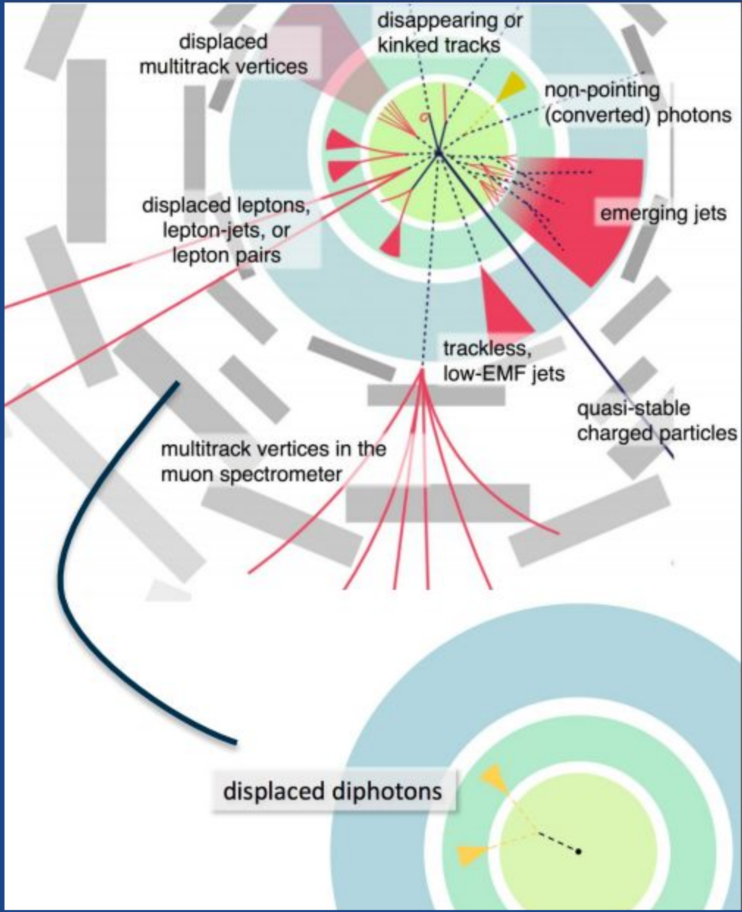
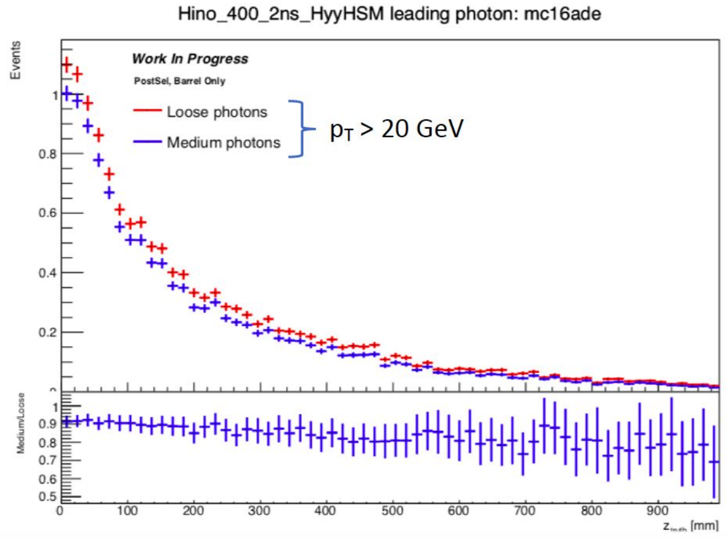


Timing and Vertexing by Photon Identification - Intro

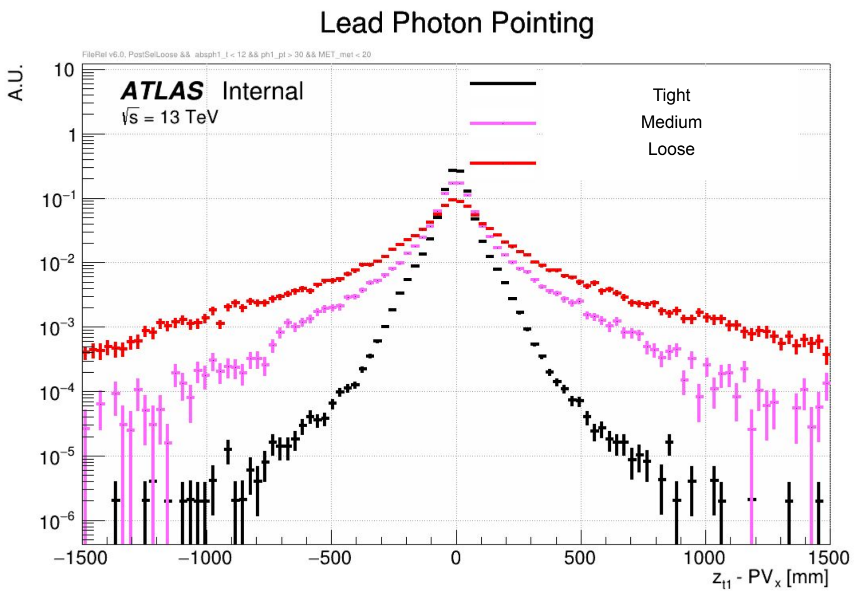
- Photons that pass Tight ID are almost certainly photons, however reconstruction efficiency for real photons is lower than for other working points, therefore you do not get all of the real photons. Loose ID lets jets pass as photons. Medium ID is intermediate.
- The nature of non-pointing photons motivates careful choice of identification working point. Tight ID imposes cuts on the shower shape variables, introduce an undesired bias against non-pointing photons.
- The use of Medium ID allows the analysis to take advantage of the lower trigger pT thresholds.

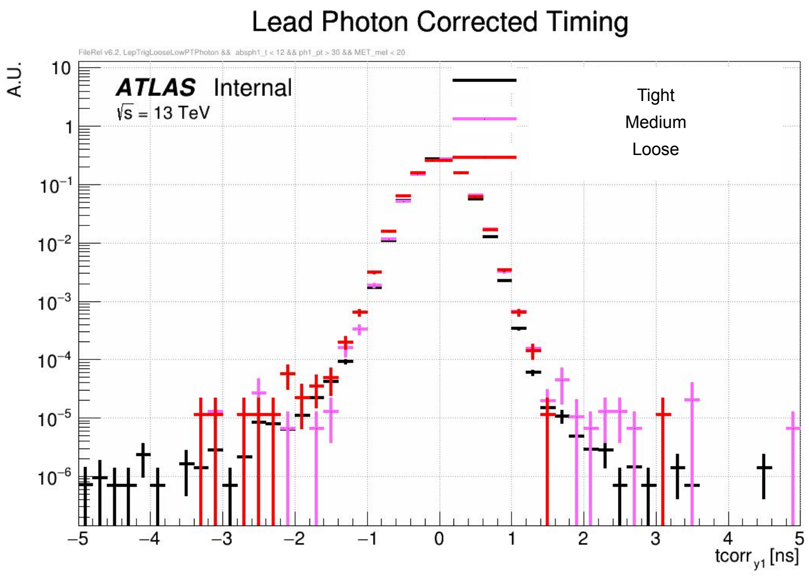


Figures: Ratio of Loose and Medium selected photons as a function of pointing.

Timing and Vertexing by Photon Identification - Real vs Fake Photons

- Real photons that are prompt in the data have much narrower pointing, timing and vertexing distributions. A jet that is identified as a photon will get a wider distribution.
- We define and compare real-enhanced and fake-enhanced samples to understand what shape systematic we should apply.



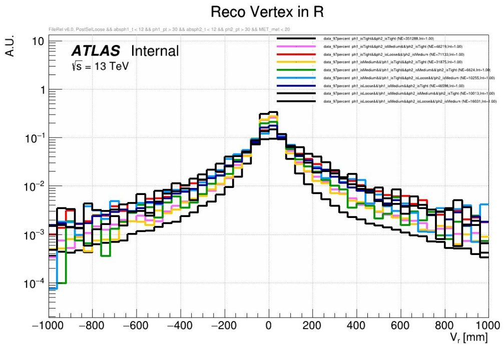


Timing and Vertexing by Photon Identification - Vertexing

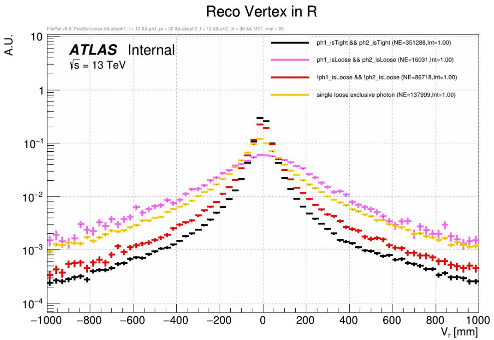
- For vertexing variables, start with brute force plotting of 9 orthogonal combinations of vertexing that encapsulate Loose, Medium, and Tight. Reweighted CR distributions to the VR MaxEcell E energy distribution.

Vertexing Combinations

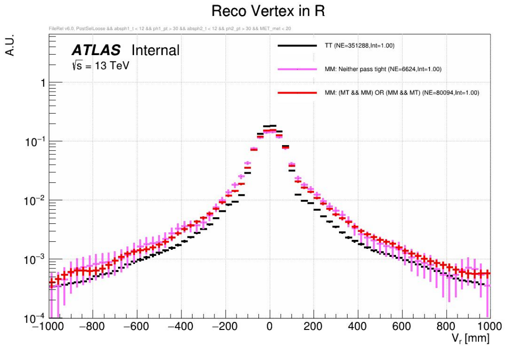
		Photon 1		
		T	M && !T	L && !M
Photon 2	T	T T	M&&!T T	L&&!M T
	M && !T	T M&&!T	M&&!T M&&!T	L&&!M M&&!T
	L && !M	T L&&!M	M&&!T L&&!M	L&&!M L&&!M



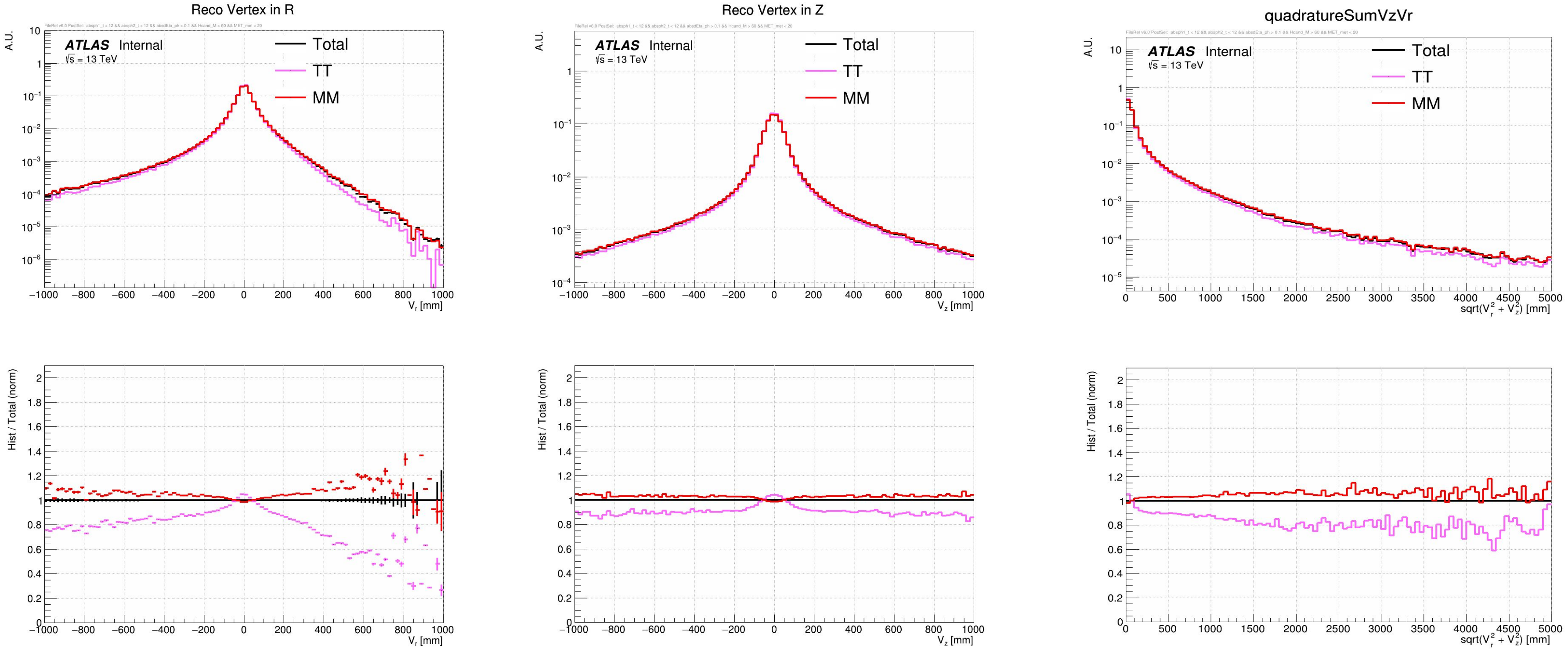
- Group 9 combinations into TightTight, LooseLoose, not LooseLoose and Single Loose Exclusive Photon that has exactly one loose photon.



- Group TT, MM (neither pass tight), MM (one pass tight).

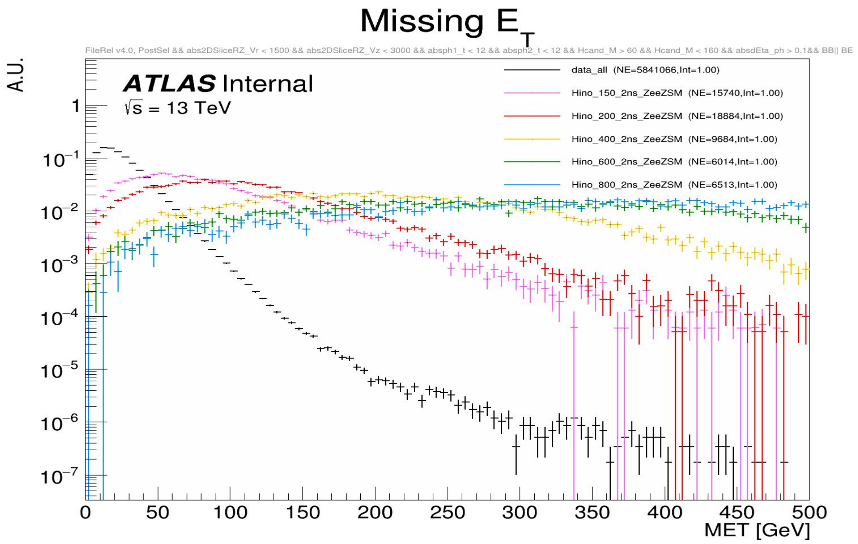


➢ Decided to drop categories with Loose and only use Medium tree selection. Compare TT, MM (neither pass tight and one is medium not tight and one is tight), and Total (sum).. Reweighted CR distributions to the SR MaxEcell_E energy distribution.

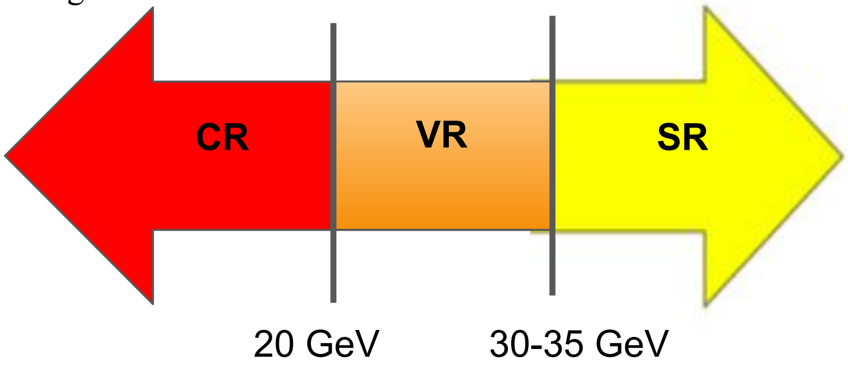


Validation Region Signal Contamination Study - Introduction

We choose our different analysis regions via MET (Missing Transverse Energy) since the MET in background data is much softer than MET in our signal Monte Carlo simulation.



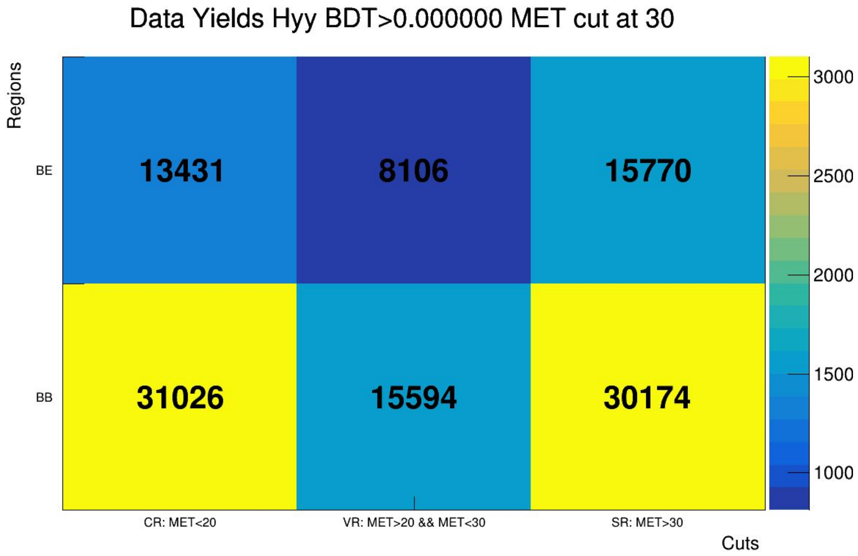
- Control Region (CR), has low MET which produces a background-enriched region with negligible signal contamination.
- Signal Region (SR), has higher MET which produces a signal-enriched region that drives the signal extraction but adds negligible constraints on the background parameters.
- This study aims to optimize the MET lower and upper cuts on the Validation Region (VR) to produce an intermediate MET region with enough events to give a good background estimation and has low signal contamination.



Validation Region Signal Contamination Study - Signal Contamination Percentage

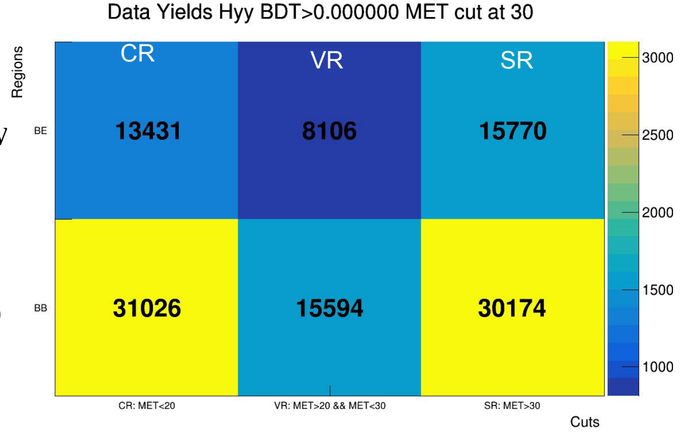
- ➢ We calculate event yields (total number of events that we expect to get after some set of selections) and compare how many events we get in BB vs BE region.

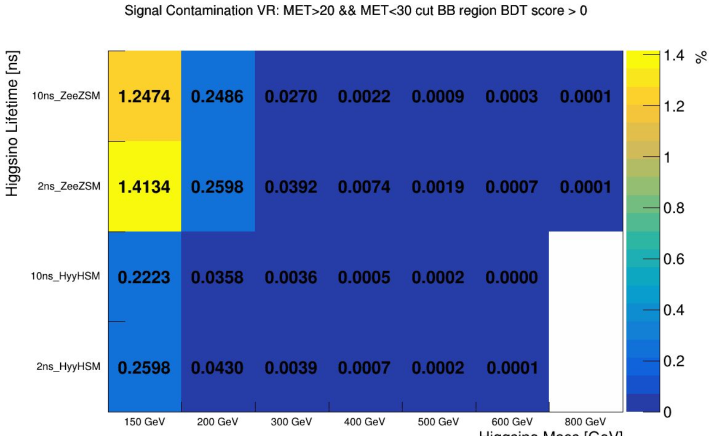
$$Signal\ Contamination\ Percentage = 100 * \frac{Signal\ Event\ Yields}{Data\ Event\ Yields}$$



Validation Region Signal Contamination Study - MET cut

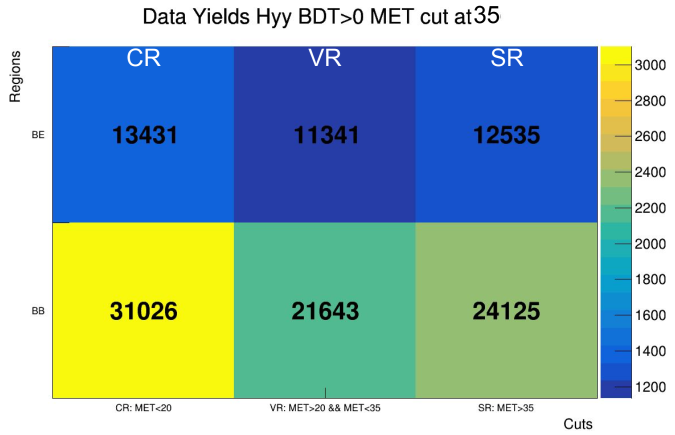
Narrow range VR (MET 20-30)

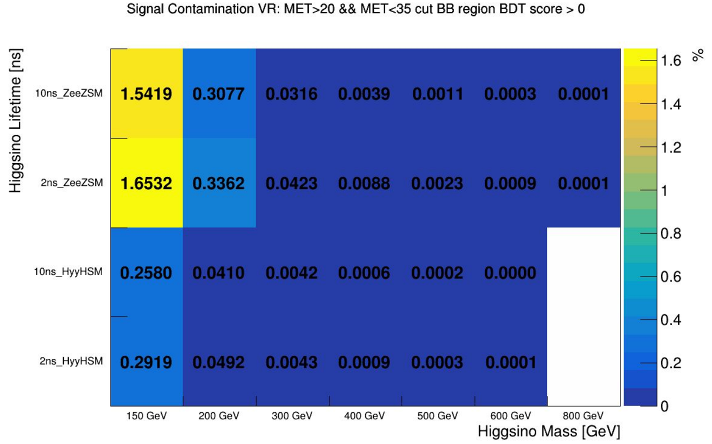




vs

Wide range VR (MET 20-35)

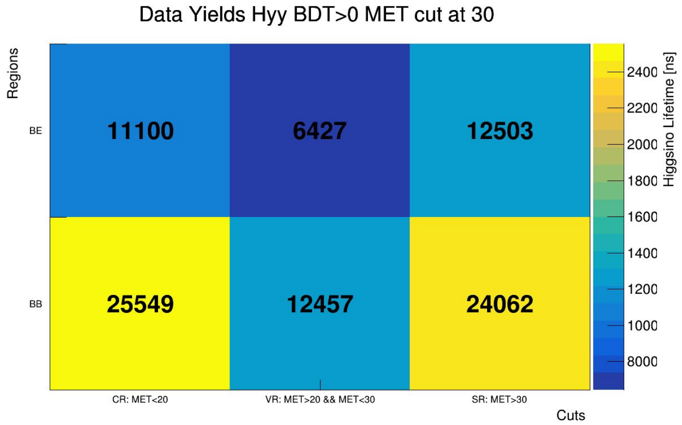


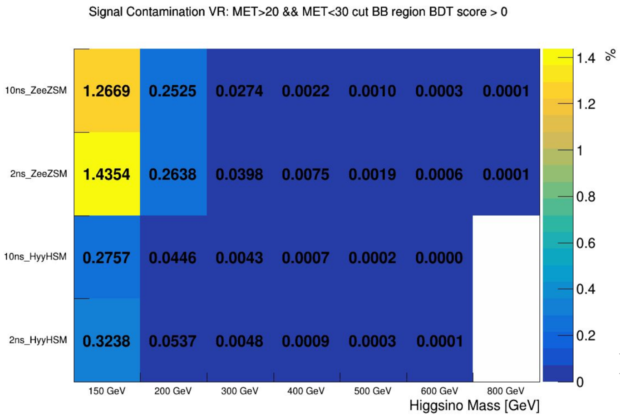


- ➢ A 35 GeV cut provides similar levels of background statistics (data yields) between the VR and SR.
- ➢ A 30 GeV cut has lower signal contamination than a 35 GeV cut.
- ➢ Therefore, 30 GeV MET cut is the optimized boundary between VR and SR.

Validation Region Signal Contamination Study - Myy Cut

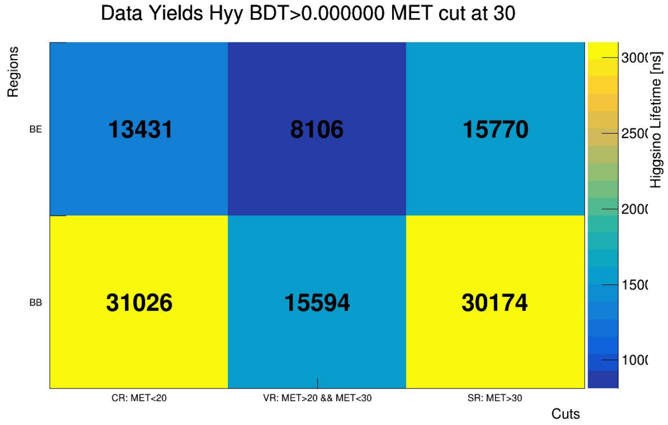
Both Myy cuts

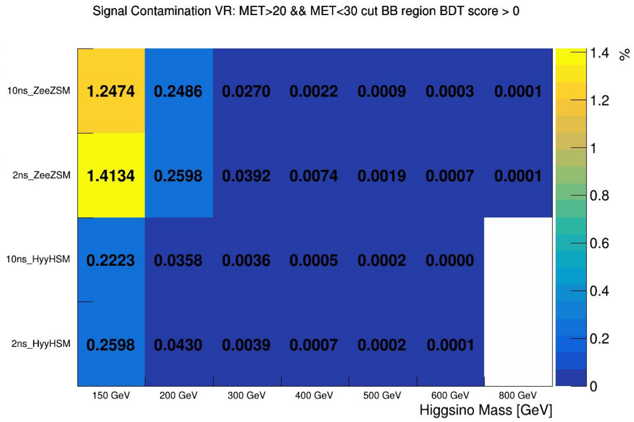




vs

Dropping upper Myy cut

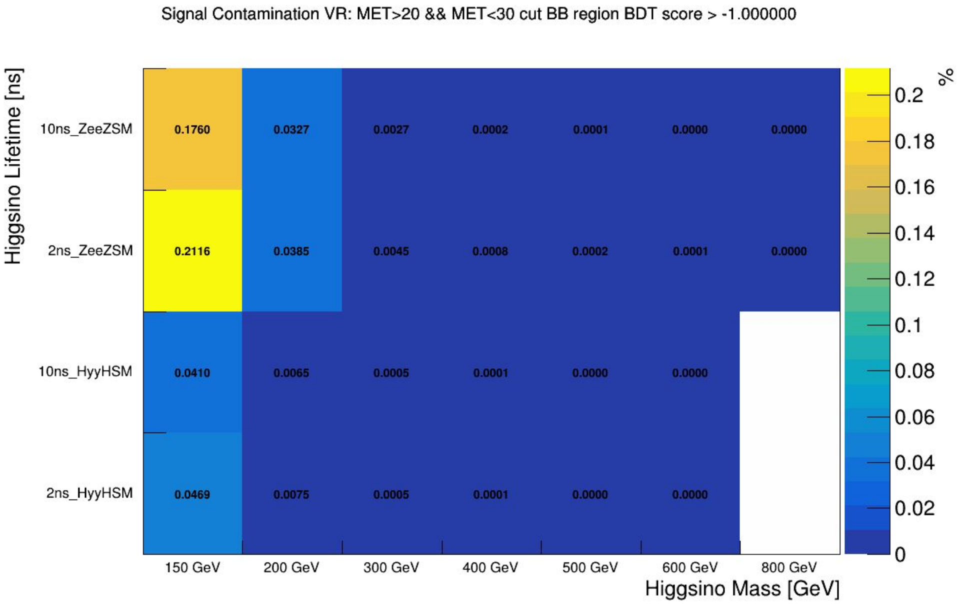


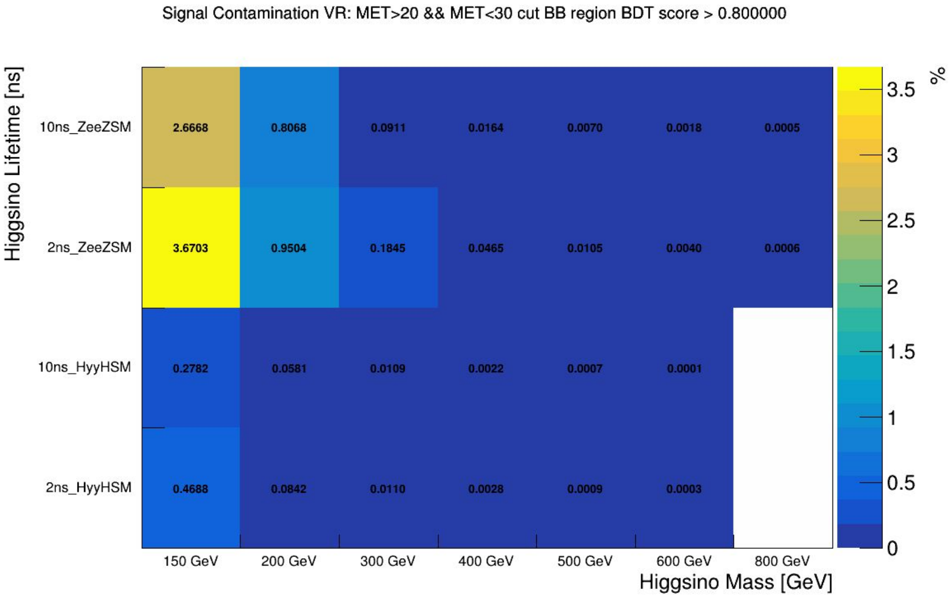


- ➢ Higgs Candidate Mass (Myy) cuts: HCand_M > 60 GeV && HCand_M < 160 GeV
- ➢ This plots study the effects of dropping the upper Myy cut, contributed to the decision to drop it, therefore only cutting at HCand_M > 60 GeV.

Validation Region Signal Contamination Study - BDT score

We want to use a Boosted Decision Tree (BDT) to determine which variables will give us the strongest discrimination between signal and background.





The precise value of BDT score cut has a significant impact on our signal contamination in both the CR and VR.
The higher the BDT score cut, the higher the signal contamination.

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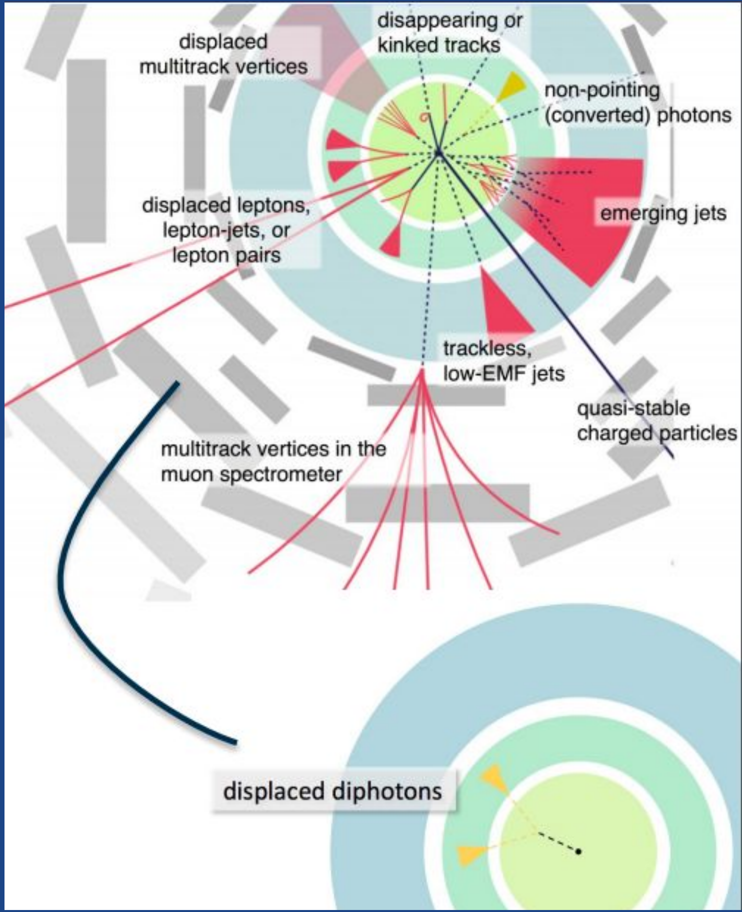

Conclusions and Next Steps

- ➢ We are performing a trackless search for a displaced di-EM resonance. Benchmark model is a long-lived higgsino with a displaced H→yy or Z→ee. Sensitive variables include LAr Timing, and a novel Calo-Vertexing approach.

- ➢ Individualized studies Timing and Vertexing by Photon Identification and Validation Region Signal Contamination helped find optimized cuts.

- ➢ My signal contamination studies continue to inform the analysis strategy. I have made progress on the medium photon ID study, and will pass it along to someone else to be finalized.

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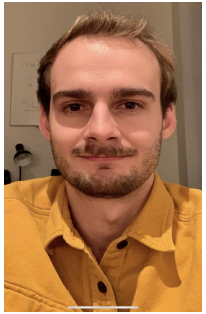

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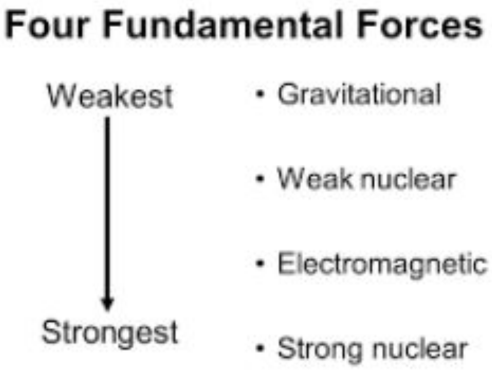
More plots of this analysis can be found here

Backup

The Standard Model of Particle Physics - Gauge Bosons



- ➢ Gauge Bosons
  - force carriers that mediate interactions between the fermions
- ➢ The last force, gravitational force, is theorized to be carried by a Graviton.

Gauge boson		Spin	Charge	Mass	Force
photon	γ	1	0	0	electromagnetic
W-boson	$W^{\pm}$	1	± 1	$80.4\ GeV$	weak
Z-boson	Z^0	1	0	$91.2\ GeV$	weak
gluons	g	1	0	0	strong
graviton	G	2	0	0	gravitation

Figure 2: Nathal Severijns, KU Leuven

- Dark Matter
  - An exact discrete Z2 symmetry of SUSY, called R-parity, gives a stable Lightest Supersymmetric Particle (LSP) which could, if it weakly interacts with the other particles, be a viable Dark Matter Particle.

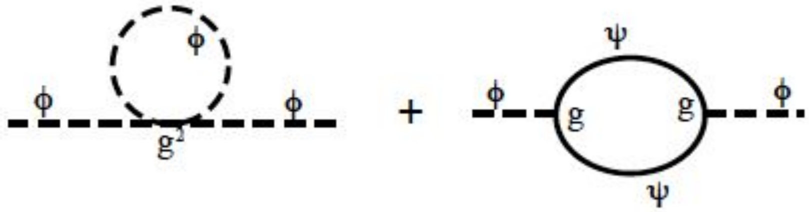


Figure: One loop diagrams which yield a corrections to the scalar mass

- Higgs radiative corrections
  - In the SM, the Higgs mass receives contribution from one-loop radiative corrections. This contribution is proportional to the square of the momentum running in the loop.
  - In SUSY, the loop diagrams, that are quadratically divergent cancel, term by term against the equivalent diagrams involving superpartners.

$$m_h^2 = m_{h,tree}^2 + c\frac{g^2}{4\pi^2}M_{pl}^2, \qquad without\ SUSY$$

$$m_h^2 = m_{h,tree}^2\left(1 + c'\frac{g^2}{4\pi^2}\ln\left(\frac{M_{pl}}{M_W}\right)\right) \qquad with\ SUSY$$

Figure: Observable Higgs mass equations with and without SUSY

Search for Displaced Diphoton Resonances - Purpose

- ➢ Of the many new particles predicted in SUSY, sensitivity and therefore mass exclusions are generally weakest for supersymmetric electroweak bosons (electroweakinos), due to their low production cross sections in proton collisions and decays that are kinematically similar to SM background processes.

- ➢ This search focuses on a specific set of SUSY models with Gauge Mediated Supersymmetry Breaking (GMSB), which have some notable distinctions from the nominal paradigm.
    - ○ Specifically, the \ninoone is unstable and dominantly decays to an electroweak boson and a gravitino \gravino lightest supersymmetric particle (LSP), which similarly can only be measured as MET (Missing Transverse Energy/momentum).

- ➢ The search is performed on the full Run 2 ATLAS dataset, corresponding to 139fb-1 of pp collisions with a center-of-mass energy of sqrt s= 13 TeV.

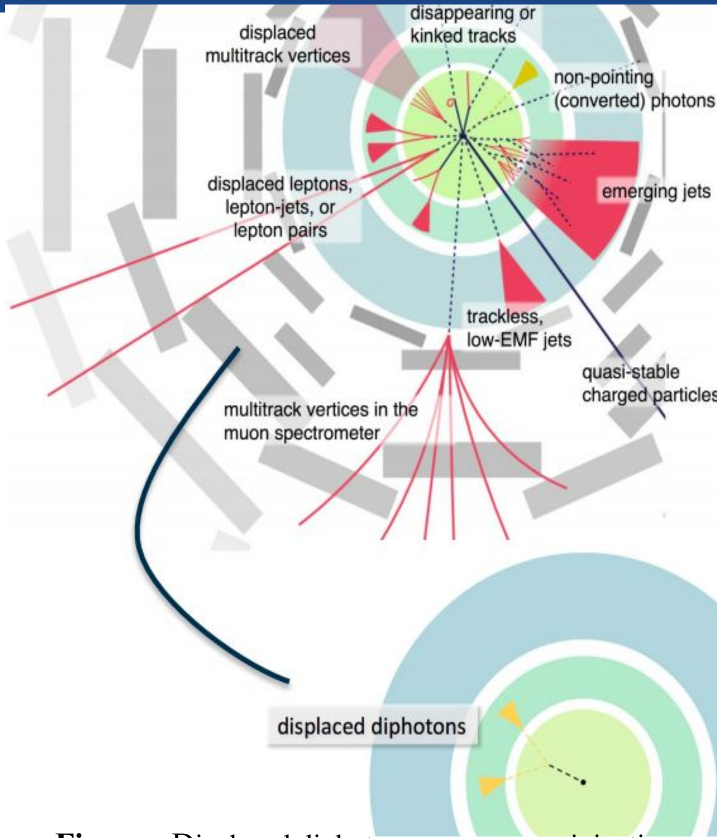


Figure: Displaced diphoton resonances originating from the decay of a long-lived particle.